

A thesis submitted to the Department of Physics, Chemistry, and Pharmacy (FKF) at the University of Southern Denmark (SDU) in partial fulfillment of the requirements for the degree of

Master of Science in Physics

“Light-Shining through a Cosmic Wall”

Searches for spectral upturns due to photon to axion-like particle (ALP) conversions using H.E.S.S. and *Fermi*-LAT observations

Dominik Pastuszka Malek

Supervised by: Manuel Meyer
Atreya Acharyya

In collaboration with the Axion ALP DM Group at the Centre for Cosmology and Particle Physics Phenomenology (CP3) and the H.E.S.S. and *Fermi*-LAT scientific collaborations.

Odense
June 1, 2026

Acknowledgments

This work would not have been possible without the extensive guidance, support, and patience of my supervisors, Manuel Meyer and Atreya Acharyya, to whom I am extremely grateful. Thank you for the opportunity to work on such a fascinating topic, for your trust in me, and for pushing me to do my best. I have learned an enormous amount over these months, and it has been a truly rewarding experience. You have both been excellent mentors.

Thanks to everyone at the Axion ALP DM group, for welcoming me into the group and creating such a friendly and open work environment.

Many thanks to the members of the H.E.S.S. and *Fermi*-LAT collaborations, for their help, cross-checks, and for making me feel part of the scientific community.

Thanks to everyone at the master’s student office, for the good times, the Danish lessons, and the many walks around campus, as well as the rest of the CP3 hallway “residents” and all the wonderful people I met in Odense. *Tusind tak!*

Finally, I would like to thank my friends from Spain, as well as my whole family, particularly my mother, sister, and grandparents, who have always supported me throughout my academic journey.

And to whoever is reading this thesis — thank you as well. I gave it my best.

— *Onwards and upwards!*

Abstract

The study of high-energy (≥ 100 MeV) and very-high-energy (≥ 100 GeV) gamma rays provides a unique observational window into the Universe, especially the most energetic extragalactic sources such as active galactic nuclei (AGN) or gamma-ray bursts (GRBs). When traveling over cosmological distances, these photons are attenuated due to interactions with the extragalactic background light (EBL). This attenuation could be partially mitigated by introducing axion-like particles (ALPs), a proposed beyond-Standard Model particle and dark-matter candidate that allows photon-to-ALP oscillations in strong magnetic fields. The main goal of this work is to search for and model the spectral upturns produced by this effect in several astrophysical sources.

An analysis of the spectral energy distributions of various extragalactic sources is presented using gamma-ray data from both the *Fermi* Large Area Telescope (LAT) and the High Energy Stereoscopic System (H.E.S.S.). The search for spectral upturns is then performed by statistically constraining the parameter space of possible breaks in the intrinsic model, which can then be related to the parameters describing the ALP contribution.

In this work, we focus on light ALPs ($m_a \leq 10^{-3}$ neV), considering conversions within the intergalactic magnetic field (IGMF) and the galactic magnetic field (GMF) of the Milky Way. We observe low-significance hints for the preference of ALP-induced upturns within the H.E.S.S. data at couplings of order $g_{a\gamma} \sim 4 \cdot 10^{-11} \text{ GeV}^{-1}$ or $g_{a\gamma} \sim 6 \cdot 10^{-11} \text{ GeV}^{-1}$ (depending on the EBL model considered). This preference vanishes after the inclusion of *Fermi*-LAT data, which breaks any degeneracy within the upturn models by providing a lower-energy constraint on our spectra. Performing a simplified statistical analysis of these results allows placing preliminary constraints on the ALP coupling of order $g_{a\gamma} \gtrsim 8.89 \cdot 10^{-12} \text{ GeV}^{-1}$ for the most conservative EBL model, and $g_{a\gamma} \gtrsim 1.92 \cdot 10^{-12} \text{ GeV}^{-1}$ for the most constraining model.

These preliminary results showcase the potential of joint *Fermi*-LAT and H.E.S.S. analyses both for constraining the allowed ALP parameter space and further studying gamma-ray propagation across cosmological distances over different astrophysical environments.

Contents

1	Introduction and motivation	5
2	Theoretical background	9
2.1	The Standard Model of particle physics and beyond	9
2.2	Axions and axion-like particles	12
2.2.1	Interactions and mixing of photons with axion-like particles	15
2.3	Active galactic nuclei and blazars as astrophysical sources of (very) high energy gamma rays	20
2.4	The transparency of the Universe to gamma rays	25
2.4.1	Cosmological gamma-ray propagation and attenuation due to the extragalactic background light	26
2.4.2	Effects of photon to axion-like particle conversions on gamma-ray propagation and spectral upturns	28
3	Instrumentation and observational data	30
3.1	Ground-based imaging Cherenkov telescopes and the High Energy Stereoscopic System (H.E.S.S.)	31
3.2	Space-based pair-conversion gamma-ray telescopes and the <i>Fermi</i> Large Area Telescope (<i>Fermi</i> -LAT)	34
3.3	Data analysis framework for gamma-ray astronomy	35
3.3.1	Low-level data reduction and processing	36
3.3.2	Statistical data analysis framework and binned likelihood-based modeling	40
3.4	Source selection, observation periods, and instrument configuration	42
4	Intrinsic spectral energy distribution modeling	46
4.1	Initial spectral fit, time variability analysis, and segmentation of H.E.S.S. data	46
4.2	<i>Fermi</i> -LAT data analysis	52
4.3	H.E.S.S. data analysis	55
4.4	Joint <i>Fermi</i> -LAT and H.E.S.S. data analysis	60
5	Spectral upturn modeling and simulations	62
5.1	Modeling the likelihood of spectral upturns	65
5.2	Simulations of spectral upturns due to photon to axion-like particle conversions	72
6	Likelihood analysis of spectral upturns due to photon to axion-like particle conversions	77
6.1	Upturn likelihood curves across axion-like particle couplings	78
6.2	Upturn likelihood across extragalactic background light models	82
6.3	Preliminary constraints on the axion-like particle parameter space	83
6.4	Monte Carlo methods for significance and threshold estimation	87
7	Conclusions and future outlook	90
	References	105
	Appendix	106
A	Light curves and time variability analysis of H.E.S.S. observations	106
B	Upturn modeling likelihood results	121

1 Introduction and motivation

ASTRONOMY, or the study of the cosmos, its components, and the processes that occur within it, is possibly one of the oldest natural sciences to exist, and has been a subject of human interest since prehistoric times [1]. In this way, the night sky has motivated numerous fundamental questions regarding the origins and nature of the different observed celestial bodies, as well as the nature of matter itself and the origin of the Universe. Throughout the millennia, the best studies that could be performed to tackle these questions were the limited observations of the visible light emitted by these objects through the naked eye. With the technological and scientific advancements of the last centuries, improved optical telescopes have been developed that have allowed us to study in great detail the visible emission for an ever-increasing amount of astrophysical objects [2], enabling the characterization of their history, evolution, and composition.

However, focusing our study on just the visible emission also presents a significant limitation. The importance of multi-wavelength studies, considering photons emitted with energies spanning the full electromagnetic spectrum, was quickly established throughout the twentieth century [3], with the discovery of emission from astrophysical sources not only in the visible range, but also in the radio, microwave, infrared, ultraviolet, X-ray, and gamma-ray energy ranges. Of particular interest is the observed emission of gamma rays since, due to their high energies, this radiation could only be produced in some of the most extreme environments, involving intricate and highly-energetic particle acceleration processes [4]. The detection of such highly-energetic radiation has also been proven to be a complex task, as these photons would simply pass through any optical system unaffected, requiring detection methods akin to those used in particle detectors and the development of new observational techniques. The benefits, however, far outweigh the technical detectability difficulty. Gamma rays, which are not deflected by magnetic fields and thus point directly back to their origin [5], allow us to directly probe some of the most energetic processes and environments in the Universe, as well as their propagation, often of cosmological scales, from distant sources [6].

Despite the success of extending astronomy towards the multi-wavelength regime, or even considering multi-messenger studies with gravitational or neutrino radiation [7], numerous issues within astrophysics and particle physics remain, at the time of writing this thesis, unresolved. These include, among others, the apparent requirement for additional, gravitating matter within the Universe that has not yet been observed directly [8], or inconsistencies within the current description of all fundamental particles and the interactions that may occur between them [9]. In these cases, gamma-ray studies are also particularly useful, as due to their extremely high energies, they offer direct probes into physical processes not observable on Earth, both in regards to their emission and propagation, thus providing an interesting window into high-energy astroparticle physics.

The study of the gamma-ray emission from extragalactic sources thus provides a unique observational opportunity to study some of the most energetic processes and environments in the Universe, while also offering a possible probe for observational effects of novel physics [10]. Active galactic nuclei (AGN), and in particular, blazars, provide highly accelerated cosmic rays and, most importantly, gamma-ray photons within the high-energy (HE, between 100 MeV up to 100 GeV) and very-high-energy (VHE, above 100 GeV) regimes. This makes

such gamma rays ideal probes for studying not only the emission processes of various sources, but also any propagation effects, such as the attenuation due to interactions with background radiation fields, or possible beyond Standard Model physics and its observational effects on this propagation [11].

The current best model we have to explain all known fundamental particles and the interactions allowed between them is given by the Standard Model (SM) of particle physics [6]. This model describes all known matter by introducing three families of quarks and leptons, which make up all the (baryonic) matter, and may interact via three of the fundamental forces: strong, weak, and electromagnetic. Despite being considered as one of the best theories ever conceived, with a great track record of successful predictions and great success in explaining all known processes and interactions, it is widely considered as an incomplete, lower-energy manifestation of a more general underlying theory [12], with some of the main reasons for this being its many clear limitations. Perhaps among the greatest of such limitations is the absence of the gravitational interaction, which as of yet could not have been included successfully within the model. For our current context, however, we will be focusing on two other problems within the Standard Model: the strong CP problem, and the dark matter problem.

The strong CP problem can be summarized as an apparent fine-tuning problem within the mathematical description of the strong interaction within the Standard Model. The presence of a term within the Lagrangian function corresponding to this interaction, which in principle allows for the violation of a certain symmetry resulting as the combined effect of the CP (charge conjugation and parity) operators, seems to be incompatible with the measured observables associated to it, such as the neutron electric dipole moment [13], which suggest the term must vanish [14]. This naturally leads us to ask the question: if the theory does not enforce a strict conservation of such symmetry, allowing the associated parameter to take any value, why does this parameter appear to be zero?

The dark matter problem provides an additional motivation for searches of physics, and in particular other types of particles, beyond the Standard Model [8, 15]. Numerous independent observations have established the need for an additional, non-luminous, gravitationally-interacting form of matter, such as the dynamics of galaxy clusters [16], their gravitational lensing [17], and the flat rotation curves of spiral galaxies [18]. This evidence has only been further reinforced on cosmological scales, where the observed cosmic microwave background (CMB) anisotropies and the large-scale structure of the Universe require a dominant dark matter component to be reproduced within the standard cosmological model [19].

One compelling proposal that could, in principle, solve both of these limitations, is a beyond Standard Model particle: the axion [20, 21, 22]. This particle is obtained as a consequence of attempting to solve the strong CP problem by introducing an additional symmetry to our model, promoting the problematic parameter into a dynamic field. This new, approximate symmetry can then be spontaneously broken, which would lead to the appearance of a new massive pseudo Nambu-Goldstone boson. Despite the original axion presenting a very specific relation between its mass and the coupling to the electromagnetic field, generalizations of these particles were soon introduced in the form of axion-like particles (ALPs). These particles are generalizations of the axion where the relation between their mass and coupling has been

relaxed, and which are further motivated from effects in various extensions of the Standard Model, such as string theory [23]. Interestingly, by introducing ALPs, we can also tackle the problem of dark matter, since these particles, or at least, for some of their masses and couplings, could contribute to the dark matter content of the Universe. This makes some ALPs potential candidates for cold dark matter, as they could be produced non-thermally in the early Universe and thus present a non-relativistic population [24, 25, 26].

Both the axion and ALPs present properties which strongly depend on how this new symmetry, and thus particle, is included within the SM. In this work, we will analyze their most general properties, and focus mainly on their interaction with the photon field and its main consequences. This interaction occurs via a coupling term involving the electromagnetic field, which allows for a non-zero conversion probability between photons and ALPs when propagating under an external magnetic field [27], in a process akin to the flavor oscillations of massive neutrinos [28].

Numerous experimental searches for detecting axions have been conducted and are continuously being developed, focusing mainly on exploiting their aforementioned oscillations with the photon field, with current measurements only providing exclusion regions within the mass-coupling parameter space. One particularly interesting experiment, with special interest to us, is the Light Shining through a Wall (LSW) experiment [29], in which the axion-photon oscillation under magnetic fields is taken advantage of in order to detect modified photon propagation effects after their conversion into an ALP, transmission through an opaque material, and subsequent reconversion into a photon [30]. In this project, we will be considering a very similar setup as to the LSW experiment. However, instead of producing the ideal environment for photon-axion conversions to occur within a laboratory setting, we will use the Universe and its opaqueness to highly-energetic gamma rays as the wall, with blazars offering ideal emitters for this case [12].

Blazars are perfect candidates for the study of gamma-ray emission and propagation effects, as they host powerful jets oriented closely towards our line of sight, producing extremely energetic radiation to travel directly towards us. During their cosmic travel, the gamma-ray photons can interact with lower energy background photons, the extragalactic background light (EBL), composed by the combined radiation emitted throughout the history of the Universe from all stars and galaxies [31]. This interaction produces an observable gamma-ray attenuation due to the pair-production of charged particles which will then get deflected, effectively lowering the observed gamma-ray flux at the highest energies from these distant sources.

The main result of including ALPs arises from the interesting fact that, if we consider their oscillations into photons, this attenuation could be partially suppressed. This is due to the fact that the axion propagation will not be affected by this cosmic attenuation, as these particles will not interact with any background radiation fields. Therefore, we may consider a scenario in which the emitted gamma rays from an extragalactic source convert into ALPs within the intergalactic magnetic field (IGMF), after which they travel freely without any absorption until they reach the Milky Way, whose galactic magnetic field (GMF) will cause them to reconvert into detectable gamma rays. Through this process, a partial alleviation of the expected attenuation could be achieved, effectively producing an increased flux of

1 INTRODUCTION AND MOTIVATION

photons at the highest energies [32]. This can be observed as a characteristic spectral upturn, occurring at the energies for which the Universe is thought to become increasingly opaque to gamma rays. The search for these spectral hints of ALPs is the main objective of this project.

In this work, we will be working with data obtained from two gamma-ray observatories. First, the High Energy Stereoscopic System (H.E.S.S.) [33] is a ground-based observatory array located in the southern hemisphere that allows for detecting gamma-ray signals by measuring the resulting Cherenkov radiation emitted by relativistic particles within the electromagnetic air showers caused by gamma-ray interactions with the Earth's atmosphere. This observatory will provide the main data for searches of spectral effects due to photon-ALP conversions, with its sensitivity well within the energy range where we expect possible upturns to occur. On the other hand, we also consider the *Fermi* Large Area Telescope [34], one of the most sensitive space-based gamma-ray telescopes which continuously probes the gamma-ray sky and studies gamma-ray emission directly via the detection of charged electron-positron pairs created in its interior. This instrument will offer a lower-energy constraint on the intrinsic spectral shape of our sources, effectively limiting the parameter space for which upturns are allowed within the data.

During this work, we will consider a dataset of various AGN sources, in particular, blazars, and perform a search for spectral upturns due to the effect of photon to ALP oscillations. First, we will reduce, process, and analyze the data obtained directly from the gamma-ray telescopes to obtain the spectral energy distribution (SED) of each source. In order to accomplish this, we will also perform a time variability analysis and separate the observational time period into statistically independent time blocks that correspond to physically distinct emission states of our AGN. Once all spectral models have been obtained for our sources and their associated time segmentation periods, we perform an upturn modeling by combining the obtained model with a spectral break. This model includes an additional term that emulates a spectral upturn. This new, upturned model, is then fitted again to the data, scanning over a physically motivated range of upturn parameters in order to obtain the likelihood of an upturn being present in the data. Finally, we can then perform numerical simulations of photon-ALP conversions during their journey from the target source to Earth, modeling both the Intergalactic Magnetic Field (IGMF) and the magnetic field present in the Milky Way (GMF). The methodology followed then allows for a comparison between the modeled photon-ALP upturns and those obtained from the simulations, thus enabling the computation of the associated upturn likelihood and the derivation of preliminary constraints on the ALP parameter space.

This work mainly follows a methodology already introduced previously within our group [35], with the main contributions of this work being the extension of the analysis to include data in the *Fermi*-LAT energy range, and the inclusion of three new additional sources that could offer further constraints. The results found for the case of H.E.S.S.-only data seem to be consistent with the results found in previous works, while the new results including *Fermi*-LAT offer, as expected, stronger bounds on the allowed upturn parameter space and thus a stronger constraint on the allowed magnetic field coupling of the ALPs obtained via the likelihood analysis of ALP-induced upturns.

This thesis is organized as follows. Section 2 contains the main theoretical background of the

project. This includes a brief summary of the Standard Model of particle physics and its limitations, the motivation and properties of axions and ALPs and their interactions with the photons field. We then change our focus towards the astrophysical context, introducing AGNs and blazars as our primary sources, the processes involved in conventional gamma-ray propagation, and how photon-ALP conversions affect this propagation in the scenario studied in this project.

Following this, Section 3 will focus on the instrumental and experimental aspect of gamma-ray detection and data analysis, including a description of the observatories that will be used, their data products, and the statistical framework used in the data analysis.

With this, we conclude the theoretical and instrumental background, and focus on the first steps of the analysis in Section 4, where the methodology and results of performing a spectral energy distribution modeling for our sources is presented, both for individual H.E.S.S. and joint *Fermi*-LAT and H.E.S.S. datasets. Next, Section 5 describes how the modeling of upturns is performed for each source, performing a statistical search for the best-fit upturn parameters, and the methodology followed for simulating the ALP-induced upturns.

Finally, Section 6 showcases the main findings of this project via a likelihood analysis comparing the ALP-induced upturn model with the model from the null hypothesis. From this, a likelihood curve of ALP-caused upturn is found for a range of physically motivated coupling values, from which we can obtain the detection significance and preliminary exclusion regions in the ALP parameter space.

2 Theoretical background

IN this chapter, the main theoretical background behind astrophysical searches for spectral hints of axion-like particles (ALPs) is presented. We begin with a brief summary of the Standard Model (SM) in Section 2.1, whose limitations serve as motivation to introduce axions and ALPs in Section 2.2, which may present interactions with the photon field and allow for photon-ALP conversions, as described in Section 2.2.1. We then switch our focus to the environments in which the effects of these conversions may be observable, focusing on active galactic nuclei and blazars in Section 2.3, which produce highly energetic gamma-ray radiation. We then discuss the conventional gamma-ray propagation scenario from such extragalactic sources (Section 2.4.1), and how introducing photon-ALP conversions modifies this scenario (Section 2.4.2), reducing the overall opacity of the Universe towards the high- and very-high energy gamma rays.

2.1 The Standard Model of particle physics and beyond

CURRENTLY, our best understanding of the physics that occurs at the level of all known fundamental particles, including the interactions that may occur between them, is described by the Standard Model (SM) of particle physics. The main accomplishment of this model is the systematic description of three of the four fundamental interactions, the unified electroweak interaction and the strong force, in the framework of a quantum field theory (QFT), as well as a classification and characterization of the different types of particles or the fields associated to them. Of course, summarizing the complete SM is a daunting task,

especially considering its complexity. Therefore, in this section, we will only provide a brief summary of the philosophy behind the SM, and some of its most important and relevant results and limitations for the context of this work.

In the QFT framework, the complete model, including all of its particles and allowed interactions, can be described with a Lagrangian density function $\mathcal{L}_{\text{SM}}$, which can be subdivided into terms or sectors for each one of the interactions: the quantum chromodynamics (QCD) sector given by $\mathcal{L}_{\text{QCD}}$ and the unified electroweak theory sector combining quantum electrodynamics (QED) interaction $\mathcal{L}_{\text{QED}}$ and the weak interaction, with additional contributions to include, for example, the Higgs mechanism.

As a consequence of this description, particles can be classified into two fundamental types, fermions and bosons, including the well-known gauge bosons that mediate the interactions (photons γ , gluons g , $W^\pm$, Z), the Higgs boson (H), three families of quarks (the positively-charged u , c , t and negatively-charged d , s , b , which then combine into hadrons: baryons or mesons) and three families of leptons (e^- , μ^- , τ^- , and their associated neutrinos ν_e , ν_μ , ν_τ), all of which also present corresponding anti-particles.

Interestingly, this formulation of the SM displays a high degree of symmetry, such that the overall description of the physics is invariant under certain operations, thus preserving the expected or postulated symmetries (such as translational and rotational symmetries, as well as reference frame invariance). This allows us to summarize the SM as a combined symmetry group: $SU(3) \times SU(2) \times U(1)$. This symmetry group fully defines the SM, allowing us to predict the existence of all the aforementioned particles and their interactions from symmetry considerations exclusively.

Therefore, the study of the different symmetries the SM provides an important tool into studying particle physics, and can be done by analyzing how the Lagrangian $\mathcal{L}_{\text{SM}}$ behaves under different transformations. We may, for instance, consider certain discrete operations that are expected to keep the model invariant, such as charge conjugation $\mathcal{C}$ (in which the electric charge as well as all other internal quantum numbers of the particle change sign, converting it into its antiparticle), parity $\mathcal{P}$ (a spatial-coordinate inversion), and time inversion $\mathcal{T}$ (changing the sign of the temporal coordinate), and study how they act on the Lagrangian.

Despite the SM being considered as one of the most successful and precise theories ever developed, with numerous successful predictions and confirming tests, it nevertheless contains numerous problems yet to be solved such as, mainly the non-inclusion of the gravitational interaction, the violation of certain symmetries, or the problem of dark matter (the latter two being of particular interest to us) [36, 37]. Another limitation of the SM is the apparent requirement of numerous parameters not provided by the theory, requiring their experimental estimation and leading to possible fine-tuning problems [6].

Of particular interest is a parameter θ that may be included in the Lagrangian for the strong interaction sector of the SM due to the complex, non-trivial structure of QCD vacuum states [20]. The associated term can be written explicitly as [14, 38]:

$$\mathcal{L}_\theta = \theta \frac{g^2}{32\pi^2} G_A^{\mu\nu} \tilde{G}_{A\mu\nu}, \quad (1)$$

where θ is a scalar parameter, g the strong coupling constant, G the gluon field strength (with A corresponding to the color index), and $\tilde{G}$ its associated dual. The issue arises when we study how this term behaves under the application of the discrete $\mathcal{C}$, $\mathcal{P}$, and $\mathcal{T}$ operators introduced earlier. Considering how each term of this Lagrangian transforms under these operators, and invoking the CPT theorem, which states that any local Lorentz-invariant quantum field theory is invariant under the combined $\mathcal{CPT}$ transformation, we can reach the conclusion that the combined result of $\mathcal{CP}$ is not conserved. In principle, this is not a problem, as CP violation is physically allowed across the SM. The issue arises when an attempt to observe this violation in the strong sector is performed in an experimental setting, where this violation is not observed.

One possible way of probing this CP-violating term is the experimental measurement of the value for the parameter θ , which will manifest itself in the form of a non-zero permanent electric dipole moment in the neutron, such that the following proportionality exists [39]:

$$|d_n| \sim 10^{-16} \bar{\theta} e \text{ cm}, \quad (2)$$

where e is the elementary charge, and $\bar{\theta} = \theta - \arg \det \mathcal{M}_q$ is the associated invariant observable that includes the vacuum angle parameter θ from Eq. (1) and the quark mass matrix $\mathcal{M}_q$ [14]. It is important to note that both terms defining this observable correspond to angular variables or phases, periodic under shifts by 2π [40]. Therefore, the parameter $\bar{\theta}$ is an angle, which can be represented in the interval $\bar{\theta} \in [-\pi, +\pi]$, and is initially expected to be of order unity, in the absence of any additional constraints or symmetries [39].

Remarkably, performing the experimental determination of d_n with increasing precision has only led to obtain what is currently the best measurement, of $|d_n| \sim 10^{-26} e \text{ cm}$ [13], which would require an almost vanishing parameter $\bar{\theta} < 10^{-10}$ [23, 38]. This discrepancy is the foundation of the strong CP problem: despite CP symmetry violation being, in principle and according to the current form of the SM, theoretically allowed, this symmetry breaking is not observed in nature, and any measurement of its consequences leads to the vanishing of the parameter associated to the problematic term.

Numerous solutions have been proposed to this problem, among which one of particular interest involves the addition of a new particle to our model. Let us first, however, motivate the inclusion of additional particles by redirecting our attention towards the second considered limitation of the SM, that is, the apparent underestimation of gravitating matter in the Universe.

Throughout the years, increasing evidence from astrophysical observations has pointed towards the existence of additional matter in the Universe that is seemingly undetectable by current observations yet modifies the dynamics of various systems [8, 15]. The first observational hints of this problem appeared after studies on the motion of distant galaxy clusters [16], which showed a mismatch between the estimated mass of the cluster computed from visible matter and the dynamic mass obtained from the measurement of velocity distributions of the individual galaxies [6]. Later studies on the rotation curves of spiral galaxies [18], where additional gravitating, but otherwise invisible, matter appeared to be required to explain the observed flat rotation curves, as well as studies on the gravitational lensing of galaxy clusters [17], further motivated astrophysicists to search for the missing dark matter (DM). In fact,

performing a fit of the current Λ CDM cosmological model to data from observations, such as the temperature fluctuations in the cosmic microwave background (CMB) [6], requires a large percentage of DM present in the Universe, contributing up to around 85% of the total mass, or approximately 27% of the total mass-energy content, of the Universe [9, 15]. This matter must interact gravitationally and, at most, very weakly with the Standard Model. Additionally, it must also be stable, and satisfy certain requirements necessary for the large-scale structure formation in the Universe and other cosmological constraints, such as being non-relativistic (cold), with a sufficient energy density [19]. Most importantly, DM cannot be baryonic, and must therefore necessarily be a novel form of matter, possibly in the form of a new fundamental particle.

As we have seen, the considered limitations of the SM, mainly the non-observation of the theoretically allowed CP violation, and the inability to provide a solution to the DM problem, provides an excellent motivation for searches for physics beyond the SM, and in particular, of additional novel forms of matter.

In the rest of this work, we will be focusing on a very specific attempt to solve these problems that originally arose as a possible solution to the strong CP problem and whose subsequent generalization could also be considered a possible DM candidate: the axion, and axion-like particles (ALPs). It is important to note, however, that despite having spent some time introducing these limitations and using them as the main motivation for our work, we will not be attempting to solve them directly. Rather, we will consider this new kind of particle and the characteristic properties it displays in order to study the gamma-ray propagation of extragalactic sources and search for hints of novel physics.

2.2 Axions and axion-like particles

AMONG the numerous solutions suggested to the previously described limitations of the SM, focusing mainly on the strong CP problem, perhaps one of the most intriguing proposals comes in the form of including an additional global continuous symmetry to the model. Denoted $U(1)_{\text{PQ}}$, this new symmetry could allow for an effective parameter $\theta = 0$ to vanish when measured after its spontaneous breaking, enforcing CP conservation in the strong sector of the SM and thus solving the strong CP problem [41]. This additional symmetry then acts as the basis of the Peccei-Quinn (PQ) mechanism, through which the problematic parameter θ is promoted to a dynamical field, and leads to the appearance of a new particle, the axion [21, 22]. This new particle would then be a pseudo Nambu-Goldstone boson, a pseudo-scalar (zero-spin with odd parity) particle with non-vanishing mass m_a resulting from the spontaneous breaking at a characteristic scale f_a of the approximate global symmetry $U(1)_{\text{PQ}}$.

The inclusion of the axion within the SM also requires considering possible interactions it may present with the SM particles [14]. Although numerous approaches of performing this inclusion have been considered, each leading to different axion models, they all present a series of common properties that arise directly from the PQ mechanism [30]. These model-independent properties are, mainly, its low mass, feeble interactions via couplings to the gluon, fermion, meson and, most importantly, photon fields [42], and large lifetimes for such low coupling and mass values (considerably larger than the age of the Universe, thus ensuring

the stability of the axion) [21, 30].

From its coupling to the gluon field, the axion can be found to absorb the previously-problematic θ parameter into the axion field whose potential has a minimum at $\theta = 0$, ensuring conservation of $\mathcal{CP}$ and providing a solution to the strong CP problem [30].

The axion couples to different fields, such as for example to the gluon field via:

$$\mathcal{L}_{ag} = \left(\frac{a}{f_a} - \bar{\theta} \right) \frac{\alpha}{8\pi} G^{A\mu\nu} \tilde{G}_{\mu\nu}^A, \quad (3)$$

where a is the axion field and α is the fine structure constant. From this Lagrangian term, a relation between the mass of the axion m_a and the relevant symmetry-breaking scale f_a can be found [23]:

$$m_a \approx 6 \cdot 10^{-6} \text{ eV} \left(\frac{10^{12} \text{ GeV}}{f_a} \right). \quad (4)$$

Perhaps the most important property of the axion relevant to our study is its coupling to the electromagnetic field, a direct consequence of the PQ mechanism which occurs via the relevant effective Lagrangian term [30]:

$$\mathcal{L}_{a\gamma} = -\frac{1}{4} g_{a\gamma\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a, \quad (5)$$

where a represents the field of the axion, F is the electromagnetic field tensor (with its corresponding dual $\tilde{F}$), and $g_{a\gamma\gamma}$ the coupling strength between the axion and the electromagnetic field. This coupling occurs between the axion and two photons, which allows for processes such as the decay of an axion into two photons and the conversion of a photon into an axion (and viceversa) within external magnetic fields [27]. In this project, we will focus exclusively on the latter photon-axion conversion, an essential characteristic of the axion which acts as the main mechanism for both laboratory and astrophysical axion searches. Throughout the remainder of this work, we will also make use of the shorthand notation $g_{a\gamma}$ in order to refer to the relevant two-photon axion coupling.

The previous Lagrangian term in Eq. (5) also allows for the computation of $g_{a\gamma}$ in terms of f_a as [12]:

$$g_{a\gamma} \approx 0.8 \cdot 10^{-10} k^{-1} \left(\frac{10^7 \text{ GeV}}{f_a} \right) \text{ GeV}^{-1}, \quad (6)$$

where k is a model-dependent dimensionless parameter of order $k \sim 1$ [12]. Combining Eqs. (4, 6) yields a strict relation between the mass of the axion m_a and its coupling to the photon $g_{a\gamma}$, a characteristic property of the axion [12, 32]:

$$m_a \approx 0.7k \left(g_{a\gamma} \cdot 10^{10} \text{ GeV} \right) \text{ eV}. \quad (7)$$

Axion-like particles (ALPs) are generalizations of the axion, in which the strict relation given by Eq. (7) is relaxed such that its mass m_a and photon coupling $g_{a\gamma}$ are considered as fully independent parameters. This is motivated by the prediction of a broad range of ALPs in numerous extensions of the SM, such as the string “axiverse” scenario [23], which features ALPs with masses ranging from 10^{-10} eV all the way down to 10^{-33} eV, while explicit string

theory compactifications could also accomodate heavier ALPs, with masses in the eV range [43].

Many of the original properties of the axion are present in ALPs, and they also inherit a coupling term of the form Eq. (5) from the original axion formulation, allowing for conversions between ALPs and photons.

In the remainder of the project, we will discuss exclusively ALPs, treating the previously introduced strong CP-solving axion denoted QCD axion as a particular case. Furthermore, we will consider only interactions between the ALPs and photons via the coupling $g_{a\gamma}$, assuming light ALPs with masses $m_a \ll 1$ eV and weak couplings $g_{a\gamma}$ below the electroweak scale [12].

The full Lagrangian density function describing ALPs can be written as [12]:

$$\mathcal{L}_{\text{ALP}} = \mathcal{L}_a + \mathcal{L}_{a\gamma} = \frac{1}{2} \partial^\mu a \partial_\mu a - \frac{1}{2} m_a^2 a^2 - \frac{1}{4} g_{a\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a. \quad (8)$$

Additionally to solving the strong CP problem, ALPs can act as potential candidates for DM. This is due to ALPs, including the QCD axion, presenting the necessary requirements to act as cold DM (CDM): their weak coupling to matter renders them effectively collisionless, interacting mainly gravitationally, and a non-relativistic population of ALPs could be present at the current stage of the Universe to account for the required DM energy density [39, 42]. Both the QCD axion, as well as ALPs, could be created in the early Universe through numerous proposed mechanisms, such as the misalignment mechanism (or generalizations of it, among other string-theory effects) [39, 44].

The misalignment (or vacuum realignment) mechanism [24, 25] provides a non-thermal axion and ALP production process. In the early Universe, the PQ symmetry is spontaneously broken at energy scales $T \sim f_a$, at which point a potential is established. Due to a large Hubble expansion rate $H \gg m_a$, the field remains frozen with a value misaligned with respect to its minimum, and it behaves as a massless particle. The axion acquires a non-zero mass either due to non-perturbative QCD effects at the corresponding QCD phase transition (for the QCD axion), or due to alternative string theory effects (for ALPs in general) [30, 35]. As the Universe continues to expand and the expansion rate reaches $H \sim m_a$, the field begins to coherently oscillate around the minimum of its potential, corresponding to an energy density that evolves as pressureless matter, and producing a relic abundance which could be consistent with cold (non-relativistic) DM requirements [44].

As mentioned previously, the conversion between photons and ALPs allowed by the interaction term in the Lagrangian given by Eq. (5) acts as the main channel through which experimental searches for ALPs are performed. In particular, the main strategy typically involves either applying strong magnetic fields onto electromagnetic radiation to cause such conversions, or to observe them indirectly via effects this photon-ALP mixing could cause, for example, in observations of astrophysical sources and environments. The independent mass and coupling pair $(m_a, g_{a\gamma})$ obtained by relaxing the strict axion relation in Eq. (7) generates a two-dimensional parameter space that fully characterizes different ALPs, thus prompting searches across a wide variety of parameter value choices. In general, efforts to search for ALPs can be divided into experimental laboratory and astrophysical searches, which attempt

to perform either a direct detection or an indirect observation of the effects photon-ALP conversions produce [42].

Numerous experiments and observational campaigns have been developed. As of yet, however, none of these approaches have yielded any positive results, although they did place strong constraints on the allowed parameter space for ALPs by excluding different regions in the mass-coupling space [6]. The constraints obtained as of writing this thesis are represented in Figure 1 across the physically-meaningful parameter space, including constraints from both laboratory searches, astrophysical observations, and cosmological considerations.

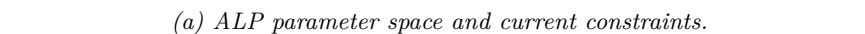
Some of the main laboratory ALP searches include light shining through a wall (LSW) experiments such as the first Any Light Particle Search (ALPS I) experiment [29] (with the current ALPS II, providing improved upper limits on the coupling strength, not shown in Figure 1), or experiments studying the effect of photon-ALP conversions on the polarization of light, such as the PVLAS experiment [45]. Direct detection experiments can be mainly divided into helioscope experiments, in which ALPs produced in the Sun are searched for by experiments such as the CERN Axion Solar Telescope (CAST) [46], and haloscope experiments which perform searches for ALPs in the local DM density of our galaxy, with experiments such as the Axion Dark Matter eXperiment (ADMX) [47]. Constraints on the ALP parameter space can also be obtained from cosmology, in particular, considering their observable effects on Big Bang nucleosynthesis (BBN) and the cosmic microwave background (CMB) [48]. Currently, however, the best constraints are still obtained from astrophysical observations and studies. At high ALP masses, strong constraints are obtained by studying the cooling rate of stars, most prominently within globular clusters, and how additional ALP emission could affect their lifetimes [49, 50]. At lower masses, constraints are obtained from searches of ALP-induced effects across the electromagnetic spectrum, mainly considering the radio and gamma-ray ranges, in the observed spectra from different astrophysical sources [11], as well as from other ALP phenomenology in various environments [42].

As we can see, the coupling of the ALP with the photon field, and as a consequence their permitted conversions under magnetic fields, provide an essential mechanism through which ALP effects could be observable, thus motivating searches for ALPs across the wide allowed parameter space via numerous different experimental, theoretical, and astrophysical methodologies. Therefore, a detailed study on this photon-ALP mixing is required and will be the goal of the following section.

2.2.1 Interactions and mixing of photons with axion-like particles

THE inclusion of ALPs into the standard model introduces a coupling term in the photon field, allowing for two main interactions between photons and ALPs: the decay of a heavy axions ($m_a \sim 10$ eV) into two photons [52], or conversions between photons and ALPs within magnetic fields [27]. These conversions can either occur due to virtual photons supplied by an external magnetic field, or due to the fields generated by other nucleons, the so-called Primakoff effect [53]. In this project, we will consider exclusively the case of photon-ALP oscillations that occur for light ALPs under external magnetic fields, such as those from different astrophysical environments, in a process resembling neutrino oscillations [28].

In order to study this effect, let us consider a photon beam propagating across an environment



where an external field is present, allowing for possible photon-ALP oscillations. The full Lagrangian describing the photon-ALP beam is given by [54]:

$$\mathcal{L}_{\text{ALP}} = \mathcal{L}_\gamma + \mathcal{L}_{\text{HEW}} + \mathcal{L}_a + \mathcal{L}_{a\gamma}, \quad (9)$$

where $\mathcal{L}_\gamma$ is the usual photon Lagrangian term:

$$\mathcal{L}_\gamma = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu}, \quad (10)$$

and $\mathcal{L}_{\text{HEW}}$ represents the Heisenberg-Euler-Weisskopf effective Lagrangian which includes additional corrections due to QED vacuum polarization to the photon propagator [12]:

$$\mathcal{L}_{\text{HEW}} = \frac{2\alpha^2}{45m_e^4} \left[(\vec{E}^2 - \vec{B}^2)^2 + 7(\vec{E} \cdot \vec{B})^2 \right], \quad (11)$$

where α_s is the fine structure constant ($\alpha = e^2/(4\pi\epsilon_0\hbar c) \approx 1/137$) and m_e the mass of the electron. We also rewrite explicitly the ALP Lagrangian term corresponding to the electromagnetic coupling in Eq. (5) explicitly in terms of the electric field of the photon and the external magnetic field:

$$\mathcal{L}_{a\gamma} = g_{a\gamma} \vec{E} \cdot \vec{B} a. \quad (12)$$

Let us consider the propagation of a monochromatic photon beam with energy E along the y -axis (with origin at y_0) within a non-relativistic (i.e. cold) ionized plasma medium characterized by an electron number density n_e in the presence of an external, homogeneous magnetic field $\vec{B}$. From the presence of the scalar product between the fields in the considered Lagrangian, we can clearly see that only the transversal component of the magnetic field $B_\perp$ will couple to the ALP. Furthermore, the scalar product will only be non-zero for photon polarization states that are parallel to the plane formed by the transversal magnetic field component and the propagation direction, such that only one polarization actually mixes with ALPs [32, 54].

The propagating photons will induce charge screening effects within the plasma, resulting in a plasma frequency $\omega_{\text{pl}} = (4\pi\alpha n_e/m_e)^{1/2} \approx 3.69 \cdot 10^{-11} (n_e/\text{cm}^{-3})^{1/2} \text{ eV}$ [12]. From the Lagrangian in Eq. (9) one can obtain the equations of motion of the system after applying the short-wavelength approximation $E \gg m_a$ [27]. If the initial photon beam is polarized along a certain direction, this takes the form of a Schrödinger-like equation:

$$\left(i \frac{d}{dy} + E + \mathcal{M} \right) \psi(y) = 0, \quad (13)$$

where $\psi(y) = (A_x(y), A_z(y), a(y))^T$ is the state function built by the two possible photon polarizations A and the ALP state a . More generally, this state can be described in terms of a density matrix, constructed as $\psi(y) \rightarrow \rho(y) = \psi \otimes \psi^\dagger$. This is particularly useful for considering unpolarized beams, such as in the case of X-ray or gamma-ray photons, as polarization measurements are not yet possible [54]. In this case, Eq. (13) take the form of a Liouville-von Neumann equation:

$$i \frac{d\rho(y)}{dy} = [\rho, \mathcal{M}]. \quad (14)$$

2.2 Axions and axion-like particles

In both cases, we have defined a mixing matrix $\mathcal{M}$. Ignoring Faraday rotation effects, which are negligible for photons in the gamma-ray regime, and choosing the z -axis aligned with the transverse component of the magnetic field, this matrix can be written as [12]:

$$\mathcal{M} = \begin{pmatrix} \Delta_{\perp} & 0 & 0 \\ 0 & \Delta_{\parallel} & \Delta_{a\gamma} \\ 0 & \Delta_{a\gamma} & \Delta_a \end{pmatrix}. \quad (15)$$

Each momentum difference term Δ defined in the mixing matrix represents the photon-ALP mixing including the relevant parameters of the plasma medium, as well as QED vacuum polarization, photon dispersion or absorption, and any other relevant effects. These can be written schematically (omitting coefficients) as [55]:

$$\Delta_{\{\perp, \parallel\}} \sim \Delta_{\text{pl}} + \Delta_{\text{QED}} + \Delta_{\gamma, \text{disp}} + \Delta_{\gamma, \text{abs}} + \dots \quad (16)$$

The plasma term can be written explicitly in terms of the plasma frequency as $\Delta_{\text{pl}} = -\omega_{\text{pl}}/(2E)$, and the QED vacuum polarization (which can also be neglected for weak magnetic fields [12]) $\Delta_{\text{QED}} = \alpha E/(45\pi)(B_{\perp}/B_{\text{cr}})^2$ will depend on the critical magnetic field $B_{\text{cr}} = m_e^2/|e|$. Lastly, the symmetric off-diagonal terms are defined in terms of the magnetic field strength $\Delta_{a\gamma} = g_{a\gamma}B_{\perp}/2$, and the kinetic ALP term is given by $\Delta_a = -m_a^2/(2E)$ [54, 55].

The photon dispersion term $\Delta_{\gamma, \text{disp}}$ will depend on the relevant background radiation fields and their energy density (in the case of CMB, $\Delta_{\gamma, \text{disp}} = 44\alpha^2 U_{\text{CMB}}/(135m_e^4)E$, where U_{CMB} is the total CMB energy density), while the complex absorption term $\Delta_{\gamma, \text{abs}} = -i\Gamma_{\text{abs}}/2$ will depend on the inverse mean free path or interaction rate Γ_{abs} along the propagation direction, which will include absorption due to background fields (most relevantly, the extragalactic background light, described in Section 2.4.1) [55]. This absorption is then included within only the photon terms in the diagonal of Eq. (15), leaving the ALPs unaffected [32].

In order to solve the problem at hand via the transfer matrix method, we begin by considering the diagonalization of the mixing matrix Eq. (15) such that [54]:

$$\mathcal{M}_D = W\mathcal{M}W^\dagger = \begin{pmatrix} \Delta_{\parallel} & 0 & 0 \\ 0 & (\Delta_a + \Delta_{\parallel} - \Delta_{\text{osc}})/2 & 0 \\ 0 & 0 & (\Delta_a + \Delta_{\parallel} + \Delta_{\text{osc}})/2 \end{pmatrix}, \quad (17)$$

where the eigenvalues are defined in terms of a new oscillation momentum difference:

$$\Delta_{\text{osc}} = \left[(\Delta_a - \Delta_{\parallel})^2 + 4\Delta_{a\gamma}^2 \right]^{1/2} = \left[\left(\frac{|m_a^2 - \omega_{\text{pl}}^2|}{2E} \right)^2 + g_{a\gamma}^2 B_{\perp}^2 \right]^{1/2}, \quad (18)$$

which can be interpreted as an oscillation wave number, such that $\Delta_{\text{osc}} = 2\pi/L_{\text{osc}}$ [12]. The matrices W can then be written in terms of trigonometric functions of the photon-ALP mixing angle $\theta_{a\gamma}$, defined as [12, 54]:

$$\theta_{a\gamma} = \frac{1}{2} \arctan \left(\frac{2\Delta_{a\gamma}}{\Delta_{\perp} - \Delta_a} \right) \approx \frac{1}{2} \arctan \left(\frac{2g_{a\gamma}EB_{\perp}}{m_a^2 - \omega_{\text{pl}}^2} \right). \quad (19)$$

Which ultimately allows us to compute the final transfer matrix $\mathcal{T}$ which will determine the evolution of our photon-ALP beam density matrix:

$$\mathcal{T} = W^\dagger e^{i\mathcal{M}_D} W. \quad (20)$$

With this transfer function, we can now write the resulting density matrix of our system at any position along the propagation direction:

$$\rho(y) = \mathcal{T} \rho(y_0) \mathcal{T}^\dagger, \quad (21)$$

where y_0 corresponds to the source of the photon-ALP beam. In the case where the magnetic field orientation forms an arbitrary angle with the direction of propagation, one can still obtain both the new mixing and transfer matrices via the usual similarity relation by applying the corresponding rotation matrix [12]. The general probability expectation value between two general states is given by [32]:

$$P_{\rho_1, \rho_2} = \langle \mathcal{T} \rangle_{1,2} = \text{Tr} \left(\rho_2 \mathcal{T} \rho_1 \mathcal{T}^\dagger \right). \quad (22)$$

With this, we can now compute the probability of a photon converting into an ALP after traveling a distance y (considering $y_0 = 0$) as the expectation value of the transfer matrix between the initial photon and final ALP states:

$$P_{a\gamma} = \langle \mathcal{T} \rangle_{a\gamma} = \sin^2(2\theta_{a\gamma}) \sin^2\left(\frac{\Delta_{\text{osc}} y}{2}\right) = \left(\frac{g_{a\gamma} B_\perp}{\Delta_{\text{osc}}}\right)^2 \sin^2\left(\frac{\Delta_{\text{osc}} y}{2}\right), \quad (23)$$

The conversion probability becomes maximal whenever $\Delta_{\text{osc}} \approx g_{a\gamma} B_\perp$ or equivalently $\theta_{a\gamma} \approx \pi/4$, the so-called strong mixing regime, in which the probability becomes independent on both the energy E and mass of the ALP m_a , and is given exclusively by the sinusoidal term:

$$P_{a\gamma} = \sin^2\left(\frac{g_{a\gamma} B_\perp y}{2}\right) \approx \left(\frac{g_{a\gamma} B_\perp y}{2}\right)^2, \quad (24)$$

where the second approximation corresponds to a small angle approximation, considering a total distance traveled $y \ll L_{\text{osc}}$ [30]. Formally, the strong mixing regime can be defined in terms of the following energy range [55, 56]:

$$\frac{|m_a^2 - \omega_{\text{pl}}^2|}{2g_{a\gamma} B_\perp} \leq E \leq \frac{90\pi B_{\text{cr}}^2 g_{a\gamma}}{7\alpha B_\perp}. \quad (25)$$

Throughout this study, we will consider ALP parameters within this strong-mixing regime, in order to maximize the observational effects of photon-ALP conversions. This corresponds to very-light ALPs with $m_a \sim 10^{-3}$ neV with couplings in the order of $g_{a\gamma} \sim 10^{-11} \text{ GeV}^{-1}$.

In general, when considering the propagation of a photon-ALP beam, conversions might happen across M different magnetic field environments, and in each one of them, the structure of the magnetic field itself might not be homogeneous. In this case, it is convenient to still apply this same transfer matrix methodology, although now dividing each environment into N_M individual domains of coherence length L in which the field and the properties of the

2.3 Active galactic nuclei and blazars as astrophysical sources of (very) high energy gamma rays

plasma can be considered as constant and homogeneous. The resulting transfer matrix will then be given as the ordered product, from the source to the observer, of the individual transfer matrices found within each environment, across all environments [55]:

$$\mathcal{T}_{\text{tot}} = \prod_{m=1}^M \prod_{n=1}^{N_M} \mathcal{T}_{m,n} \quad (26)$$

where each transfer matrix $\mathcal{T}_{m,n}$ corresponds to the matrix computed for the propagation across domain n , across all domains, for each environment m . This allows us to compute the photon survival probability considering an initial state $\rho(0)$:

$$P_{\gamma\gamma} = \text{Tr} \left[(\rho_{11} + \rho_{22}) \mathcal{T}_{\text{tot}} \rho(0) \mathcal{T}_{\text{tot}}^\dagger \right], \quad (27)$$

where the states $\rho_{11} = \text{diag}(1, 0, 0)$, $\rho_{22} = \text{diag}(0, 1, 0)$, and $\rho(0) = \text{diag}(1/2, 1/2, 0)$ correspond to the initially unpolarized state [55].

2.3 Active galactic nuclei and blazars as astrophysical sources of (very) high energy gamma rays

SEARCHES for physics beyond the Standard Model require careful identification of astrophysical sources that can serve as probes for studying the possible photon-ALP conversions. Active galactic nuclei (AGN) are particularly well-suited for this purpose, due to their extremely powerful emission and location at cosmological distances [57]. In this section, we will briefly describe their main properties and morphology, with particular focus on the subclass of blazars and their gamma-ray emission.

The discovery of a wide variety of extragalactic sources with high luminosities, possessing unique properties [57], and often variable emission originating from extremely compact regions located at high redshifts [58], led to an increasingly specific classification scheme [58, 59, 60]. This prompted discussions on whether all of these classifications were truly due to intrinsic physical characteristics [58, 59, 60], which ultimately led to the development of the currently-accepted AGN unification scheme [61]. The central idea of this unification scheme revolves around the consideration that most of these sources actually correspond to a single type of object, the AGN, whose observed properties can be explained to a high degree by geometric considerations due to its orientation with respect to our line of sight and a series of truly physical properties [58].

AGNs are defined as the highly compact regions located in the center of some galaxies (on the order of 1% of all galaxies [62]) which present intense, and in some cases highly variable, emission across a wide range of energies in the electromagnetic spectrum. Their luminosities are often orders of magnitude higher than the radiating power of entire galaxies [63], and can vary within timescales of days or even hours [64]. The main mechanism that powers this emission is believed to be the accretion of matter onto a supermassive black hole (SMBH), with total masses (expressed in terms of solar masses) typically above $10^6 M_\odot$ and as high as $10^{10} M_\odot$ located at their core [6]. In this accretion process, sustained by the friction and subsequent infall of rotating gas onto the black hole [65], a disk of rapidly rotating and thermally emitting (mainly in the optical-UV and soft X-ray ranges) matter is formed. In

some cases, an additional gas cloud corona above the disk is expected to form with even higher temperatures [65].

In certain cases (approximately 10% of AGNs [62]), powerful symmetric jets are formed, which anisotropically emit collimated particles at extremely high energies in opposite directions perpendicular to the plane of the accretion disk. These jets are responsible for producing and accelerating cosmic rays well into the VHE regime, and possibly even beyond [66]. Surrounding the accretion disk are two gas clouds: the inner broad-line region (BLR) responsible for the emission containing optical-UV broad spectral lines, and the outer, narrow-line emitting region (NLR). Around the core components of the AGN, a dust torus is located, which obscures the accretion disk and re-emits the UV radiation it receives from it in the IR energy range [4, 6, 67].

The described AGN morphology, in which each of its components is responsible for a specific kind of emission via different relevant processes, offers a direct explanation of the distinct observed properties across sources of this kind depending on the orientation and therefore on which components can be seen directly and which are obscured. If the AGN is viewed with our line of sight coinciding with the plane of the accretion disk, the central SMBH, the accretion disk, and possibly the BLR, will be fully obscured by the dust contained in the torus, and therefore, depending on the presence of jets, a radio-quiet Seyfert 2 or a radio-loud galaxy with narrow lines will be observed. Modifying the angle of our line of sight might allow us to obtain a direct view of the BLR and additional broad lines in the spectrum, such as in the case of Seyfert 1 or BLR galaxies. Orientations with relatively small inclination angles with respect to the axis of the jet allow to also view the thermal emission from the accretion disk, producing a quasar source. Finally, if our line of sight is closely aligned with the jet axis, the main emission observed will be exclusively that of the jet itself, whose extremely intense emission at very high energies prevents the observation of any other component. This is the case of blazars, the main class of sources considered in this work. A useful diagram summarizing this unified scheme of AGNs and their morphology is shown in Figure 2, along with an example of the multi-wavelength view of an AGN.

Blazars, which correspond to AGN objects viewed with a line of sight closely aligned to the axis of the jet, are of particular interest in our context due to their extremely energetic emission. Photons are boosted due to the relativistic motion of the components of the jet, producing a Doppler shift which increases the observed brightness of the source, making the jet emission easily “outshine” the emission from any other components [65]. As a consequence, blazars, observed mostly as point-like sources, dominate the TeV sky [6, 58] with 89 currently identified [70]. An important characteristic of blazar sources is their extreme variability, with flaring periods in which their spectral flux may vary, in some cases, by more than an order of magnitude in time scales as low as minutes [62], although this variability is not always present or may be interrupted by long periods in which the source remains in a quiescent state. These objects can be further subdivided into two classes: flat-spectrum quasars (FSRQs), in which emission from a BLR can be observed, and BL Lac (BL) objects otherwise.

With our blazar sample introduced, let us now consider the broadband, non-thermal continuum emission that is emitted by these sources. The emission of a source is typically studied by its differential photon flux $\Phi = dN/(dtdAdE)$, representing the number of photons N per

2.3 Active galactic nuclei and blazars as astrophysical sources of (very) high energy gamma rays

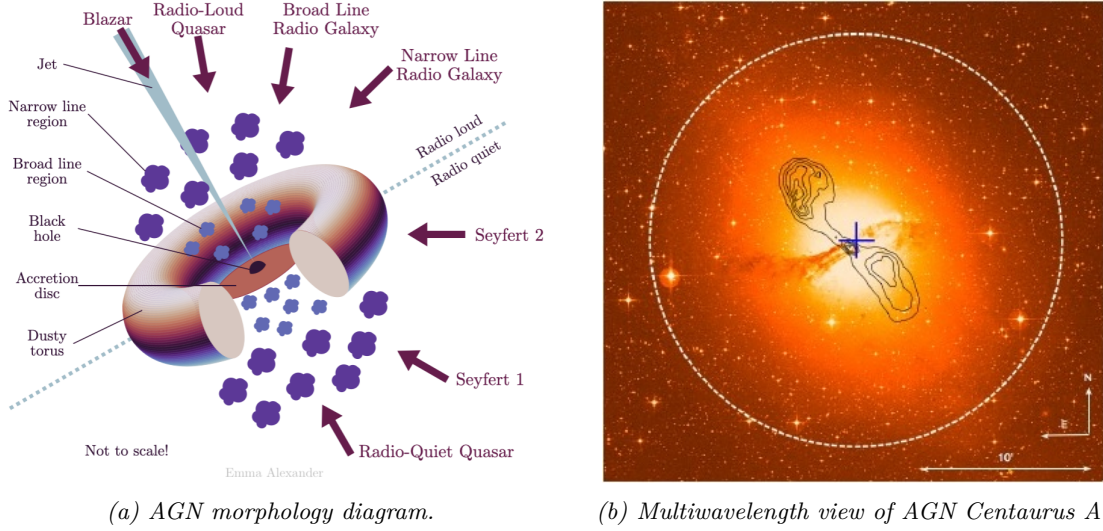


Figure 2: (a) Schematic representation of the morphology of a generic AGN, including its main components. The solid arrows represent the classification of the AGN depending on the orientation with which it is observed, with a distinction made across the accretion disk plane to distinguish between radio quiet and radio loud galaxies. Credit: E. L. Alexander, University of Manchester (2002) [68]. (b) Optical view of AGN Centaurus A, overlaid with radio contours in black, and the center of VHE gamma-ray emission as the blue cross. Credit: H.E.S.S. Collaboration (2009) [69].

unit energy E , time t , and area A . For simplicity, throughout this section let us assume that the emitted and observed flux are equal, so as to only consider a single spectral flux Φ (the distinction will be made explicit with the inclusion of propagation effects in the next section). Let us also simplify the notation to $\Phi = dN/dE$ with an implicit dependence on differential elements of time and area.

In order to represent this quantity, typically a spectral energy distribution (SED) plot is employed, in which the differential flux of a source is shown across a range of energies, oftentimes rescaled such that $\Phi_{\text{SED}} = E^2 dN/dE$ purely for visualization purposes. The SED of a source allows for a description of its emission state. An example of a broadband SED plot of blazar PG 1553+113, one of the sources studied in this work, is displayed in Figure 3. Immediately visible from this plot is the characteristic “double-bump” shape of the SED in which two clear peaks are present. The first peak is located, in this case, at $10^{-8} \text{ GeV} = 10 \text{ eV}$ in the UV range, although in general it can be found anywhere between the infrared and the X-ray energy ranges. The second peak is typically located in the gamma-ray region.

Attempts to fully describe and model the broadband SED of AGNs and blazars are actively pursued taking advantage of observational data for all detected sources, motivated by the attempt to explain how these objects produce such high-energy particles and why their spectra have this particular shape.

The first peak observed in the SED of a generic blazar source can be fully attributed to the synchrotron radiation emitted by a population of relativistic electrons whose trajectory is modified due to the Lorentz interactions under external magnetic fields. As a consequence

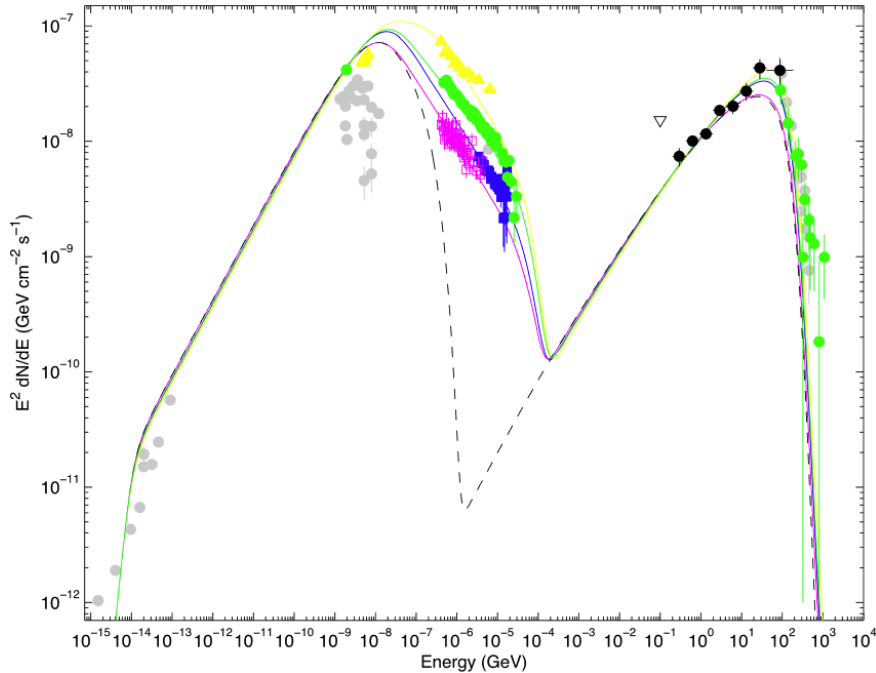


Figure 3: Broadband spectral energy distribution (SED) of AGN blazar HBL source PG 1553+113. The characteristic “double bump” appearance of the spectrum is clearly visible. The observations from various instruments used to reconstruct this plot are shown by the different color points, combining data from KVA (optical), Suzaku (X ray), MAGIC (gamma rays), Swift-XRT and UVOT (X rays), RXTE, and archival data marked in light gray in the radio, optical-UV and X-ray ranges. Most relevant to us is the inclusion of data from Fermi-LAT, marked with the black points, and H.E.S.S. observations in green. The full SED is fitted using a SSC model, represented as the various continuous lines with each color corresponding to different model choices. Credit: A. A. Abdo et al. (2010) [71].

of this deflection, the accelerated electrons will emit synchrotron photons, whose energy between the optical and up to the soft X rays will depend on the energies of the seed electrons. Depending on where the synchrotron peak is found in the SED of BL Lac objects, these can be classified into low-synchrotron-peaked BL Lacs (LBL, with their maximum in the infrared regime), intermediate (IBL, with the peak between the optical and UV), and high-synchrotron-peaked (HBL, at X-ray energies). FSRQs are typically classified as below LBLs in terms of the location of their maxima [62].

For the case of the second, higher-energy peak, the discussion is much more nuanced. In particular, two major types of models have been developed, depending on which particles and processes are involved. A useful boundary is set depending on whether the protons energies within the jet of the AGN surpass the corresponding photo-pion-production energy threshold. If proton energies remain below this scale, leptonic models are invoked, while otherwise hadronic or hybrid models may be employed [72].

Leptonic models consider the observed high-energy emission peak as resulting from inverse

2.3 Active galactic nuclei and blazars as astrophysical sources of (very) high energy gamma rays

Compton (IC) processes, in which relativistic electrons transfer part of their energy to soft photons, resulting in the photons being boosted to high energies [6]. This is in contrast to the usual Compton scattering, where high-energy photons scatter off low-energy electrons at rest, accelerating the electrons to higher energies. In the context of AGNs, the synchrotron processes responsible for the lower-energy peak in the SED could provide both the required populations of low-energy photons and high-energy electrons, in which case we talk about a synchrotron self-Compton (SSC) process [72].

The SSC model describes the high-energy peak as a consequence of IC scattering of the synchrotron photons off of the same relativistic electron population that produced the lower-energy peak. This minimal leptonic model has been found to describe the broadband gamma-ray emission across the SED of many blazar sources [73].

In some cases, the IC scattering may occur with a seed photon population outside the jet, not corresponding to the self-synchrotron population, in which case an external Compton (EC) model is used. These photons could originate from the emission of other components of the AGN, such as the accretion disk or re-emission by the torus [72, 74]. The standard SSC model is typically used to explain the emission in BL Lac objects, while the EC scenario is often associated with FSRQs [75]. More complex models may also be defined, in which different photon absorption and pair-production processes are taken into account by the inclusion of numerous parameters into the model [72, 76].

An alternative to leptonic models is the hadronic scenario, in which the gamma rays are considered to be produced via the interactions between highly energetic accelerated protons with the soft photons from the synchrotron or bremsstrahlung radiation emitted by electrons, producing either charged or neutral pions, the latter of which will decay into high-energy photons [6]. Other decay channels of the pion, both neutral (e.g. $\pi^0 \rightarrow \gamma + \gamma$) and charged (e.g. $\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \bar{\nu}_\mu + \nu_e + \nu_\mu$) [77], as well as the synchrotron radiation from protons, muons, and other hadrons, may initiate cascades of particles that further sustain the production of gamma rays which could then form the observed peak [73]. In some cases, hybrid lepto-hadronic models are also sometimes considered, as both processes might contribute to different extents to the emission of a blazar [72].

After briefly summarizing the main emission mechanisms of AGNs and in particular blazars, we are now interested in developing spectral models ϕ that describe the resulting observed spectrum Φ . However, in the case of our gamma-ray study, we do not aim to construct a full broadband model, but rather models that can be applied within the narrow energy band considered. In these cases, the spectra can typically be approximated by a simple power-law model, such that we can describe the differential flux as:

$$\phi_{\text{PL}}(E; E_0, N_0, \Gamma) = N_0 \left(\frac{E}{E_0} \right)^{-\Gamma}, \quad (28)$$

where we have defined a set of spectral parameters, in particular the index Γ , normalization or amplitude N_0 , and reference energy E_0 , that will differ for each source. While the normalization and reference energy are typically correlated, such that a change in the reference will be compensated by a change in normalization, the spectral index Γ will remain invariant, being particularly useful to characterize the shape of the spectral emission within the considered energy band.

In some cases, the high-energy SED peak occurs near or even within the studied energy range, in which case the spectra will present significant curvature. In these cases, the simplest model with curvature often chosen to describe the differential flux at these energies is the log-parabola model:

$$\phi_{\text{LP}}(E; E_0, N_0, \beta, \alpha) = N_0 \left(\frac{E}{E_0} \right)^{-\alpha - \beta \log(E/E_0)}, \quad (29)$$

where E_0 and N_0 are again the associated reference and normalization, with α acting as the effective spectral index, while the parameter β quantifies the curvature present in the spectra.

Due to their strong variability, the SED of blazars may change substantially across different emission states within very different timescales. Therefore, the form of the model and the corresponding parameters that best explain the emission will typically differ between flaring periods or emission states.

Up until this point, we have followed the assumption that the observed and emitted spectrum of the blazar source are exactly the same, and therefore the models we select describe exactly the SED of the gamma-ray emission. By doing so, we are ignoring any possible modification that the photon flux could undergo during its propagation across such cosmological distances. In order to properly model the SED of a source, we must therefore consider the propagation of the photons across the intergalactic medium (IGM), and the different interactions and processes, including any beyond SM or ALP effects, that may result in its modification of the flux, which is precisely what we will study in the following sections.

2.4 The transparency of the Universe to gamma rays

WHEN studying the gamma-ray emission from distant objects, it is not enough to simply describe how this radiation is created and emitted in the target source. This is due to the fact that the Universe is not completely transparent to the propagation of photons, and depending on the considered energy scale, interactions with background fields could result in a change in the number of photons that reach the observer without interacting. This is particularly important when considering the propagation across large distances, such as in the case of gamma-ray extragalactic emission, despite the fact that their high energies allow us to neglect certain low-energy interactions. A certain level of opacity is therefore expected for photons propagating across the Universe, whose main consequence will be the modification of the observed differential photon flux Φ_{obs} with respect to the actual flux Φ_{emit} emitted by the studied source.

In the context of gamma rays, the relevant interactions that they may present are pair-production processes, in which the emitted photons interact with lower-energy background photon fields producing charged particles which will get deflected, thus producing an effective decrease or attenuation in the photon flux. Accurate modeling of this process is essential in order to distinguish between the spectral features present in the SED of a source caused by physical effects in the emission process and the attenuation due to the propagation of this signal. It is the objective of the following Section 2.4.1 to present a full description of the absorption process relevant to gamma-ray astronomy.

On the other hand, when studying effects of physics beyond the Standard Model (PBSM), such as those arising from photon-ALP oscillations, an additional modification to the observed spectrum is introduced, which may produce an increase in the observed photon flux. Section 2.4.2 will focus on describing the photon-ALP conversion scenario considered in this work, and the way it could produce modifications to the observed SED of blazars.

Following the notation introduced in Section 2.2.1, the full effect of such propagation can be described with a photon survival probability $P_{\gamma\gamma}$, such that [12]:

$$\Phi_{\text{obs}} = P_{\gamma\gamma} \Phi_{\text{emit}}, \quad (30)$$

with $P_{\gamma\gamma}$ containing the conventional-physics description of photon propagation and EBL attenuation, as well as the inclusion of photon-ALP conversion effects.

2.4.1 Cosmological gamma-ray propagation and attenuation due to the extragalactic background light

ATTENUATION of gamma rays may occur via various processes, although the most relevant in our case is the two-photon pair-production or Breit-Wheeler process, in which the high-energy gamma ray interacts with soft photons from a background field, producing a pair of charged particles and no photons in the final state. This process can be schematically represented as $\gamma + \gamma_{\text{EBL}} \rightarrow e^- + e^+$, where we have denoted this background field as the extragalactic background light (EBL), whose origin we will discuss shortly. In order for this process to be kinematically allowed, the initial state must contain enough available energy, which occurs whenever the following relation involving a threshold energy on the background photons is satisfied [6, 78, 79]:

$$E_{\text{EBL}} \geq E_{\text{EBL,thr}} = \frac{2(m_e c^2)^2}{E(1 - \cos \phi)}, \quad (31)$$

where E is the energy of the gamma-ray photon, E_{EBL} is the energy of the background EBL photon, and ϕ is the angle between their trajectories. The associated cross section for this process is given by [79]:

$$\sigma_{\gamma\gamma} = \frac{3\sigma_T}{16} (1 - \beta^2) \left[(3 - \beta^4) \ln \left(\frac{1 + \beta}{1 - \beta} \right) - 2\beta(2 - \beta^2) \right], \quad (32)$$

where σ_T is the Thomson cross section and β represents the velocity of the final electron or positron which, in the center of mass frame, corresponds to $\beta = (1 - E_{\text{EBL,thr}}/E_{\text{EBL}})^{1/2}$. The cross section given by Eq. (32) reaches a maximum, considering gamma rays in the VHE regime, between 1 GeV and 100 TeV, which corresponds to background photons in the optical and IR ranges, respectively. The attenuation resulting from a background with such characteristics is directly observed in various extragalactic VHE emitters [31, 80].

Through observations performed by studying the spectra of extragalactic sources across a wide range of redshifts, the spectrum of the EBL can be obtained [11], which has been found to present prominent maxima at the relevant energies where the previous Breit-Wheeler cross section is maximized. In particular, the EBL consists of two main components. The first is the cosmic optical background (COB) spanning wavelengths between approximately 0.1 and

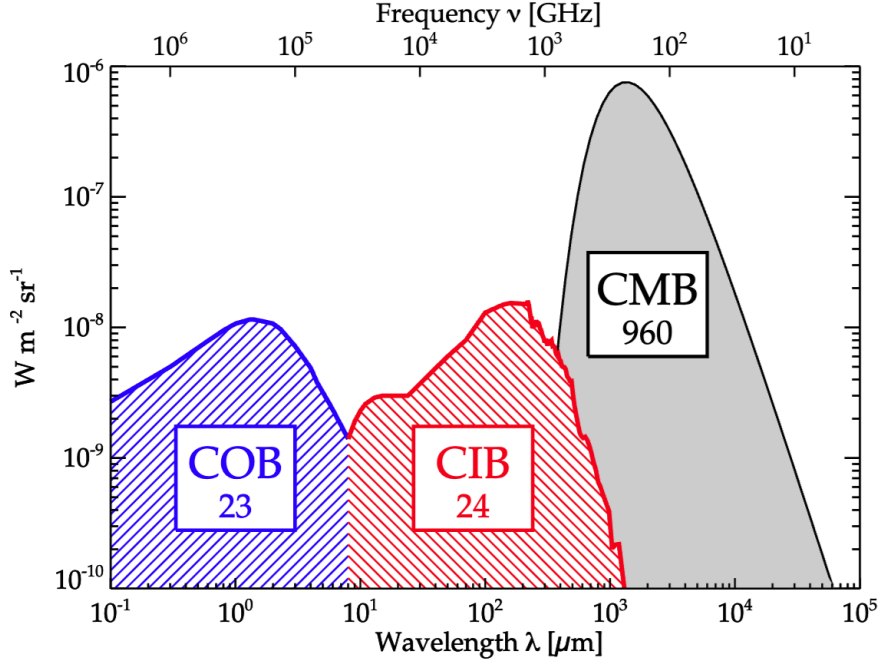


Figure 4: Schematic diagram of the spectral energy distribution (SED) of the background photon fields relevant for gamma-ray astronomy, including the extragalactic background light (EBL) and its two main components: the cosmic optical background (COB) and the cosmic infrared background (CIB). The cosmic microwave background (CMB) is also shown. Credit: H. Dole et al. (2006) [81].

$10\ \mu\text{m}$ which can be attributed to emission from stars, the intra-halo light (IHL), or optical AGN emission, among others [31]. The cosmic infrared background (CIB) corresponds to the second main component of the EBL, and its emission across wavelengths from $10\ \mu\text{m}$ to approximately $1\ \text{mm}$ is attributed to dust re-emission [11]. Thus, the full EBL can be interpreted as the accumulated radiation field which contains the integrated light from all extragalactic, not necessarily resolved sources, as well as any diffuse background, emitted throughout the history of the Universe [12, 31, 78]. Figure 4 displays schematically the shape of the EBL along with its main components across a range of wavelengths, including as well the CMB.

The effect of the EBL absorption on the observed flux from extragalactic gamma-ray sources, given by $P_{\gamma\gamma}$, can be parametrized as an exponential attenuation, such that Eq. (30) becomes:

$$\Phi_{\text{obs}}(E) = e^{-\tau(E,z)} \Phi_{\text{emit}}(E), \quad (33)$$

where $\tau(E, z)$ is defined as the optical depth function which characterizes the expected opacity of the Universe to photons emitted at a given energy E and redshift z . This optical depth can be computed by the following integral over distance, scattering angle, and EBL photon

energy [6, 78, 79]:

$$\begin{aligned} \tau(E, z) = & \int_0^z d\ell(z) \int_{-1}^{+1} d\cos\phi \frac{1 - \cos\phi}{2} \\ & \times \int_{E_{\text{EBL,th}}}^{\infty} dE_{\text{EBL}} n_{\text{EBL}}(E_{\text{EBL}}, z) \sigma_{\gamma\gamma}(E, E_{\text{EBL}}, z, \cos\phi), \end{aligned} \quad (34)$$

where n_{EBL} represents the photon number density of the EBL for photons of given energy and redshift, and $d\ell$ represents the line element as a function of redshift, whose explicit form will depend on the adopted cosmological model [11]. Due to the expansion of the Universe, the photon energies will also depend on the redshift along the line of sight, with the emitted energy rescaled by a factor $(1+z)$ with respect to the observed energy [6, 11, 67].

EBL attenuation will become increasingly prominent for sources located farther away, that is, for sources at higher redshift values z and gamma-ray energies E . A characteristic “horizon” may be defined by considering the energy at which the optical depth reaches a value $\tau(E, z) = 1$, which will represent the redshift-dependent point at which the Universe is considered opaque to the emission [6]. In this work, we will also consider a more strict threshold for energies at which $\tau(E, z) = 2$, with energies above corresponding to the “optically thick” regime.

The quantity n_{EBL} is the main problem in the correct computation of the optical depth, as the photon density of the EBL as a function of wavelength and redshift is typically not known. Direct observations of this quantity are possible, although highly complicated due to contamination from galactic sources or the diffuse contamination due to the zodiacal light [78, 82]. Therefore, observational attempts to reconstruct the EBL usually provide either upper or lower limits on its intensity. An alternative approach is to construct models of the EBL that would allow the optical depth integral to be computed, although in this case, the main difficulty arises from determining how the luminosity density evolves with redshift [78]. Different approaches have been developed in order to obtain this quantity, resulting in a great variety of models, such as the following models considered in this work described in [83, 84, 85, 86]. The optical depth, along with the expected EBL absorption, for a subset of sources considered in this work (which we will introduce in Section 3.4) is represented in Figure 5.

2.4.2 Effects of photon to axion-like particle conversions on gamma-ray propagation and spectral upturns

As we have seen in the previous section, the Universe exhibits a certain degree of opacity to the propagation of gamma rays, which increases for high energies and at large distances or redshifts. This has a direct observational effect on the observed spectra of extragalactic sources such as blazars, which present an exponentially-driven attenuation at the highest energies. The goal of this subsection is to present the main motivation of this work: possible effects which could counteract this attenuation and modify the observed high-energy spectra of the gamma rays emitted by distant sources.

Several observational campaigns have found possible indications of an increased transparency of the Universe when studying various blazar sources, suggesting that folding the expected emission spectral models with the presented EBL models significantly overestimates the

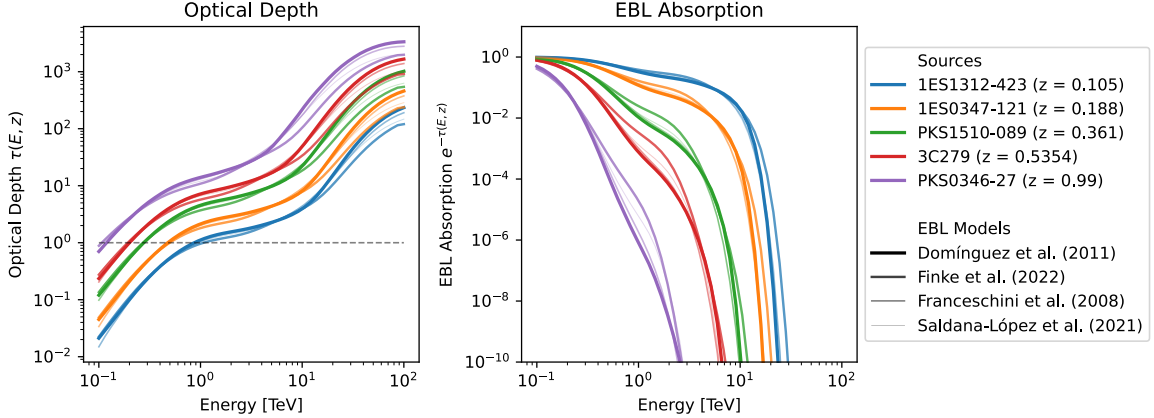


Figure 5: Optical depth and EBL attenuation for a subset of sources considered in this work with different redshift values, obtained with different EBL models (in particular, [83, 84, 85, 86], respectively) represented by different line widths. The dashed horizontal line on the optical depth plot represents $\tau = 1$, with energies corresponding to higher optical depths belonging to the so-called “optically-thick” regime.

total attenuation of the emitted gamma rays [87, 88]. These results have prompted the consideration of numerous alternatives that could explain such transparency, for example through the modification of the intrinsic spectra of distant blazars, leading to a paradoxical correlation between their intrinsic spectral index and redshift [12, 32].

Attempts to solve this apparent excessive transparency problem have also been proposed by introducing effects of physics beyond the SM. One example is through the violation of Lorentz invariance (LIV), which introduces additional effective terms in the dispersion relation of particles leading to modifications in the EBL pair-production process and thus deviations in the propagation of gamma rays at the highest energies [6, 11, 89].

In this work, we will consider the scenario in which gamma-ray propagation is modified due to the introduction of axions and ALPs (Section 2.2) and, in particular, due to photon-ALP conversions (Section 2.2.1) occurring within different astrophysical environments that the gamma rays must traverse in their cosmic journey beginning with their emission in distant blazars (Section 2.3) and concluding with their detection, at which point their spectra will contain features that might differ from the expected EBL attenuation (Section 2.4.1).

This scenario begins with the emission of gamma rays from a blazar source. The photons must then traverse cosmological distances across the intergalactic medium (IGM), a diffuse ionized medium made up of mostly hydrogen and helium at extremely low densities, with an electron number density of $n_e \sim 10^{-7} \text{ cm}^{-3}$ [12], that occupies the space between galaxies [90] and which also contains the EBL photons. An intergalactic magnetic field (IGMF) is thought to be present within the IGM, which could allow for photons to convert into ALPs. Although its exact properties are largely unknown, including its field strength and morphology, the IGMF is thought to be highly turbulent, presenting low field strength values currently bounded to the approximate range $10^{-15} \text{ G} \lesssim B \lesssim 10^{-9} \text{ G}$ [91] over coherence lengths of order 1 Mpc [12]. In this magnetic field, some photons could get converted into ALPs, which would

then propagate across the IGM without interacting with the EBL photons, and thus not suffering any attenuation. Due to the uncertainties in its morphology, the IGMF is modeled by considering a sequence of domains, each with a length equal to the coherence length, with a magnetic field strength within the observational bound randomly oriented [12].

Once the photon-ALP beam has reached our galaxy, in which a much higher electron number density of $n_e \approx 1.1 \cdot 10^{-2} \text{ cm}^{-3}$ is present [12], the magnetic field of the Milky Way may again act as a conversion environment where a fraction of ALPs could re-convert into detectable gamma-ray photons. Unlike the IGMF, the galactic magnetic field (GMF) has been widely studied and numerous models have been developed that describe it. In this work we will consider the Jansson-Farrar (2012) model [92] which, based on observational data, describes the GMF as a three-component field consisting of a disk field, an extended toroidal halo field, and an out-of-plane field.

As a consequence of this scenario, a fraction of the original emitted gamma rays convert into ALPs within the IGMF, and travel unaffected by the EBL or any other attenuation, until reaching the Milky Way. Within the GMF, a re-conversion may occur, producing an overall increase in the number of photons compared to the expectation from EBL absorption alone. In this case, the relation given by Eq. (30) now contains a photon survival probability $P_{\gamma\gamma}$ which includes the effects of both the EBL absorption acting on the gamma rays, and the effects of photon-ALP conversions.

In the astrophysical propagation scenario discussed here, we are considering exclusively the magnetic fields present in the IGMF and the Milky Way, which provide a minimal setup under which searches for spectral upturns can be performed. This represents a necessary simplification, as including additional environments severely complicates the ALP simulation and the required methodology and statistical treatment. However, several other magnetic fields could also significantly affect the results. In particular, it is also possible to consider the magnetic fields within the host galaxy [93] or its components [12], the blazar jet [94], and other galaxies or clusters of galaxies if present within the line of sight [95, 96]. All of these environments present magnetic fields, allowing for photon-ALP conversions to occur within them [12, 97].

3 Instrumentation and observational data

DETECTING increasingly energetic electromagnetic radiation has proven to be a highly complex task, in particular for energies surpassing magnitudes of 10 MeV, presenting unique experimental challenges that distinguish it from the detection of higher wavelength photons. In fact, gamma-ray observatories must approach this problem with techniques often used in high-energy particle detector, rather than typical astronomical approaches. Additionally, gamma-ray photons span multiple decades of energies, from 100 keV to more than 100 TeV, strongly suggesting the need for more than one observational technique to effectively cover the entire potentially detectable energy range [98].

When attempting to develop such gamma-ray observatories, we must consider the interactions that these highly energetic photons might suffer when they arrive at Earth, in particular, due to pair production and bremsstrahlung in the atmosphere, which will lead to important

energy losses and preventing direct gamma-ray photons from reaching the ground. Indirect gamma-ray detection with ground-based observatories is still possible, as we will soon see, by measuring the emission from the electromagnetic showers these highly-energetic incident gamma rays cause in the atmosphere. An alternative detection strategy is also possible by placing the detectors outside the influence of the atmosphere, developing space-based instruments, which does allow for direct gamma-ray detection although with a limited sensitivity due to the limited detector size. In this way, a multi-instrument approach is particularly useful, as it would allow for the study of HE gamma rays via space-based instruments and simultaneous VHE observations from ground-based telescopes, thus covering a large range of observable energies.

In the following, the fundamental working principles of two gamma-ray telescopes will be introduced, whose observational data will be used throughout the analysis presented in this work: the ground-based High Energy Stereoscopic System (H.E.S.S.) (Section 3.1), which enables us to study the energy range where we expect the characteristic upturns caused by photon-ALP conversions to occur, and the *Fermi* Large Area Telescope (LAT) (Section 3.2) which allows us to extend our intrinsic spectral analysis to lower energies thus placing a stronger constraint on the shape of the spectral model. In Section 3.3, we will then switch our focus towards the data produced by these telescopes, the software used, how the data is processed at the level of individual observations (Section 3.3.1) and the fundamental statistical framework for the main data analysis and modeling (Section 3.3.2) Finally, Section 3.4 will provide an overview of the source selection for this project, including which observations were considered as our main data to analyze, as well as the considered instrument configuration.

3.1 Ground-based Imaging Atmospheric Cherenkov Telescopes (IACTs) and the High Energy Stereoscopic System (H.E.S.S.)

HIGHLY energetic primary cosmic rays arriving to Earth, typically consisting of protons, electrons, nuclei, and photons, suffer numerous interactions as they encounter different kinds of particles and molecules found in the upper levels of the atmosphere, producing a sequential cascade of secondary particles in the form of atmospheric particle showers. Depending on the nature of the original cosmic ray and its energy, whether that is a charged particle or an energetic gamma-ray photon, different interactions will become important. In either case, a cascade or shower of secondary particles will develop as a consequence of sequential and repeated interactions, such that the initial energy of the cosmic ray will be effectively dissipated over a spatially-extended area across numerous secondary particles. In order to study this process in detail, we must therefore make a distinction between hadronic and electromagnetic showers.

Let us begin by considering the case of an electromagnetic shower, initiated by a cosmic gamma ray entering our atmosphere. The relevant energy-loss processes are therefore pair-production and bremsstrahlung.

The process of pair-production occurs due to a highly-energetic photon which, when interacting with a nucleus N , generates an electron-positron pair: $\gamma + N \rightarrow e^- + e^+ + N$. The minimum threshold energy of the original gamma ray for this process to occur is given by the sum of the rest masses of the produced particles $2m_e c_0^2$ (approximately 1.022 MeV, with c_0 the speed

3.1 Ground-based imaging Cherenkov telescopes and the High Energy Stereoscopic System (H.E.S.S.)

of light in vacuum) [99]. The pair-production process allows for the conversion of the original photon into a pair of charged particles which can, in turn, interact with the nuclei in the atmosphere such that their trajectory is modified and their velocity decreases. This energy loss is carried out via the emission of a bremsstrahlung photon $e^\pm + N \rightarrow e^\pm + N + \gamma_{\text{brem}}$. These photons could then again participate in pair-production processes, generating more charged particles that will emit bremsstrahlung, and thus generating a cascade of secondary particles until the energies dissipate below the threshold of pair-production, at which point other, lower-energy interactions must be considered.

In the alternative scenario of the atmospheric shower being initialized by a charged cosmic ray, a similar particle cascade will develop, although in this case, the main processes involved will include interactions that produce secondary charged particles which may then decay into additional photons (e.g. via the π^0 decay chain) or, for example, muons $\mu^\pm$, which contribute to the muonic component of the shower. This process also occurs iteratively, leading to additional pair-production and bremsstrahlung, with energies eventually falling below the relevant threshold for these processes.

Both types of atmospheric showers will produce highly-energetic charged particles, whose velocities could be above the speed of light in the atmosphere, considered a dielectric medium with a (altitude-dependent) refractive index n . When this occurs, $v > c_0/n$, the particle will cause an asymmetric polarization pattern in the medium, whose relaxation will lead to the emission of photons, Cherenkov radiation, in the direction of propagation, with an opening angle $\cos \theta_c = c_0/(vn)$ (which also depends on the height) [100]. This radiation produces a continuous spectrum with a peak in the UV range, and is very short-lived, lasting only a few nanoseconds [6].

The detection of Cherenkov radiation therefore provides a way of indirectly observing the properties of the incident gamma rays, and is the fundamental working principle behind imaging atmospheric Cherenkov telescopes (IACTs), providing some of the most sensitive detector design for observing high energy gamma rays above 50 GeV and into the VHE range above 100 GeV [98]. Importantly, the energy dependence of the opening angle of the Cherenkov radiation allows for the distinction of radiation originating from electromagnetic and hadronic showers.

Perhaps one of the most successful types of IACTs developed and currently in operation is the High Energy Stereoscopic System (H.E.S.S.), depicted in Figure 6. This observatory consists of an array of five telescopes located in the Khomas highland region of Namibia, Africa, at an altitude of about 1800 m above sea level, known for good observational and atmospheric conditions [101]. All of its telescopes are mounted on altitude-azimuth mounts allowing for precise tracking of positions in the sky [98], and a design offering small fields of view (comparable to the angular size of the Cherenkov radiation cone) is chosen in order to reduce as much as possible the contribution of the night sky background radiation, which is the dominant background observed [102].

The operation of this observatory can be divided into two main phases. The first phase, HESS-I, began in December 2003 after the construction and commissioning of four telescopes, denoted CT1-4. Each telescope contains 382, 60 cm in diameter, remotely-adjustable round mirrors arranged in a Davies-Cotton hexagonal configuration with a total diameter of 13 m.



Figure 6: Image of the High Energy Stereoscopic System (H.E.S.S.) at its location in Namibia. The larger telescope in the center is the second phase upgrade CT5, while the smaller telescopes correspond to CT1-4. Credit: S. Wagner, H.E.S.S. Collaboration [69].

This offers each telescope a large effective surface area (107 m^2) that enables the focusing of the faint Cherenkov radiation onto the camera sensors located at a distance of 15 m from the mirrors. Each camera is constructed by a hexagonal arrangement of 960 photomultiplier tubes (PMTs), with each having a field of view of 0.16 deg in diameter on the sky, with a total field of view of 5 deg in diameter [103], and trigger rates of the order of the Cherenkov light [102]. This configuration offers an overall lower-energy threshold of approximately 100 GeV [33].

The second major phase of the experiment began in July 2012, with the inclusion of an additional, larger CT5 telescope, with a rectangular parabolic configuration with an equivalent diameter of 28 m composed by 876 hexagonal mirrors of 90 cm in diameter, with a focal length of 36 m at which the camera is located. This configuration offers a larger 614 m total area, lowering the energy threshold to $\sim 30\text{ GeV}$ [98] and thus allowing the detection of fainter electromagnetic showers. Event reconstruction algorithms have been updated to make sure this new telescope can be used in both a stereoscopic configuration combined with the other four telescopes, and a monoscopic setting [98, 104].

Additional upgrades were carried out between 2015 and 2016 of the camera electronics of the original four CT1-4 telescopes, in the so-called HESS-1U era. A major upgrade to the CT5 camera was carried out in October 2019, which began the current HESS-FC (FlashCam) era of the H.E.S.S. mission [101]. This new CT5 camera consists of 1758 PMTs, each offering a smaller 0.08 deg field of view for a total field of view of 3.2 deg [69].

Data taken by H.E.S.S. consists of a sequence of individual observational runs, each lasting on average 28 min (depending on atmospheric conditions or possible technical interruptions) during which the telescopes are pointing and tracking a specific position in the sky [105]. The telescopes must be operated in clear, moonless nights to ensure the faint Cherenkov light can be detected [98]. Each observation is typically performed in the so-called “wobble mode”, where the pointing direction is slightly offset from the target position enabling simultaneous background estimation [104].

The cameras in all telescopes then construct images corresponding to the detected atmospheric showers. The utilization of various telescopes in a stereoscopic configuration is an essential

3.2 Space-based pair-conversion gamma-ray telescopes and the *Fermi* Large Area Telescope (*Fermi*-LAT)

feature, providing an increase in the accuracy of reconstructing the original gamma ray against utilizing a single telescope, since this way additional positional information on the air shower can be obtained [106].

A set of Hillas parameters [107] are then computed that can be used to reconstruct the properties of the original gamma ray, as well as serve as an additional filter for removing the hadronic shower background. The telescope images can also be used as an additional data quality selection filter, by rejecting events taken during bad weather conditions, a bad mean trigger rate, or issues in the electronics, such as dead camera pixels [33]. In the later Section 3.3.1 we describe in more detail how this reconstruction occurs and how the backgrounds are estimated.

3.2 Space-based pair-conversion gamma-ray telescopes and the *Fermi* Large Area Telescope (*Fermi*-LAT)

SPACE-BASED detection of gamma rays is typically performed by instruments based on event reconstruction from the properties of particles generated via pair-production processes within their interior. In this project, we will focus our attention on the currently most sensitive such space-based detector, the *Fermi* Large Area Telescope (*Fermi*-LAT), launched aboard the *Fermi* Gamma-ray Space Telescope (FGST, formerly GLAST) on the 11th of June 2008 with operations and data acquisition beginning shortly thereafter. The satellite itself contains two instruments, the main gamma-ray observatory in the form of the LAT [108], and a Gamma-ray Burst Monitor (GBM) [109].



Figure 7: Computer rendering of the *Fermi* Large Area Telescope (LAT) in orbit. Credit: C. Smith, NASA's Goddard Space Flight Center (USRA/GESTAR) [110].

The LAT detects gamma rays by measuring the trajectory, energy, and arrival time of the electron-positron pairs produced via photon pair-production in its interior, employing a sequence of instruments on-board that enable this pair production process, detect and track their positions over time, and automatically reject the signal originating from charged cosmic rays.

The satellite, depicted in Figure 7, is located on low-Earth orbit (at an approximate altitude between 520 and 540 km above ground level), completing a full orbit every 95.33 min, with a total effective collection area of 0.65 m^2 (above 1 GeV), out of which 80% is the tracker

area sensitive to gamma-ray photons with energies between 20 MeV and 300 GeV. The LAT offers a large field of view of 2 sr and a high energy-dependent angular resolution that reaches 0.2 deg at energies above 10 GeV [102]. In contrast to H.E.S.S. or other pointing ground-based observatories, the *Fermi*-LAT is designed in such a way that it performs a continuous survey of the gamma-ray sky, always pointing away from the Earth and following an alternating path to allow for an equal exposure time across the full sky [98].

The instrument itself can be divided into three main components. The first component is the converter-tracker, constructed with a combination of 36 layers of silicon microstrip detectors interleaved with 16 layers of tungsten foil (out of which 12 are at the front part of the instrument, and 4 in the back) [111]. The employment of converter foils with high atomic number facilitates the pair-production process, whose cross-section at high energies typically scales with the atomic number [102]. Whenever a gamma-ray particle arrives at the tracker, it will eventually interact via a pair-production process, $\gamma + N \rightarrow e^- + e^+ + N$, in which the incident particle converts into a pair of charged particles. These charged particles will then travel across the silicon detectors, which through scintillation will provide a way of detecting where the particle hit each foil. As the charged particles travel across the foils, they will leave behind a trail through which we can track their position over time. By combining the tracks of both pairs of particles, the original directional properties of the incident particle can be reconstructed.

The second main component of the LAT is the calorimeter. After the charged pair of particles is produced and they travel across the full length of the tracker, they will encounter a calorimeter, consisting of a section of an 8 layers arrays of caesium-iodide crystal scintillators which generate a signal proportional to the energy of the particle, which is then measured by photodiodes. The measurement of this signal therefore allows for the reconstruction of the energy carried by the original incident particle on the LAT [98].

Finally, the third main component of the instrument is an external layer of plastic scintillators which surrounds the LAT and acts as a filtering shield for rejecting any unwanted signal detected by the instrument. This autocoincidence detector is triggered whenever an unwanted charged cosmic ray, considered as background noise, arrives at the telescope, producing a signal detected by photomultiplier tubes (PMTs) that is used as a veto to reject any detection in the tracker or calorimeter due to charged particles. Typically, the instrument is triggered at a rate of approximately 3 kHz, mainly due to proton background signals, and approximately 90% of those events are rejected automatically by this detector [98].

3.3 Data analysis framework for gamma-ray astronomy

IN the following sections, general approaches to the data analysis methodology used within gamma-ray observatories are presented, focusing particularly on the two telescopes introduced in the previous section: the *Fermi*-LAT and H.E.S.S. Despite the important differences they present in detecting and reconstructing gamma-ray photons, thanks to the great efforts of the community a standardized data handling workflow has been developed using publicly available and open-source tools and file formats, allowing for applying a consistent workflow for the data analysis across multiple instruments [112]. Similarly, great effort has been put into developing a consistent statistical likelihood-based modeling methodology, and essential

component that allows to adequately analyze the limited, sparse, and background-dominated photon count data [113, 114, 115].

The overall data analysis methodology followed in this work can be divided into two steps: an initial data reduction process, and the high-level data analysis. The data reduction begins by considering the individual low-level photon detection data from each telescope and, by combining it with instrument-specific response functions, generating data files that can then be used directly to perform the higher-level spectral analysis of each source. A brief summary of low-level data reduction process, which considers the raw observational gamma-ray data and processes it for compatibility with high-level analysis tools, is given in the following Section 3.3.1.

Once the data reduction process has been completed, the resulting analysis-ready Flexible Image Transport System (FITS) files are then utilized to perform the main data analysis, with which we may compute the final science products such as, for example, the light curves used to study the time variability of a source, or the modeling of its SED. This analysis relies heavily on the statistical likelihood-based modeling described in Section 4.

In this work, we will utilize `GammaPy` 2.0 [116] as the main analysis software, an open-source `Python` library which is quickly becoming a standard for single- and multi-instrument gamma-ray data analysis within the community, being fully compatible with data from both *Fermi*-LAT and H.E.S.S. For the case of LAT data, however, the initial processing must be performed in `FermiPy` 1.4.0 [117], a library based on `FermiTools` (formerly `ScienceTools`) with which we can generate the required files for analysis in `GammaPy` as well as run an additional preliminary analysis that serves as an additional cross-check.

3.3.1 Low-level data reduction and processing

BOTH *Fermi*-LAT and H.E.S.S. present numerous similarities in terms of how data is taken and processed, allowing us to define a general data processing, reduction, and analysis framework. The overall data reduction and processing can be subdivided into three main tasks: the reconstruction and selection of gamma-ray events, the generation or selection of instrument response functions (IRFs), and the background emission estimation.

The result of performing an observation with any of the considered gamma-ray telescopes will typically yield a list of photons counts detected by each instrument. Each count corresponds to a gamma ray with a “true” energy E_{true} arriving from a direction $\vec{P}_{\text{true}}$ that produces a signal in our detector. As we have seen throughout this section, rather than measuring these quantities directly, we must rely on reconstructing them from the measurement of secondary particles and their properties. Therefore, the best we can do is to obtain a set of reconstructed energies E and directions $\vec{P}$. The reconstruction process itself is heavily instrument-dependent, although it is also an essential component which directly affects the sensitivity of the telescope. Similarly, an additional event selection process must be applied to reject any noisy signal by maximizing the gamma-ray photon count while minimizing misclassified events.

The LAT reconstructs the gamma rays utilizing various algorithms with, as inputs, the tracks left by the electron-positron pairs in the tracker-converter, the energy measured in

the calorimeter, and the additional veto from the anticoincidence detector [118, 119]. Event selection is performed by applying various quality cuts on each detected event, both on-board the instrument and within the ground station, based on event types, zenith angle, or data quality and instrument operation cuts.

On the other hand, IACT reconstruction algorithms typically revolve around the obtained atmospheric shower images in each telescope which characterize the properties of the detected Cherenkov radiation. Originally, the reconstruction of the properties of the gamma rays producing the atmospheric shower were obtained from the computed Hillas parameters of the shower [107], which could then also serve as an additional rejection filter for hadronic showers due to their morphology. More advanced reconstruction algorithms have also been developed, leading to a substantial increase in the sensitivity of the telescopes, such as the template-based Image Pixel-wise fit for Atmospheric Cherenkov Telescopes (ImPACT) [120, 121], which performs likelihood-based fitting of the observed data onto pre-generated templates. Algorithms based on neural networks can also be used to improve the event reconstruction process [122, 123]. Data selection is performed by rejecting data taken in not optimal conditions, based, for example, on atmospheric conditions, resulting in irregularities in the reconstructed shower images [33]. Additional quality cuts can then be applied based on reconstruction-related parameters, allowing different event selection configurations optimized for specific analysis goals, with the standard configuration typically corresponding to a compromise between background rejection and signal efficiency based on the angular distance to the target (θ^2 distribution) of the reconstructed events.

In both cases, the way each instrument reconstructs the photons not only depends on the algorithm applied, but also on numerous parameters such as the external conditions under which the photon was detected or the operational status of the telescope and its numerous components, among many others. It is therefore necessary to include, along with the reconstructed photon data, information regarding how the telescope operated and what is the expected reconstruction signal from the instrument at the moment of observation. This is done by including a series of IRFs, which relate the properties of the reconstructed gamma ray with its true values. An exact determination of the IRFs is impossible, as the true properties of the incident gamma ray are never known, which is why probabilistic approaches must be considered, typically involving the performance of extensive Monte Carlo simulations, modeling the response of the instrument and the reconstructed properties for different incident gamma rays under different configurations of the telescope. The IRFs are an essential part in making sure the photon data is analyzed properly, and their quality directly affects the sensitivity of the instrument, requiring for the generation of reliable and high-quality IRFs [34, 119].

Typically, these IRFs can be factorized into the following distinct and independent components:

$$\text{IRF}(E, \vec{P}|E_{\text{true}}, \vec{P}_{\text{true}}) = A_{\text{eff}}(E_{\text{true}}, \vec{P}_{\text{true}}) \cdot \text{PSF}(E, \vec{P}|\vec{P}_{\text{true}}) \cdot E_{\text{disp}}(E, \vec{P}|E_{\text{true}}), \quad (35)$$

where each component corresponds to [33, 34]:

- The effective area A_{eff} describes the total effective available area for detection of the instrument, depending on the energy and direction of the incident gamma ray, as well as the limited detector efficiency.

- The point-spread function PSF, which quantifies the probability distribution function of the reconstructed photon direction given the true photon parameters. This can be conceptually thought of as the effective “spread” in spatial dimensions, or the apparent observed size of a point-like source.
- The energy dispersion E_{disp} , that quantifies the probability of an incident photon being reconstructed with a given energy. This factor is similar conceptually to the PSF but measuring the energy “spread” instead of the spatial “spread”. An energy dispersion bias parameter can be computed $E_{\text{disp, bias}}$ which quantifies the average deviation between the reconstructed and true energies.

For ground-based IACTs, the observations are carried out in a run-wise basis, with each observation performed under different atmospheric conditions, with varying positions of the target in the sky, including its zenith angle or possible offset with respect to the pointing directions. Therefore, in order to analyze H.E.S.S. data, it is required to generate IRFs for a large number of parameters and include them along each observation and its resulting photon count data [112]. *Fermi*-LAT, on the other hand, operates in a continuous sky-survey mode in mostly stable conditions outside any atmospheric influence, allowing for the development of stable IRFs that are available as complementary files to the photon counts, and which depend mainly on the orientation and operation status of the telescope or the event class [112]. Over time, these IRFs have been constantly updated, improving the sensitivity of the telescope, with the current so-called Pass 8 event analysis scheme representing the latest and most efficient IRFs available [34, 119].

Despite the fact that an event selection data filtering is applied initially to both *Fermi*-LAT and H.E.S.S. observations, an inherent background will still be present within our data mainly caused by other gamma-ray sources being present within the studied region, whether resolved or unresolved, or any diffuse emission from the galactic plane or isotropic sky background [98]. Additional sources of noise might also be present due to misclassified cosmic-ray events of hadronic showers, or noise from the components of each instrument. Therefore, as a last step, the background must be estimated and accounted for, which will also depend heavily on the instrument considered.

For the case of the LAT, the background can be estimated defining a full model of the region of interest studied, such that we include separately the source we want to study, along with any other known sources found nearby. Additionally, pre-generated background templates are made public along with each major IRF Pass release, including the diffuse galactic emission and an isotropic emission template. The type and initial parameters of the models for all the sources included are obtained from incremental *Fermi* Gamma-ray LAT (FGL) catalogs, with the latest 4FGL based on 14 years of data and containing more than 7000 identified sources [111, 124, 125]. The overall region is then fully modeled in a likelihood-based approach (as will be described in the next Section 3.3.2).

The background for observations from H.E.S.S. are generated for each observational run following a different approach. Performing the observations in “wobble mode” at an offset from the target source (typically ± 0.5 deg) allows for the simultaneous estimation of the background for each run directly from the observations of the target [104]. This is performed by, first, defining a circular on-region centered at the source (whose radius will usually

correspond to the desired quality cuts, justified from the angular distribution of the counts in this region, depending on the reconstruction algorithm). From this region, we may obtain a total of N_{on} counts. Similarly, off-regions are then defined, which will provide a photon count of N_{off} . There are two main methodologies for defining these regions.

The reflected-regions method places the off-regions following a circular pattern around the pointing direction, at the same radial distance or offset as the source. Similarly, the ring-background method places increasingly larger, concentric off regions centered at the target position [33].

In either case, additional exclusion regions of arbitrary size and shape may be placed to mask any known gamma-ray sources in the vicinity. A normalization factor α is then defined as the ratio of the exposure time, observed counts, and acceptance in each type of region. With this approach, we may estimate the number of counts attributed to the source as $N_{\text{src}} = N_{\text{on}} - N_{\text{bkg}}$, where the background counts are estimated as $N_{\text{bkg}} = \alpha N_{\text{off}}$ [126].

The described data reduction process and how it is performed will also differ depending on the considered instrument. The raw data obtained by the LAT is automatically processed by both its on-board instruments and the ground operations center station, thus not requiring any low-level data reduction or processing by the user. The IRFs and background templates are then developed and maintained by the *Fermi* team, and all data is made publicly available by the *Fermi* Science Support Center (FSCC) [127]. In order to ensure compatibility with `GammaPy`, an initial processing and setup step must be performed within `FermiPy` including as input the required processing configuration (such as the IRF version, which backgrounds to include, or the energy range of the photons considered). The resulting `FITS` files can then be loaded into `GammaPy`, which constructs the corresponding `Datasets` object containing the IRFs and all the sources in the RoI and backgrounds as `MapDataset` objects.

Data obtained by H.E.S.S. is available exclusively within the computational cluster of the collaboration, with smaller public data releases being made available mainly for testing purposes [105]. Therefore, in this case, a more thorough data reduction process is required in order to obtain the data for analysis. Typically, most of the data is processed by members of the collaboration and is made available internally as production data releases, using (among others) the ImPACT reconstruction algorithm with standard cuts covering most of the observational runs throughout the operational history of the observatory. However, in some cases (particularly, in the case of very recent data for which this process has not yet been completed, or considering alternative cuts or reconstruction configurations), these production releases do not contain the required observational runs, and a manual data reduction must be performed. This typically involves utilizing the internal H.E.S.S. Analysis Package (HAP) software, based on `ROOT` [128]. Once the `FITS` files have been generated or extracted from the low-level data, we can then complete the data reduction process within `GammaPy` by processing all runs (and defining the desired energy range, any safe masks on the energy range, and other additional data filtering), obtaining the final `SpectrumDatasetOnOff` objects (per observational run) ready for the main analysis.

3.3.2 Statistical data analysis framework and binned likelihood-based modeling

DEFINING the observations as a set of photon count data and IRFs allows for our approach to be compatible with a maximum likelihood analysis approach, based on the ideas developed for the EGRET mission (the precursor of the *Fermi*-LAT) [115].

Our main goal is to fully describe the gamma-ray emission of a source given a sequence of observations. This involves the development of a mathematical model $\phi(E, \theta) \sim dN/dE$ that would describe the observed differential photon flux or spectral energy distribution of that source in terms of a series of spectral parameters θ (examples of such spectral models relevant to our analysis are given in Section 2.3). Therefore, the problem reduces to finding the optimal parameters of our model that best fit the observed spectrum of the source. The approach followed to obtain these parameters is the likelihood analysis method, where a likelihood function $\mathcal{L}$ is defined that quantifies how well our model describes the observed data, and is then maximized over the spectral parameters, optimizing our model. In particular, a binned approach is applied, in which both the spectral and spatial dimensions of our data are divided into bins, combining individual photon events with similar energies and positions into the same bins, reducing the statistical noise and computational cost [129].

Applying a forward-folding approach in which we convolve our model with the IRFs, factorized as described in Eq. (35), over the full observation time t_{obs} , allows us to obtain an estimate of the expected photon distribution given by our model at each bin per reconstructed energy and direction [130]:

$$m_i(\theta; E, \vec{P}) dE d\vec{P} = t_{\text{obs}} \int \int dE_{\text{true}} d\vec{P}_{\text{true}} \text{IRF}(E, \vec{P} | E_{\text{true}}, \vec{P}_{\text{true}}) \phi(\theta; E_{\text{true}}, \vec{P}_{\text{true}}). \quad (36)$$

This offers us a (binned) photon count for our model m_i , which we may compare to the observed photon count n_i . In practice, this integral is performed numerically by performing an additional binning over the true energy and direction and computing the sum across these bins [129].

Typically, the observed signal consists of a sparse distribution of photons corresponding to discrete, low frequency events. It is therefore usual to assume the photon counts will be distributed following a Poisson distribution. The probability of detecting a certain number of counts n_i in a given bin i is then given by:

$$p_i(n_i | m_i) = \frac{m_i^{n_i} e^{-m_i}}{n_i!}. \quad (37)$$

The likelihood $\mathcal{L}$ can then be defined as the product of this binned probability multiplied across all bins (both spatial and spectral, as required by the instrument or analysis approach) [112]:

$$\mathcal{L}(\theta) = \prod_{i=1}^{N_{\text{bins}}} p_i(n_i | m_i). \quad (38)$$

Usually, minimizing the log-likelihood is much more convenient numerically, defined such that:

$$\log \mathcal{L}(\theta) = \sum_{i=1}^{N_{\text{bins}}} [n_i \log(m_i) - m_i]. \quad (39)$$

In practice, it is also useful to define a fit statistic closely related to the log-likelihood as $S(\theta) = -2 \log \mathfrak{L}$. Depending on the instrument considered and the way the background model is obtained, this is computed via different approaches. For the case of *Fermi*-LAT, where the background is fully modeled, the relevant fit statistic is the Cash statistic, defined as [131]:

$$C_{\text{stat}} = -2 \sum_{i=1}^{N_{\text{bins}}} [n_i \log(m_{i,\text{src}} + m_{i,\text{bkg}}) - (m_{i,\text{src}} + m_{i,\text{bkg}})]. \quad (40)$$

H.E.S.S. obtains the background counts separately via off-region observations, which requires a more nuanced treatment by defining the following W-statistic [130]:

$$W_{\text{stat}} = -2 \sum_{i=1}^{n_{\text{bins}}} \left[n_{i,\text{on}} \log(m_{i,\text{src}} + m_{i,\text{bkg}}) + n_{i,\text{off}} \log\left(\frac{m_{i,\text{bkg}}}{\alpha}\right) - m_{i,\text{src}} - \left(1 + \frac{1}{\alpha}\right) m_{i,\text{bkg}} \right], \quad (41)$$

where $n_{i,\text{on(off)}}$ represent the on-region (off-region) counts, and similarly $m_{i,\text{src(bkg)}}$ the estimated source (background) counts, for each bin, and α the normalization factor between the on-region and off-region. In the case where data from multiple N_{inst} instruments is modeled jointly, the described approach can easily be extended by combining all likelihoods as [112]:

$$\mathfrak{L}_{\text{joint}}(\theta) = \prod_{j=1}^{N_{\text{inst}}} \mathfrak{L}_j(\theta) \iff \log \mathfrak{L}_{\text{joint}}(\theta) = \sum_{j=1}^{N_{\text{inst}}} \log \mathfrak{L}_j(\theta). \quad (42)$$

Both the C -stat and W -stat are implemented within **GammaPy** such that the treatment of these statistics is automatic, and the total statistic resulting from the joint modeling (denoted as `total_stat`) combines both approaches in a compatible manner.

With the relevant likelihood functions now defined, we can now attempt to modify the parameters of our model to maximize it and find the optimal set of parameters. This optimization problem is carried out by numerically minimizing the log-likelihood (or, equivalently, maximizing the likelihood function), via the backend **IMINUIT** available for use in **GammaPy** which implements numerous minimization algorithms [132].

Once the best-fit parameters are found, we can then go on and compare different models or parameter choices, which essentially reduces to a model or hypothesis testing problem, where a null hypothesis model with parameters θ_0 is tested against an alternative with θ_1 . Simply comparing the resulting (log) likelihoods of each fit is not enough, as one could obtain increasingly high-valued likelihoods by simply adding parameters to the model, thus a more nuanced approach is required by defining a proper test statistic (TS) that will quantify how much the data prefers one model versus another. A standard approach is to consider following log-likelihood ratio test (LRT):

$$\text{TS} = -2 \log \frac{\mathfrak{L}_0(\theta_0)}{\mathfrak{L}_1(\theta_1)} = -2 [\log \mathfrak{L}_0(\theta_0) - \log \mathfrak{L}_1(\theta_1)] = S_0(\theta_0) - S_1(\theta_1), \quad (43)$$

such that higher values $\text{TS} > 0$ imply preference for the alternative hypothesis model.

An important consequence of this TS comes from its asymptotical behaviour given by Wilks' theorem [133], which states that, asymptotically, the log-likelihood ratio TS will approach the

chi-squared χ^2 distribution under the null hypothesis with degrees of freedom corresponding to the difference in dimensionality within the parameter spaces between the considered models [134]. Formally, this theorem applies whenever the models are nested, that is, where the null hypothesis can be obtained from the alternative model by considering a certain parameter selection (this will be especially relevant in Section 6, when we discuss the statistical comparison between the fundamentally non-nested ALP and no-ALP models in our study). This parameter choice must also not correspond to values on the boundary of the allowed parameter range, although generalizations of the theorem exist, such as Chernoff’s theorem [135] which allows for the application of Wilks’ theorem as an approximation [134]. In the particular case where the models differ by a single parameter, the TS will then follow χ^2_1 , and the significance of the alternative model against the null hypothesis can be approximated as:

$$\sigma_{\text{TS}} = \sqrt{\text{TS}} [\sigma]. \quad (44)$$

In some cases, especially in **FermiPy**, this statistic is often reported per source, comparing the likelihood with and without that source included in the RoI model.

Another important application of this theorem is the study of whether an observation leads to the positive detection of a source, or whether an additional source must be included within the model, and at which statistical confidence level this detection could be claimed to be. This is again a hypothesis testing problem, with one of the models (the null hypothesis) presenting a vanishing flux amplitude parameter $N_0 = 0$. For the case of *Fermi*-LAT observations, this can be performed directly by comparing the TS value these models offer as shown in Eq. (43). In the case of H.E.S.S. observations, however, an alternative approach has been developed in order to adequately compute the statistical significance considering on-off region observations. This is given by the Li & Ma (1983) significance formula [113]:

$$\sigma_{\text{Li \& Ma}} = \sqrt{2} \left[N_{\text{on}} \log \left(\frac{1 + \alpha}{\alpha} \frac{N_{\text{on}}}{(N_{\text{on}} + N_{\text{off}})} \right) + N_{\text{off}} \log \left((1 + \alpha) \frac{N_{\text{off}}}{N_{\text{on}} + N_{\text{off}}} \right) \right]^{1/2} [\sigma], \quad (45)$$

which is the standard way of claiming detection significance when the background is obtained directly from off-region observations. This expression can also be directly obtained by following the same underlying likelihood approach as the one used to derive the W-stat defined in Eq. (41).

3.4 Source selection, observation periods, and instrument configuration

HAVING presented the fundamental theoretical background of this work as well as the instrumentation used and the methodology we will apply in order to perform the main analysis, we are now in the position of describing the kinds of gamma-ray sources we are mainly interested in studying for spectral hints of photon to ALP conversions. In particular, we will adopt an approach in which a dataset of numerous sources is used to perform a statistically robust search for upturns, making sure that our results do not depend on a single, particularly favorable case, but rather reflect an overall trend accross multiple sources.

As mentioned in Section 2.3, blazars are very good candidates for sources of high and very high energy gamma rays due to their jet being aligned with our field of view. In particular, we are interested in high-frequency-peaked BL Lacertae (HBL), which present their second

SED peak in the X-ray and gamma-ray bands. However, we also allow other types of blazars in order to increase our statistics, as long as they present emission in the optically thick regime (with optical depths above $\tau > 2$). On the other hand, we require that the redshift of each source must be high enough as to present EBL attenuation at our considered energy ranges (such that any upturn could be detectable above the expected attenuated signal), but not high-enough as to completely remove any VHE emission. In our case, we have an overall redshift range of $0.1 < z < 1.0$. Of course, as with any point-like source analysis, we require sufficient observation time performed on the source, and a detection with enough statistical significance. We also preferably select sources where no strong confusion is present as to any other sources present in the near vicinity. The main limitation for these conditions will come from H.E.S.S. observations, as due to its pointing nature observation time of any sky region will be limited, while *Fermi*-LAT allows for a continuous observation of all the sky. As mentioned previously, the main hints of photon-ALPs upturns will be found in the H.E.S.S. energy range, and the observations from *Fermi*-LAT will serve as a lower-energy constraint on the intrinsic spectrum.

Since blazars are highly variable sources, it is not enough to select just the targets of our study, but also perform a time selection. In particular, we will be interested in both long-term observations of non-variable or quiescent sources (which we can usually consider across the whole observational campaign) and in periods where a source exhibits flaring, where the flux intensity increases drastically over highly variable time scales (that could last between months to just a few minutes). Ideally, all sources would be observed by both instruments considered during the same observational periods. However, in this case, the *Fermi*-LAT data acts as the main limitation, as the H.E.S.S. observational operation predates it by almost 6 years. Therefore, an important time selection consideration must be performed for each one of the sources.

When selecting observational periods, we are mainly interested in selecting start and end dates for each source in which observations from both *Fermi*-LAT and H.E.S.S. are available, which as mentioned can only occur for observations after August 2008. Whenever this selection is met, we can be sure that we are observing the source at the same physical emission state. However, in some cases, good candidates are observed before this time period, and a careful individual treatment is required. For those sources that have been found to have no strong flaring period (that is, their flux emission is approximately constant over long periods of time), and whose observations with H.E.S.S. predate the *Fermi*-LAT observation mission either fully or in part, an average of 14 years of data (from 04-08-2008 15:43:36 UTC to 04-08-2022 15:43:36 UTC) has been considered for the *Fermi*-LAT observations, ensuring enough count statistics and at least a similar emission state. However, there are cases where the H.E.S.S. observations show significant variability and flaring periods that predate the *Fermi*-LAT. In these cases, taking the average again would result in mixing different physical states of our source, and the spectral energy distribution modeling will turn out to be completely unreliable. Therefore, in these case, an exception to the rule must be made and only H.E.S.S. data is considered.

The main data selection is motivated by the available H.E.S.S. observation for our sources of interest, which have been selected following previous and related studies [32, 35, 52, 136]. Table 1 summarizes all 14 sources considered, including their position in the sky, redshift, and

3.4 Source selection, observation periods, and instrument configuration

specific kind of blazar type they can be classified as. Similarly, Figure 8 shows the position of all these sources in a sky map.

Most of these sources correspond to high-peaked BL Lac objects (HBL), which usually correspond to the most energetic emitters within the blazar class, with three FSRQ objects and a single IBL also present. All of these sources have published H.E.S.S. detections, with available contemporaneous *Fermi*-LAT data for all except PKS 2155-304 and H 2356-309, for which we have considered data from H.E.S.S. only. Out of all these sources, 11 correspond to those considered in previous analyses [35], and three new sources have been added as a contribution to the dataset: 3C 279 (bright flare in January 2018 [137]), PKS 0346-27 (single detection night 3-4 November 2021 [138]), and PKS 0903-57 (six-night observation campaign in April 2020 [139]). These sources were selected as they present detected emission within their optically thick energy regime.

Source Name	Position (RA, DEC) [deg]	Redshift z	Type	Ref.
1ES 0229+200	38.2025, 20.2880	0.139	HBL	[140]
1ES 0347-121	57.3467, -11.9908	0.188	HBL	[141]
1ES 0414+009	64.2183, 1.0900	0.287	HBL	[142]
1ES 1101-232	165.9071, -23.4919	0.186	HBL	[143]
1ES 1312-423	198.7642, -42.6139	0.105	HBL	[144]
1RXS J101015.9-311909	152.5662, -31.319	0.142	HBL	[145]
3C 279	194.0415, -5.7887	0.535	FSRQ	[137]
H 2356-309	359.7825, -30.6275	0.165	HBL	[146]
PG 1553+113	238.9293, 11.1901	0.434	HBL	[147]
PKS 0346-27	57.1538, -27.8215	0.990	FSRQ	[138]
PKS 0447-439	72.3529, -43.8358	0.343	HBL	[148]
PKS 0903-57	136.2315, -57.5833	0.262	IBL	[139]
PKS 1510-089	228.2106, -9.1000	0.361	FSRQ	[149]
PKS 2155-304	329.7167, -30.2256	0.117	HBL	[150]

Table 1: Summary table containing the selected sources names, their position in the sky as the right ascension and declination in degrees within the International Celestial Reference System (ICRS, with positions at epoch J2000) [151], and their measured redshift. The source type classification is obtained from the TeVCat catalogue [70]. The naming convention of each source follows the corresponding catalog where each source was first detected or studied in detail. For each source, we also include the reference article in which the source was first detected at TeV-energies.

For H.E.S.S., we select exclusively data obtained by the four CT1-4 telescopes, excluding CT5 to avoid combining different configurations or introducing further systematic uncertainties. Only observations with zenith angles below 60 deg were considered. The reconstruction configuration for all sources used was **ImPACT**, with standard cuts across most sources. In the case of 3C 279 and PKS 0346-27, loose cuts were utilized, which allow for more photons to

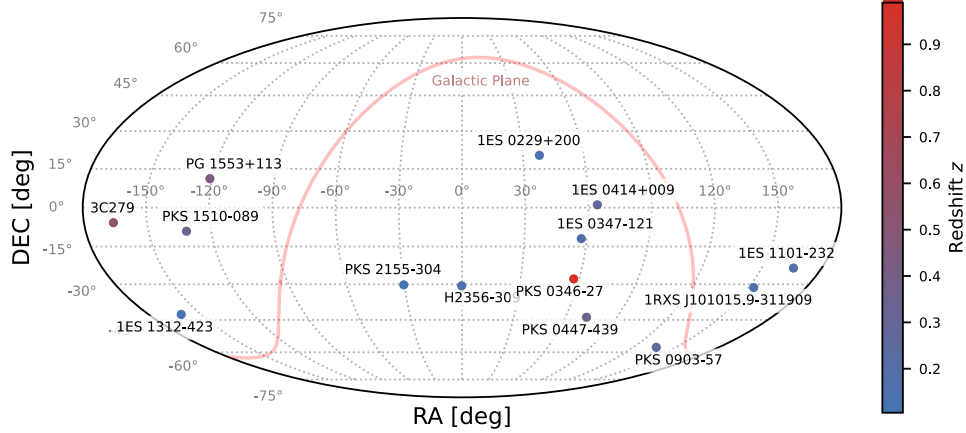


Figure 8: Sky map of all the sources considered in this work, represented in the ICRS using the Mollweide projection in equatorial coordinates. The associated redshift of each source is represented by its color. Also plotted in faint red is the galactic plane.

be reconstructed and increases the overall photon statistics, which is particularly useful for observations with relatively short total exposure times. Exceptionally, for PG 1553+113, the hybrid configuration was used, with a larger on-region radius, which improved the numerical convergence for this source. This does not affect the analysis itself, as we only consider observations taken exclusively with CT1-4. In both the standard and loose cut configurations, the on-region radius was selected to be the default optimal value for each configuration. The data, covering the energy range from 0.1 to 31.6 TeV, was taken in wobble mode with an offset of 0.5 deg, allowing for background estimation using the reflected-regions method. Exclusion regions were found to not be required for most of the sources, except for the case of 1ES 1312-423 due to its proximity with Centaurus A, which was masked. The dataset was generated by considering the counts, exposure, and energy dispersion data, with a safe mask on the energy constructed by selecting only energies for which the dispersion bias is above 10%. An additional offset filter was included, rejecting any observation in which the pointing direction was separated by more than 2.5 deg from the target position. In order to obtain this data, a manual low-level data extraction was performed with the internal software HAPTools, with subsequent processing and reduction in GammaPy.

The *Fermi*-LAT data was obtained directly from the publicly available data center service, considering the time selection contemporaneous to the H.E.S.S. data whenever possible as mentioned earlier. During the data querying, a search radius of 20 deg from the target position was considered, in an energy range between 1 and 300 GeV, obtaining both the photon counts and spacecraft (IRF) data. Following the recommended analysis for point-like sources, we pair this data with the latest Pass 8 IRFs associated to the SOURCE event class, considering events detected from both the front and back of the instrument. A zenith angle cut of 90 deg was also considered in order to remove any Earth limb emission effects. The diffuse background templates were also obtained in accordance to the IRFs and event class considered, given by the Galactic diffuse emission template `gll_iem_v07` and the isotropic emission from `iso_P8R3_SOURCE_V3_v1`. The latest, 4FGL DR4 catalog `gll_psc_v35` was also

considered as the initial spectral model for all the known gamma-ray sources that may be present within the RoI.

4 Intrinsic spectral energy distribution modeling

OUR analysis begins with a study of the spectral energy distribution of our sources. A thorough intrinsic SED analysis is essential for our study, as it will serve as the baseline model throughout our work. Due to the extreme time variability often exhibited by blazars, it is equally important to also adequately consider, within the available observation periods, which time segments can be treated as corresponding to a single emission state, and which correspond to either flaring or low-emission periods.

Section 4.1 begins with an initial study of the H.E.S.S. data, obtaining the main properties of all available observations and the total statistical detection significance of each object. An initial spectral fit is also performed, which will serve as a baseline for the computation of the corresponding light curves which display the variability of a source in both its spectral flux and index. A time variability analysis is then performed, allowing us to obtain a final segmentation of our observations into separate time blocks.

We then move on to study each one of these time blocks separately, with the certainty that physically different emission states are treated individually. The main intrinsic spectrum analysis will then be performed sequentially, beginning with the *Fermi*-LAT analysis in Section 4.2, analysis of H.E.S.S. data in Section 4.3, and finally obtaining the joint model for both instruments in Section 4.4.

4.1 Initial spectral fit, time variability analysis, and segmentation of H.E.S.S. data

TO gain an overall perspective on the general attributes of the available H.E.S.S. data (which, at this stage, are stored as individual `SpectrumDatasetOnOff` objects within `GammaPy` for each observation and source), we begin by computing the good time intervals (GTIs) for each observation, enabling us to determine the total exposure time for each target. A time selection is performed between the minimum and maximum edges of all GTIs, and the per-observation datasets are stacked into a single `SpectrumDatasetOnOff` object. An energy binning is defined, considering 4 bins per decade between the energy ranges 0.1 and 31.6 TeV. For each source, the total Li & Ma significance [113] is computed following Eq. (45) and the corresponding `GammaPy` implementation via `WStatCountsStatistic`. The total available observation time and their corresponding dates, as well as the Li & Ma significance, can be found in Table 2.

The detection significance varies considerably across our sources, and it is highly correlated to the total time each source has been observed, which is the expected behavior. An exceptionally bright source turns out to be PKS 2155-304, with a significance of 327.27σ obtained after 68.1 hr of observation time. Most sources present significances between 10σ and 50σ with highly variable observational times. The least significant source considered is PKS 0346-27, which is also expected due to the very short observation period, since in this case only a single detection night is selected.

4 INTRINSIC SPECTRAL ENERGY DISTRIBUTION MODELING

Source	Available data [hr.]	Time range [DD.MM.YYYY]	Significance [σ]
1ES 0229+200	167.279	11.09.2004 – 08.01.2019	26.609
1ES 0347-121	55.010	26.08.2006 – 31.12.2013	19.212
1ES 0414+009	82.226	03.10.2005 – 17.10.2010	10.933
1ES 1101-232	104.867	17.04.2004 – 28.05.2019	24.942
1ES 1312-423	115.879	15.04.2004 – 12.07.2010	8.545
1RXS J101015.9-311909	56.207	11.02.2007 – 17.04.2010	10.080
3C 279	3.553	24.01.2018 – 29.01.2018	13.420
H 2356-309	169.702	16.06.2004 – 08.11.2009	31.250
PG 1553+113	76.230	25.07.2006 – 03.05.2019	36.167
PKS 0346-27	1.870	03.11.2021 – 04.11.2021	3.772
PKS 0447-439	18.480	09.11.2009 – 07.12.2010	10.446
PKS 0903-57	13.675	13.04.2020 – 17.04.2020	45.946
PKS 1510-089	22.623	20.03.2009 – 10.05.2016	6.323
PKS 2155-304	68.094	30.06.2006 – 20.09.2006	327.266

Table 2: Total available H.E.S.S. observation time of each source considered in this work, along with the full observational time range, and the total detection significance.

Studying the evolution of the (expectedly highly-variable) emission of each source is essential for our purposes, as incorrectly combining observations corresponding to different emission states could lead to either an averaging or overestimating of any possible spectral features within the SEDs.

This time variability analysis will be performed by analyzing the light curves for our sources, in which the spectral flux is plotted over time. These curves are constructed considering a simplified spectral model, such as a simple power-law without any EBL attenuation, with the spectral index and reference energy being left as a choice to the analyzer. In our case, we consider a power-law, as given by Eq. (28) and implemented as `PowerLawSpectralModel`, whose free parameters Γ and N_0 are found by running an initial fit on the data across the full observational period. As initial values, we consider the default selection $\Gamma = 2$ and $N_0 = 1 \cdot 10^{-12} \text{ TeV s}^{-1} \text{ cm}^{-2}$. These initial parameters are also bounded to ensure they remain within physically meaningful value ranges, and to improve numerical convergence¹.

The fitting procedure (here and throughout the remainder of this work) follows the maximum-likelihood methodology described in Section 6 and is performed in two sequential steps. First, the reference energy is set to $E_0 = 1 \text{ TeV}$, and an initial fit is performed. After this, the model is re-evaluated at the decorrelation or pivot energy $E_0 = E_{\text{dec}}$, defined as the energy for which the correlation between the parameters is minimal (ensuring minimal statistical error in the flux). This decorrelation energy is computed as $E_{\text{dec}} = E_0 \exp [\text{cov}(N_0, \Gamma) / (N_0 \Delta \Gamma^2)]$ [152]. In any case, E_0 is always treated as a frozen parameter, not varying during the fit.

¹These bounds on the parameters enforce their values to be within the ranges $\Gamma \in [0, 6.5]$ and $N_0 \in [10^{-15}, 10^{-8}] \text{ TeV s}^{-1} \text{ cm}^{-2}$. However, in some cases, either the index or normalization bounds must be slightly modified in order to improve numerical convergence.

The computation of the light curve is performed by the `LightCurveEstimator` class implemented in `GammaPy`, which obtains the flux across the full observation period for a given time binning by considering a power-law model with only N_0 being free to vary. We consider a nightly binning in time (considering intervals of 12 hr centered at midnight on each day), with energy edges given by the stacked dataset, and a time selection tolerance of approximately 20 min to ensure observations around the length of a single H.E.S.S. run are adequately considered. The result of this is a light curve in which the spectral flux and its variability can be observed across the full time range.

In order to properly account for sections in time during which the flux is in a similar state, and separate those emission states with significant differences, we apply a statistically-motivated segmentation of the binned flux data using the Bayesian block algorithm [153]. This algorithm allows us to convert the light curves into discrete blocks where the studied property remains stable. This method is based on performing a likelihood fit of a piece-wise constant model to the data, attempting to find the optimal change points at which a significant variability in the flux is observed beyond its associated uncertainty. Various choices for the fitness function are available, and a penalty on the number of blocks found is introduced to prevent overfitting [153].

The Bayesian block algorithm used here is implemented as the `stats.bayesian_blocks` function in `astropy` 7.1.0 [154]. In our case, the built-in `measures` fitness function is used, which assumes that the data correspond to a measured sequence with normally-distributed or Gaussian errors. The function then returns the time-ordered edges of all found Bayesian blocks, constructed exclusively on the flux points and thus ignoring any upper limits. These time blocks serve as our initial time segmentation for each source. Once the block edges have been found, the light curve is reconstructed, using these time values as the new binning.

Additionally, a variability study on the spectral index is also performed by running a power-law fit for each light curve flux point individually, obtaining a light curve which tracks the values of the index across the observational time range. The Bayesian blocks algorithm is then applied on the index light curve, and the resulting index light curve is similarly reconstructed.

Some representative examples of the obtained light curves can be seen in Figure 9, while the light curves for all the sources in our dataset are shown in Appendix A.

The spectral variability is highly dependent on the considered source, with some (e.g. 1ES 1101-232 and H 2356-309) presenting relatively stable emission, and others (e.g. PKS 0903-57 and, most prominently, PKS 2155-304) being considerably variable. In certain sources, the resulting average flux per Bayesian block seems to lie relatively lower than the flux points themselves (as in the case of 1ES 0414+009, 1ES 1312-423, and PKS 1510-089), which could be caused by effects due to numerical convergence issues. This effect, however, does not affect our analysis, as we are interested in the edges of the found Bayesian blocks, and not necessarily the resulting average flux across each block (as a separate analysis per-block will be performed explicitly in the following sections). Lastly, for sources with short observational time ranges or low photon count statistics (mainly 3C 279 and PKS 0346-27), the found Bayesian blocks have been extended to cover the full time range, as no significant variability within such short times is observed.

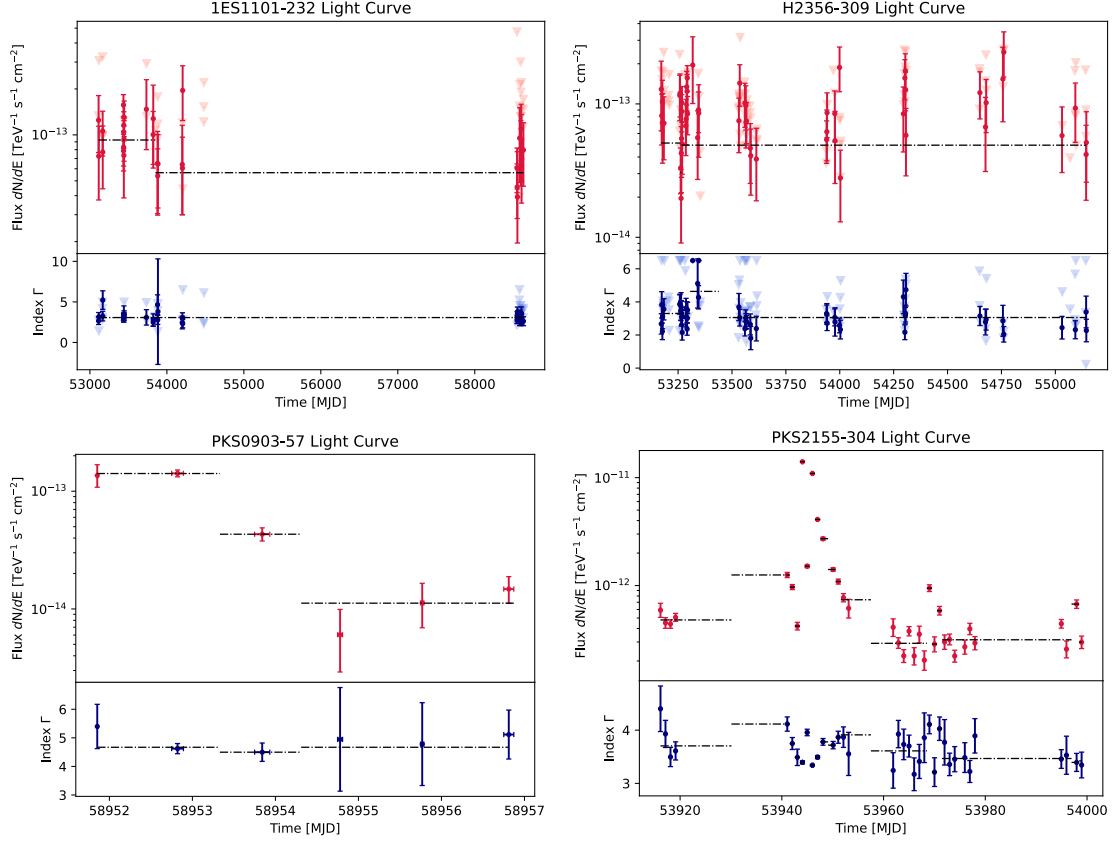


Figure 9: Nightly-binned *H.E.S.S.* light curves obtained for a subset of four of the blazar sources considered in this work. In the upper plot of each figure, the usual light curve is shown representing the detected differential flux dN/dE in units $\text{TeV s}^{-1} \text{cm}^{-2}$, with the computed flux points indicated alongside their statistical uncertainties and upper limits (denoted by transparent, downwards-pointing triangles). In the lower plot of each figure, the evolution of the spectral index is also shown, computed at each bin. The Bayesian blocks found by the algorithm are shown as horizontal dashed lines, with the time values corresponding to dates in the modified Julian day (MJD) format. The remaining plots for all sources in our dataset can be found in Appendix A.

While this Bayesian block approach offers an excellent initial time segmentation of our sources, an improved selection can be obtained by considering which of these Bayesian blocks actually represent physically distinct emission states. Although most sources can be considered to be in a single emission state with just one Bayesian block, this approach is especially useful for highly variable sources for which many blocks are found, mainly PKS 2155-304 whose highly-variable emission is divided initially into 19 different blocks. This approach can also be motivated by the fact that, for certain sources, the variability in flux does not always correspond to variability in the index values, possibly indicating that certain separate blocks found on the flux light curve could represent the same (or very similar) physical state.

Following this reasoning, a further spectral evolution analysis is performed, in which the normalization and index parameters found for each Bayesian block are plotted together along with their uncertainties and the corresponding statistical significance ellipses representing the

uncertainty at different confidence levels. The ellipses are computed by diagonalizing the covariance sub-matrix of the relevant free parameters, in this case $\text{cov}(\Gamma, N_0)$, with eigenvalues w_1, w_2 , and eigenvectors v_1, v_2 . The semi-axes are then given by $r_{a,b}^2 = 4\Gamma_{\text{inc}}^{-1}(1, l) \cdot w_{1,0}^2$. Here, Γ_{inc} is the regularized, upper-incomplete gamma function, whose inverse is directly implemented within `scipy` [155] as `scipy.special.gammainccinv`, and l the corresponding confidence level at 1 degree of freedom, given by 0.68, 0.95, and 0.99 for the considered 1σ , 2σ , and 3σ confidence levels, respectively. Each ellipse is then plotted, centered at the corresponding index-amplitude point, and rotated by the angle $\alpha = \arctan(v)$, where v is the eigenvector associated to the maximal eigenvalue [156].

Through this procedure, if two contiguous blocks are found to be overlapping within statistical uncertainties, we can consider them to correspond to physically equivalent emission states. On the contrary, non-contiguous overlapping blocks, or blocks that do not overlap, must be treated separately. In our case, we combine all contiguous blocks whose ellipses present an overlap at least at the 3σ level. Figure 10 displays some examples of the obtained ellipse plots, with Appendix A containing these plots for all the sources in our dataset.

By observing these ellipse plots, we can clearly see that in most sources, just one ellipse is present, corresponding to the single Bayesian block found. The curvature in these ellipses can be attributed to the logarithmic scale on the normalization axis and a non-zero ellipse rotation angle, which encodes the correlation between the parameters. In sources with detected variability, a lot of the blocks can actually be combined into the same physical emission states, such as in the case of PKS 2155-304 (reducing the total time segmentation from 19 blocks to just 8), PG 1553+113, or H 2356-309. Other variable sources also present time blocks sufficiently separated in time to warrant independent treatment, as is the case for 1ES 1101-232 and PKS 0903-57. Most sources, however, can be treated as a single time block corresponding to the full observation period.

Our study presents, in general, good agreement with similar studies, such as [35, 52]. The main differences found correspond to the fact that, despite finding the expected variability within the light curves of PG 1553+113 and H 2356-309, the spectral evolution study allows for the combination of all found Bayesian blocks into a single time segment, indicating that we can treat them as stable sources. This is surprising, as each of these sources were originally separated into two blocks in the cited work.

For PG 1553+113, one possible approach in order to make both analyses consistent could be to manually define the time segmentation into two blocks, the data between 2013 and 2017, and the data taken in 2019, since the variability in flux does present a significant change between these two periods (although this difference is not present in the index values). Possible reasons as to why these blocks end up overlapping each other are the high uncertainties in both the flux and index values, as well as the relatively high rotation angle the ellipses present. This pronounced rotation suggests a high correlation between the parameters, which could be alleviated (at least partially) by recomputing the decorrelation energy at each block and performing the fit with this new value for the reference energy. In our case, however, we have decided to fix the reference energy to that of the complete dataset for the variability analysis, and combine the blocks in order to remain methodologically consistent.

For H 2356-309, the obtained light curve does not show significant variability in the spectral

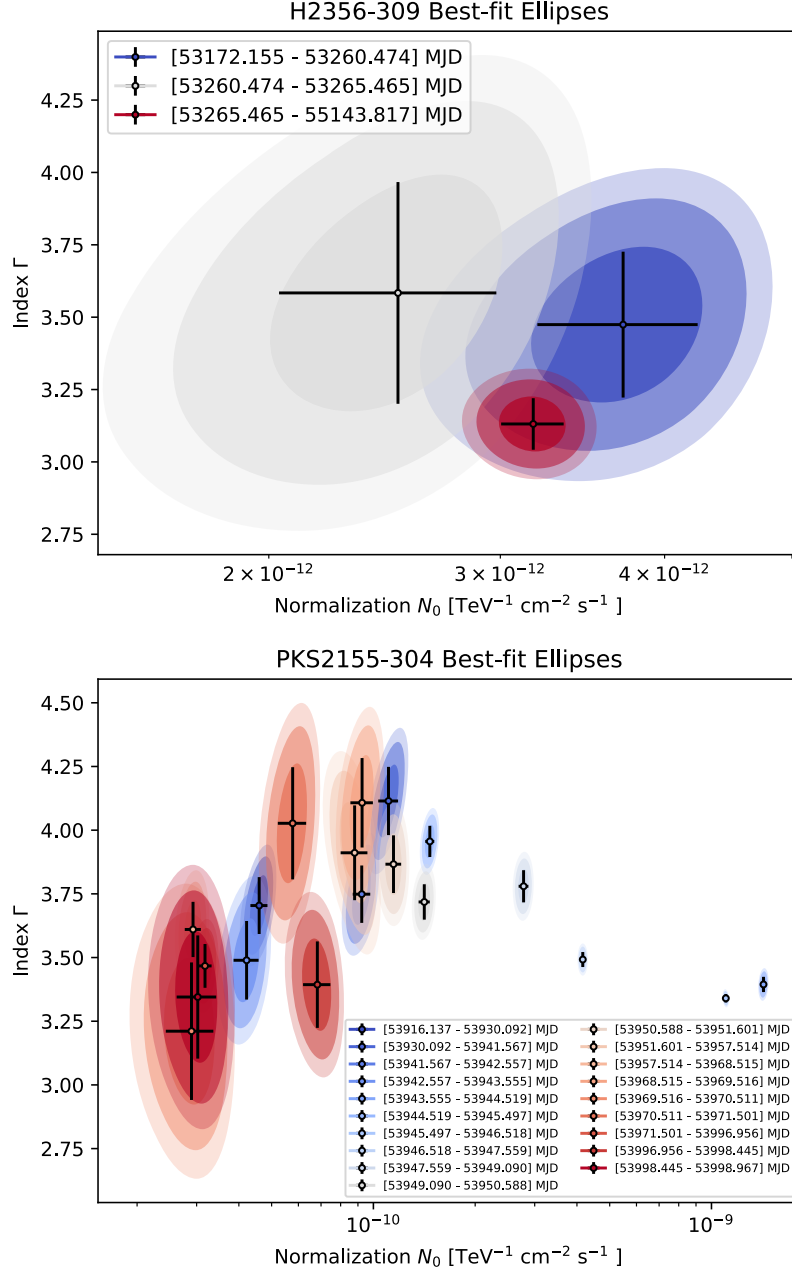


Figure 10: Spectral evolution analysis of some sources out of our blazar dataset, with the index Γ and normalization N_0 parameters plotted along with their uncertainties and the ellipses corresponding to 1σ , 2σ , and 3σ confidence levels, with the latter being used to combine different blocks for the final segmentation. In the legend, the list of Bayesian blocks found by the algorithm for the flux light curve are denoted by their start and end times in the modified Julian day (MJD) format. The remaining plots for all sources in our dataset can be found in Appendix A.

flux beyond statistical uncertainties, with three Bayesian blocks found with very similar average flux values. The variability is more pronounced in the index values, with an apparent index-flaring state that approximately corresponds to the blocks found for the flux. However, the best-fit ellipses present a high degree of overlap, even if we were to ignore their rotation angle, suggesting a single time block is sufficient to describe the emission from this source.

Another interesting case is that of 1ES 1101-232. For this source, we find two distinct Bayesian blocks on the flux, whose associated ellipses do not overlap at all, thus requiring their separate treatment. This variability is not present in previous analyses [35, 52], and is also not accompanied by any variability in the spectral flux. However, apart from the aforementioned sources, generally all other sources in our dataset present light curves and a final time segmentation that is fully consistent with our expectations based on previous work.

The segmentation obtained for the new sources is also consistent with our initial expectations. Both 3C 279 and PKS 0346-27 correspond to relatively short observation periods, and thus no significant variability can be adequately detected (especially in the case of PKS 0346-27, corresponding to a single detection night, rendering the variability analysis trivial). For PKS 0903-57, the found time segmentation is also consistent with the published results [139], as the authors also describe an overall decrease in flux during the first three nights, and its stabilization for the remaining three (which, as we will see later, is also associated to a change in the best-fit spectral model shape).

The final time segmentation obtained for each source will be shown explicitly in the following sections, such as in Section 4.3 with Table 4, displaying the individual time blocks along with the results of the fit performed for each source considered.

As a final remark, in order to account for any possible flaring in the *Fermi*-LAT data that is not significantly detected by H.E.S.S., an additional check has been performed with the publicly available light curves obtained from LAT observations [157], finding no additional undetected flaring periods for any of our sources within the considered time periods.

4.2 *Fermi*-LAT data analysis

AFTER performing the initial H.E.S.S. time variability analysis and obtaining the final time segmentation for all of our sources, we can now focus on performing the main intrinsic spectral analysis for each source and time block in our dataset. We will begin by analyzing the data from the *Fermi*-LAT, as its 4FGL catalog will serve as an initial ansatz for the spectral model of our sources and their initial parameters.

This analysis is performed by considering a region of interest (RoI) centered at the position of each source, with an angular size of 10 deg, and a spatial binning of 0.1 deg per pixel. The energy is binned at 2 bins per decade, considering an energy range between 1 and 300 GeV. The relevant time selection is explicitly provided in terms of mission elapsed time (MET) from the start of the LAT operations, and corresponds to the time segmentation found in the previous section.

To begin our analysis, we initialize the required `GTAnalysis` class from `FermiPy` specifying the configuration file, which contains all the analysis choices required for the data analysis and processing. In particular, we select the `SOURCE` event classes (class ID 128) corresponding

to both `FRONT` and `BACK` photon detections (type ID 3). Additional filtering is provided via the data quality selection `DATA_QUAL>0`, and selecting only observations during nominal instrument operation via `LAT_CONFIG == 1`. A zenith angle cut is set at 90 deg, to account for emission from the Earth’s limb.

Following the recommendations from the `GammaPy` community [130], in order to make the resulting data fully compatible between the two frameworks, energy dispersion is disabled with a binning set to `edisp_bins = 0`, and explicitly disabled for the isotropic and galactic diffuse background models. The functions `gta.compute_psf` and `gta.compute_drm` are then used to compute the required IRFs in a format compatible with `GammaPy`. For the analysis, we consider the latest `PASS 8` IRFs adequate for point-like source analyses (`P8R3_SOURCE_V3`), with the associated isotropic `iso_P8R3_SOURCE_V3_v1` and galactic `gll_iem_v07` diffuse background templates.

Once the setup has been performed, and all required files generated, we may begin our analysis. In order to model the RoI, we include all the sources within the 10 deg area, including the diffuse backgrounds. In order to account for gamma rays entering our RoI from outside, nearby sources, we also include sources within a wider 20 deg region into our model. These sources, with their spatial and spectral models and associated initial parameters, are taken directly from the 4FGL DR4 catalog `gll_psc_v35` [125].

The `FermiPy` analysis can then be performed by, first, freeing the spectral parameters of our target source, considered as either a power-law or log-parabola, defined by Eqs. (28, 29), respectively, as well as the normalization of the diffuse backgrounds. The spectral parameters of sources within 3 deg of the center are free to vary during the fit, as well as the normalization of the diffuse backgrounds and any significant sources with a $TS > 10$ within the full RoI.

An initial maximum-likelihood fit is performed, with which we obtain the best-fit parameters for all sources to our data. Afterwards, low-significance ($TS < 5$) sources are removed from the RoI, and a search for additional sources is performed via the `find_sources` routine. Finally, a last optimization and fit is performed, which yields the final model of the RoI. This initial `FermiPy` analysis is used as both a required step that generates the files for the subsequent `GammaPy` analysis, as well as an additional cross-validation analysis, to ensure both frameworks provide comparable results and that no errors were introduced when migrating the data and models between the two libraries.

In our specific use case, in order to load the resulting files and models into `GammaPy`, we found it necessary to manually redefine the energy dispersion matrix as a purely diagonal response matrix (as in some cases, certain bins were erroneously truncated). Similarly, the counts, exposure, and background maps in our dataset have been extended to properly account for models outside the RoI, which were then merged into a single `TemplateSkyModel`. An additional step was also required to ensure compatibility between the `FermiPy` and `GammaPy` model definitions and accommodate the different parameter naming conventions.

The resulting `MapDataset` in `GammaPy` then contains all the photon counts data, the relevant IRFs, as well as the spatial and spectral models of all sources present within the RoI and nearby as `SkyModel` objects. The model also includes the diffuse galactic and isotropic backgrounds. A maximum-likelihood analysis is then performed once again, although in this

4.2 *Fermi*-LAT data analysis

case only allowing the parameters of the target source to vary, as well as the normalization of the diffuse backgrounds.

Similarly to the procedure in the previous section, the decorrelation energy was computed, and the model was re-fit on this new reference energy, providing the final results which are summarized in Table 3. In the context of this work, systematic uncertainties in the *Fermi*-LAT analysis are not considered, as they are expected to be subdominant. This is due to the fact that the main uncertainties corresponding to the data at this energy range are expected to be dominated by statistics. Furthermore, the ALP-upturn sensitivity is given primarily by the higher-energy H.E.S.S. data, and the joint likelihood analysis for the combined data will suppress any systematic contribution from the LAT.

Source Name	Observation Range [DD.MM.YYYY]	N_0 [GeV ⁻¹ cm ⁻² s ⁻¹]	Γ	β	E_0 [GeV]
1ES 0229+200	04.08.2008 – 04.08.2022	$(7.58 \pm 1.00) \cdot 10^{-12}$	1.70 ± 0.10	–	6.63
1ES 0347-121	04.08.2008 – 04.08.2022	$(3.09 \pm 0.32) \cdot 10^{-11}$	1.77 ± 0.08	–	3.60
1ES 0414+009	04.08.2008 – 04.08.2022	$(3.38 \pm 0.31) \cdot 10^{-11}$	1.78 ± 0.07	–	4.17
1ES 1101-232	04.08.2008 – 04.08.2022	$(1.21 \pm 0.13) \cdot 10^{-11}$	1.60 ± 0.08	–	6.26
1ES 1312-423	04.08.2008 – 04.08.2022	$(1.28 \pm 0.14) \cdot 10^{-11}$	1.70 ± 0.07	–	6.03
1RXS J101015.9-311909	04.08.2008 – 04.08.2022	$(2.05 \pm 0.16) \cdot 10^{-11}$	1.71 ± 0.06	–	5.92
3C 279	24.01.2018 – 29.01.2018	$(6.17 \pm 0.64) \cdot 10^{-08}$	2.51 ± 0.17	–	1.97
PG 1553+113	03.06.2013 – 10.05.2019	$(3.82 \pm 0.25) \cdot 10^{-09}$	1.39 ± 0.01	0.13 ± 0.04	2.64
PKS 0346-27	03.11.2021 – 04.11.2021	$(3.10 \pm 1.72) \cdot 10^{-09}$	1.89 ± 0.55	–	3.22
PKS 0447-439	09.11.2009 – 07.12.2010	$(1.05 \pm 0.06) \cdot 10^{-09}$	1.99 ± 0.06	–	2.93
PKS 0903-57	13.04.2020 – 13.04.2020	$(8.35 \pm 2.13) \cdot 10^{-07}$	2.13 ± 0.38	-0.01 ± 0.09	0.90
PKS 0903-57	14.04.2020 – 15.04.2020	$(8.38 \pm 1.35) \cdot 10^{-08}$	2.46 ± 0.25	–	2.03
PKS 0903-57	15.04.2020 – 17.04.2020	$(9.67 \pm 1.03) \cdot 10^{-08}$	2.19 ± 0.14	–	2.36
PKS 1510-089	20.03.2009 – 10.05.2016	$(2.29 \pm 0.23) \cdot 10^{-09}$	2.36 ± 0.14	–	2.23

Table 3: Results obtained by performing a spectral fit of the target source model to the *Fermi*-LAT data. The observation ranges correspond to either the 14-year averaged time selection, for non-variable sources with no contemporaneous LAT data, or the time range of the corresponding H.E.S.S. final segmentation. Variable sources with no contemporaneous LAT data have been omitted, and the source 1ES 1101-232 has been merged into a single, averaged time block.

Overall, the results presented here are in agreement, within uncertainties, with published studies of these sources, in particular comparing the value of the spectral indices [138, 142, 144, 148, 158, 159]. Deviations are found in 1ES 0229+200 [140], 1ES 1101-232 [136], and 1RXS J101015.9-311909 [145], with our indices being lower than the reported $\Gamma = 2.5 \pm 0.2$, $\Gamma = 1.9 \pm 0.2$, and $\Gamma = 2.1 \pm 0.2$, respectively. However, all these studies were performed during different observational periods than those considered here, and thus certain differences are expected.

The sources 3C 279 and PG 1553+113, also present significant differences with published results (with reported $\Gamma = 1.99 \pm 0.04$ and $\Gamma = 1.68 \pm 0.03$, respectively) [71, 160]. In these cases, however, the best-fit spectral model differs (as the one shown here corresponds to the

best-fit model for the joint *Fermi*-LAT and H.E.S.S. data, as described in Section 4.4), and thus different parameter values are also expected. Finally, for PKS 0903-57, the results also present differences beyond uncertainties for the index parameter [139], with our results being overall higher. This can also be attributed to the different time segmentation considered. Despite certain differences in the obtained results, we do not expect these to affect the final results on ALP upturns.

Figure 11 displays the results of this spectral analysis for a subset of sample sources from our dataset, displaying the final SED obtained by both **FermiPy** and **GammaPy**, which we find to be in excellent agreement. Each one of these plots displays the SED obtained for our model, along with the statistical uncertainties at the 1σ level as shaded regions. The flux points have been calculated in both **FermiPy** and **GammaPy** with the built-in tools, following the approach described in [161, 162], in which the differential flux is computed via a likelihood fit considering the best-fit model for each energy bin. This allows also to compute asymmetric uncertainties for the flux points (at 1σ significance) and, in the case where the significance is low ($\sigma < 2$), upper limits on the flux. For the upper limits, we consider a lower error of 20% of the corresponding flux value. These confidence levels for flux point uncertainties and upper limits are applied to all spectral modeling throughout the thesis.

4.3 H.E.S.S. data analysis

THE spectral modeling of our sources for the H.E.S.S. data is performed fully within **GammaPy**. Once the data has been properly reduced and prepared, we can load it in **GammaPy** as a **Datasets** object containing, for each observation, a **SpectrumDatasetOnOff** class. A time selection is applied selecting the corresponding final time segmentation based on the Bayesian blocking and spectral variability analysis carried out in Section 4.1, and the dataset is generated. A resampling of the energy axis is also performed, in which we apply a binning of 4 bins per decade across the full considered energy range between 0.1 TeV and 31.6 TeV.

As an initial selection, we consider the resulting best-fit spectral model obtained from the *Fermi*-LAT analysis (which, in turn, is based on the 4FGL DR4 initial model choice), chosen as either a power-law or log-parabola spectral model (Eqs. (28, 29), respectively). In order to ensure numerical convergence, we convert all the parameters into the relevant H.E.S.S. (TeV) energy scale, and the reference energy is reset initially to 1 TeV.

In order to account for EBL absorption, the library **EBLTable 0.6.3** [163] is used to define the absorption model based on tabulated optical depth data, including the redshift z of the source as an input. This is incorporated into **GammaPy** as a **TemplateSpectralModel**, which is then combined with the base spectral model into a **CompoundSpectralModel**. As a baseline for our study, we consider the Domínguez et al. EBL model (2011) [83], although this same analysis is also performed for the models by Finke et al. (2022) [84], Franceschini et al. (2008) [85], and Saldana-Lopez et al. (2021) [86]. Optionally, a spatial model may also be taken from the *Fermi*-LAT fit and included into the resulting **SkyModel**, although its parameters will remain frozen and therefore not contribute during the likelihood computation.

As previously, the spectral parameters of the source are obtained by performing a maximum-likelihood fit. The initial values are taken as the best-fit *Fermi*-LAT parameters, with a

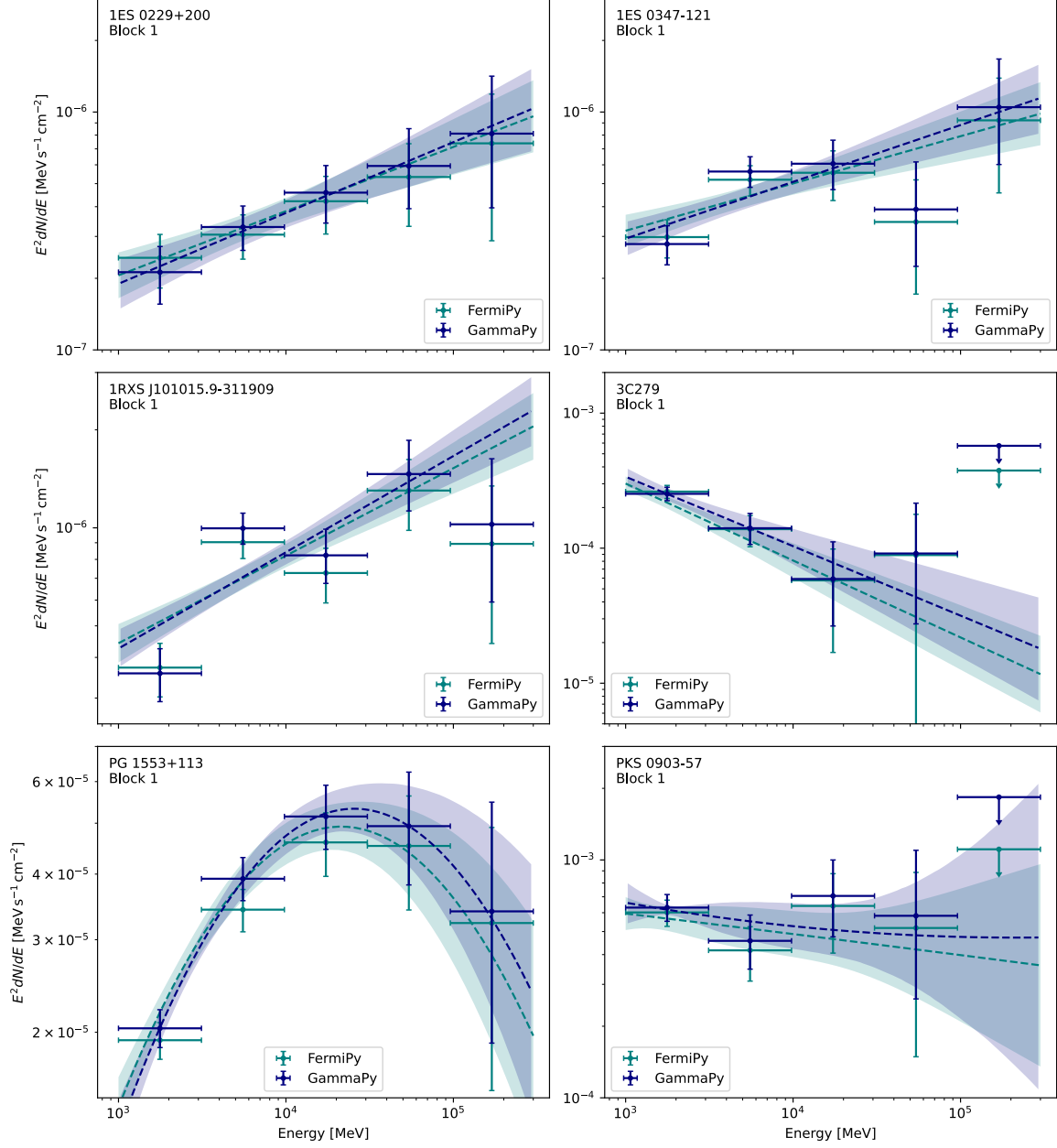


Figure 11: Obtained SED models for the Fermi-LAT data considering a sample of sources from our dataset. In light blue are shown the spectral model (discontinuous line), the associated uncertainty (shaded region), and the flux points and upper limits with their associated uncertainties, obtained with *FermiPy*. Similarly, in dark blue, the model and flux points obtained via *GammaPy* are shown.

reference energy of 1 TeV, are bounded to remain within a physically meaningful range, improving numerical convergence. The fit itself is also performed sequentially, re-evaluating the model at the decorrelation energy as the reference to obtain the final results.

However, at this point, we must consider the possible systematic uncertainties introduced when analyzing H.E.S.S. data. These systematic uncertainties may affect our results by modifying or otherwise distorting the obtained spectrum, modifying the ALP likelihood. These may arise from, for example, imperfect modeling of the atmosphere, efficiency and response of the instruments, the event reconstruction process, or the data reduction and analysis process, along with the different relevant parameter choices considered [112]. During the analysis, these usually correspond to a shift of the energy scale, the modification of the IRF shape, and thus different levels of error on the spectral parameters. One approach towards computing these uncertainties is performing multiple analyses with different parameter choices [33].

An alternative approach is considered in this work, by considering a modified likelihood term which includes an additional parameter to account for this energy shift [112]. In our case, we introduce an energy rescaling of the form $E \rightarrow E(1 + s)$, where an additional bias parameter s is introduced. This parameter is then left free to vary, such that the systematic uncertainty in the energy scale is profiled over during the likelihood fit. We impose a Gaussian prior on this parameter with a width of $\sigma_s = 0.15$ corresponding to the usual H.E.S.S. 15% uncertainty in the energy scale [33]. This is implemented in `GammaPy` by defining a new `BiasedCompoundSpectralModel`, which includes the bias parameter and performs the energy-rescaled evaluation of any initial spectral model introduced as an input. An additional `BiasedPriorSpectrumDatasetOnOff` was also implemented to ensure compatibility of the `SpectrumDatasetOnOff` dataset class in `GammaPy` with our biased model. This includes a redefinition for the computation of the total statistic or log-likelihood, taking into account the Gaussian prior, such that:

$$\log \mathcal{L}_{\text{bias}}(\theta, s) = \log \mathcal{L}(\theta) - \frac{s^2}{2\sigma_s^2}, \quad (46)$$

where $\log \mathcal{L}(\theta)$ represents the usual log-likelihood for the data. The implementation of these classes was performed following the code structure of their parent classes, ensuring compatibility with other standard `GammaPy` features. This enables us to easily include this model in `Datasets` objects, evaluate it at any given energies, and plot the resulting SED, utilizing the standard `SpectralModel` functions.

With this approach, the likelihood fit is then run one last time, with the reference energy set to the decorrelation energy, and including this new bias parameter to account for the systematic uncertainties. This allows us to obtain the final H.E.S.S. intrinsic spectral analysis results, which are summarized in Table 4.

The results shown here are, overall, consistent with previous works [35], presenting similar values for the index and normalization across most sources (although, due to the unavailability of uncertainties, only a qualitative comparison can be performed). In particular, we obtain an index slightly higher for 1ES 0229+200 than the reported value, while for 1ES 0414+009 and PKS 1510-089, our index is lower, although still within our uncertainties. The highly-variable

PKS 2155-304 also shows the expected different spectral states with varying curvature, while the rest of the sources can be described consistently with a simple power-law model. In the case of PG 1553+113, the best-fit model for the joint *Fermi*-LAT and H.E.S.S. data corresponds to a log-parabola (as we will see in Section 4.4). However, when considering only the H.E.S.S. data, a power-law offers a better fit, resulting in a curvature parameter consistent with $\beta = 0$. We have also found that performing the analysis with the full log-parabola model significantly improved the numerical convergence for this source.

For the case of the new sources, the spectral parameters obtained for PKS 0346-27 differ from those reported in [138] and present high uncertainties, as is expected, due to the limited observation time for this source. These results suggest that a H.E.S.S.-only fit does not properly converge for this source, requiring to combine it with data from *Fermi*-LAT. Considering the source PKS 0903-57, the differences between the reported index values in the literature [139] and those obtained here are also somewhat expected, as we are considering a different time segmentation (based on the Bayesian blocks found, rather than a nightly binning). However, we have managed to observe the same variability in the index value, presenting an overall decrease in time, and the evolution from a log-parabola into a power-law best-fit model.

In most cases, the bias parameter included corresponds to a small shift in energies, fully consistent with $s = 0$. Perhaps the only exceptions to this are PKS 2155-304, where blocks 6 and 7 are best described with a relatively-high value for the bias of $s \sim -0.15$, although their associated uncertainties are almost of the same order. This is fully expected, as we are only considering data from H.E.S.S. The main advantage of including this bias parameter will be more visible in Section 4.4, where this energy shift will attempt to compensate for any differences with the spectrum obtained from the *Fermi*-LAT instrument.

Similarly, the SED obtained for a small subset of sources is displayed in Figure 12, including explicitly the individual contributions from the statistical and systematic uncertainties towards our model.

As an additional validation step, a cross-check has been performed internally within the H.E.S.S. collaboration for each one of the sources in the dataset by comparing the light curves from Section 4.1 as well as the SED and best-fit model parameters for the “baseline” H.E.S.S. data (corresponding to an average SED obtained from the complete observation time range available for the considered data). The results shown here are based on data from the HAP-HD (Heidelberg) analysis chain, which relies on the H.E.S.S. Analysis Package (HAP) framework. Via this cross-validation process, our results have been found to be fully compatible and in good agreement with an independent analysis performed within the HAP-Fr (France) analysis chain, based on the `Model++` software [164]. The cross-checks were already performed for the sources present in previous related works [35], for which a direct comparison was made, and they were then extended by including the three new sources considered in this work. Due to the agreement of this data, we conclude that no fundamental errors in the analysis or processing procedure of H.E.S.S. data are present.

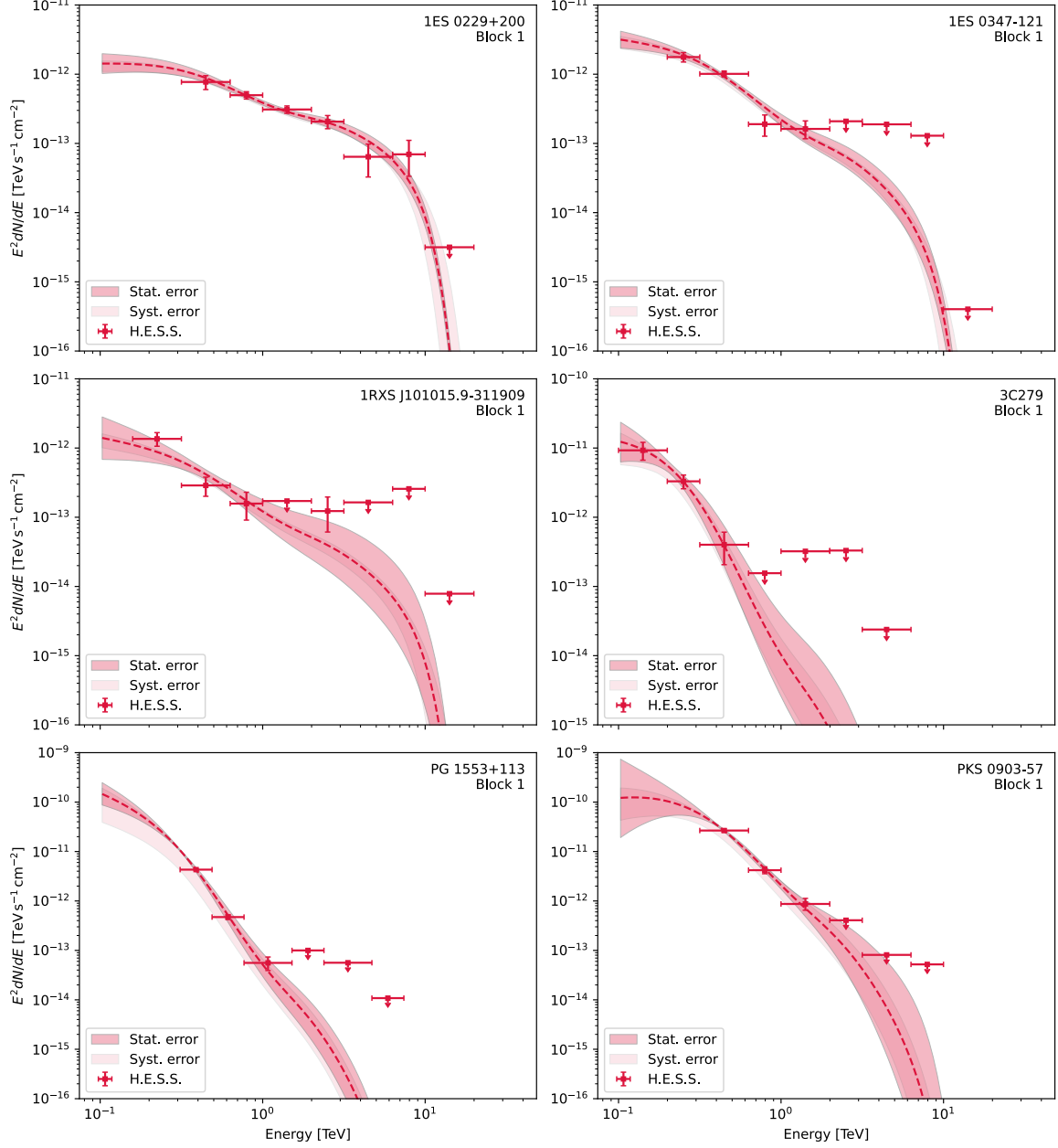


Figure 12: Obtained SED models for a sample of sources from our dataset considering the Domínguez et al. (2011) EBL model [83]. In red are shown the spectral model (discontinuous line) as well as the computed flux points with their uncertainties and upper limits. The uncertainty of the model is plotted displaying explicitly the contribution of the statistical (in darker shade of red) and systematic (in lighter shade) uncertainties.

4.4 Joint *Fermi*-LAT and H.E.S.S. data analysis

Source Name	Observation Range [DD.MM.YYYY]	N_0 [TeV ⁻¹ cm ⁻² s ⁻¹]	Γ	β	E_0 [TeV]	$s_{\text{H.E.S.S.}}$
1ES0229+200	11.09.2004 – 08.01.2019	$(1.53 \pm 0.70) \cdot 10^{-12}$	1.91 ± 0.14	–	1.08	0.001 ± 0.153
1ES0347-121	26.08.2006 – 31.12.2013	$(1.38 \pm 1.37) \cdot 10^{-11}$	2.22 ± 0.23	–	0.43	0.022 ± 0.300
1ES0414+009	03.10.2005 – 17.10.2010	$(7.82 \pm 4.36) \cdot 10^{-12}$	1.61 ± 0.42	–	0.46	-0.009 ± 0.148
1ES1101-232	17.04.2004 – 24.04.2006	$(1.03 \pm 0.47) \cdot 10^{-11}$	1.84 ± 0.13	–	0.52	-0.066 ± 0.139
1ES1101-232	23.05.2006 – 28.05.2019	$(9.17 \pm 3.70) \cdot 10^{-12}$	1.77 ± 0.15	–	0.48	0.016 ± 0.138
1ES1312-423	15.04.2004 – 12.07.2010	$(1.37 \pm 0.66) \cdot 10^{-12}$	2.29 ± 0.32	–	0.68	0.011 ± 0.149
1RXSJ101015.9-311909	21.12.2006 – 17.04.2010	$(4.22 \pm 2.22) \cdot 10^{-12}$	2.40 ± 0.46	–	0.46	0.036 ± 0.158
3C279	24.01.2018 – 29.01.2018	$(3.26 \pm 2.17) \cdot 10^{-10}$	2.07 ± 0.98	–	0.21	-0.001 ± 0.150
H2356-309	16.06.2004 – 08.11.2009	$(9.08 \pm 3.55) \cdot 10^{-12}$	2.05 ± 0.10	–	0.47	0.039 ± 0.131
PG1553+113	03.06.2013 – 10.05.2019	$(6.36 \pm 5.21) \cdot 10^{-10}$	3.11 ± 0.57	0.00 ± 0.01	0.31	0.030 ± 0.148
PKS0346-27	03.11.2021 – 04.11.2021	$(1.37 \pm 1.27) \cdot 10^{-09}$	2.07 ± 2.77	–	0.17	-0.001 ± 0.150
PKS0447-439	09.11.2009 – 07.12.2010	$(6.68 \pm 4.29) \cdot 10^{-11}$	1.83 ± 0.43	–	0.45	-0.015 ± 0.147
PKS0903-57	13.04.2020 – 13.04.2020	$(6.91 \pm 4.49) \cdot 10^{-10}$	2.60 ± 0.63	0.41 ± 0.61	0.42	0.019 ± 0.147
PKS0903-57	14.04.2020 – 15.04.2020	$(8.33 \pm 5.73) \cdot 10^{-11}$	2.63 ± 0.39	–	0.48	-0.015 ± 0.149
PKS0903-57	15.04.2020 – 17.04.2020	$(2.03 \pm 1.40) \cdot 10^{-10}$	2.92 ± 0.19	–	0.46	0.012 ± 0.147
PKS1510-089	20.03.2009 – 10.05.2016	$(2.87 \pm 1.71) \cdot 10^{-11}$	1.29 ± 0.76	–	0.41	0.014 ± 0.148
PKS2155-304	30.06.2006 – 27.07.2006	$(2.24 \pm 1.10) \cdot 10^{-10}$	3.02 ± 0.09	–	0.36	-0.005 ± 0.135
PKS2155-304	28.07.2006 – 28.07.2006	$(3.21 \pm 1.08) \cdot 10^{-09}$	2.62 ± 0.04	–	0.42	-0.005 ± 0.103
PKS2155-304	28.07.2006 – 29.07.2006	$(9.04 \pm 4.54) \cdot 10^{-10}$	2.89 ± 0.25	0.38 ± 0.15	0.32	0.013 ± 0.147
PKS2155-304	29.07.2006 – 30.07.2006	$(2.76 \pm 0.89) \cdot 10^{-09}$	2.20 ± 0.14	0.37 ± 0.04	0.40	-0.028 ± 0.108
PKS2155-304	30.07.2006 – 31.07.2006	$(1.20 \pm 0.56) \cdot 10^{-09}$	2.47 ± 0.20	0.36 ± 0.07	0.37	-0.056 ± 0.140
PKS2155-304	01.08.2006 – 01.08.2006	$(3.13 \pm 1.97) \cdot 10^{-10}$	3.10 ± 0.10	–	0.44	-0.154 ± 0.142
PKS2155-304	02.08.2006 – 04.08.2006	$(1.49 \pm 0.90) \cdot 10^{-10}$	3.09 ± 0.09	–	0.43	-0.159 ± 0.136
PKS2155-304	05.08.2006 – 20.09.2006	$(1.29 \pm 0.65) \cdot 10^{-10}$	2.46 ± 0.23	0.30 ± 0.12	0.35	-0.045 ± 0.155

Table 4: Results for the spectral parameters of each source obtained from the maximum-likelihood analysis of the H.E.S.S. data, considering the baseline Domínguez et al. (2011) EBL model [83]. In particular, shown are the final time segmentation obtained for each source, and the spectral parameters: normalization N_0 and index Γ . In the case of log-parabola being preferred as the spectral model, the additional β parameter is also included. All parameters are obtained by considering as reference energy E_0 the decorrelation energy E_{dec} . The last column includes the bias parameter $s = s_{\text{H.E.S.S.}}$.

4.4 Joint *Fermi*-LAT and H.E.S.S. data analysis

ONCE the individual spectral modeling has been performed on both the *Fermi*-LAT data as well as the H.E.S.S. data, for each one of our sources and time segmentation periods, we may now perform a joint analysis combining both datasets in `GammaPy` into a single `Datasets` object, and performing a multi-instrument spectral modeling across the whole energy range between 1 GeV and 31.6 TeV, following the maximum-likelihood method described in Section 3.3.2 with a joint log-likelihood given by Eq. (42).

The fit procedure is exactly the same as in the previous sections, where an initial fit of our models to the data is performed with a fixed initial energy (in this case, maintained as the decorrelation energy found from the H.E.S.S.-only fit), and re-run using the new decorrelation energy corresponding to the full dataset. As usual, only the target source remains free in these fits, which is present for both the LAT and H.E.S.S. datasets. In this case, however,

two main considerations must be taken into account.

Firstly, in order to correctly include the H.E.S.S. systematic uncertainties, we must utilize the `BiasedPriorSpectrumDatasetOnOff` with a `BiasedCompoundSpectralModel`. This requires a definition of two separate `SkyModel` objects for our source, an unbiased version to be evaluated in the LAT energy range, and the model containing the bias parameter for H.E.S.S. data. The intrinsic spectral parameters (except for the additional bias parameter) are shared and linked between these models.

Secondly, in order to properly account for the EBL absorption, the template spectral EBL model must be recomputed using `EBLTable` considering an extended energy range across both instruments. In principle, EBL attenuation will not affect the data from *Fermi*-LAT, as the optical depth is typically $\tau < 1$ for the relevant energy range. However, slight variations in the spectrum may still be observable when studying highly-redshifted sources, in particular for energies when the sensitivity of the LAT and H.E.S.S. overlap.

A summary of the obtained results for the intrinsic spectral modeling of the joint *Fermi*-LAT and H.E.S.S. datasets, considering the baseline Domínguez et al. EBL model (2011) [83] can be found in Table 5.

Comparing our results with similar studies [52], we observe broadly consistent spectral parameters. The computed decorrelation energies are all within the energy bounds for both instruments considered. The wide range spanned by the flux normalization in terms of orders of magnitude (between $10^{-12} \text{ TeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$ to $10^{-06} \text{ TeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$) could be explained by the fact that, in our study, we evaluate the model at the decorrelation energy computed for the joint *Fermi*-LAT and H.E.S.S. dataset, instead of fixing it to that obtained for a single instrument. The spectral index values are mostly consistent, within uncertainties, across all sources considered. However, some discrepancies are found, for example in the cases of 1ES 0347-121, 1ES 0414+009, 1ES 1101-232, PG 1553+113, PKS 0447-439, PKS 1510-089, or some blocks of PKS 2155-304. Some of these discrepancies could be attributed to slightly different time segmentations for each source, or variations in the analysis or data reduction methodologies. The preference for a log-parabola spectral model is consistent with the reference, mostly occurring for PG 1553+113 and certain blocks of PKS 2155-304, as well as the first time block of PKS 0903-57 [139]. Finally, the obtained bias parameters are also comparable to the literature, often with values compatible with zero, and with high uncertainties. Exceptions to this are 1ES 0347-121, 1ES 1101-232, 1ES 1312-423, as well as blocks 6 and 7 of PKS 2155-304, where the value of the parameter exceeds its uncertainty, indicating a non-zero energy shift preferred.

Figure 13 and Figure 14 display the resulting best-fit spectral models for all the sources in our dataset.

Once this fit has been completed, we also perform an additional intrinsic model curvature test. For each source and block in the time segmentation, we compare the resulting total fit statistic obtained for the dataset considering both a power-law and log-parabola models. In order to study exclusively the intrinsic spectrum without EBL attenuation effects, we limit the fit to energies $E < E(\tau = 2)$ below the optically-thick regime defined. A test statistic is then computed between the two models, with the log-parabola model being chosen whenever

5 SPECTRAL UPTURN MODELING AND SIMULATIONS

Source Name	Observation Range [DD.MM.YYYY]	N_0 [TeV ⁻¹ cm ⁻² s ⁻¹]	Γ	β	E_0 [TeV]	$s_{\text{H.E.S.S.}}$
1ES 0229+200	11.09.2004 – 08.01.2019	$(9.16 \pm 2.25) \cdot 10^{-12}$	1.70 ± 0.06	–	0.32	-0.089 ± 0.106
1ES 0347-121	26.08.2006 – 31.12.2013	$(1.47 \pm 0.24) \cdot 10^{-10}$	1.66 ± 0.05	–	0.08	-0.089 ± 0.081
1ES 0414+009	03.10.2005 – 17.10.2010	$(3.46 \pm 0.35) \cdot 10^{-09}$	1.77 ± 0.06	–	0.02	0.012 ± 0.081
1ES 1101-232	17.04.2004 – 24.04.2006	$(7.53 \pm 1.37) \cdot 10^{-11}$	1.63 ± 0.06	–	0.15	-0.087 ± 0.081
1ES 1101-232	23.05.2006 – 28.05.2019	$(1.46 \pm 0.21) \cdot 10^{-10}$	1.56 ± 0.05	–	0.09	0.095 ± 0.089
1ES 1312-423	15.04.2004 – 12.07.2010	$(8.17 \pm 0.95) \cdot 10^{-10}$	1.82 ± 0.05	–	0.03	0.178 ± 0.113
1RXS J101015.9-311909	21.12.2006 – 17.04.2010	$(2.88 \pm 0.20) \cdot 10^{-09}$	1.78 ± 0.03	–	0.02	0.250 ± 0.001
3C 279	24.01.2018 – 29.01.2018	$(2.58 \pm 0.43) \cdot 10^{-06}$	2.58 ± 0.11	–	0.01	0.015 ± 0.116
H 2356-309	16.06.2004 – 08.11.2009	$(9.08 \pm 3.55) \cdot 10^{-12}$	2.05 ± 0.10	–	0.47	0.039 ± 0.131
PG 1553+113	03.06.2013 – 10.05.2019	$(4.21 \pm 3.15) \cdot 10^{-10}$	2.47 ± 0.43	0.11 ± 0.06	0.10	-0.062 ± 0.144
PKS 0346-27	03.11.2021 – 04.11.2021	$(1.30 \pm 0.82) \cdot 10^{-08}$	1.94 ± 0.23	–	0.06	0.007 ± 0.138
PKS 0447-439	09.11.2009 – 07.12.2010	$(1.12 \pm 0.08) \cdot 10^{-07}$	1.73 ± 0.05	–	0.01	0.014 ± 0.068
PKS 0903-57	13.04.2020 – 13.04.2020	$(3.65 \pm 2.04) \cdot 10^{-10}$	2.84 ± 0.22	0.09 ± 0.03	0.48	-0.027 ± 0.115
PKS 0903-57	14.04.2020 – 15.04.2020	$(1.14 \pm 0.45) \cdot 10^{-08}$	2.42 ± 0.11	–	0.06	-0.022 ± 0.138
PKS 0903-57	15.04.2020 – 17.04.2020	$(2.57 \pm 1.24) \cdot 10^{-09}$	2.48 ± 0.11	–	0.17	0.015 ± 0.140
PKS 1510-089	20.03.2009 – 10.05.2016	$(7.12 \pm 0.73) \cdot 10^{-07}$	2.30 ± 0.09	–	0.01	-0.098 ± 0.099
PKS 2155-304	30.06.2006 – 27.07.2006	$(2.24 \pm 1.10) \cdot 10^{-10}$	3.02 ± 0.08	–	0.36	-0.005 ± 0.135
PKS 2155-304	28.07.2006 – 28.07.2006	$(3.21 \pm 1.08) \cdot 10^{-09}$	2.62 ± 0.04	–	0.42	-0.005 ± 0.103
PKS 2155-304	28.07.2006 – 29.07.2006	$(9.04 \pm 4.54) \cdot 10^{-10}$	2.89 ± 0.25	0.38 ± 0.15	0.32	0.013 ± 0.147
PKS 2155-304	29.07.2006 – 30.07.2006	$(2.76 \pm 0.89) \cdot 10^{-09}$	2.20 ± 0.14	0.37 ± 0.04	0.40	-0.028 ± 0.108
PKS 2155-304	30.07.2006 – 31.07.2006	$(1.20 \pm 0.56) \cdot 10^{-09}$	2.47 ± 0.19	0.36 ± 0.07	0.37	-0.056 ± 0.140
PKS 2155-304	01.08.2006 – 01.08.2006	$(3.13 \pm 1.97) \cdot 10^{-10}$	3.10 ± 0.10	–	0.44	-0.154 ± 0.142
PKS 2155-304	02.08.2006 – 04.08.2006	$(1.49 \pm 0.90) \cdot 10^{-10}$	3.09 ± 0.09	–	0.43	-0.159 ± 0.136
PKS 2155-304	05.08.2006 – 20.09.2006	$(1.29 \pm 0.65) \cdot 10^{-10}$	2.46 ± 0.23	0.30 ± 0.12	0.35	-0.045 ± 0.155

Table 5: Results for the spectral parameters of each source obtained from the joint likelihood modeling of the Fermi-LAT and H.E.S.S. data, considering the baseline Domínguez et al. (2011) EBL model [83]. In particular, shown are the final time segmentation obtained for each source, and the spectral parameters: normalization N_0 and index Γ . In the case of a log-parabola being preferred as the spectral model, the additional β parameter is also included. All parameters are obtained by considering as reference energy E_0 the decorrelation energy E_{dec} . The last column includes the bias parameter evaluated only for the H.E.S.S. model.

$\text{TS} > 4$, that is, at the 2σ level. In case the initial spectral model considered is not the best intrinsic model found by this approach, the full analysis is repeated with this new model. In this way, the tables displaying the results shown throughout the previous sections already included information from this curvature test. This test can also be performed individually by FermiPy on the LAT data alone, although by including data from H.E.S.S., which may present considerable overlap, a better estimate can be obtained.

5 Spectral upturn modeling and simulations

WITH the main intrinsic spectral analysis complete, we can now focus our attention towards performing the main search for spectral upturns in our sources, and in particular whether these upturns could be explained by the photon-ALP conversion scenario we consider.

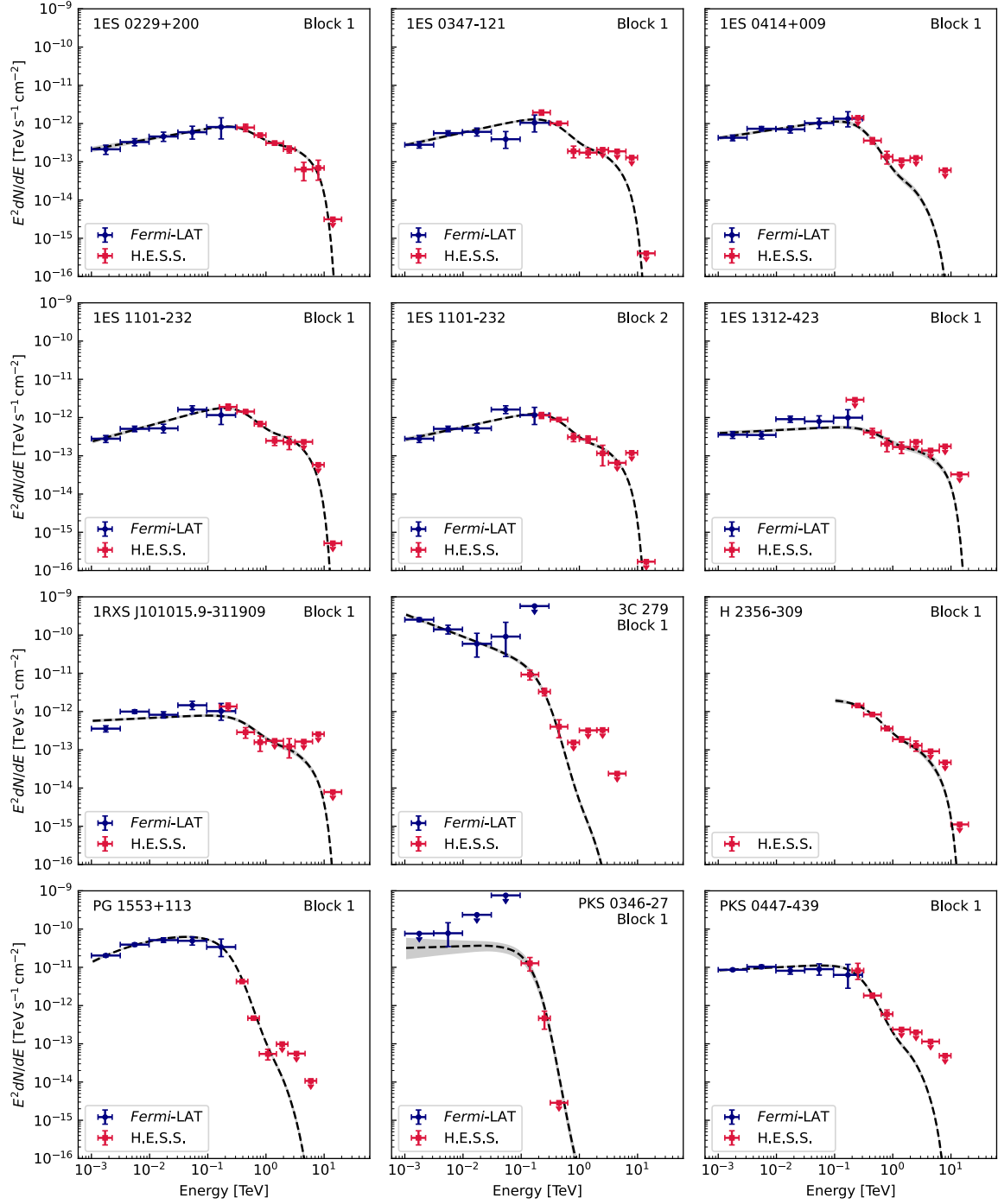


Figure 13: Obtained joint Fermi-LAT and H.E.S.S. SED for the sources considered in this work considering the Domínguez et al. (2011) EBL model [83]. In blue, the flux points or upper limits corresponding to the Fermi-LAT data, and in red, those for H.E.S.S. The model is shown as the discontinuous line, with the shaded region being the associated uncertainty.

5 SPECTRAL UPTURN MODELING AND SIMULATIONS

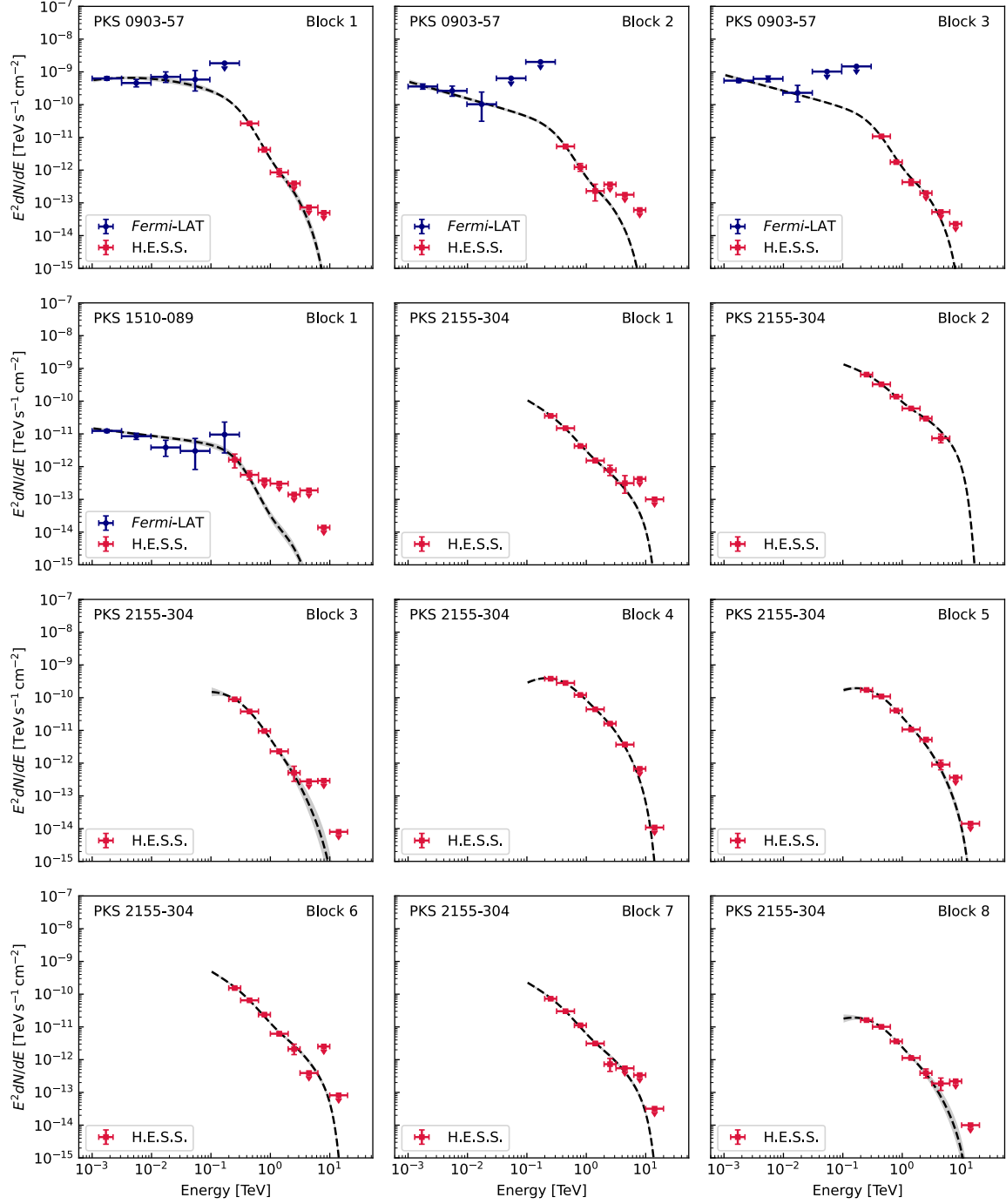


Figure 14: Continuation of Figure 13.

In order to accomplish this, we will separate the task into two parts.

To begin, in Section 5.1 we will perform a statistical search for upturns purely by performing a likelihood fit of a spectral model which includes an upturn in the form of a smooth spectral break. This allows us to obtain a measure of the likelihood that such an upturn is favored by the data.

The next step, presented in Section 5.2, will then be to perform simulations of the photon-ALP beam propagation scenario across the considered astrophysical environments in order to obtain a measure of what the expected upturns look like when caused by oscillations of the emitted gamma rays with ALPs. In this step, we will therefore need to numerically compute the photon survival probability, and quantify the expected boost in the spectrum by incorporating photon-ALP conversion effects.

5.1 Modeling the likelihood of spectral upturns

In order to perform a search for possible upturns within our data, the main strategy will be to attempt to fit our data with a custom spectral model. This new model will include the intrinsic model folded with the EBL absorption, $\phi_{\text{int}} \cdot \phi_{\text{EBL}}$, as well as an additional multiplicative term in the form of a smooth spectral break defined as:

$$\phi_{\text{brk}} = \left[\left(1 - \frac{E}{E_{\text{brk}}} \right)^{\Delta\Gamma/\beta_{\text{brk}}} \right]^{-\beta_{\text{brk}}}, \quad (47)$$

where $\Delta\Gamma = \Gamma_{\text{brk}} - \Gamma$ is the difference of spectral index before and after the break, and β_{brk} is a smoothing factor. To ensure the break corresponds to an upturn in the spectra expected by our photon-ALP conversion scenario, we enforce $\Delta\Gamma < 0$, that is, the spectrum hardens after the break energy E_{brk} , leading to higher photon fluxes at the highest energies. We also set $\beta = 1$ and fix it throughout the analysis.

Therefore, the total model that will be used to fit our data and quantify the likelihood of an upturn being present will be given by a combination of the intrinsic model, including EBL, and this additional spectral break. The smooth spectral break model given by Eq. (47) can be thought of as a generalization of the `BrokenPowerLawSpectralModel` class available in `GammaPy`, that has been modified to allow for the use of any other model as the intrinsic spectral model for our source (both with and without EBL attenuation). Our implementation of this `SmoothBrokenSpectralModel` (a custom `SpectralModel`), defines this additional multiplicative factor and its relevant parameters, and specifies how its evaluation must be carried out. The total spectral model can then be defined as a `CompoundUpturnSpectralModel`.

The search for spectral upturns in our data is performed for both the case of only H.E.S.S. data, in an attempt to reproduce the results from previous work [35], and for the novel case including both *Fermi*-LAT and H.E.S.S. Treating both cases separately also allows us to identify the effects of the inclusion of the LAT data towards constraining the possible upturns.

We consider, initially, the best-fit intrinsic models found for either the H.E.S.S. fit described in Section 4.3 or the joint *Fermi*-LAT and H.E.S.S. modeling from Section 4.4, in both cases including the considered EBL absorption model. The intrinsic model is then combined with the new break model Eq. (47).

5.1 Modeling the likelihood of spectral upturns

We then define a grid over the spectral break parameters selecting physically-motivated ranges for the break parameters. The selection of these ranges is defined considering where upturns due to photon-ALP oscillations could occur for light ALPs in the strong mixing regime, for the considered astrophysical environments, as well as taking into account the sensitivity of our instruments. In particular, we consider an energy range for the spectral break to occur above energies at which the optical depth equals unity, $E_{\text{brk}} \geq E(\tau = 1)$. This lower bound will be different for each source, and below these energies we do not expect to be able to distinguish any upturn signatures due to the fact that EBL attenuation will be negligible. An upper limit for the break energy is considered at $E_{\text{brk}} \leq 31.6 \text{ TeV}$, which was also used as the energy bound for the data reduction, above which the sensitivity of H.E.S.S. is reduced drastically. The change in index will be bounded between the values $\Delta\Gamma = 0$, which implies $\Gamma_{\text{brk}} = \Gamma$ and therefore no upturn, and $\Delta\Gamma = -5$ which corresponds to an extremely sharp upturn. In order to improve the numerical convergence, instead of selecting $\Delta\Gamma = 0$, we instead choose $\Delta\Gamma = -0.01$, as the vanishing index difference implies a degeneracy for the break energy.

Following these considerations, a maximum-likelihood fit is performed, fitting our upturn model onto the data across the grid defined by each break parameter. This grid is constructed with a logarithmic binning in energies and linear binning in the index difference, with a total of 20 points for each.

In an iterative process, we loop over each point in the parameter grid and perform a fit with only the intrinsic spectral parameters being left free (that is, the normalization N_0 , index Γ , and, if present, β). The bias parameter which accounts for H.E.S.S. systematics is also kept frozen during the fit, and therefore does not contribute to the final fit statistic. At the beginning of each iteration, the parameters of the model are reset to their initial best-fit values.

For each point in our grid, we perform a convergence check (beyond the standard fit result status given by `GammaPy`) to make sure the fit has been successful. We do this by checking that all parameters have converged to values within the allowed range, and not saturated to one of the boundaries (which would inflate the fit statistic, as the uncertainty of the parameter is pushed to zero). Each fit is attempted up to 10 times if it fails to converge at any point. In some cases, in order to improve the convergence, we have found it necessary to also relax the boundaries of the free intrinsic parameters and allow for a wider range of values (even though the optimized parameters don't necessarily converge to values within this range). For all sources, the final fits across all points in the grid converge correctly.

The result of this is a two-dimensional likelihood grid across the considered upturn parameter space, in which each point has an associated total fit statistic of our upturn model, that is, how favorable each upturn parametrization is given our data. This total statistic will therefore be the sum of the W_{stat} from H.E.S.S. and, if present, the Cash statistic C_{stat} from the *Fermi*-LAT fit, as described in Section 3.3.2. This procedure is then repeated for each source in our dataset, each time block found, and across the different EBL models considered. In the remainder of this work, we will also denote this total fit statistic as the C -statistic.

A selection of certain examples of these likelihood grids can be found in Figure 15, while the plots for all the considered sources and time blocks in this work can be found in Appendix B.

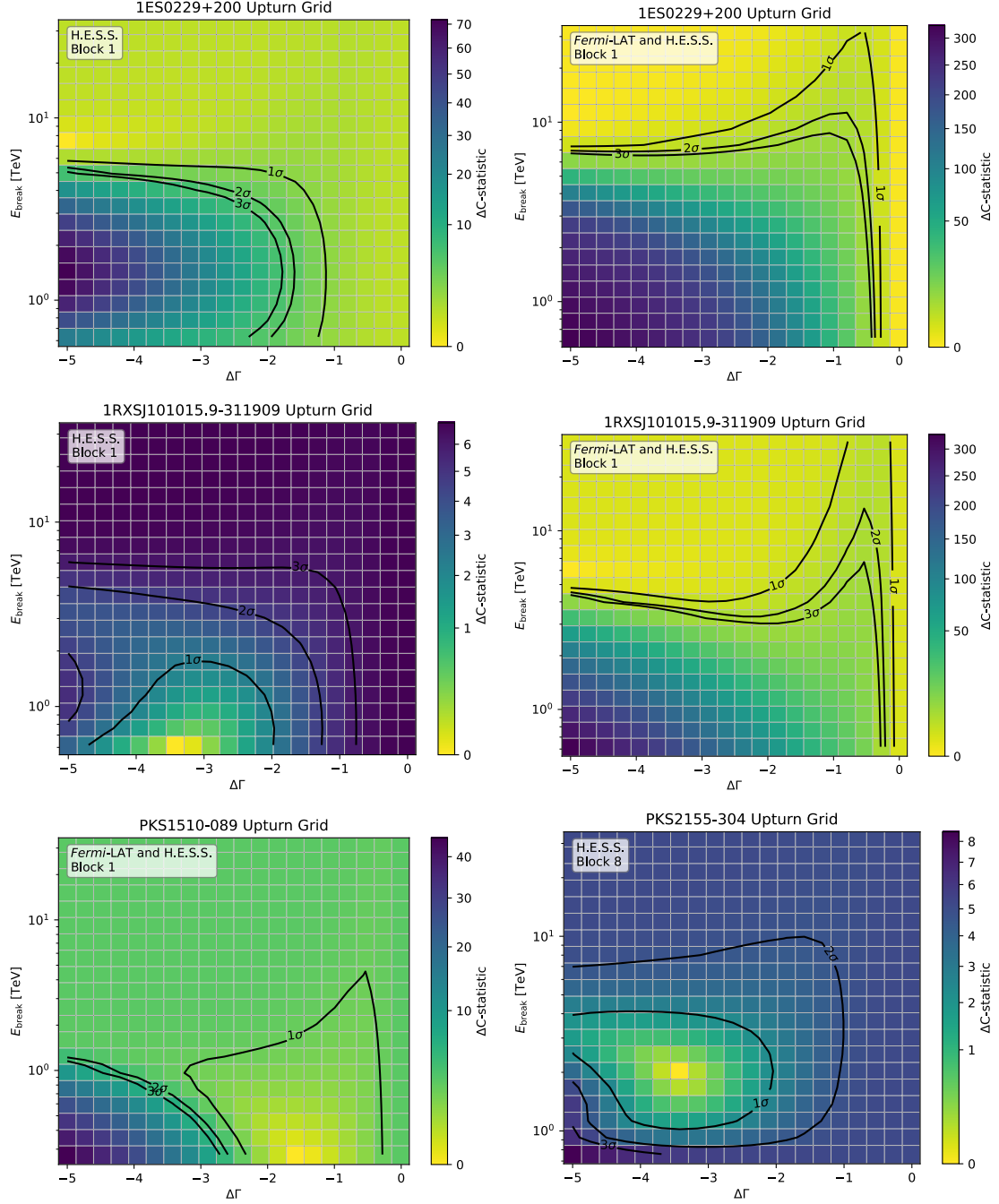


Figure 15: Sample of upturn grids (break energy E_{brk} , in TeV, versus index change $\Delta\Gamma$) obtained for a selection of the considered sources in this work, for both H.E.S.S.-only and joint Fermi-LAT and H.E.S.S. datasets. The value in each point is represented by the colorbar, with higher values (darker colors) representing regions where an upturn offers a worse fit, compared to the lighter colors. The grids are normalized, such that the best-fit upturn model corresponds to a null total statistic. Contours are plotted corresponding to 1σ , 2σ , and 3σ confidence levels. The color map has been rescaled on a square root scale for visualization purposes. The remaining plots for all sources and time blocks in our dataset, for the considered baseline EBL model, can be found in Appendix B.

In these plots, we present the grid defined by the break energy E_{brk} , expressed in TeV and shown in the vertical axis, and the index difference $\Delta\Gamma$, in the horizontal axis, with the value of the total statistic found from the fit displayed at each point by the corresponding color bar. We have subtracted the best-fit point across the grid, such that the best-fit upturn model corresponds to a zero total statistic. For higher values of ΔC_{stat} , the upturn model is increasingly disfavorable by the data. This can be easily visualized, with lighter sections of the plots corresponding to “allowed” upturns that present a relatively good fit to the data, and dark sections corresponding to “constrained” regions of the upturn parameters, where the inclusion of the upturn considerably worsens the overall fit quality. Additionally, whenever possible, statistical significance contours are also plotted at the 1σ , 2σ , and 3σ levels.

We will begin our discussion of these plots by considering those corresponding to H.E.S.S.-only data, focusing on the sources in common with previous analyses. In this case, we find results mostly consistent with the previous work [35], with sharp, low-energy upturns being generally rejected by the data across all sources, displaying significant variability as to how large the constrained upturn parameter regions are. Generally, the best-fit models seem to be distributed along the edges of the grids opposite the statistically-disfavored region (that is, either sharp upturns with very high break energies, or very subtle upturns across all break energy values).

For certain sources (e.g. 1ES 0229+200 and 1ES 0347-121), the best-fit model seems to be much closer to the high ΔC_{stat} region, indicating a possible hint of a preferred upturn with “well-defined” parameters. Perhaps the most surprising cases are PKS 1510-089, and certain blocks of PKS 2155-304 (in particular, blocks 3, 4, 5, and 8), in which upturns with intermediate-high $\Delta\Gamma$ values seem to be favored by the data at lower energies (below 10 TeV). In the case of PKS 1510-089, this corresponds to relatively low TS values, although the other cases seem to present a much higher statistical significance, possibly hinting at the preference of an upturn in the data.

Another very interesting case is 1RXS J101015.9-311909, in which a “band” of preferred upturns can be seen, with a best-fit occurring at $\Delta\Gamma \sim -3.5$ and $E_{\text{brk}} \sim 0.6$ TeV, and with relatively low TS values extending across the surrounding region in the parameter space. This is another case of a source which seems to favor our upturn model, although the overall TS values are also lower than in the other sources.

The inclusion of *Fermi*-LAT data, which represents a major contribution with respect to previous analyses [35], introduces significant modification to the upturn likelihood grids. The general trend observed across our sources can be visualized by considering the first row of Figure 15, corresponding to 1ES 0229+200. Here, the inclusion of LAT data substantially extends the region of disfavored upturn parameters towards larger break energies and smaller index differences. This is exactly the expected behavior, also hypothesized in [35], as by including data from this instrument, we are effectively strongly constraining the intrinsic spectrum of our sources. This breaks a degeneracy present in the H.E.S.S.-only analysis, in which certain upturn models could present good fit statistics despite a poor description of the low-energy spectral shape. This manifests itself within the grids as a broad upturn-allowed region, and is then reduced by performing a joint fit with both instruments.

An interesting exception to the general behavior found is PKS 1510-089. As we have discussed,

the upturn grid obtained with data from only H.E.S.S. displayed a slight preference for low-energy upturns with low index difference. Including data from the LAT, however, does not seem to resolve this as in the other sources. Instead, the best-fit model is “pushed” into higher-valued $\Delta\Gamma$ still located at the lowest energies. The usual, high-TS region is still present, and now rules out the previous best-fit model, and any upturn occurring at low energies at high index change. This behavior appears to suggest a possible preference for the upturn case that is also present when considering LAT data, although the overall ΔC_{stat} values obtained across the grid seem much lower than the other sources.

An additional feature also appears in the case of the joint *Fermi*-LAT and H.E.S.S. upturn grids in the form of an elongated constraining region extending towards high energies at low $\Delta\Gamma$ values. This is observed across most, but not all, sources (it is missing in, for example, 1ES 0414+009, 3C 279, PKS 0346-27, the first two blocks of PKS 0903-57, and PKS 1510-089). This effect is also visible in certain H.E.S.S.-only sources, mainly in various blocks (2, 6, and 7) of PKS 2155-304, all of which correspond to grids where high TS values are obtained. It can be preliminarily hypothesized that this effect is correlated with grids presenting high statistical significances and prominent differences of the total fit statistic between the best-fit and worse-fit regions, and could indicate that subtle upturns are mostly ruled out in our data across all break energy values.

Another way the inclusion of *Fermi*-LAT data appears to improve the results is by breaking a possible degeneracy present when considering the log-parabola model, which includes the additional curvature β parameter. When considering data from H.E.S.S. alone, in the cases where the source-block pair is best described by a log-parabola, low ΔC_{stat} values are obtained, and the results seem to be poorly constrained, with best-fit upturn models often located at low energies and with extremely-high index differences. However, including LAT data seems to resolve this issue. This effect is most evident for the sources PG 1553+113 and 1RXS J101015.9-311909, where the joint fit removes the irregular grid shape and substantially increases the ΔC_{stat} values across the grid.

It is also interesting to showcase and discuss in detail the upturn grids obtained for the new sources considered in this study. In particular, the plots obtained for 3C 279 and PKS 0346-27 can be found in Figure 16, and for both a similar discussion can be applied. Considering the upturn grids obtained from the H.E.S.S. data, in both cases we obtain an upturn-constraining region at the expected position (sharp upturns and low break energies), with 3C 279 presenting a localized best-fit model close to that region, while for PKS 0346-27 this best-fit region is distributed across most of the parameter space. However, in both cases, the overall TS values obtained are extremely low, no statistical significance contours can be computed, and therefore, we cannot extract any meaningful information on the preference of upturns for these data.

By performing the joint fit, in both upturn grids the TS values are increased, indicating a greater fit statistic difference between the upturn model and the best-fit model. In this sense, we can clearly see how the inclusion of data from the LAT significantly improves the modeling of upturns. However, the final high-TS regions are still small compared to the other sources, indicating that neither of these sources provide strong constraints on the presence of upturns and that, therefore, they will not contribute much to our further study. Out of the two, 3C

5.1 Modeling the likelihood of spectral upturns

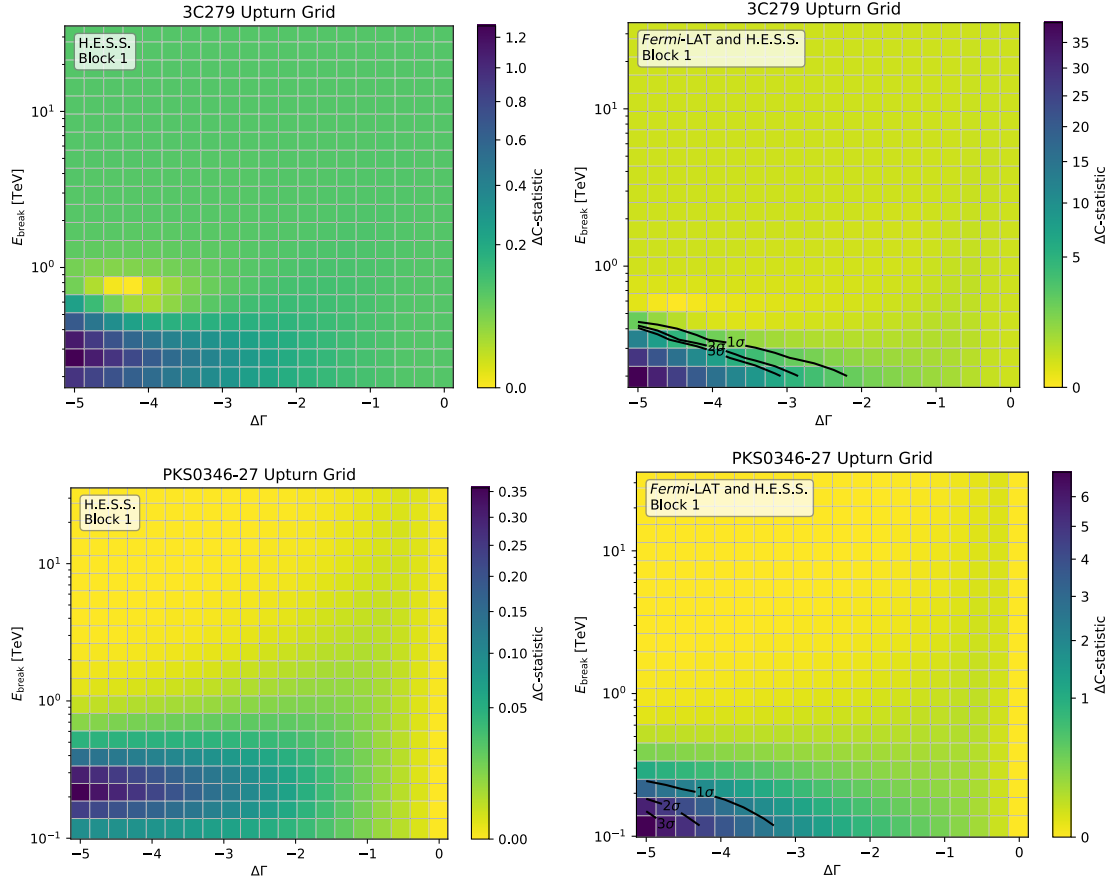


Figure 16: Upturn grids obtained for two of the new sources included in this work, 3C 279 and PKS 0346-27, showcasing the normalized total fit statistic across the considered spectral break parameter space. The upturn grids shown correspond to the H.E.S.S.-only data (on the left column), and the joint Fermi-LAT and H.E.S.S. fit (right column). The EBL model considered is the baseline Domínguez et al. (2011) [83].

279 will provide most of the upturn constraints, with TS values comparable to those obtained for PKS 1510-089. The main reason for these suboptimal results is the limited emission in the optically thick regime at energies above $\tau = 2$ for both of these sources. This could be improved by, for example, extending the observation dataset to cover a broader time span.

Similarly, the upturn grids obtained for all three blocks of PKS 0903-57 can be found in Figure 17.

In this case, the results are much more promising. For the H.E.S.S.-only case, the upturn grids show the expected appearance with statistically-significant upturn-excluding regions, although for the first time block, the TS values are much lower than expected, such that no real conclusions can be obtained. This could be caused by a possible degeneracy between the log-parabola model (and in particular, the additional β parameter) and the upturn model, causing the fits to not converge properly despite resulting in physically coherent parameter values. However, when including data from the LAT, this degeneracy appears to be broken

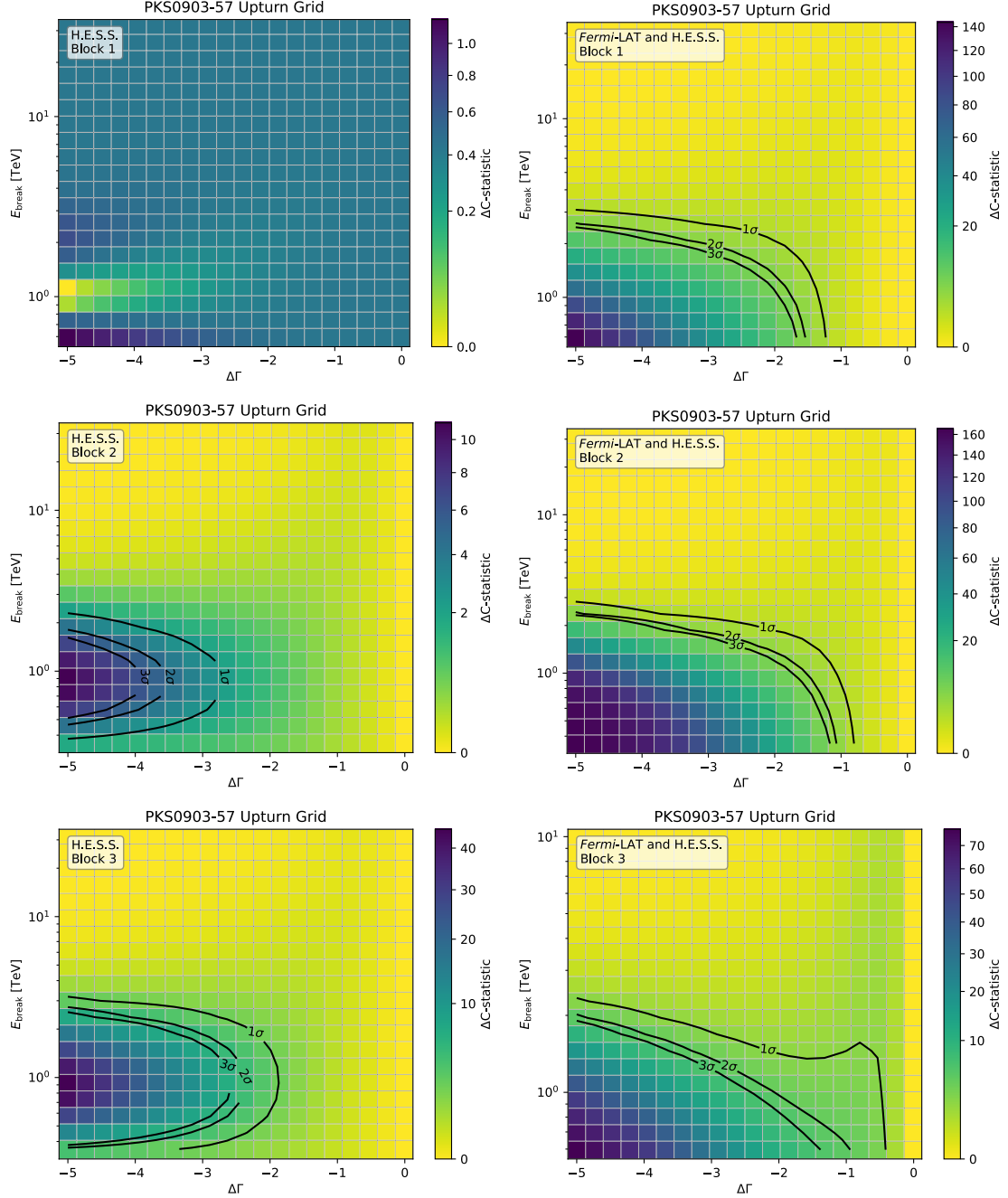


Figure 17: Upturn grid plots for the different time segmentation blocks (given by each row) obtained for the third new source considered in this work, PKS 0903-57, displaying the total fit statistics across the considered spectral break parameter space. The upturn grids shown correspond to the H.E.S.S.-only data (on the left column), and the joint Fermi-LAT and H.E.S.S. fit (right column). The EBL model considered is the baseline Domínguez et al. (2011) [83].

5.1 Modeling the likelihood of spectral upturns

for the first block, and we obtain good upturn-constraining regions across all blocks with sufficiently high TS values comparable to other sources. The best results are obtained from the second time block, with a well-defined high-TS region. In this case, the source appears to be much more useful for our study than the previous two discussed, and its contribution towards the final results are expected to be significant.

As we have seen, the upturn modeling presented in this section allows us to determine where an upturn, characterized by its index change and break energy, could be favorable by our data, providing regions where the fit is significantly worsened from the best-fit upturn model. In this regard, it is therefore interesting to study how this best-fit model looks like when compared to the intrinsic SED of our sources. An example of such comparison is given in Figure 18, where the two models are compared for some sources.

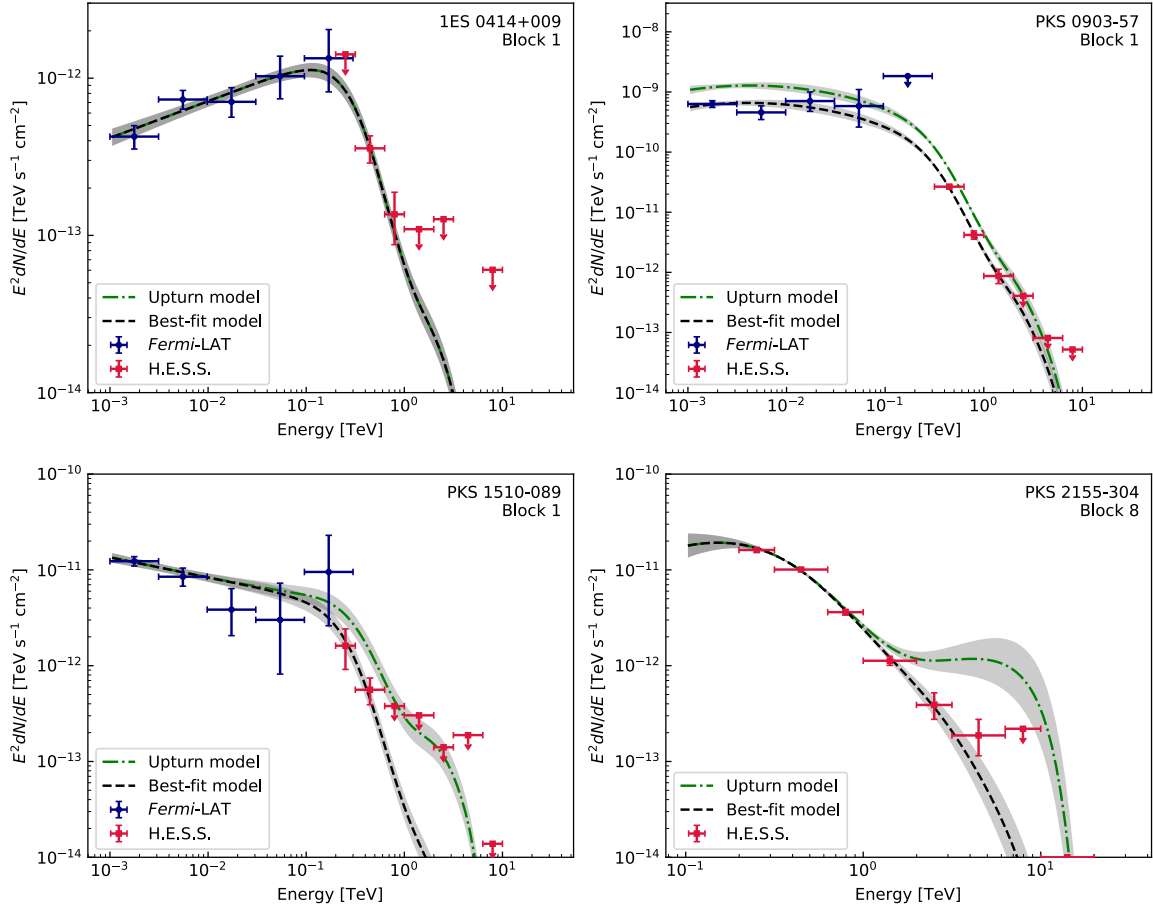


Figure 18: Example of the best-fit models found for a subset of the considered sources, for the cases of both a standard intrinsic model including EBL absorption, obtained in Section 4 (shown as the discontinuous gray line) and the upturn model which also includes a spectral break (as the green line). The flux points correspond to those computed with best-fit intrinsic model, with no upturn or spectral break.

In particular, we can see how, in some sources, the best-fit model is consistent with no upturn

being present, such as the case of 1ES 0414+009, for which the best-fit occurs for the spectral break parameters $\Delta\Gamma = -5$ and $E_{\text{brk}} = 31.6$ TeV (a very sharp upturn at the highest energy, which is equivalent to the no-upturn case). We also find, in PKS 0903-57 (Block 1) that a slight deviation from the intrinsic model seems to provide a better fit, with $\Delta\Gamma = -0.01$ and $E_{\text{brk}} \sim 0.9$ TeV. Finally, we also present two cases where an upturn seems preferred: PKS 1510-089, with $\Delta\Gamma \sim -1.58$ and $E_{\text{brk}} \sim 0.28$ TeV, and PKS 2155-304 (Block 8), with $\Delta\Gamma = -3.42$ and $E_{\text{brk}} \sim 2.02$ TeV. From these plots, we can also observe how the inclusion of data from *Fermi*-LAT helps constrain the lower-energy range of the SED, providing further constraints, and how only considering H.E.S.S. data could lead to various upturn models providing a reasonably good fit.

It must be noted, however, that the best-fit upturn model at each point in the grid may only differ slightly from neighboring points, as can be seen from the broad, diffuse regions where the upturn model displays low ΔC_{stat} values close to zero. Because of this, the shown best-fit upturns could be chosen with many different parameters, affecting the observed spectral shape, without a significant difference in the fit statistic. Therefore, these plots must be interpreted mostly qualitatively, as the claim of the presence of a spectral upturn requires a careful likelihood analysis.

5.2 Simulations of spectral upturns due to photon to axion-like particle conversions

UP to this point, the upturn search has been performed by purely modeling the data with an upturned spectral model, and thus without any contribution of ALPs. We now turn our attention towards studying whether these upturn models are compatible with photon-ALP conversions. For this purpose, it is therefore required to compute and characterize the expected upturns caused by this effect.

This study can be performed by computing the photon survival probability $P_{\gamma\gamma}$ resulting from the propagation of a photon-ALP beam across the considered astrophysical magnetic field environments, mainly, the intergalactic magnetic field (IGMF) and the galactic magnetic field (GMF), as described in Section 2.4.2, including any possible mixing effects summarized in Section 2.2.1. The propagation of such a photon-ALP beam considering mixing between the two particles can be computed following a transfer matrix approach which, in practice, must be implemented numerically via simulations. The main difficulty in our case is the lack of available information on the IGMF, which requires we treat it as a cell-like environment subdivided into numerous domains where the magnetic field is oriented randomly, rendering any analytical computation completely impractical.

The required transfer matrix method for photon-ALP beam propagation across astrophysical sources is implemented within **GammaALPs** 0.4.1 [55], an open-source **Python** library which solves the photon-ALP equations of motion and implements the required environment models used in this work. This framework allows for the definition of a source, characterized by its redshift z and position in the sky, as well as an ALP with its characteristic mass and coupling to the electromagnetic field. Considering an initially-unpolarized state density matrix $\rho = (1, 1, 0)/2$, and after defining the relevant astrophysical environments (in order of appearance from the source to the observer), the software then computes the final photon

5.2 Simulations of spectral upturns due to photon to axion-like particle conversions

survival probability $P_{\gamma\gamma}$ of the complete propagation scenario, taking into account both EBL absorption and photon-ALP mixing [55].

In our case, we define an ultra-light ALP with mass $m_a = 1 \cdot 10^{-3}$ neV, and consider couplings such that we remain within the strong-mixing regime, considering $g_{a\gamma} \in [10^{-13}, 10^{-10}] \text{ GeV}^{-1}$. The strong-mixing regime condition is satisfied for these values since, as described in Section 2.2.1, the plasma term ω_{pl} will dominate over m_a in the oscillation wave number Δ_{osc} , as seen from Eq. (18). This will provide the most optimistic scenario for photon-ALP mixing, while also allowing us to extend our results towards lower energies (as long as $m_a \ll \omega_{\text{pl}}$).

The astrophysical environments considered are, first, the IGMF. This environment is treated as a cell-like structure divided into numerous domains, of coherence length $L \sim 1 \text{ Mpc}$, in which a constant magnetic field of strength $B = 1 \text{ nG}$ is present and randomly oriented. We also consider an electron number density given by $n_e = 10^{-7} \text{ cm}^{-3}$ and the corresponding EBL absorption model considered in each case. These parameters are compatible with the currently known observational bounds, and are selected considering the constraints which provide the most optimistic photon-ALP conversion probabilities [56]. For each source, 100 independent realizations of the random IGMF are performed to account for the stochastic nature of the magnetic field orientations. The second environment considered is the GMF, for which we use the Jansson-Farrar (2012) model [92], which does not require the specification of any additional parameters.

Once the environments, source, and ALP are all defined, we can proceed to run the simulation, which must be performed for each source in our dataset and each EBL model considered. Here, the time variability does not affect the results, and therefore we do not need to perform the simulation for each time block. In order to fully probe the coupling parameter space, we compute the photon survival probability for each value of $g_{a\gamma}$ within the considered range. The result of each simulation is therefore the probability $P_{\gamma\gamma}$, which quantifies the fraction of photons that survive their propagation, from source to observer, including effects of EBL absorption and photon-ALP conversions.

From the photon survival probability, we can also obtain the “boost”, or the expected spectral upturn that would be observed within the SED of our sources due to photon-ALP mixing. This can be done by simply correcting the resulting photon survival probability $P_{\gamma\gamma}$ for the EBL absorption, multiplying by the inverse factor $e^{+\tau(E,z)}$.

In Figure 19 we have shown an example of the results of these simulations for two sources at different redshifts, displaying both the photon survival probability $P_{\gamma\gamma}$ and the expected spectral “boost”. In particular, these results are shown for two different ALP coupling values, $g_{a\gamma} = 10^{-11} \text{ GeV}^{-1}$ and $g_{a\gamma} = 5 \cdot 10^{-11} \text{ GeV}^{-1}$, and considering the baseline Domínguez et al. (2011) EBL model [83]. Here, we can clearly see how, for smaller coupling values, $P_{\gamma\gamma}$ follows very closely the expected EBL absorption, indicating no significant increase in detected photons except for the highest energies, where a greater discrepancy appears between the two curves. As we consider couplings with higher values, we can clearly observe how, due to photon-ALP mixing, photons reaching the observer exceed substantially what would be expected with EBL absorption alone, with this excess becoming prominent at higher energies.

From this same figure, we have also obtained the expected spectral upturn that would be

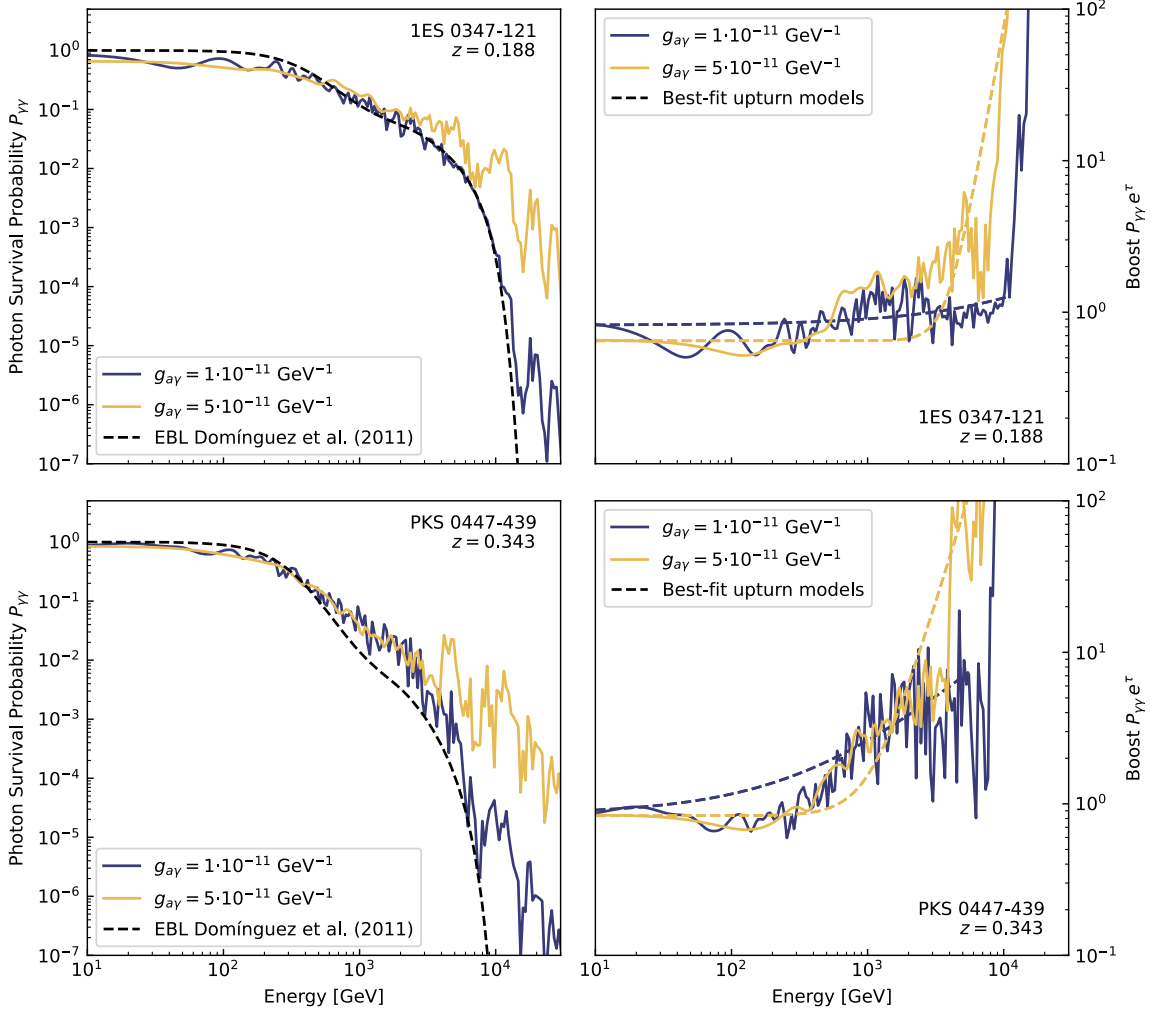


Figure 19: Photon-ALP propagation simulation results from low-intermediate redshift sources (1ES 0347-121, on the top row, and PKS 0447-439, on the bottom row). On the left column, the resulting photon survival probability for each source, obtained from a single simulation iteration of the photon-ALP beam propagation and conversion. On the right column, the corresponding expected upturn or boost to the gamma-ray signal obtained by correcting for EBL absorption the photon survival probability. The discontinuous lines show the best-fit to the upturn signal considering the model given by Eq. (47), multiplied by an additional normalization parameter $N_{0,ALP}$. In each plot, two distinct cases are shown for the corresponding ALP couplings of $g_{a\gamma} = \{1, 5\} \cdot 10^{-11} \text{ GeV}^{-1}$ (in blue and yellow, respectively).

observed in our spectra. Here, we can also clearly see how increasing the coupling value $g_{a\gamma}$ produces more pronounced upturns, while lower-coupling upturns are typically subtle or dominated by the random signal due to the IGMF. Furthermore, increasing the redshift of the considered source makes the upturns occur at lower energies, thus making them more detectable, exactly as expected.

A similar plot to Figure 19 is given in Figure 20 for two sources with higher redshift values. In these cases, we can observe how for both coupling values considered, the photon survival

5.2 Simulations of spectral upturns due to photon to axion-like particle conversions

probability is well above the expected EBL absorption, indicating that distant sources which present heavy suppression due to EBL offer the best probes for spectral effects of photon-ALP mixing (at the expense, of course, of a heavily limited available signal from observations, which is not considered here). We can also observe how at such high redshifts, the signal seems to be more strongly dominated by random fluctuations due to the IGMF. Another interesting feature in this plot can be seen when comparing the expected spectral upturn for each coupling value, where the previous clear difference between the high- and low-value couplings seems to not be present, and both cases present similar boosts in appearance.

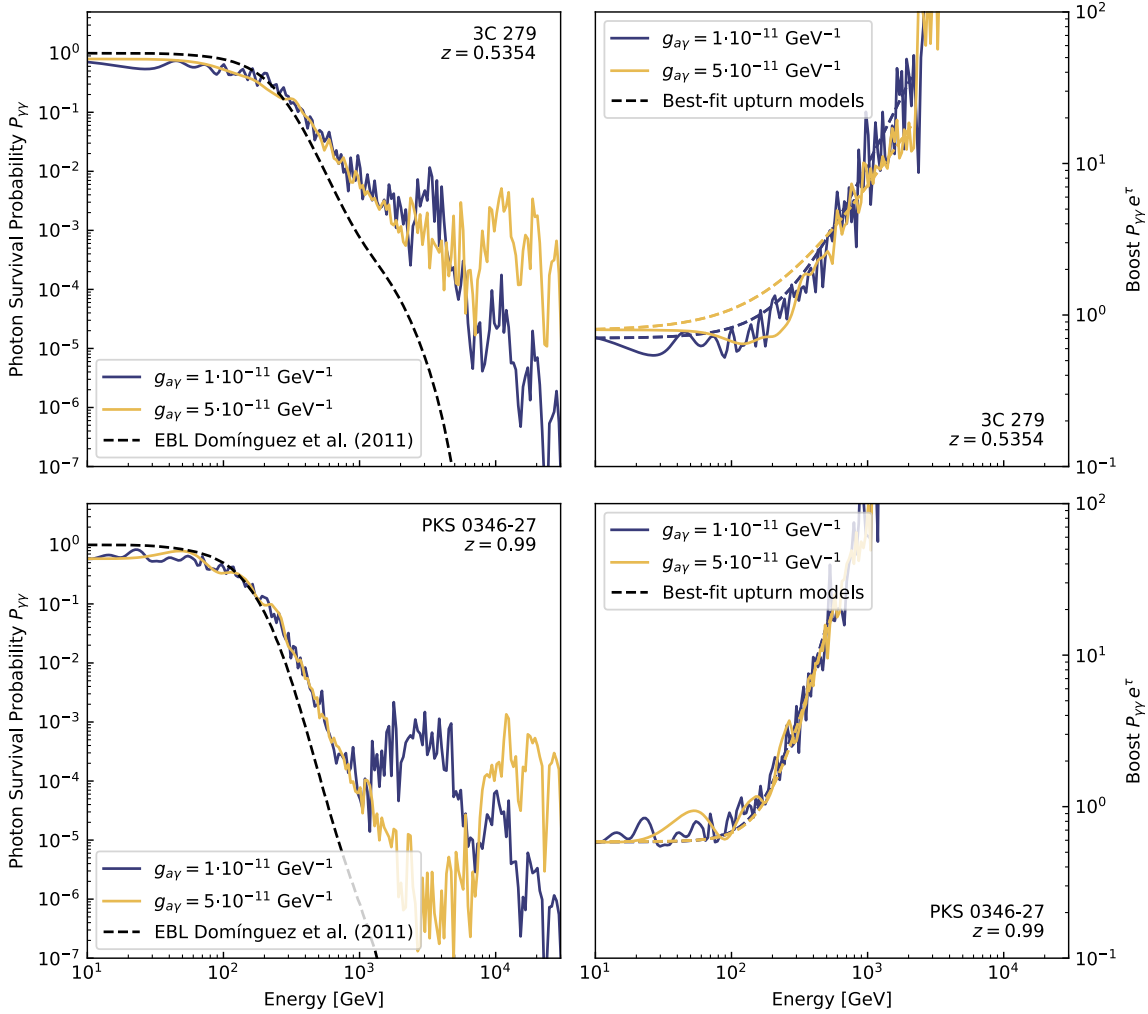


Figure 20: Photon-ALP propagation simulation results from intermediate-high redshift sources (3C 279, on the top row, and PKS 0346-27, on the bottom row). On the left column, the resulting photon survival probability for each source obtained from a single simulation iteration of the photon-ALP beam propagation and conversion. On the right column, the corresponding expected upturn or boost to the gamma-ray signal obtained by correcting for EBL absorption the photon survival probability. The discontinuous lines show the best-fit to the upturn signal considering the model given by Eq. (47), multiplied by an additional normalization parameter $N_{0,ALP}$. In each plot, two distinct cases are shown for the corresponding ALP couplings of $g_{a\gamma} = \{1, 5\} \cdot 10^{-11} \text{ GeV}^{-1}$ (in blue and yellow, respectively).

In order to be able to compare these simulated spectral upturns, caused by photon-ALP mixing, with the upturns modeled in Section 5.1, we perform a fit of $P_{\gamma\gamma} e^\tau$ with the same upturn model given by Eq. (47), including an additional normalization term $N_{0,\text{ALP}}$ bounded closely to the value of the curve at the lowest energy considered. This fit is performed with the `SciPy` library, considering the same bounds and parameters as in Section 5.1. Since we are interested in the spectral upturn caused by ALPs, and not the EBL “divergence” caused by the e^τ term, we restrict the fit to energies below a threshold given by $E < E(\tau = 10)$, above which the EBL contribution fully dominates over the upturn signal. This enables us to compute the parameters $\Delta\Gamma_{\text{ALP}}$ and $E_{\text{brk,ALP}}$, which can then be directly compared with the previous results, allowing us to obtain the likelihood of the photon-ALP mixing process causing the possible upturns observed in our data.

6 Likelihood analysis of spectral upturns due to photon to axion-like particle conversions

WE begin this section by briefly summarizing the results obtained up to this point, which we will use in order to estimate how well the effects of photon-ALP mixing could explain the possible upturns observed in our data.

The main results obtained in Section 5.1 are our two-dimensional, fit-statistic grid plots obtained for each source, which describe how well our data can be described by the corresponding intrinsic model, including EBL absorption, and an additional spectral break term, characterized by the break energy E_{brk} and the change in index $\Delta\Gamma$. Each point in the resulting grid has an associated total fit statistic, which quantifies which upturn parameters are favored by our data, and for which the fit is significantly worse.

On the other hand, in Section 5.2, we have focused our attention towards obtaining, via numerical simulations of photon-ALP mixing in the considered astrophysical environments, the resulting photon survival probability $P_{\gamma\gamma}$. From this, the expected spectral upturn signal $P_{\gamma\gamma} e^\tau$ is obtained after correcting for EBL absorption. The obtained upturns have then been modeled by performing a fit with the same smooth-break spectral model as in Section 5.1, which allows us to directly characterize each upturn by the associated parameters $E_{\text{brk,ALP}}$ and $\Delta\Gamma_{\text{ALP}}$. These simulations have been performed multiple (100) times each, to account for the randomly oriented magnetic fields within the IGM, and across a range of ALP coupling values $g_{a\gamma} \in [10^{-13}, 10^{-10}] \text{ GeV}^{-1}$, ensuring that the strong-mixing regime condition given by Eq. (25) is fulfilled throughout.

This methodology enables us to perform direct comparisons of the parameters $E_{\text{brk,ALP}}$ and $\Delta\Gamma_{\text{ALP}}$ found from the photon-ALP mixing simulations, with the parameters E_{brk} and $\Delta\Gamma$ obtained by modeling upturns in our data. This, in turn, allows us to associate a fit-statistic to each ALP upturn by computing the associated parameters. How this comparison is performed, and how the final likelihood of ALP-induced upturns is obtained, is described in detail in Section 6.1. In Section 6.2, we then present these results across the different EBL models considered in this work. In Section 6.3 we discuss the methodology applied to estimate, preliminarily, possible constraints on the ALP parameter space that could be obtained from the results of this work. Finally, in Section 6.4, we conclude with a discussion on the required

work in regard to the computation of the correct statistical constraint thresholds that could then be used to obtain the final ALP parameter space constraints.

6.1 Upturn likelihood curves across axion-like particle couplings

IN order to obtain an estimate of how well the simulated upturns caused by photon-ALP mixing fit with our data, we need to compute the fit-statistic or likelihood of these upturns, which we have obtained previously and characterized by $E_{\text{brk,ALP}}$ and $\Delta\Gamma_{\text{ALP}}$, considering a model which allows for a direct comparison with our previous upturn grid plots. The approach considered in this work is to directly interpolate each ALP upturn parameter pair onto these grids. In practice, this must be performed for all 100 pairs of ALP upturn parameters, and for each coupling value considered. The interpolation step is implemented via the `RectBivariateSpline` class from the `scipy.interpolate`, which constructs an interpolated upturn grid considering a 1-degree spline and evaluates it at the point where the ALP upturns are found from the simulations.

Illustrative examples of this interpolation process are visualized in Figure 21, where the upturn grids for one of our sources is shown, overlaid with the parameters of the best-fit ALP upturn model, obtained from each one of our simulations. In this plot, we can observe how this distribution evolves for different coupling $g_{a\gamma}$ values (a behavior common across our sources). For low couplings $g_{a\gamma} < 1 \cdot 10^{-11} \text{ GeV}^{-1}$, the ALP upturn parameters are grouped together at very high values of $\Delta\Gamma$ and E_{brk} , representing compatibility with the case of no upturn. As we increase the coupling to $g_{a\gamma} \sim 1 \cdot 10^{-11} \text{ GeV}^{-1}$, the interpolated upturn points begin to move towards lower values of $\Delta\Gamma$, and for even higher couplings $g_{a\gamma} \gtrsim 2.5 \cdot 10^{-11} \text{ GeV}^{-1}$, the probed values of E_{brk} also decrease towards lower energies. Increasing the coupling even more makes the best-fit points once again collapse into a smaller region of sharp upturns with high values of $\Delta\Gamma$ at low energies. This behavior is exactly what we expect: low couplings will not produce very prominent upturns in our spectra, while higher couplings will produce sharper upturns at lower energies. With this, we may estimate what the (interpolated) fit statistic value is for each ALP upturn parameter.

In order to select the most representative values for the parameters of these ALP upturns (and exclude outliers due to the intrinsic randomness), we consider the fifth percentile of these parameters, and obtain their associated likelihood values from the upturn grid, which we denote as C_{ALP} . From these upturn grid plots, we may also obtain an estimate for the likelihood of the no-ALP case, $C_{\text{No-ALP}}$, taken as the value located at $\Delta\Gamma \sim 0$ at high E_{brk} energies. We then keep track of these two likelihoods for each source and time block across a single EBL model.

In order to carry out the required statistical study, two different hypothesis tests can be performed, each considering a different test statistic (TS): one regarding what is the likelihood that photon-ALP oscillations cause the upturns and for which ALP coupling this occurs (the ALP detection significance), and the other one regarding how well each coupling compares against the best-fit ALP scenario (the ALP likelihood curve).

First, let us consider the computation of the ALP detection significance. In this case, we want to compare the best-fit ALP upturn case against the alternative case, with no upturns.

6 LIKELIHOOD ANALYSIS OF SPECTRAL UPTURNS DUE TO PHOTON TO AXION-LIKE PARTICLE CONVERSIONS

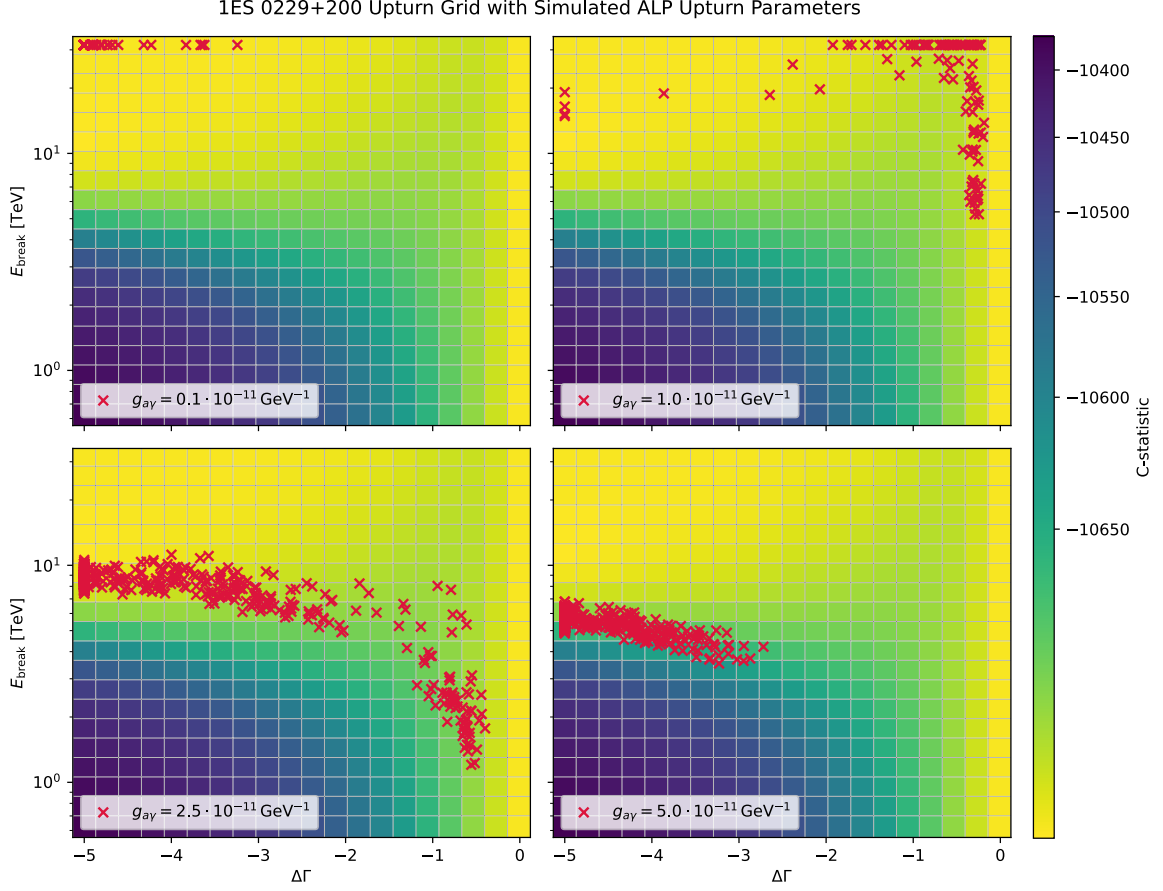


Figure 21: Example upturn likelihood grid for one of our sources, 1ES 0229+200, obtained as described in Section 5.1, shown for the baseline Domínguez et al. (2011) EBL model [83]. Each red cross on the plot represents the best-fit upturn parameters, $\Delta\Gamma_{\text{ALP}}$ and $E_{\text{brk,ALP}}$, corresponds to the fit performed on the simulated spectral boost caused by photon-ALP upturn conversions, as in Section 5.2. From top to bottom, left to right, an evolution across a range of ALP couplings $g_{a\gamma} \in \{0.1, 1.0, 2.5, 5.0\} \cdot 10^{-11} \text{ GeV}^{-1}$.

For this, the following TS can be used:

$$\text{TS}_{\text{ALP,det}} = \min_{g_{a\gamma}} \left(\sum_{i=1}^{\text{src}} C_{\text{ALP}}^{(i)}(g_{a\gamma}) \right) - \sum_{i=1}^{\text{src}} C_{\text{No-ALP}}^{(i)}, \quad (48)$$

where $C_{\text{ALP}}^{(i)}$ is the fit statistic obtained from the simulated ALP upturn parameters interpolated onto the upturn likelihood grids, and $C_{\text{No-ALP}}^{(i)}$ (constant for each source and time block) corresponds to the null hypothesis, obtained from the likelihood grid point corresponding to $\Delta\Gamma \sim 0$ at the maximum considered break energy. Taking the minimum of the first term over all couplings ensures we are comparing against the best-fit ALP case. For both of these quantities, the superscript (i) indicates the source-block pair, over which we perform the summations.

One may also compute the curve of the obtained ALP interpolated fit-statistics against its

best-fit case, which allows us to study how the preference for ALPs changes across all coupling parameter values $g_{a\gamma}$ with respect to the best-fit case. For this, we define the following test statistic:

$$\text{TS}_{\text{ALP}}(g_{a\gamma}) = \sum_{i=1}^{\text{src}} C_{\text{ALP}}^{(i)}(g_{a\gamma}) - \min_{g_{a\gamma}} \left(\sum_{i=1}^{\text{src}} C_{\text{ALP}}^{(i)}(g_{a\gamma}) \right), \quad (49)$$

which represents the profile likelihood ratio of relative preference of ALP upturns versus the best-fit ALP upturn case (under the ALP hypothesis). By definition, the coupling at which $\text{TS}_{\text{ALP}}(g_{a\gamma}) = 0$ corresponds to the ALP parameter $g_{a\gamma}$ that best describes the observed upturns, while values $\text{TS}_{\text{ALP}}(g_{a\gamma}) > 0$ indicate relatively worse fits. Thus, higher values of this TS indicate a preference for the null, no-ALP hypothesis.

We compute the ALP curve given by Eq. (49) from the values C_{ALP} for each source and time block in our dataset, as well as for all four EBL models considered in this work. We will also separate the study, as usual, into the individual results obtained from H.E.S.S. data exclusively, as well as from the joint dataset of *Fermi*-LAT and H.E.S.S. observations.

Figure 22 displays the obtained ALP likelihood curve for our baseline EBL model considering data from H.E.S.S., including the individual contribution of each source and the total summed curve. As we can see, for low couplings below $g_{a\gamma} < 4 \cdot 10^{-12} \text{ GeV}^{-1}$, the TS remains practically constant, at values $\text{TS}_{\text{ALP}}(g_{a\gamma}) \sim 2.71$. For couplings $4 \cdot 10^{-12} \text{ GeV}^{-1} < g_{a\gamma} < 3 \cdot 10^{-11} \text{ GeV}^{-1}$, the ALP hypothesis likelihood gradually reaches a local minimum. Finally, there is a clear and abrupt global minimum at approximately $g_{a\gamma} \sim 4 \cdot 10^{-11} \text{ GeV}^{-1}$, after which the curve drastically increases reaching $\text{TS}_{\text{ALP}}(g_{a\gamma}) > 20$.

Most of the sources (and their corresponding time segmentation blocks) contribute to various degrees towards the total curve. In general, we can see how certain individual contributions begin at some constant TS value for low couplings, and then display a rapid decrease to zero at higher couplings. On the contrary, other sources present the opposite behavior, with their TS values only increasing significantly at high coupling values. Clearly, both cases contribute to the presence of a minimum in the total likelihood curve. Finally, certain sources present low TS values for all coupling values, thus not contributing significantly to the total ALP likelihood.

In particular, the sources that seem to contribute the most at $g_{a\gamma} < 3 \cdot 10^{-11} \text{ GeV}^{-1}$ are blocks 4, 5, 6, and 7 from PKS 2155-304, both blocks of 1ES 1101-232, 1RXS J101015.9-311909, all with $C_{\text{ALP}}^{(i)} > 9$. On the other hand, the dominant sources at high couplings $g_{a\gamma} > 3 \cdot 10^{-11} \text{ GeV}$ are 1ES 0229+200, both blocks of 1ES 1101-232, H 2356-309, and blocks 5, 6, and 7 from PKS 2155-304.

Most importantly, the presence of a clear global minimum in this curve suggests that, for couplings $g_{a\gamma} \sim 3 \cdot 10^{-11} \text{ GeV}^{-1}$, a possible preference for the case of ALP-induced upturns is present in the H.E.S.S. data. However, this could also be interpreted by considering that the H.E.S.S. data cannot properly constrain the ALP upturns at these couplings. In fact, returning to the example plots in Figure 21, we can see how at similar coupling values, the ALP upturn parameters are scattered across a wide upturn parameter space, including the region at low E_{brk} and low-intermediate $\Delta\Gamma$ for which the H.E.S.S.-only upturn likelihood grids offer only limited constraints.

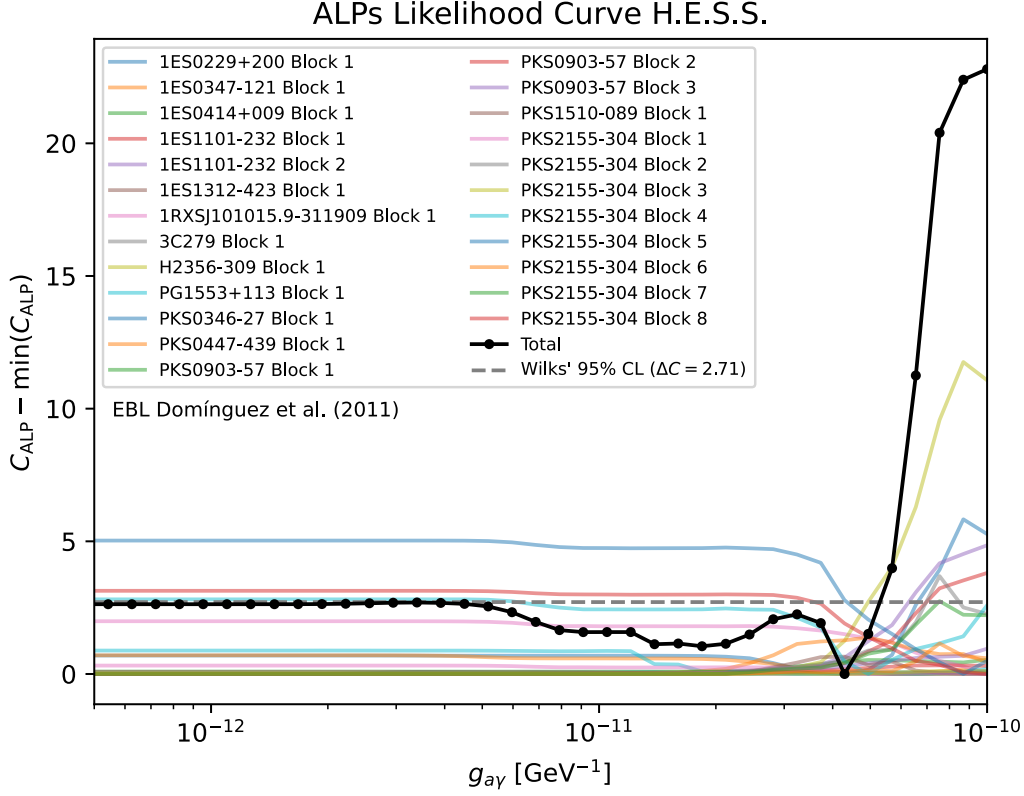


Figure 22: ALP likelihood curve computed using Eq. (49), considering the baseline EBL model, for the H.E.S.S. dataset. Here, we display the relative preference of the ALP upturns versus the best-fit ALP upturn across the considered coupling $g_{a\gamma}$ values. The individual, colored lines represent the individual contributions of each source. The horizontal, dashed line represents the 95% confidence level given by Wilks' theorem, assuming its applicability (for a detailed discussion on this, we refer to Section 6.4).

The inclusion of *Fermi*-LAT data is exactly what is needed to properly study this effect. By increasing the unfavorable upturn parameters in the upturn grids obtained in Section 5.1, we can determine whether this apparent ALP preference is a physical result, or the effect of the upturn degeneracy when no constraints on the lower-energy intrinsic spectra are available. Figure 23 shows a similar plot to Figure 22, for the baseline EBL model, considering the multi-instrument dataset.

The most striking feature that can be observed in this plot is the absence of the previous ALP-preferring minimum, which directly suggests the minimum present in the previous plot is not the result of any ALP detection, but rather the consequence of insufficient low-energy information to fully constrain the intrinsic spectrum. The fact the total curve monotonically increases with increasing couplings indicates that the best-fit for the ALP case occurs at $g_{a\gamma} \rightarrow 0$, and any non-zero coupling will provide a worse fit to our data. Thus, the curve is fully consistent with the null hypothesis, providing a useful probe into (preliminarily) constraining allowed coupling values (which will be discussed in more detail in the next

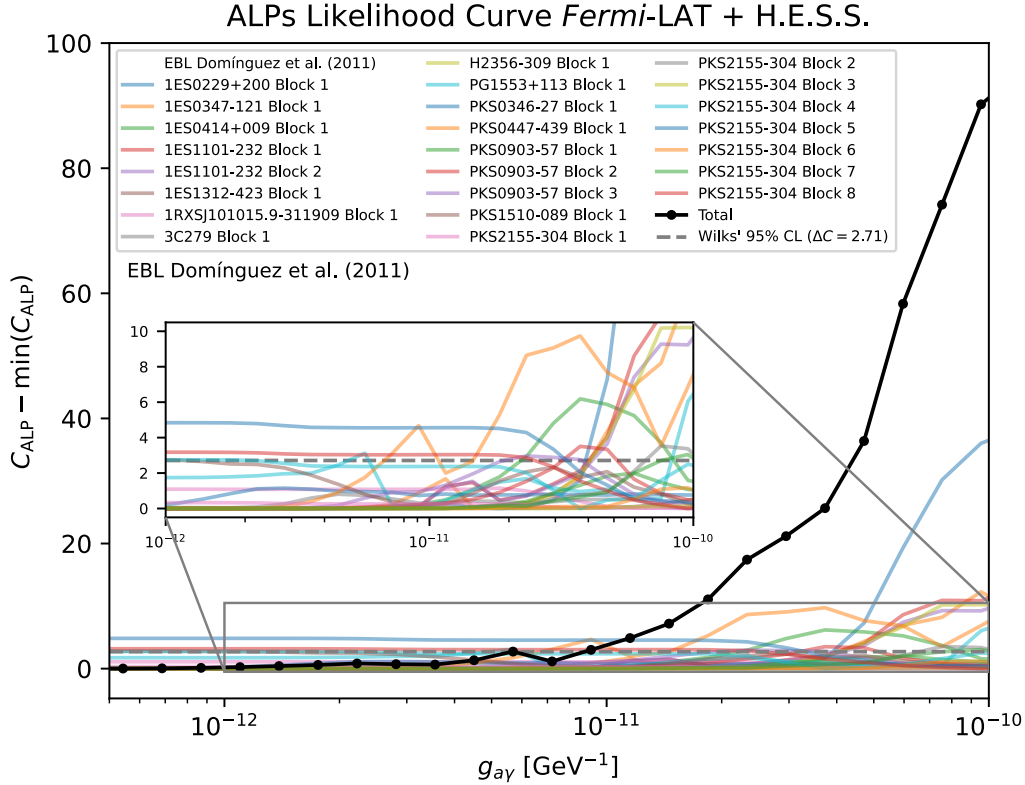


Figure 23: ALP likelihood curve computed using Eq. (49), considering the baseline EBL model, from the joint Fermi-LAT and H.E.S.S. analysis. Here, we display the relative preference of the ALP upturns versus the best-fit ALP upturn across the considered coupling $g_{a\gamma}$ values. The individual, colored lines represent the individual contributions of each source. The horizontal, dashed line represents the 95% confidence level given by Wilks' theorem, assuming its applicability (for a detailed discussion on this, we refer to Section 6.4).

section). In this case, the main contributing sources to this curve are 1ES 0347-121, both blocks of 1ES 1101-232, 1RXSJ 101015.9-311909, and PKS 0447-439.

6.2 Upturn likelihood across extragalactic background light models

THE same analysis described in the previous section can be applied for the different EBL models considered in this work. This is especially interesting for our study, as we consider physics that can possibly affect the observed gamma-ray attenuation. In this way, we also make sure our discussion is generally valid across multiple models, excluding the possibility of only the baseline model presenting or rejecting upturns, and quantifying what the variation of this effect is across different EBL models.

For this reason, beyond the already-studied Domínguez et al. (2011) model [83], we also consider Finke et al. (2022) [84], Franceschini et al. (2008) [85], and Saldana-López et al. (2021) [86]. Therefore, the full analysis pipeline described throughout the last chapters has been applied across all of our sources for each one of these EBL models.

Once more, we will separate our discussion into, first, the results obtained considering only data from H.E.S.S. The corresponding ALP upturn likelihood curve is shown in the first subplot of Figure 24, displayed for all four EBL models across the considered ALP coupling range.

The results obtained from H.E.S.S. observations on the likelihood of ALP-induced upturns are consistent across all EBL models, indicating that our previous results are not due to the considered baseline EBL model. The minima that these curves reach occur at slightly differing coupling values, with $g_{a\gamma} \sim 4 \cdot 10^{-11} \text{ GeV}^{-1}$ for the Domínguez et al. (2011) and Franceschini et al. (2008) models and $g_{a\gamma} \sim 6 \cdot 10^{-11} \text{ GeV}^{-1}$ for Finke et al. (2022) and Saldana-López et al. (2021). Furthermore, as can be observed by the relative offset between the curves at low couplings, the model by Finke et al. (2022) yields the most prominent minimum, with $\text{TS}_{\text{ALP}} \sim 14$, with Domínguez et al. (2011) offering a much lower $\text{TS}_{\text{ALP}} \sim 3$ value at the minimum. Importantly, the overall shape of the ALP likelihood curves are consistent across all EBL models, and all display the common feature of a minimum being present, at similar coupling values, with differing relative TS values at this minimum. Thus, the strongest apparent ALP signal occurs for the Finke et al. (2022) model.

The joint *Fermi*-LAT and H.E.S.S. analysis also shows agreement with the results in Section 6.1, with the obtained ALP likelihood curves across EBL models being shown in the second plot in Figure 24.

The form of the ALP likelihood curves is consistent across EBL models, with all displaying the same exponential-like growth when considering higher couplings. The model by Finke et al. (2022) seems to reach the maximum at the same coupling value as the Saldana-López et al. (2021) model. The model by Franceschini et al. (2008) also reaches a local maximum at this point, for approximately $g_{a\gamma} \sim 3 \cdot 10^{-11} \text{ GeV}^{-1}$. All of these three models also show a local minimum right after this peak, at couplings $g_{a\gamma} \sim 7 \cdot 10^{-11} \text{ GeV}^{-1}$, although increasing the coupling values further shows again a strictly increasing behavior. The model by Domínguez et al. (2011) seems to increase in TS_{ALP} values much slower than the others, only reaching a maximum at $g_{a\gamma} \sim 10^{-10} \text{ GeV}^{-1}$. Since the model by Finke et al. (2022) shows higher overall values in TS_{ALP} , it will serve as the most-constraining source, while the model by Domínguez et al. (2011) is, once again, the most conservative model in terms of computing preliminary ALP upturn constraints.

6.3 Preliminary constraints on the axion-like particle parameter space

THE ALP upturn analysis performed on data exclusively from H.E.S.S. seems to suggest an apparent preference of an upturn, at approximately $g_{a\gamma} \sim 4 \cdot 10^{-11} \text{ GeV}^{-1}$ or $g_{a\gamma} \sim 6 \cdot 10^{-11} \text{ GeV}^{-1}$, depending on the EBL model considered. On the other hand, the analysis of the joint *Fermi*-LAT and H.E.S.S. dataset leads to an overall monotonically increasing curve with $\text{TS}_{\text{ALP}}(g_{a\gamma}) > 0$, with the best-fit ALP upturn case occurring at couplings $g_{a\gamma} \rightarrow 0$, suggesting a preference for the no-ALP hypothesis. This behavior has also been found to be consistent across EBL models. Therefore, it is of interest to perform a statistical study to determine, first, what is the significance of the ALP preference for the H.E.S.S. data, and second, for the joint multi-instrument analysis, to study whether meaningful, albeit preliminary, constraints can be placed on those ALP coupling values which lead to a

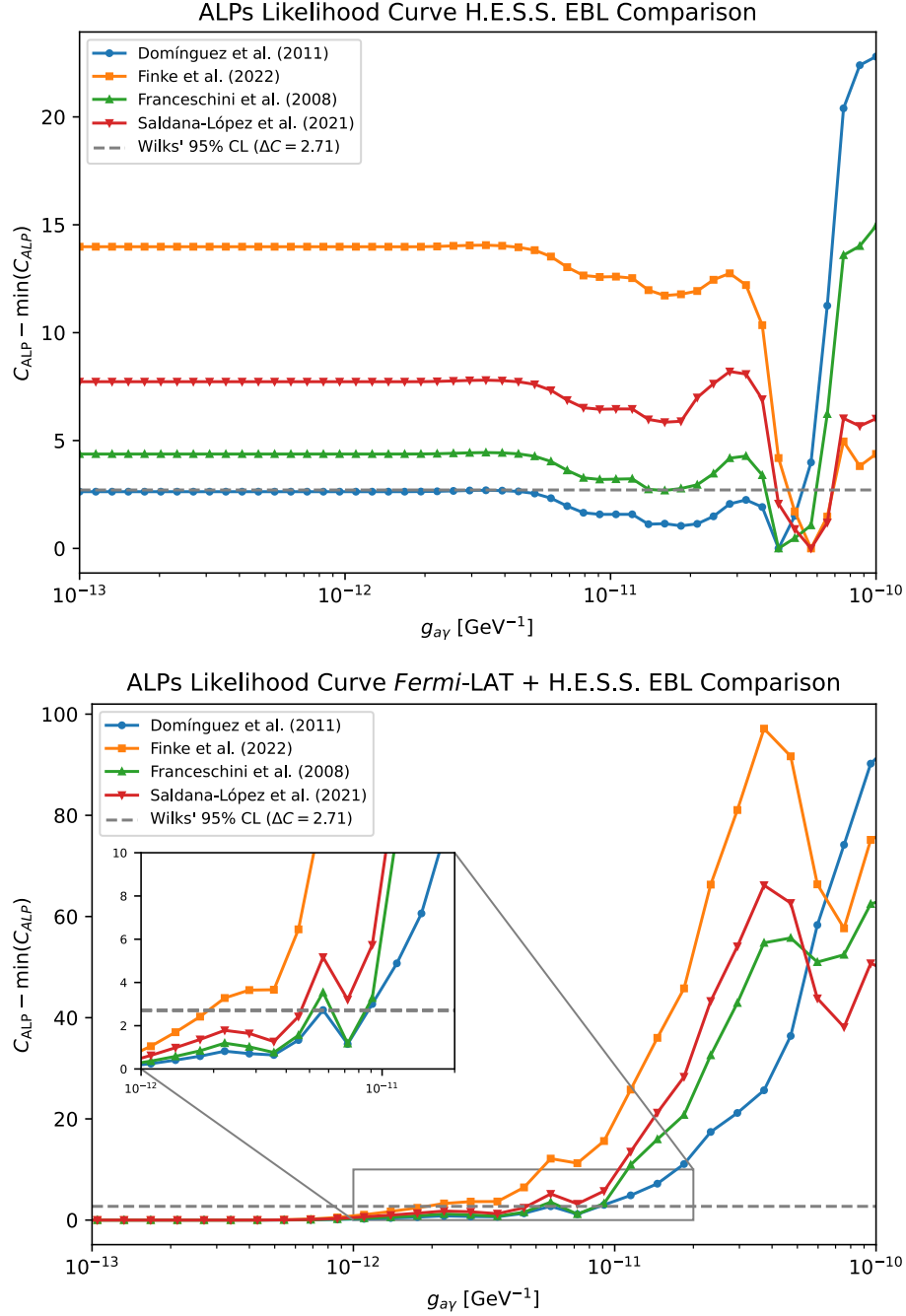


Figure 24: Likelihood curve obtained for the H.E.S.S. (top) and joint *Fermi*-LAT and H.E.S.S. (bottom) datasets, representing the likelihood of upturns caused by photon-ALP conversions, computed for different EBL models. The preliminary statistical threshold of 2.71, corresponding to a confidence level of 95%, is displayed as the dashed line and computed assuming Wilks' theorem applies (for a detailed discussion on this, we refer to Section 6.4).

significantly worse fit to the data.

In order to do so, we will begin our discussion with the consideration, as we have been doing throughout the thesis, of Wilks’ theorem (introduced in Section 3.3.2). Importantly, we must keep in mind that this is a major oversimplification of our problem. This is due to the fact that the required conditions for the applicability of this theorem (in particular, requirement for the models to be nested) are not automatically fulfilled, something we will discuss in detail in Section 6.4. Nevertheless, this approach can still be used, tentatively, to obtain some preliminary constraints on the ALP parameter space, which provide a useful discussion and lead towards the required additional work on this project.

For the H.E.S.S. analysis, and for each EBL model, in Table 6 we present the coupling at which the ALP preference is maximal (corresponding to the best-fit point with minimal TS), as well as the associated TS value and statistical significance obtained by assuming Wilks’ theorem can be applied.

EBL Model	$g_{a\gamma,\min}$ [10^{-11} GeV $^{-1}$]	TS_{ALP}	Wilks’ significance
Domínguez et al. (2011)	4.29	2.63	1.62σ
Finke et al. (2022)	5.69	13.99	3.74σ
Franceschini et al. (2008)	4.29	4.37	2.09σ
Saldana-López et al. (2021)	5.69	7.72	2.77σ

Table 6: Coupling $g_{a\gamma,\min}$ corresponding to the best-fit ALP upturn model, computed from the H.E.S.S. analysis, for each EBL model considered. In the third column, the TS_{ALP} computed as Eq. (49) at $g_{a\gamma,\min}$, and the associated significance, assuming Wilks’ theorem, displayed in the last column.

These ALP detection significance values are in good agreement with results found in previous studies [35]. In our case, the best-fit ALP coupling occurs slightly above the expected $g_{a\gamma}$ value, although this is to be expected, as our analysis has a greater precision in the coupling due to a larger number of sampled points. The final significance values are also compatible with the reference work, although in our case, the higher test statistic indicates an even stronger preference for the ALP case at the minimum.

Following this, the ALP detection significance computed for each EBL model using the joint *Fermi*-LAT and H.E.S.S. is presented in Table 7. Here, the best-fit model that includes upturns due to photon-ALP conversions is located at the lowest considered couplings, indicating a clear preference for $g_{a\gamma} \rightarrow 0$ at the best fit, which is consistent with the results we found for the baseline EBL in the previous section. The obtained TS values for this case are also negligibly small, indicating an overall preference for the null, no-ALP hypothesis.

As a consequence of the fact that the best-fit ALP model is located at zero coupling, corresponding to the null or no-ALP hypothesis, we may consider the corresponding ALP likelihood curve obtained from the joint dataset as an approximation of the TS associated to comparing the ALP versus no-ALP hypotheses. This would allow us to compare between these hypotheses and place preliminary constraints on the coupling $g_{a\gamma}$ for any given confidence level.

6.3 Preliminary constraints on the axion-like particle parameter space

EBL Model	$g_{a\gamma, \min}$ [10^{-13} GeV $^{-1}$]	TS_{ALP}	Wilks' significance
Domínguez et al. (2011)	2.10	0.02	0.15σ
Finke et al. (2022)	2.10	0.04	0.21σ
Franceschini et al. (2008)	2.70	0.03	0.17σ
Saldana-López et al. (2021)	3.40	0.03	0.18σ

Table 7: Coupling $g_{a\gamma, \min}$ corresponding to the best-fit ALP upturn model, computed from the joint Fermi-LAT and H.E.S.S. analysis, for each EBL model considered. In the third column, the TS_{ALP} computed as Eq. (49) at $g_{a\gamma, \min}$, and the associated significance assuming Wilks' theorem displayed in the last column.

Throughout the previous sections, we have been presenting plots of the ALP likelihood curve overlaid with the threshold given by Wilks' theorem, at a 95% confidence level, corresponding to a $TS \sim 2.71$. This threshold is represented as the gray, dashed line in Figure 22, Figure 23, as well as Figure 24. In order to attempt to place preliminary constraints, we may then consider the intersecting point at which our ALP likelihood curves cross this threshold. We can then claim to reject any ALP signal corresponding to upturns with higher coupling values.

From Figure 24, we can observe how each ALP likelihood curve, corresponding to the different EBL models, crosses this threshold at a different coupling values. Preliminary constraints can be computed by linearly interpolating between the points $g_{a\gamma}$ where the crossing with Wilks' threshold. In the case of multiple such crossing points occur (e.g. in the case of the Domínguez et al. (2011) and Franceschini et al. (2008) EBL models), we consider the one corresponding to higher couplings, corresponding to more conservative results. The preliminary constraints on the coupling by this method are summarized in Table 8. In particular, the model by Finke et al. (2022) seems to provide the strongest constraints, allowing us to reject ALP couplings above $g_{a\gamma} \sim 2 \cdot 10^{-12}$ GeV $^{-1}$. The second, most constraining model, appears to be the one by Saldana-López et al. (2021), which constrains couplings above $g_{a\gamma} \sim 5 \cdot 10^{-12}$ GeV $^{-1}$. Finally, both Domínguez et al. (2011) and Franceschini et al. (2008) display very similar behaviour in this aspect, rejecting ALP upturns with couplings above the value $g_{a\gamma} \sim 9 \cdot 10^{-12}$ GeV $^{-1}$.

EBL Model	Preliminary constraints $g_{a\gamma}$ [10^{-12} GeV $^{-1}$]
Domínguez et al. (2011)	8.89
Finke et al. (2022)	1.92
Franceschini et al. (2008)	8.66
Saldana-López et al. (2021)	4.61

Table 8: Preliminary constraints on the ALP coupling $g_{a\gamma}$ obtained from the ALP upturn likelihood modeling using data from Fermi-LAT and H.E.S.S. for each EBL model considered in this study. These results were obtained by linearly interpolating between the points where a crossing between the ALP upturn likelihood curve and Wilks' 95% confidence level threshold occurred. For sources where multiple such crossings are present, we consider only the last at highest coupling values, corresponding to the most conservative case.

6.4 Monte Carlo methods for significance and threshold estimation

THROUGHOUT the previous sections, we have computed a likelihood curve $\text{TS}_{\text{ALP}}(g_{a\gamma})$, given by Eq. (49), that compares the relative likelihood of an ALP upturn compared to the best-fit upturn case. From the joint *Fermi*-LAT and H.E.S.S. analysis we have found that the minimum of this log-likelihood curve occurs at small coupling values $g_{a\gamma} \rightarrow 0$ compatible with the null hypothesis. This allowed us to interpret the corresponding curve as an approximation to the actual TS which compares the ALP upturn hypothesis versus the null hypothesis:

$$\lambda(g_{a\gamma}) = \sum_{i=1}^{\text{src}} \left[C_{\text{ALP}}^{(i)}(g_{a\gamma}) - C_{\text{No-ALP}}^{(i)}(g_{a\gamma}) \right]. \quad (50)$$

Furthermore, when discussing the obtained results, we have continuously made use of Wilks' theorem, assuming that the test statistic $\text{TS}_{\text{ALP,det}}$ given by Eq. (48) is asymptotically distributed as a χ_1^2 distribution, as described in Section 3.3.2. This theorem was extensively used to both compute the statistical significance associated to the ALP upturns, and to place preliminary constraints on the probed ALP coupling parameter space.

In our case, the conditions required for the applicability of this theorem, mainly, the requirement for the alternative and null hypothesis models to be nested, are not fulfilled. This is due to the fact that the ALP likelihood values, obtained from interpolating the upturns obtained from the simulations onto the data-based upturn likelihood grid, produce a dependence on coupling value, the intrinsic spectral parameters of the source, and all the nuisance parameters included within the photon-ALP beam propagation simulation, that despite not being of direct physical interest to our study, must be taken into account in our model and which undoubtedly affect the final results. These parameters also include the stochastic realizations of the IGMF, and the associated magnetic field strength. This introduces an intrinsic variance in the likelihood that is not present in the null hypothesis. Furthermore, the no-ALP model doesn't contain any magnetic field parameters, and thus the two models have different parameter spaces that cannot be related to each other, making the two hypotheses compared in Eq. (49) fundamentally non-nested.

As a consequence of this, the ALP detection significance and constraint values provided in Section 6.3 are merely tentative, preliminary results, obtained by considering the threshold provided in the hypothetical case in which Wilks' theorem could be applied. In order to adequately perform the corresponding hypothesis testing between the ALP and no-ALP cases, a more detailed statistical method must be applied.

The reason the discussion in Section 6.4 is still interesting, at least qualitatively, is due to the fact that we expect the real ALP constraint threshold, which will now depend on $g_{a\gamma}$, to be, in the most optimistic scenario, comparable to the threshold given by Wilks' theorem, or in the more conservative case, within the same order of magnitude or at most reasonably close. Considering where the ALP likelihood curves intersect this new statistical threshold will allow us to place precise constraints on the ALP coupling values, at the desired significance level.

To compute the exact statistical thresholds required for this problem, we need to obtain the null-hypothesis TS distribution, for which extensive Monte Carlo simulations are typically required [134, 165]. The methodology developed for similar studies involves simulating new

data, or pseudo-experiments, from the initial best-fit model, which includes exclusively the intrinsic model and the EBL absorption term. In this way, we generate multiple pseudo-experiments, to which we then apply the full analysis pipeline presented here, including a re-fit of the intrinsic spectrum and the upturn modeling to obtain the relevant likelihood grids. Then, we can again interpolate the upturn parameters obtained from the ALP mixing simulations, obtaining an array of ALP likelihoods for each pseudo-experiment. With this, a histogram of TS values is obtained, comparing the no-ALP versus ALP upturn hypotheses, which can be modeled with a χ^2 distribution. From this fit, we can then obtain the number of degrees of freedom required to describe the TS distribution. Once the corresponding best-fit χ^2 distribution is known, considered as an estimate for the null-hypothesis TS distribution, we may then obtain the threshold value corresponding to a given p-value (e.g. 0.95, for a 95% confidence level), yielding the required TS threshold over which we can reject the no-ALP hypothesis [165]. This process has to be performed, in principle, for each coupling value $g_{a\gamma}$, source, and time block.

Performing this many Monte Carlo simulations across the different parameters required is very computationally demanding, although several optimizations of this process are possible. As we have seen, the Domínguez et al. (2011) model provides, overall, the most conservative results in terms of relative ALP upturn likelihoods, as seen in Section 6.2, justifying its selection as the main model with which we compute the threshold. Alternatively, the most constraining model for our study is Finke et al. (2022), which may be considered to obtain the most restrictive constraints on the ALP parameter space.

Similarly, instead of computing Eq. (50) for all sources and obtaining the total sum, we may also consider either sampling randomly across our dataset, constructing an overall threshold that will asymptotically converge towards the total threshold, or considering a single source which could provide useful constraints.

Following this second approach, we have determined which sources are expected to provide the most constraining threshold. This is done based on the coupling value at which each profile likelihood curve from Eq. (49) crosses the qualitative threshold given by Wilks' theorem. Figure 25 displays the likelihood curve and the considered statistical threshold, with the first five sources that cross the threshold highlighted.

From this figure, we can observe how PG 1553+113 crosses this threshold at the earliest couplings. However, this source then displays an overall decrease in TS for higher couplings, and only becomes a dominant contribution at the highest coupling values at $g_{a\gamma} > 8 \cdot 10^{-11} \text{ GeV}^{-1}$, which disqualifies it as a significantly-constraining source for our test. The next four sources do seem to be good candidates for our analysis. Given in order of the coupling at which the considered crossing occurs, these are PKS 0447-439, block 3 of PKS 0903-57, 1ES 0414+009, and block 2 of PKS 0903-57.

The computation of the required statistical threshold represents the natural continuation of this project, and is currently being undertaken as a work in progress. For the simplest case, we have considered computing the threshold via the aforementioned Monte Carlo approach for PKS 0447-439 exclusively, using simulated data obtained from its best-fit model and running the full analysis pipeline numerous times in order to estimate the required $\text{TS}_{\text{No-ALP}}$ distribution. Similarly, the baseline EBL model is chosen, as it will provide the

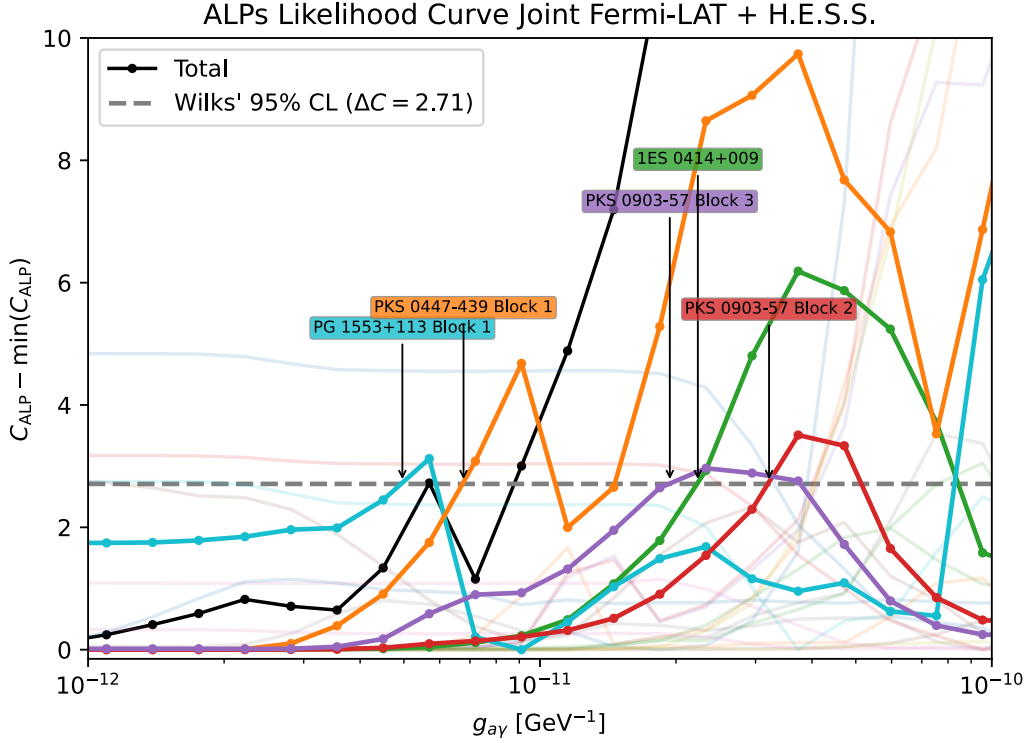


Figure 25: Likelihood curve given by Eq. (49) across a range of ALP couplings $g_{a\gamma}$, along with the threshold given by Wilks' theorem for a 95% confidence level. Highlighted are five sources that have been selected as possibly good candidates for performing the Monte Carlo analysis in order to compute an adequately constraining statistical threshold.

most conservative thresholds. Once the computations are performed, we may compute a preliminary threshold curve with which we can obtain the required ALP parameter space constraints.

In the most optimistic case, for which the threshold is of the order of that given by Wilks' theorem, we expect to place constraints on ALP couplings above $g_{a\gamma} \sim 2 \cdot 10^{-12} \text{ GeV}^{-1}$, for the Finke et al. (2022) model, and for a value between $g_{a\gamma} \sim 5 \cdot 10^{-12} \text{ GeV}^{-1}$ and $g_{a\gamma} \sim 10^{-11} \text{ GeV}^{-1}$ for the other EBL models. In the case of an obtained threshold much higher than Wilks', it may still be possible to place constraints on the ALP coupling. For example, if the threshold is found much higher, at approximately $\text{TS} \sim 20$, the corresponding threshold crossings would occur such that possible constraints could be placed at parameters up to $g_{a\gamma} \sim 3 \cdot 10^{-11} \text{ GeV}^{-1}$.

Provided we remain within the strong-mixing regime, as given by the condition in Eq. (25) and the corresponding environment-dependent parameters, the photon-ALP conversion probability will not depend on the mass of the ALP and, therefore, the resulting constraints can be extended towards masses below $m_a < 10^{-3} \text{ neV}$.

7 Conclusions and future outlook

THROUGHOUT this work, we have performed a search for spectral upturns caused by the conversions of photons to axion-like particles (ALPs) using observational gamma-ray data of numerous blazar sources from the *Fermi* Large Area Telescope (LAT) and the High Energy Stereoscopic System (H.E.S.S.) observatories. This analysis was carried out by developing a fully `Python`-based analysis pipeline built around the `GammaPy` library, integrating as well `FermiPy` for the LAT data, `EBLTable` for modeling the EBL attenuation, and `GammaALPs` to perform numerical photon-ALP conversion simulations. The two main contributions with respect to previous work [35] are the inclusion of additional sources (3C 279, PKS 0346-27, and PKS 0903-57) potentially interesting for this study, and the inclusion of *Fermi*-LAT data, which constrained the lower-energy spectra of our sources and improved significantly the results on computing upturn likelihoods via a multi-instrument analysis approach. This analysis, which includes a time variability analysis, the intrinsic spectral modeling, upturn modeling, and photon-ALP conversion simulations, was performed sequentially, and has allowed us to place preliminary constraints onto the ALP parameter space after considering a simplified statistical analysis. The results were obtained separately considering data from H.E.S.S. only, as well as for the full, combined *Fermi*-LAT and H.E.S.S. dataset, allowing us to directly study the effects of the inclusion of this instrument. Similarly, multiple extragalactic background light (EBL) attenuation models were considered [83, 84, 85, 86], obtaining consistent results across all models.

We have managed to replicate, to great extent, previous reported results using data from H.E.S.S. [35], where an apparent preference for upturns is hinted at couplings between $g_{a\gamma} = 4.29 \cdot 10^{-11} \text{ GeV}^{-1}$ and $g_{a\gamma} = 5.69 \cdot 10^{-11} \text{ GeV}^{-1}$. This behavior, present across all EBL models, is concluded to be the result of degeneracies within the H.E.S.S. data, and not a true upturn signal.

The novel results obtained from the multi-instrument dataset eliminate any preference for upturns, offering results consistent with a preference for ALP-induced upturns at $g_{a\gamma} \rightarrow 0$. This allows us to probe the ALP parameter space for light axions $m_a \leq 10^{-3} \text{ neV}$, placing preliminary constraints for couplings $g_{a\gamma} \gtrsim 1.92 \cdot 10^{-12} \text{ GeV}^{-1}$ for the most constraining case, and $g_{a\gamma} \gtrsim 8.89 \cdot 10^{-12} \text{ GeV}^{-1}$ in the most conservative scenario. This demonstrates how, by the inclusion of LAT data, the constraints and overall results are considerably strengthened, as expected. However, these results were obtained based on a simplified statistical interpretation of our ALP-induced upturn likelihood results. A discussion has been presented, offering the methodology required to obtain the final constraints via Monte Carlo approaches.

Despite this region of the ALP parameter space ($m_a \leq 10^{-3} \text{ neV}$ and $g_{a\gamma} \sim 10^{-12}$) having already been probed by other studies [166, 167] ($m_a \leq 10^{-4} \text{ neV}$ with $g_{a\gamma} \leq 2.6 \cdot 10^{-12} \text{ GeV}^{-1}$, and $m_a \leq 10^{-3} \text{ neV}$ with $g_{a\gamma} \leq 6.3 \cdot 10^{-13} \text{ GeV}^{-1}$, respectively), our results allow placing preliminary constraints for light ALPs at similar coupling values, by means of a different and independent methodology, based on spectral upturn effects in the gamma-ray spectra of blazars due to photon-ALP conversions, rather than irregularities in the X-ray range of the SED from other radio galaxies, as in the cited references. Furthermore, our analysis is based on a large dataset of blazar sources, rather than a single source.

For the new sources included, we have found that both 3C 279 and PKS 0346-27 provide weak constraints and a limited contribution towards the final results. This was partially expected, as despite being potential candidates for these studies, their observation periods were relatively short (in total, approximately 4 and 2 hours, respectively), and they presented limited gamma-ray emission in the optically thick region ($\tau > 2$). However, PKS 0903-57 has proven to be a good candidate, providing significant contributions across all of its time blocks towards the preliminary constraints found.

The main analysis begins with the intrinsic spectral analysis of each source, which was performed in two steps. Firstly, a time variability analysis, segmenting the data for each source into separate, statistically-significant distinct time blocks via a Bayesian block algorithm, and a spectral variability analysis, based on the best-fit ellipses for the spectral parameters across the found blocks. This yielded a final segmentation of 24 independent time blocks in total. Secondly, the main spectral analysis was performed, considering both single- and multi-instrument analyses for each instrument. Overall, we have found general agreement with published results [35, 52], although discrepancies were also found in various sources, which were discussed in the text and suggest a requirement for future work, in order to ensure consistency between the reported values.

Next, the upturn analysis was performed, also in two main steps. First, an upturn modeling was performed by performing a fit of a spectral model including an upturn across a physically-motivated parameter space. The resulting upturn likelihood grids then display which upturns are favored in the data. These grid plots obtained from the H.E.S.S. data disfavor steep, low-energy upturns, although a wide range of upturn parameters provide similar, low fit statistic values, indicating similar preference. In certain sources, an apparent preference for upturns can be observed (most prominently, in 1RXS J101015.9-311909, PG 1553+113, PKS 1510-089, and certain blocks of PKS 2155-304), although this has been found to be caused by degeneracies arising from the absence of low-energy spectral constraints when considering data from H.E.S.S. only. These results have also been found in agreement with previous studies [35]. The inclusion of *Fermi*-LAT data resolves this, as it produces, in general, an increase in the disfavored region of the upturn parameter space, and thus most hints of upturn preferences disappear. An interesting exception to this is PKS 1510-089, which seems to preserve a preference for subtle, low-energy upturns, even when considering both instruments.

Next, we simulate the photon-ALP propagation using **GammaALPs** across the considered astrophysical environments (the intergalactic magnetic field, IGMF, and the galactic magnetic field, GMF, of the Milky Way). This gives us the physical and expected ALP-induced upturns in our spectra. We consider light ALPs with $m_a = 10^{-3}$ neV, with coupling values $g_{a\gamma} \in [10^{-13}, 10^{-10}] \text{ GeV}^{-1}$ so as to ensure the strong-mixing regime conditions are met (ensuring maximal photon-ALP mixing probability, independent of the mass). A discussion is presented on how, for higher coupling values, the observed photon survival probability predicts more photons arriving at the observer than by considering EBL alone, consistent with our expectations and the main motivation for this work. The results from these simulations are then compared with the previous upturn grids by interpolating the best-fit ALP upturn parameters, which allows us to compute the associated likelihood to each ALP-induced upturn.

7 CONCLUSIONS AND FUTURE OUTLOOK

As future work, further analysis can be performed following a similar methodology to study the multiple other parameters and environment choices. One example could be extending the study to include additional magnetic field environments where photon-ALP mixing could occur, such as the blazar jet [94] or the magnetic field of the host galaxy [93]. Similarly, further sources and observation periods can be continuously added to our dataset, as more observations and flaring periods are observed across blazar sources.

Similarly, the inclusion of other types of sources, such as transient gamma-ray bursts (GRBs), could prove to be excellent sources of additional observation data with which we could further probe the allowed ALP parameter space. In this work, a preliminary attempt to study GRB 180720B [168] has been attempted, although the results were unsatisfactory due to limited photon counts, and the requirement of different telescope (CT5) and data processing configurations due to the transient nature of the source.

This leads to the fact that data from the CT5 telescope from H.E.S.S. is not included within this study. Using this telescope would provide additional, low-energy data for the sources observed after it began operations (2012), offering a higher overlap between the H.E.S.S. and *Fermi*-LAT data, and possibly increasing the photon count statistics for fainter or transient objects. The analysis of combined data with CT1-4 and CT5 is made increasingly more accessible, in particular with the “event types” analysis workflow [169], which will make CT1-5 analyses much easier to perform, with a consistent analysis configuration.

On this same note, the Cherenkov Telescope Array Observatory (CTAO) [102] and its more than 60 telescopes planned will provide the next big step towards studies of fundamental physics and physics beyond the Standard Model [170], including ALPs [171]. This array of imaging atmospheric Cherenkov telescopes (IACTs) will extend the sensitivity range for gamma-ray energies between 20 GeV and as high as 300 TeV, offering sufficient sensitivity at the highest energies to better probe the energy range where photon-ALP mixing effects are most prominent, expected to place constraints on ALP coupling values of order $g_{a\gamma} \sim 10^{-12} \text{ GeV}^{-1}$ for light ALPs $m_a \lesssim 100 \text{ neV}$ [56, 170, 171, 172, 173].

Lastly, it is important to point out that our study, including the constructed blazar dataset as well as the considered methodology (either with just H.E.S.S. and *Fermi*-LAT data, as considered in this work, or with the inclusion of future CTA data), can be adapted and extended in order to study other effects of physics beyond the Standard Model (e.g. Lorentz invariance violation) [11]. The study of gamma-ray propagation across the IGMF can also provide further constraints on EBL models, its photon density, and possibly the relevant cosmological parameters [174, 175].

References

- [1] A. M. Cherepashchuk. “History of the Universe History”. In: *Physics—Uspekhi* 56.5 (2013), pp. 509–530.
- [2] G. Stratta and A. Santangelo. “X- and Gamma-Ray Astrophysics in the Era of Multi-messenger Astronomy”. In: *Handbook of X-ray and Gamma-ray Astrophysics*. Springer Nature Singapore, 2022, pp. 1–31. ISBN: 9789811645440. DOI: 10.1007/978-981-16-4544-0_134-1. URL: http://dx.doi.org/10.1007/978-981-16-4544-0_134-1.
- [3] H. A. Abt. “The growth of multiwavelength astrophysics”. In: *Publications of the Astronomical Society of the Pacific* 105.686 (1993), pp. 437–437.
- [4] A. Acharyya, P. M. Chadwick, and A. M. Brown. “Locating the gamma-ray emission region in the brightest Fermi-LAT flat-spectrum radio quasars”. In: *Monthly Notices of the Royal Astronomical Society* 500.4 (2021), pp. 5297–5321.
- [5] A. Addazi, J. Alvarez-Muniz, R. A. Batista, et al. “Quantum gravity phenomenology at the dawn of the multi-messenger era — A review”. In: *Progress in Particle and Nuclear Physics* 125 (2022), p. 103948. ISSN: 0146-6410. DOI: <https://doi.org/10.1016/j.pnpnp.2022.103948>.
- [6] A. De Angelis and M. J. M. Pimenta. *Introduction to Particle and Astroparticle Physics*. en. Undergraduate Lecture Notes in Physics. Milano: Springer Milan, 2015. ISBN: 978-88-470-2687-2. DOI: 10.1007/978-88-470-2688-9. URL: <http://link.springer.com/10.1007/978-88-470-2688-9>.
- [7] P. Mészáros, D. B. Fox, C. Hanna, and K. Murase. “Multi-messenger astrophysics”. In: *Nature Reviews Physics* 1.10 (2019), pp. 585–599.
- [8] G. Bertone and D. Hooper. “History of dark matter”. en. In: *Reviews of Modern Physics* 90.4 (Oct. 2018), p. 045002. ISSN: 0034-6861, 1539-0756. DOI: 10.1103/RevModPhys.90.045002.
- [9] J. Ellis. “Physics Beyond the Standard Model”. In: *Nuclear Physics A* 827.1–4 (Aug. 2009). arXiv:0902.0357 [hep-ph], pp. 187c–198c. ISSN: 03759474. DOI: 10.1016/j.nuclphysa.2009.05.034.
- [10] M. Meyer. “Searches for Axionlike Particles Using Gamma-Ray Observations”. en. In: arXiv:1611.07784 (Nov. 2016). arXiv:1611.07784 [astro-ph]. DOI: 10.48550/arXiv.1611.07784. URL: <http://arxiv.org/abs/1611.07784>.
- [11] J. Biteau and M. Meyer. “Gamma-ray Cosmology and Tests of Fundamental Physics”. In: *Galaxies* 10.2 (Feb. 2022). arXiv:2202.00523 [astro-ph], p. 39. ISSN: 2075-4434. DOI: 10.3390/galaxies10020039.
- [12] G. Galanti and M. Roncadelli. “Axion-like Particles Implications for High-Energy Astrophysics”. en. In: *Universe* 8.5 (Apr. 2022), p. 253. ISSN: 2218-1997. DOI: 10.3390/universe8050253.
- [13] C. Abel, S. Afach, N. J. Ayres, et al. “Measurement of the permanent electric dipole moment of the neutron”. en. In: *Physical Review Letters* 124.8 (Feb. 2020). arXiv:2001.11966 [hep-ex], p. 081803. ISSN: 0031-9007, 1079-7114. DOI: 10.1103/PhysRevLett.124.081803.
- [14] R. D. Peccei. “The Strong CP Problem and Axions”. en. In: vol. 741. arXiv:hep-ph/0607268. 2008, pp. 3–17. DOI: 10.1007/978-3-540-73518-2_1. URL: <http://arxiv.org/abs/hep-ph/0607268>.

- [15] A. H. G. Peter. “Dark Matter: A Brief Review”. en. In: arXiv:1201.3942 (Jan. 2012). arXiv:1201.3942 [astro-ph]. DOI: 10.48550/arXiv.1201.3942. URL: <http://arxiv.org/abs/1201.3942>.
- [16] F. Zwicky. “The Coma Cluster of Galaxies”. In: *Publications of the Astronomical Society of the Pacific* 63.371 (1951), pp. 61–71. ISSN: 00046280, 15383873. URL: <http://www.jstor.org/stable/40672858> (visited on 05/19/2026).
- [17] D. Clowe, M. Bradač, A. H. Gonzalez, et al. “A Direct Empirical Proof of the Existence of Dark Matter”. In: *The Astrophysical Journal Letters* 648.2 (Sept. 2006), pp. L109–L113. DOI: 10.1086/508162. arXiv: astro-ph/0608407 [astro-ph].
- [18] V. C. Rubin and W. K. Ford Jr. “Rotation of the Andromeda Nebula from a Spectroscopic Survey of Emission Regions”. In: *The Astrophysical Journal Letters* 159 (Feb. 1970), p. 379. DOI: 10.1086/150317.
- [19] J. d. Swart, G. Bertone, and J. v. Dongen. “How Dark Matter Came to Matter”. en. In: *Nature Astronomy* 1.3 (Mar. 2017). arXiv:1703.00013 [astro-ph], p. 0059. ISSN: 2397-3366. DOI: 10.1038/s41550-017-0059.
- [20] R. D. Peccei. “A Short Review of Axions”. In: *High energy physics. Proceedings, 19th International Conference, ICHEP 1978, Tokyo, Japan, August 23-August 30, 1978* ().
- [21] S. Weinberg. “A New Light Boson?” en. In: *Physical Review Letters* 40.4 (Jan. 1978), pp. 223–226. ISSN: 0031-9007. DOI: 10.1103/PhysRevLett.40.223.
- [22] F. Wilczek. “Problem of Strong P and T Invariance in the Presence of Instantons”. In: *Phys. Rev. Lett.* 40 (5 Jan. 1978), pp. 279–282. DOI: 10.1103/PhysRevLett.40.279. URL: <https://link.aps.org/doi/10.1103/PhysRevLett.40.279>.
- [23] A. Arvanitaki, S. Dimopoulos, S. Dubovsky, N. Kaloper, and J. March-Russell. “String Axiverse”. In: *Physical Review D* 81.12 (2010). arXiv:0905.4720 [hep-th], p. 123530. ISSN: 1550-7998, 1550-2368. DOI: 10.1103/PhysRevD.81.123530.
- [24] J. Preskill, M. B. Wise, and F. Wilczek. “Cosmology of the invisible axion”. In: *Physics Letters B* 120.1 (1983), pp. 127–132. ISSN: 0370-2693. DOI: [https://doi.org/10.1016/0370-2693\(83\)90637-8](https://doi.org/10.1016/0370-2693(83)90637-8). URL: <https://www.sciencedirect.com/science/article/pii/0370269383906378>.
- [25] L. F. Abbott and P. Sikivie. “A cosmological bound on the invisible axion”. In: *Physics Letters B* 120.1-3 (1983), pp. 133–136.
- [26] M. Dine and W. Fischler. “The not-so-harmless axion”. In: *Physics Letters B* 120.1-3 (1983), pp. 137–141.
- [27] G. Raffelt and L. Stodolsky. “Mixing of the photon with low-mass particles”. en. In: *Physical Review D* 37.5 (Mar. 1988), pp. 1237–1249. ISSN: 0556-2821. DOI: 10.1103/PhysRevD.37.1237.
- [28] G. Bellini, L. Ludhova, G. Ranucci, and F. L. Villante. “Neutrino Oscillations”. en. In: *Advances in High Energy Physics* 2014.1 (2014), p. 191960. ISSN: 1687-7365. DOI: 10.1155/2014/191960.
- [29] K. Ehret. *The ALPS Light Shining Through a Wall Experiment - WISP Search in the Laboratory*. 2010. arXiv: 1006.5741 [hep-ex]. URL: <https://arxiv.org/abs/1006.5741>.
- [30] I. G. Irastorza. “An introduction to axions and their detection”. en. In: *SciPost Physics Lecture Notes* (Mar. 2022). arXiv:2109.07376 [hep-ph], p. 45. ISSN: 2590-1990. DOI: 10.21468/SciPostPhysLectNotes.45.

- [31] S. Porras-Bedmar and M. Meyer. “Niebla: an open-source code for modelling the extragalactic background light”. en. In: arXiv:2510.20664 (Oct. 2025). arXiv:2510.20664 [astro-ph]. DOI: 10.48550/arXiv.2510.20664. URL: <http://arxiv.org/abs/2510.20664>.
- [32] A. De Angelis, G. Galanti, and M. Roncadelli. “Relevance of axionlike particles for very-high-energy astrophysics”. en. In: *Physical Review D* 84.10 (Nov. 2011), p. 105030. ISSN: 1550-7998, 1550-2368. DOI: 10.1103/PhysRevD.84.105030.
- [33] T. H. Collaboration and F. Aharonian. “Observations of the Crab Nebula with H.E.S.S”. en. In: *Astronomy & Astrophysics* 457.3 (Oct. 2006). arXiv:astro-ph/0607333, pp. 899–915. ISSN: 0004-6361, 1432-0746. DOI: 10.1051/0004-6361:20065351.
- [34] F.-L. Collaboration. “The Fermi Large Area Telescope On Orbit: Event Classification, Instrument Response Functions, and Calibration”. In: *The Astrophysical Journal Supplement Series* 203.1 (Nov. 2012). arXiv:1206.1896 [astro-ph], p. 4. ISSN: 0067-0049, 1538-4365. DOI: 10.1088/0067-0049/203/1/4.
- [35] R. J. Cecil. “The Astrophysical Search For Axion Like Particle Signatures In Gamma-Ray Propagation”. English. PhD thesis. University of Hamburg, Feb. 2025.
- [36] M. K. Gaillard, P. D. Grannis, and F. J. Sciulli. “The standard model of particle physics”. en. In: *Reviews of Modern Physics* 71.2 (Mar. 1999), S96–S111. ISSN: 0034-6861, 1539-0756. DOI: 10.1103/RevModPhys.71.S96.
- [37] J. Ellis. “Limits of the Standard Model”. In: arXiv:hep-ph/0211168 (Nov. 2002). arXiv:hep-ph/0211168. DOI: 10.48550/arXiv.hep-ph/0211168. URL: <http://arxiv.org/abs/hep-ph/0211168>.
- [38] P. Svrcek and E. Witten. “Axions In String Theory”. In: *Journal of High Energy Physics* 2006.06 (2006). arXiv:hep-th/0605206, pp. 051–051. ISSN: 1029-8479. DOI: 10.1088/1126-6708/2006/06/051.
- [39] L. D. Duffy and K. v. Bibber. “Axions as dark matter particles”. In: *New Journal of Physics* 11.10 (2009), p. 105008.
- [40] P. Sikivie. “Invisible axion search methods”. en. In: *Reviews of Modern Physics* 93.1 (Feb. 2021), p. 015004. ISSN: 0034-6861, 1539-0756. DOI: 10.1103/RevModPhys.93.015004.
- [41] R. D. Peccei and H. R. Quinn. “Constraints imposed by CP conservation in the presence of pseudoparticles”. en. In: *Physical Review D* 16.6 (1977), pp. 1791–1797. ISSN: 0556-2821. DOI: 10.1103/PhysRevD.16.1791.
- [42] C. B. Adams, N. Aggarwal, A. Agrawal, et al. “Axion Dark Matter”. en. In: arXiv:2203.14923 (Mar. 2023). arXiv:2203.14923 [hep-ex]. DOI: 10.48550/arXiv.2203.14923. URL: <http://arxiv.org/abs/2203.14923>.
- [43] N. Gendler, D. J. E. Marsh, L. McAllister, and J. Moritz. “Glimmers from the Axiverse”. In: arXiv:2309.13145 (Oct. 2024). arXiv:2309.13145 [hep-th]. DOI: 10.48550/arXiv.2309.13145. URL: <http://arxiv.org/abs/2309.13145>.
- [44] K. Choi, S. H. Im, and C. S. Shin. “Recent Progress in the Physics of Axions and Axion-Like Particles”. en. In: *Annual Review of Nuclear and Particle Science* 71.1 (2021), pp. 225–252. ISSN: 0163-8998, 1545-4134. DOI: 10.1146/annurev-nucl-120720-031147.

- [45] Y. N. Gnedin, M. Y. Piotrovich, and T. Natsvlshvili. “PVLAS experiment: some astrophysical consequences”. In: *Monthly Notices of the Royal Astronomical Society* 374.1 (2007), pp. 276–281.
- [46] K. Zioutas, S. Andriamonje, V. Arsov, et al. “First results from the CERN axion solar telescope”. In: *Physical review letters* 94.12 (2005), p. 121301.
- [47] N. Du, N. Force, R. Khatiwada, et al. “Search for invisible axion dark matter with the axion dark matter experiment”. In: *Physical review letters* 120.15 (2018), p. 151301.
- [48] D. Cadamuro and J. Redondo. “Cosmological bounds on pseudo Nambu-Goldstone bosons”. In: *Journal of Cosmology and Astroparticle Physics* 2012.02 (2012), pp. 032–032.
- [49] A. Ayala, I. Domínguez, M. Giannotti, A. Mirizzi, and O. Straniero. “Revisiting the bound on axion-photon coupling from Globular Clusters”. In: *arXiv preprint arXiv:1406.6053* (2014).
- [50] G. G. Raffelt. *Stars as laboratories for fundamental physics: The astrophysics of neutrinos, axions, and other weakly interacting particles*. University of Chicago press, 1996.
- [51] C. O’Hare. *cajohare/AxionLimits: AxionLimits*. <https://cajohare.github.io/AxionLimits/>. Version v1.0. July 2020. DOI: 10.5281/zenodo.3932430.
- [52] A. Acharyya, R. Cecil, M. Meyer, and S. Porras-Bedmar. “Gamma-Ray Constraints on Heavy Axion-Like-Particle Decays from Fermi-LAT and H.E.S.S. Blazar Spectra”. en. [In preparation].
- [53] H. Primakoff. “Photo-Production of Neutral Mesons in Nuclear Electric Fields and the Mean Life of the Neutral Meson”. In: *Phys. Rev.* 81 (5 Mar. 1951), p. 899. DOI: 10.1103/PhysRev.81.899. URL: <https://link.aps.org/doi/10.1103/PhysRev.81.899>.
- [54] N. Bassan, A. Mirizzi, and M. Roncadelli. “Axion-like particle effects on the polarization of cosmic high-energy gamma sources”. In: *Journal of Cosmology and Astroparticle Physics* 2010.05 (May 2010). arXiv:1001.5267 [astro-ph], pp. 010–010. ISSN: 1475-7516. DOI: 10.1088/1475-7516/2010/05/010.
- [55] M. Meyer, J. Davies, and J. Kuhlmann. “gammaALPs: An open-source python package for computing photon-axion-like-particle oscillations in astrophysical environments”. In: *Proceedings of 37th International Cosmic Ray Conference — PoS(ICRC2021)*. ICRC2021. Sissa Medialab, June 2021, p. 557. DOI: 10.22323/1.395.0557. URL: <http://dx.doi.org/10.22323/1.395.0557>.
- [56] M. Meyer, D. Montanino, and J. Conrad. “On detecting oscillations of gamma rays into axion-like particles in turbulent and coherent magnetic fields”. en. In: *Journal of Cosmology and Astroparticle Physics* 2014.09 (Jan. 2017). arXiv:1406.5972 [astro-ph], pp. 003–003. ISSN: 1475-7516. DOI: 10.1088/1475-7516/2014/09/003.
- [57] T. M. Heckman and P. N. Best. “The Coevolution of Galaxies and Supermassive Black Holes: Insights from Surveys of the Contemporary Universe”. en. In: *Annual Review of Astronomy and Astrophysics* 52.1 (Aug. 2014), pp. 589–660. ISSN: 0066-4146, 1545-4282. DOI: 10.1146/annurev-astro-081913-035722.
- [58] P. Padovani, D. M. Alexander, R. J. Assef, et al. “Active galactic nuclei: what’s in a name?” en. In: *The Astronomy and Astrophysics Review* 25.1 (Nov. 2017), p. 2. ISSN: 0935-4956, 1432-0754. DOI: 10.1007/s00159-017-0102-9.

- [59] A. M. Mickaelian. “AGN Zoo and Classifications of Active Galaxies”. In: *Iranian Journal of Astronomy and Astrophysics* 2.1 (July 2015), pp. 1–38.
- [60] L. Spinoglio and J. A. Fernández-Ontiveros. “AGN types and unification model”. en. In: *Proceedings of the International Astronomical Union* 15.S356 (Oct. 2019), pp. 29–43. ISSN: 1743-9213, 1743-9221. DOI: 10.1017/S1743921320002549.
- [61] C. M. Urry and P. Padovani. “Unified schemes for radio-loud active galactic nuclei”. In: *Publications of the Astronomical Society of the Pacific* 107.715 (1995), pp. 803–803.
- [62] J. Holder. “TeV Gamma-ray Astronomy: A Summary”. en. In: *Astroparticle Physics* 39–40 (Dec. 2012). arXiv:1204.1267 [astro-ph], pp. 61–75. ISSN: 09276505. DOI: 10.1016/j.astropartphys.2012.02.014.
- [63] G. L. Mura, G. Busetto, S. Ciroi, et al. “Relativistic plasmas in AGN jets - From synchrotron radiation to gamma-ray emission”. In: *The European Physical Journal D* 71.4 (Apr. 2017). arXiv:1702.06779 [astro-ph], p. 95. ISSN: 1434-6060, 1434-6079. DOI: 10.1140/epjd/e2017-70745-2.
- [64] M.-H. Ulrich, L. Maraschi, and C. M. Urry. “Variability of active galactic nuclei”. In: *Annual Review of Astronomy and Astrophysics* 35.1 (1997), pp. 445–502.
- [65] P. Schneider. *Extragalactic Astronomy and Cosmology: An Introduction*. en. Berlin, Heidelberg: Springer Berlin Heidelberg, 2015. ISBN: 978-3-642-54082-0. DOI: 10.1007/978-3-642-54083-7. URL: <https://link.springer.com/10.1007/978-3-642-54083-7>.
- [66] G. Bhatta. “Blazar jets as possible sources of ultra-high energy photons: a short review”. In: *Universe* 8.10 (Oct. 2022). arXiv:2209.13158 [astro-ph], p. 513. ISSN: 2218-1997. DOI: 10.3390/universe8100513.
- [67] M. Meyer. “The opacity of the universe for high and very high energy gamma-rays”. In: (2013).
- [68] E. L. Alexander. “Magnetic Fields Around Radio Galaxies”. PhD thesis. University of Manchester, 2002.
- [69] H.E.S.S. Collaboration. *H.E.S.S. Collaboration*. [Online; Accessed 7 May 2026]. URL: <https://hess-experiment.eu/>.
- [70] S. P. Wakely and D. Horan. “TeVCat: An online catalog for Very High Energy Gamma-Ray Astronomy”. In: *International Cosmic Ray Conference* 3 (2008). [Online; Accessed 30 May 2026], pp. 1341–1344. URL: <https://tevcat2.tevcat.org/>.
- [71] A. A. Abdo, M. Ackermann, M. Ajello, et al. “Fermi Observations of the Very Hard Gamma-Ray Blazar PG 1553+113”. In: *The Astrophysical Journal* 708.2 (Dec. 2009), p. 1310. DOI: 10.1088/0004-637X/708/2/1310. URL: <https://doi.org/10.1088/0004-637X/708/2/1310>.
- [72] M. Böttcher. “Modeling the emission processes in blazars”. In: *Astrophysics and Space Science* 309.1 (2007), pp. 95–104.
- [73] M. Boettcher. “Modeling the Spectral Energy Distributions and Variability of Blazars”. In: arXiv:1205.0539 (May 2012). arXiv:1205.0539 [astro-ph]. DOI: 10.48550/arXiv.1205.0539. URL: <http://arxiv.org/abs/1205.0539>.
- [74] Z. Fan, X. Cao, and M. Gu. “A test of external Compton models for gamma-ray active galactic nuclei”. In: *The Astrophysical Journal* 646.1 (2006), pp. 8–15.

- [75] D. Bégué, N. Sahakyan, H. Dereli-Bégué, et al. “Modeling Blazar Broadband Emission with a Convolutional Neural Network. I. Synchrotron Self-Compton Model”. In: *The Astrophysical Journal* 963.1 (Feb. 2024), p. 71. DOI: 10.3847/1538-4357/ad19cf.
- [76] J. D. Finke. “External compton scattering in blazar jets and the location of the gamma-ray emitting region”. In: *The Astrophysical Journal* 830.2 (2016), p. 94.
- [77] T. Unbehaun. “Joint-instrument analyses with GammaPy”. MA thesis. Friedrich-Alexander-Universität, 2020.
- [78] E. Dwek and F. Krennrich. “The Extragalactic Background Light and the Gamma-ray Opacity of the Universe”. en. In: *Astroparticle Physics* 43 (Mar. 2013). arXiv:1209.4661 [astro-ph], pp. 112–133. ISSN: 09276505. DOI: 10.1016/j.astropartphys.2012.09.003.
- [79] H. Collaboration, H. Abdalla, A. Abramowski, et al. “Measurement of the EBL spectral energy distribution using the VHE gamma-ray spectra of H.E.S.S. blazars”. en. In: *Astronomy & Astrophysics* 606 (Oct. 2017), A59. ISSN: 0004-6361, 1432-0746. DOI: 10.1051/0004-6361/201731200.
- [80] H. Collaboration, A. Abramowski, F. Acero, et al. “Measurement of the extragalactic background light imprint on the spectra of the brightest blazars observed with H.E.S.S.”. en. In: *Astronomy & Astrophysics* 550 (Feb. 2013), A4. ISSN: 0004-6361, 1432-0746. DOI: 10.1051/0004-6361/201220355.
- [81] H. Dole, G. Lagache, J.-L. Puget, et al. “The cosmic infrared background resolved by Spitzer: Contributions of mid-infrared galaxies to the far-infrared background”. In: *Astronomy & Astrophysics* 451.2 (May 2006), pp. 417–429. ISSN: 1432-0746. DOI: 10.1051/0004-6361:20054446. URL: <http://dx.doi.org/10.1051/0004-6361:20054446>.
- [82] E. Pueschel. “The Extragalactic Background Light: Constraints from TeV Blazar Observations”. en. In: *Proceedings of 35th International Cosmic Ray Conference — PoS(ICRC2017)*. Bexco, Busan, Korea: Sissa Medialab, Oct. 2017, p. 1107. DOI: 10.22323/1.301.1107. URL: <https://pos.sissa.it/301/1107>.
- [83] A. Domínguez, J. R. Primack, D. J. Rosario, et al. “Extragalactic background light inferred from AEGIS galaxy-SED-type fractions: EBL from AEGIS galaxy-SED-type fractions”. en. In: *Monthly Notices of the Royal Astronomical Society* 410.4 (Feb. 2011), pp. 2556–2578. ISSN: 00358711. DOI: 10.1111/j.1365-2966.2010.17631.x.
- [84] J. D. Finke, M. Ajello, A. Domínguez, et al. “Modeling the Extragalactic Background Light and the Cosmic Star Formation History”. en. In: *The Astrophysical Journal* 941.1 (Dec. 2022), p. 33. ISSN: 0004-637X, 1538-4357. DOI: 10.3847/1538-4357/ac9843.
- [85] A. Franceschini, G. Rodighiero, and M. Vaccari. “Extragalactic optical-infrared background radiation, its time evolution and the cosmic photon-photon opacity”. In: *Astronomy & Astrophysics* 487.3 (2008), pp. 837–852. ISSN: 1432-0746. DOI: 10.1051/0004-6361:200809691. URL: <http://dx.doi.org/10.1051/0004-6361:200809691>.
- [86] A. Saldana-Lopez, A. Domínguez, P. G. Pérez-González, et al. “An observational determination of the evolving extragalactic background light from the multiwavelength HST/CANDELS survey in the Fermi and CTA era”. en. In: *Monthly Notices of the Royal Astronomical Society* 507.4 (2021). arXiv:2012.03035 [astro-ph], pp. 5144–5160. ISSN: 0035-8711, 1365-2966. DOI: 10.1093/mnras/stab2393.

- [87] F. Aharonian, A. G. Akhperjanian, A. R. Bazer-Bachi, et al. “A low level of extragalactic background light as revealed by gamma-rays from blazars”. en. In: *Nature* 440.7087 (Apr. 2006), pp. 1018–1021. ISSN: 0028-0836, 1476-4687. DOI: 10.1038/nature04680.
- [88] M. Errando, R. Bock, D. Kranich, et al. “Discovery of very high energy gamma-rays from the flat spectrum radio quasar 3C 279 with the MAGIC telescope”. en. In: *AIP Conference Proceedings*. Heidelberg (Germany): AIP, 2008, pp. 423–426. DOI: 10.1063/1.3076698. URL: <https://pubs.aip.org/aip/acp/article/1085/1/423-426/609344>.
- [89] M. Lorentz and P. Brun. “Limits on Lorentz invariance violation at the Planck energy scale from HESS spectral analysis of the blazar Mrk 501”. In: *EPJ Web of Conferences*. Vol. 136. EDP Sciences. 2017, p. 03018.
- [90] N. Tejos. “The Intergalactic Medium”. In: arXiv:2504.12539 (Apr. 2025). arXiv:2504.12539 [astro-ph]. DOI: 10.48550/arXiv.2504.12539. URL: <http://arxiv.org/abs/2504.12539>.
- [91] F. Aharonian, J. Aschersleben, M. Backes, et al. “Constraints on the Intergalactic Magnetic Field Using Fermi-LAT and H.E.S.S. Blazar Observations”. en. In: *The Astrophysical Journal Letters* 950.2 (2023), p. L16. ISSN: 2041-8205, 2041-8213. DOI: 10.3847/2041-8213/acd777.
- [92] R. Jansson and G. R. Farrar. “A New Model of the Galactic Magnetic Field”. en. In: *The Astrophysical Journal* 757.1 (2012). arXiv:1204.3662 [astro-ph], p. 14. ISSN: 0004-637X, 1538-4357. DOI: 10.1088/0004-637X/757/1/14.
- [93] F. Tavecchio, M. Roncadelli, and G. Galanti. “Photons to axion-like particles conversion in Active Galactic Nuclei”. en. In: *Physics Letters B* 744 (May 2015), pp. 375–379. ISSN: 0370-2693. DOI: 10.1016/j.physletb.2015.04.017.
- [94] J. Davies, M. Meyer, and G. Cotter. “Relevance of jet magnetic field structure for blazar axionlike particle searches”. en. In: *Physical Review D* 103.2 (Jan. 2021). arXiv:2011.08123 [astro-ph], p. 023008. ISSN: 2470-0010, 2470-0029. DOI: 10.1103/PhysRevD.103.023008.
- [95] D. Malyshev, L. Zadorozhna, Y. Bidasyuk, A. Santangelo, and O. Ruchayskiy. “Constraints on axion-like particles from active galactic nuclei seen through galaxy clusters”. en. In: *Nature Astronomy* (Aug. 2025). ISSN: 2397-3366. DOI: 10.1038/s41550-025-02621-8. URL: <https://www.nature.com/articles/s41550-025-02621-8>.
- [96] C. Grimaud, D. Malyshev, and E. Moulin. “Sensitivity to Axion-like Particle dark matter with very-high-energy gamma-ray observations of Active Galactic Nuclei located behind Galaxy Clusters”. In: *arXiv preprint arXiv:2603.12009* (2026).
- [97] G. Galanti and M. Roncadelli. “Behavior of axion-like particles in smoothed out domain-like magnetic fields”. en. In: *Physical Review D* 98.4 (Aug. 2018). arXiv:1804.09443 [astro-ph], p. 043018. ISSN: 2470-0010, 2470-0029. DOI: 10.1103/PhysRevD.98.043018.
- [98] S. Funk. “Ground- and Space-Based Gamma-Ray Astronomy”. en. In: *Annual Review of Nuclear and Particle Science* 65.1 (Oct. 2015), pp. 245–277. ISSN: 0163-8998, 1545-4134. DOI: 10.1146/annurev-nucl-102014-022036.
- [99] J. Hubbell. “Electron-positron pair production by photons: A historical overview”. en. In: *Radiation Physics and Chemistry* 75.6 (2006), pp. 614–623. ISSN: 0969806X. DOI: 10.1016/j.radphyschem.2005.10.008.

- [100] R. Mirzoyan. “Handbook of X-ray and Gamma-ray Astrophysics”. In: (2024). DOI: 10.1007/978-981-19-6960-7. URL: <http://dx.doi.org/10.1007/978-981-19-6960-7>.
- [101] G. Pühlhofer, F. Leuschner, and H. Salzmänn. “H.E.S.S.: The High Energy Stereoscopic System”. In: *Handbook of X-ray and Gamma-ray Astrophysics*. Springer Nature Singapore, Dec. 2023, pp. 1–41. ISBN: 9789811645440. DOI: 10.1007/978-981-16-4544-0_69-2. URL: http://dx.doi.org/10.1007/978-981-16-4544-0_69-2.
- [102] R. Poggiani. *High Energy Astrophysical Techniques*. en. UNITEXT for Physics. Cham: Springer International Publishing, 2017. ISBN: 978-3-319-44728-5. DOI: 10.1007/978-3-319-44729-2. URL: <http://link.springer.com/10.1007/978-3-319-44729-2>.
- [103] F. Aharonian, A. Akhperjanian, K.-M. Aye, et al. “Calibration of cameras of the H.E.S.S. detector”. en. In: *Astroparticle Physics* 22.2 (Nov. 2004), pp. 109–125. ISSN: 09276505. DOI: 10.1016/j.astropartphys.2004.06.006.
- [104] M. Holler, D. Berge, C. v. Eldik, et al. “Observations of the Crab Nebula with H.E.S.S. Phase II”. en. In: arXiv:1509.02902 (2015). arXiv:1509.02902 [astro-ph]. DOI: 10.48550/arXiv.1509.02902. URL: <http://arxiv.org/abs/1509.02902>.
- [105] H.E.S.S. Collaboration. *H.E.S.S. First Public Test Data Release*. arXiv:1810.04516 [astro-ph]. 2018. DOI: 10.5281/zenodo.1421098. URL: <http://arxiv.org/abs/1810.04516>.
- [106] A. Kohnle, F. Aharonian, A. Akhperjanian, et al. “Stereoscopic imaging of air showers with the first two HEGRA Cherenkov telescopes”. In: *Astroparticle Physics* 5.2 (1996), pp. 119–131. ISSN: 0927-6505. DOI: [https://doi.org/10.1016/0927-6505\(96\)00011-4](https://doi.org/10.1016/0927-6505(96)00011-4). URL: <https://www.sciencedirect.com/science/article/pii/0927650596000114>.
- [107] A. M. Hillas. “Cerenkov light images of EAS produced by primary gamma”. In: *19th Intern. Cosmic Ray Conf-Vol. 3*. OG-9.5-3. 1985.
- [108] Fermi-LAT Collaboration and W. B. Atwood. “The Large Area Telescope on the Fermi Gamma-ray Space Telescope Mission”. In: *The Astrophysical Journal* 697.2 (2009). arXiv:0902.1089 [astro-ph], pp. 1071–1102. ISSN: 0004-637X, 1538-4357. DOI: 10.1088/0004-637X/697/2/1071.
- [109] C. Meegan, G. Lichti, P. N. Bhat, et al. “THE FERMI GAMMA-RAY BURST MONITOR”. en. In: *The Astrophysical Journal* 702.1 (2009), pp. 791–804. ISSN: 0004-637X, 1538-4357. DOI: 10.1088/0004-637X/702/1/791.
- [110] NASA STEM Team. *What Is the Fermi Gamma-ray Space Telescope?* [Online; Accessed 7 May 2026]. URL: <https://www.nasa.gov/learning-resources/for-kids-and-students/what-is-the-fermi-gamma-ray-space-telescope-grades-5-8/>.
- [111] S. Abdollahi, F. Acero, M. Ackermann, et al. “Fermi Large Area Telescope Fourth Source Catalog”. In: *The Astrophysical Journal Supplement Series* 247.1 (Mar. 2020), p. 33. DOI: 10.3847/1538-4365/ab6bcb. URL: <https://doi.org/10.3847/1538-4365/ab6bcb>.
- [112] C. Nigro, C. Deil, R. Zanin, et al. “Towards open and reproducible multi-instrument analysis in gamma-ray astronomy”. en. In: *Astronomy & Astrophysics* 625 (May 2019), A10. ISSN: 0004-6361, 1432-0746. DOI: 10.1051/0004-6361/201834938.

- [113] T.-P. Li and Y.-Q. Ma. “Analysis methods for results in gamma-ray astronomy”. In: *Astrophysical Journal, Part 1 (ISSN 0004-637X)*, vol. 272, Sept. 1, 1983, p. 317–324. 272 (1983), pp. 317–324.
- [114] S. N. Zhang and D. Ramsden. “Statistical data analysis for gamma-ray astronomy”. en. In: *Experimental Astronomy* 1.3 (1990), pp. 145–163. ISSN: 0922-6435, 1572-9508. DOI: 10.1007/BF00462037.
- [115] J. R. Mattox, D. Bertsch, J. Chiang, et al. “The likelihood analysis of EGRET data”. In: *Astrophysical Journal v. 461*, p. 396 461 (1996), p. 396.
- [116] A. Donath, R. Terrier, Q. Remy, et al. “Gammapy: A Python package for gamma-ray astronomy”. In: *Astronomy & Astrophysics* 678 (2023), A157.
- [117] M. Wood, R. Caputo, E. Charles, M. D. Mauro, J. Magill, and J. Perkins. “Fermipy: An open-source Python package for analysis of Fermi-LAT Data”. In: arXiv:1707.09551 (2017). arXiv:1707.09551 [astro-ph]. DOI: 10.48550/arXiv.1707.09551. URL: <http://arxiv.org/abs/1707.09551>.
- [118] D. Malyshev and L. Mohrmann. “Analysis Methods for Gamma-ray Astronomy”. In: arXiv:2309.02966 [astro-ph]. 2024, pp. 1–53. DOI: 10.1007/978-981-16-4544-0_177-1. URL: <http://arxiv.org/abs/2309.02966>.
- [119] W. Atwood, A. Albert, L. Baldini, et al. “Pass 8: Toward the Full Realization of the Fermi-LAT Scientific Potential”. In: arXiv:1303.3514 (Mar. 2013). arXiv:1303.3514 [astro-ph]. DOI: 10.48550/arXiv.1303.3514. URL: <http://arxiv.org/abs/1303.3514>.
- [120] R. D. Parsons and J. A. Hinton. “A Monte Carlo Template based analysis for Air-Cherenkov Arrays”. en. In: *Astroparticle Physics* 56 (Apr. 2014). arXiv:1403.2993 [astro-ph], pp. 26–34. ISSN: 09276505. DOI: 10.1016/j.astropartphys.2014.03.002.
- [121] R. D. Parsons, M. Gajdus, and T. Murach. “HESS II Data Analysis with ImPACT”. en. In: arXiv:1509.06322 (2015). arXiv:1509.06322 [astro-ph]. DOI: 10.48550/arXiv.1509.06322. URL: <http://arxiv.org/abs/1509.06322>.
- [122] T. Murach, M. Gajdus, and R. D. Parsons. “A Neural Network-Based Monoscopic Reconstruction Algorithm for H.E.S.S. II”. en. In: arXiv:1509.00794 (2015). arXiv:1509.00794 [astro-ph]. DOI: 10.48550/arXiv.1509.00794. URL: <http://arxiv.org/abs/1509.00794>.
- [123] M. de Naurois and L. Rolland. “A high performance likelihood reconstruction of gamma-rays for imaging atmospheric Cherenkov telescopes”. In: *Astroparticle Physics* 32.5 (Dec. 2009), pp. 231–252. ISSN: 0927-6505. DOI: 10.1016/j.astropartphys.2009.09.001. URL: <http://dx.doi.org/10.1016/j.astropartphys.2009.09.001>.
- [124] F.-L. collaboration, S. Abdollahi, F. Acero, et al. “Incremental Fermi Large Area Telescope Fourth Source Catalog”. en. In: *The Astrophysical Journal Supplement Series* 260.2 (2022). arXiv:2201.11184 [astro-ph], p. 53. ISSN: 0067-0049, 1538-4365. DOI: 10.3847/1538-4365/ac6751.
- [125] J. Ballet, P. Bruel, T. Burnett, B. Lott, F.-L. Collaboration, et al. “Fermi Large Area Telescope fourth source catalog data release 4 (4FGL-DR4)”. In: *arXiv preprint arXiv:2307.12546* (2023).
- [126] S. Gillessen and H. L. Harney. “Significance in gamma-ray astronomy - the Li & Ma problem in Bayesian statistics”. en. In: *Astronomy & Astrophysics* 430.1 (Jan. 2005), pp. 355–362. ISSN: 0004-6361, 1432-0746. DOI: 10.1051/0004-6361:20035839.

- [127] NASA / GSFC. *Fermi SSC - LAT Photon, Event, and Spacecraft Data Query*. <https://fermi.gsfc.nasa.gov/cgi-bin/ssc/LAT/LATDataQuery.cgi>. [Online; accessed 18-May-2026]. 2026.
- [128] R. Brun and F. Rademakers. “ROOT: An object oriented data analysis framework”. In: *Nucl. Instrum. Meth. A* 389 (1997). Ed. by M. Werlen and D. Perret-Gallix, pp. 81–86. DOI: 10.1016/S0168-9002(97)00048-X.
- [129] Fermi-LAT Collaboration. *Fermi-LAT Documentation*. <https://fermi.gsfc.nasa.gov/>. [Online; Accessed 15-May-2026].
- [130] GammaPy Development Team. *GammaPy 2.0 Documentation and User Guide*. <https://docs.gammapy.org/2.0/index.html>. [Online; Accessed 15-May-2026].
- [131] W. Cash. “Parameter estimation in astronomy through application of the likelihood ratio”. en. In: *The Astrophysical Journal* 228 (Mar. 1979), p. 939. ISSN: 0004-637X, 1538-4357. DOI: 10.1086/156922.
- [132] H. Dembinski, P. Ongmongkolkul, C. Deil, et al. “scikit-hep/iminuit: v”. In: *Zenodo* (2020).
- [133] S. S. Wilks. “The large-sample distribution of the likelihood ratio for testing composite hypotheses”. In: *The annals of mathematical statistics* 9.1 (1938), pp. 60–62.
- [134] S. Algeri, J. Conrad, and D. A. Van Dyk. “A method for comparing non-nested models with application to astrophysical searches for new physics”. en. In: *Monthly Notices of the Royal Astronomical Society: Letters* 458.1 (Mar. 2016), pp. L84–L88. ISSN: 1745-3925, 1745-3933. DOI: 10.1093/mnrasl/slw025.
- [135] H. Chernoff. “On the distribution of the likelihood ratio”. In: *The Annals of Mathematical Statistics* (1954), pp. 573–578.
- [136] H. Collaboration: A. Abramowski, F. Aharonian, et al. “Search for extended gamma-ray emission around AGN with H.E.S.S. and Fermi-LAT”. en. In: *Astronomy & Astrophysics* 562 (Feb. 2014), A145. ISSN: 0004-6361, 1432-0746. DOI: 10.1051/0004-6361/201322510.
- [137] G. Emery, M. Cerruti, A. Dmytriiev, et al. “Observations of the FSRQ 3C 279 during the flaring state of 2017 and 2018 with HESS”. In: *arXiv preprint arXiv:1908.06784* (2019).
- [138] S. Wagner, B. Rani, H. Collaboration, et al. “Enhanced HE and VHE gamma-ray activity from the FSRQ PKS 0346-27”. In: *The Astronomer’s Telegram* 15020 (2021), p. 1.
- [139] A. Acharyya, F. Aharonian, F. Ait Benkhali, et al. “Scrutinizing the 2020 multiwavelength outburst of PKS 0903-57 through observations with H.E.S.S.” In: *Journal of High Energy Astrophysics* 53 (2026), p. 100599. ISSN: 2214-4048. DOI: <https://doi.org/10.1016/j.jheap.2026.100599>. URL: <https://www.sciencedirect.com/science/article/pii/S2214404826000510>.
- [140] F. Aharonian, A. G. Akhperjanian, U. Barres de Almeida, et al. “New constraints on the mid-IR EBL from the HESS discovery of VHE γ -rays from 1ES 0229+200”. In: *Astronomy and Astrophysics* 475.2 (Nov. 2007), pp. L9–L13. DOI: 10.1051/0004-6361:20078462. arXiv: 0709.4584 [astro-ph].
- [141] F. Aharonian, A. G. Akhperjanian, U. Barres de Almeida, et al. “Discovery of VHE γ -rays from the distant BL Lacertae 1ES 0347-121”. In: *Astronomy and Astrophysics* 473.3

- (Oct. 2007), pp. L25–L28. DOI: 10.1051/0004-6361:20078412. arXiv: 0708.3021 [astro-ph].
- [142] H. E. S. S. Collaboration, A. Abramowski, F. Acero, et al. “Discovery of hard-spectrum γ -ray emission from the BL Lacertae object 1ES 0414+009”. In: *Astronomy and Astrophysics* 538, A103 (Feb. 2012), A103. DOI: 10.1051/0004-6361/201118406. arXiv: 1201.2044 [astro-ph.HE].
 - [143] F. Aharonian, A. G. Akhperjanian, A. R. Bazer-Bachi, et al. “Detection of VHE gamma-ray emission from the distant blazar 1ES 1101-232 with HESS and broadband characterisation”. In: *Astronomy and Astrophysics* 470.2 (Aug. 2007), pp. 475–489. DOI: 10.1051/0004-6361:20077057. arXiv: 0705.2946 [astro-ph].
 - [144] HESS Collaboration, A. Abramowski, F. Acero, et al. “HESS and Fermi-LAT discovery of γ -rays from the blazar 1ES 1312-423”. In: *Monthly Notices of the RAS* 434.3 (Sept. 2013), pp. 1889–1901. DOI: 10.1093/mnras/stt1081. arXiv: 1306.3186 [astro-ph.HE].
 - [145] H. E. S. S. Collaboration, A. Abramowski, F. Acero, et al. “Discovery of VHE γ -ray emission and multi-wavelength observations of the BL Lacertae object 1RXS J101015.9-311909”. In: *Astronomy and Astrophysics* 542, A94 (June 2012), A94. DOI: 10.1051/0004-6361/201218910. arXiv: 1204.1964 [astro-ph.HE].
 - [146] F. Aharonian, A. G. Akhperjanian, A. R. Bazer-Bachi, et al. “Discovery of very high energy γ -ray emission from the BL Lacertae object H 2356-309 with the HESS Cherenkov telescopes”. In: *Astronomy and Astrophysics* 455.2 (Aug. 2006), pp. 461–466. DOI: 10.1051/0004-6361:20054732. arXiv: astro-ph/0607569 [astro-ph].
 - [147] F. Aharonian, A. G. Akhperjanian, A. R. Bazer-Bachi, et al. “Evidence for VHE γ -ray emission from the distant BL Lac PG 1553+113”. In: *Astronomy and Astrophysics* 448.2 (Mar. 2006), pp. L19–L23. DOI: 10.1051/0004-6361:200600010. arXiv: astro-ph/0601545 [astro-ph].
 - [148] H. E. S. S. Collaboration, A. Abramowski, F. Acero, et al. “Discovery of TeV γ -ray emission from PKS 0447-439 and derivation of an upper limit on its redshift”. In: *Astronomy and Astrophysics* 552, A118 (Apr. 2013), A118. DOI: 10.1051/0004-6361/201321108. arXiv: 1303.1628 [astro-ph.HE].
 - [149] H. E. S. S. Collaboration, A. Abramowski, F. Acero, et al. “H.E.S.S. discovery of VHE γ -rays from the quasar PKS 1510-089”. In: *Astronomy and Astrophysics* 554, A107 (June 2013), A107. DOI: 10.1051/0004-6361/201321135. arXiv: 1304.8071 [astro-ph.HE].
 - [150] F. Aharonian, A. G. Akhperjanian, A. R. Bazer-Bachi, et al. “Multi-wavelength observations of PKS 2155-304 with HESS”. In: *Astronomy and Astrophysics* 442.3 (Nov. 2005), pp. 895–907. DOI: 10.1051/0004-6361:20053353. arXiv: astro-ph/0506593 [astro-ph].
 - [151] E. Fomalont. “The International Celestial Reference System”. In: *The Science of Calibration*. Ed. by S. Deustua, S. Allam, D. Tucker, and J. A. Smith. Vol. 503. Astronomical Society of the Pacific Conference Series. May 2016, p. 177.
 - [152] A. Abdo, M. Ackermann, M. Ajello, et al. “Fermi observations of TeV-selected active galactic nuclei”. In: *The Astrophysical Journal* 707.2 (2009), pp. 1310–1333.
 - [153] J. D. Scargle, J. P. Norris, B. Jackson, and J. Chiang. “Studies in astronomical time series analysis VI. Bayesian block representations”. en. In: *The Astrophysical*

- Journal* 764.2 (Feb. 2013), p. 167. ISSN: 0004-637X, 1538-4357. DOI: 10.1088/0004-637X/764/2/167.
- [154] Astropy Collaboration, A. M. Price-Whelan, P. L. Lim, et al. “The Astropy Project: Sustaining and Growing a Community-oriented Open-source Project and the Latest Major Release (v5.0) of the Core Package”. In: *The Astrophysical Journal* 935.2, 167 (Aug. 2022), p. 167. DOI: 10.3847/1538-4357/ac7c74. arXiv: 2206.14220 [astro-ph.IM].
 - [155] P. Virtanen, R. Gommers, T. E. Oliphant, et al. “SciPy 1.0: Fundamental Algorithms for Scientific Computing in Python”. In: *Nature Methods* 17 (2020), pp. 261–272. DOI: 10.1038/s41592-019-0686-2.
 - [156] S. Navas et al. “Review of particle physics”. In: *Phys. Rev. D* 110.3 (2024), p. 030001. DOI: 10.1103/PhysRevD.110.030001.
 - [157] S. Abdollahi, M. Ajello, L. Baldini, et al. “The Fermi-LAT Light Curve Repository”. en. In: *The Astrophysical Journal Supplement Series* 265.2 (Apr. 2023). arXiv:2301.01607 [astro-ph], p. 31. ISSN: 0067-0049, 1538-4365. DOI: 10.3847/1538-4365/acbb6a.
 - [158] Y. Tanaka, L. Stawarz, J. Finke, et al. “EXTREME BLAZARS STUDIED WITH FERMI-LAT AND SUZAKU: 1ES 0347- 121 AND BLAZAR CANDIDATE HESS J1943+ 213”. In: *The Astrophysical Journal* 787.2 (2014), p. 155.
 - [159] A. Abdo, M. Ackermann, I. Agudo, et al. “Fermi Large Area Telescope and multi-wavelength observations of the flaring activity of PKS 1510-089 between 2008 September and 2009 June”. In: *The Astrophysical Journal* 721.2 (2010), pp. 1425–1447.
 - [160] Z. Shah, V. Jithesh, S. Sahayanathan, R. Misra, and N. Iqbal. “Study on temporal and spectral behaviour of 3C 279 during 2018 January flare”. In: *Monthly Notices of the Royal Astronomical Society* 484.3 (2019), pp. 3168–3179.
 - [161] H. Abdalla, A. Abramowski, F. Aharonian, et al. “The HESS Galactic plane survey”. In: *Astronomy & Astrophysics* 612 (2018), A1.
 - [162] F. Acero, M. Ackermann, M. Ajello, et al. “Fermi large area telescope third source catalog”. In: *The Astrophysical Journal Supplement Series* 218.2 (2015), p. 23.
 - [163] M. Meyer. *EBLTable*. Version v0.5. Nov. 2022. DOI: 10.5281/zenodo.7312062.
 - [164] B. Khelifi, A. Djannati-Ataï, L. Jouvin, et al. “HAP-Fr, a pipeline of data analysis for the HESS-II experiment”. en. In: *Proceedings of The 34th International Cosmic Ray Conference — PoS(ICRC2015)*. The Hague, The Netherlands: Sissa Medialab, Aug. 2016, p. 837. DOI: 10.22323/1.236.0837. URL: <https://pos.sissa.it/236/837>.
 - [165] J. Davies, M. Meyer, and G. Cotter. “Constraints on axionlike particles from a combined analysis of three flaring *Fermi* flat-spectrum radio quasars”. en. In: *Physical Review D* 107.8 (Apr. 2023). arXiv:2211.03414 [astro-ph], p. 083027. ISSN: 2470-0010, 2470-0029. DOI: 10.1103/PhysRevD.107.083027.
 - [166] M. D. Marsh, H. R. Russell, A. C. Fabian, B. R. McNamara, P. Nulsen, and C. S. Reynolds. “A new bound on axion-like particles”. In: *Journal of Cosmology and Astroparticle Physics* 2017.12 (2017), pp. 036–036.
 - [167] J. Sisk-Reynés, J. H. Matthews, C. S. Reynolds, H. R. Russell, R. N. Smith, and M. D. Marsh. “New constraints on light axion-like particles using Chandra transmission grating spectroscopy of the powerful cluster-hosted quasar H1821+ 643”. In: *Monthly Notices of the Royal Astronomical Society* 510.1 (2022), pp. 1264–1277.

- [168] H. Abdalla, R. Adam, F. Aharonian, et al. “A very-high-energy component deep in the γ -ray burst afterglow”. In: *Nature* 575.7783 (2019), pp. 464–467.
- [169] R. Guedes Lang, T. Unbehaun, L. Mohrmann, S. Steinmassl, J. Hinton, and S. Funk. “Event types in H.E.S.S.: A combined analysis for different telescope types and energy ranges”. en. In: *Astronomy & Astrophysics* 706 (Feb. 2026), A291. ISSN: 0004-6361, 1432-0746. DOI: 10.1051/0004-6361/202557730.
- [170] CTA Consortium, H. Abdalla, H. Abe, et al. “Sensitivity of the Cherenkov Telescope Array for probing cosmology and fundamental physics with gamma-ray propagation”. In: *Journal of Cosmology and Astroparticle Physics* 2021.02 (Feb. 2021). arXiv:2010.01349 [astro-ph], pp. 048–048. ISSN: 1475-7516. DOI: 10.1088/1475-7516/2021/02/048.
- [171] M. Meyer and J. Conrad. “Sensitivity of the Cherenkov Telescope Array to the detection of axion-like particles at high gamma-ray opacities”. en. In: *Journal of Cosmology and Astroparticle Physics* 2014.12 (Dec. 2014). arXiv:1410.1556 [astro-ph], pp. 016–016. ISSN: 1475-7516. DOI: 10.1088/1475-7516/2014/12/016.
- [172] CTA Consortium. *Science with the Cherenkov Telescope Array*. World Scientific, 2019. DOI: 10.1142/10986. eprint: <https://www.worldscientific.com/doi/pdf/10.1142/10986>. URL: <https://www.worldscientific.com/doi/abs/10.1142/10986>.
- [173] A. Kartavtsev, G. Raffelt, and H. Vogel. “Extragalactic photon-ALP conversion at CTA energies”. en. In: *Journal of Cosmology and Astroparticle Physics* 2017.01 (Jan. 2017), pp. 024–024. ISSN: 1475-7516. DOI: 10.1088/1475-7516/2017/01/024.
- [174] H. Abdalla, H. Abe, F. Acero, et al. “Sensitivity of the Cherenkov Telescope Array for probing cosmology and fundamental physics with gamma-ray propagation”. In: *Journal of Cosmology and Astroparticle Physics* 2021.02 (2021), pp. 048–048.
- [175] J. Biteau and D. A. Williams. “The extragalactic background light, the Hubble constant, and anomalies: conclusions from 20 years of TeV gamma-ray observations”. In: *The Astrophysical Journal* 812.1 (2015), p. 60.

Appendix

This appendix presents supplementary plots obtained for all of the sources considered in this work. In particular, Appendix A shows the light curves and best-fit ellipses for the time variability analysis of the H.E.S.S. data of our sources, along with the Bayesian blocks and time segmentation. Appendix B shows the upturn likelihood grid plots obtained for each source, considering both the H.E.S.S.-only analysis, and the joint analysis of *Fermi*-LAT and H.E.S.S. data (for sources where it is possible).

A Light curves and time variability analysis of H.E.S.S. observations

The following figures show the light curves and time evolution of the emitted flux observed for each of the sources in our dataset are shown, including also the evolution of the spectral index. Below each figure, the best-fit ellipses are also plotted for each one of the Bayesian blocks found from the flux light curve. Each ellipse plot displays the 1σ uncertainties associated to each parameter, as well as the 1σ , 2σ , and 3σ confidence ellipses, with the error bars corresponding to projections onto each axis of the semi-minor and semi-major axes of the ellipse. In the legend are included the time ranges for each Bayesian block found.

For sources where only a single block is found (e.g. 1ES 1312-423, 1RXS J101015.9-311909 or 3C 279), the final time segmentation is extended to cover the full observation period.

The high rotation angle of certain best-fit ellipses (e.g. in 1RXS J101015.9-311909 or PKS 1510-089) indicates a high correlation between the index and normalization parameters, which could be improved by evaluating the fit at the decorrelation energy of each Bayesian block. In the plots shown here, the reference energy with which each fit is performed is computed for each source, and kept fixed to that value throughout all time blocks found.

In some cases, numerical convergence issues affect the appearance of certain plots, as described below for the relevant sources. These issues do not affect the results of the main analysis, as we are mainly interested in the time edges of each Bayesian block, and in particular mainly for variable sources, and additional spectral analyses will be performed for each block separately. In particular, the value of the flux evaluated for each Bayesian block in the light curve of some sources is placed significantly below the flux points themselves (this can be observed in 1ES 0414+009, 1ES 1312-423, and to some extent in PKS 1510-089). This is possibly caused by numerical convergence discrepancies when reevaluating the light curve. Similarly, in PG 1553+113, only two of the three found blocks are visible in the ellipse plot (due to numerical convergence issues), and thus the problematic block was removed from the time variability analysis. Lastly, due to low photon statistics and only an upper limit found for the flux, the ellipse for PKS 0346-27 presents an apparent diverging shape towards zero normalization.

1ES 0229+200

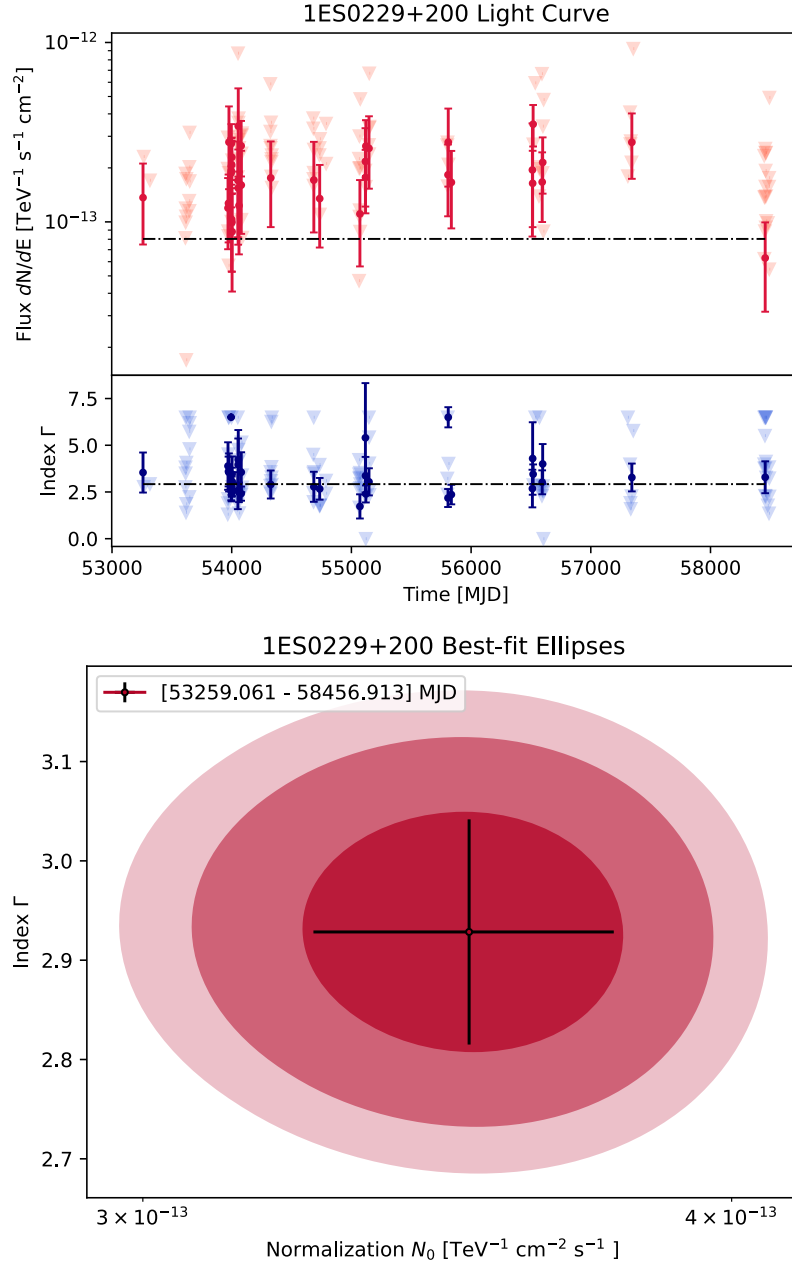


Figure A1: Spectral evolution and best-fit confidence ellipses for 1ES 0229+200, showing the spectral index Γ and normalization N_0 for each Bayesian block, with σ , 2σ , and 3σ confidence contours. Block dates are given in the modified Julian day (MJD) format.

1ES 0347-121

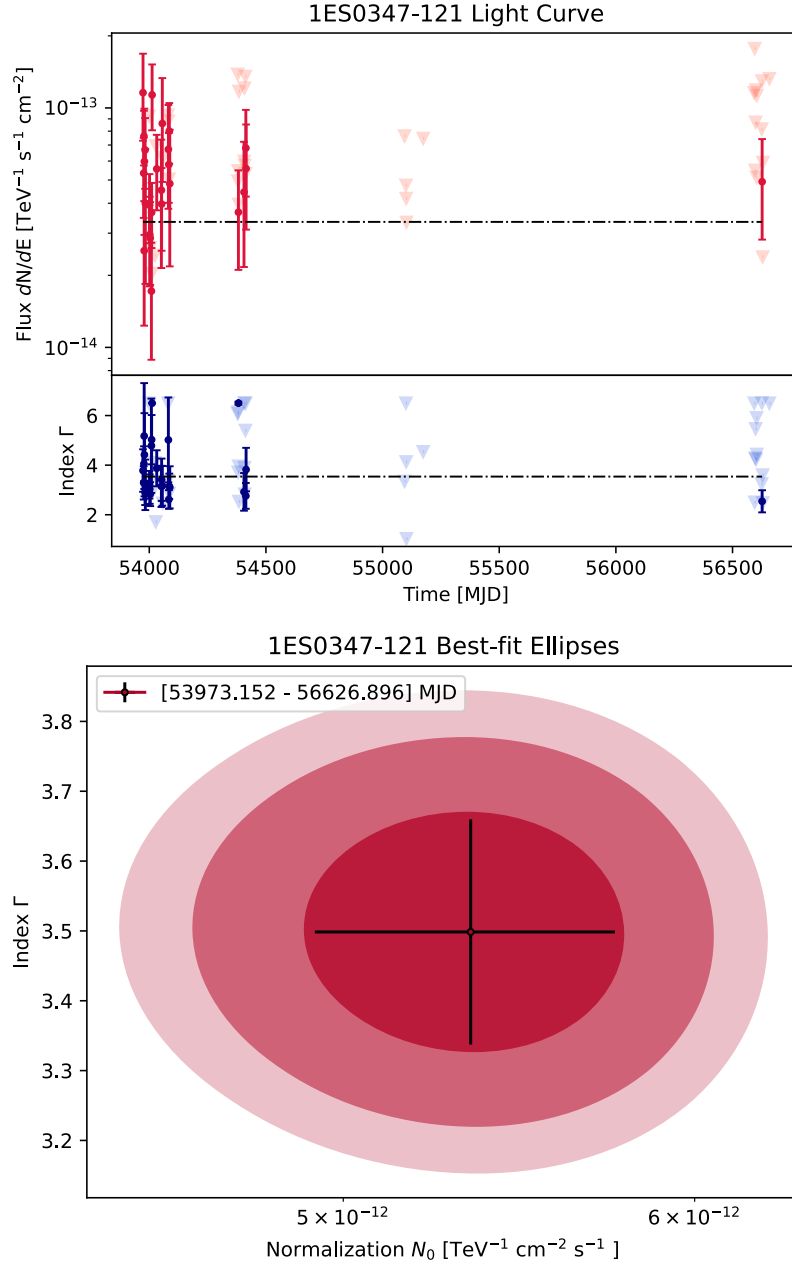


Figure A2: Spectral evolution and best-fit confidence ellipses for 1ES 0347-121, showing the spectral index Γ and normalization N_0 for each Bayesian block, with σ , 2σ , and 3σ confidence contours. Block dates are given in the modified Julian day (MJD) format.

1ES 0414+009

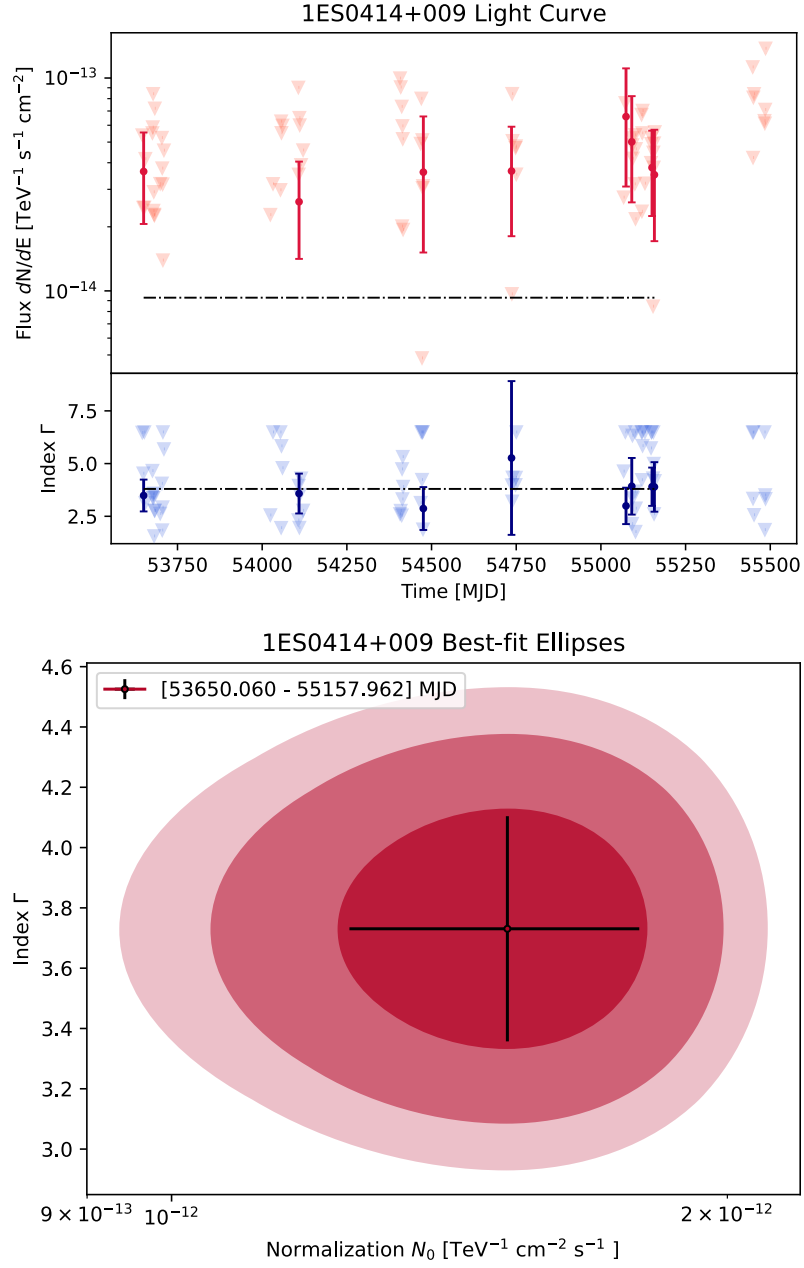


Figure A3: Spectral evolution and best-fit confidence ellipses for 1ES 0414+009, showing the spectral index Γ and normalization N_0 for each Bayesian block, with 2σ , and 3σ confidence contours. Block dates are given in the modified Julian day (MJD) format.

1ES 1101-232

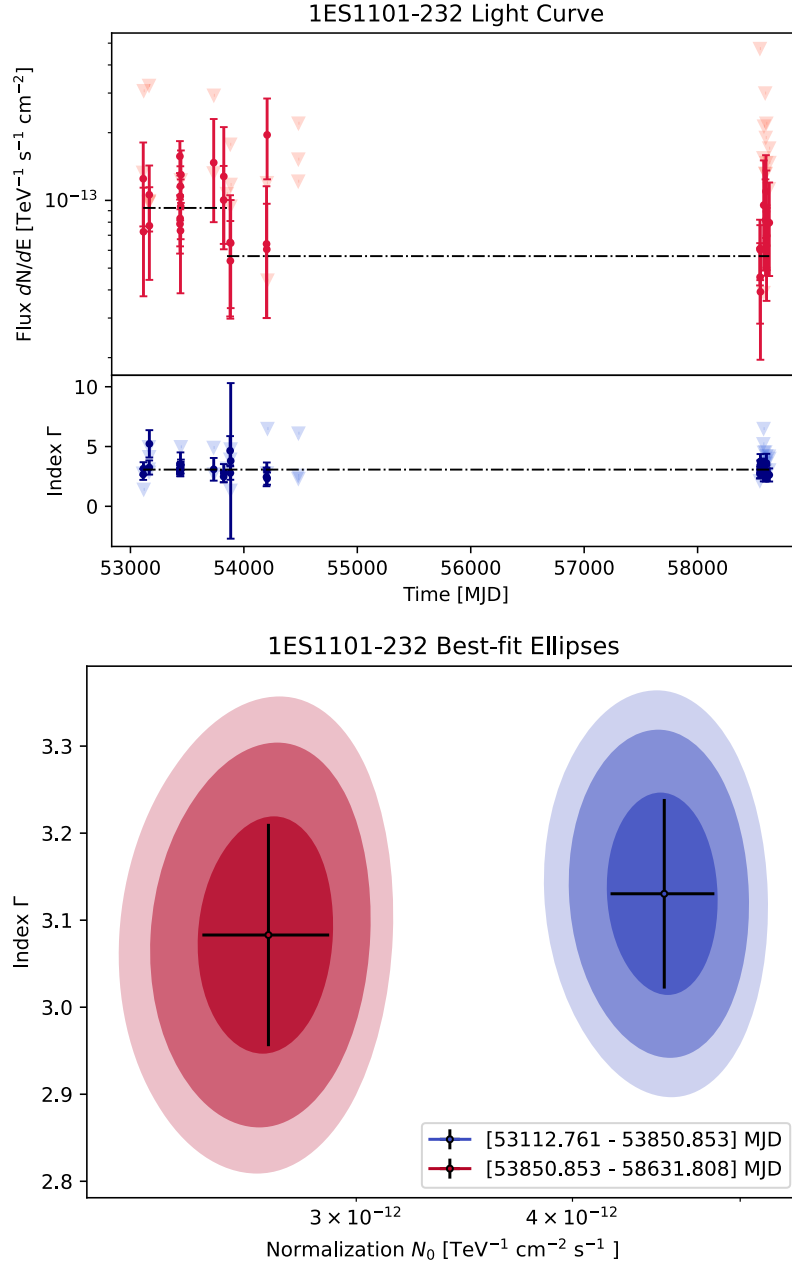


Figure A4: Spectral evolution and best-fit confidence ellipses for 1ES 1101-232, showing the spectral index Γ and normalization N_0 for each Bayesian block, with 1σ , 2σ , and 3σ confidence contours. Block dates are given in the modified Julian day (MJD) format.

1ES 1312-423

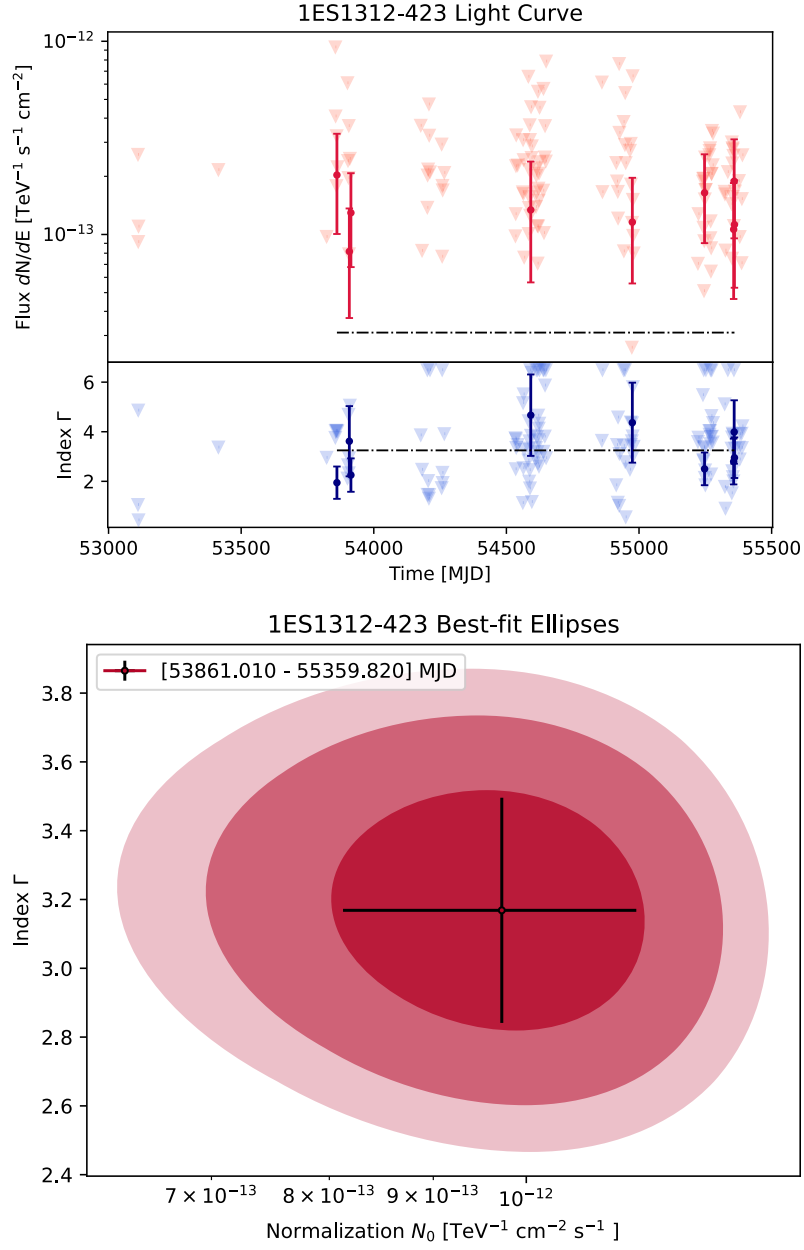


Figure A5: Spectral evolution and best-fit confidence ellipses for 1ES 1312-423, showing the spectral index Γ and normalization N_0 for each Bayesian block, with σ 2 σ , and 3 σ confidence contours. Block dates are given in the modified Julian day (MJD) format.

1RXS J101015.9-311909

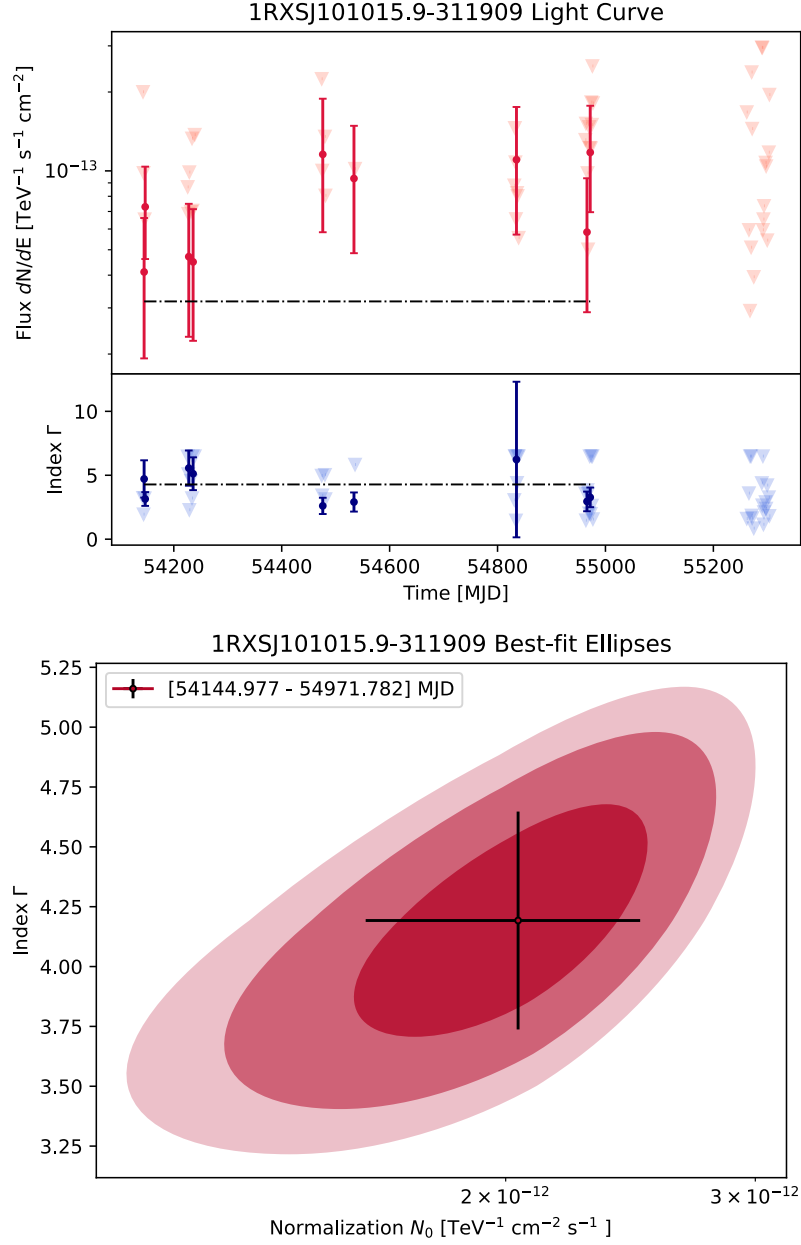


Figure A6: Spectral evolution and best-fit confidence ellipses for 1RXS J101015.9-311909, showing the spectral index Γ and normalization N_0 for each Bayesian block, with σ , 2σ , and 3σ confidence contours. Block dates are given in the modified Julian day (MJD) format.

3C 279

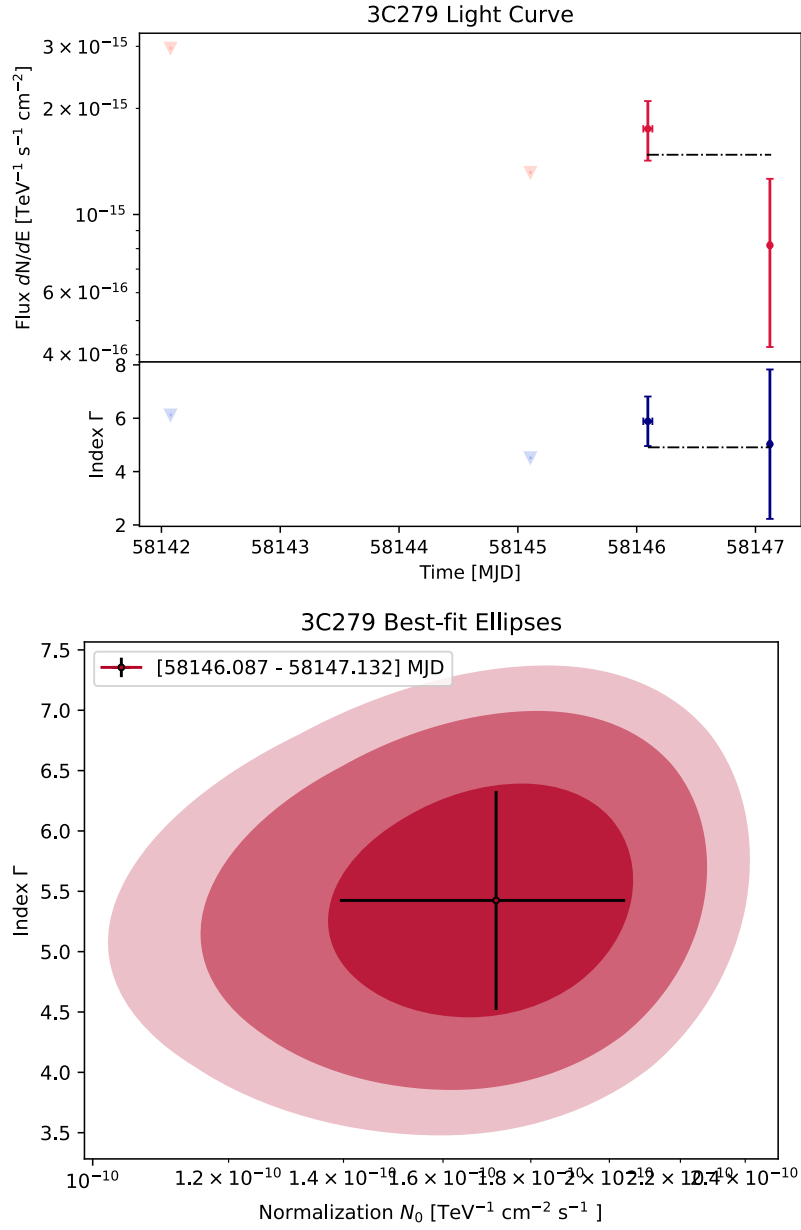


Figure A7: Spectral evolution and best-fit confidence ellipses for 3C 279, showing the spectral index Γ and normalization N_0 for each Bayesian block, with 1σ , 2σ , and 3σ confidence contours. Block dates are given in the modified Julian day (MJD) format.

H 2356-309

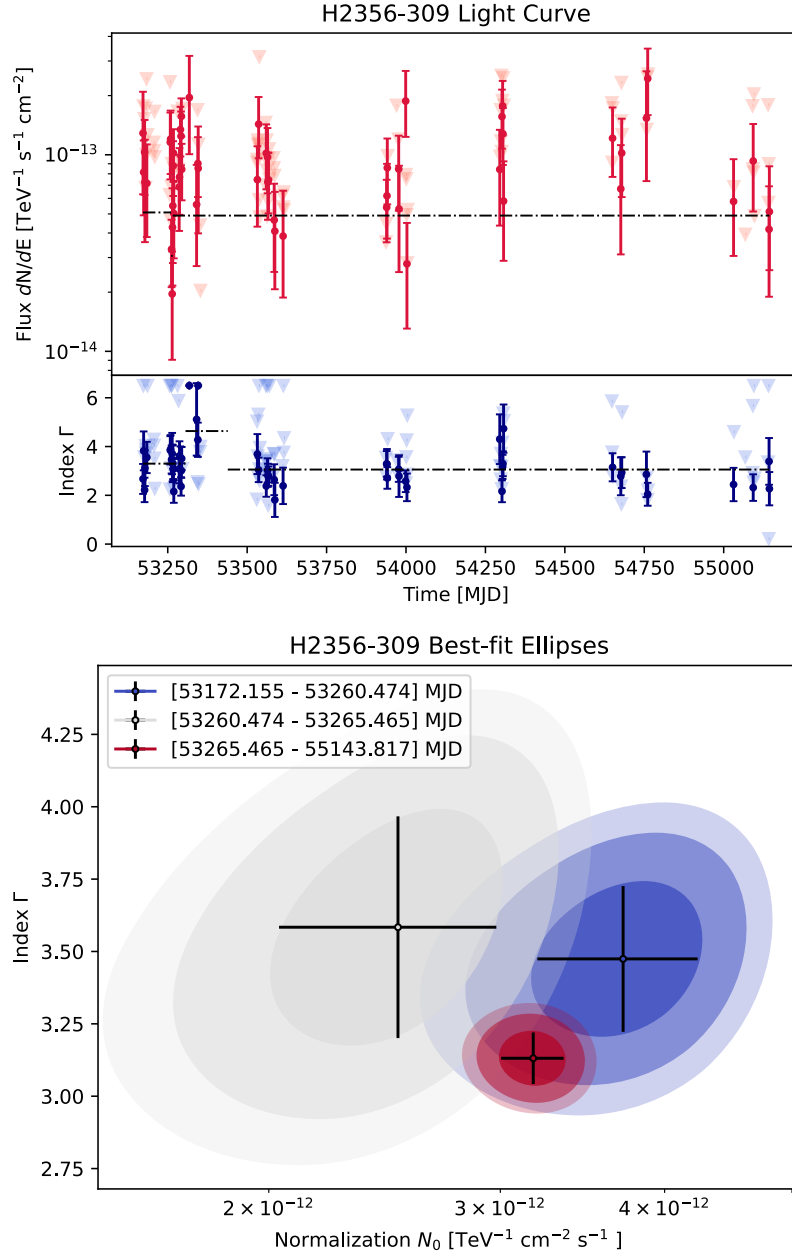


Figure A8: Spectral evolution and best-fit confidence ellipses for H 2356-309, showing the spectral index Γ and normalization N_0 for each Bayesian block, with σ 2 σ , and 3 σ confidence contours. Block dates are given in the modified Julian day (MJD) format.

PG 1553+113

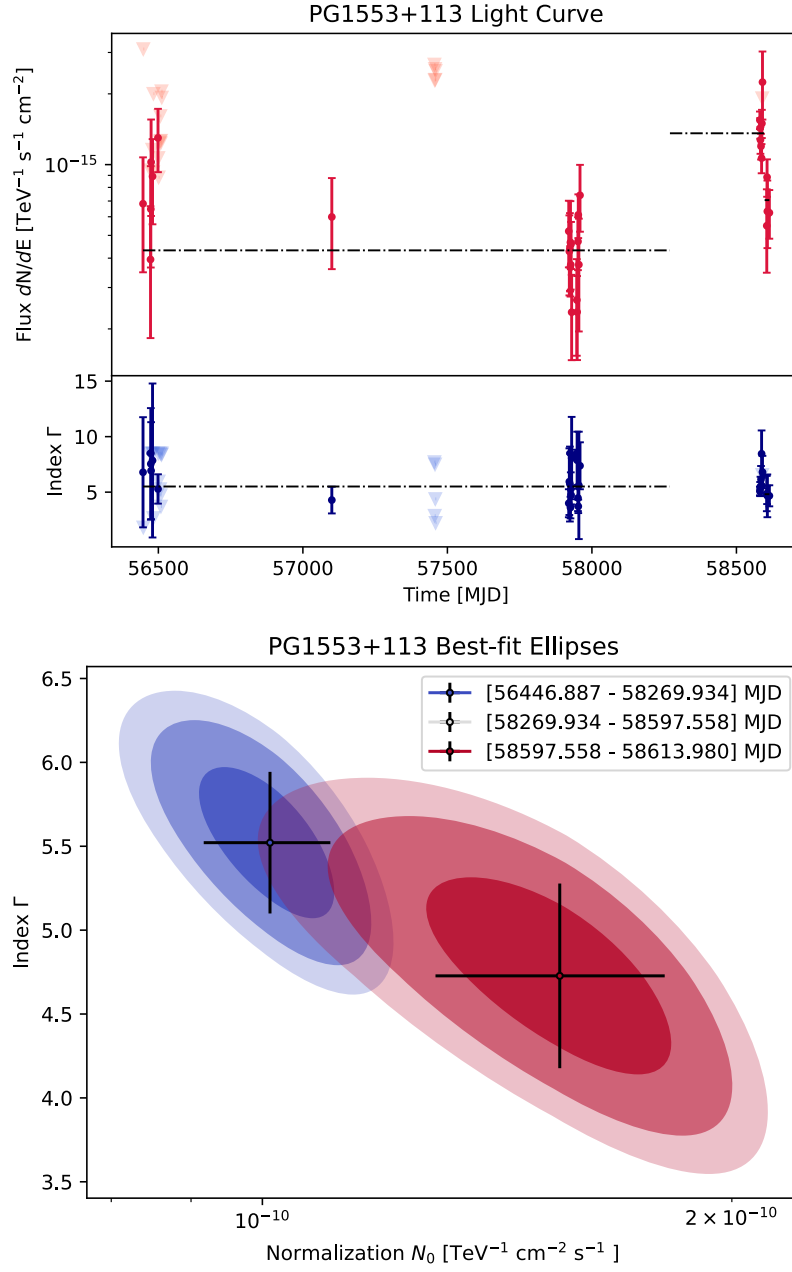


Figure A9: Spectral evolution and best-fit confidence ellipses for PG 1553+113, showing the spectral index Γ and normalization N_0 for each Bayesian block, with σ , 2σ , and 3σ confidence contours. Block dates are given in the modified Julian day (MJD) format.

PKS 0346-27

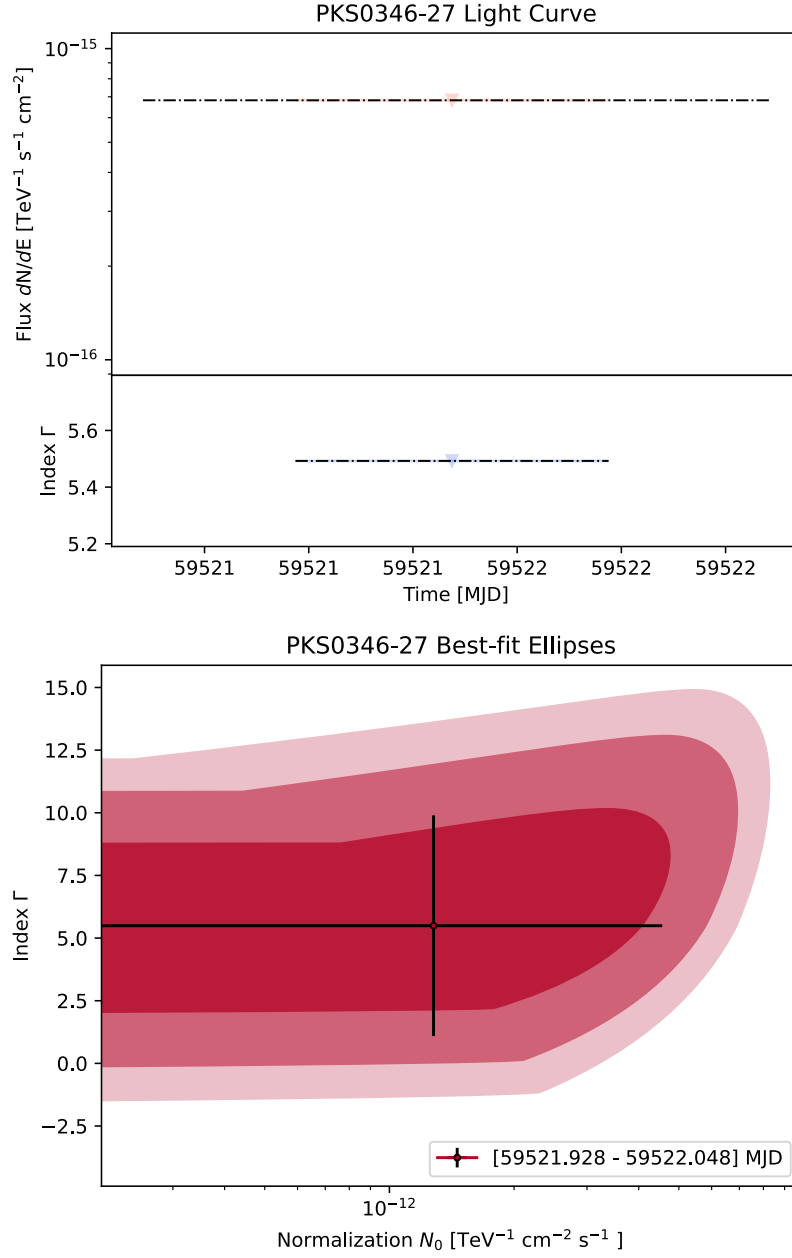


Figure A10: Spectral evolution and best-fit confidence ellipses for PKS 0346-27, showing the spectral index Γ and normalization N_0 for each Bayesian block, with σ , 2σ , and 3σ confidence contours. Block dates are given in the modified Julian day (MJD) format.

PKS0447-439

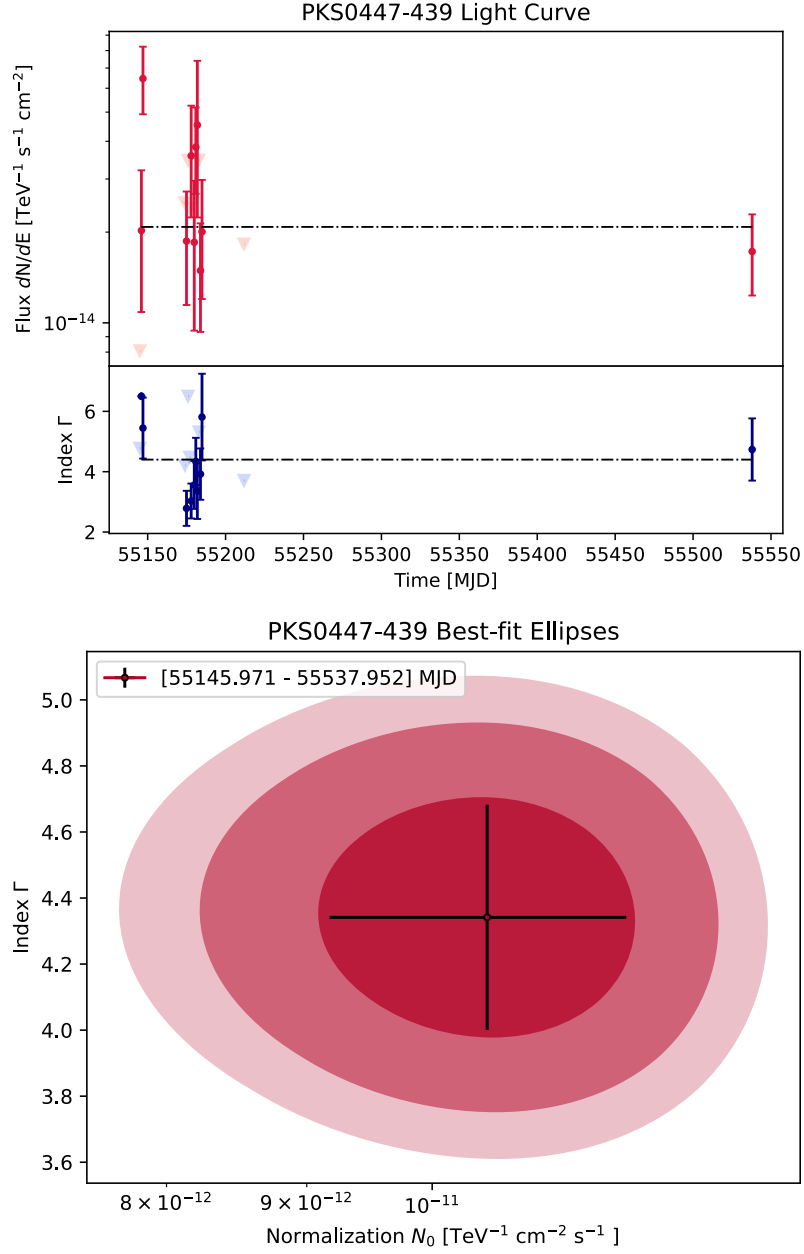


Figure A11: Spectral evolution and best-fit confidence ellipses for PKS 0447-439, showing the spectral index Γ and normalization N_0 for each Bayesian block, with σ 2σ , and 3σ confidence contours. Block dates are given in the modified Julian day (MJD) format.

PKS 0903-57

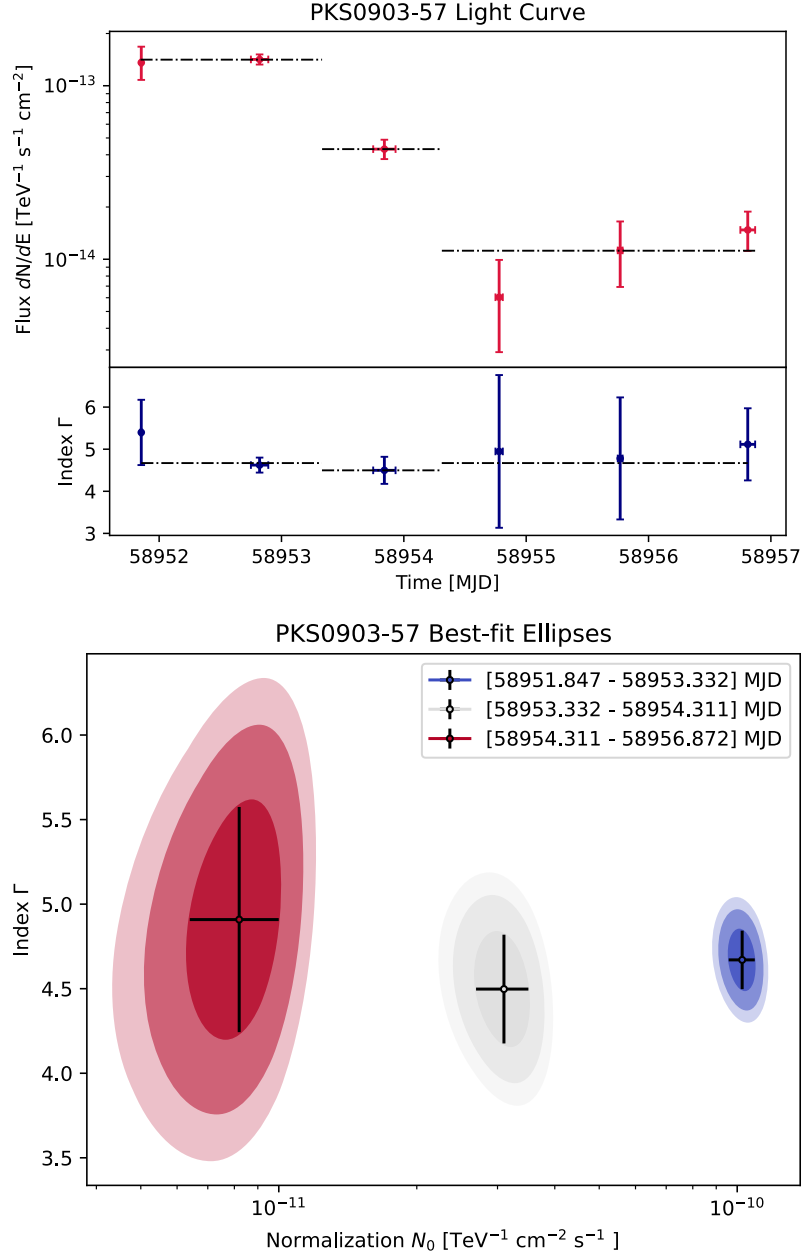


Figure A12: Spectral evolution and best-fit confidence ellipses for PKS 0903-57, showing the spectral index Γ and normalization N_0 for each Bayesian block, with σ 2 σ , and 3 σ confidence contours. Block dates are given in the modified Julian day (MJD) format.

PKS 1510-089

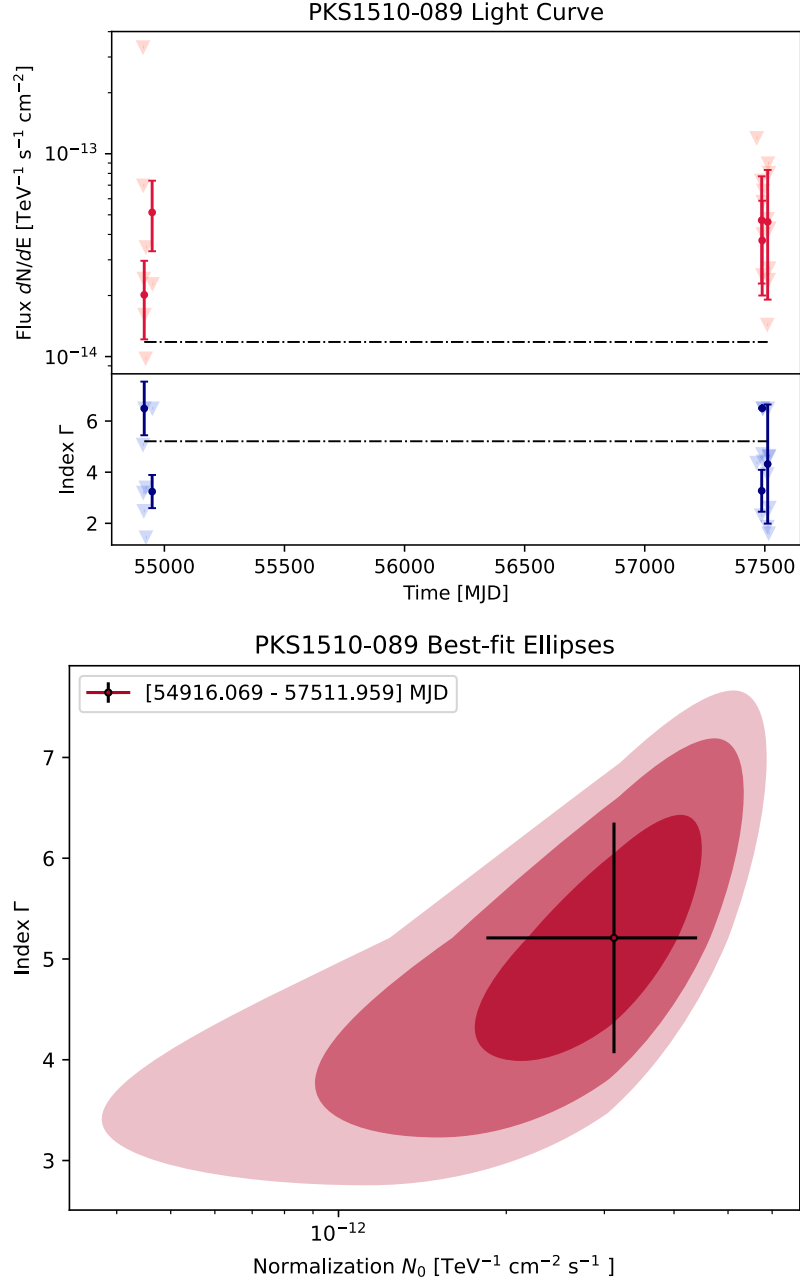


Figure A13: Spectral evolution and best-fit confidence ellipses for PKS 1510-089, showing the spectral index Γ and normalization N_0 for each Bayesian block, with σ , 2σ , and 3σ confidence contours. Block dates are given in the modified Julian day (MJD) format.

PKS 2155-304

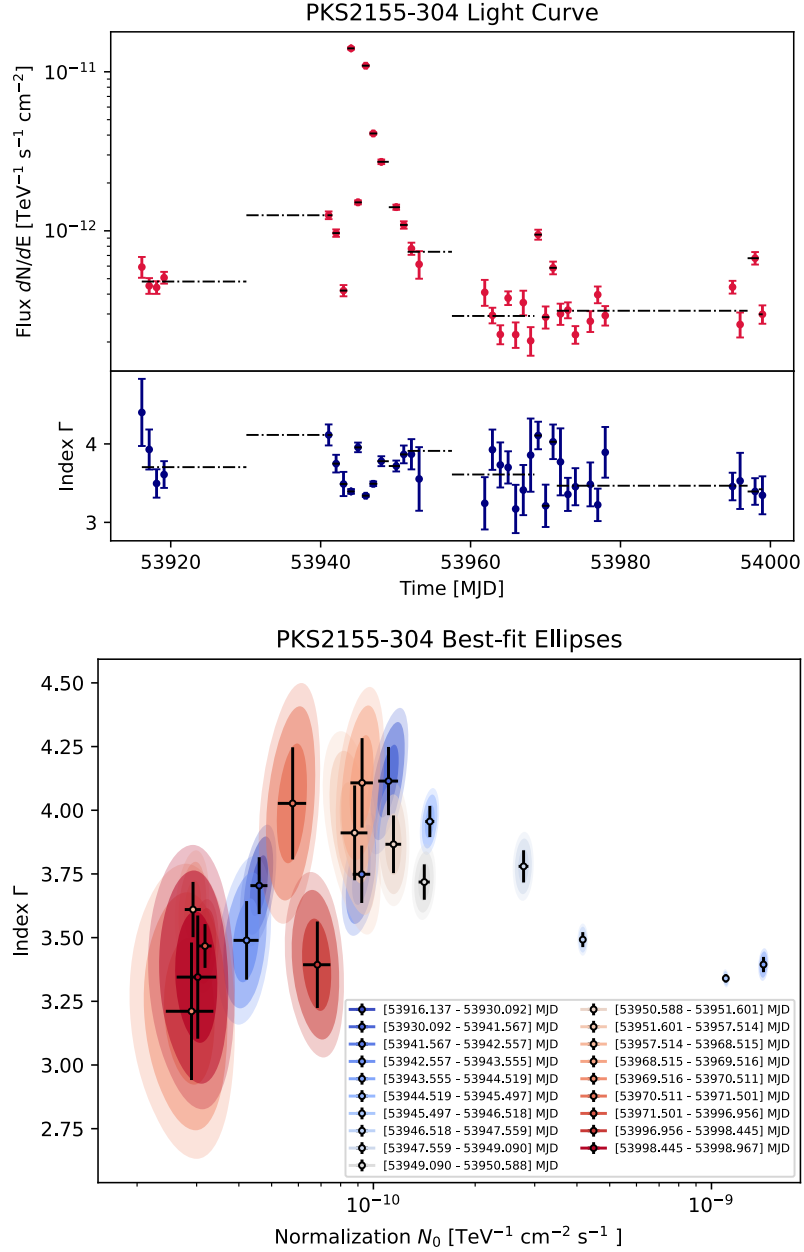


Figure A14: Spectral evolution and best-fit confidence ellipses for PKS 2155-304, showing the spectral index Γ and normalization N_0 for each Bayesian block, with σ 2σ , and 3σ confidence contours. Block dates are given in the modified Julian day (MJD) format.

B Upturn modeling likelihood results

In the following, the obtained upturn likelihood grids are shown for each one of the sources and time blocks considered, after subtracting the total statistic obtained for the best-fit point on the grid (denoted as ΔC_{stat}). On the left, we show the results considering only data from H.E.S.S., while on the right, if available, the joint *Fermi*-LAT and H.E.S.S. results are shown. All results shown here have been calculated with the Domínguez et al. (2011) EBL model [83], with similar plots being obtained for the other three EBL models considered in this work, omitted from the appendix for brevity as no significant differences are found. In each plot, whenever possible, the statistical contours are also shown, corresponding to 1σ , 2σ , and 3σ levels.

In general, most sources present a very similar behaviour. For the upturn grids obtained via H.E.S.S. data exclusively, we typically observe an exclusion region (where the total fit statistic is much higher than the best-fit model) at sharp upturns $\Delta\Gamma \sim 5$ and low break energies $E_{\text{brk}} \sim 1$ TeV. By including the data from *Fermi*-LAT, this exclusion region is typically larger, spanning a wider range of both break energy and index differences, thus excluding a wide range of possible upturns.

For the case of H 2356-309 and PKS 2155-304, only H.E.S.S. data are considered as these sources have been found to be variable during the observational time period with no contemporaneous *Fermi*-LAT data.

For certain sources, a preference for upturns can be found, to various degrees, in the H.E.S.S. data, mainly: 1RXSJ 101015.9-311909, 3C 279, PG 1553+113, PKS 0346-27, block 1 of PKS 0903-57, and blocks 3, 4, 5 and 8 of PKS 2155-304. Slight preferences are also found for 1ES 0229+200 and 1ES 0347-121. In most cases, the inclusion of *Fermi*-LAT data removes this preference. An exception is PKS 1510-089, which displays a preference for upturns in both datasets.

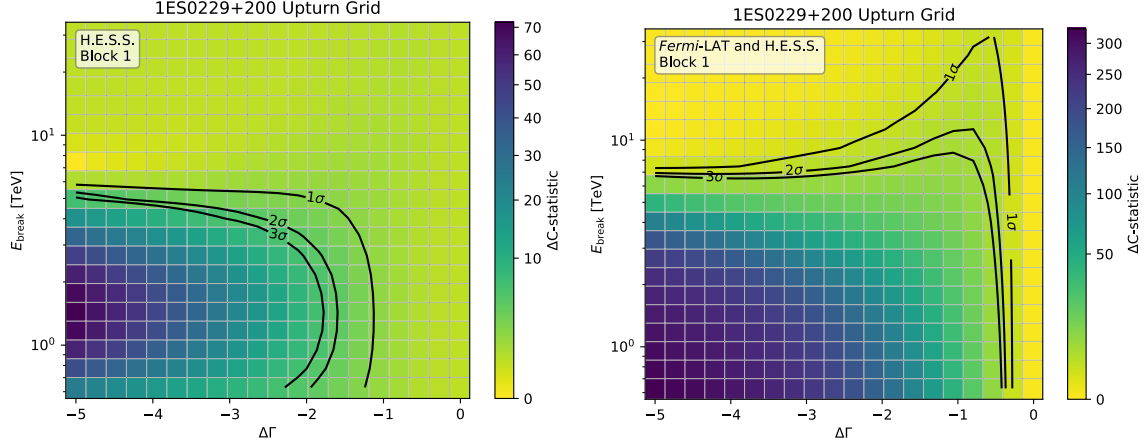
1ES 0229+200


Figure B1: Upturn likelihood grids obtained for 1ES 0229+200 using the individual H.E.S.S. (left) and joint Fermi-LAT and H.E.S.S. (right) datasets, using the baseline EBL model by Domínguez et al. (2011) [83]. Each point displays the obtained total fit statistic, normalized by subtracting the minimum value across the grid.

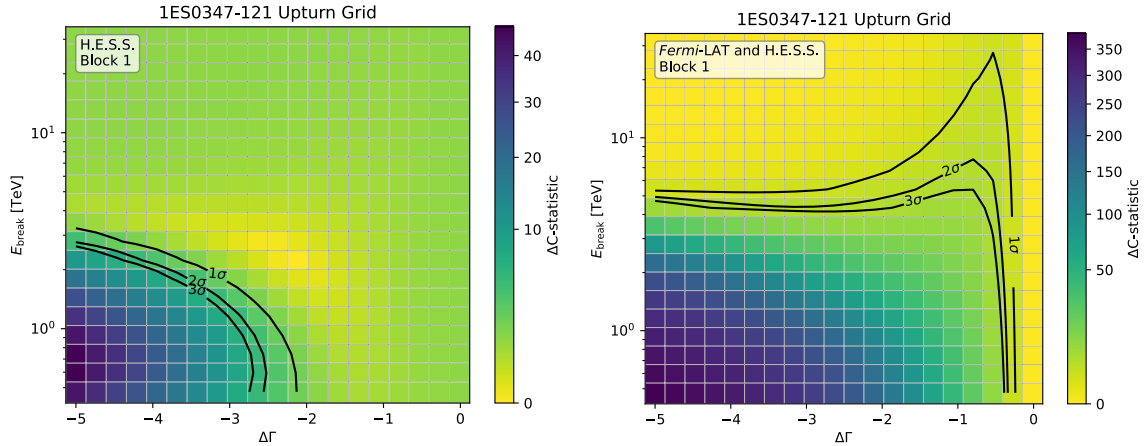
1ES 0347-121


Figure B2: Upturn likelihood grids obtained for 1ES 0347-121 using the individual H.E.S.S. (left) and joint Fermi-LAT and H.E.S.S. (right) datasets, using the baseline EBL model by Domínguez et al. (2011) [83]. Each point displays the obtained total fit statistic, normalized by subtracting the minimum value across the grid.

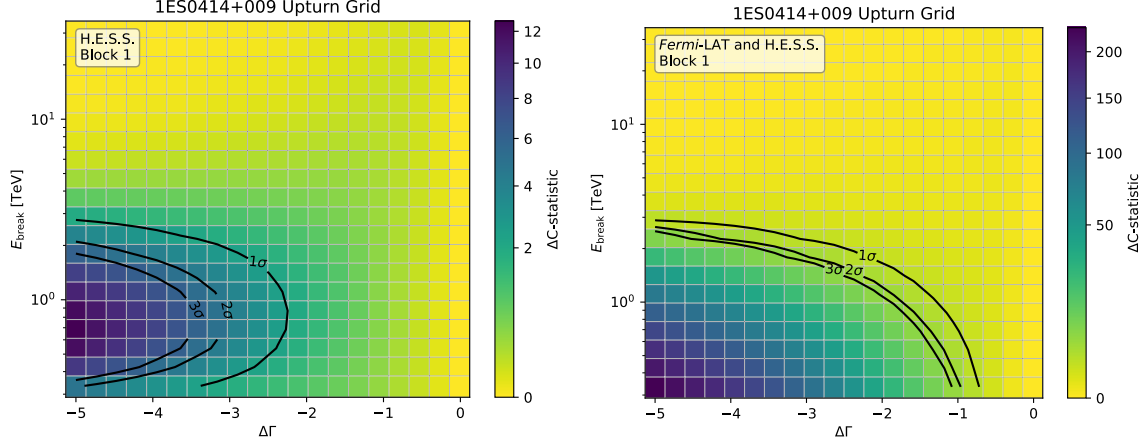
1ES 0414+009


Figure B3: Upturn likelihood grids obtained for 1ES 0414+009 using the individual H.E.S.S. (left) and joint Fermi-LAT and H.E.S.S. (right) datasets, using the baseline EBL model by Domínguez et al. (2011) [83]. Each point displays the obtained total fit statistic, normalized by subtracting the minimum value across the grid.

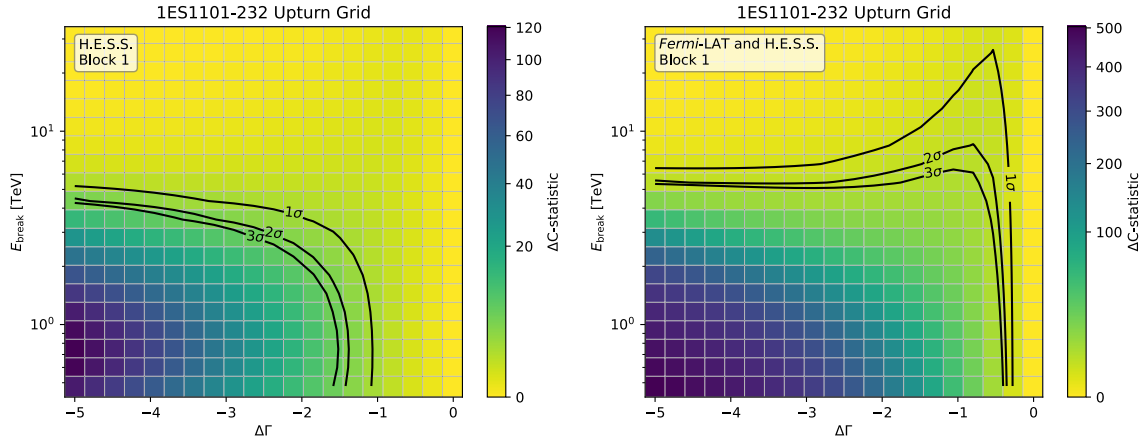
1ES 1101-232 (Block 1)


Figure B4: Upturn likelihood grids obtained for 1ES 1101-232 (Block 1) using the individual H.E.S.S. (left) and joint Fermi-LAT and H.E.S.S. (right) datasets, using the baseline EBL model by Domínguez et al. (2011) [83]. Each point displays the obtained total fit statistic, normalized by subtracting the minimum value across the grid.

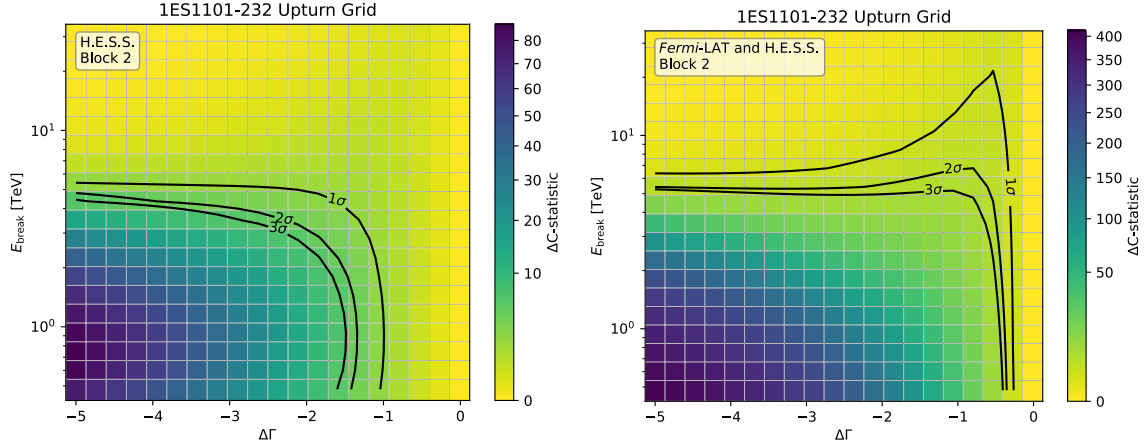
1ES 1101-232 (Block 2)


Figure B5: Upturn likelihood grids obtained for 1ES 1101-232 (Block 2) using the individual H.E.S.S. (left) and joint Fermi-LAT and H.E.S.S. (right) datasets, using the baseline EBL model by Domínguez et al. (2011) [83]. Each point displays the obtained total fit statistic, normalized by subtracting the minimum value across the grid.

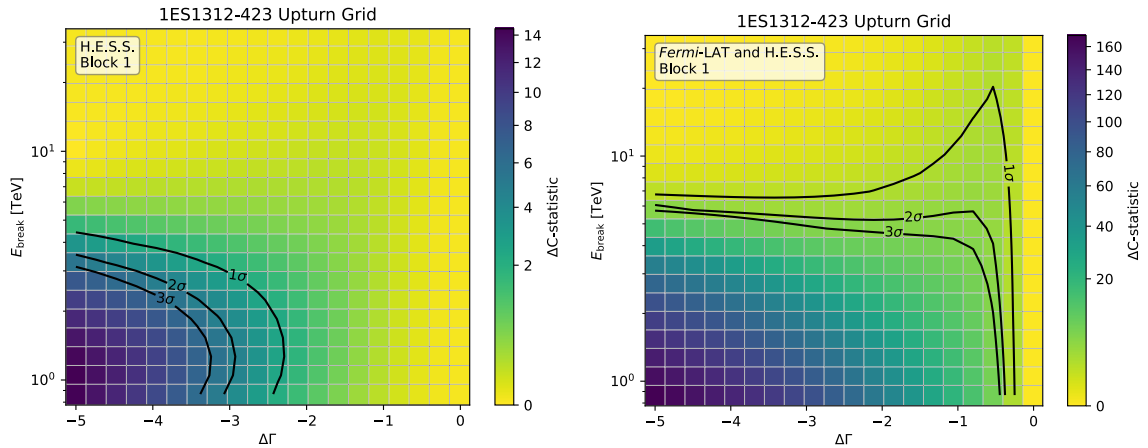
1ES 1312-423


Figure B6: Upturn likelihood grids obtained for 1ES 1312-423 using the individual H.E.S.S. (left) and joint Fermi-LAT and H.E.S.S. (right) datasets, using the baseline EBL model by Domínguez et al. (2011) [83]. Each point displays the obtained total fit statistic, normalized by subtracting the minimum value across the grid.

1RXS J101015.9-311909

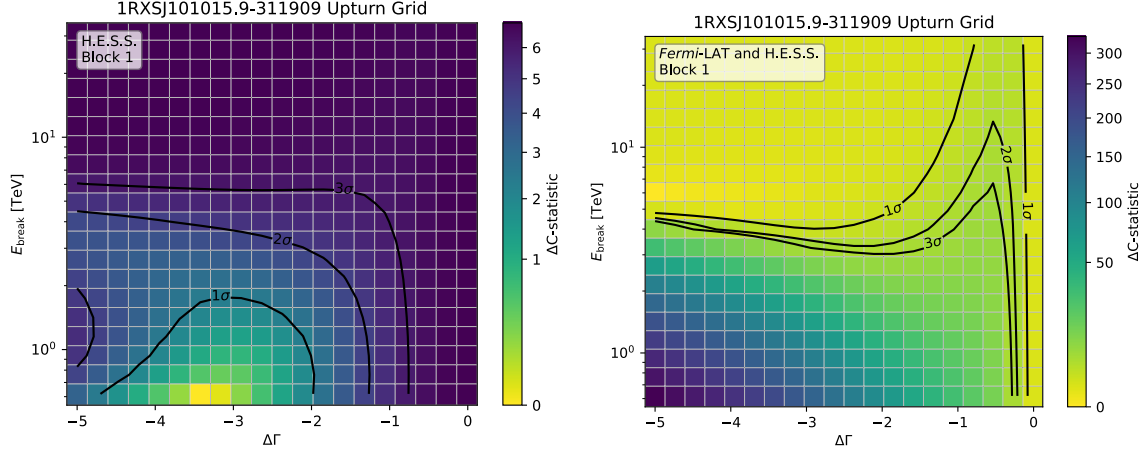


Figure B7: Upturn likelihood grids obtained for 1RXS J101015.9-311909 using the individual H.E.S.S. (left) and joint Fermi-LAT and H.E.S.S. (right) datasets, using the baseline EBL model by Domínguez et al. (2011) [83]. Each point displays the obtained total fit statistic, normalized by subtracting the minimum value across the grid.

3C 279

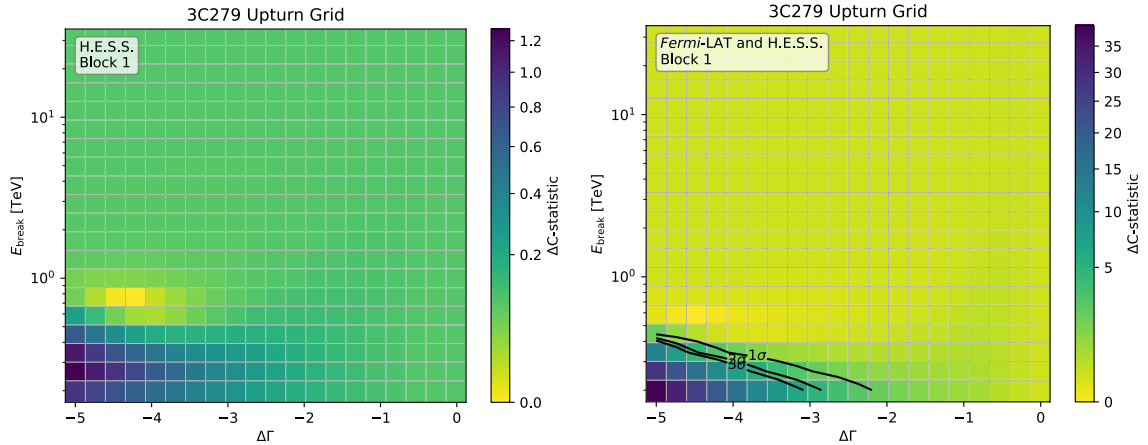


Figure B8: Upturn likelihood grids obtained for 3C 279 using the individual H.E.S.S. (left) and joint Fermi-LAT and H.E.S.S. (right) datasets, using the baseline EBL model by Domínguez et al. (2011) [83]. Each point displays the obtained total fit statistic, normalized by subtracting the minimum value across the grid.

H 2356-309

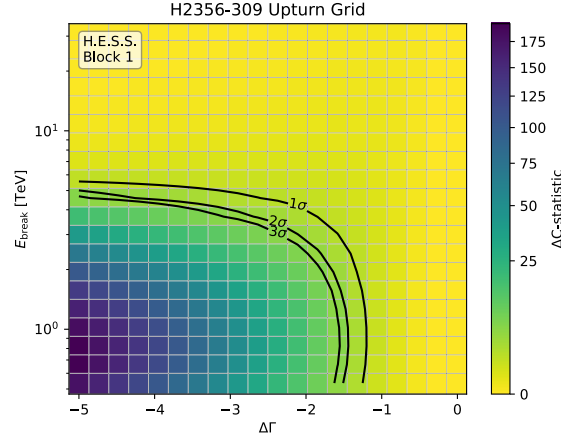


Figure B9: Upturn likelihood grids obtained for H 2356-309 using the individual *H.E.S.S.* dataset (as no contemporaneous *Fermi-LAT* data is available), using the baseline EBL model by Domínguez et al. (2011) [83]. Each point displays the obtained total fit statistic, normalized by subtracting the minimum value across the grid.

PG 1553+113

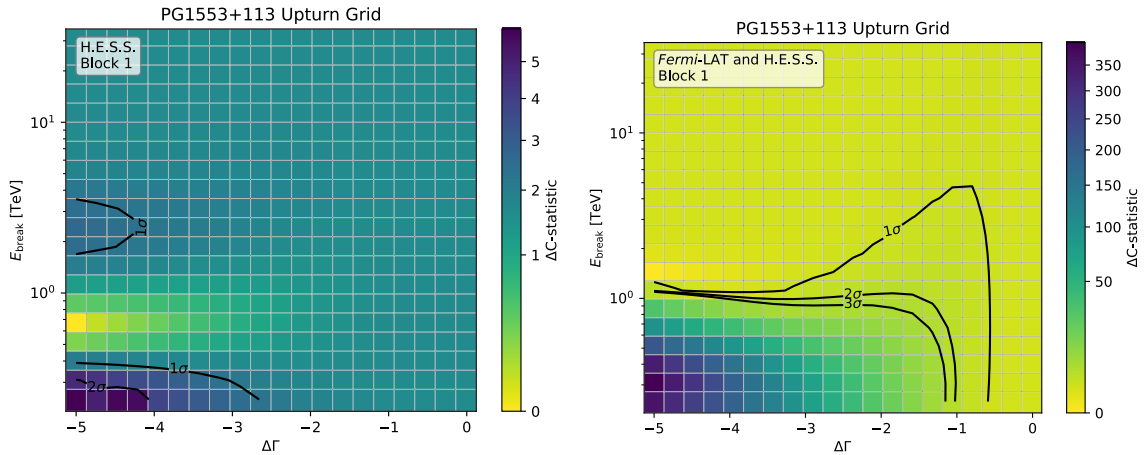


Figure B10: Upturn likelihood grids obtained for PG 1553+113 using the individual *H.E.S.S.* (left) and joint *Fermi-LAT* and *H.E.S.S.* (right) datasets, using the baseline EBL model by Domínguez et al. (2011) [83]. Each point displays the obtained total fit statistic, normalized by subtracting the minimum value across the grid.

PKS 0346-27

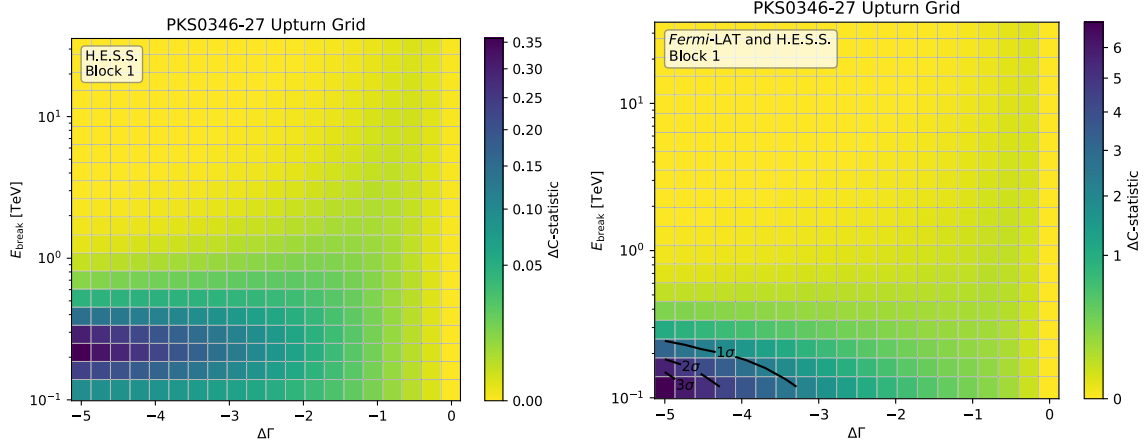


Figure B11: Upturn likelihood grids obtained for PKS 0346-27 using the individual H.E.S.S. (left) and joint Fermi-LAT and H.E.S.S. (right) datasets, using the baseline EBL model by Domínguez et al. (2011) [83]. Each point displays the obtained total fit statistic, normalized by subtracting the minimum value across the grid.

PKS 0447-439

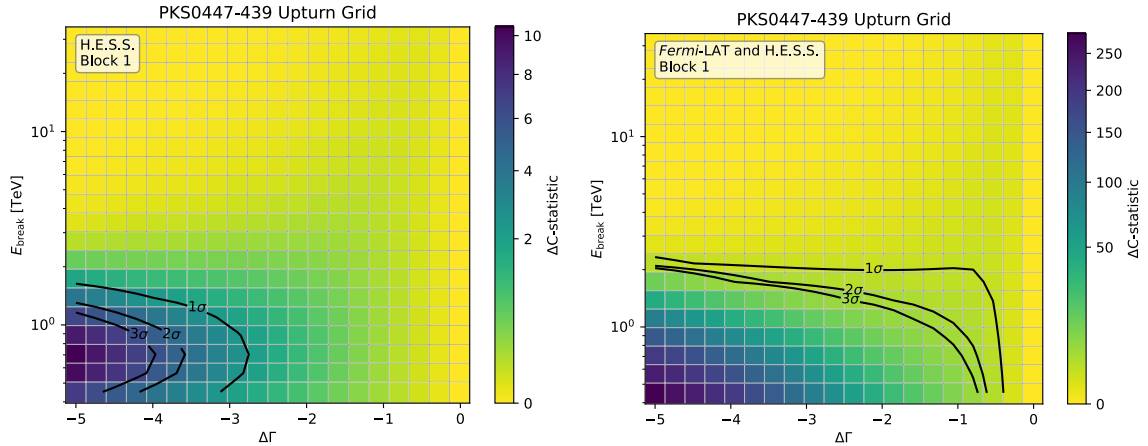


Figure B12: Upturn likelihood grids obtained for PKS 0447-439 using the individual H.E.S.S. (left) and joint Fermi-LAT and H.E.S.S. (right) datasets, using the baseline EBL model by Domínguez et al. (2011) [83]. Each point displays the obtained total fit statistic, normalized by subtracting the minimum value across the grid.

PKS 0903-57 (Block 1)

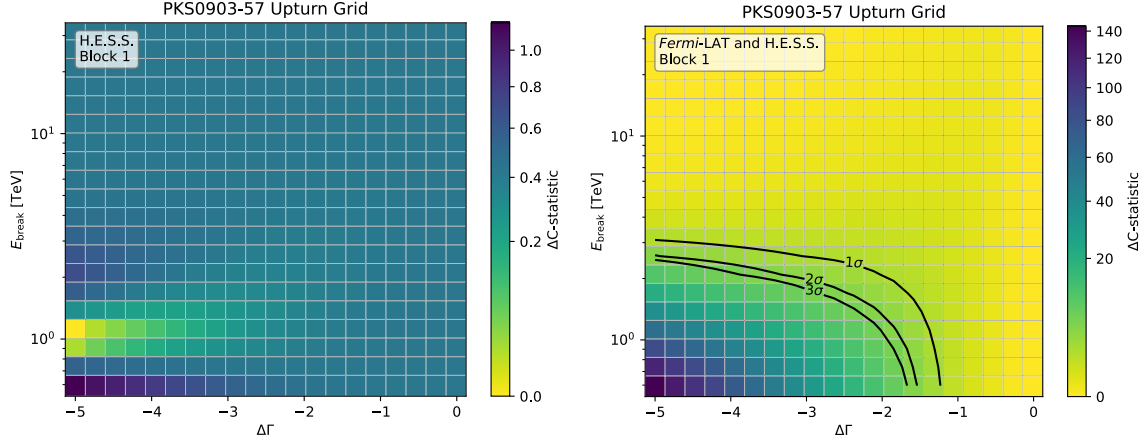


Figure B13: Upturn likelihood grids obtained for PKS 0903-57 (Block 1) using the individual H.E.S.S. (left) and joint Fermi-LAT and H.E.S.S. (right) datasets, using the baseline EBL model by Domínguez et al. (2011) [83]. Each point displays the obtained total fit statistic, normalized by subtracting the minimum value across the grid.

PKS 0903-57 (Block 2)

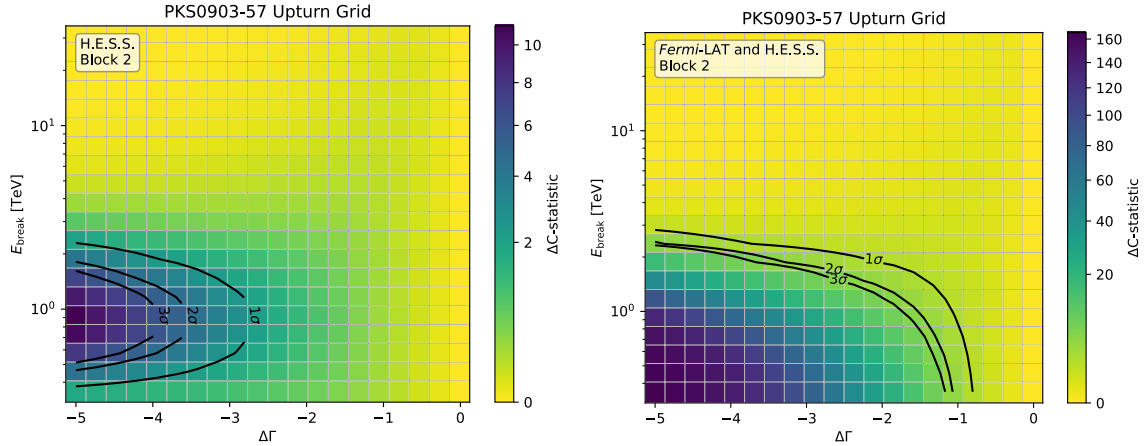


Figure B14: Upturn likelihood grids obtained for PKS 0903-57 (Block 2) using the individual H.E.S.S. (left) and joint Fermi-LAT and H.E.S.S. (right) datasets, using the baseline EBL model by Domínguez et al. (2011) [83]. Each point displays the obtained total fit statistic, normalized by subtracting the minimum value across the grid.

PKS 0903-57 (Block 3)

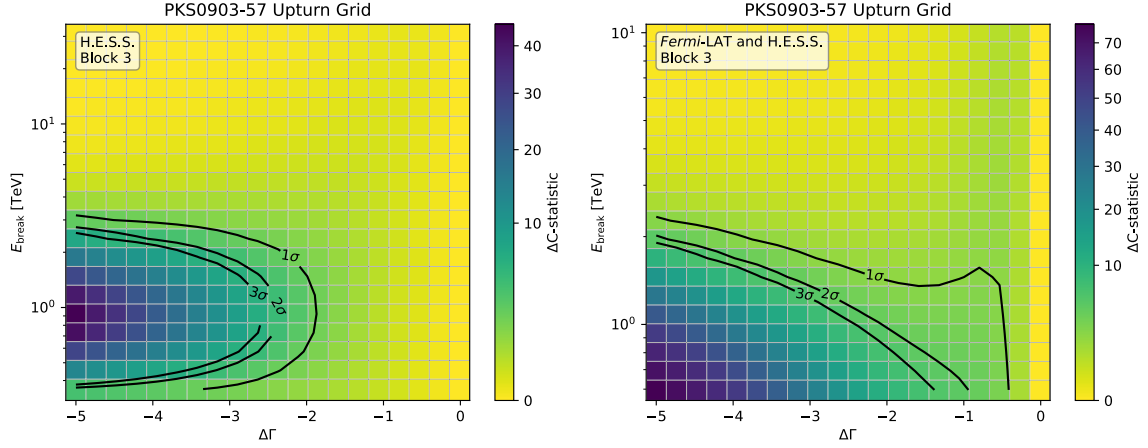


Figure B15: Upturn likelihood grids obtained for PKS 0903-57 (Block 3) using the individual H.E.S.S. (left) and joint Fermi-LAT and H.E.S.S. (right) datasets, using the baseline EBL model by Domínguez et al. (2011) [83]. Each point displays the obtained total fit statistic, normalized by subtracting the minimum value across the grid.

PKS 1510-089

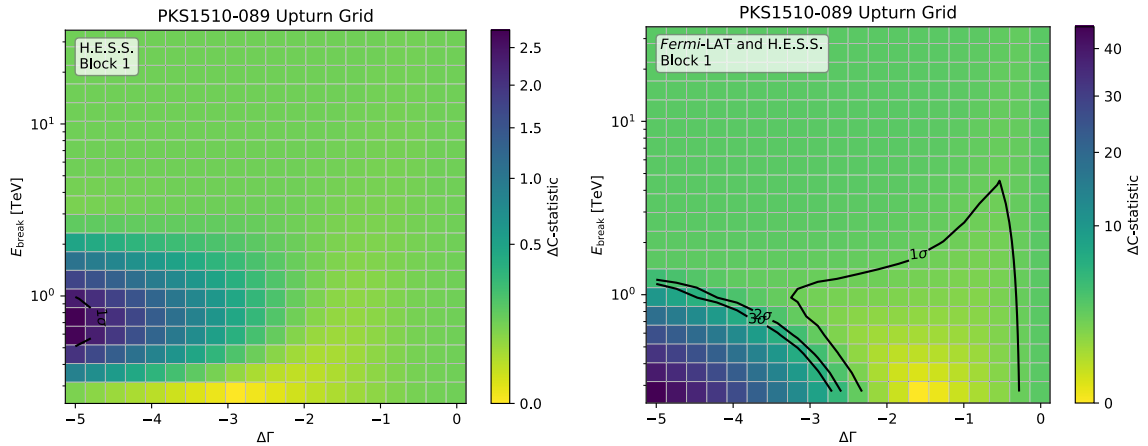


Figure B16: Upturn likelihood grids obtained for PKS 1510-089 using the individual H.E.S.S. (left) and joint Fermi-LAT and H.E.S.S. (right) datasets, using the baseline EBL model by Domínguez et al. (2011) [83]. Each point displays the obtained total fit statistic, normalized by subtracting the minimum value across the grid.

PKS 2155-304 (Blocks 1 & 2)

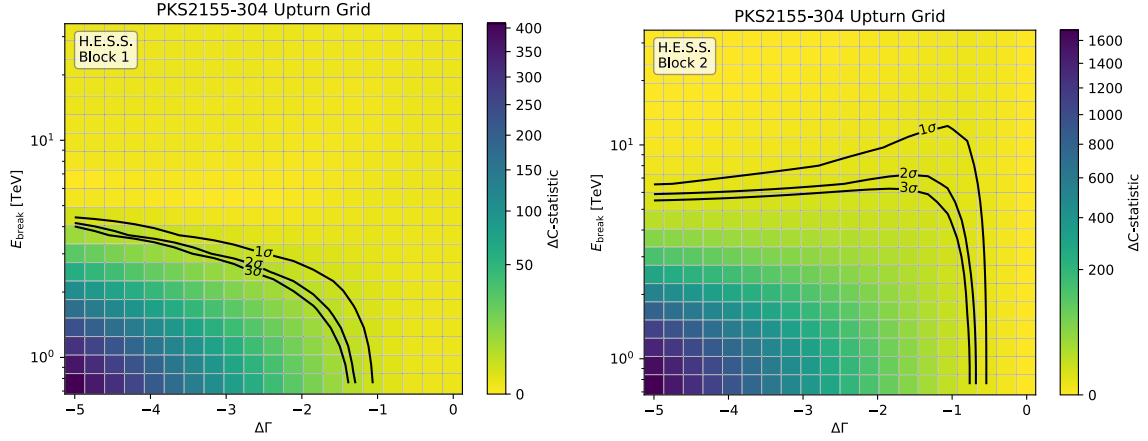


Figure B17: Upturn likelihood grids obtained for PKS 2155-304 Block 1 (left), and Block 2 (right), using the individual H.E.S.S. dataset (as no contemporaneous Fermi-LAT data is available), using the baseline EBL model by Domínguez et al. (2011) [83]. Each point displays the obtained total fit statistic, normalized by subtracting the minimum value across the grid.

PKS 2155-304 (Blocks 3 & 4)

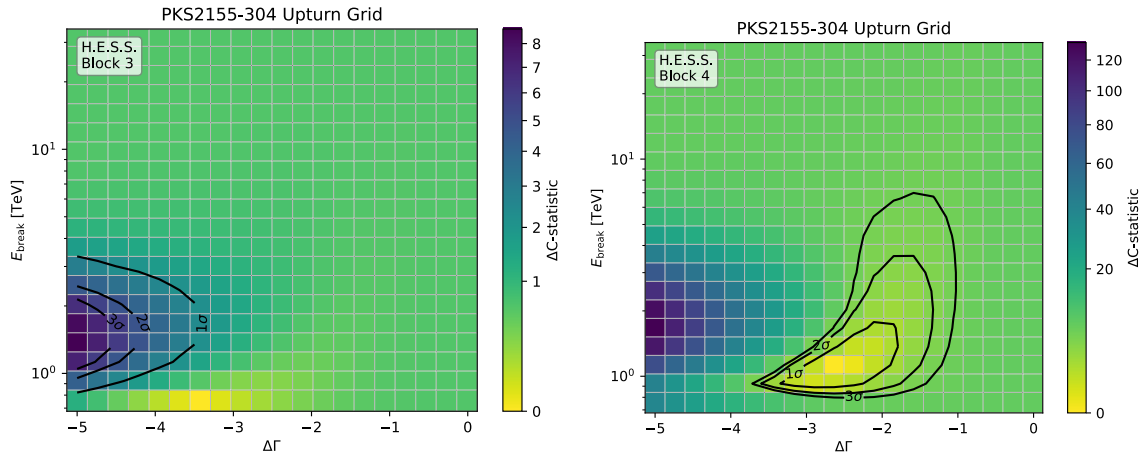


Figure B18: Upturn likelihood grids obtained for PKS 2155-304 Block 3 (left), and Block 4 (right), using the individual H.E.S.S. dataset (as no contemporaneous Fermi-LAT data is available), using the baseline EBL model by Domínguez et al. (2011) [83]. Each point displays the obtained total fit statistic, normalized by subtracting the minimum value across the grid.

PKS 2155-304 (Blocks 5 & 6)

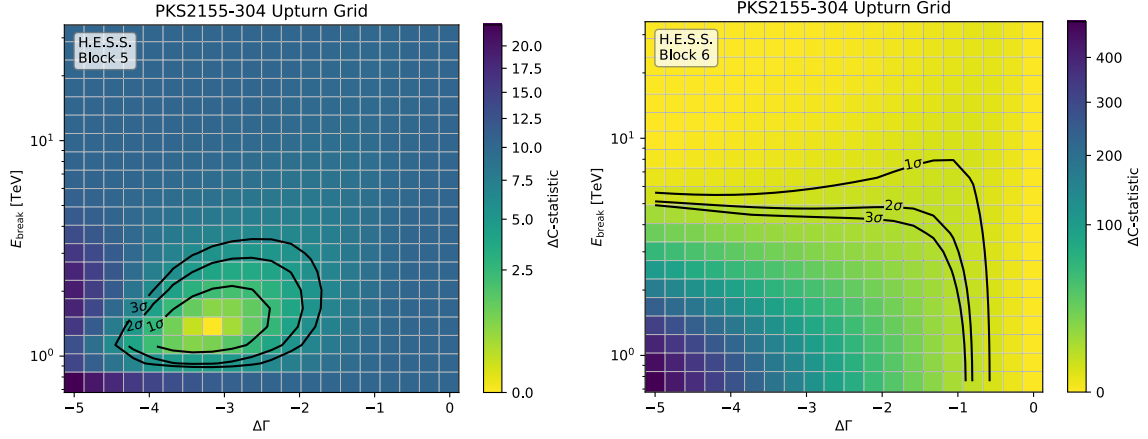


Figure B19: Upturn likelihood grids obtained for PKS 2155-304 Block 5 (left), and Block 6 (right), using the individual H.E.S.S. dataset (as no contemporaneous Fermi-LAT data is available), using the baseline EBL model by Domínguez et al. (2011) [83]. Each point displays the obtained total fit statistic, normalized by subtracting the minimum value across the grid.

PKS 2155-304 (Blocks 7 & 8)

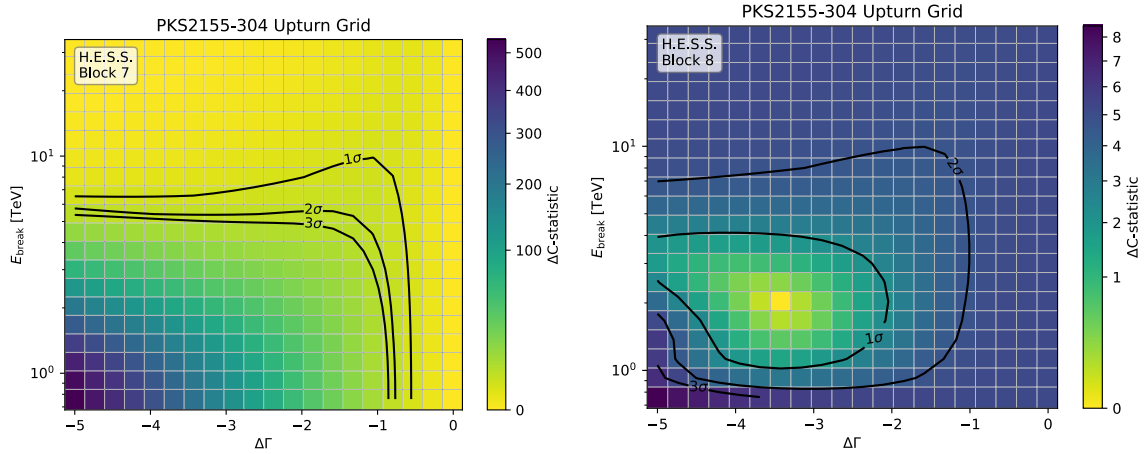


Figure B20: Upturn likelihood grids obtained for PKS 2155-304 Block 7 (left), and Block 8 (right), using the individual H.E.S.S. dataset (as no contemporaneous Fermi-LAT data is available), using the baseline EBL model by Domínguez et al. (2011) [83]. Each point displays the obtained total fit statistic, normalized by subtracting the minimum value across the grid.