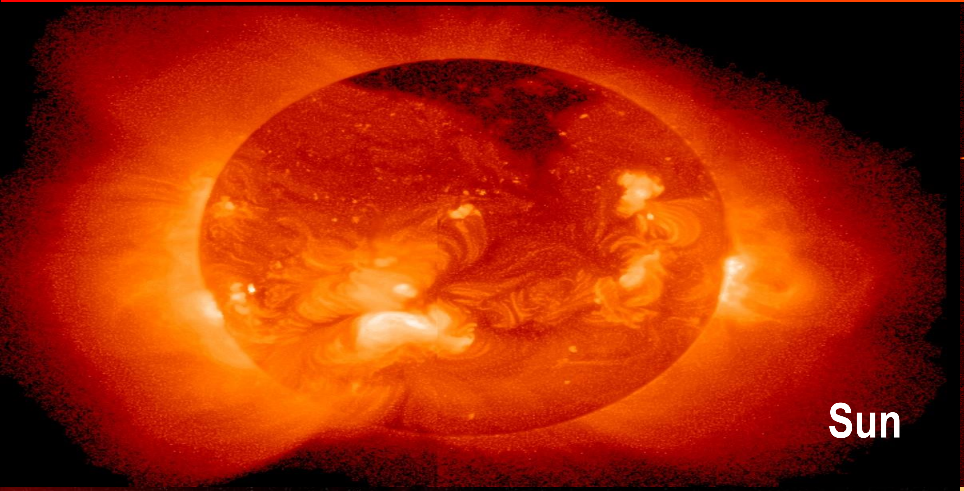
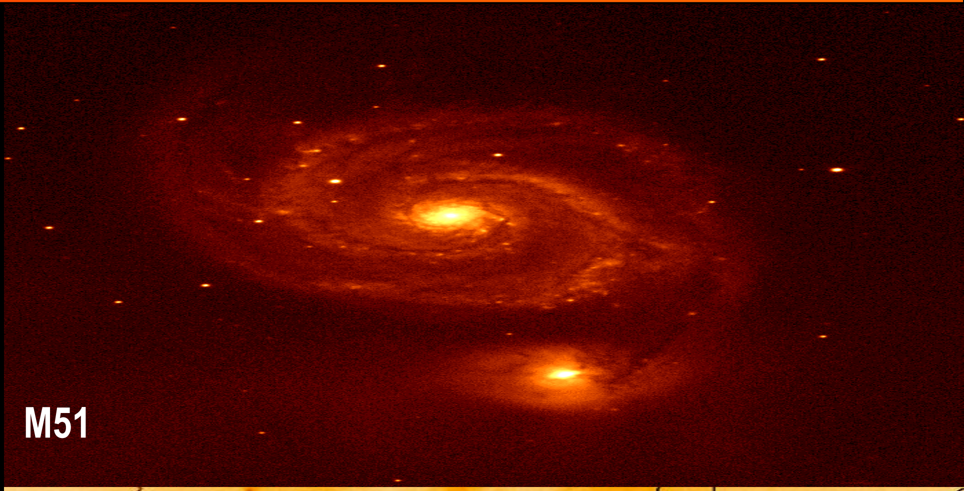
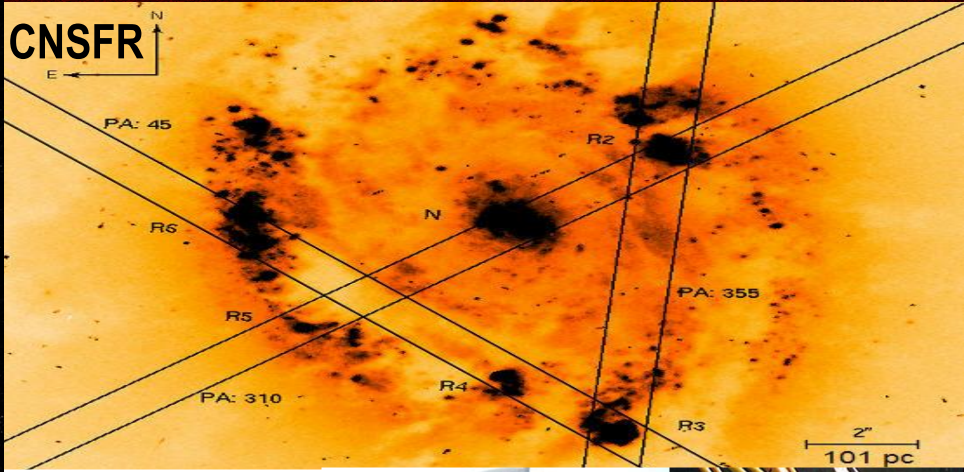
# Unravelling the nonlinear physics of high-Z regions with neural networks





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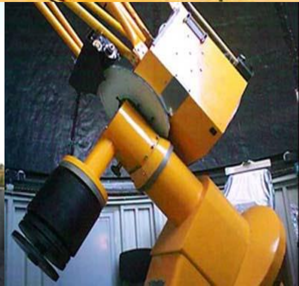


# Fundamental → Functional parameters



Imaging → Emission Line Fluxes (I) →

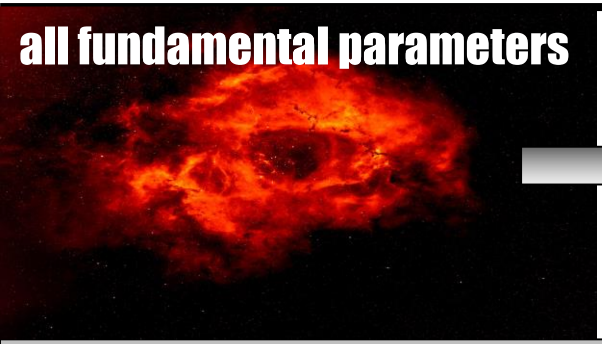
- De-projection Theory
- Photoionisation Modelling & Simulation
- **Empirical Relations & Calibrations**

} → Physics & knowledge

$$Z = f(I_1, I_2, \ldots, I_n)$$

**S23** **O23** **Abundance indicators**

$$Z = f(x_1, x_2, \ldots, x_n)$$




**S23** Abundance indicator

**T*** Effective Temperature

**Z** Metallicity

**eta** Softness parameter

**U** Ionisation parameter



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# The **IDEAL** Indicator $x_n$?



- Would be **MONOTONIC** with respect to metallicity **Z**
- Would be observationally **detectable** up to **high Z**
- Would have **low** average **dispersion** (least-square error)
- Would span a **W I D E** range of **Z** when empirically-calibrated using **REAL** galaxy data

## & IF ALL THAT WENT PERFECTLY…

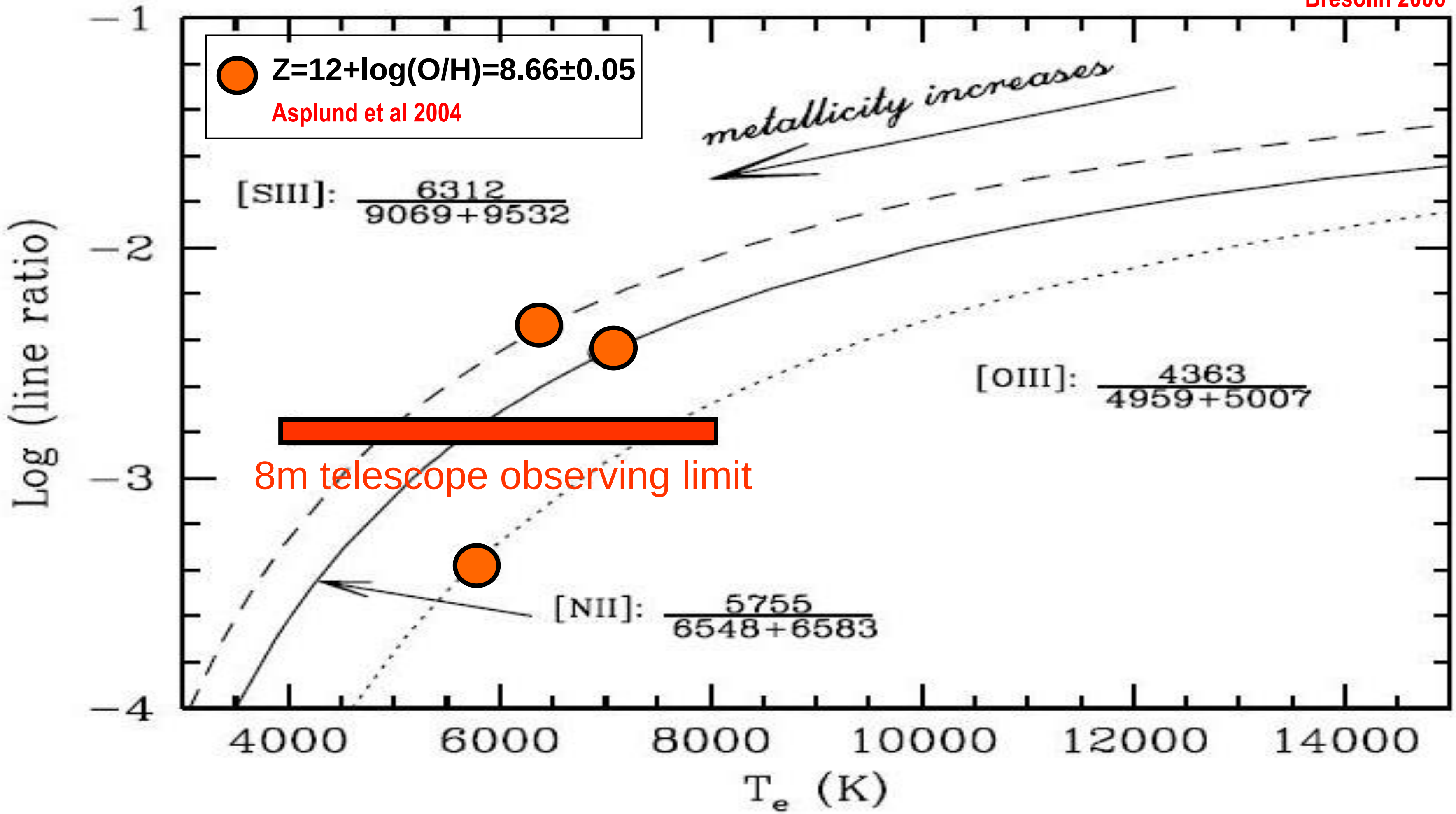
It would also be independent of chemical evolution and have an understandable behaviour with Z → ?

# Observational Limits at high Z



## Commonly used auroral-to-nebular emission line ratios…

Bresolin 2006



# Indicators in HII-like regions



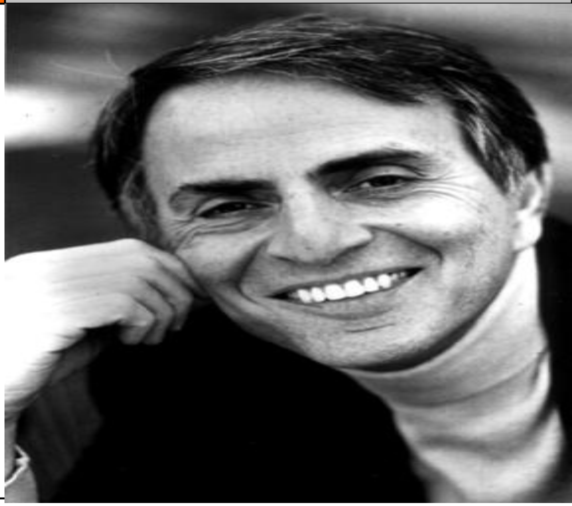
Galactic HII-Regions | Extra-Galactic HII-Regions | HII Galaxies | **CNSFRs?**

| Parameter | Validity | Dispersion |
|---|---|---|
| ↑ $O_{23}$ | $Z < 8.0$ | 0.12 |
| ~ $O_{23}$ | $8.0 \leq Z \leq 8.4$ | 1.30 |
| ↓ $O_{23}$ | $Z > 8.4$ | 0.20 |
| N2 | up to $Z_\odot$ | 0.24 |
| $S_{23}$ | up to $Z_\odot$ | 0.16 |
| $S_{234}$ | up to $Z_\odot$ | $<0.10$ |
| $S_{23}/O_{23}$ | all Z | 0.27 |

Perez-Montero 2002

# AI: An opportunity





## Scale-invariant And Genetic Algorithm Network (SAGAN)

**Dimensional Analysis**
Taylor & Diaz 2006

**$10^3$ ERROR REDUCTION**
Taylor 2005

**Net DNA Ecoding**
- Architecture
- Weights
- Node Functions

**+ Genetic Operators**
- Mutation
- Cross-over

**+ Pruning Algorithm**

→ **EQUATIONS**

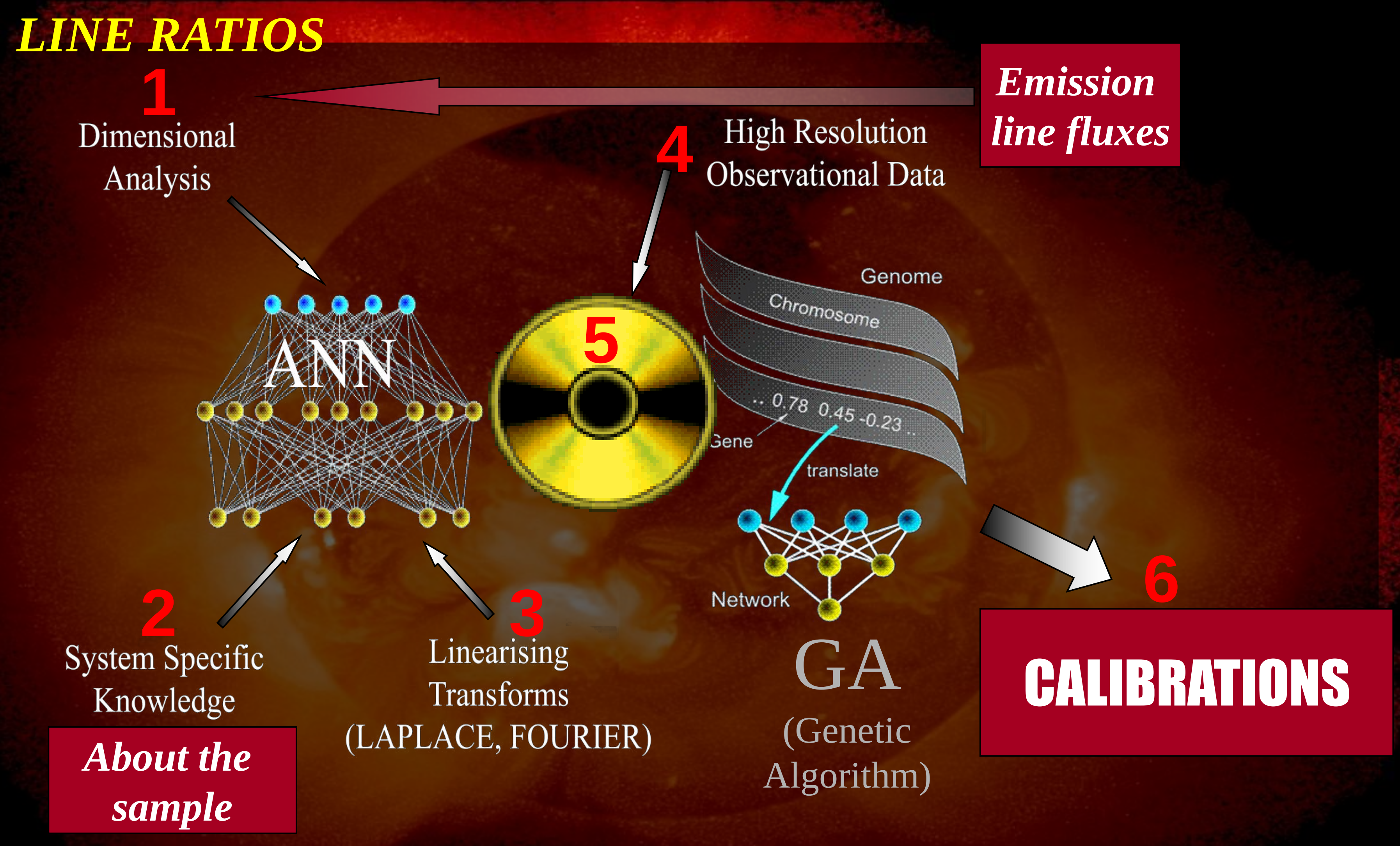
**Multi-Layer Perceptron**

**+ Back-Propagation**

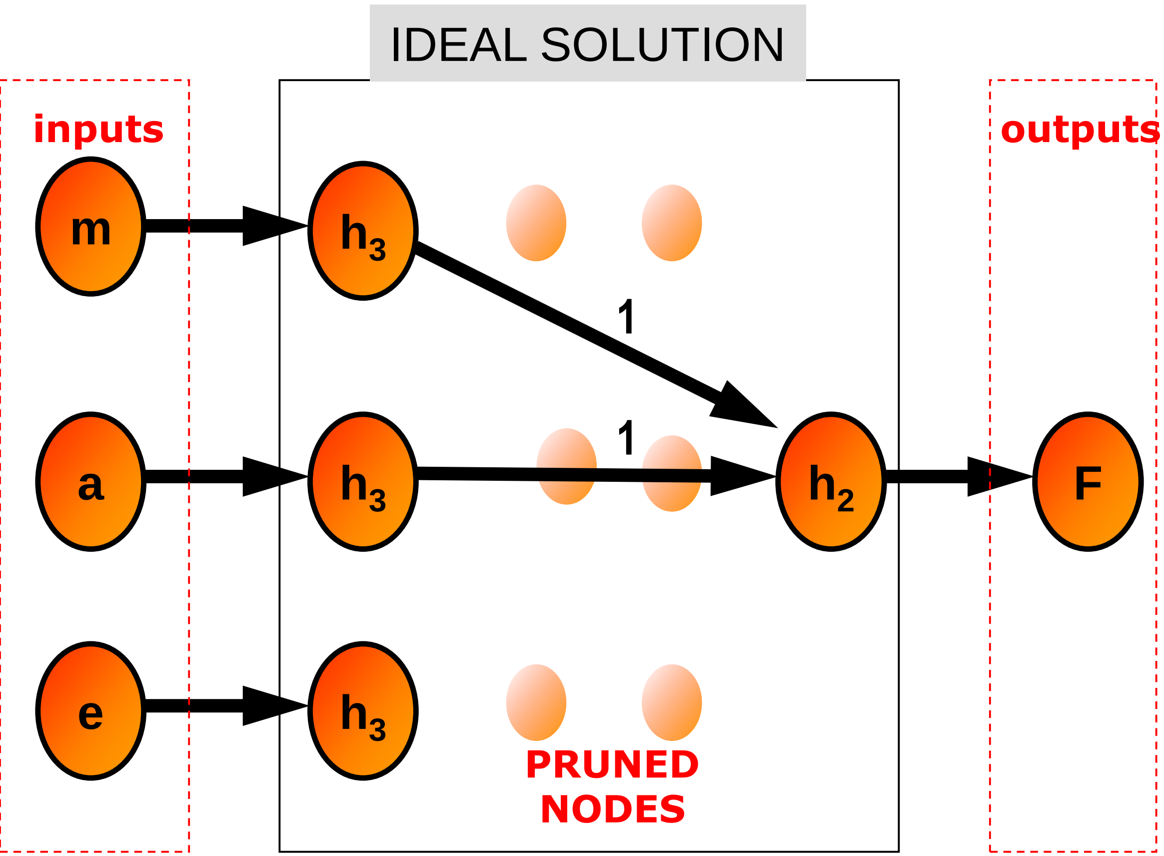
→ **UNIVERSAL FUNCTION APPROXIMATOR**
Taylor 2005

# A new strategy





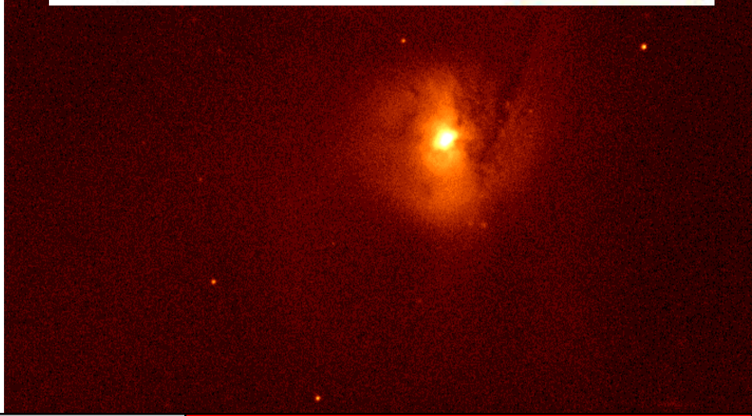
# How it Works: e.g. Newton's Law




$$F = e^{\{\ln m + \ln a\}} = e^{\ln ma} = ma$$

***Neural Node Functions***

| | | |
|---|---|---|
| $h(s)_1 = s$ | Linear |
| $h(s)_2 = e^s$ | Power Laws |
| $h(s)_3 = \ln\lvert s\rvert$ | |
| $h(s)_4 = 1/(1+e^{-s})$ | Sigmoids |
| $h(s)_5 = (1+e^{-s})/2(1+e^{-s})$ | |
| $h(s)_6 = \tanh s$ | Trig. Functions |
| $h(s)_7 = \sin s$ | |
| $h(s)_8 = \cos s$ | |
| $h(s)_9 = e^{-s^2}$ | Gaussians |
| $h(s)_{10} = 1$ | Constants |





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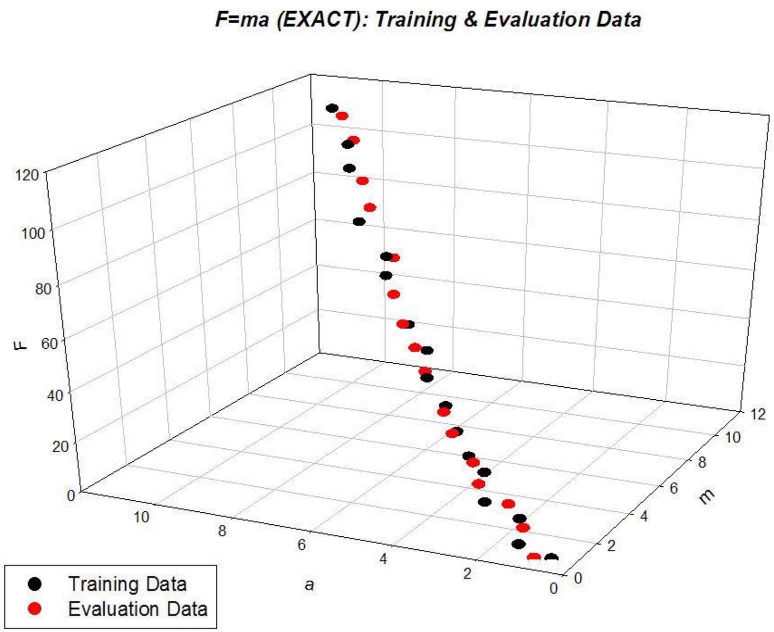
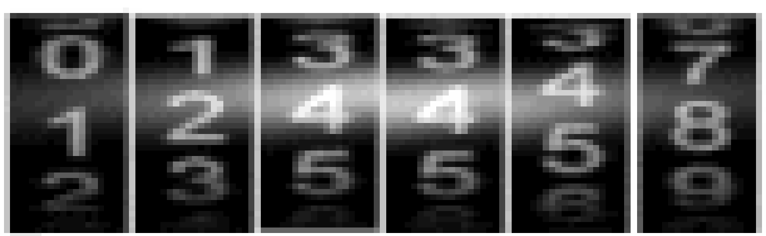
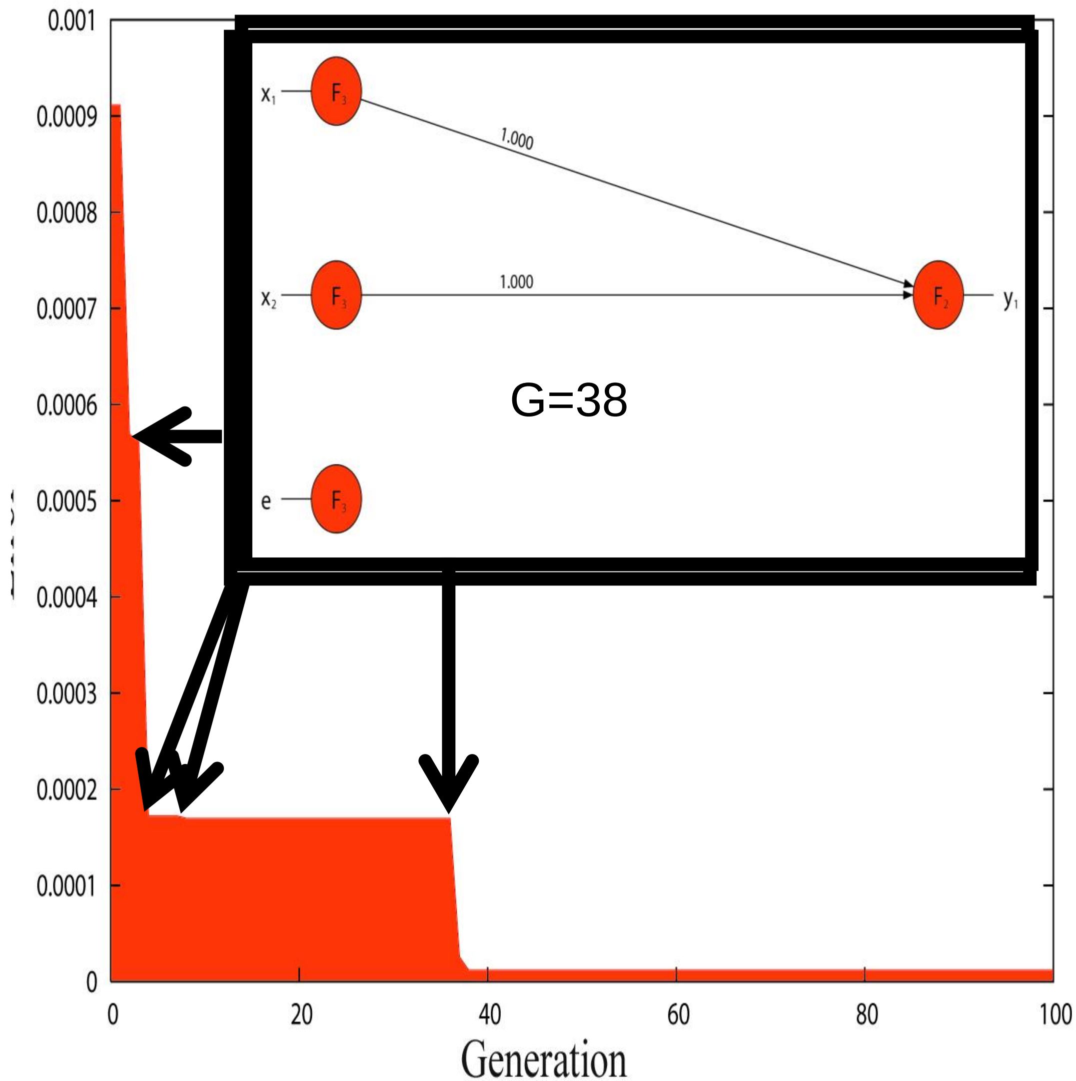
# Newton’s Law: F=ma (EXACT)

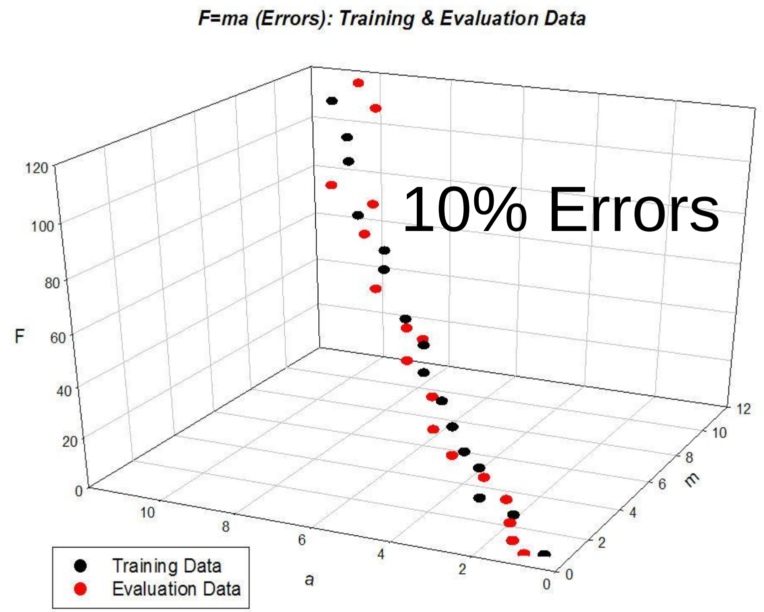


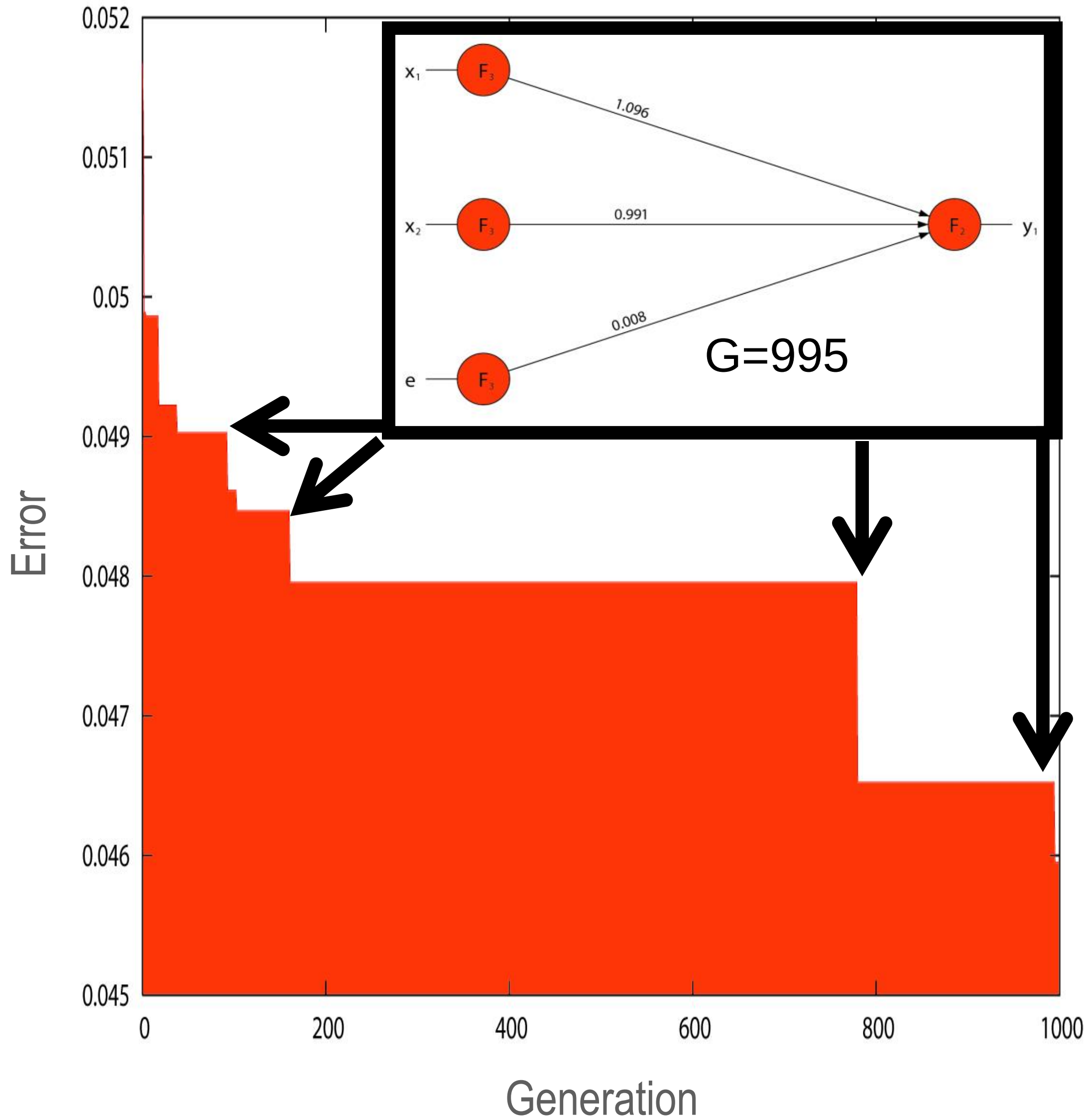




# Newton's Law: F=ma (10% Errors)



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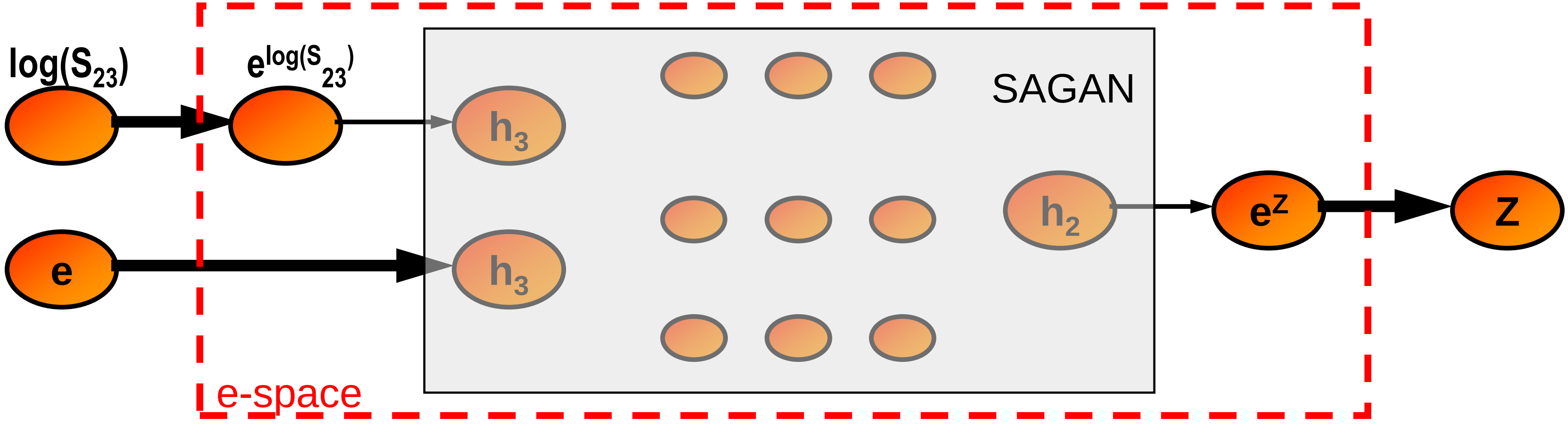
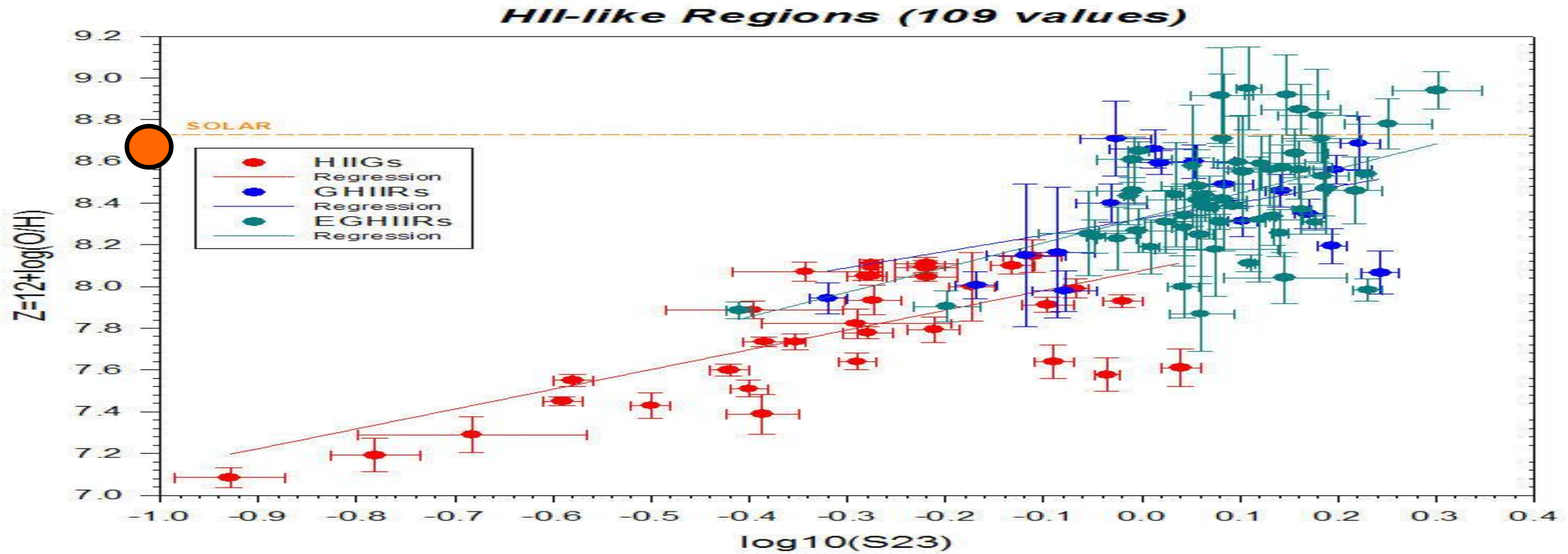
# HII-like regions: HIIGs, GHIIRs & EGHIIRs

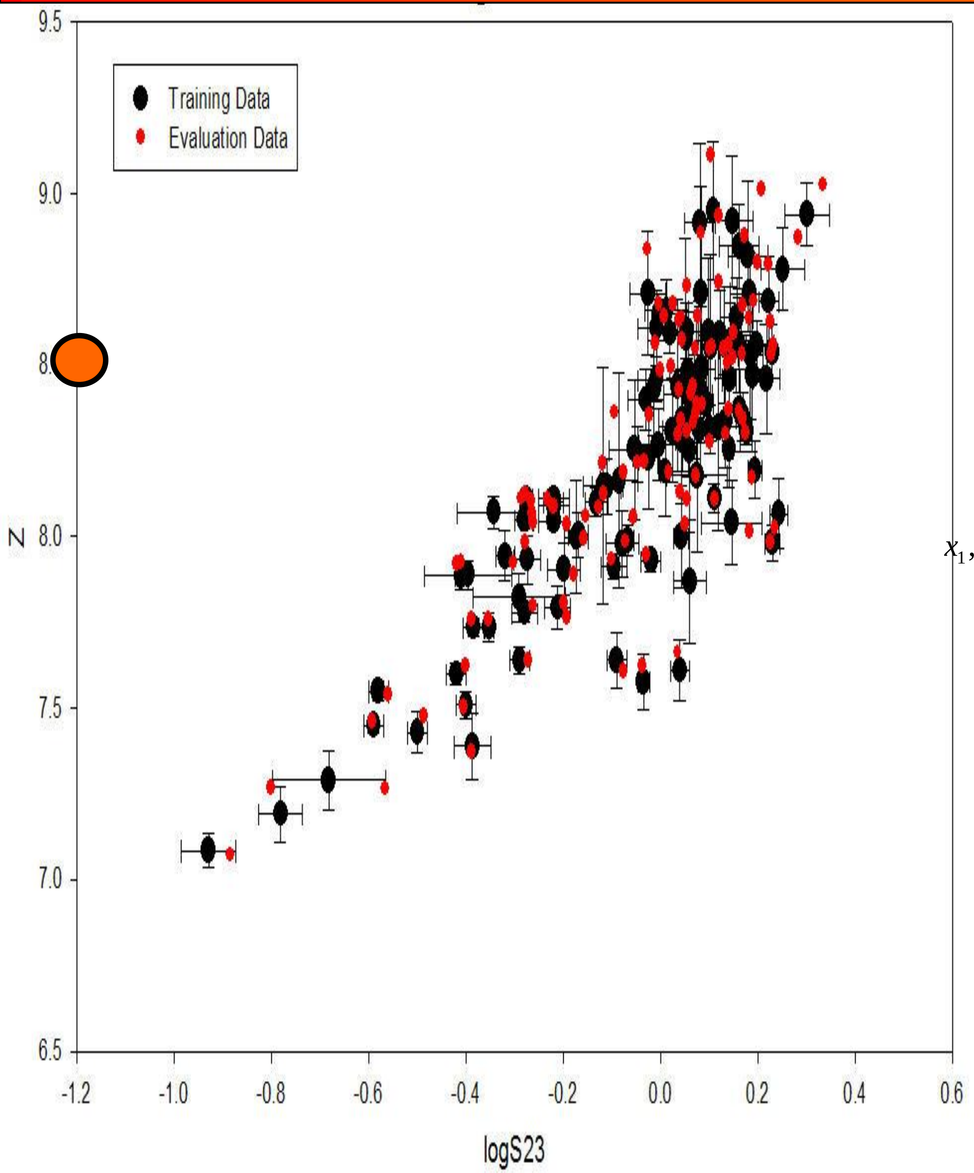




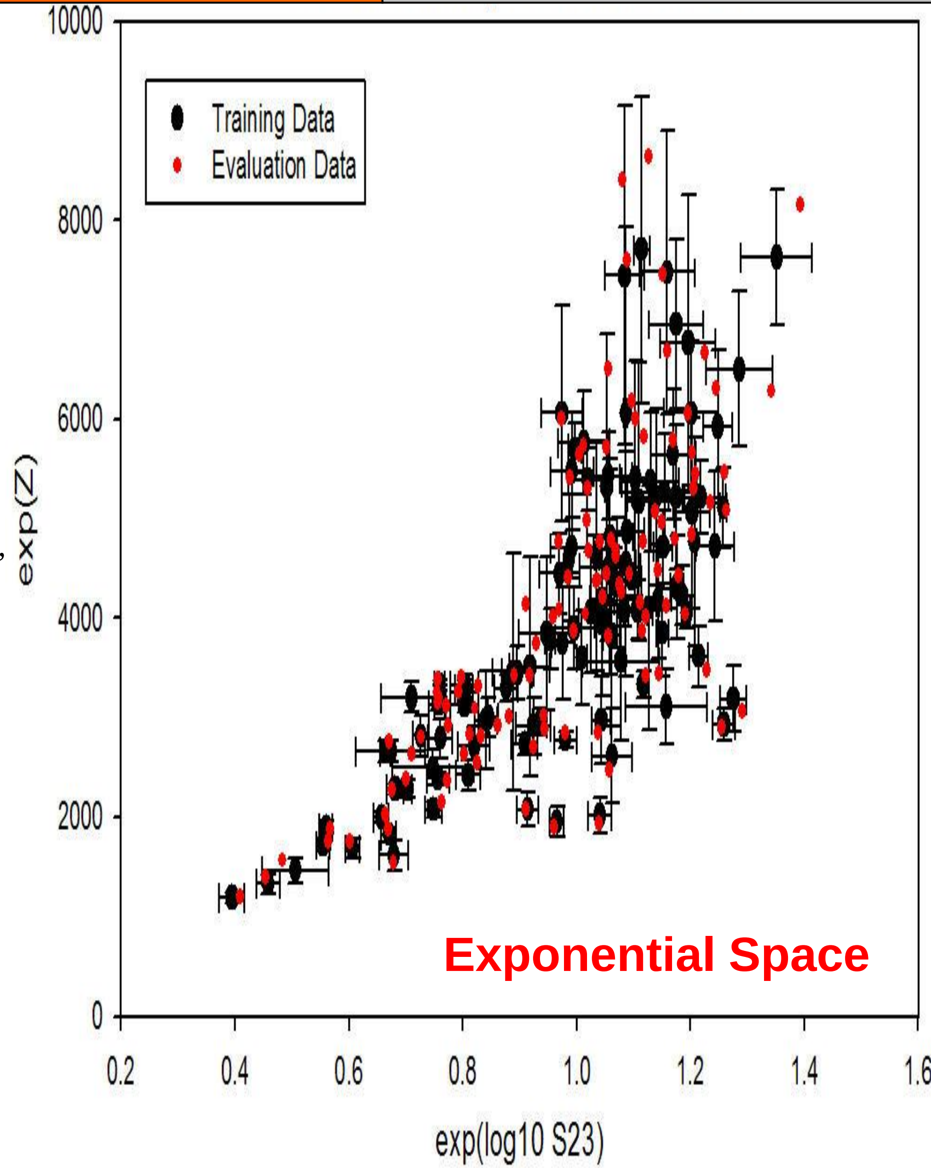



# Training & Evaluation Data






$x_1,$



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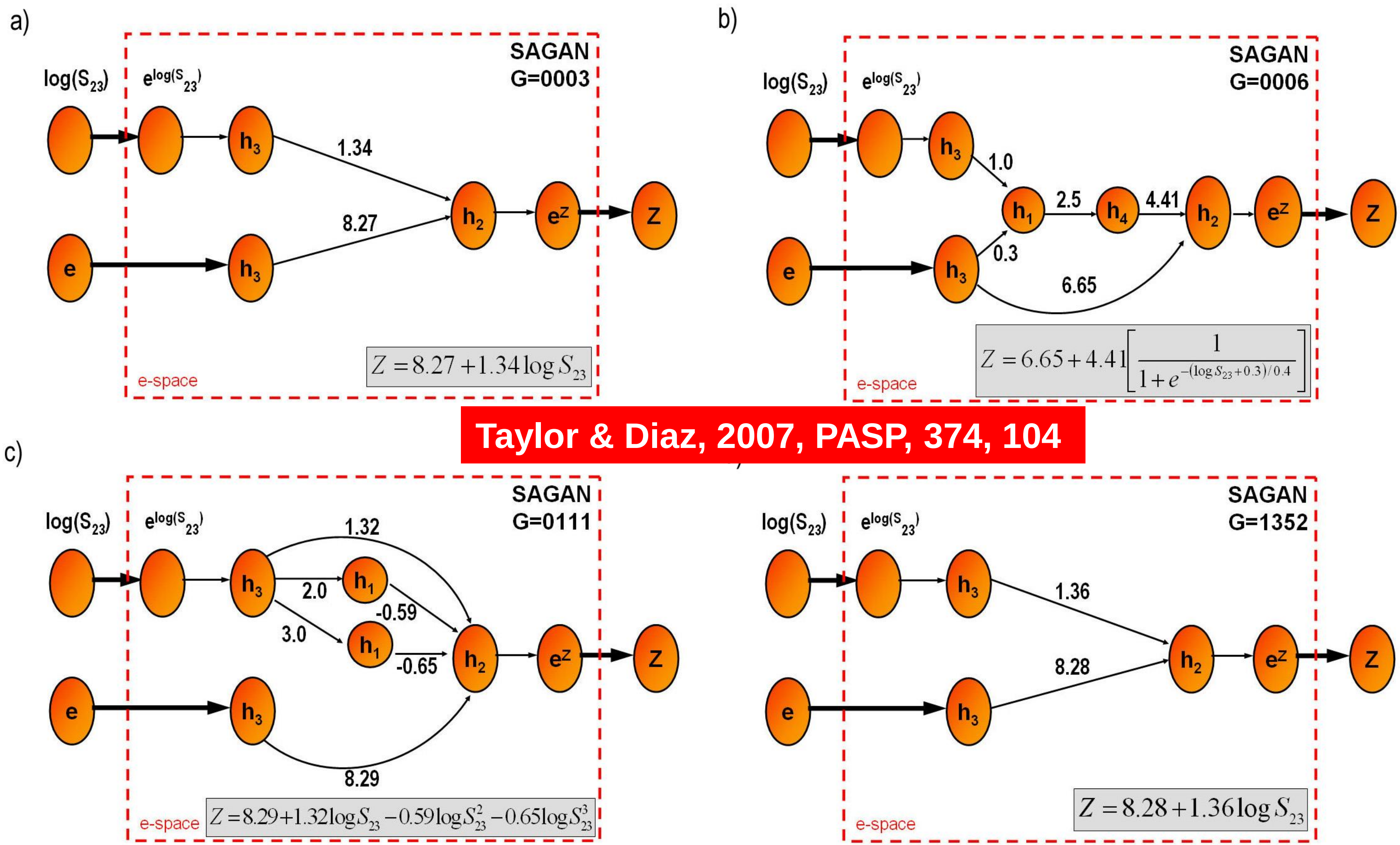
# SAGAN Evolution (2 days on a dual 3Ghz PC)




**Taylor & Diaz, 2007, PASP, 374, 104**



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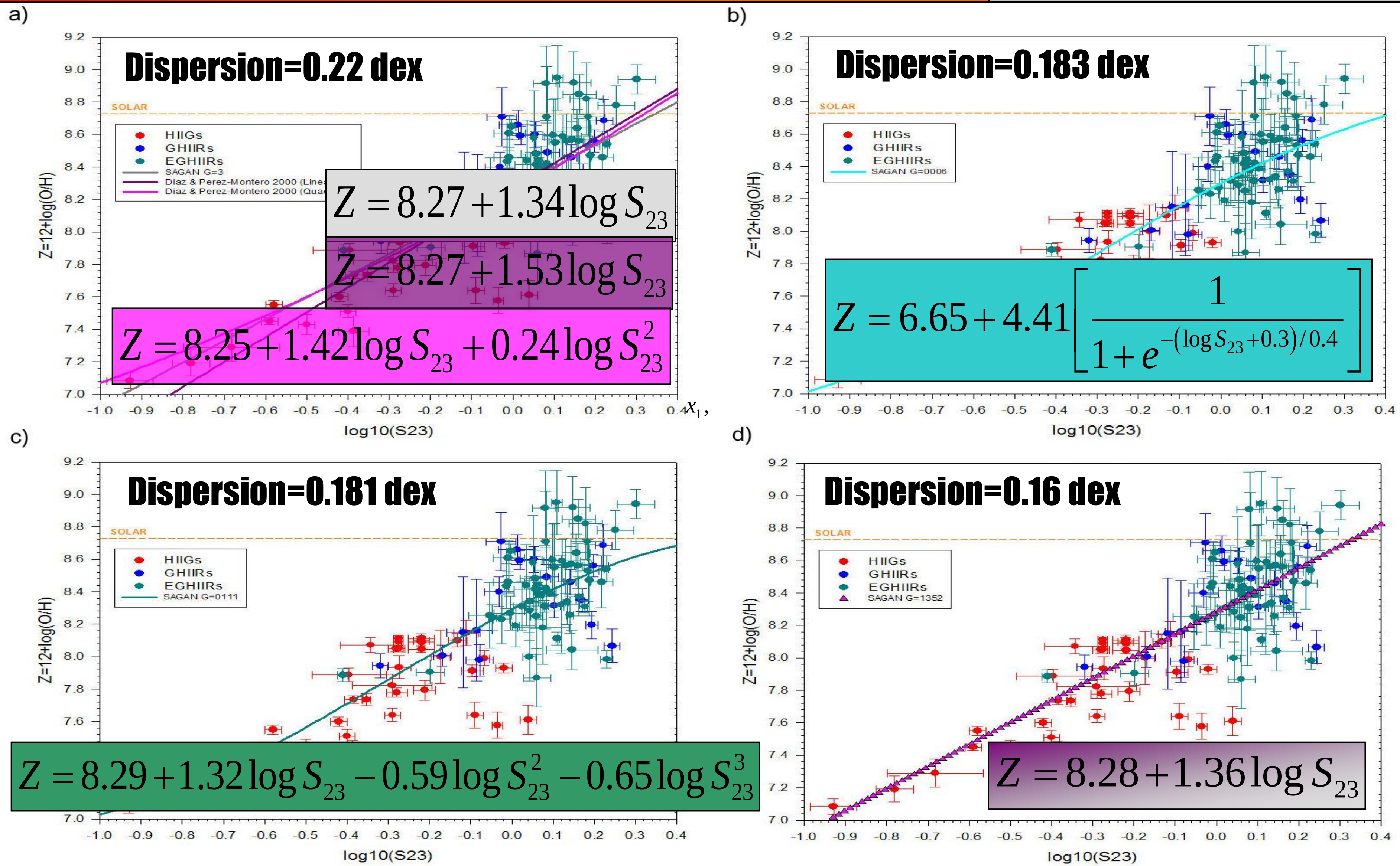
# Evolution of the calibration: Z=f(S23)





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# Fitting & n-D Calibrations



$$Z(O/H) = f(c, \underbrace{x_1, x_2, \ldots, x_n})$$

e.g. Dimensionless Line Ratios

$$x_1 = O_{23} = ([OII]_{\lambda 3727+\lambda 3739} + [OIII]_{\lambda 4959+\lambda 5007})/H_\beta$$

$$x_2 = S_{23} = ([SII]_{\lambda 6717+\lambda 6731} + [SIII]_{\lambda 9069+\lambda 9532})/H_\beta$$

- **Needs a big and homogeneous data-set**
- **Can potentially reduce subjectivity**
- **Can potentially identify new indicators**

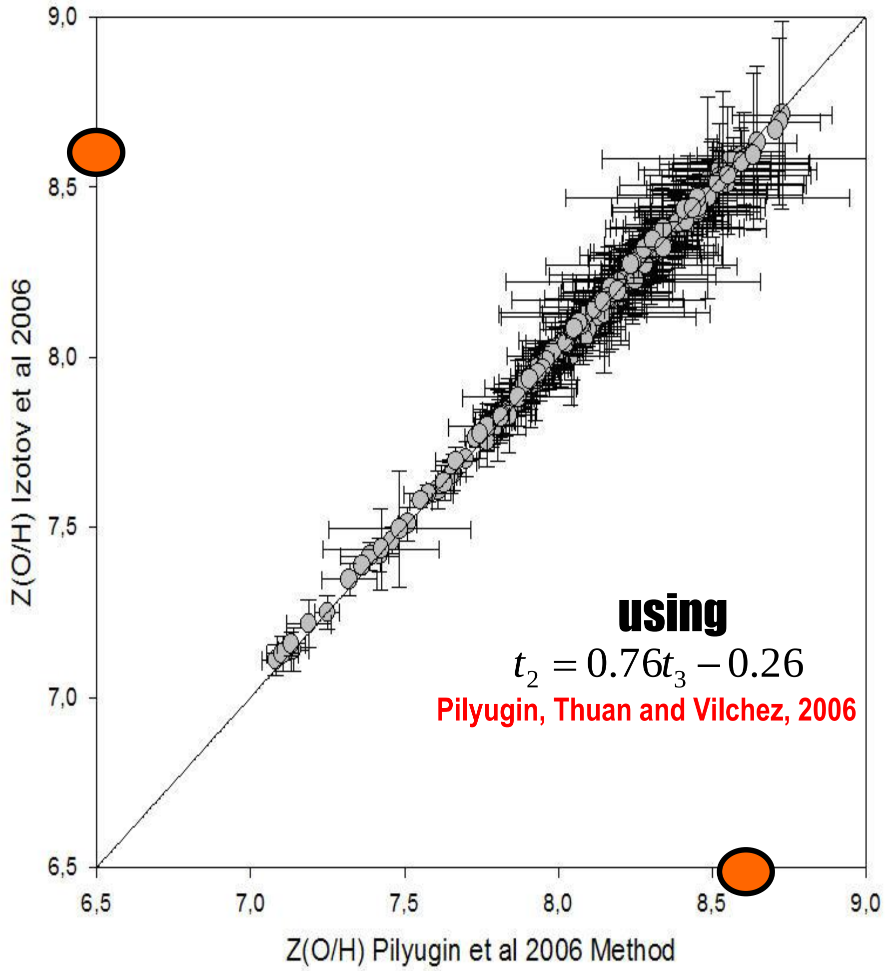
# A sample for n-D studies



| | |
|---|---|
| 1 | Izotov et al. 2006, A&A, 448, 955I. |
| 2 | Díaz, Terlevich, Pagel, Vílchez & Edmunds, 1987, MNRAS, 226, 19. |
| 3 | Pastoriza, Dottori, Terlevich, Terlevich & Díaz, 1993, MNRAS, 260, 177. |
| 4 | González-Delgado et al., 1994, ApJ, 437, 239. |
| 5 | Castellanos, Díaz & Terlevich, 2002, MNRAS, 329, 315. |
| 6 | Skillman, Terlevich, Kennicutt, Garnett & Terlevich, 1994, ApJ, 431, 172 |
| 7 | Skillman & Kennicutt, 1993, ApJ, 411, 655 |
| 8 | González-Delgado et al., 1995, ApJ, 439, 604. |
| 9 | Bresolin, Schaerer, González-Delgado & Stasinska, 2005, A&A, 441, 981. |
| 10 | Lequeux, Peimbert, Rayo, Serrano & Torres-Peimbert, 1979, A&A, 80, 155. |
| 11 | Kunth & Sargent, 1983, ApJ, 273, 81 |
| 12 | French, 1980, ApJ, 240, 41 |
| 13 | Izotov & Thuan, 1998, ApJ, 500, 188. |
| 14 | Pagel, Simonson, Terlevich & Edmunds, 1992, MNRAS, 255, 325. |
| 15 | Dinerstein & Shields, 1986, ApJ, 311, 45. |
| 16 | Kennicutt, Bresolin & Garnett, 2003, ApJ, 591, 801. |
| 17 | Garnett & Kennicutt, 1994, ApJ, 426, 123. |
| 18 | Shields & Searle, 1978, ApJ, 222, 821 |
| 19 | Vílchez, Pagel, Díaz, Terlevich & Edmunds, 1988, MNRAS, 235, 633 |
| 20 | Kwitter & Aller, 1981, MNRAS, 195, 939. |
| 21 | Vílchez, Pagel, Díaz, Terlevich & Edmunds, 1988, MNRAS, 235, 633 |
| 22 | Garnett, Kennicutt & Bresolin, 2004, ApJ, 607, L21. |
| 23 | Bresolin, Garnett & Kennicutt, 2004, ApJ, 615, 228. |
| 24 | Peimbert, Peña & Torres-Peimbert, 1986, A&A, 158, 266 |
| 25 | Garnett, Shields, Skillman, Sagan & Dufour, 1997, ApJ, 489, 63. |
| 26 | Díaz, Terlevich, Pagel, Vílchez & Edmunds, 1987, MNRAS, 226, 19. |
| 27 | Vermeij, Damour, van der Hulst & Baluteau, 2002, A&A, 390, 649 |
| 28 | Vílchez & Esteban, 1996, MNRAS, 280, 720 |
| 29 | Dennefeld & Stasińska, 1983, A&A, 118, 255 |
| 30 | Hägele, Pérez-Montero, Díaz, Terlevich & Terlevich, 2006, MNRAS, |
| 31 | Kehrig, Vílchez, Telles, Cuisinier & Pérez-Montero, 2006 A&A |
| 32 | Izotov, Thuan & Lipovetsky, 1994, ApJ, 435, 647 |
| 33 | Terlevich, Melnick, Masegosa, Moles & Copetti, 1991, A&ASS, 91, 285 |
| 34 | Guseva, Izotov & Thuan, 2000, ApJ, 531, 776. |
| 35 | Kniazev et al, 2004, ApJS, 153, 429K. |

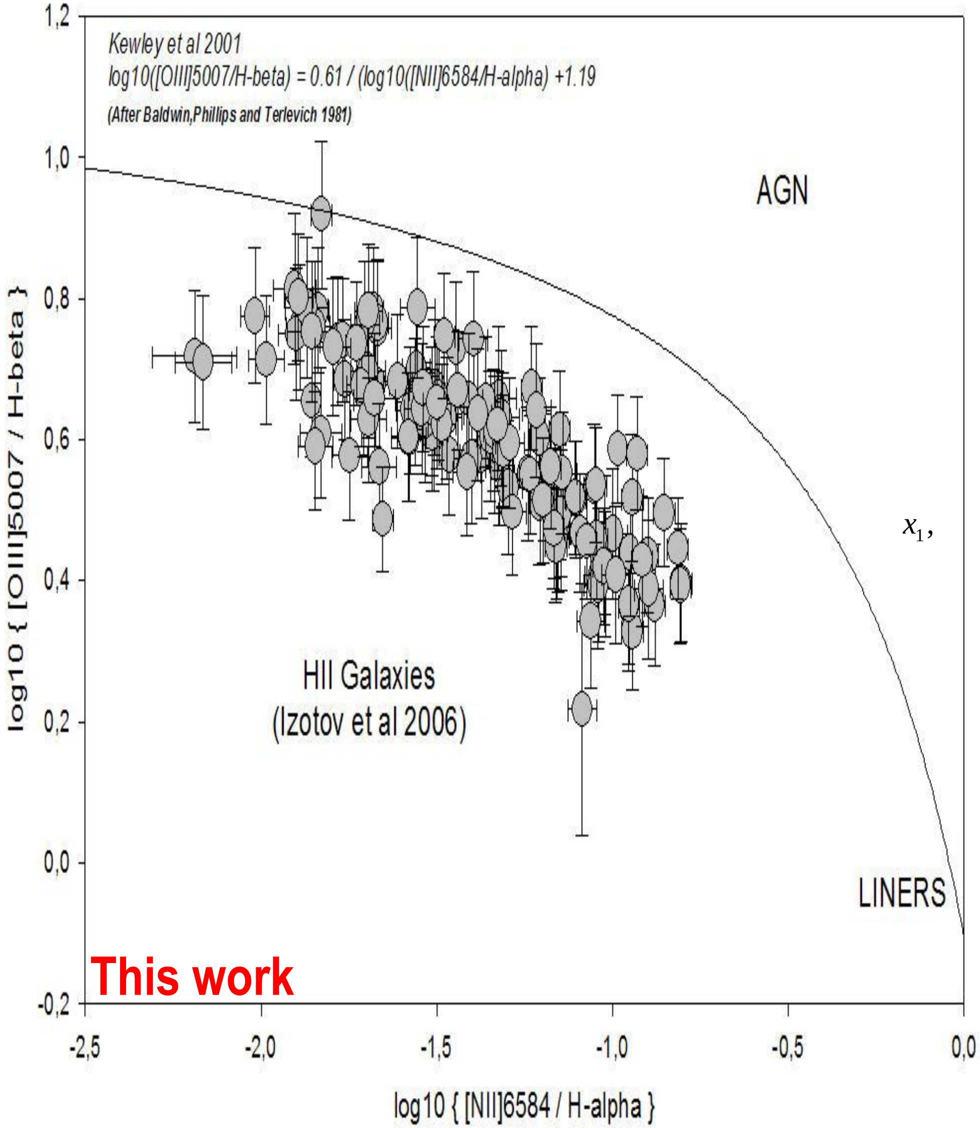
| | |
|---|---|
| 1 | H12 |
| 2 | H11 |
| 3 | H10 |
| 4 | H9 |
| 5 | H-delta |
| 6 | H-gamma |
| 7 | H-beta |
| 8 | H-alpha |
| 9 | [He I] 5876 |
| 10 | [He II] 4686 |
| 11 | [O II] 3727+ 3739 |
| 12 | [O III] 4363 |
| 13 | [O III] 4959 |
| 14 | [O III] 5007 |
| 15 | [O I] 6300 |
| 16 | [O II] 7325 |
| 17 | [N II] 6548 |
| 18 | [N II] 6584 |
| 19 | [S II] 6312 |
| 20 | [S II] 6717 + 6731 |
| 21 | [S III] 9069 |
| 22 | [S III] 9532 |
| 23 | [Ne III] 3868 |
| 24 | [Fe III] 4658 |
| 25 | [Fe III] 4988 |
| 26 | [Ar IV] 4740 |
| 27 | [Ar IV] 7136 |

Izotov et al 2006 → 144 objects
(another 163 from other sources)



# Data classification with the BPT plot





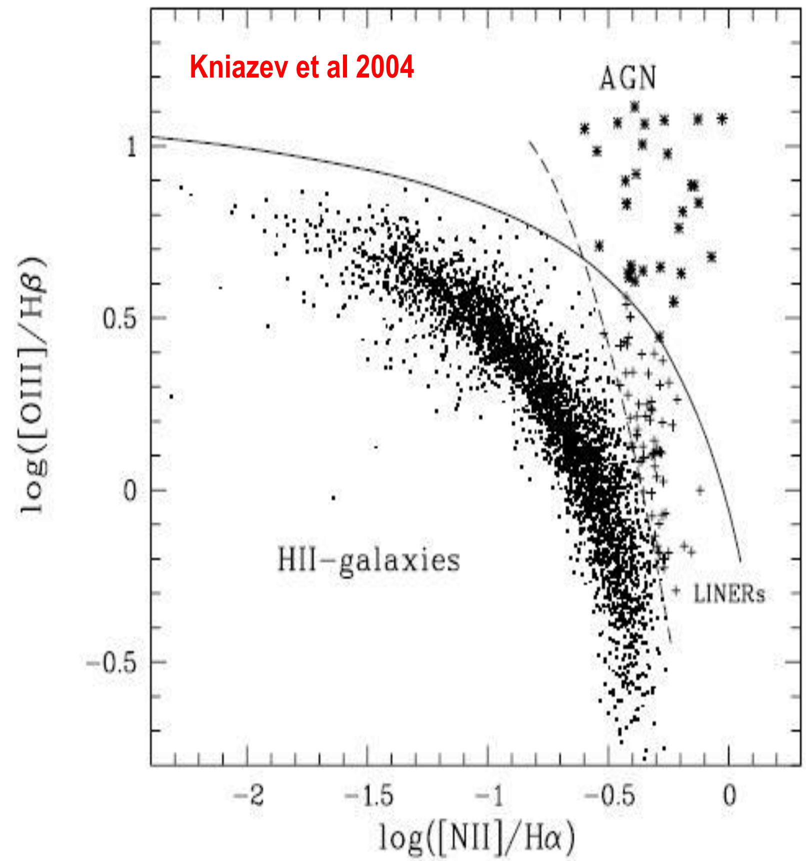




FIG. 2.—Classification diagram for all preselected ELGs (~5000 spectra). Galaxies identified as AGNs are shown as asterisks, and galaxies identified as LINERs are shown as crosses. The other ELGs are plotted as filled circles. The dashed line separates regions of H II-type and AGN/LINER spectra following Veilleux & Osterbrock (1987) and Baldwin et al. (1981). The solid line shows models from Kewley et al. (2001) that were used for AGN/LINER separation.



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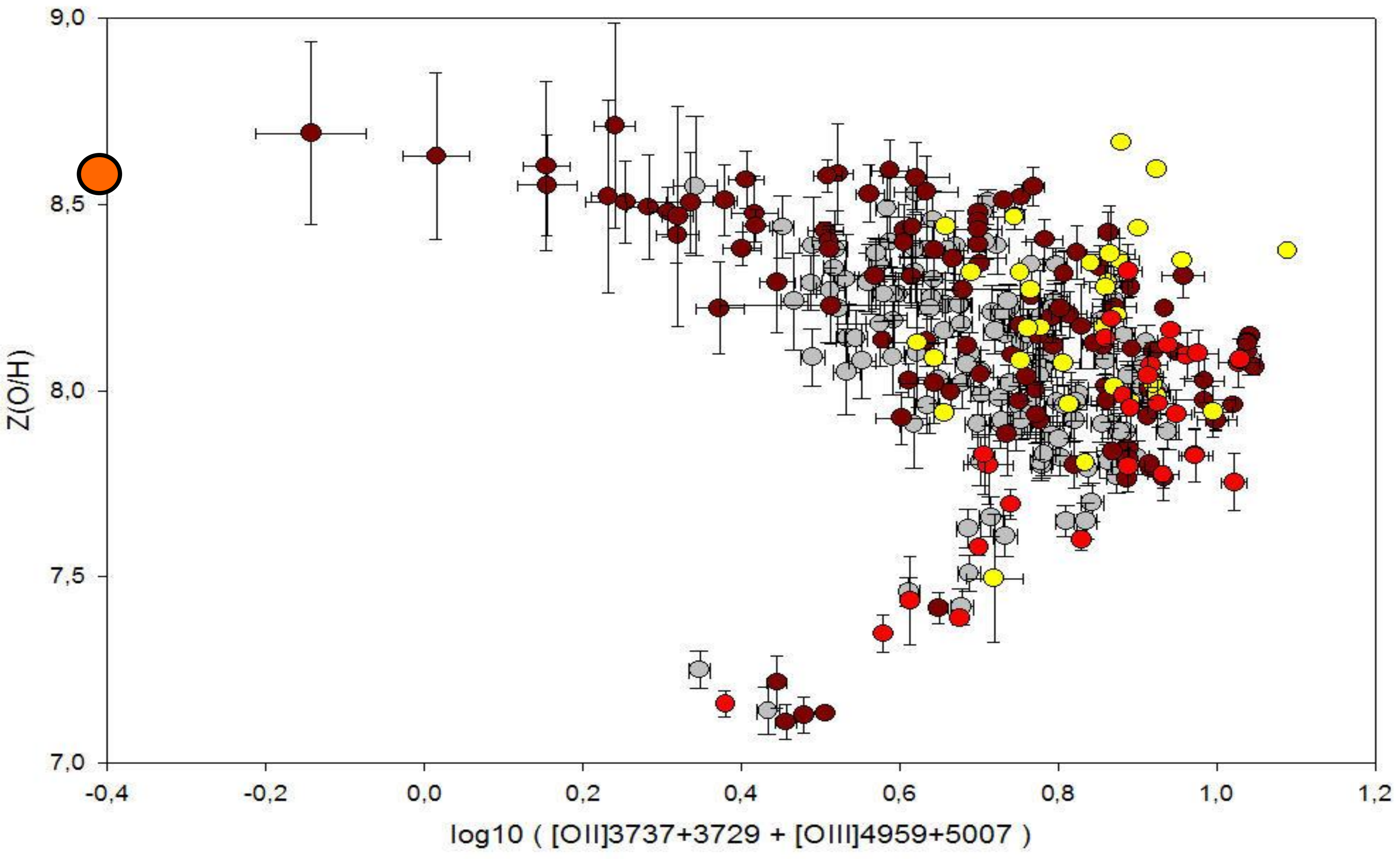
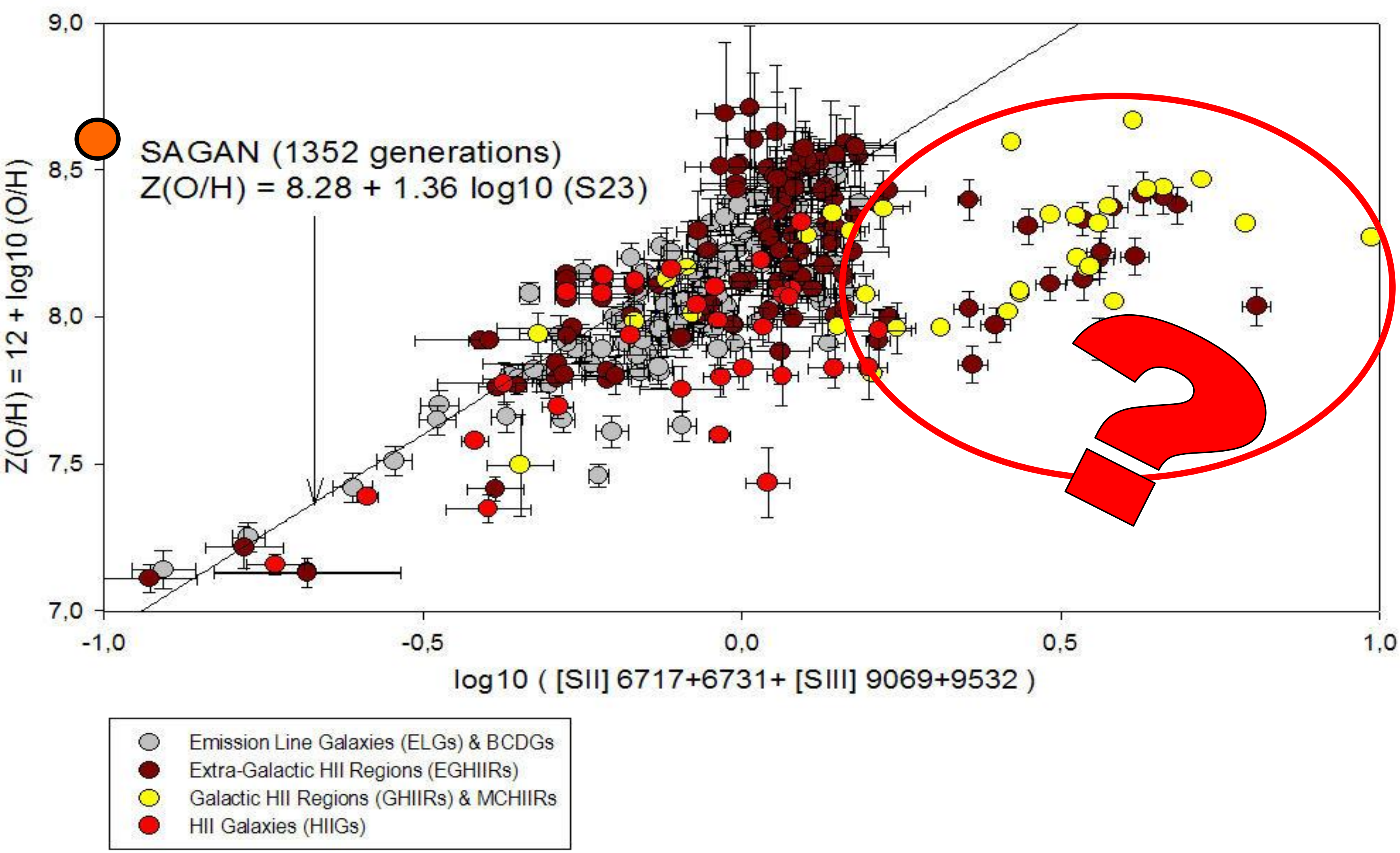
# Metallicity and $O_{23}$





# Metallicity and $S_{23}$





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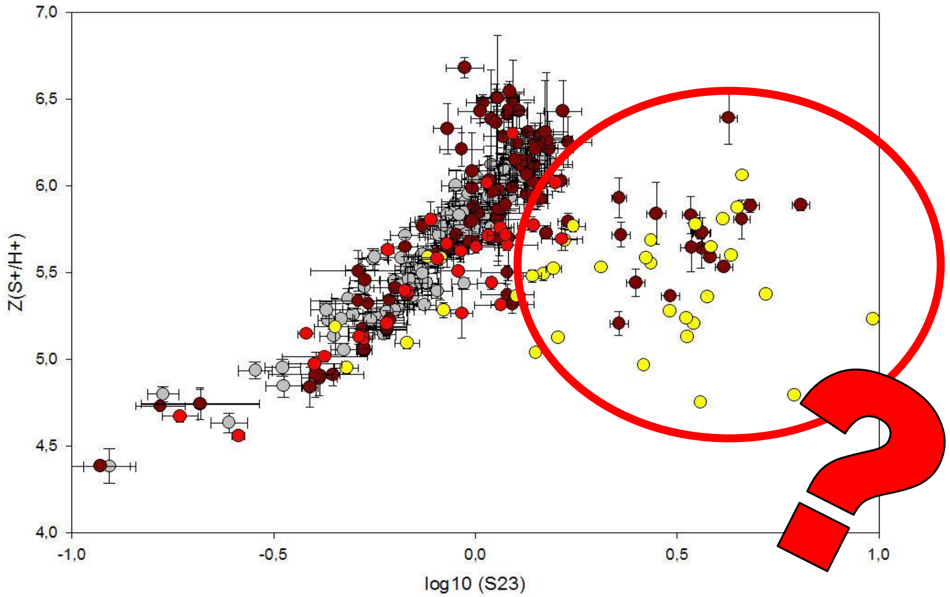
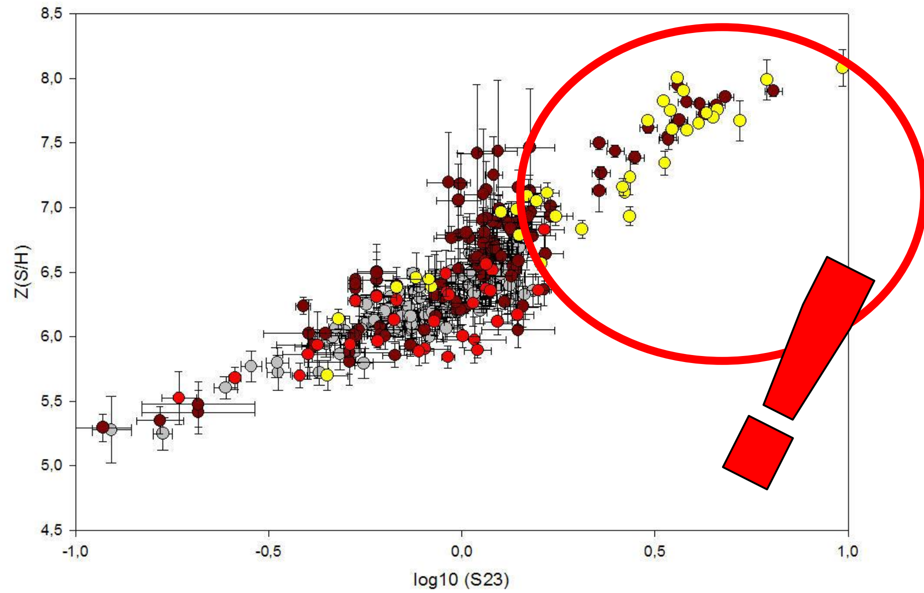
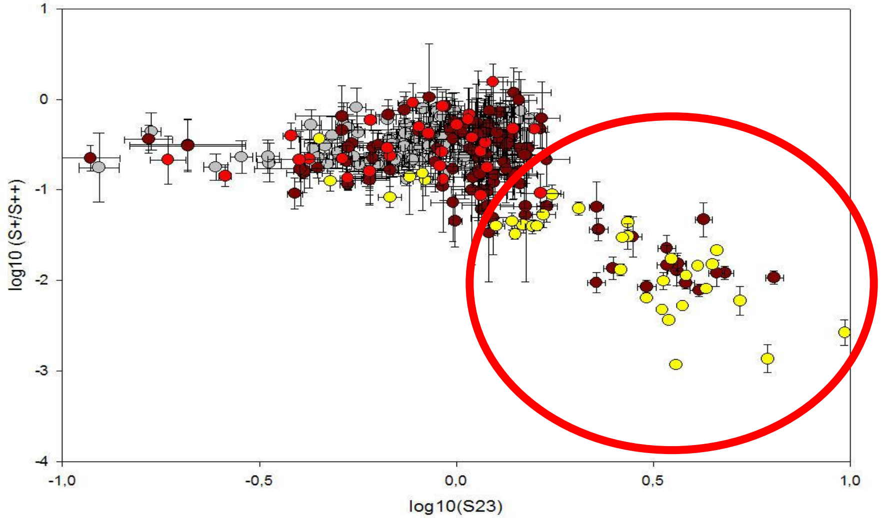
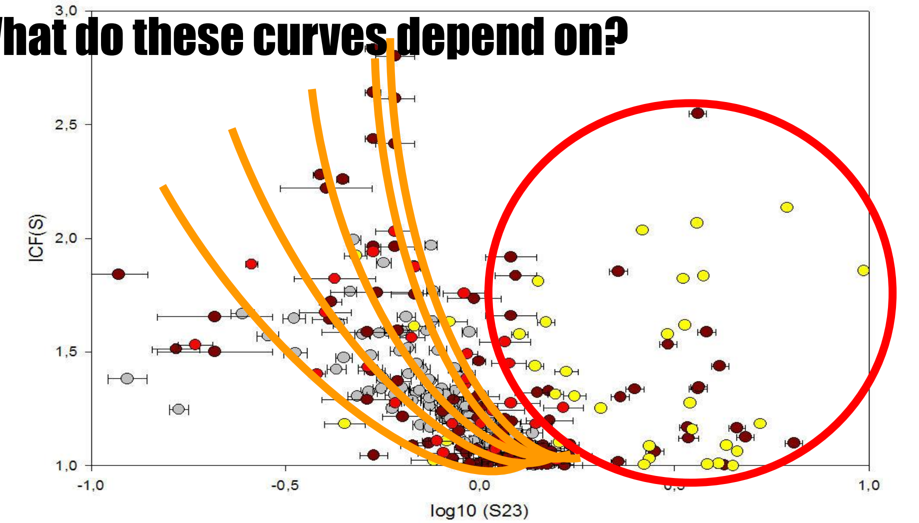
# The role of S (S+, S2+, S, ICF)





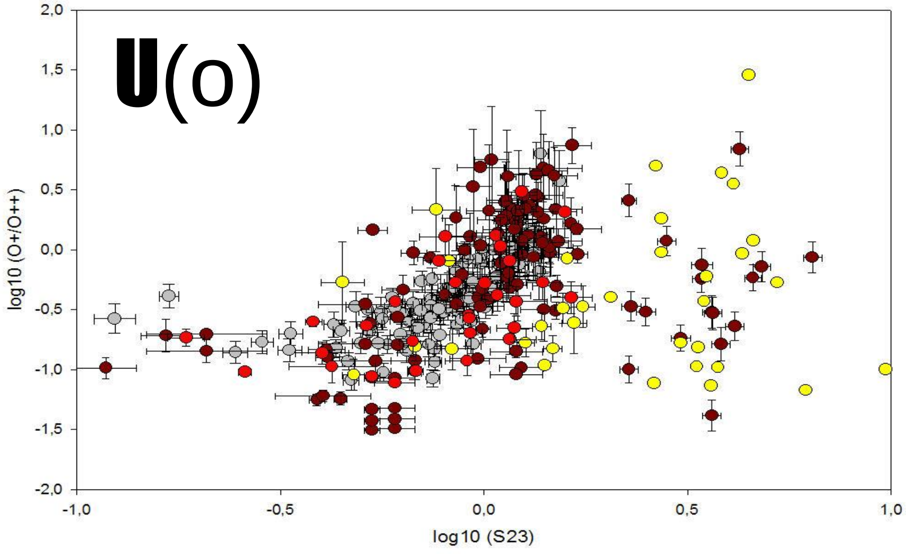



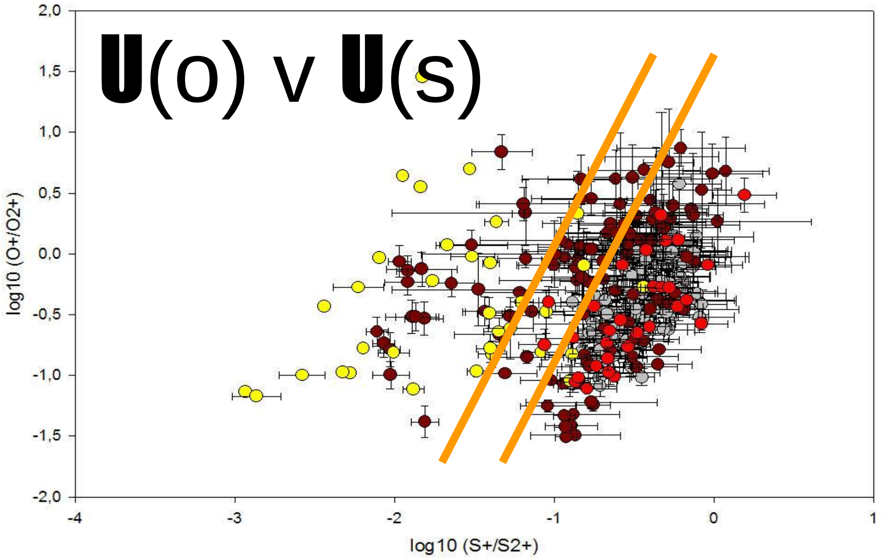



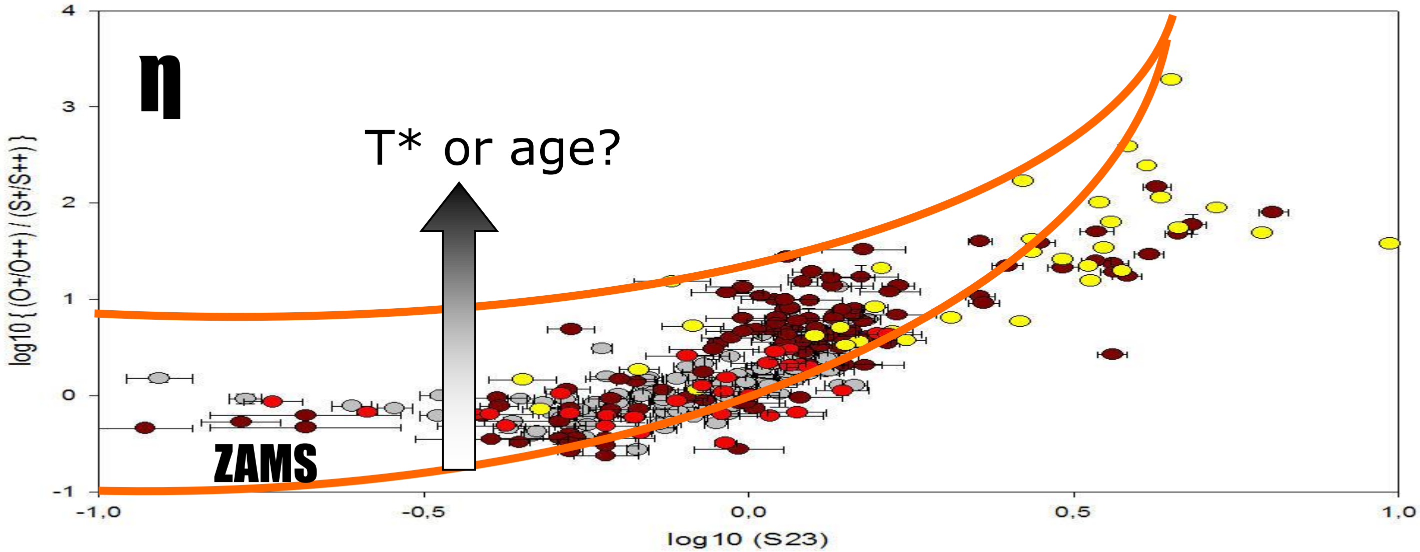



# Trends of U and η with $S_{23}$





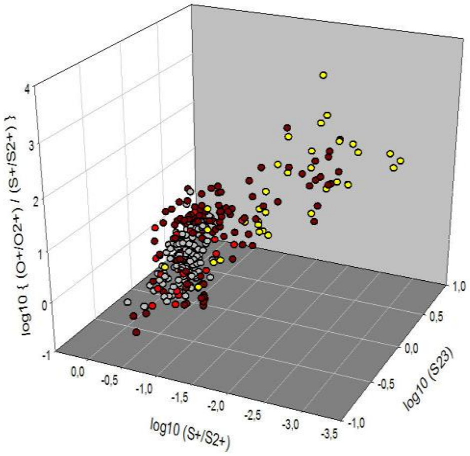



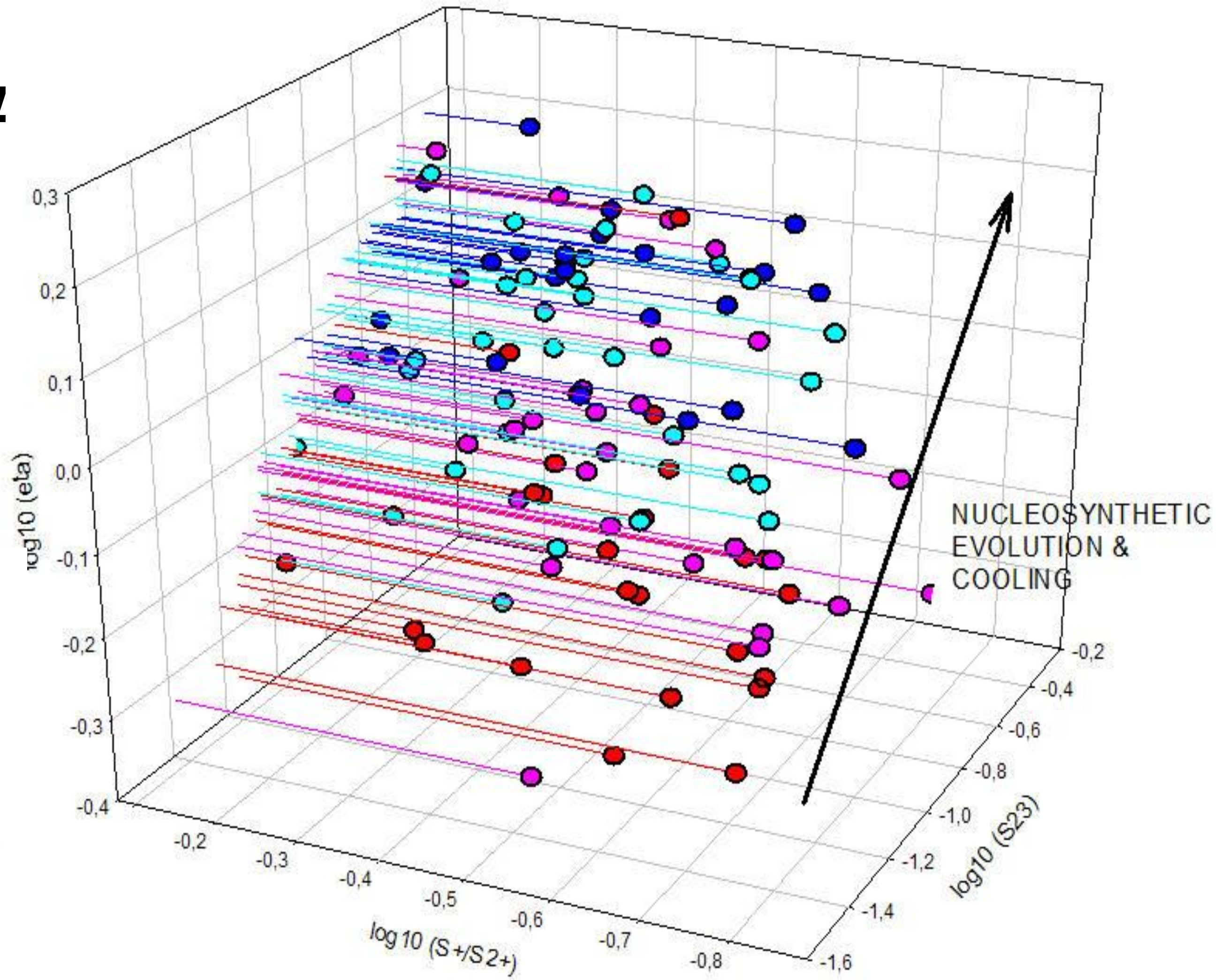



# Data in the η-U-$S_{23}$ space



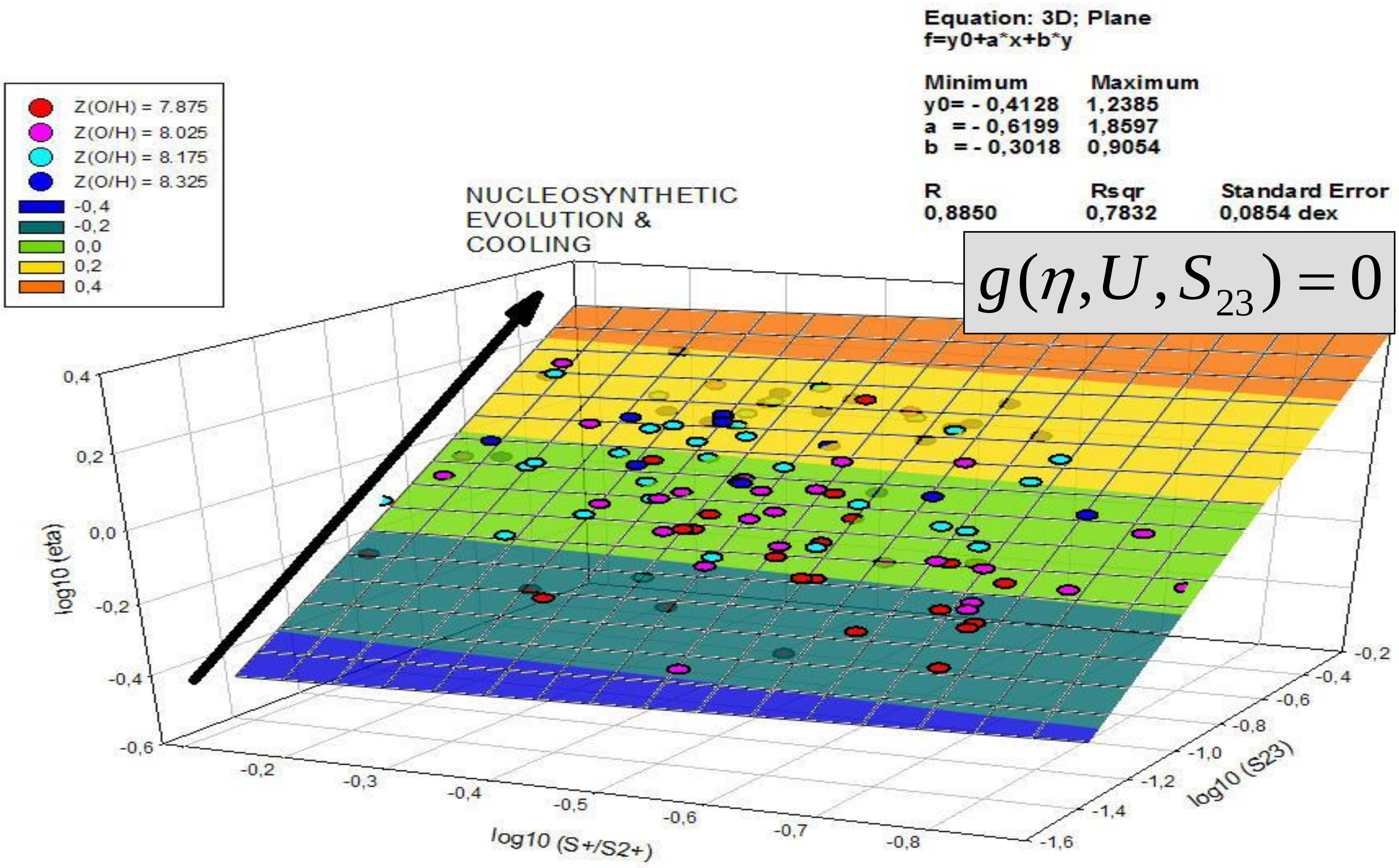
## Clustering objects with Z



# Fitting with a plane






$$g(\eta, U, S_{23}) = 0$$



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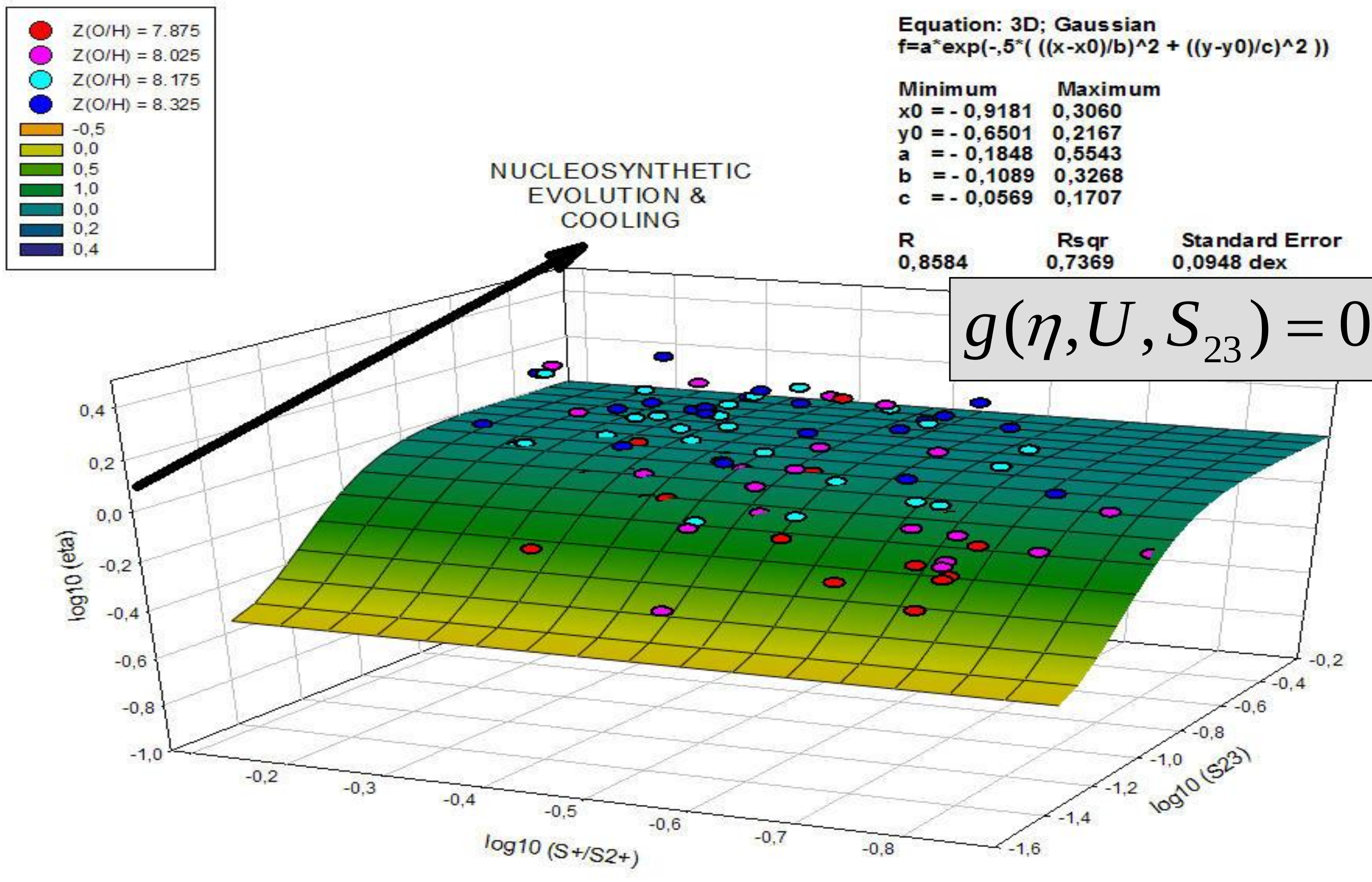
# Fitting with a Gaussian surface






$$g(\eta, U, S_{23}) = 0$$



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# The biggest question...



$$Z(O/H) = f(c, x_1, x_2, \ldots, x_n)$$

$$g(\eta, U, S_{23}) = 0$$

This mapping is possible if we can define a scale of effective temperature T* using empirical measures **ONLY**. But how?

# Ideas for the Future

- To find new n-D indicators & improve calibrations of the form: $Z=f(c, x_1,x_2 \dots x_n)$ for HII-like regions and then for AGNs and PNs
- Find the relation $g(\eta,U,S_{23})=0$ and to test its robustness
- To investigate finding an empirical scale for T*

*On behalf of myself, Pepe and Angeles, I would like to thank Guille Hägele, Enrique Perez-Montero and Mariluz Martin for kindly making observational data available and to everyone who has patiently and carefully taken accurate images*

**Many thanks**



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& Angeles Diaz