Abell 39 – Forty years on

The perfect photoionisation benchmark for stellar evolution

A39 - **O[III] λ5007**

Jacoby et al (2001)

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OVERVIEW

WHY A39?

AN OBSERVATIONAL ANALYSIS OF A39

CLASSIFYING A39

3D DUST-RT MODELLING WITH MoCaSsIN

Why study nebulae (apart from their beauty)?

- Nebulae (HII regions, PNs and SNRs) are important probes of:

  1) the end states of stars Pagel (1997)

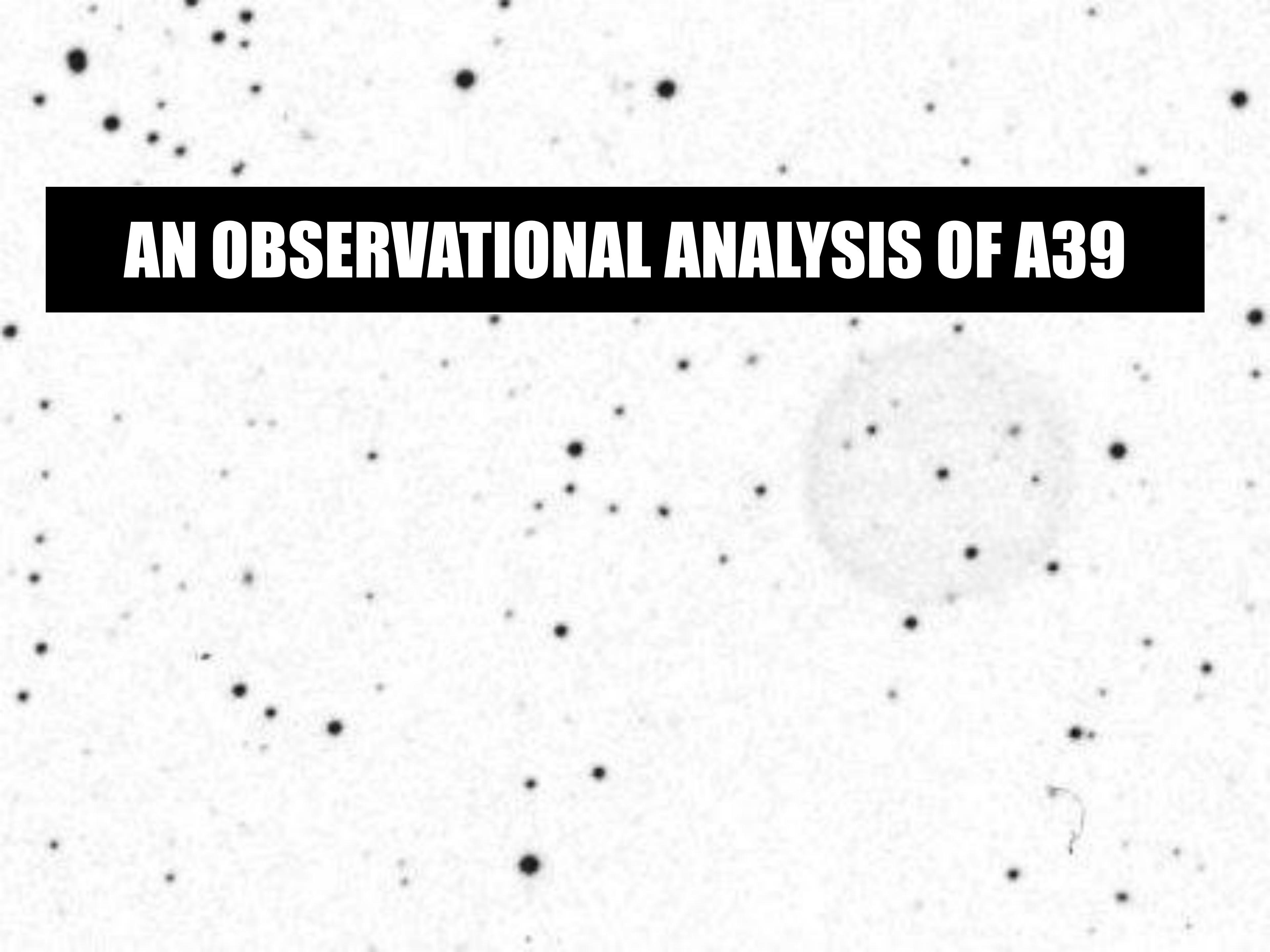
  2) the chemical evolution of the universe Pagel (1997)

  3) cosmological distances using PNLFs Jacoby (1992)

Why study such a simple nebula such as A39?

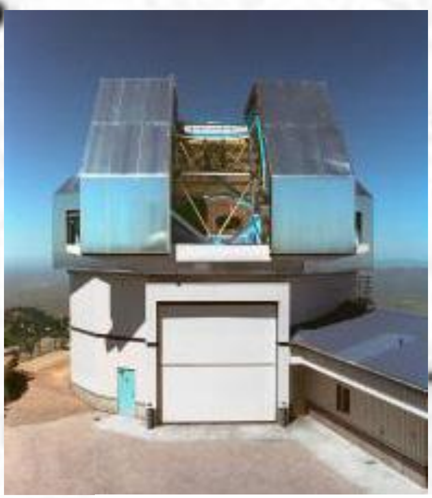
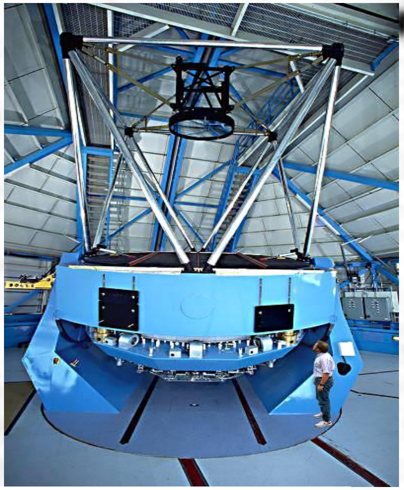
- It is 99.6% Spherical → perfect for photoionisation modelling!
- PN-ISM interaction ≈ 0 & no knots → ideal to test:
  1) the values of the primordial abundances
  2) atomic / molecular physics *in vivo*
  3) dust-RT
  4) Stellar atmosphere theory and the mass loss stage of PNs
- It is relatively unstudied (only 1 dedicated publication!)
- Ideal case to assess our progress in astrophysics after 40 years

AN OBSERVATIONAL ANALYSIS OF A39

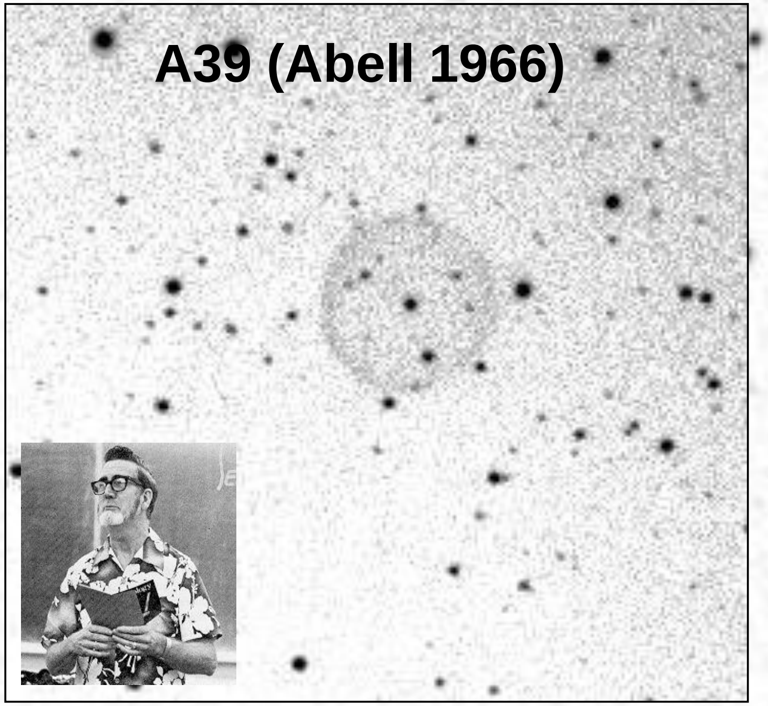


Observations of A39 thirty years apart (and colour optics)


1.2m (48˝) Schmidt – Oschin, Palomar

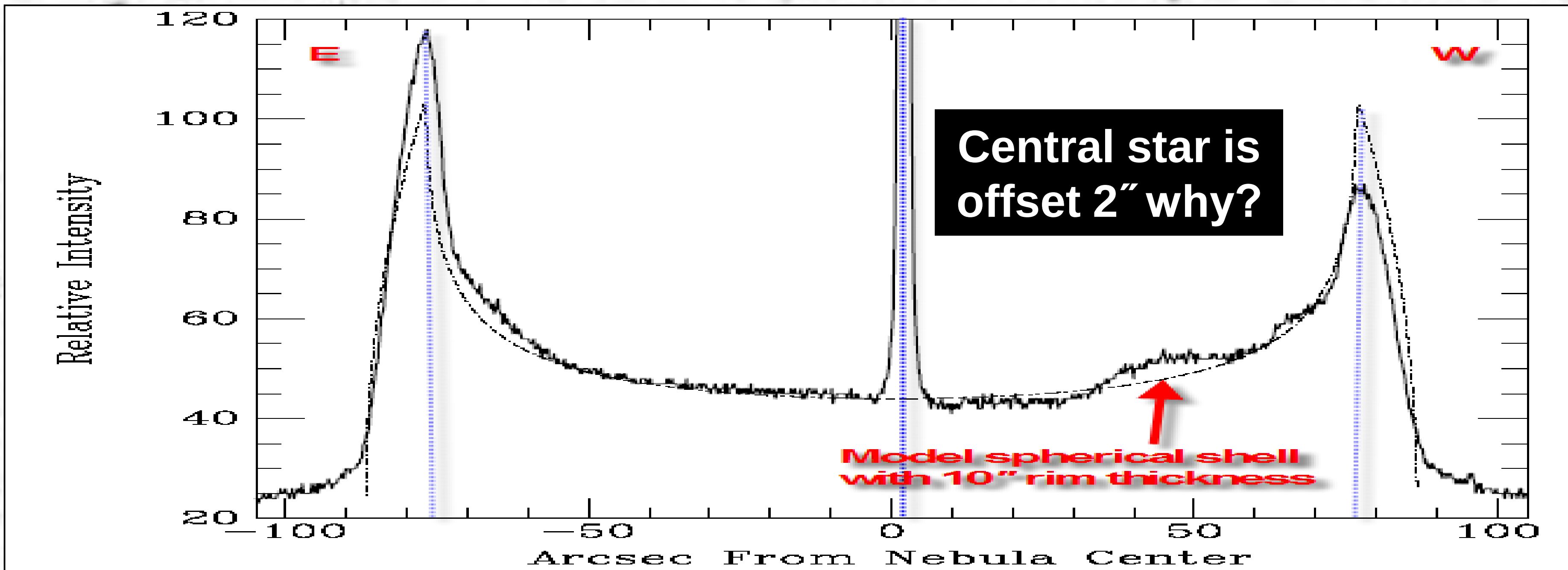



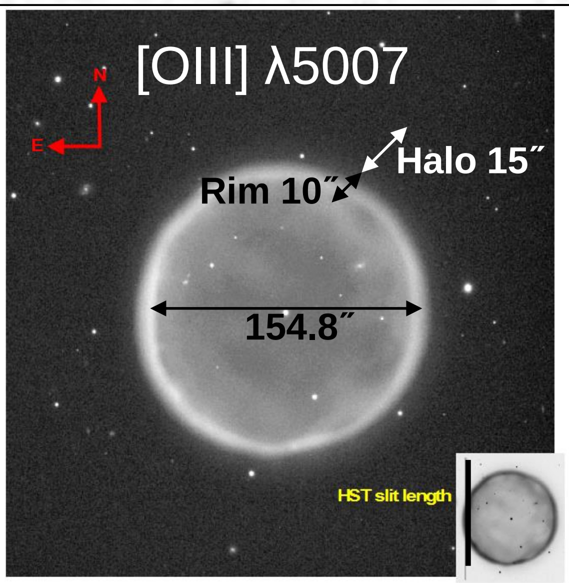
3.5m (138˝) WIYN, Kitt Peak

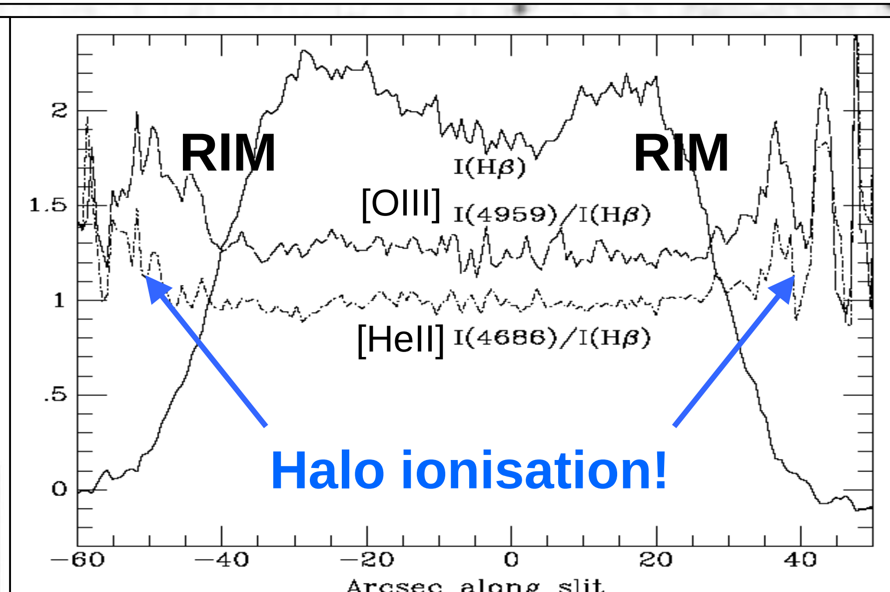


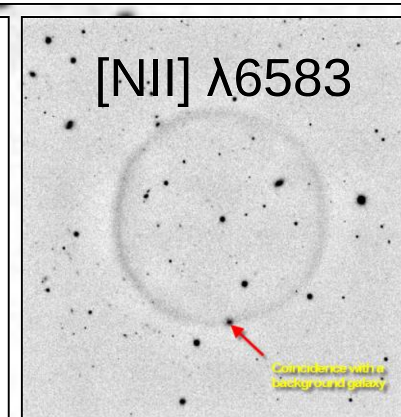
Observations of A39 at Kitt Peak in 1997

Jacoby et al (2001)





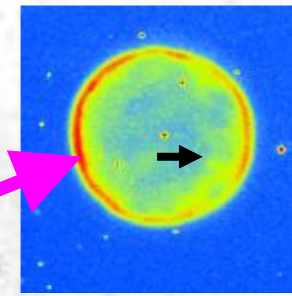




The central star is moving ≈ 1km/s! Why?

- The central star offset ≈ 2″ = 0.02pc (at 2.1kpc) = 6.3×10^{11}km
- The derived nebular age (from $v_{expansion}$) ≈ 23,000 years = 7.26×10^{11}s

→ The drift velocity = 0.86 kms^{-1}



DILEMMA! The rim FURTHEST from the star is brighter!

Opposite of what's expected if there is ISM interaction

Perhaps due to asymmetric mass loss → higher density

→ higher brightness at left rim? Jacoby et al (2001)

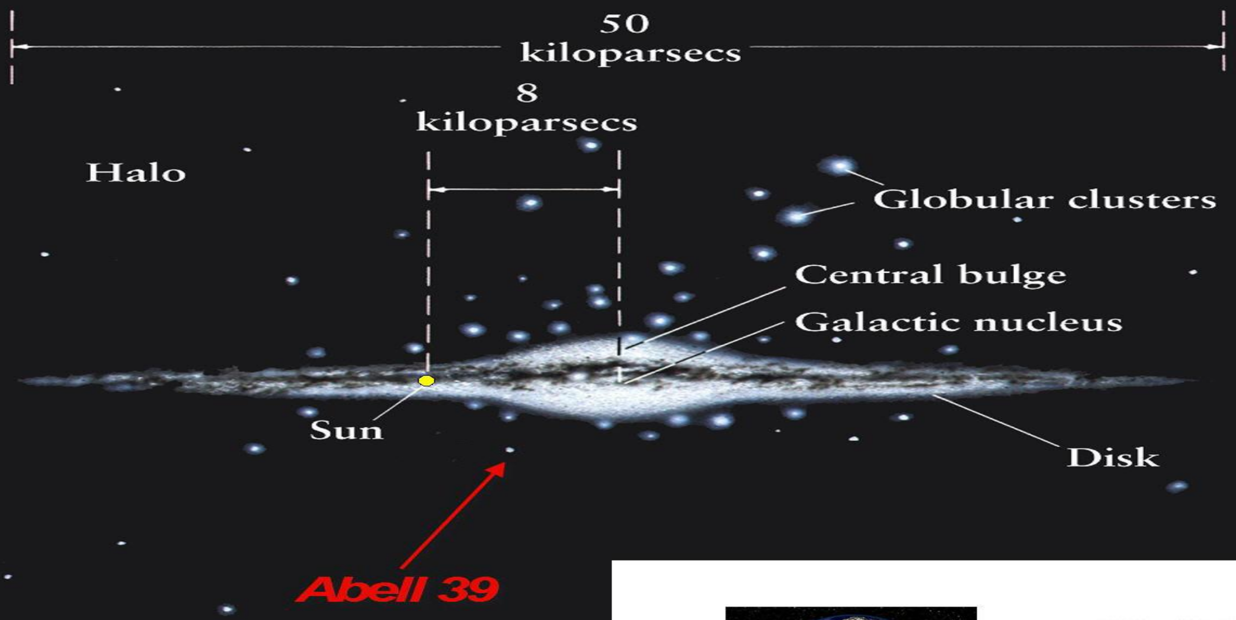
Conservation of momentum ΔM ≈ 0.05 $M_\odot$ → 0.9 kms^{-1}

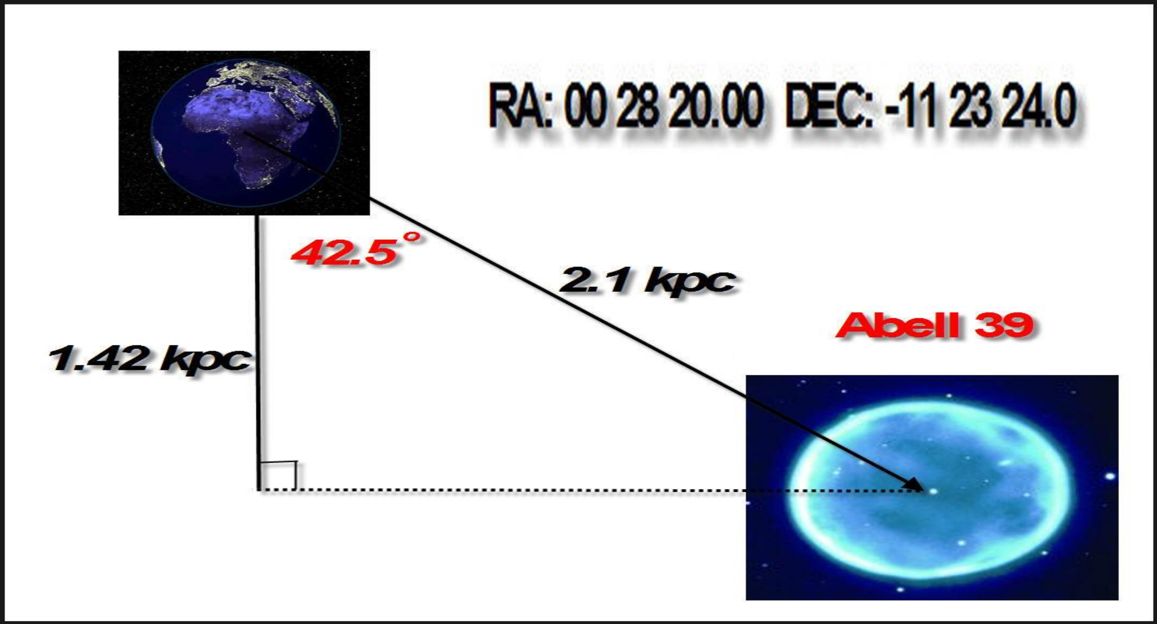
But! The star also has a redshift of 40kms^{-1} Napiwotzki(1999)

→ Is is orbiting another invisible body?!

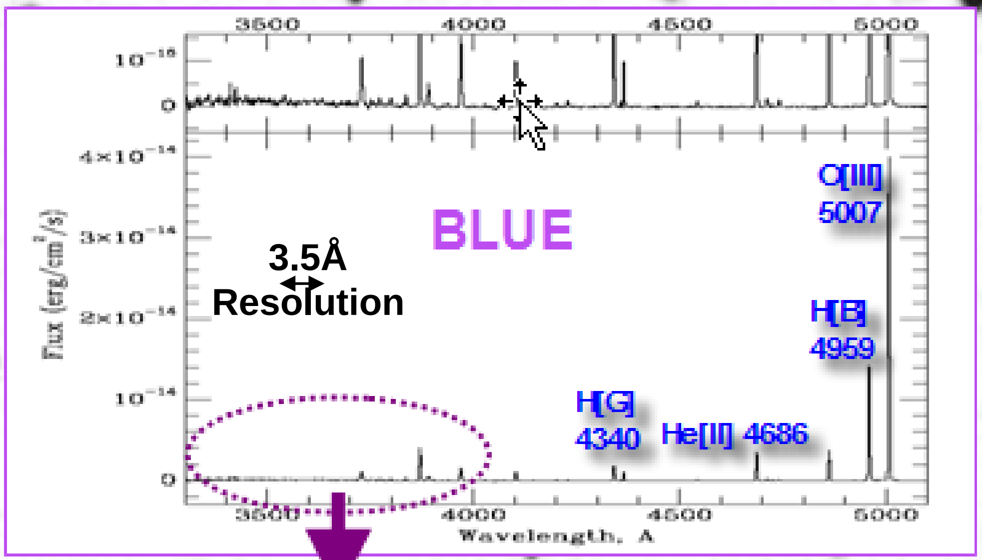
(Link with "variability of central star" identified by Abell?)

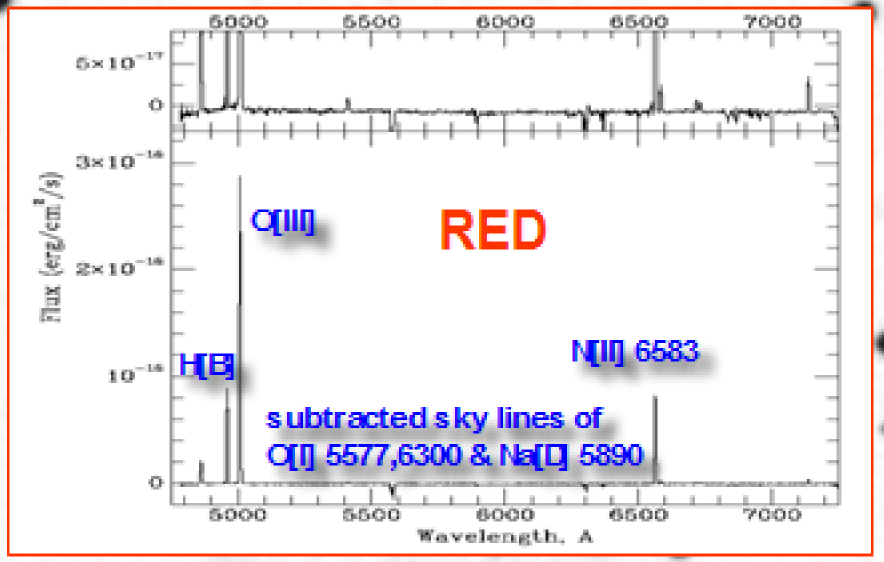
Orientating A39 in the Milky Way

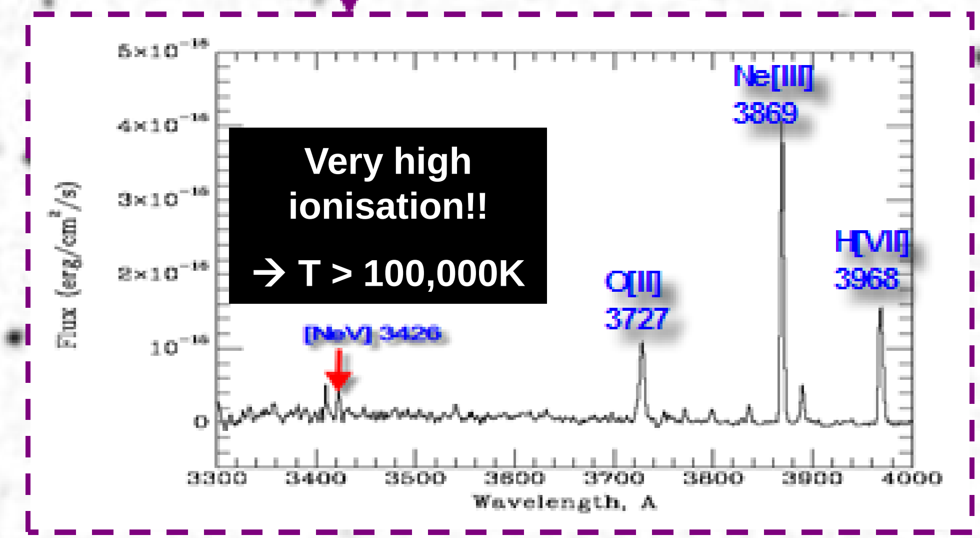


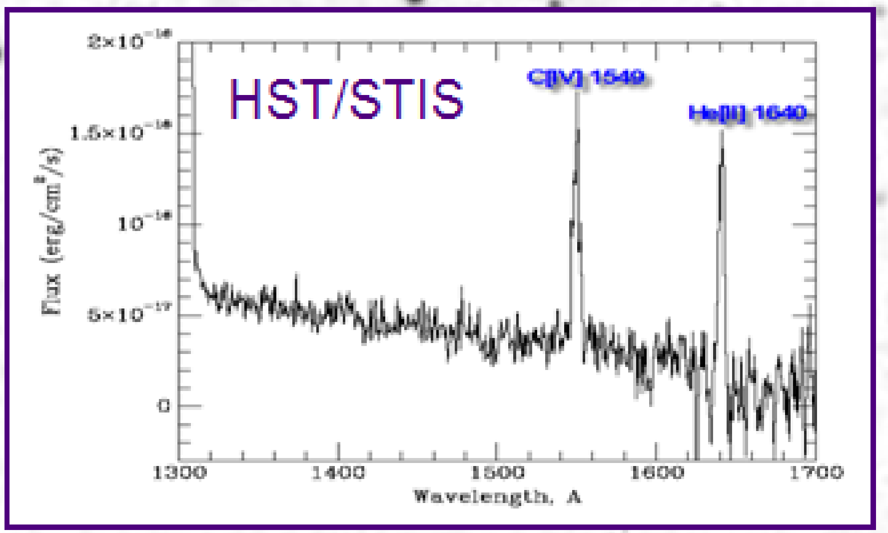


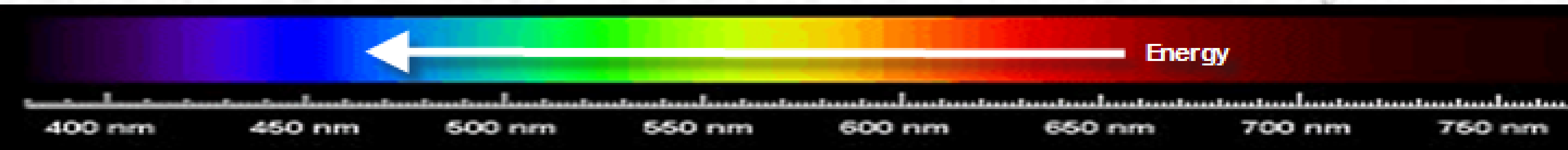
The line emission spectra in visible (WIYN) and UV (HST)





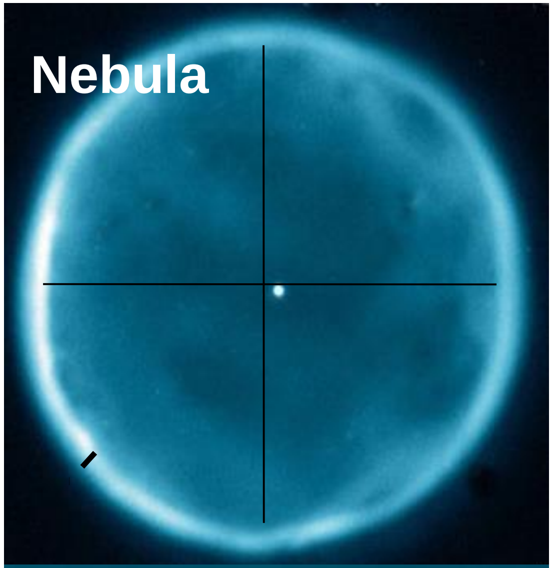


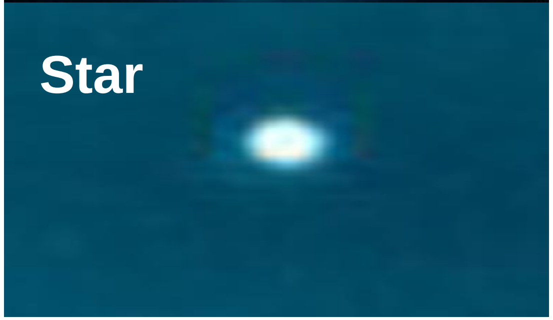


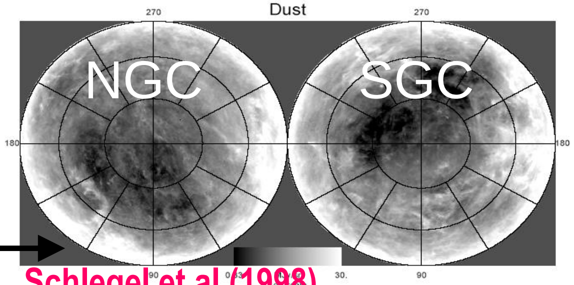


So how does 30 years improve imaging?

		ABELL (1966)	2006
Number of observations		7	19
Nebula observed diameter	(arcsec)	174	154.8
Nebula rim thickness	(arcsec)	N/A	10.1
Nebula halo thickness	(arcsec)	N/A	15
Nebular electron density	(cm^{-3})	48	30
Nebular electron temperature	(K)	N/A	15,000
Nebular mass	(rel to Sun)	0.2	0.6
Nebula derived distance	(pc)	918	2100
Nebula expansion velocity	(kms^{-1})	N/A	34
Nebula derived age	(years)	N/A	23,000
Central star classification		variable WD	DO
Central star offset	(pc)	N/A	0.02
Central star photoelectric magnitude	V(550nm)	15.6	15.6
(further reddening estimate)	B(440nm)-V	-0.33	-0.33
	U(365nm)-B	-1.23	N/A
Central star temperature	T(K)	45,709	150,000
	logT(K)	4.66	5.176
Central star luminosity	(W)	5.66×10^{27}	9.4×10^{27}
Central star luminosity	(rel to Sun)	14.79	15.6
	log(L/L⊙)	1.17	1.196
Central star abs magnitude	(M_V)	5.79	3.9
Central star bol magnitude		1.825	1.76
Central star radius	(rel to Sun)	0.062	0.00073
Central star mass	(rel to Sun)	0.2	0.61
Reddening (log extinction at H(β) (≡5%↓)	cH(β)	N/A	0.049
Reddening from H I col density past A39	c[E(B-V=0.06]	N/A	0.08

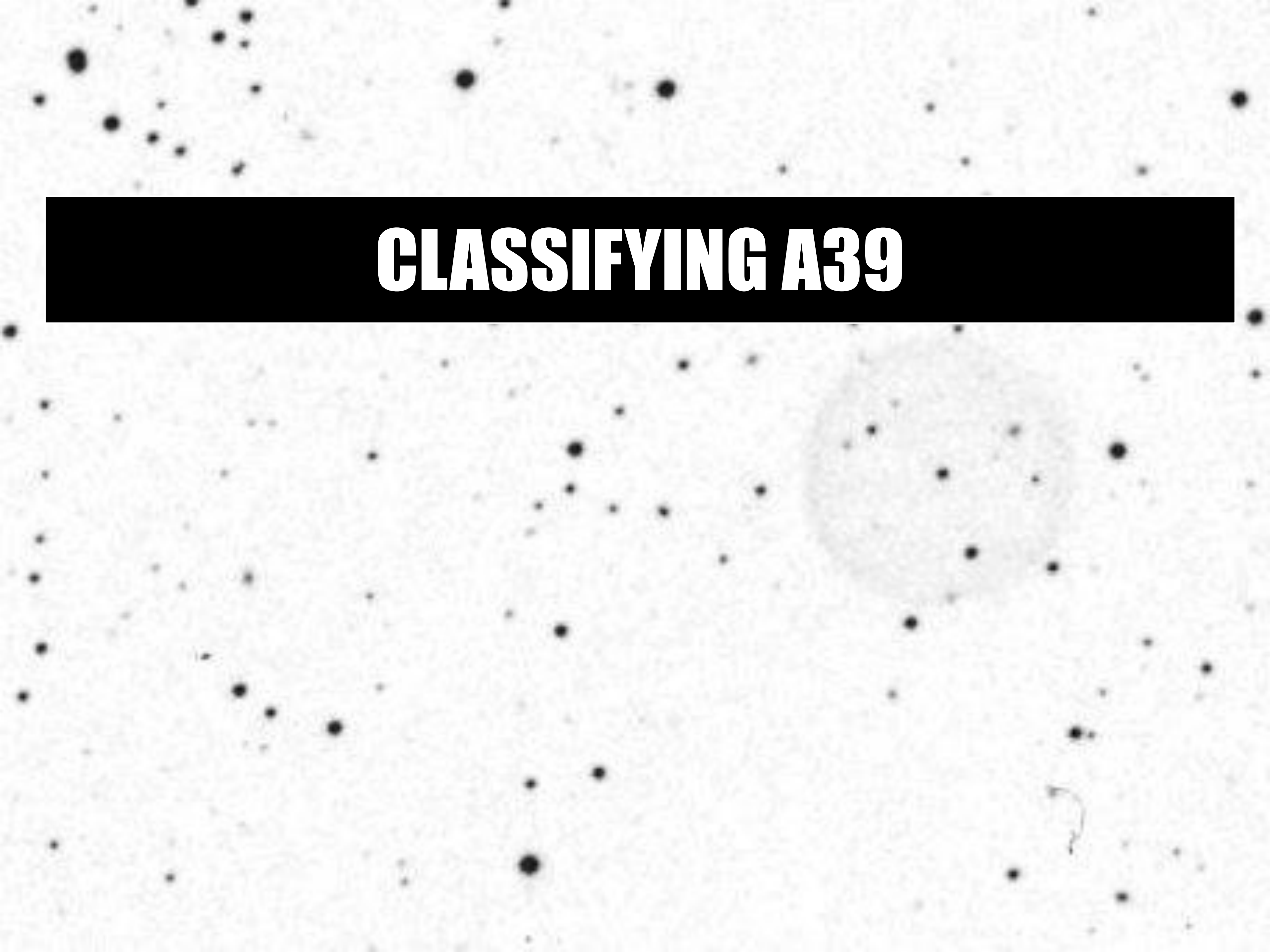




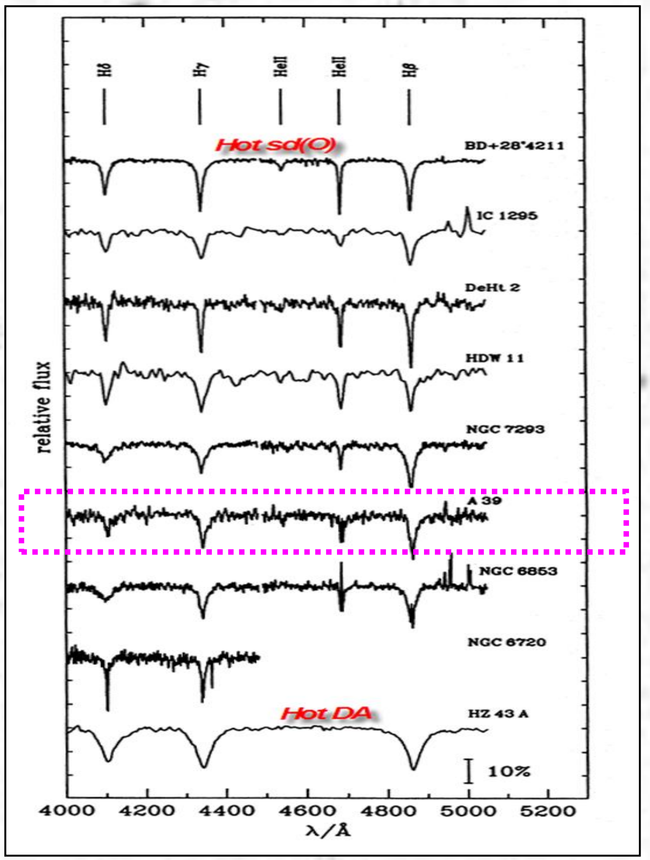


Schlegel et al (1998)

CLASSIFYING A39

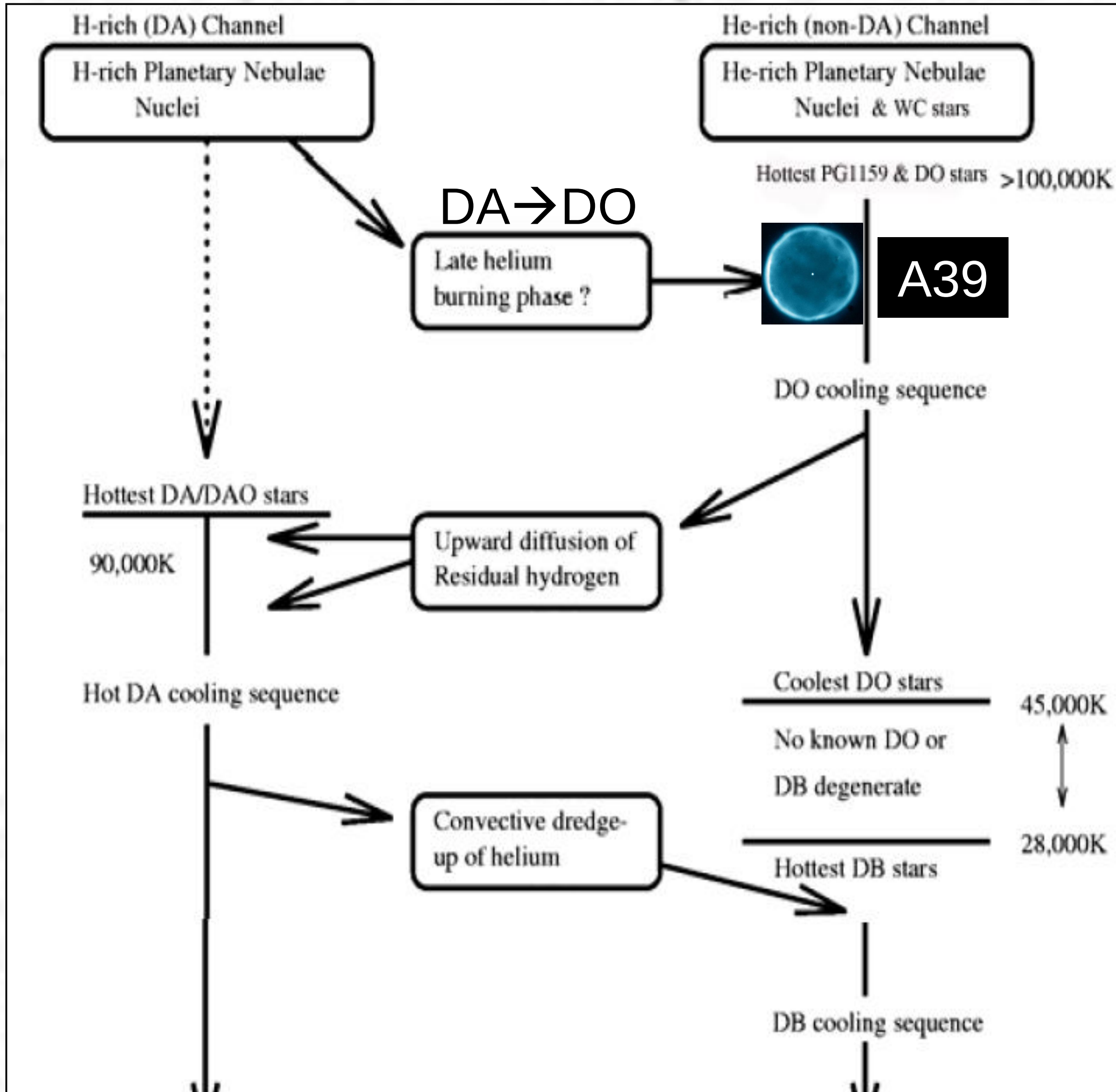


WD classification



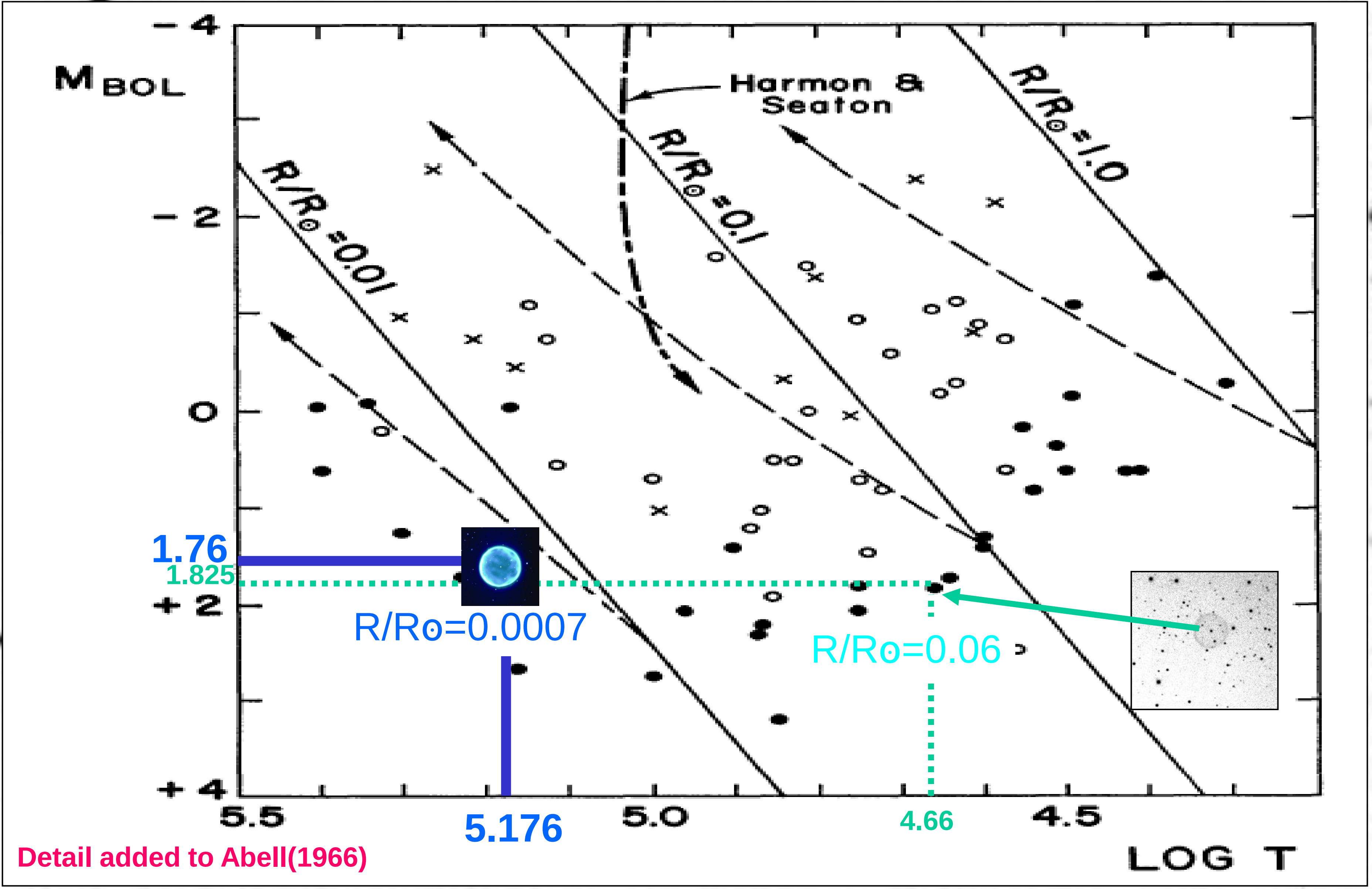
Spectral Type	Characteristics
DA	Only Balmer lines; no He I or metals present
DB...........	He I lines; no H or metals present
DC	Continuous spectrum, no lines deeper than 5% in any part of the electromagnetic spectrum
DO	He II strong; He I or H present
DZ	Metal lines only; no H or He lines
DQ	Carbon features, either atomic or molecular in any part of the electromagnetic spectrum
P.............	Magnetic white dwarfs with detectable polarization
H	Magnetic white dwarfs without detectable polarization
X.............	Peculiar or unclassifiable spectrum
E.............	Emission lines are present
?	Uncertain assigned classification; a colon (:) may also be used
V.............	Optional symbol to denote variability

Napiwotzki et al(1995)



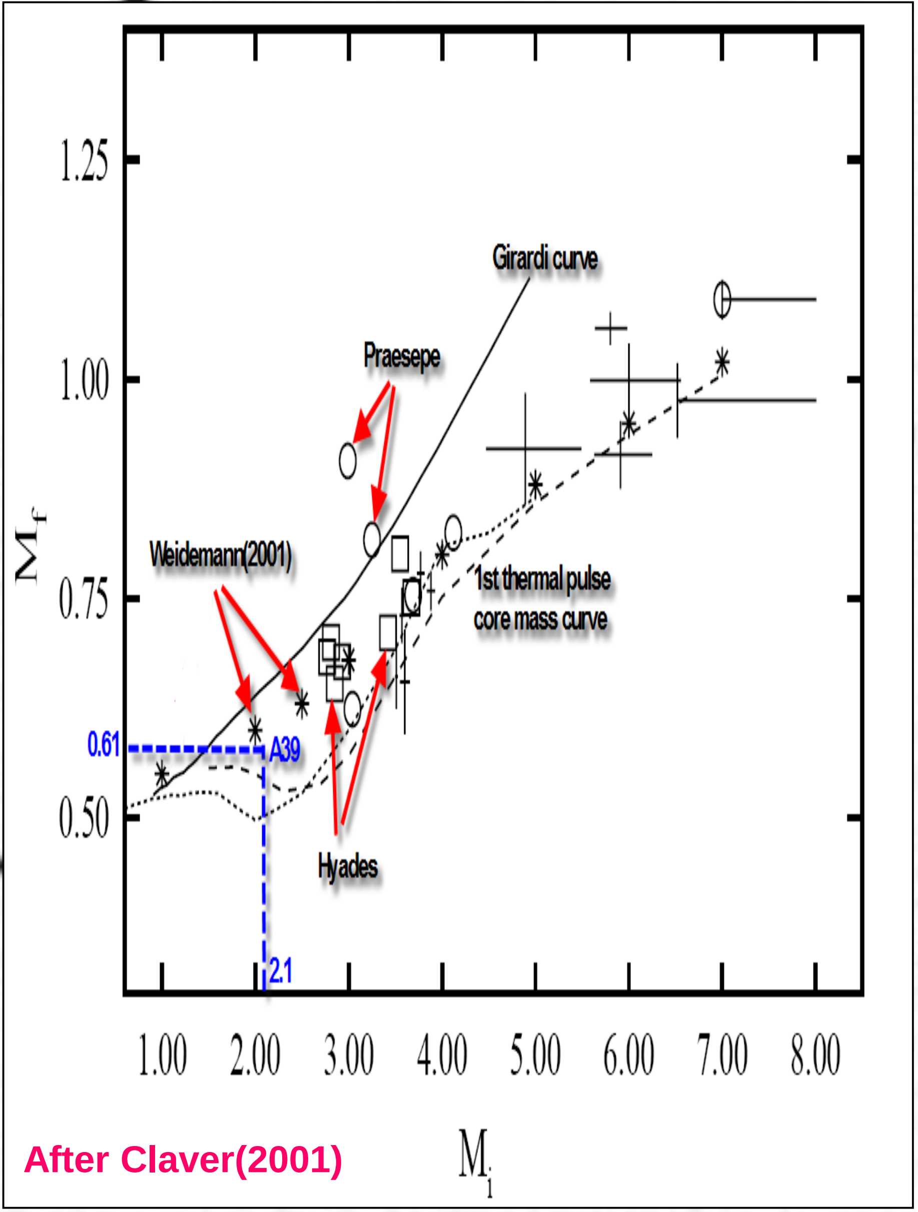
Barstow(2005)

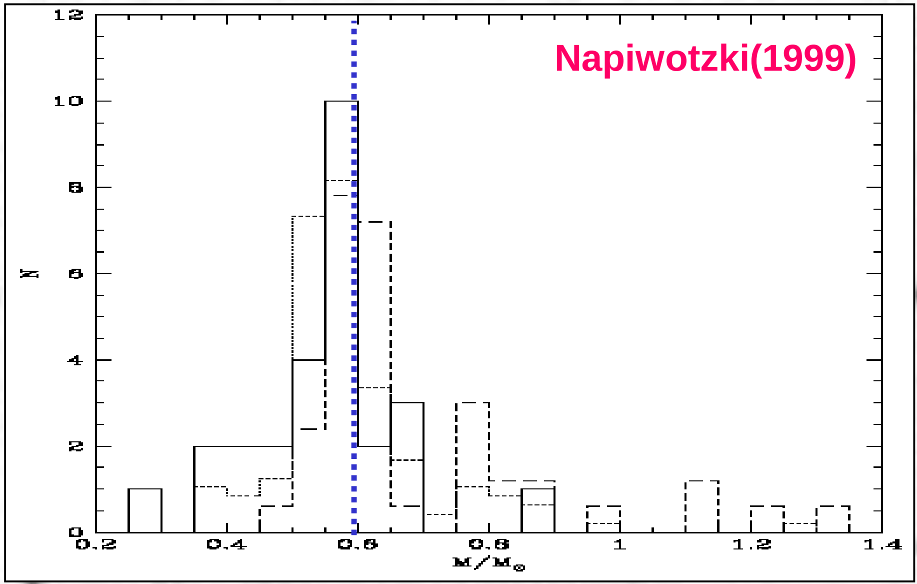
Stellar atmosphere theory I: The WD radius

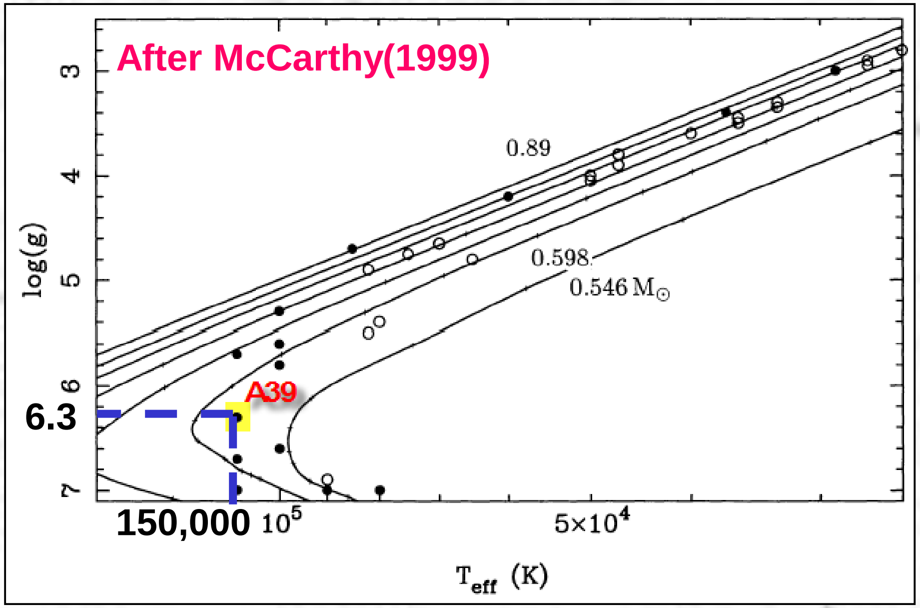


Detail added to Abell(1966)

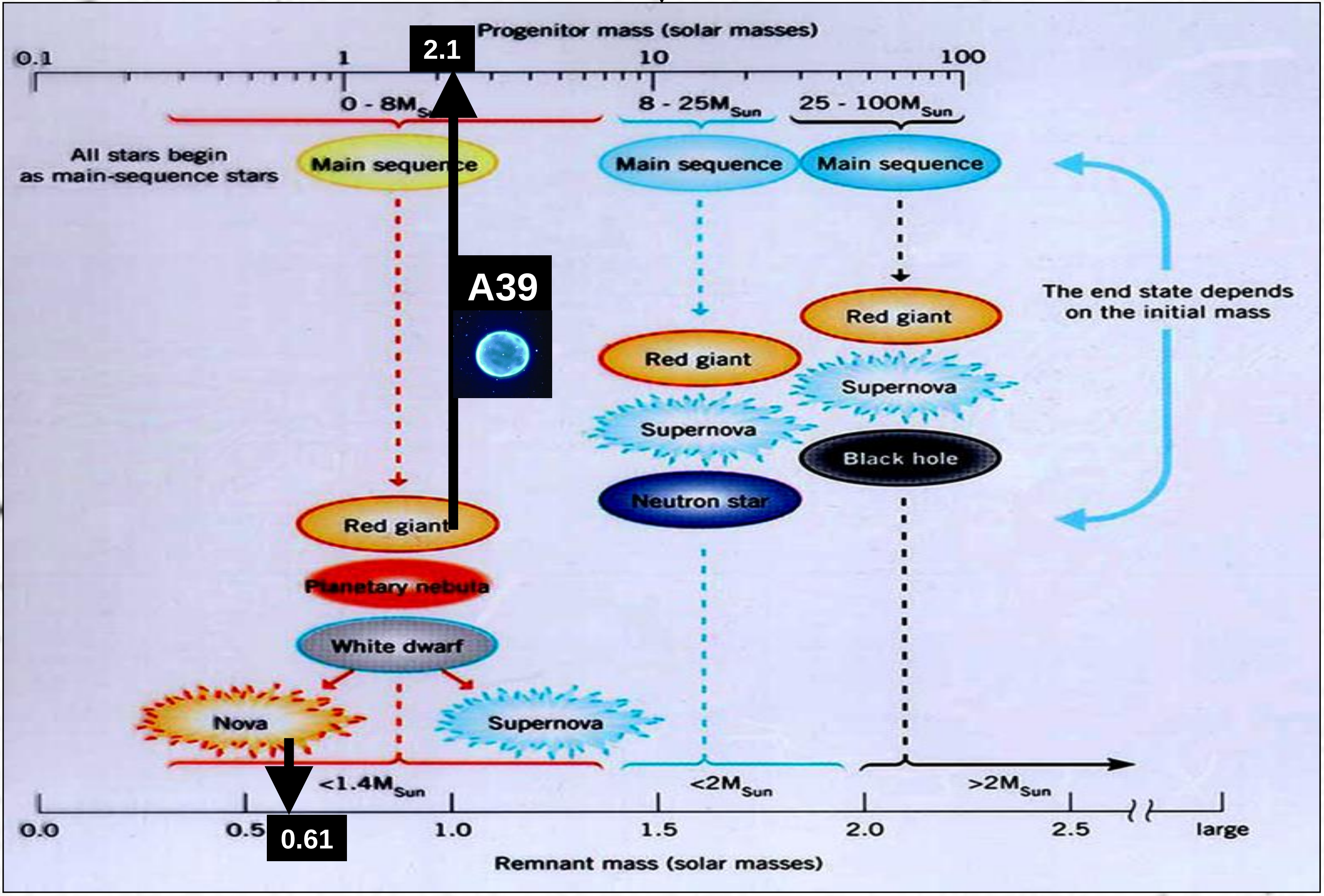
Stellar atmosphere theory II: The WD progenitor mass



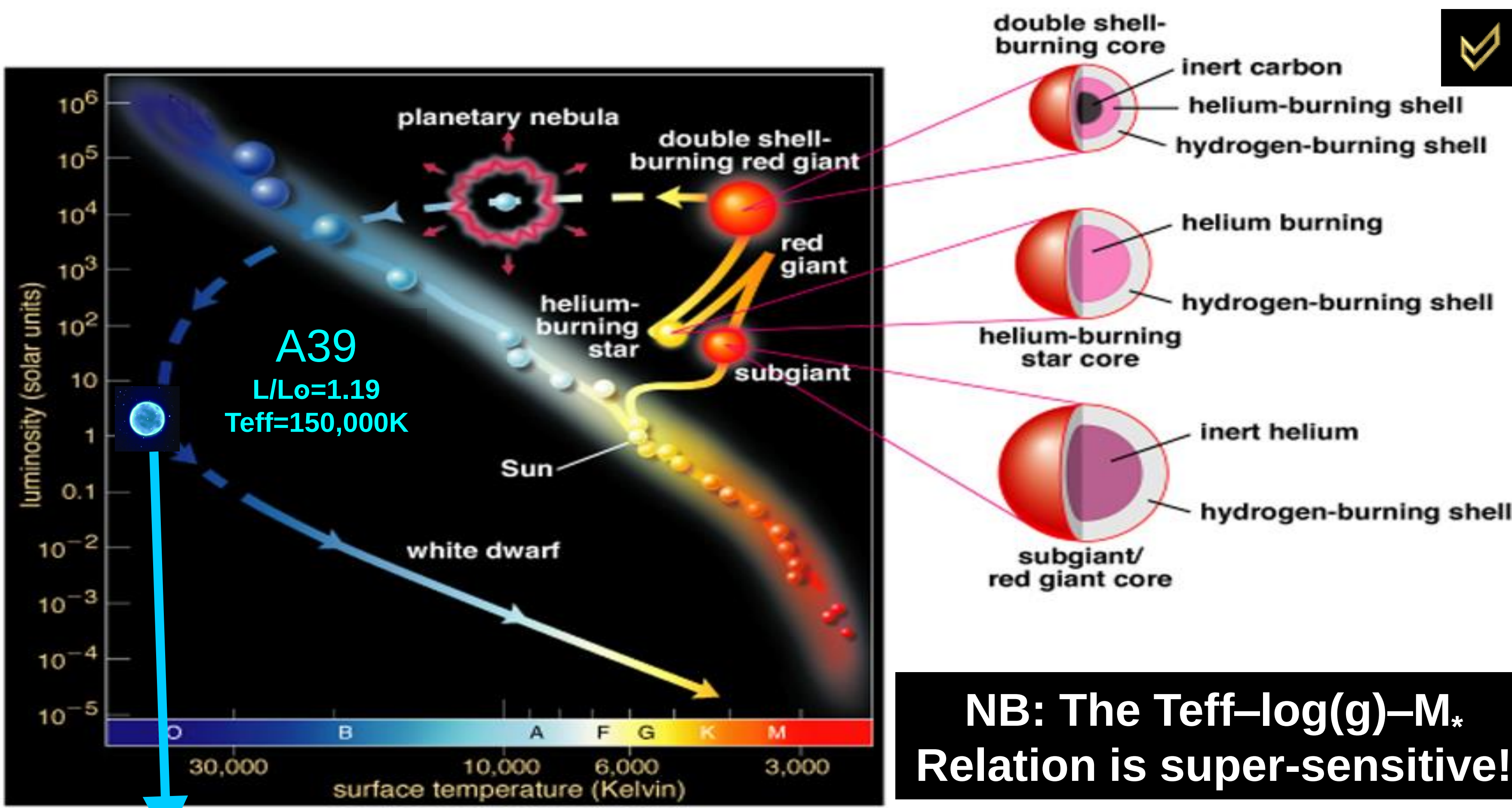




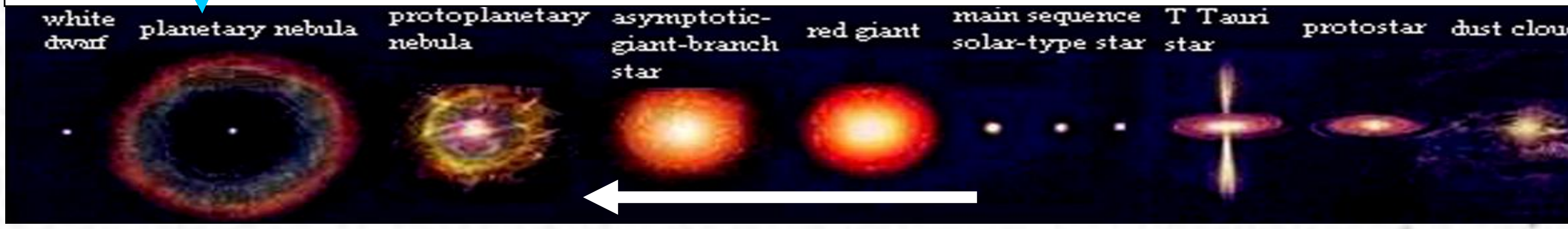
Stellar atmosphere theory III: Progenitor-remnant history



Stellar atmosphere theory IV: A39 on the HR diagram



NB: The Teff–log(g)–M$_*$ Relation is super-sensitive!



3D DUST-RT MODELLING WITH MoCaSsIN

MOCASSIN is evolving rapidly…

= 3D Monte-Carlo radiative-transfer(RT) gas code

→ To enable modelling of arbitrary geometries, inhomogeneous regions or multiple sources

Benchmarked Ercolano et al (2003a)

+ Addition of dust grain radiative transfer

→ WD2001 - Model Weingarter-Draine(2001)

Benchmarked Ercolano et al (2005)

+ Inclusion of molecular lines for PDRs and PNs

→ To enable object-ISM coupling studies

In Progress

+ Extension of high energy atomic transitions to X-ray

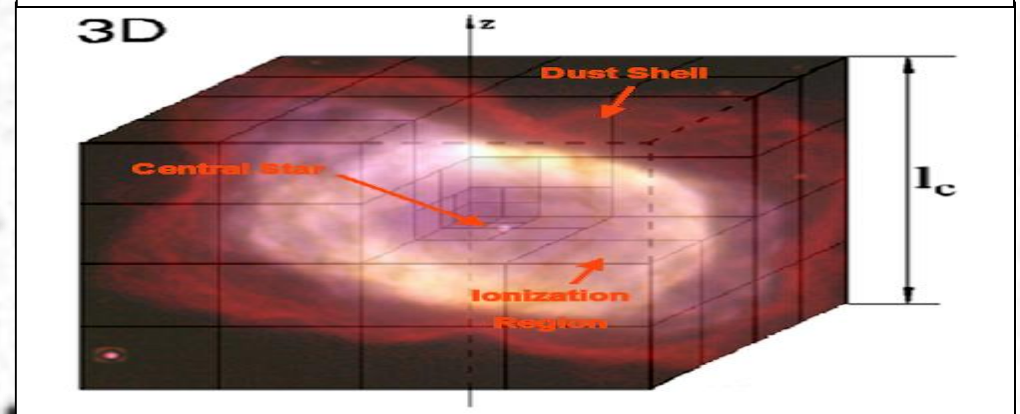
→ To model very high energy regions & AGNs

Ercolano et al (2007)

Dusty MoCaSsIN V2.0

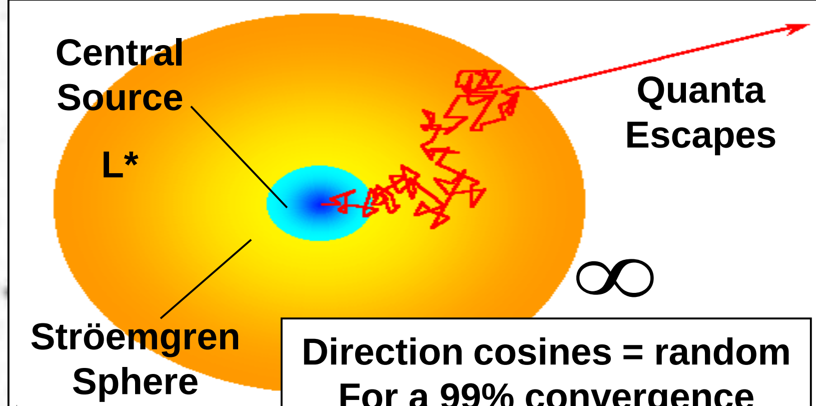
- Originally developed by Barbara Ercolano from UCL for the study of photoionized regions
- Parallel (MPI) F90 4Mb GPL code

Ionised region on 3D Cartesian adjustable grid
Multiple sources possible and dust-RT (WD2001)
Constant (ρ, T_e, κ_ν etc) in each cell
Thermal balance & ionisation equil. in each cell



Radiation field divided into *N* monochromatic constant E quanta containing *n* photons at freq. *v* → *E cons.*

$$\varepsilon(\nu) = nh\nu = \varepsilon_0 \qquad \frac{L_*}{N} = \frac{\varepsilon_0}{\Delta t}$$



Direction cosines = random
For a 99% convergence
→ 40 million quanta!

spectrum → n, opacities → absorptions
gas emissivities → n re-emited quanta
cross-sections → v of quanta

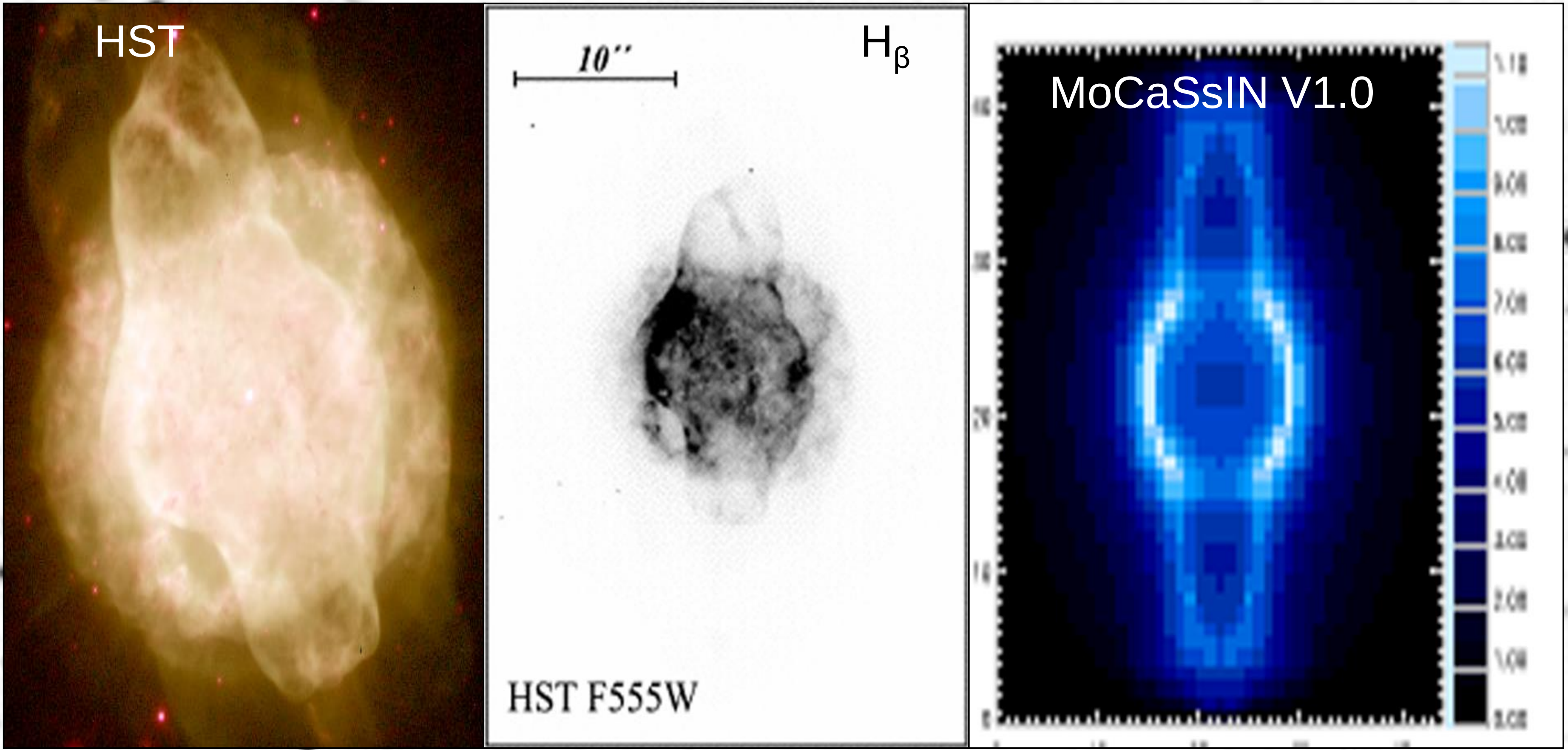
Mean intensity of rad. Field

$$J_\nu = \frac{1}{4\pi}\left(\frac{\varepsilon_0}{\Delta t}\right)\frac{1}{V}\sum_{d\nu} l$$

Integrated power in any spectral line

$$L_{\rm line} = \frac{\varepsilon_0}{\Delta t}\sum_{i=1}^{i_{\rm max}}\sum_{j=1}^{j_{\rm max}}\sum_{k=1}^{k_{\rm max}} N_{\rm line}(x_i, y_j, z_k)$$

For example…



Modelling of NGC 3918

Ercolano et al(2003)

Benchmarking 3D gas RT and 1D & 2D dust-RT

3D Gas code V1.0

benchmarked successfully based on

Lexington 2000 standards for:

1) Standard HII region ($T_* = 40000$ K)

2) Low excitation HII region ($T_* = 20000$ K)

3) High excitation planetary nebula ($T_* = 150000$ K)

4) Optically thin planetary nebula ($T_* = 75000$ K)

Table 3. Deviation (per cent) of the Monte Carlo method from the formal solution for the prediction of some significant line fluxes in the benchmark models.

Ercolano (2003a)

Line	HII40	HII20	PN150	PN75
Hβ	2.7	9.5	5.8	2.8
He I 5876 Å	5.2	6.3	0.96	4.5
[N II] 6584 Å	7.6	4.9	8.5	4.8
[O II] 5007 Å	3.1	12.0	4.0	1.1
[S III] 9532 Å	5.8	5.0	2.0	2.0

< 8%

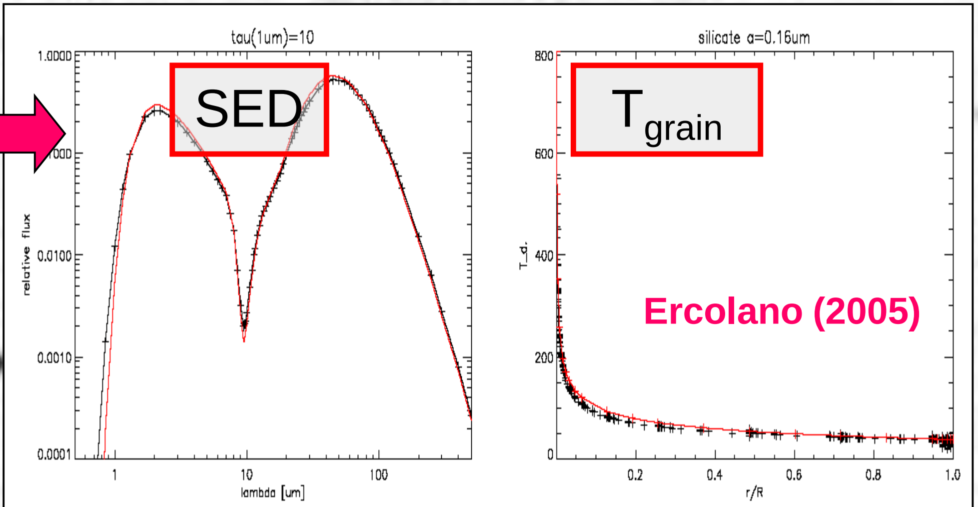
3D gas + dust code V2.01

benchmarked successfully for

1D dust clouds and 2D dust disks:

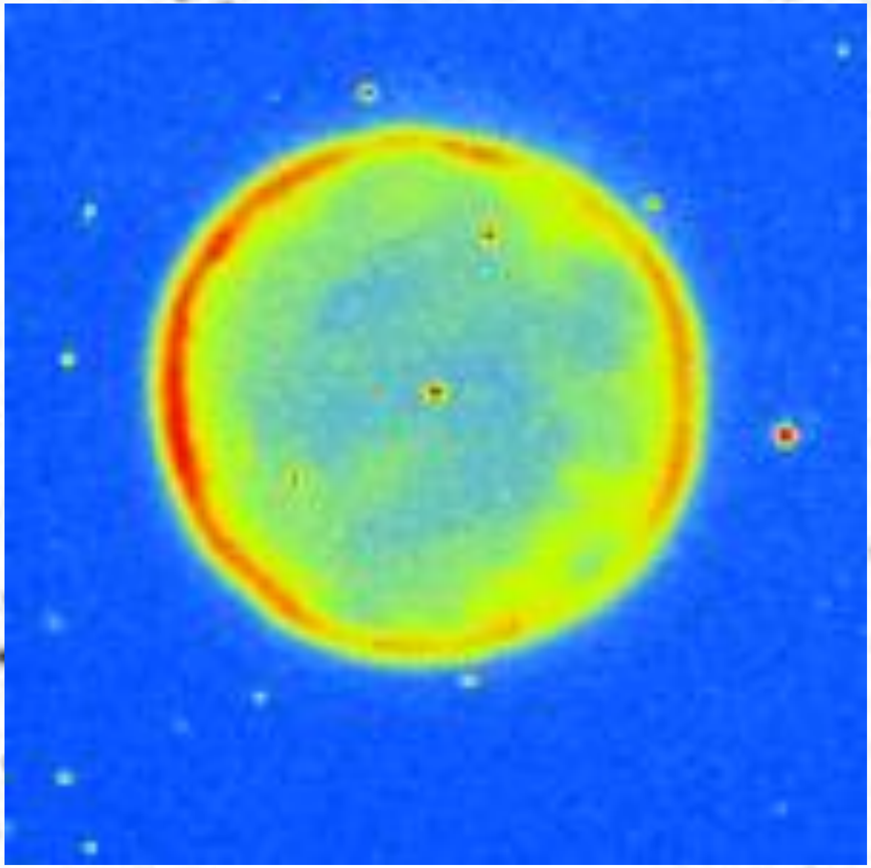
1) 1D pure dust clouds Ivezic (1997)

2) 2D pure dust disks Pascucci (2004)



Spherically symmetric, homogeneous benchmark model

Modelling A39 with MOCASSIN coming soon….



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