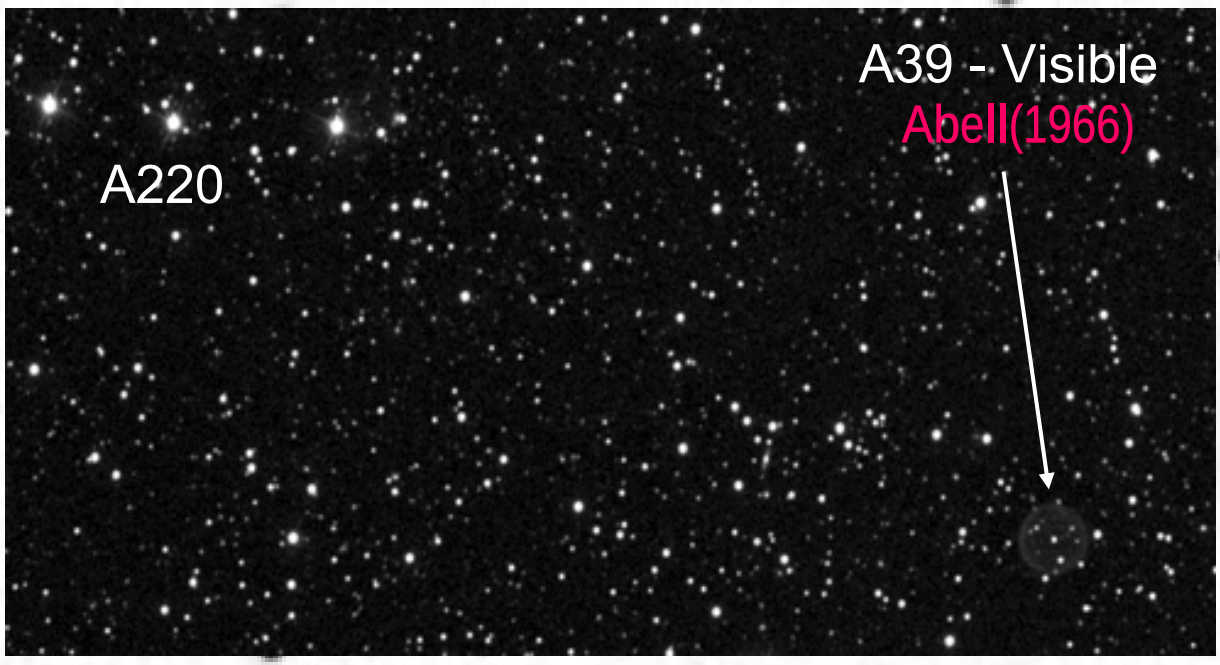
Abell 39 – Forty years on

The perfect photoionisation benchmark for stellar evolution



A39 - **O[III] λ5007**
Jacoby (2001)



Dr Michael Taylor
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OVERVIEW

3D DUST-RT PHOTOIONISATION MODELLING

BENCHMARK CASES

→ WHY A39?

AN OBSERVATIONAL ANALYSIS OF A39

CLASSIFYING A39

SOME THOUGHTS

3D DUST-RT PHOTOIONISATION MODELLING

We are attempting a holistic approach to model radiative transfer

= 3D Monte-Carlo radiative-transfer(RT) gas code V1.0 — Benchmarked



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

Ercolano et al (2003a)

+ Addition of dust grain-RT V3.0 — Benchmarked



→ *WD2001 - Model* Weingarter-Draine(2001)

Ercolano et al (2005)
Taylor (2006)

+ Inclusion of molecular lines for PDRs and PNs — In Progress



→ *To enable object-ISM coupling studies*

Ercolano

+ Identifying dust extinction & composition using AI — In Progress



→ *To develop a consistant dust grain model*

Taylor (2006)

+ Extension of high energy atomic transitions to X-ray — TO DO



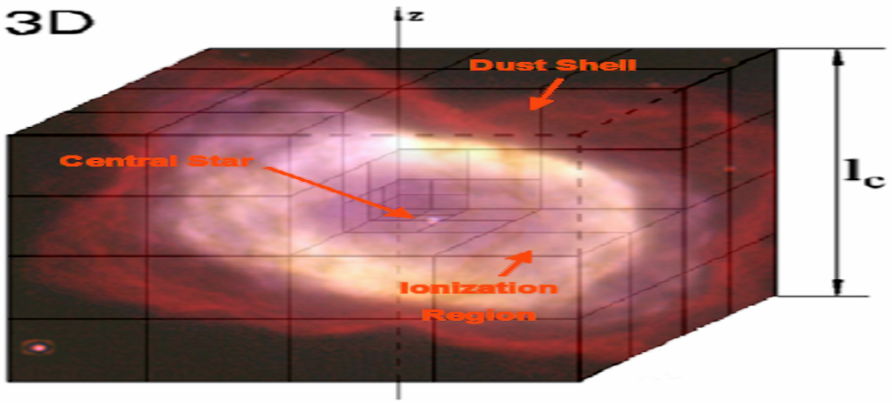
→ *To model very high energy regions & AGNs*

?

MoCaSsIN = Monte Carlo Simulations in Ionised Nebulae

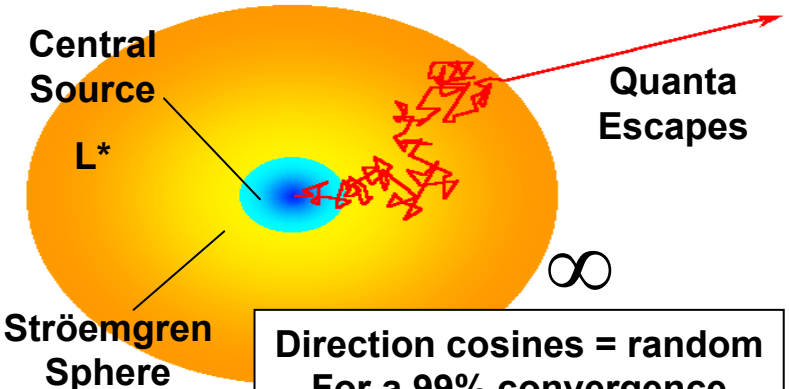
- Originally developed by Barbara Ercolano from UCL for the study of photoionized regions
- Parallel (MPI) F90 4Mb GPL code

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 monochromatic constant E quanta containing *n* photons at freq. *ν* → *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

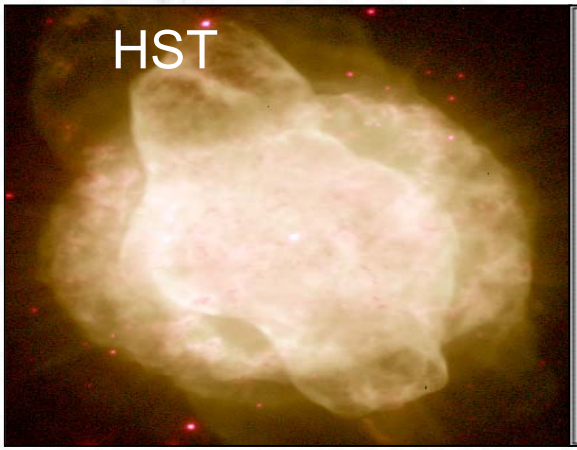
$$J_\nu = \frac{1}{4\pi}\left(\frac{\varepsilon_0}{\Delta t}\right)\frac{1}{V}\sum_{d\nu} l$$

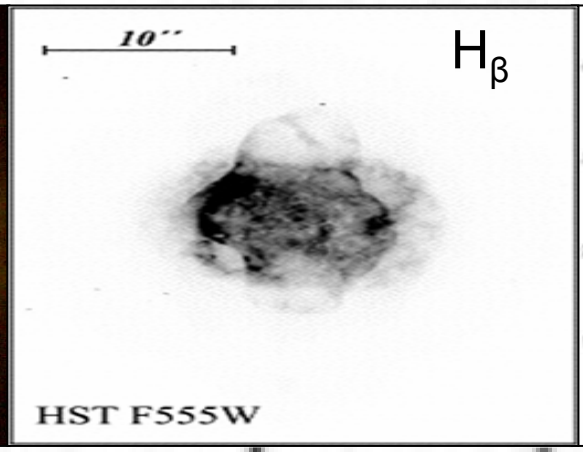
Integrated power in any spectral line

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

For example…

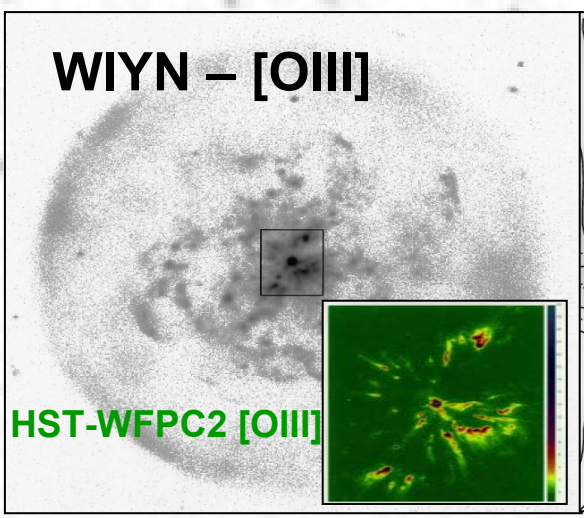
3D gas-RT modelling of bipolar PN NGC 3918

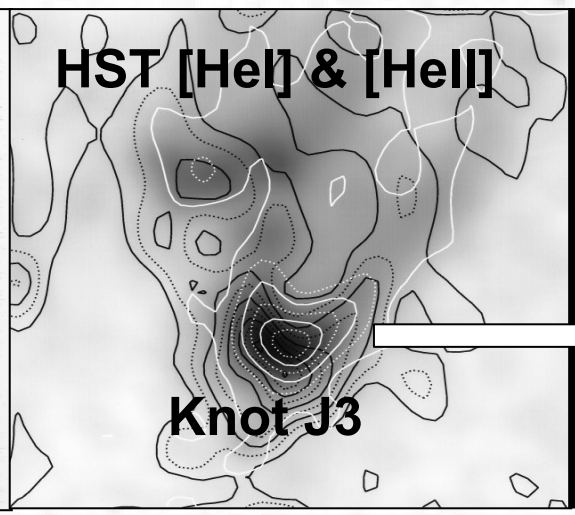


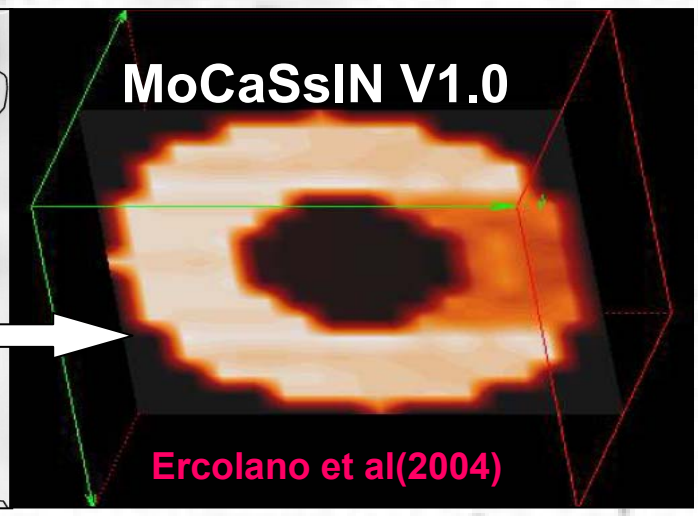




3D gas-RT modelling of knot J3 in born again PN A30







BENCHMARK CASES

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

3D Gas code V1.0

benchmarked successfully w.r.t.

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 pure dust code V2.01

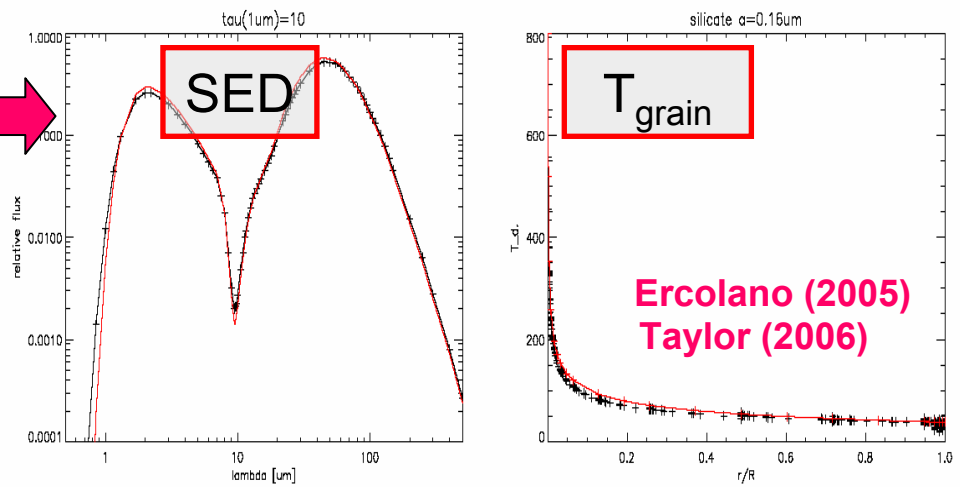
benchmarked successfully for

1D dust clouds and 2D dust disks:

1) 1D pure dust clouds Ivezic (1997)

2) 2D pure dust disks Pascucci (2004)

But, NOT 3D gas dust-RT (yet!)



Spherically symmetric, homogeneous benchmark model

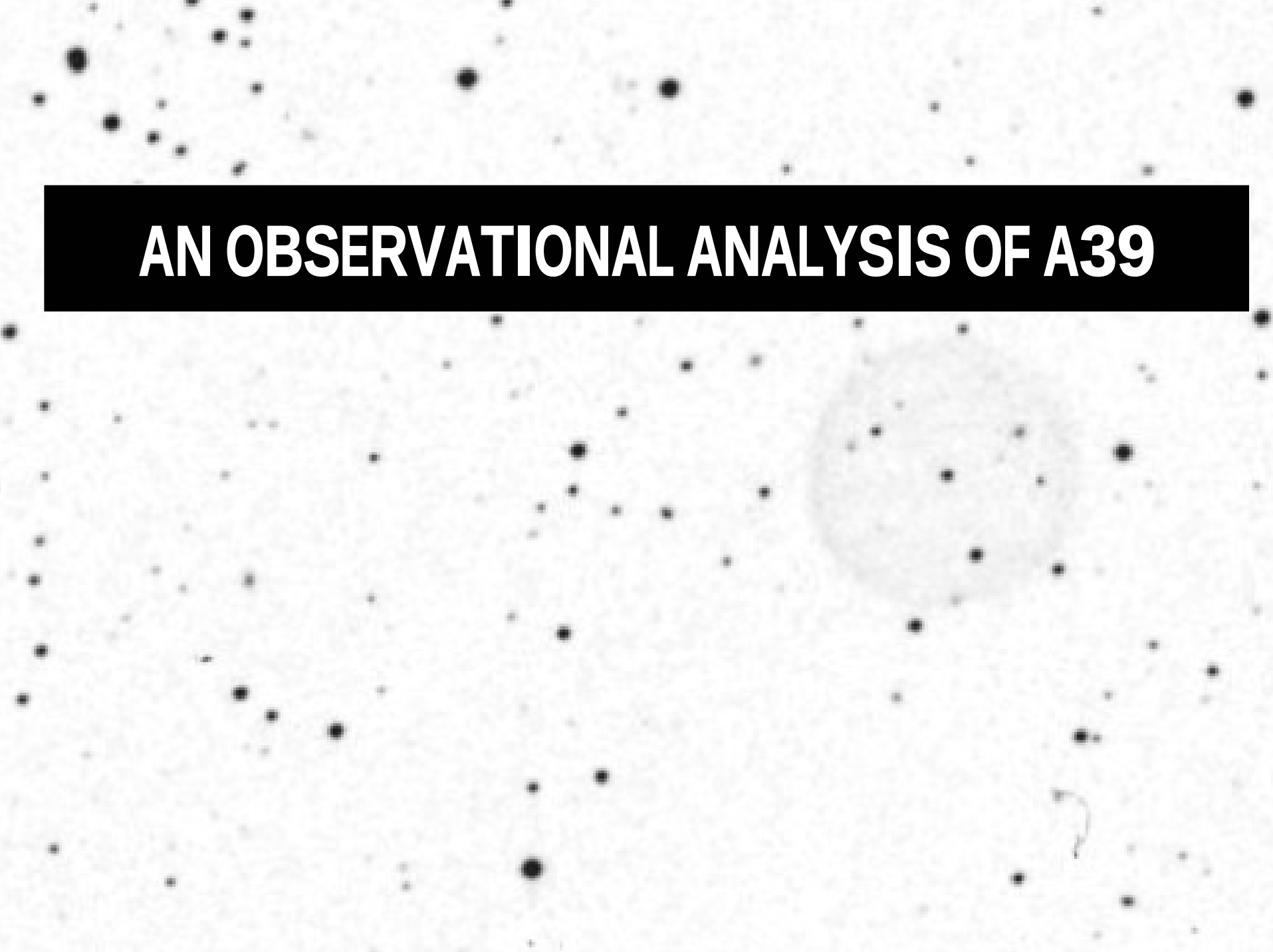

WHY A39 ?

Why study such a simple nebula such as A39?

- It is 99.6% Spherical → easiest case for modelling! (1D→3D)
- PN-ISM interaction ≈ 0 & no knots → ideal to test for example:

1) the abundance discrepancy & t^2 Wesson et al (2005), Liu(1998)
2) atomic / molecular physics from lab to space
3) dust-RT Voshchinnikov (2003), Li & Greenberg(2002)
4) how structure scrambles the spectra Williams (1992)
5) the mass loss stage of PNs Pagel (1997)

AN OBSERVATIONAL ANALYSIS OF A39

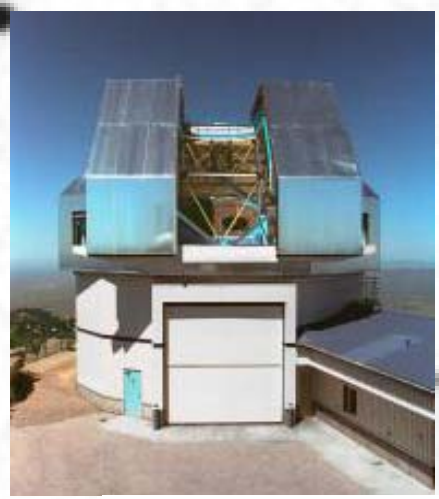


Observations of A39 thirty years apart (and colour optics)



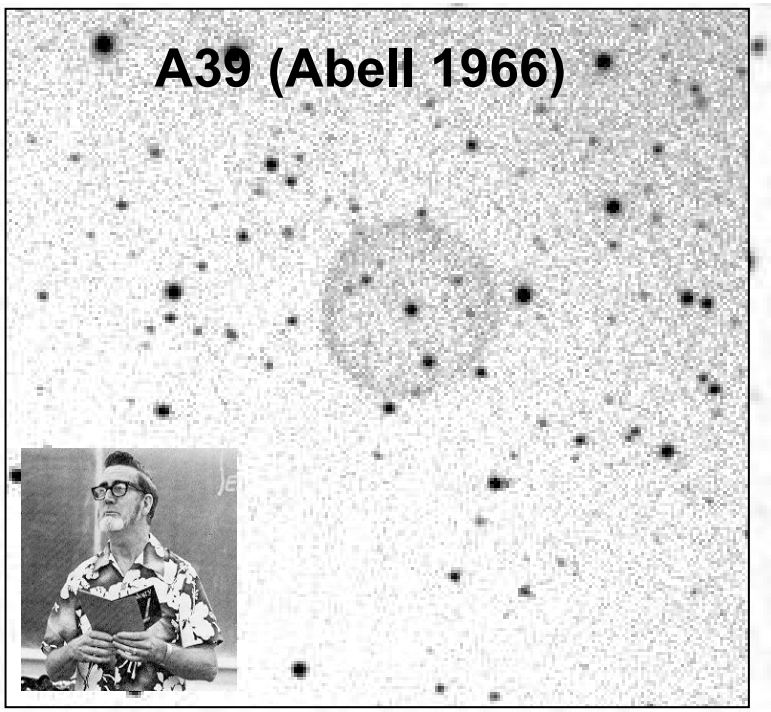


1.2m (48″) Schmidt – Oschin, Palomar





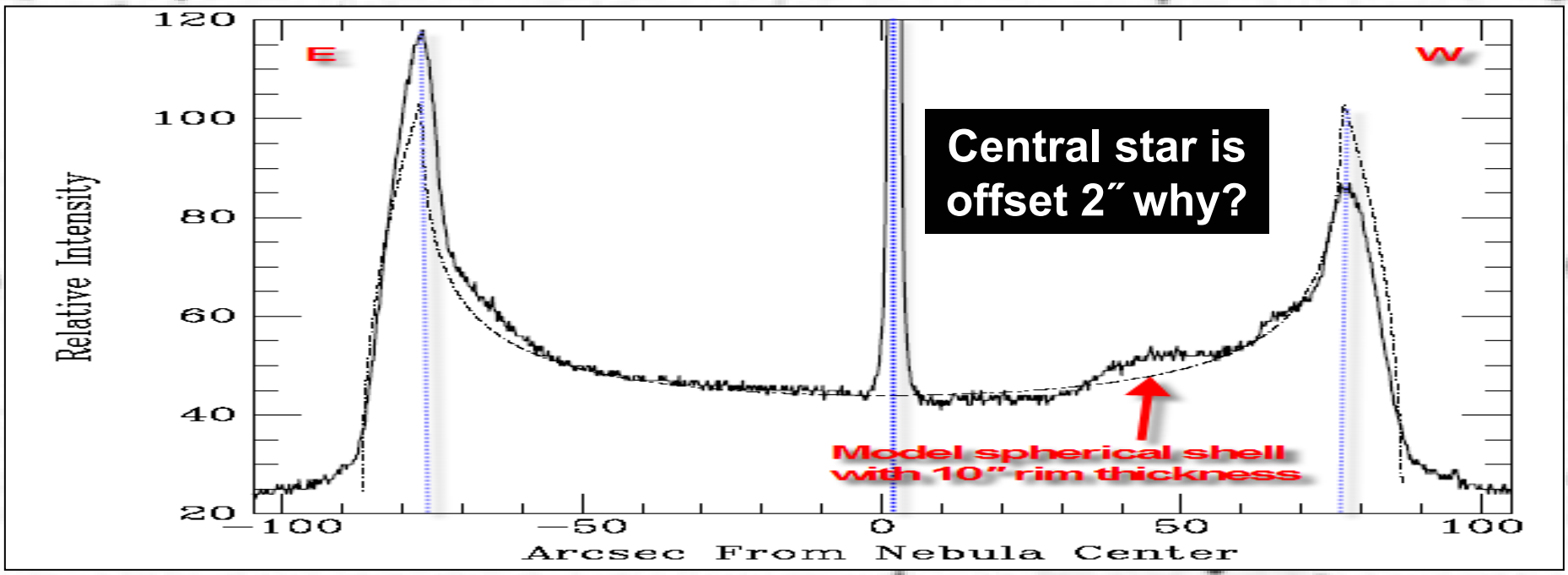
3.5m (138″) WIYN, Kitt Peak

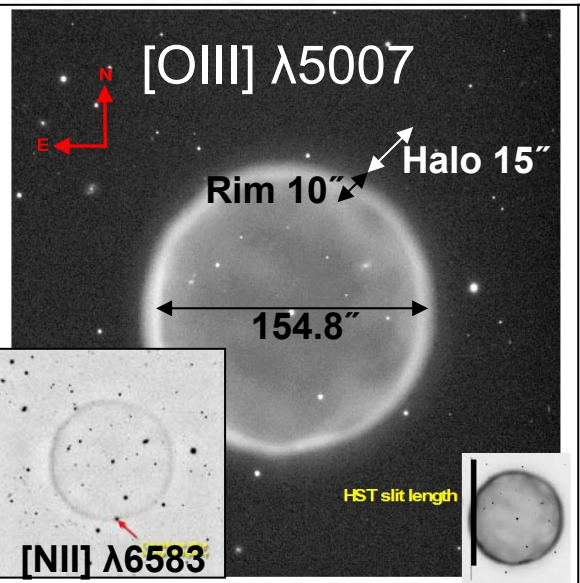


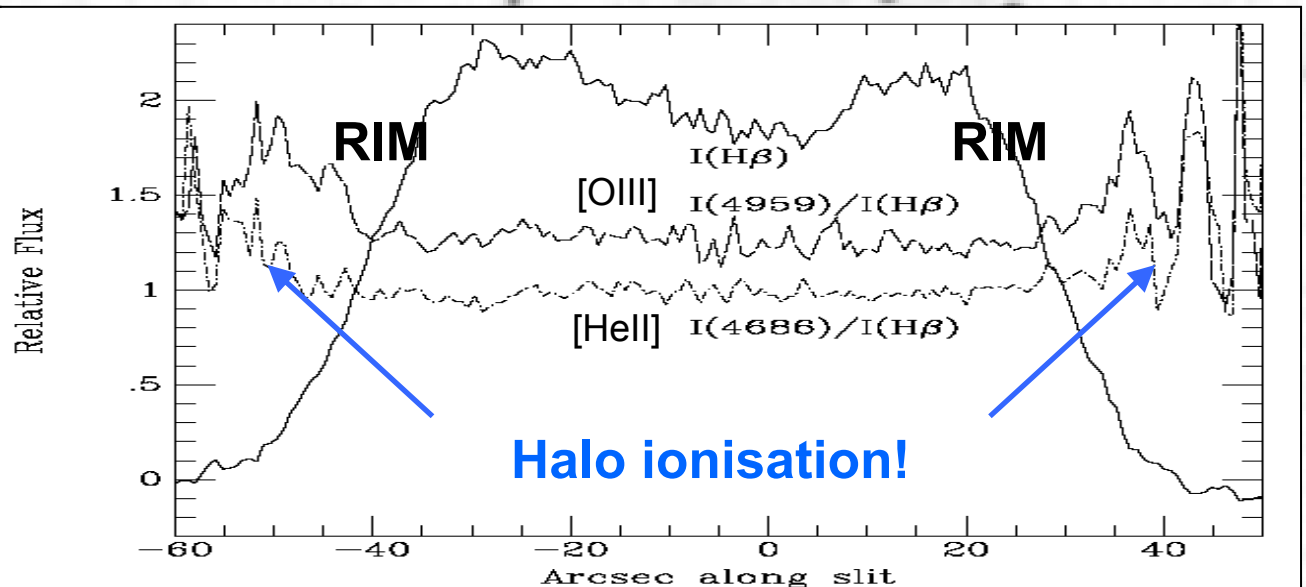


Observations of A39 at Kitt Peak in 1997

Jacoby et al(2001)



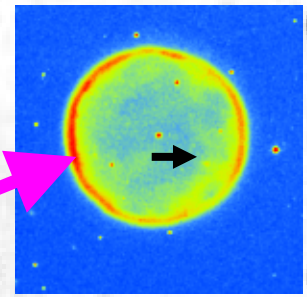




The central star is moving ≈ 1km/s! Why?

- 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)

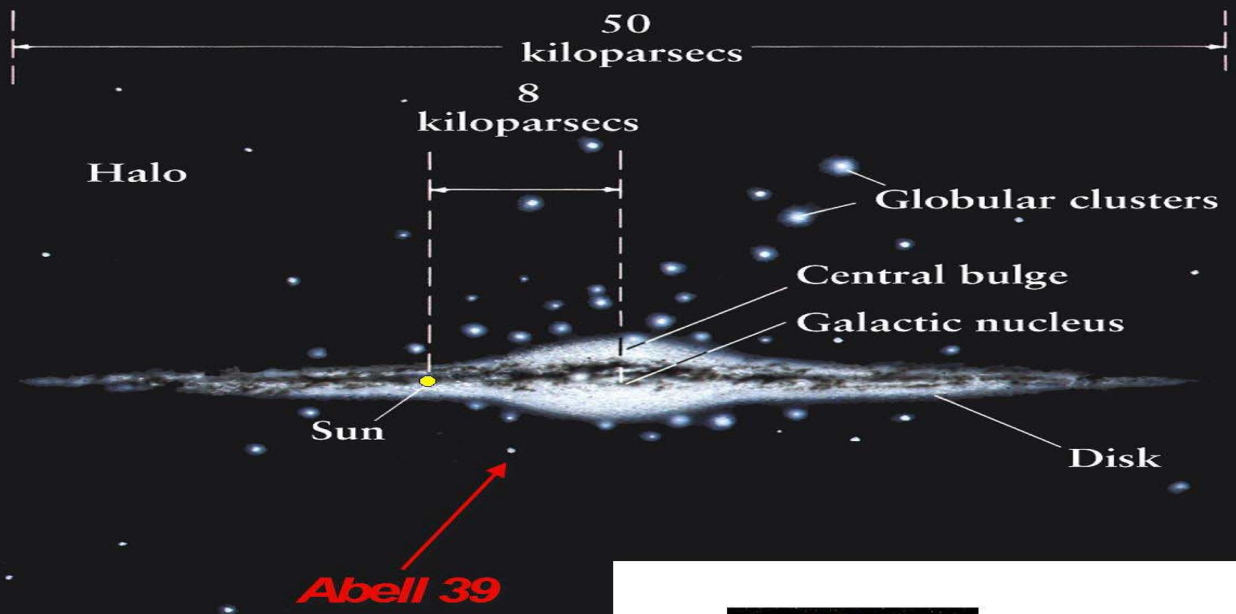
Conservation of momentum ΔM ≈ 0.05 M⊙ → 0.9 kms^{-1}

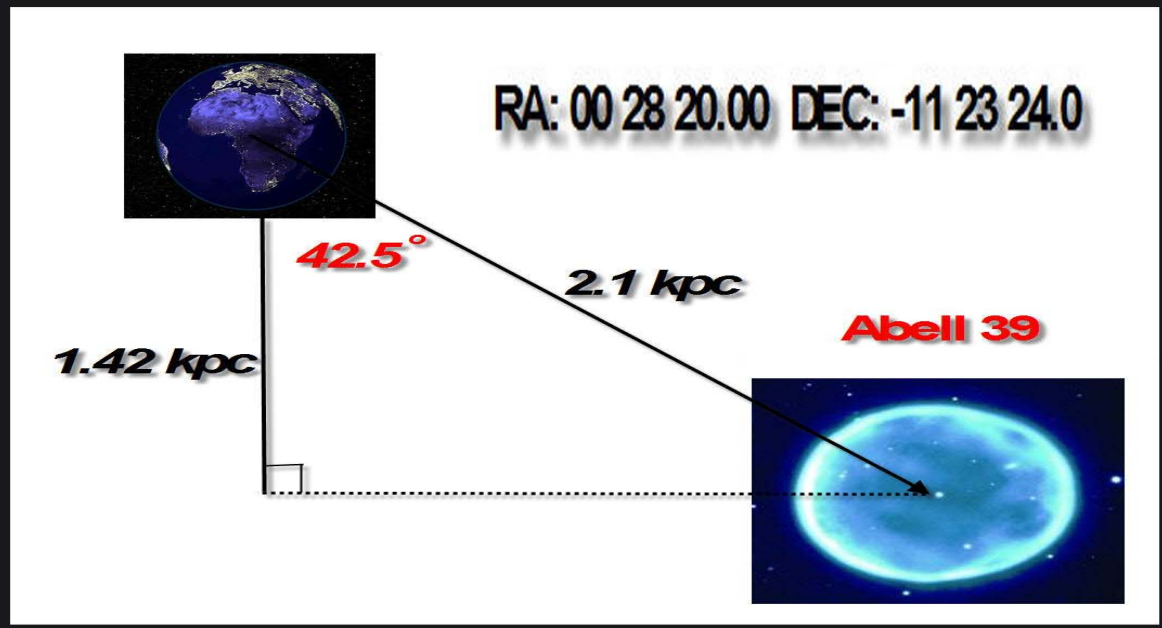
But! The star also has a redshift of 40kms^{-1} Napiwotzki(1999)

→ Is is orbiting another invisible body?!

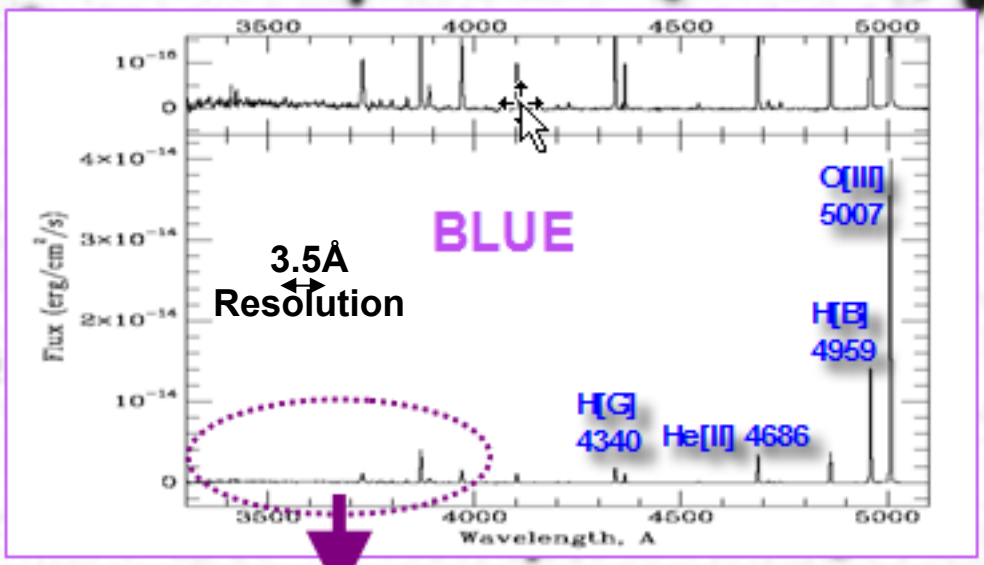
(Link with "variability of central star" identified by Abell?)

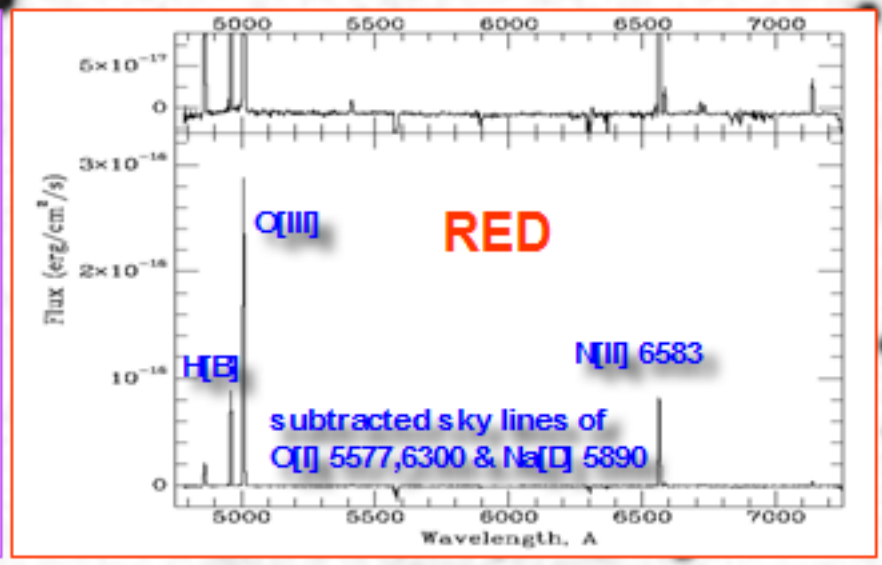
Orientating A39 in the Milky Way

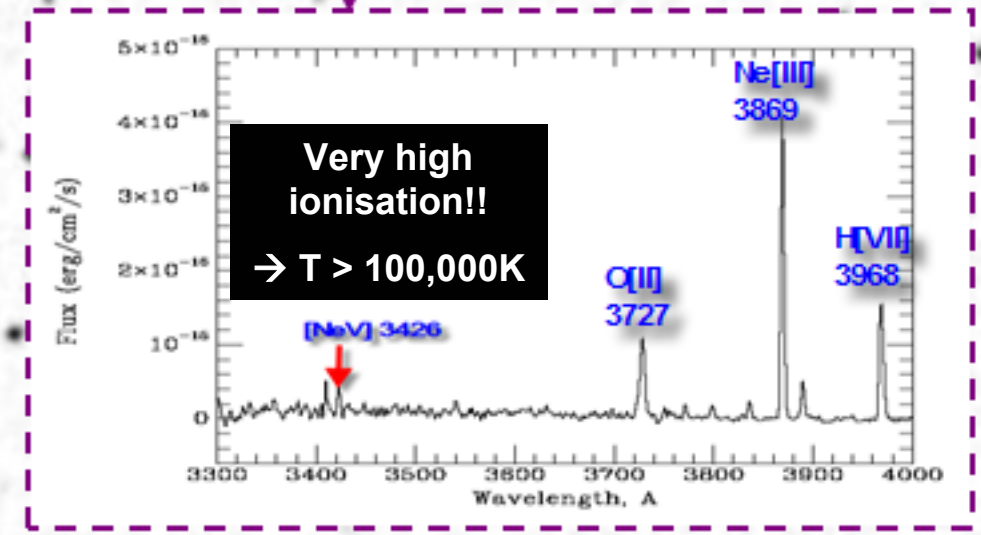


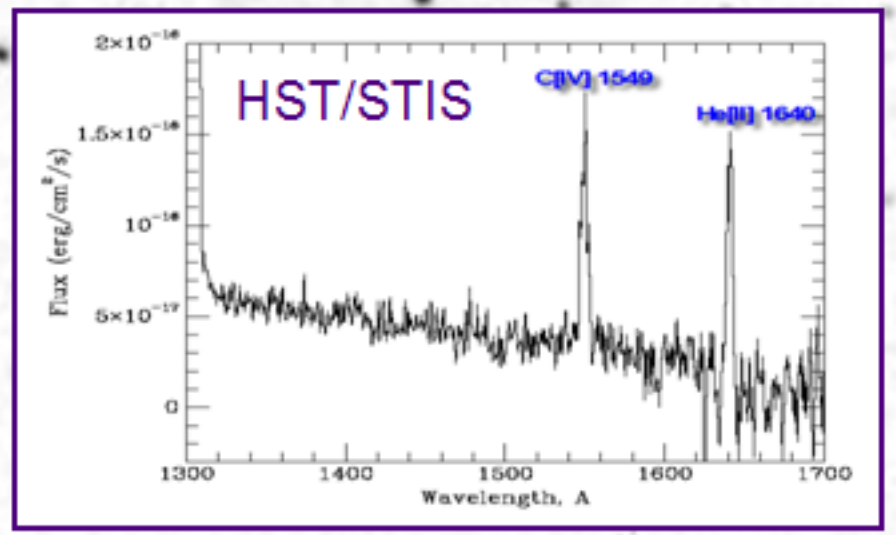


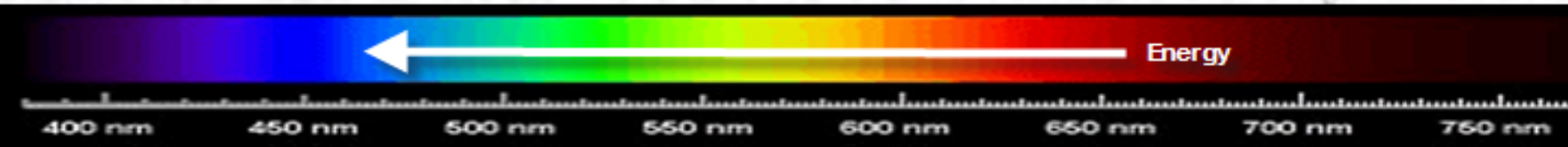
The line emission spectra in visible (WIYN) and UV (HST)











Emission line analysis (in brief!)

- **e^- density(n_e) and shell mass → Missing mass of 0.4M⊙ in halo**

  [SII] λλ6716/6731=1.48 → n_e<100cm^{-3}

  surface brightness in Hβ recomb. line → ne ≈ 30cm^{-3} → M_{shell} = 2x10^{33}g ≈ 1M⊙

- **e- temperature** [OIII] λλ5007/4363=48 **→ Te =15,400K**

- **Timescales → Atomic equilibrium**

  Expansion age ≈ 23,000yr, H-recomb. time ≈ $1/\alpha_A n_e$ ≈ 3,400yr, thermal time ≈ 600yr

- **Photoelectric heating rate(G) → Nebula is only ionised by its star**

  mean photo e^- energy <ε> ≈ <hv – 13.6ev> = 5eV → $G=n^2\alpha_B\langle\varepsilon\rangle \approx 2.3\times10^{-9}$ eVcm^{-3}s^{-1}

  >> heating rates from cosmic rays, the CMB and diffuse galactic ionising rad

- **Ionising photons and optical depth**

  The total recombination rate in the nebula $R_{recom} = L(H\beta)\alpha_B/4\pi j_B(H\beta) \approx 2.0\times10^{45}$s^{-1} Jacoby 2001

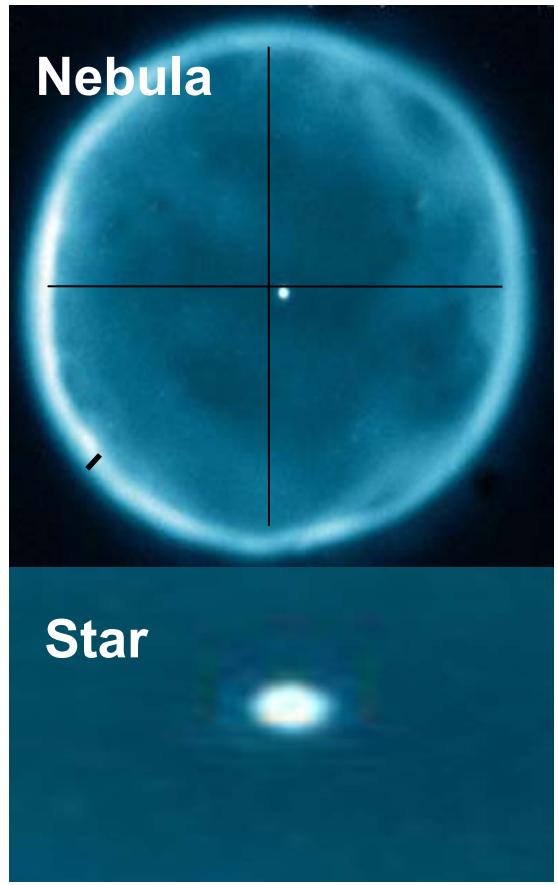
  At 2.1kpc the V magnitude of 15.6 → absolute magnitude M_V = 3.9. For T_*=150,000K, the number of H-ionising photons from Rauch stellar continua (normalised to M_V) >> R_{recom}

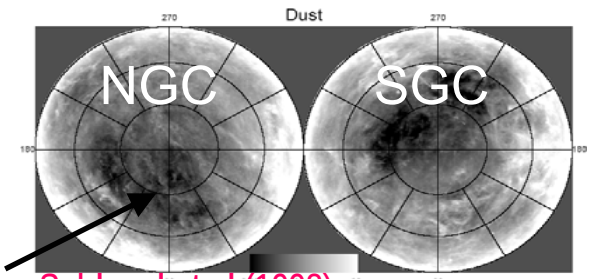
  → nebula absorbs a small % of *photons → matter bounded

  → τ_{Lyman}≈0.01 → gas is optically thin → H is fully ionised

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	15,400
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 (Balmer decriment)	cH(β)	N/A	0.049
Reddening (H I col density past A39	c[E(B-V=0.06]	N/A	0.08

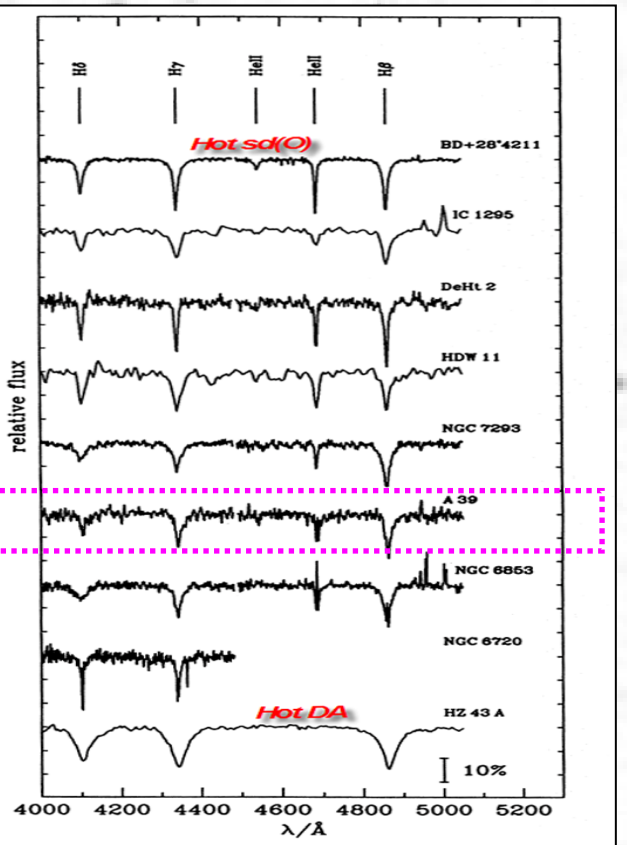




Schlegel et al (1998)

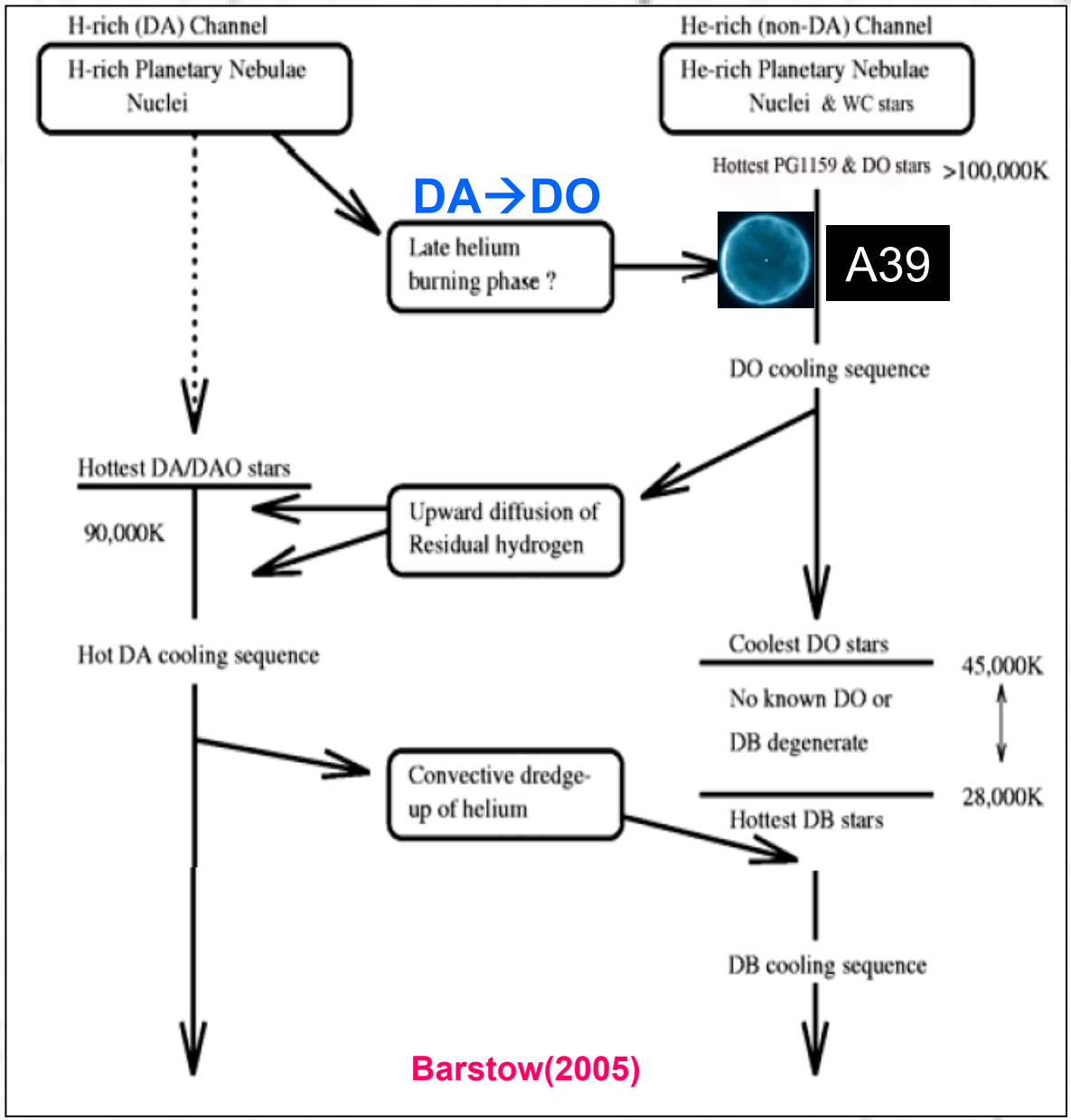

CLASSIFYING A39

WD classification



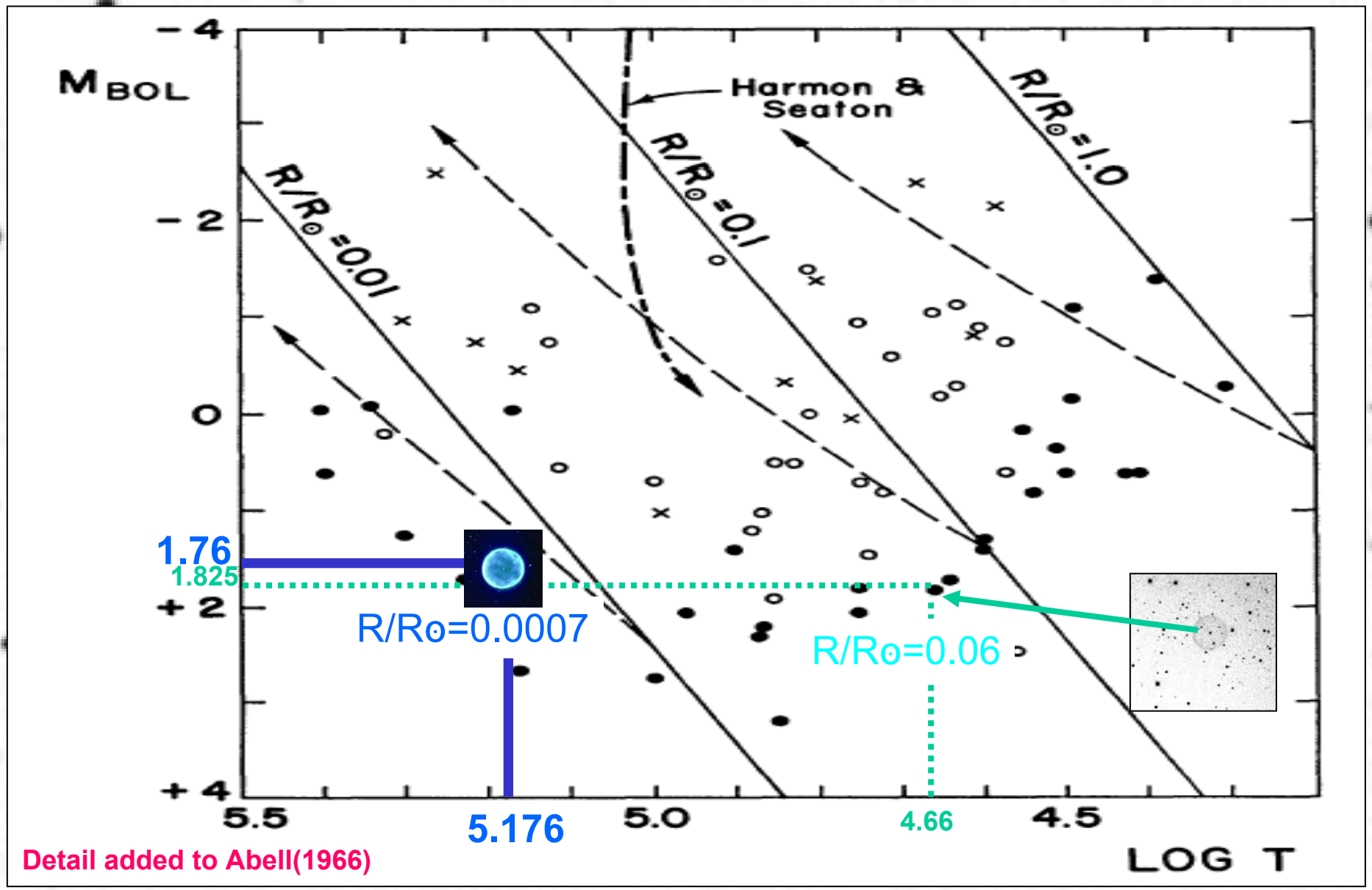
Spectral Type	Characteristics
DA	Only Balmer lines; no He I or metals present
DB	He I lines; no H or metals present
DC	Continuous spectrum, no lines deeper than 5% in any part of the electromagnetic spectrum
DO	He II strong; He I or H present
DZ	Metal lines only; no H or He lines
DQ	Carbon features, 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)

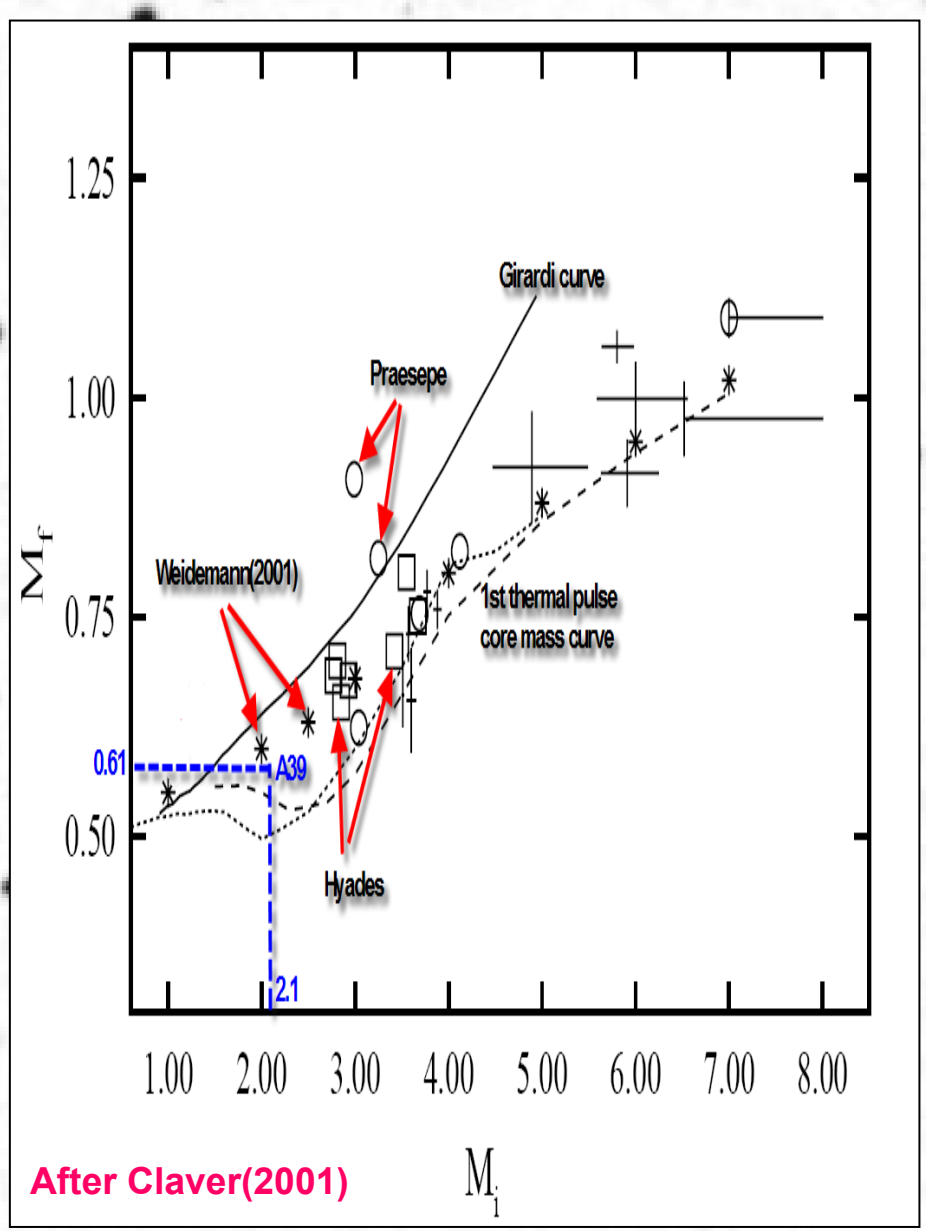


Barstow(2005)

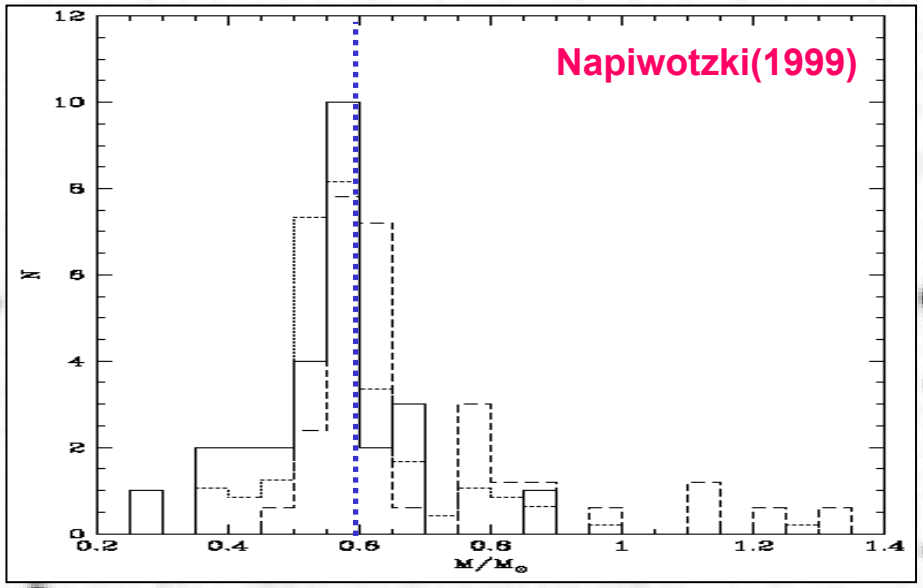
The WD radius

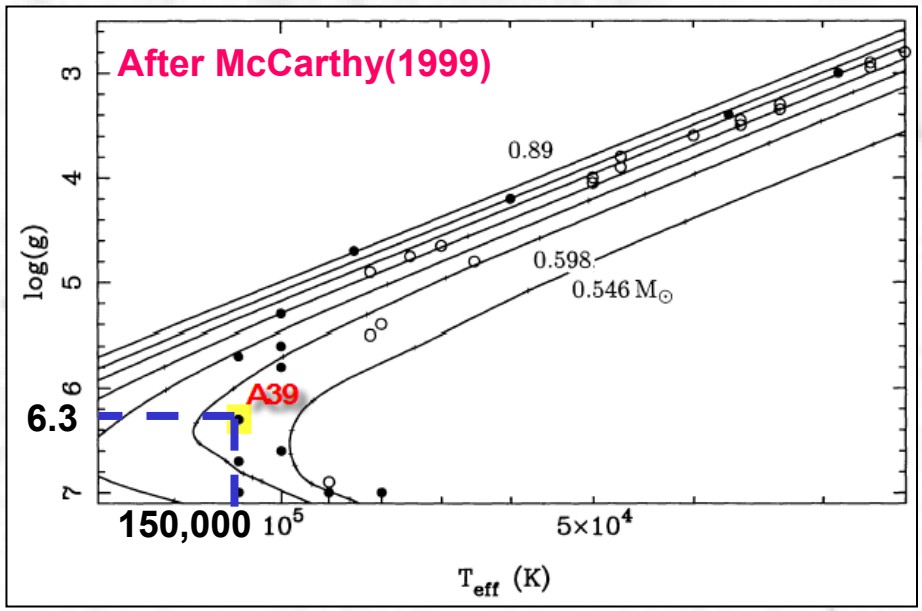


The WD progenitor mass

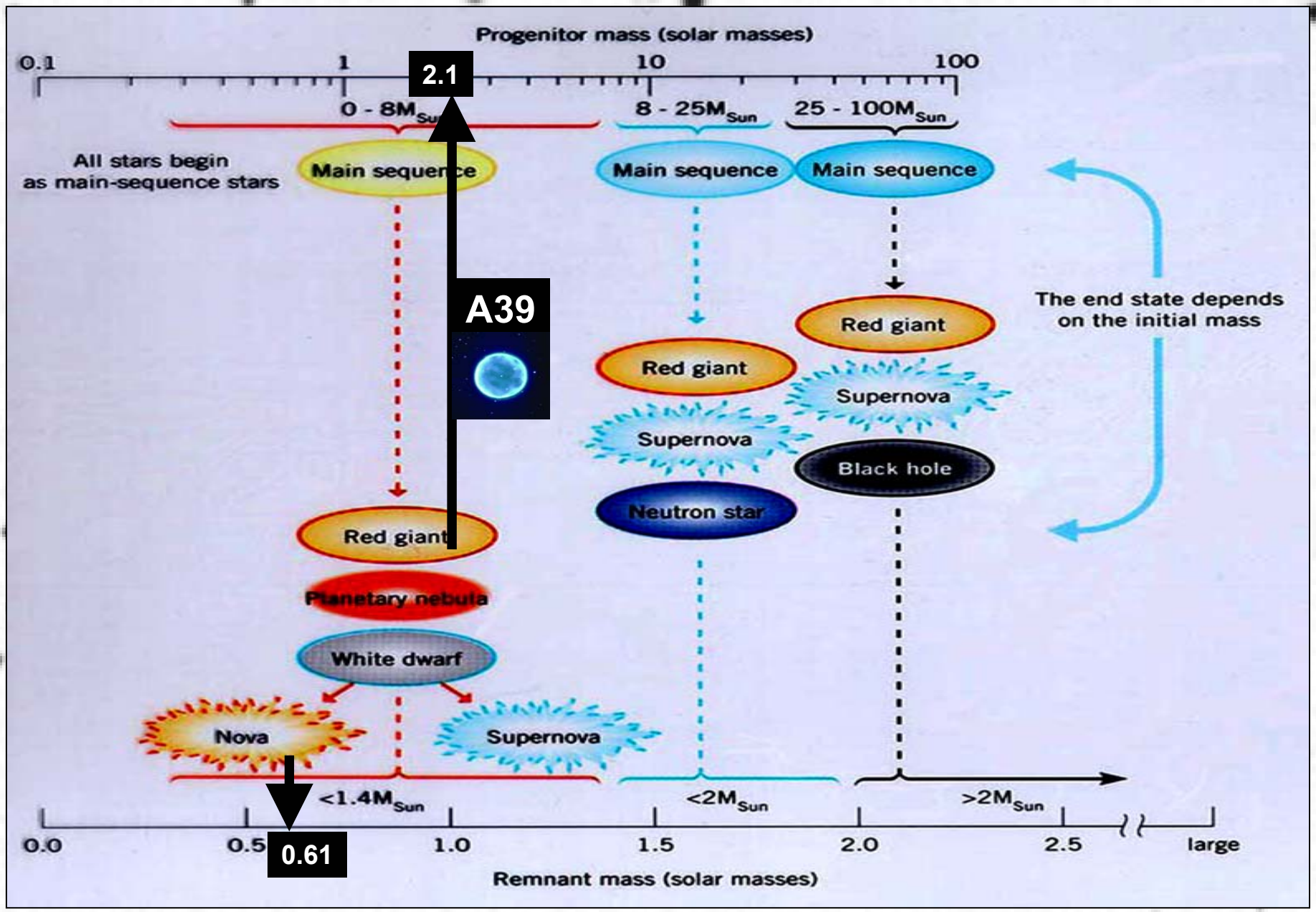


After Claver(2001)

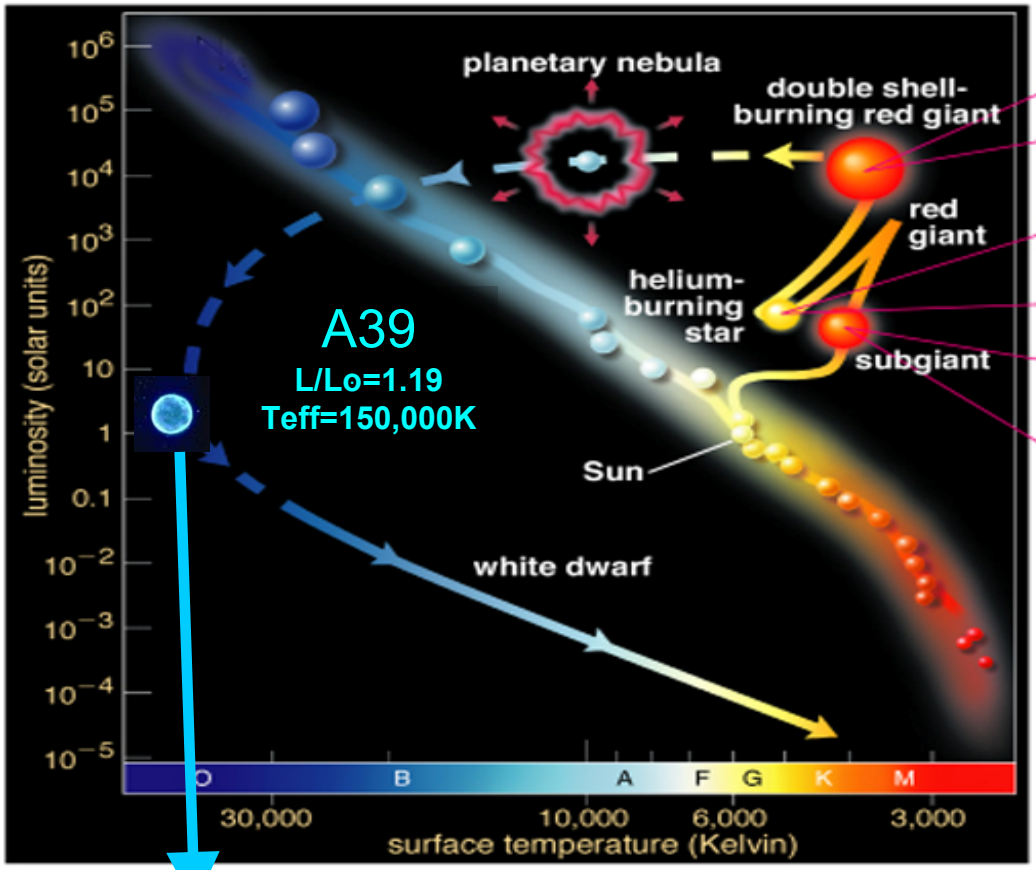


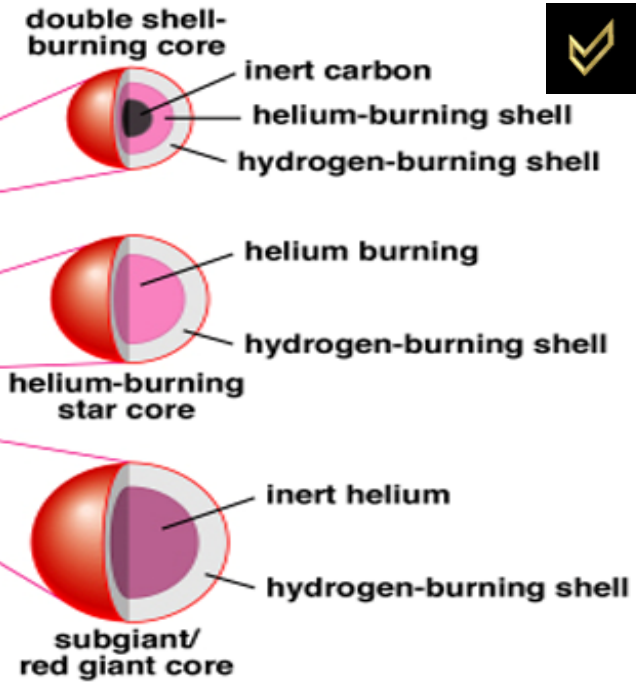


WD progenitor-remnant history?

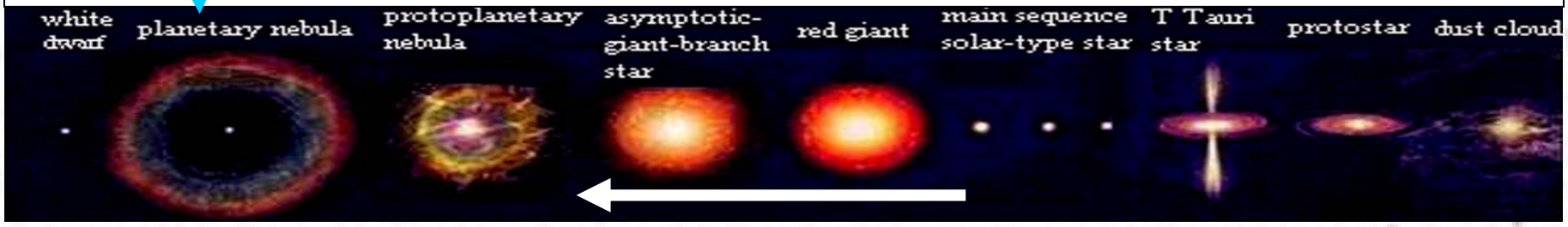


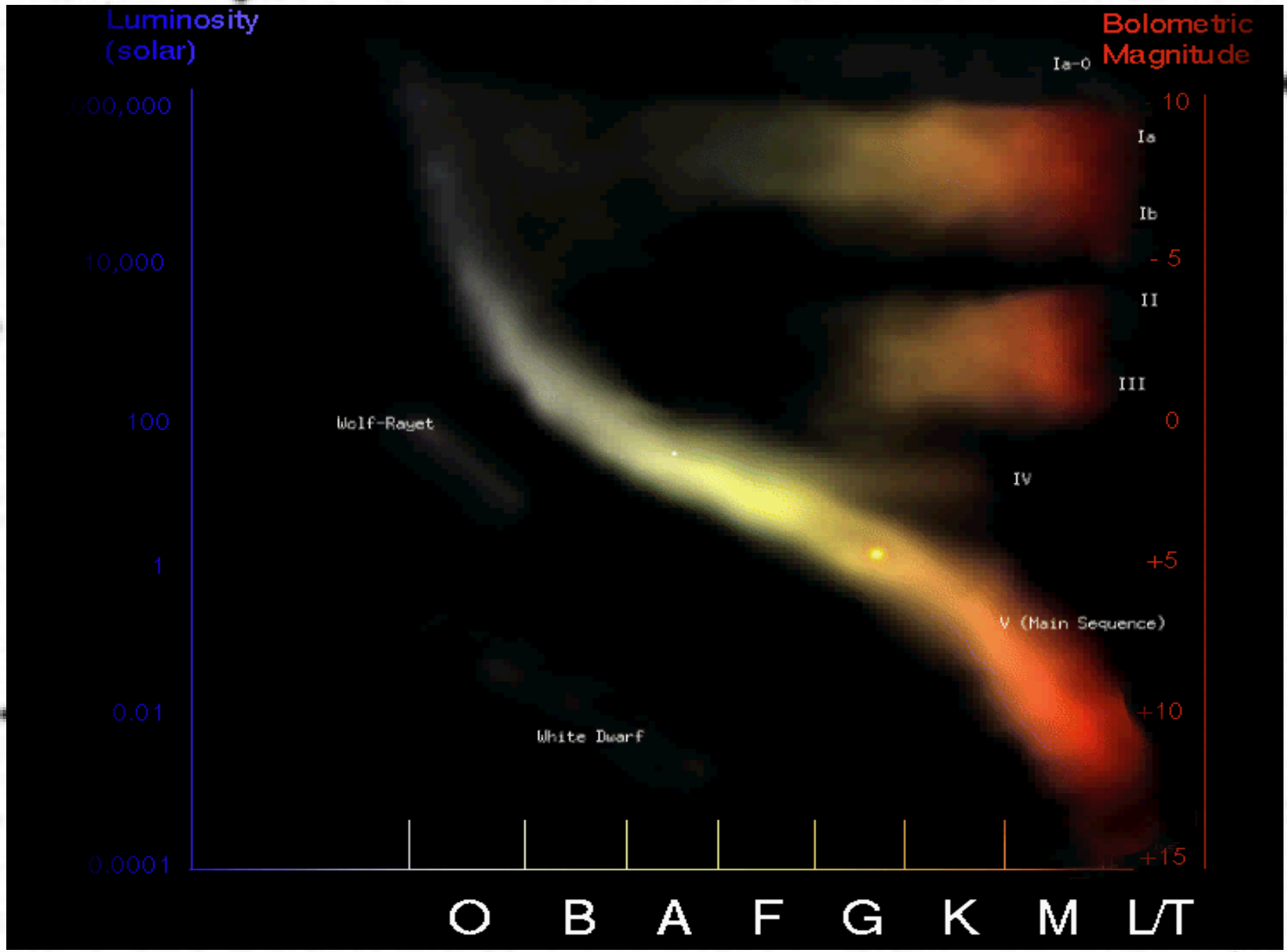
A39 on the HR diagram





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




Luminosity
(solar)
Bolometric
Magnitude
Ia-0
Ia
Ib
II
III
IV
V (Main Sequence)
Wolf-Rayet
White Dwarf
000,000
10,000
100
1
0.01
0.0001
- 10
- 5
0
+5
+10
+15
O
B
A
F
G
K
M
L/T

SOME THOUGHTS (very naïve ones!)

- Advanced stellar atmosphere models are crucial → T_{eff}, log(g), M_*
  - → precise progenitor-remnant histories
  - → affects the PNLF for extra-galactic distance measures
  - → determination of mass locked up in black dwarves?

- Maybe there are more hot DO WDs than we thought ?
  - → may alter chemical evolution/nucleosynthesis scenarios?

- 3D dust-RT models may help constrain and identify the cold H-deficient component of nebular gas responsible for enhancing ORLs (since t^2 appears unable to resolve abundance discrepancy). I have a hunch it is dust!

Many thanks! Over to you… (suggestions please!)

