Massive stars close to the Eddington limit

Artwork: Jose Groh, image credits: SOAR, Eta Car (N. Smith, NASA)

Jose Groh (Max-Planck-Institute for Radioastronomy, Germany)

Collaborators

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MAX-PLANCK-GESELLSCHAFT

Max-Planck-Institut für Radioastronomie

Outline

1. **Very massive stars: evolution, mass loss, and the Eddington limit**

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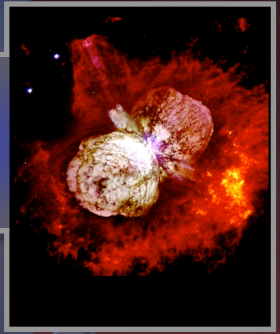
2. The Luminous Blue Variable stage: living near the Eddington limit

(a) Observational consequences



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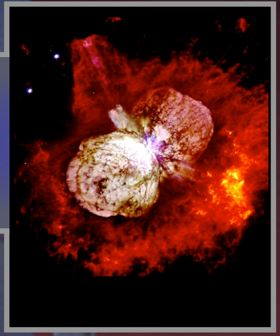
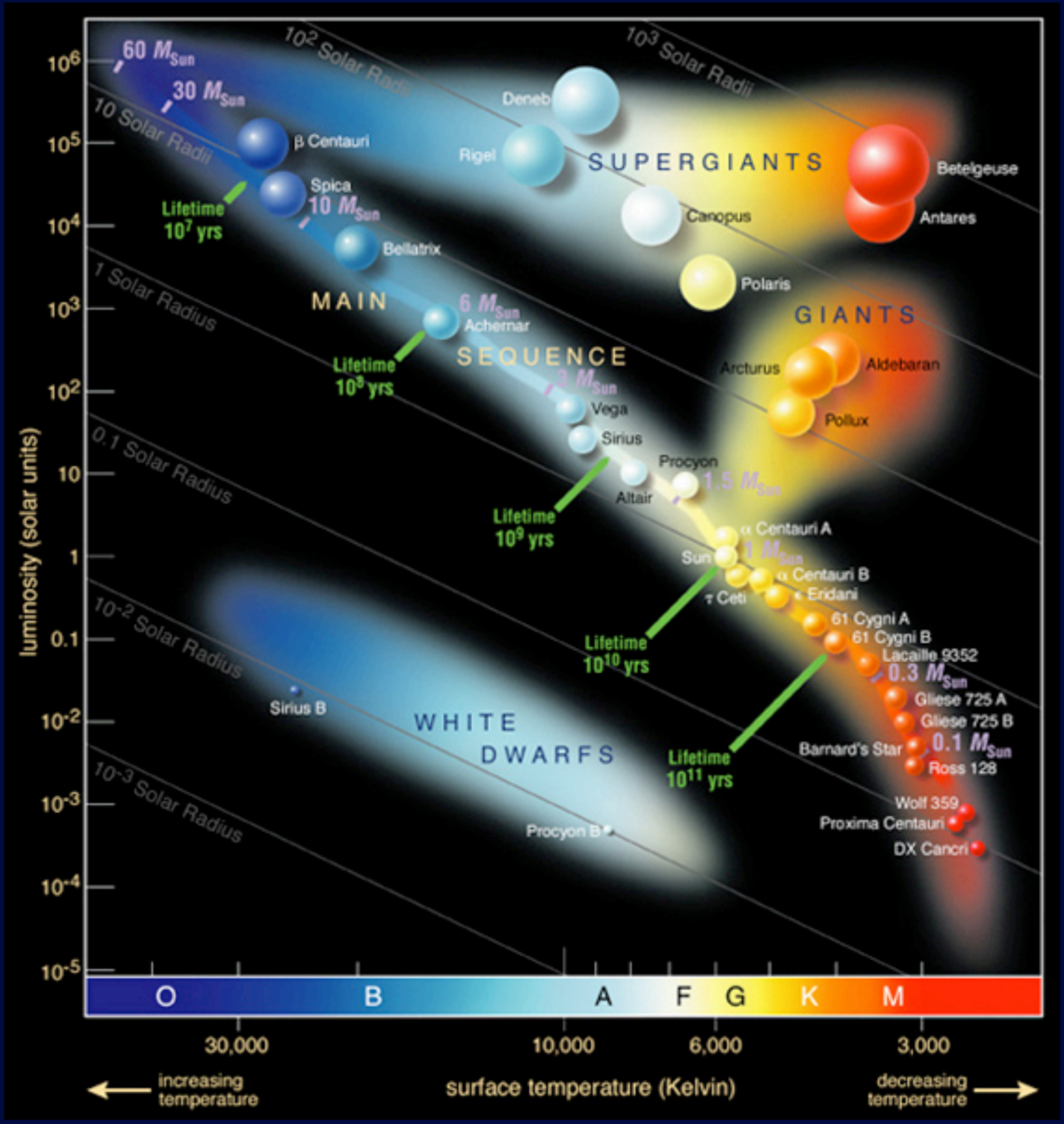


(b) Open points and science opportunities with *SOAR*

1. Very massive stars
Impact on galactic scales

1. Very massive stars
Location in the HR diagram



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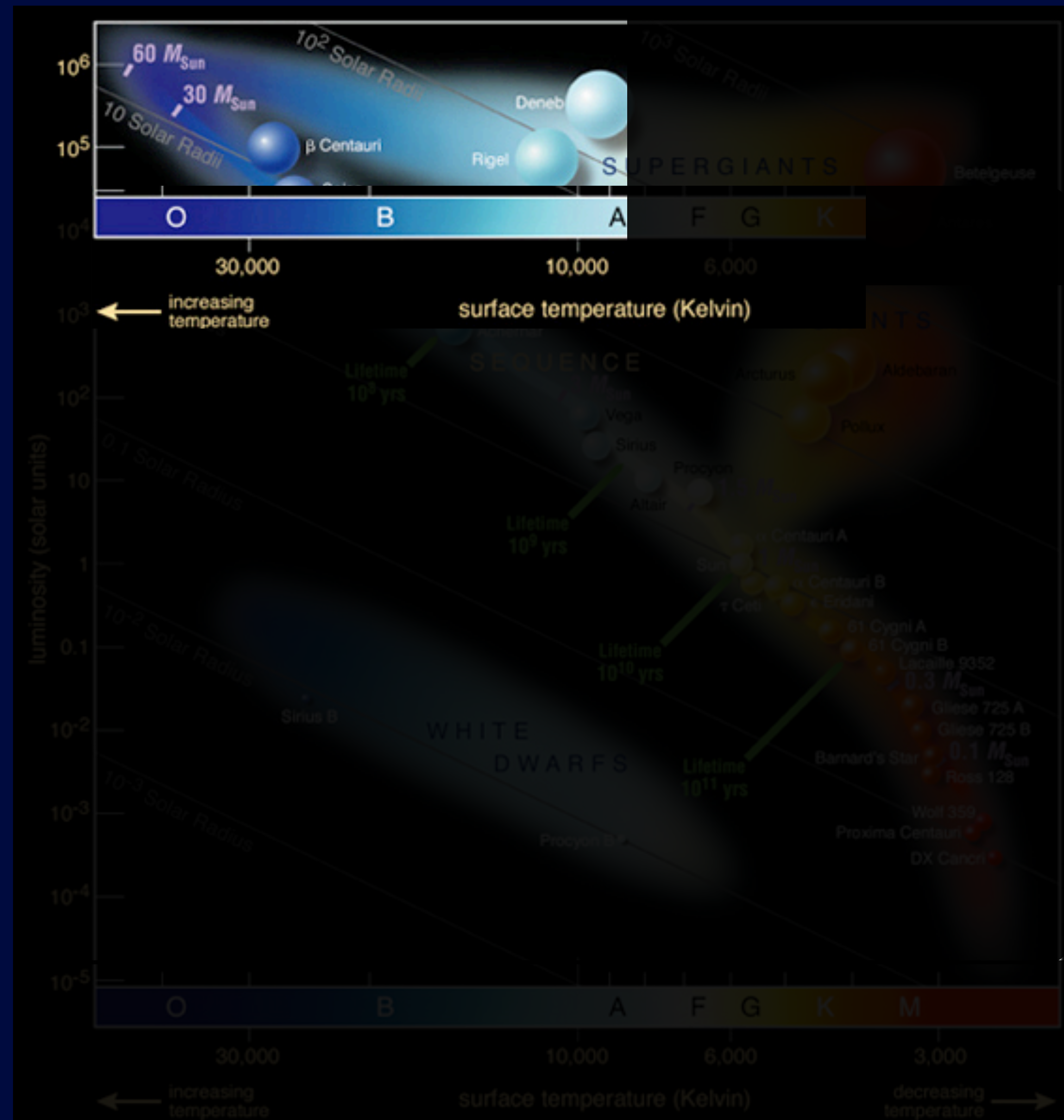

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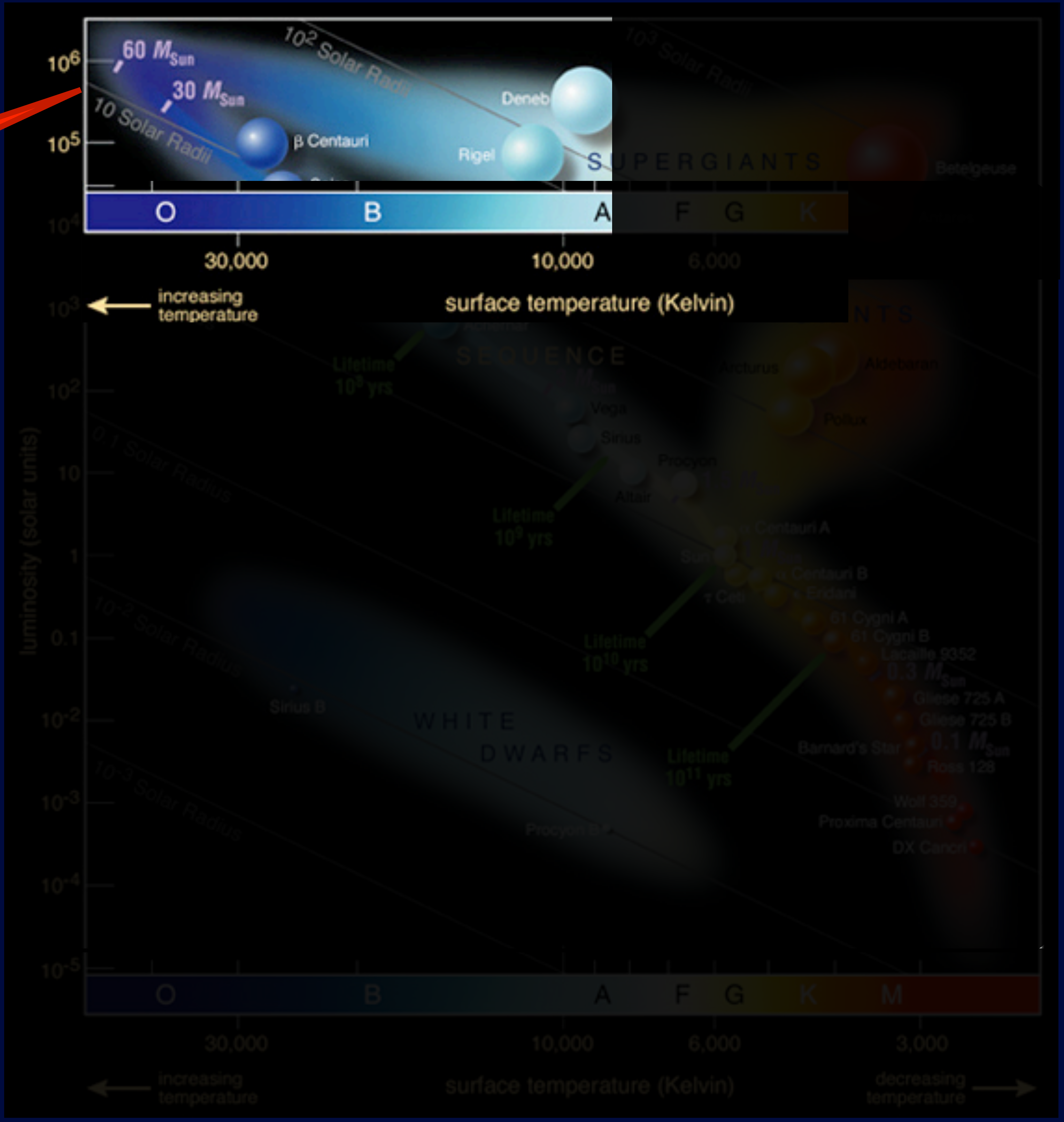
Very luminous ($L \sim 10^6\ L_\odot$)



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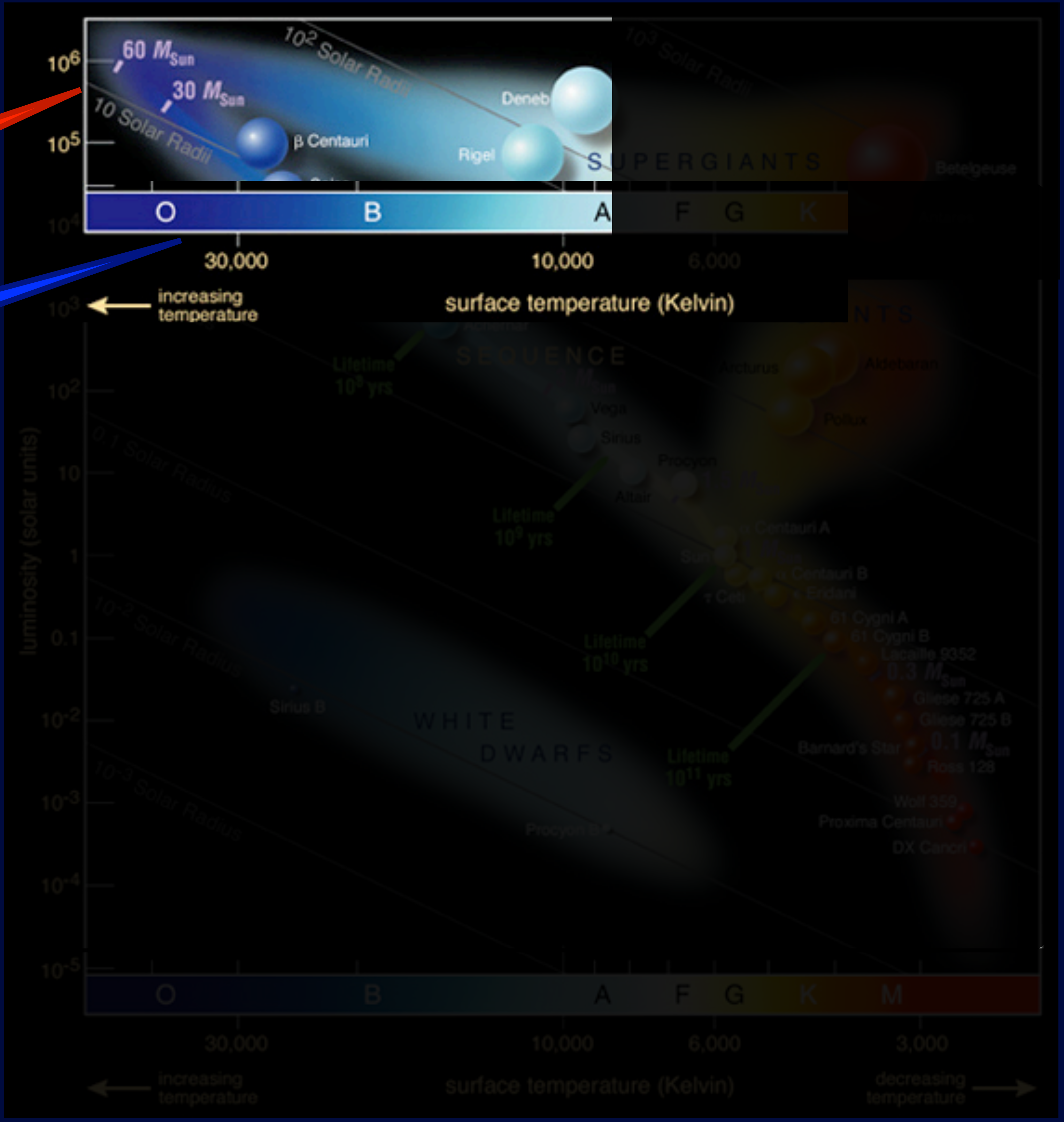

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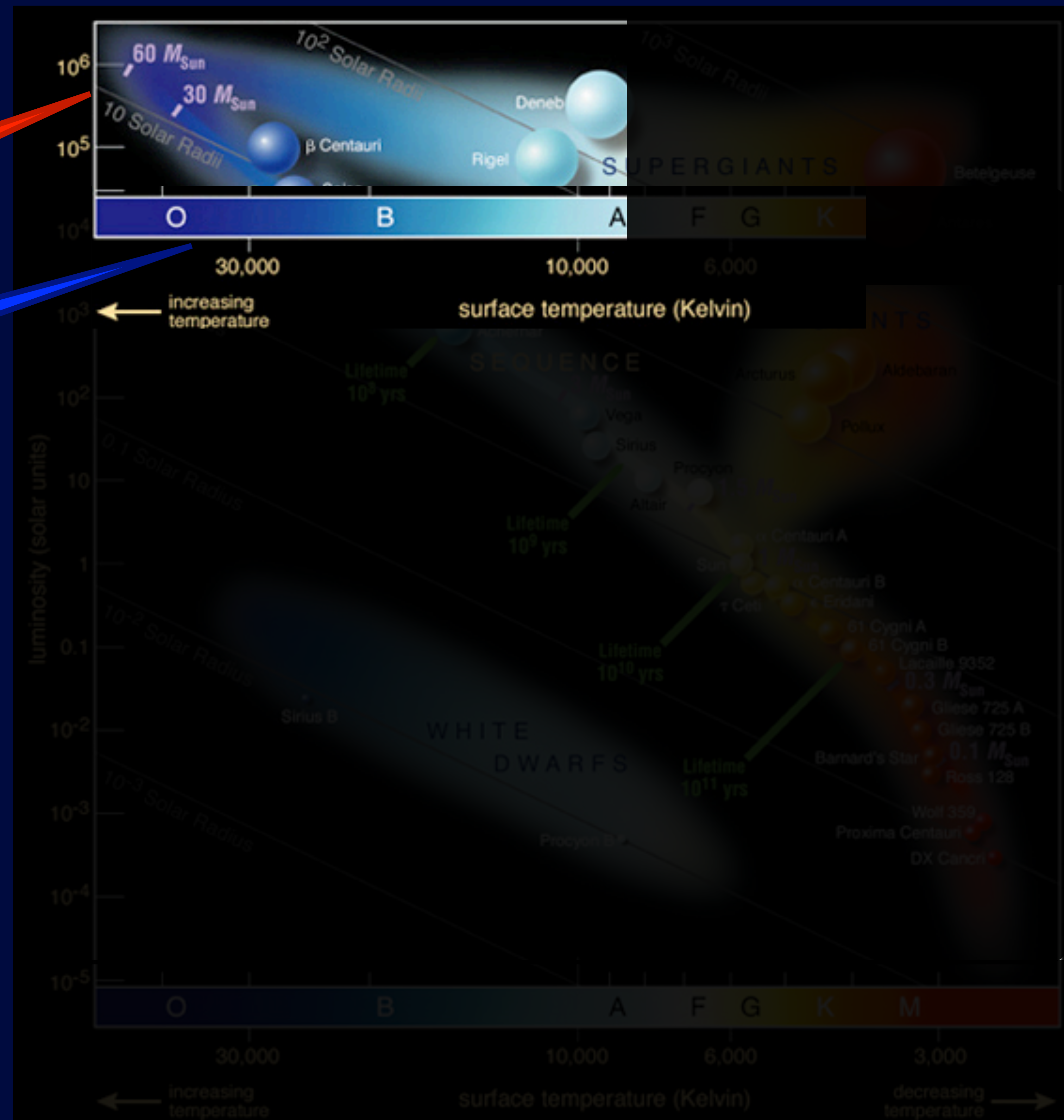
Strong radiative pressure leads to powerful stellar winds which have key effect on stellar evolution

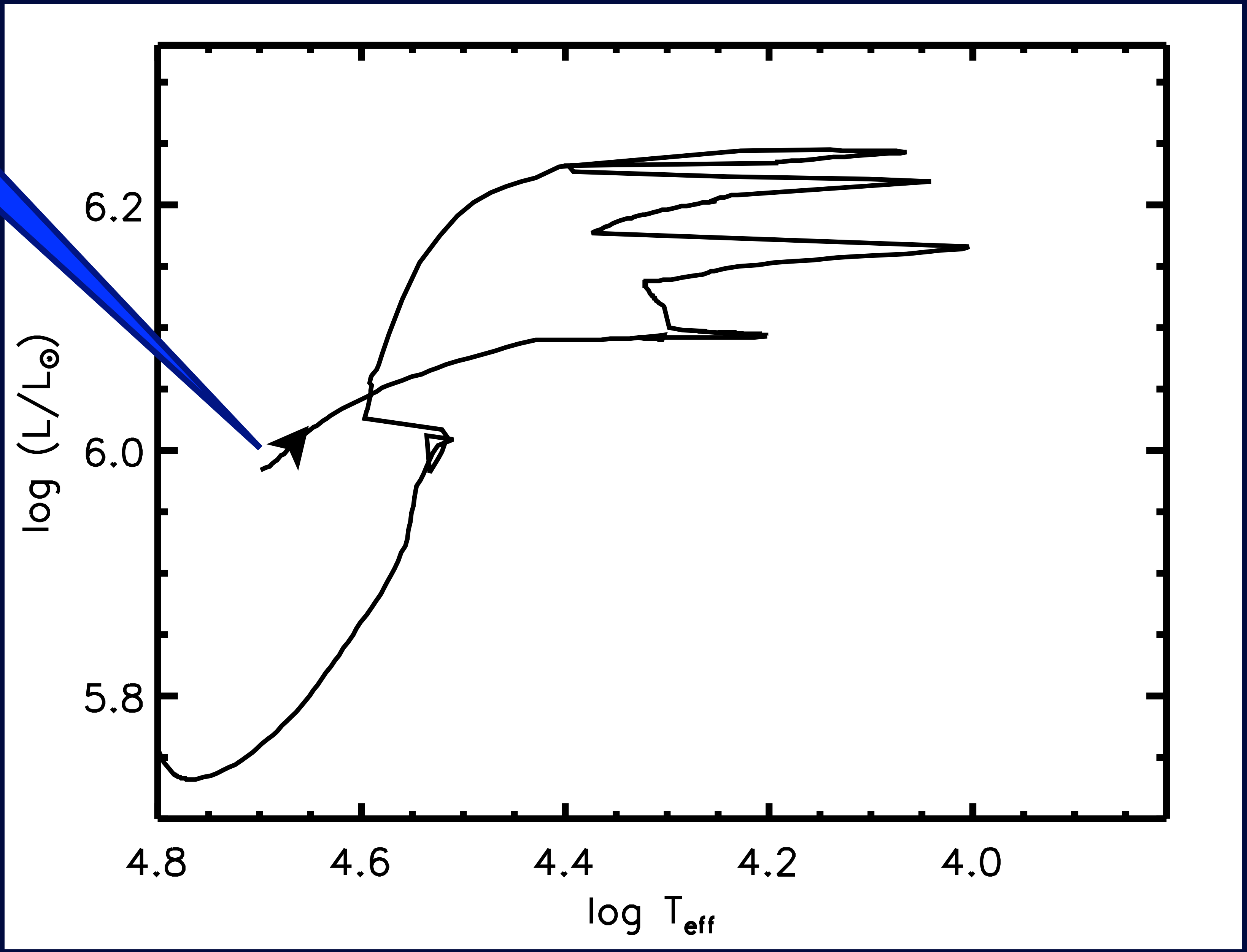


1. Very massive stars

Mass loss and the fate: evolution of an 85 $M_\odot$ star

O-type → Luminous Blue Variable → WR → SN

Assuming a standard mass-loss rate prescription (Vink+01)



(evol. tracks from Meynet & Maeder 2003)

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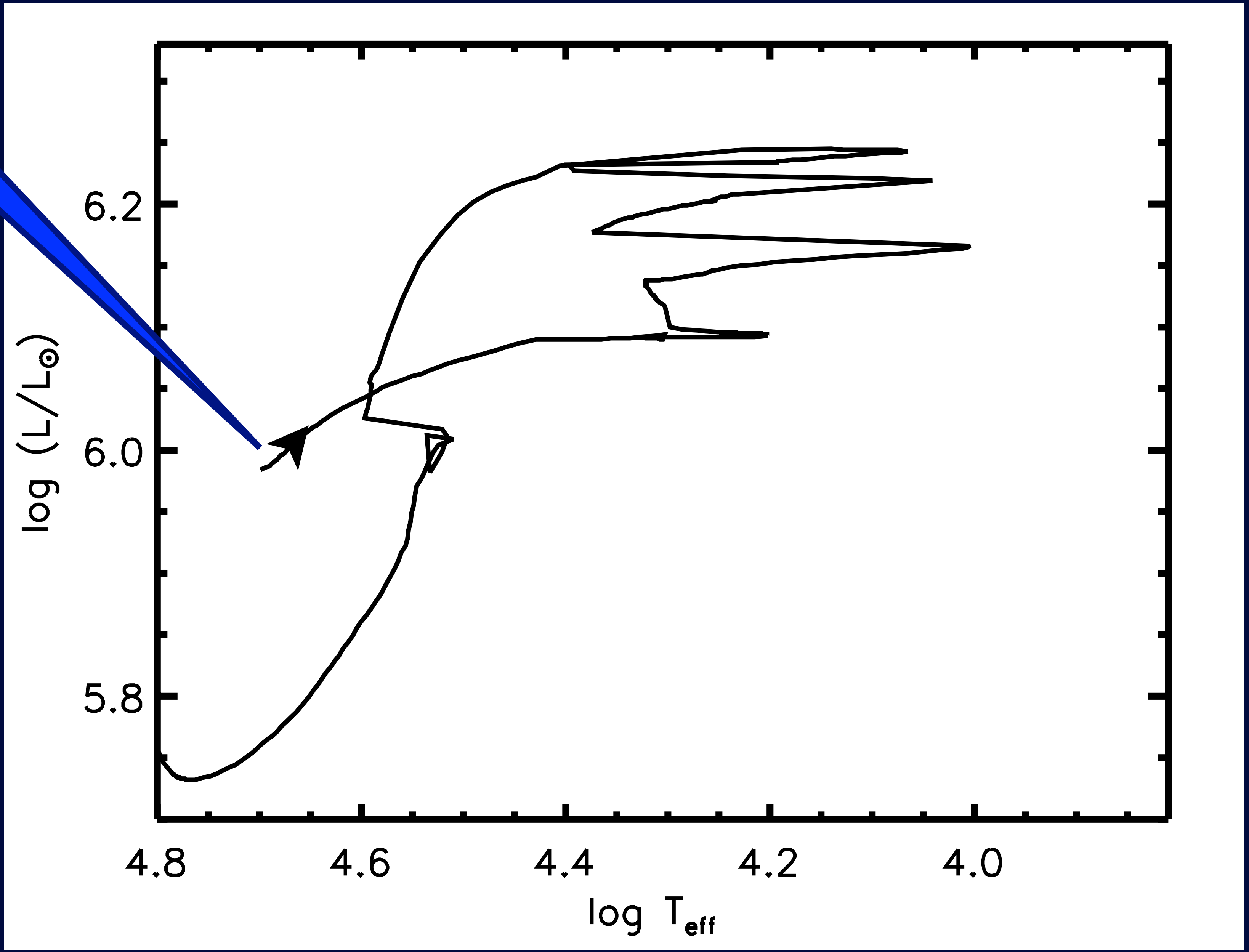

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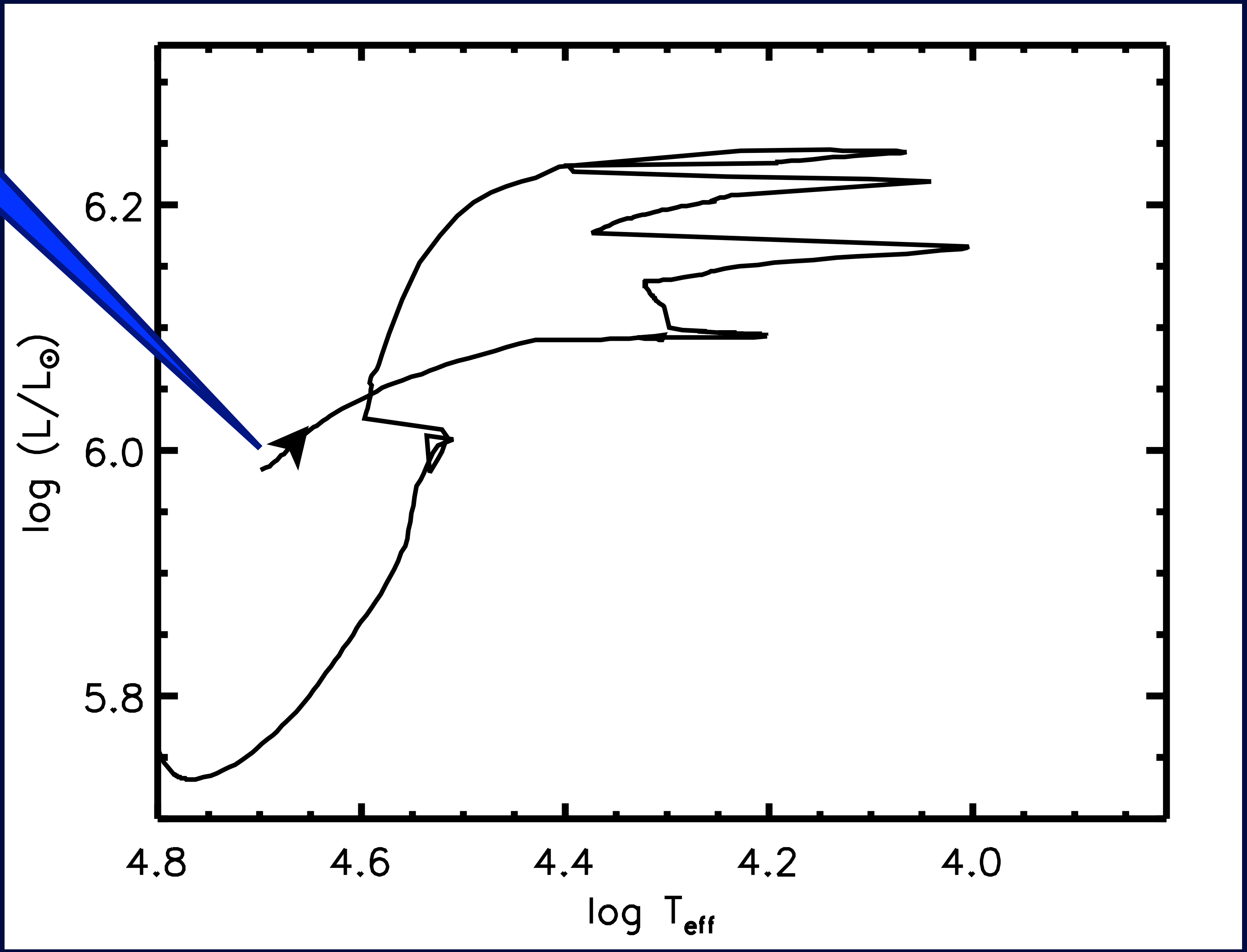

Mass-loss rate as a function of time ultimately determines the fate of a massive star (Chiosi & Maeder 1986).

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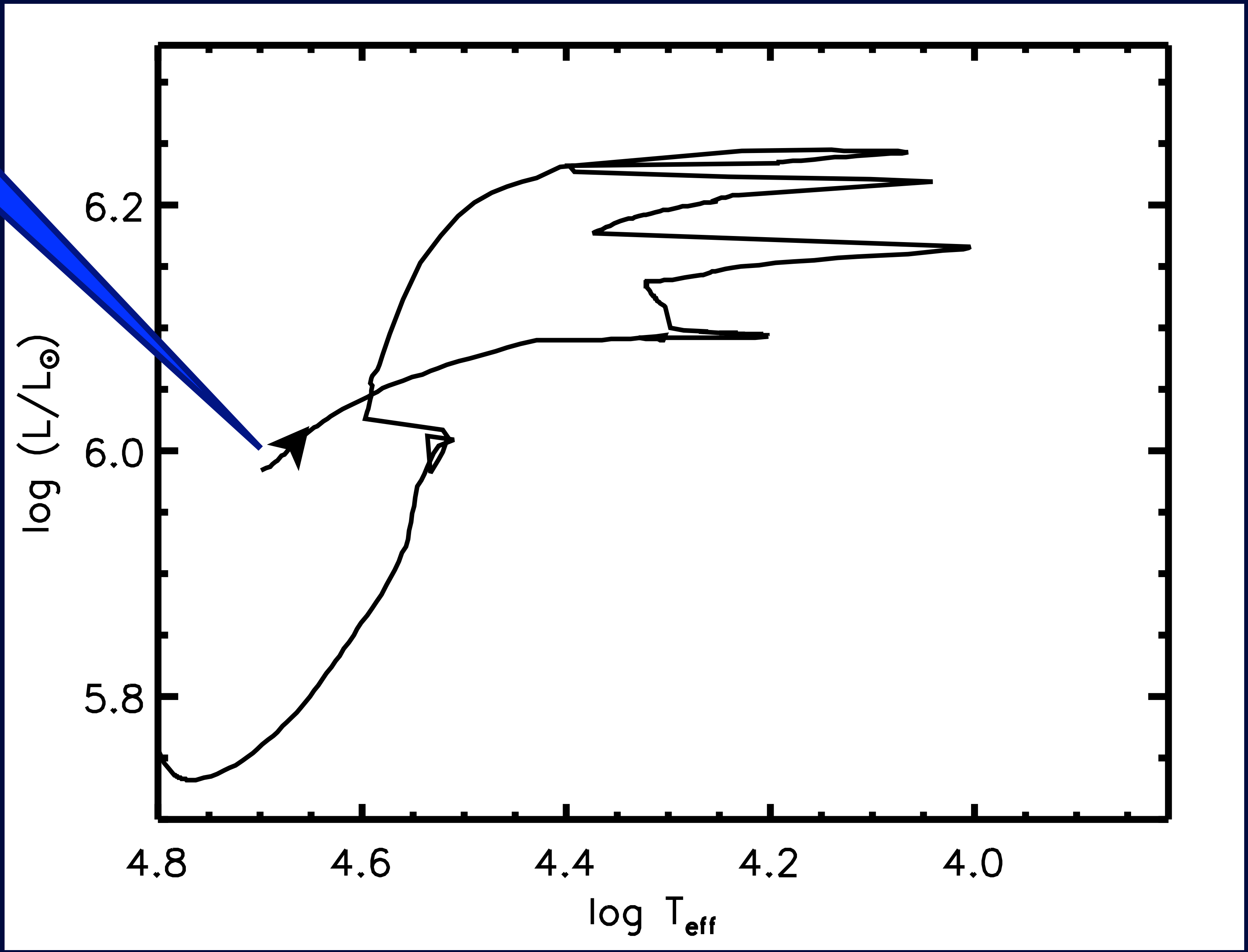

Mass-loss rate as a function of time ultimately determines the fate of a massive star (Chiosi & Maeder 1986).

When is the star going to explode, how, and after losing how much mass?

(evol. tracks from Meynet & Maeder 2003)

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Mass loss and the proximity to the Eddington limit

What is the key physical mechanism that regulates mass loss in massive stars?

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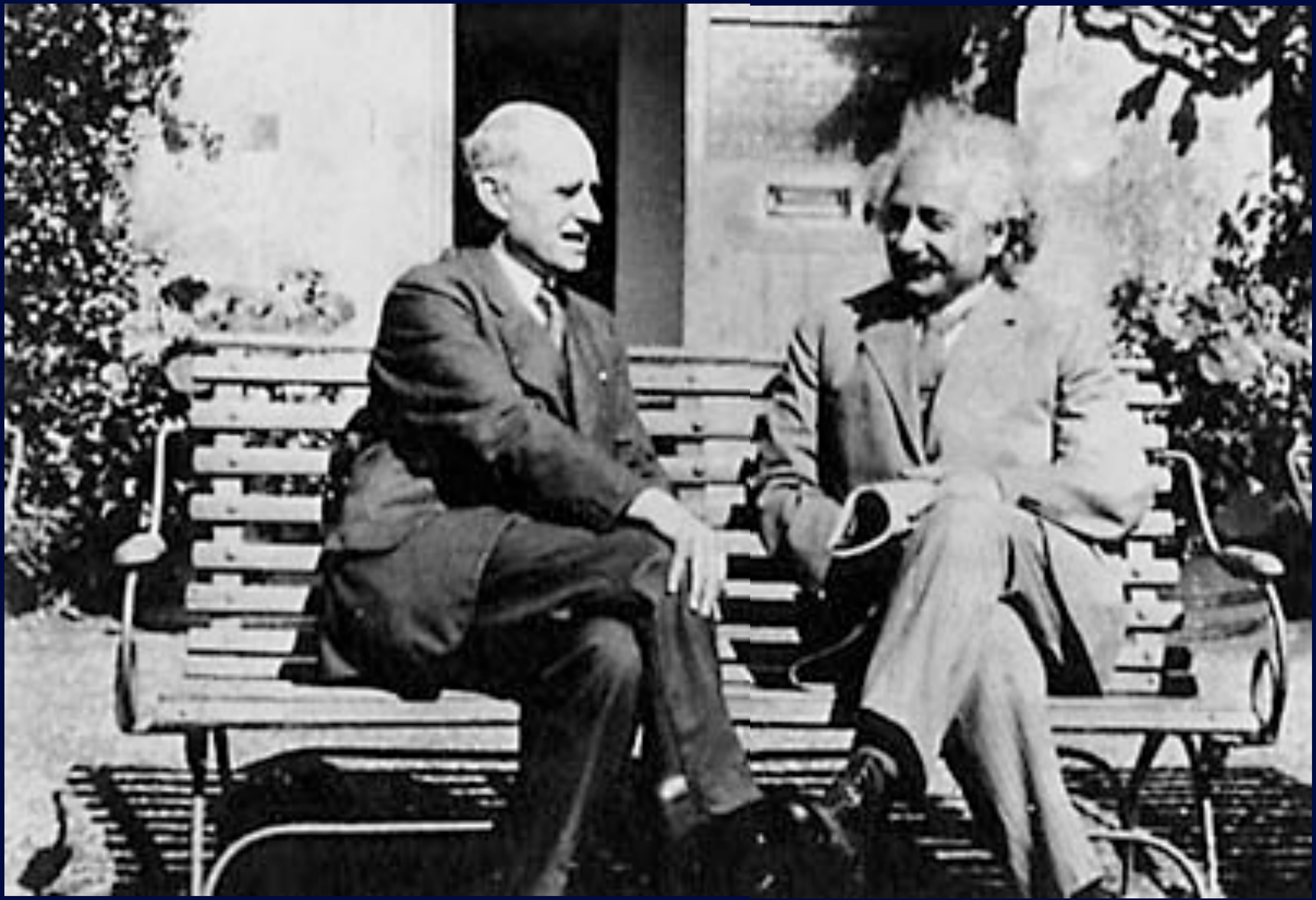
Proximity to the Eddington limit.
Eddington *what?*

1. The Eddington Limit
Radiative force vs. gravity



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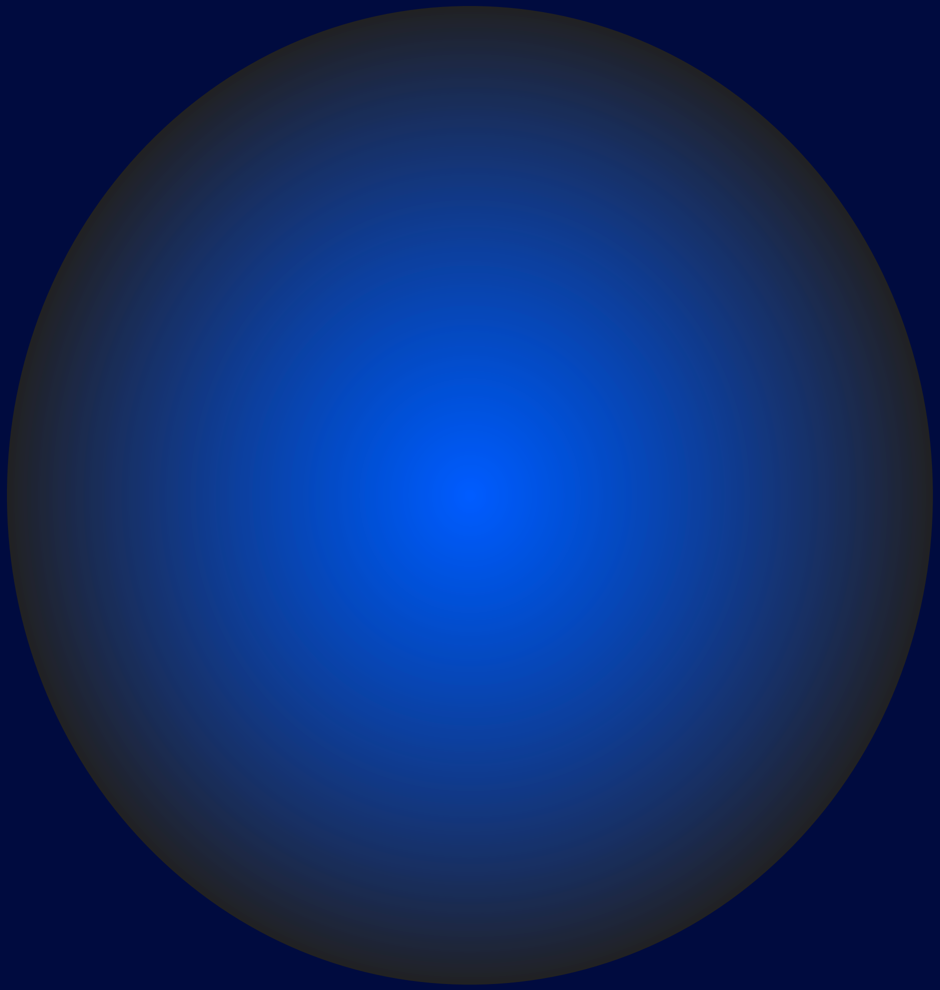

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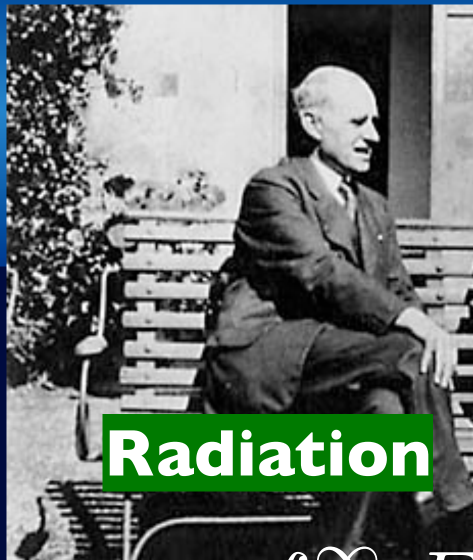

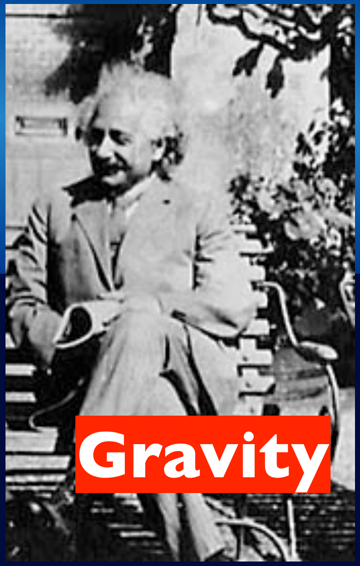

$$g_{rad} = \int_0^\infty \frac{F_\nu k_\nu}{c}\, d\nu$$

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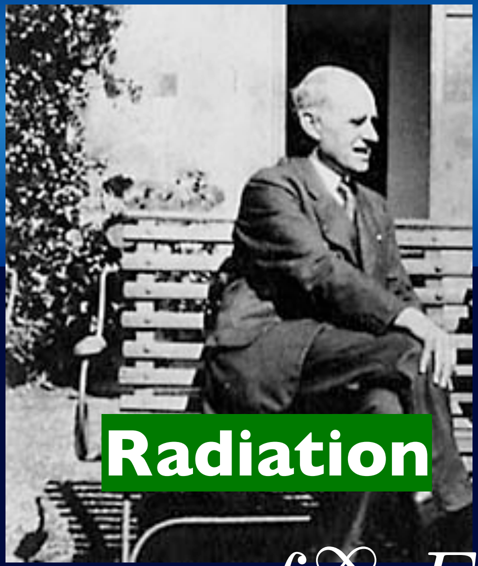

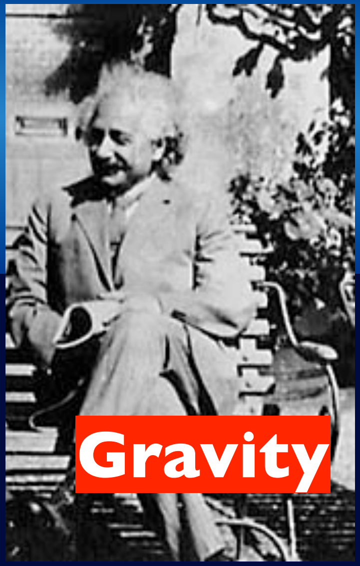

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On free-electrons only:

$$g_e = \frac{k_e L}{4\pi c r^2}$$

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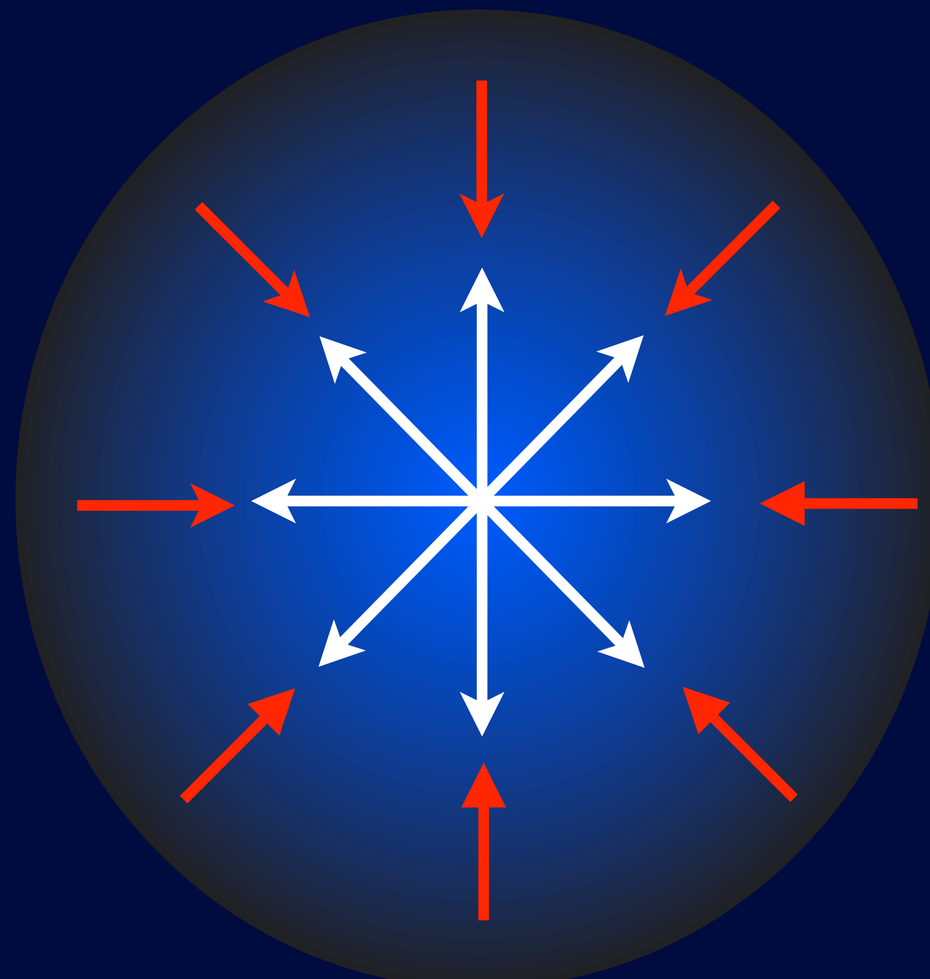

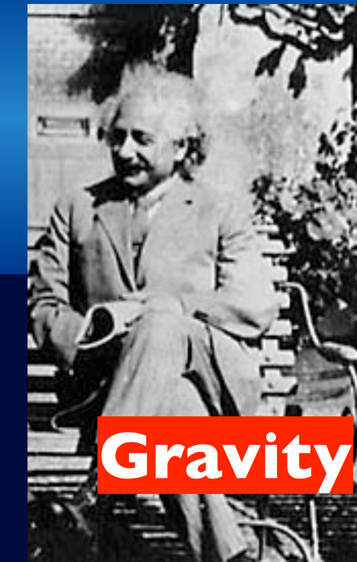

Gravity:

$$g_{grav} = \frac{GM}{r^2}$$

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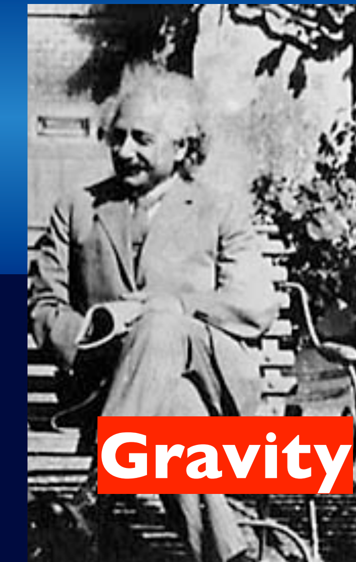

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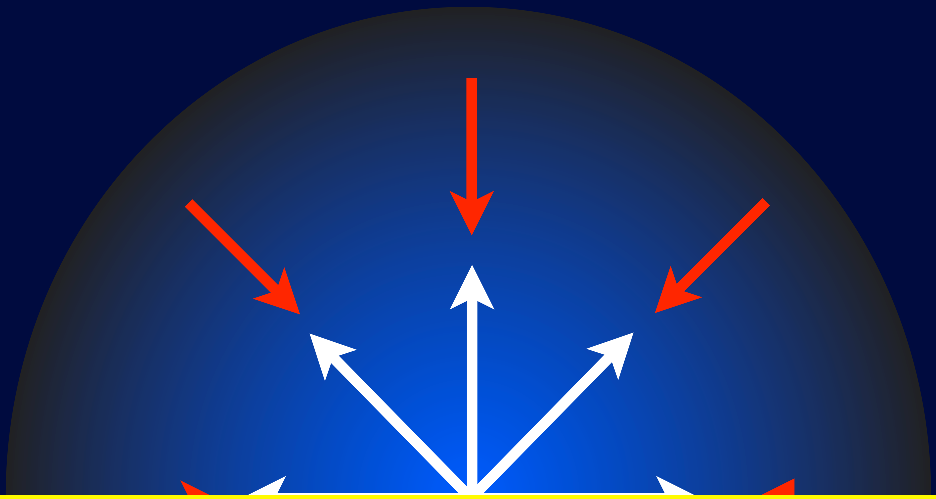

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(Classical) Eddington parameter $\Gamma_e \equiv \dfrac{g_e}{g_{grav}}$

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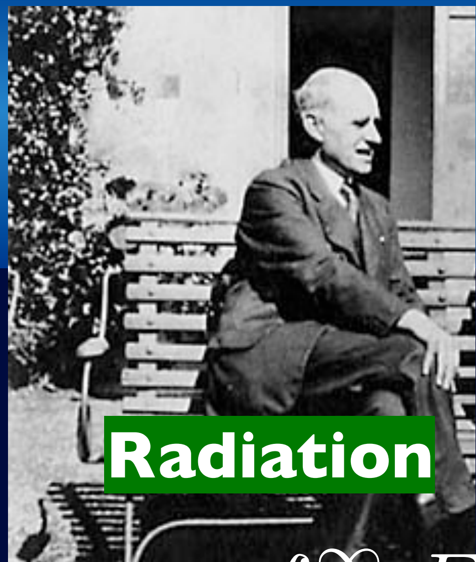

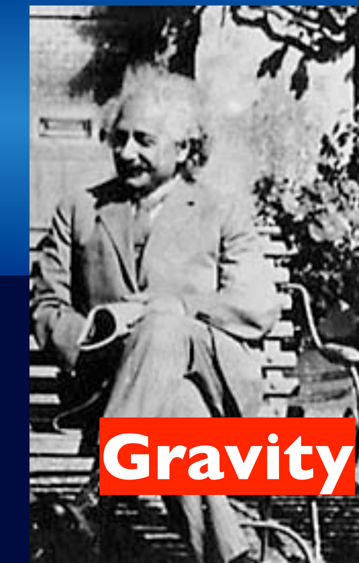

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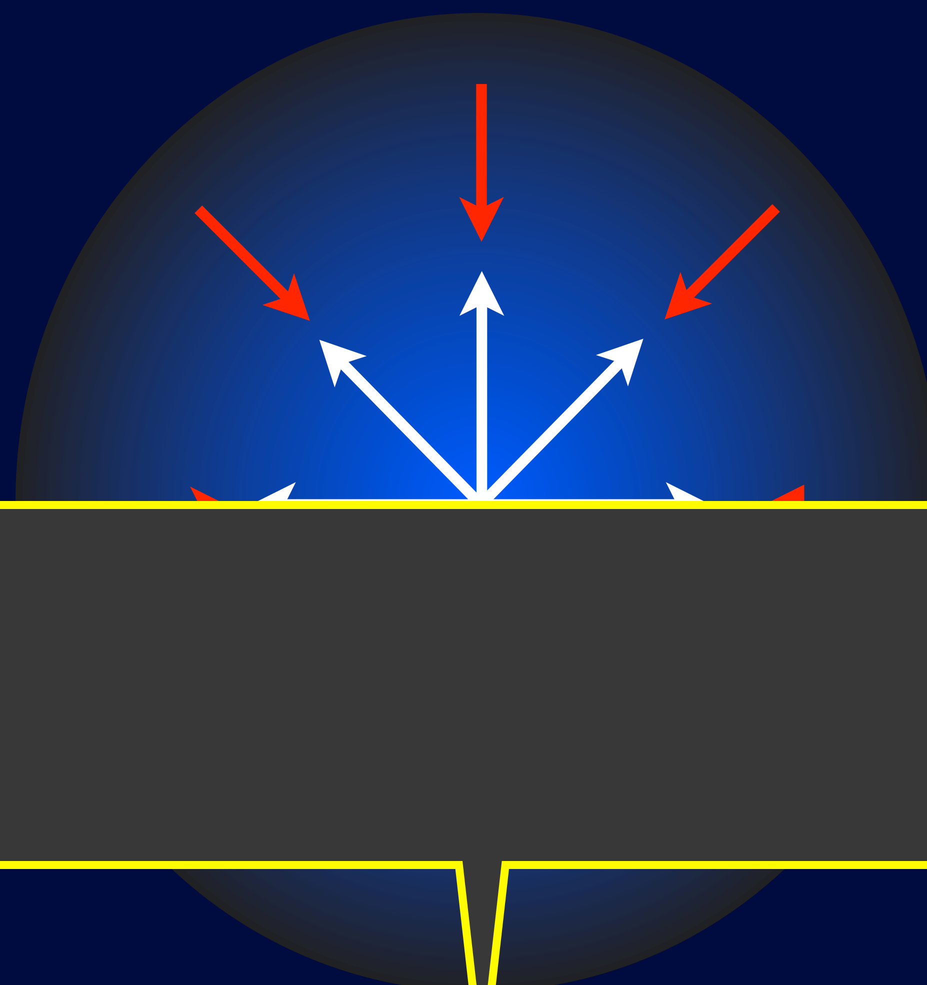

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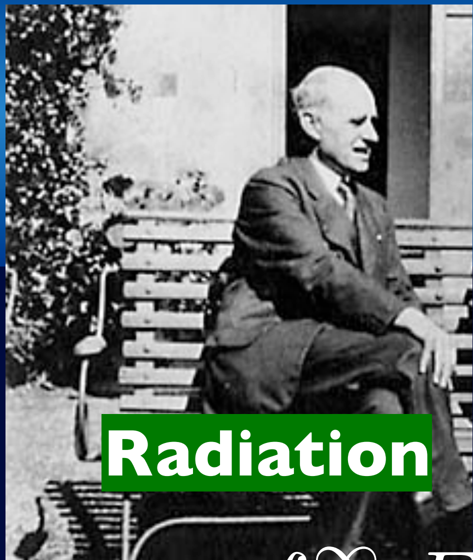

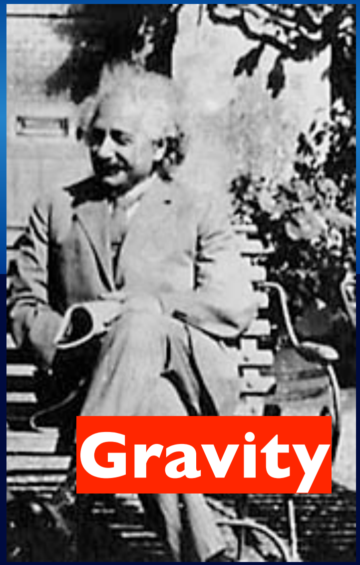

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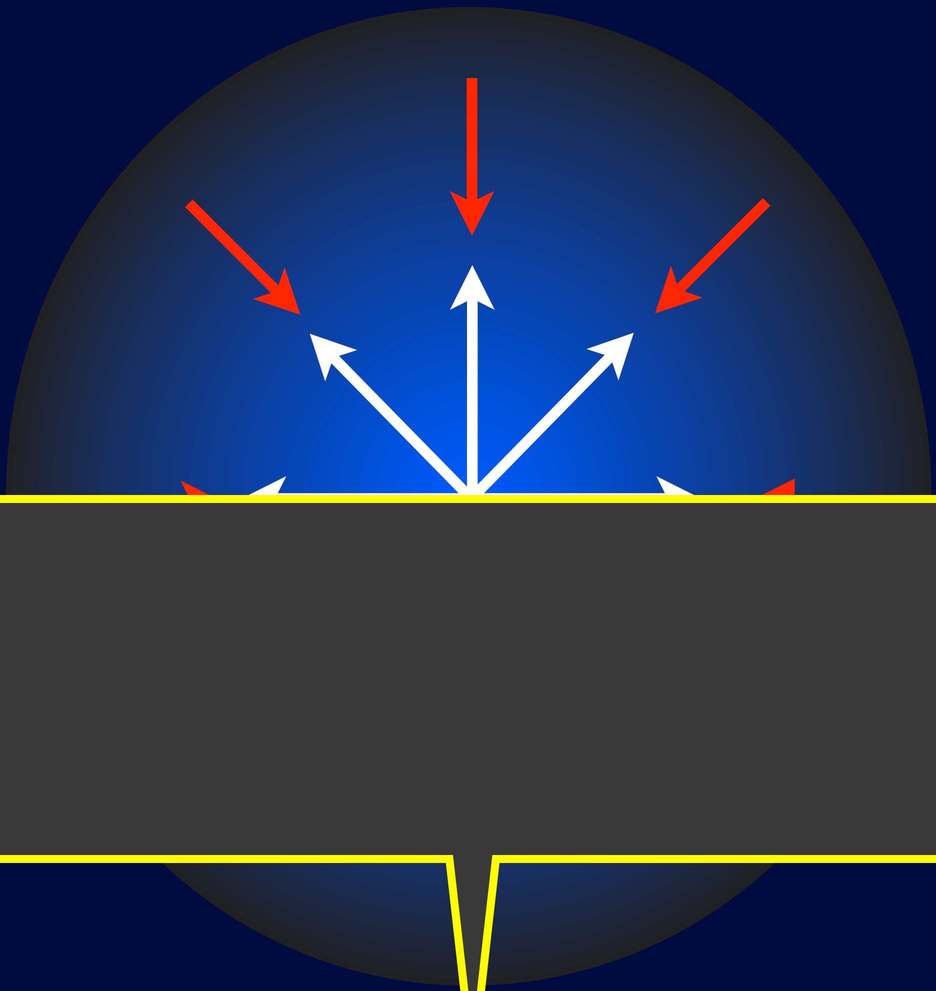

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(Classical) Eddington limit occurs when $\dfrac{k_e\, L}{4\pi G c M} = 1$

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Eddington parameter for different stars

$$\Gamma = \frac{k\,L}{4\pi G c M} \simeq 2\times10^{-5}\,\frac{L/L_\odot}{M/M_\odot}\,\frac{k}{k_e}$$

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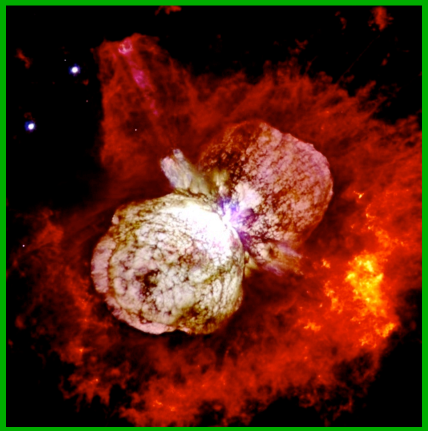
As $L \propto M^{3\text{-}4}$, Γ is significantly large for massive stars.



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Eddington parameter during the Main Sequence: at the zero age

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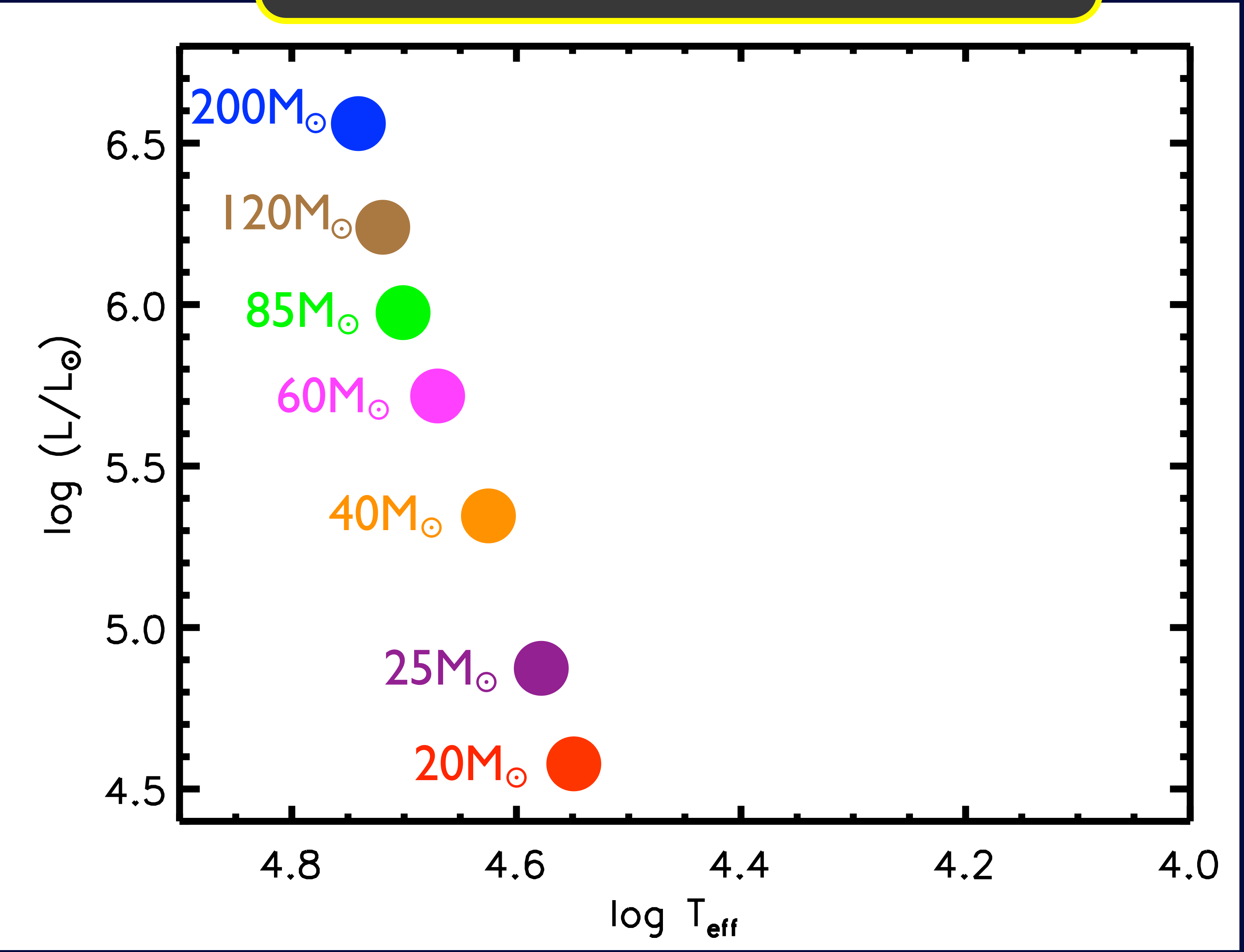

(evol. tracks from Meynet & Maeder 2003, Crowther+ 2010)

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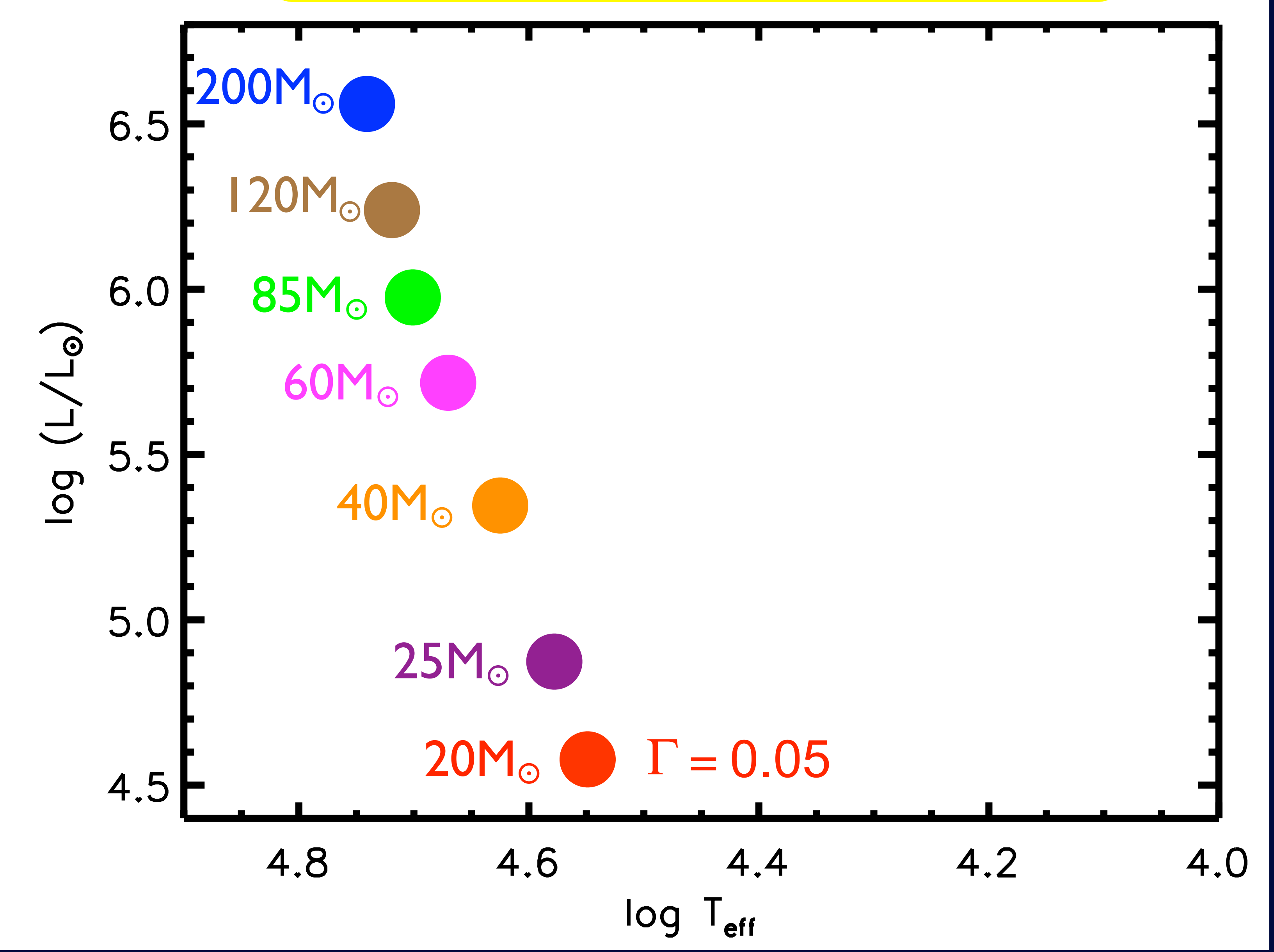

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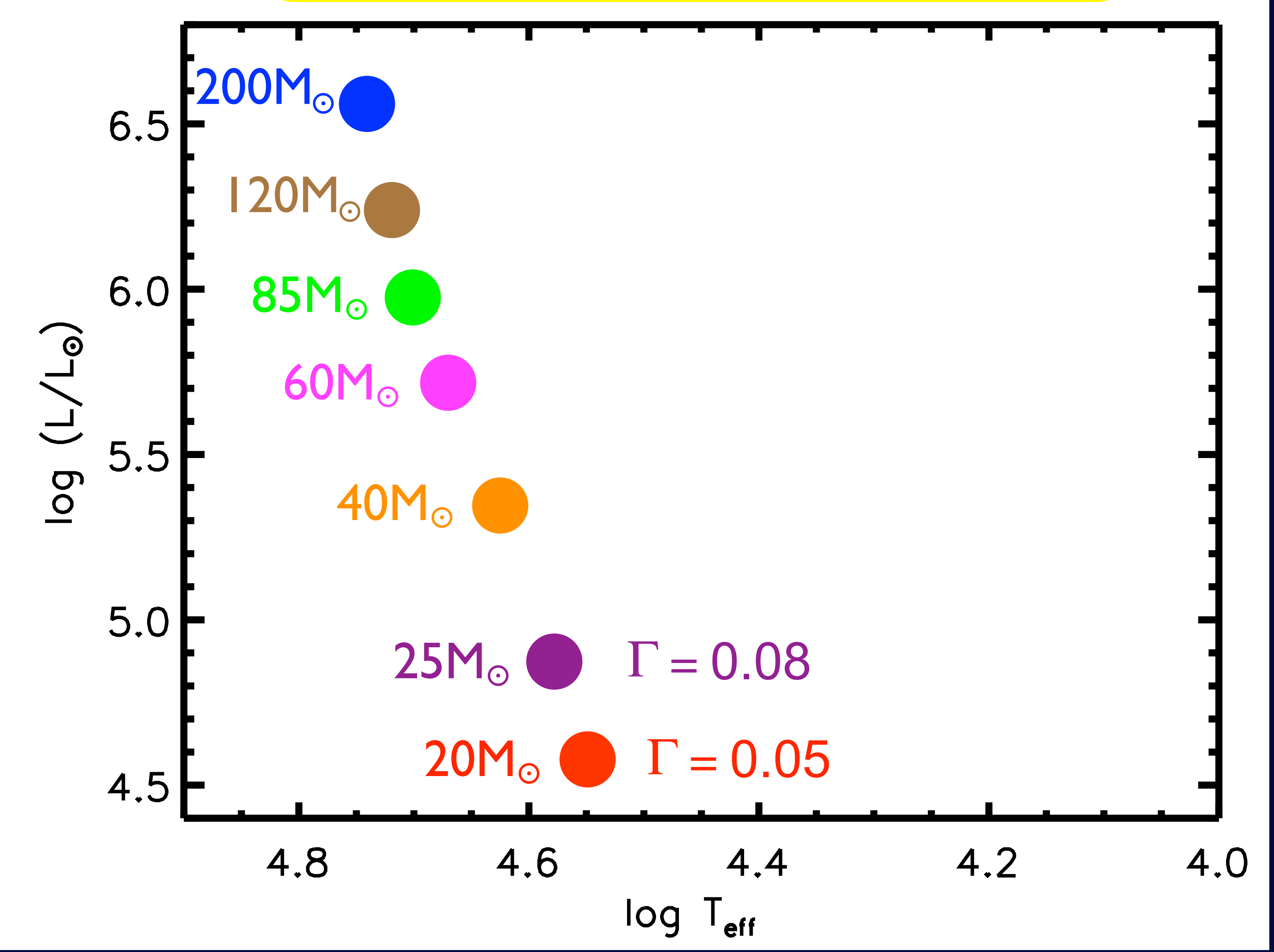

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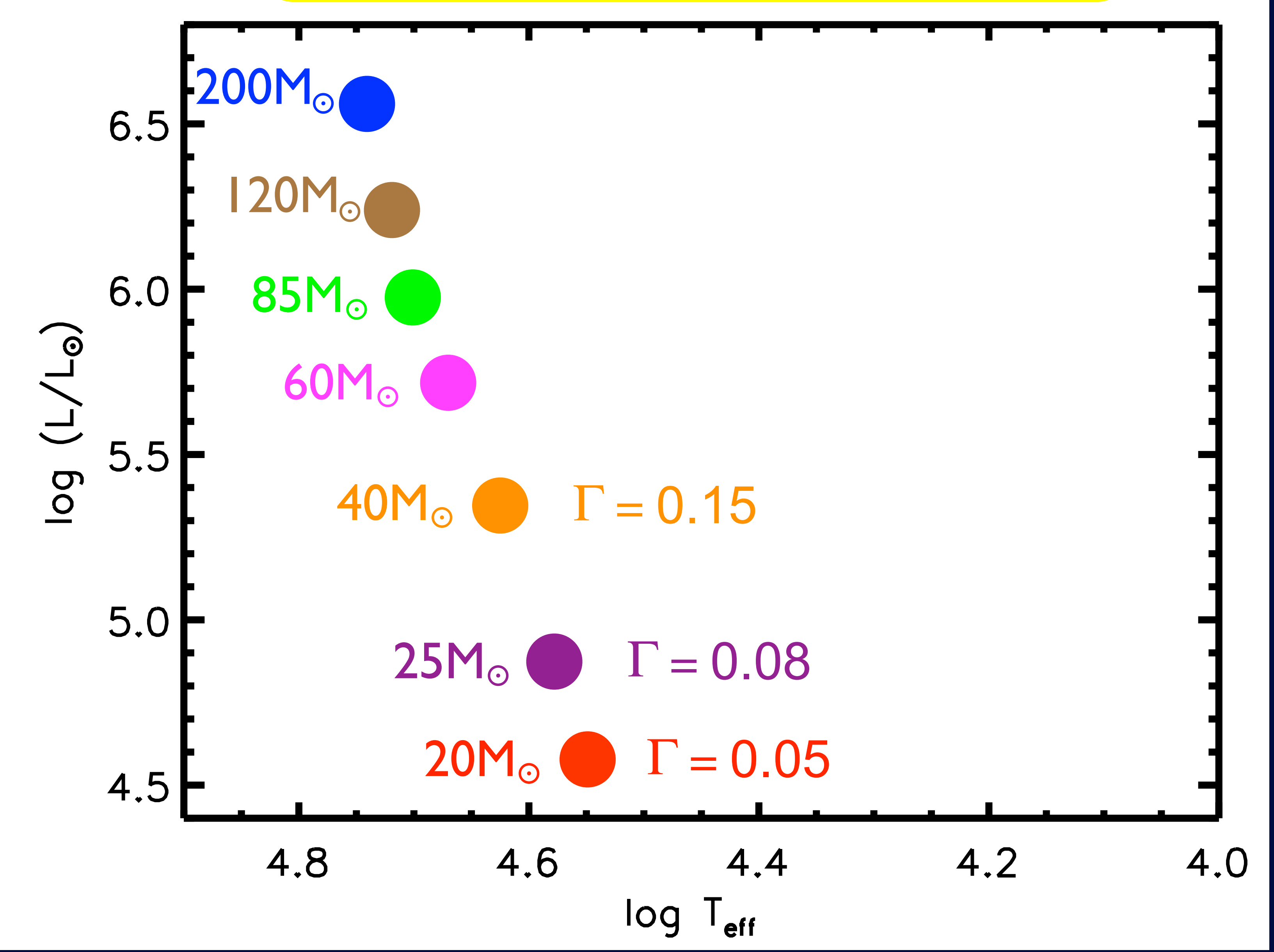

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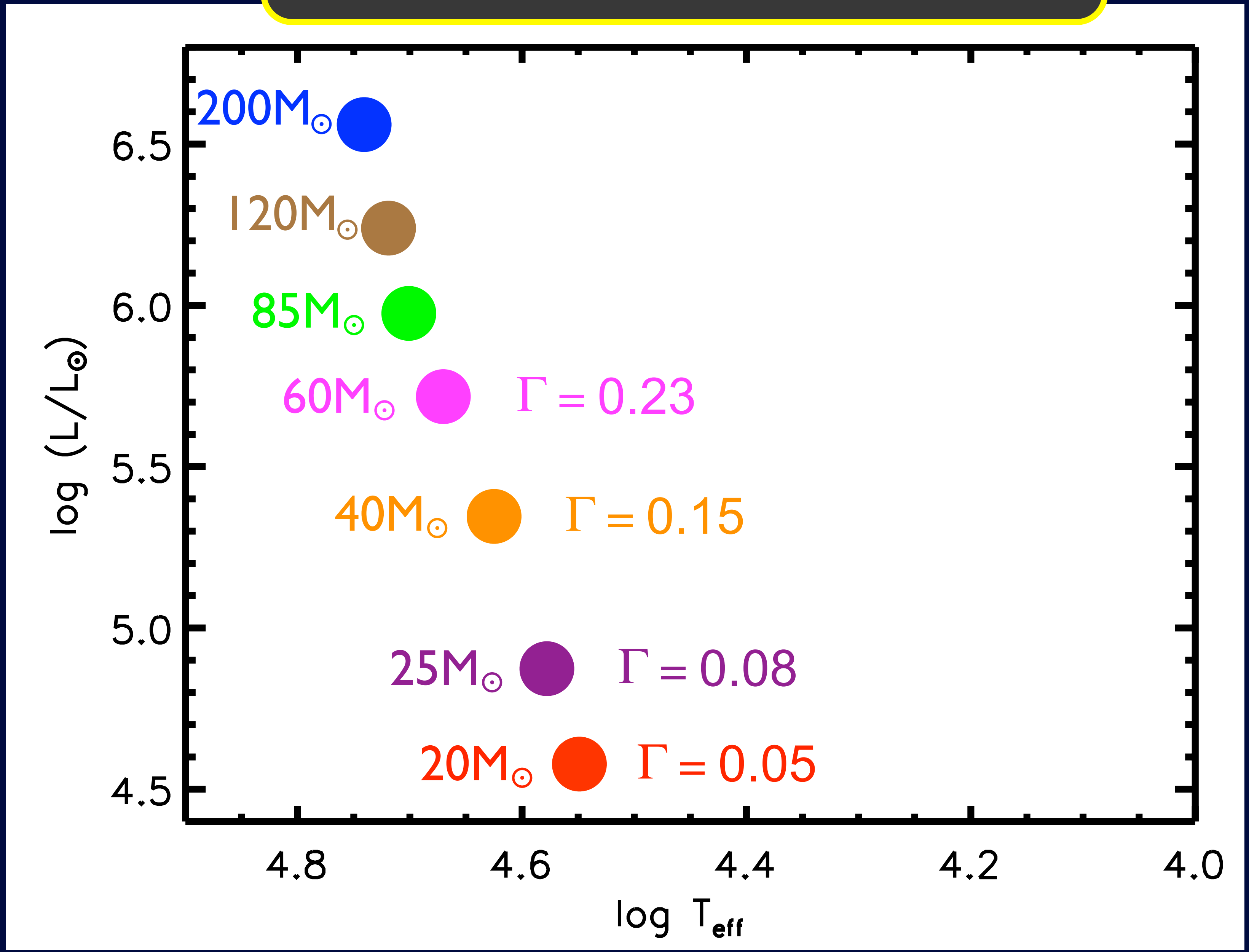

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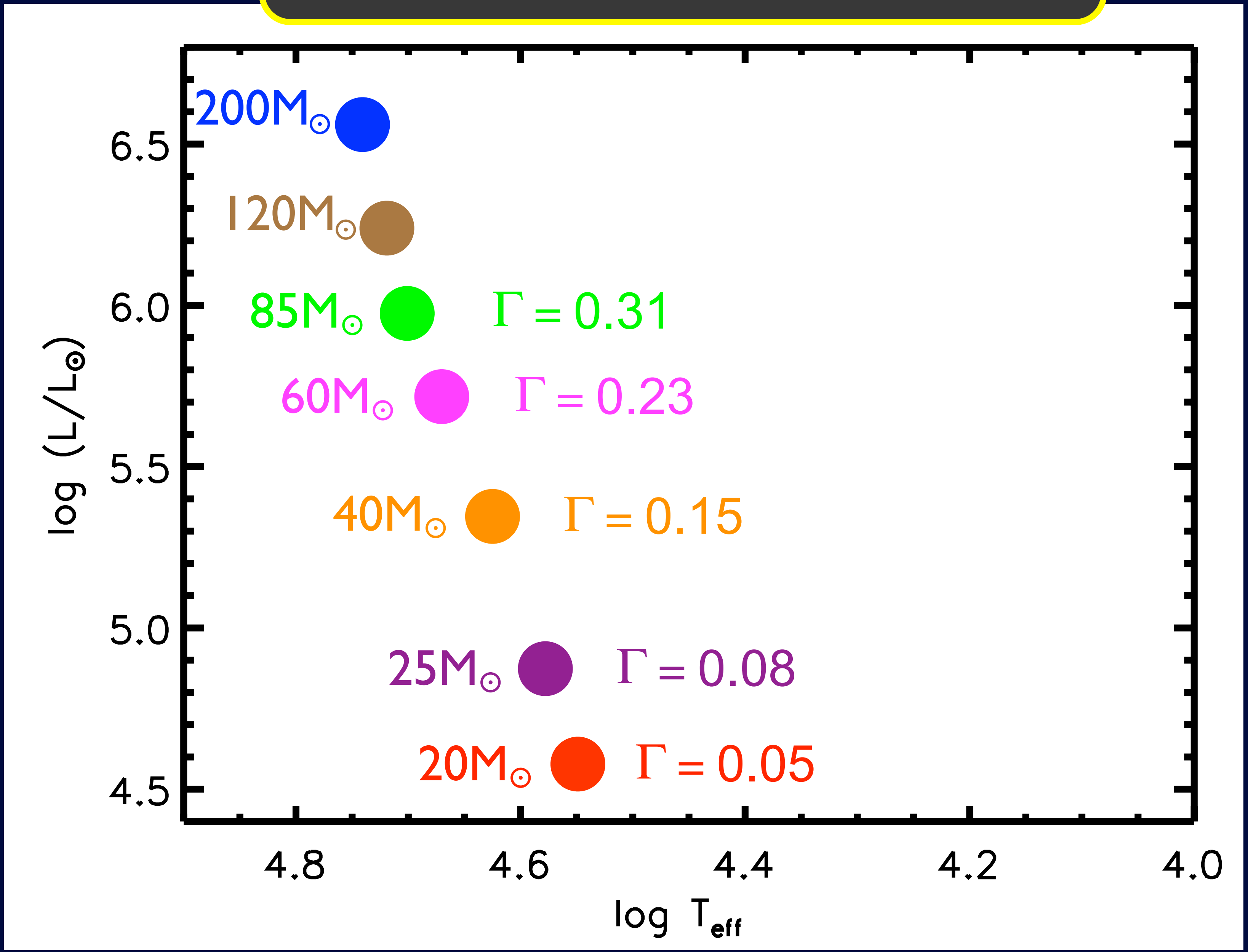

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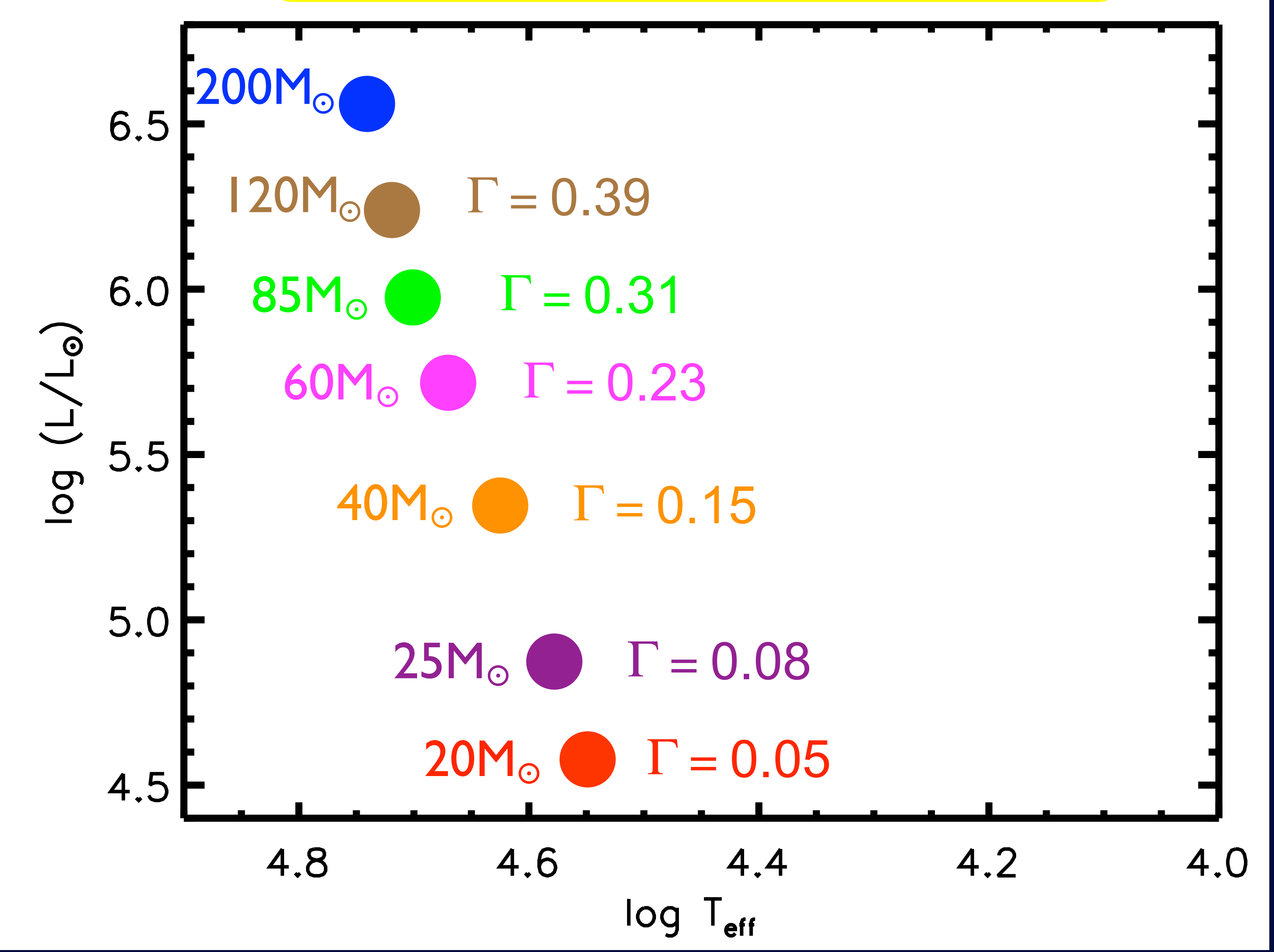

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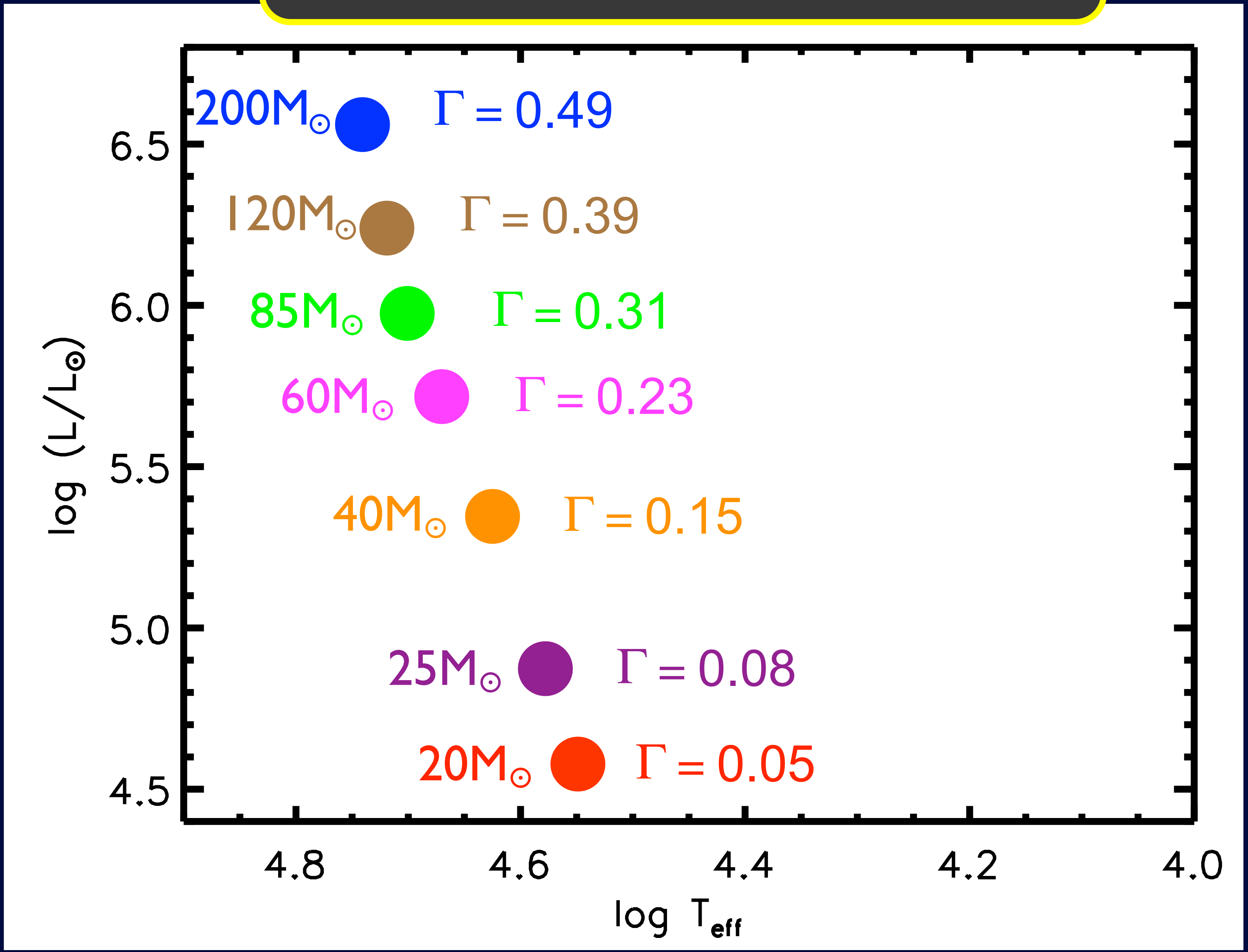

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Eddington parameter during the Main Sequence: at halftime

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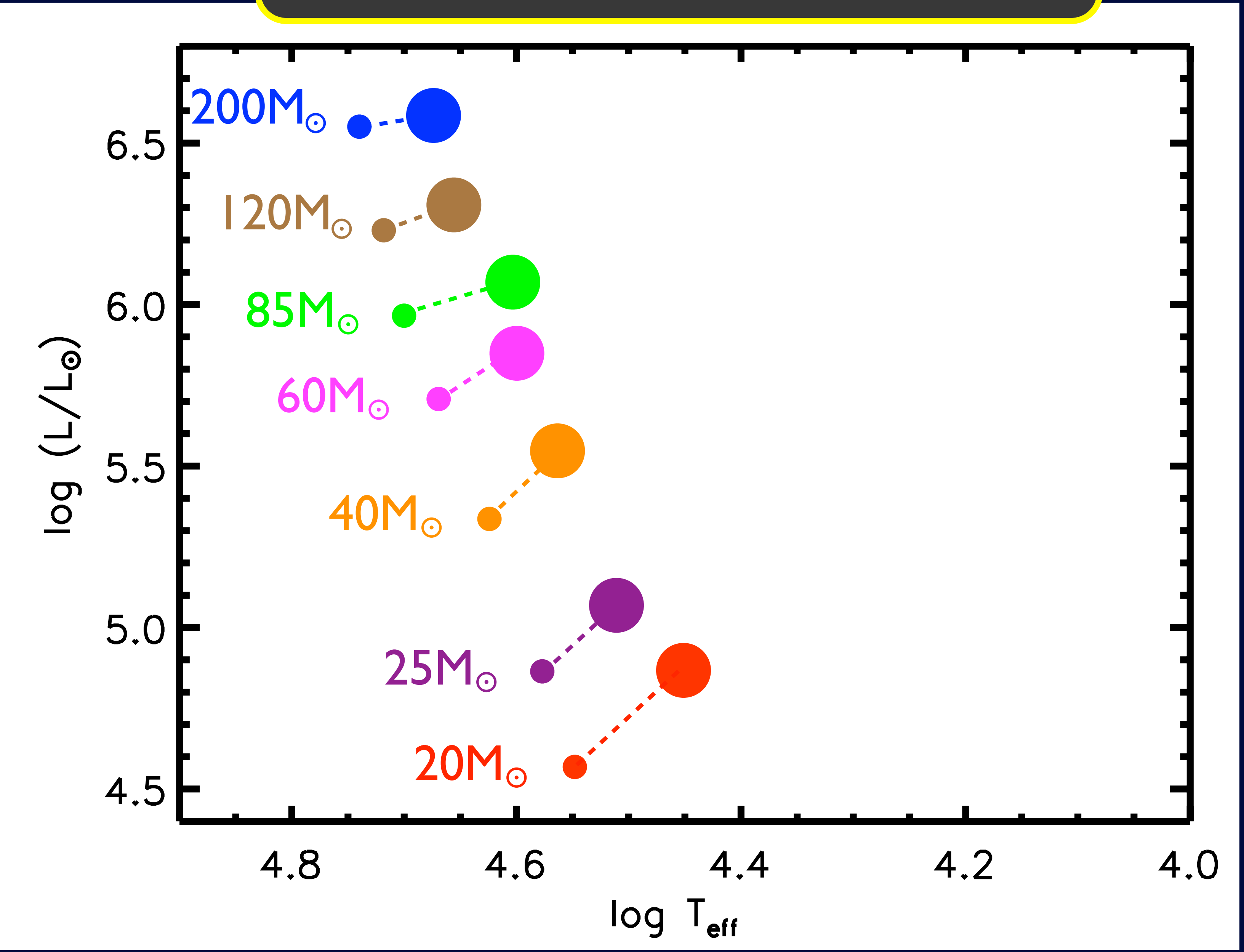

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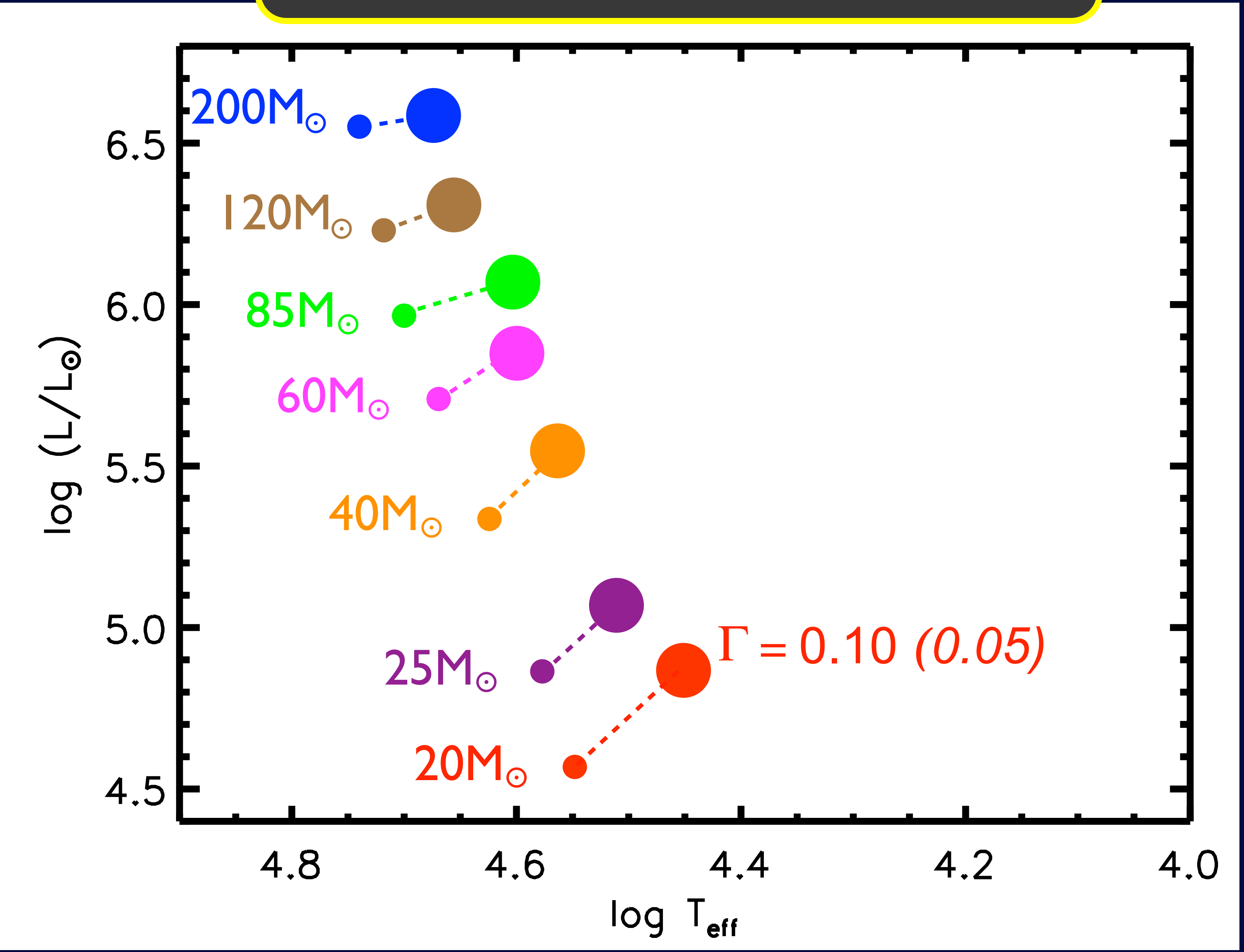

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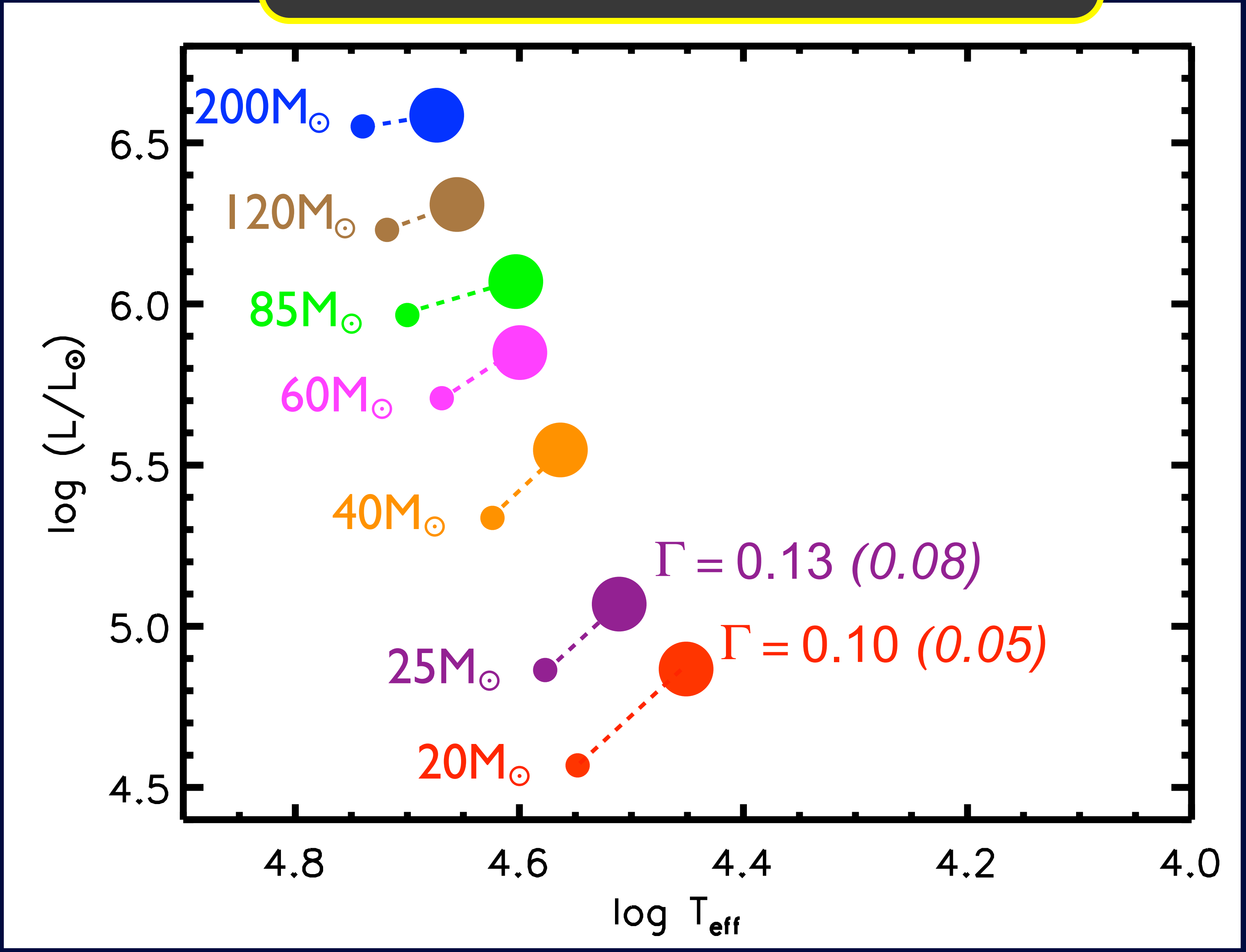

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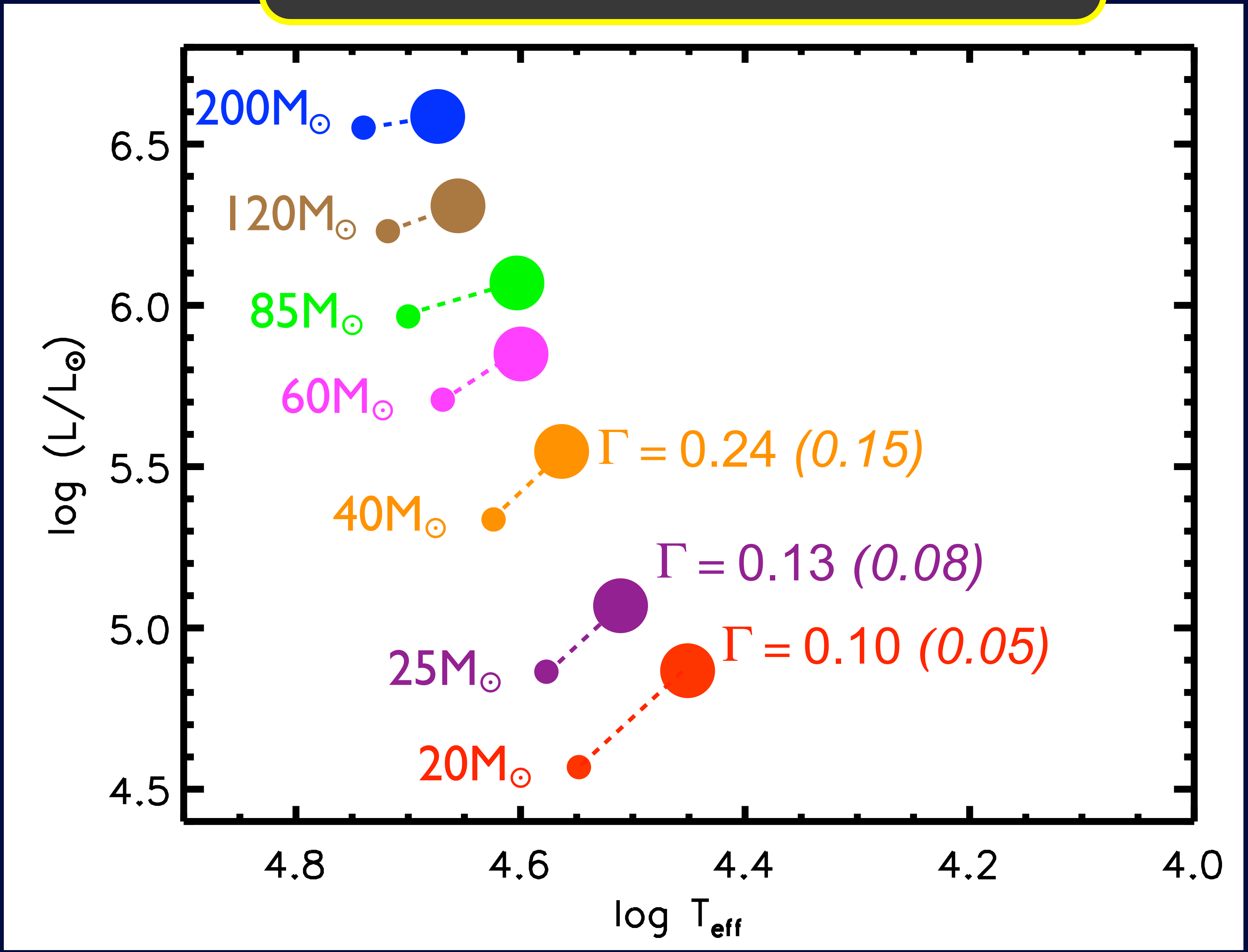

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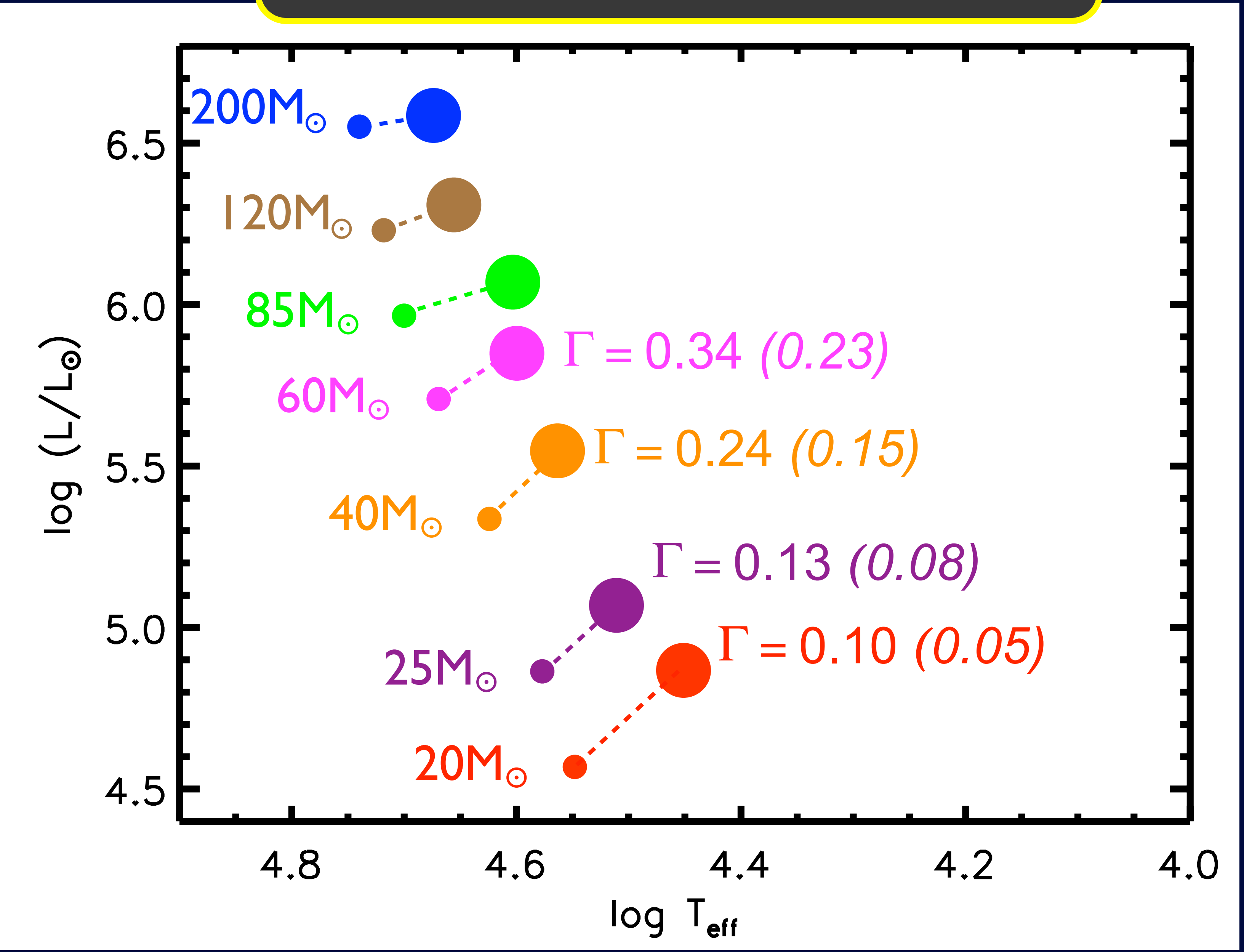

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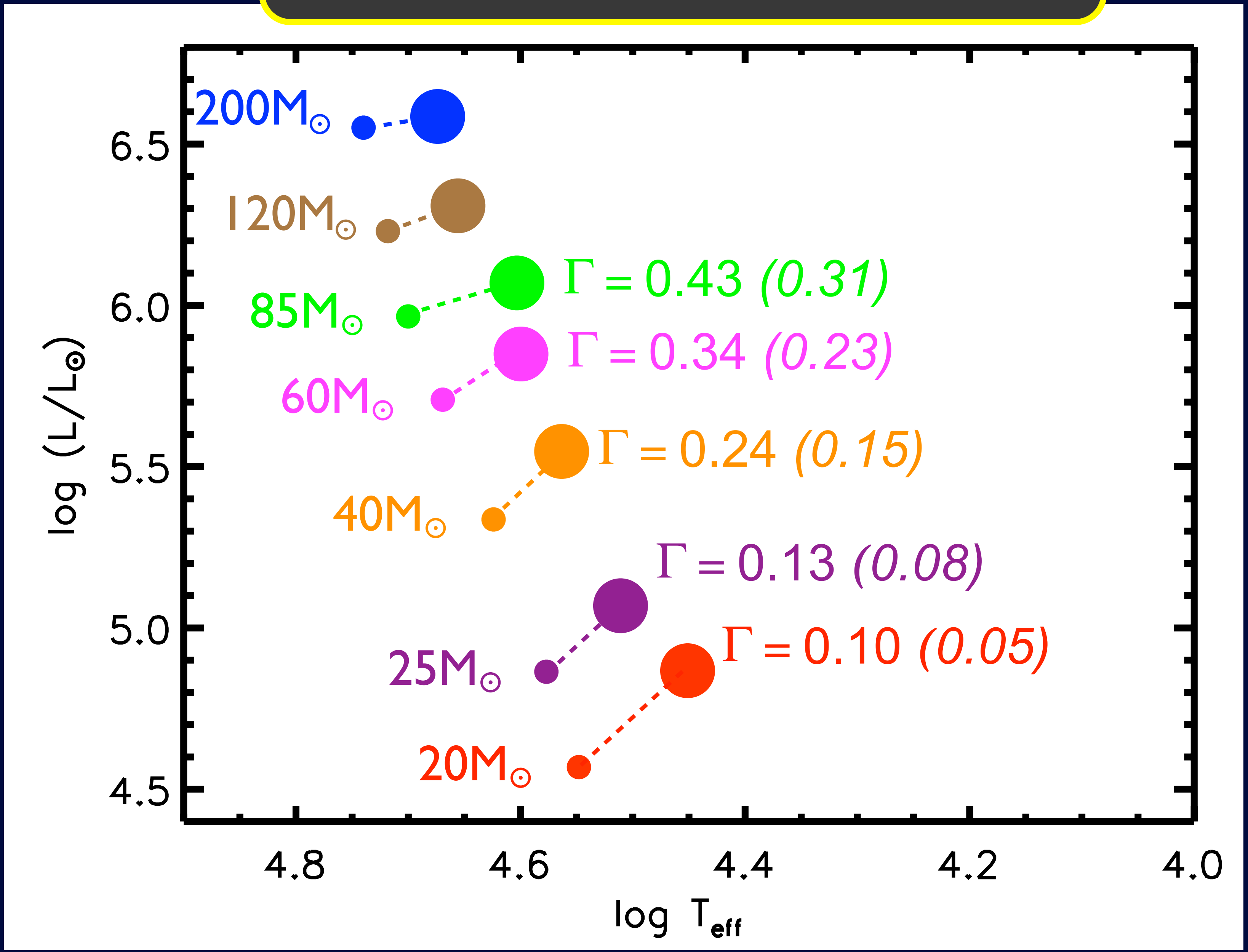

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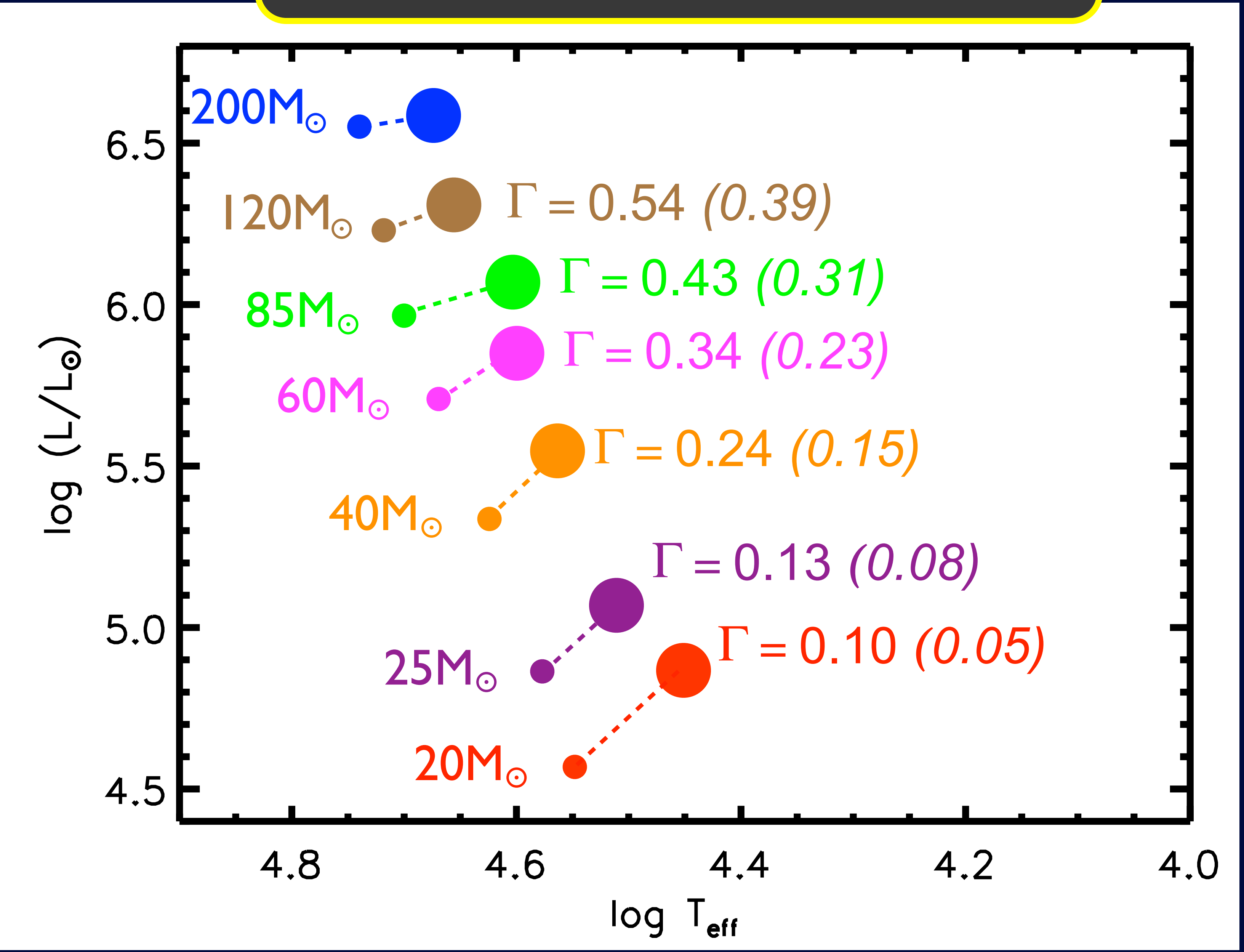

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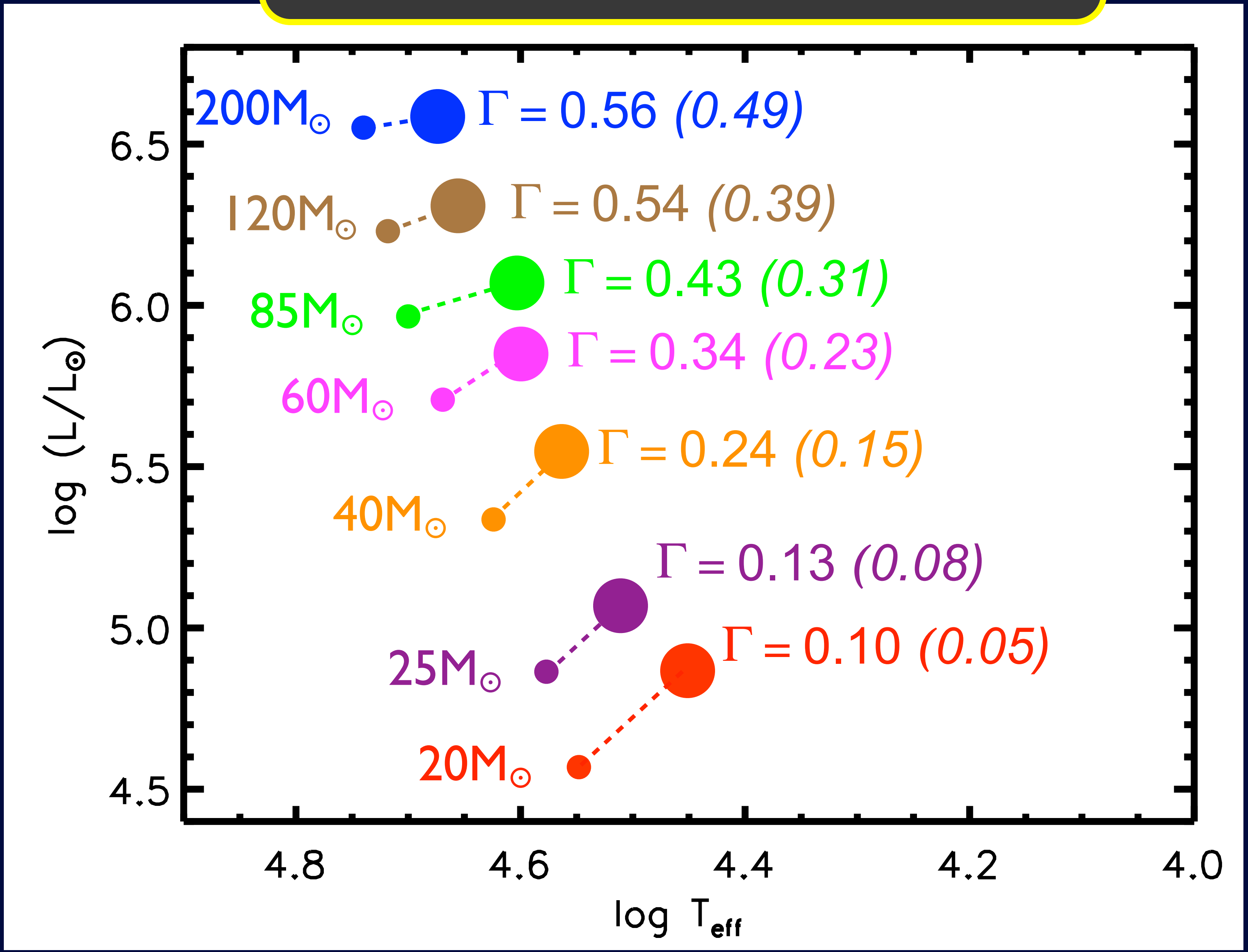

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Eddington parameter during the Main Sequence: at the end

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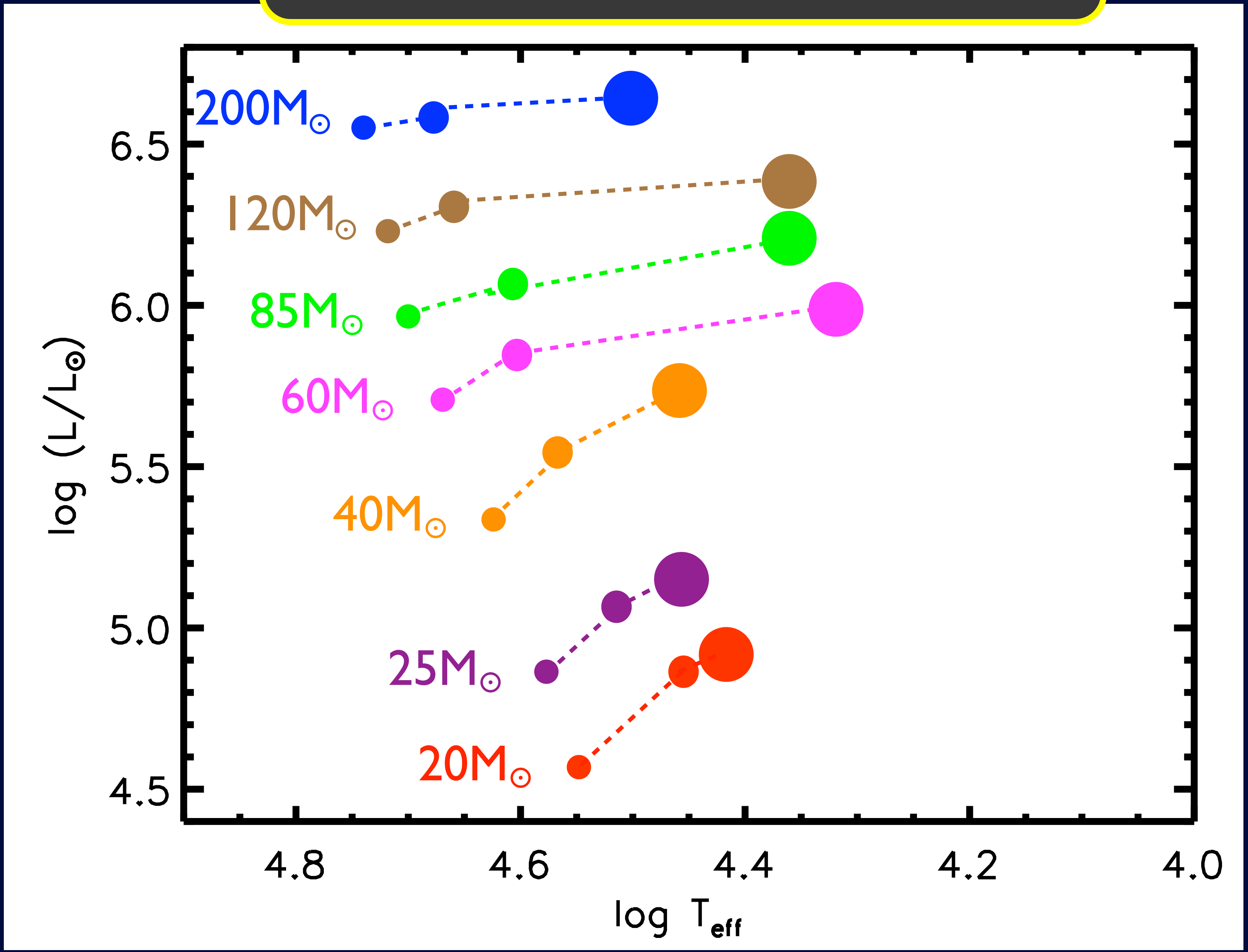

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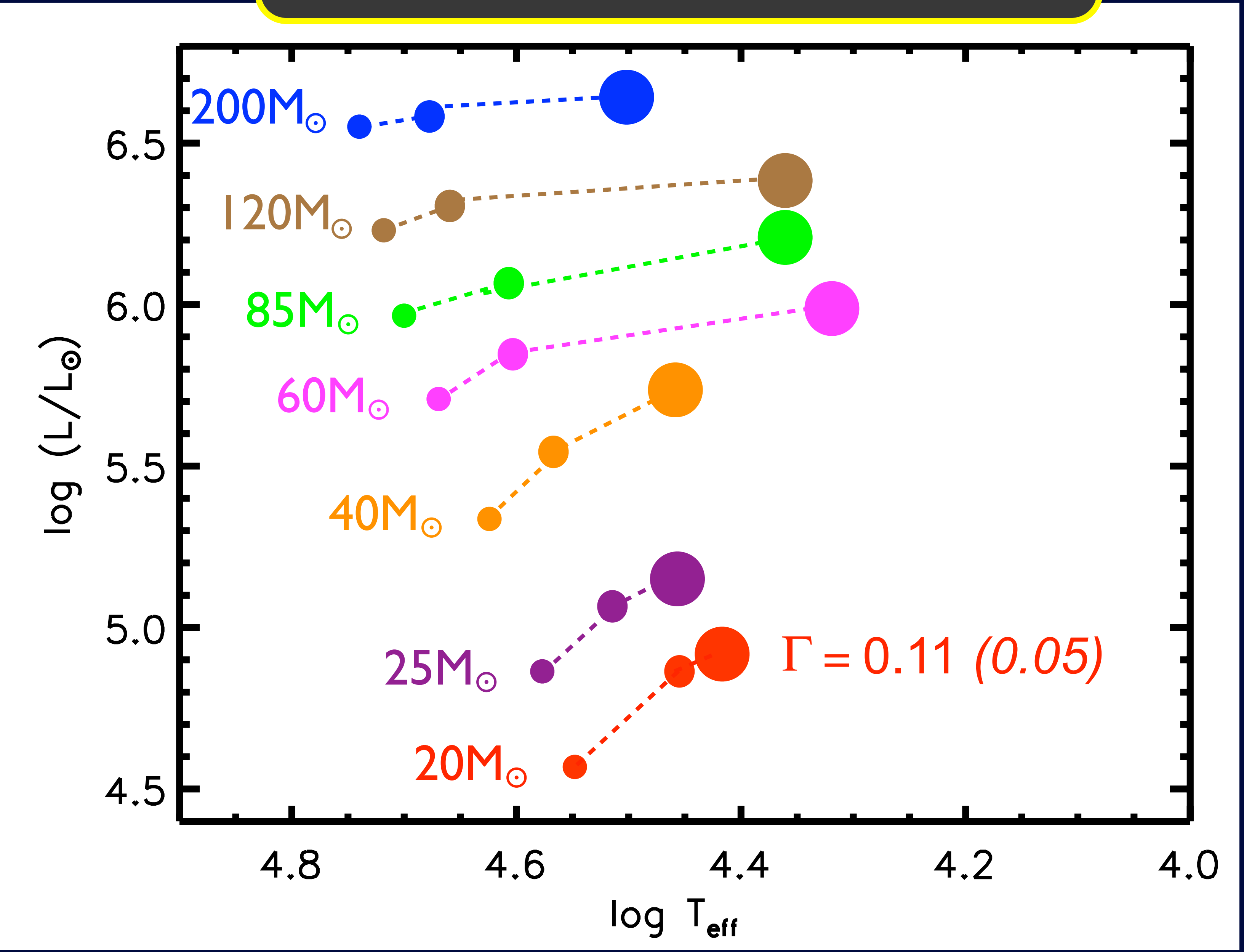
Eddington parameter during the Main Sequence: at the end

$$\Gamma = \frac{k\,L}{4\pi G c M} \simeq 2\times10^{-5}\,\frac{L/L_\odot}{M/M_\odot}\,\frac{k}{k_e}$$



(evol. tracks from Meynet & Maeder 2003, Crowther+ 2010)

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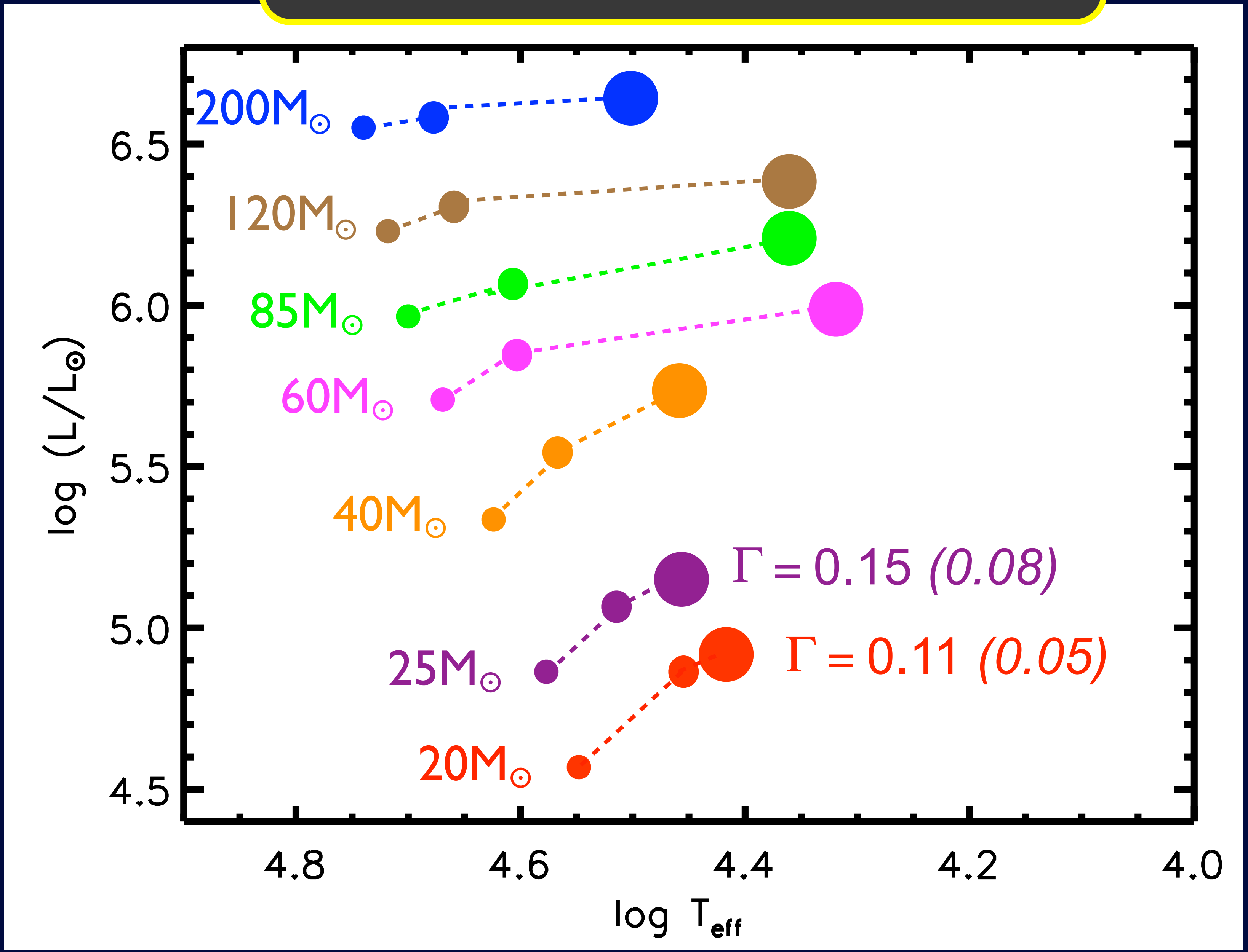

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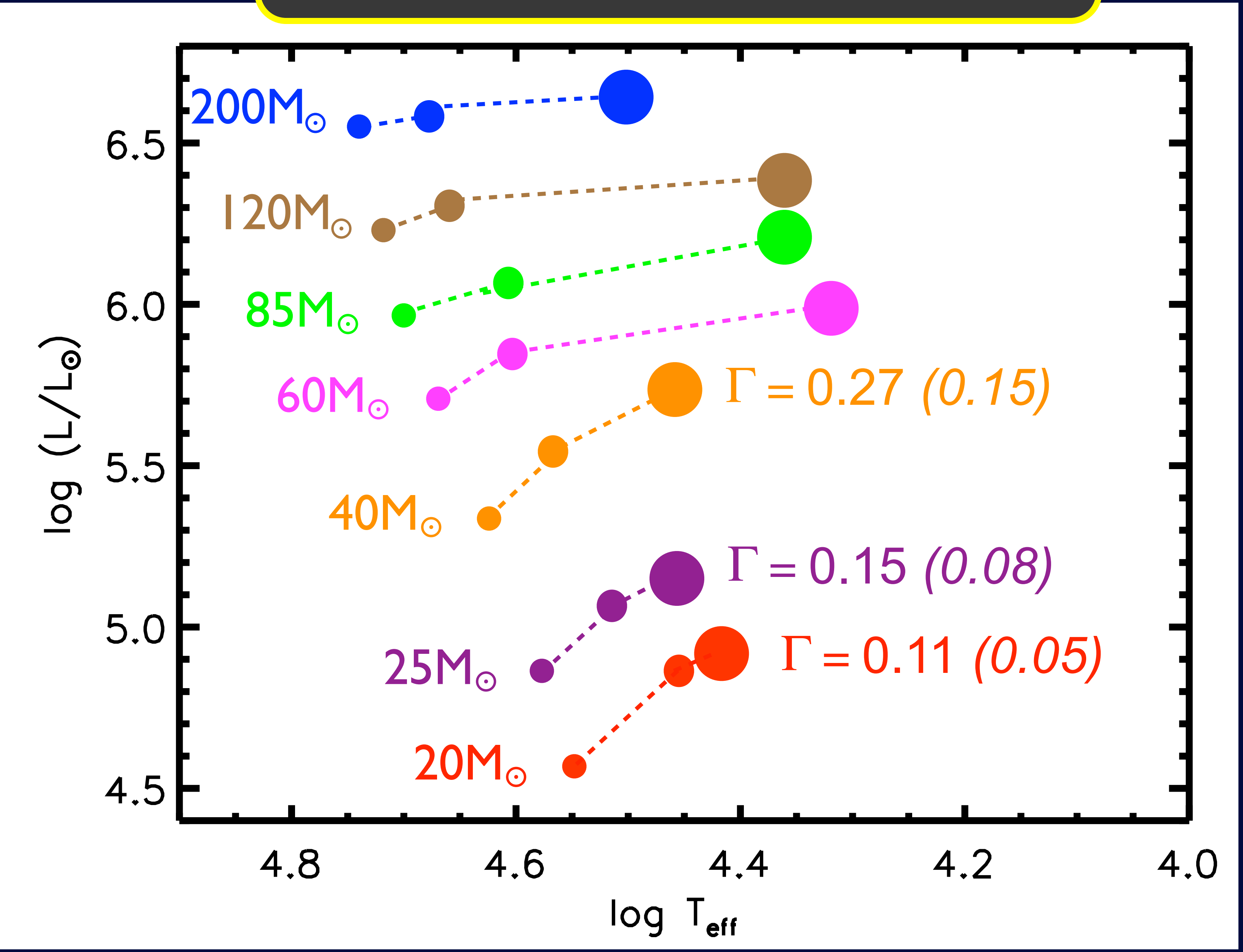

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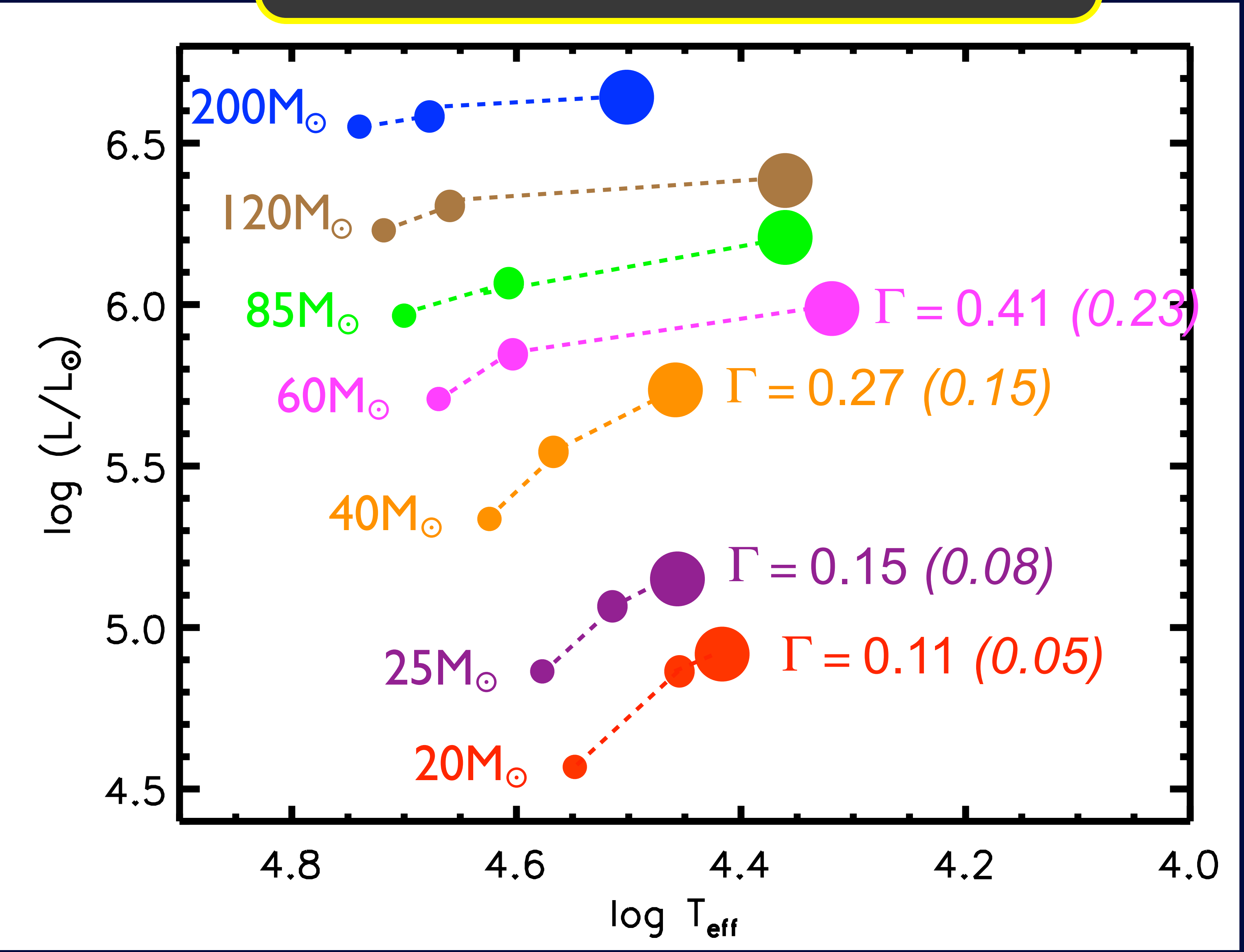

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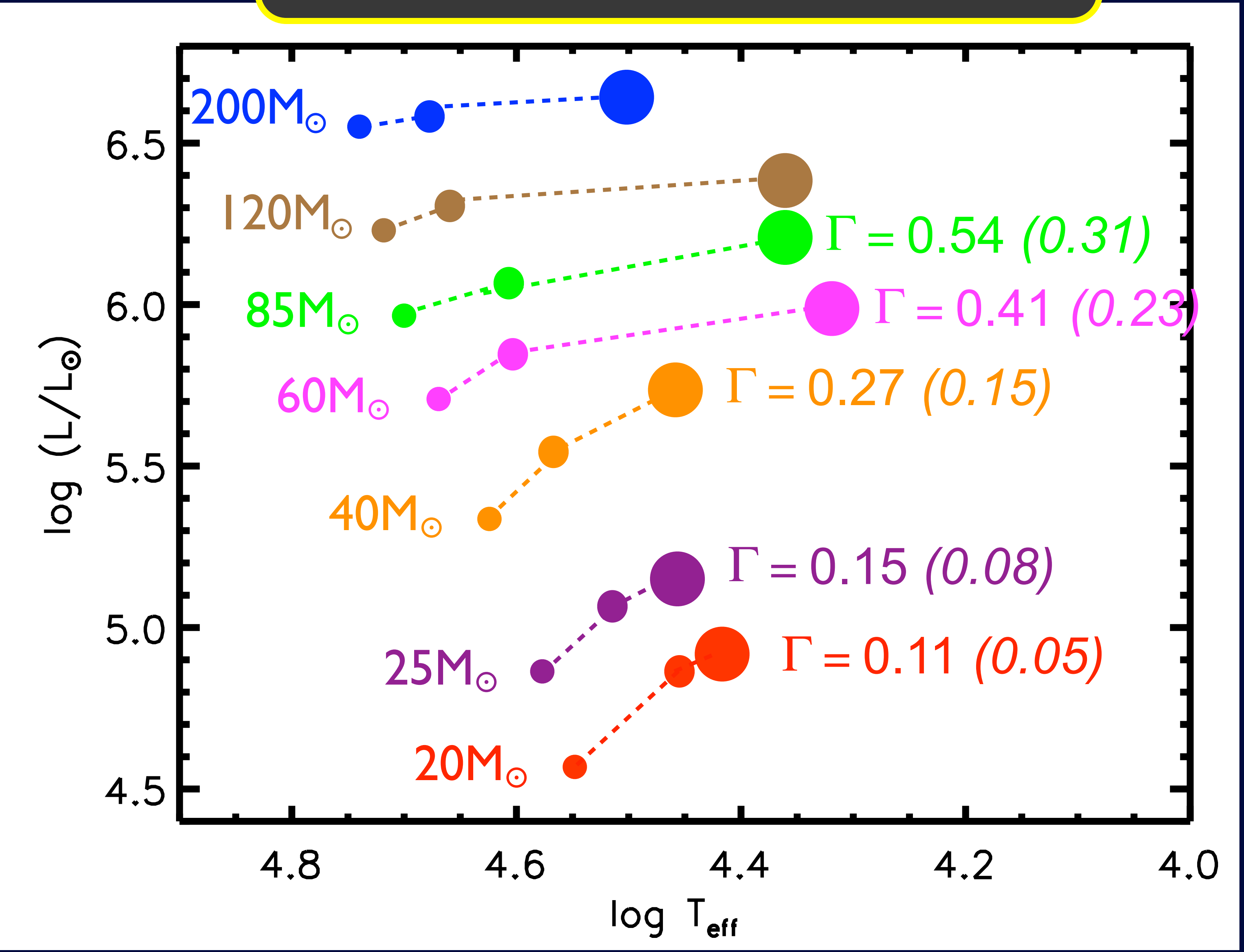

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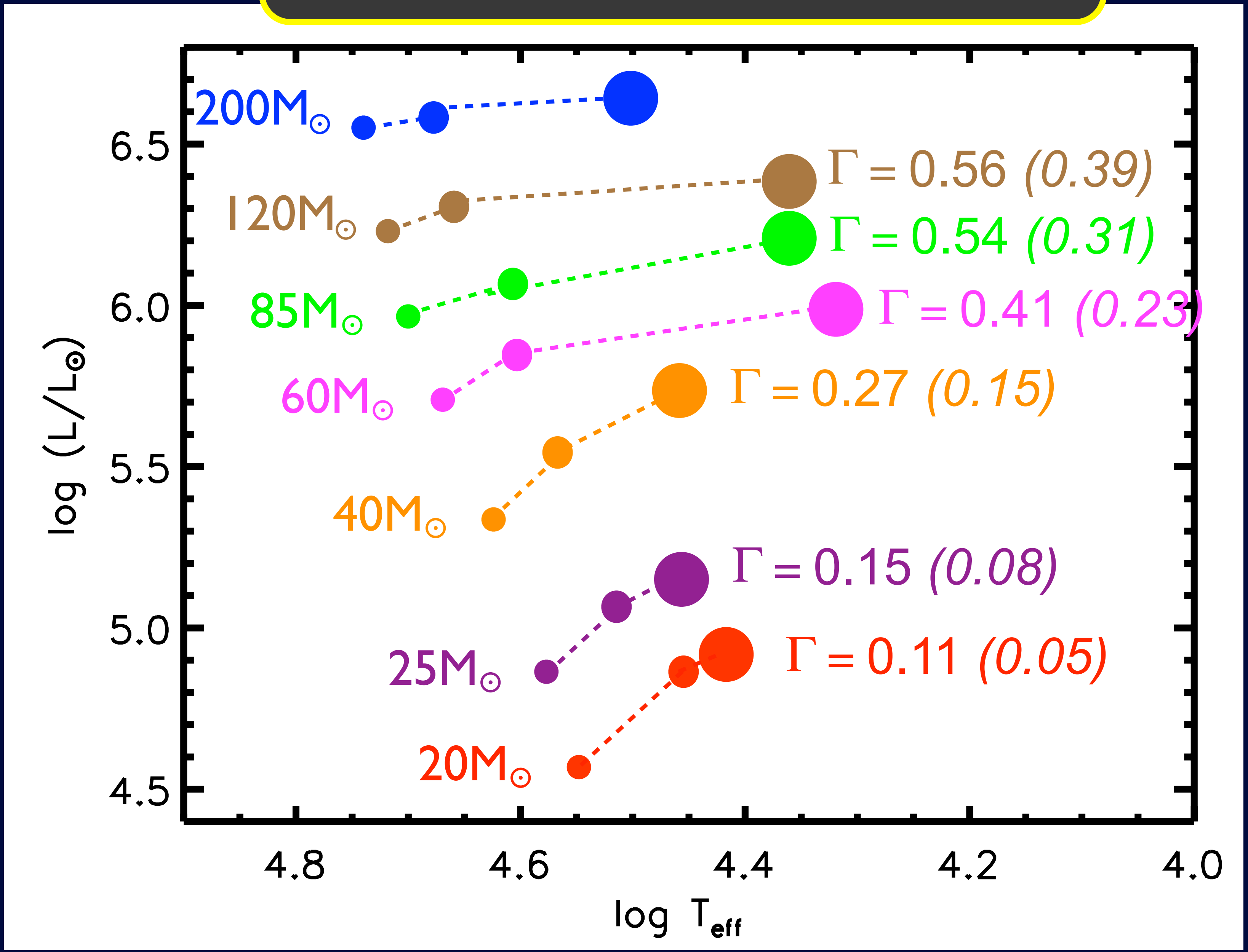

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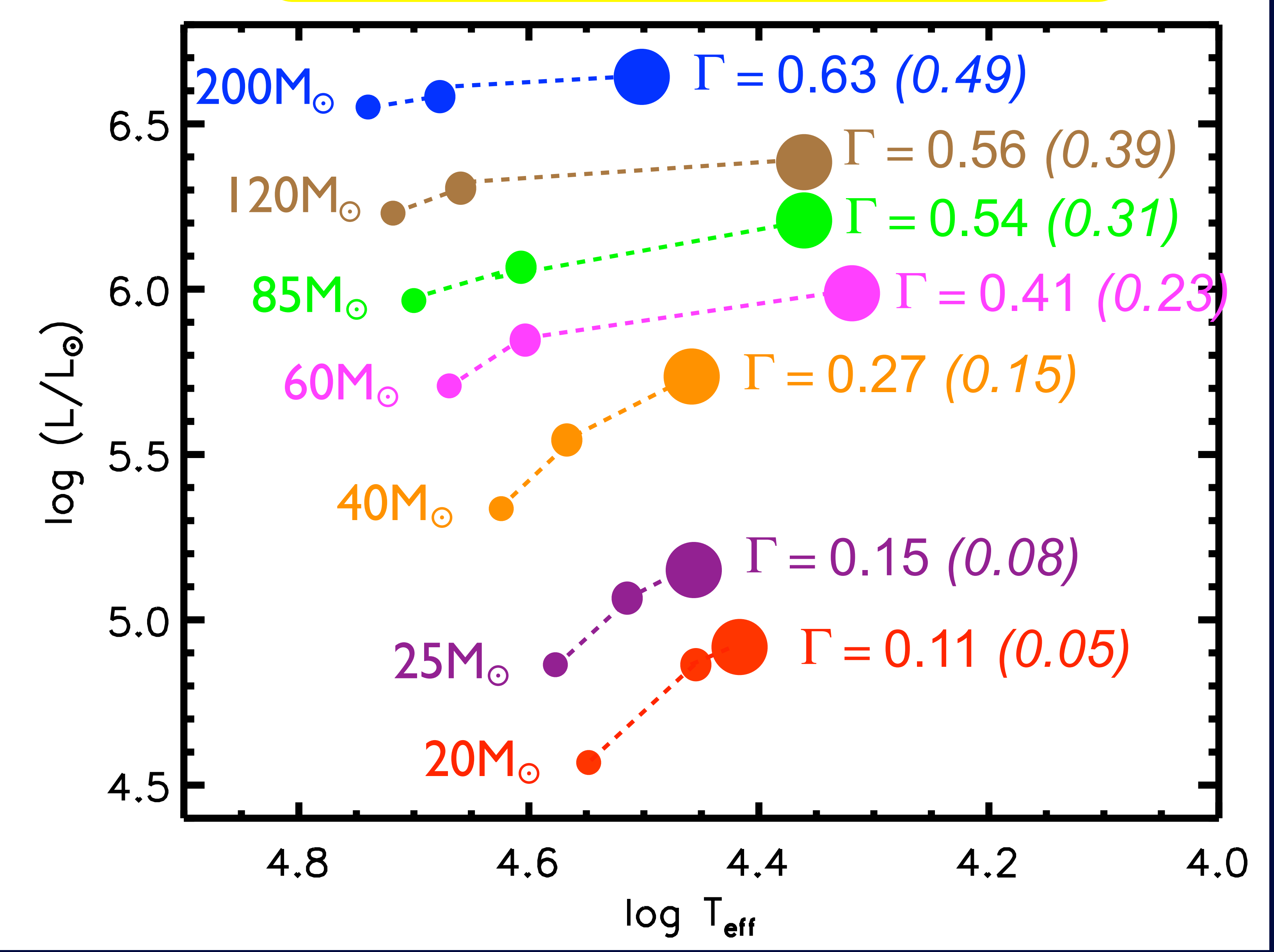

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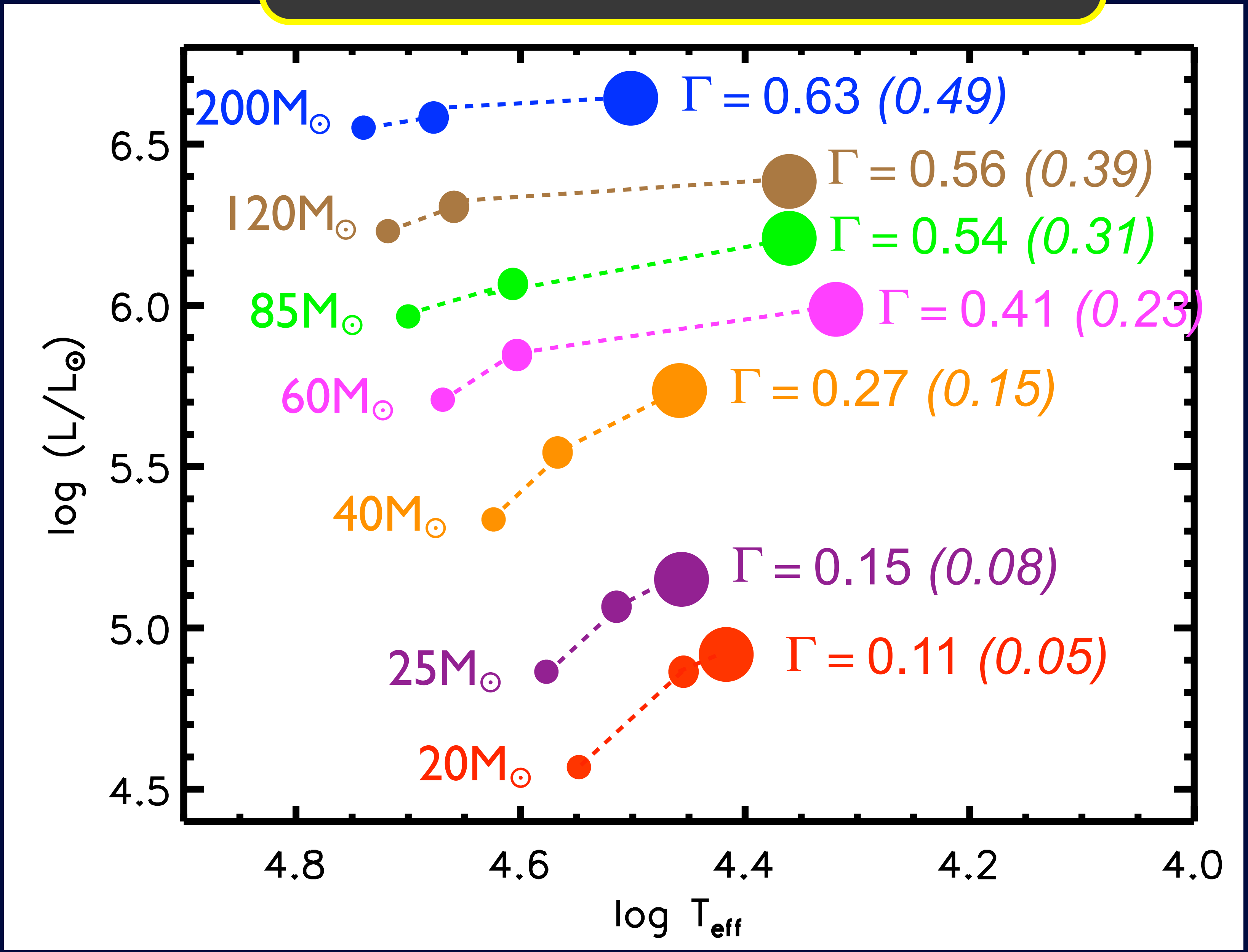

Massive stars are doomed to have complicated lives:
physics of stellar evolution + mass loss = high Γ

(evol. tracks from Meynet & Maeder 2003, Crowther+ 2010)

1. The Eddington Limit
Mass-loss rate as a function of the Eddington parameter

What could be worse?

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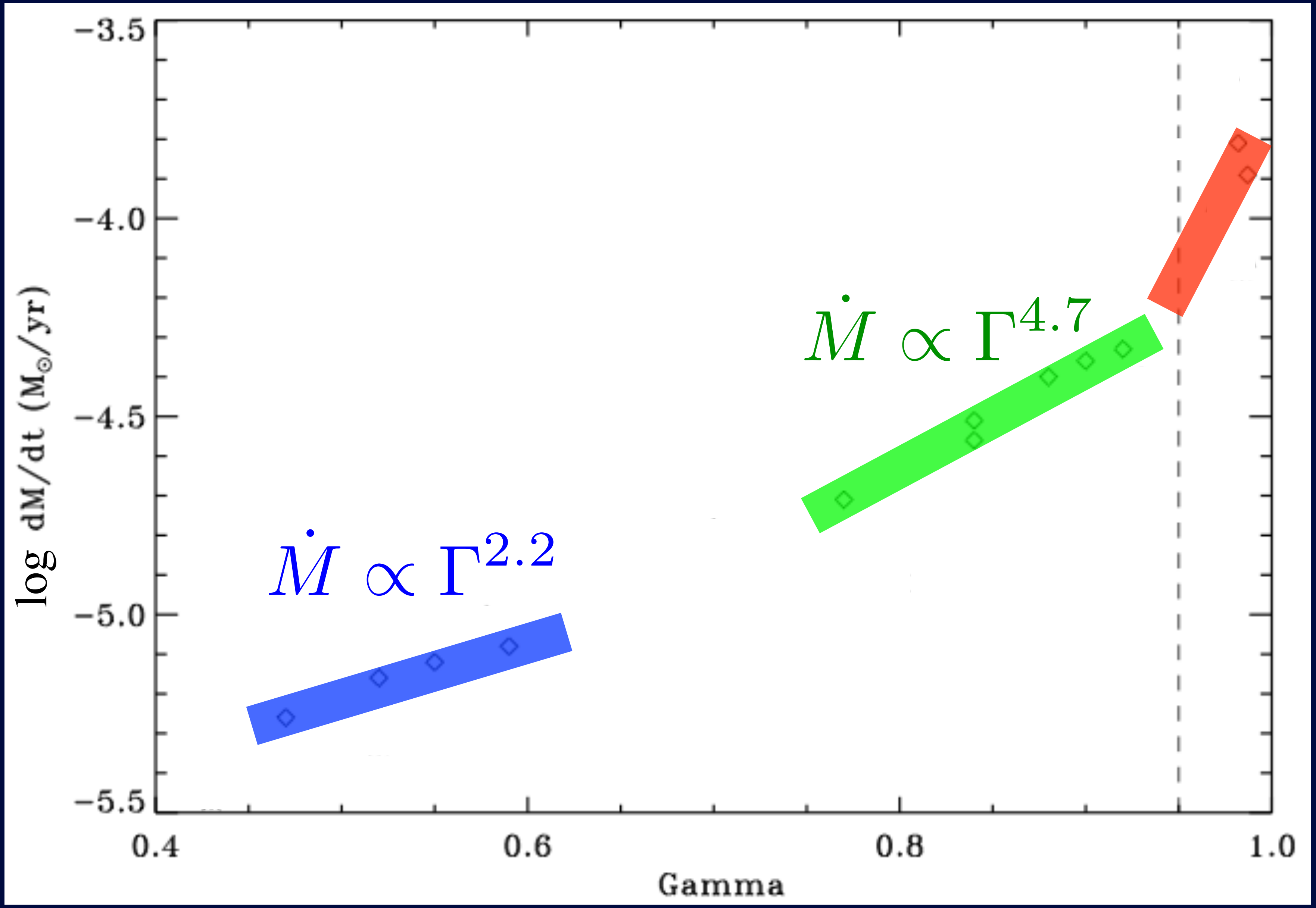
Mass-loss rate as a function of the Eddington parameter

What could be worse?

The mass-loss rate increases considerably as a function of Γ.



(adapted from Vink+ 2011)

1. The Eddington Limit

Positive feedback: the mass-loss rate and the Eddington parameter

(see e.g. Meynet & Maeder 2003, Smith & Conti 2008)

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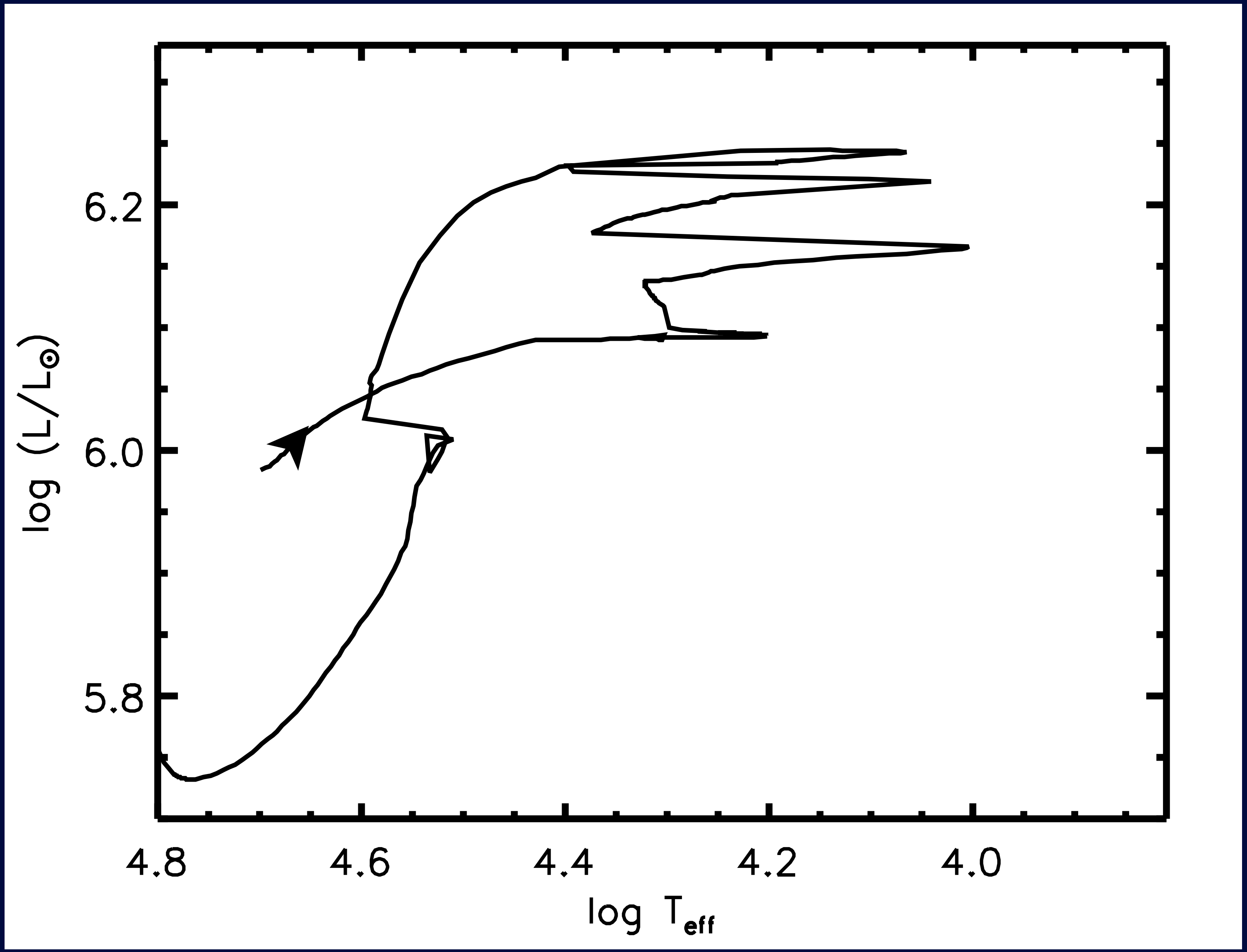
What are the implications for stellar evolution?

(see e.g. Meynet & Maeder 2003, Smith & Conti 2008)

1. The Eddington Limit
Evolution of an 85 solar mass star without rotation

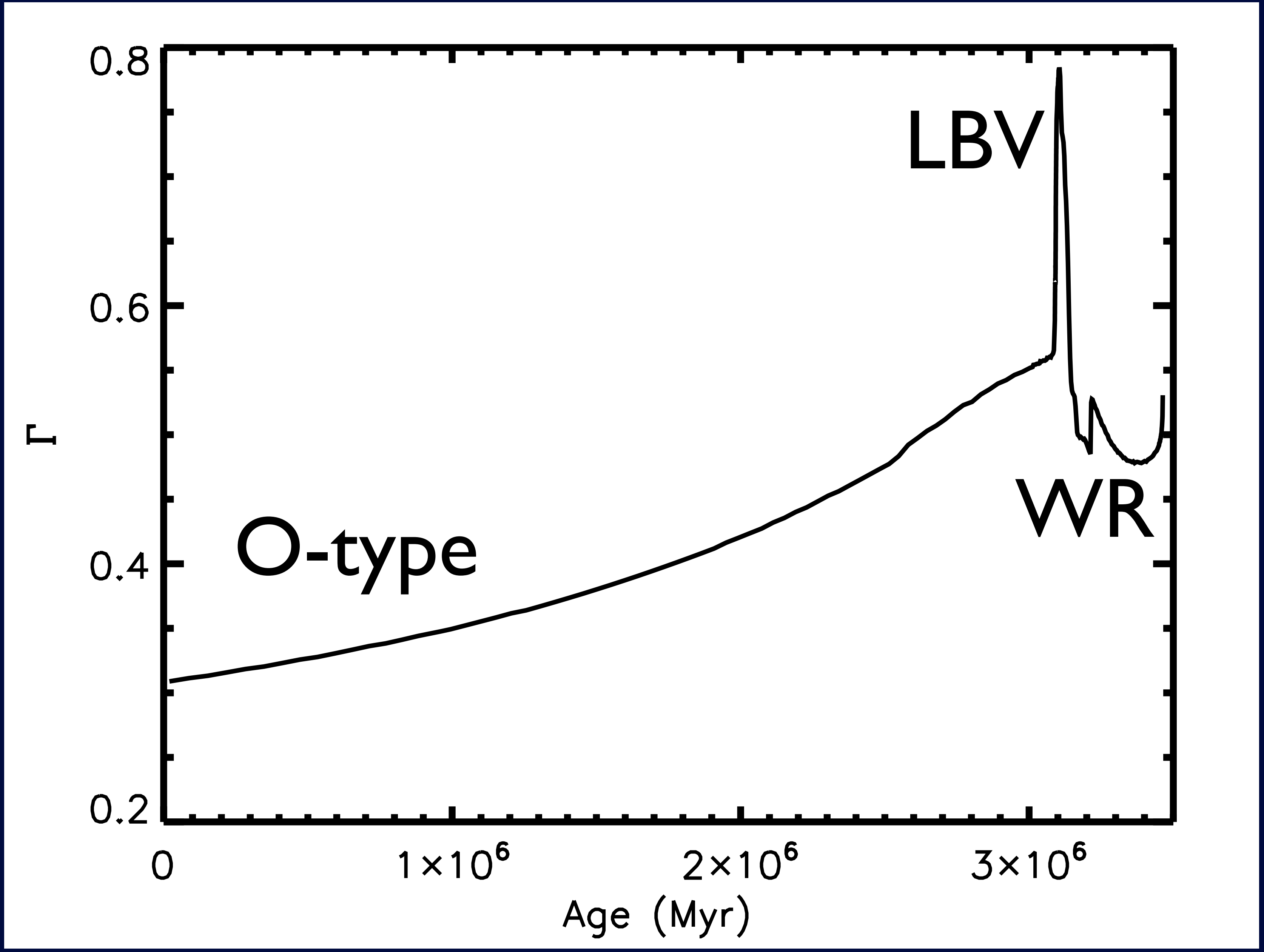
O-type → Luminous Blue Variable → WR → SN



(evol. tracks from Meynet & Maeder 2003)

1. The Eddington Limit
Evolution of an 85 solar mass star without rotation

There will be a short evolutionary phase (LBV) when a significant amount of the mass will be lost. Affects the fate of massive stars.



Jose Groh - Massive stars close to the Eddington limit

(evol. tracks from Meynet & Maeder 2003)

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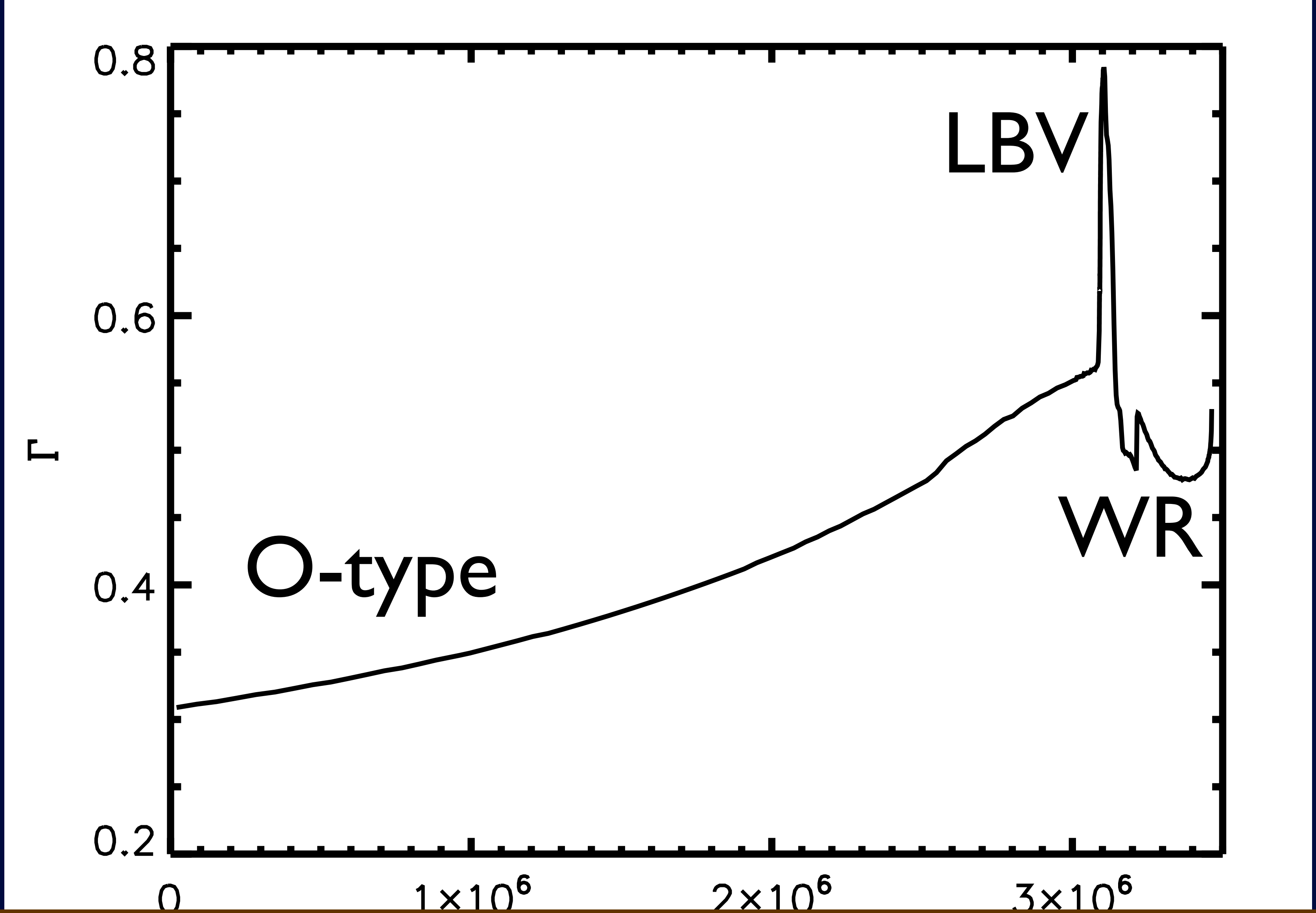
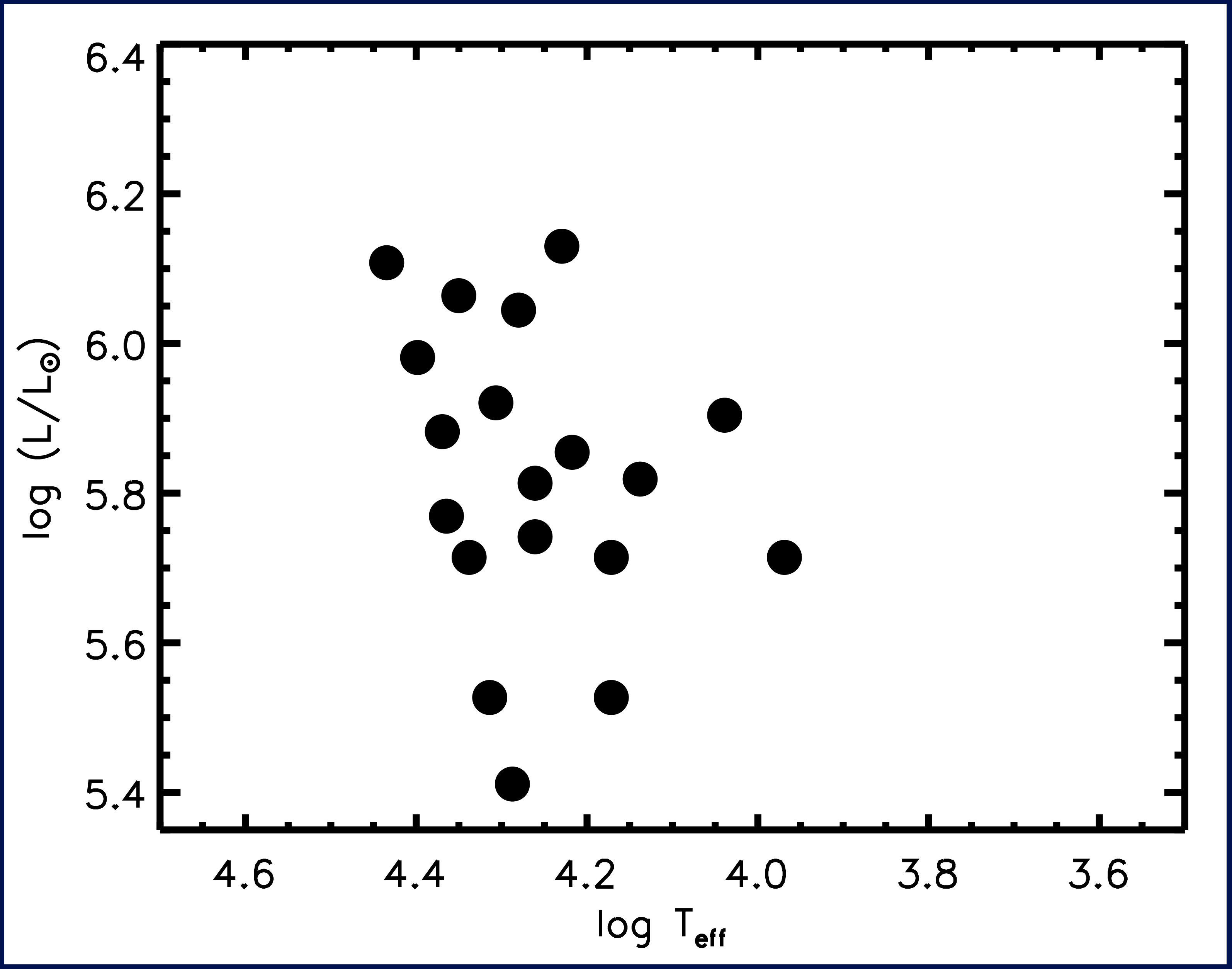


Theoretical definition of an LBV based on evolutionary models: evolved massive stars close to the Eddington limit.

(evol. tracks from Meynet & Maeder 2003)

2. LBVs: living near the Eddington limit

Location of candidates and confirmed Galactic LBVs in the HR diagram



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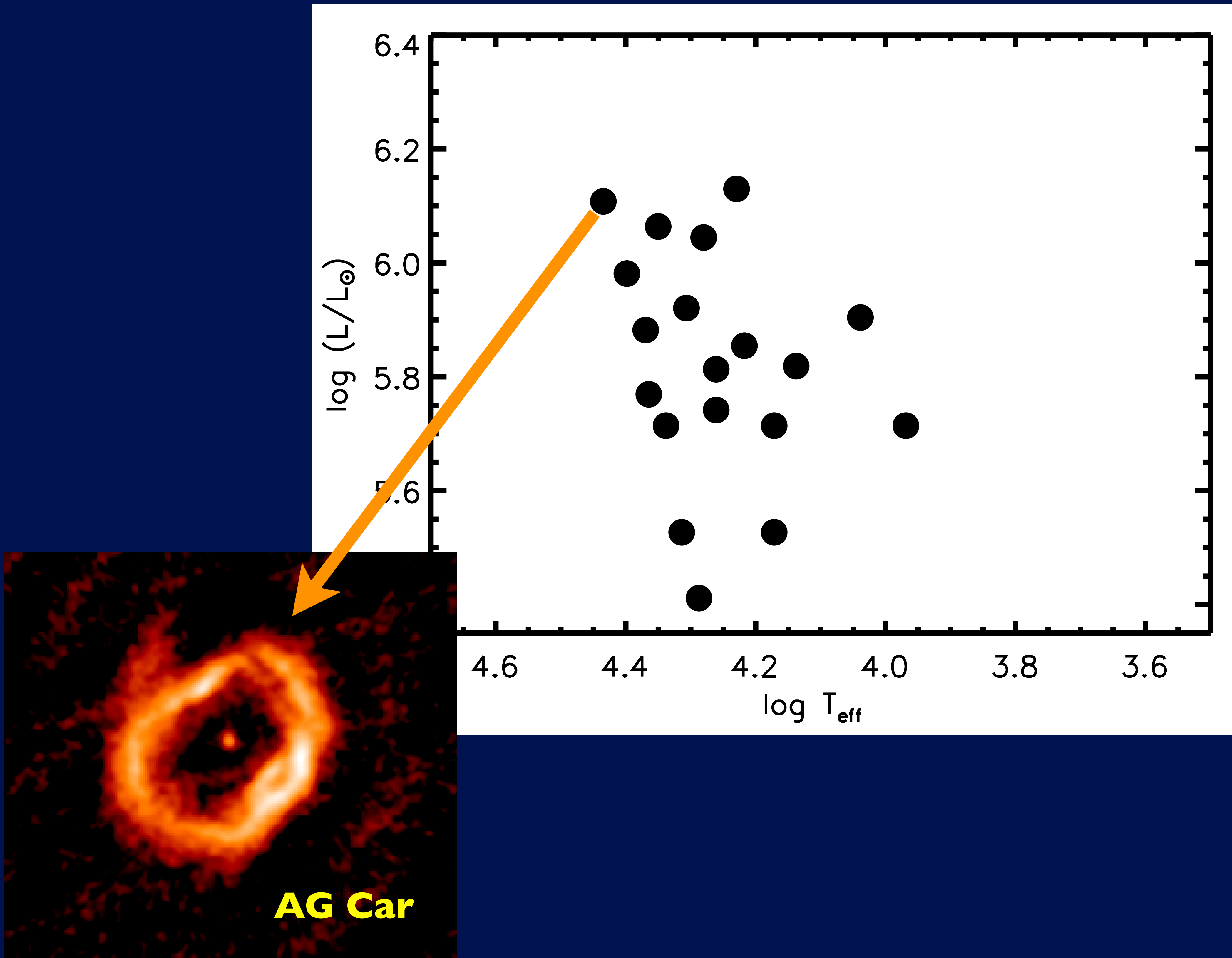

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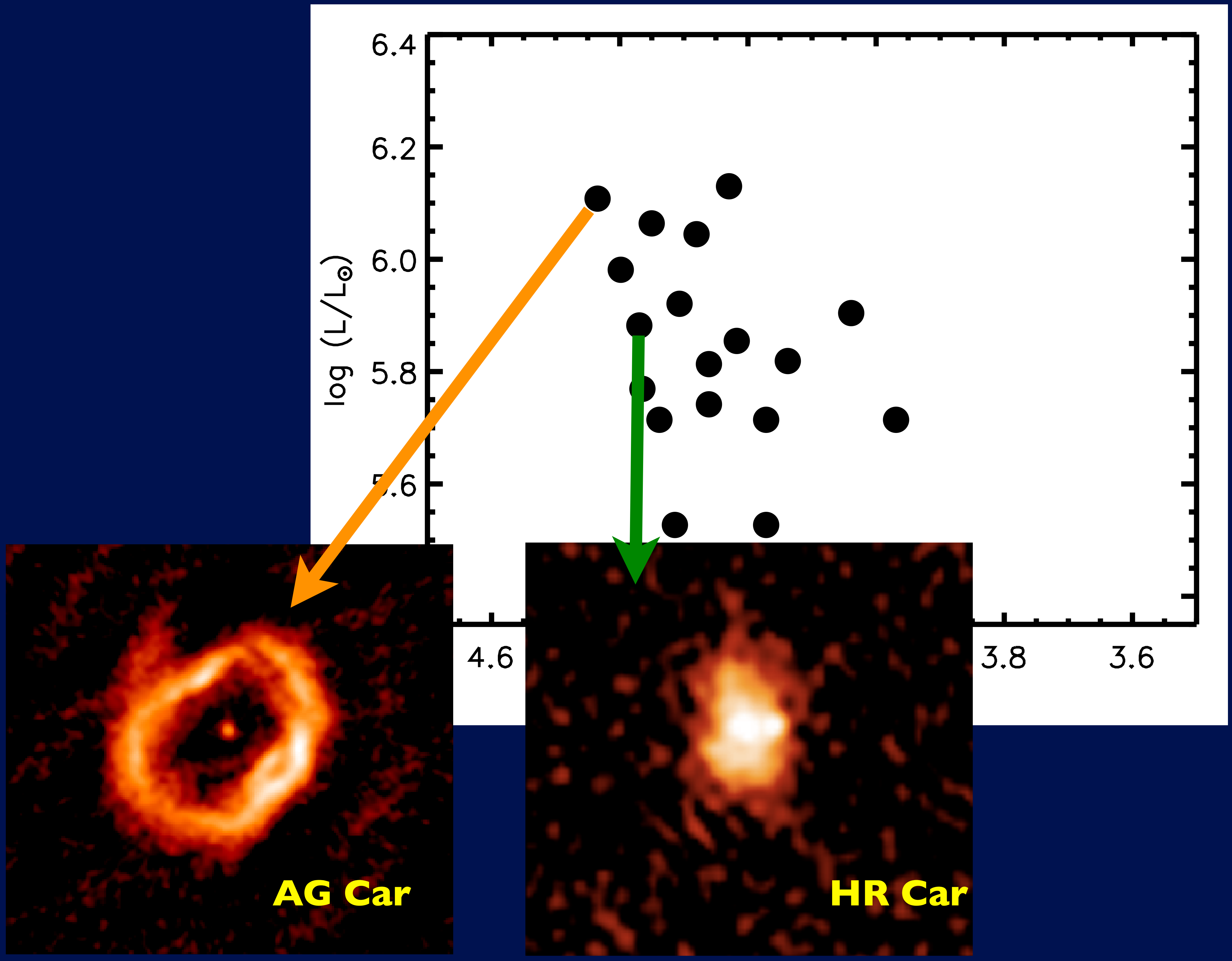

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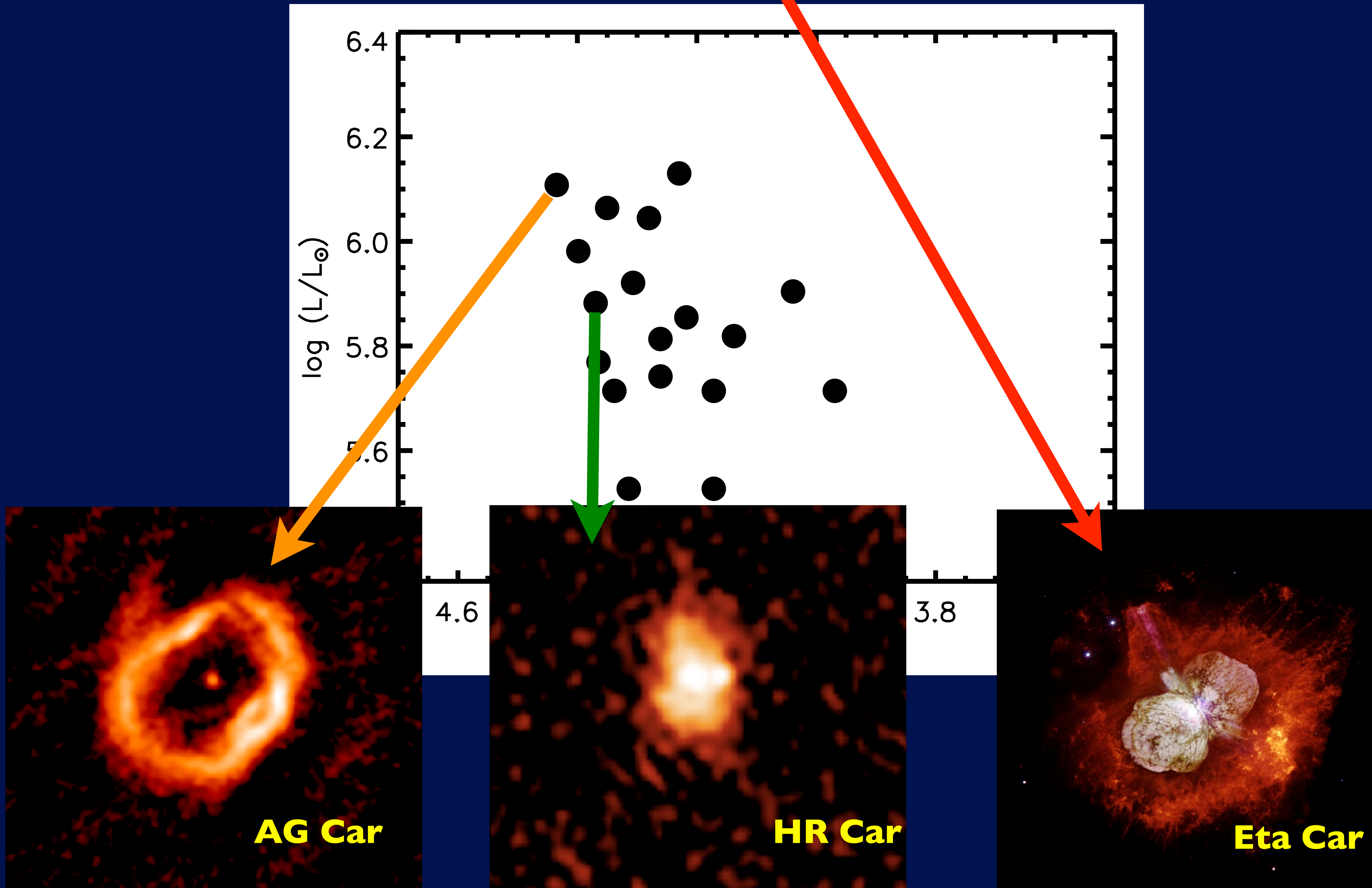
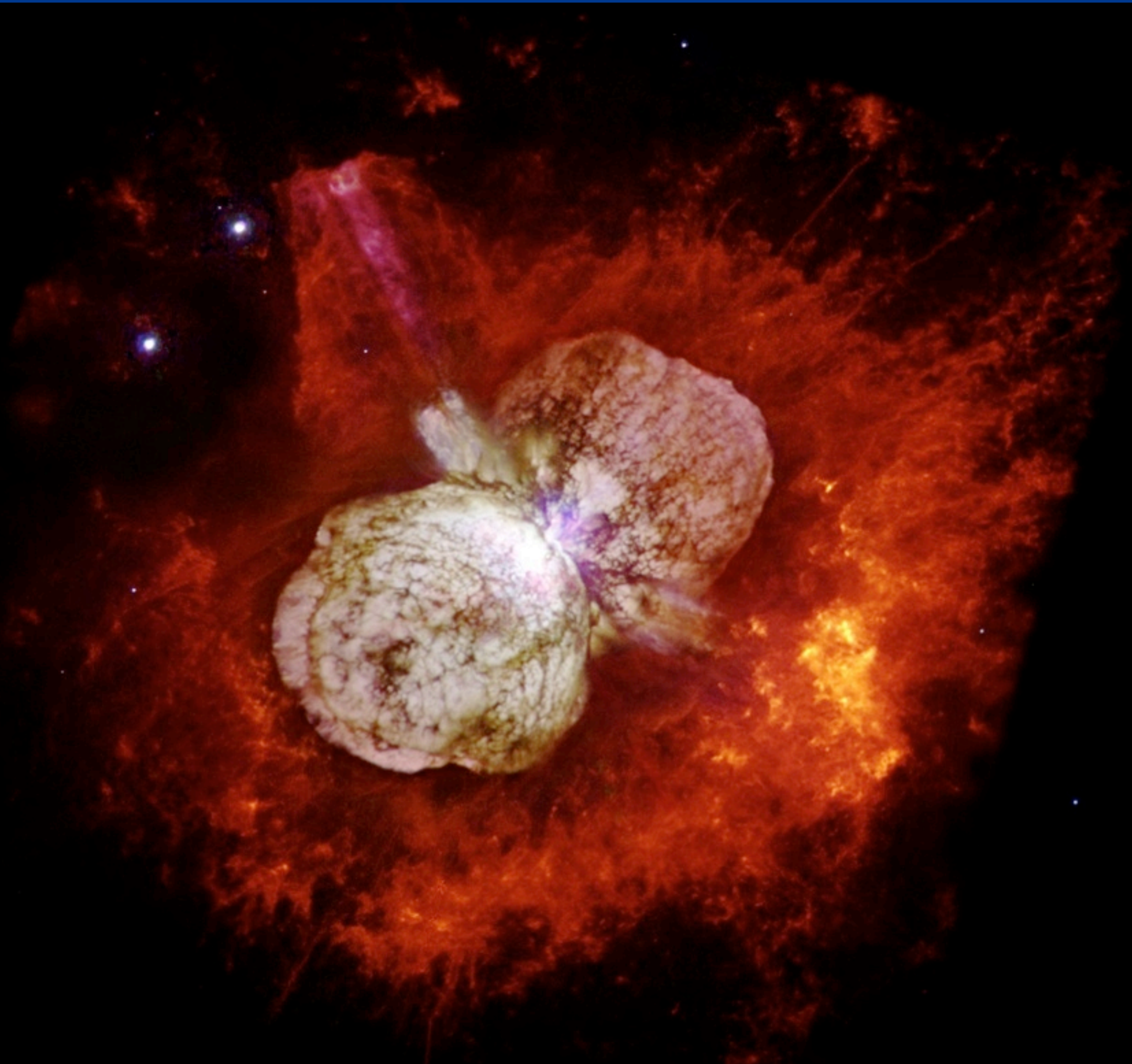


2. LBVs: living near the Eddington limit
Eta Carinae and the role of binarity



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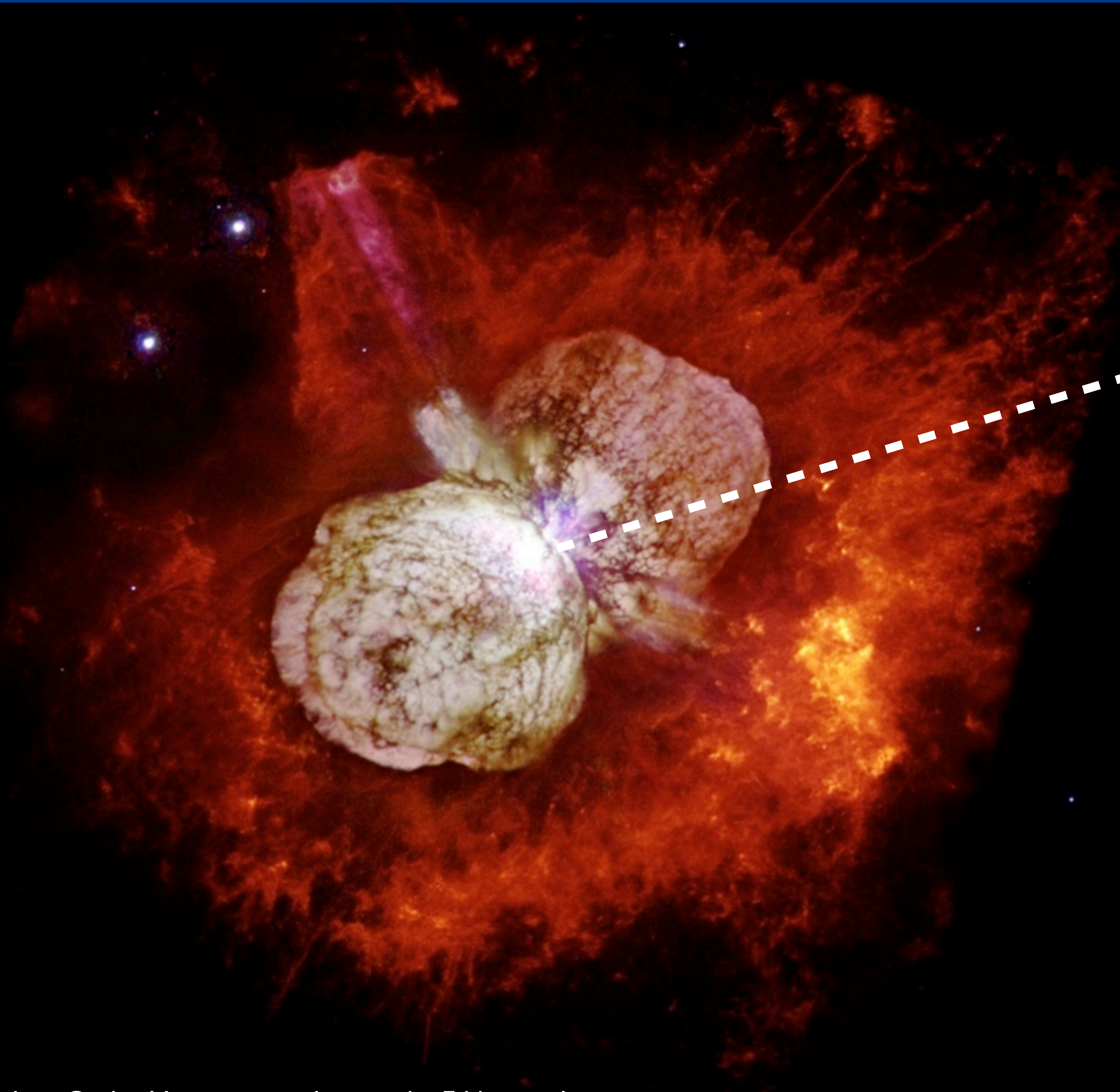

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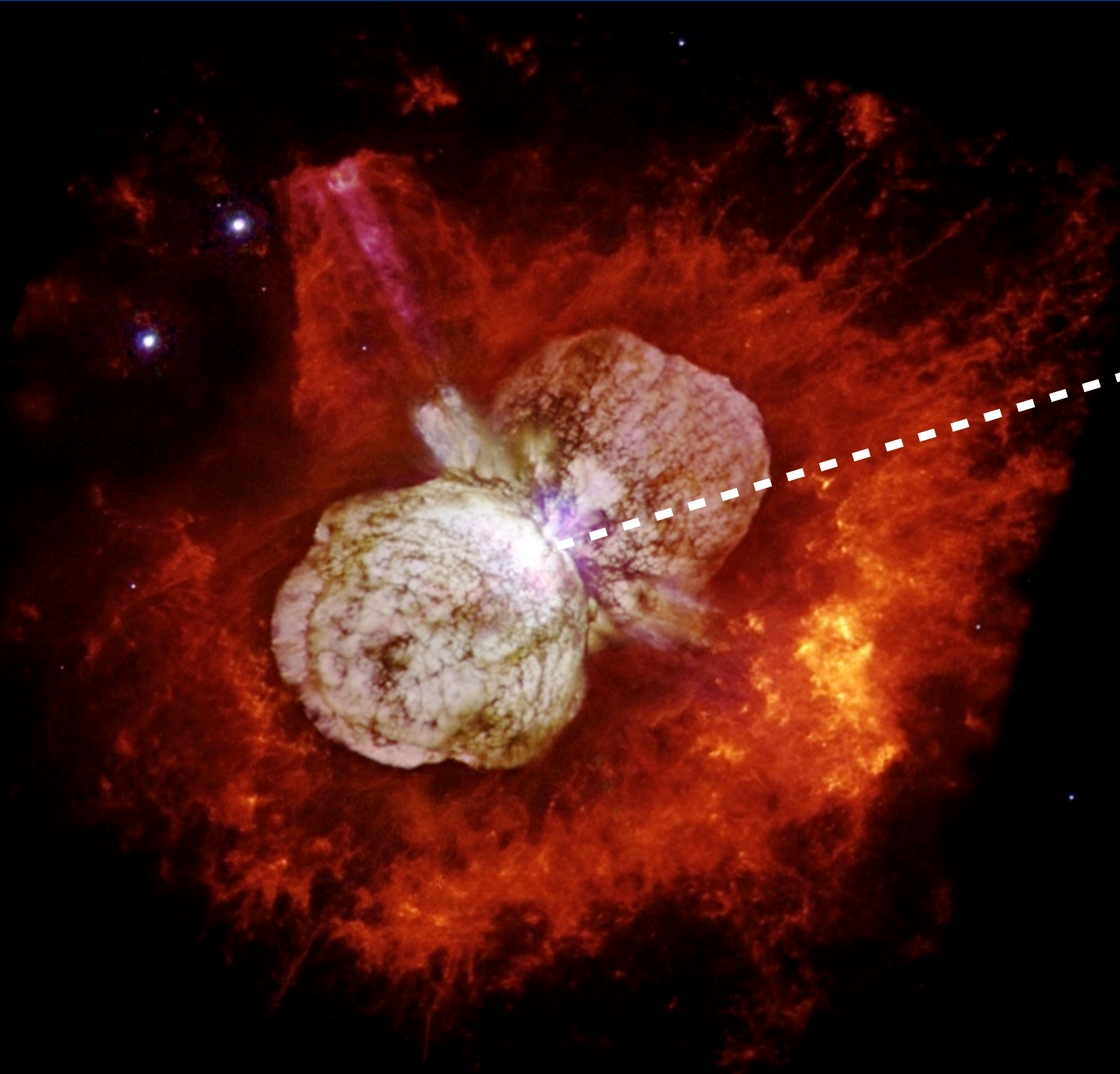


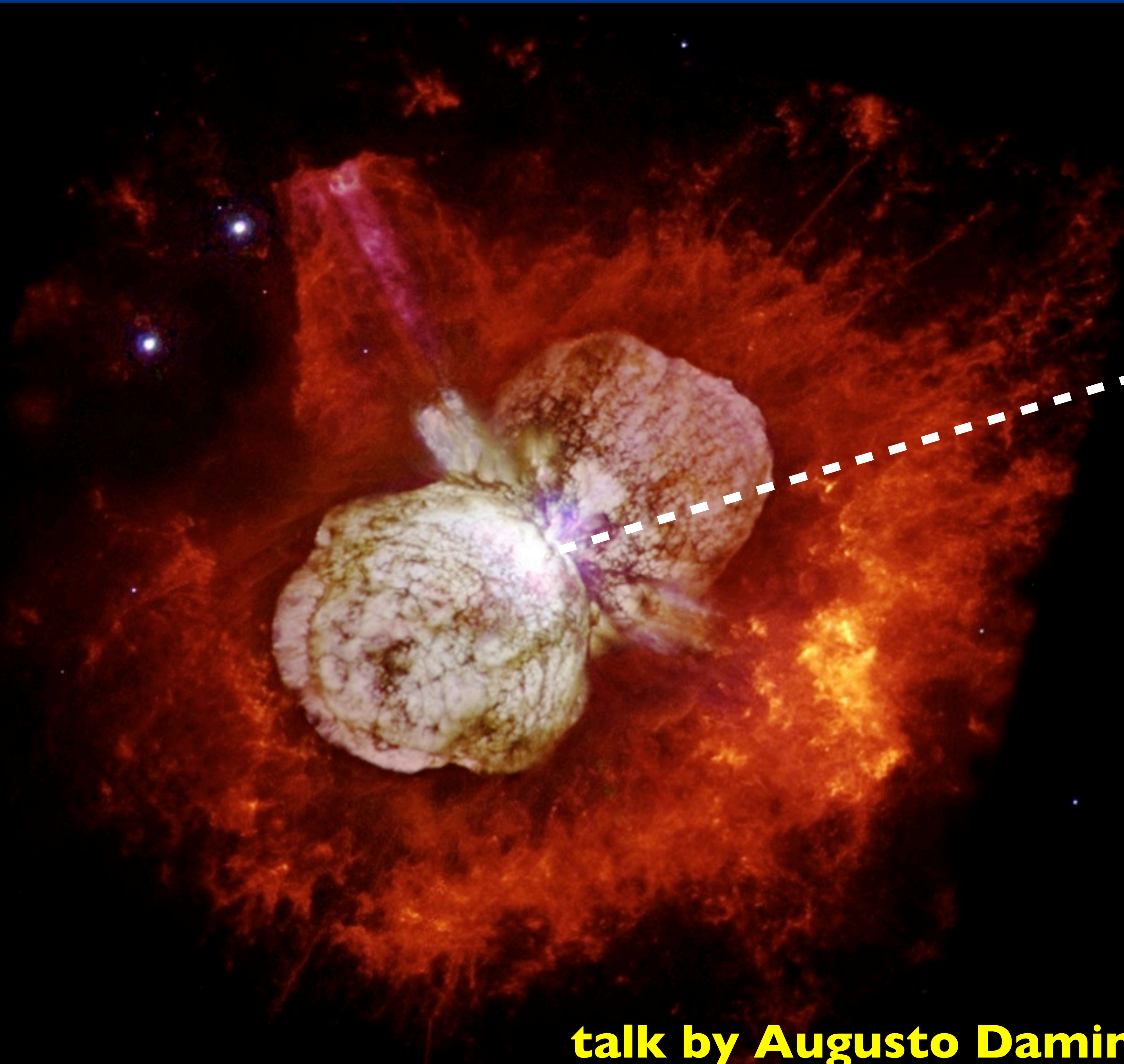
Eta Car B

Eta Car A

Period = 5.5 years

2. LBVs: living near the Eddington limit

Eta Carinae and the role of binarity



Period = 5.5 years

wind-wind collision zone

talk by Augusto Damineli

2. LBVs: living near the Eddington limit

How do we observationally recognize an LBV?

Observational consequences of living near the Eddington limit

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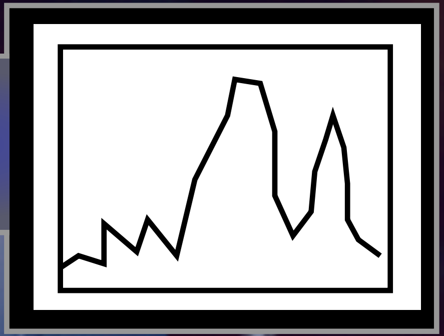
(a) S Doradus type variability



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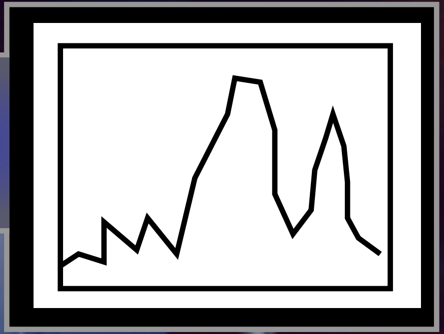
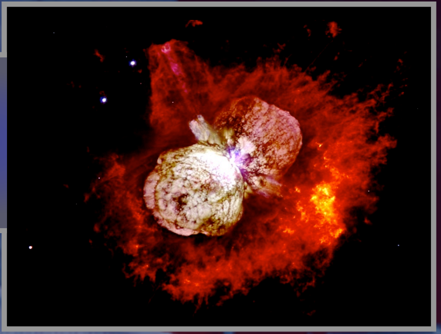


(b) Giant eruptions



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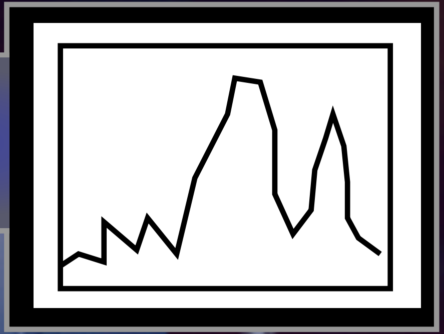

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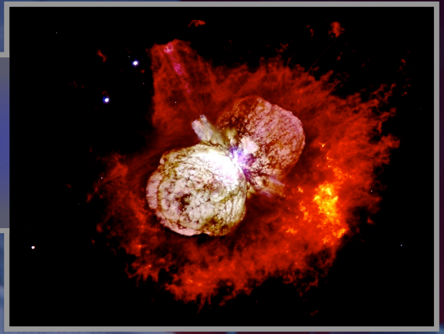
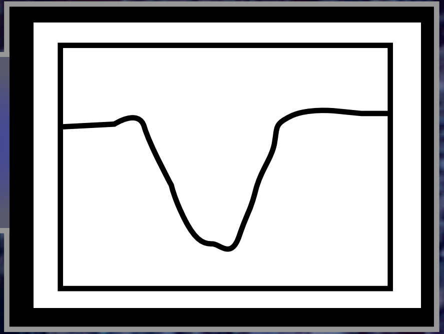


(c) Rapid rotation



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How do we observationally recognize an LBV?

Observational consequences of living near the Eddington limit

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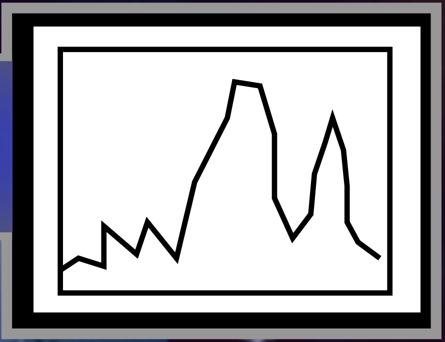
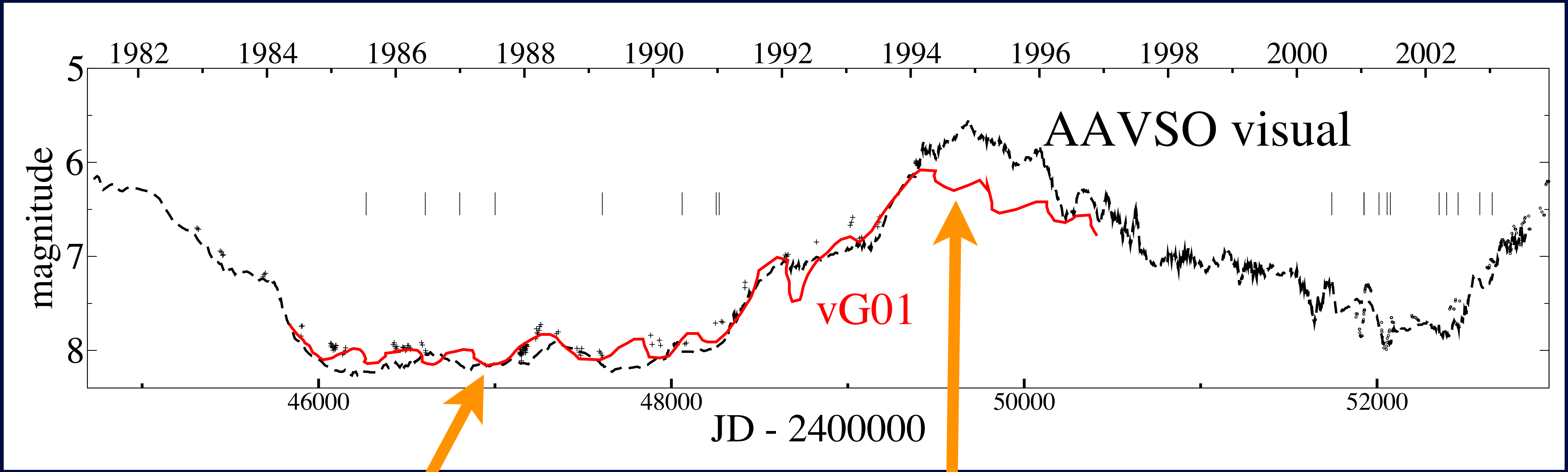


2. LBVs: living near the Eddington limit
a) The S-Dor type variability: photometric changes

V-band lightcurve of AG Car shows variability of ~2 mag



(Groh+ 2009a)

Minimum=blue, hot star

Maximum=redder, cooler star

LBVs appear blue (i.e. hot) during visual minimum and become redder (i.e. cooler) at visual maximum (van Genderen 1979).

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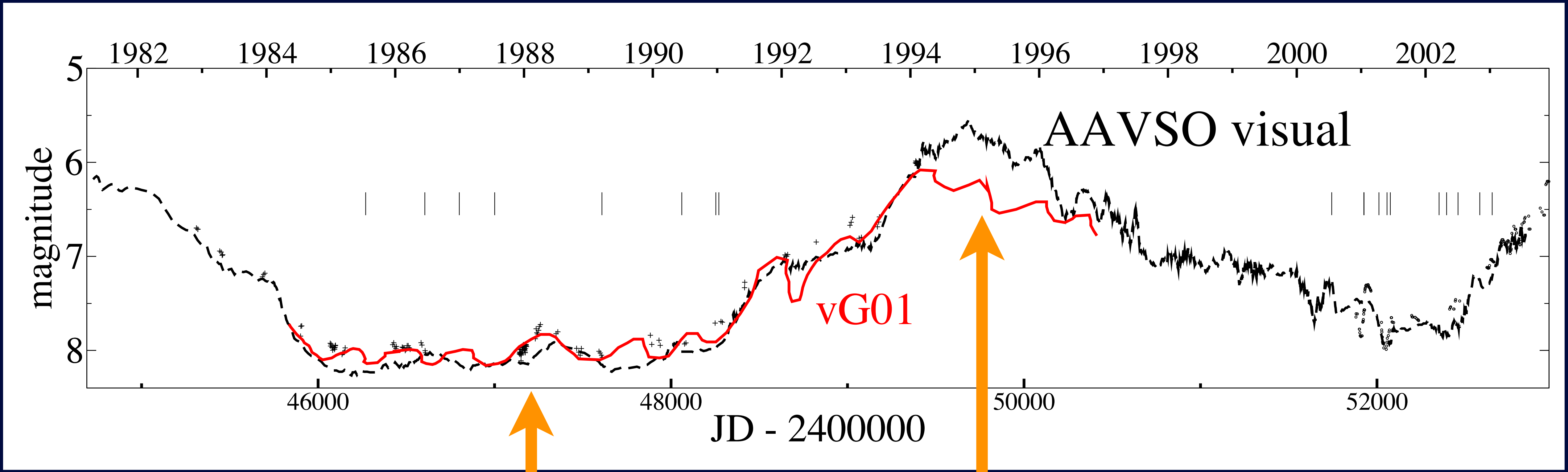

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Minimum=small stellar radius **Maximum=large stellar radius**

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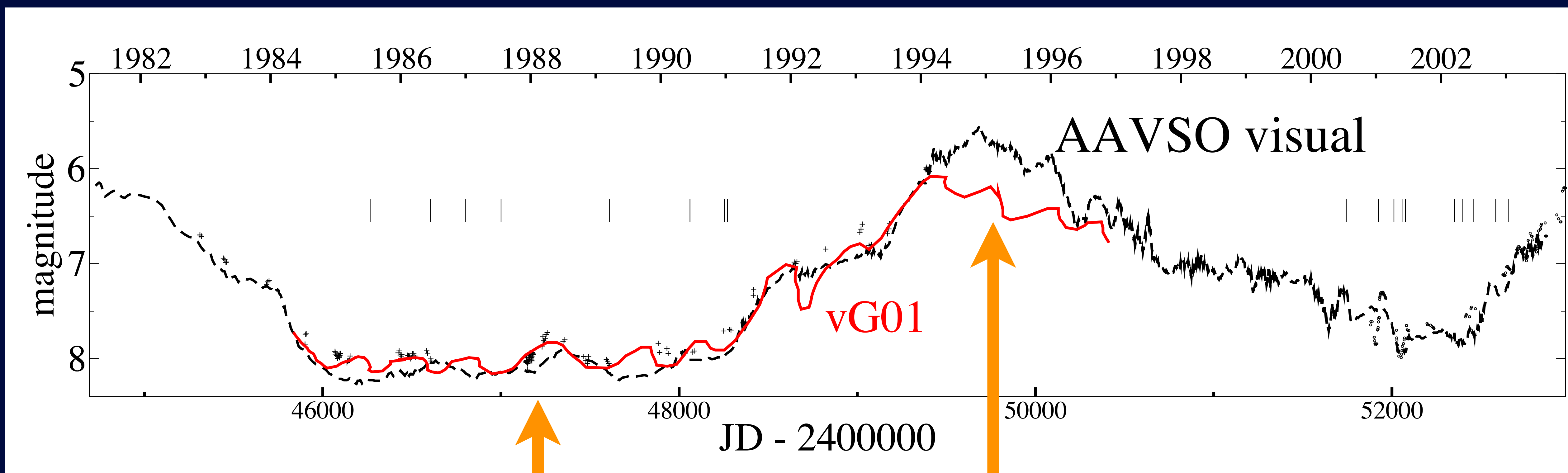

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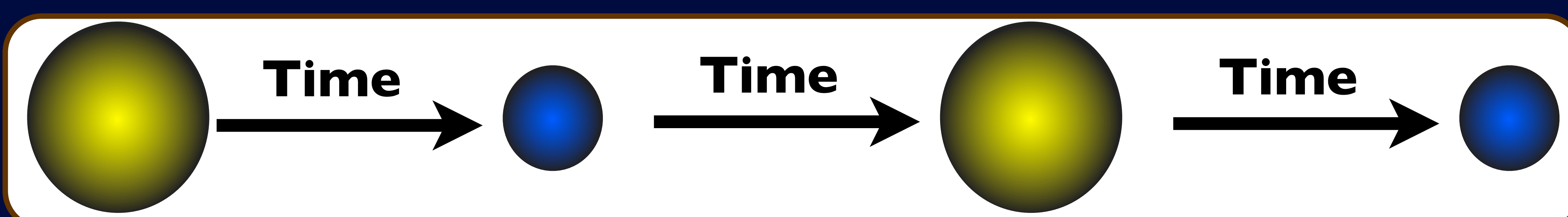
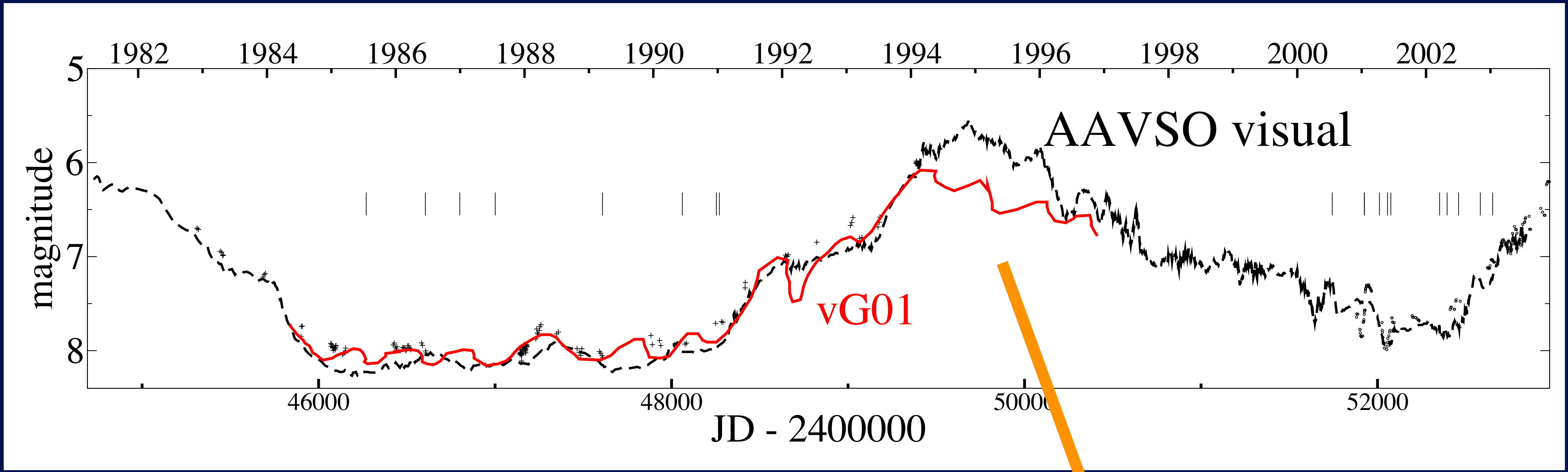


2. LBVs: living near the Eddington limit

a) The S-Dor type variability: changes in the spectral type



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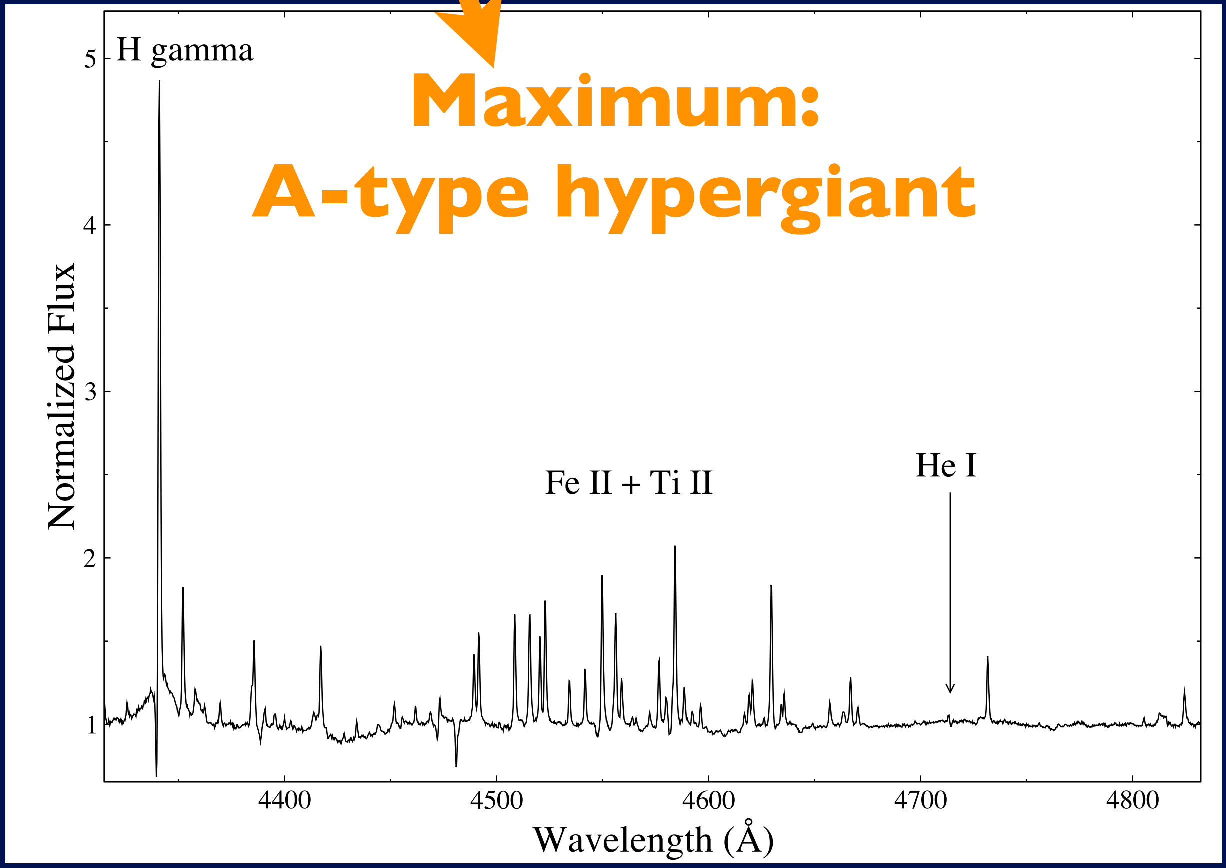

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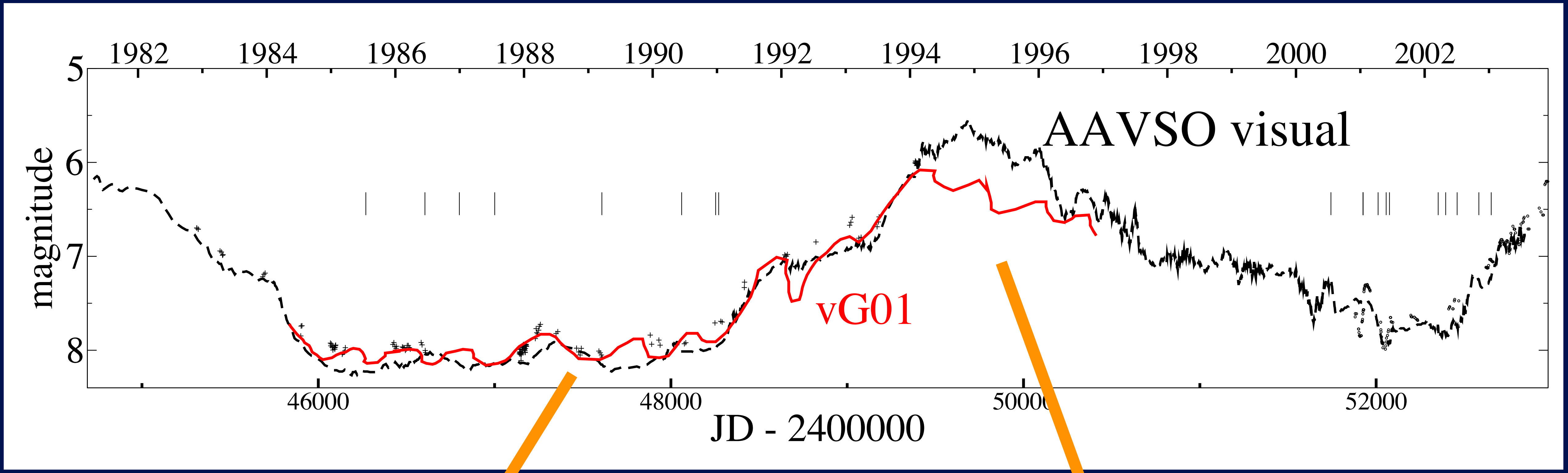

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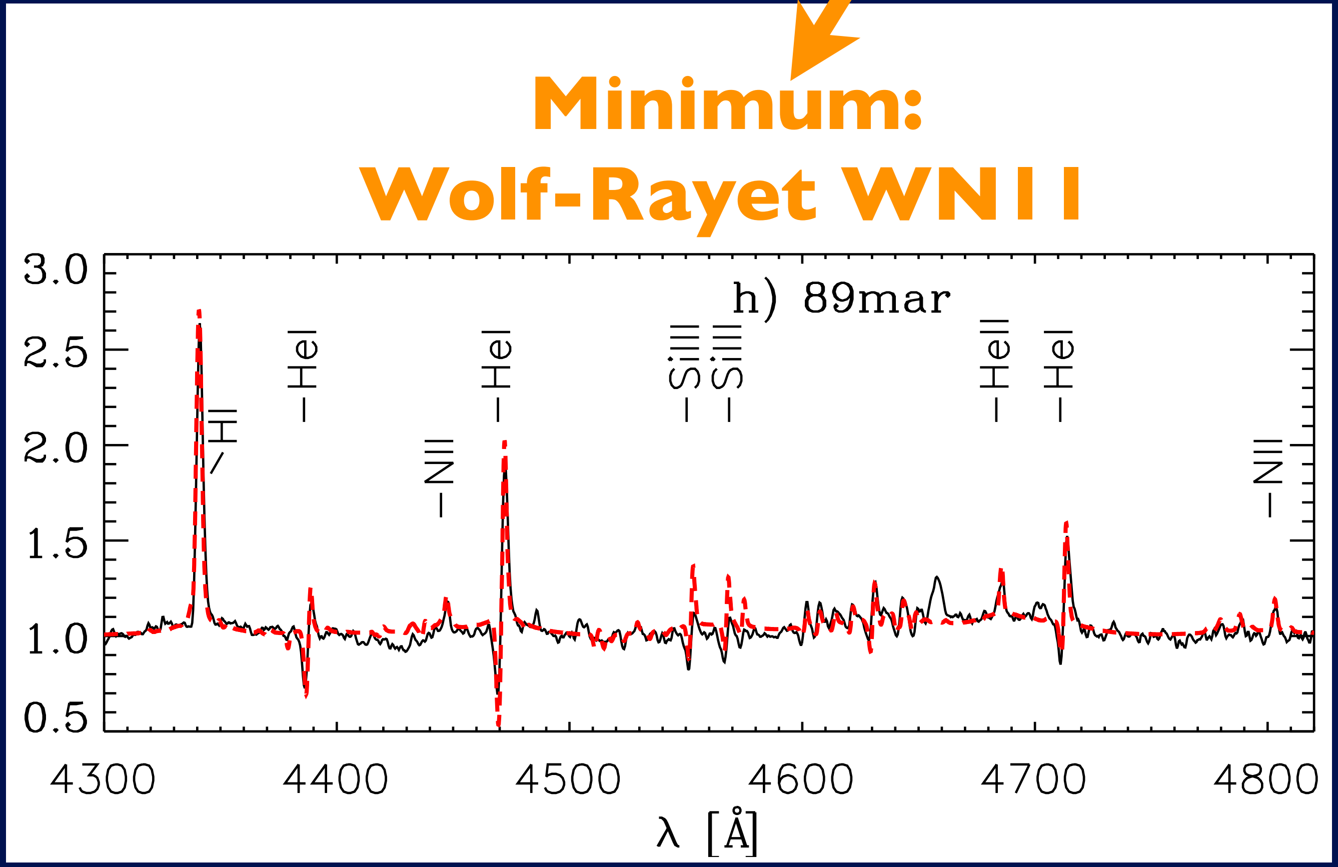
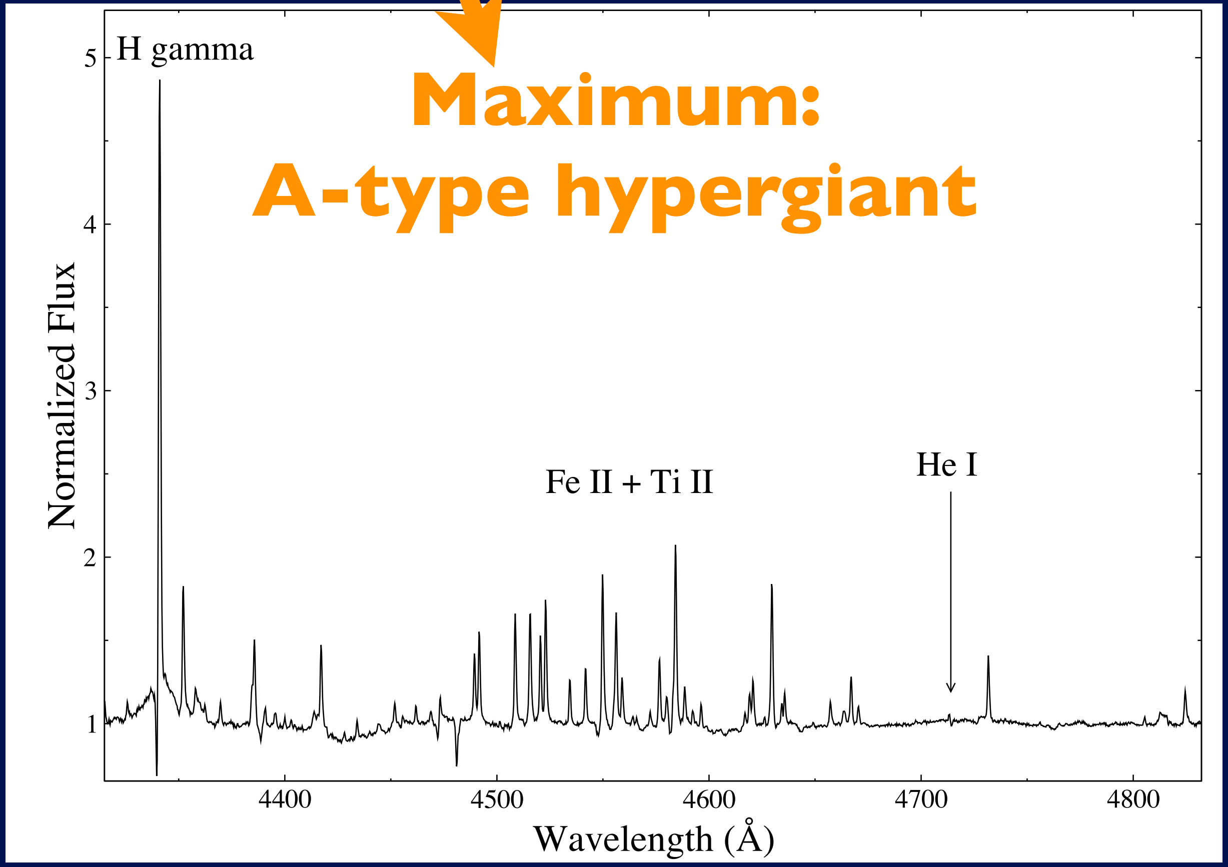
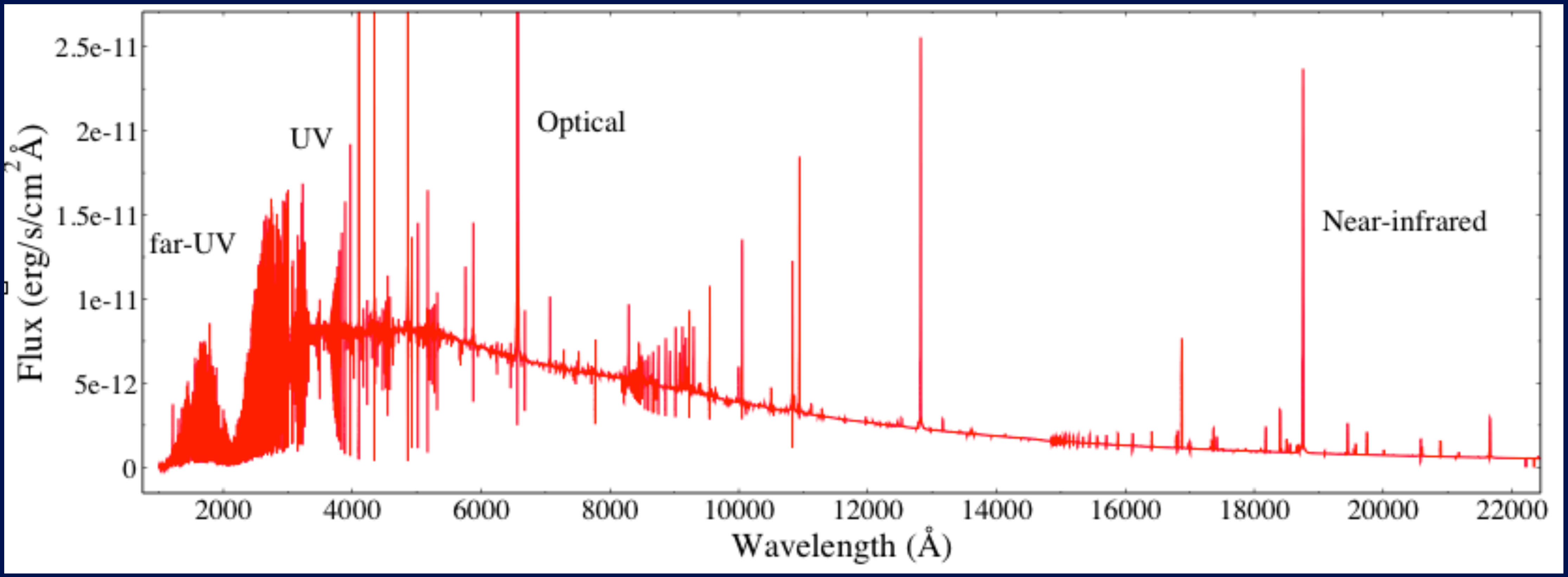




2. LBVs: living near the Eddington limit
a) The S-Dor type variability: modeling the spectrum

- input parameters: L, Teff, Mdot, wind terminal velocity, v(r), abundances, distance

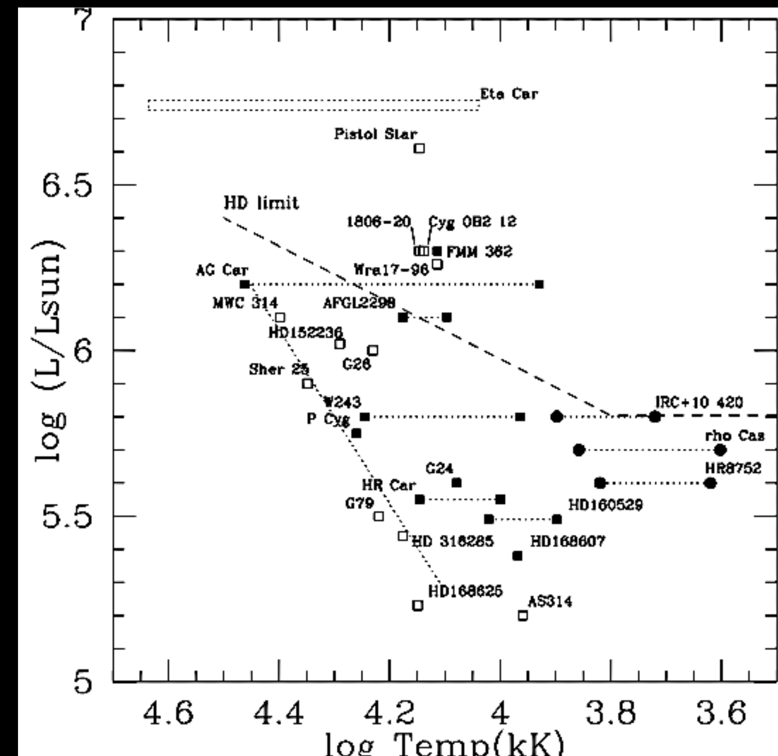
Synthetic model spectrum

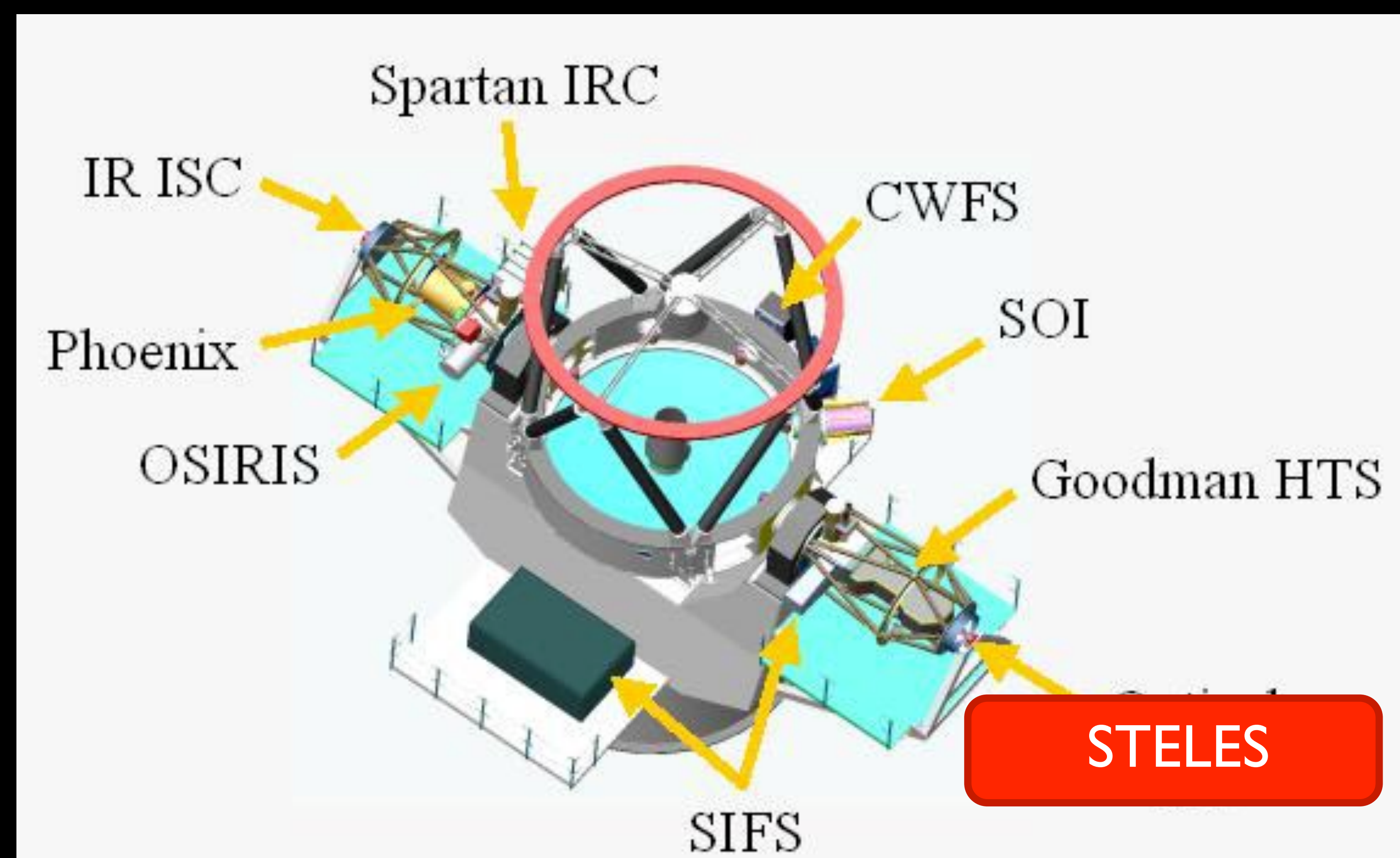


Comparison to the observations

2. LBVs: living near the Eddington limit

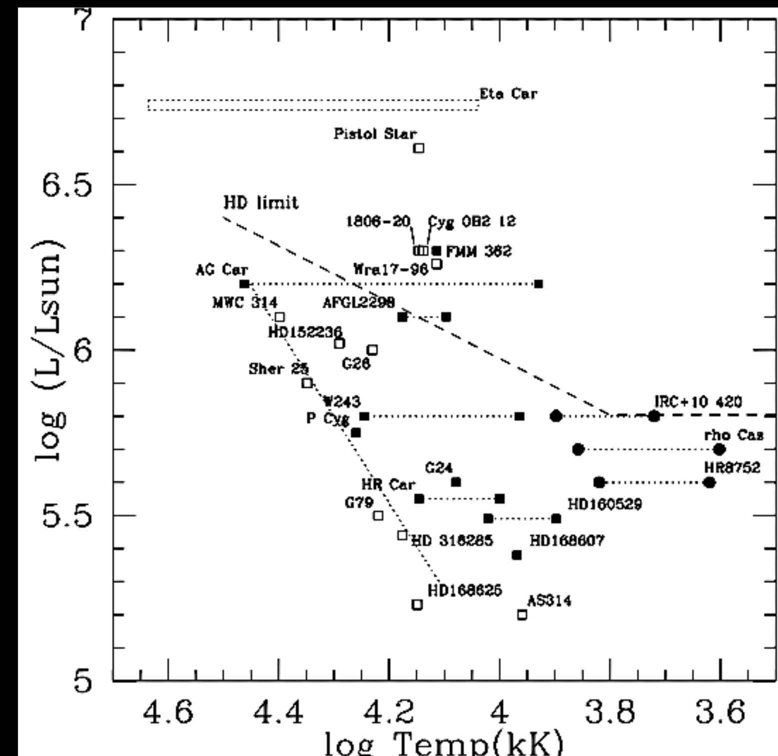
a) S Dor type variability: science opportunities with *SOAR*

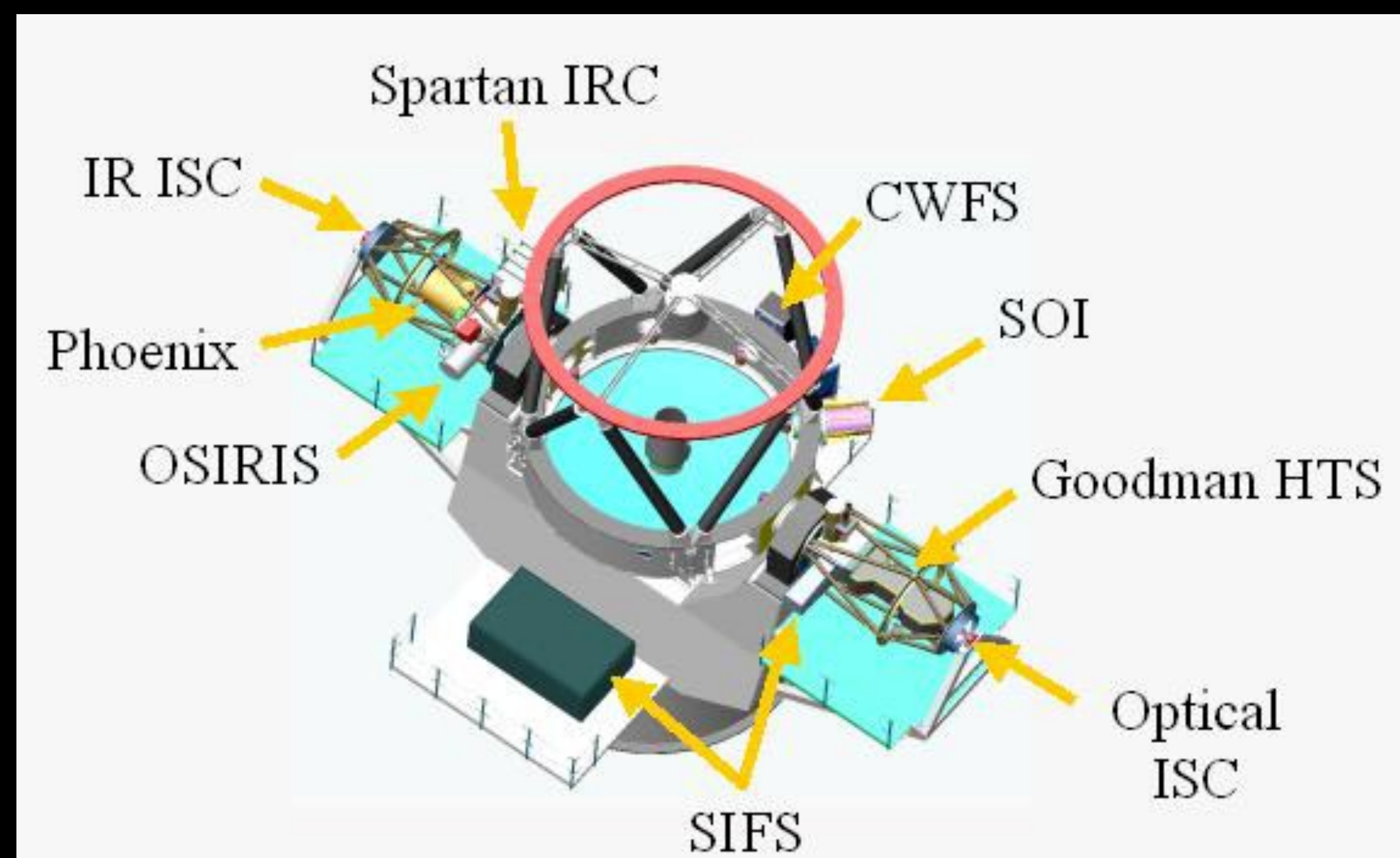




2. LBVs: living near the Eddington limit
a) S Dor type variability: science opportunities with *SOAR*

Spectroscopic monitoring of LBVs in the Galaxy and Local Group: evolution of the stellar and wind properties.





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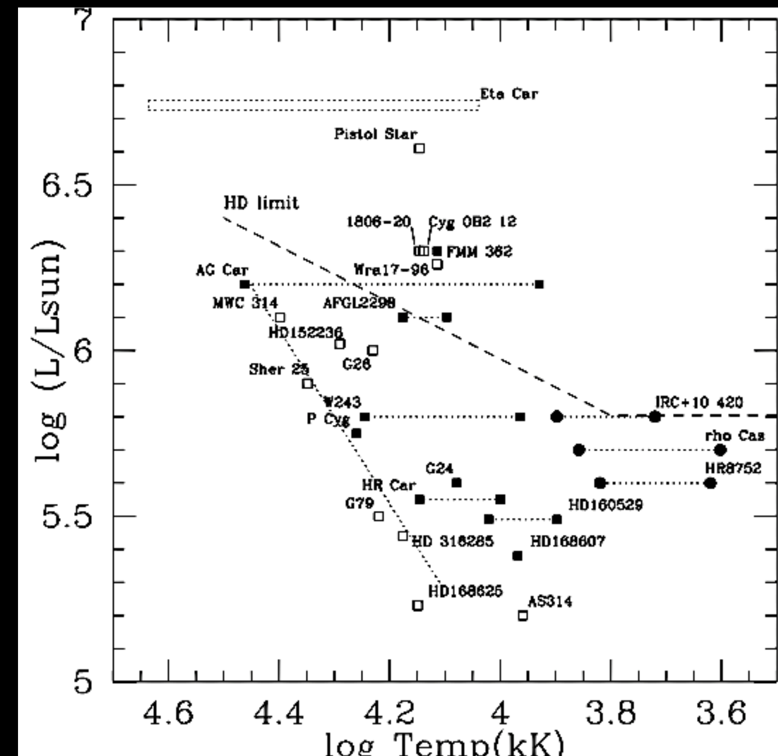

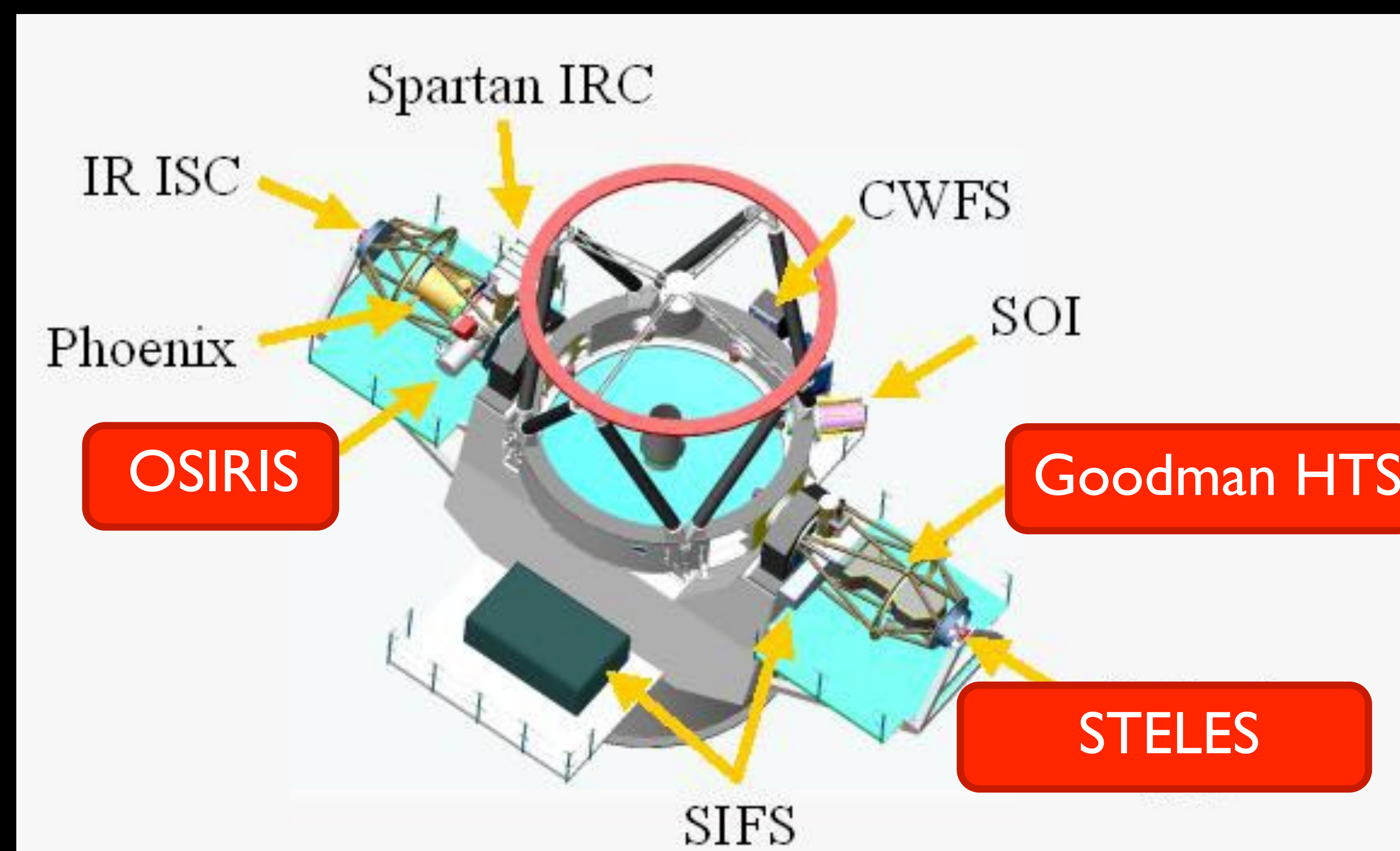

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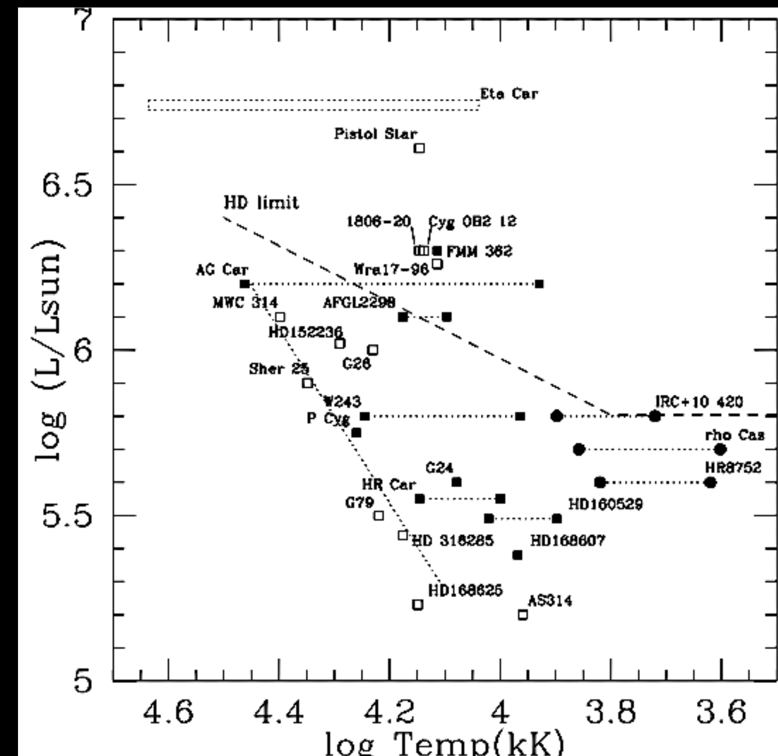

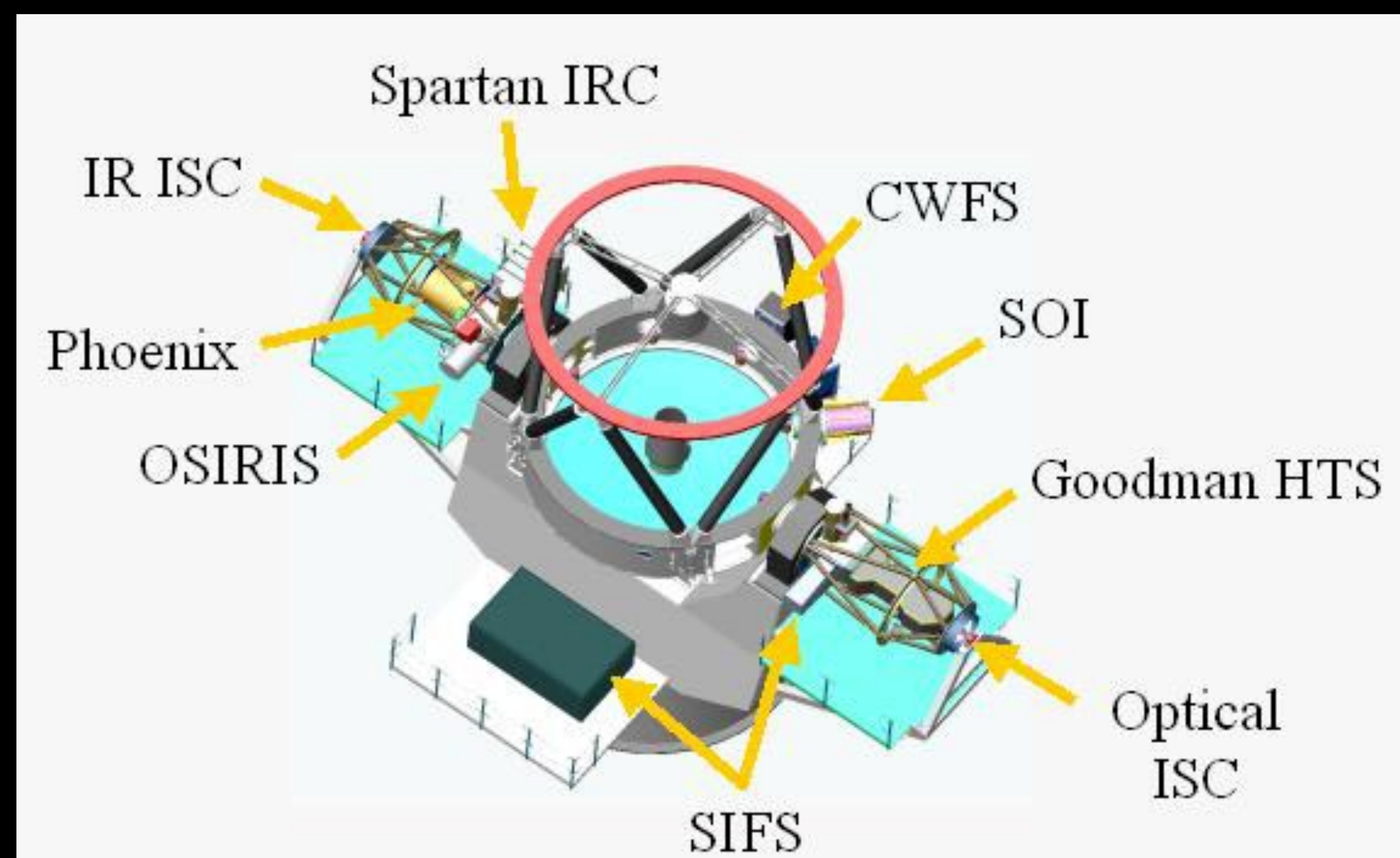

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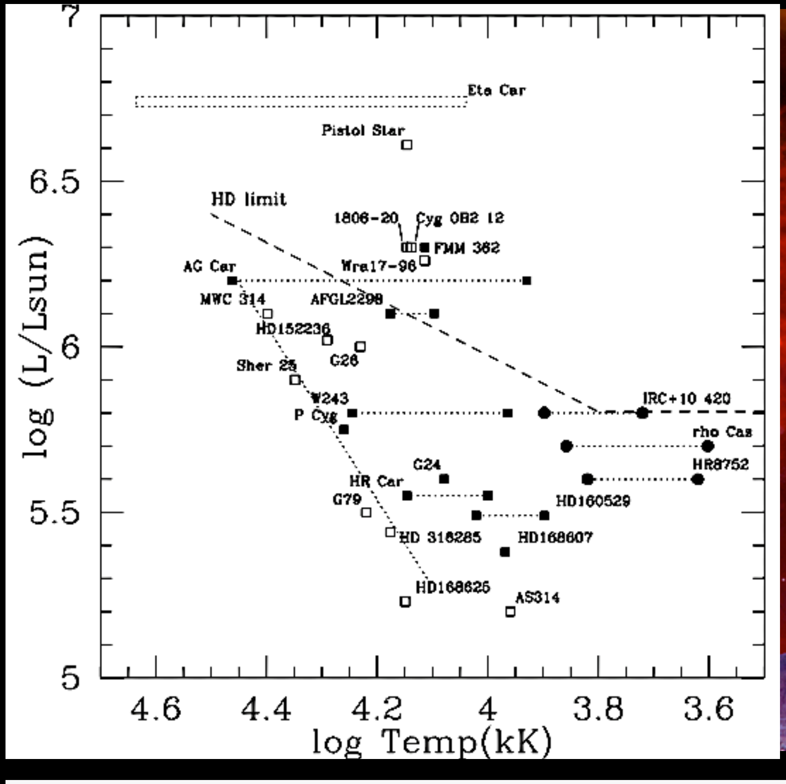

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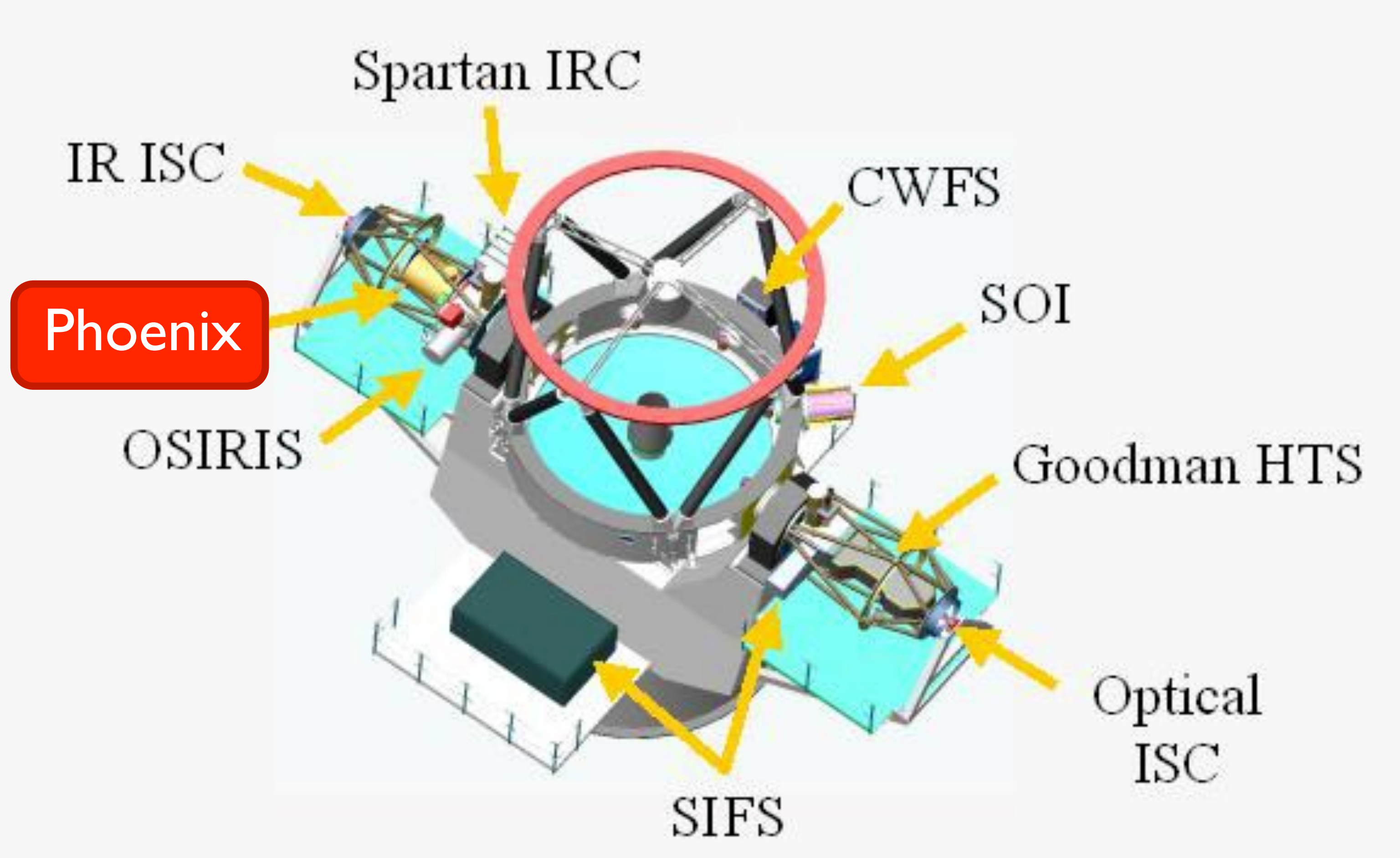
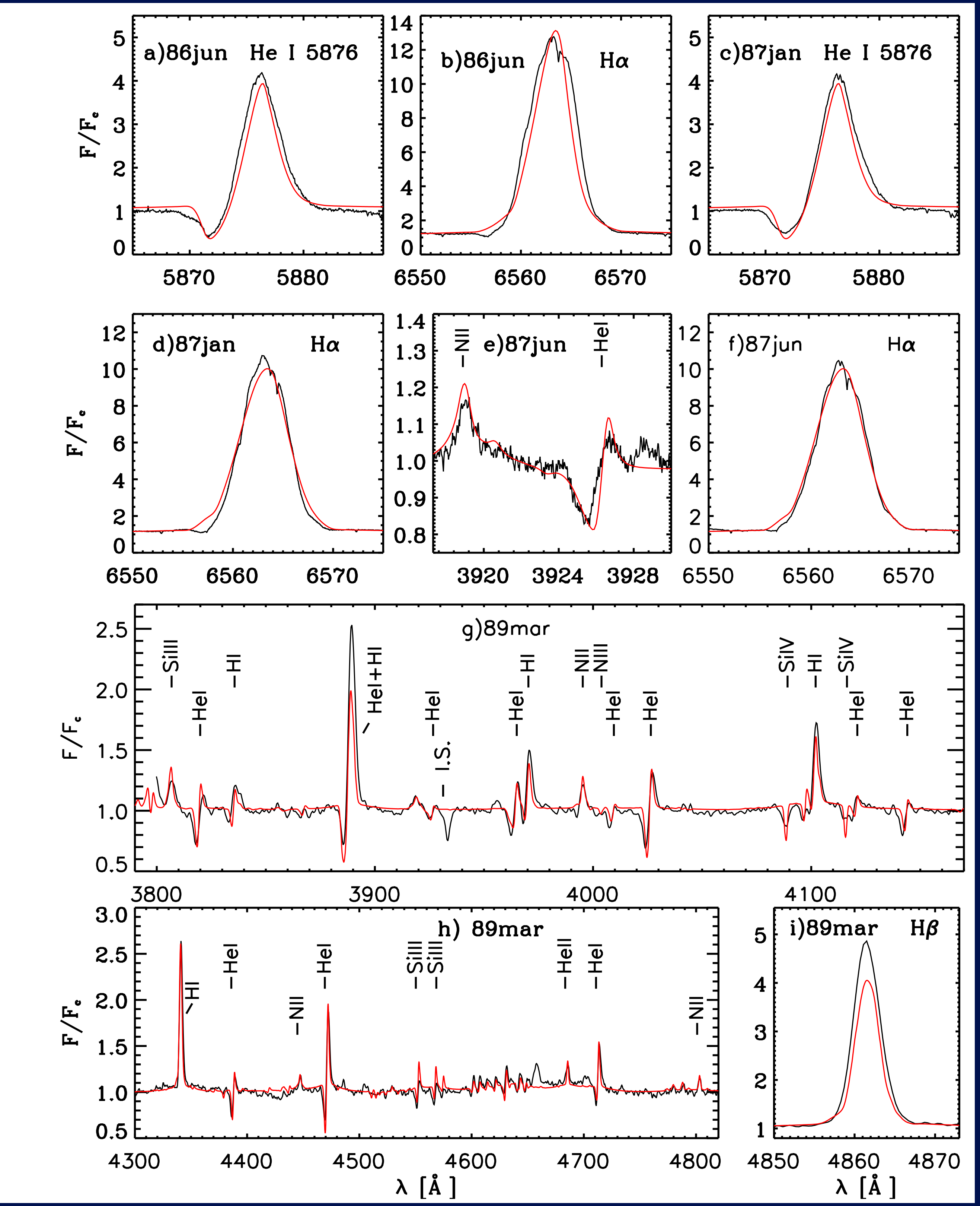


2. LBVs: living near the Eddington limit
a) S Dor type variability: modeling the spectrum of AG Car

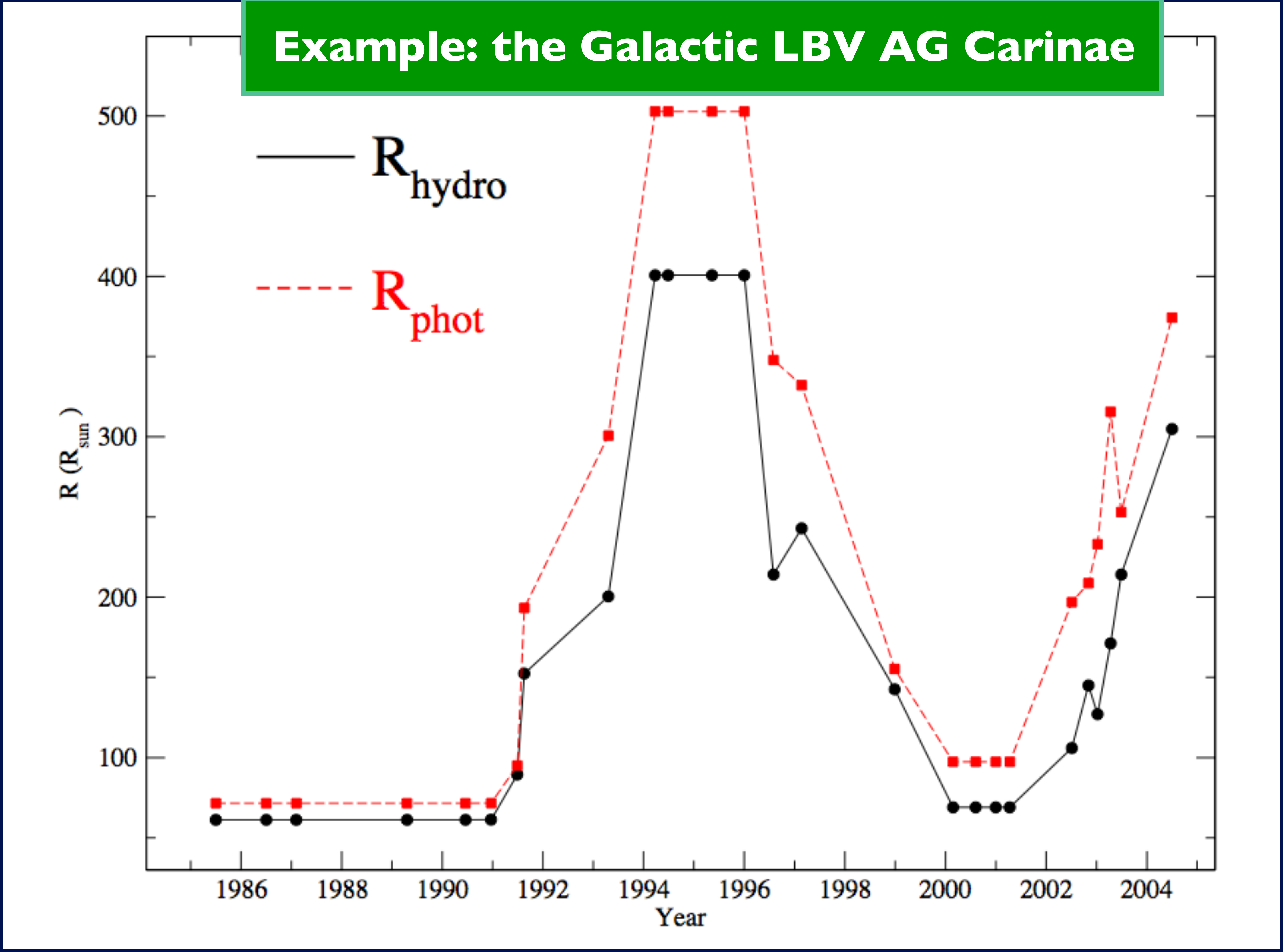
- Observations of the LBV AG Carinae (black) x model (red)



(Groh+ 2009a)

2. LBVs: living near the Eddington limit
a) Changes of the stellar radius during the S-Dor cycle

Example: the Galactic LBV AG Carinae



(Groh+ 2009a, 2011a, 2011b in prep.)

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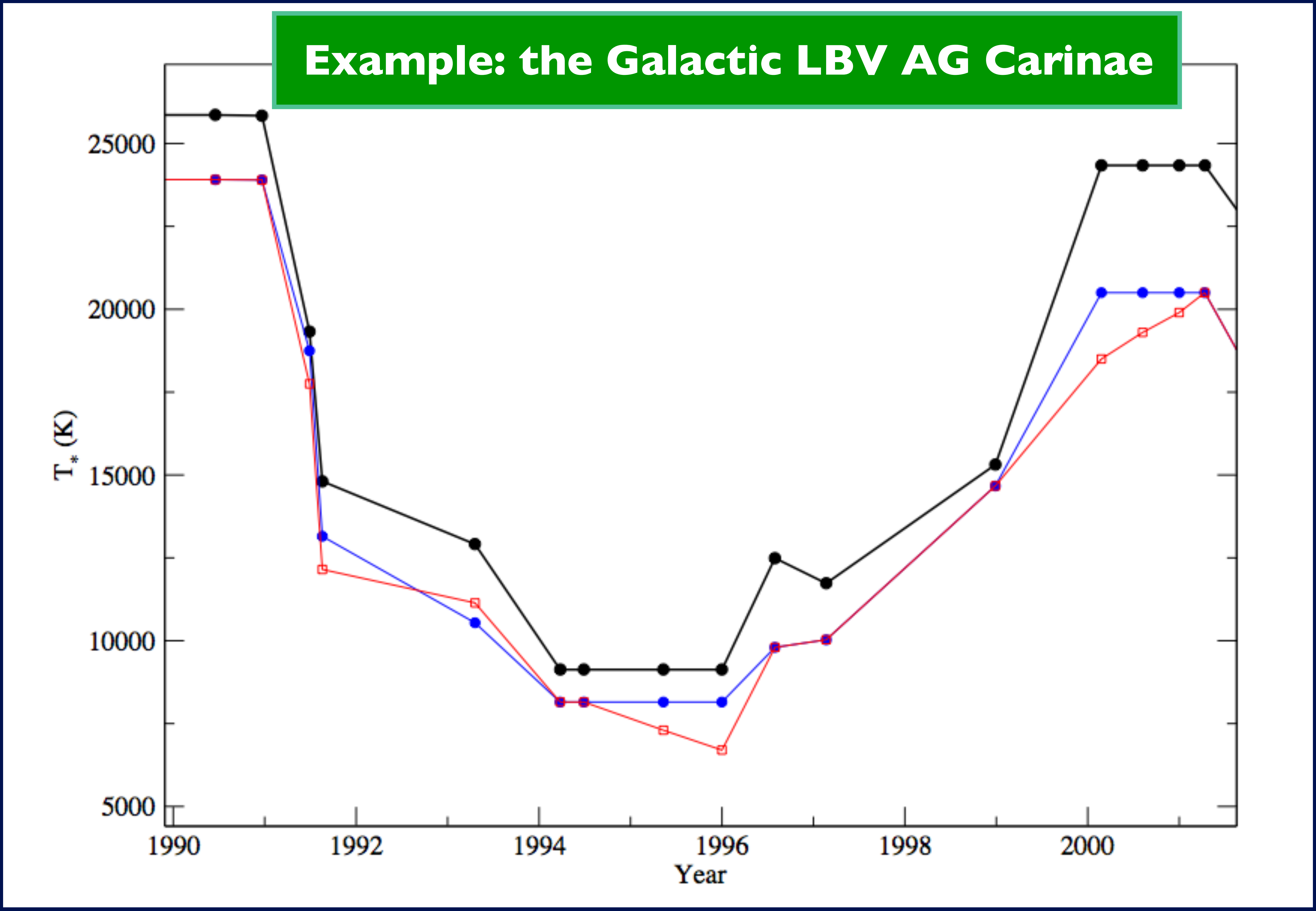
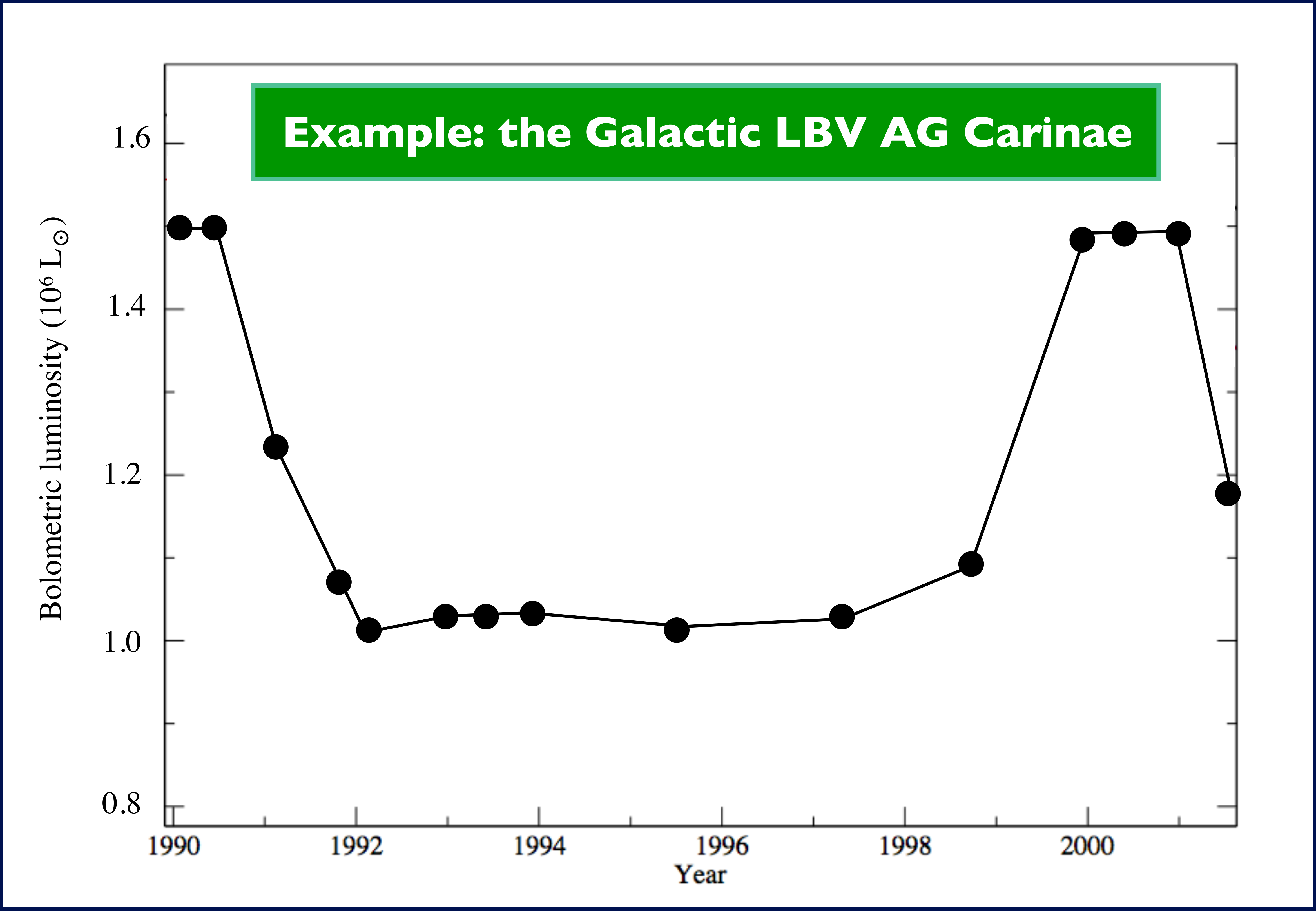
a) Changes of the effective temperature during the S-Dor cycle



(Groh+ 2009a, 2011a, 2011b in prep.)

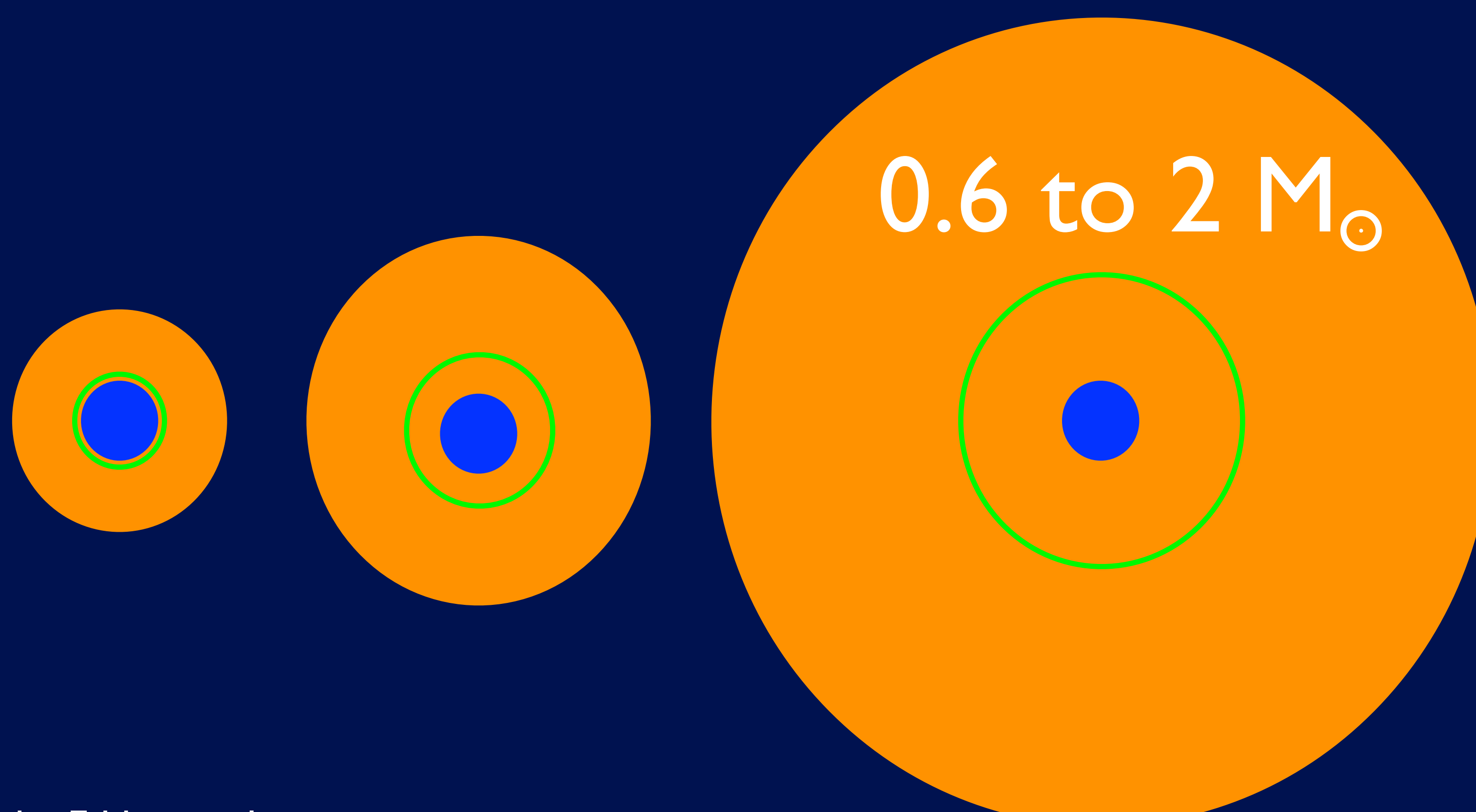
2. LBVs: living near the Eddington limit
a) Changes of the bolometric luminosity during the S-Dor cycle



(Groh+ 2009a, 2011a, 2011b in prep.)

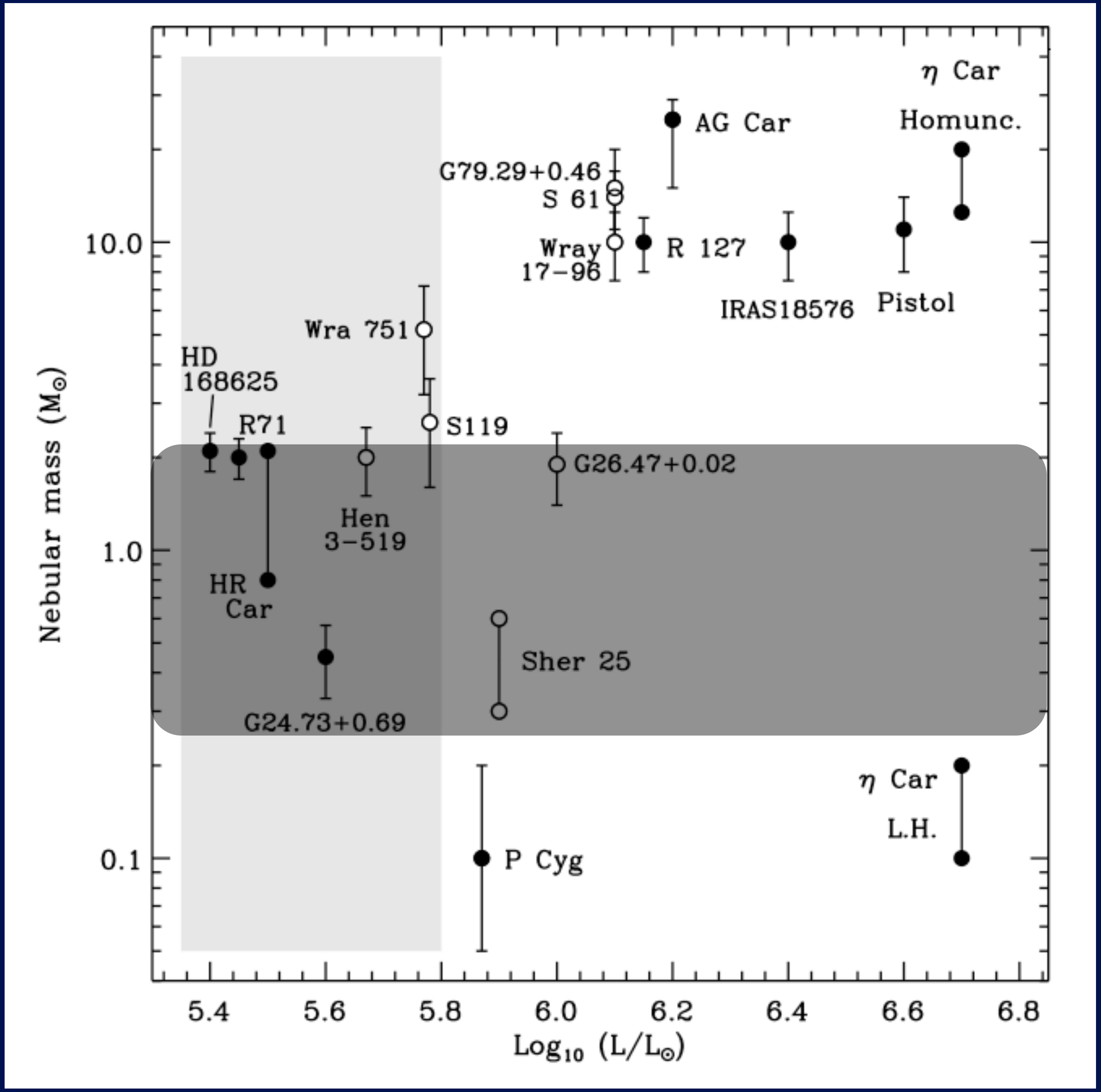
2. LBVs: living near the Eddington limit
a) Why does the *inferred* bolometric luminosity changes?

- Energy is used to expand the outer layers of the star (Lamers 1995); i.e. *intrinsic* bolometric luminosity does not change.
  - Lbol is reduced by a factor of 1.5 during 3 years = 10^{47} erg
  - Average expansion from 85 to 115 $R_\odot$: $\Delta E_{\rm rad} = \frac{G M_{\rm exp} M_{\rm eff}}{R_\odot} \left\{ \frac{1}{85} - \frac{1}{115} \right\}$
  - Amount of mass involved in the expansion: 0.6 to 2 $M_\odot$



2. LBVs: living near the Eddington limit
a) Why does the inferred bolometric luminosity changes?

- Amount of mass involved in the expansion: 0.6 to 2 Msun
- Comparable with the mass of the nebulae around low-luminosity LBVs
- Is there any relationship between S-Dor cycles and giant eruptions?

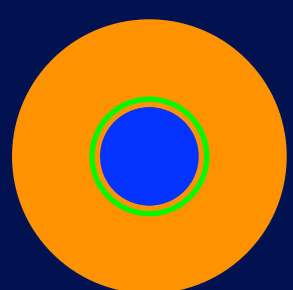


(Smith & Owocki 2006)

2. LBVs: living near the Eddington limit

a) S Dor type variability could be a *failed* Giant Eruption

Hot



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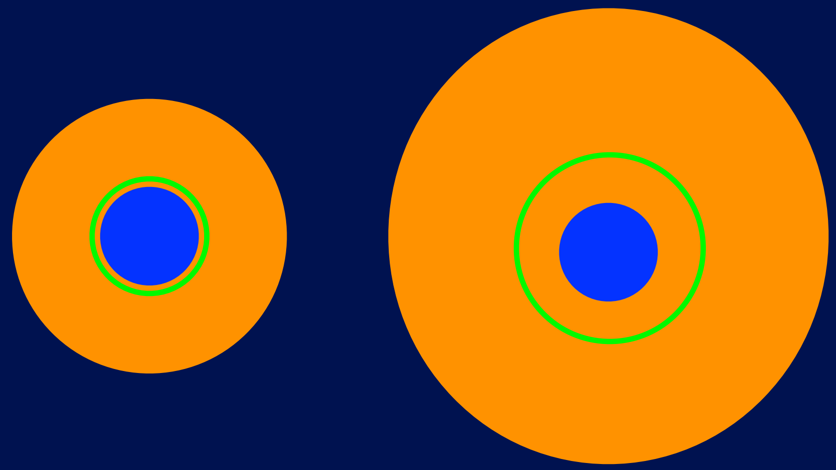

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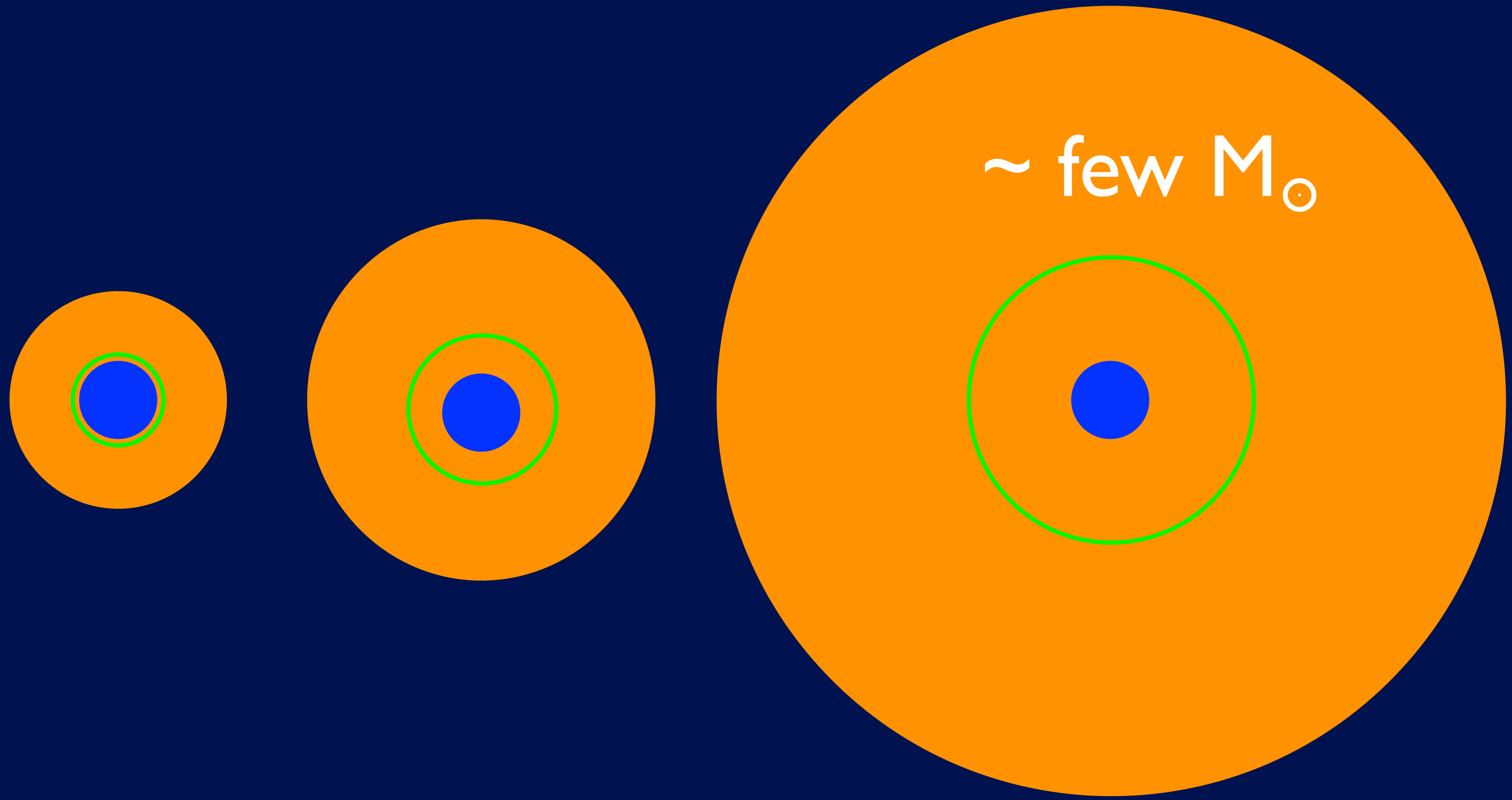
Hot

Cool



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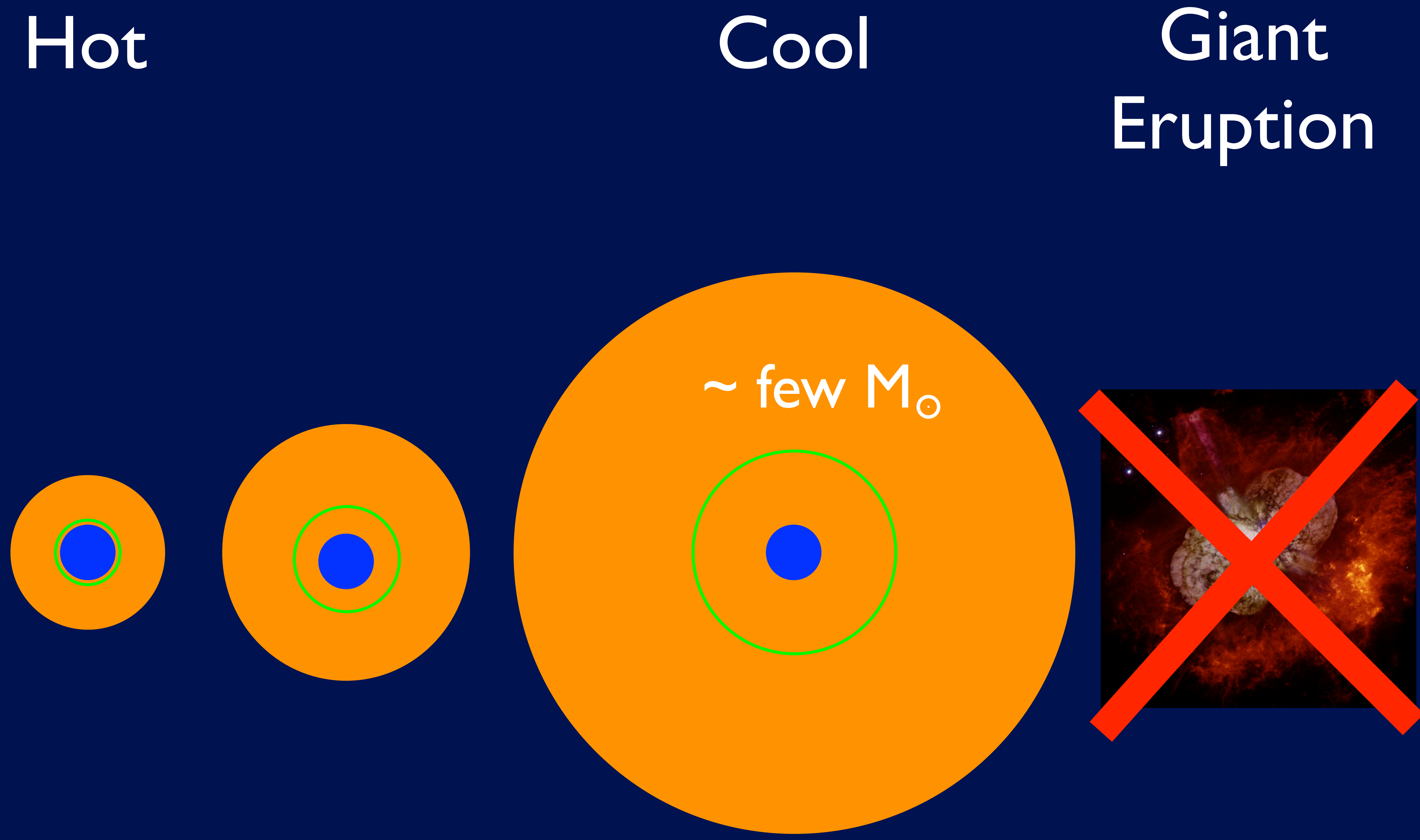
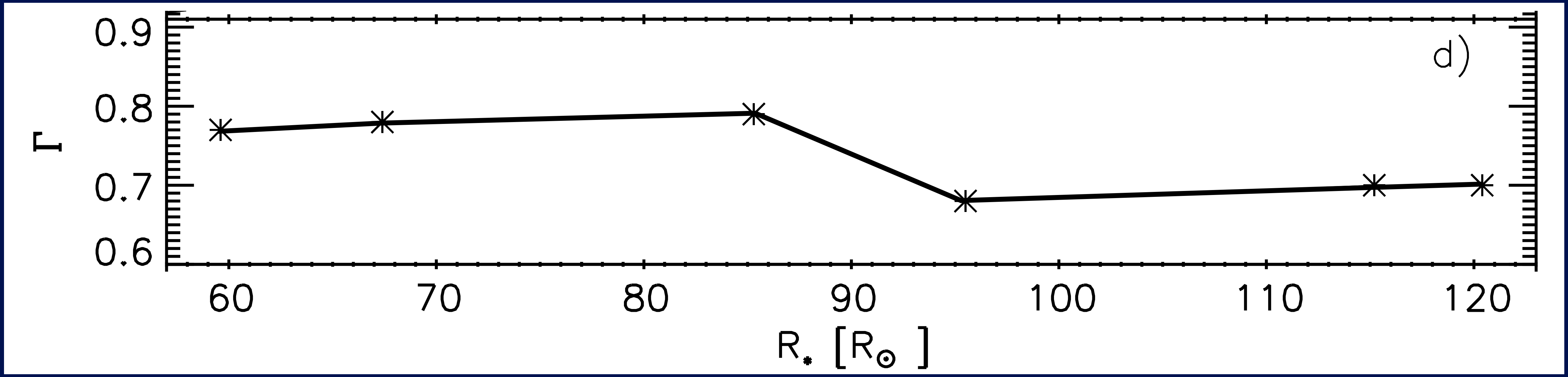


2. LBVs: living near the Eddington limit
a) Constraining the Eddington parameter

AG Car: a massive star evolving close to the Eddington limit



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a) The S-Dor type variability in a nutshell

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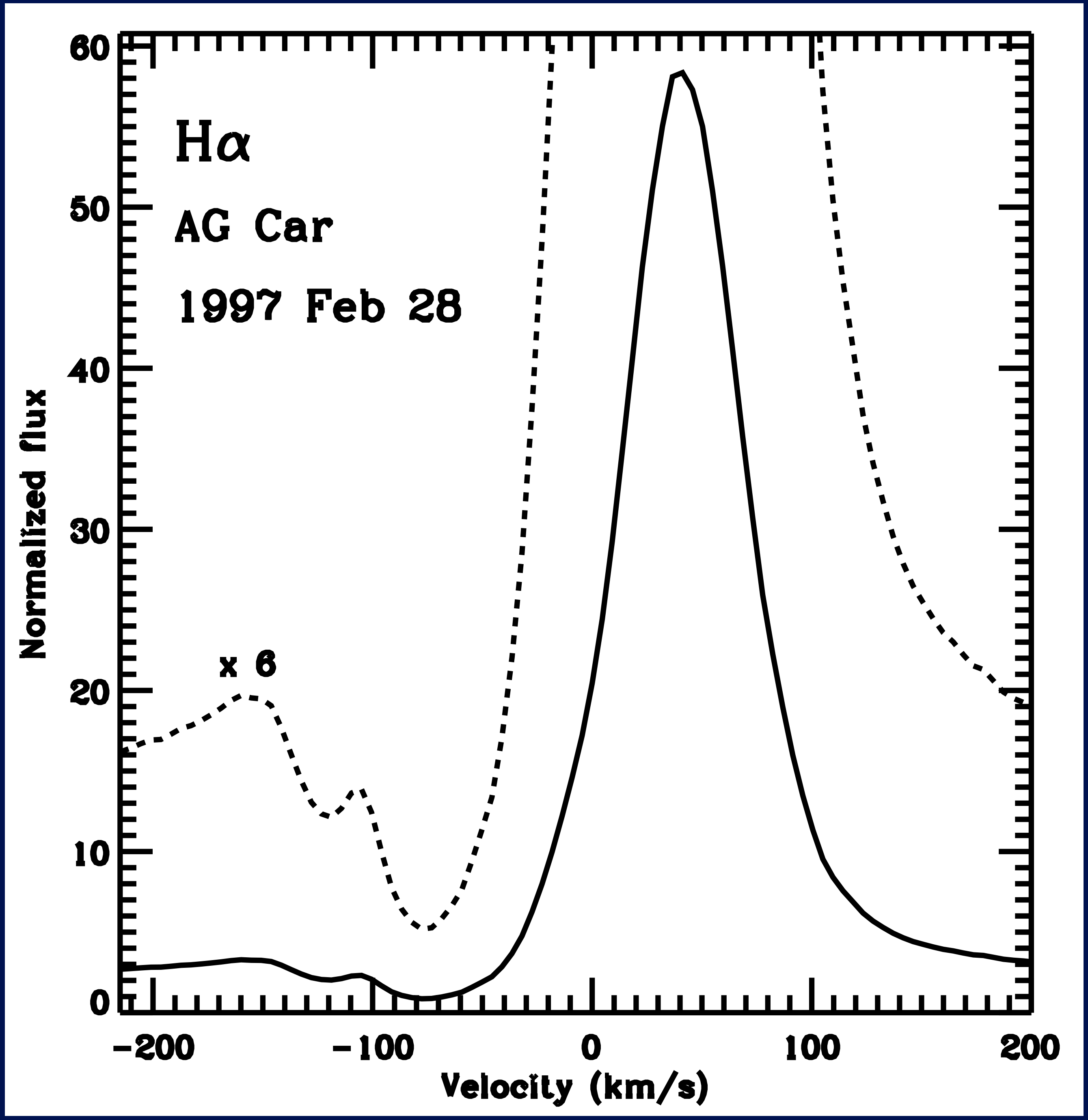
- Identification requires long-term monitoring (decades);

2. LBVs: living near the Eddington limit

a) Shortcut for ID'ing a star as an LBV having S Dor type variability

Double P-Cygni absorptions in hydrogen lines



(Groh & Vink 2011)

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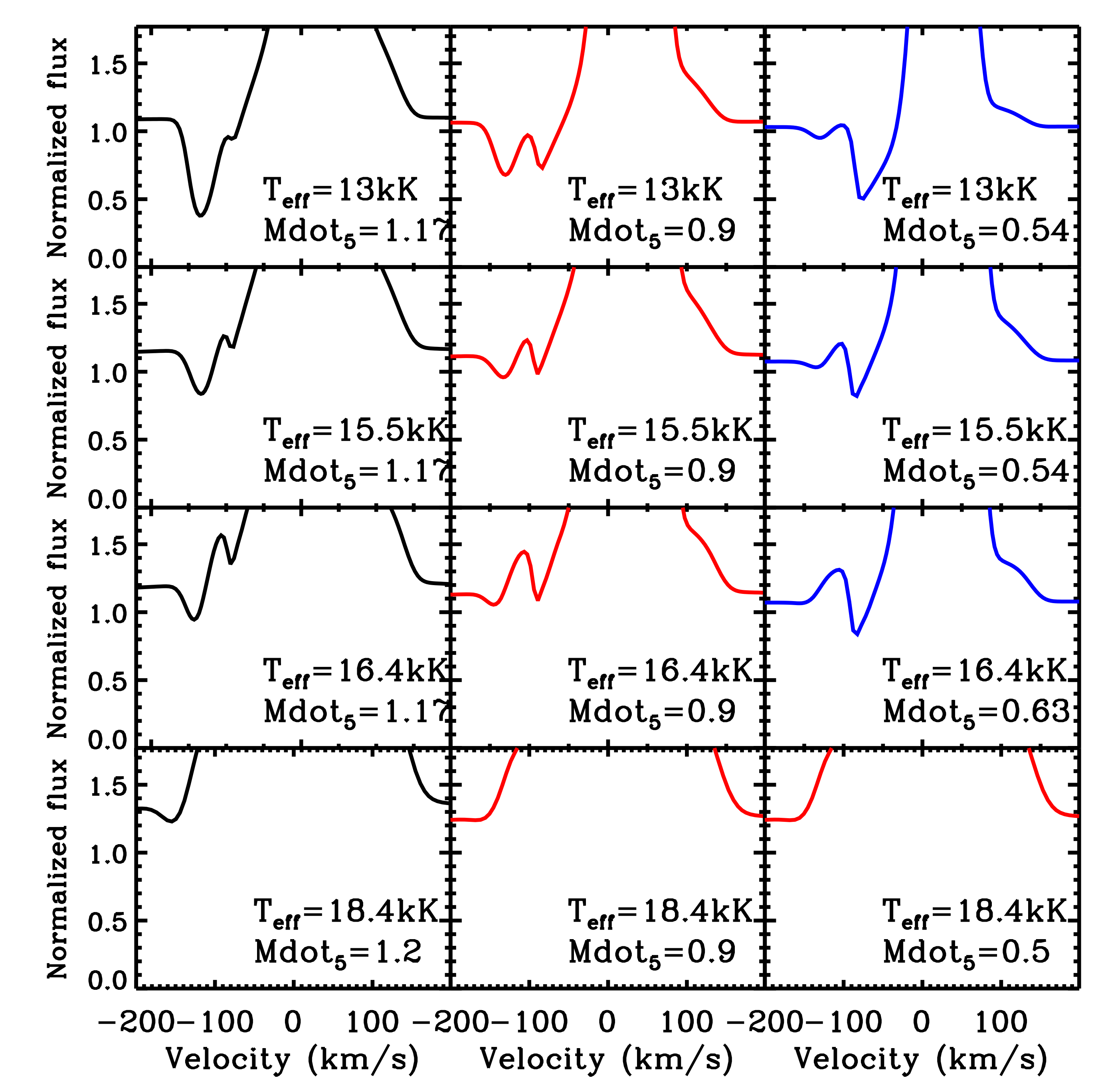
Double absorption in P-Cygni-type line profiles lets you ID a star as an LBV with single epoch observations!



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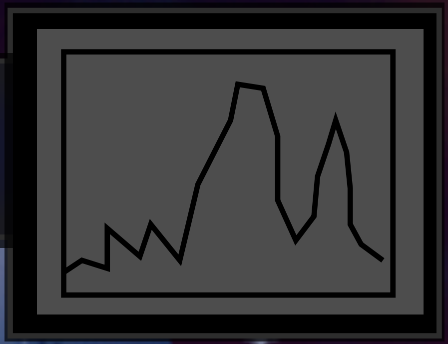
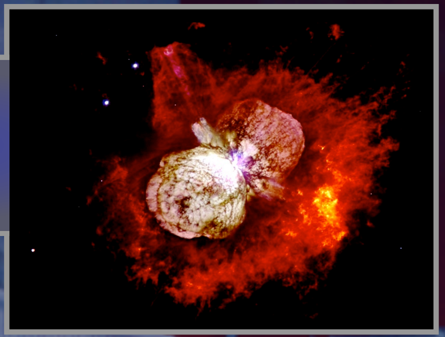
How do we observationally recognize an LBV?

Observational consequences of living near the Eddington limit

(a) S Doradus type variability



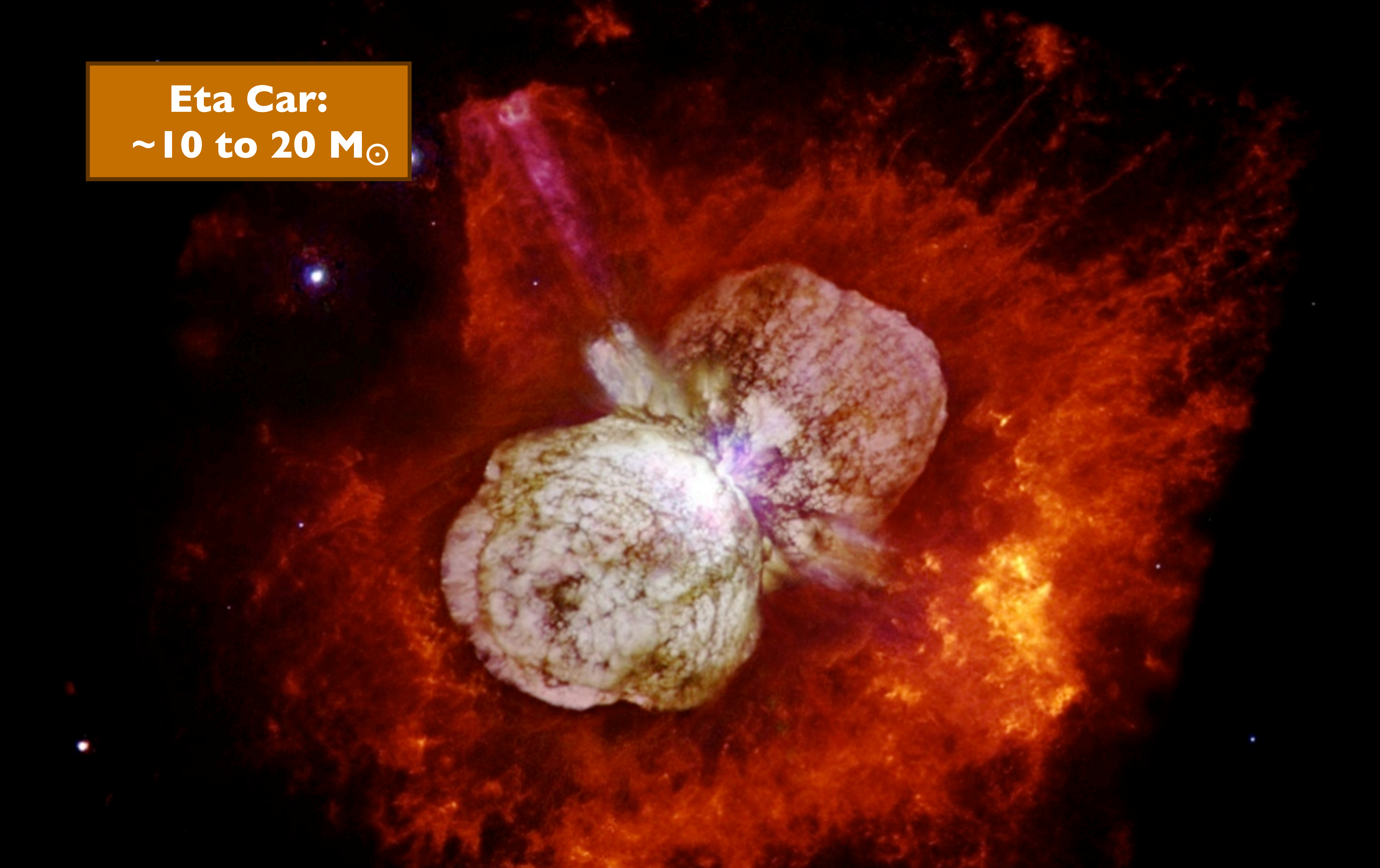
(b) Giant eruptions



2. LBVs: living near the Eddington limit

b) Giant Eruptions: sudden ejection of a few to tens of solar masses

Eta Car:
~10 to 20 $M_\odot$



(Credit: N. Smith, J. Morse, NASA/ESA)

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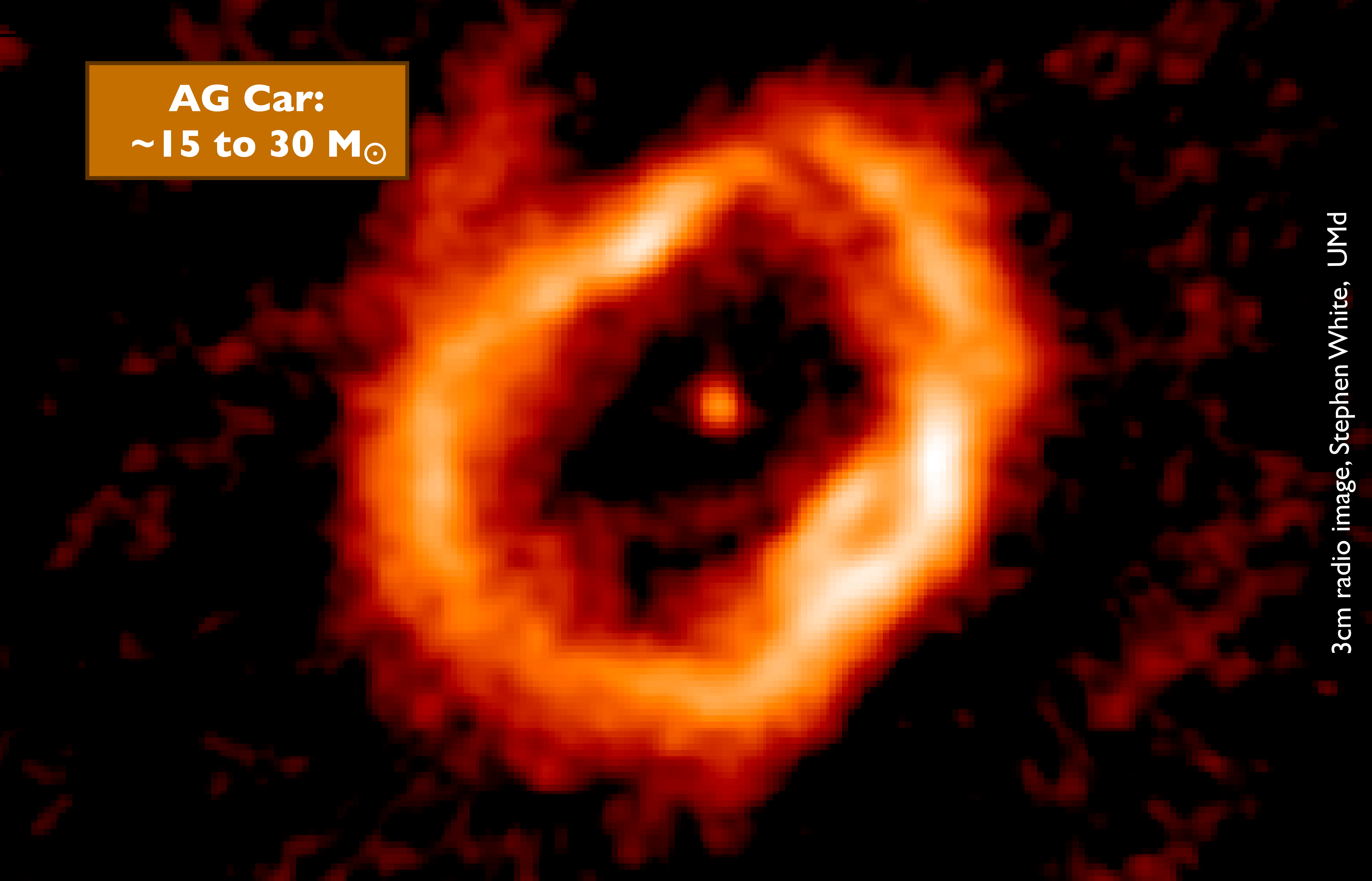

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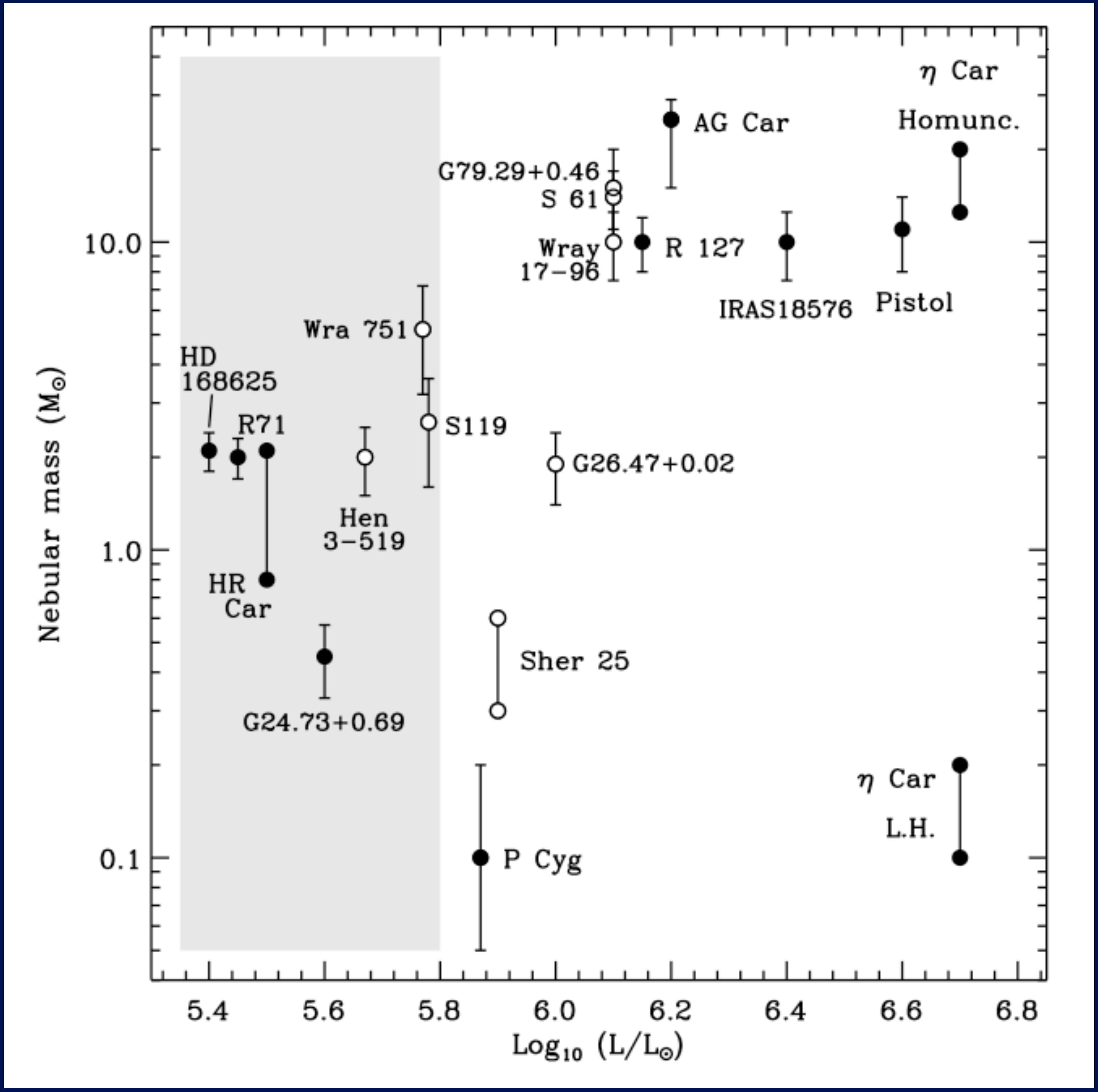
b) Giant Eruptions: nebular mass around LBVs and LBV candidates



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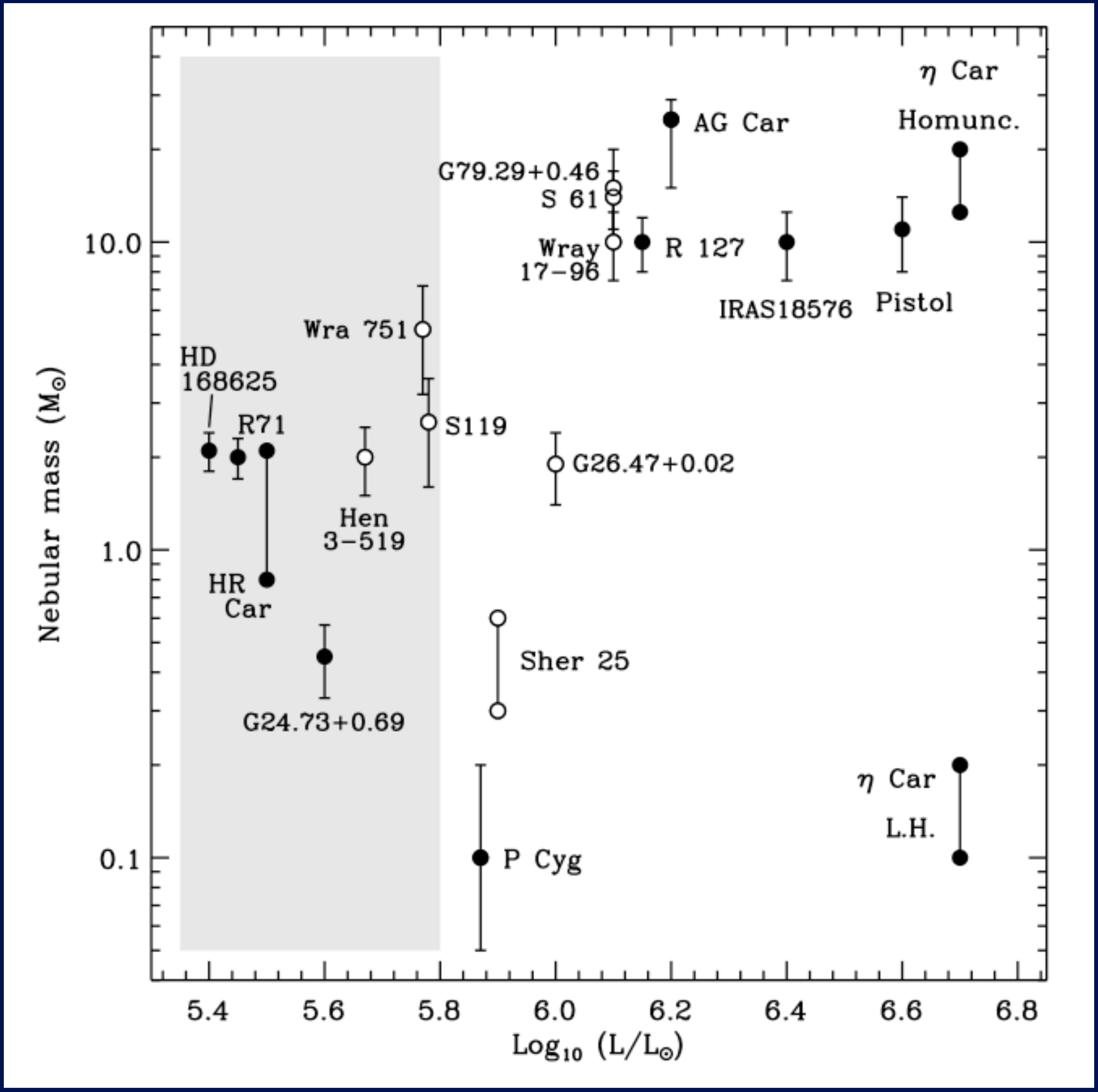
b) Giant Eruptions: nebular mass around LBVs and LBV candidates

Was all the mass ejected in a single eruptive event?

Rough mass determination and generally include only the ionized mass. What is the amount of neutral + molecular gas?

Kinematical and other structural properties of these nebulae.

Insights on the central stars via scattered light on the nebula.



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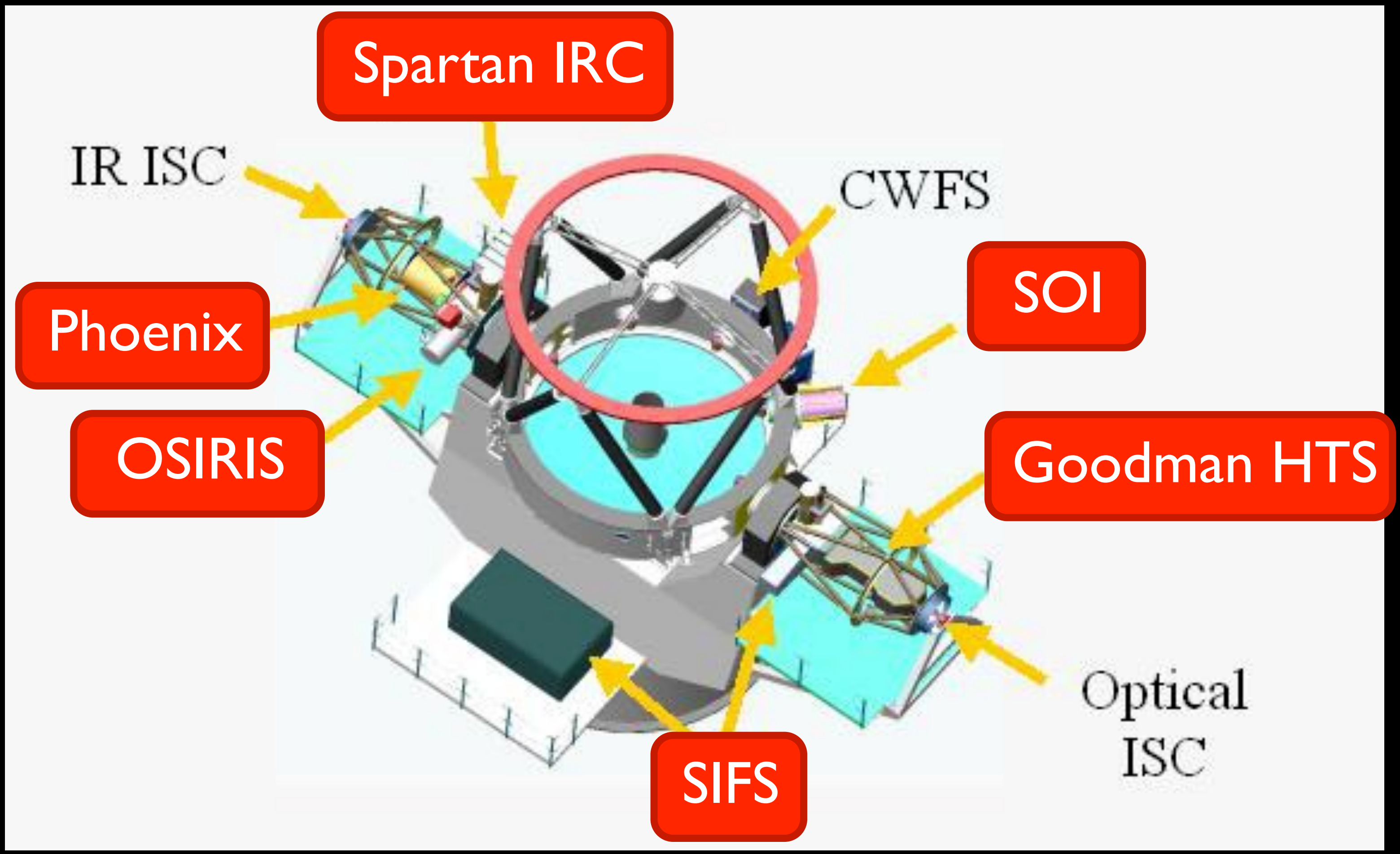
b) Giant Eruptions: science opportunities with *SOAR*



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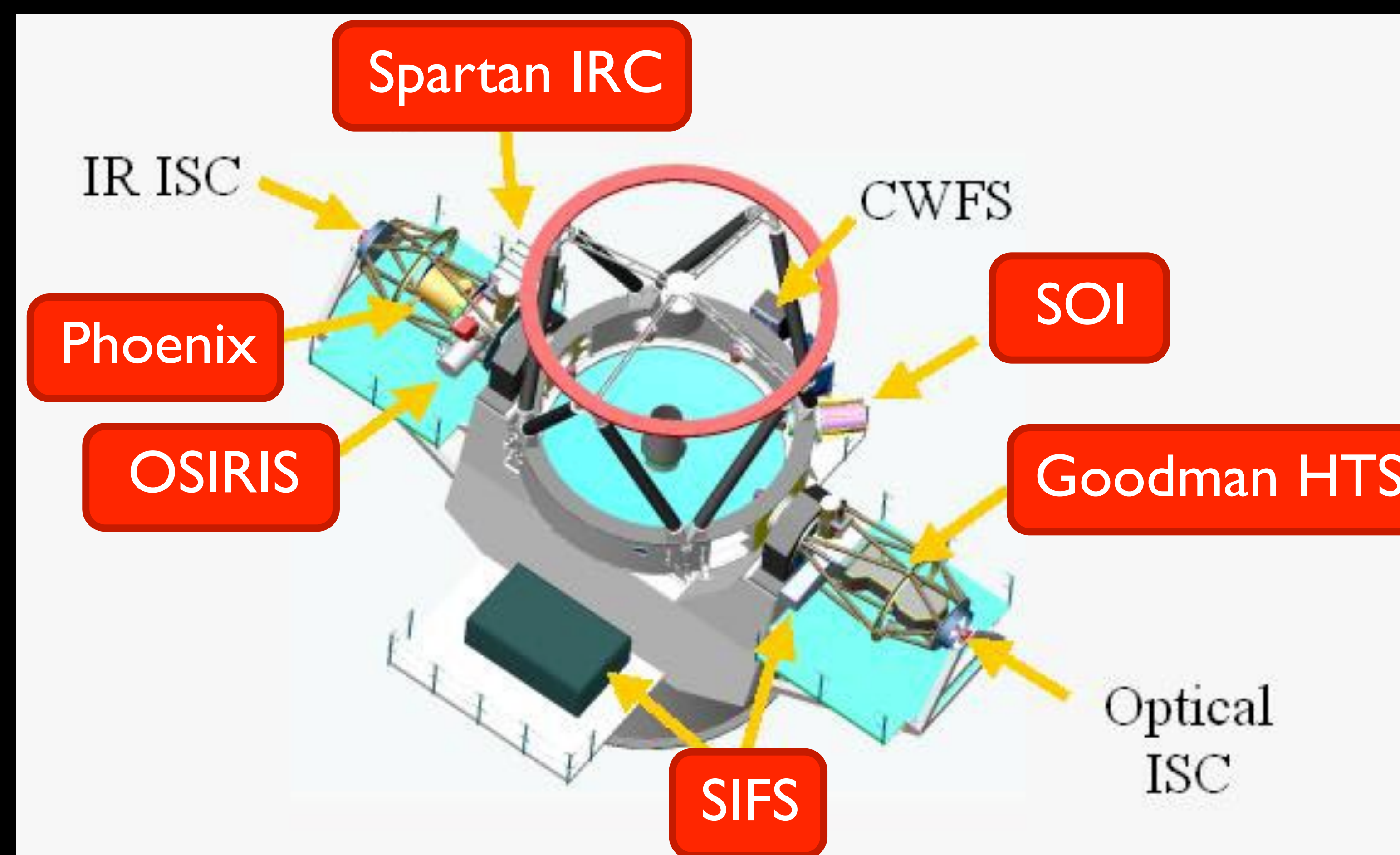

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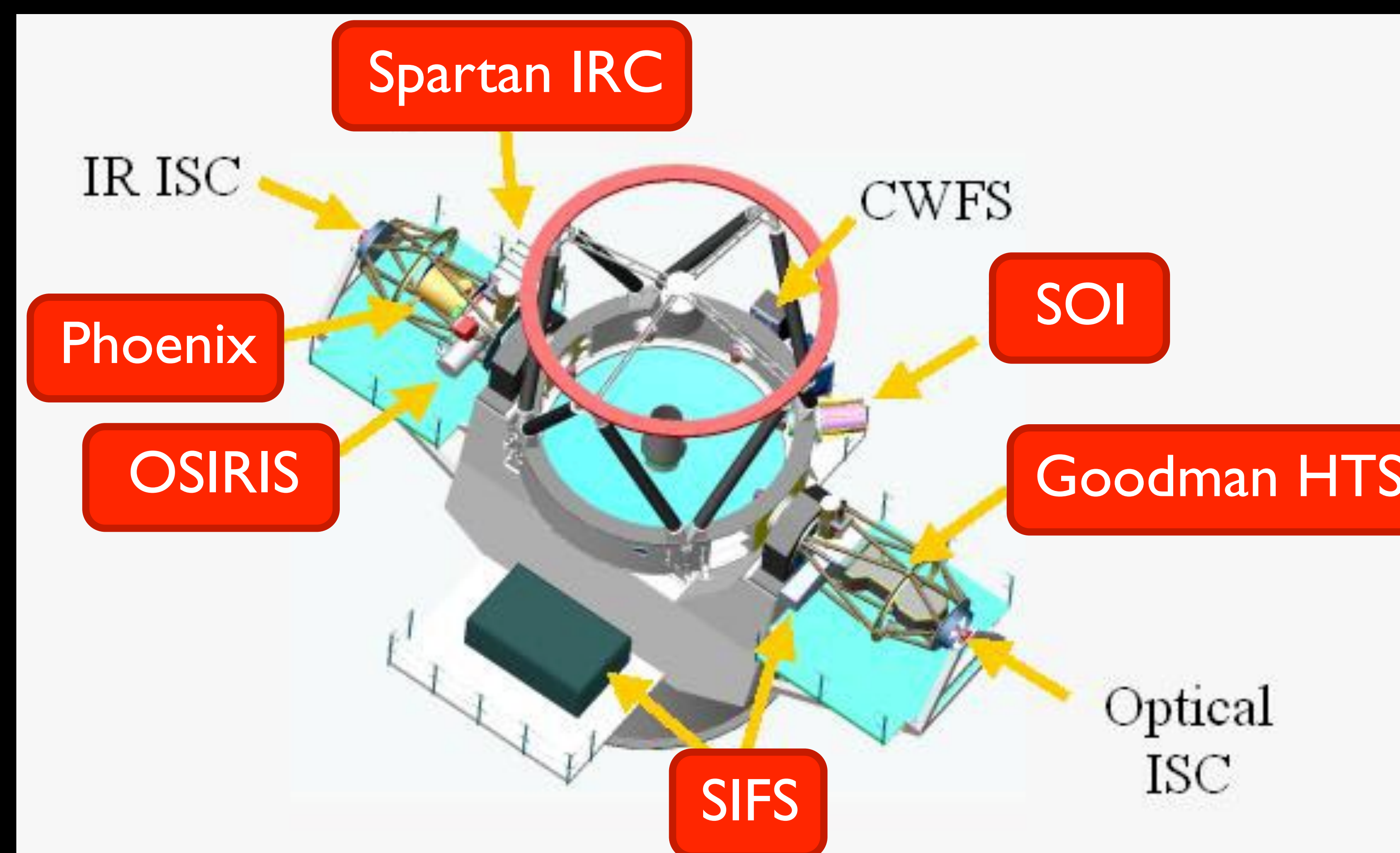

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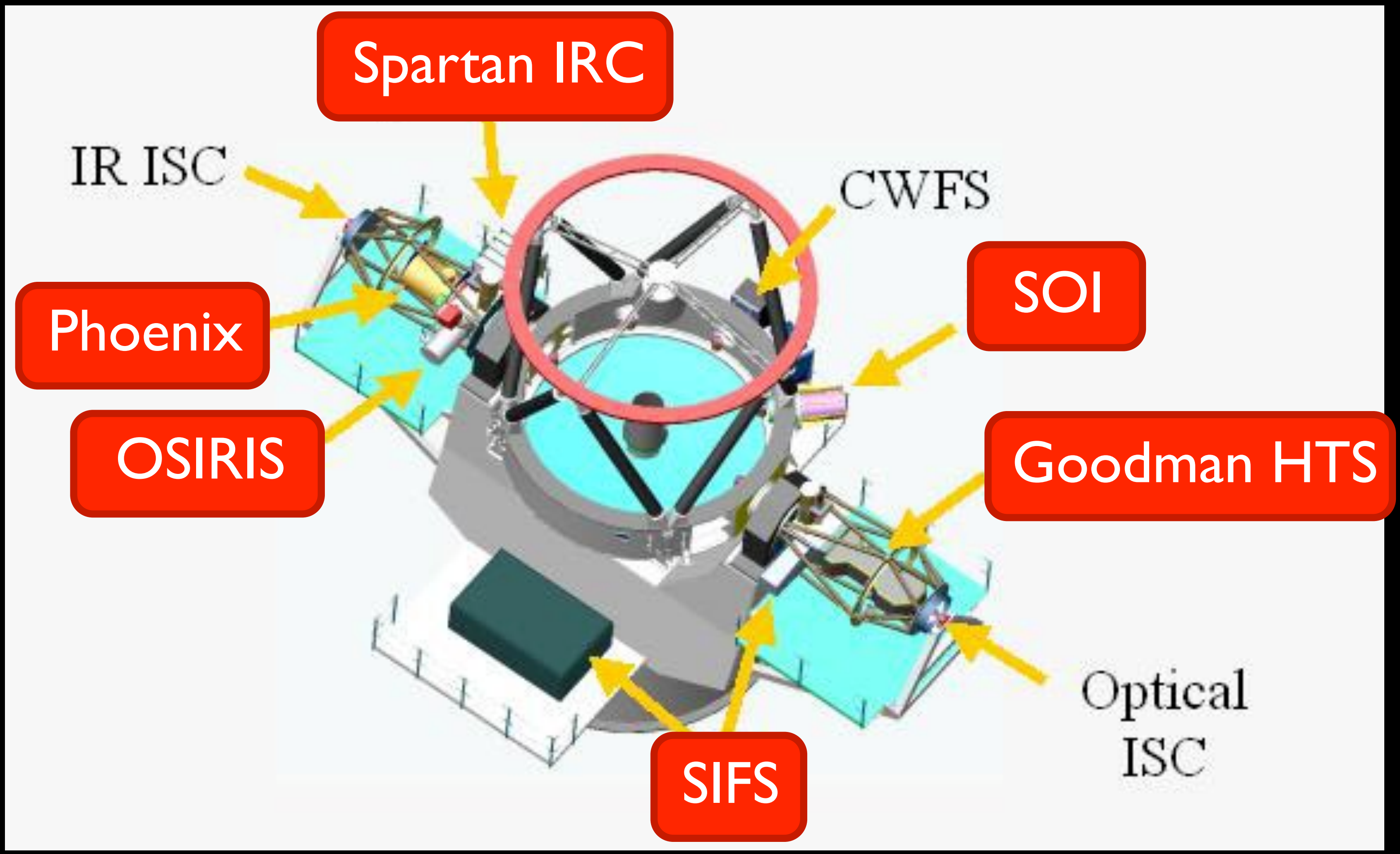

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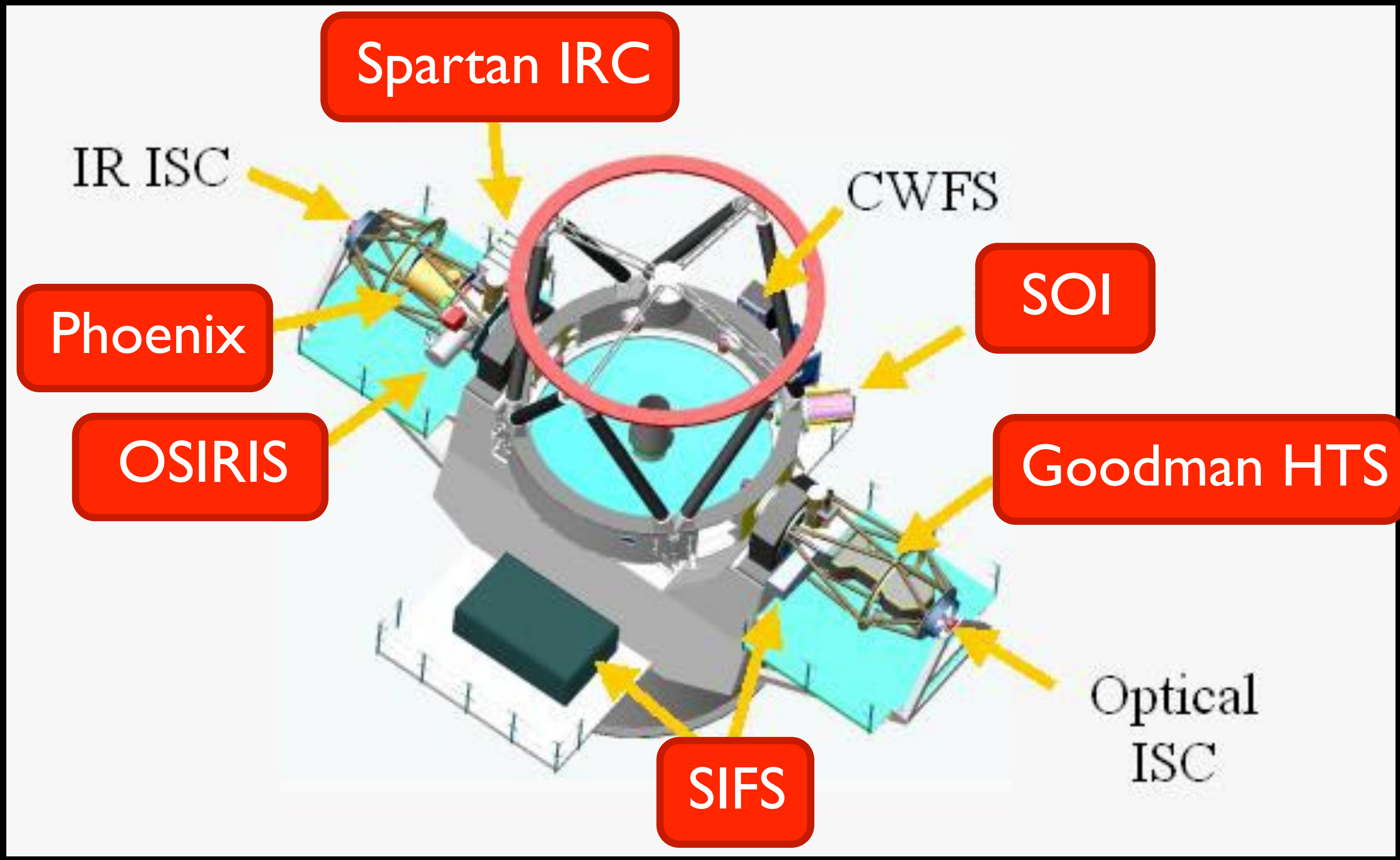

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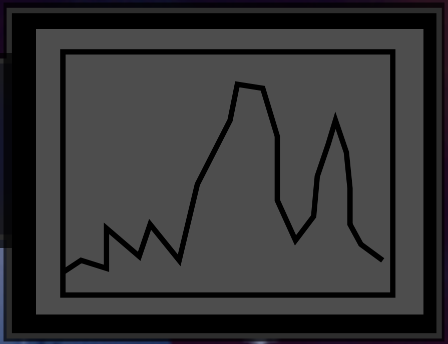

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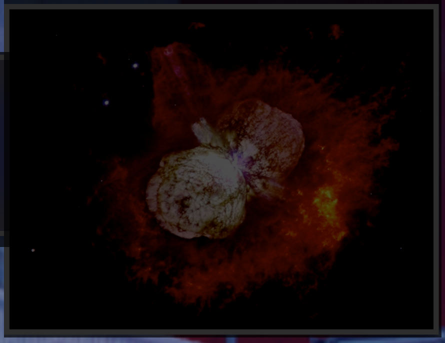
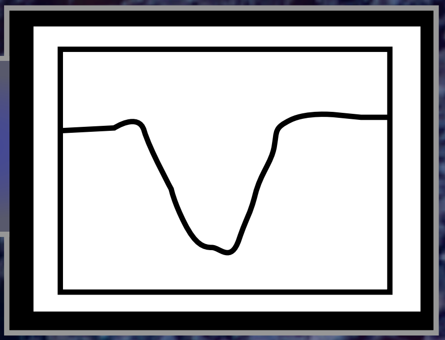


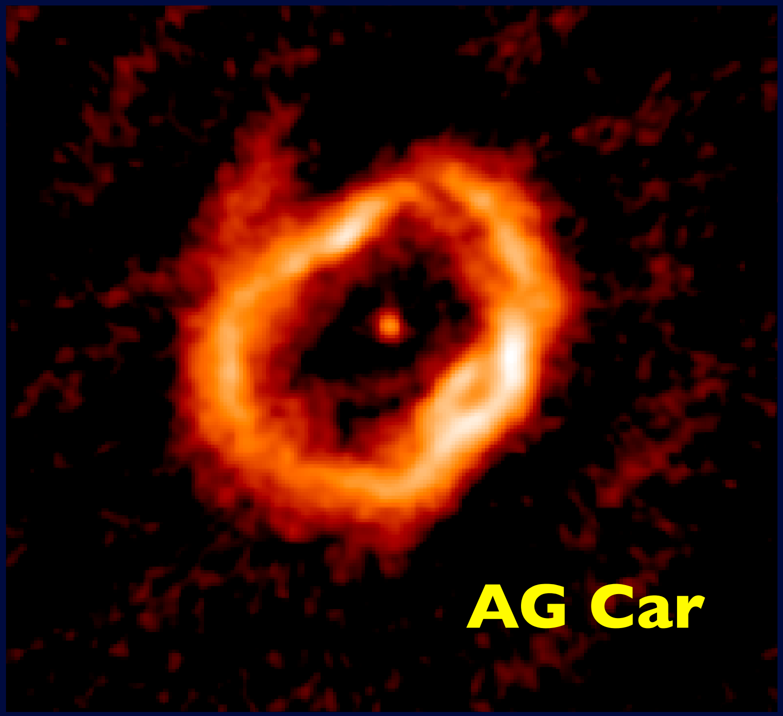
(c) Rapid rotation



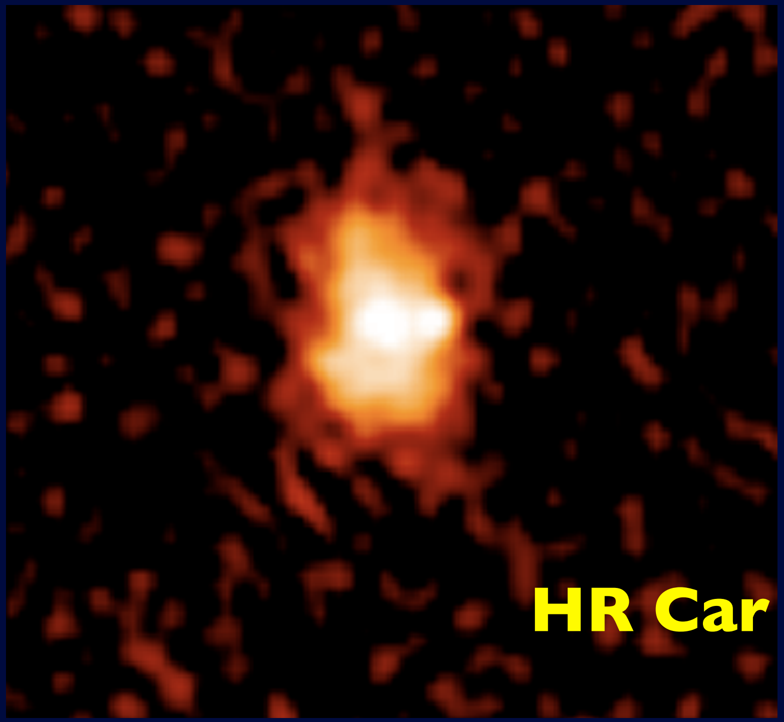
2. LBVs: living near the Eddington limit
c) Rapid rotation: bringing the star closer to the Eddington

- Fast rotation makes the star more unstable and bring it closer to the modified Eddington limit; relationship with S-Dor variability?
- Giant eruptions: fast rotation is often invoked to explain the kinematics and bipolar shape of ejected nebulae around LBVs (e.g., Weis 2003; Smith et al. 2006).

(Credit: N. Smith, J. Morse, NASA/ESA)

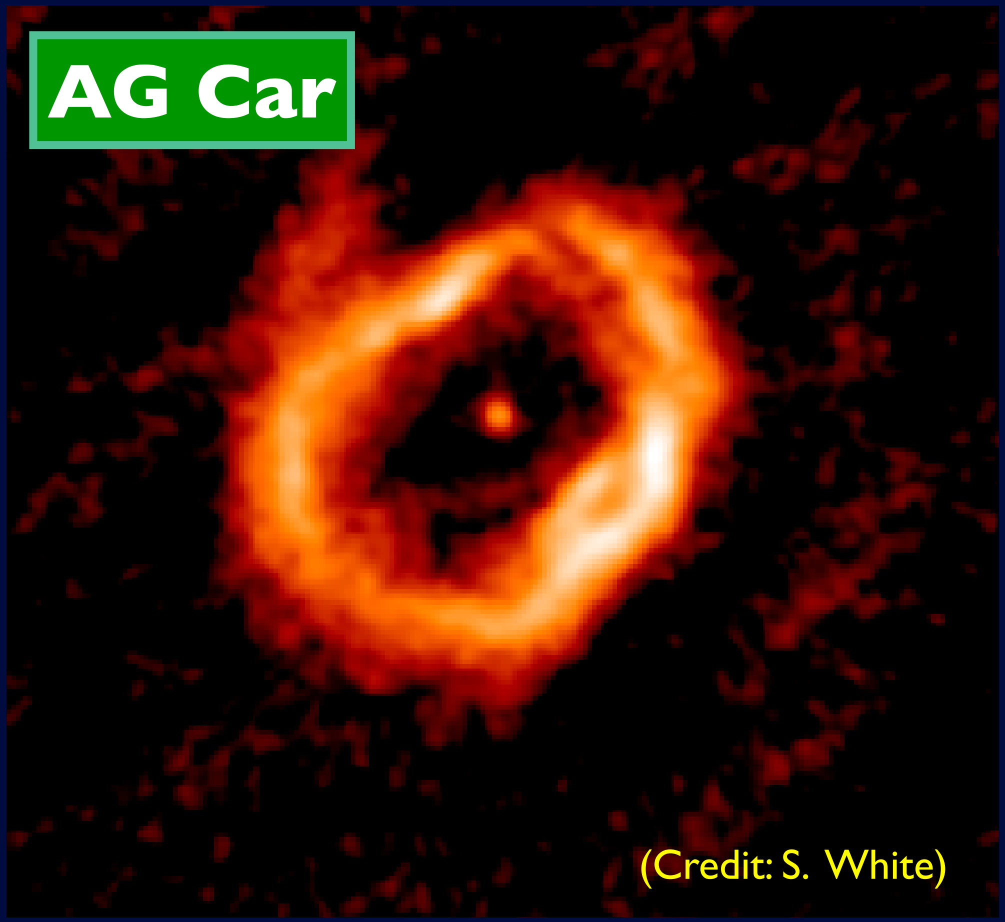


(Credit: S. White)



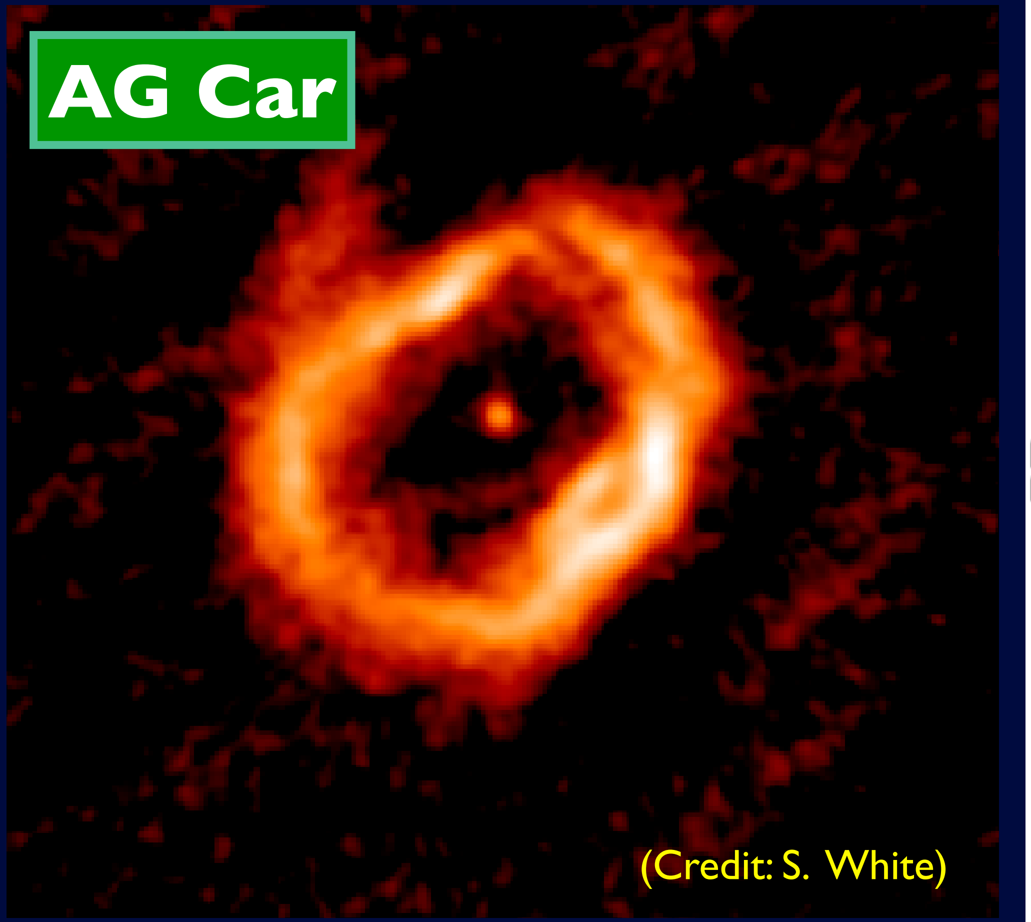
(Credit: S. White)

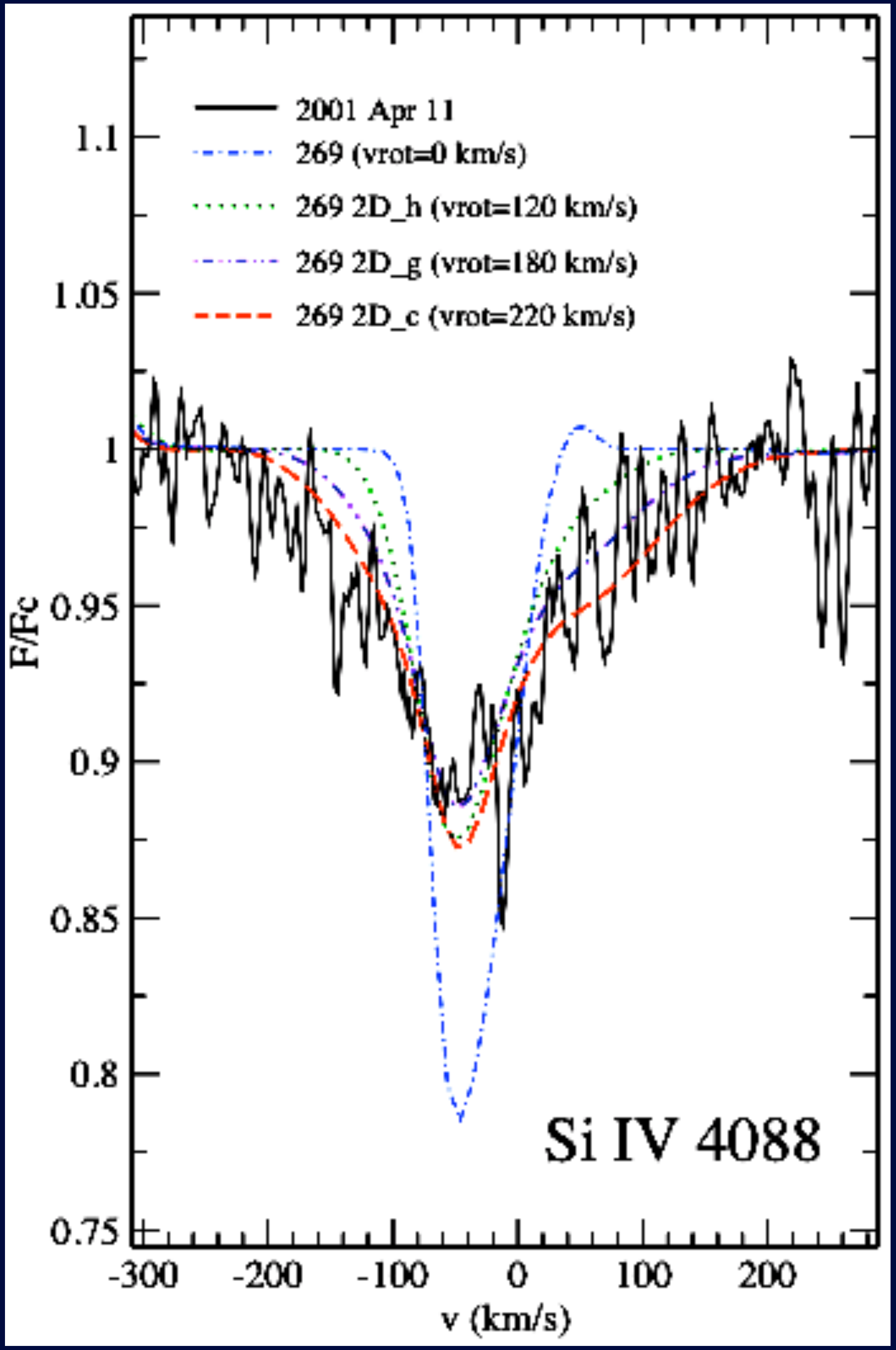
2. LBVs: living near the Eddington limit
c) Rapid rotation: broadening of spectral lines



2. LBVs: living near the Eddington limit
c) Rotational broadening of the Si IV 4088 line in AG Car

- Rotational velocity of AG Car is > 0.9 of the critical velocity for break-up during visual minimum.

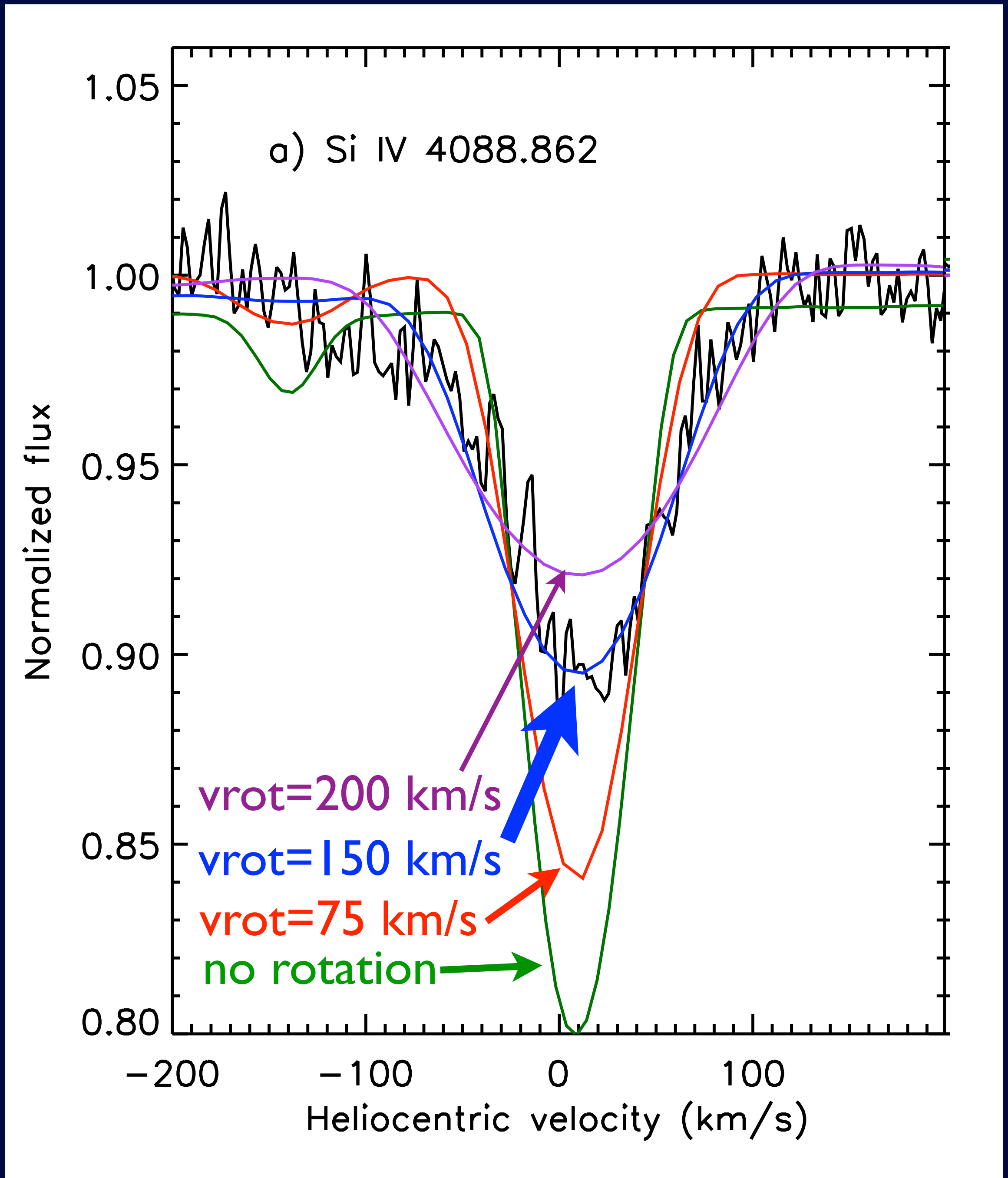




(Groh et al. 2006)

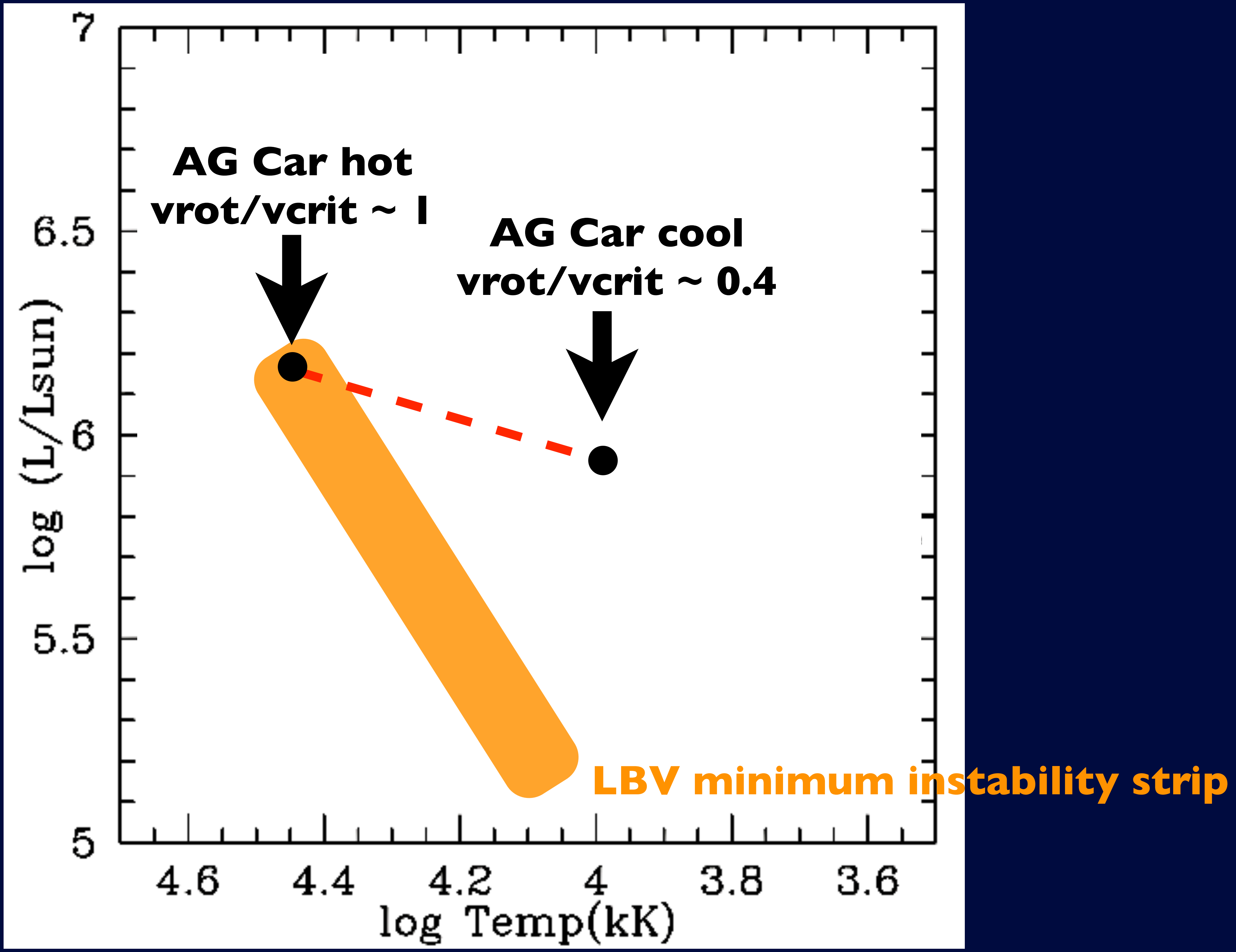
2. LBVs: living near the Eddington limit
c) Rotational broadening of the Si IV 4088 line in HR Car

- Rotational velocity 150 ± 20 km/s (assuming i=30°, Nota et al. 97)
- Rotational velocity is 0.9 ± 0.2 of the critical velocity for break-up



(Groh et al. 2009b)

2. LBVs: living near the Eddington limit
c) Bona fide, strong variable LBVs are fast rotators



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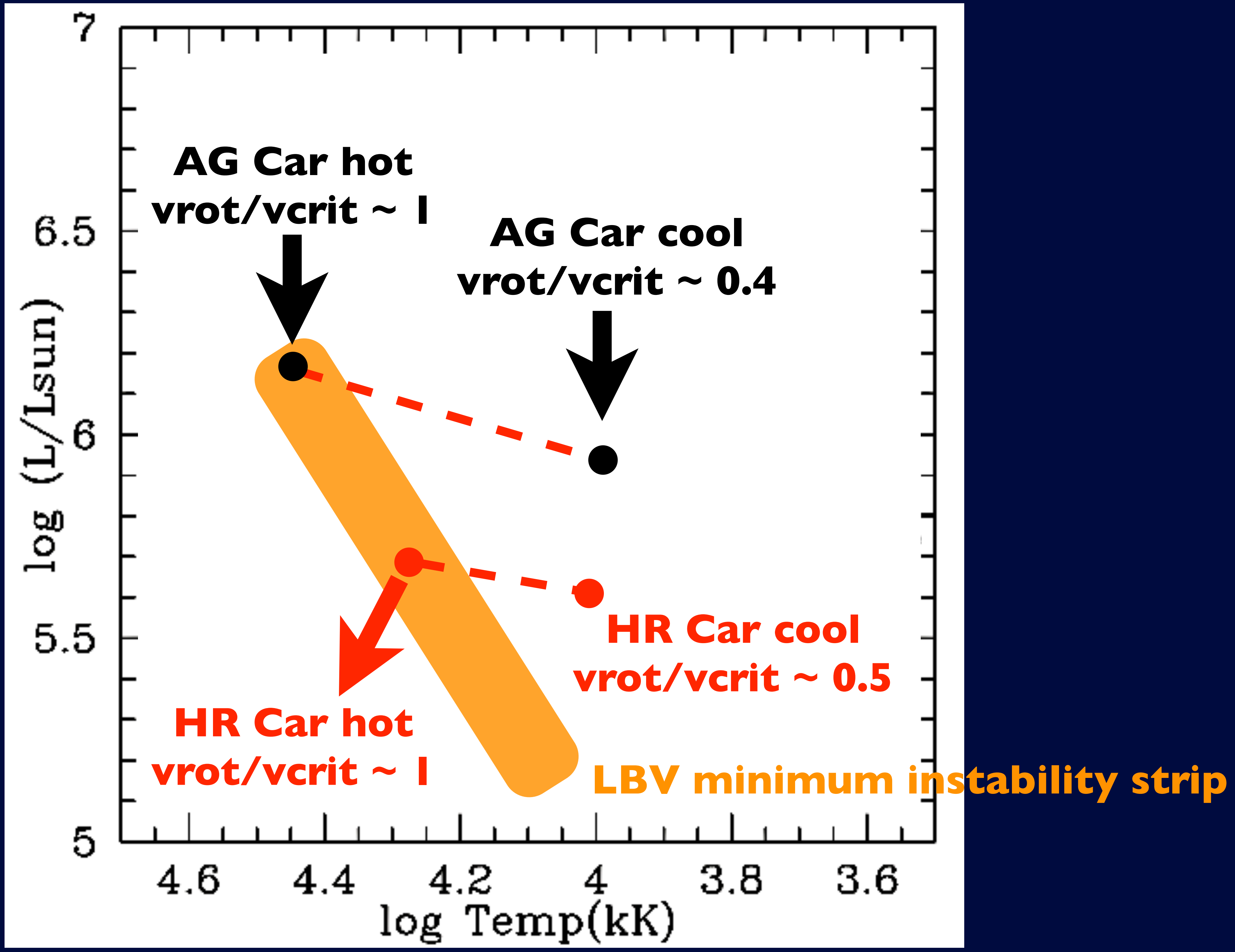
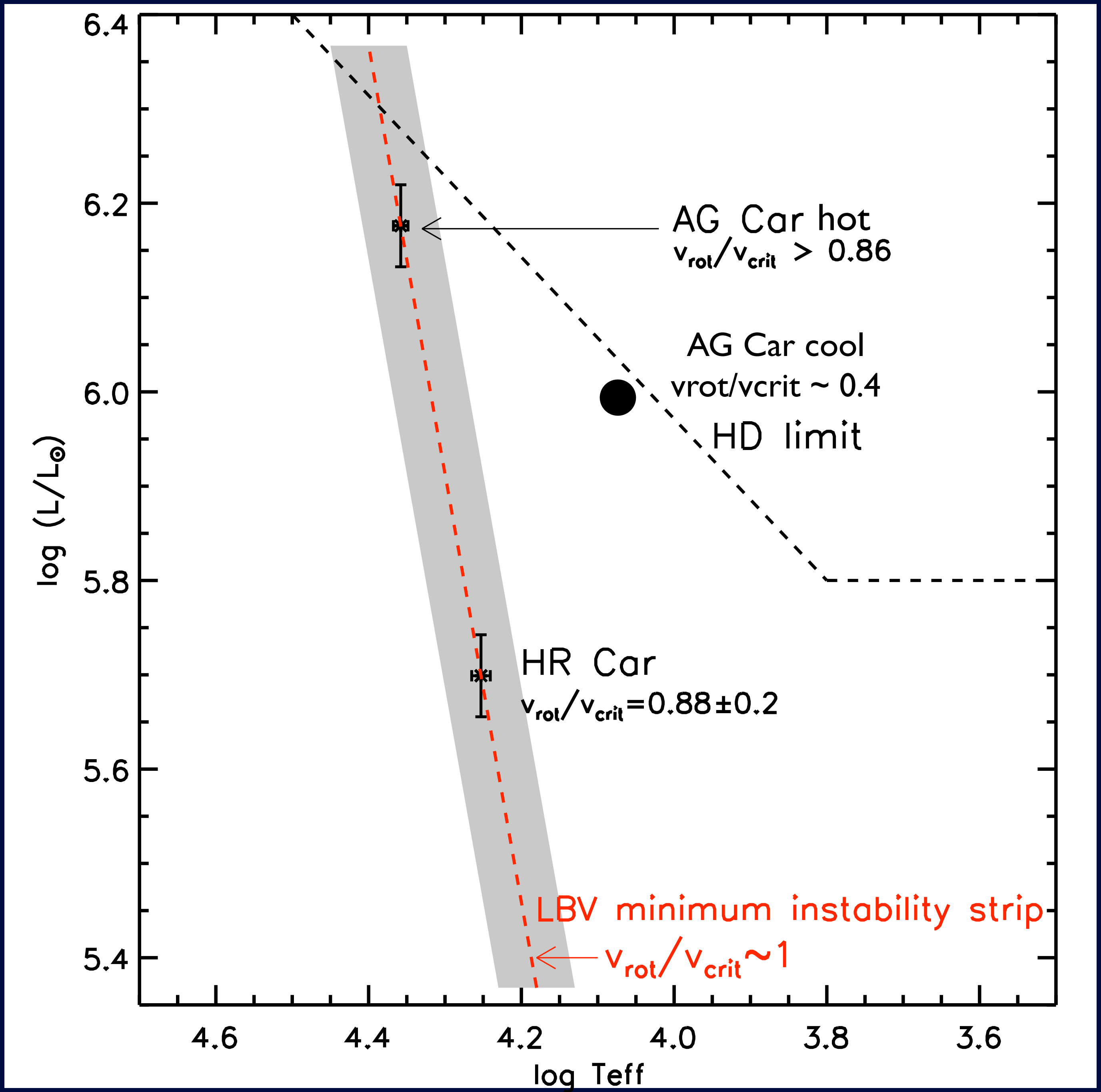


Fast rotation is characteristic in LBVs with S-Dor-type variability

2. LBVs: living near the Eddington limit

c) Rotation implies in a forbidden region for LBVs in the HR diagram



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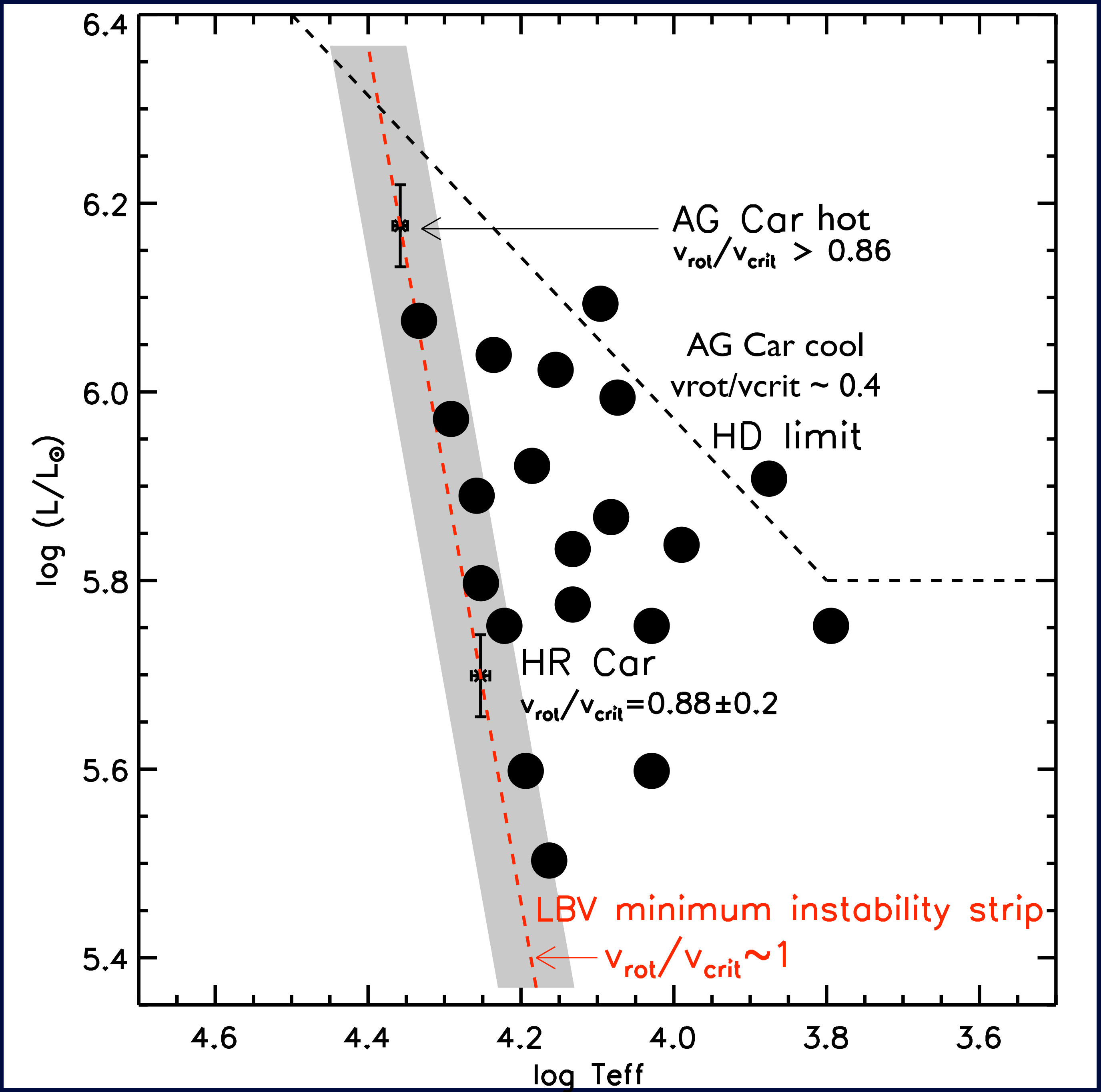

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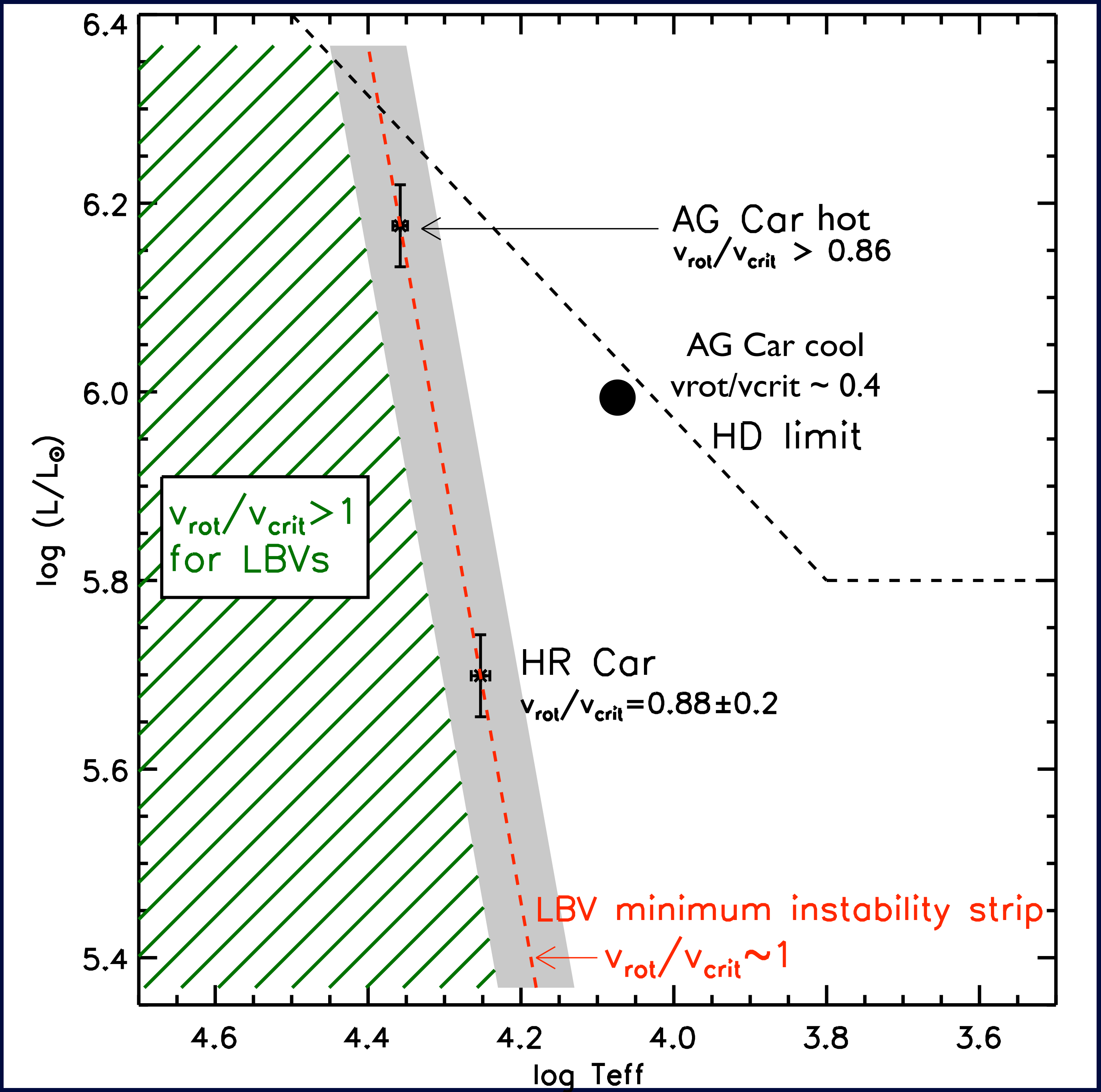

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To the left of the LBV strip, a forbidden zone with vrot/vcrit >1 is present, explaining why no LBVs have been detected in this zone.

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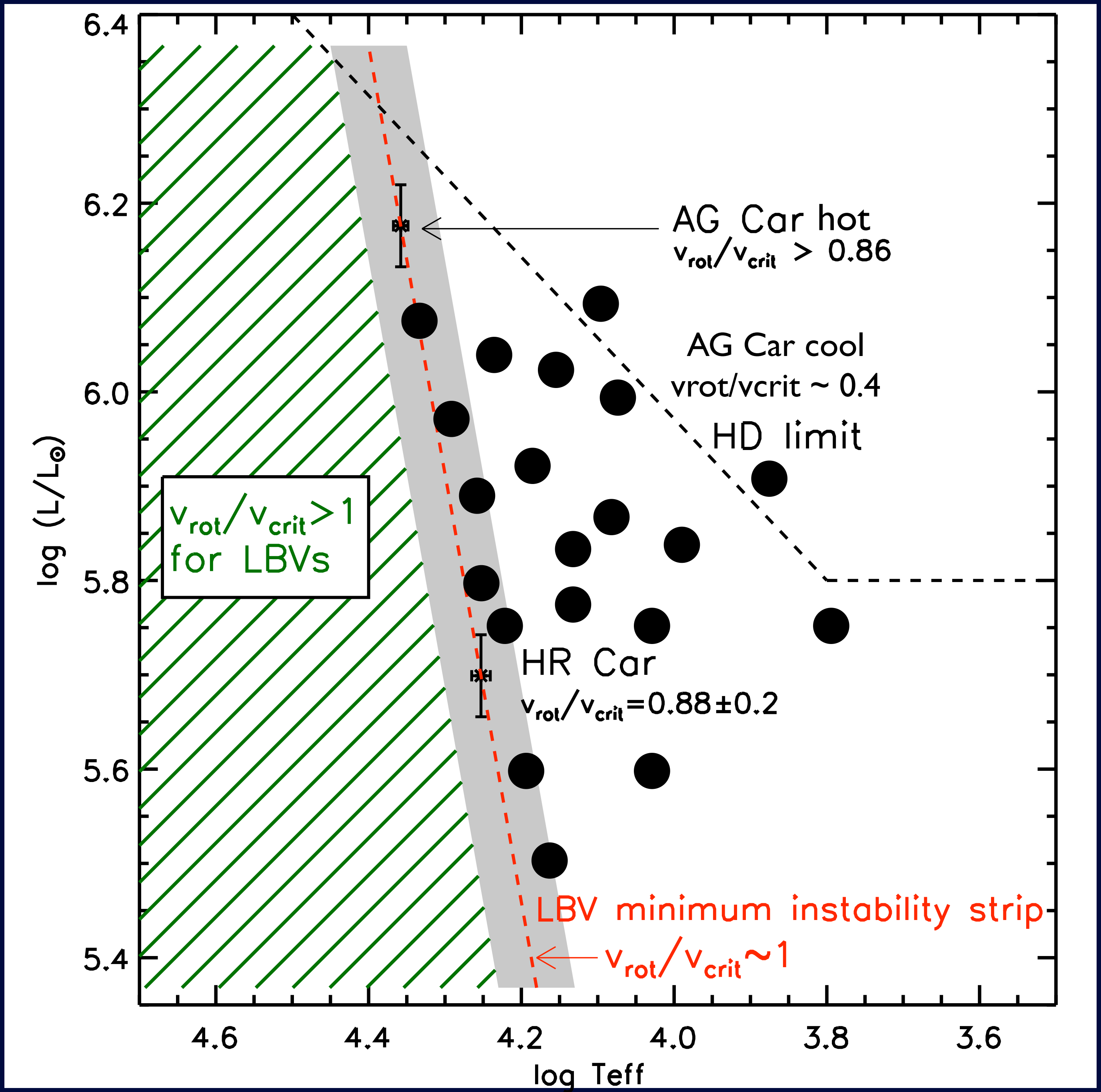

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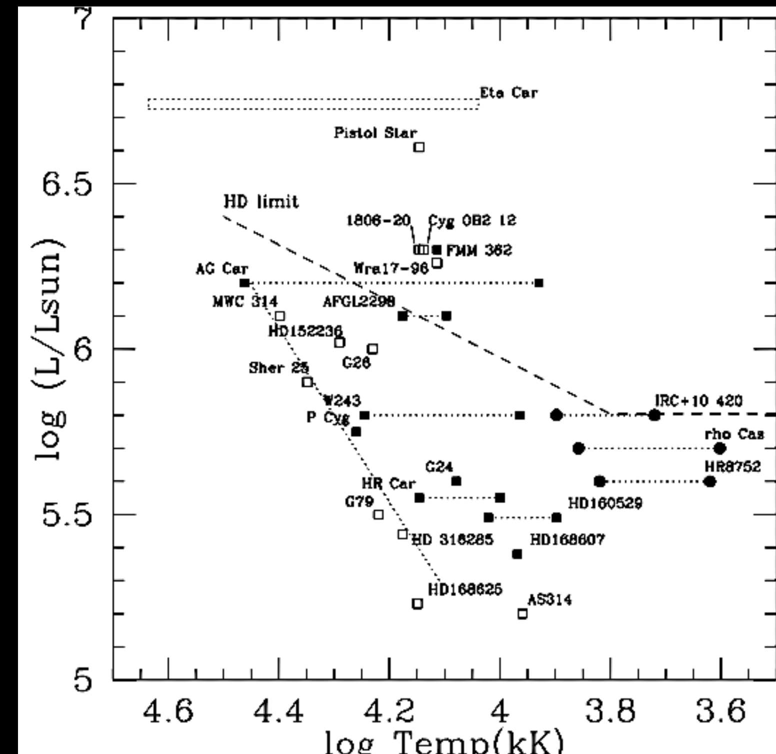
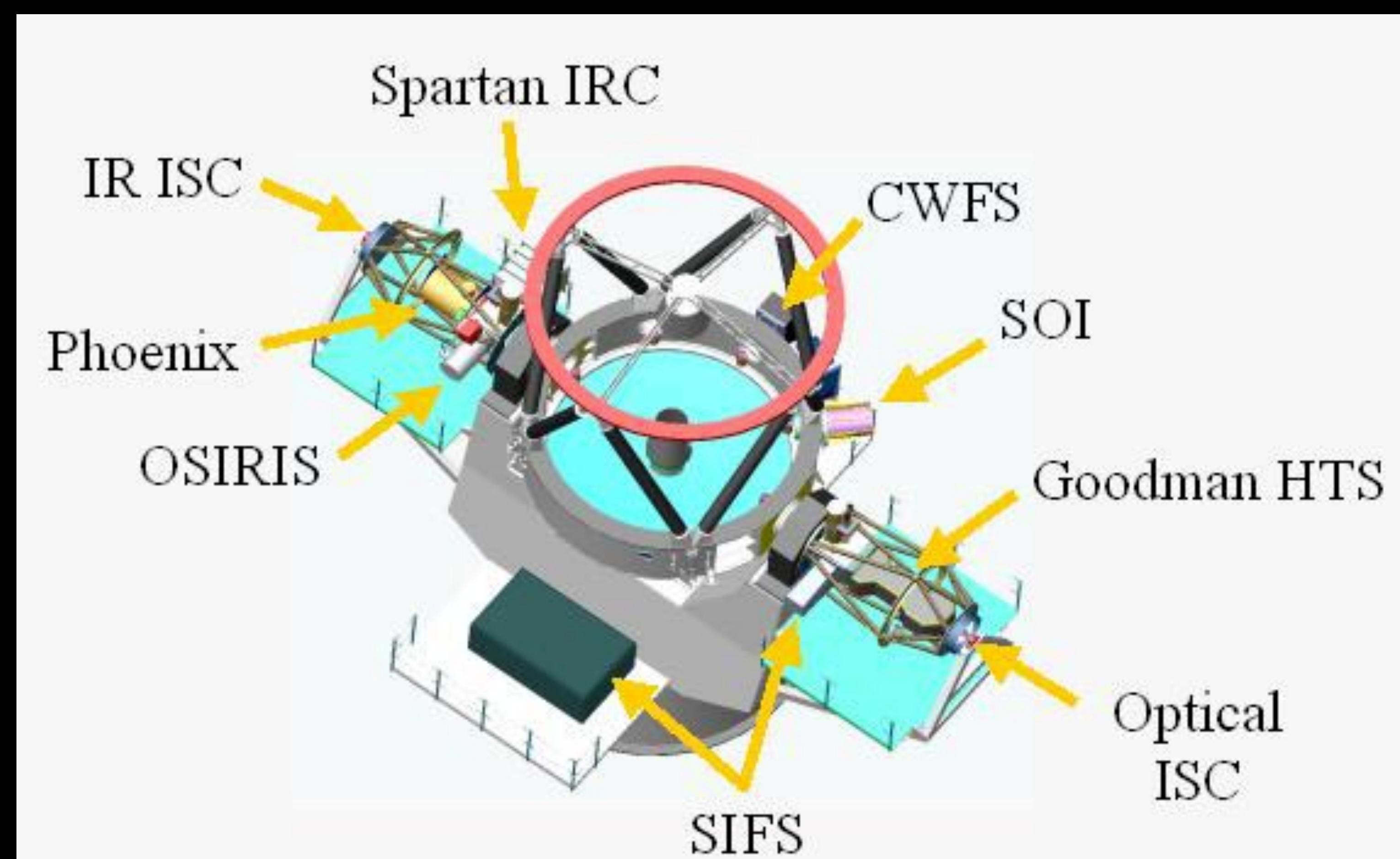
c) Rapid rotation in LBVs: science opportunities with *SOAR*





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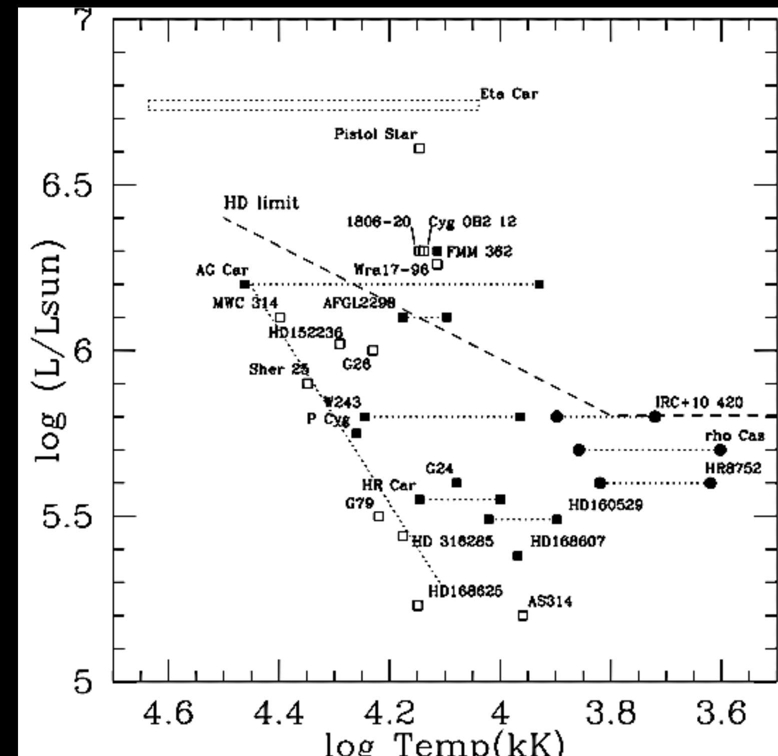
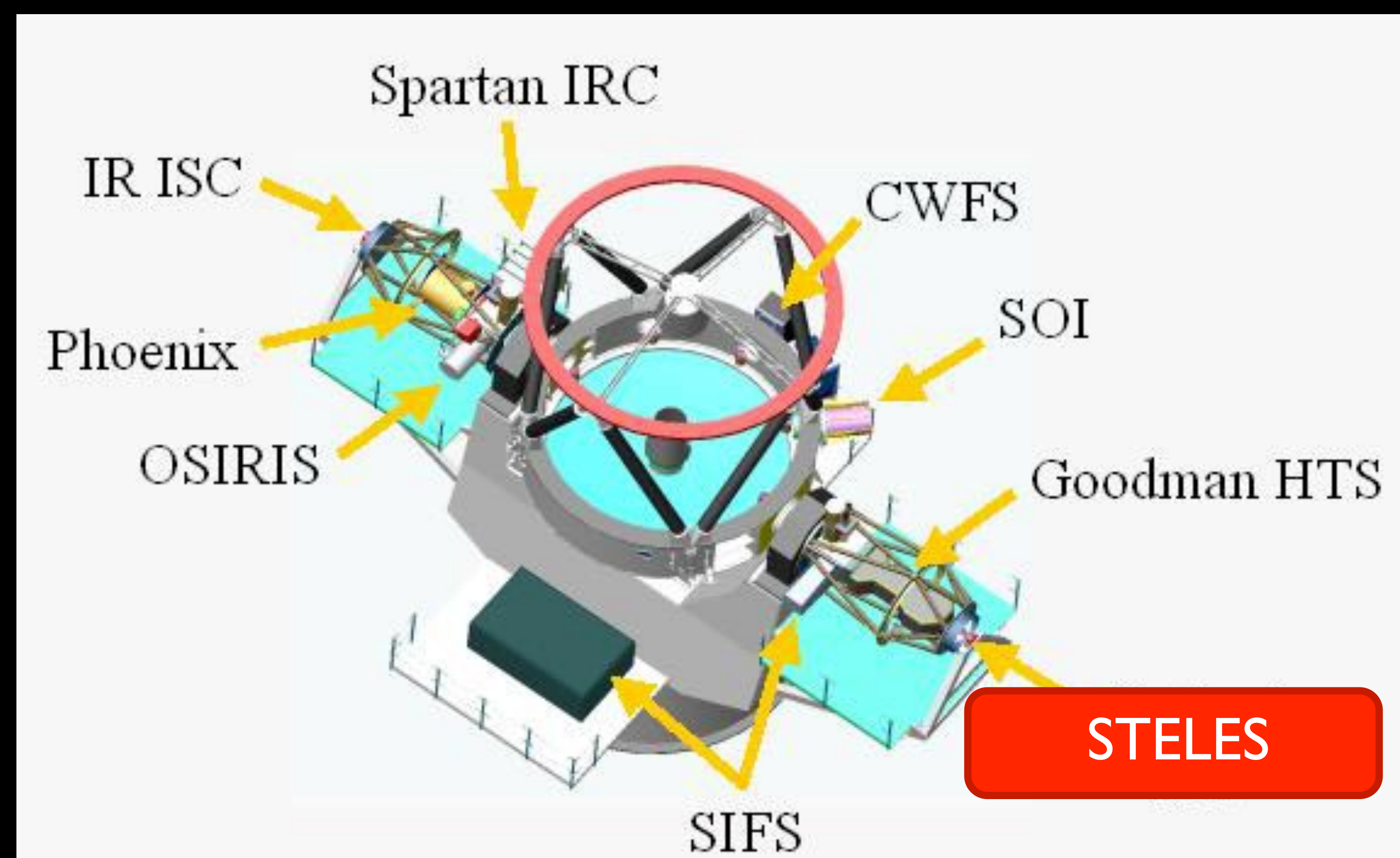
Determination of the rotational velocity of LBVs in the Galaxy and Local Group.

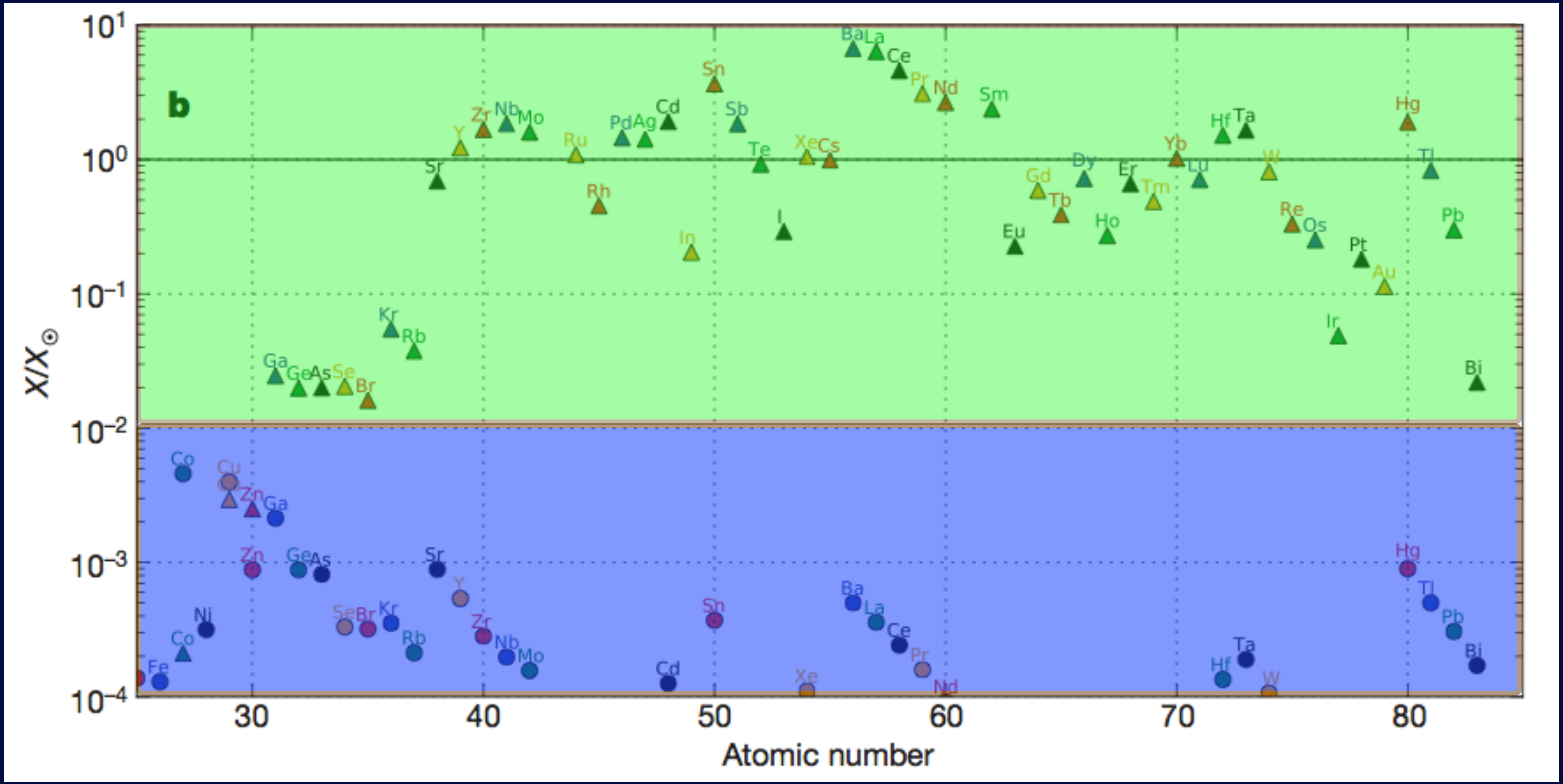




2. LBVs: living near the Eddington limit

c) Signatures from fast-rotating massive stars in the early Universe

Observations of metal-poor stars in the Galactic Bulge indicate an overabundance of s-process elements (Chiappini+ 2011).



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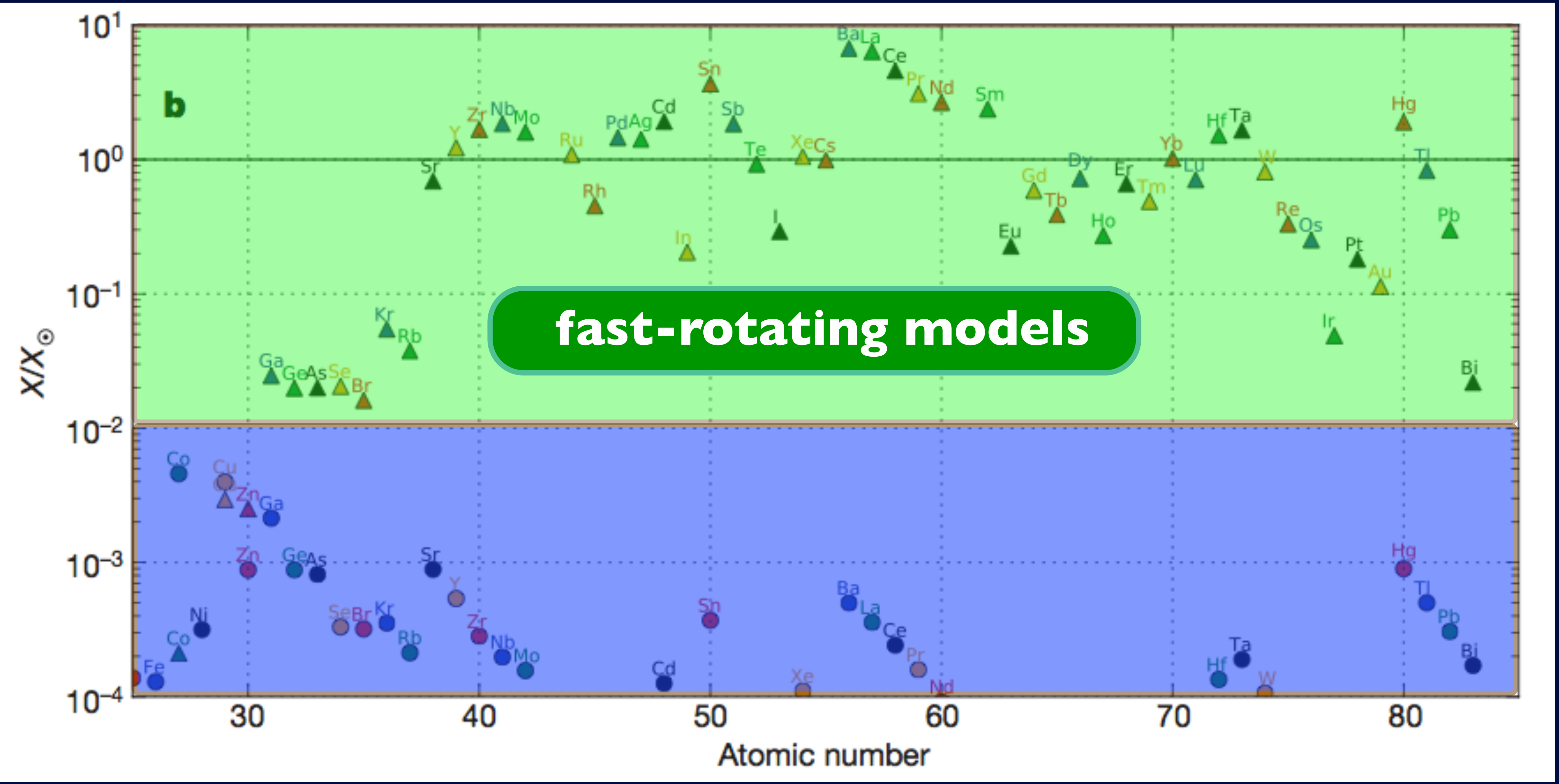

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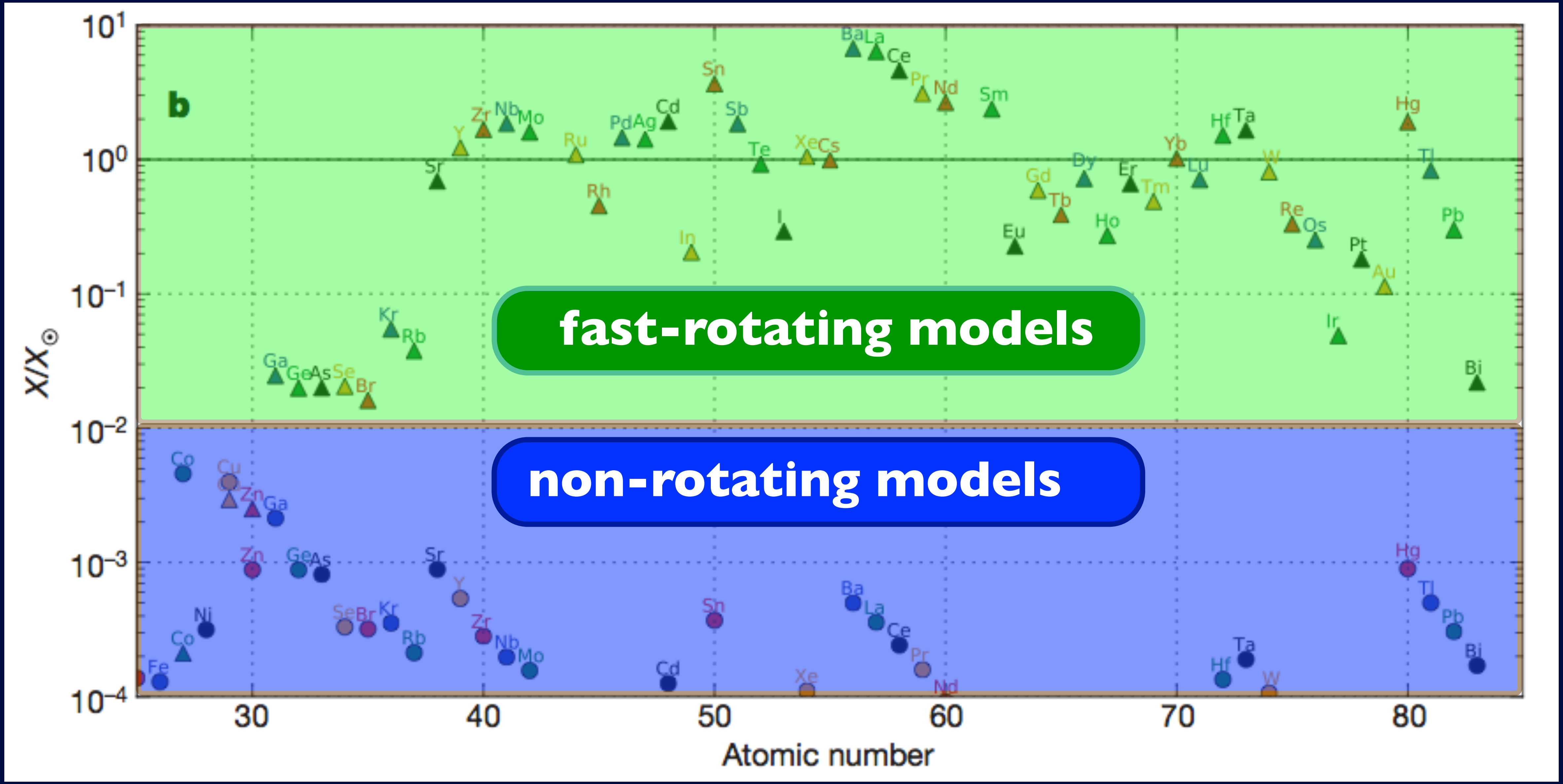

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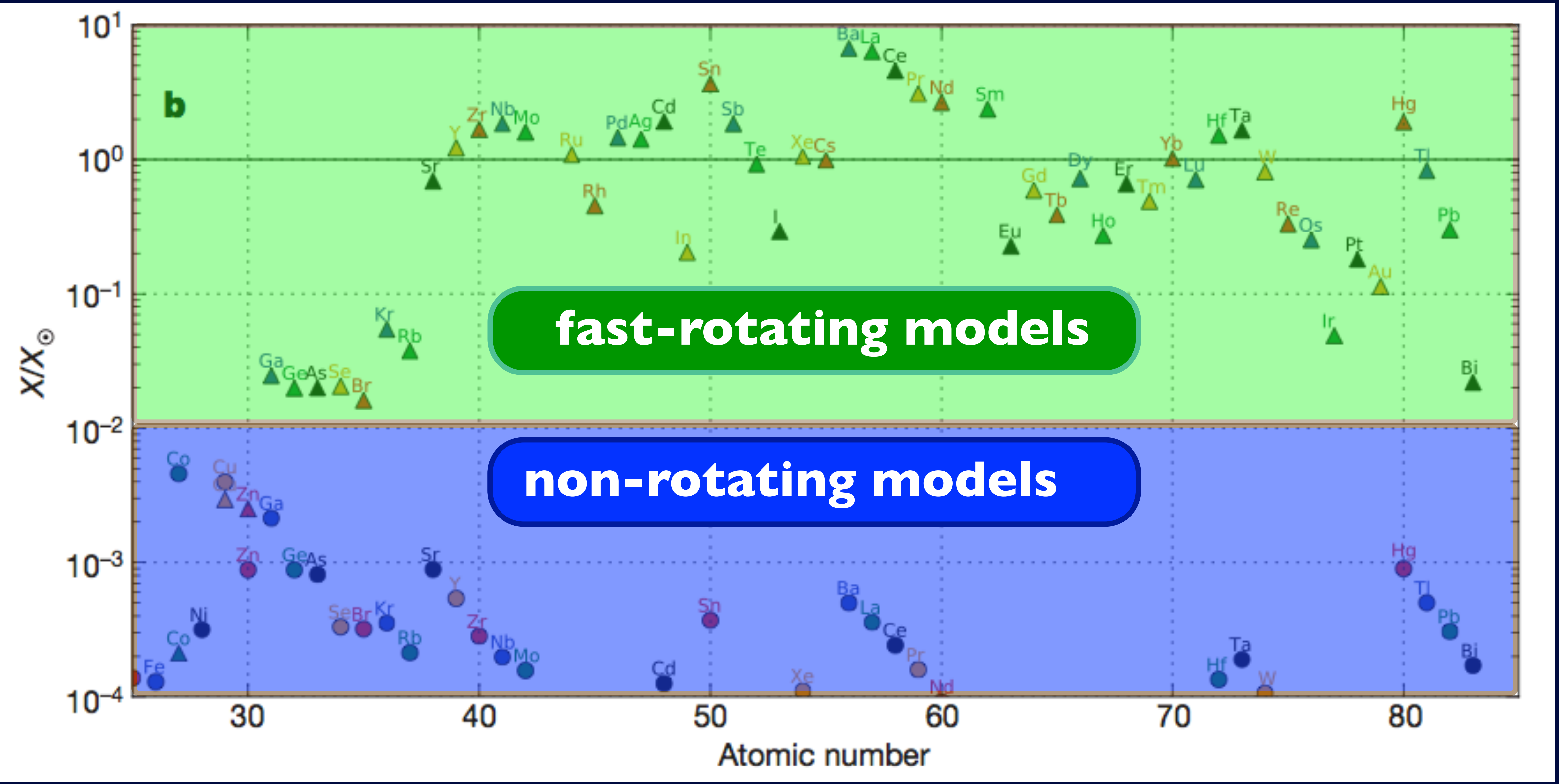

Connection with GRBs?

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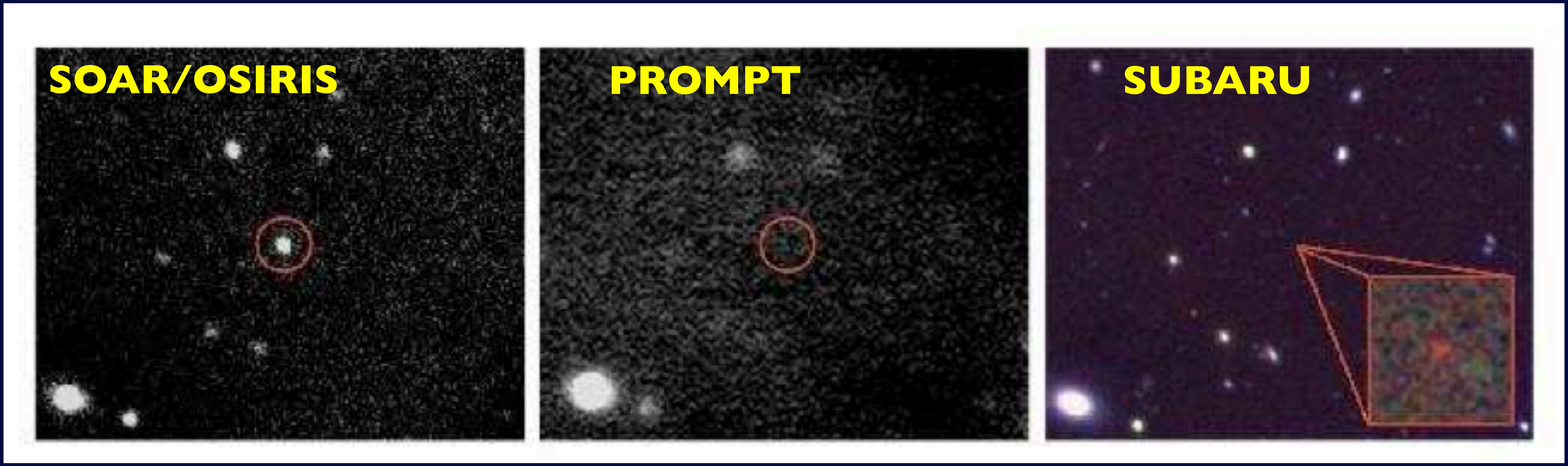

(Haislip et al. 2007)

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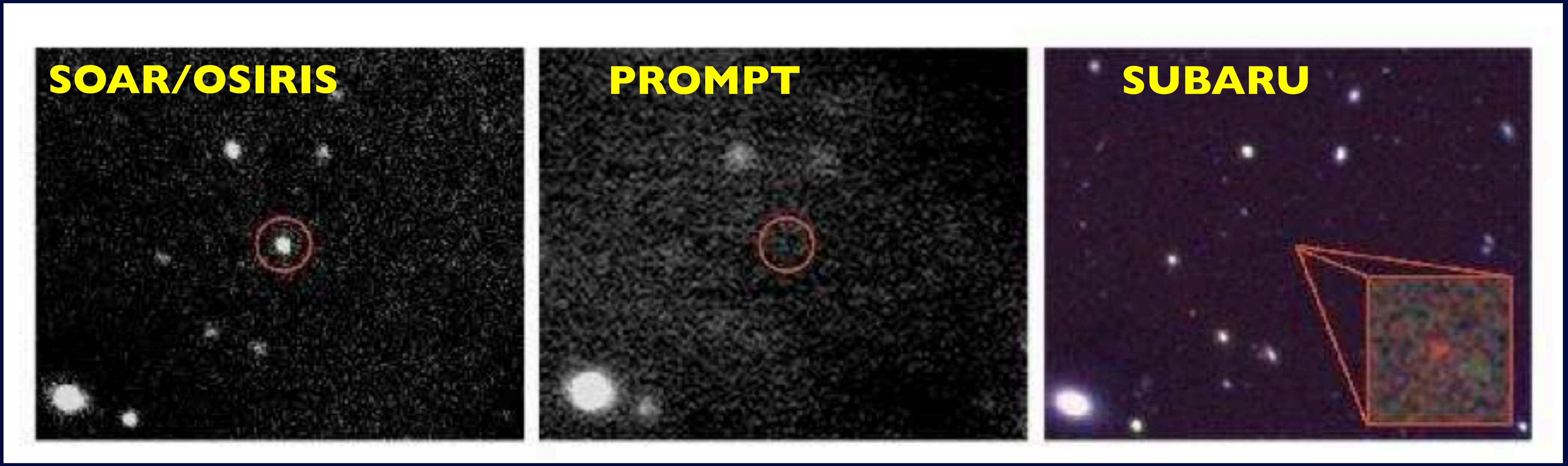
Connection with GRBs? The afterglow of GRB 050904 discovered by SOAR



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Concluding remarks

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The Eddington parameter is the ratio between the outward radiative force and the inward gravitational force, and depends on the opacity and L/M.

Concluding remarks

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Observational consequences of the star being close to the Eddington limit: S Doradus type variability, Giant Eruptions, and rapid rotation.

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Changes in the stellar parameters on timescales of decades.

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S Dor type variability: slow pulsation, irregular, non-periodic. Changes in the stellar parameters on timescales of decades.

Giant Eruptions: ejection of several solar masses during a few years, similar to what Eta Carinae did in the 1840's.

Rapid rotation: regulates the position of LBVs in the HR diagram during visual minimum; set the presence of a forbidden-region for LBVs in the HR diagram; relationship to the first generation of stars in the Universe and GRBs.

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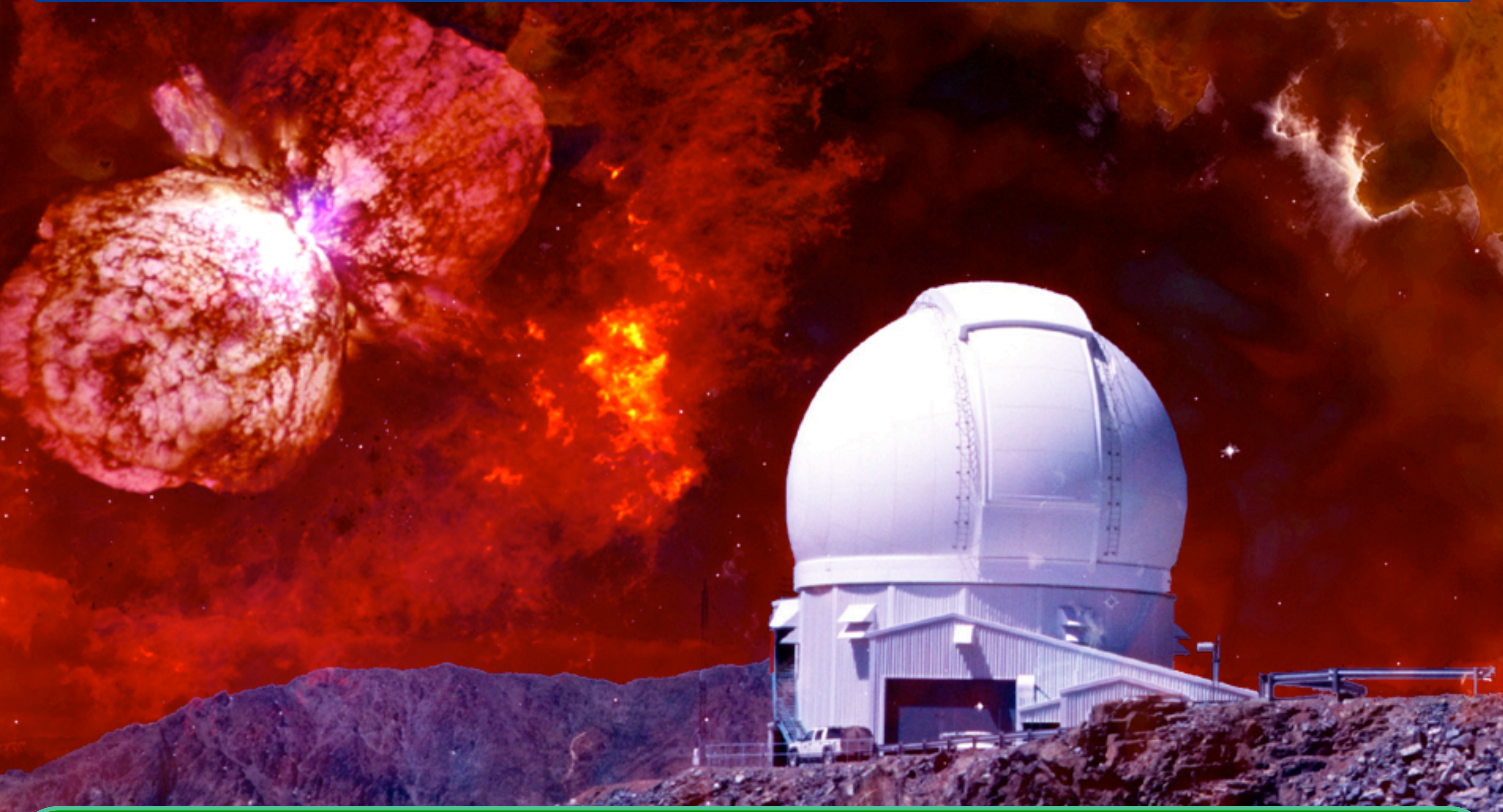

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