Stellar sources of ionizing radiation

Ylva Götberg

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Science and
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Austria

Interacting binaries at ISTA

Stellar and binary evolution,
Hot star spectroscopy,
Binary stellar populations and their spectra

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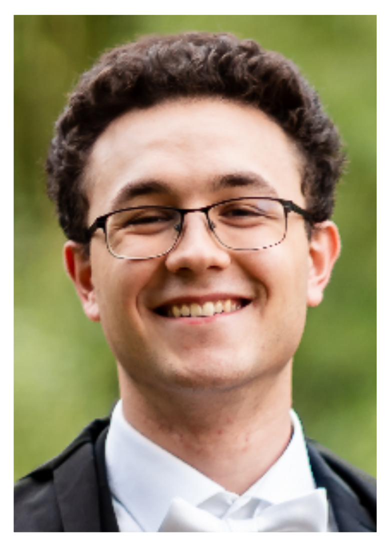
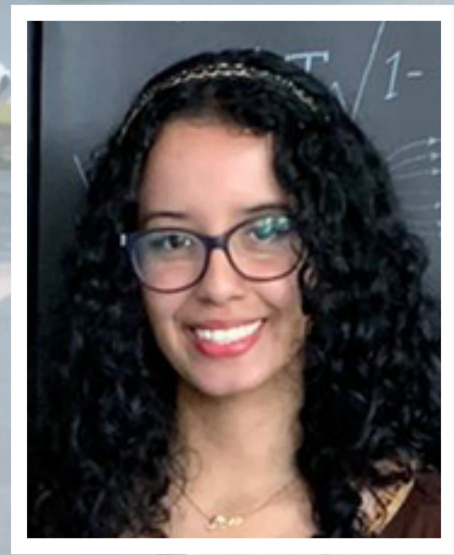


Andrei Cristea
(PhD student ‘23)

Dandan Wei
(ISTA fellow ‘24)

Debasish Dutta
(PhD student ‘24)



Angie Davila
(Intern ’25)

Syafira Putri
(Intern ’25)

Outline

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1) Stars that ionize

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2) Hard ionizing radiation

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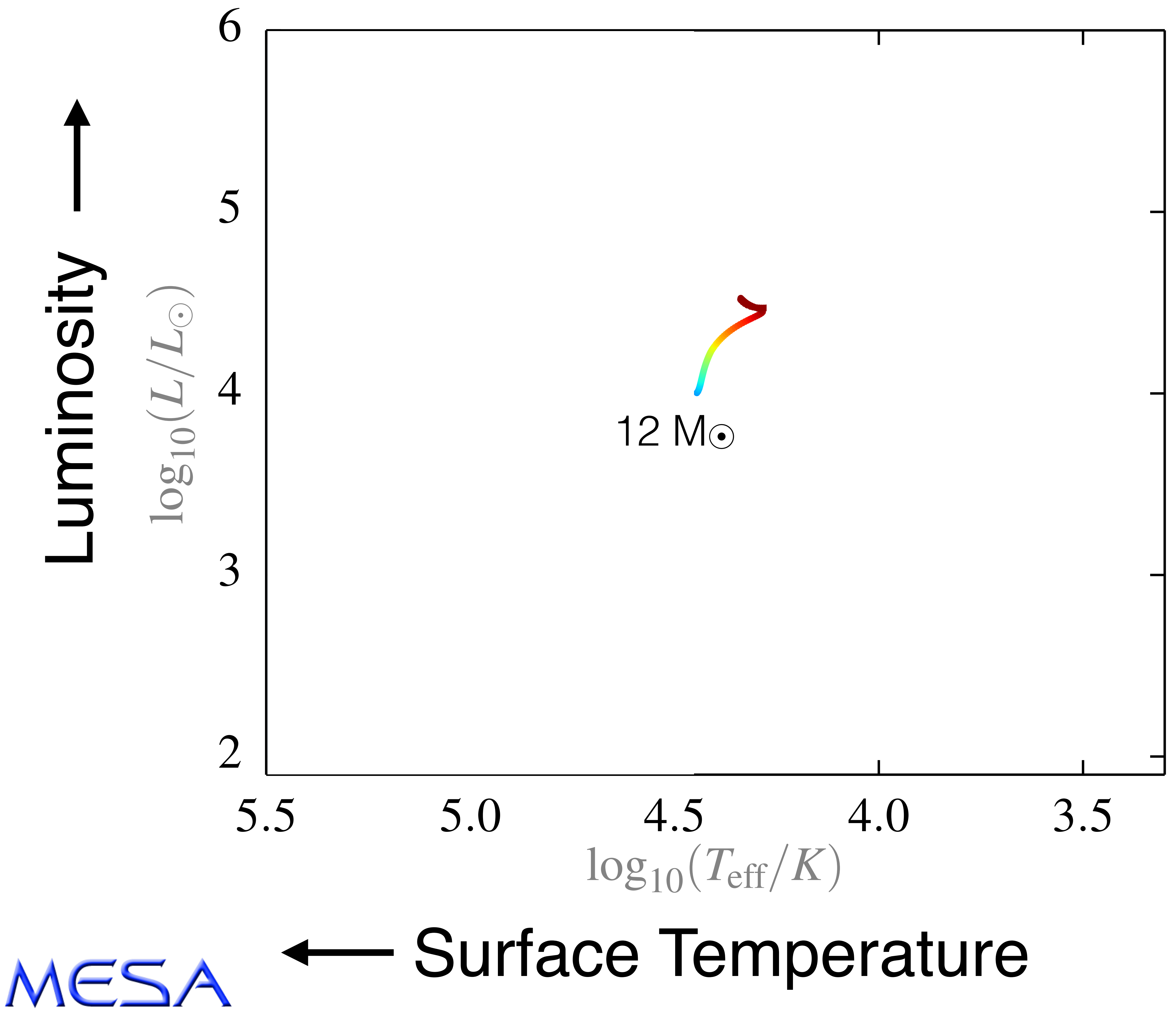
2) Hard ionizing radiation
3) Where do we go next?

Massive stellar evolution



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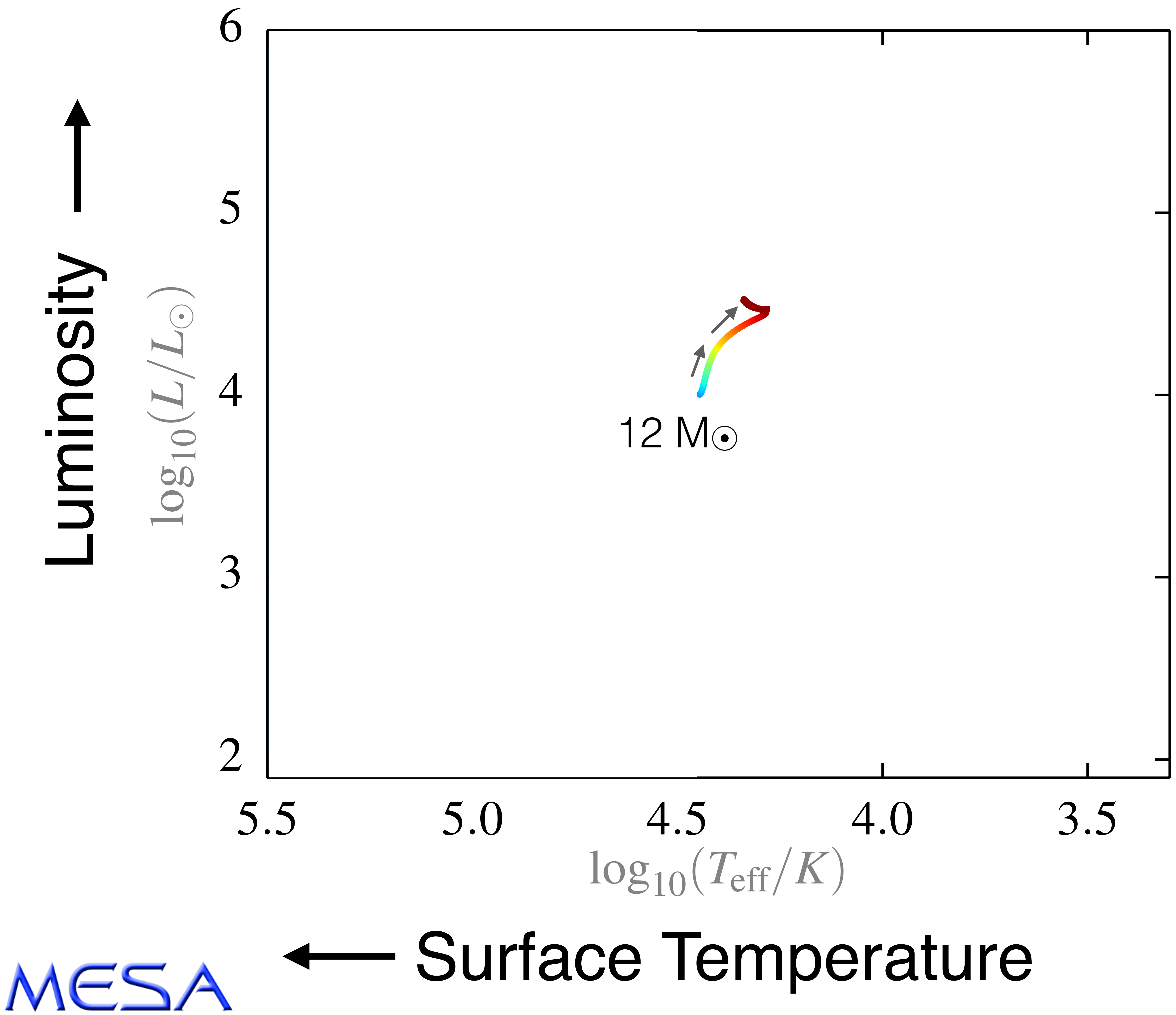
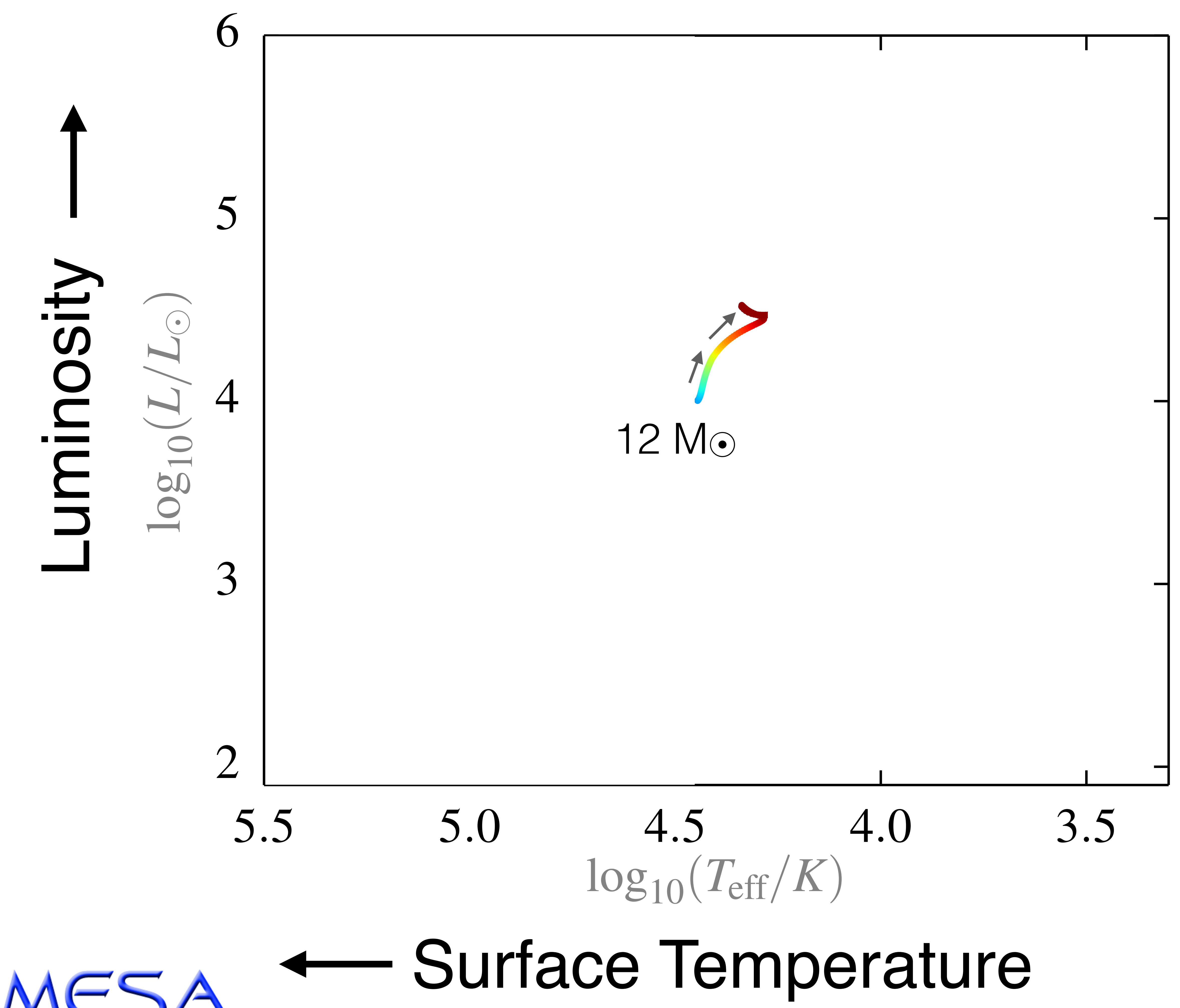
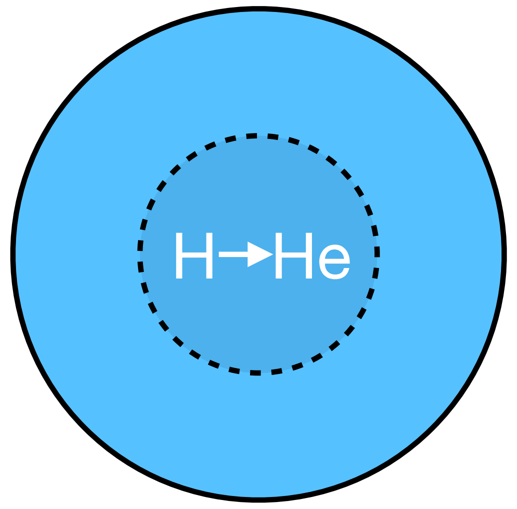


MESA

Massive stellar evolution





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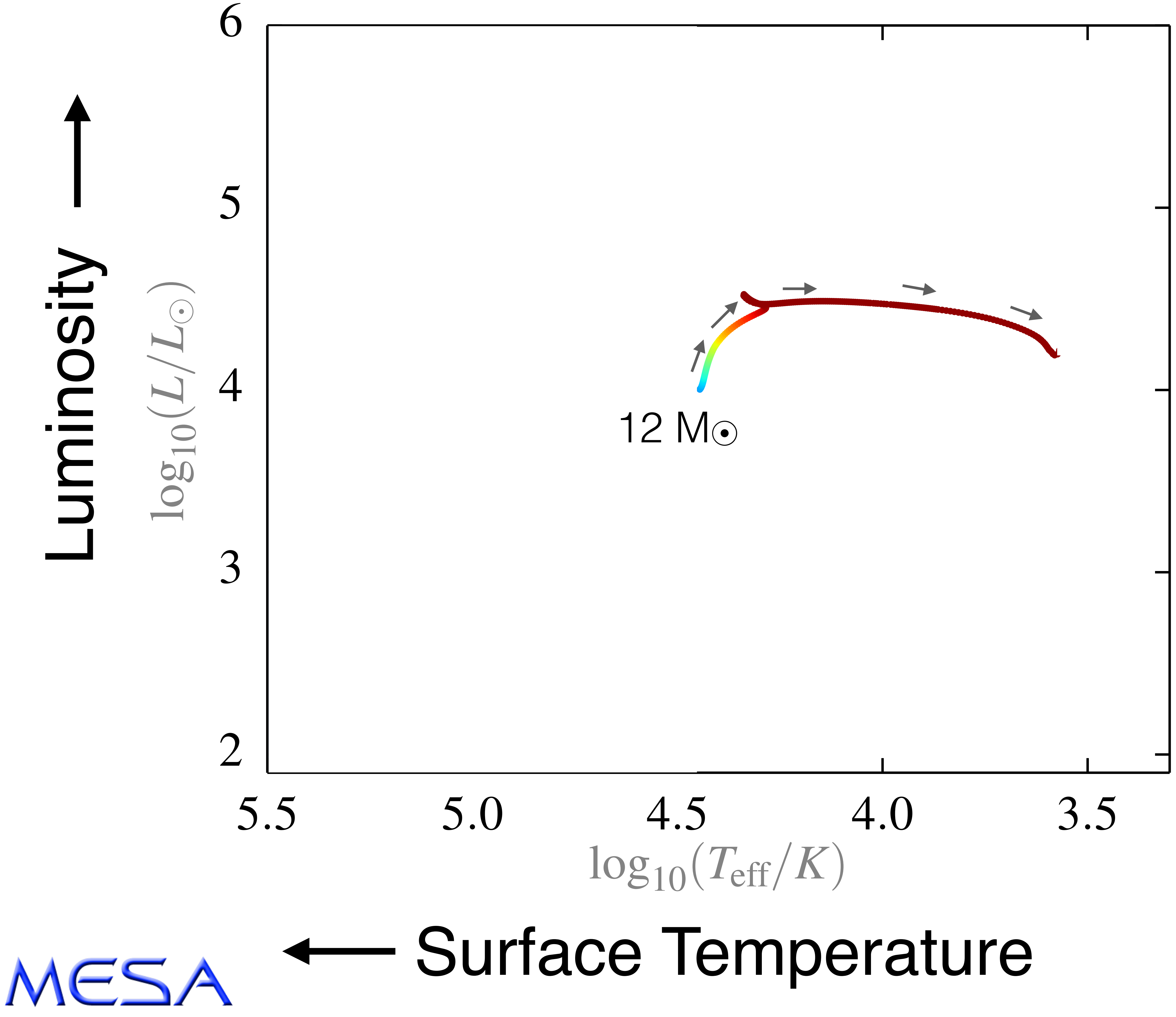

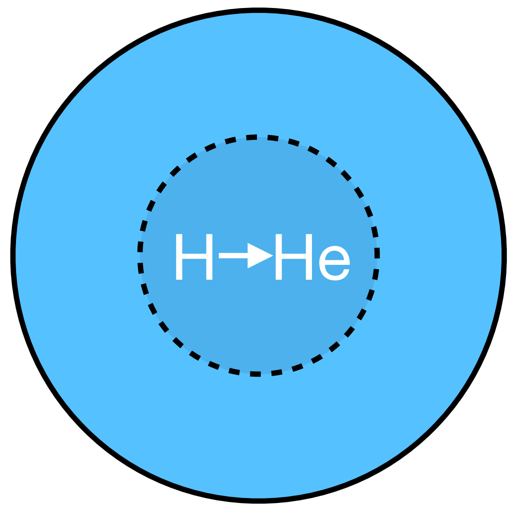

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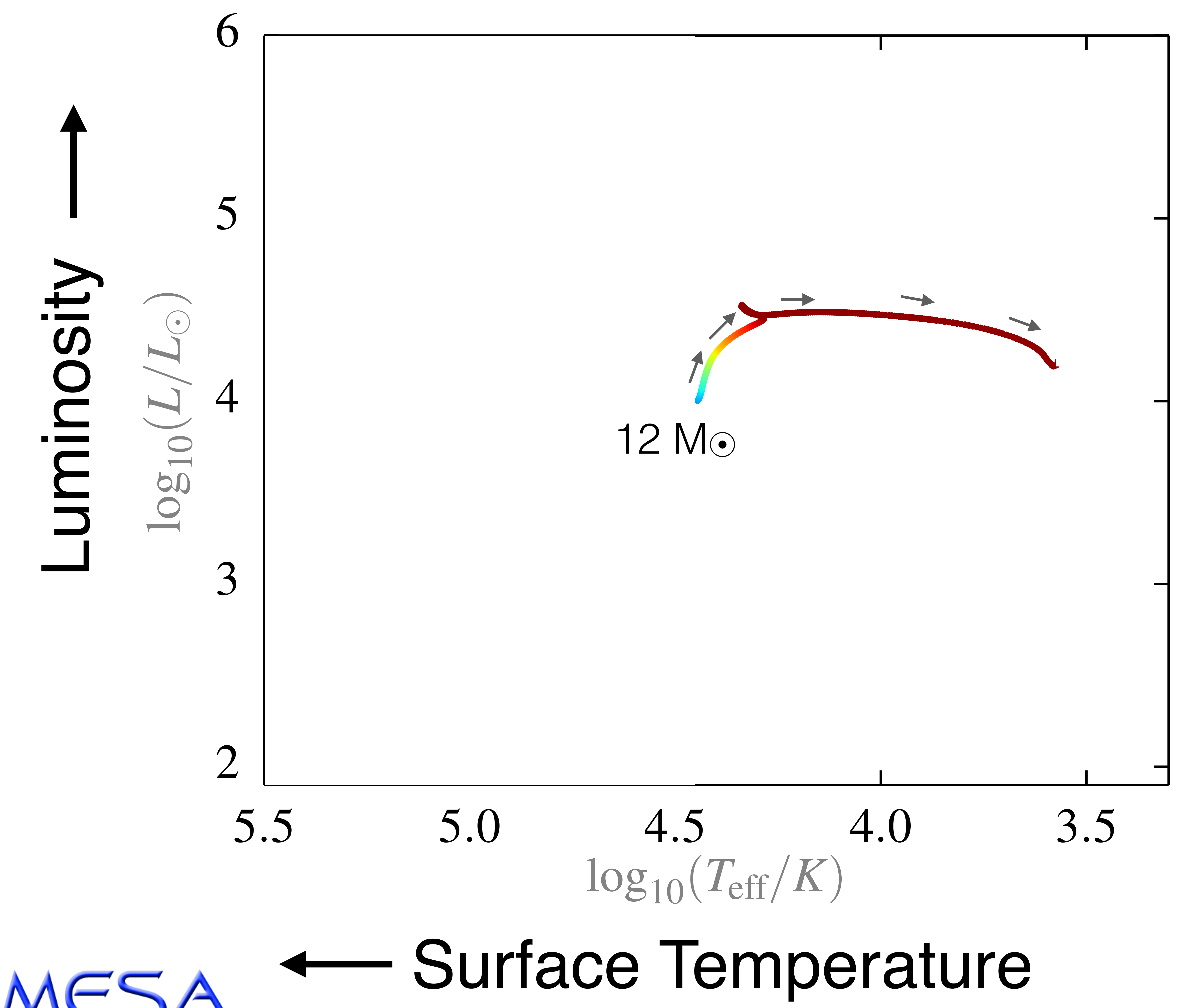

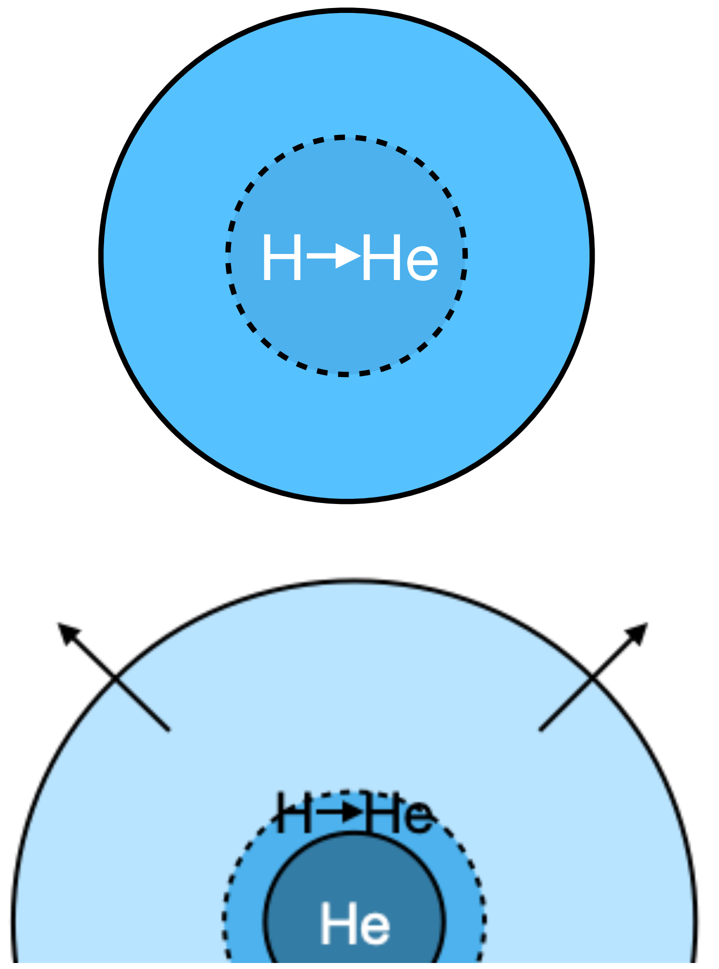

Stage 1: Hydrogen fuses to helium in the center - a helium core is created. Main sequence.

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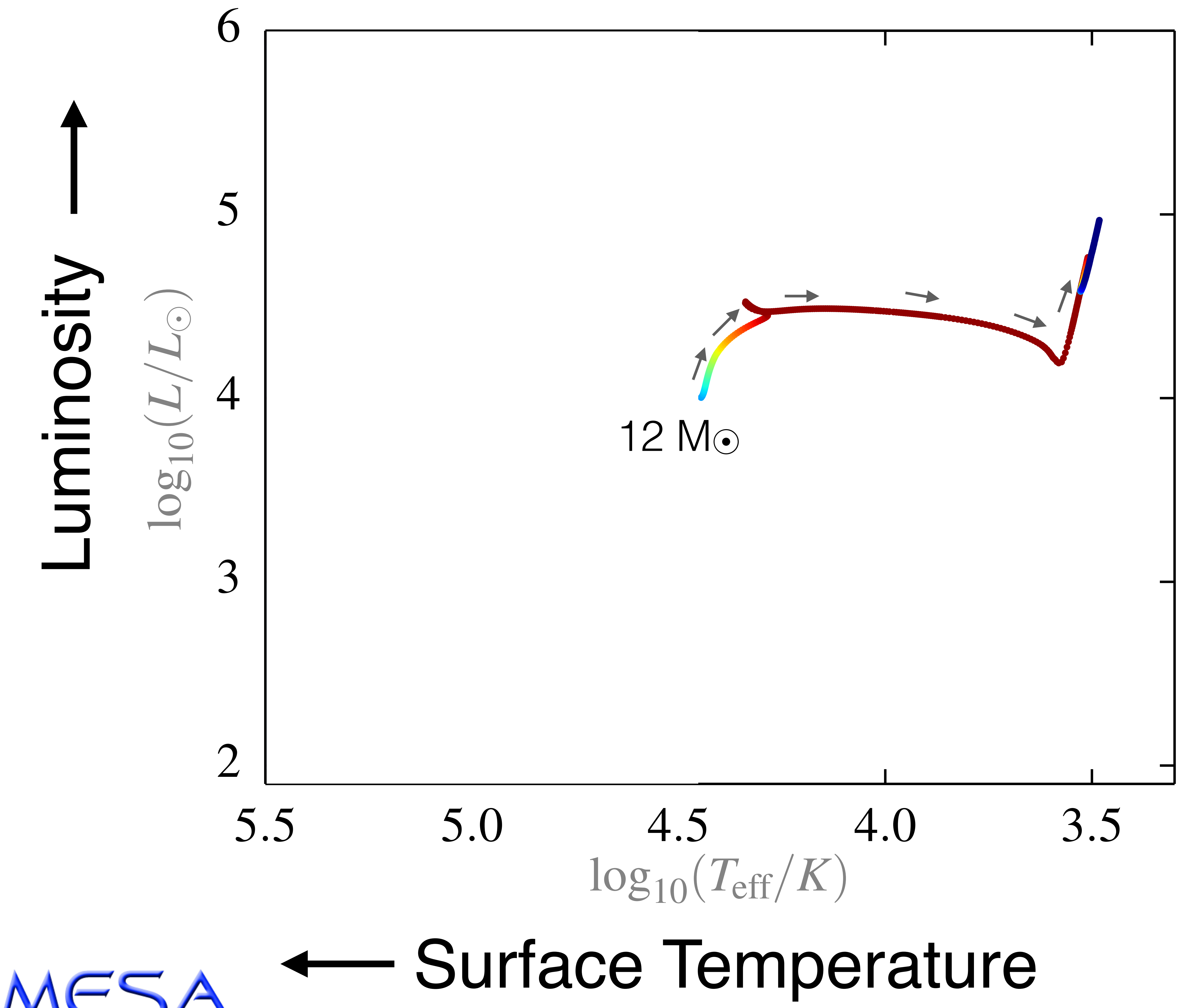

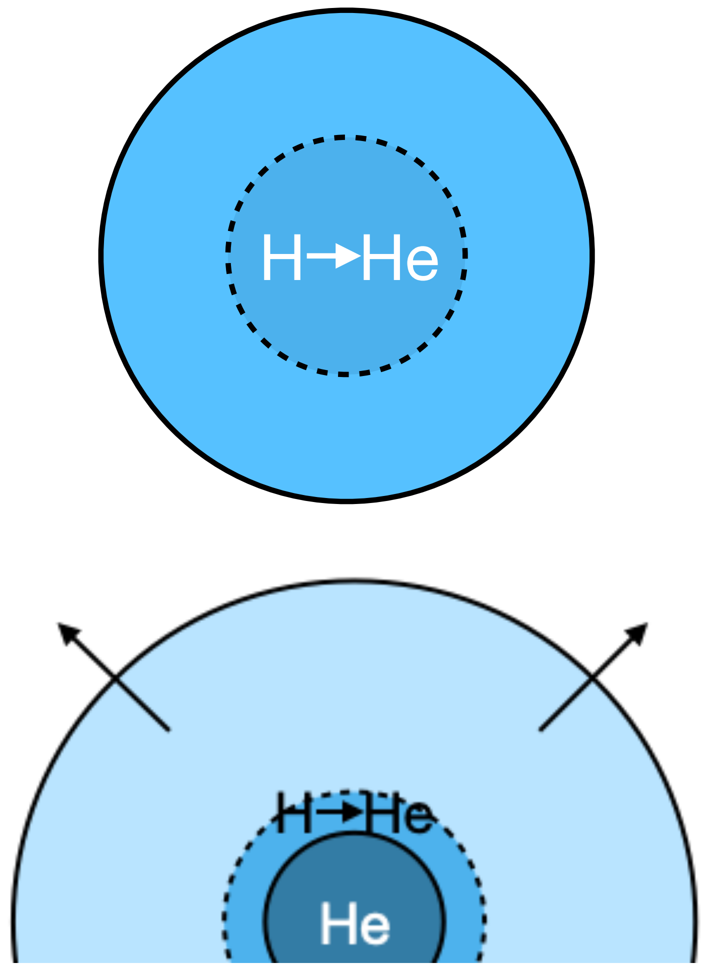

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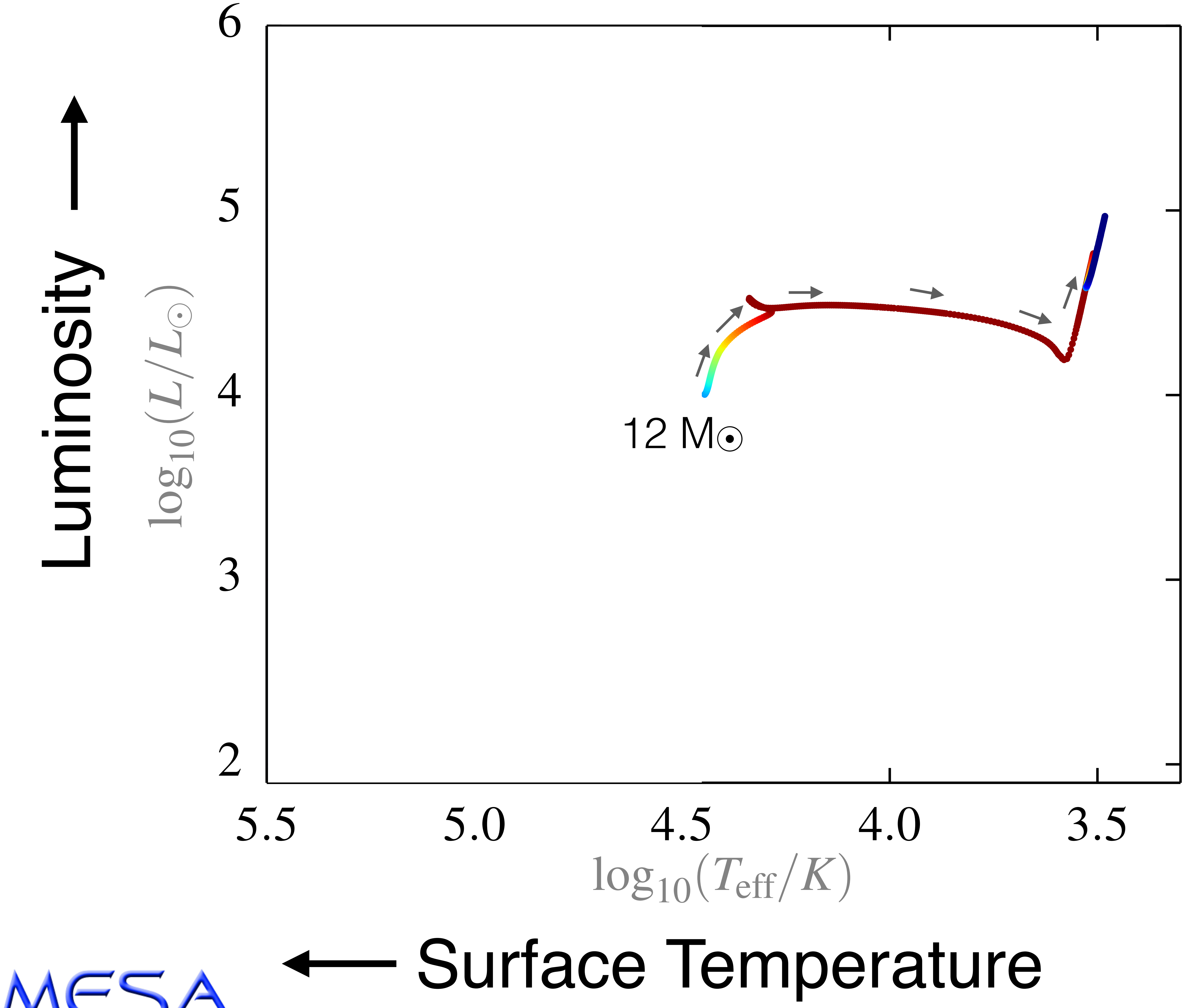

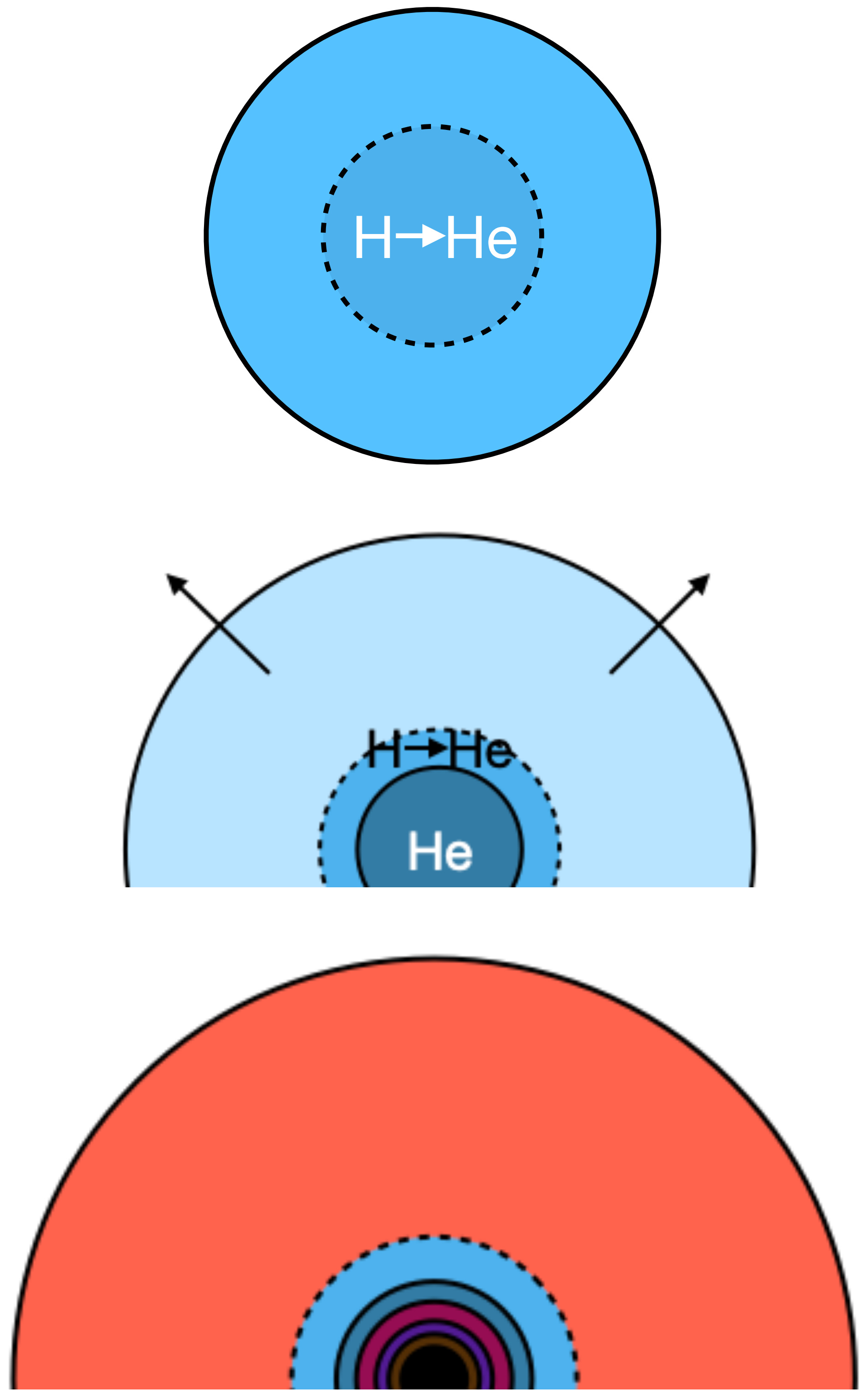

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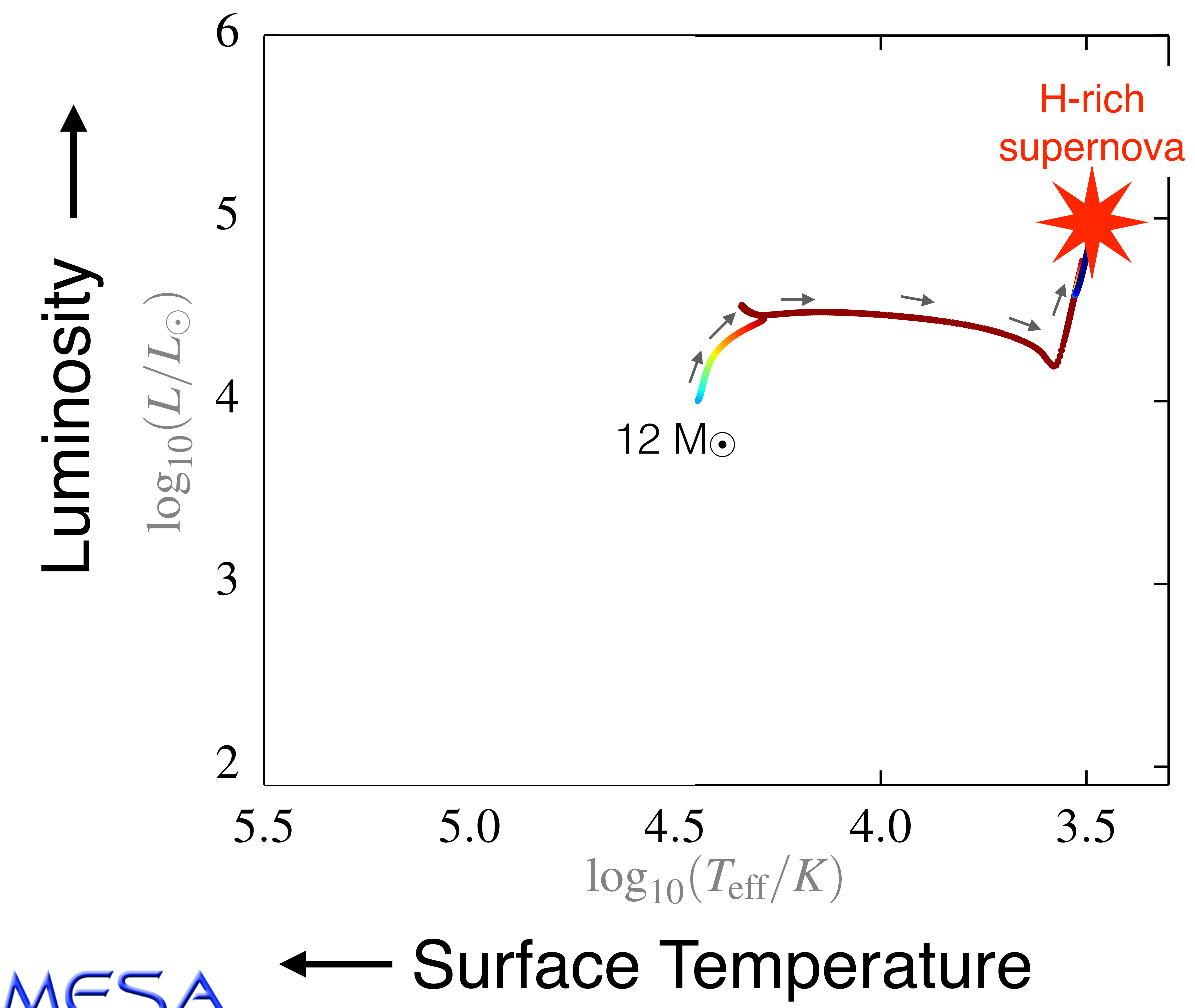

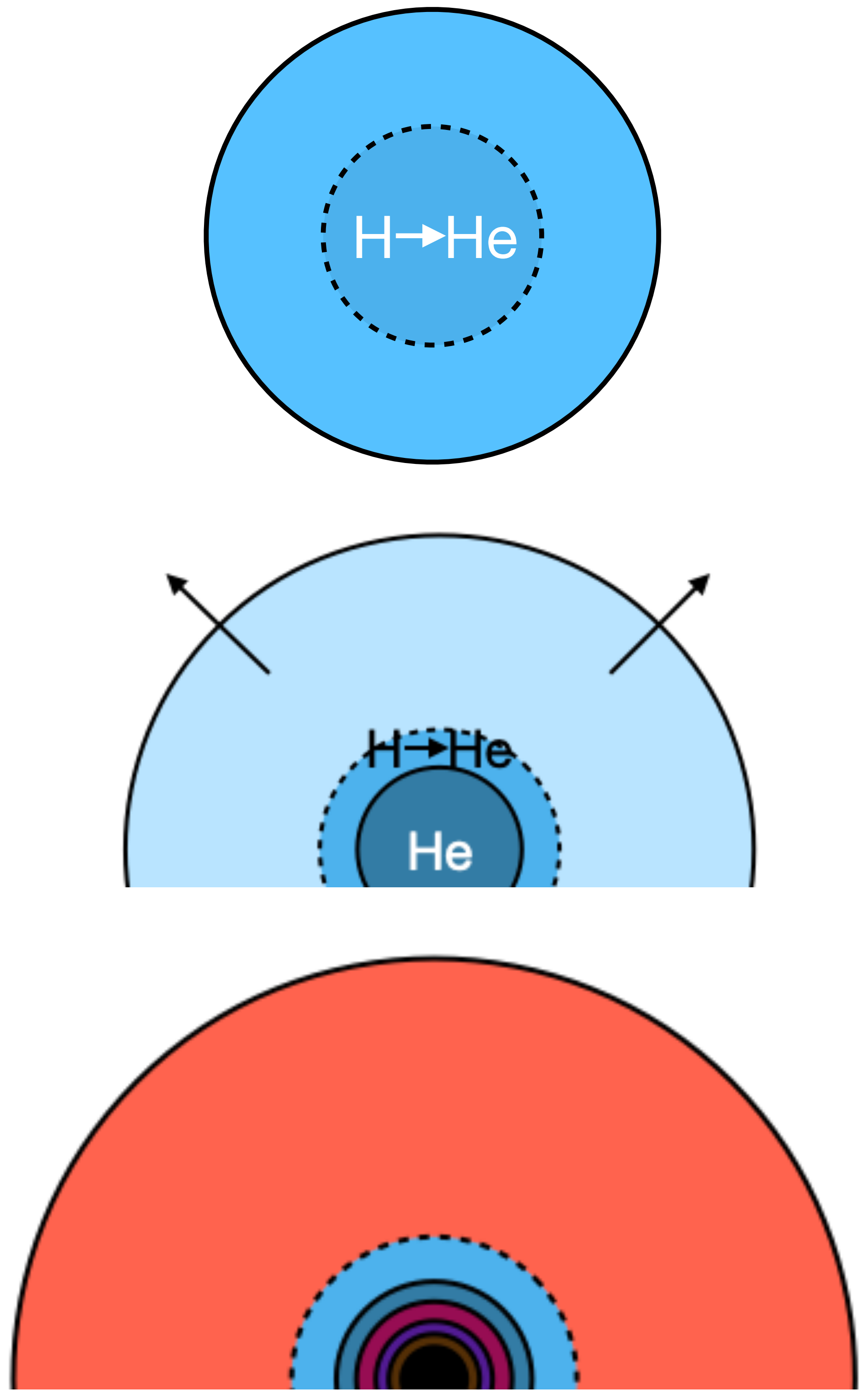

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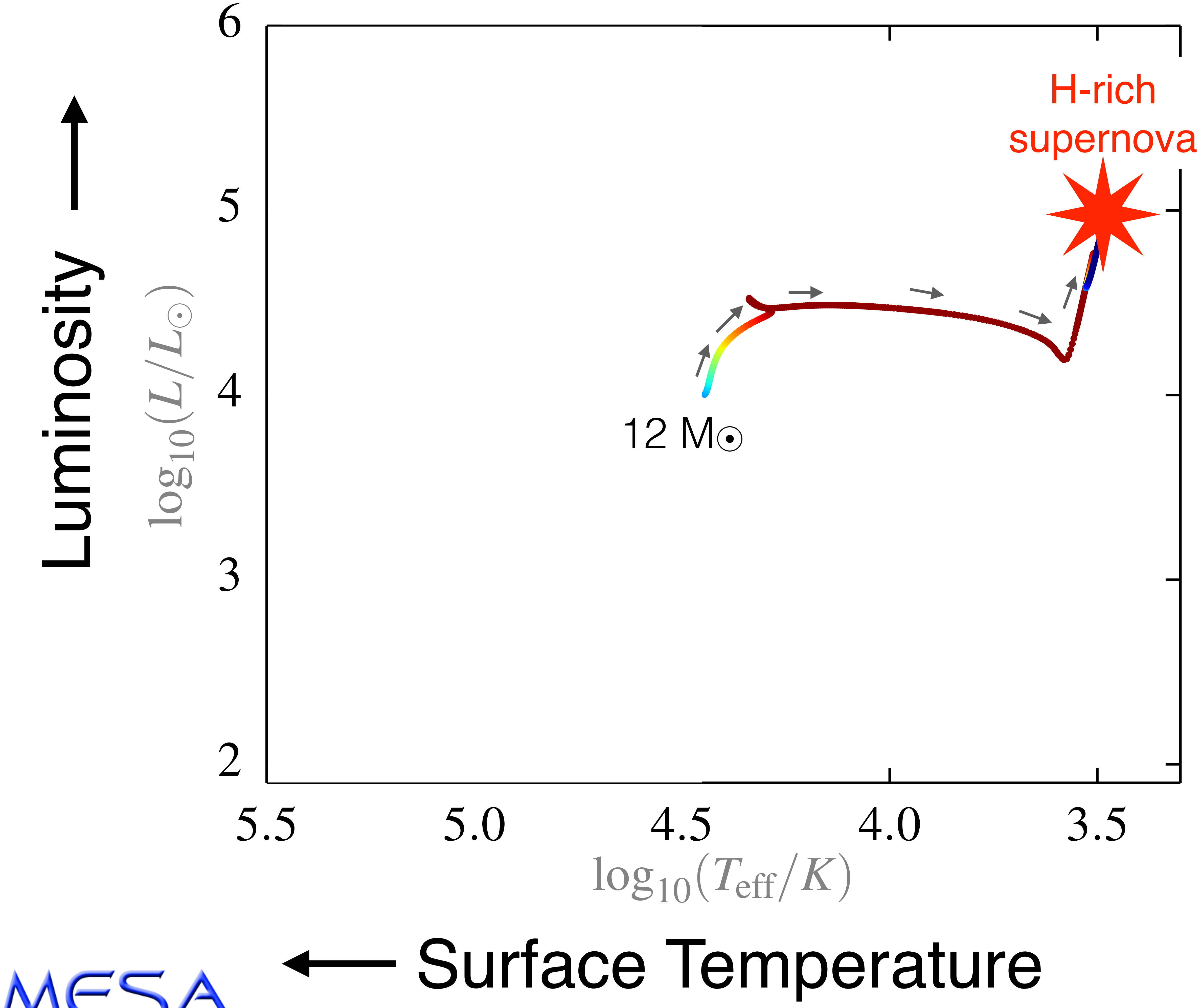

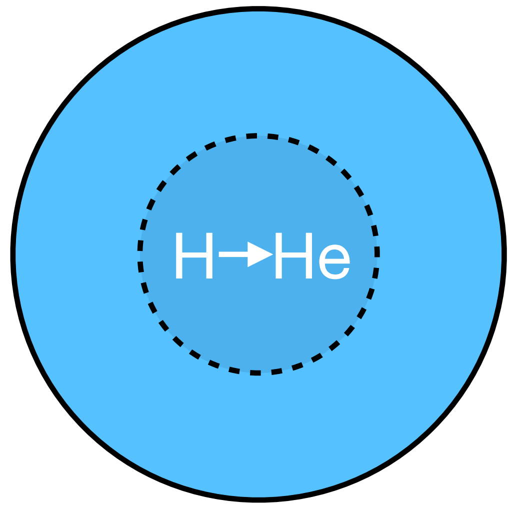

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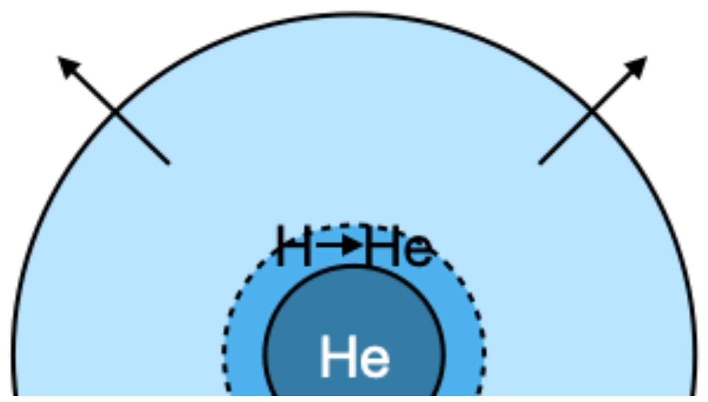

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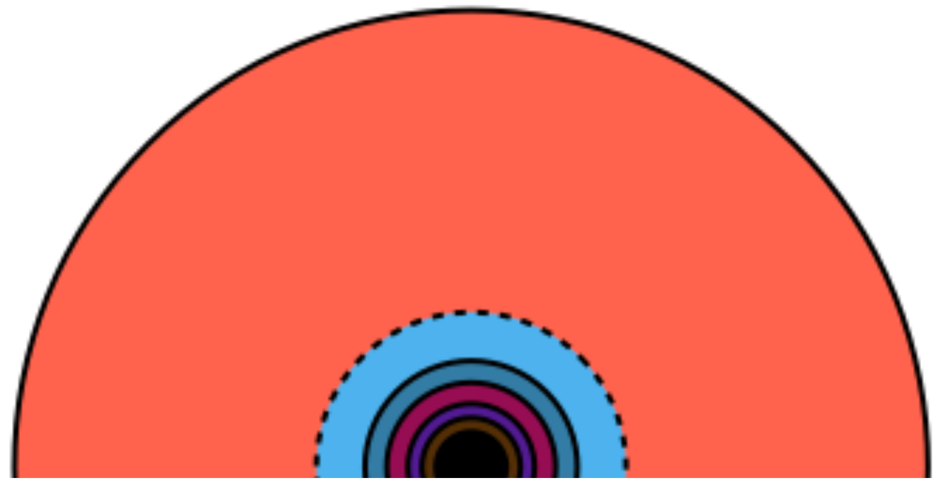

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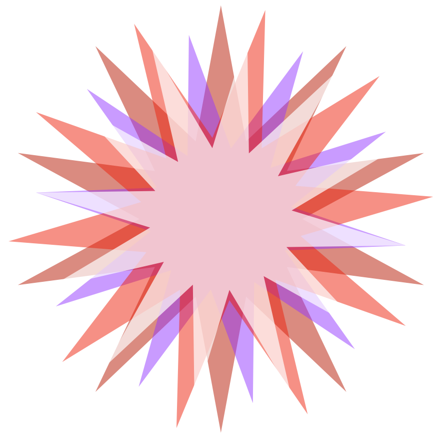

Stage 4: The core collapses, resulting in a supernova.

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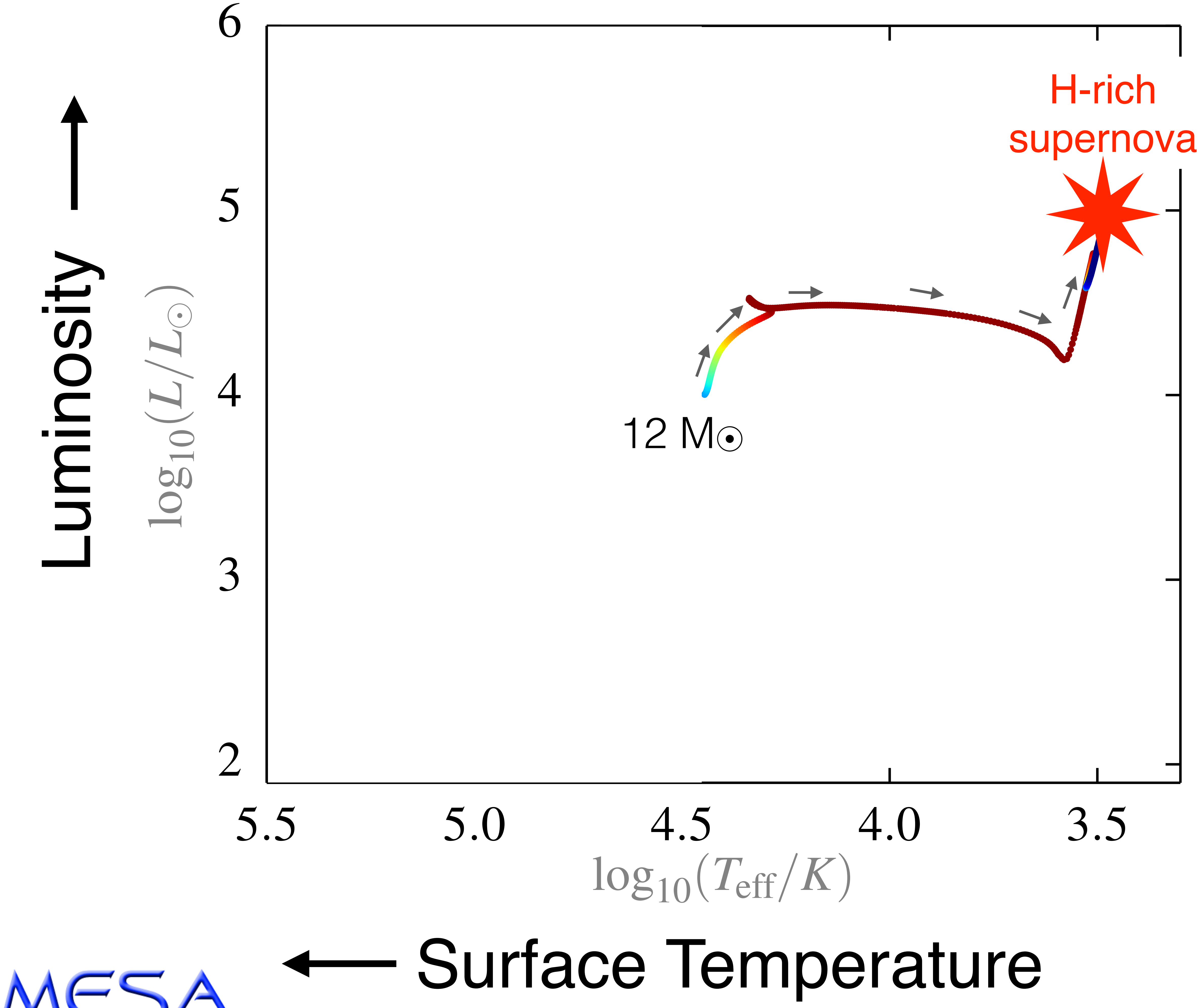

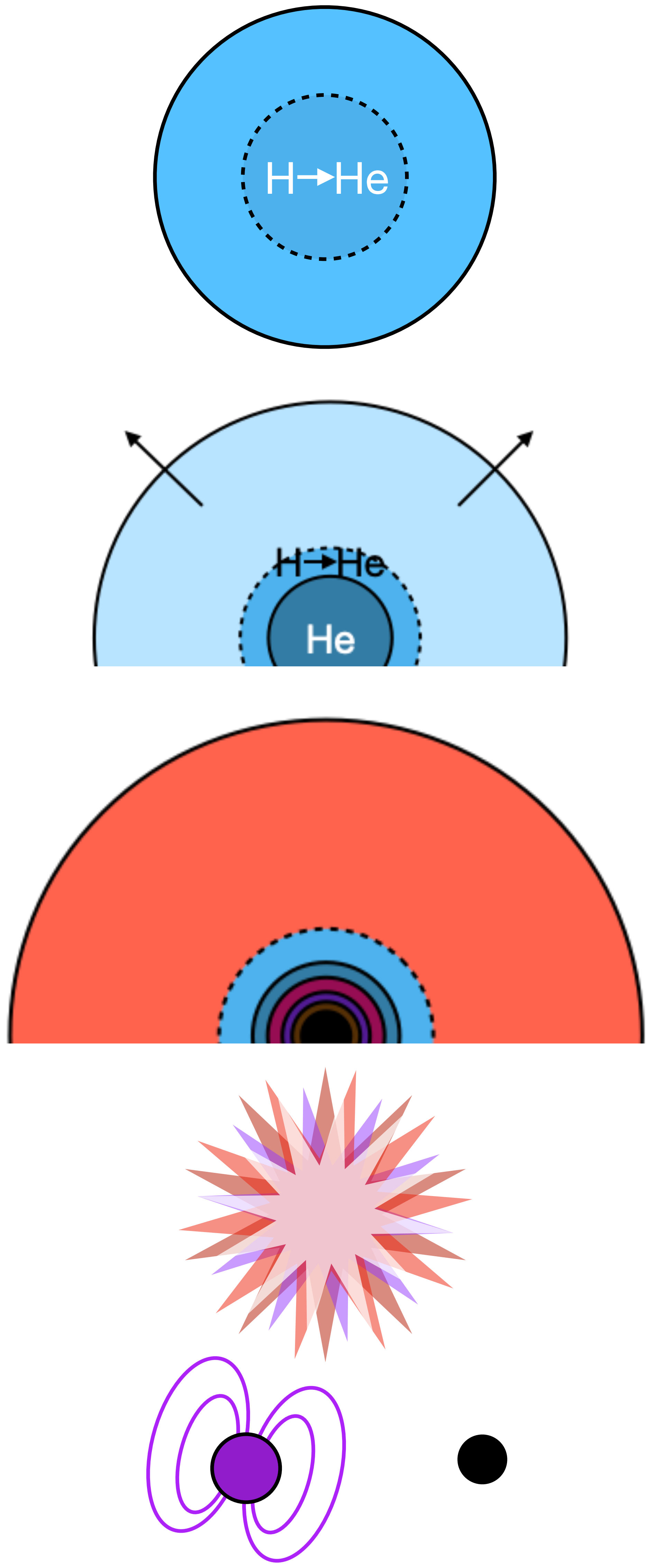

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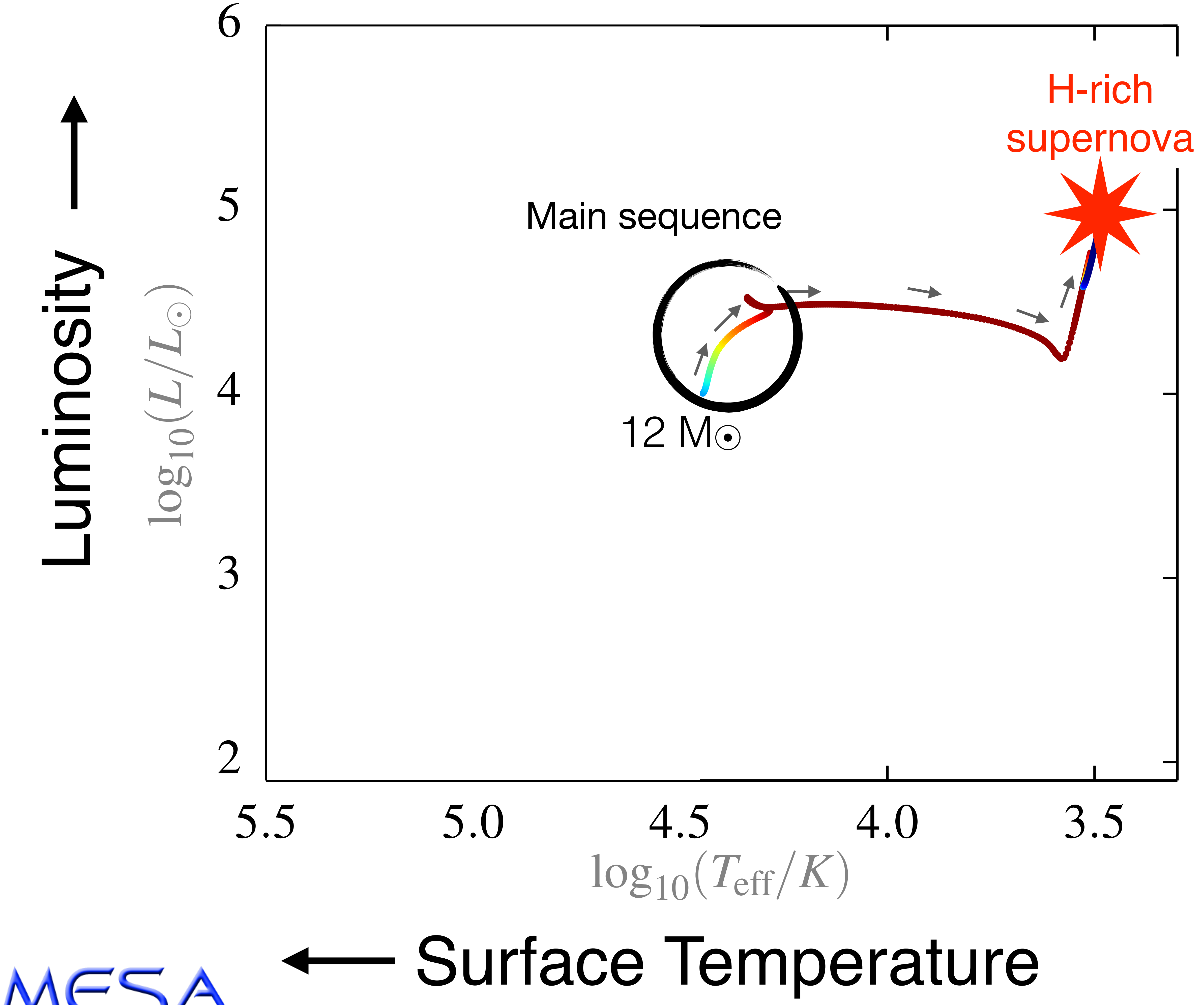
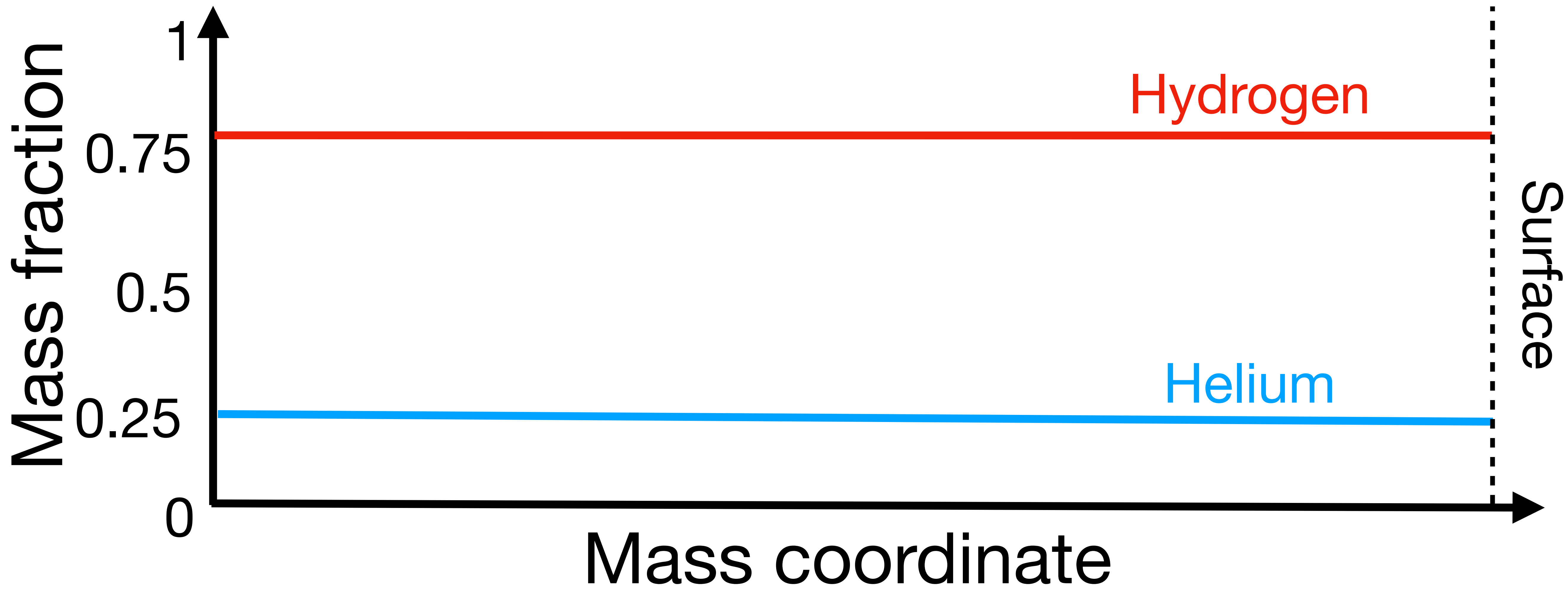
Stage 5: A neutron star or black hole is left.

Massive stellar evolution



A massive star at zero-age main-sequence:



MESA

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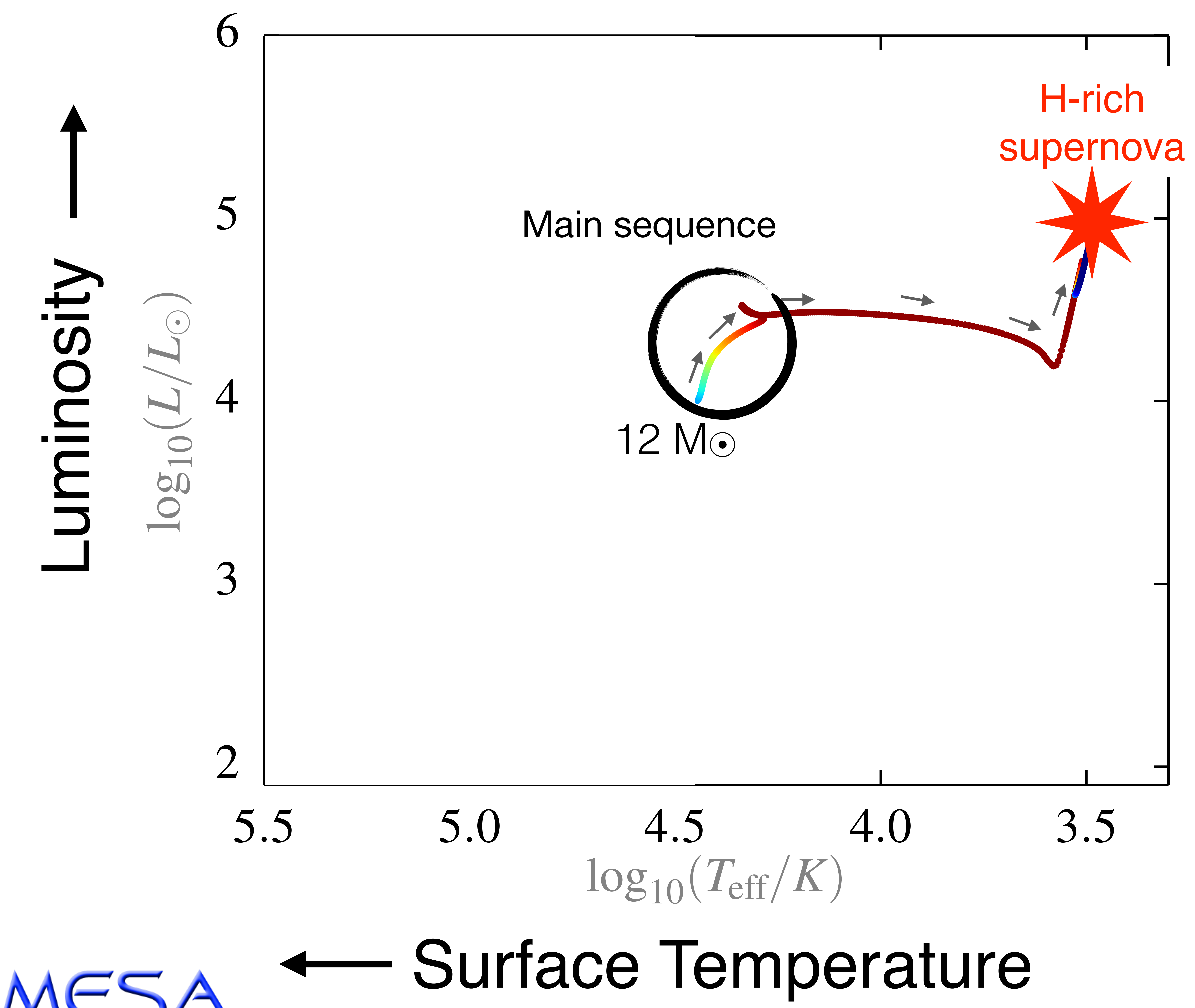

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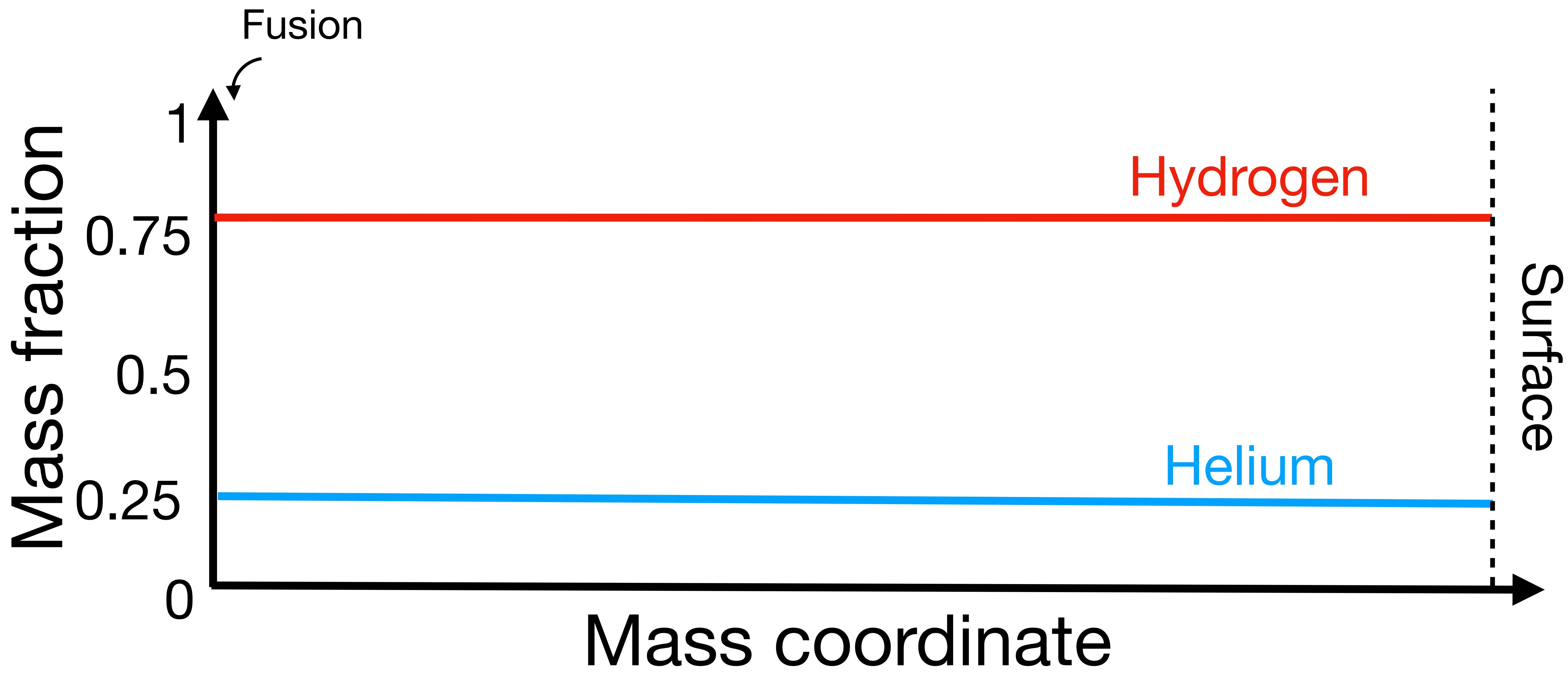

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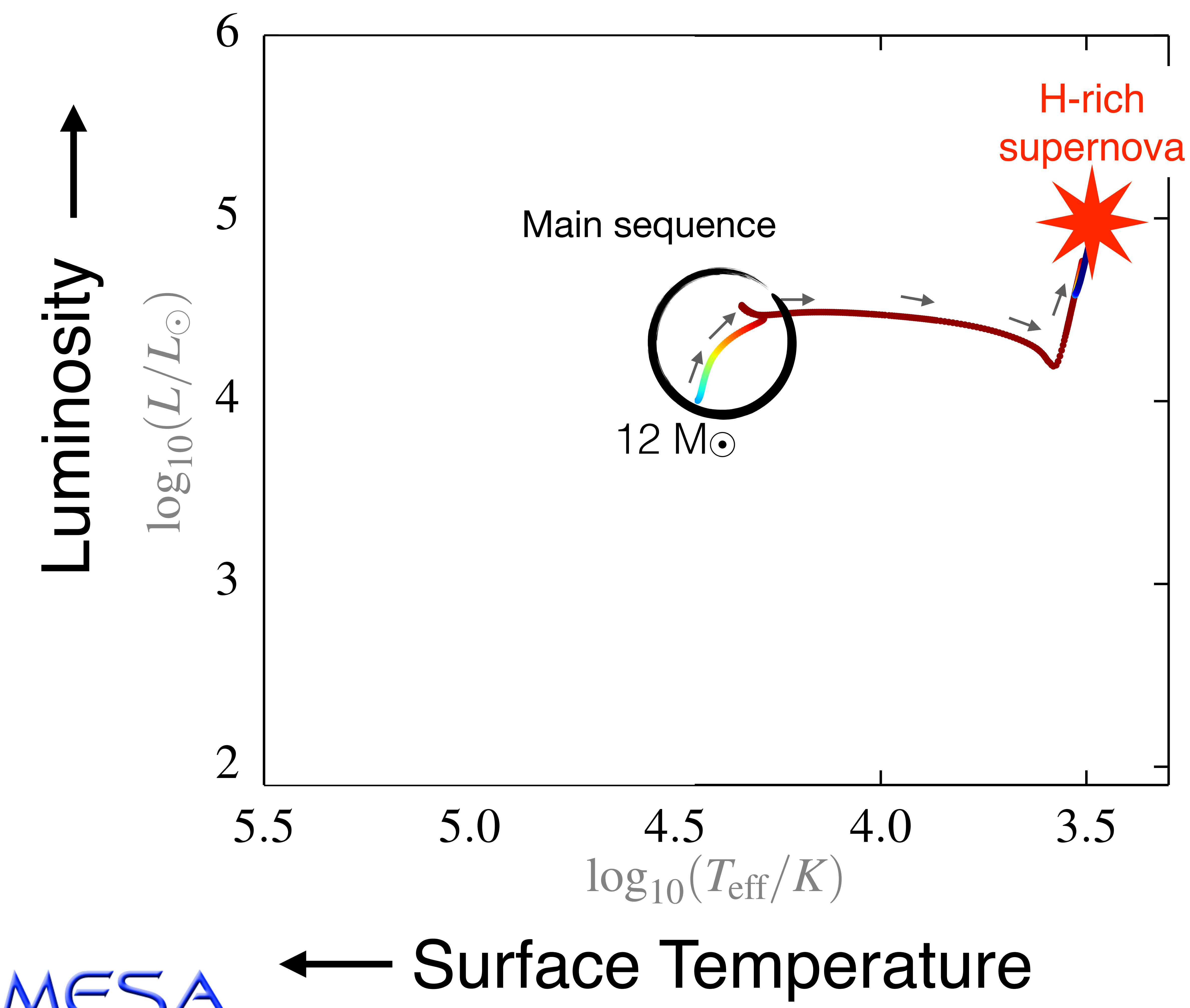

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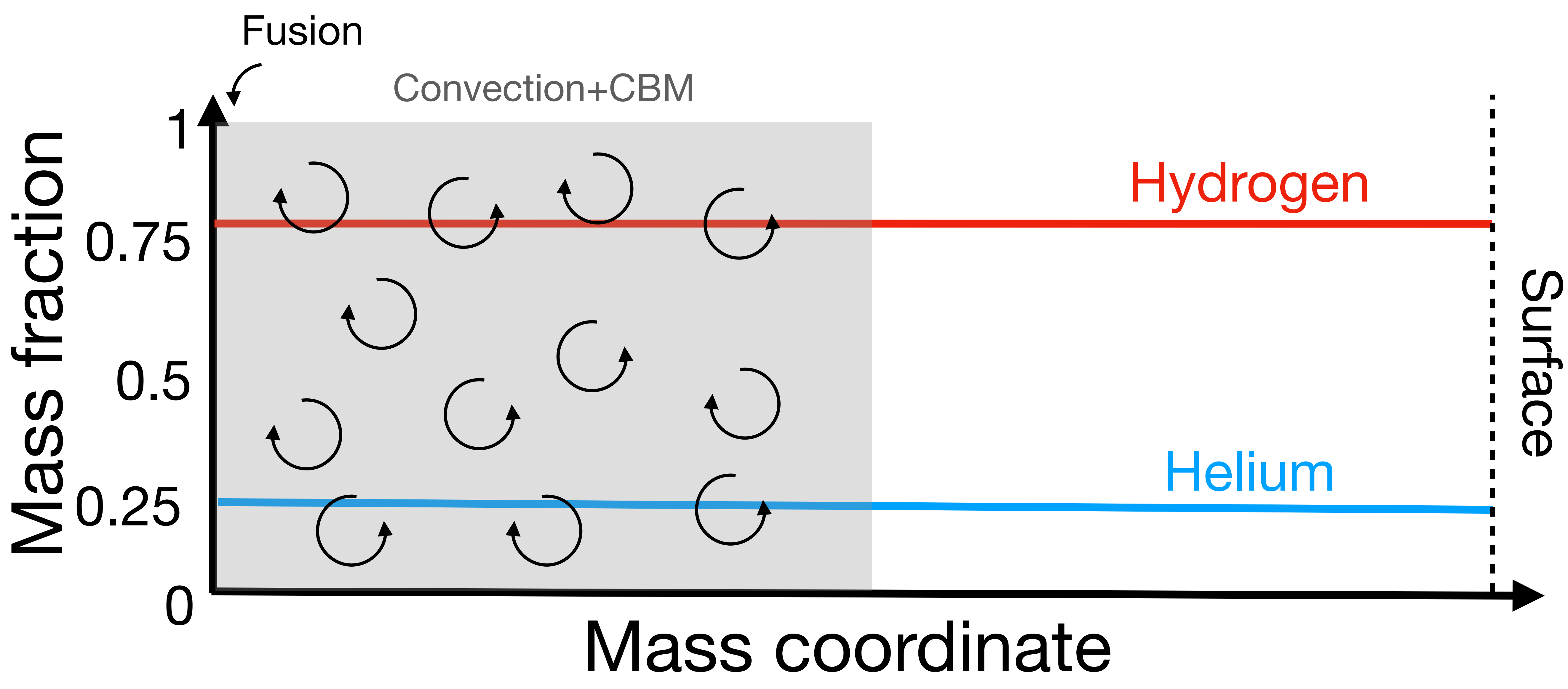

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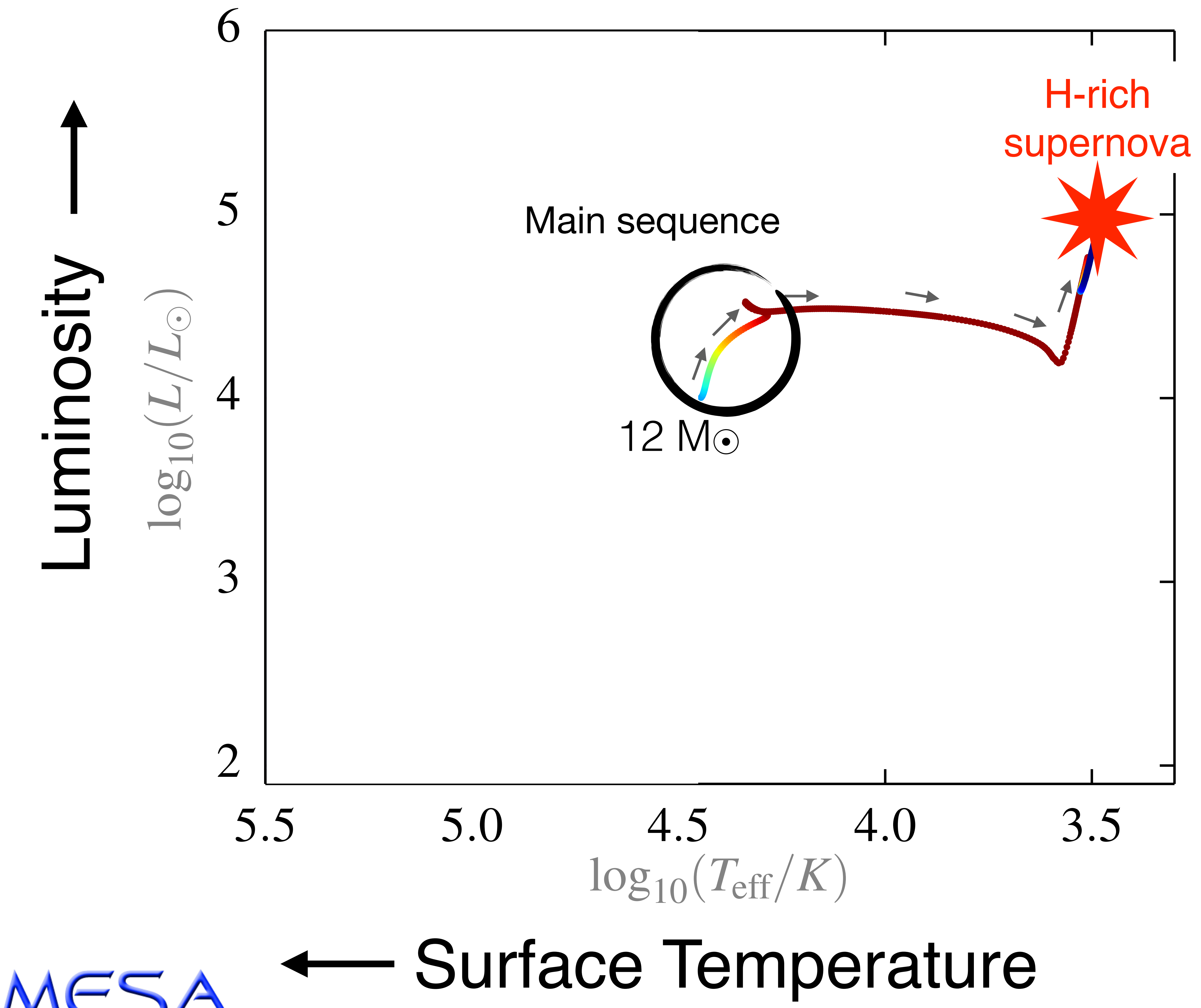

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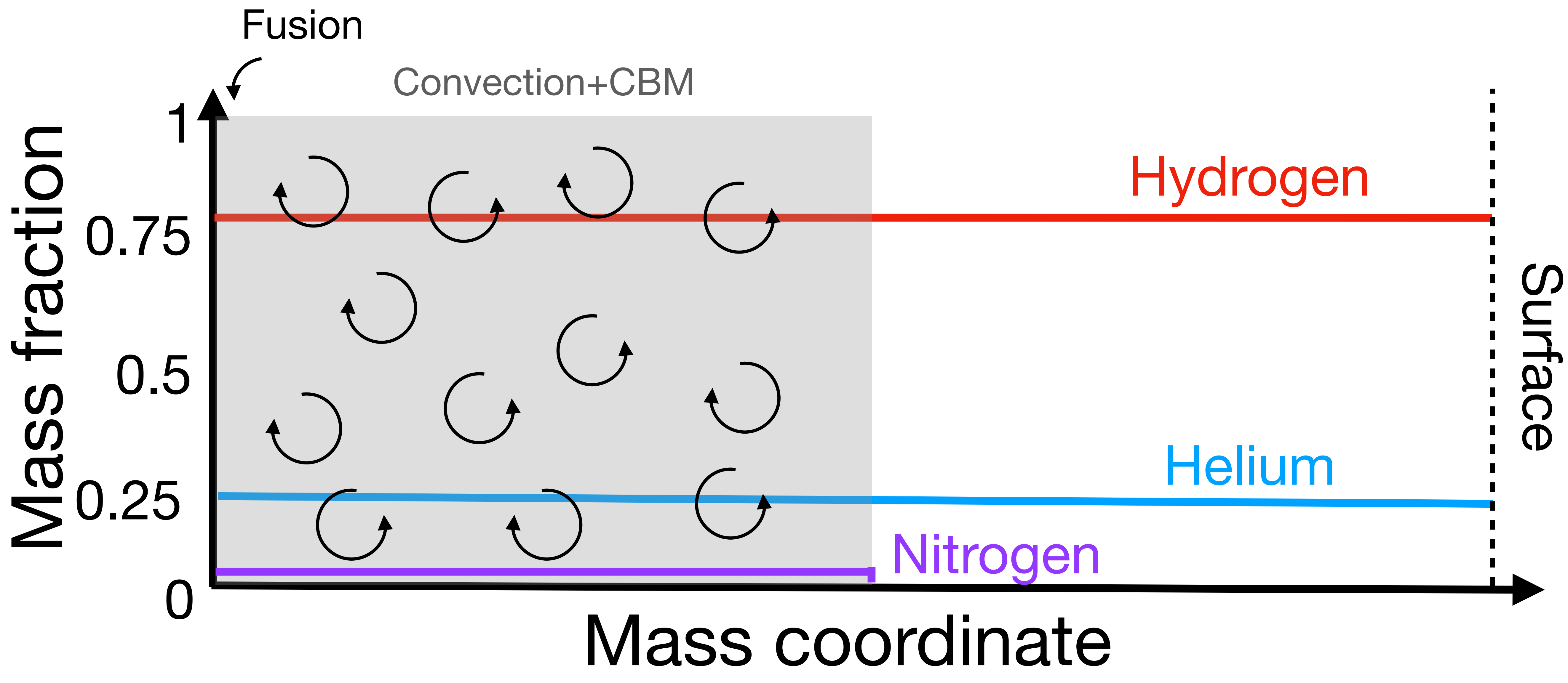

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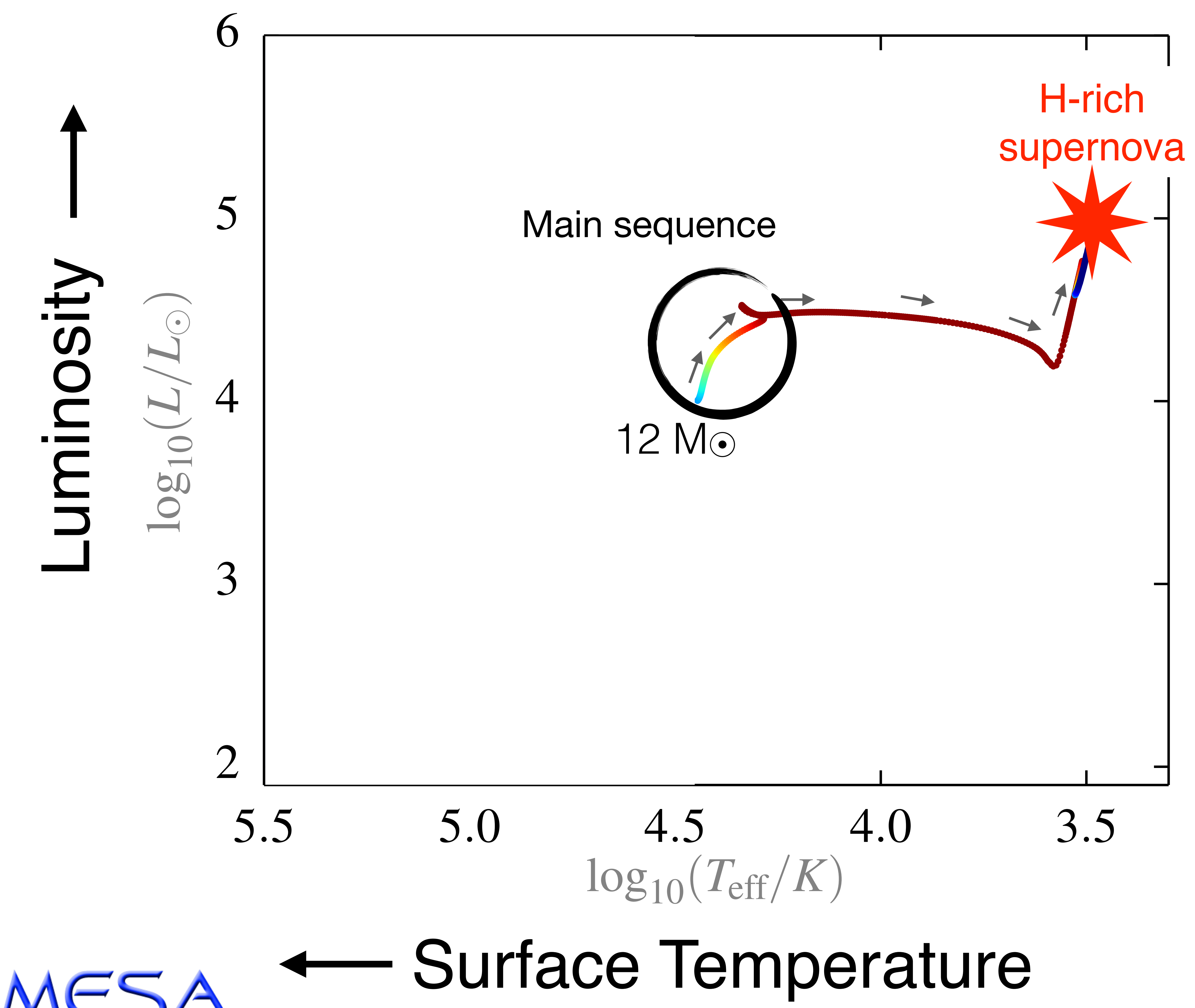

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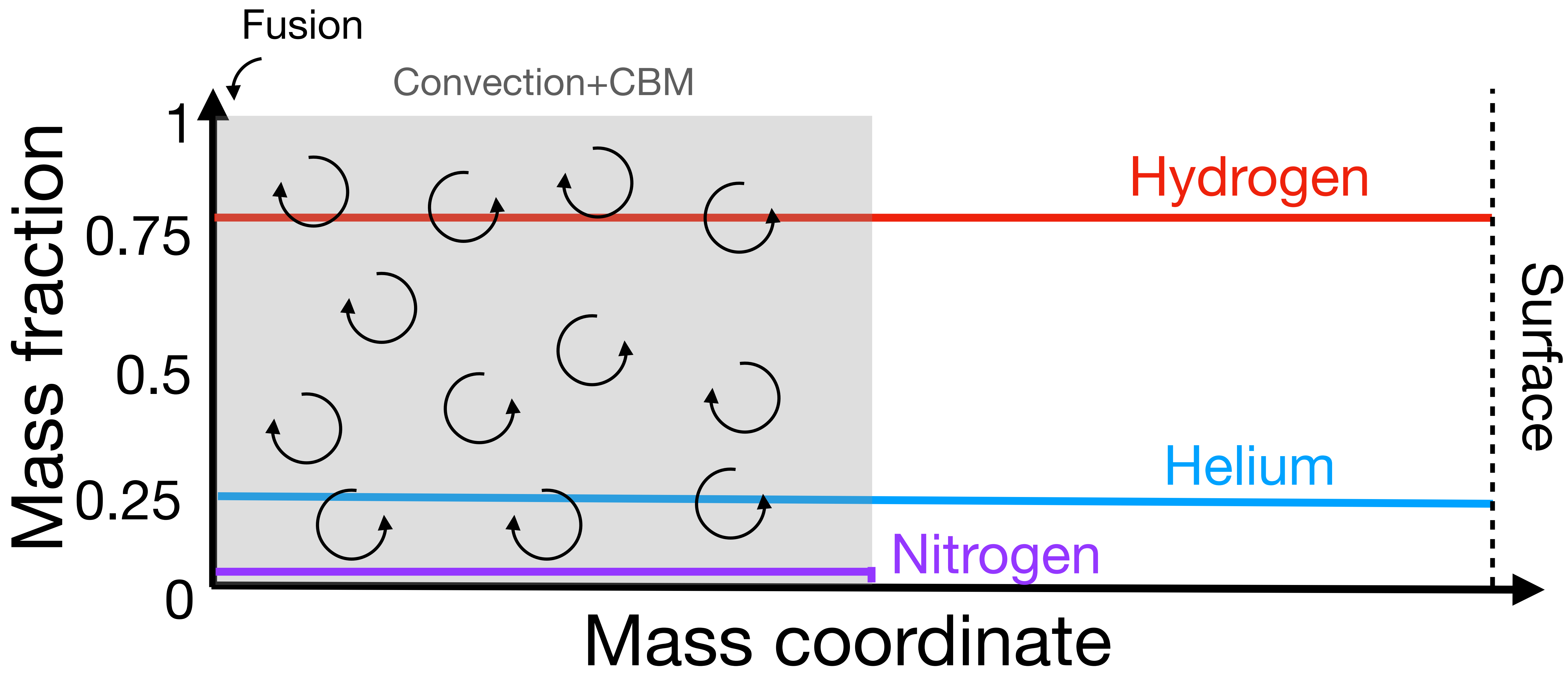
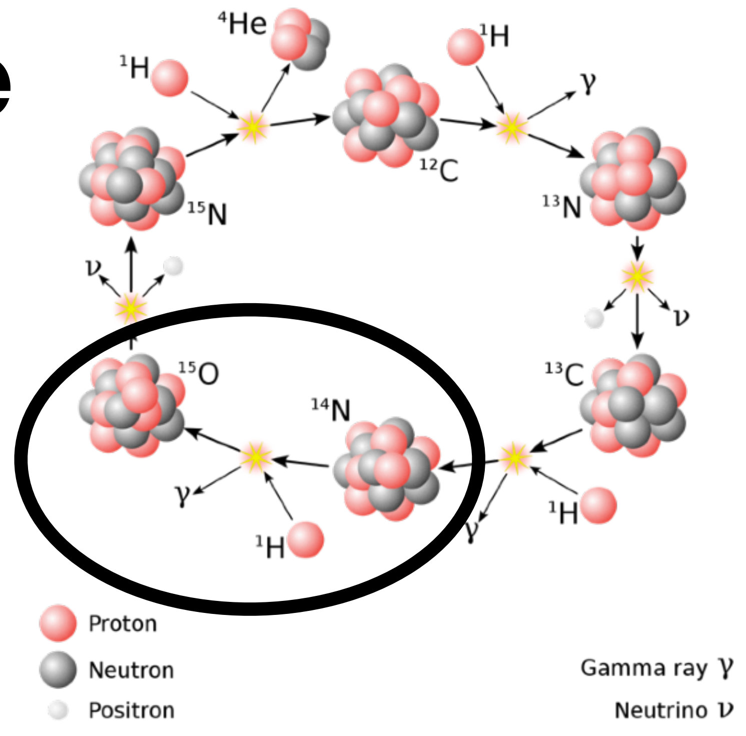


CNO cycle

Slowest reaction -> build up of nitrogen



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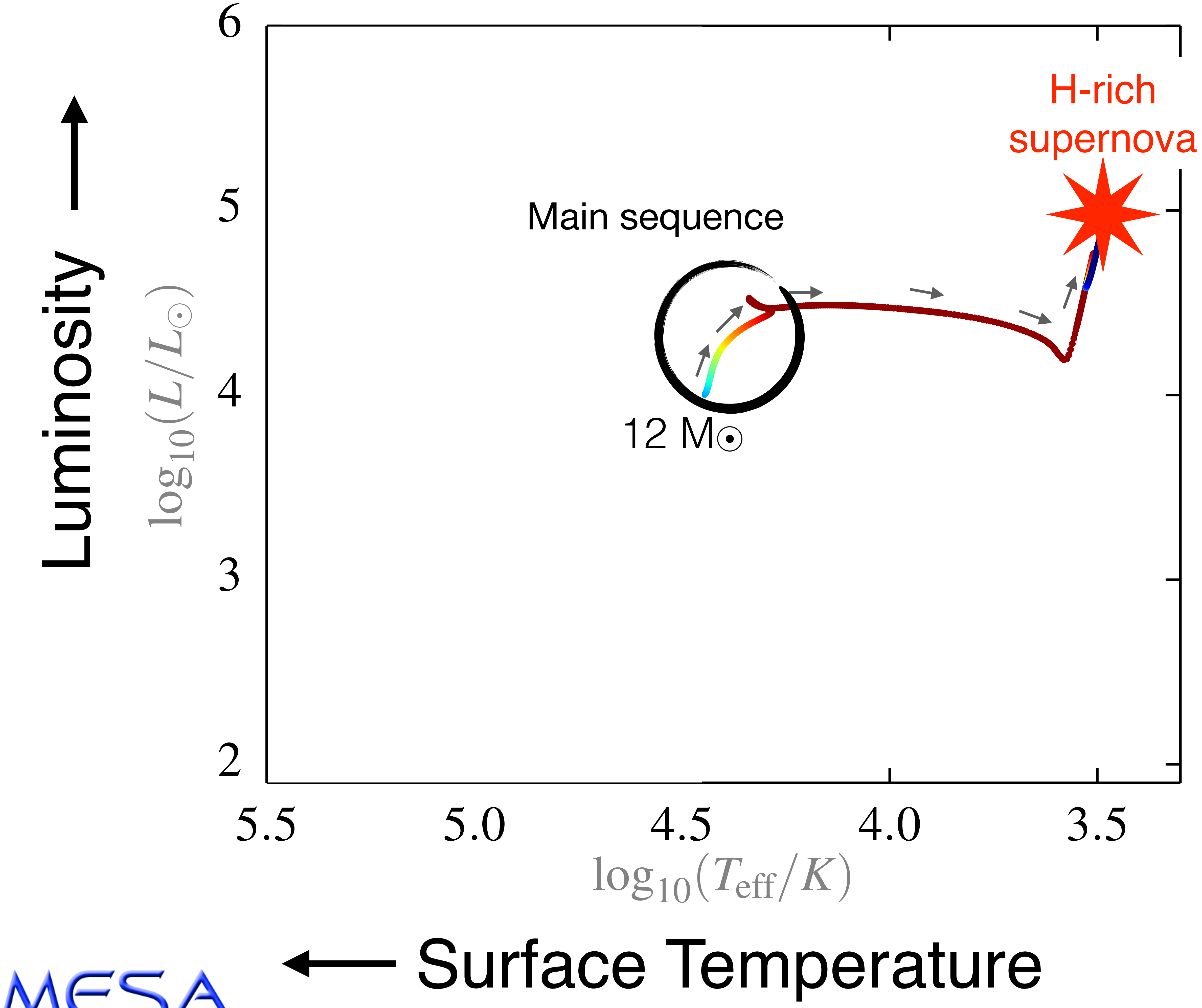
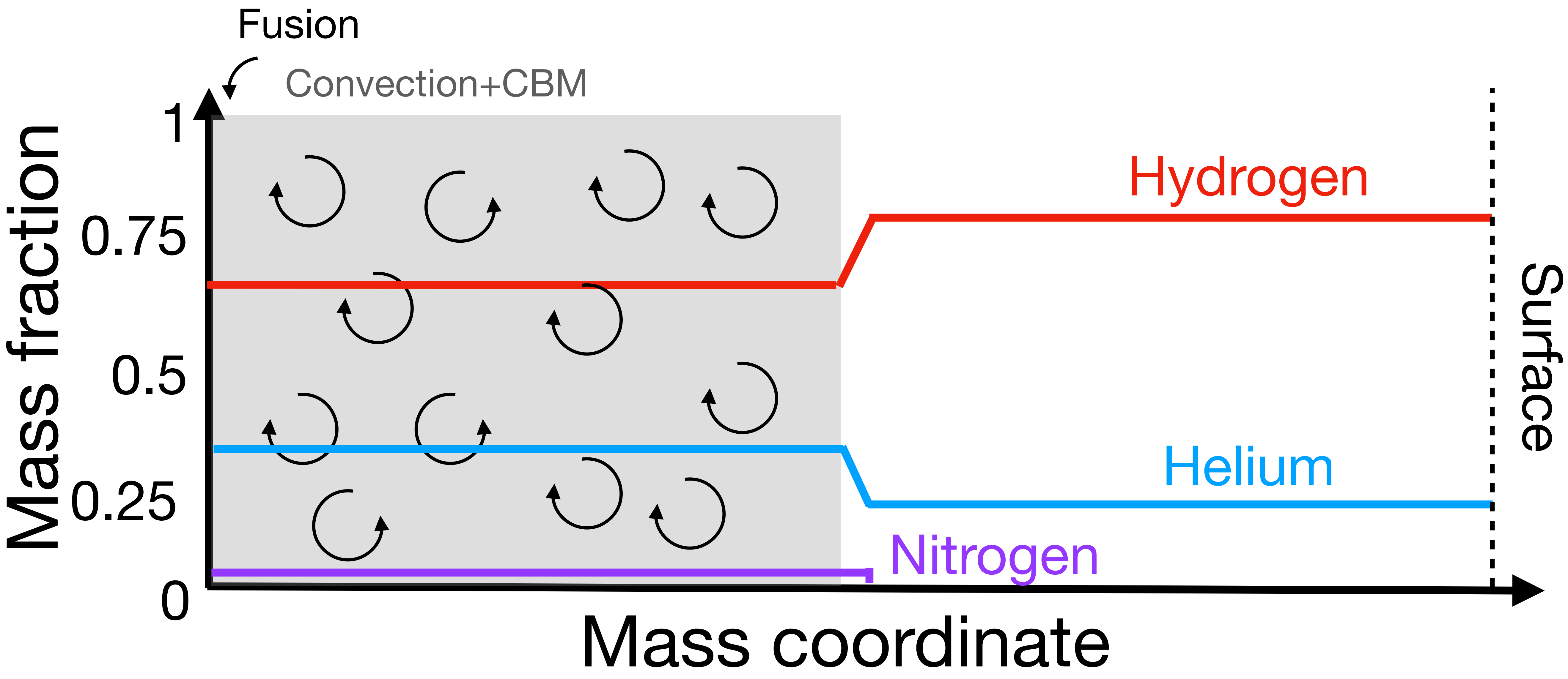


A massive star during main-sequence:



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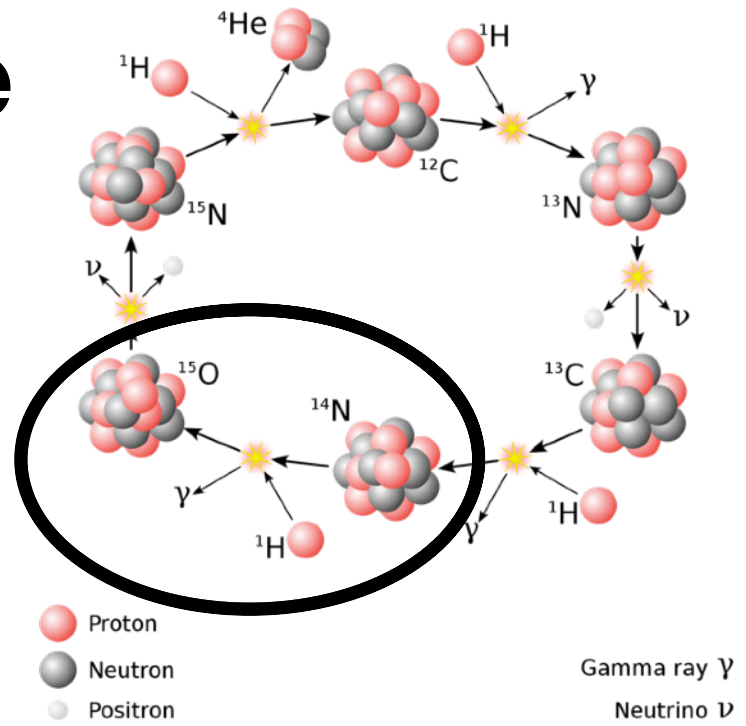

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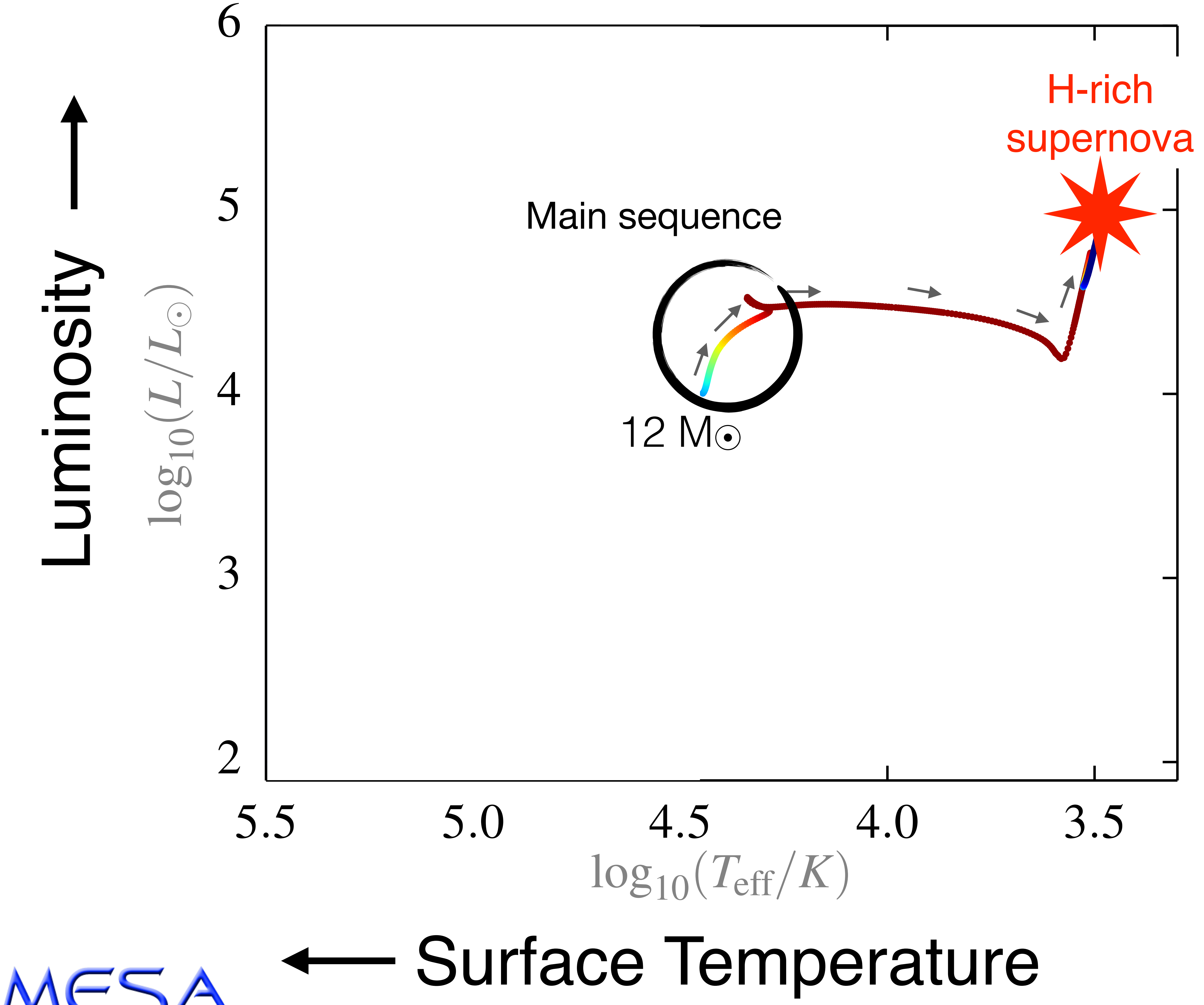
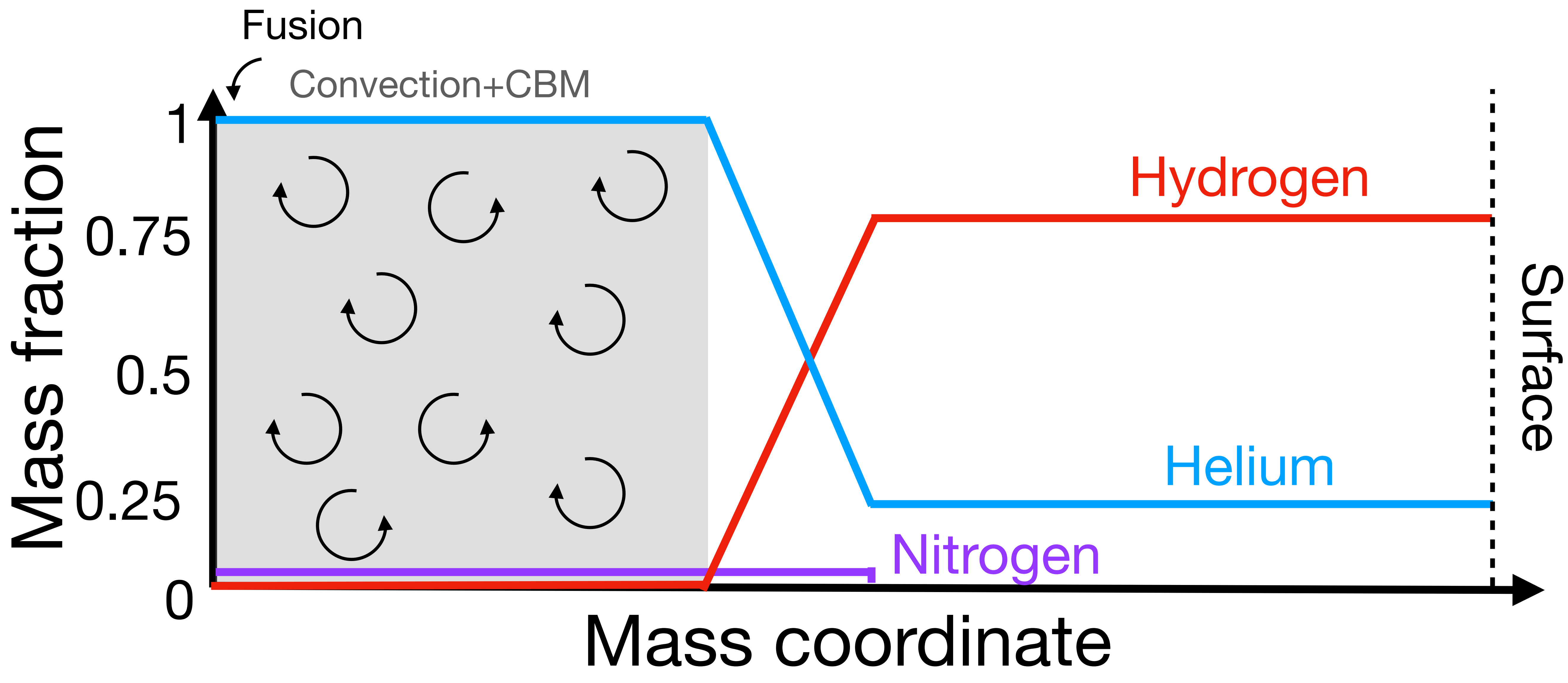


MESA

A massive star at terminal-age main-sequence:



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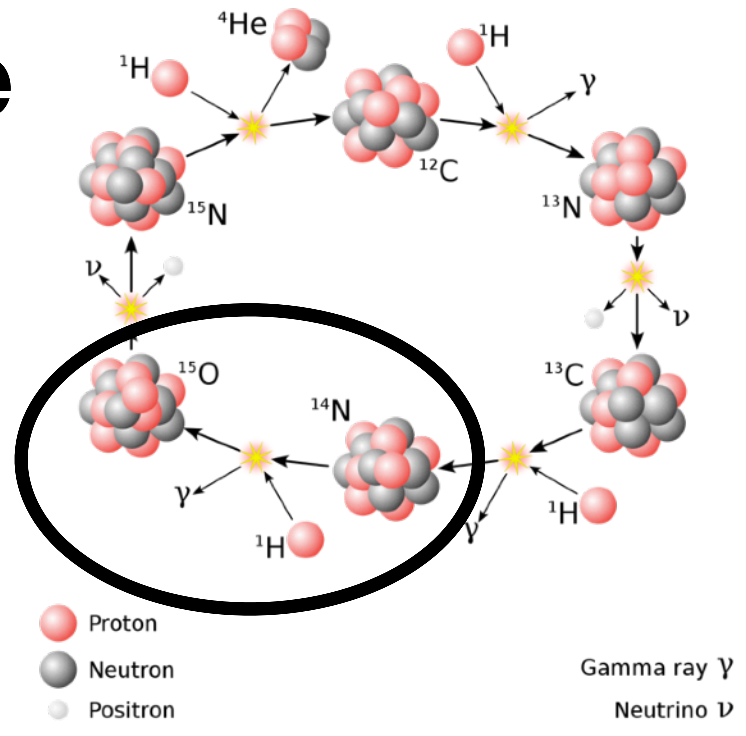
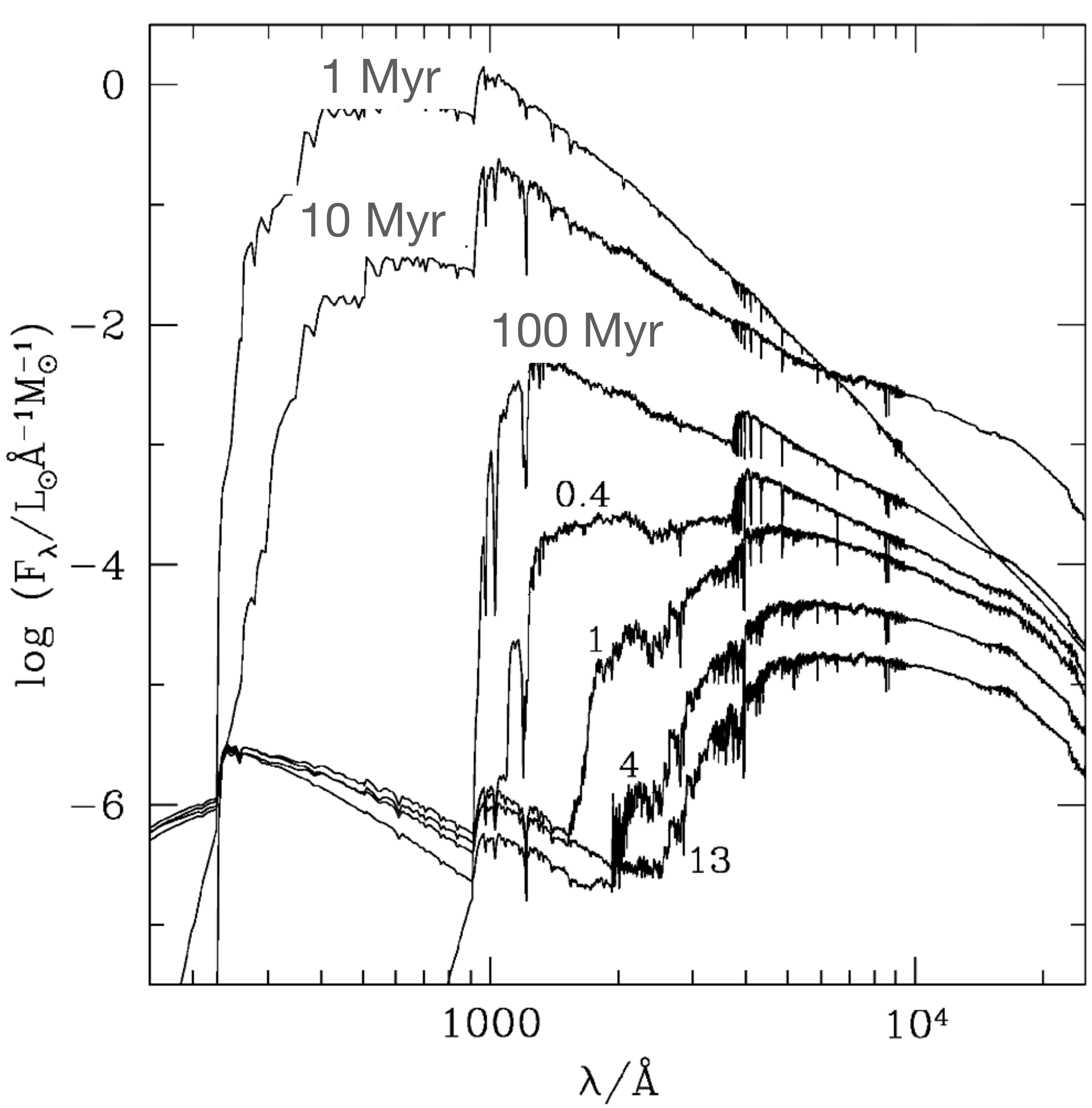


1) Stars that ionize

Massive single stars

The well-known ionizing stars: OB and WR stars

Most of the ionizing radiation is created by hot, massive, OB and Wolf-Rayet stars. This is well produced in spectral population synthesis models



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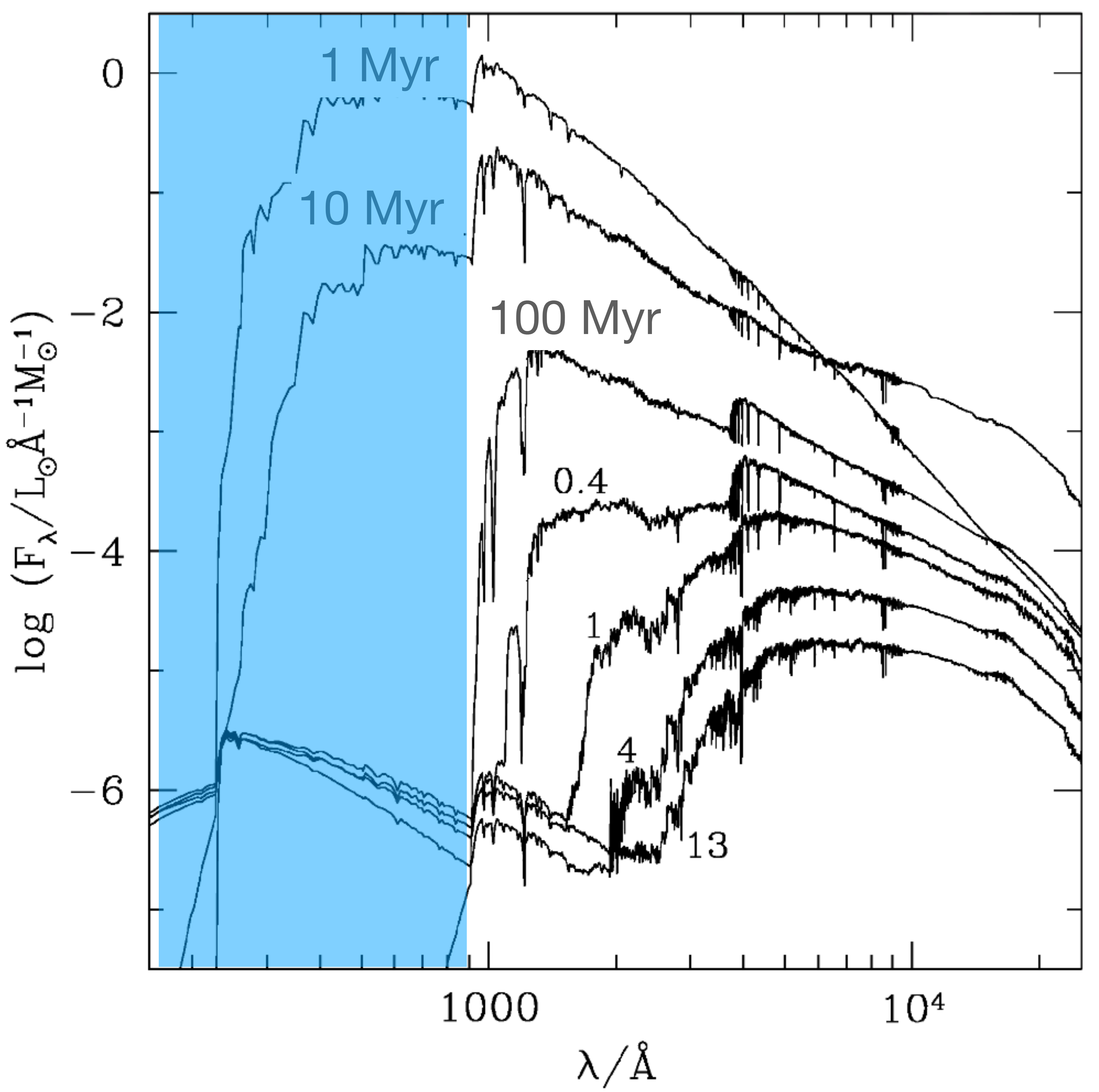
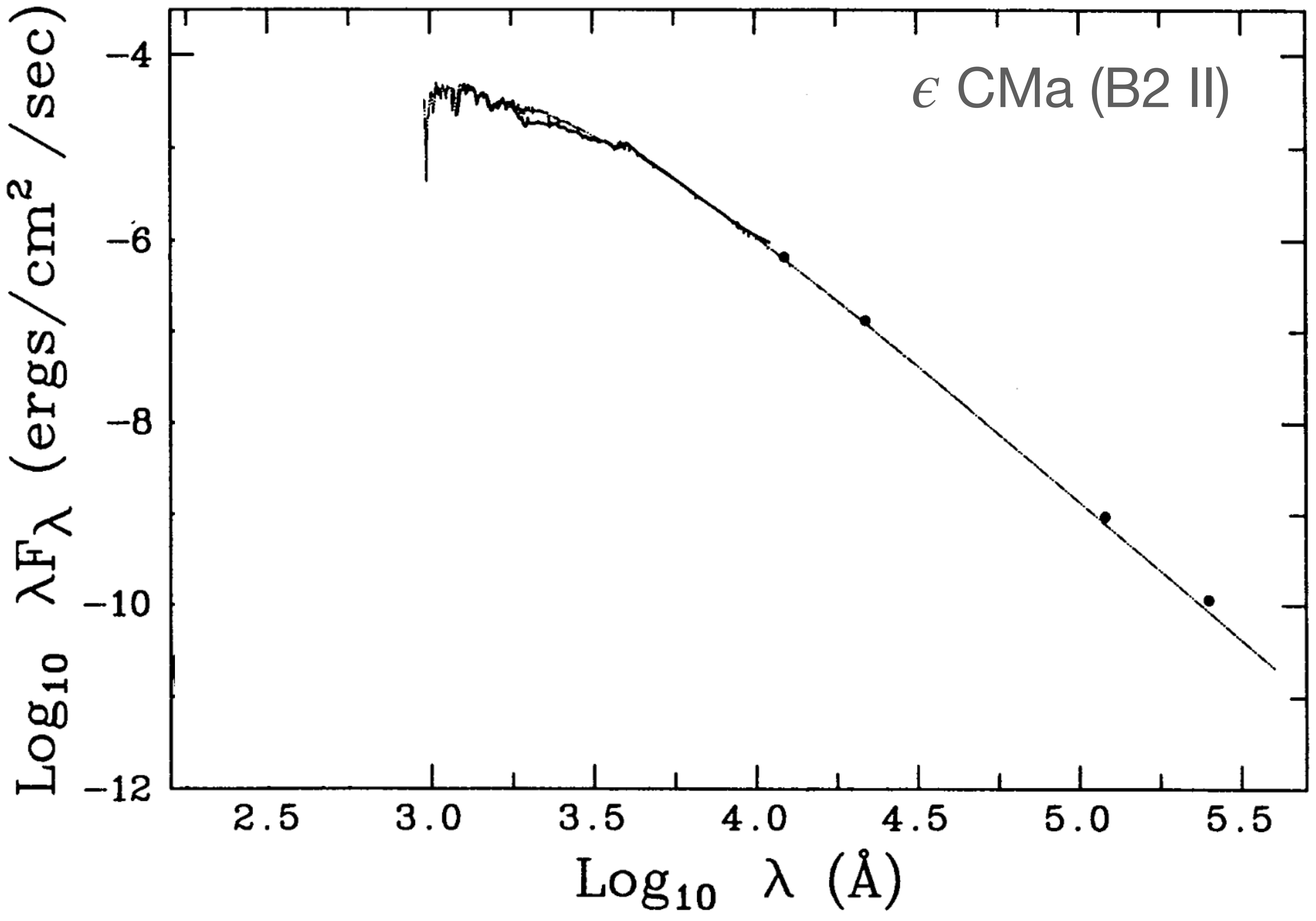


Extremely scarce direct measurements in the EUV

Only two massive stars have direct detections of ionizing radiation. This was observed by the Extreme Ultraviolet Explorer (EUVE) through a tunnel largely free from gas.
Cassinelli et al. (1995, 1996)



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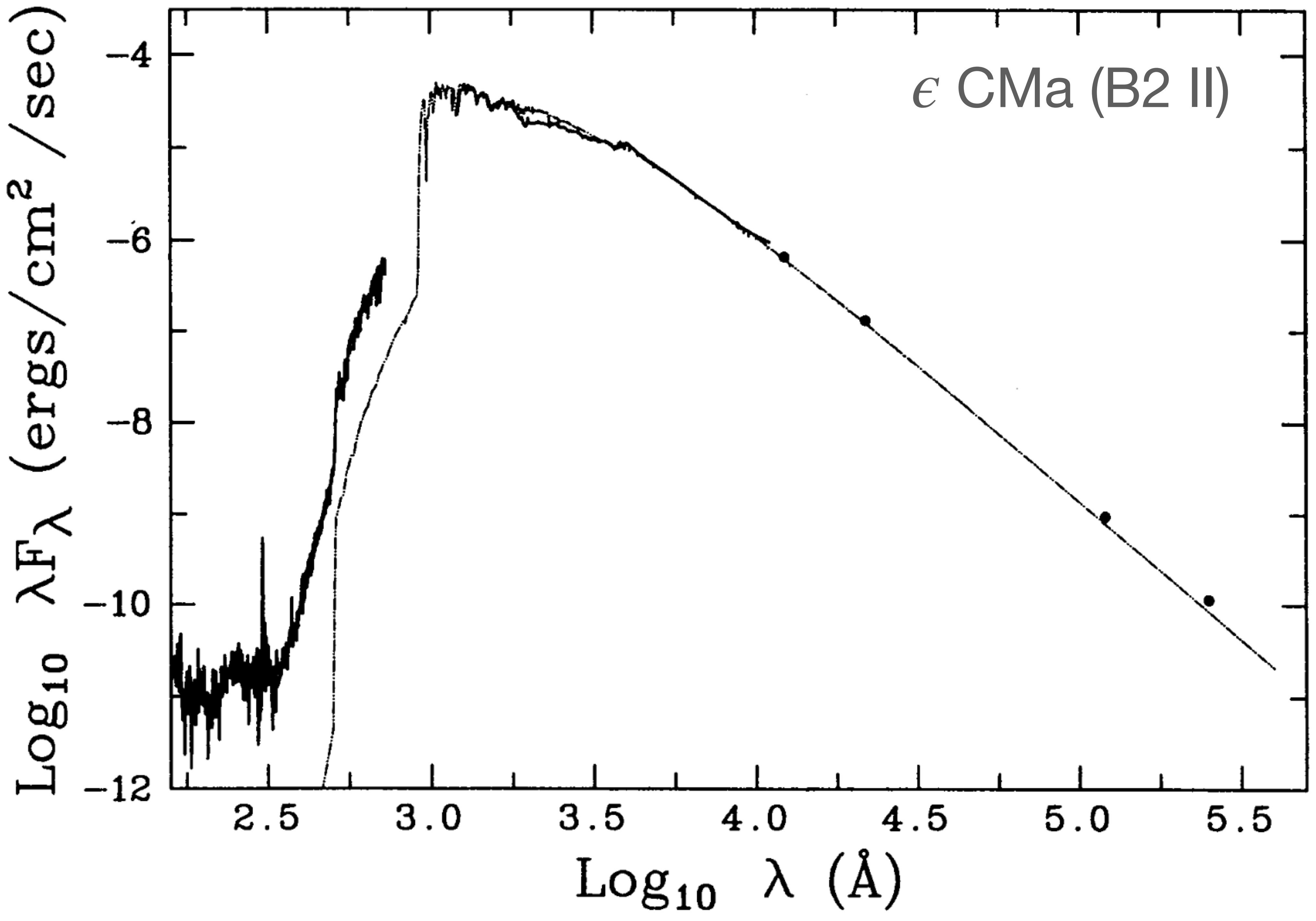

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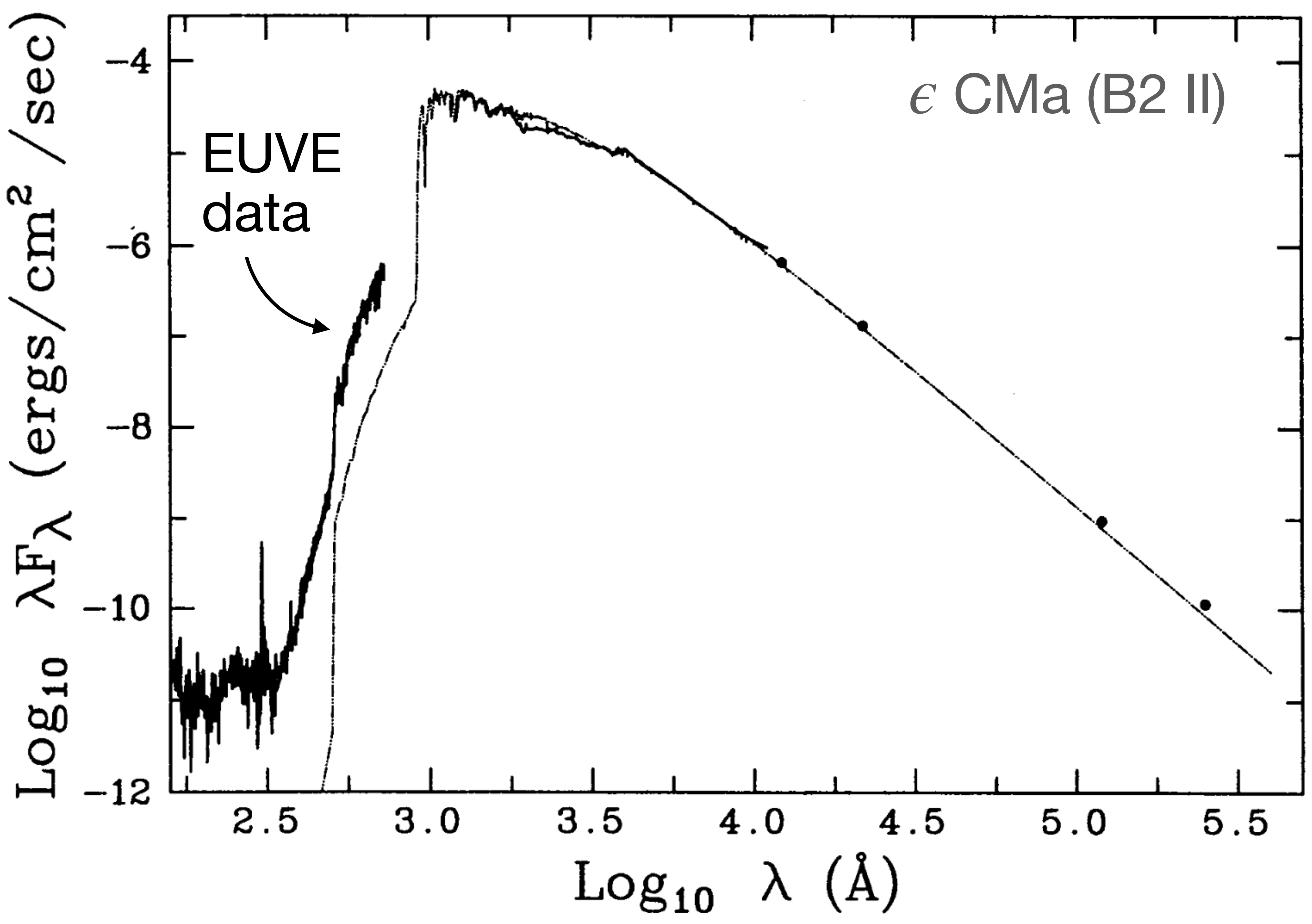

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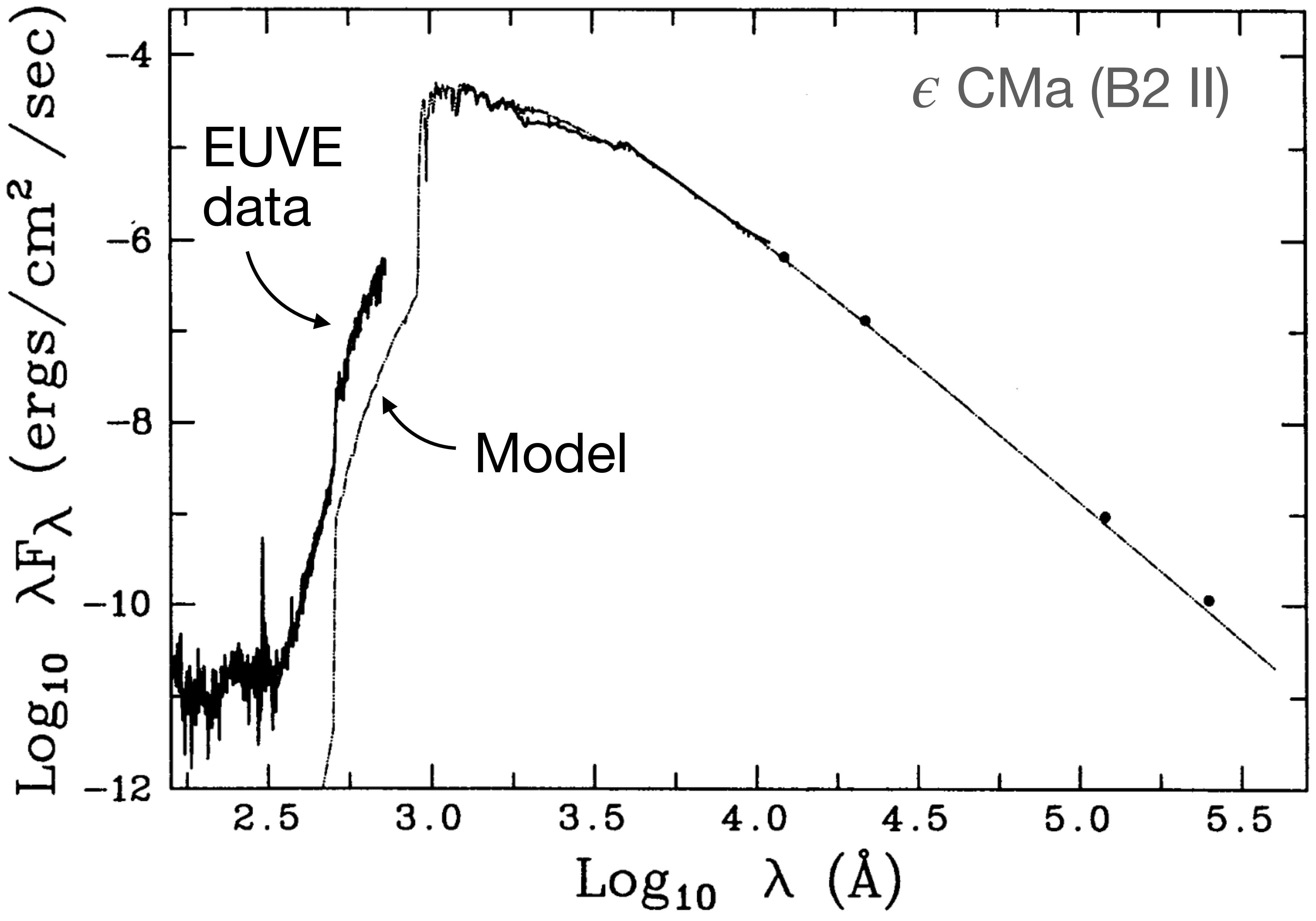

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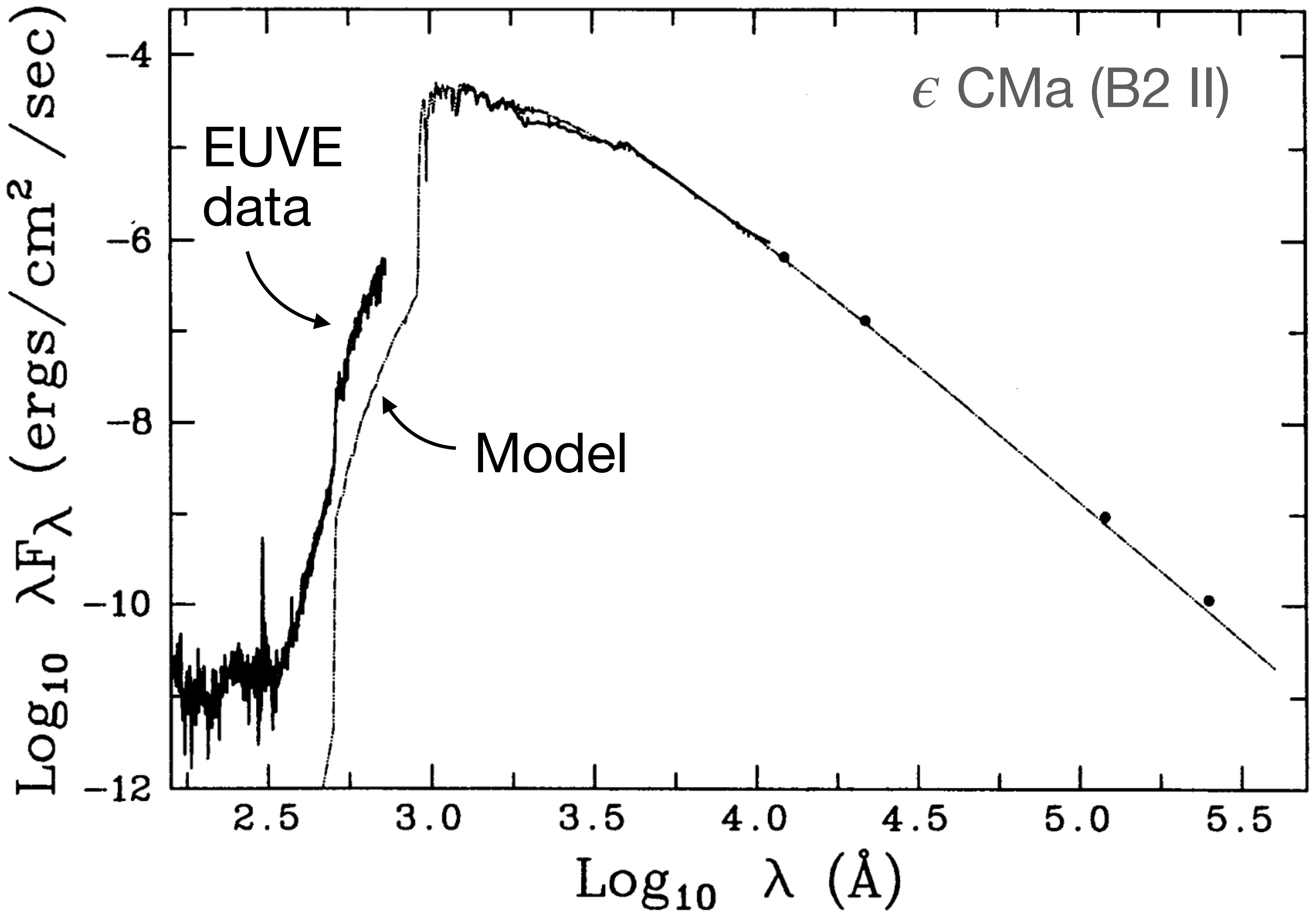

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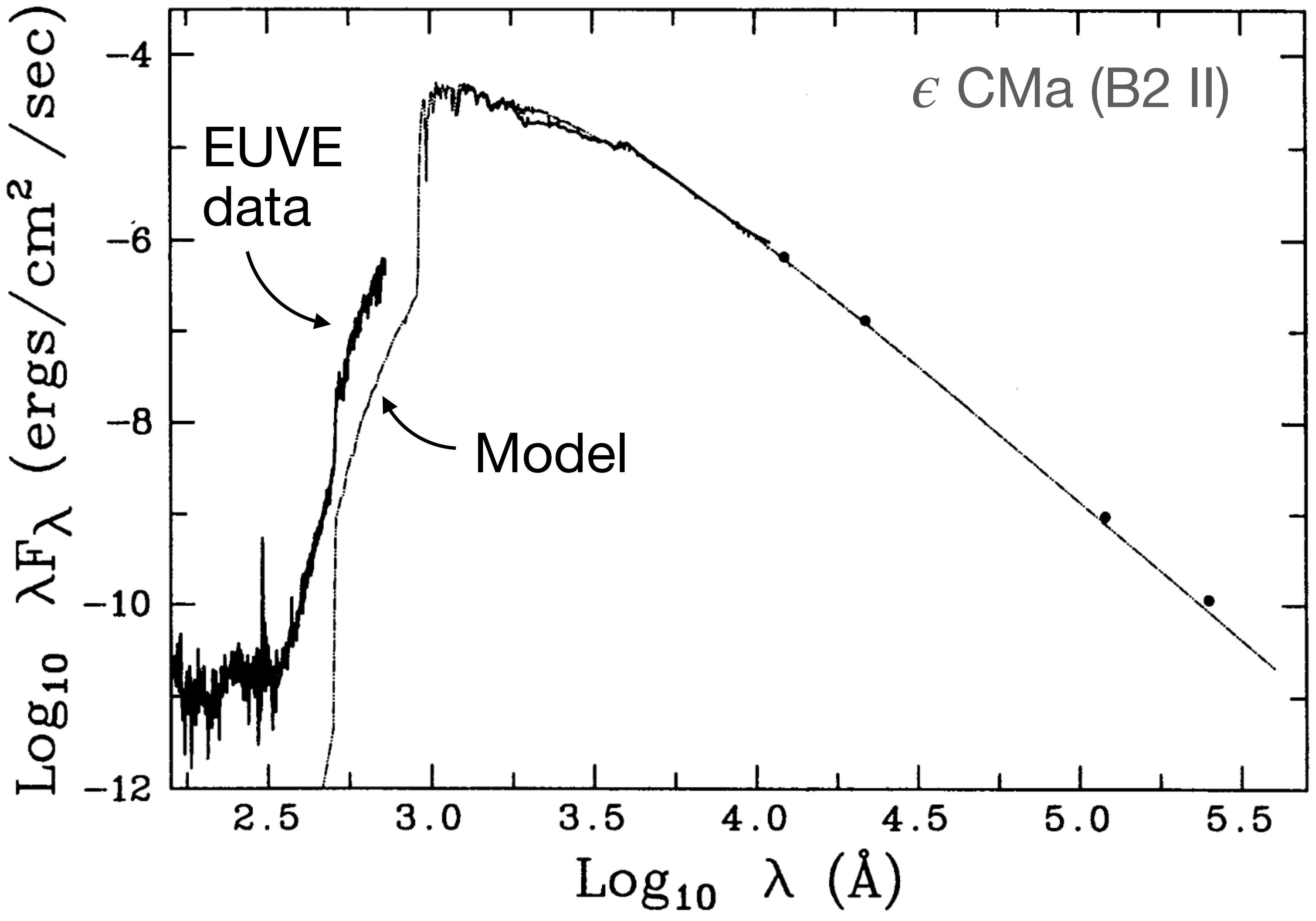

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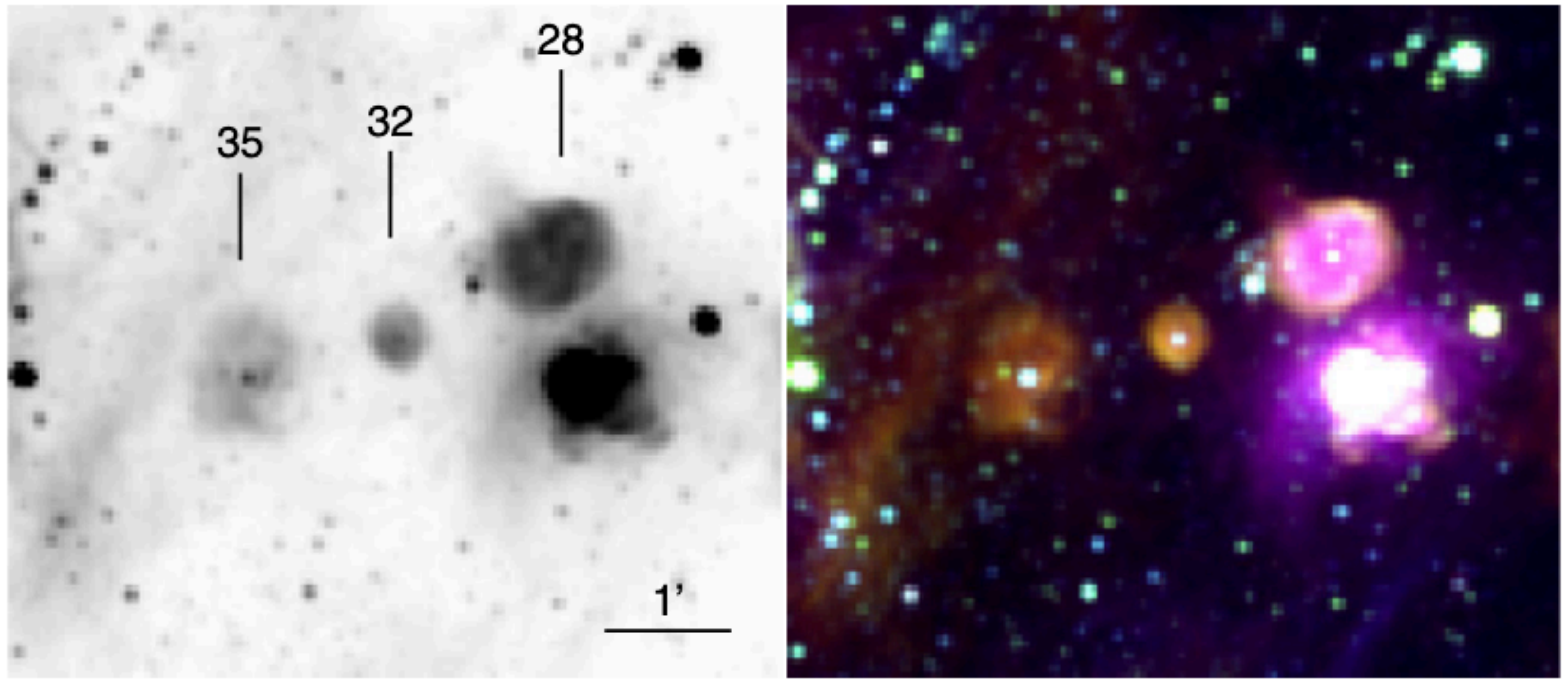
→ Observational constraints that help guide stellar atmosphere codes are almost non-existent. As a result, the ionizing emission from stars remains uncertain.

See also Shull et al. (2024)

Indications from indirect methods

Observations of Strömgren spheres exist - here is an example from Zastrow et al. (2013) as part of the Magellanic Cloud Emission Line Survey (MCELS).



(a) MCELS L 28, MCELS L 32, MCELS L 35

The figure shows three bubbles shining in Hα (left) and a color image (right) of Hα (red), [OIII] λ5007 (blue), [SII] λ6720 (green). Each bubble hosts a central massive star (O5.5 - 28, B0 - 32 & 35).

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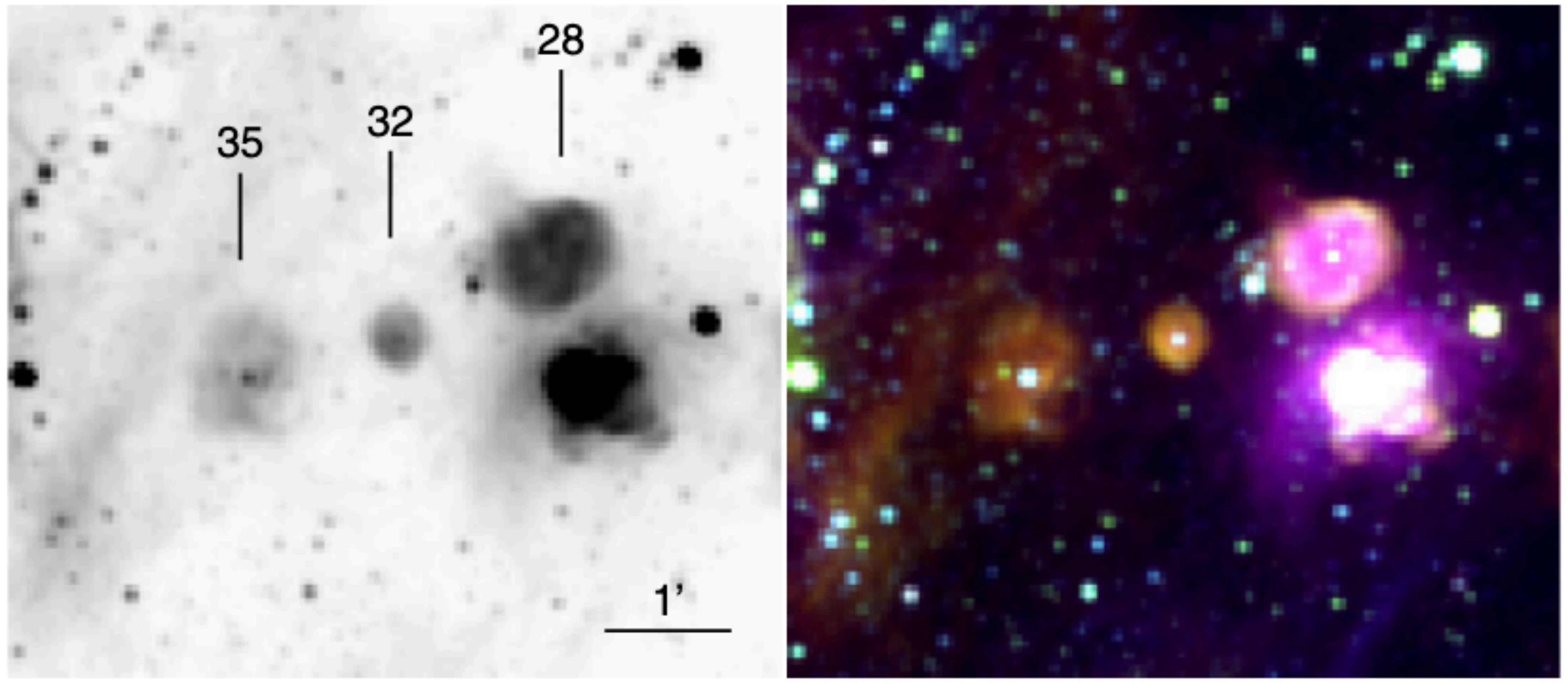

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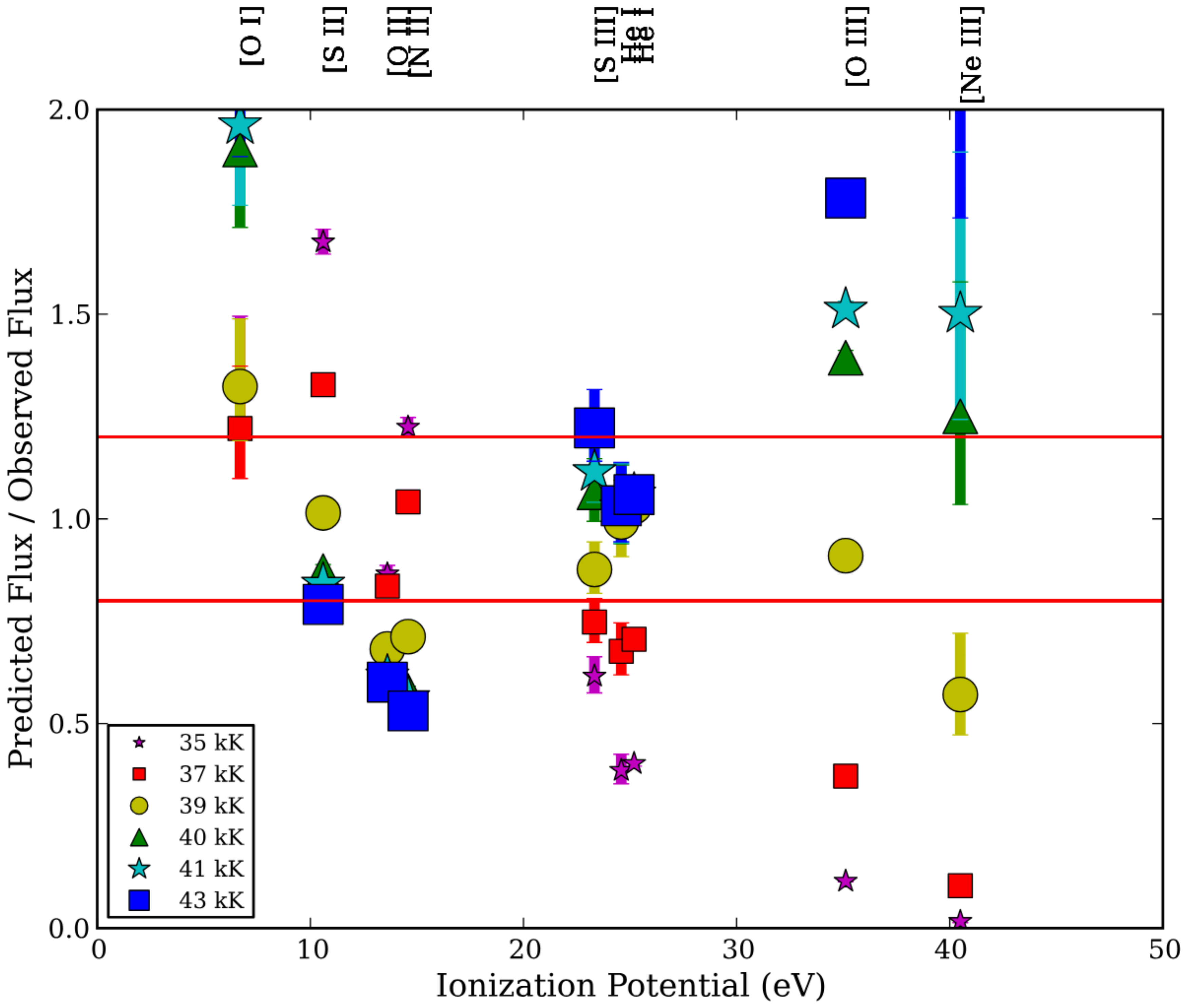

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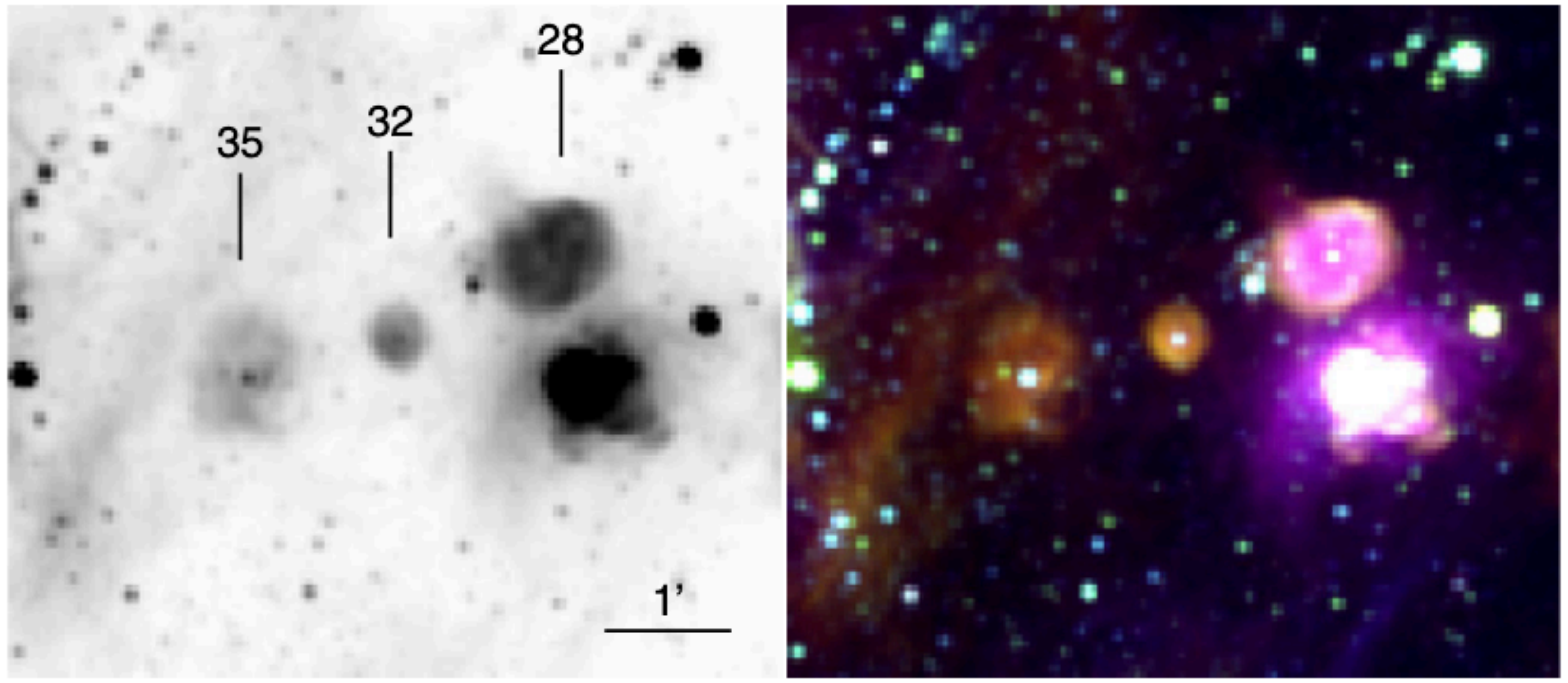

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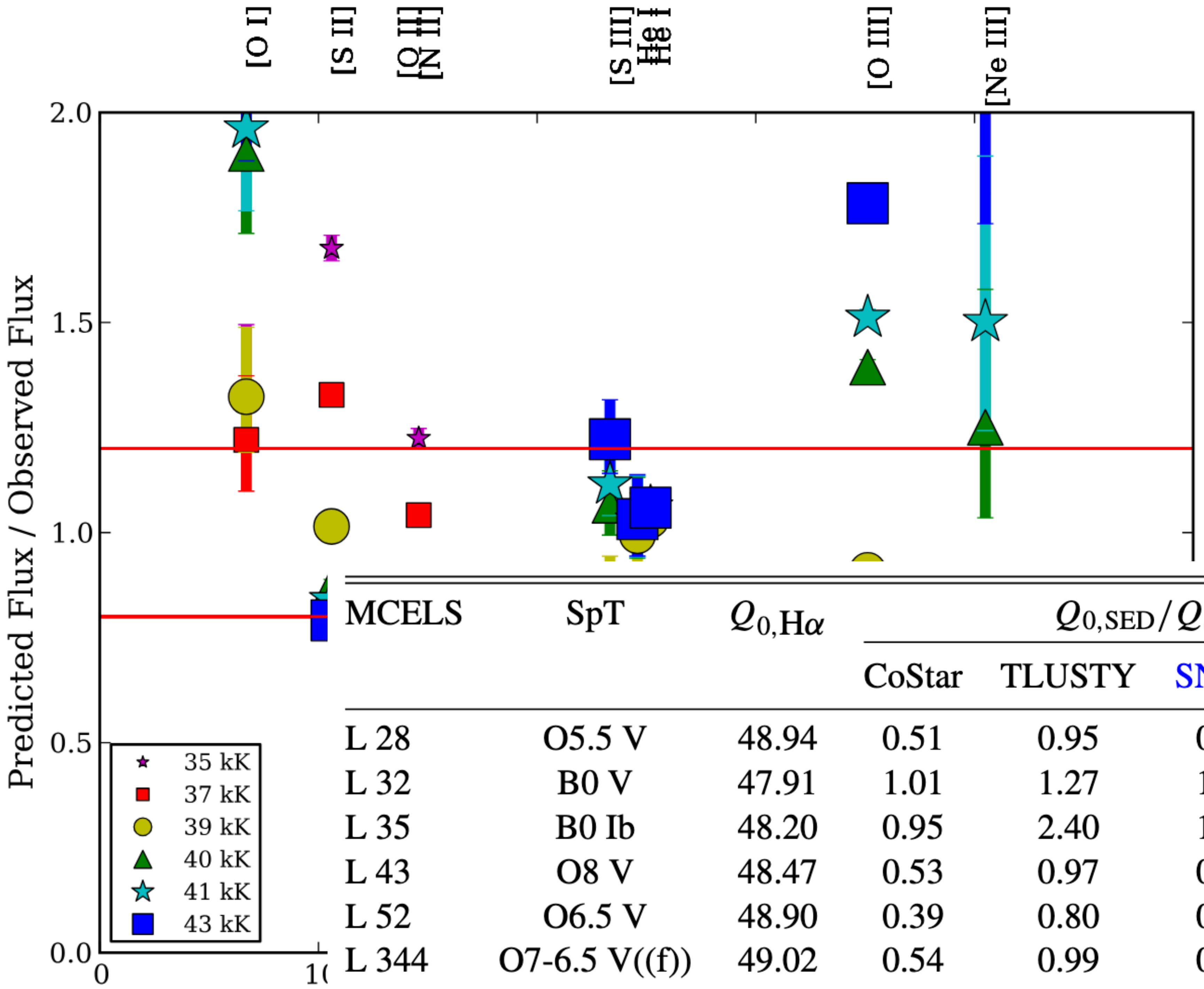
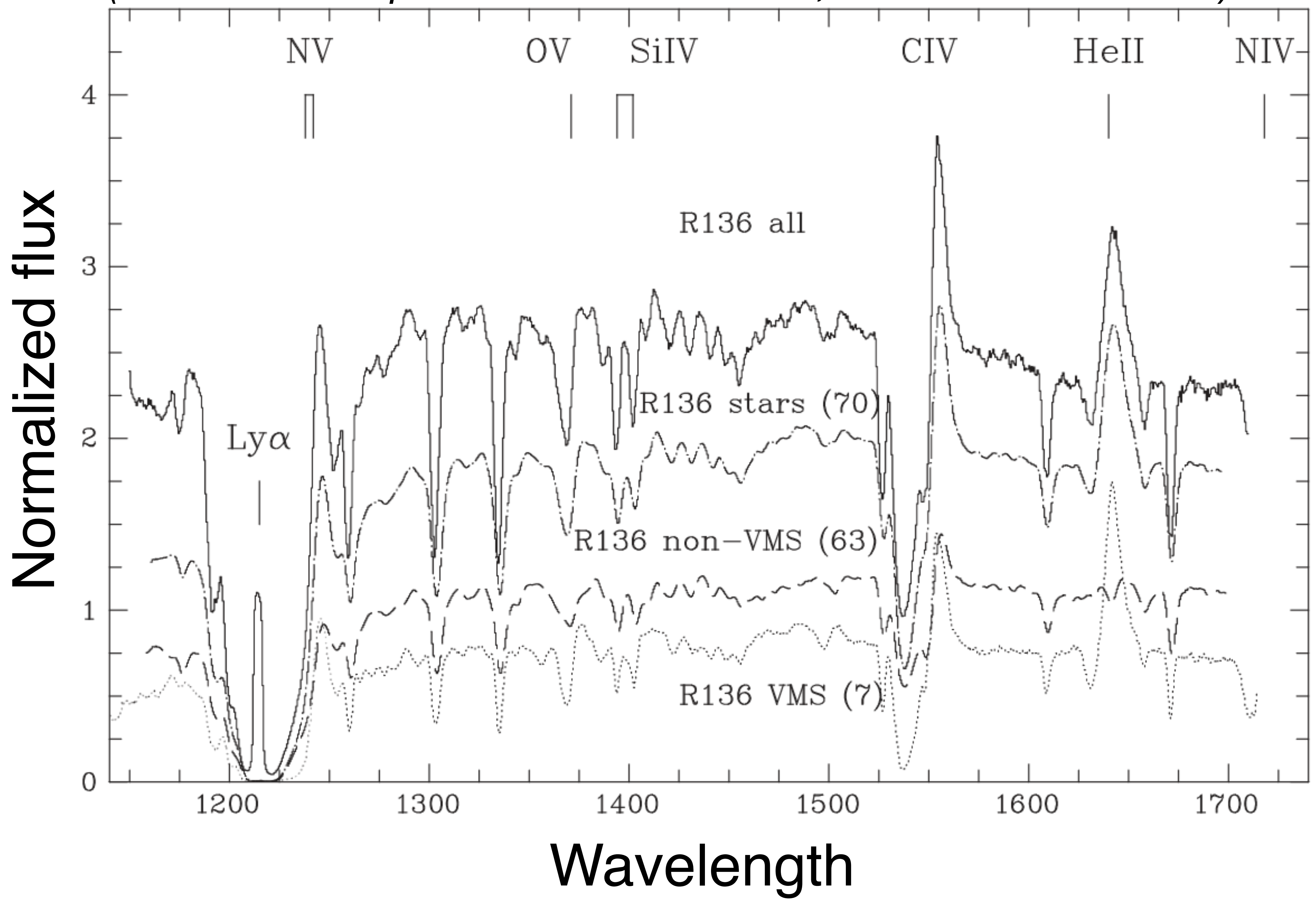


MCELS	SpT	$Q_{0,\mathrm{H}\alpha}$	$Q_{0,\mathrm{SED}}/Q_{0,\mathrm{H}\alpha}$			
			CoStar	TLUSTY	SNC02	WM-basic
L 28	O5.5 V	48.94	0.51	0.95	0.67	0.71
L 32	B0 V	47.91	1.01	1.27	1.08	0.84
L 35	B0 Ib	48.20	0.95	2.40	1.62	0.95
L 43	O8 V	48.47	0.53	0.97	0.79	0.74
L 52	O6.5 V	48.90	0.39	0.80	0.64	0.62
L 344	O7-6.5 V((f))	49.02	0.54	0.99	0.80	0.75
L 345	B0.5 Iab	48.18	. . .	0.16–0.47	. . .	. . .
L 346	O9 V[a]	48.48	1.06	1.84	1.27	1.36
L 351	O6.5 V	49.37	0.27	0.55	0.42	0.39
L 390	O9 V	48.65	0.66	1.01	1.16	1.60
L 394	O9 V	47.99	2.94	5.36	4.37	4.08
L 283b[b]	O6.5 V((f))	48.51	0.70	1.44	1.10	1.02

The upper mass limit (VMSs)

The very massive stars (VMS, >100 $M_\odot$) are perhaps the best at ionizing and they produce He II emission!

(30 Doradus super star cluster in LMC, Crowther et al. 2016)



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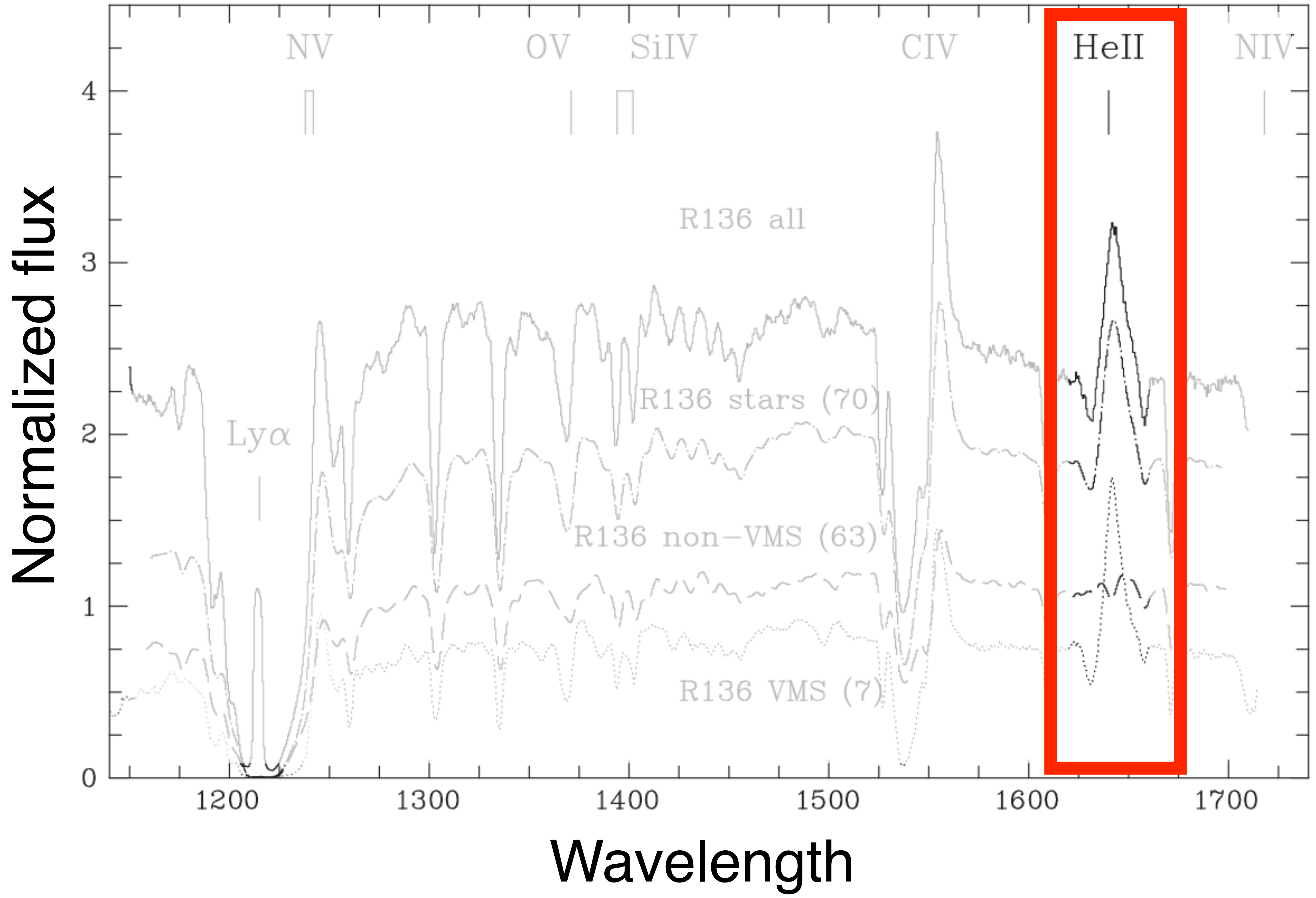

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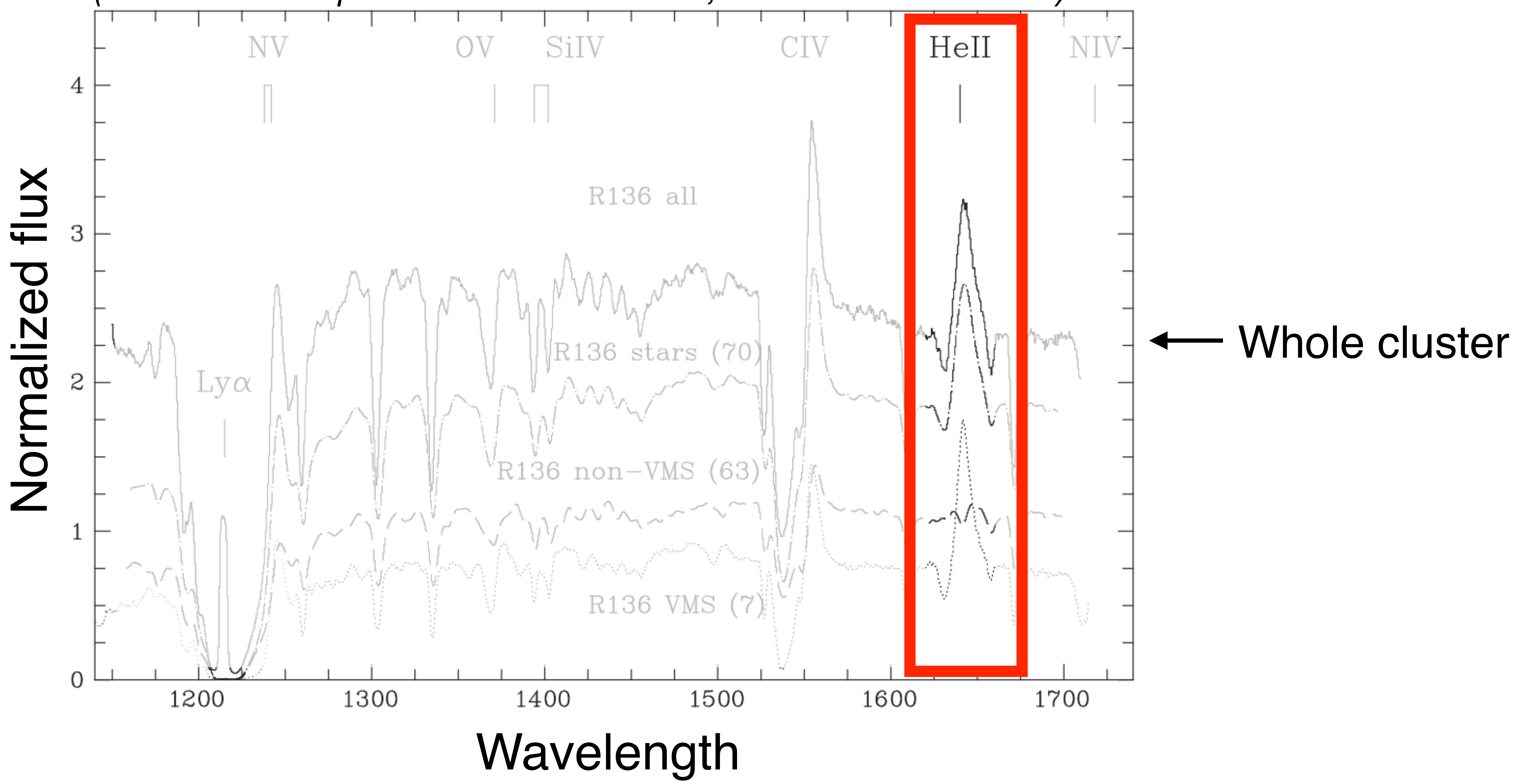

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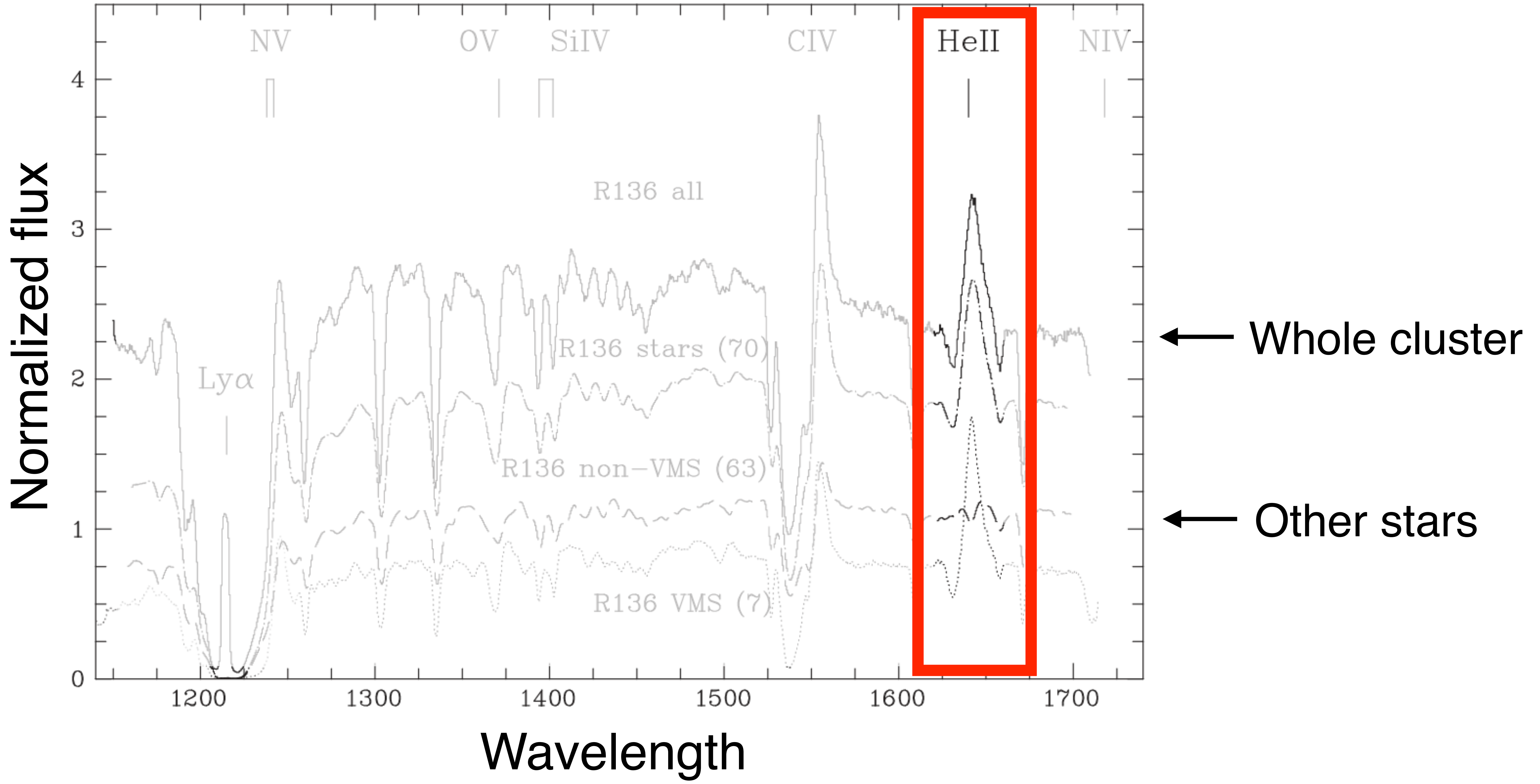

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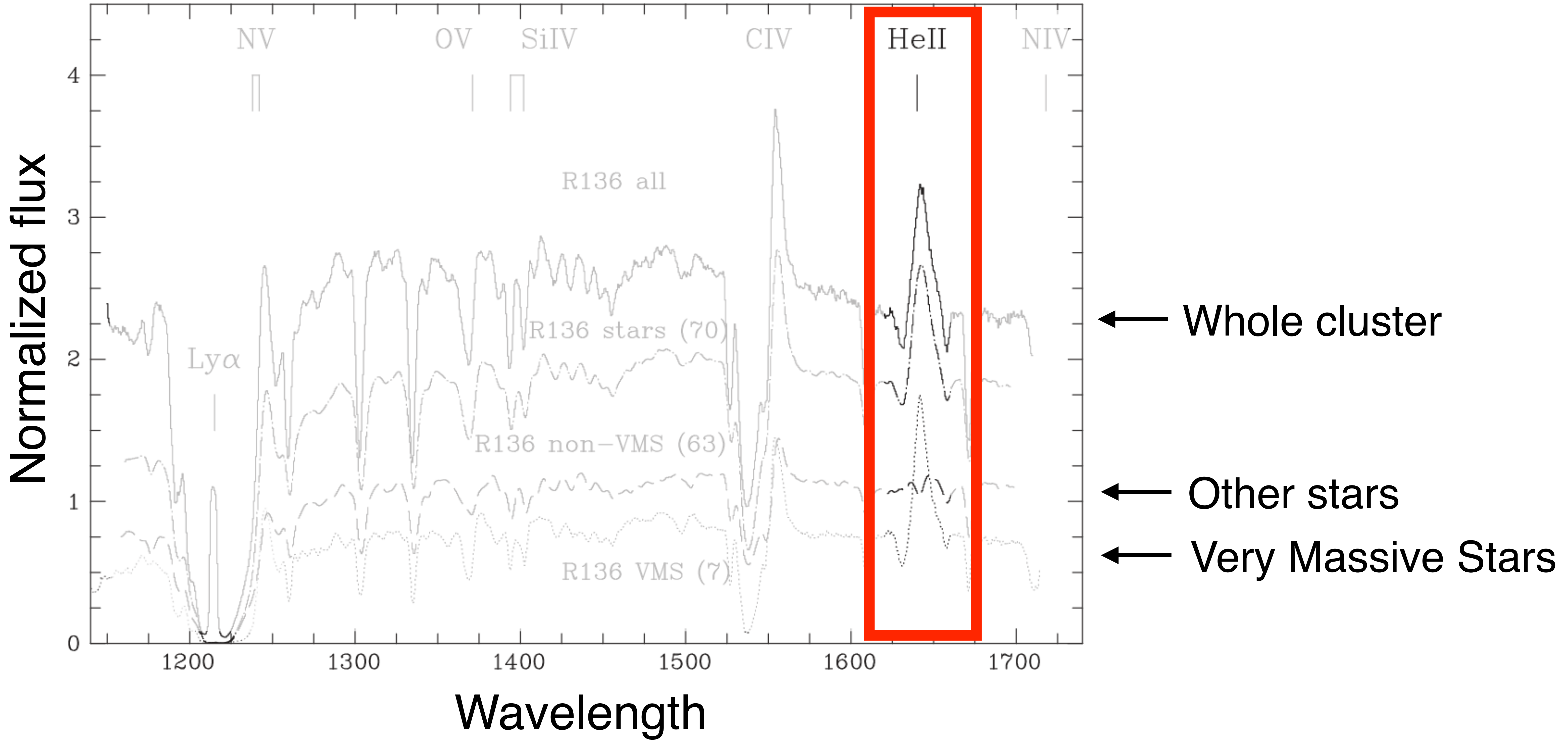

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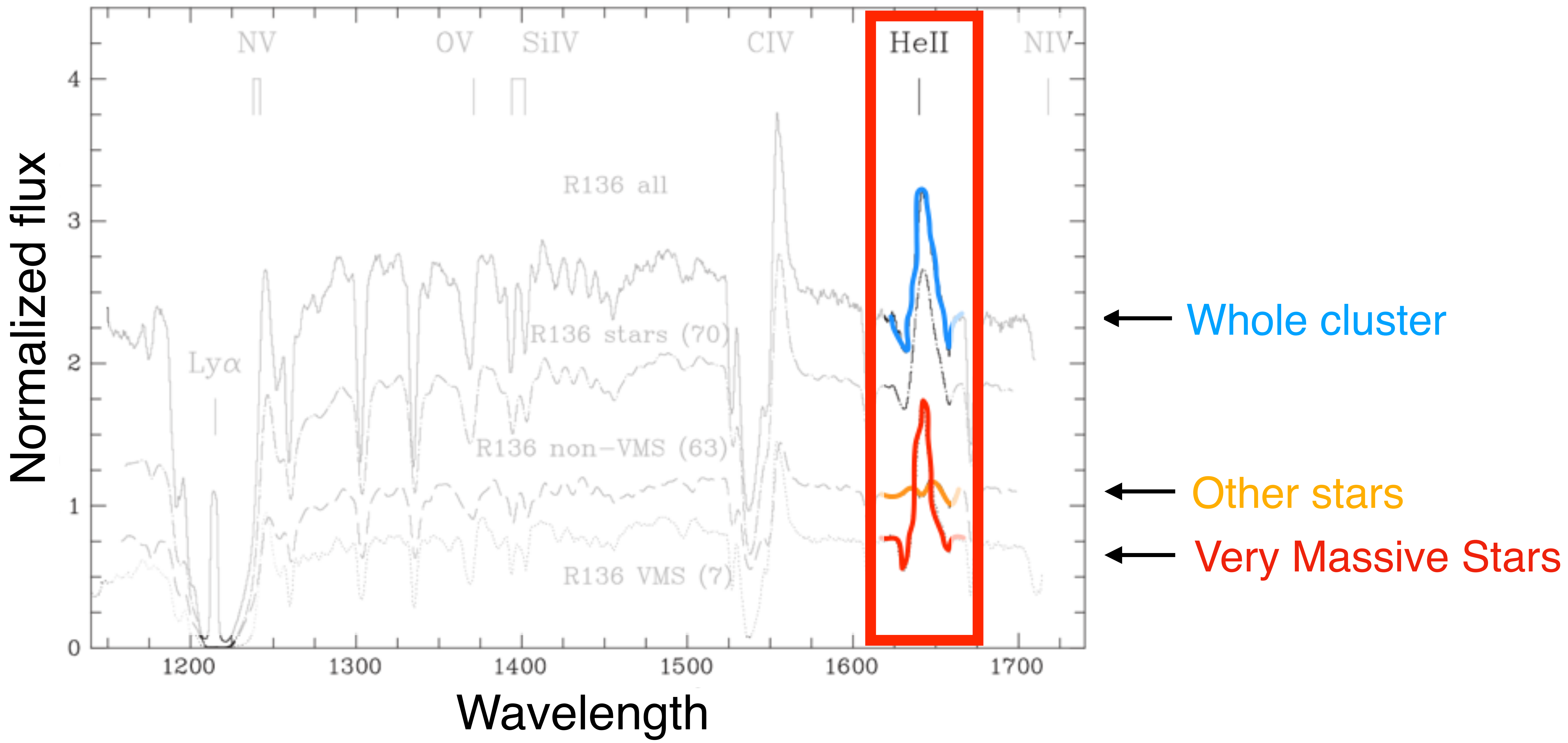

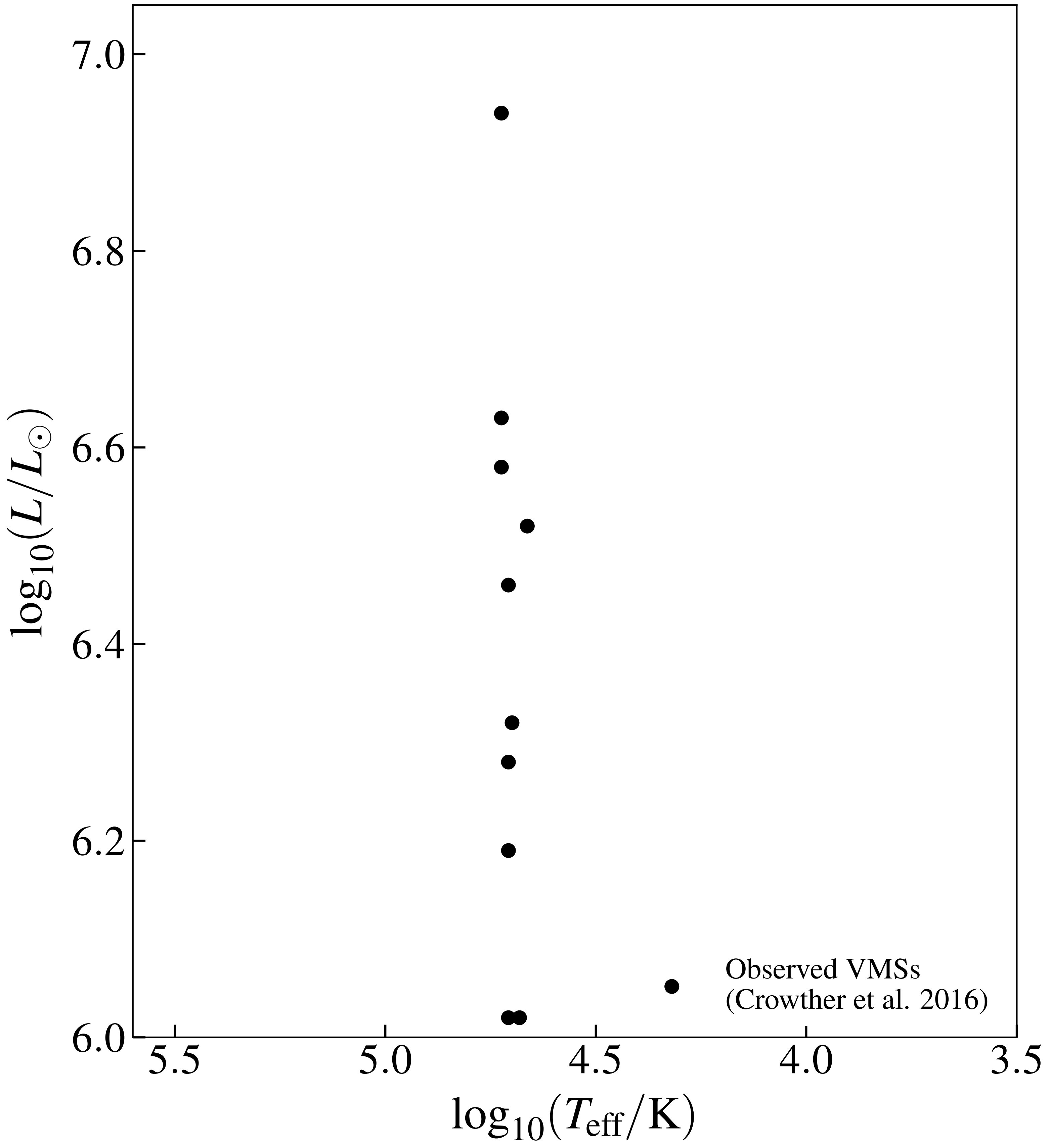

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The upper mass limit (VMSs)

… but we do not really know how very massive stars evolve, because (1) we do not have enough benchmark observations, (2) stellar wind mass loss is not sufficiently understood, and (3) VMSs could very likely be products of binary interaction.

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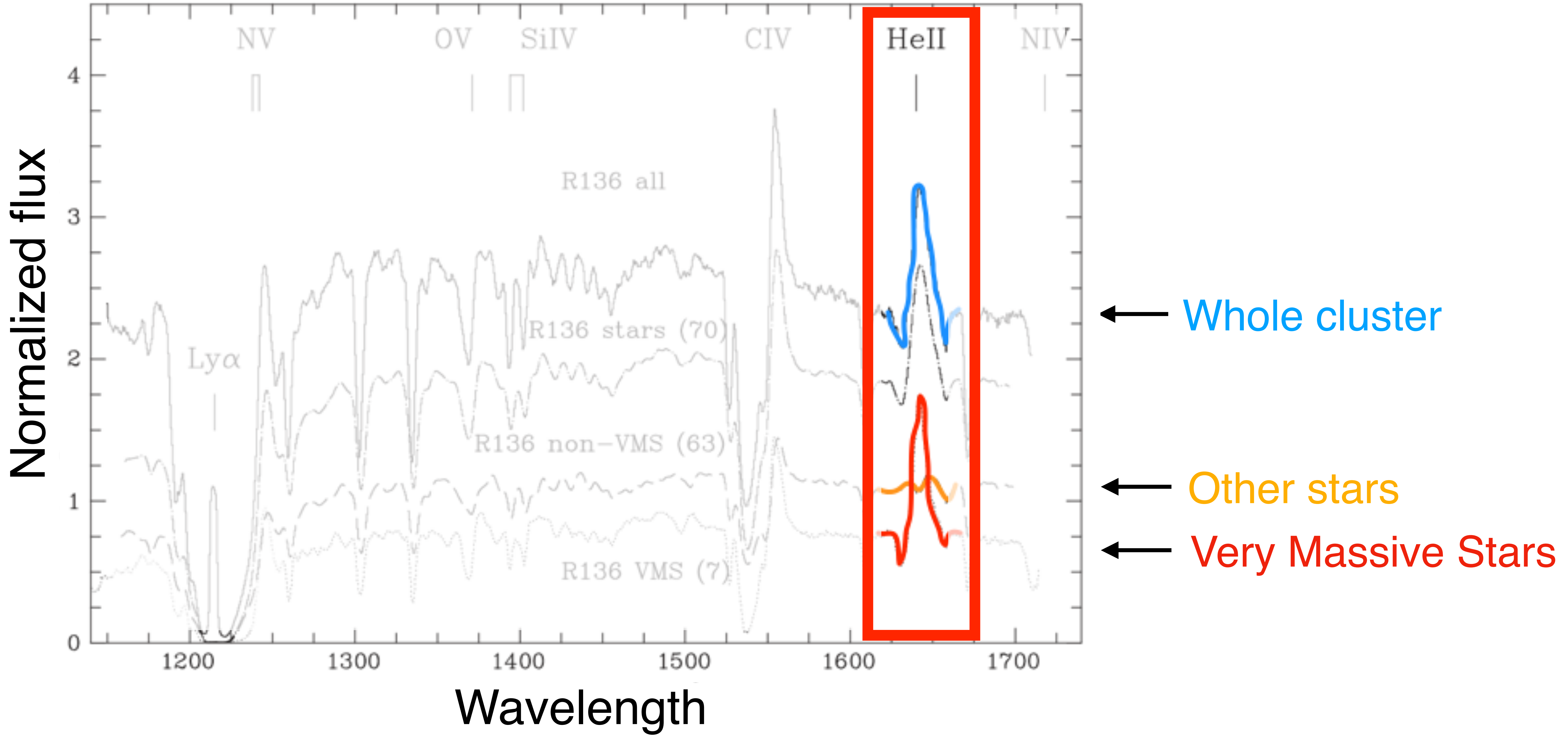

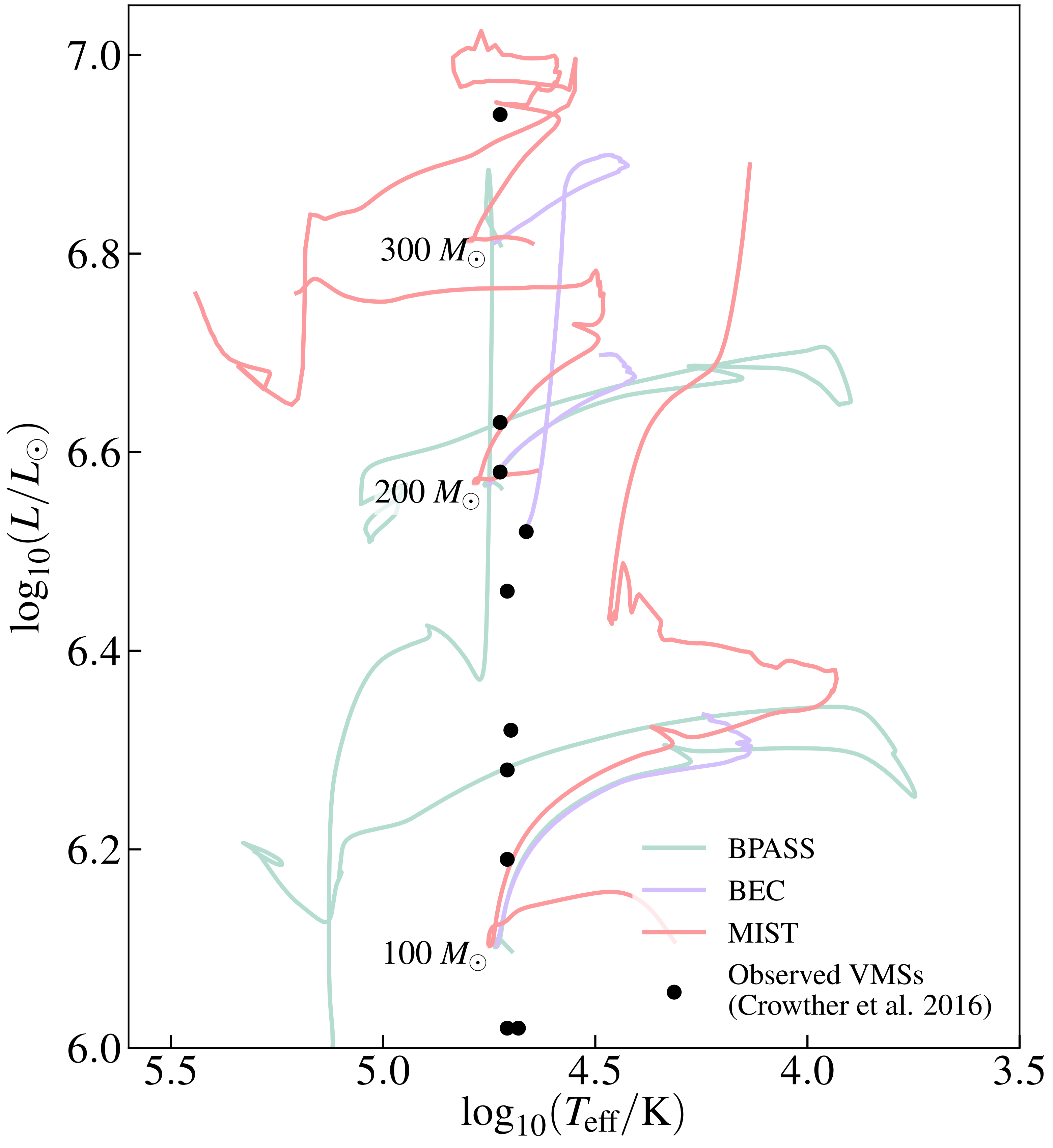

Rotational velocities of massive stars

The projected rotation rate of OB stars seem to match a broader Poisson distribution of the actual rotation rate with a peak around 150 km/s.

(see also Huang et al., 2010, Dufton et al., 2011, de Mink et al., 2013)

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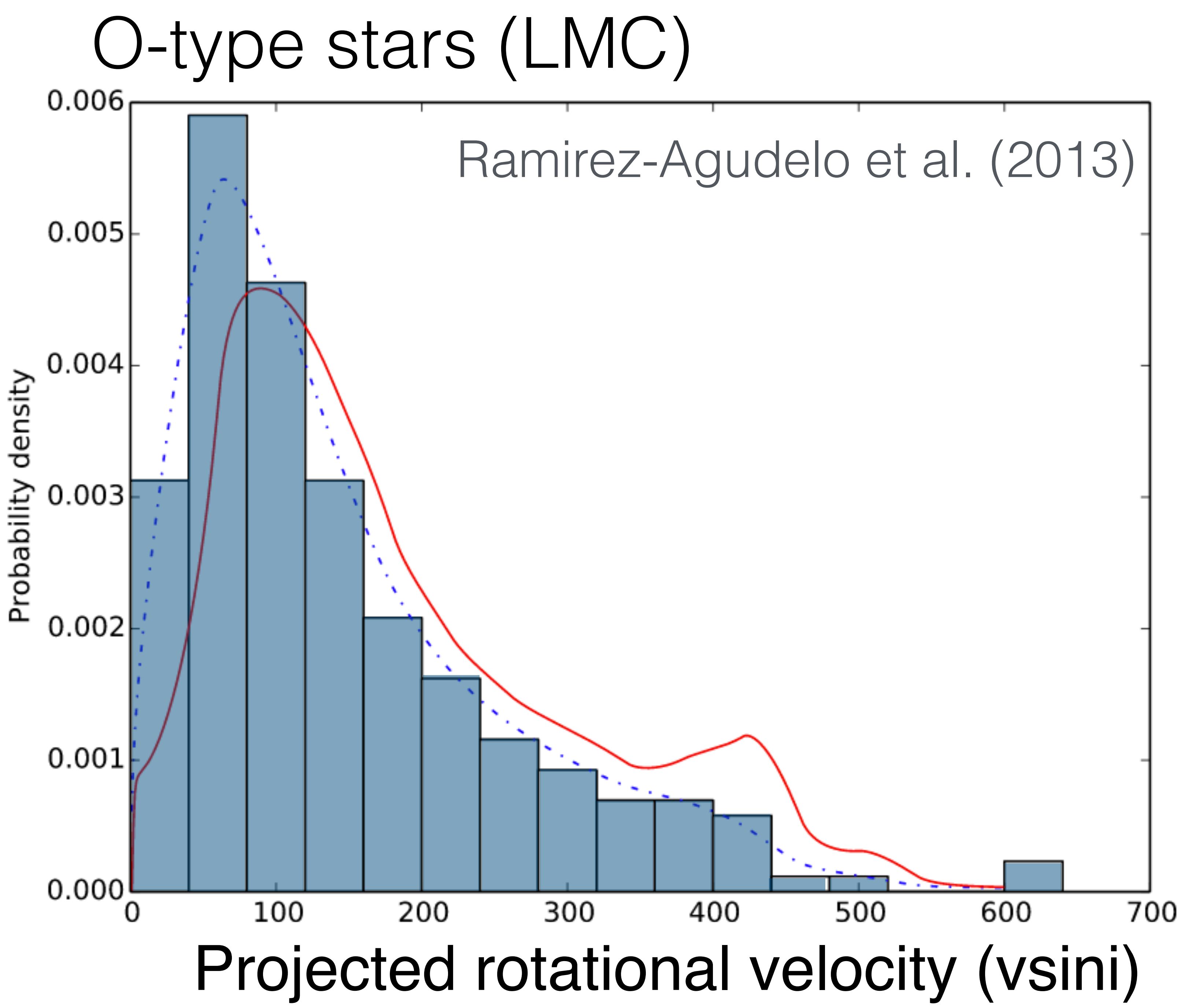

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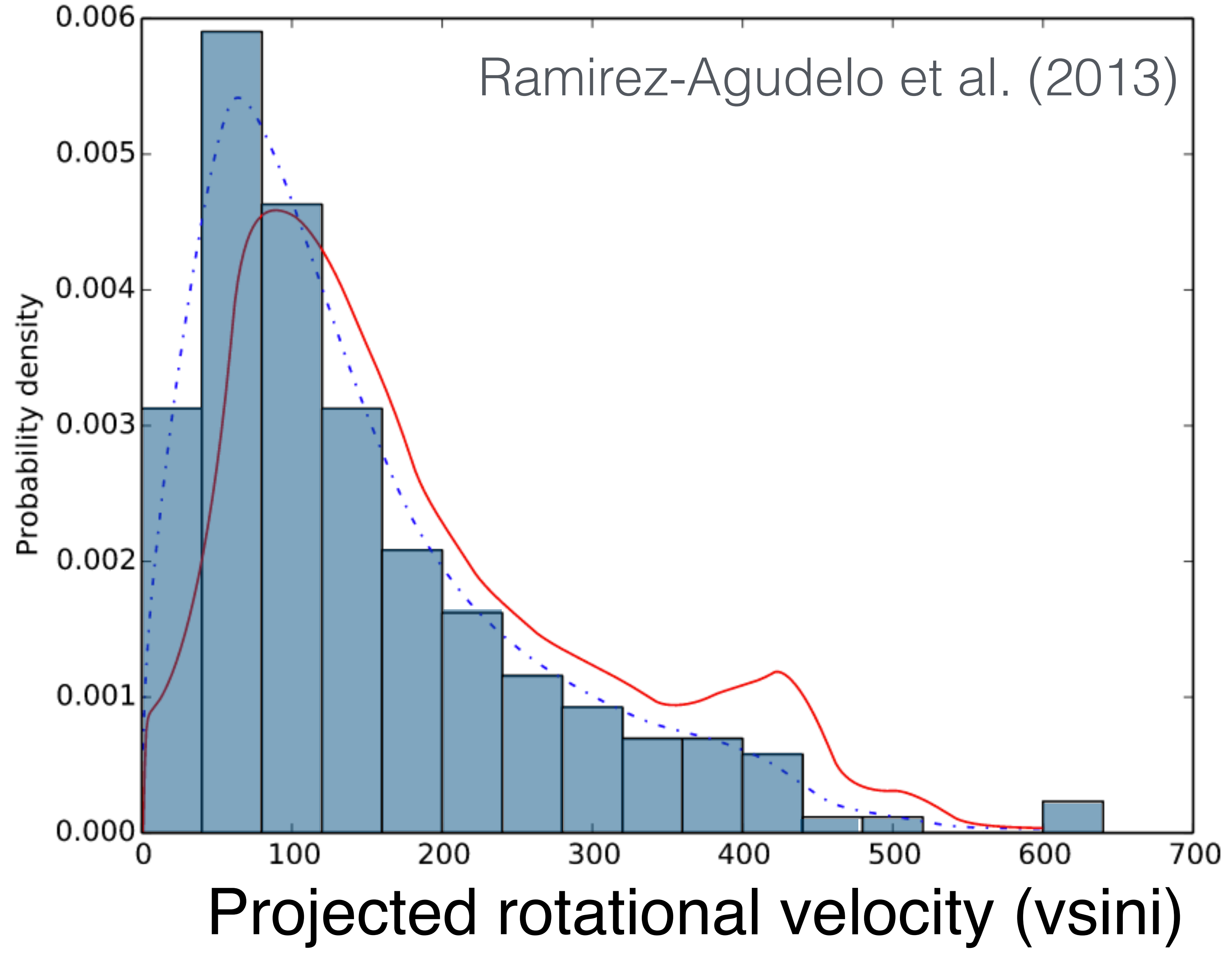

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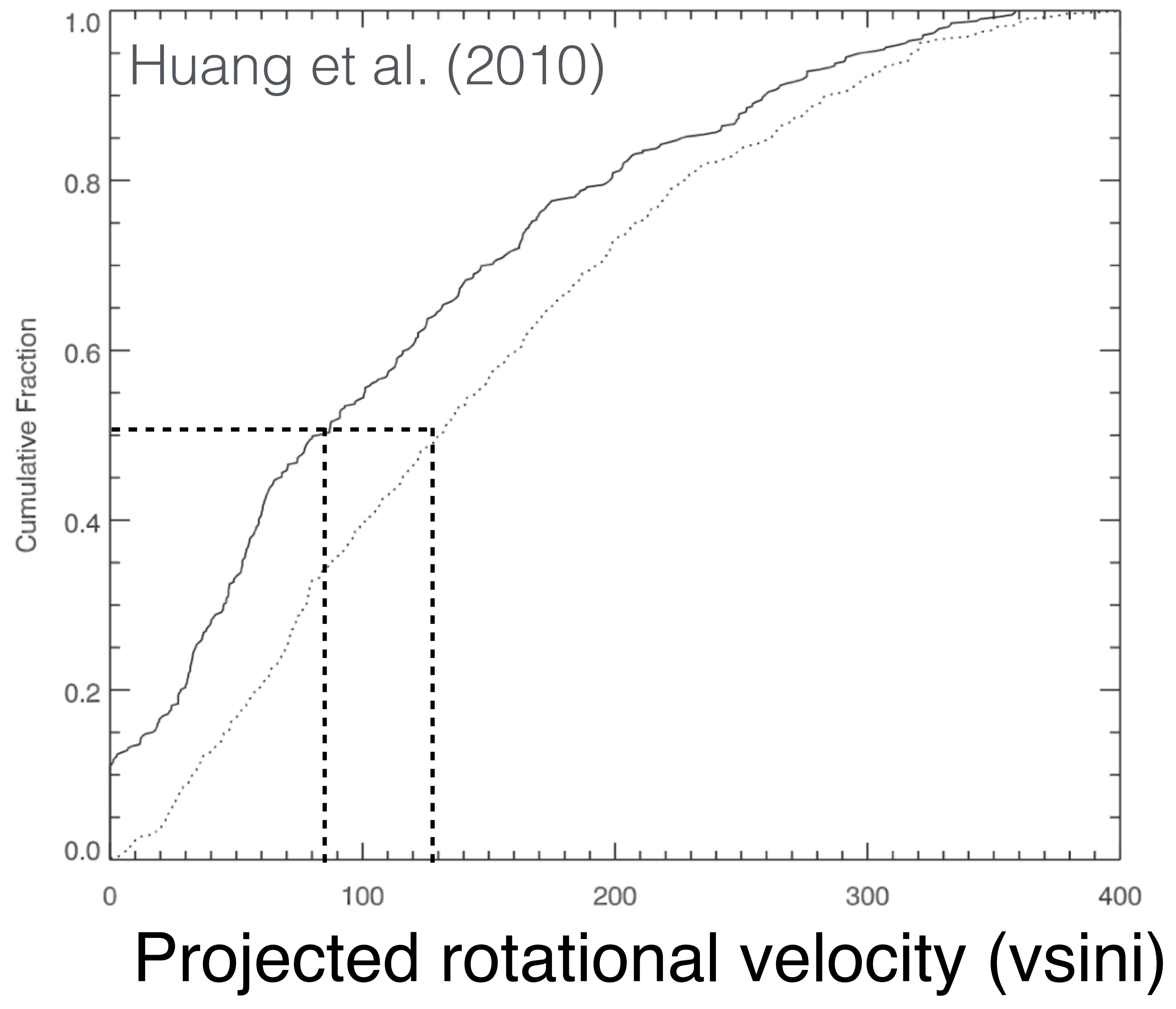

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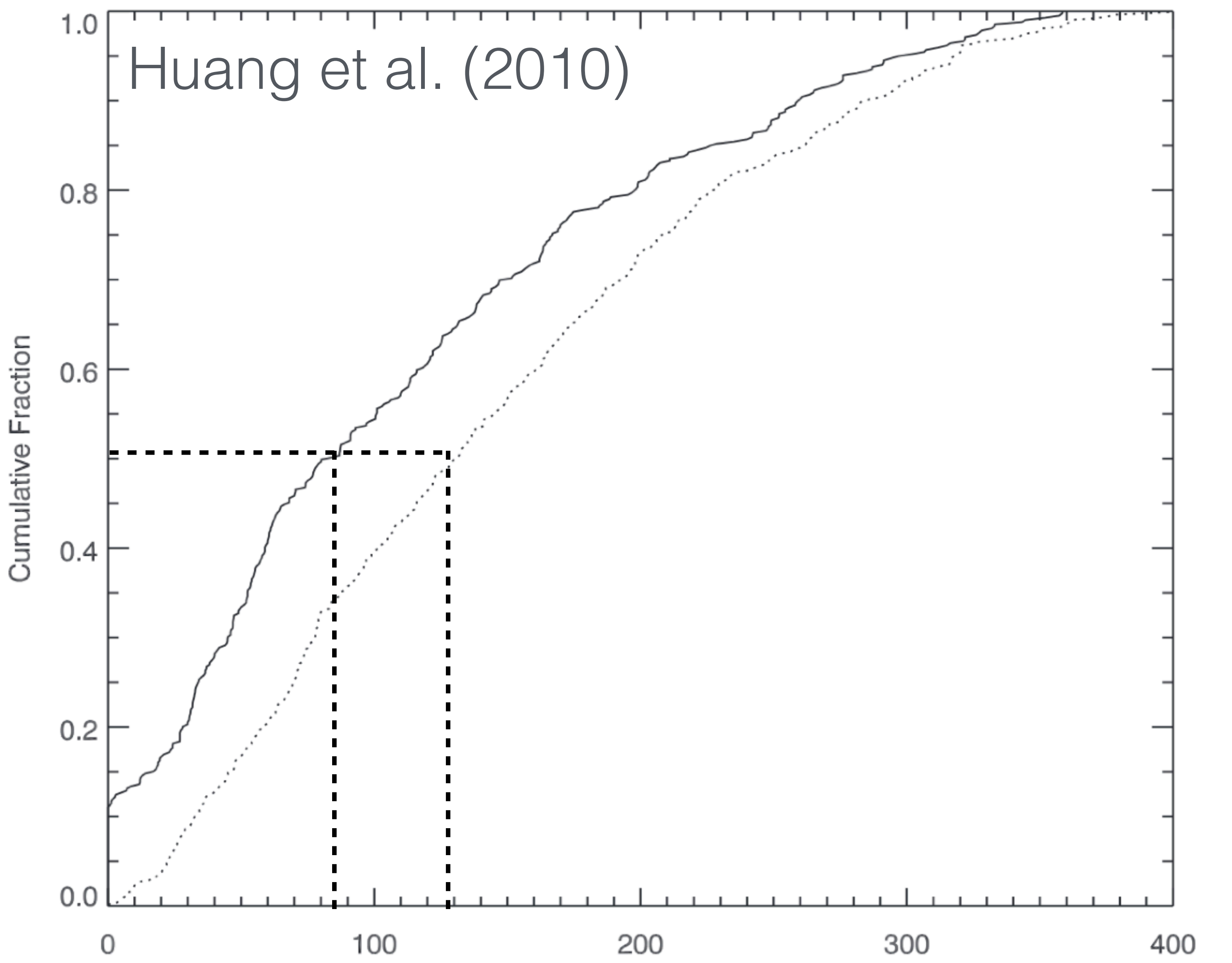

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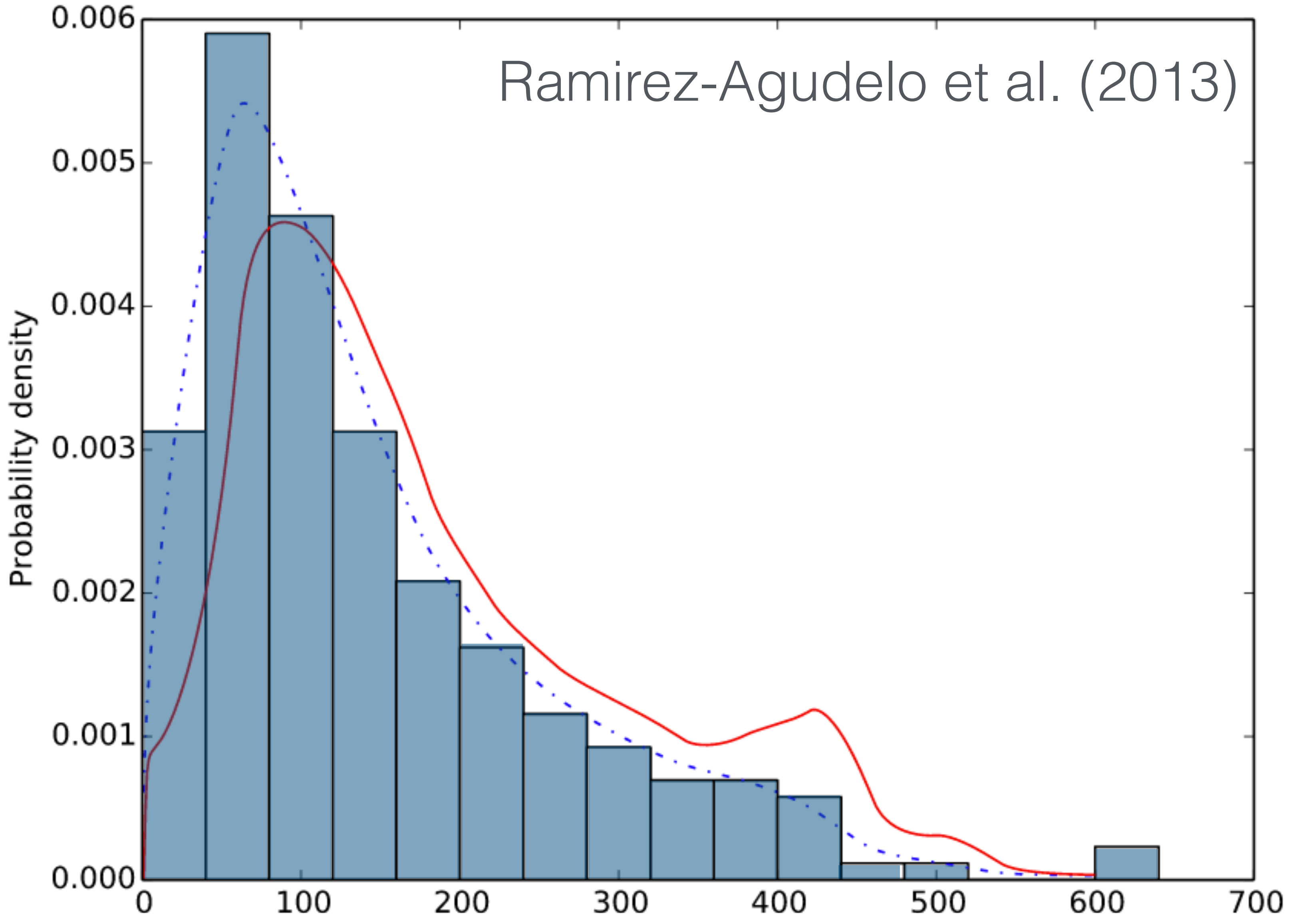

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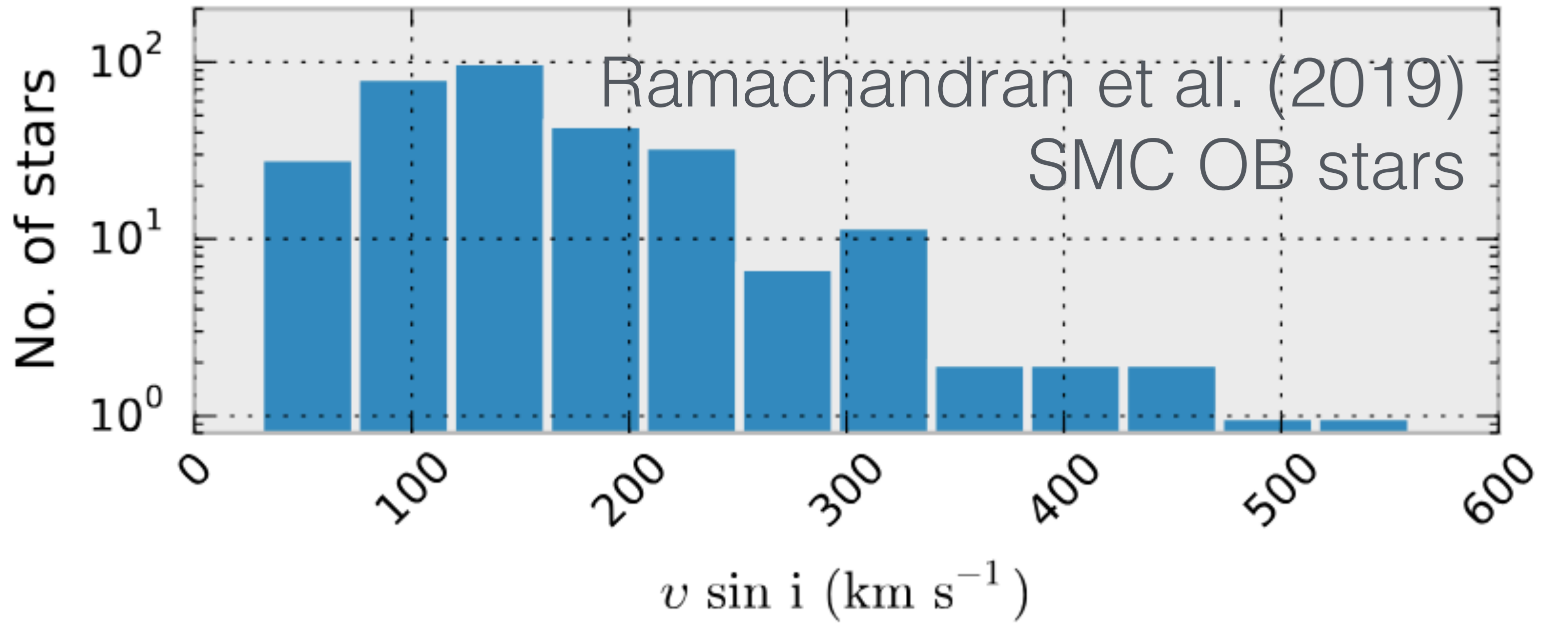

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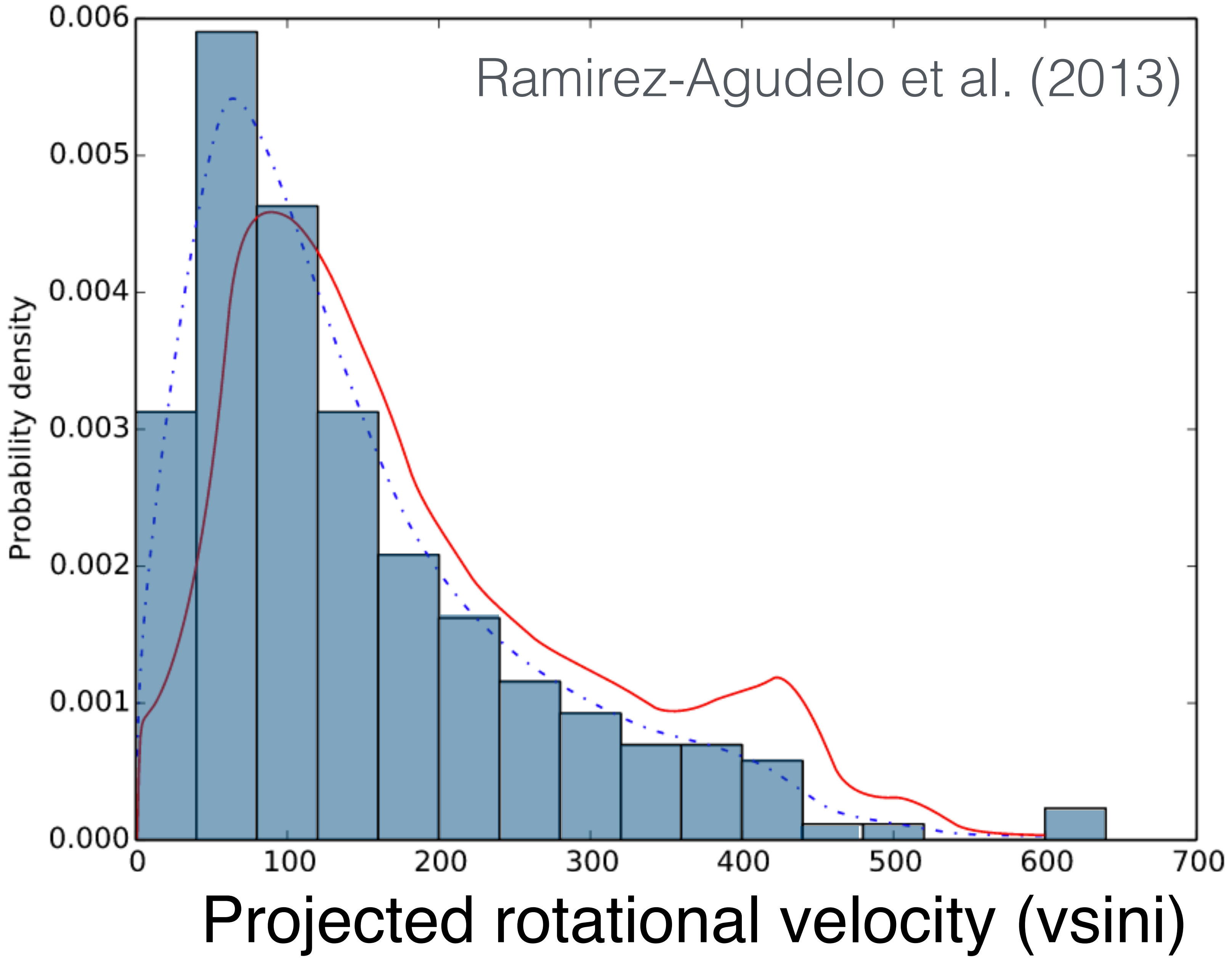

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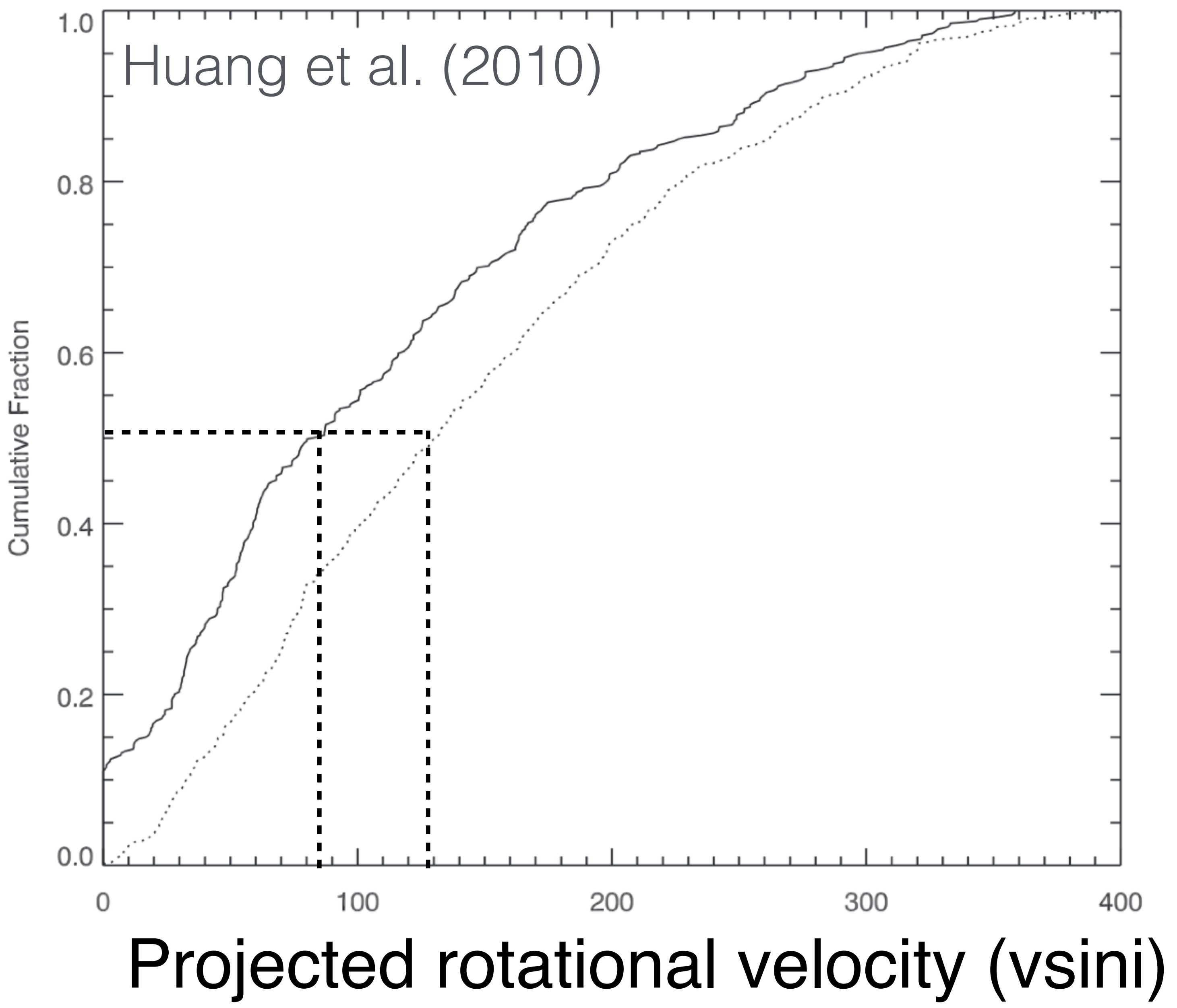

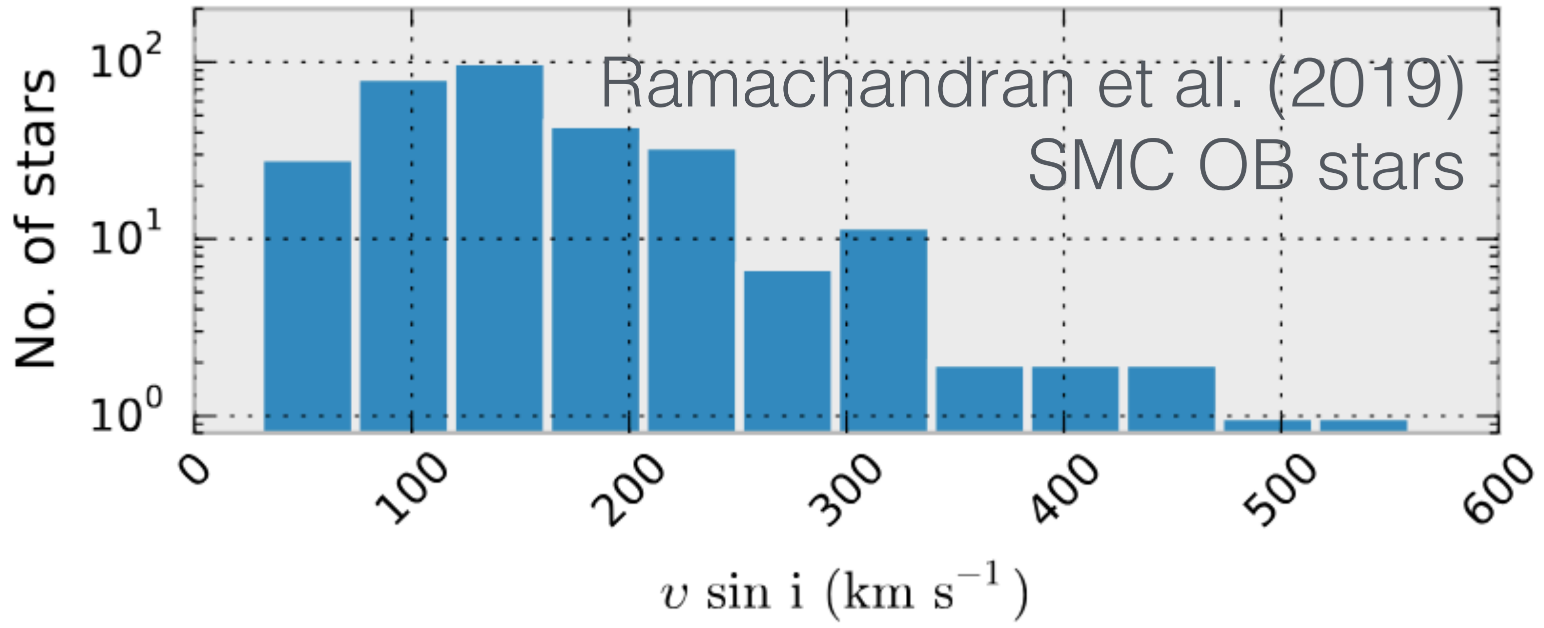

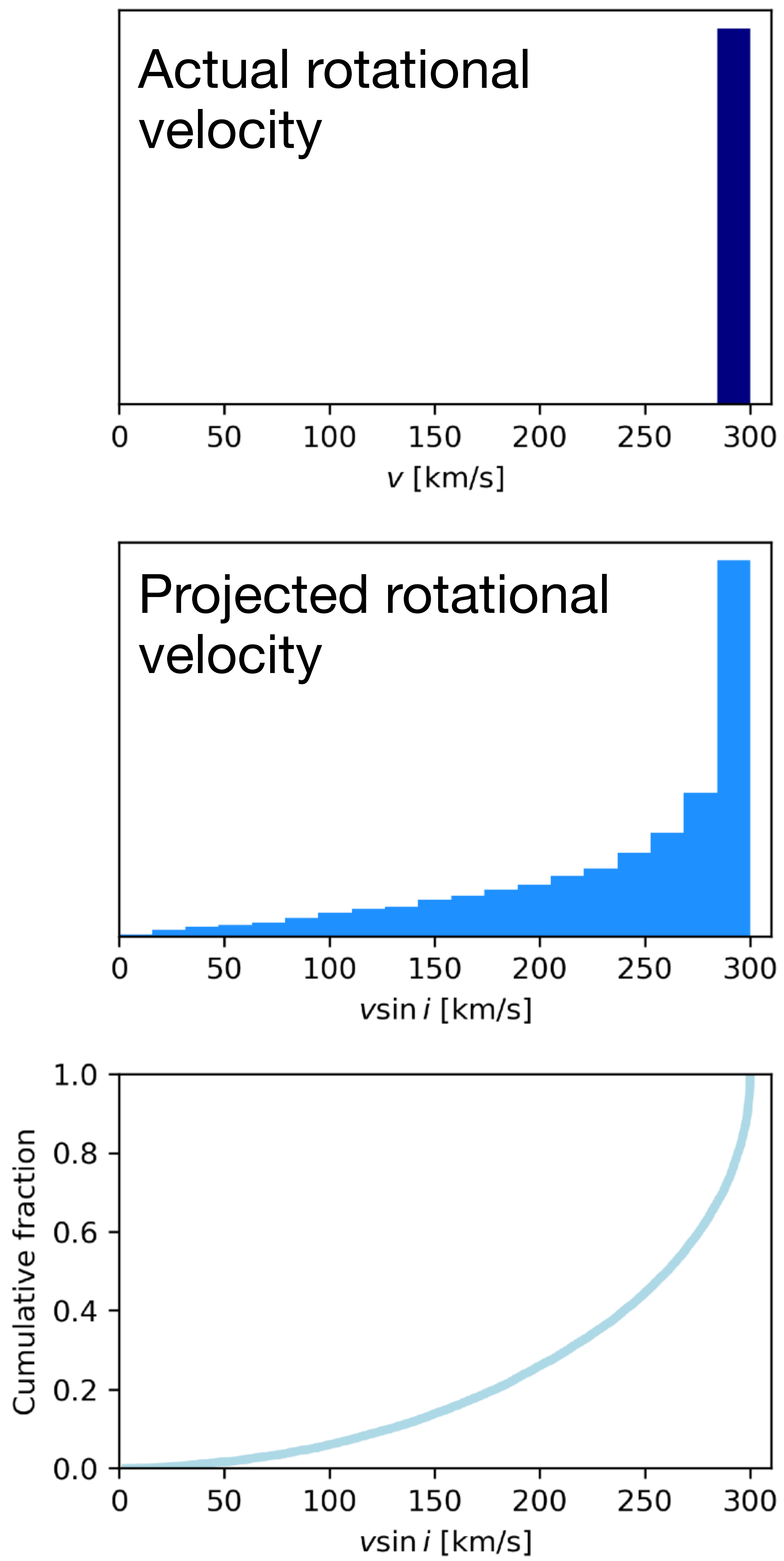

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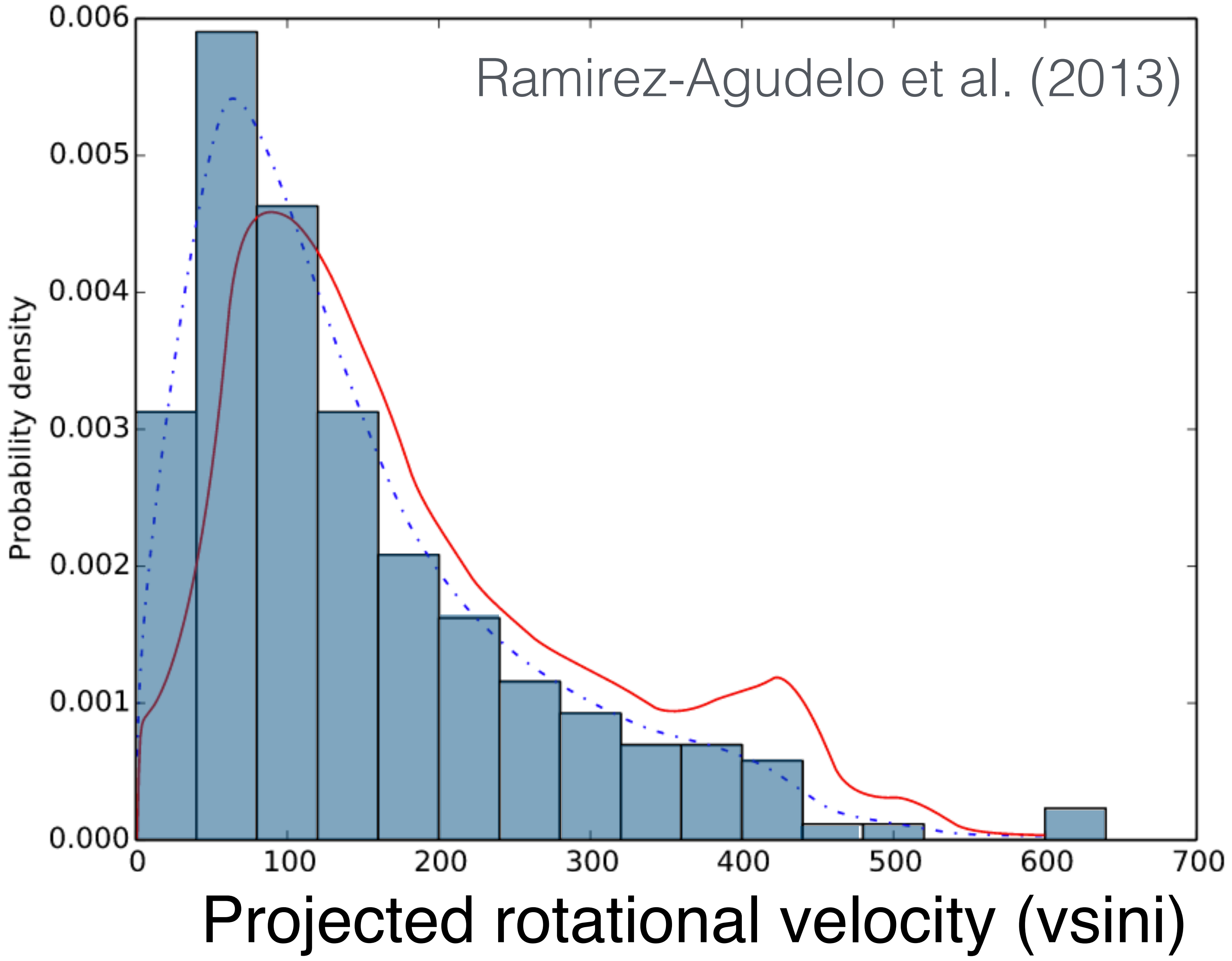

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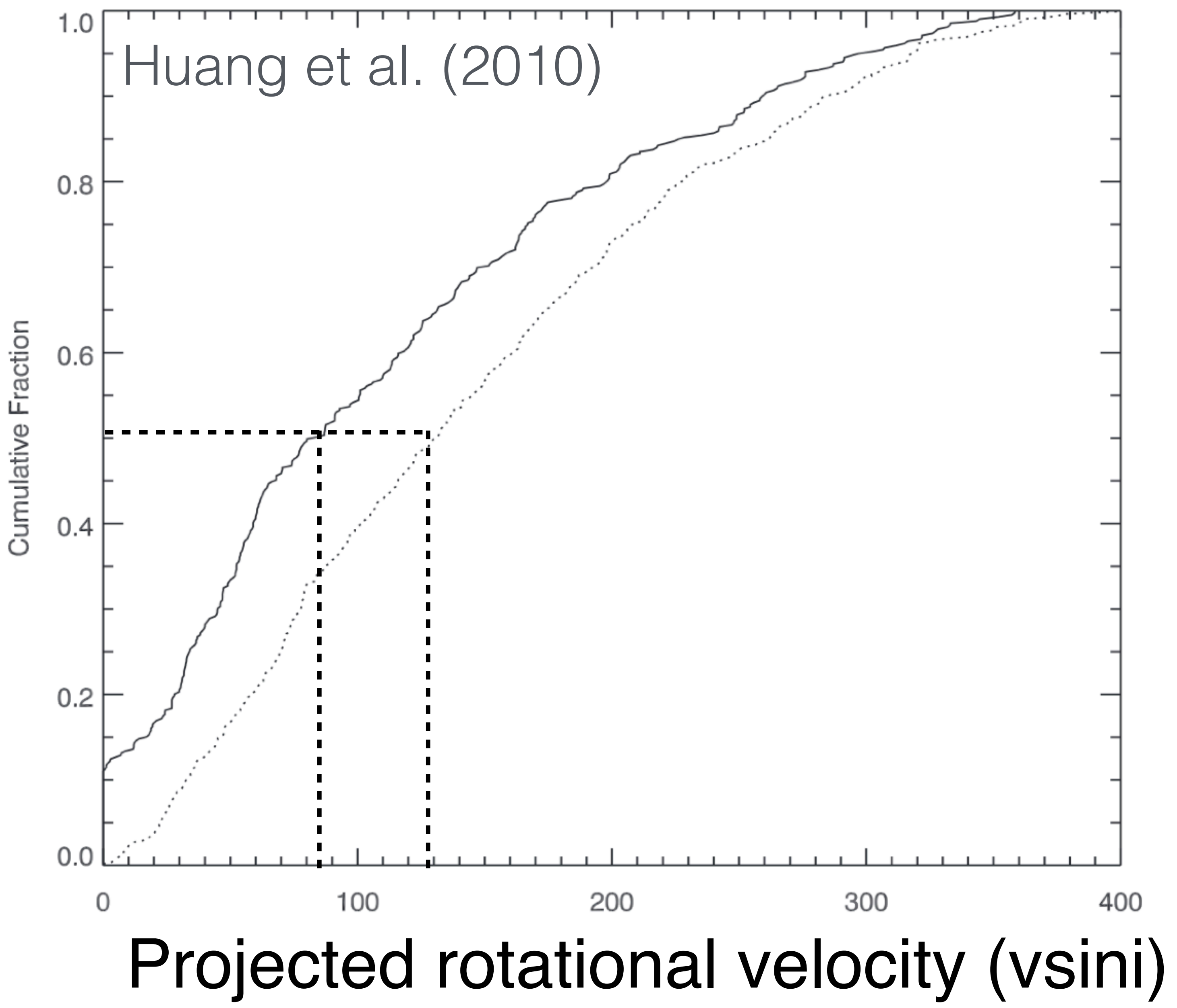

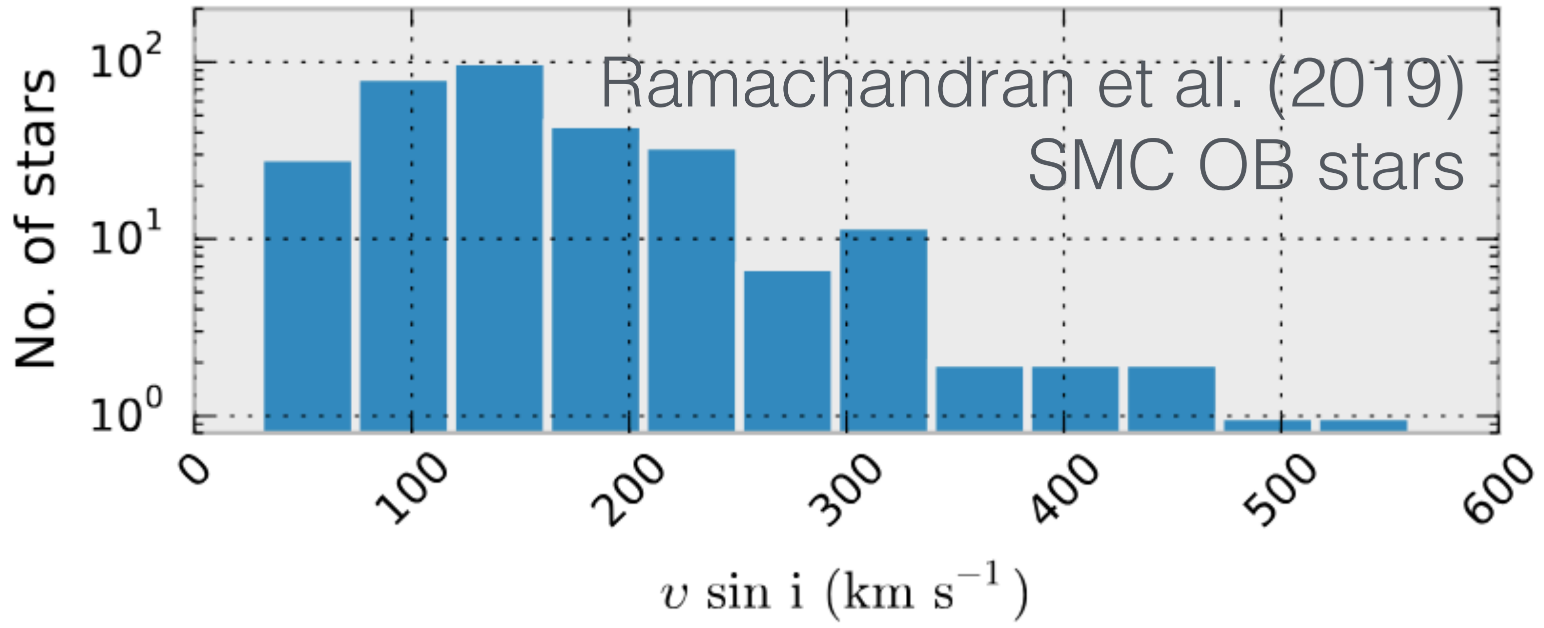

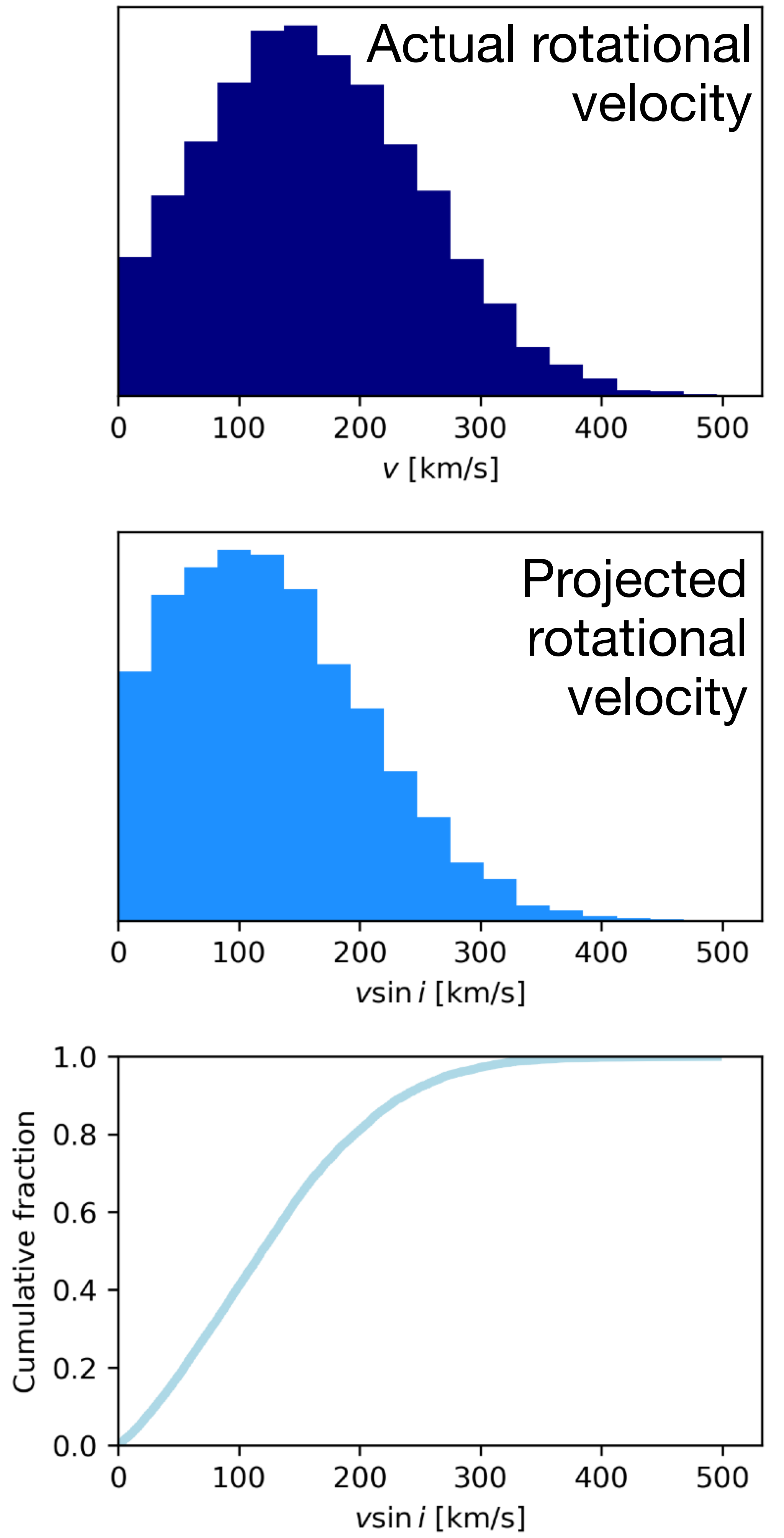

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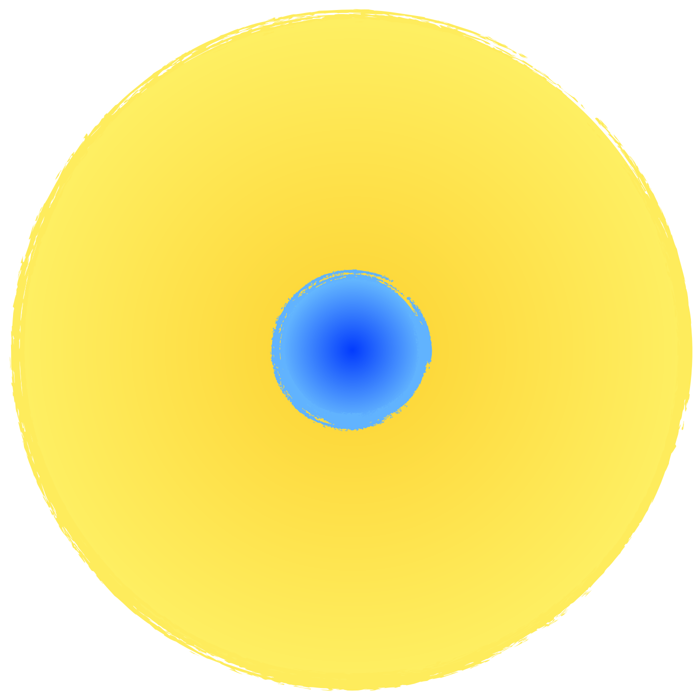
Effect of stellar rotation

Rotational mixing: Meynet, Maeder, Yoon, Szécsi, Langer, Sana, de Mink, Brott…

Effect of stellar rotation

Non-rotating star



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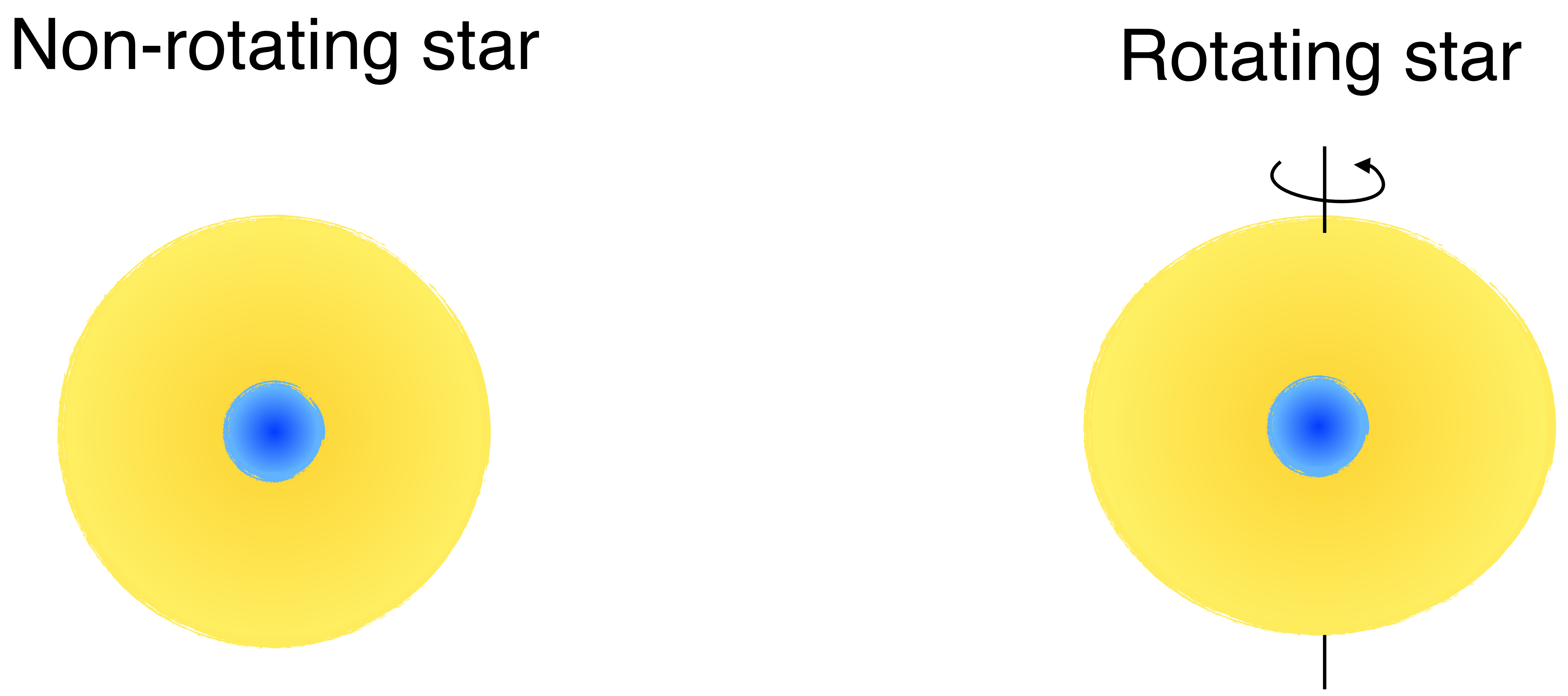

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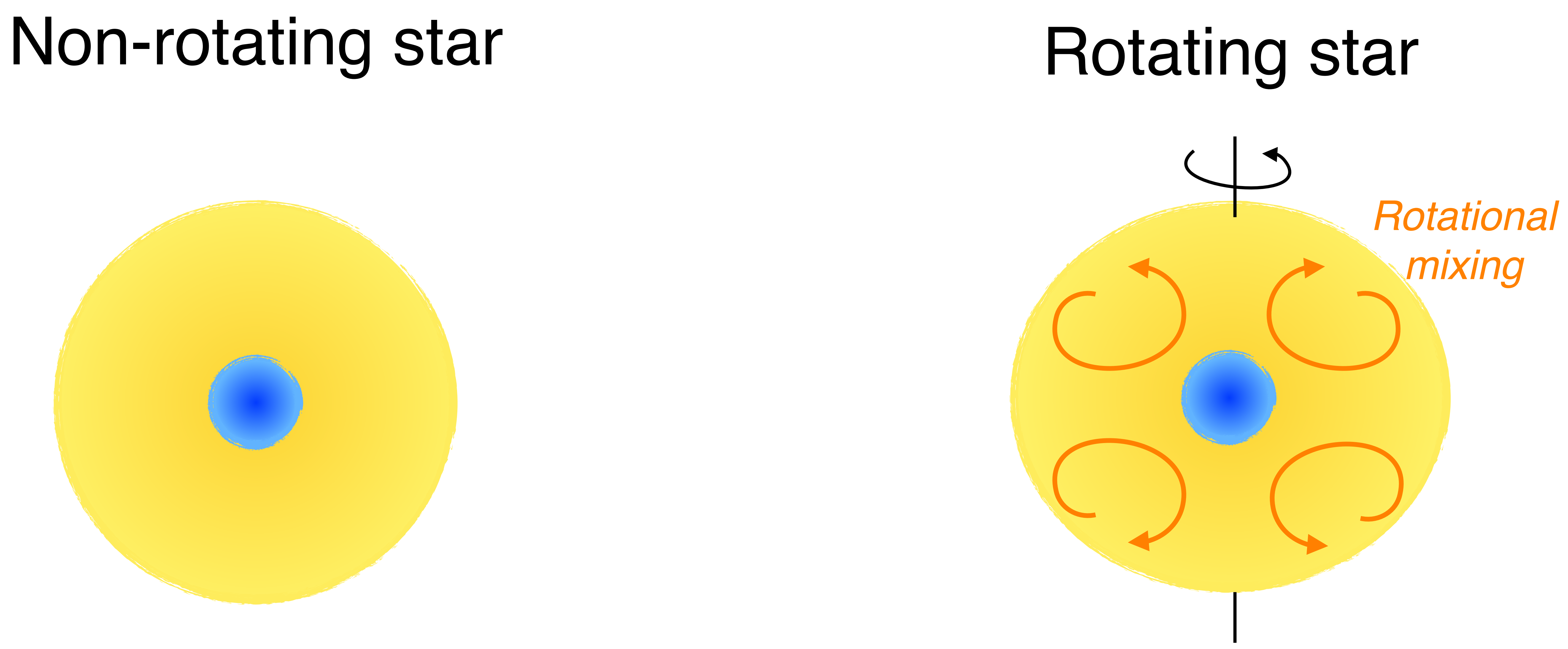

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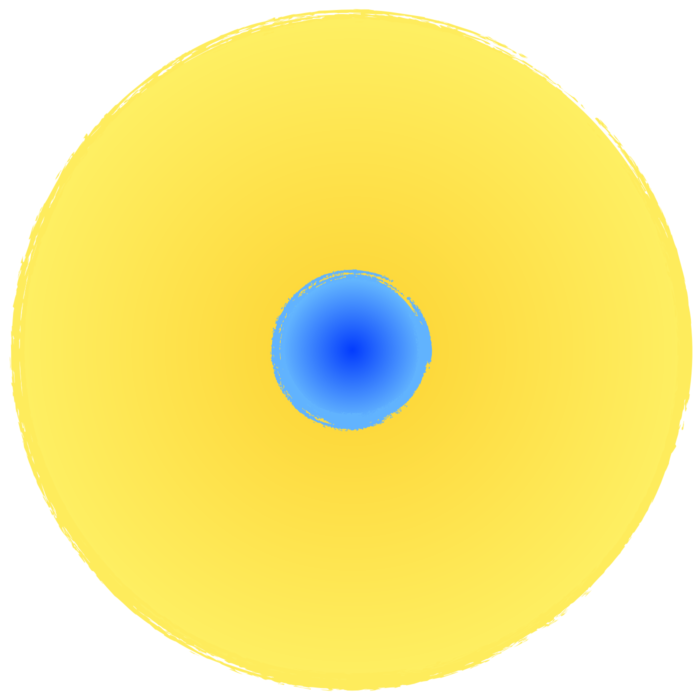

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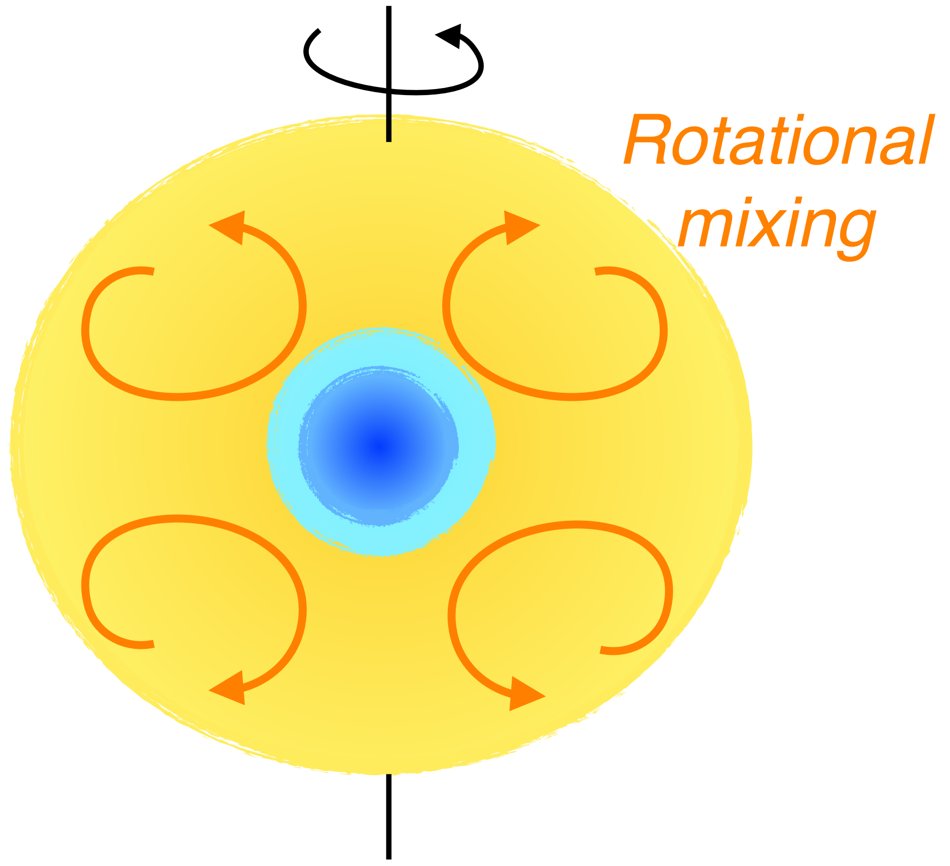

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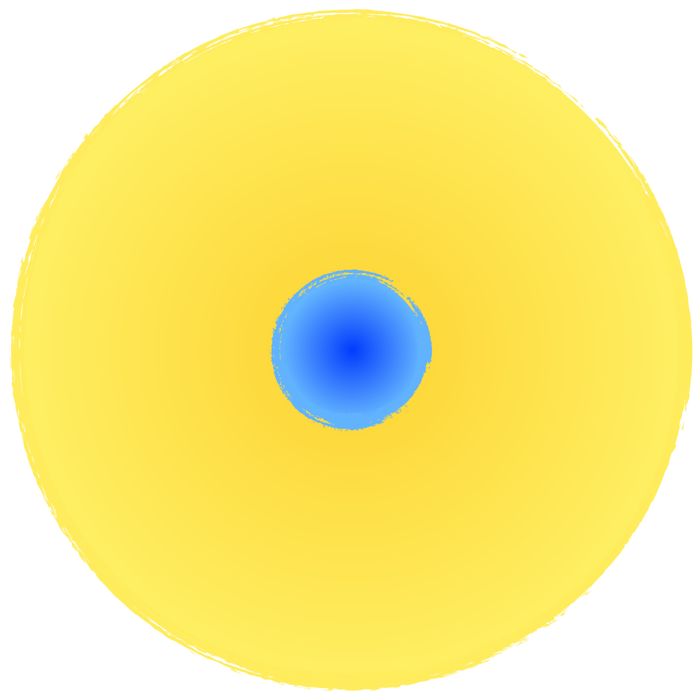

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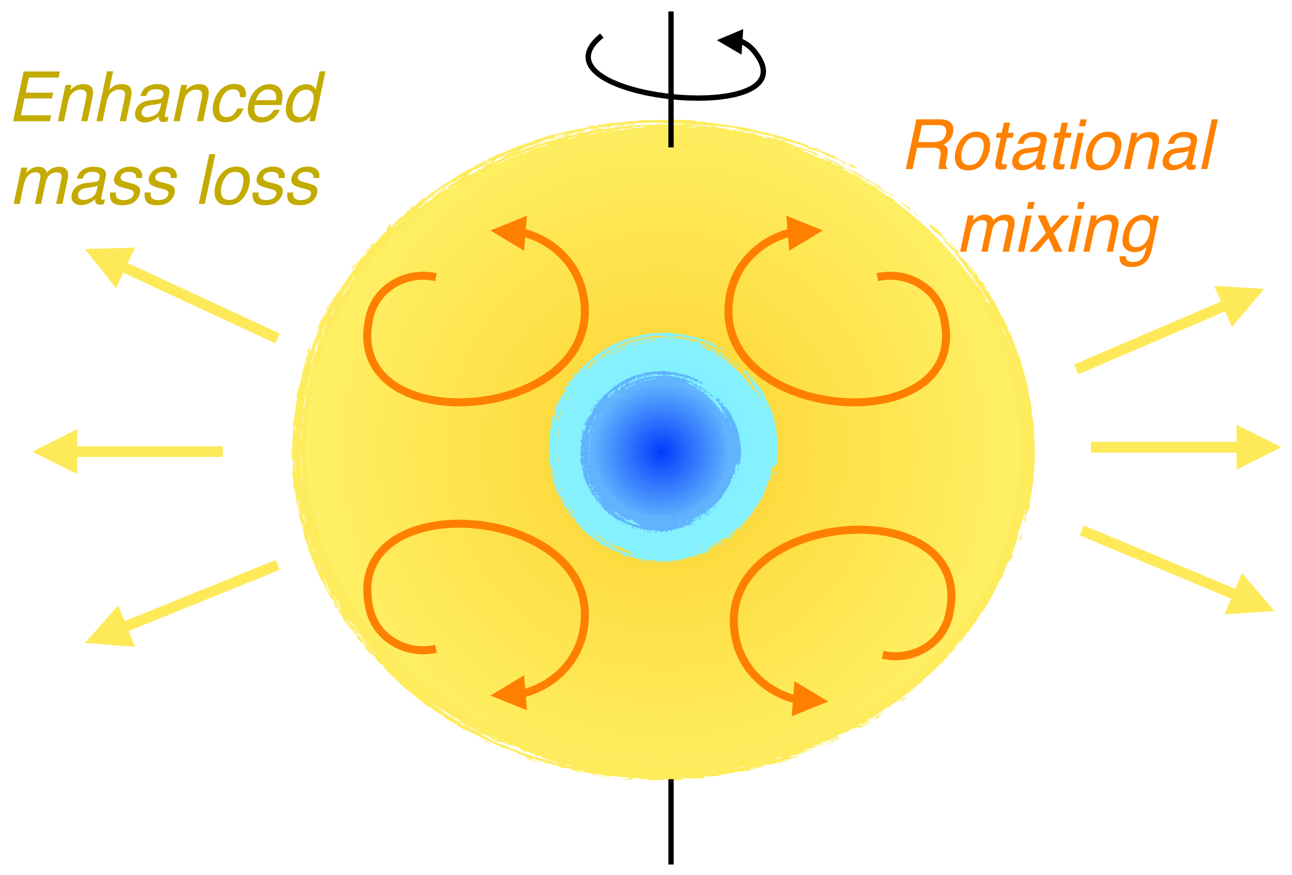

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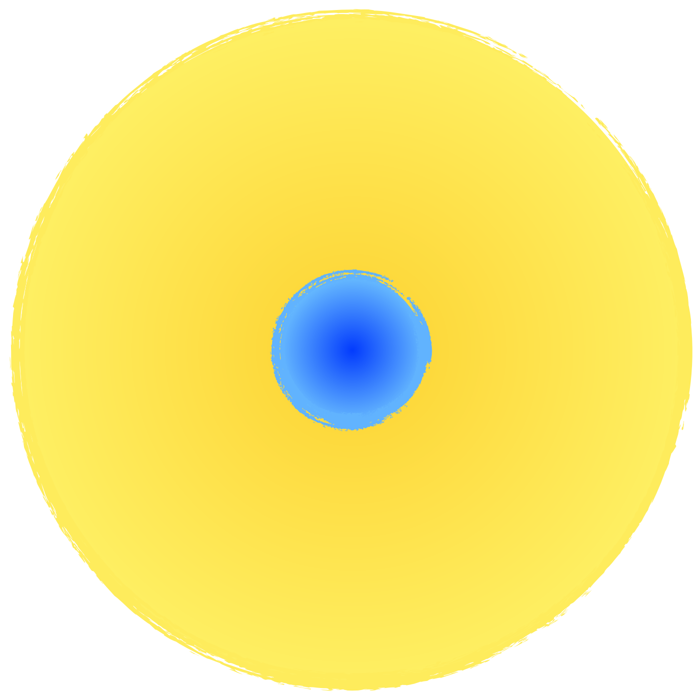

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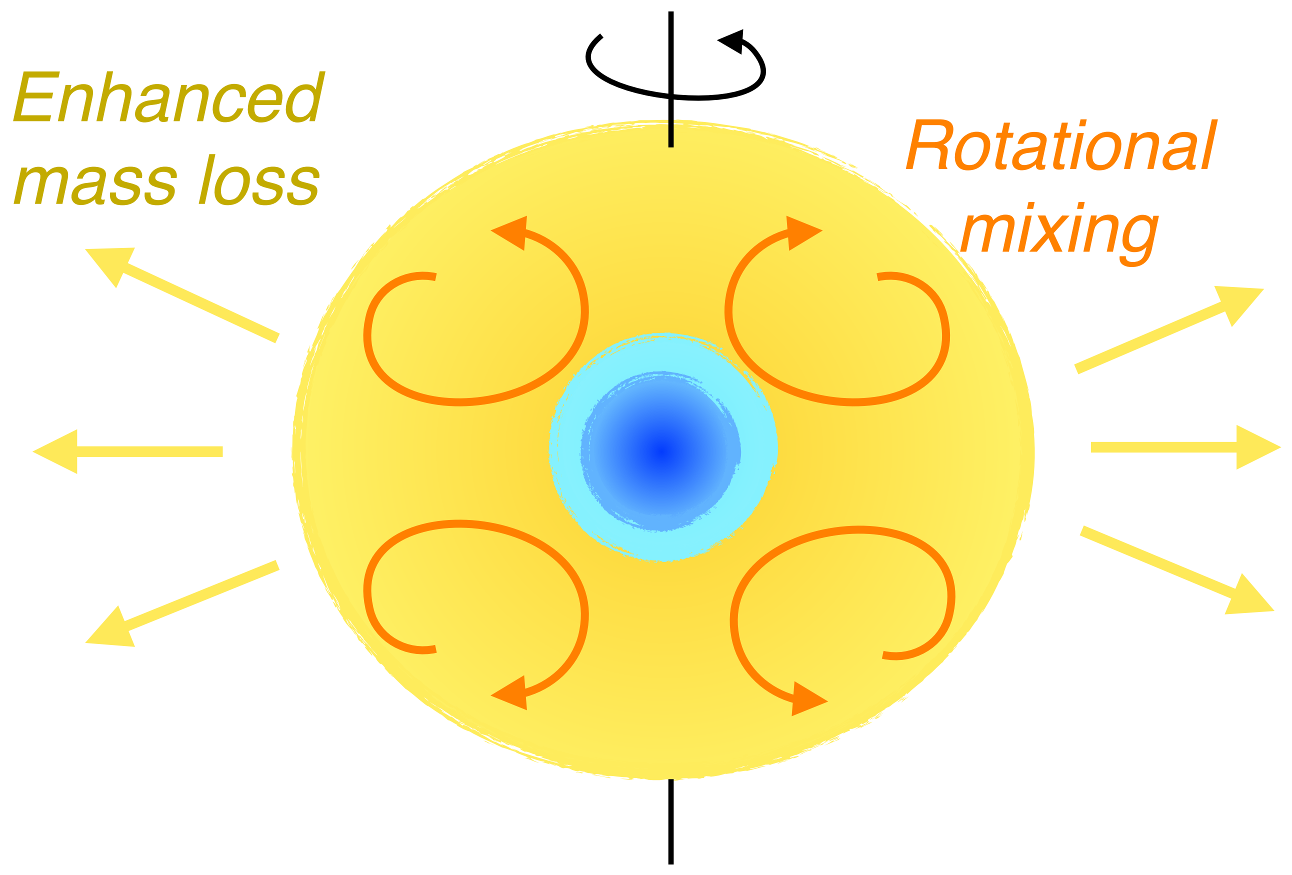

In extreme cases:
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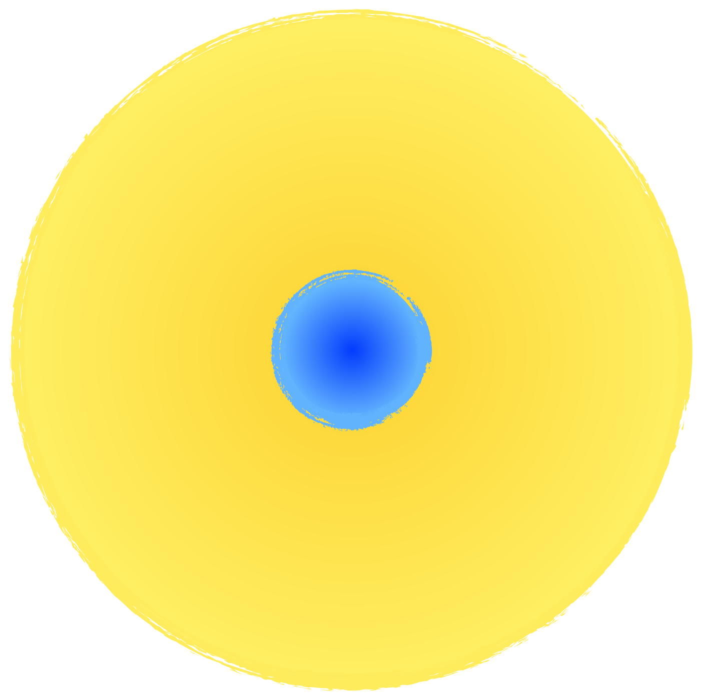

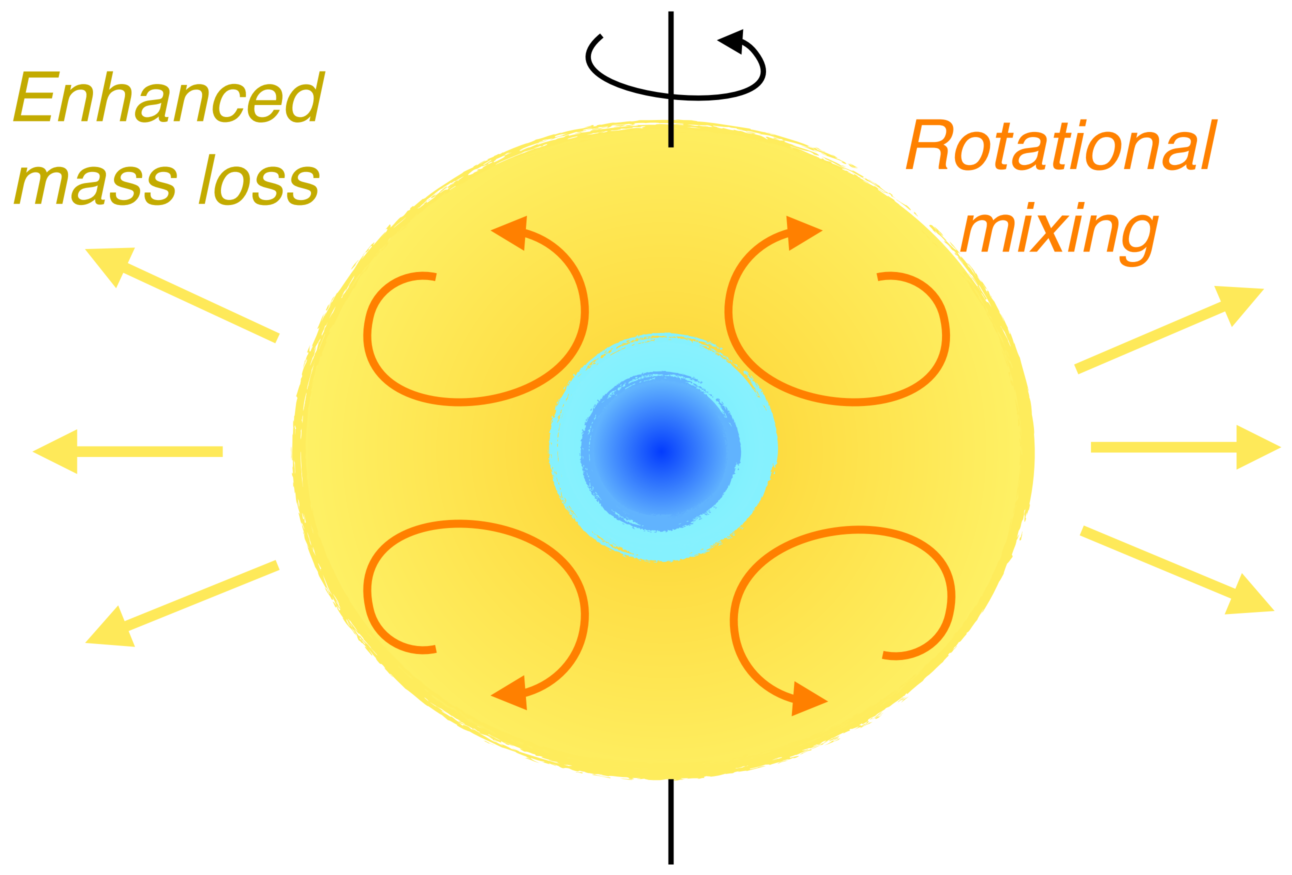

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Medium rotaton (v $\lesssim$ 500 km/s)

- Increased ionization because more Wolf-Rayet stars are formed

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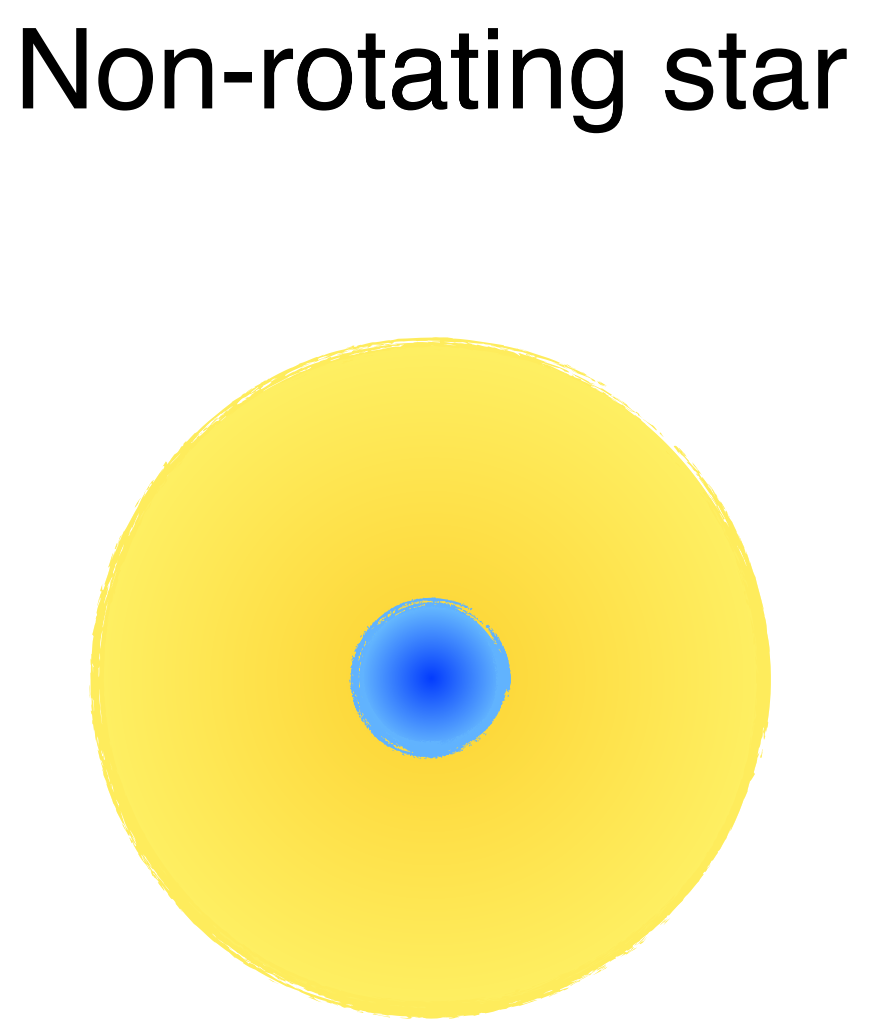
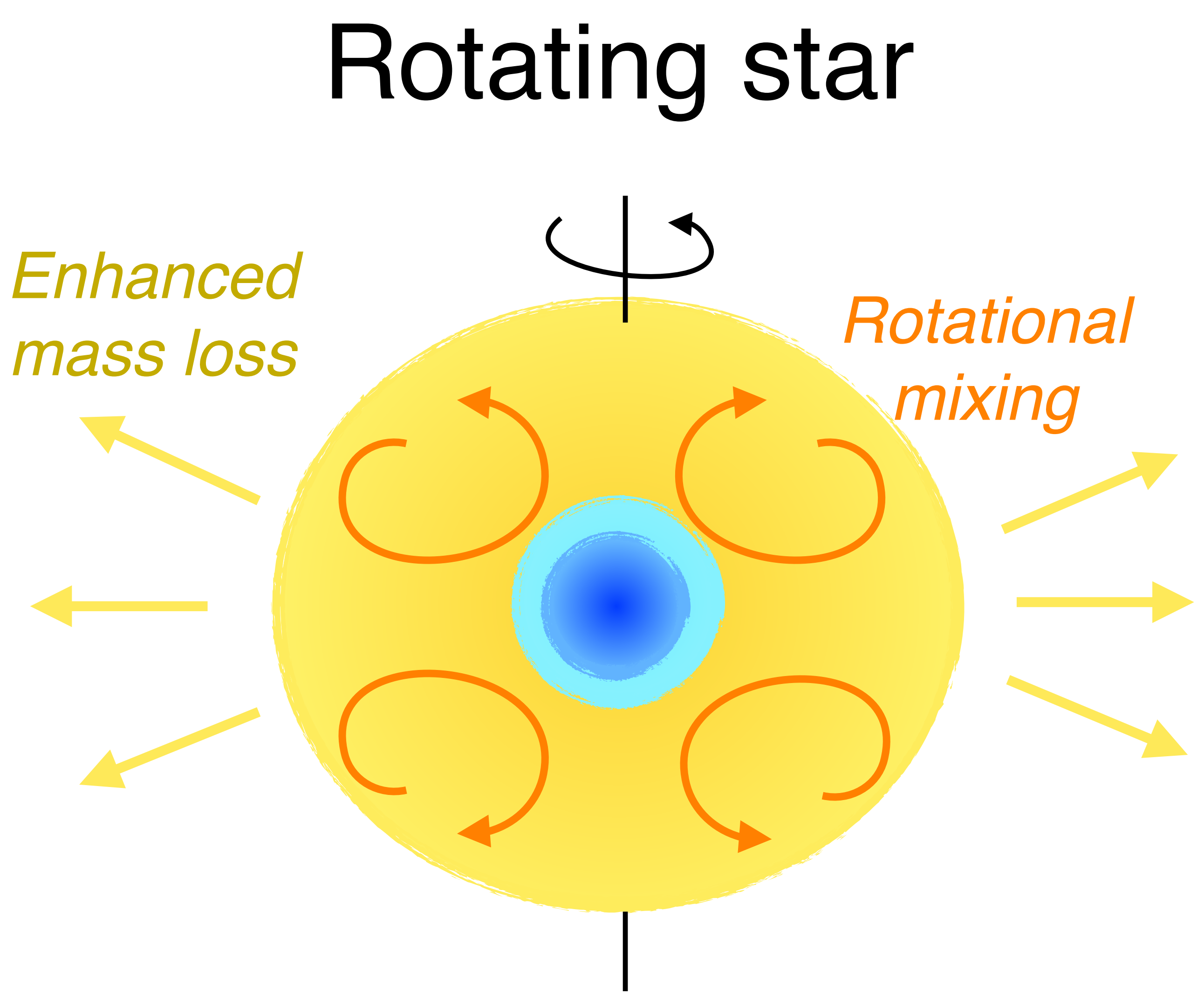




In extreme cases: chemically homogeneous evolution?

Medium rotaton (v $\lesssim$ 500 km/s)

- Increased ionization because more Wolf-Rayet stars are formed

High rotaton (v $\gtrsim$ 500 km/s) + high mass (> 20 $M_\odot$) and low metallicity (Z $\lesssim$ $Z_\odot$/2)

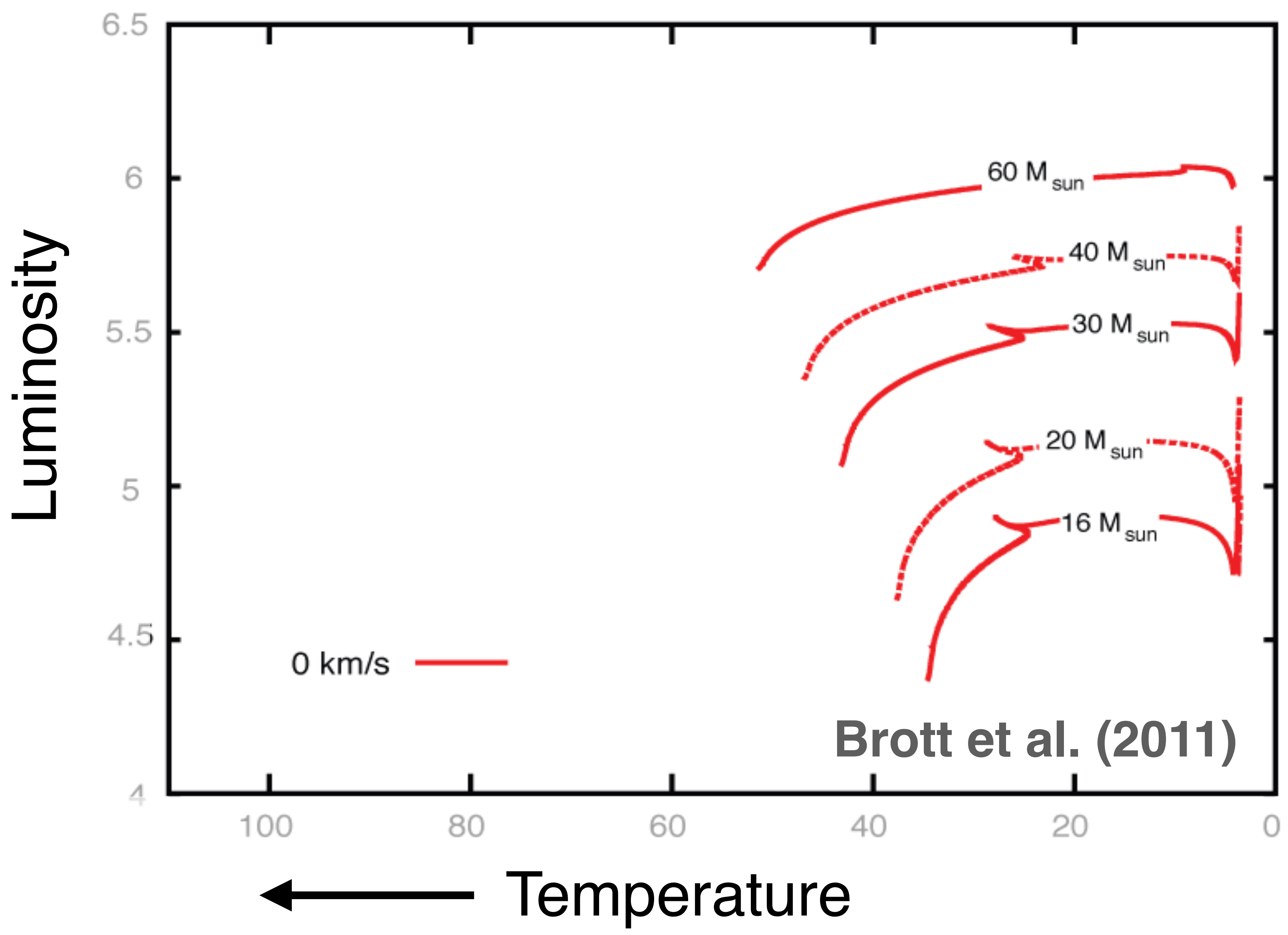
- Chemically homogeneous evolution results in helium stars

Rotational mixing: Meynet, Maeder, Yoon, Szécsi, Langer, Sana, de Mink, Brott…

Effect of stellar rotation

Rotation is predicted to be able to cause significant mixing inside the very rapidly rotating stars, leading the evolutionary tracks to evolve to bluer, hotter, and more luminous stars…

Only at low-Z



cf. Yoon & Langer (2005), Brott et al., (2011), Szécsi et al. (2016)

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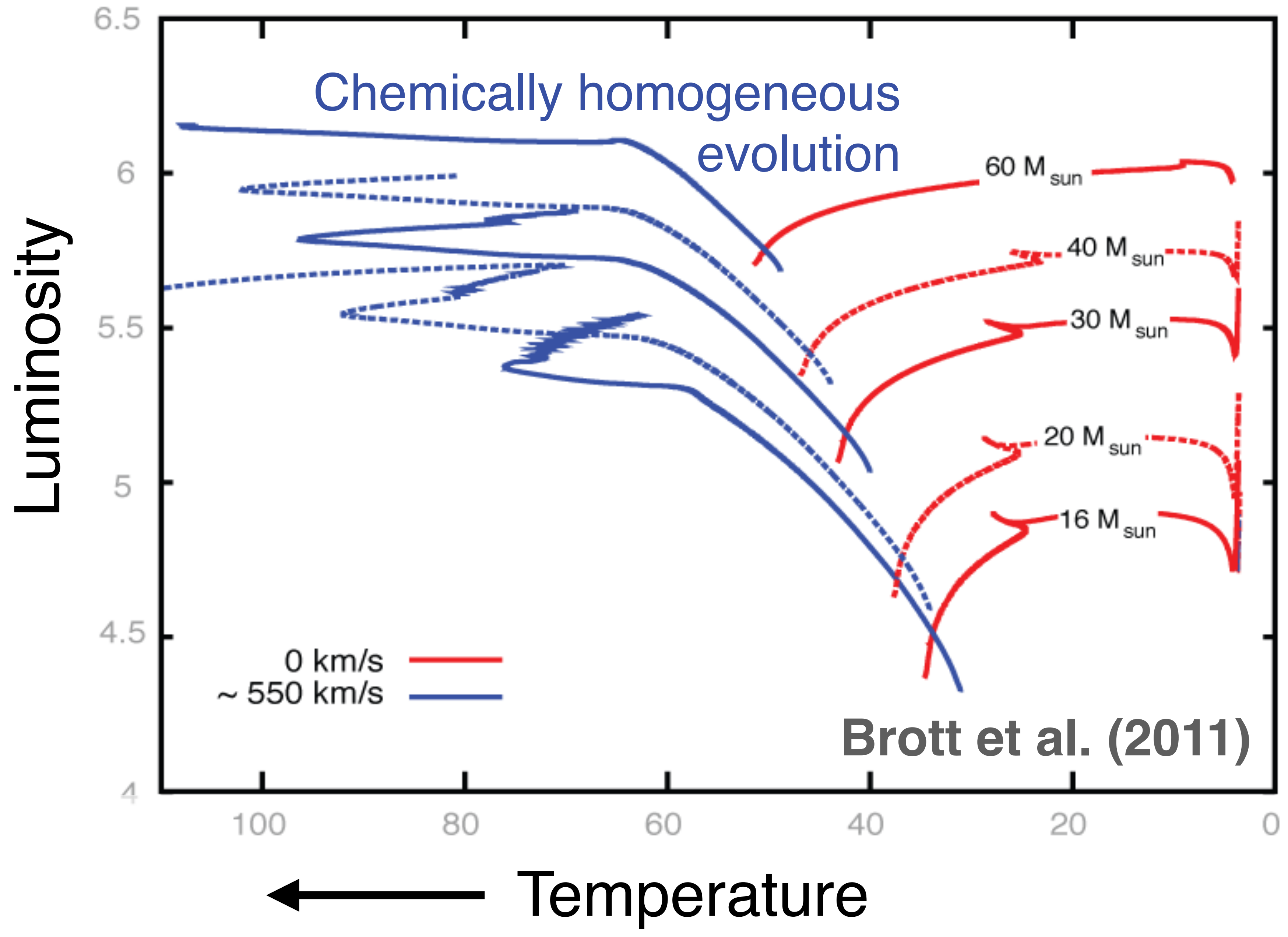

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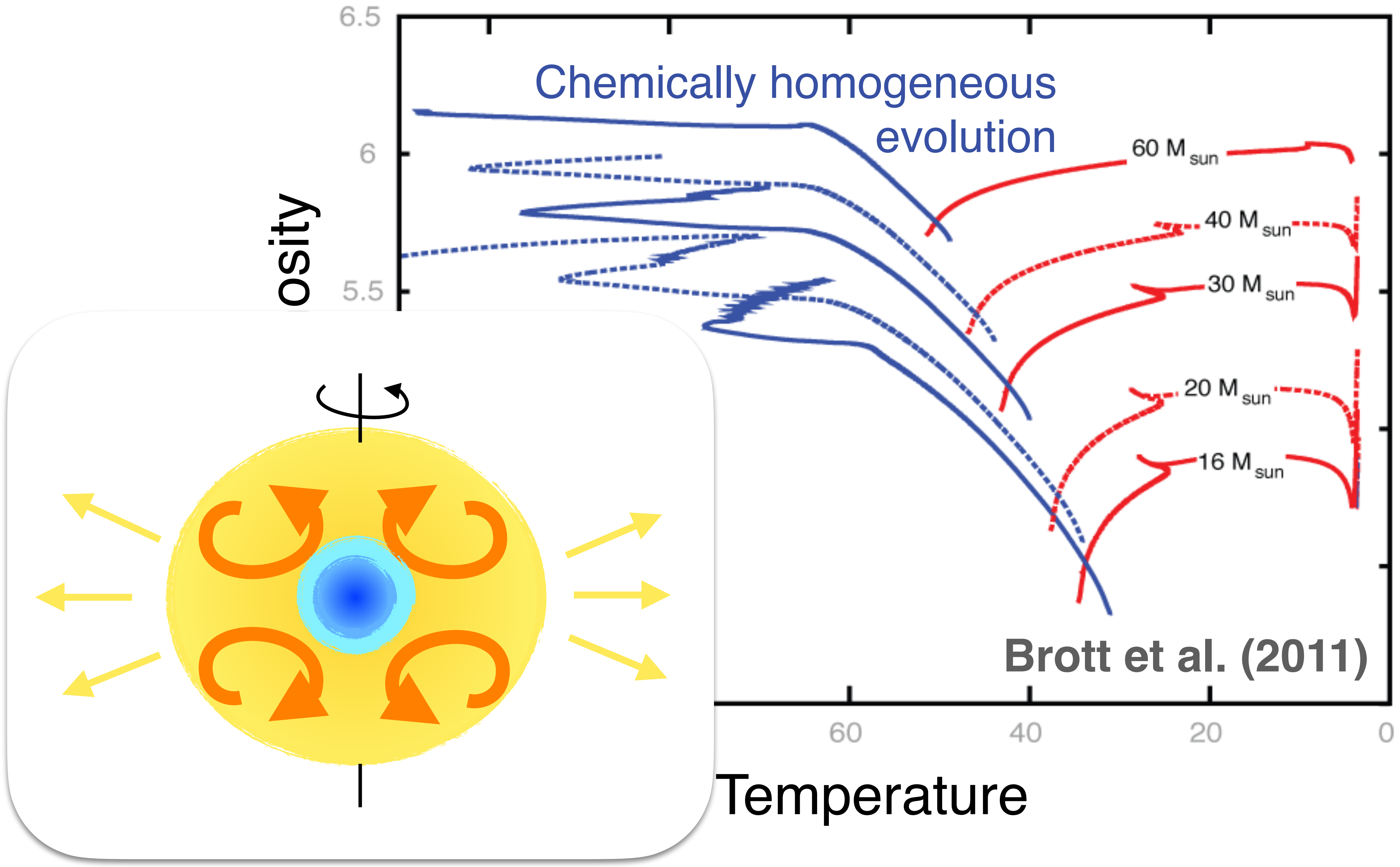

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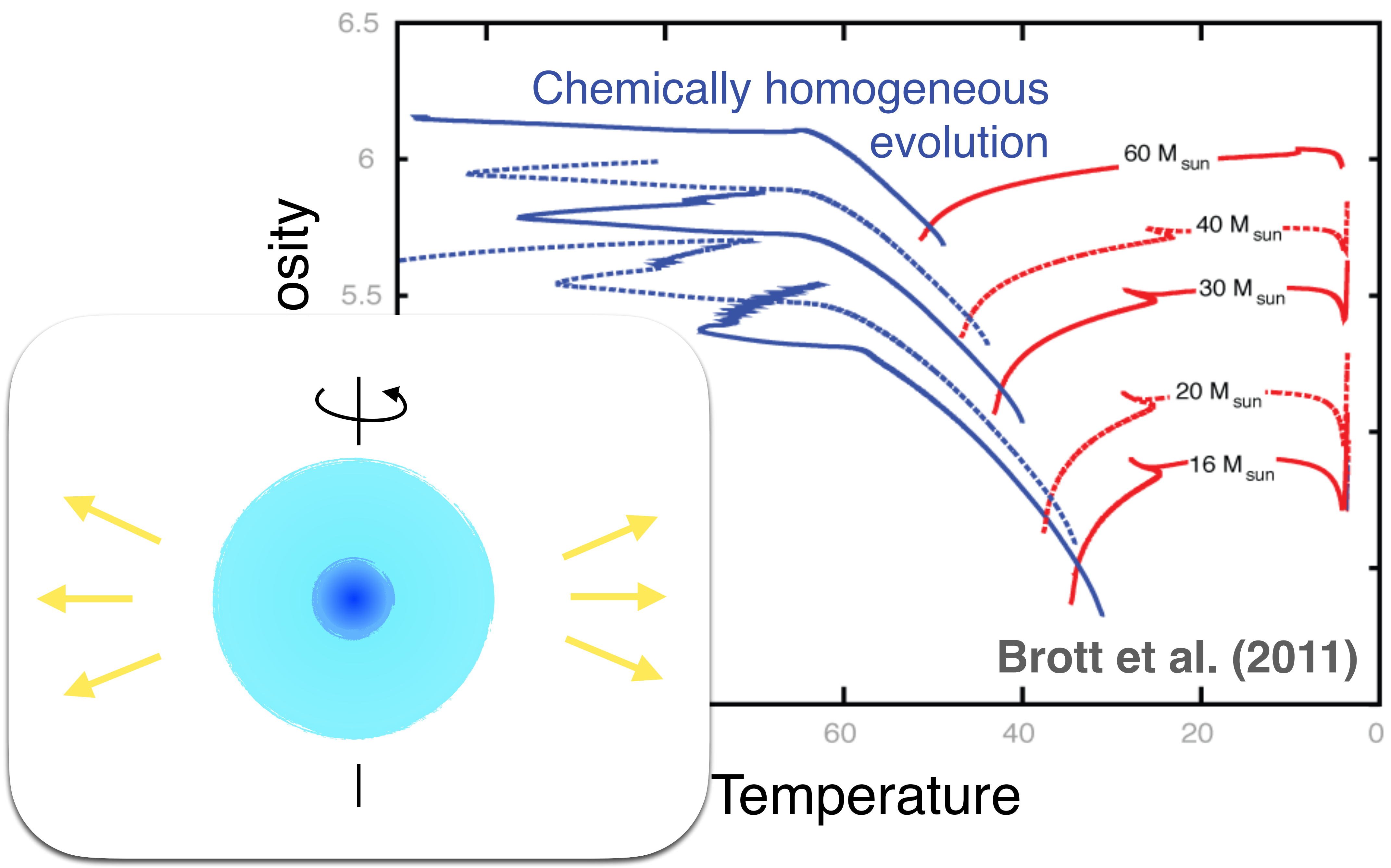

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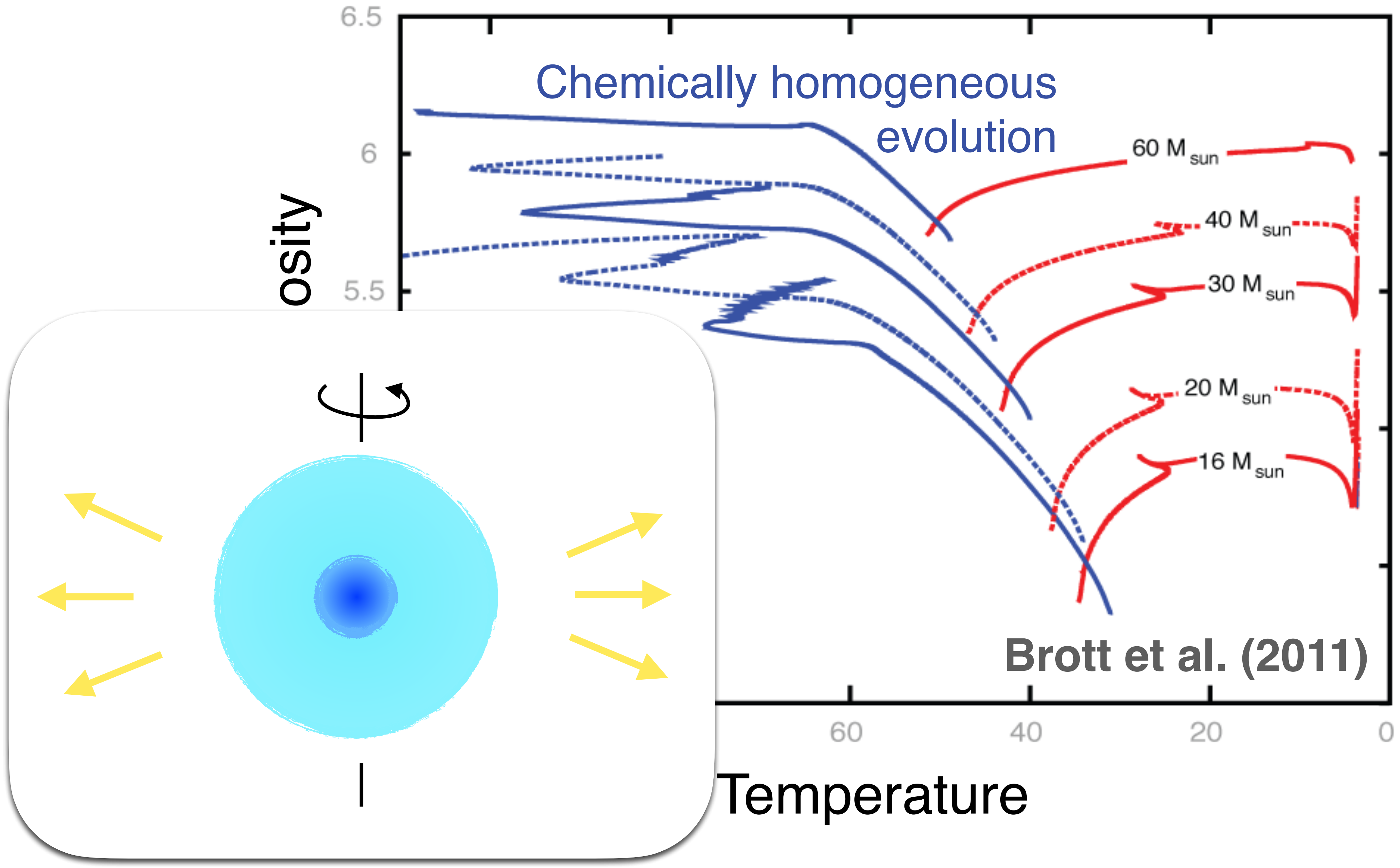
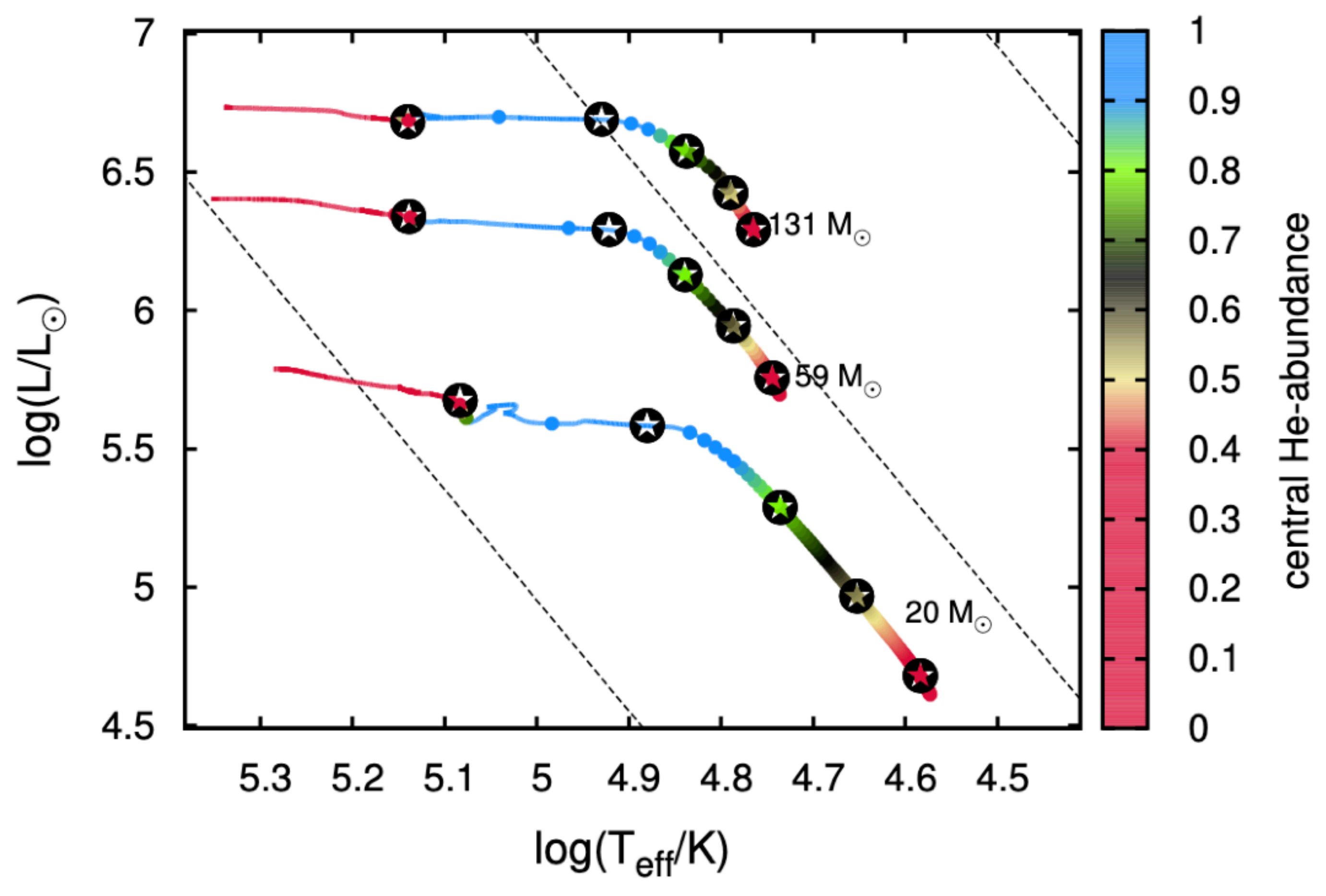


Chemically homogeneously evolving stars should show (1) high ionizing emission, (2) rapid rotation, (3) enhanced helium and nitrogen.



Szécsi et al. (2015), Kubátová et al. (2019)

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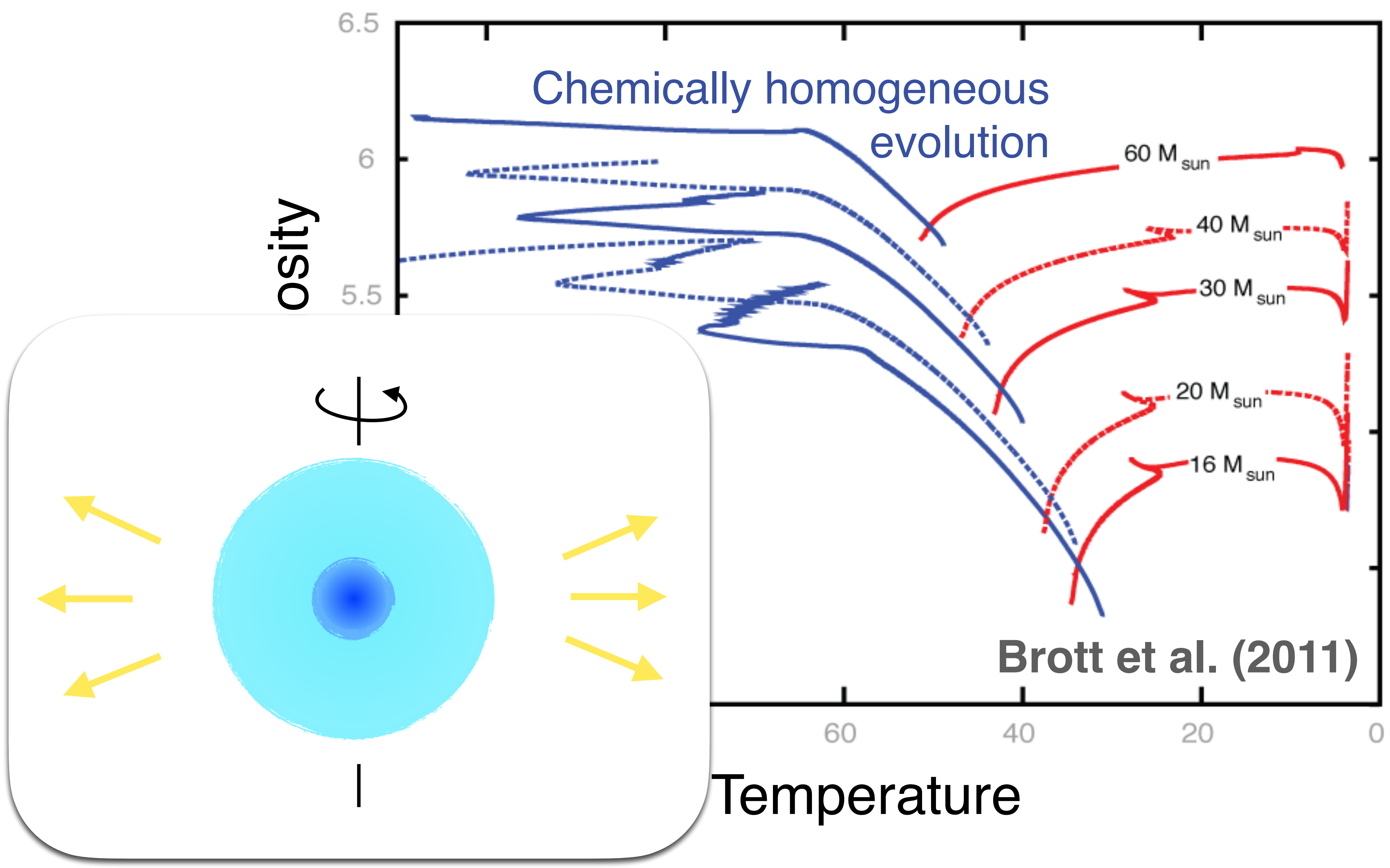

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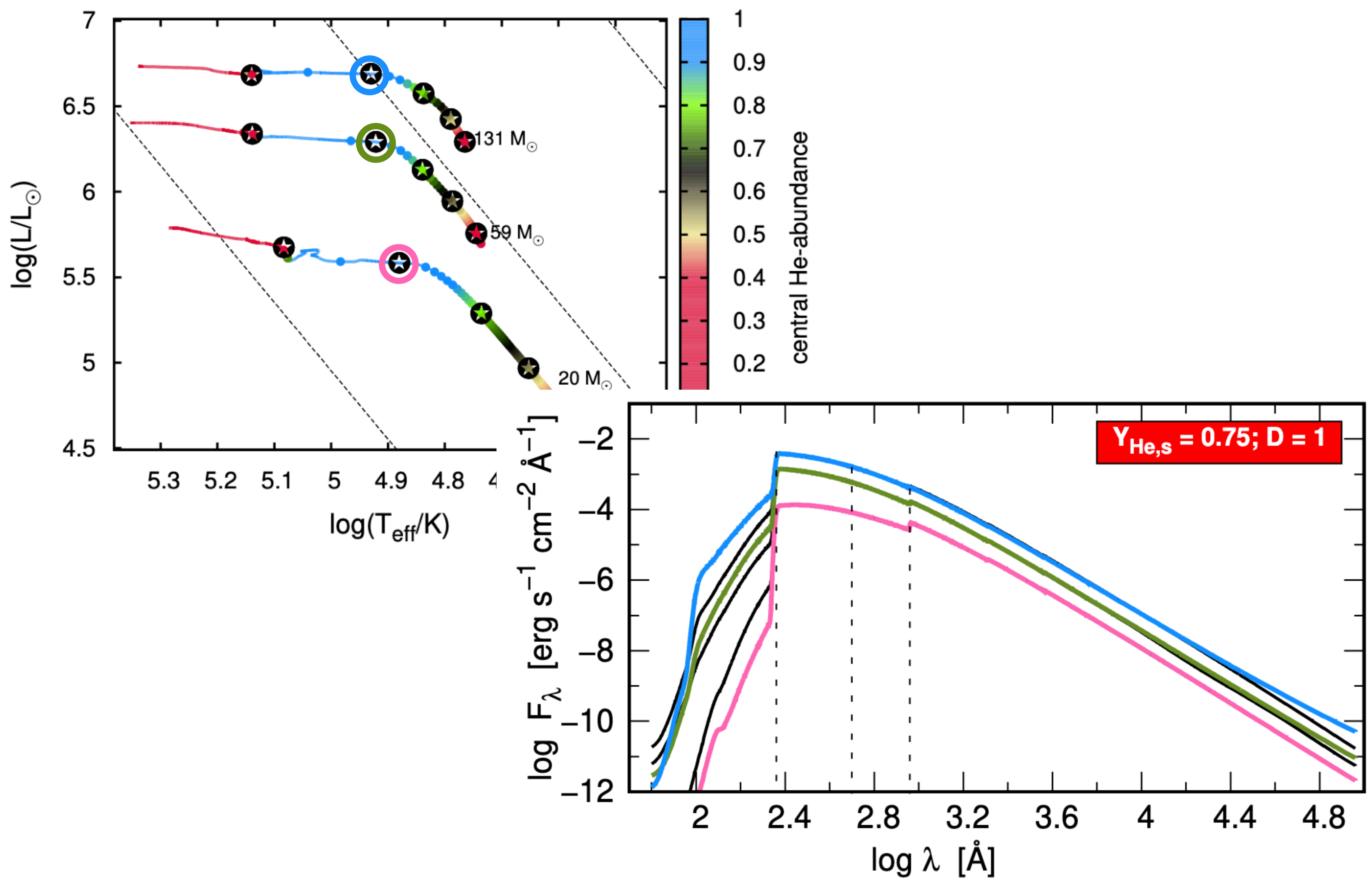

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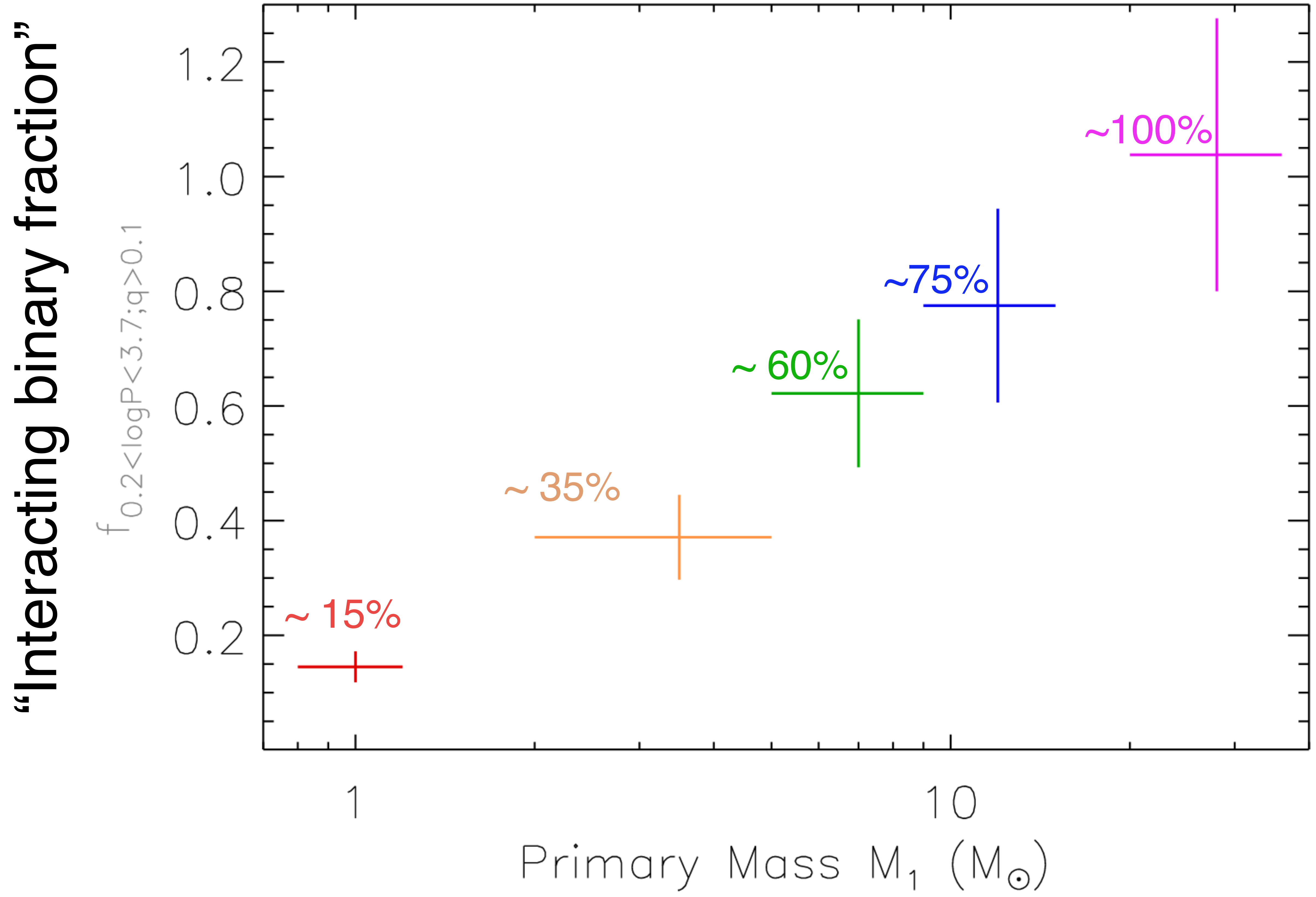
1) Stars that ionize

(Mostly) binaries

Binary interaction *is* the normal stellar evolution

The fraction of binaries that will interact is high
(Moe & DiStefano, 2017)



(Öpik 1924, Abt & Levy 1978, Sana et al. 2012, Chini et al. 2012, Kudritzski et al. 2014, Raghavan et al. 2010, Offner et al. 2023, etc.)

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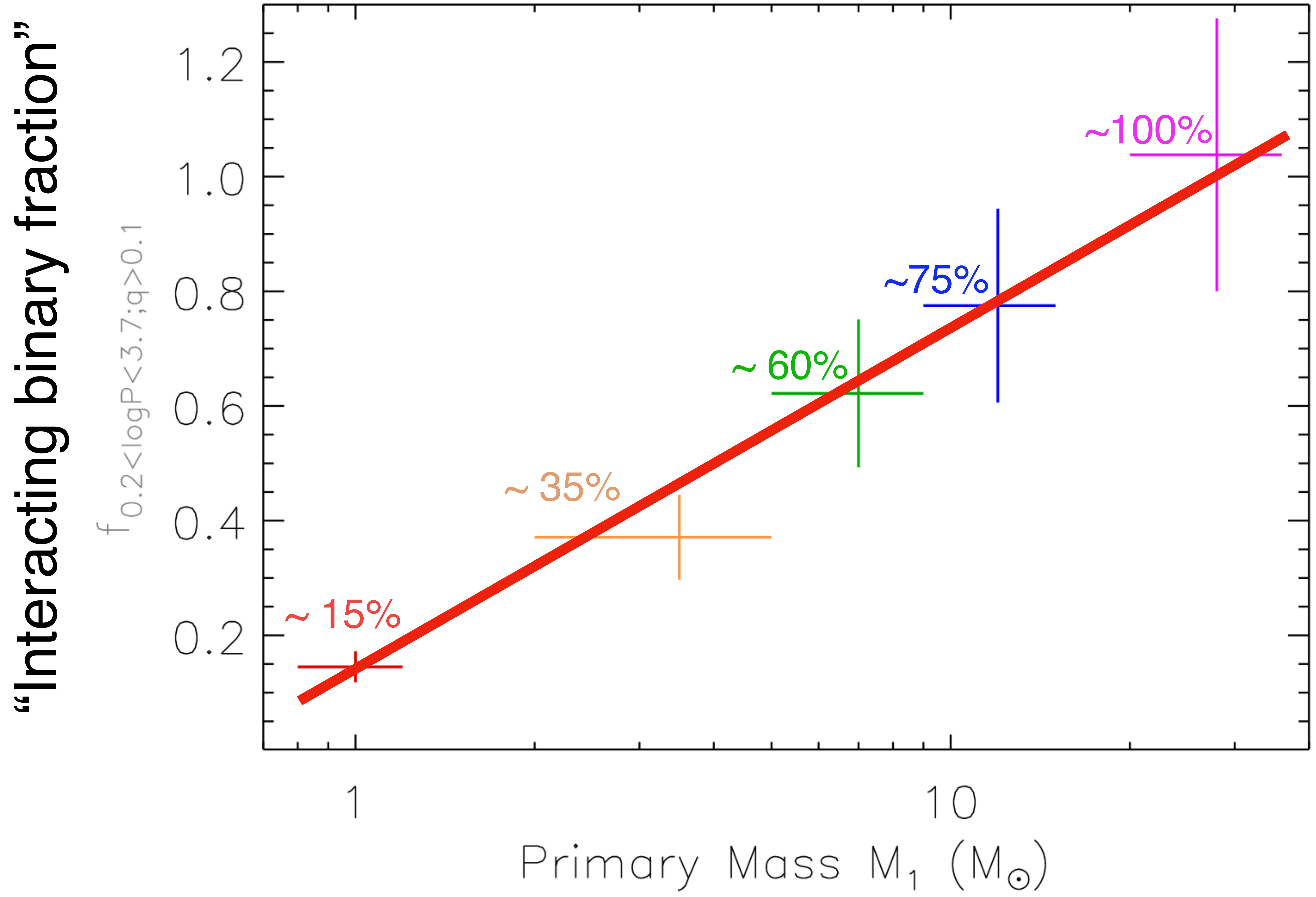

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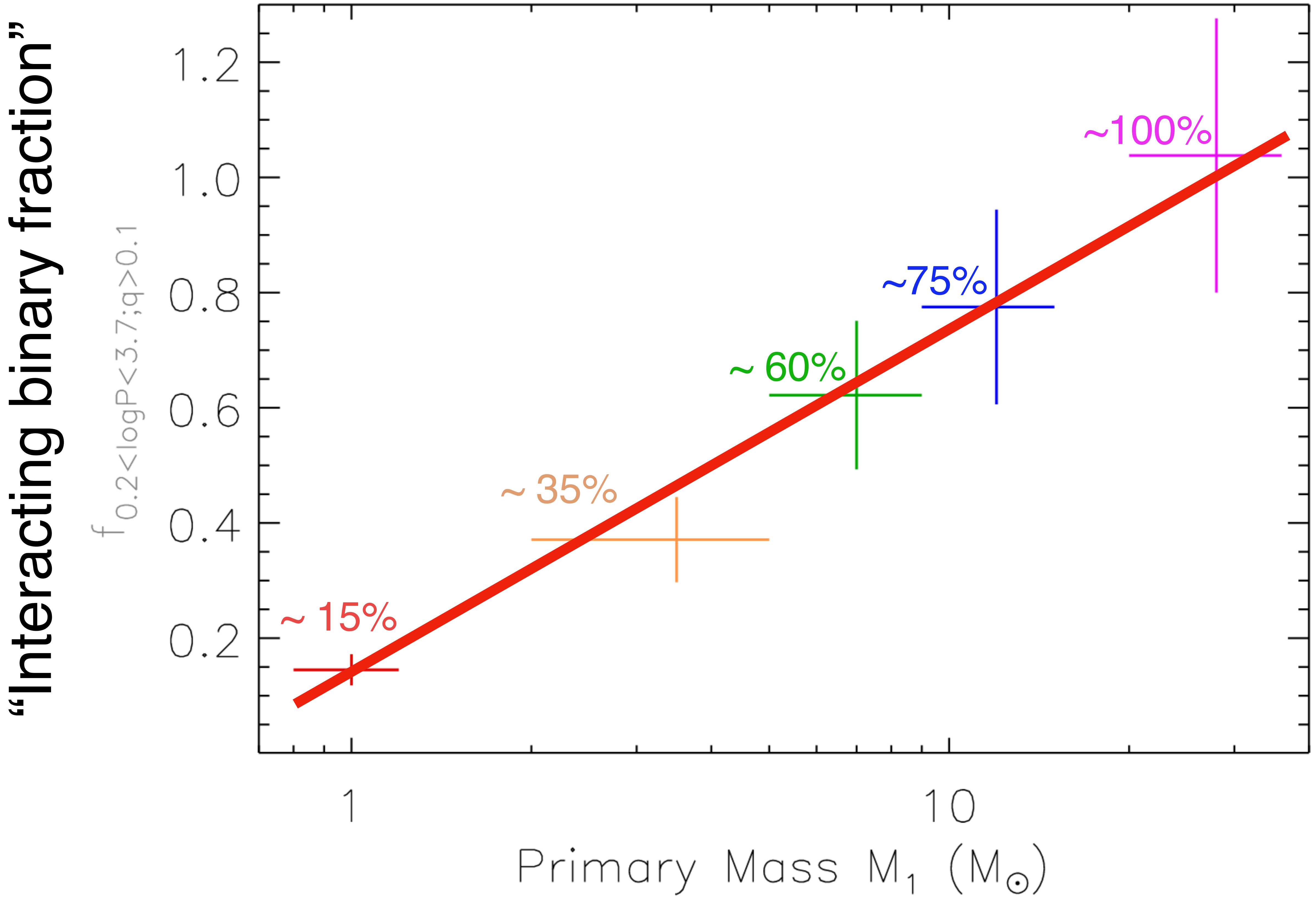

For stars > 5 $M_\odot$,
> 50% interact with a binary companion.

For stars > 30 $M_\odot$,
all interact.

(Öpik 1924, Abt & Levy 1978, Sana et al. 2012, Chini et al. 2012, Kudritzski et al. 2014, Raghavan et al. 2010, Offner et al. 2023, etc.)

What is binary interaction?

70 % of massive stars interact in binaries
(Sana et al., 2012)

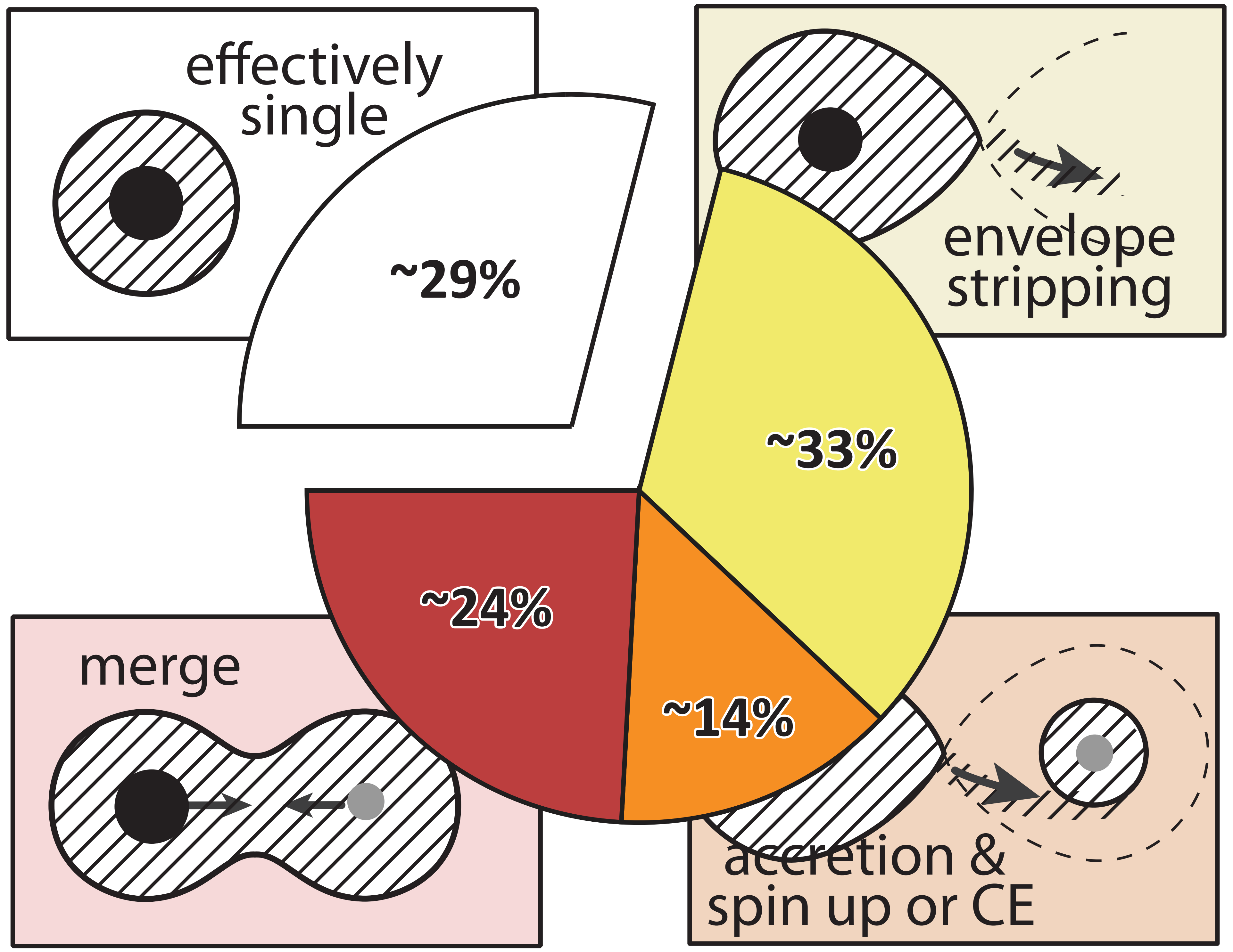

Figure credit: S. E. de Mink
(see also Vanbeveren et al. 1980/2007, Eldridge et al. 2008, Schneider et al. 2014/15)

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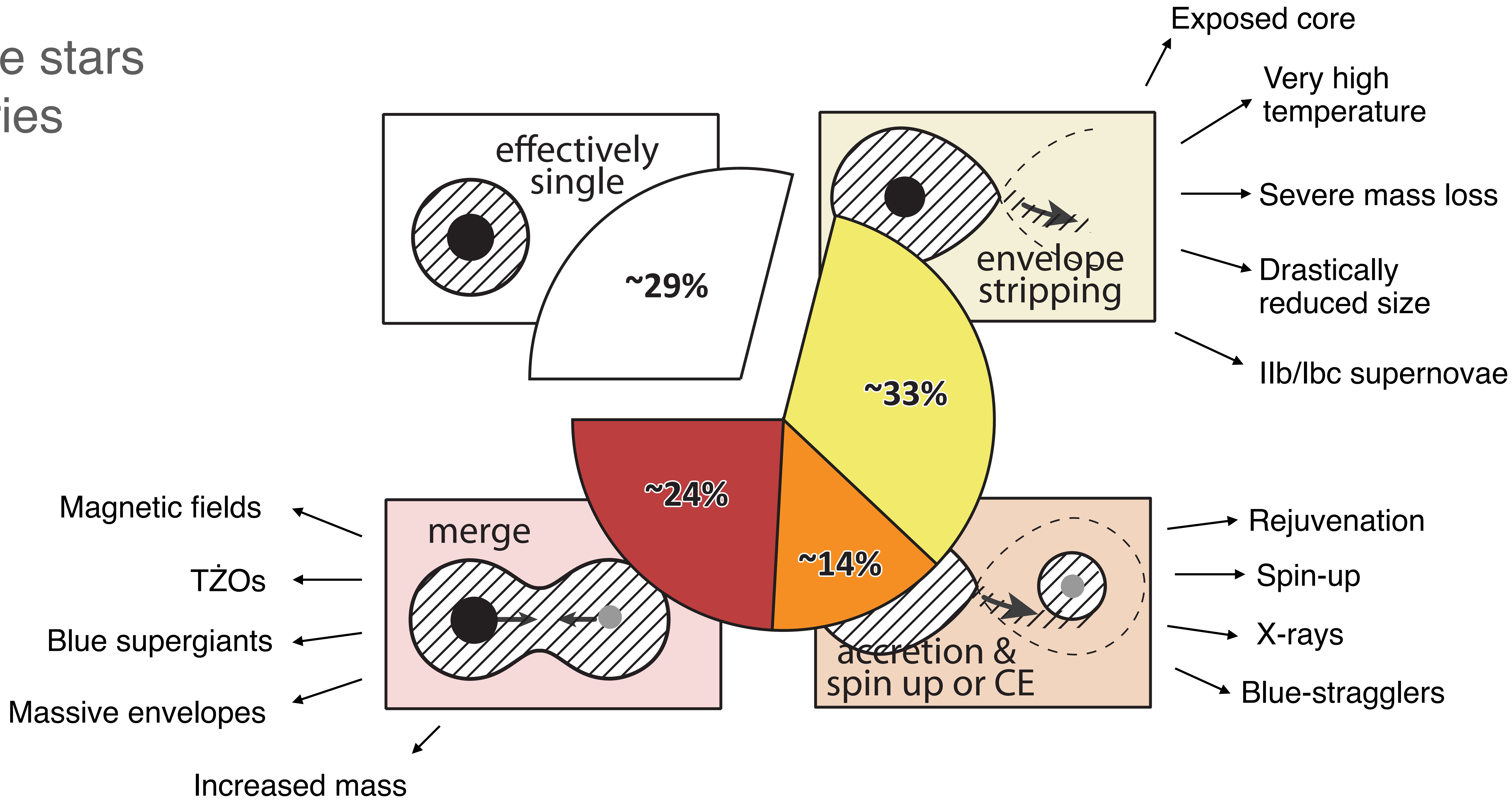

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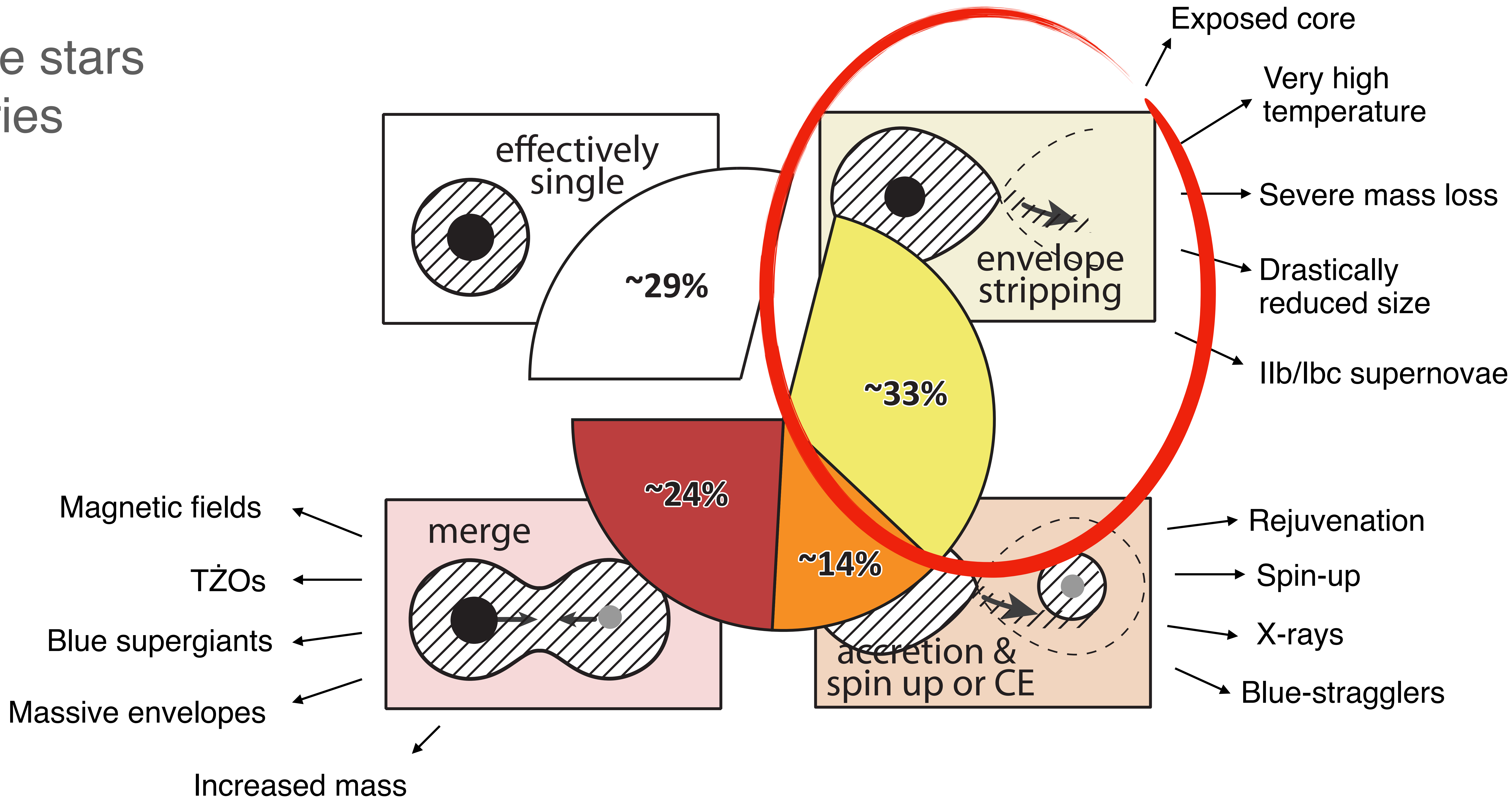

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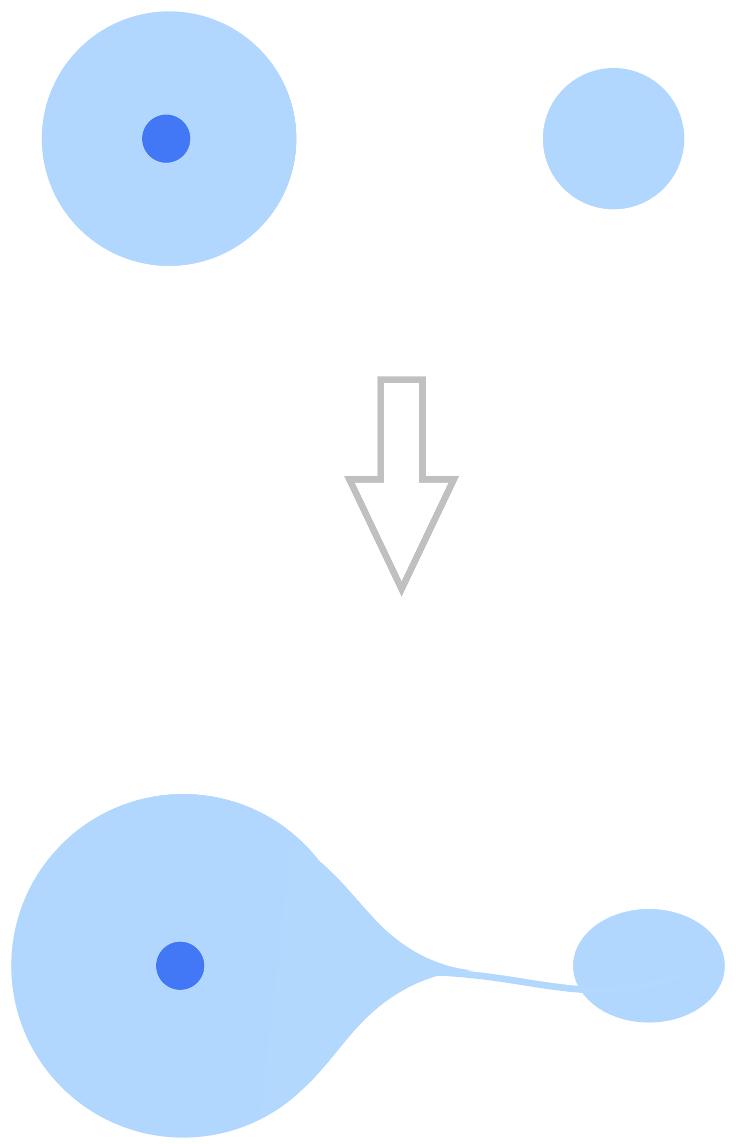
Envelope-stripping and stripped stars

Stripped stars are exposed stellar cores made mostly out of helium. They are very hot and compact, but with bolometric luminosities similar to red supergiants.

Envelope-stripping and stripped stars



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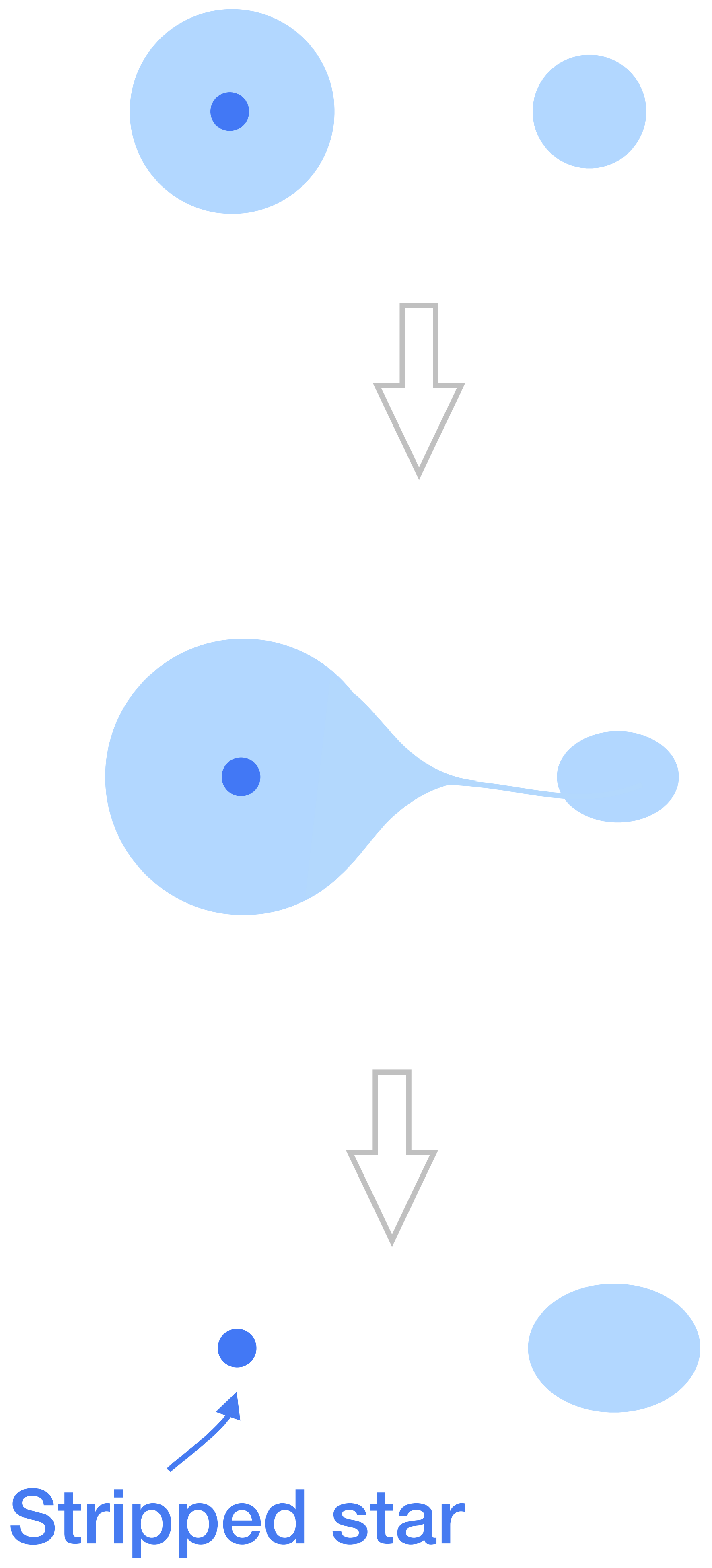

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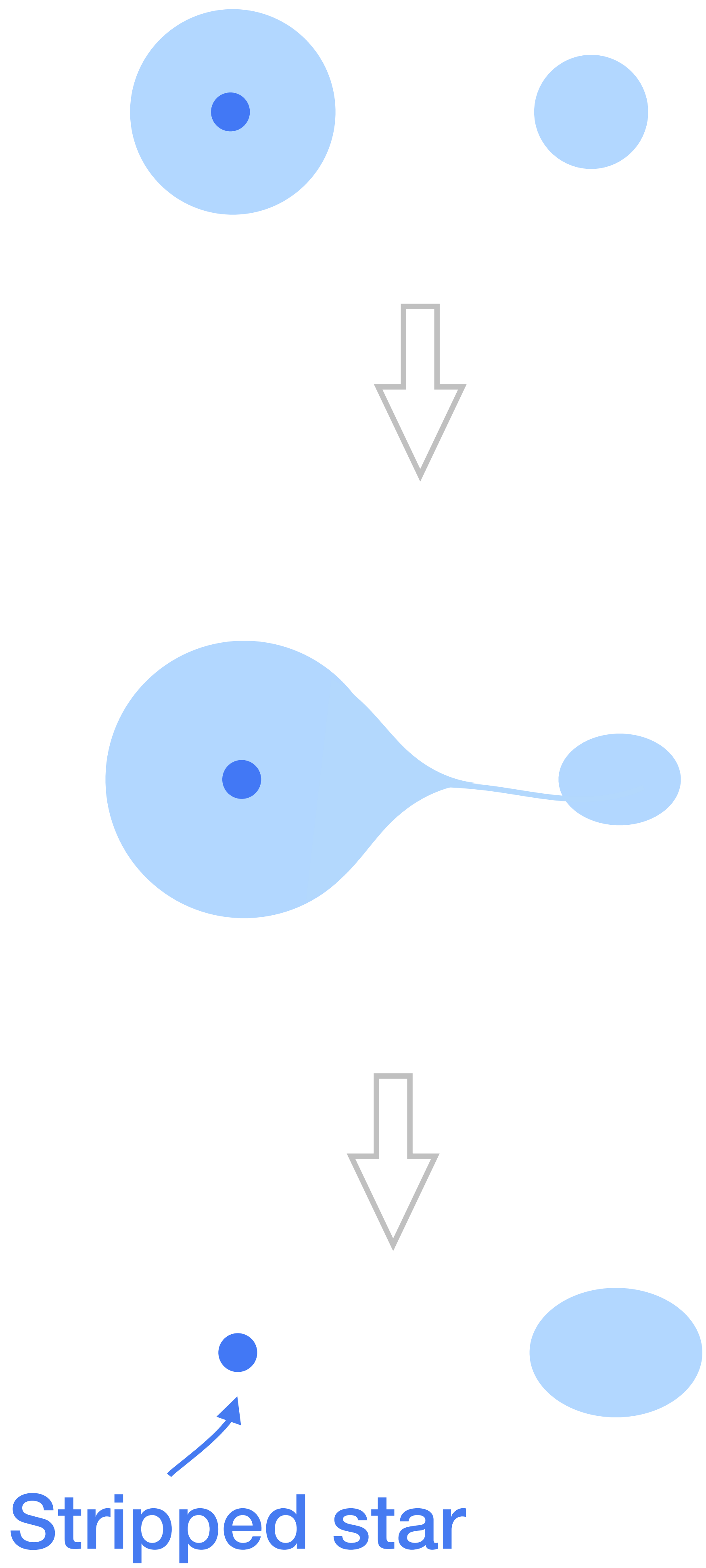

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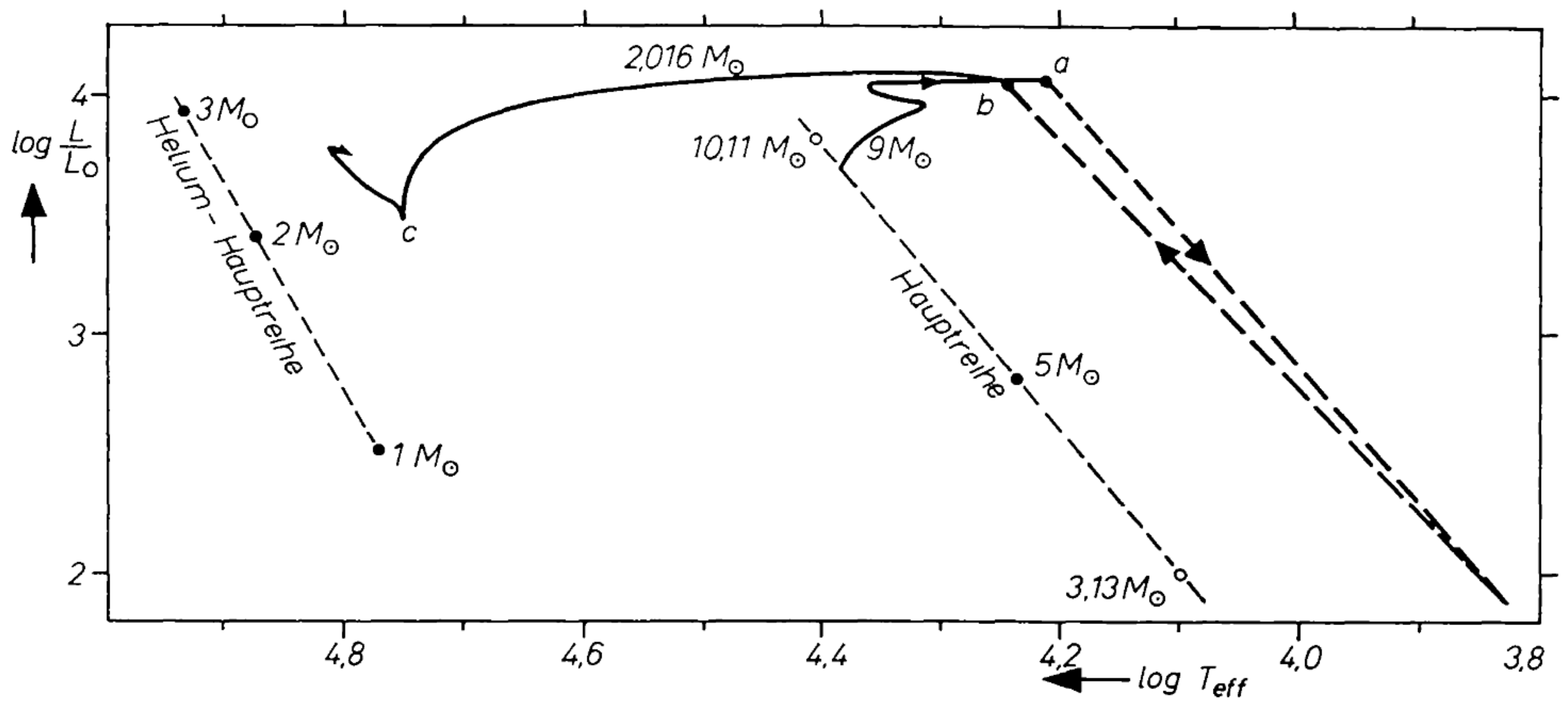

(Kippenhahn & Weigert, 1967)

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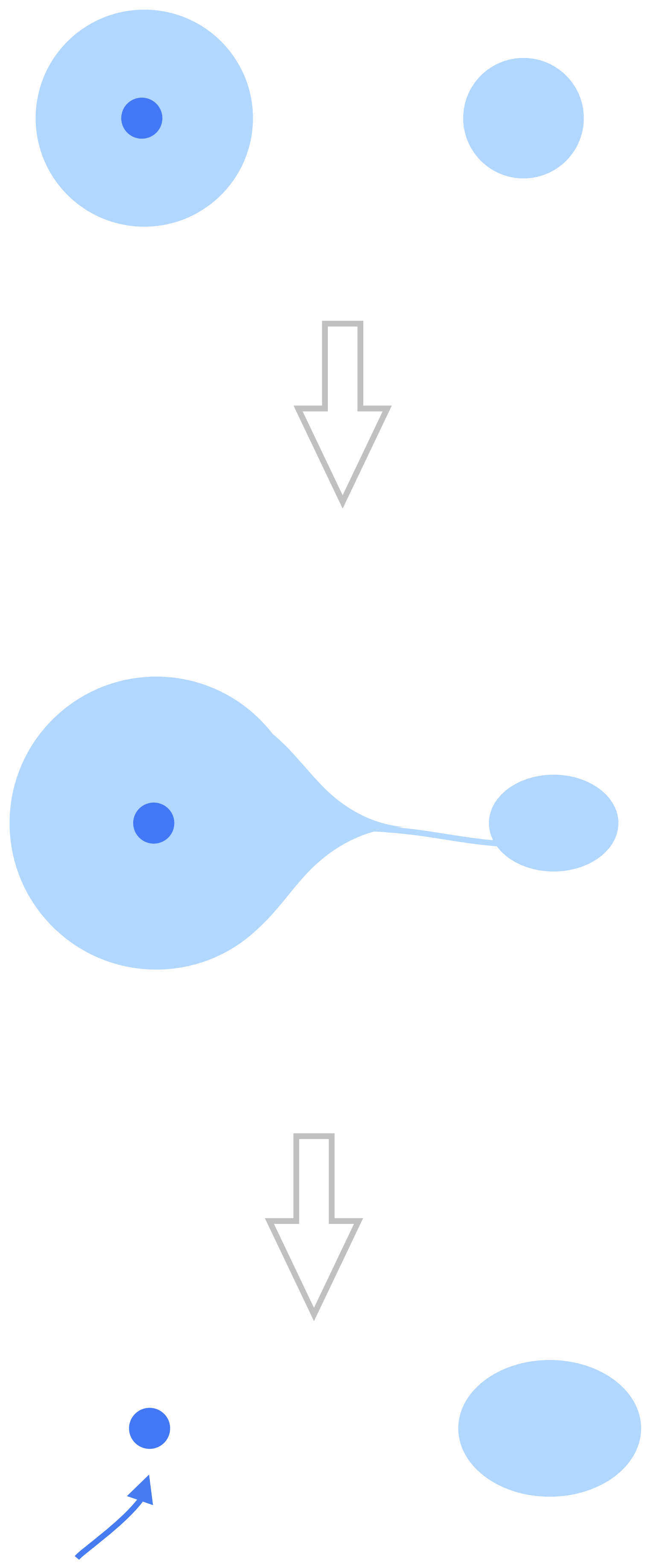

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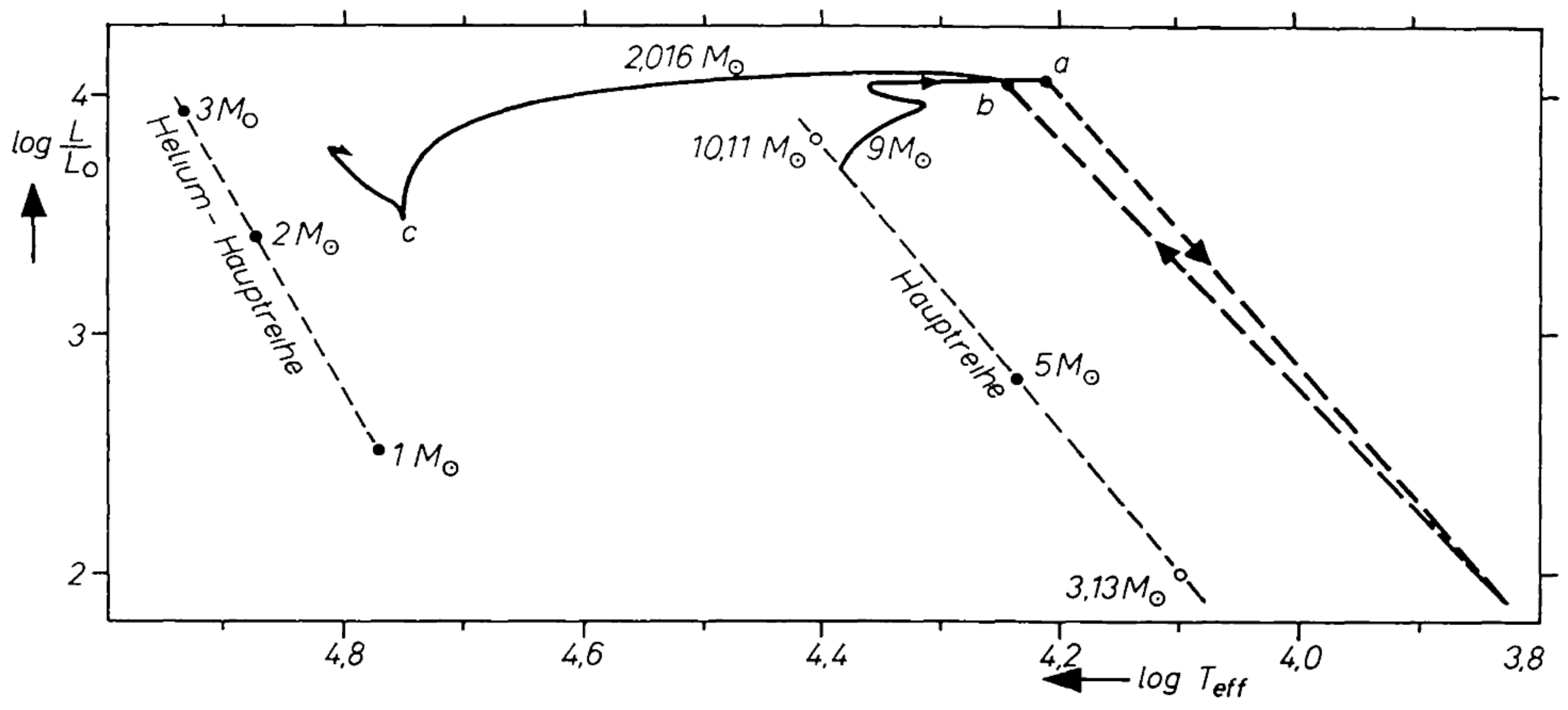

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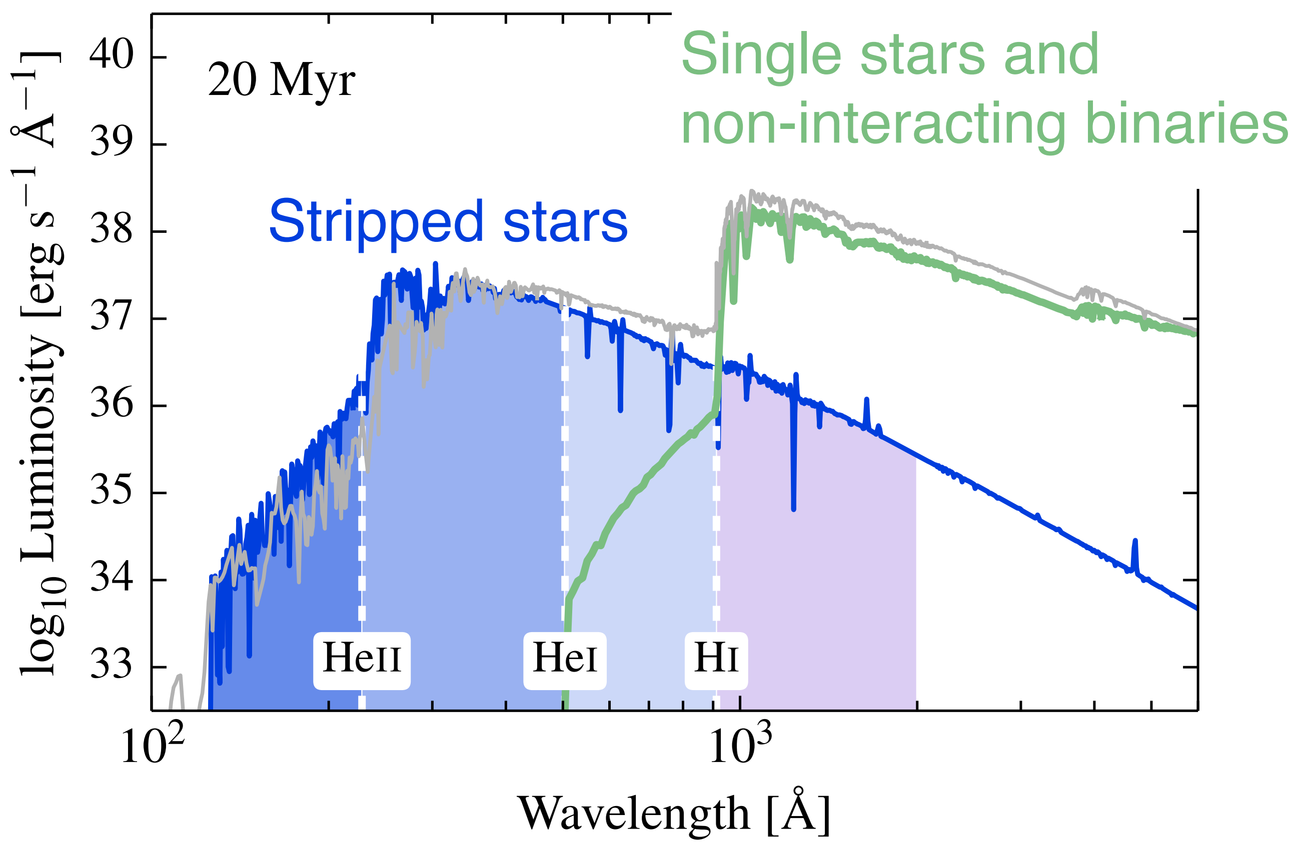
… and they are promising sources for both H- and He- ionizing radiation



Götberg et al. (2019), see also Stanway et al. (2016)

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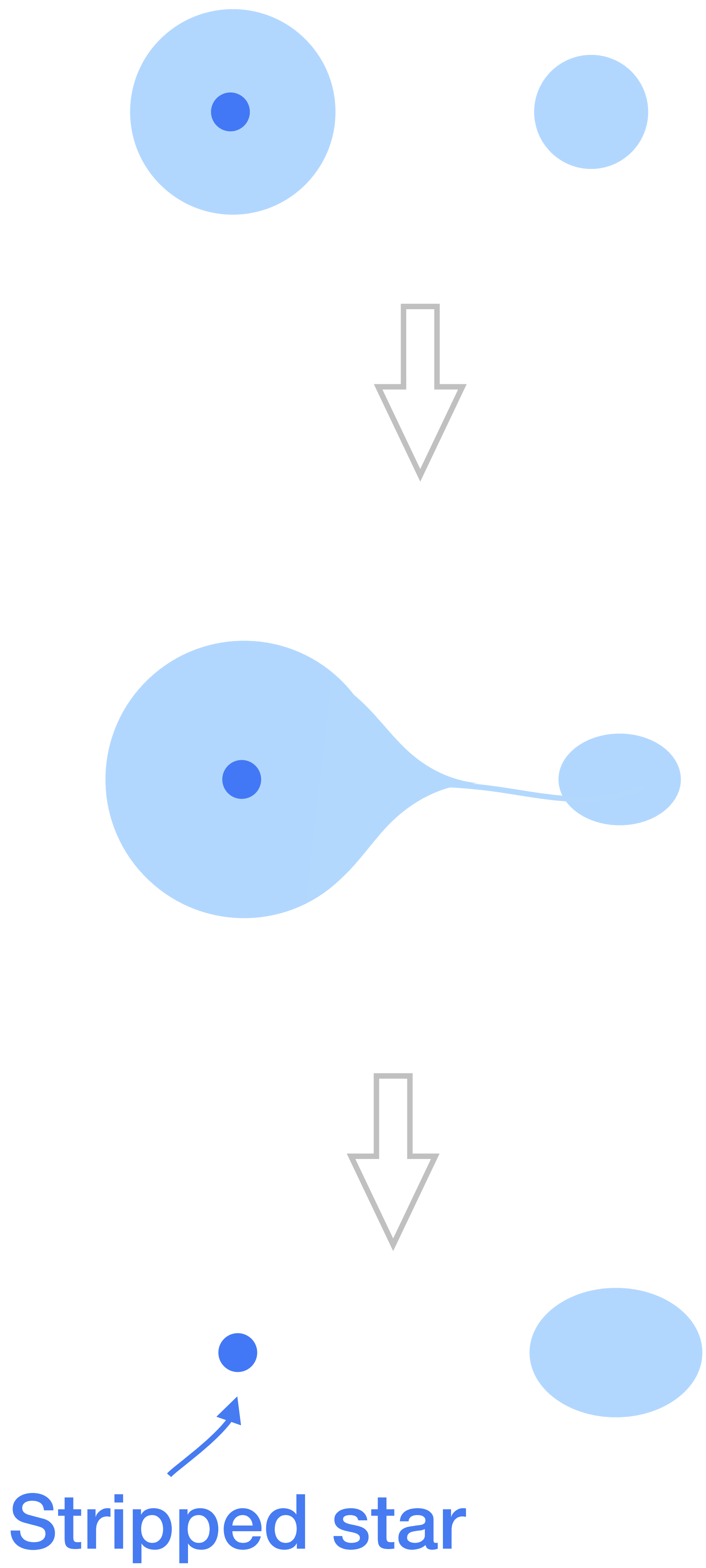

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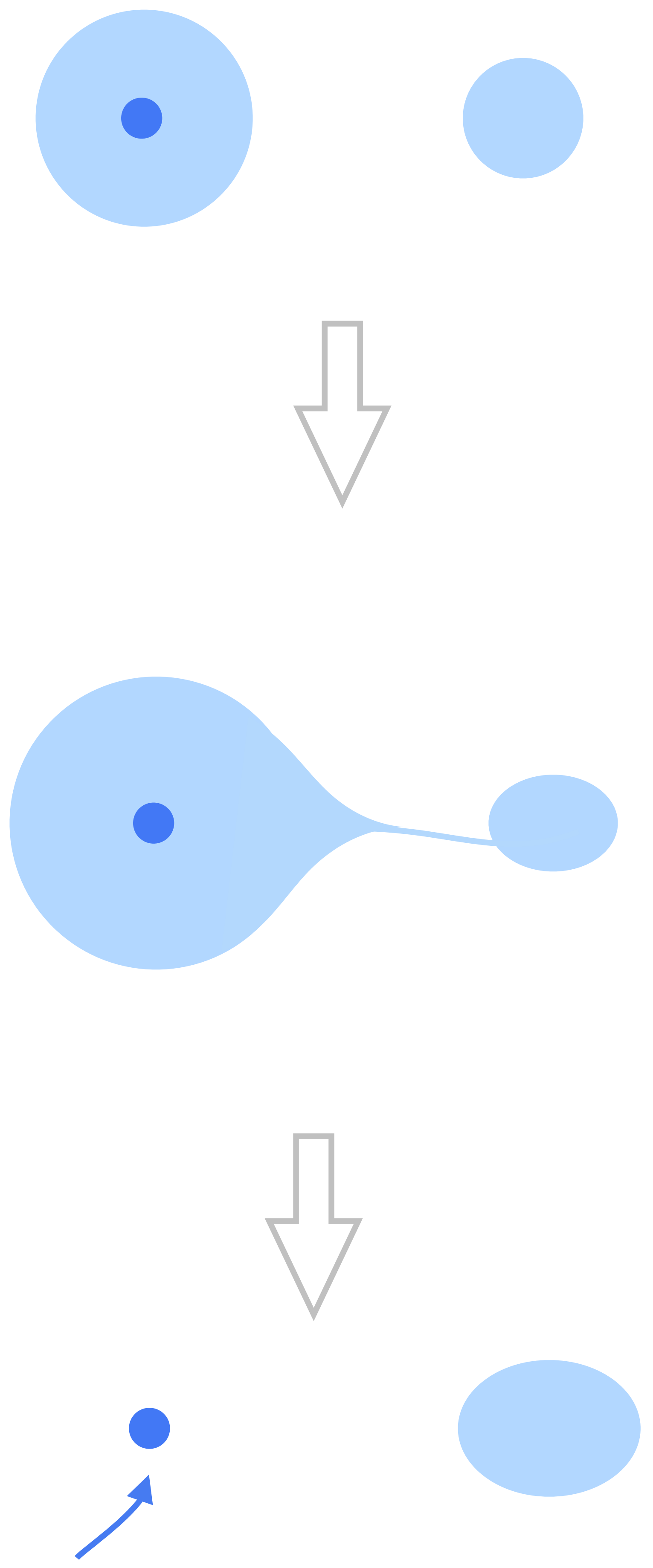

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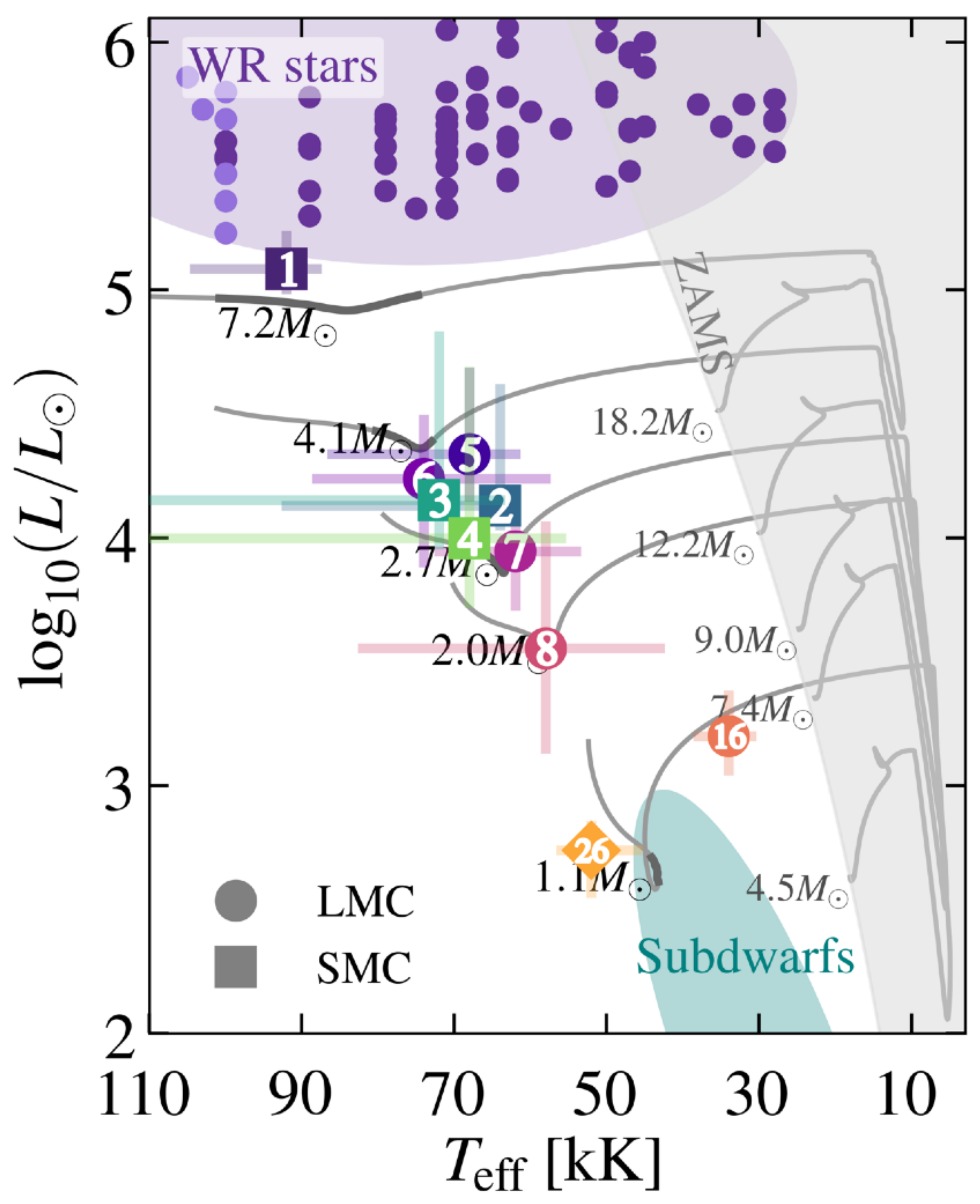

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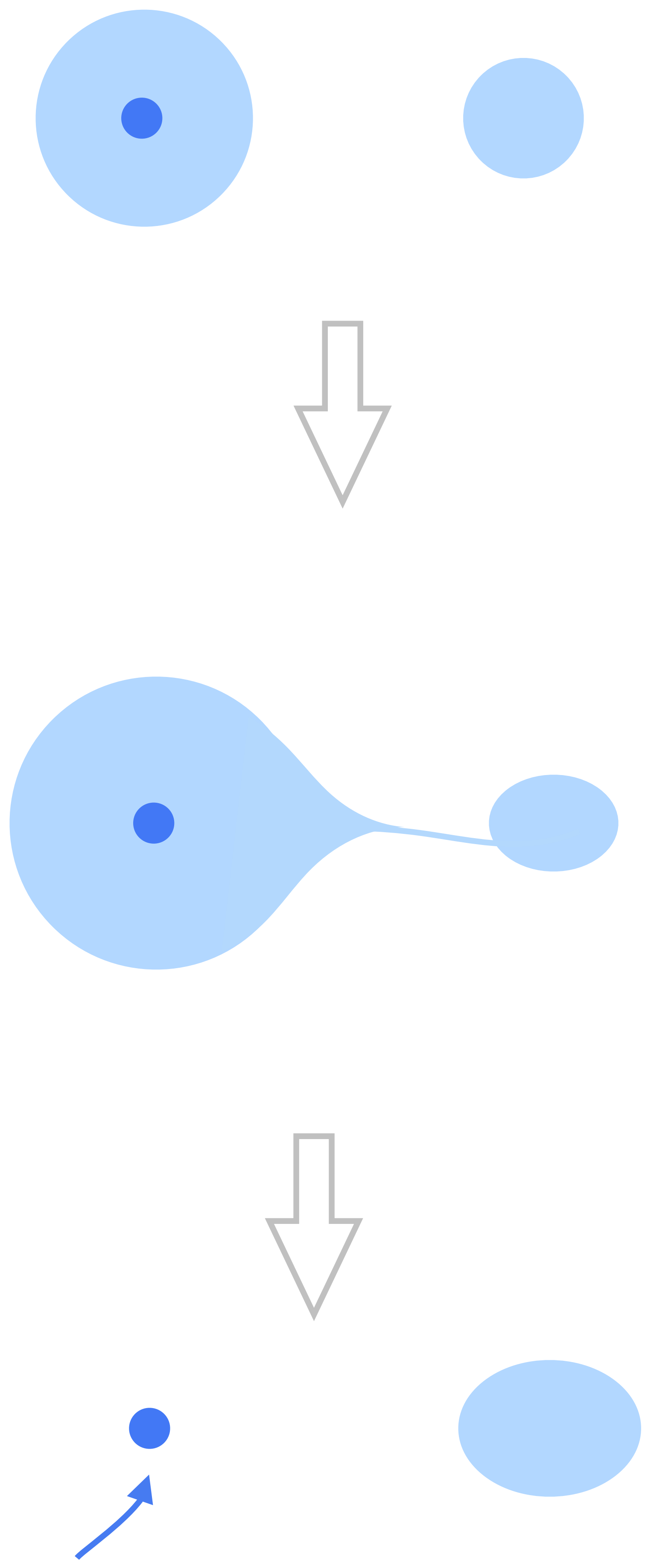

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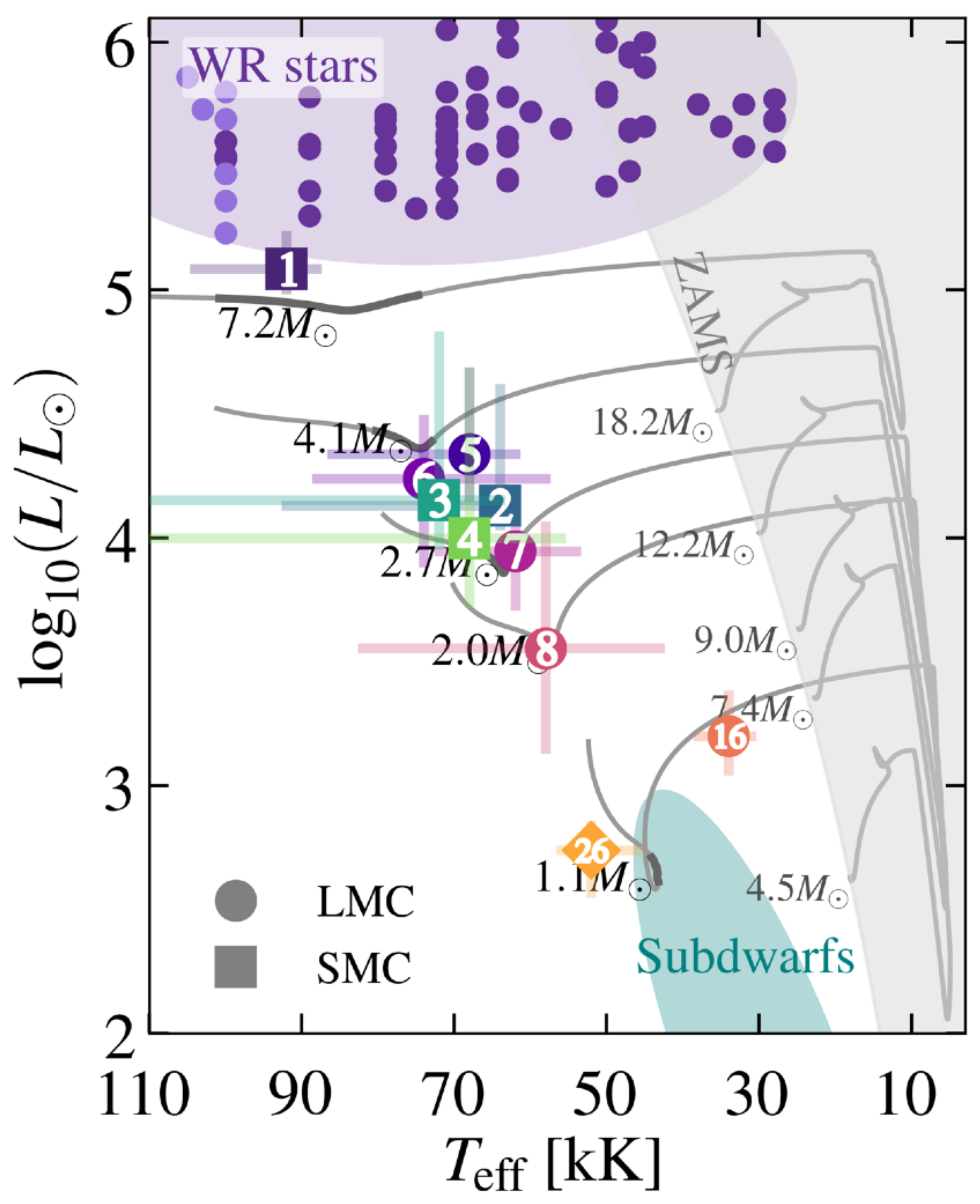

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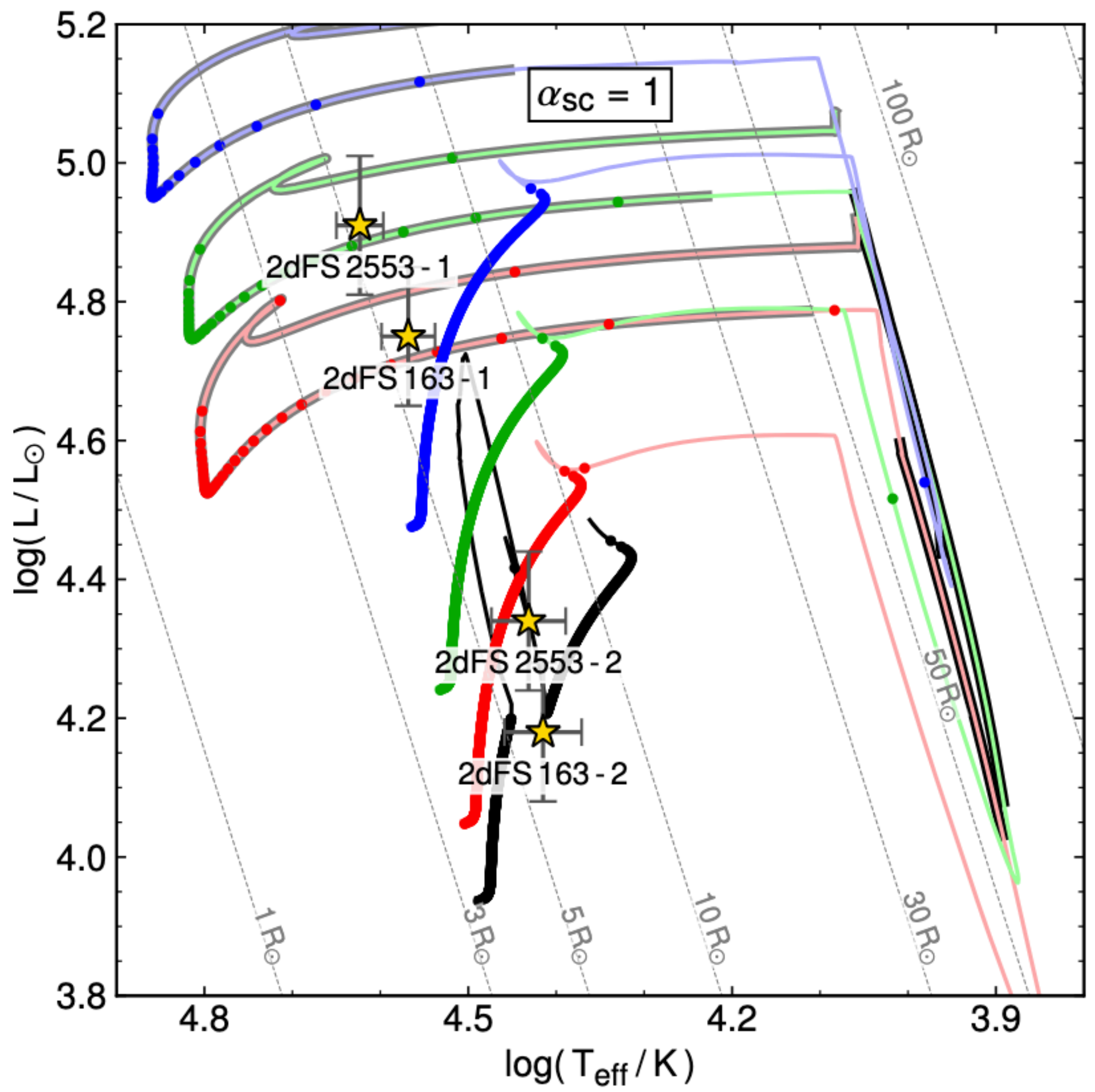
Cool, puffed-up stripped stars in the Milky Way and Magellanic Clouds



Ramachandran et al. (2023)

What is binary interaction?

70 % of massive stars interact in binaries
(Sana et al., 2012)

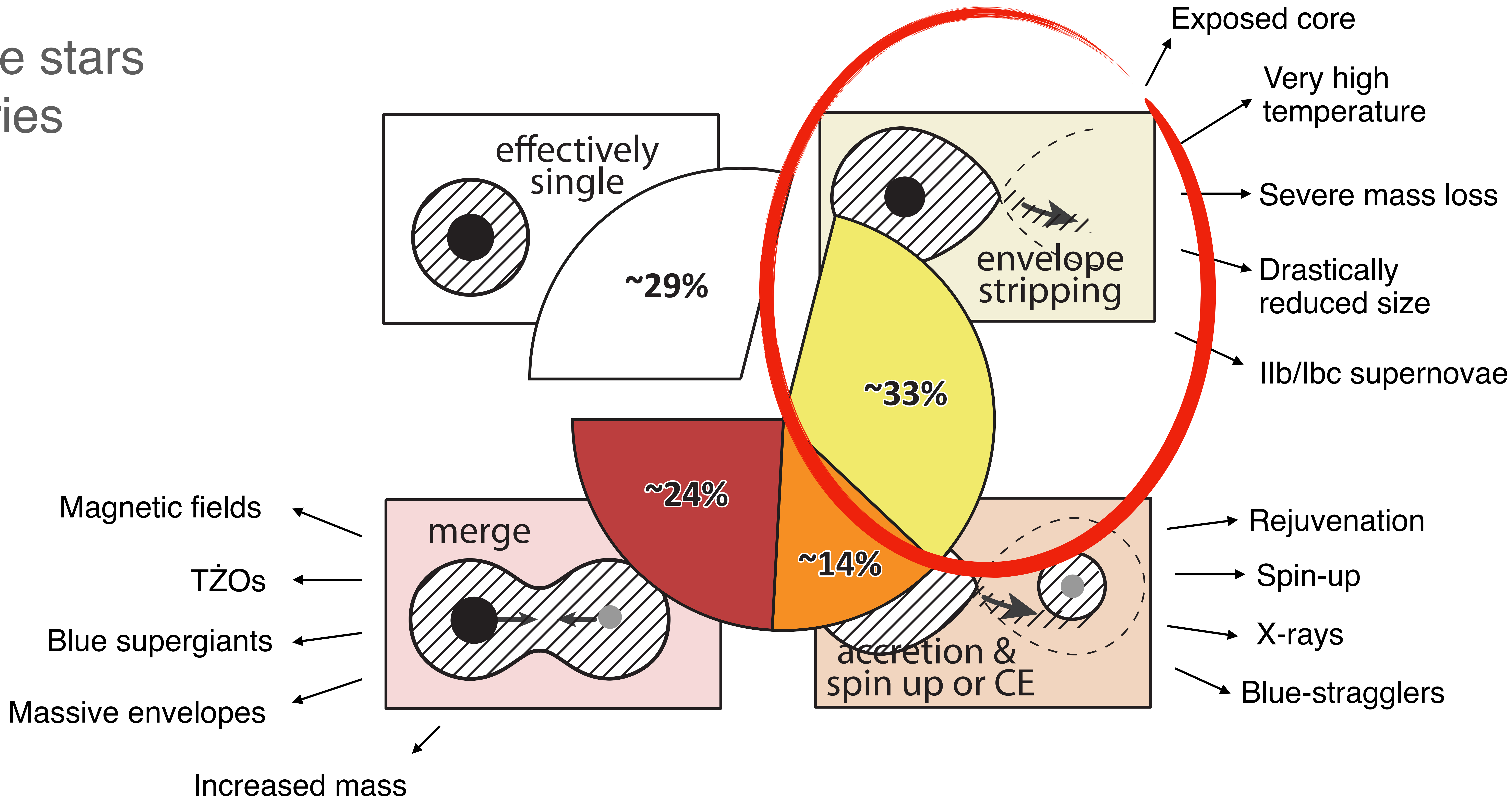


Figure credit: S. E. de Mink
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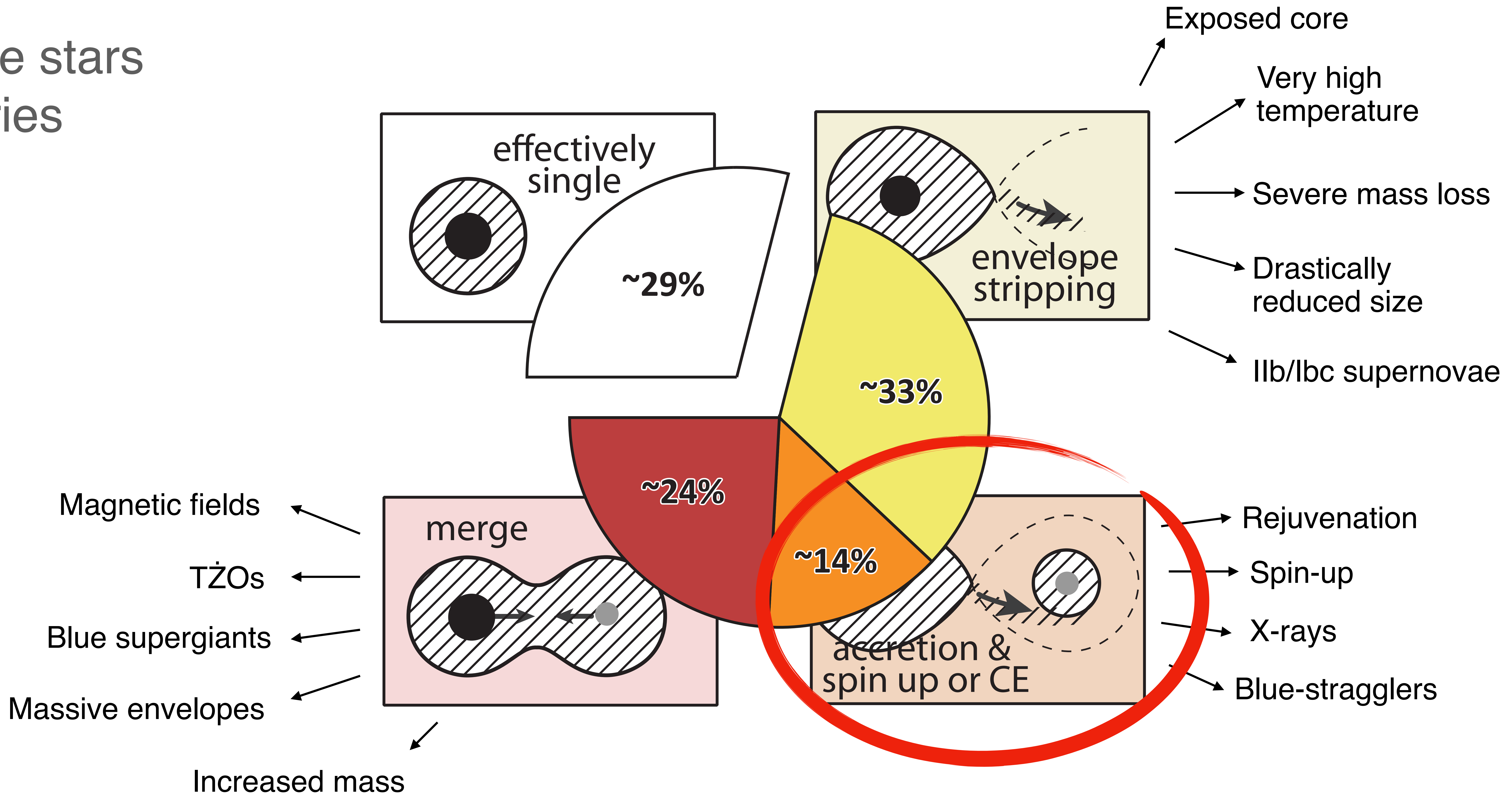

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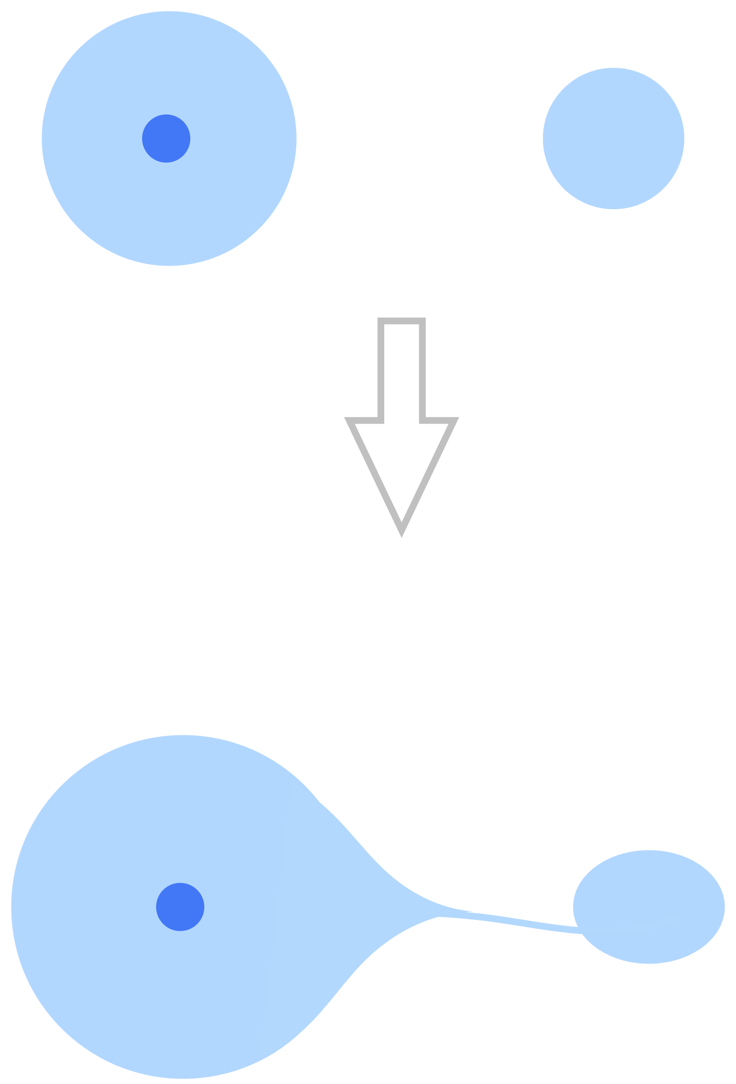
Accreting stars 1: stellar accretors and rotation



The second star accretes material during mass transfer and spins up because the accretion stream doesn't hit exactly in the center of the star. If the material is efficiently accreted, the accretor star grows in mass and rejuvenates into a massive blue straggler.

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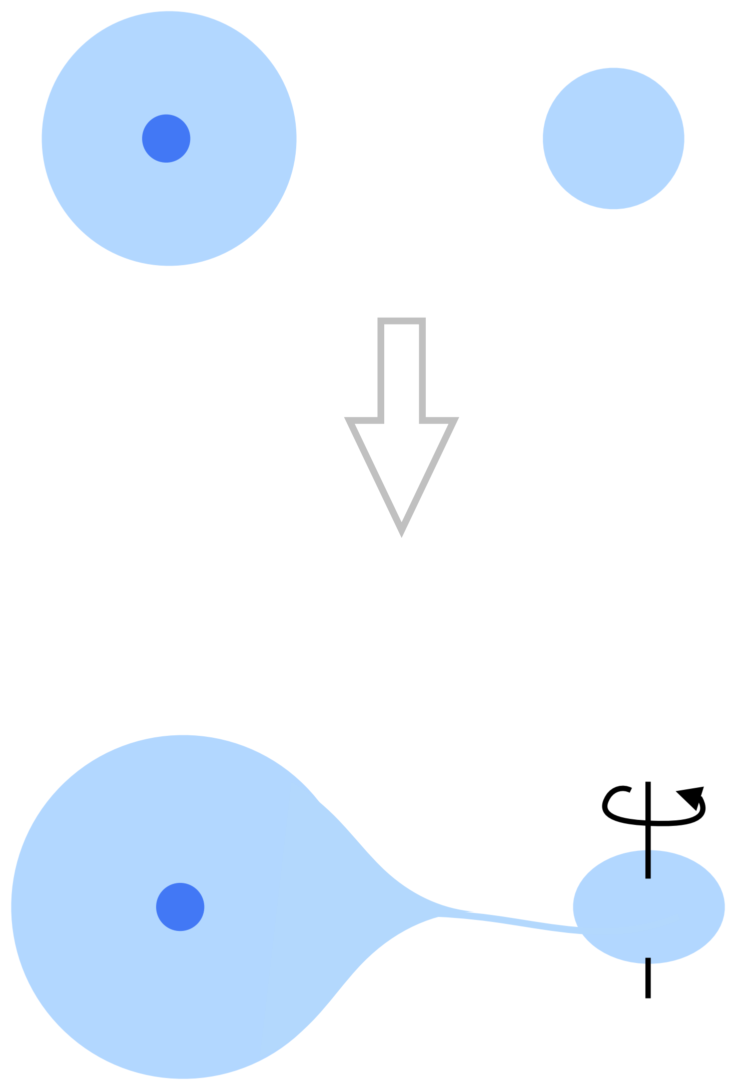

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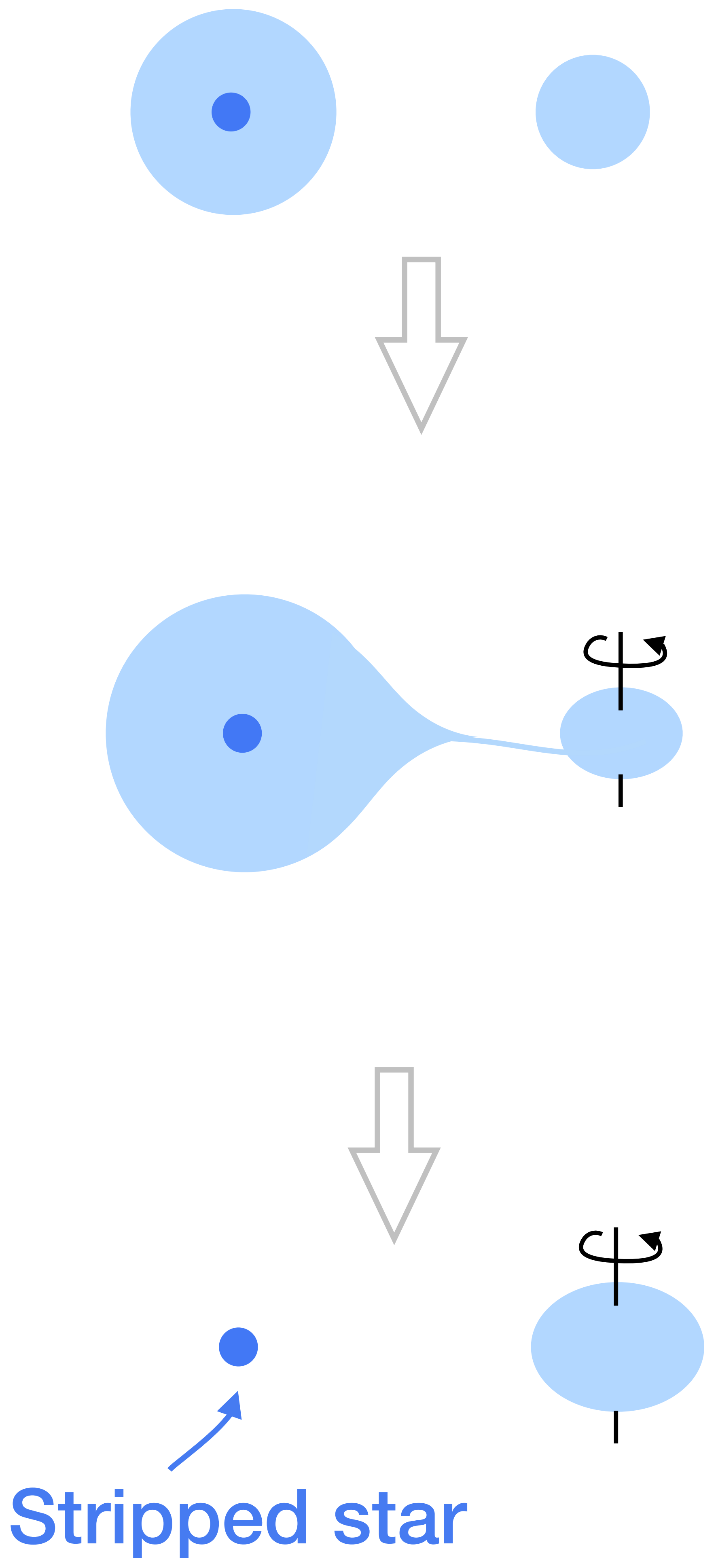

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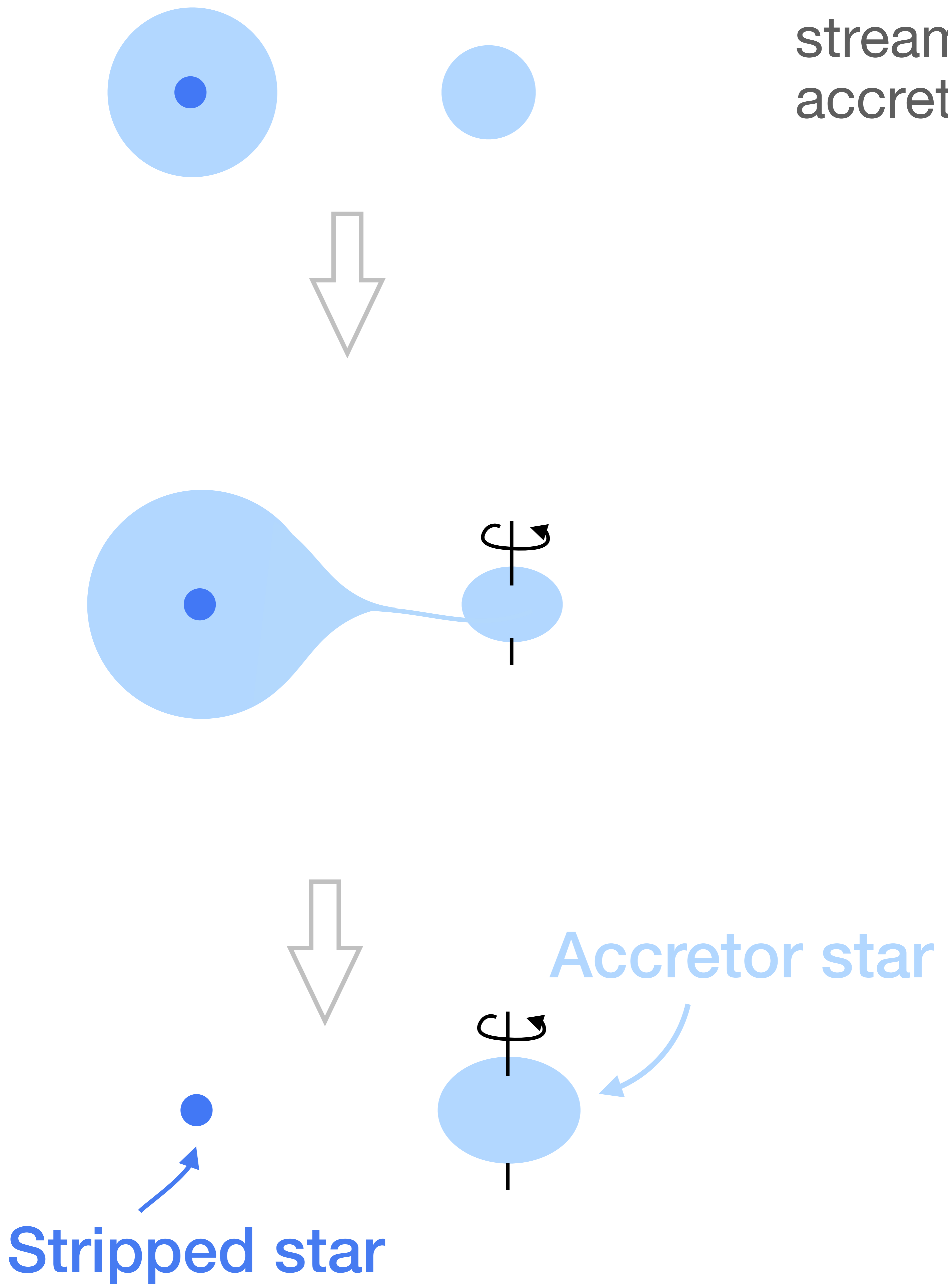

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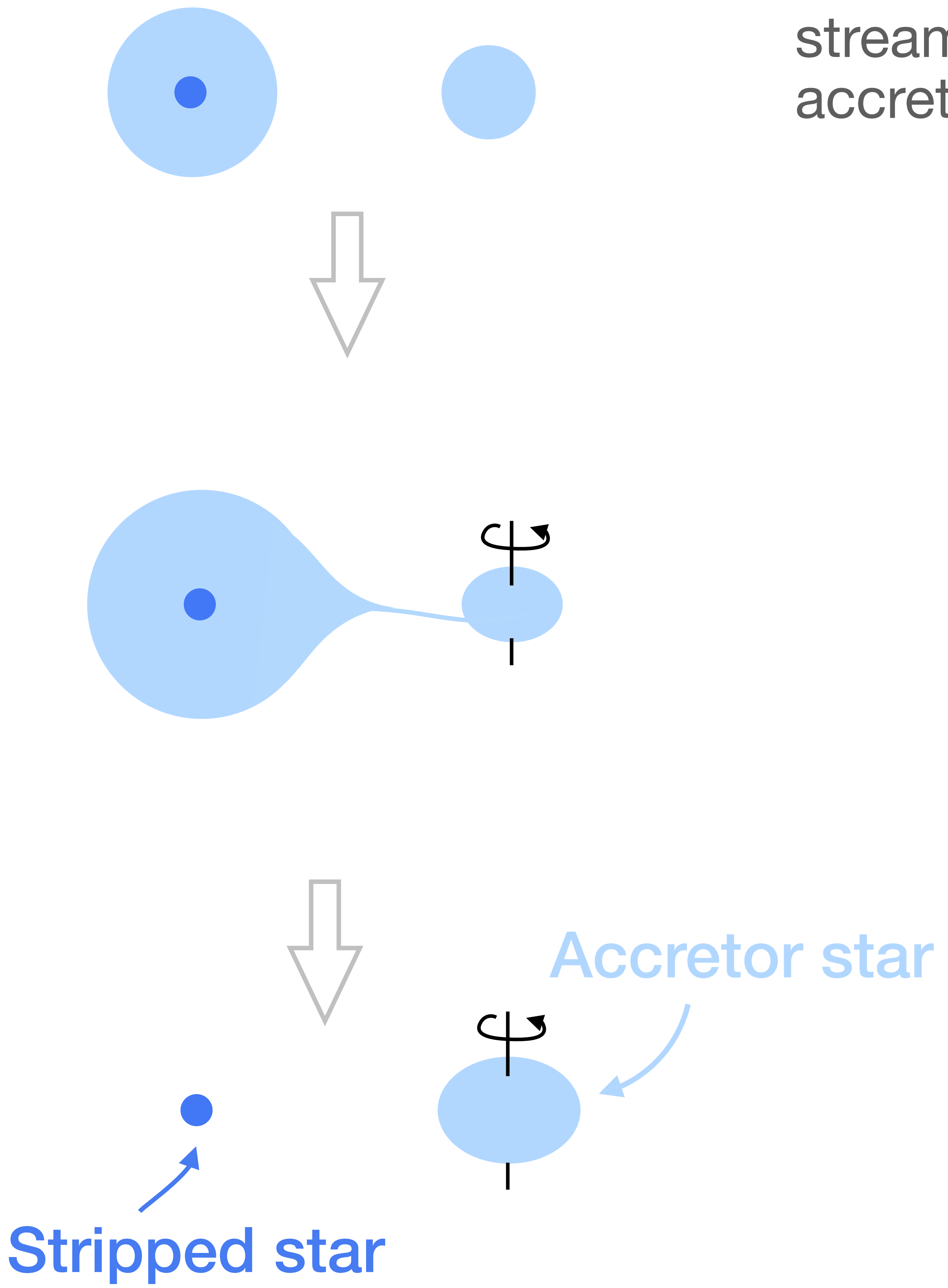

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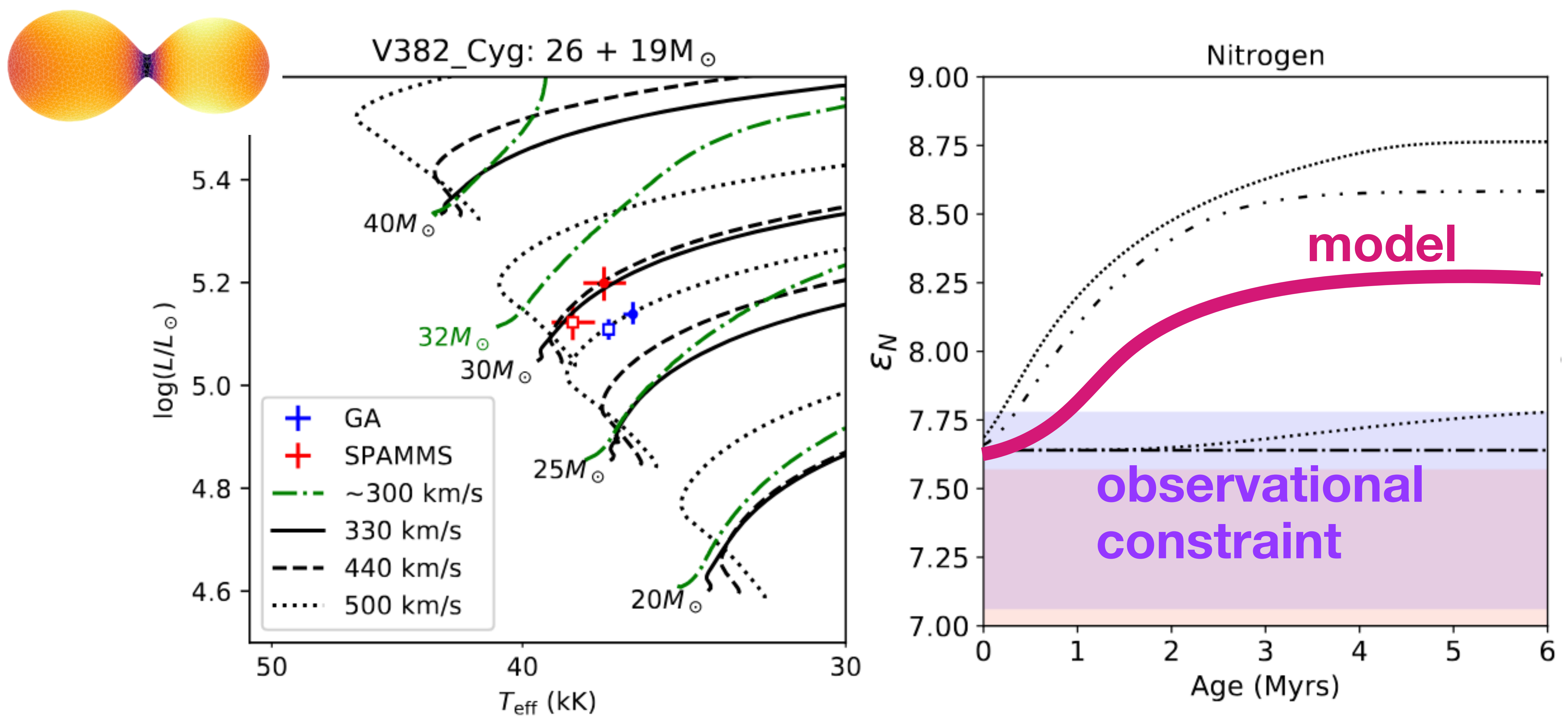
Rotational mixing remains unconfirmed observationally



Abdul-Masih et al. (2021)

Accreting stars 1: stellar accretors and rotation

If rotational mixing is efficient for spun-up accretors, it will change how much H and He+ ionizing emission a population outputs
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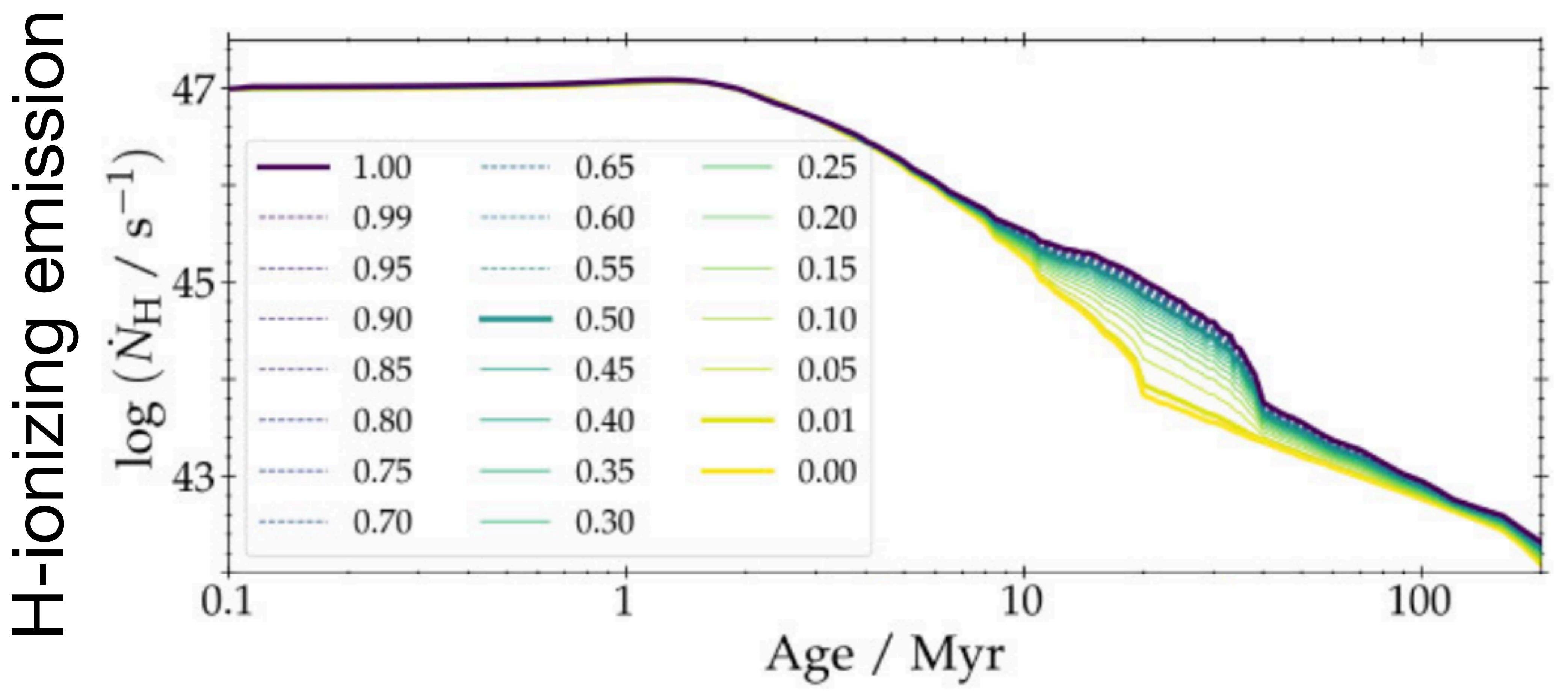

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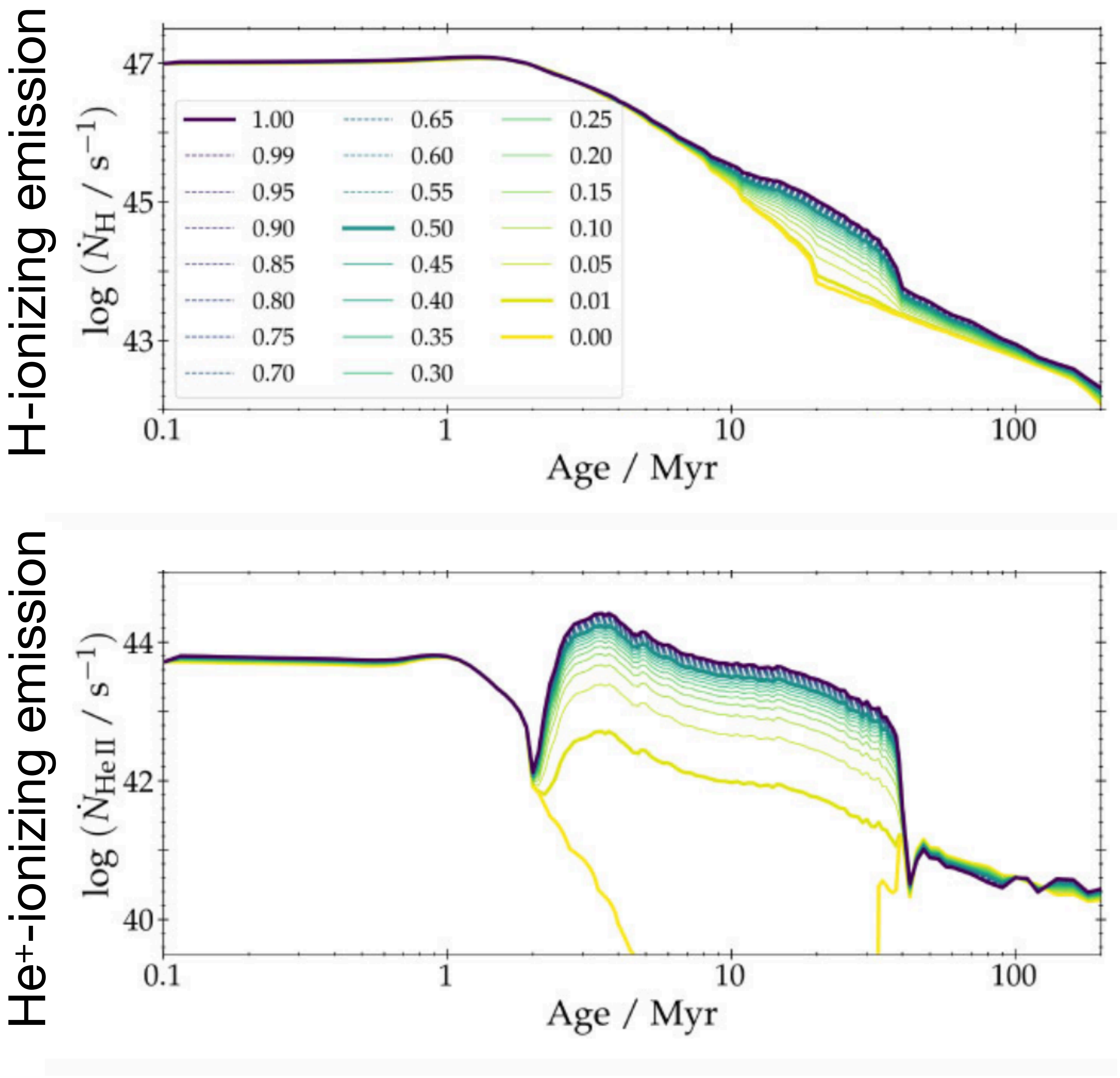
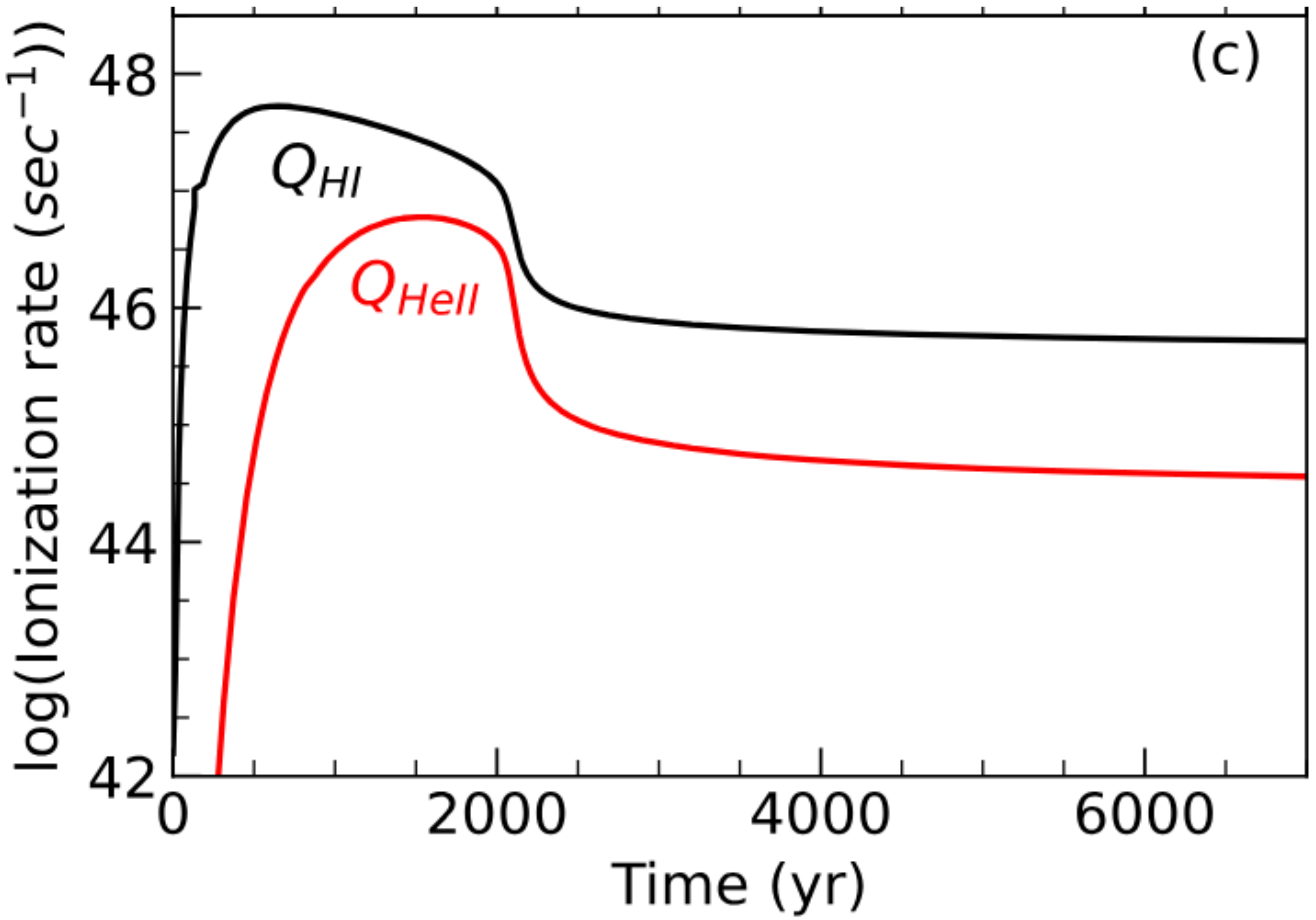


Accreting white dwarfs - hard ionizing sources

White dwarfs that accrete material rapidly can reach both extreme temperatures and high luminosities!
(Souropanis et al., 2022, 2023)



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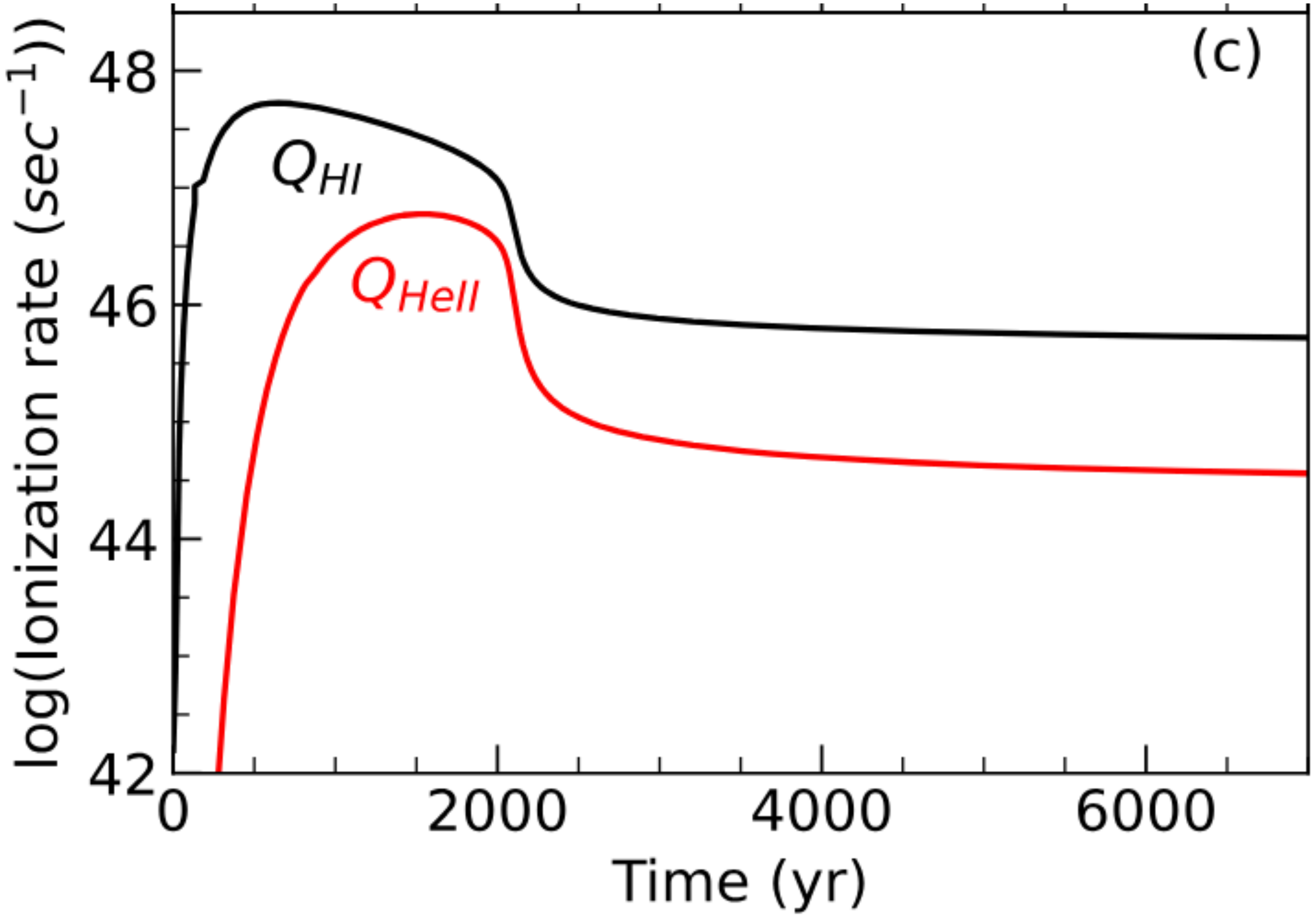

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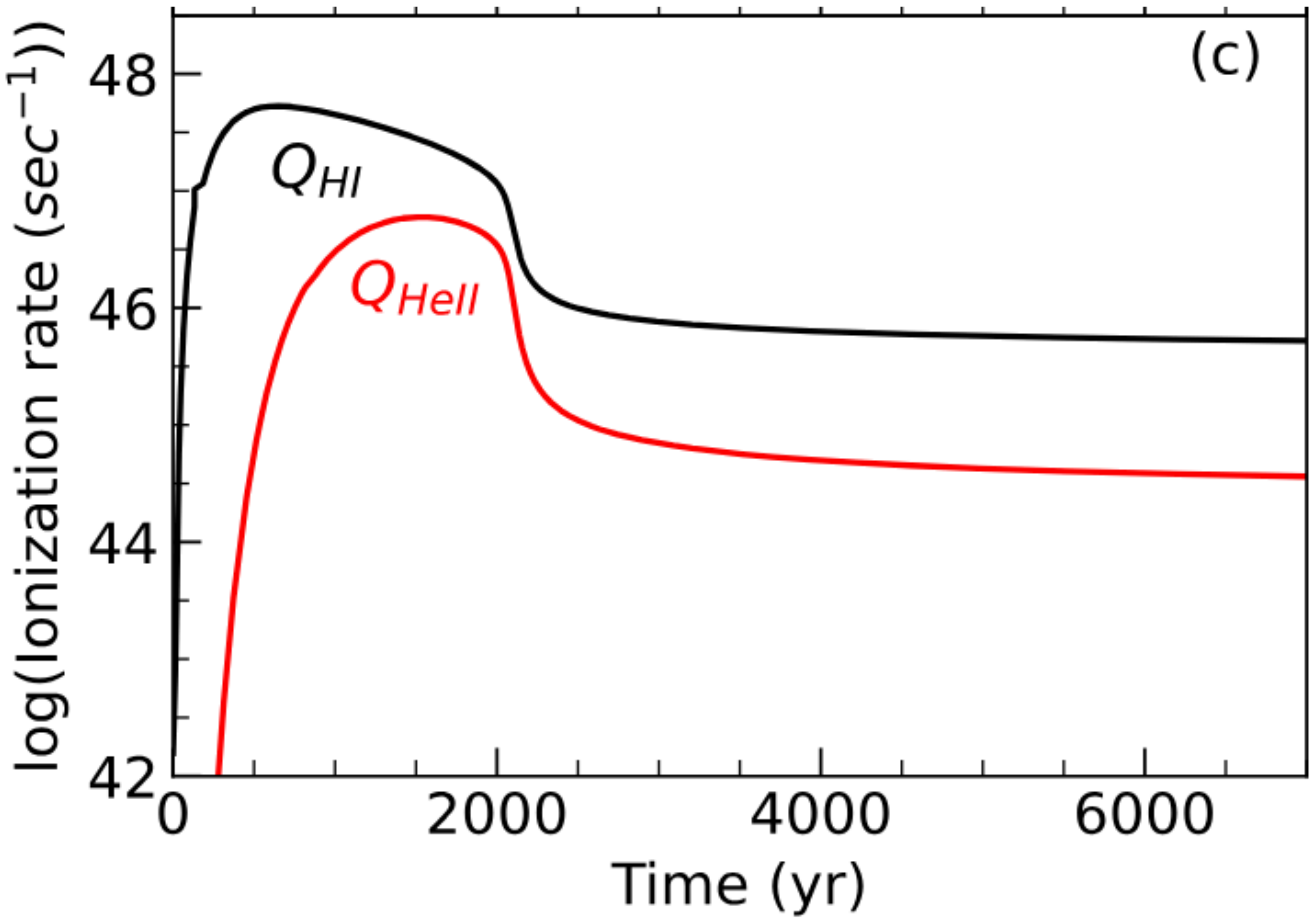

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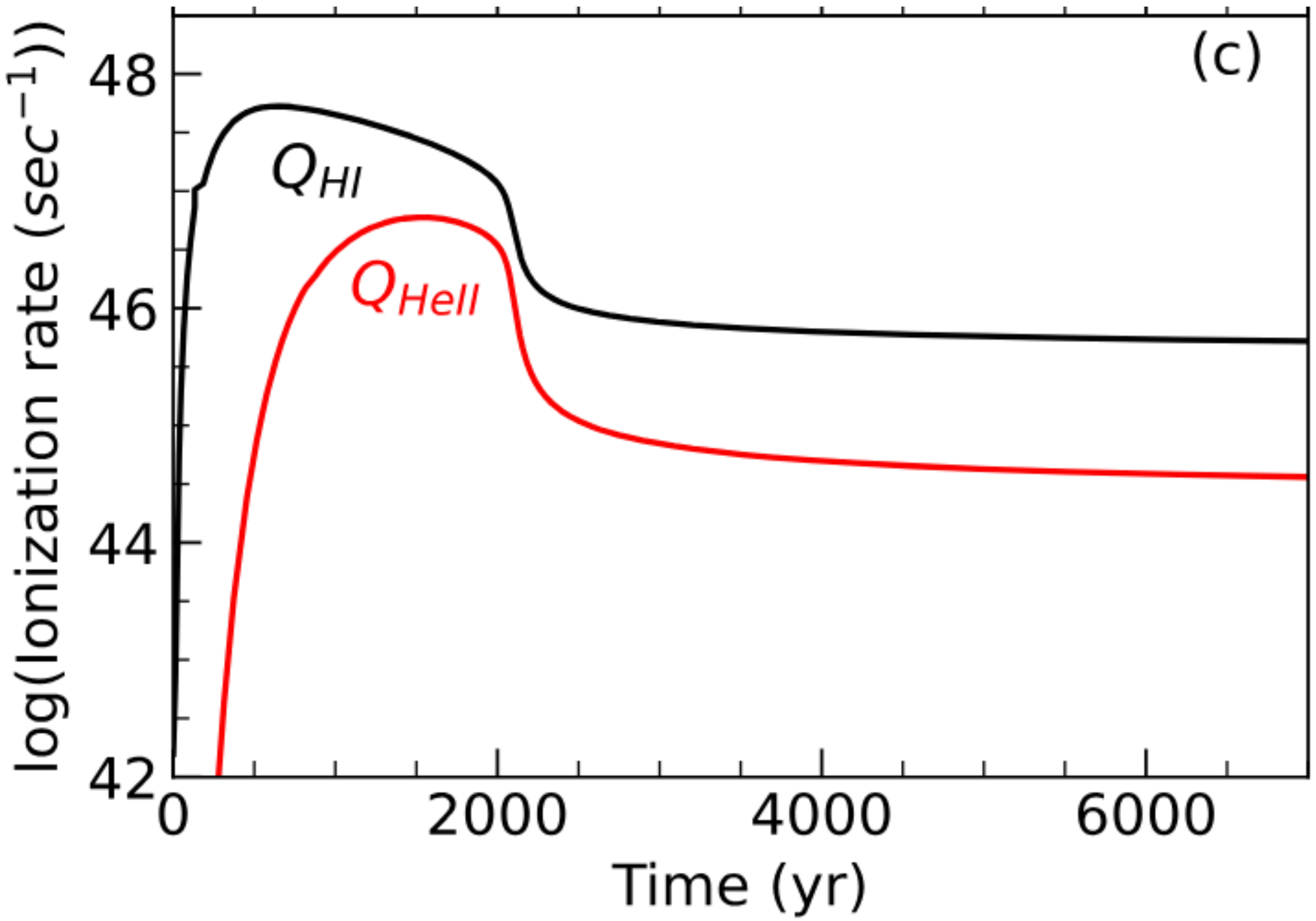

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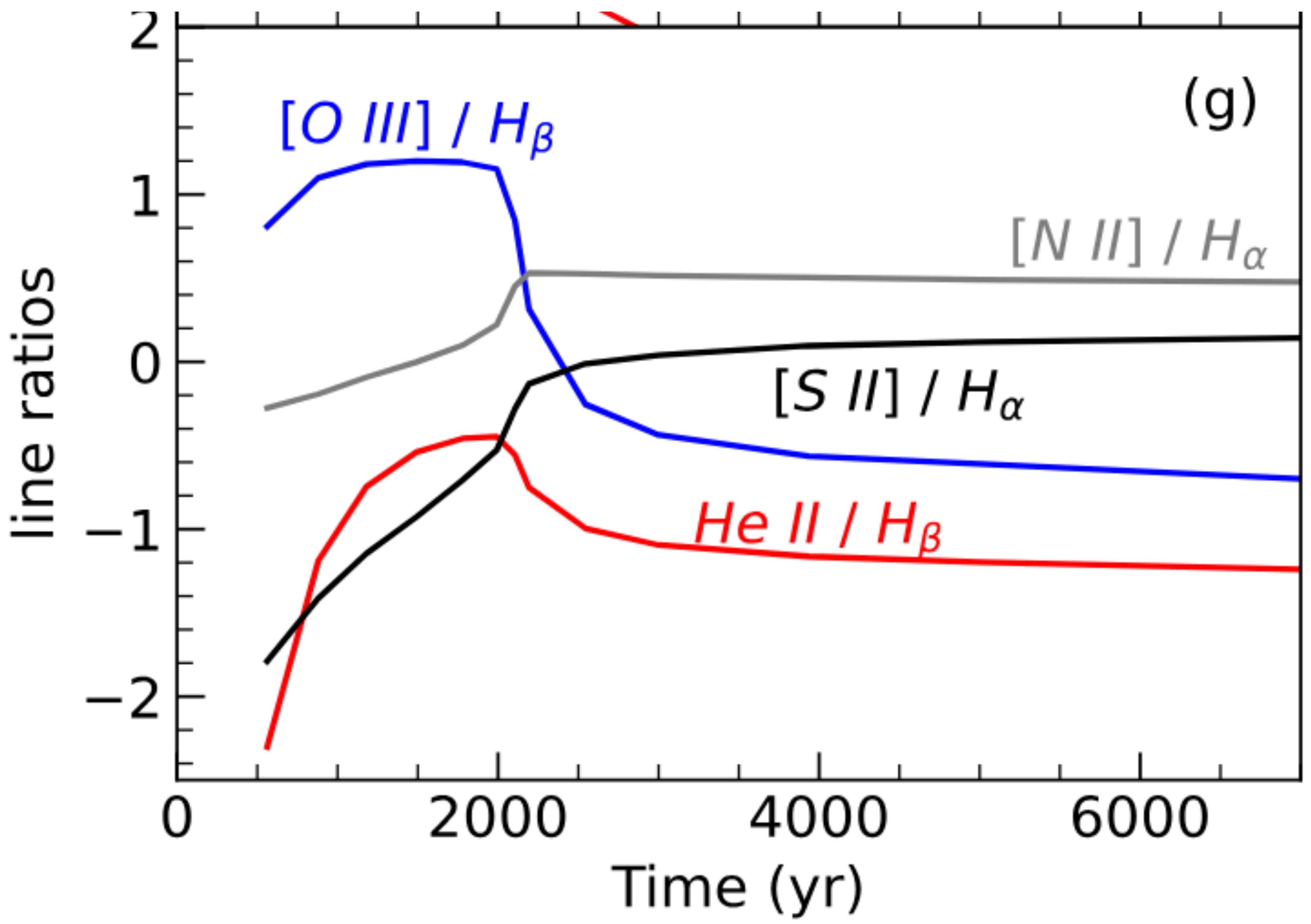

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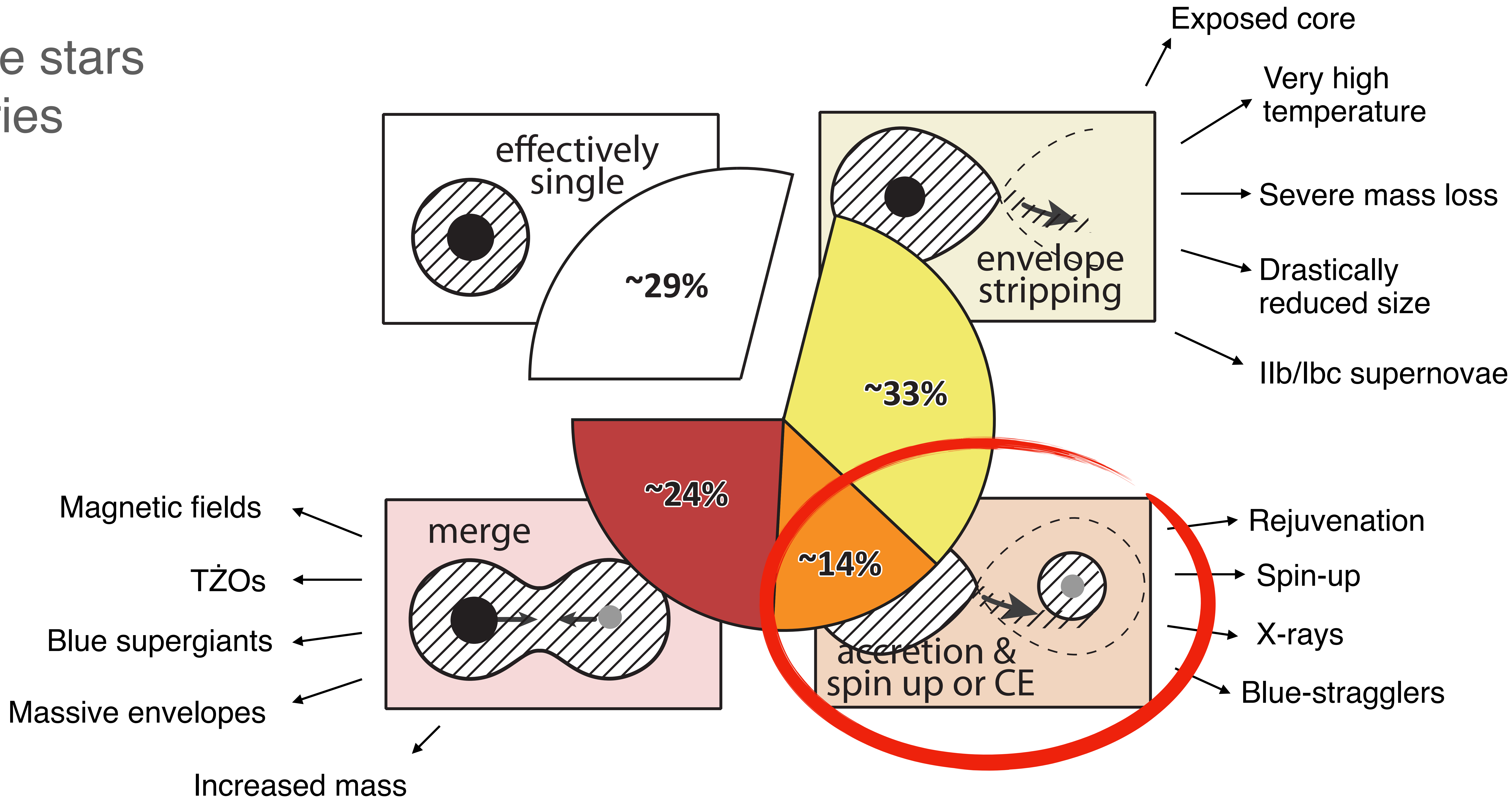

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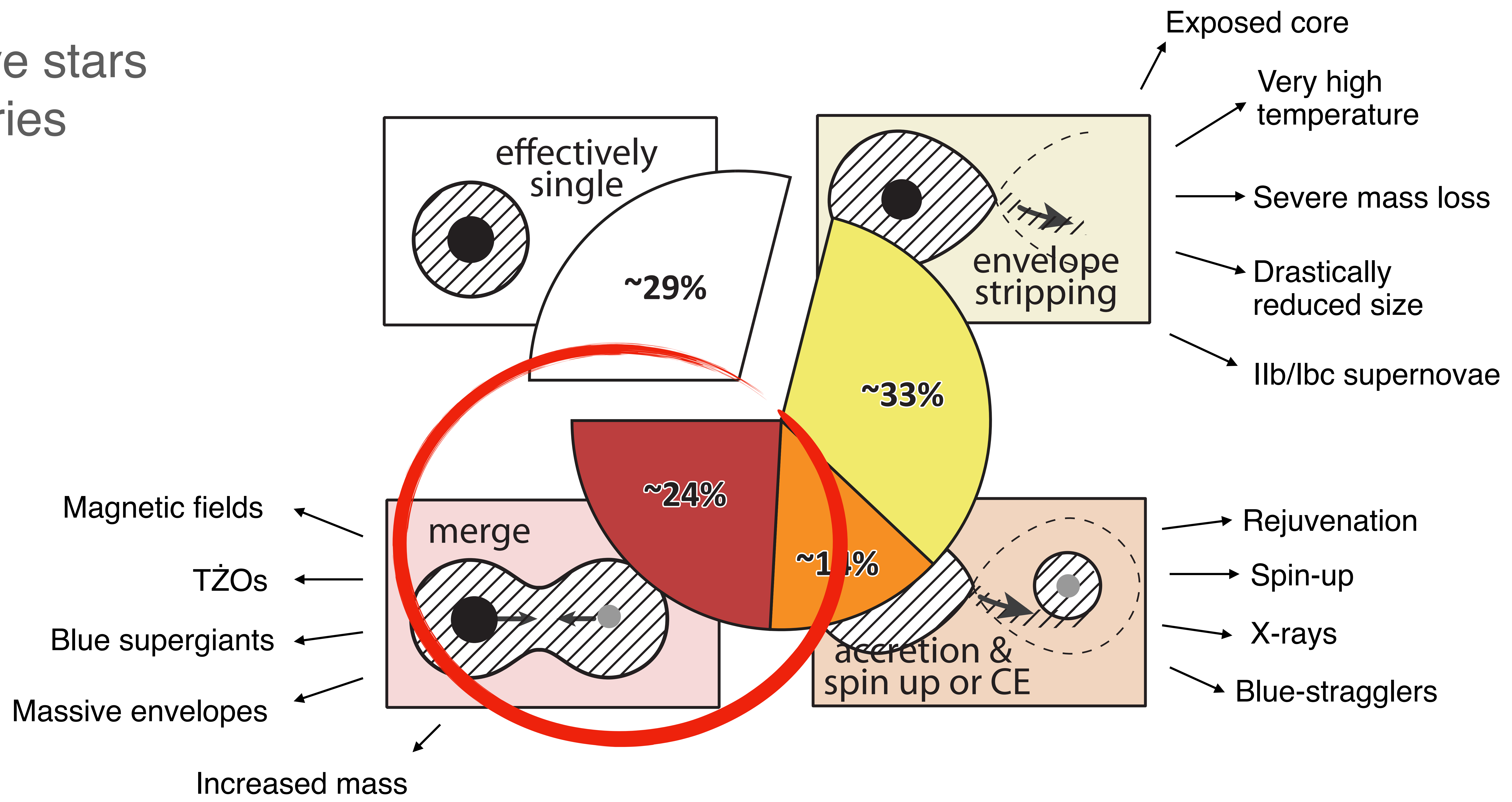

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Stellar merger products = magnetic stars?

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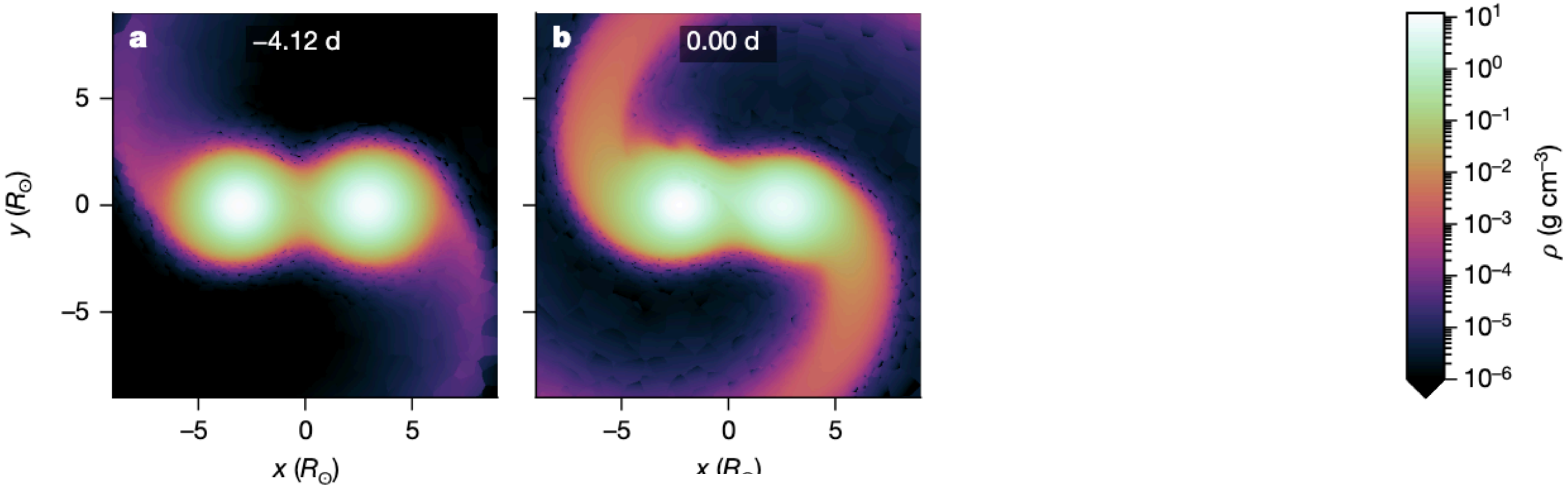

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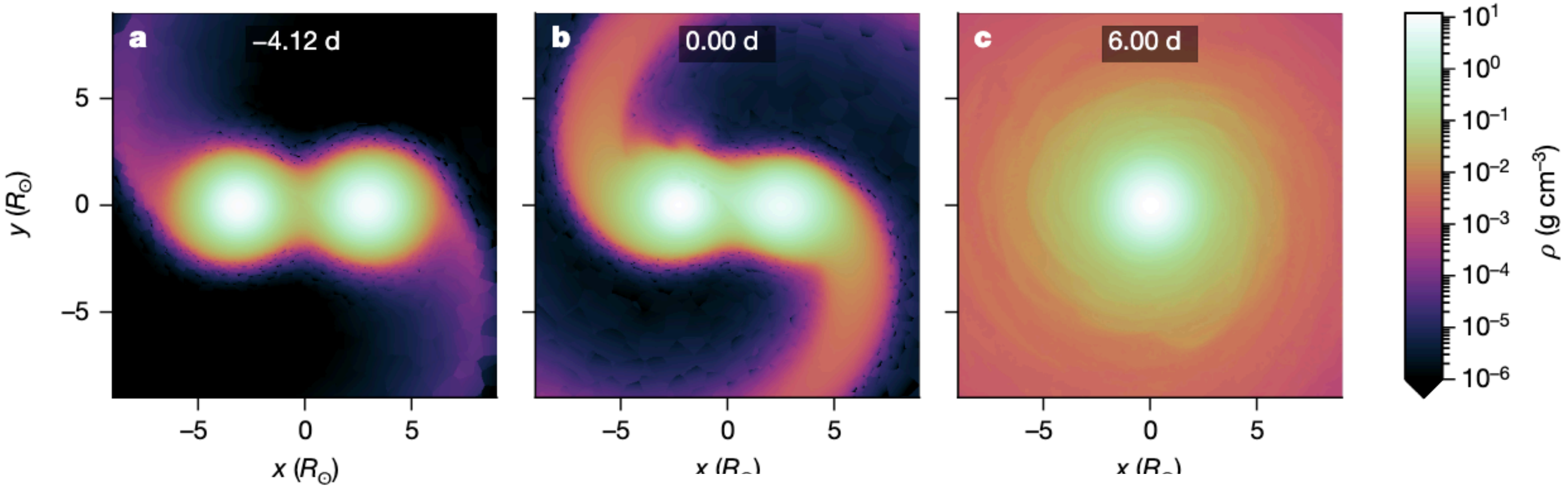

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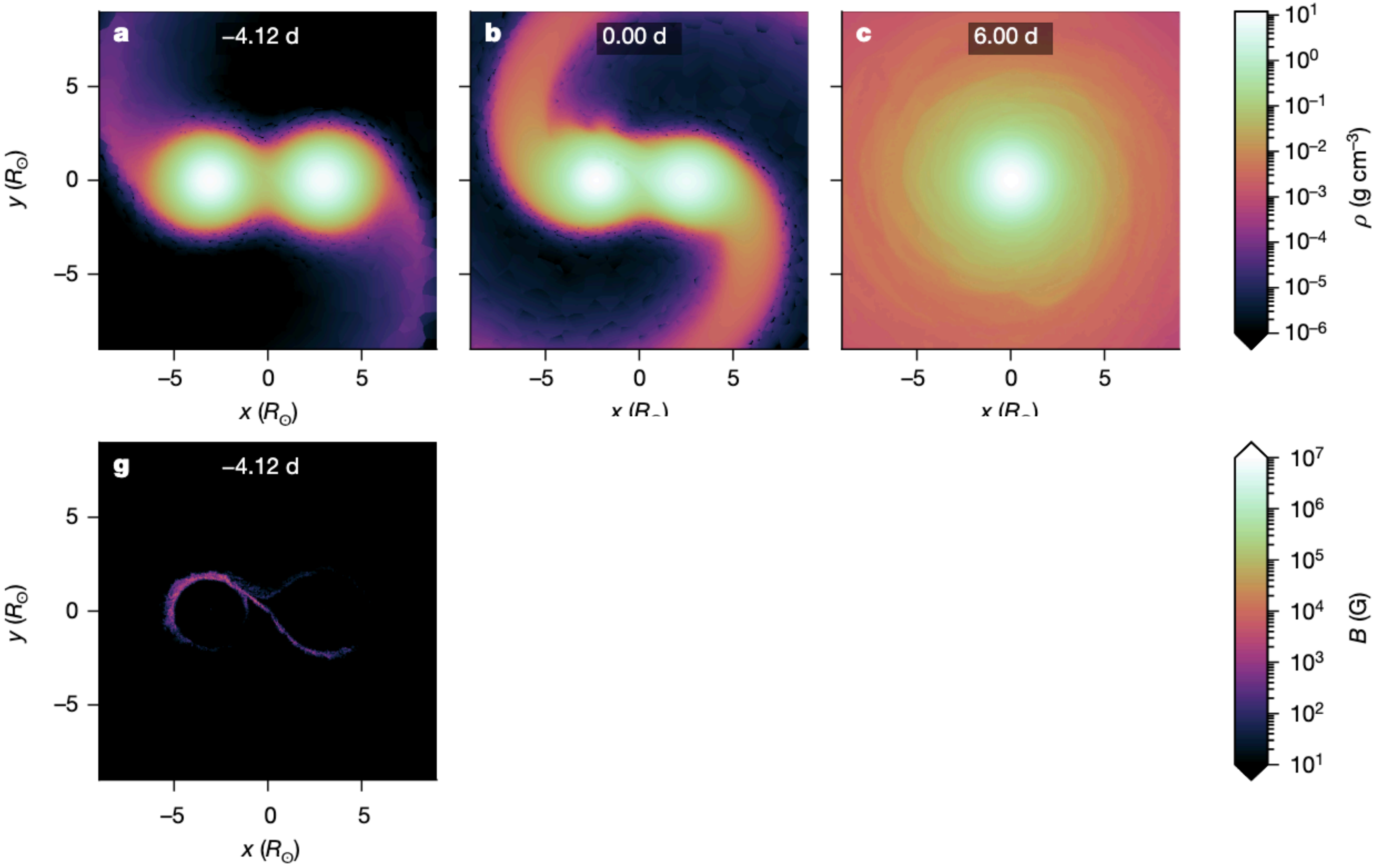

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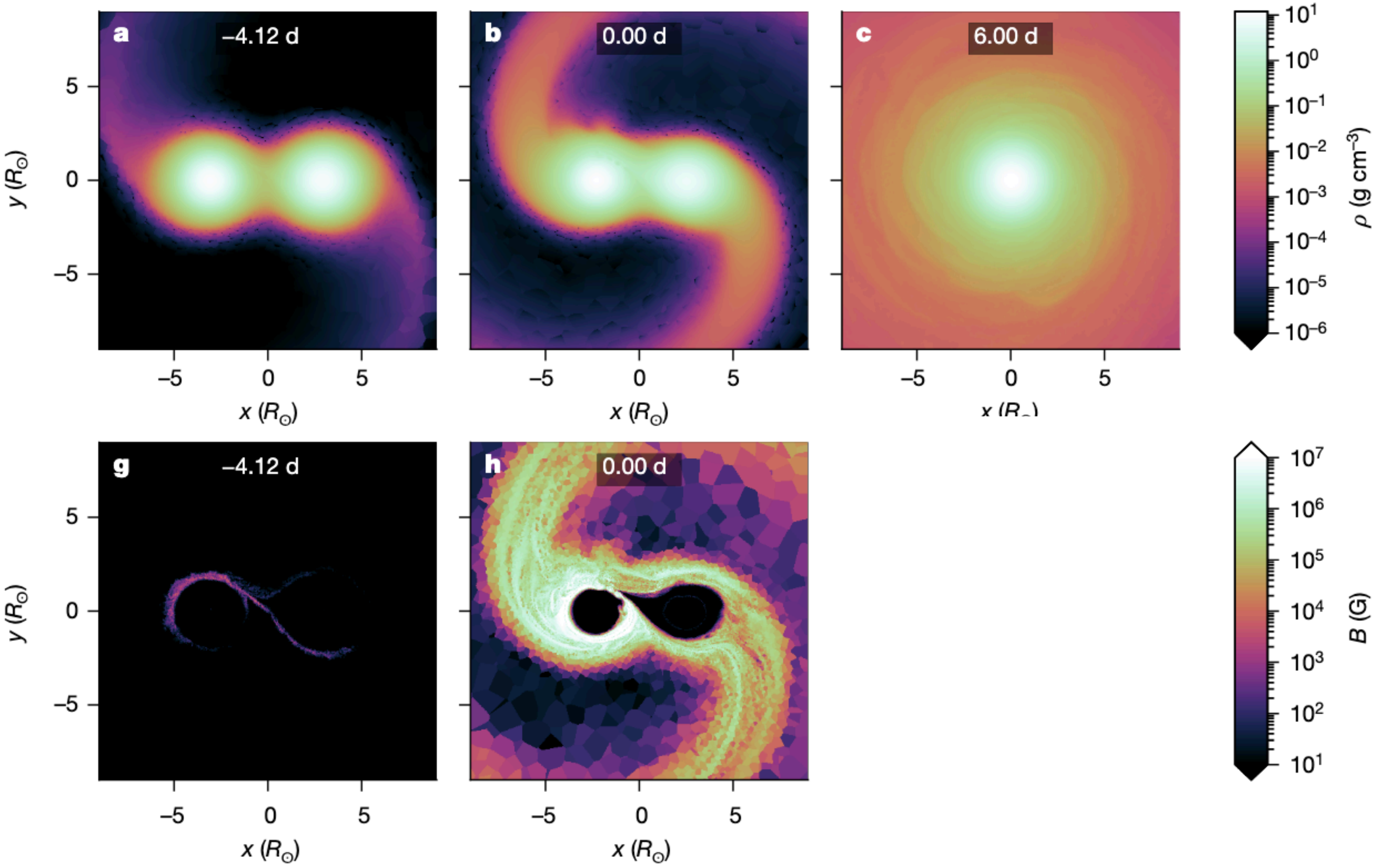

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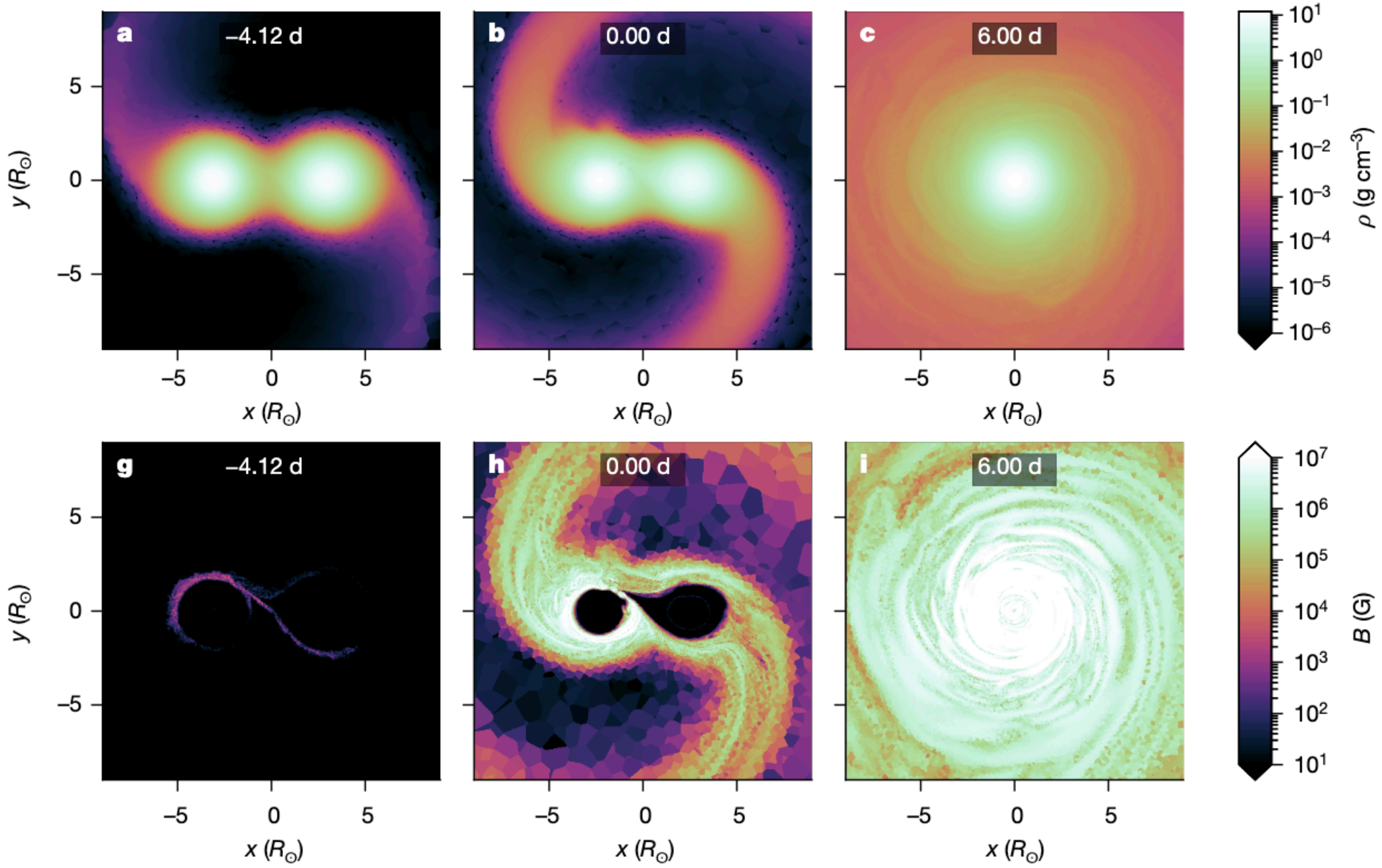

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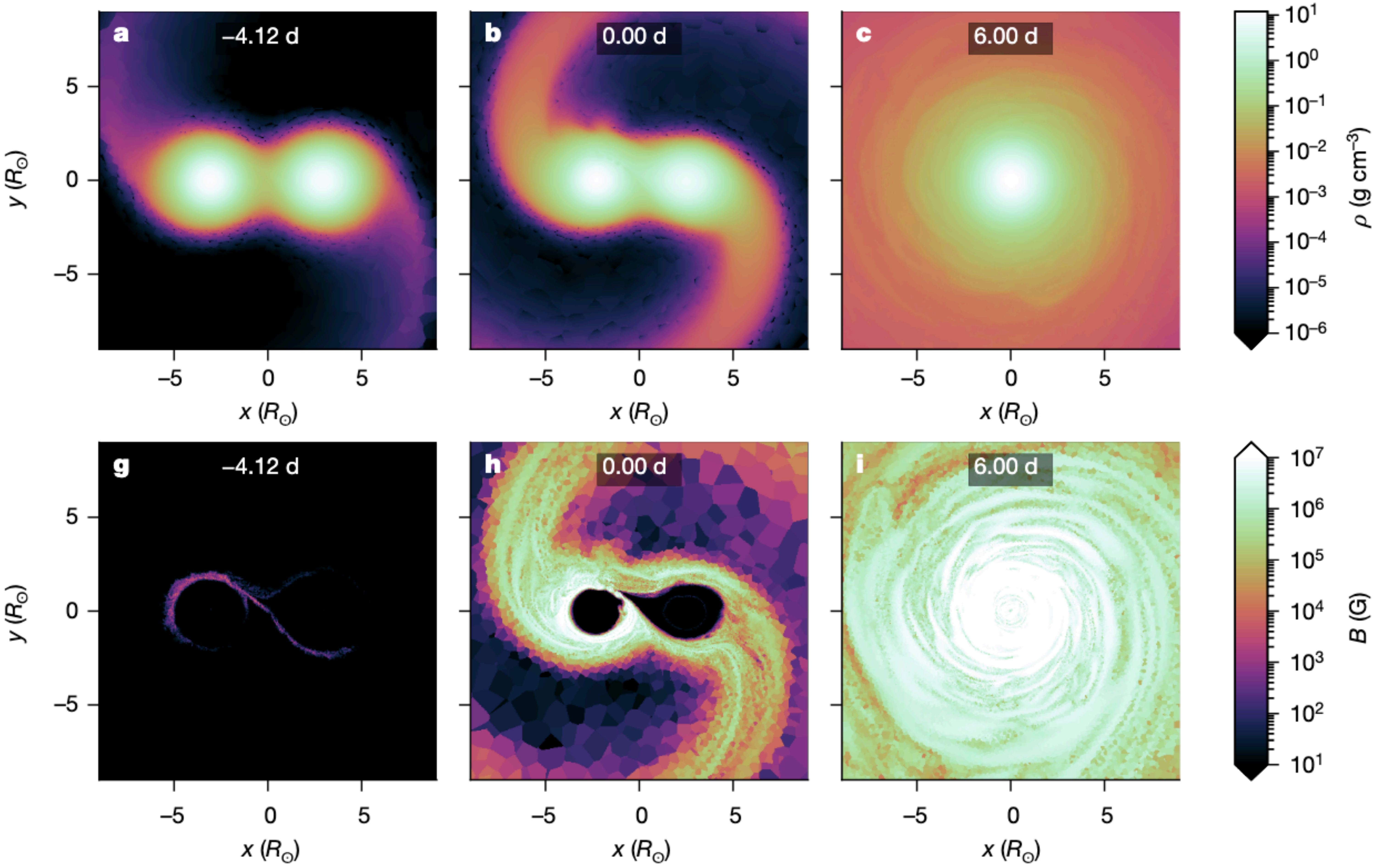
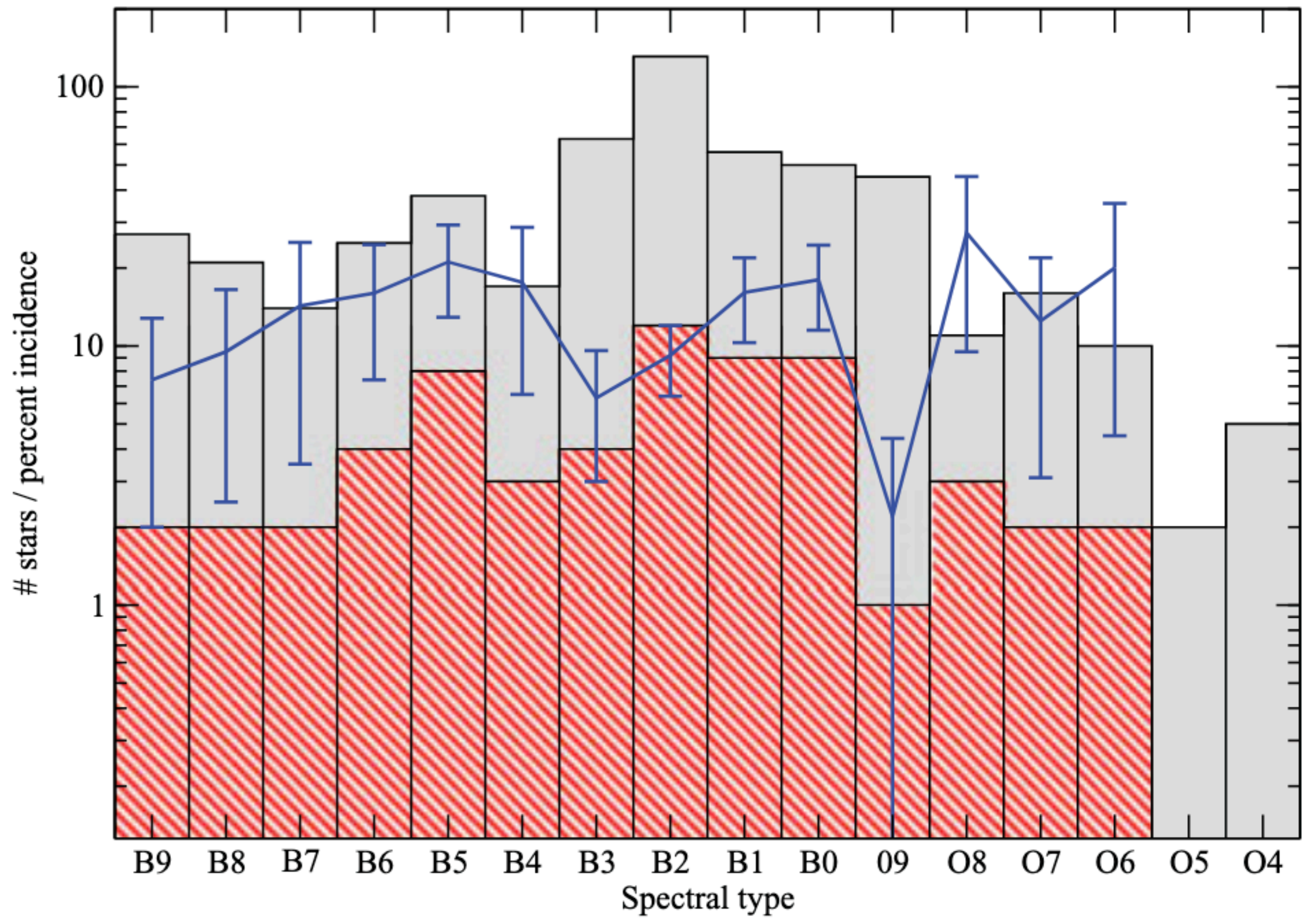
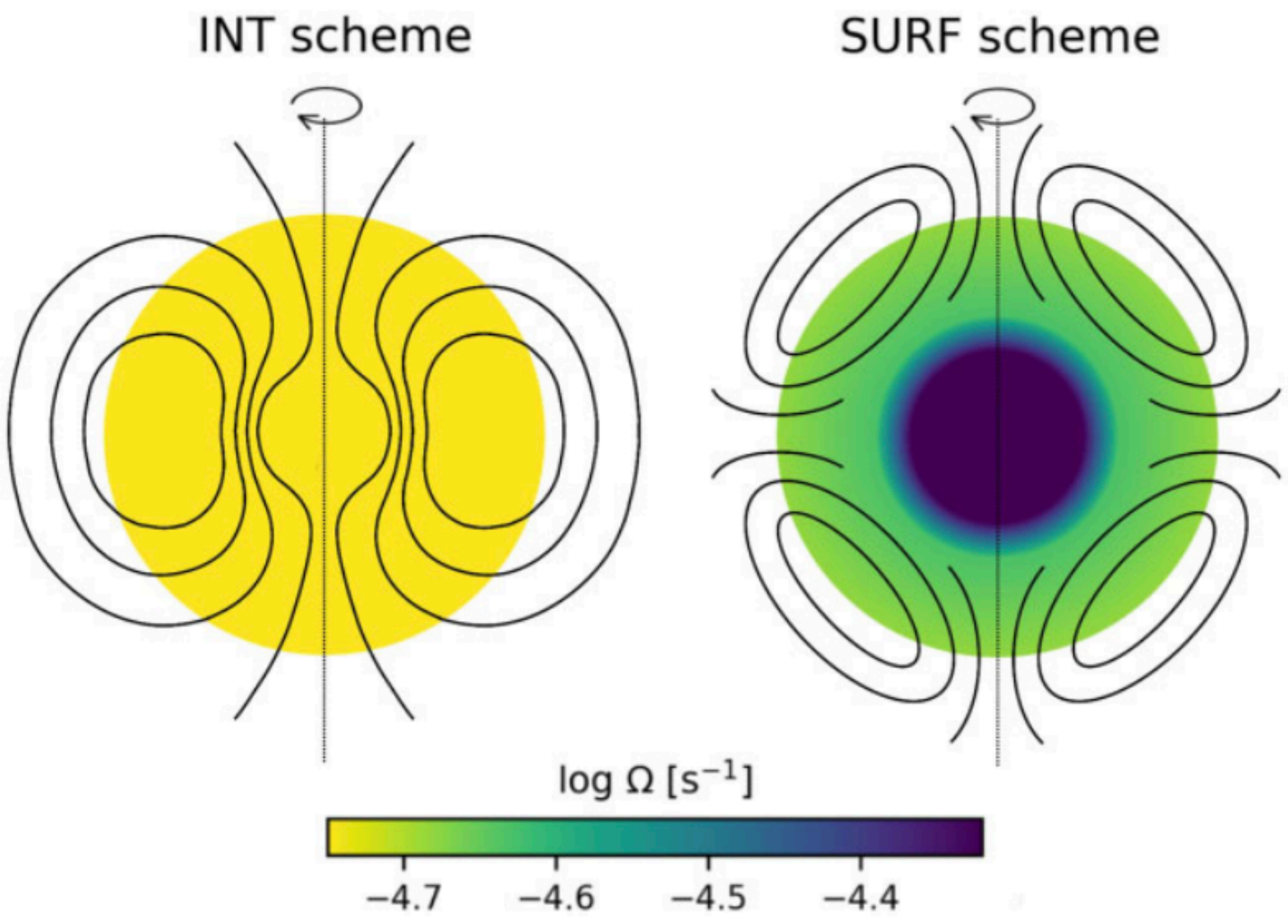


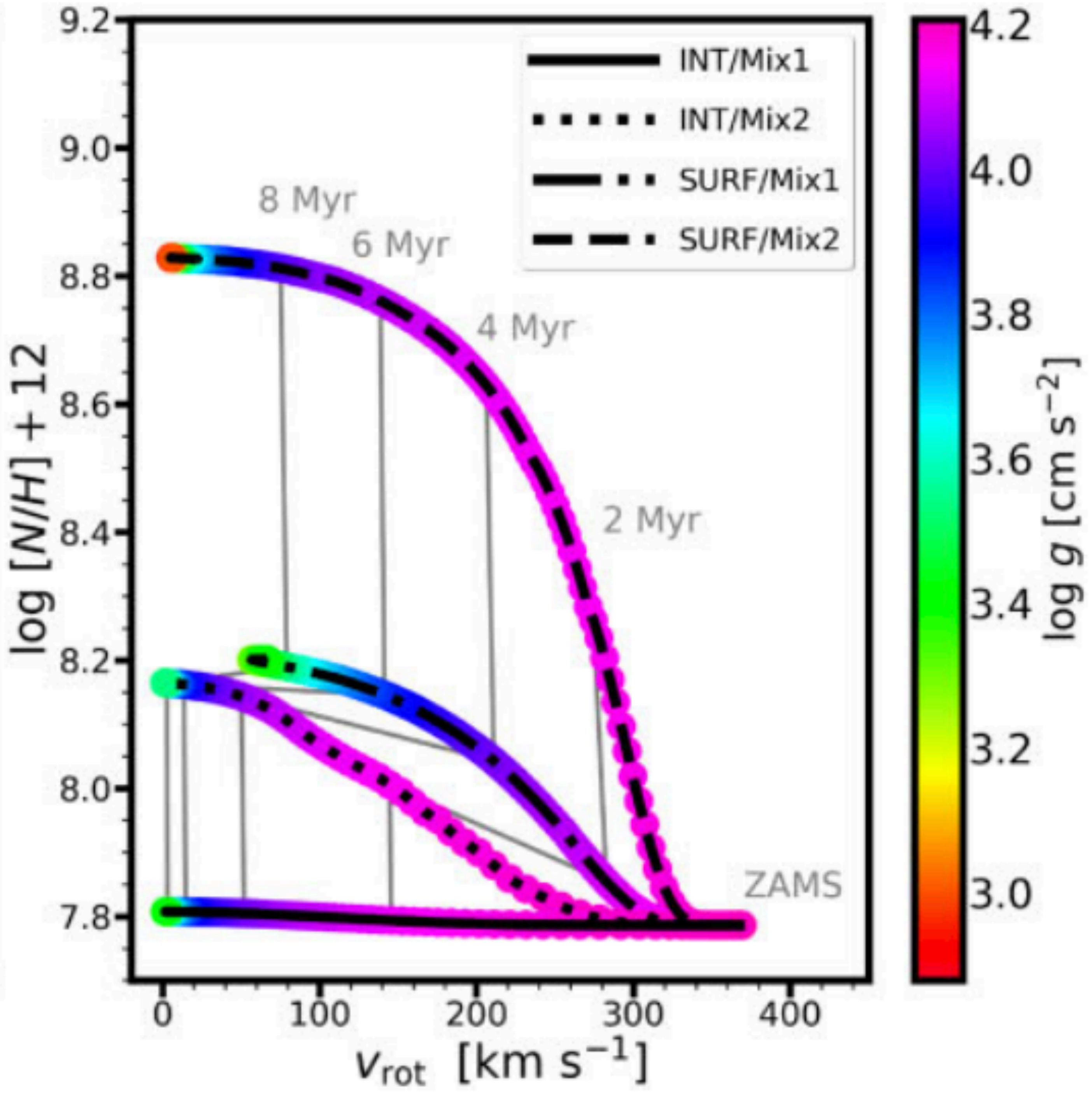


About 7% of massive main-sequence stars are magnetized
(Wade et al., 2014, MiMeS project)

Stellar merger products = magnetic stars?

The evolution of magnetized stars is under active research. Depending on the magnetic field morphology and how the magnetic field influences mixing, the star could (1) avoid wind mass loss, (2) induce strong shear, (3) experience rapid spin down…
(e.g., Keszthelyi et al., 2020, 2022)





(Note: assumes rotational mixing is efficient.)

2) Hard ionizing radiation

The He II problem

Stellar populations appear to emit an unexpected amount of He^+ ionizing emission.

So far, we do not know what sources produce the majority of these photons.

(Olivier et al. 2021, Shirazi & Brinkmann 2012, Nanayakkara et al. 2019, Saxena et al. 2020, etc…)

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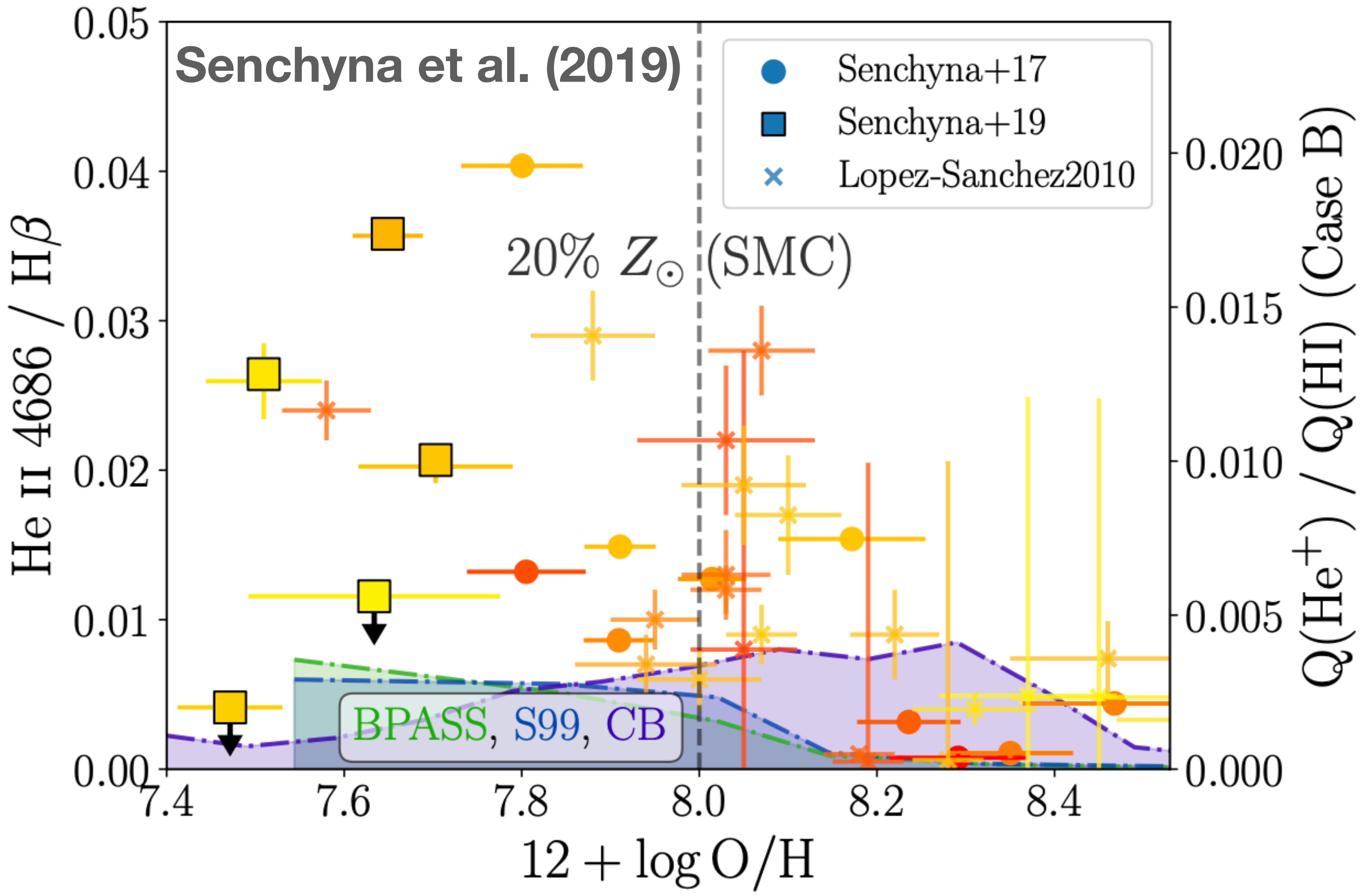

Local star-forming galaxies also show that He II emission is more prominent at low metallicities

(Olivier et al. 2021, Shirazi & Brinkmann 2012, Nanayakkara et al. 2019, Saxena et al. 2020, etc…)

Hard ionizing radiation from stripped stars

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(PhD, ISTA)

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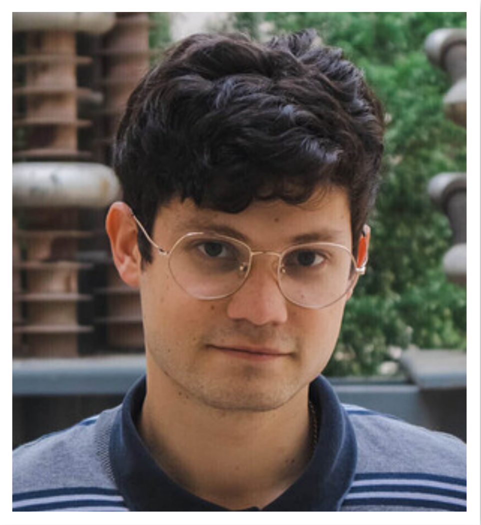

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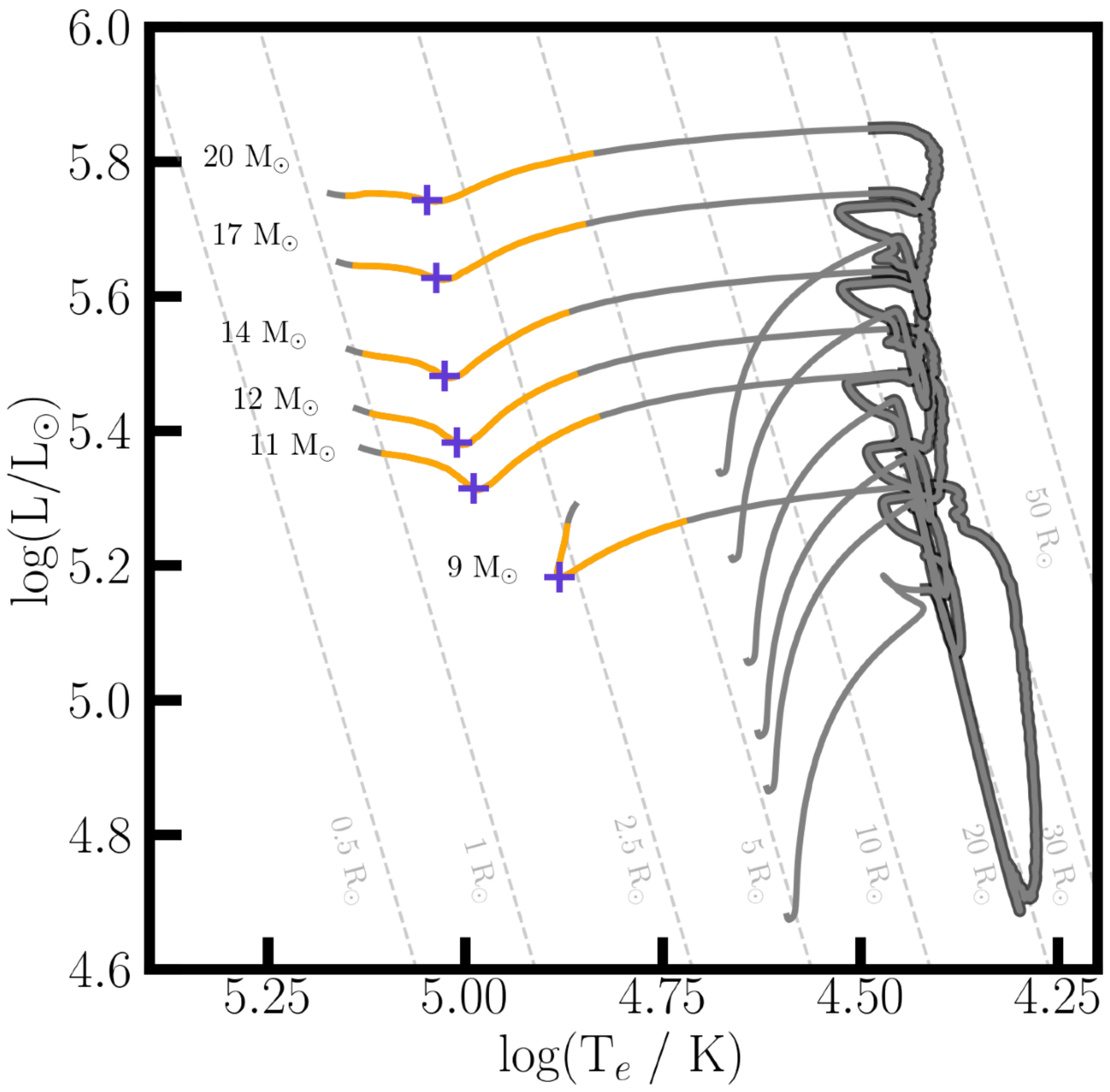

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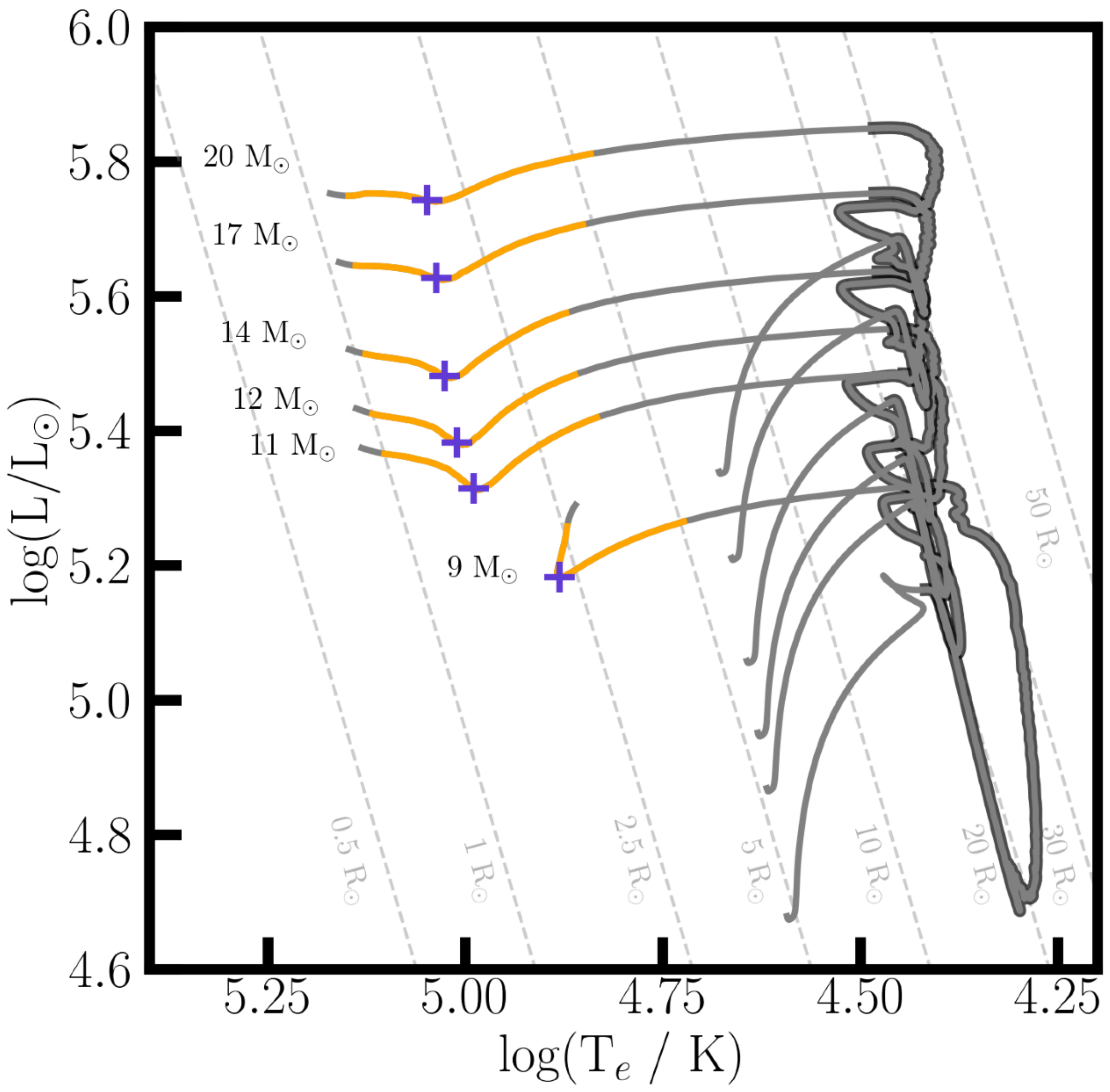

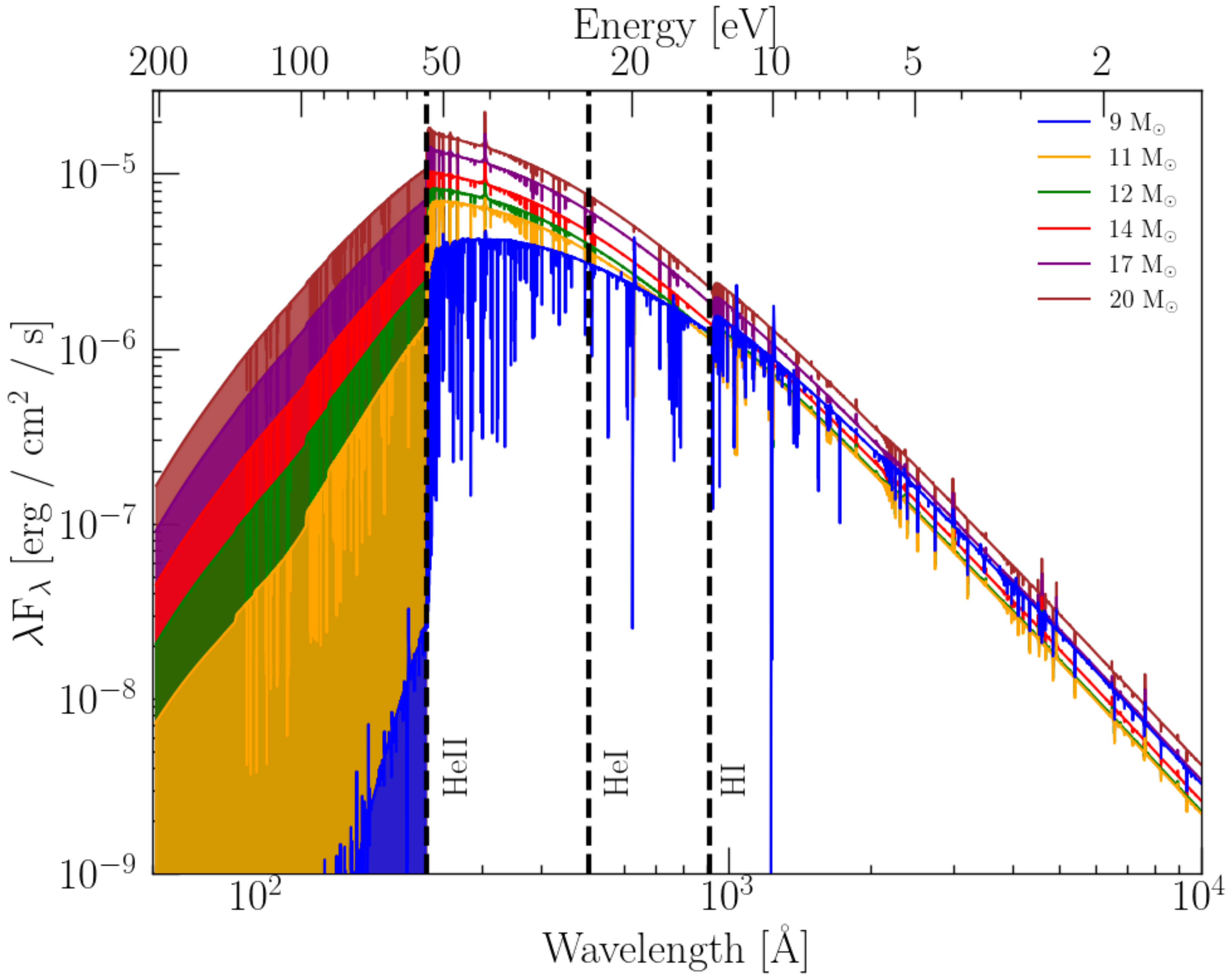

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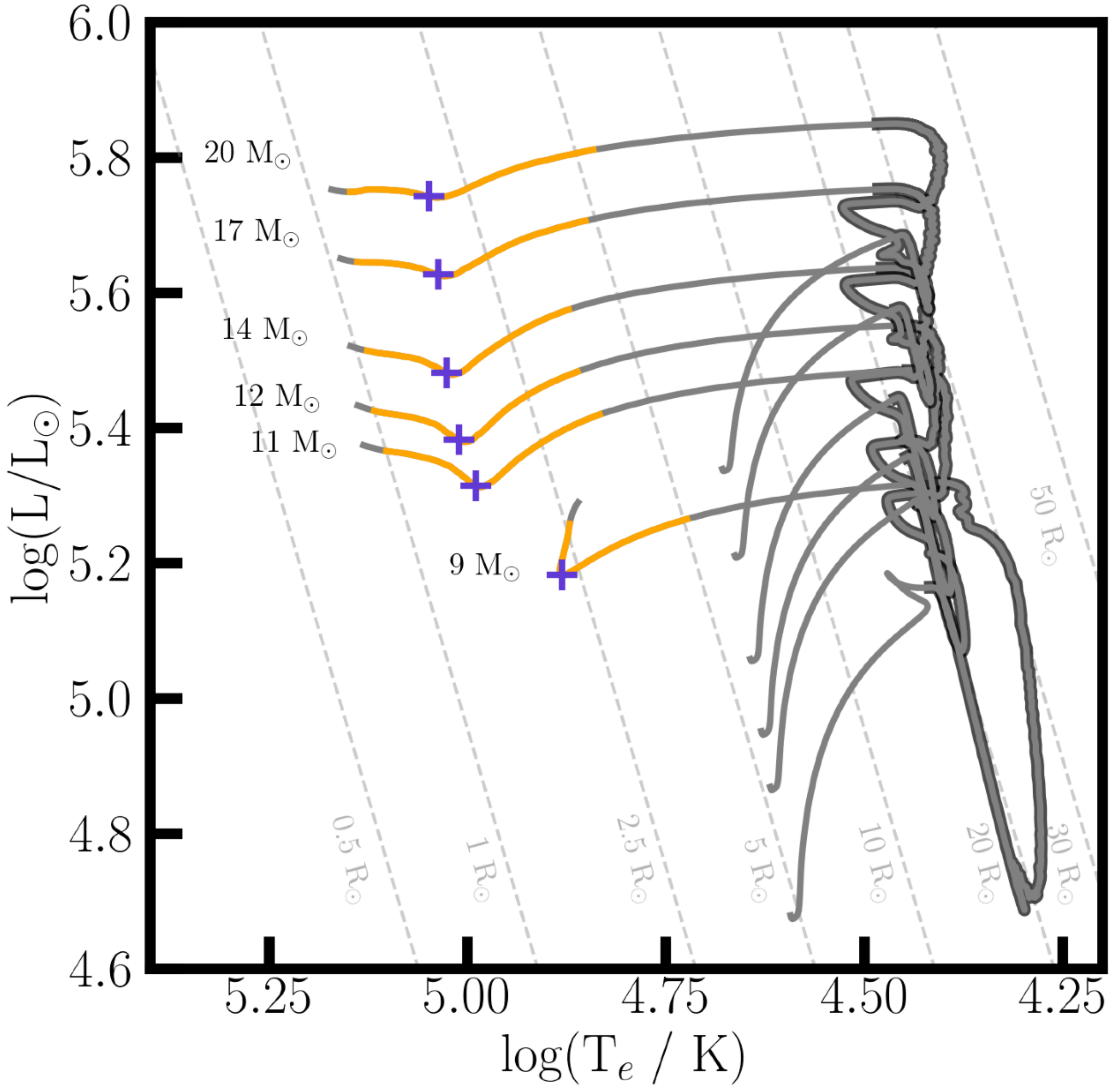

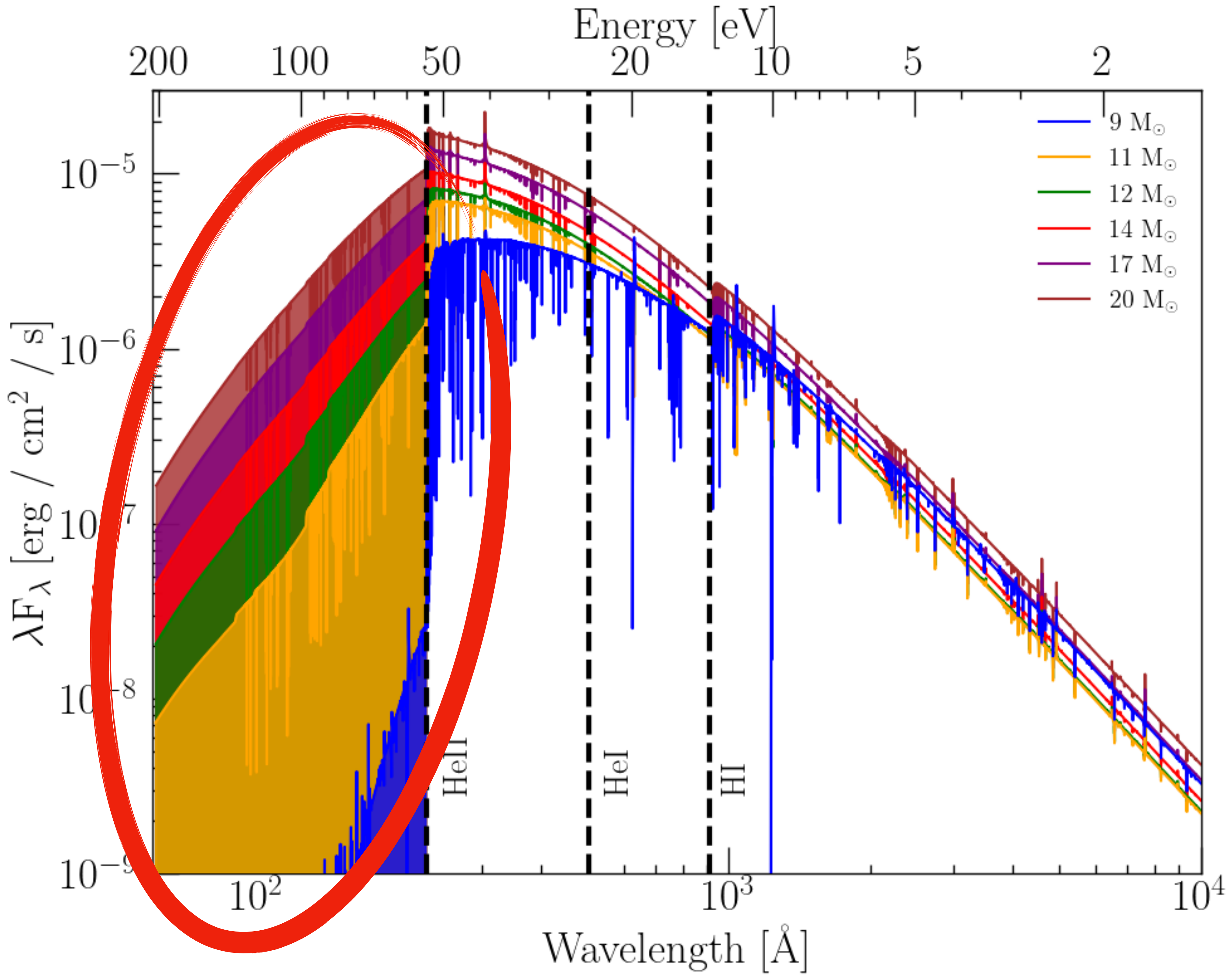

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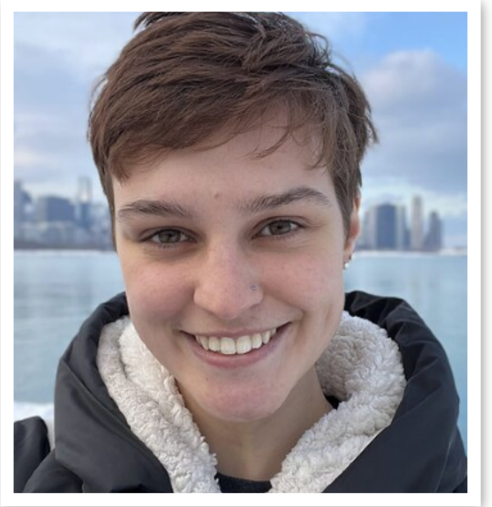

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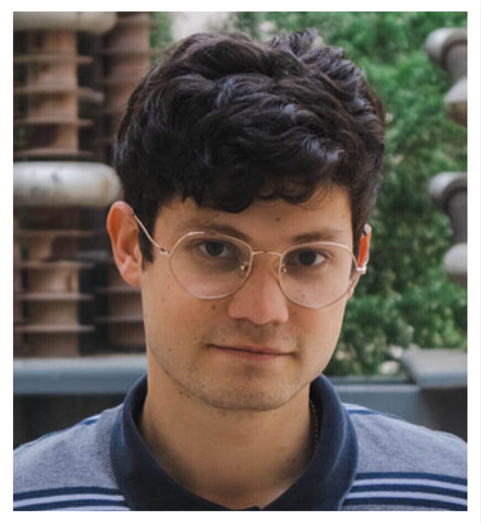

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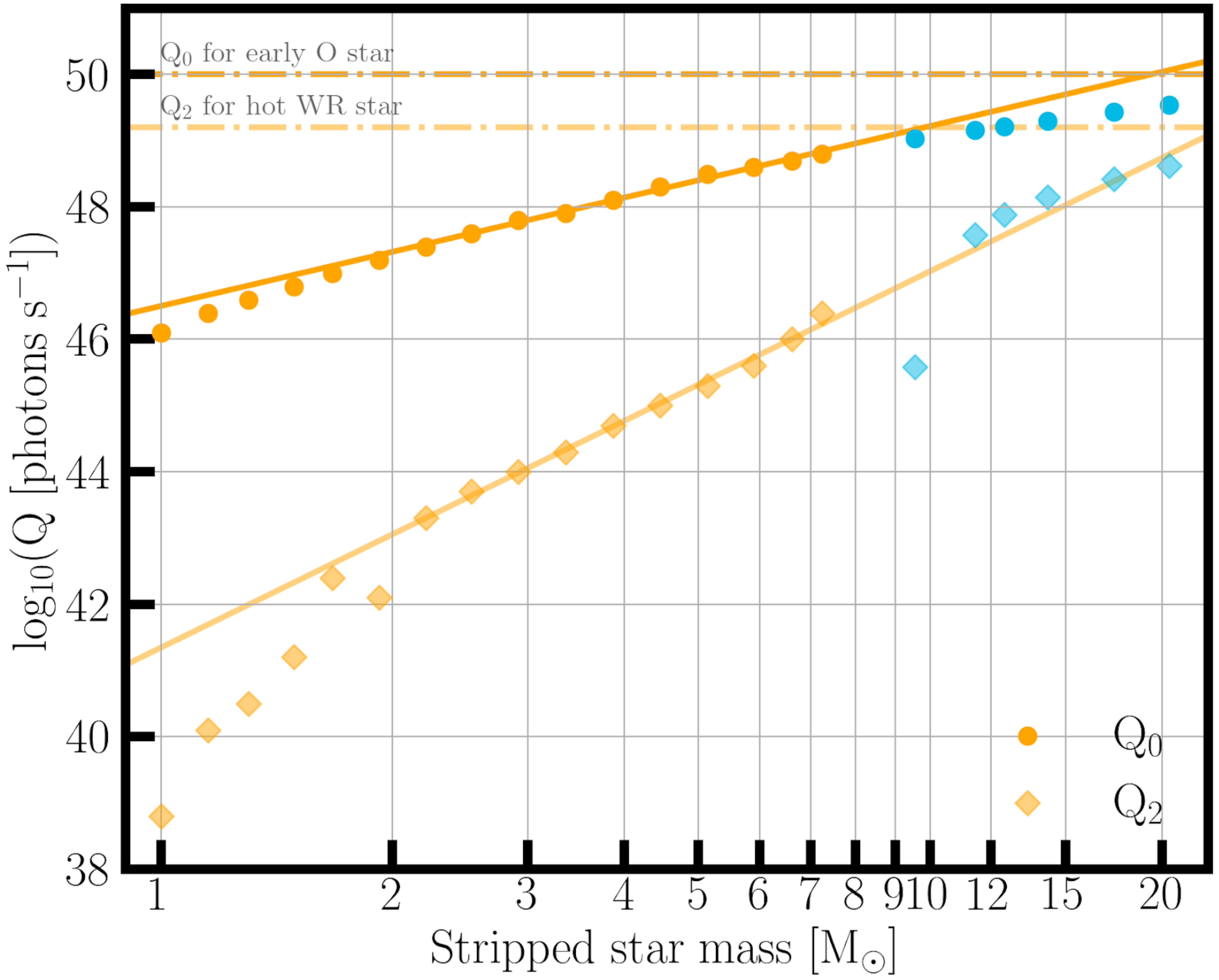

Hovis-Afflerbach, Götberg, et al. (2025)

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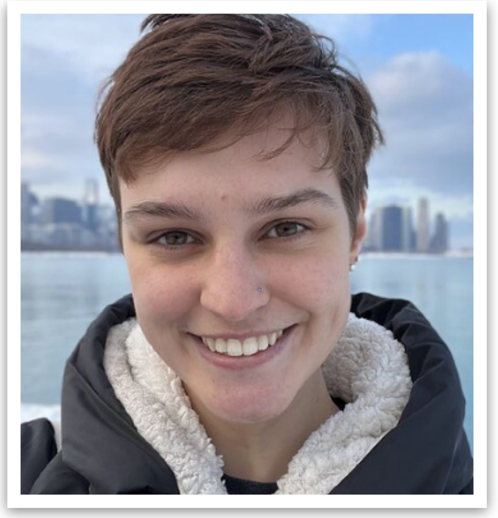

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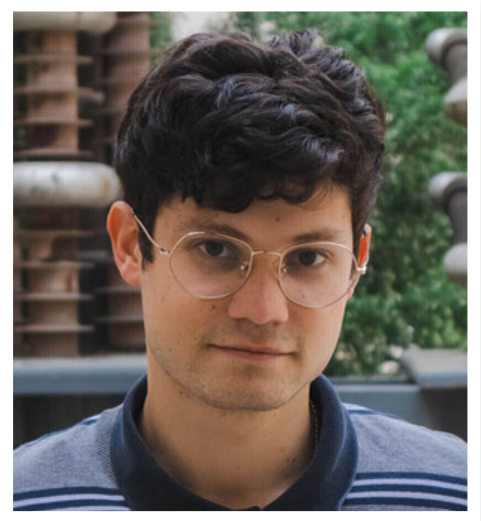

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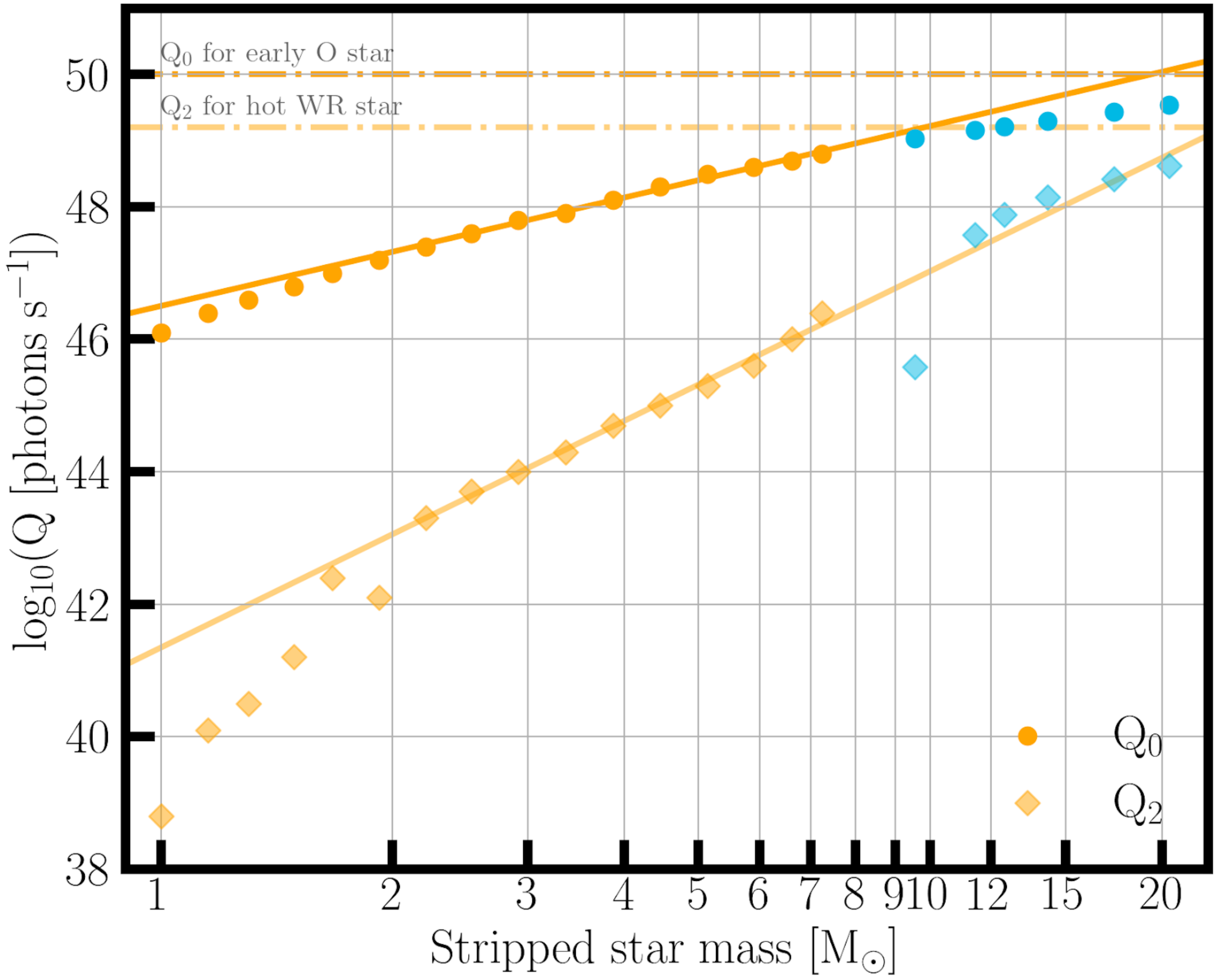

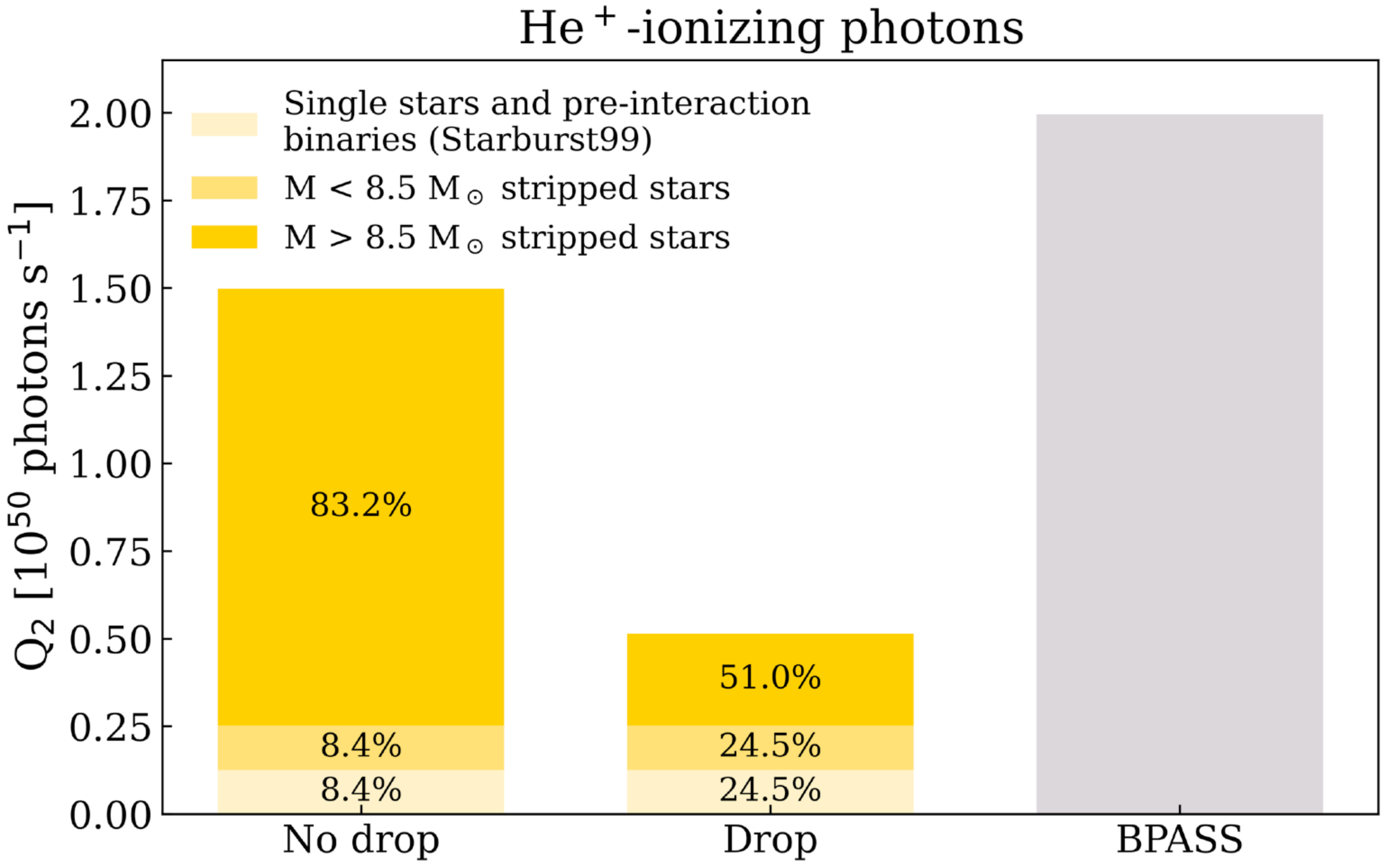

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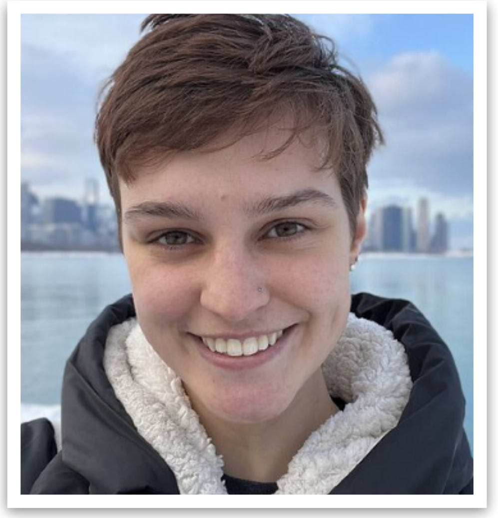
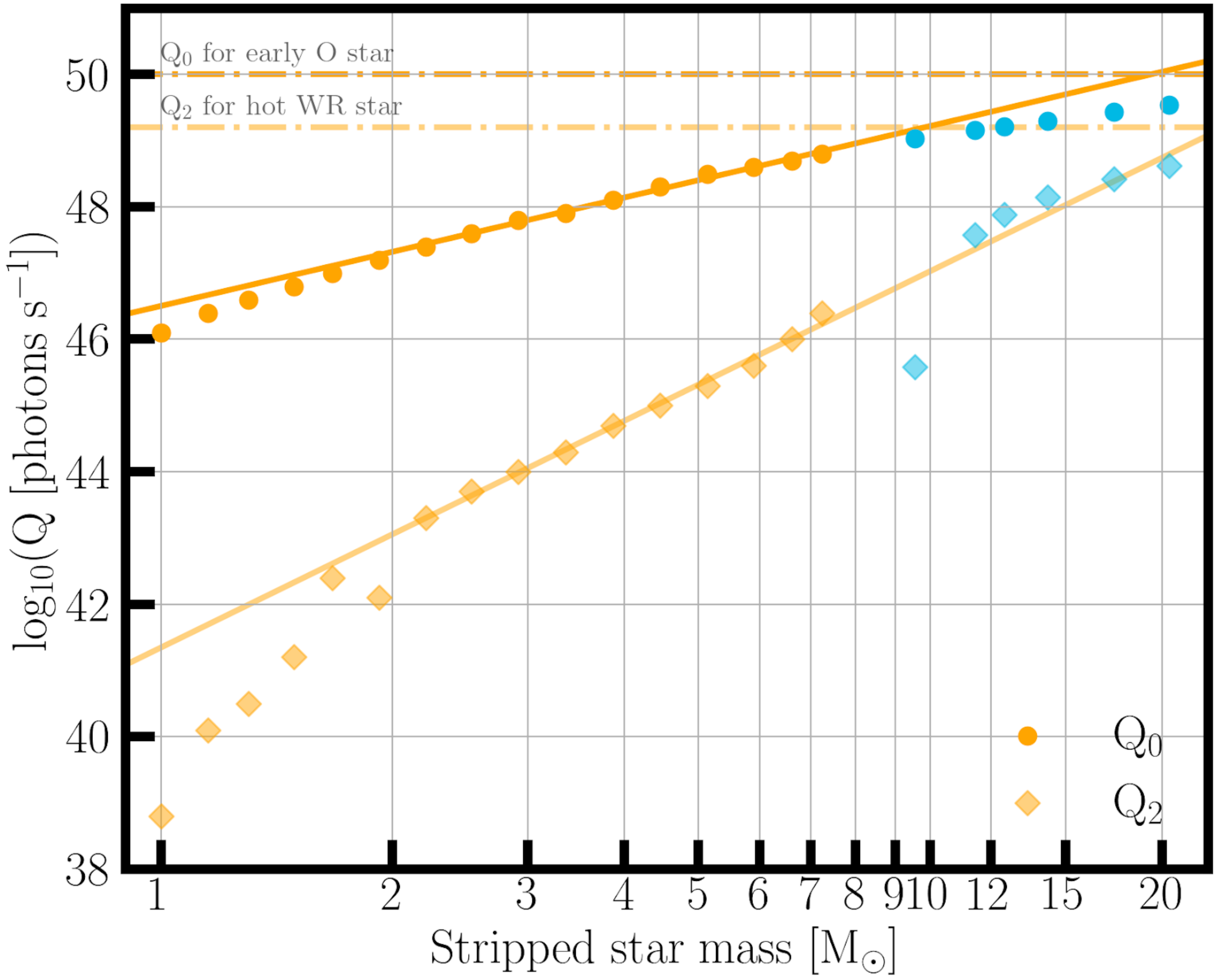
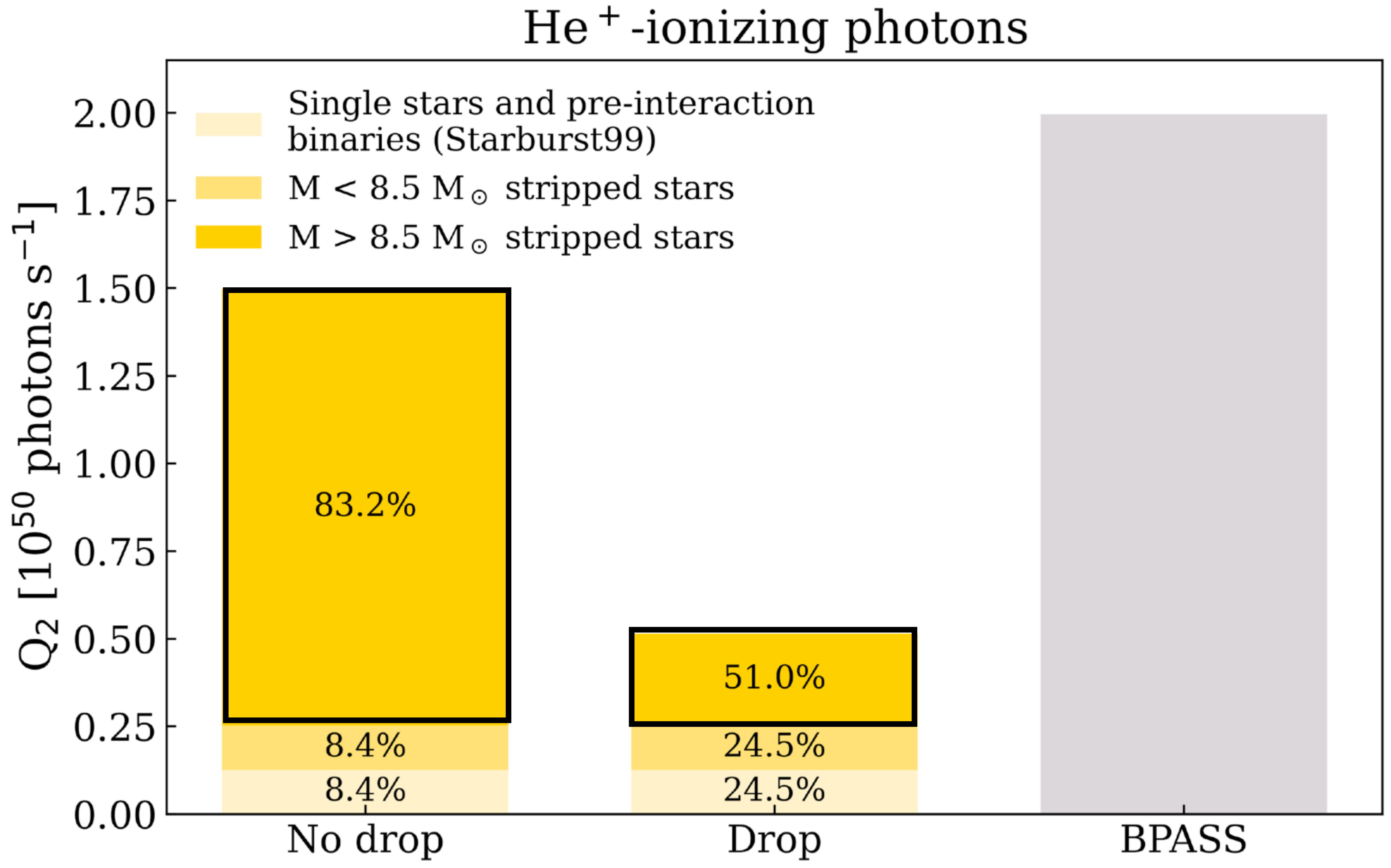


Beryl Hovis-Afflerbach
(PhD, Northwestern)

Benjamín Navarrete
(PhD, ISTA)

Massive helium-stars should exist in low-metallicity environments ($Z \lesssim Z_\odot/5$) — and they boost the He^+ ionizing emission by a factor of 2-5.





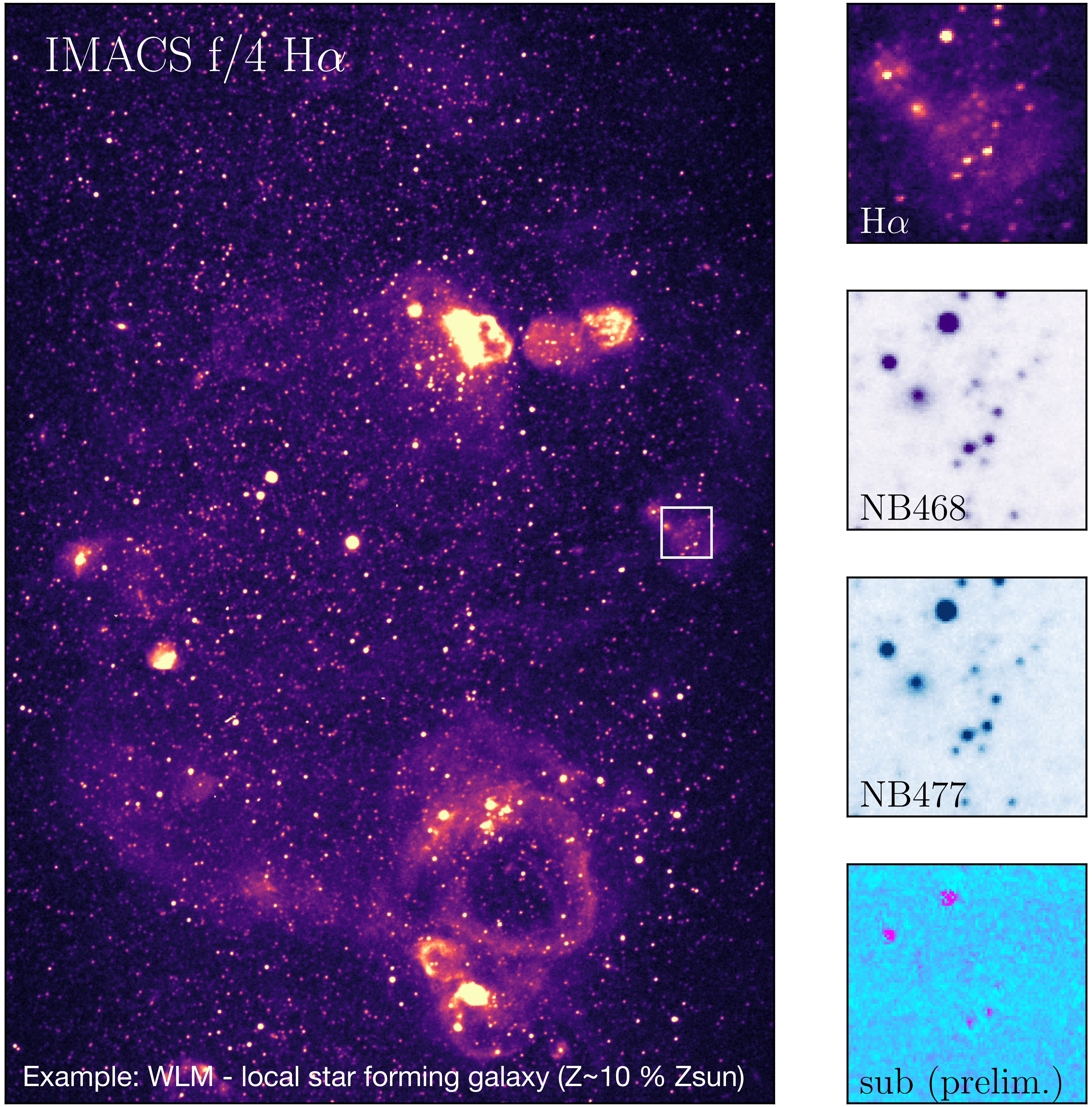
Hovis-Afflerbach, Götberg, et al. (2025)

HeII **E**mission in **L**ocal **G**alaxies with **I**MACS

PI: **Senchyna** & Götberg

- What sources emit the hard He+ ionizing radiation found in low-Z star-forming galaxies?
- HeII 4686 narrowband (off and on band) filters for IMACS f/4 + multislit masks

Peter Senchyna



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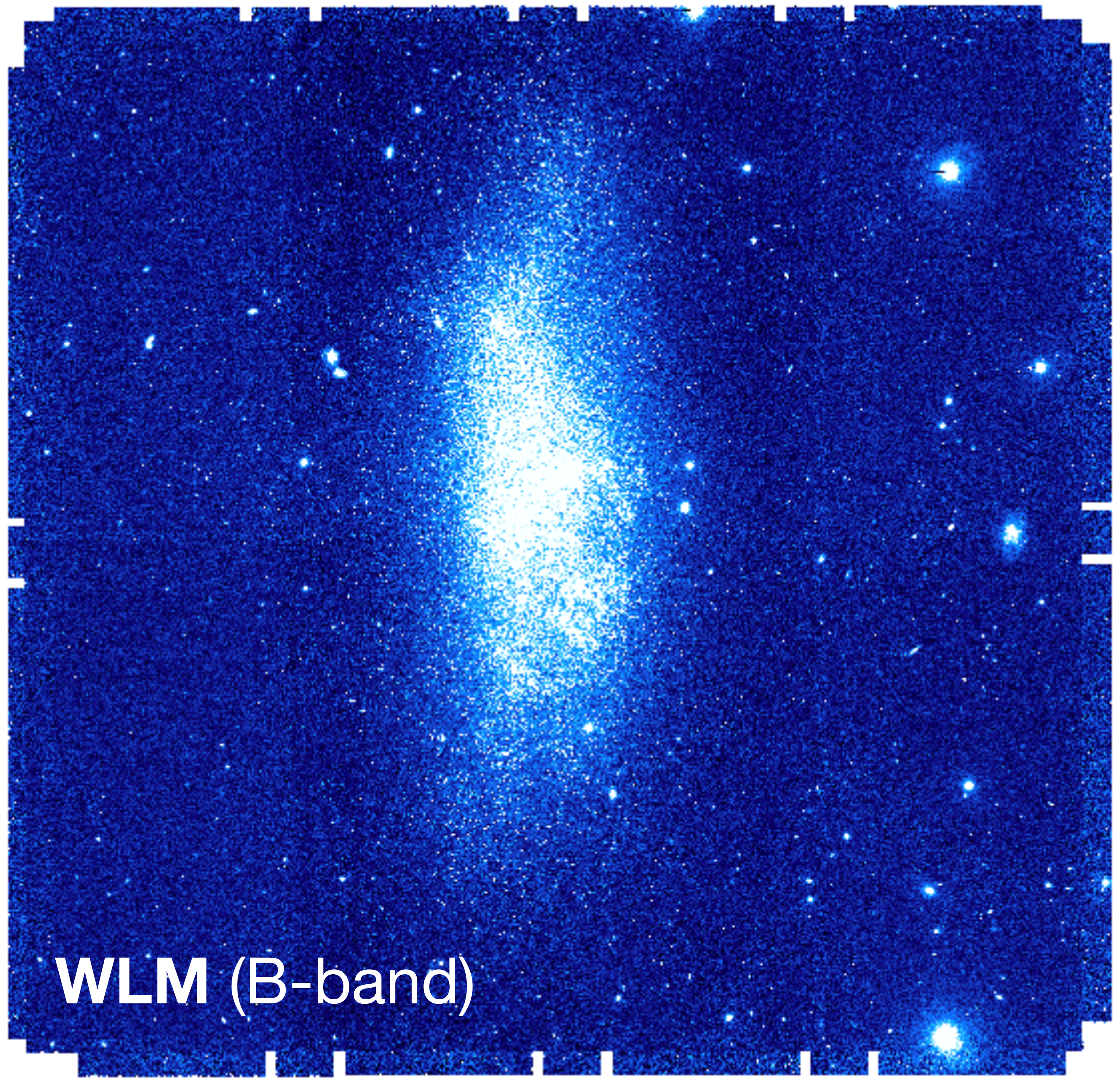
Upcoming: Isolated He II emitters



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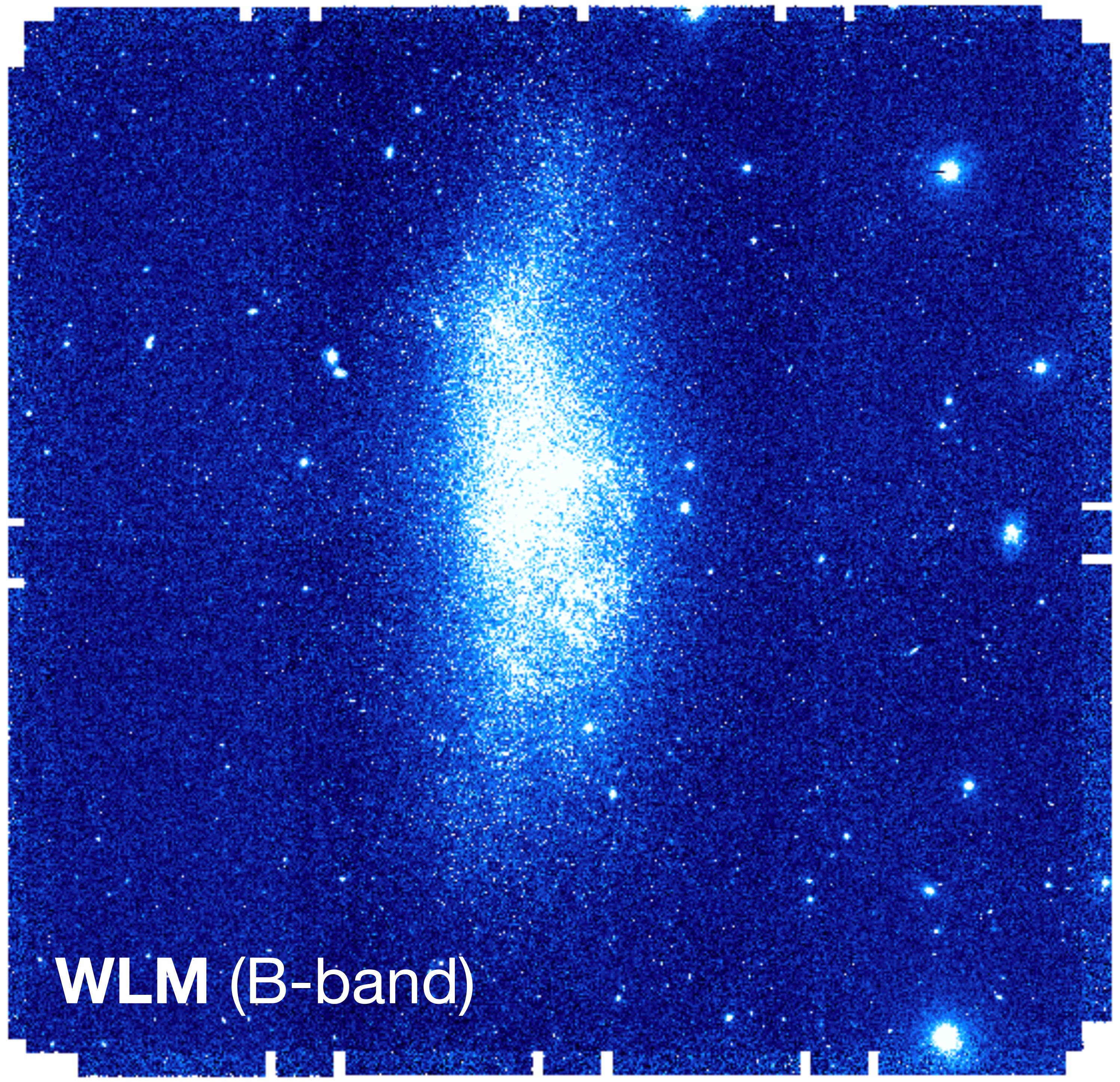

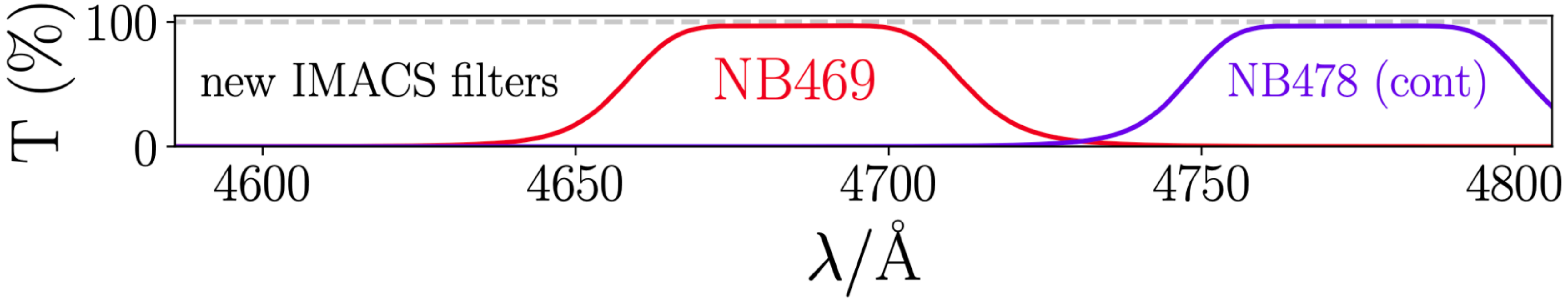

Peter Senchyna

Helgi

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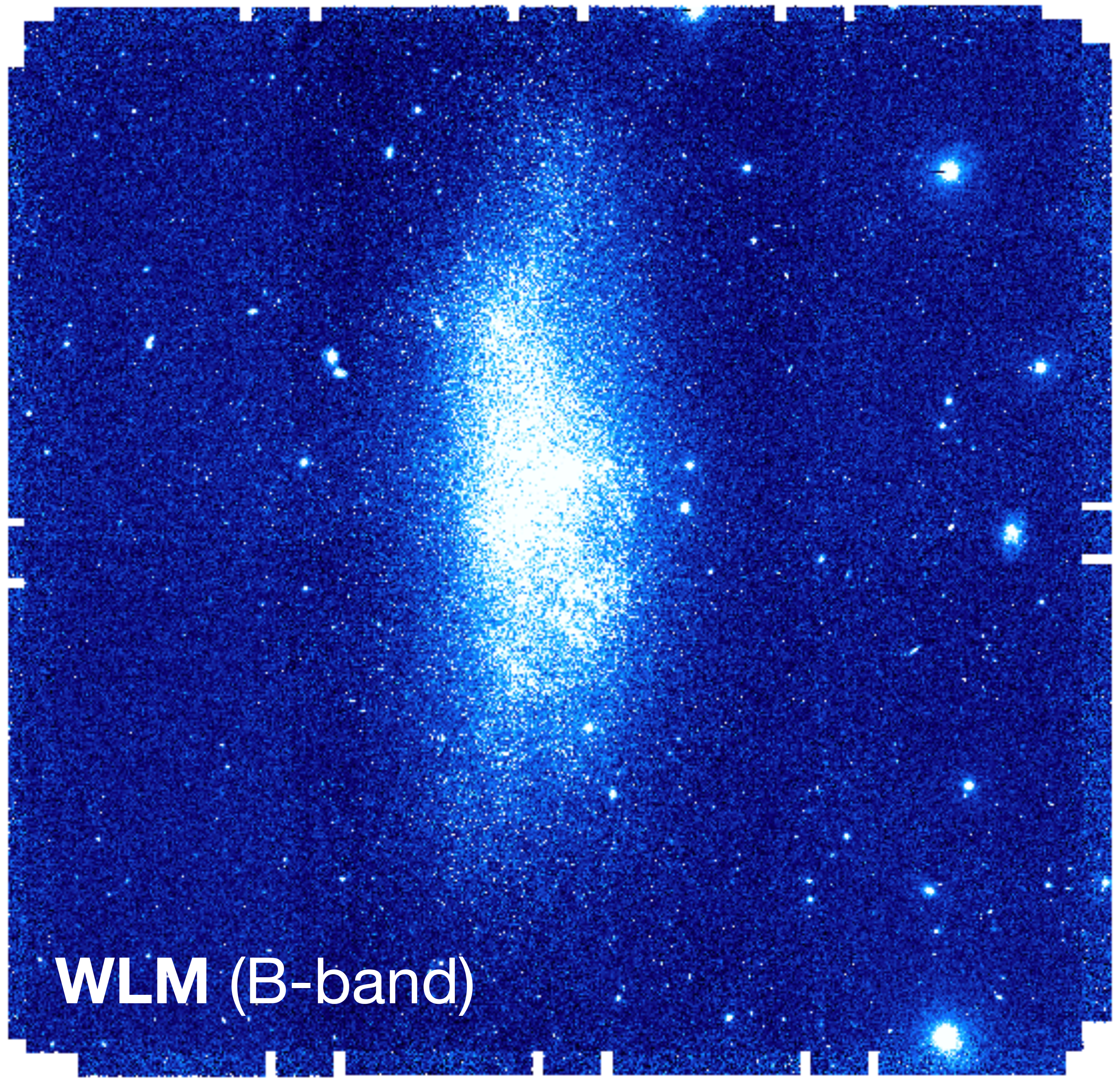

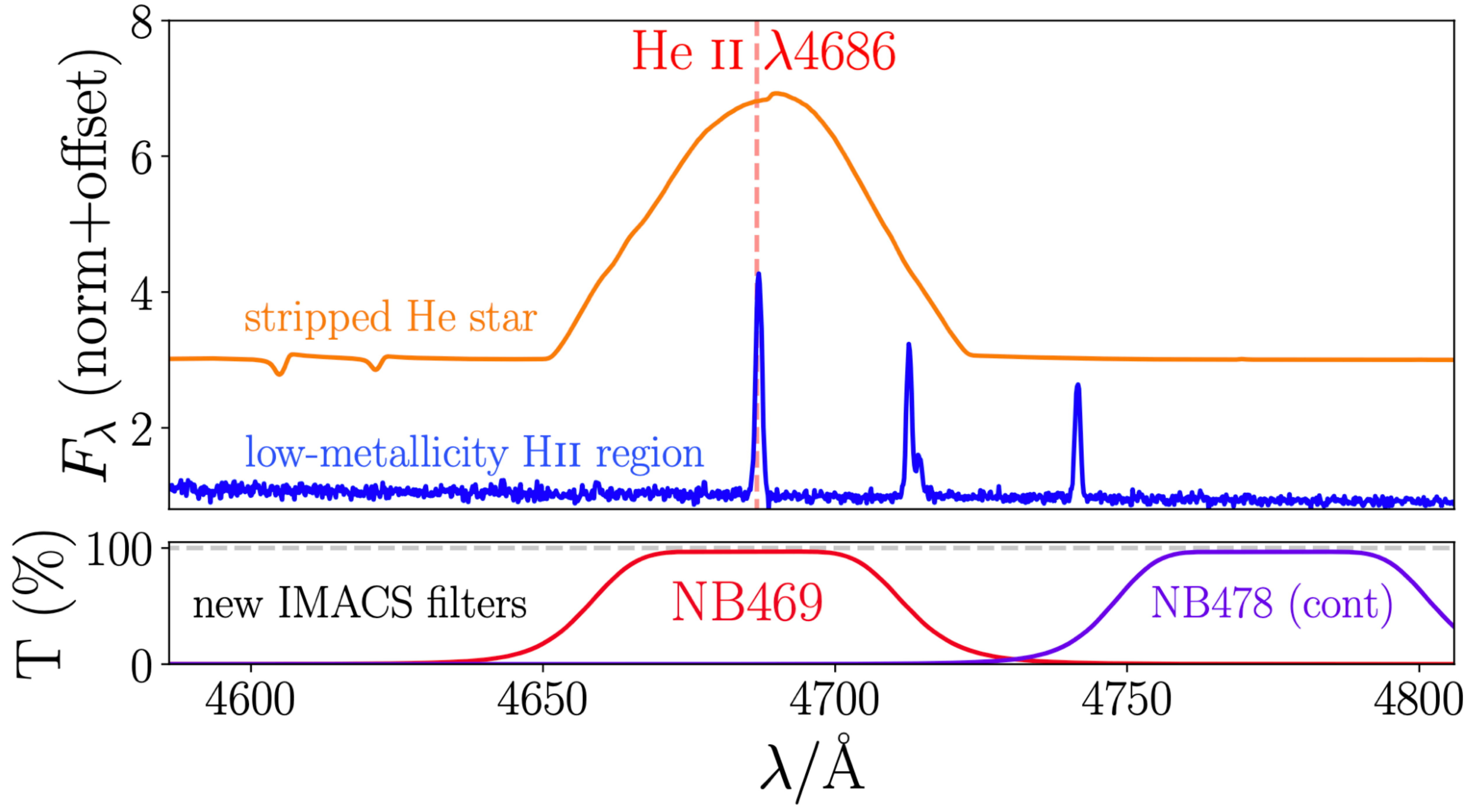

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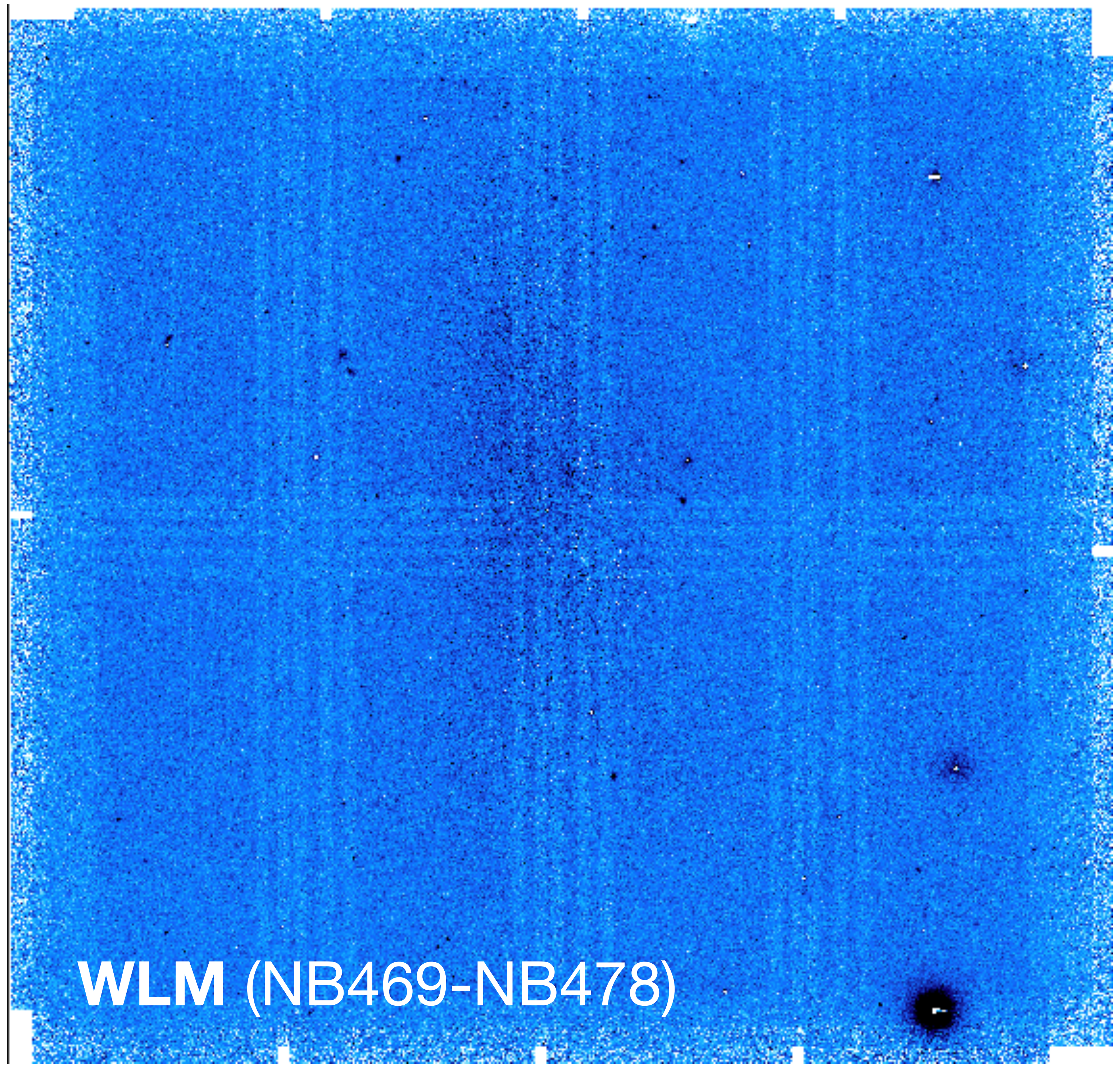

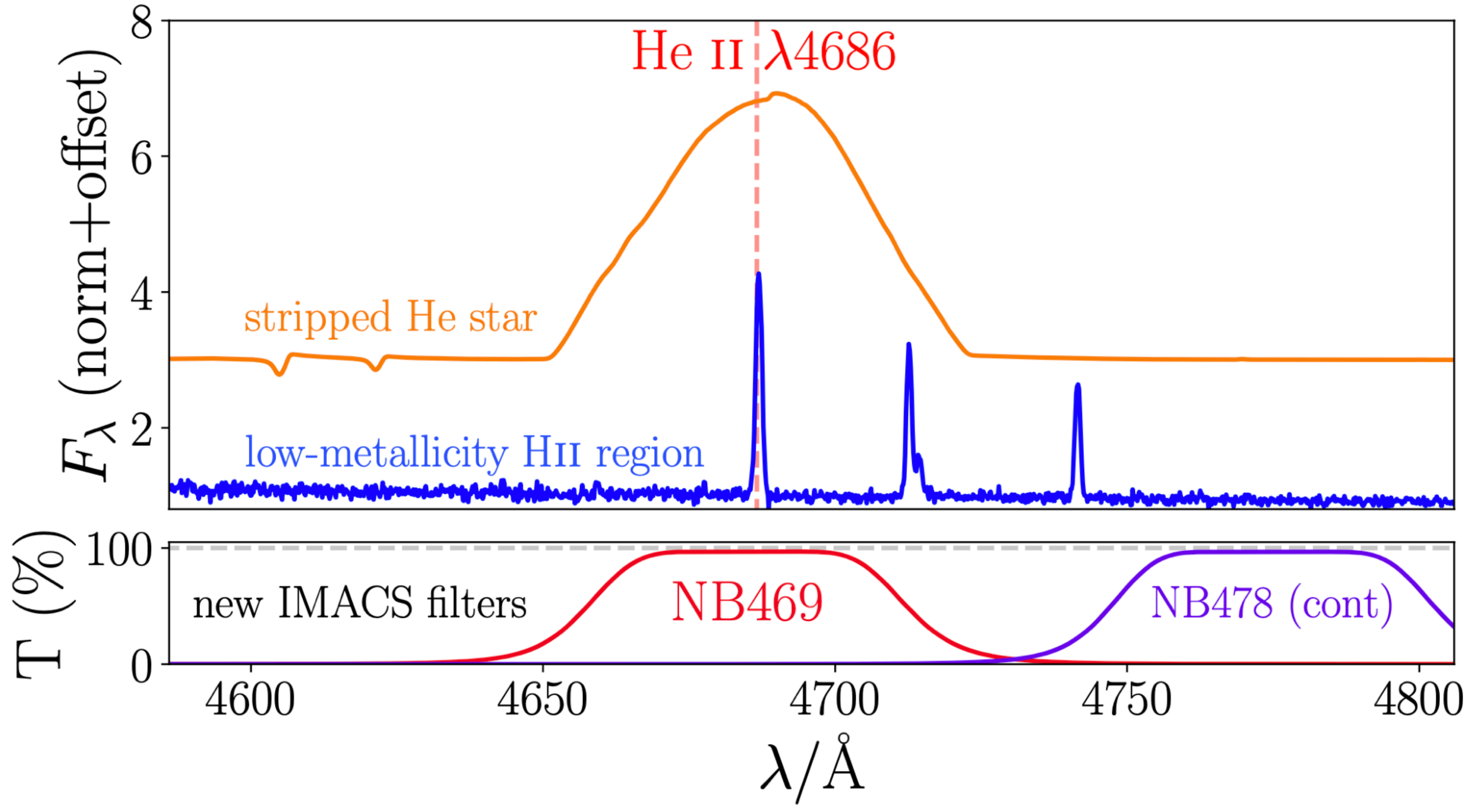

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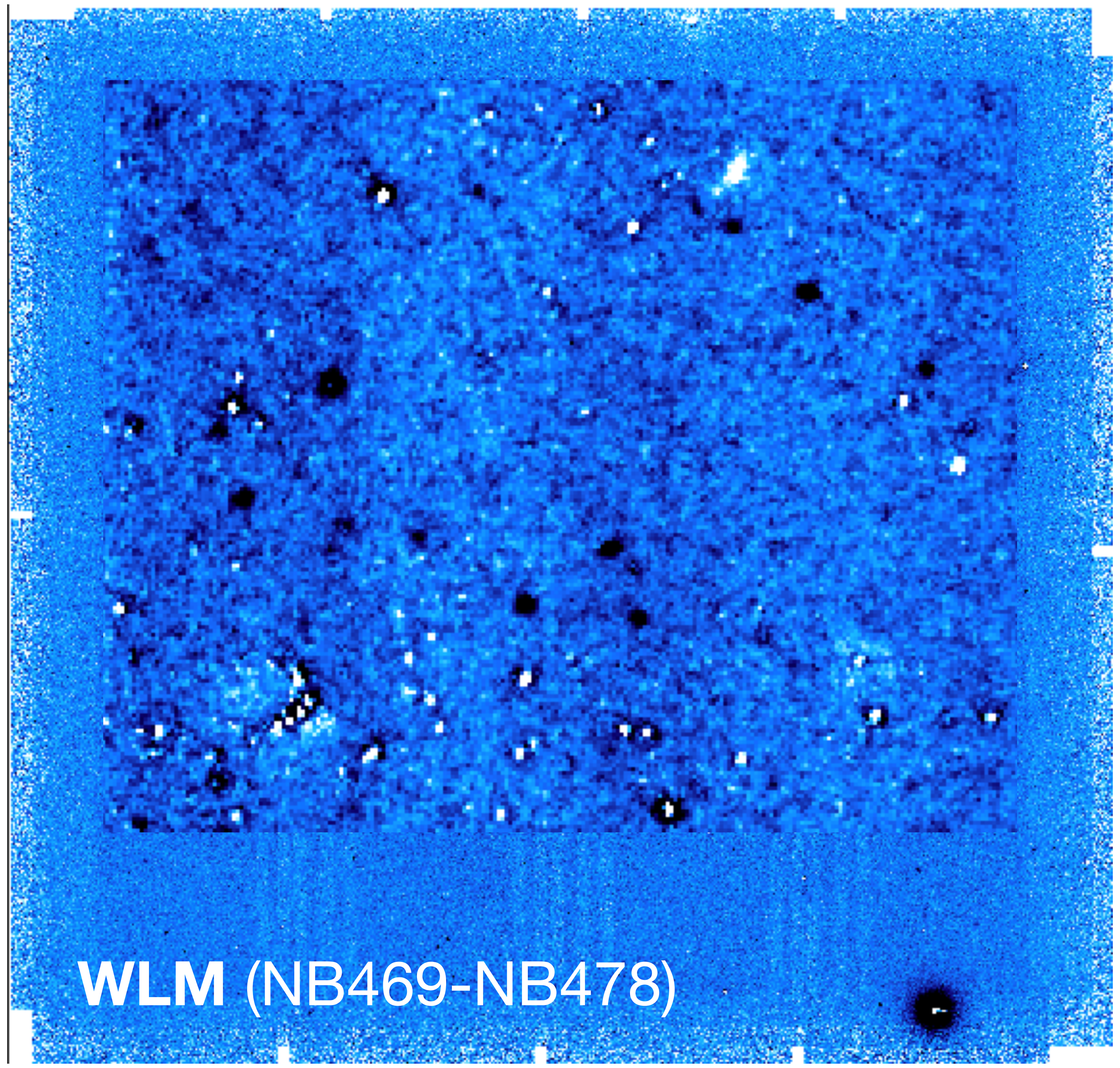

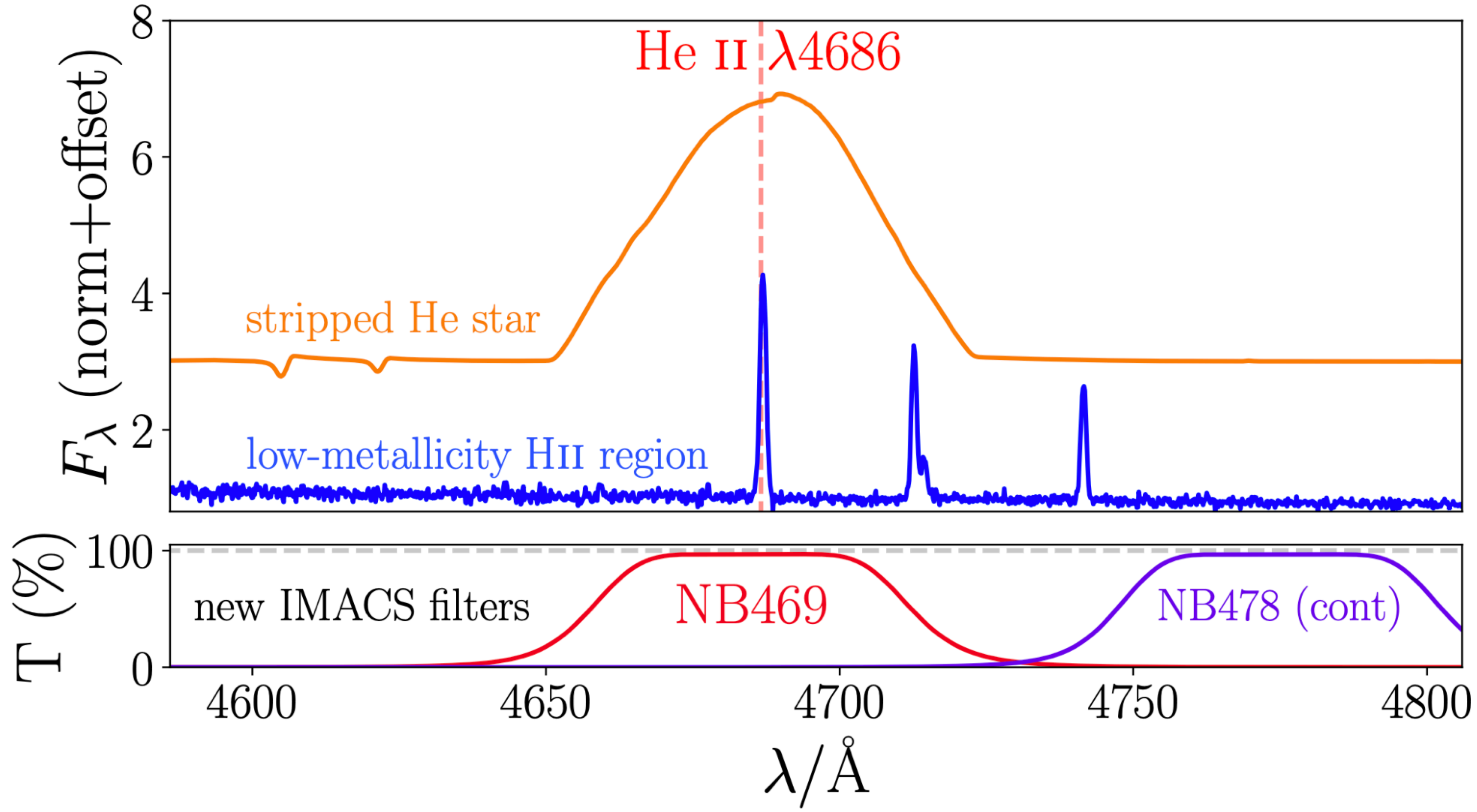

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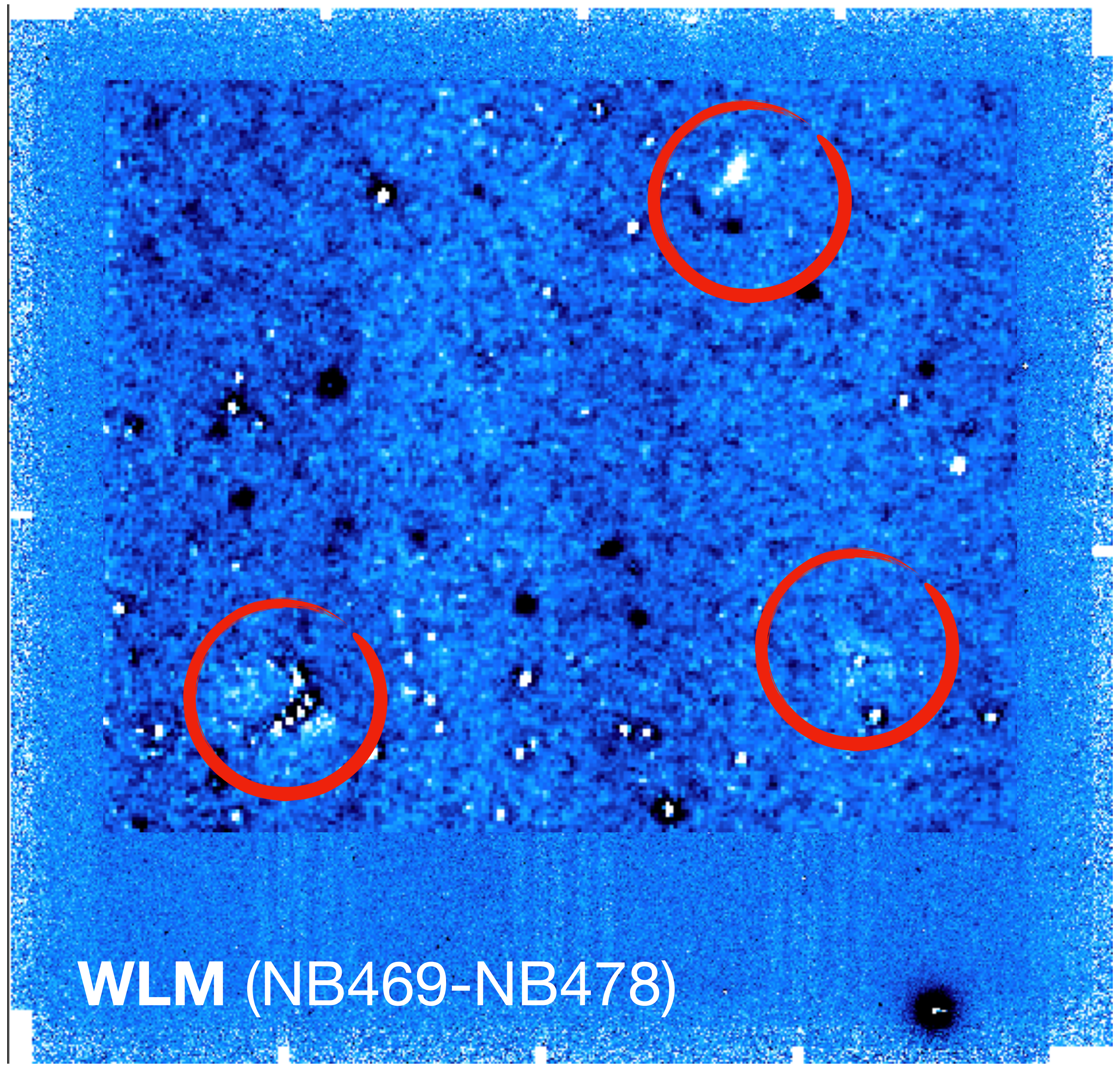

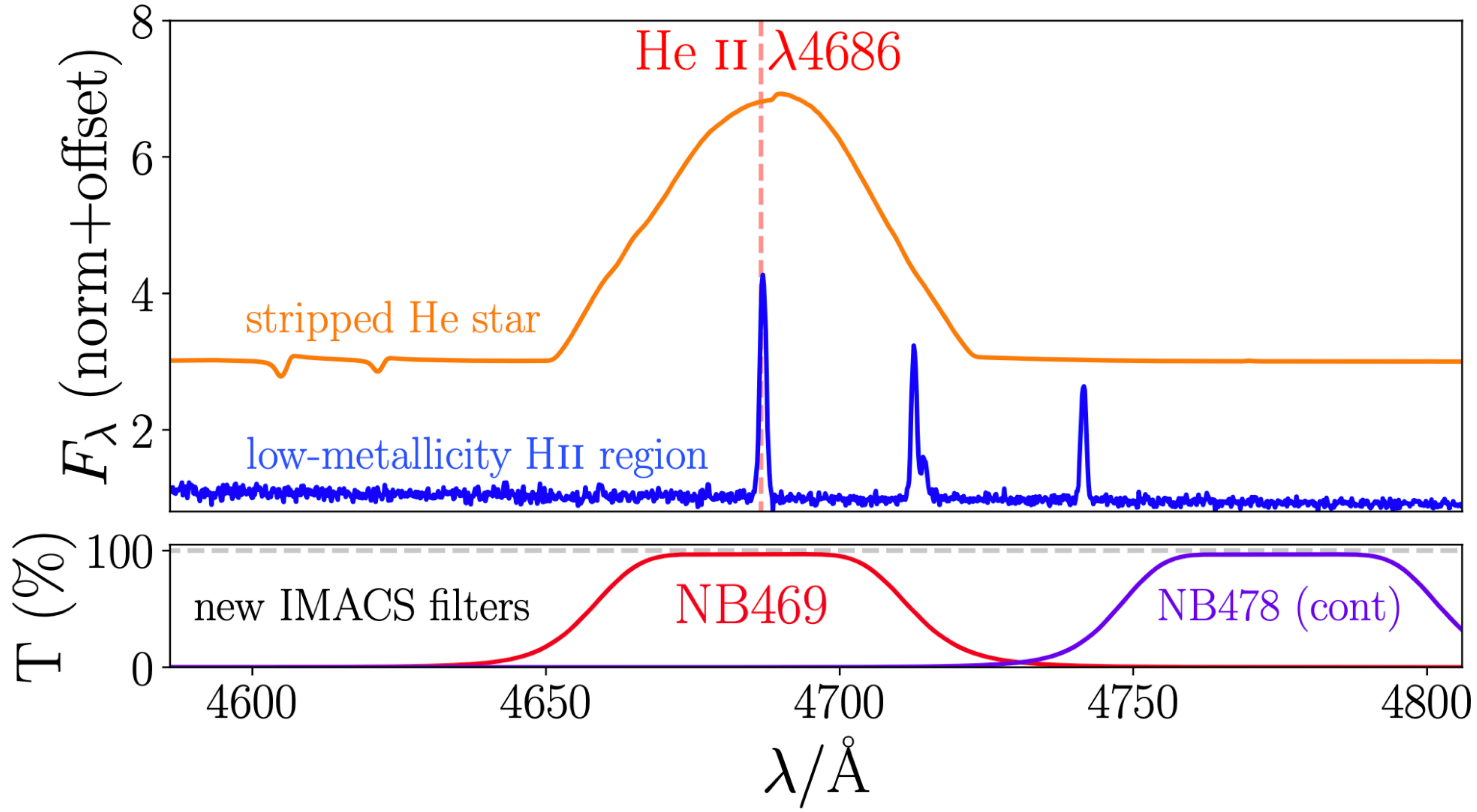

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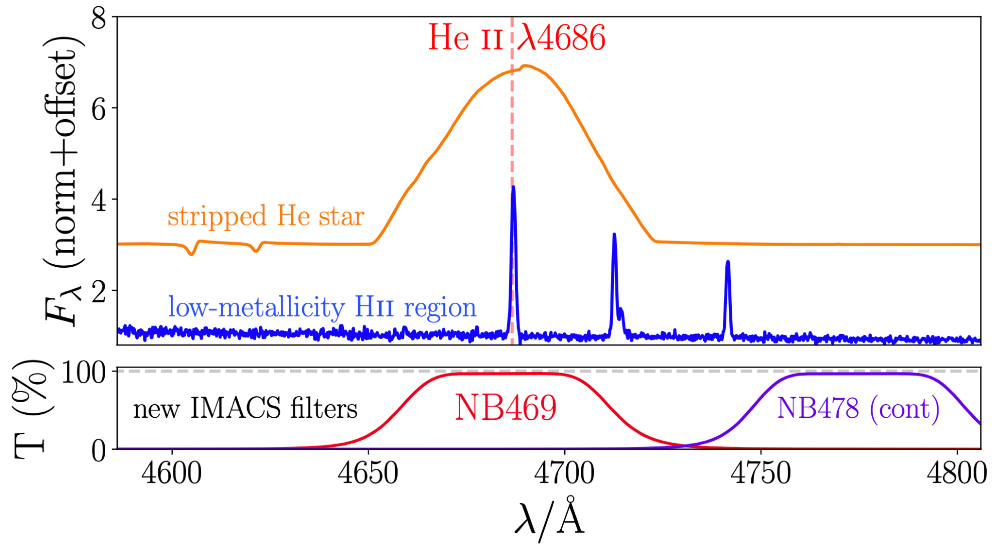

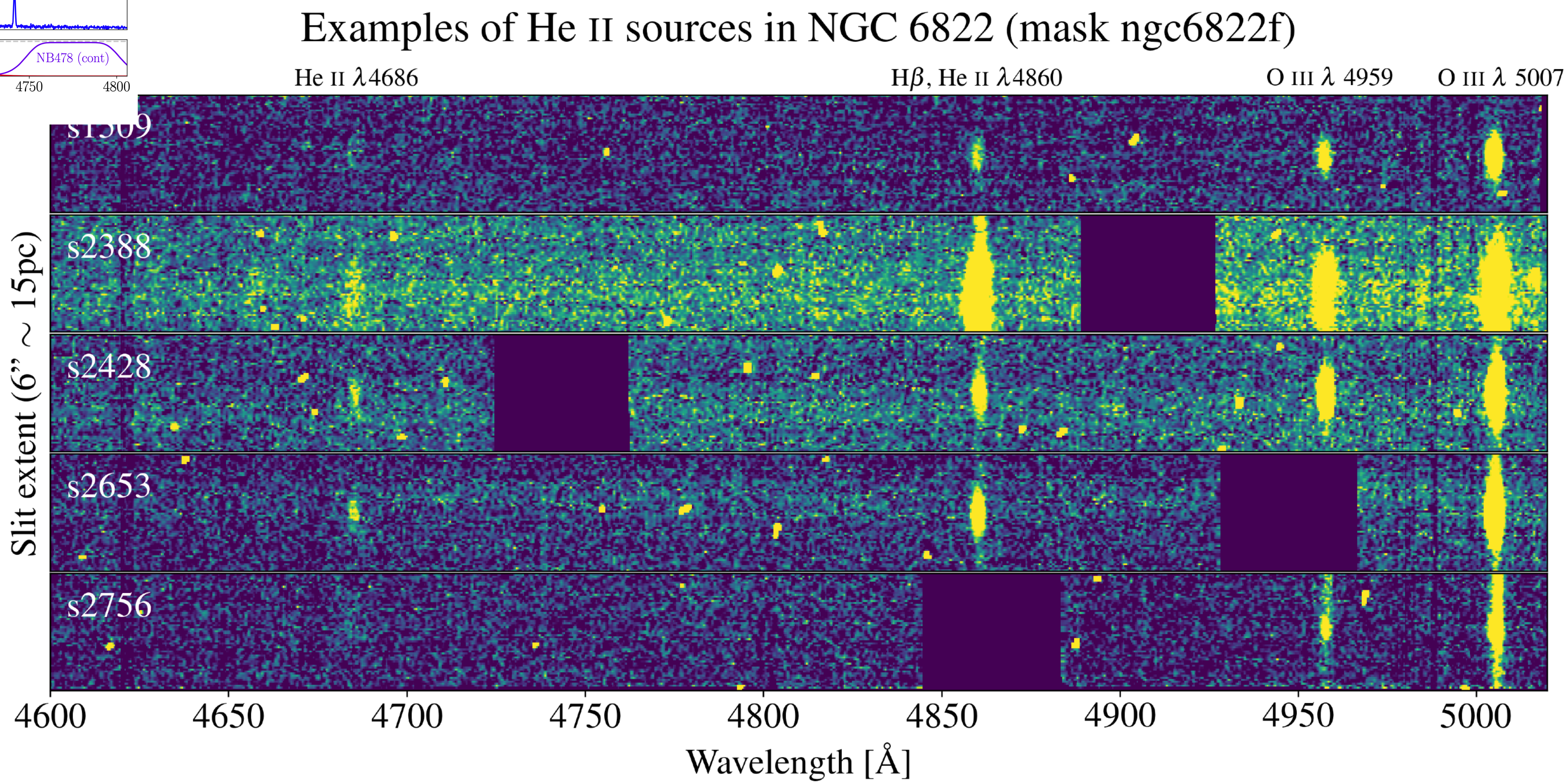

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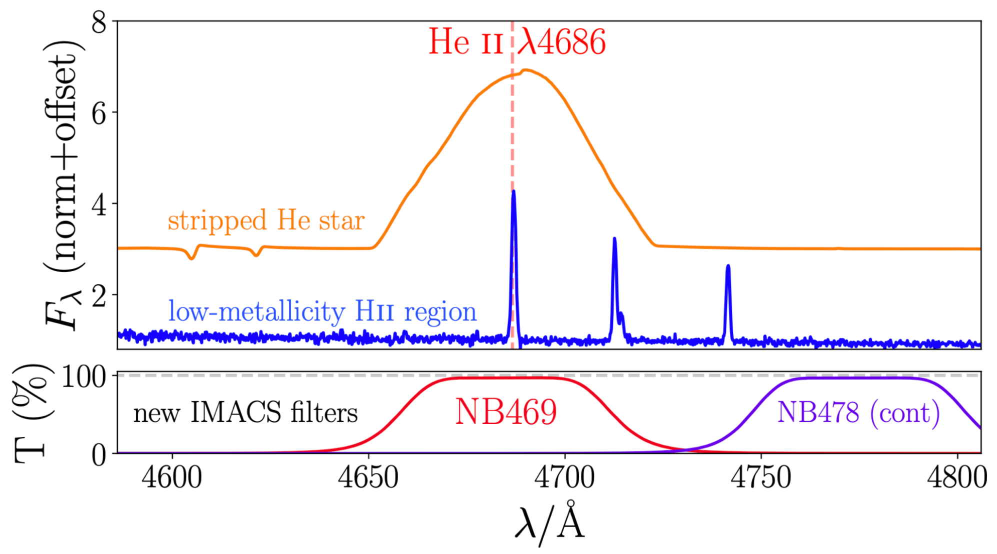

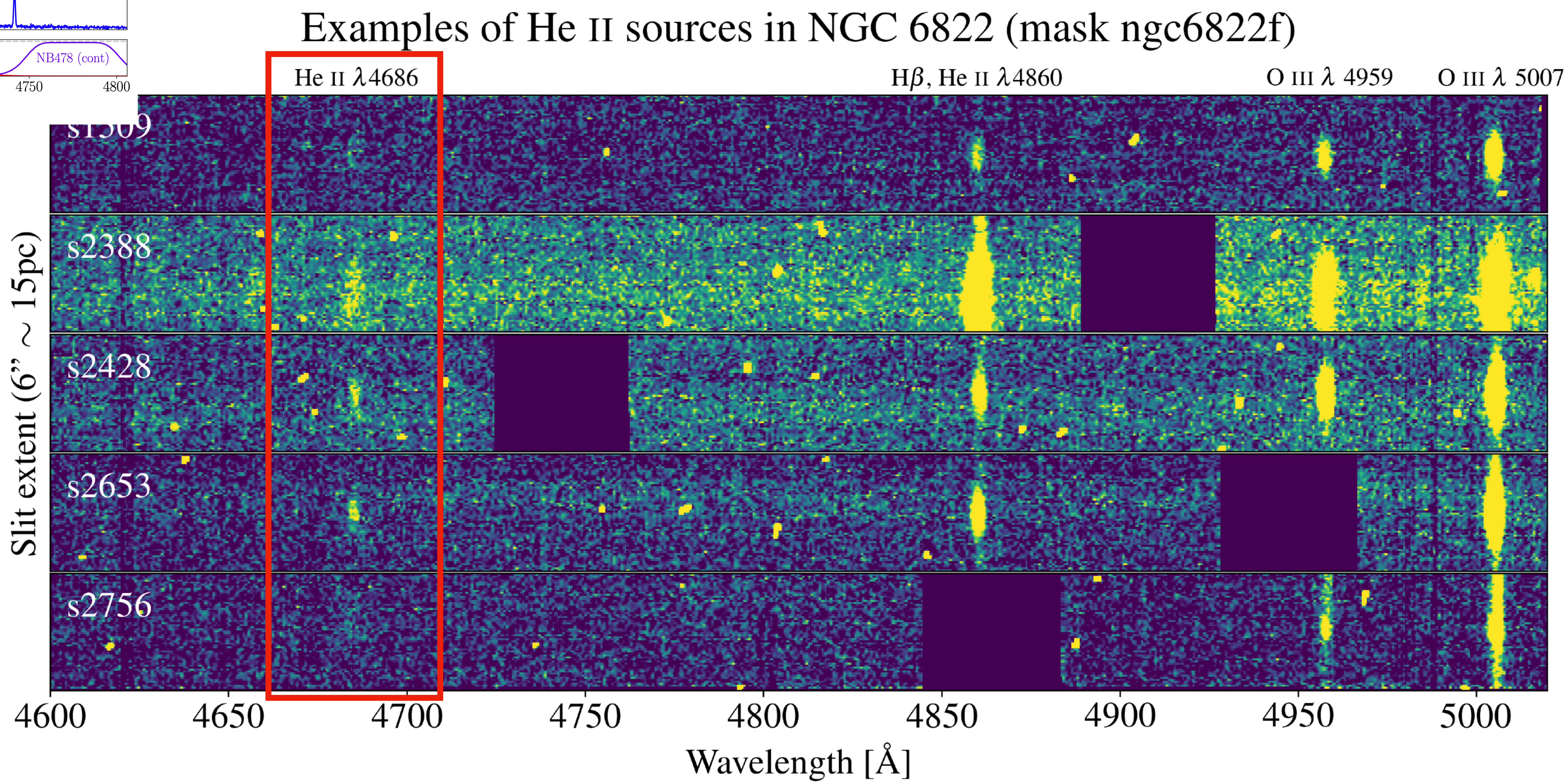

Peter Senchyna

3) Ongoing and future directions

Low-Z: the need for benchmark stars

Observations of individual stars are **necessary** for calibrating both evolutionary and spectral models - therefore also for confirming the validity of spectral population synthesis.

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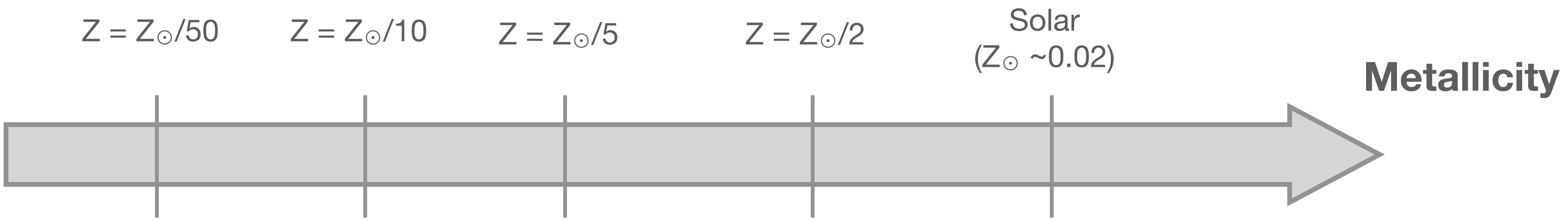

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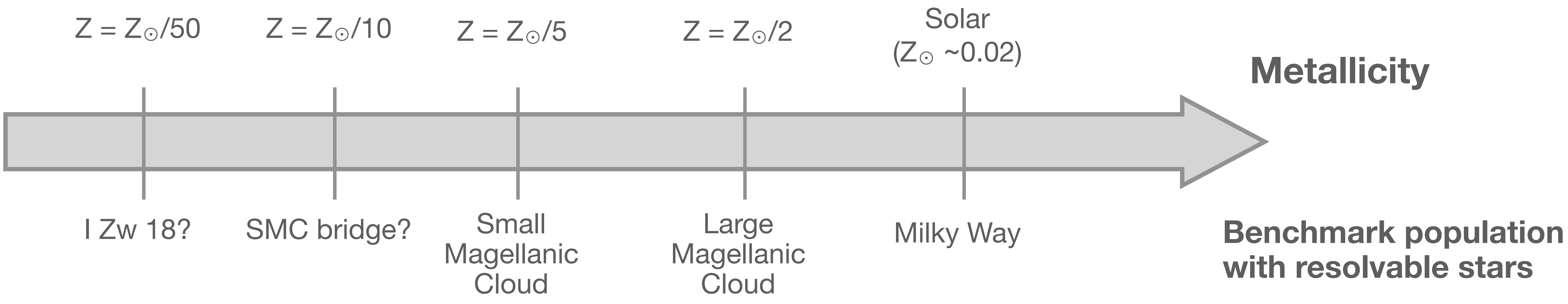

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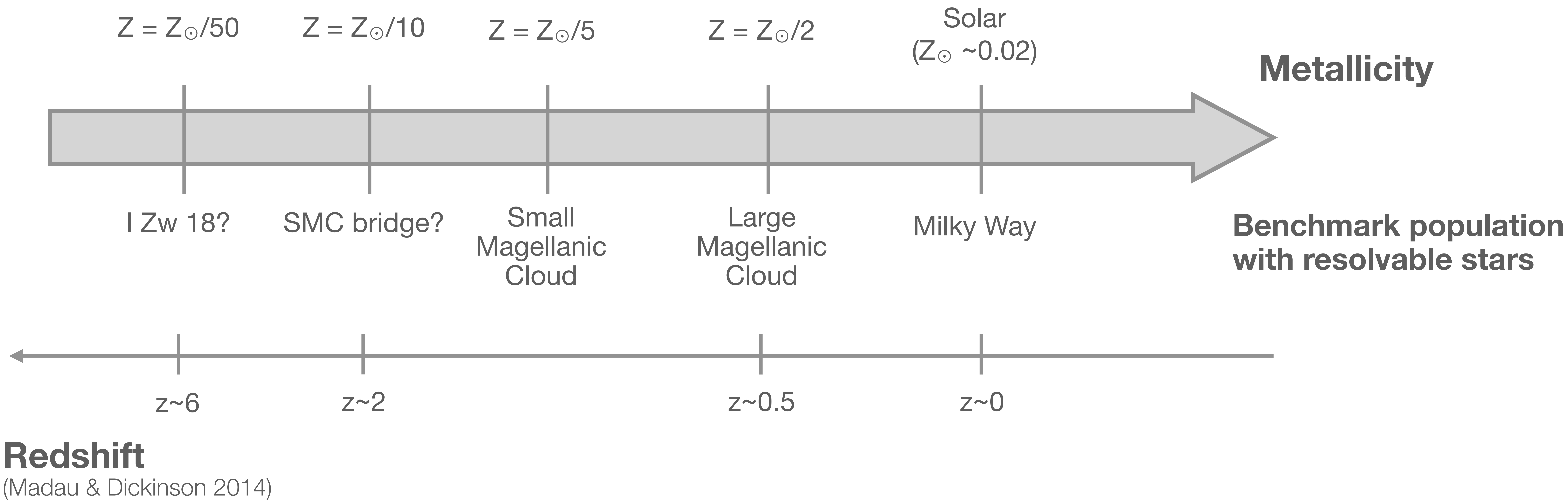

Very low metallicity massive stars

The sample of very low-metallicity massive stars is growing, but (1) do these really match evolutionary models?, and (2) are we missing the very massive stars?

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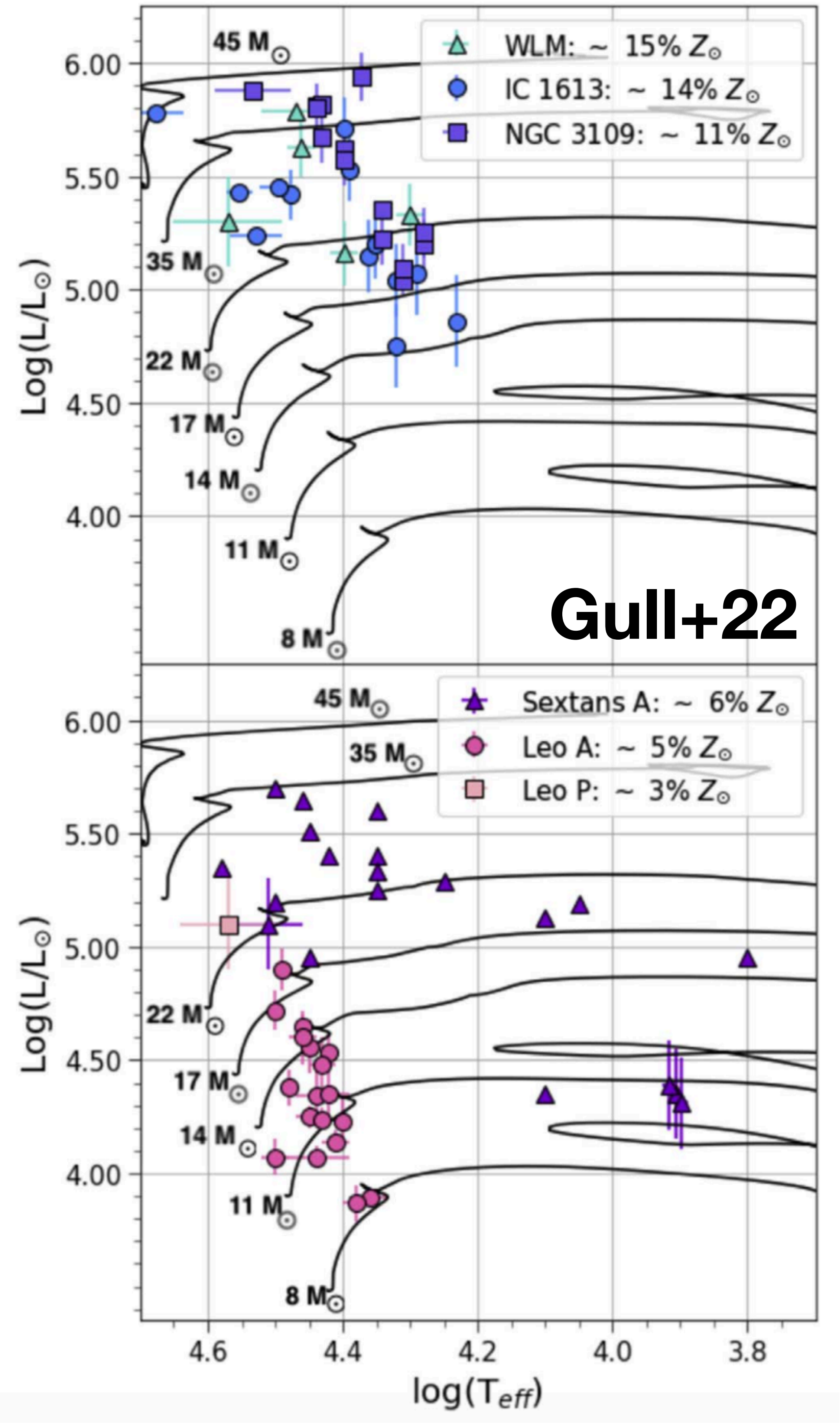

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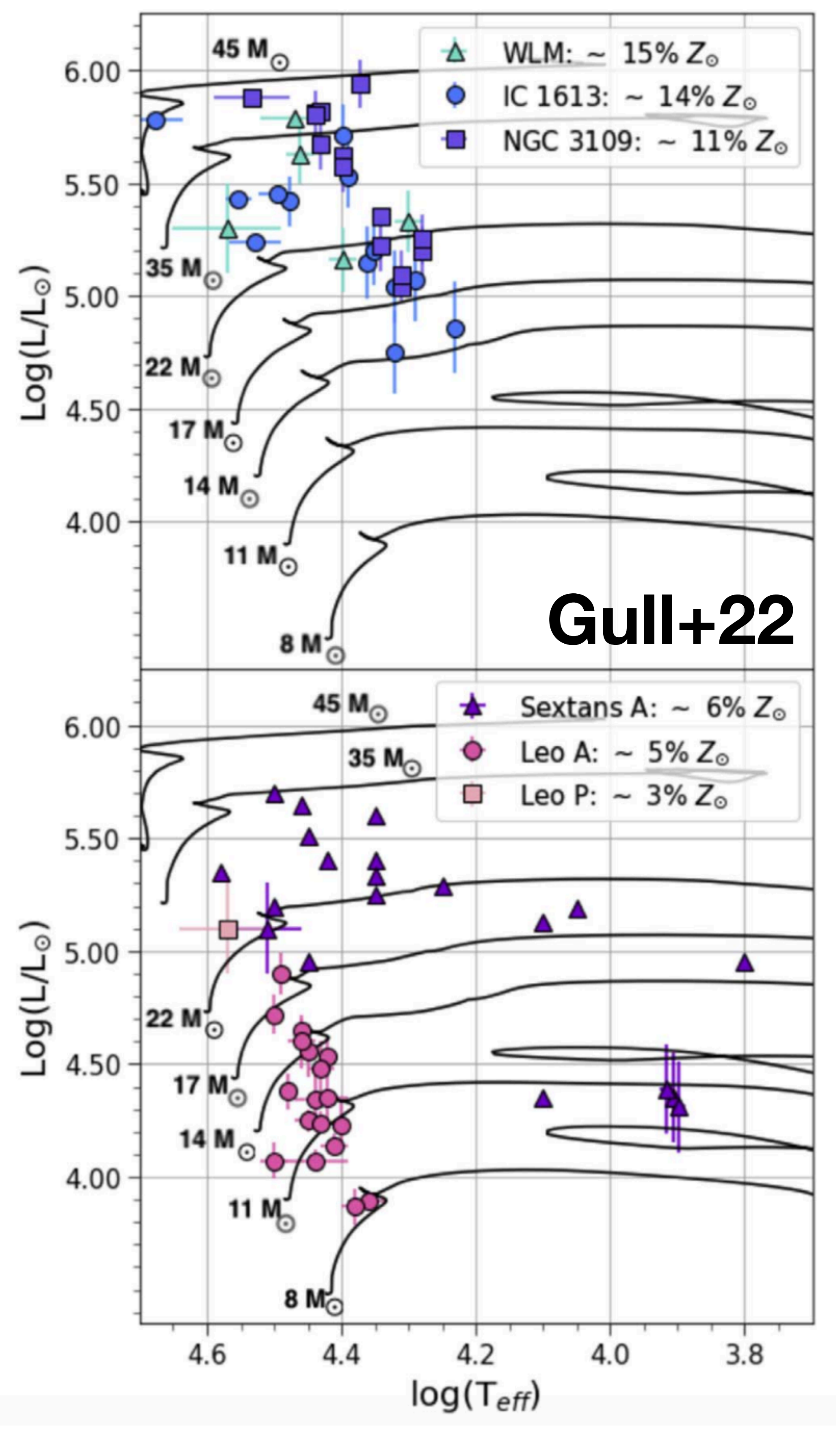

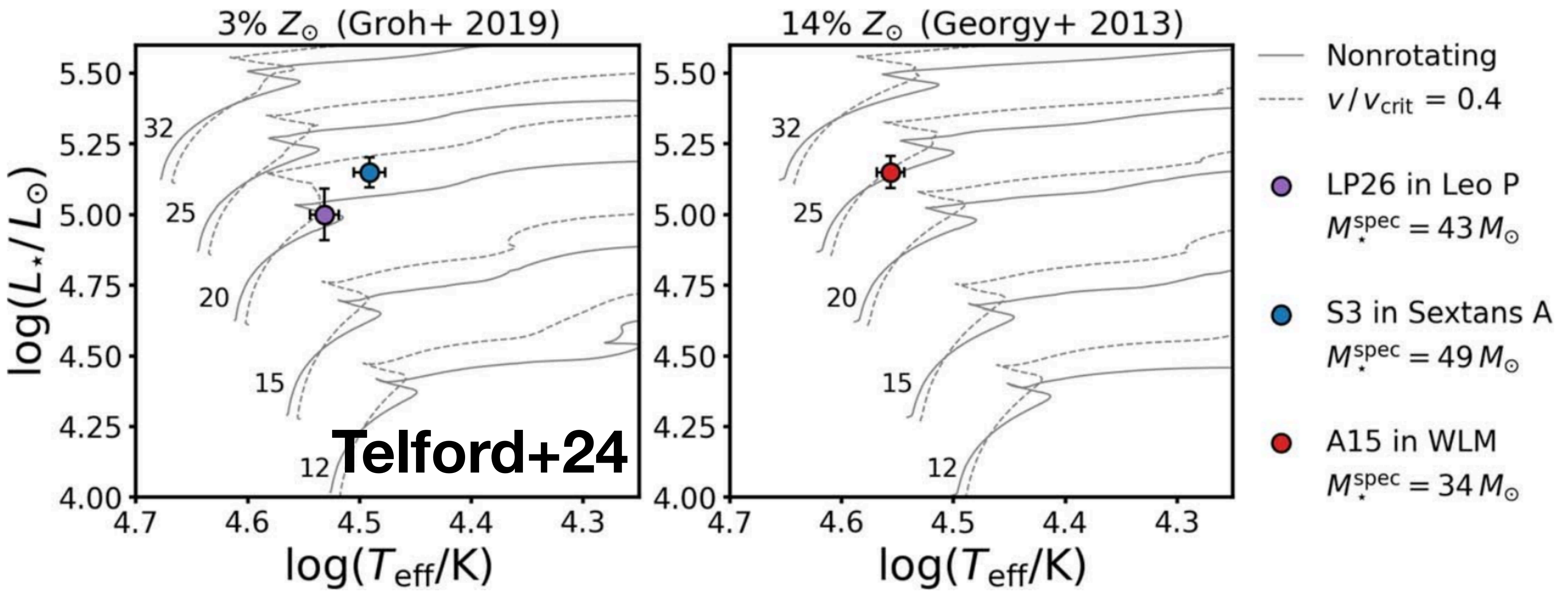

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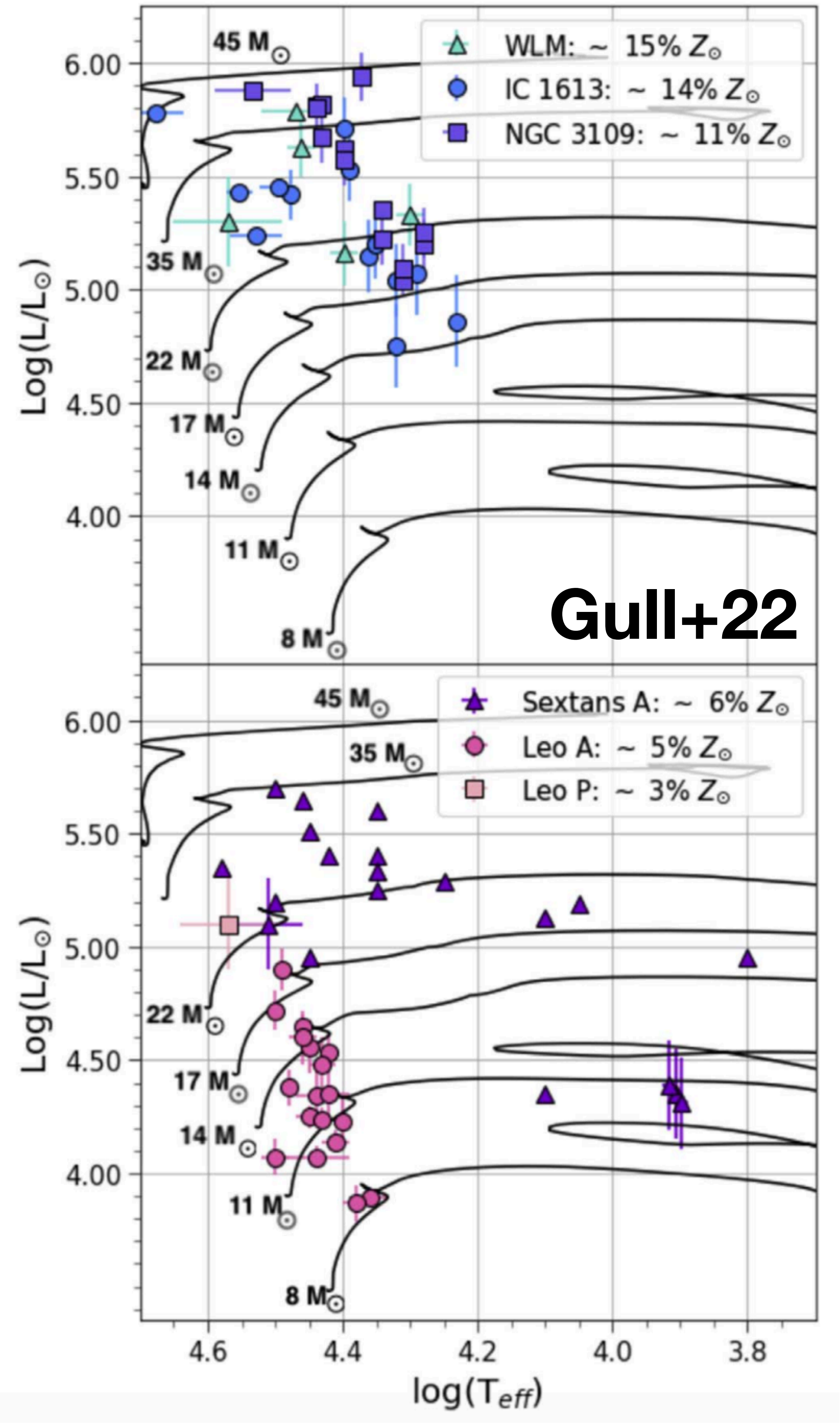
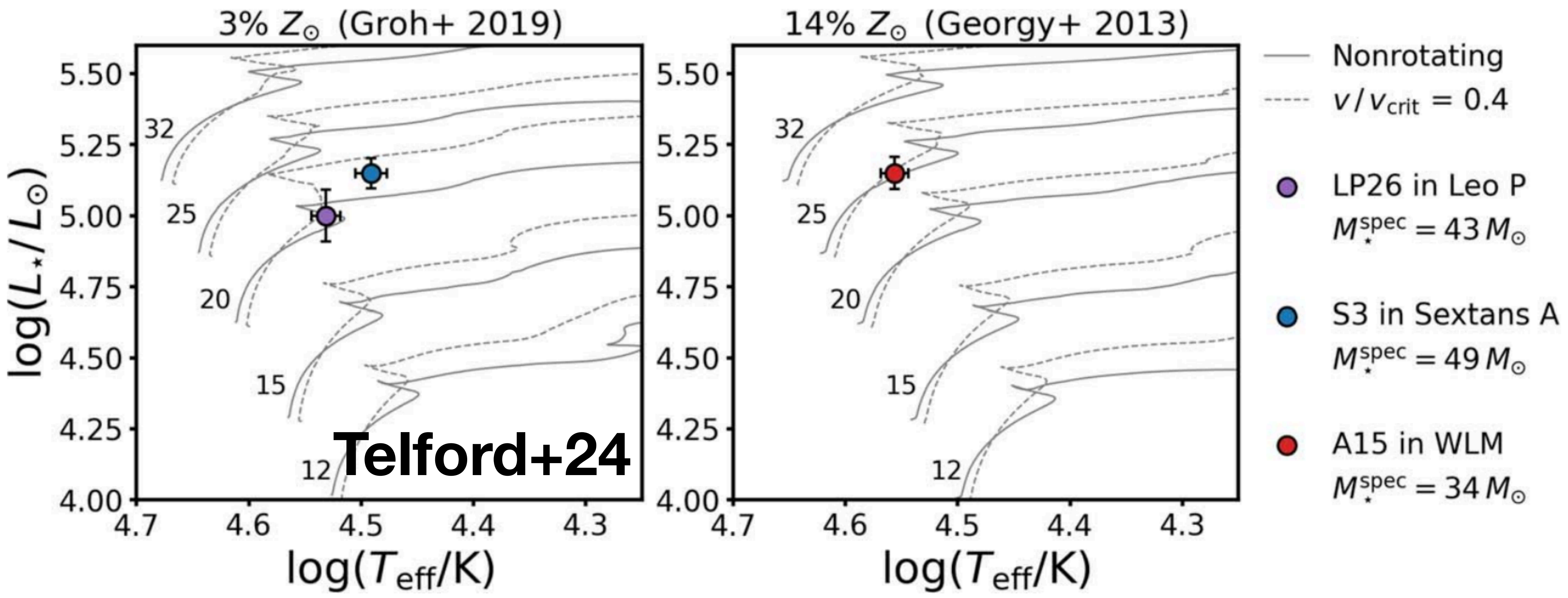
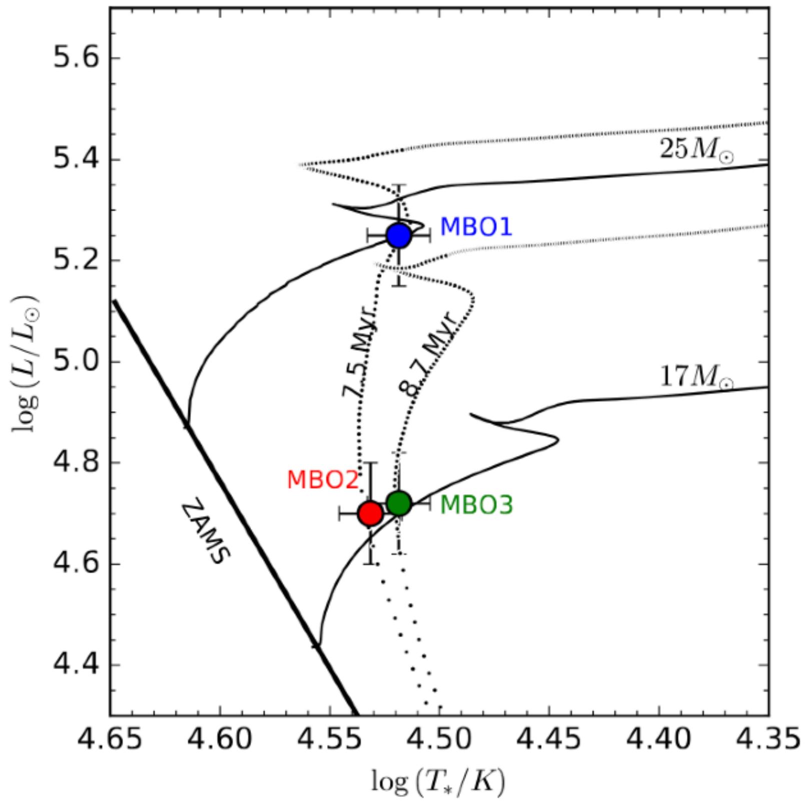




Magellanic Bridge (~10% Z$_\odot$)



Ramachandran+22
(see also Schösser+25)

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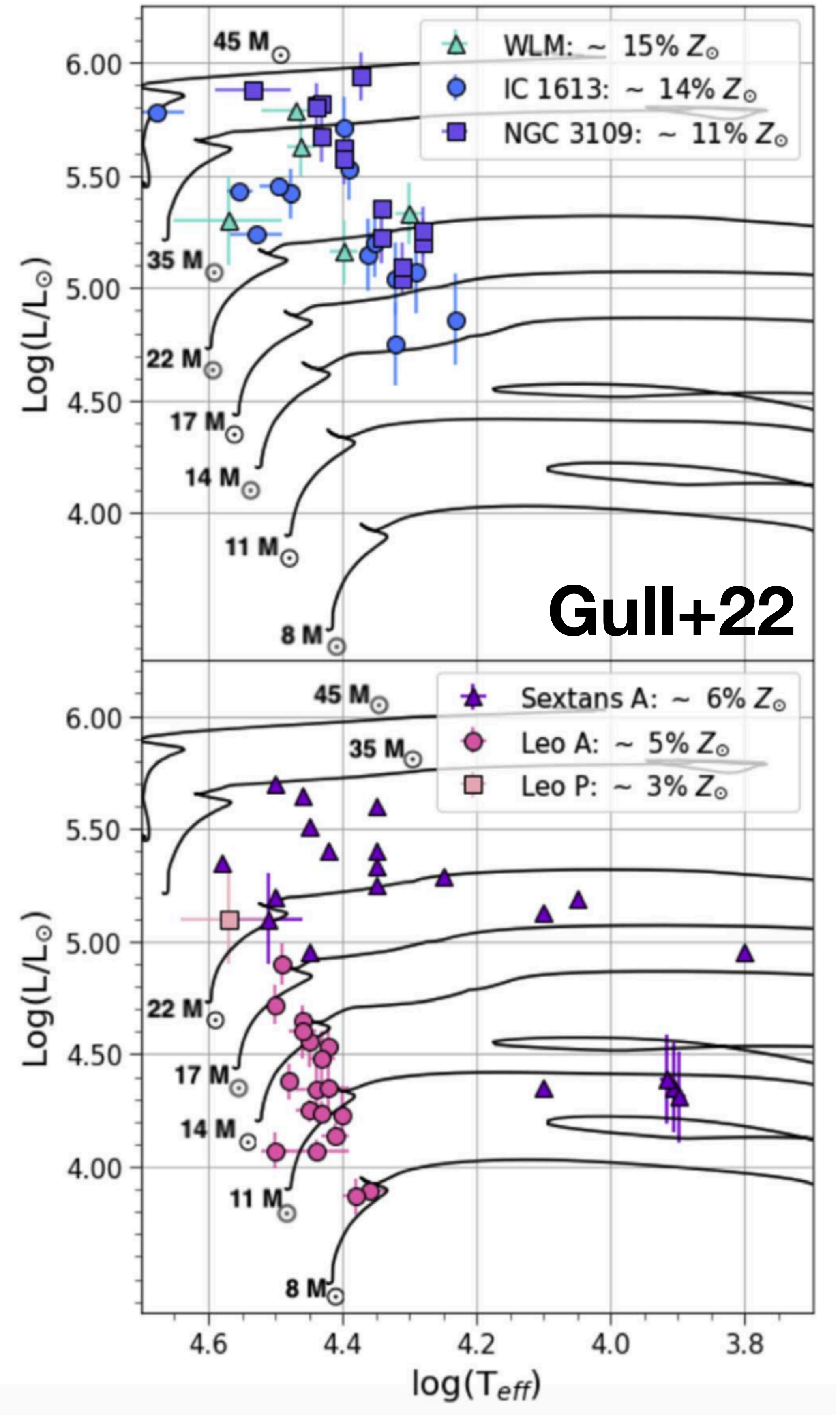

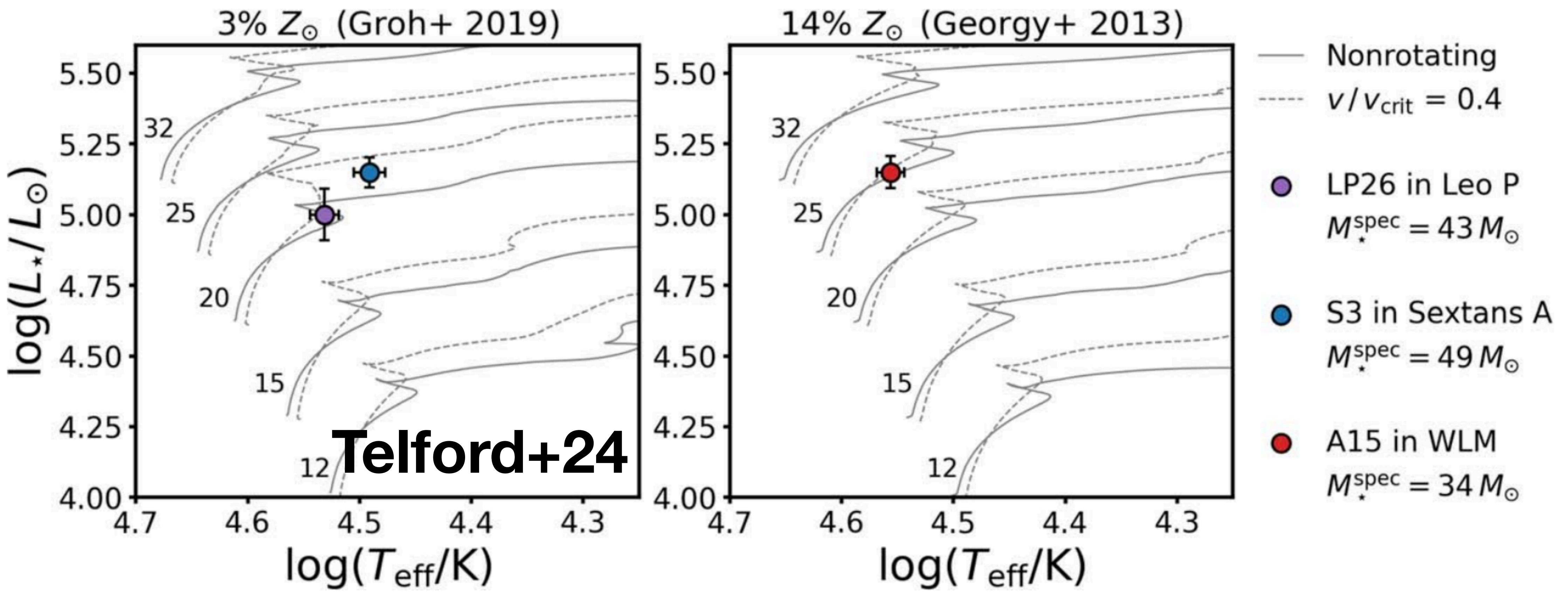

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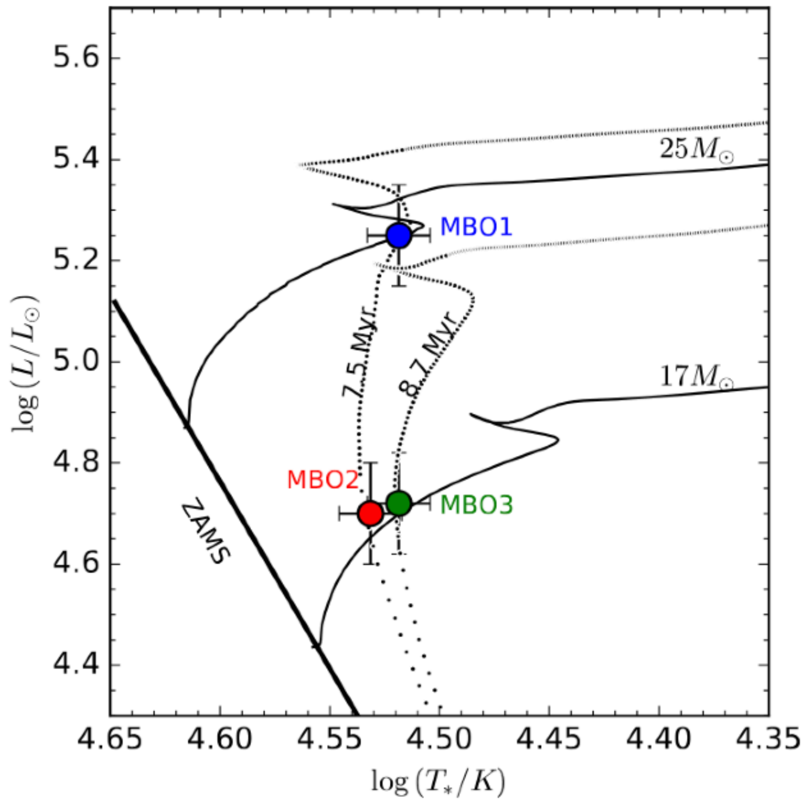

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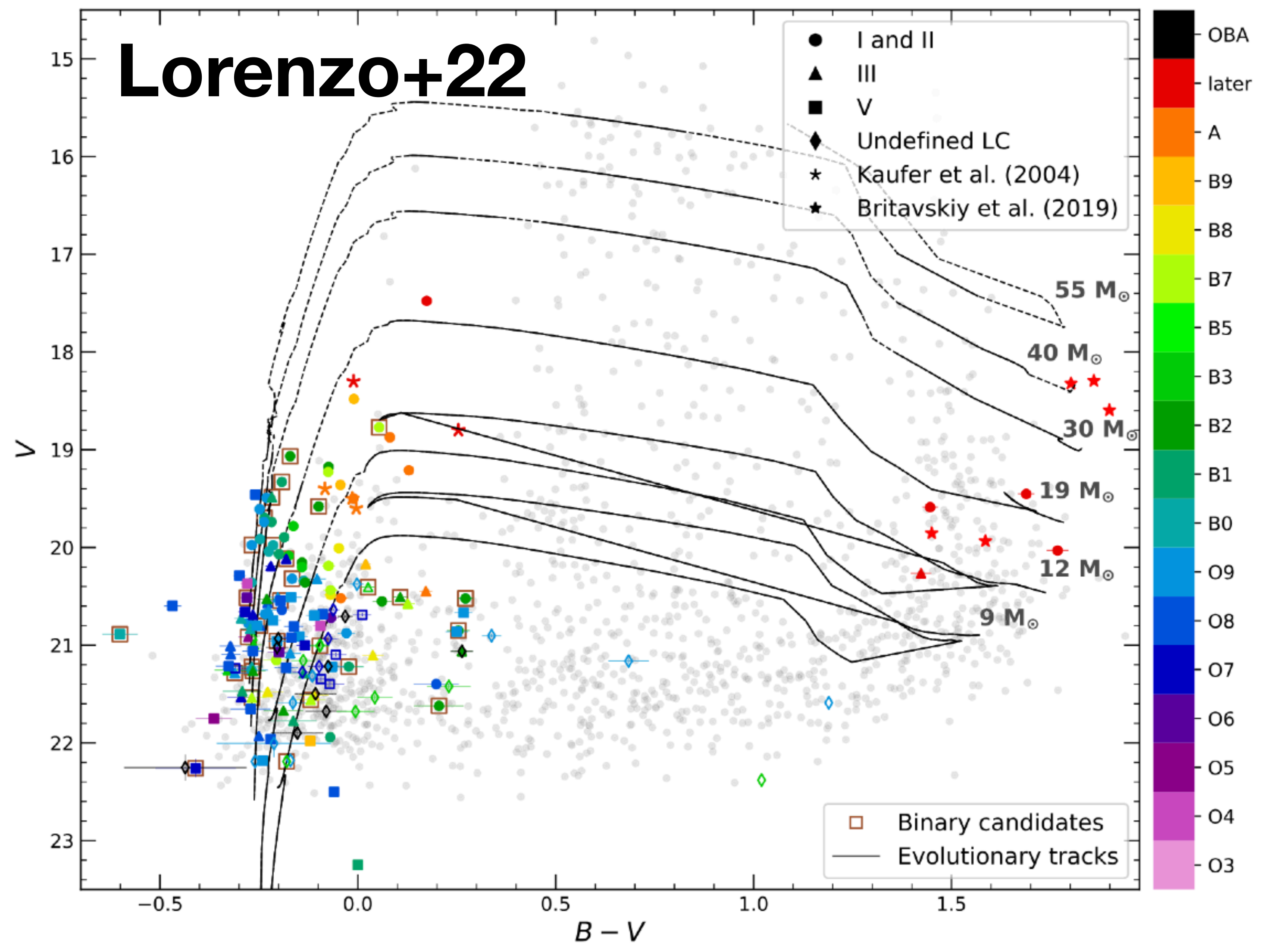
Sextans A (~6% $Z_\odot$)



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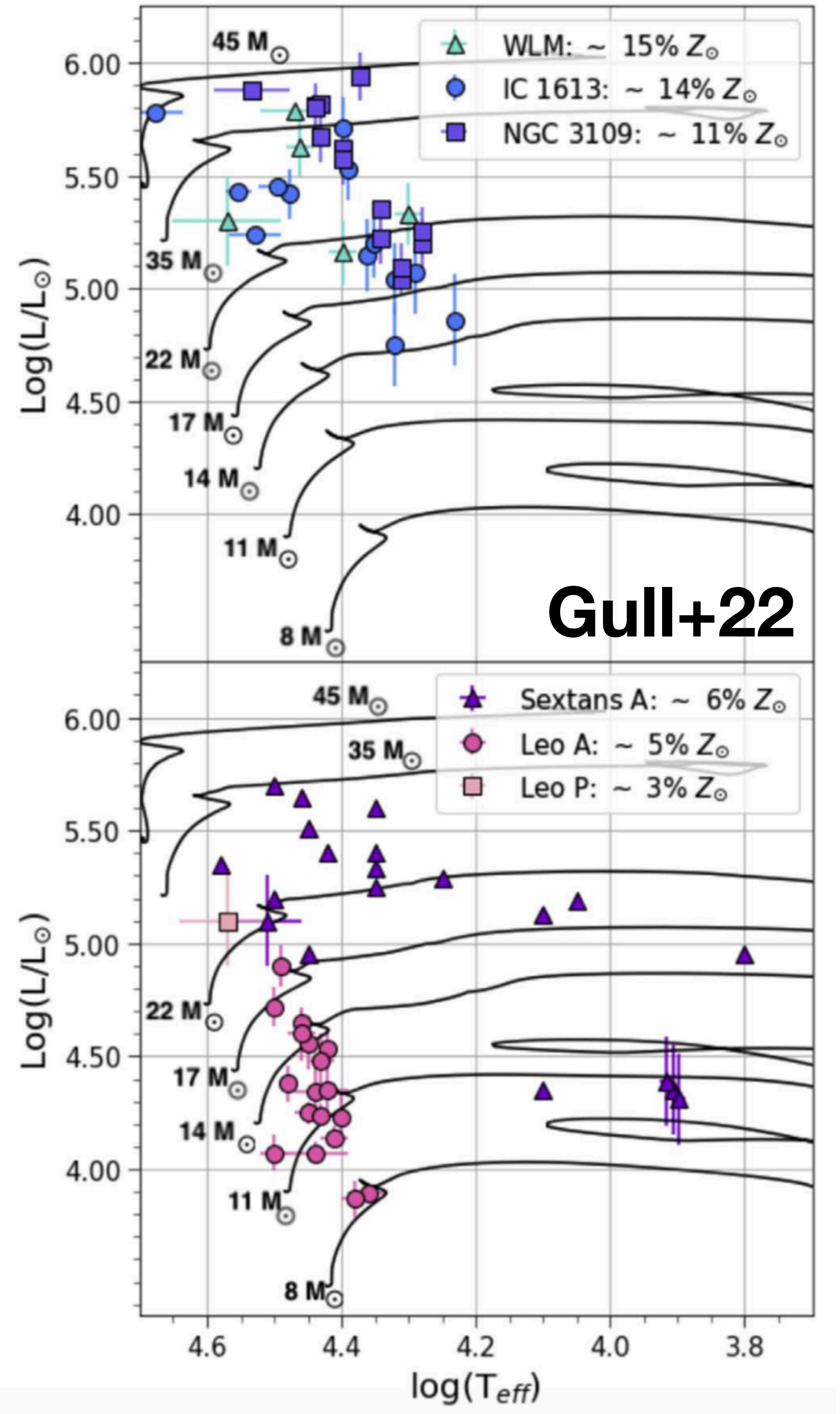
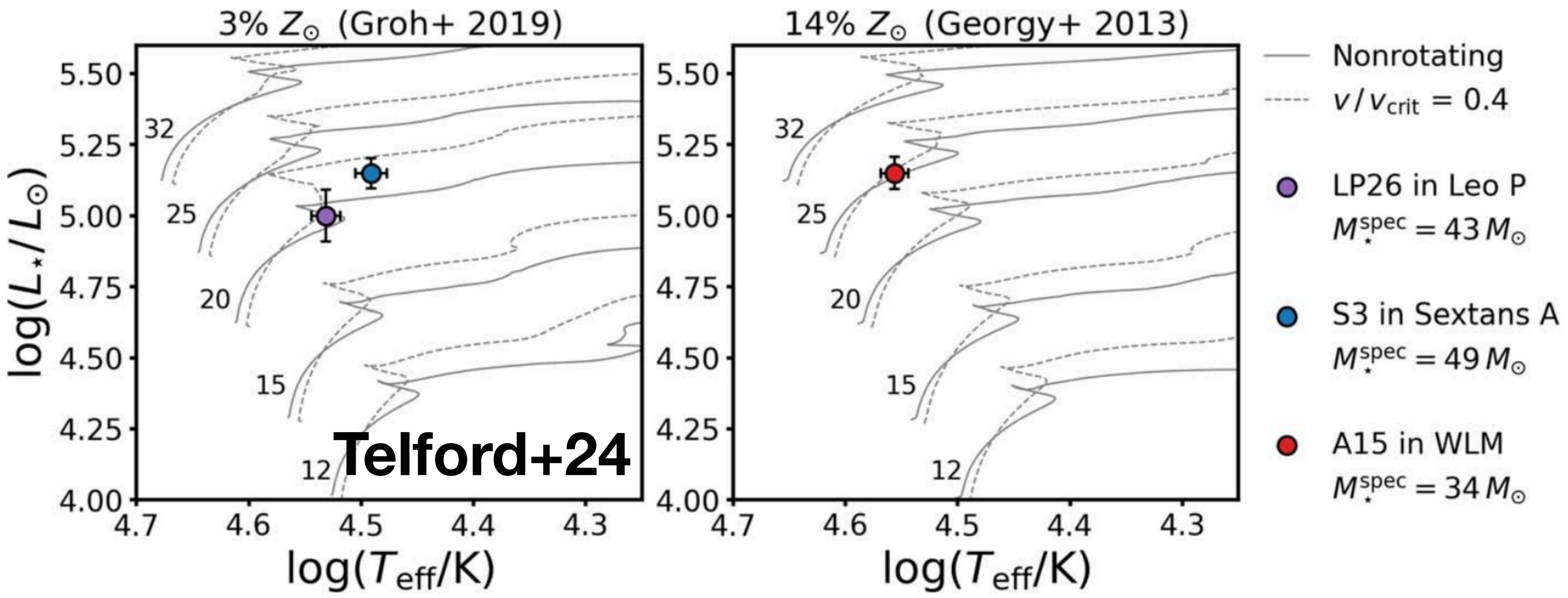
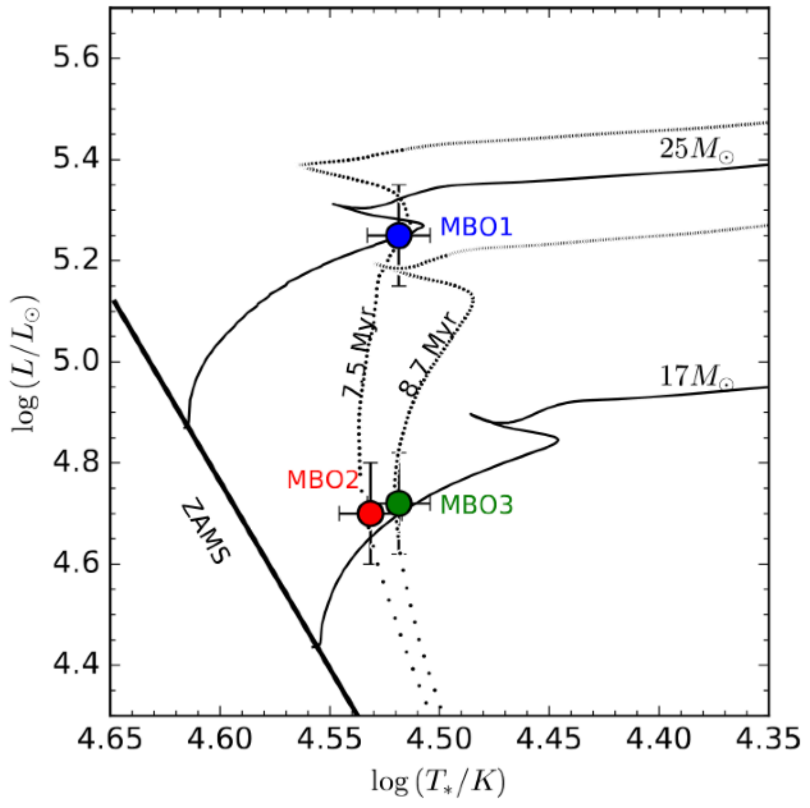




Magellanic Bridge (~10% Z⊙)



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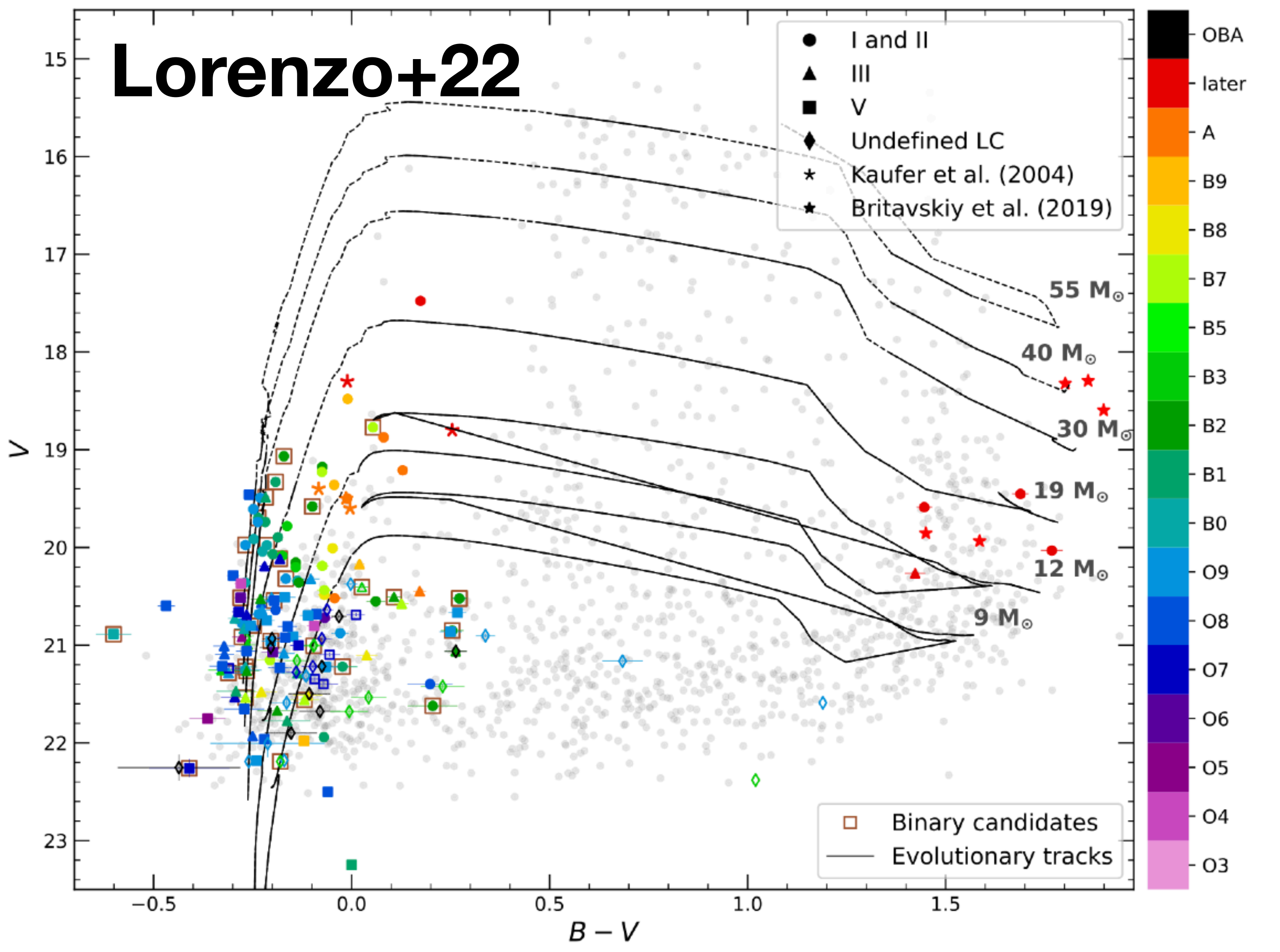

See Göran Östlin's talk on resolved stellar populations in I Zw 18.

Binarity at Low Metallicity (BLOeM)

BLOeM is an ESO large program which attempts to address both binary interaction and massive star evolution at low metallicity. BLOeM contains 25 epochs of VLT/FLAMES spectra for almost 1000 massive OB stars in the Small Magellanic Cloud.
(Shenar et al., 2024)

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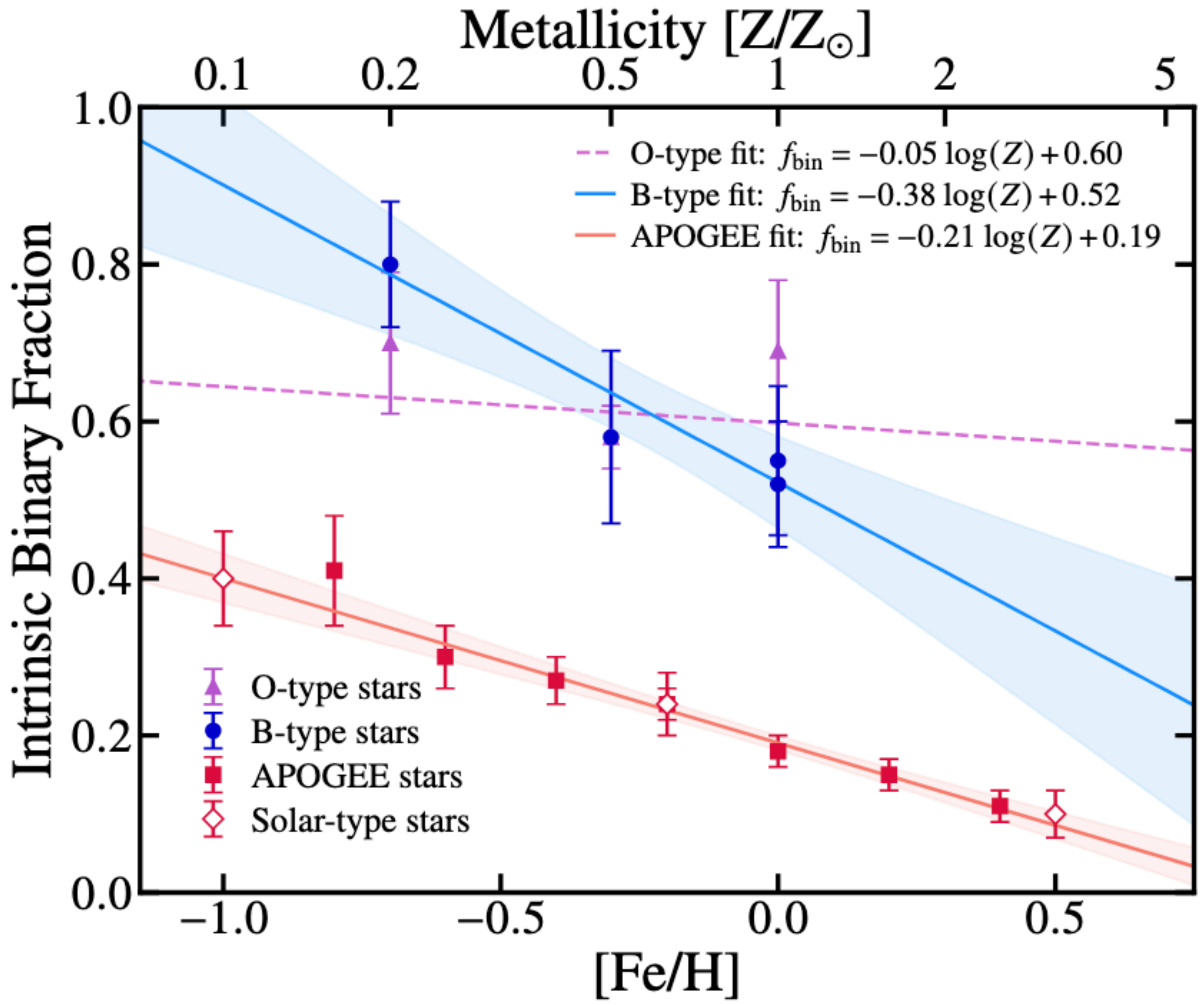
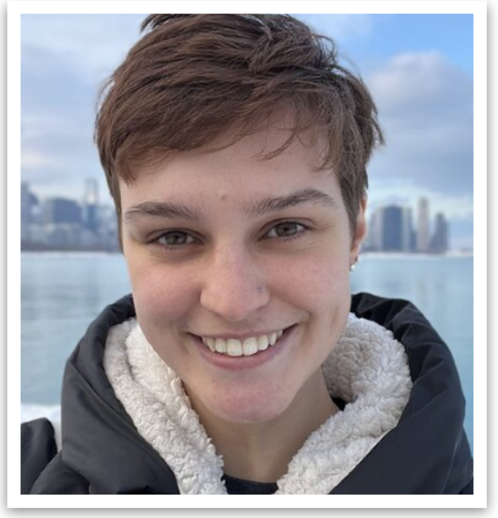


Massive stars are perhaps even more commonly in binaries at low metallicity
(Villaseñor et al., 2025, Sana et al. 2025)

Towards a statistical population of stripped stars



Beryl Hovis-Afflerbach
(PhD, Northwestern)

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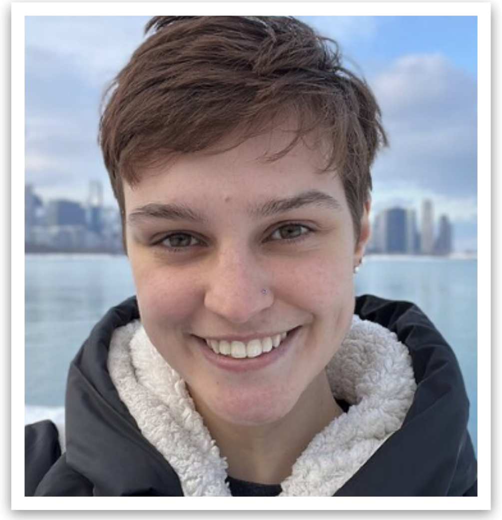

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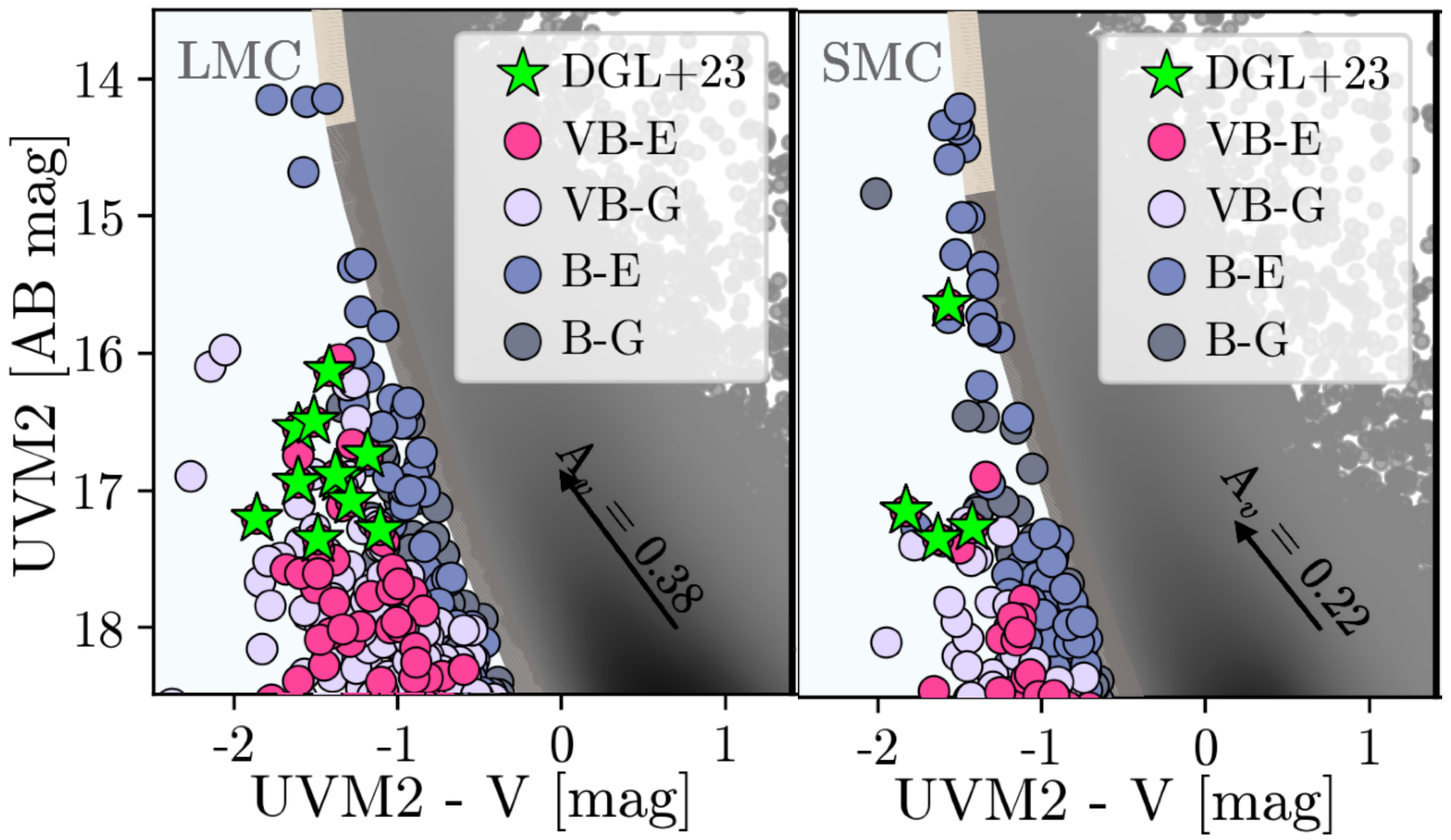

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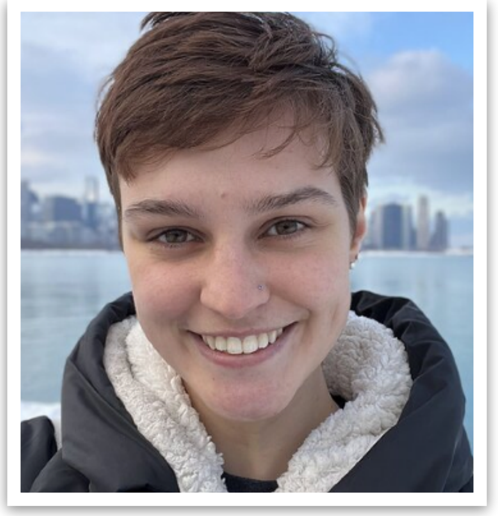

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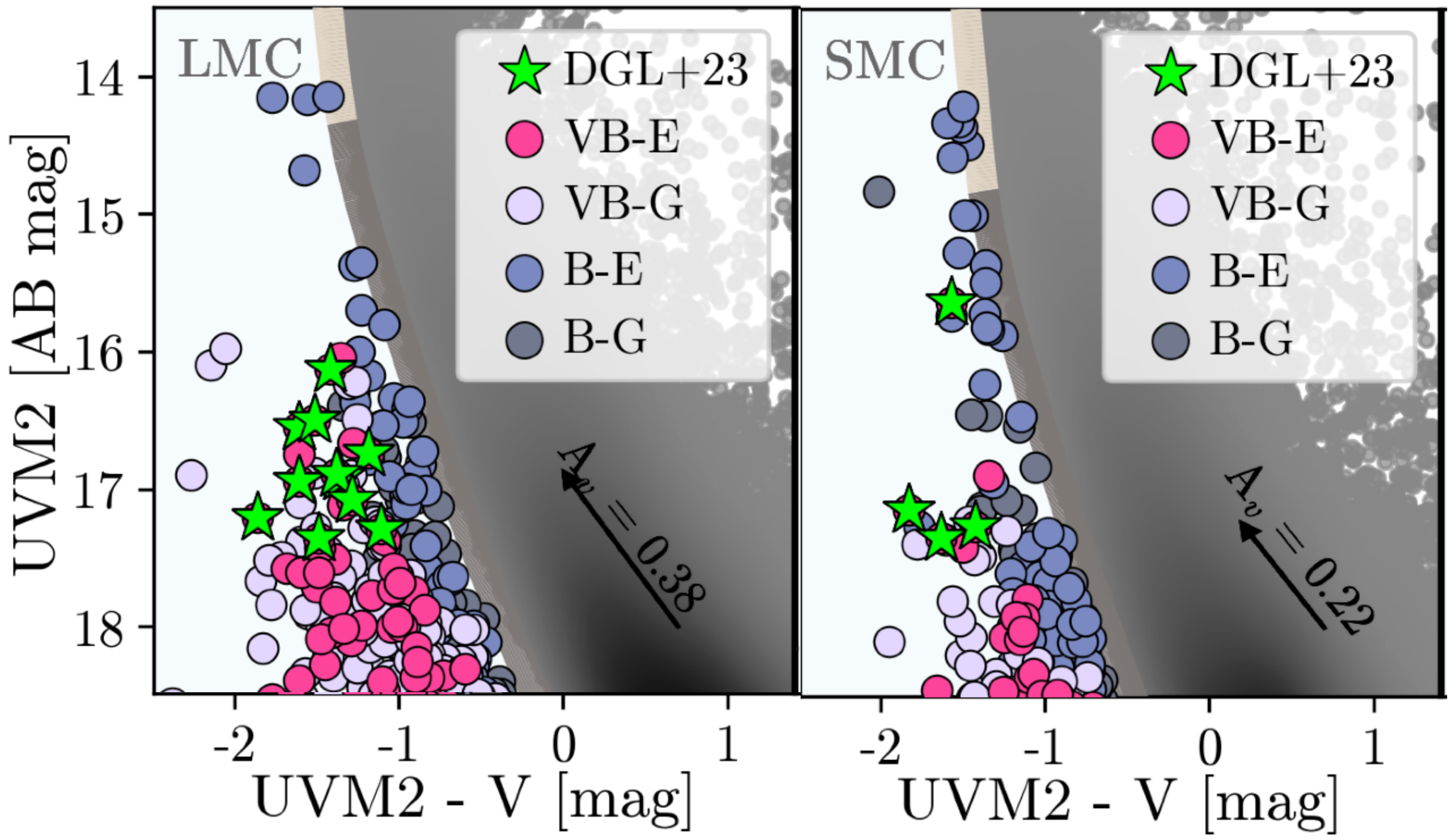


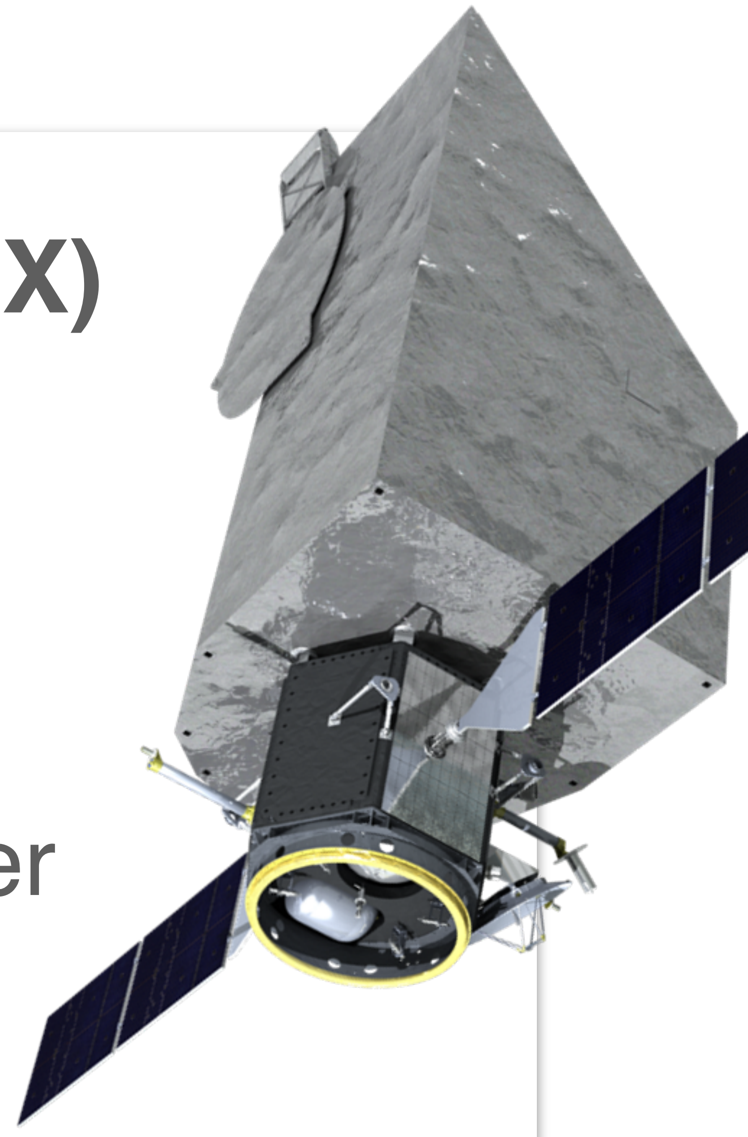
Ultraviolet Explorer (UVEX)

Approved NASA MIDEX
Planned launch: 2030

FUV & NUV bands for imager with FOV ~10 square deg.

R > 1000 spectrograph with coverage 1150-2650 Å

Within Science Pillar 1: Map the entire mass range of stripped stars in the Magellanic Clouds



Summary

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Hard ionizing emission

Ongoing efforts

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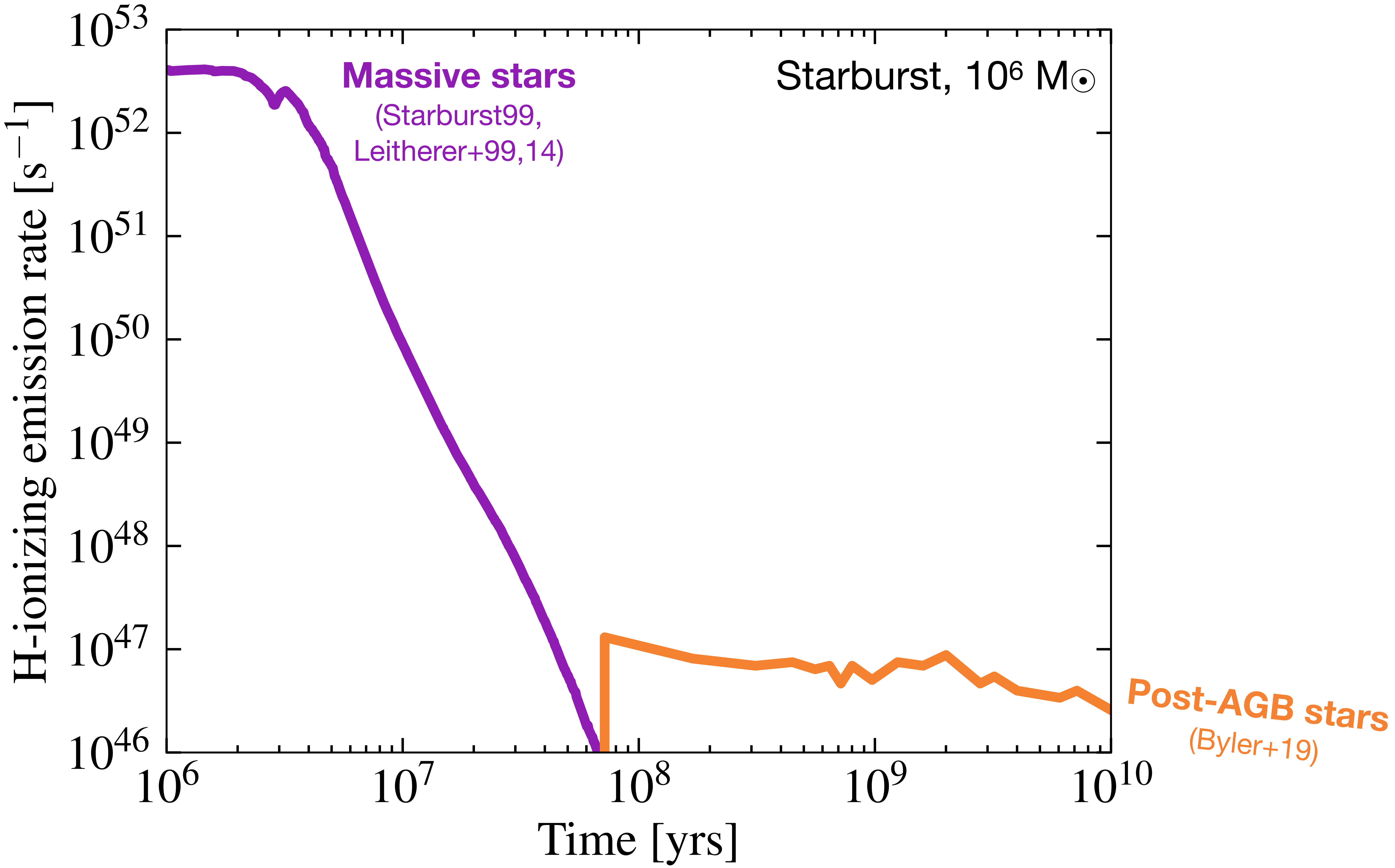
- Binary properties of massive stars are being tracked in the SMC (BLOeM)
- Larger candidate samples of stripped stars underway (e.g., UVEX)

Backup slides

Accreting stars 2: compact object accretors



The figure is preliminary

(cf. van Bever+99, Bruzual & Charlot 03, Woods & Gilfanov 13, Eldridge+17, Senchyna+19)

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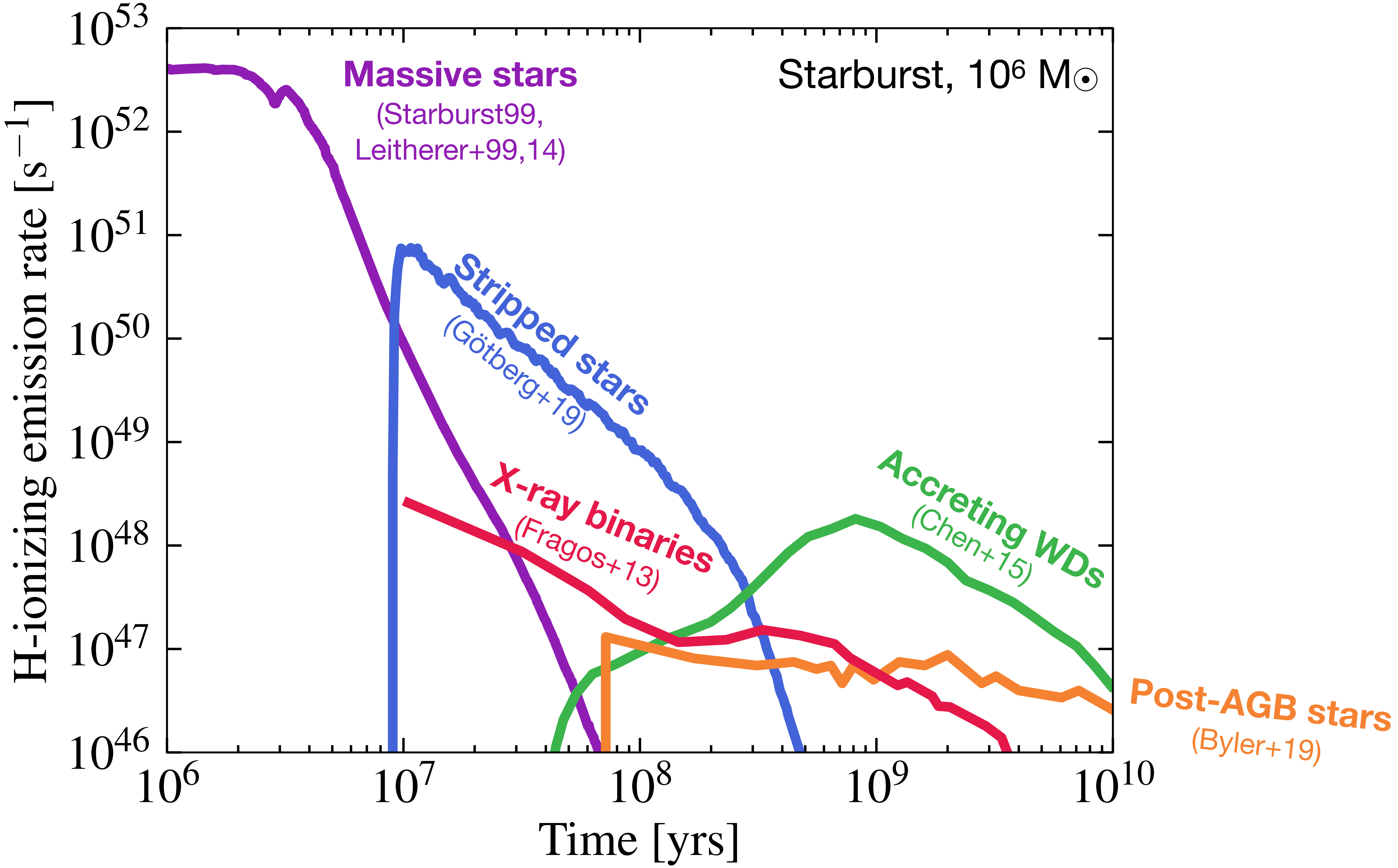

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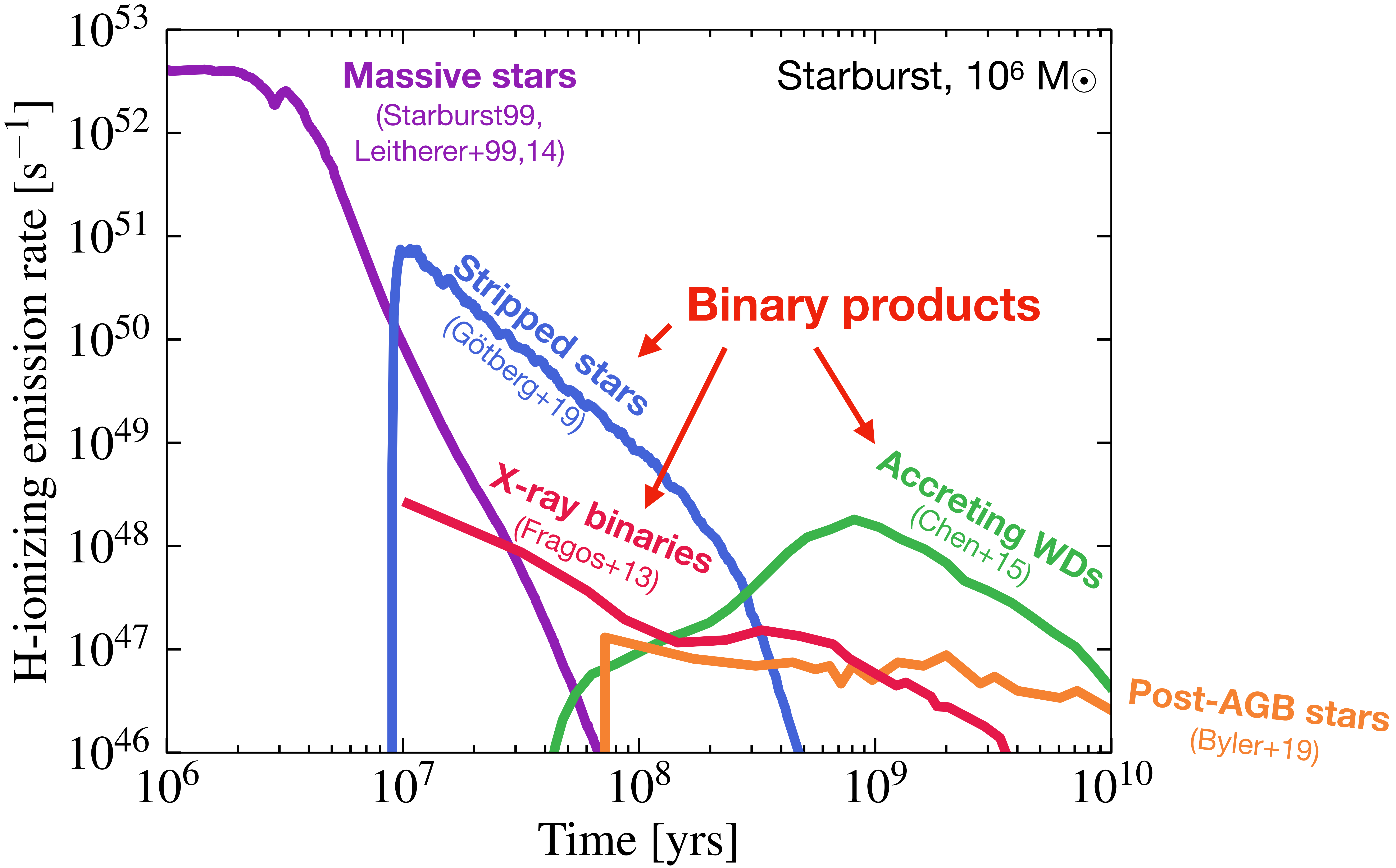

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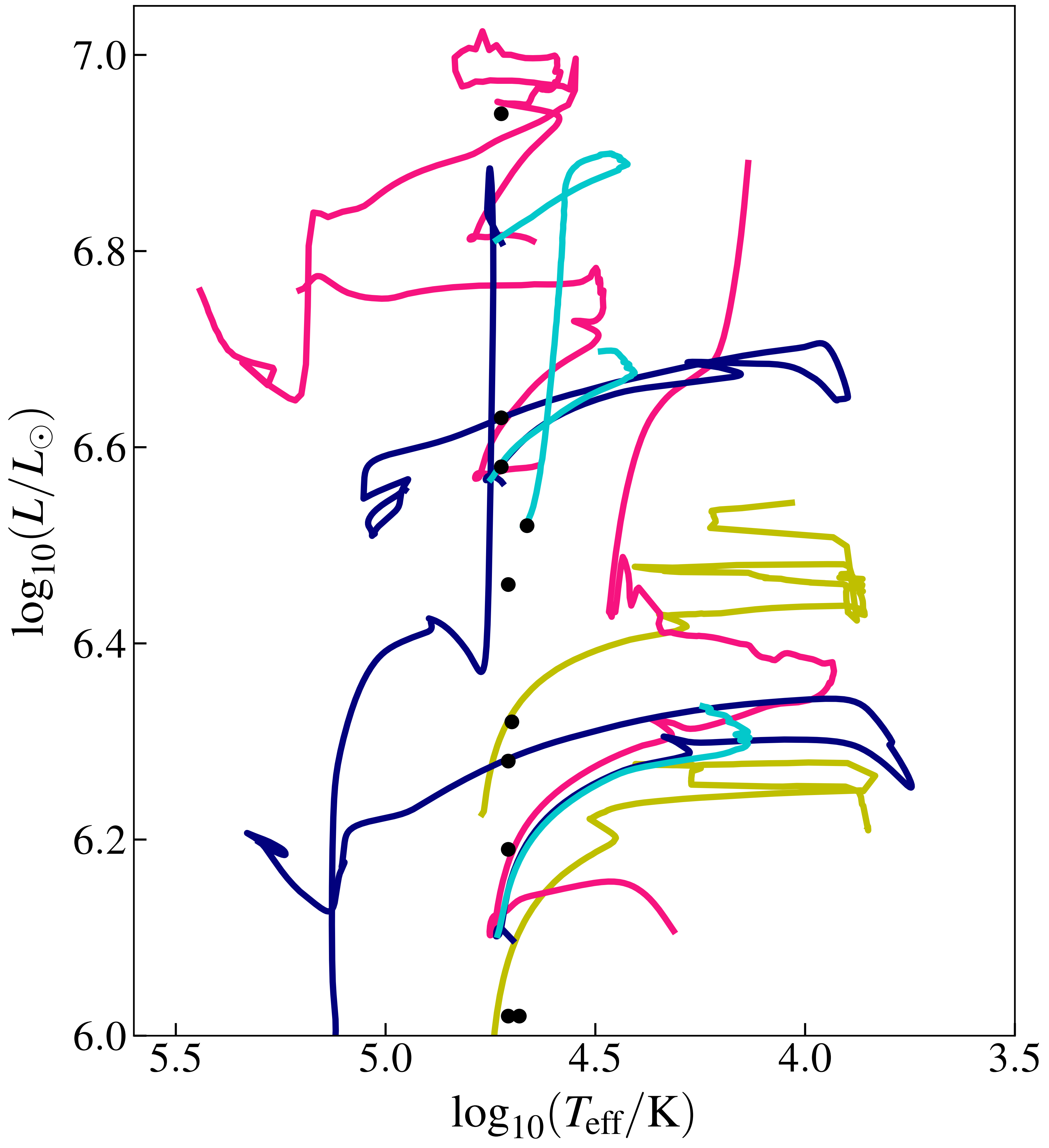
The upper mass limit (VMSs)

Pink - MIST (MESA)

Dark blue - BPASS

Yellow - GENEC?

Cyan - BEC



Spectral morphology of massive low-Z helium stars

Benjamín Navarrete
(PhD, ISTA)