Hot stars

In the UVEX era

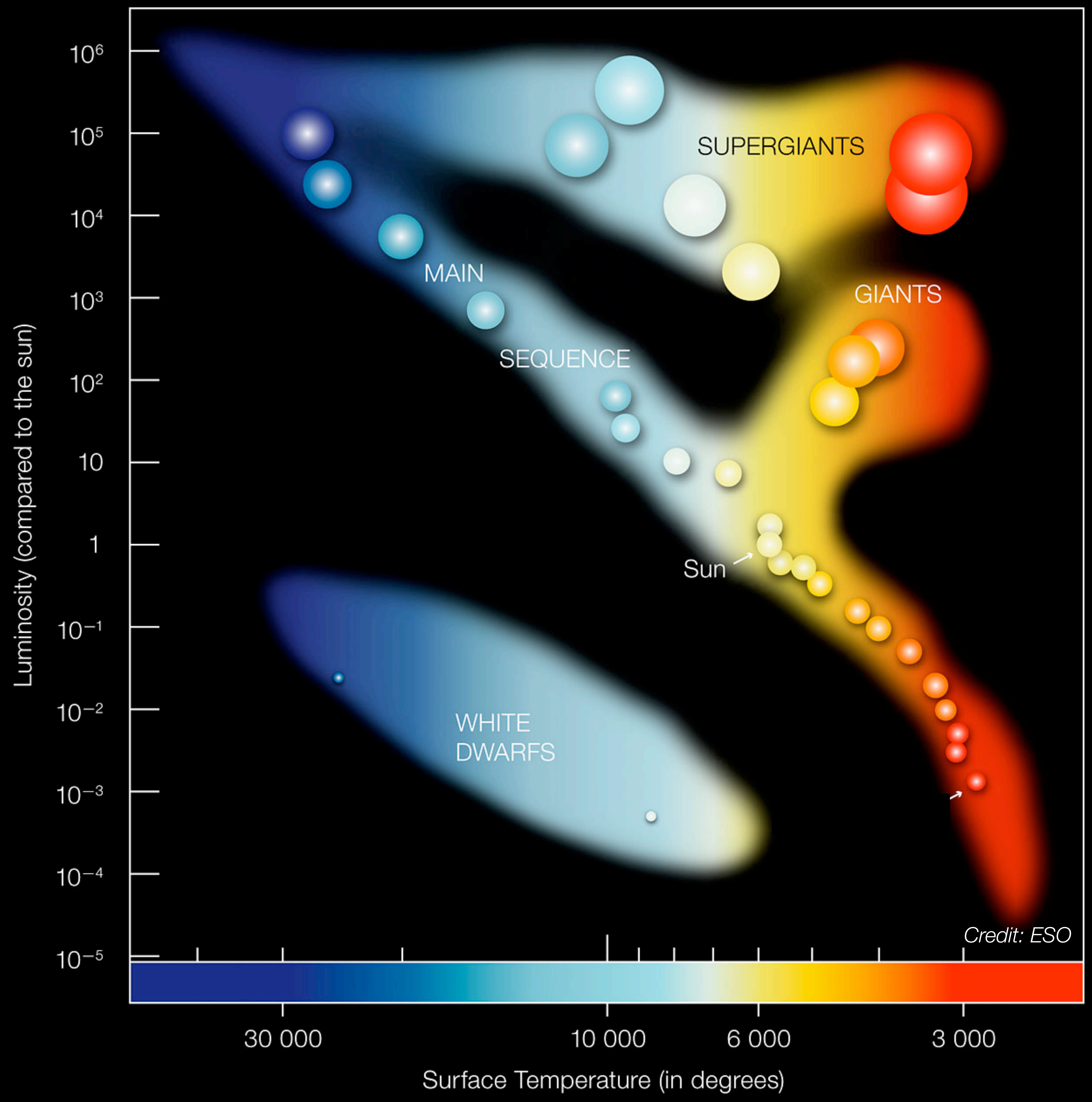
The Tarantula nebula observed with JWST

Ylva Götberg

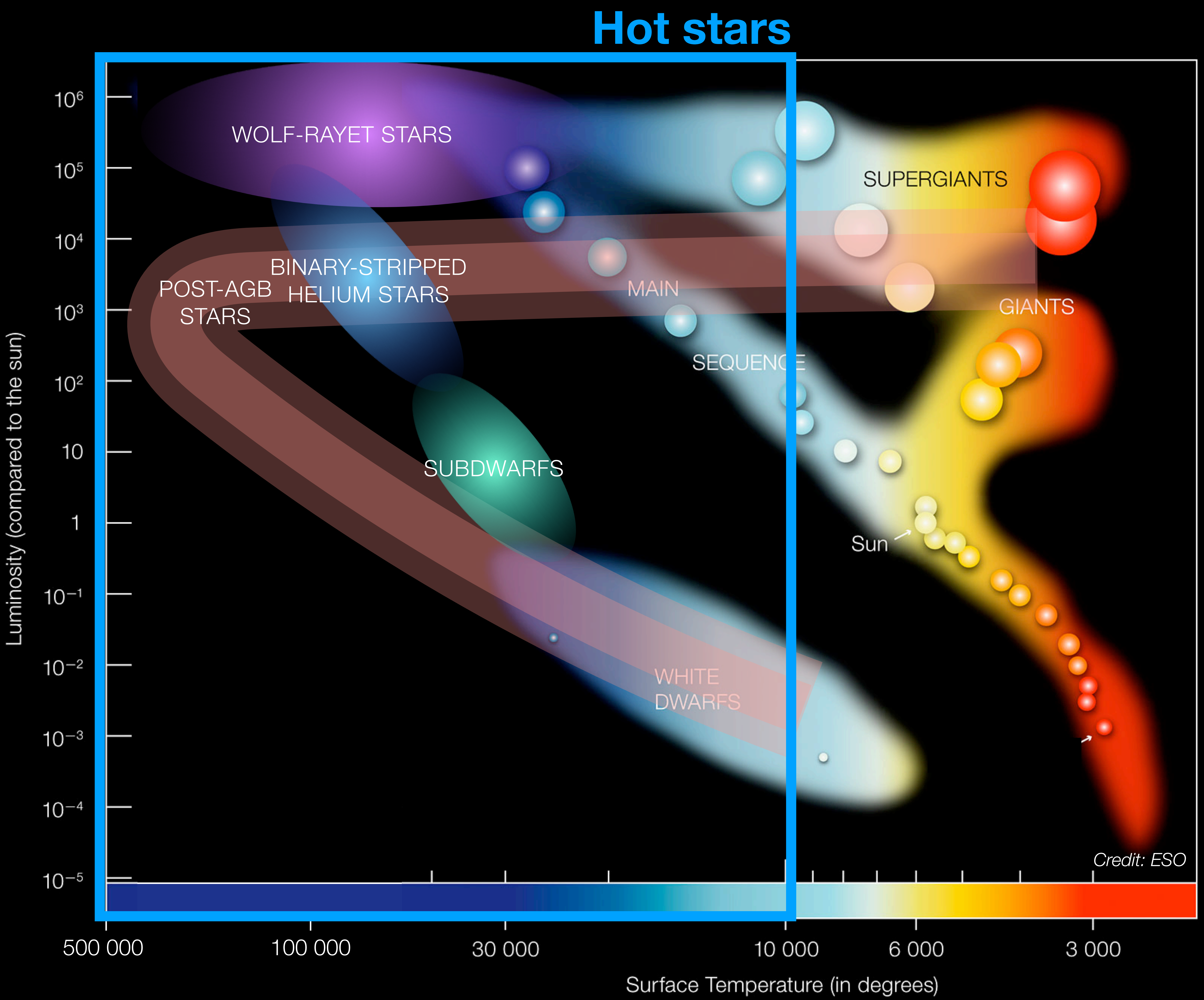
Carnegie Observatories

NHFP NASA Hubble Fellowship Program

Carnegie Science | Observatories



Luminosity (compared to the sun)
10⁶
10⁵
10⁴
10³
10²
10
1
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
SUPERGIANTS
MAIN
SEQUENCE
GIANTS
Sun
WHITE
DWARFS
Credit: ESO
30 000
10 000
6 000
3 000
Surface Temperature (in degrees)



Hot star types:

- OB stars (normally main-sequence stars)
- White dwarfs
- Post-AGB stars (central-star planetary nebulae, pre-WD, …)
- Subdwarfs (result from envelope-stripping or merger)
- Wolf-Rayet stars
- Binary stripped helium stars (result from envelope-stripping)

Importance of hot stars

Ionizing radiation

Reionization, IGM heating, star formation, diffuse ionized gas…

Uncertain: the amount and hardness of ionizing emission from hot stars

What stars caused reionization?

Gravitational waves

Detections with LIGO/Virgo/Kagra, LISA and other future instruments

Uncertain: the evolutionary pathways leading to GW emission

What stars result in GWs?

Chemical yields

Universe's metallicity evolution, stars' metallicity

Uncertain: amount and composition of past, present and future ejecta/wind

How do stars pollute?

Supernovae

Mechanical feedback, chemical yields

Uncertain: evolution that leads to explosion, how common certain explosions are

Which are the progenitors of SNe?

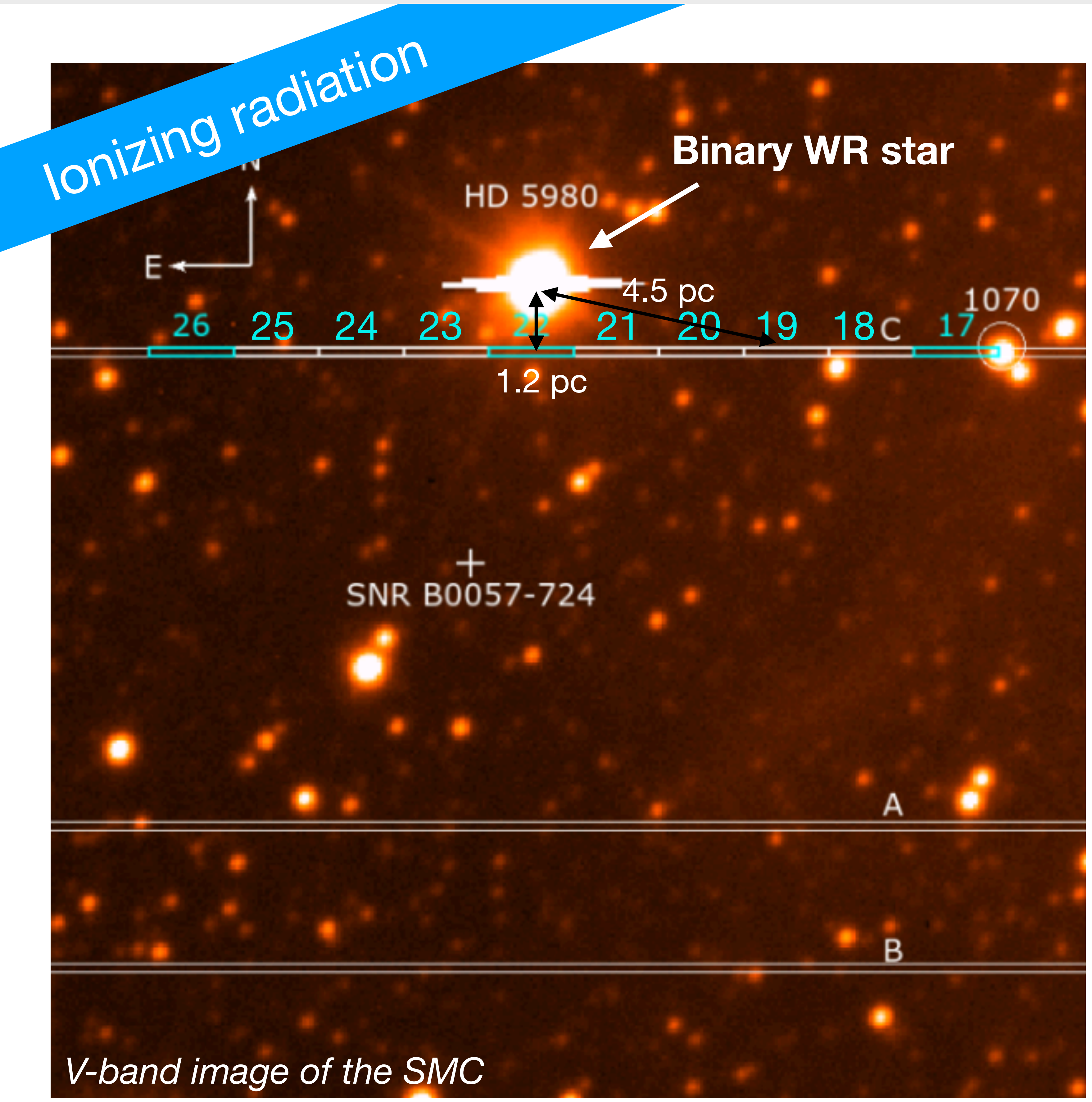
Stellar exotica

Stellar populations, metallicity impact

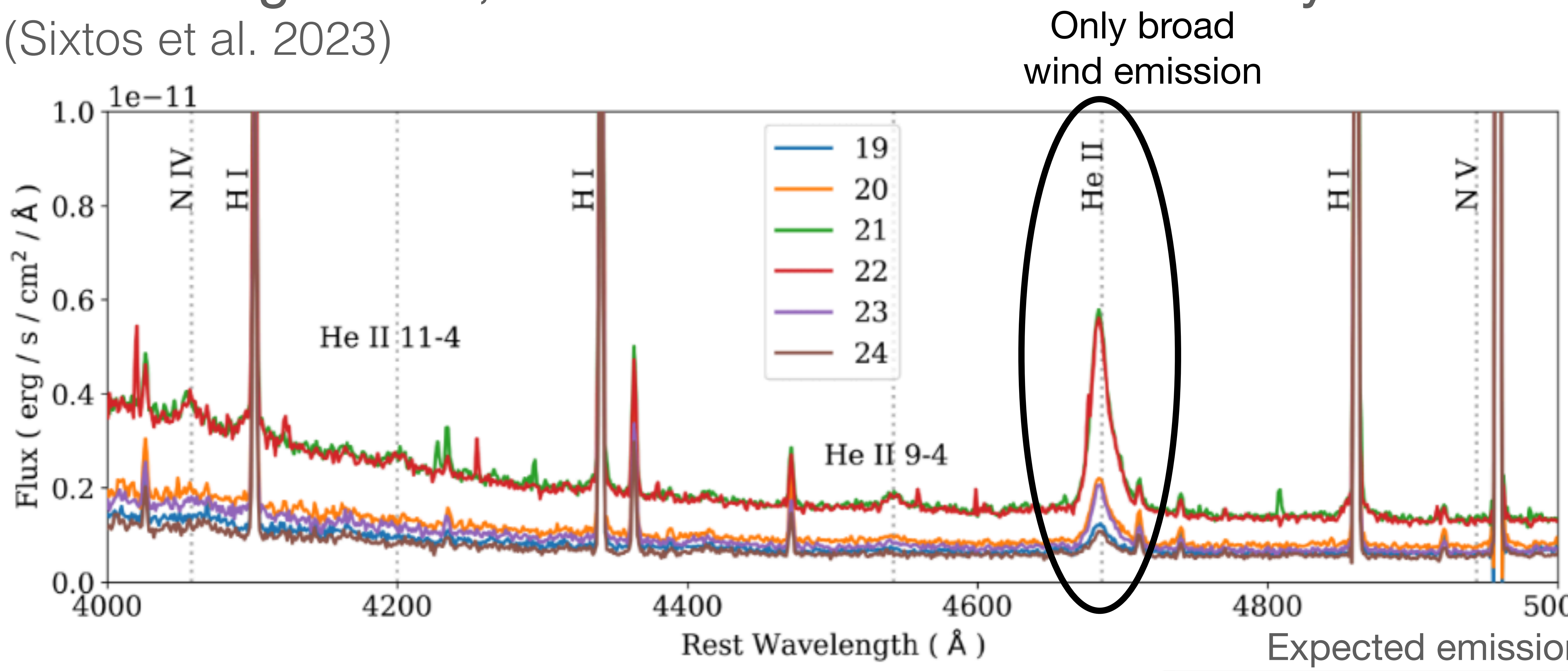
Uncertain: do we understand and have we found all stellar exotica?

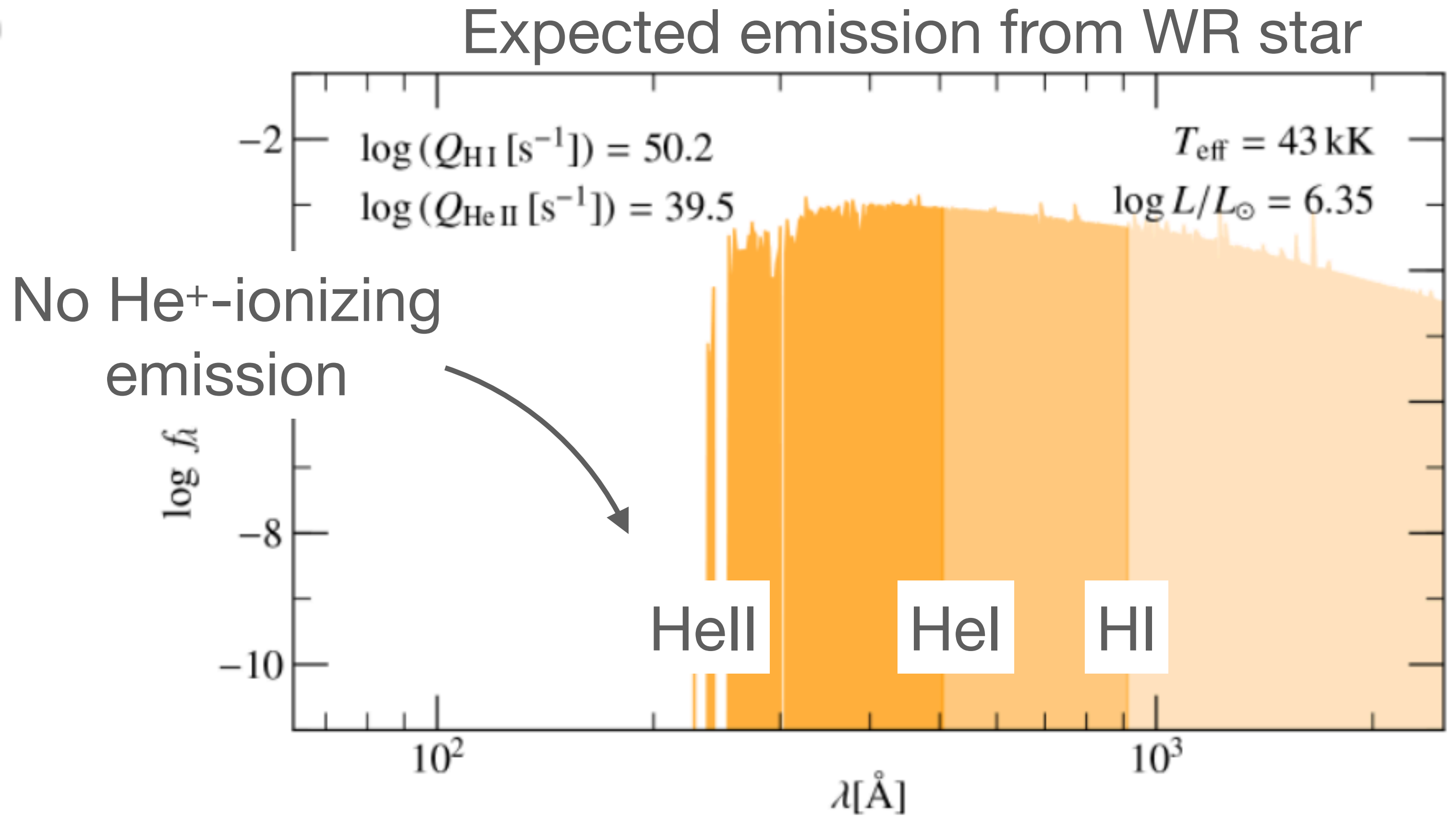
How do exotic stars contribute?

Nebular HeII emission — not from the most massive stars?



While WR stars are the common explanation for nebular HeII emission in distant galaxies, no evidence found from nearby source (Sixtos et al. 2023)

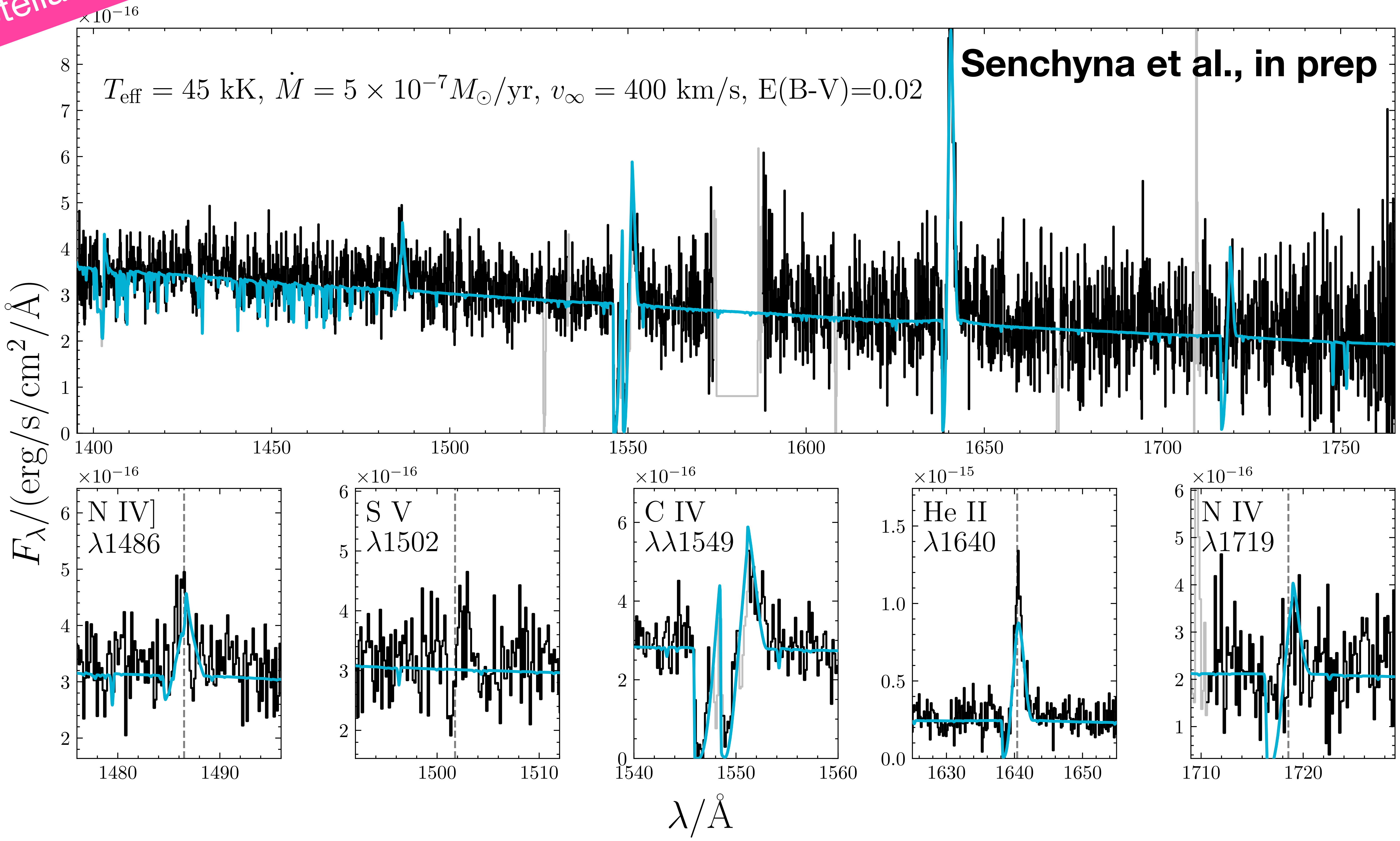




(see also Senchyna et al. 2019, Saxena et al. 2020, 21, Schaerer et al. 2019, Stark et al. 2015…)

Peculiar hot star found in Leo A

Stellar exotica

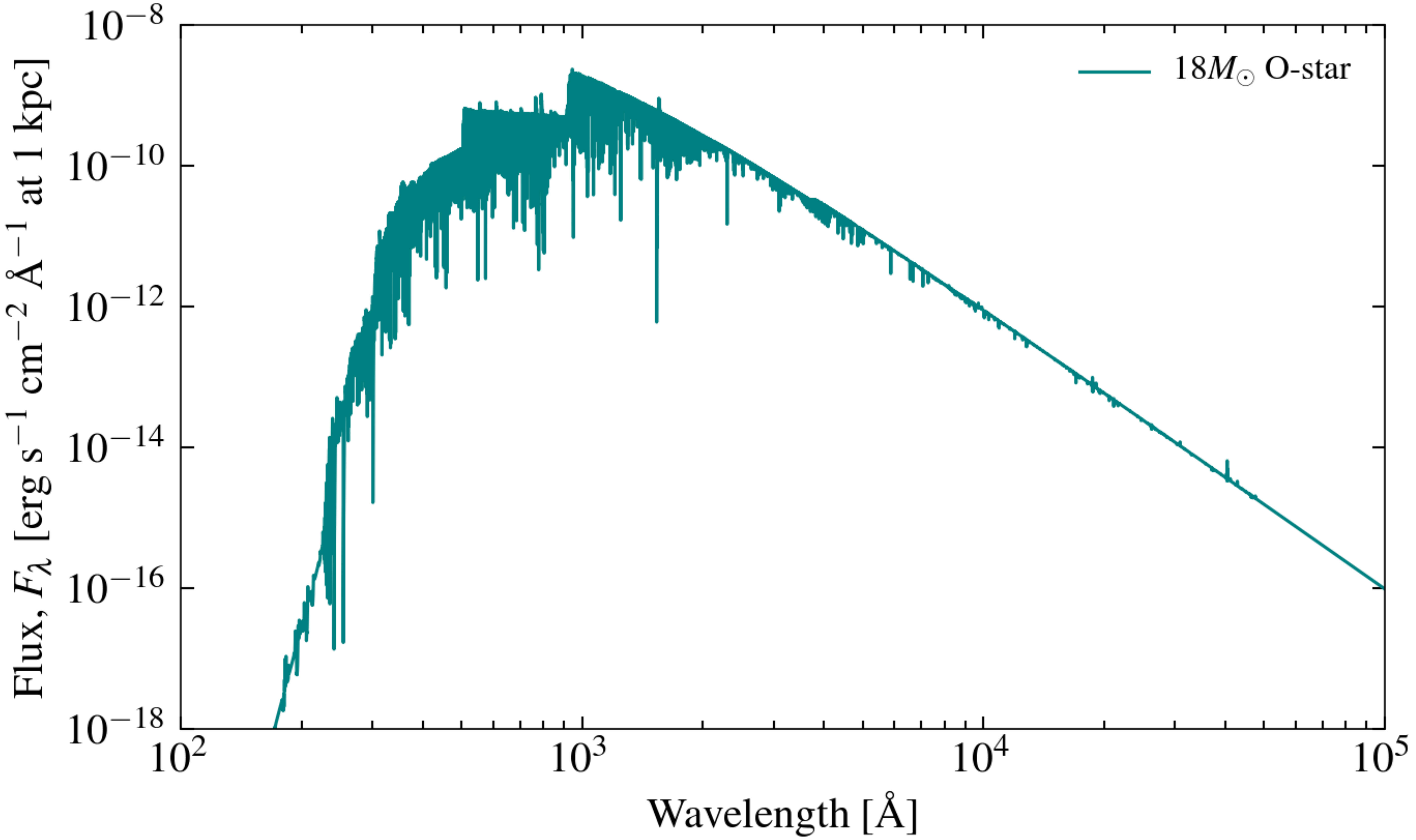


- Emission line star found in 0.1$Z_\odot$ galaxy Leo A
- Must be hot: CIV, HeII, NIV…
- Outflow extremely slow: ~400 km/s
- Brightness similar to late O-stars
- Motion of ~100 km/s detected

(see also Gull et al. 2022, Shenar et al. under review, Groh et al. 2008, Klencki et al. 2021)

Spectral energy distribution of hot stars

Optical and infrared colors are almost the same for hot stars — UV makes a distinction



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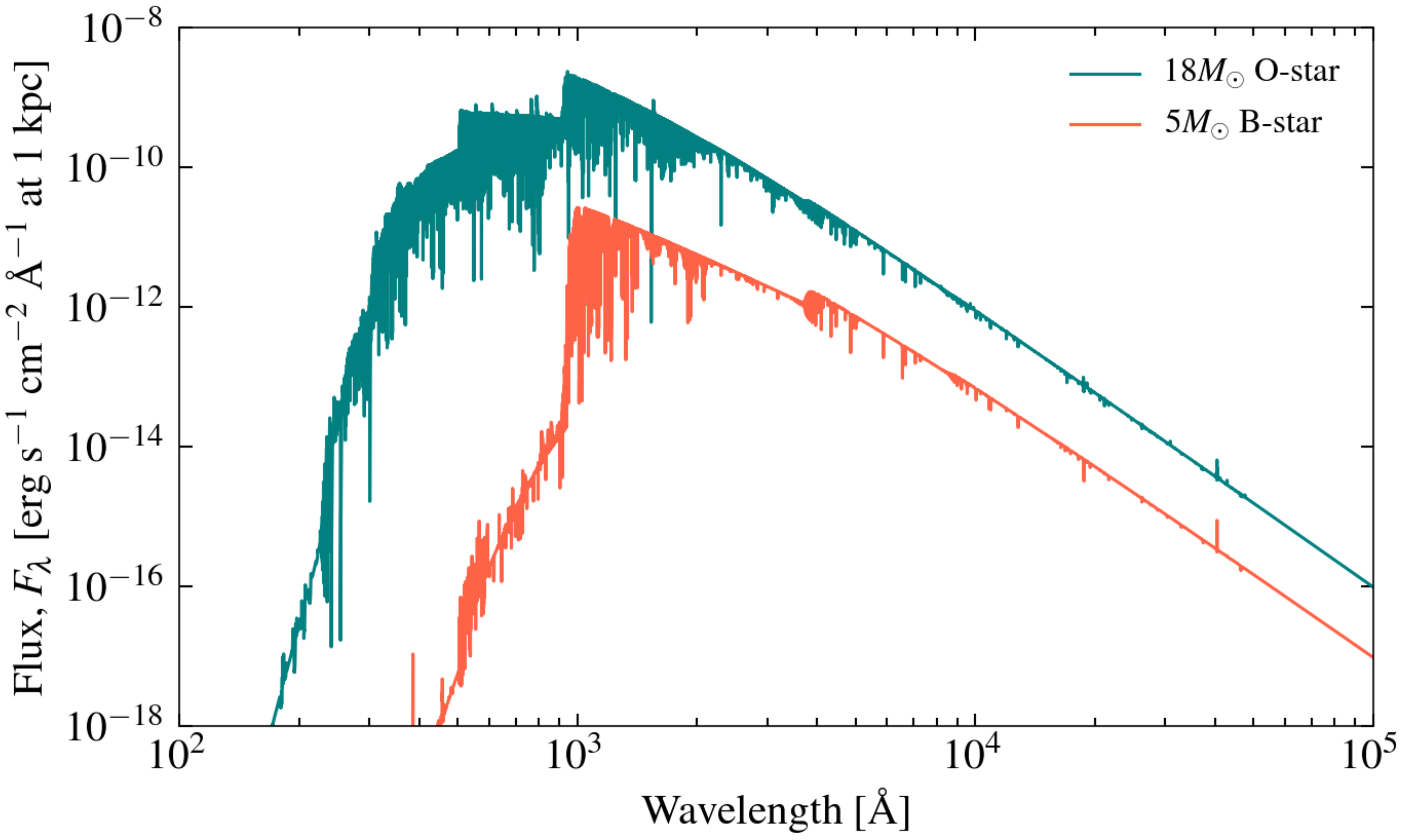

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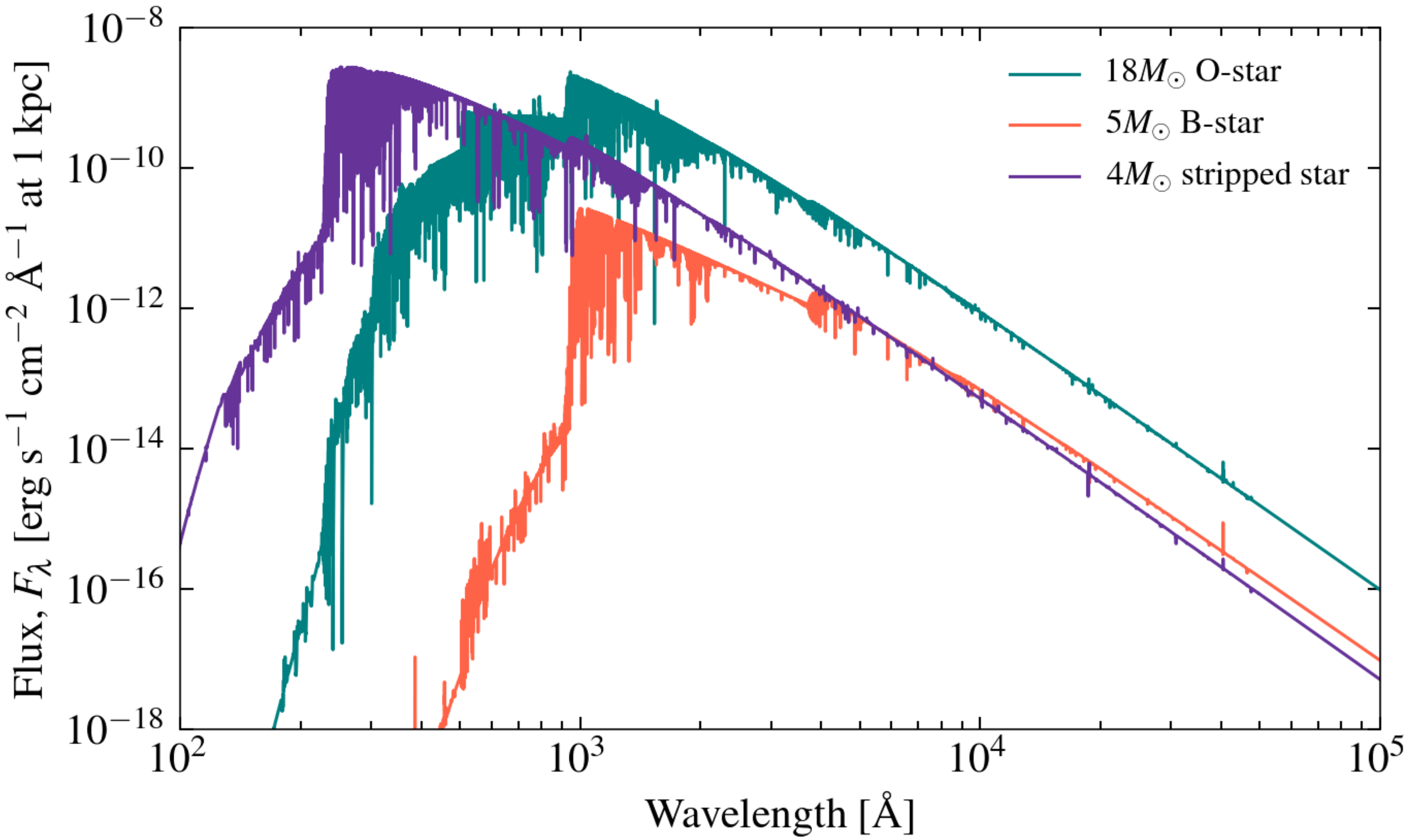

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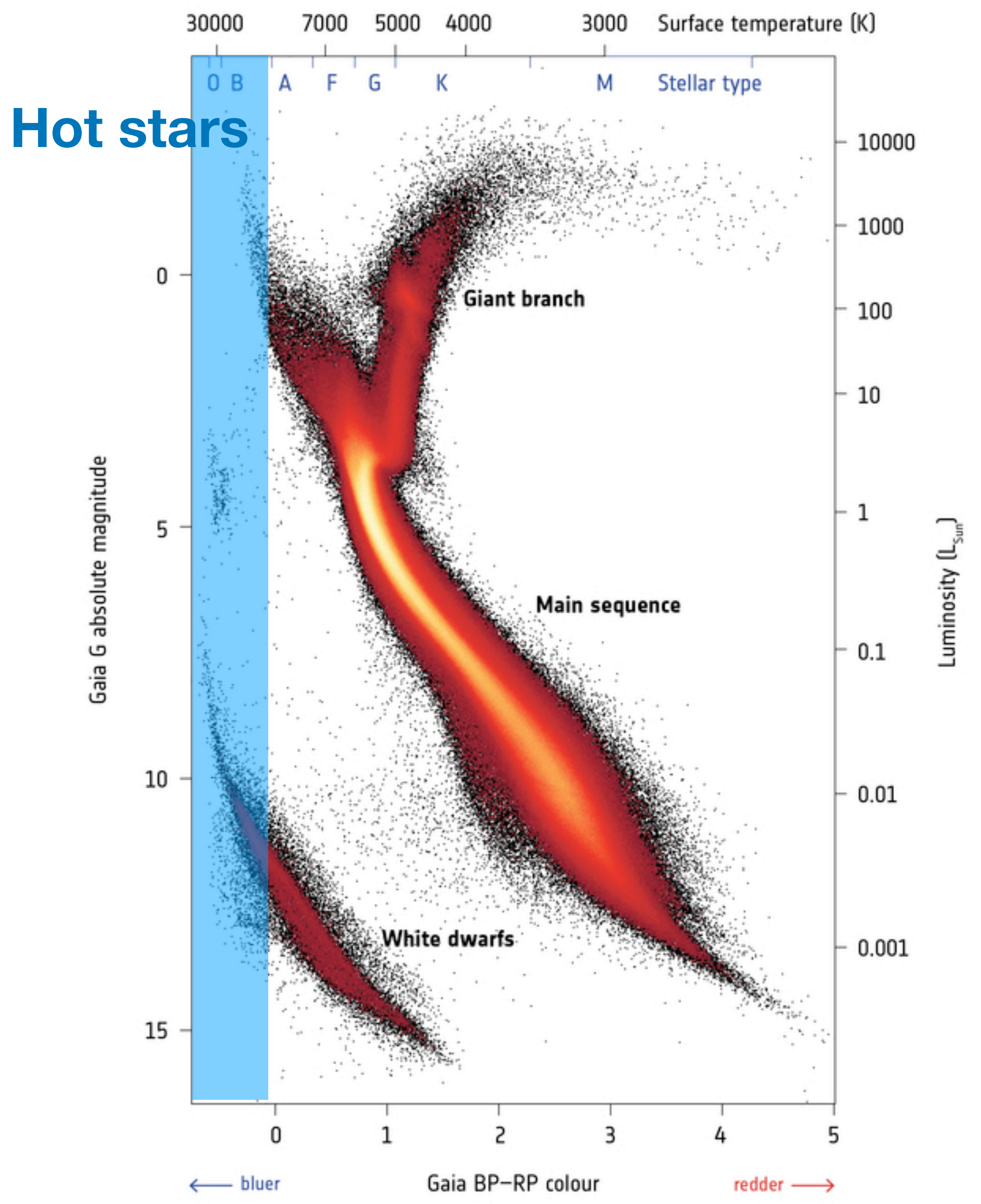
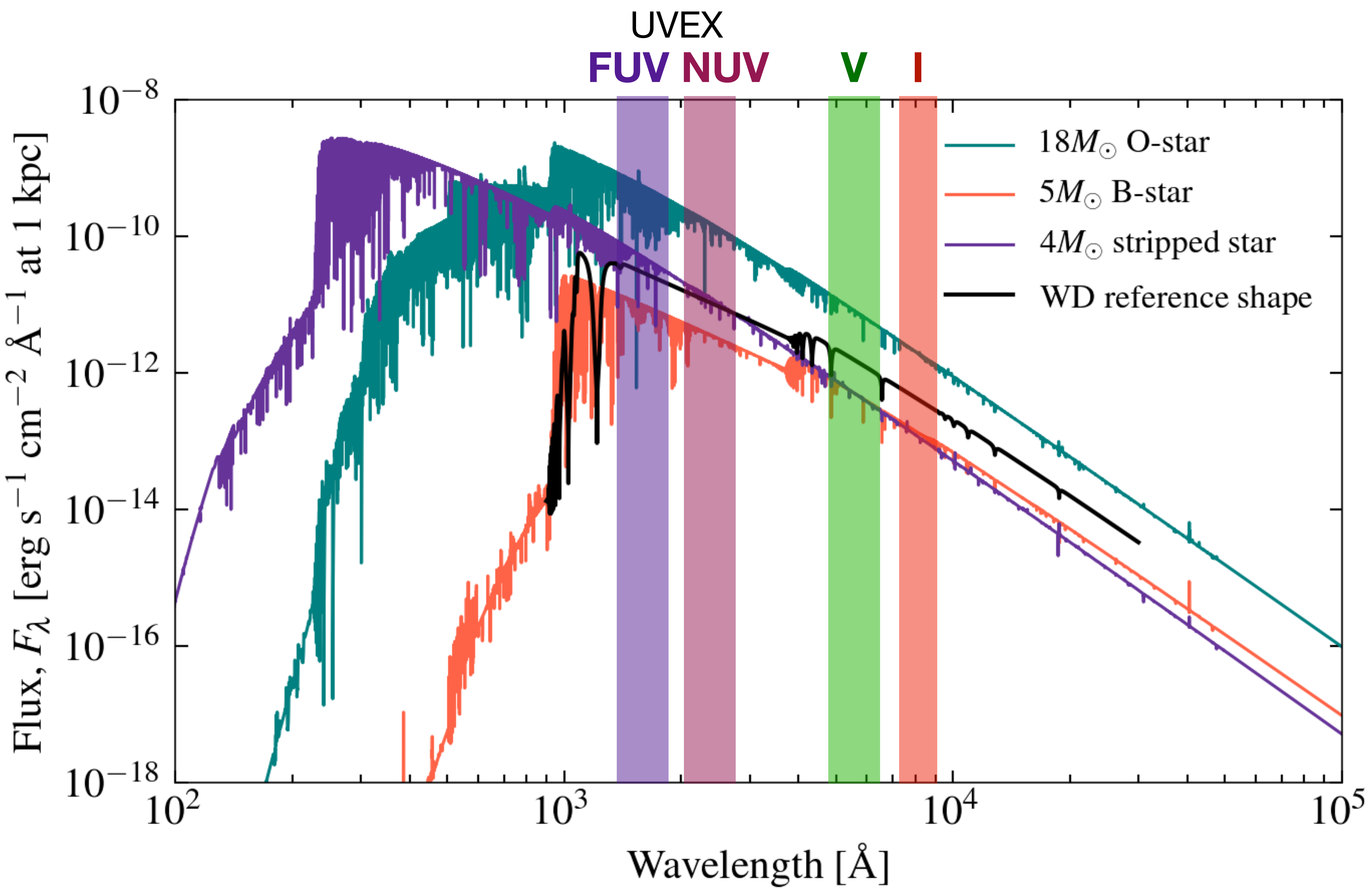
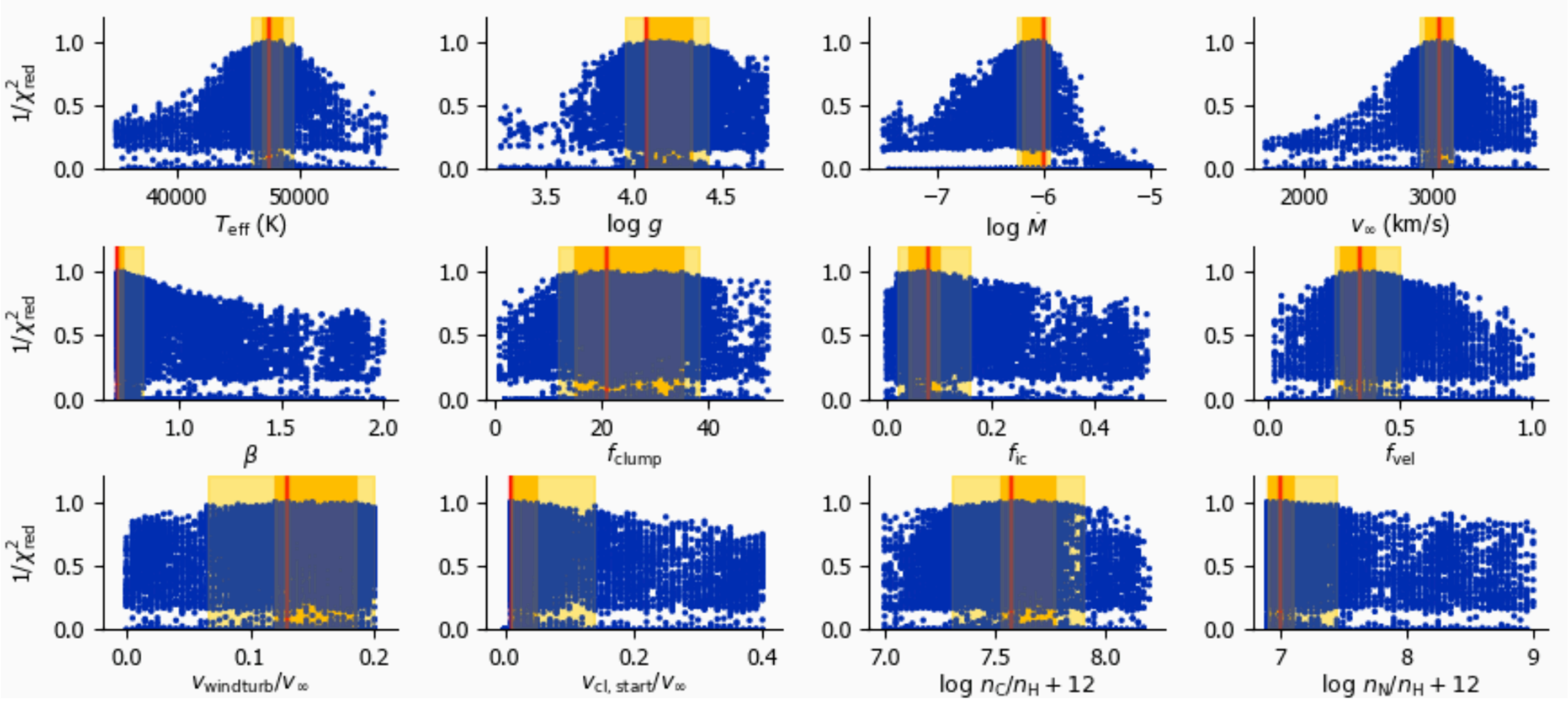




Importance of **ultraviolet**

Mass loss from hot stars

Wind mass loss relevant for BH masses, explosion, X-rays, binary orbital evolution, GW mergers…



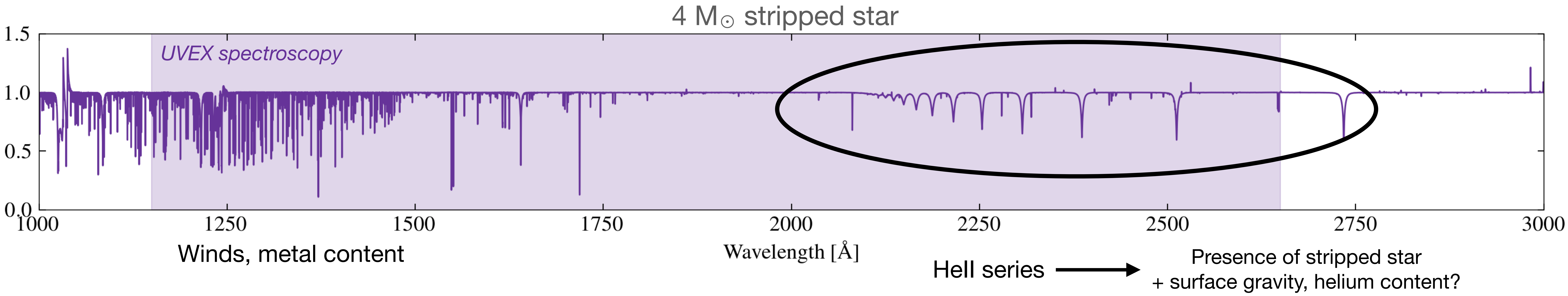
Fitting UV spectra reveal most likely wind parameters (Brands et al. 2022)

Paul Crowther's talk

(Crowther et al. 2016, Bestenlehner et al. 2014, 20, Hawcroft et al. 2022, …)

Stellar properties from NUV spectrum

Near-UV spectroscopy contains HeII lines useful for property determination (log g, T_{eff}, Y_{surf})



The discovery of 10 subdwarfs orbiting Be stars

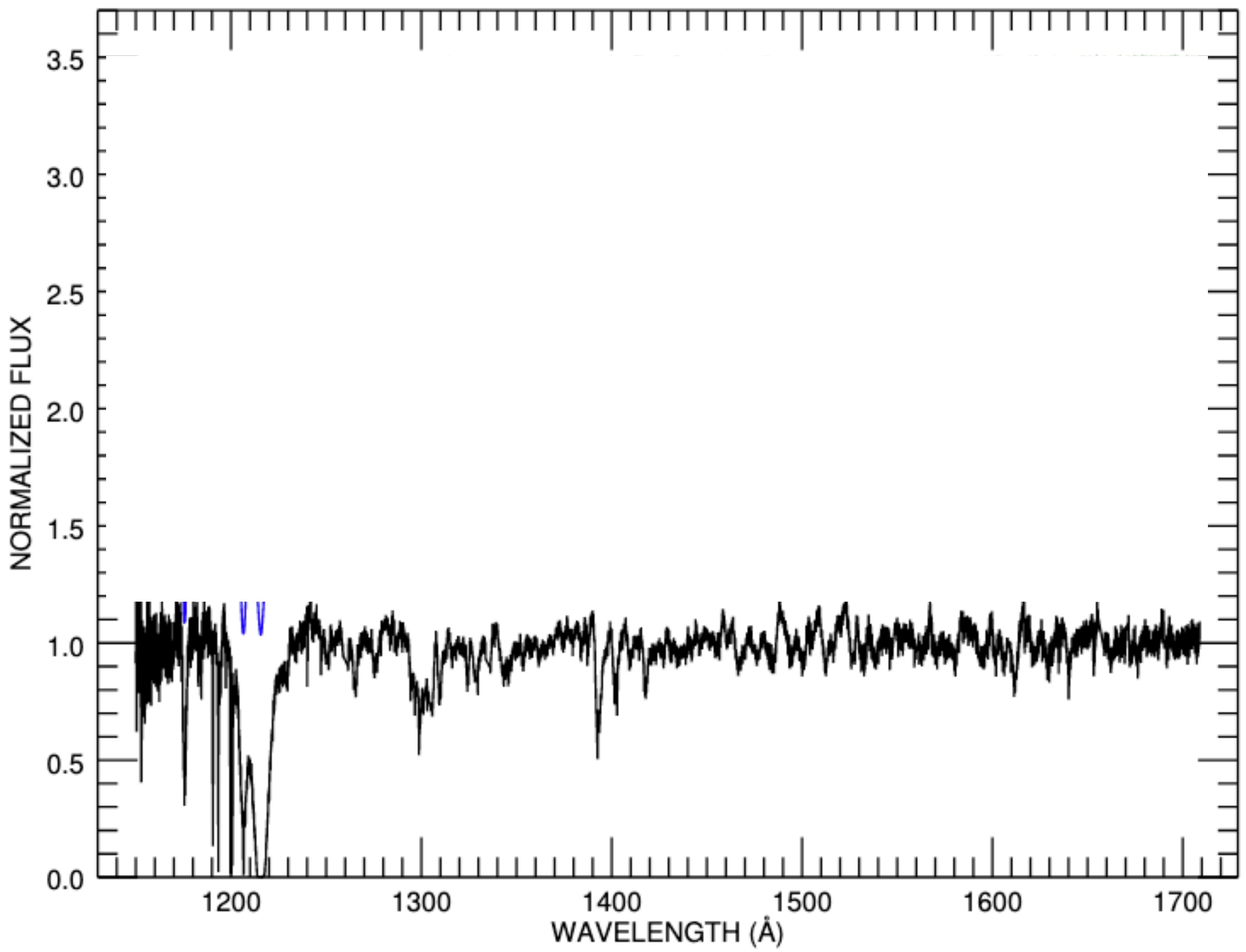
With cross-correlation using UV spectra (HST/COS), low-mass stripped stars discovered to orbit rapidly spinning Be stars
(Wang et al. 2021)

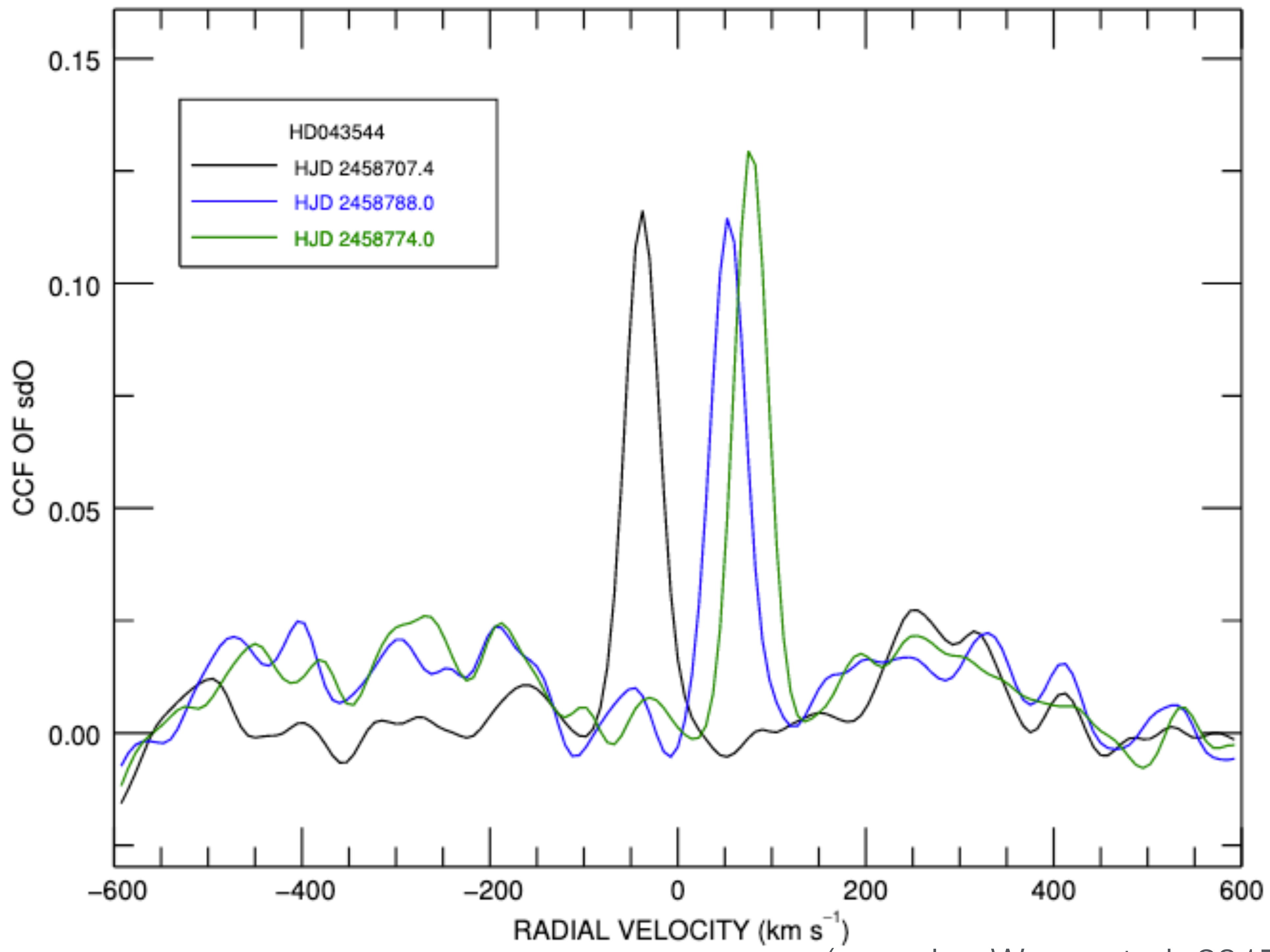
UV flux contribution from stripped star: ~2-10%
$M_{strip} < 1\ M_{\odot}$, early Be star (~8-15 $M_{\odot}$)

Hot star model

Be star model

Observed spectrum

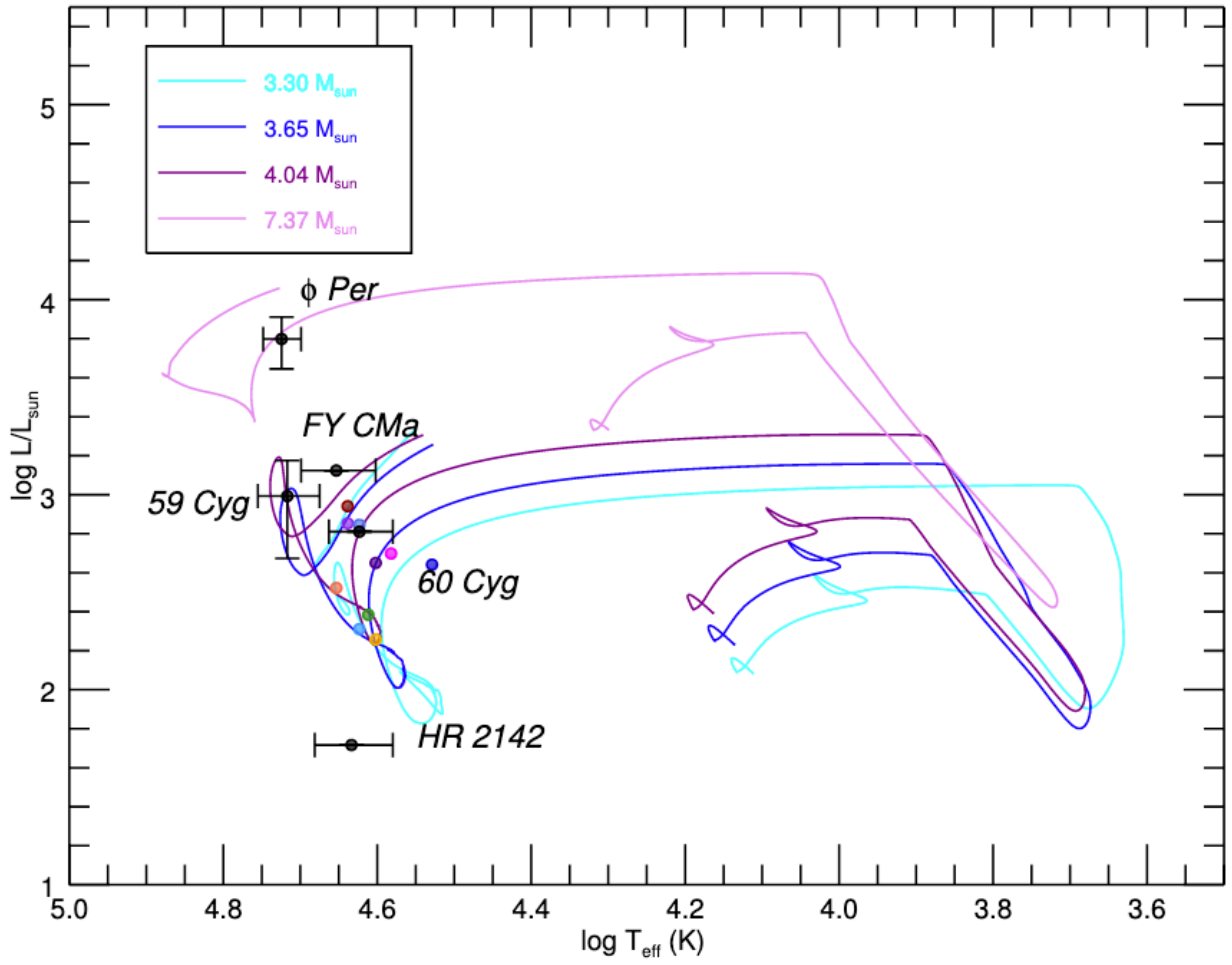




(see also Wang et al. 2017, 2018 using IUE data)

The discovery of 10 subdwarfs orbiting Be stars

With estimated masses of <1 $M_{\odot}$, mass transfer *must* have been conservative (early Be companions)
(Wang et al. 2021)



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An observational survey for stars stripped in binaries

PI: Götberg & Drout

Maria Drout

Bethany Ludwig

- **Discovery:** Drout & Götberg et al., under review
- **Stellar parameters of stripped stars:** Götberg et al., under review

In collaboration with: J.H. Groh, S.E. de Mink, **B. Hovis-Afflerbach**, N. Smith, **A. Carpenter**, **A. Roc**, **A. O'Grady**, K. Breivik, D. Lang, K. Auchettl, C. Johnston, J. Zhang, P. Senchyna

Credit: NASA/Swift/S. Immler (Goddard) and M. Siegel (Penn State)

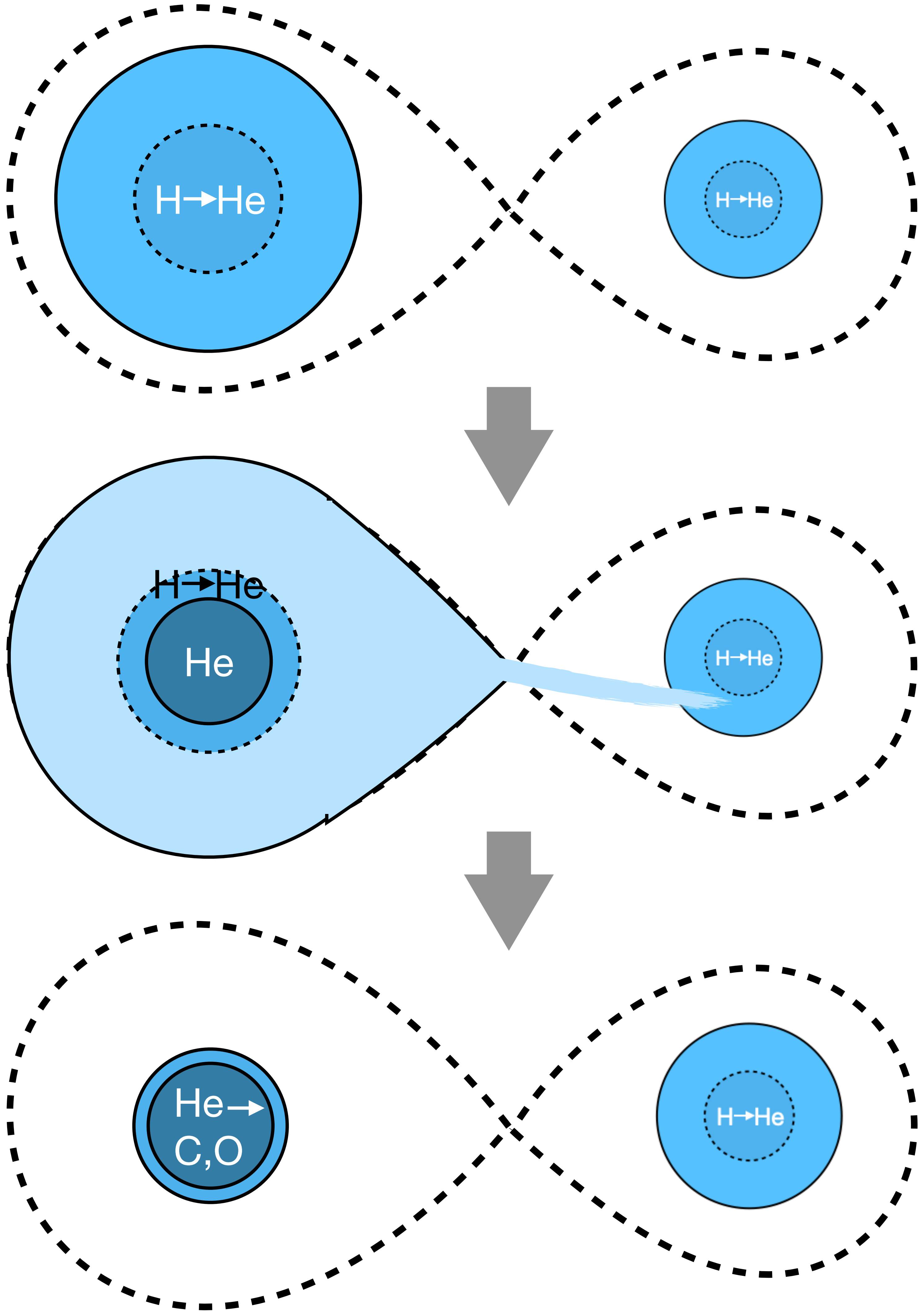
Swift/UVOT maps of the Magellanic Clouds (Siegel+14, 15, 19)

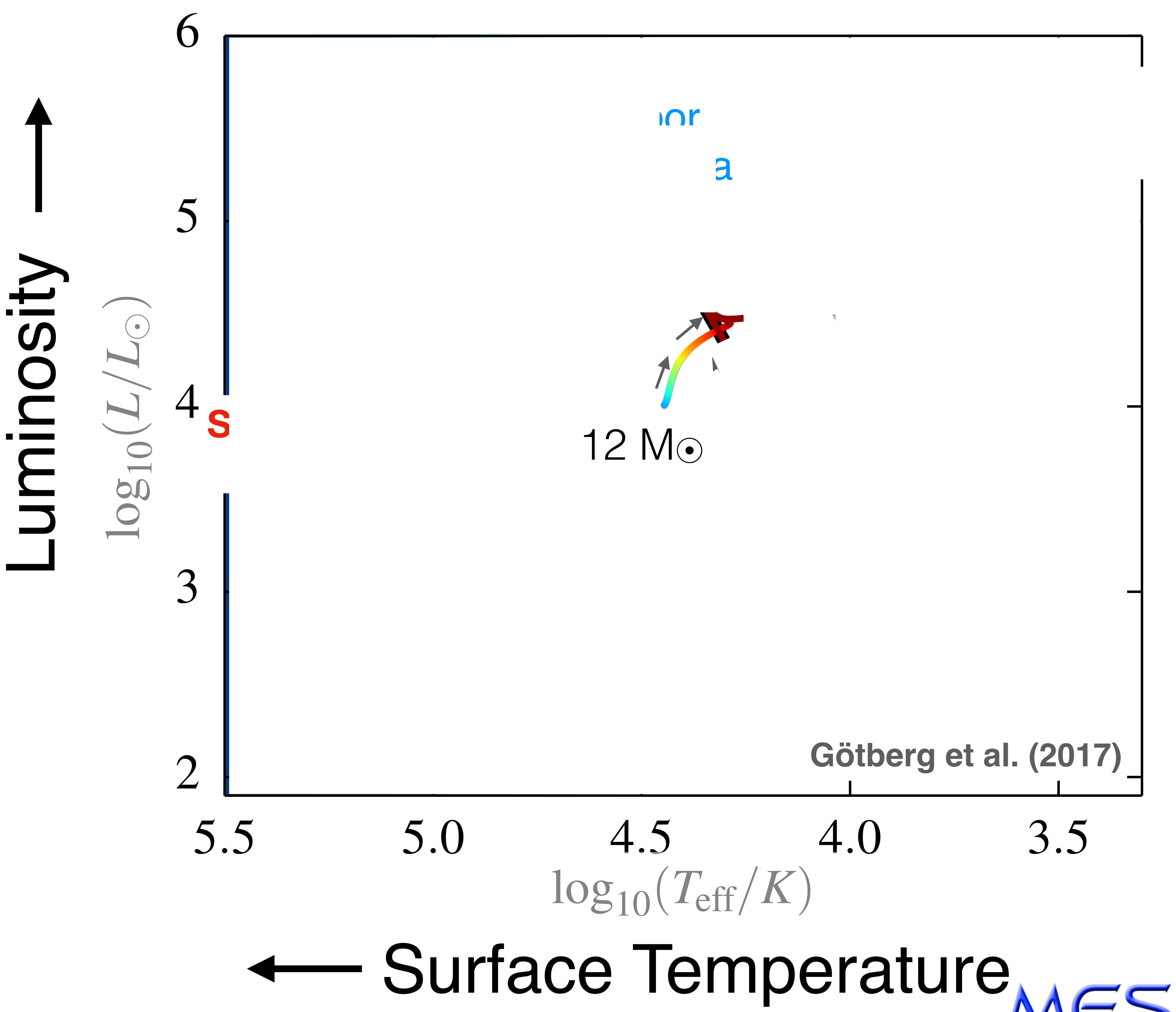
The creation of a stripped star

1. Central hydrogen fusion

2. Envelope-stripping

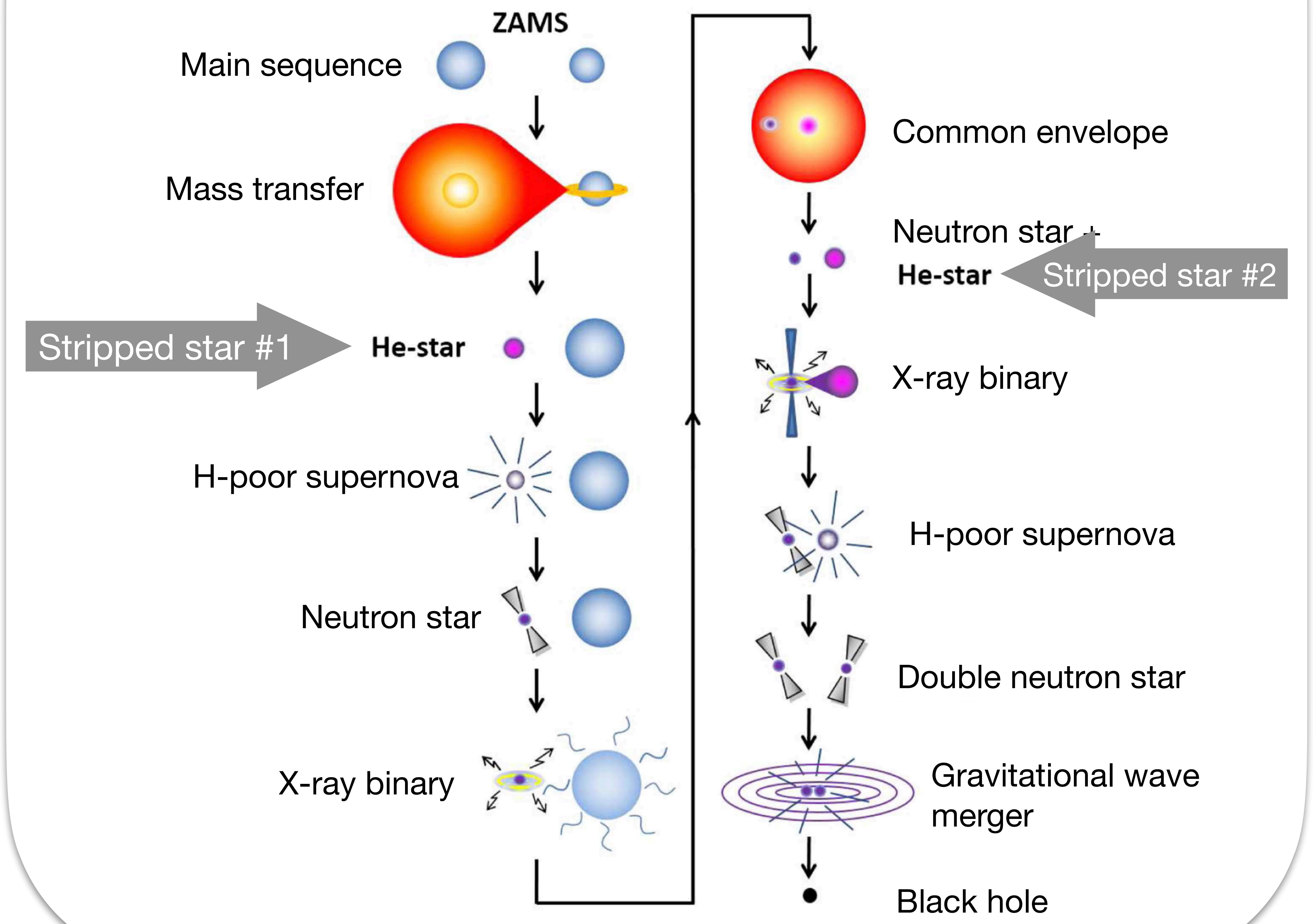
3. Helium core exposed — a stripped star





Where are the stripped stars?

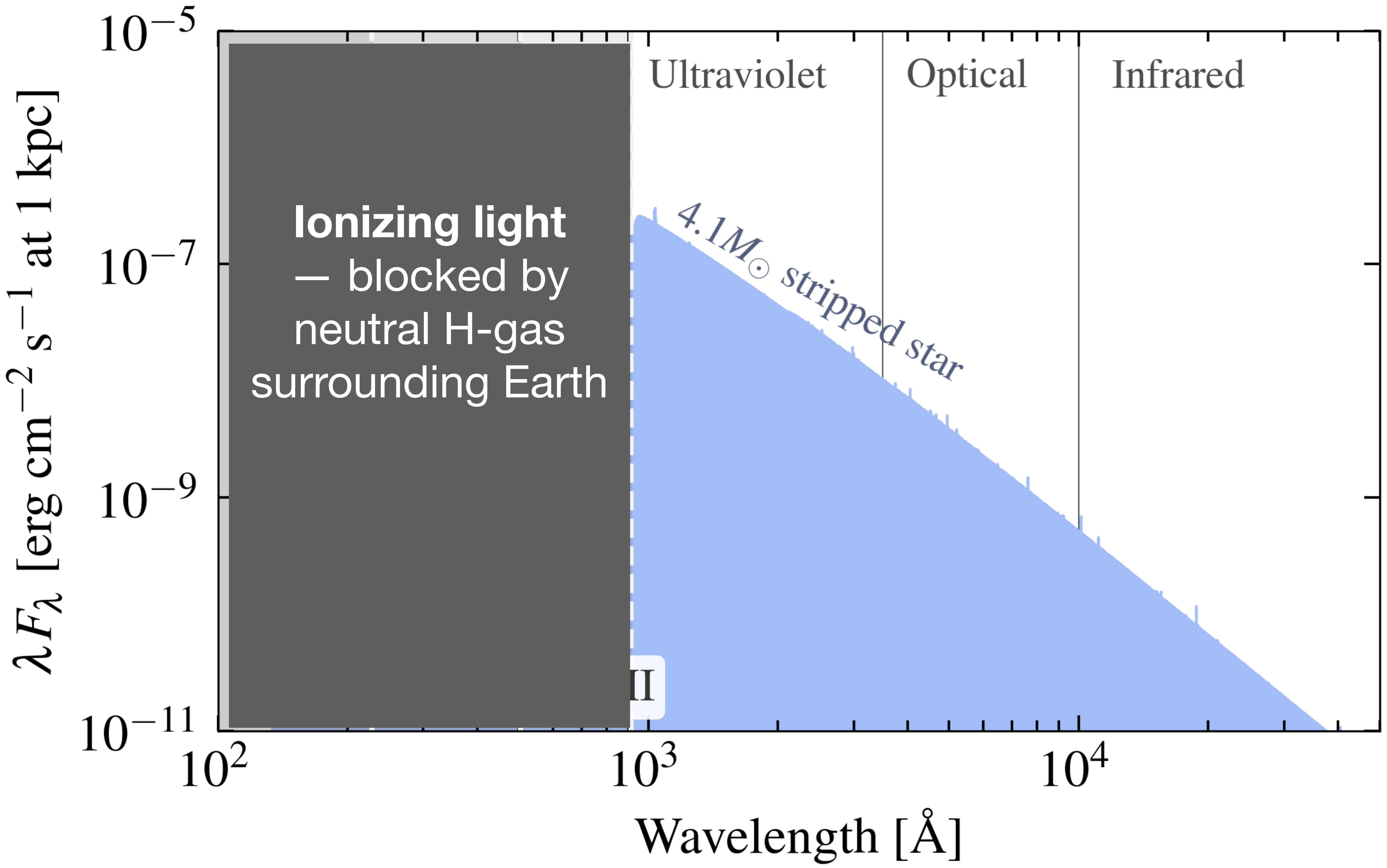
Two stripped stars necessary for merging binary neutron stars
(Tauris et al. 2017, Ye et al. 2020)



Expected number of stripped stars	Observed number of stripped stars
Thousands in the Milky Way	**1?** (Groh+08, Shenar+23)
Hundreds in the Magellanic Clouds	**0**
(**Götberg et al. 2019**, see also Wu+19, Sana+12)	

UV excess: a way to identify stripped stars

Some stripped star systems should have UV excess
Götberg et al. (2017, 2018)



(see also Pols & Marinus 1994, Lepo & Van Kerkwijk 2013)

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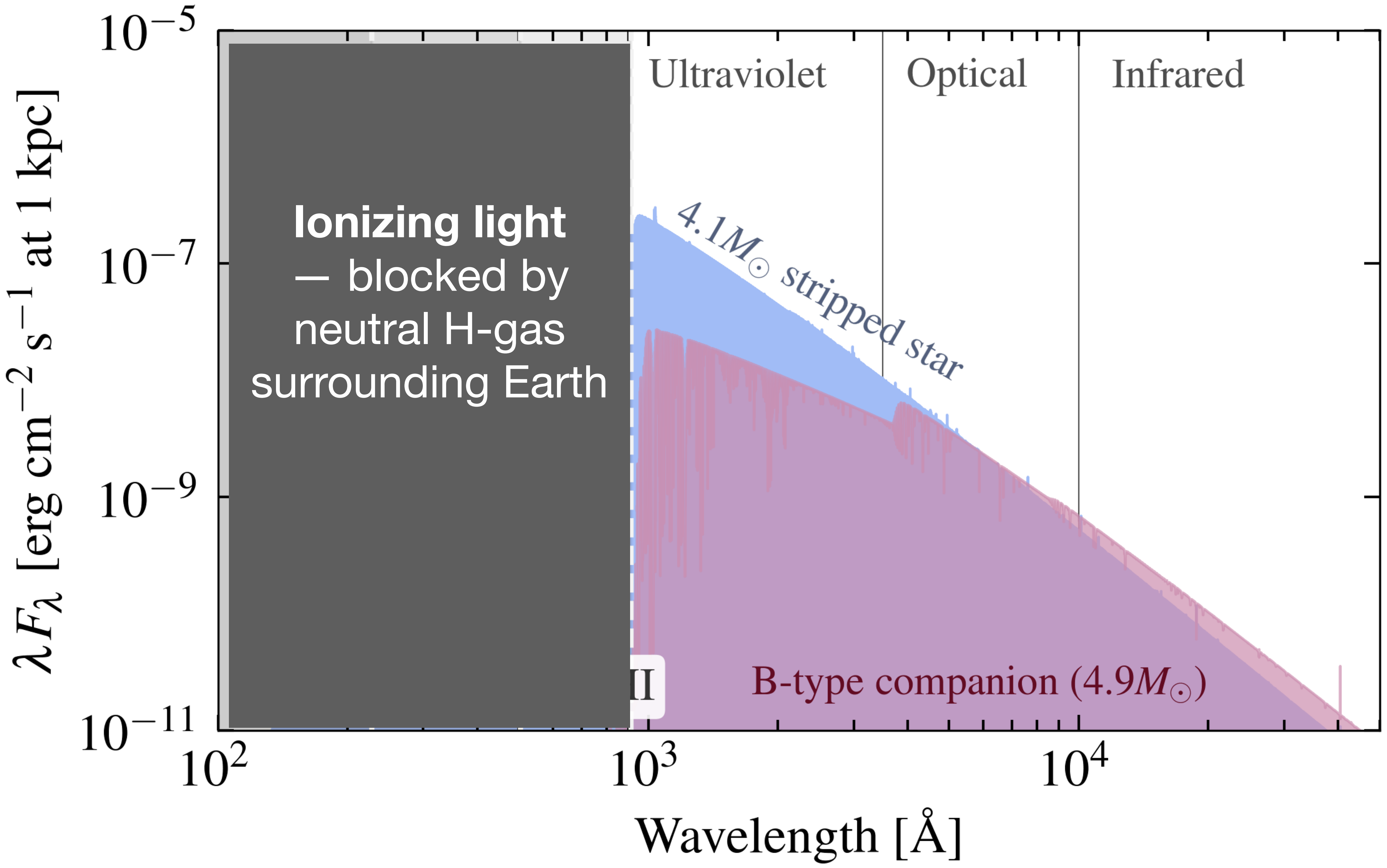

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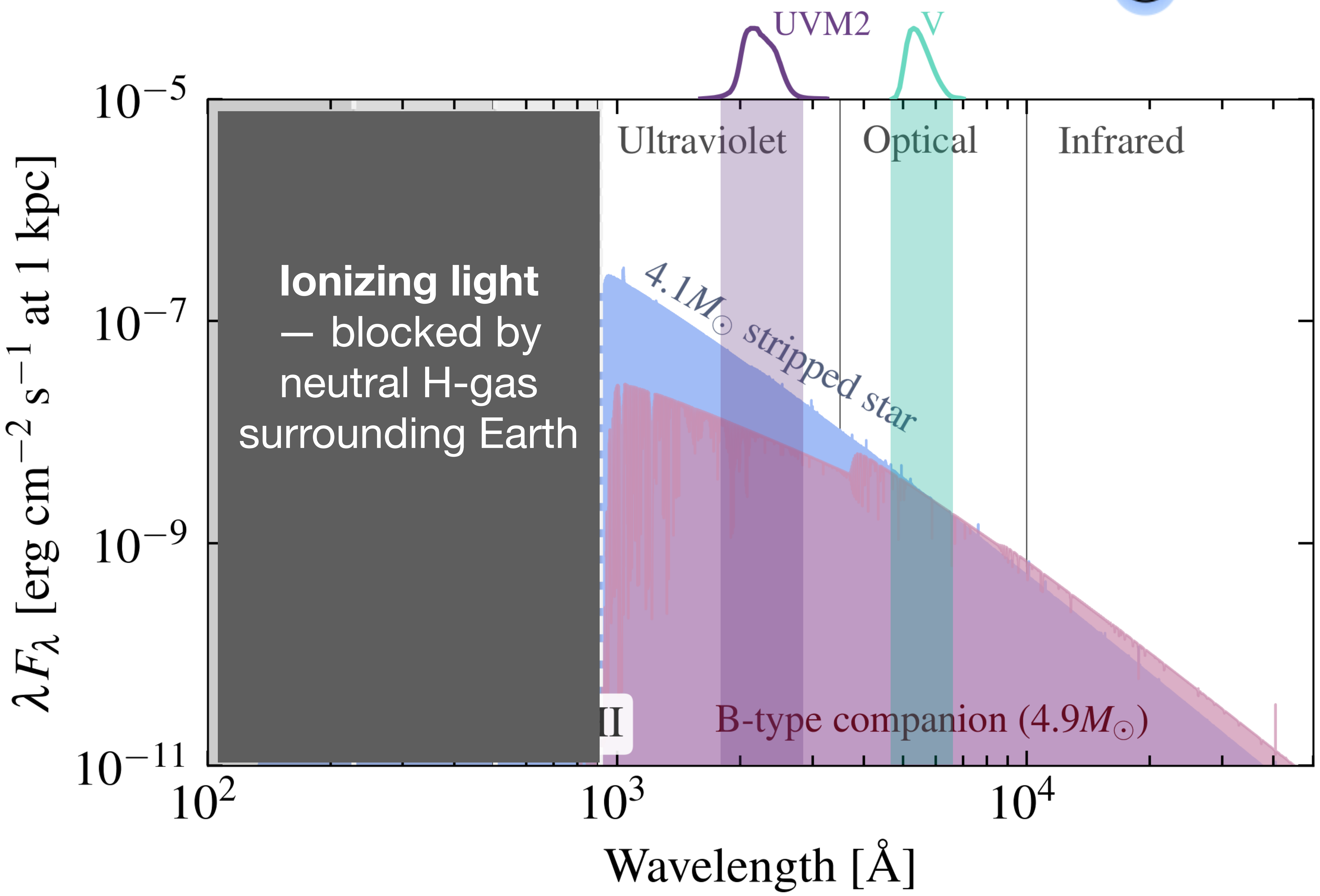

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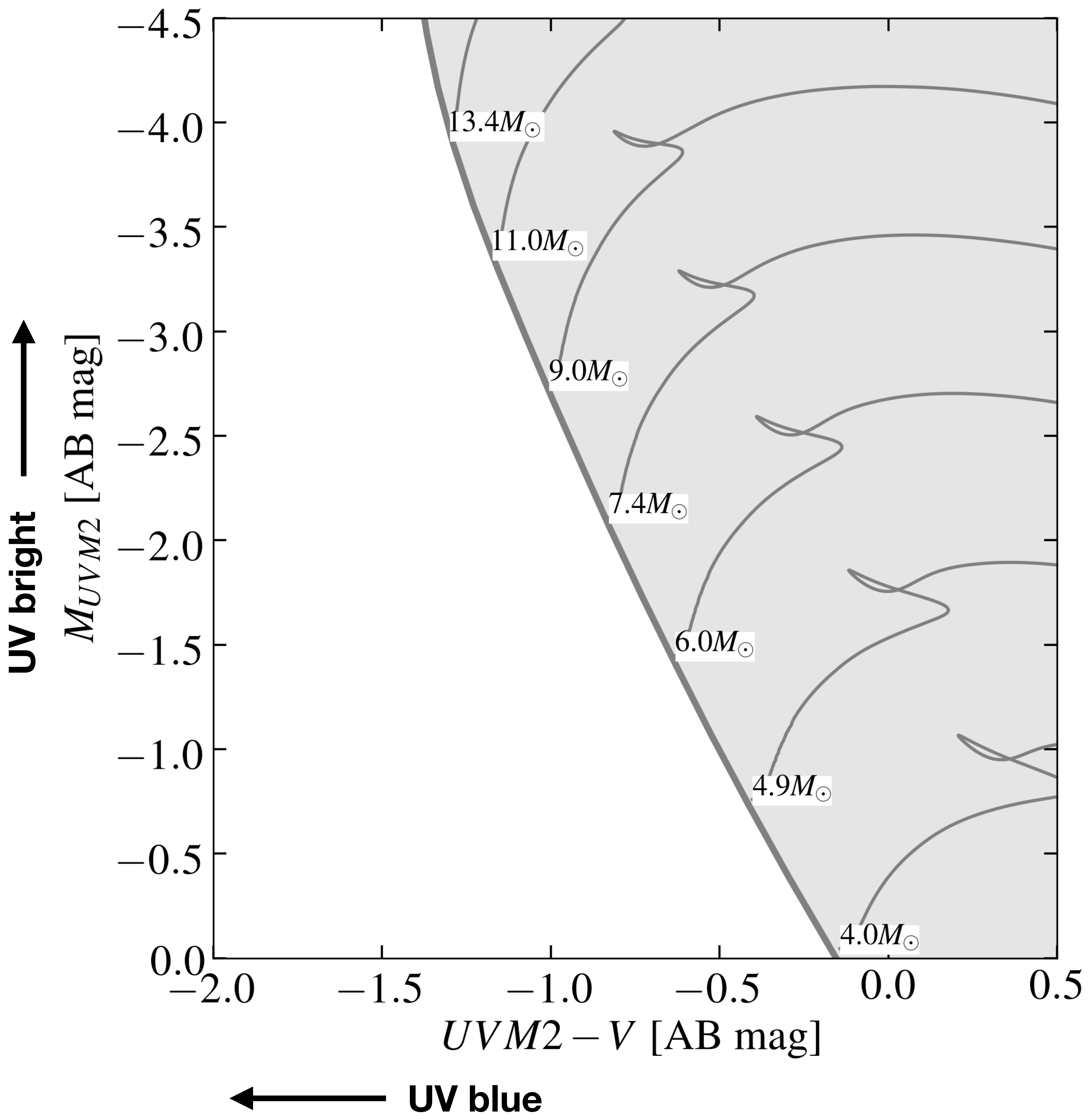

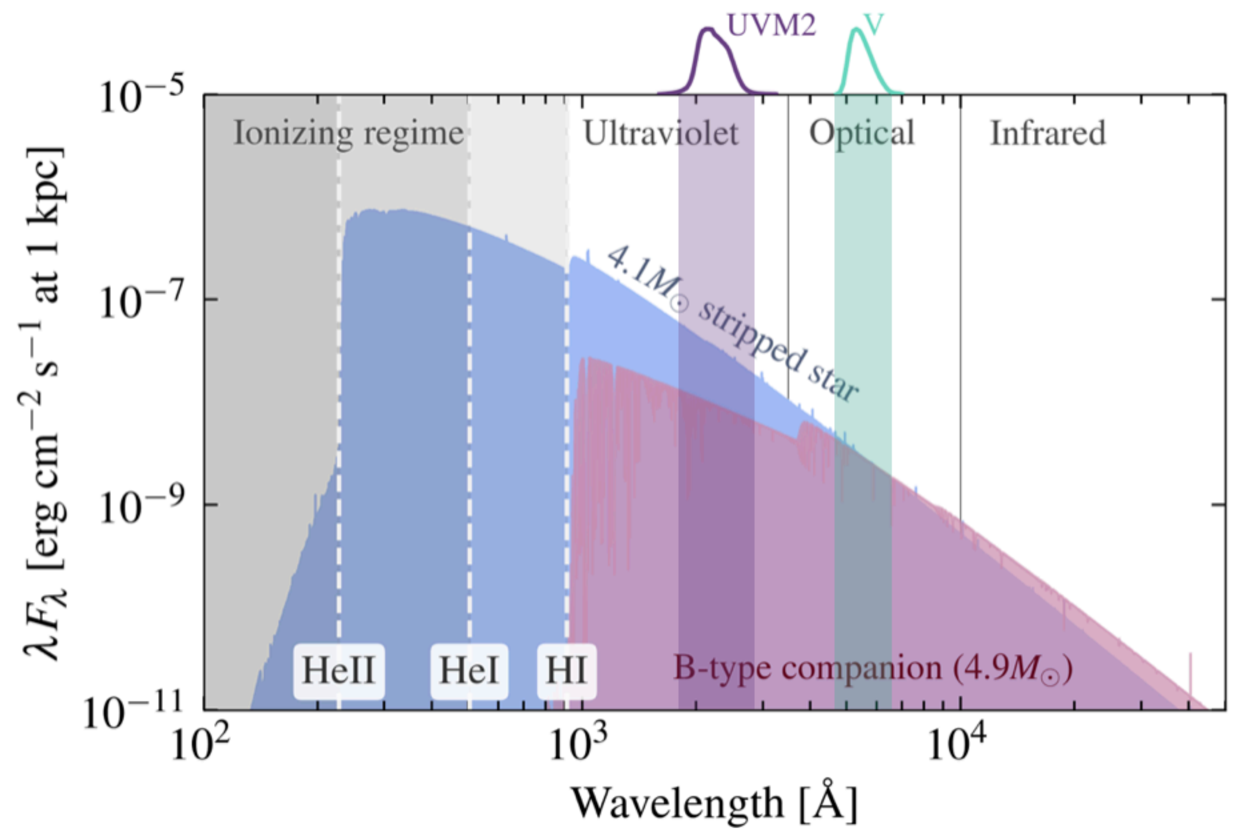

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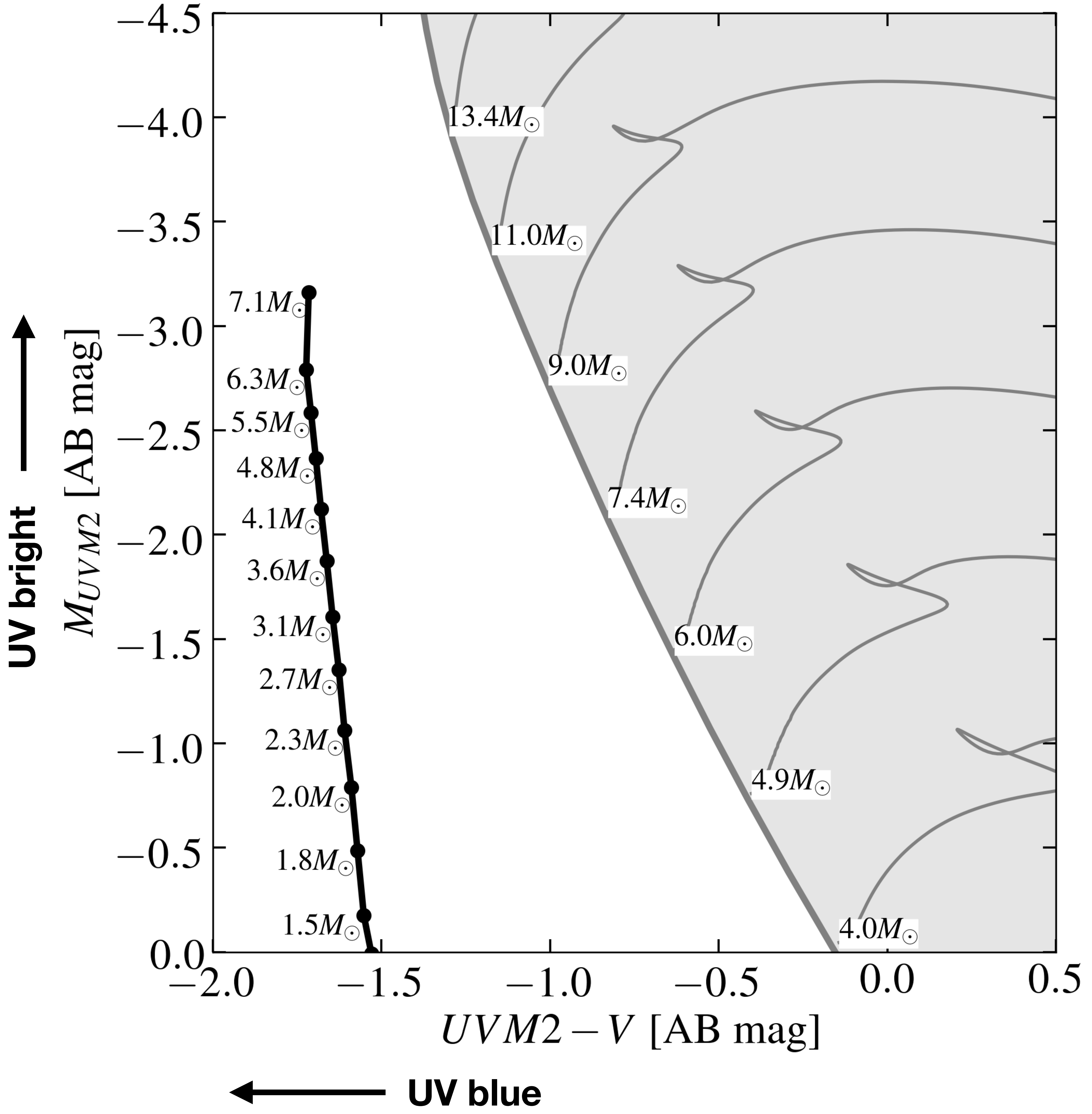

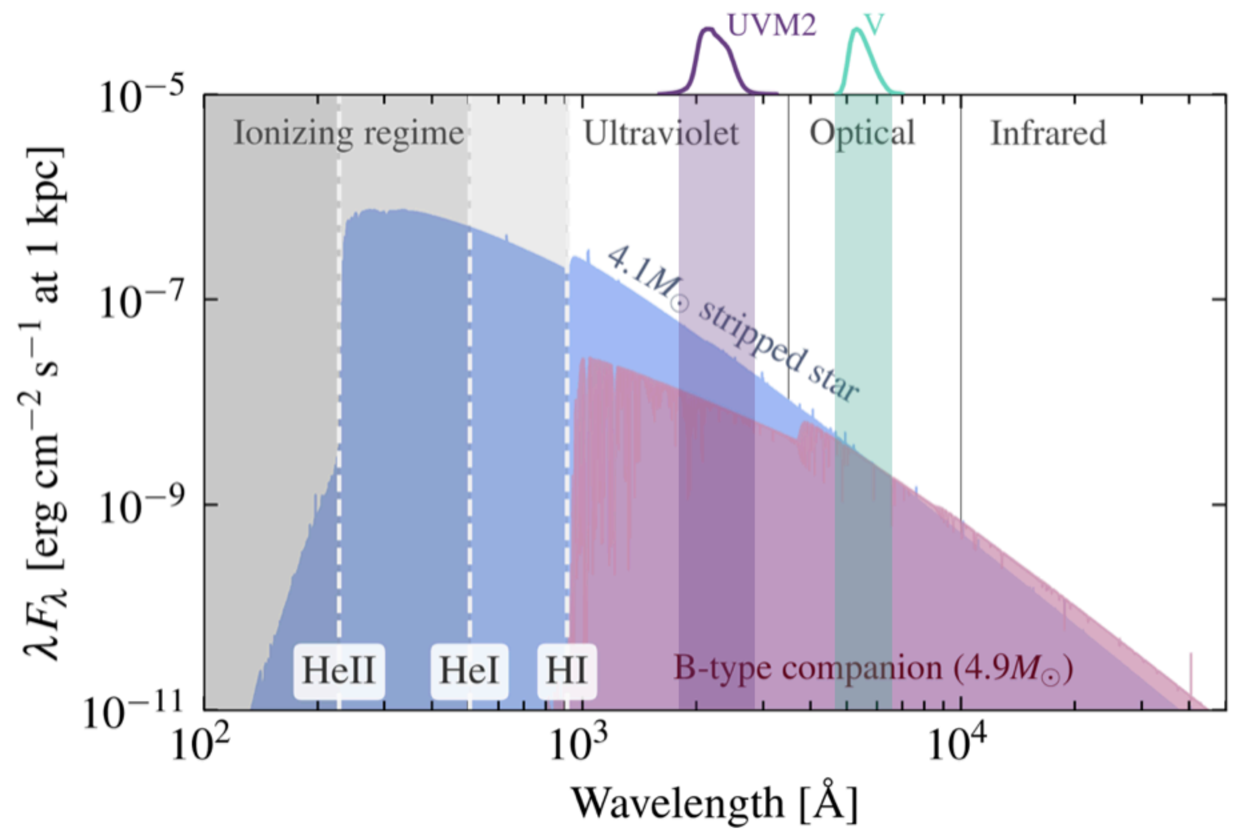

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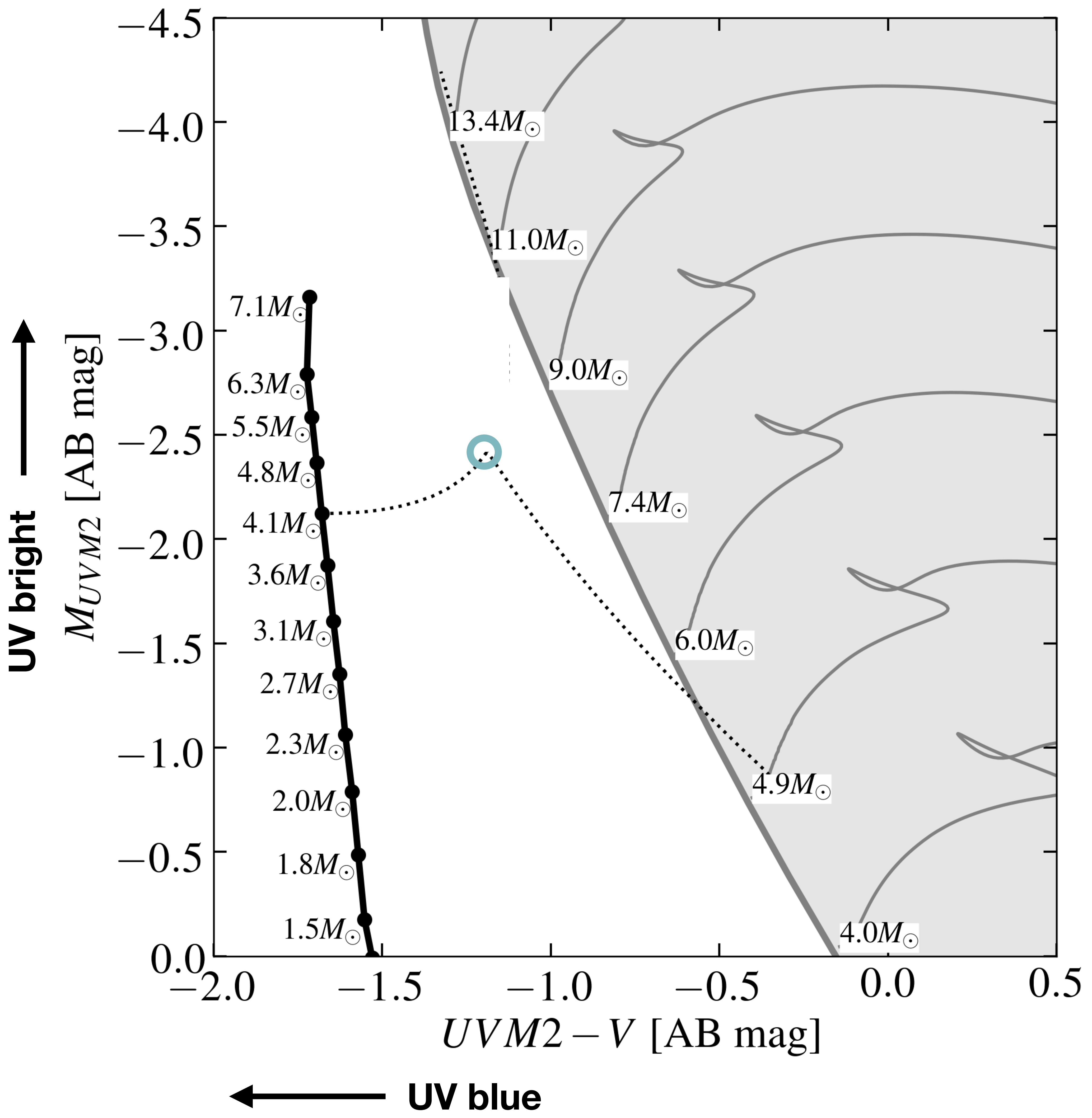

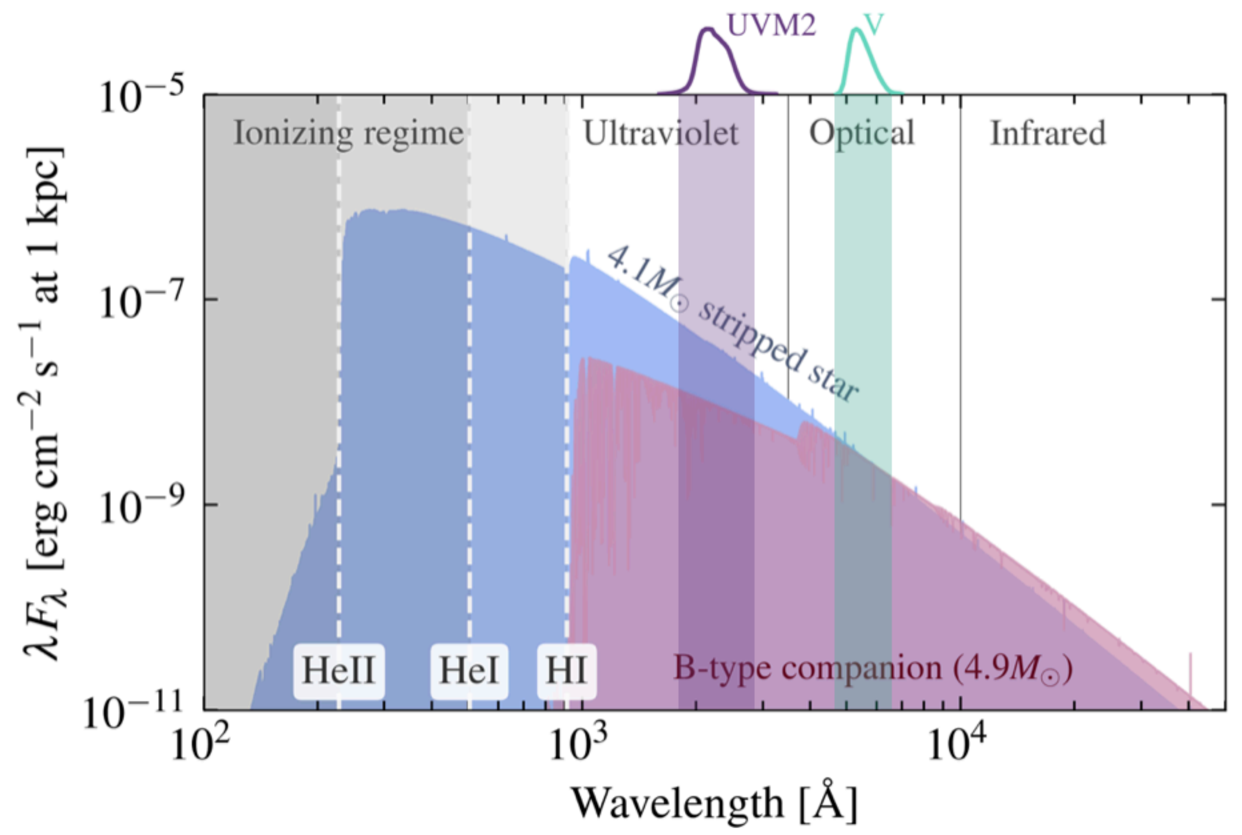

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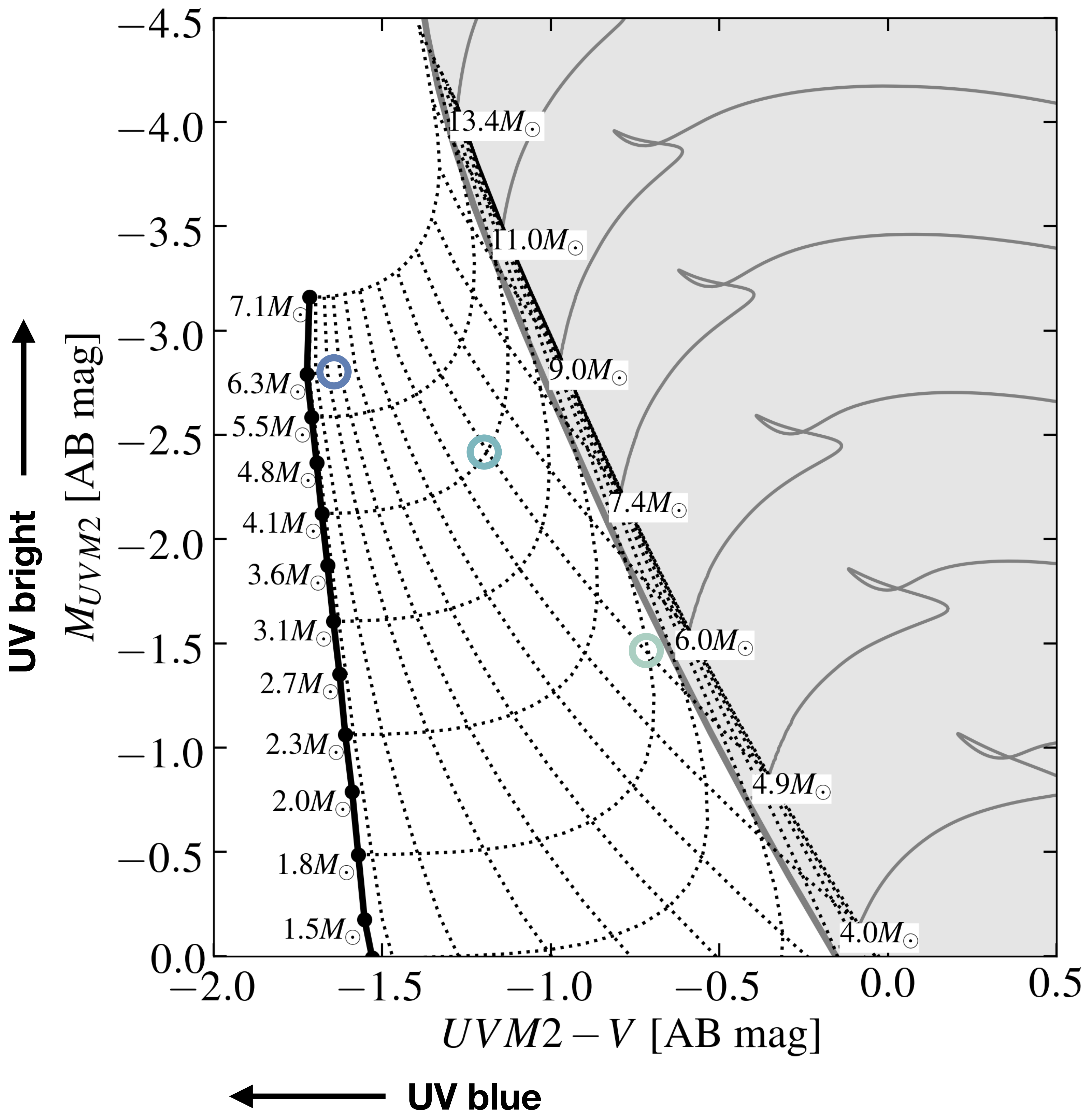

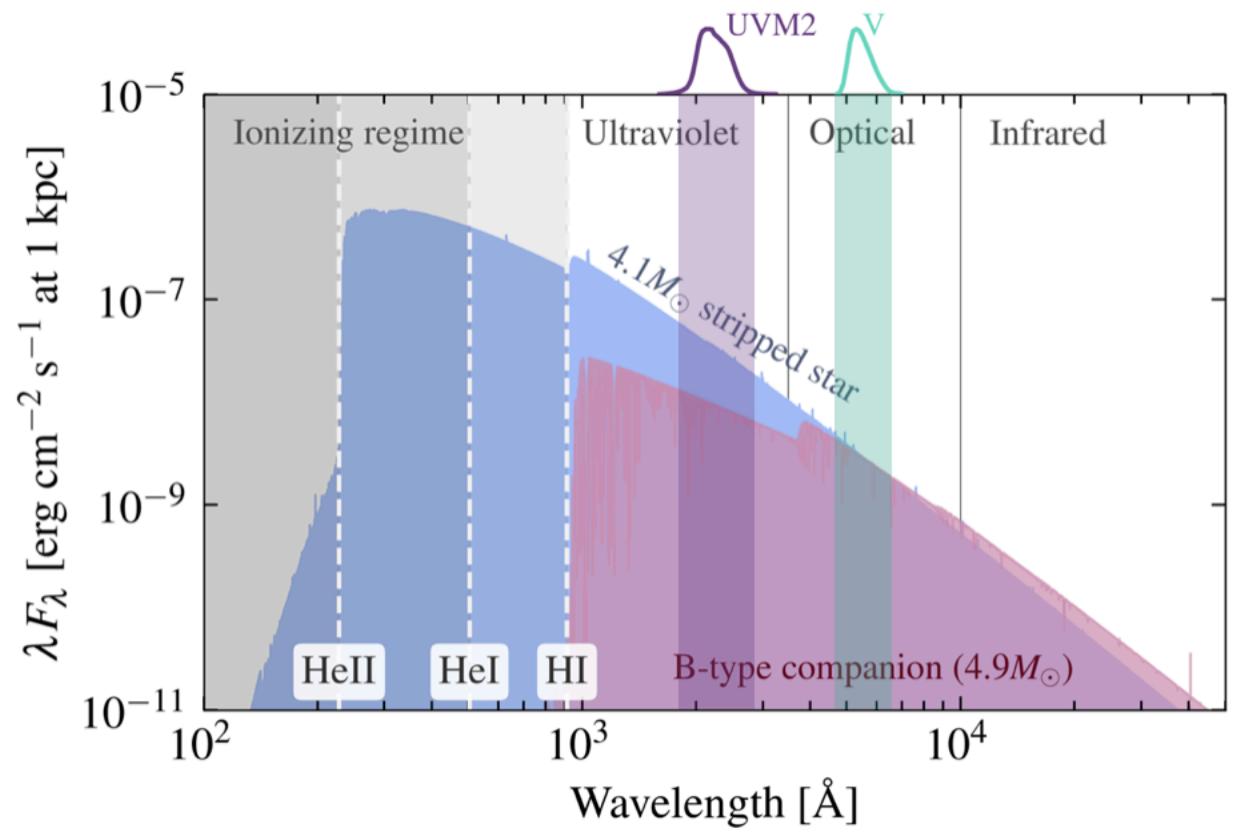

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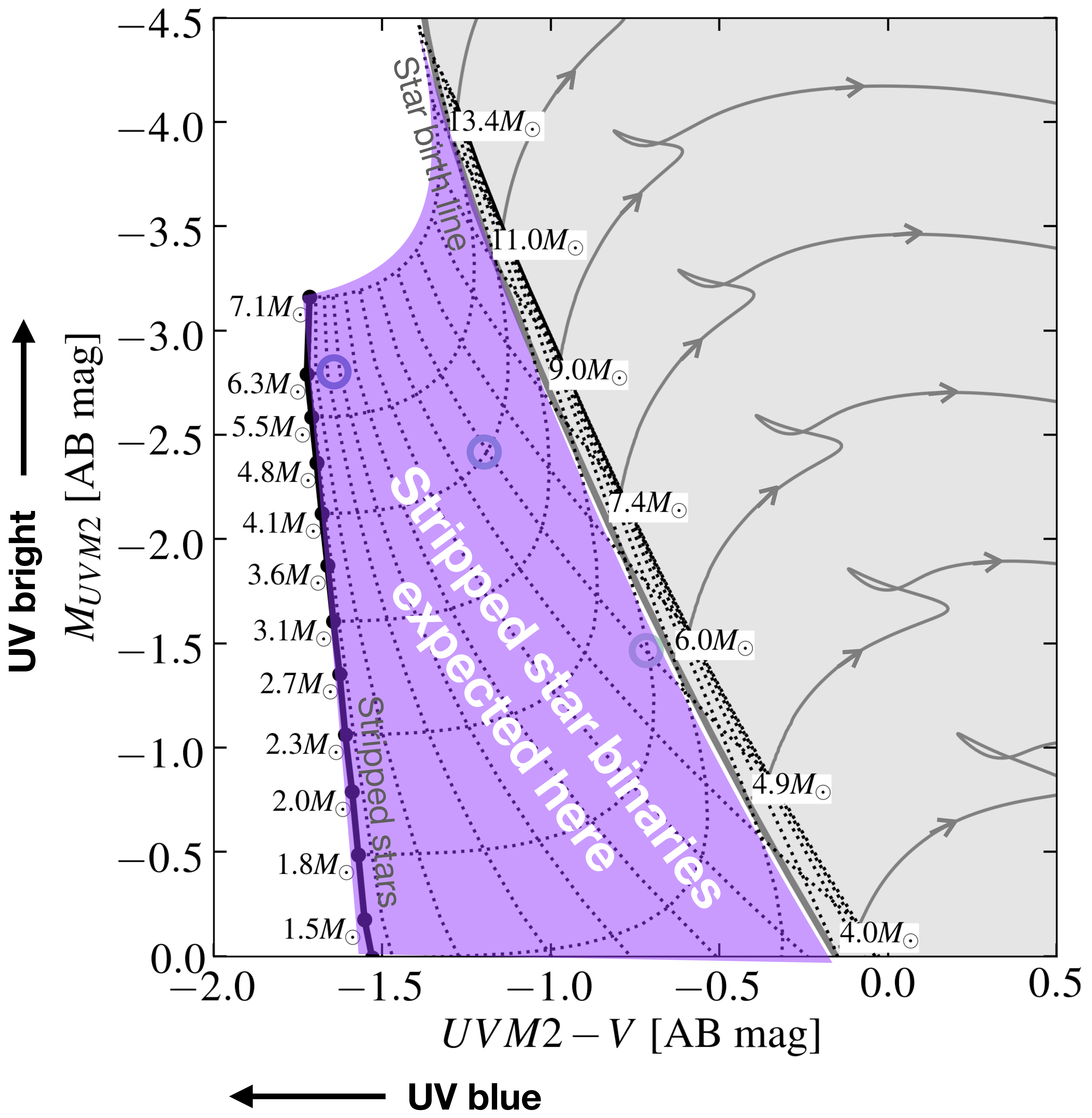
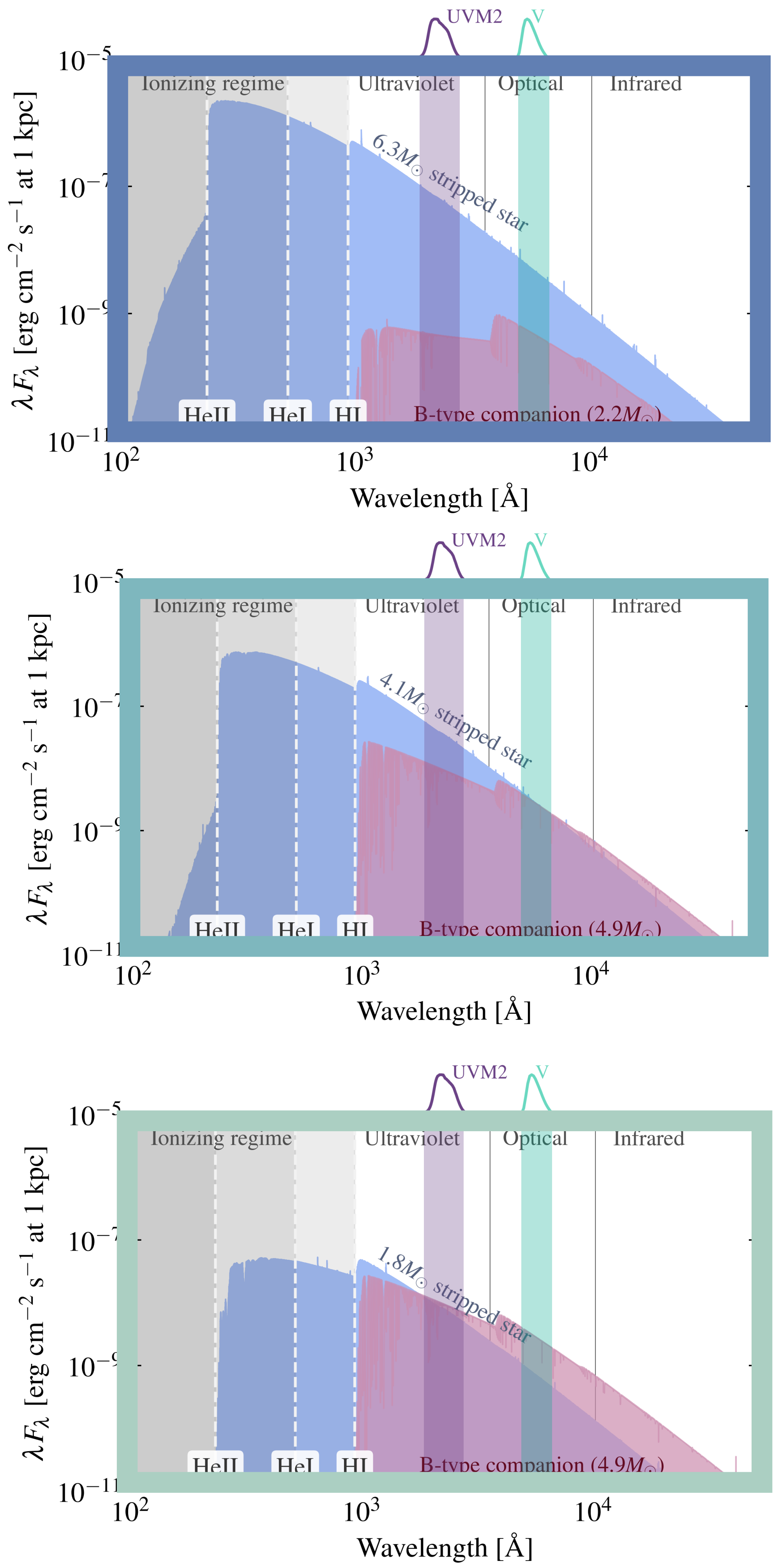




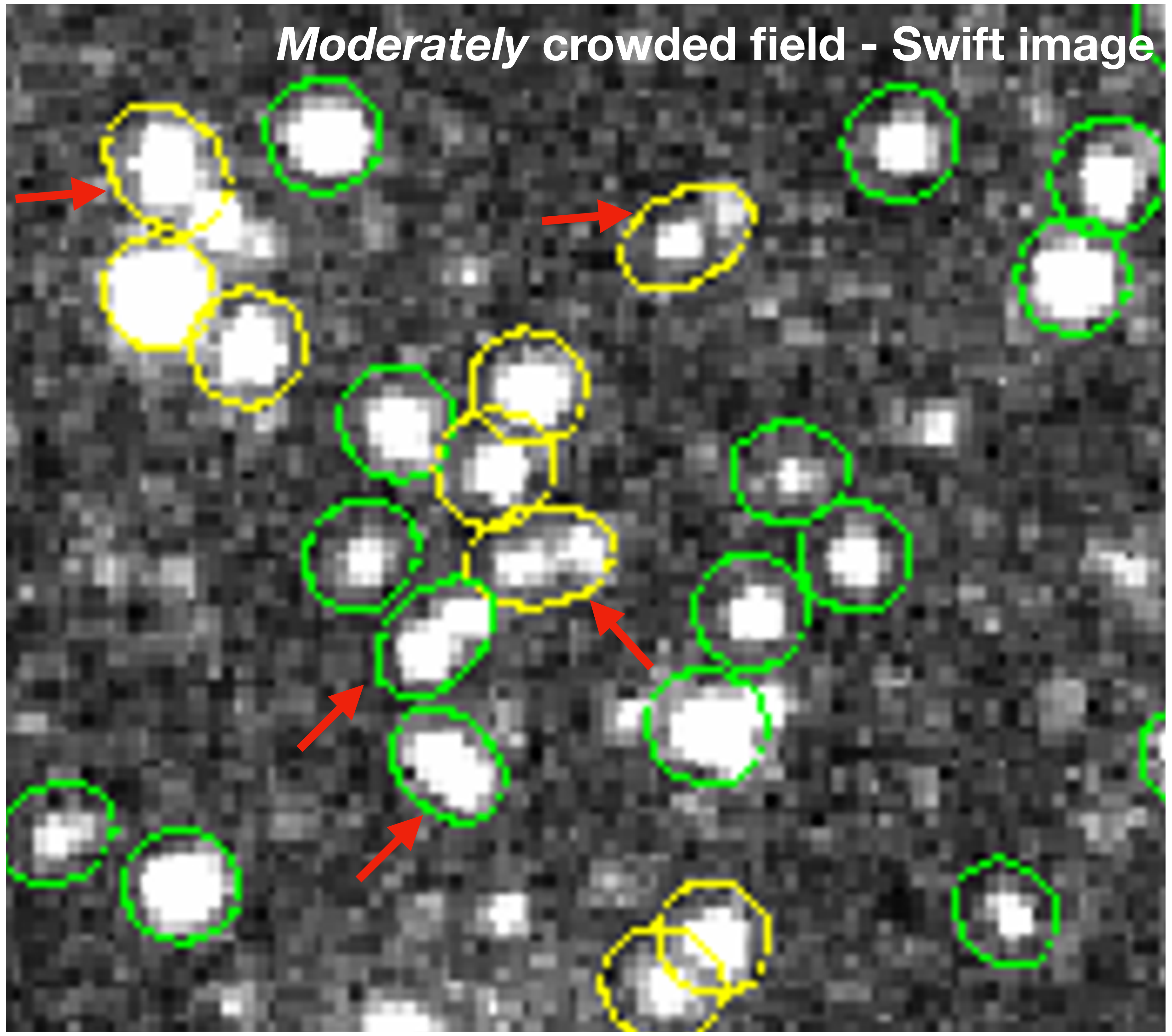
(see also Pols & Marinus 1994, Lepo & Van Kerkwijk 2013)

The importance of careful photometry reduction

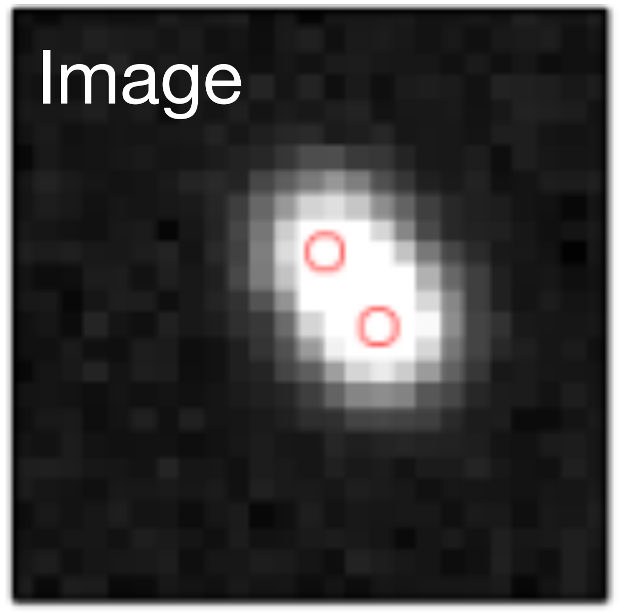
Bethany Ludwig

Crowding is an issue: multiple sources interpreted as one in standard reduction routines!

Ludwig et al. (in prep.)



A more sophisticated technique is needed: *The Tractor*



The Tractor forward modeling code: Lang, Hogg, Schlegel 2016

Candidate identification

Theoretical prediction

Actual observations

Drout & Götberg et al. (under review), Ludwig et al. (in prep)

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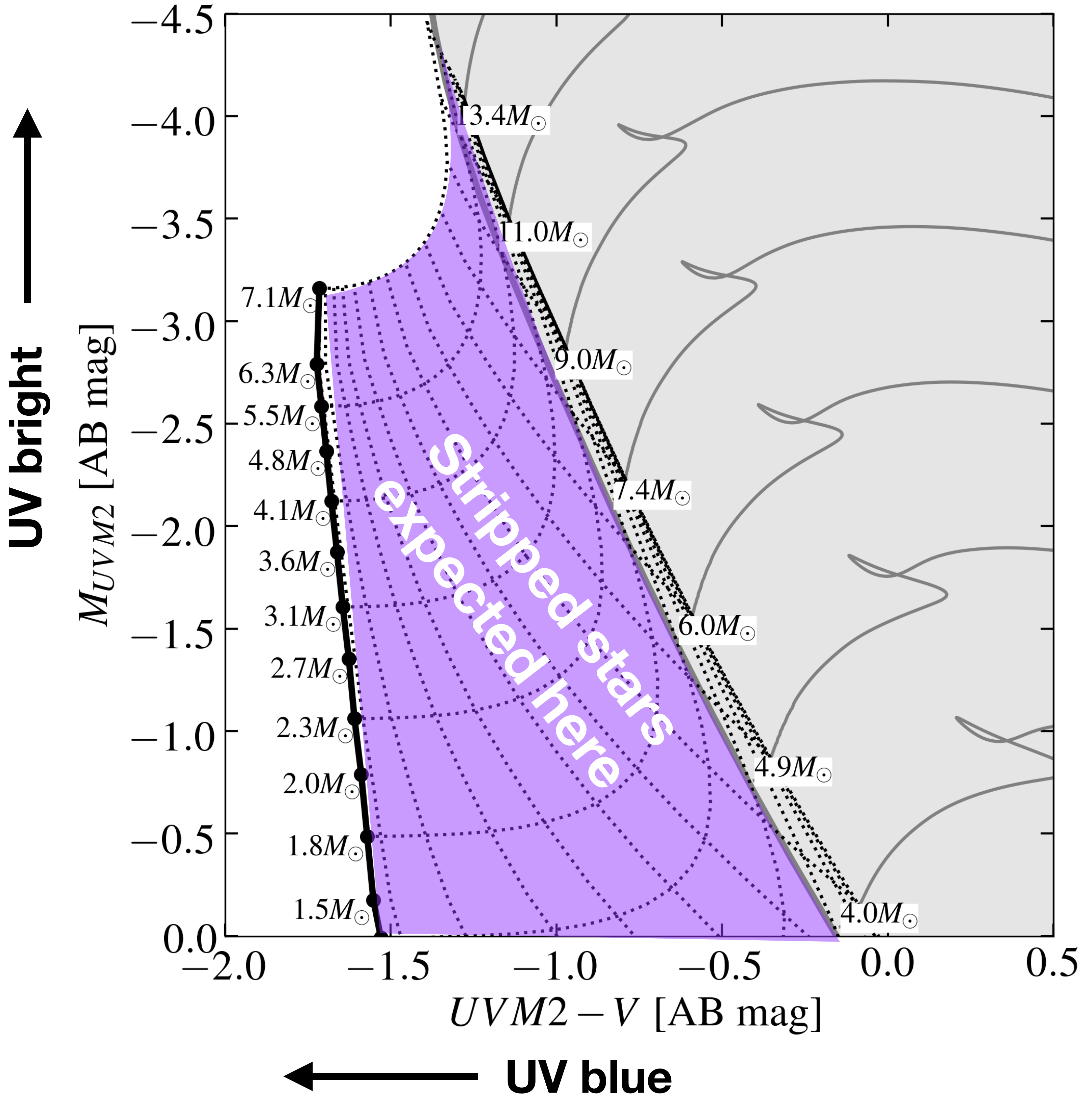

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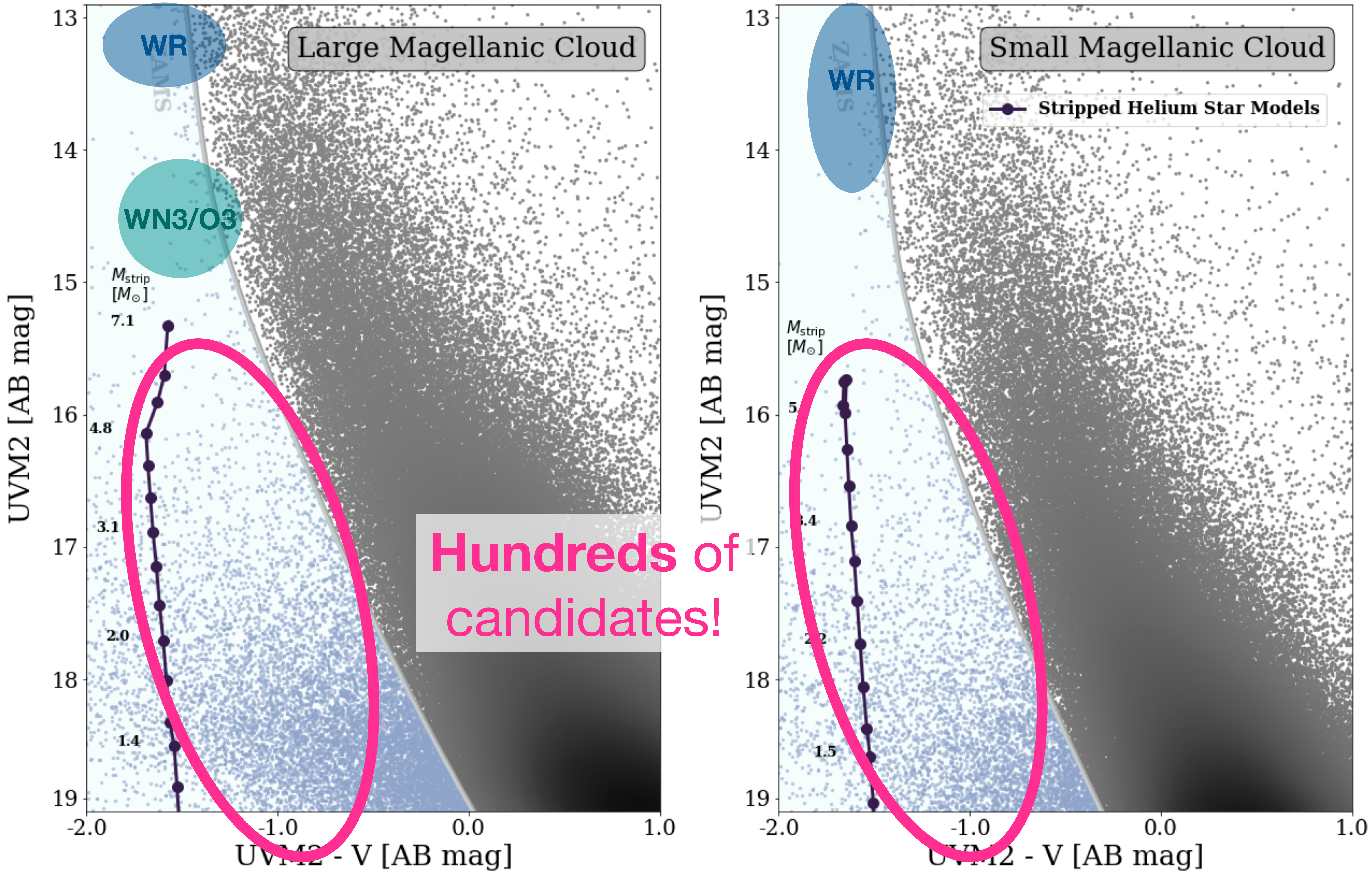

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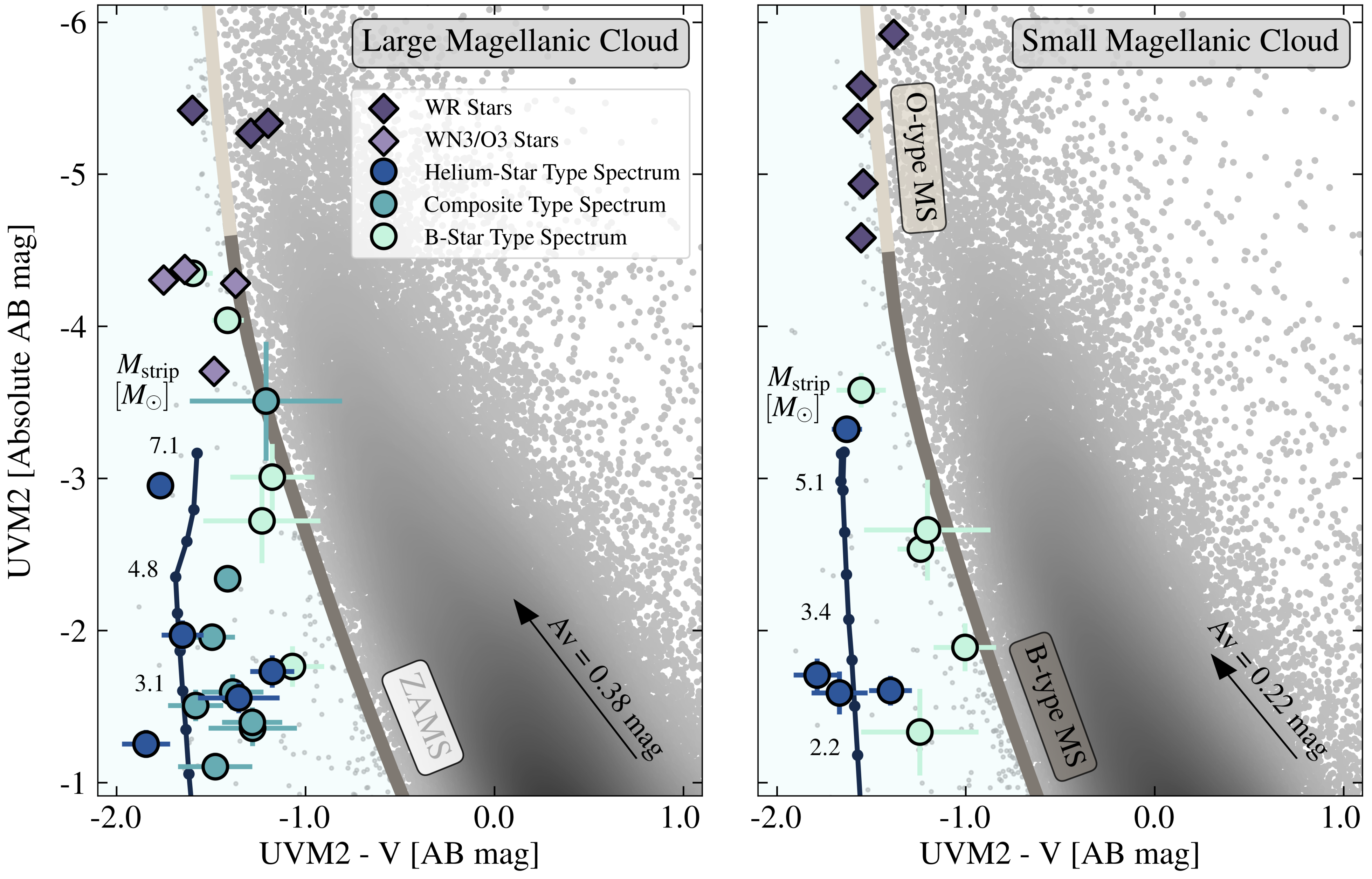
Optical spectroscopic follow-up



Spectroscopic targets: large circles (25 stars)

The Magellan Baade telescope MagE spectrograph

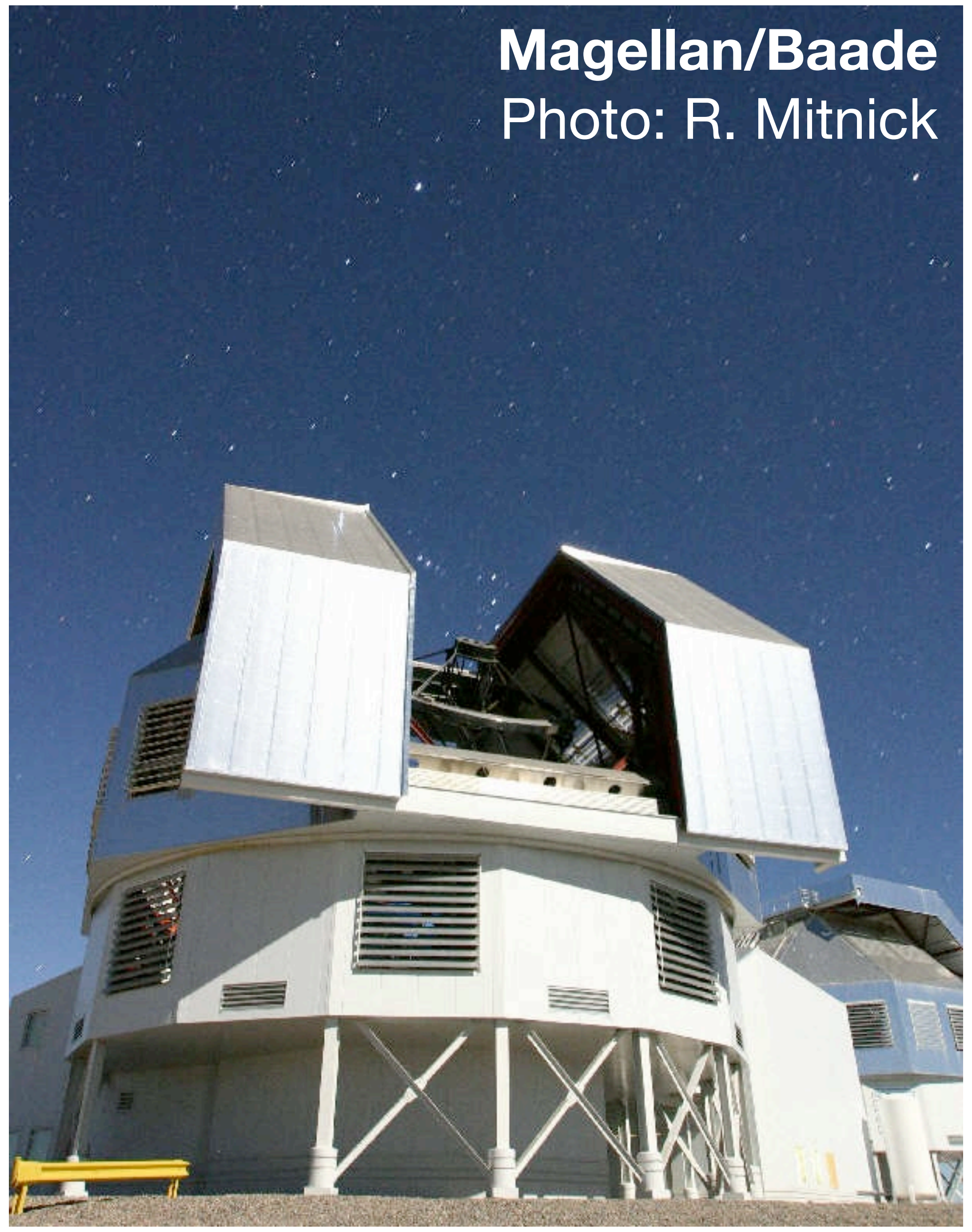
PI: Götberg & Drout, 2019B-2022B

R ~ 4000

Wavelength range ~3700-7000 Å

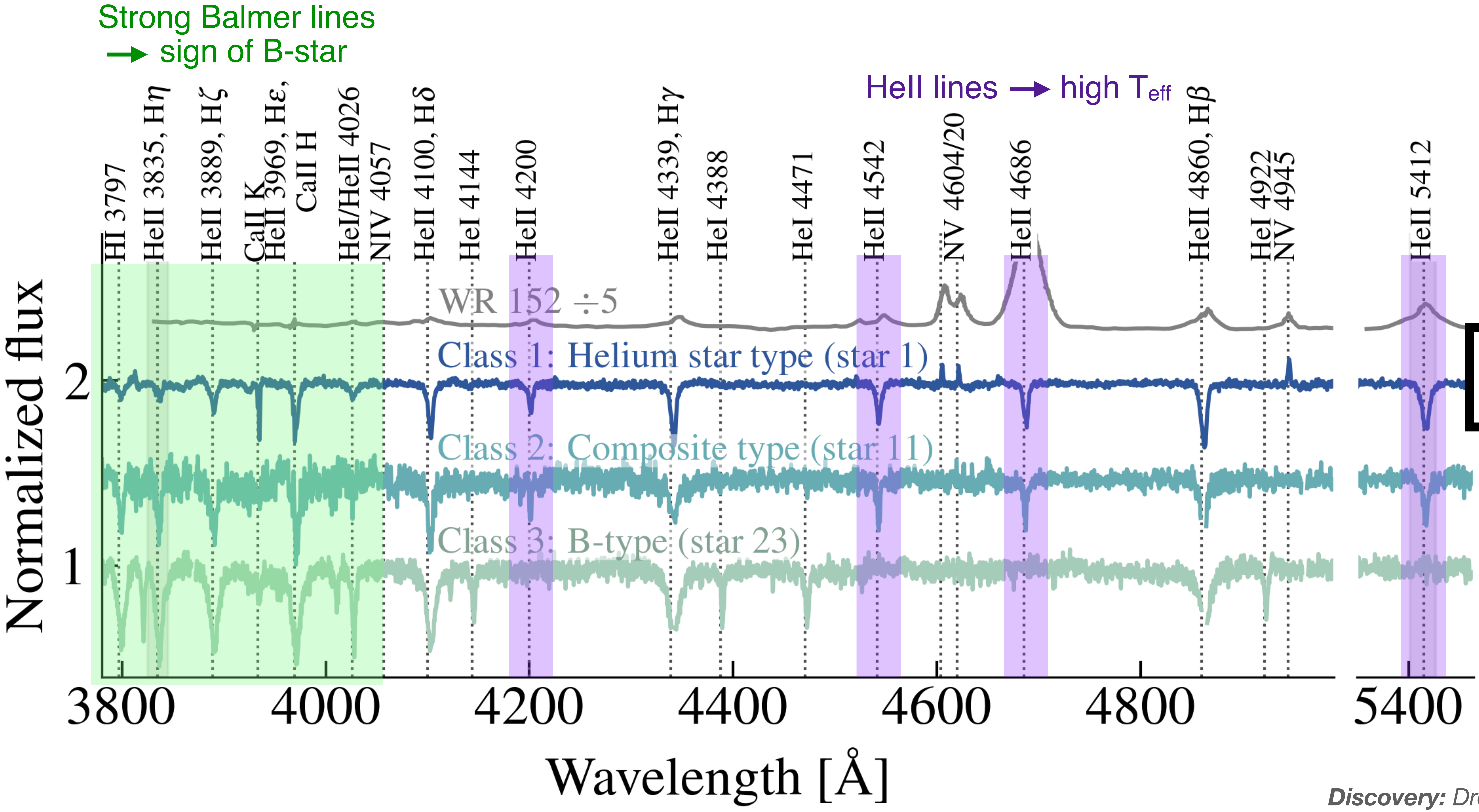
Exposure times ~0.5-1.5 hours

SNR ~ 30-120



Discovery: *Drout & Götberg et al., under review, Science*

Spectral morphology



Find stellar properties

"Helium-star type": 8 stars

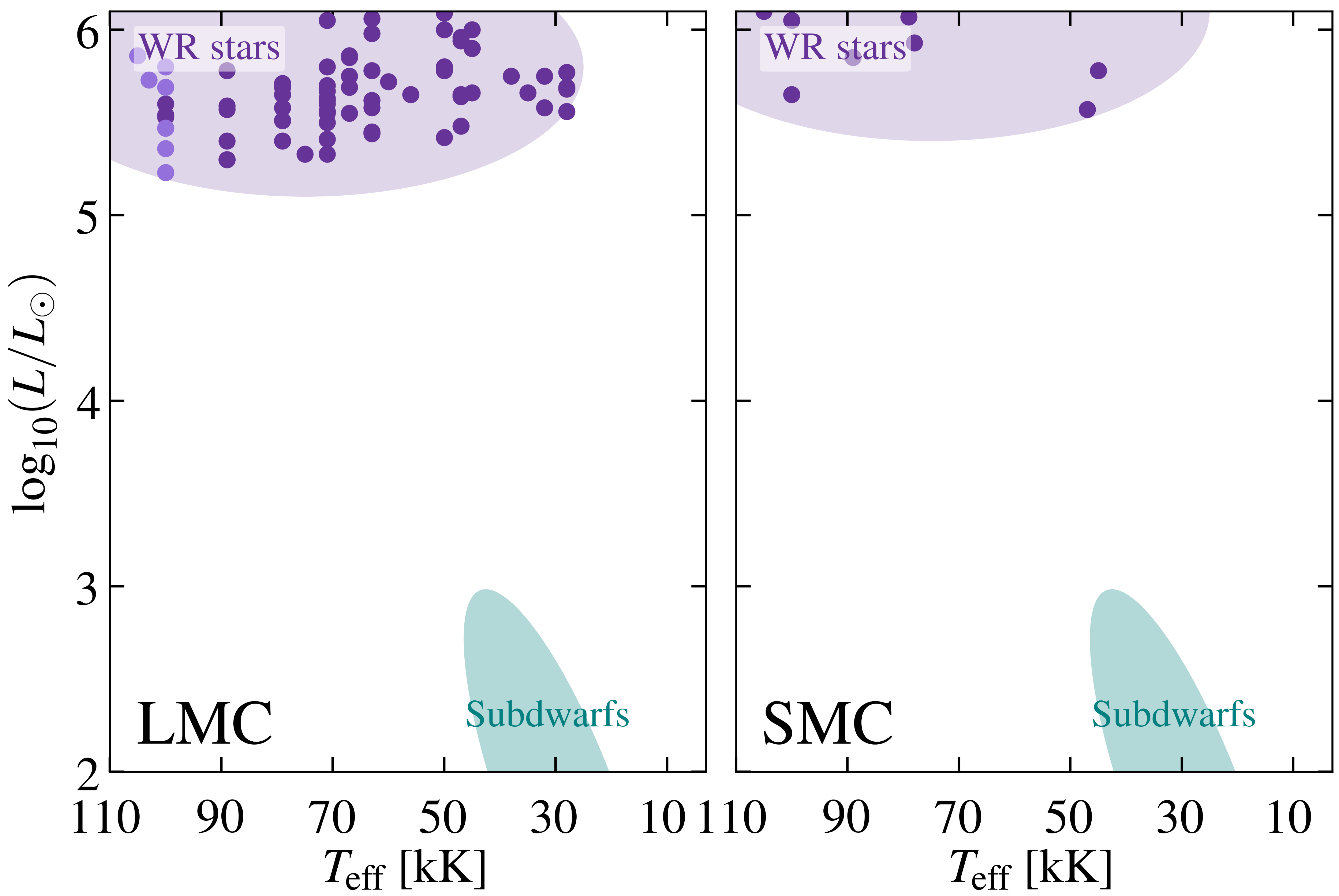
"Composite": 8 stars

"B-type": 10 stars

Discovery: *Drout & Götberg et al., under review*

Stellar properties from spectral fitting

The stars in the spectroscopic sample have stellar properties that match stripped stars with ~2-8 $M_\odot$



Stellar properties: *Götberg et al., under review*

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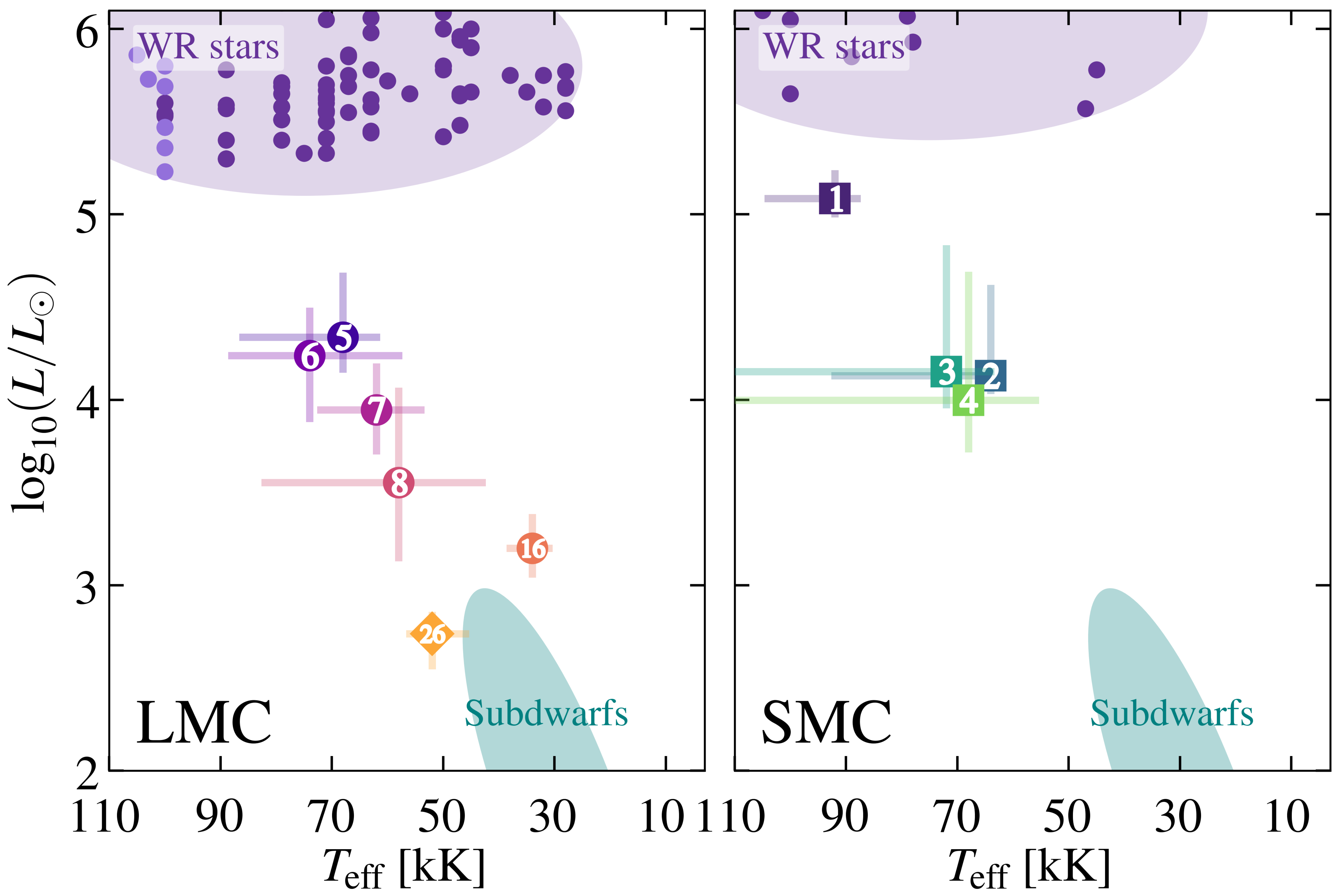

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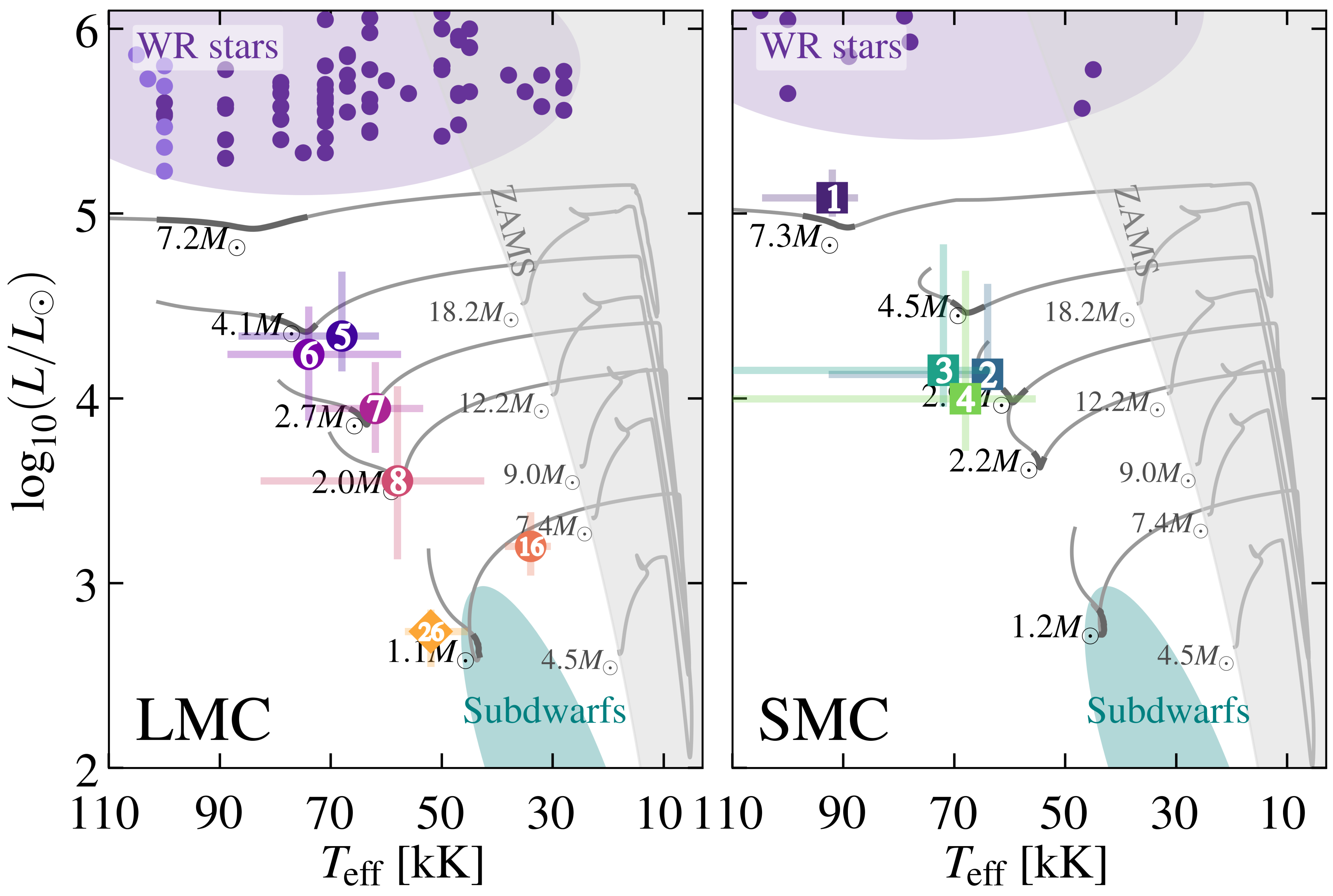
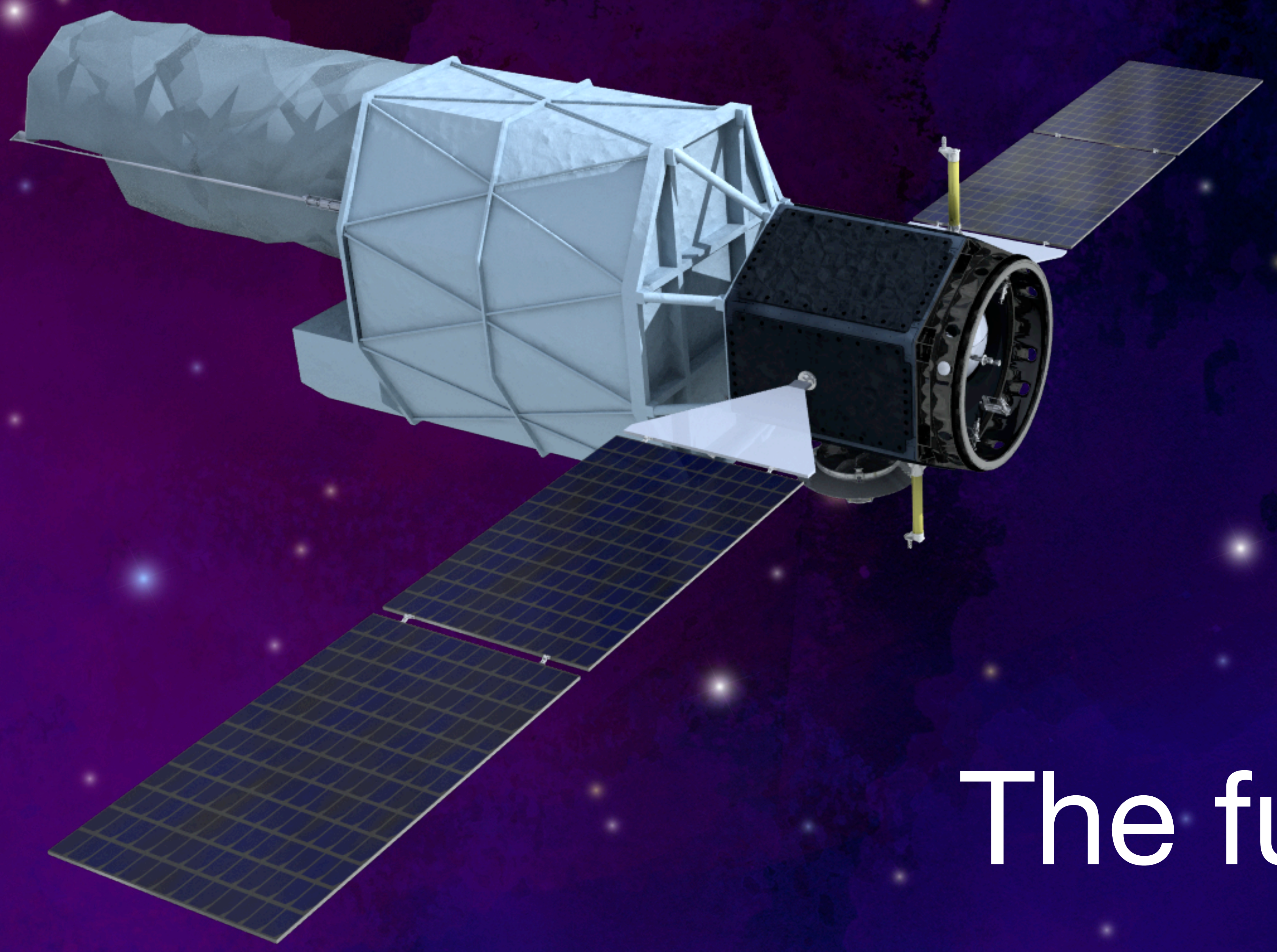


H-poor (IIb) or H-free (Ib) supernovae

Star	$T_{\rm eff}$ [kK]	$\log_{10} g$	$X_{\rm H,surf}$	$X_{\rm He,surf}$	$\log_{10} L_{\rm bol}$ [$L_\odot$]	$R_{\rm eff}$ [$R_\odot$]	$M_{\rm evol}$ [$M_\odot$]
Star 1	92^{+12}_{-4}	$5.0^{+0.1}_{-0.1}$	$0.40^{+0.05}_{-0.10}$	$0.59^{+0.10}_{-0.05}$	$5.09^{+0.13}_{-0.08}$	$1.37^{+0.02}_{-0.12}$	$8.41^{+1.00}_{-0.61}$
Star 2	64^{+28}_{-2}	$5.0^{+0.4}_{-0.3}$	$0.35^{+0.20}_{-0.20}$	$0.64^{+0.20}_{-0.20}$	$4.13^{+0.47}_{-0.08}$	$0.94^{+0.01}_{-0.18}$	$3.33^{+1.82}_{-0.19}$
Star 3	72^{+54}_{-8}	$5.4^{+0.6}_{-0.5}$	$0.10^{+0.25}_{-0.09}$	$0.89^{+0.09}_{-0.25}$	$4.15^{+0.66}_{-0.18}$	$0.77^{+0.04}_{-0.23}$	$3.39^{+3.00}_{-0.44}$
Star 4	68^{+52}_{-12}	$5.1^{+0.6}_{-0.4}$	$0.30^{+0.30}_{-0.20}$	$0.69^{+0.20}_{-0.30}$	$4.00^{+0.67}_{-0.26}$	$0.72^{+0.08}_{-0.22}$	$3.01^{+2.50}_{-0.59}$
Star 5	68^{+18}_{-6}	$4.5^{+0.3}_{-0.2}$	$0.01^{+0.00}_{-0.00}$	$0.98^{+0.00}_{-0.00}$	$4.34^{+0.33}_{-0.17}$	$1.06^{+0.06}_{-0.15}$	$4.06^{+1.45}_{-0.54}$
Star 6	74^{+14}_{-16}	$5.0^{+0.3}_{-0.3}$	$0.35^{+0.20}_{-0.15}$	$0.64^{+0.15}_{-0.20}$	$4.24^{+0.24}_{-0.34}$	$0.80^{+0.09}_{-0.08}$	$3.74^{+0.91}_{-0.94}$
Star 7	62^{+10}_{-8}	$4.8^{+1.2}_{-0.5}$	$0.01^{+0.34}_{-0.00}$	$0.98^{+0.00}_{-0.34}$	$3.95^{+0.23}_{-0.22}$	$0.81^{+0.07}_{-0.08}$	$2.91^{+0.64}_{-0.48}$
Star 8	58^{+24}_{-15}	$5.0^{+1.0}_{-0.7}$	$0.05^{+0.40}_{-0.04}$	$0.94^{+0.04}_{-0.40}$	$3.55^{+0.49}_{-0.41}$	$0.59^{+0.09}_{-0.09}$	$2.14^{+1.00}_{-0.56}$
Star 16	34^{+4}_{-3}	$4.2^{+0.6}_{-0.2}$	$0.35^{+0.25}_{-0.15}$	$0.64^{+0.15}_{-0.25}$	$3.20^{+0.17}_{-0.14}$	$1.15^{+0.09}_{-0.09}$	$1.63^{+0.21}_{-0.16}$
Star 26[a]	52^{+4}_{-6}	$5.7^{+0.3}_{-0.7}$	$0.01^{+0.19}_{-0.00}$	$0.98^{+0.00}_{-0.19}$	$4.14^{+0.11}_{-0.18}$	$1.44^{+0.08}_{-0.05}$	$3.42^{+0.34}_{-0.48}$
Star 26[b]	52^{+4}_{-6}	$5.7^{+0.3}_{-0.7}$	$0.01^{+0.19}_{-0.00}$	$0.98^{+0.00}_{-0.19}$	$2.74^{+0.10}_{-0.17}$	$0.29^{+0.02}_{-0.01}$	$1.17^{+0.08}_{-0.14}$

There are stripped stars sufficiently massive to explode ($M_{\rm init}$ > 8 $M_\odot$, $M_{\rm He}$ > 2.5 $M_\odot$)

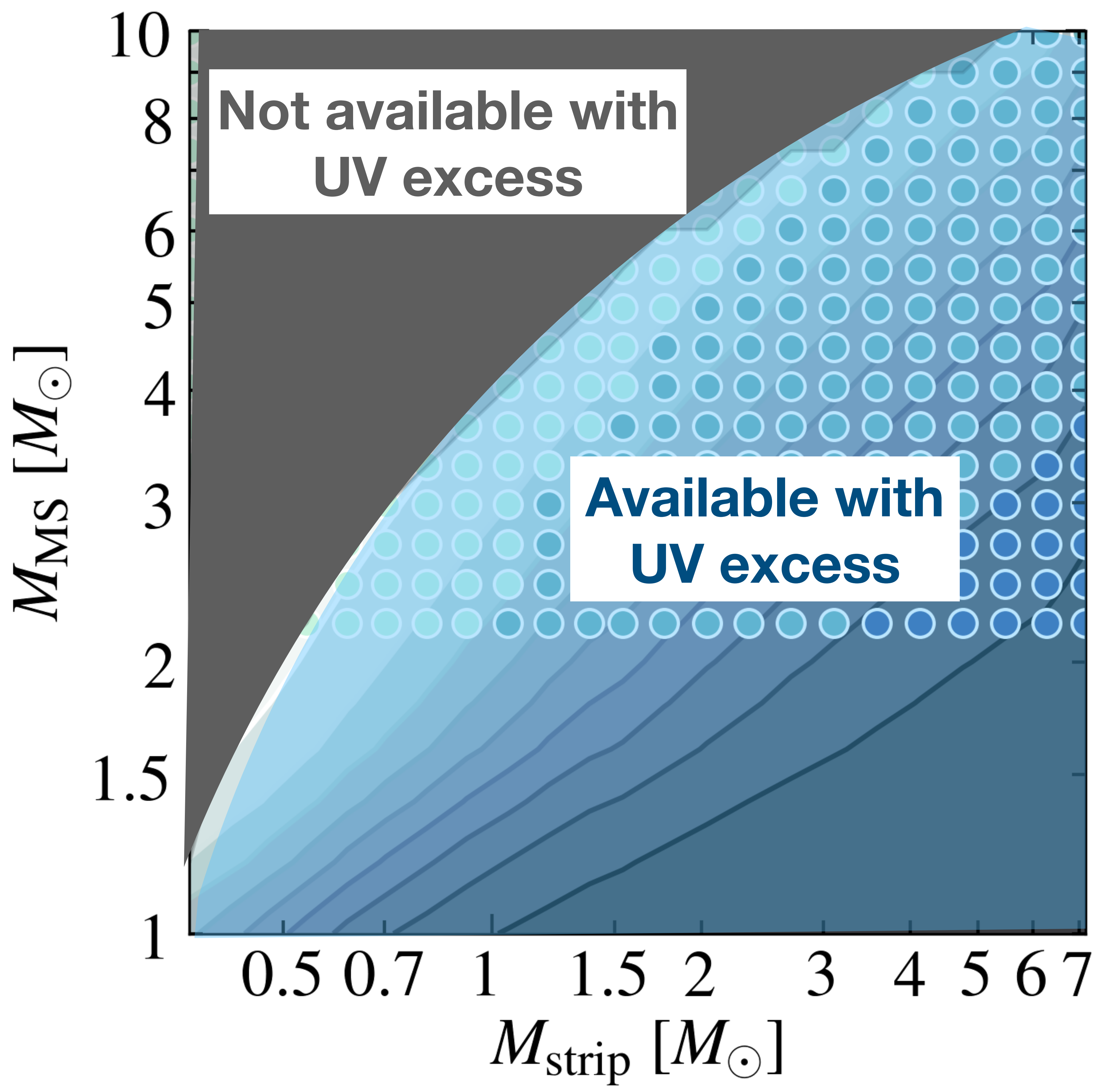
Stellar properties: *Götberg et al., under review*

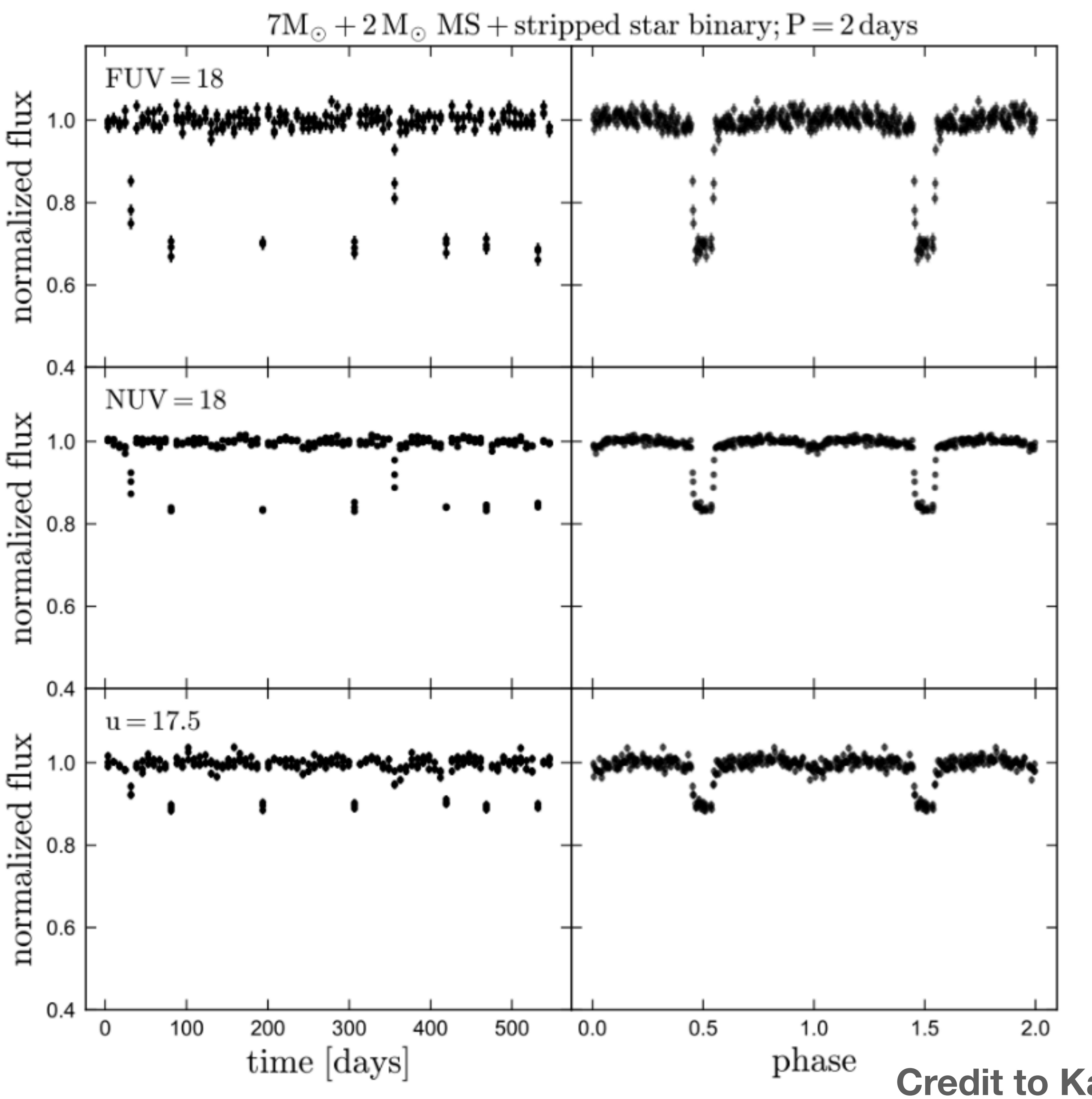


The future with **UVEX**

Eclipsing binaries

Stripped star binaries with higher mass companions detectable using eclipses!

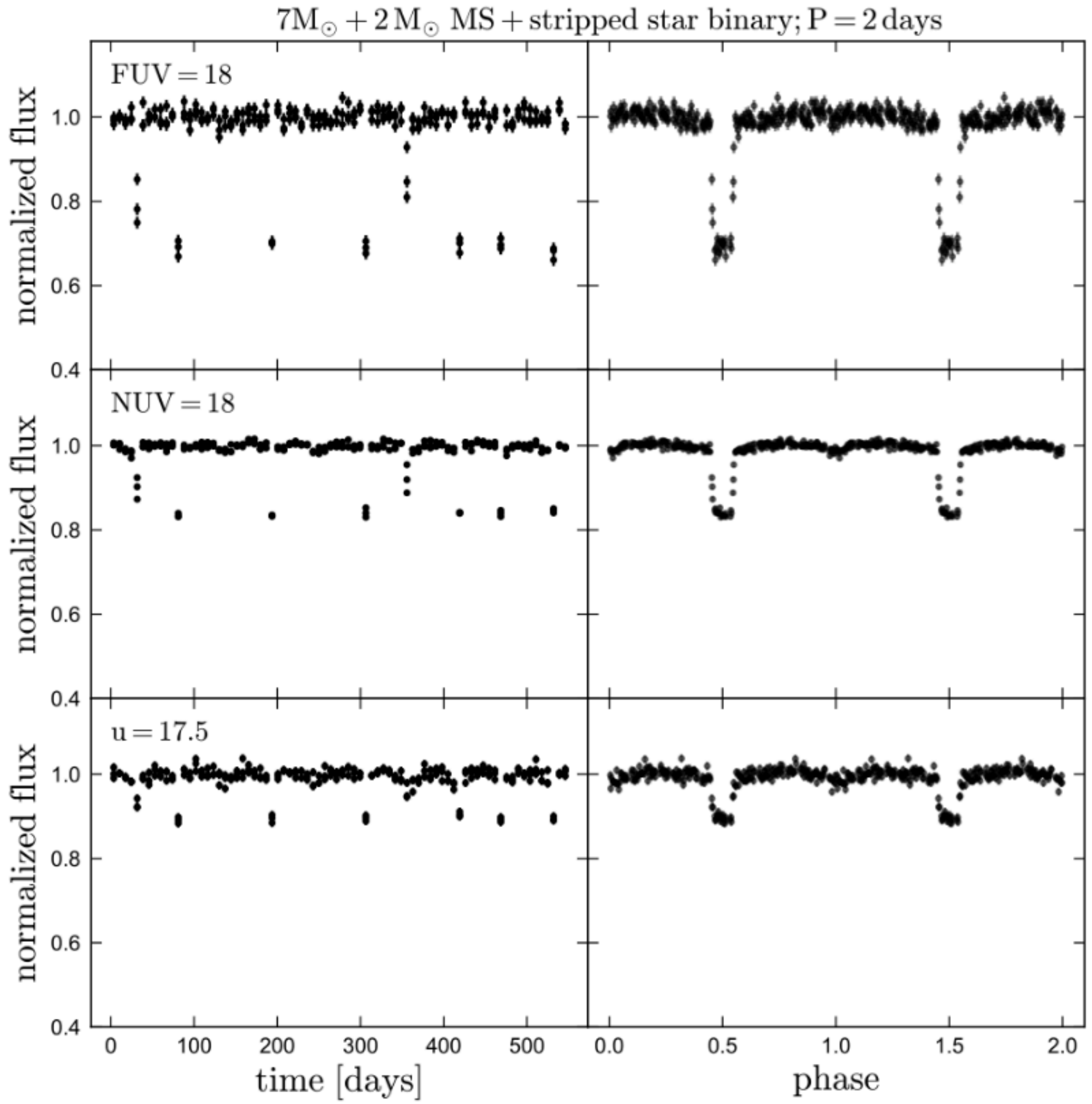


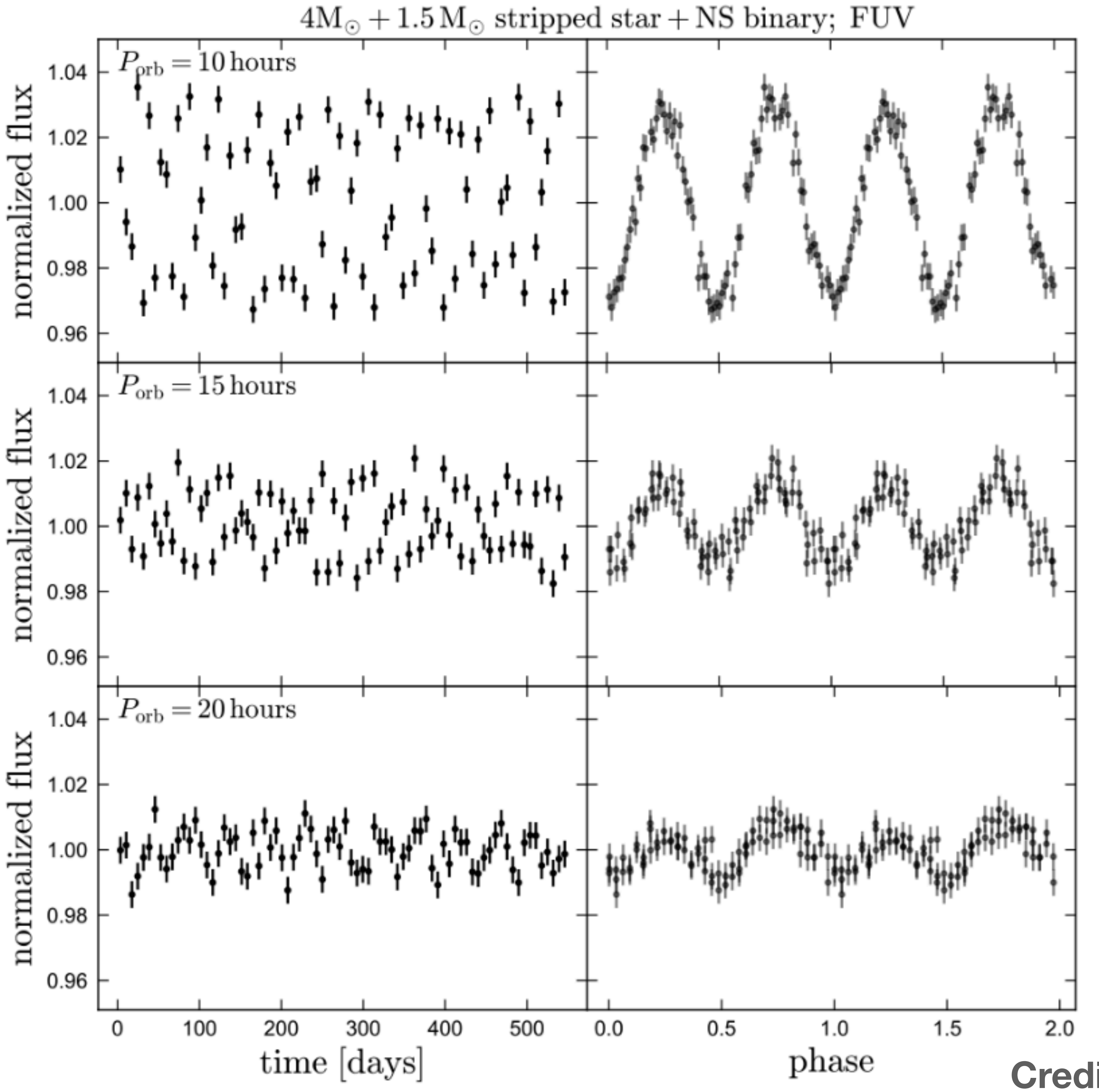


Credit to Kareem El-Badry

Eclipsing binaries

Neutron star companions recognizable with ellipsoidal variations and Doppler beaming.





Credit to Kareem El-Badry

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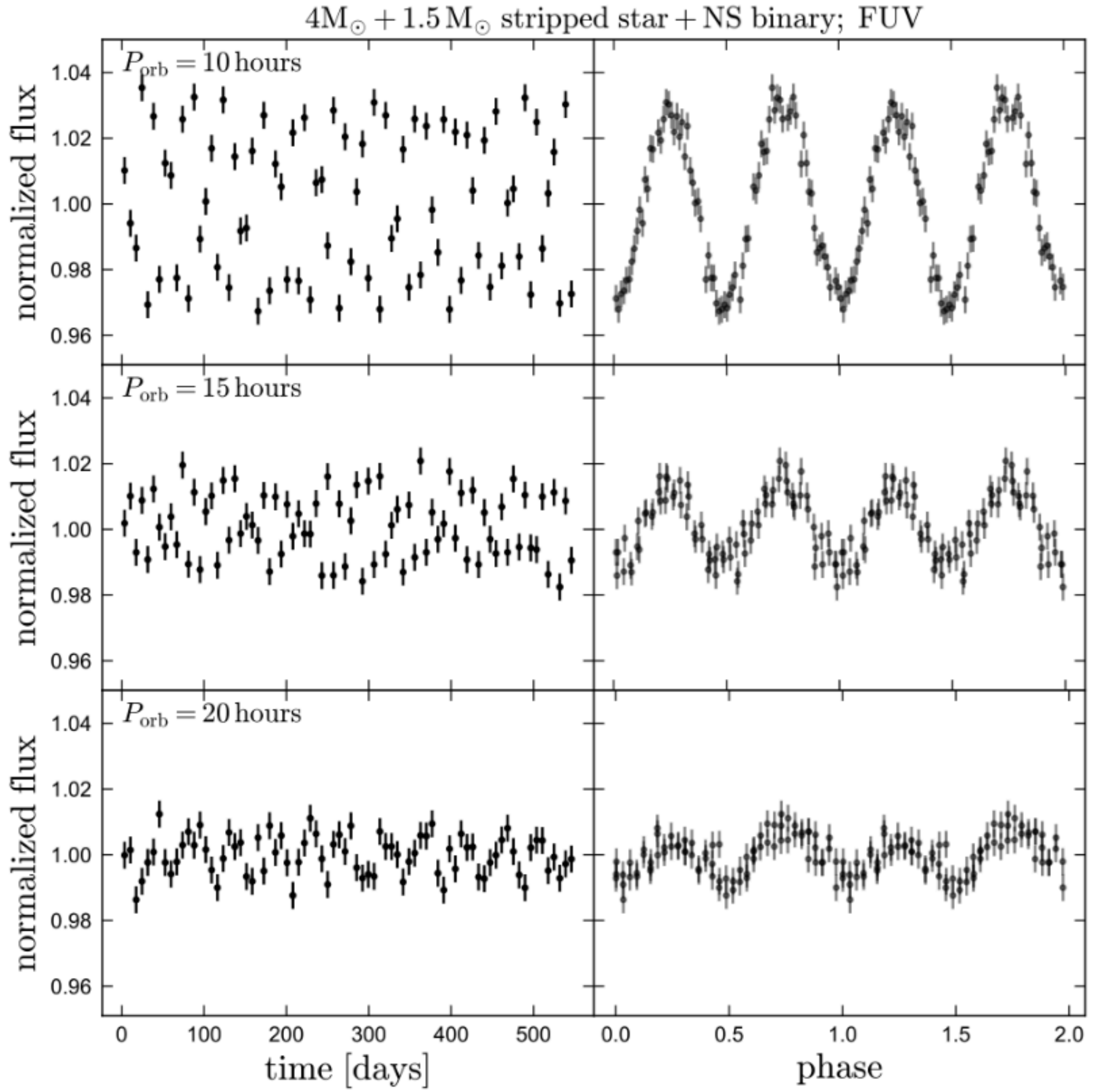
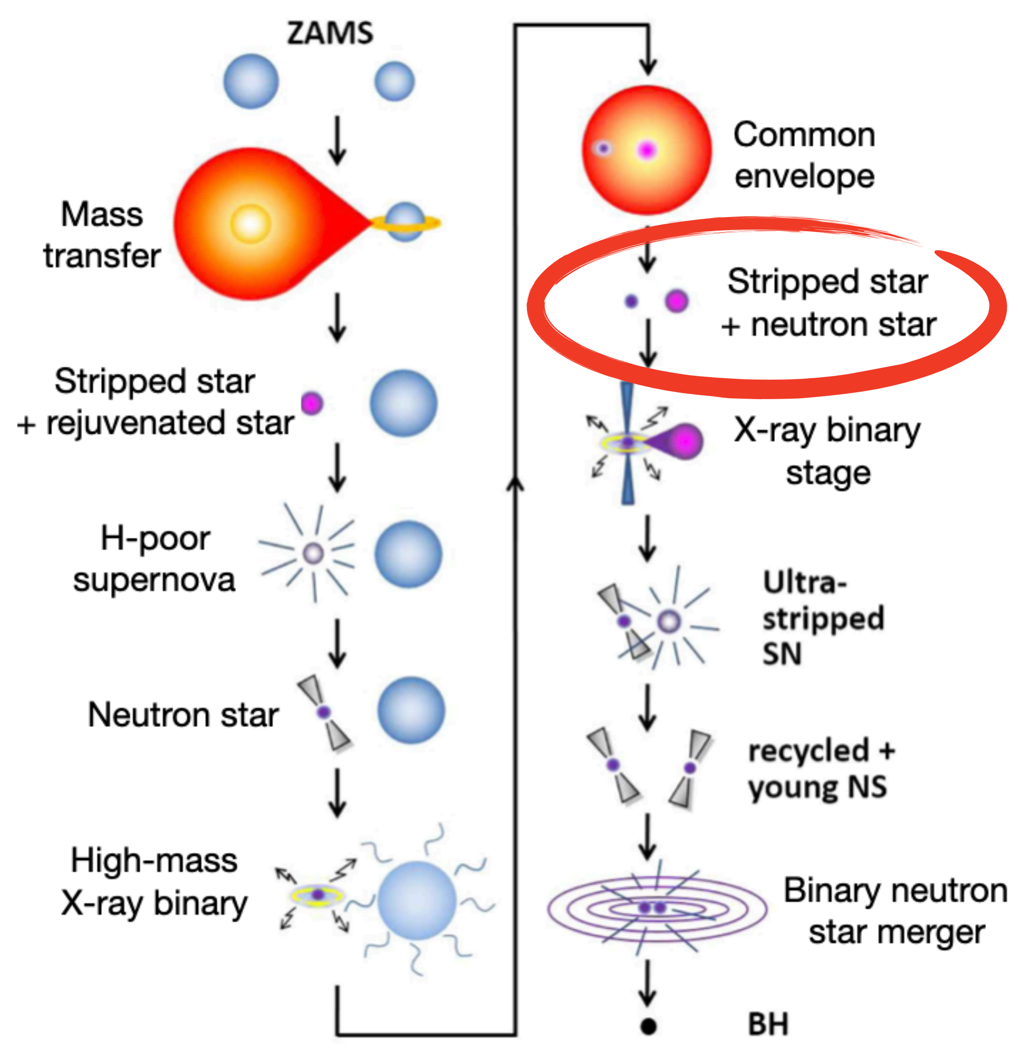
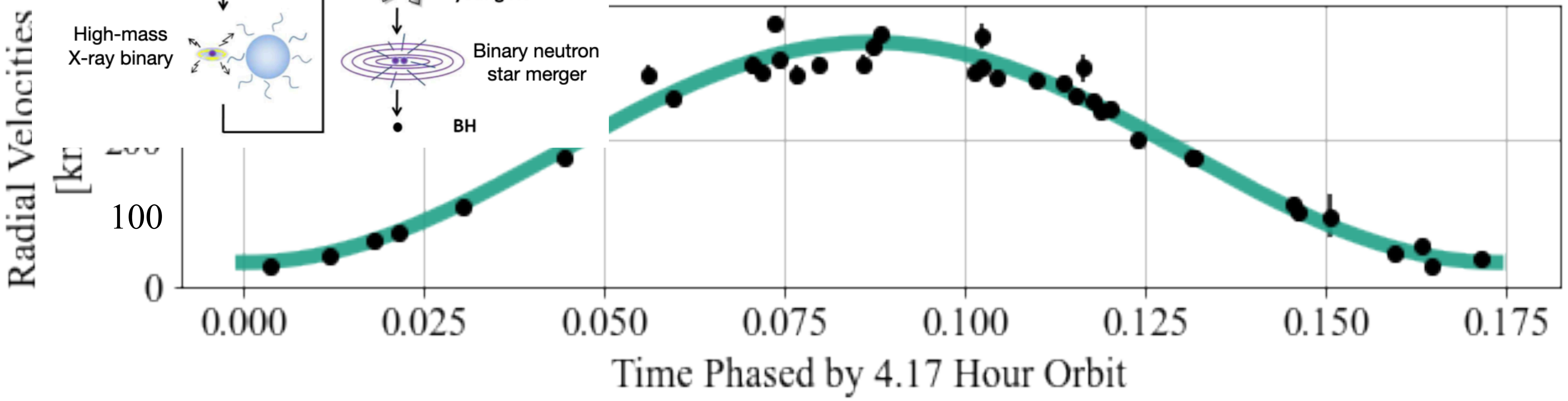


Credit to Kareem El-Badry

A ~4 M$_\odot$ stripped star orbiting a ~1 M$_\odot$ compact object every 4.2 hours (Ludwig, Götberg et al. in prep.)

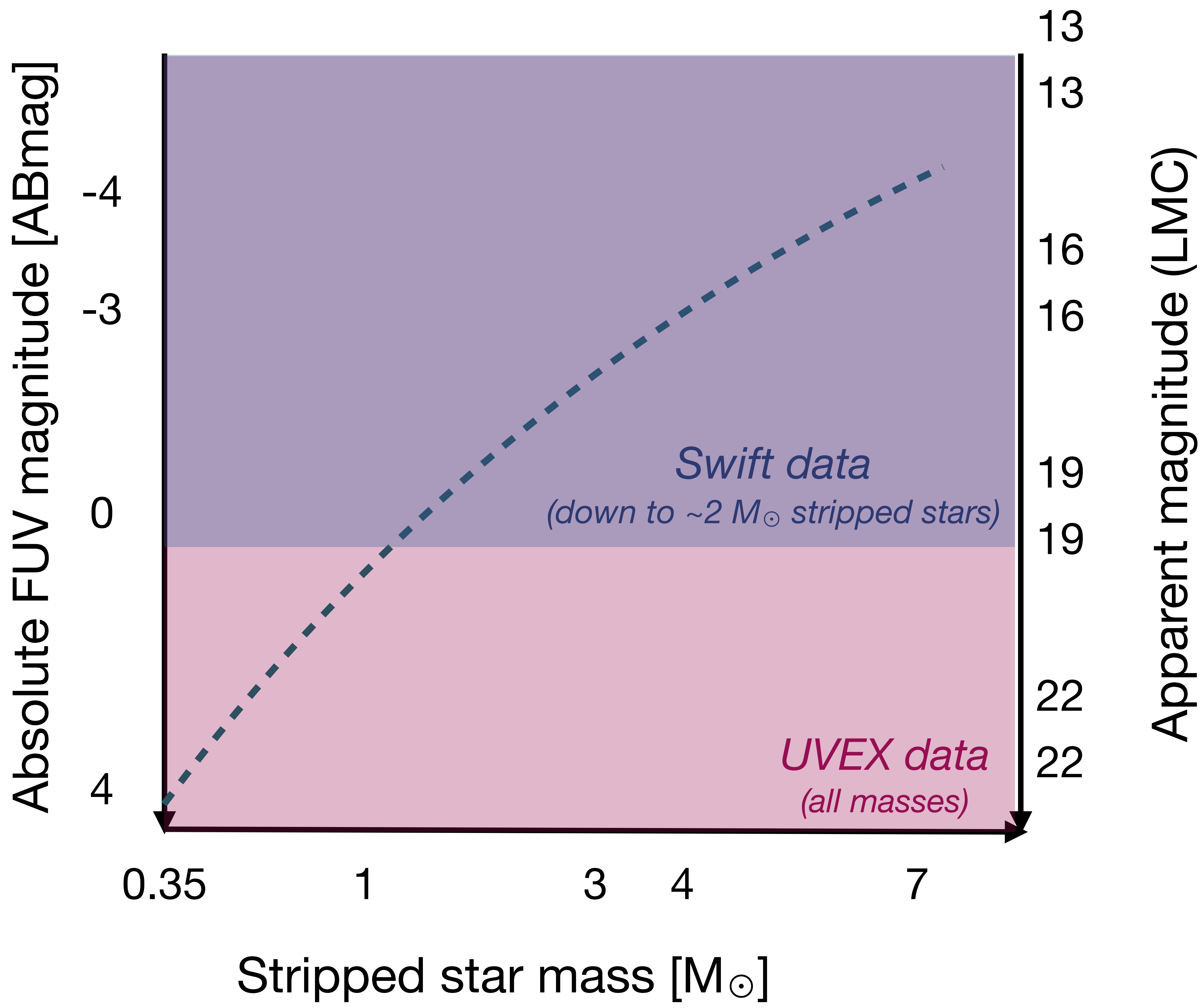




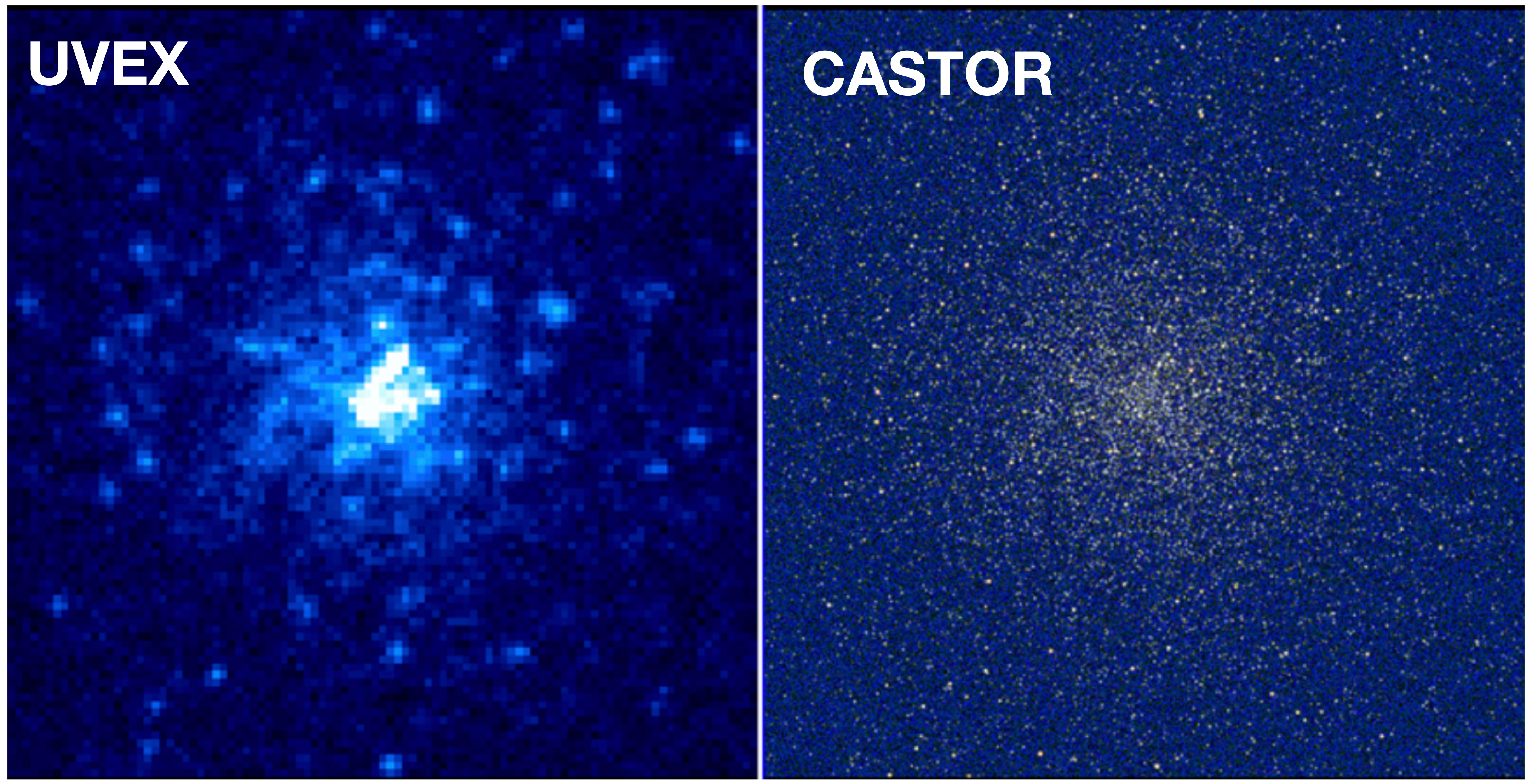
LISA GW source if Galactic!
(cf. Götberg+20b)

Bethany Ludwig
(PhD, U Toronto)

Deeper imaging

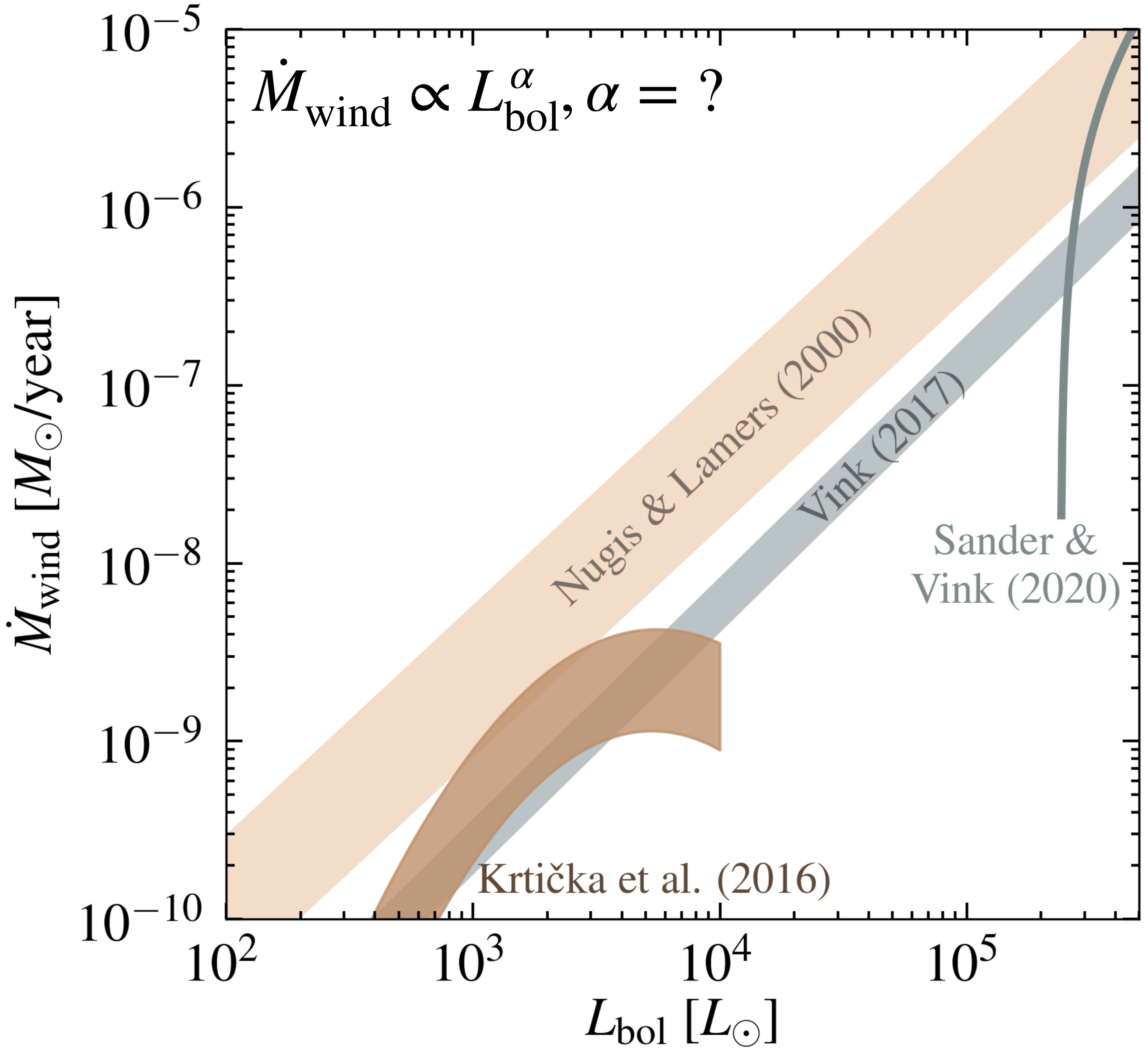


Synergy with CASTOR in crowded regions



Understanding wind mass loss from hot, helium-rich stars

Order-of-magnitude increase in UV spectra!
~100 stripped stars & ~1000 OB stars



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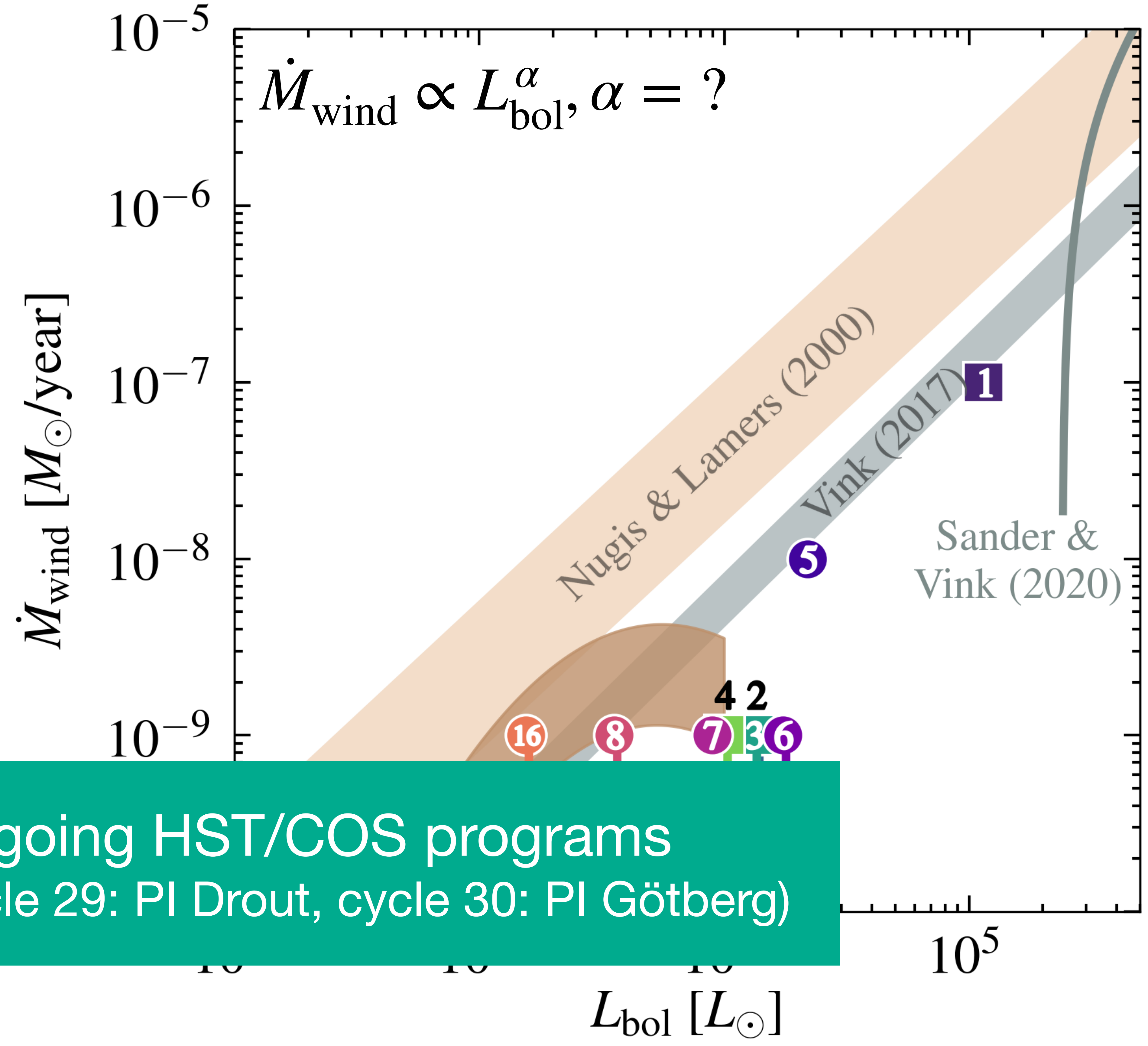
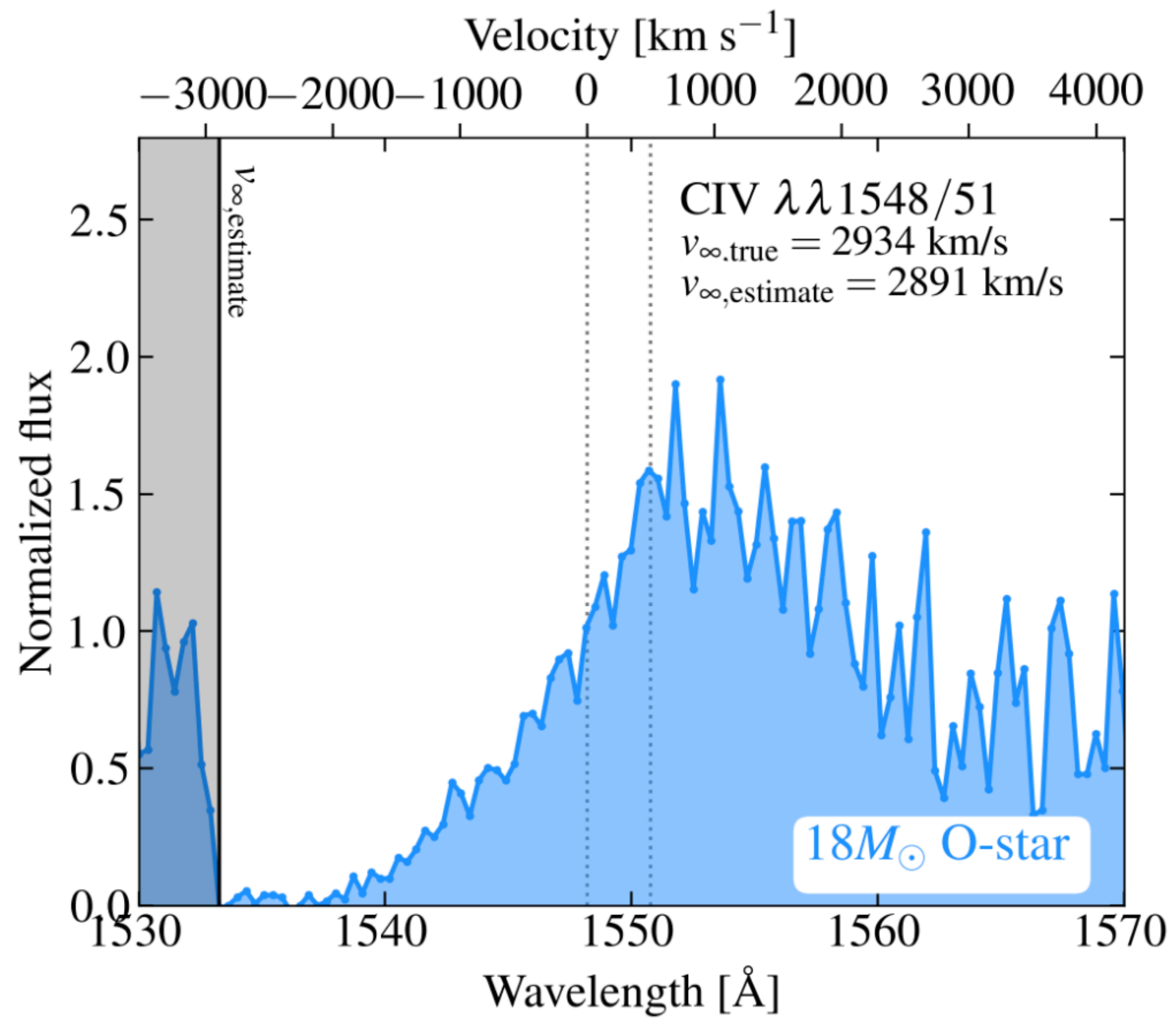
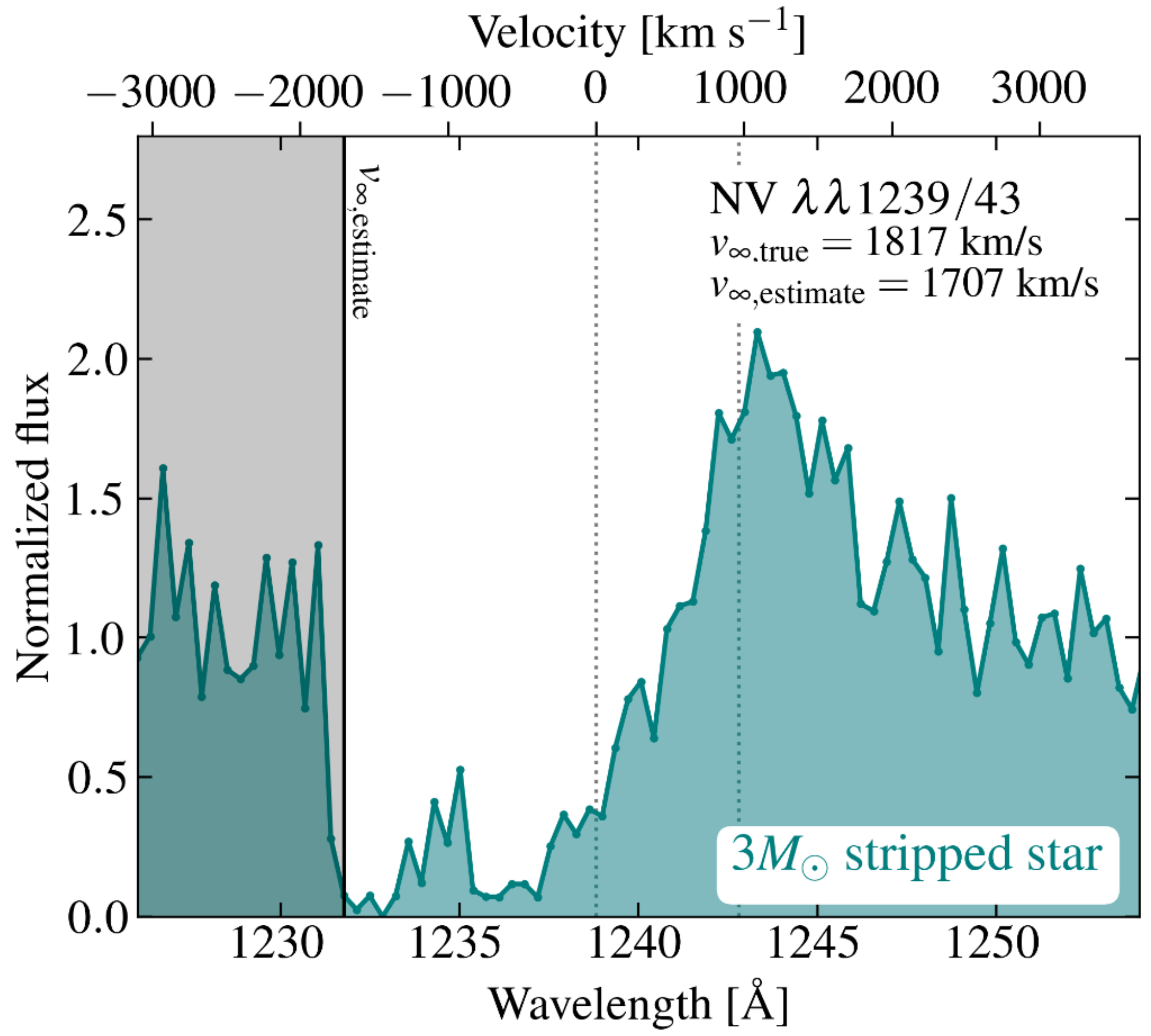


Ongoing HST/COS programs
(cycle 29: PI Drout, cycle 30: PI Götberg)





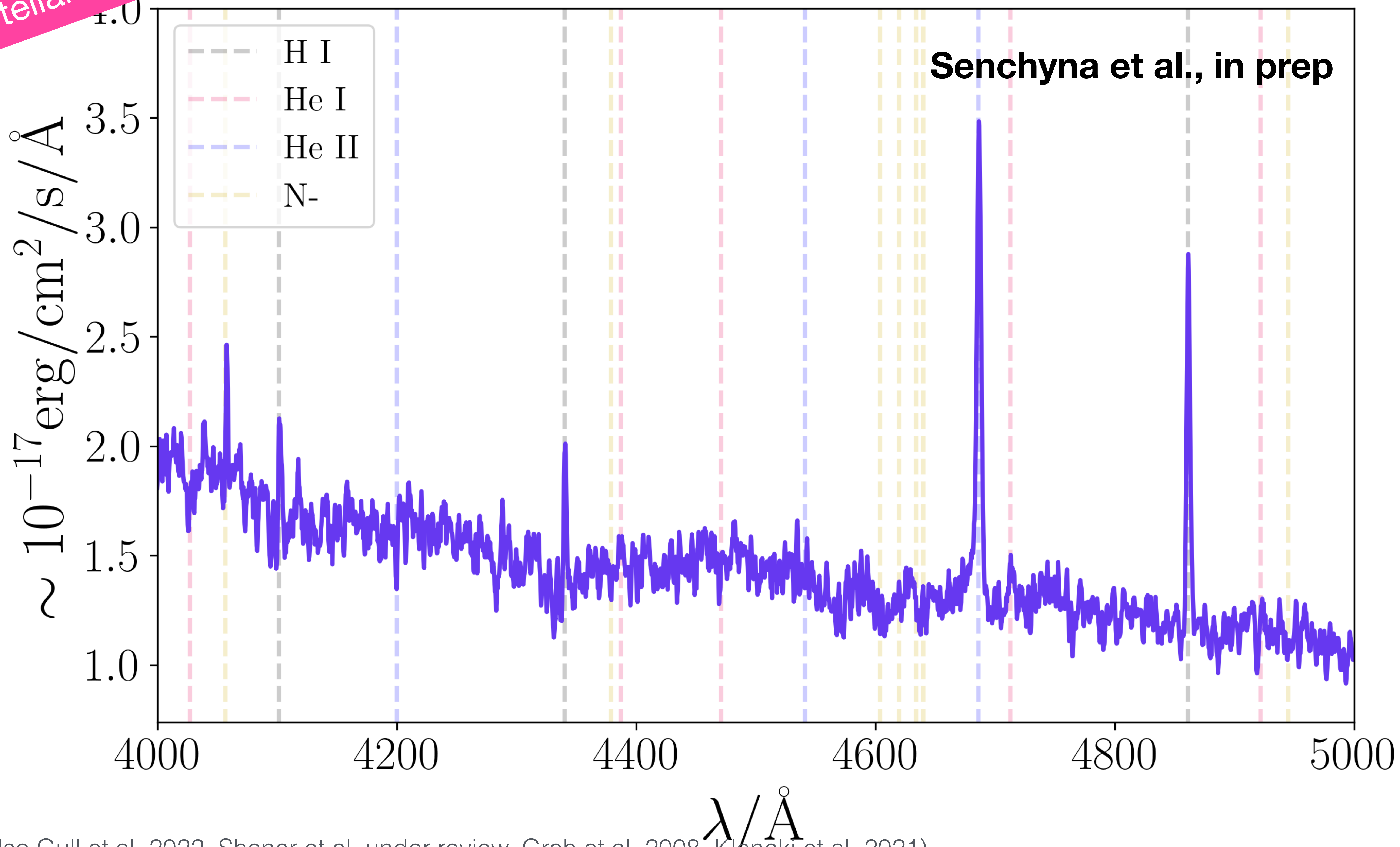
Summary: Hot stars

- Understanding hot stars is important for understanding ionizing radiation, supernovae and gravitational waves
- UV is a necessary wavelength range for tracing binary products, stellar winds, stellar properties…
- UV imaging is useful for distinguishing different types of hot stars, and for variability of hot stars (eclipsing binaries)
- UV spectroscopy is important for stellar winds, surface composition, stellar properties…
- UVEX will access: 1) the whole mass range of stripped stars, 2) stripped stars with higher mass companions, 3) understanding wind mass loss from hot stars

Backup

Peculiar hot star found in Leo A

Stellar exotica



- Emission line star found in $0.1Z_\odot$ galaxy Leo A
- Must be hot: CIV, HeII, NIV…
- Outflow extremely slow: ~400 km/s
- Brightness similar to XXX
- Motion of ~100 km/s detected

(see also Gull et al. 2022, Shenar et al. under review, Groh et al. 2008, Klencki et al. 2021)