TOSCA, Siena
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Winds from very massive stars

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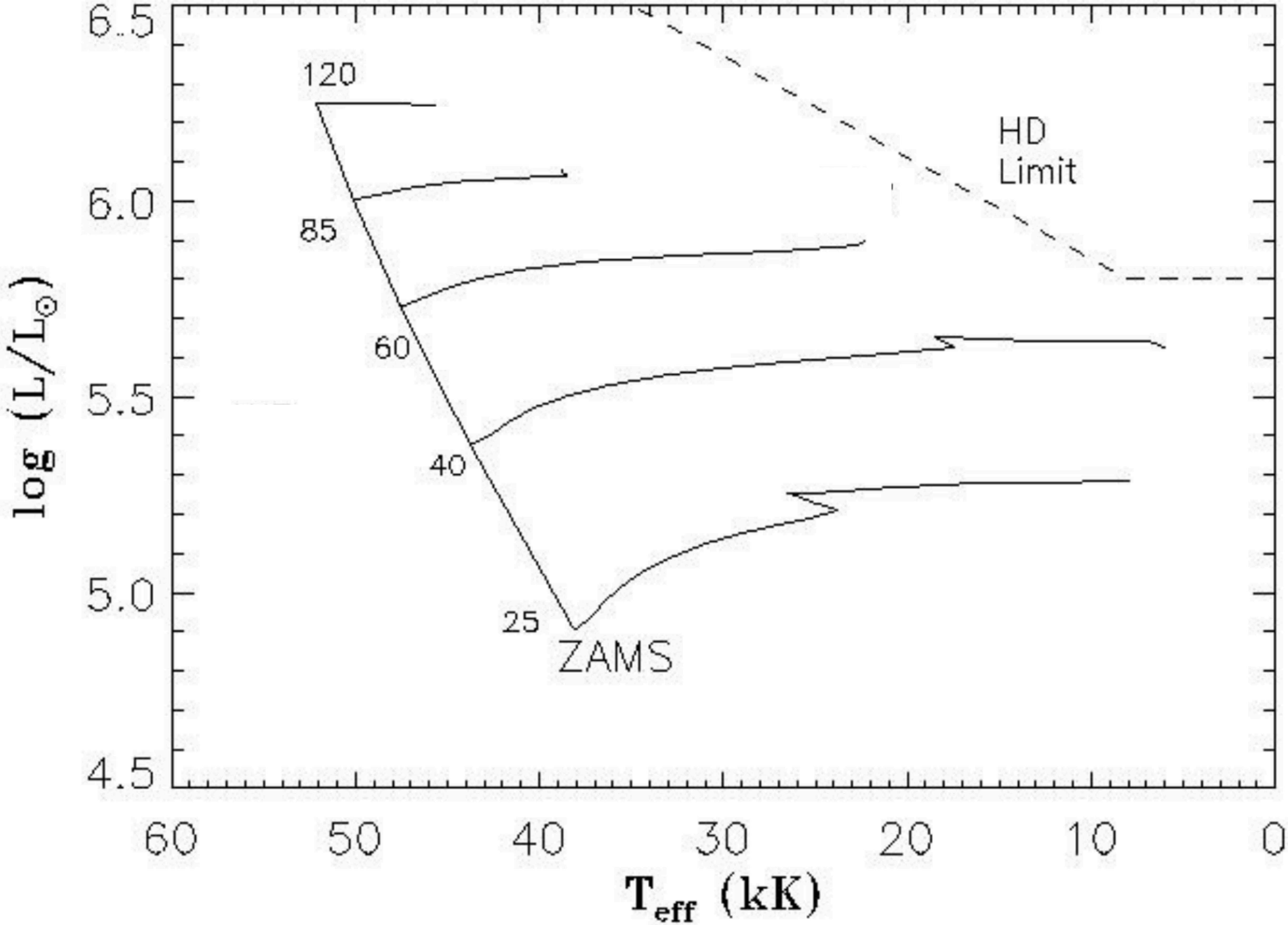
Definition:

- Very massive stars can be defined as stars born with initial mass $\sim 100 - 1000\ M_\odot$

Where would we expect VMSs in the HR Diagram?



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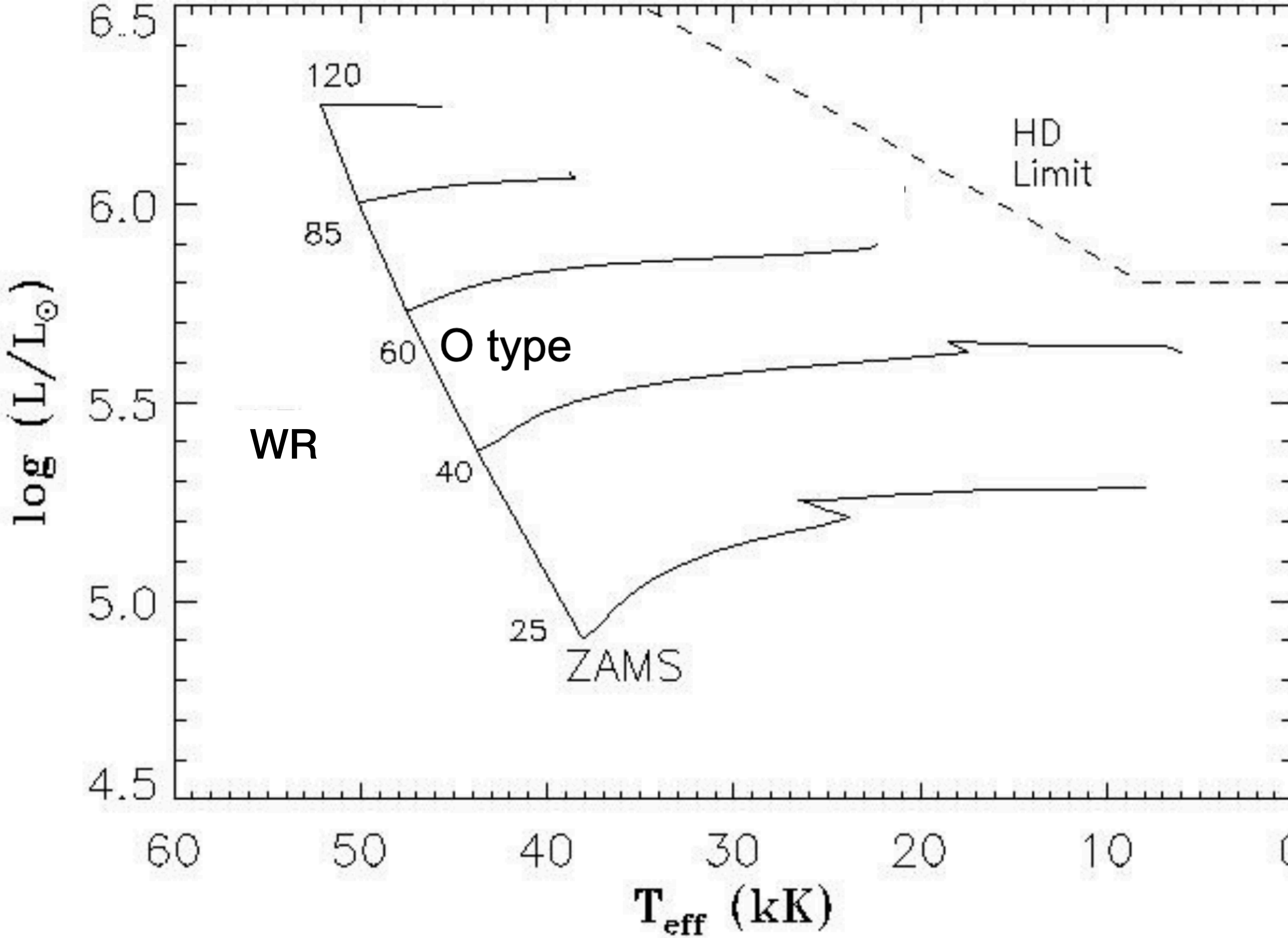

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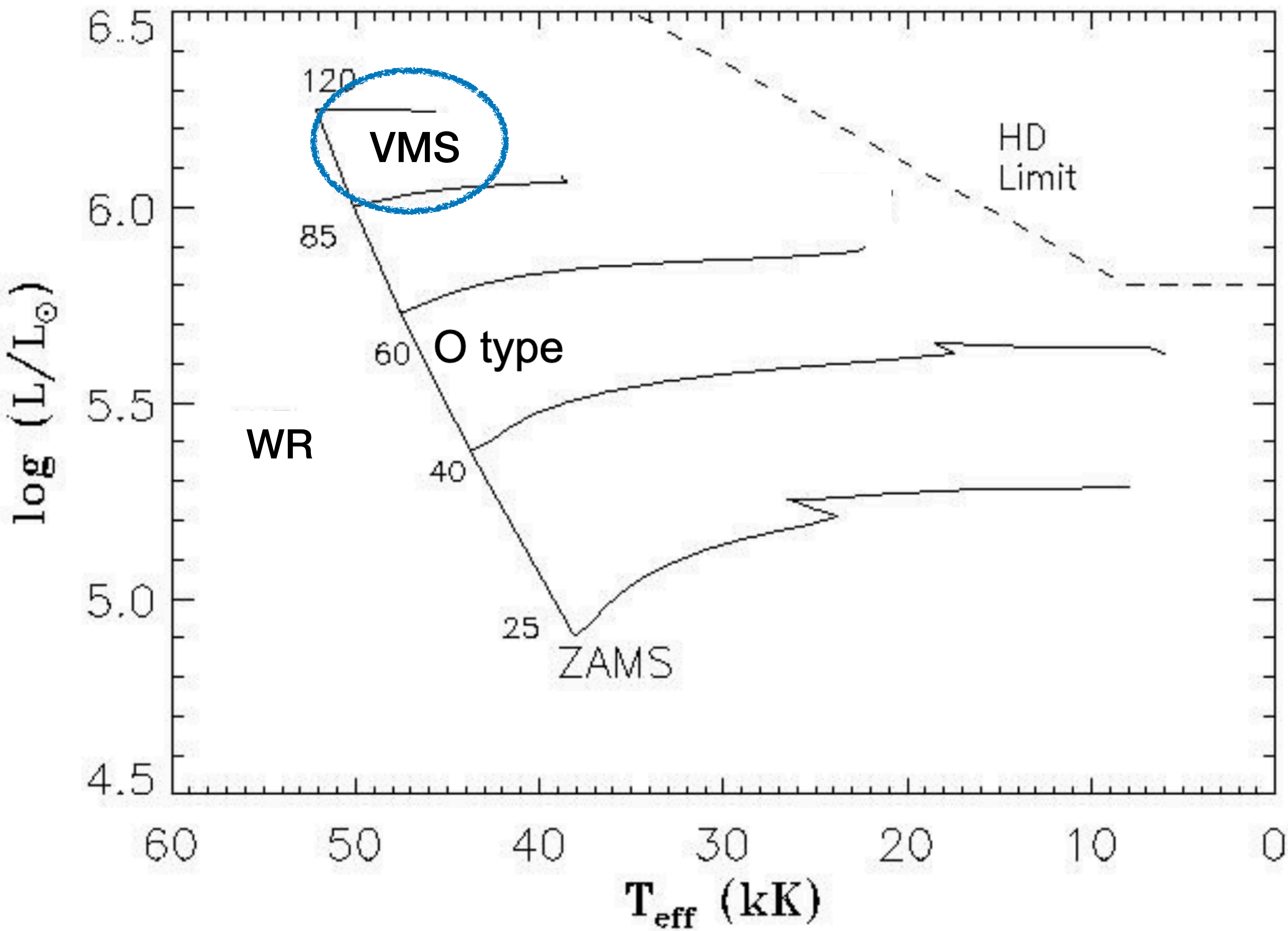
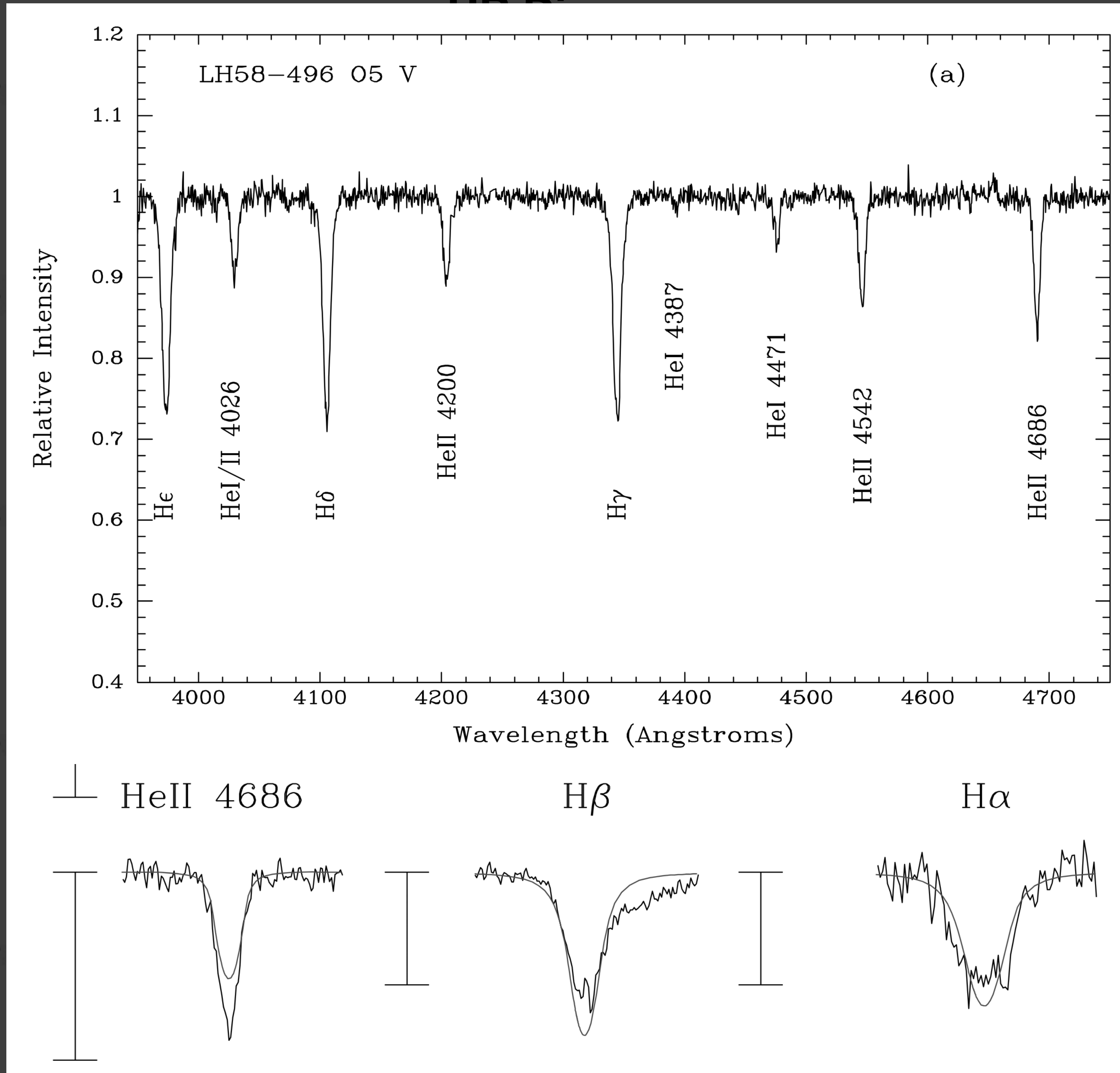
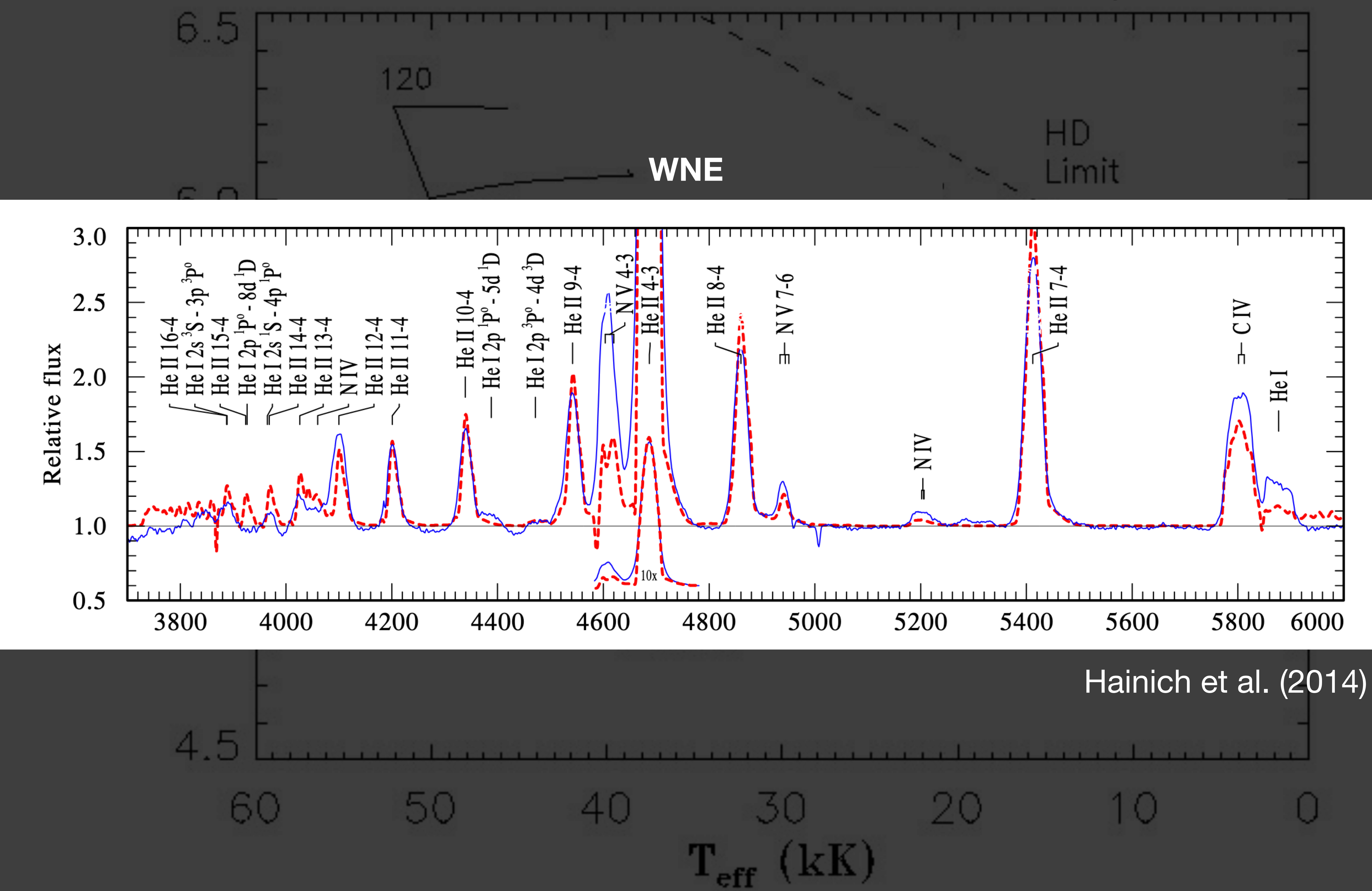


O5 V



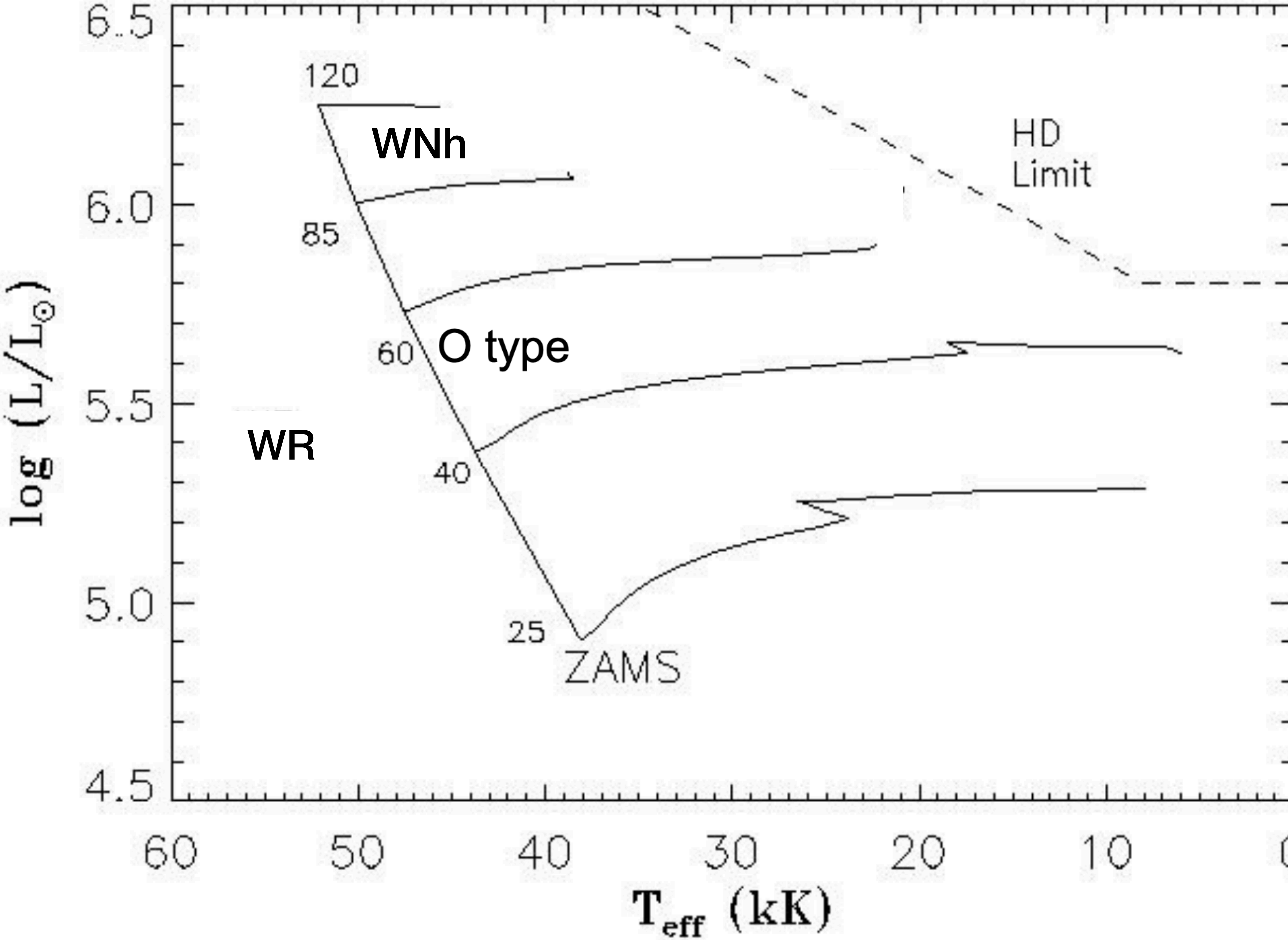
Massey et al. (2005)

Where would we expect VMSs in the HR Diagram?



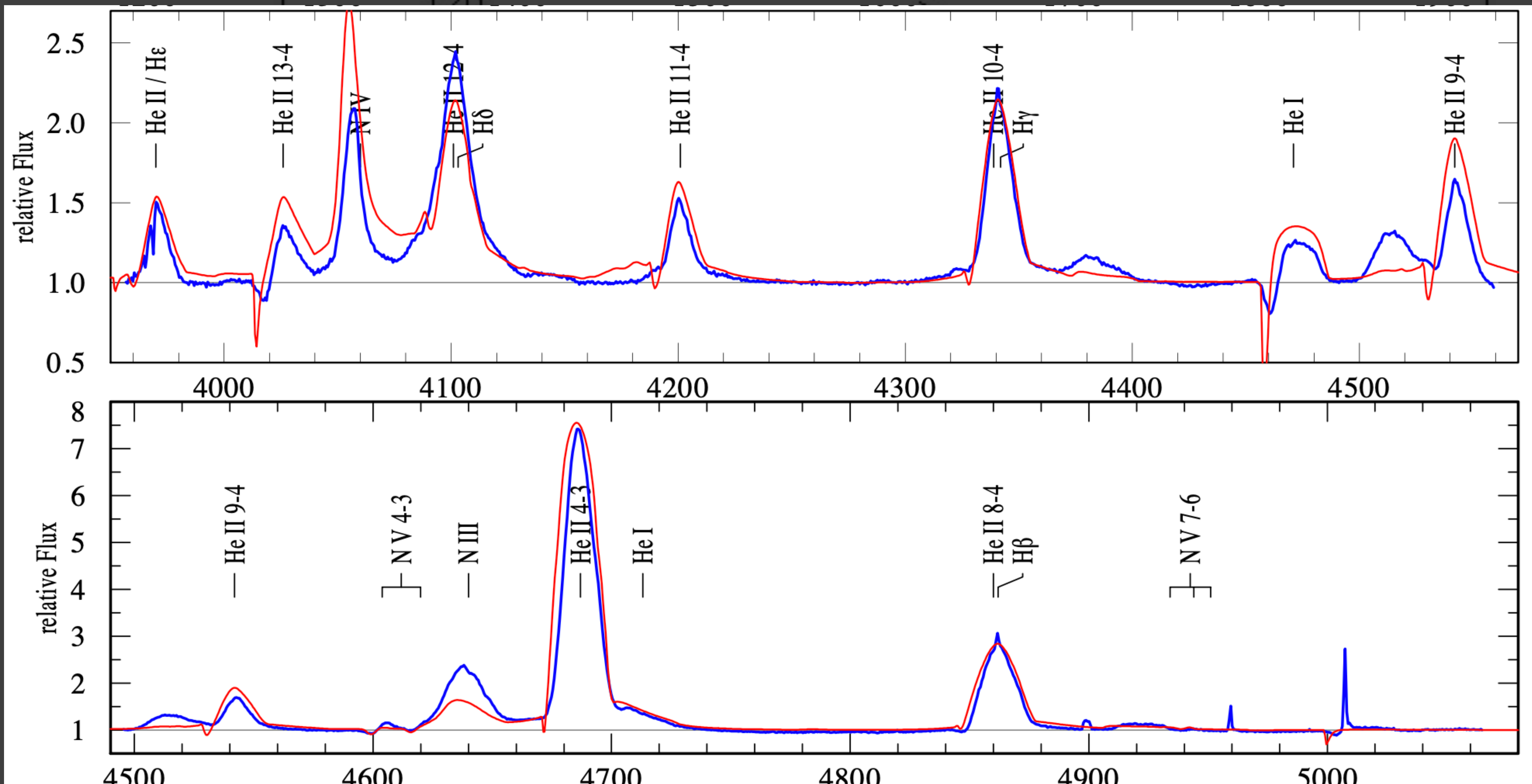
Hainich et al. (2014)

Where would we expect VMSs in the HR Diagram?



HR Diagram

WN7h

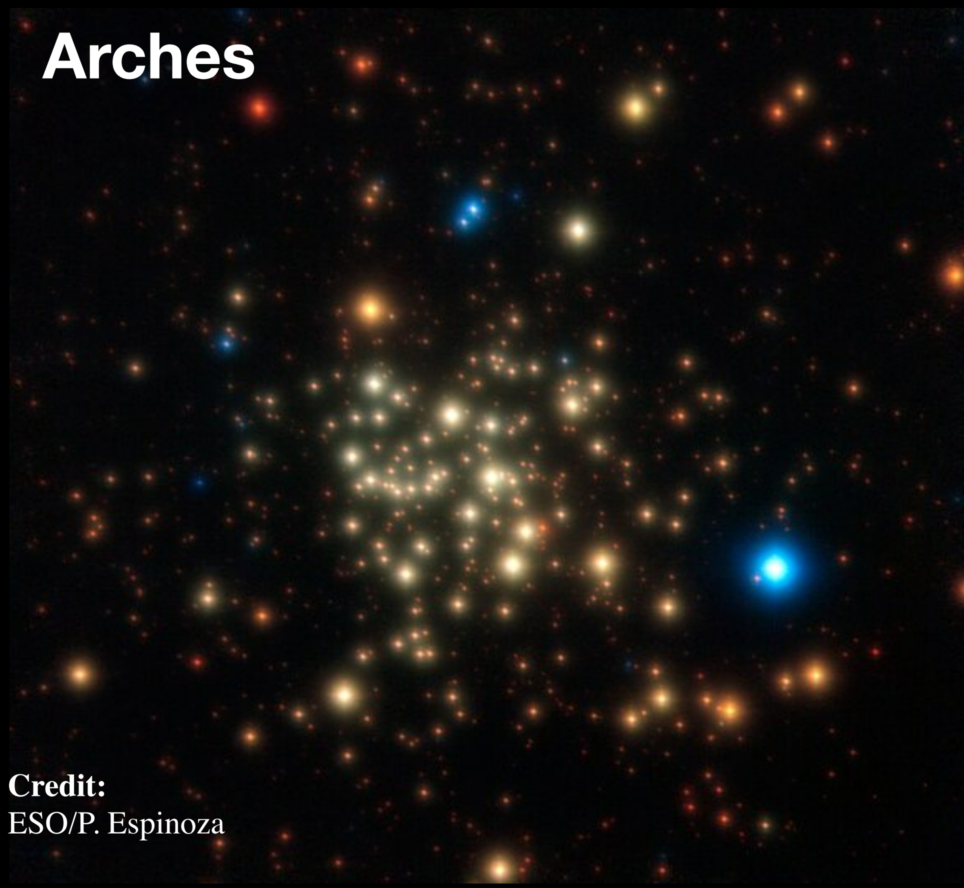


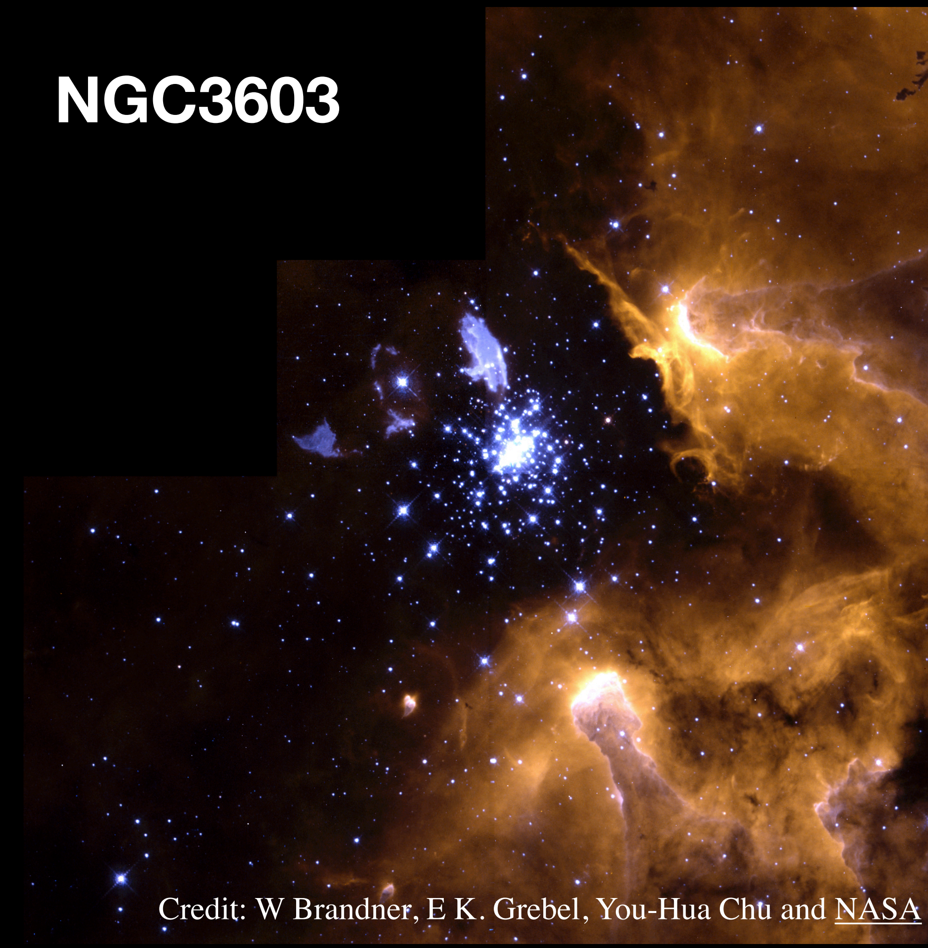
VFTS 108, Bestenlehner et al. (2014)

Existence of VMSs:

- Very massive stars can be defined as stars born with initial mass $100 - 1000\ M_{\odot}$
- Found in young, massive clusters. Top heavy IMF was found in 30 Dor with empirical evidence for stars up to $250\,M_{\odot}$

Existence of VMSs:





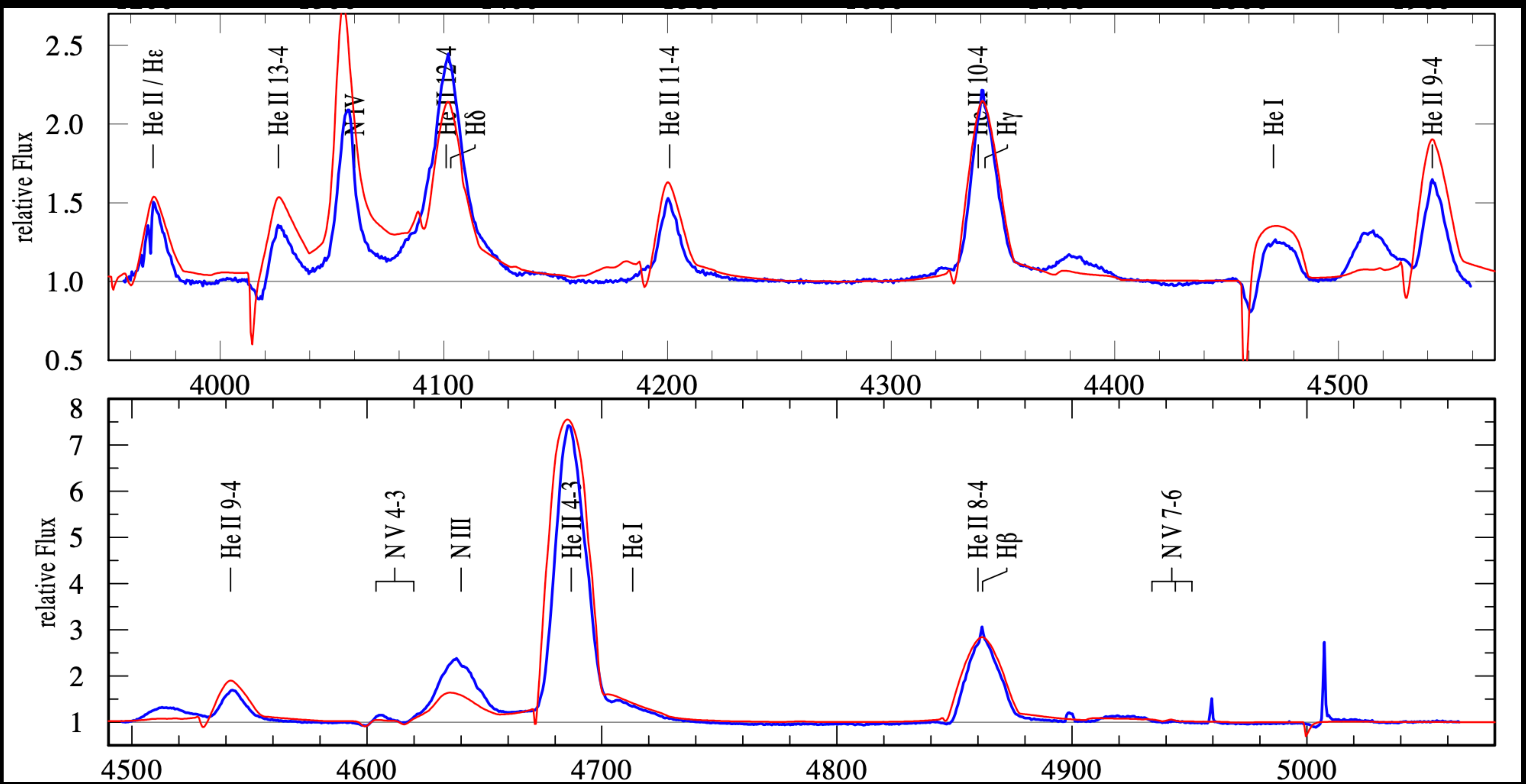
First gen?

Spectral properties of VMSs:

WR spectra - strong emission lines indicative of strong winds

N lines - H-burning products near the surface

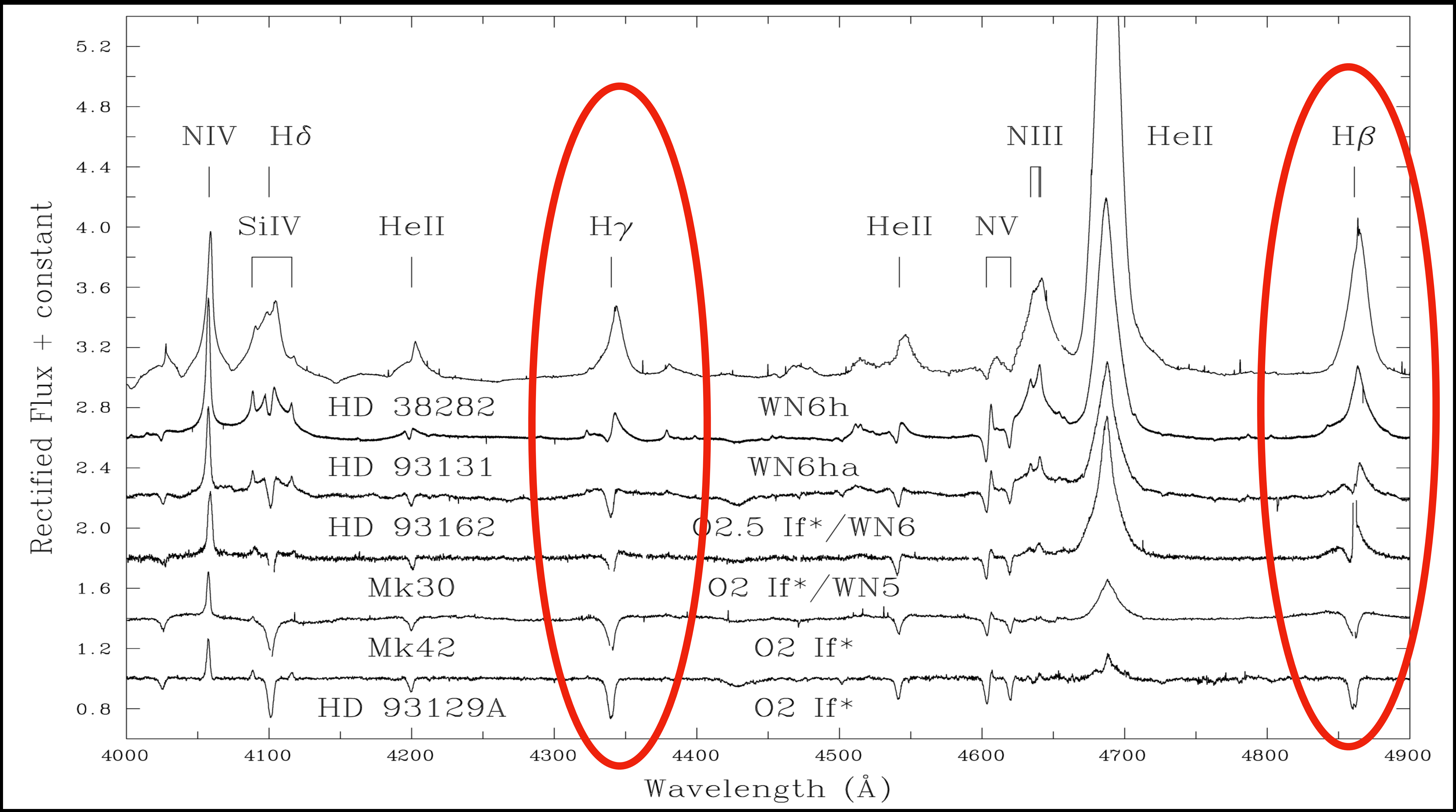
Hydrogen lines - envelope is not fully stripped



VFTS 108, Bestenlehner et al. (2014)

Spectral properties of VMSs:

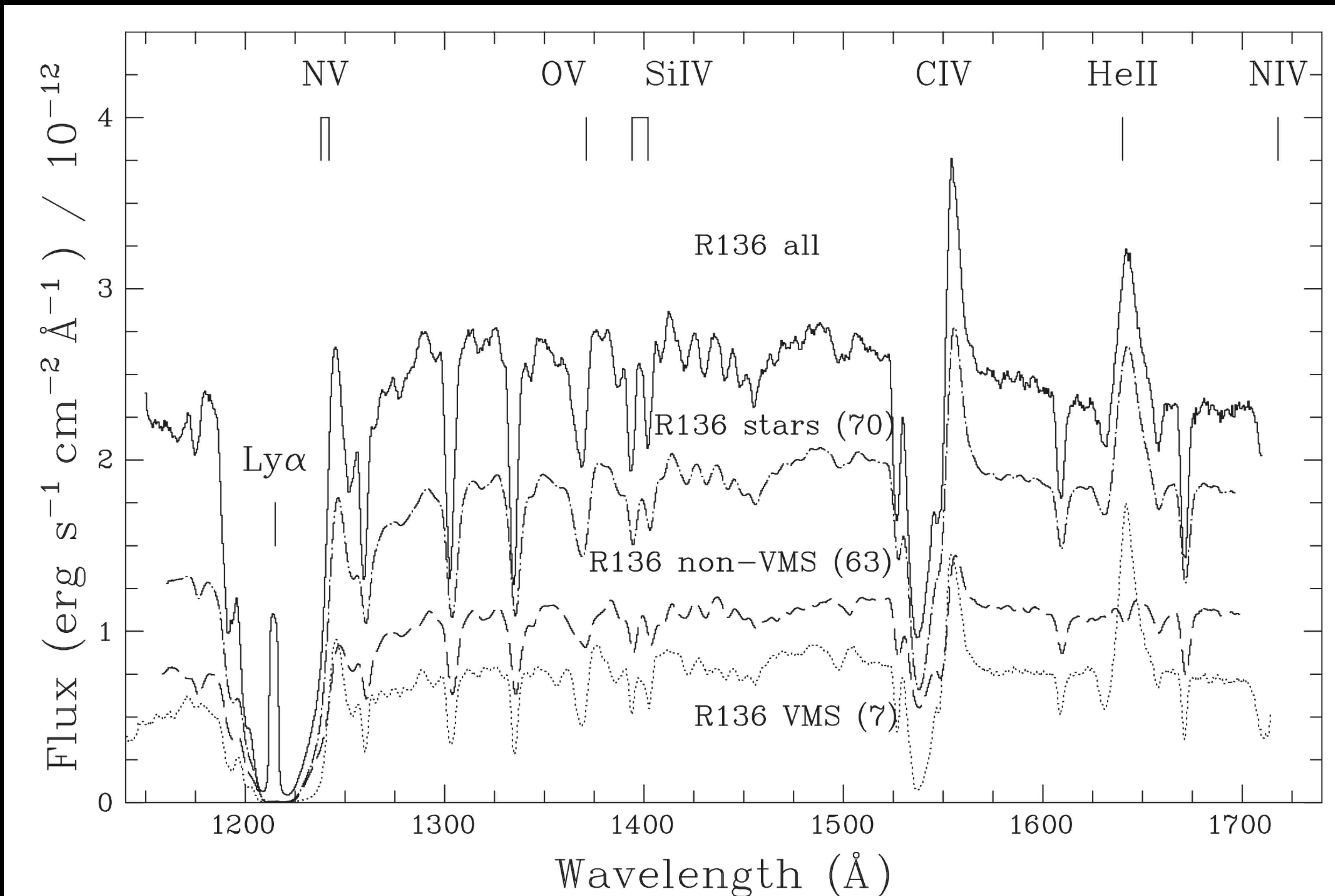
Forms a continuation of the spectral sequence above O stars



Crowther & Walborn (2011)

Spectral properties of VMSs:

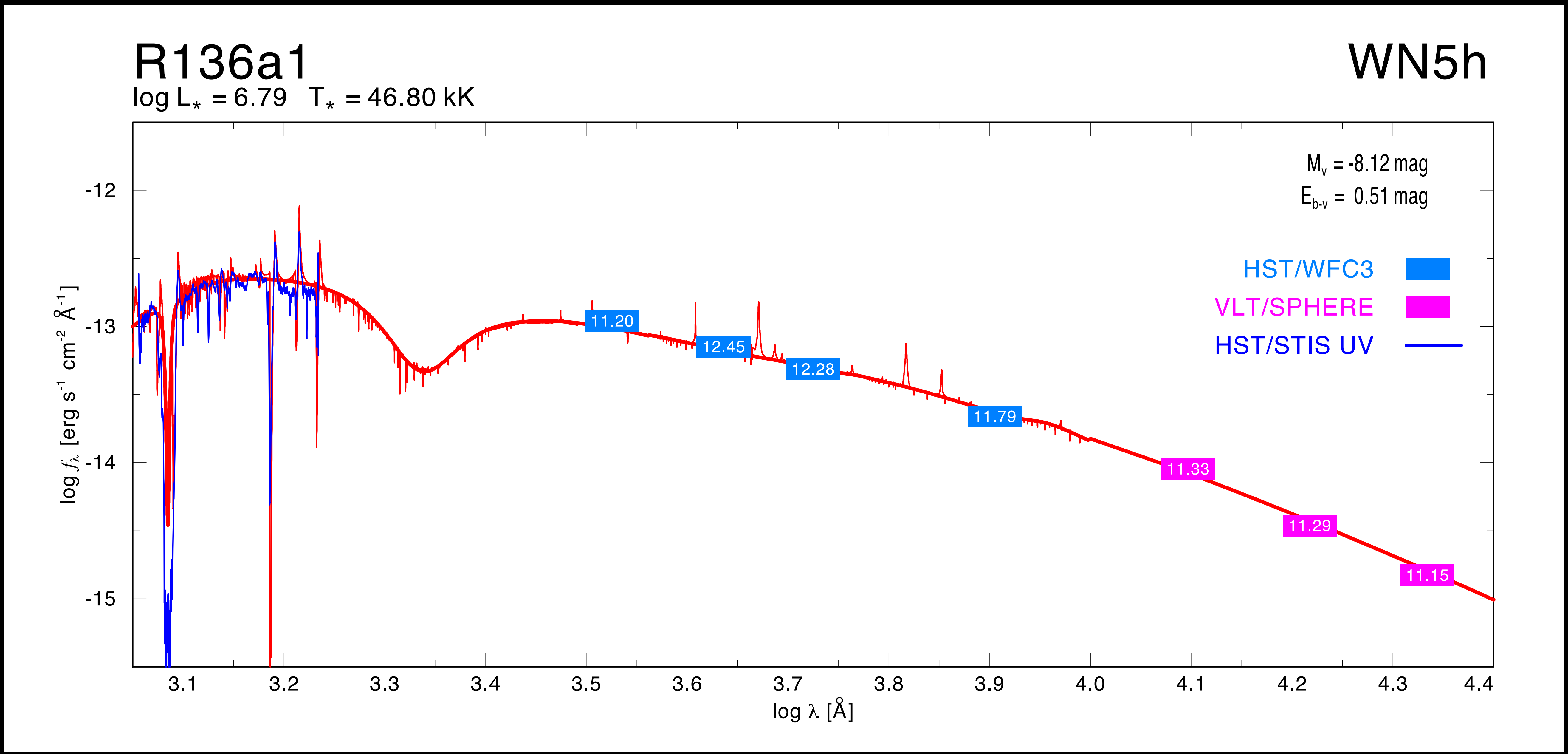
Unlikely to be resolved into a bunch of O stars



Crowther et al. (2016)

Luminosities and temperatures of VMSs:

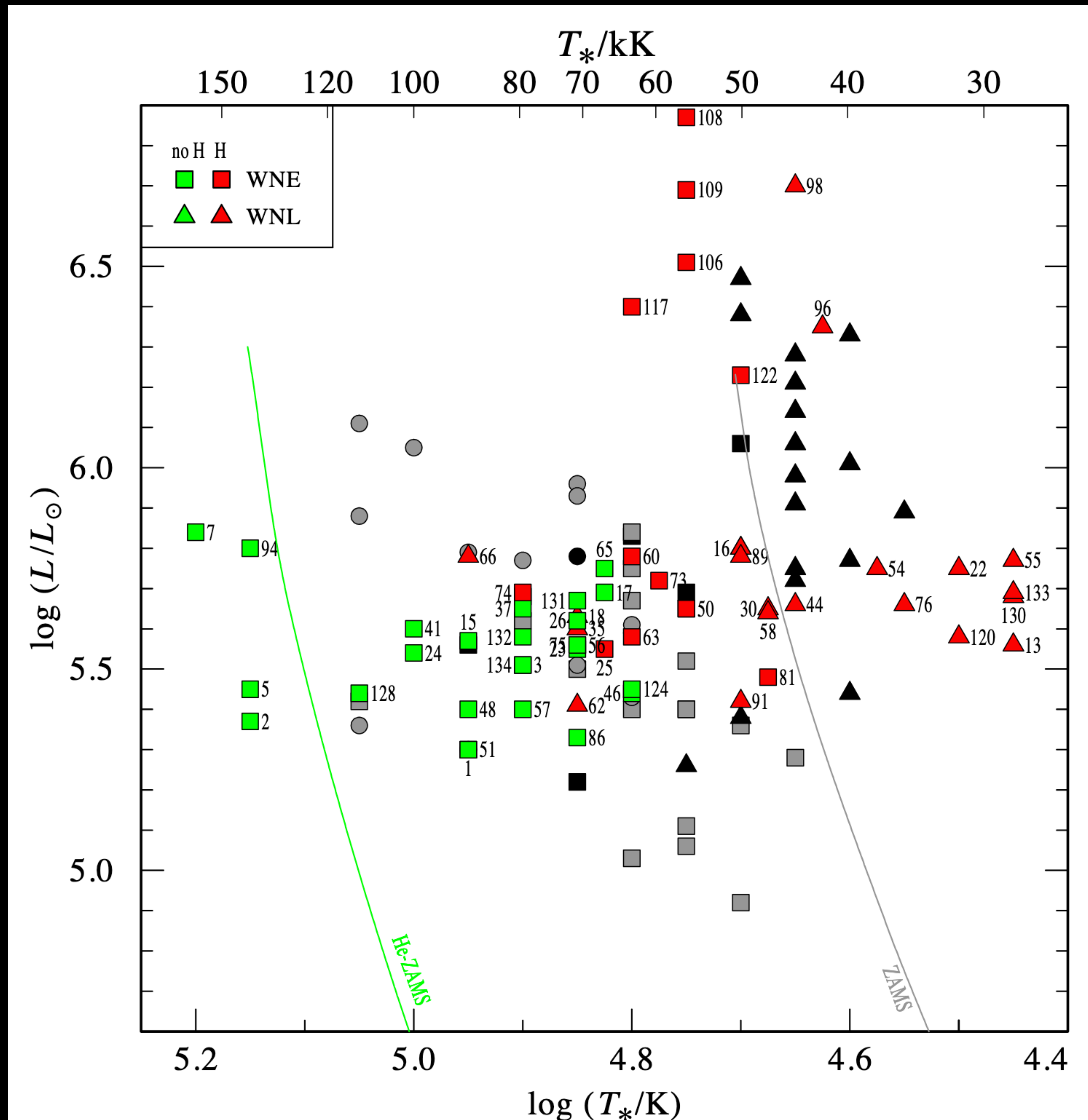
Very luminous - typical luminosities in excess of $10^6 L_\odot$



de Marchi et al. (2011)

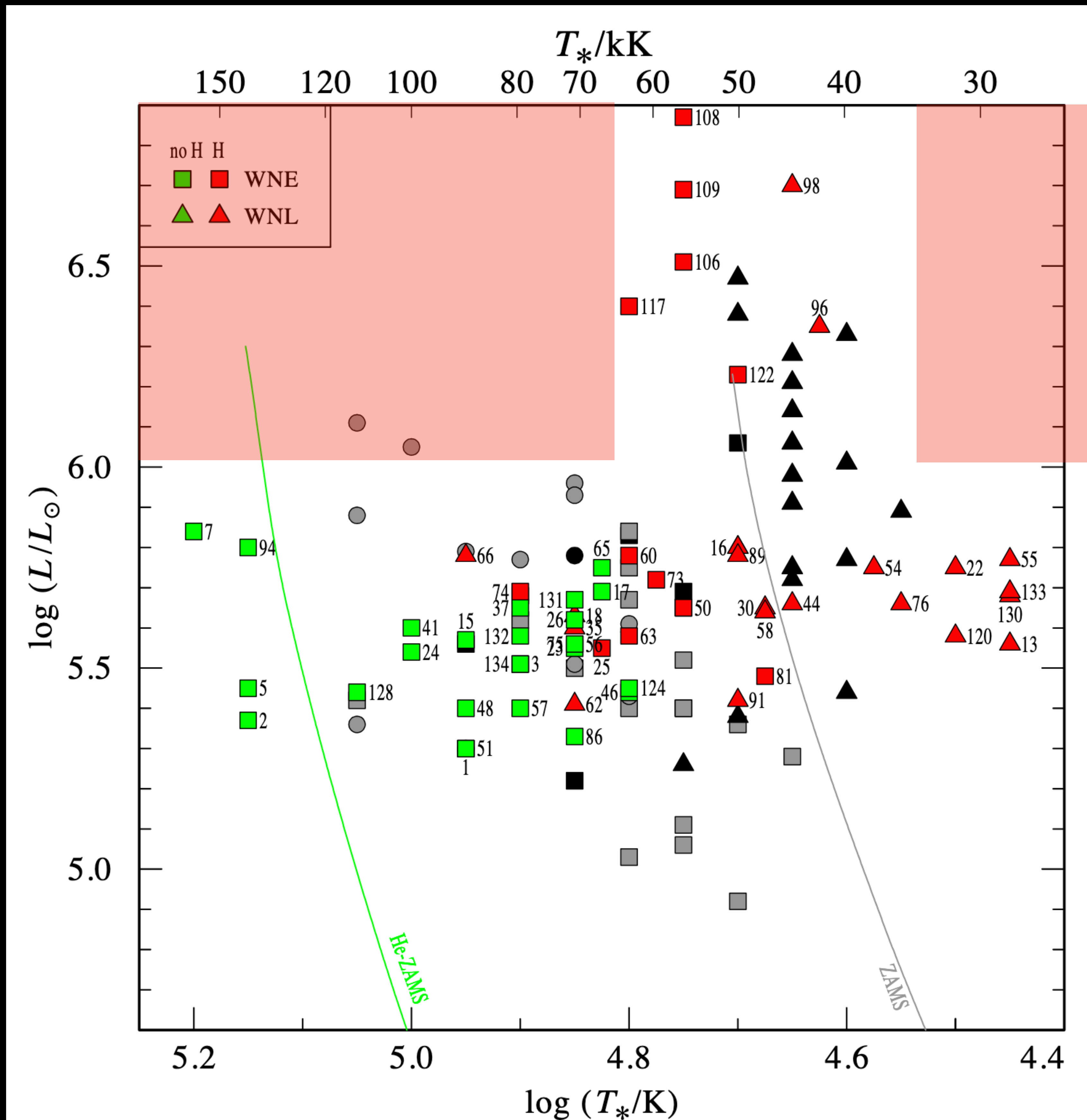
Crowther et al. (2016)

Luminosities and temperatures of VMSs:



Hainich et al. (2014)
Hamann et al. (2019)

Luminosities and temperatures of VMSs:



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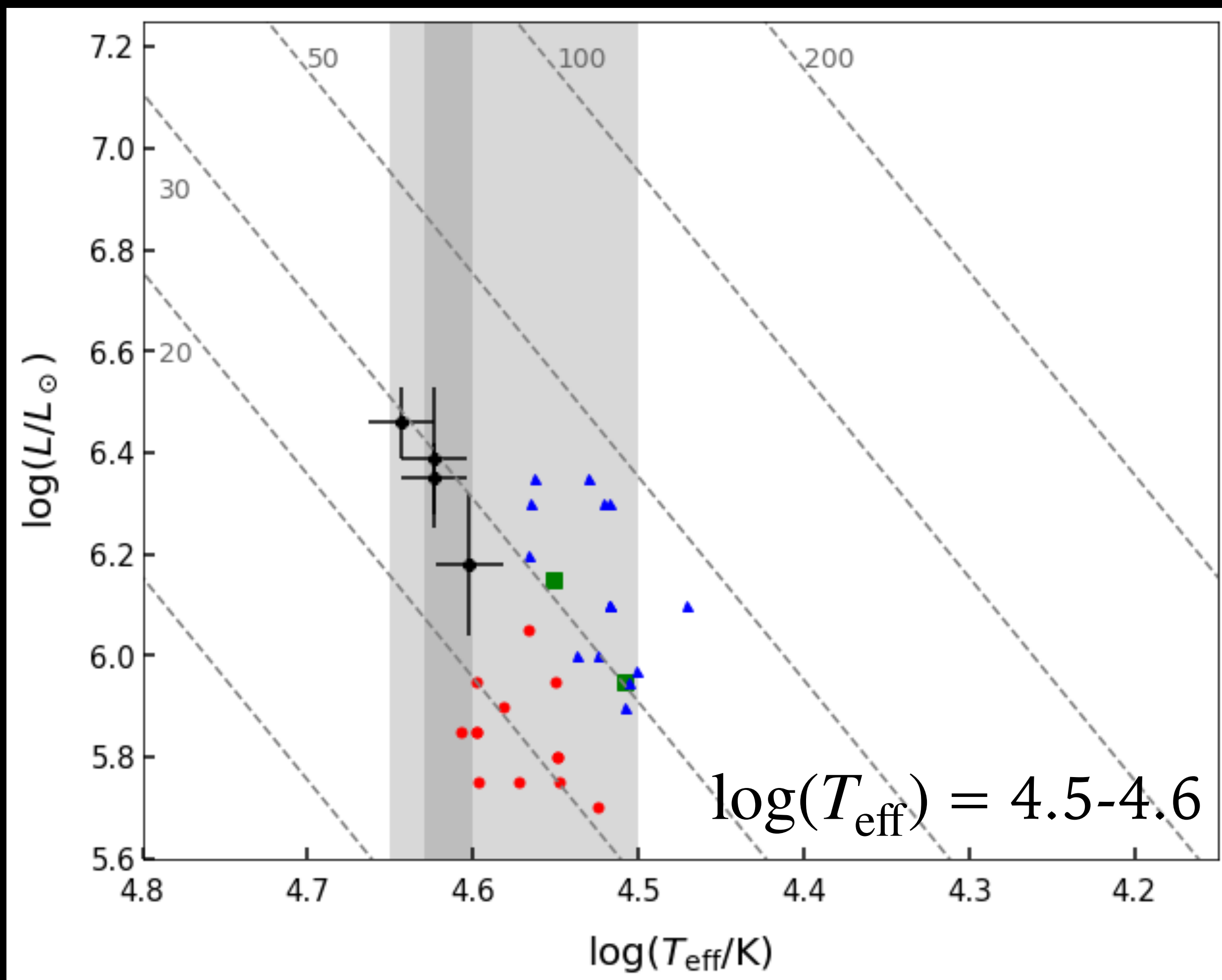
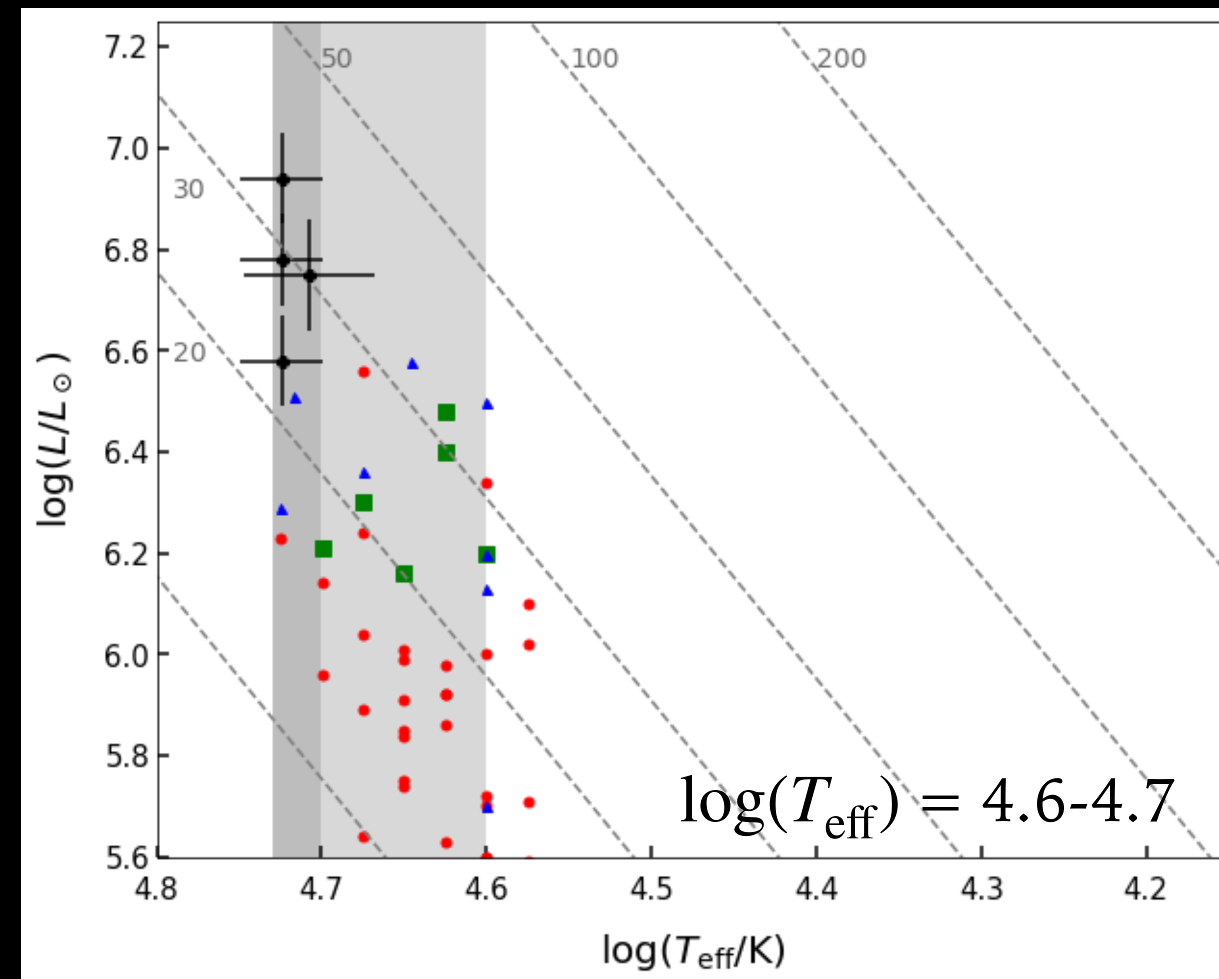




O, Of/WN, WNh stars in the Arches, Martins et al. (2008)

NGC3603, Crowther et al. 2010

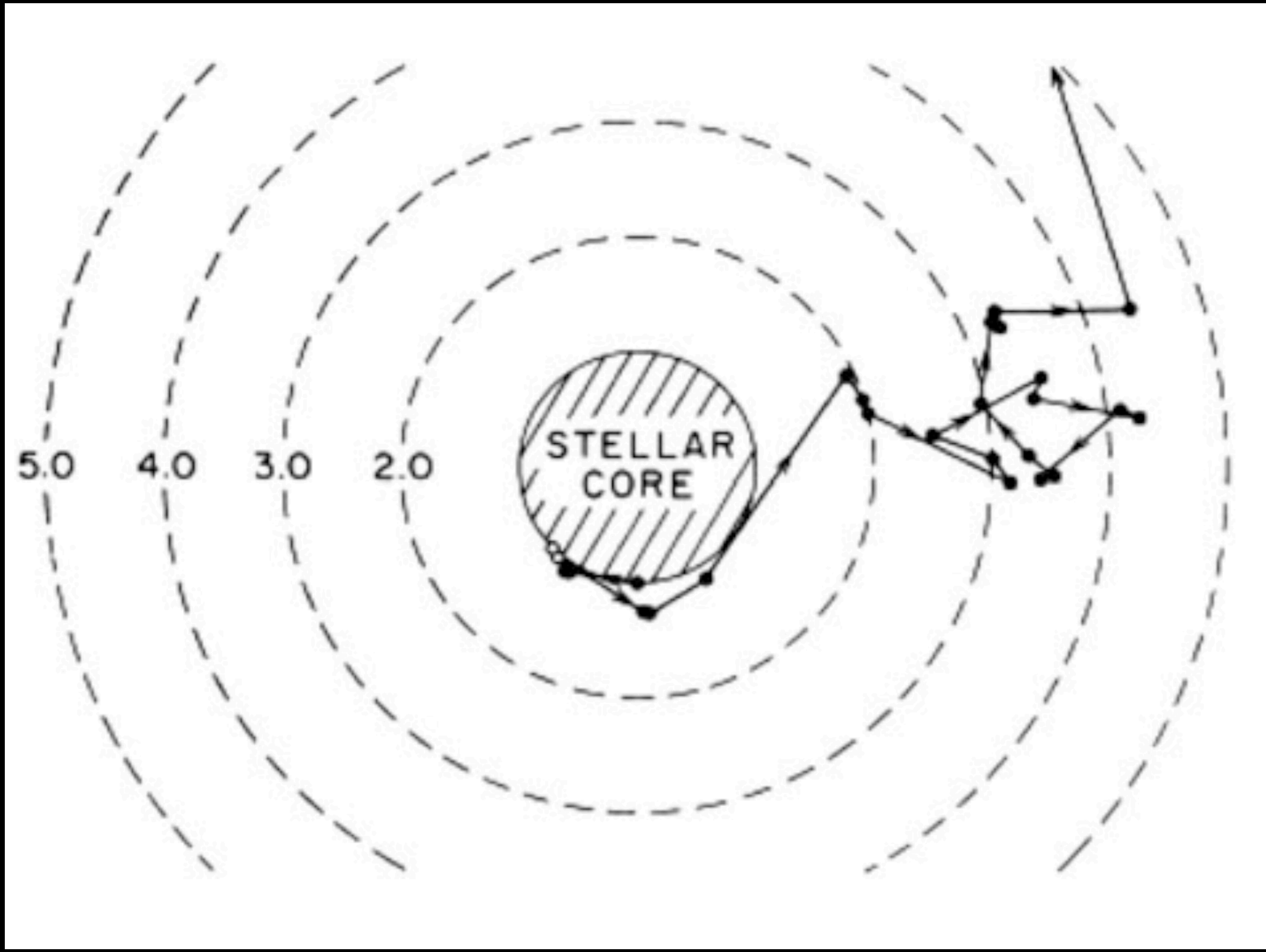
O, Of/WN, WNh stars in the 30 Dor, Bestenlehner et al. (2014)

R136 core, Crowther et al. 2010

Winds of VMSs: Multiple scattering

See talks on stellar winds by Jon and Andreas

- Photons can transfer momentum multiple times in the wind.
- Wind efficiency factor measures averaged efficiency of momentum transfer from radiation to gas

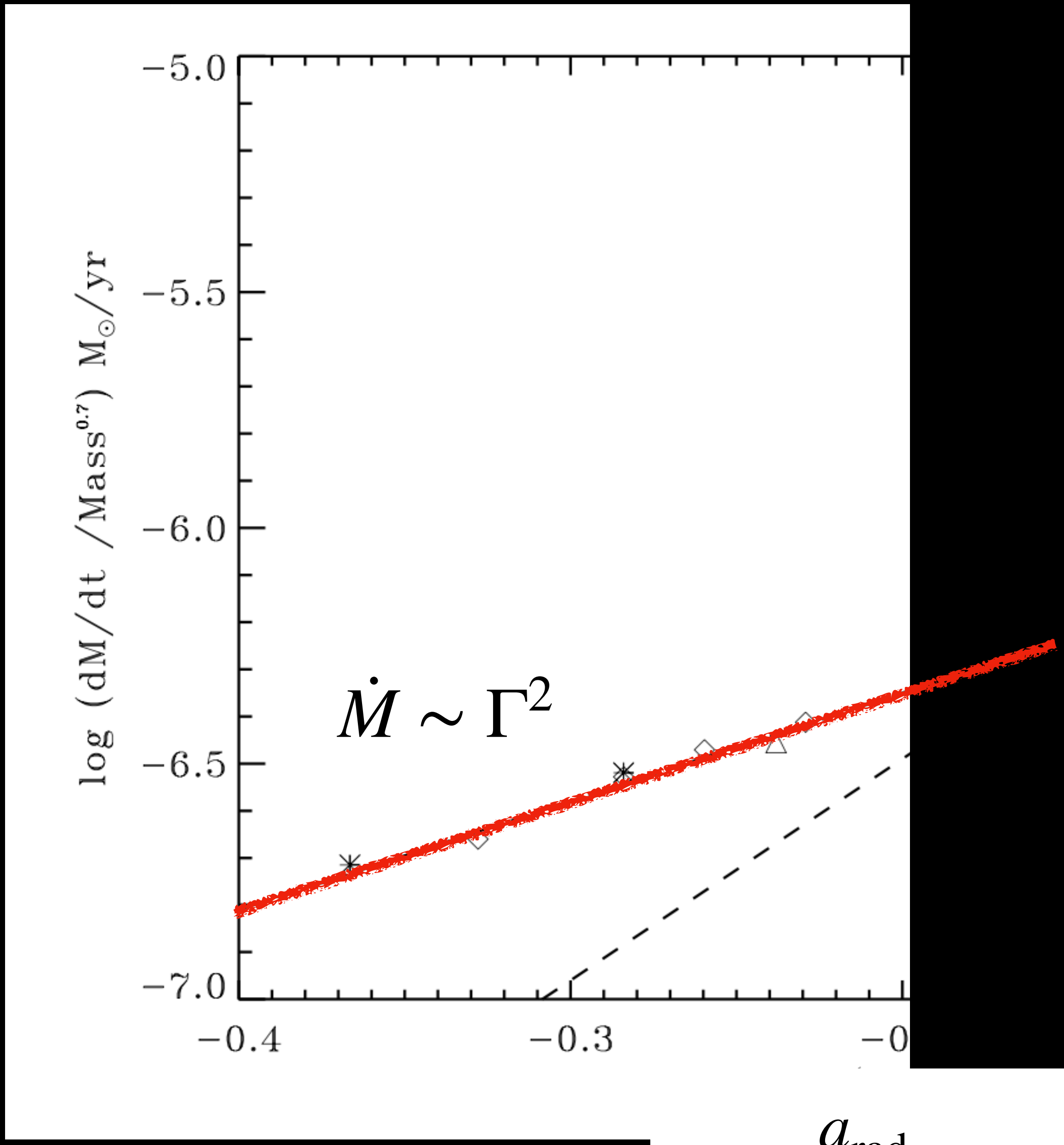


$$\eta = \frac{\dot{M} v_\infty}{L/c} > 1$$

Abbott & Lucy (1985), Analytical: Gayley, Owocki & Cranmer (1995)

VMS mass-loss predictions: Monte-Carlo models

- Multiple scattering included (Abbott & Lucy 1985, Vink et al. 2000, 2001)

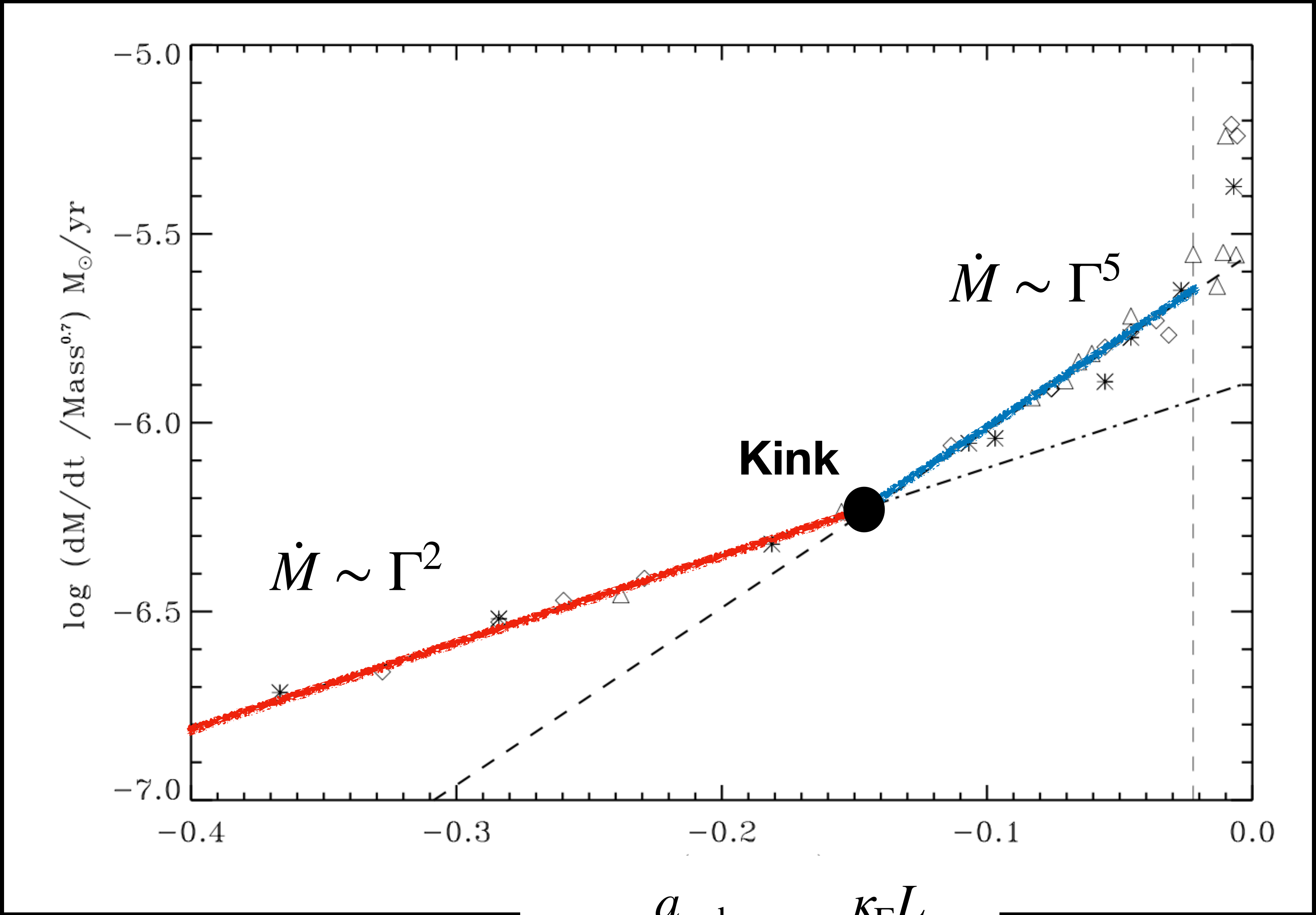


Vink et al. 2011

$$\Gamma = \frac{a_{\rm rad}}{a_{\rm grav}} = \frac{\kappa_{\rm F} L}{4\pi G c M}$$

VMS mass-loss predictions: Monte-Carlo models

- Multiple scattering included (Abbott & Lucy 1985, Vink et al. 2000, 2001)
- Above the kink, $\dot{M} \sim \Gamma^5 \implies$ Mass loss is enhanced above the kink

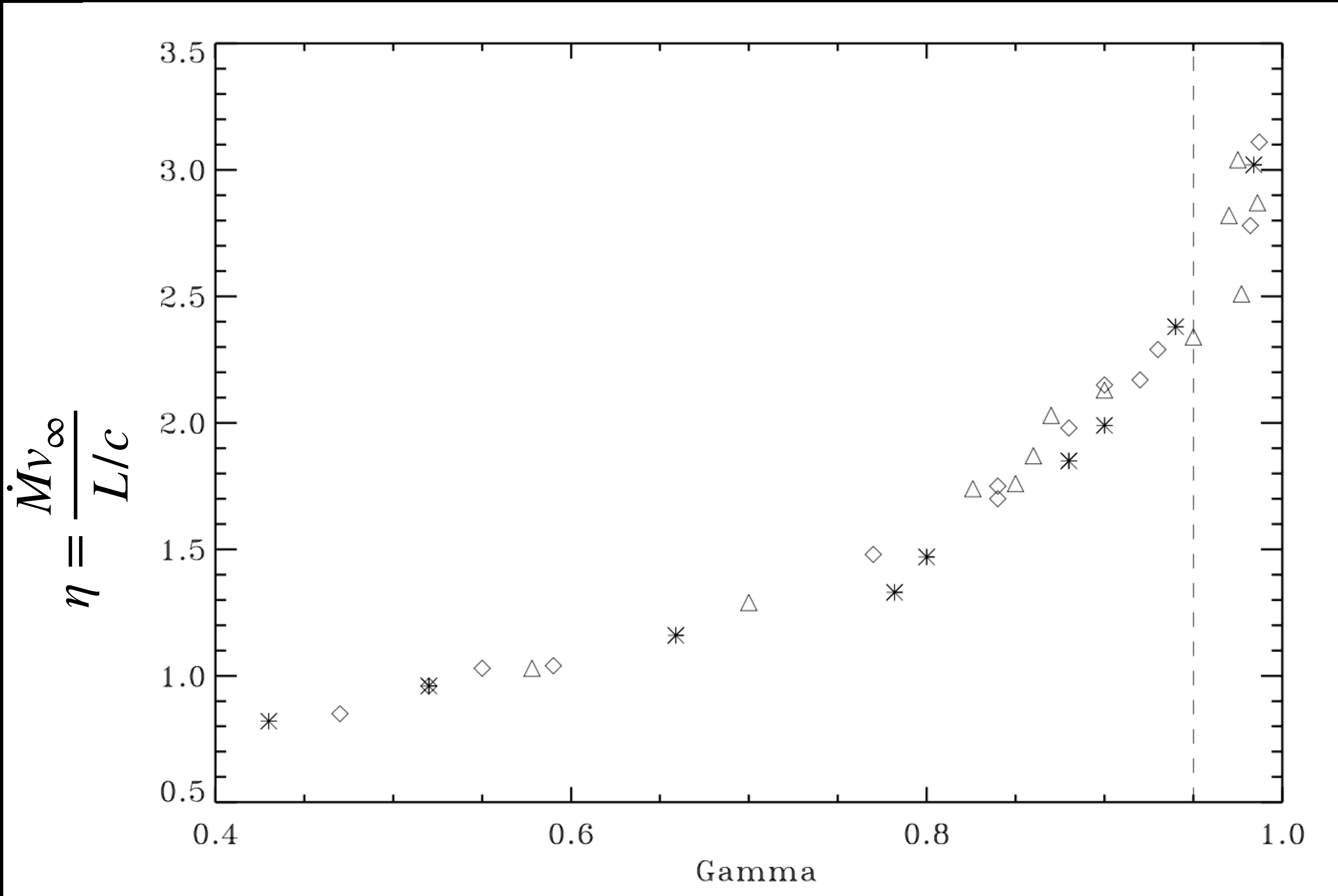


Vink et al. 2011

$$\Gamma = \frac{a_{\rm rad}}{a_{\rm grav}} = \frac{\kappa_{\rm F} L}{4\pi G c M}$$

VMS mass-loss predictions: Monte-Carlo models

At the kink, $\eta \approx 1$



Vink et al. 2011

VMS mass-loss predictions: Monte-Carlo models

Hydro-dynamic EOM

$$\int_{R_*}^{\infty} 4\pi r^2 \rho v \frac{dv}{dr}\, dr + \int_{R_s}^{\infty} \frac{GM}{r^2}(1-\Gamma)\rho 4\pi r^2\, dr = 0$$

$$\int_{R_*}^{\infty} \dot{M}\frac{dv}{dr}\, dr = \dot{M} v_{\infty} = 4\pi GM \int_{R_s}^{\infty} (\Gamma(r)-1)\rho\, dr$$

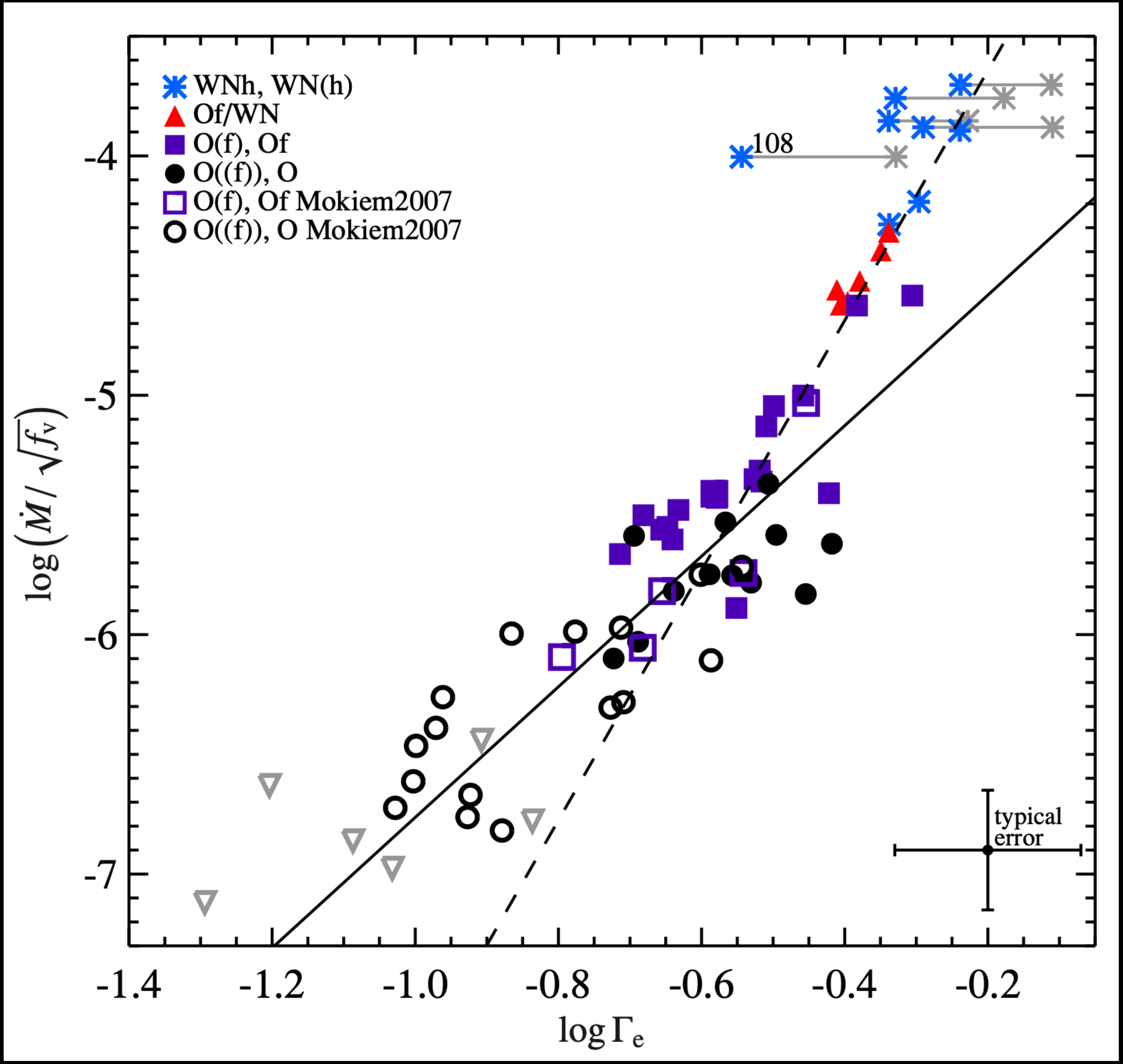
$$\dot{M} v_{\infty} \simeq \frac{4\pi GM}{\kappa}(\Gamma - 1)\tau_{\mathrm{F,s}} = \frac{L}{c}$$

$$\dot{M} v_{\infty} = \frac{L}{c}\tau_{\mathrm{F,s}}$$

At the kink, $\eta \approx \tau_{\mathrm{F,s}} \approx 1$

Vink & Gräfener 2012

Wind kink empirically confirmed!



Bestenlehner et al. (2014)

Kink implementation: how to implement?

$$\eta \approx 1 \implies \frac{\dot{M} v_\infty}{L/c} \approx 1$$

Very accurate measure of mass loss at the transition!

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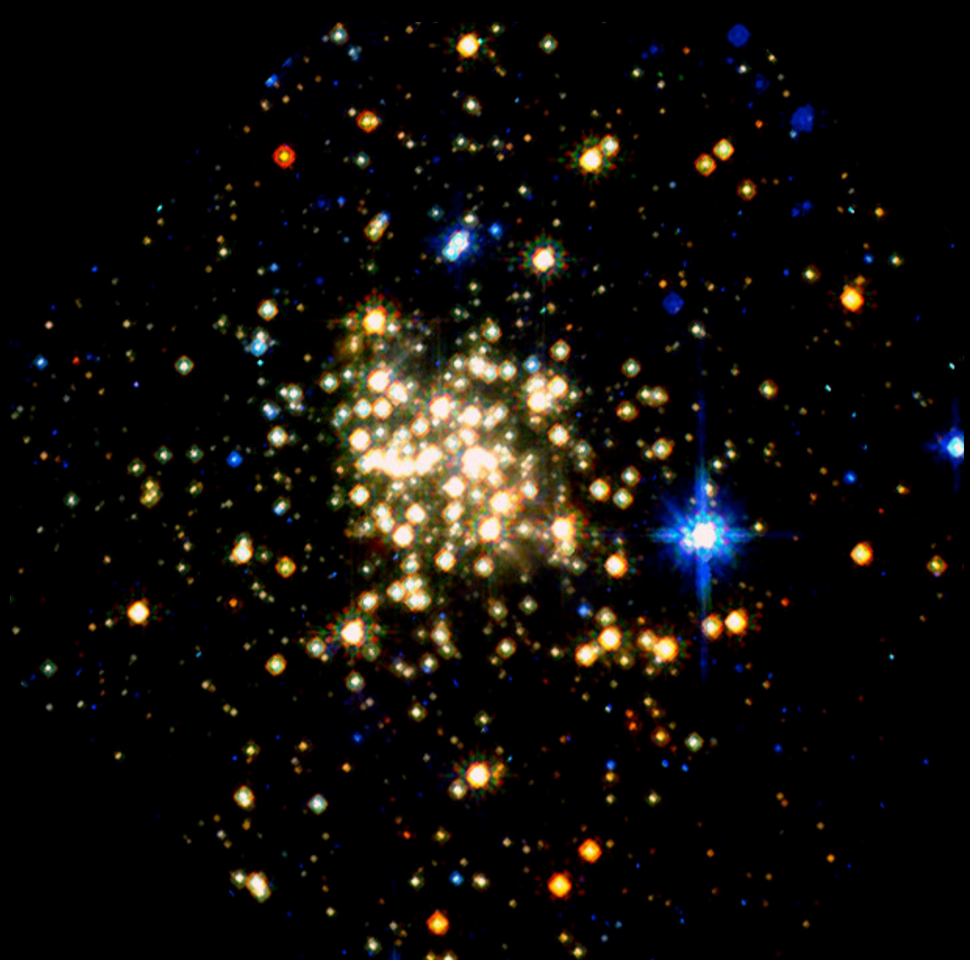
In search of young, massive clusters with both O and WNh stars

Arches Cluster



30 Dor region

Kink implementation: how to implement?

$$\eta \approx 1 \implies \frac{\dot{M} v_\infty}{L/c} \approx 1$$

Very accurate measure of mass loss at the transition!

In search of young, massive clusters with both O and WNh stars

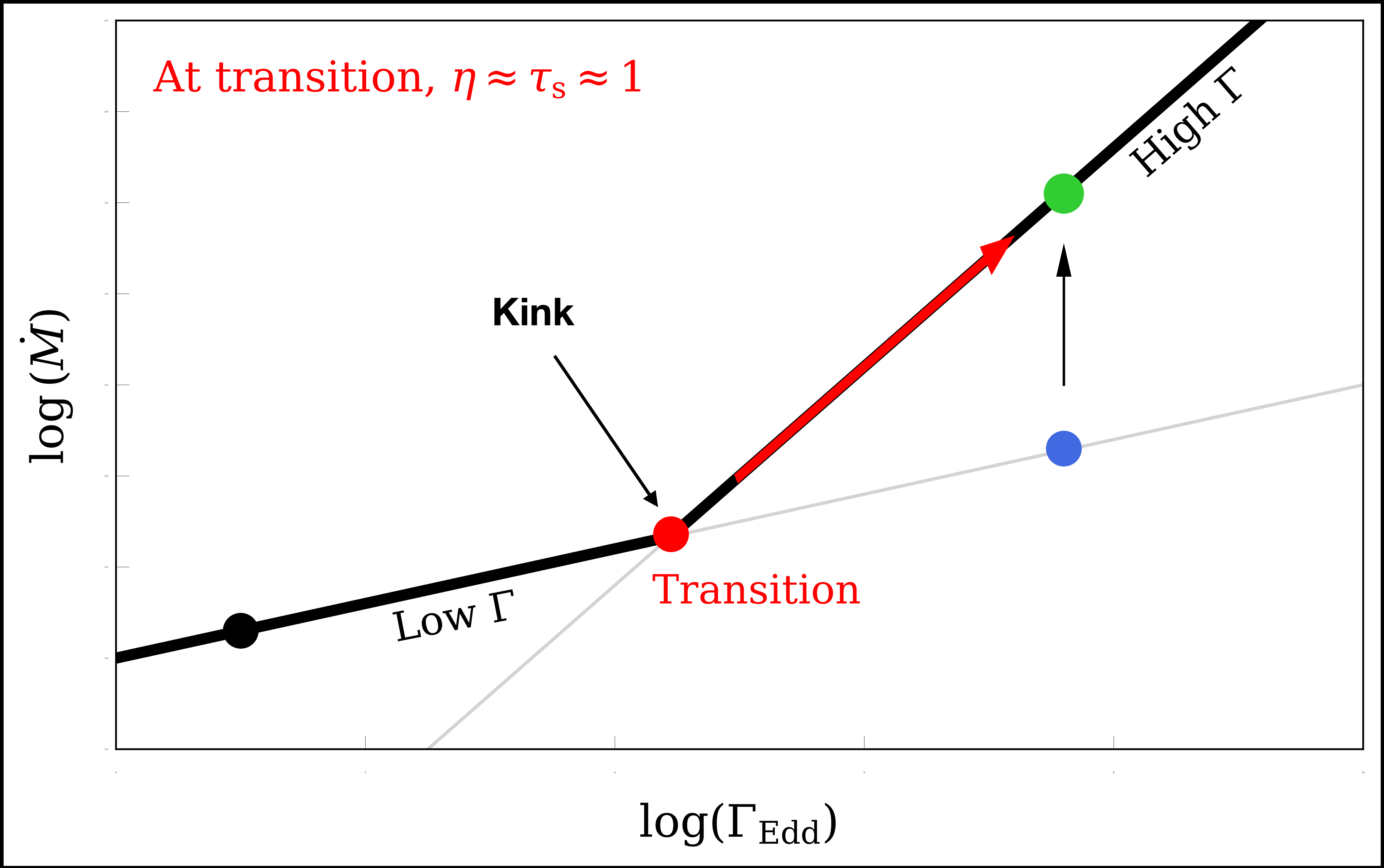
Arches Cluster

- Roughly solar metallicity Z ~ 0.02
- Transition luminosity is $\log(L/L_\odot) \approx 6$
- Transition mass loss $\log \dot{M} \approx -5.3$

30 Dor region

- Roughly half solar
- Transition luminosity is $\log(L/L_\odot) \approx 6.3$
- Transition mass loss $\log \dot{M} \approx -5.$

Kink implementation: how to implement?



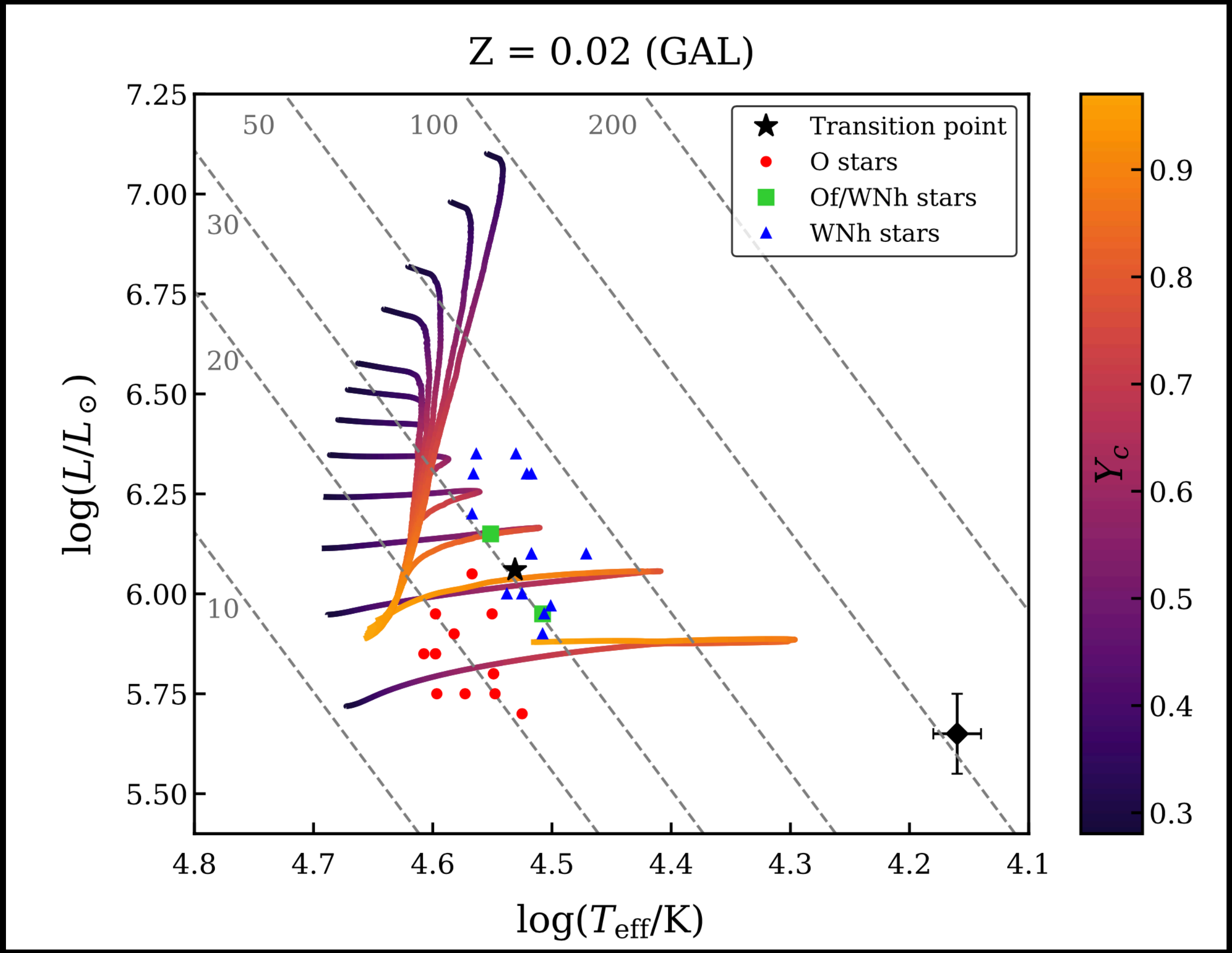
$$\eta = \frac{\dot{M} v_\infty}{L/c} \sim 1$$

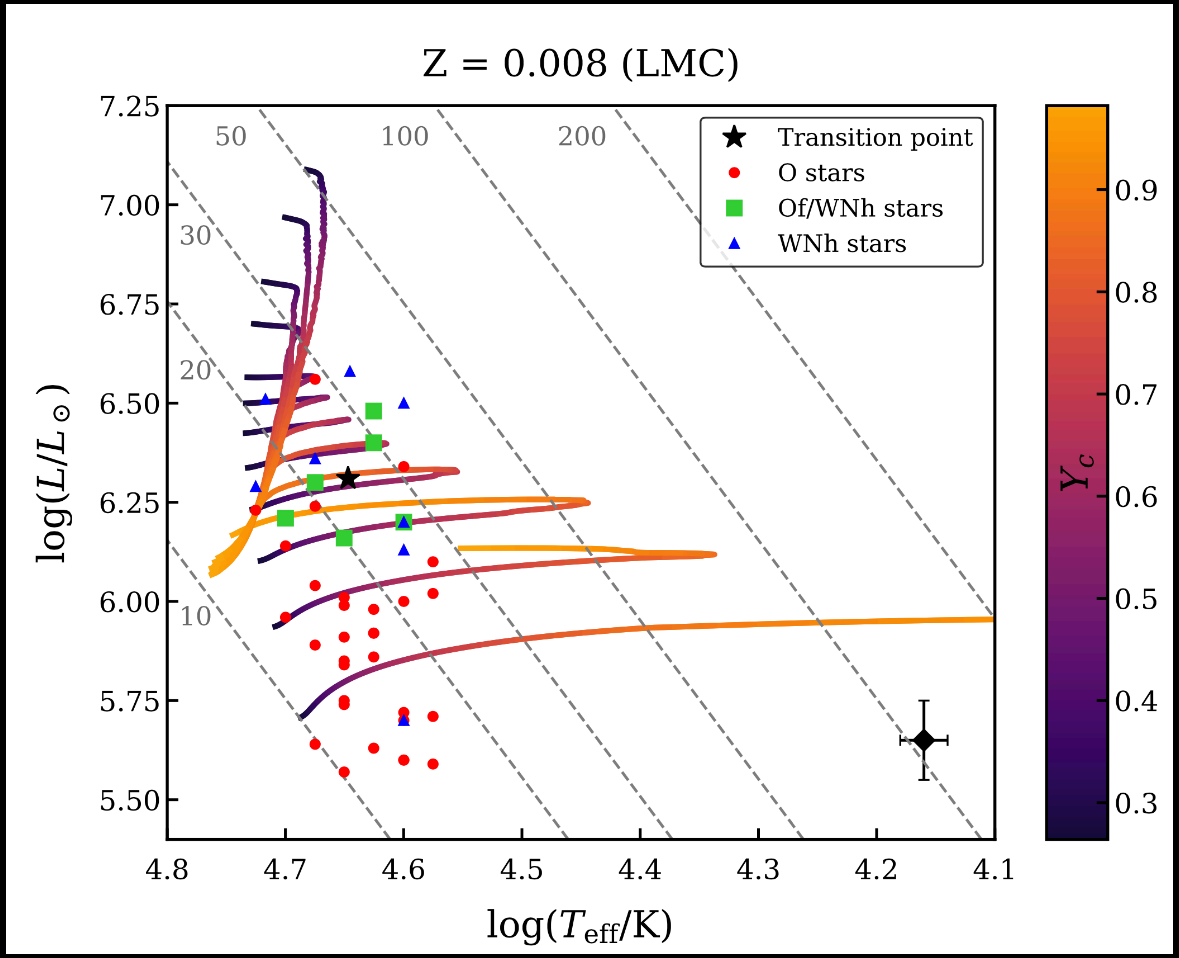
Implications of strong VMS winds: Vertical evolution

MESA

- VMSs evaporate - starts to eat into the core - luminosity drops
- VMSs in the Local Universe could be evolving vertically downwards

Sabhahit et al. (2022, 2023)

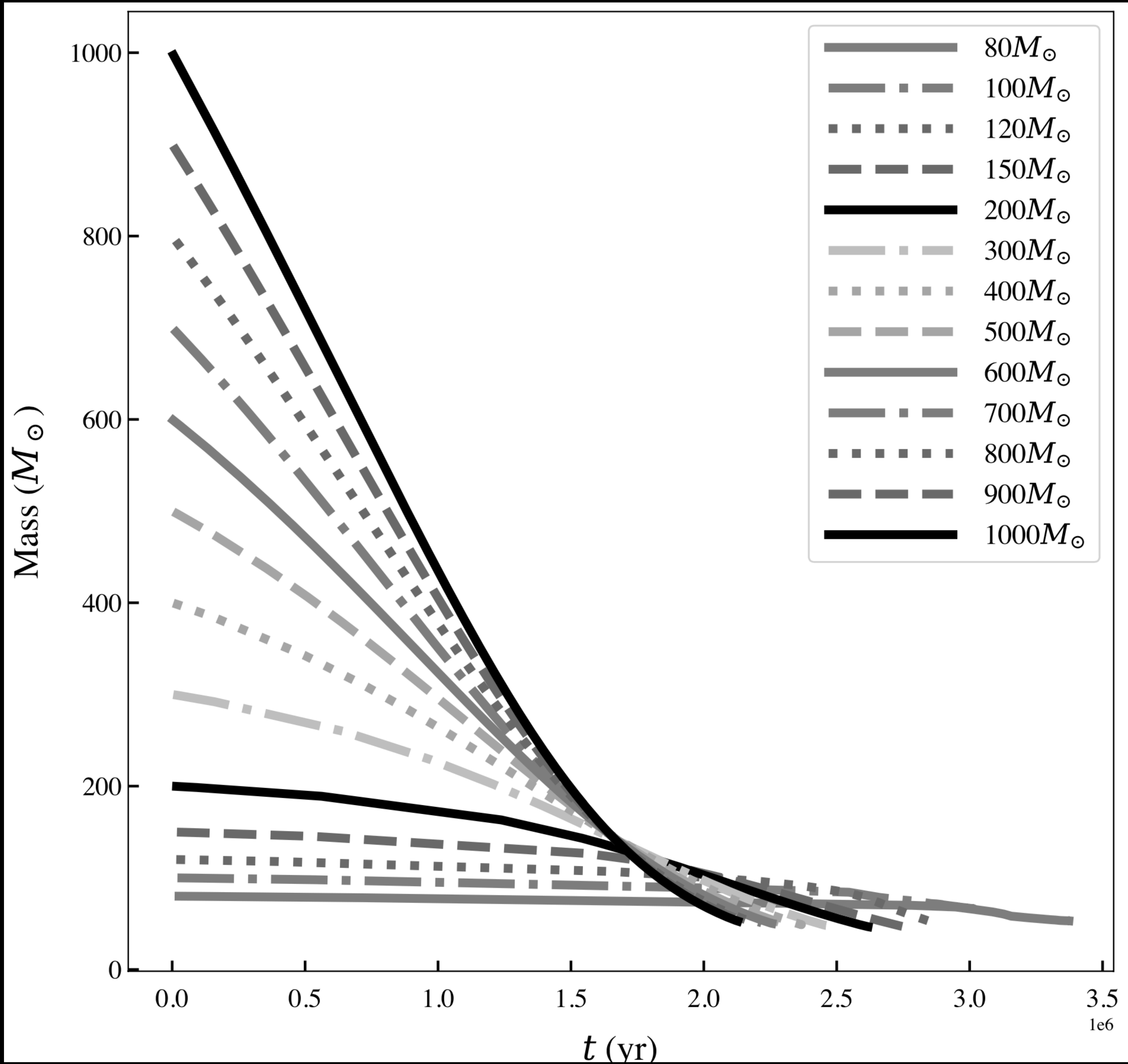




Naturally explains the narrow range of observed temperatures!

Implications of strong VMS winds: Mass turnover point

MESA

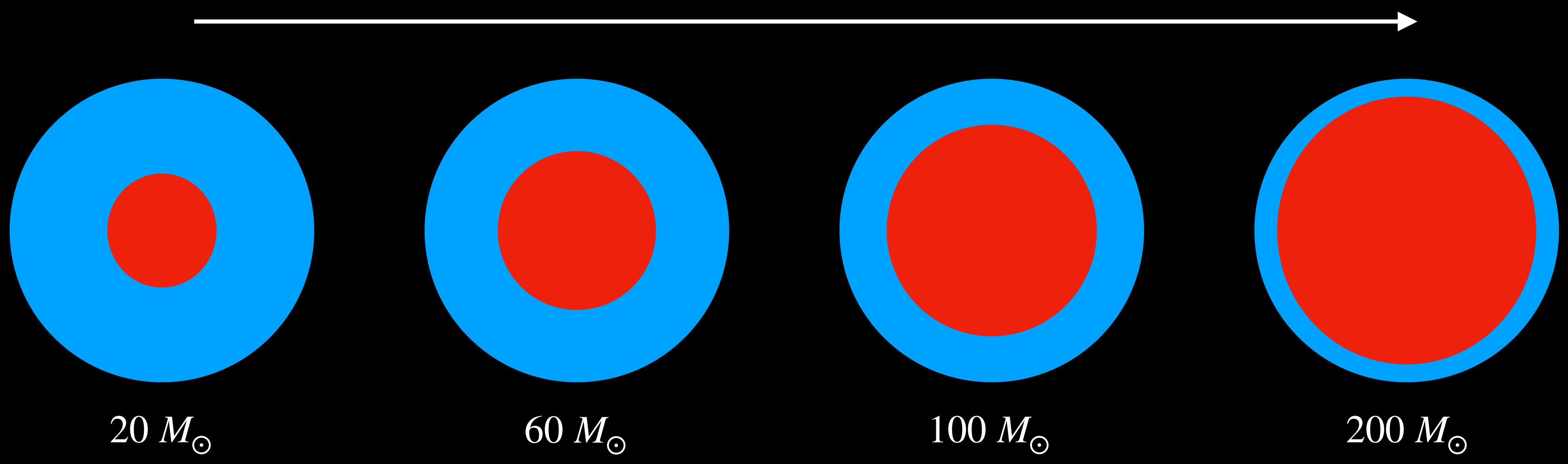


Higgins et al. (2022, 2023)

Sabhahit et al. (2022, 2023)

Implications of strong VMS winds: Chemical Homogeneous evolution

Relative mass of the conv. core to total increases with initial mass



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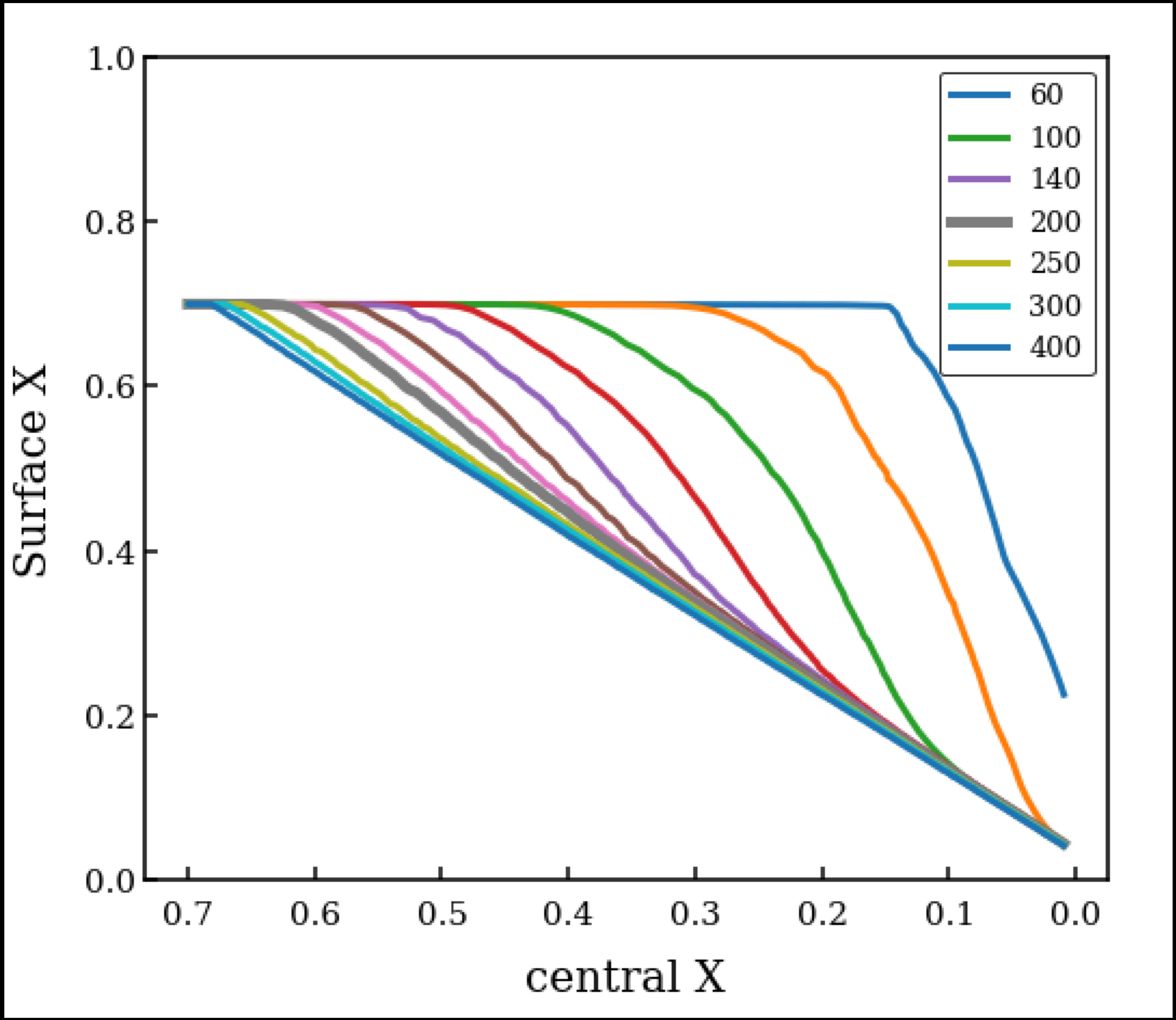
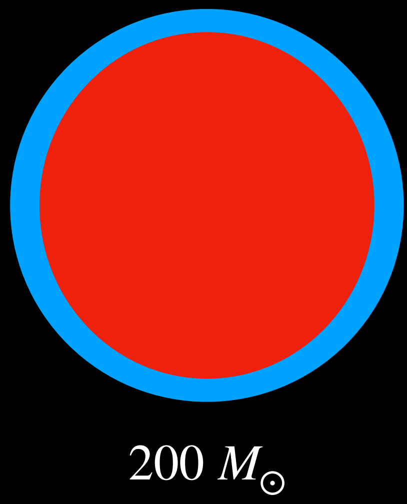


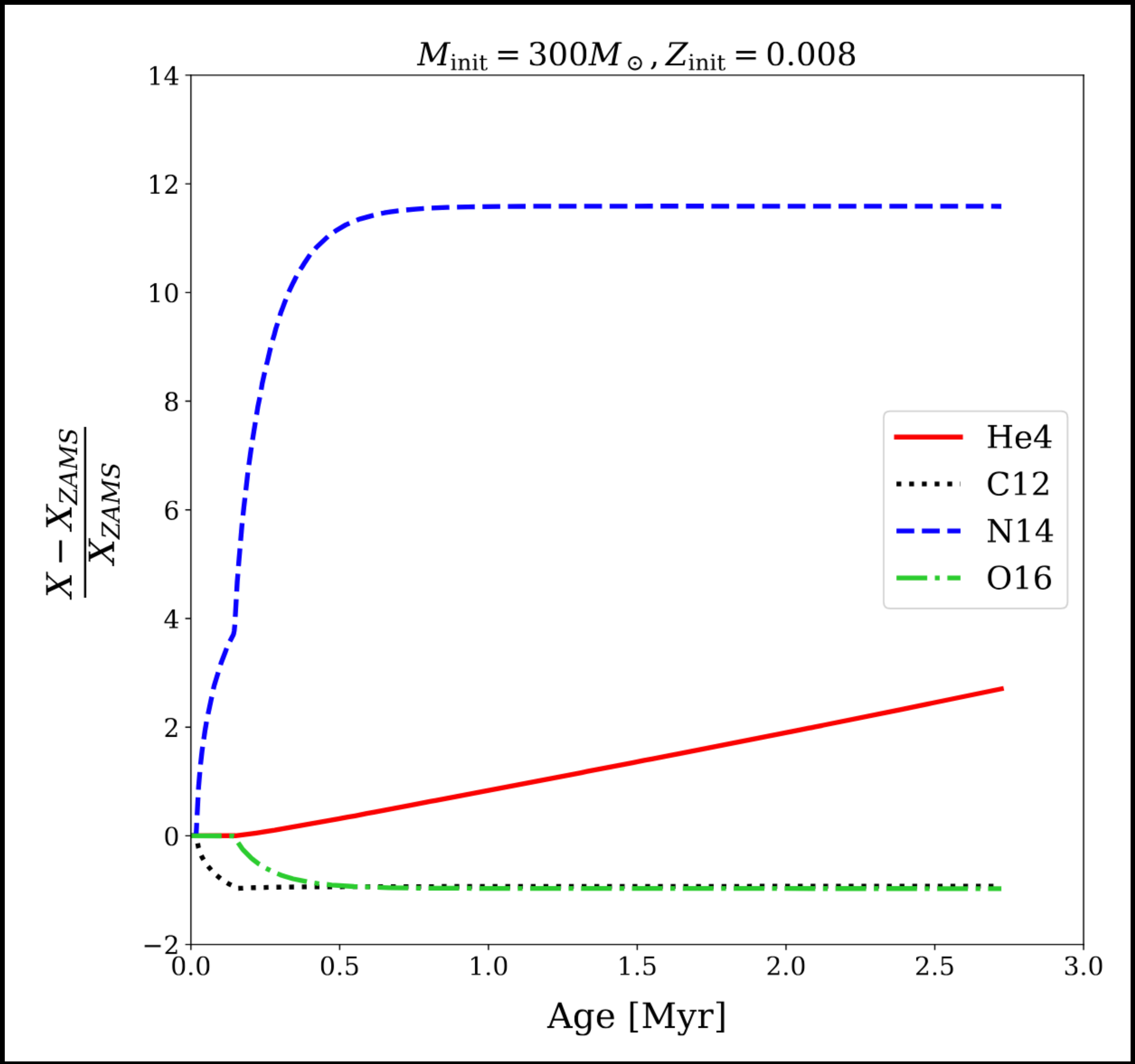
Higgins et al. (2022, 2023)
Sabhahit et al. (2022, 2023)

Implications of strong VMS winds: Wind yields

MESA



- H-burning products can easily reach the surface.. could be important for GCs (Vink 2018)
- N enhancement in High-z galaxies
- Na/O anti-correlations in GCs

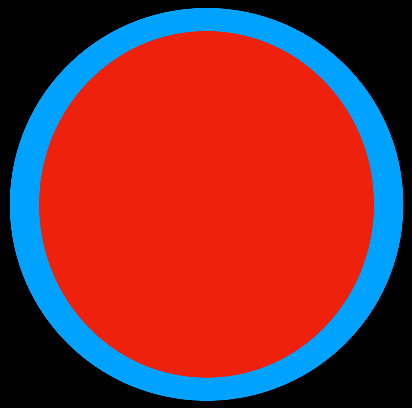


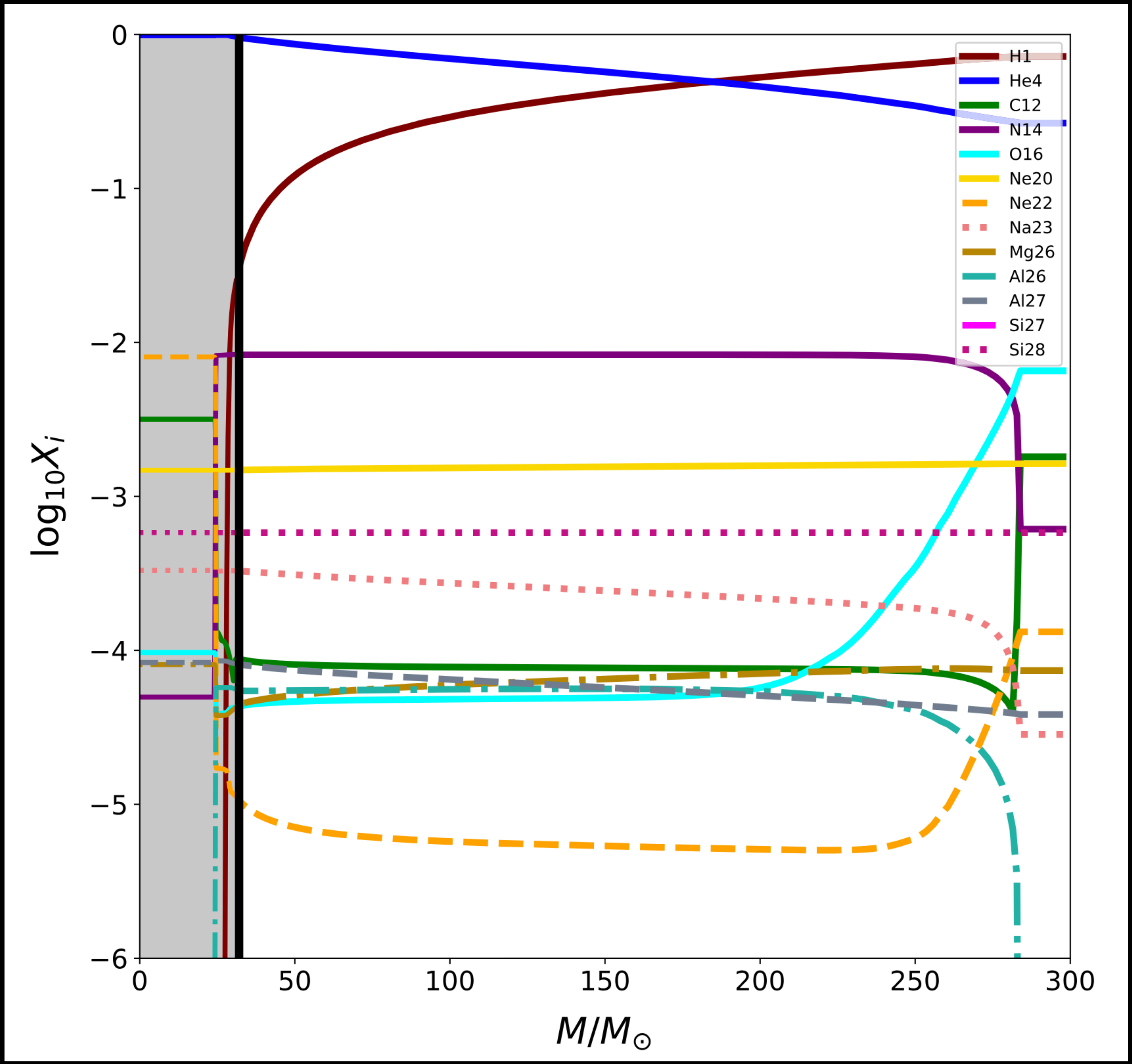
Vink (2023)

Implications of strong VMS winds: Wind yields

MESA

Models with strong VMS winds eject ~2x more He, N, Ne, Na and Si, and up to 10x more Al than previous models



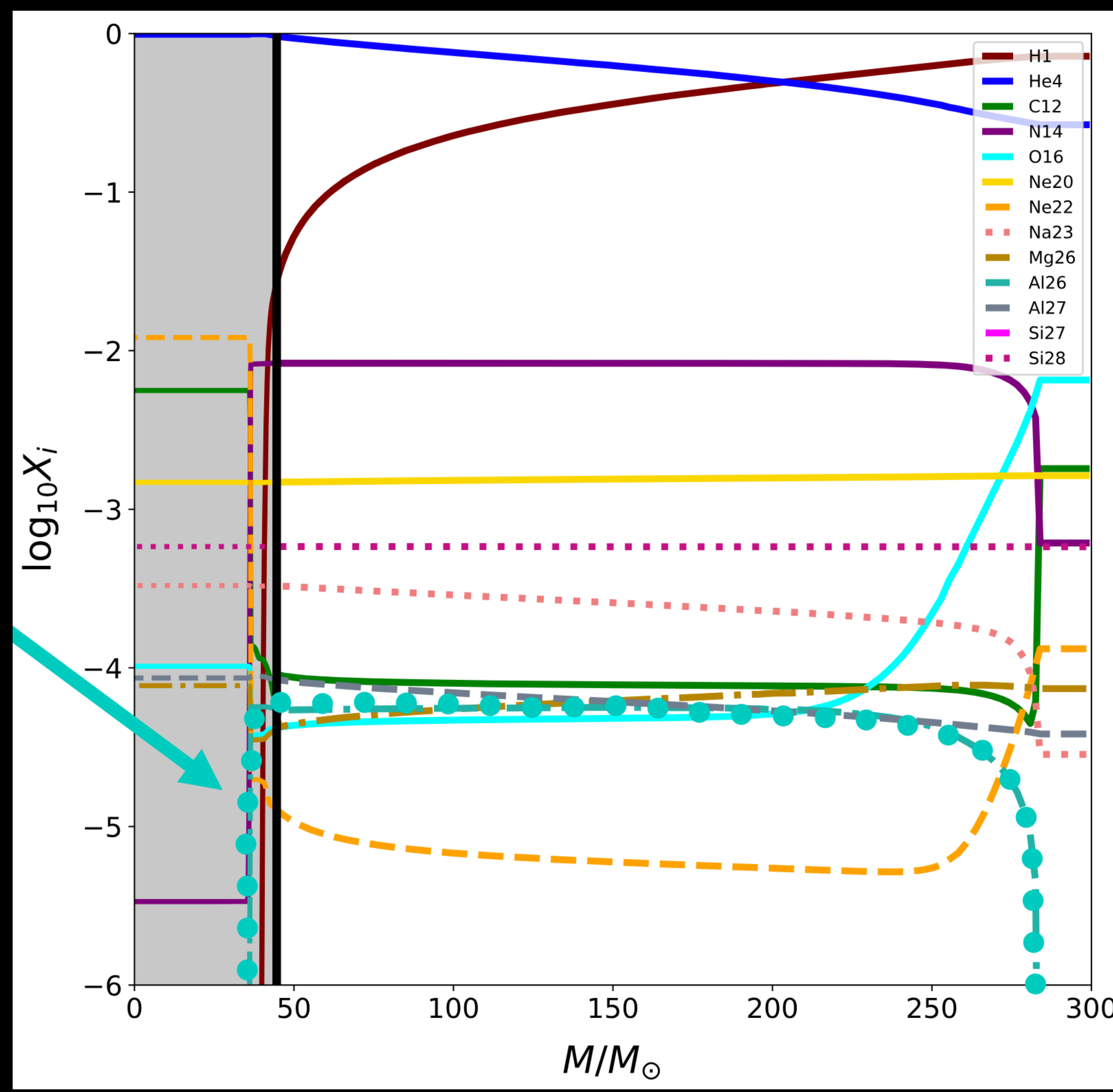


Higgins et al. (2023)

Implications of strong VMS winds: ^{26}Al in our Galaxy

MESA

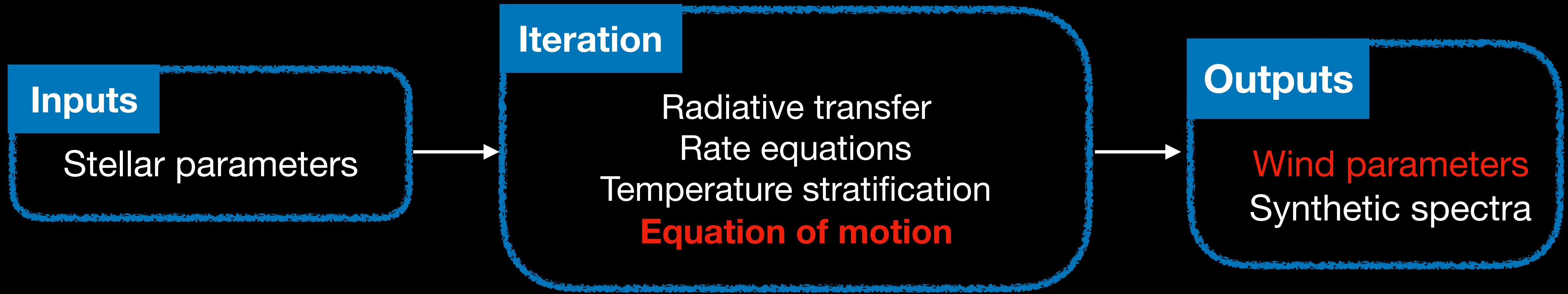
- Significant mass of 26Al observed in our Galaxy - key heating source during formation of Earth
- Emits in Gamma-rays when decaying to 26Mg - 1.805 Mev photon
- VMSs eject 10^{-3} to $10^{-2}\,M_{\odot}$ of 26Al

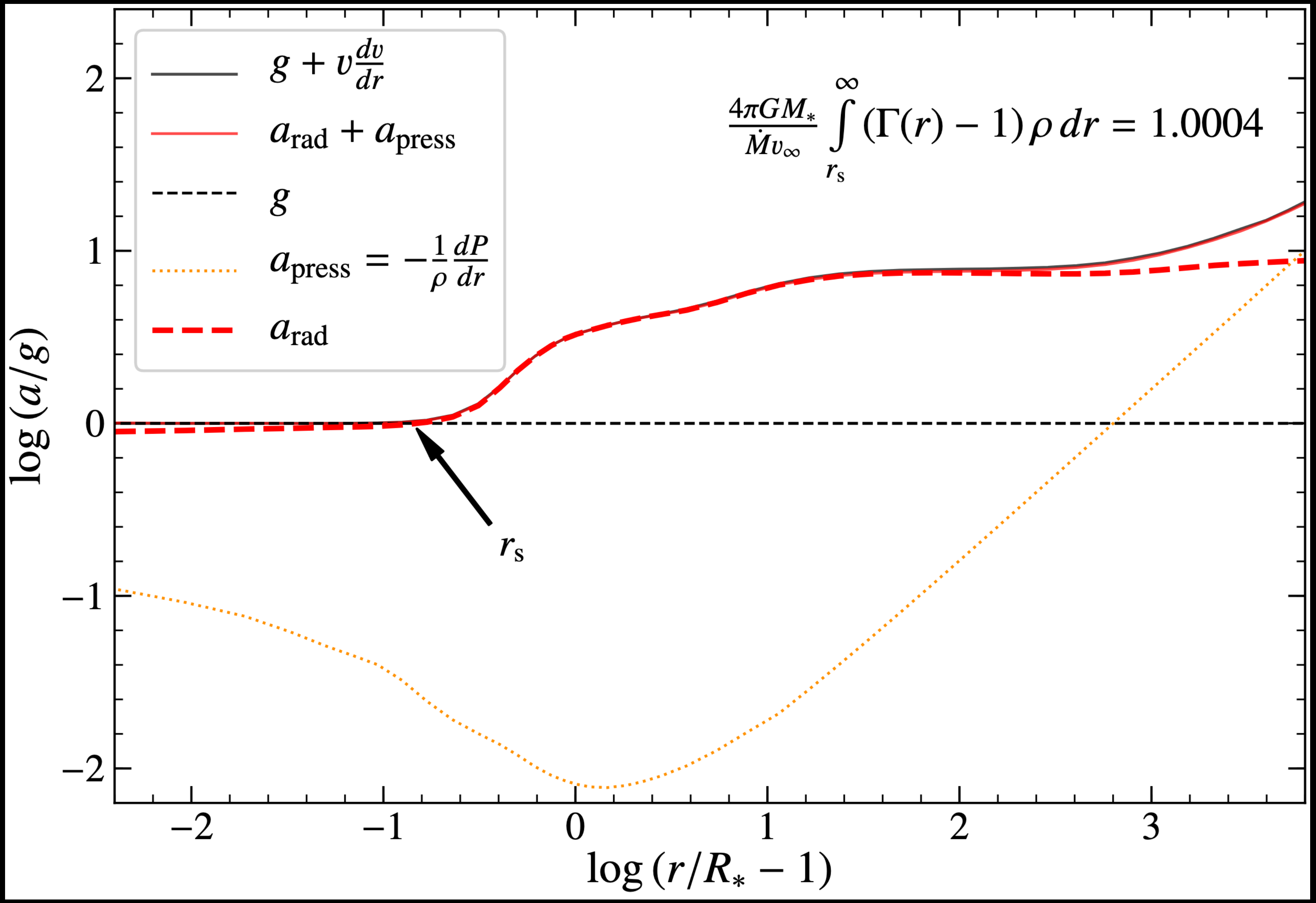


Higgins et al. (2023)

What next?

PoWR^{HD}



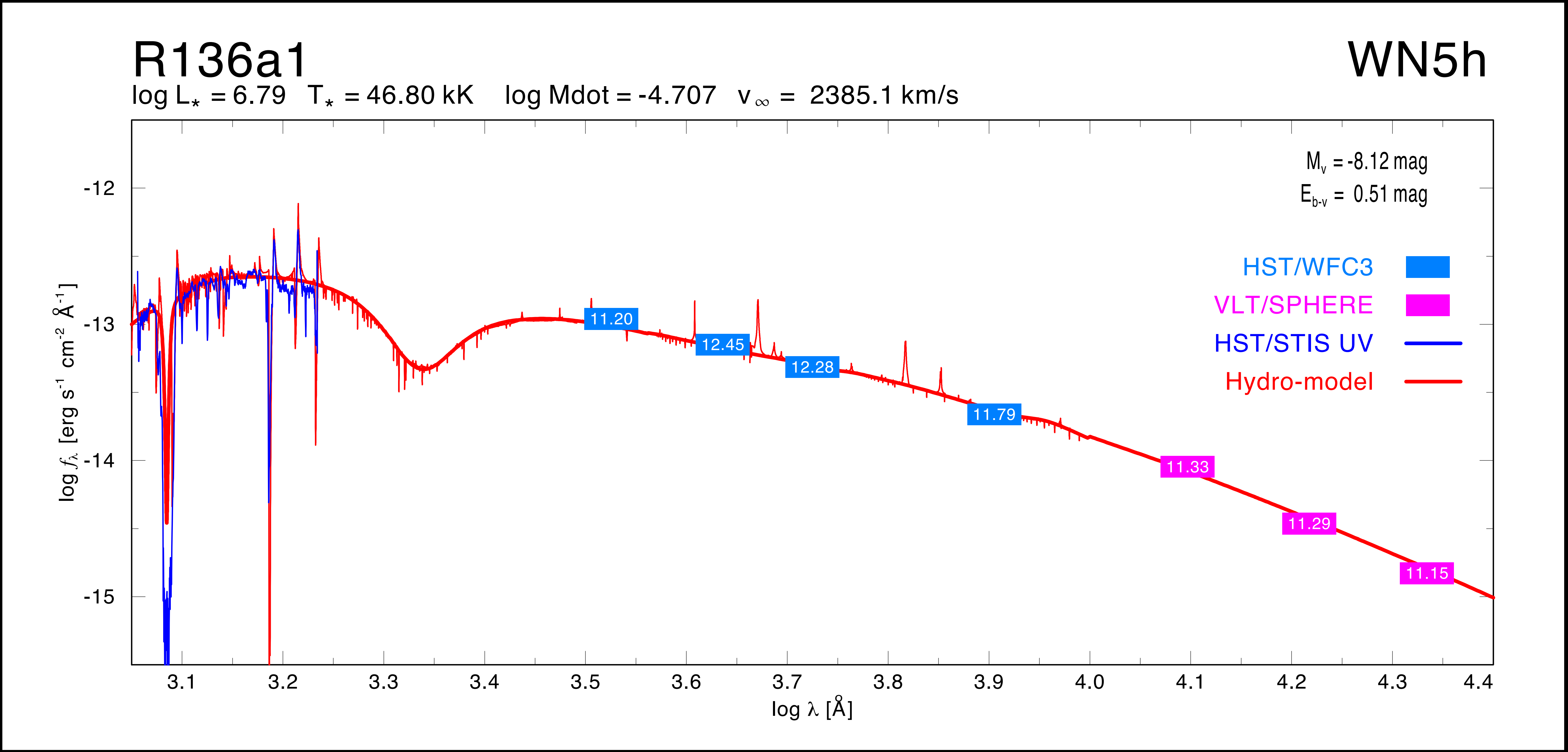


Sander et al. (2017), Sabhahit et al. (2023)

What next?

PoWR HD

Hydro-model spectra of R136a1

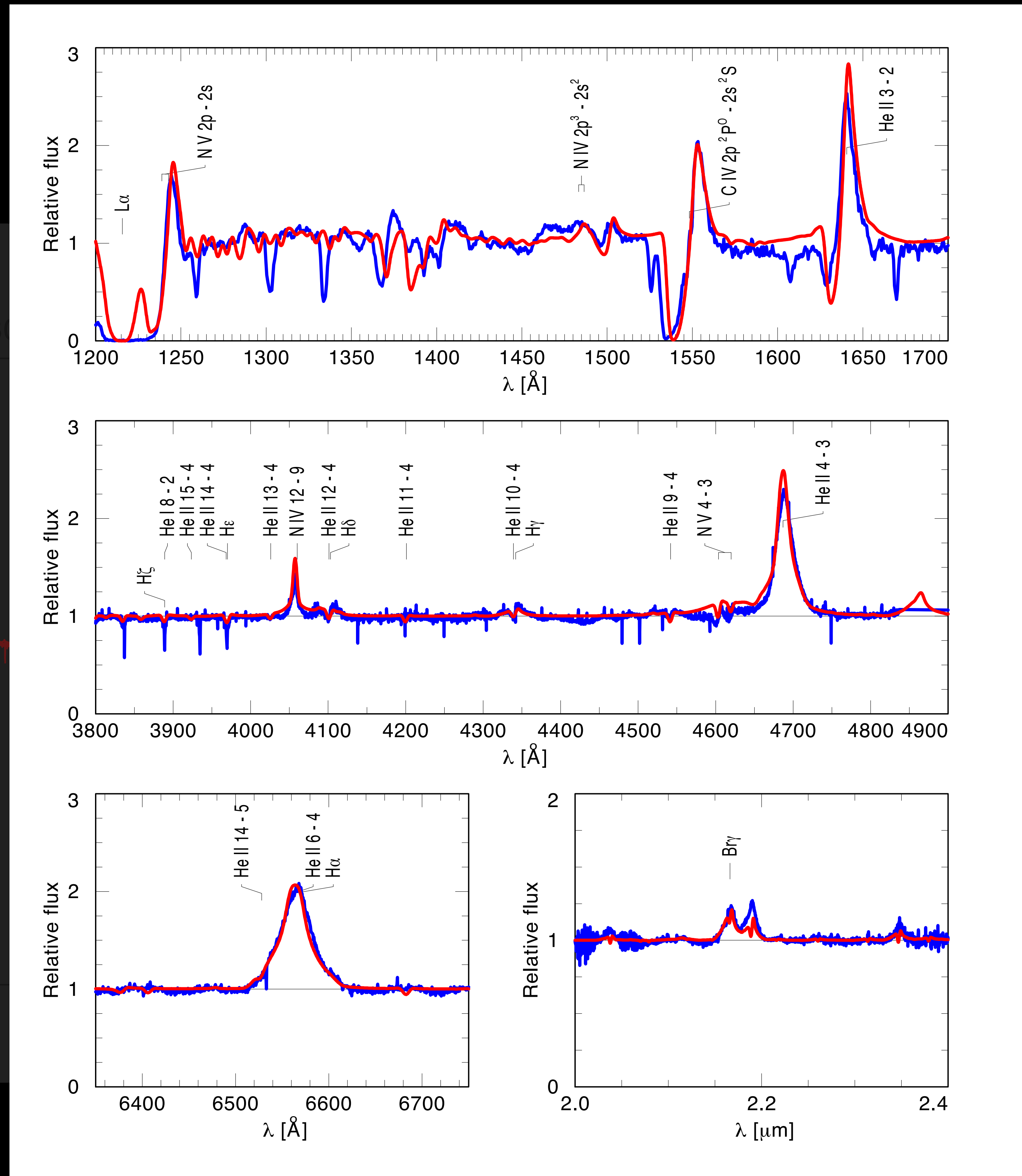


What next?

PoWR^{HD}

$$\log(\dot{M}) = -4.7$$

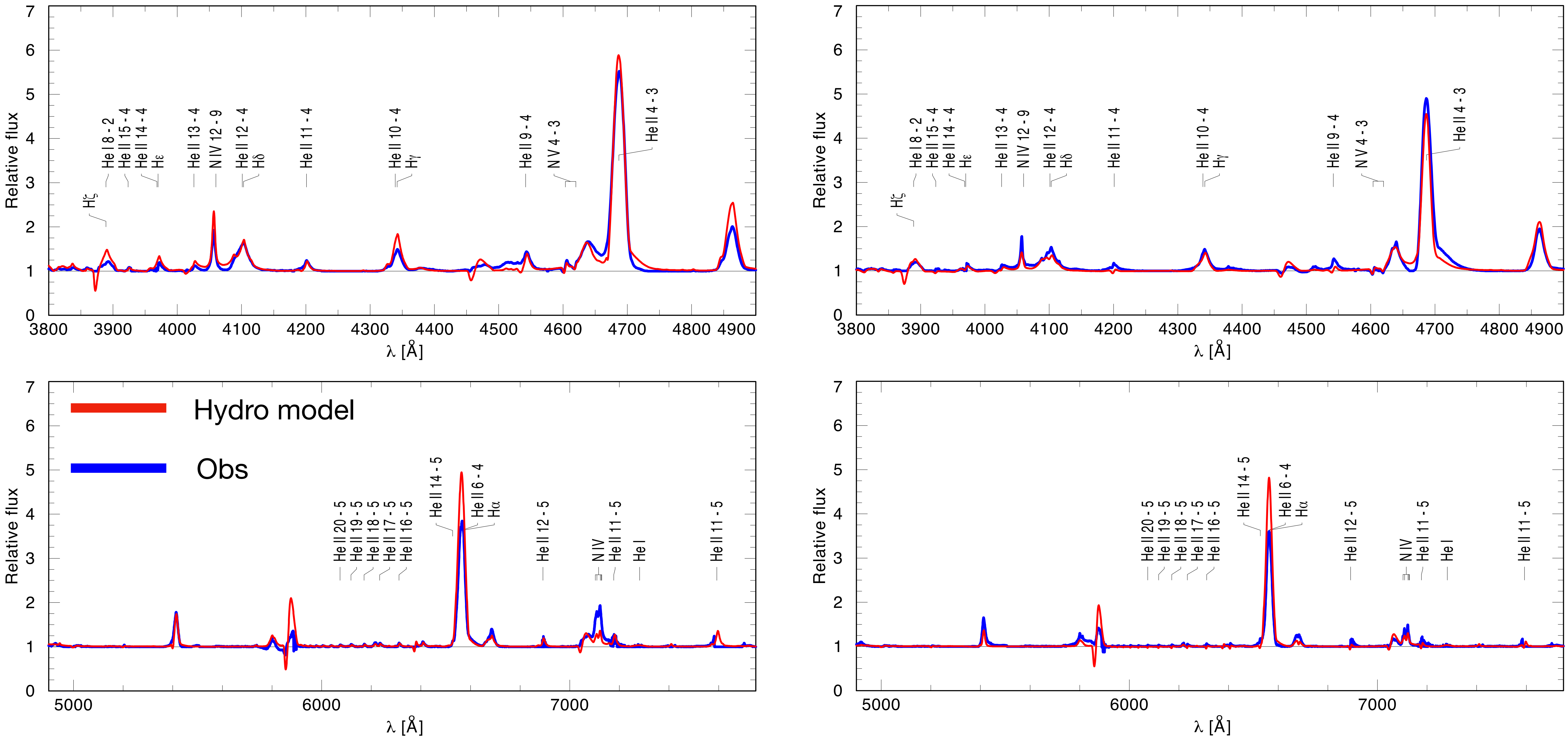
$$v_\infty = 2400\,\mathrm{km/s}$$



What next?

PoWR HD

R144 - WNh + WNh binary in LMC with dynamical mass estimate



$\log \dot{M} = -4.489$

$v_\infty = 1374\,\mathrm{km/s}$

$\log \dot{M} = -4.586$

$v_\infty = 1244\,\mathrm{km/s}$

Conclusions

- VMSs - above $100\,M_{\odot}$.. found In young, massive clusters
- Multiple scattering in winds - Kink transition to high eta and high Gamma - steeper Gamma dependence
- Application of kink in young, massive clusters hosting both O and WNh stars
- Implications of strong VMS winds - vertical evolution, wind yields, N in High-z galaxies and Na/O anti-correlations in GCs, 26Al in the Galaxy

Thank you!