

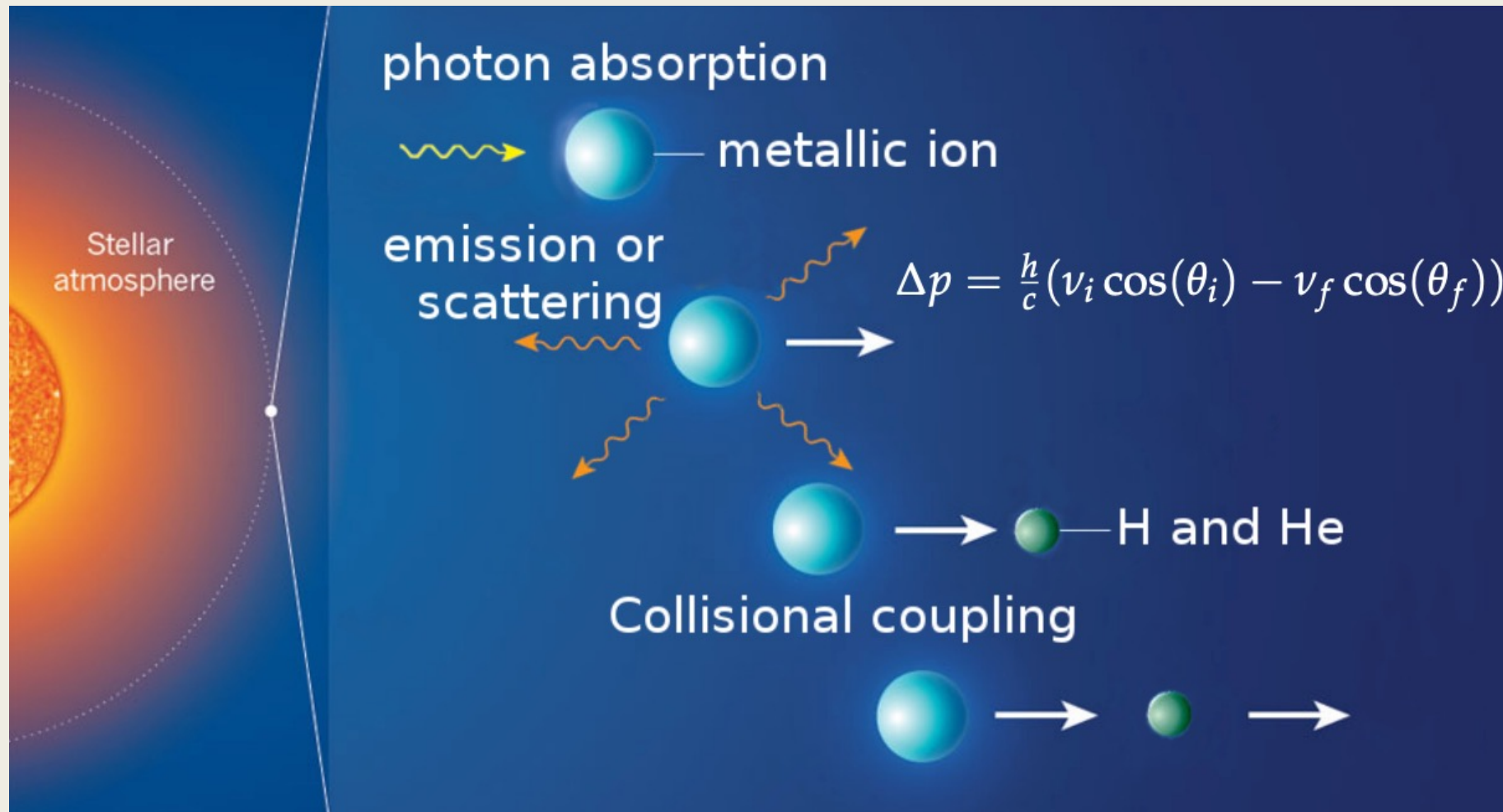
STELLAR WIND MASS LOSS

Manos Zapartas

Stellar structure
and Nucleosynthesis
MSc Course



Line-driven winds mechanism from hot massive stars

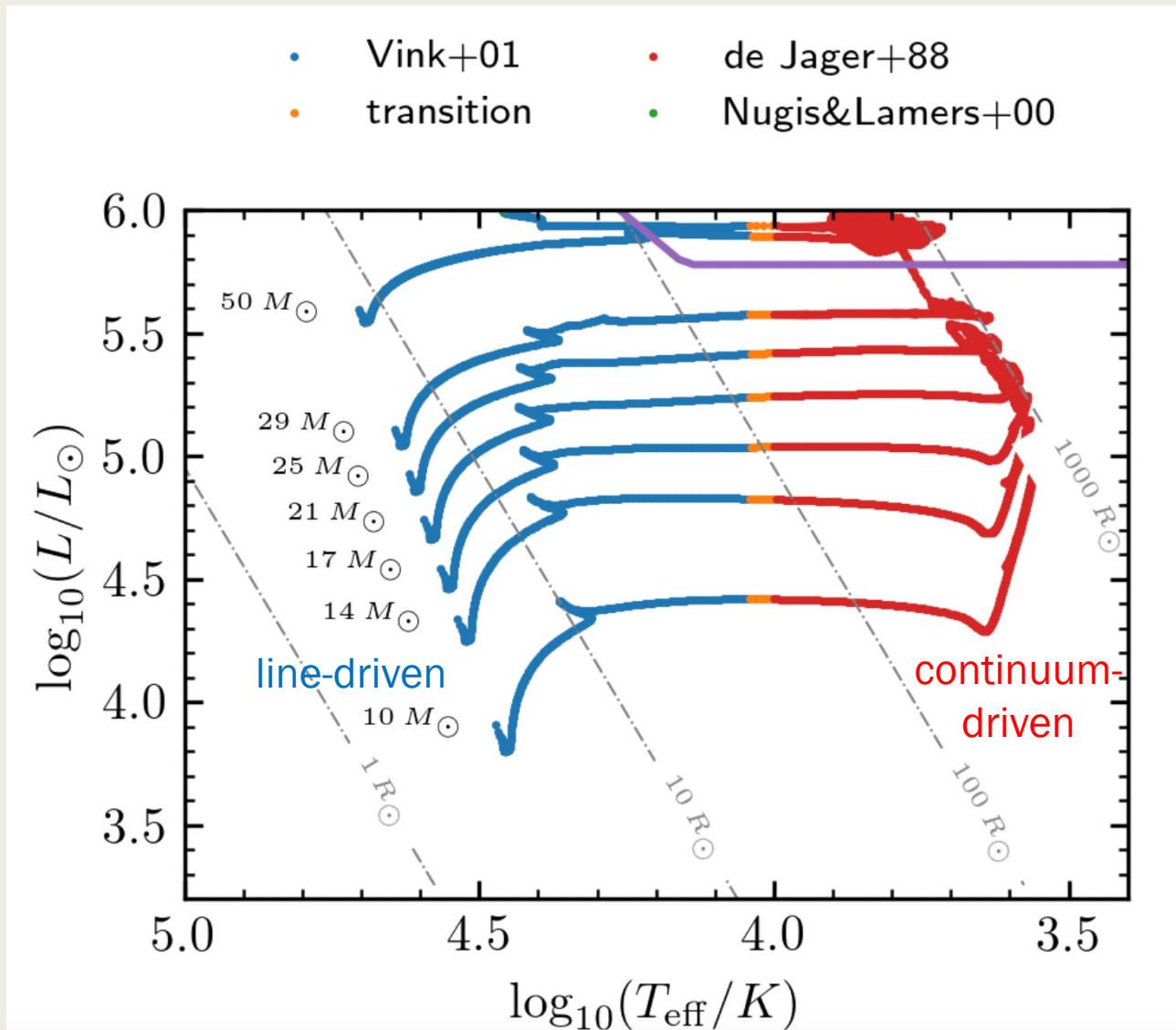


- O/B-type stars
- Wolf-Rayet (discussed later)

Metallicity dependence of line driven winds! Weak winds at low-Z,

$$\dot{M} \propto \left(\frac{Z}{Z_{\odot}} \right)^x \quad x \sim 0.6-1.2$$

Mass loss prescriptions in stellar tracks



Observational constraints:

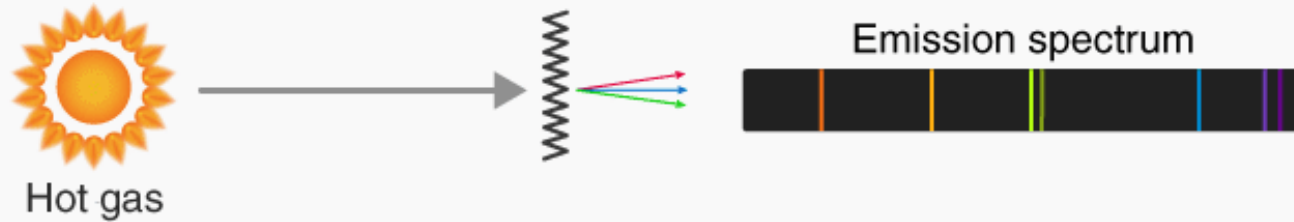
Line-driven winds (in hot stars) → P Cygni line profile

- Absorption vs Emission lines: Contrast

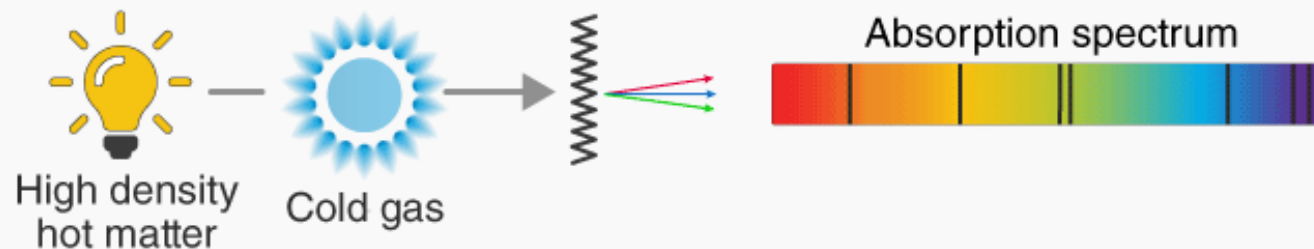
EMISSION VS. ABSORPTION SPECTRA



(a) Emission Spectra

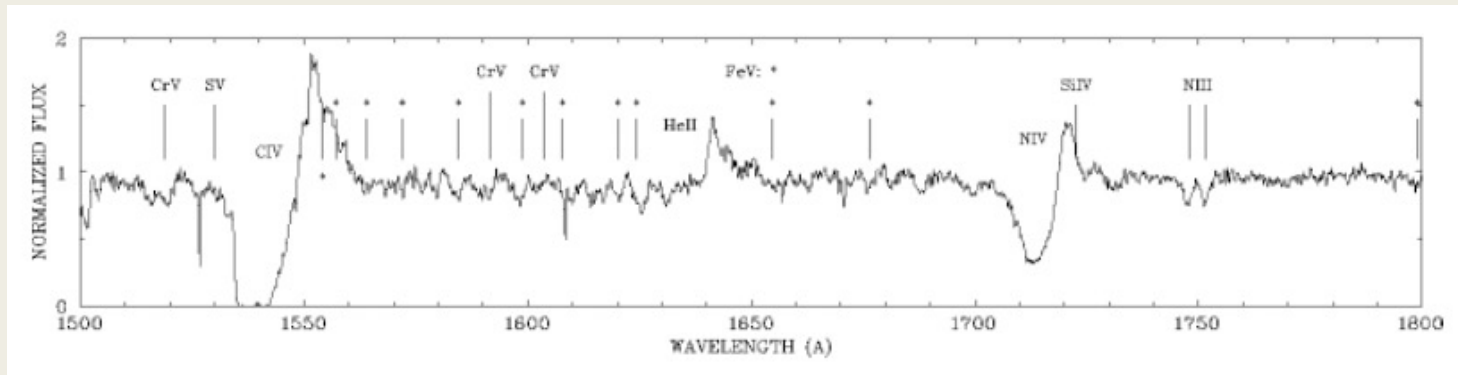
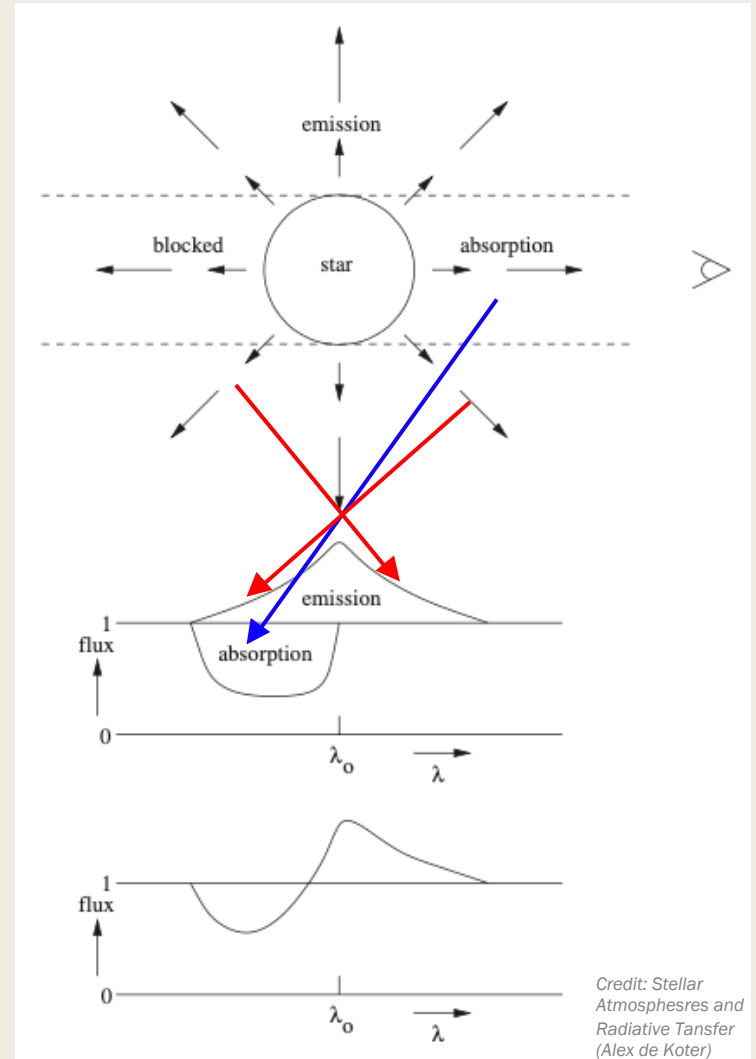


(b) Absorption Spectra



Observational constraints: Line-driven winds (in hot stars) → P Cygni line profile

- Blue shifted Absorption Component
- Red shifted Emission Component
 - *emission because no star behind: no contrast*

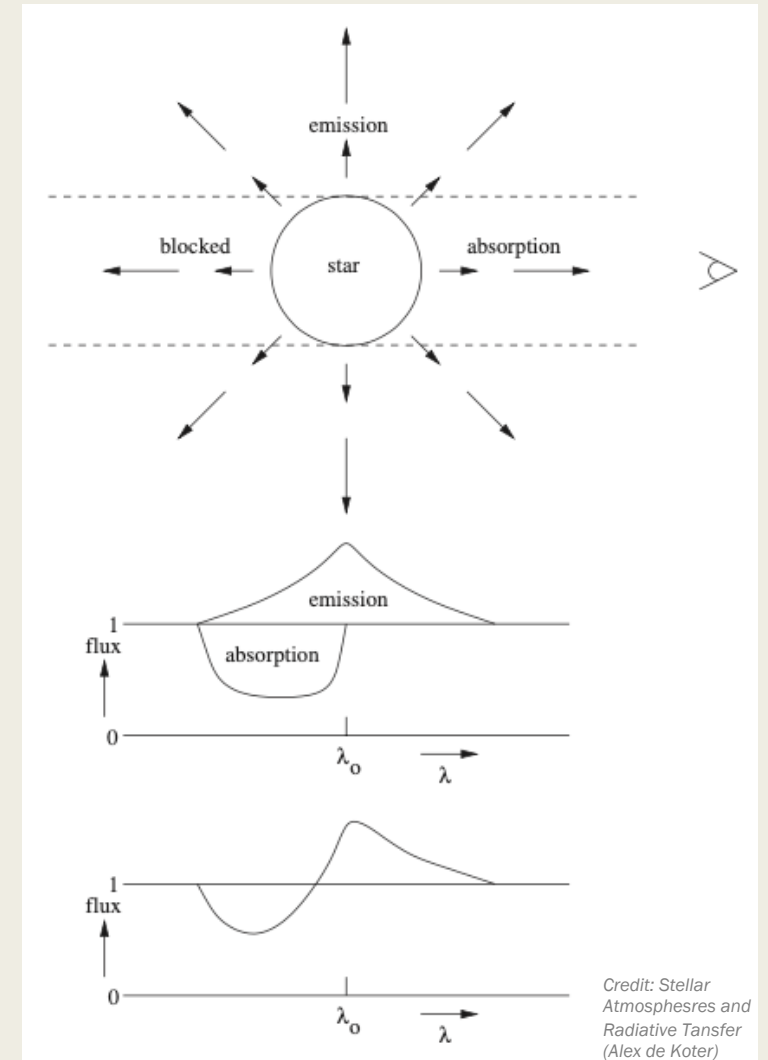


Observational constraints:

Line-driven winds (in hot stars) → P Cygni line profile

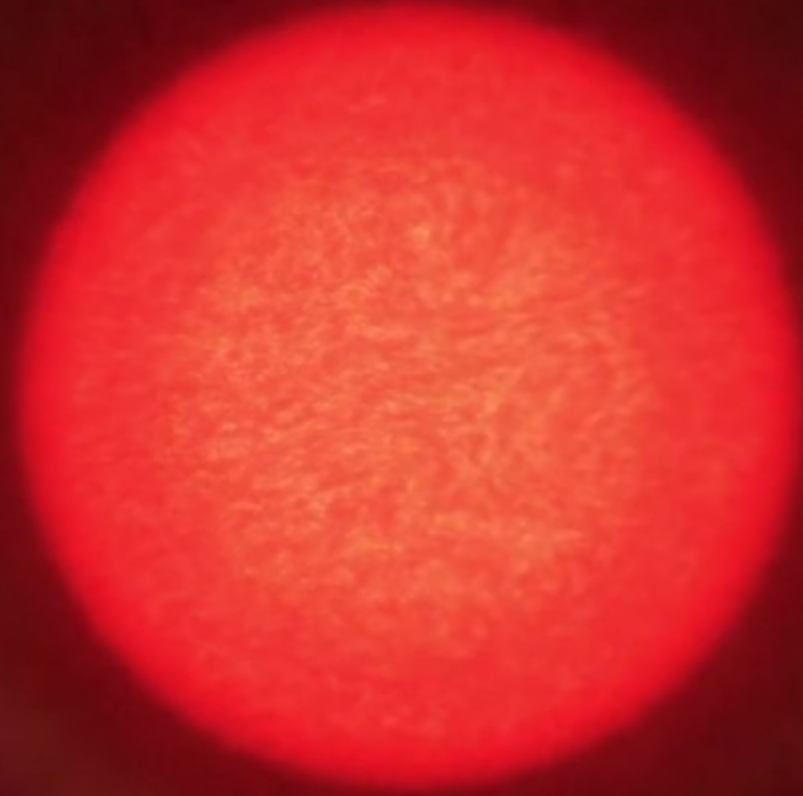
- Blue shifted Absorption Component
- Red shifted Emission Component
 - *emission because no star behind: no contrast*
- Assumptions commonly needed:
 - Velocity structure: $v(r) = v_{\infty} \left(1 - \frac{r_0}{r}\right)^{\beta}$ with $\beta \sim 1$
 - small beta, steeper acceleration (in space)
 - Chemical composition and ionization fraction
 - Spherical symmetry
 - Steadiness and (often) homogeneity

$$\dot{M} = 4\pi r^2 \rho(r) v(r)$$

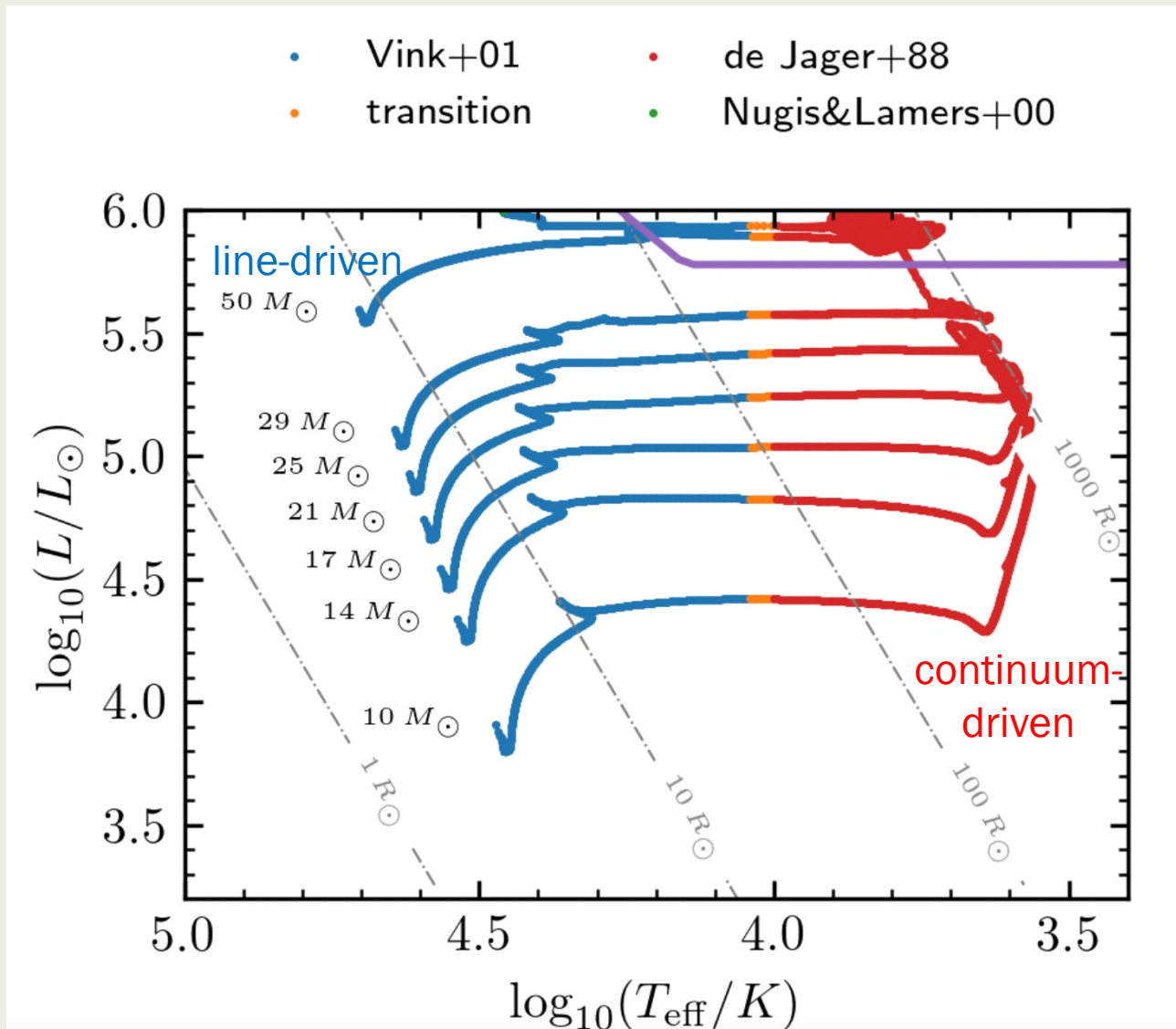


Continuum / (dust?)-driven mass loss from cold stars

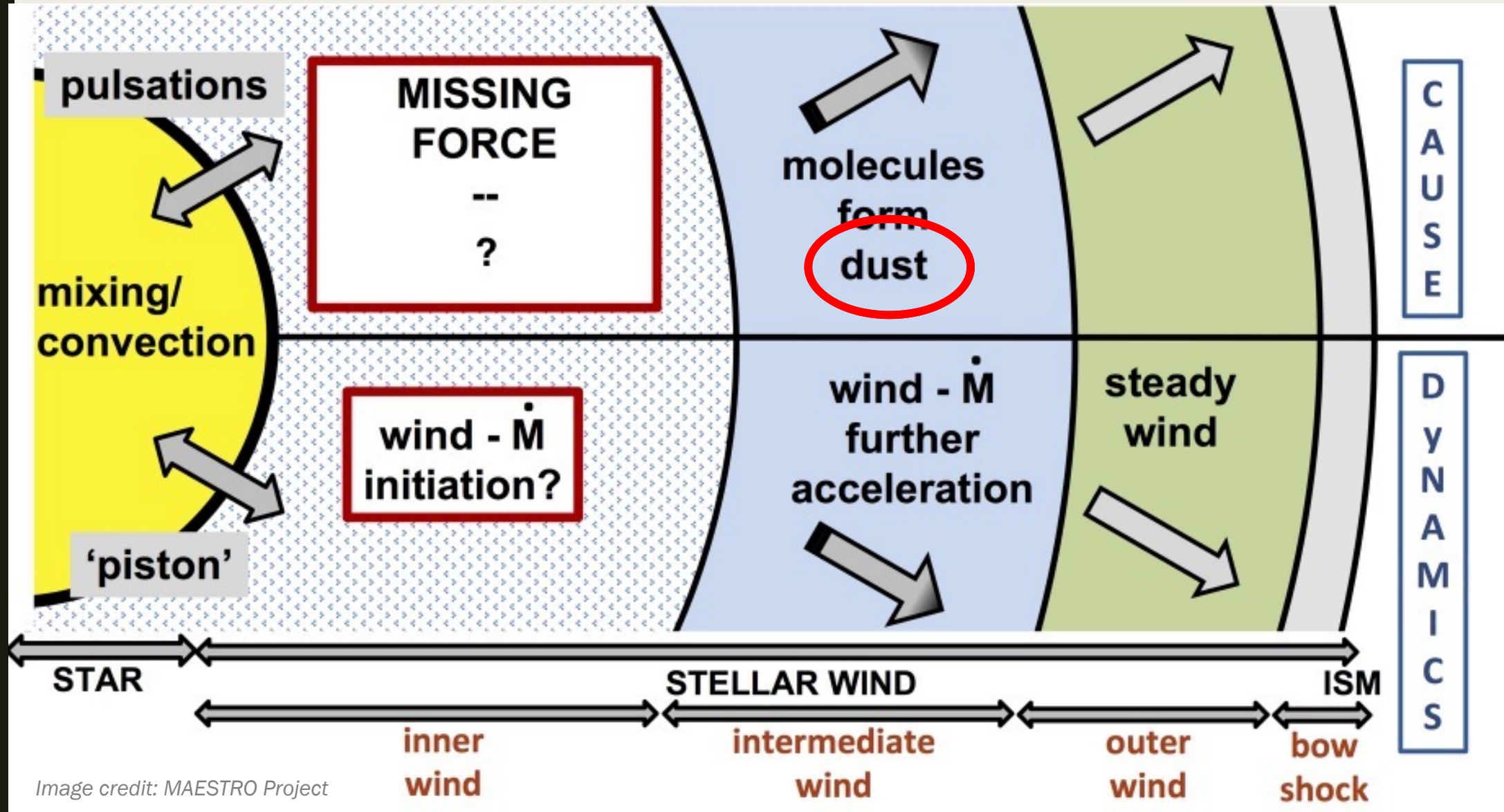
(red supergiants, red giants, asymptotic giant branch)



Mass loss prescriptions in stellar tracks

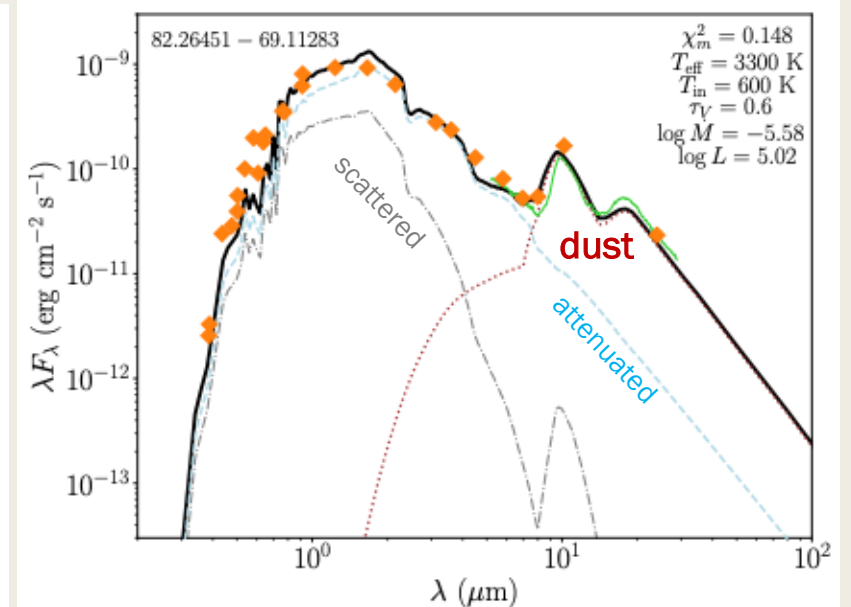
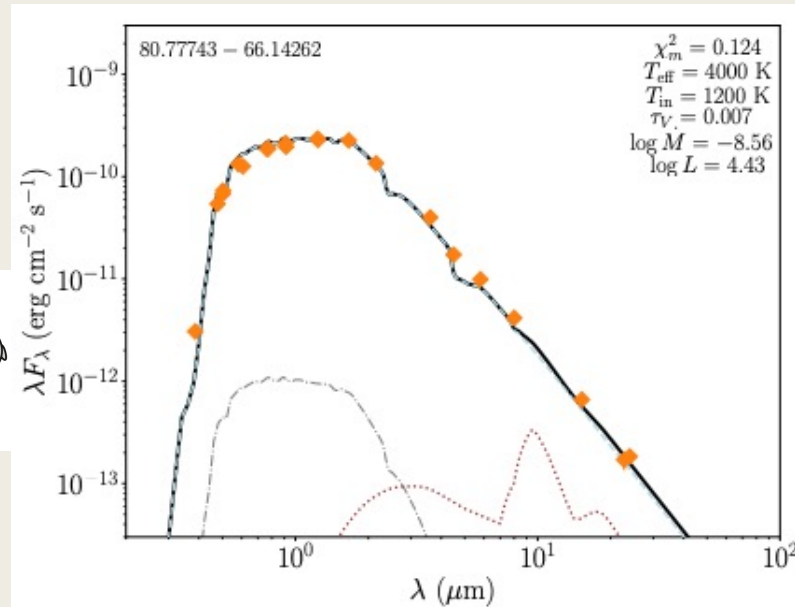
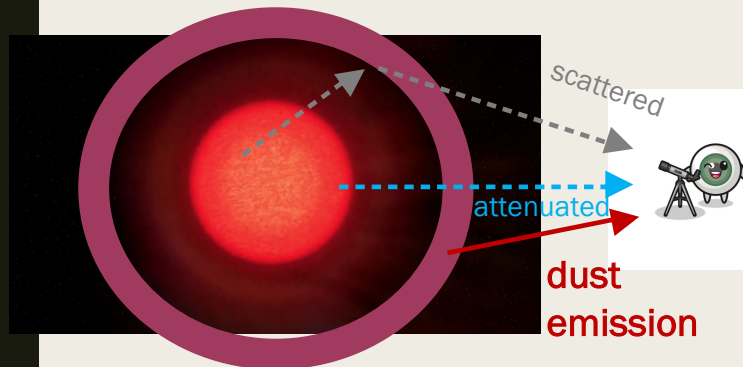


Possible geometry of cool winds



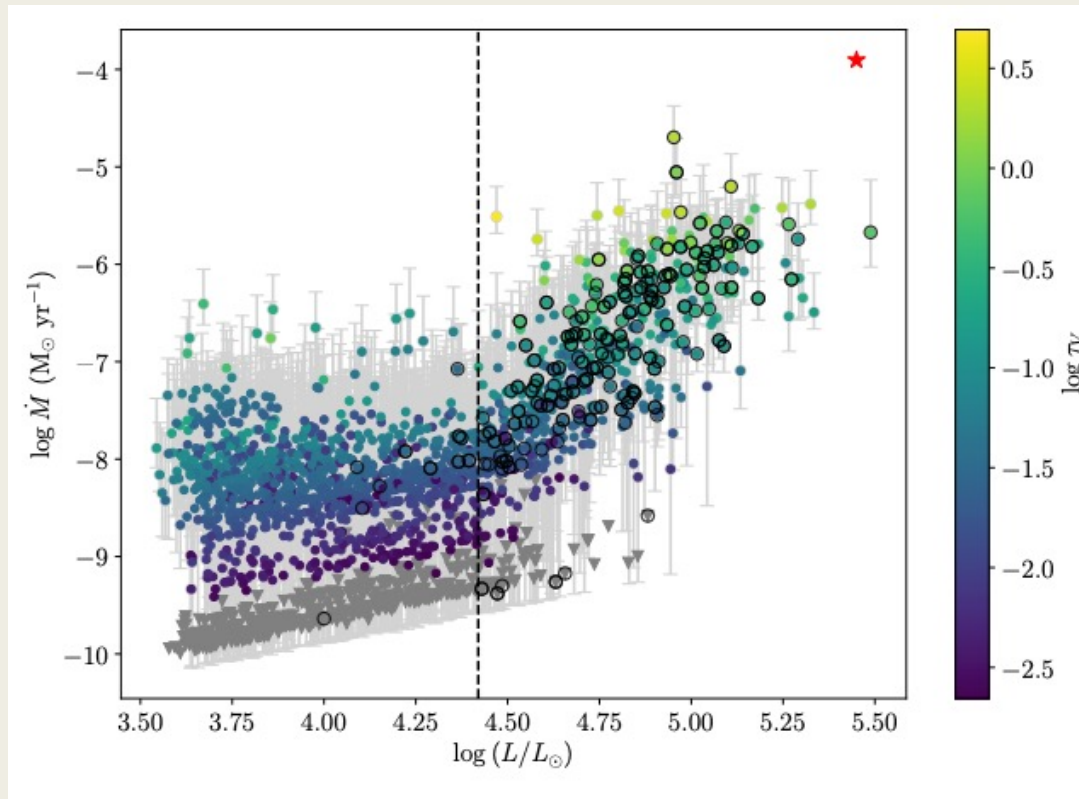
Observational constraints: Continuum/dust(?) - driven winds (in cold stars) → IR excess from dust

- Dust absorption of visual light and re-emission in IR
- Dust is solid particles. Only in temperature $\sim < 1200$ K
- A dust-to-gas ratio needs to be assumed
- Not clear if dust is the driver of the mass loss or just by-product

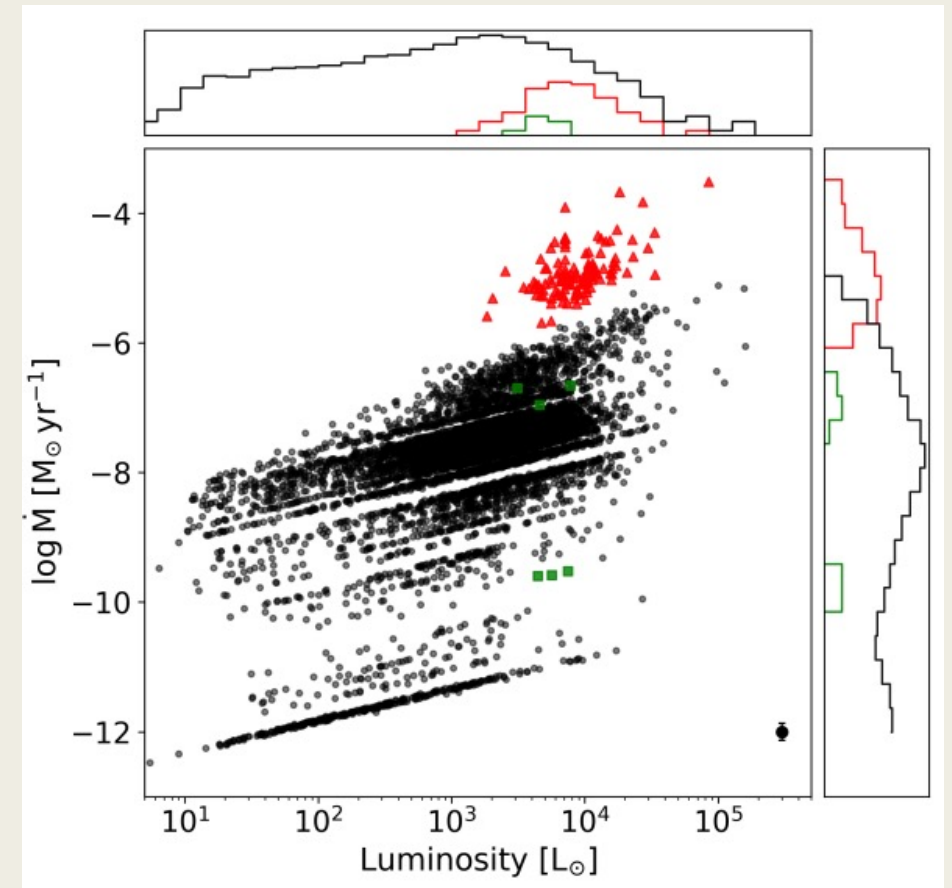


Mass loss of Red Supergiants and AGB stars

- Mass loss always dependent on Luminosity



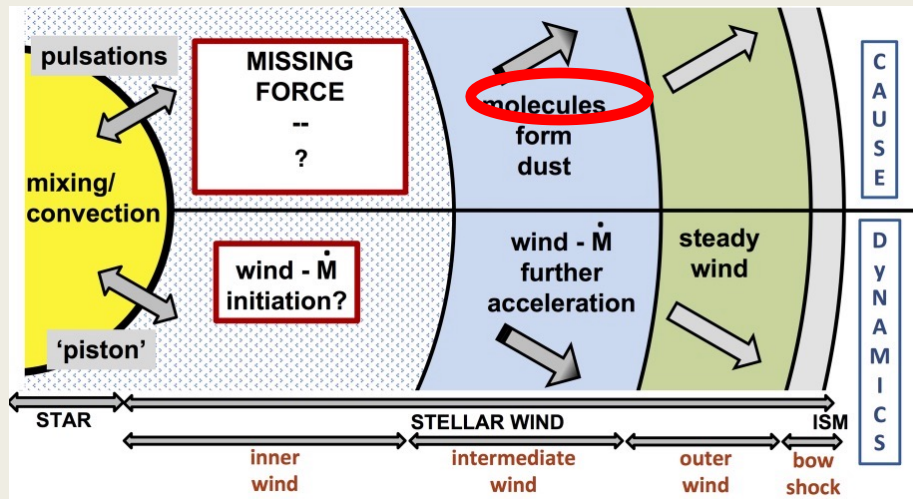
Antoniadis+2024



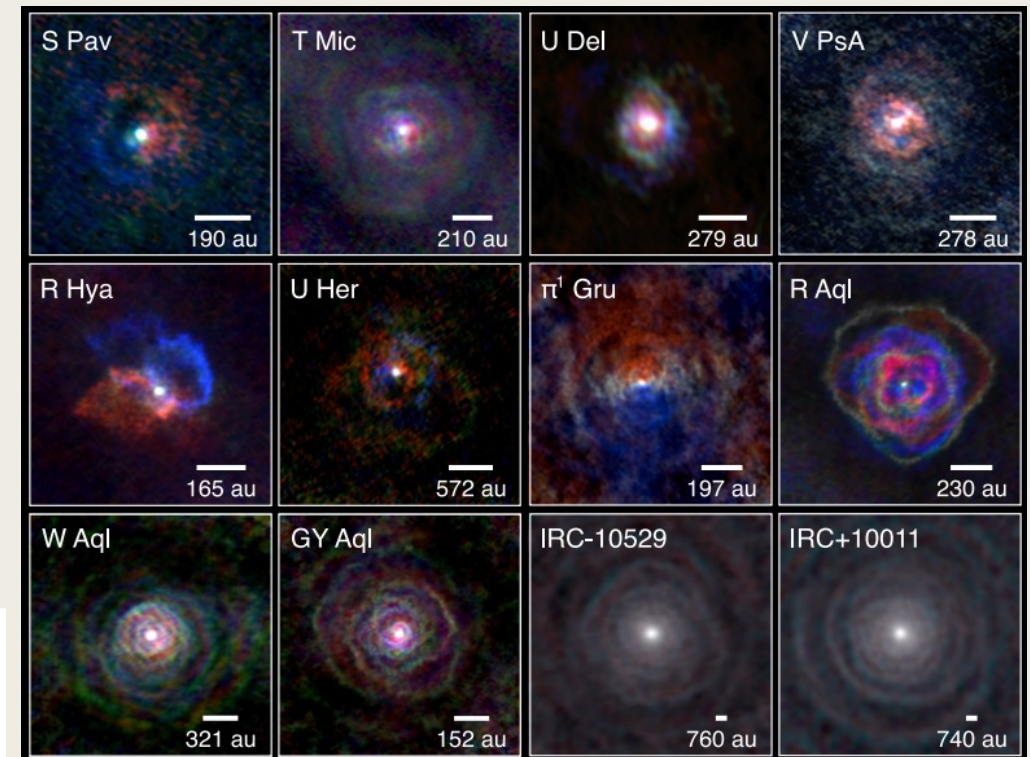
Liberatori+2026

Observational constraints: Continuum/dust(?) - driven winds (in cold stars) → CO molecules

- CO molecules, following the lost mass
 - *vibrational or rotational band (millimeters and sub-millimeters; ALMA)*
- No dust-to-gas ratio assumption



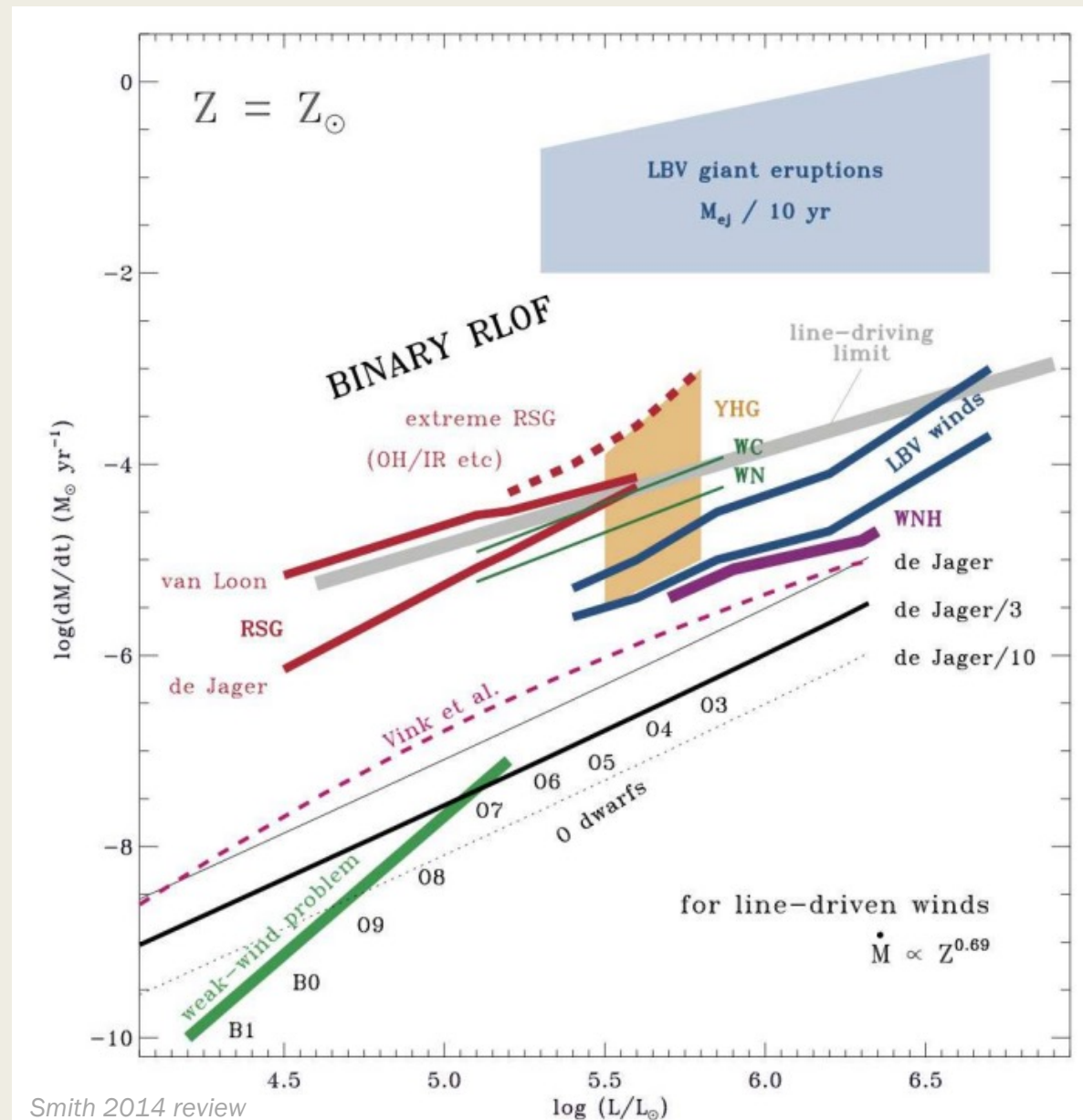
Gallery of AGB winds. Emission maps of 12 AGB stars are shown, derived from the ATOMIUM $^{12}\text{CO } v=0 \text{ J} = 2-1$ data. For each star, emission that is redshifted with respect to the local standard of rest velocity is shown in red, blueshifted emission is in blue, and rest velocity is in white. The scale bars have an angular extent of $1''$. Sources are ordered by increasing mass-loss rate, from left to right, and from top to bottom. Figure based on Figure 1 of Decin et al. (2020).



Wind mass loss rates in stellar models

- (semi-)Empirical parametric models:

$$\dot{M}(L, T_{\text{eff}}, Z, R, M, \dots)$$

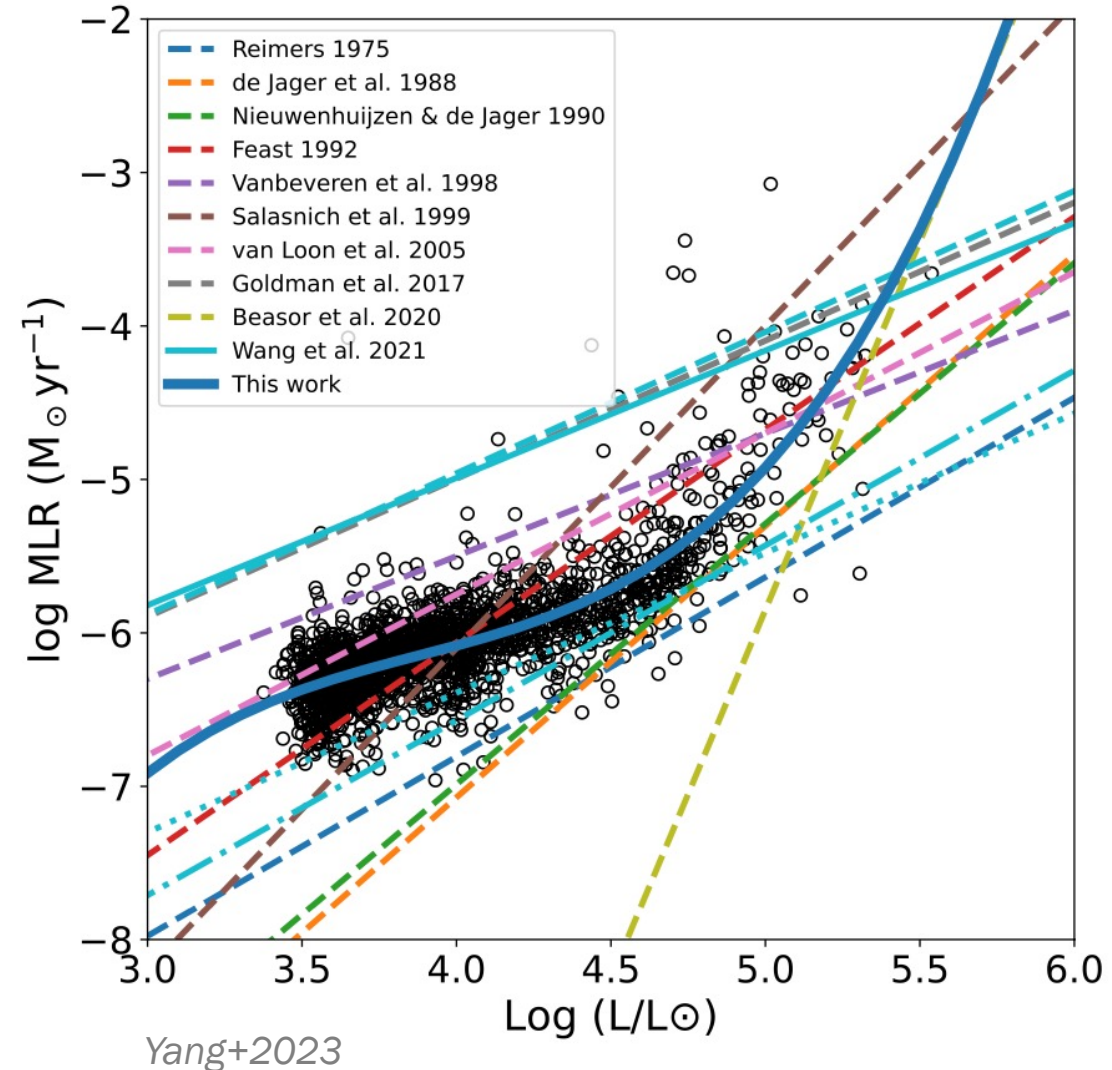


Mass loss of Red Supergiants (or Red Giants or Asymptotic giant branch)

- Uncertainty of orders of magnitudes
- Uncertainty of the metallicity dependence
 - *probably weak or no dependence for RSG winds*

Table 4: Mass-loss rate prescriptions from different works.

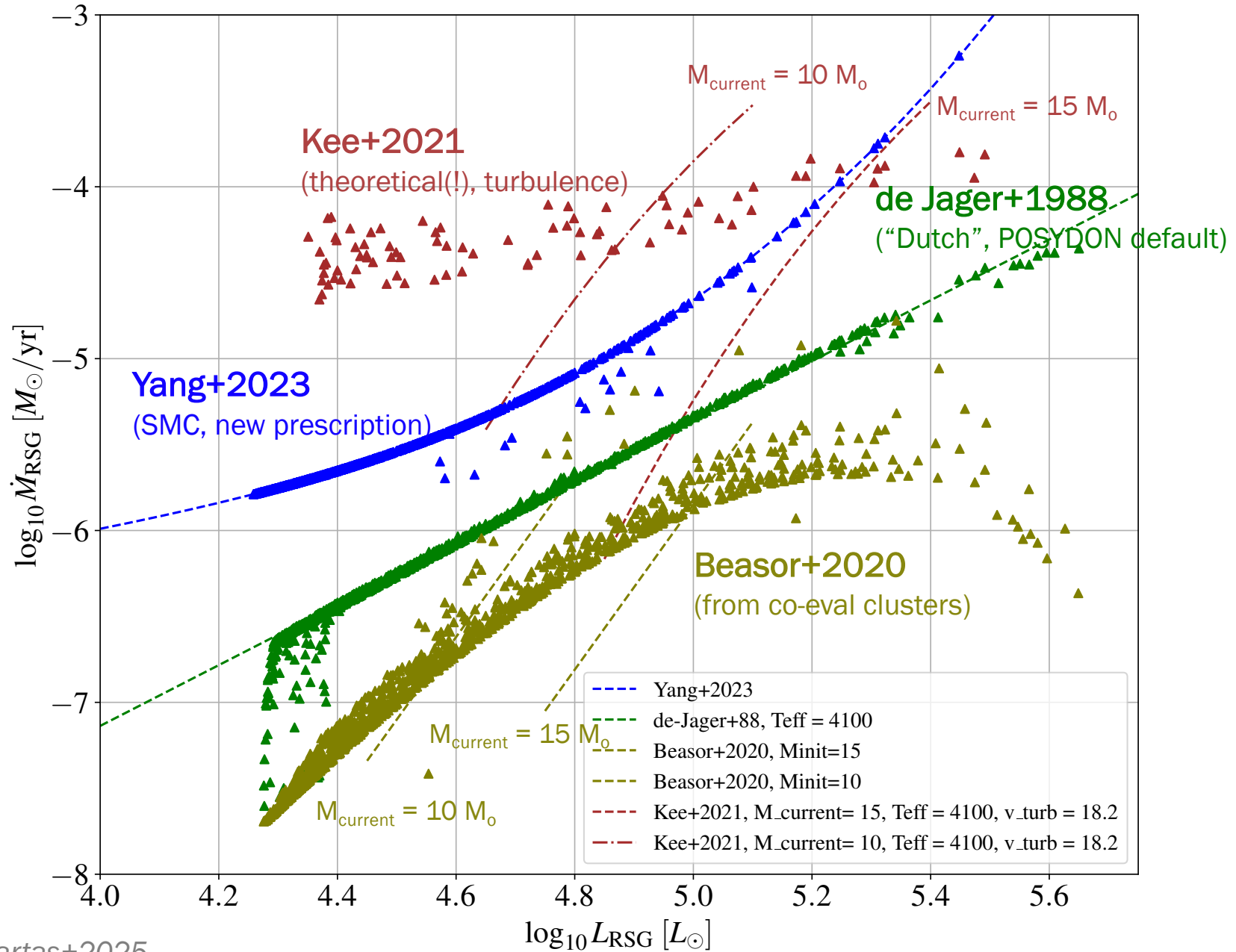
\dot{M} relation ($M_{\odot} \text{ yr}^{-1}$)	DUSTY mode	Reference	Sample
$\dot{M} = 10^{-8.158} L^{1.769} T_{\text{eff}}^{1.676}$	-	de Jager et al. (1988)	Milky Way
$\dot{M} = 10^{-5.56} \left(\frac{L}{10^4}\right)^{1.05} \left(\frac{T_{\text{eff}}}{3500}\right)^{-6.3}$	RDW Analytic	van Loon et al. (2005)	LMC
$\dot{M} = 1.06 \times 10^{-5} \left(\frac{L}{10^4}\right)^{0.9} \left(\frac{P}{500d}\right)^{0.75} \left(\frac{r_{\text{rel}}}{200}\right)^{-0.03}$	RDW	Goldman et al. (2017)	LMC
Analytic solution (see reference)	-	Kee et al. (2021)	-
$\log \dot{M} = -21.5 - 0.15 M_{\text{ini}} + 3.6 \log L$	Steady-state, r^{-2}	Beasor et al. (2023)	Galactic clusters
$\log \dot{M} = 0.45(\log L)^3 - 5.26(\log L)^2 + 20.93 \log L - 34.56$	RDW	Yang et al. (2023)	SMC
$\log \dot{M} = 0.26 \log L - 14.19 \log\left(\frac{T_{\text{eff}}}{4000}\right) - 9.17, \log L < 4.4$	Steady-state, r^{-2}	This work	LMC
$\log \dot{M} = 2.5 \log L - 31.78 \log\left(\frac{T_{\text{eff}}}{4000}\right) - 17.47, \log L \geq 4.4$			



Mass loss importance

- **Evolution** of stars how they look like, in which part of the HRD they are found
- **Feedback and chemical enrichment** to their environment
- For massive stars:
 - *How the **supernova** will look like (and actually whether it will explode!)*
 - *what kind of **compact object** (and its mass)*

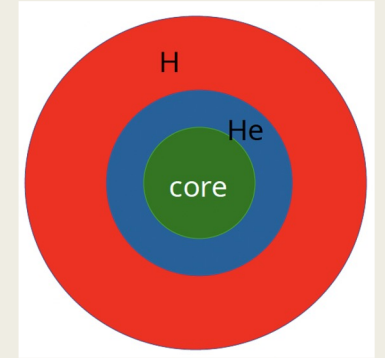
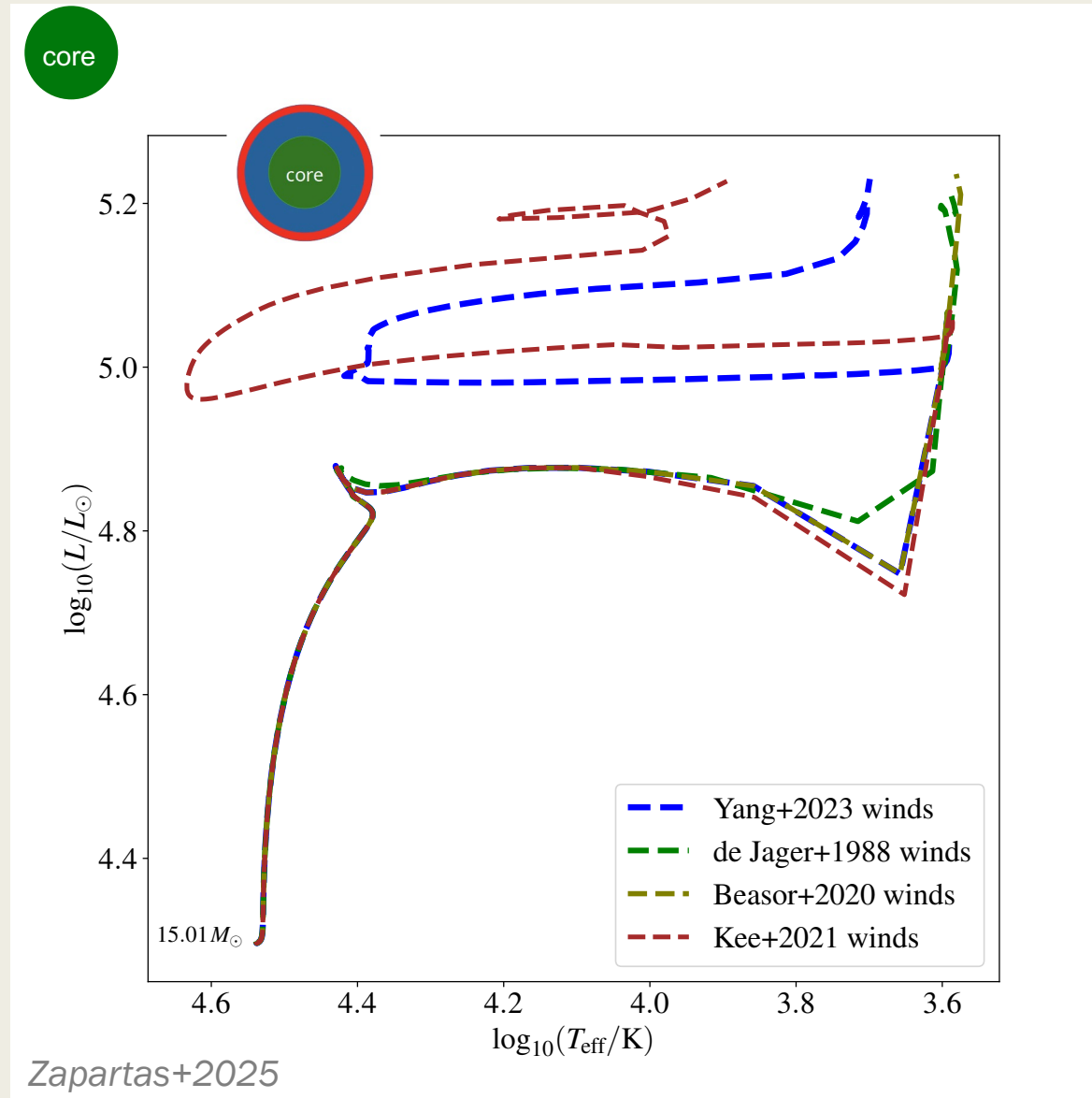
Example uncertainties of RSG winds



MESA

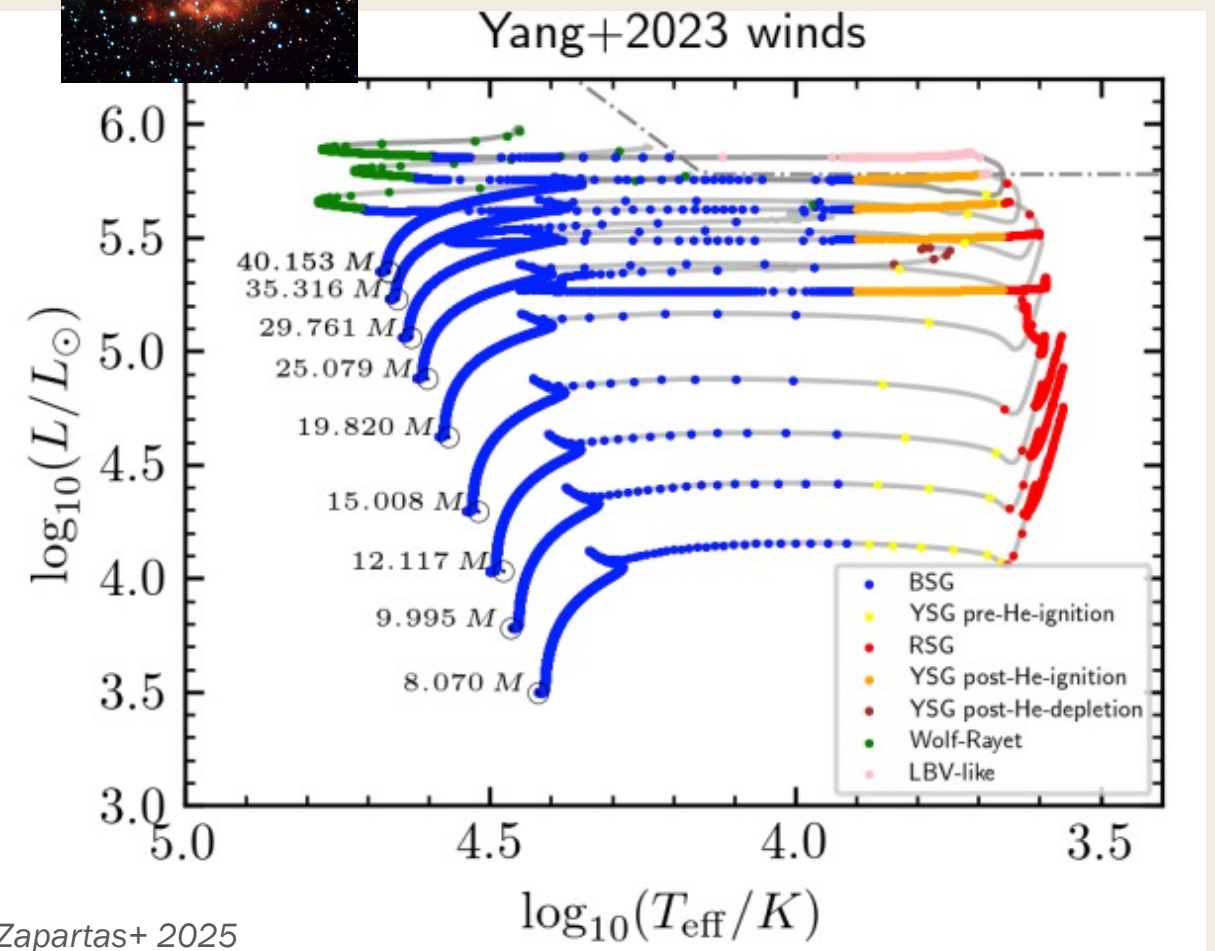


Affecting stellar track at the HRD



Extreme mass loss at high luminosity?

- Wolf-Rayet stars
 - *Hydrogen-poor (i.e., “helium”) stars of high luminosity and very strong, optically-thick winds*



Extreme mass loss at high luminosity?

- Humphreys-Davidson limit

Figure 2. The HR Diagram, M_{Bol} vs. $\log T_e$, for the luminous stars in the Milky Way from [25].

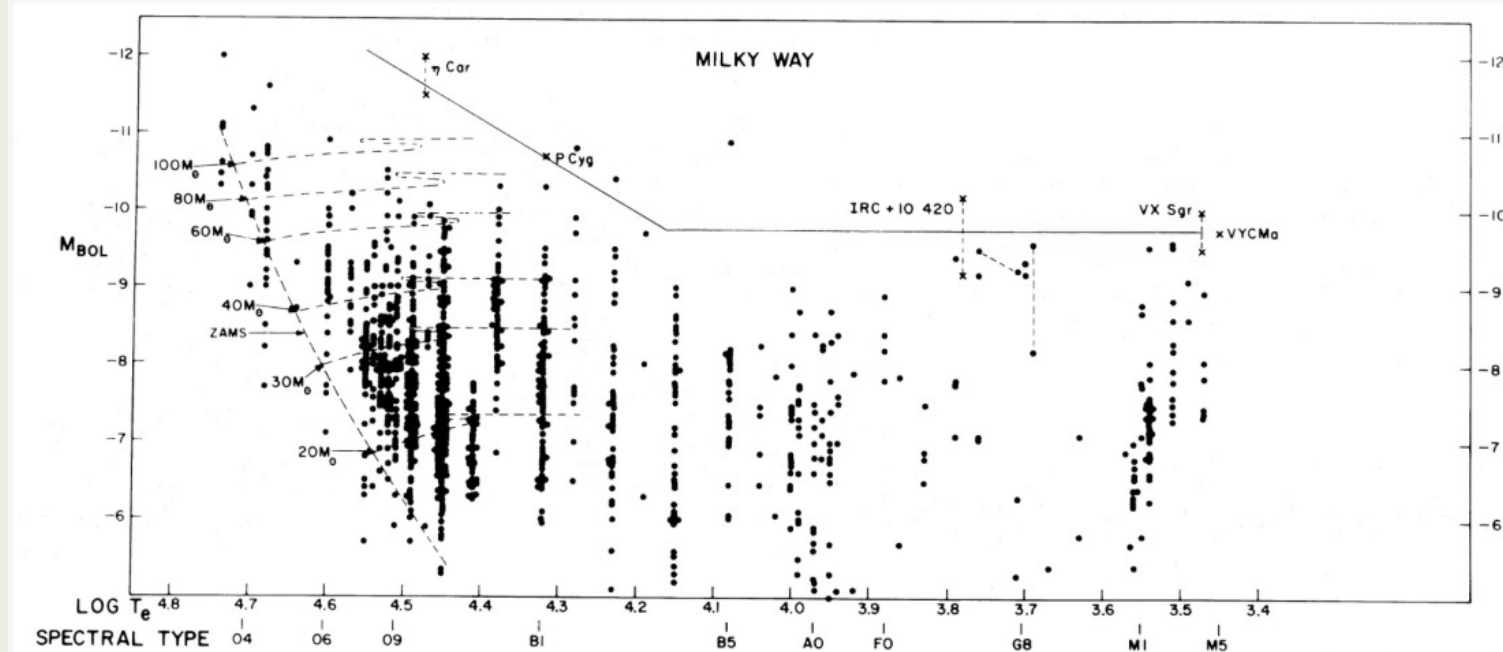
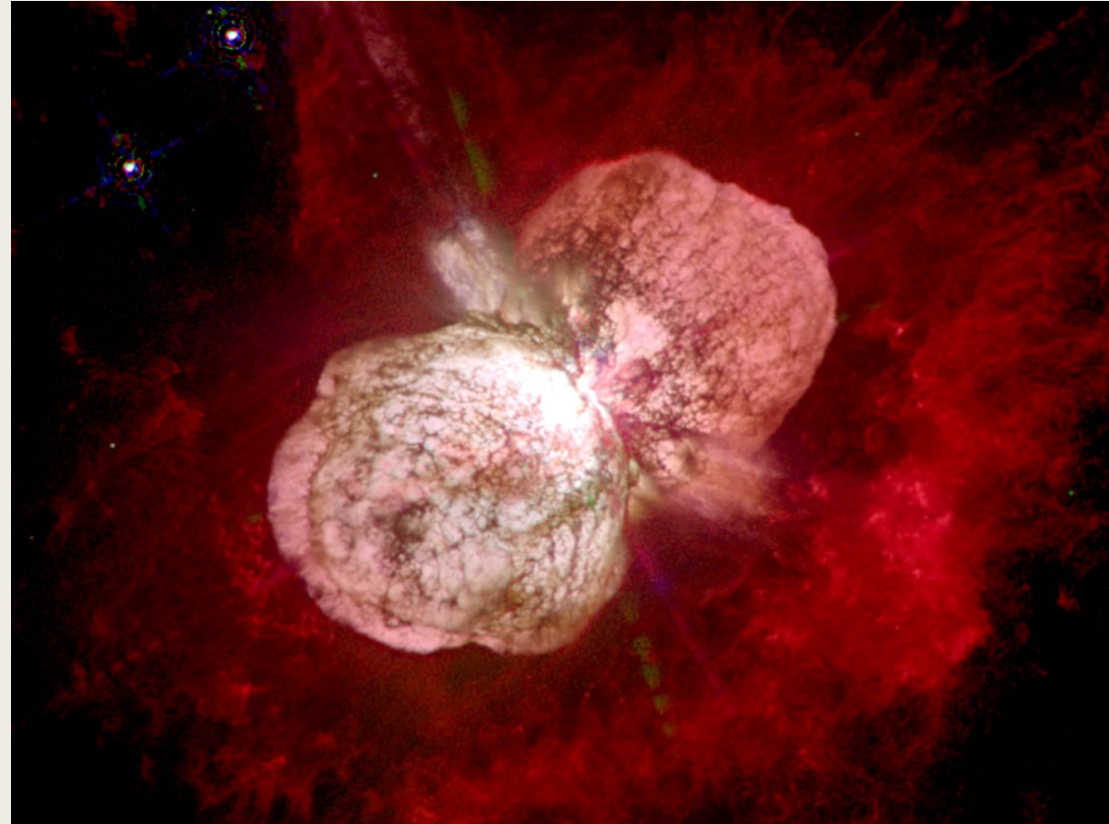
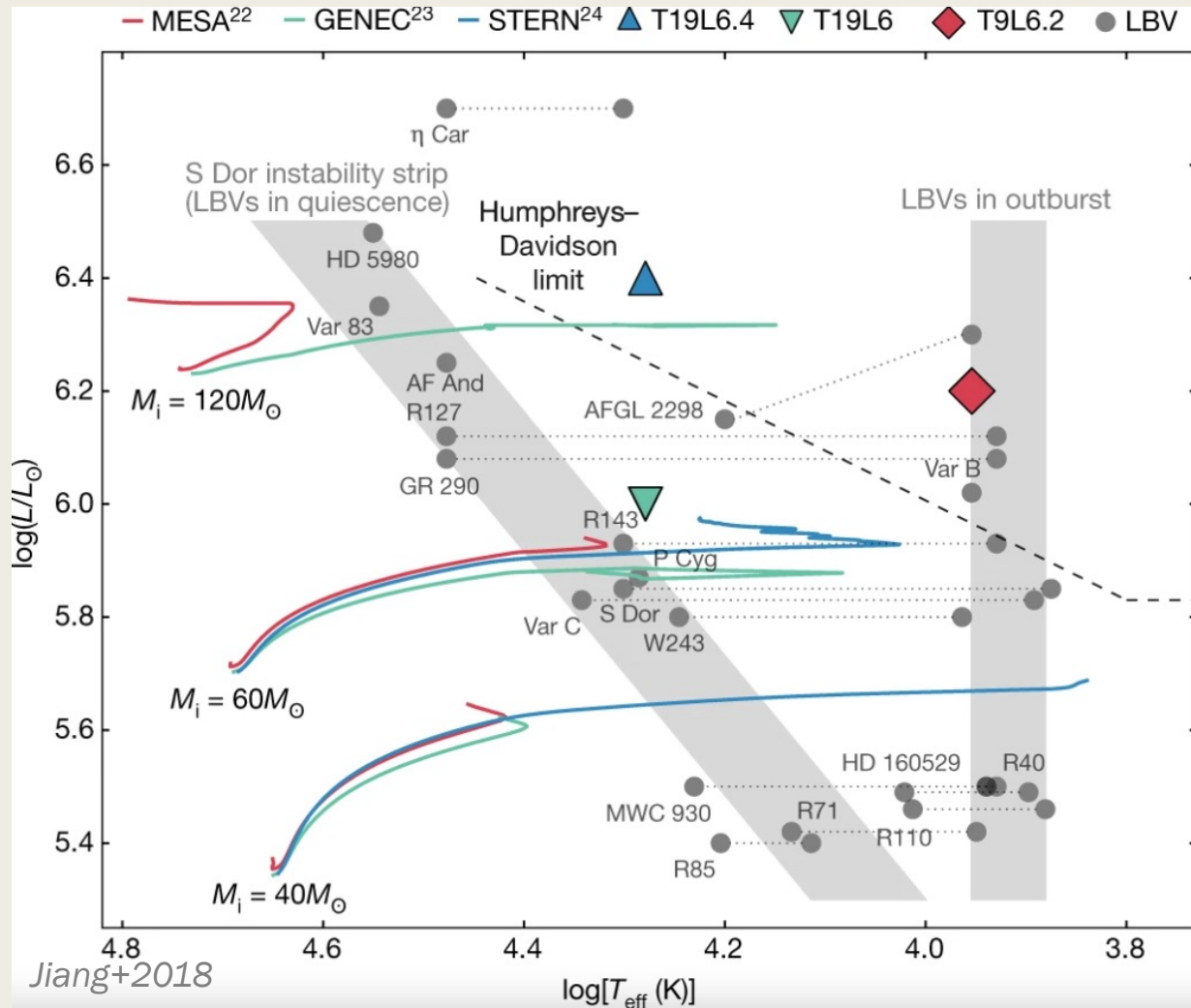


FIG. 3.—The “theoretical” H-R diagram, M_{bol} versus $\log T_e$, for the galactic supergiants. The position of the ZAMS and evolutionary tracks with mass loss are shown. The solid line defines the approximate upper boundary of the supergiant luminosities. The positions of two peculiar stars, η Car and P Cyg, and three supergiant infrared sources are also indicated.

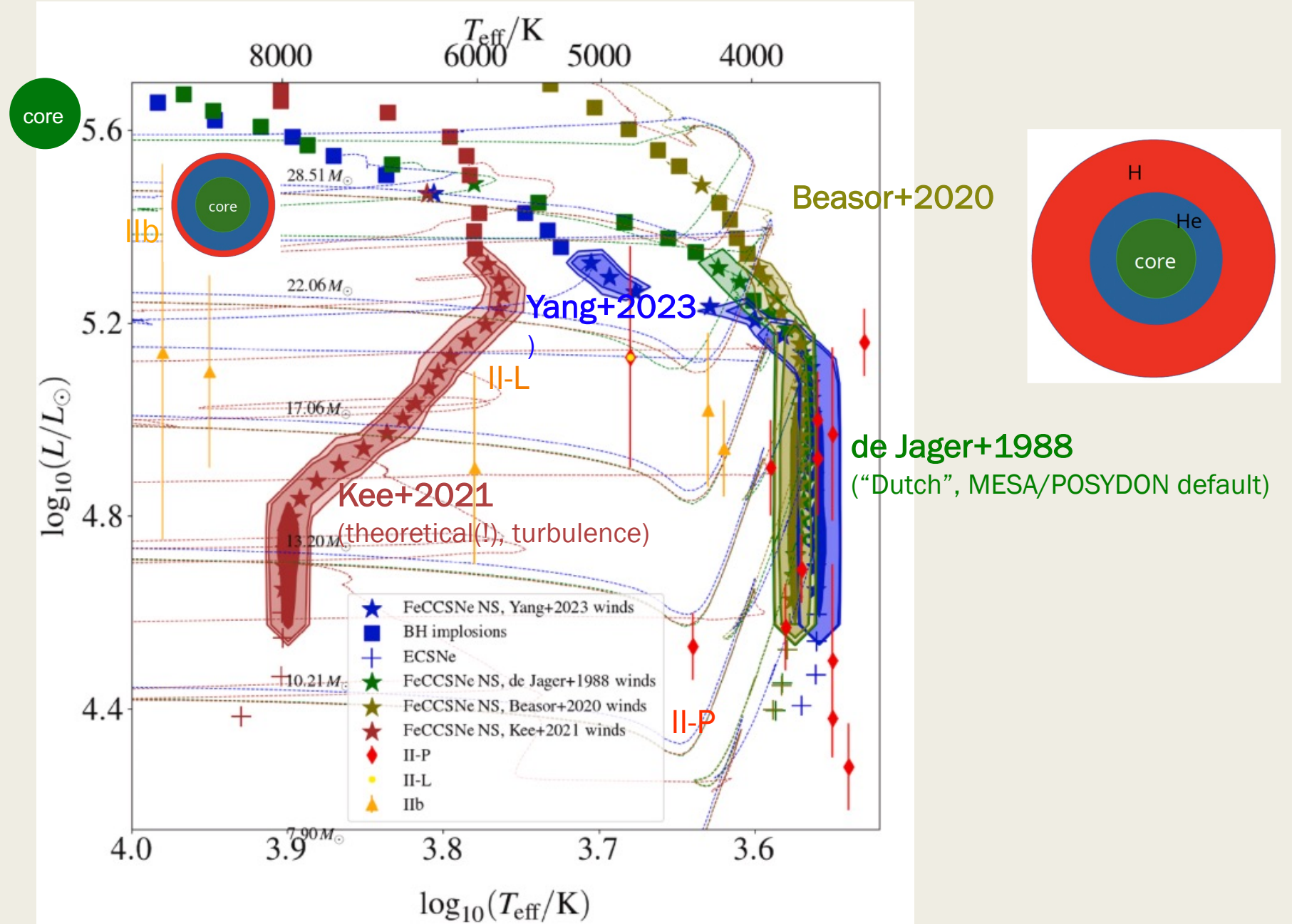
- Potentially related to Eddington Factor

$$L_{Edd} = \frac{4\pi cGM}{\kappa} \approx 3.3 \times 10^4 \left(\frac{M}{M_{\odot}} \right) L_{\odot}$$

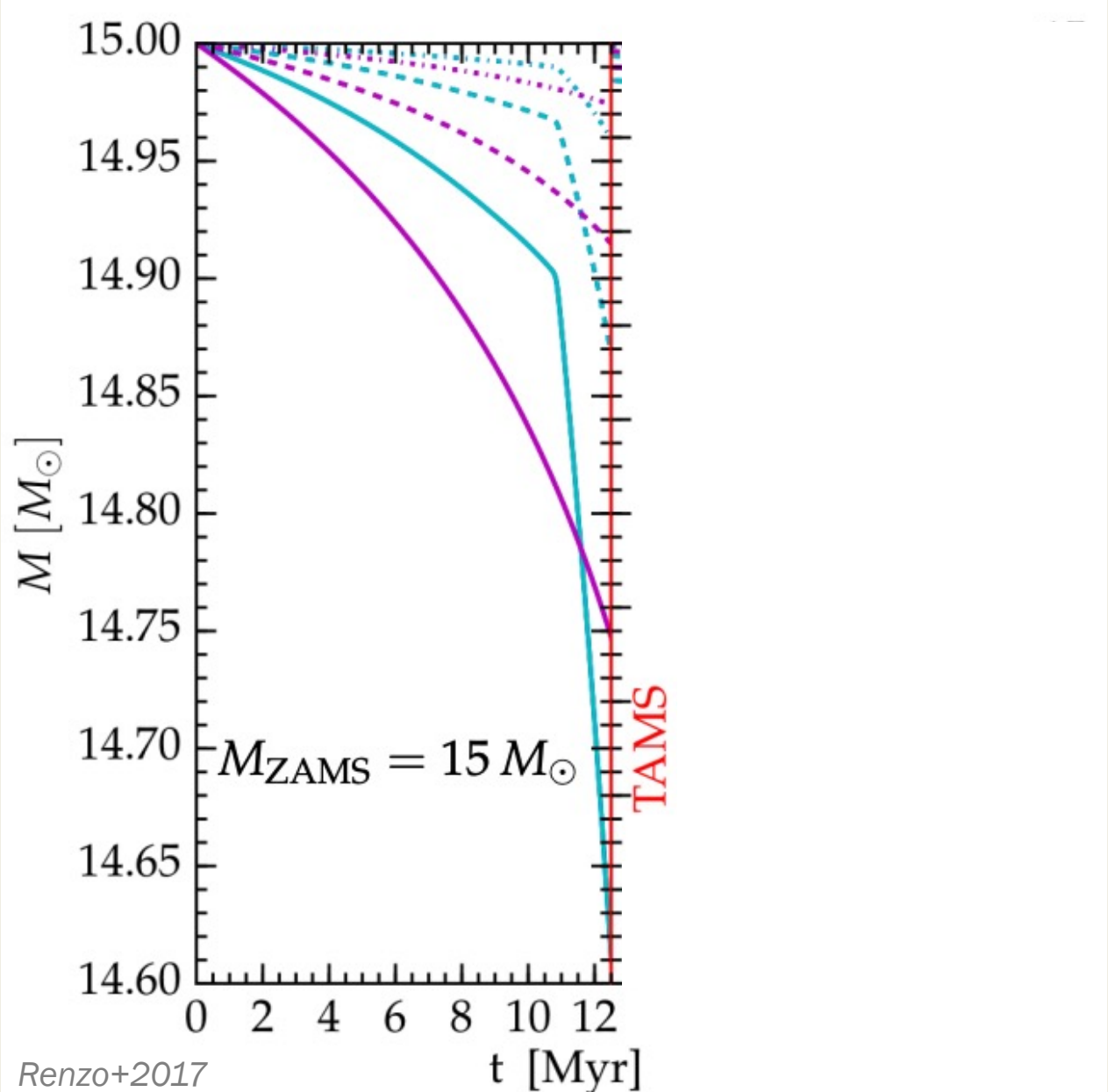
Episodic/Eruptive mass loss, Luminous Blue Variables



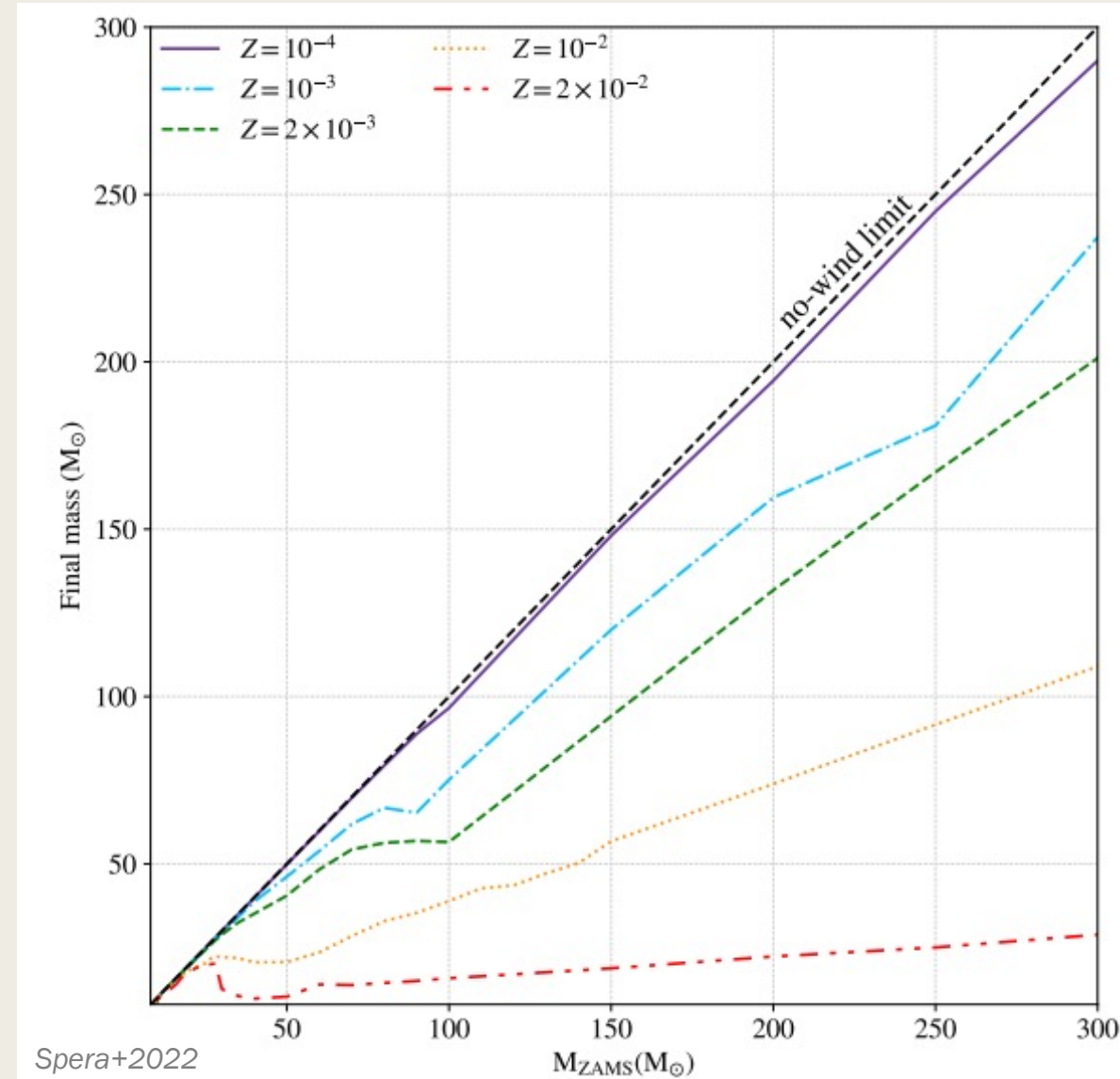
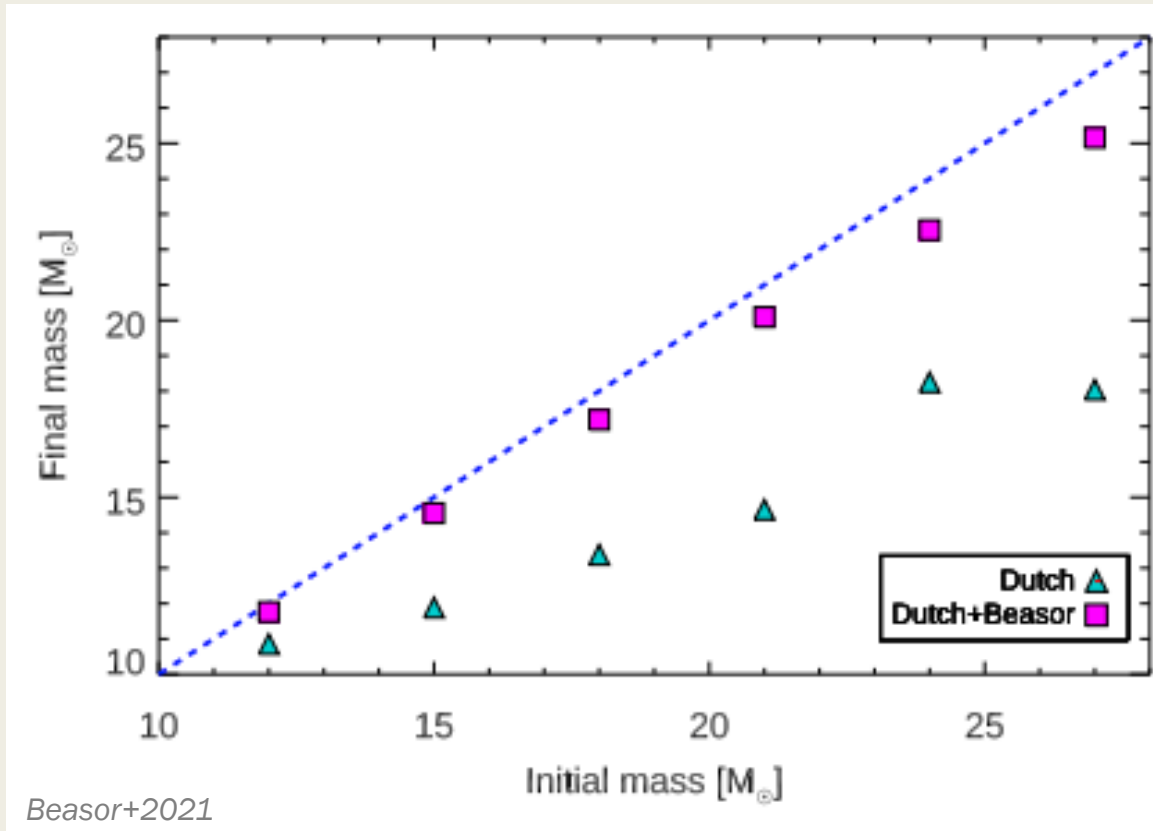
Final position of stars, how their supernova will look like!



Uncertain final mass



Uncertain initial-final mass relation and compact object mass!



- Uncertain Black Hole masses!
 - Massive black holes mostly at low- Z ?

To be discussed later...

- Rotationally-enhanced winds (extra mass loss from highly spinning stars)
- Magnetic braking (winds at low-mass magnetic stars spin down the star)

Questions?



Backup slides

Regimes that (default) models are not valid

1000 Msun

- extreme mass loss rate etc. So strong Luminosity that not really in hydrostatic equilibrium. optically thick winds.
- Still accreting, still at “formation”: Burning of H during accretion. Photon tiring
- Equation of State (EOS) extrapolation? extreme photon momentum?



1 Earth mass

- Rocky planet, very very different EOS
 - *Solid, liquid, not gas.*
 - *coulomb forces, not just thermal pressure. solids, crystals, phase transitions (liquids to solids)*
 - *solid resist to deformation*
- Energy transport.
 - *Processes like conduction*
 - *no radiation going outward*
 - *maybe movement in the liquid*
- Not a “self-gravitating plasma”

