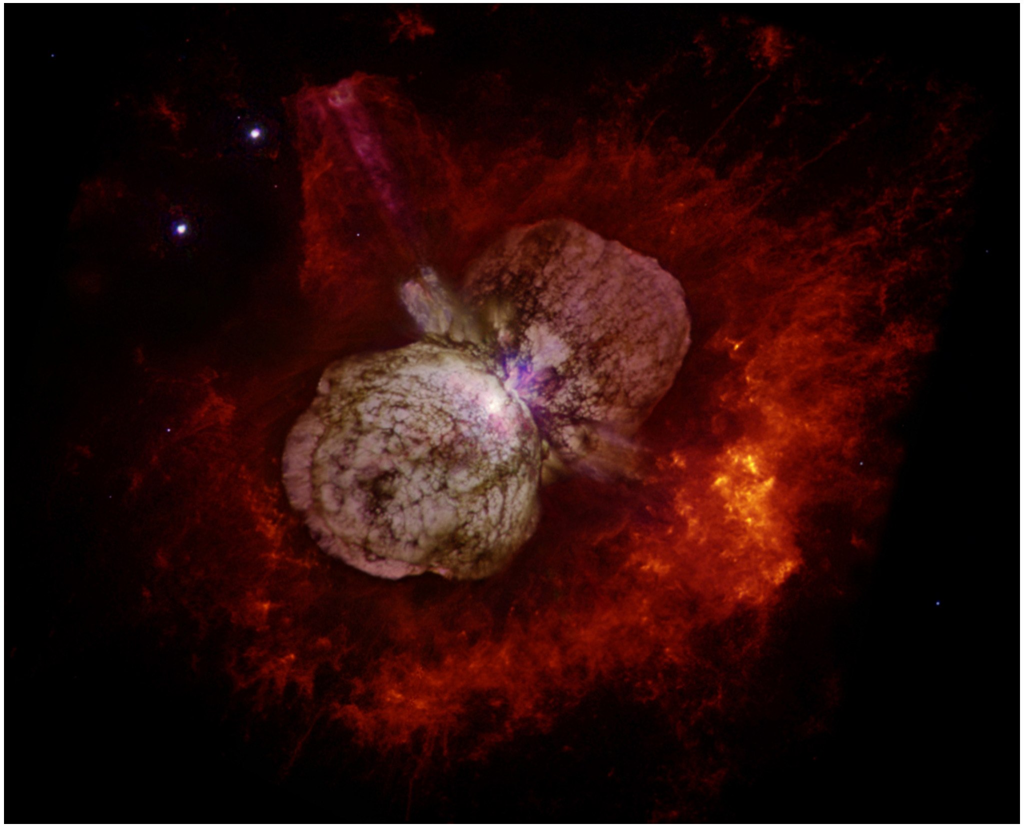
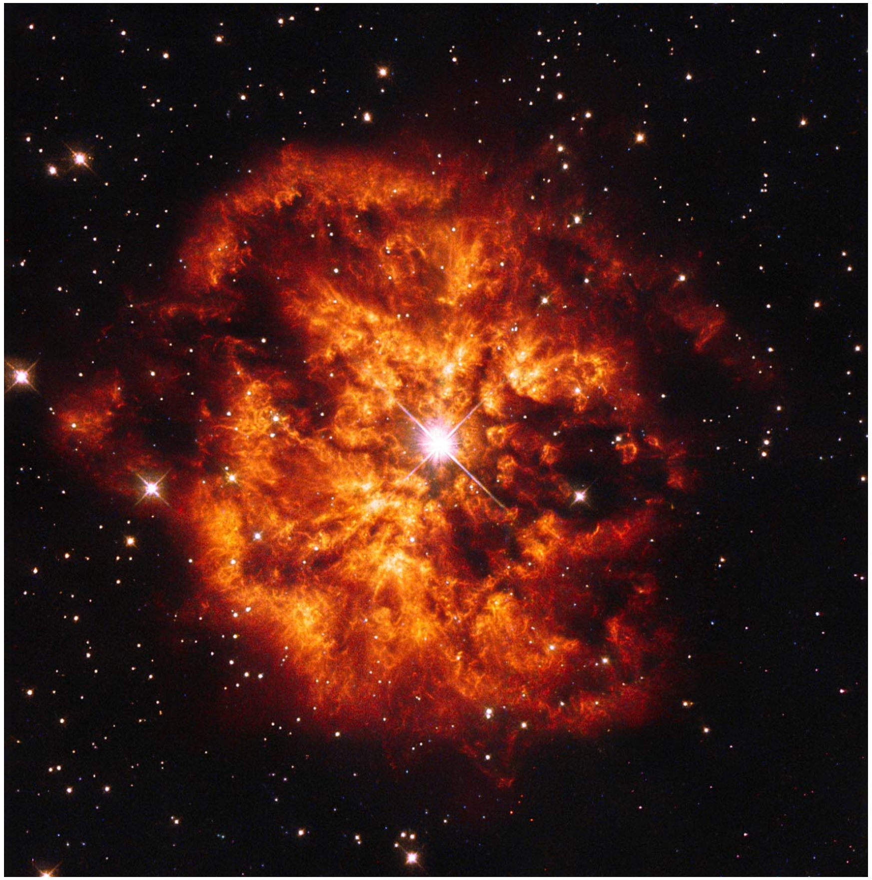
Gravitational wave (GW) progenitors **Michela Mapelli**

Lecture 2.
Massive star evolution





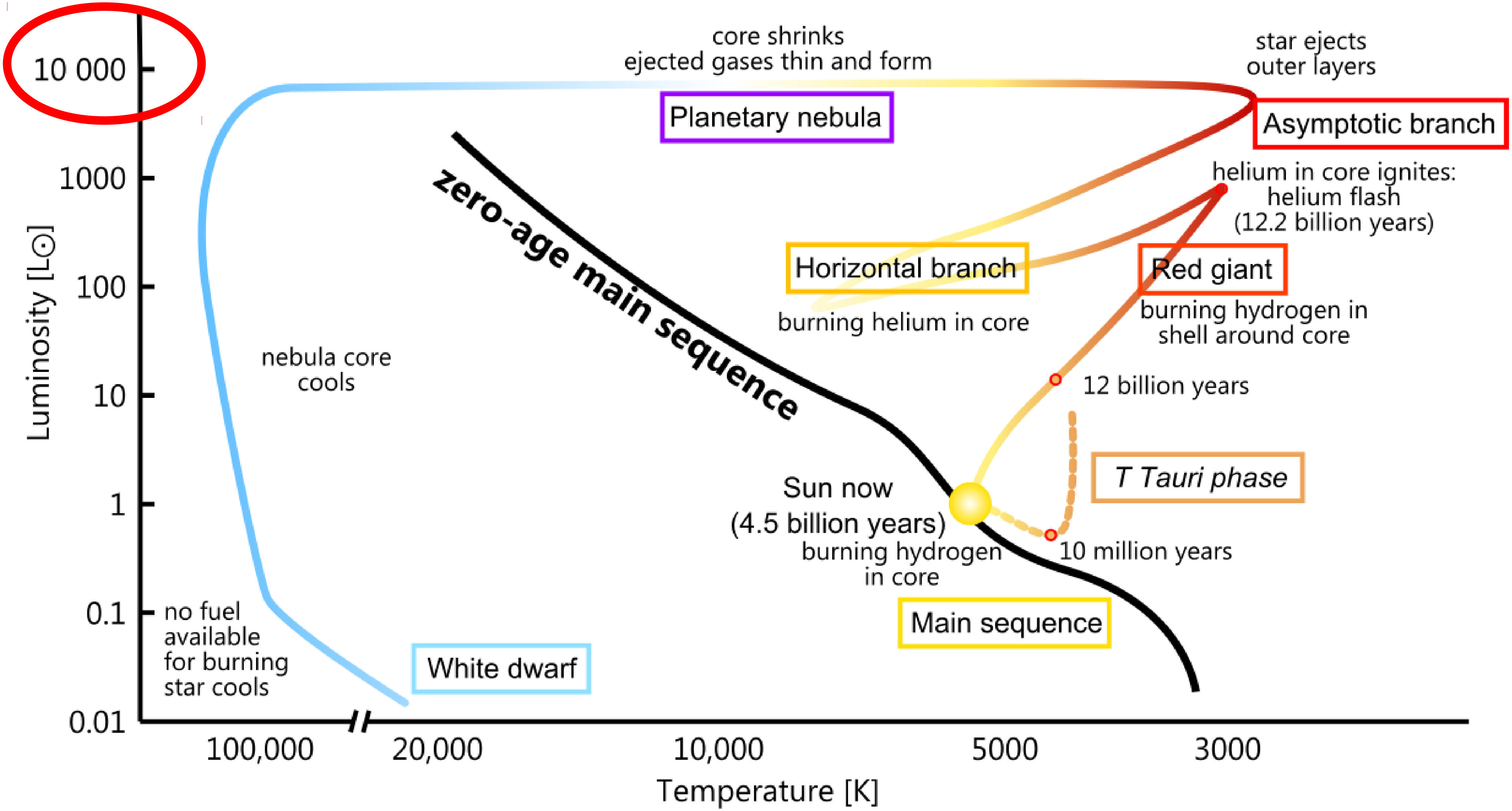
Innsbruck, October 24 2017

Black holes and Neutron stars form from MASSIVE stars (>9 Msun)

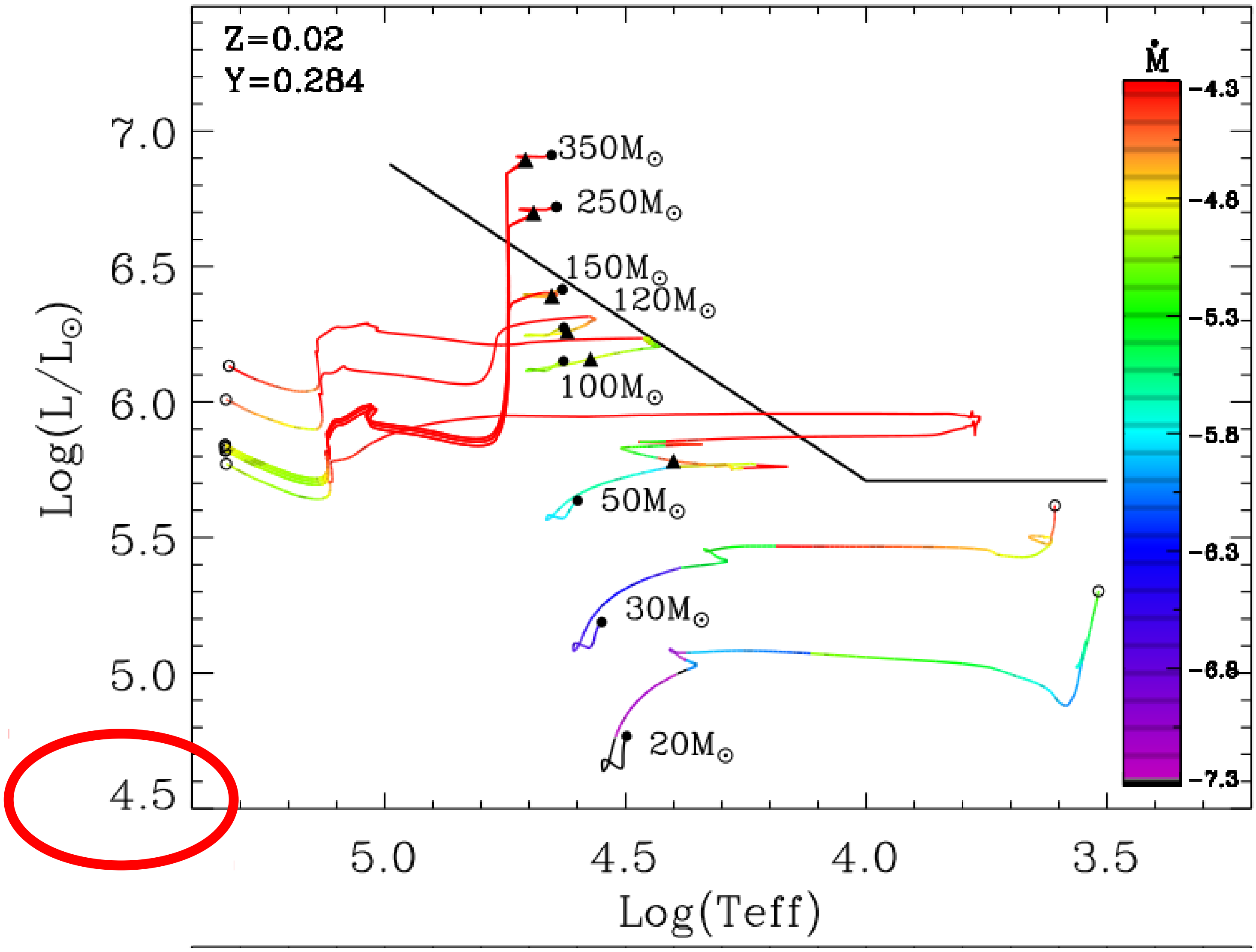
Basic notions of stellar evolution: see starev_part1.pdf

What are the main differences between massive and low-mass stars?

Sun evolution in HR diagram



Massive star evolution in HR diagram



Chen, Bressan et al. 2015

Few crucial definitions: METALLICITY

Metallicity in astrophysics is NOT same as chemistry

Metals in Astro: every element heavier than Helium

Measured with Z = FRACTION of elements heavier than He

$$X + Y + Z = 1.0$$

If M = total mass of system

$X = m_p / M$ $Y = m_{He} / M$ $Z = \sum_i m_i / M$

Cosmological values:
$X \sim 0.75$, $Y \sim 0.25$, $Z \sim 0$

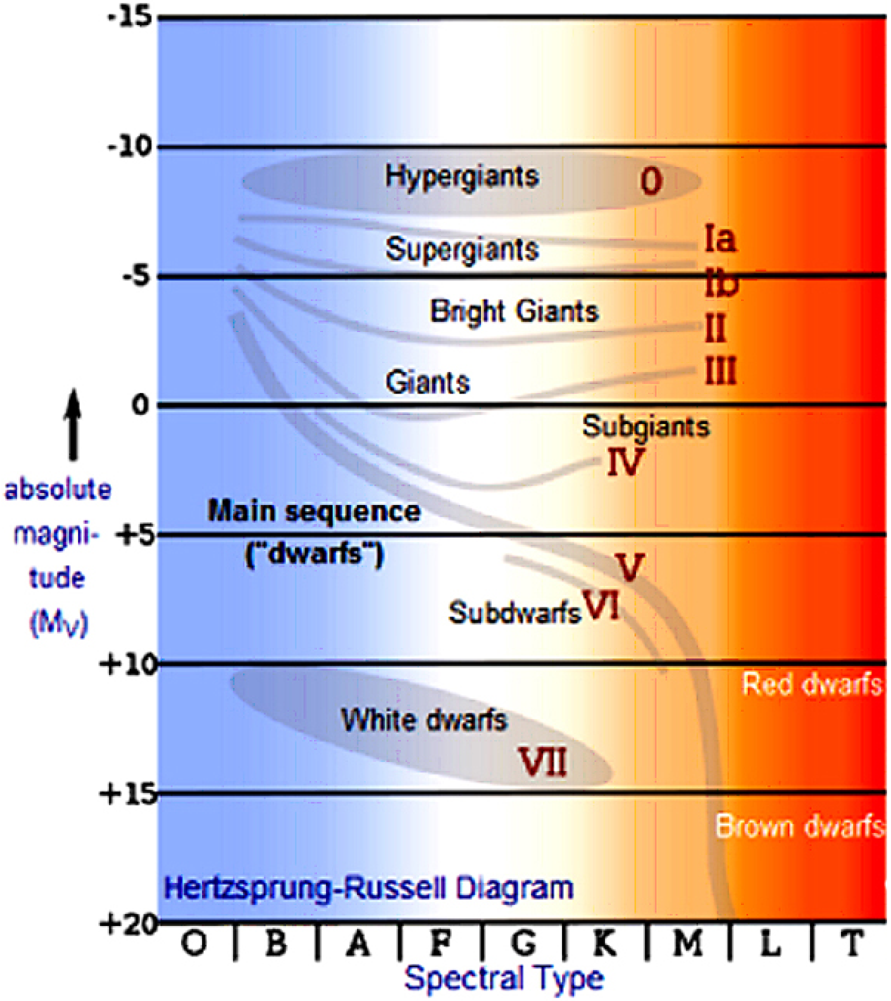
Sun values:
$X \sim 0.73$, $Y \sim 0.25$, $Z \sim 0.02$

Few crucial definitions:

Main sequence (MS): sequence defined in the HR diagram by stars burning Hydrogen (H) in their core

Zero-age main sequence (ZAMS): initial main sequence (when stars just enter main sequence after contracting to equilibrium)

O-type star (full name O-type main sequence star, spectral classification O V): main sequence star (V) of O- spectral type, i.e. very luminous (>10^4 Lsun) and blue (>30'000 K)



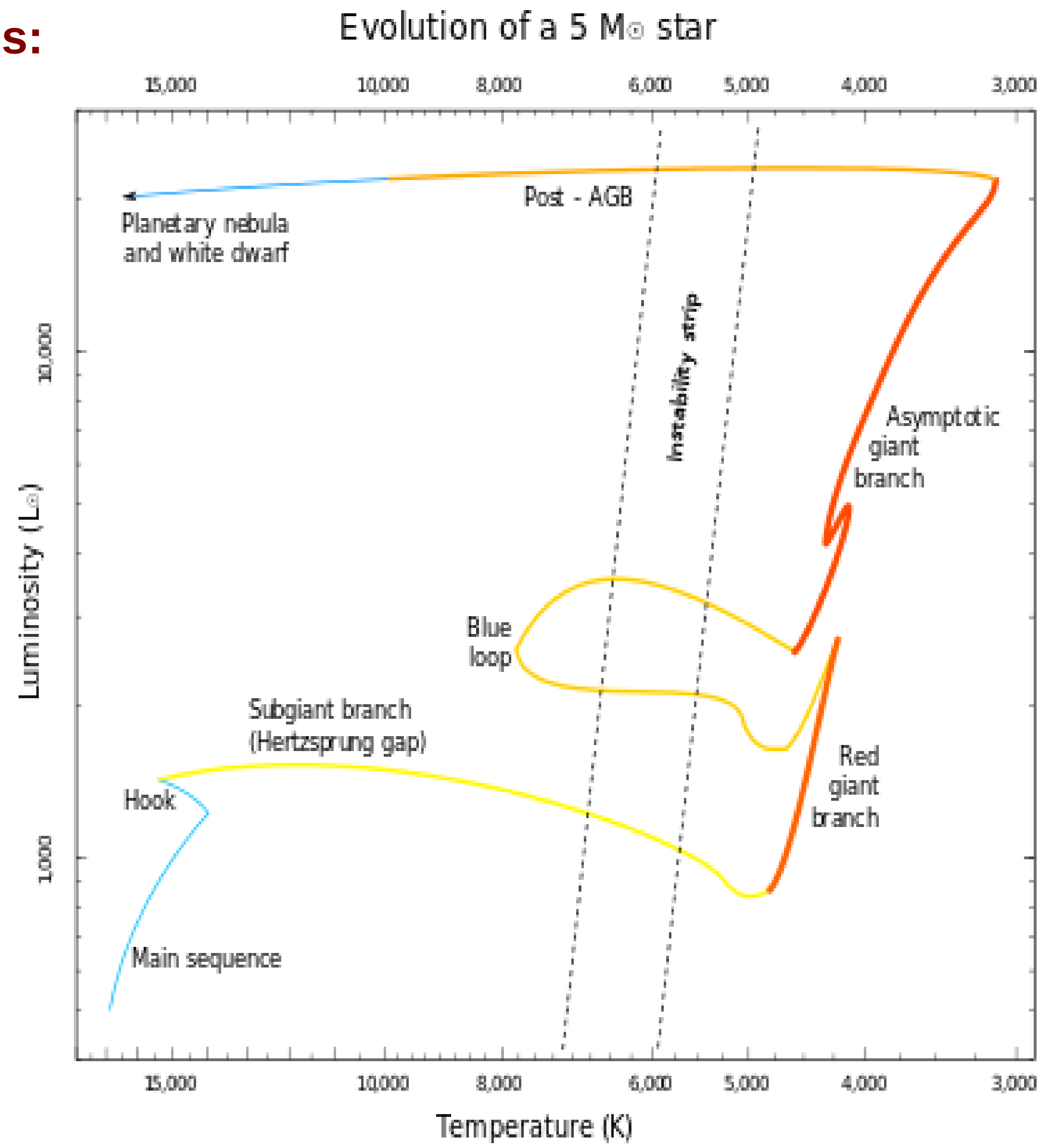
Few crucial definitions:

Hertzsprung gap (HG):
region of the HR diagram occupied by stars which do not burn H in their core any longer, but have not yet started burning H in shell

Red giant branch (RGB):
region of the HR diagram occupied by stars with He core which burn H in shells

Blue loop (BL): region of the HR diagram occupied by stars which burn He in core

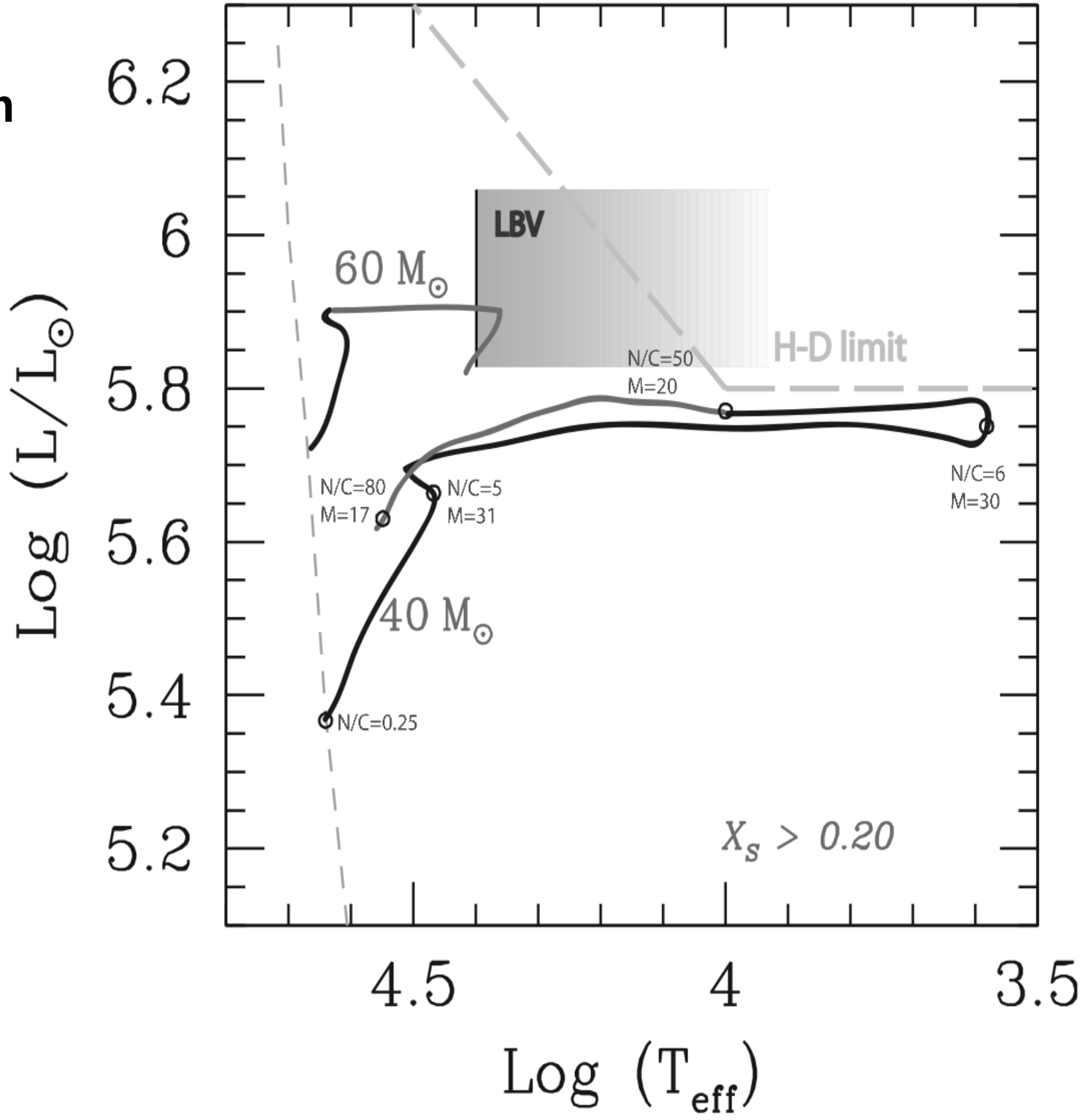
Asymptotic giant branch
(**AGB**, only stars 1 – 8 Msun):
region of HR diagram occupied by stars with Carbon-Oxygen (CO) core, which burn He in shell and H in more external shell



Few crucial definitions:

Humphreys-Davidson (HD) limit:

empirically derived region in HR diagram which is avoided by stars,
physically corresponds to region where radiation pressure cannot be balanced by gravity (above Eddington limit)



Luminous blue variable (LBV) star:

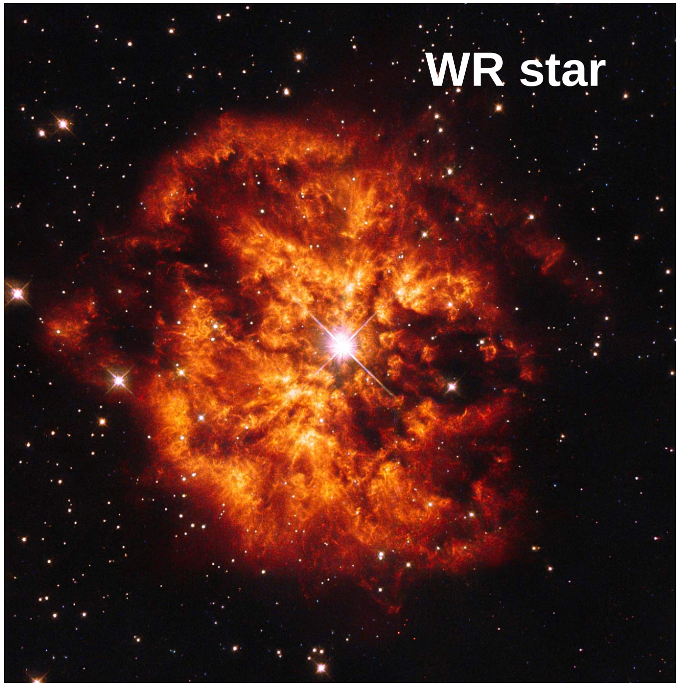
Very luminous and blue star
with H envelope
blue-ward and inside the HD limit

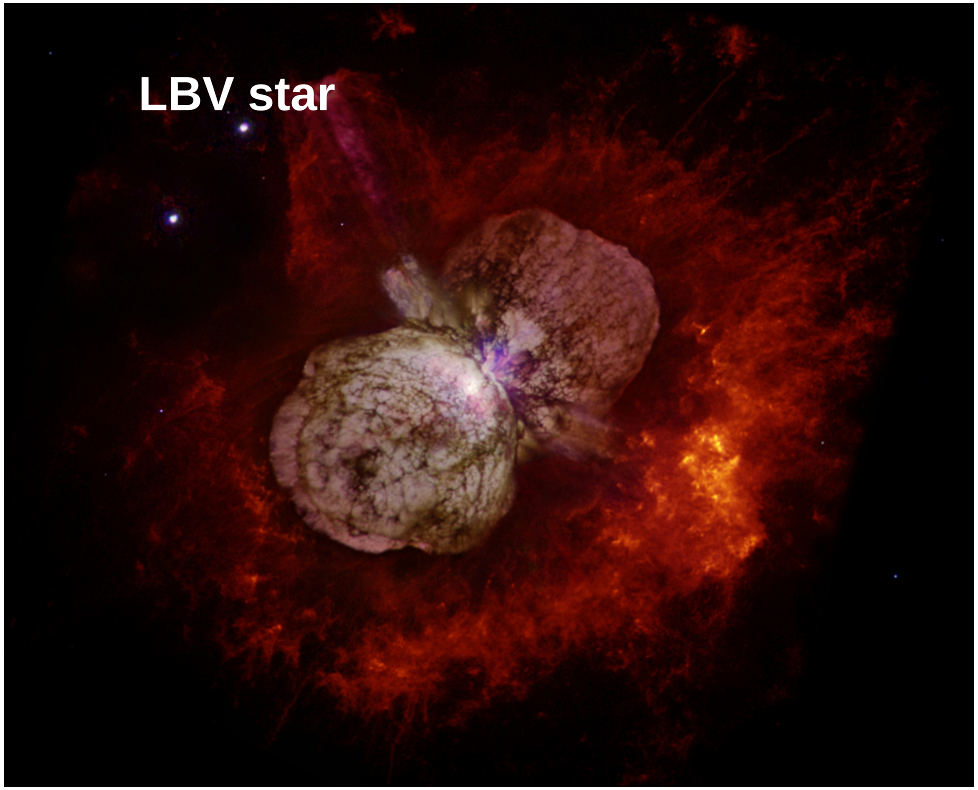
Wolf – Rayet (WR) star:

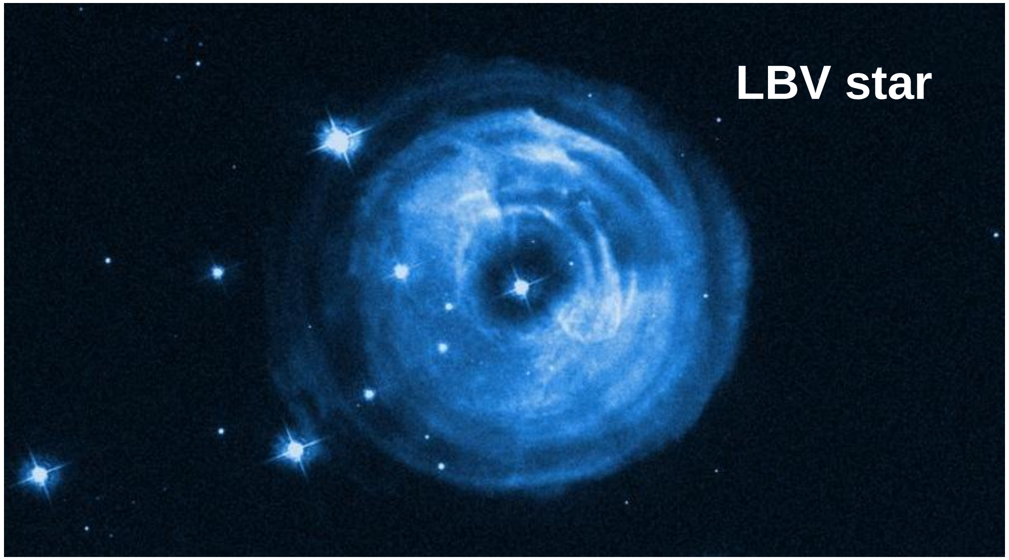
massive star (>20 Msun)
with (almost) NAKED He core
Temperature >50'000 K

STELLAR WINDS:

Stars with luminosity > 10^4 Lsun lose substantial fraction of mass by stellar winds





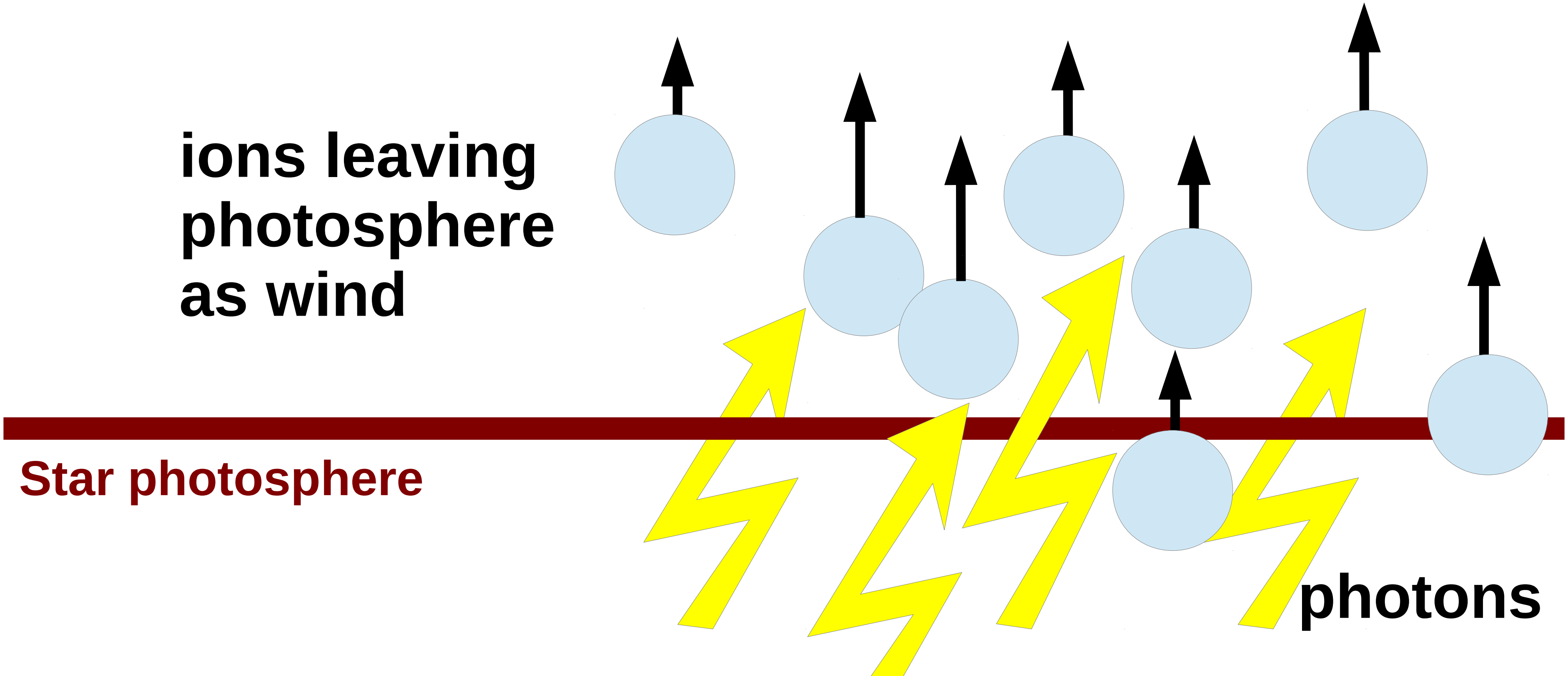


STELLAR WINDS:

Photons in atmosphere of a star couple with ions
→ transfer linear momentum to the ions and unbind them

Coupling through resonant METAL LINES (especially Fe lines)
→ MASS LOSS DEPENDS ON METALLICITY

(Vink+ 2001, 2005, 2011; see Vink+ 2016 for a short review)



LINE-DRIVEN STELLAR WIND THEORY:

* hot massive star radiating at luminosity L

* outer layers accelerated by radiation pressure through absorption in metal lines (Kudritzki 1998; Kudritzki & Puls 2000)

* maximum total momentum from radiation field : L / c

$$\longrightarrow \quad \dot{M}\, v_\infty = f(L/c)$$

* wind is accelerated as

$$v(r) = v_\infty \left(1 - \frac{R_*}{r}\right)^\beta$$

From Bresolin & Kudritzki 2004

LINE-DRIVEN STELLAR WIND THEORY:

Local violation of mass conservation and hydrostatic equilibrium

$$dm = 4\,\pi\,\rho r^2\,dr \longrightarrow \dot{m} = 4\,\pi\,\rho r^2\,v$$

$$0 = -\frac{1}{\rho}\,\frac{dP}{dr} - \frac{G\,m(r)}{r^2} \longrightarrow v\,\frac{dv}{dr} = -\frac{1}{\rho}\,\frac{dP}{dr} - \frac{G\,m(r)}{r^2} + g_{\rm rad}$$

Radiative acceleration:

$$g_{\rm rad} = \underset{\Big\downarrow}{g_{\rm rad}^{\rm Th}} + \underset{\Big\downarrow}{g_{\rm rad}^{\rm lines}} + \underset{\Big\downarrow}{g_{\rm rad}^{\rm ff,bf}}$$

Thomson scattering
(constant reduction of gravity)

Line driven winds

free-free
bound-free
transitions – negligible

From Bresolin & Kudritzki 2004

LINE-DRIVEN STELLAR WIND THEORY:

$$g_{\rm rad}^{\rm lines} \propto N_{\rm eff}$$

***$N_{\rm eff}$* = effective number of metal lines (Castor+ 1975; Pauldrach+ 1986)**

where $$N_{\rm eff} \propto Z^{1-\alpha}$$

Can be used to solve equation of motion:

$$\dot{m} \sim (N_{\rm eff}\,L)^{1/\alpha}\,\left[m_*\,(1-\Gamma)\right]^{1-1/\alpha}$$

$$\longrightarrow \quad \dot{m} \propto Z^{(1-\alpha)/\alpha}$$

$$(1-\alpha)/\alpha = 0.5 - 1.0$$

From Bresolin & Kudritzki 2004

Early models (e.g. Abbott 1982, Kudritzki et al. 1987, Leitherer et al. 1992):

analytic models: each photon interacts with an ion a single time and then is absorbed or goes away

Most important lines: C IV, Si IV, N IV.

Prediction:

$$\dot{m} \propto Z^{0.5}$$

Vink et al. (2001) for O-type stars:

Monte Carlo approach to wind calculation:
allows to consider multiple scatterings for each photon

Most important lines: Fe lines (because many lines even if each one is weaker)

Prediction:

$$\dot{m} \propto Z^{0.85}$$

Vink et al. (2001) for O-type stars:

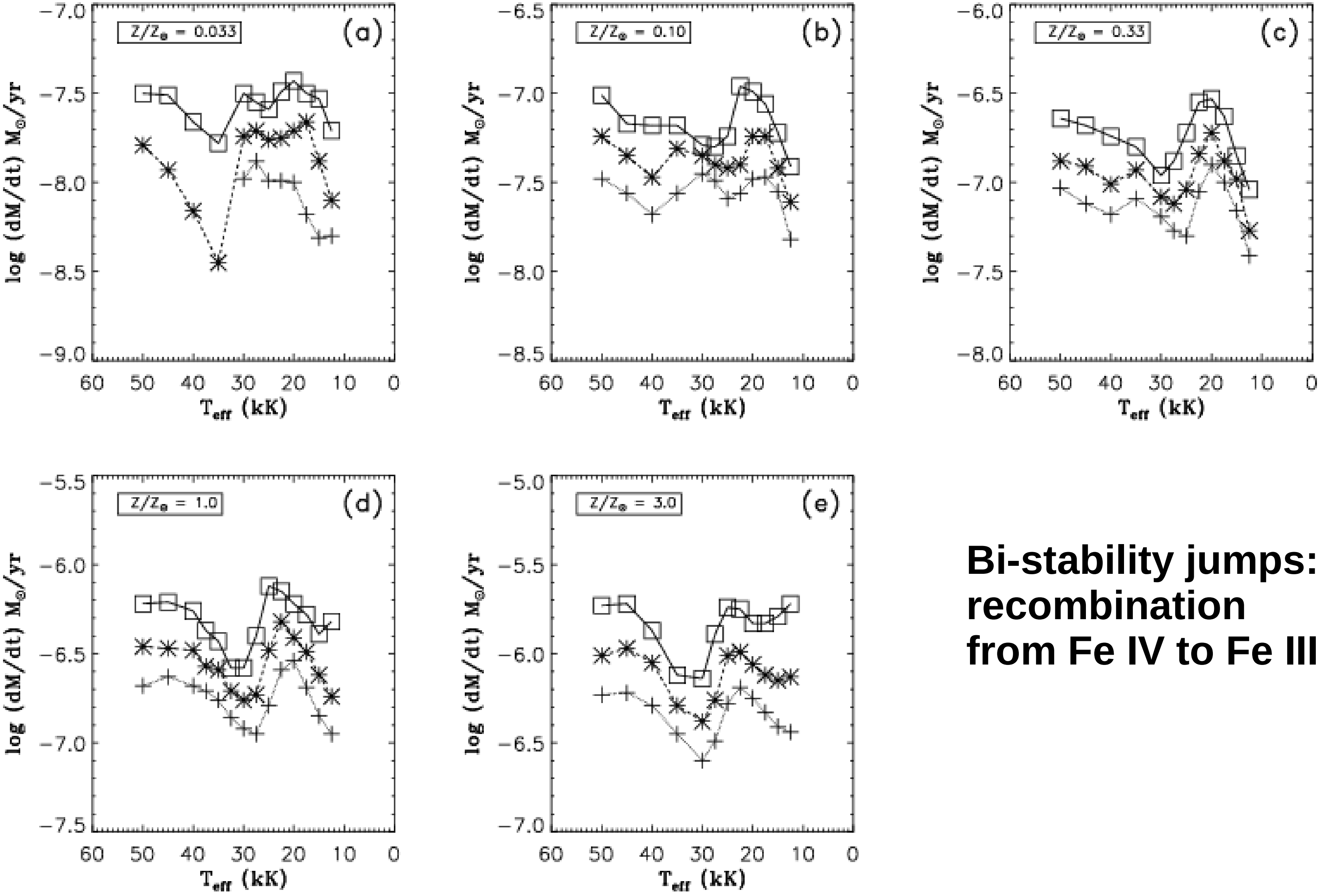
If 12'500 K < *T* < 25'000 K

$$\begin{aligned}\log \dot{M} = \quad & -6.688 + 2.210\ \log\left(\frac{L}{10^5\ L_\odot}\right) \\ & -1.339\ \log\left(\frac{M}{30\ M_\odot}\right) - 1.601\ \log\left(\frac{V}{2.0}\right) \\ & +\alpha\ \log\left(\frac{Z}{Z_\odot}\right) + 1.07\ \log\left(\frac{T}{20000\ \mathrm{K}}\right)\end{aligned}$$

If 25'000 K < *T* < 50'000 K

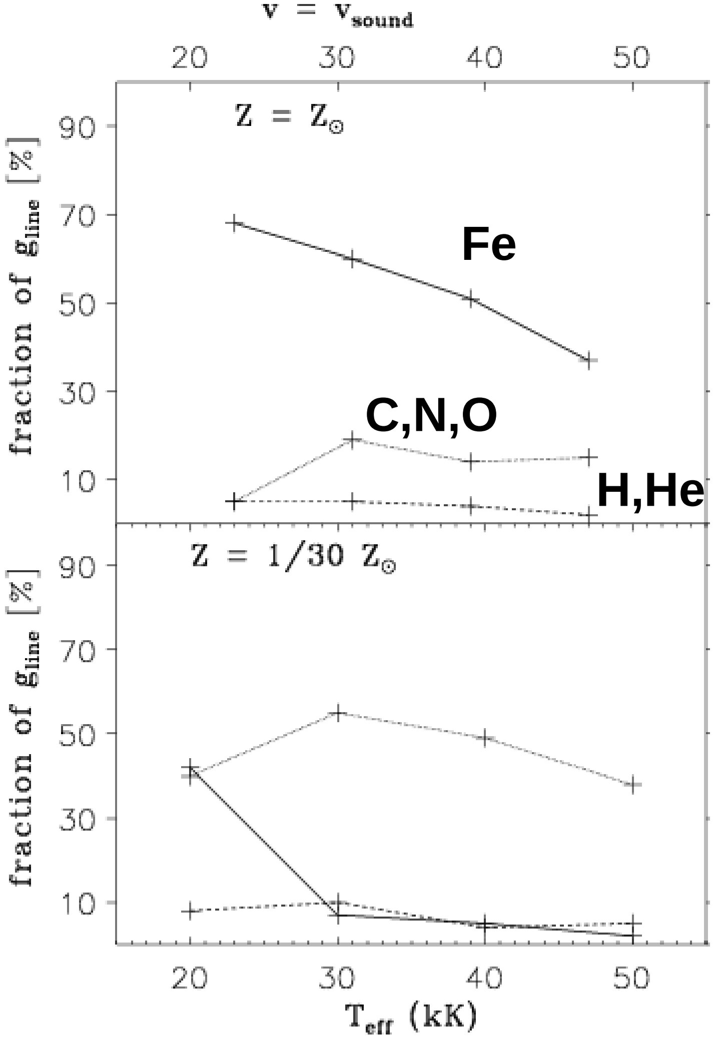
$$\begin{aligned}\log \dot{M} = \quad & -6.697 + 2.194\ \log\left(\frac{L}{10^5 L_\odot}\right) \\ & -1.313\ \log\left(\frac{M}{30\ M_\odot}\right) - 1.226\ \log\left(\frac{V}{2.0}\right) \\ & +\alpha\ \log\left(\frac{Z}{Z_\odot}\right) + 0.933\ \log\left(\frac{T}{40000\ \mathrm{K}}\right) \\ & 10.92\ \left[\log\left(\frac{T}{40000\ \mathrm{K}}\right)\right]^2\end{aligned}$$

Vink et al. (2001) for O-type stars:

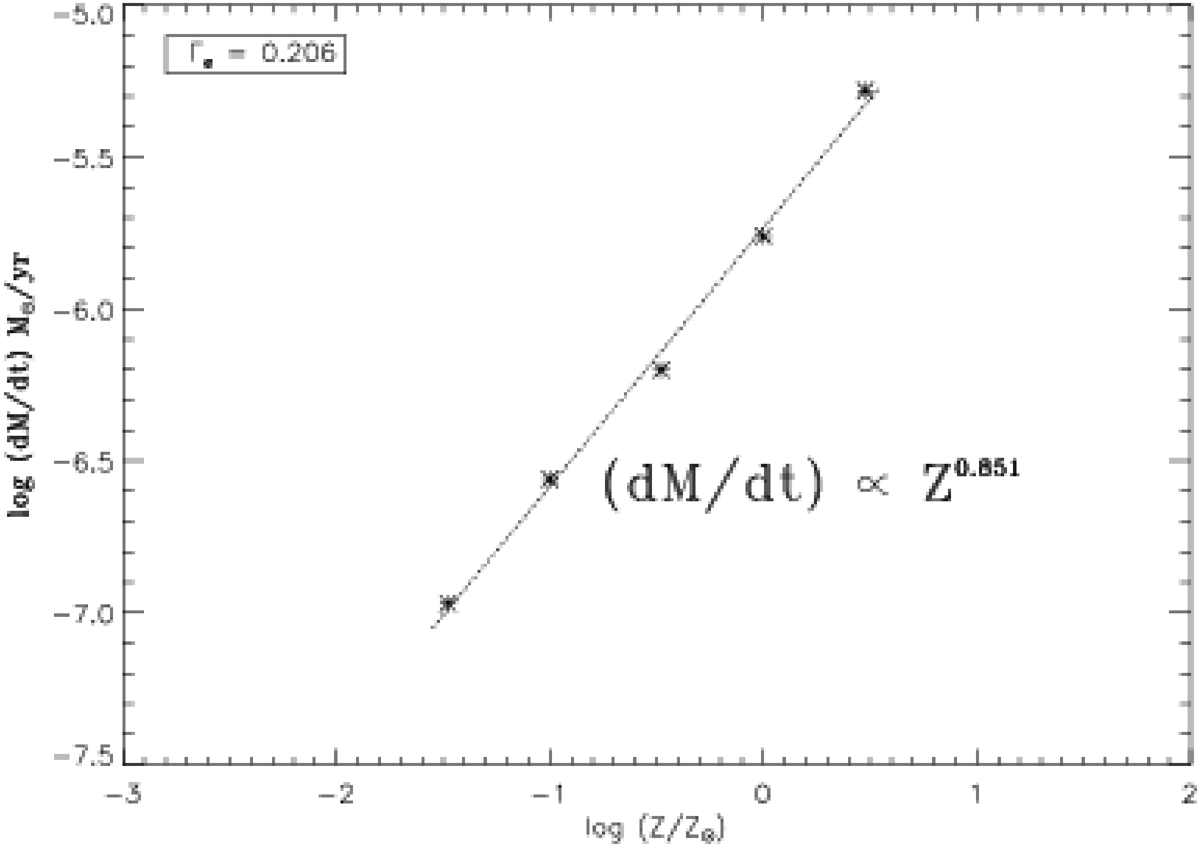


Bi-stability jumps: recombination from Fe IV to Fe III

Vink et al. (2001) for O-type stars:



Trend with metallicity



Fe most important at high Z

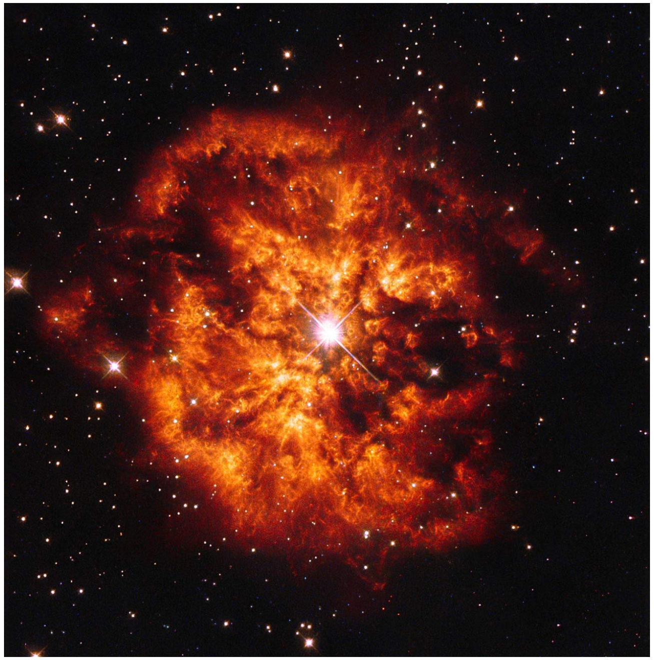
What about post-main sequence?

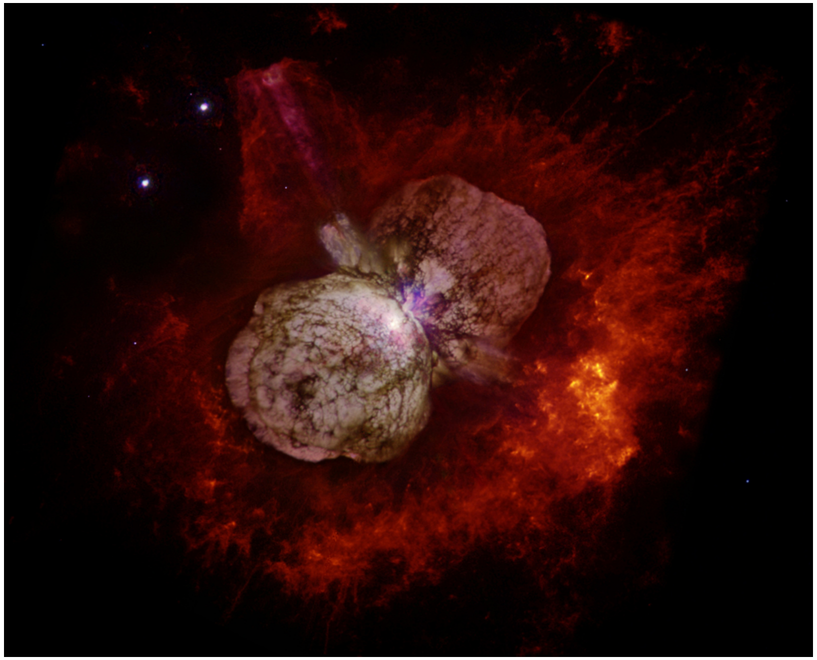
Vink & de Koter (2005); Graefener & Hamann (2008); Vink et al. (2011)

Same dependence on metallicity also after main sequence (eg WR stars)

$$\dot{m} \propto Z^{0.85}$$

Problems: wind clumping, envelope inflation, eruptions

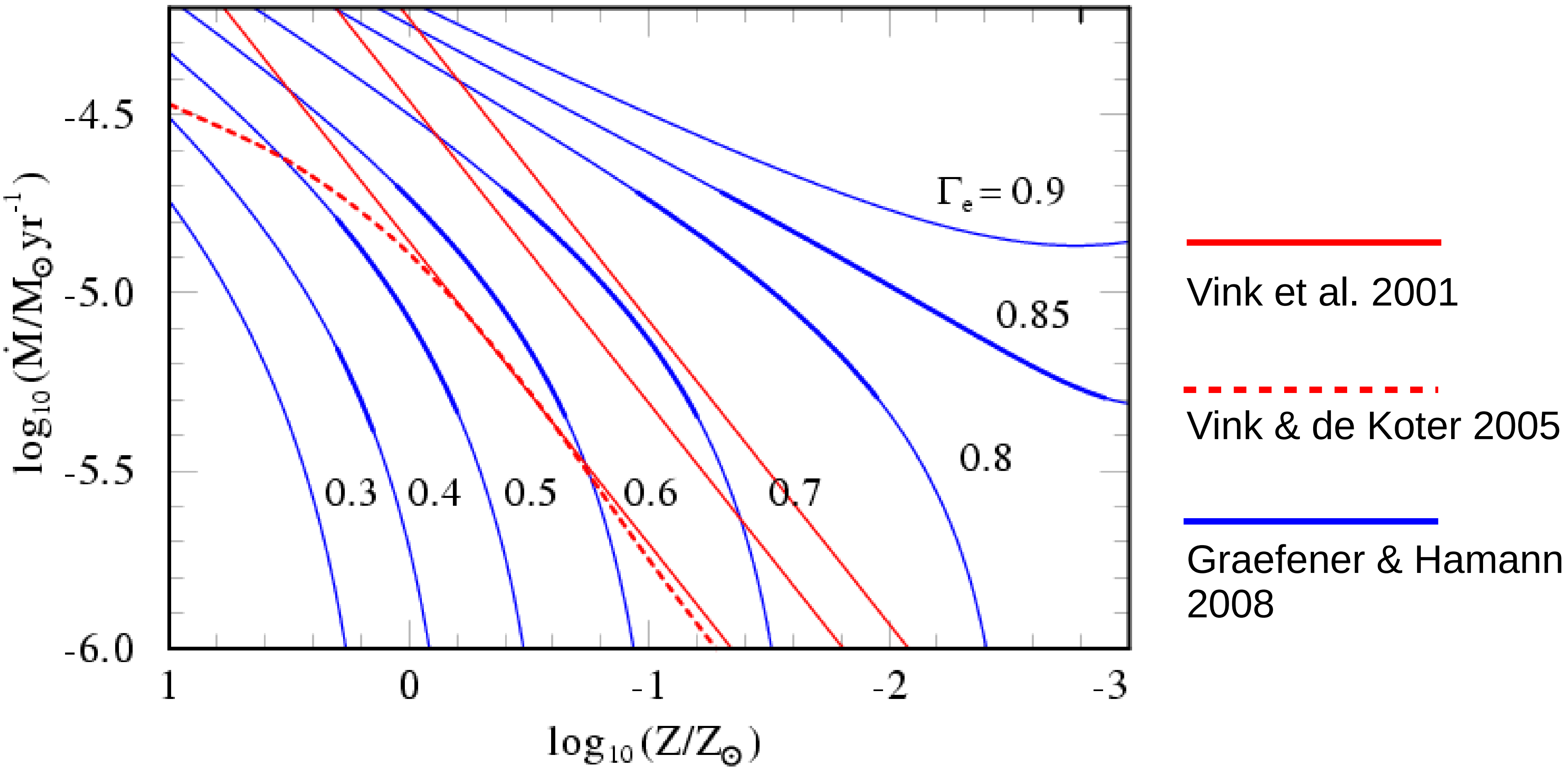




Radiation pressure dominated stars

If star has $\Gamma \sim 1$, stellar winds must be enhanced by radiation pressure

Graefener & Hamann 2008 suggest that metallicity dependence is strongly suppressed



Radiation pressure dominated stars

If star has Γ ~ 1, stellar winds must be enhanced by radiation pressure

Graefener & Hamann 2008 suggest that metallicity dependence is strongly suppressed

e.g. Chen, Bressan et al. 2015:

$$\dot{m} \propto Z^{\beta}$$

$$\beta = 0.85 \quad \mathrm{if}\,\Gamma \leq 2/3$$

$$\beta = 2.45 - 2.4\,\Gamma \quad \mathrm{if}\,\Gamma > 2/3$$

Cold stars (red giants and super-giants):

Winds are mostly DUST driven

many rotational and vibrational lines: less effective than transition lines but much larger cross section → continuum

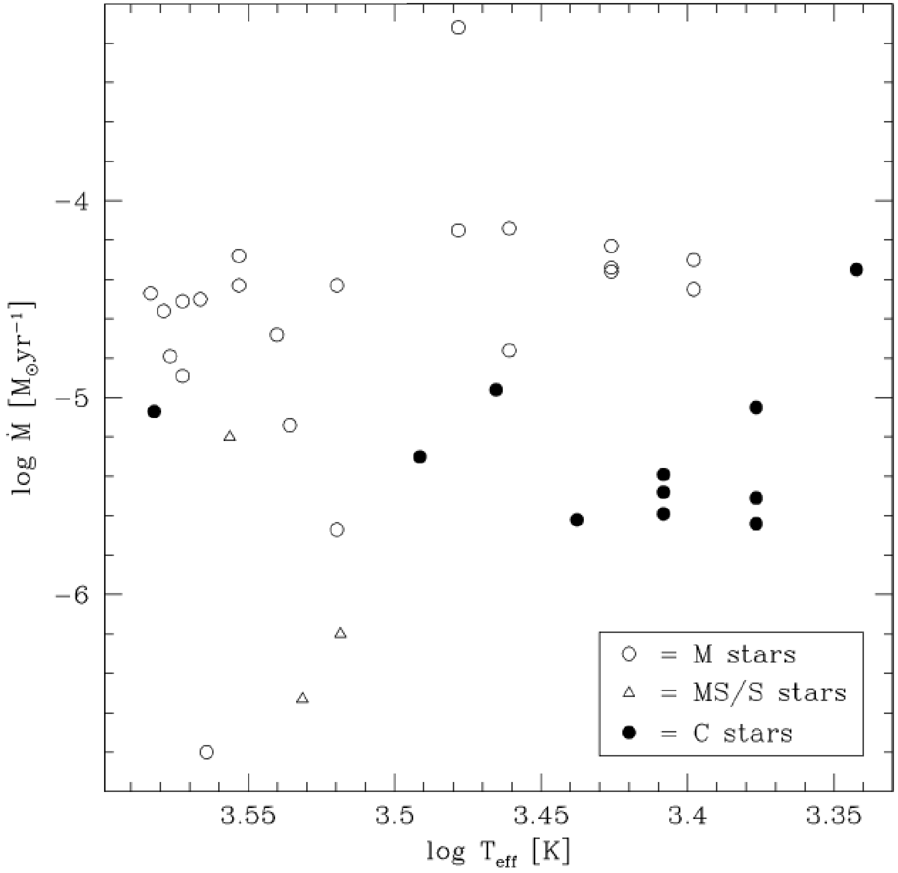
e.g. empirical formula from Van Loon et al. 2005

$$\log \dot{M} = -5.65 + 1.05\,\log\left(\frac{L}{10000\,\mathrm{L}_\odot}\right) - 6.3\,\log\left(\frac{T_{\rm eff}}{3500\,\mathrm{K}}\right)$$

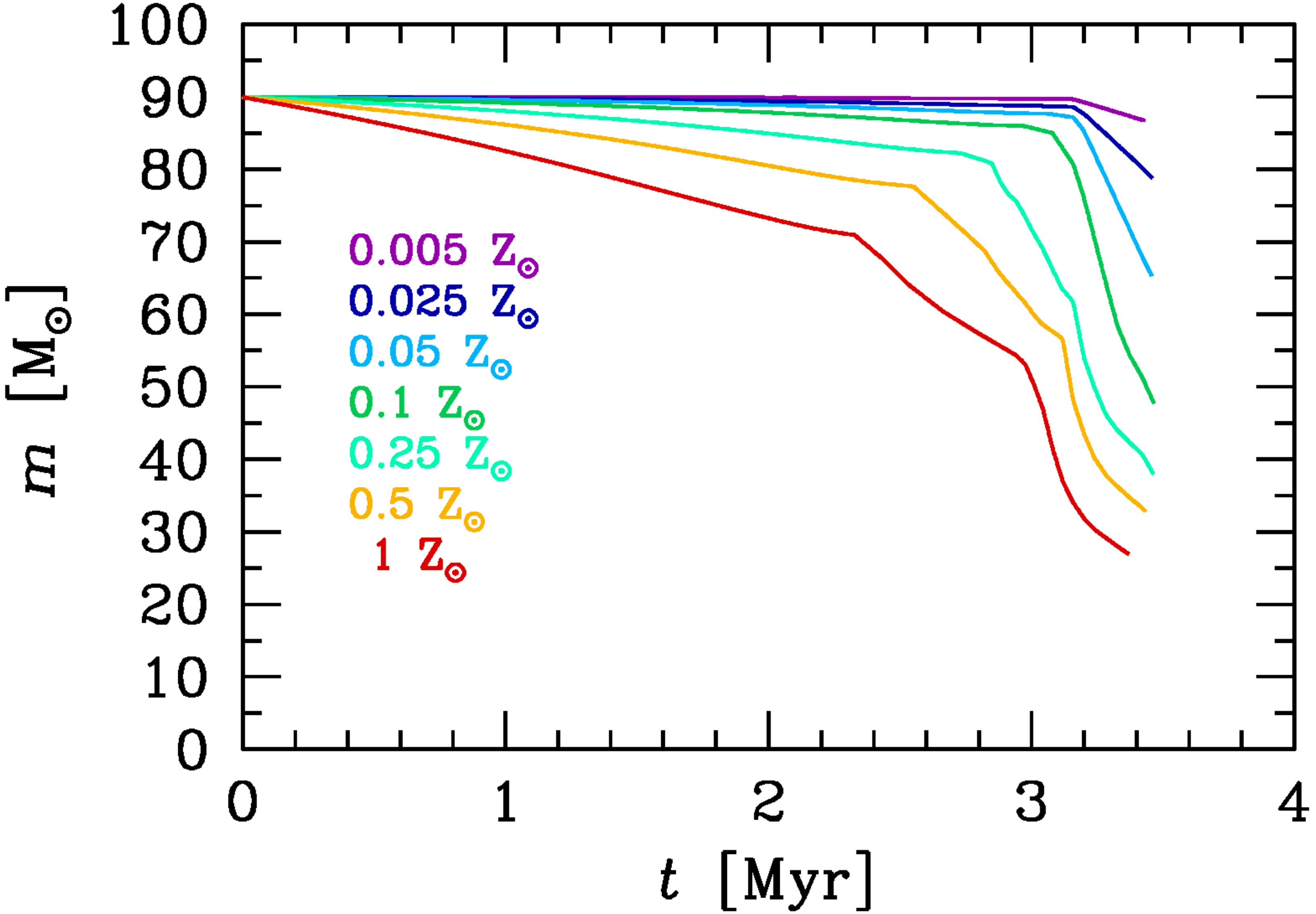
(for red supergiants and AGB stars)

Need low temperature to form dust,

but data are messy

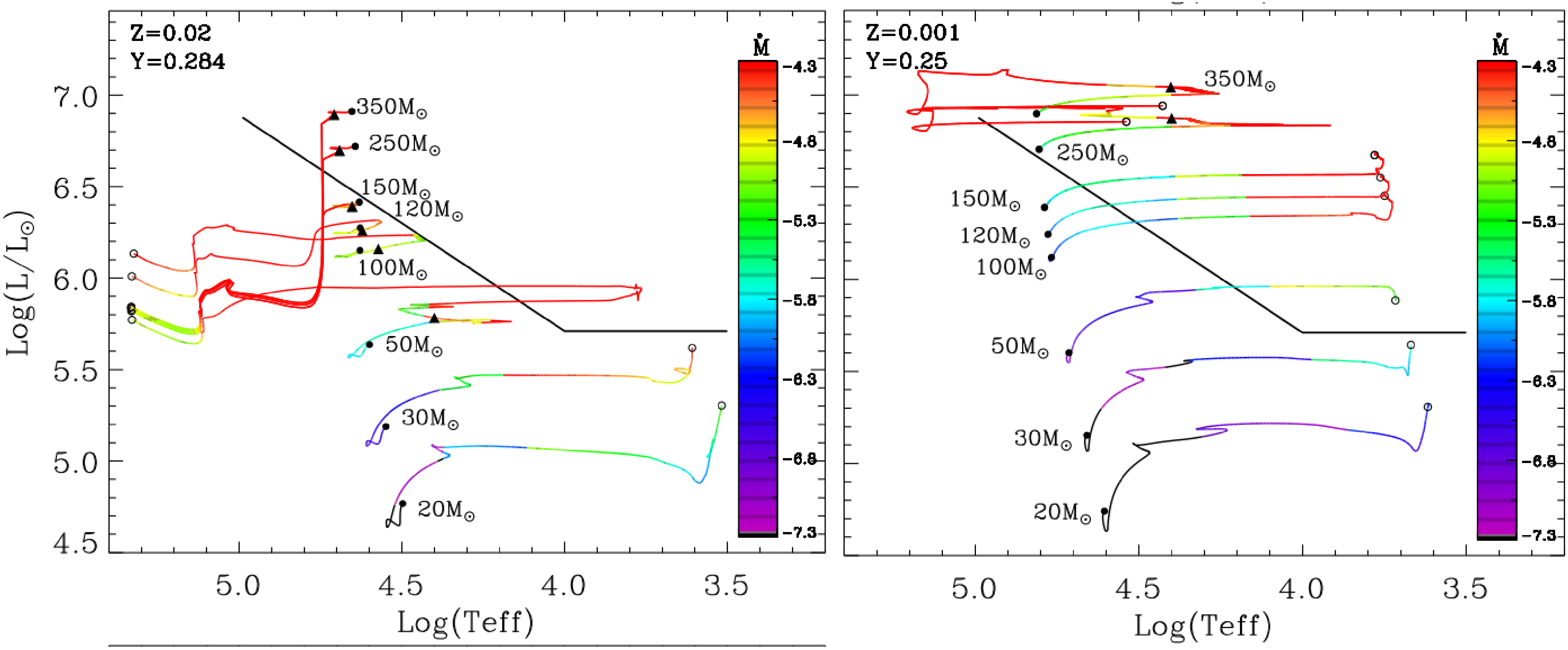


Putting pieces together: mass loss



Models from PARSEC stellar evolution code (Bressan+ 2012; Tang+ 2014; Chen, Bressan+ 2015)

Putting pieces together: mass loss

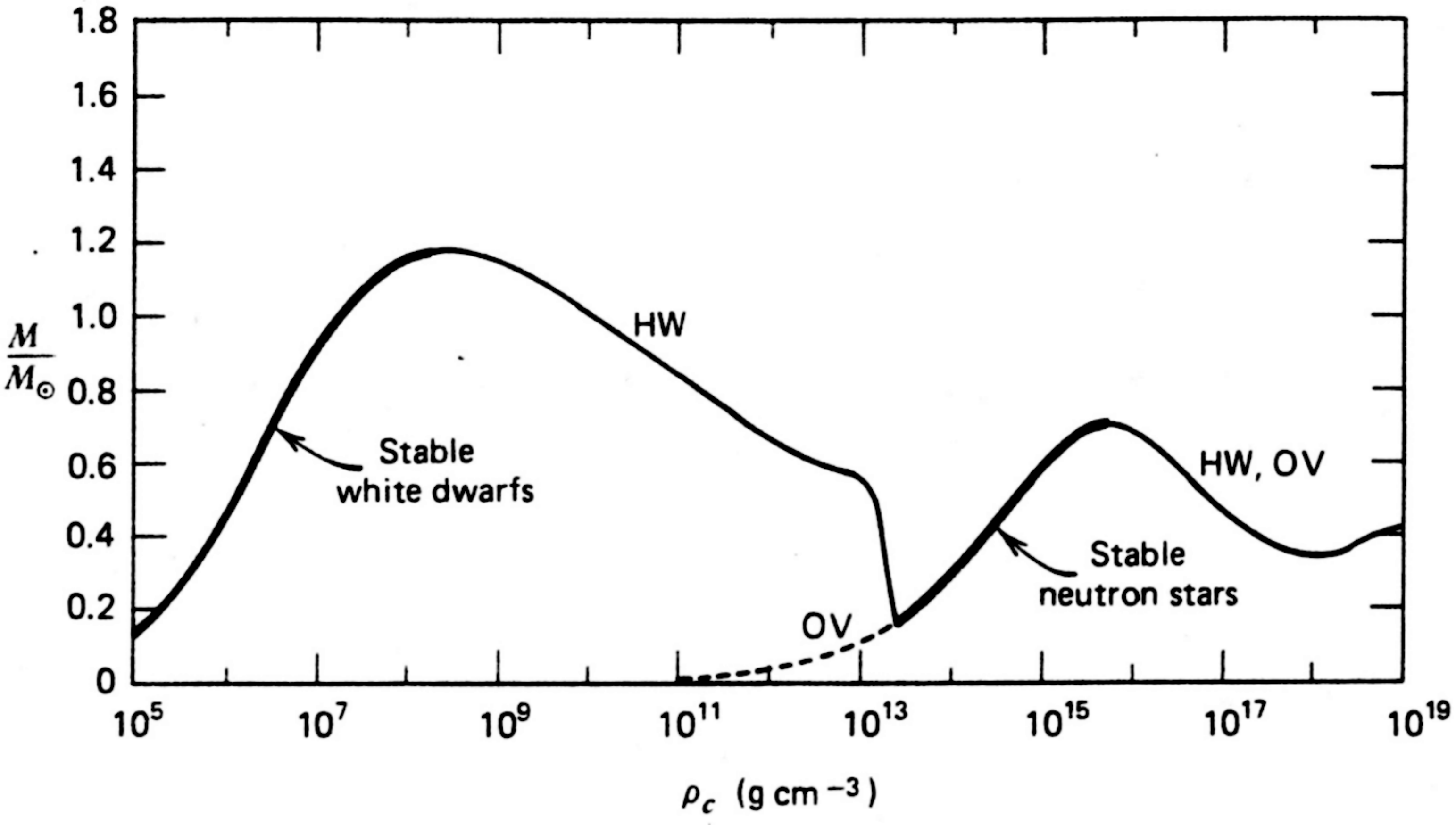


Models from PARSEC stellar evolution code (Bressan+ 2012; Tang+ 2014; Chen, Bressan+ 2015)

What happens when nuclear fuel is over?

White dwarves, neutron stars, black holes: see starev_part2.pdf

Outcomes of Oppenheimer – Volkoff equation:



From Shapiro & Teukolsky 1983, Black holes, white dwarfs, and neutron stars, Wiley

THANK YOU