Università di Pisa - Dipartimento di Fisica

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Systematic Study of Mass Loss in the Evolution of Massive Stars

Mathieu Renzo

advisors:

Prof. S. N. Shore, Prof. C. D. Ott

Outline

Introduction

- Importance of Massive Stars
- How do they lose mass?

Stellar Winds

- Outline of the Theory
- Methods
- Results: Amplitude of the Uncertainty
- Results: Blue Loops in $15M_{\odot}$ models

Impulsive Mass Loss Events

- Motivations for This Study
- Methods
- Results: Wind + Impulsive Mass Loss
- Results: pre-SN Stripped Structures

Conclusions

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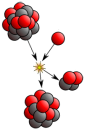
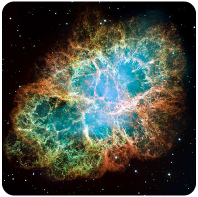
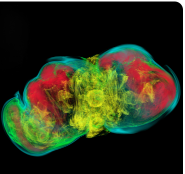
Why are Massive Stars Important?

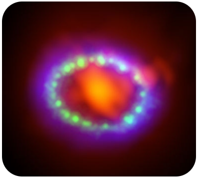
$$M_{\rm ZAMS} \gtrsim 8 - 10\, M_\odot$$

- Nucleosynthesis
- Chemical Evolution of Galaxies
- Effects on Star Formation
- Re-ionization Epoch
- Observations of Farthest Galaxies
- Catastrophic Events









Mass Loss – Why does it Matter...

... for the environment of the stars?

- Pollution of the InterStellar Medium (ISM)
- Tailoring of the CircumStellar Material (CSM)
- Effects on the Star Formation

... for the stellar structure?

- Evolutionary Timescales
- Final Fate (BH, NS or WD?)
- Light Curve and Explosion Spectrum
- Appearance: CSM and Wind Features (e.g. WR)
- Role in the Solution of the RSG Problem ?

Possible Mass Loss Mechanisms

Radiative Driving

$\Downarrow$

Stellar Winds

Dynamical Instabilities

$\Downarrow$

LBVs, Impulsive Mass Loss, Pulsations, Super-Eddington Winds

Binary interactions

$\Downarrow$

Roche Lobe OverFlows (RLOF)

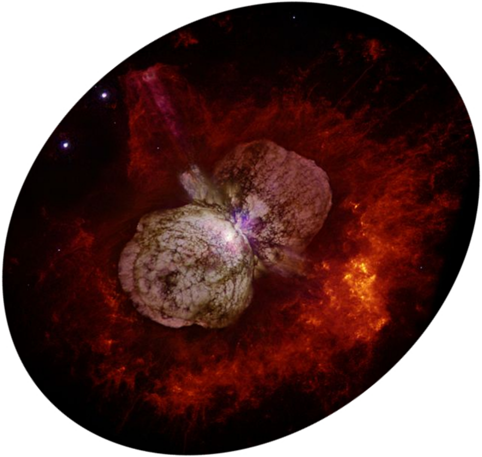


Figure: η Carinae.

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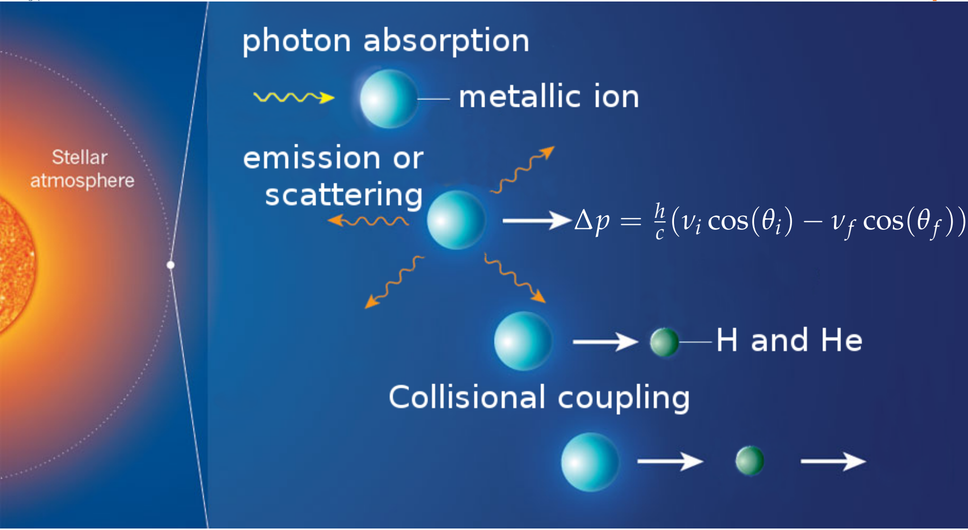
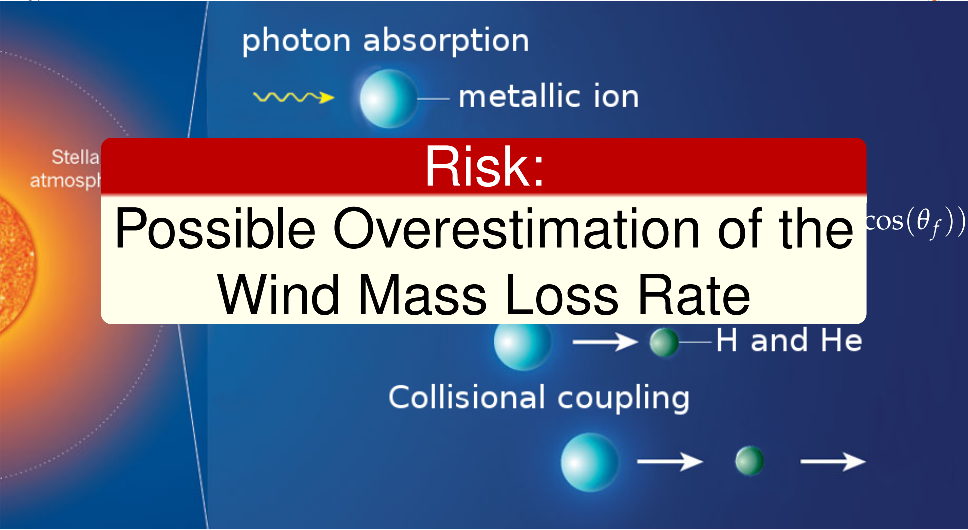
Radiatively Driven Winds in One Slide



Problems: High Non-Linearity and Clumpiness:

$f_{\mathrm{cl}} \stackrel{\mathrm{def}}{=} \frac{\langle\rho^2\rangle}{\langle\rho\rangle^2} \neq 1 \Rightarrow$ Inhomogeneities $\Rightarrow \dot{M} \neq 4\pi r^2 \rho v(r)$

Radiatively Driven Winds in One Slide



Risk:

Possible Overestimation of the Wind Mass Loss Rate

Problems: High Non-Linearity and Clumpiness:

$$f_{\rm cl} \stackrel{\rm def}{=} \frac{\langle \rho^2 \rangle}{\langle \rho \rangle^2} \neq 1 \Rightarrow \text{Inhomogeneities} \Rightarrow \dot{M} \neq 4\pi r^2 \rho v(r)$$

Mass Loss in MESA

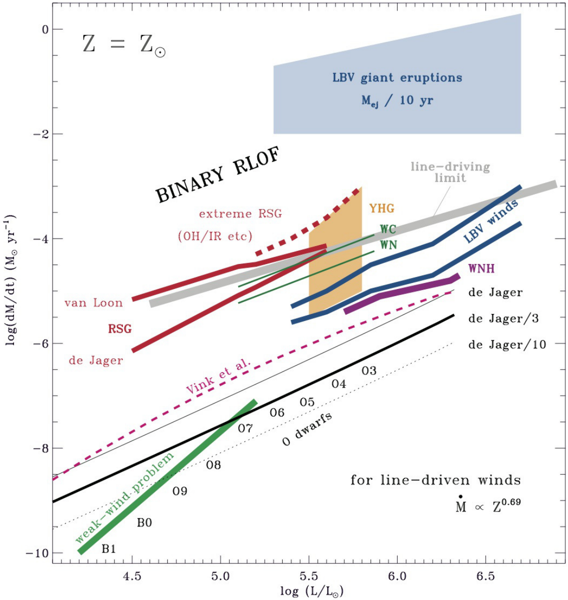


Figure: From Smith 2014, ARA&A, 52, 487S

(Semi–)Empirical parametric models. Uncertainties encapsulated in efficiency factor:

$$\dot{M}(L, T_{\rm eff}, Z, R, M, \ldots)$$
$$\Downarrow$$
$$\eta \dot{M}(L, T_{\rm eff}, Z, R, M, \ldots)$$

η is a free parameter:

$$\eta \in [0, +\infty)$$

Different dM/dt algorithms with MESA

Grid of $Z_\odot \simeq 0.019$, non-rotating stellar models:

- Initial mass:

$$M_{\mathrm{ZAMS}} = \{15,\ 20,\ 25,\ 30\}\ M_\odot;$$

- Efficiency:

$$\eta \equiv \sqrt{f_{\mathrm{cl}}} = \left\{1,\ \frac{1}{3},\ \frac{1}{10}\right\}\ ;$$

- Different combinations of wind mass loss rates for "hot" ($T_{\mathrm{eff}} \geq 15\ [\mathrm{kK}]$), "cool" ($T_{\mathrm{eff}} < 15\ [\mathrm{kK}]$) and WR stars:

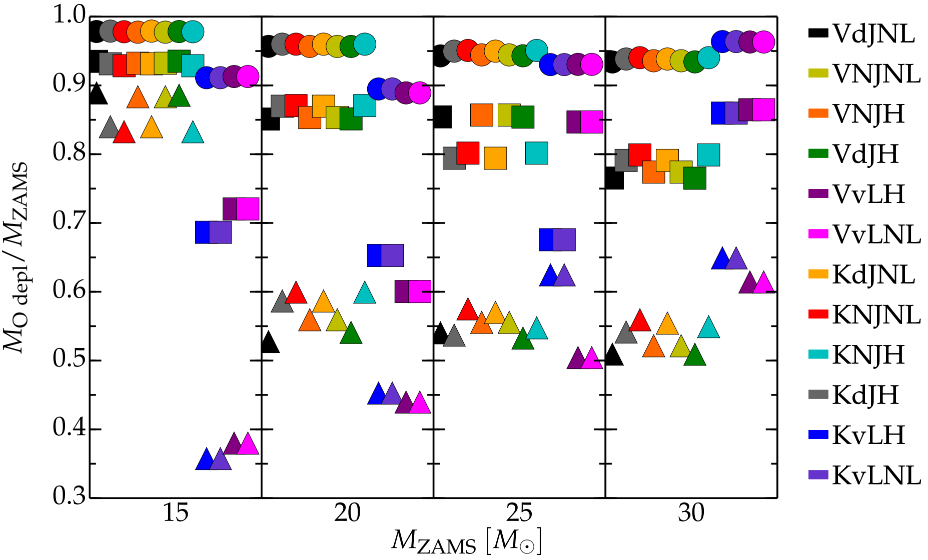
Kudritzki *et al.* '89; Vink *et al.* '00, '01;

Van Loon *et al.* '05; Nieuwenhuijzen *et al.* '90;

De Jager *et al.* '88;

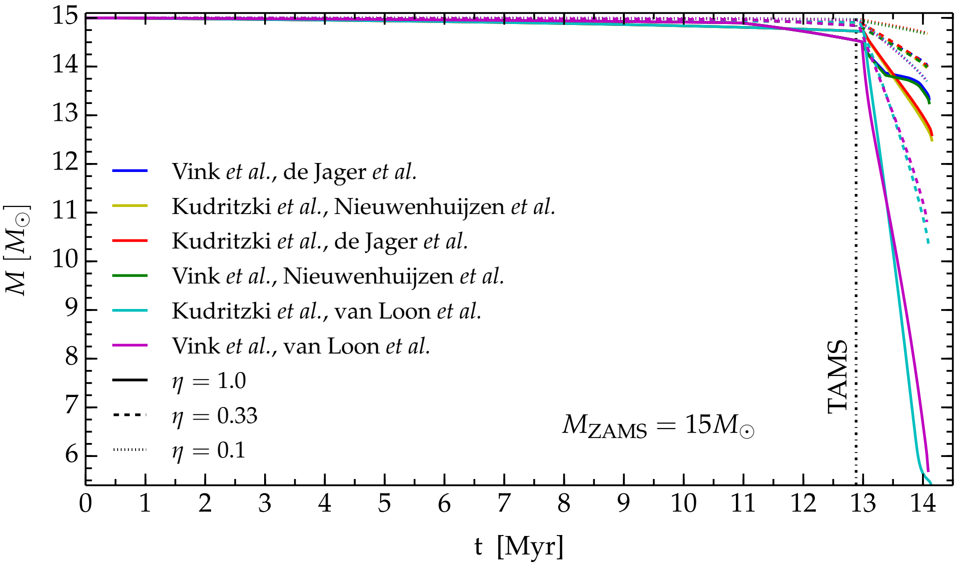
Nugis & Lamers '00; Hamann *et al.* '98.

Results: Relative Final Mass

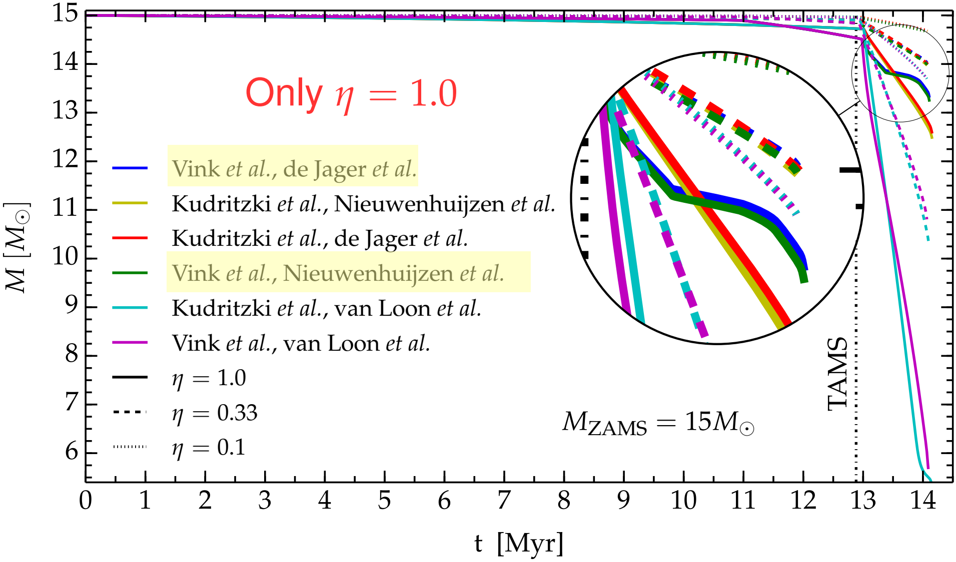


Diamonds $\Leftrightarrow \eta = 1.0$, Squares $\Leftrightarrow \eta = 0.33$, Circles $\Leftrightarrow \eta = 0.1$.

$M(t)$ for $M_{ZAMS} = 15M_{\odot}$ with MESA

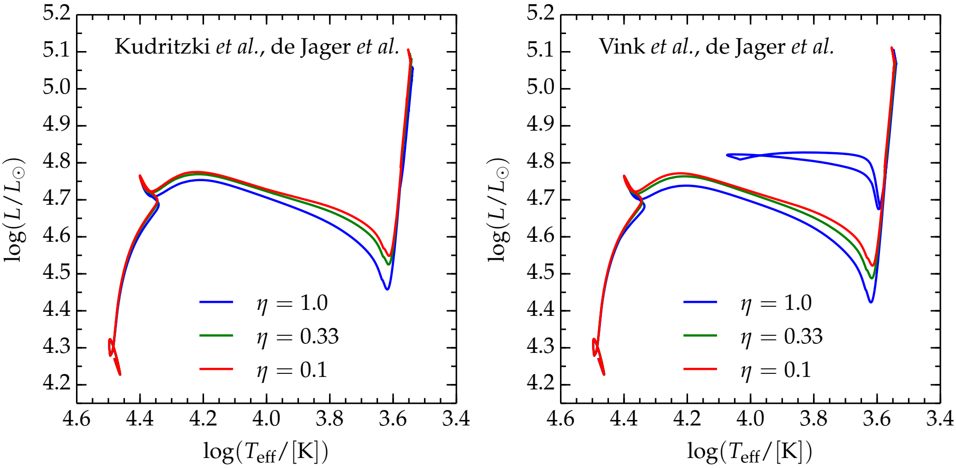


$M(t)$ for $M_{ZAMS} = 15M_{\odot}$ with MESA



Comparison of Hot Wind Algorithms

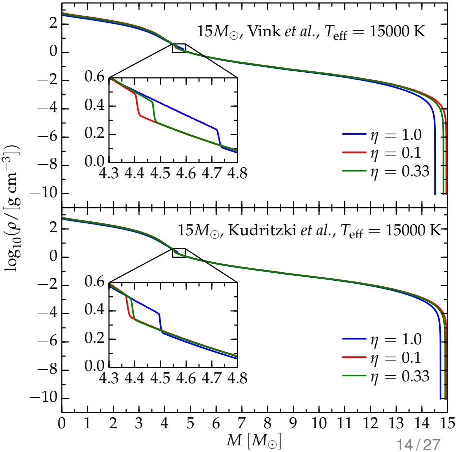
Example: $M_{\mathrm{ZAMS}} = 15 M_\odot$ evolutionary tracks



$\Rightarrow$ Early ("hot") wind influences subsequent evolution

Why Blue Loops? 1/2

- Blue loop ⇔ Large He-core
- Convection mixes H down, determining $M_{\rm He}$
- μ is higher in He-rich regions



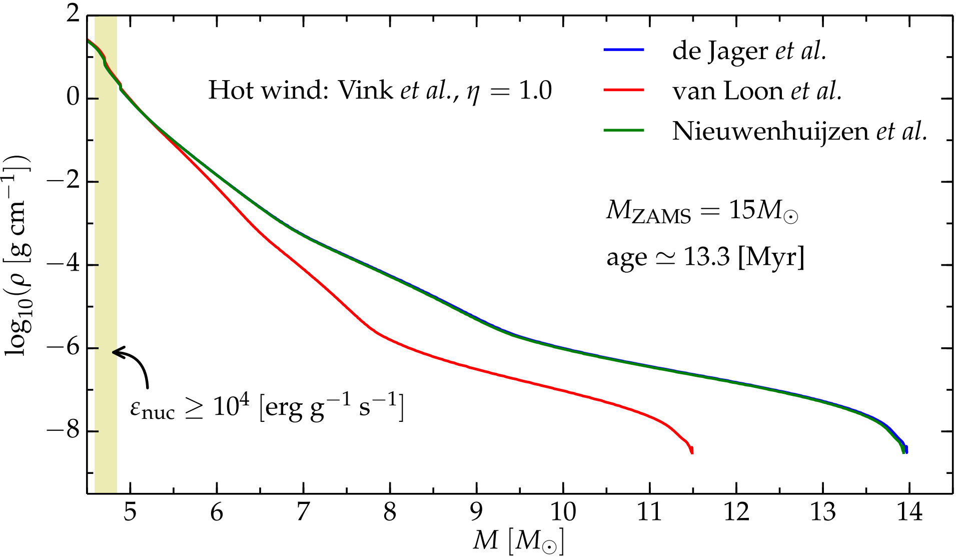
Why Blue Loops? 2/2

- Blue loop starts when H-burning shell reaches the edge of the He core
- Lower μ and higher $X \Rightarrow$ Variations of $\varepsilon_{\rm nuc}$
- Envelope responds on its thermal timescale

$$\Downarrow$$

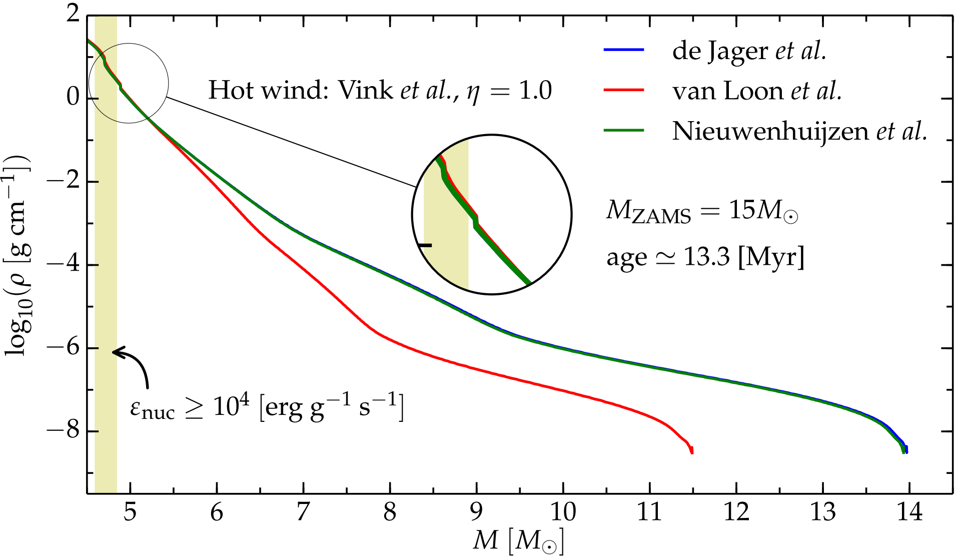
- if $\eta < 1 \Rightarrow$ He core edge too deep for Blue Loops
- Vink *et al.* rate yields larger cores allowing for Blue Loops

Why **not** Blue Loops?



Density profiles at the onset of Blue Loops

Why **not** Blue Loops?



Ideal gas EOS: $P_{\rm gas} = \frac{\rho}{\mu m_p} k_b T$

Summary

Results of the Comparison of Wind Algorithms:

- η has a larger influence on the final mass than the wind algorithm;
- Early ("hot phase") mass loss influences the further evolution;
- $\dot{M}$ is more uncertain when it is higher (RSG phase);
- Different algorithmic representations of stellar winds $\Rightarrow$ Qualitatively different evolutionary tracks;
- Small number (8) of WR stars, none with $\eta < 1$ $\Rightarrow$ Other mass loss mechanism(s) to form WR?

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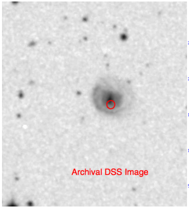
Why Impulsive Mass Loss?

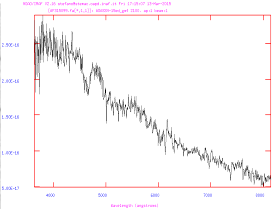
Observational Evidence:

- LBVs
- Progenitors of H-poor core collapse SNe ($\sim 30\%$)
- Dense CSM for Type IIn SNe

Theory: Dynamical Events $\Rightarrow$ MESA not ready

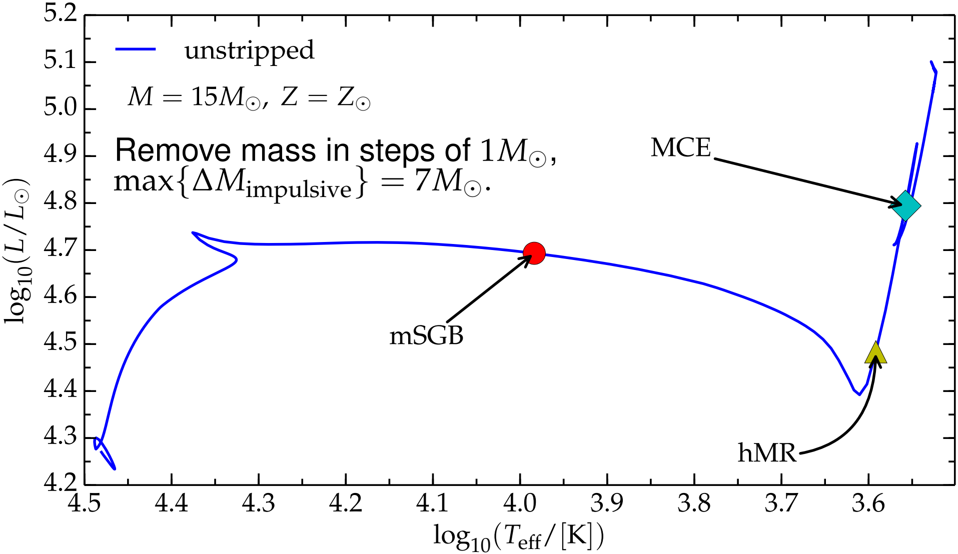
- Pulsational Instabilities
- Roche Lobe Overflow in binaries
- Catastrophic Eruption(s)





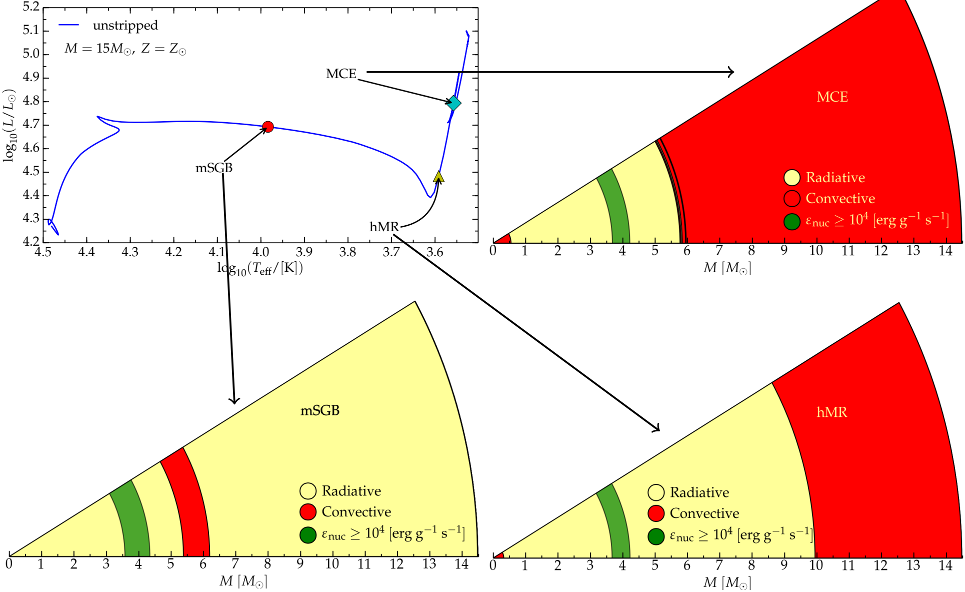
$$\Delta M_{\rm wind} \ll \Delta M_{\rm impulsive} \text{ (?)}$$

The Stripping Process



Red dot: $T_{\rm eff} = 10^4$ [K]; **Yellow Triangle**: $R \geq R_{\rm max}/2 = 375R_\odot$;
Cyan Diamond: Maximum Extent Convective Envelope.

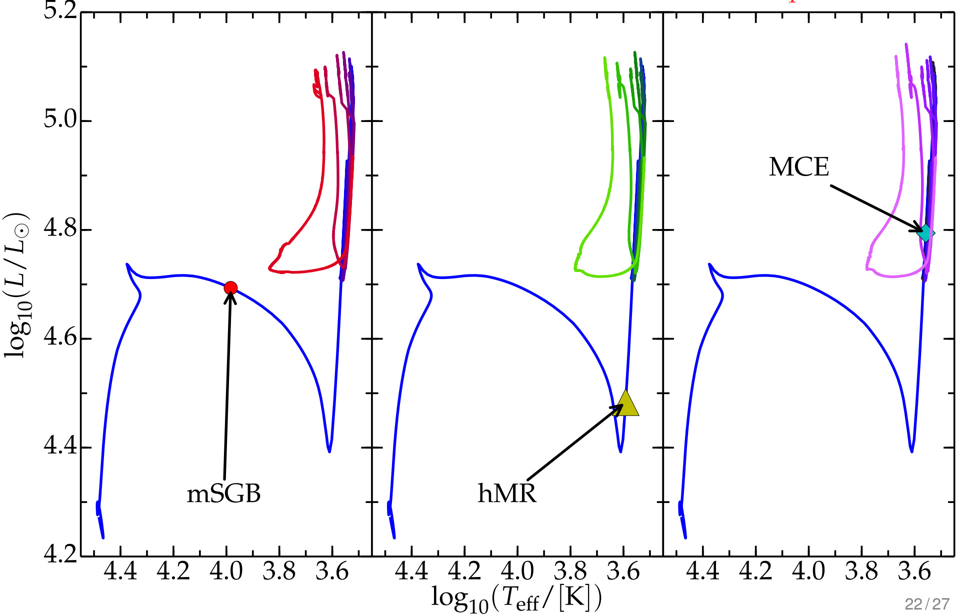
Chosen Stripping Points



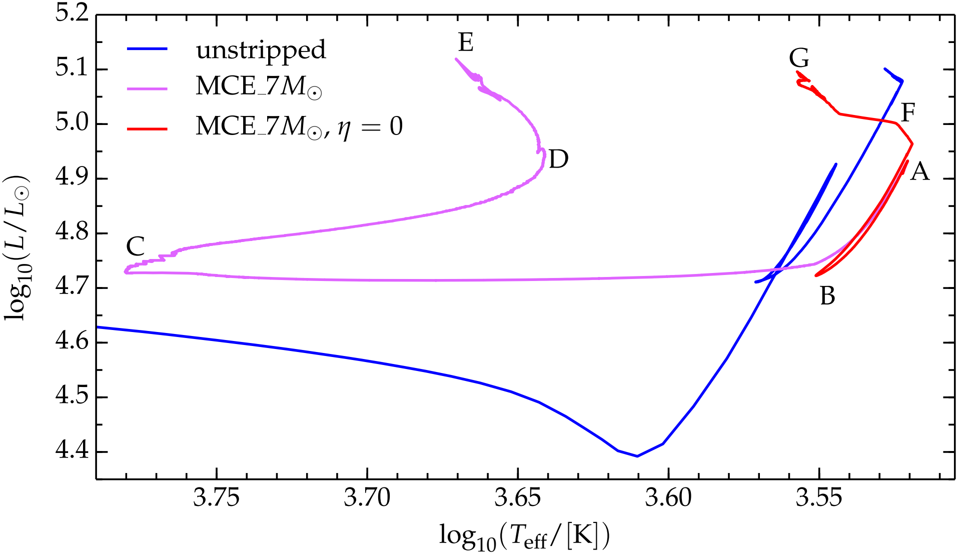
$$t(\mathrm{MCE}) - t(\mathrm{mSGB}) \simeq 10^4\ [\mathrm{yr}] \ll 14.13 \times 10^6\ [\mathrm{yr}]$$

Stripped series on the HR diagram

Evolutionary tracks depend only on $\Delta M_{\text{impulsive}}$

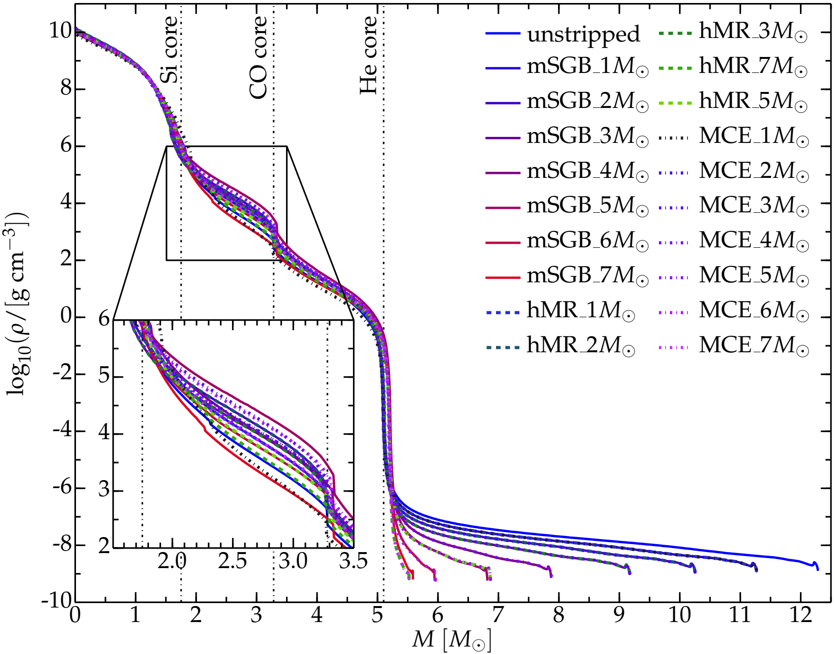


Evolution toward Higher $T_{\rm eff}$



Impulsive + wind mass loss drives blueward evolution

pre-SN Stripped Structures



Light Curves from Stripped Models

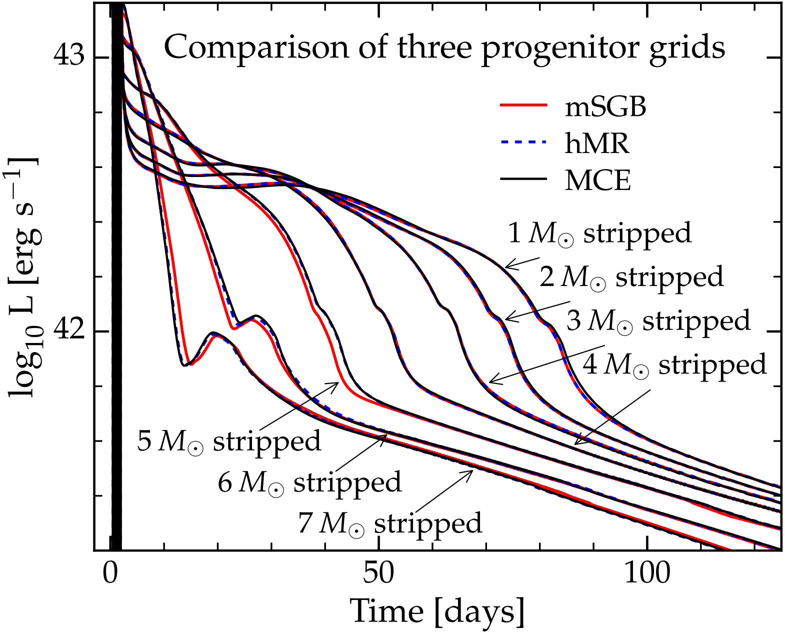


Figure: Morozova *et al.* – eprint arXiv:1505.06746

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Conclusions

- Large systematic uncertainties in massive star mass loss rates
- Different algorithms $\Rightarrow$ Qualitatively different evolutionary tracks
- Uncertainty increases at higher M_{ZAMS} and η

- Combined impulsive + wind mass loss drives blueward evolution
- Does impulsive mass loss have an effect on the “Explodability” of the star?

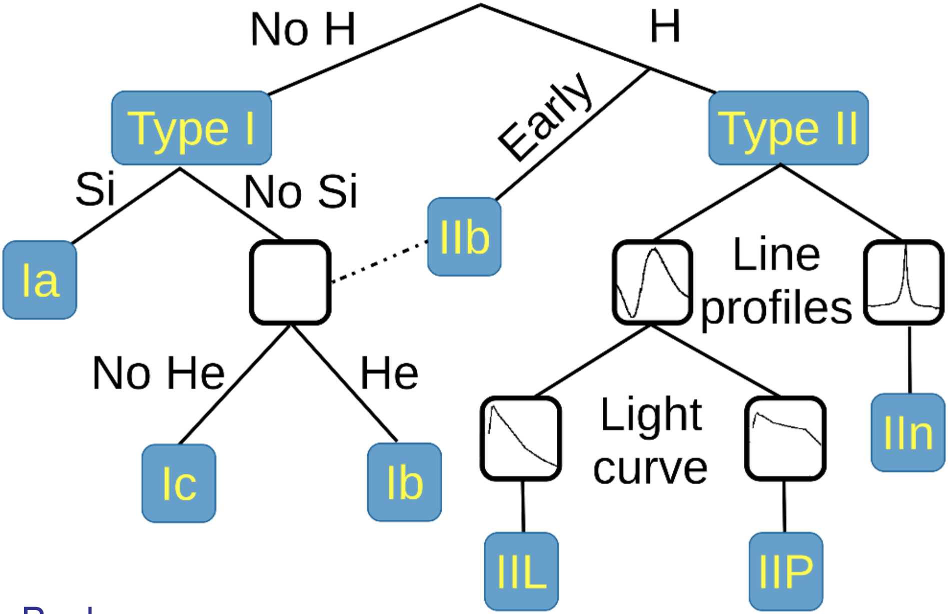
Thank you for your attention.

Figure Credits

Roughly in order of appearance.
Some figure where modified.
Figure not listed are from myself.
Click for original link.

- 30 Doradus (Tarantula Nebula)
- Observative HR
- Crab Nebula
- Orion
- Reionization Epoch
- Bubble Nebula
- SN1987A
- CCSN entropy rendering
- SN observations
- η Car
- Betelgeuse
- Mass Loss Rate plot
- AG car
- Type Ib SN
- WR 124
- WR spectra
- P Cygni line profile:S. N. Shore "Astrophysical Hydrodynamics", Wiley-VCH, 2007.
- P Cygni (34 Cyg)

Supernova Taxonomy



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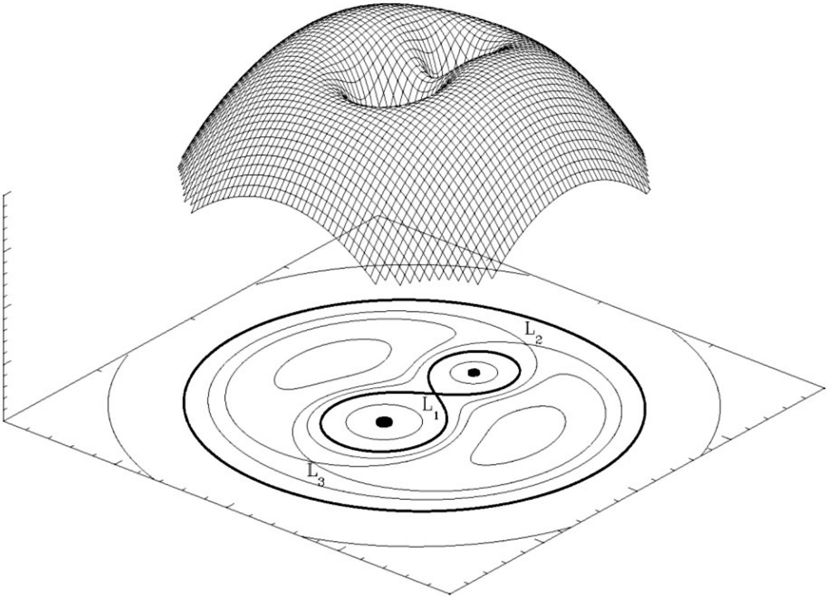
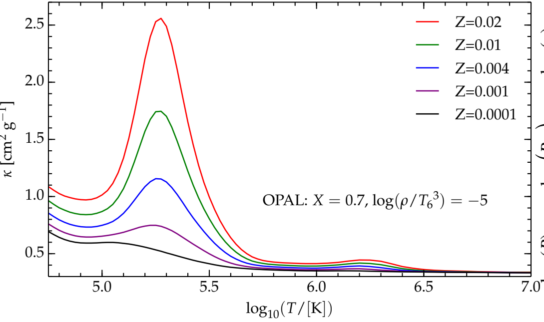
Roche Lobe OverFlow

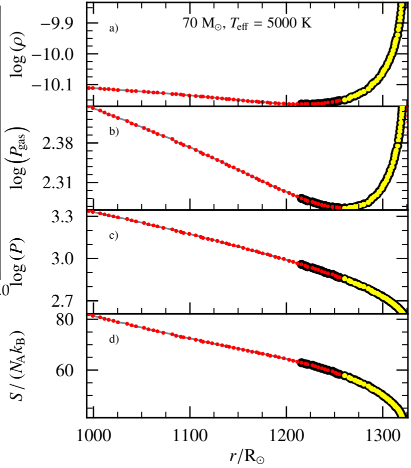
Mass Transfer in Binaries



MESA nearly super-Eddington Regime

$$L_{\rm Edd} \stackrel{\rm def}{=} \frac{4\pi G M(R) c}{\kappa(r)}\,, \qquad \frac{dP_{\rm gas}}{dr} = \frac{dP_{\rm rad}}{dr}\left[\frac{L_{\rm Edd}}{L_{\rm rad}} - 1\right]$$





$$M_{\rm ZAMS} \gtrsim 20 M_\odot \Rightarrow \text{insufficient } F_{\rm conv}^{\rm MLT}$$

Figure: From Paxton *et al.* 2013, ApJS, 208, 5p

MLT++:

$$\nabla_T - \nabla_{\rm ad} \to \alpha_\nabla f_\nabla (\nabla_T - \nabla_{\rm ad})$$
$$\alpha_\nabla \equiv \alpha_\nabla(\beta, \Gamma_{\rm Edd}),\ f_\nabla \ll 1$$

Wind Oservational Diagnostics

- P Cygni line profiles
- Optical and near UV lines (e.g. Hα)
- Radio and IR continuum excess
- IR spectrum of molecules (e.g. CO)
- Maser lines (for low density winds)

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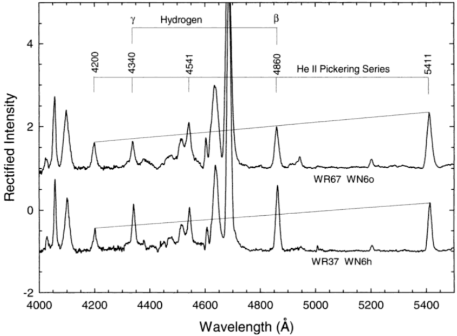
Assumptions commonly needed:

- Velocity structure: $v(r) \simeq \left(1 - \frac{r}{R_*}\right)^\beta$ with $\beta \simeq 1$
- Chemical composition and ionization fraction
- Spherical symmetry: $\dot{M} = 4\pi r^2 \rho v(r)$
- Steadiness and (often) homogeneity

$\dot{M}$ derived from fit of (a few) spectral lines.
No theoretical guaranties coefficients are constant.

Wolf-Rayet Stars



Observational Definition:

Based on spectral features indicating a **Strong Wind**:

- Hydrogen Depletion ($\neq$ Lack of Hydrogen)
- Broad Emission Lines
- Steep Velocity Gradients

Sub-categories: WN,WC,WO,WNL, etc.

Computational Definition (MESA):

- $X_s < 0.4$

Impossible to distinguish sub-categories without spectra!

Evolution of a Massive Star in one Slide

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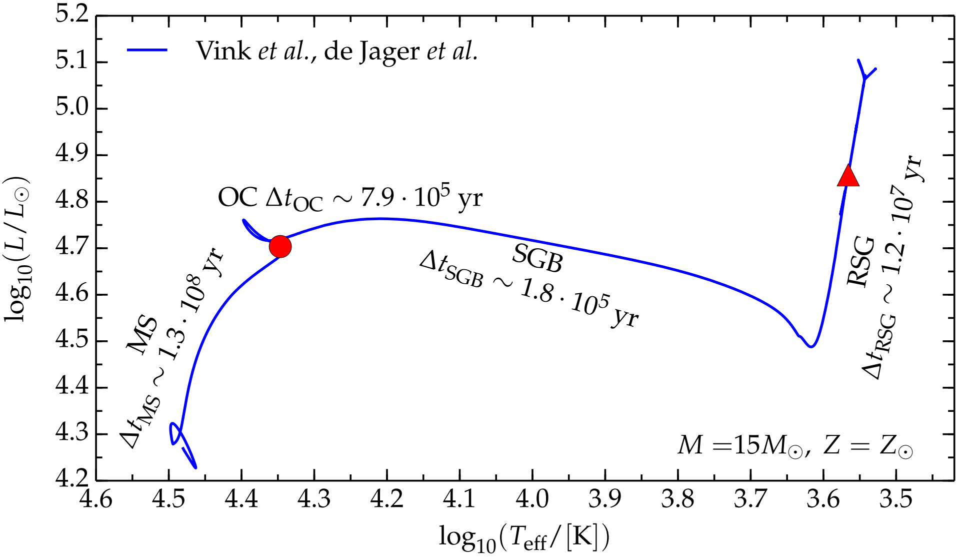

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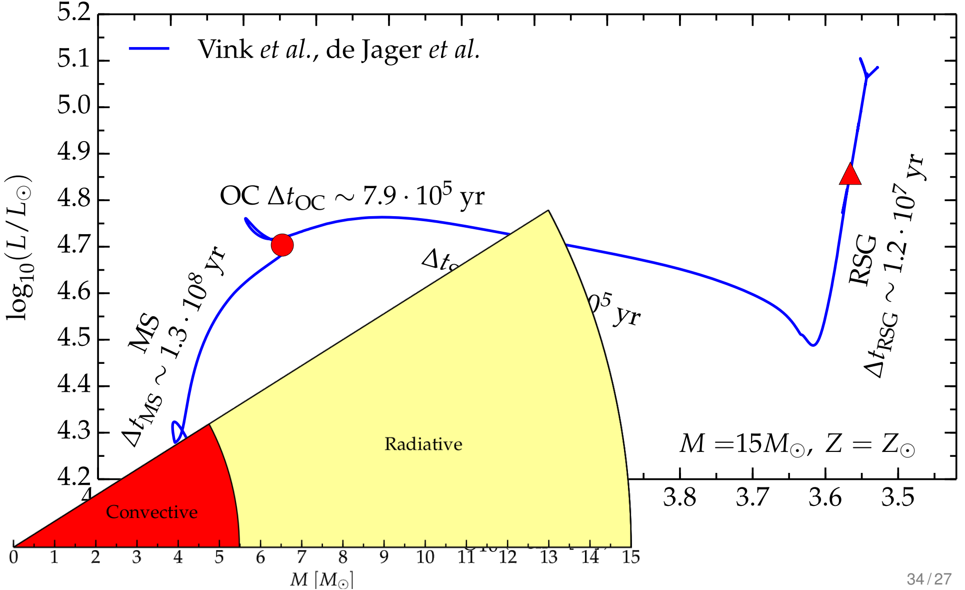

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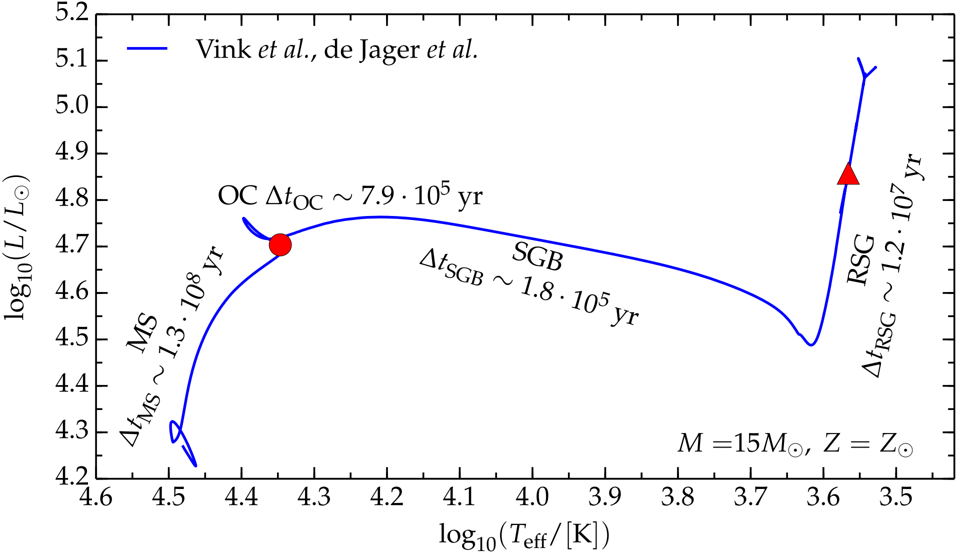

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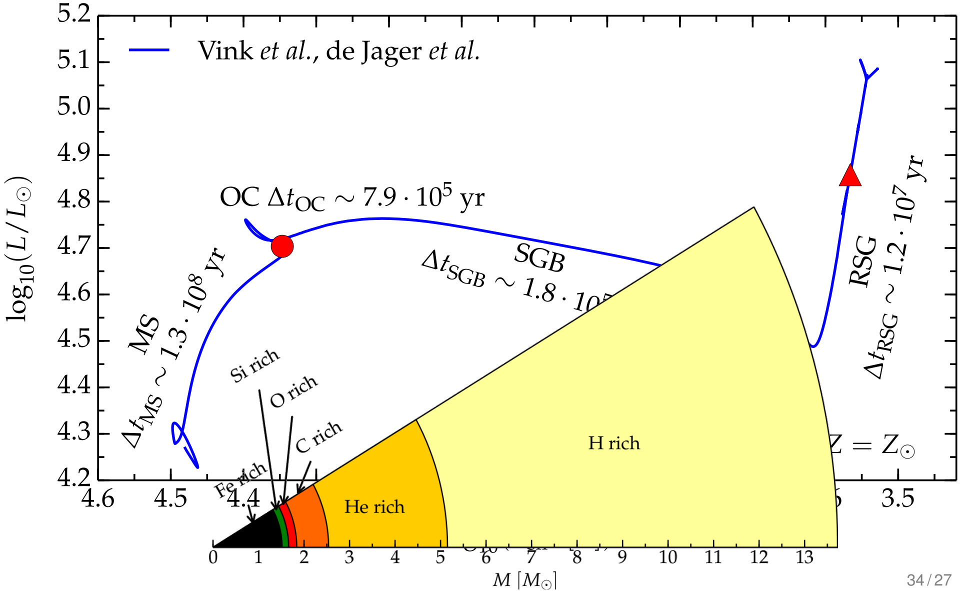
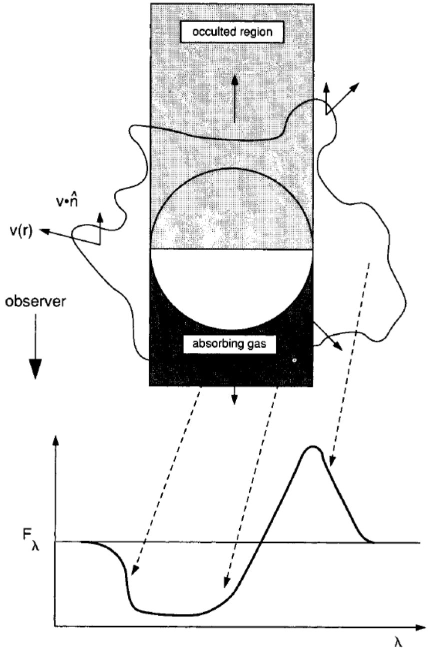


P Cygni Line Profiles



- Blue shifted Absorption Component
- Red shifted Emission Component
- Broadening from scattering into the line of sight

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

Assuming:

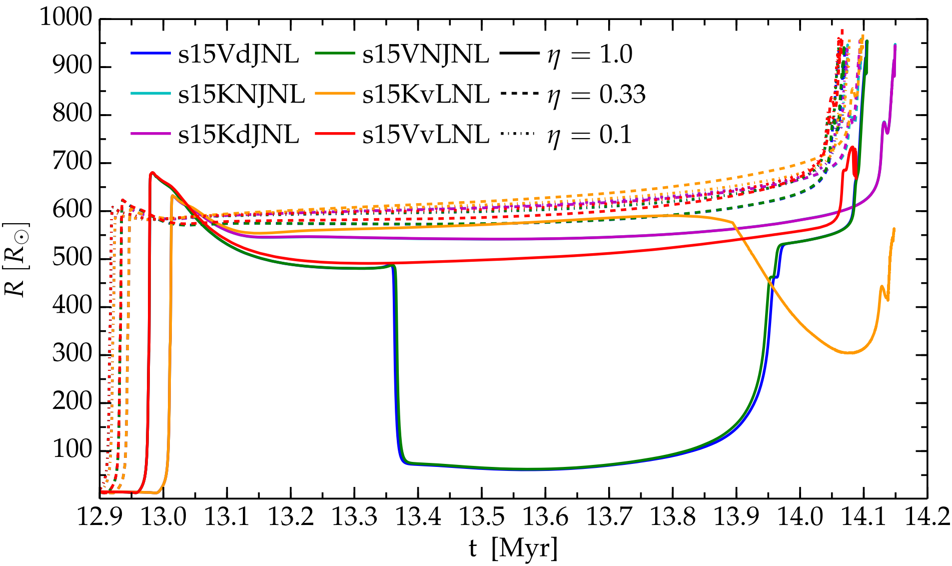
Chemical composition

Velocity Structure

the fit of the line profile gives ρ

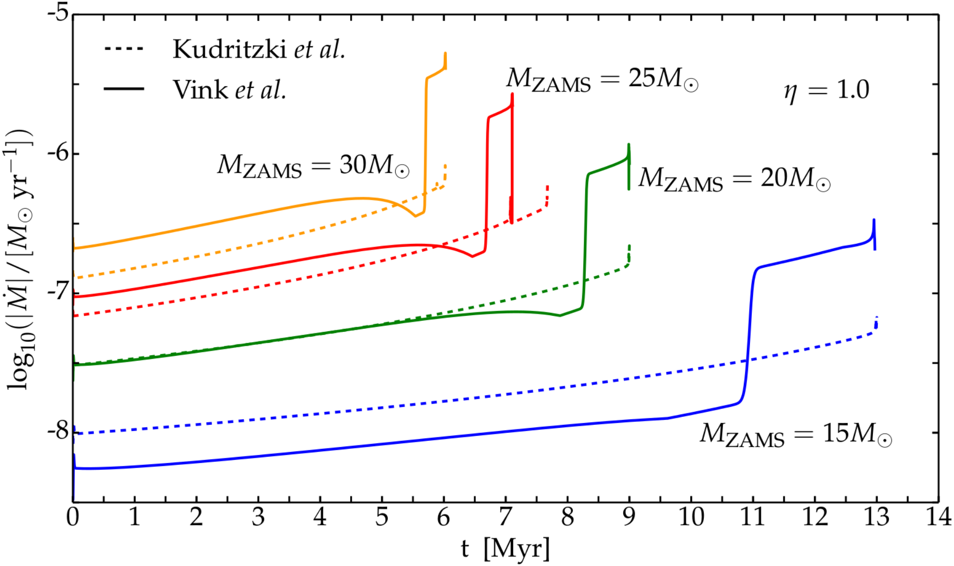
Figure: 34 Cyg or P Cygni, first star to show the eponymous profile.

$R(t)$ for $15M_\odot$ Models during Blue Loops

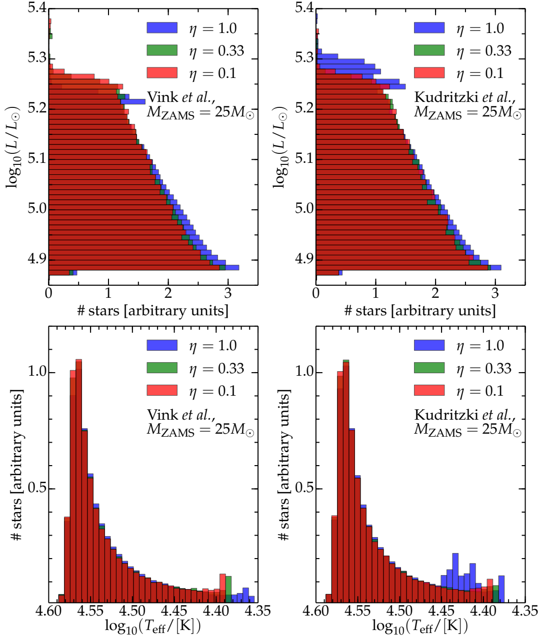


End of the hot evolutionary phase

Vink *et al.* only: $T_{\text{jump}} \sim 25\ [\text{kK}]\ \Rightarrow$ $Fe^{3+} \rightarrow Fe^{2+}$

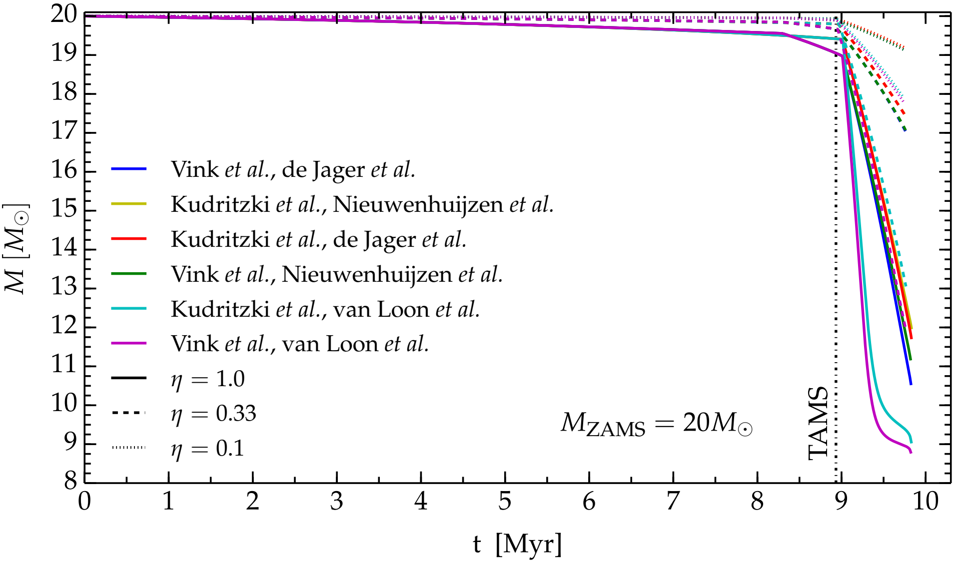


Stellar counts

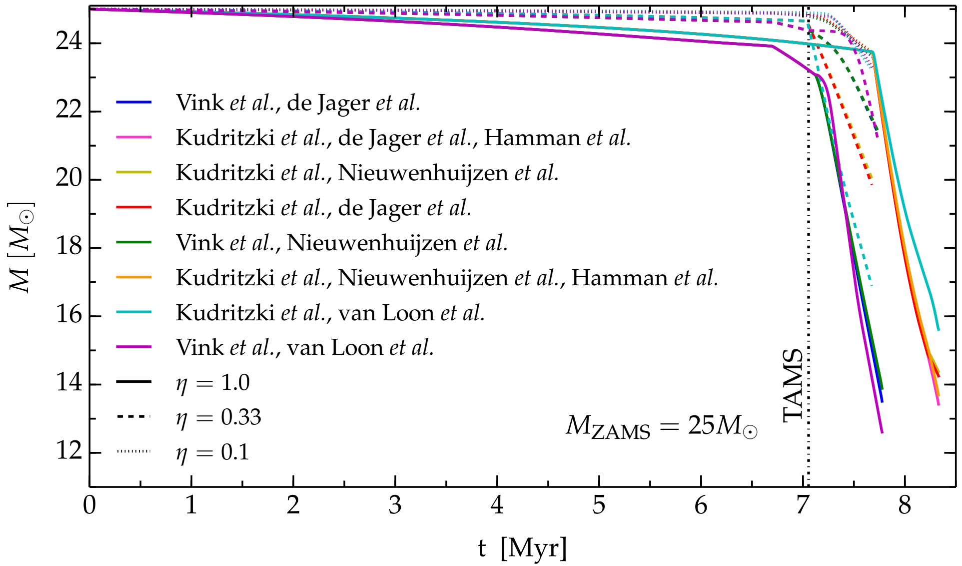


- Cannot be compared to clusters or single populations
- Higher $\eta \Rightarrow$ lower $M \Rightarrow$ slower evolution
- Different cut-offs in L and $T_{\rm eff}$
- Kudritzki *et al.* rate with $\eta = 1.0$ produces a loop in the HR diagram tracks, resulting in the over-population shown.

$M(t)$ for $M_{\mathrm{ZAMS}} = 20 M_{\odot}$ with with MESA



$M(t)$ for $M_{ZAMS} = 25M_{\odot}$ with with MESA



$M(t)$ for $M_{\rm ZAMS} = 30 M_\odot$ with with MESA