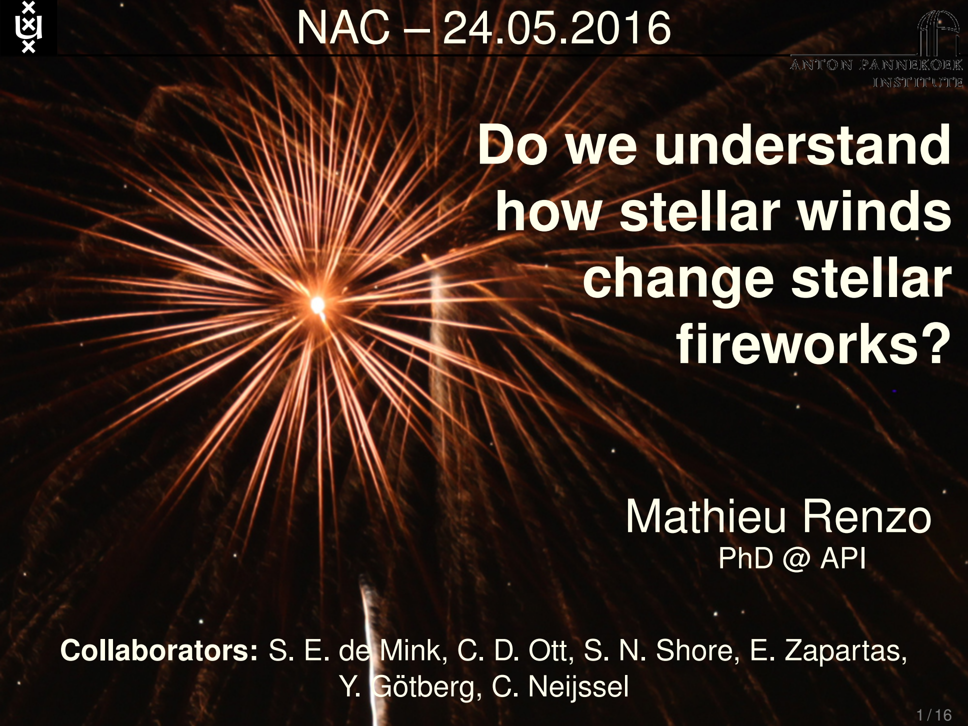
NAC – 24.05.2016



Do we understand how stellar winds change stellar fireworks?

Mathieu Renzo
PhD @ API

Collaborators: S. E. de Mink, C. D. Ott, S. N. Shore, E. Zapartas, Y. Götberg, C. Neijssel

Outline

Importance of Massive Stars...

- ... and their mass loss

Stellar Winds

- Outline of the Theory
- Treatment in Evolutionary Codes

Preliminary Results

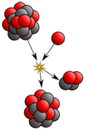
- Final Masses
- Impact on the core structure

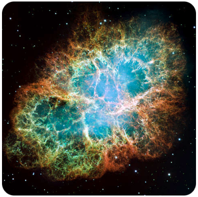
Conclusions

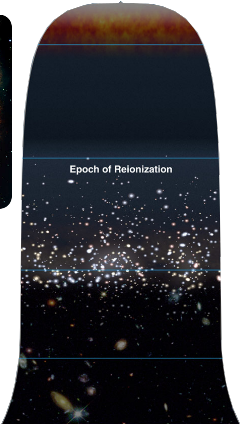
Why are Massive Stars Important?

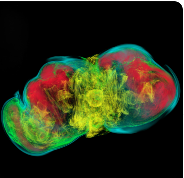
$$M_{\mathrm{ZAMS}} \gtrsim 8 - 10\, M_{\odot}$$

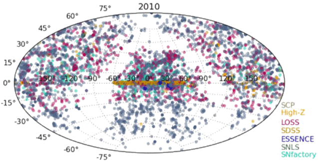
- Nucleosynthesis
- Chemical Evolution of Galaxies
- Effects on Star Formation
- Re-ionization Epoch
- Observations of Farthest Galaxies
- Catastrophic Events

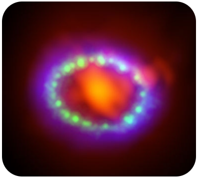












Mass Loss – Why does it Matter...

... 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
- Appearance & Classification (e.g. WR)
- Light Curve and Explosion Spectrum
- Final Fate (BH, NS or WD?)

Possible Mass Loss Mechanisms

Radiative Driving

$\Downarrow$

Stellar Winds

Dynamical Instabilities

$\Downarrow$

LBVs, Pulsations,
Super-Eddington Winds,
Centrifugal Disk Shedding

Binary interactions

$\Downarrow$

Roche Lobe OverFlows
(RLOF)

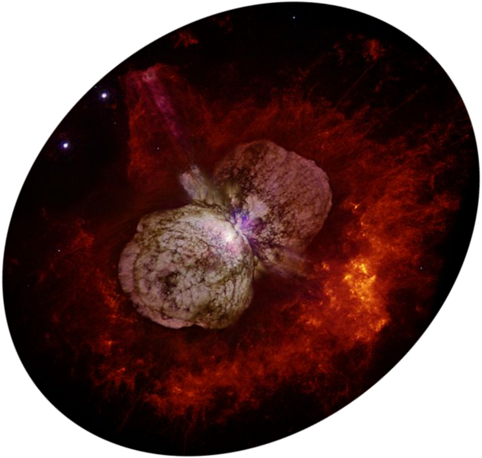


Figure: η Carinae.

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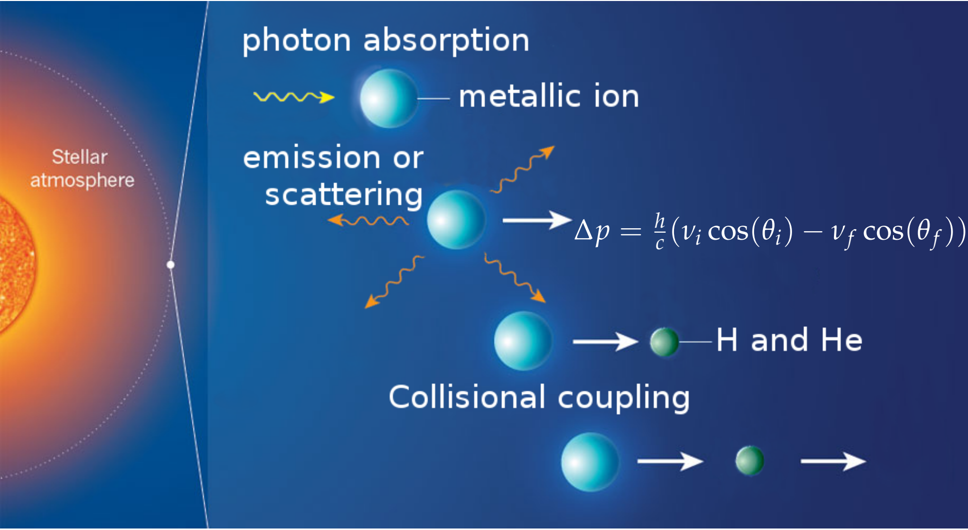
Radiatively Driven Winds in One Slide



Stellar atmosphere

photon absorption

metallic ion

emission or scattering

$\Delta p = \frac{h}{c}(\nu_i \cos(\theta_i) - \nu_f \cos(\theta_f))$

H and He

Collisional coupling

Problems: High Non-Linearity and Clumpiness:

$f_{\mathrm{cl}} \overset{\mathrm{def}}{=} \frac{\langle\rho^2\rangle}{\langle\rho\rangle^2} \neq 1 \Rightarrow$ 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:

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

Mass Loss in MESA

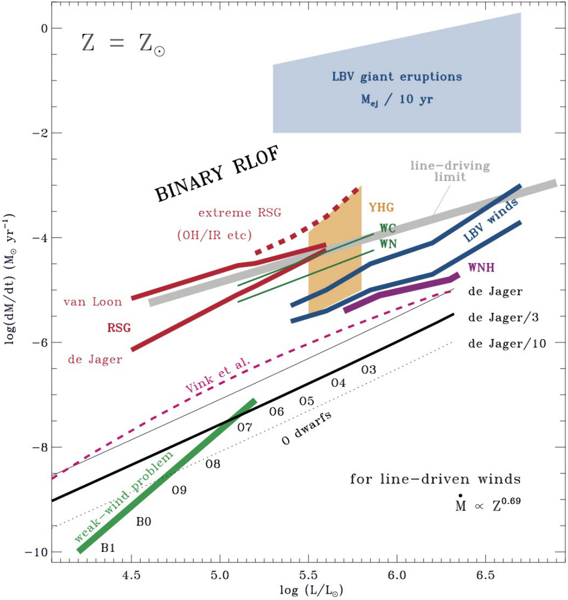


Figure: From Smith 2014, ARA&A, 52, 487S

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

$$\dot{M}(L, T_{\rm eff}, Z, R, M, ...)$$

$$\Downarrow$$

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

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:

$$M_{\rm ZAMS} = \{15,\ 20,\ 25,\ 30,\ 35\}\ M_\odot;$$

- Efficiency:

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

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

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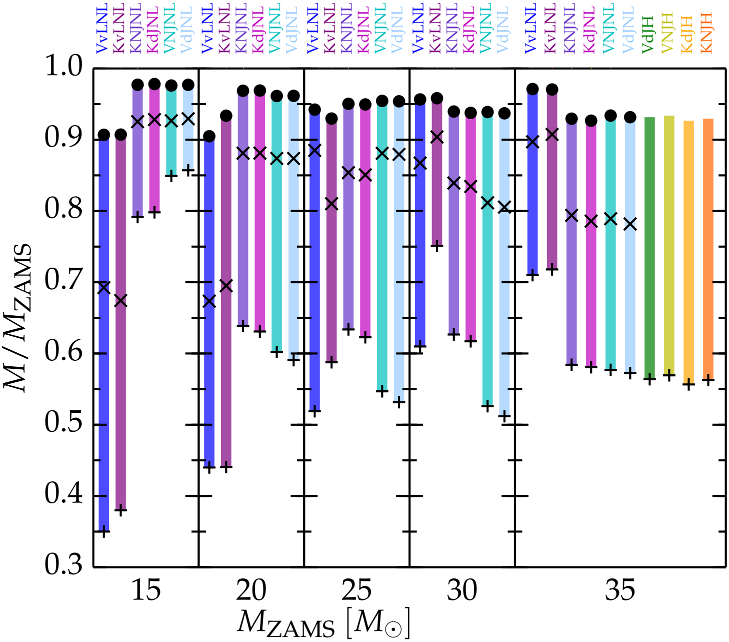
Results 1: Impact on the Final Mass



Legend:

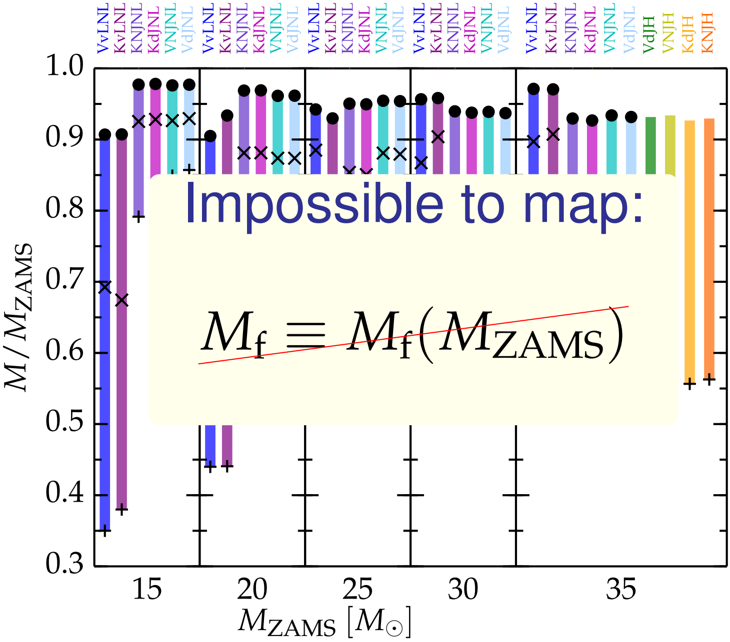
● $\eta = 0.1$

× $\eta = 0.33$

+ $\eta = 1.0$

- $\eta \rightarrow$ largest uncertainty
- Dust driven (**vL**) → very high mass loss for lower M_{ZAMS}.

Results 1: Impact on the Final Mass



Impossible to map:

$$\cancel{M_{\rm f} \equiv M_{\rm f}(M_{\rm ZAMS})}$$

Legend:

● $\eta = 0.1$

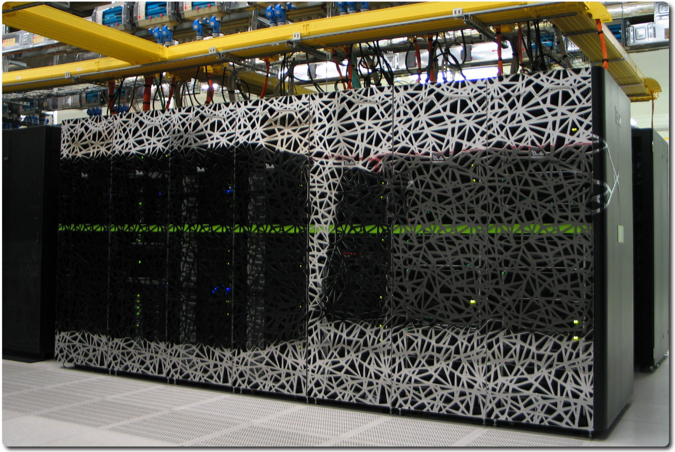
x $\eta = 0.33$

\+ $\eta = 1.0$

- $\eta \rightarrow$ largest uncertainty
- Dust driven (**vL**) $\rightarrow$ very high mass loss for lower $M_{\rm ZAMS}$.

Computing Advanced Burning Stages

- Initially small effect ⇒ $N_{\mathrm{zones}} \gtrsim 20\,000$;
- Complex nuclear burning ⇒ $N_{\mathrm{iso}} \gtrsim 200$;

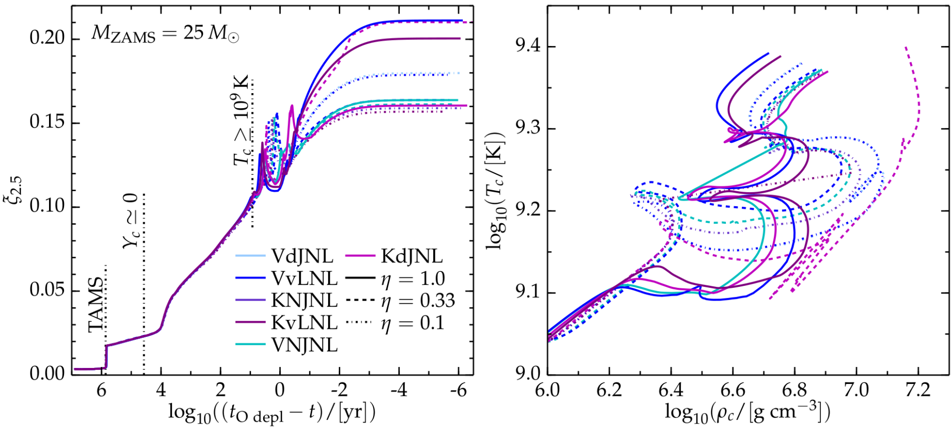


SurfSara's Cartesius Computer.

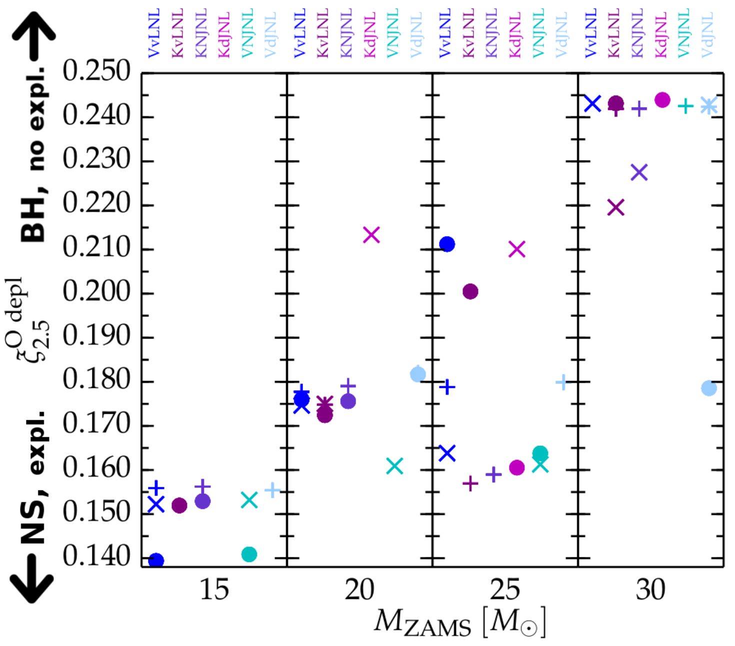
Results 2: Core Structure

Compactness Parameter: $\xi_{2.5}(t) \overset{\text{def}}{=} \frac{2.5/M_\odot}{R(\mathcal{M})/1000\ \text{km}}$

- “Large” $\xi_{2.5}$ ⇒ harder to explode ⇒ BH formation
- “Small” $\xi_{2.5}$ ⇒ easier to explode ⇒ NS formation



Results 2: $\xi_{2.5}$ @ Oxygen Depletion



(Reduced grid)

Legend:

- ● $\eta = 0.1$
- **x** $\eta = 0.33$
- **+** $\eta = 1.0$

Post O burning evolution

$\Downarrow$

Core contraction

$\Downarrow$

Amplification of the differences.

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Conclusions:

- η has a larger influence on the final mass than the wind algorithm;
- Early ("hot phase") mass loss influences the further evolution;
- Uncertainties in stellar winds prevent to go back in time and infer M_{ZAMS} of observed evolved stars;
- Different algorithmic representations of stellar winds ⇒ Qualitatively different evolutionary tracks, and *predicted* final fate;

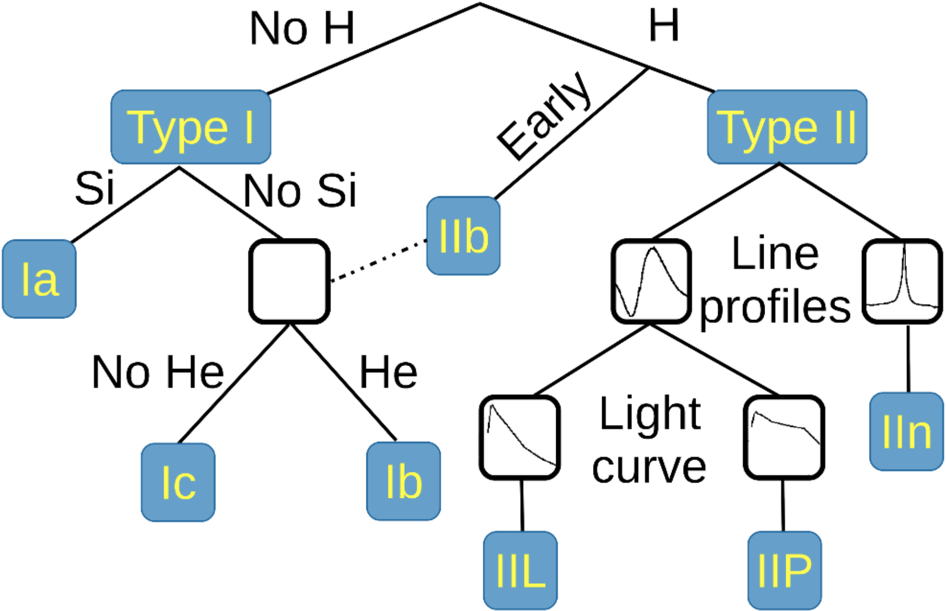
(...Cartesius still crunching numbers for post-O burning evolution...)

Thank you!

Outline

Backup slides

Supernova Taxonomy



No H

H

Type I

Early

Type II

Si

No Si

IIb

Ia

Line profiles

No He

He

Light curve

IIn

Ic

Ib

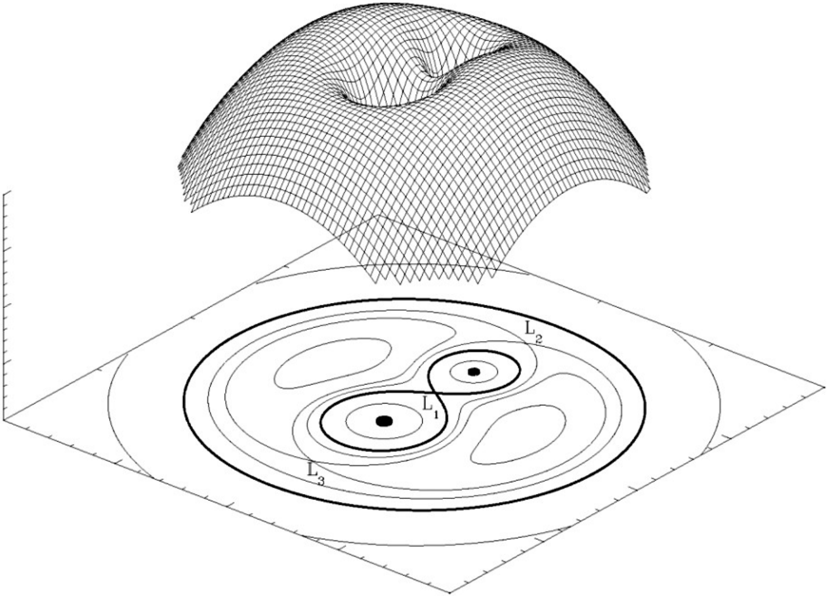
IIL

IIP

Back

Roche Lobe OverFlow

Mass Transfer in Binaries



Wind Oservational Diagnostics

◂ Back

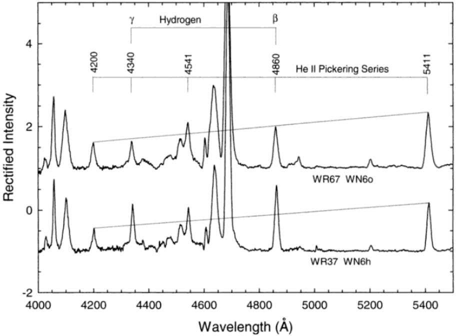
- P Cygni line profiles
- Optical and near UV lines (e.g. Hα)
- Radio and IR continuum excess
- IR spectrum of molecules (e.g. CO)
- Maser lines (for low density winds)

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!

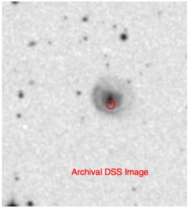
Why Impulsive Mass Loss?

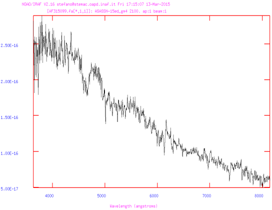
Observational Evidence:

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

Theory: Dynamical Events $\Rightarrow$ MESA not ready

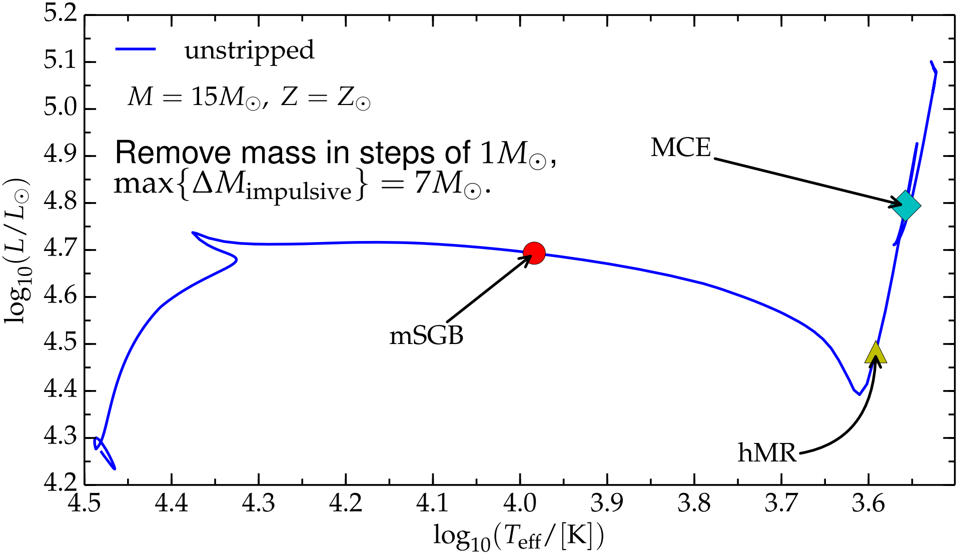
- Pulsational Instabilities
- Roche Lobe Overflow in binaries
- Catastrophic Eruption(s)





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

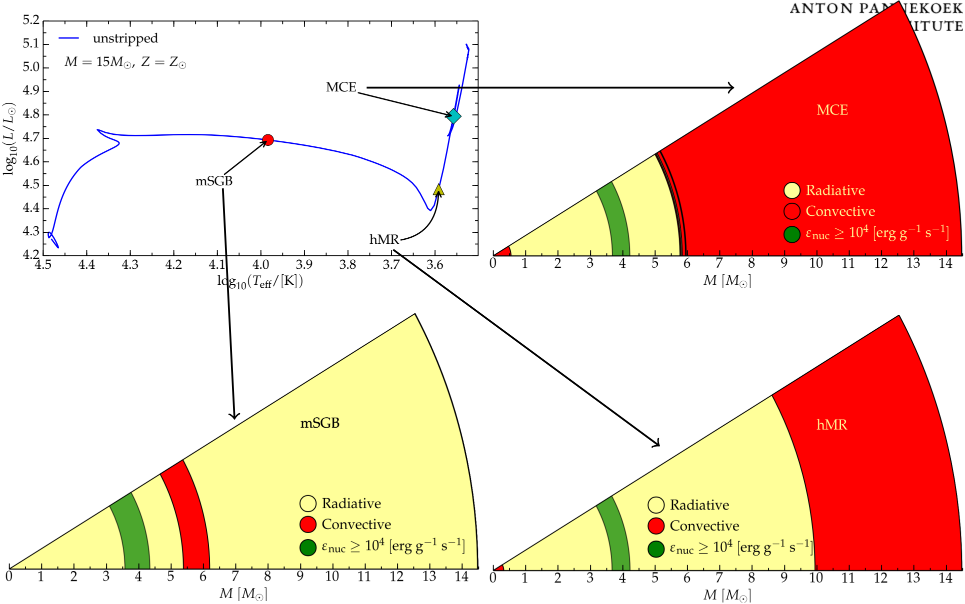
The Stripping Process



Remove mass in steps of $1M_\odot$, $\max\{\Delta M_{\mathrm{impulsive}}\} = 7M_\odot$.

Red dot: $T_{\mathrm{eff}} = 10^4$ [K]; **Yellow Triangle**: $R \geq R_{\mathrm{max}}/2 = 375R_\odot$;
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

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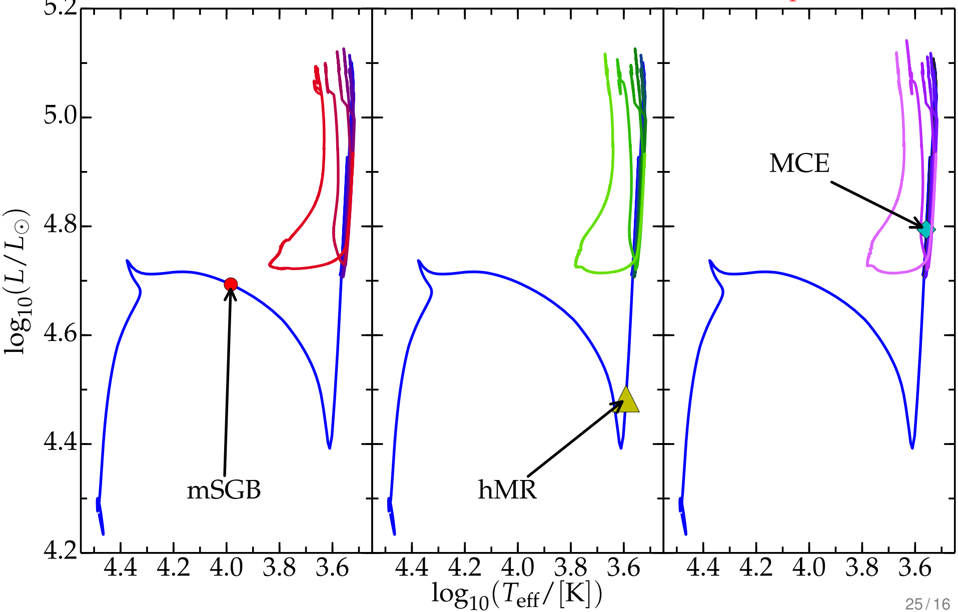
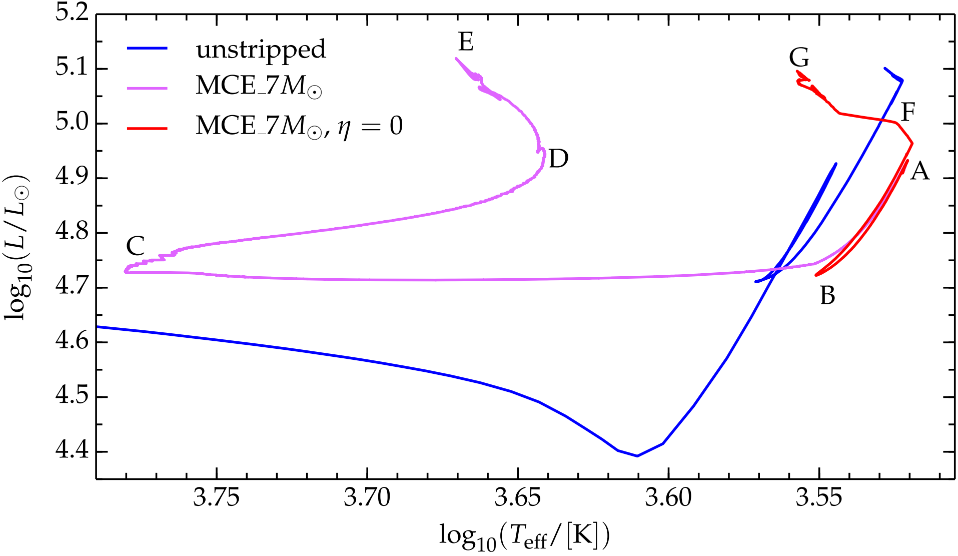
Evolutionary tracks depend only on $\Delta M_{\mathrm{impulsive}}$

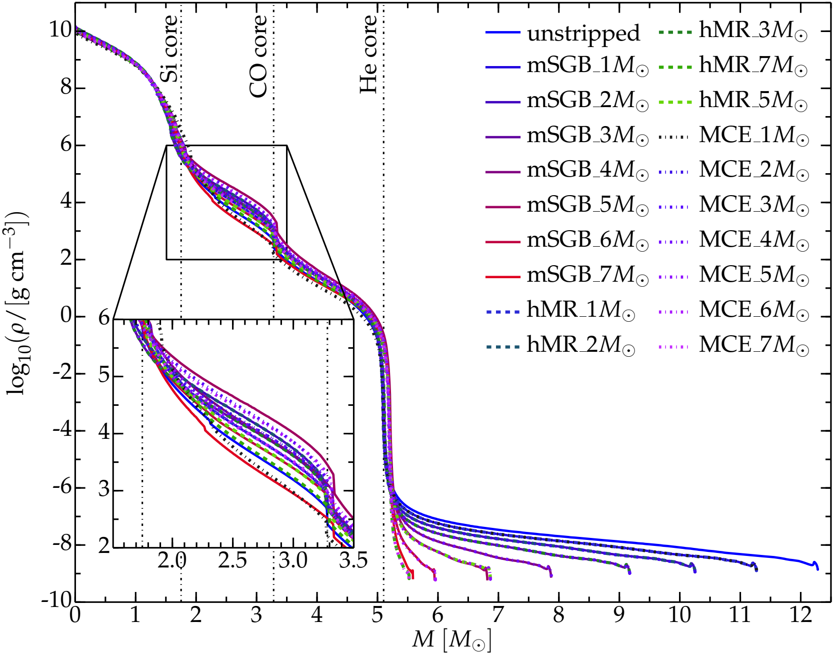


Evolution toward Higher T_{eff}



Impulsive + wind mass loss drives blueward evolution

pre-SN Stripped Structures



Light Curves from Stripped Models

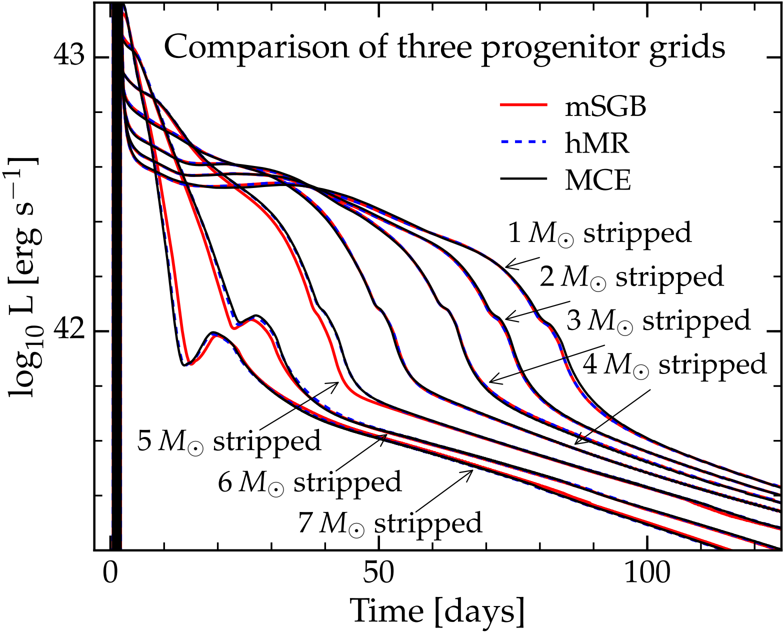
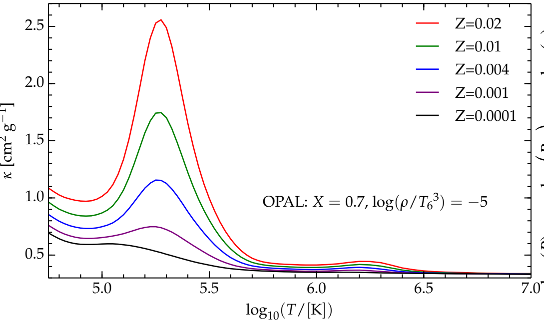
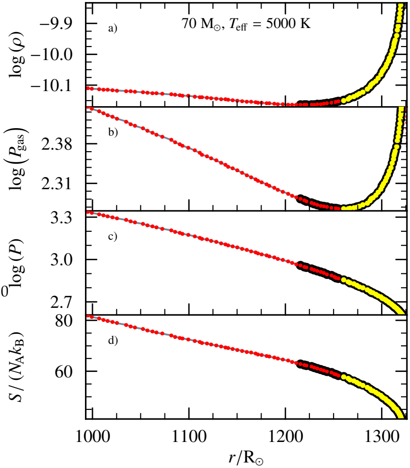


Figure: Morozova *et al.* – ApJ,814,63M

MESA nearly super-Eddington Regime

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





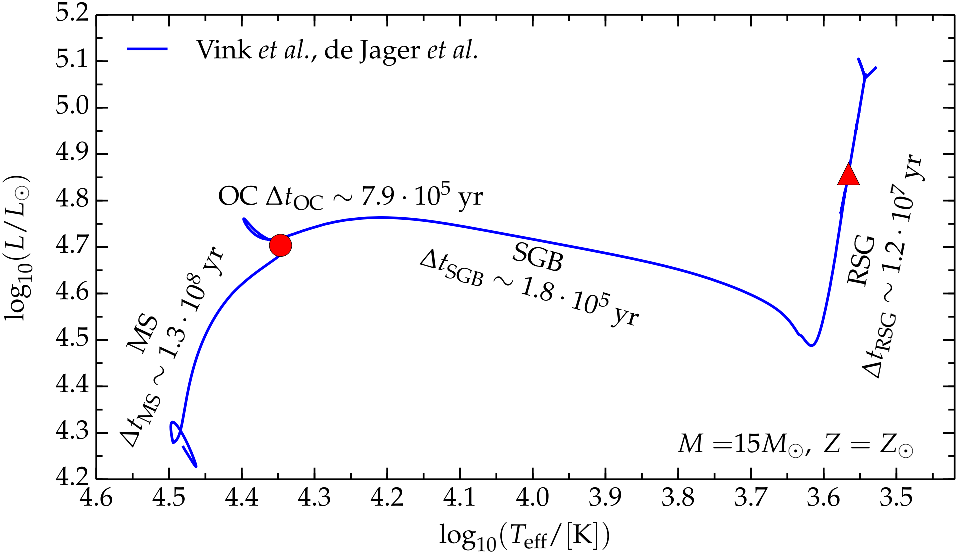
$M_{\mathrm{ZAMS}} \gtrsim 20 M_\odot \Rightarrow$ insufficient $F_{\mathrm{conv}}^{\mathrm{MLT}}$

MLT++:

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

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

Evolution of a Massive Star in one Slide



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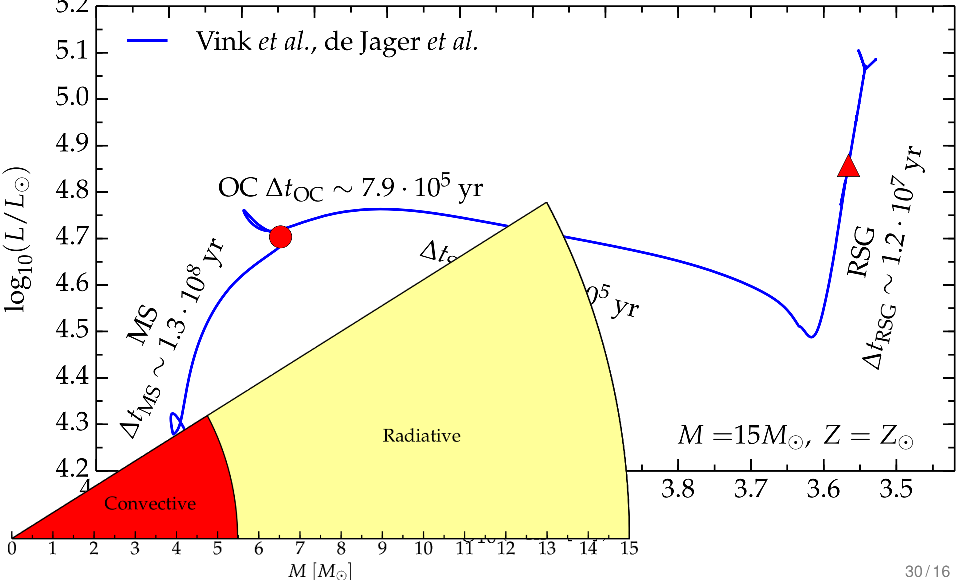

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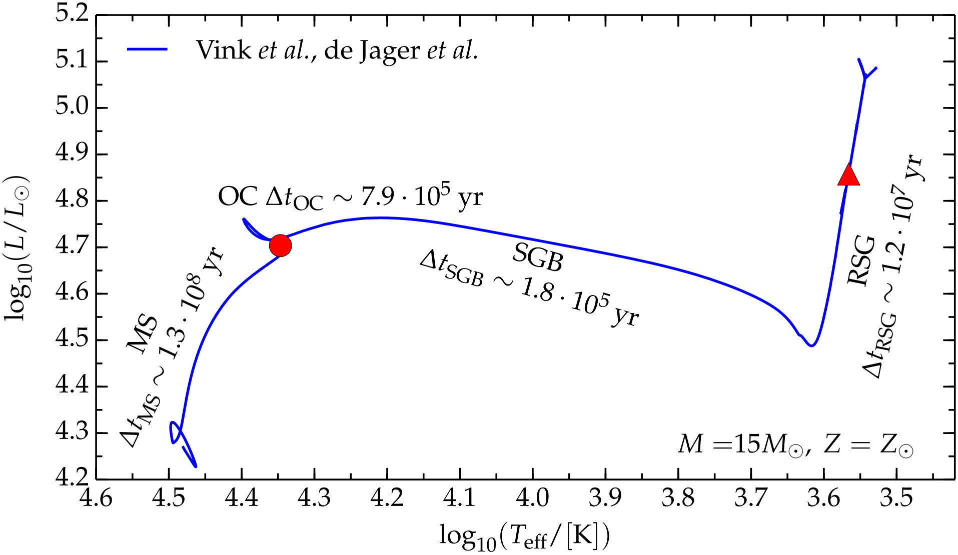

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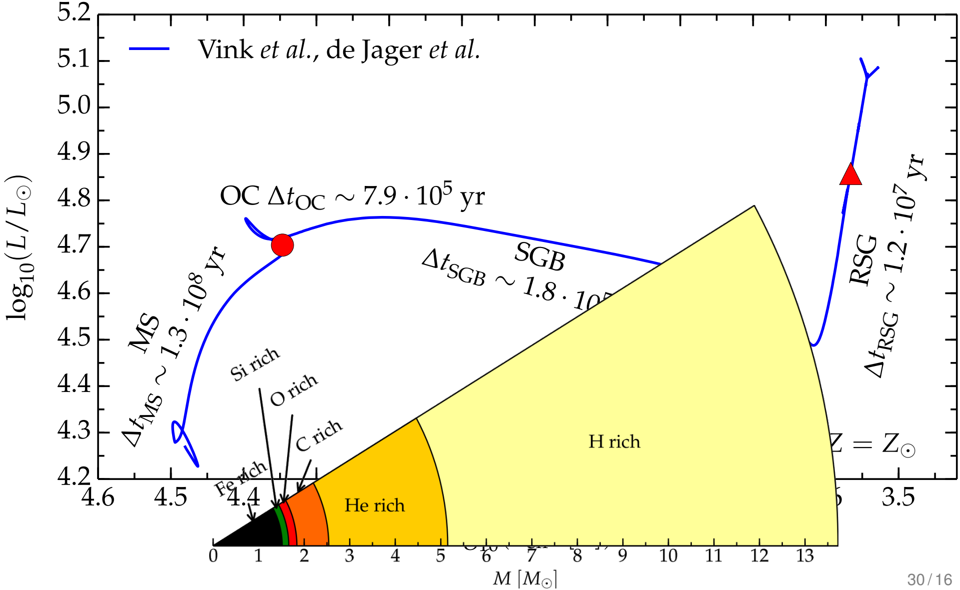
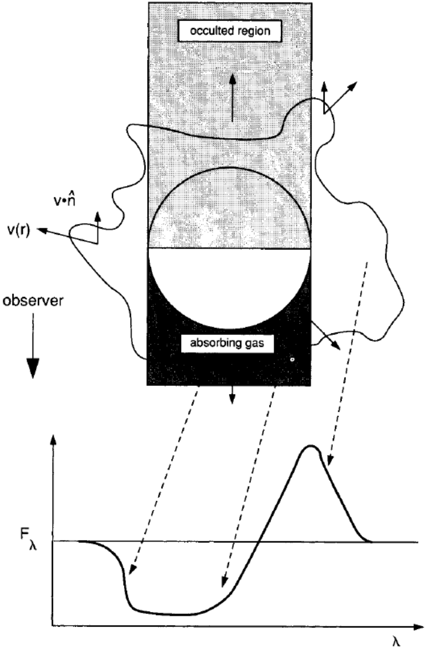


P Cygni Line Profiles



- 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

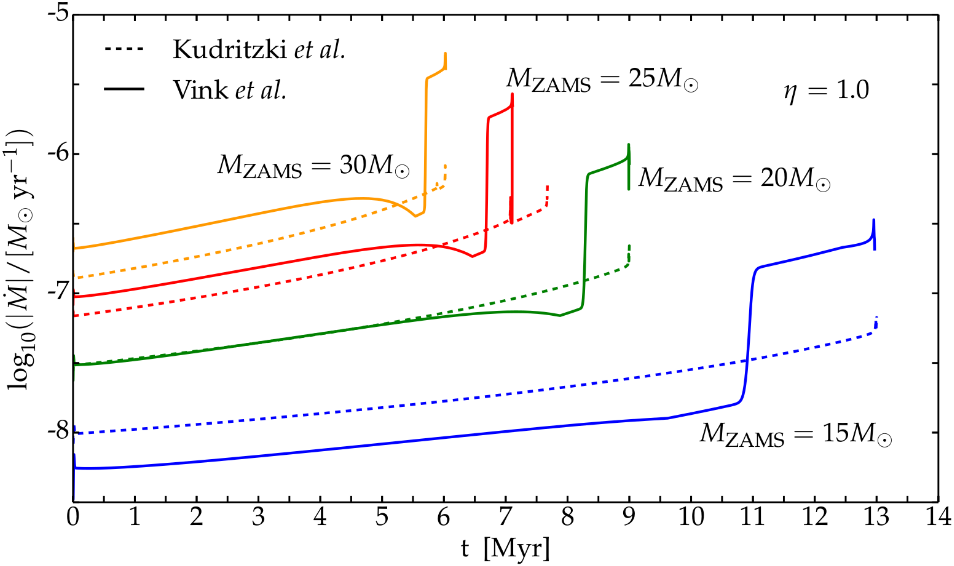
Velocity Structure

the fit of the line profile gives ρ

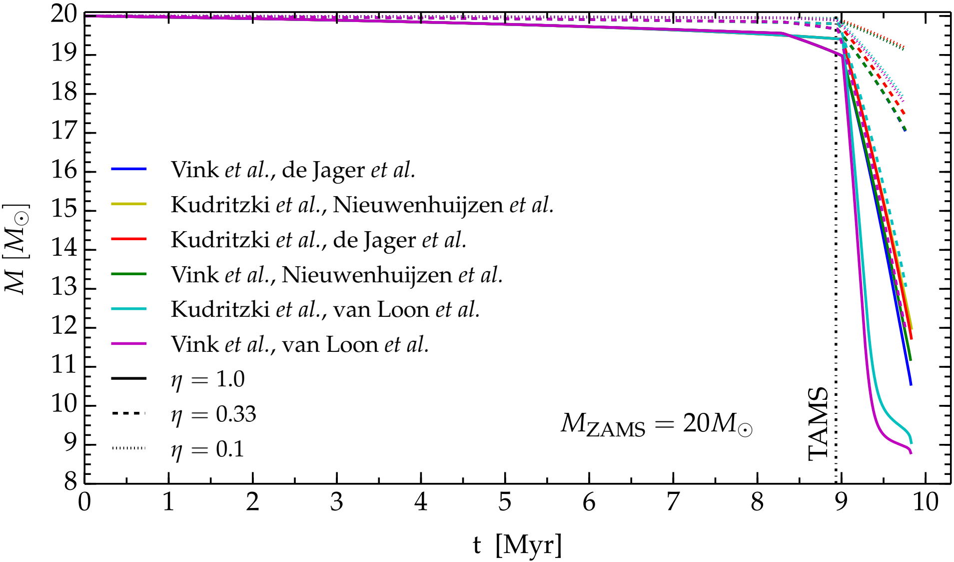
Figure: 34 Cyg or P Cygni, first star to show the eponymous profile.

End of the hot evolutionary phase

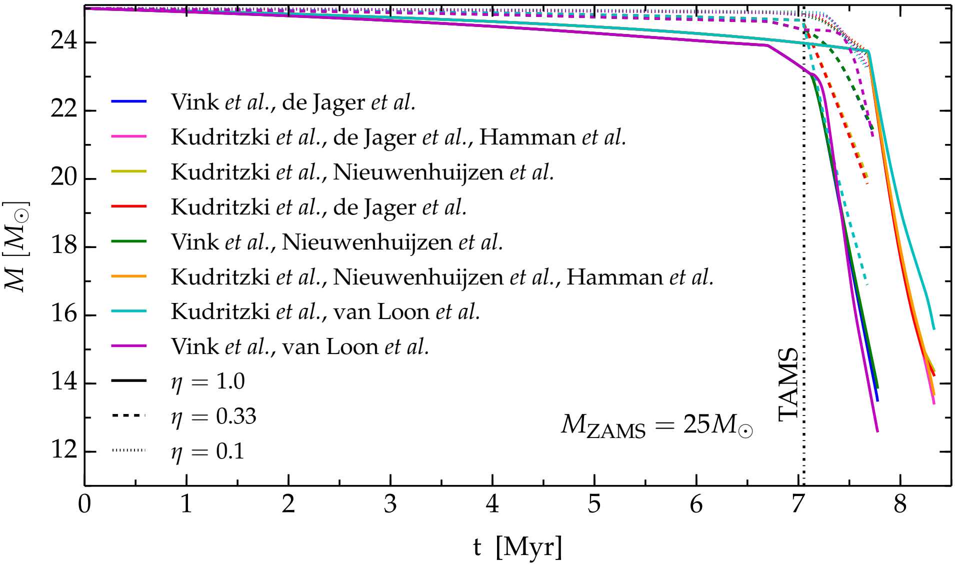
Vink *et al.* only: $T_{\text{jump}} \sim 25\ [\text{kK}] \ \Rightarrow \text{Fe}^{3+} \rightarrow \text{Fe}^{2+}$



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



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



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

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