The Impact of Mass Loss on the Final Structure and Fate of Massive Stars

Mathieu Renzo
PhD in Amsterdam

Collaborators: C. D. Ott, S. N. Shore, S. E. de Mink, E. Zapartas, Y. Götberg, C. J. Neijssel, A. Piro, V. Morozova

NASA, JPL-Caltech, Spitzer Space Telescope

Outline

Possible Mass Loss Channels

- Radiatively Driven Stellar Winds
- Roche Lobe Overflow
- Impulsive Events

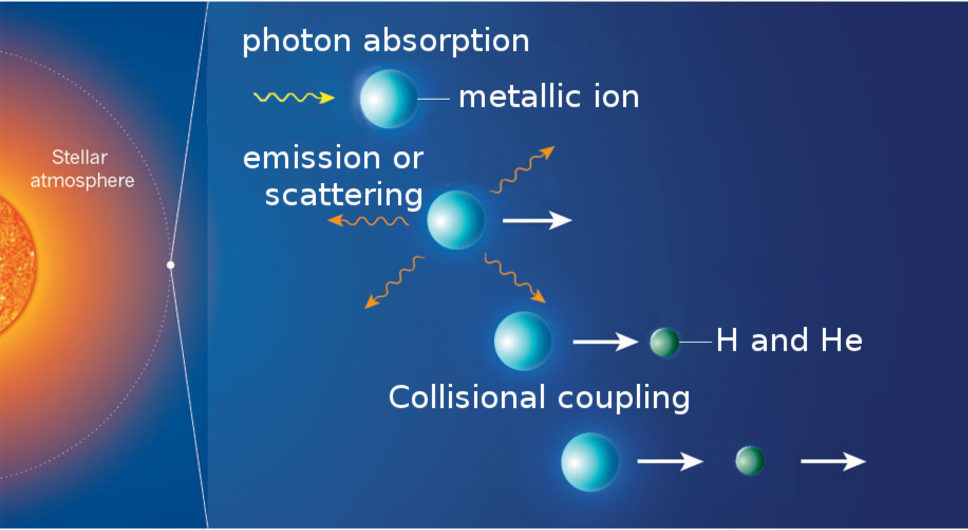
Effect of Winds on the Late Stellar Structure

- pre-SN Mass
- Core Structure & "Explodability"

Light Curves from post-Impulsive Mass Loss

- Numerical Experiment of Stripping
- Pre-SN Stripped Structures
- Resulting Lightcurves

Conclusions



Problems: High Non-Linearity and Clumpiness:

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

Massive Stars Come in Binaries

Up to ∼70% of Massive Stars will interact with their companion

(e.g. Mason *et al.* '09, Sana & Evans '12, Sana *et al.* '12, Kobulnicky *et al.* '14)

Impulsive Mass Loss Event

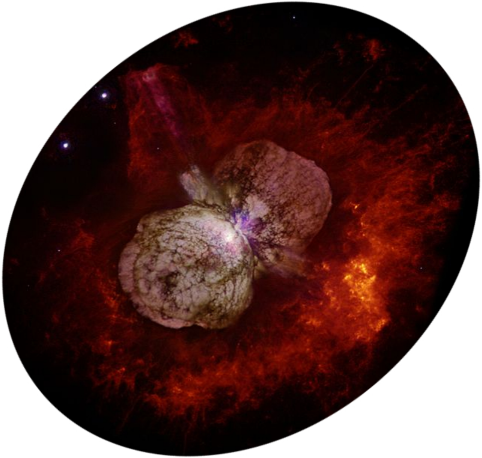
ANTON PANNEKOEK INSTITUTE

"Dynamical Instabilities"

$\Downarrow$

LBVs,
Pulsations,
Super-Eddington Winds,
Centrifugal Disk Shedding,
Common Envelope Ejection

(Possibly triggered by
Mass Accretion in a Binary)



η Car, Credits: NASA/ESA

Outline

ANTON PANNEKOEK
INSTITUTE

Possible Mass Loss Channels

- Radiatively Driven Stellar Winds
- Roche Lobe Overflow
- Impulsive Events

Effect of Winds on the Late Stellar Structure

- pre-SN Mass
- Core Structure & “Explodability”

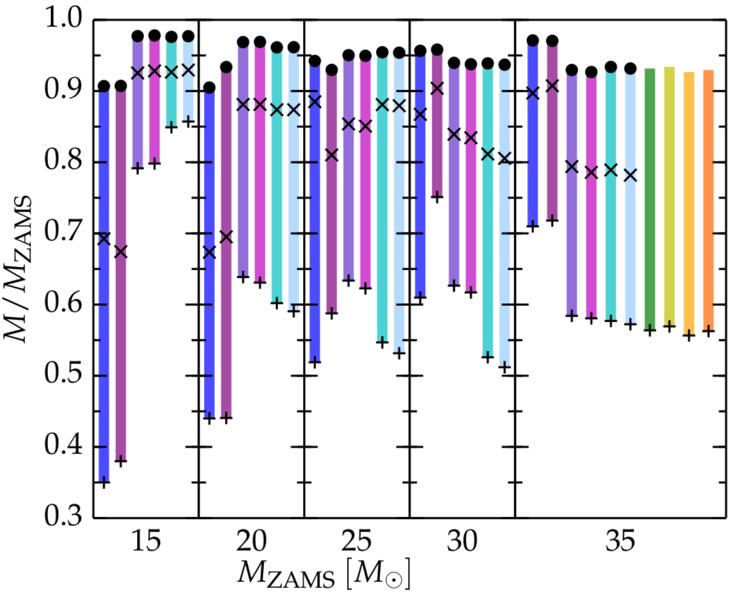
Light Curves from post-Impulsive Mass Loss

- Numerical Experiment of Stripping
- Pre-SN Stripped Structures
- Resulting Lightcurves

Conclusions

Impact on the Final Mass

ANTON PANNEKOEK INSTITUTE



MESA

Legend:

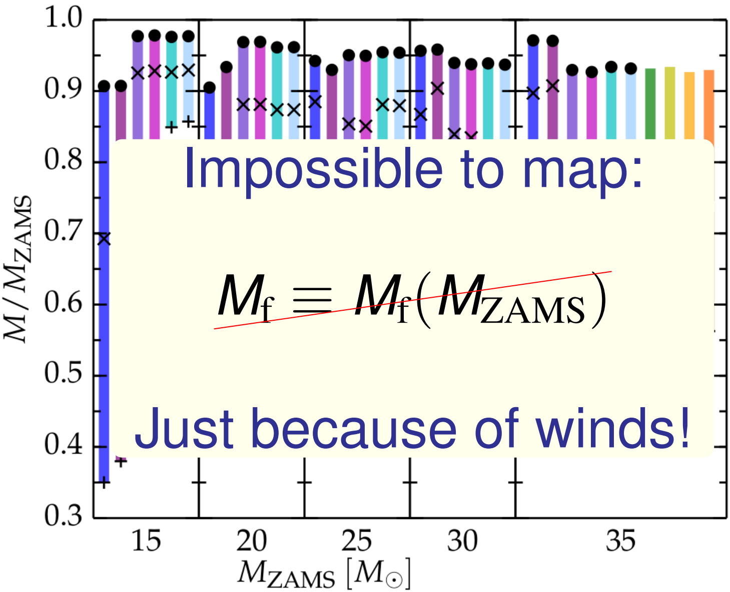
- • $\eta = 0.1$
- x $\eta = 0.33$
- + $\eta = 1.0$

$\eta \rightarrow$ largest uncertainty

Renzo *et al.*, in prep.

Impact on the Final Mass

ANTON PANNEKOEK INSTITUTE



Impossible to map:

$$M_f \equiv M_f(M_{\rm ZAMS})$$

Just because of winds!

MESA

Legend:

- • $\eta = 0.1$
- x $\eta = 0.33$
- + $\eta = 1.0$

$\eta \rightarrow$ largest uncertainty

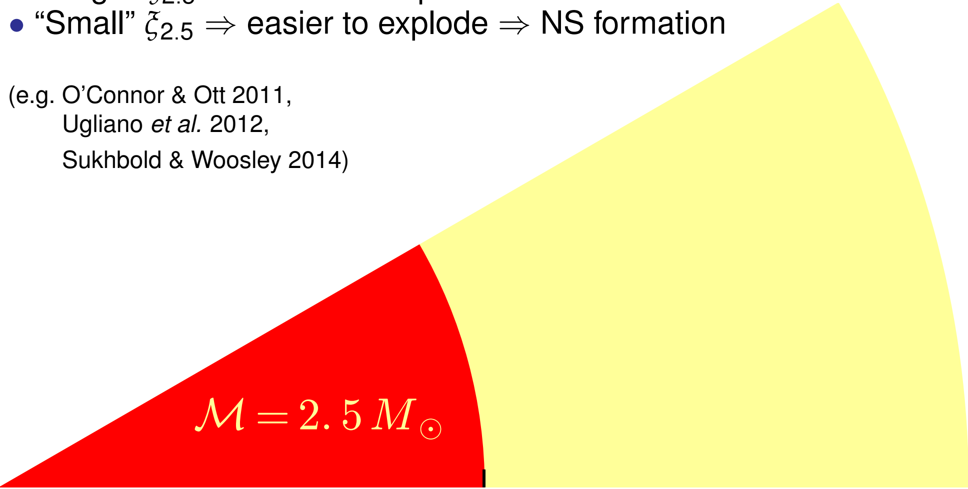
Renzo *et al.*, in prep.

ANTON PANNEKOEK INSTITUTE

$$\xi_{\mathcal{M}}(t) \stackrel{\text{def}}{=} \frac{\mathcal{M}/M_\odot}{R(\mathcal{M})/1000\ \mathrm{km}}$$

- "Large" $\xi_{2.5}$ $\Rightarrow$ harder to explode $\Rightarrow$ BH formation
- "Small" $\xi_{2.5}$ $\Rightarrow$ easier to explode $\Rightarrow$ NS formation

(e.g. O'Connor & Ott 2011,
Ugliano *et al.* 2012,
Sukhbold & Woosley 2014)

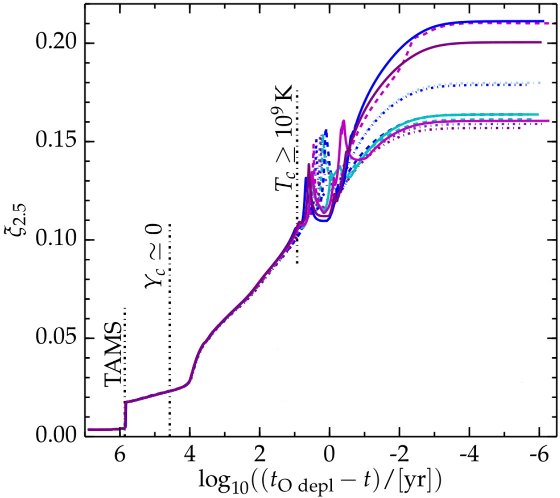


not to scale! $R(\mathcal{M})$

Core Structure @ O depletion

ANTON PANNEKOEK INSTITUTE

$M_{\mathrm{ZAMS}} = 25\,M_{\odot}$ MESA models

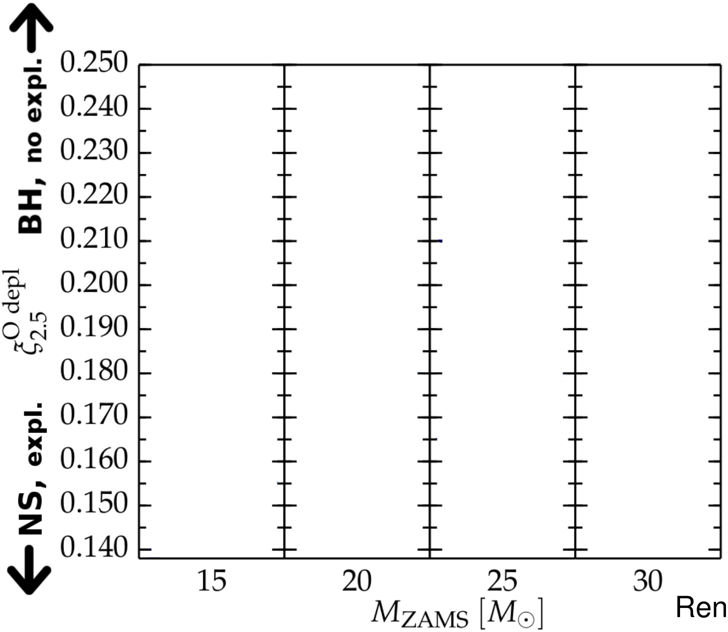


Renzo *et al.*, in prep.

Critical point: Ne core burning/C shell burning

Challenges: Nuclear Network & Spatial Resolution

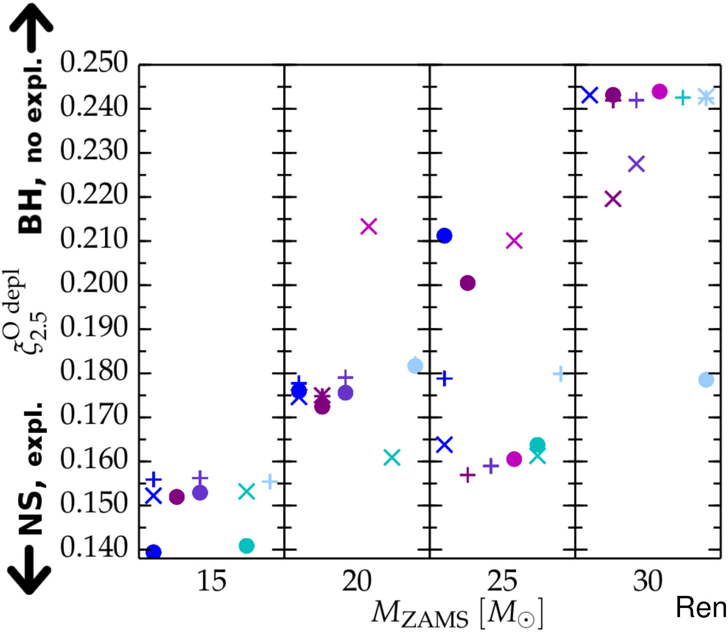
ANTON PANNEKOEK INSTITUTE



Renzo *et al.*, in prep.

$\xi_{2.5}$ @ Oxygen Depletion

ANTON PANNEKOEK INSTITUTE



Legend:

- • $\eta = 0.1$
- x $\eta = 0.33$
- + $\eta = 1.0$

Post O burning evolution

$\Downarrow$

Core contraction

$\Downarrow$

Amplification of the differences.

Renzo *et al.*, in prep.

ANTON PANNEKOEK INSTITUTE

Possible Mass Loss Channels

- Radiatively Driven Stellar Winds
- Roche Lobe Overflow
- Impulsive Events

Effect of Winds on the Late Stellar Structure

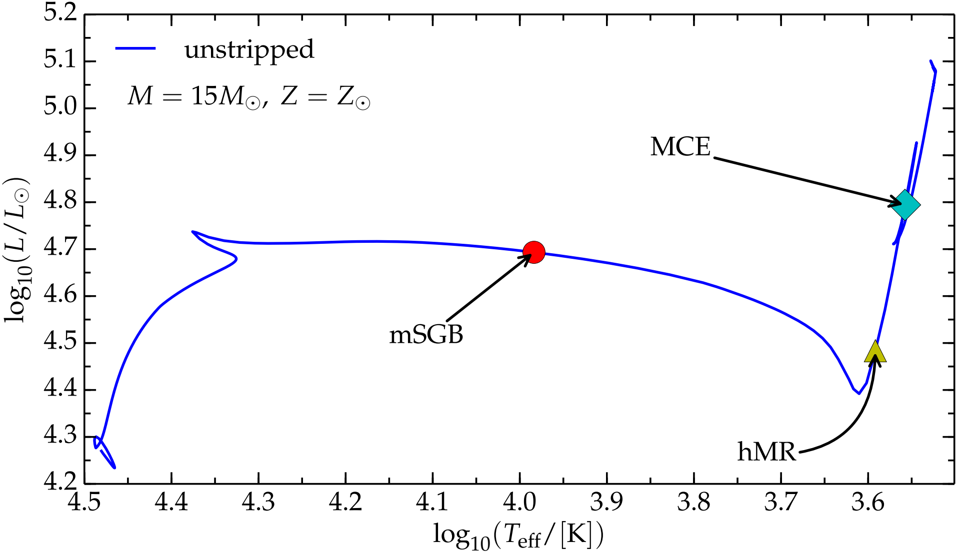
- pre-SN Mass
- Core Structure & “Explodability”

Light Curves from post-Impulsive Mass Loss

- Numerical Experiment of Stripping
- Pre-SN Stripped Structures
- Resulting Lightcurves

Conclusions

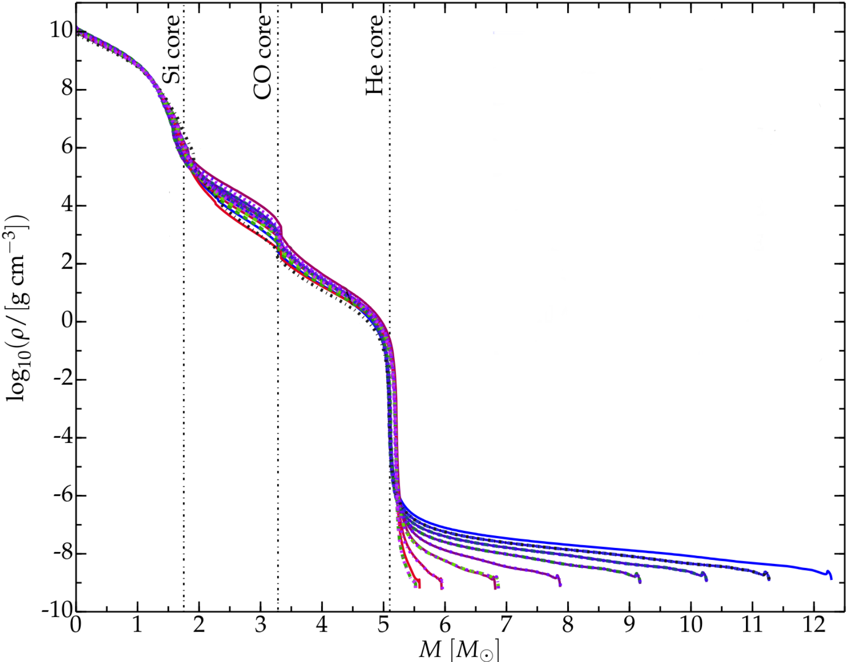
The Stripping Process



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

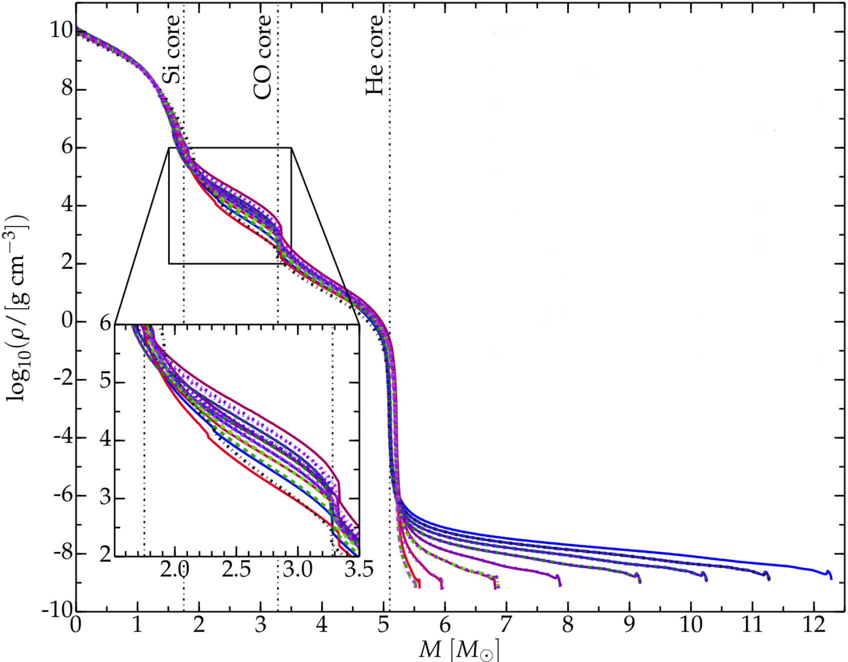
Morozova *et al.* 2015 – ApJ,814,63M

Pre-SN Stripped Structures



Morozova *et al.* 2015 – ApJ,814,63M

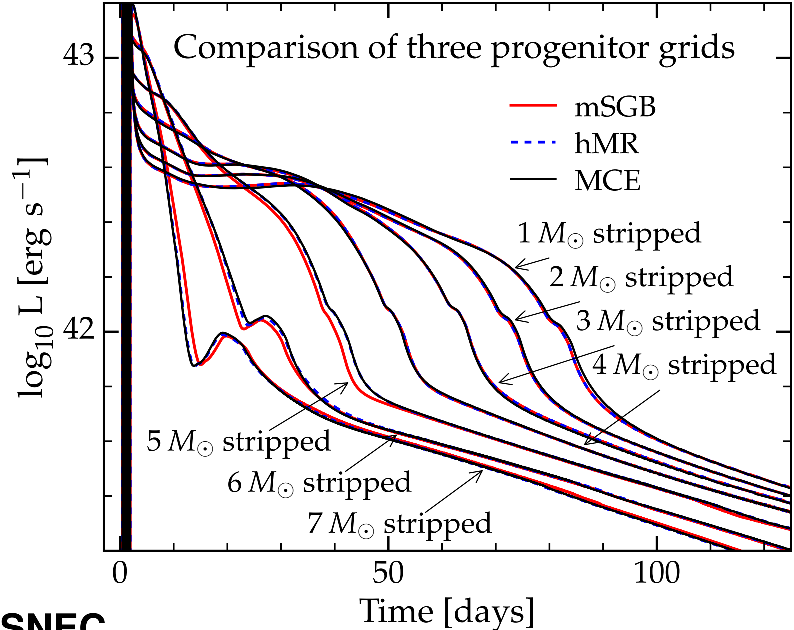
Pre-SN Stripped Structures



Morozova *et al.* 2015 – ApJ,814,63M

Light Curves from Stripped Models

ANTON PANNEKOEK INSTITUTE



Morozova *et al.* 2015 – ApJ,814,63M

SNEC

Possible Mass Loss Channels

- Radiatively Driven Stellar Winds
- Roche Lobe Overflow
- Impulsive Events

Effect of Winds on the Late Stellar Structure

- pre-SN Mass
- Core Structure & "Explodability"

Light Curves from post-Impulsive Mass Loss

- Numerical Experiment of Stripping
- Pre-SN Stripped Structures
- Resulting Lightcurves

Conclusions

Summary

ANTON PANNEKOEK INSTITUTE

- Systematic uncertainties in modeling mass loss:
  - pre-explosion mass $\Rightarrow$ no $M_\mathrm{f} \equiv M_\mathrm{f}(M_\mathrm{ZAMS})$ map;
  - core density profile $\Rightarrow$ "explodability";
  - surface abundances $\Rightarrow$ SN spectrum and type.

Role of Binaries:

- Observational constraints $\Rightarrow$ colliding winds;
- Possibly cause of mass loss (RLOF, CE, accretor);
- RLOF can leave some H-rich material $\Rightarrow$ role in SNIIL?

Summary

ANTON PANNEKOEK INSTITUTE

- Systematic uncertainties in modeling mass loss:
  - pre-explosion mass $\Rightarrow$ no $M_{\mathrm{f}} \equiv M_{\mathrm{f}}(M_{\mathrm{ZAMS}})$ map;
  - core density profile $\Rightarrow$ "explodability";
  - surface abundances $\Rightarrow$ SN spectrum and type.

Role of Binaries:

- Observational constraints $\Rightarrow$ colliding winds;
- Possibly cause of mass loss (RLOF, CE, accretor);
- RLOF can leave some H-rich material $\Rightarrow$ role in SNIIL?

Thank you!

ANTON PANNEKOEK
INSTITUTE

Backup slides

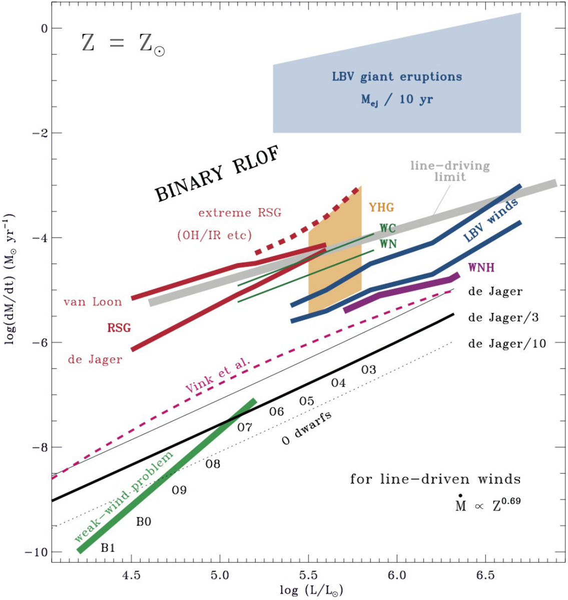


Figure: From Smith 2014, ARA&A, 52, 487S

(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

ANTON PANNEKOEK INSTITUTE

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

- Initial mass:

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

- Efficiency:

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

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

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

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

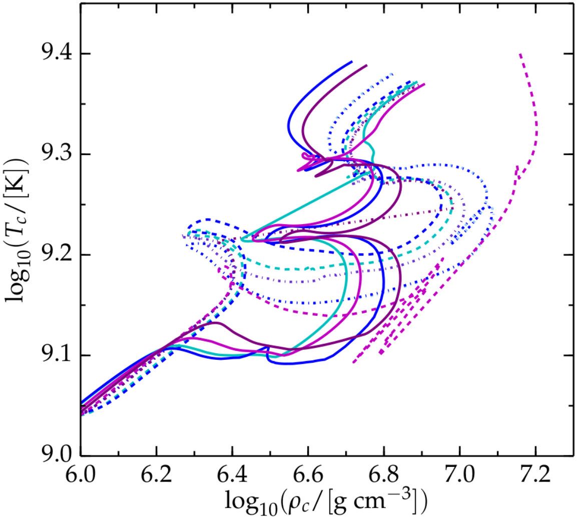
De Jager *et al.* '88;

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

Core Structure @ O depletion

ANTON PANNEKOEK INSTITUTE

$M_{\text{ZAMS}} = 25\,M_\odot$ MESA models



Critical point: Ne core burning/C shell burning

ANTON PANNEKOEK
INSTITUTE

Back

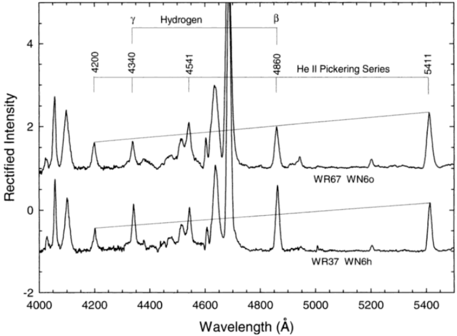
- P Cygni line profiles
- Optical and near UV lines (e.g. Hα)
- Radio and IR continuum excess
- IR spectrum of molecules (e.g. CO)
- Maser lines (for low density winds)

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

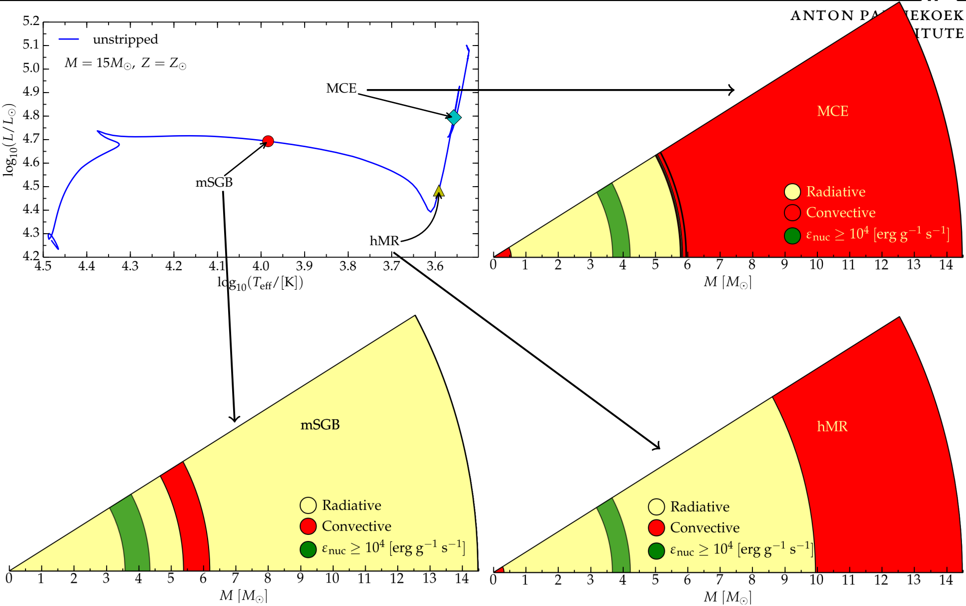
Sub-categories: WN,WC,WO,WNL, etc.

Computational Definition (MESA):

- $X_s < 0.4$

Impossible to distinguish sub-categories without spectra!

Chosen Stripping Points

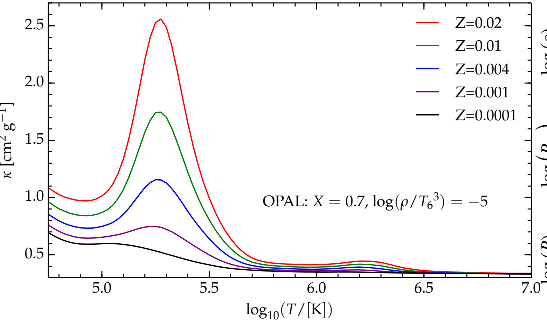


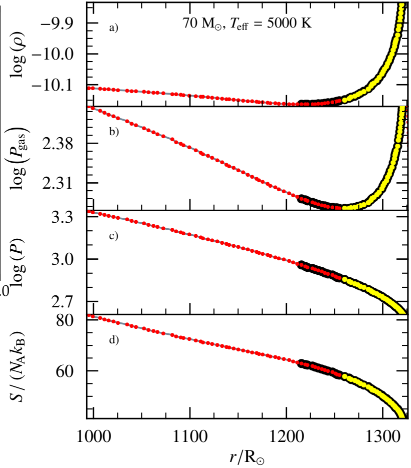
$$t(\mathrm{MCE}) - t(\mathrm{mSGB}) \simeq 10^4 \ [\mathrm{yr}] \ll 14.13 \times 10^6 \ [\mathrm{yr}]$$

MESA nearly super-Eddington Regime

ANTON PANNEKOEK INSTITUTE

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





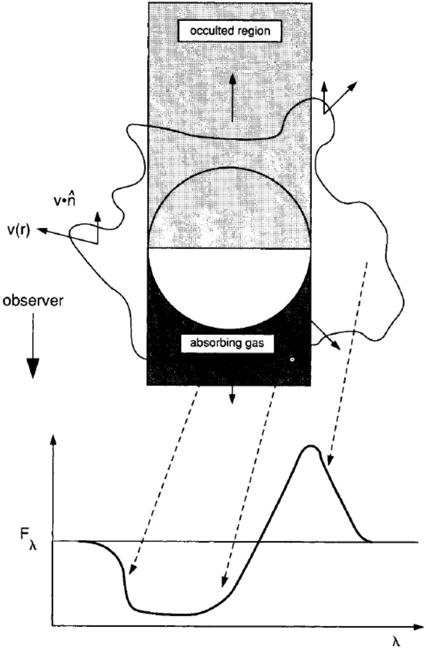
$M_{\rm ZAMS} \gtrsim 20 M_\odot \Rightarrow$ insufficient $F_{\rm conv}^{\rm MLT}$

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

MLT++:

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

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.

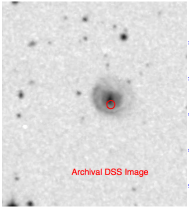
Why Impulsive Mass Loss?

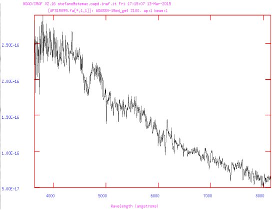
Observational Evidence:

- 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)



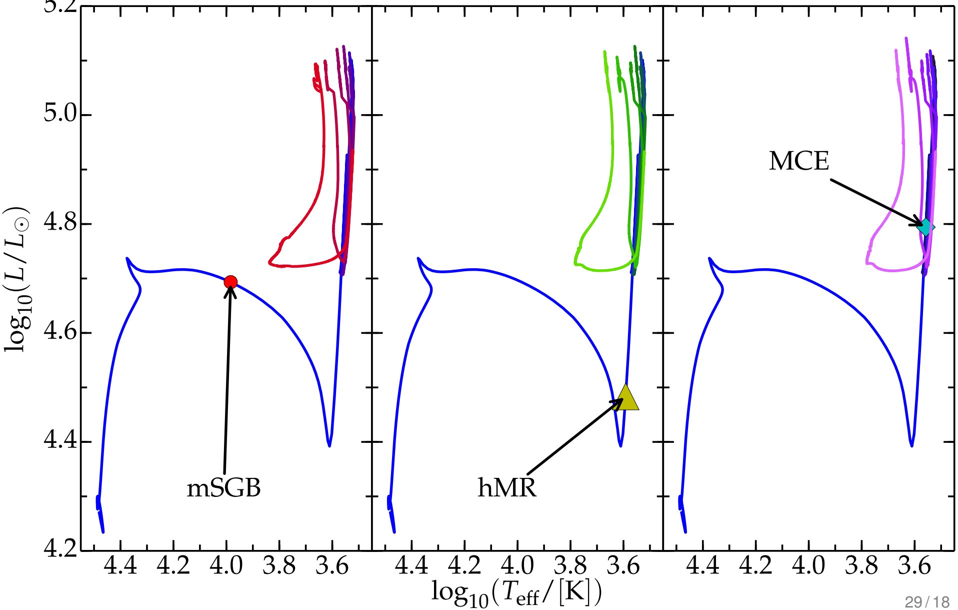


$$\Delta M_{\rm wind} \ll \Delta M_{\rm impulsive} \ (?)$$

Stripped series on the HR diagram

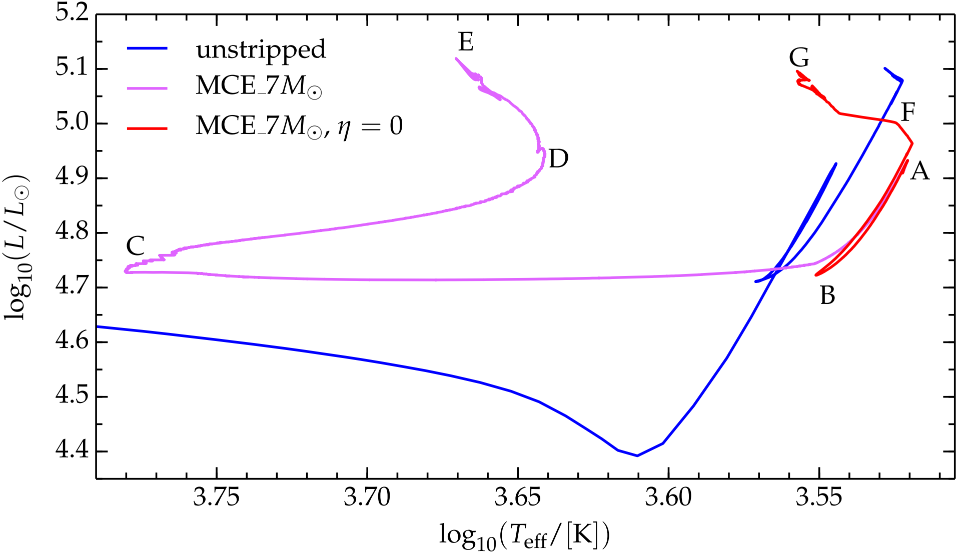
ANTON PANNEKOEK INSTITUTE

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



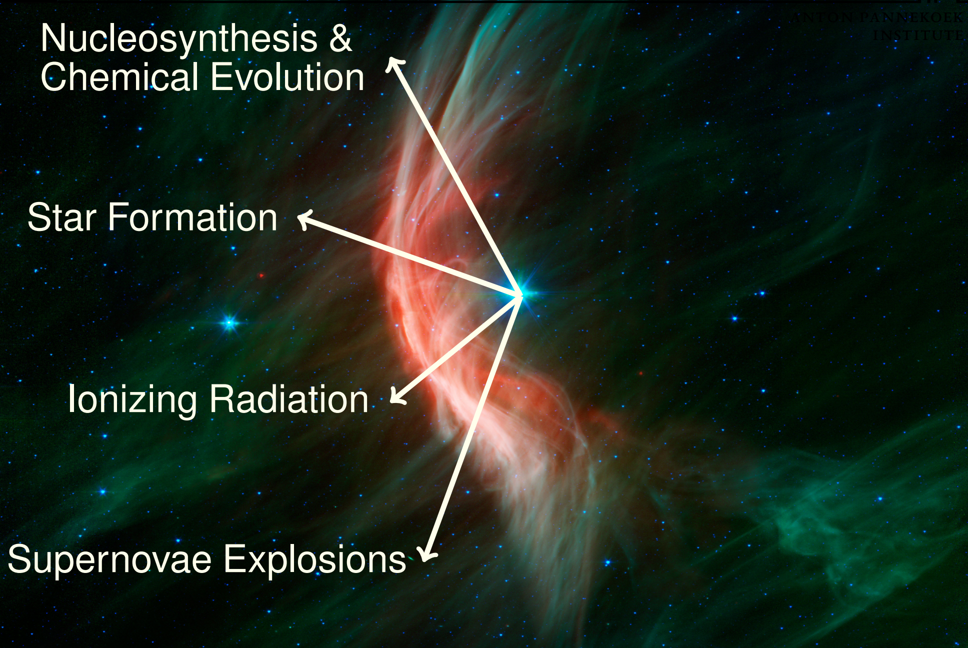
Evolution toward Higher T_{eff}

ANTON PANNEKOEK INSTITUTE



Impulsive + wind mass loss drives blueward evolution

Why are Massive Stars Important?



NASA, JPL-Caltech, Spitzer Space Telescope

Why are Massive Stars Important?

Nucleosynthesis & Chemical Evolution

Star Formation

Ionizing Radiation

Supernovae Explosions

Mass loss for the environment:

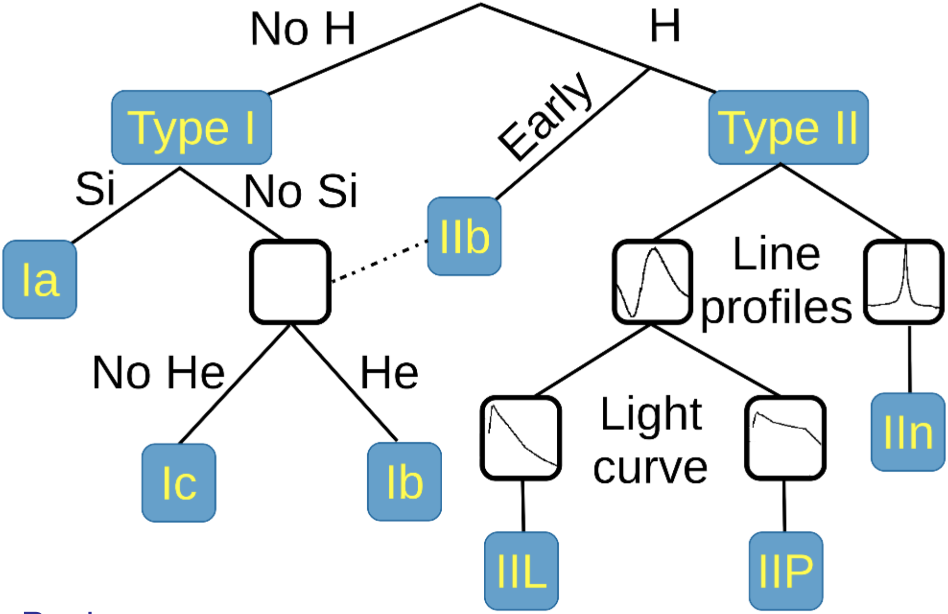
- Pollution of ISM
- Tailoring of CSM
- Trigger for Star Formation

Mass loss for the star

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

NASA, JPL-Caltech, Spitzer Space Telescope

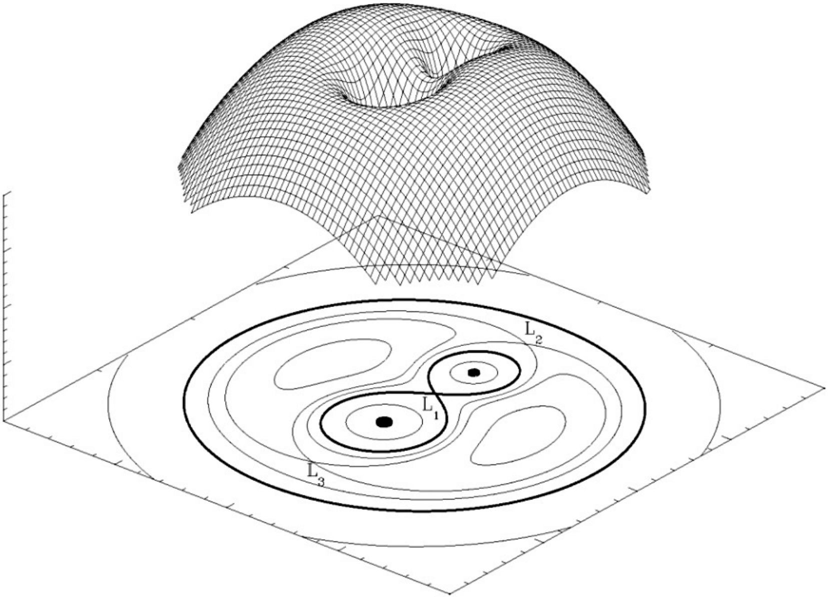
Supernova Taxonomy



◂ Back

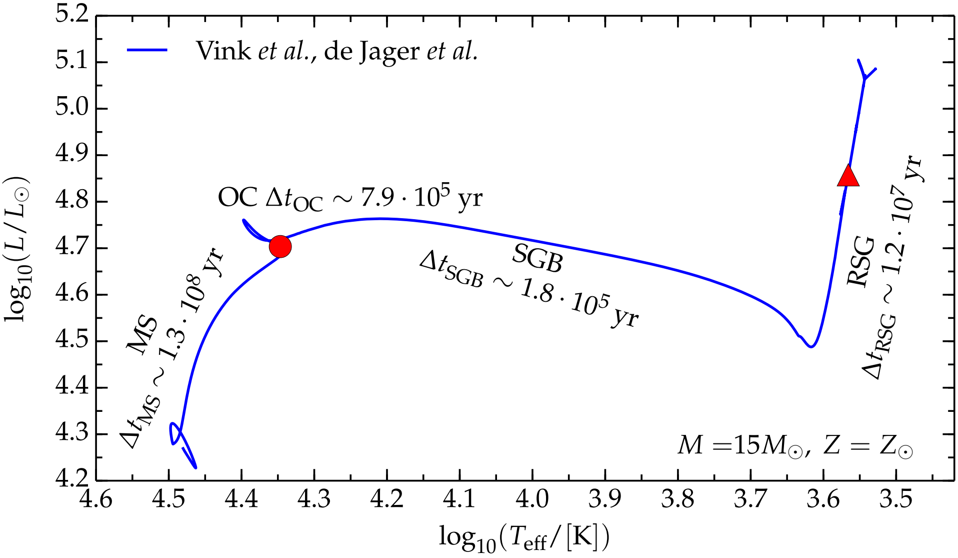
Roche Lobe OverFlow

Mass Transfer in Binaries

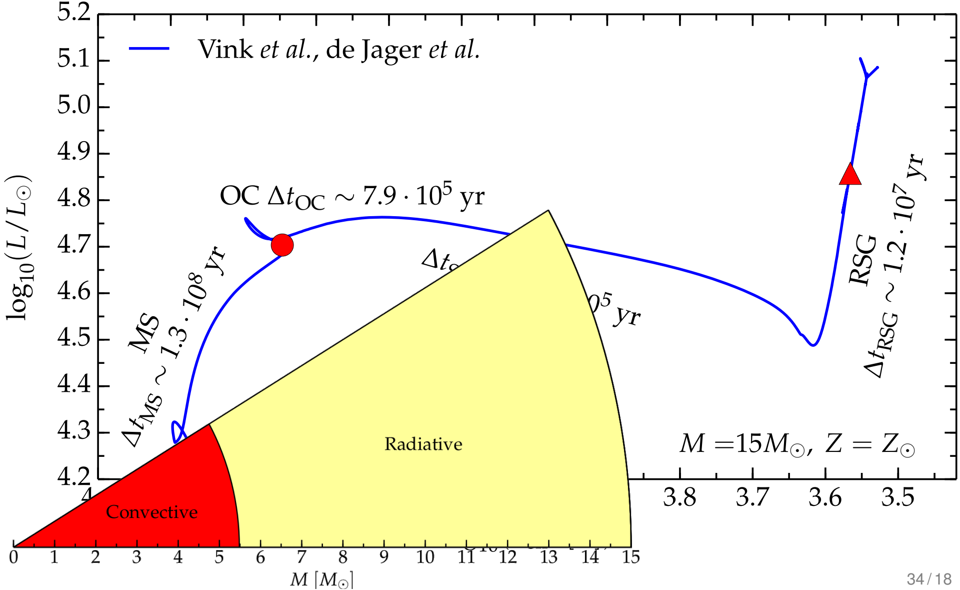


Evolution of a Massive Star in one Slide

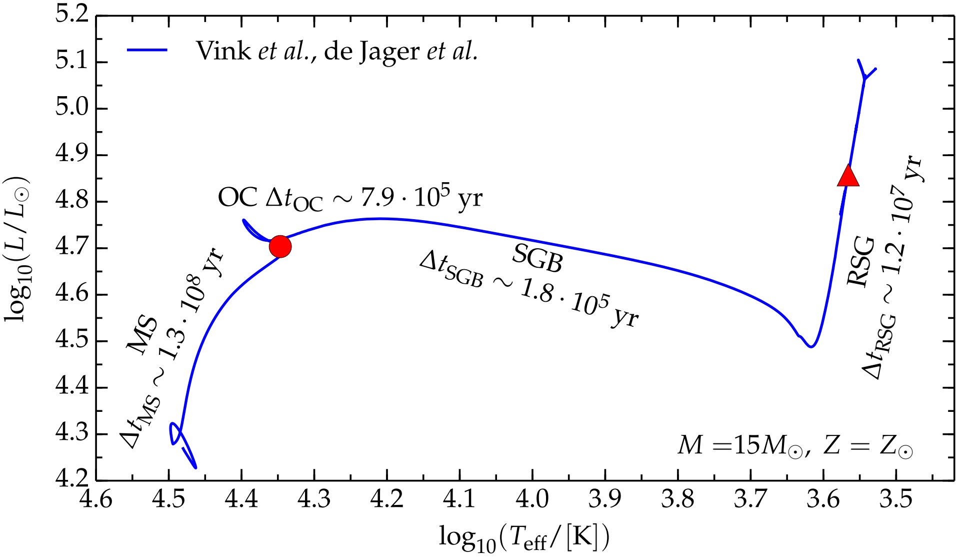
ANTON PANNEKOEK
INSTITUTE



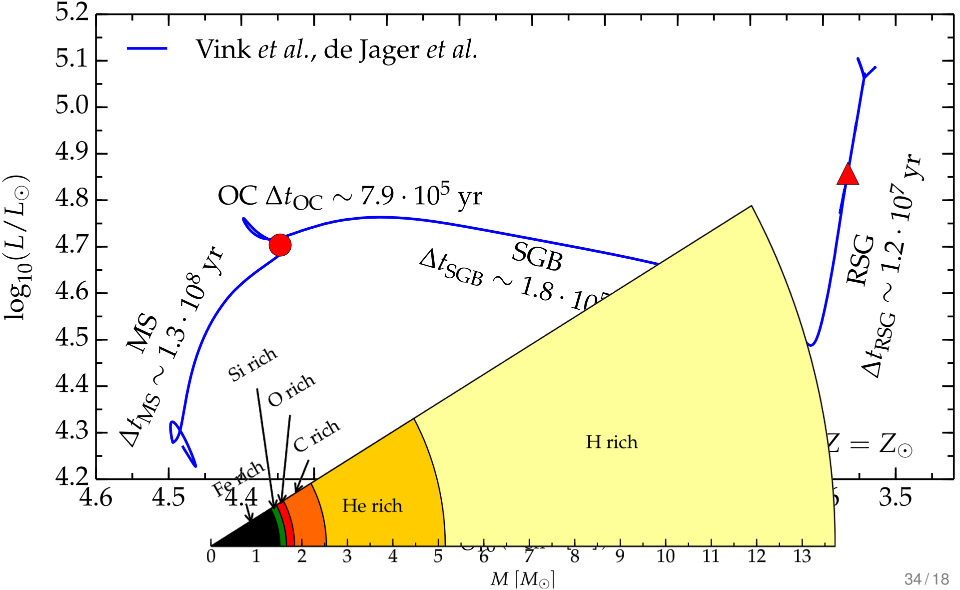
Evolution of a Massive Star in one Slide



Evolution of a Massive Star in one Slide



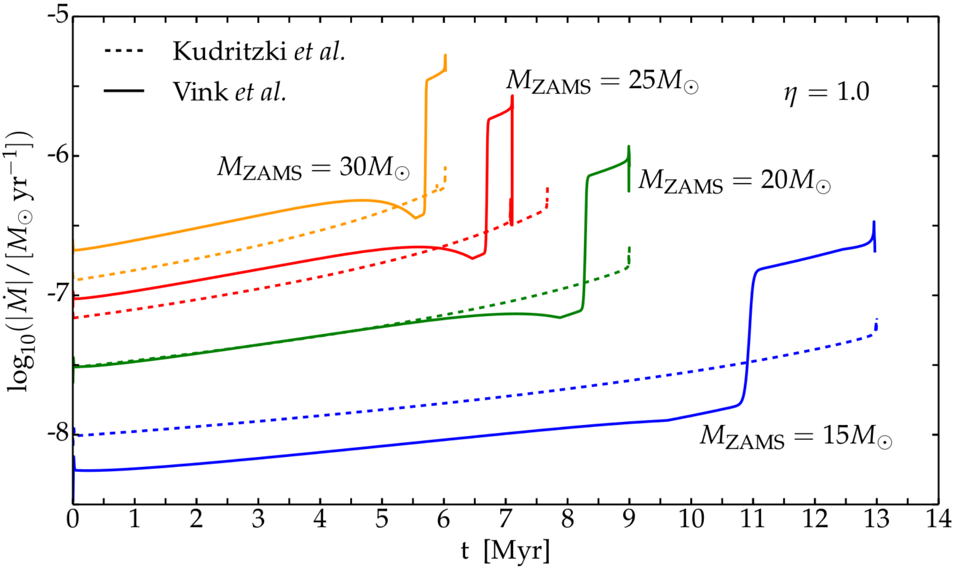
Evolution of a Massive Star in one Slide



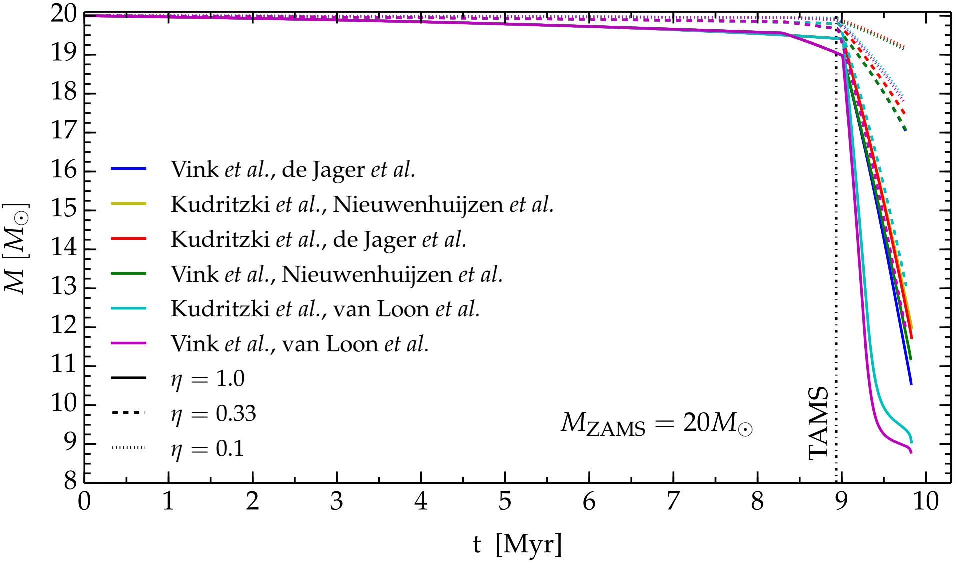
End of the hot evolutionary phase

ANTON PANNEKOEK INSTITUTE

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

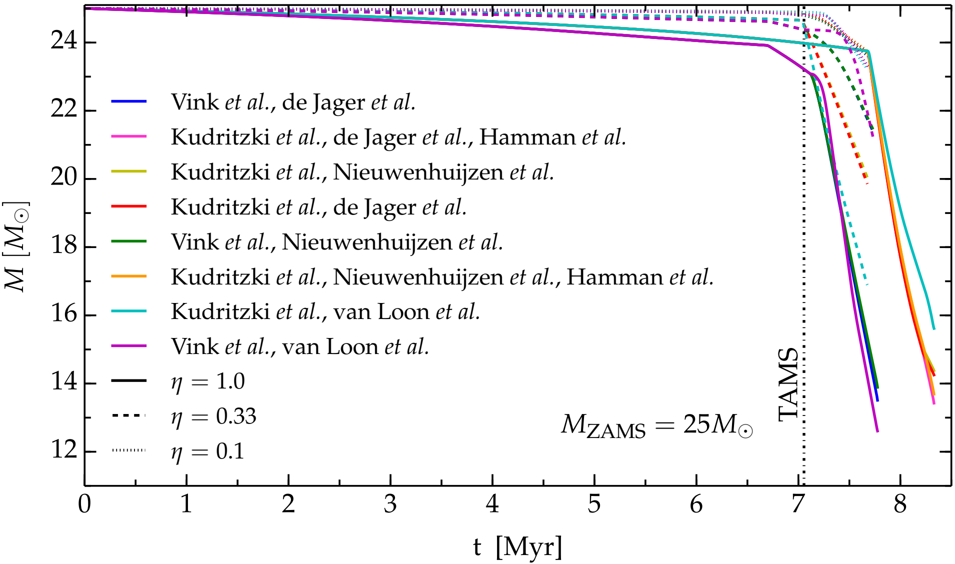


$M(t)$ for $M_{\rm ZAMS} = 20 M_\odot$ with with MESA



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

ANTON PANNEKOEK INSTITUTE



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

ANTON PANNEKOEK INSTITUTE