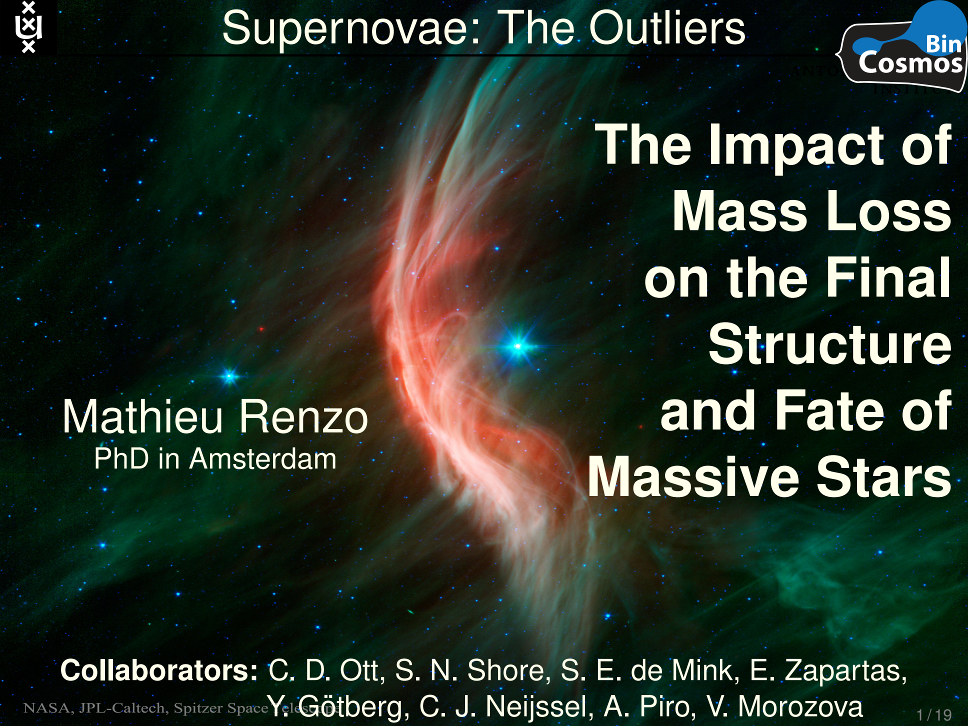


The Impact of Mass Loss on the Final Structure and Fate of Massive Stars

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

Mass loss channels

- Radiatively driven stellar winds
- Roche lobe overflow
- Impulsive events

Winds: to explode or not to explode?

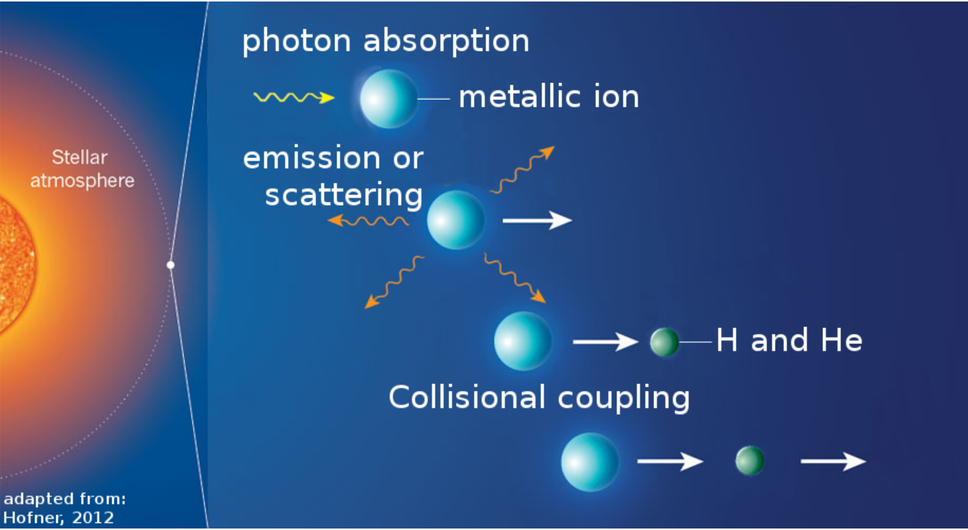
- pre-SN mass
- Core structure & “explodability”

Light curves post-impulsive mass loss

- Numerical experiment of stripping
- Pre-SN stripped structures
- SNEC light curves

Conclusions

Radiatively Driven Winds in One Slide



Problems: High Non-Linearity and Clumpiness:

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

Massive Stars Come in Binaries

Credits: ESO, L. Calçada,M. Kornmesser, S. E. de Mink

Up to $\sim$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)

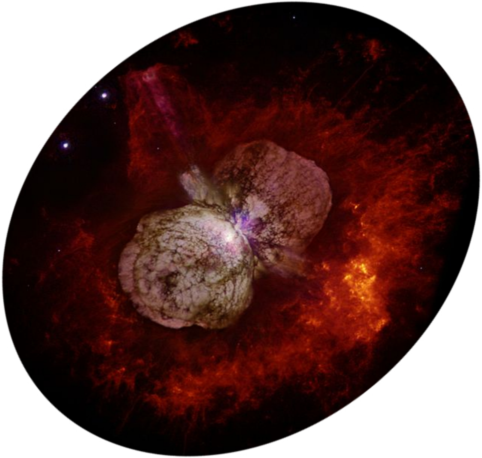
Impulsive Mass Loss Event

“Dynamical Instabilities”

⇓

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

(Possibly triggered by
Mass Accretion in a Binary)



η Car, Credits: NASA/ESA

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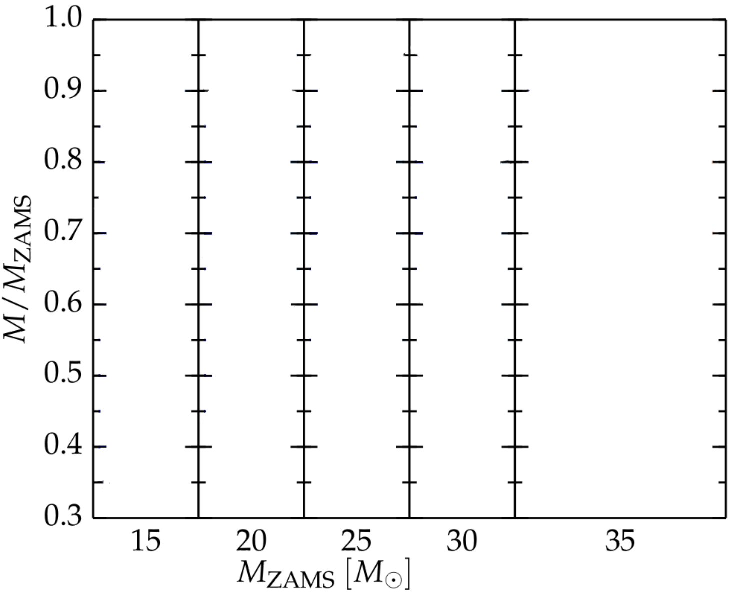
Impact on the Final Mass



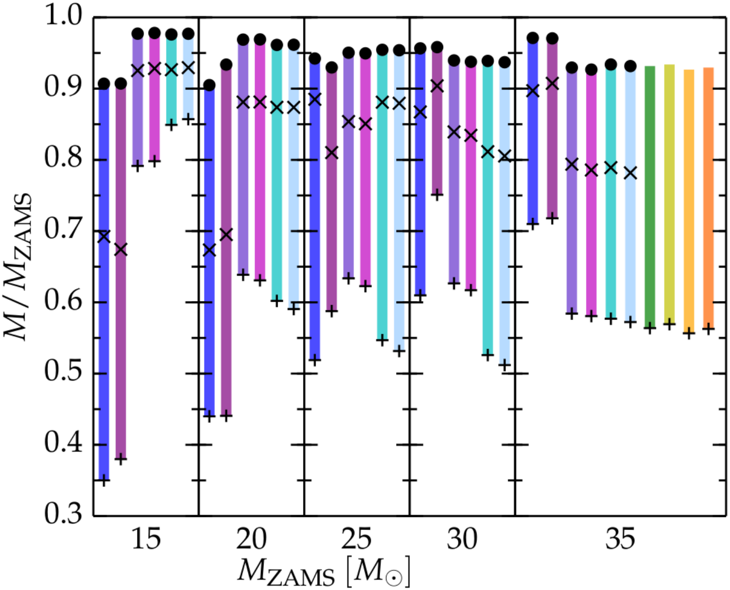
MESA

Legend:

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

Renzo *et al.*, in prep.

Impact on the Final Mass



MESA

Legend:

- ● $\eta = 0.1$
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$\eta \rightarrow$ largest uncertainty

Renzo *et al.*, in prep.

Impact on the Final Mass

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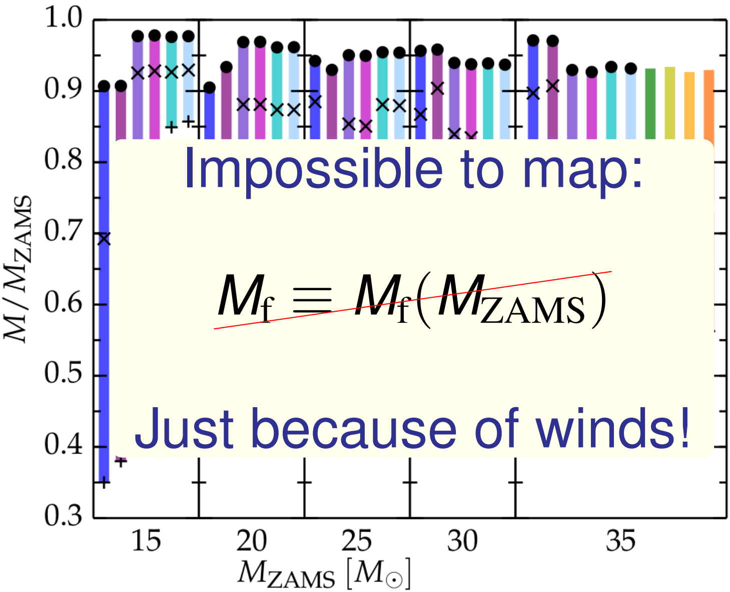

Impossible to map:

$$\cancel{M_f \equiv M_f(M_{\mathrm{ZAMS}})}$$

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.

“Explodability” & Compactness Parameter

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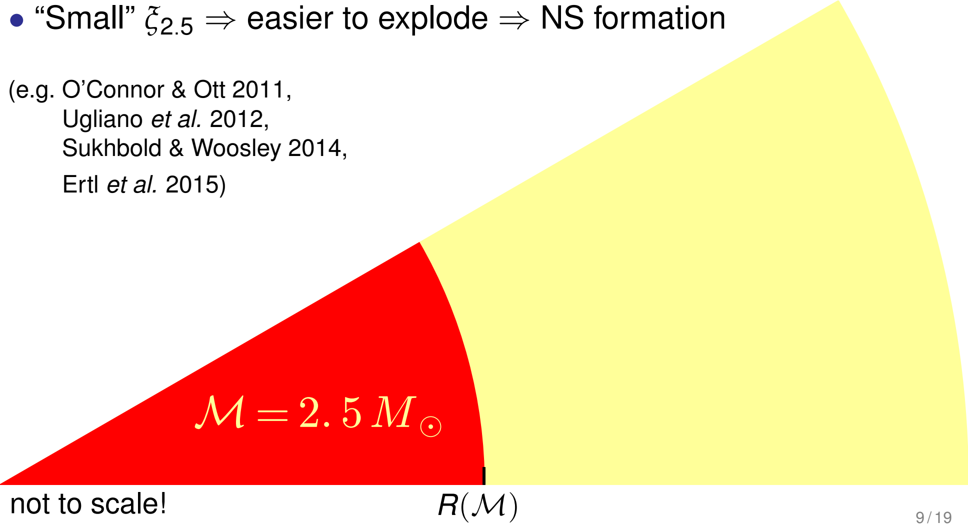
$$\xi_{\mathcal{M}}(t) \overset{\text{def}}{=} \frac{\mathcal{M}/M_\odot}{R(\mathcal{M})/1000\ \mathrm{km}}$$

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

(e.g. O’Connor & Ott 2011,
Ugliano *et al.* 2012,
Sukhbold & Woosley 2014,
Ertl *et al.* 2015)



not to scale!

Core Structure @ O depletion

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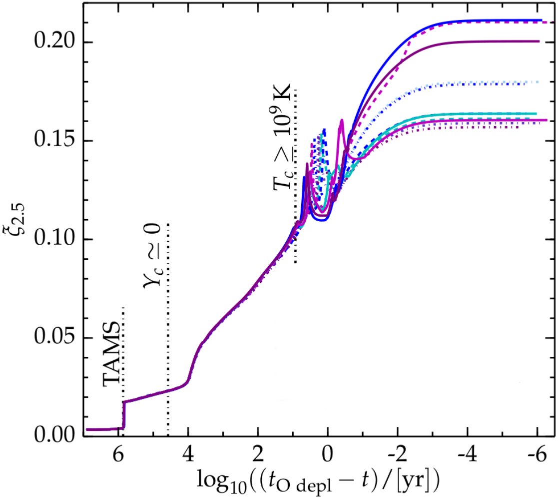
$M_{\mathrm{ZAMS}} = 25\,M_{\odot}$ MESA models

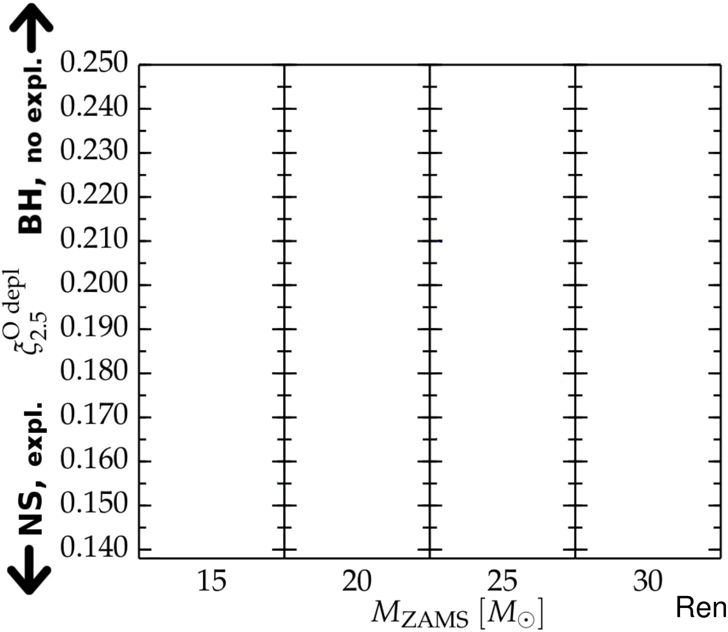


Renzo *et al.*, in prep.

Critical point: Ne core burning/C shell burning

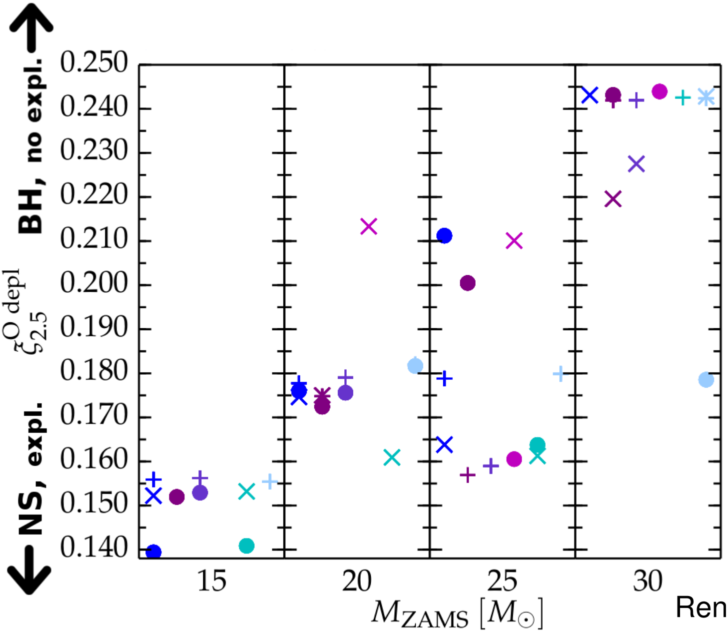
Challenges: Nuclear Network & Spatial Resolution

$\xi_{2.5}$ @ Oxygen Depletion



Renzo *et al.*, in prep.

$\xi_{2.5}$ @ Oxygen Depletion



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.

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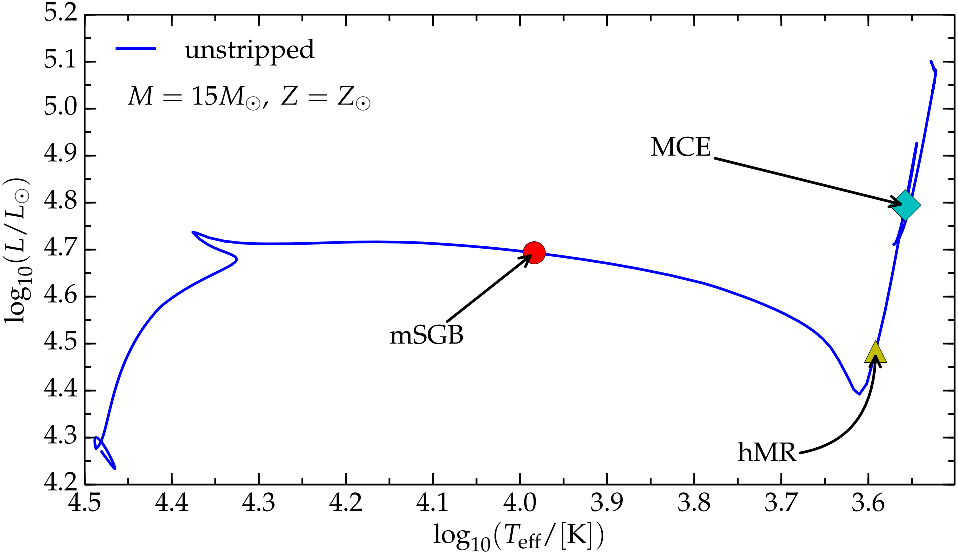
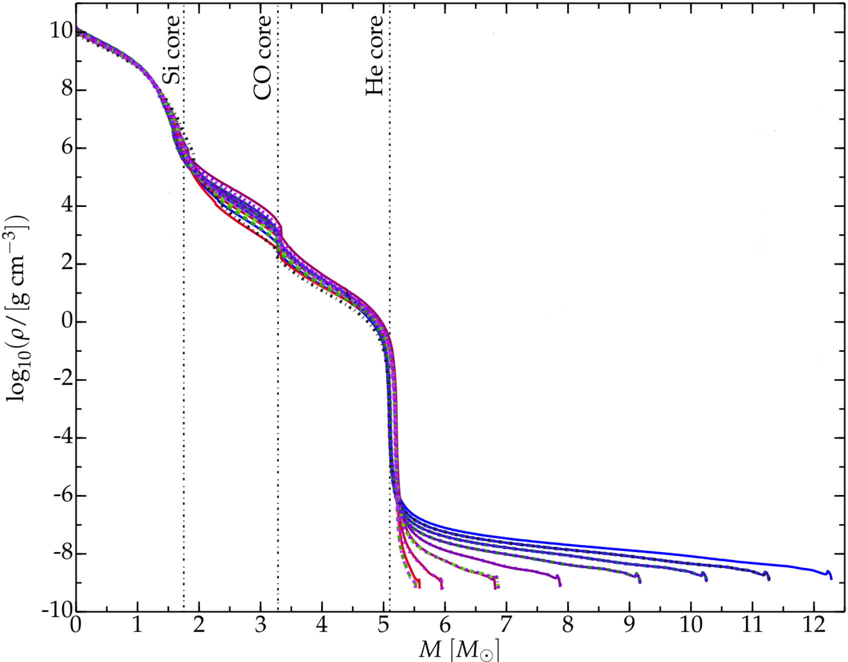
The Stripping Process



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

Morozova *et al.* 2015 – ApJ,814,63M

Pre-SN Stripped Structures



Morozova *et al.* 2015 – ApJ,814,63M

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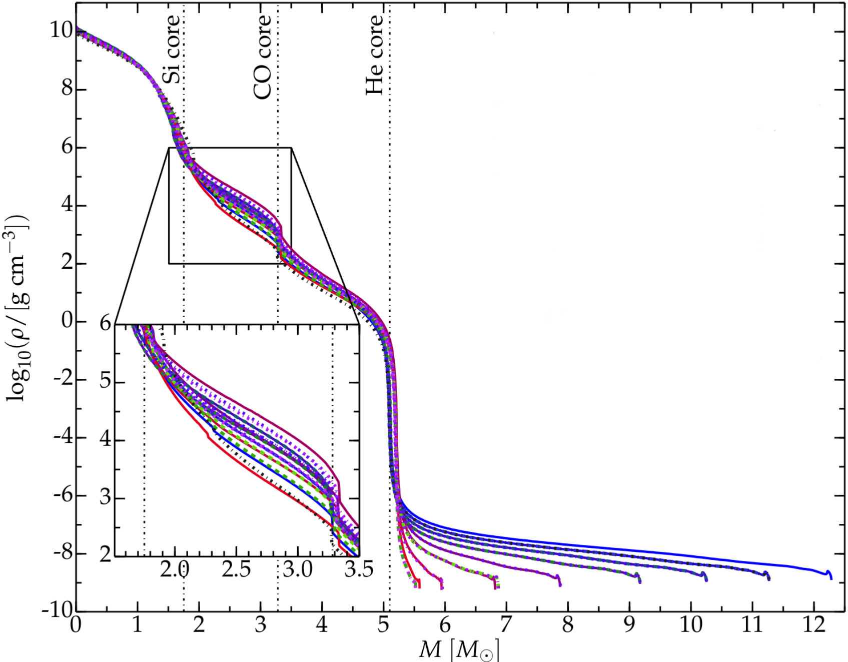
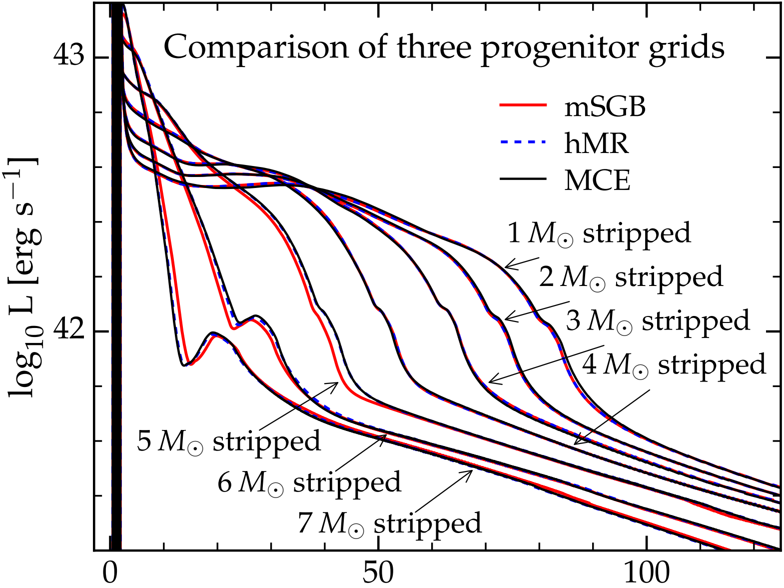


Morozova *et al.* 2015 – ApJ,814,63M

Light Curves from Stripped Models



Morozova *et al.* 2015 – ApJ,814,63M

SNEC

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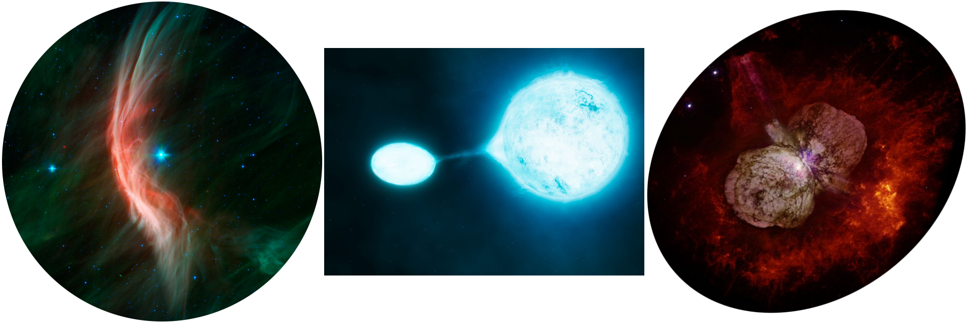
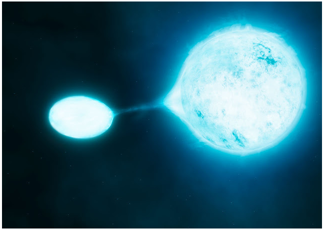
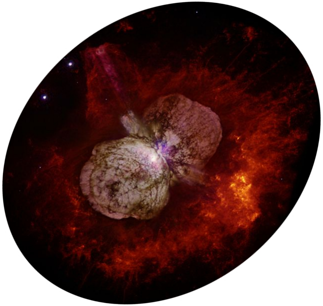
Conclusions

Summary



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

Summary

- 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.

Thank you!

Outline

Backup slides

Mass Loss in MESA

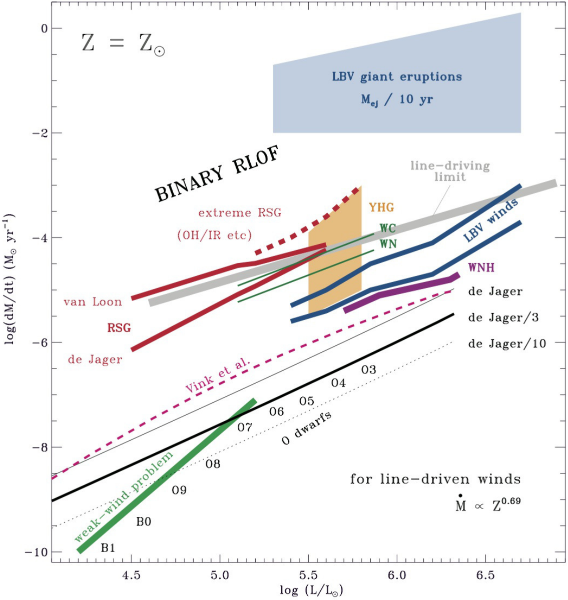


Figure: From Smith 2014, ARA&A, 52, 487S

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

$$\dot{M}(L, T_{\mathrm{eff}}, Z, R, M, \ldots)$$

$$\Downarrow$$

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

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:

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

- Efficiency:

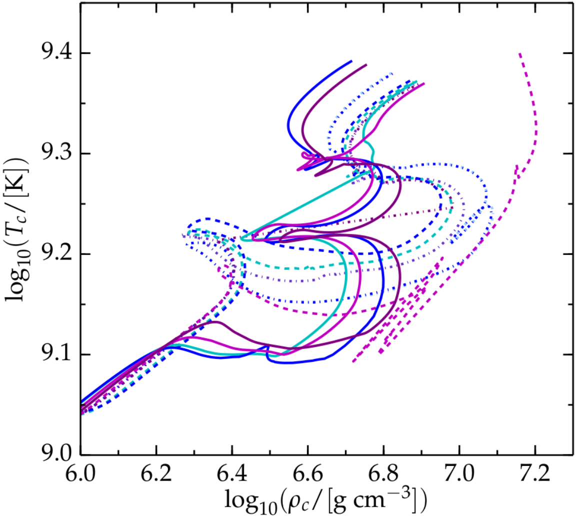
$$\eta \equiv \sqrt{f_{\mathrm{cl}}} = \left\{1,\ \frac{1}{3},\ \frac{1}{10}\right\}\ ;$$

- 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.

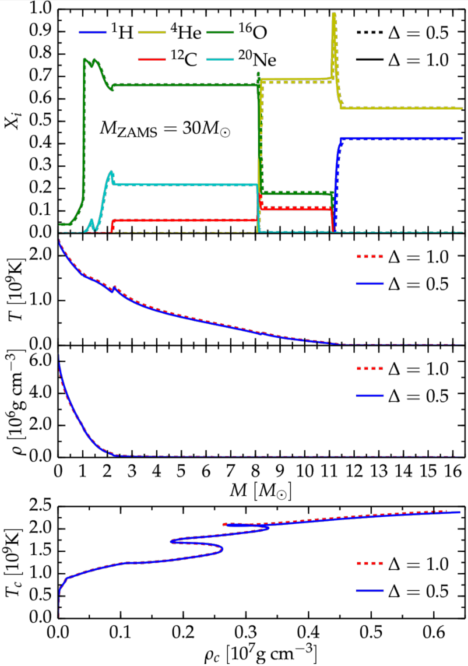
Core Structure @ O depletion

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



Critical point: Ne core burning/C shell burning

Resolution Study



Wind Oservational Diagnostics

◂ Back

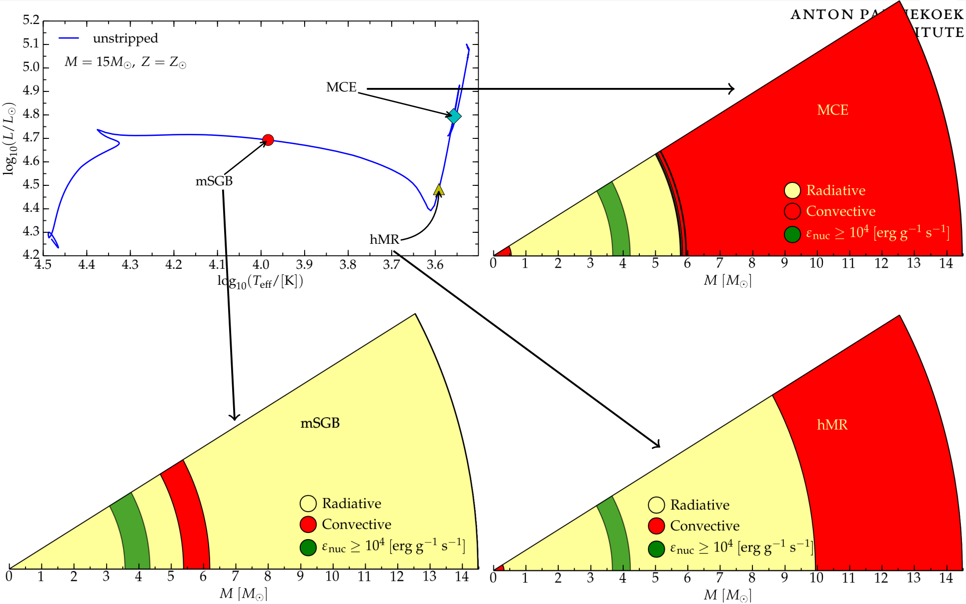
- P Cygni line profiles
- Optical and near UV lines (e.g. Hα)
- Radio and IR continuum excess
- IR spectrum of molecules (e.g. CO)
- Maser lines (for low density winds)

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.

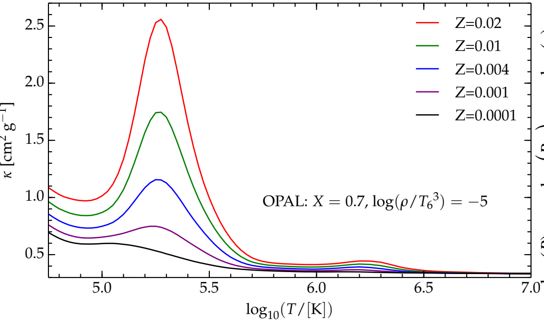
Chosen Stripping Points



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

MESA nearly super-Eddington Regime

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



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

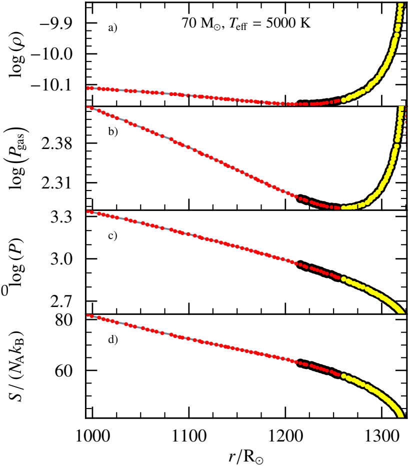


Figure: From Paxton *et al.* 2013, ApJS, 208, 5p

MLT++:

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

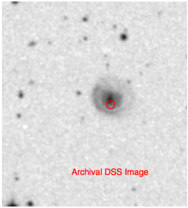
Why Impulsive Mass Loss?

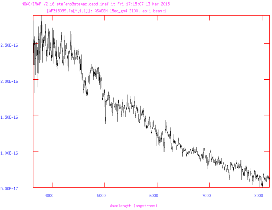
Observational Evidence:

- 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)

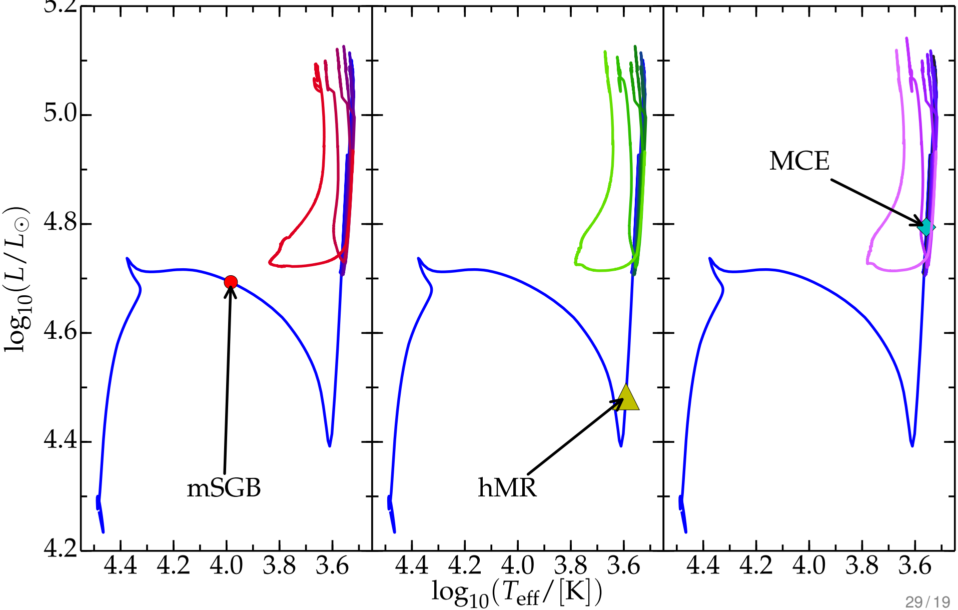




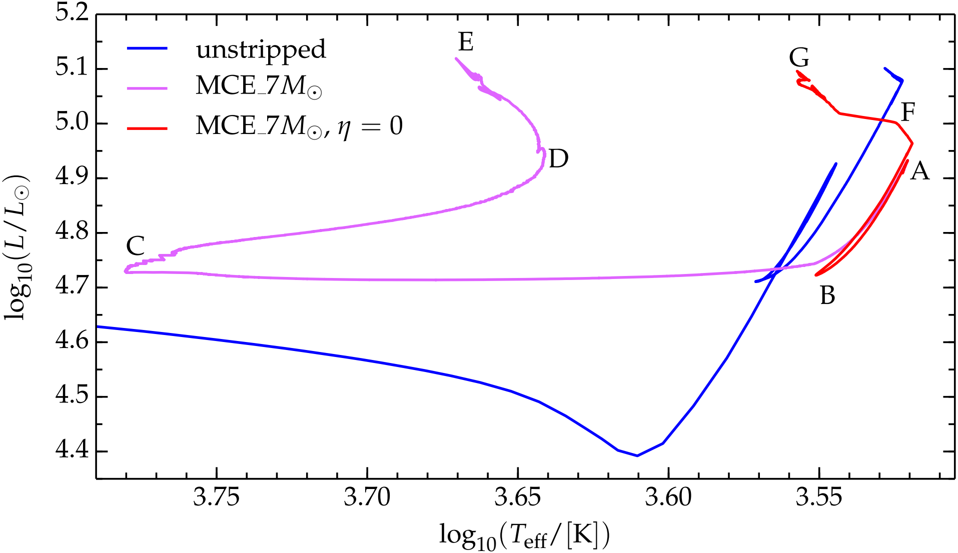
$$\Delta M_{\rm wind} \ll \Delta M_{\rm impulsive} \; (?)$$

Stripped series on the HR diagram

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



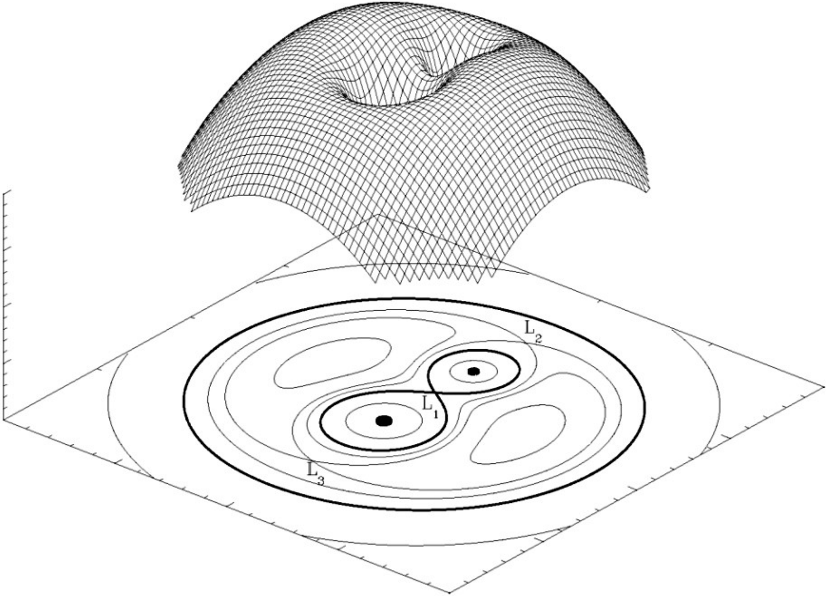
Evolution toward Higher $T_{\rm eff}$



Impulsive + wind mass loss drives blueward evolution

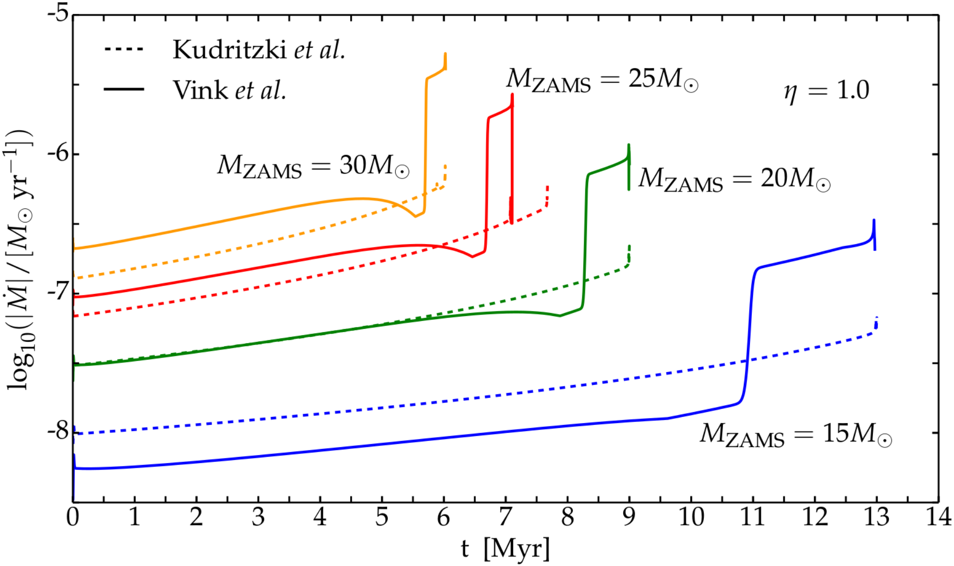
Roche Lobe OverFlow

Mass Transfer in Binaries

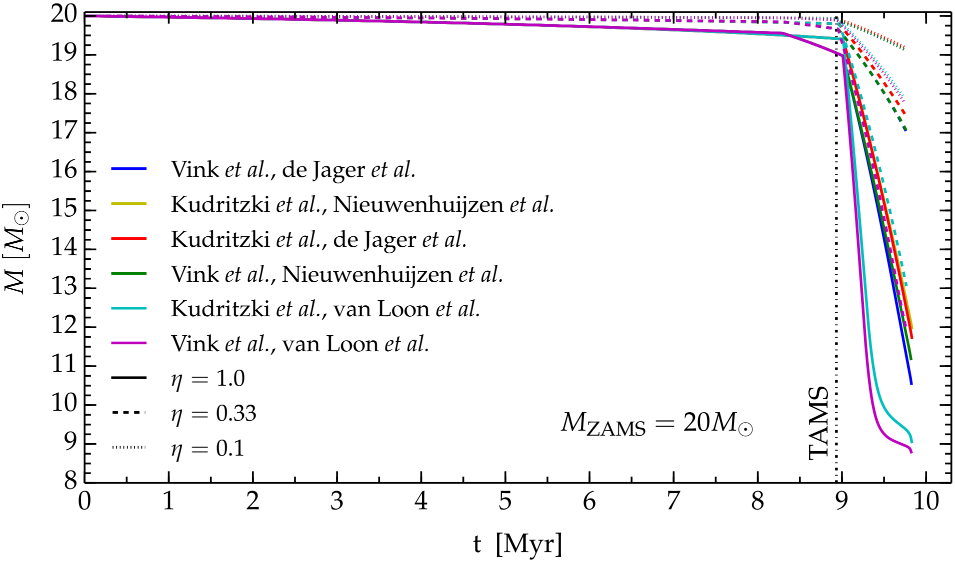


End of the hot evolutionary phase

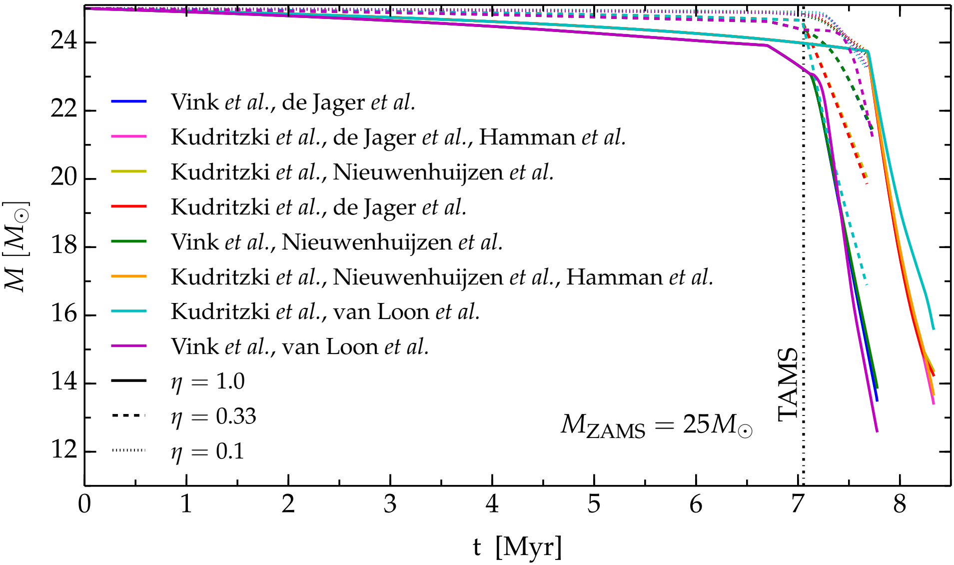
Vink *et al.* only: $T_{\rm jump} \sim 25\ [{\rm kK}] \Rightarrow {\rm Fe}^{3+} \rightarrow {\rm Fe}^{2+}$



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



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



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

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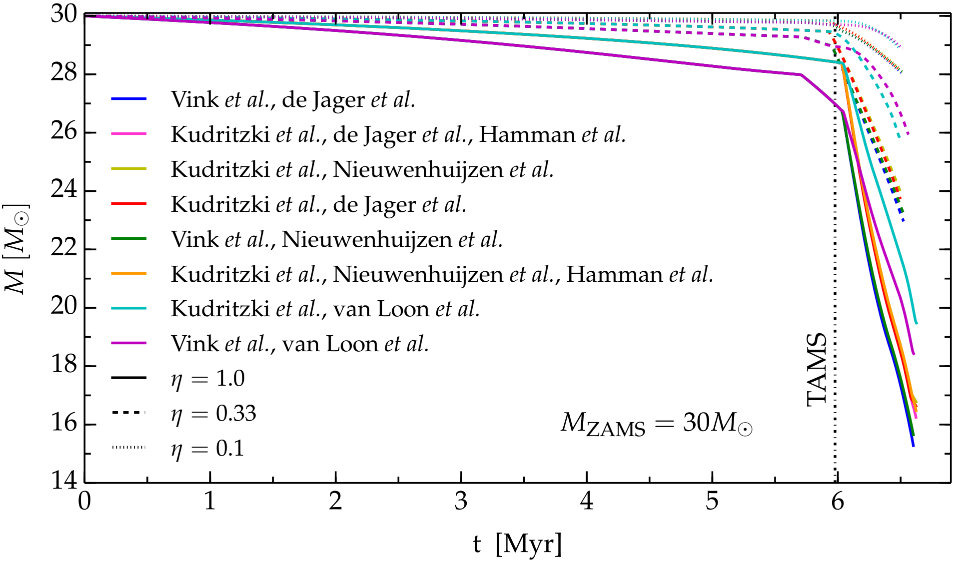

Maximum variations

M_{ZAMS} $[M_\odot]$	max ΔR $[R_\odot]$	max ΔM $[M_\odot]$	max ΔM_{He} $[M_\odot]$	max ΔM_{CO} $[M_\odot]$
15	338	9.42	0.36	0.28
20	327	10.58	0.16	0.12
25	150	10.89	0.37	0.31
30	148	13.39	0.44	0.47
35	763	14.51	3.79	3.38

Measured @ $T_c \geq 10^9\,\mathrm{K}$