Pizza Talk – 1/12/2016

The impact of mass loss on the final structure and fate of massive stars

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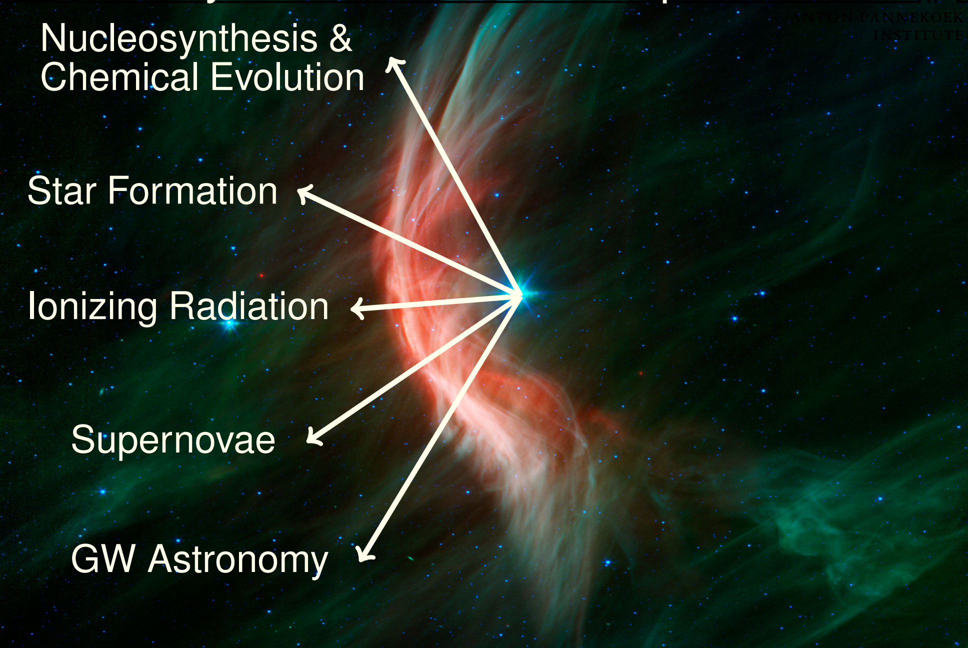
NASA, JPL-Caltech, Spitzer Space Telescope

Why are massive stars important?



Nucleosynthesis & Chemical Evolution

Star Formation

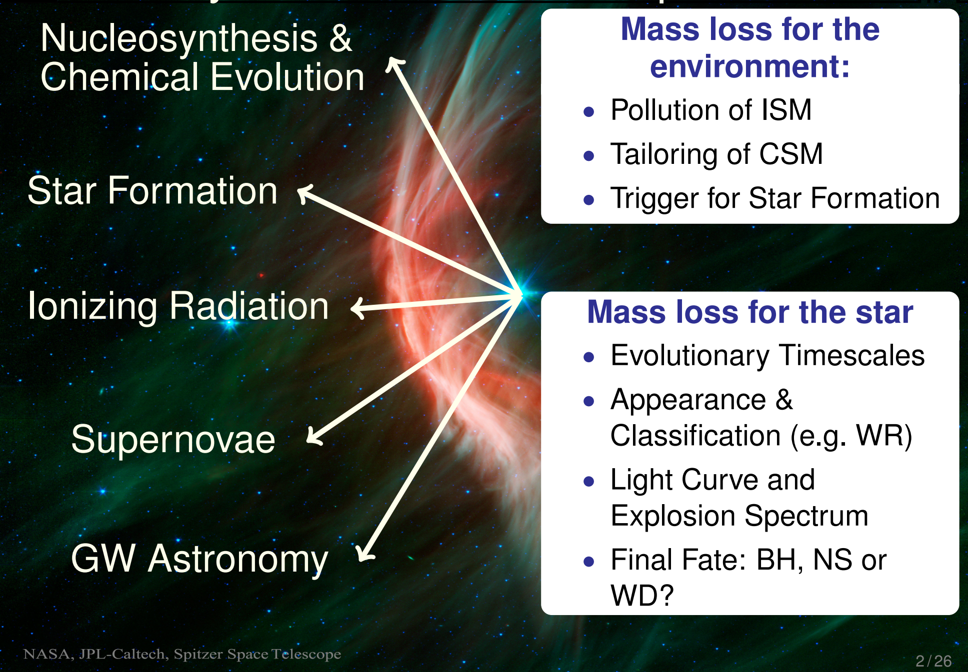
Ionizing Radiation

Supernovae

GW Astronomy

NASA, JPL-Caltech, Spitzer Space Telescope

Why is their mass loss important?



Nucleosynthesis & Chemical Evolution

Star Formation

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Mass loss for the environment:

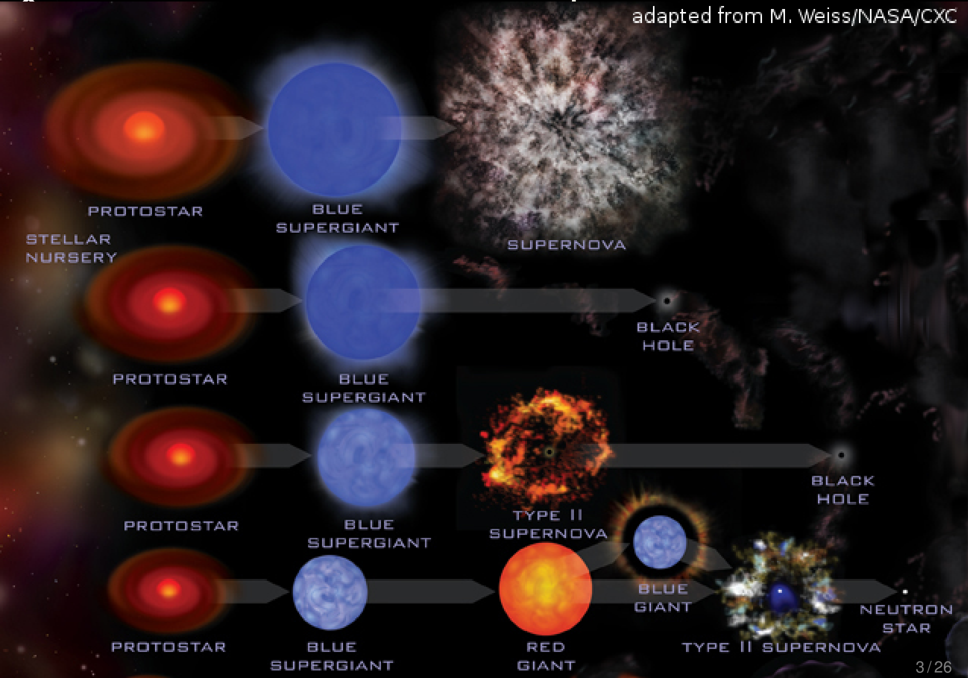
- Pollution of ISM
- Tailoring of CSM
- Trigger for Star Formation

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

The “classical” picture


adapted from M. Weiss/NASA/CXC

Outline

How do massive stars lose mass?

Stellar winds

- Line driving mechanism
- Algorithmic treatment

Impact on:

- Final mass
- Core structure

Conclusions

- Take home points

Possible Mass Loss Mechanisms

Radiative Driving

$\Downarrow$

Stellar Winds

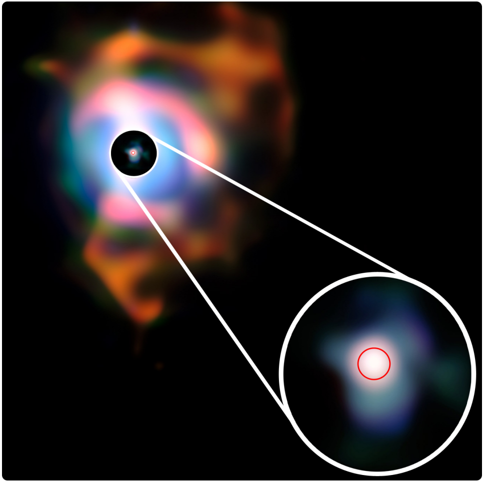


Figure: Betelgeuse

Possible Mass Loss Mechanisms

Dynamical Instabilities

⇓

LBVs, Impulsive Mass Loss,

Pulsations,

Super-Eddington Winds

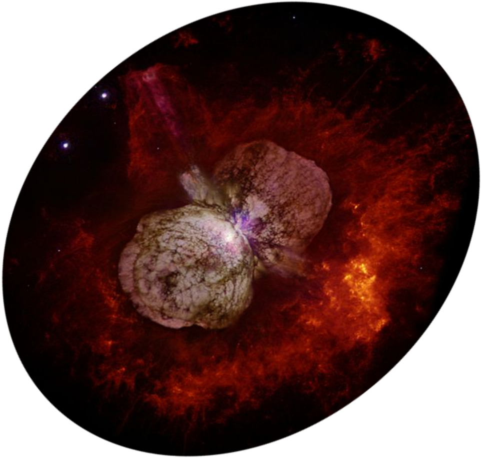


Figure: η Carinae.

Possible Mass Loss Mechanisms

Binary interactions

⇓

Roche Lobe Overflow,
Common Envelope,

Fast rotation, Mergers

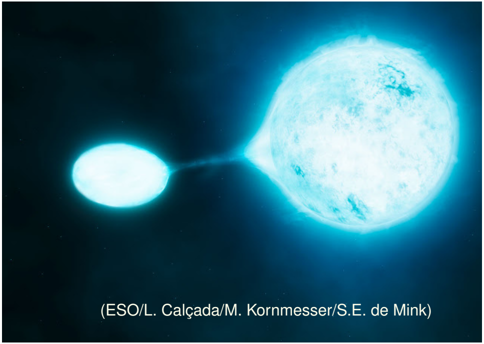

(ESO/L. Calçada/M. Kornmesser/S.E. de Mink)

Figure: Artist Impression

Possible Mass Loss Mechanisms

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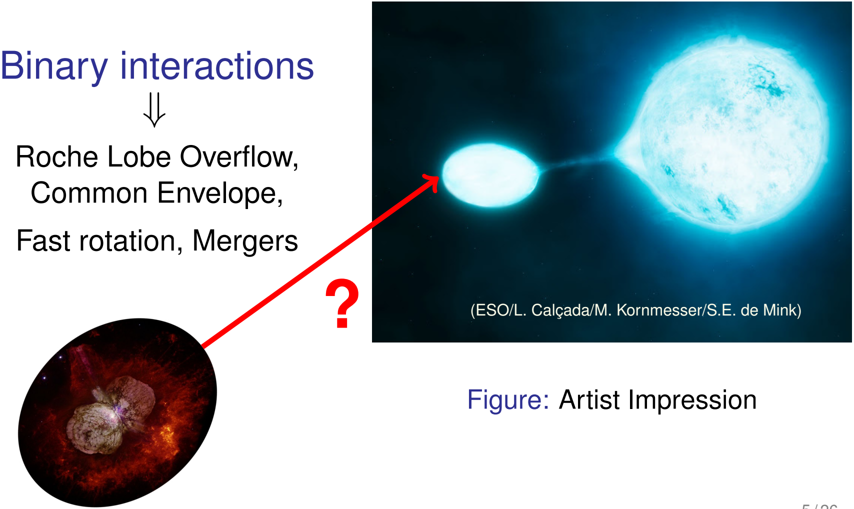
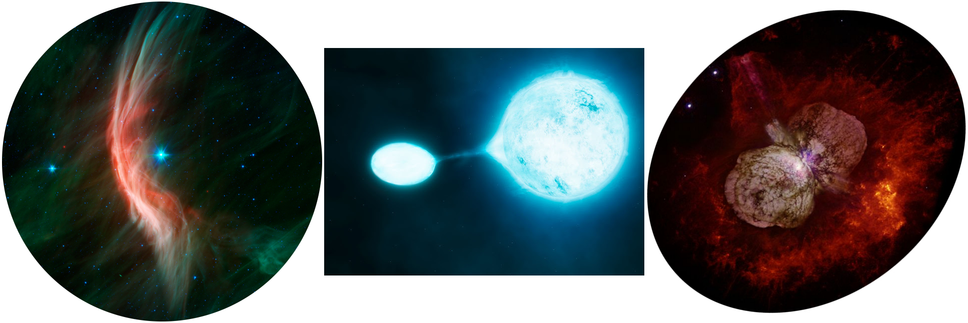


(ESO/L. Calçada/M. Kornmesser/S.E. de Mink)

Figure: Artist Impression

Mass loss is dynamical...



... but stellar evolution codes assume hydrostatic equilibrium:

$$\boxed{\frac{dP}{dr} = -\frac{Gm(r)\rho}{r^2}}$$

Open question: **Which dominates in term of total mass lost?**

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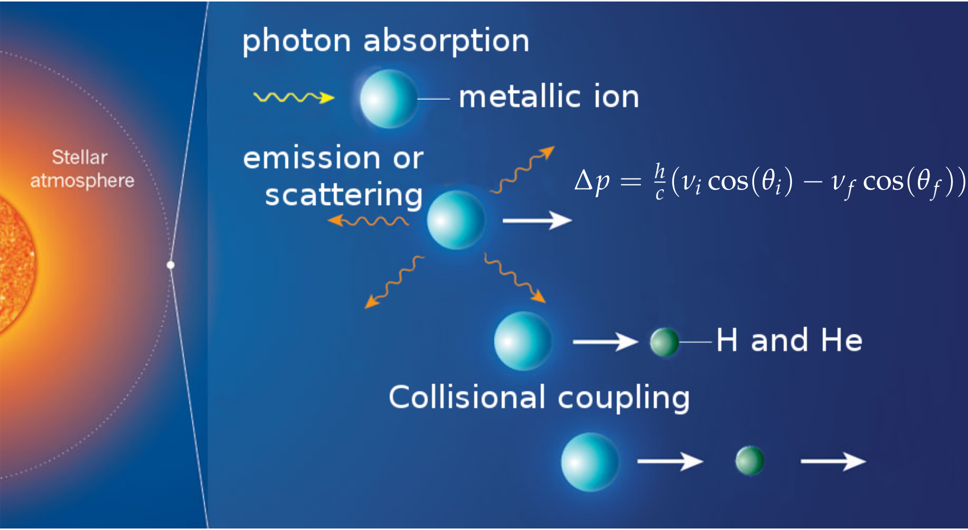
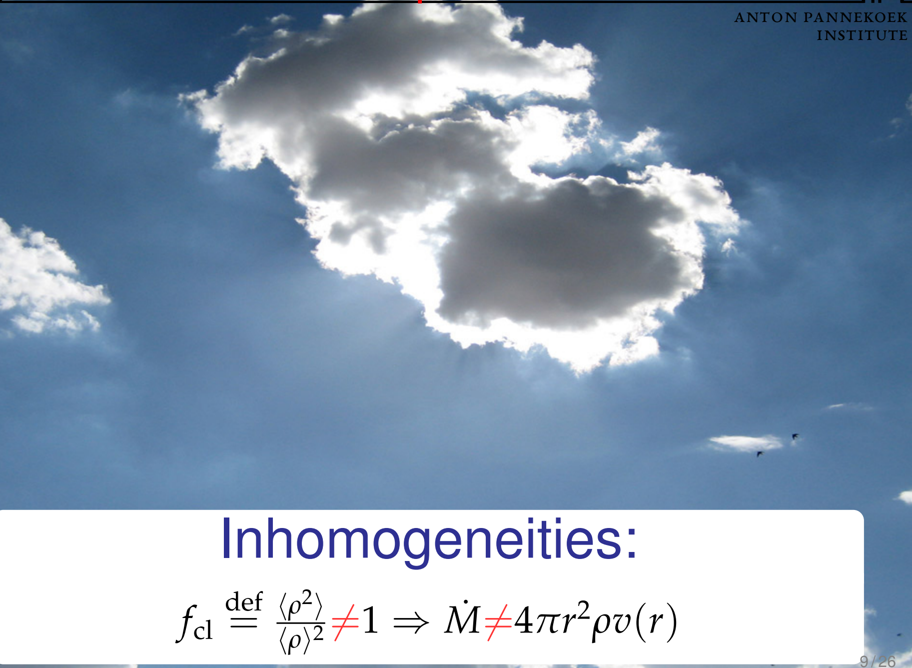
Radiatively Driven Winds in One Slide



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

Problems: High Non-Linearity and Clumpiness

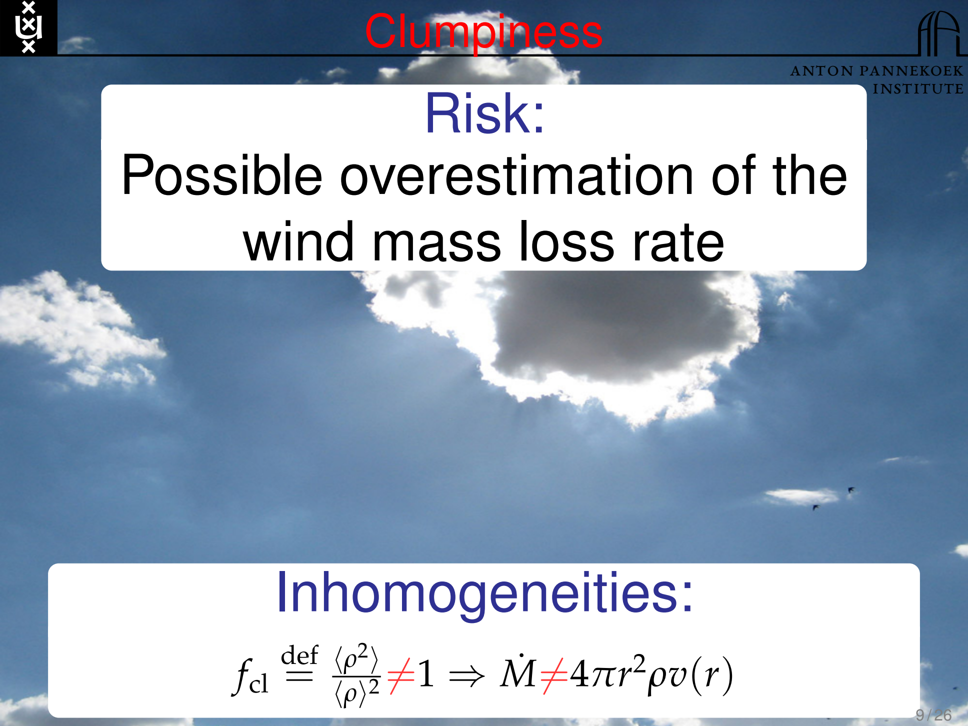
Clumpiness



Inhomogeneities:

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

Clumpiness



Risk:

Possible overestimation of the wind mass loss rate

Inhomogeneities:

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

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Mass loss in MESA

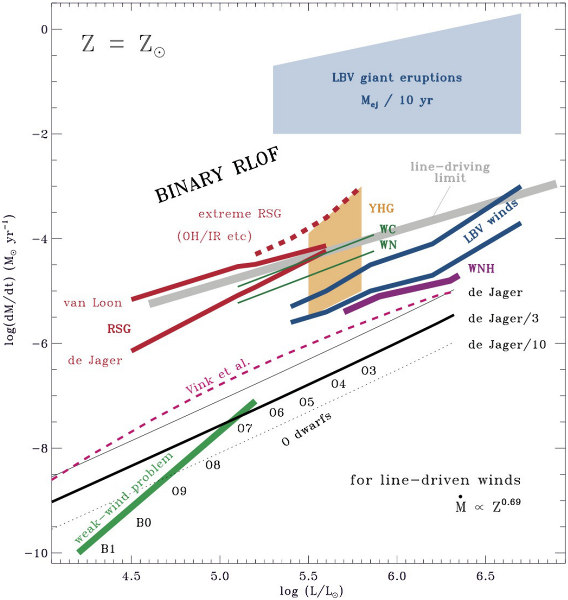


Figure: from N. Smith 2014, ARA&A, 52, 487

(Semi–)Empirical parametric models.

Efficiency factor:

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

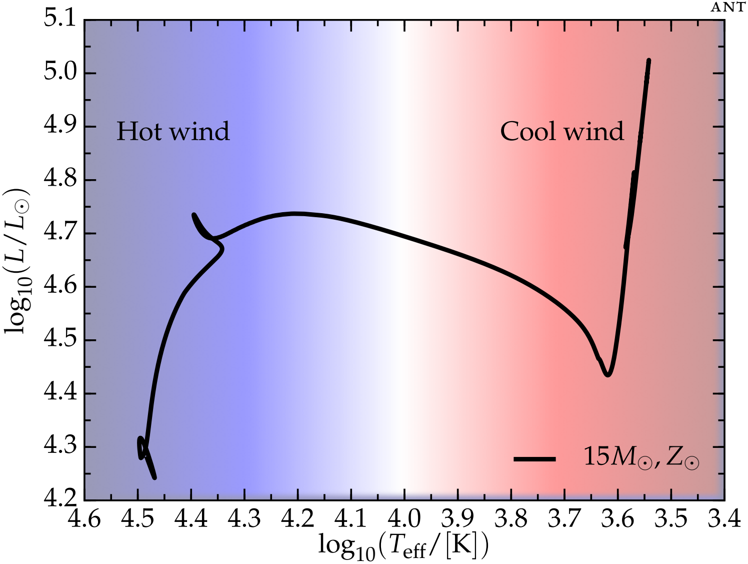
$$\Downarrow$$

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

η is a **free** parameter:

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

Combination of algorithms



WR wind $\Leftrightarrow X_s < 0.4$

MESA grid varying dM/dt

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

- Initial mass:

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

- Efficiency:

$$\eta = \{1,\ \tfrac{1}{3},\ \tfrac{1}{10}\}\ ;$$

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

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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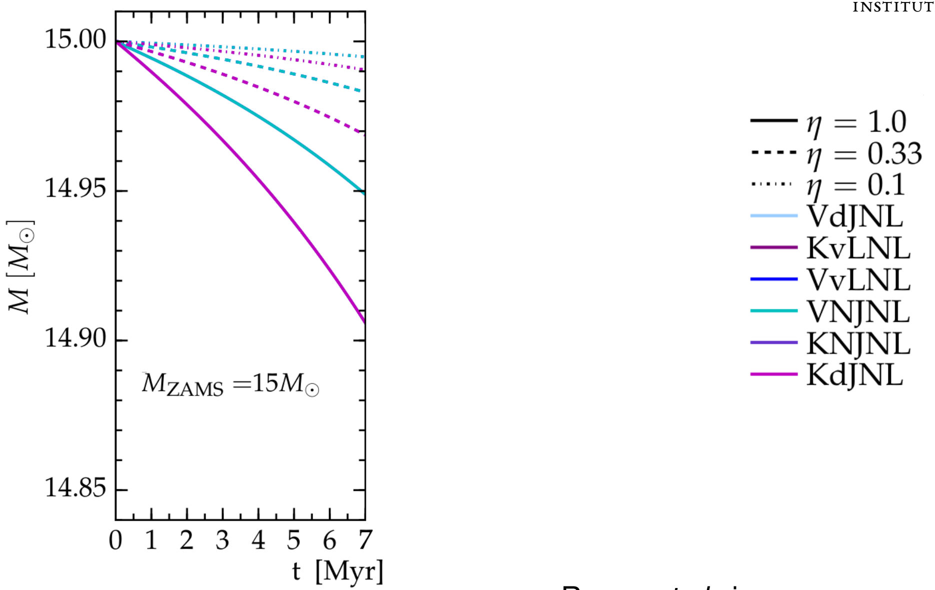
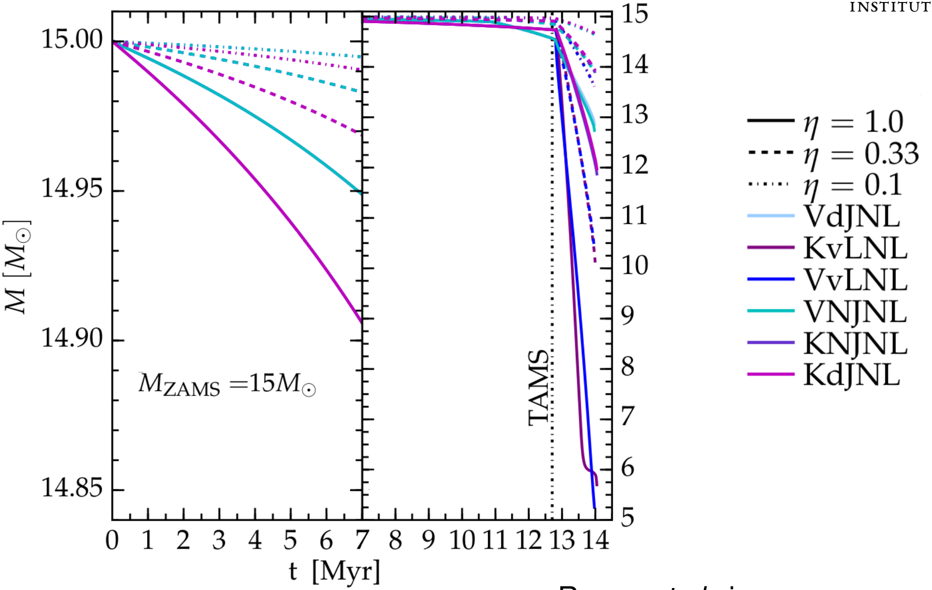
Wind mass loss history



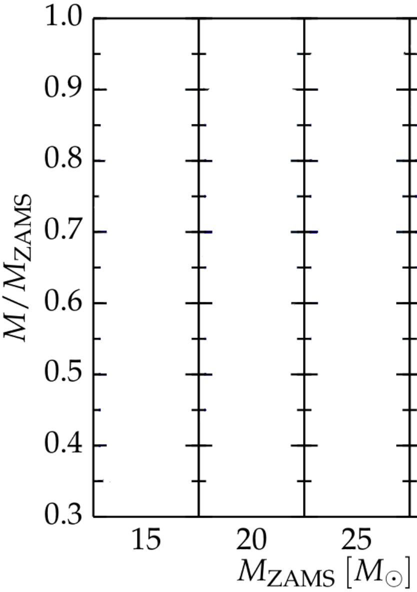
Renzo *et al.*, in prep.

Wind mass loss history



Renzo *et al.*, in prep.

Impact on the final mass



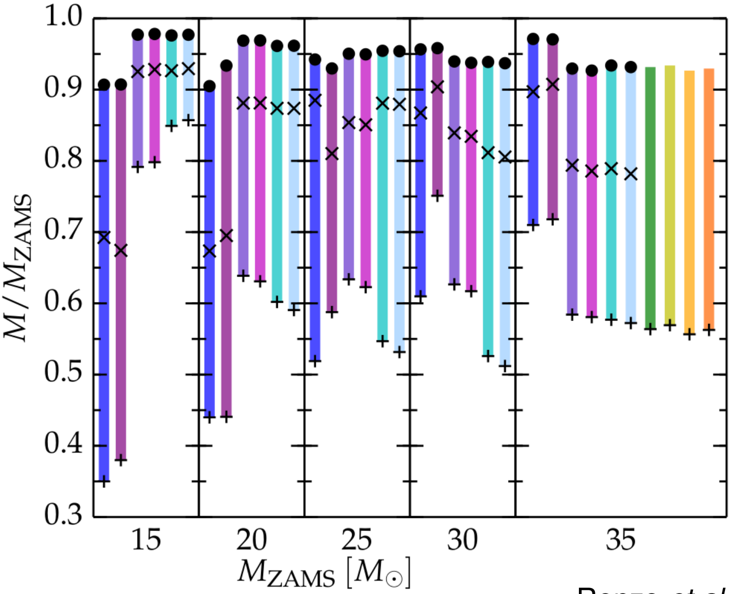
MESA

Legend:

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

Renzo *et al.*, in prep.

Impact on the final mass



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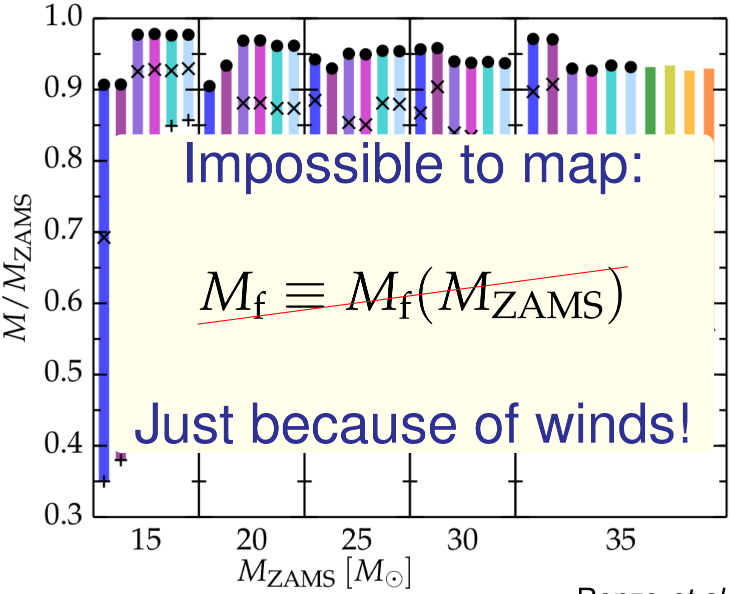
$\eta \rightarrow$ largest uncertainty

Renzo *et al.*, in prep.

Impact on the final mass



Impossible to map:

$$M_{\mathrm{f}} \equiv M_{\mathrm{f}}(M_{\mathrm{ZAMS}})$$

Just because of winds!

Legend:

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$\eta \rightarrow$ largest uncertainty

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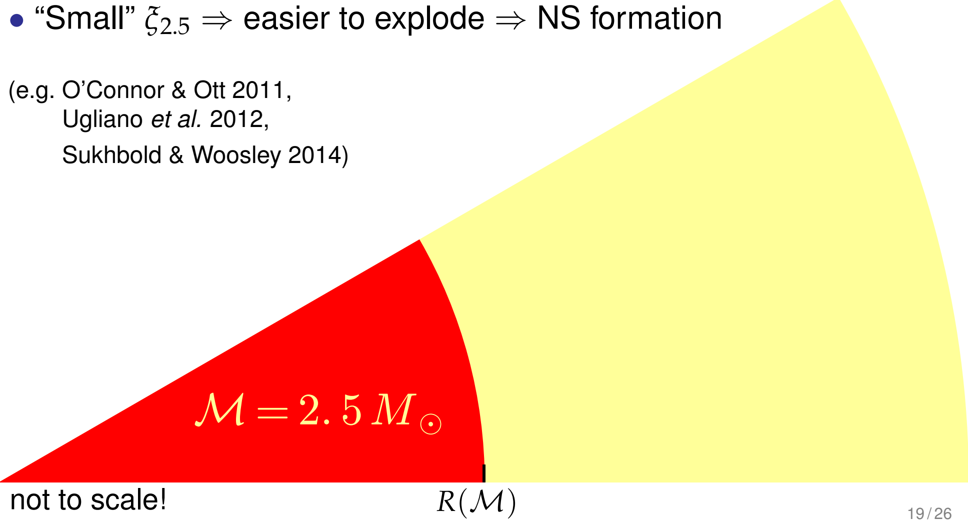
“Explodability” & Compactness

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

- “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!

Core @ O depletion

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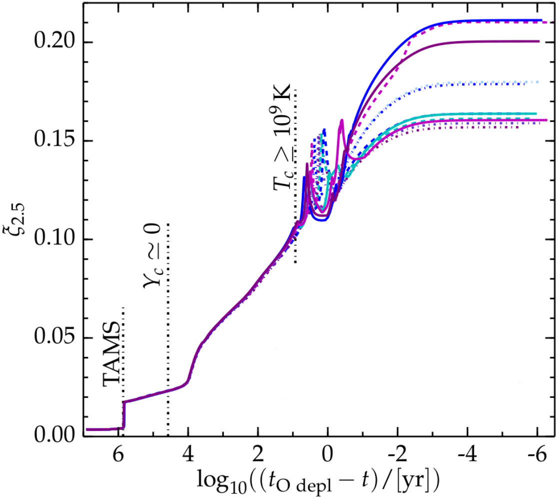
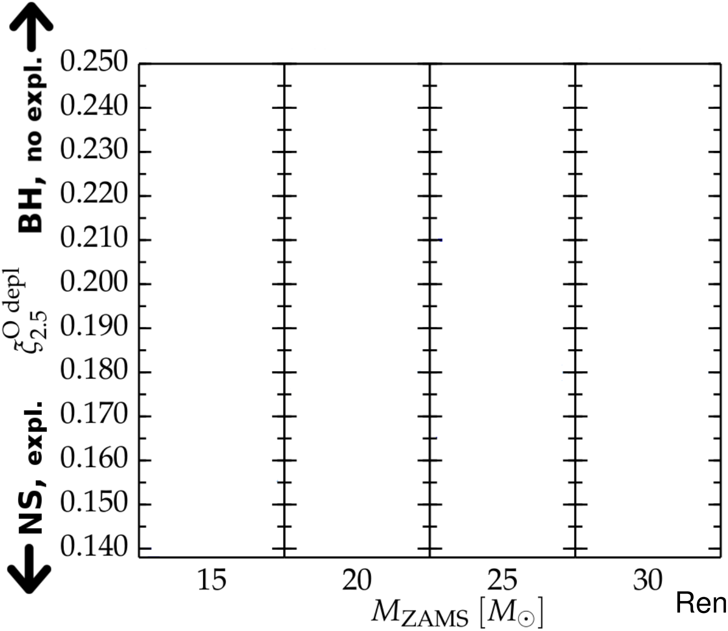
$M_{\mathrm{ZAMS}} = 25\,M_{\odot}$ MESA models



Renzo *et al.*, in prep.

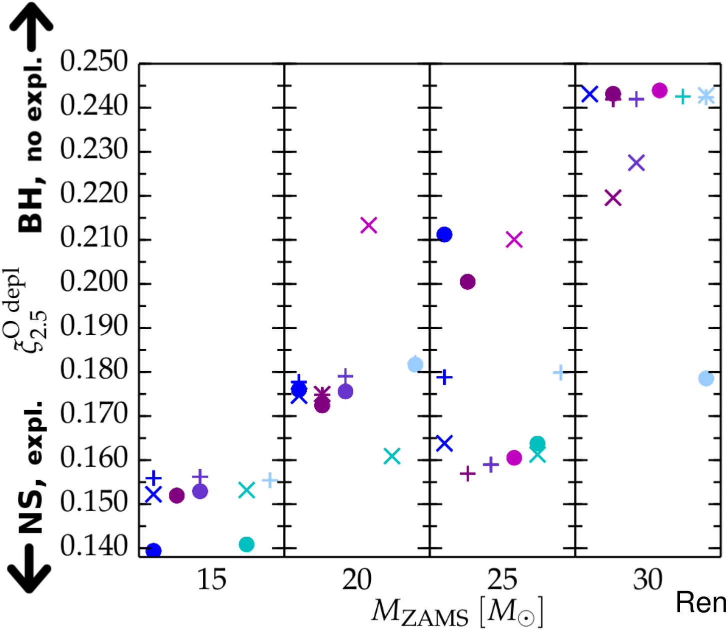
Critical point: Ne core burning/C shell burning

$\xi_{2.5}$ @ O depletion



Renzo *et al.*, in prep.

$\xi_{2.5}$ @ Oxygen Depletion



Legend:

- ● $\eta = 0.1$
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Post O burning evolution

⇓

Core contraction

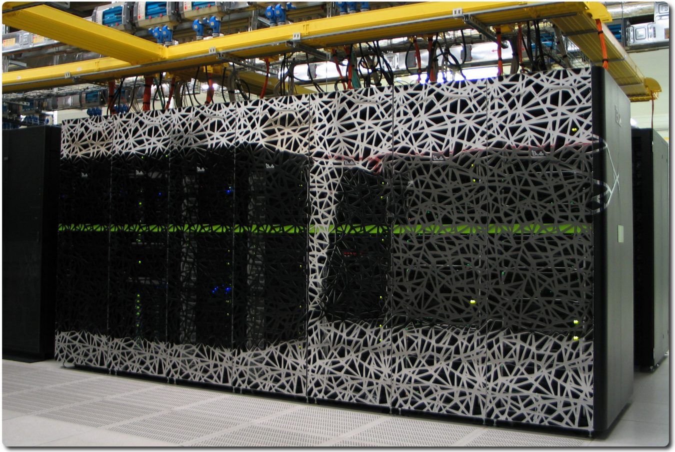
⇓

Amplification of the differences.

Renzo *et al.*, in prep.

Computing Advanced Burning Stages

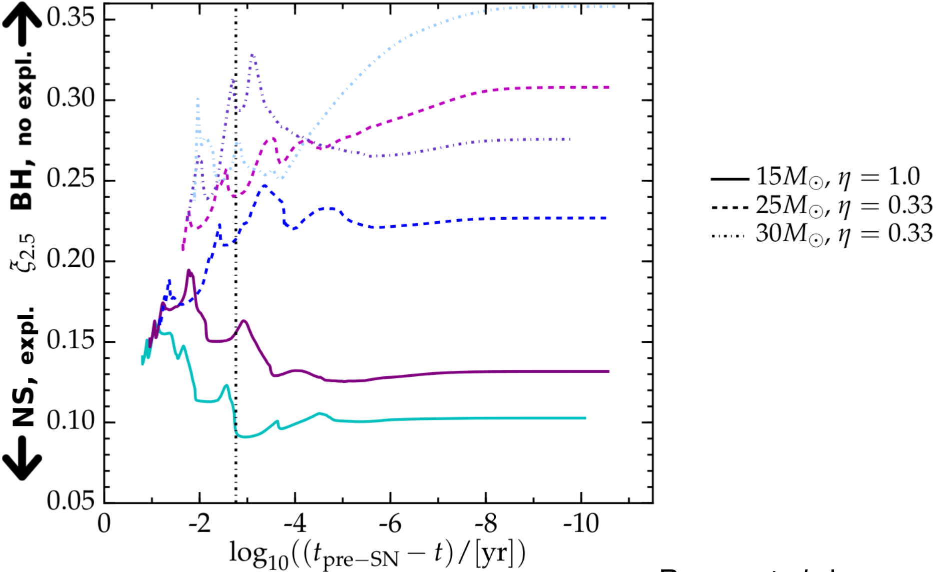
- Initially small effect ⇒ $N_{\rm zones} \gtrsim 20\,000$;
- Complex nuclear burning ⇒ $N_{\rm iso} \gtrsim 200$;



SurfSara's Cartesius Computer.

Post O burning evolution

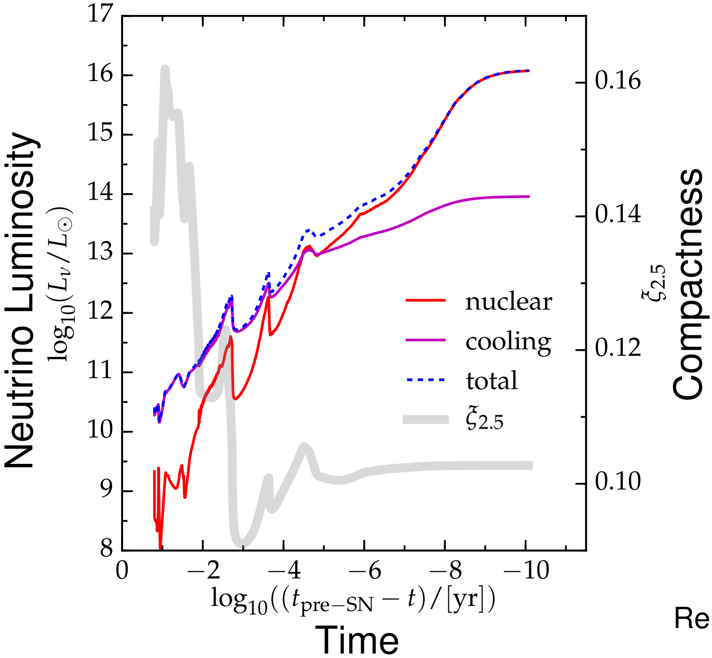
Si shell burning →



Time

Renzo *et al.*, in prep.

$\xi_{2.5}$ Oscillations



Fuel ignition in
(partially)
degenerate
environment

$\Downarrow$

Flash

Renzo *et al.*, in prep.

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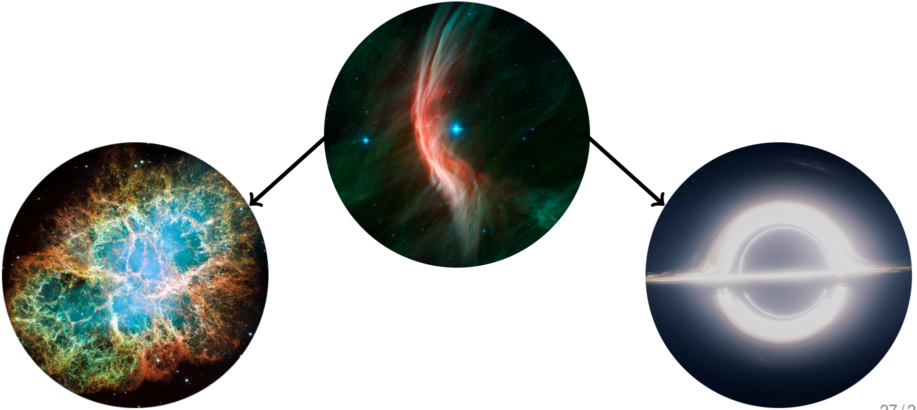
Take home points

Uncertainties in stellar winds:

- pre-SN mass ⇒ no $M_f \equiv M_f(M_{\mathrm{ZAMS}})$ map;
- core structure ⇒ “explodability” & remnant.
- stellar evolution is not done yet!



Take home points

Uncertainties in stellar winds:

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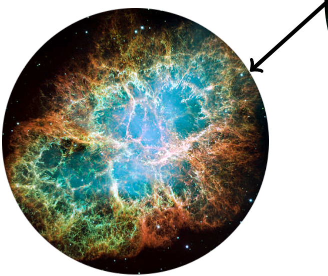

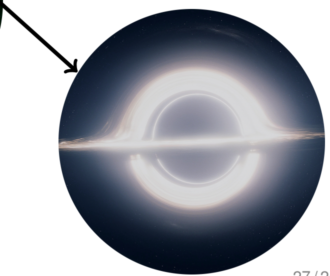

Thank you!

Outline

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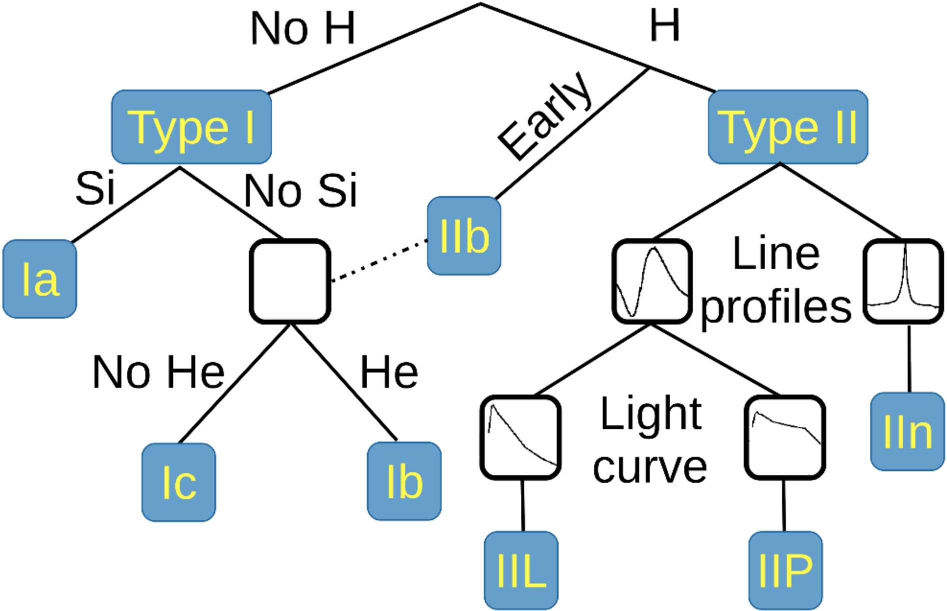
Backup slides

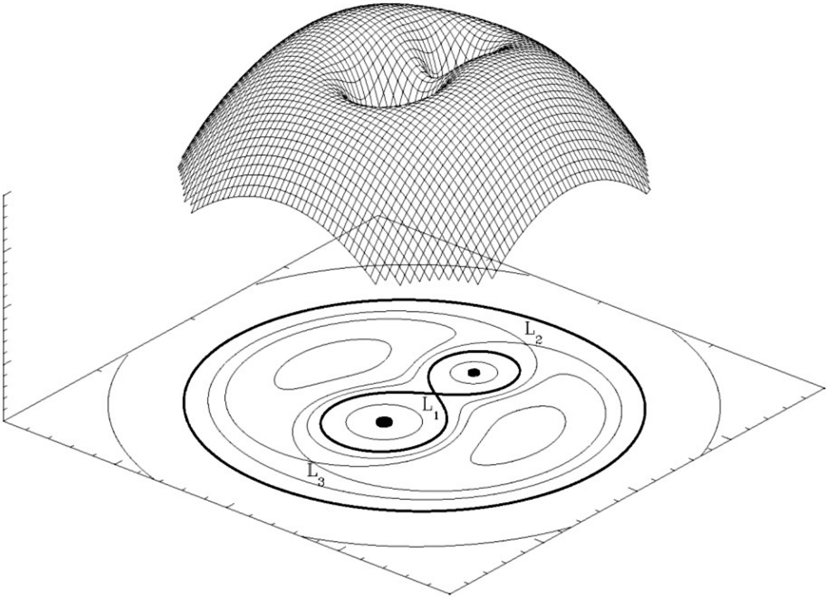
Supernova Taxonomy



Back

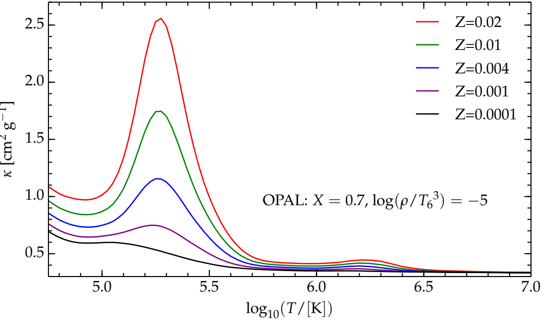
Roche Lobe OverFlow

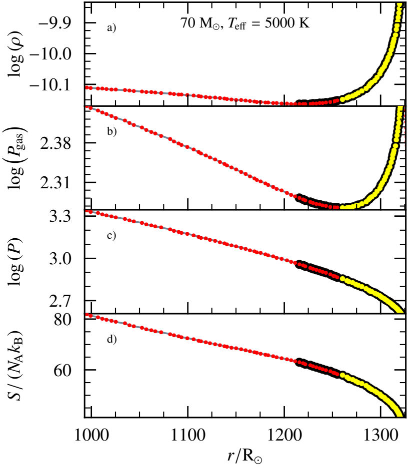
Mass Transfer in Binaries



MESA nearly super-Eddington Regime

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





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

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

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)

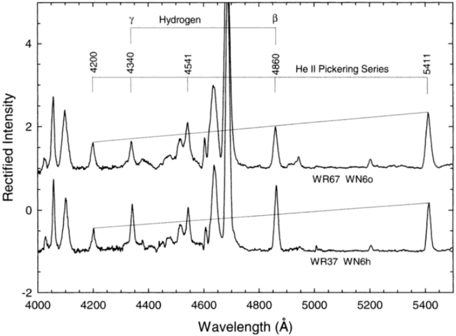
Assumptions commonly needed:

- 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.

Back

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.

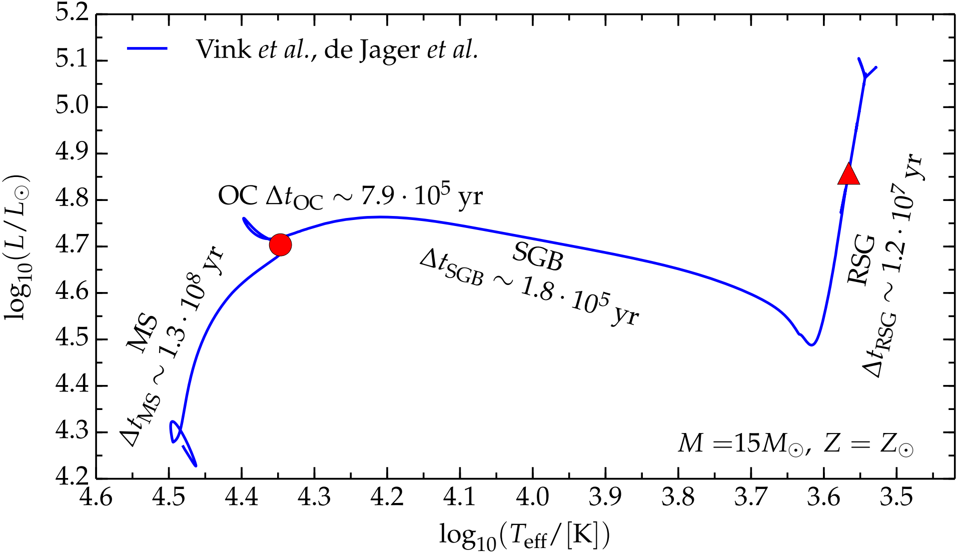
Computational Definition (MESA):

- $X_s < 0.4$

Impossible to distinguish sub-categories without spectra!

Evolution of a Massive Star in one Slide

◂ Back



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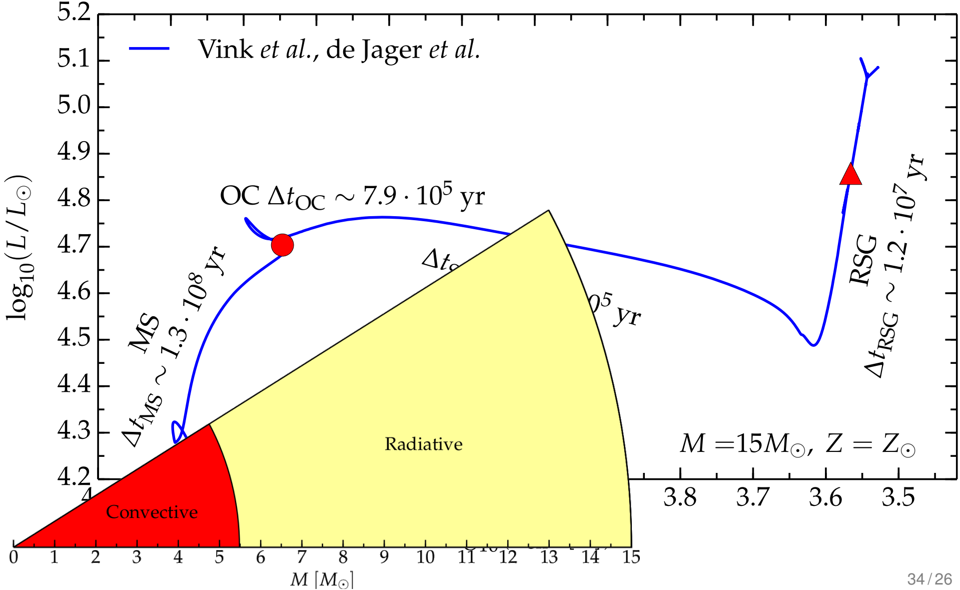

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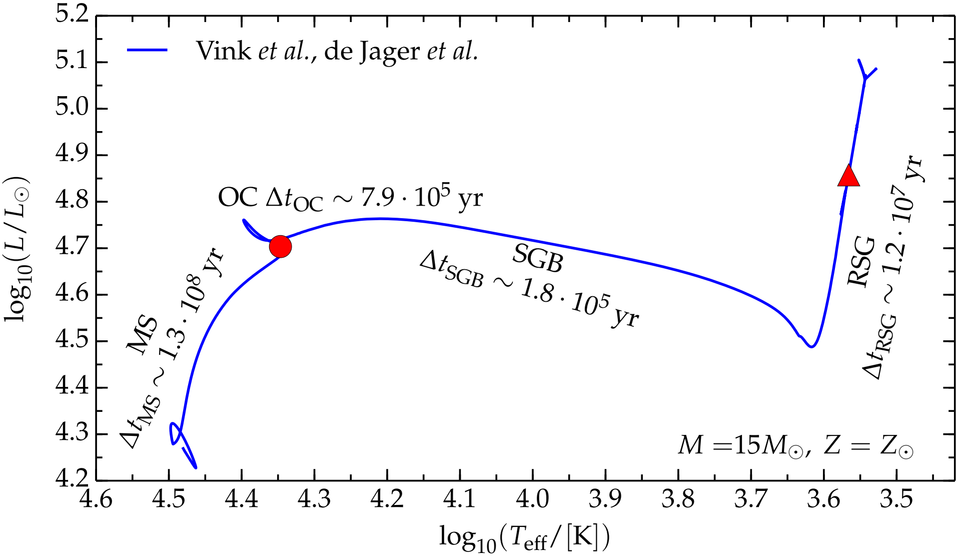

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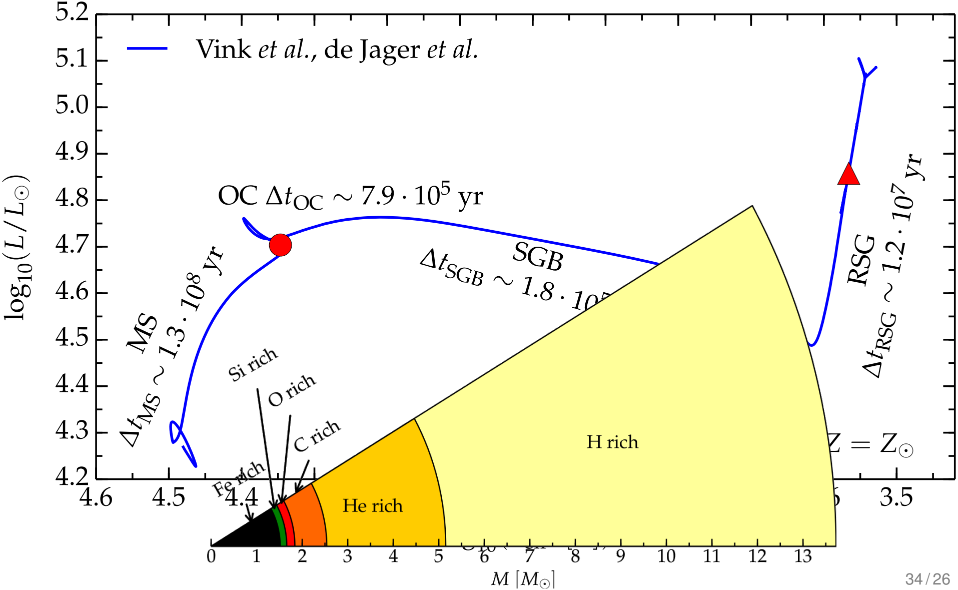
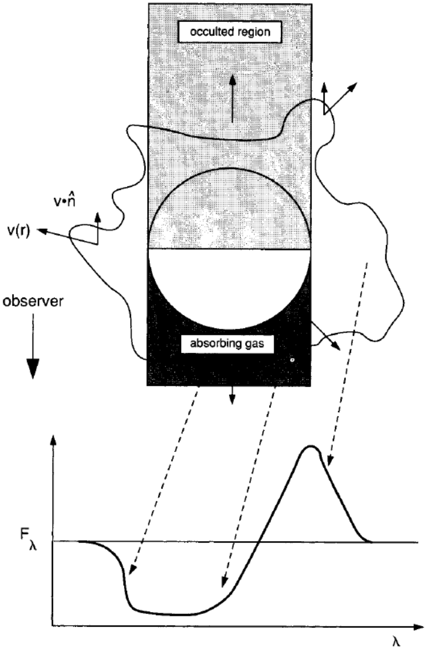


P Cygni Line Profiles



- 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.