Group meeting – May 30

The impact of stellar winds on the final structure and fate of massive stars

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NASA, JPL-Caltech, Spitzer Space Telescope

Outline

Stellar winds

- Line driving mechanism
- Algorithmic treatment

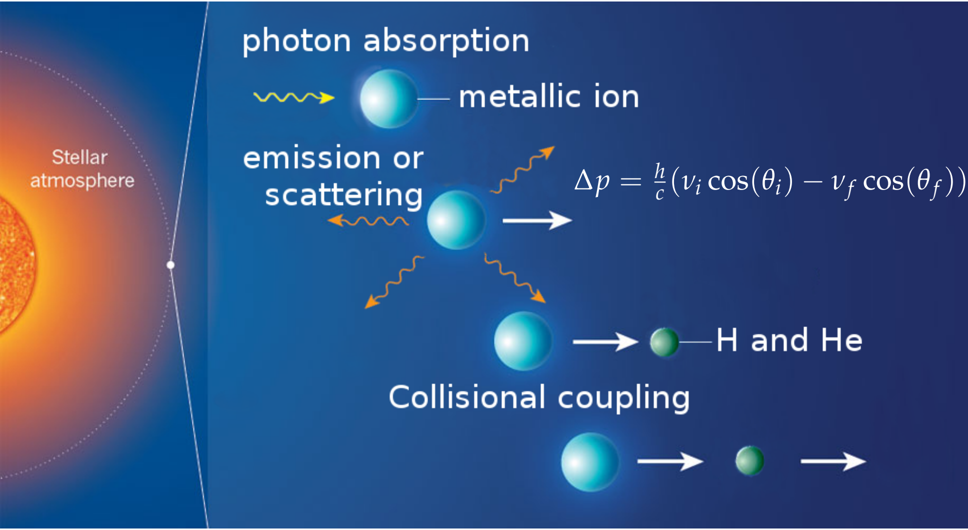
Impact on:

- Final mass & appearance
- Core structure

Conclusions

- Take home points

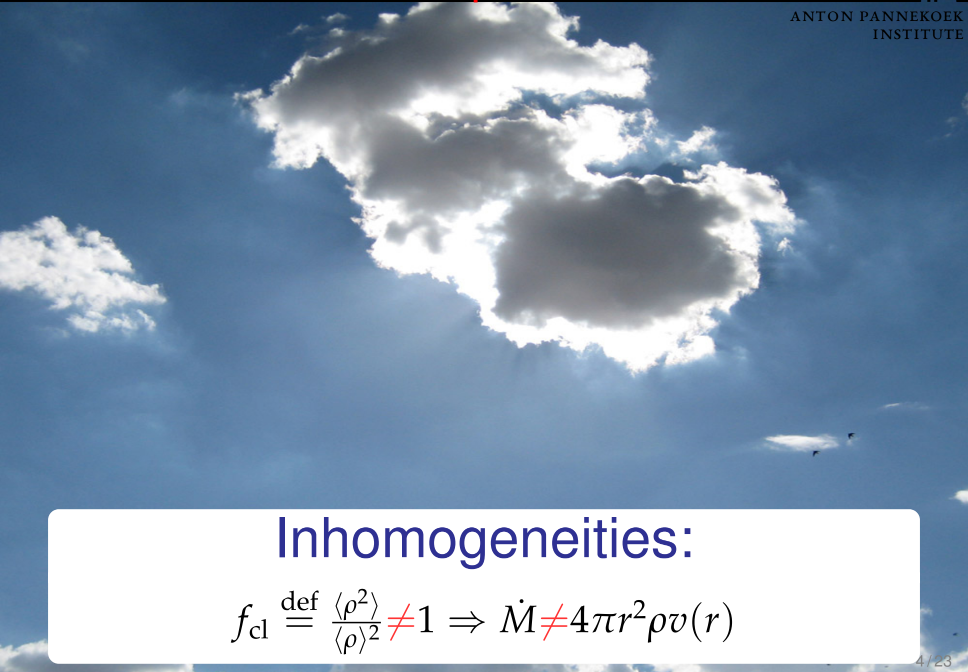
Radiatively Driven Winds in One Slide



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

Problems: High Non-Linearity and Clumpiness

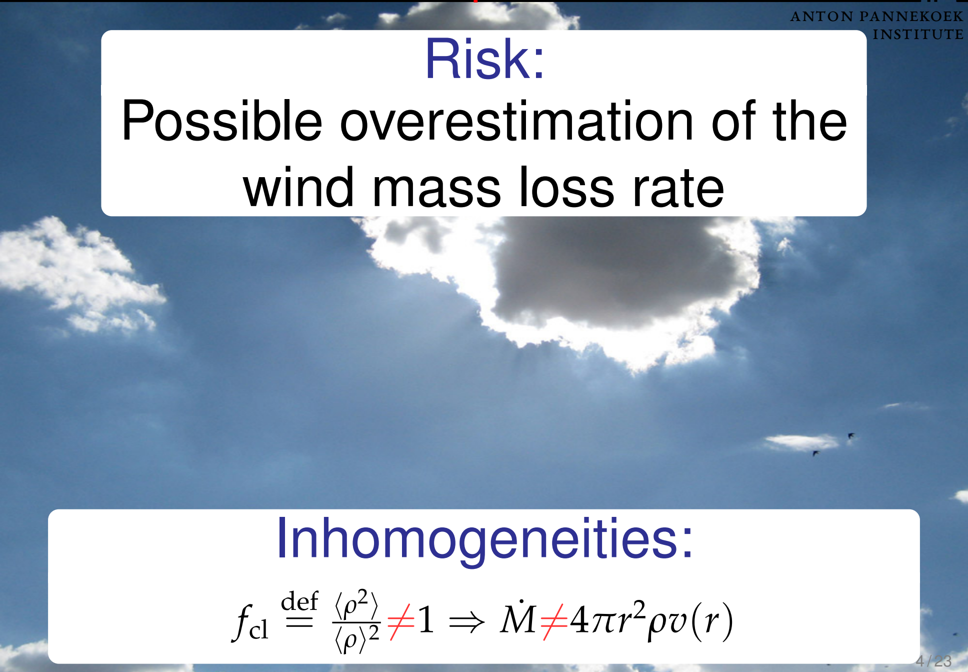
Clumpiness



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

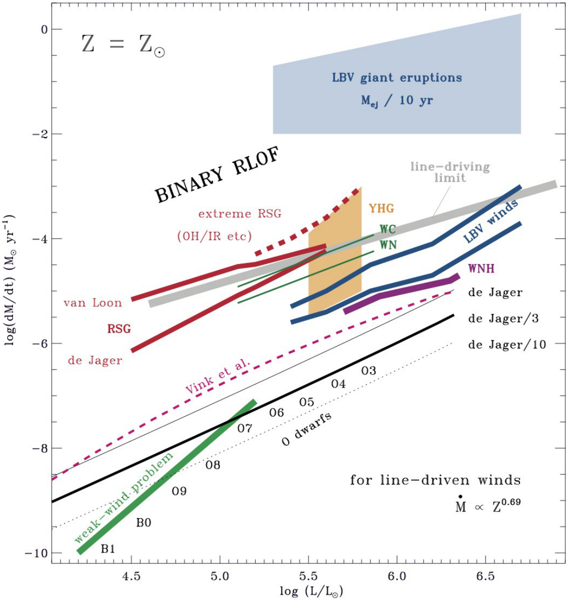


Figure: from N. Smith 2014, ARA&A, 52, 487

(Semi–)Empirical parametric models.

Efficiency factor:

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

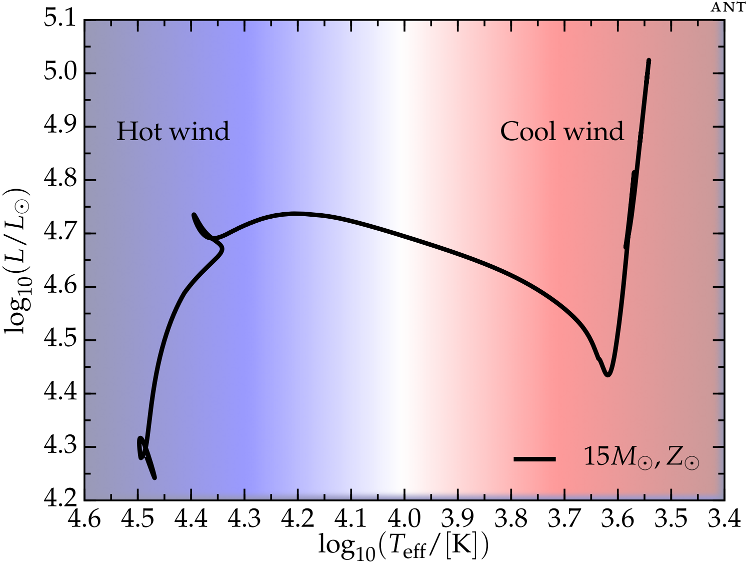
$$\Downarrow$$

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

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 $Z_\odot = 0.019$, non-rotating stellar models:

- Initial mass:

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

- Efficiency:

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

- 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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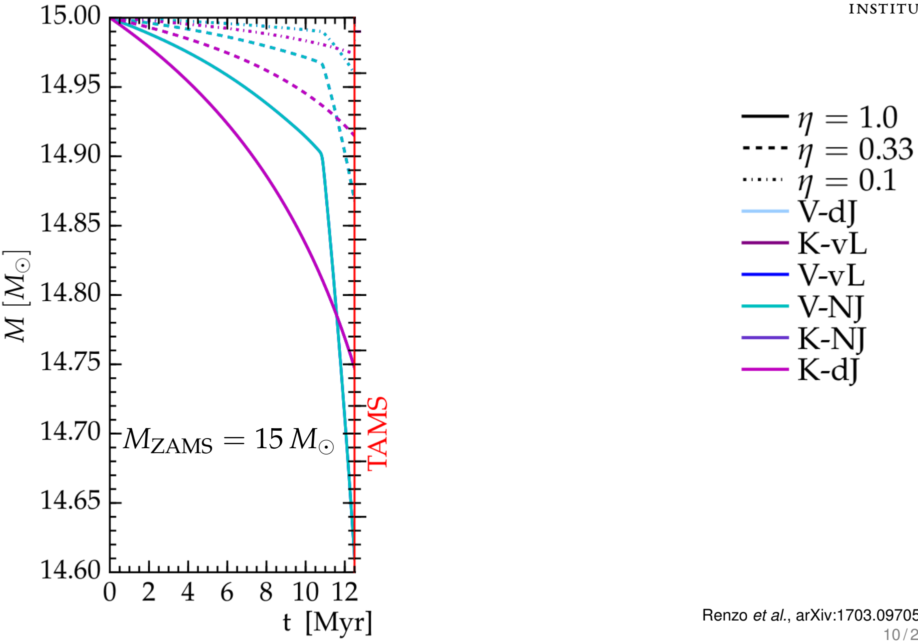
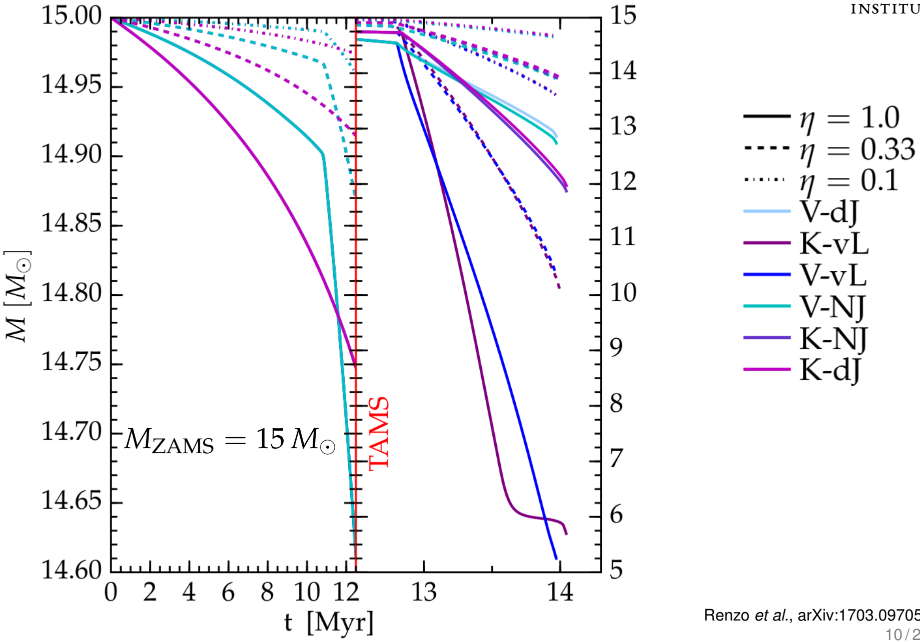
Wind mass loss history



Renzo *et al.*, arXiv:1703.09705

Wind mass loss history



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Impact on the final mass

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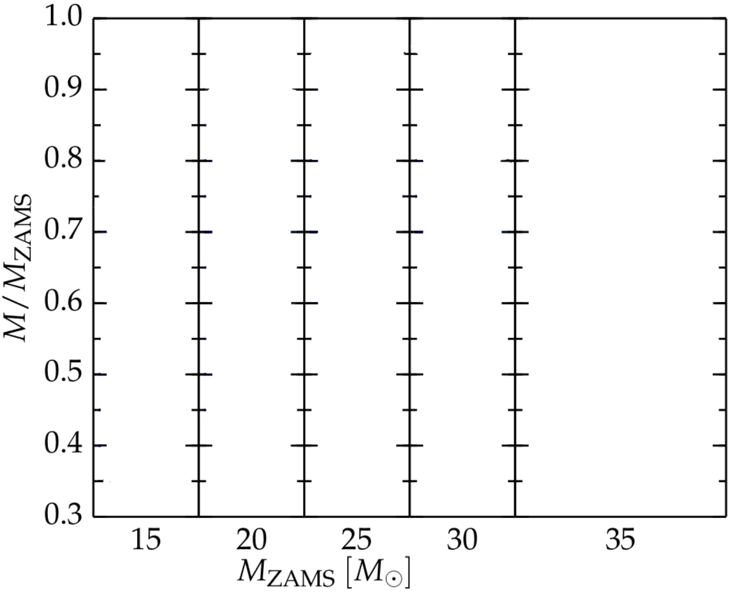


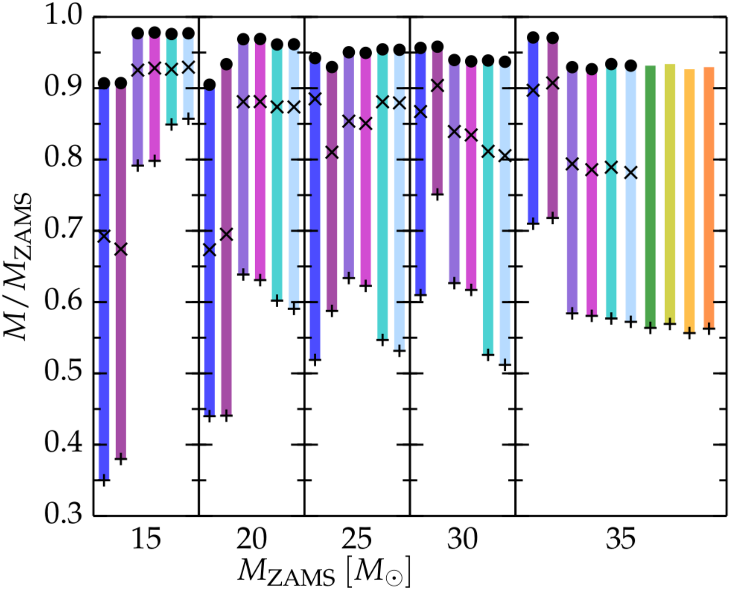
MESA

Legend:

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

Renzo *et al.*, arXiv:1703.09705

Impact on the final mass



MESA

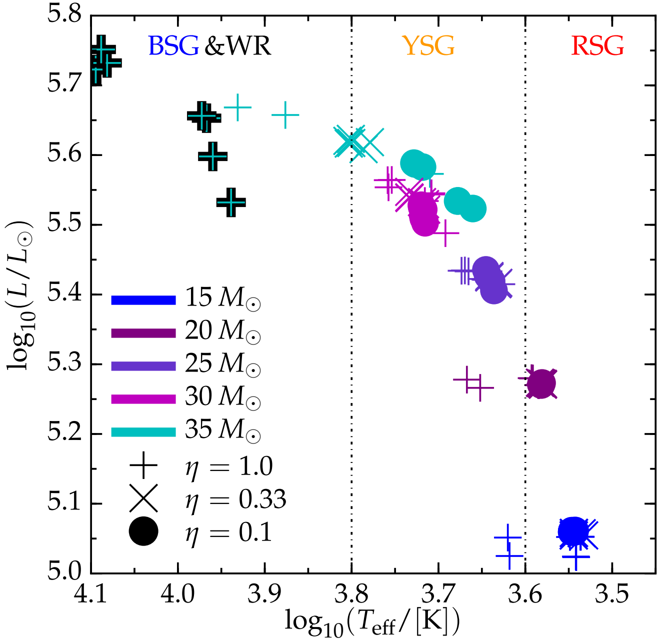
Legend:

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

$\eta \rightarrow$ largest uncertainty

Renzo *et al.*, arXiv:1703.09705

Pre-explosion appearance



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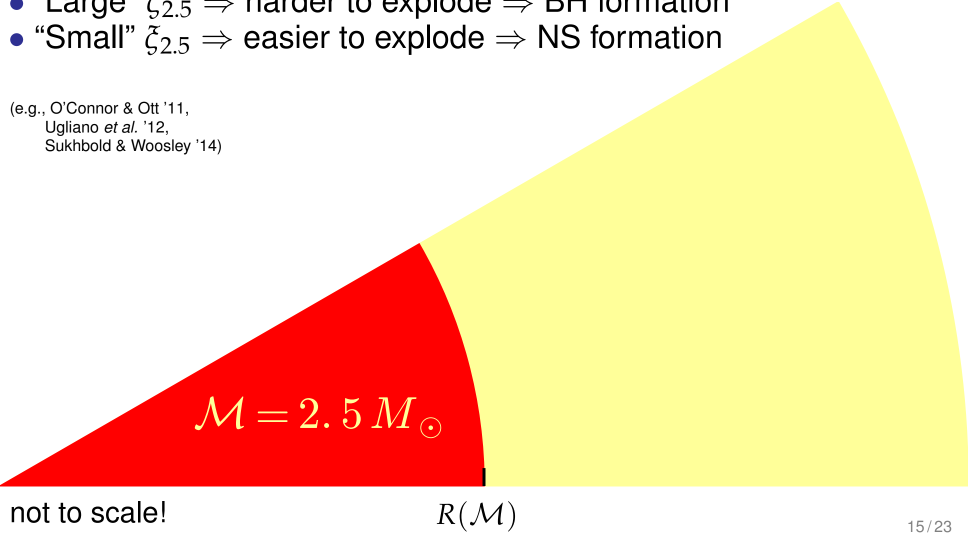
“Explodability” & Compactness

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

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

(e.g., O’Connor & Ott ’11,
Ugliano *et al.* ’12,
Sukhbold & Woosley ’14)



not to scale!

Core @ O depletion

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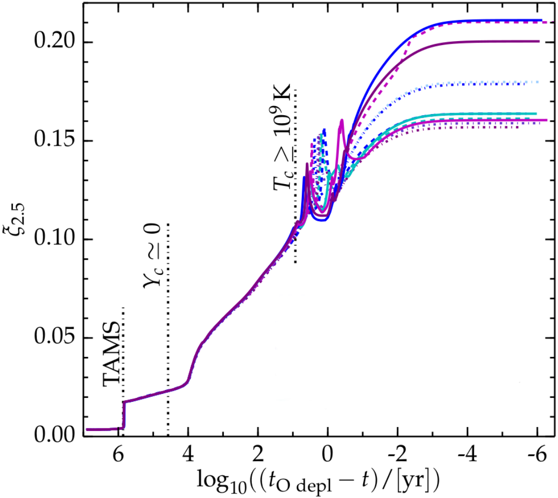
$M_{\mathrm{ZAMS}} = 25\,M_{\odot}$ MESA models



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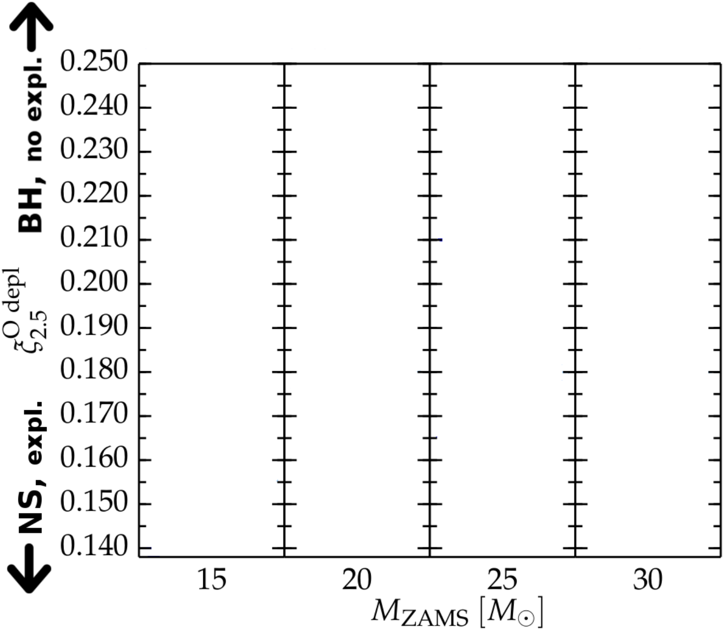
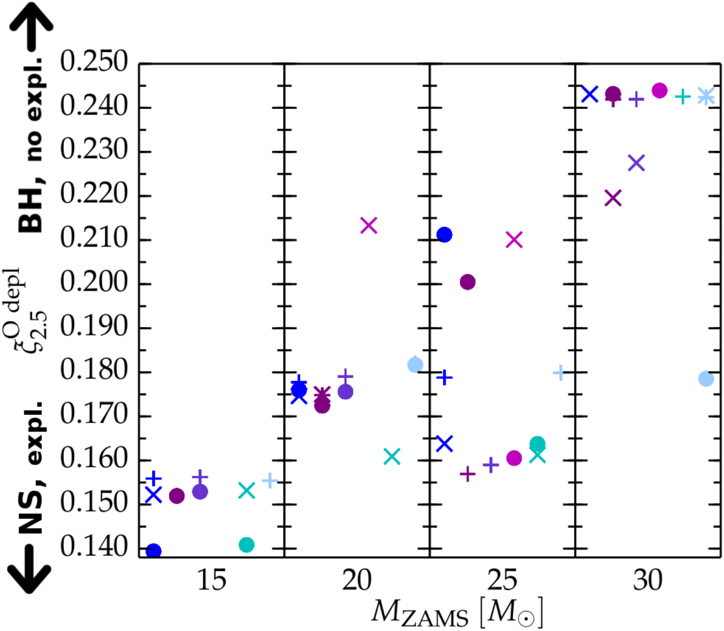
Critical point: Ne core burning/C shell burning

$\xi_{2.5}$ @ O depletion



Renzo *et al.*, arXiv:1703.09705

$\xi_{2.5}$ @ Oxygen Depletion



Legend:

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

Post O burning evolution

⇓

Core contraction

⇓

Amplification of the differences.

Renzo *et al.*, arXiv:1703.09705

Computing Advanced Burning Stages

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

$$M_\text{Ch}^\text{eff} \sim (5.83 M_\odot) Y_e^2 \left[1 + \left(\frac{s_e}{\pi Y_e} \right)^2 \right]$$

$$\texttt{approx21.net} \Rightarrow {}^{56}\text{Fe} + 2e^- \rightarrow {}^{56}\text{Cr} + 2\nu_e$$

$$Y_e(r=0) \equiv Y_e({}^{56}\text{Cr}) = 0.428$$

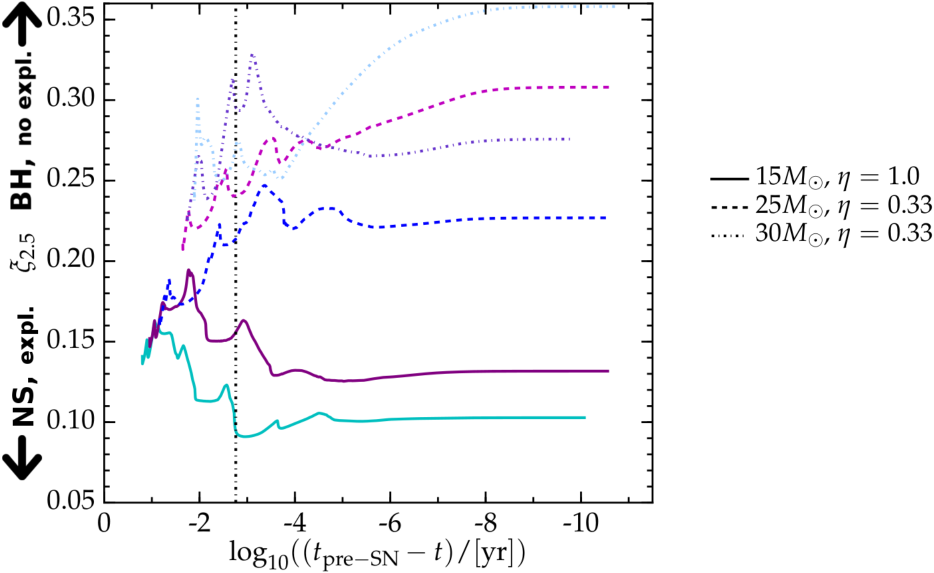
Largest array size in MESA:

$$\mathcal{L} \sim (N_\text{iso} + N_\text{zones})^2 \sim ((N_\text{iso}+5) \cdot N_\text{zones}) \cdot (3N_\text{iso}+9)$$

$\mathcal{L}$ is a `FORTRAN integer` ⇒ $\max\{\text{memory}\} = 17\,\text{Gb}$

Post O burning evolution

Si shell burning →



Time

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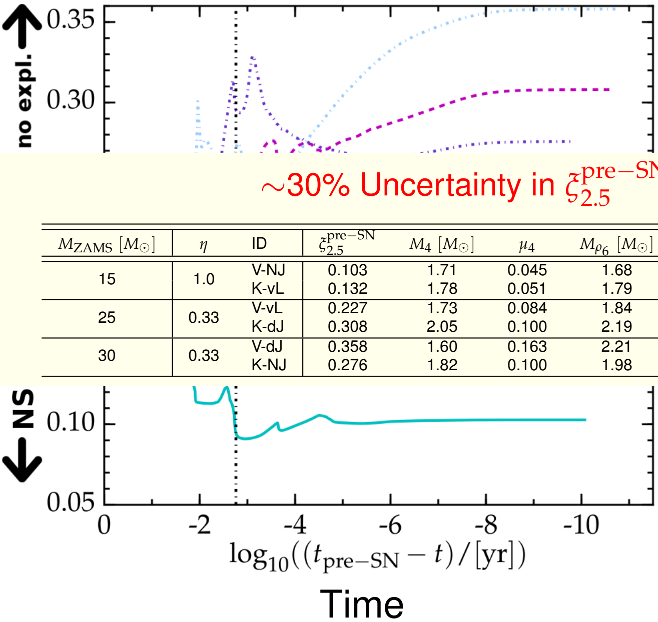
Post O burning evolution

Si shell burning →



~30% Uncertainty in $\xi_{2.5}^{\mathrm{pre-SN}}$

$M_{\mathrm{ZAMS}}\ [M_\odot]$	η	ID	$\xi_{2.5}^{\mathrm{pre-SN}}$	$M_4\ [M_\odot]$	μ_4	$M_{\rho_6}\ [M_\odot]$	$M_{\mathrm{CO}}\ [M_\odot]$	$M_{\mathrm{Fe}}\ [M_\odot]$
15	1.0	V-NJ	0.103	1.71	0.045	1.68	2.91	1.39
		K-vL	0.132	1.78	0.051	1.79	3.07	1.50
25	0.33	V-vL	0.227	1.73	0.084	1.84	6.38	1.51
		K-dJ	0.308	2.05	0.100	2.19	6.40	1.63
30	0.33	V-dJ	0.358	1.60	0.163	2.21	7.98	1.56
		K-NJ	0.276	1.82	0.100	1.98	7.90	1.58

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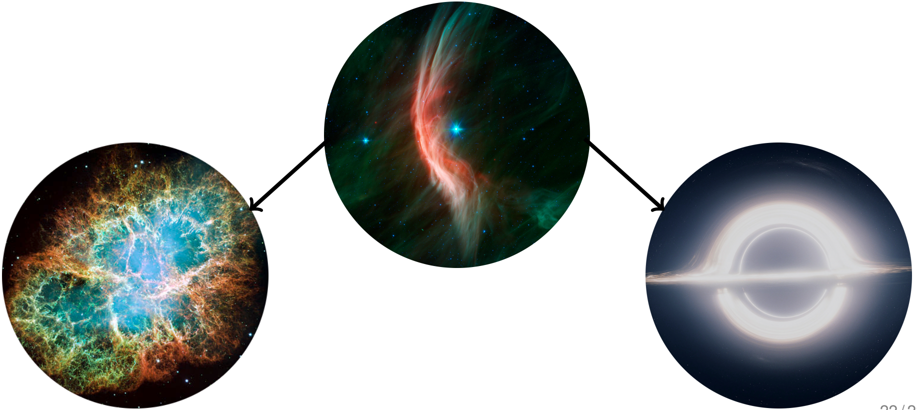
Uncertainties in stellar winds:

- pre-SN mass ⇒ no $M_f \equiv M_f(M_{\mathrm{ZAMS}})$ map;
- cannot solve “RSG problem”;
- core structure ⇒ “explodability” & remnant.



Take home points

Uncertainties in stellar winds:

- pre-SN mass ⇒ no $M_f \equiv M_f(M_{\mathrm{ZAMS}})$ map;
- cannot solve “RSG problem”;
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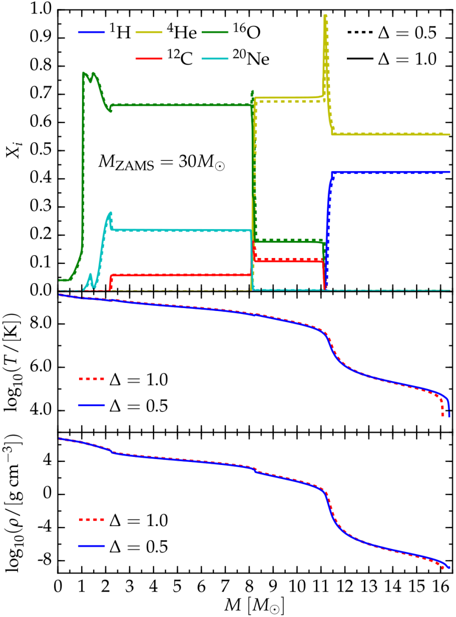
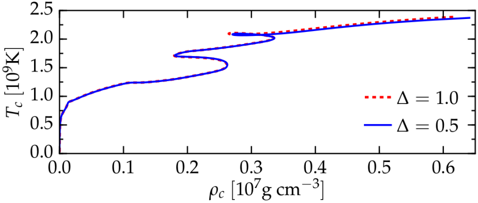
Thank you!

Outline

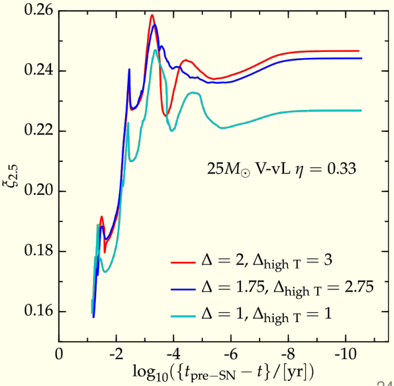
Backup slides

Resolution @ O depletion





post O depletion



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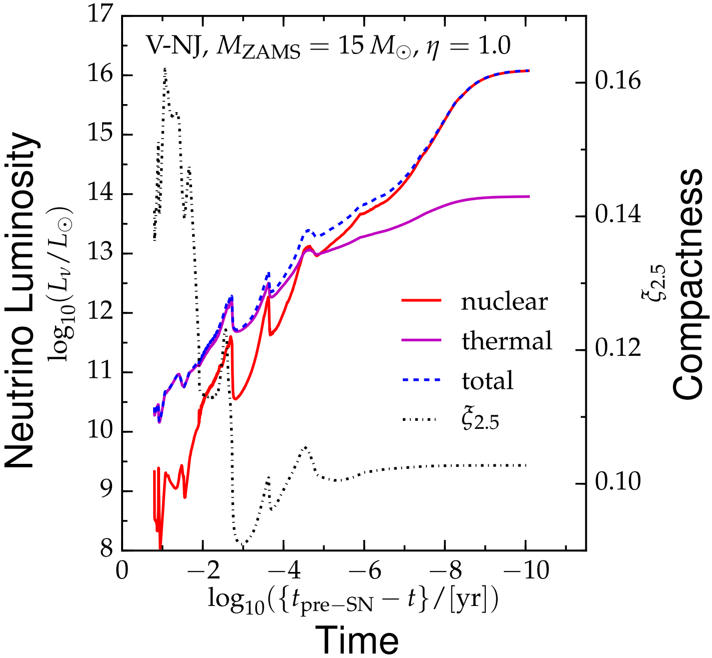
$\xi_{2.5}$ Oscillations



Fuel ignition in
(partially)
degenerate
environment

⇓

Flash

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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.

Hot phase winds

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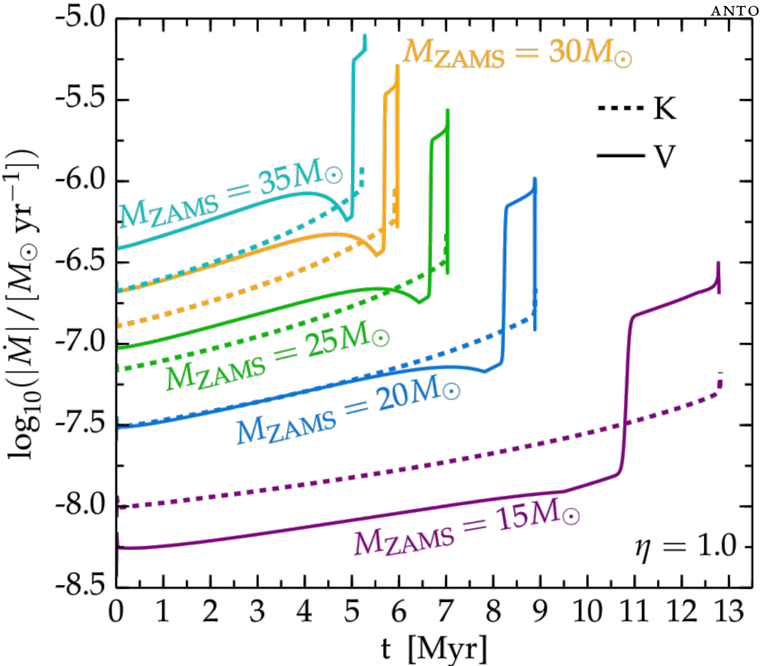
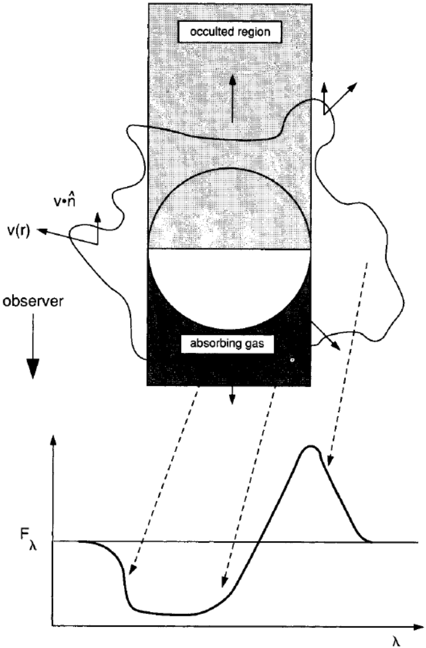


P Cygni Line Profiles



- 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.