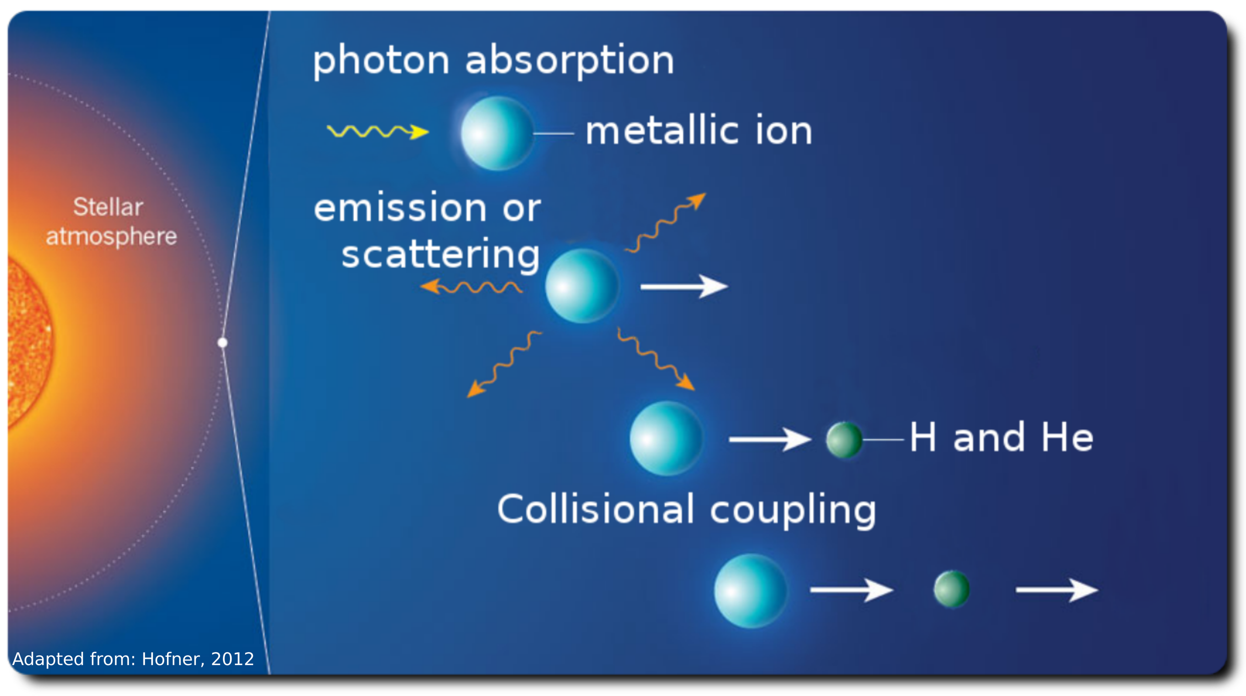
Systematic Survey of Massive Stars Mass Loss Algorithms

M. Renzo[†,1,2,3], C. D. Ott[3], S. N. Shore[1], S. E. de Mink[2]

[1]Dip. di Fisica 'Enrico Fermi', University of Pisa – [2]API, University of Amsterdam – [3]TAPIR, California Institute of Technology

ANTON PANNEKOEK INSTITUTE

PhD @ API
University of Amsterdam
http://staff.fnwi.uva.nl/m.renzo
† m.renzo@uva.nl



Line Driven Winds

- Highly non-linear: driving depends on $\kappa \equiv \kappa(\rho, v)$, because of Doppler shifts, and $\rho \equiv \rho(v, \dot{v})$ through hydrodynamics $\Rightarrow$ Driving depends on outflow itself.
- Efficiency η depends on the possible presence of over-dense clumps in the atmosphere: potential overestimation of $\dot{M}$ if interpreting the observed ρ (dominated by over-dense clumps) as the average ρ.

Too complicated to treat from first principles in Stellar Evolution Codes

⇓

Various (Semi-Empirical) Algorithmic Representations:

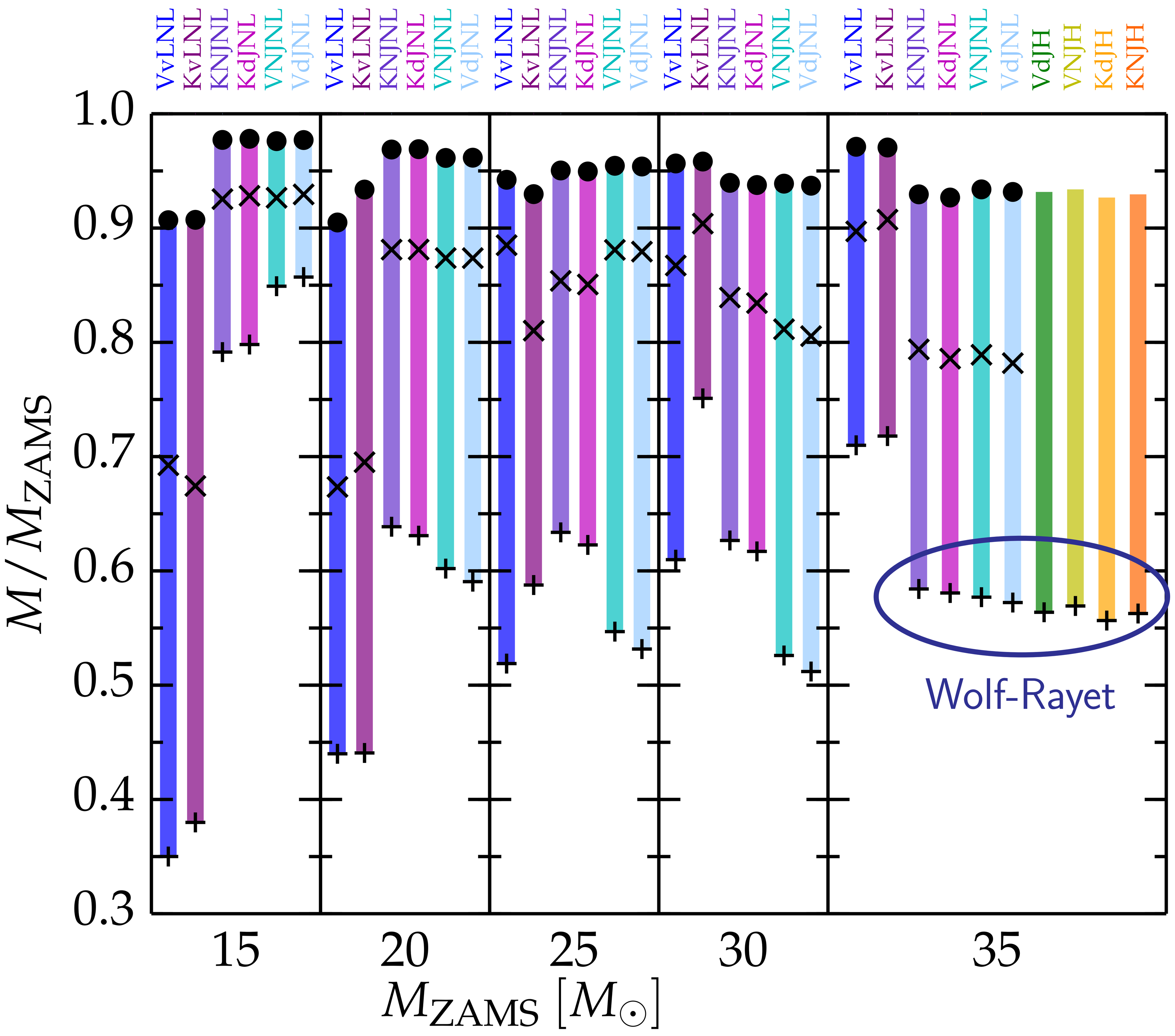
$$\dot{M} \equiv \dot{M}(L, T_{\mathrm{eff}}, Z, \mathrm{etc.}) \times \eta$$

We carry out a *systematic* comparison of the impact of these algorithms and their efficiency scale factor on the evolution and final structure of single massive stars using the MESA stellar evolution code (Paxton *et al.* 2011, 2013, 2015).

Uncertainty in the Final Mass

Impossible to go back in time using stellar models.

Systematic uncertainty in the final mass dominated by unknown η.



Legend: $+$ $\eta = 1.0$; $\times$ $\eta = 0.33$; $\bullet$ $\eta = 0.33$

Hot phase mass loss:
V = Vink *et al.* 2000, 2001; **K** = Kudritzki *et al.* 1989;
Cool phase mass loss:
dJ = de Jager *et al.* 1988; **NJ** = Nieuwenhuijzen *et al.* 1990; **vL** = van Loon *et al.* 2005;
WR mass loss:
NL = Nugis & Lamers 2000; **H** = Hamman *et al.* 1982,1985,1998
Each algorithm is a combination of these mass loss scheme (see top axis labels)

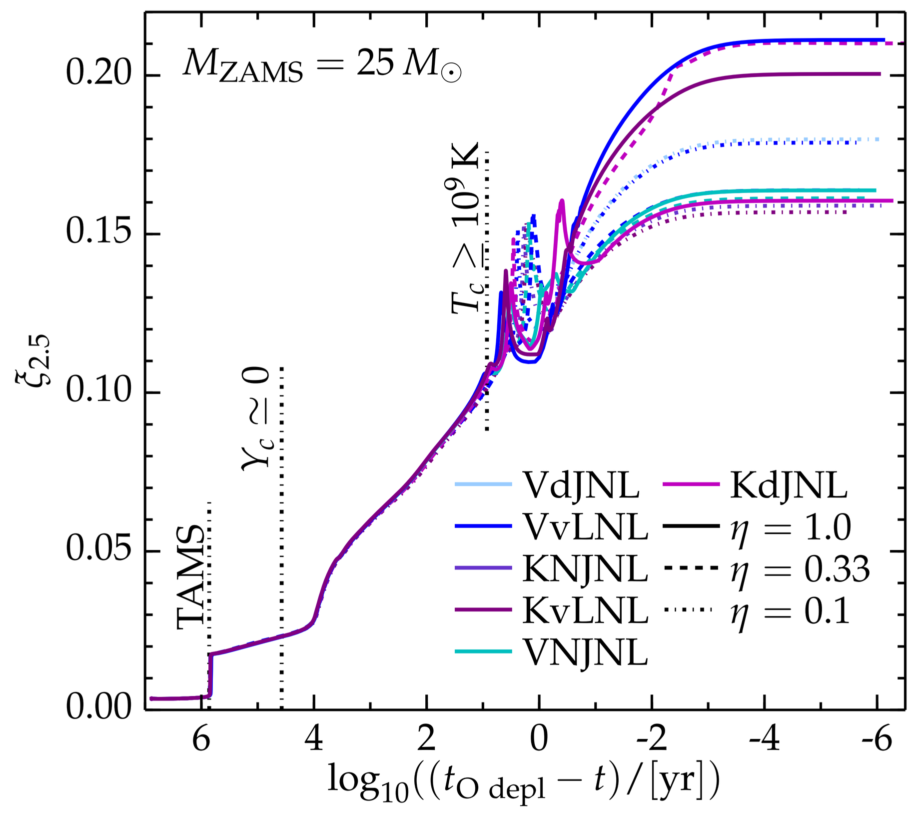
Uncertainty in the Core Structure

"Explodability" depends on the chosen algorithm:

The successful explosion of a stellar model depends on the assumptions in the treatment of mass loss.

Late core structure depends on winds

- Differences between core structures arise only in late stages: core evolutionary contraction amplifies the initially small differences;
- Critical point during neon core burning (carbon shell burning) phase for onset of significant differences;
- **Early ($\sim$ main sequence) mass loss matters for the core structure.**

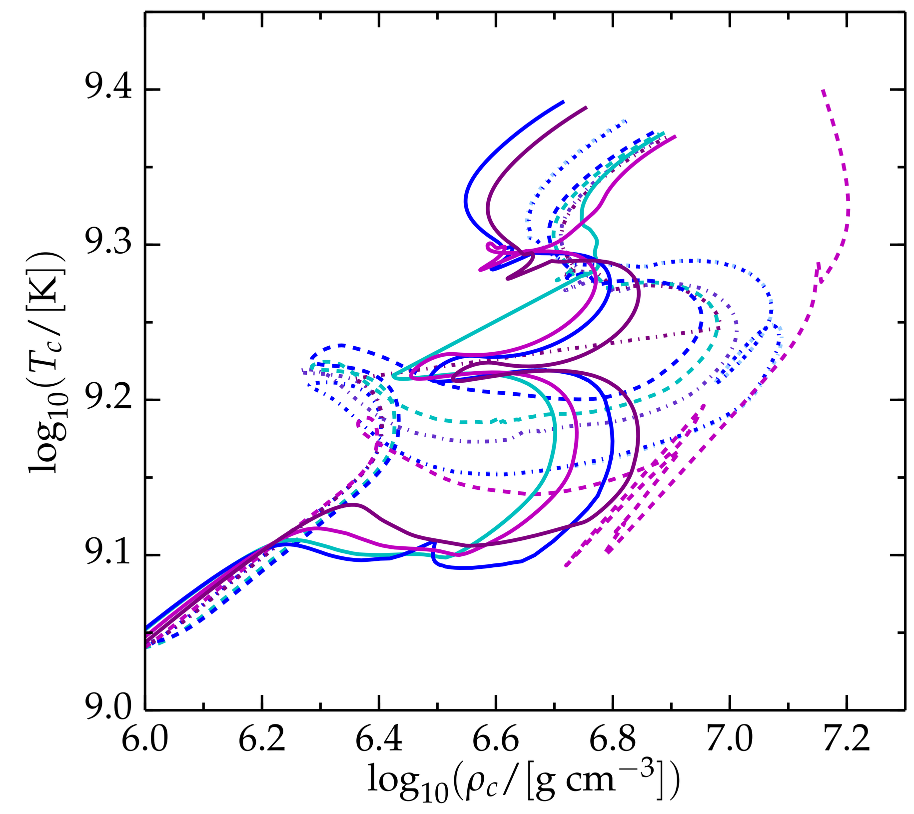


The compactness parameter

$$\xi_{2.5} \stackrel{\mathrm{def}}{=} \frac{2.5/M_\odot}{R(M_{\mathrm{bary}} = 2.5 M_\odot)/1000\,\mathrm{km}}$$

(O'connor & Ott 2011)

- Characterizes the density profile outside the (to-become) iron core;
- It is a function of time because of evolutionary contraction of the core;
- Value at onset of core-collapse can be used to predict success or failure of (neutrino driven) explosion, and nature of the compact remnant (Black Hole or Neutron Star):
  - Large values $\Rightarrow$ hard to explode $\Rightarrow$ probable BH;
  - Small values $\Rightarrow$ easier to explode $\Rightarrow$ probable NS;
- Value at Oxygen depletion is already a qualitative indicator of the SN outcome;
- $\xi_{2.5}$ **is sensitive to mass loss algorithm** after critical point of the evolution (Ne core burning / C shell burning).

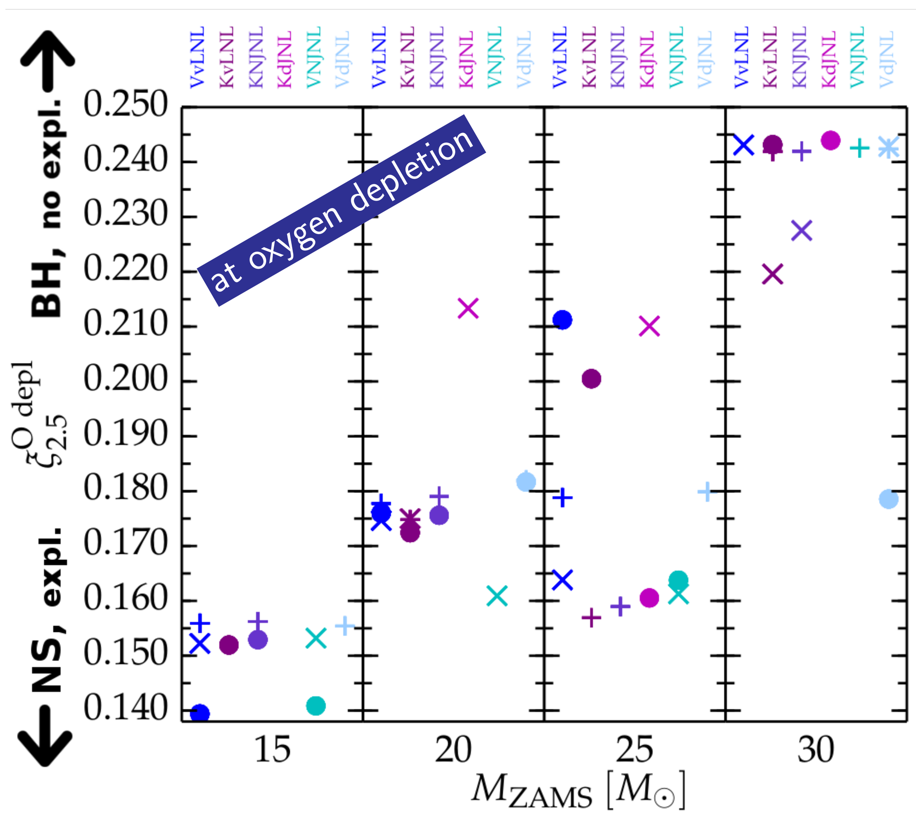


Computational challenges

- Need to capture initially small effect $\Rightarrow$ need very high spatial resolution: 20 000 – 100 000 mesh points until oxygen depletion
- Need detailed core structure $\Rightarrow$ large number of isotopes to trace weak reactions determining Y_e: 45 isotopes until O depletion, 203 afterwards.

⇓

Hard to compute very late stages until onset of core collapse (extremely slow runs)*.



Implications

- Mapping of M_{ZAMS} to remnant depends on the assumed mass loss algorithm and efficiency factor η.
- Initial condition for SN explosion simulations might be biased depending on the wind scheme.
- "Explodability windows" in mass might shift, with potentially large implications for the population of black holes and neutron stars.

Possible ways out:

- Observational constraints on wind mass loss rates using colliding wind in binaries, Be X-ray binaries, SN shock interaction with circumstellar material, and circumstellar material chemical composition, etc.
- Quantification of the systematic uncertainty due to the treatment of winds using all the algorithms available for each initial condition adopted.

* SURF SARA 's Cartesius Super computer crunching numbers for silicon burning evolution...

Renzo et al., in prep.