On the evolution and remnants of massive single and binary stars

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Motivation

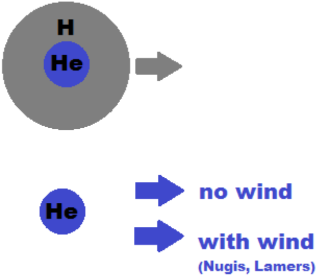
- What is the final fate of massive single stars and stars that are a member of a binary system?
- Possible mapping ZAMS mass ↔ remnant mass ↔ BH or NS?
- Type Ib/c supernovae - properties of the progenitor stars? Compact object in X-ray binaries?

Study evolution of

- single stars with $M = 15\text{-}45\ M_\odot$
- He stars with $M = 4\text{-}22\ M_\odot$ that mimic an evolution in a binary system, where the hydrogen envelope is removed by mass transfer on a timescale much shorter than core He burning (Case A,B)

Podsiadlowski et al. (1992); Woosley et al. (1995); Yoon et al. (2010); de Mink et al. (2013)

Setup of calculations



Stellar evolution code MESA, version 4740 Paxton (2011 and 2013)

Single stars:

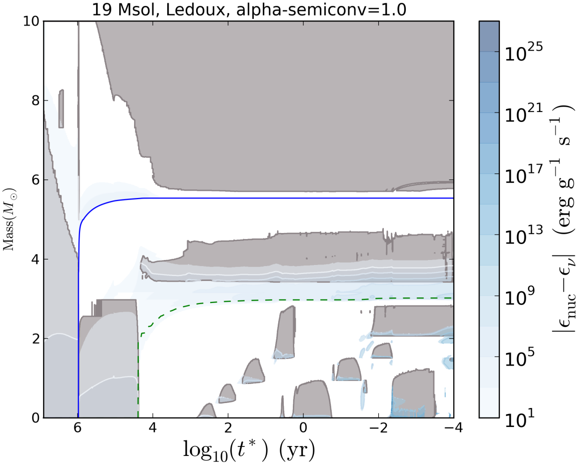
He core grows in mass due to hydrogen shell burning.

Binary stars → He stars:

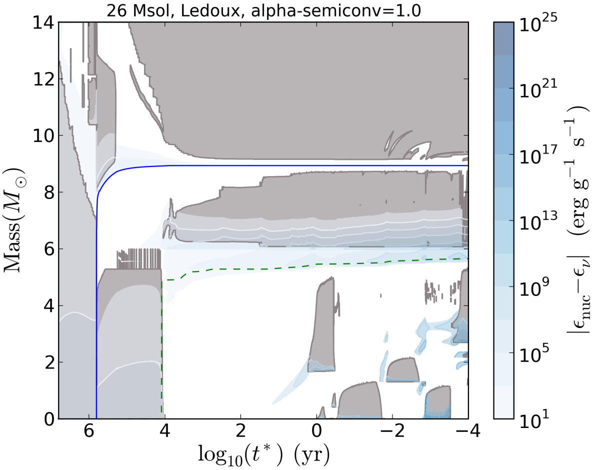
A bare He star does not grow in mass.

- Evolution without wind mass loss (low Z)
- Evolution with wind mass loss Nugis & Lamers 2000

19 $M_\odot$ star: convective Carbon-burning



26 $M_\odot$ star: radiative Carbon-burning

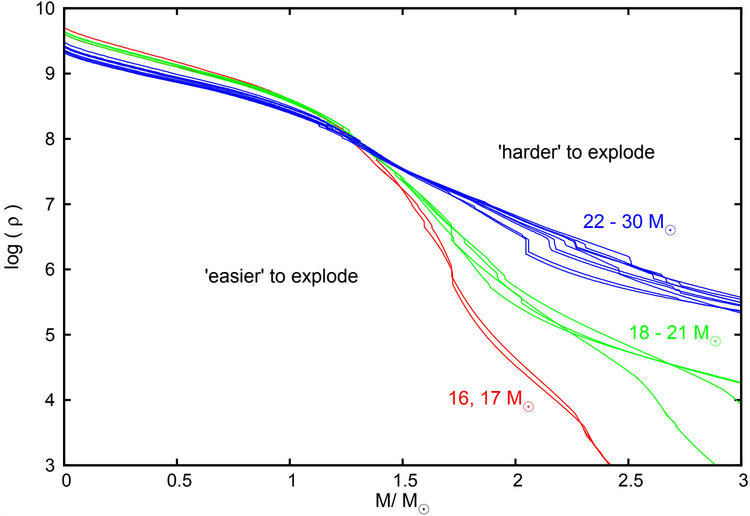


Prediction of remnant properties - central carbon burning

- If carbon abundance is 'high enough', central carbon burning overcomes neutrino losses and burns in a convective core
- Dependence on He core mass: reaction rate for $^{12}\text{C}(\alpha,\gamma)\ ^{16}\text{O}$

  Buchmann et al. (1993); Woosley and Weaver (1993)
- The lower the C abundance, the further out the first shell forms → impact on progenitor? Brown+2001; Meakin & Arnett 2006; Sukhbold & Woosley 2013

Single stars: density profiles



Compactness Parameter

Characterize the possibility of a (neutrino powered) explosion based on the 'compactness parameter' O'Connor and Ott (2011 and 2013):

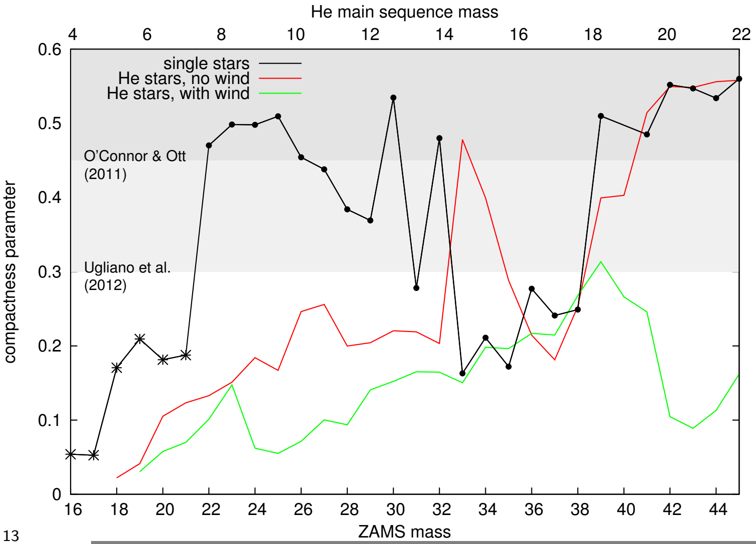
$$\boxed{\xi = \frac{M/M_\odot}{R(M)/1000km}_{t=t_{bounce}}} \qquad \text{with } M{=}2.5M_\odot$$

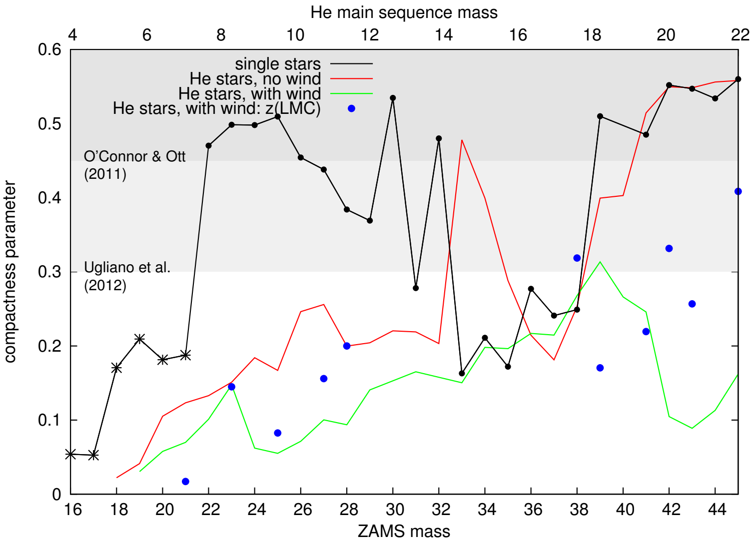
2.5 $M_\odot$ → relevant mass scale for BH formation: maximum mass at which a range of EoS can no longer support a neutron star against gravity

ξ big: R is small, the 2.5 $M_\odot$ point lies close in → hard to explode

Black Hole formation:
O'Connor & Ott (2011): $\xi_{2.5} \gtrsim 0.45$
Ugliano et al. (2012) : $\xi_{2.5} \gtrsim 0.30$

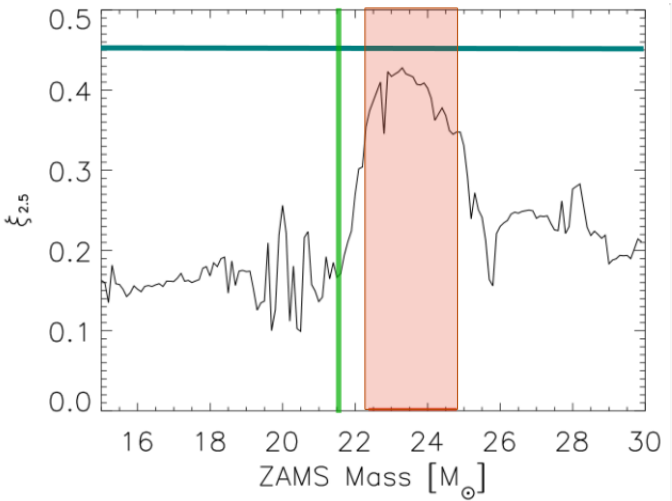
Compactness Parameter



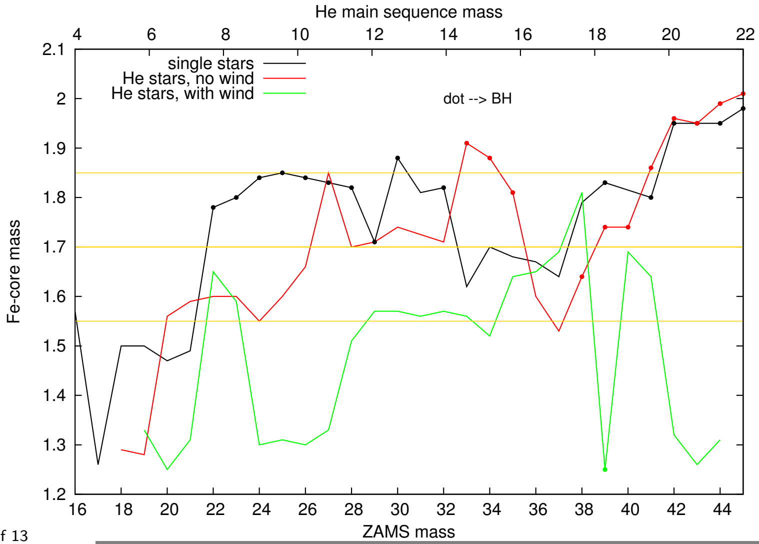

He main sequence mass
4
6
8
10
12
14
16
18
20
22
0.6
0.5
0.4
0.3
0.2
0.1
0
single stars
He stars, no wind
He stars, with wind
He stars, with wind: z(LMC)
O'Connor & Ott
(2011)
Ugliano et al.
(2012)
compactness parameter
16
18
20
22
24
26
28
30
32
34
36
38
40
42
44
ZAMS mass

The core compactness determined for 151 KEPLER pre-SN models with solar metallicity

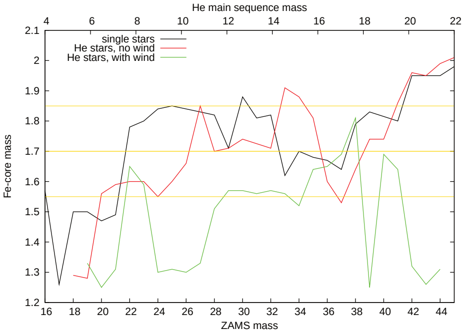
Graphics from Sukhbold & Woosley 2014; stellar evolution code KEPLER see for example Heger+2000, Köhler+2014

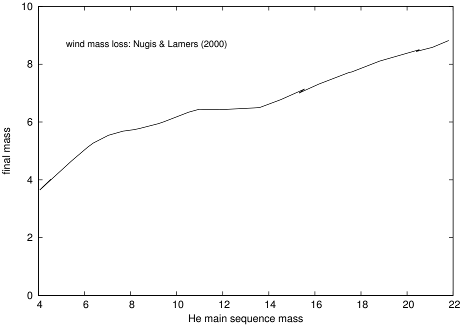


Fe-core masses - single stars & He-stars



He-stars with wind: final mass vs. initial mass





Conclusions

- Type of C-burning (convective or radiative) correlates with structure and remnant mass; additional effects for $M > 30\ M_\odot$?
- Single Stars:
  - neutron stars: $M < 21\ M_\odot$, M=31-38 $M_\odot$
  - maximum neutron star mass: 1.80 $M_\odot$
- Binary Stars without winds:
  - neutron stars: $M < 33\ M_\odot$
  - maximum neutron star mass: 1.85 $M_\odot$
- Binary Stars with winds:
  - neutron stars: 16-45 $M_\odot$ (39 $M_\odot$?)
  - maximum neutron star mass: 1.80 $M_\odot$

Outlook: Improvement of explosion models

- The correlation of the compactness parameter to the most likely remnant depends on the underlying explosion models. O'Connor & Ott, Ugliano et al. use a 'simplified neutrino treatment'
- CoCoNuT hydrodynamics code (Müller+2010): 2D code allows for general **relativistic effects**, shown to be of major importance during the post-bounce phase
- The CoCoNuT code is complemented with a solver for energy-dependent, **three-flavor neutrino transport**, VERTEX, and a new fast multi-group transport scheme

→ re-calculate subset of models to confirm/ refine trends in pre-SN evolution