The Final Fate of Massive Single and Binary Stars

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- a large fraction of supernova diversity is caused by varying envelope properties → **binary interactions** important
- do **binary interactions** affect explosion conditions/fate?

I. Principles of Stellar Evolution

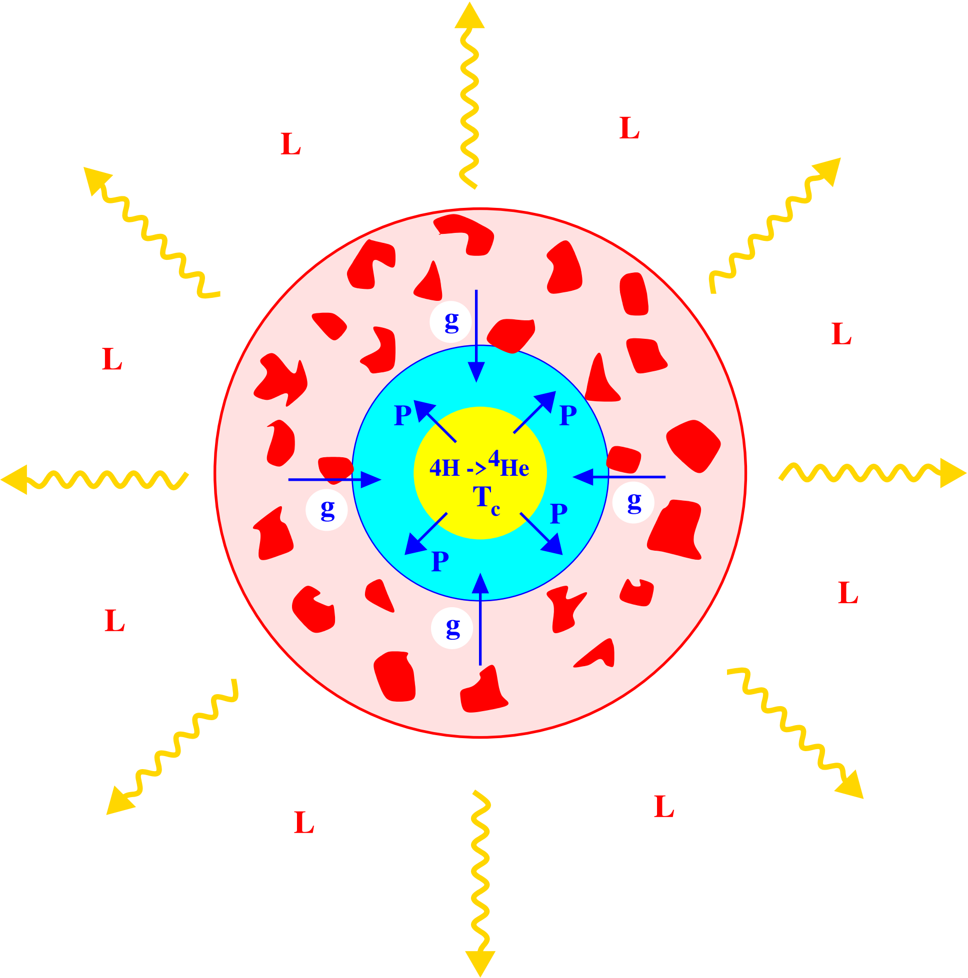
II. Binary Evolution

III. Presupernova Structures

IV. Implications for Neutrino Signals

(Other related work by Heger, Petermann, Woosley, Sukhbold, Justham, Farmer, . . .)

The Structure of Stars



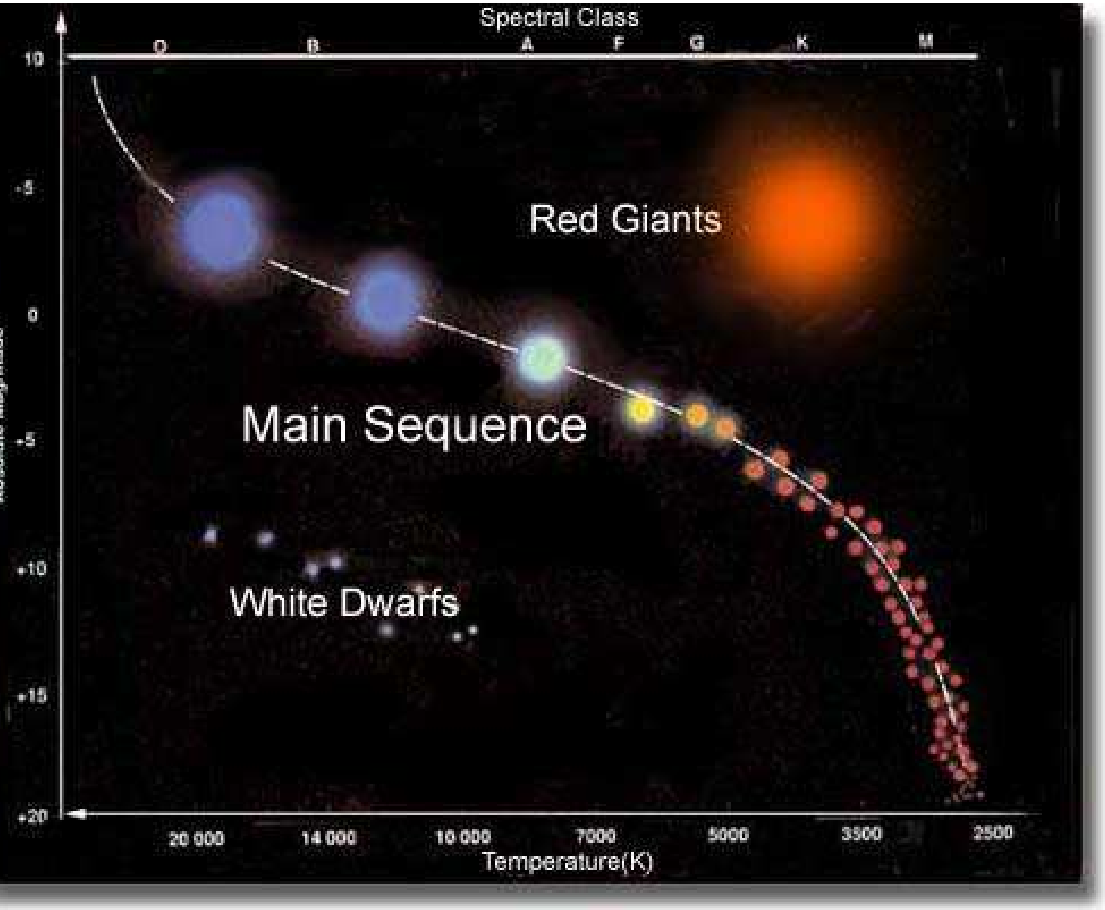
- Stars are self-gravitating bodies in dynamical equilibrium → balance of gravity and internal pressure forces
- stars lose energy by radiation from the surface

→ it takes 10 million years to radiate away the thermal energy of the Sun

→ hot stars require an energy source to avoid collapse

- Nuclear fusion:
  - → fusion of 4 protons to one helium nucleus at a central temperature of 15 million K

Stellar Evolution



- stars without nuclear energy source contract → release of gravitational binding energy
- and heat up until the next nuclear burning phase starts (at $\sim 10^8\,\mathrm{K}$)
- stellar evolution: an alternation of nuclear burning phases and contraction phases ($4\ \mathrm{H} \to {}^4\mathrm{He}$; $3\ {}^4\mathrm{He} \to {}^{12}\mathrm{C}, {}^{16}\mathrm{O}$ etc.)
- while the core contracts and becomes denser and hotter, the envelope expands → red giant
- final fate of the Sun: white dwarf composed of carbon and oxygen (size: Earth)

EVOLUTION OF MASSIVE STARS
$(M \gtrsim 10\,M_\odot)$

- massive stars continue to burn nuclear fuel beyond H and He and ultimately form an iron core
- alternation of nuclear burning and contraction phases
  - ▷ carbon burning $(T \sim 6 \times 10^8\,K)$

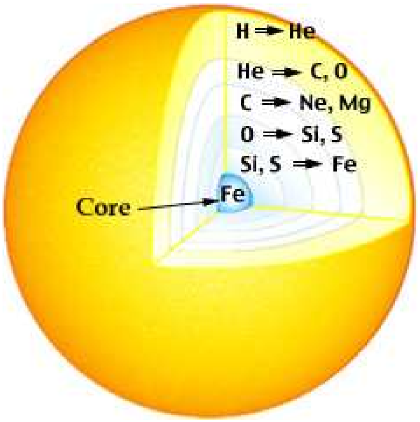
$$\begin{aligned} {}^{12}C + {}^{12}C &\rightarrow {}^{20}Ne + {}^{4}He \\ &\rightarrow {}^{23}Na + {}^{1}H \\ &\rightarrow {}^{23}Mg + n \end{aligned}$$

  - ▷ oxygen burning $(T \sim 10^9\,K)$

$$\begin{aligned} {}^{16}O + {}^{16}O &\rightarrow {}^{28}Si + {}^{4}He \\ &\rightarrow {}^{31}P + {}^{1}H \\ &\rightarrow {}^{31}S + n \\ &\rightarrow {}^{30}S + 2\,{}^{1}H \\ &\rightarrow {}^{24}Mg + {}^{4}He + {}^{4}He \end{aligned}$$

  - ▷ silicon burning: photodisintegration of complex nuclei, 100s of reactions → iron

Final Structure



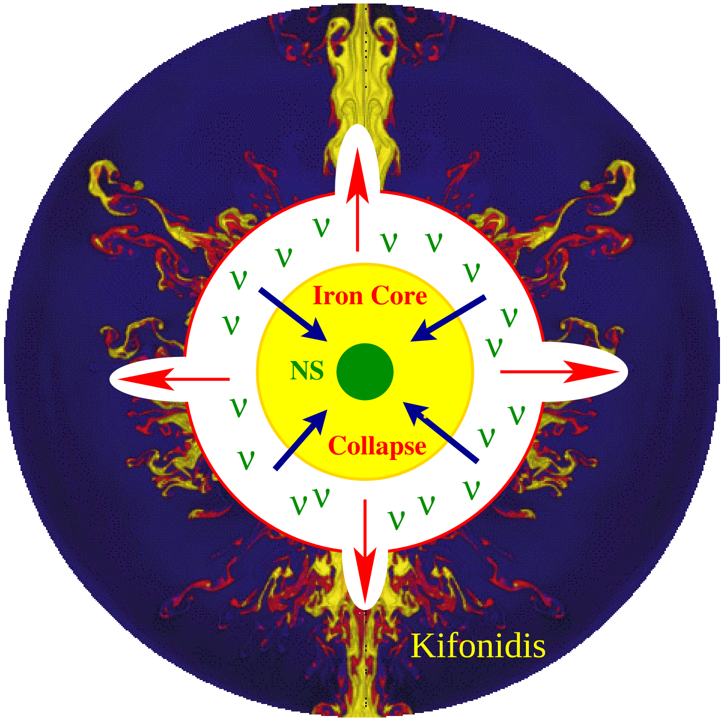
- ▷ form iron core
- ▷ iron is the most tightly bound nucleus → no further energy from nuclear fusion
- ▷ iron core surrounded by onion-like shell structure

→ core collapse

EXPLOSION MECHANISMS

- two main, completely different mechanisms

Core-Collapse Supernovae



- triggered after the exhaustion of nuclear fuel in the core of a massive star, if the iron core mass $>$ Chandrasekhar mass
- energy source is gravitational energy from the collapsing core ($\sim 10\,\%$ of neutron star rest mass $\sim 3 \times 10^{46}\,$J)
- most of the energy comes out in neutrinos (SN 1987A!)
  - ▷ unsolved problem: how is some of the neutrino energy deposited ($\sim 1\,\%$, $10^{44}\,$J) in the envelope to eject the envelope and produce the supernova?
- leaves compact remnant (neutron star/black hole)

THE FINAL FATE OF MASSIVE STARS
[SINGLE STARS]

- white dwarfs (CO, ONe, hybrid) [$\lesssim 8\,\mathrm{M}_\odot$]
- electron-capture supernovae (in degenerate ONeMg cores) [$\approx 8/9\,\mathrm{M}_\odot$]
  - ▷ low binding energy cores → easy ejection → low explosion energies/kicks → rel. low-mass neutron stars (also expected for low-mass iron cores formed in binaries)
- standard iron-core collapse [$10 - 22/23\,\mathrm{M}_\odot$]
  - ▷ standard explosion energy (~ 1 foe), standard supernova kicks, neutron-star masses
- black-hole formation [$\gtrsim 22/23\,\mathrm{M}_\odot$]
  - ▷ fast black-hole formation: little mass ejection, no supernova, no kick (disappearing stars, e.g. Kochanek)
  - ▷ fallback black holes accompanied by (faint?) supernova and black-hole kicks
- complete disruption for pair-instability supernovae (also pulsational pair instability supernovae)

Binary Interactions

- most stars are members of binary systems
- a large fraction are members of interacting binaries $(30 - 50\,\%)$

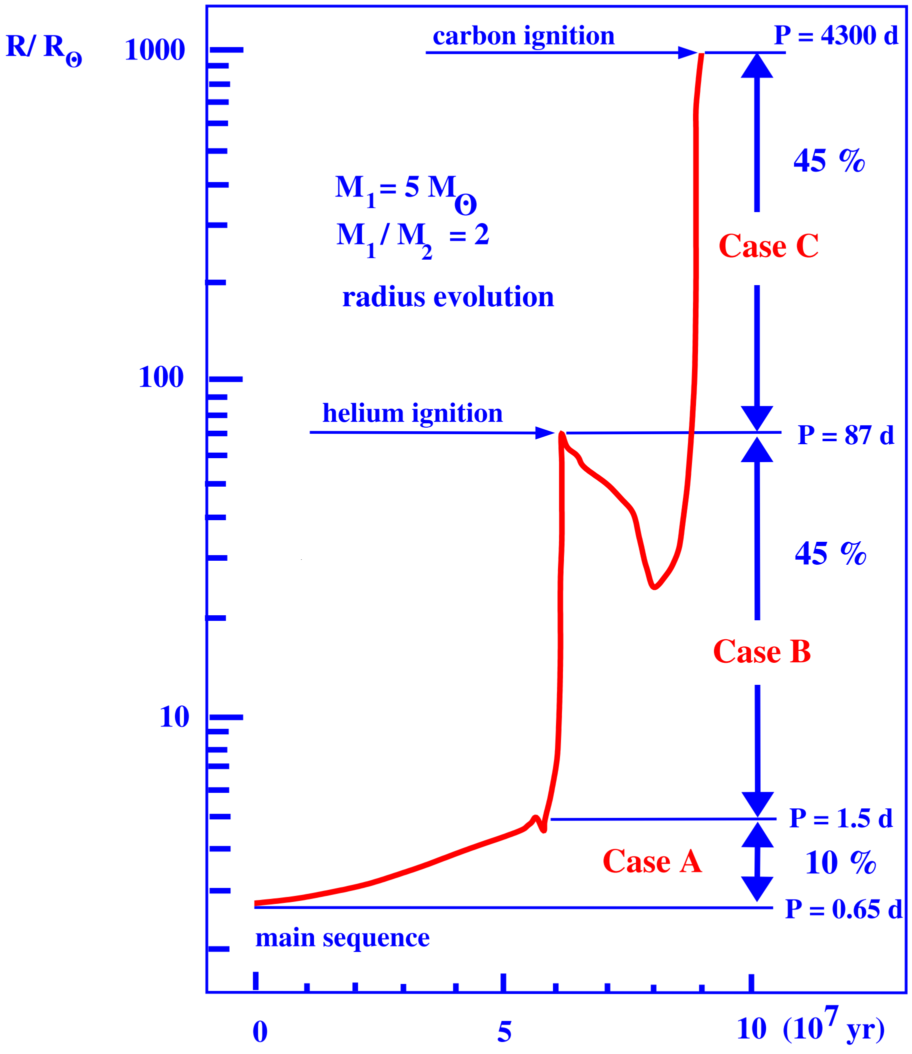
  Sana et al. (2012):

  $\boxed{75\,\%\text{ for O stars with } M \gtrsim 15\,M_\odot}$

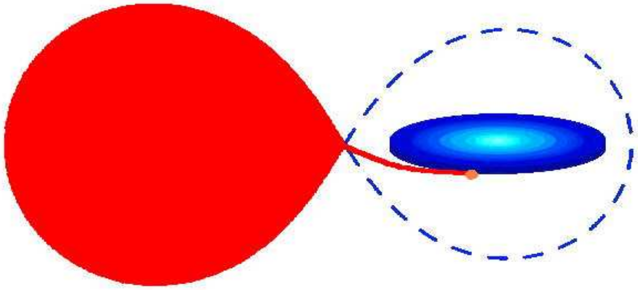
  also Kobulnicki & Fryer (2007), Mason+ (2009), . . .
- note: mass transfer is more likely for post-MS systems
- mass-ratio distribution:
  - ▷ for massive stars: masses correlated
  - ▷ for low-mass stars: less certain
- binary interactions
  - ▷ common-envelope (CE) evolution
  - ▷ stable Roche-lobe overflow
  - ▷ binary mergers
  - ▷ wind Roche-lobe overflow

Classification of Roche-lobe overflow phases

(Paczynski)

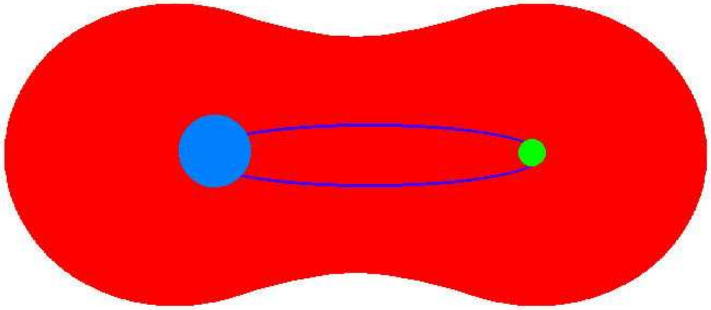


Stable Mass Transfer



- mass transfer is 'largely' conservative, except at very high mass-transfer rates
- mass loss + mass accretion
- the mass loser tends to lose most of its envelope → formation of helium stars
- the accretor tends to be rejuvenated (i.e. behaves like a more massive star with the evolutionary clock reset)
- orbit generally widens

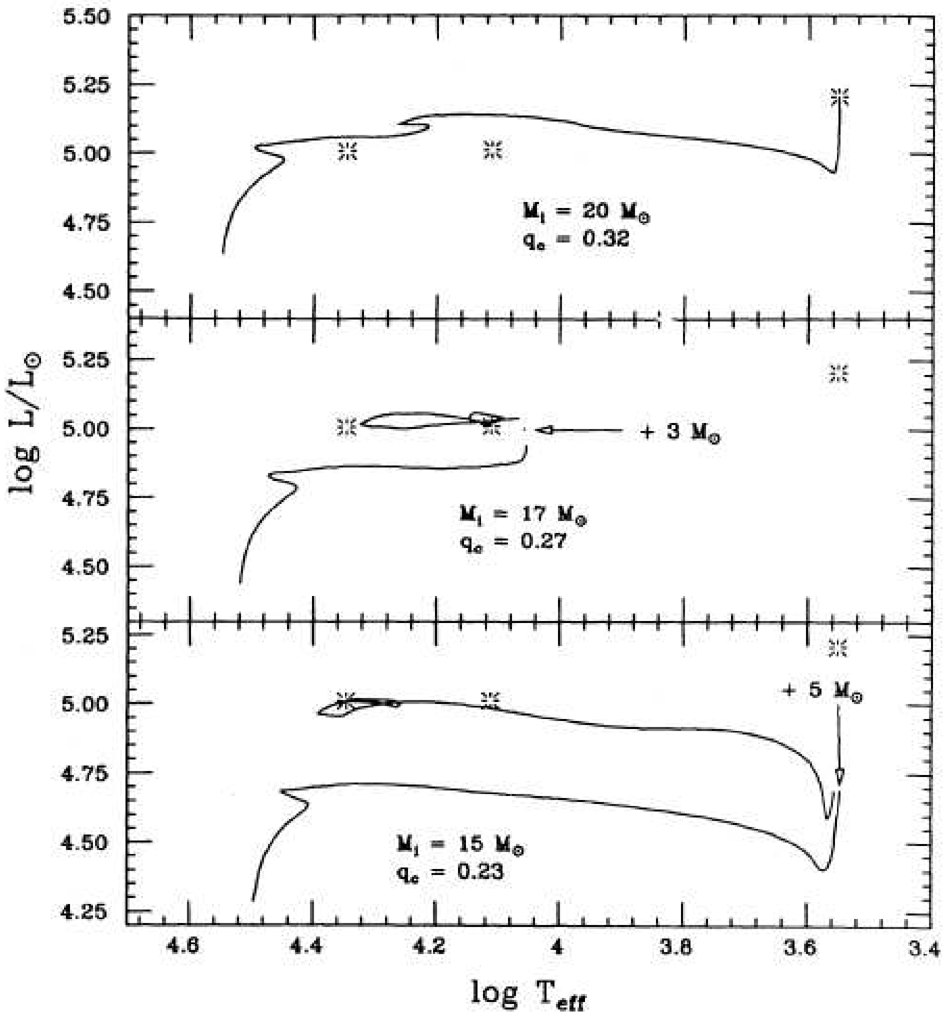
Unstable Mass Transfer



- dynamical mass transfer → common-envelope and spiral-in phase (mass loser is usually a red giant)
  - ▷ mass donor (primary) engulfs secondary
  - ▷ spiral-in of the core of the primary and the secondary immersed in a common envelope
- if envelope ejected → very close binary (compact core + secondary)
- otherwise: complete merger of the binary components → formation of a single, rapidly rotating star

The final fate of accretion stars/mergers

- stars accreting/merging after the main sequence may burn He/explode as blue supergiants (Podsiadlowski+ 1989)



Podsiadlowski+ (1989)

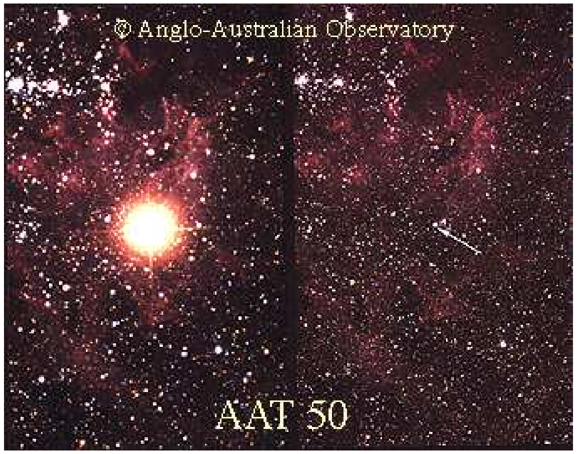
SN 1987A

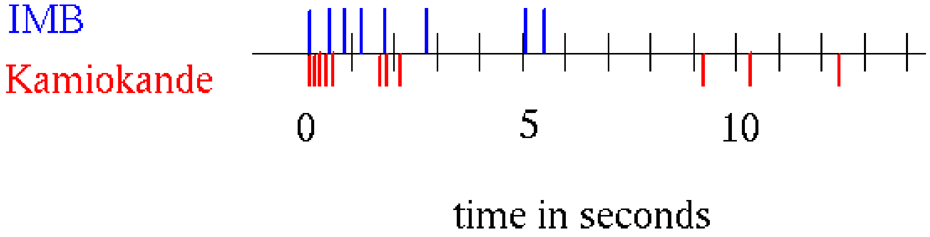
- SN 1987A in the Large Magellanic Cloud (satellite galaxy of the Milky Way) was the first naked-eye supernova since Kepler's supernova in 1604
- long-awaited, but highly unusual, anomalous supernova

Confirmation of core collapse

- neutrinos $(\overline{\nu}_e + p \rightarrow n + e^+)$, detected with Kamiokande and IMB detectors
  - ▷ confirmation: supernova triggered by core collapse
  - ▷ formation of neutron star
  - ▷ energy in neutrinos $(\sim 3 \times 10^{46}\,\mathrm{J})$ consistent with the binding energy of a neutron star

SN 1987A (LMC)





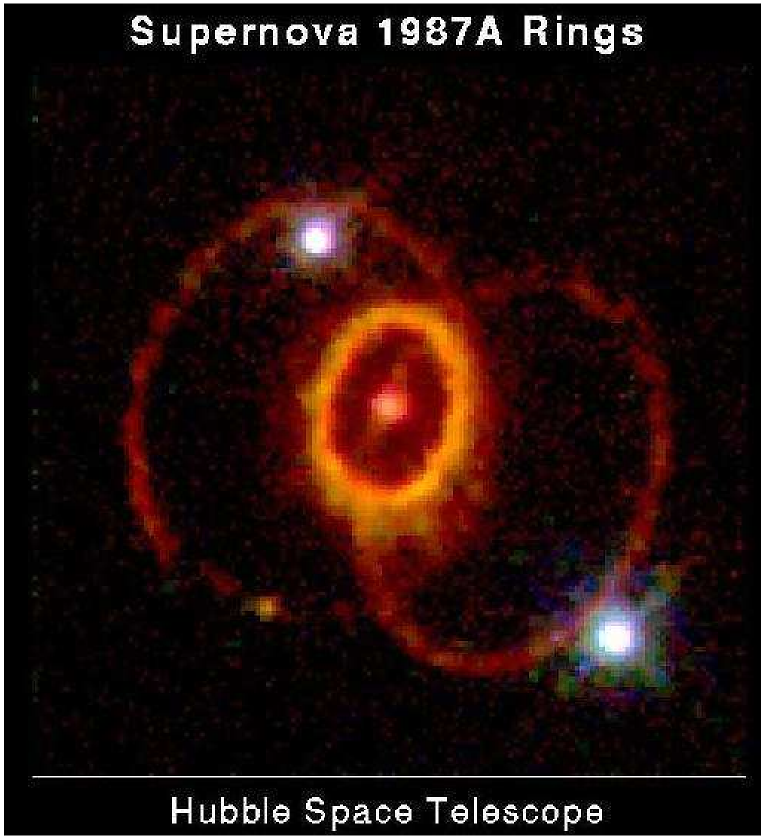
The Progenitor of SN 1987A

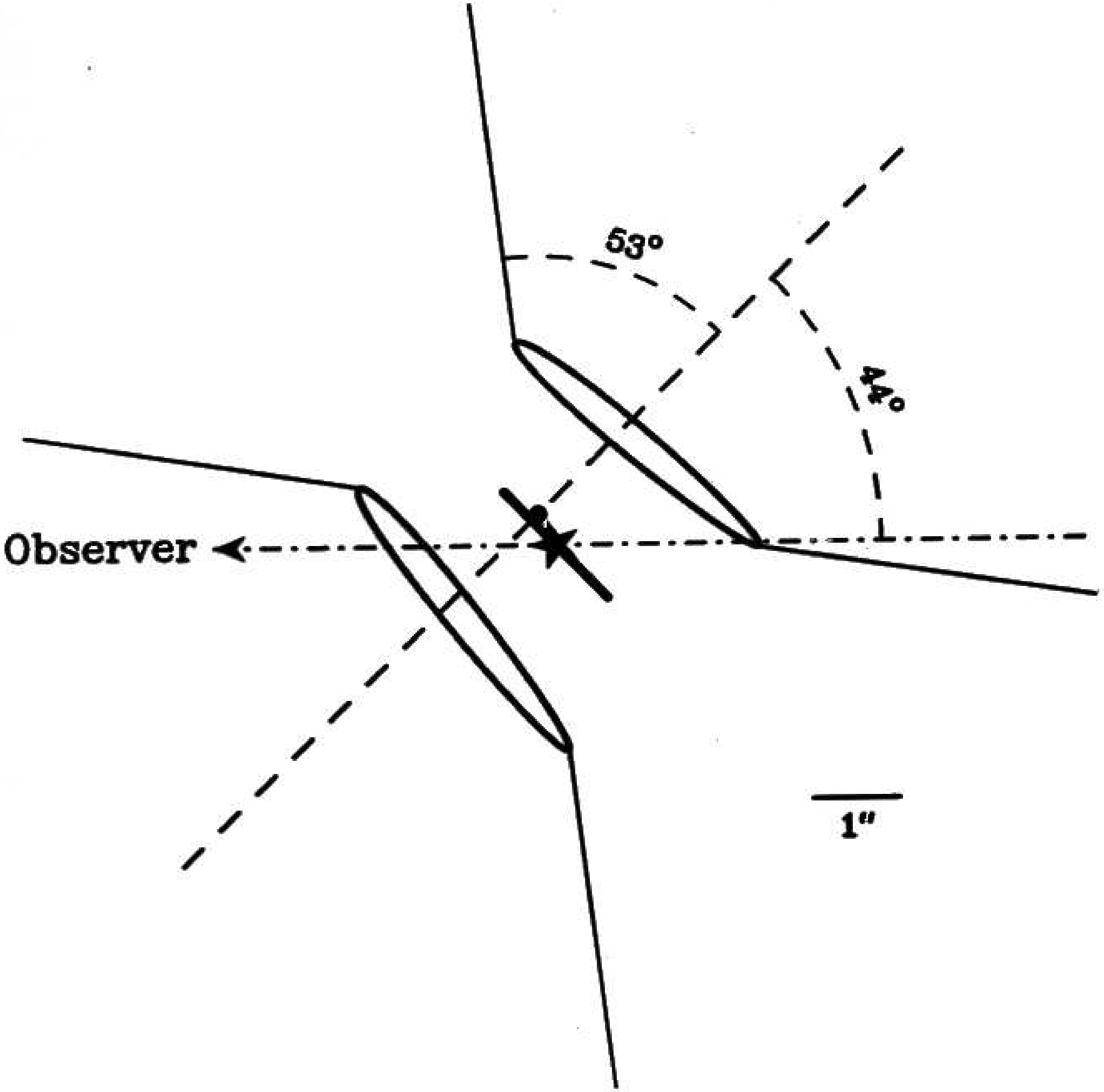
(Podsiadlowski, Ivanova, Morris)

SN 1987A: an anomalous supernova

- progenitor (SK $-69^{\circ}202$): blue supergiant with recent red-supergiant phase ($10^4\,$yr)
- chemical anomalies
- the triple-ring nebula
  - → axi-symmetric, but highly non-spherical
  - → signature of rapid rotation
- dynamical age of the nebula: $20,000\,$yr

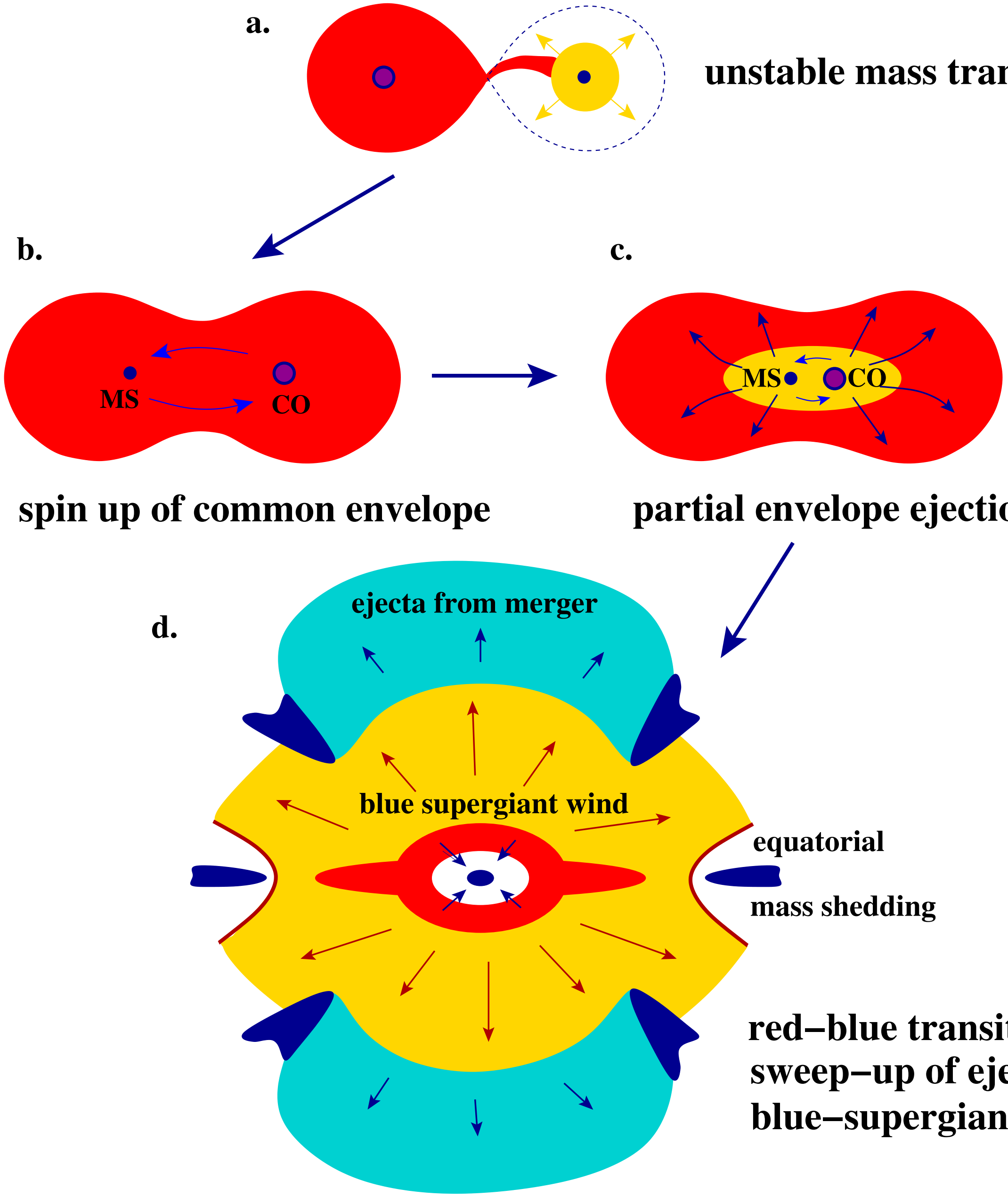
→ something unusual happened, 20,000 yr before the explosion




53°
44°
Observer
1″

Formation of the Triple-Ring Nebula

(Podsiadlowski, Morris, Ivanova)



unstable mass transfer

spin up of common envelope

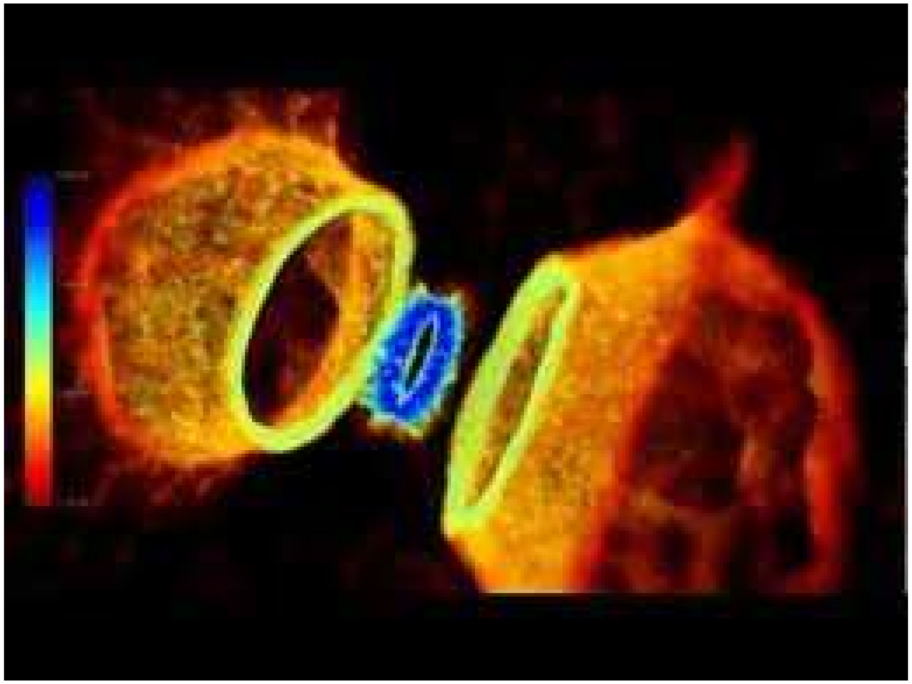
partial envelope ejection

equatorial

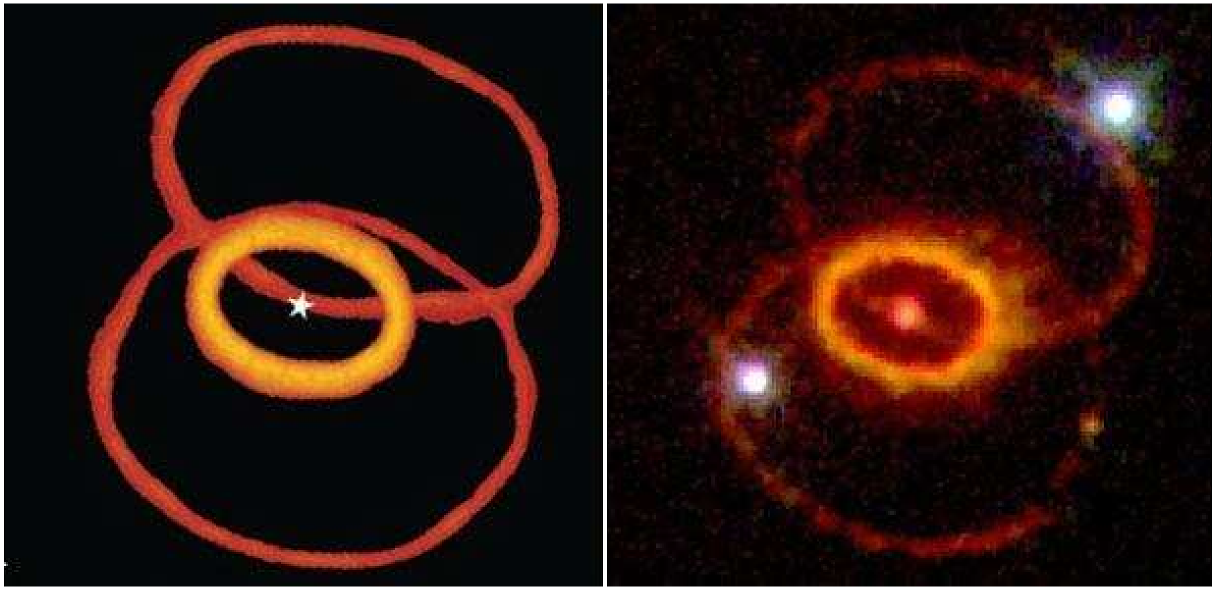
mass shedding

red−blue transition and sweep−up of ejecta by blue−supergiant wind

Final Structure



Rings: Theory vs. Observations



Eta Carinae

- Major outburst from 1840 to 1860, L up to $10^{7.4}\,\mathrm{L}_\odot$
- nebula ejected during outburst, KE 10^{50} ergs (? $10\,\%$ of SN energy!) (Smith 2003)
- ejected mass: $\sim 10\,\mathrm{M}_\odot$?!
- spectroscopic binary: $\mathrm{P_{orb}} = 5.5\,\mathrm{yr}$, $\mathrm{e} \gtrsim 0.6$ → wide binary, not directly related to outburst
- latitude dependent wind (→ rotation)
- if indeed $\sim 10\,\mathrm{M}_\odot$ have been lost with an energy of $\sim 10^{50}$ ergs, this requires dramatic dynamical event (cannot be envelope instability)

A Binary Merger?

- can provide
  - ▷ the energy for the mass ejection
  - ▷ the spin-up of the merger product
  - ▷ excess thermal energy that needs to be radiated away which drives post-eruption stellar wind with $\dot{\mathrm{M}}_{\mathrm{wind}} \sim 10^{-3}\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$

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Simulating the formation of η Carinae's surrounding nebula through unstable triple evolution and stellar merger-induced eruption

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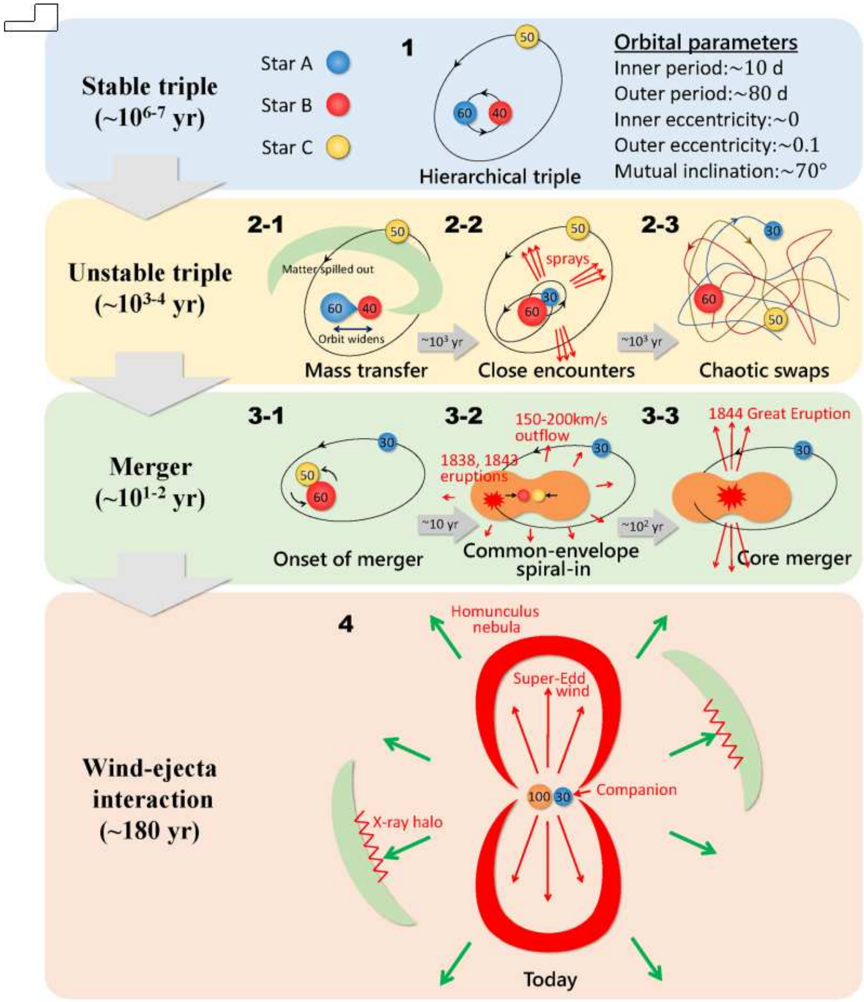
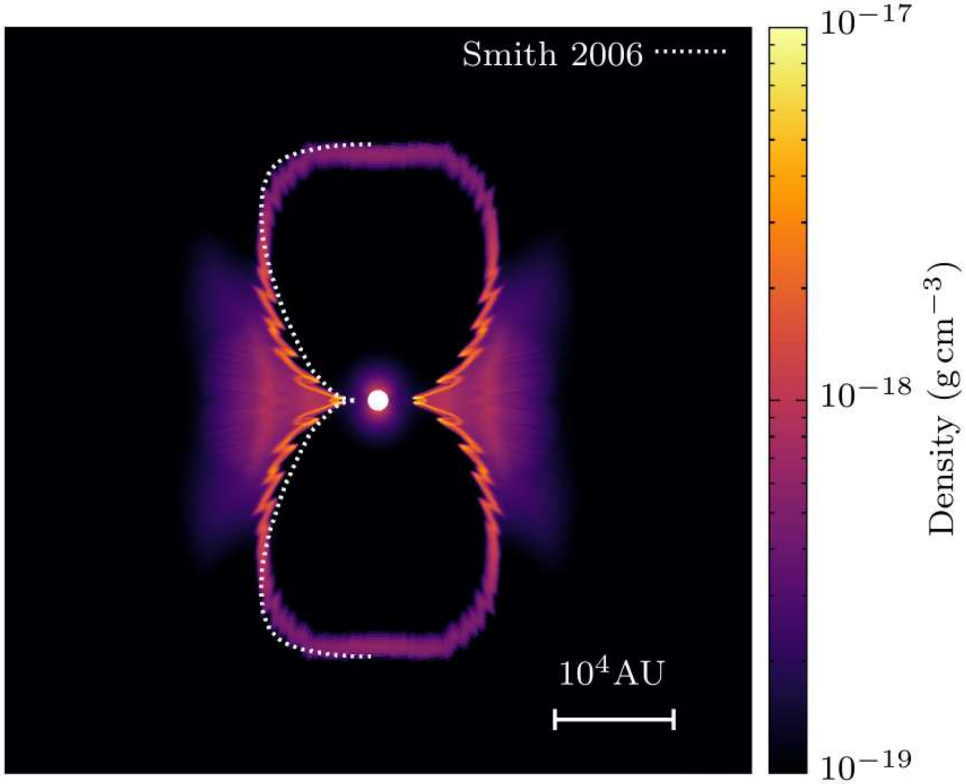
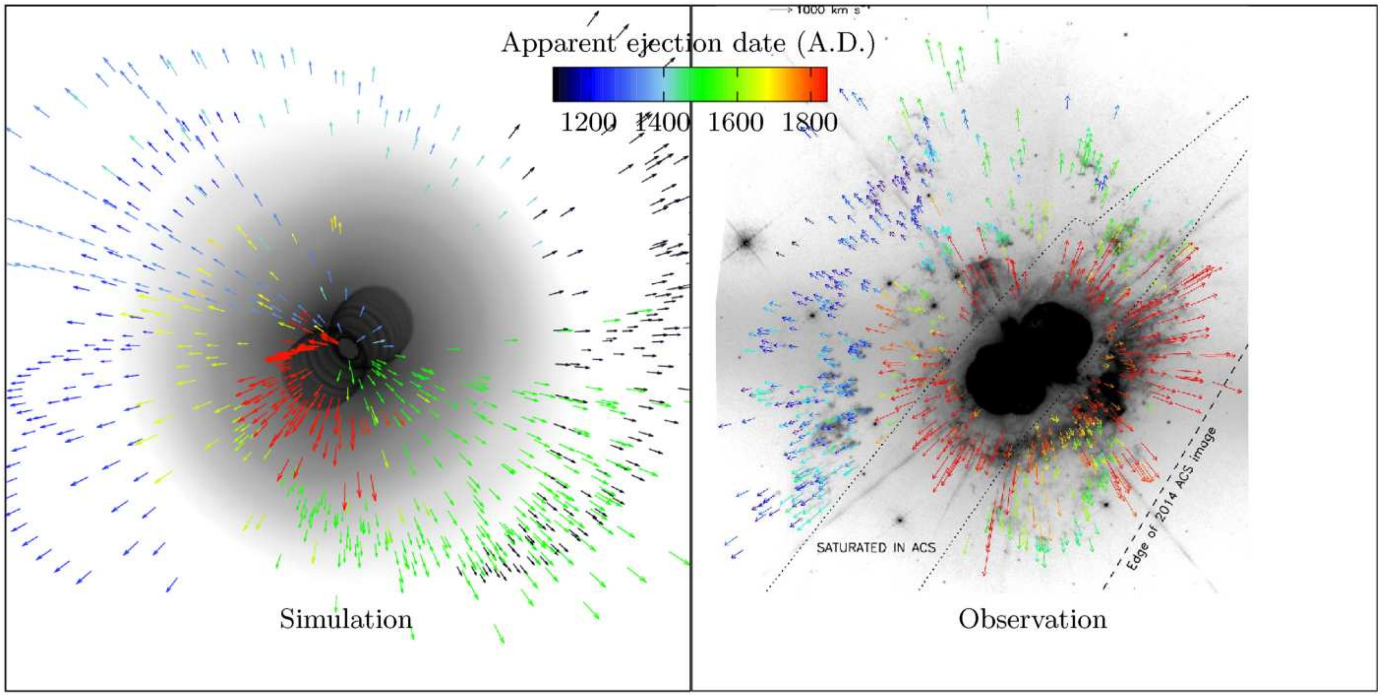



Smith 2006
10⁴ AU
10⁻¹⁷
10⁻¹⁸
10⁻¹⁹
Density (g cm⁻³)


1000 km s
Apparent ejection date (A.D.)
1200
1400
1600
1800
SATURATED IN ACS
Edge of 2014 ACS image
Simulation
Observation

He–core–burning stars (M > 20 – 25 Msun)

with H envelope

H–burning shell

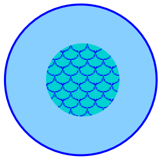
helium burning
convective core
(growing)

–-> larger CO cores with lower
C/O ratio –-> no convective carbon burning
higher entropy (more massive) iron cores

–––> BLACK HOLE

without H envelope

No H–burning shell

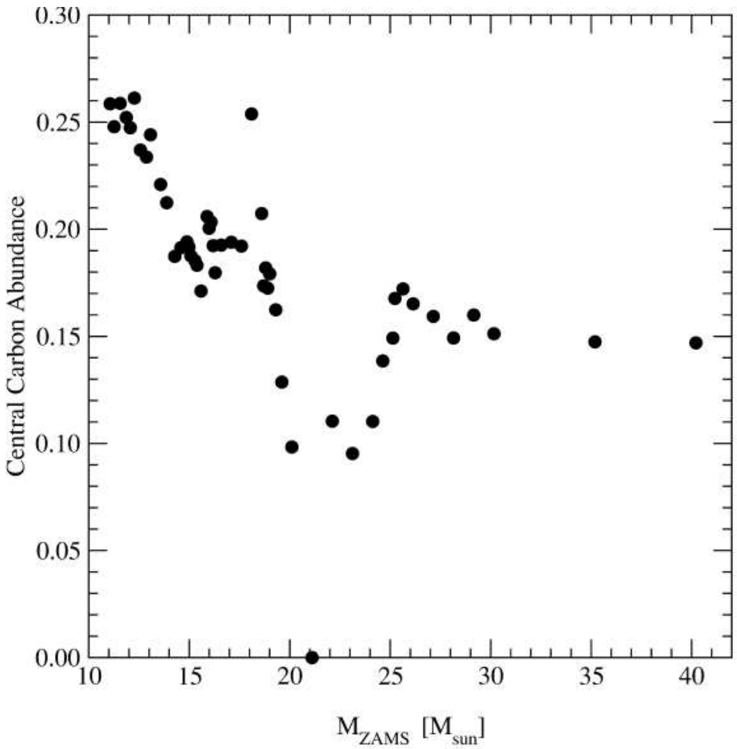


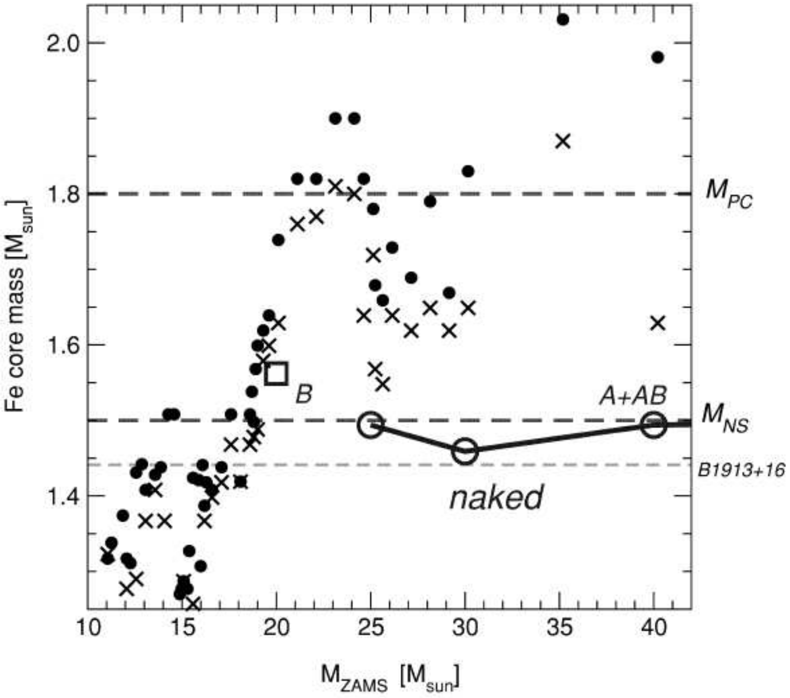
shrinking
He–burning core

smaller CO cores with higher
C/O ratio –-> convective carbon burning
lower entropy (mass) iron cores

–––> NEUTRON STAR (60/70 Msun?)

(Brown, Lee, Heger)





Brown, Heger, Langer et al. (2001)

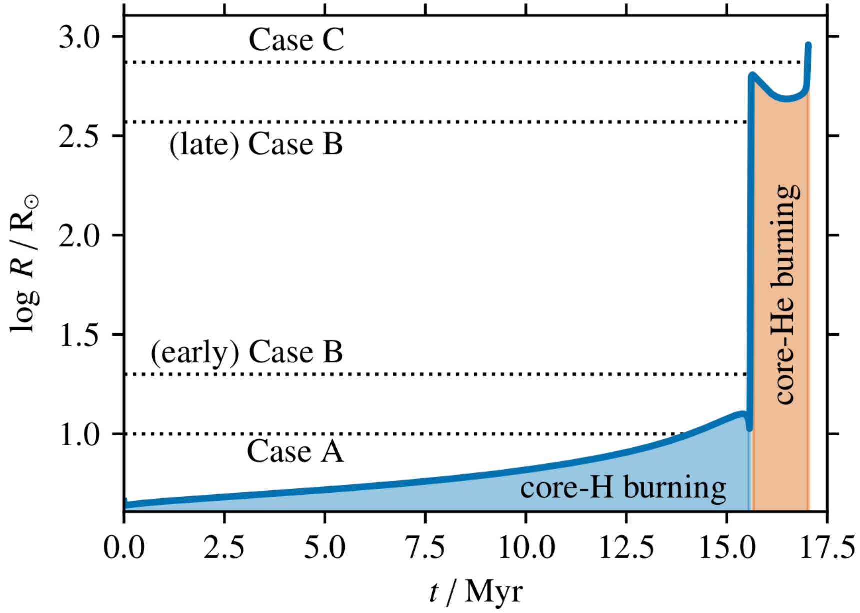
Carbon Burning and Final Fe Core Masses

(Brown et al. 2001)

- **late He-core burning:** $^{12}\mathrm{C}+\alpha$ becomes dominant and determines the final $^{12}\mathrm{C}$ fraction
  - ▷ **stars with H-burning shell:** injection of fresh He → long $^{12}\mathrm{C}+\alpha$ phase → **low final C fraction**
  - ▷ **stars without H-burning shell:** short $^{12}\mathrm{C}+\alpha$ phase → **higher final C fraction**
- **C-core burning:**
  - ▷ **high C fraction** → **convective** C burning → higher neutrino losses → lower-entropy cores → lower-mass O and ultimately Fe cores → **neutron stars**
  - ▷ **low C fraction** → **radiative** C burning → lower neutrino losses → higher-entropy cores, etc. → **black holes**

Stellar Evolution Models

- MESA (Paxton, 2011, . . .)
- mass ranges: $11 - 75\,\mathrm{M}_\odot$ (single), $15 - 100\,\mathrm{M}_\odot$ (binary), calculated up to core collapse
- $\mathrm{Z} = 0.0142$
- overshooting: $0.2\,\mathrm{H}_\mathrm{p}$ (H and He burning only), MLT++
- approximate nuclear network (21 base isotopes)
- “Dutch” wind scheme in MESA (no LBV mass loss!)
- To model binary evolution, strip envelopes at various evolutionary stages on a timescale short compared to thermal timescale
- o.k. for Case B/C, less accurate for Case A
- phenomenological model only



Parametric supernova code (Müller 2016)

- estimates neutrino heating from semi-empirical scaling laws
- outcome depends on initial mass cut (M_i) and mass (M_f) at which explosion occurs (expect similar results as in Ertl [2016])
- $\mathrm{M}_\mathrm{NS}^\mathrm{max} = 2.05\,\mathrm{M}_\odot$

Fallback, if initial explosion, but not enough to unbind the star

- explosion energy calibrated to $0.69 \pm 0.17\,\mathrm{B}$
- supernova kicks to mimic Hobbs (2005) (Maxwellian with $\sigma = 265\,\mathrm{km/s}$)

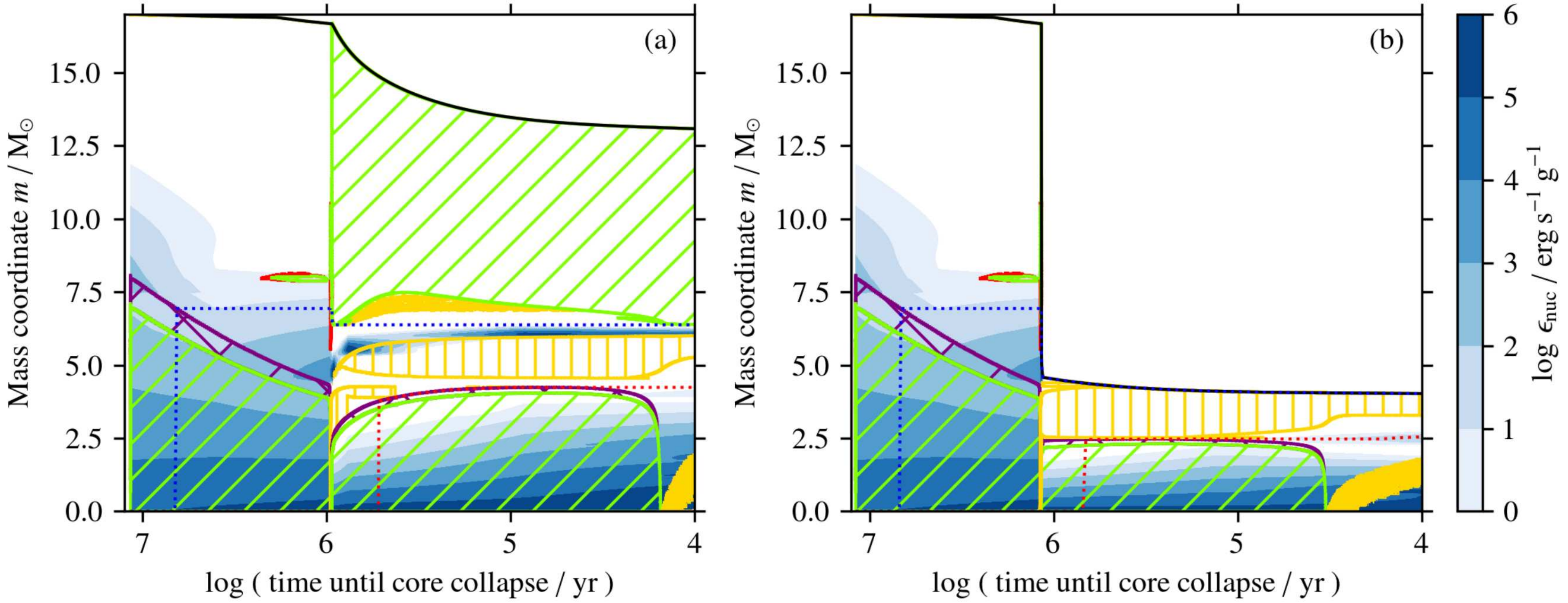
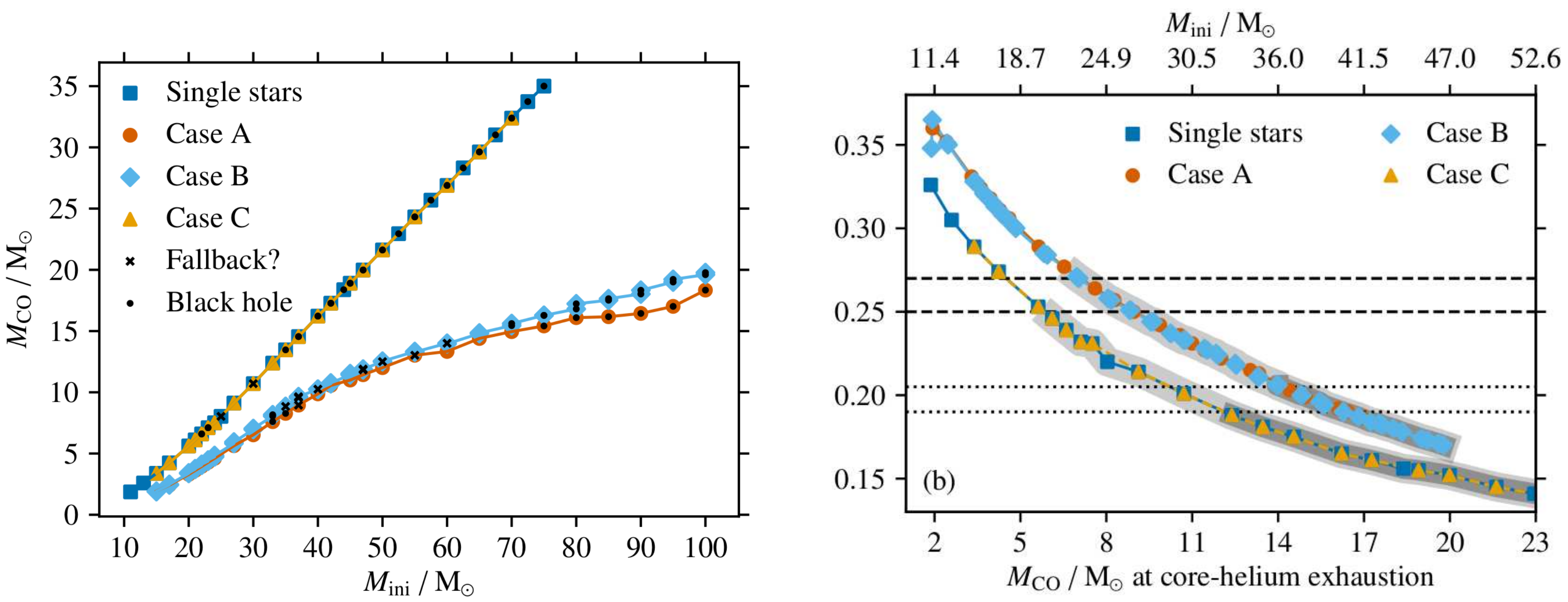


Fig. 4. Kippenhahn diagrams of core hydrogen and core helium burning of stars with an initial mass of 17 $M_\odot$. The evolution of a genuine single star (*panel a*) is contrasted with that of a star that underwent (late) Case B mass transfer (*panel b*). The blue colour-coding shows energy production by nuclear burning, and the green, yellow, purple, and red hatched regions denote convection, thermohaline mixing, convective overshooting, and semi-convection, respectively. The blue and red dotted lines indicate approximate helium and carbon cores, here defined as the mass coordinate where the helium and carbon mass fractions first exceed 0.5.



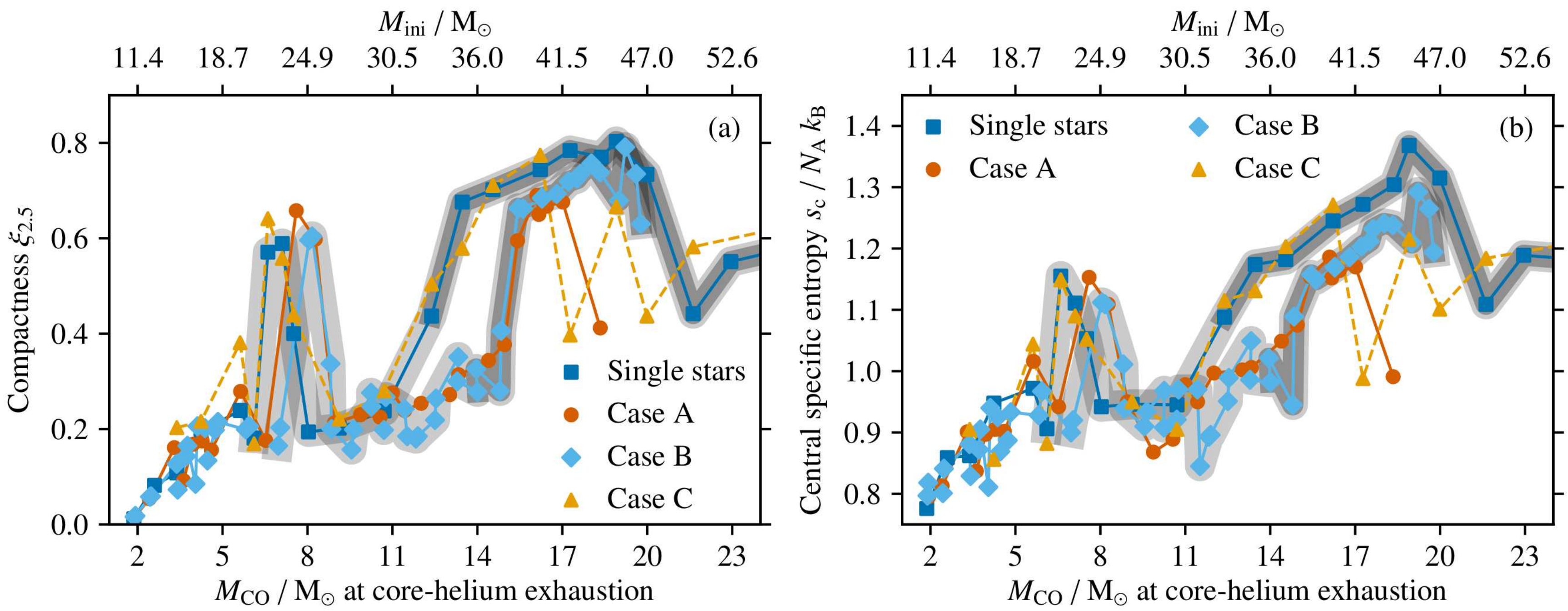


Fig. 5. Compactness $\xi_{2.5}$ (*panel a*) and dimensionless central specific entropy s_c (*panel b*) at core collapse as a function of CO core mass M_{CO}. As in Fig. 2, initial masses M_{ini} corresponding to the CO core masses of single stars are shown at the top (cf. Fig. 3), and the light-grey and darker-grey shadings are for radiative core carbon and core neon burning, respectively.

Compactness (O'Connor & Ott 2011)

- $\xi_{2.5} = \frac{M/M_\odot}{R(M)/1000\,\mathrm{km}}$ with $M = 2.5\,M_\odot$
- "measures" gravitational potential at $M = 2.5\,M_\odot$
- (approximate) proxy for explodability (alternatives: central entropy, iron core mass)

- compactness peak at $7\,M_\odot$ (single/Case C) and $8\,M_\odot$ (Case B)
- expect successful explosions (NS) below and above

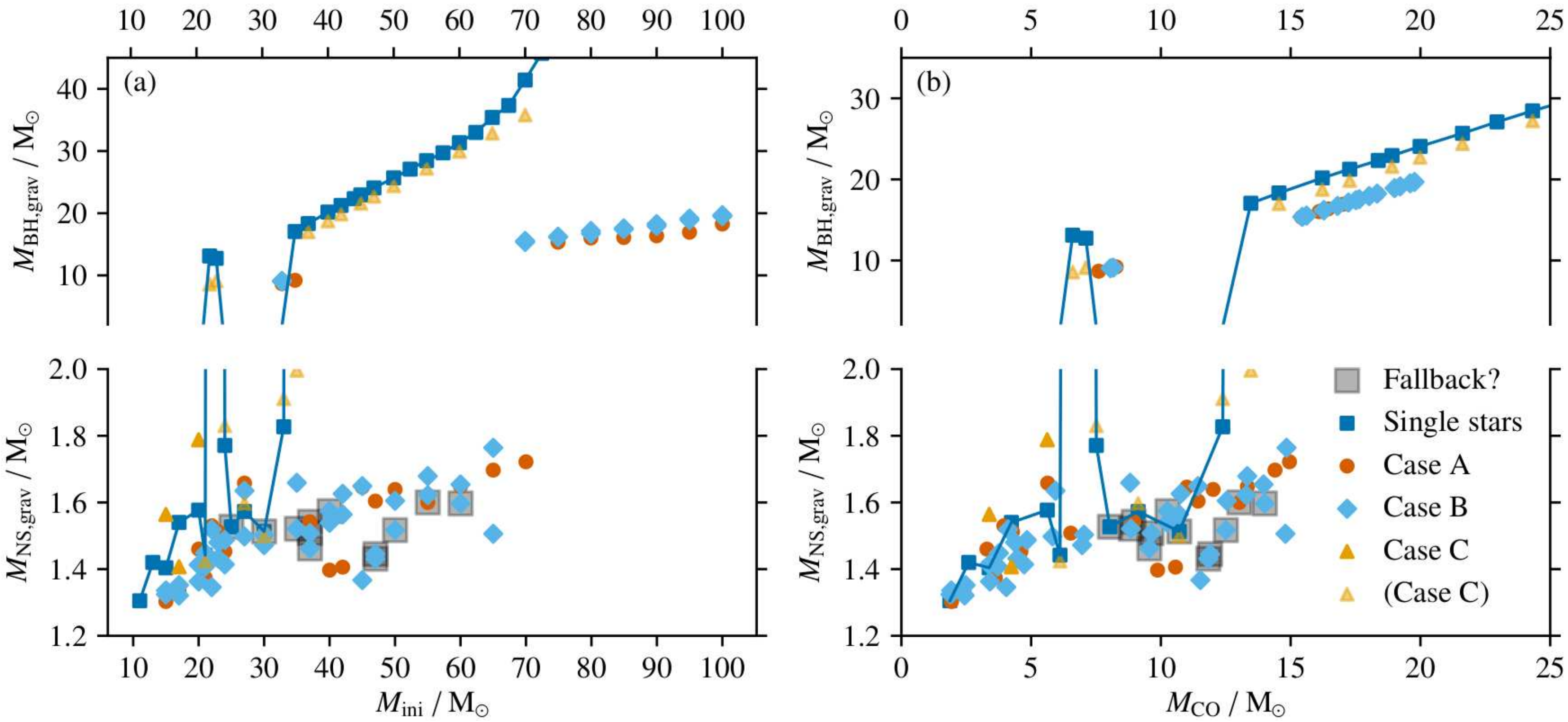
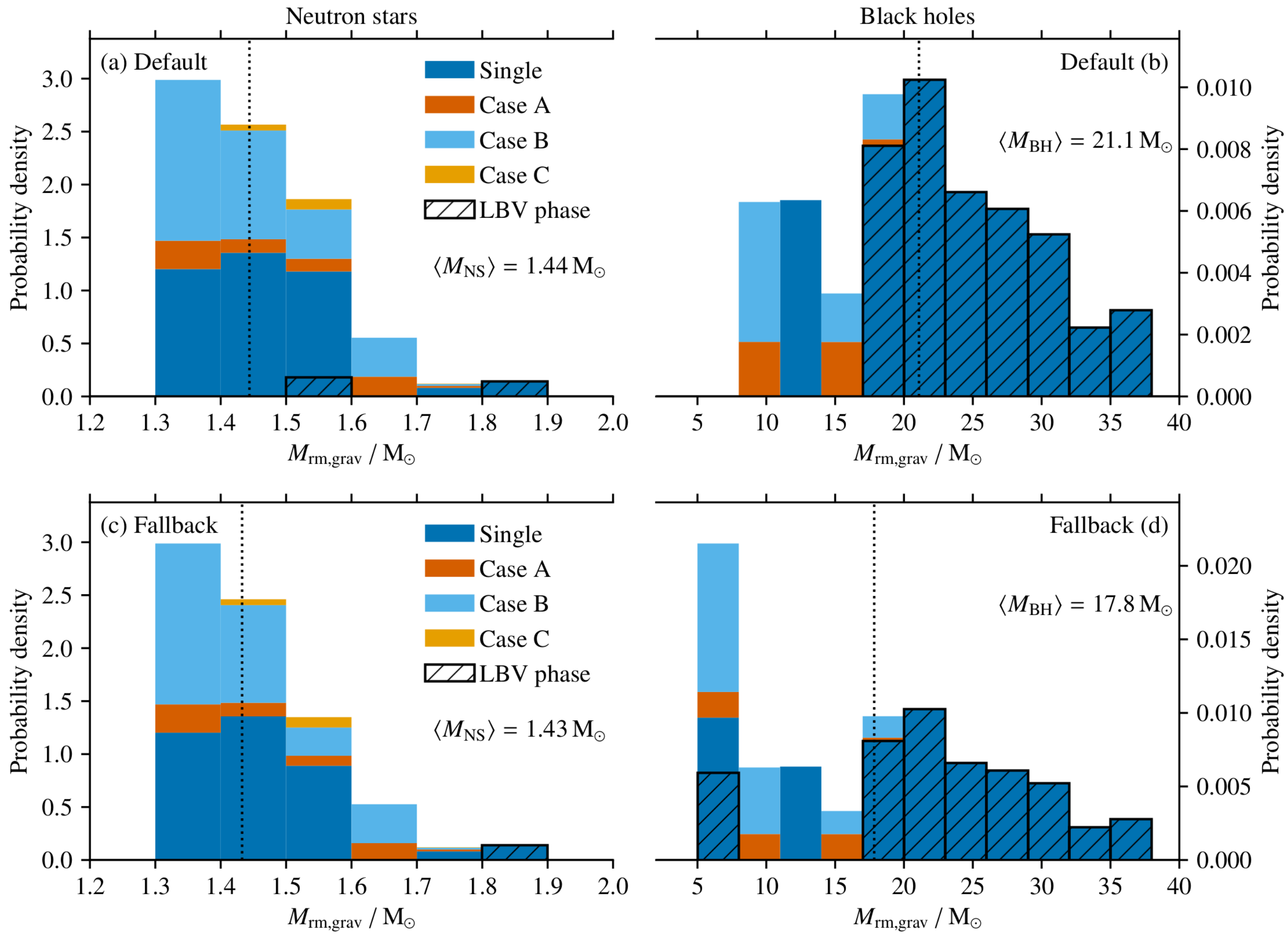


Table 1. Initial mass ranges for NS formation in our single and stripped binary star models.

Model	Initial masses for NS formation		
Single stars	$M_{\rm ini} \lesssim 21.5\,M_\odot$	and	$\approx$23.5−34.0 $M_\odot$
Case A	$M_{\rm ini} \lesssim 31.5\,M_\odot$	and	$\approx$36.0−72.5 $M_\odot$
Case B	$M_{\rm ini} \lesssim 31.5\,M_\odot$	and	$\approx$34.0−67.5 $M_\odot$
Case C	$M_{\rm ini} \lesssim 21.5\,M_\odot$	and	$\approx$23.5−36.0 $M_\odot$

- much larger range for NS formation for Case B
- note fallback cases

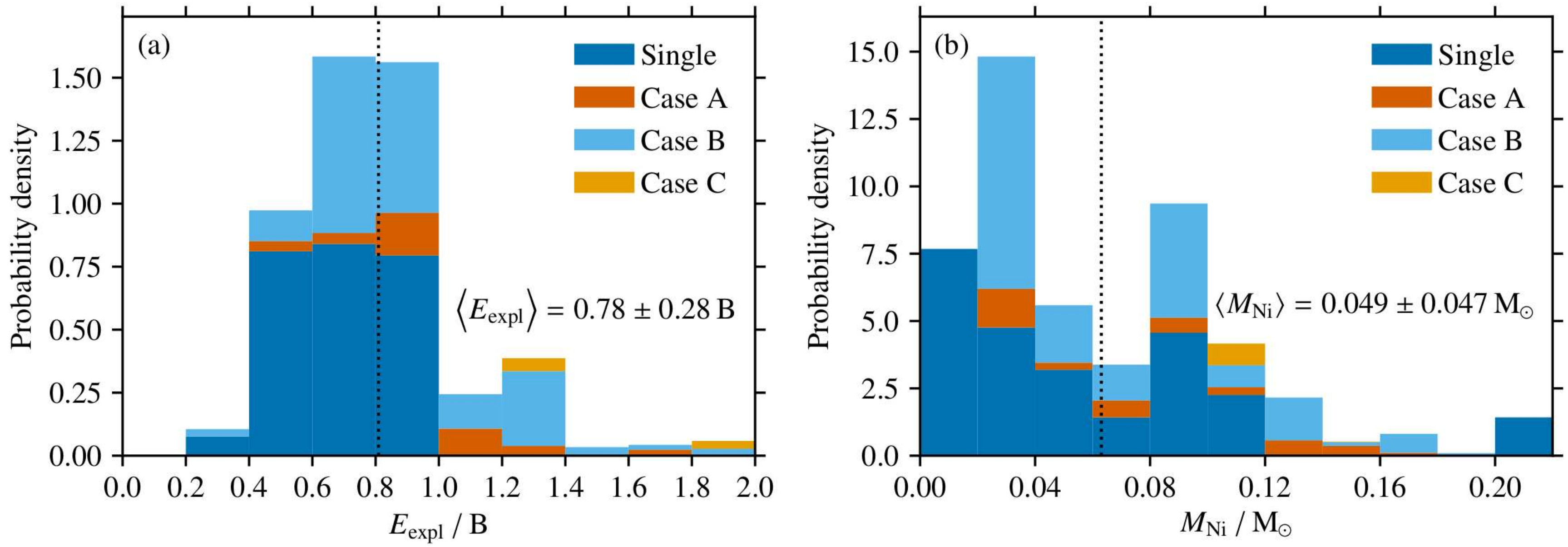


NS masses

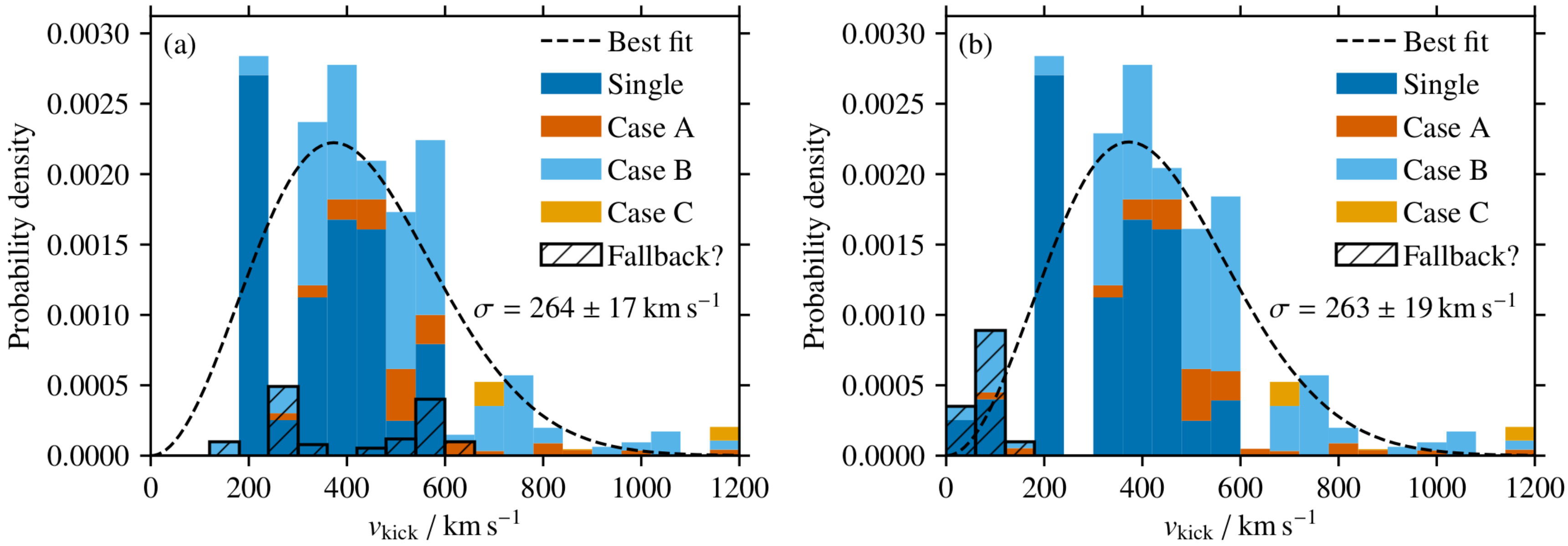
- **single:** gap between $1.6 - 1.7\,{\rm M}_\odot$ **(compactness peak)**
- tail up to $1.9\,{\rm M}_\odot$ **(single)**, $\sim 1.6\,{\rm M}_\odot$ **(Case B)**
- NS masses peak at $1.45\,{\rm M}_\odot$ **(single)** and $1.35\,{\rm M}_\odot$ **(binary)**

BH masses

- single/Case C: **bimodal**; peaks at $12.5\,{\rm M}_\odot$ and $17\,{\rm M}_\odot$ up to $50\,{\rm M}_\odot$ **(but LBV winds!)**
- Case B: bimodal: peaks at $12.5\,{\rm M}_\odot$ and $\gtrsim 17\,{\rm M}_\odot$ up to $20\,{\rm M}_\odot$
- **mass gap** ($2.0 - 8.7\,{\rm M}_\odot$) reduced by **fallback**



- **Explosion energies in stripped stars 28 % bigger (0.88 ± 0.31 B) than for SNe IIP**
- **Ni masses: $0.059\,\mathrm{M}_\odot$ (Case B), $0.039\,\mathrm{M}_\odot$ (single)**



Kicks larger for stripped (Case B) stars (315 ± 24 km/s) than single/Case C stars (222 ± 23 km/s)

BHs are much harder to form in Case B binaries than for single stars/Case C

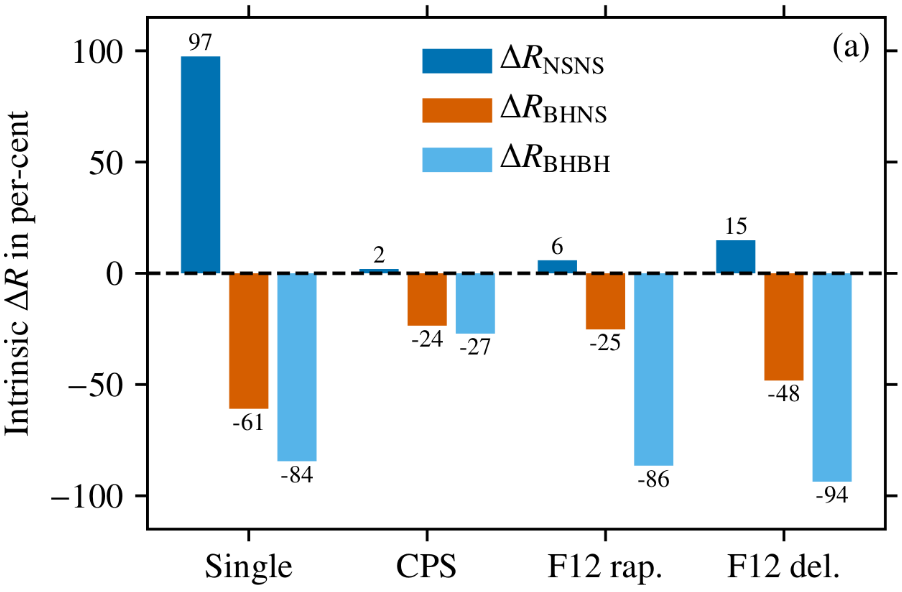
Implications for X-ray binaries

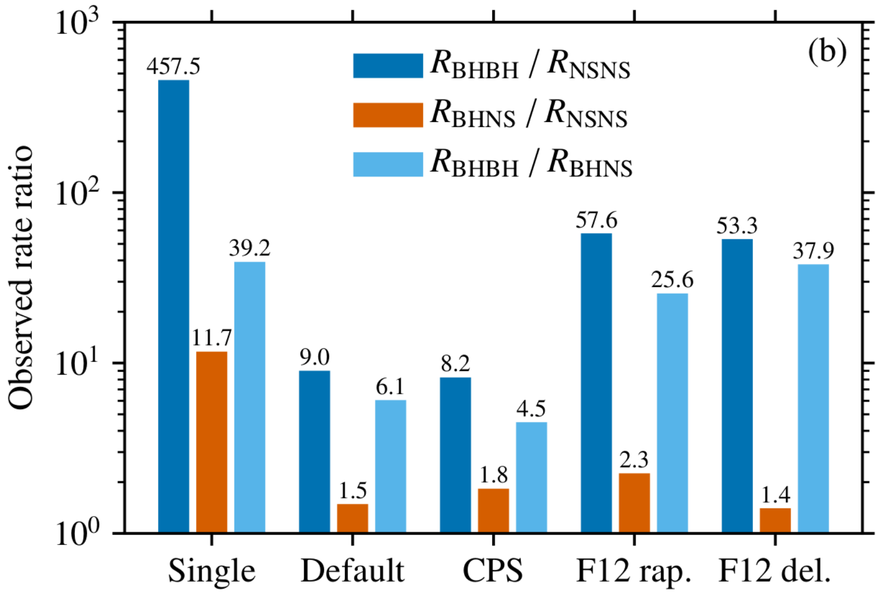
- can explain X-ray pulsars in young star clusters (i.e. Westerlund 1)
- binaries with “low-mass” BHs (e.g. GRO J1655-40) contain black holes formed from fallback (+ kicks)
- “high-mass” BHs (e.g. Cyg X-1) no kicks (Case C?)

Implications for GW detections by aLIGO

- much larger NS/BH ratio

→ fewer BH-BH, BH-NS mergers from “main” binary evolution channel (no dynamical formation, chemically homogeneous evolution)





Implications for Supernova Neutrinos

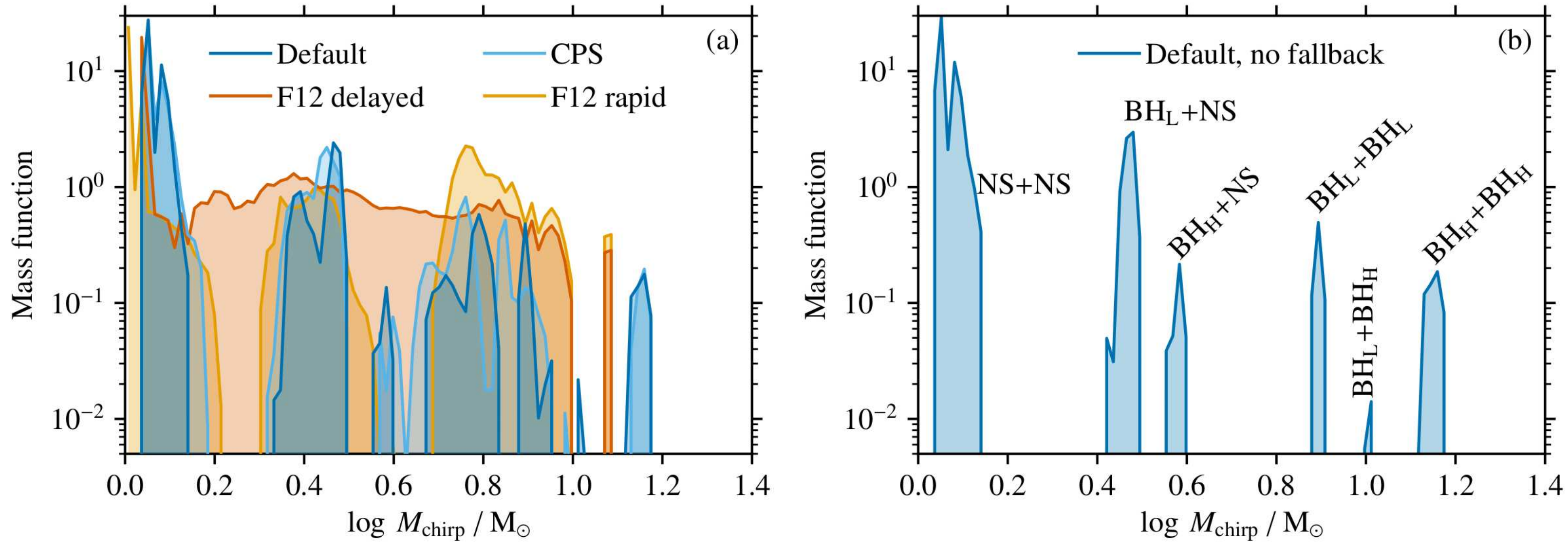
- binary evolution affects
  - ▷ the envelope structure of supernova progenitors → supernova type
  - ▷ the core structure → final fate (NS vs. BH)
- neutrino losses important during late evolution phases → core structure/fate
- neutrino signals different for
  - ▷ electron-capture supernova (low-mass NS)
  - ▷ iron core collapse (typical NS mass)
  - ▷ fallback black hole (NS neutrino signal first?)
  - ▷ fast black hole formation (sharp cutoff of neutrino signal?)

→ Can use neutrino signals to test late stages of stellar evolution

Chirp-mass distribution

$$M_{\mathrm{chirp}} = \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}}$$

- can be measured directly from the frequency evolution of GW signal



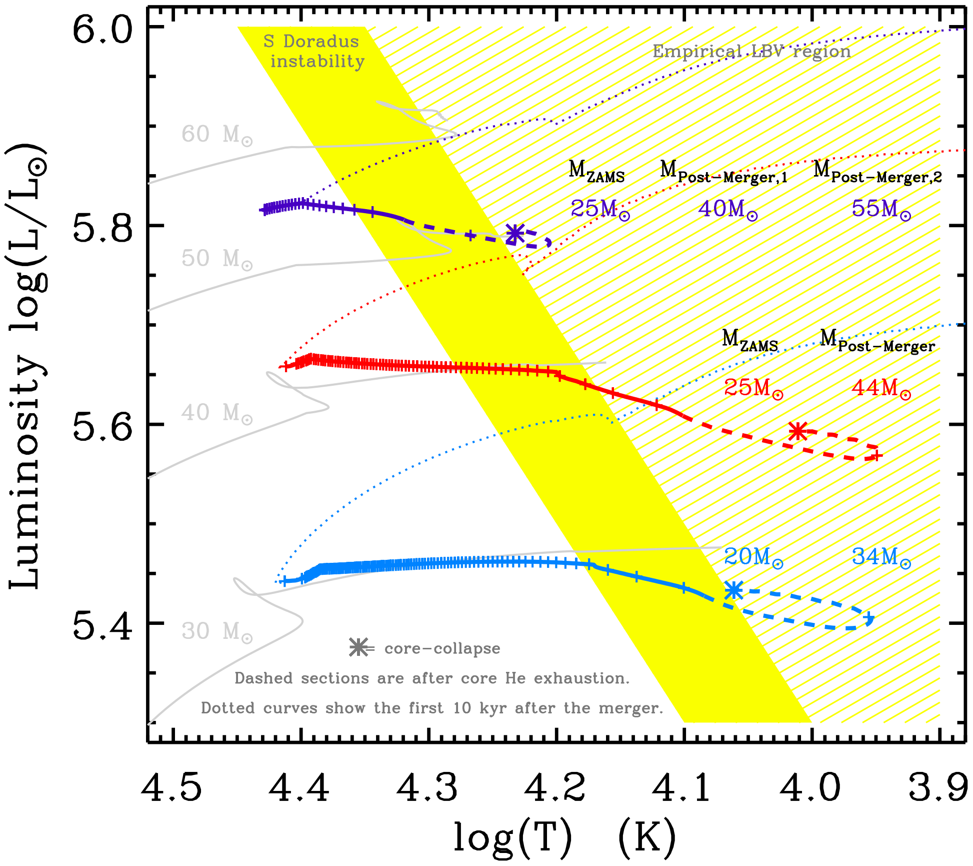
Note distinct imprint of compactness landscape in chirp-mass distribution

(Fallback will wash some of it out)

- also holds for quite massive stars (Justham+ 2014; also Vanbeveren+ 2013)
  - ▷ with relatively low-mass loss rate
  - ▷ transition to the red only after He-core burning

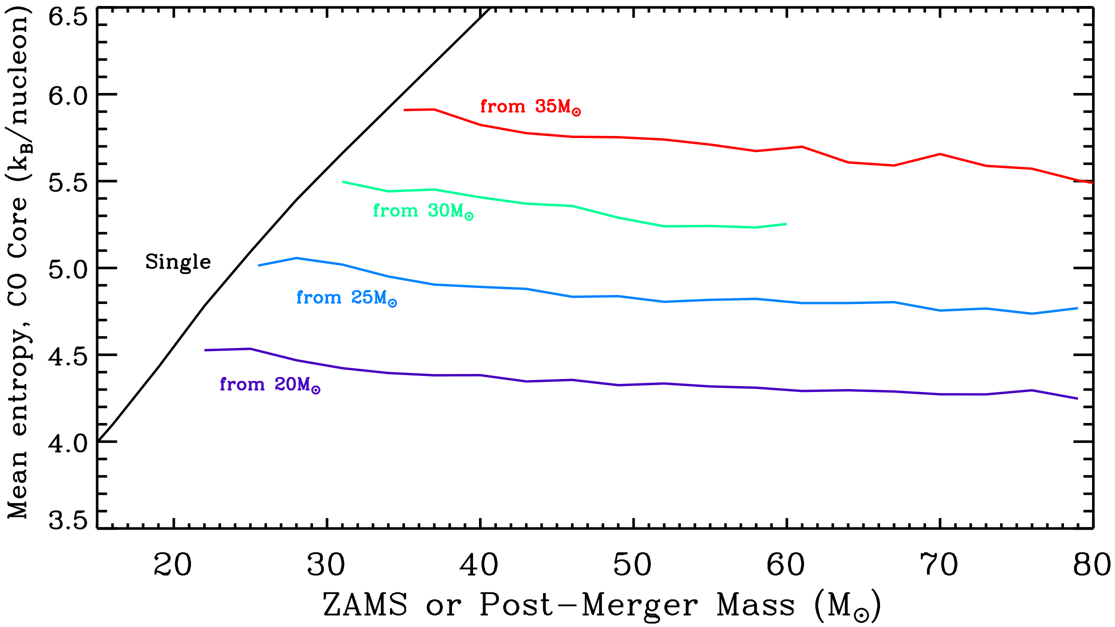
→ possibility of SN explosion in LBV phase

(with various amounts of H envelope masses)



Justham et al. (2014)

- even relatively massive stars may produce neutron stars rather than black holes (low entropy, plus core erosion)
- variety of outcomes (the mass of the merged system, the timing of the last outburst/amount of mass ejection)
- yellow supergiant progenitors/SNe IIn, Interaction SNe, PISNe

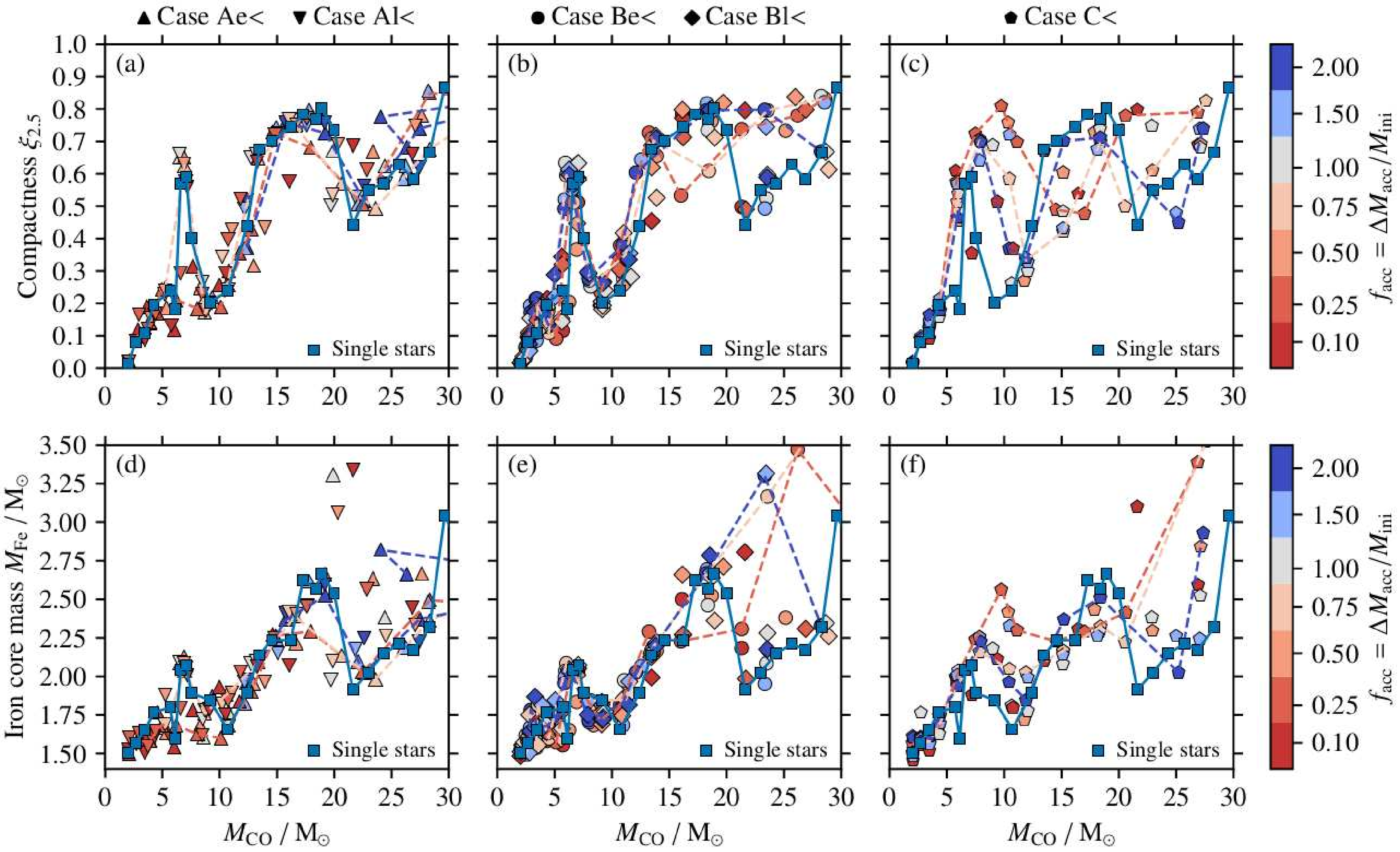


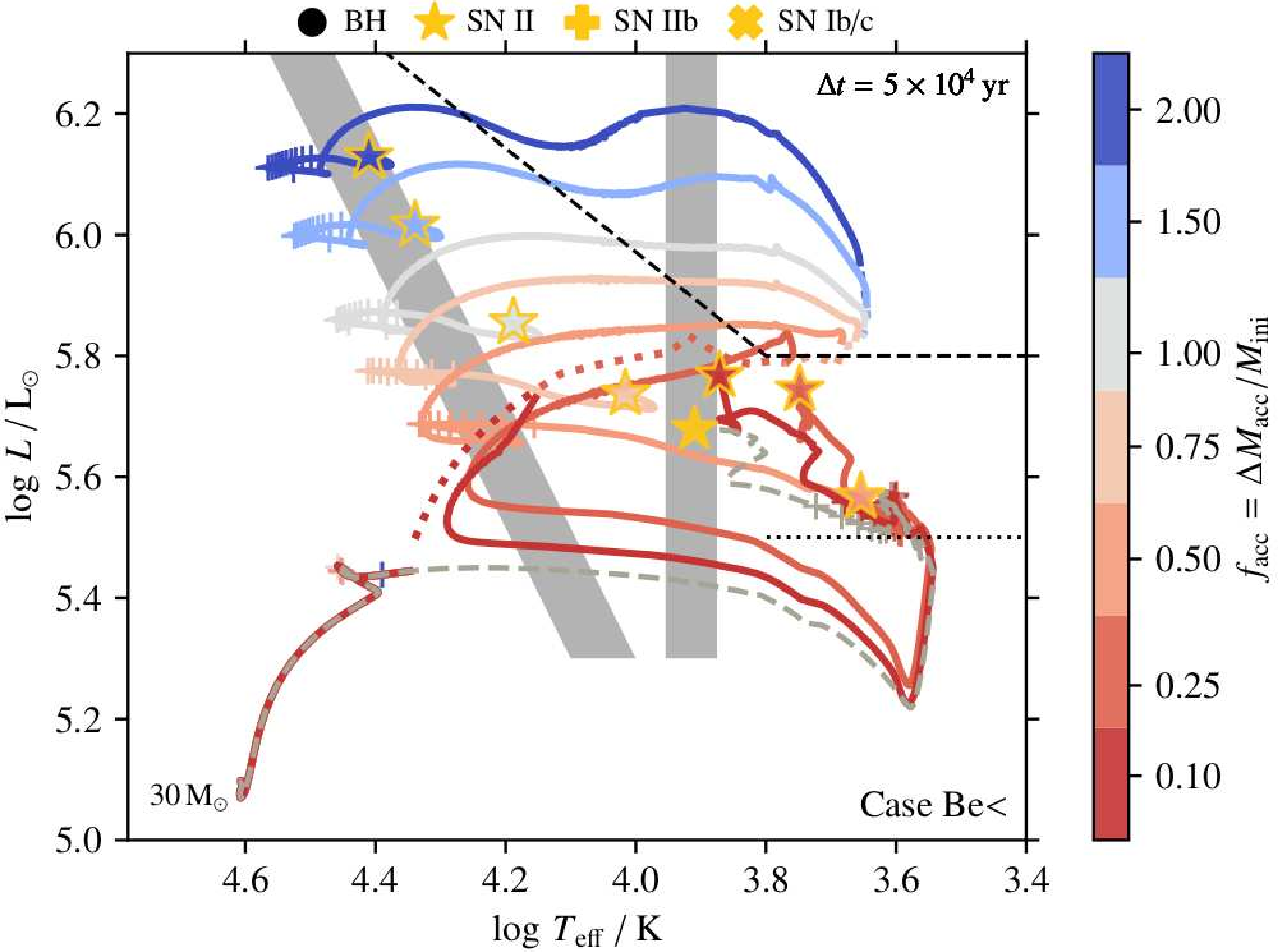
- cores of stars that have accreted have lower masses/entropies than the star would have had without accretion
- accretion stars/mergers more explodable?

The final fate of accretion stars and (simple) mergers

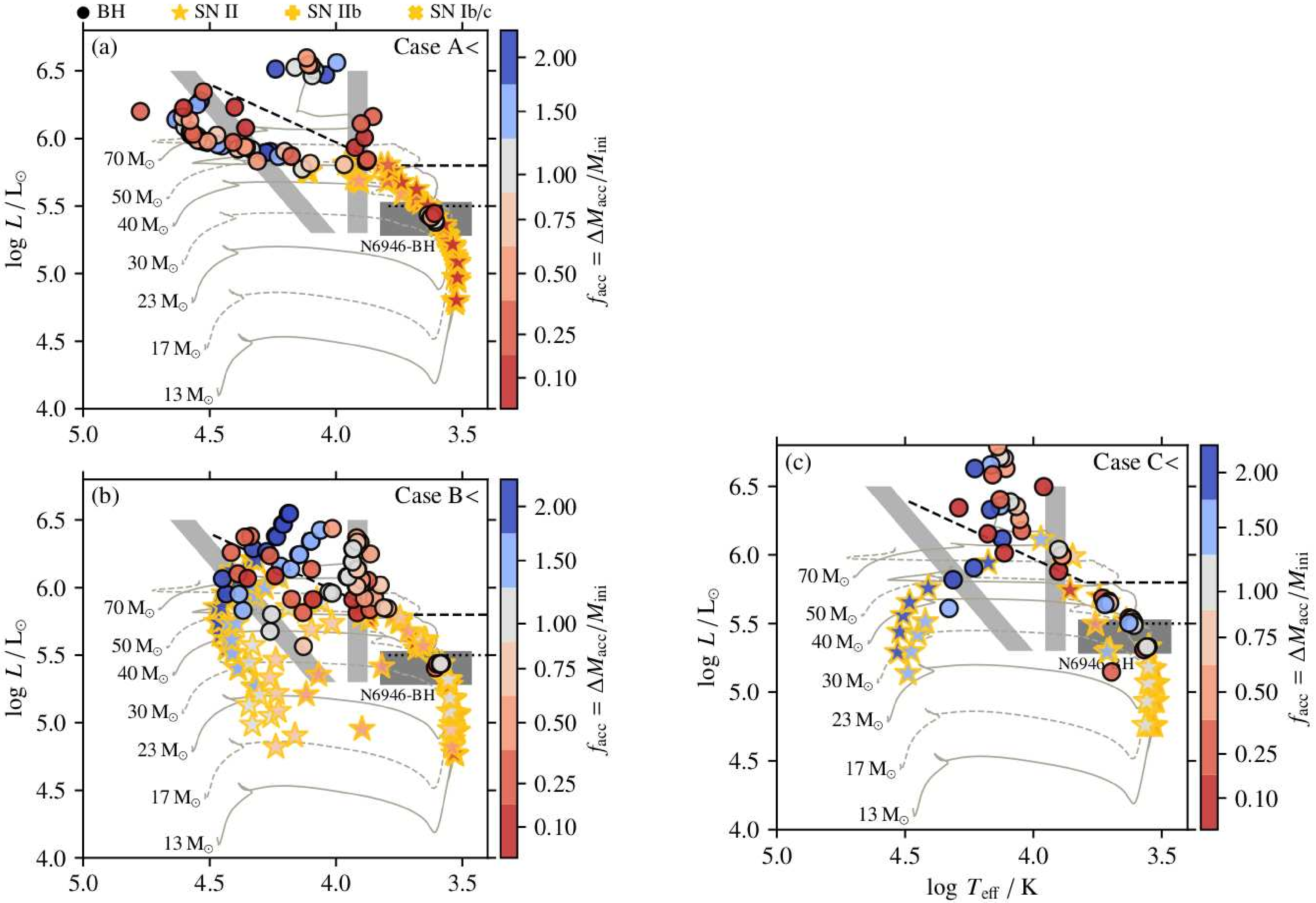
Schneider+ (2022)

- to simulate accretion and (simple) mergers, rapidly add mass at various evolutionary phases (Case A, B and C)
- reasonable for accreting stars
- may not be for mergers: no core erosion or destruction
  - ▷ requires 3d hydro simulations (Schneider, work in progress)
- purely phenomenological model (i.e. many of these systems may not be realized in actual binary situations)


▲ Case Ae<
▼ Case Al<
● Case Be<
◆ Case Bl<
⬟ Case C<
(a)
(b)
(c)
(d)
(e)
(f)
Compactness $\xi_{2.5}$
Iron core mass $M_{\rm Fe}$ / M$_\odot$
$M_{\rm CO}$ / M$_\odot$
Single stars
$f_{\rm acc} = \Delta M_{\rm acc} / M_{\rm ini}$
0.10
0.25
0.50
0.75
1.00
1.50
2.00
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.50
1.75
2.00
2.25
2.50
2.75
3.00
3.25
3.50
0
5
10
15
20
25
30



● BH
★ SN II
✚ SN IIb
✖ SN Ib/c
$\Delta t = 5 \times 10^4$ yr
30 M$_\odot$
Case Be<
log L / L$_\odot$
log $T_{\rm eff}$ / K
$f_{\rm acc} = \Delta M_{\rm acc} / M_{\rm ini}$
6.2
6.0
5.8
5.6
5.4
5.2
5.0
4.6
4.4
4.2
4.0
3.8
3.6
3.4
2.00
1.50
1.00
0.75
0.50
0.25
0.10


● BH
SN II
SN IIb
SN Ib/c
(a)
Case A<
(b)
Case B<
(c)
Case C<
N6946-BH
70 M$_\odot$
50 M$_\odot$
40 M$_\odot$
30 M$_\odot$
23 M$_\odot$
17 M$_\odot$
13 M$_\odot$
log L / L$_\odot$
log $T_{\rm eff}$ / K
$f_{\rm acc} = \Delta M_{\rm acc}/M_{\rm ini}$
4.0
4.5
5.0
5.5
6.0
6.5
5.0
4.5
4.0
3.5
0.10
0.25
0.50
0.75
1.00
1.50
2.00

The Origin of the Compactness Peak

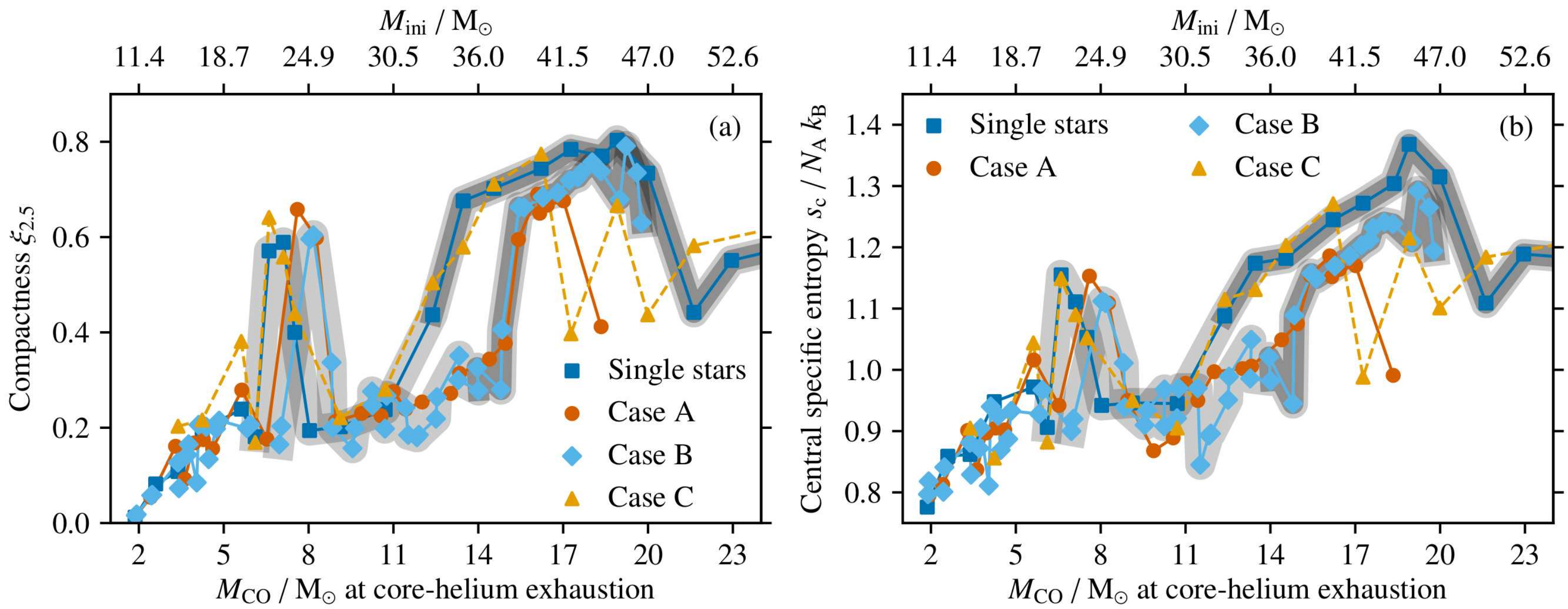


Fig. 5. Compactness $\xi_{2.5}$ (*panel a*) and dimensionless central specific entropy $s_{\rm c}$ (*panel b*) at core collapse as a function of CO core mass $M_{\rm CO}$. As in Fig. 2, initial masses $M_{\rm ini}$ corresponding to the CO core masses of single stars are shown at the top (cf. Fig. 3), and the light-grey and darker-grey shadings are for radiative core carbon and core neon burning, respectively.

- peak around $M_{\rm CO} \simeq 7\ (8)\, M_\odot$ found pretty universally in the literature (e.g. Heger, Sukhbold) → robust feature
- current working hypothesis

approaching the peak: after central C burning, phase of neutrino-driven growth of C-free core (i.e. $L_\nu > L_{\rm C-burn}$ in burning shell, no stationary C shell burning) → very fast growth of C-free core

beyond the peak: central Ne/O burning → stops core contraction soon after the end of central C burning