Lecture 17

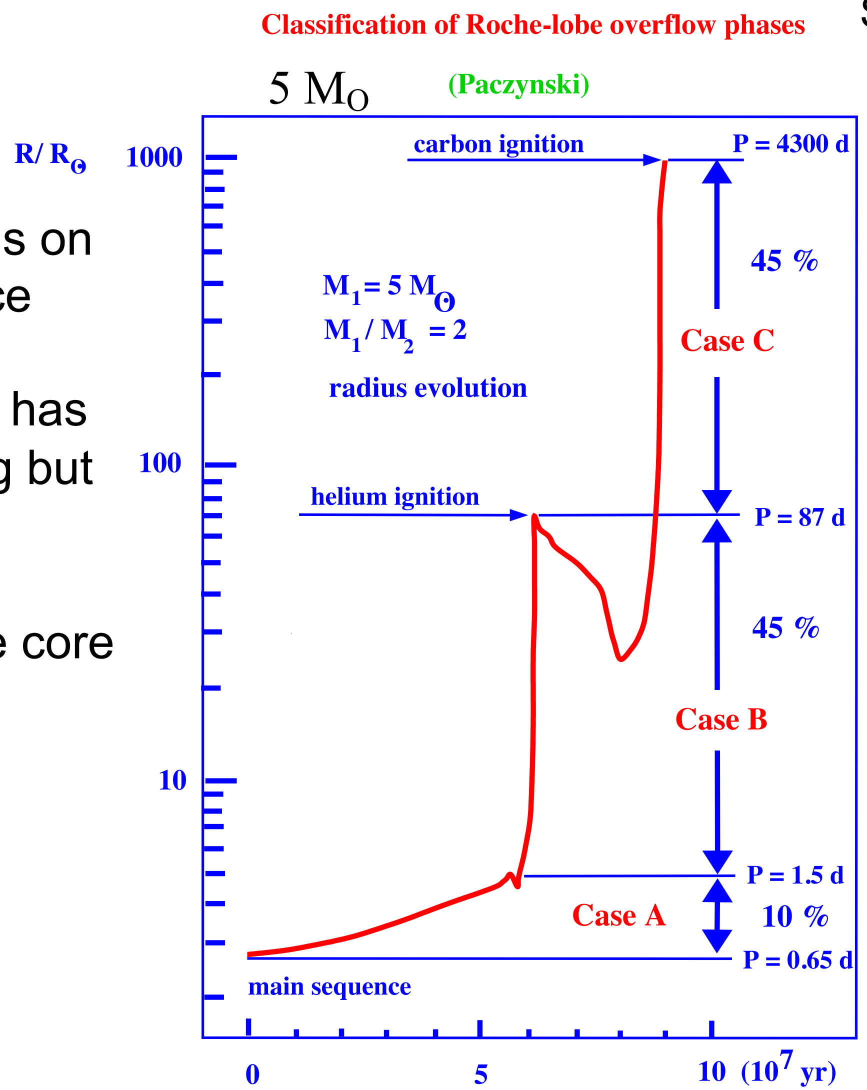
Binary Evolution

Type Ib and Ic Supernovae

Half or more of massive stars are found in binaries with such close separations that the stars will interact when one of them becomes a supergiant (Sana & Evans 2011; Sana et al. 2012). [Podsiadlowski says 30 – 50%, but in any case the fraction is large]

See class website

- Case A –the star is on the main sequence
- Case B – the star has finished H burning but not He burning
- Case C – post-He core burning



P is the maximum period below which mass exchange of the given type will occur

The rough percentage of 5 M_O stars that will interact during the given stage is indicated

Figure 1.1 The evolution of the radius of a 5 $M_\odot$ star as a function of its lifetime to illustrate the ranges in radius and orbital period for the different cases of RLOF phases, as indicated

Orbit evolution

Kepler $a^3 \propto P^2 M \quad \rightarrow \quad 3\frac{\dot{a}}{a} = 2\frac{\dot{P}}{P} + \frac{\dot{M}}{M}$

$M \equiv m_1 + m_2$

orbital angular momentum

$$J = \frac{m_1 m_2}{M}\left(\frac{2\pi a^2}{P}\right)\left(1-e^2\right)^{1/2}$$

$$= m_1 m_2 \left(\frac{G a \left(1-e^2\right)}{M}\right)^{1/2}$$

substituting for P using Kepler

$$\rightarrow \quad \frac{\dot{J}}{J} = \frac{\dot{m}_1}{m_1} + \frac{\dot{m}_2}{m_2} + \frac{1}{2}\frac{\dot{a}}{a} - \frac{1}{2}\frac{\dot{M}}{M} - \frac{1}{2}\frac{2e\dot{e}}{1-e^2}$$

$$\boxed{\frac{\dot{a}}{a} = \frac{\dot{M}}{M} + 2\frac{\dot{J}}{J} - 2\left(\frac{\dot{m}_1}{m_1} + \frac{\dot{m}_2}{m_2}\right) - \frac{e\dot{e}}{1-e^2}}$$

Conservative mass exchange

$$\frac{\dot a}{a} = \frac{\dot M}{M} + 2\frac{\dot J}{J} - 2\left(\frac{\dot m_1}{m_1} + \frac{\dot m_2}{m_2} \right) - \frac{e\,\dot e}{1-e^2}$$

circular orbit conservative mass exchange :

$e = 0 \quad \dot e = 0 \qquad \dot M = 0 \quad \dot J = 0 \quad \dot m_1 = -\dot m_2 > 0$

m_2 is the mass losing star

$$\frac{\dot a}{a} = -2\left(\frac{-\dot m_2}{m_1} + \frac{\dot m_2}{m_2} \right) = 2\,\frac{-\dot m_2}{m_2}\left(1 - \frac{m_2}{m_1} \right) > 0$$

$$\frac{\dot P}{P} = \frac{3}{2}\frac{\dot a}{a} > 0$$

Orbit expands period increases if m1>m2

Shrinks if m1<m2

If the mass losing star is the more massive component, the orbit shrinks

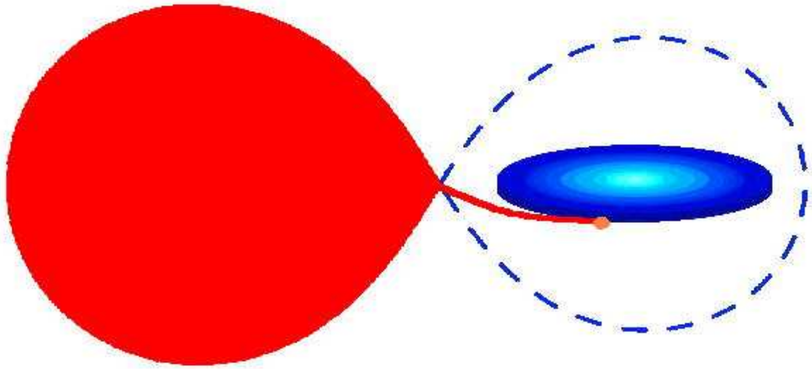


Figure 1.2 Cartoon illustrating stable mass transfer.

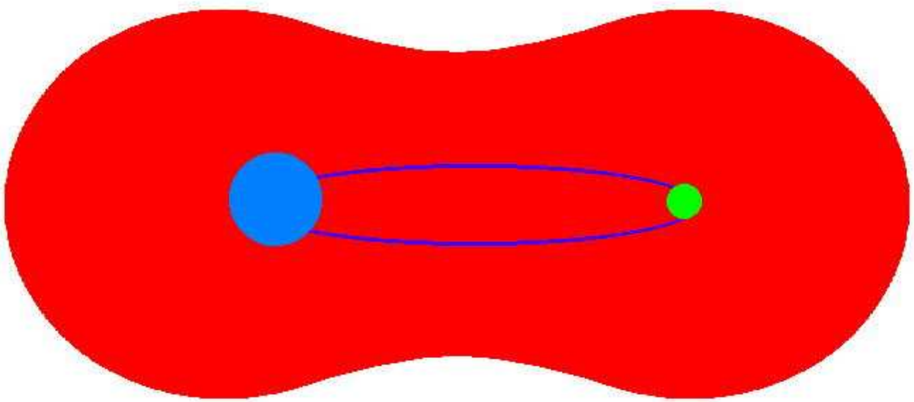
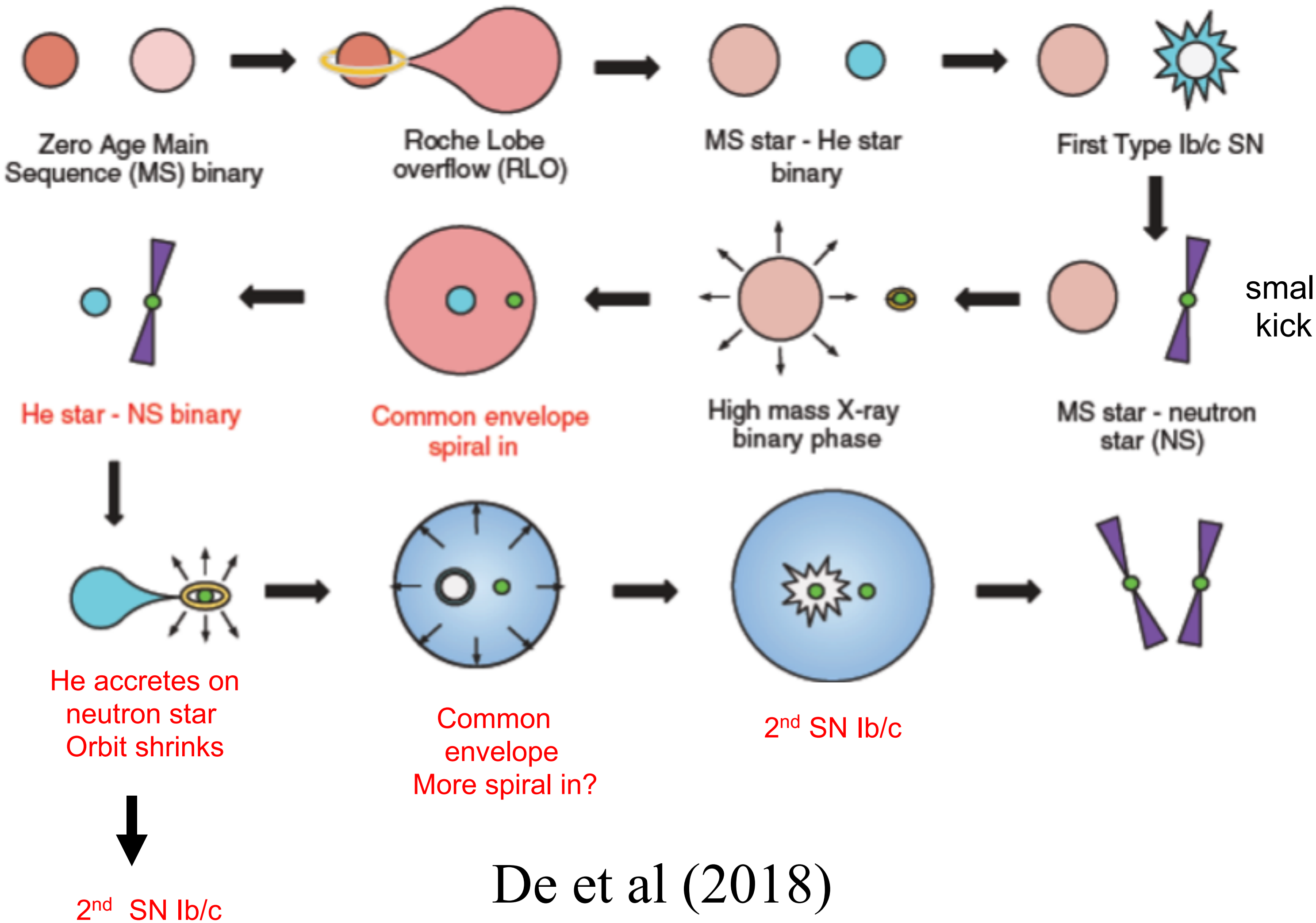


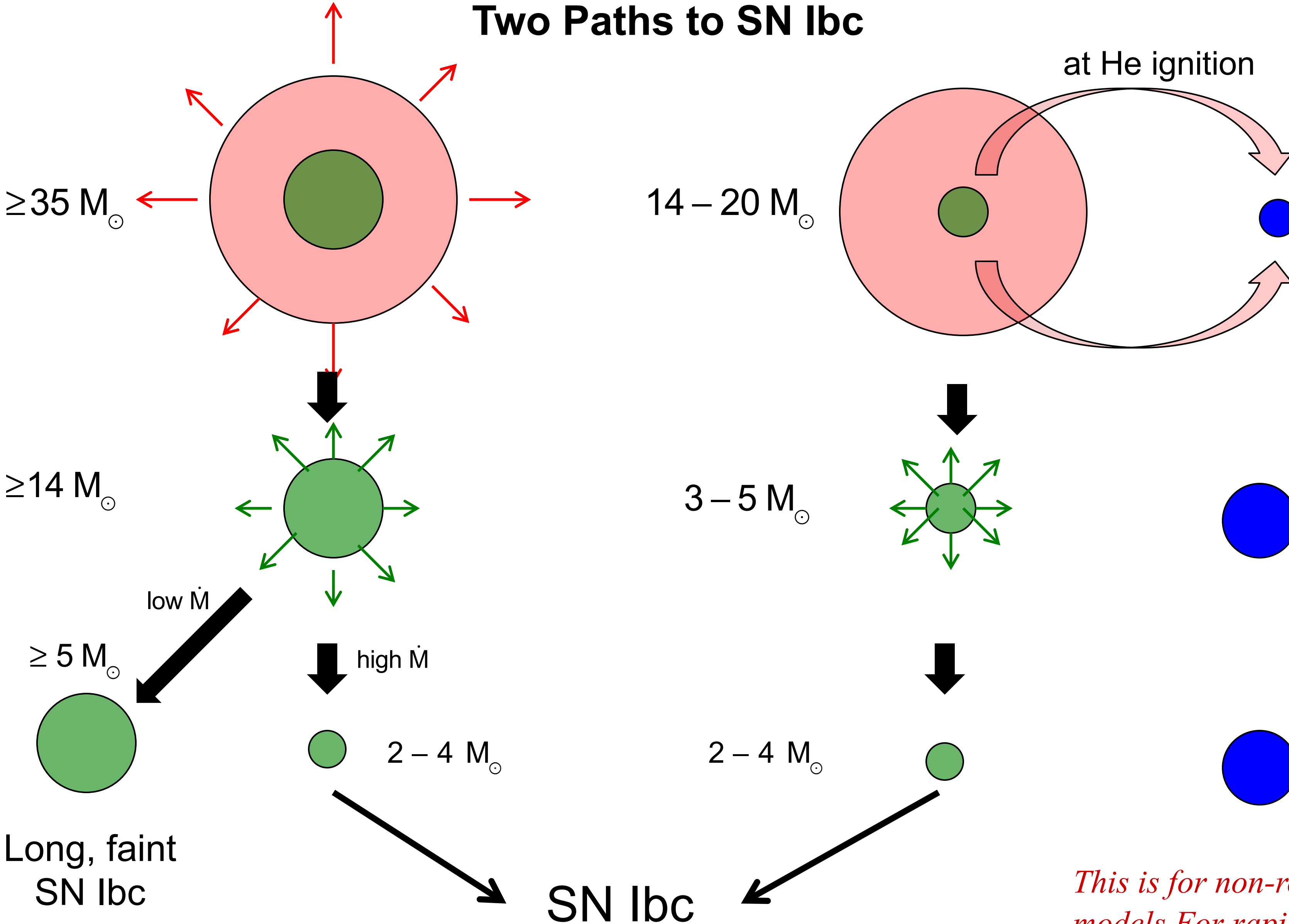
Figure 1.3 Cartoon illustrating unstable mass transfer.

The latter can lead to the formation of a "common envelope" e.g., a double neutron star system. Both stars big enough to be supernovae



De et al (2018)

Two Paths to SN Ibc



This is for non-rotating models.For rapid rotation and high final mass gamma-ray bursts may occur

Properties: Type Ib/c supernovae

- Lack hydrogen, but also lack the Si II $\lambda\lambda 6355$ feature that typifies SN Ia.

- SN Ib have strong features due to He I at 5876, 6678, 7065 and 10830 A. SN Ic lack these helium features, at least the 5876 A line. Some people think there is a continuum of properties between SN Ib and SN Ic

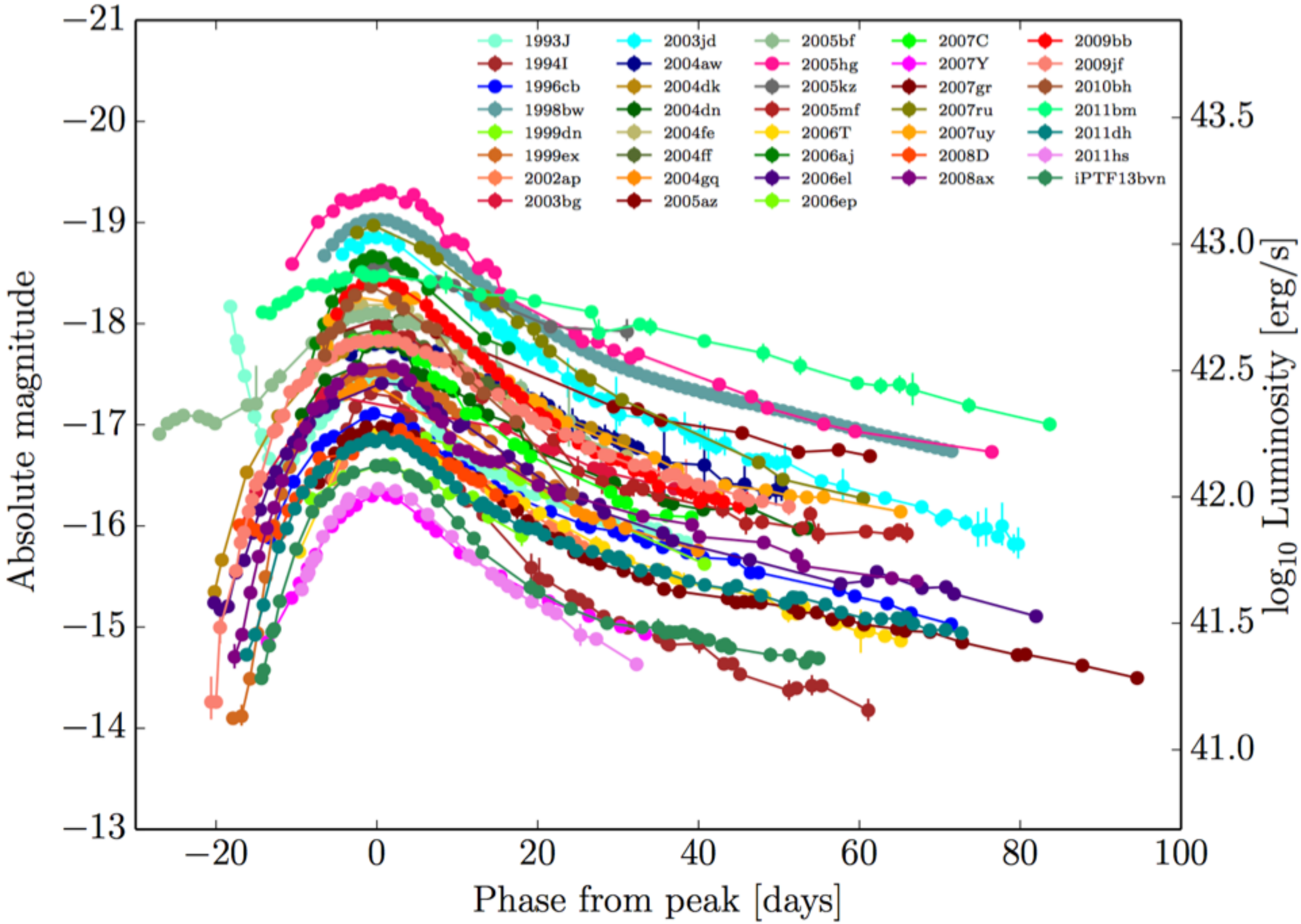
- Found in spiral and irregular galaxies. Found in spiral arms and star forming regions. Not found in ellipticals. Associated with star formation

- Often strong radio sources (unlike Type Ia). Suggests extensive mass loss.

- Fainter at peak than SN Ia by about 1.5 magnitudes. Otherwise similar light curve. Large variation in luminosities.

- Only supernovae definitely associated with gamma-ray bursts so far are Type Ic

- Cannot have high mass in the common case. Probably come from binaries



Lyman et al (2014)

- Apparently radioactive powered light curves but fainter than Ia by about 1.5 m at peak, so a few x 10^{42} erg s^{-1}

- Distinct IR light curve. No secondary peak like SN Ia

Generally believed to be the explosion of massive stars that have lost their hydrogen envelope, but how?

1) Very massive stars – single or in detached binaries – that have lost their envelopes to winds. Then the initial star mass would be > 30 solar masses and unless the remaining helium core itself lost a lot of mass the presupernova star would be quite massive (e.g. Woosley, Langer, Weaver 1993)

2) Stars of mass similar to those of common supernovae (10 – 20 M_{O}) that lose their envelope in a mass exchanging binary. Progenitors have lower mass (e.g., Woosley, Langer, Weaver 1995)

Ensman and Woosley (1988) showed SN Ib progenitors had to be less than 7 M_{O} when they died or the light curve would be too broad. < 5 was better.

Type Ib Supernovae

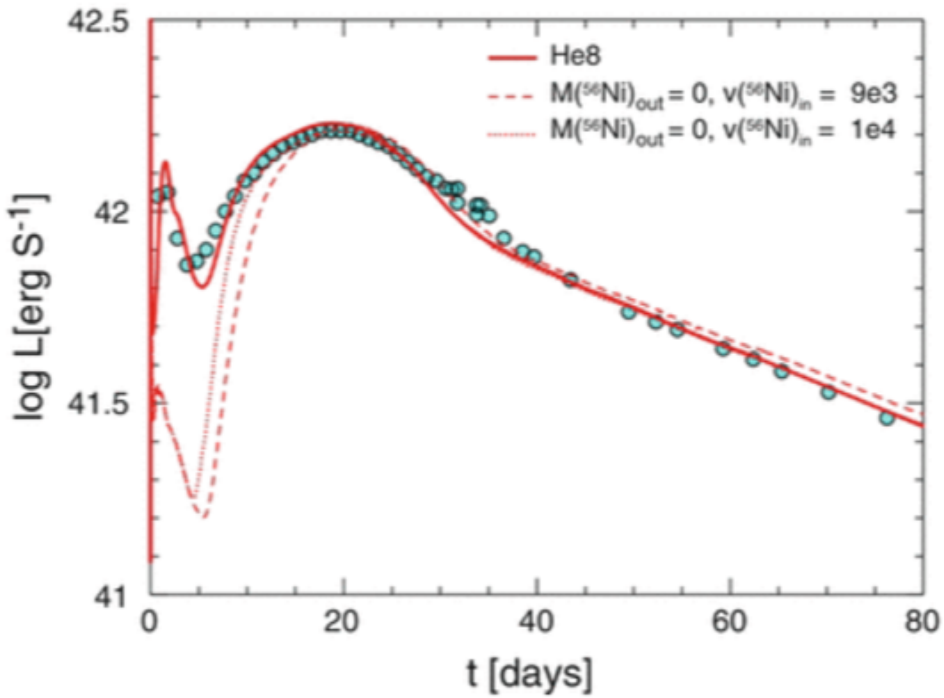
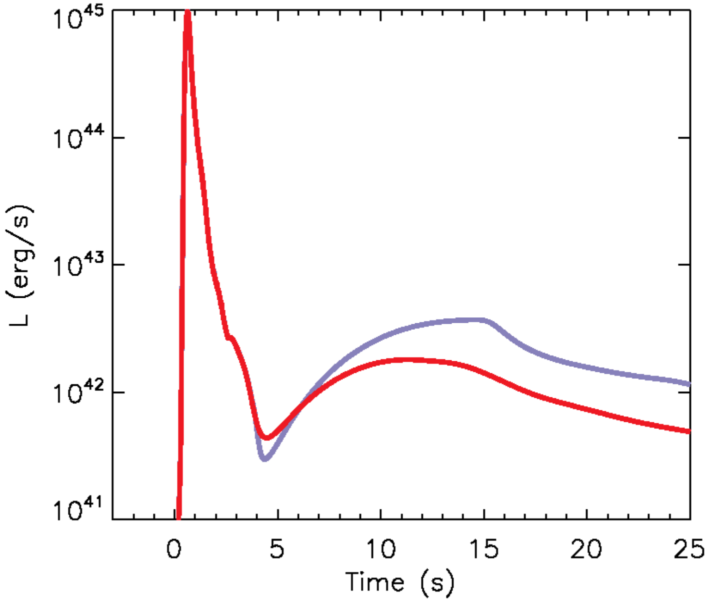
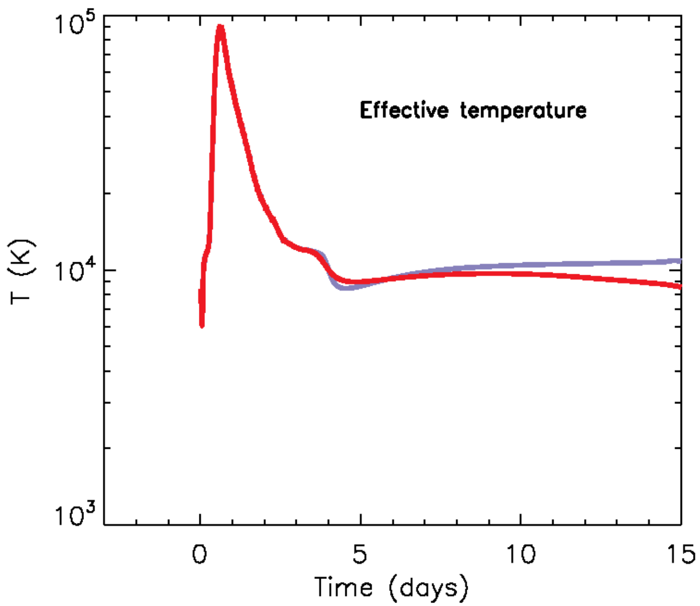


Fig. 16.5 The bolometric light curve of SN 2008D compared to three models. The best-fitting one containing a total ^{56}Ni mass of 0.07 $M_\odot$ with

Don't believe the models! The fit to the initial spike invoked an extra blob of nickel on the outside of the star. I have models where this is not necessary but the progenitor star has an extended structure instead - SEW





Blob of Ni on the outside or an extended progenitor?

Typical SN Ib Spectrum

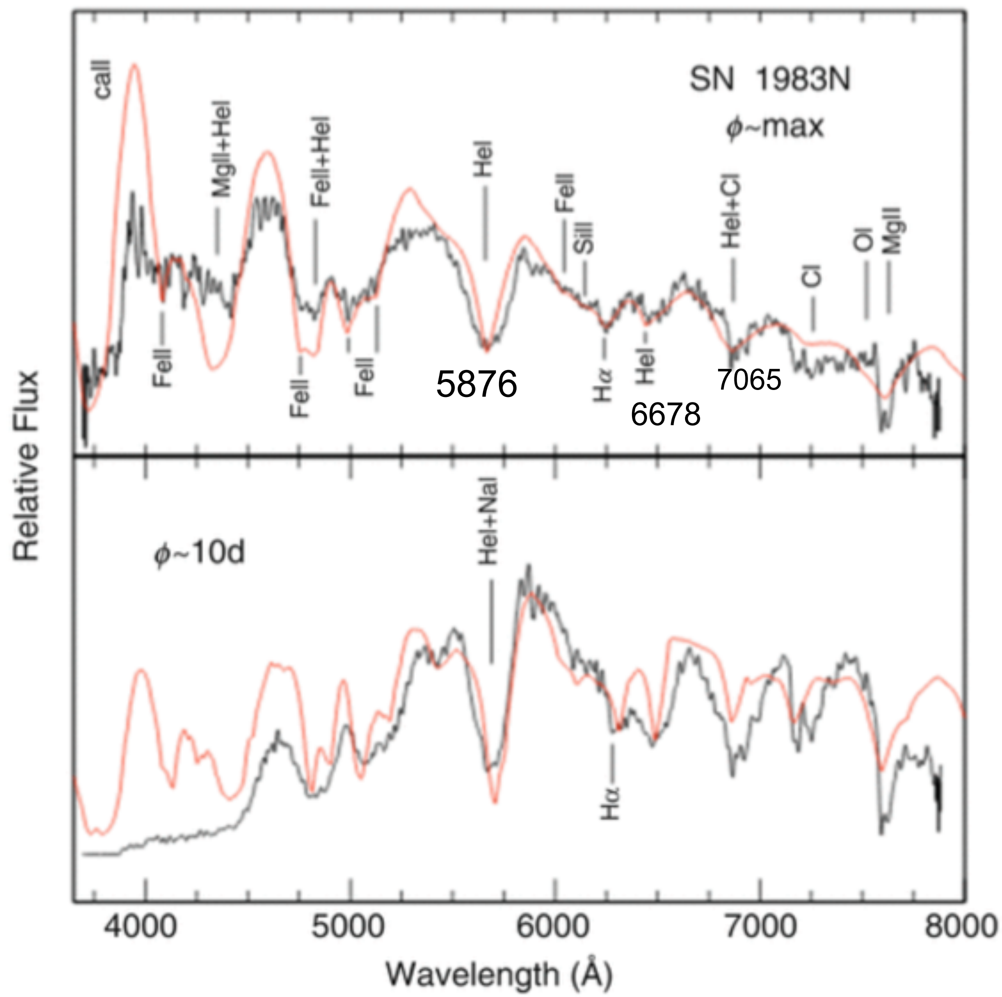
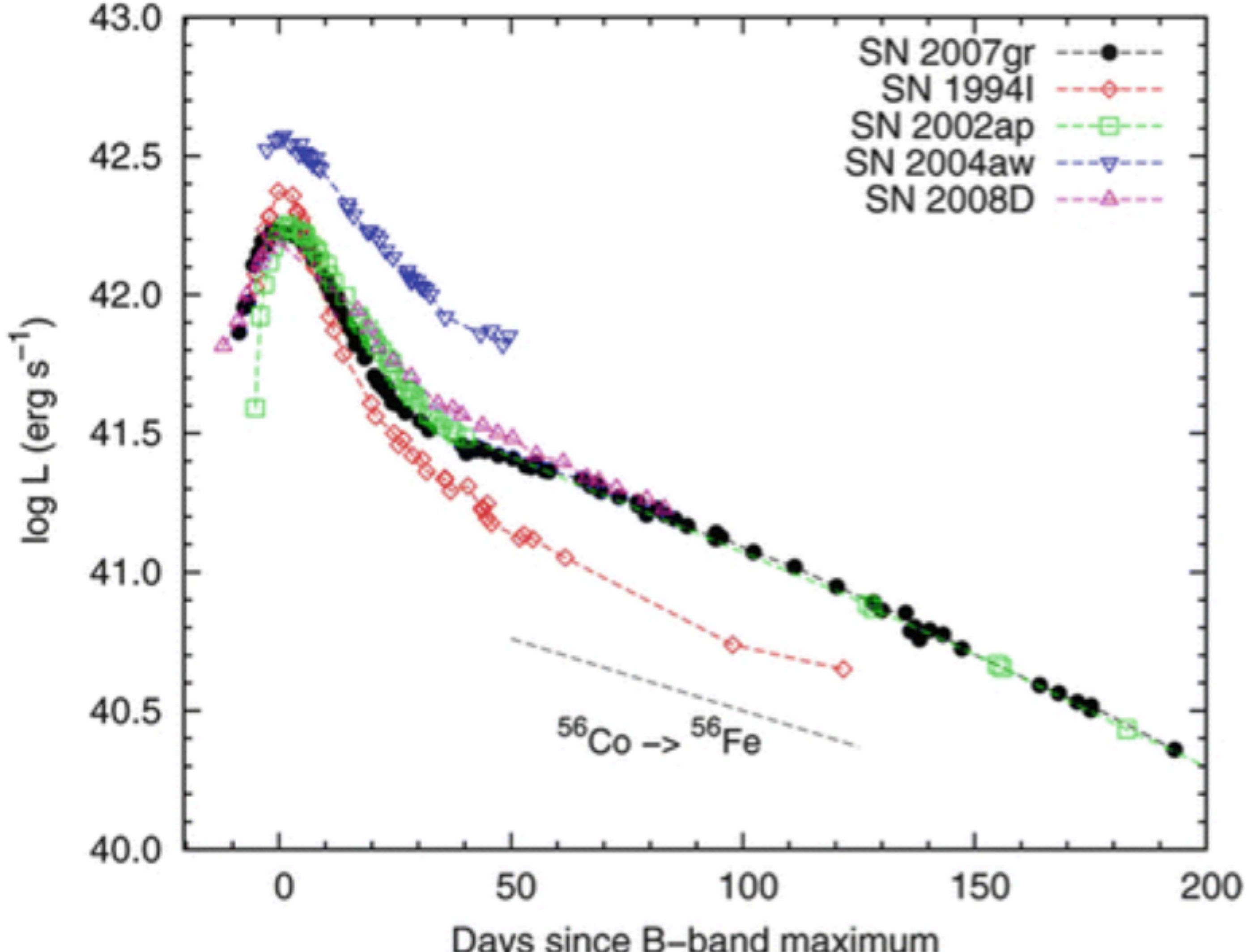


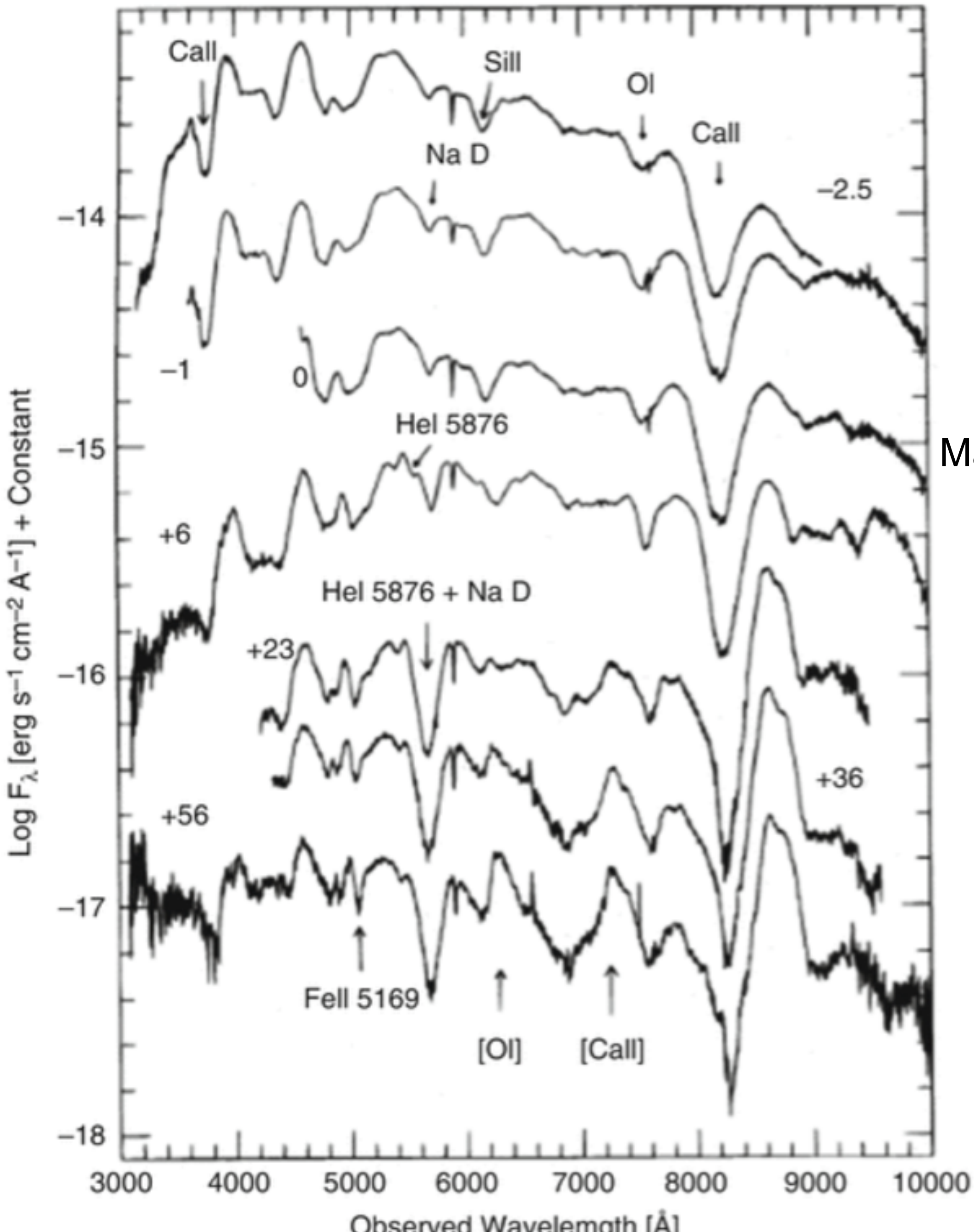
Fig. 16.2 Spectra of SN 1983N at maximum light (*top*) and 10 days later (*bottom*), compared with SYNOW synthetic spectra. From "Hydrogen and helium traces in type Ib/c supernovae" (Elmhamdi et al. 2006)

Type Ic Supernovae



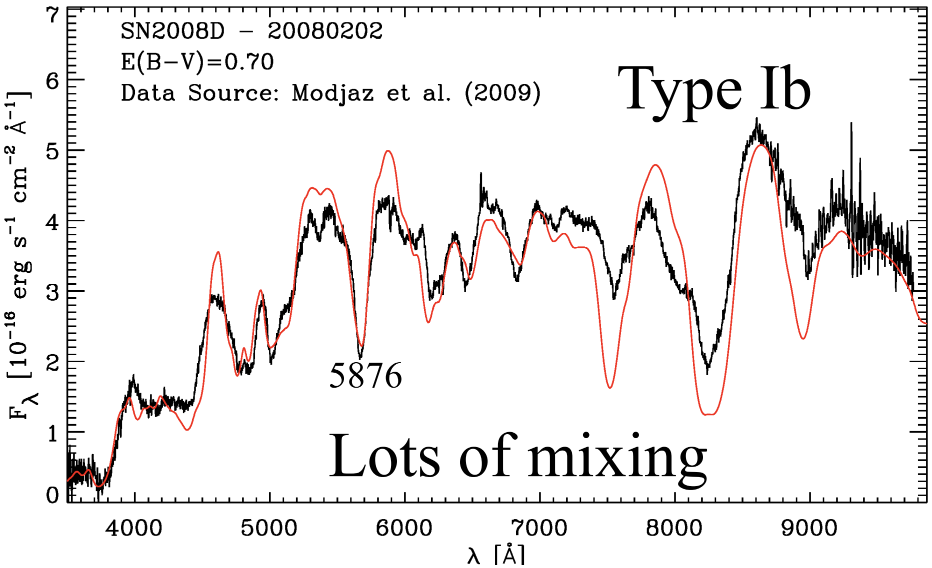
Prototypical SN Ic
SN 1994I
(Branch and Wheeler – text)

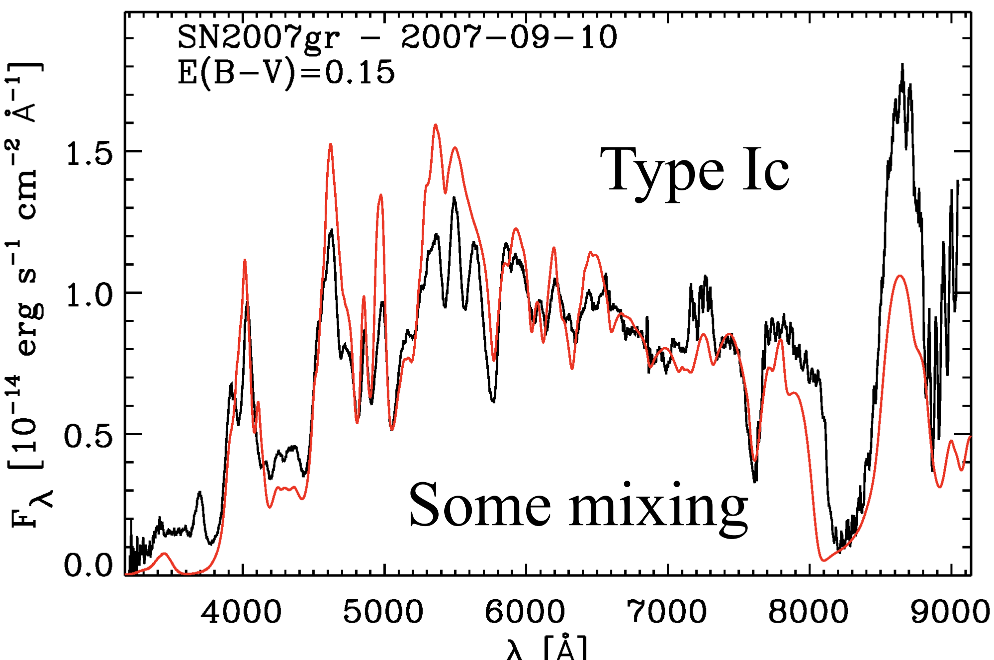
Light curve is on next page



Maximum light
t = 0

Or it could be mixing

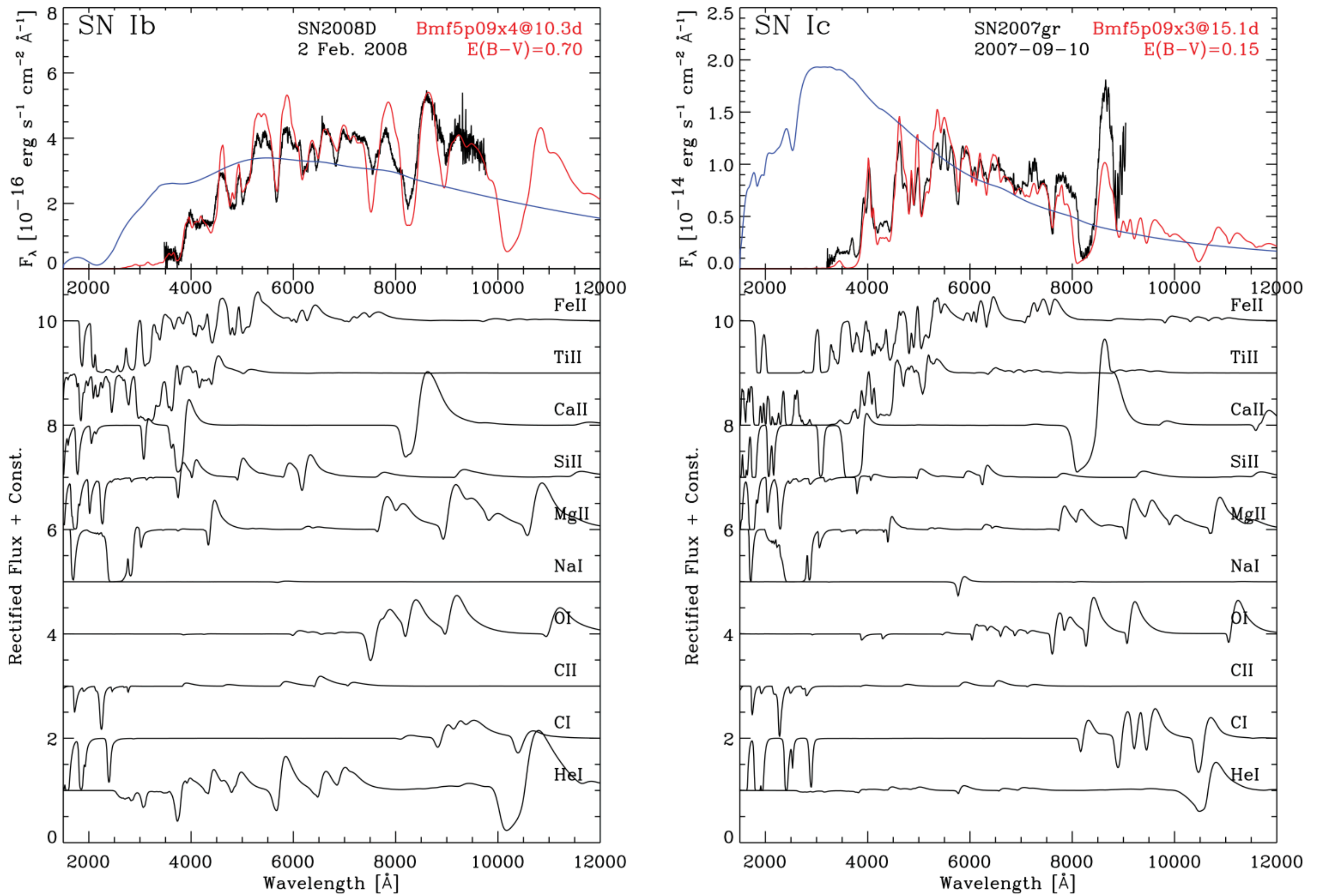




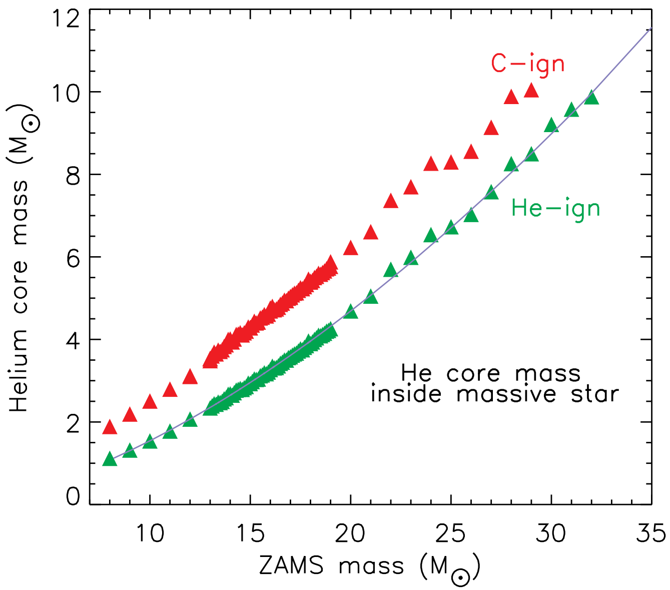
Dessart, Hillier, & Woosley, MNRAS, 424, 2139 (2012)

It is thought by many that the production of Type Ic supernovae requires the removal of the hydrogen envelope and helium shell of a very massive star in order to have a weak helium line at 5876 A.

The two models on the left are both derived from a 5.1 M_O helium star that originated from a binary pair in which each star was lighter than 25 solar masses (Yoon, Langer and Woosley 2010)


SN Ib
SN2008D
2 Feb. 2008
Bmf5p09x4@10.3d
E(B−V)=0.70
SN Ic
SN2007gr
2007-09-10
Bmf5p09x3@15.1d
E(B−V)=0.15
F_λ [10^{-16} erg s^{-1} cm^{-2} Å^{-1}]
F_λ [10^{-14} erg s^{-1} cm^{-2} Å^{-1}]
Rectified Flux + Const.
FeII
TiII
CaII
SiII
MgII
NaI
OI
CII
CI
HeI
Wavelength [Å]

The outcome of presupernova evolution is different in binaries



The size of the helium core in a massive star grows during He burning if the star retains an envelope. But suppose the envelope is lost to a companion at the beginning of helium burning.

$$M_{He,i} \approx 0.0385\, M_{ZAMS}^{1.603}$$

Woosley (2019)

This expression fits the green points.

Had the star kept its envelope until the end, its mass would be the red points

The exposed helium core then loses mass as a WR-star. It's mass shrinks further.

$$\log \dot{M}_{CO} = -9.2 + 0.85 \log\left(\frac{L}{L_\odot}\right) + 0.44 \log Y_s + 0.25 \log\left(\frac{X_{Fe}}{X_{Fe\odot}}\right)$$

Yoon (2017)

$$\log \dot{M}_{WNE} = -11.32 + 1.18 \log\left(\frac{L}{L_\odot}\right) + 0.6 \log\left(\frac{X_{Fe}}{X_{Fe\odot}}\right)$$

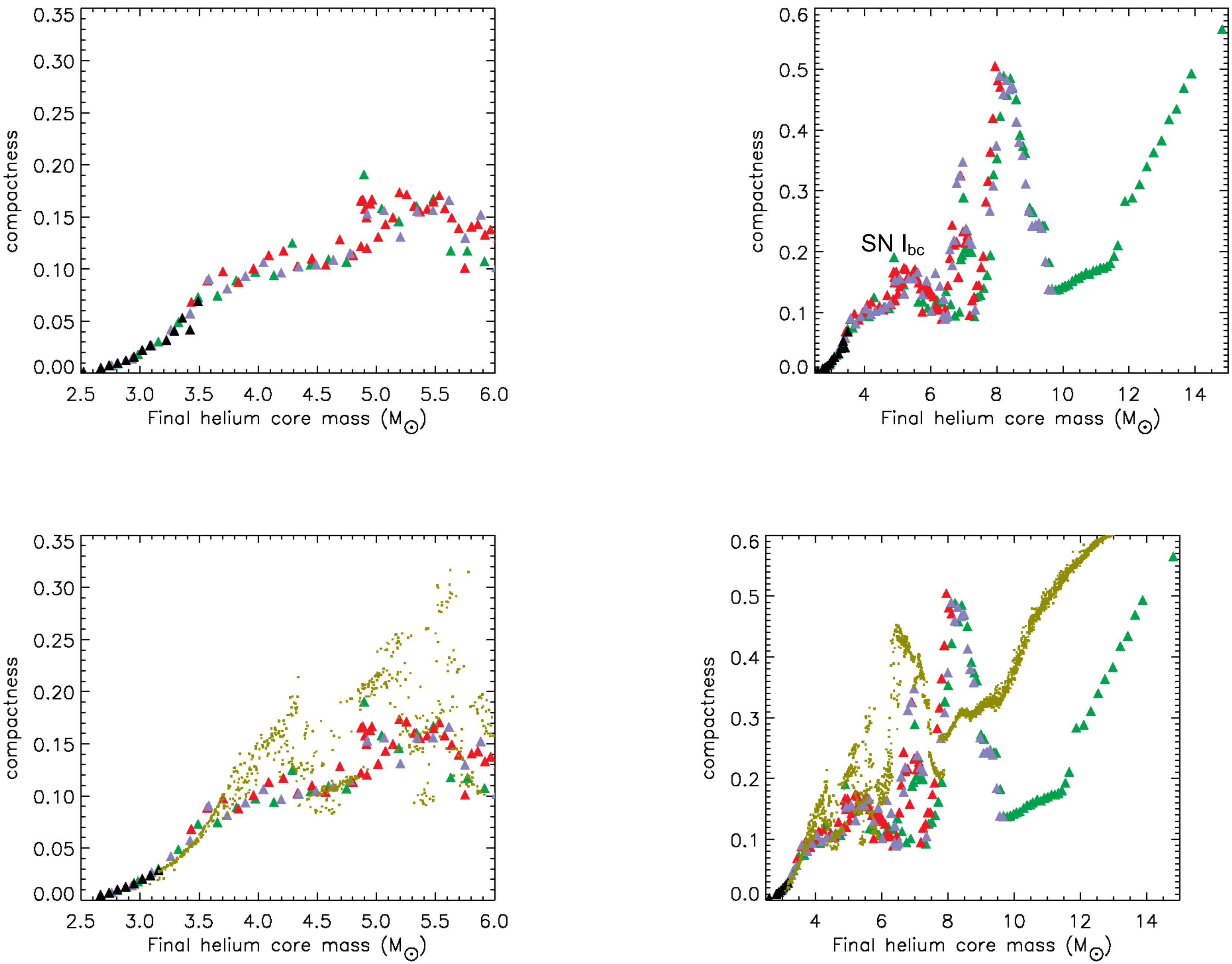
In the end, for main sequence masses up to 30 M_O the Type Ib or c progenitor mass is just

$$M_{SNIb} = 0.0548\ M_{ZAMS}^{1.4}$$

For example, for M_{ZAMS} =25 M_O the progenitor mass is 5.0 M_O. For a single star the helium core mass would have been between 8 and 9 M_O

For still higher masses the progenitor mass is just ¼ of the main sequence mass. Other mass loss rates will give different values of course and the answer will depend on metallicity.

Compactness compared with single stars



f_{WR} is a reduction factor applied to older overly large WR mass loss rates

Table 1
Properties of the Computed Sequences

No.	Z	$M_{1,i}$	$M_{2,i}$	P_i	f_{WR}	Case	P_f	$M_{1,f}$	$M_{CO,f}$	M_{He}	M_H	$\langle j_{1.4} \rangle$	Fate
1	0.02	12	8	3.0	5	B+BB	57.9	1.40[a]	1.21[a]	0.17[a]	0.0	0.33	ONeMg WD
2	0.02	12	11	4.0	5	B+BB	104.4	1.48[a]	1.24[a]	0.20[a]	0.0	0.35	ONeMg WD
3	0.02	13	11	5.0	5	B+BB	123.3	1.64[a]	1.43[a]	0.18[a]	0.0	0.22	SN Ic
4	0.02	14	12	3.0	5	A+AB+BB	118.5	1.33[a]	1.09[a]	0.22[a]	0.0	...	ONeMg WD
5	0.02	14	12	5.0	5	B+BB	30.7	2.97	1.66	1.24	1.9(−4)	0.25	SNIb
6	0.02	16	14	2.0	5	A:Contact							
7	0.02	16	14	3.0	5	A+AB+ABB	101.8	1.54[a]	1.33[a]	0.17[a]	0.0	0.39	ONeMg WD
8	0.02	16	14	4.0	5	B+BB	26.2	3.66	2.05	1.47	4.5(−3)	0.24	SNIb
9	0.02	16	14	5.0	5	B+BB	33.7	3.65	2.04	1.47	5.0(−3)	0.25	SNIb
10	0.02	18	12	3.0	5	A+AB+ABB	27.9	2.66	1.58	1.01	0.00	0.26	SNIb
11	0.02	18	12	3.0	10	A+AB+ABB	27.3	2.74	1.59	1.08	0.00	0.26	SNIb
12	0.02	18	12	5.0	10	B:Contact							
13	0.02	18	17	3.0	10	A+AB+ABB	36.2	3.03	1.68	1.27	7.9(−4)	0.25	SN Ib
14	0.02	18	17	4.0	10	A+AB	29.7	3.79	2.14	1.49	1.5(−3)	0.25	SN Ib
15[b]	0.02	18	17	4.0	10	A+AB	24.0	3.97	2.27	1.53	1.0(−3)	0.26	SNIb
16[c]	0.02	18	17	4.0	10	A+AB	50.0	3.80	2.16	1.50	2.2(−3)	0.06	SNIb
17[d]	0.02	18	17	4.0	10	A+AB	25.2	3.84	2.18	1.50	1.4(−3)	0.26	SNIb
18[e]	0.02	18	17	4.0	10	A+AB	30.6	3.73	2.14	1.43	0.00	3.57	SNIb
19	0.02	18	17	5.0	3	B	33.1	3.73	2.33	1.23	0.00	0.25	SNIb
20	0.02	18	17	5.0	5	B	32.4	4.04	2.45	1.4	0.00	0.33	SNIb
21	0.02	18	17	5.0	10	B+BB	31.5	4.41	2.51	1.68	9.9(−3)	0.26	SNIb
22	0.02	18	17	6.0	10	B	39.3	4.39	2.56	1.62	4.0(−3)	0.26	SNIb
23	0.02	25	19	6.0	10	B:Contact							
24	0.02	25	24	2.0	10	A:Contact							
25	0.02	25	24	3.0	3	A+AB	22.7	3.70	2.46	0.98	0.0	0.24	SNIb
26	0.02	25	24	3.0	5	A+AB	22.4	4.33	2.80	1.30	0.0	0.25	SNIb
27	0.02	25	24	3.0	10	A+AB	21.3	5.07	3.17	1.67	0.0	0.25	SNIb
28[d]	0.02	25	24	3.0	10	A+AB	18.9	5.08	3.19	1.66	0.0	0.32	SNIb
29	0.02	25	24	4.0	5	A + AB	21.5	4.45	2.91	1.22	0.0	0.26	SNIb
30	0.02	25	24	6.0	10	B	27.4	6.49	4.45	1.63	0.0	0.39	SNIb
31	0.02	60	40	7.0	3	A	16.8	4.95	3.70	0.25	0	0.24	SNIc
32	0.004	16	12	3.0	5	B+BB	64.75	3.91	2.22	1.54	1.6(−2)	0.24	SNIb
33	0.004	16	14	3.0	5	B+BB	19.6	3.90	2.21	1.53	1.6(−2)	0.24	SNIb
34	0.004	16	14	5.0	5	B+BB	21.8	3.84	2.19	1.51	1.2(−2)	0.24	SNIb
35	0.004	18	12	5.0	5	B+BB	14.4	4.64	2.76	1.68	1.7(−2)	0.31	SNIb
36	0.004	18	12	8.0	5	B+BB	24.33	4.56	2.68	1.67	1.5(−2)	0.33	SNIb
37	0.004	18	17	3.0	5	A+AB	18.4	4.42	2.55	1.67	2.6(−2)	0.26	SNIb
38	0.004	18	17	3.0	10	A+AB	14.4	4.58	2.61	1.77	2.7(−2)	0.26	SNIb
39	0.004	18	17	6.0	5	B+BB	27.0	4.57	2.71	1.65	1.6(−2)	0.27	SNIb
40	0.004	25	12	3.0	5	A:Contact							
41	0.004	25	12	6.0	5	B:Contact							
42	0.004	25	19	3.0	5	A+AB	10.2	7.09	4.87	2.03	6.5(−3)	0.32	SNIb
43	0.004	25	24	3.0	5	A+AB	13.0	7.31	5.05	2.07	8.7(−3)	0.28	SNIb
44	0.004	25	24	6.0	5	B:Contact							
45	0.004	40	30	4.0	5	A+AB	9.31	12.0	9.42	1.24	0.0	0.56	BH

Woosley (2019)

TABLE 8. CRITICAL MASSES IN CLOSE BINARY SYSTEMS

ZAMS Star [$M_\odot$]	Initial He star [$M_\odot$]	Pre-SN Mass [$M_\odot$]	Characteristics
<13	<2.4	-	SAGB star, WD
13 - 13.5	2.4 - 2.5	2.0 - 2.1	SAGB star, rad-expansion ECSN, fast SN Ib, little ^{56}Ni
13.5 - 16	2.5 - 3.2	2.1 - 2.6	Si Flash, rad-expansion, peculiar SN Ib
16 - 30	3.2 - 10	2.6 - 7	Ordinary SN Ib, Ic
30 - 120	10 - 60	7 - 30	Mostly BH, Massive SN Ic
120 - 140	60 - 70	30 - 35	Weak PPISN, BH
140 - 250	70 - 125	35 - 62	Strong PPISN, BH
250 - 500	125 - 250	62 - 133	PISN, no remnant
>500	>250	> 133	Black holes

PPISN will reduce the BH mass to < 46 M_O

NOTE. — These are for non-rotating solar metallicity stars using the standard mass loss rate. The "Initial He star masses" corresponding to a given ZAMS mass are quite uncertain

What makes the difference between a Ib and a Ic - i.e., why are the helium lines present in the former and not the latter. It could be a mass stripping effect – the helium has been pealed off

Initial M_{He}	Pre_SN Mass	Surface helium
3.5	2.57	0.99
5	3.43	0.99
7	4.45	0.99
9	4.87	0.49
12	5.43	0.21
16	6.34	0.21
20	7.39	0.19

Start Ic here?

What is not He at the surface is mostly C+O

Woosley (2019) Mdot*1.5

MERGERS

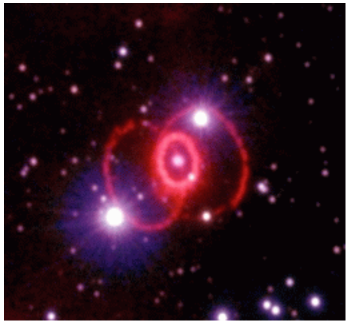
"Since a large fraction of the orbital binding energy is released in a merger, the merger process itself might resemble a faint supernova ("supernova impostor"), such as the outburst of eta Carinae in the 19th century.

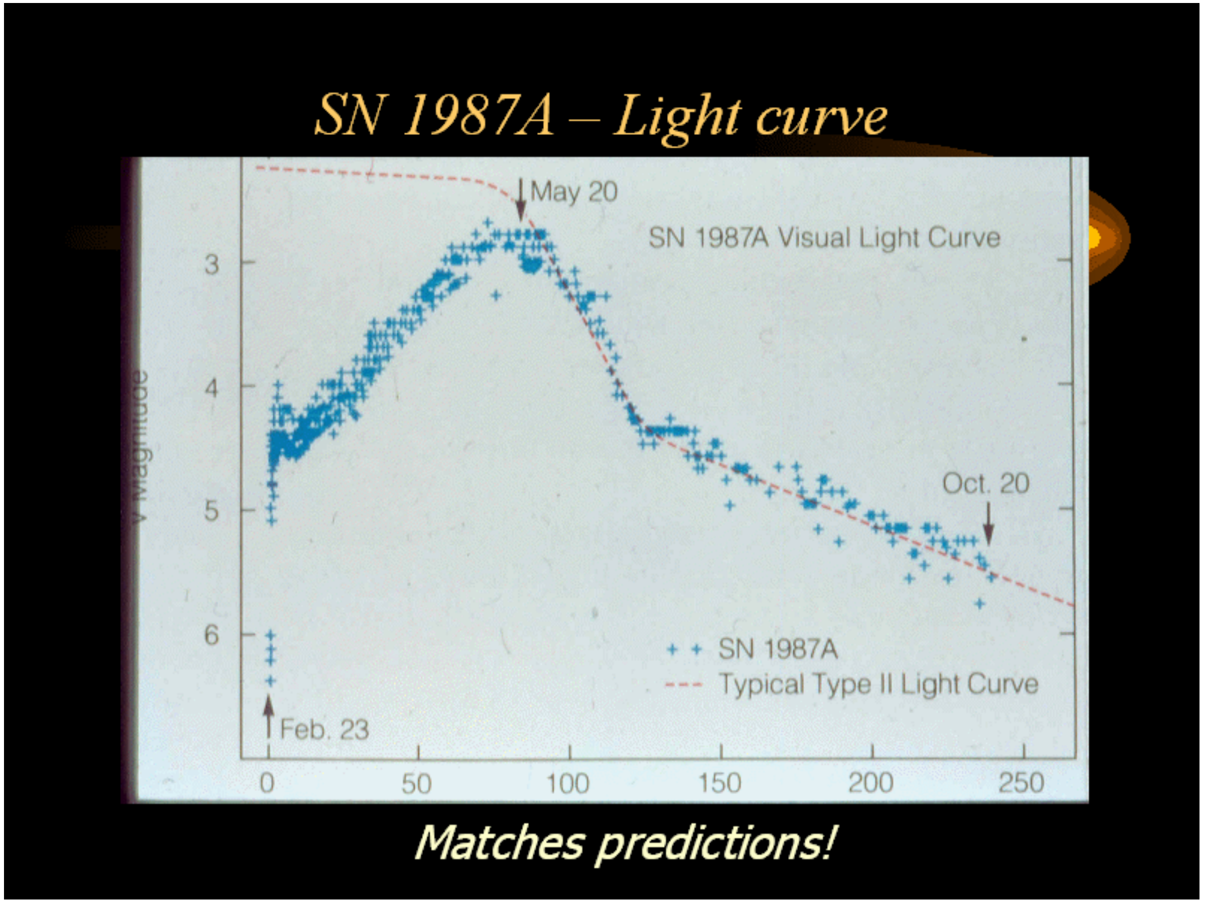
After the merger, the remnant will be a rapidly rotating supergiant, at least initially rotating near break-up at the equator. This is probably the major channel for producing B[e] supergiants, which are evolved stars rotating near breakup."

About 10% [up to 10%?] of massive stars are expected to experience a merger in their lives. The time scale may be long (radiative envelopes with steep density gradient) or long (convective envelope)

Podsiadlowski, Morris & Ivanova 2006

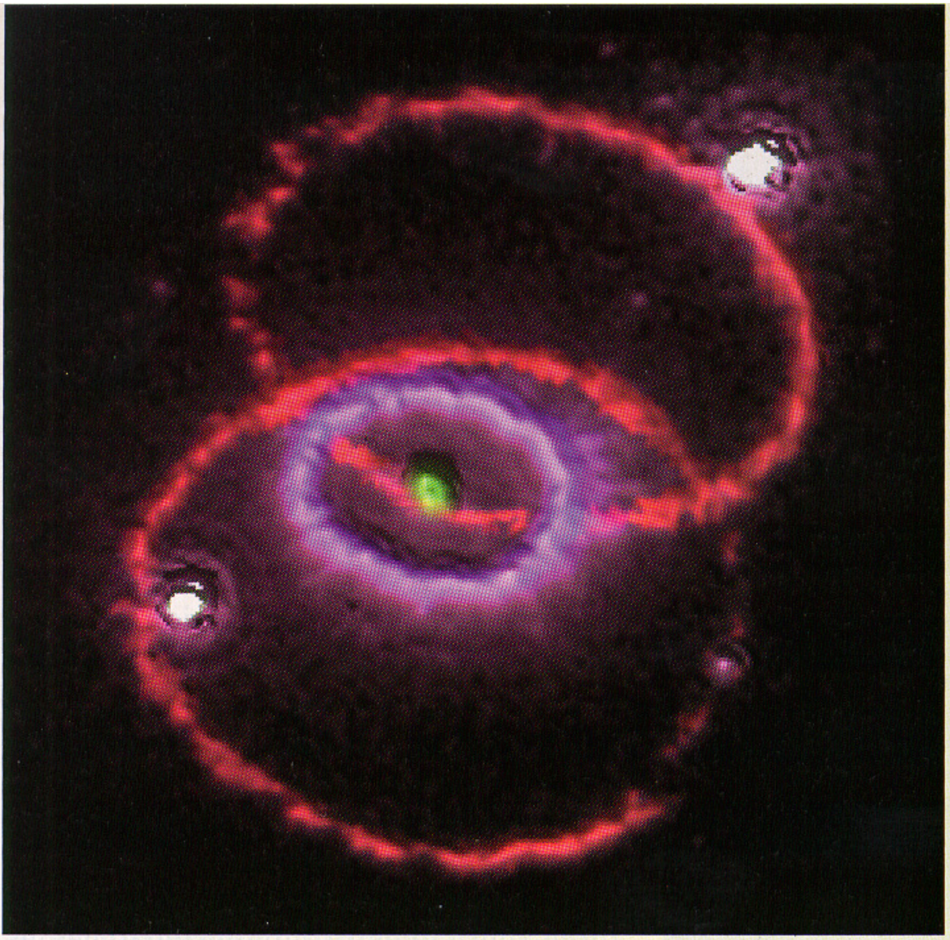
SN 1987A – the explosion of a BLUE SUPERGIANT

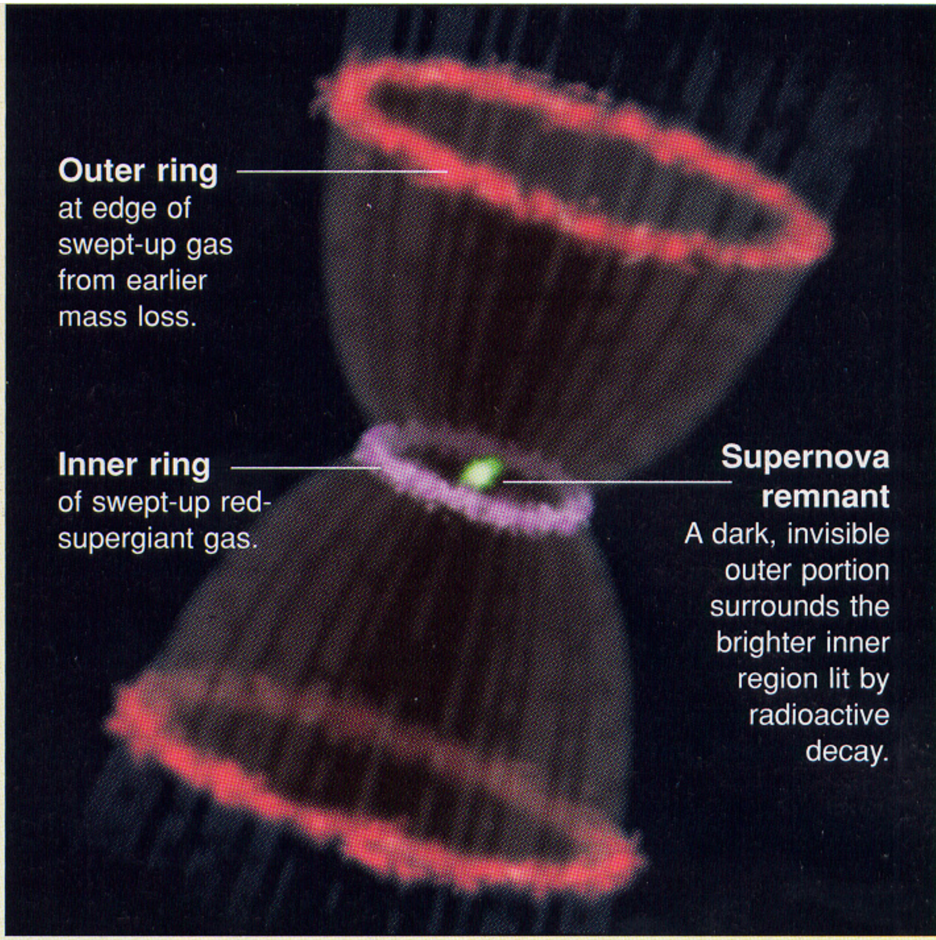




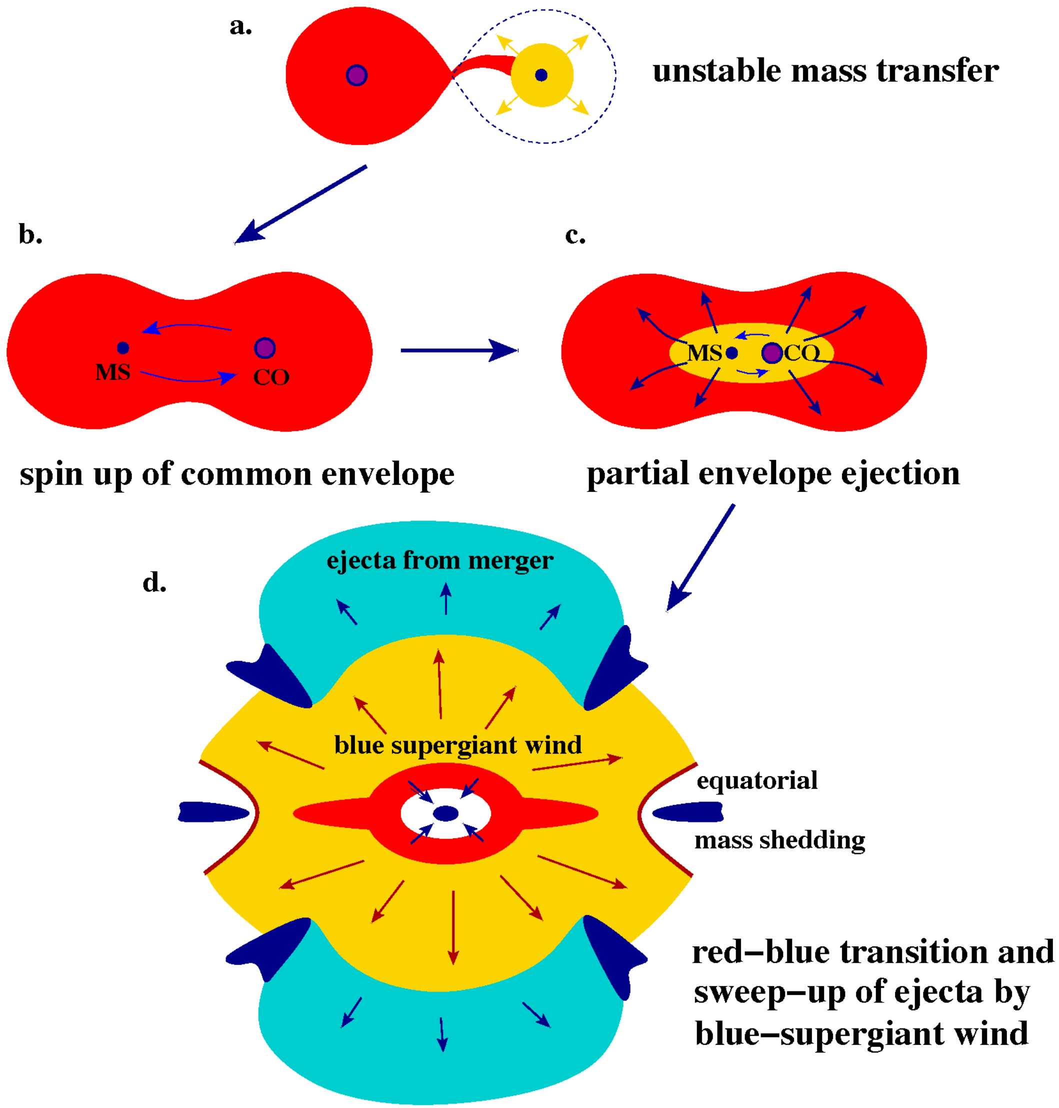
https://purcell.ssl.berkeley.edu/~korpela/astro10/html/lec11/img62.html

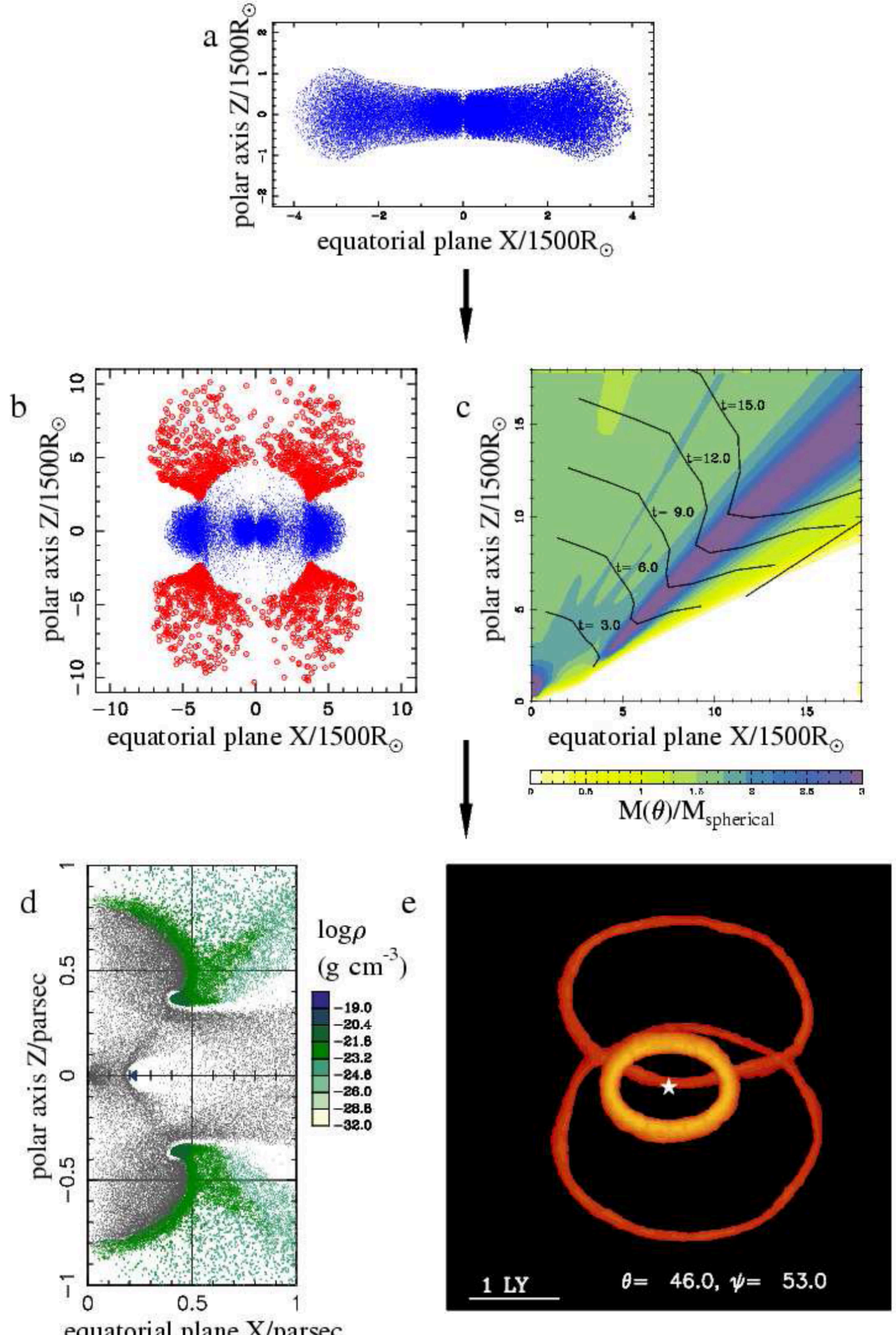
SN 1987A - Rings





Sky and Telescope


a.
unstable mass transfer
b.
MS
CO
spin up of common envelope
c.
MS
CO
partial envelope ejection
d.
ejecta from merger
blue supergiant wind
equatorial
mass shedding
red–blue transition and
sweep–up of ejecta by
blue–supergiant wind



a
polar axis Z/1500R⊙
equatorial plane X/1500R⊙
b
polar axis Z/1500R⊙
equatorial plane X/1500R⊙
c
t=15.0
t=12.0
t= 9.0
t= 6.0
t= 3.0
polar axis Z/1500R⊙
equatorial plane X/1500R⊙
M(θ)/M_spherical
d
logρ
(g cm^-3)
-19.0
-20.4
-21.8
-23.2
-24.6
-26.0
-28.8
-32.0
polar axis Z/parsec
equatorial plane X/parsec
e
1 LY
θ= 46.0, ψ= 53.0

Merger by Gravitational Radiation

Chris Hirata, CIT, Lecture XV, 12/2/11

$$t_{GW} = 3.3\times 10^{17}\ \text{years}\ \frac{\left(a/1\,\text{AU}\right)^4}{M_1 M_2\left(M_1+M_2\right)/M_\odot^3}$$

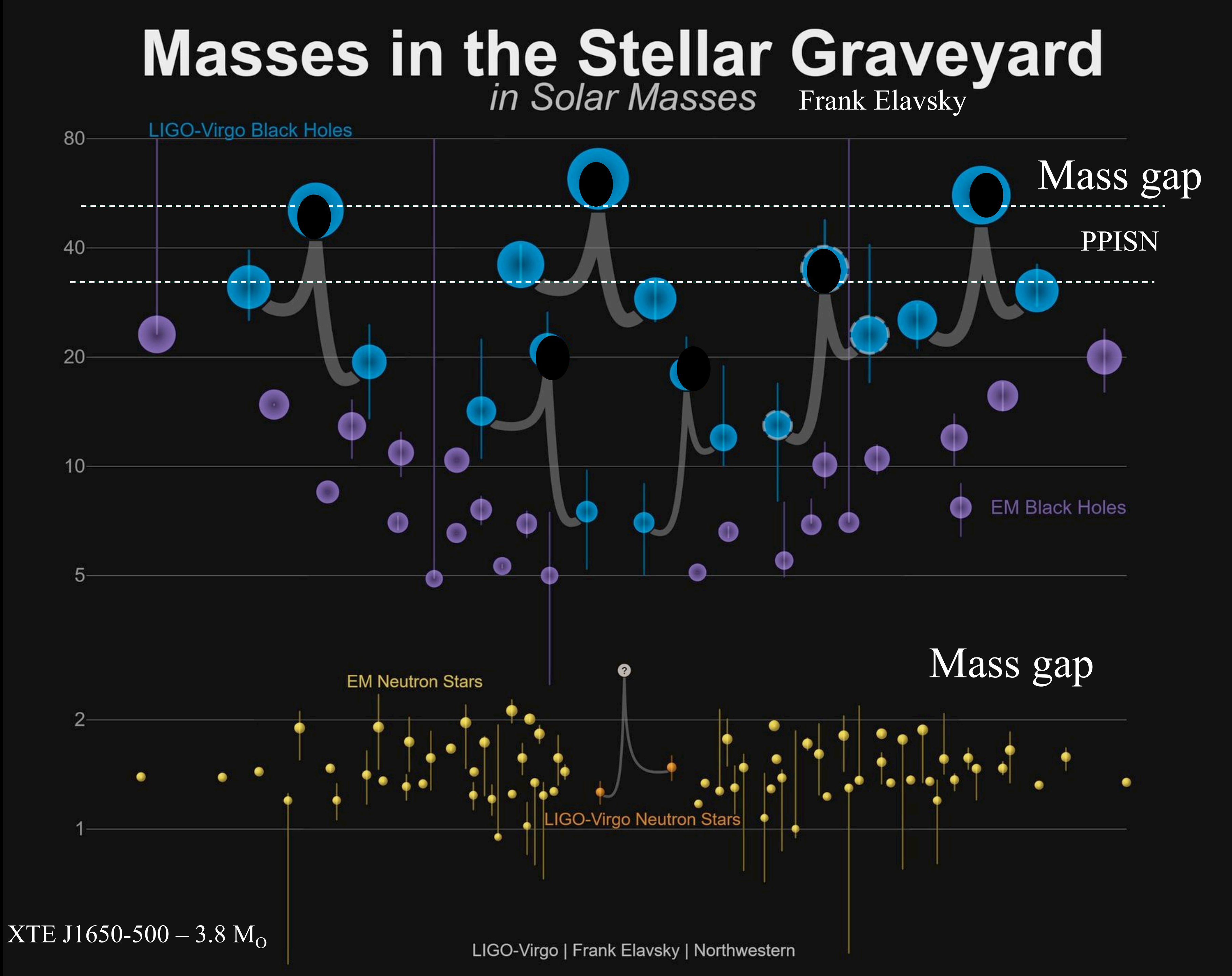
e.g., in a Hubble time, 10^{10} years, two 1.4 $M_\odot$ objects will merge if their initial separation is less than 0.02 AU, i..e., 4.3 $R_\odot$. This corresponds to an initial period of 16 hours.

Two 10 $M_\odot$ objects will merge if their separation is 19 $R_\odot$. There are many known systems of compact objects with known periods much less than this. E.g., binary pulsar 1913+16 (Taylor and Weisberg 1989) has a period of 7.75 hours.

- J0106-1000 contains a pair of WDs (0.17 M_O primary + 0.43 M_O invisible secondary) at a separation of 0.32 R_O. The two WDs will merge in 37 Myr. Probably will make a single He-burning star. Gianninas et al (2014) list about two dozen WDs that will merge in a Hubble time. Most are low mass.

- The Galactic WD merger rate per WD is R_{merge} = $(9.7 \pm 1.1) \times 10^{-12}$ yr^{-1}. Integrated over the Galaxy lifetime, this implies that 8.5-11 per cent of all WDs ever formed have merged with another WD. 15% of these mergers would have to make a SN Ia to explain the Galactic rate (Badenes and Maoz 2018). May be difficult.

- Galactic DNS merger rate of $21(+28-14)$ Myr^{-1} based on 3 Galactic DNS systems (Chruslinka et al (2017)


Masses in the Stellar Graveyard
in Solar Masses
Frank Elavsky
LIGO-Virgo Black Holes
80
40
20
10
5
2
1
Mass gap
PPISN
EM Black Holes
Mass gap
EM Neutron Stars
LIGO-Virgo Neutron Stars
XTE J1650-500 – 3.8 M_O
LIGO-Virgo | Frank Elavsky | Northwestern

For an IMF that is a power-law: $\xi(\log M)=NM^{\Gamma}$

$$\int_{M_L}^{<M>} \frac{dM}{M^{1-\Gamma}} = \int_{<M>}^{M_U} \frac{dM}{M^{1-\Gamma}} \qquad \int \frac{dM}{M^{1-\Gamma}} = \frac{M^{\Gamma}}{\Gamma}$$

$$<M>^{\Gamma} - M_L^{\Gamma} = M_U^{\Gamma} - <M>^{\Gamma}$$

$$<M> = \left(\frac{1}{2}\right)^{1/\Gamma} (M_U^{\Gamma} + M_L^{\Gamma})^{1/\Gamma}$$

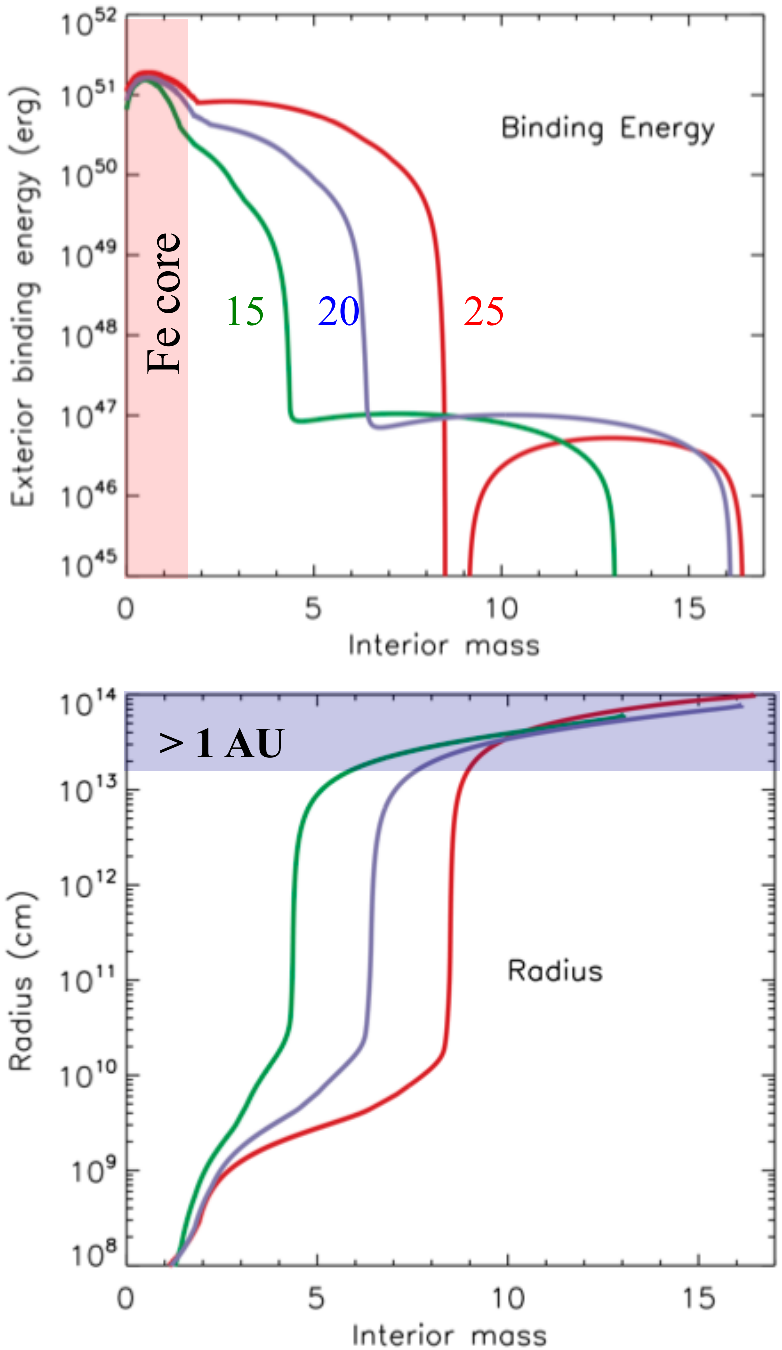
$$\boxed{<M> \approx 0.5^{1/\Gamma} M_L \approx 1.67 M_L} \qquad if\ M_U \gg M_L$$

$$\Gamma = \frac{d\log\xi}{d\log M} \approx -1.35 \qquad (Salpeter)$$

This gives the average mass above a certain threshold for an assumed power law slope.

For example, if all stars above 9 solar masses become supernovae, the median supernova mass is (9)(1.67) = 15 solar masses. If only stars from 9 to 20 M_O become supernovae, retain the M_U term and get 13 solar masses. *Half of all supernovae probably come from stars lighter than 13 M_O.*

$$dN = \xi(\log M)\, d(\log M)\, \frac{dt}{T_0}$$



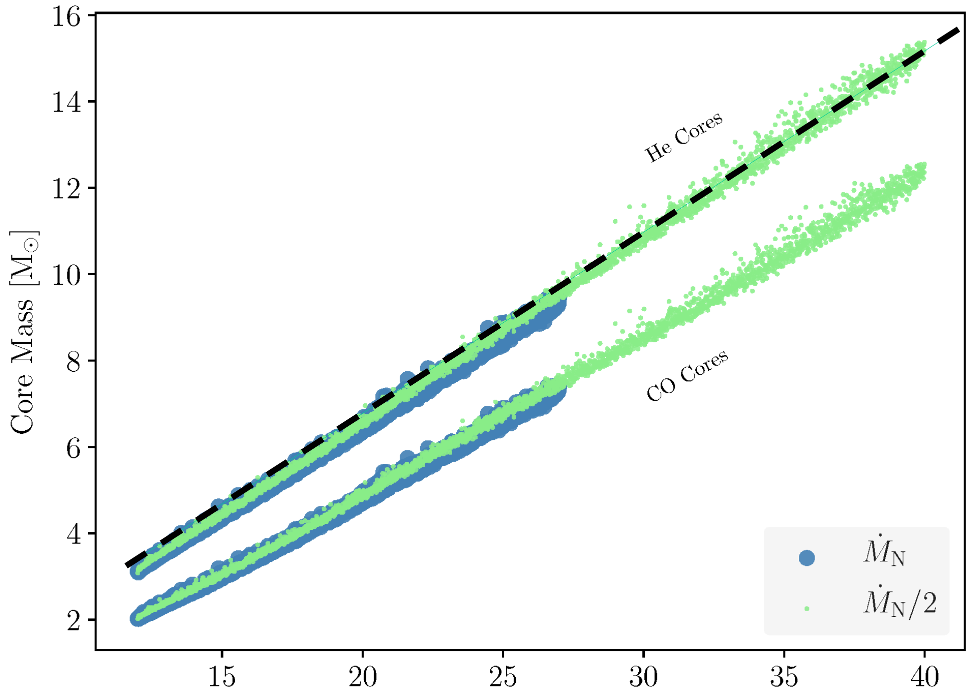
For massive stars that would make black holes the relevant mass is generally the helium core.

The hydrogen envelope is very loosely bound and has a large radius.

PreSN mass loss, gravity waves, neutrino mass loss, binary interaction would all act to remove the envelope.

$$1\,M_\odot \textit{ of ionized hydrogen at } 13.6\ eV\,/\,atom = 2.6\times10^{46}\ \text{erg}$$

Simple Estimate of Average BH Mass



$$M_{He\,core} = 0.43 M_{ZAMS} - 2.0\,M_\odot \qquad M_{ZAMS} < 27\,M_\odot$$
$$= 0.51 M_{ZAMS} - 4.2\,M_\odot \qquad M_{ZAMS} \geq 27\,M_\odot$$

$4.4\,M_\odot$ at $M_{ZAMS} = 15\,M_\odot$

$16.2\,M_\odot$ at $M_{ZAMS} = 40\,M_\odot$

If assume a) zero mass loss and b) all stars above 18 M_O make black holes then the average black hole mass is 5/3 *18 = $\boxed{30\ M_O.}$ The average helium core mass, a better estimate of black hole mass in a binary is the helium core mass 0.51*30 -4.2 = $\boxed{11.1\ M_O.}$

These are both very approximate. The envelope may not all fall in or may be lost to winds and the helium core may lose mass after being uncovered in a binary system. 18 M_O is not a sharp cutoff, etc.

Stellar Death Summary
Single Stars

He Core *well known*	Main Seq. Mass *Poorly known*	Supernova Mechanism without rotation
$1.5 \leq M \leq 3.5$	$8 \leq M \leq 13$	Electron capture on lower end Fe core collapse. Neutron star.
$3.5 \leq M \leq 32$	$13 \leq M \leq 75$	Fe core collapse to neutron star or a black hole.
$32 \leq M \leq 62$	$75 \leq M \leq 140$	Pulsational pair instability followed by Fe core collapse to a black hole
$62 \leq M \leq 133$	$140 \leq M \leq 260$	Pair instability supernova (single pulse, no remnant)
$M \geq 133$	$M \geq 260$	Pair instability. Black hole, no explosion

Heger and Woosley (ApJ, 2002, 2016)
Woosley (ApJ 2017)

STELLAR DEATH SUMMARY - BINARIES

Woosley (2019)

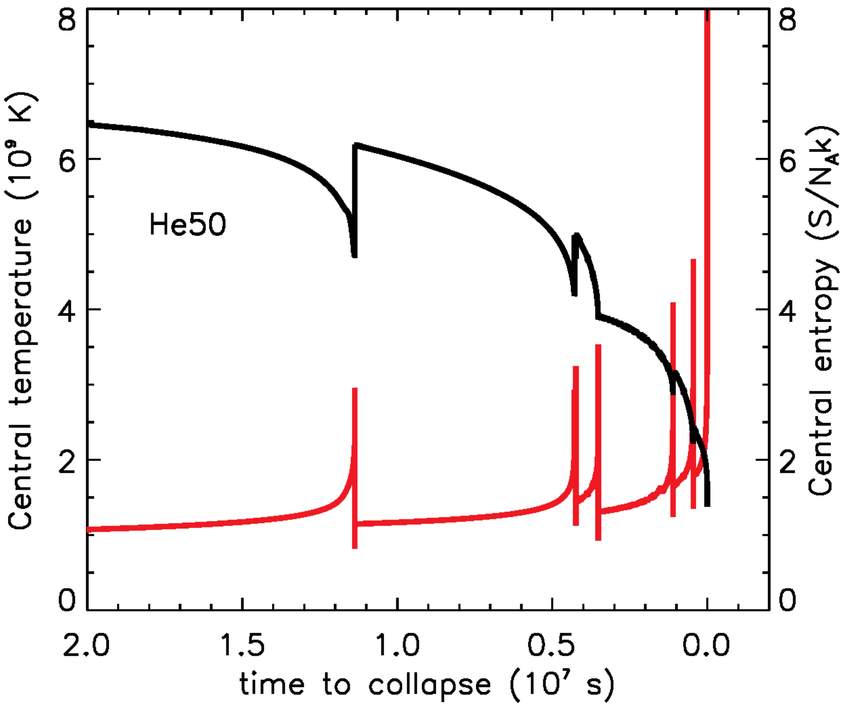
TABLE 8. CRITICAL MASSES IN CLOSE BINARY SYSTEMS

ZAMS Star [$M_\odot$]	Initial He star [$M_\odot$]	Pre-SN Mass [$M_\odot$]	Characteristics
<13	<2.4	-	SAGB star, WD
13 - 13.5	2.4 - 2.5	2.0 - 2.1	SAGB star, rad-expansion ECSN, fast SN Ib, little ^{56}Ni
13.5 - 16	2.5 - 3.2	2.1 - 2.6	Si Flash, rad-expansion, peculiar SN Ib
16 - 30	3.2 - 10	2.6 - 7	Ordinary SN Ib, Ic
30 - 120	10 - 60	7 - 30	Mostly BH, Massive SN Ic
120 - 140	60 - 70	30 - 35	Weak PPISN, BH
140 - 250	70 - 125	35 - 62	Strong PPISN, BH
250 - 500	125 - 250	62 - 133	PISN, no remnant
>500	>250	> 133	Black holes

PPISN will reduce the BH mass to < 46 M_O

NOTE. — These are for non-rotating solar metallicity stars using the standard mass loss rate. The "Initial He star masses" corresponding to a given ZAMS mass are quite uncertain

$70\ M_O < M < 140\ M_O$
Pulsational Pair Instability Supernovae (PPISN)

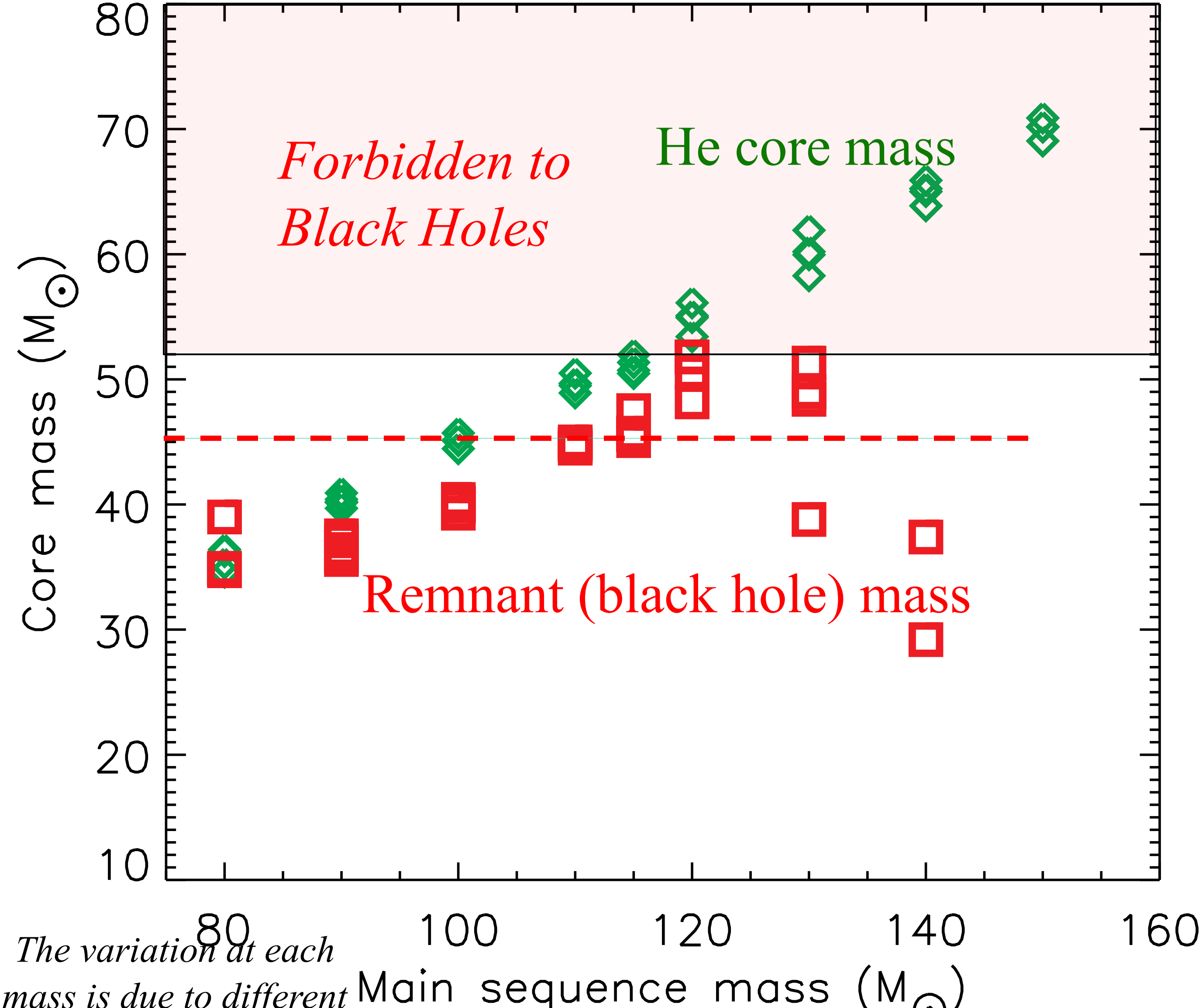


E.g., 50 $M_\odot$ helium core pulses until 46.7 $M_\odot$ is left then evolves to core collapse

- A thermonuclear instability encountered at oxygen ignition that affects helium cores from 30 to 65 M_O . Main sequence masses 70 M_O to 140 M_O.
- Usually removes all remaining hydrogen envelope and part of the remaining helium core before collapsing to a black hole. Easy to model explosion, but mass loss history is uncertain.
.
- Rare events, ~1% of super-novae neglecting mass loss. Probably much lower in regions of solar metallicity.

Woosley (2017)

64 models

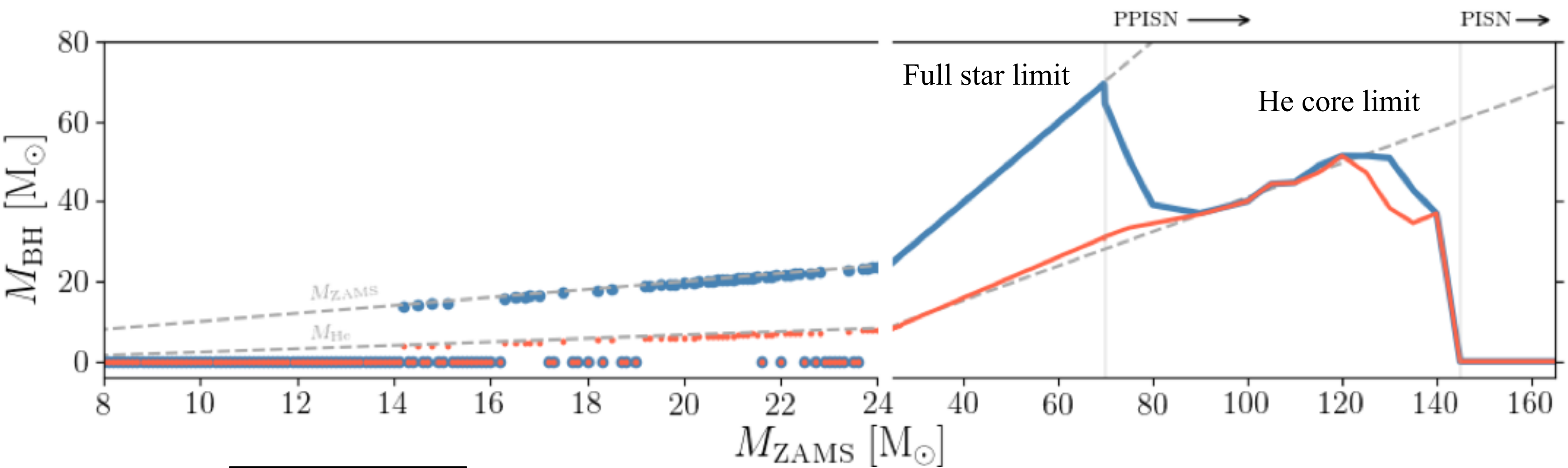


No black holes will be born in close binaries with mass between 52 and 133 solar masses. Many will have masses near 35 – 45 solar masses

No remnant until 260 M_O

The variation at each mass is due to different assumed mass loss rates in the precollapse star

No Mass Loss Except for PPISN



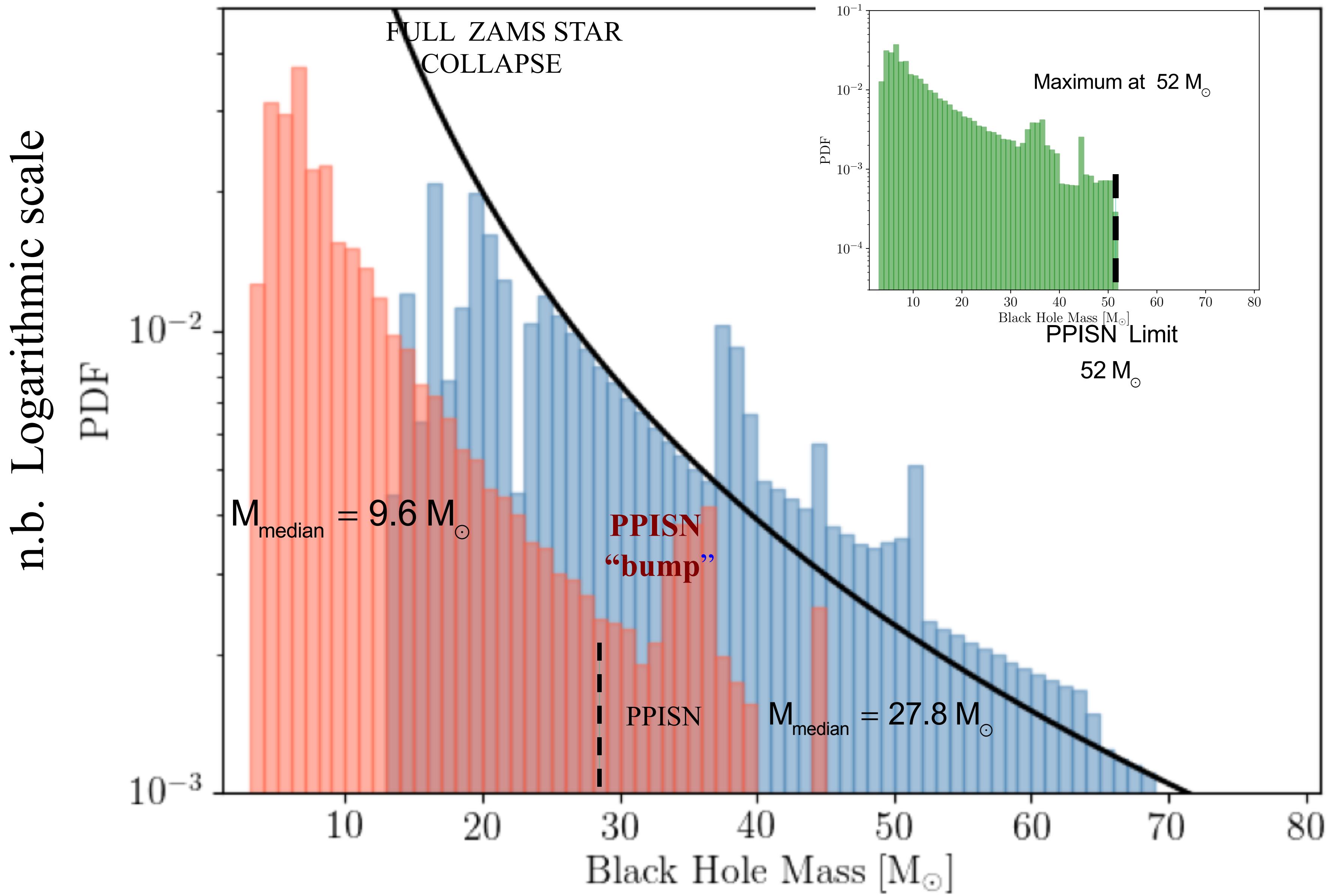
For $M < 70\ M_O$, blue points are the original mass of the star and red, the helium core. Might be appropriate for Pop III

No black hole at all for masses above ~70 M_O (PPISN threshold) up to 133 M_O (He cores at top of PPSN range)

No black hole masses above 52 M_O derived from stars that have lost their envelopes (or never had one)

Seeing a ~65 M_O BH in a merger might require a dynamical origin

Zero Mass Loss Limit (Pop III?)



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Whereas Chris Belczynski and Daniel Holz believe that astrophysical black holes should not exist in the mass range between 55 and 130 solar masses because of pair instability;

and whereas Carl Rodriguez and Sourav Chatterjee believe that such black holes could form in dynamical environments and continue to participate in mergers;

they wager a \$100 bottle of wine that, within the first 100 GW compact binary coalescence detections, at least one will have a component in the 55 – 130 $M_\odot$ range. If individual events have mass ranges straddling the interval boundary, the betting parties agree that Ilya Mandel will serve as an arbiter of the statistical evidence.

Signed in Aspen, CO, on 10 Feb. 2017

Chris Belczynski
/Chris Belczynski/

/Daniel Holz/

Carl Rodriguez
/Carl Rodriguez/

Sourav Chatterjee
/Sourav Chatterjee/

/Witnessed by Ilya Mandel/

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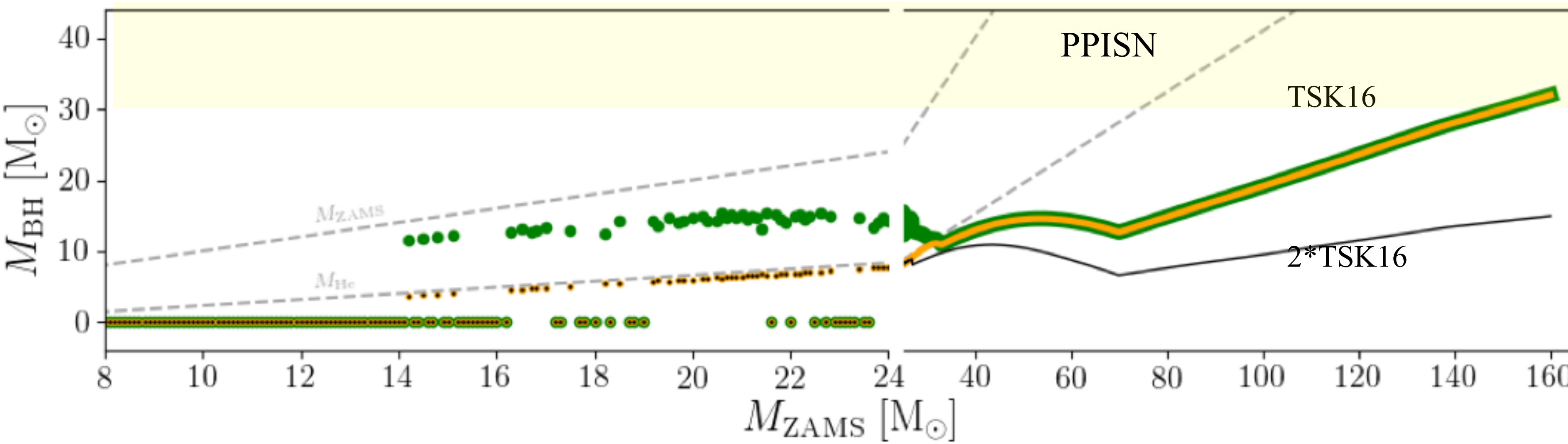
Solar Metallicity, Normal Mass loss

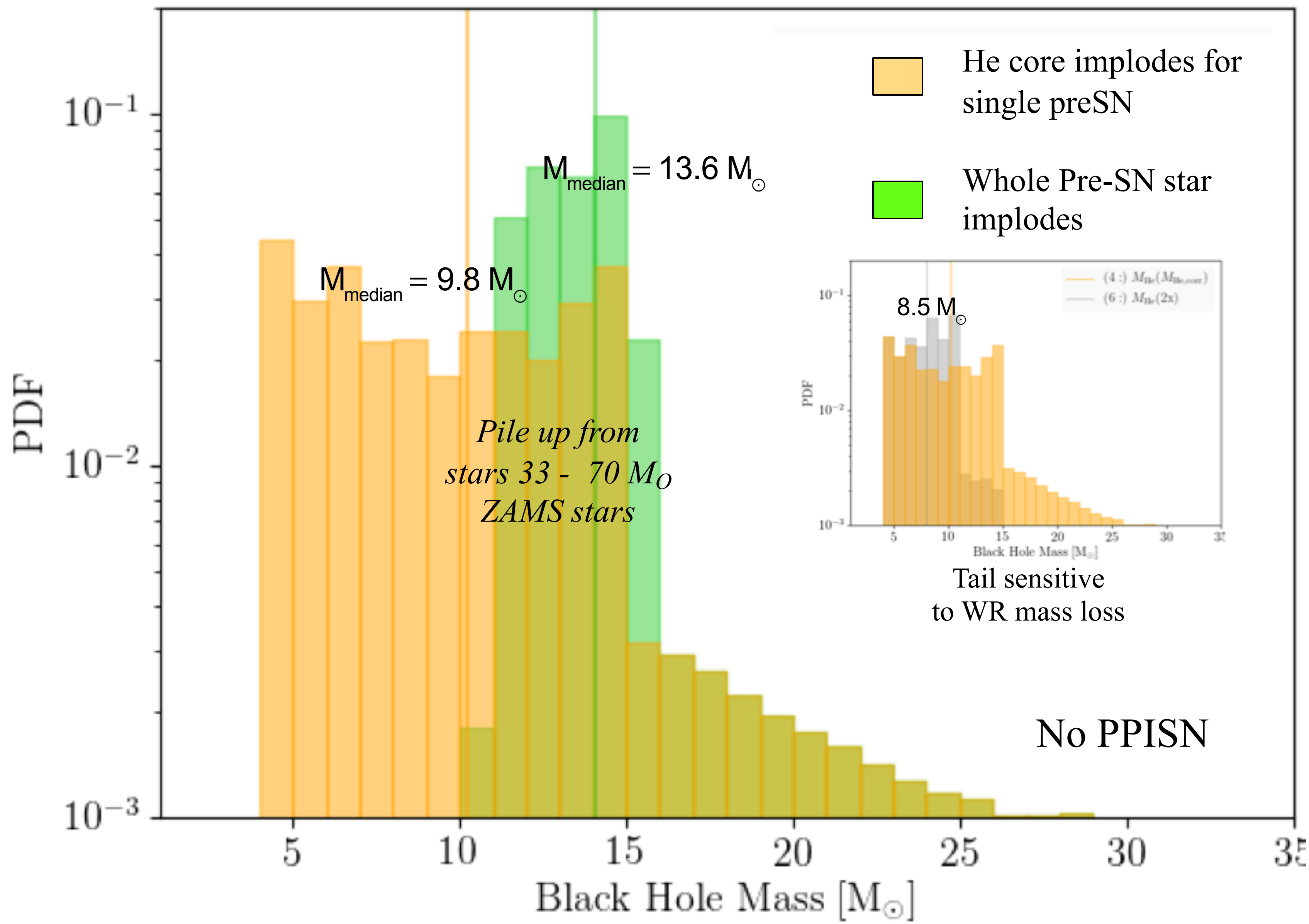


Green points are the full presupernova mass and yellow points are the helium cores – assuming envelope retention .

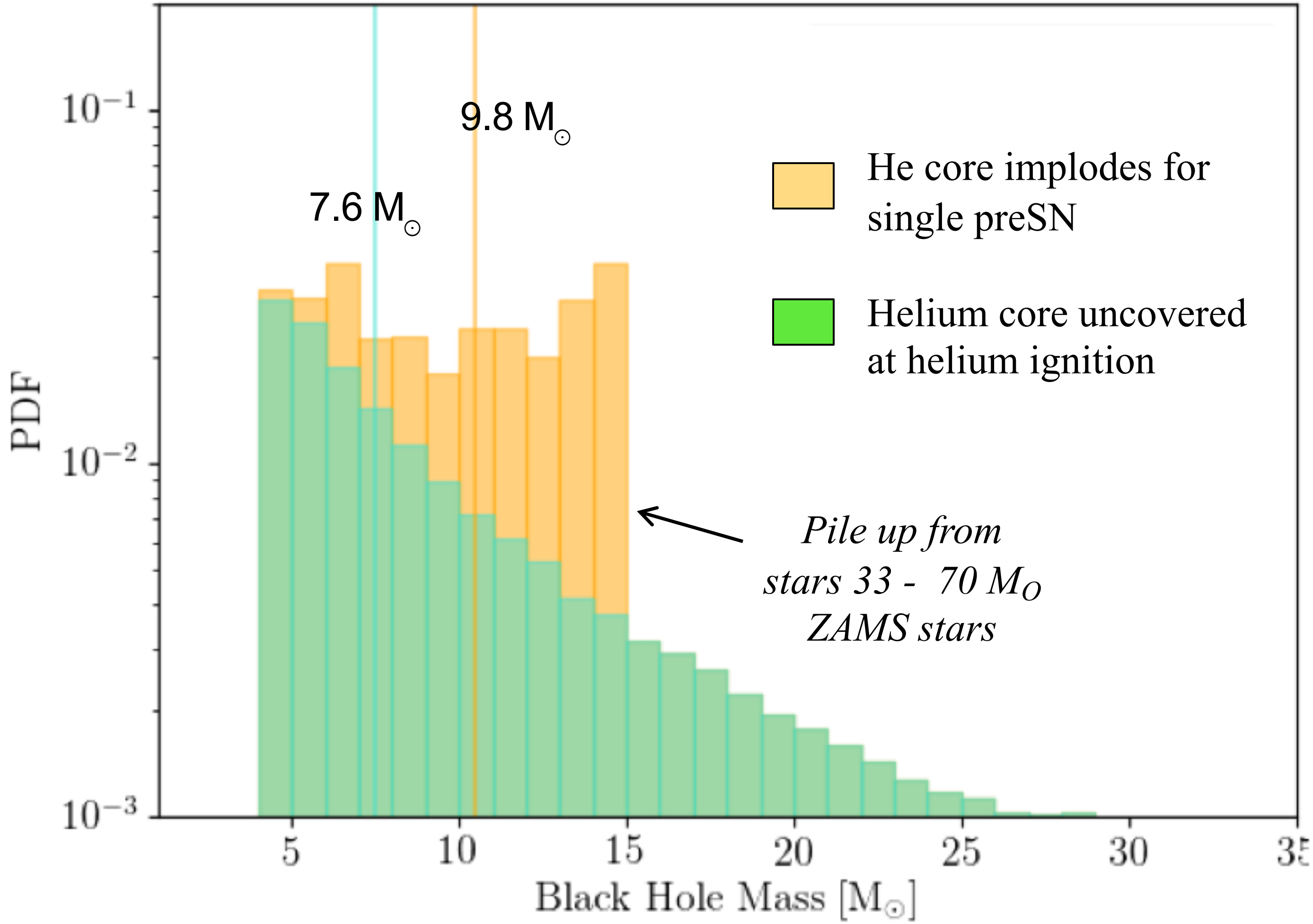
Above 33 M_O the helium core is revealed and experiences mass loss according to Tramper, Sans, and DeKoter (2016). Similar results to Ekstrom et al (2012)

Between 33 and 70 M_O mass loss is less because appreciable helium is burned before the envelope is lost

Solar Metallicity; Normal Mass Loss, Single stars



Correction for binary evolution - in progress



Single stars - helium core collapses (after uncovering and mass loss in stars over 32 M_O) – orange

Bare helium cores uncovered at onset of helium core burning plus TSK16 mass loss - turquoise [also appropriate for CHE]

	Minimum	Maximum	Median	Mean
No mass loss Full star collapse	13.8	69.4	27.8	31.2
Normal mass loss Full star collapse	10.9	32.0	13.6	14.1
No mass loss Helium core collapse	3.71	51.4	9.6	13.7
Normal mass loss Helium core collapse	4.01	32.0	9.8	10.3
WR-Mass loss rate times 2	4.00	14.9	8.4	8.0
Bare cores	6.90	46.0	~10	~10

unlikely