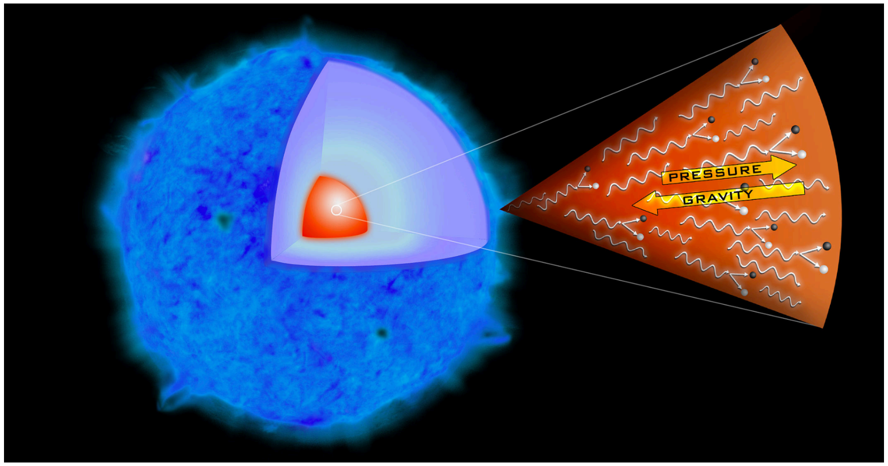
Lecture 18

Pair Instability Supernovae,



The bigger the star the greater the binding energy that must be provided to reverse the implosion. Thus bigger stars achieve a higher "bounce" temperature and burn more fuel to heavier elements.

$M_{ZAMS} \geq 85\,M_\odot$ — Barkat, Rakavy and Sack (1967); Rakavy, Shaviv and Zinamon (1967)

$M(\text{helium core}) \geq \sim 35\ M_\odot$

- Helium core mostly convective and radiation a large part of the total pressure. $\Gamma \sim 4/3$. Contracts and heats up after helium burning. Ignites carbon burning radiatively while already contracting rapidly.

- Above 1×10^9 K, pair neutrinos accelerate the evolution. Contraction accelerates. Pair concentration increases. Energy goes into rest mass of pairs rather than increasing pressure, $\Gamma < 4/3$.

- Oxygen and (off-center) carbon burn explosively liberating a large amount of energy. At very high masses, silicon burns to ^{56}Ni. At still higher masses photo-disintegration is encountered and the collapse continues.

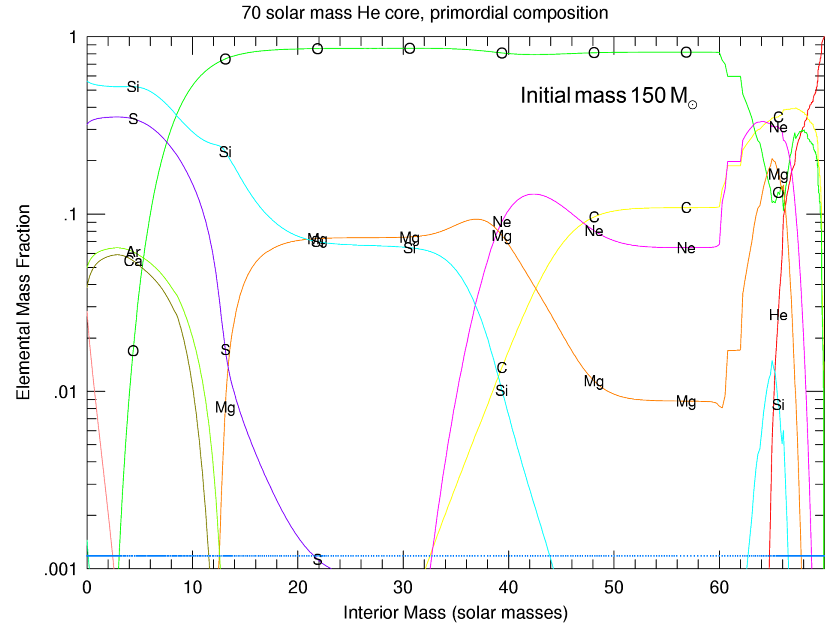
- The star completely, or partially explodes for helium cores up to 133 solar masses. Above that a black hole is formed.

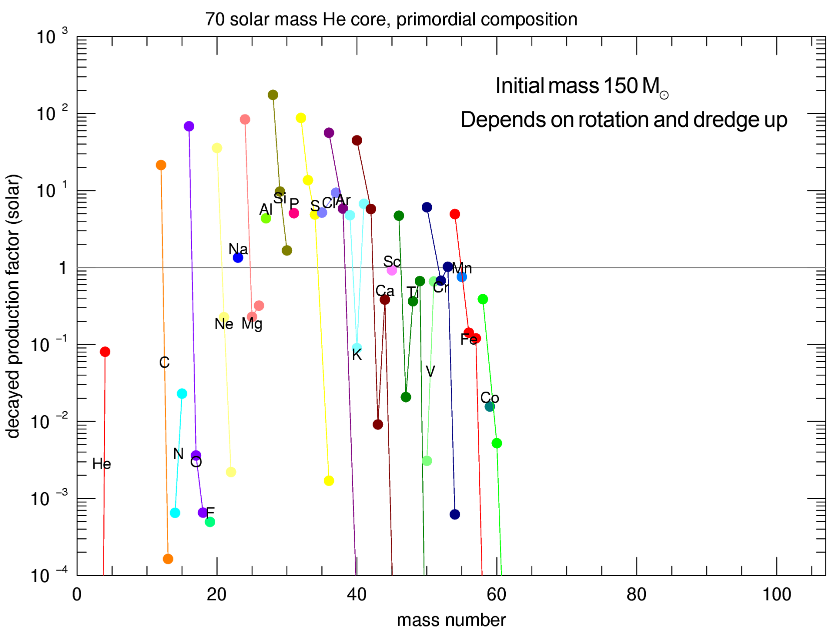
Mass	T_c (K)	ρ_c (g cm^{-3})
65	1.741×10^9	3.158×10^5
70	3.570×10^9	2.001×10^6
75	3.867×10^9	2.544×10^6
80	3.876×10^9	2.316×10^6
85	4.025×10^9	2.479×10^6
90	4.197×10^9	2.699×10^6
95	4.355×10^9	2.902×10^6
100......	4.533×10^9	3.195×10^6
105......	4.720×10^9	3.577×10^6
110......	4.931×10^9	4.079×10^6
115......	5.140×10^9	4.637×10^6
120......	5.390×10^9	5.423×10^6
125......	5.734×10^9	6.766×10^6
130......	6.169×10^9	9.012×10^6

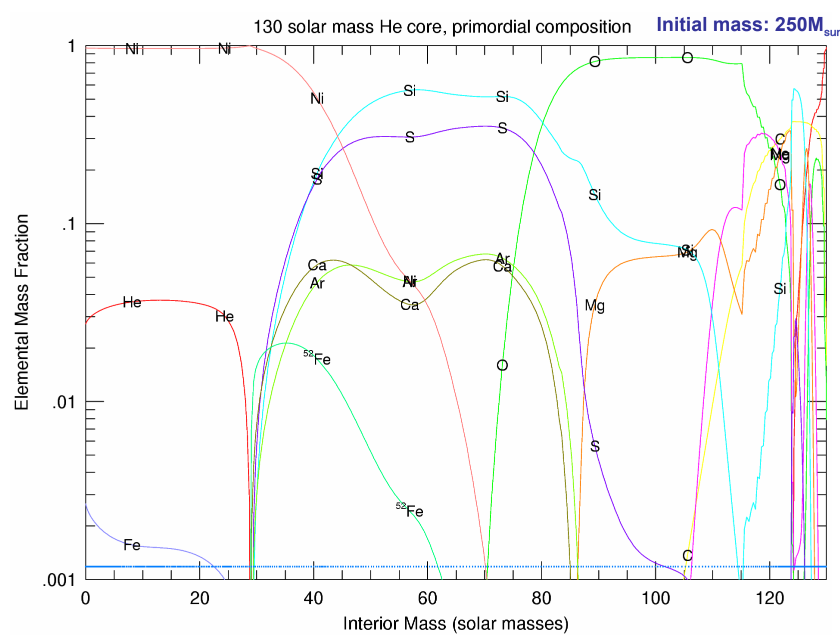
PAIR INSTABILITY SUPERNOVAE

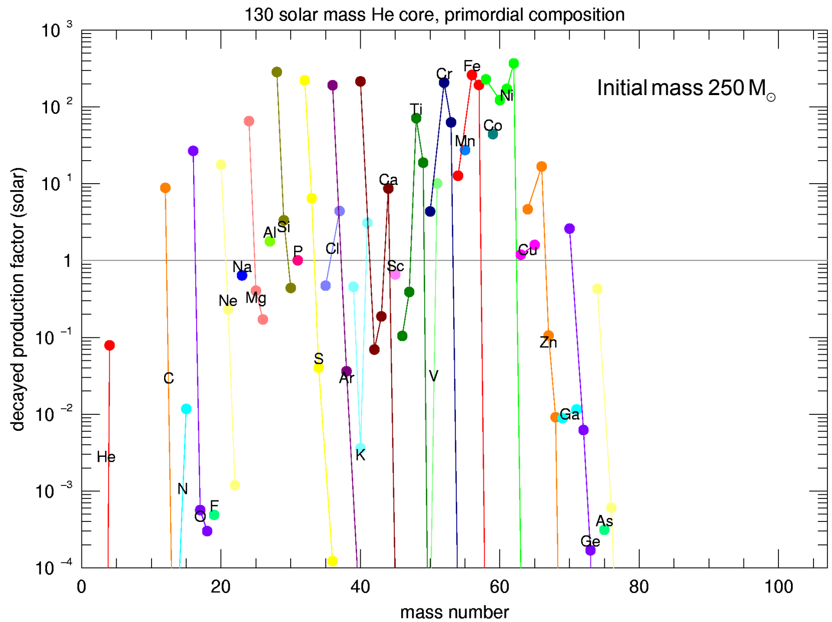
He Core	Main Seq. Mass	Supernova Mechanism
$2 \le M \le 35$	$10 \le M \le 85$	Fe core collapse to neutron star or a black hole
$35 \le M \le 60$	$85 \le M \le 140$	Pulsational pair instability followed by Fe core collapse
$60 \le M \le 133$	$140 \le M \le 260$	Pair instability supernova (single pulse)
$M \ge 133$	$M \ge 260$	Black hole

Woosley, Blinnikov and Heger (Nature 2007)







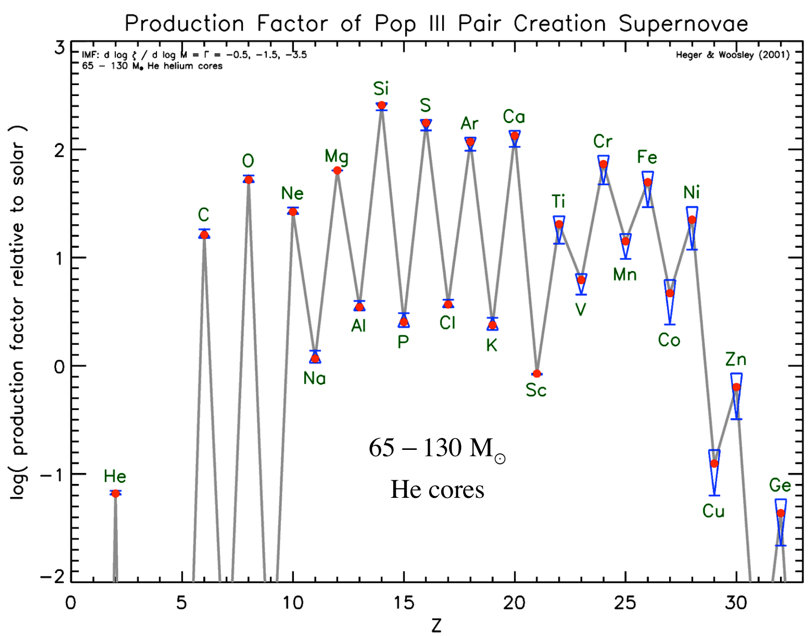


Big odd-even effect and deficiency of neutron rich isotopes.

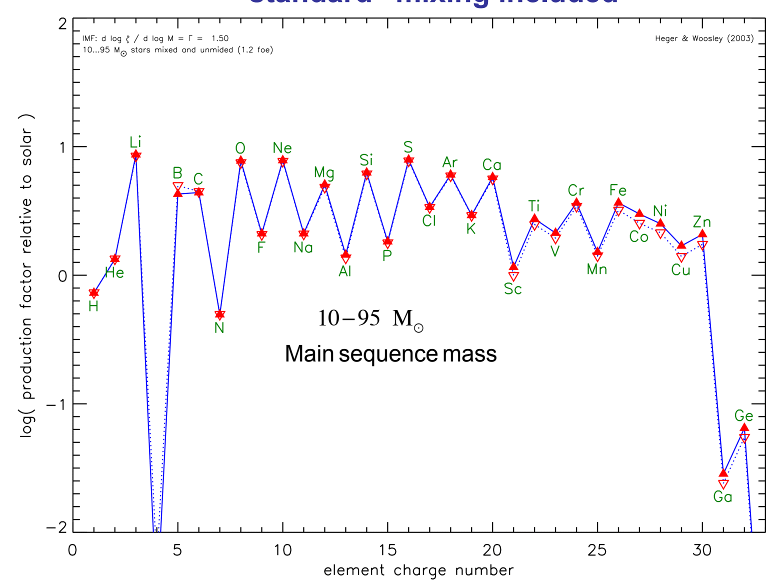
Star explodes right after helium burning so neutron excess is determined by initial metallicity which is very small.

$$\mathrm{CNO} \rightarrow {}^{14}\mathrm{N}\ (\alpha,\gamma)\ {}^{18}\mathrm{F}\ (\mathrm{e}^{+}\upsilon)\ {}^{18}\mathrm{O}\ (\alpha,\gamma)^{22}\ \mathrm{Ne}$$

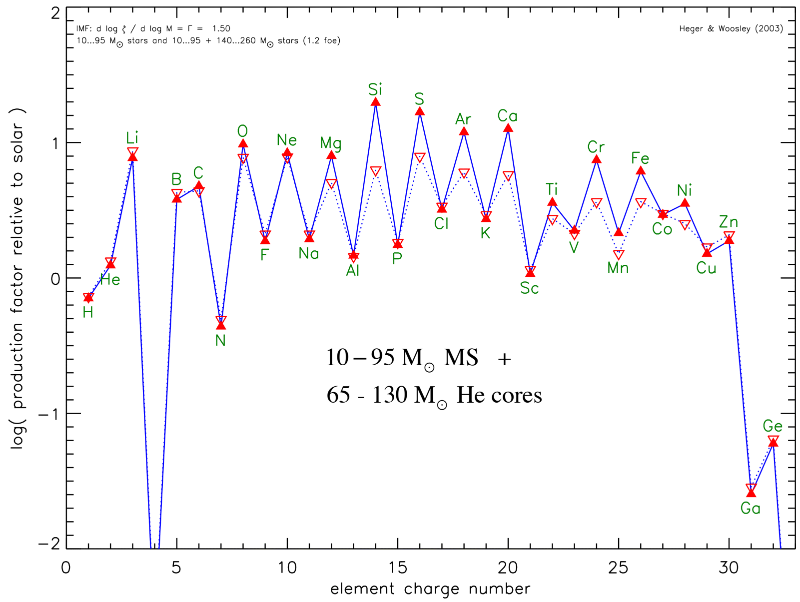
$$\eta \approx 0.002 \left(\frac{Z}{Z_{\odot}} \right)$$



Production factor of massive Pop III stars – "standard" mixing included



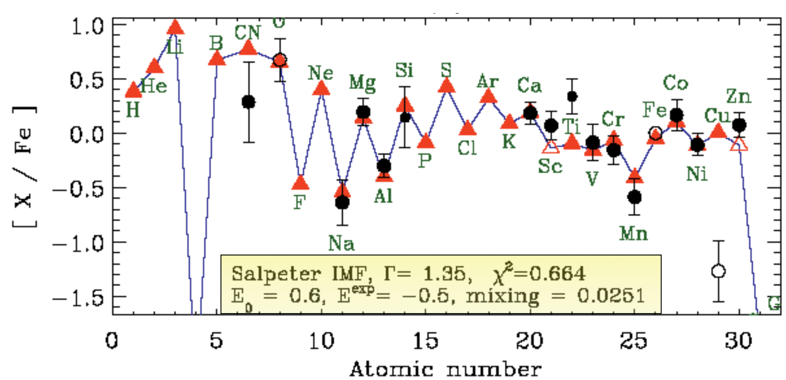
Production factor of massive and very massive Pop III stars



Very metal poor stars do not show such large odd-even effects and this is sometimes taken to imply that the number of these very massive stars was small.

However, the production of the iron group does not begin until quite heavy masses so this does not preclude some subset of pair instability supernovae from being “first generation stars”.

Lai et al. 2008, *ApJ*, **681**, 1524

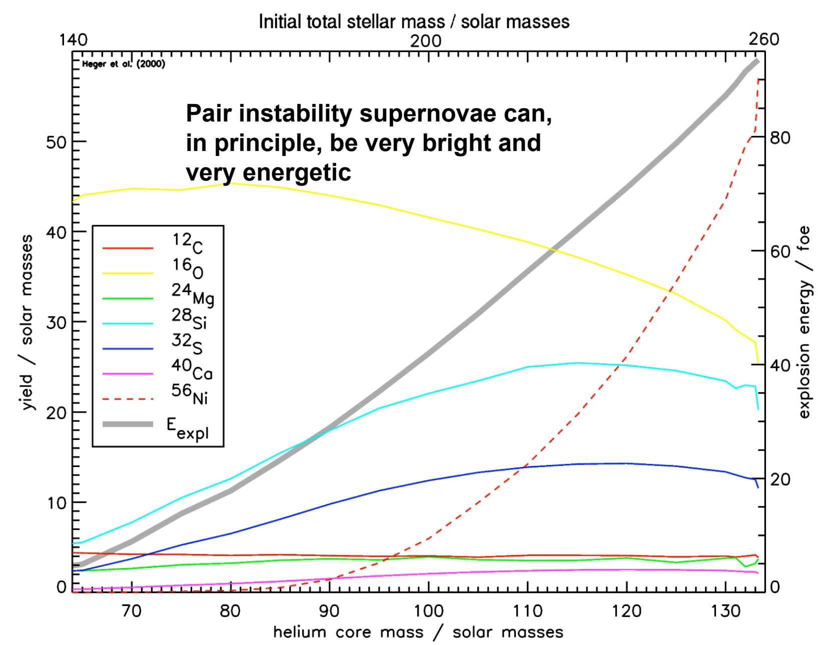


28 metal poor stars in the Milky Way Galaxy
-4 < [Fe/H] < -2; 13 are < -.26

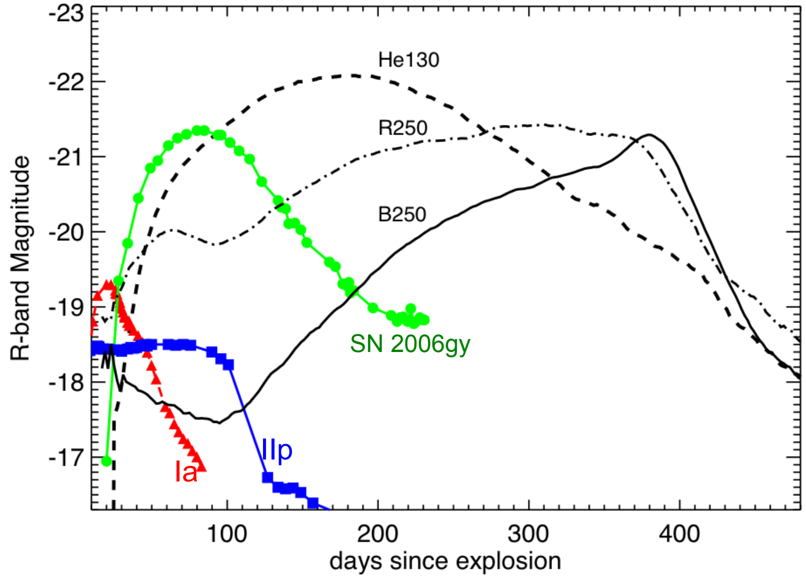
Cr I and II, non-LTE effects; see also Sobeck et al (2007)

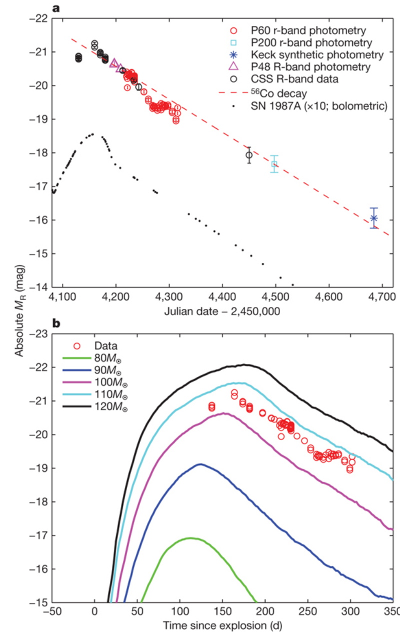
$KE = E_o (20/M)^{E_{exp}}$ B

mixing 0.1 would have been "normal"



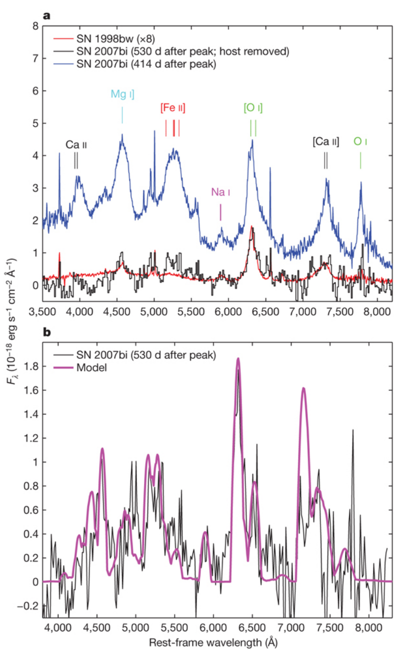
Some are very bright





Gal-Yam et al (2009, *Nature*), SN 2007bi may have been (they say "was") a pair-instability supernova.

Best fit requires a helium core with about 100 solar masses and an explosion energy ~10^{53} erg.



The late time spectrum suggests the presence of 8 to 11 solar masses of ^{56}Ni was made in the explosion (^{56}Fe by the time the observations were made).

Red-shifted light curve of a bright pair-instability SN

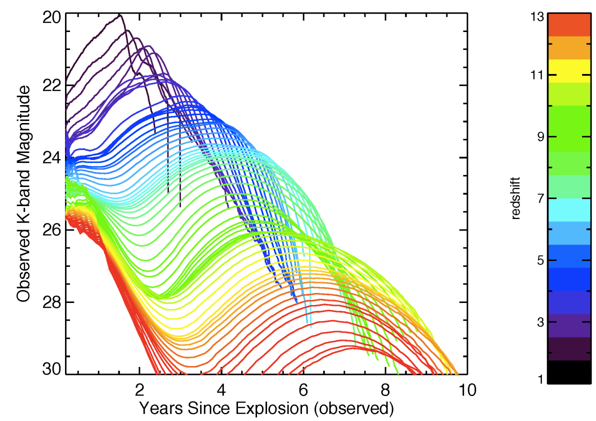
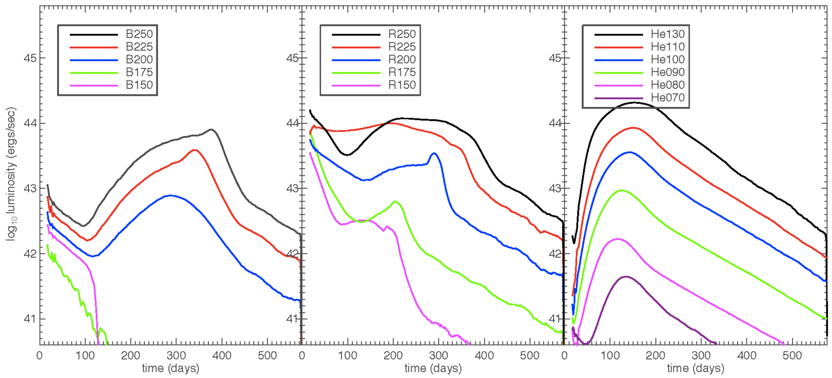


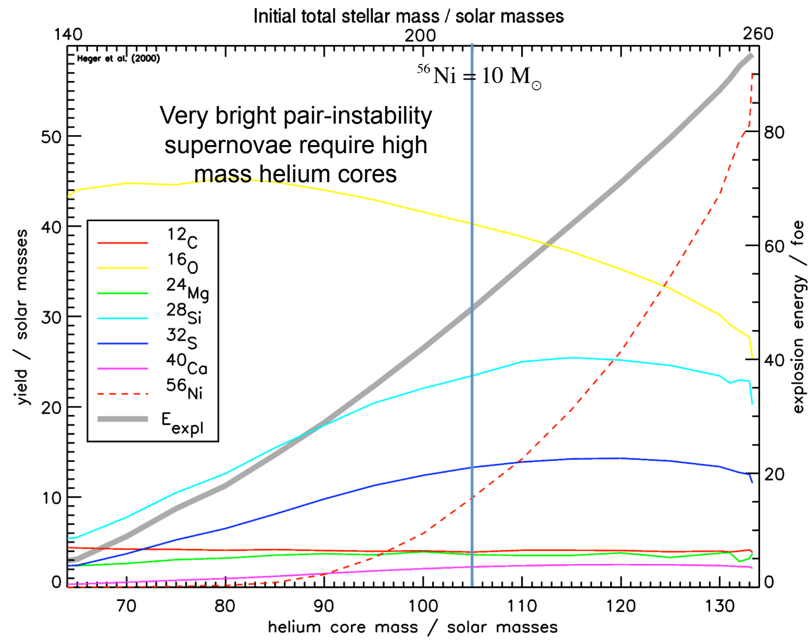
Fig. 12.— Observed K-band light curve of model R250 as a function of redshift. The effects of cosmological redshift, dimming, and time-dilation have all been included. For $z > 7$, one is observes the rest-frame UV, and the initial thermal component of the light curve is brighter than the later radioactively powered peak.

But actually a wide variety of outcomes is possible

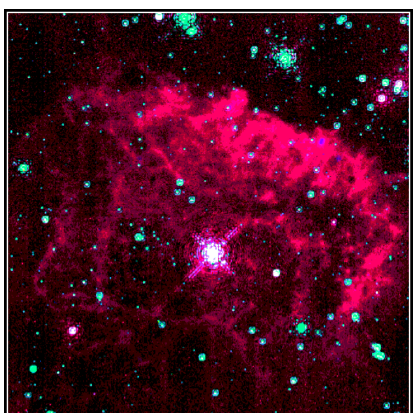


Blue Supergiants — Red Supergiants — Helium Cores

(Kasen, Woosley and Heger 2011)



The great uncertainty is whether the stars that make them both formed and retained the necessary high helium core mass when the star died.

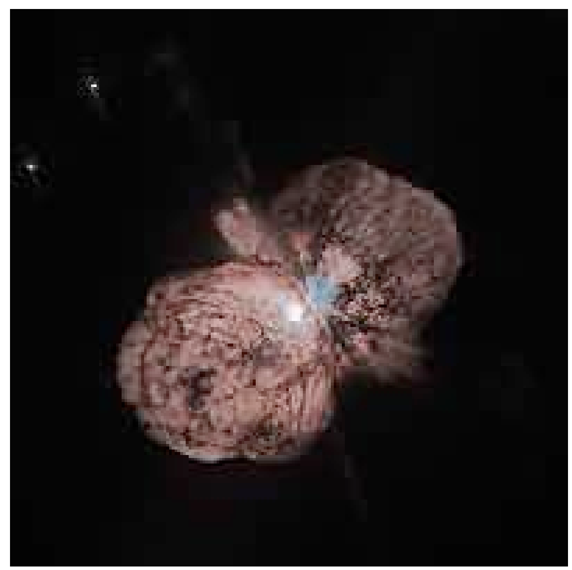


Pistol Nebula and Massive Star HST • NICMOS
PRC97-33 • ST ScI OPO • D. Figer (UCLA) and NASA

Particularly uncertain is the mass loss rate for luminous blue variable stars. Could some stars retain enough mass to be pair SN even today?

The Pistol Star

- Galactic star
- Extremely high mass loss rate
- Initial mass: 150 (?)
- Will die as much less massive object



Eta Carina

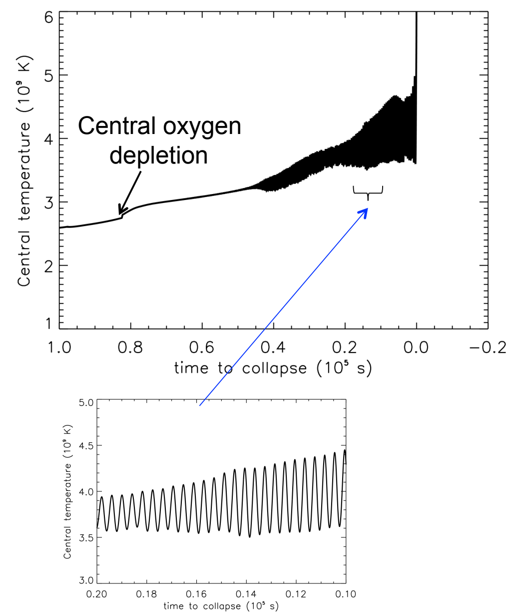
Thought to be over 100 solar masses

Giant eruption in 1843. Supernova-like energy release. 2nd rightest star in the sky. V = -0.8
12 - 20 solar masses of material were ejected in less than a decade.

8000 light years distant. Doubled its brightness in 1998- 1999. Now visble V = 4.7.

Pulsational Pair Instability
(should be more common than PSN)

Starting at helium core masses ~35 solar masses, or about 85 solar masses on the main sequence, post carbon-burning stars experience a pulsational instability in nuclear energy generation that comes about because of pair production



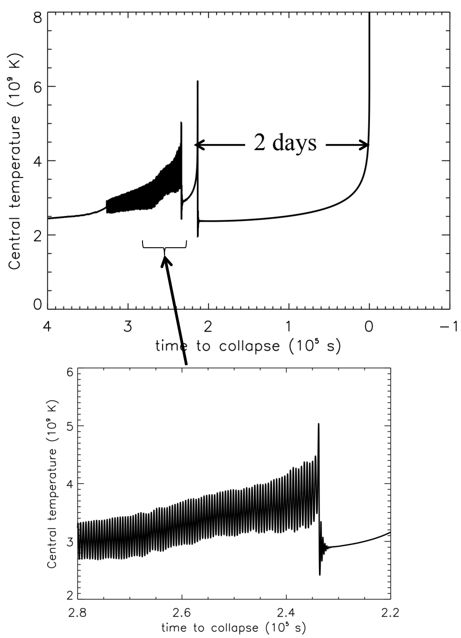
80 $M_\odot$

Helium core 35.7 $M_\odot$

Pulsational instability begins shortly after central oxygen depletion when the star has about one day left to live (t = 0 here is iron core collapse).

Pulses occur on a hydrodynamic time scale for the helium and heavy element core (~500 s).

For this mass, there are no especially violent single pulses before the star collapses..

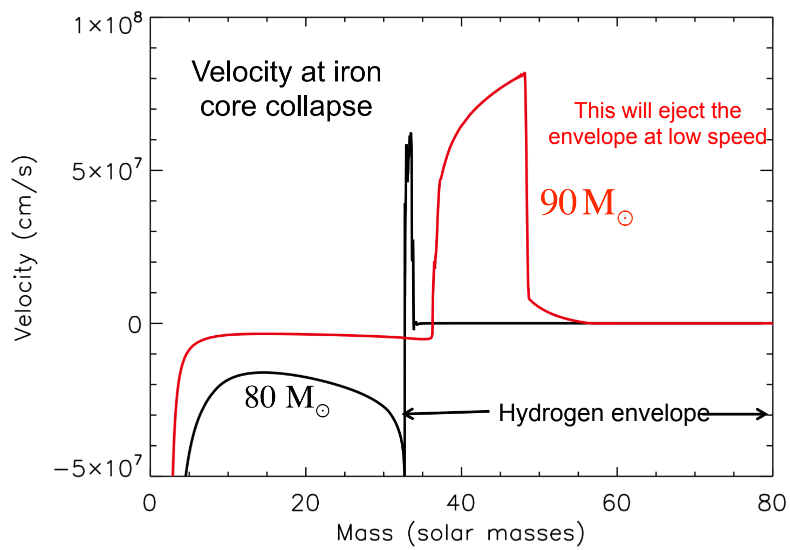


90 $M_\odot$

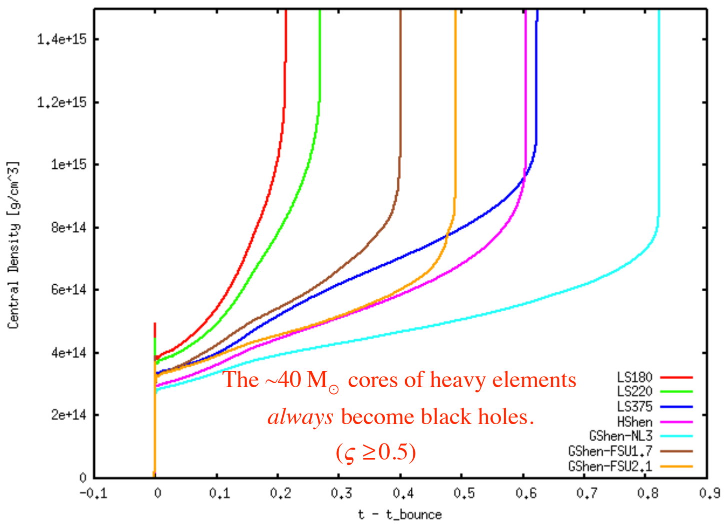
Helium core 41.3 $M_\odot$

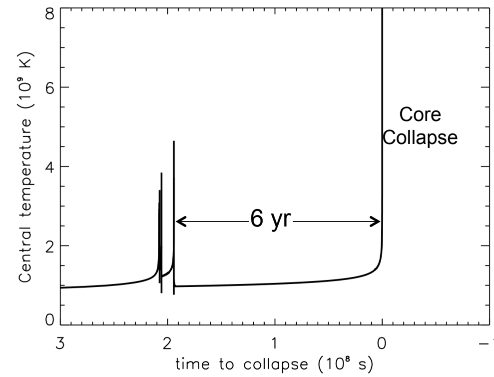
Pulses commence again after central oxygen depletion, but become more violent. Two strong pulses send shock waves into the envelope.

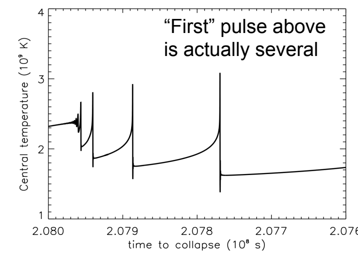
Two days later the iron core collapses.



Chritian Ott (private communication 2011)





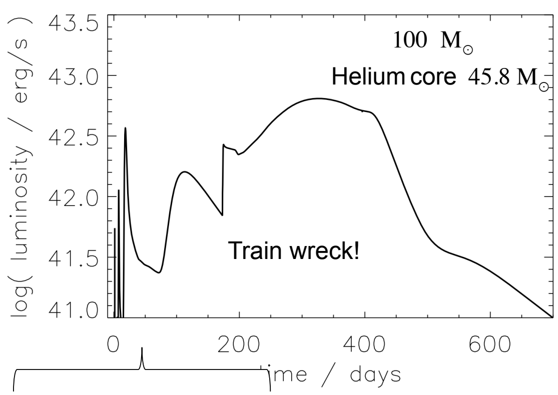


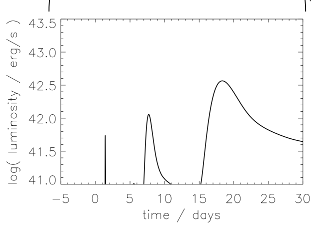
100 $M_\odot$

Helium core 45.8 $M_\odot$

The instability has now shifted to oxygen ignition at the center of the star. The pulses are much more violent and occur at increasing intervals.

The total duration of the pulses however is still only 5 months. The supernova will be almost continuous.





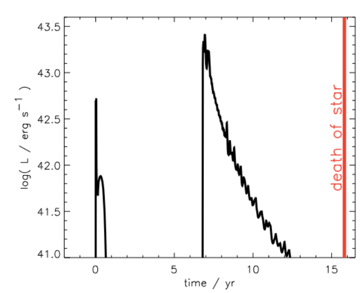
The actual light curve would be smooth due to mixing and light propagation delay times.

Core collapse 4 years later produced no observable event.

For helium cores in this mass range the total duration of pulses, ~months, is comparable to the duration of the light curve. Late time energy input leads to a very brilliant, long lasting supernova. The appearance would be affected by pre-explosive mass loss.

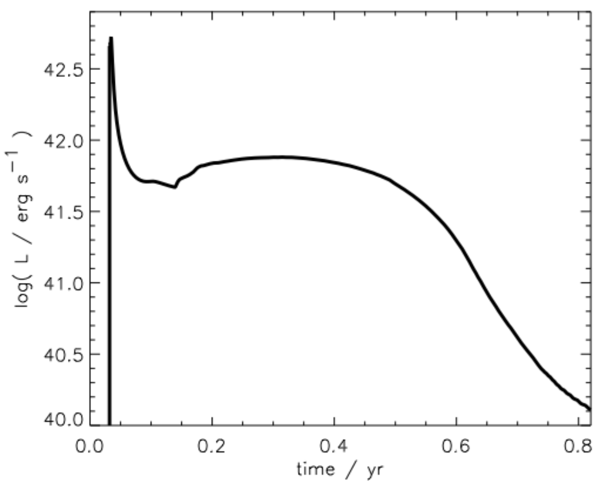
For still larger helium cores, the pulses become more violent and the intervals between them longer. Multiple supernovae occur but usually just one of them is very bright.

Finally at a helium core of about 60 solar masses the entire star explodes in a single pulse – the traditional "pair-instability" supernova

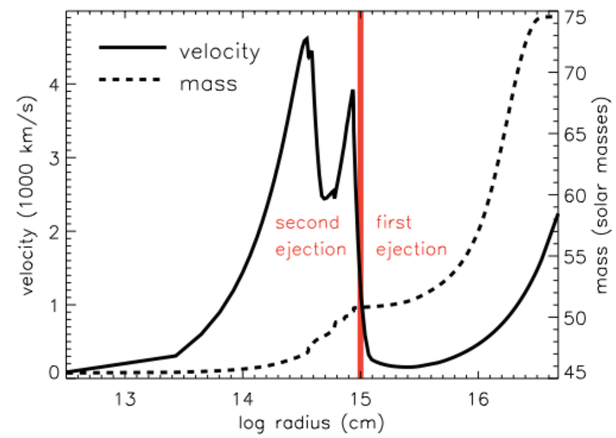


Helium Core	Number Pulses	Energy Range	Interval Range
M_{sun}		10^{51} erg	years
48	6	.11- 2.4	.02 - 0.26
51	4	.44 - 3.7	0.09 - 0.9
52	4	.94 - 3.1	.01 - 3.0
54	3	2.1 - 3.2	0.03 - 12
56	3	1.3 - 3.3	.01 - 110

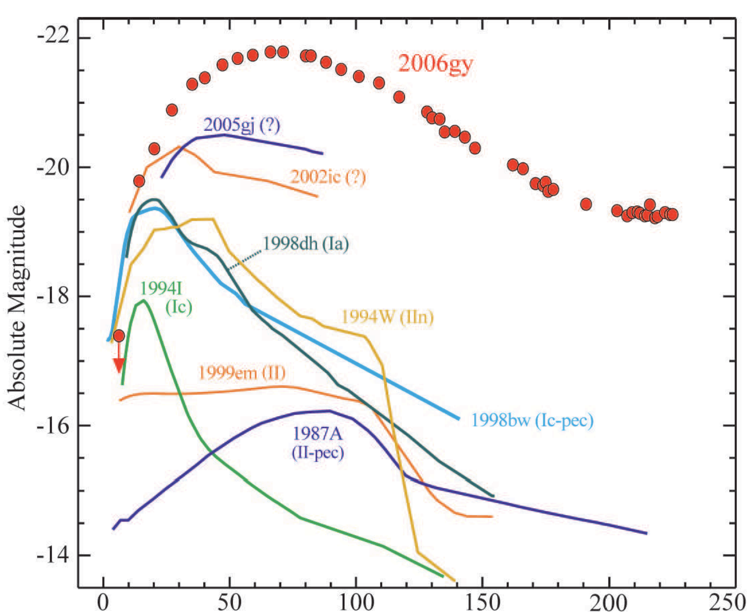
Woosley, Blinnikov, and Heger (Nature, 2007)



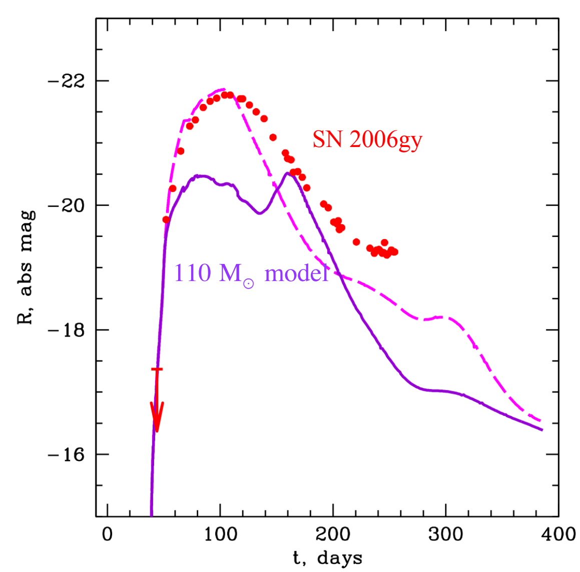
log(L / erg s^{-1})
time / yr



velocity
mass
second ejection
first ejection
velocity (1000 km/s)
mass (solar masses)
log radius (cm)



2006gy
2005gj (?)
2002ic (?)
1998dh (Ia)
1994I (Ic)
1994W (IIn)
1999em (II)
1998bw (Ic-pec)
1987A (II-pec)
Absolute Magnitude

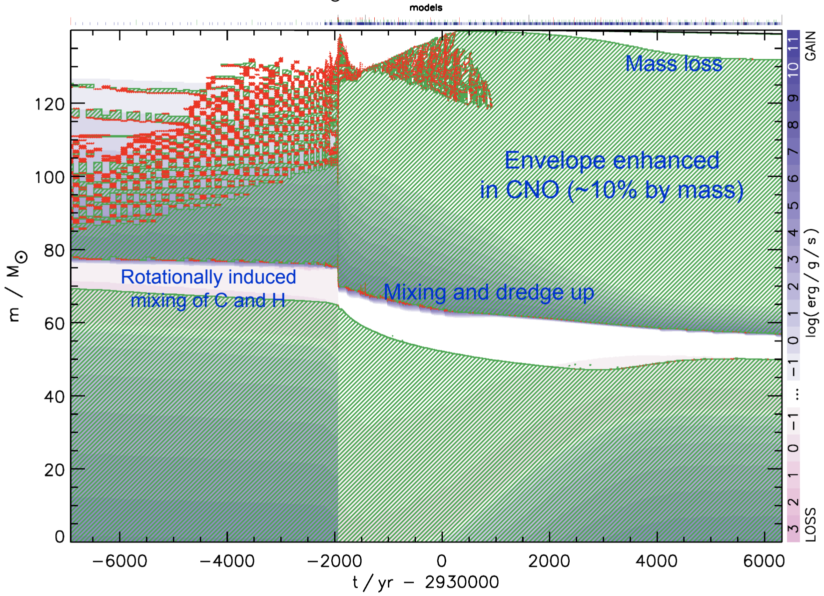


SN 2006gy
110 M$_\odot$ model
R, abs mag
t, days

Pulsational Pair Supernovae (PPSN)
Five possible outcomes

- The whole star becomes a black hole (possible for the lightest masses – less than about 80 solar masses with little rotation
- The envelope is ejected with very low speed producing a long, faint supernova and leaving a black hole ~ 40 solar masses
- The pulses all finish in less than 1 day (shock crossing time for the envelope). One long supernova not unlike an ordinary SN IIp but no tail and a black hole ~40 solar masses
- Strong pulses occur weeks to years after the first mass ejection. Collisions of shells produce a very bright supernova and a black hole ~40 solar masses
- If the time between pulses becomes years, as it does for the heaviest of the PPSN, one may have multiple supernovae - and a 40 solar mass black hole..

140 $M_\odot$ ($X_{cent-He} \approx 0.33$)

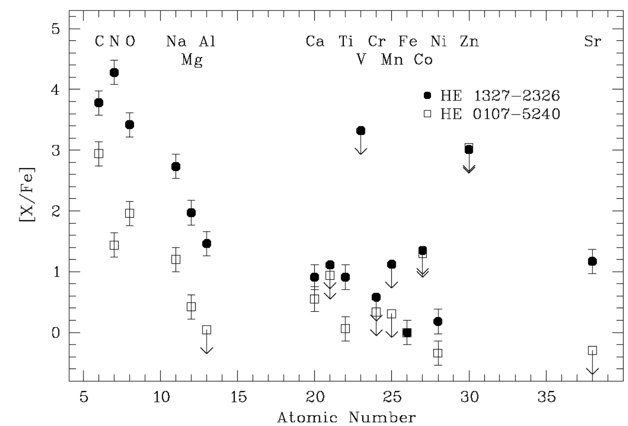


PPSN – Nucleosynthetic Implications

Since anywhere from most to all of the carbon oxygen core collapses to a black hole the nucleosynthesis is limited to what exists in the hydrogen envelope (H, He, plus CNO from dredge up), and some elements from the outer helium core (C, O, Ne, Mg). In particular there is no explosive nucleosynthesis and no iron group elements are made.

This is especially interesting for first generation (Pop III) stars.

Qualitative agreement with what is seen in the oldest stars in the galaxy – the ultra-iron-poor stars



Frebel et al (2008)

140 $M_\odot$ Model produces

18 $M_\odot$	H
55 $M_\odot$	He
3.5 $M_\odot$	C
8.5 $M_\odot$	N
14 $M_\odot$	O
0.5 $M_\odot$	Ne
40 $M_\odot$	Black hole

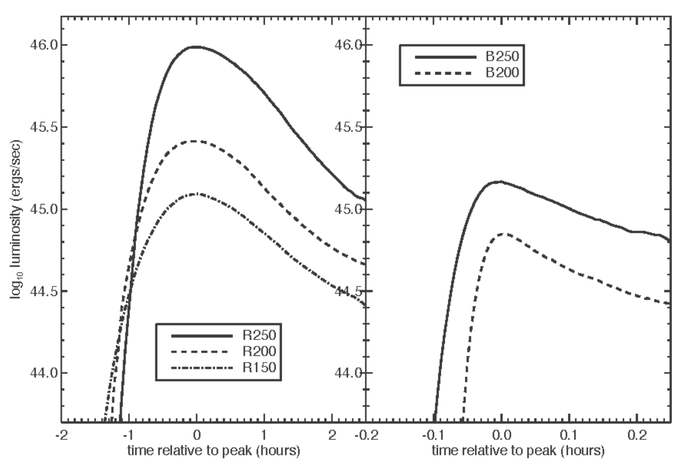
Pulsational – Pair Instability Progenitors
(Zero metallicity, including rotation and mass loss)

Main Seq	He core (He-burn)	He-core (final)	Outcome
80	40.6	30	CC
90	47.0	34	weak PPSN
100	53.9	39	PPSN
110	61.0	47	PPSN
120	67.4	48	PPSN
130	72.5	49	PPSN
140	79.2	54	PPSN
150	82.7	55	PPSN
160	90.2	59	PPSN
170	93.9	63	Pair SN (no Fe)
180	102.2	65	Pair SN (no Fe)

Pulsational – Pair Instability Progenitors
(Solar metallicity, no rotation and reduced mass loss)

Main Seq	He core (He-burn)	He-core (final)	Outcome
80	35.9	35.8	weak PPSN
90	41.0	40	PPSN
100	45.9	43.3	PPSN
110	51.5	46.3	PPSN
120	56.0	49.8	PPSN
130	58.1	52.7	PPSN
140	63.5	57	PPSN

Shock break-out in pair-instabilty supernovae



T_{color} = 2 – 4 x 10^5 K T_{color} = 6 – 8 x 10^5 K

Kasen, Woosley, and Heger (2011)
see also Whalen et al (2013)

General Relativistically Unstable Main Sequence Stars – Fowler, Hoyle, Feynman, Iben, etc.

$$G_{\rm rel} \equiv G\left(1 + \frac{P}{\rho c^2} + \frac{2GM}{rc^2} + \frac{4\pi P r^3}{m_r c^2}\right)$$

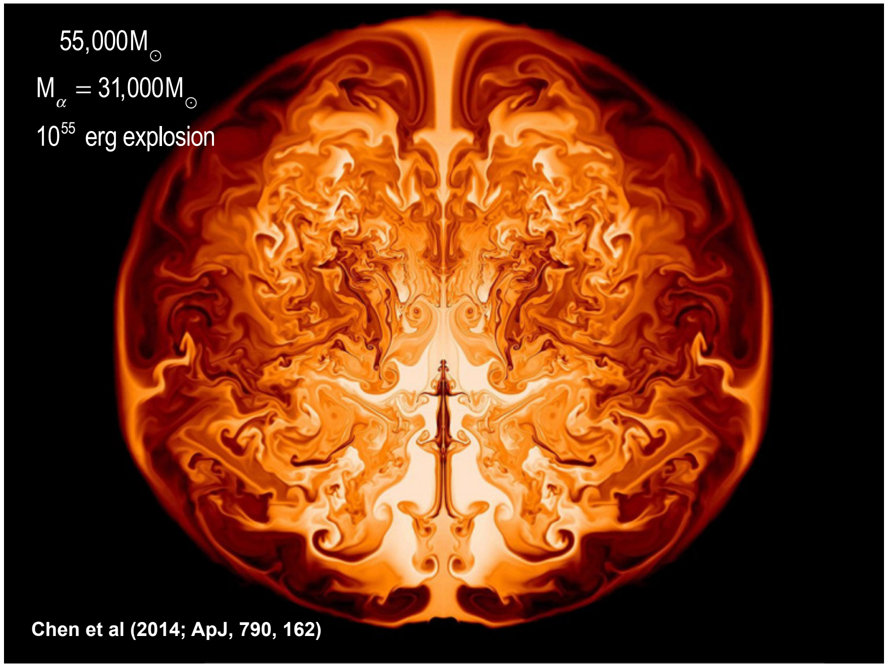
Fuller, Woosley and Weaver (1986)

TABLE 1

RESULTS

Initial Mass $M/10^5\ M_\odot$ (1)	Initial Metallicity $Z_{\rm init}$ (2)	Fate (3)	Cumulative Time for $L > 10^{45}$ ergs s^{-1} [a] (4)
1	0	Stable	...
5	0	Black hole	...
5	2×10^{-3}	Black hole	...
5	5×10^{-3}	2.1×10^{56} ergs He: 0.249 → 0.282	$> 3 \times 10^7$ s
5	1×10^{-2}	2×10^{56} ergs He: 0.247 → 0.275	$> 2.6 \times 10^8$ s
2.5	0	Black hole	...
10	0	Black hole	...
10	6×10^{-3}	Black hole	...
10	1×10^{-2}	2.5×10^{57} ergs He: 0.25 → 0.42	$> 10^8$ s

[a] The quantity L is the photon luminosity.


55,000M$_\odot$
$M_\alpha = 31,000M_\odot$
10^{55} erg explosion
Chen et al (2014; ApJ, 790, 162)