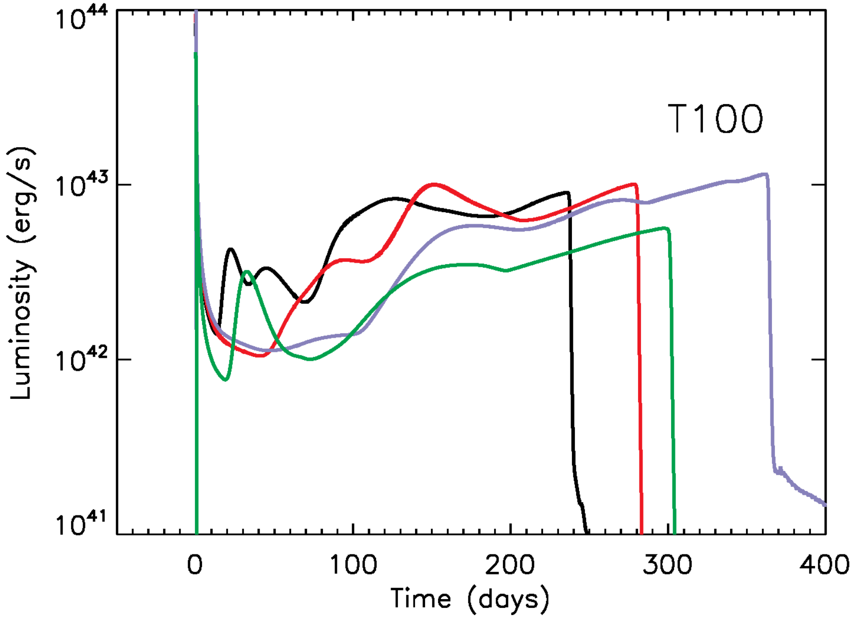
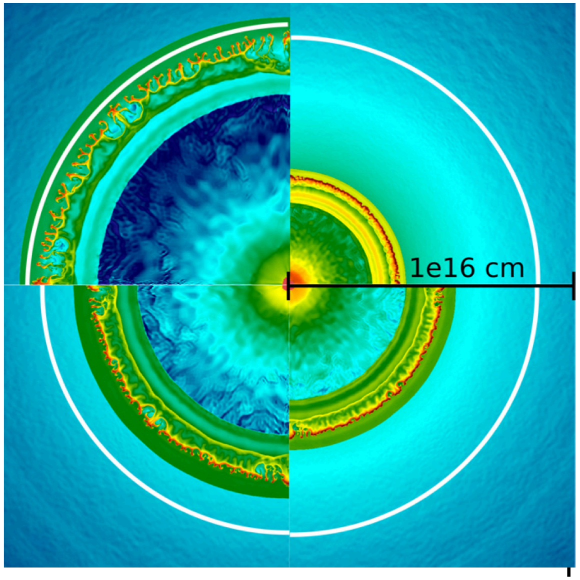
PULSATIONAL PAIR-INSTABILITY SUPERNOVAE

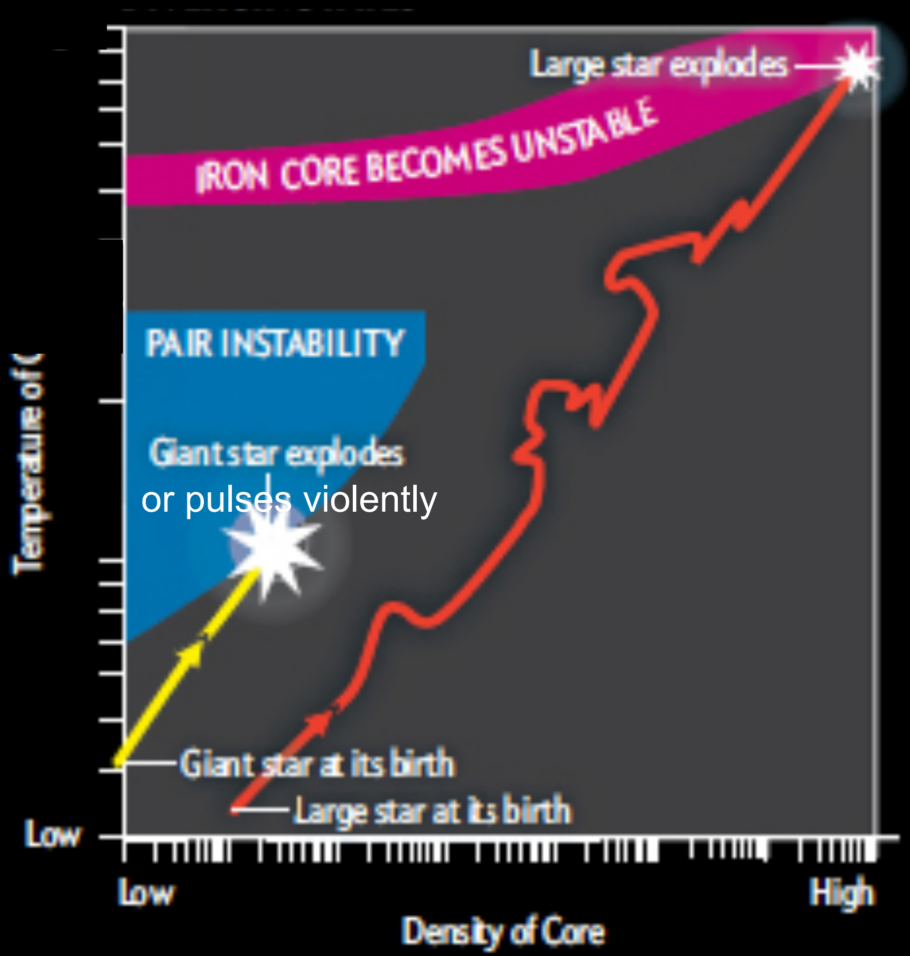
- Stan Woosley
UCSC





$\gamma + \gamma \rightarrow e^{+} + e^{-}$; Pair Instability

Fowler and Hoyle (1964); Barkat et al (1967); Rakavy and Shaviv (1967)



Gal-Yam (2012)

- Structural Γ in core reduced below 4/3 in oxygen shell burning (lighter cores) or in center after carbon depletion (heavier cores)
- Happens only at high entropy (low density at a given T) and thus only in the most massive stars.
- Infrequent or non-existent in solar metallicity stars
- Outcome most sensitive to helium core mass

SUMMARY
PAIR-INSTABILITY SUPERNOVAE
(without rotation)

He Core *well known*	Main Seq. Mass *Poorly known*	Supernova Mechanism
$2 \leq M \leq 30$	$8 \leq M \leq 75$	Fe core collapse to neutron star or a black hole
$30 \leq M \leq 64$	$70 \leq M \leq 140$	Pulsational pair instability followed by Fe core collapse (to a black hole?)
$64 \leq M \leq 133$	$140 \leq M \leq 260$	Pair instability supernova (single pulse, no remnant)
$M \geq 133$	$M \geq 260$	Black hole

Heger and Woosley (ApJ, 2002)
Woosley, Blinnikov and Heger (Nature 2007)

(Because they are massive)
PPISN ARE RARE

~1%

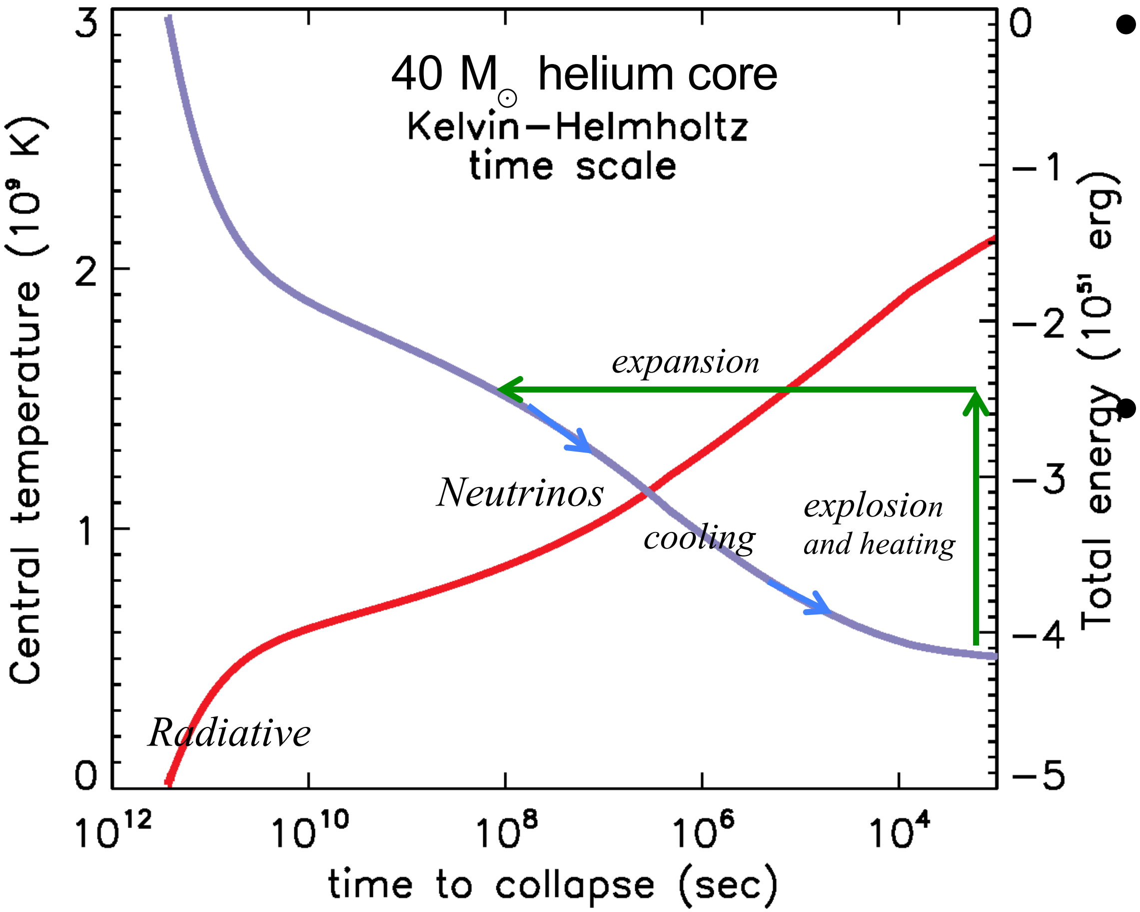
Assume all stars above 8 M_0 become supernovae and
stars from 70 to 140 M_0 become PPISN, and take
an upper mass limit of 150 M_0 (not important). Assume a Salpeter
IMF for which $\Gamma = -1.35$

$$f_{PPISN} \approx \frac{70^{\Gamma} - 140^{\Gamma}}{8^{\Gamma} - 150^{\Gamma}} = 0.033$$

If use 80 instead of 70 get 0.024. Rotation will increase the fraction. Having some stars between 8 and 70 make black holes increases the fraction.

But this is only of stars that have sufficiently low metallicity ($0.1 - 0.3\ Z_0$?) to retain their helium core intact as a presupernova. Still they are probably more abundant than ordinary pair instability supernovae ($140 - 260\ M_0$) and much more abundant than the rare very luminous PISN (M > about 200 M_O)

THE PULSATIONAL- PAIR ENGINE

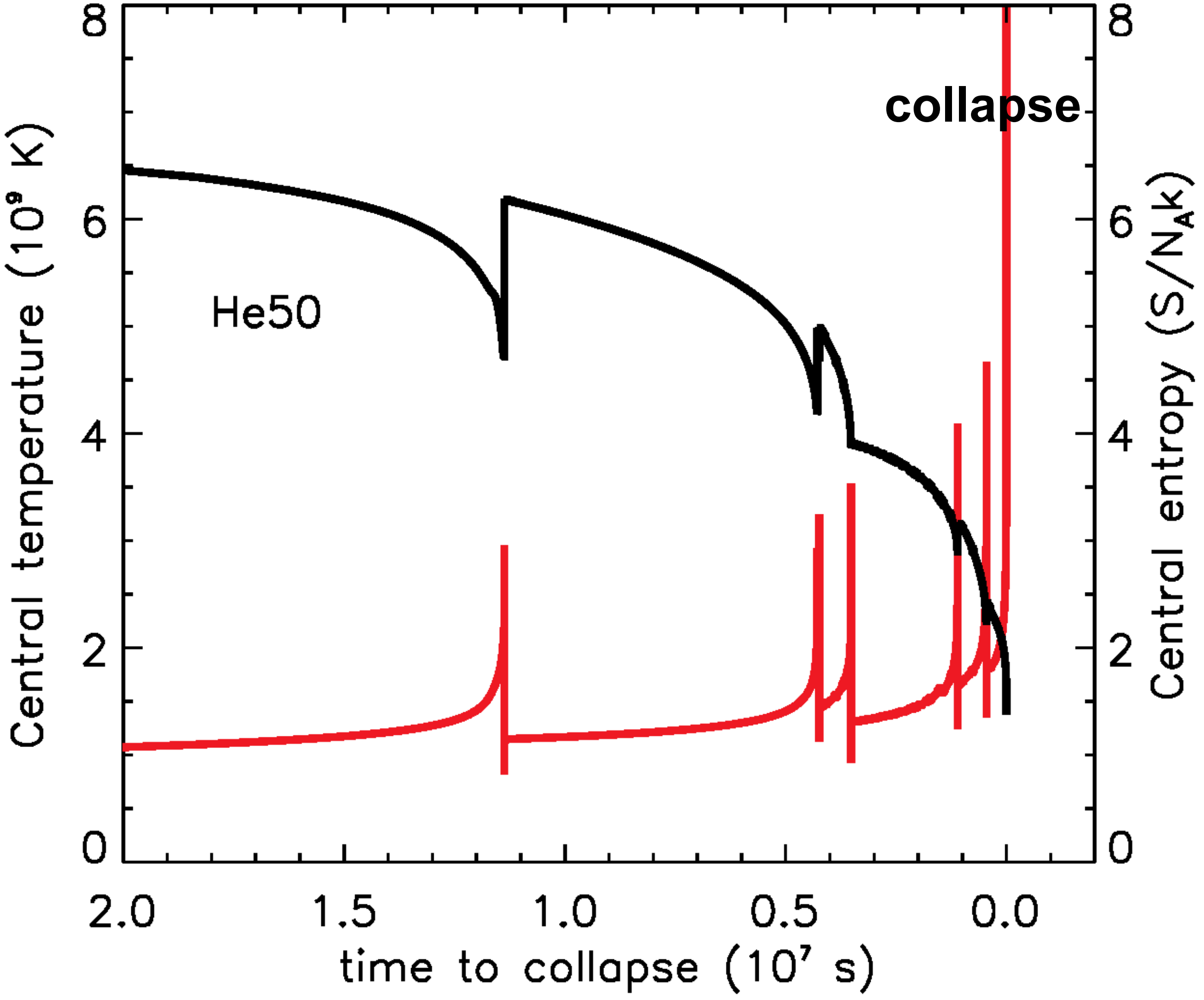


40 M$_\odot$ Kelvin-Helmholtz

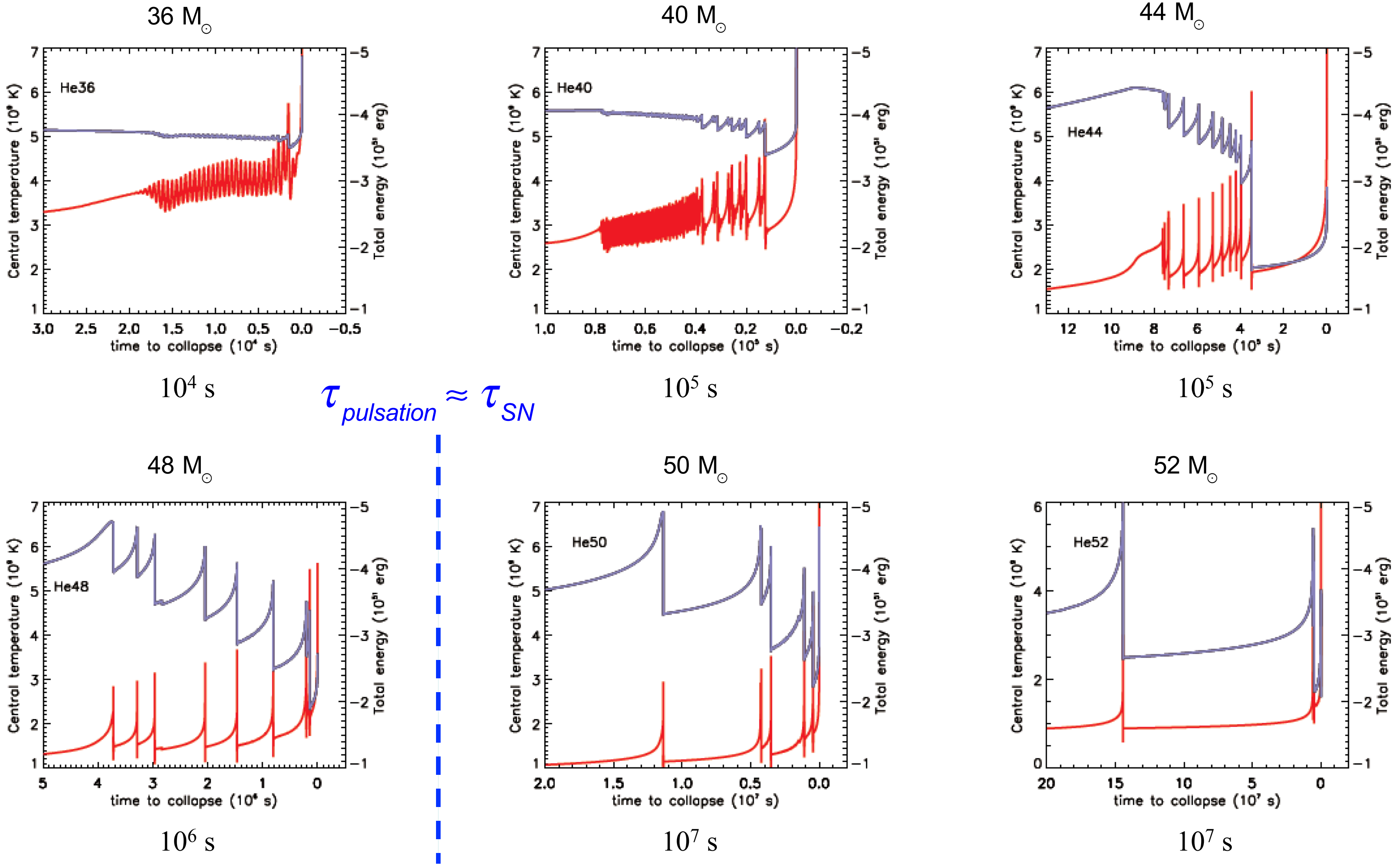
Contraction (no burning)

- More energetic pulses take a longer time to recur – more energy means more expansion to a less tightly bound star
- Since 40 M$_O$ is a typical core mass for PPISN, the maximum duration of all pulsing activity is about 10,000 yr. This is an upper bound to the pulsing activity There will be no PPISN that last longer. Models confirm this
- An explosion energy of ~4 x 10^{51} erg will unbind the star and make a PISN.

Over time this pulsing activity reduces the entropy and reduces the fuel (oxygen) available to burn.



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

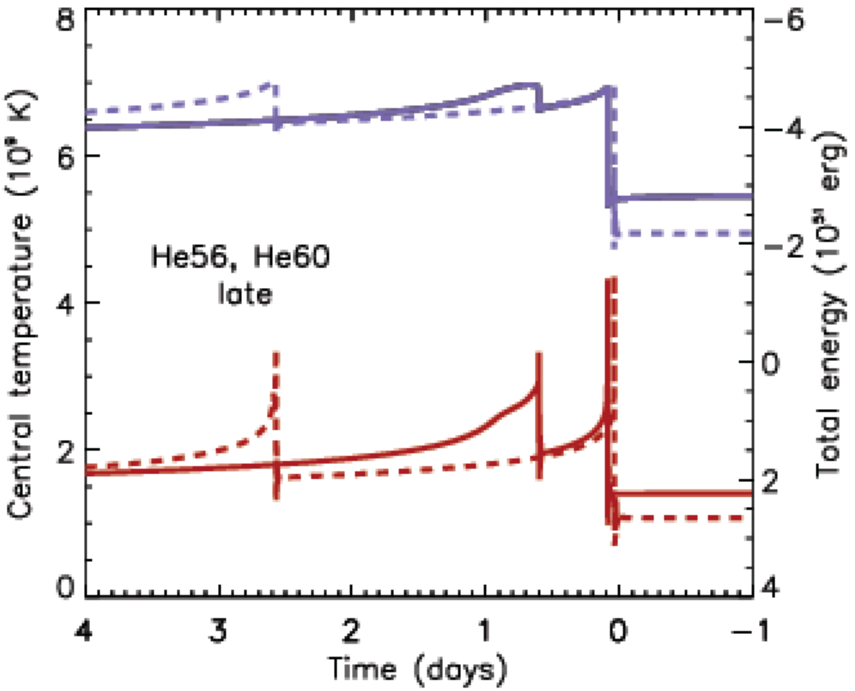


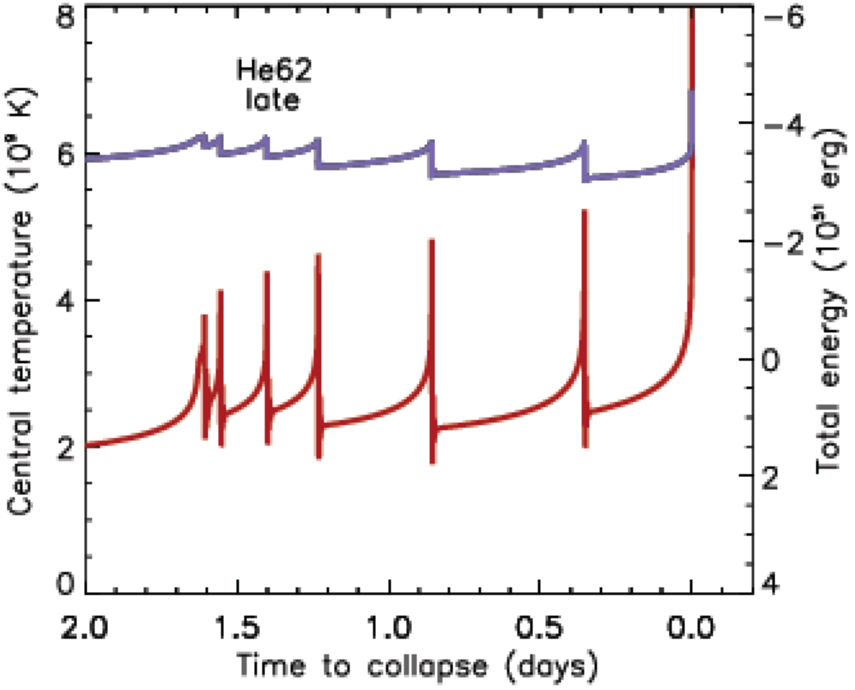
$\tau_{pulsation} \approx \tau_{SN}$

Central temperature and gravitational binding energy as a function of time (measured prior to iron core collapse for helium cores of 36, 40, 44, 48, 50 and 52 solar masses. As the helium core mass increases the pulses become fewer in number, less frequent, and more energetic

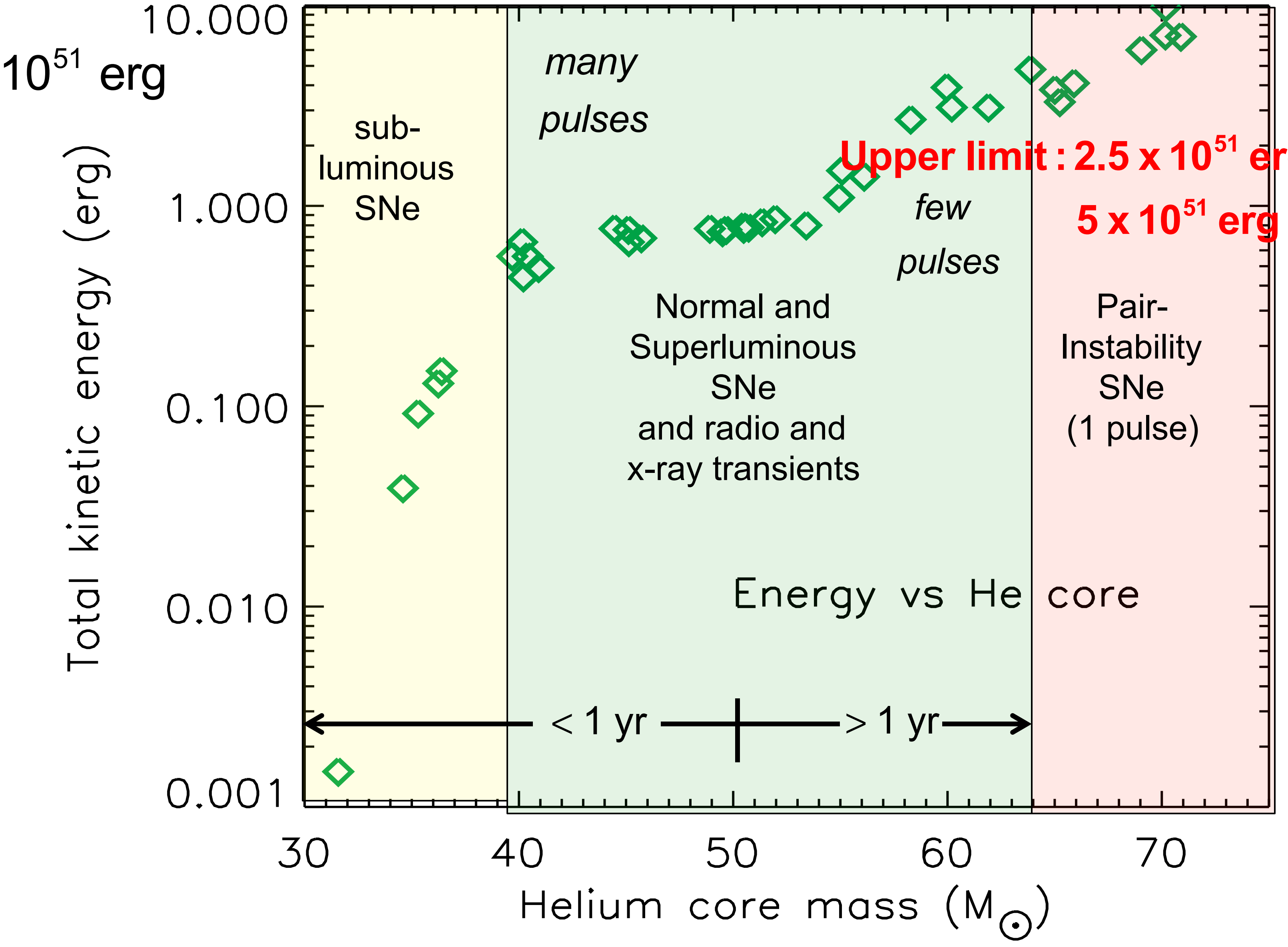
From 52 to 62 M_O get a single strong pulse followed by a long wait, then several pulses in rapid succession, then collapse. During the long delay L_{star} near 10^{40} erg $s^{-1.}$ CSM interaction as well.

	He56	He60	He62
t_{1-2}	1060 y	2680 y	7000 y
t_{coll}	91 d	6.0 y	0





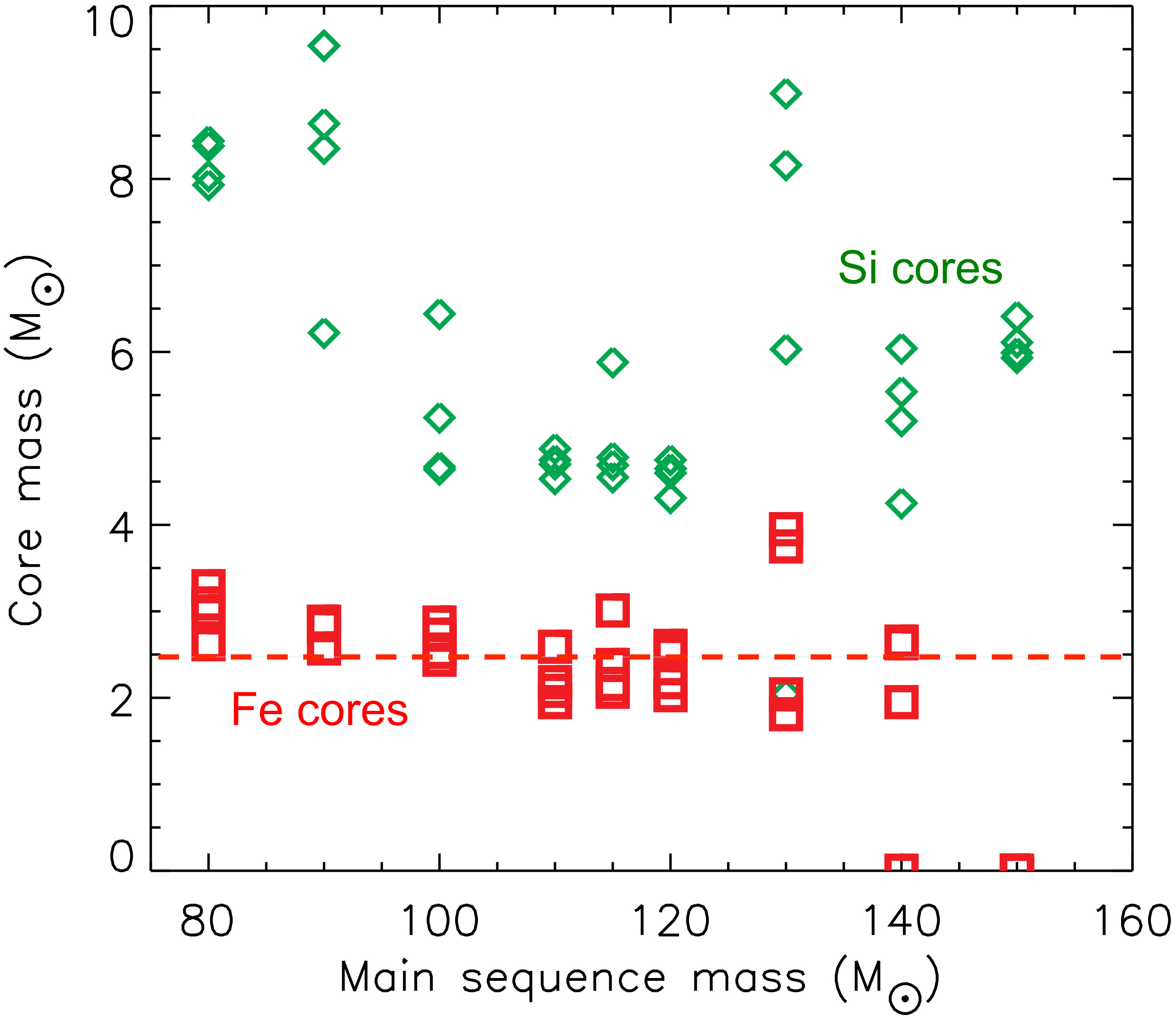
FULL STAR MODELS
TOTAL ENERGY IN PULSES



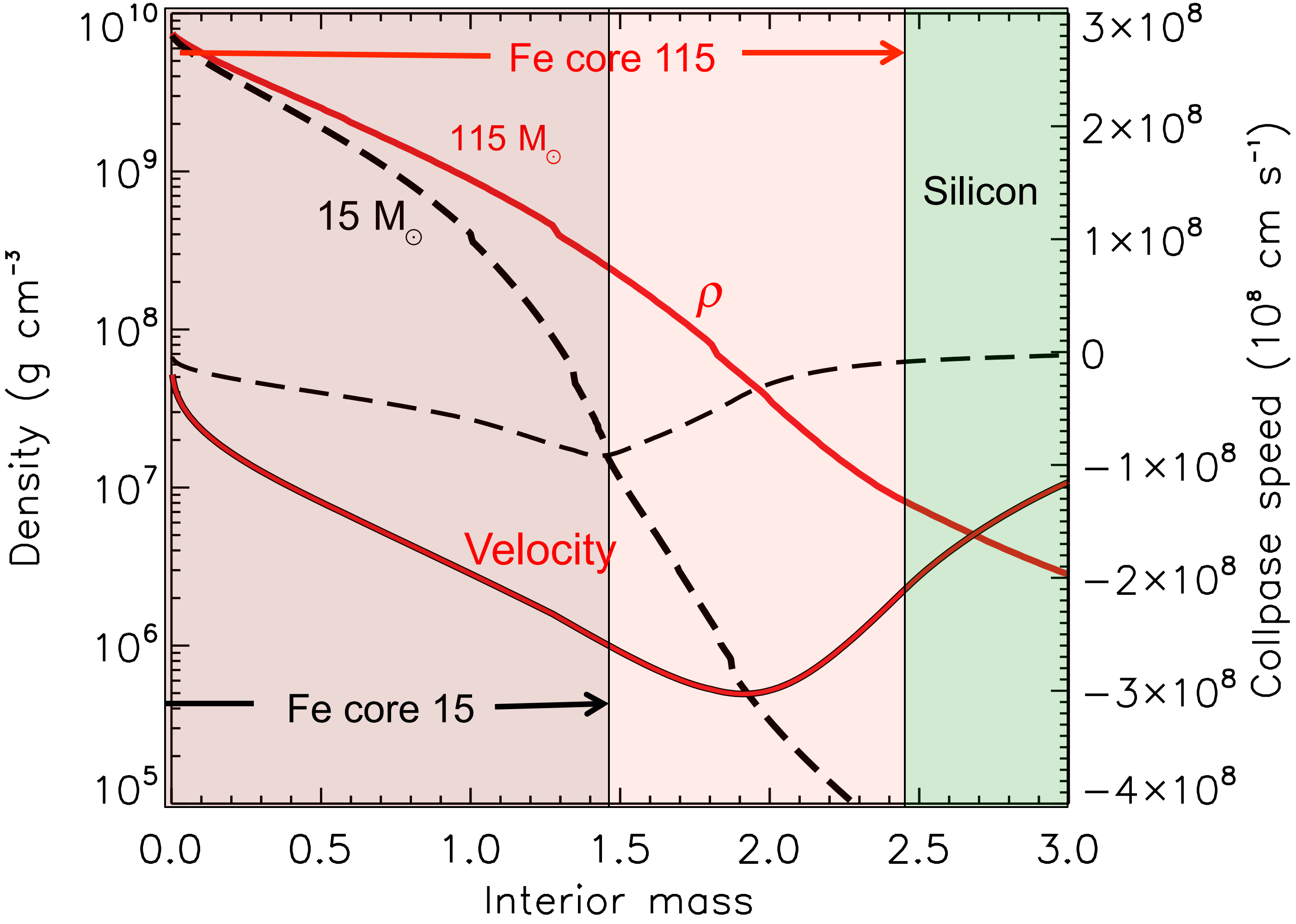
Upper limit : 2.5 x 10^{51} erg - He core

5 x 10^{51} erg - full star

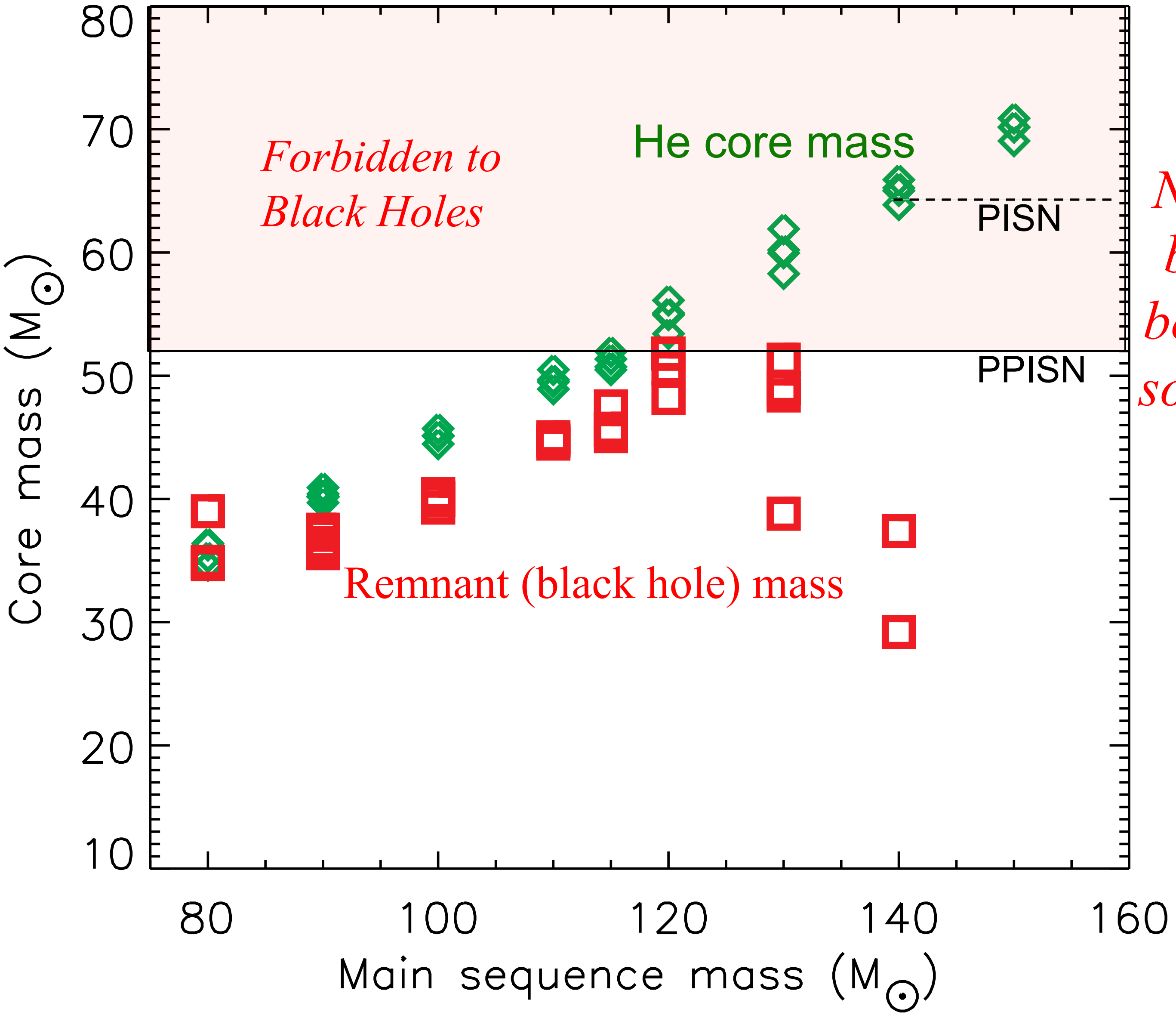
The iron cores are large and the star will not explode unless it rotates rapidly. Binding energy outside Fe core ~ 4 x 10^{51} erg.



Iron Core Probably Collapses to a Black Hole



But the rotation rate can be substantial - milliseconds



No black holes will be born with mass between 52 and 133 solar masses in tight binary systems..

Many will have masses near 35 – 50 solar masses

No remnant until 260 M_O

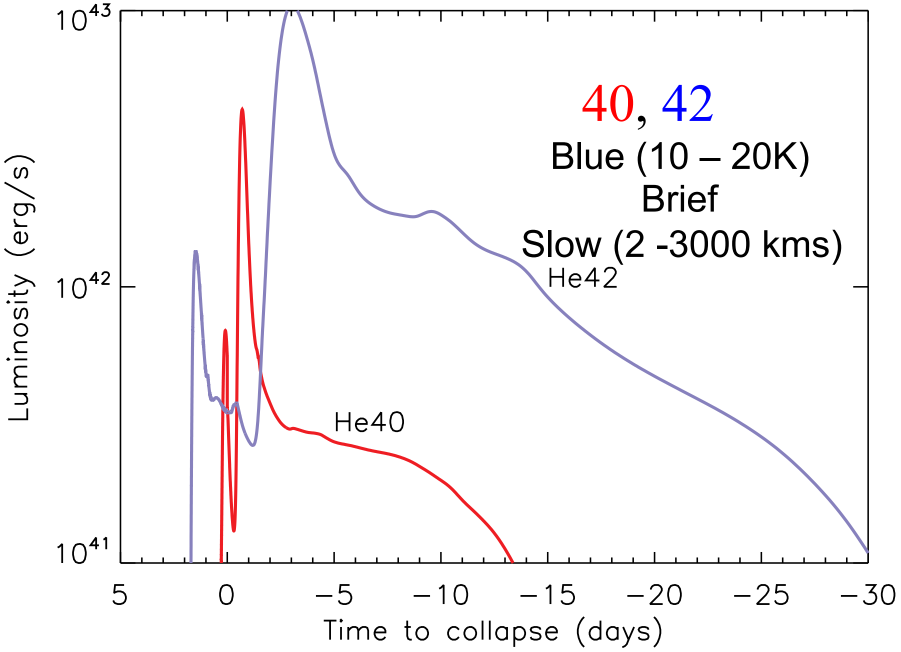
However in detached systems with negligible mass loss and rotation (wide binaries with very low Z and slow rotation), black hole masses up to about 70 M_0 are allowable.

This assumes that the hydrogen envelope is not lost and all of it participates in the collapse.

Model	Mass Loss	M_{preSN} (M_O)	M_{He} (M_O)	M_{final} (M_O)	M_{eject} (M_O)	KE (10^{47} erg)
T70B	.25	59.6	30.5	59.6	0	0
T70C	.125	64.7	30.7	64.7	< 1	0.5
T70D	0	70	31.6	65	18	15

Above 133 M_0 black holes are always allowable.

Helium (or CO) Core Light Curves

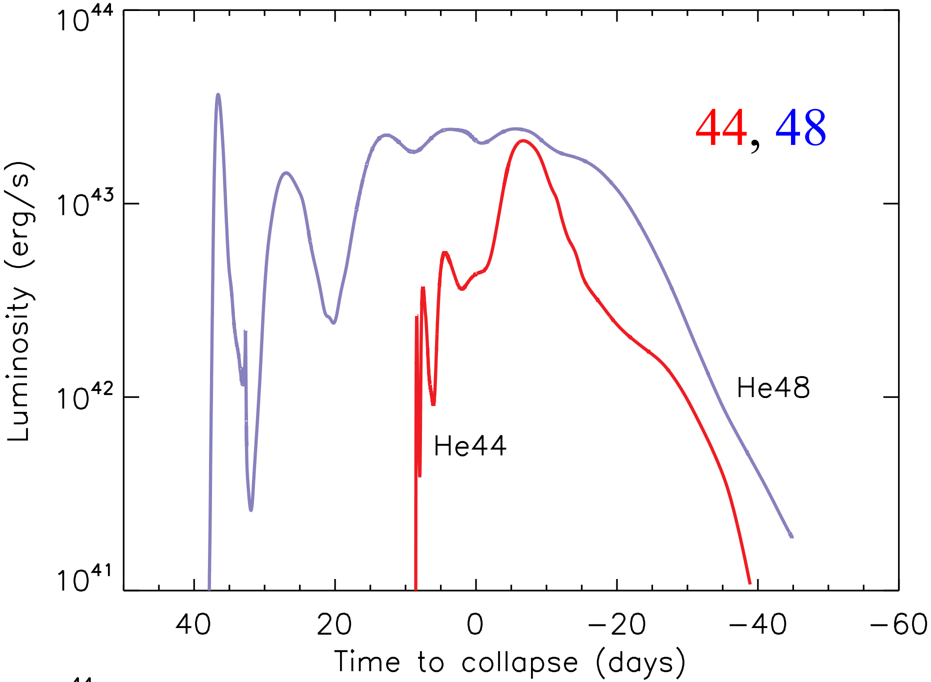


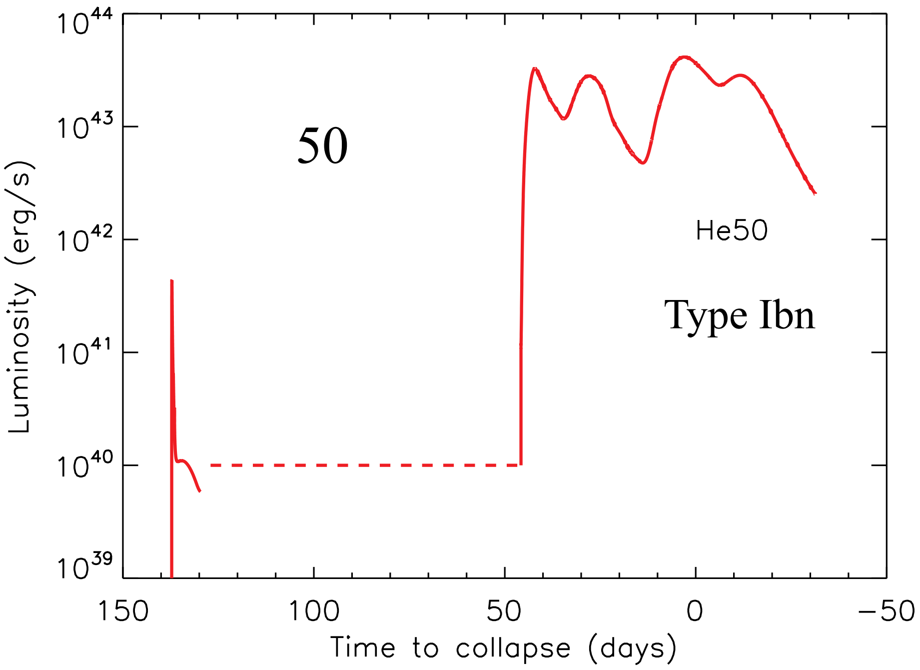
40, 42

Blue (10 – 20K)

Brief

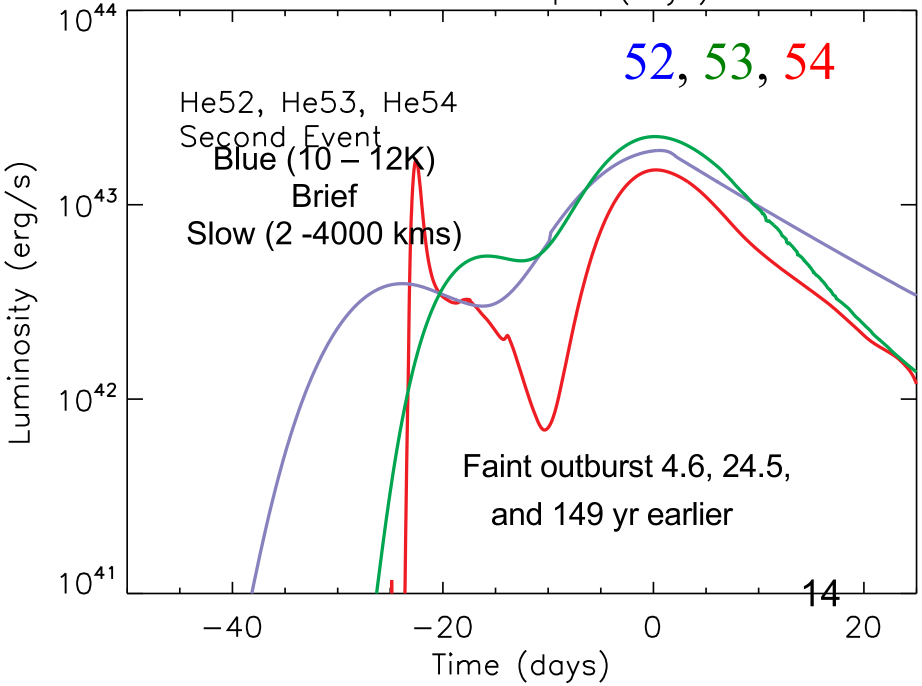
Slow (2 -3000 kms)





50

Type Ibn



Blue (10 – 12K)

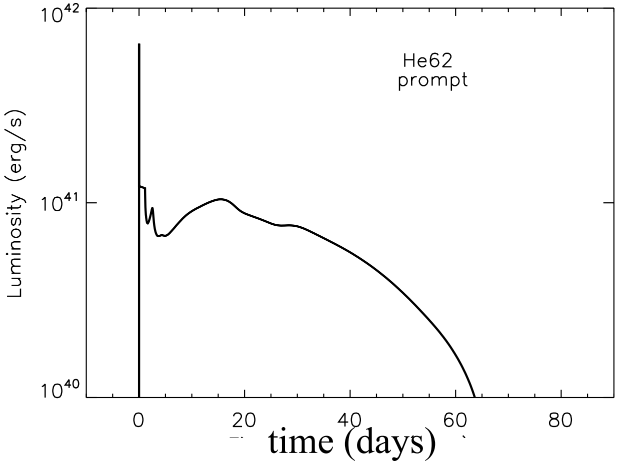
Brief

Slow (2 -4000 kms)

Faint outburst 4.6, 24.5,

and 149 yr earlier

For still heavier helium cores the initial faint outburst is followed by a long wait and then several flashes in rapid succession just before the star dies.

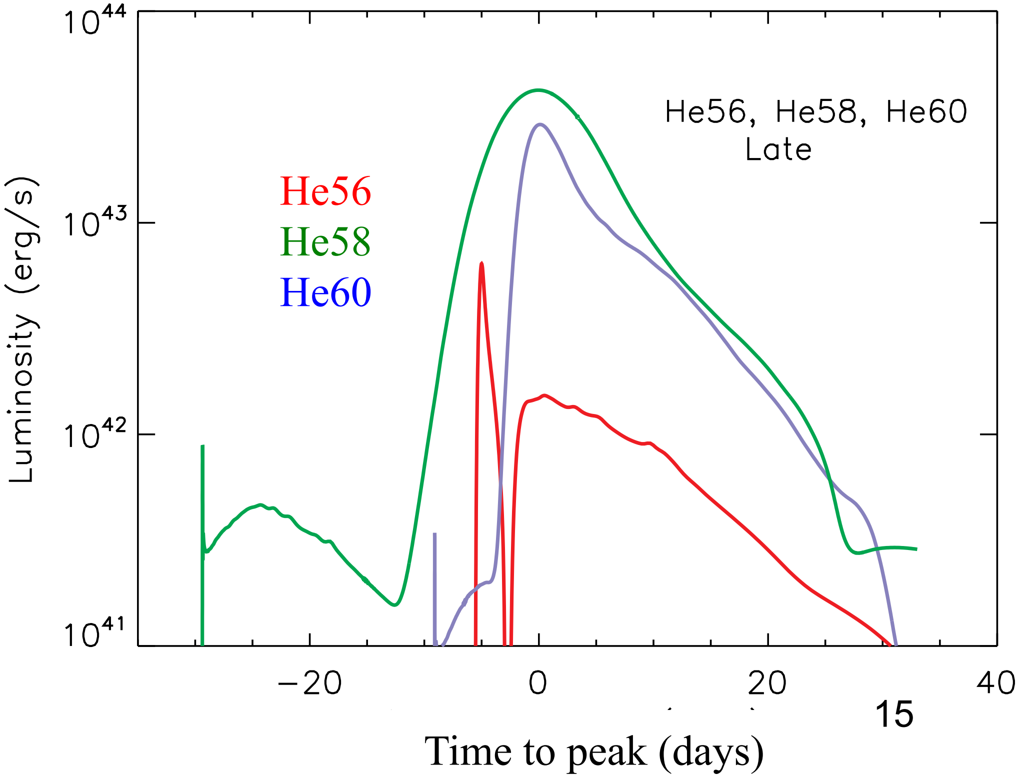


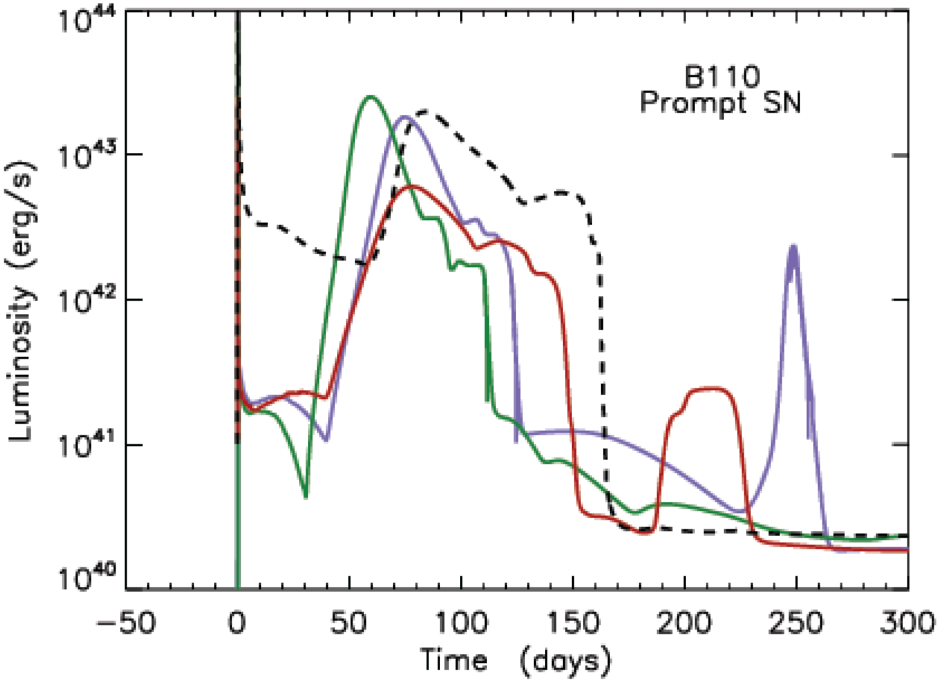
τ-precursor

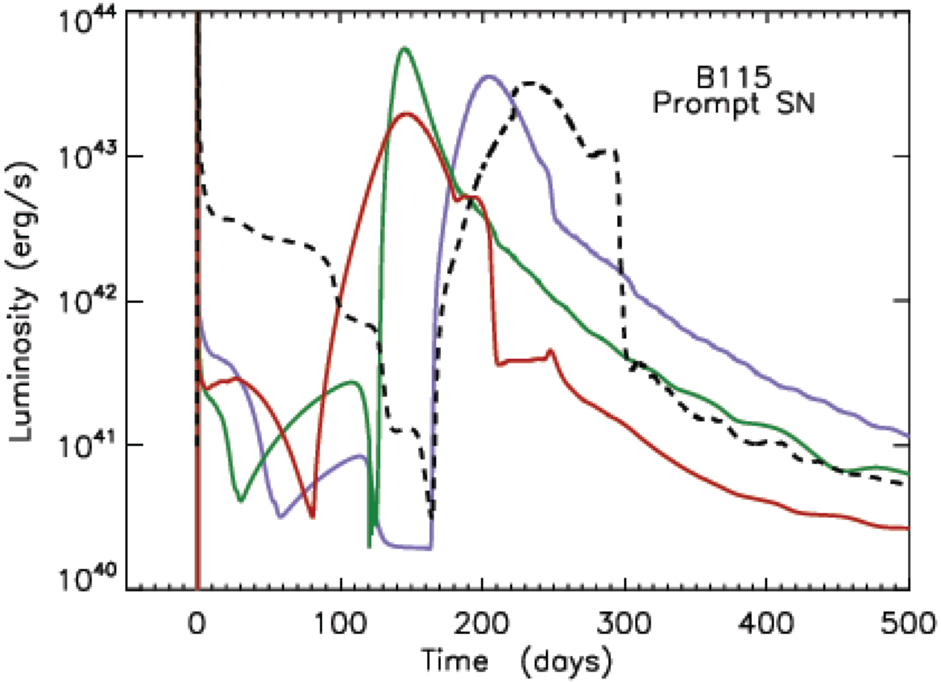
56 -1080 y
58 -2530 y
60 -2690 y

collapse

56 – +84 d
58 – +3.4 d
60 – +5.9 y

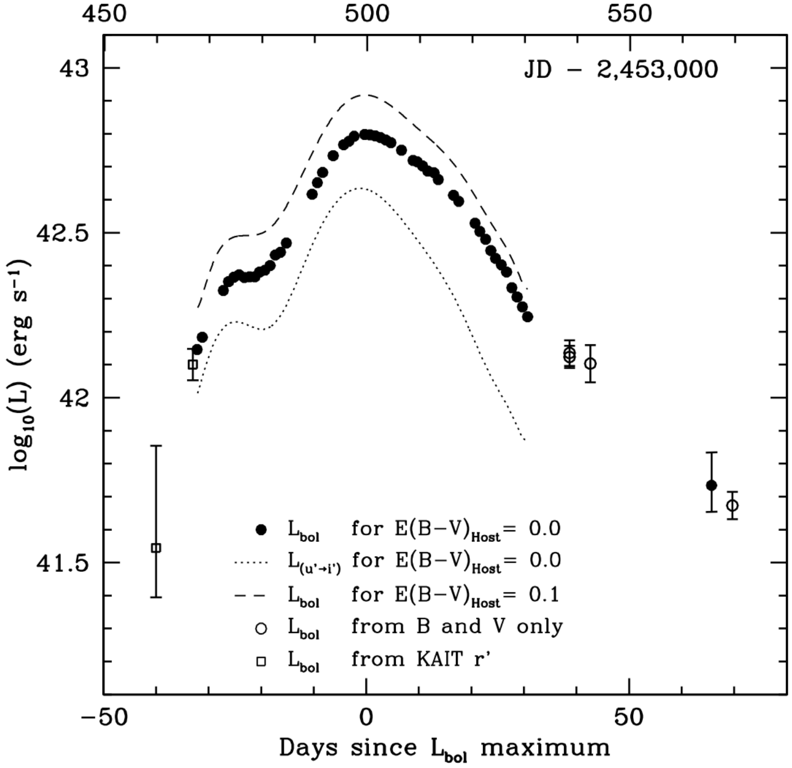




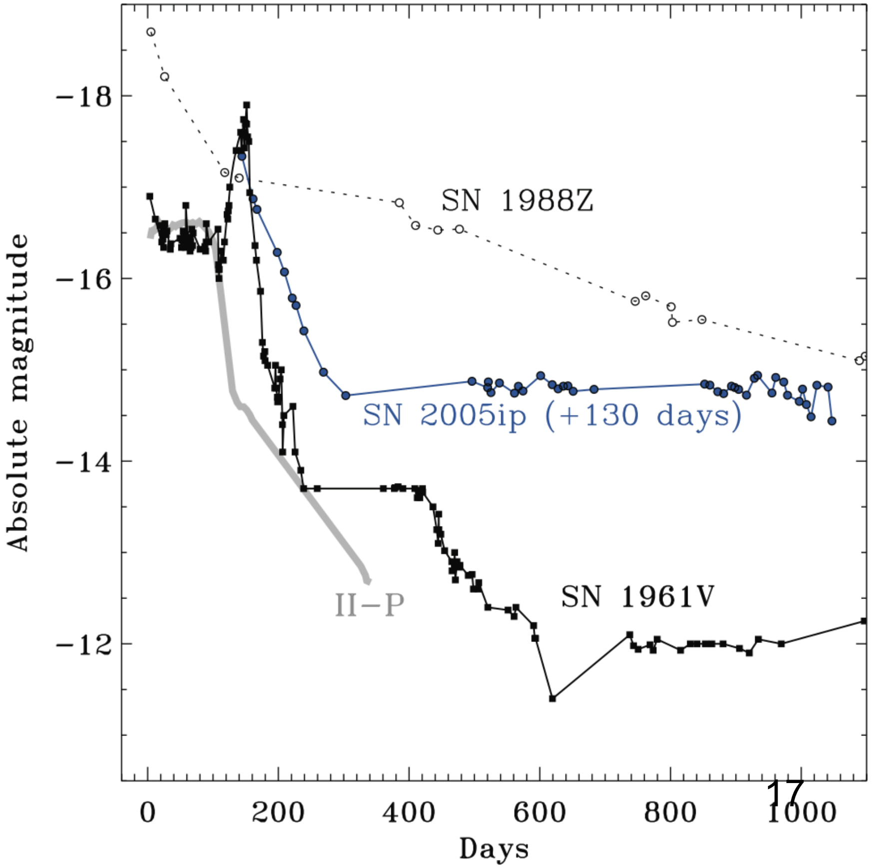


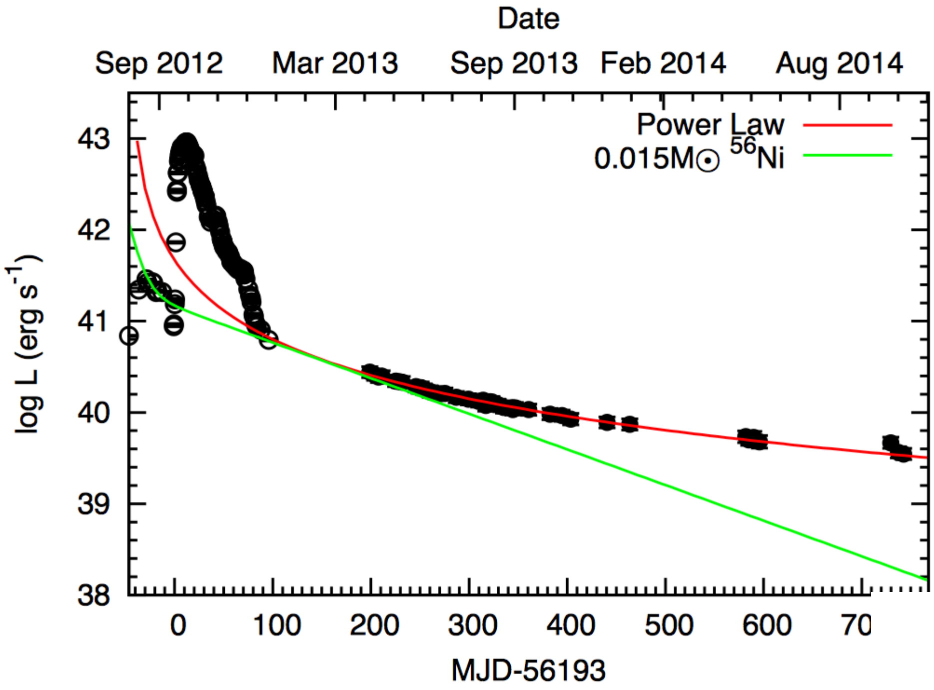
Blue supergiants and LBV’s can give similar “precursors” as the compact envelope is ejected in an 87A-like outburst and then impacted by a shell

SN2005bf – Folatelli et al (2006)
Type Ib/c with hi v H



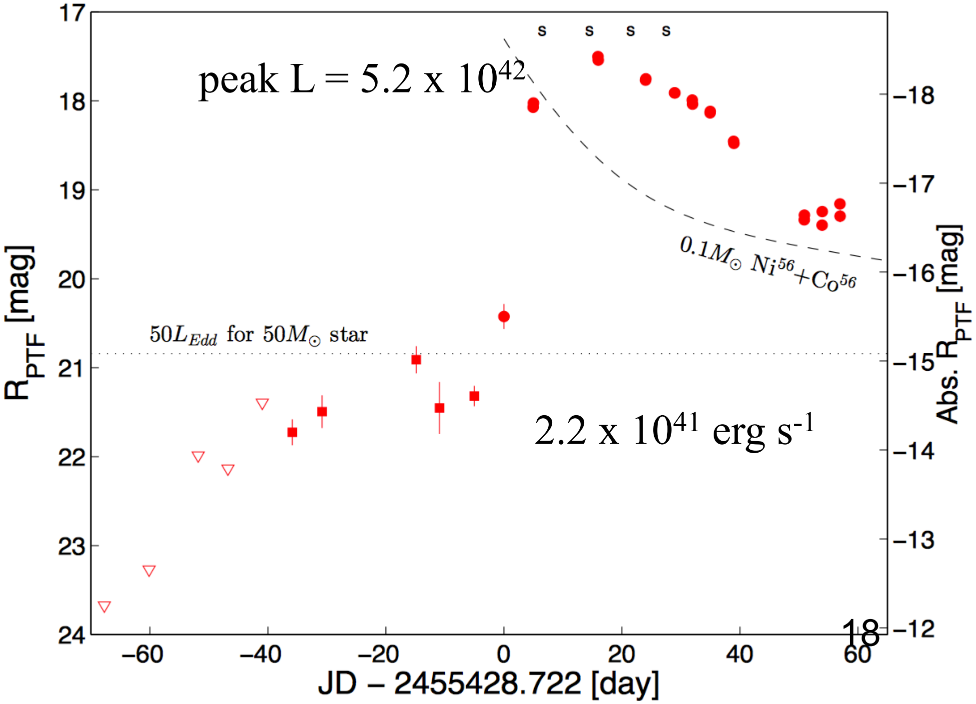
SN 1961v and 2005ip
figure from Smith et al (2011)
Type IIn





SN 2009ip – Fraser et al (2015)
2012 outburst preceded by
SN imposter in 2009. Type IIn?

SN 2010mc – Ofek et al (2013)
Type IIn
"with a pre-explosive ouburst"

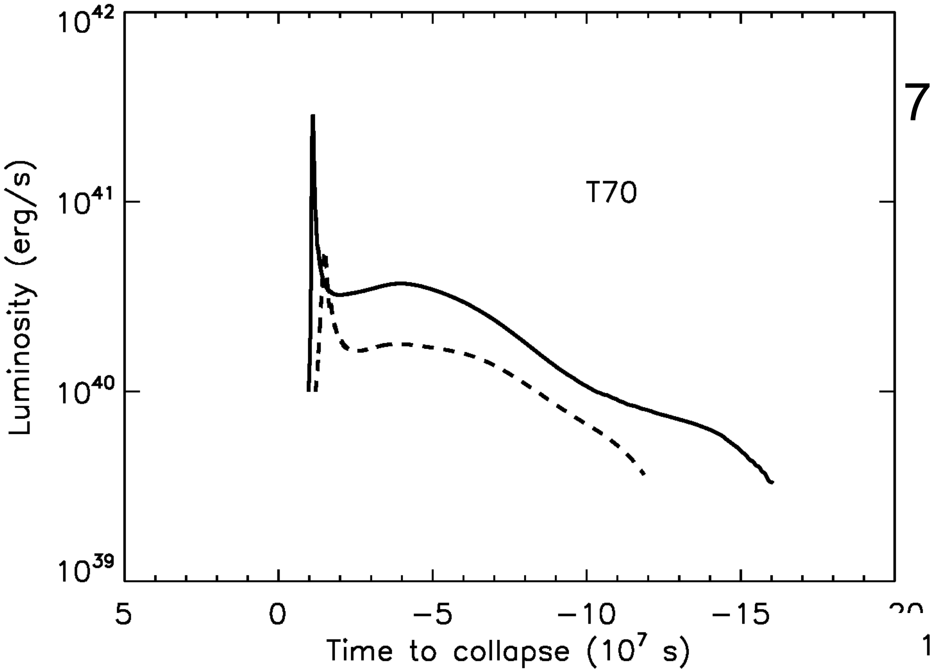

peak L = 5.2 x 10^{42}

2.2 x 10^{41} erg s^{-1}

Summary Type I PPI Supernovae – no rotation

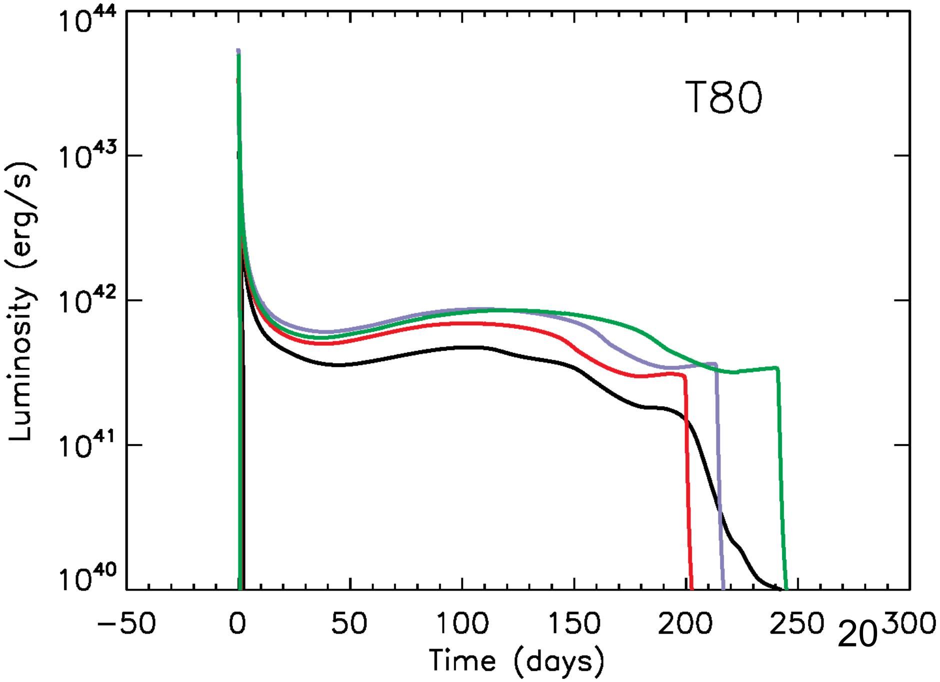
- A variety of transients are possible lasting from days to several thousand years. The optically bright ones last 20 to 100 days, but shorter fainter ones are common.
- Maximum L is a few x 10^{43} erg s. Analogues may be Type Ibn and IIbn SN (the latter if the core has retained just a little H)
- Frequently a plateau followed by a dramatic rise in L
- Maximum total radiated energy is 1 – 2 x 10^{50} erg .Maximum KE 2.5 x 10^{51} erg.
- Total mass ejected in optically bright events is less than about 8 solar masses
- Probably leave a population of 35 –52 solar mass black holes (up to 70 solar masses in detached systems)

EXPLOSIONS IN RED SUPERGIANTS (10% Z_O)

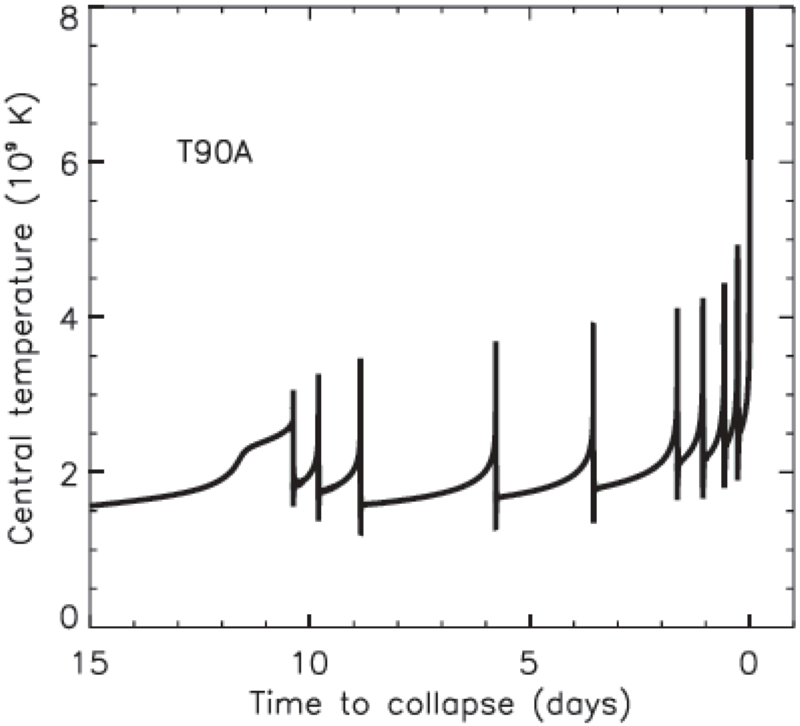


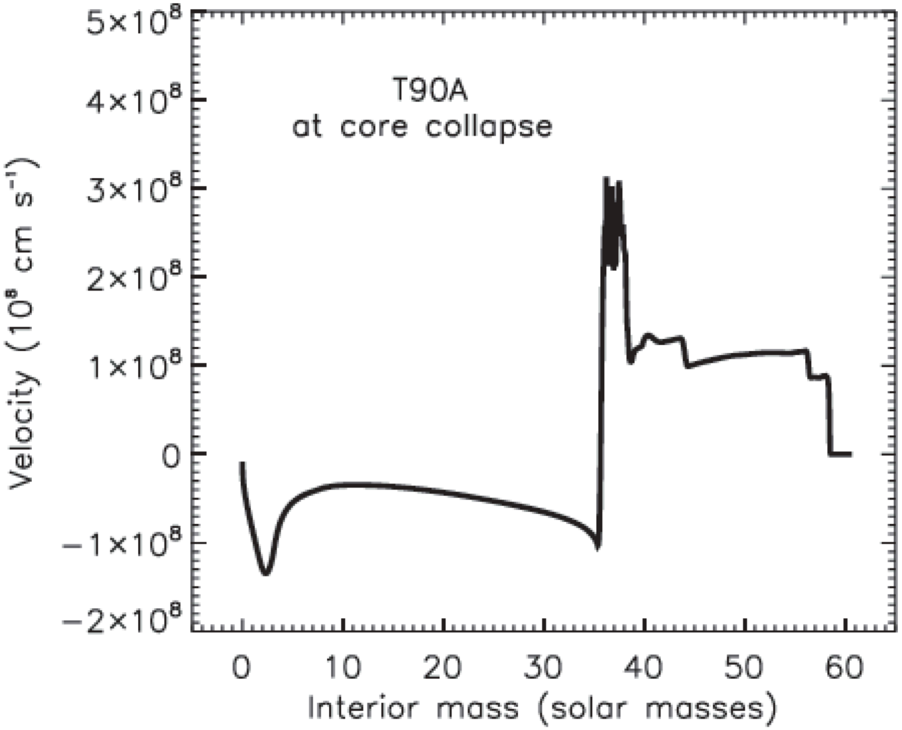
70 $M_\odot$ - barely unbind outer part of the hydrogen envelope. Very faint "red" (3000 K) slow transients - several years. Luminosity less than 10^{41} erg s^{-1}, speeds ~ 100 km s^{-1}. KE ~ 10^{48} erg

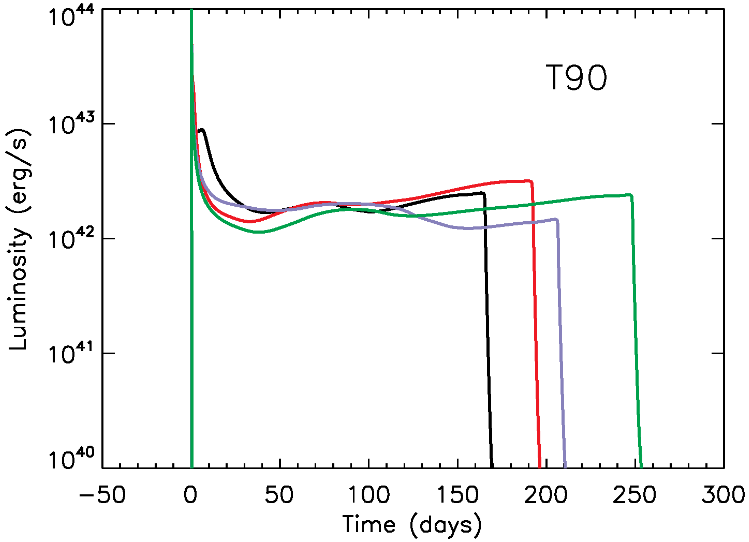
80 $M_\odot$ - entire envelope ejected. Duration of pulses still much less than duration of plateau. Total energy about 10^{50} erg. Relaively faint SN IIp. Peak L ~ 10^{42} erg s^{-1}



These may be the more common events.


T90A
Central temperature (10⁹ K)
0
2
4
6
8
15
10
5
0
Time to collapse (days)


T90A
at core collapse
Velocity (10⁸ cm s⁻¹)
5×10⁸
4×10⁸
3×10⁸
2×10⁸
1×10⁸
0
−1×10⁸
−2×10⁸
0
10
20
30
40
50
60
Interior mass (solar masses)



T90A is the red curve

90 $M_\odot$ - rather ordinary SN IIp 5 x 10^{50} erg but no radioactive tails. There can be tails due to CSM interaction though.

$$L = 0.5\,\dot{M}\frac{v_{shock}^3}{v_{wind}} \sim 10^{41}\,\text{erg s}^{-1}$$

for e.g. $\dot{M} = 10^{-4}\ M_\odot\ y^{-1}$;

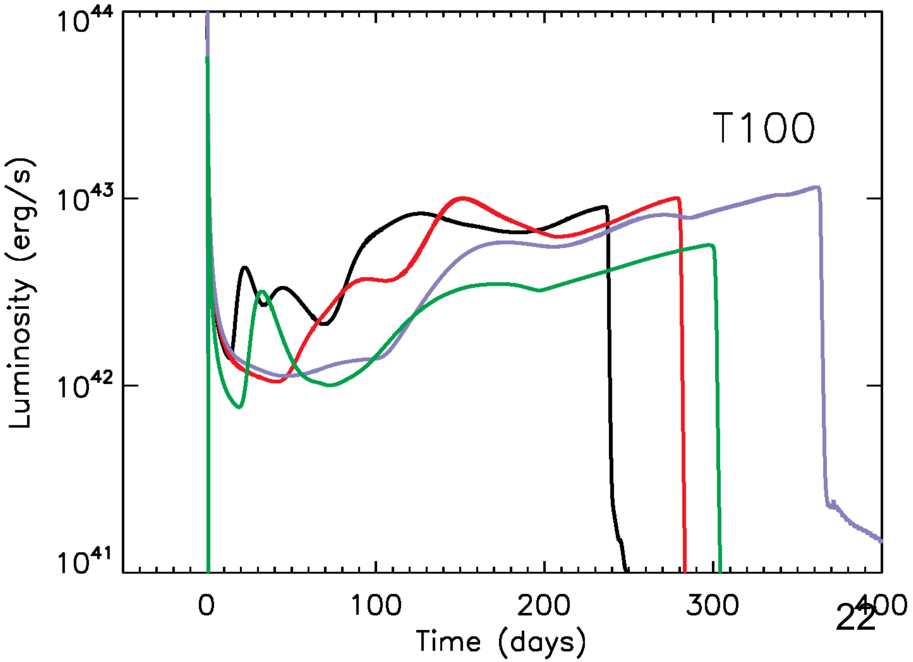
$v_{wind} = 50$ km s^{-1} $v_{shock} = 5000$ km s^{-1}

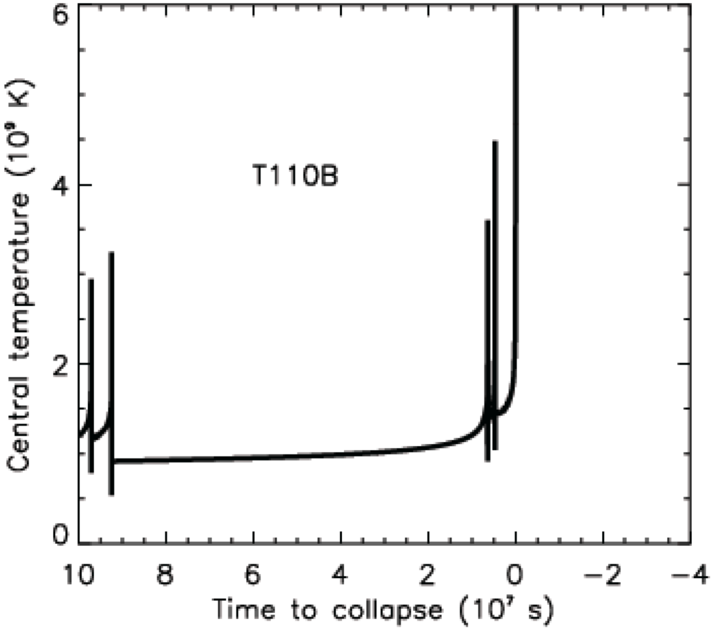
100 $M_\odot$ – structured light curves with the effects of multiple pulses becoming visible. Shells colliding while SN is in progress.

$L_{max} \approx 0.5 - 1 \times 10^{43}$ erg s^{-1}

Total light 1 - 2 x 10^{50} erg

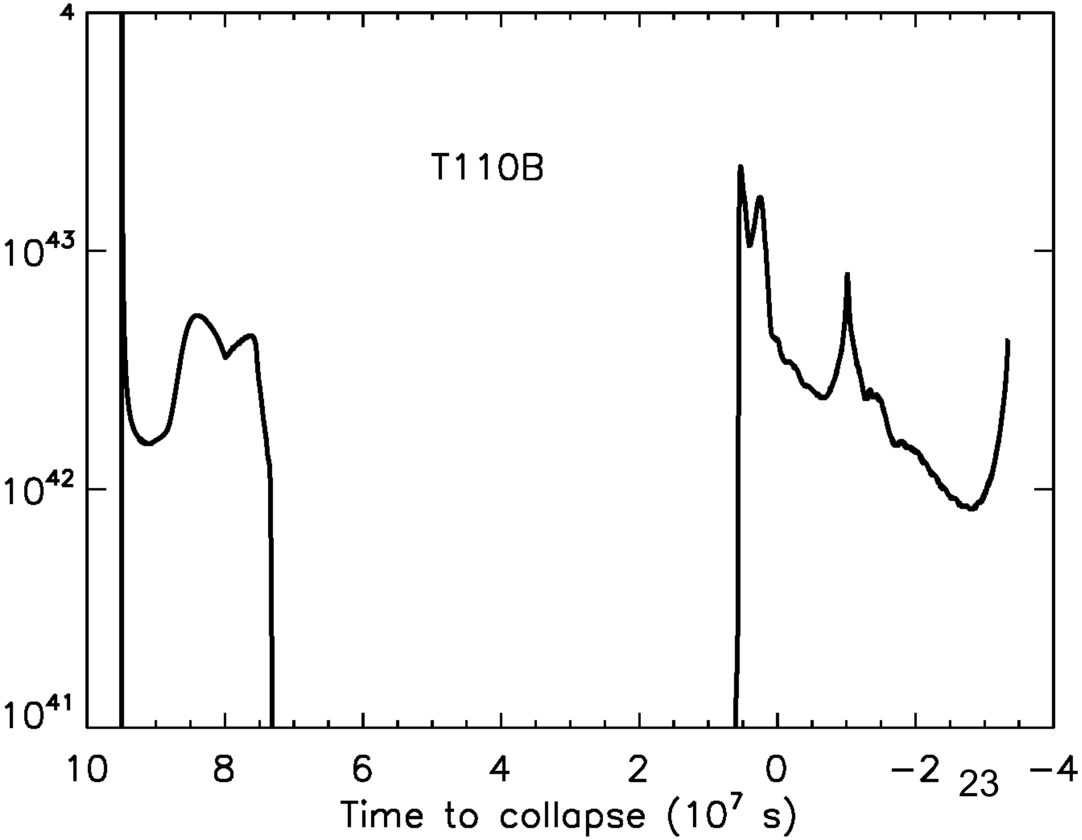
KE ~ 7 x 10^{50} erg





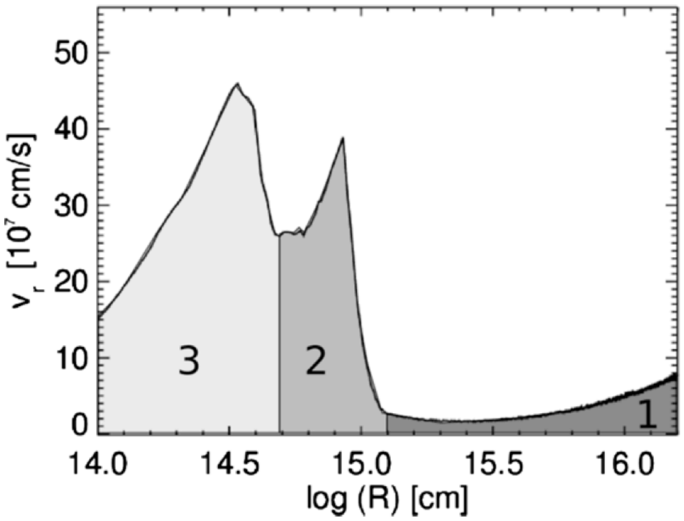
For higher helium core masses than 50 solar masses strong pulses are occur over a period of years rather than months leading to separate recurring supernovae

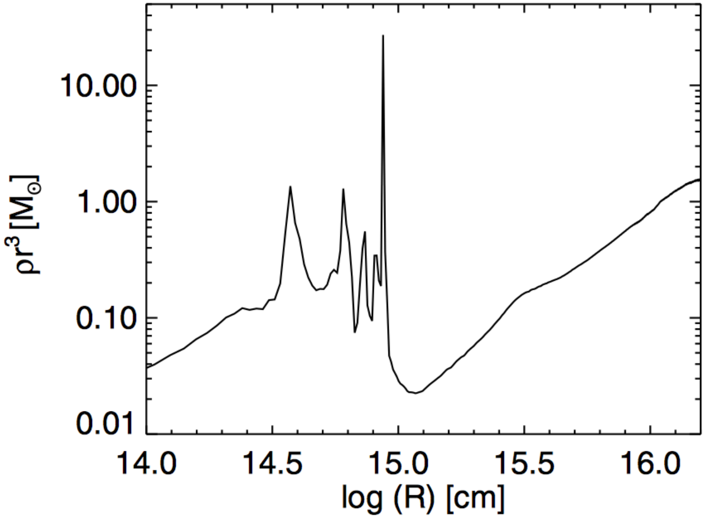
The first pulses ejects the entire envelope in a rather ordinary SN lip. That will be the case for heavier stars as well. Subsequent pulses, usually near the end, eject He and CO rich shells that run into the H-He envelope and each other making bright long-lasting structured events

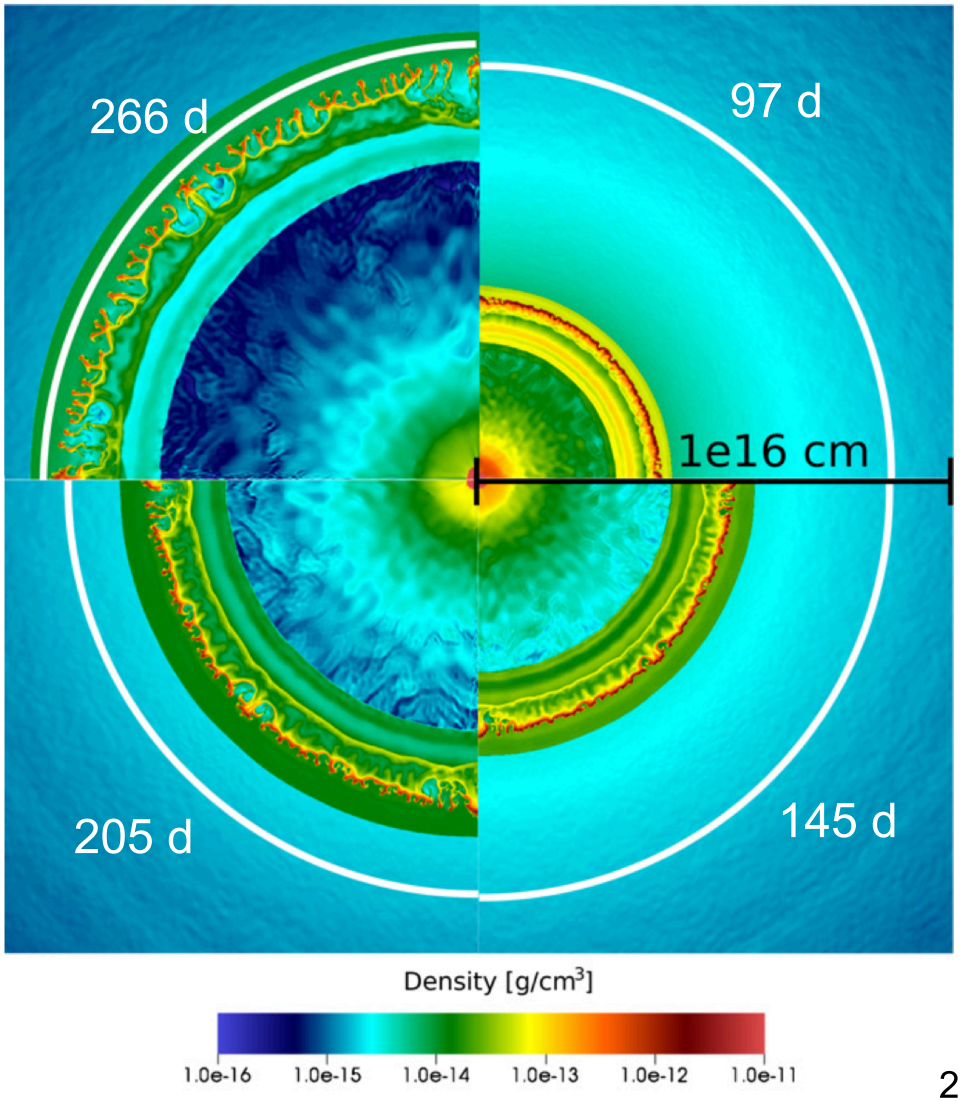


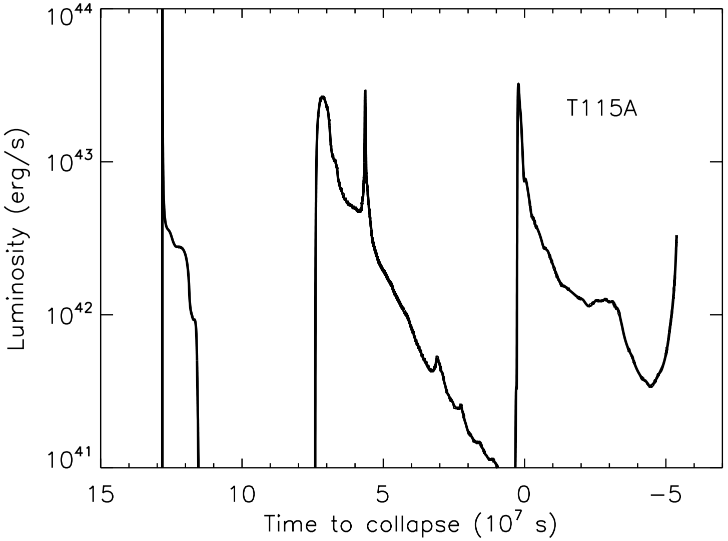
Mixing in PPISN

Chen et al (2014)

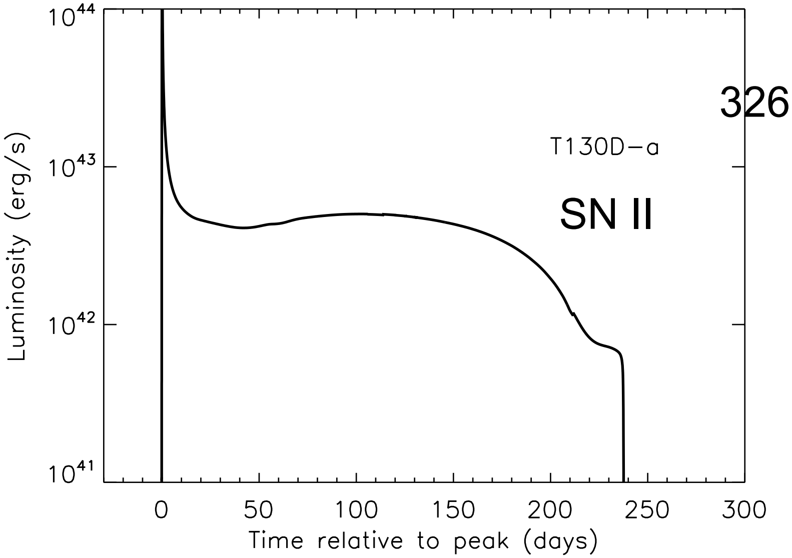






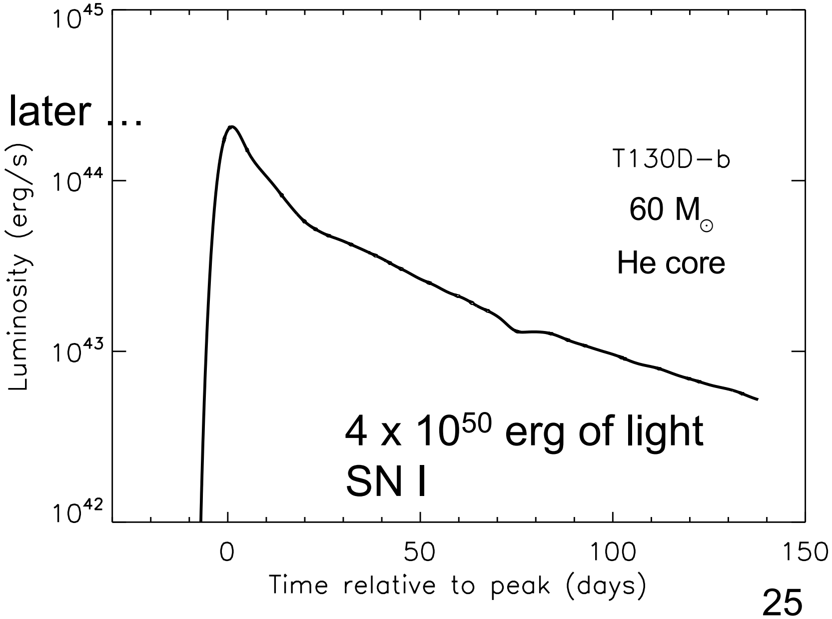


At the highest masses, the intervals between pulses become longer and the pulses more energetic. Supernovae can be separated by long periods during which the star remains shining with a luminosity near 10^{40} erg s^{-1} inside what may be a bright radio or x-ray source



SN II

3260 years later …



60 $M_\odot$

He core

4 x 10^{50} erg of light

SN I

PPISN SLSN TYPE II SUMMARY – NO ROTATION

- Faint long red transients for lightest PPISN, 10^{40} – 10^{42} erg s^{-1}

- Luminosities of 10^{42} – 10^{44} erg s^{-1} possible in more massive models. Some last up to ~400 days (500 days?).

- Recurring supernovae for M over 105 solar masses

.

- Often “double hump” light curves – especially for LBV and BSG

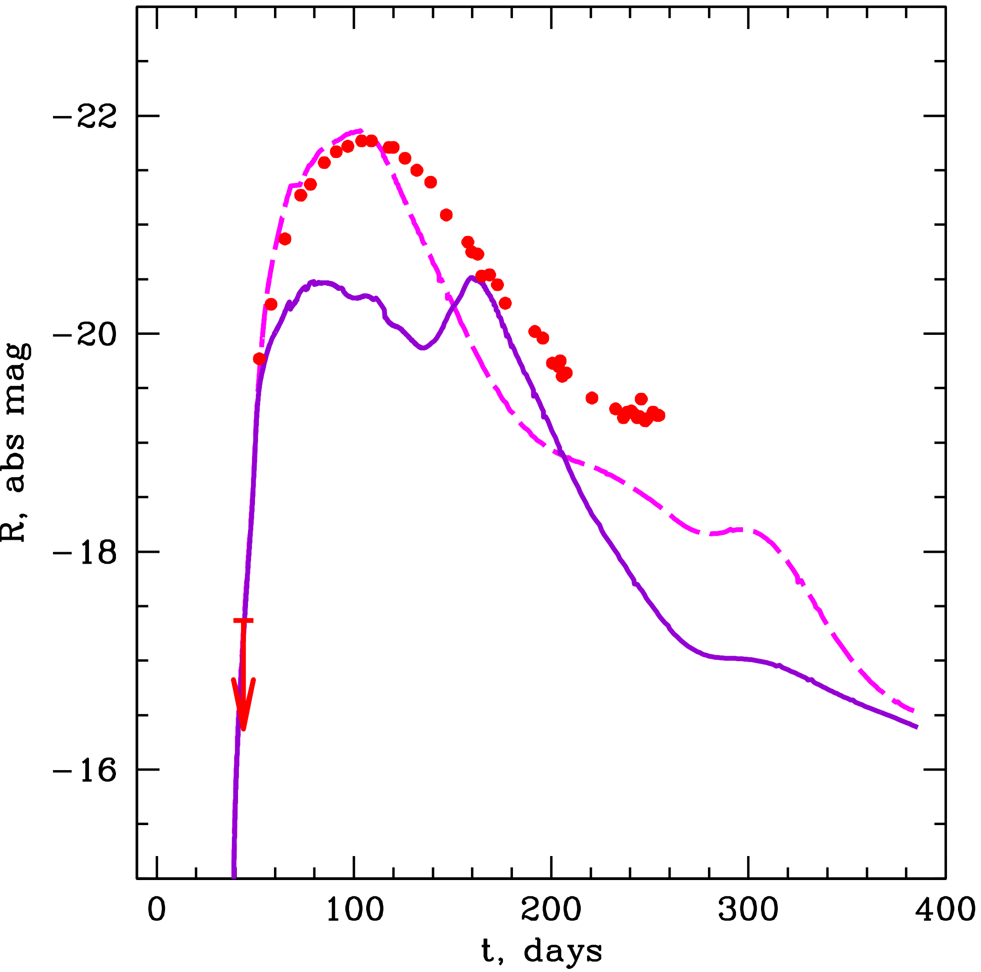
- Transients can last in total several thousand years. In between there may be a bight radio/x-ray transient with a 10^{40} erg s^{-1} star-like object embedded. Bright SN comes at the end.

- Total kinetic energy in the ejected mass cannot exceed 5 x 10^{51} erg (from pulses alone). This is shared among several pulses and only a fraction can be radiated. 5 x 10^{50} erg is the greatest value seen.

SUPERLUMINOUS SUPERNOVE

SN 2006gy

Woosley, Blinnikov, & Heger(2007)



Good agreement with the light curve required a doubling of the velocity in the 110 M_O model considered, which corresponded to a total explosion energy of 2.9 x 10^{51} erg. This is feasible for a full star.

Smith et al (2010) however estimate a total energy *in light* of 2.4 x 10^{51} erg. Unfortunately this may not be achievable in an unboosted PPISN (i.e., purely thermonuclear PPISN).

SUPERLUMINOUS SUPERNOVAE

e.g. SN 2003ma - 3.6 x 10^{51} erg of light (Rest et al 2011)
SN 2006gy - 2.4 x 10^{51} erg " (Smith et al 2010)
SN 2005ap - 1.7 x 10^{51} erg " (Quimby et al 2011)
SN 2008es - 1.1 x 10^{51} erg " (Miller et al 2009)
etc.

It does not seem likely that either pair or purely thermonuclear pulsational pair models can explain these events.

Therefore, magnetar formation seems necessary, either to give the light curve directly or to provide the ~10^{52} erg explosions needed to make light hydrodynamically in the PPISN model.

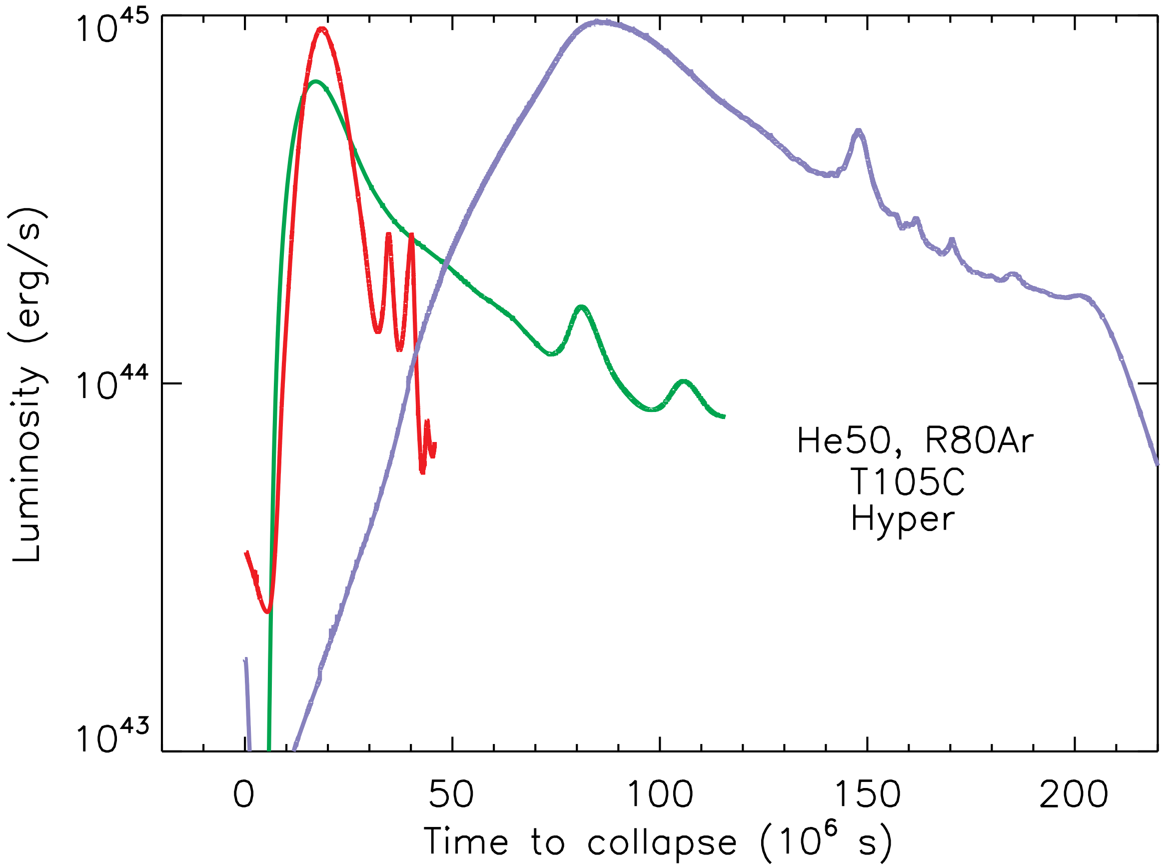
Necessary, but is it possible?

MODELS WITH ROTATION (including magnetic torques)

Model	**v_{rot} (km s$^{-1)}$_**	**M_{preSN} (M_O)**	**M_{He} (M_O)**	**M_{Fe} (M_O)**	**J_{Fe} (10^{48} erg s)**	$a_{remnant}$ (Jc/GM^2) M_{grav} = 2	**τ pulsar (ms)**	**Mass –Ej (M_O)**
R70	175	54.4	41.7	2.92	6.4	0.072	2.0	17.4
R80	180	62.2	47.8	2.00	3.3	0.071	3.8	18.6
R80r	195	62.5	56.0	2.74	7.2	0.069	1.7	14.7
R90	180	68.8	56.0	1.83	3.0	0.063	4.2	20.7
C70	260	40.7	-	2.88	14	0.18	0.9	2.6
C80	250	44.9	-	2.67	11	0.089	1.1	4.5
C90	245	49.4	-	2.60	8.1	0.10	1.6	6.0

“R” models had 50% standard rotation; ”C” models had 25%
A neutron star moment of inertia of 2.0 x 10^{45} gm cm^2 was assumed

Very Energetic Terminal Explosions in PPISN



see also
Chatzopoulos et al
(2016)

Model	Description	Type	KE*	Light	^{56}Ni
He50	He-core	Ib or Ic	2.1 x 10^{52}	1.2 x 10^{51}	2.7 M_O
R80Ar	Rapid rot.	Ib or Ic	1.4 x 10^{52}	2.5 x 10^{51}	1.8 M_O
T105C	H-star	II	2.0 x 10^{52}	6.6 x 10^{51}	2.5 M_O

* Plus about 4 x 10^{51} erg for the binding energy of the star

CONCLUSIONS - SLSN

- SLSN with $E_{light} > 5 \times 10^{50}$ erg can be made in a PPISN context, but need explosion energies greater than thermonuclear pulses can (apparently) provide
.
- Maximum light from PPISN pulses alone ~ 5×10^{50} erg, usually much less.

- Superluminous supernovae from PPISN may require the birth of a magnetar, either to make an very energetic explosion (10^{52} erg) or to contribute to the light curve directly.

- The explosions may therefore be related generically to GRBs *and thus may be asymmetric*