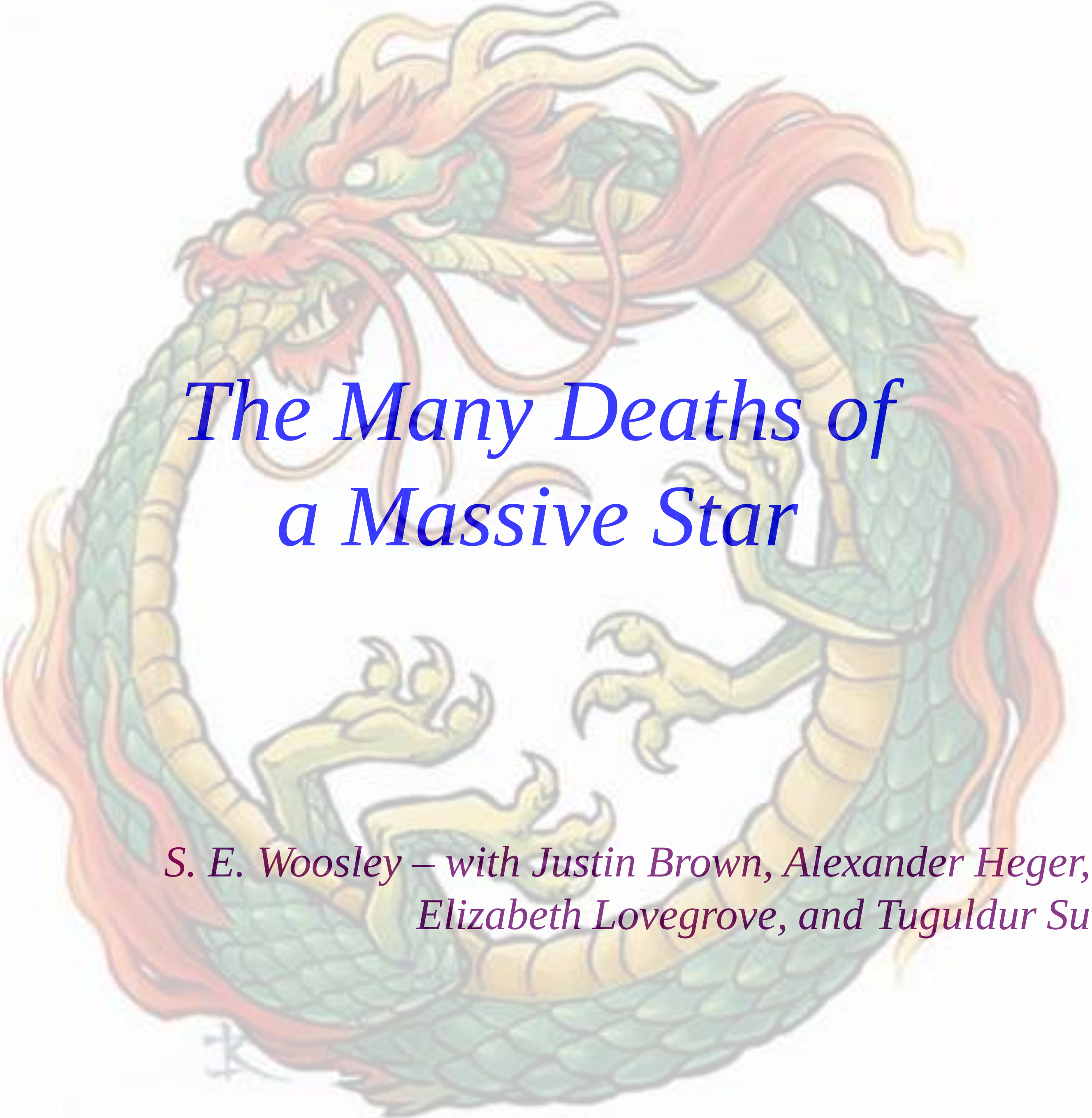


The Many Deaths of a Massive Star

S. E. Woosley – with Justin Brown, Alexander Heger,
Elizabeth Lovegrove, and Tuguldur Sukhbold

This talk will explore a few of the reasons for, and consequences of black hole formation in massive stars

- What sets the compactness, and hence the "explodability" of a massive star? Why do models differ?

- What is the minimum upper bound for successful explosions based upon nucleosynthesis?

- What are the observable characteristics of prompt black hole formation in ordinary massive stars?

- On the upper end, what are the characteristics of pulsational pair-instability supernovae?

“*COMPACTNESS*”

(Sukhbold and Woosley, 2012 – in preparation)

How a star dies is determined by its properties at birth – its mass, composition, rotation rate, and binary membership.

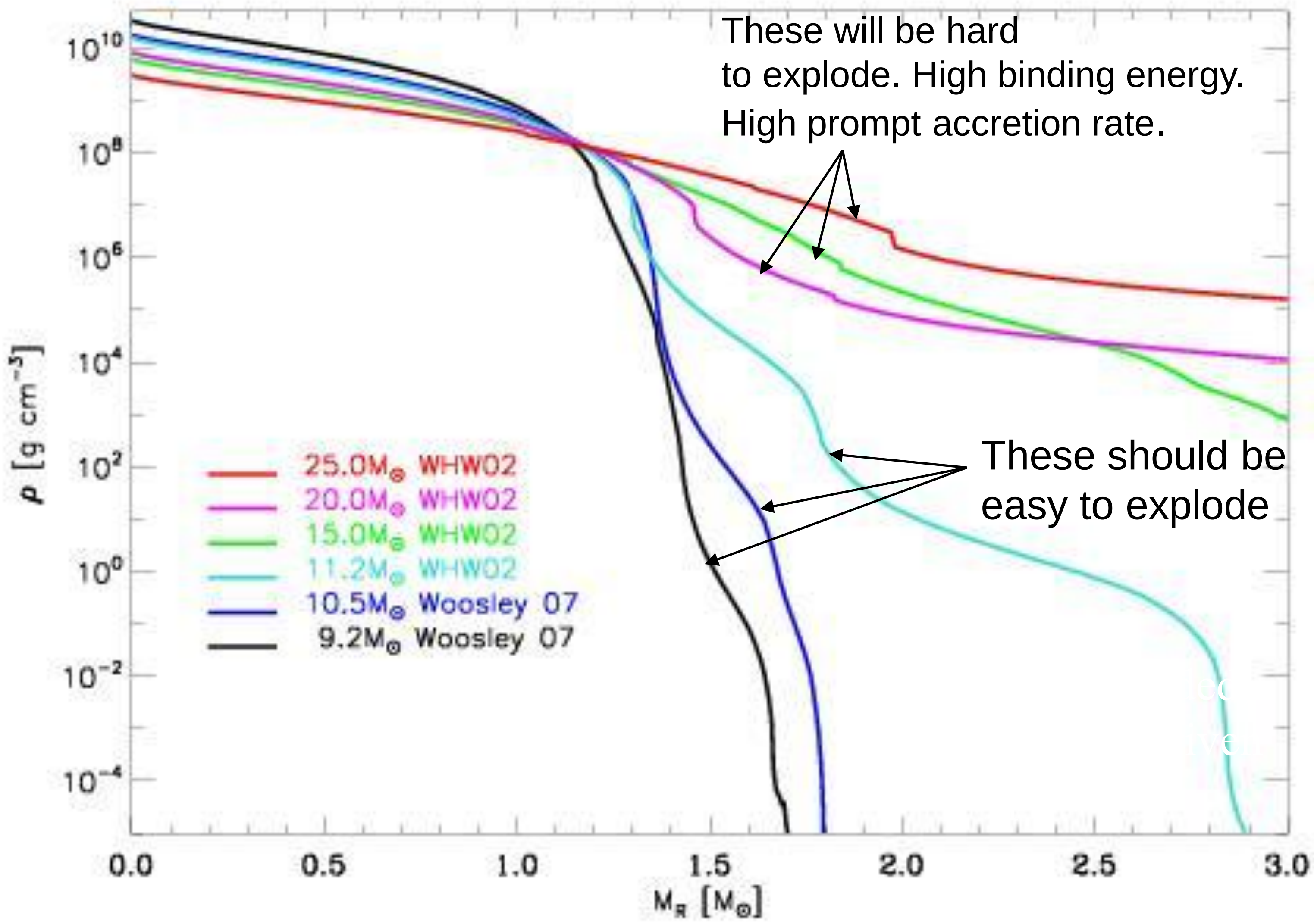
Mass affects the “central engine” by determining the density structure in the inner few solar masses of the presupernova star.

$$P_c \sim \frac{GM\rho}{R} \Rightarrow \frac{T_c^3}{\rho_c} \propto \mu^3 M^2$$ (for an ideal gas and e.g., constant density)

$$S = \text{const} + \ln \frac{N_A k}{\mu}\frac{T^{3/2}}{\rho} + \frac{4a}{3}\frac{T^3}{\rho}$$ (heavier stars have higher entropy,

i.e., are less degenerate)

Density Profiles of Supernova Progenitor Cores



These will be hard
to explode. High binding energy.
High prompt accretion rate.

These should be
easy to explode

O’Connor and Ott, *ApJ*, **730**, 70, (2011)

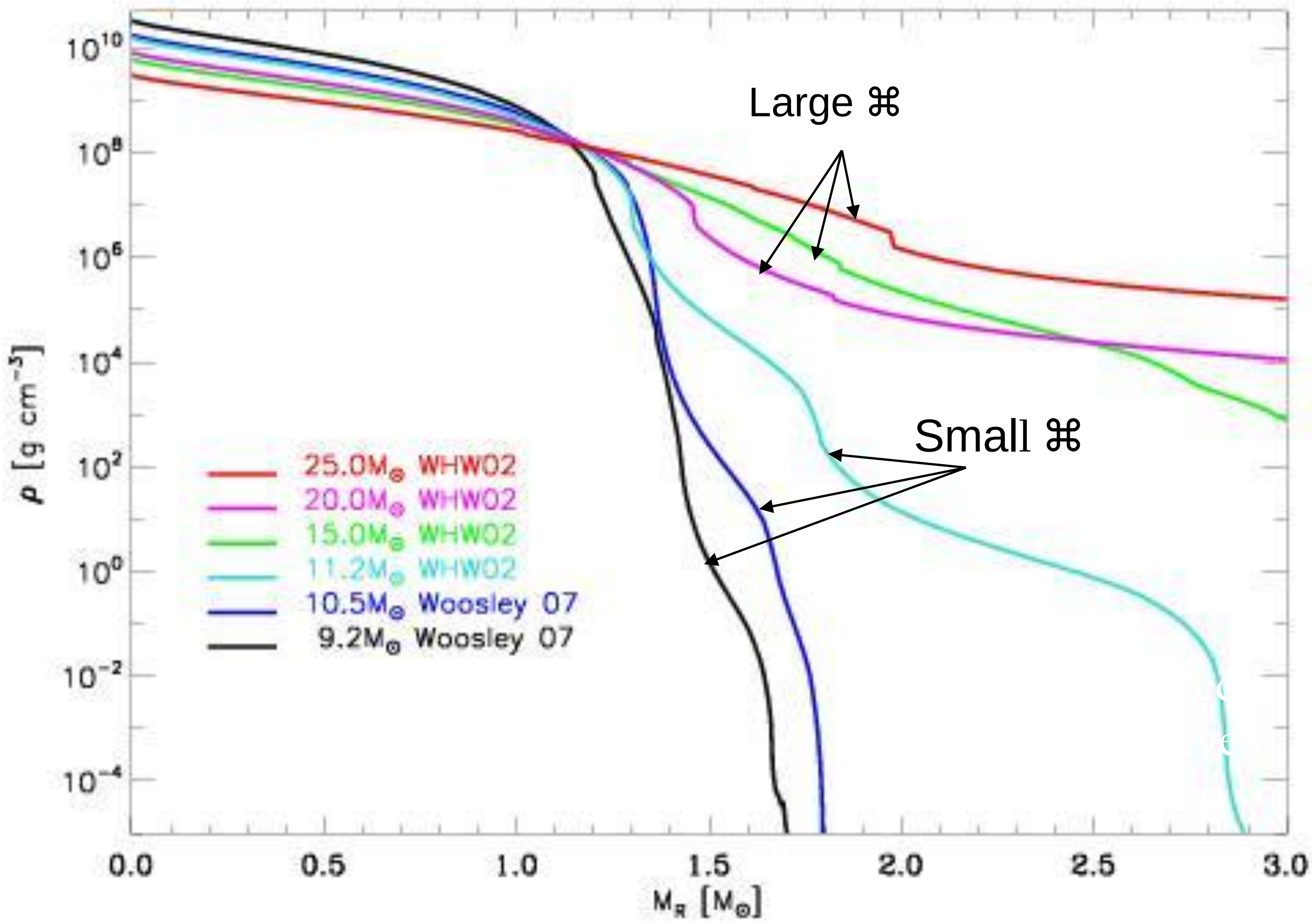
Characterize possibility of a neutrino-powered explosion based upon the compactness parameter📪 ⌘📪

$$x_M = \frac{2.5}{R(M_{bary} = 2.5M_{\odot})/1000 \ \mathrm{km}} \Bigg|_{t-bounce}$$

If R is small and the 2.5 solar mass point lies close in, then ⌘ is big. The star is hard to explode. Based upon a serie of 1D models OO11 find stars with ⌘ over 0.45 are particularly difficult to explode.

$$\boxed{x(\mathrm{explosion}) < 0.45}$$

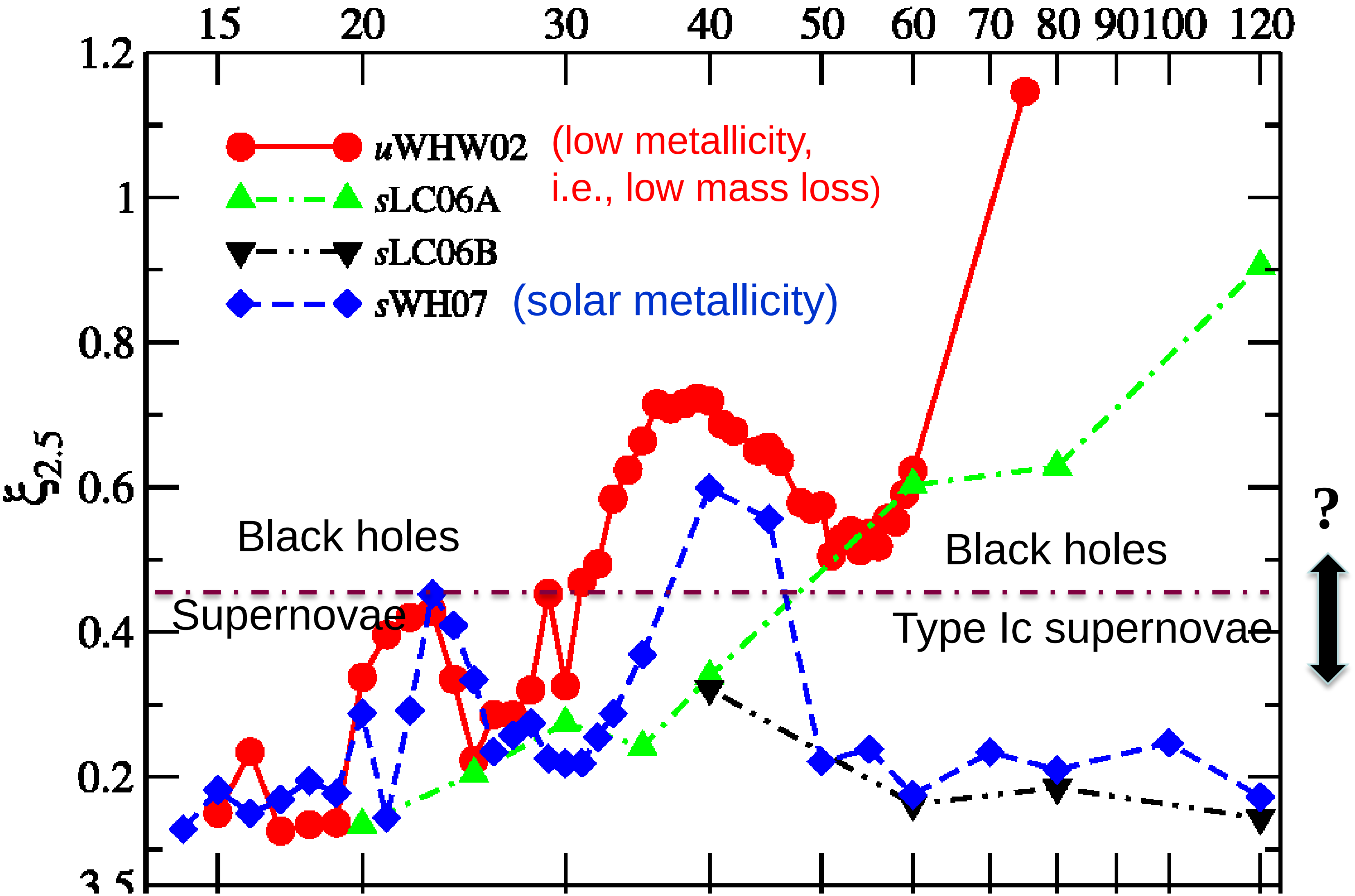
Density Profiles of Supernova Progenitor Cores



Large ⌘

Small ⌘

O’Connor and Ott (2011)



(low metallicity,
i.e., low mass loss)

(solar metallicity)

Black holes

Supernovae

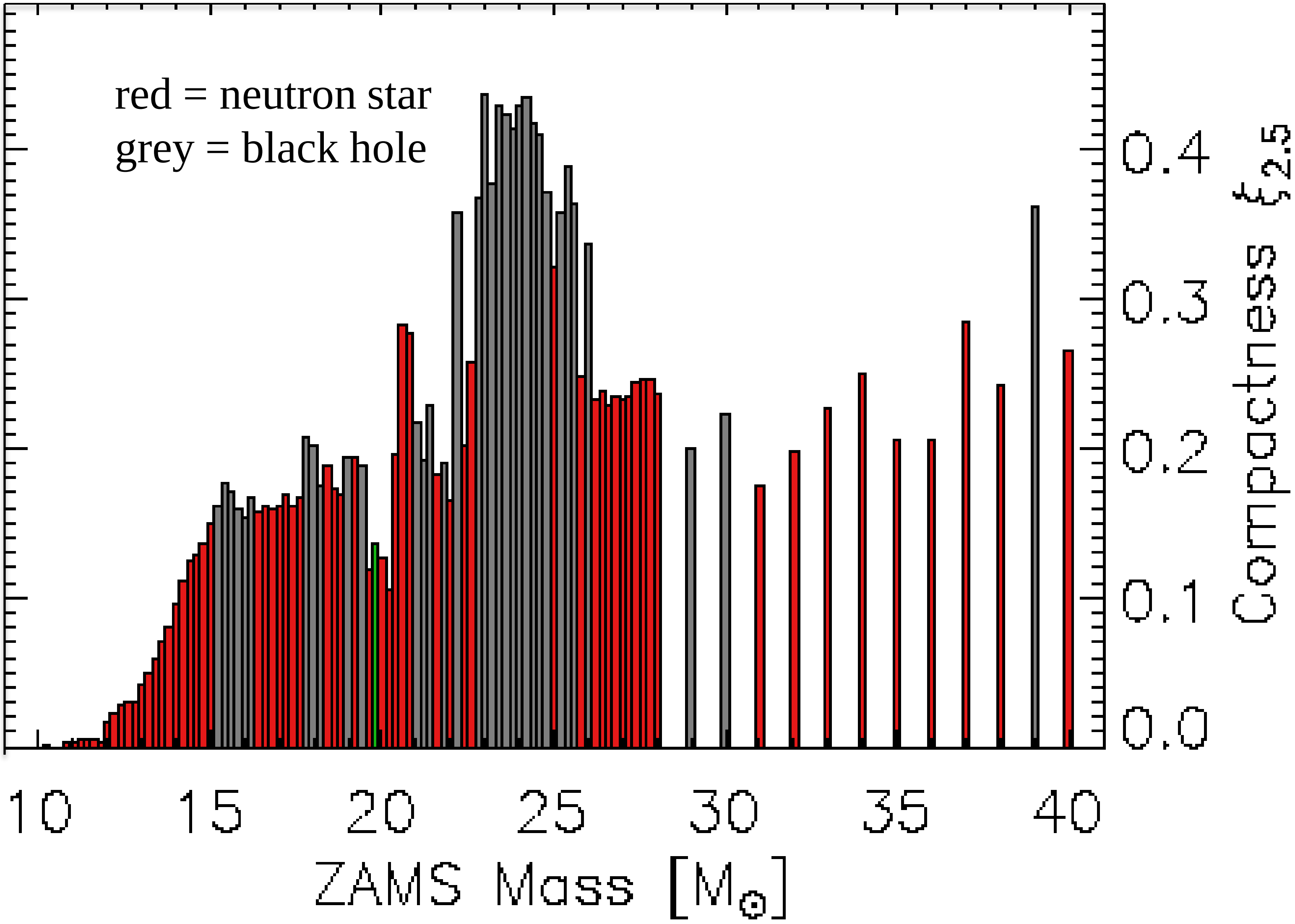
Black holes

Type Ic supernovae

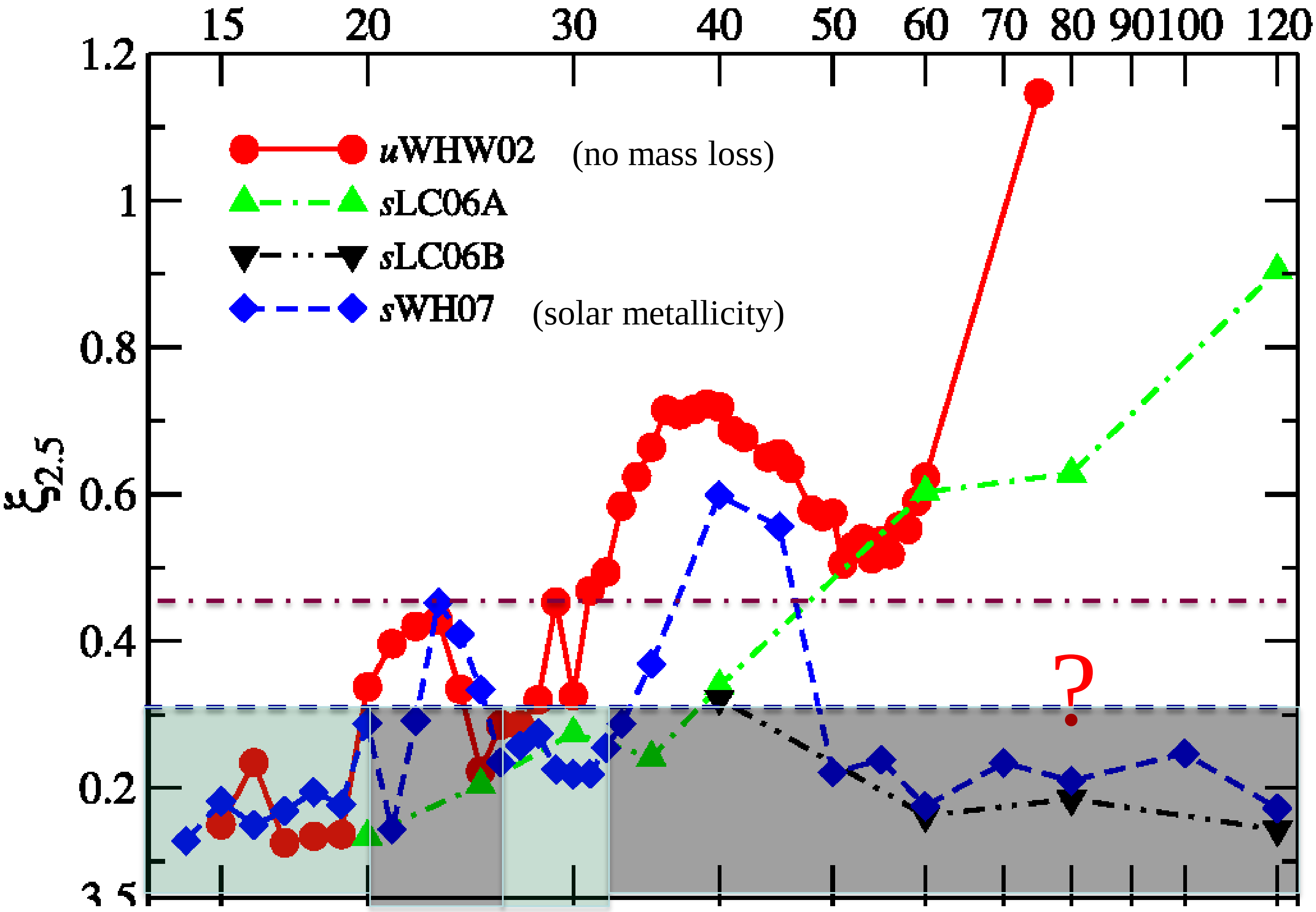
?

Results up here sensitive to
poorly known mass loss rates

Ugliano, Janka, Marek, and Arcones (2012)
using 102 solar metallicity models from Woosley et al (2002)
Maybe ☒ = 0.2 more appropriate? Big error bar



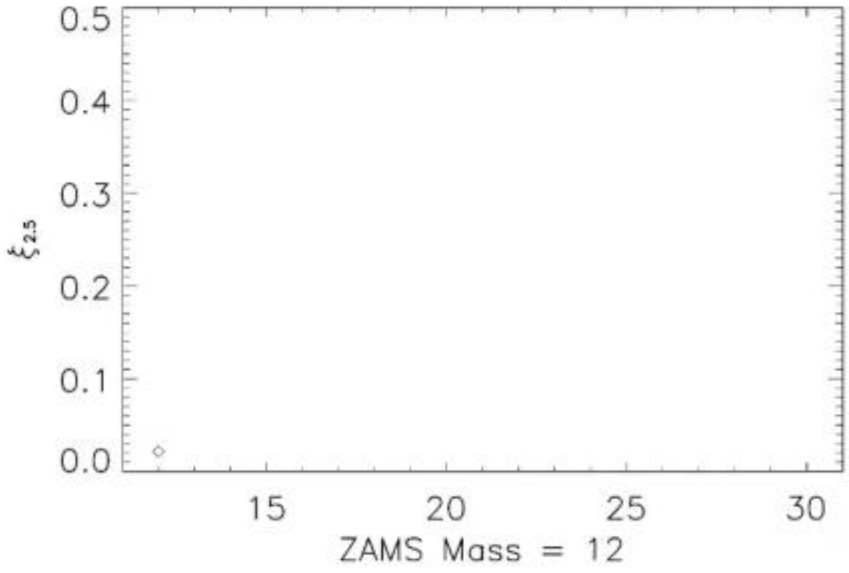
$V_{crit} \approx$ 0.2 - 0.3 may be more appropriate?



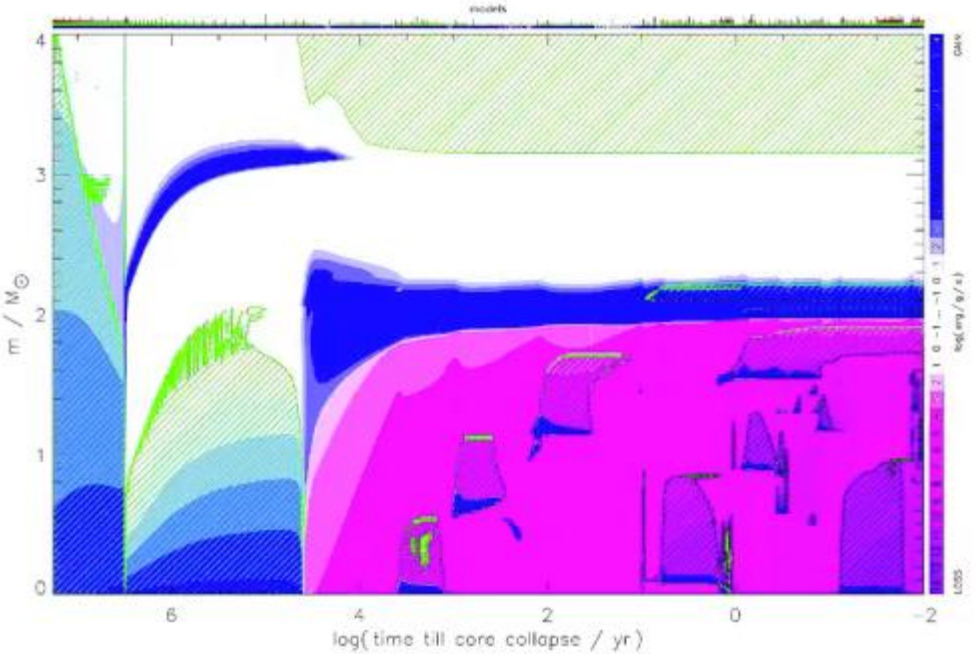
O'Connor and Ott (2011)

Sukhbold and Woosley (2012, in prep)

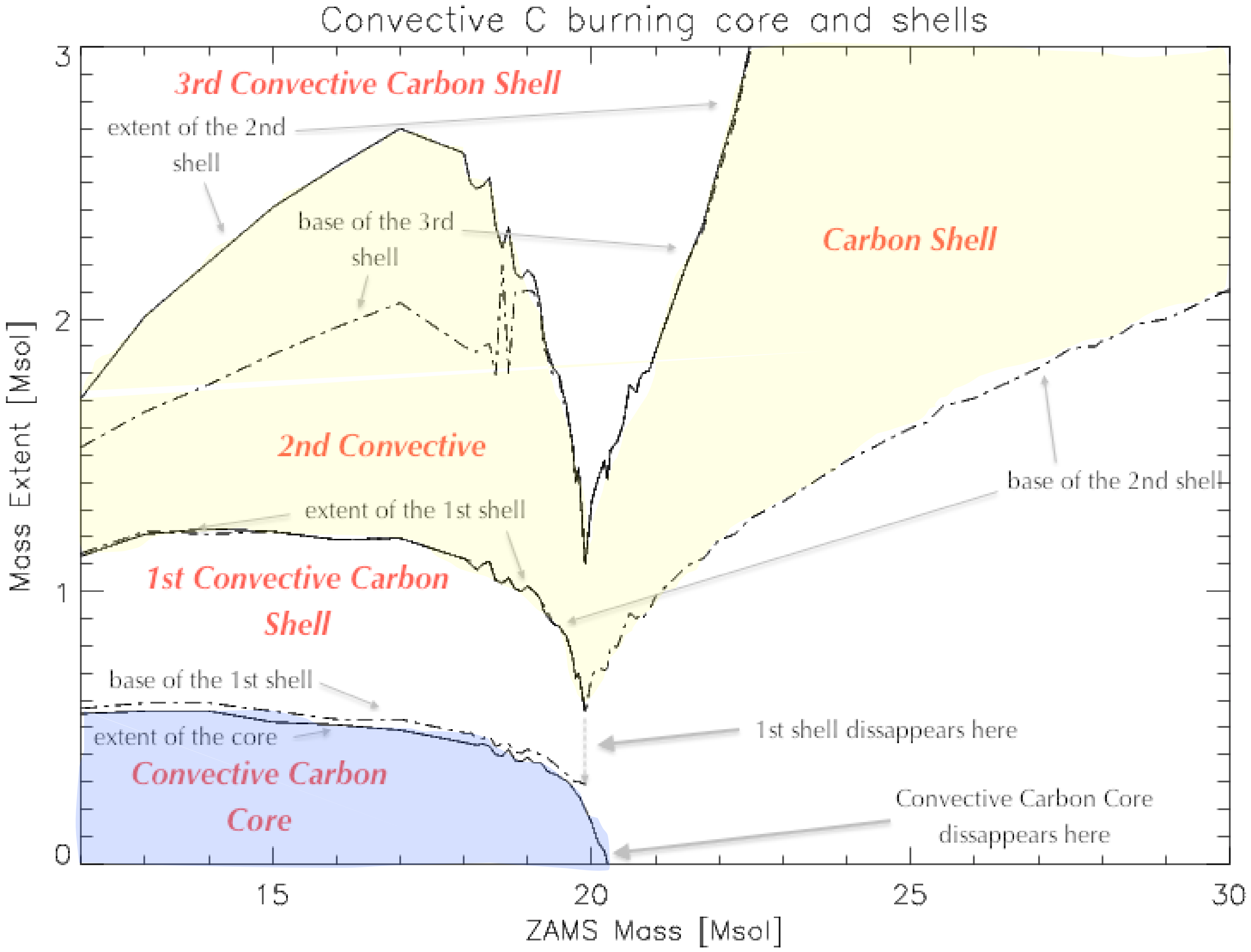
The compactness of the pre-supernova star is set by the carbon burning activity that precedes its death. Above 20 Msun, carbon burns radiatively in the center of the star (see also Barkat 1990, Les Houches; Timmes, Woosley, and Weaver 1996)



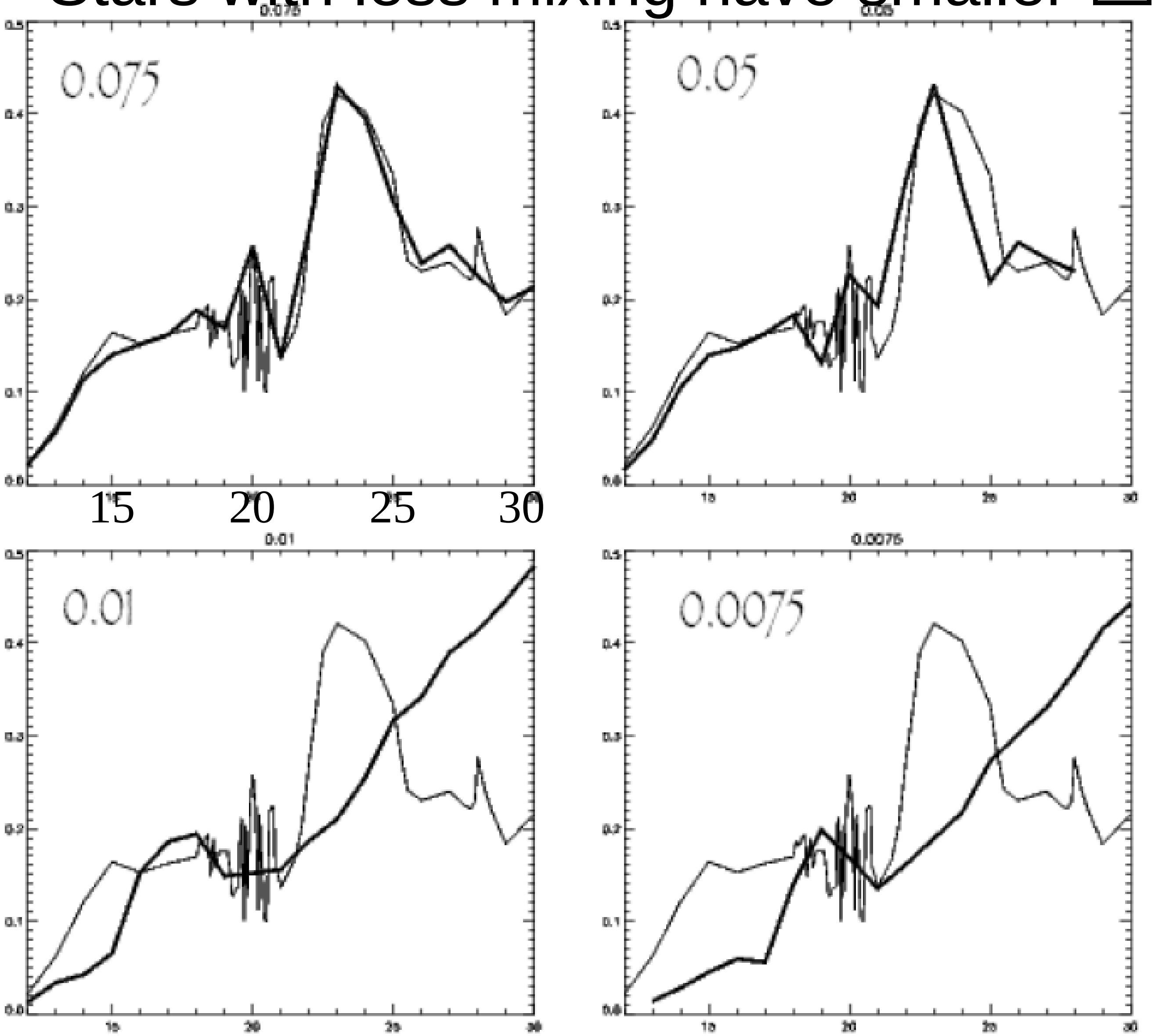
The purple region indicates neutrino losses are dominant (i.e., post carbon ignition). Blue is positive energy generation. Note carbon, oxygen and silicon burning shells.



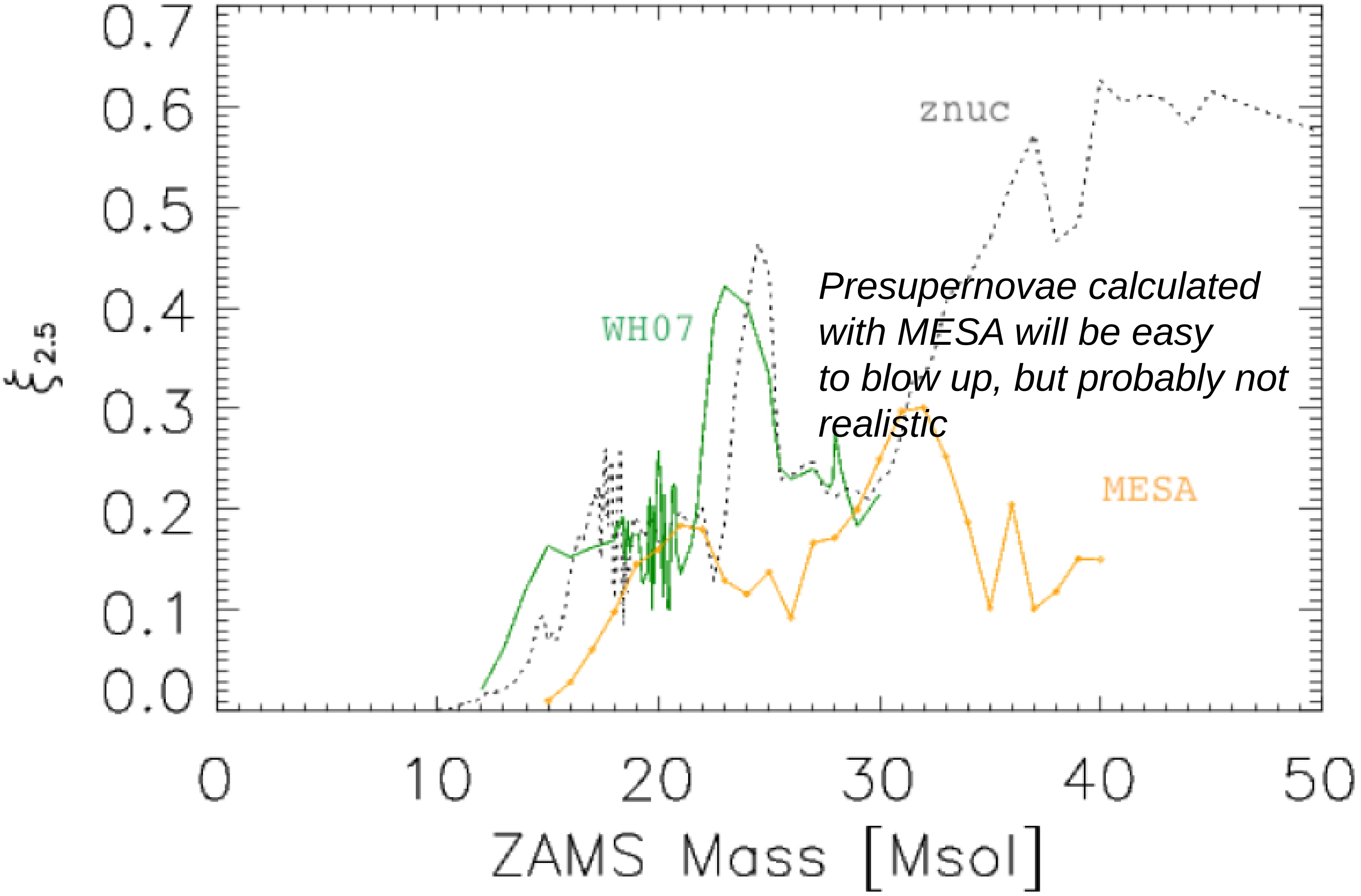
log time until death


Convective C burning core and shells
3rd Convective Carbon Shell
extent of the 2nd shell
base of the 3rd shell
Carbon Shell
2nd Convective
extent of the 1st shell
base of the 2nd shell
1st Convective Carbon Shell
base of the 1st shell
extent of the core
1st shell dissappears here
Convective Carbon Core
Convective Carbon Core dissappears here
Mass Extent [Msol]
0
1
2
3
15
20
25
30
ZAMS Mass [Msol]

Effect of “semiconvection”. Default = 0.1
Stars with less mixing have smaller ☒

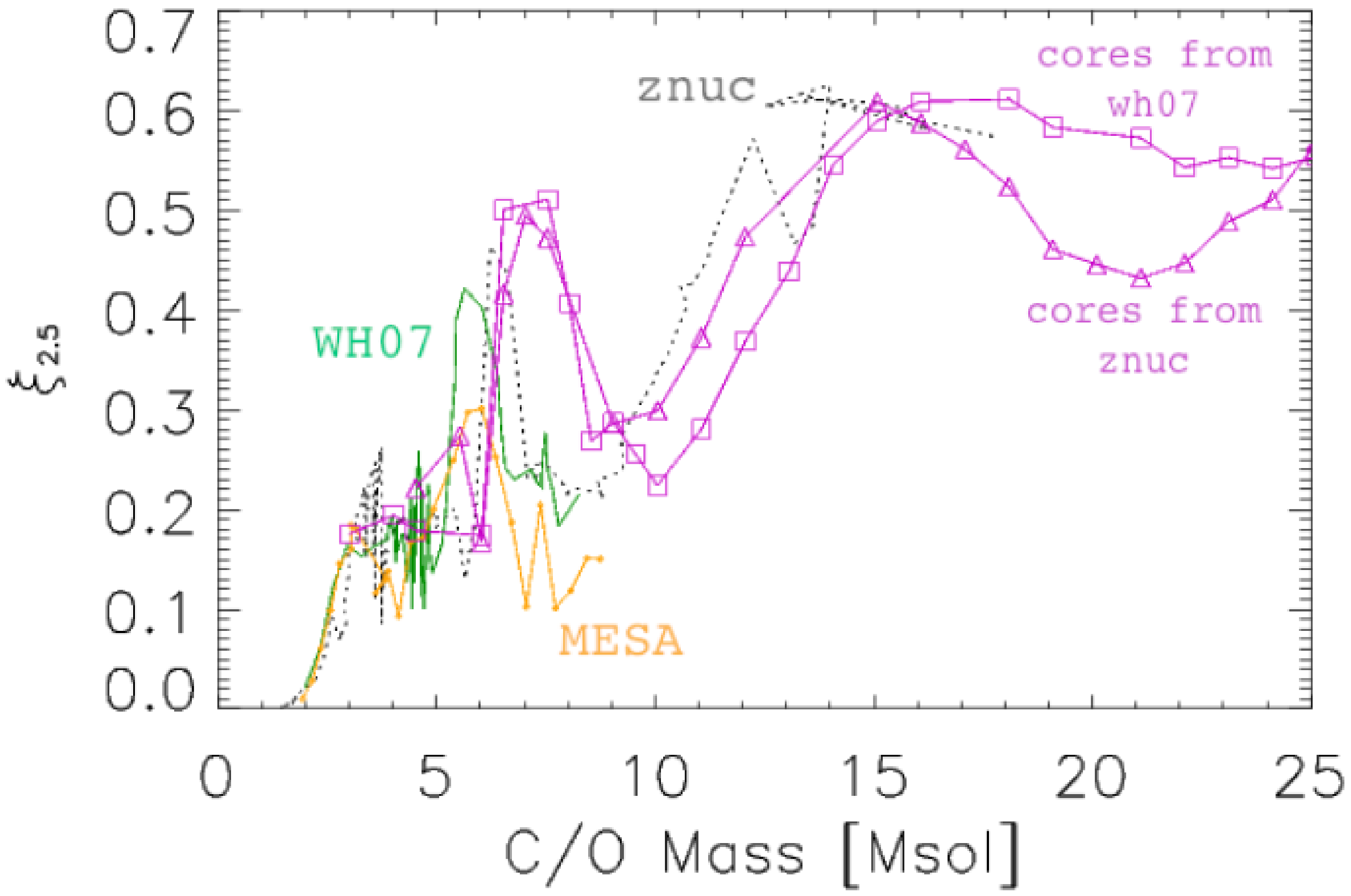


Results from various codes and for various metallicities do not agree well when plotted against main sequence mass

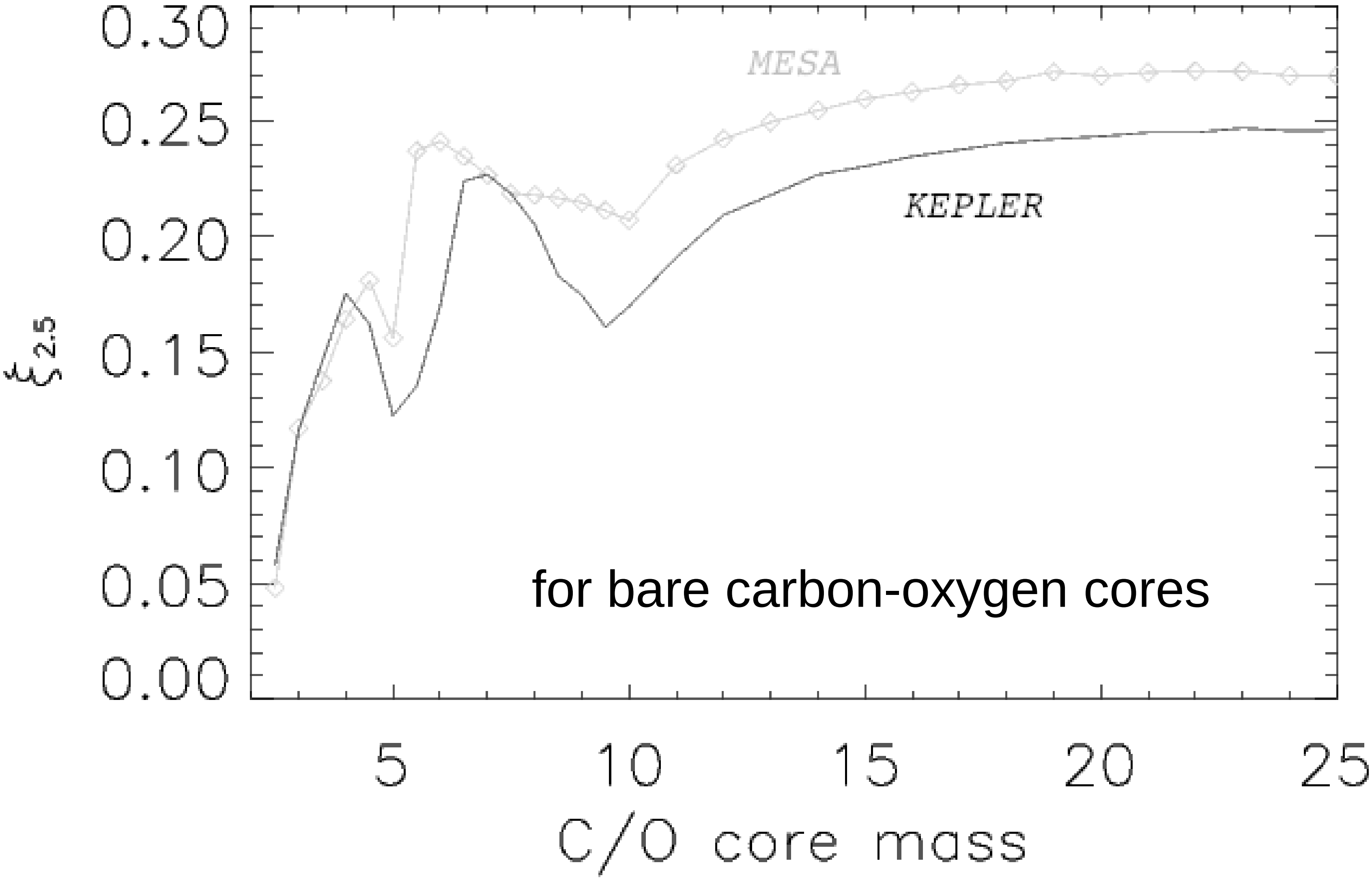


Presupernovae calculated with MESA will be easy to blow up, but probably not realistic

Much better agreement is achieved by plotting *vs* the CO core mass. WH07 and MESA stop at 8 Msun because of mass loss in solar metallicity stars.



MESA-KEPLER Comparison



for bare carbon-oxygen cores

Summary so far:

- The compactness of the core is non-monotonic with main sequence mass. Islands of “explodability”,

- For “standard settings”, the evolution of stars below 20 solar masses is qualitatively different from those above

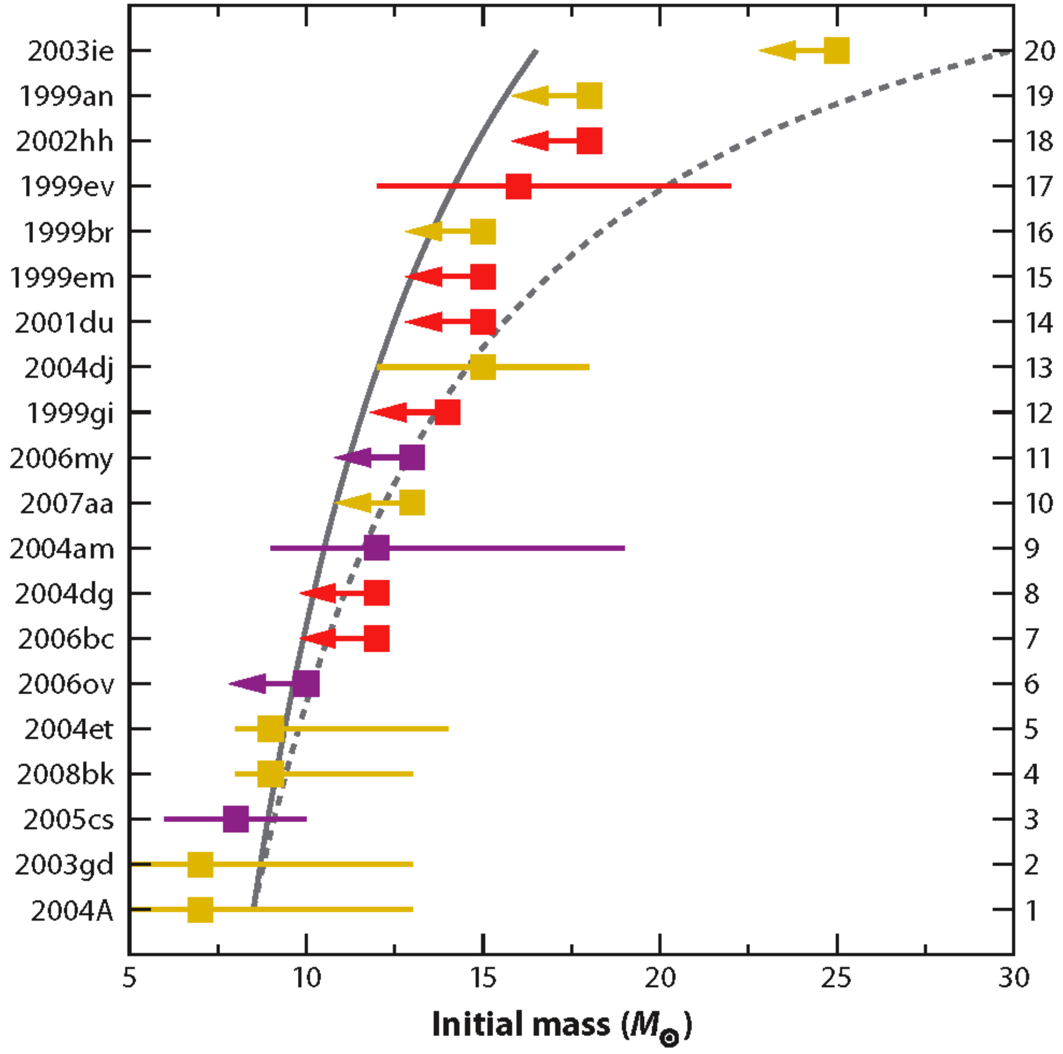
- The results are sensitive to semiconvection and convective overshoot

- The carbon-oxygen core mass at death is a better indicator or compactness than the main sequence mass. < 5 Msun may be relatively relatively easy to explode.

What we feel in our bones about the heaviest supernova?

Brown and Woosley (2012)

Presupernova stars – Type IIp and II-L

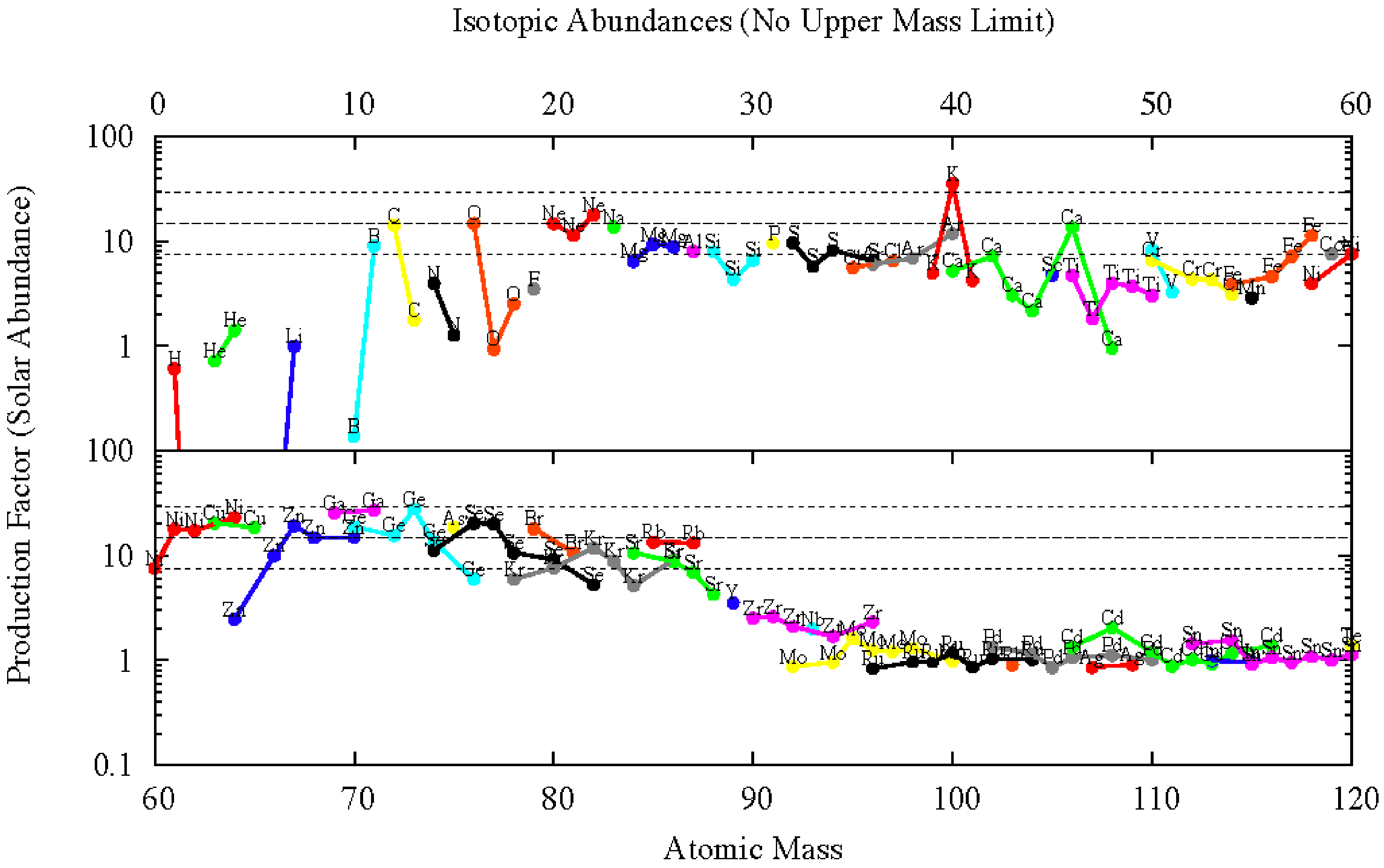


Smartt, 2009
ARAA

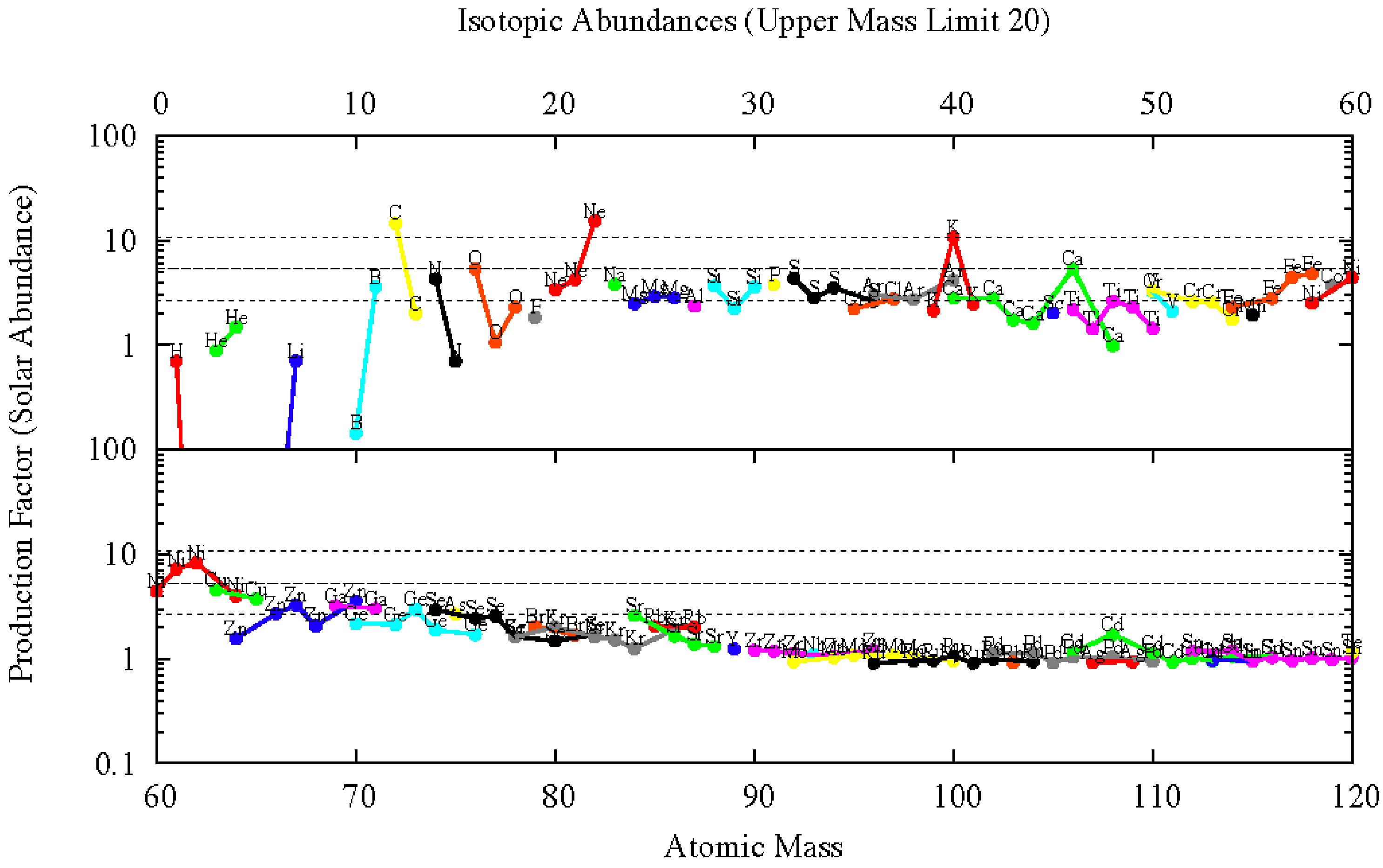
Progenitors heavier than 20 solar masses excluded at the 95% confidence level.

The solid line is for a Salpeter IMF with a maximum mass of 16.5 solar masses. The dashed line is a Salpeter IMF with a maximum of 35 solar masses

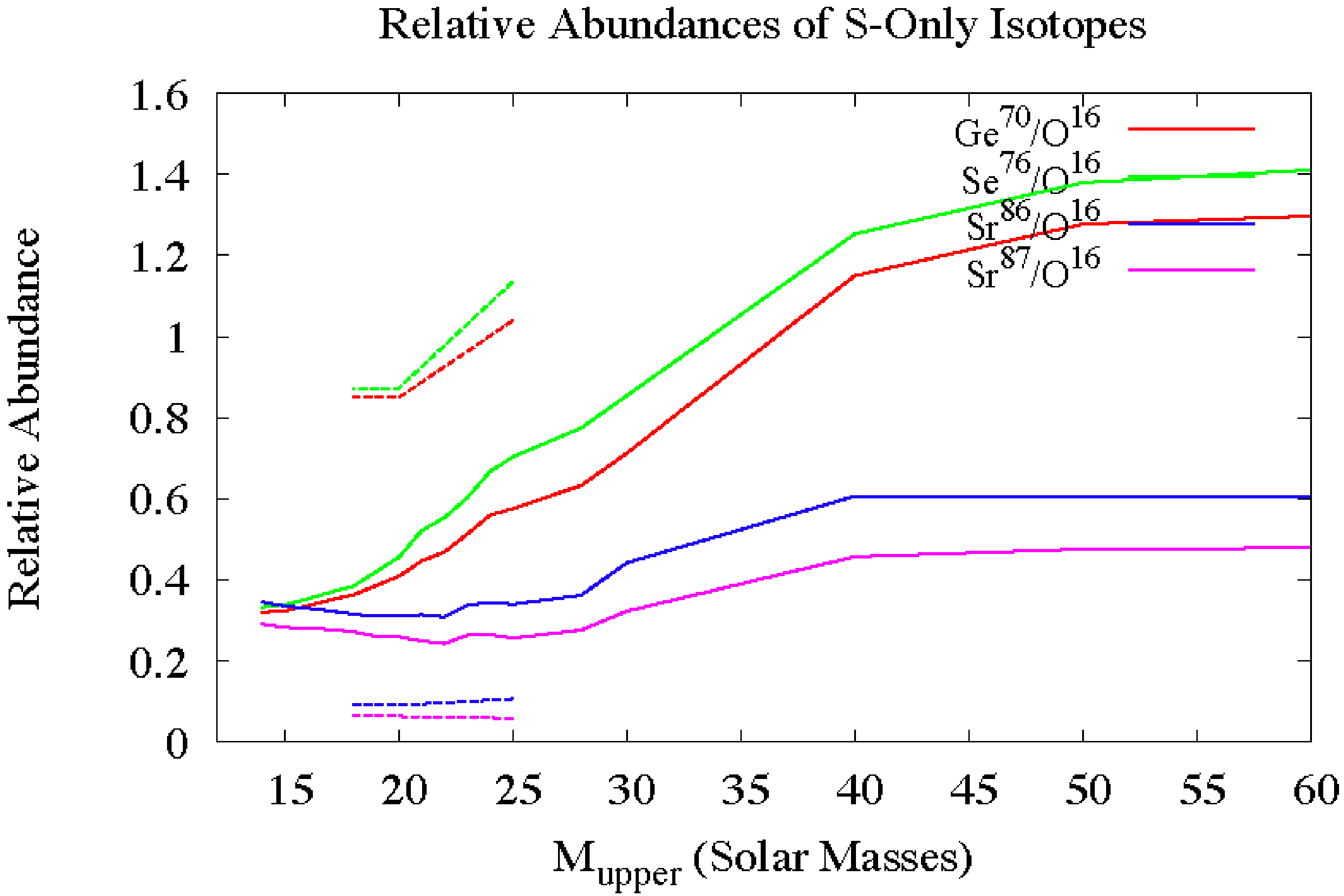
Woosley and Heger (2007) – yields from 11 – 120 solar masses



Brown and Woosley (2012, in prep) find little change if M_{upper} is reduced from 120 solar masses to 40 solar masses, but there are significant alterations if M_{upper} is reduced much more.



As M_{upper} is reduced less heavy elements are made in a generation of stars. Carbon, from presupernova mass loss stays undiminished but oxygen synthesis is reduced. ^{22}Ne also is high. Both problems could be alleviated by using lower mass loss rates, but the overall SN rate to make ^{16}O is now 3 times bigger. The s-process is lost!



The “weak” s-process is ascribed to massive stars. For best current values of the ^{22}Ne(a,n)^{25}Mg reaction rate, current models suggest problems if M_{upper} is less than about 30 solar masses, but 20 solar masses is in the error bar if the maximum allowed rate is used

Summary:

- Best nucleosynthesis is obtained for large values of $M_{upper.}$ Reduction below 40 Msun leads to a diminished goodness of fit.
- A value of M_{upper} as low as 20 solar masses might be tolerated (for this model set) only if the current mass loss rates are too large and the current value for $^{22}Ne(a,n)^{25}Mg$ is too large
- Reducing M_{upper} much below 30 Msun requires a much larger supernova rate if the production of oxygen is to be maintained. The increase is a factor of 2 for M_{upper} = 28 and a factor of 3 for M_{upper} = 3.

“**UNNOVAE**” – The direct collapse of a massive star to a black hole. (Kochanek)

Nadyozhin (1980) Ap and Spac Sci, 69, 115

A stellar core becomes somewhat less massive due to neutrinos radiated away during its collapse in a neutron star or a black hole. The paper deals with the hydrodynamic motion of stellar envelope induced by such a mass loss. Depending on the structure of the outer stellar layers, the motion results either in ejection of an envelope with mass and energy proper for Nova outbursts; or nearly instantaneous excitation of strong pulsations of the star; or lastly in a slow slipping away of the whole stellar envelope.

15 Msun RSG SN progenitor
Net BE external to 4.4 Msun 1.0 x 10^{47} erg

25 Msun RSG SN progenitor
Net BE external to 8.4 Msun 1.0 x 10^{47} erg

Grav Mass = Baryonic mass – Cold binding energy + Epsilon*accretion

$$M_G = M_B - BE_{\mathrm{cold}} + M_T$$

$$\frac{dM_T}{dt} = -\frac{M_T}{\tau_\nu} + \frac{\epsilon G M_G}{c^2 R}\frac{dM_B}{dt}$$

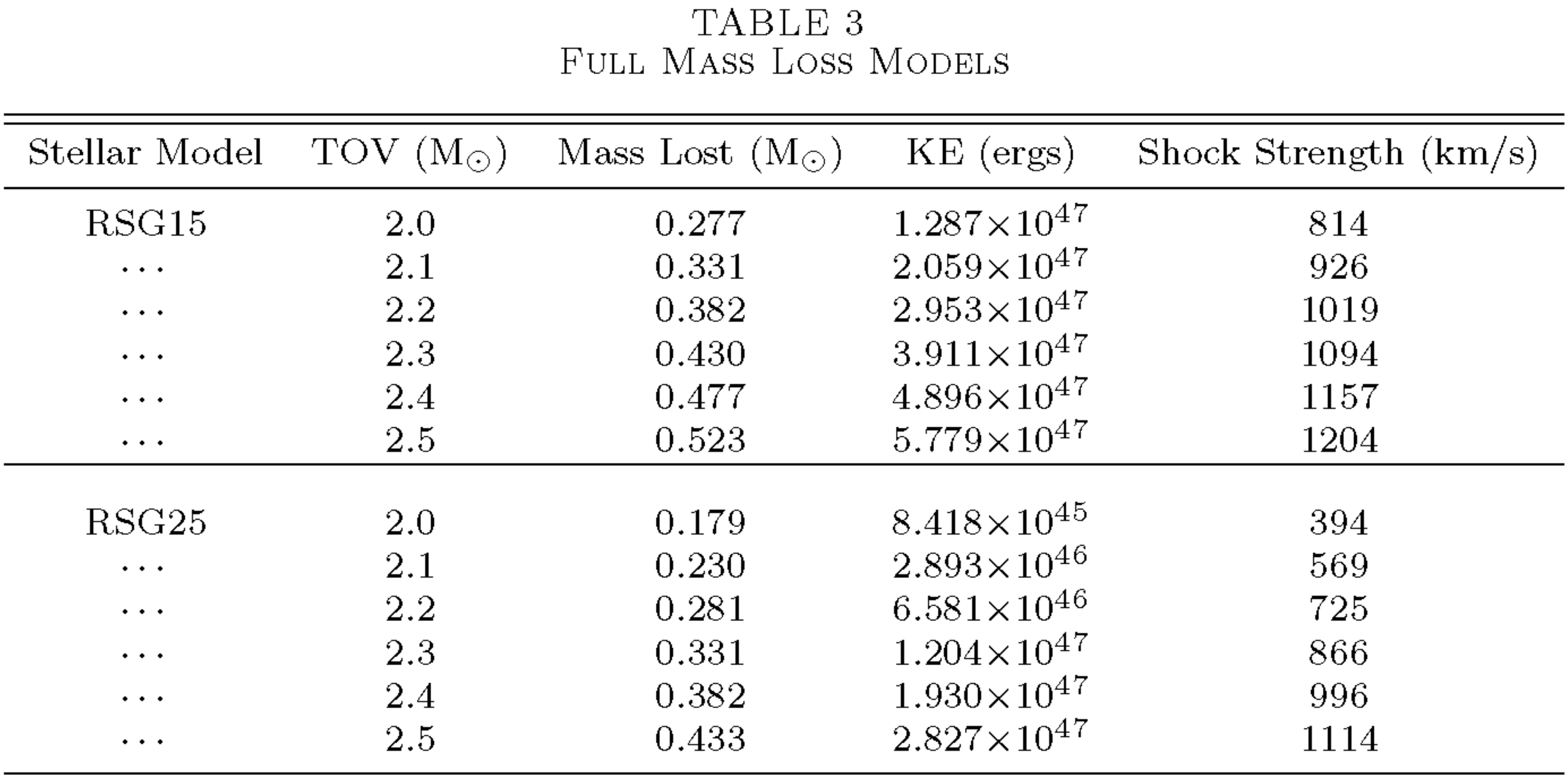
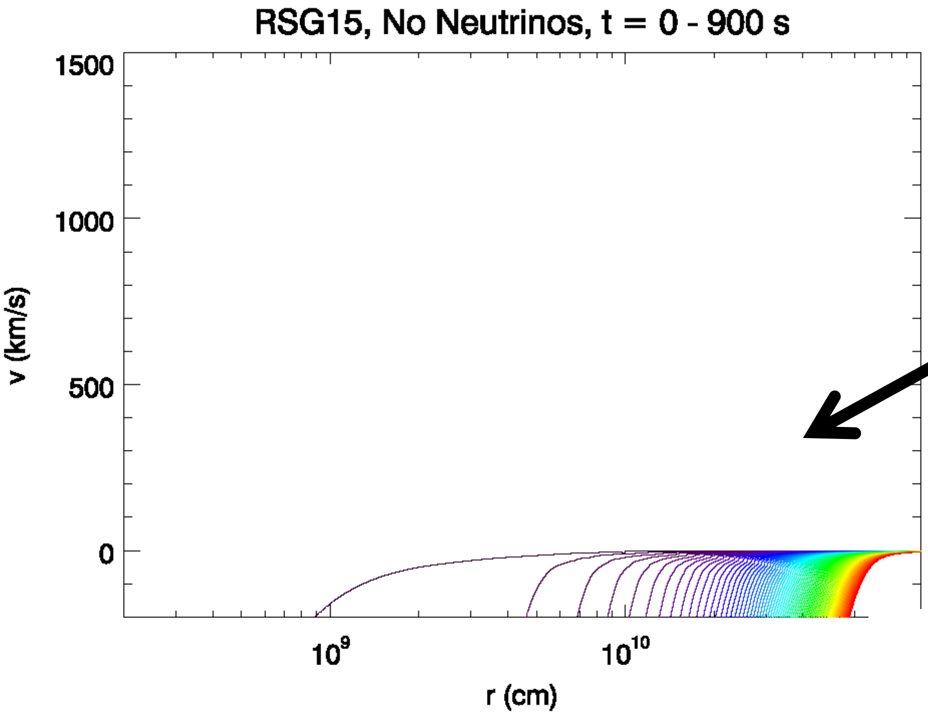


TABLE 3
FULL MASS LOSS MODELS

Stellar Model	TOV ($M_\odot$)	Mass Lost ($M_\odot$)	KE (ergs)	Shock Strength (km/s)
RSG15	2.0	0.277	1.287×10^{47}	814
⋯	2.1	0.331	2.059×10^{47}	926
⋯	2.2	0.382	2.953×10^{47}	1019
⋯	2.3	0.430	3.911×10^{47}	1094
⋯	2.4	0.477	4.896×10^{47}	1157
⋯	2.5	0.523	5.779×10^{47}	1204
RSG25	2.0	0.179	8.418×10^{45}	394
⋯	2.1	0.230	2.893×10^{46}	569
⋯	2.2	0.281	6.581×10^{46}	725
⋯	2.3	0.331	1.204×10^{47}	866
⋯	2.4	0.382	1.930×10^{47}	996
⋯	2.5	0.433	2.827×10^{47}	1114

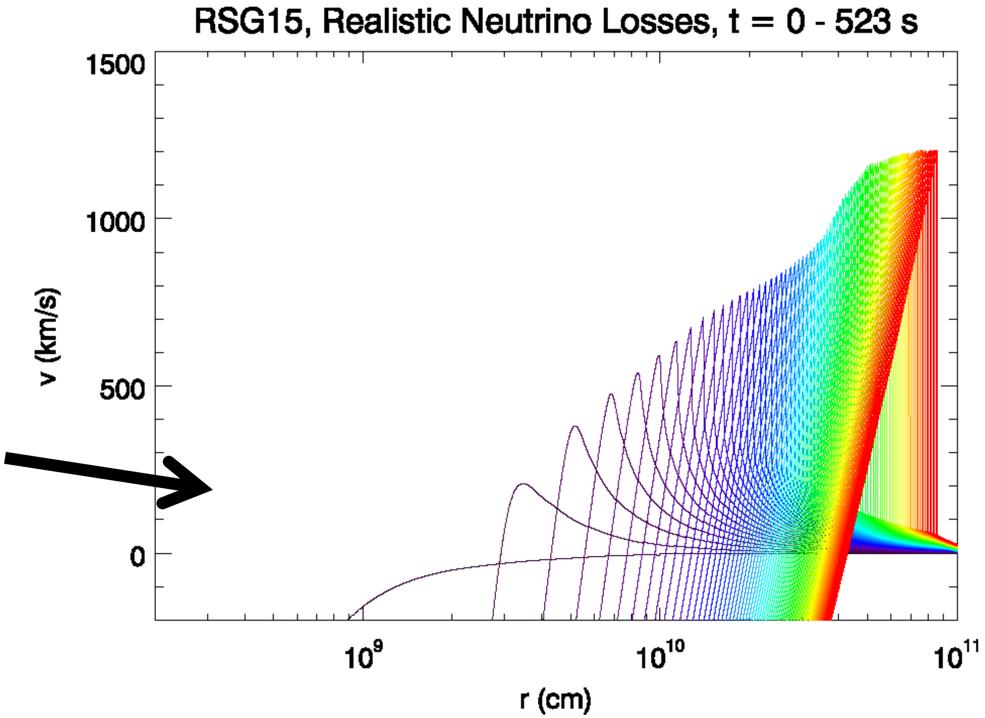
BH formation is more likely in the 25 Msun case and there,
the ejection of the envelope depends on the neutron star EOS.

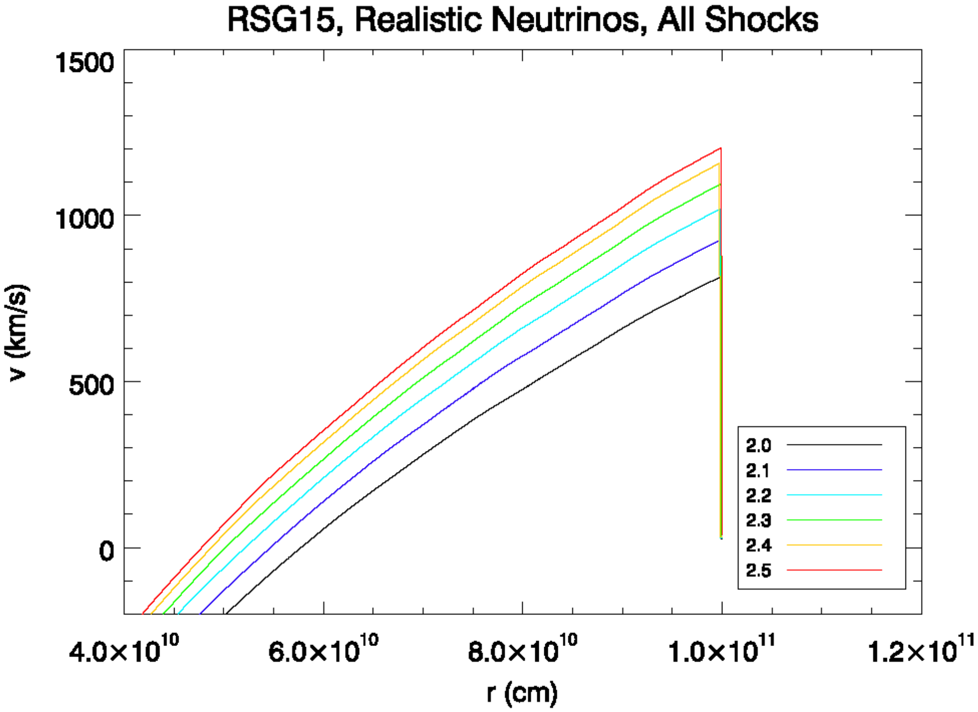


15 solar mass red supergiant Continued collapse after a failed explosion (prompt black hole formation)

1D with CASTRO

Including neutrino "mass loss" with a TOV parameter of 2.5 solar masses (0.523 solar masses lost over an interval of ~3 seconds).



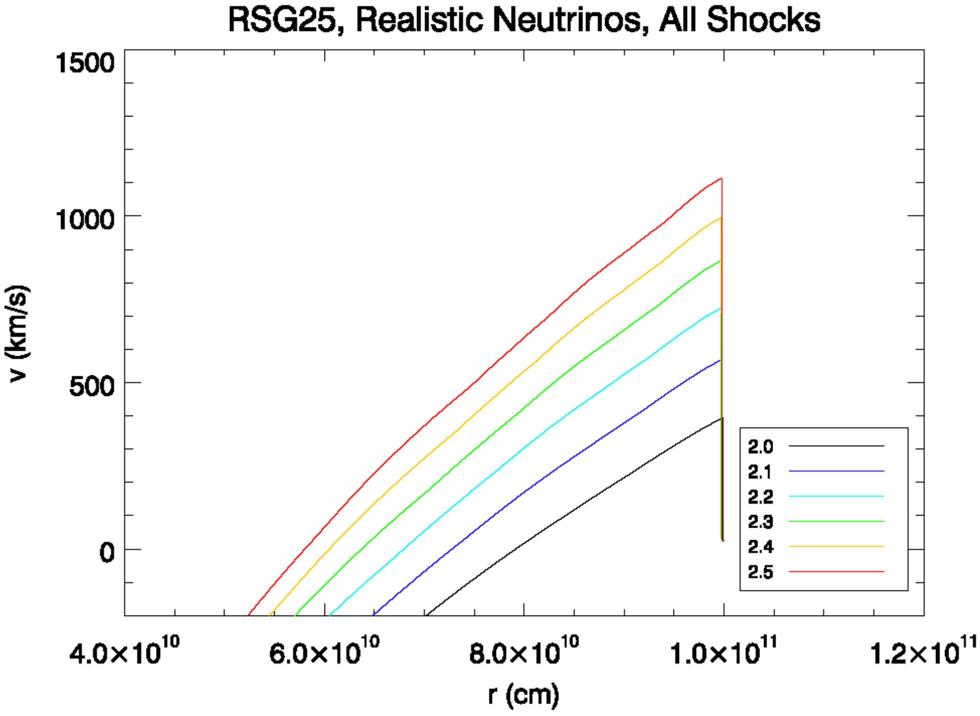


15 solar masses

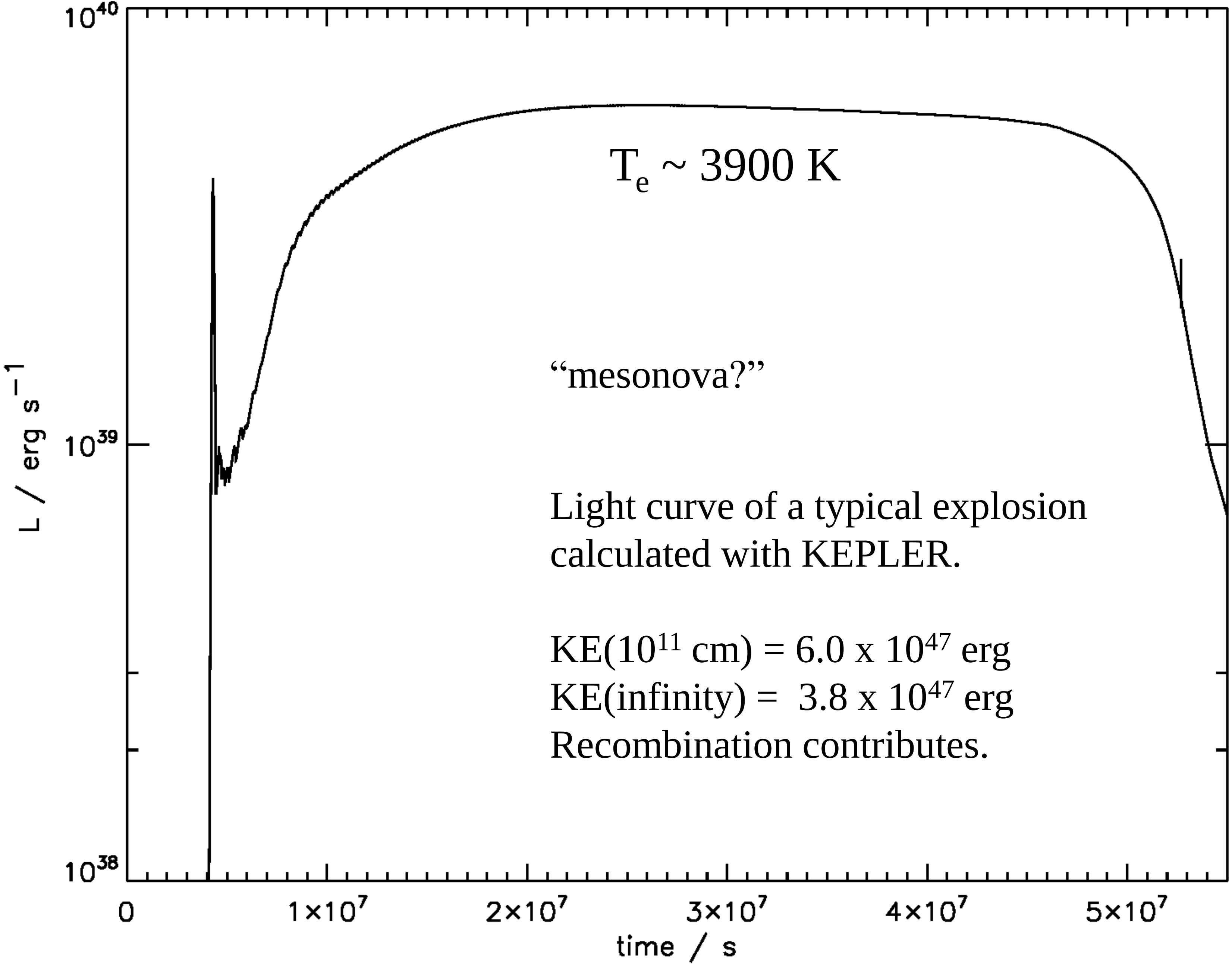
The strength of the shock depends on the maximum binding energy of a neutron star.

25 solar masses

10^{11} cm is well outside of the helium core.



Faintest "supernova" ever calculated!

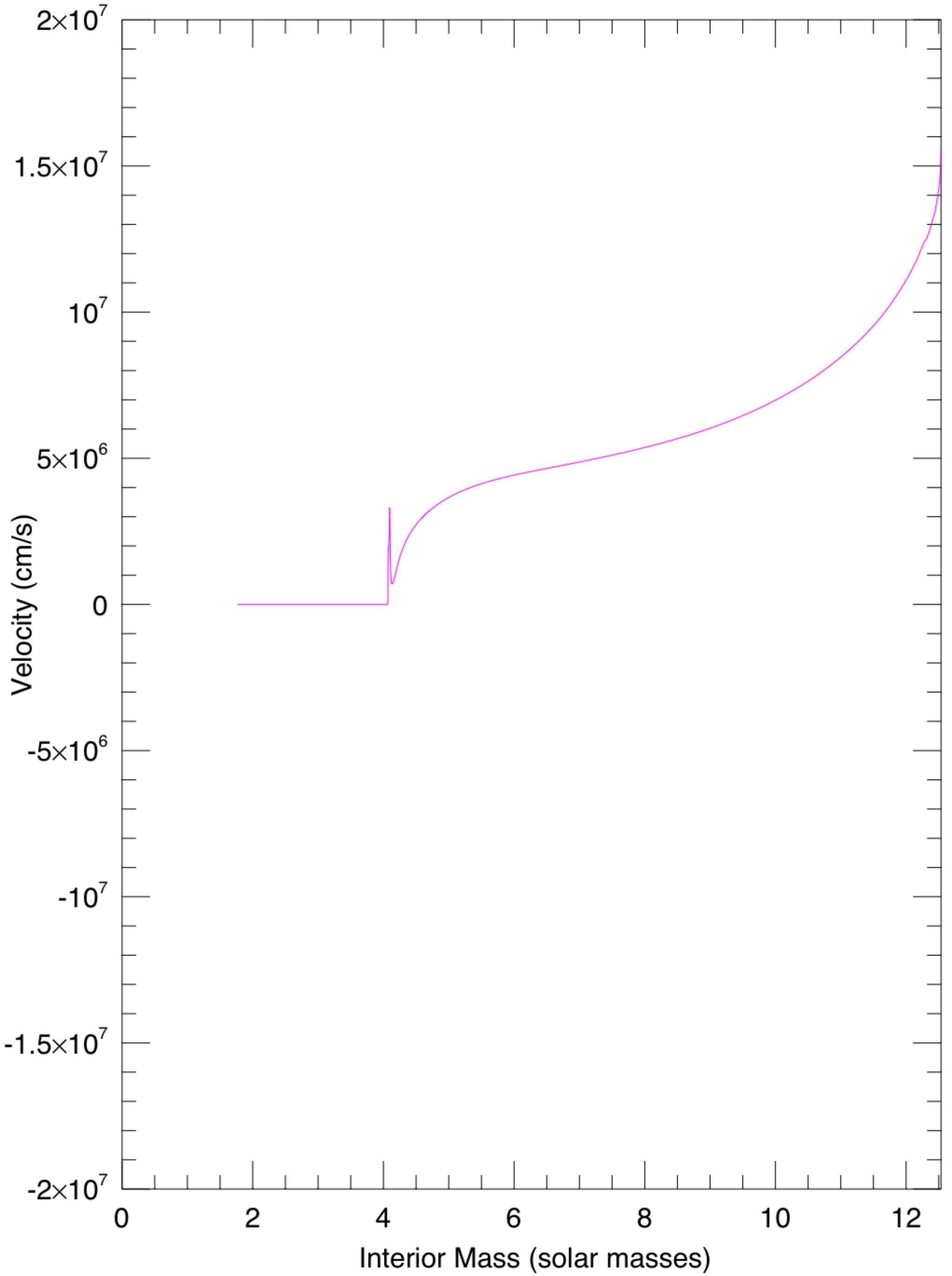


$T_e \sim 3900$ K

"mesonova?"

Light curve of a typical explosion calculated with KEPLER.

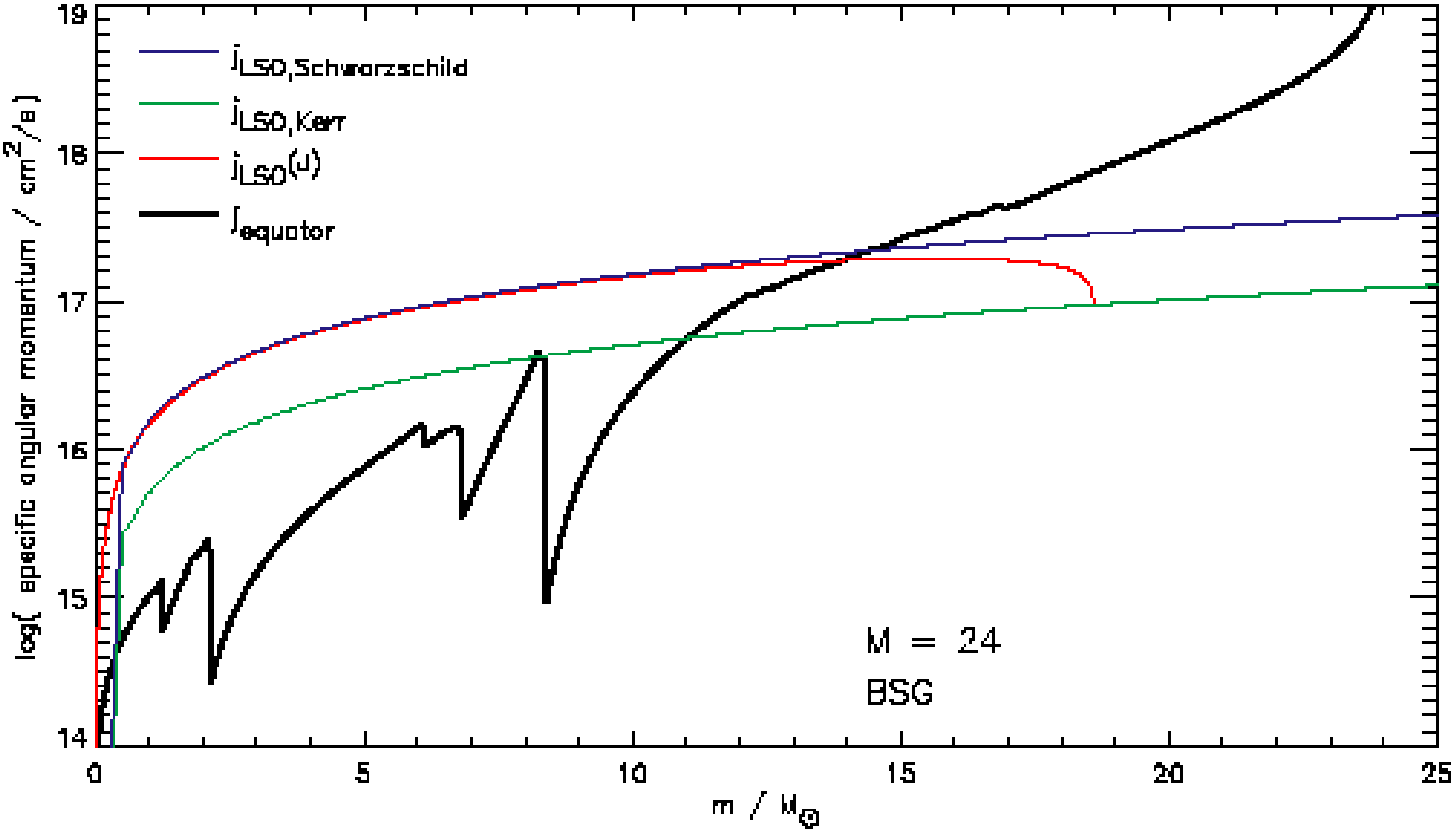
KE(10^{11} cm) = 6.0 x 10^{47} erg
KE(infinity) = 3.8 x 10^{47} erg
Recombination contributes.



2×10^7
1.5×10^7
10^7
5×10^6
0
-5×10^6
-10^7
-1.5×10^7
-2×10^7
Velocity (cm/s)
0
2
4
6
8
10
12
Interior Mass (solar masses)

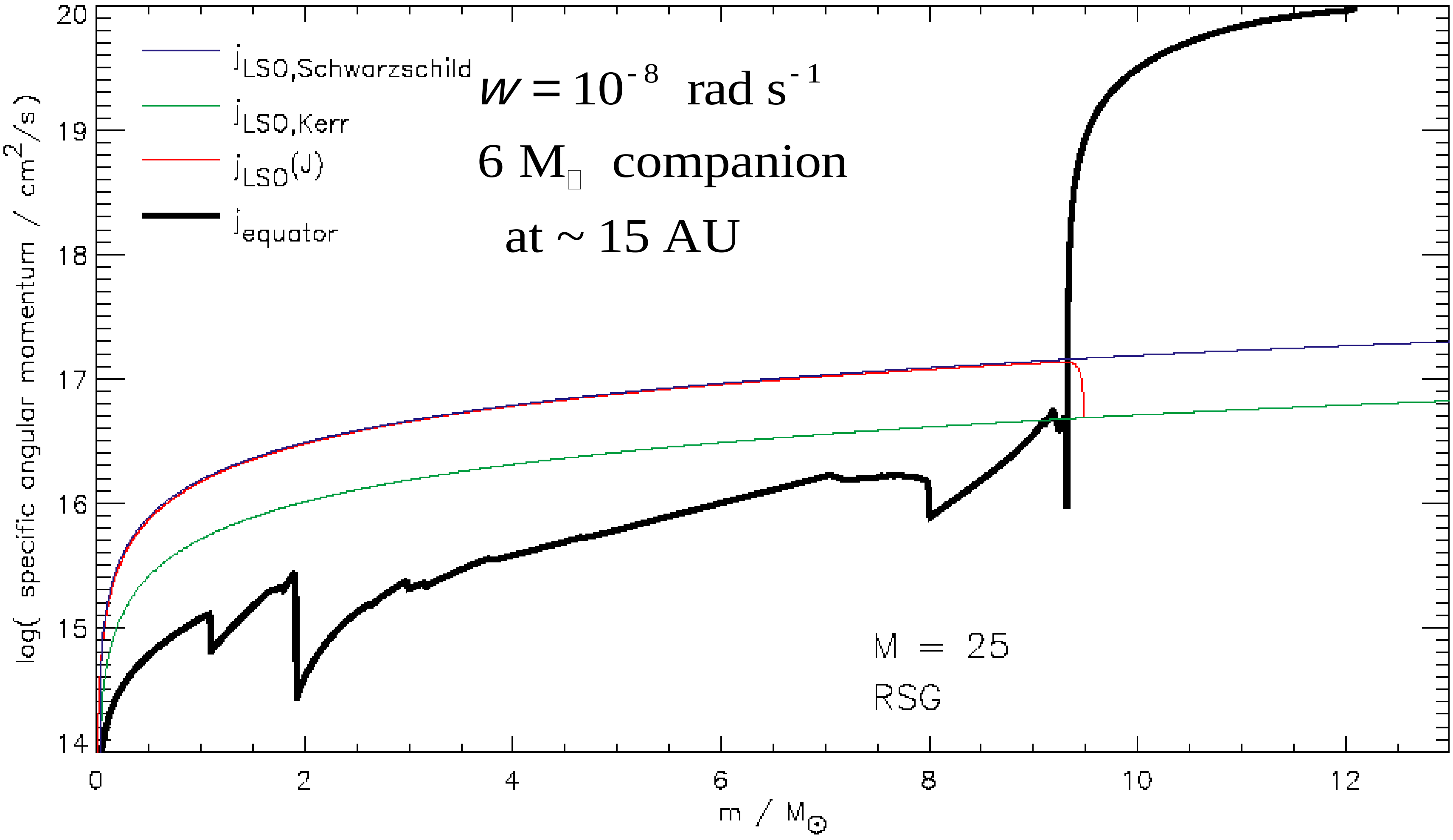
v ~ 100 km/s

Suppose there really is no outgoing shock…



24 solar mass evolved with rotation and angular momentum transport by magnetic torques, but no mass loss (Woosley and Heger 2012)

Prompt black hole formation in a tidally locked RSG
(main sequence mass 25 solar masses)



$w = 10^{-8}$ rad s^{-1}

$6\ M_{\odot}$ companion

at ~ 15 AU

Woosley and Heger (2012) ApJ, 752, 32

TABLE 1. SUMMARY OF MODEL CHARACTERISTICS

Type	Model	$M_{\rm disk}$ (M$_\odot$)	R (cm)	$R/v_{\rm esc}$ (s)	$\dot{M}$ (10^{-4} M$_\odot$ s^{-1})	1% $\dot{M}c^2$ (10^{48} erg s^{-1})
BSG	V24	10.0	0.4 - 10 $\times 10^{12}$	20,000	5	9
	V36	10.2	1 - 50 $\times 10^{12}$	60,000	1	2
RSG-loZ	O25	0.	1.2 $\times 10^{14}$	10^7	...	...
RSG-bin	S25	2.8	0.1 - 9 $\times 10^{13}$	3×10^6	0.01	0.02
Pair SN	Z250A	19.6	0.9 - 8 $\times 10^{13}$	3×10^5	0.7	1
	Z250B	20.6	0.4 - 6 $\times 10^{13}$	10^5	2	4
	Z250C	12.1	0.2 - 2 $\times 10^{13}$	3×10^4	4	8
WR-bin	8A	0.18	2.5 - 5 $\times 10^{10}$	100	20	40
	8B	1.19	1 - 5 $\times 10^{10}$	100	100	200
	16A	0.01	3 - 4 $\times 10^{10}$	100	1	2
	16B	0.83	2 - 4 $\times 10^{10}$	40	200	300

Summary:

- Some RSG supernovae eject a substantial fraction of their envelopes when they die – no matter what. Others, the more massive ones, may eject a lot less depending upon the neutron star EOS.

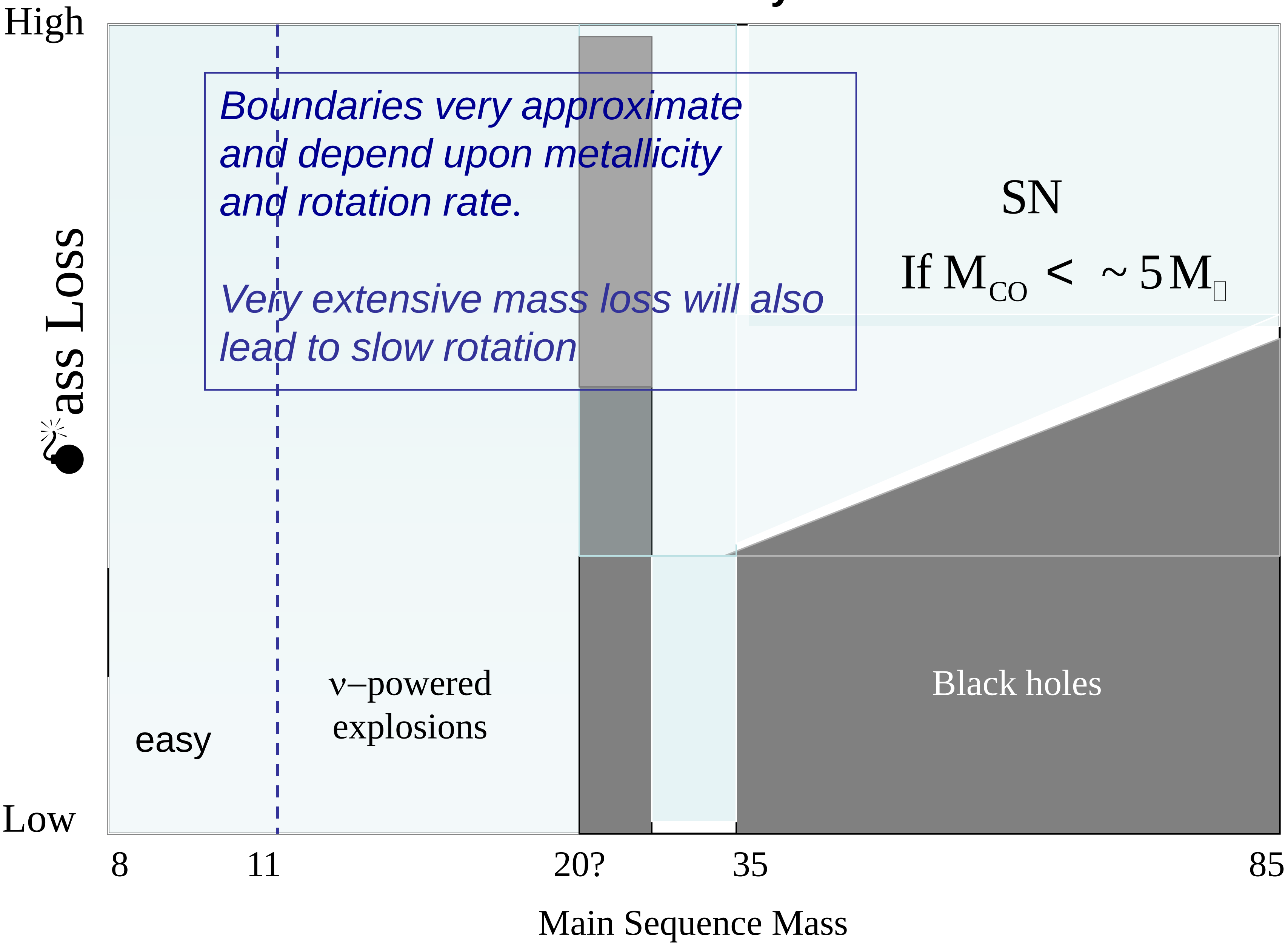
- Long GRBs from RSG progenitors may therefore frequently be suppressed

- BSG progenitors have ~100 times the binding energy in their envelopes (10^{49} erg vs 10^{47} erg) and may make long GRBs but only hours to days, not years

- A subset of “luminous red novae” may be related to the death of massive stars (but very low v)

- Also acoustic transport during carbon burning might lead to envelope ejection in RSGs
  (Quataert and Shiode 2012, MNRAS, 423, 92)

Solar Metallicity



Boundaries very approximate and depend upon metallicity and rotation rate.

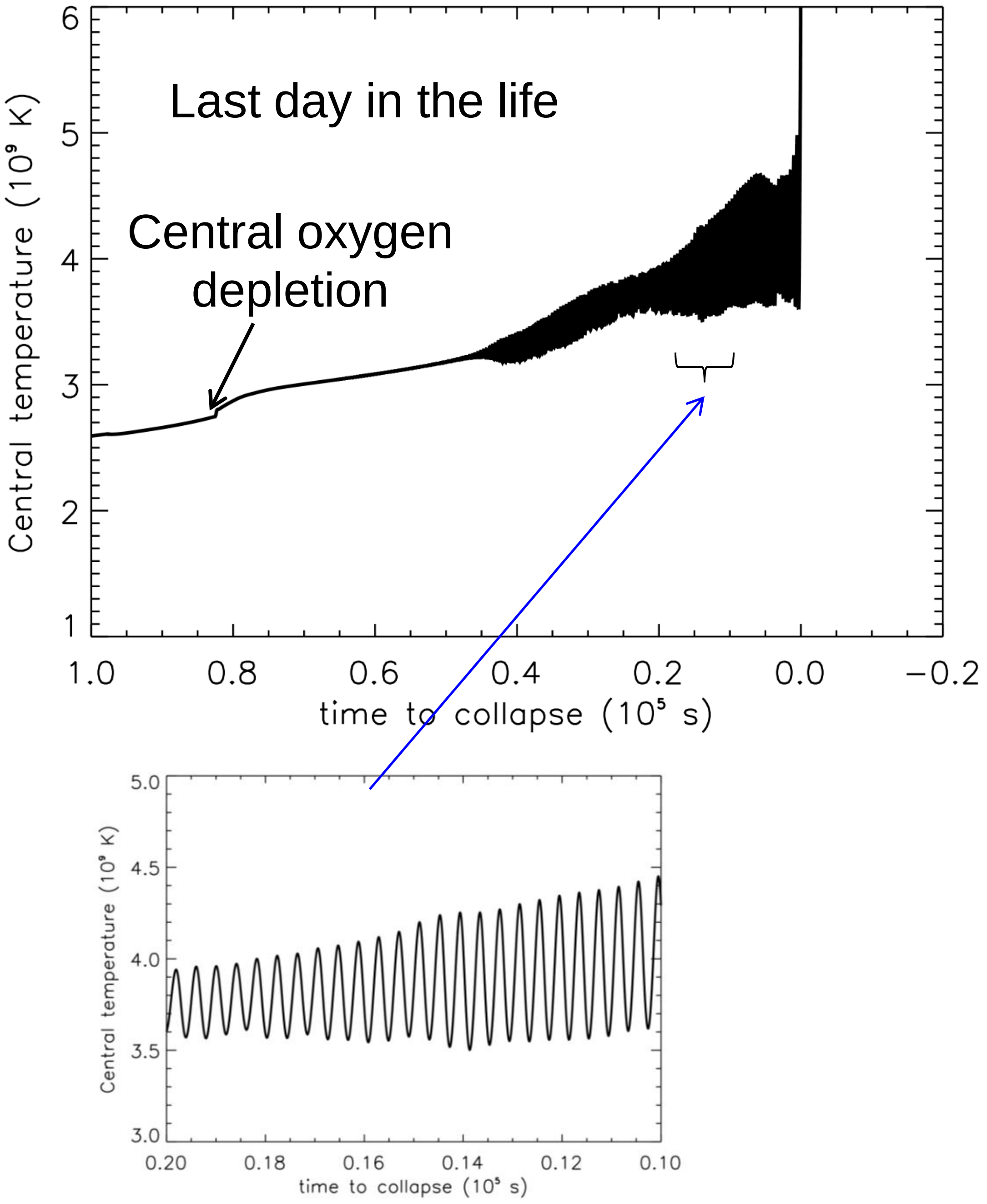
Very extensive mass loss will also lead to slow rotation

What about above 85 Solar Masses?

Pulsational Pair
Instability Supernovae

80 $M_{\odot}$

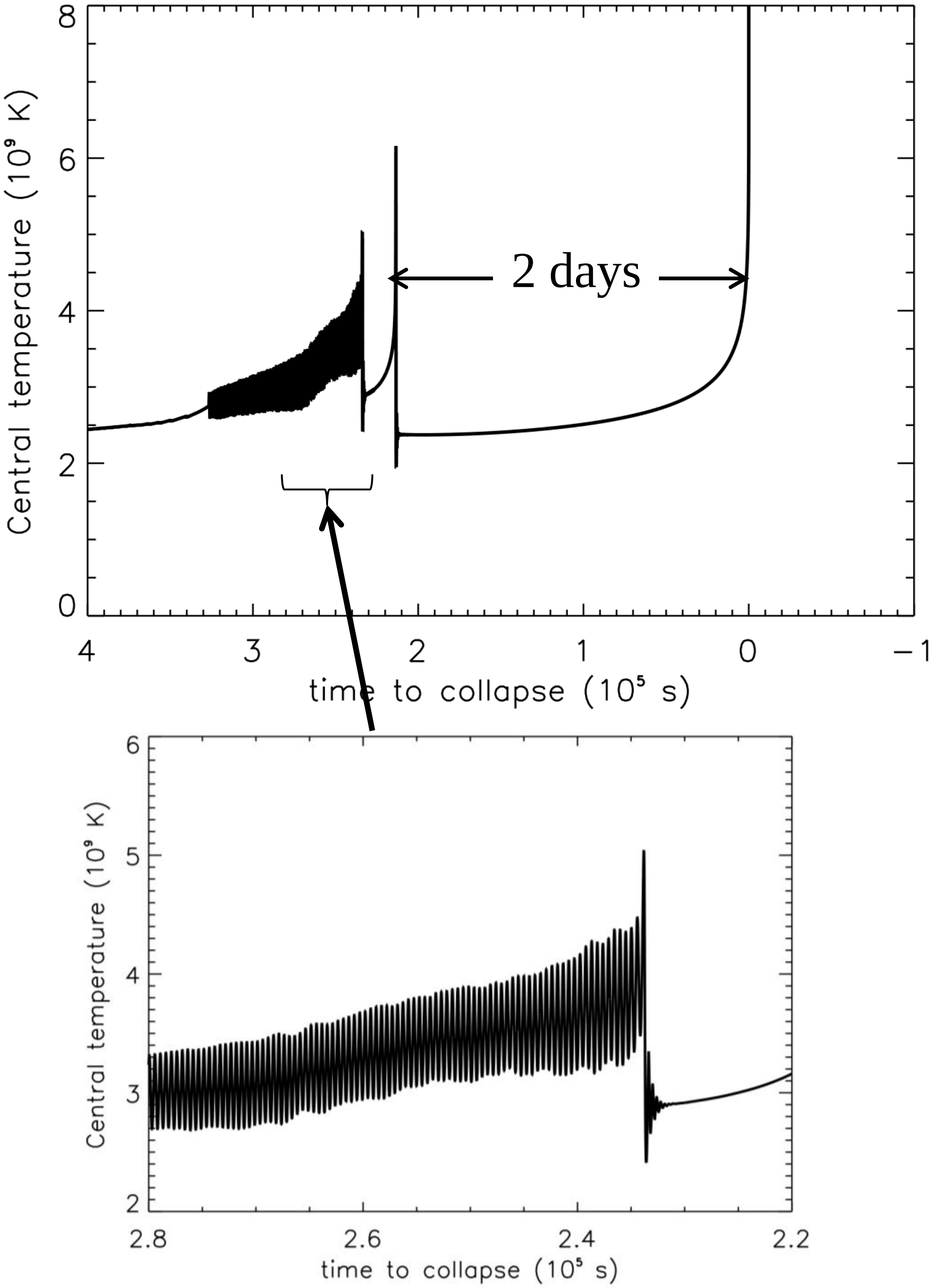
Helium core 35.7 $M_{\odot}$



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. Nevertheless, there may be mass ejection.

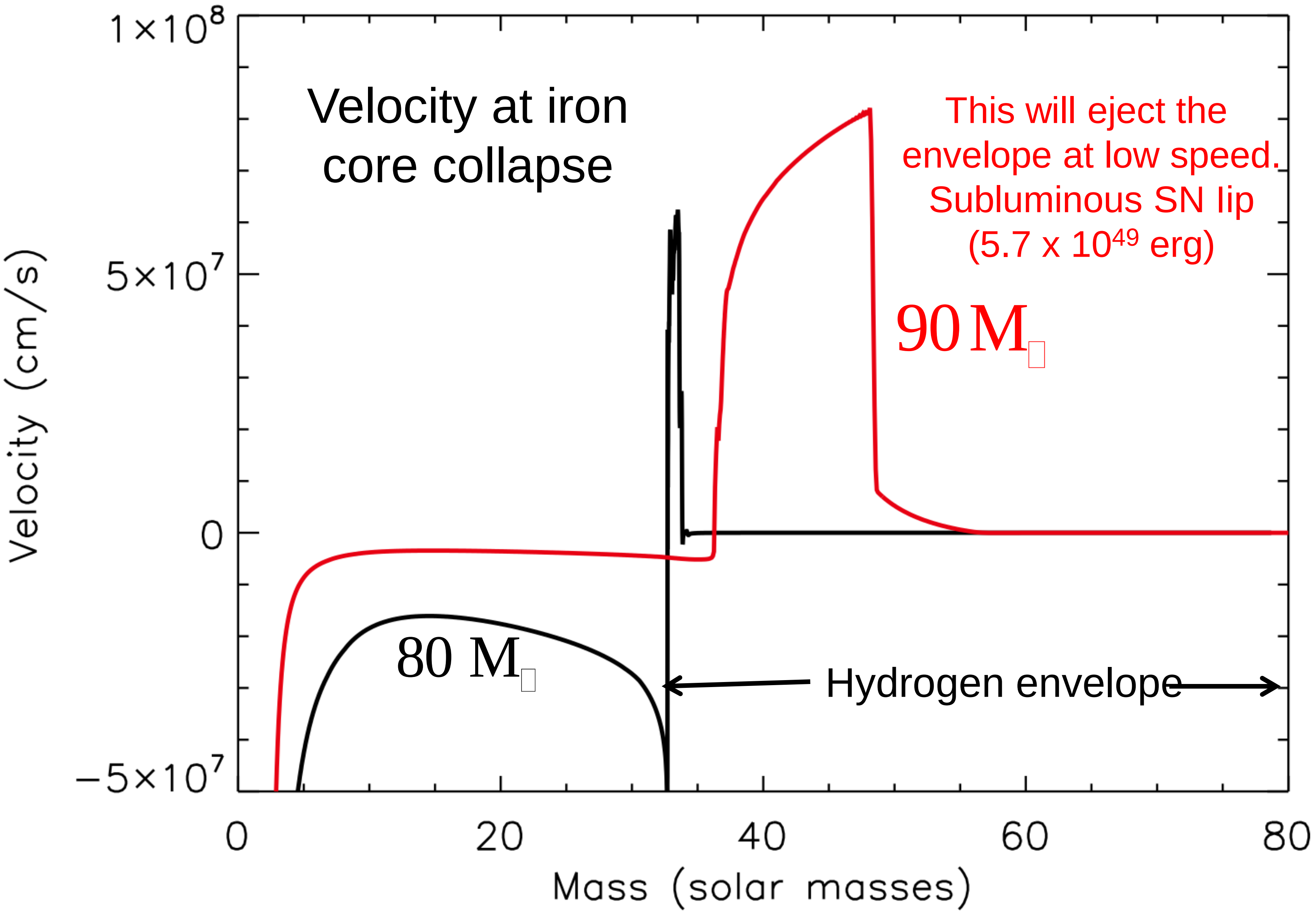


90 $M_{\odot}$

Helium core 41.3 $M_{\odot}$

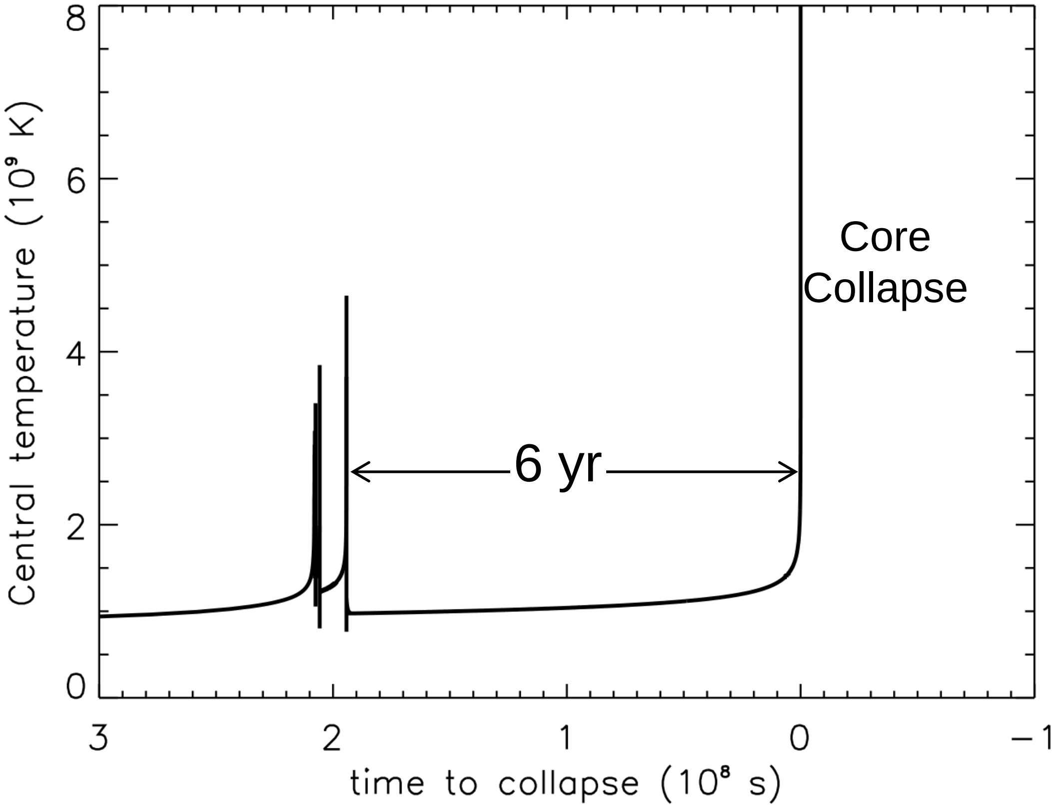
Pulses commence again after central oxygen depletion, but become more violent. Two strong pulses send shock waves into the envelope. The envelope is ejected (sub-luminous SN)

Two days later the iron core collapses (probably to a black hole).



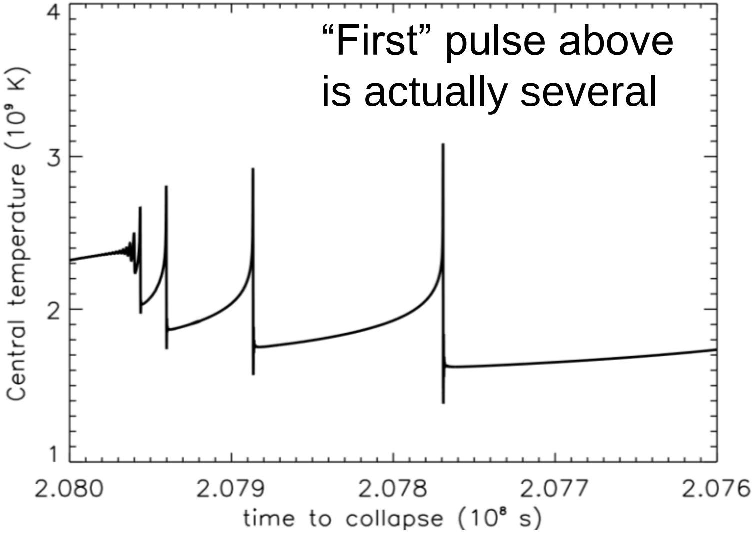
100 $M_{\odot}$

Helium core 45.8$M_{\odot}$



Core Collapse

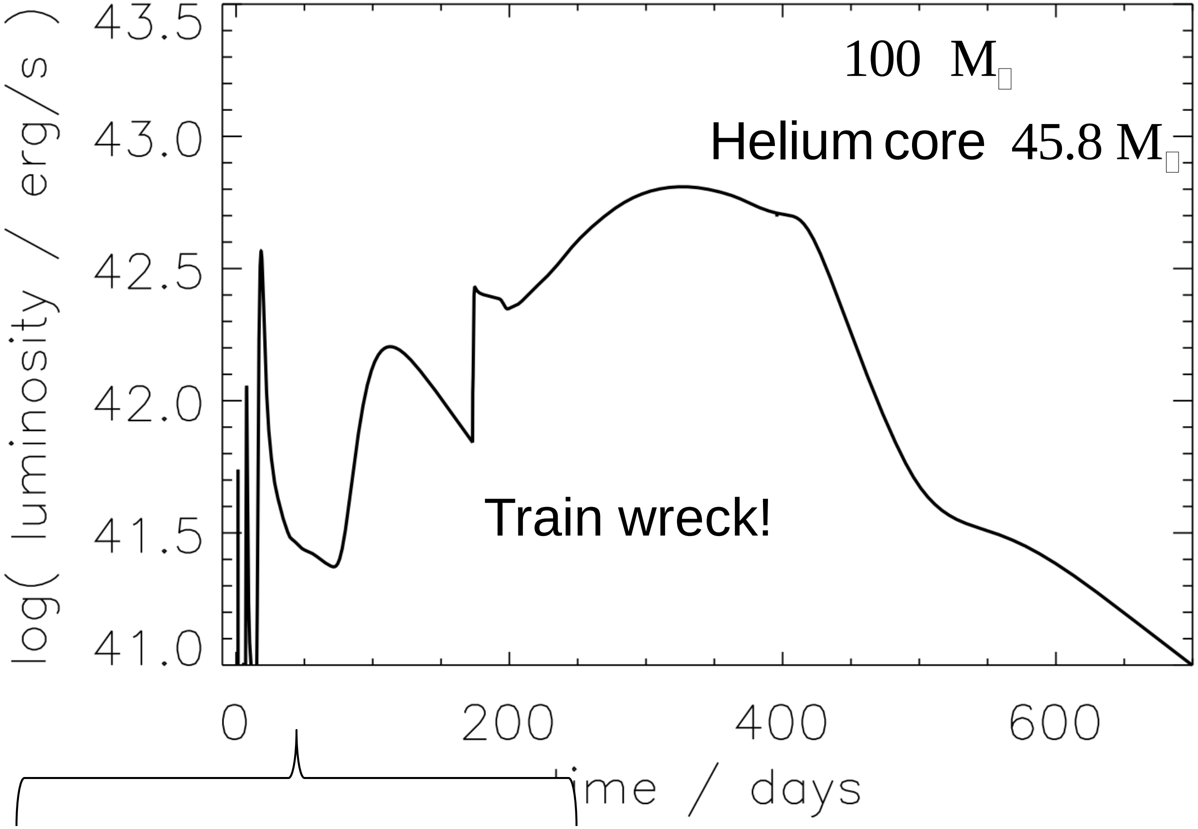
6 yr



“First” pulse above is actually several

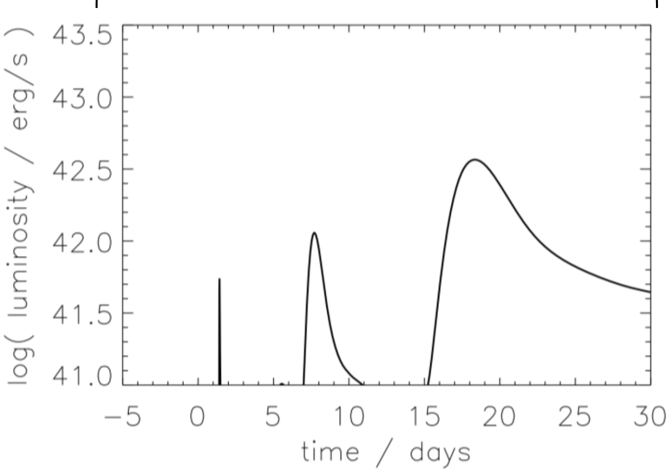
The instability has now shifted to oxygen ignition at the center of the star. The pulses are much more violent and occur at longer intervals.

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



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

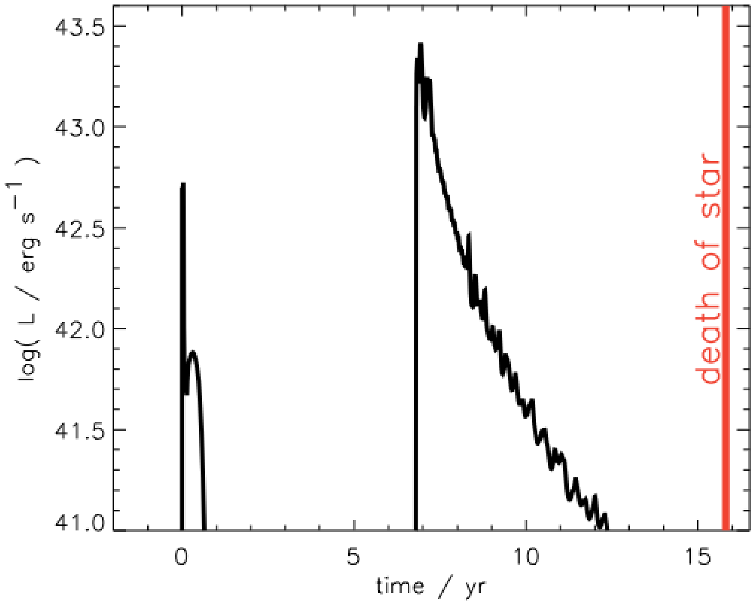
Core collapse 6 years later might produce no observable event.



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 brilliant, long lasting supernova. The appearance would be affected by pre-explosive mass loss.

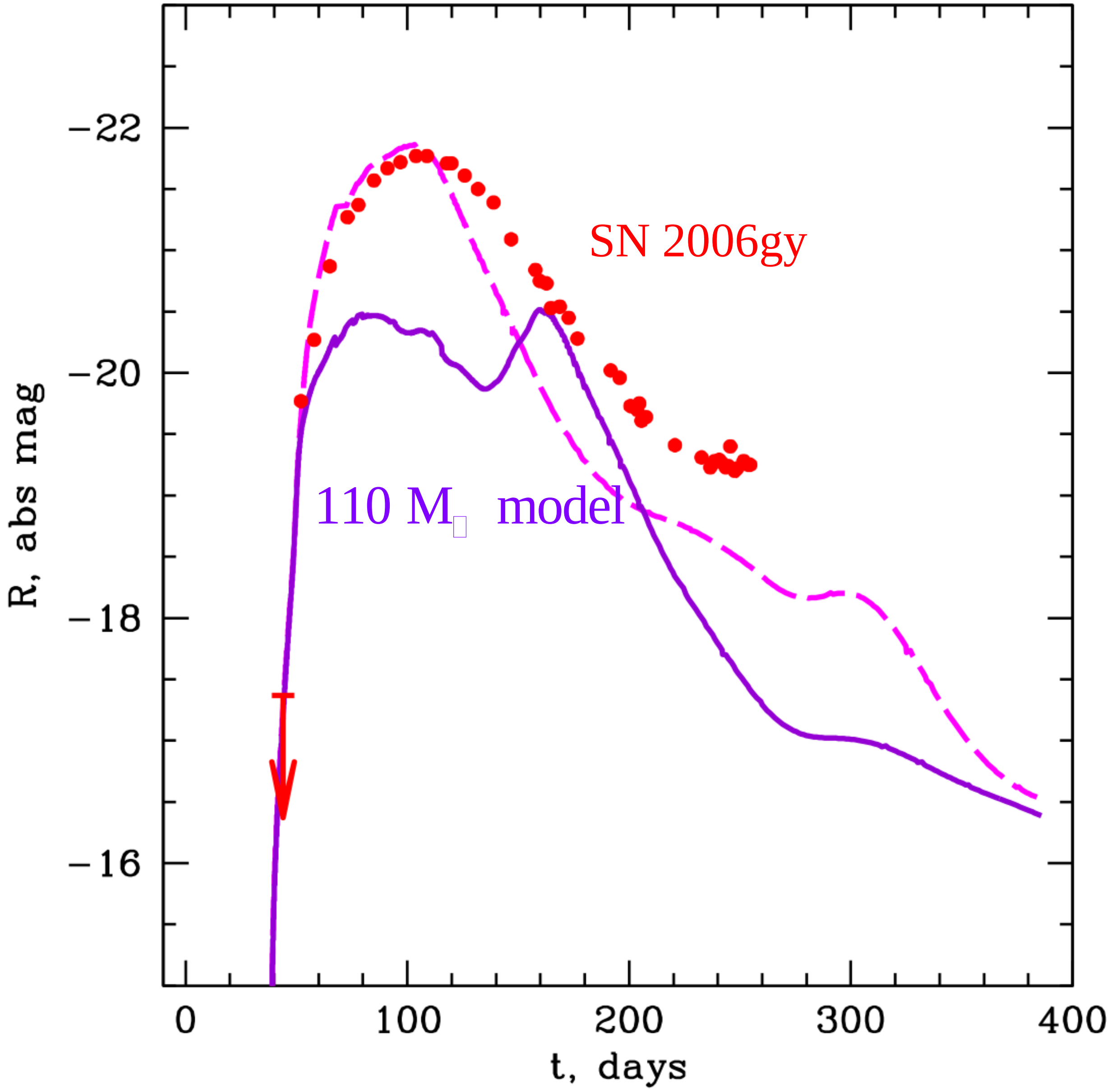
For still larger helium cores, the pulses become more violent and the intervals between them longer. Multiple supernovae occur but usually just one of them is very bright.

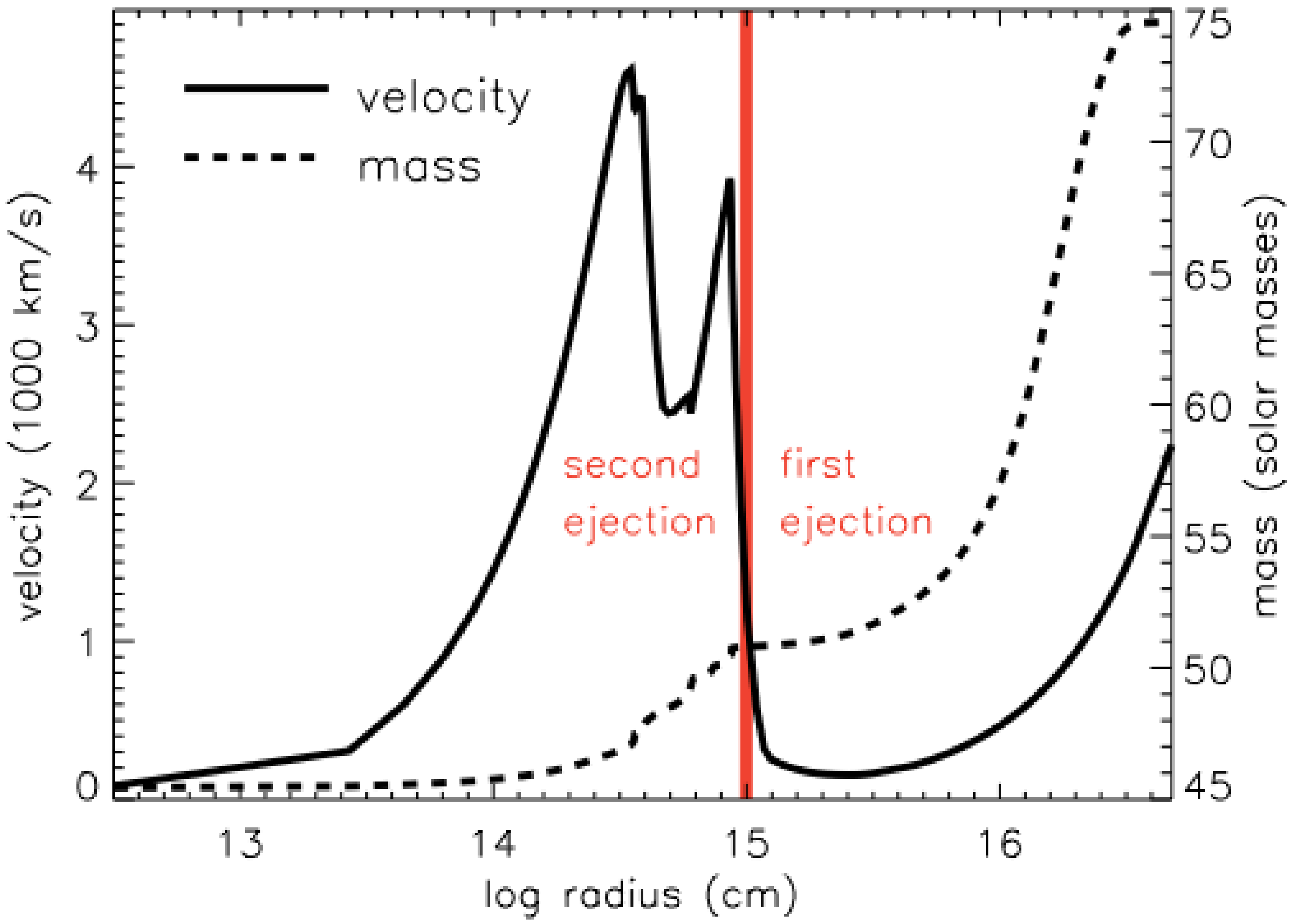
Finally at a helium core of about 60 solar masses the entire star explodes in a single pulse – the traditional “pair-instability” supernova



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)


SN 2006gy
110 M⊙ model
R, abs mag
−22
−20
−18
−16
0
100
200
300
400
t, days



see paper by Ken Shen

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

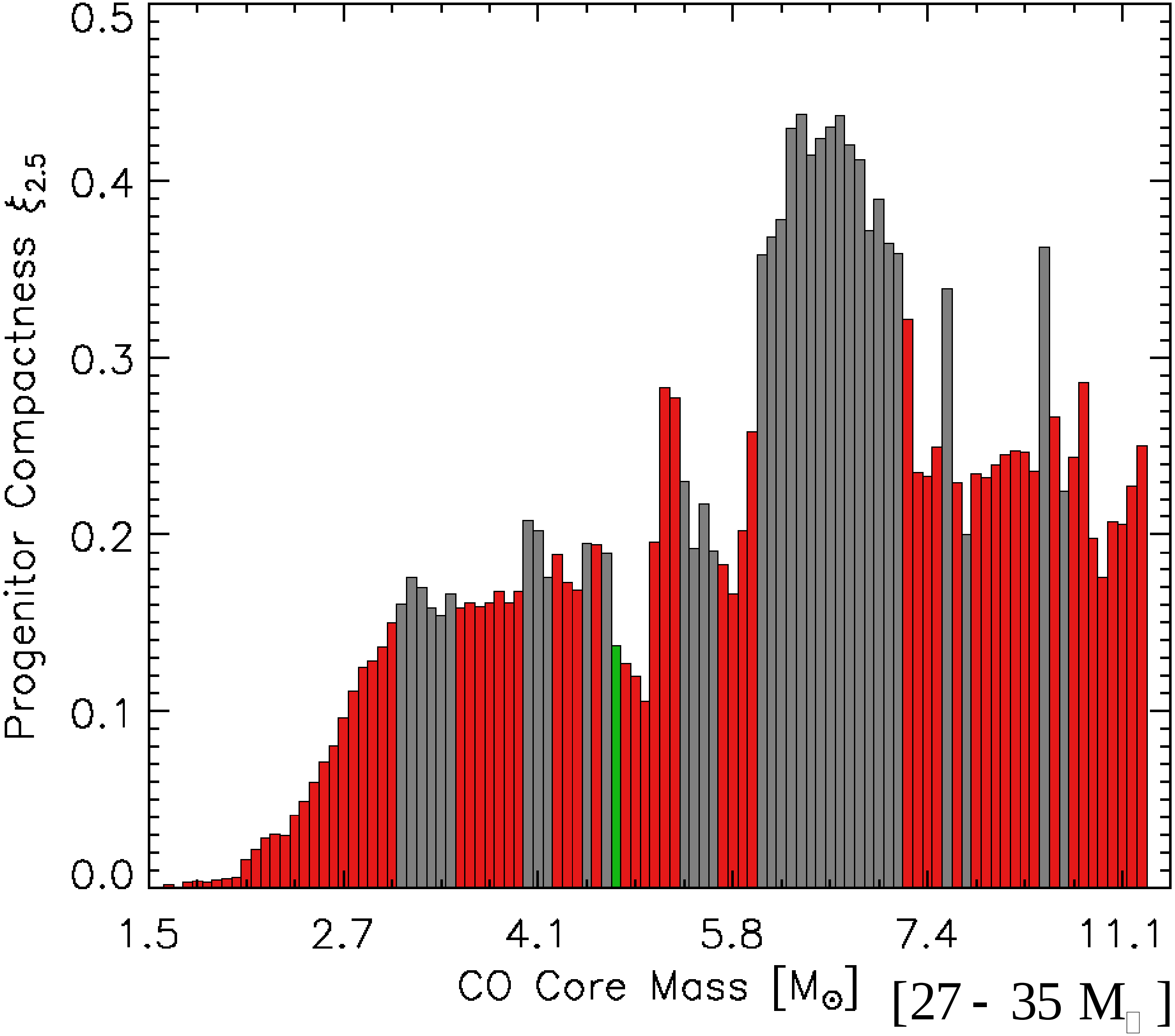
Pulsational Pair Supernovae (PPSN)
Five possible outcomes

- The whole star becomes a black hole (possible for the lightest masses – under 80 solar masses)
- 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 can 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 faint supernovae - and a 40 solar mass black hole..

Other Important Observations

- All these varieties of explosions could happen in bare helium cores with the same masses. The supernovae need not be Type II
- In general PPSN will leave behind black holes of about 40 solar masses
- The principal nucleosynthetic components are carbon, nitrogen and oxygen with some neon, magnesium, and silicon.
- Could explain some “supernova imposters” but not a general solution to all or even most.

Janka – private communication (this meeting)



[27 - 35 $M_\odot$]

Janka – private communication – this meeting