The Death of Massive Stars
and
The Birth of Black Holes[*]

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*** What gravitational radiation can and is telling us**

8 to 75 $M_\odot$ *

Major uncertainty
How they explode
(and mass loss on upper end)

Above 10.3 solar masses, all stars ignite oxygen and silicon burning centrally and stably. Product may be a neutron star (light end) or black hole (heavy end), but a stable iron core is an intermediary.

> 75 $M_\odot$

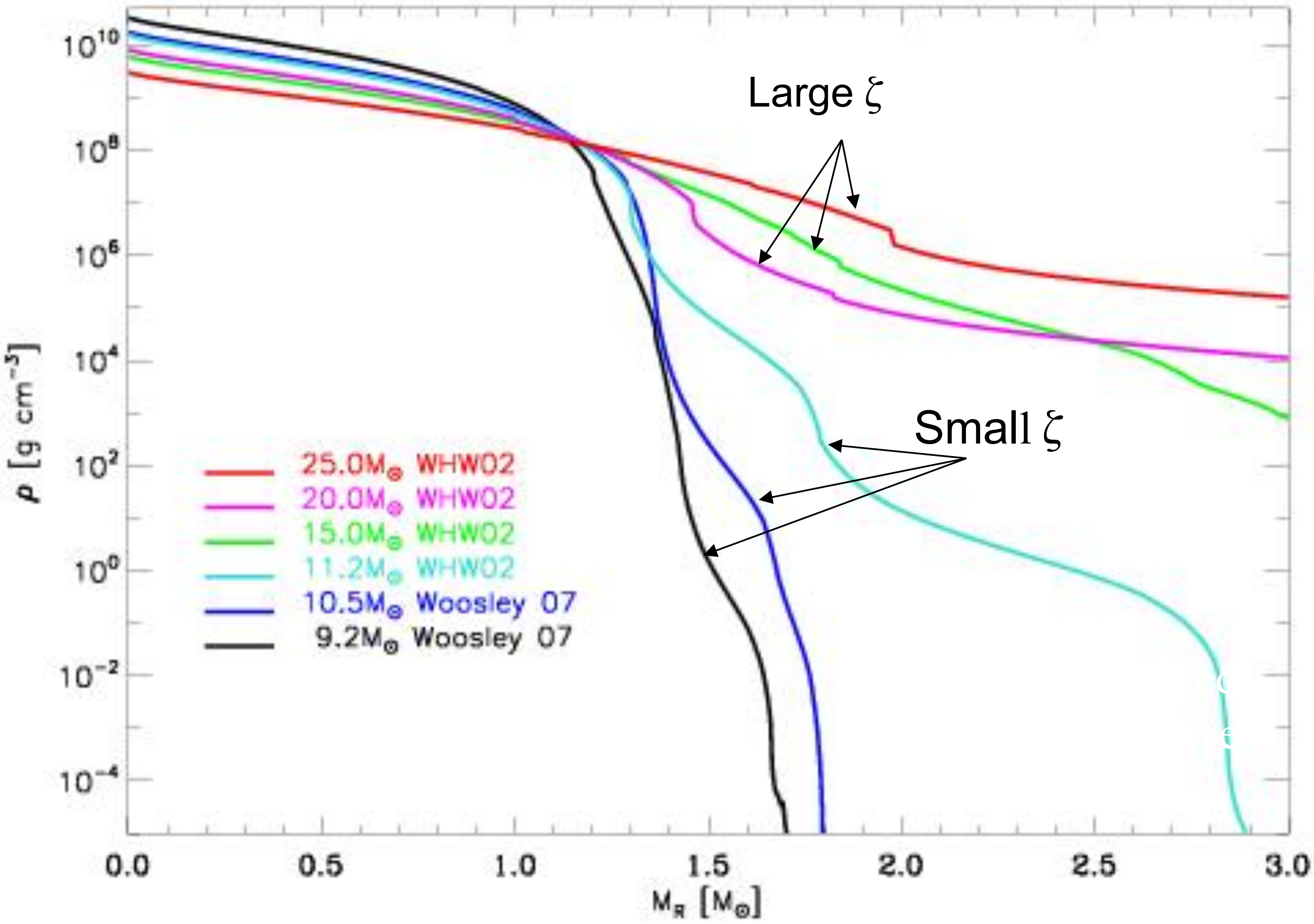
Major uncertainty
Mass loss

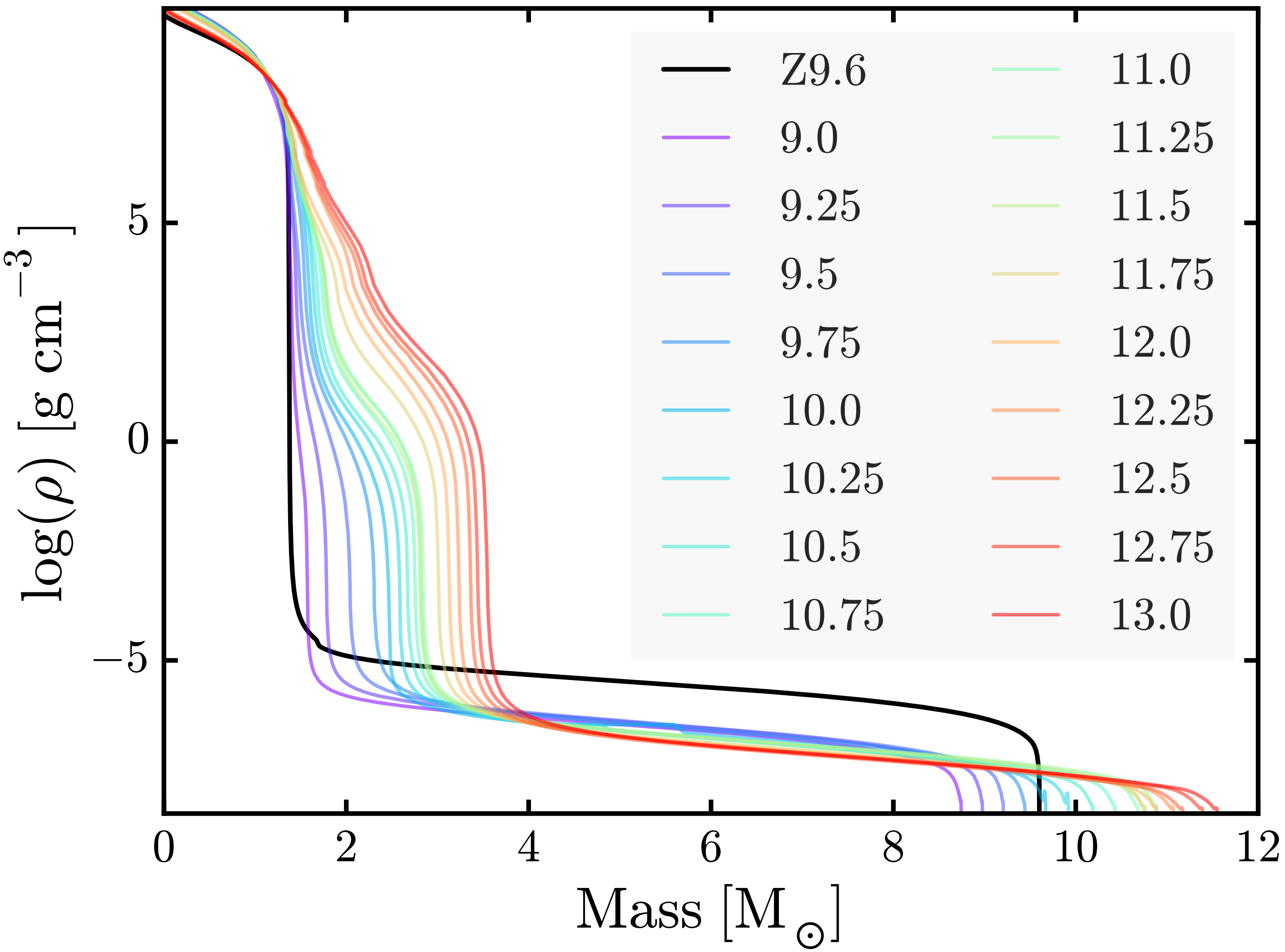
Oxygen and silicon burning unstable due to pair instability. The instability may completely disrupt the star or just shake off the outer layers. An iron core in hydrostatic equilibrium may (75 – 140 M_O) or may not (above 140 M_O) form

- Limiting masses somewhat lower for rotating stars (75 -> 60) and and may be altered by binary mass exchange.

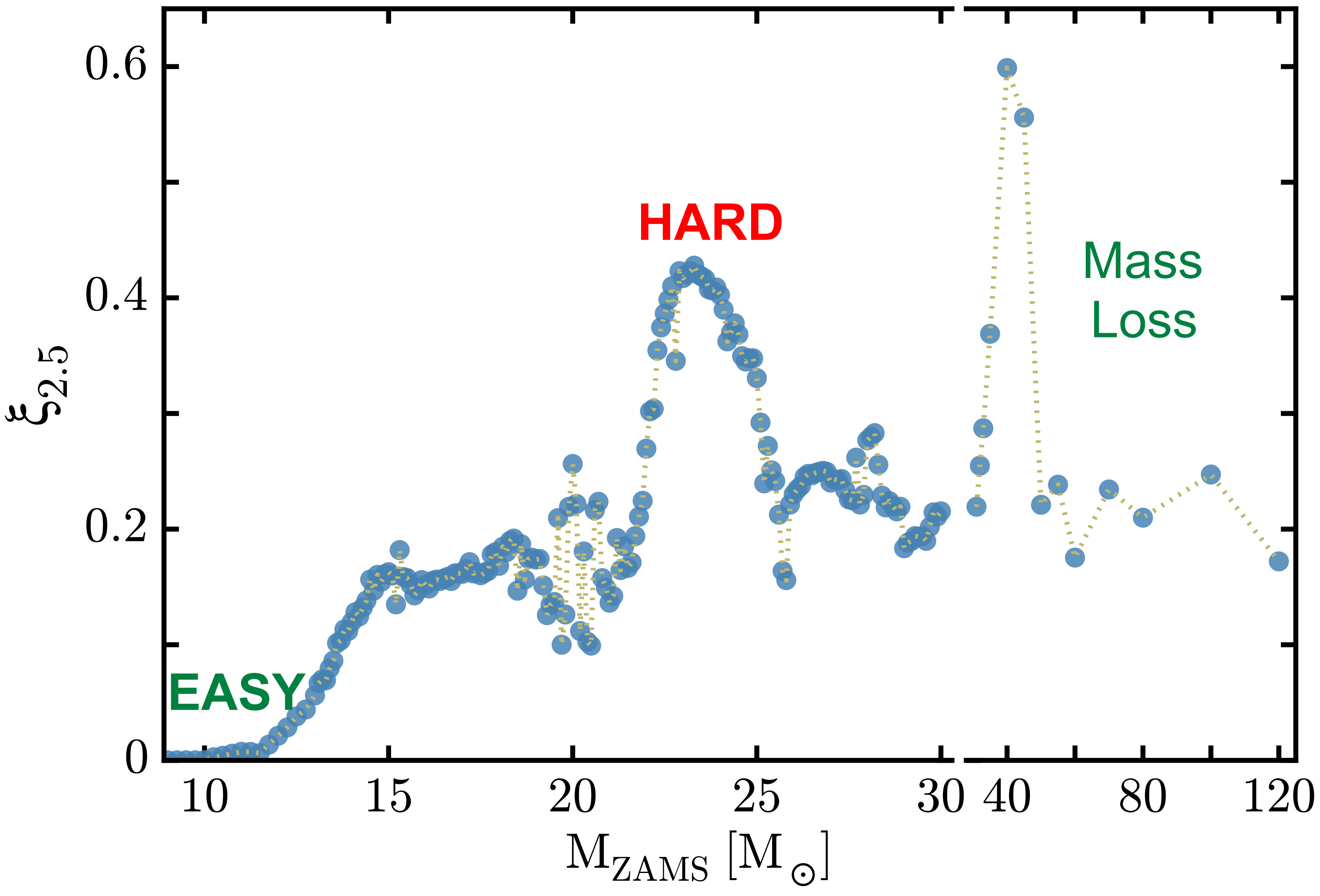
Density Profiles of Supernova Progenitor Cores

“Low” Mass Supernovae

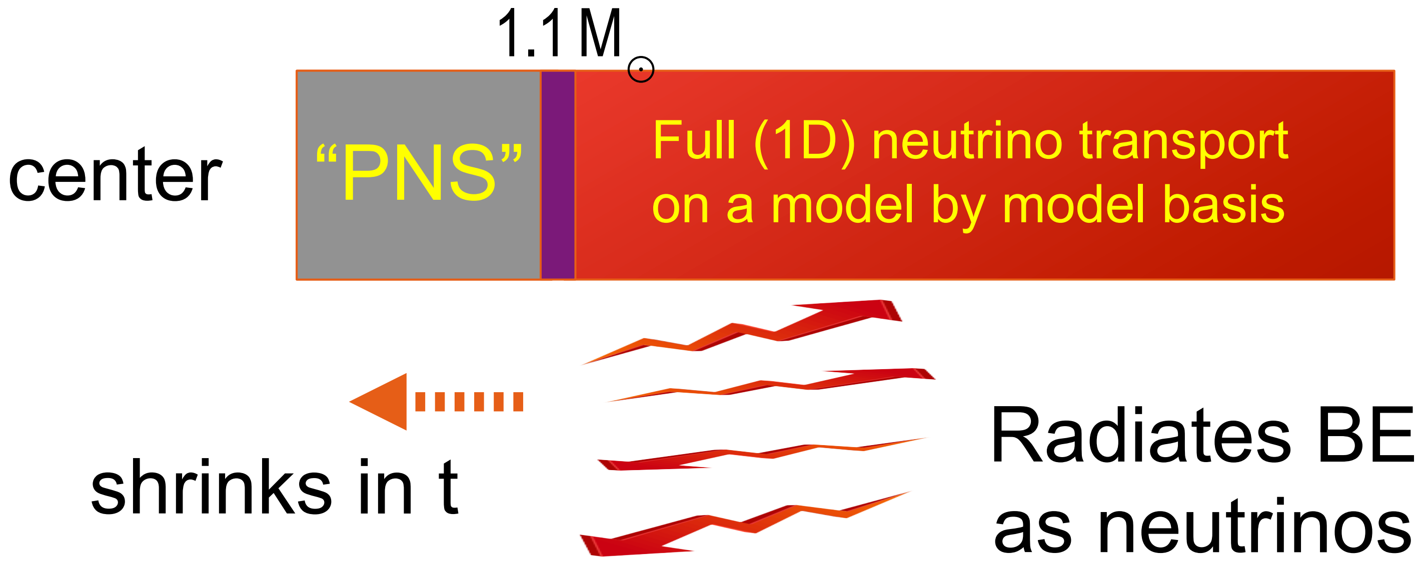



log(ρ) [g cm^{-3}]
Mass [M$_\odot$]
5
0
−5
0
2
4
6
8
10
12
Z9.6
9.0
9.25
9.5
9.75
10.0
10.25
10.5
10.75
11.0
11.25
11.5
11.75
12.0
12.25
12.5
12.75
13.0

“EXPLODABILITY”



1D Neutrino-Transport Calculation with a standard central 1.1 $M_\odot$



1.1 $M_\odot$

center

“PNS”

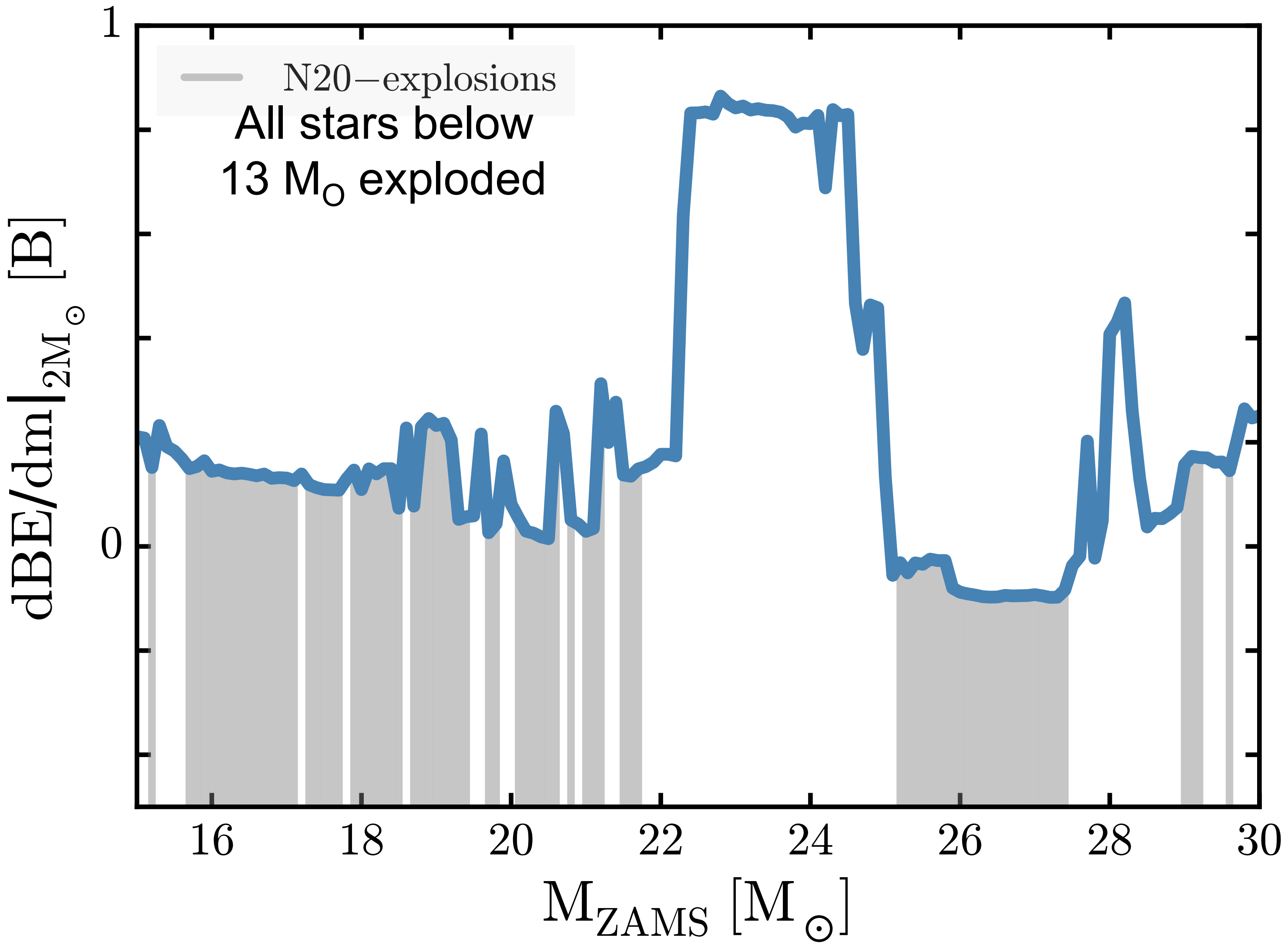
Full (1D) neutrino transport on a model by model basis

shrinks in t

Radiates BE as neutrinos

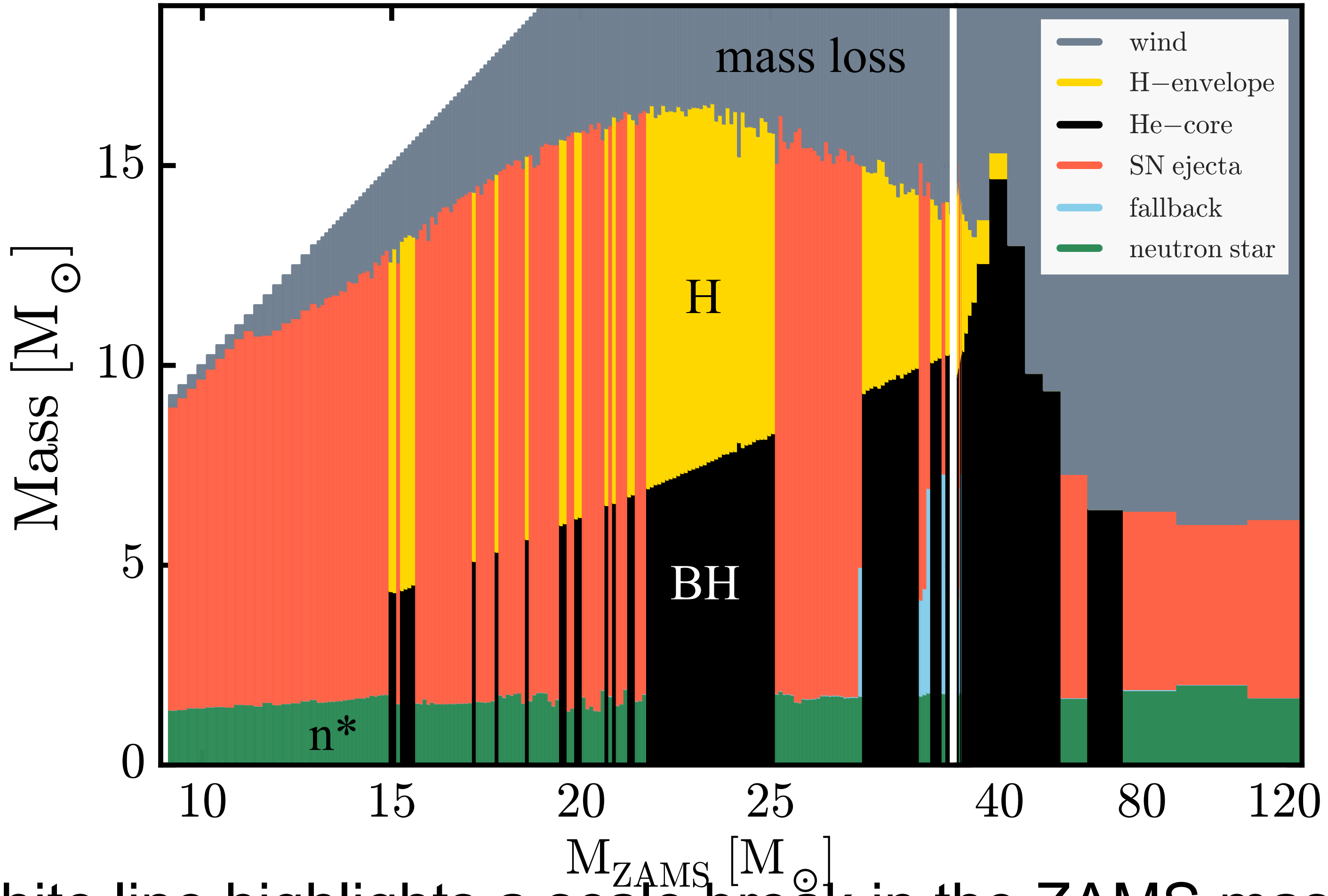
Survey by Sukhbold, Ertl, Woosley, Brown, and Janka (2016)

see also Ugliano, Janka, Marek, and Arcones (2012)
[*ApJ*, **757**, 60]



Above 30 $M_\odot$ results are sensitive to mass loss. For solar metallicity the helium core may be uncovered and shrink, making the star easier to explode. For low metalliicty and low mass loss all stars above 30 $M_\odot$ are very difficult to explode.

Solar metallicity



The white line highlights a scale break in the ZAMS mass axis.
About 1/3 of the explosions make black holes
The maximum mass BH is 15 $M_\odot$.

For one central engine: W18 (produces 87A well)

Average explosion energy: 7.2×10^{50} erg

Average neutron star baryonic mass: 1.56 $M_\odot$

Average neutron star gravittaional mass: 1.40 $M_\odot$

Average BH mass (He core): 9.05 $M_\odot$

Average BH mass (whole star): 13.6 $M_\odot$

Average ^{56}Ni production: 0.043 - 0.053 $M_\odot$

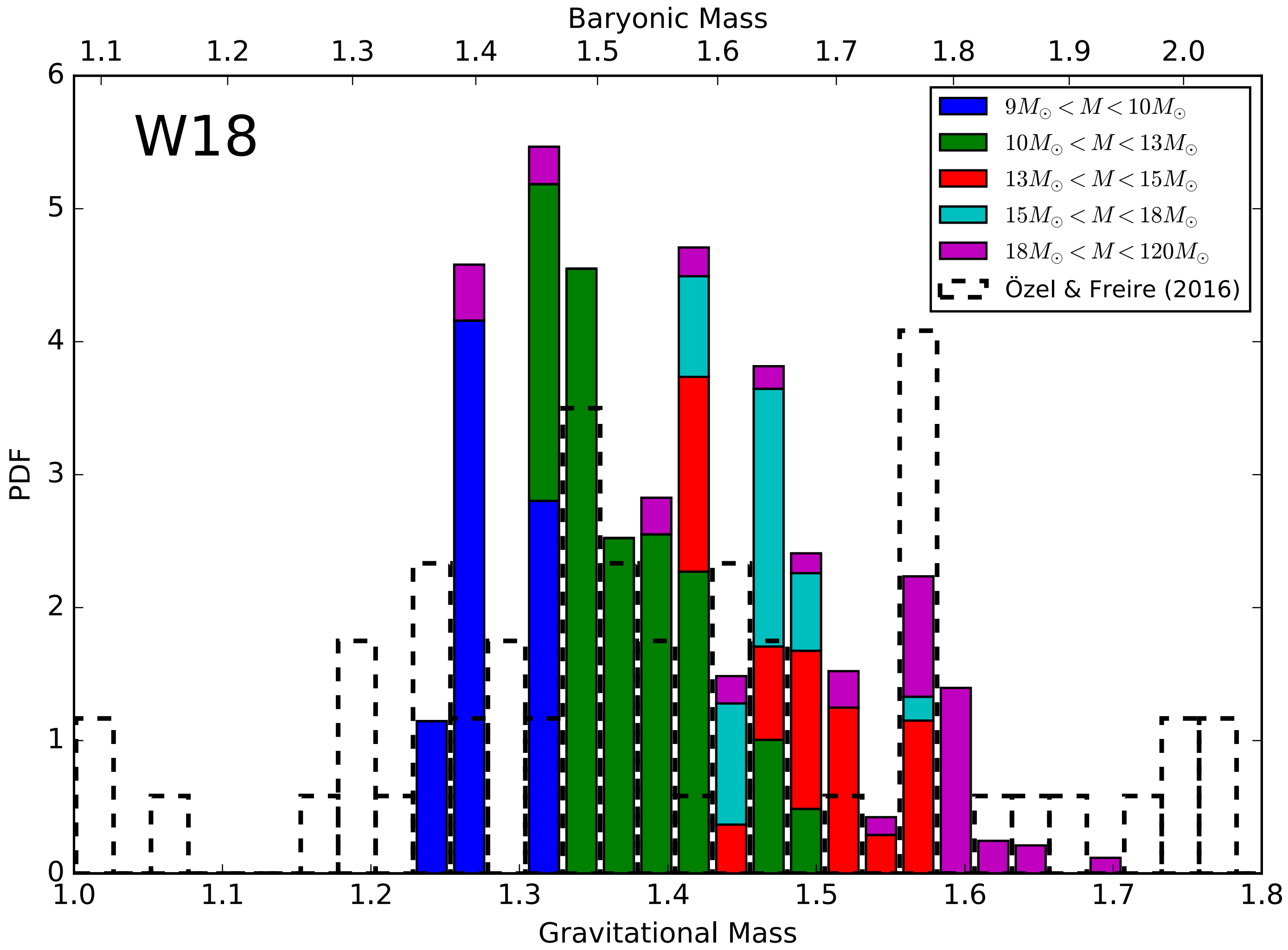
Percent of stars that explode: 67% ⇒ BH 33%

Fraction greater than 12 $M_\odot$: 48%

Fraction greater than 20 $M_\odot$: 9%

Fraction greater than 30 $M_\odot$: 2%

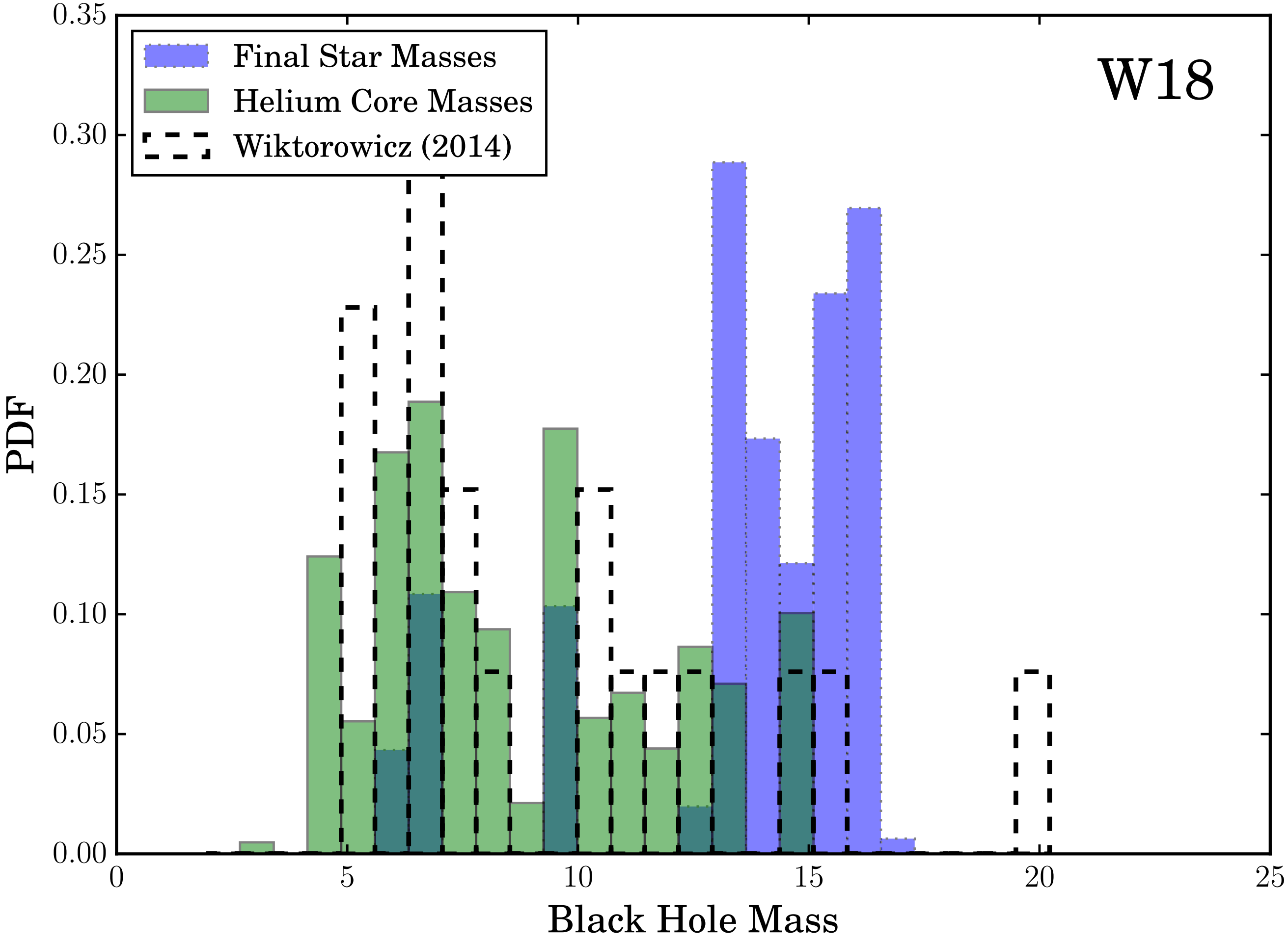
NEUTRON STARS



Average gravitational mass 1.40 $M_\odot$

(IMF weighted)

BLACK HOLE MASS DISTRIBUTION



The average mass if only the heium core implodes is 9.05 $M_{\odot}$ If the entire remaining star implodes the average for solar metallicity stars is 13.6 $M_{\odot}$. Both masses will be larger at lower metallicity.

IMPLICATIONS FOR GW DETECTION FROM BH MERGERS

- Models including approximate magnetic torques (Spruit) suggest that most neutron stars and black holes are born slowly rotating (Heger et al 2005) a~ 0.01 – 0.1 for helium core. More if H envelope collapses.

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- More massive stars and stars with lower metallicity have cores that rotate more rapidly (expect a correlation of Z (z?) and M with rotation rate).

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- A key question is whether black holes are, in some cases, born rotating very rapidly (a ~ 0.5 to 1?). Their detection would lend support the collapsar model for GRBs. Their non-detection would lean against it. Distribution of j in the SN progenitor is a complicating factor.

IMPLICATIONS FOR GW DETECTION FROM BH MERGERS

- Note the existence of a “mass gap” between about 2 and 5 solar masses. For the solar metallicity models studied, explosions were either failures or robust. Fall back was generally negligible. Whether this gap persists at lower metallicity is an interesting question.

- Another very interesting question is whether the hydrogen envelope participates in the collapse when the central engine fails

- Does the upper mass (~15 M_O for solar metallciity) increase – as expected - with decreasing metallicity. Are the average and maximum black hole masses bigger at lower metalliciity. (GW 150914 suggests that they are).
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- It is interesting that of detections so far, one contained a 8 M_O and 14 M_O mass black hole. These stars collapsed and did not make neutron stars. This is consistent with current theoretical prejudice, but what about magnetars?

Pair-Instability and Pulsational-Pair Instability Supernovae

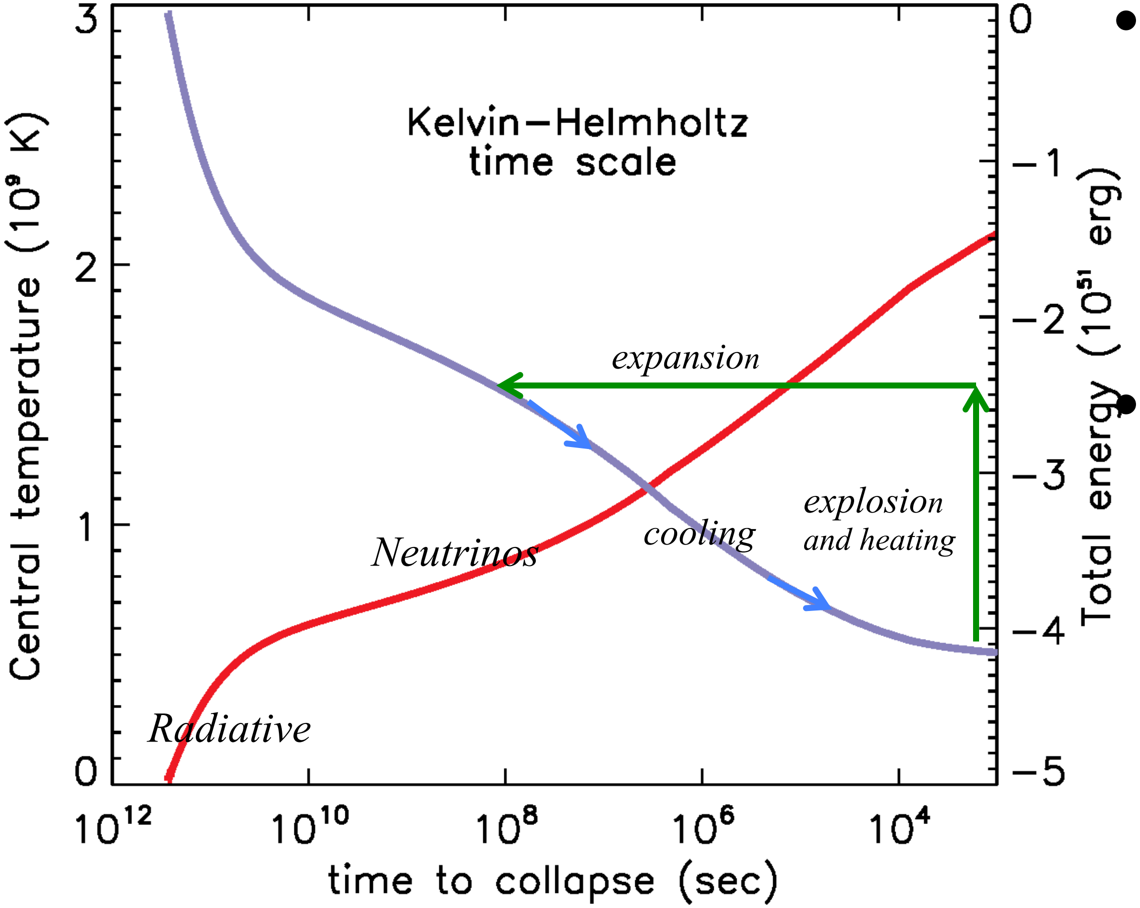
SUMMARY
PAIR-INSTABILITY SUPERNOVAE

He Core *well known*	$\omega=0$ Main Seq. Mass *Poorly known*	Supernova Mechanism	without rotation
$2 \leq M \leq 32$	$8 \leq M \leq 75$	Fe core collapse to neutron star or a black hole	
$32 \leq M \leq 64$	$75 \leq M \leq 140$	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)

THE PULSATIONAL- PAIR ENGINE

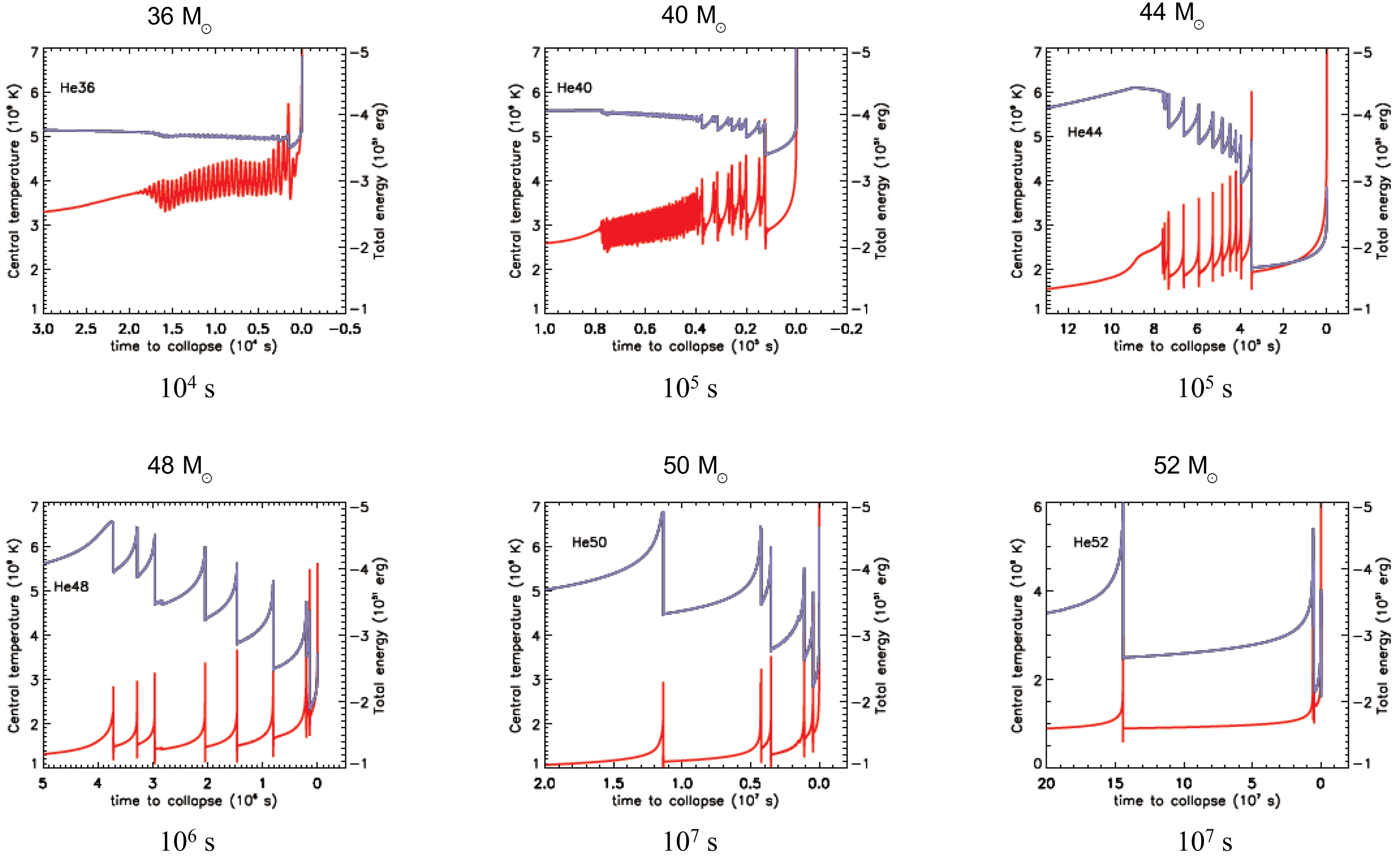
$M_{He} = 30 - 64\ M_{\odot}$



40 $M_{\odot}$ He core Kelvin-Helmholtz

Contraction (no burning)

- More energetic pulses take a longer time to recur – more energy means 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.


36 $M_\odot$ — 10^4 s

40 $M_\odot$ — 10^5 s

44 $M_\odot$ — 10^5 s

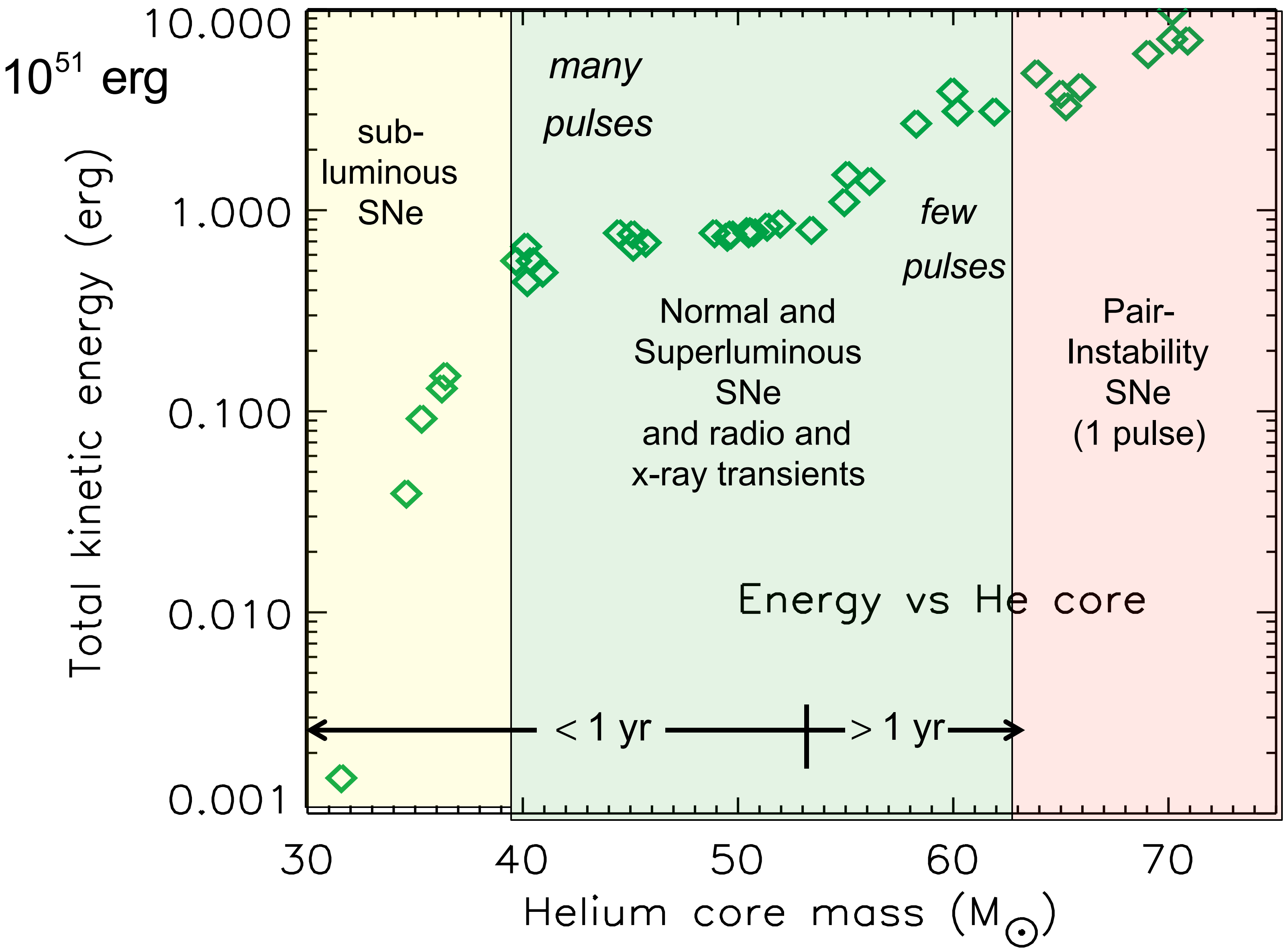
48 $M_\odot$ — 10^6 s

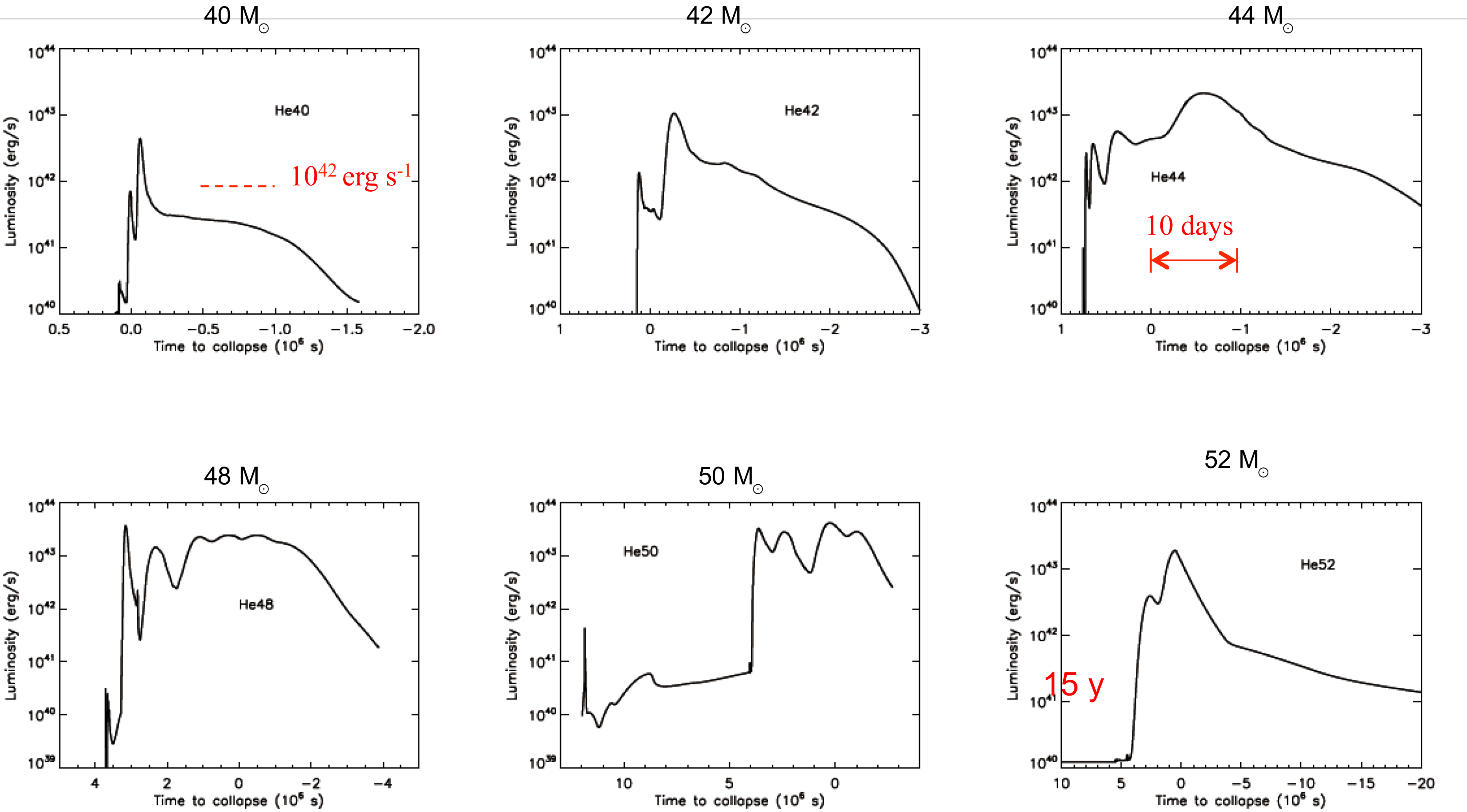
50 $M_\odot$ — 10^7 s

52 $M_\odot$ — 10^7 s

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

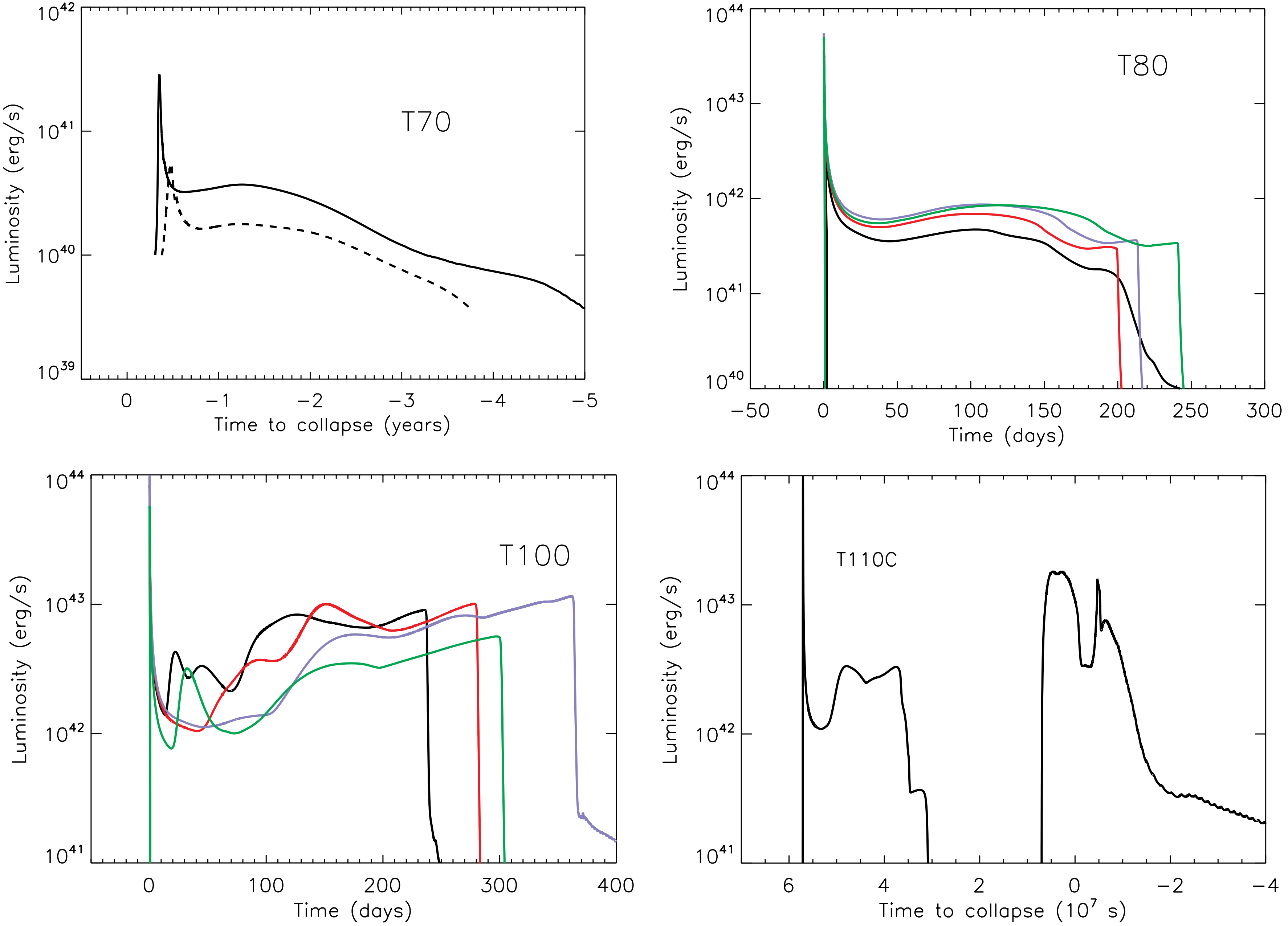
TOTAL ENERGY IN PULSES





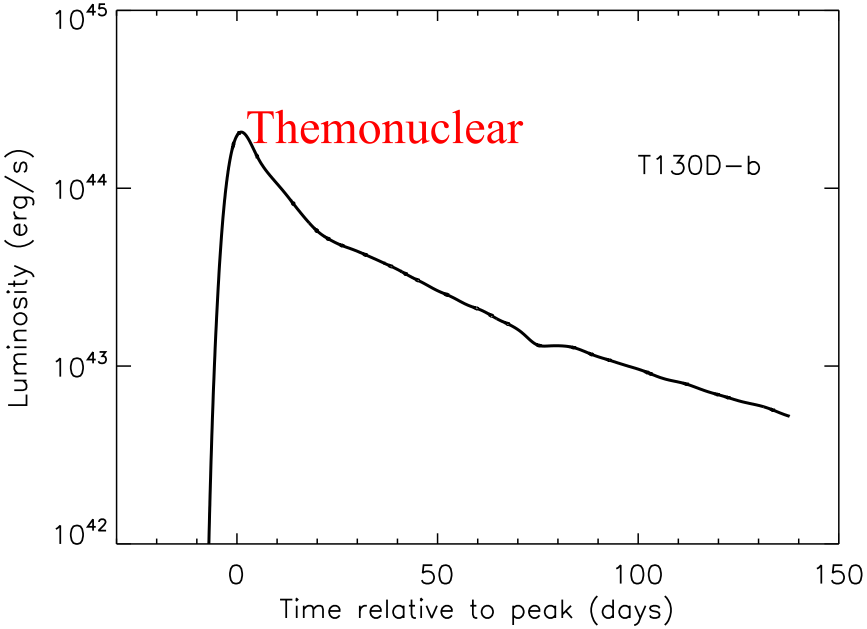
only final pulses shown

Type I (bolometric) light curves for various He/CO core masses. Time is in units of 10^6s and the maximum luminosity on the grid is 10^{44} erg s^{-1}.



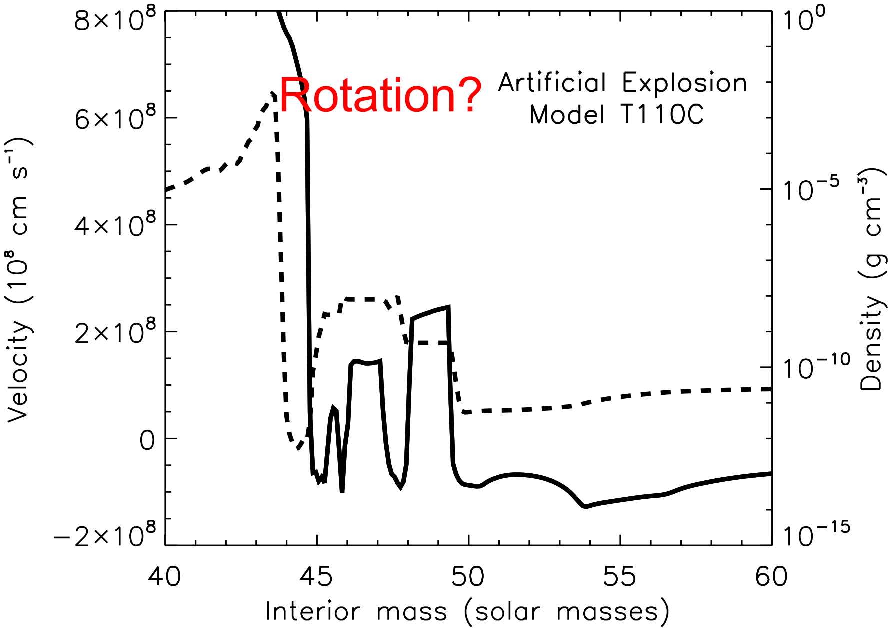
T70
Luminosity (erg/s)
10^{42}
10^{41}
10^{40}
10^{39}
0
−1
−2
−3
−4
−5
Time to collapse (years)
T80
Luminosity (erg/s)
10^{44}
10^{43}
10^{42}
10^{41}
10^{40}
−50
0
50
100
150
200
250
300
Time (days)
T100
Luminosity (erg/s)
10^{44}
10^{43}
10^{42}
10^{41}
0
100
200
300
400
Time (days)
T110C
Luminosity (erg/s)
10^{44}
10^{43}
10^{42}
10^{41}
6
4
2
0
−2
−4
Time to collapse (10^7 s)

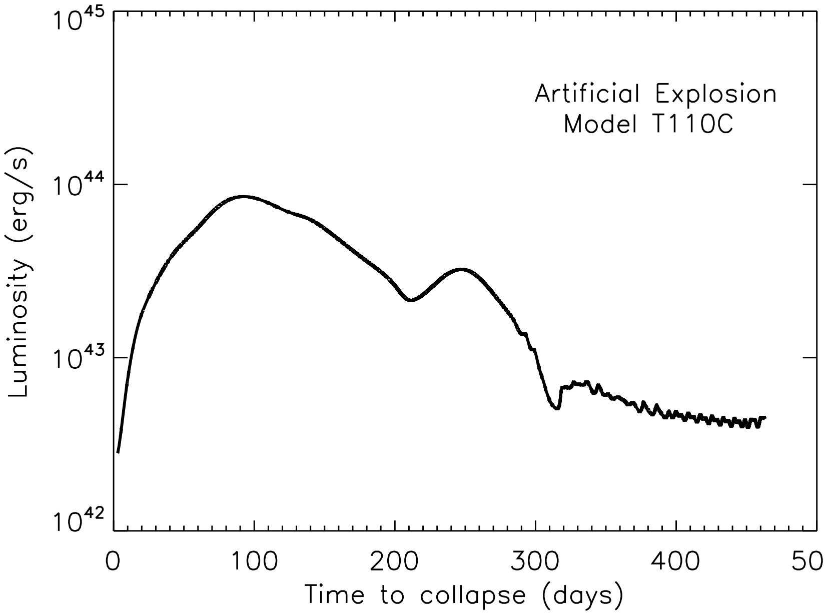
Superluminous Supernovae



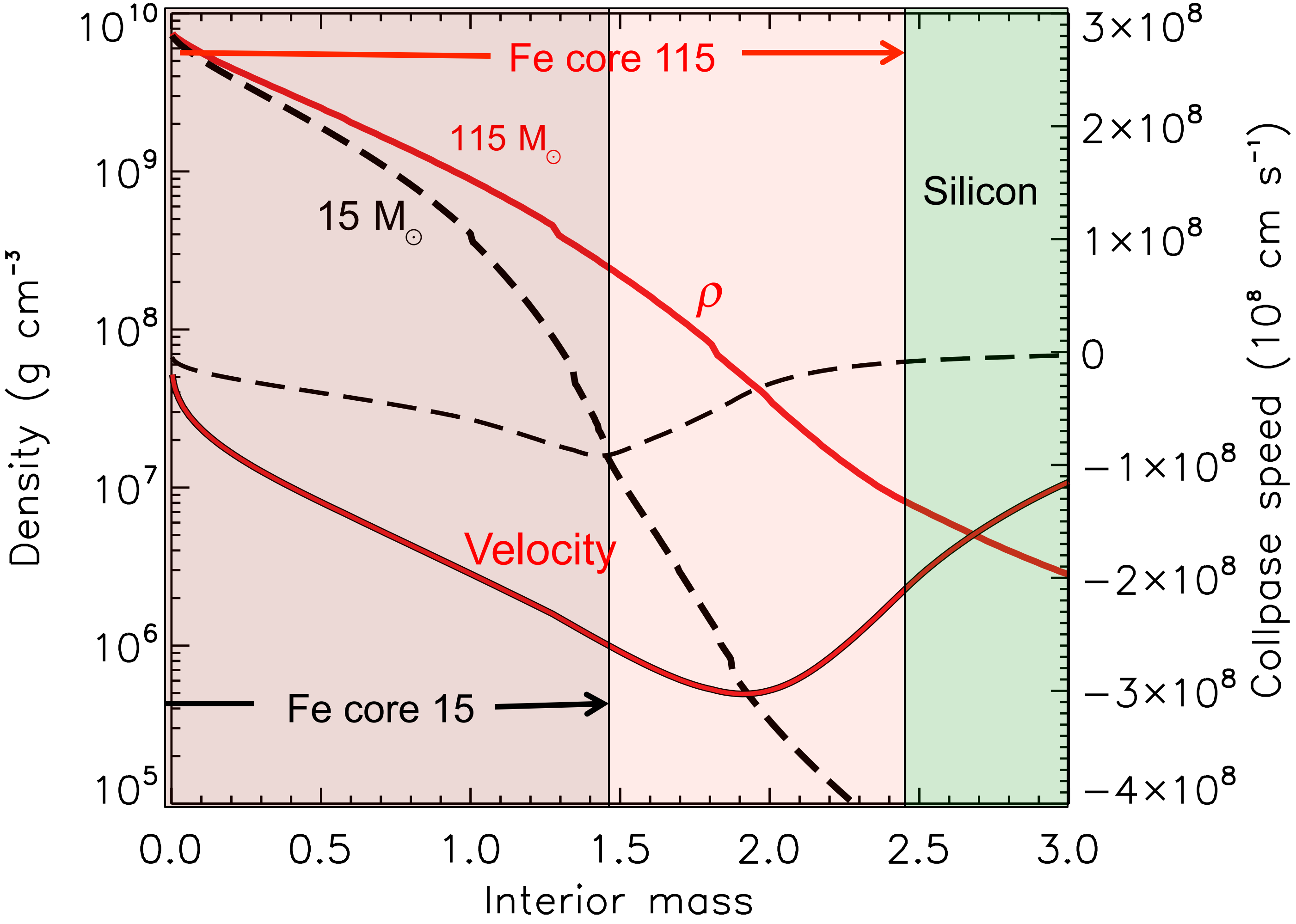
Left: Brightest PPSN calculated total $E_{rad} = 4.5 \times 10^{50}$ erg (1/3 of the relative KE in the pulses)

Below: Artificial explosion in which the dying iron core was forced to explode producing a KE at infinity of 2.2×10^{51} erg (total explosion 7×10^{51} erg)

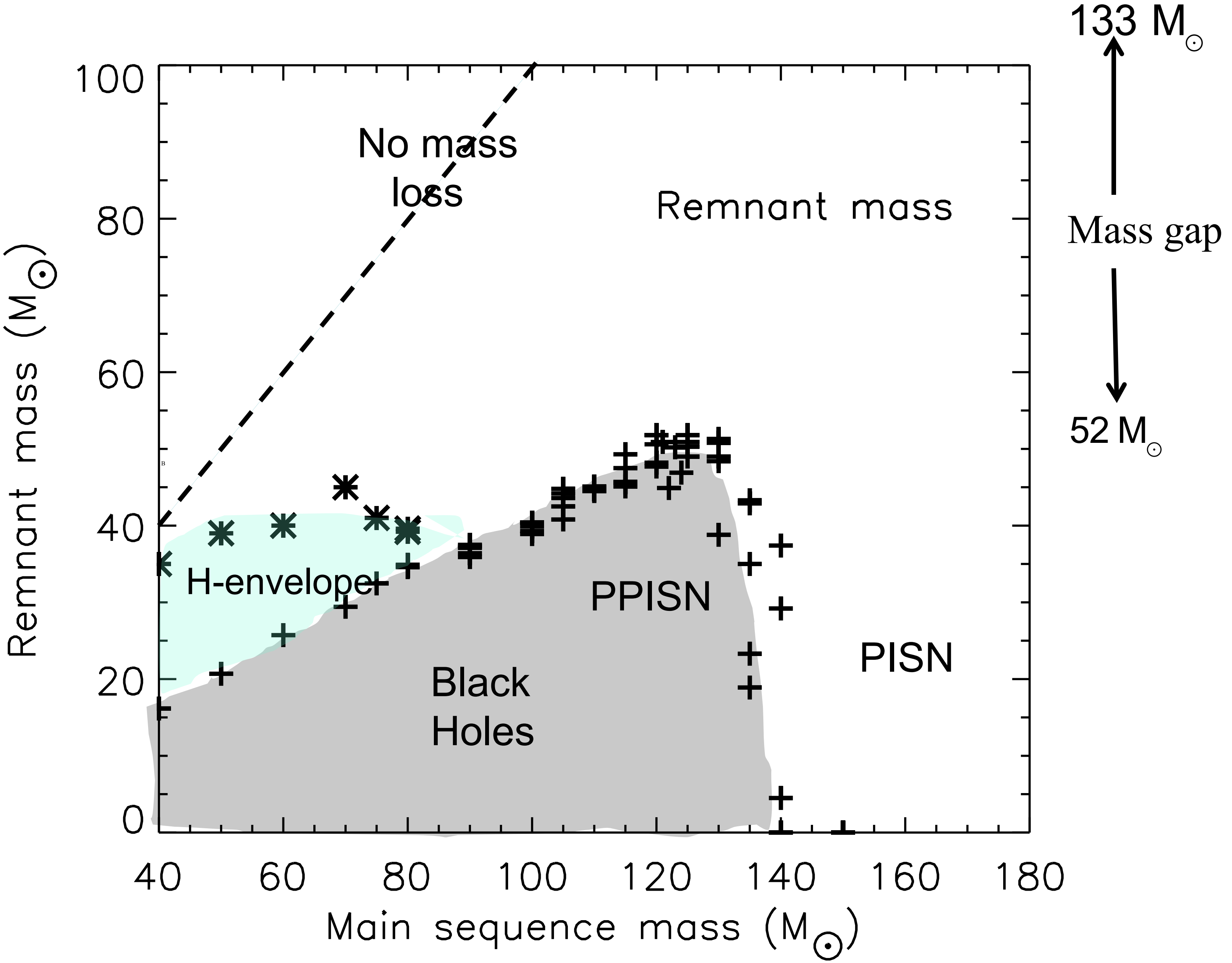




Iron Core Probably Collapses to a Black Hole (?)



But the rotation rate can be substantial !



Pepared for 10% Z$_\odot$

rotation can shift the scale on the bottom

Woosley (2016)

PPI SN SUMMARY

- A variety of transients are possible lasting from days to several thousand years. The optically bright ones last 20(SN I) to 500 days (SN II), but shorter fainter ones are common.

- Maximum L is rarely 10^{44} erg s^{-1} if the event is powered only by thermonuclear pulses. Usually quite blue.

- Maximum total radiated energy is 1 – 2 x 10^{51} erg Maximum KE = 4 x 10^{51} erg. More energy requires a magnetar (no BH) or BH accretion (large j).

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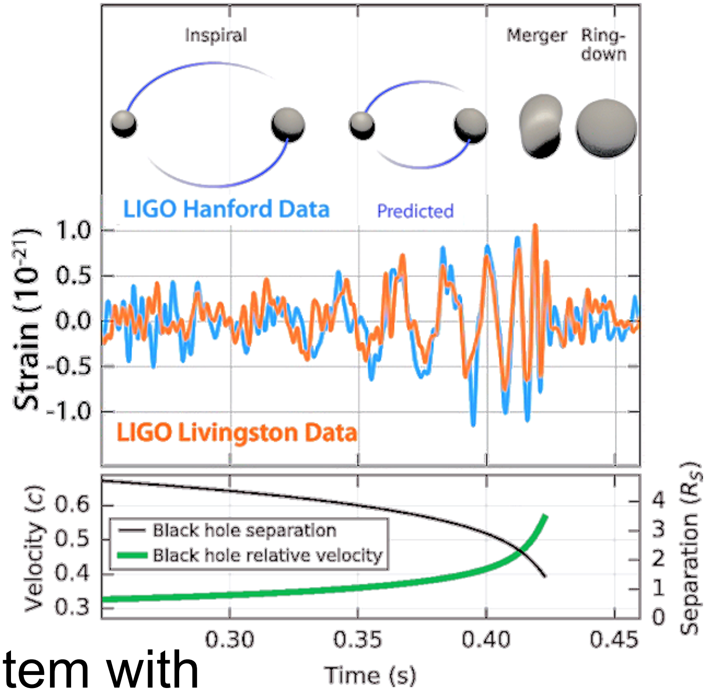
- Leave a population of 30 – 50 solar mass black holes, but no black holes over 52 M_O (except at very low metallicity?)

GW 150914



- 28 +- 4 and 36+4-5 solar masses. Sum ~ 65 M_O

- Likely the product of two stars in a binary system with ZAMS 70 and 90 M_O (60 and 70 M_O with rotation). Interestingly at least one of these would have been a PPISN along the way and ejected its envelope explosively

- Impossible to make at solar metallciity.

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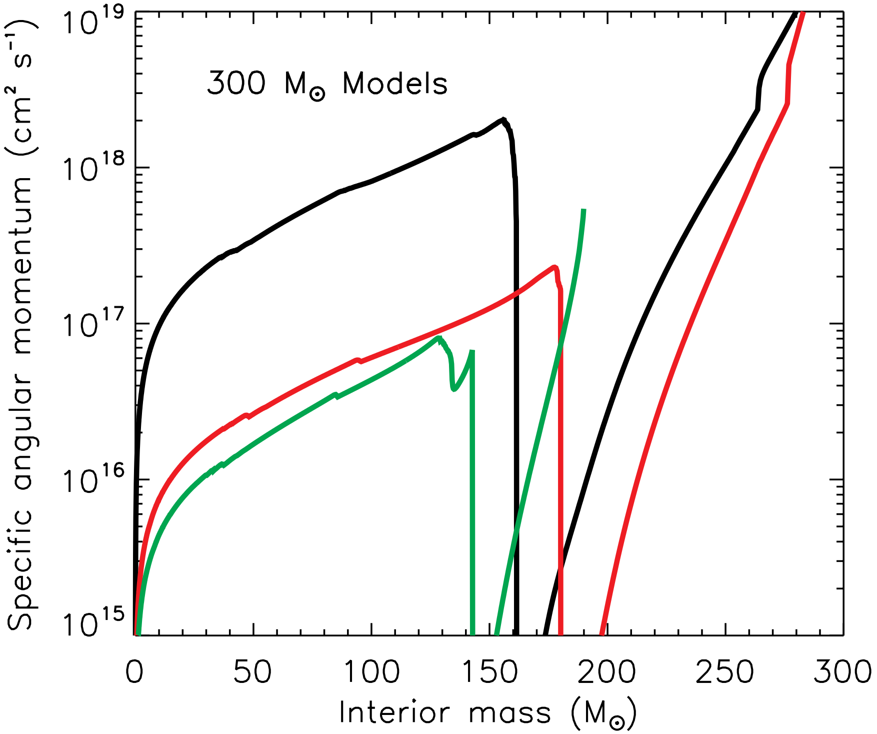
Woosley (2016)

SINGLE STAR MODELS FOR GW 150914



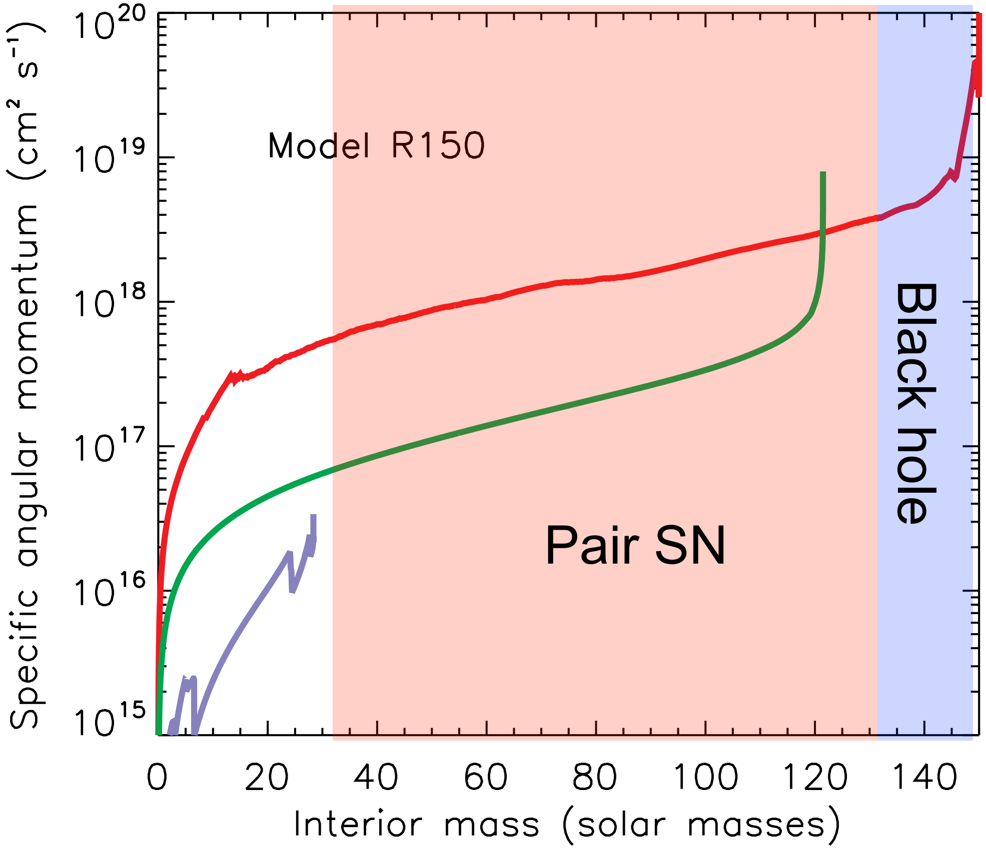
Black line – no mass loss or magnetic torques – like Fryer et al (2001)

Red line – no mass loss but include magnetic trques

Green line – include torques and mass loss for Z = 10% solar

When magnetic torques and rotation are included, single star models that once seemed promising for producing core fission now lack sufficient angular momentum to do so.

BEST SHOT AT A SINGLE STAR MODEL

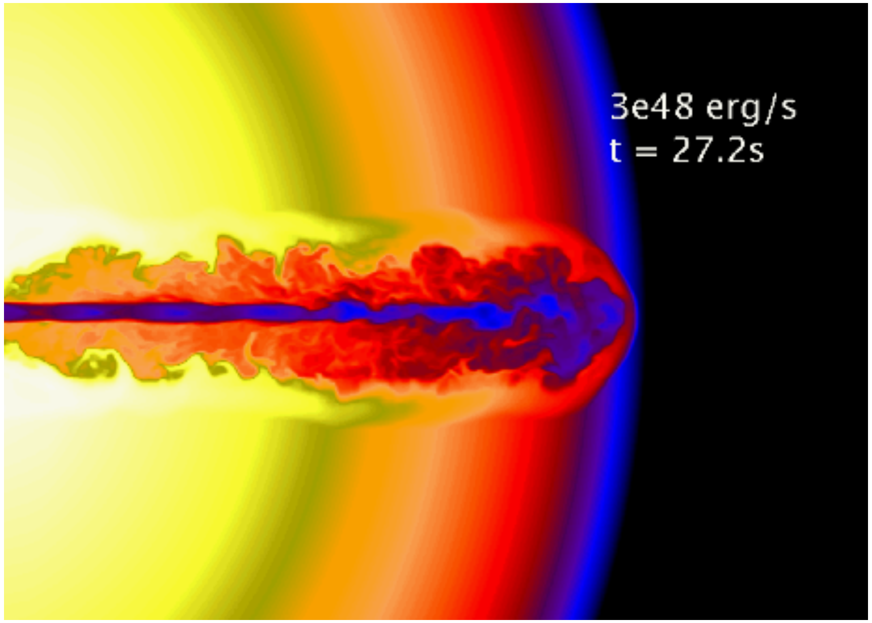


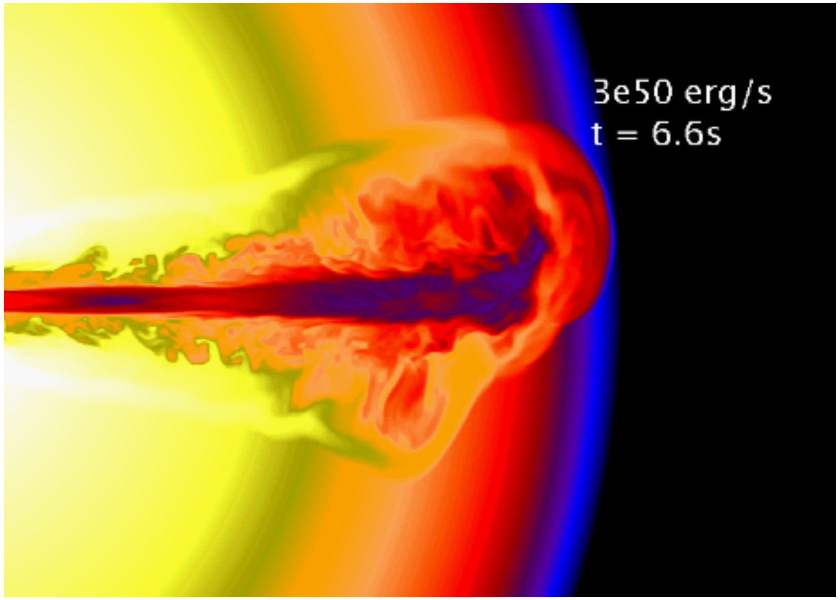
Chemically homogeneous evolution of a rapidly rotating 150 solar mass star with 10% solar metallicity.

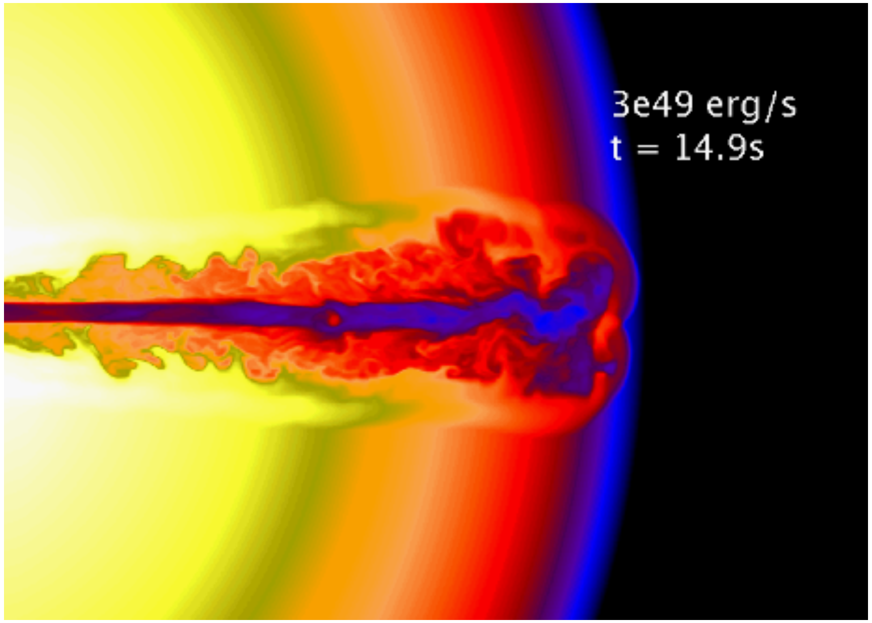
Each model had an initial total angular momentum of 10^{54} erg s, or an equatorial rotational speed of 310 km s^{-1}. All models included magnetic torques.

red line - no mass loss
blue line - normal mass loss for given metallicity
green line - 10% normal mass loss

Core bifurfation only possible for extremely small mass loss







3D studies of relativistic jets by Woosley & Zhang (2007)

Jets were inserted at 10^{10} cm in a WR star with radius 8 x 10^{10} cm. Jets had initial Lorentz factor of 5 and total energy 40 times mc^2.

CONCLUSIONS

- There should be a mass "gap" between 52 and 133 solar masses where no black holes are found.
- Another mass gap from 2 – 5 solar masses may be metallicity sensitive
- Most black holes are born with spins a ~ 0.01 – 0.1, but the detection of a single black hole with Kerr parameter a ~1would be supportive of the collapsar model for GRBs.
  Should be rare though. Maybe < 1%.

- Both the average mass black hole (currently 9 solar masses) and the upper bound (currently 15 solar masses) should increase with decreasing metallicity. This is necessary to explain GW 150914.

- GW 150914 was not the death of a single star (Loeb 2016), but the merger of two black holes. One or both black hole progenitors were pulsational -pair-instability supernovae along the way

- GW 150914 probably did not produce a detectable GRB. If a single star makes a GRB, there should be a characteristic delay of ~10 s between the onset of the GW signal and the GRB (though see Perna et al (2016)).