Supernovae, GRBs and Black Hole Formation

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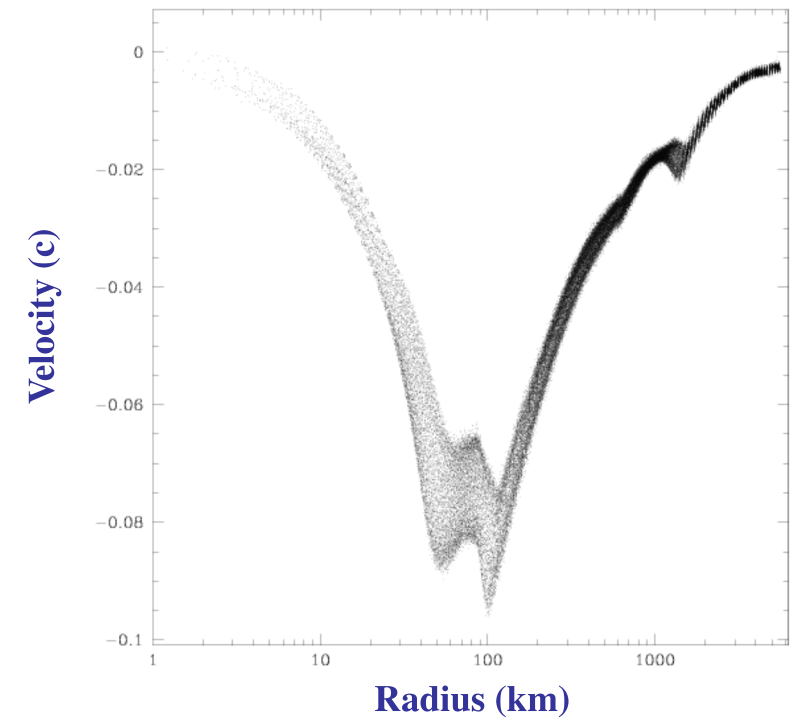
- Current Status of Core-Collapse Supernovae
- BHs and Fallback
- BH mass distributions

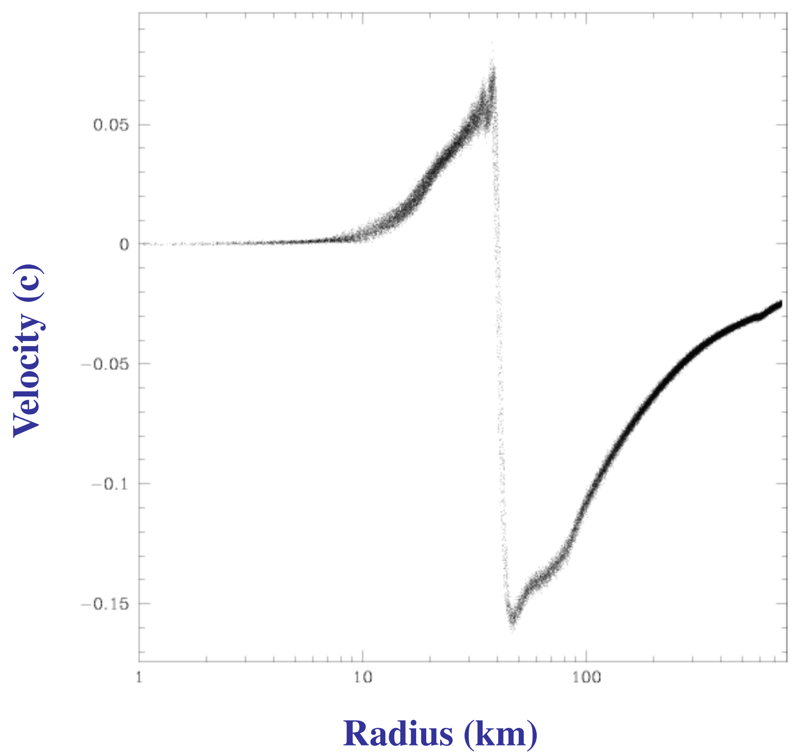
Neutrino-Driven Supernova Mechanism

Temperature and Density of the Core Becomes so High that:

- **Iron dissociates into alpha particles**
- **Electrons capture onto protons**

Core collapses nearly at freefall!



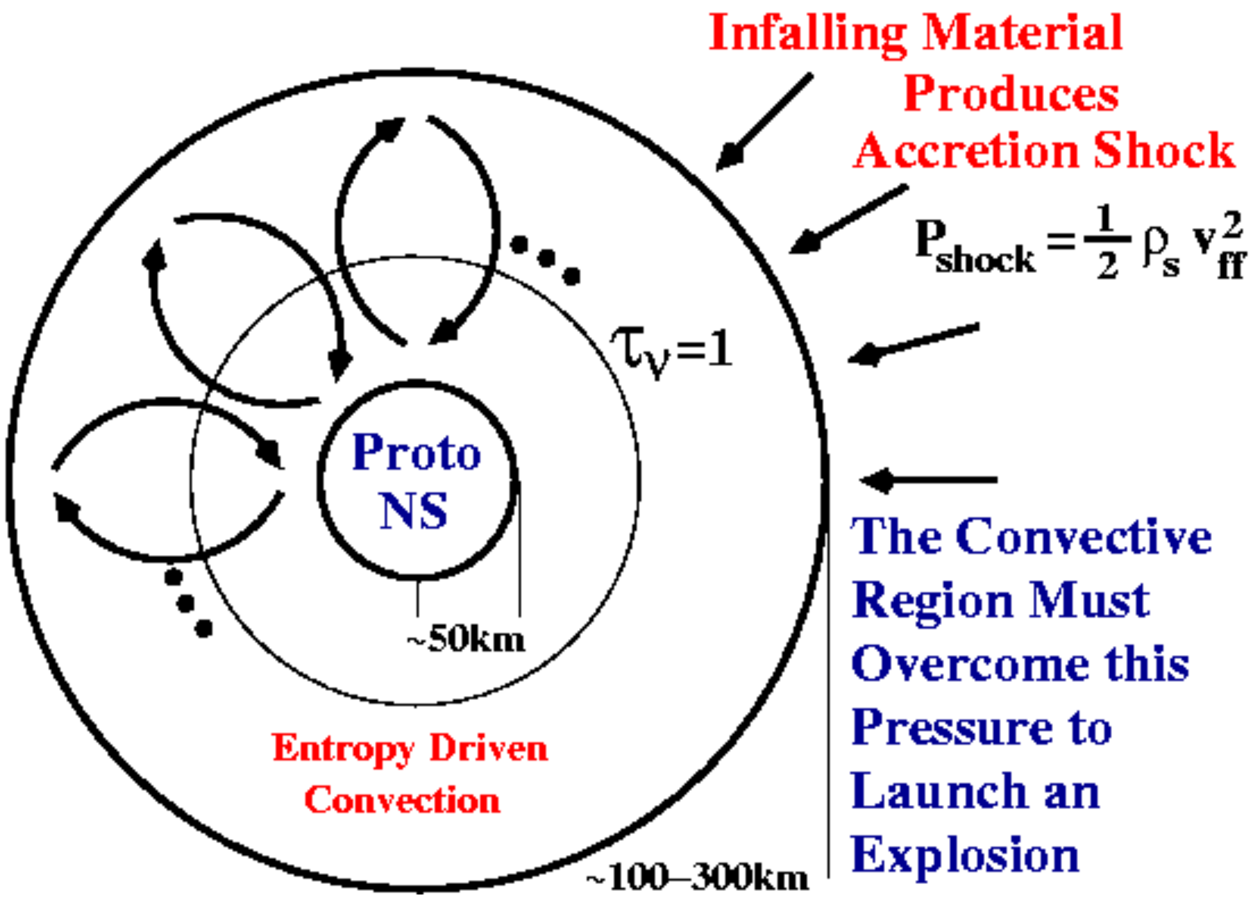


Core reaches nuclear densities

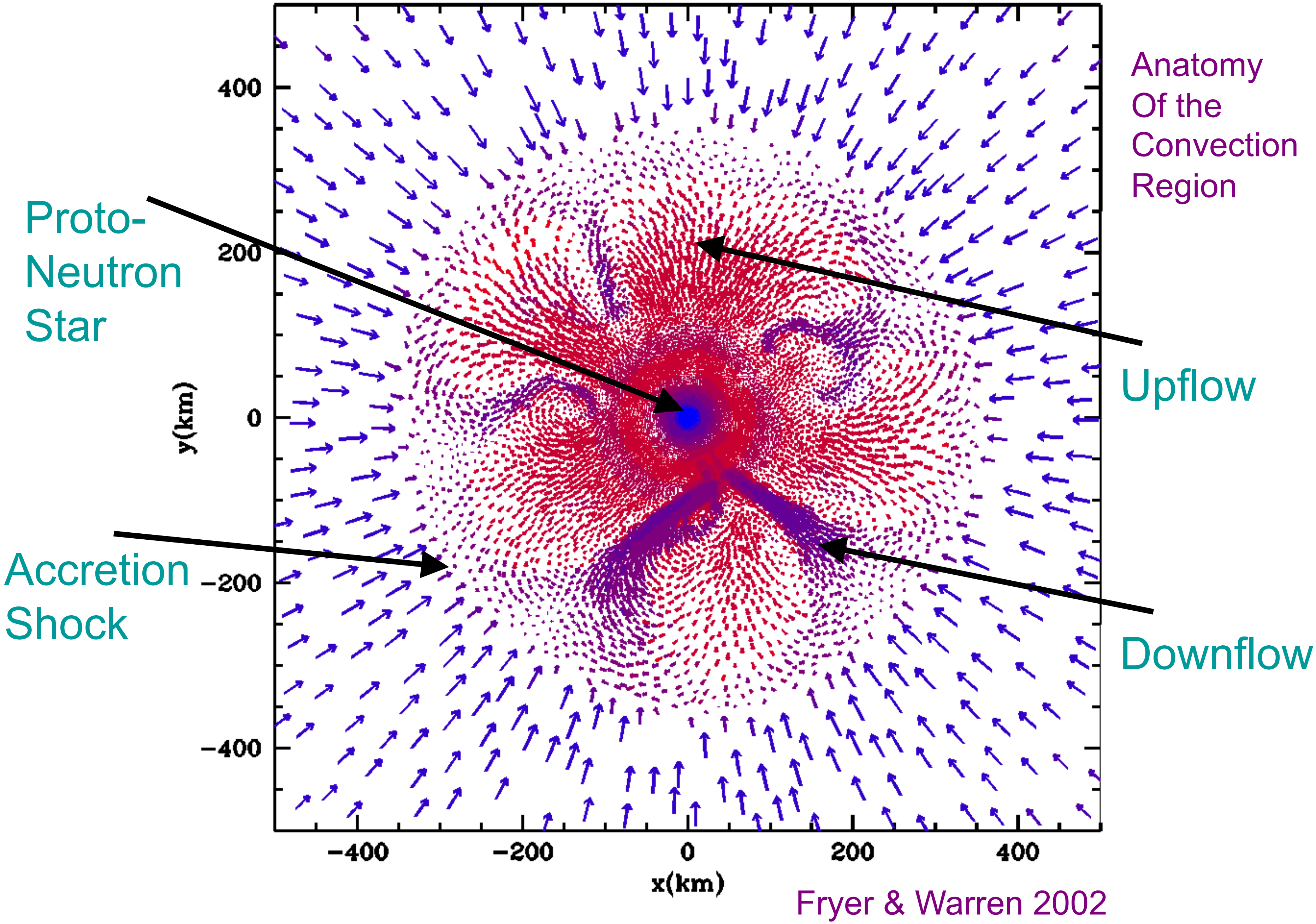
- **Nuclear forces and neutron degeneracy increase pressure**

Bounce!

Neutrino-Driven Supernova Mechanism: Convection

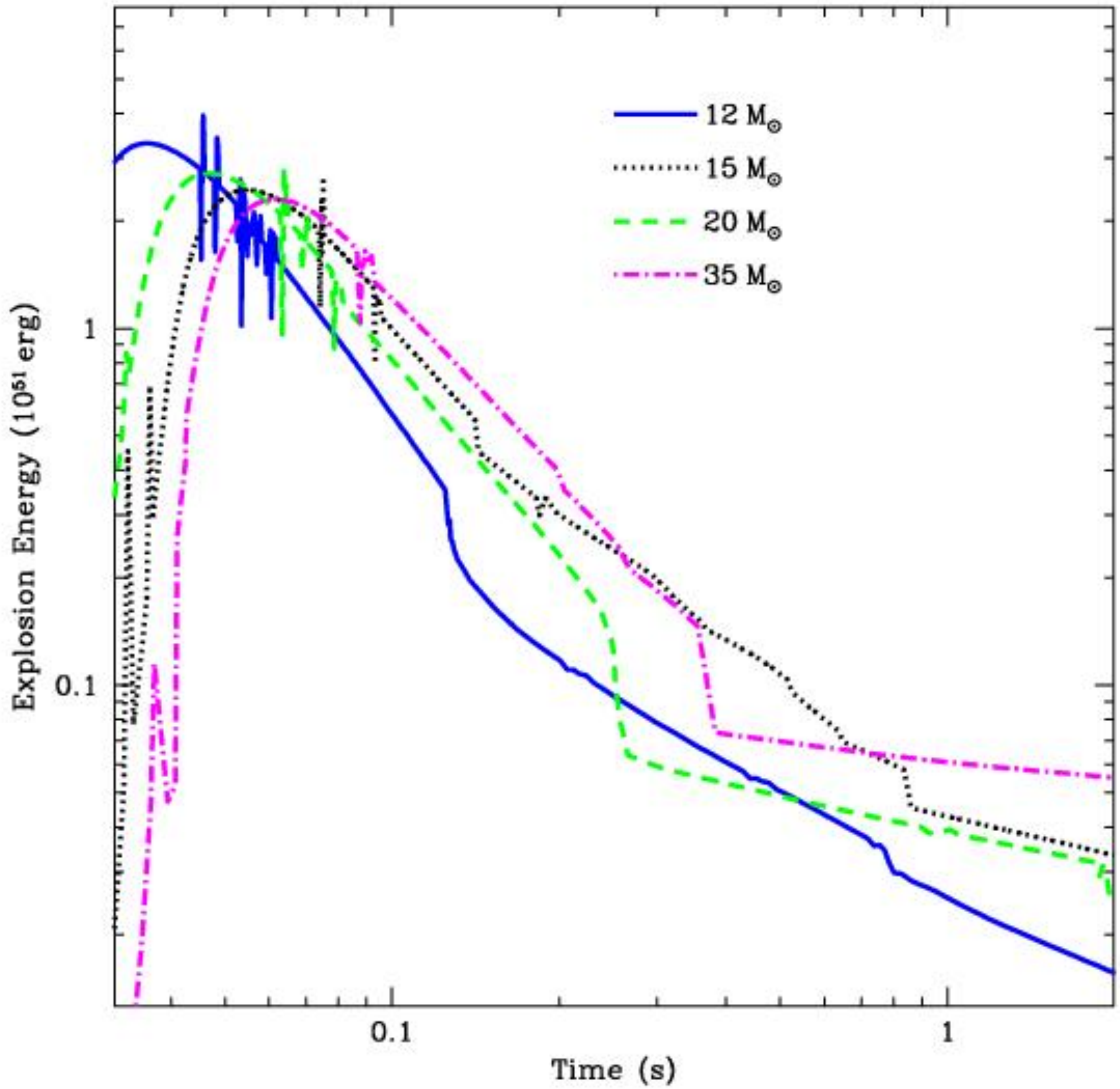


Fryer 1999



Anatomy
Of the
Convection
Region
Proto-
Neutron
Star
Upflow
Accretion
Shock
Downflow
400
200
0
−200
−400
y(km)
x(km)
Fryer & Warren 2002

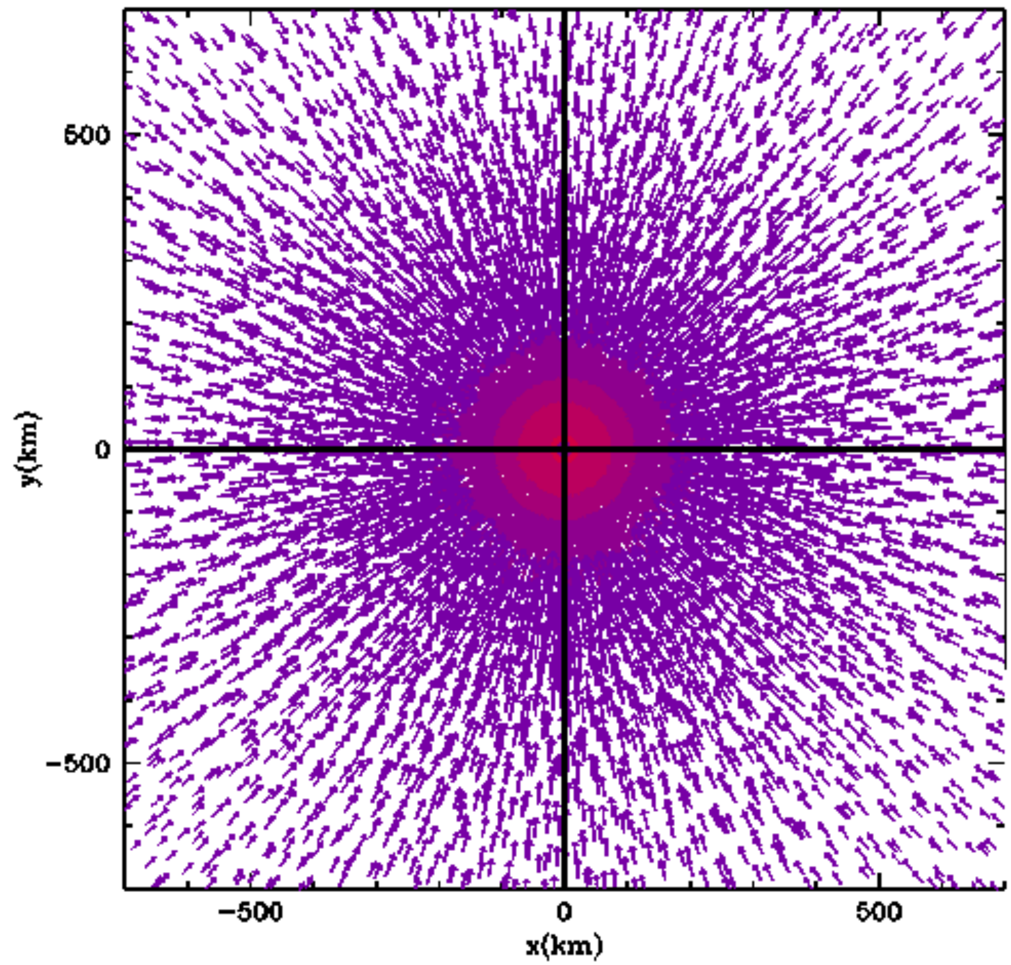
The convective engine also explains why, even though the collapse releases 10^{53} ergs of energy, the observed explosion is only a few times 10^{51} ergs.



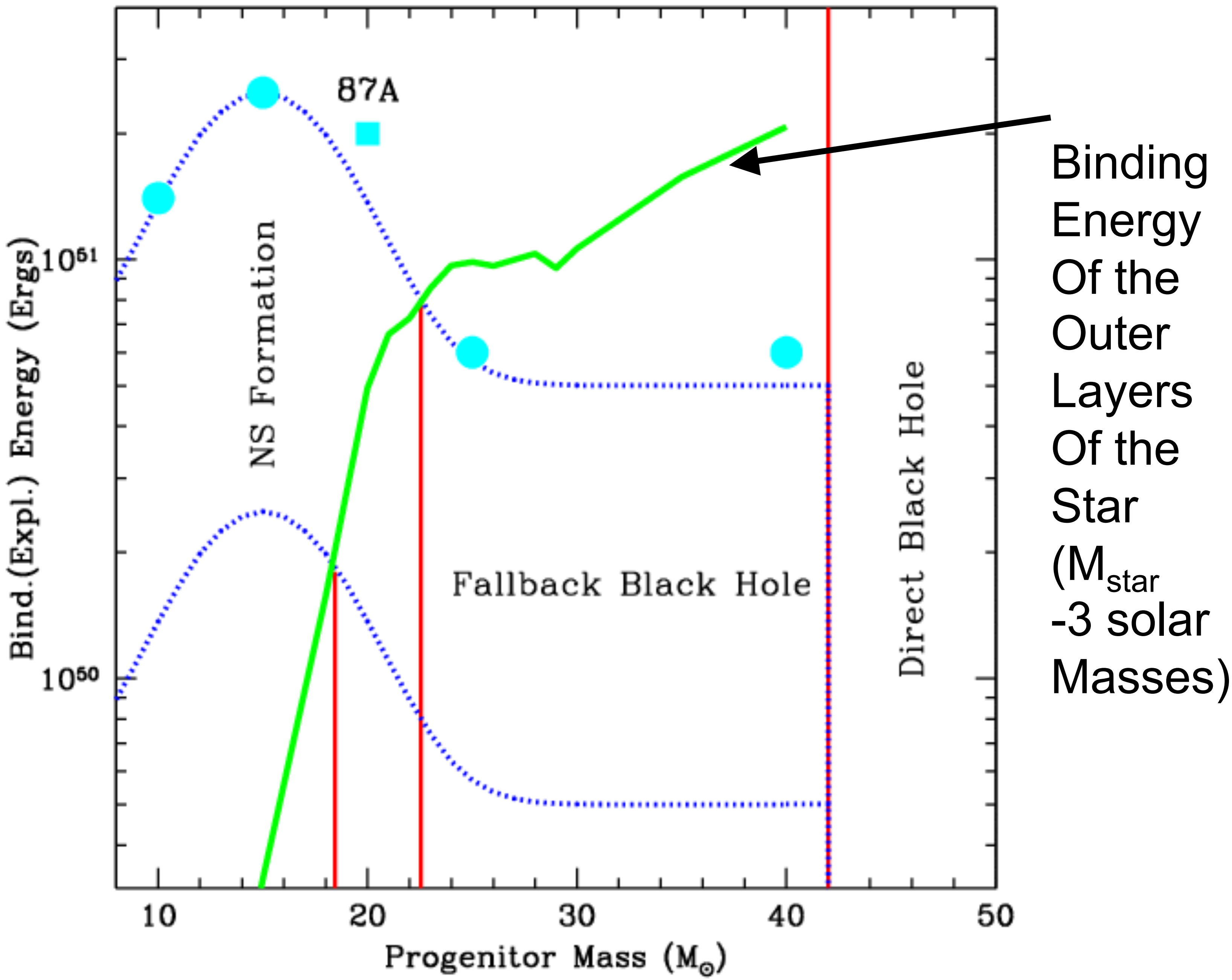
The Convection-Enhanced explosion has now been confirmed by ALL groups. The difficulty lies in understanding the convection.

A number of questions have arisen:

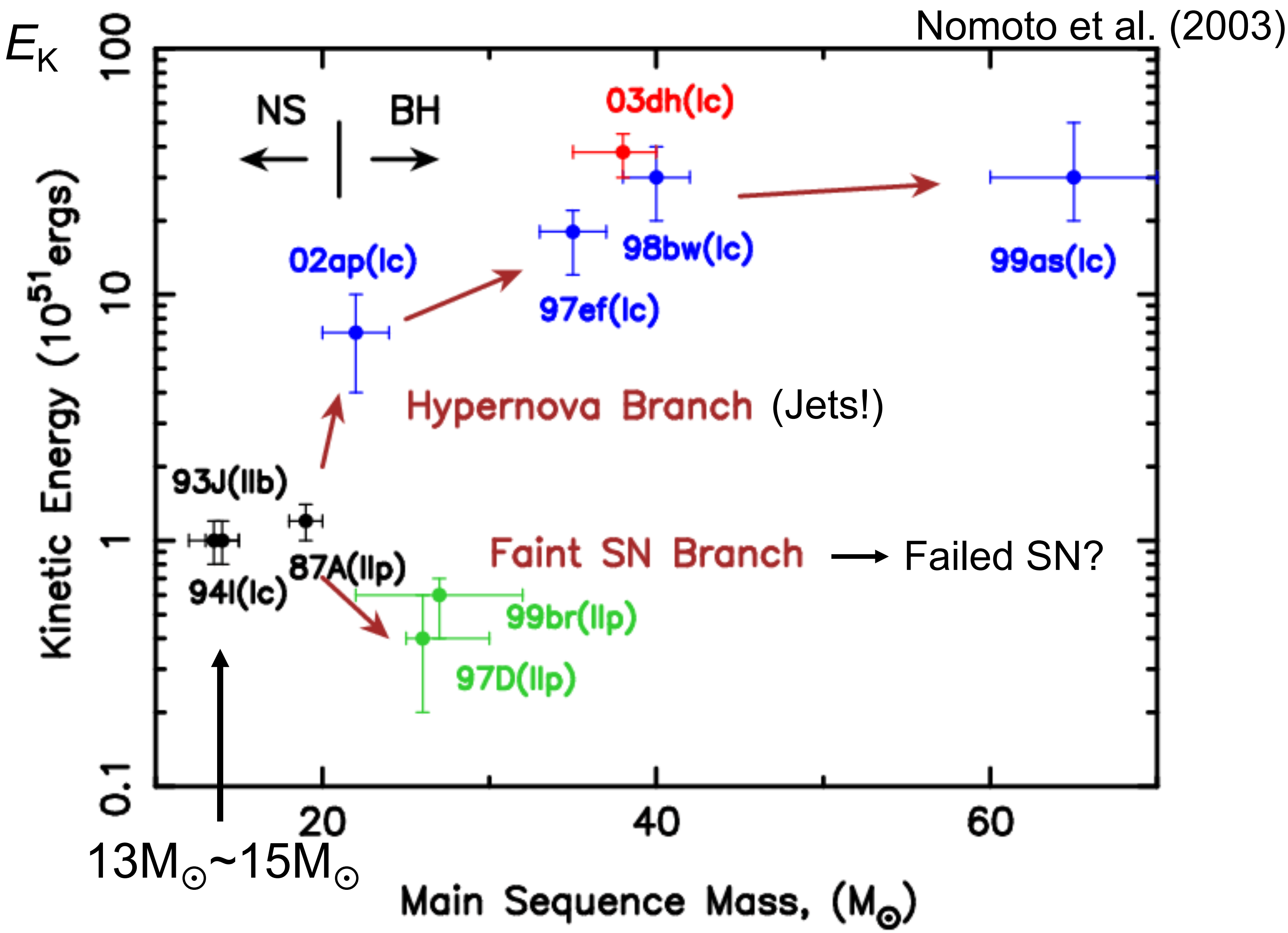
- Is SASI driven by advective-acoustic instabilities or pure pressure waves?
- Herant (1995) argued that RT instabilities would merge leading to low-mode convection. Is it SASI or RT? RT certainly plays a role.
- We are under-resolved and are damping out convection (some PPM codes severely damp convection). Tests are important!



Fryer 1999


87A
NS Formation
Fallback Black Hole
Direct Black Hole
10^{51}
10^{50}
Bind.(Expl.) Energy (Ergs)
10
20
30
40
50
Progenitor Mass ($M_\odot$)
Binding Energy Of the Outer Layers Of the Star (M_{star} -3 solar Masses)

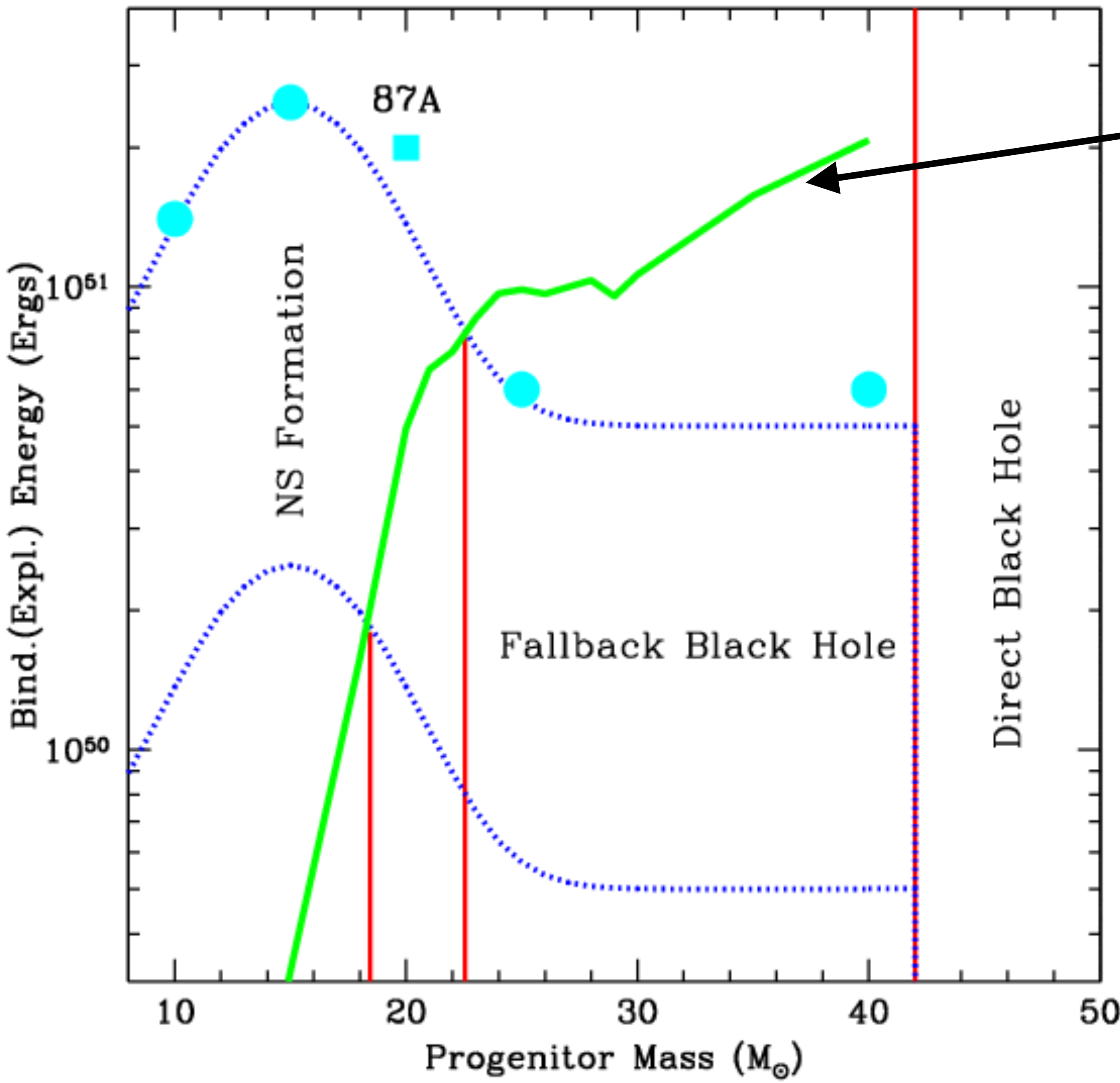
Supernovae/Hypernovae



Supernova Results

- Under the standard mechanism, strong supernova explosions occur only if the mechanism drives the explosion soon after bounce (first 150ms).
- Caveats: other mechanisms (e.g. magnetic field mechanisms) can produce strong late-time explosion energies.

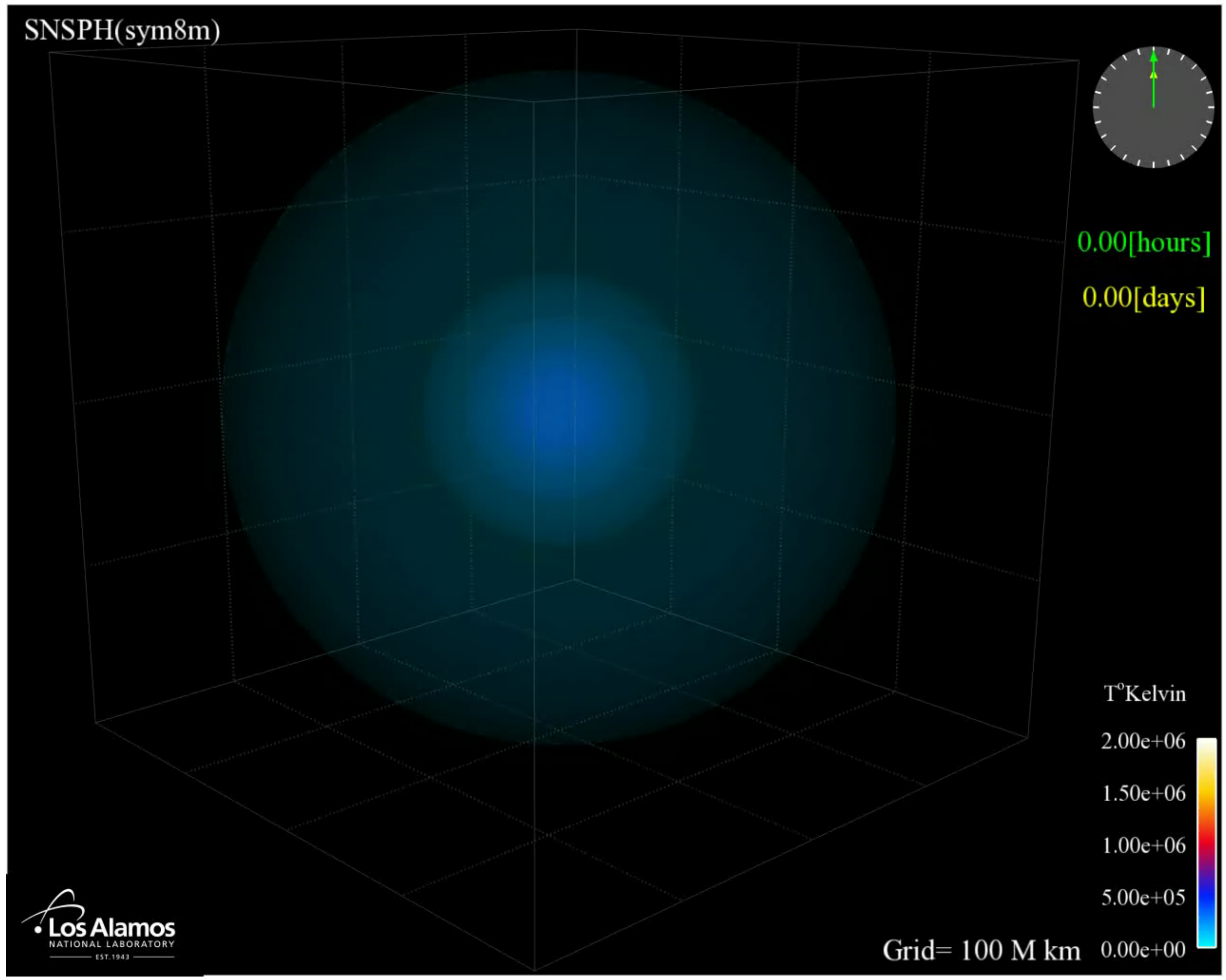
Fryer 1999



Binding Energy Of the Outer Layers Of the Star (M_{star} -3 solar Masses)

Although all groups get explosions, they are weak. Material will fall back!

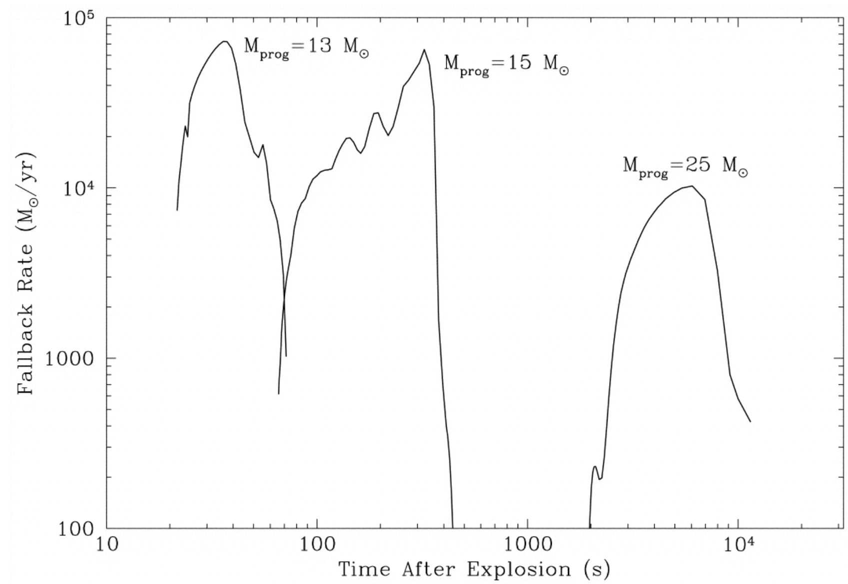
Colgate (1971) argued the some of the shocked material would lose enough energy as it pushed against the stellar envelope that it would not have enough energy to escape the compact remnant. After 3 decades, this we are back to understanding this cause of fallback.



Energy vs. Density Profile

- Colgate (1971) argued that fallback simply as pressure support was lost and kinetic energy used up in ejecting the star – prediction was that fallback happened early.
- Woosley (1989) argued that the reverse shock produced as the explosion moves through the hydrogen envelope would drive fallback – prediction was that fallback should happen late.
- Simulations show that large amounts of fallback only occur early (reverse shock argument a minor effect).

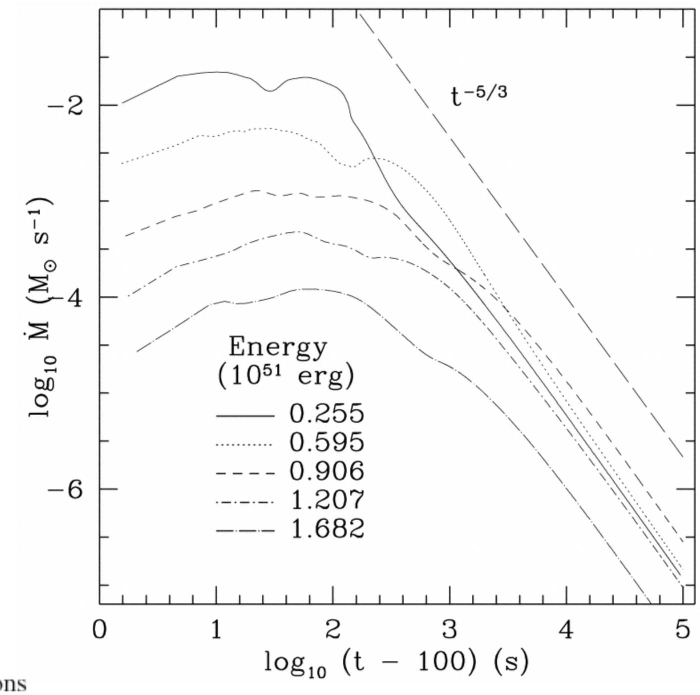
Fryer, Colgate, Pinto 1999



- This means that the stronger the explosion (and the smaller the star binding energy), the less fallback you will have.

Understanding Fallback

- Fryer et al. 1999, MacFadyen et al. 2001, Fryer et al. 2007, Zhang & Woosley 2008, Fragos et al. 2009, Fryer 2009, Ugliano et al. 2012
- Modern calculations focus on multi-dimensional effects
- All confirm Colgate picture.



Fallback in GRBs, MacFadyen et al. 2001

Table 3
Three-Dimensional Explosions

Model Name	$f_{velocity}$	$E_{explosion}$ (10^{51} erg)	Initial M_{BH} ($M_{\odot}$)	V_{kick} (kms^{-1})	Y_{MgAl} ($M_{\odot}$)	Y_{Si} ($M_{\odot}$)	Y_{Ca} ($M_{\odot}$)	Y_{Ti} ($M_{\odot}$)	Y_{FePeak} ($M_{\odot}$)	R[a] ($M_{\odot}$)
1Jet2[b]	2.0	1.1	6.3	790	0.007	0.02	0.001	6×10^{-6}	0.02	0.6
1Jet.8	0.8	0.30	6.4	300	0.007	0.02	0.0007	3×10^{-7}	0.001	0.9
2Jet2	2.0,1.5	1.7	5.8	250	0.01	0.04	0.002	9×10^{-6}	0.04	0.4
2Jet3.5n	3.5,3.0	0.21	6.5	200	0.007	0.01	0.0002	5×10^{-8}	9×10^{-7}	3
LM0.2	0.2	0.083	6.8	20	0.004	0.0007	7×10^{-5}	3×10^{-16}	2×10^{-20}	5
LM0.4	0.4	0.13	6.6	80	0.005	0.0009	8×10^{-5}	1×10^{-14}	2×10^{-20}	5
LM0.6	0.6	0.22	6.4	200	0.007	0.002	8×10^{-5}	2×10^{-10}	3×10^{-13}	8
LM0.7	0.7	0.28	6.1	310	0.009	0.006	8×10^{-5}	1×10^{-9}	2×10^{-12}	10
LM0.8	0.8	0.37	5.9	420	0.01	0.02	4×10^{-4}	1×10^{-7}	1×10^{-7}	2

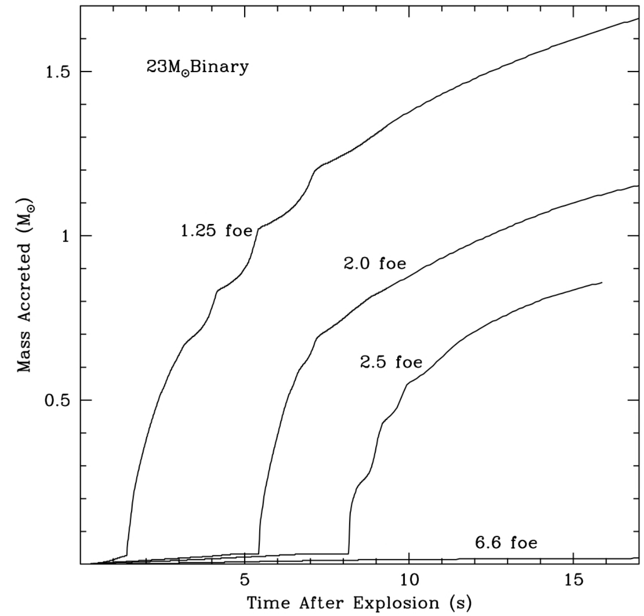
Notes.

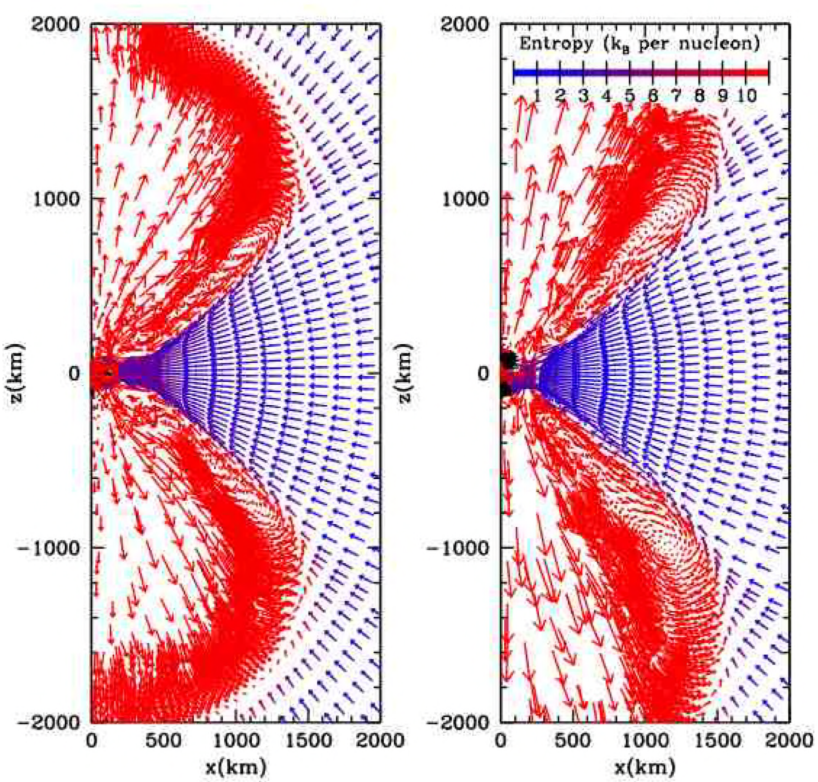
[a] $R = (Y_{MgAl}/Y_{MgAl,\odot})/(Y_{Ca}/Y_{Ca,\odot})$

[b] We have three sets of models: one-sided narrow opening angle (30°) termed 1Jetx, two-sided narrow opening angle (30°) termed 2Jetx, and one-sided broad opening angle (45°) termed low-mode explosions (LMx). In all models, beyond the opening angle, we decrease the explosion velocity from our standard value by 0.1. In the opening, we use the factor $f_{velocity}$. Note that in 2Jet3.5n, we have a narrower opening angle (15°).

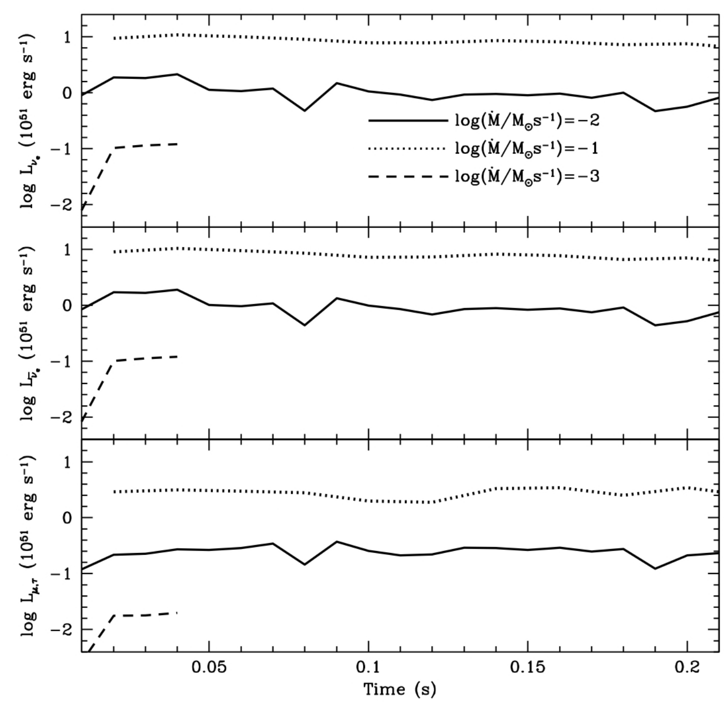
3D Fallback from Fragos et al. 2009

- Fallback accretion rates high in the first 10s.
- Can lead to high neutrino emission (in excess of cooling NS)
- Can eject material, especially if there is a modest amount of angular momentum.



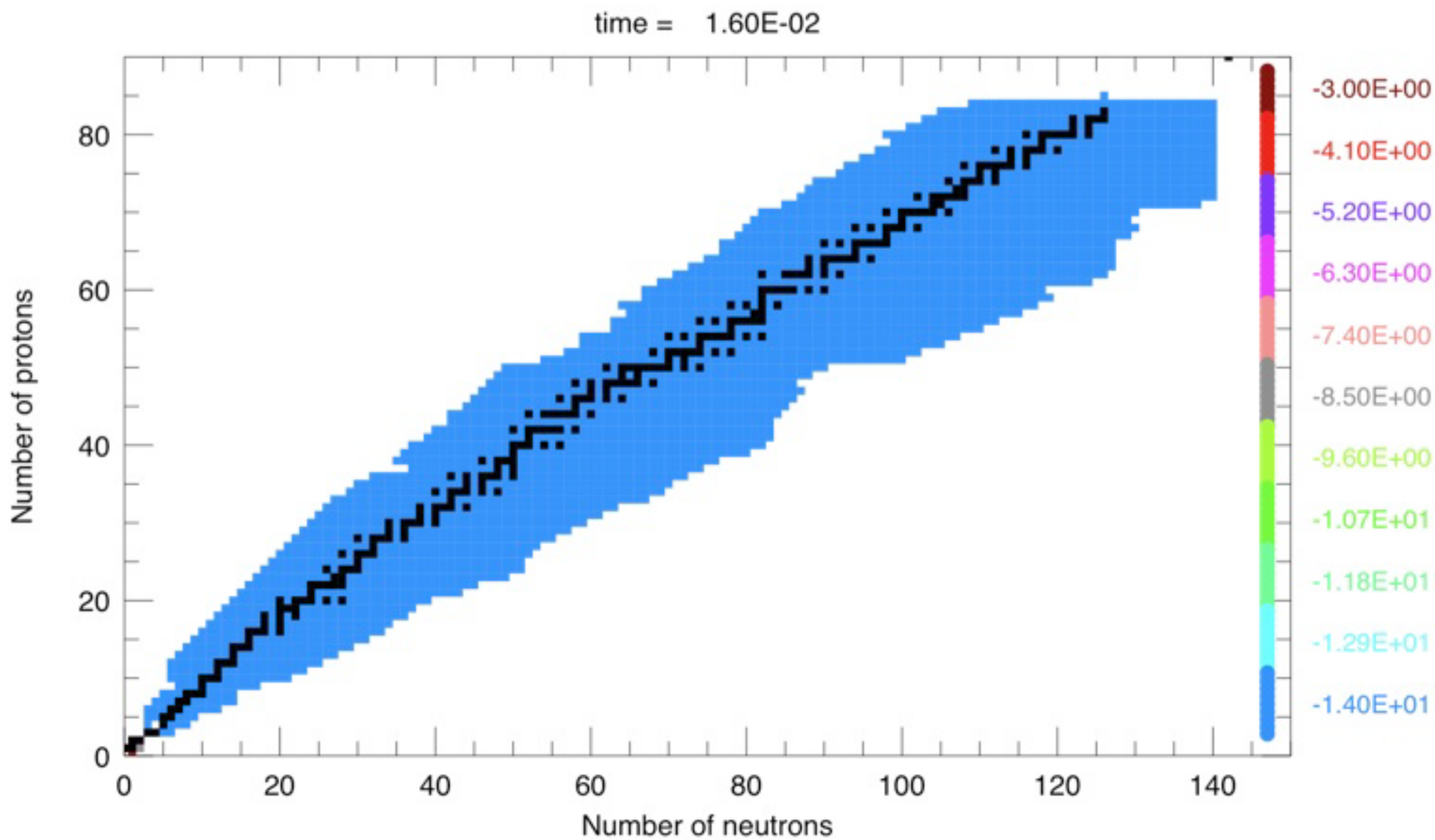


Fryer 2009



Fallback may also be a site to produce the r-process

Ejecta from fallback follow trajectories with a rapid density drop followed by a slow density decline. Perfect for "disequilibrium" nucleosynthesis (Meyer 2002).



Fryer, Herwig, Hungerford, and Timmes (2006)

Putting the pieces together

- Delayed explosions are weaker
- Weaker explosions produce more fallback

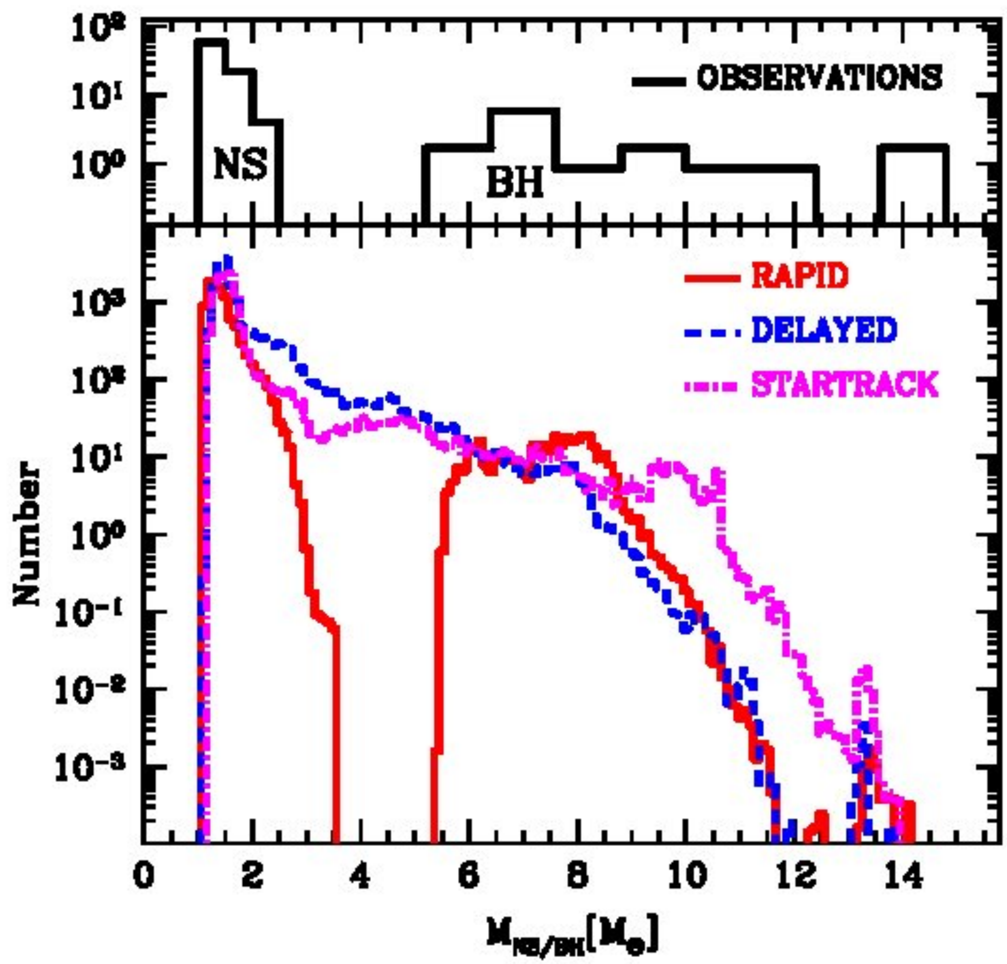
➢ Delayed explosions produce black holes in the 2.5-6 solar mass range.

➢ Neutron Stars are produced in strong explosions that occur within 150ms of core bounce.

➢ Most massive black holes are produced in explosion-free collapses.

Black hole formation

- When the explosion is weak or fails, a black hole is formed.
- Our understanding of the supernova engine has helped us predict the mass distribution of black holes.
- In particular, we now believe we understand the gap in in black hole masses between ~2-5 solar masses.



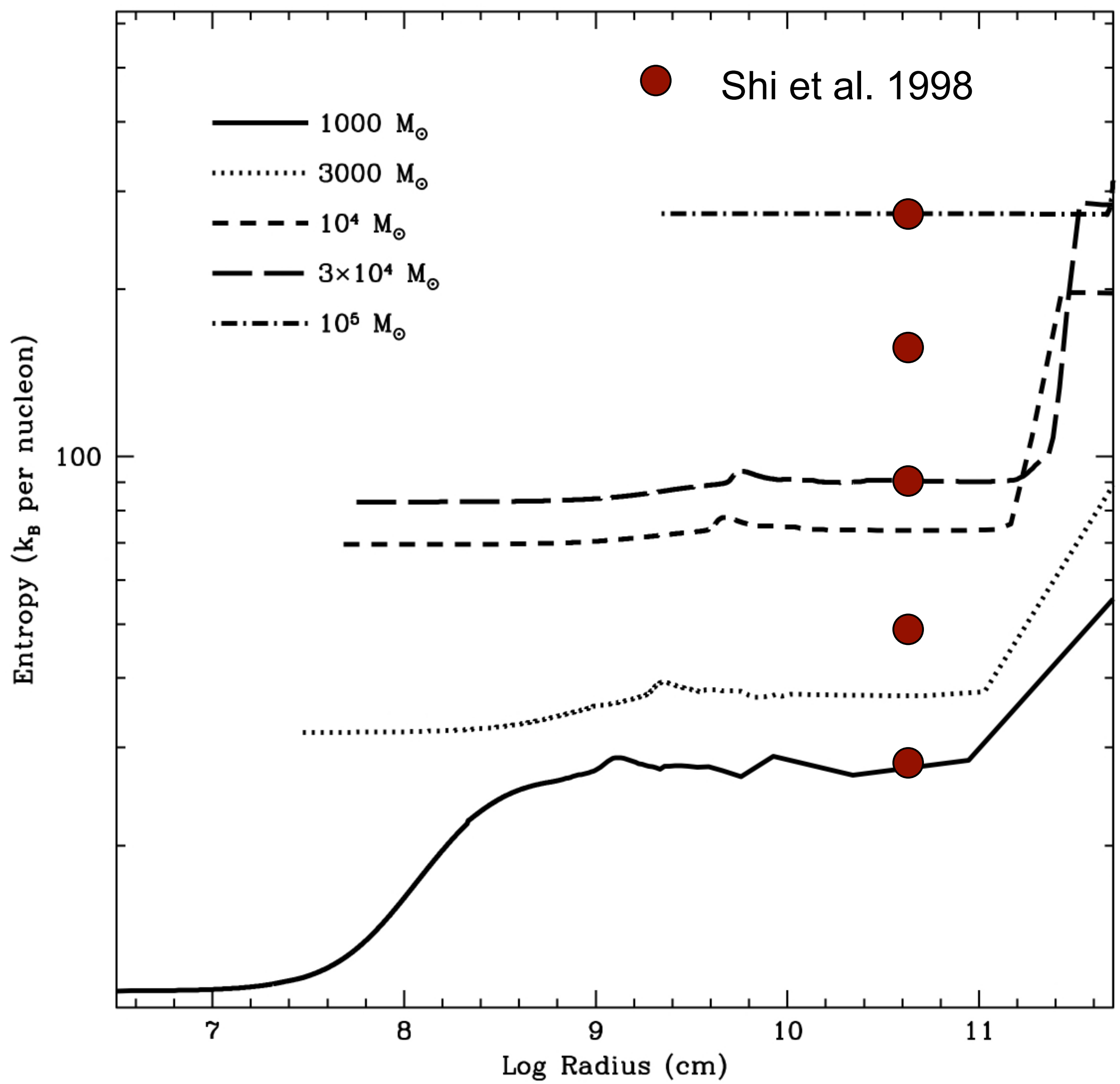
Belczynski et al. 2012

BH features and the SN engine

- Delayed explosions (>150ms) produce weaker explosions.
- Weak explosions produce the most fallback.
- The lowest-mass black holes are formed in fallback.
- The existence, or lack thereof, of black holes between 2.5-5 solar masses constrains the explosion time and hence constrains the explosion mechanism.

Supermassive Stars

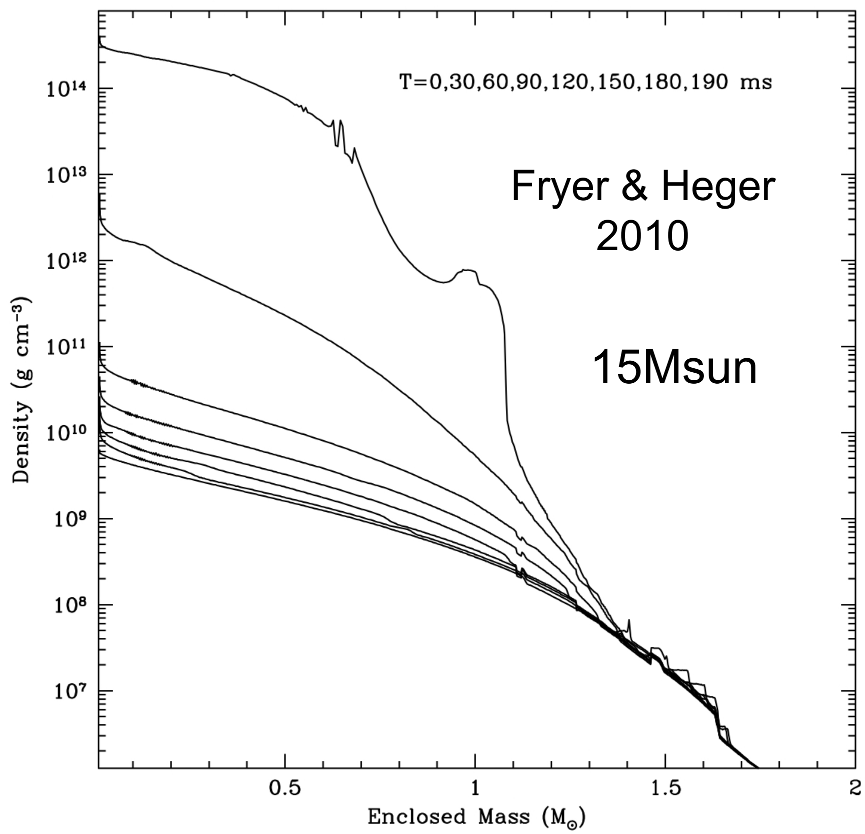
- The higher the stellar mass, the higher the entropy at collapse.
- Higher entropies alter pressure support (electron degeneracy less important)
- Higher entropies alter nature of neutrino cooling

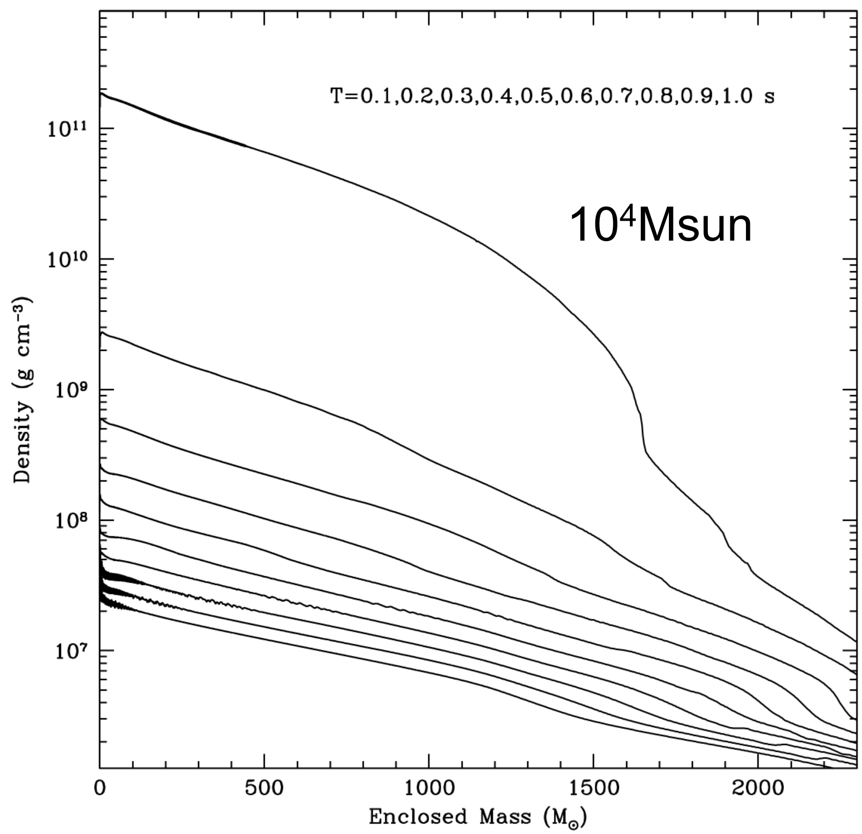


Fryer & Heger 2010

Supermassive Stars

- For normal core collapse, the loss of electron degeneracy pressure leads to a dramatic collapse of the inner core. The collapse halts only when the core reaches nuclear densities.
- For supermassive collapse, the entire star compresses, forming a proto-black hole.





Fryer, Woosley & Heger 2001