Observational Constraints on the Supernova Engine

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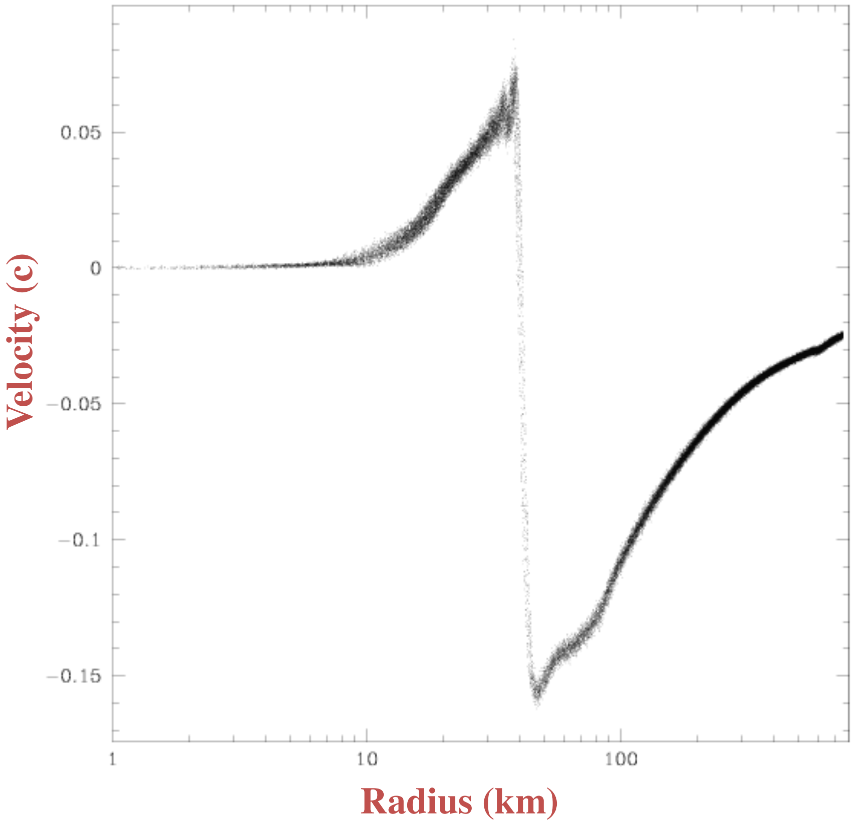
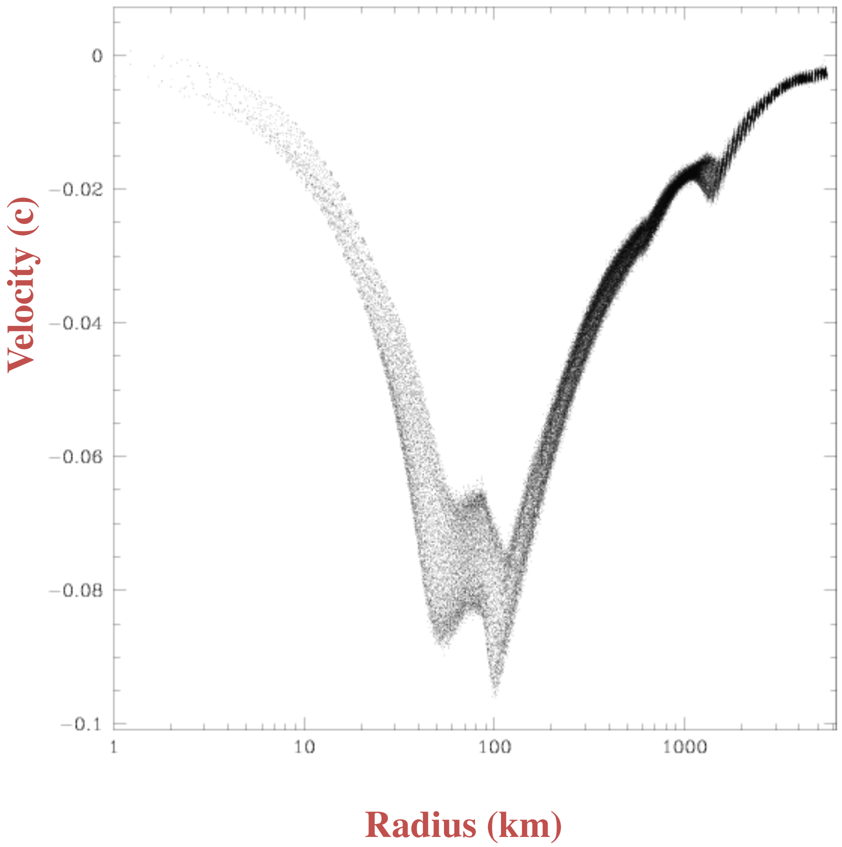
Neutrino-Driven Supernova Mechanism

Temperature and Density of the Core Becomes so High that:

- Iron dissociates into alpha particles
- Electrons capture onto protons

Core collapses nearly at freefall!



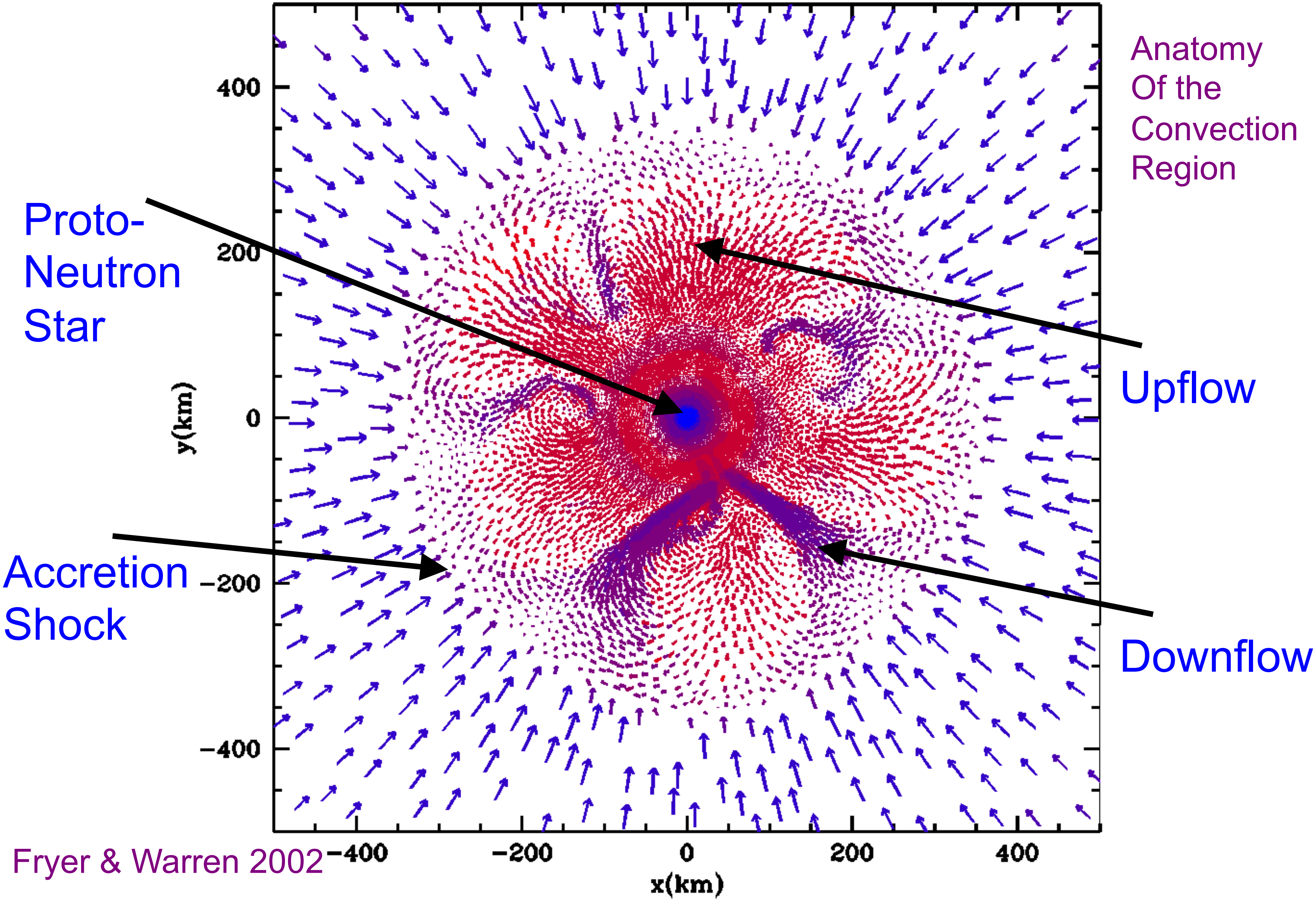


Core reaches nuclear densities

Nuclear forces and neutron degeneracy increase pressure

Bounce!

The Herant et al. (1994) Convective Supernova Engine



Anatomy Of the Convection Region

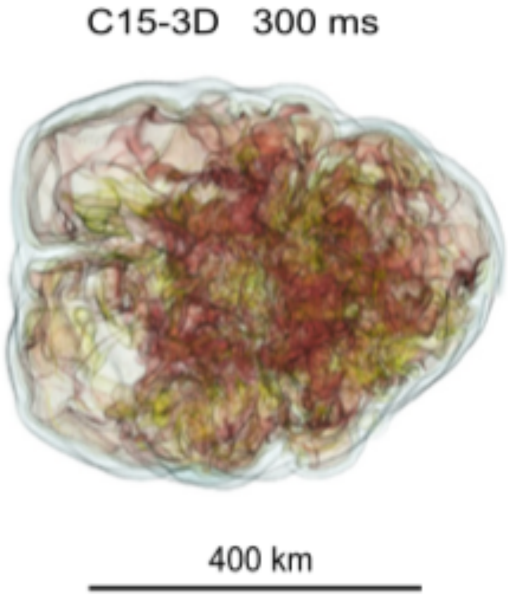
Proto-Neutron Star

Upflow

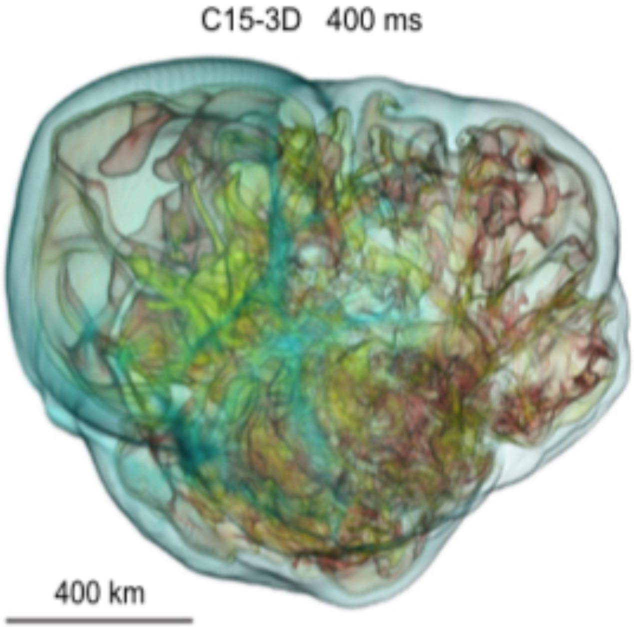
Accretion Shock

Downflow

Fryer & Warren 2002

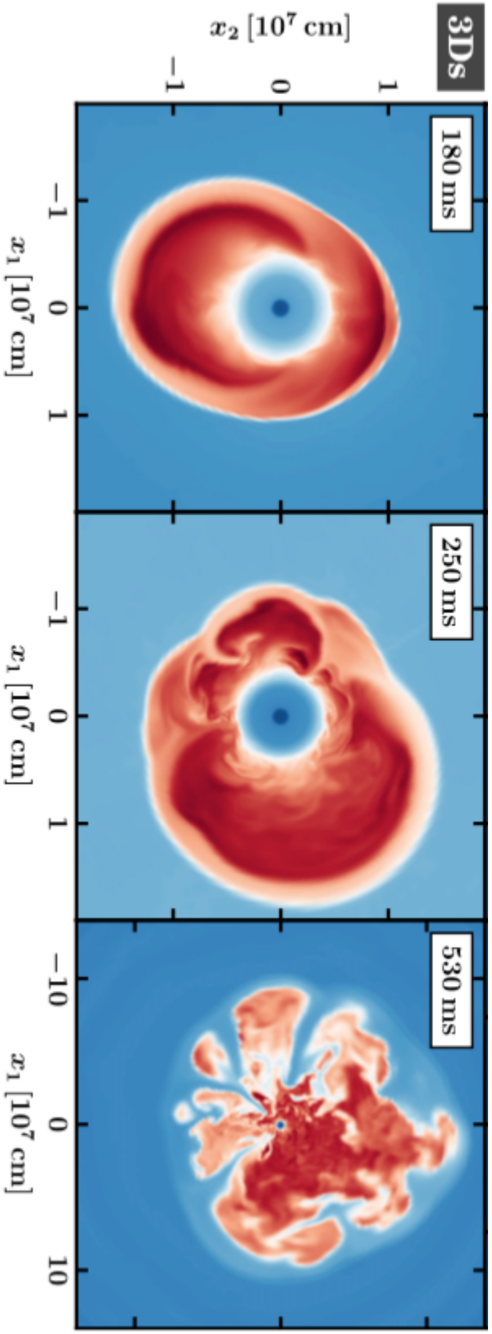


Lentz et al. 2015



Depending on the physics, most groups now produce explosions with this convective engine. Current arguments focus on the:

- Most important physics
- Source of instabilities



Melson et al. 2015

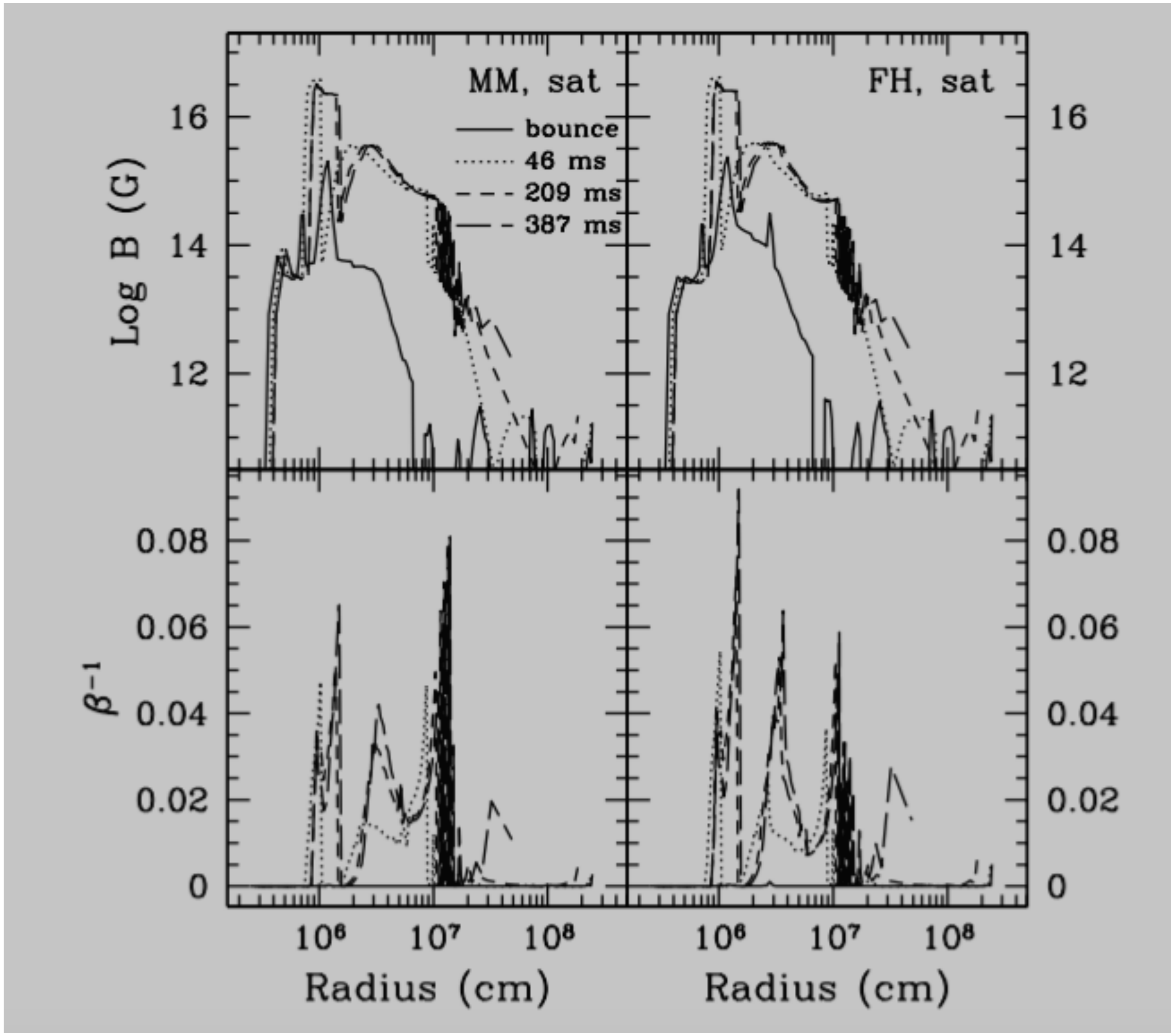
Alternate engines

For long-duration gamma-ray bursts, a class of black-hole accretion disk engines have been proposed. Here, magnetic fields our wound up in the disk formed with the high-angular momentum layers fall onto a failed supernova.

If the core is rapidly-rotating, a disk can form around the proto-neutron star.

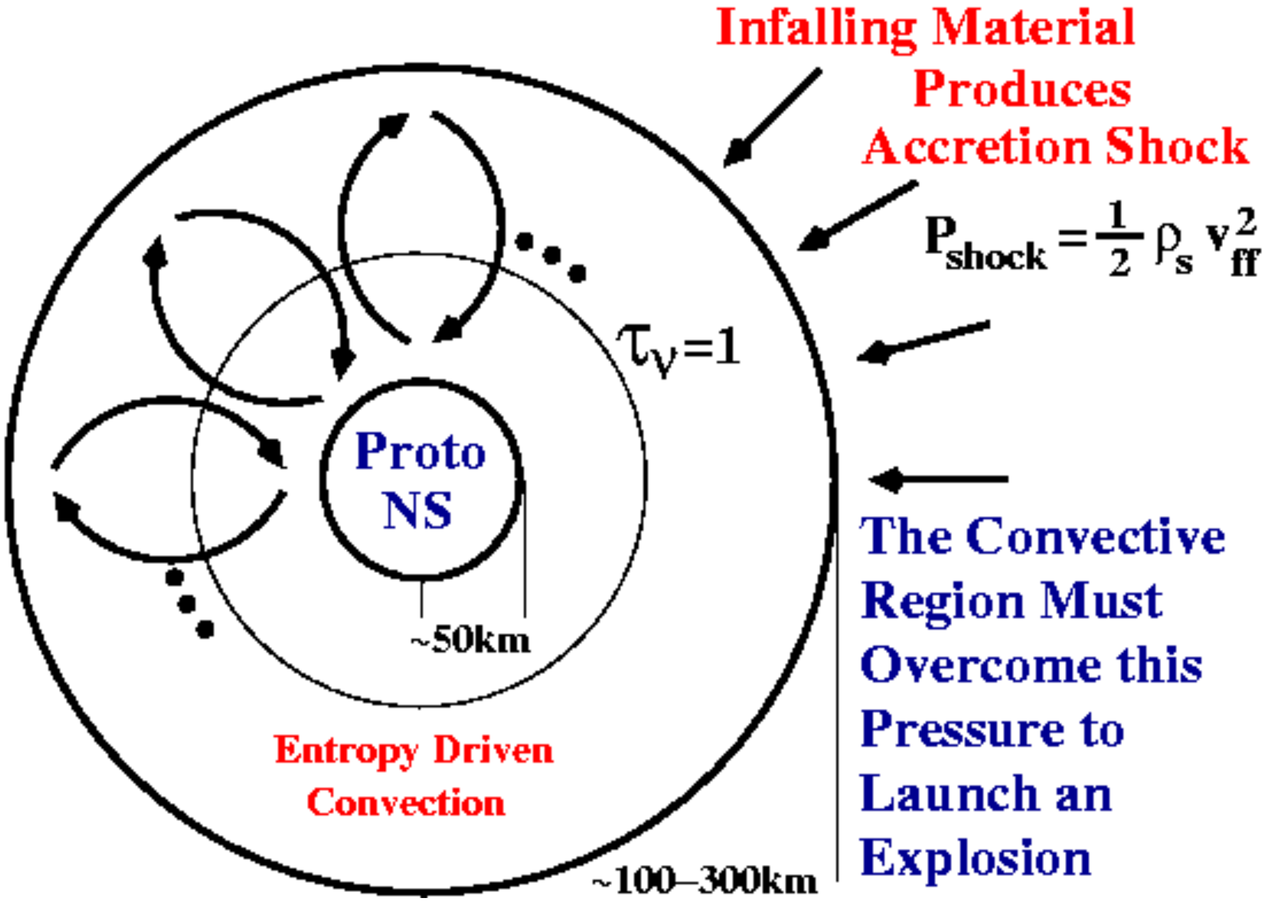
If strong magnetic fields form (and not buried) in a rapidly rotating neutron star, magnetar engines may also work.

Both magnetic field engines predict jet-like explosions.



Akiyama et al. 2003

Neutrino-Driven Supernova Mechanism: Convection



Infalling Material Produces Accretion Shock

$$P_{shock} = \frac{1}{2} \rho_s v_{ff}^2$$

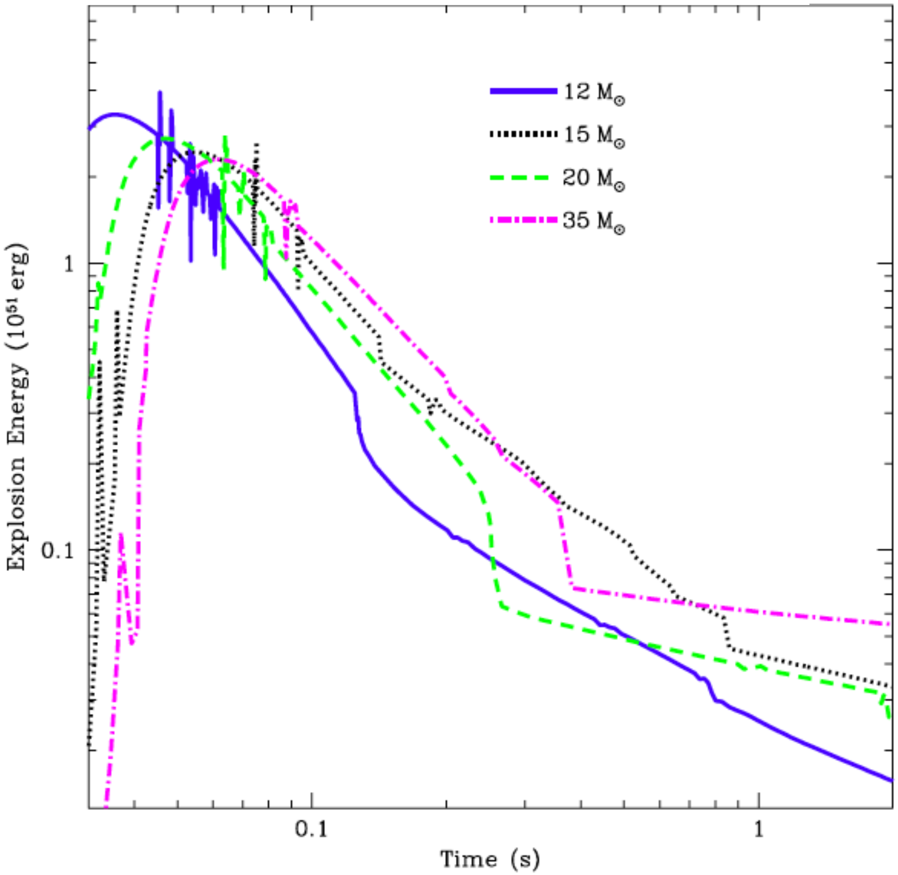
The Convective Region Must Overcome this Pressure to Launch an Explosion

Fryer 1999

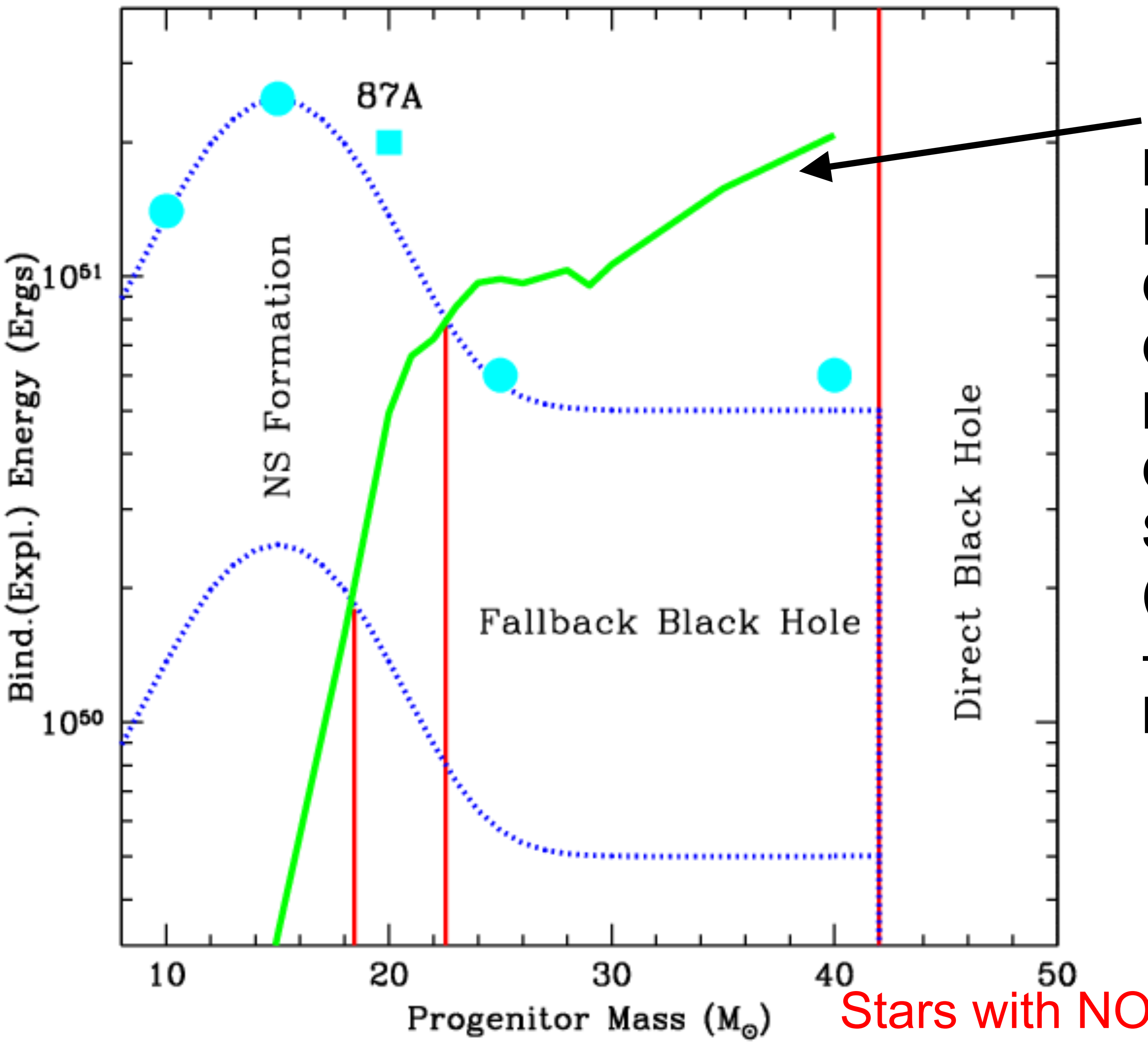
$$P_{\rm shock}(r) = 1/2\rho_{\rm shock} v_{\rm free-fall} = (2GM_{\rm NS})^{0.5}\dot{M}_{\rm acc}/(8\pi r_{\rm shock}^{2.5})$$

$$\begin{aligned} u_{\rm convection}(r) \;&=\; 3\left[4.7\times 10^{8}\frac{M_{\rm NS}}{M_{\odot}}\frac{10k_{\rm B}{\rm nucleon}^{-1}}{S_{\rm rad}}\left(\frac{10^{6}{\rm cm}}{r}-\frac{10^{6}{\rm cm}}{r_{\rm shock}}\right)+\right. \\ &\left. 1.2\times 10^{6}\left(\frac{M_{\rm NS}}{M_{\odot}}\frac{\dot{M}_{\rm acc}}{M_{\odot}{\rm s}^{-1}}\right)^{1/4}\left(\frac{2\times 10^{7}{\rm cm}}{r_{\rm shock}}\right)^{5/8}\right]^{4} {\rm erg\,cm}^{-3}. \end{aligned}$$

- For most stars, the maximum energy is a few times 10^{51} erg. Fallback can increase this value, but not by too much.
- This is a natural explanation for the energy, but it means that this engine can not explain hypernovae.



Fryer 1999

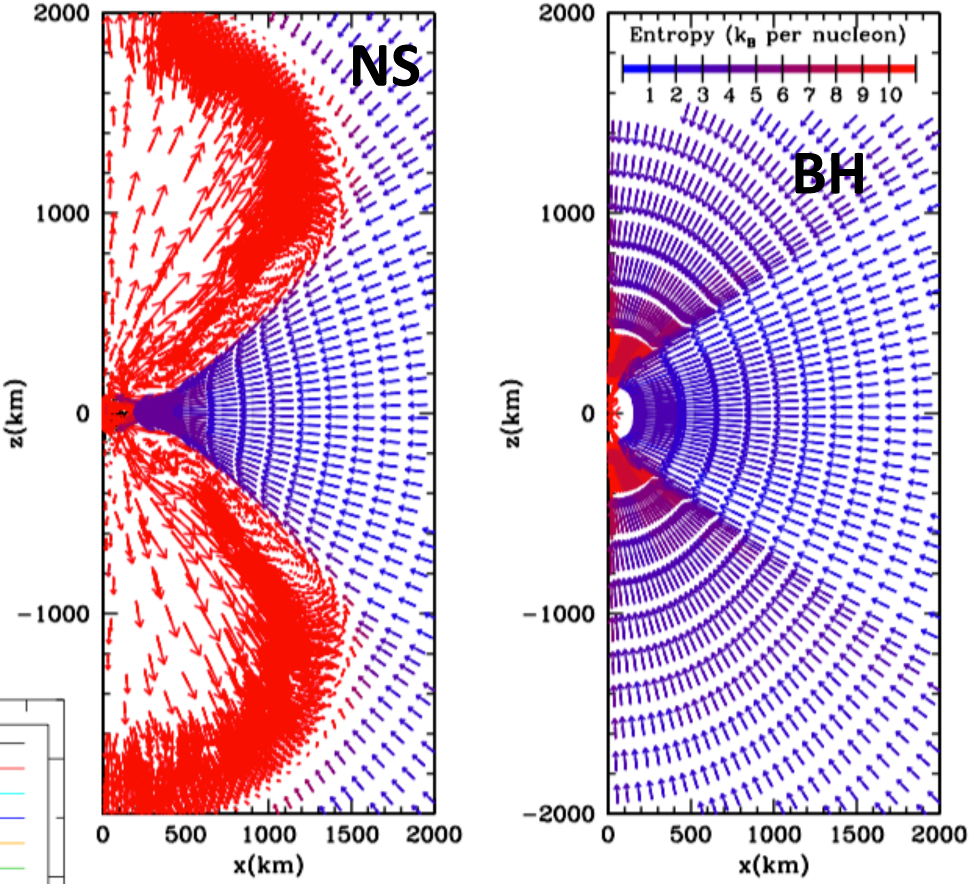


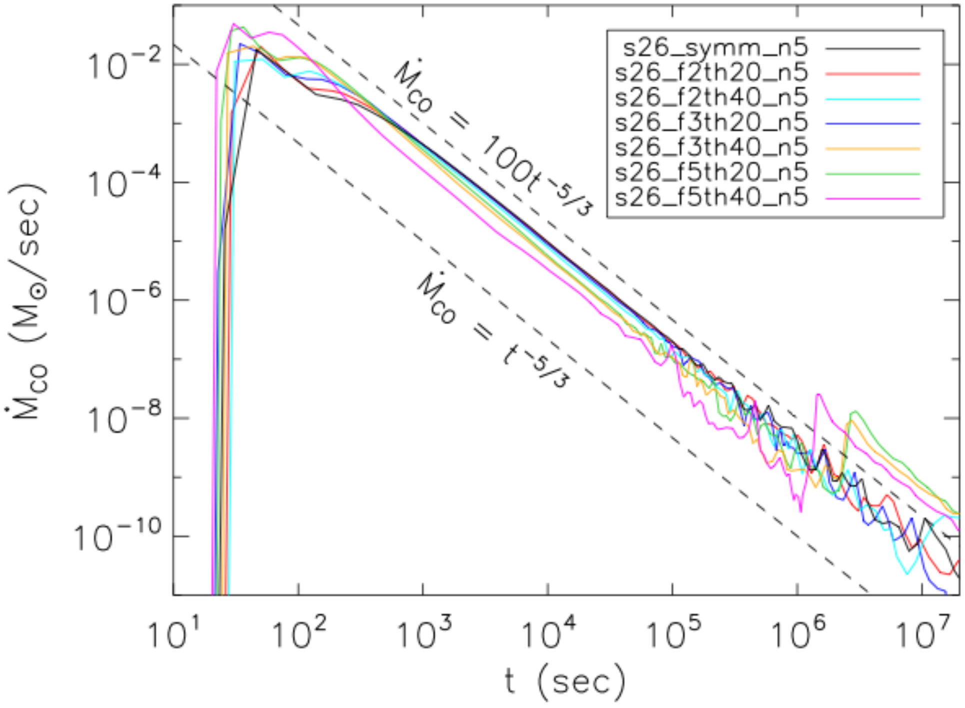
Binding
Energy
Of the
Outer
Layers
Of the
Star
(M_{star}
-3 solar
Masses)

Stars with NO mass-loss

Fallback rates

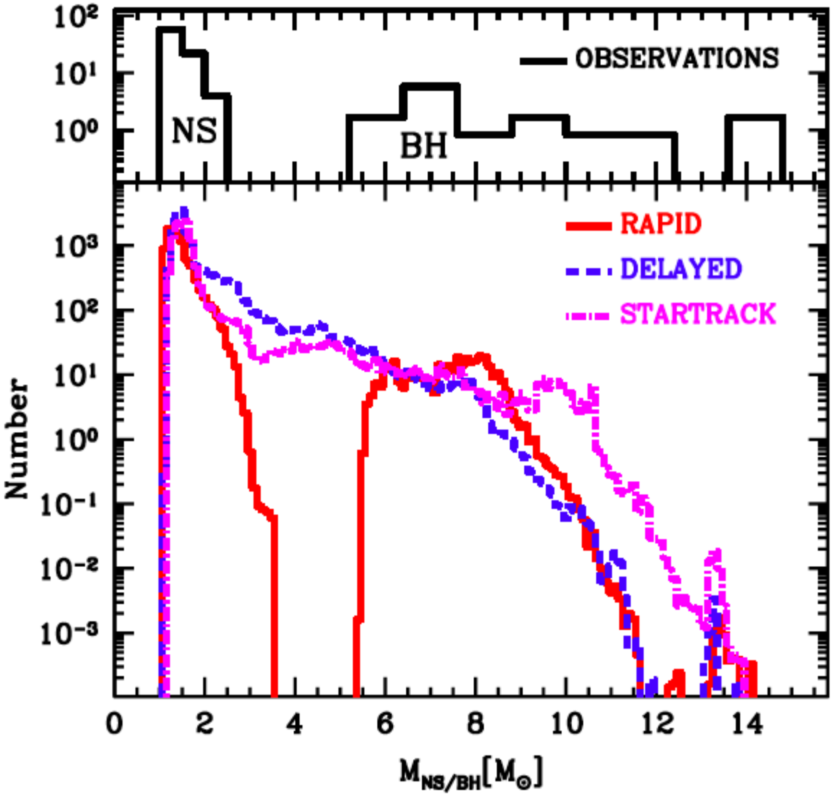
It is difficult to avoid fallback. Strong explosions have ~0.1 Msun of fallback. Weak explosions allow a range of fallback from 0.1+ Msun. Most happens at early times, but at the level of 10^{-4} Msun, this can happen even a year after the explosion.



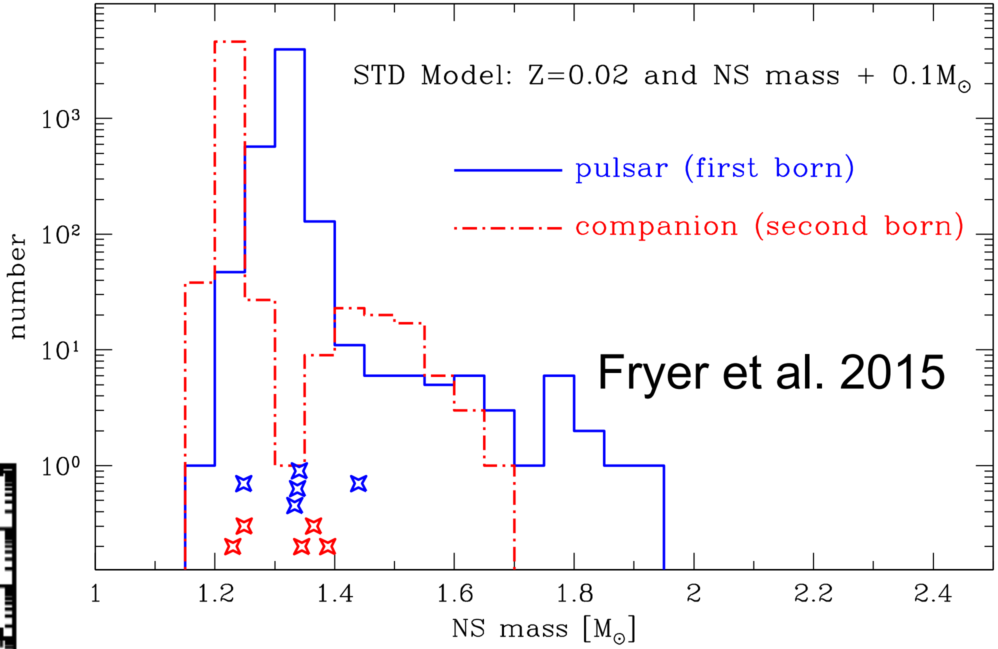


With rotation (even if not enough to form a disk), a significant fraction of the fallback can be re-ejected if the compact remnant is a neutron star.

Distribution of Neutron and Black Hole Masses



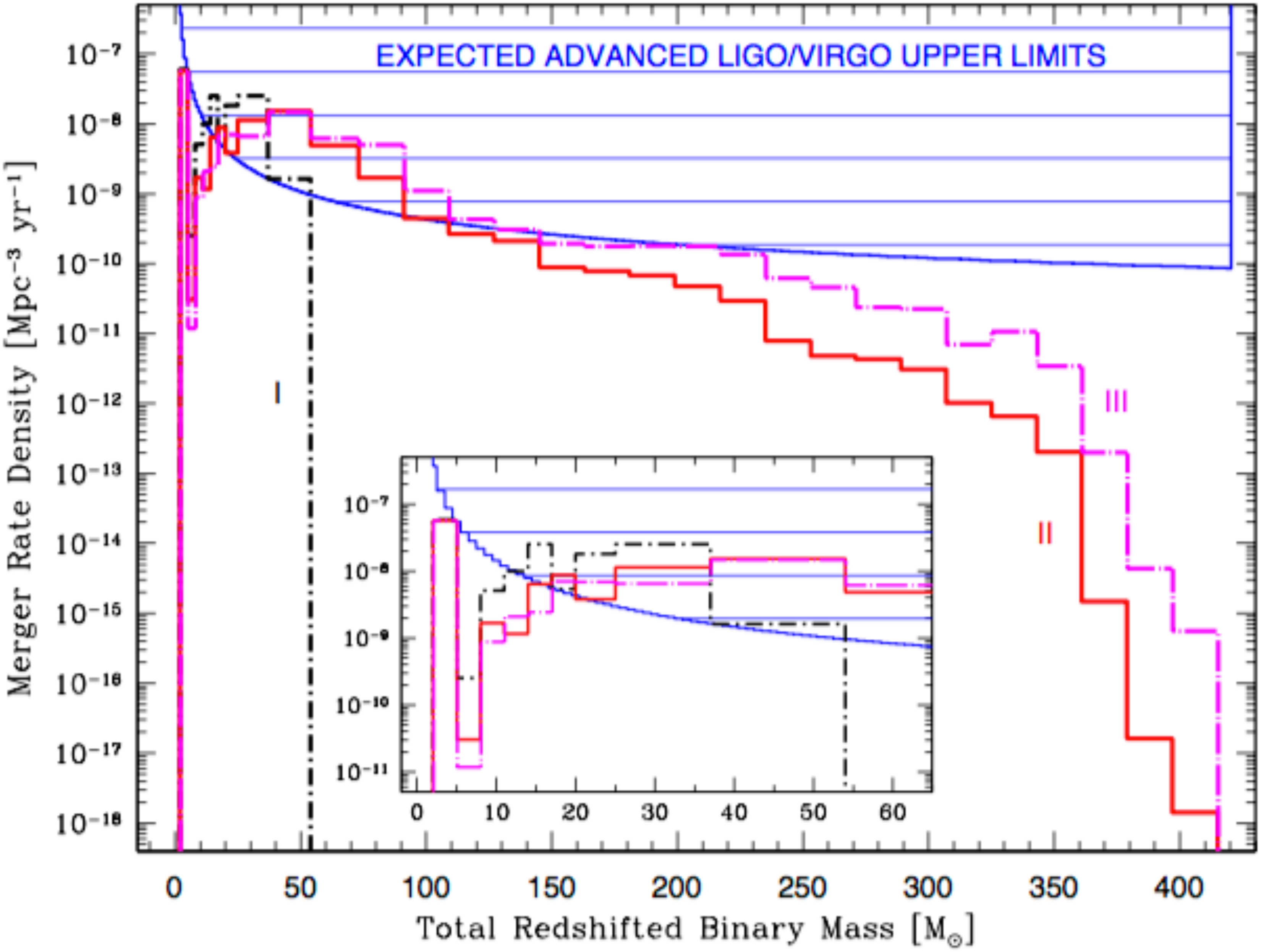
Belczynski 2012



Fryer et al. 2015

Both the NS-BH mass gap and the distribution of NSs must be fit by any explosion model. Since these masses have all evolved from close binaries, we must also include binary effects.

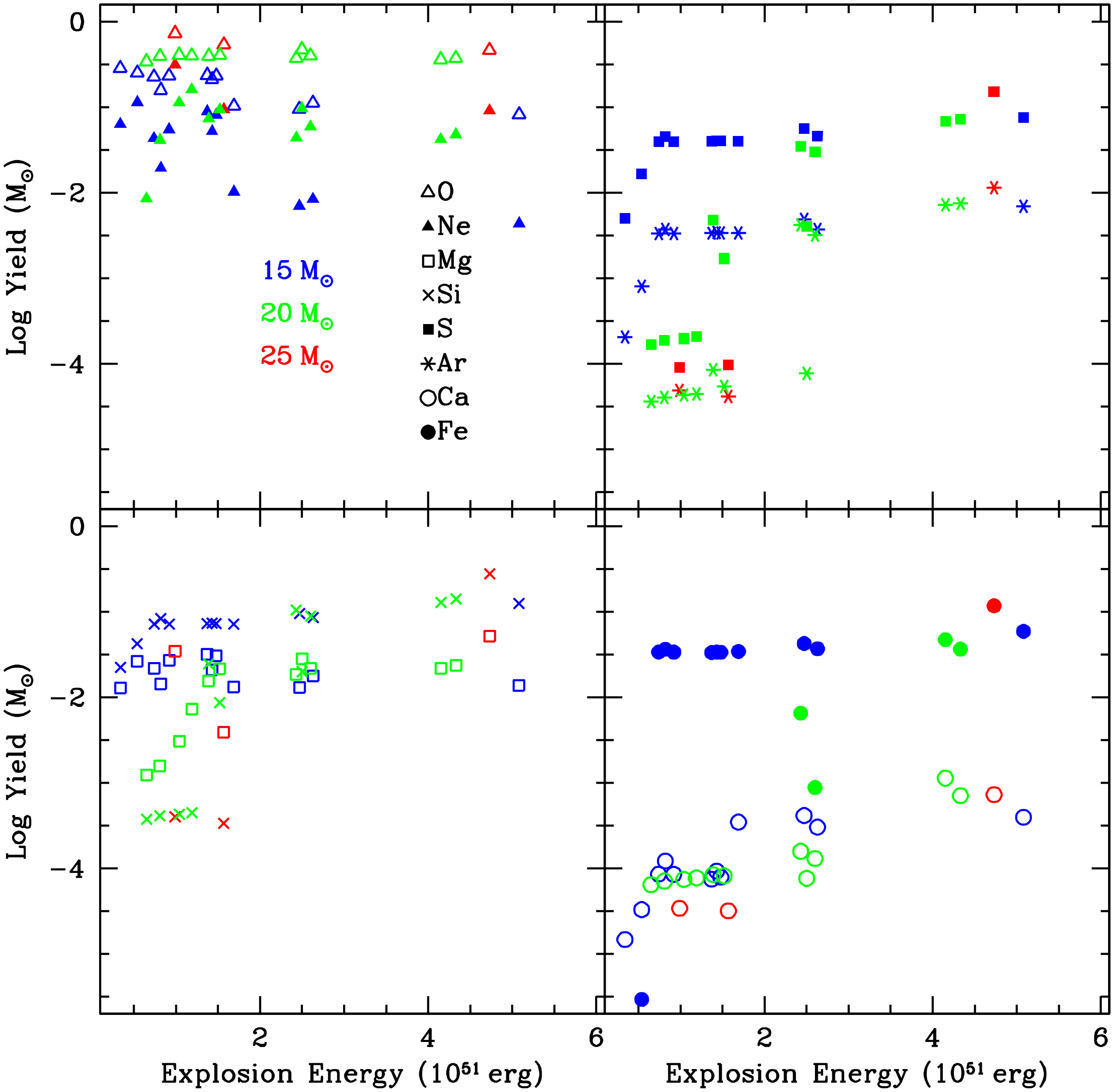
Belczynski et al. 2016



Yields

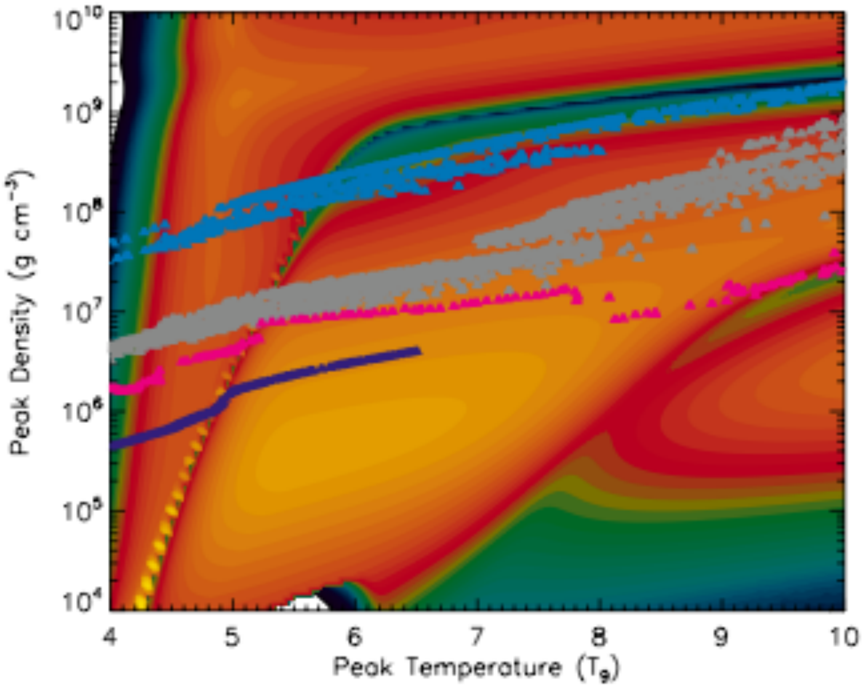
Supernova expel the yields made during stellar evolution. The supernova shock alters these yields, destroying some material and making others.

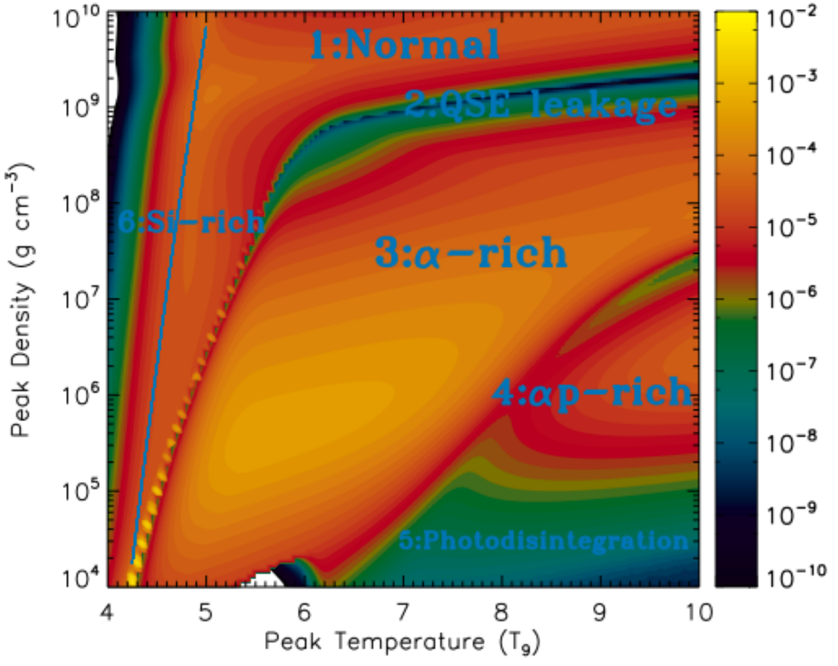
The elements made in the innermost ejecta are most sensitive to the amount of fallback.

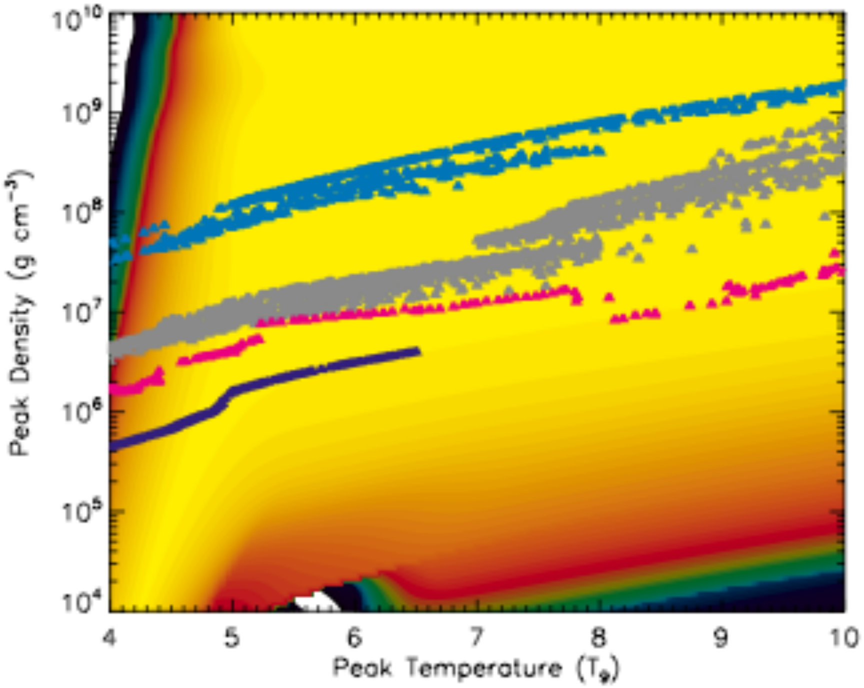


To understand mixing, we must compare elements produced at the engine to remnants, making this a turbulent burn problem.

Magkotsios et al. 2010 studied the ^{56}Ni and ^{44}Ti yields.

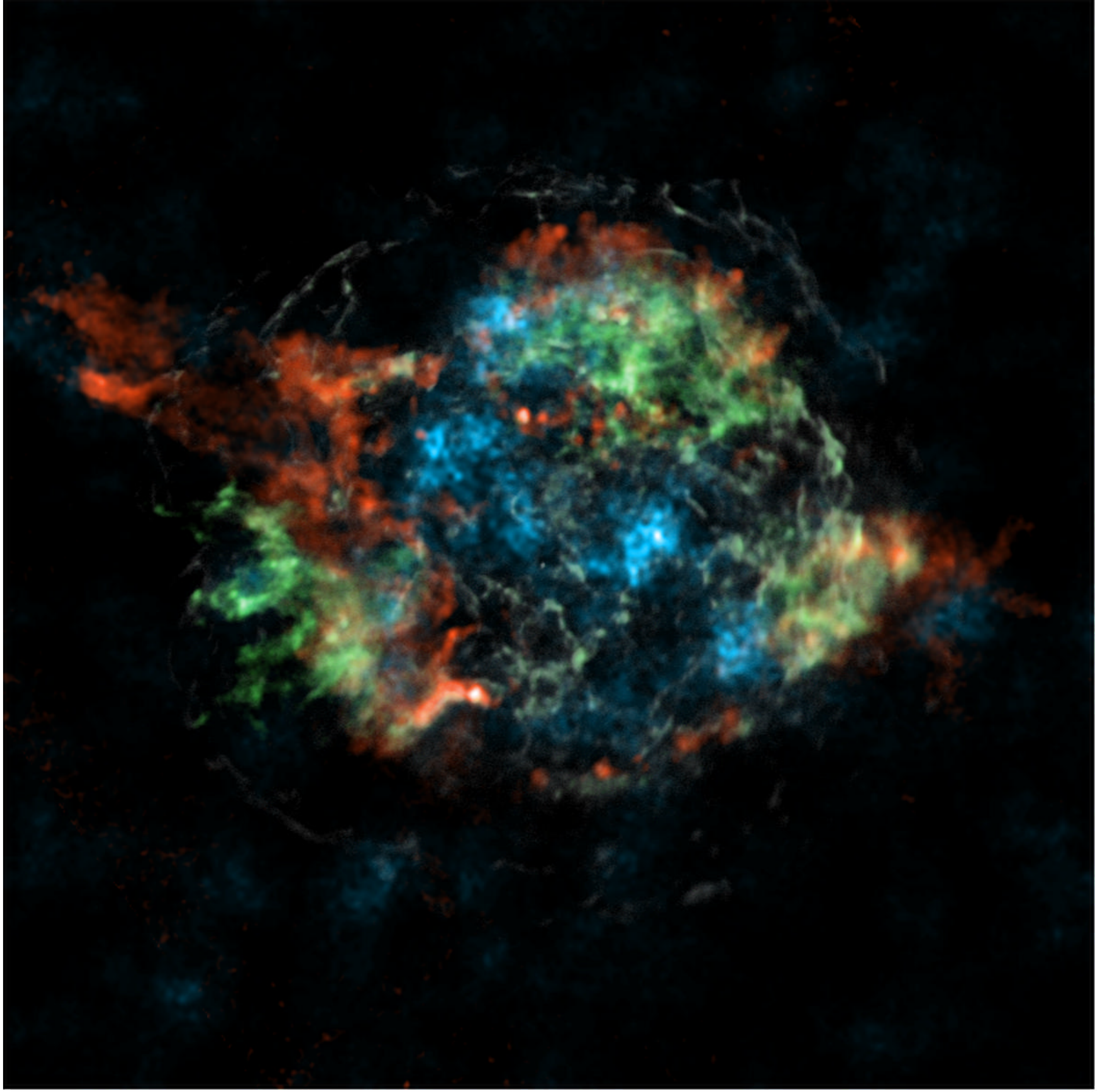






NuSTAR demonstrates low-mode convection in the engine (Greffenstette et al. 2014)

- ^{44}Ti is produced in the core (near the convective engine).
- Because NuSTAR detects the decay emission from ^{44}Ti, it provides a direct probe of the engine.
- The structure shows a low mode explosion.
- More on observations from Brian Grefenstette and simulations by Janka.



Conclusions

Convection-enhanced supernova engine explains many aspects of normal supernovae:

- near foe energies
- remnant mass range (yes, but model can predict a range of results)
- yields (but range predicted)
- generic asymmetries
- ^{44}Ti distribution in Cas A

Magnetic field models may explain:

- more energetic explosions (would require tuning to explain peak at ~foe energies)
- remnant masses (predictions?)
- yields (with turning)
- generic asymmetries
- Not Cas A