Neutrinos and the Supernova Engine

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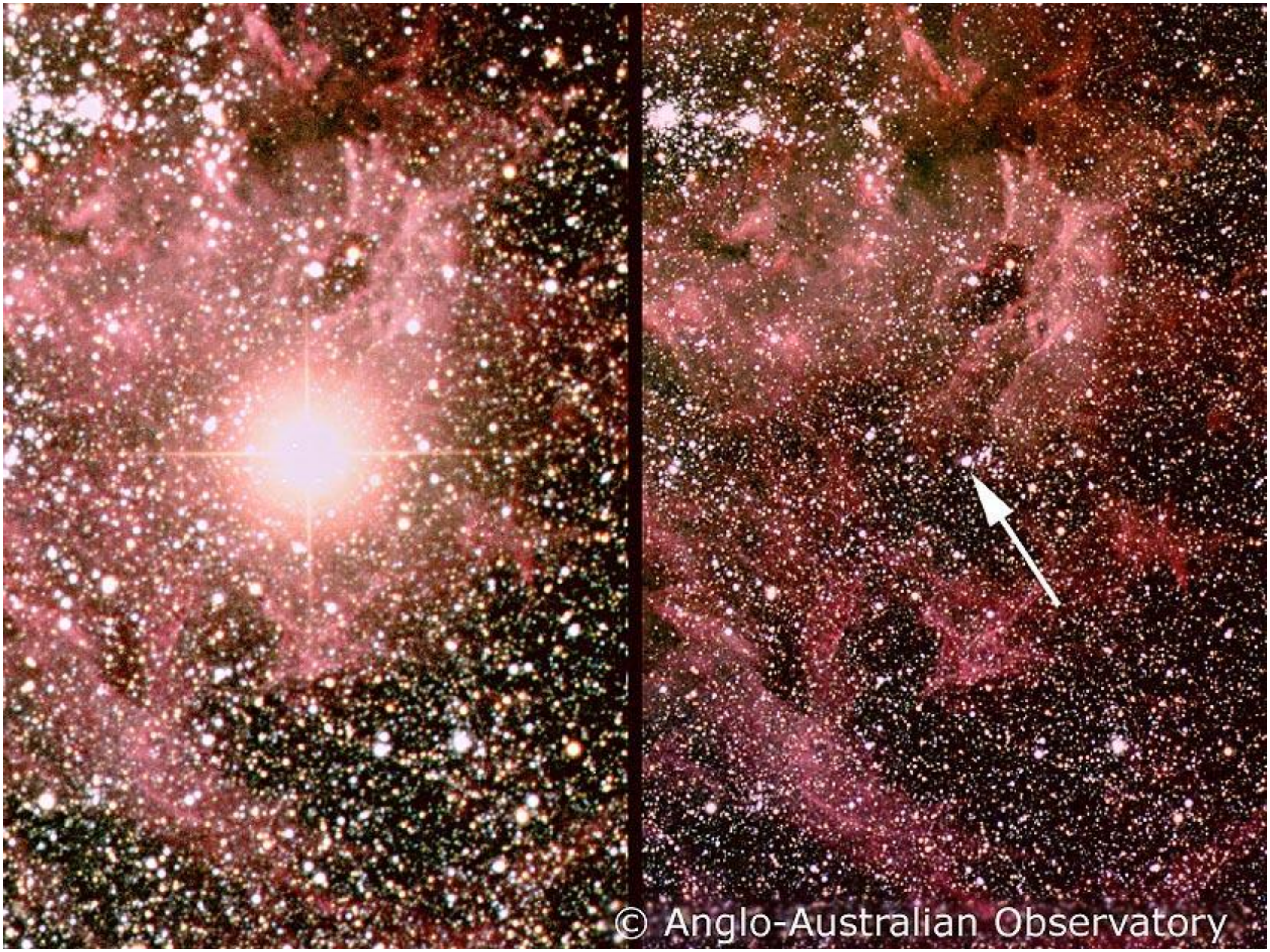
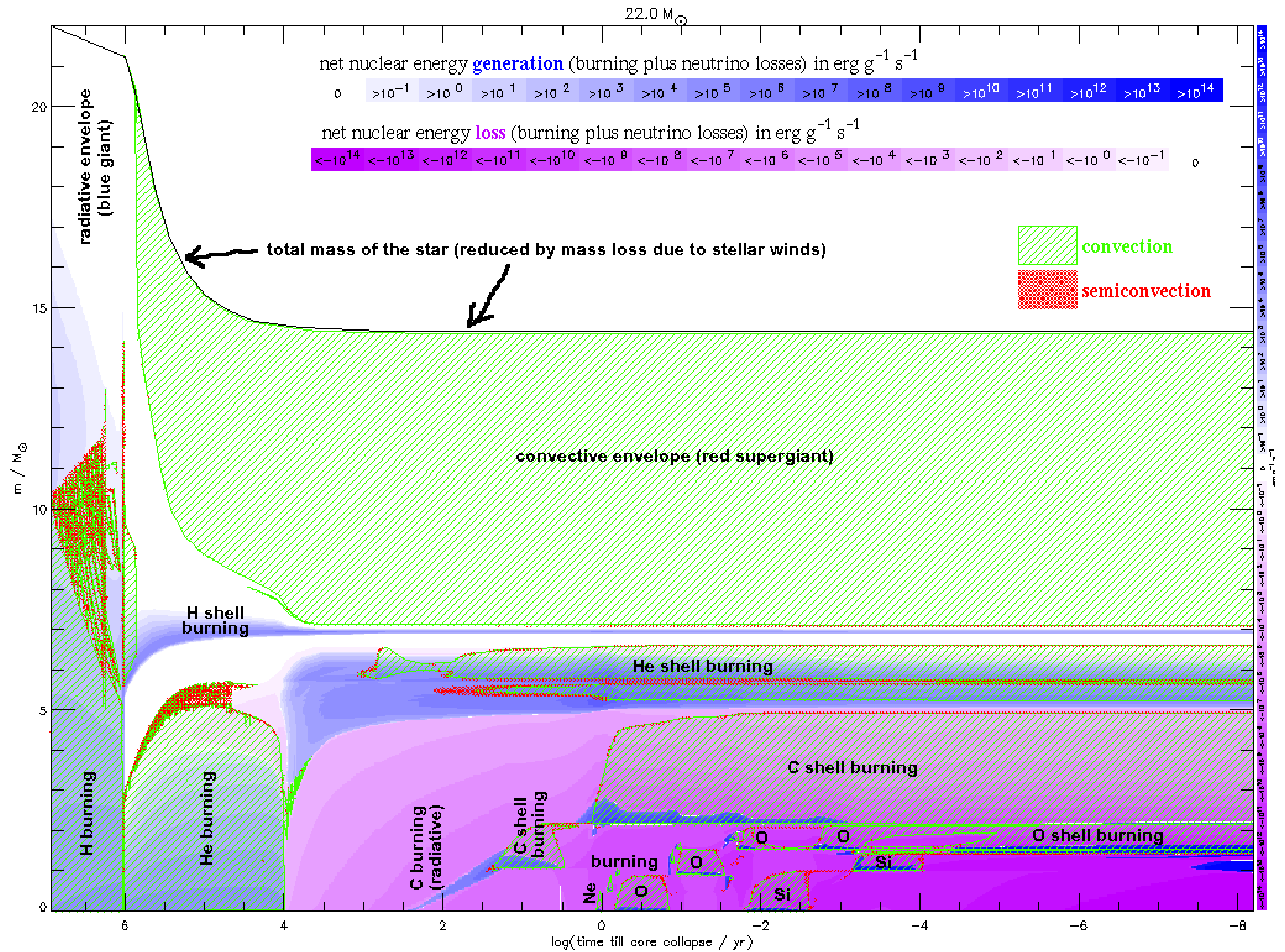
- Why we believe in the convective engine
  - Success AND Failure
  - Explosion Energies
  - Asymmetries
  - Remnants
- Neutrinos
  - explosion
  - nucleosynthesis
  - kicks
  - …

Supernova 1987A



After – SN 1987A

Before – Sanduleak -69 202



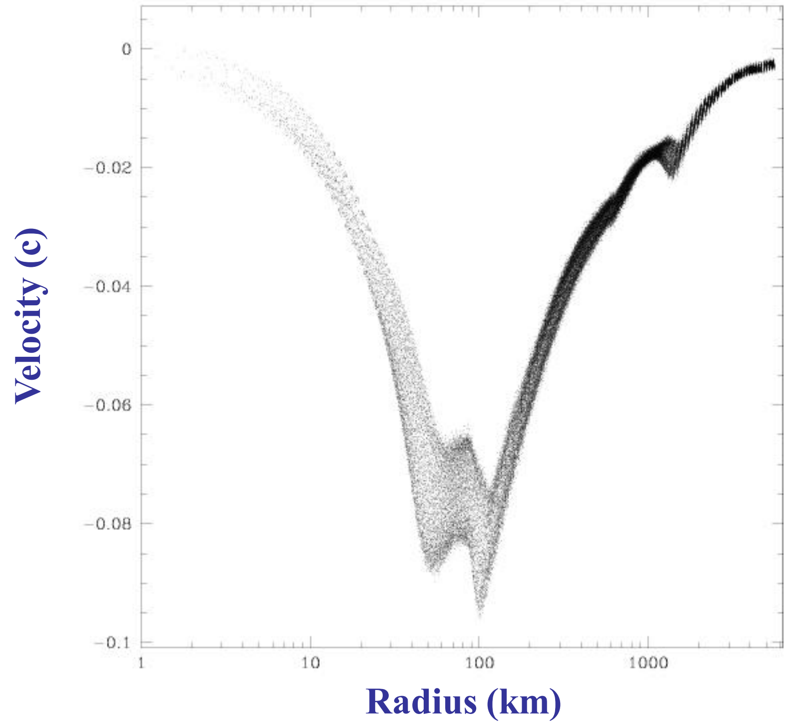
22.0 M⊙
net nuclear energy generation (burning plus neutrino losses) in erg g^-1 s^-1
net nuclear energy loss (burning plus neutrino losses) in erg g^-1 s^-1
convection
semiconvection
total mass of the star (reduced by mass loss due to stellar winds)
radiative envelope (blue giant)
convective envelope (red supergiant)
H shell burning
He shell burning
C shell burning
O shell burning
H burning
He burning
C burning (radiative)
C shell burning
Ne burning
O
O
O
O
Si
Si
m / M⊙
log(time till core collapse / yr)

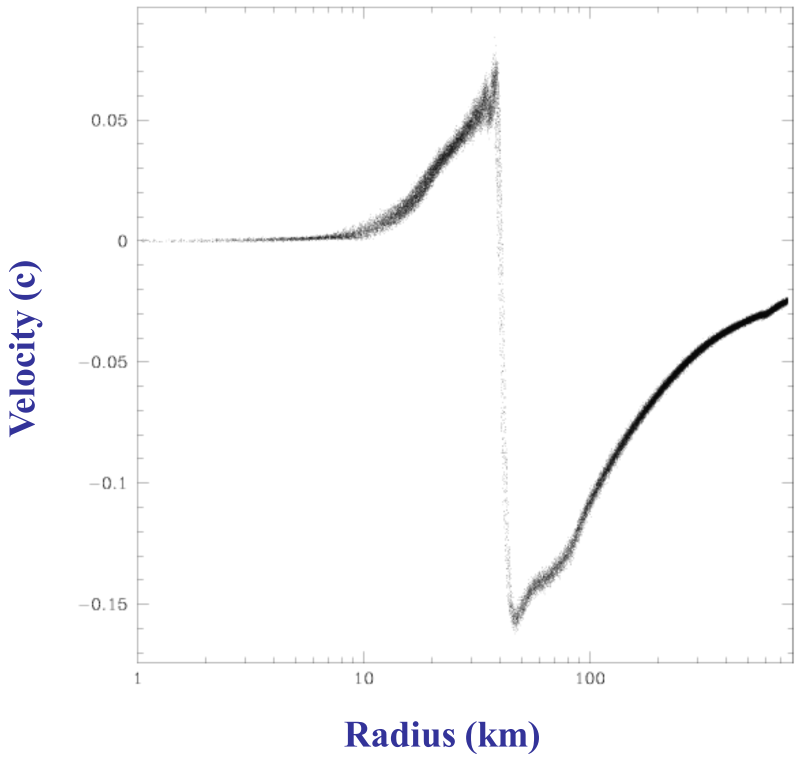
Neutrino-Driven Supernova Mechanism

Temperature and Density of the Core Becomes so High that:

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

Core collapses nearly at freefall!



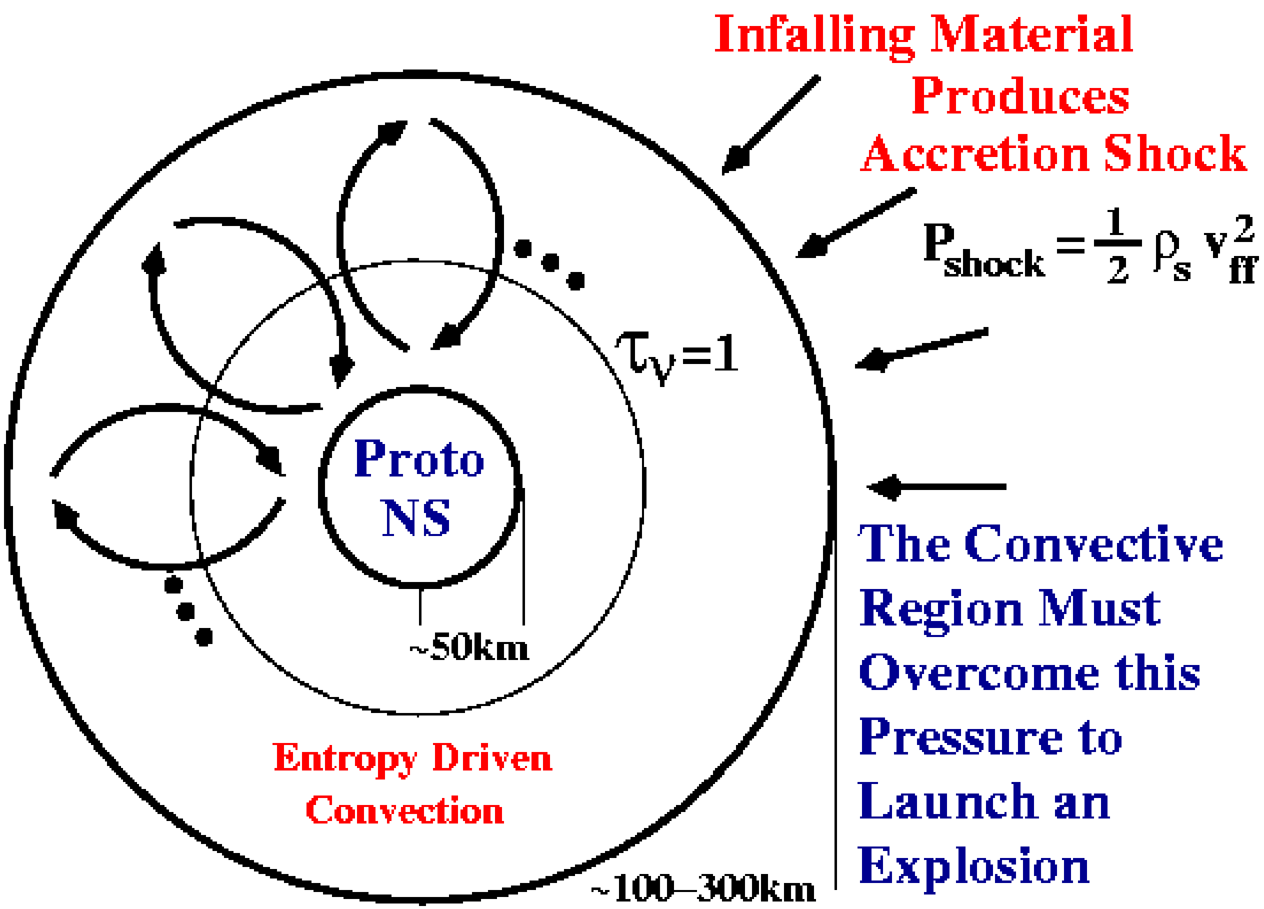


Core reaches nuclear densities

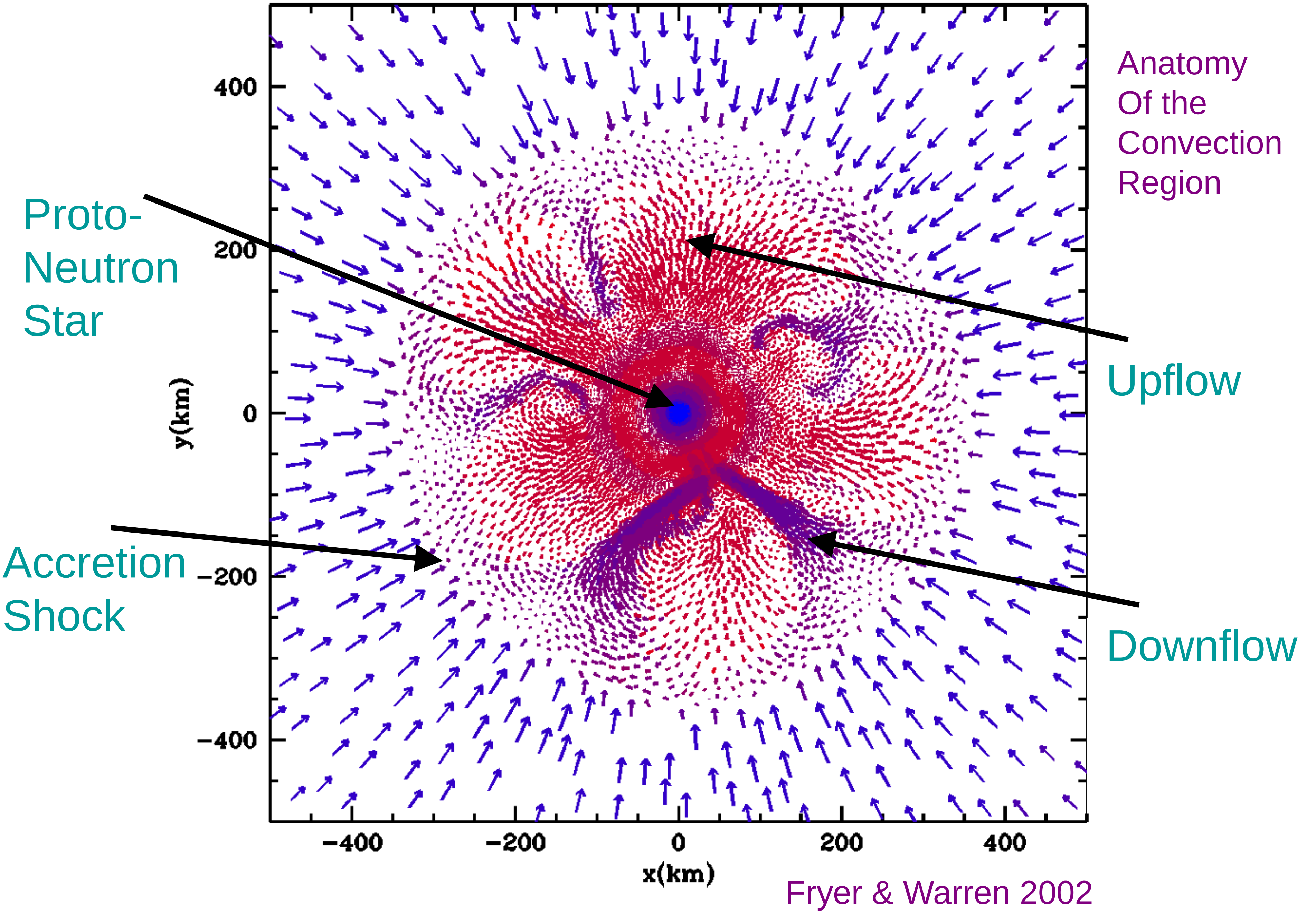
Nuclear forces and neutron degeneracy increase pressure

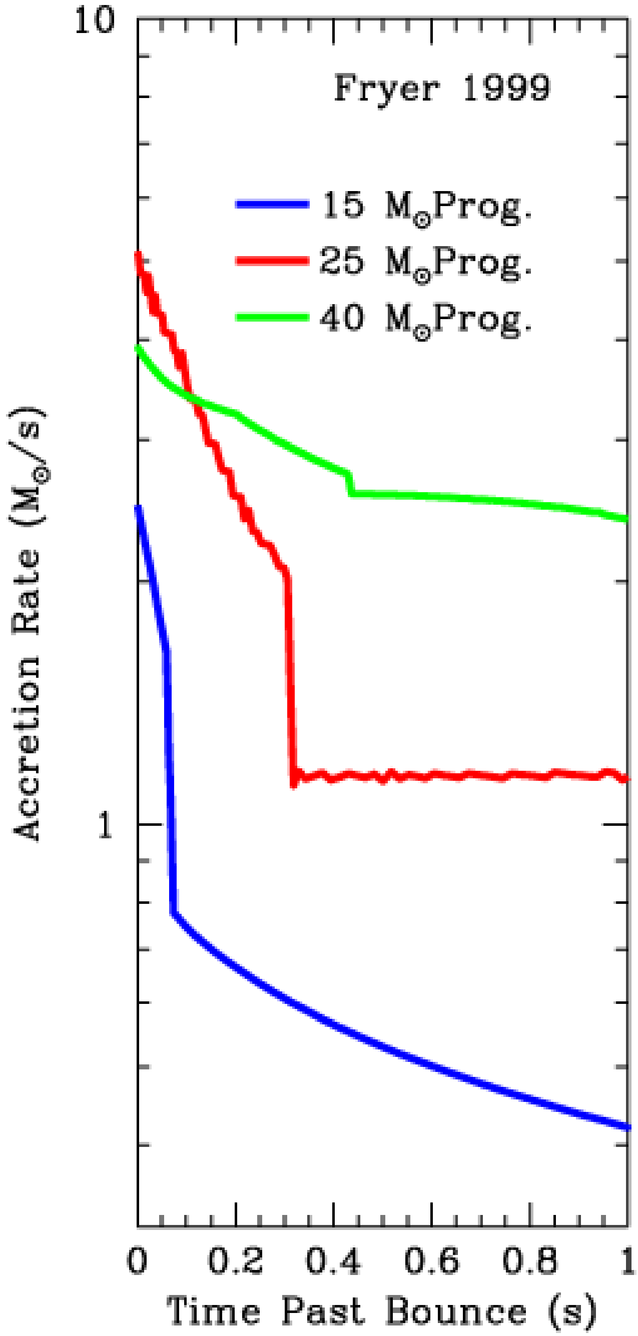
Bounce!

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)
−400
−200
0
200
400
x(km)
Fryer & Warren 2002



$$P_{Shock} \approx \frac{1}{2}\rho v_{ff}^2$$

$$\approx \frac{(2GM_{encl})^{1/2}}{8\pi R_S^{2.5}}\dot{M}_S$$

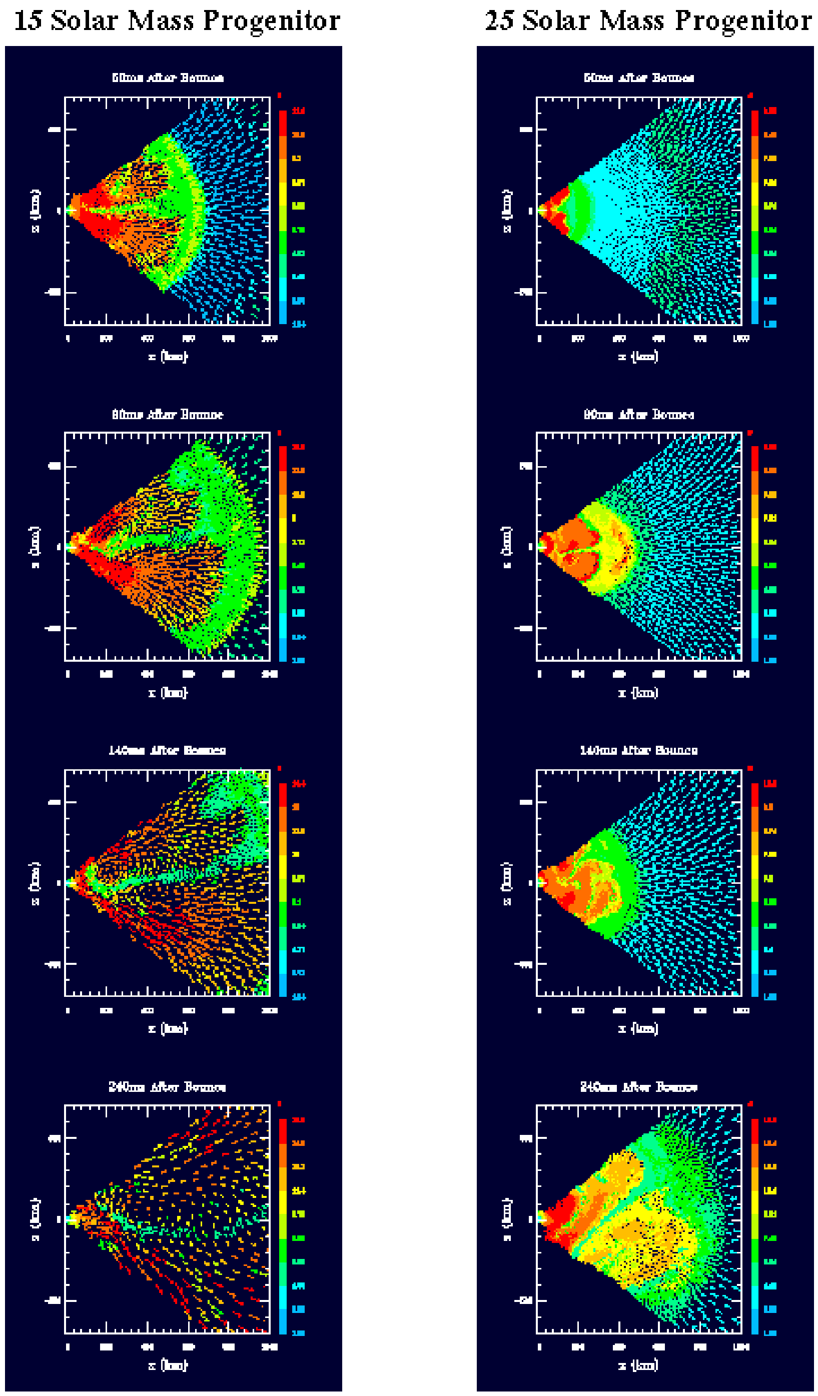
Massive Stars Have Higher Infall Rates →Requires More Energy To Explode

Burrows & Goshy 1993

As the accretion rate from infall decreases, the pressure at the "lid" decreases, making an explosion more likely.

The Sensitive Supernova Engine

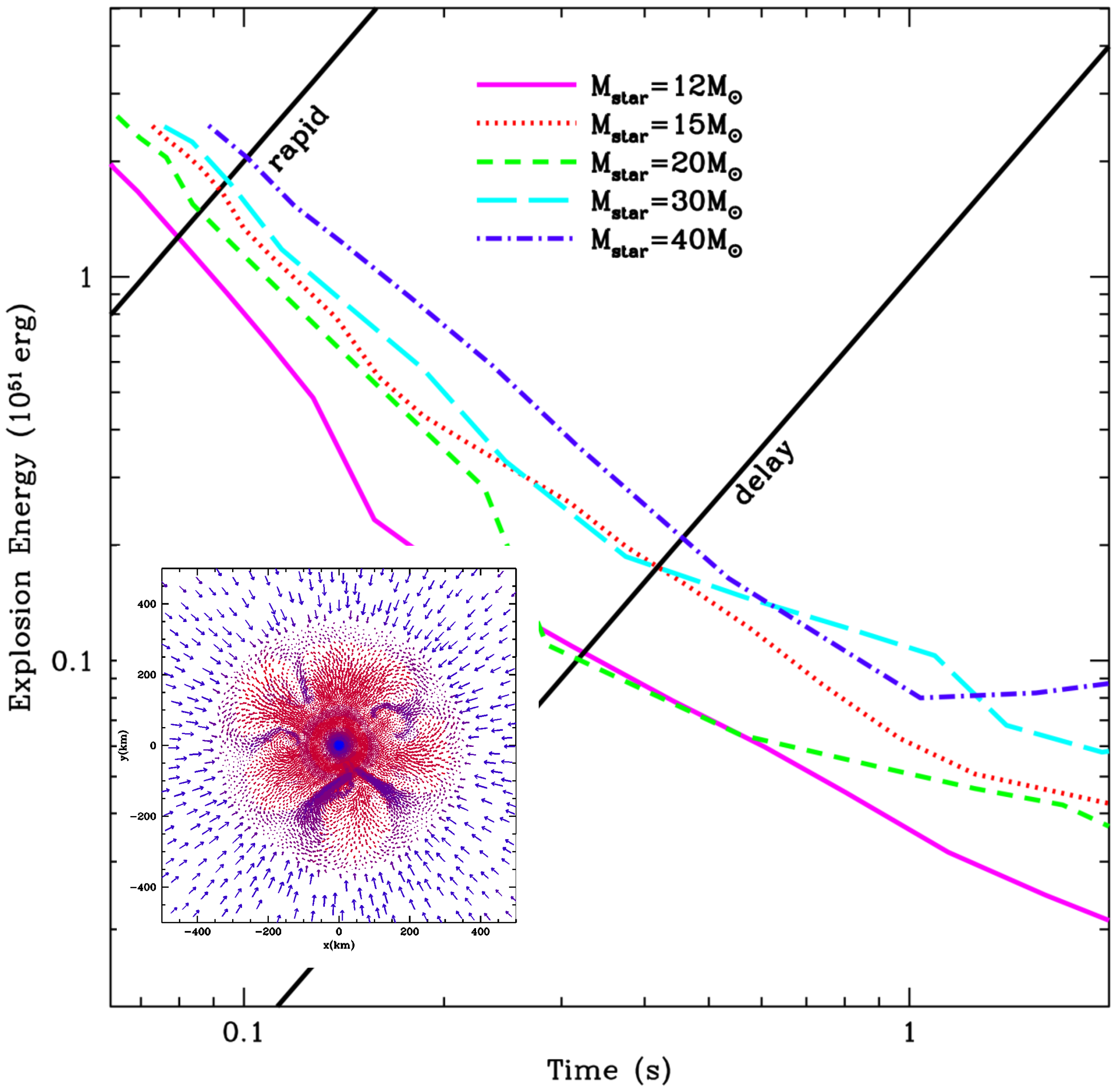
• Although most stellar collapses produce supernovae, 10-40% produce weak or no explosions, despite the fact that the cores don't look all that different.
• Stellar cores are not so different. If they aren't very different, than the explosion mechanism must be sensitive to details such that we are on the cliff between success and failure.
•However, there is a trend. More massive stars tend to have slower starts and take longer to explode.



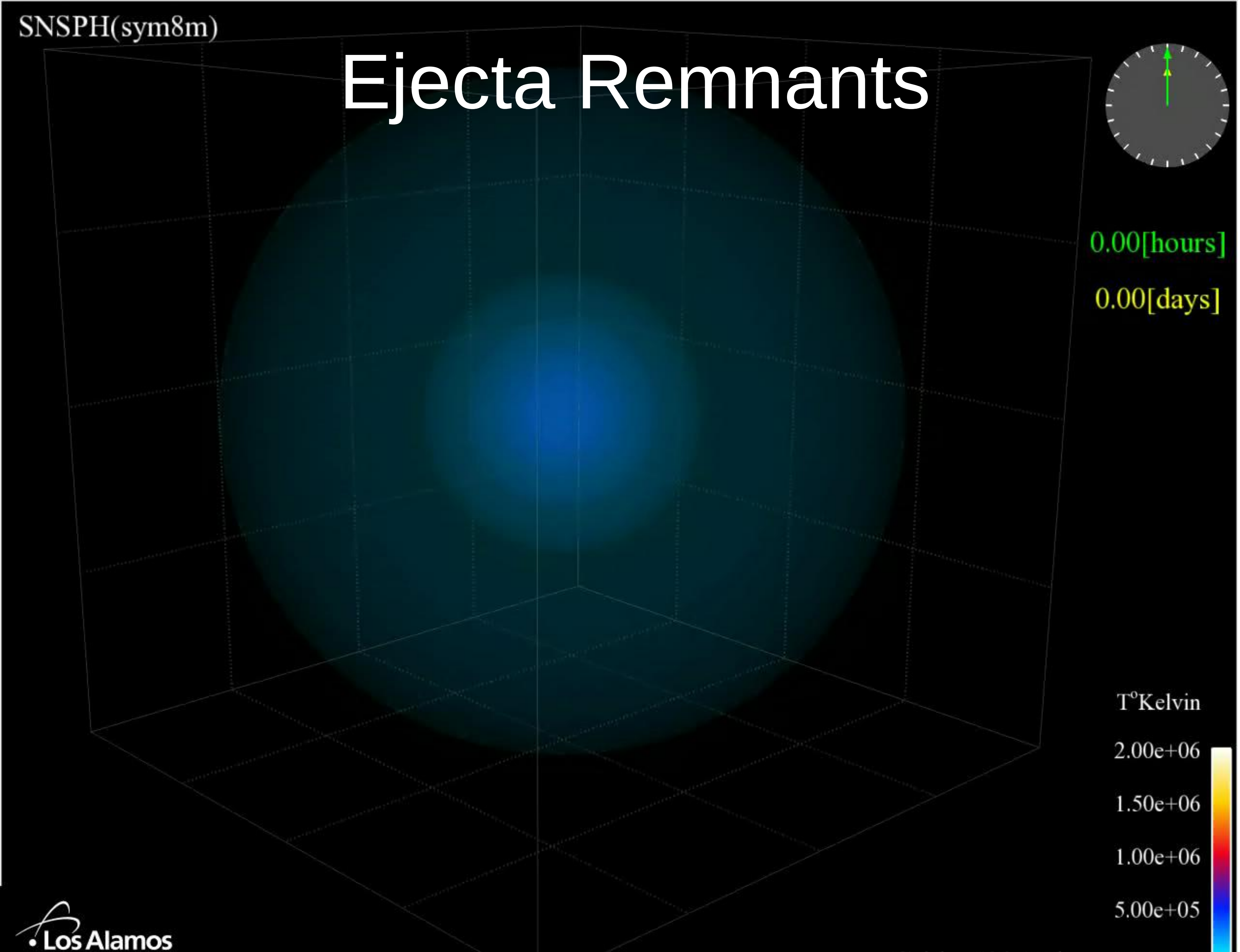
Supernova Energies

The collapse of the core releases ~10^{53}erg of potential energy. And yet, supernovae are ~10^{51}erg. Any supernova mechanism must explain this low efficiency (stellar collapse also produce hypernovae which are more efficient).

In this convective mechanism, the energy is roughly equal to the energy stored in the convective region, determined by the "lid" produced by infalling material. Because it decreases with time, the maximum energy also decreases with time, peaking at a few times 10^{51} erg at early times.

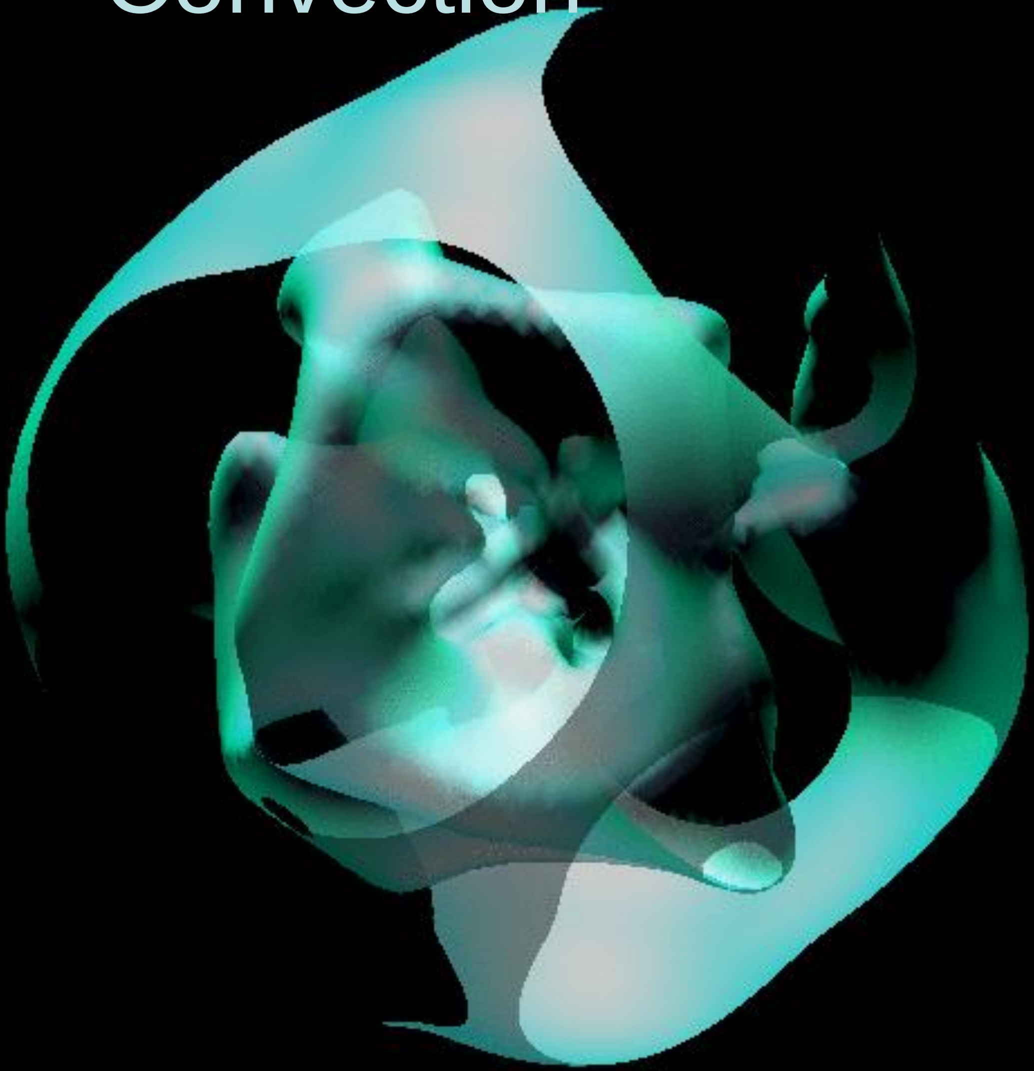


Ejecta Remnants



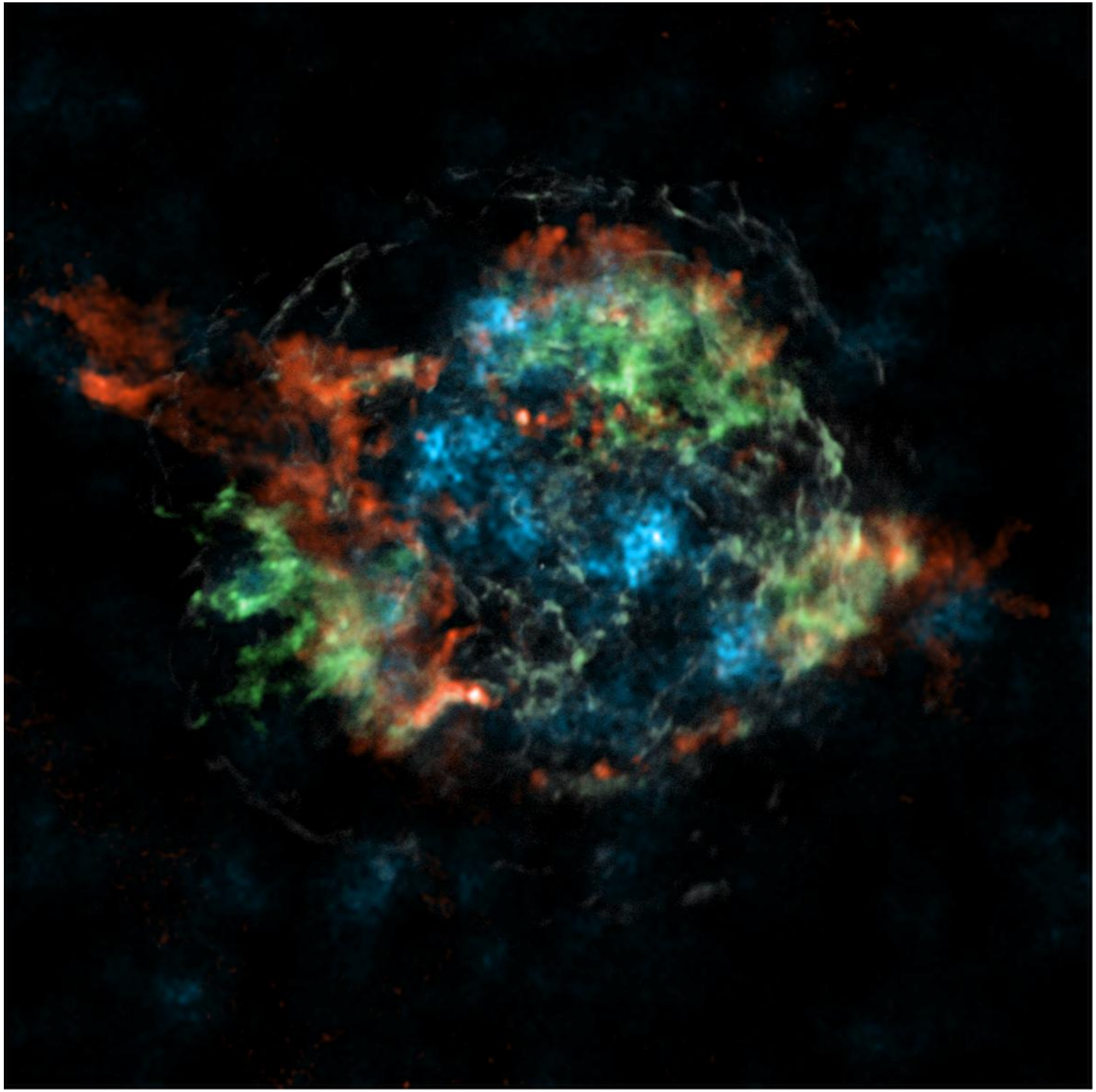
Ejecta Remnants – Probing Low Mode Convection

- In most simulations, low mode convection driven by Rayleigh-Taylor or advective-acoustic instabilities seem to dominate the flows.
- Although this has dominated the focus of theorists for nearly 20 years, until recently, we had no evidence of such flows.



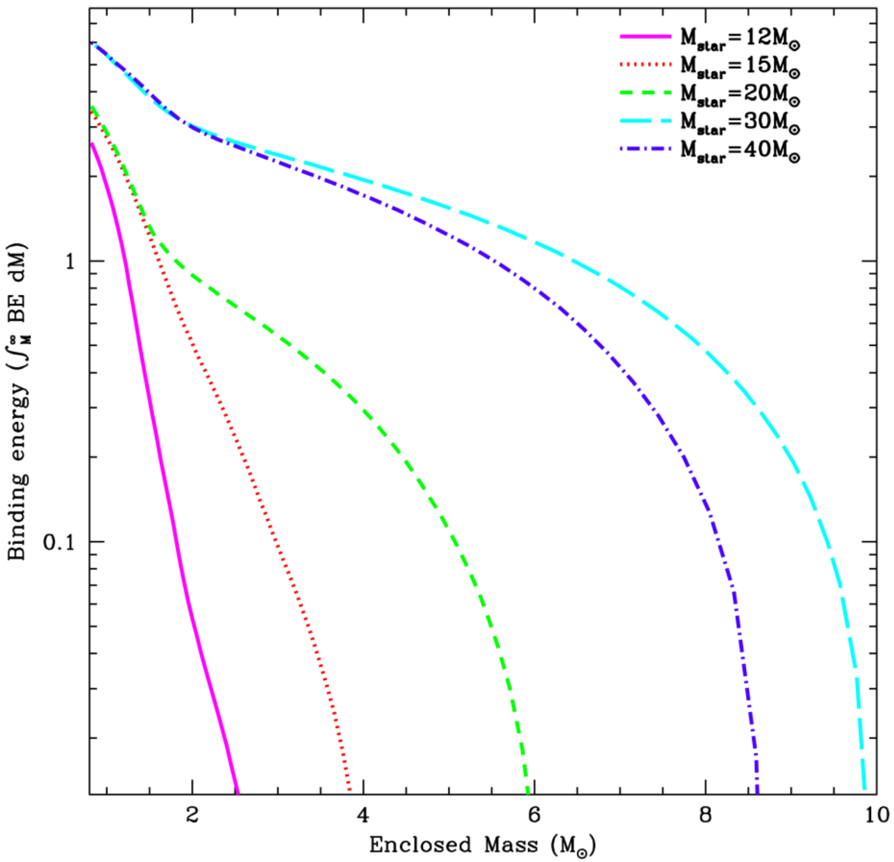
NuSTAR has provided a new window in the supernova mechanism

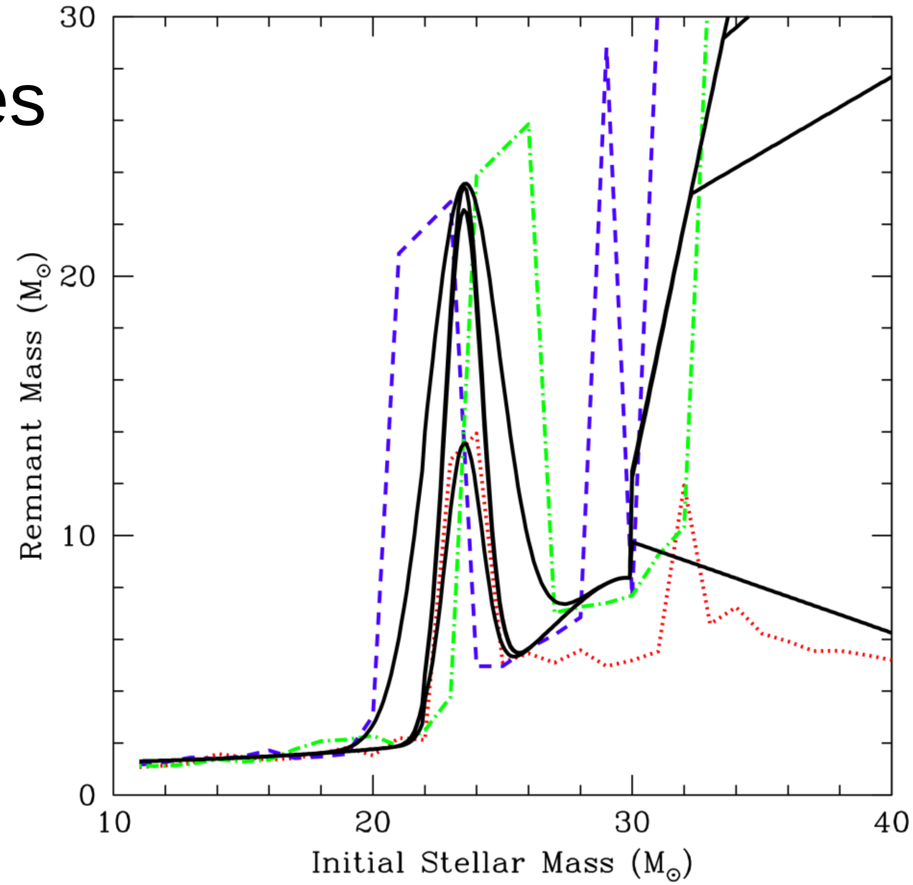
Greffenstette et al. 2014



Compact Remnant Masses

Although the cores between different progenitors are not so different, the binding energy of stars increases dramatically with mass.

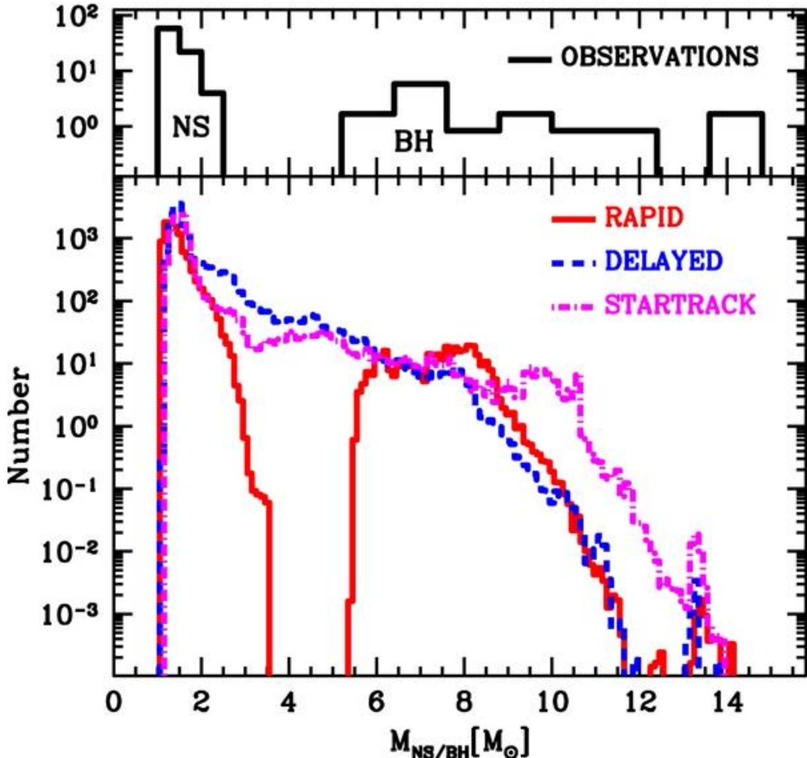




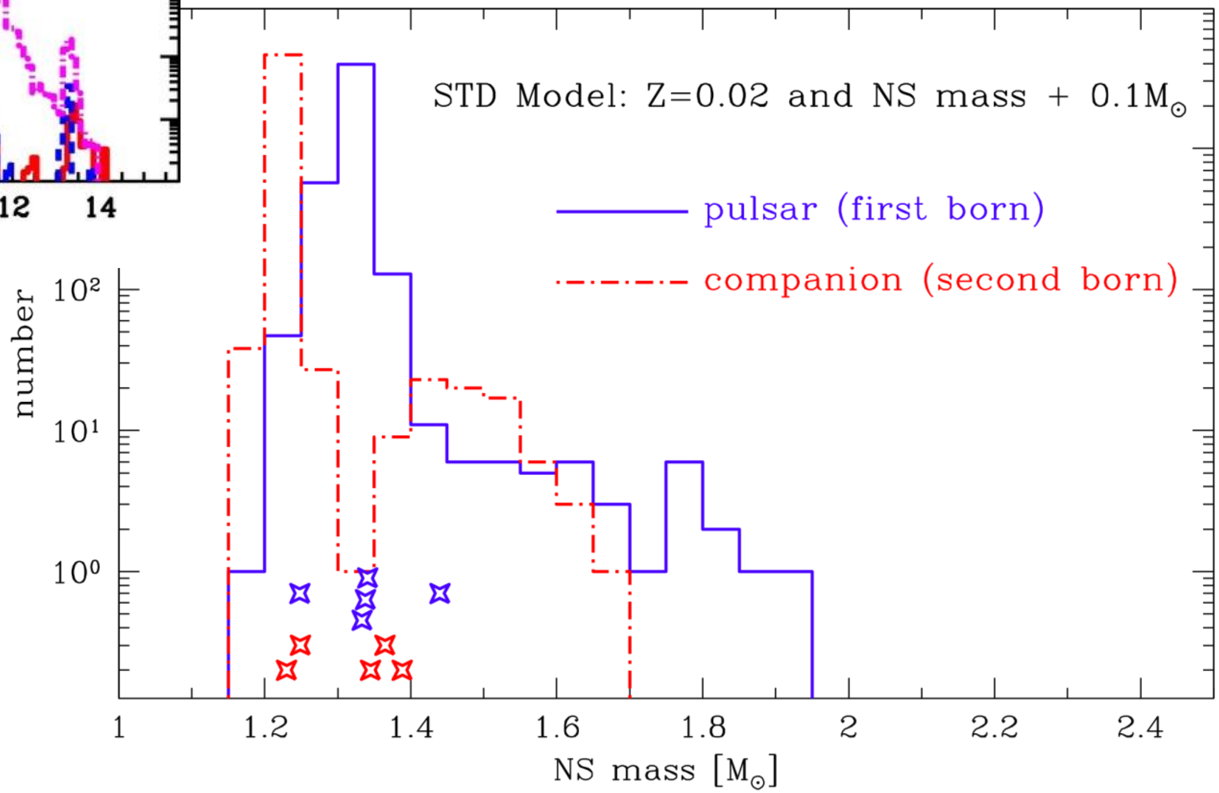
Assuming the explosion energy goes into ejecting the outer layers first, we can estimate the final remnant mass.

Progenitor models dominate the errors in this analysis.

Distribution of BNS Masses



If the gap in remnants between 2 and 4 solar masses is real, it is unlikely that fallback is that common. Although we do not believe this is a binary selection effects, observational selection effects may persist.



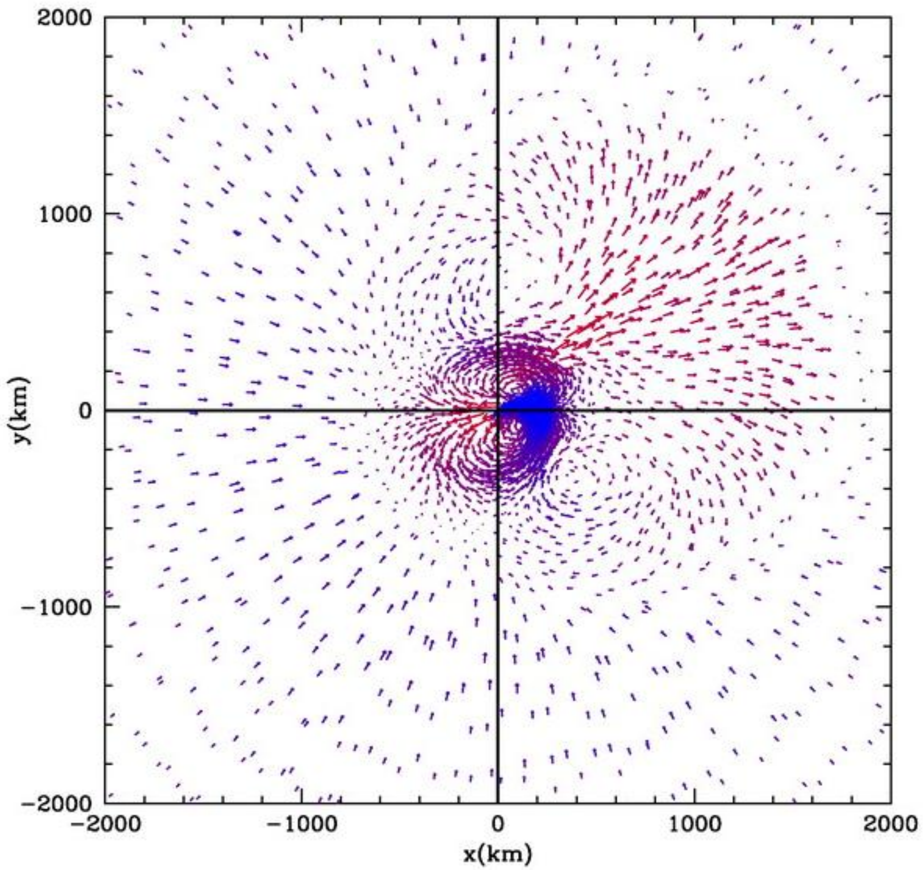
Advanced LIGO can dramatically increase the number of compact masses, allowing us to probe this mass distribution in more detail.

Role of Neutrinos

- Because we are on a cliff, changing aspects of the neutrinos (e.g. cross-sections, oscillations) can play a role in the explosion. But other uncertainties make this a difficult issue to study.
- Neutrinos do play an important role in determining the electron fraction (or neutron richness) of the ejecta. This can play an important role in the nucleosynthesis.
- Neutrinos could explain the proper motions observed neutron star and black hole populations.
- Neutrino cooling an important probe of the neutron star equation of state.

Pulsar Kicks

- Neutron stars AND black holes have been observed with high spatial velocities.
- In general, these kicks are assumed to be produced by asymmetries in the supernova ejecta.
- However, a number of kick mechanisms have been proposed invoking asymmetric neutrino emission, most requiring strong magnetic fields.
- The neutrino mechanism could work equally well in systems that form black holes, not the case for ejecta mechanisms.



Kusenko and collaborators invoke asymmetric neutrino emission in strong magnetic fields in the proto-neutron star. Oscillations to sterile neutrinos allow this asymmetry to escape, preserving the asymmetry. The kick may be in the same direction as the ejecta asymmetry.

Summary

- Evidence is growing that the convective engine (most likely driven by neutrino heating) is at the heart of most normal supernovae.
- As such, neutrinos will play a role in many aspects of supernovae: explosion energy, nucleosynthesis, kicks, …