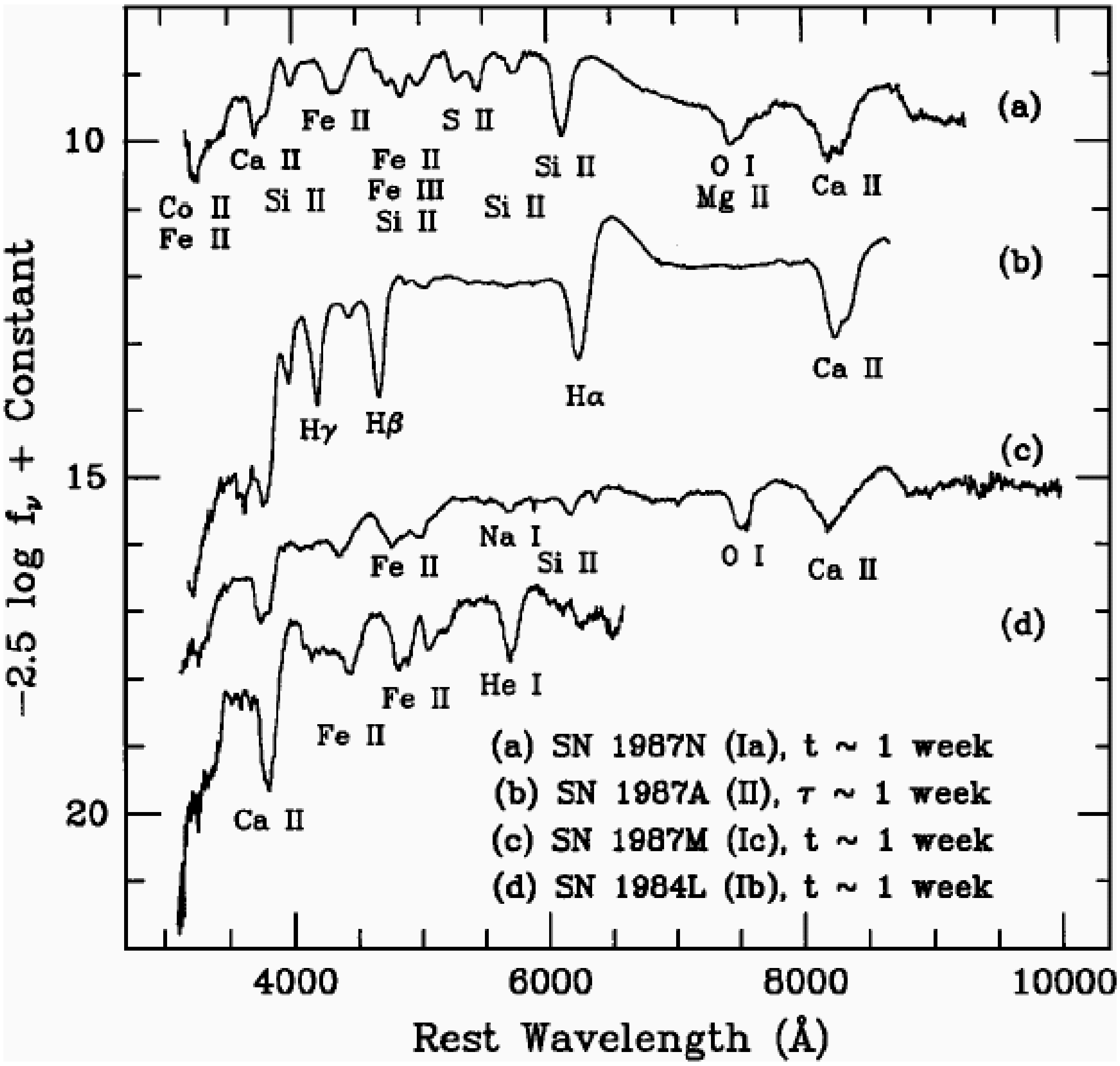
Type II supernovae

Spectroscopic classification reviewd by Fillipenko (1997):



- Type I: defined by absence of hydrogen in spectrum.
- Type II: hydrogen present.

Type I SN are further subdivided according to,

- Si II line at 615 nm – defining attribute of Type Ia.
- He I is present in Type Ib but not Type Ic.

Type II SN and Type Ib / Ic SN have never been seen in elliptical galaxies, and are typically in or near spiral arms / HII regions.

Implies association with massive star formation.

Thought to represent core collapse of stars with $M > 8M_\odot$. Distinction between Type II and Ib / Ic probably that the latter have lost their hydrogen envelopes via mass transfer or winds prior to explosion.

Energetics of all types of the order of 10^{51} erg.

Main stages in core collapse SN,

(1) Formation of an iron core, which grows until it exceeds the Chandrasekhar mass.

(2) Collapse of the core, assisted by,

   – Endothermic photodisintegration.
   – Inverse beta decay, which allows additional neutrino losses and also reduces the population (and pressure) of degenerate electrons.

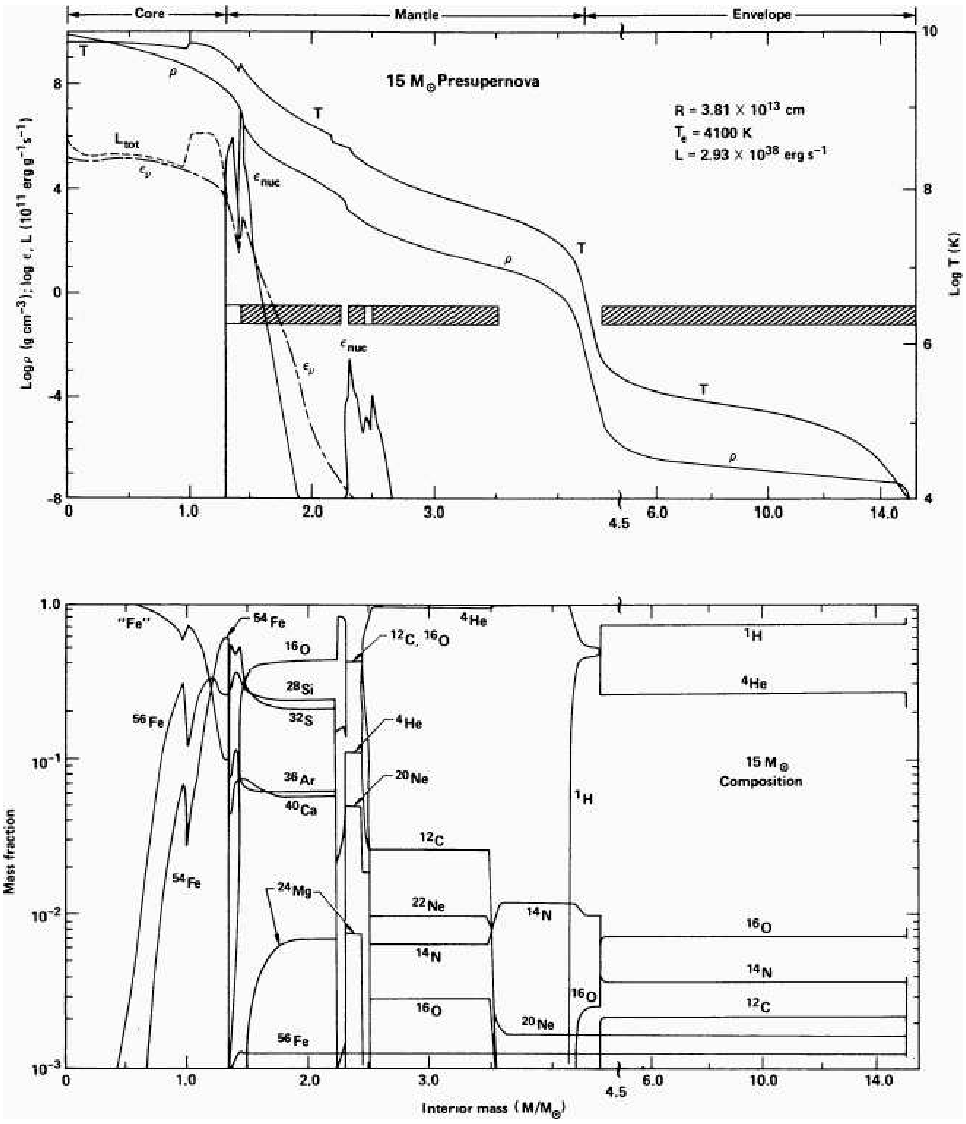
   ...which both reduce the pressure support.

(3) A rebound in the collapse when the central density reaches nuclear density.

(4) Generation of a shock wave which, *if it can propagate out of the infalling matter*, will explode the star.

(5) Further collapse of the core to a black hole if the mass is too large to yield a stable cold neutron star.

Structure of a SN progenitor just prior to collapse (Woosley & Weaver 1986):

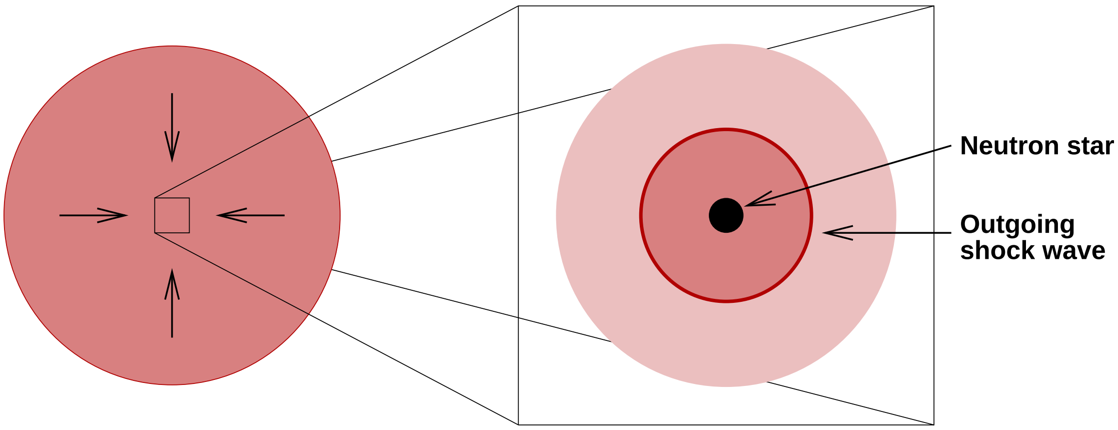


Note presence of two main shell sources. Inner $2 - 3M_{\odot}$ of material has been burned to heavy elements at point core exceeds Chandrasekhar mass.

Prompt explosions

Simplest mechanism for supernova explosion:

- Equation of state stiffens suddenly (ie $\Gamma_1 > 4/3$) when collapsing core reaches nuclear densities of $\rho \sim$ several $\times 10^{14}$ gcm^{-3}.
- Resulting *bounce* sends a shock wave outward through the star. Available energy is a fraction of the binding energy of a cold neutron star – of the order of 10^{52} erg.
- Shock propagates out of the inner core to the outer mantle of the star, blowing it apart.



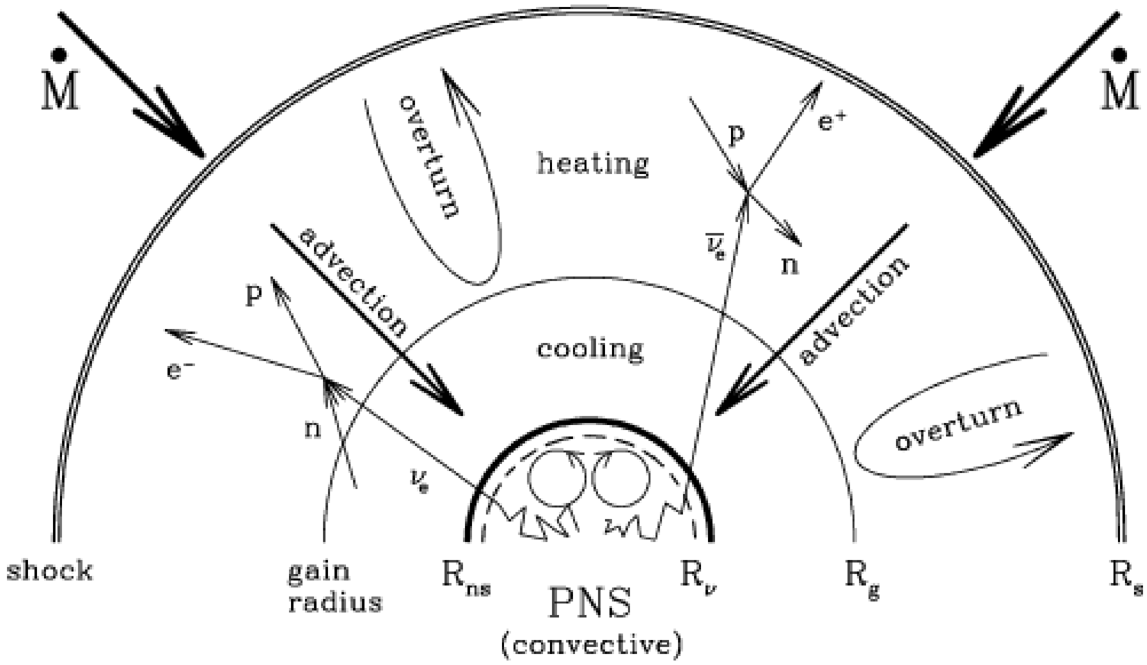
This mechanism fails. The innermost $2 - 3M_\odot$ of the star has already burned beyond helium to heavy elements, which get dissociated by the high temperatures behind the shock, weakening it.

Energy required to dissociate heavy elements is $\approx$ 8 MeV per nucleon $\rightarrow 1.6 \times 10^{52}$ erg $M_\odot^{-1}$. Shock has insufficient energy to propagate out of the core.

Delayed explosions

Most work concentrates on models for delayed explosions powered by neutrinos:

- Neutronization in the proto-neutron star creates a large flux of neutrinos, with total energy a few $\times 10^{52}$ erg.
- These escape *slowly* ($\tau \gg \tau_{free-fall}$) from the core.
- Fraction are absorbed by the post-shock material, heating it and reviving the shock.



Neutrino heating will win over neutrino cooling outside some *gain radius*.

Neutrino emission processes

- Nuclear reactions leading to neutonization, eg,

$$e^- + p \rightarrow n + \nu.$$

- URCA process,

$$\begin{aligned} (Z, A) + e^- &\rightarrow (Z-1, A) + \nu \\ (Z-1, A) &\rightarrow (Z, A) + e^- + \bar{\nu} \end{aligned}$$

  ie cooling of stellar matter via neutrino pair emission.

- Pair annihilation,

$$e^- + e^+ \rightarrow \nu + \bar{\nu}.$$

- Photoneutrino process,

$$\gamma + e^- \rightarrow e^- + \nu + \bar{\nu}.$$

- ...plus several others.

Total energy loss in neutrinos is extremely large for core collapse conditions. eg for pair production at $\rho = 10^9$ gcm^{-3} and $kT \approx m_e c^2$ the luminosity of a $M_\odot$ of material is $10^{11} L_\odot$.

Neutrino-matter interactions

Comprehensive review in Burrows & Thompson (2002), astro-ph/0211404.

Summary: characteristic cross-section for neutrino matter interactions is,

$$\sigma_0 = \frac{4}{\pi}\frac{G_F^2 m_e^2}{\hbar^4} = 1.7 \times 10^{-44}\ \mathrm{cm}^2$$

where G_F is the Fermi coupling constant (measuring the strength of weak nuclear reactions). Total cross-section (integrated over angles) for several processes scales as the neutrino energy E_ν^2. eg for coherent scattering of neutrinos off nuclei,

$$\nu + (\mathrm{Z},\mathrm{A}) \rightarrow \nu + (\mathrm{Z},\mathrm{A})$$

total cross-section is,

$$\sigma_{\nu A} = \sigma_0 \left(\frac{A^2}{24}\right)\left(\frac{E_\nu}{m_e c^2}\right)^2 .$$

In the inner regions of the proto-neutron star, nuclei have been destroyed and neutrino absorption on free neutrons is important,

$$\nu + n \rightarrow e^- + p$$

with a similar E_ν^2 scaling.

Neutrino trapping

For coherent scattering at $E_\nu = 40$ MeV and $A = 56$, find,

$$\sigma_{\nu A} \approx 1.4 \times 10^{-38}\ \mathrm{cm}^2$$

corresponding to a mean free path at $\rho = 10^{12}$ gcm^{-3} of,

$$\lambda \sim 10^4\ \mathrm{cm}.$$

Somewhat better calculation, including energy dependence of the emitted neutrinos as a function of density, gives,

$$\lambda \simeq 3 \times 10^4 \rho_{12}^{-5/3}\ \mathrm{cm}$$

where ρ_{12} is density in units of 10^{12} gcm^{-3}. A comparison of the neutrino diffusion time via a random walk (cf lecture 16) with the free-fall collapse time defines a trapping density,

$$\rho_{trap} \sim 10^{11}\ \mathrm{gcm}^{-3}.$$

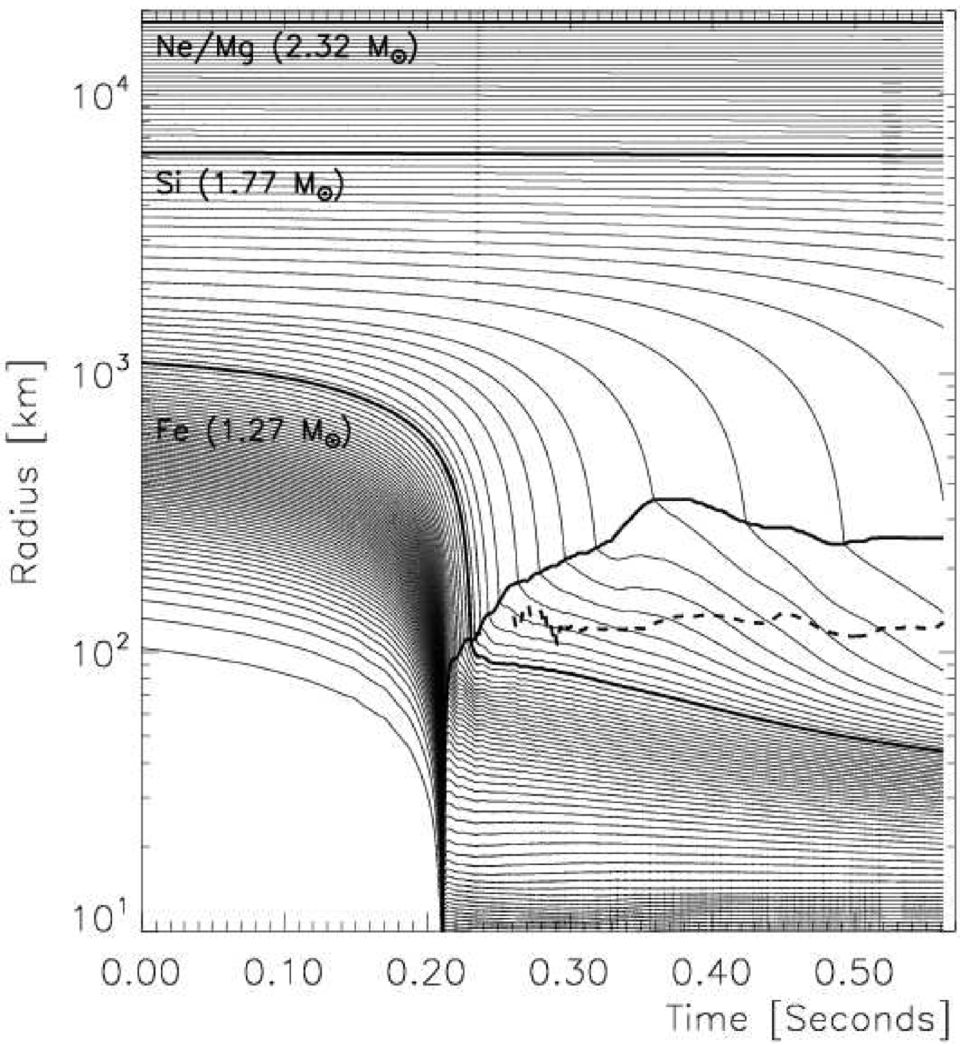
Implications,

- Neutrinos have to diffuse out of the proto-neutron star on a timescale of seconds.
- Significant fraction (of the order of 10%) can interact with matter in the critical post-shock region.

Recent 1D (spherical symmetry) simulations of core collapse include full radiative transport of neutrinos ('Boltzmann transport'). Examples,

- Rampp & Janka, ApJ, 539, L33 (2000).
- Mezzacappa et al., PhRvL, 86, 1935 (2001).

For realistic progenitors, these models also fail to explode:



Convection

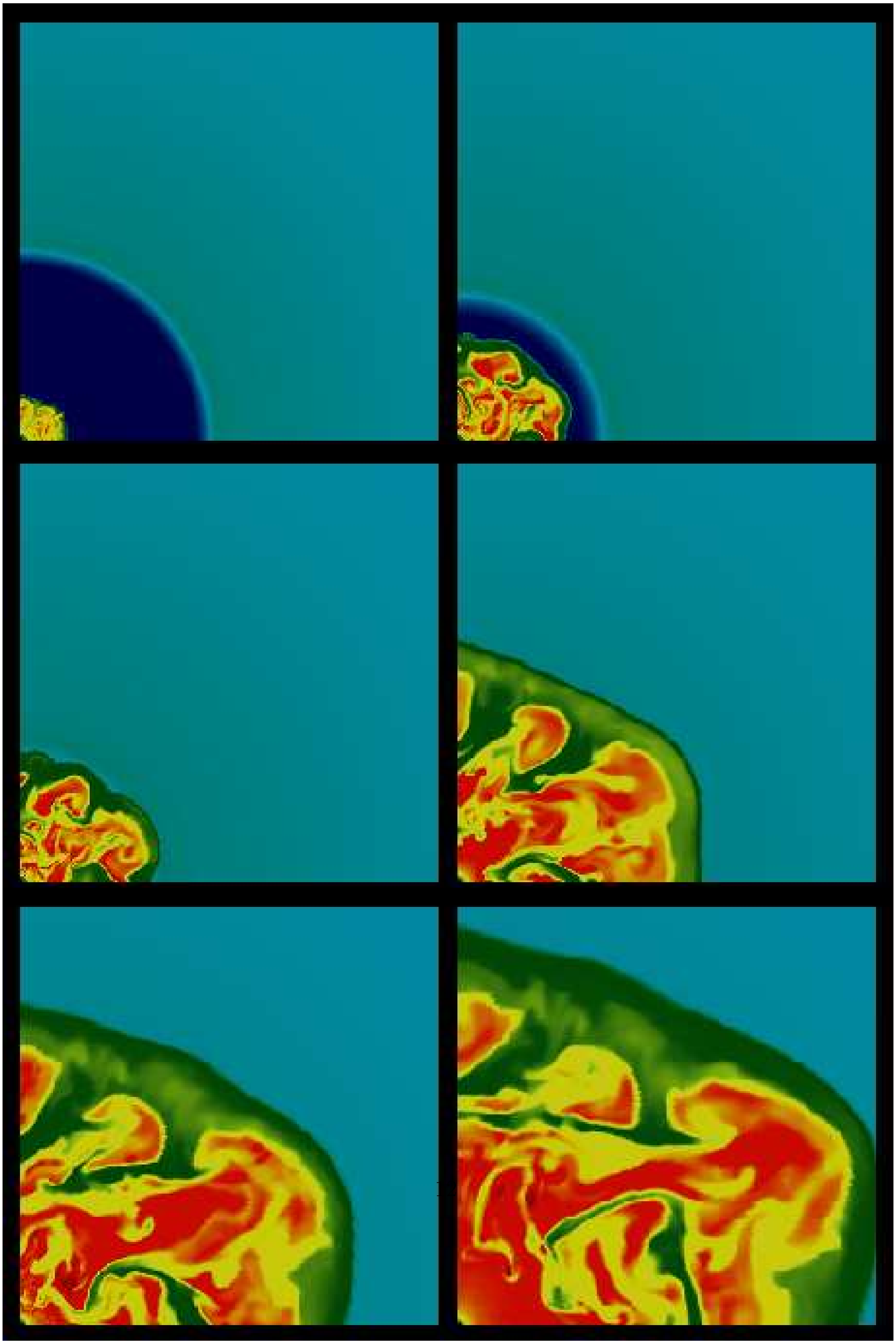
Most frequently invoked extra physics is convection.

- Convection in the proto-neutron star could allow neutrino emission on a shorter timescale than predicted by the random walk argument $\rightarrow$ more effective heating in the gain region. Not currently popular.
- Convection in the post-shock region also improves the efficiency of energy transport to the shock. Large energy deposition from neutrinos means little doubt this region is unstable.

General agreement that convection in 2D or 3D improves the chances of an explosion (Burrows, Hayes & Fryxell 1995; Fryer & Warren 2002) compared to 1D mdoels.

But, 2D / 3D calculations do not incorporate as detailed neutrino physics.

Fig. 2.−−Explosion Sequence in Entropy: 2500 km Scale



Rotation

Collapsar models for gamma-ray bursts produce explosions without any appeal to neutrino heating.

- Collapse of a rotating core leads to a black hole of a few solar masses plus a rotating disk with a significant mass.
- Accretion of $1M_\odot$ with an efficiency of ~ 0.1 releases a few 10^{53} erg of energy.
- Jet powered by this energy accelerates to very high Lorentz factor as it propagates down the density gradient at the edge of the star.

If viewed almost directly down the jet axis $\rightarrow$ GRB.

Energy deposition also disrupts the star. At most angles see something like a SN, perhaps accompanied by an X-ray flash.

Wheeler, Meier & Wilson (2002) have attempted to revive interest in a similar model for ordinary SN. Main attraction – 'natural' explanation for significantly asymmetric events. But unclear whether rotation in typical stellar cores is high enough.