Nuclear Astrophysics: The origin of heavy elements

Lecture 2: Core-collapse supernovae

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Isolde lectures on nuclear astrophysics
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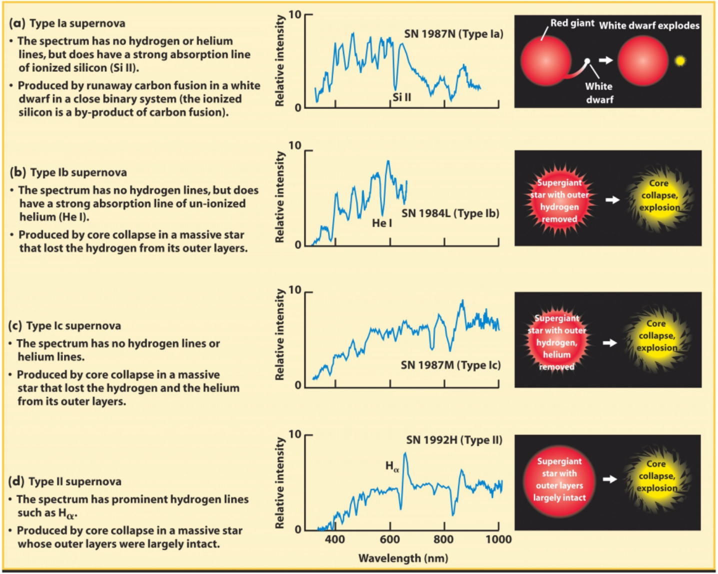
Supernova types

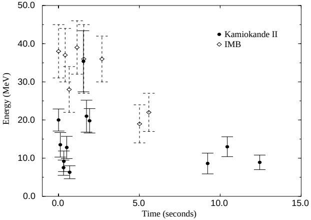


SN1987A

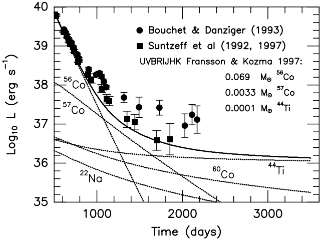
Type II supernova in LMC
($\sim$ 55 kpc)

- $E_{\text{grav}} \approx 10^{53}$ erg
- $E_{\text{rad}} \approx 8 \times 10^{49}$ erg
- $E_{\text{kin}} \approx 10^{51}$ erg = 1 Bethe

neutrinos $E_\nu \approx 2.7 \times 10^{53}$ erg

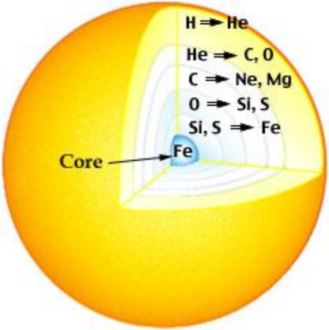


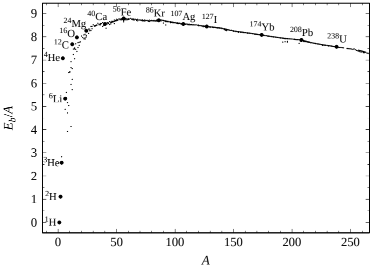
light curve



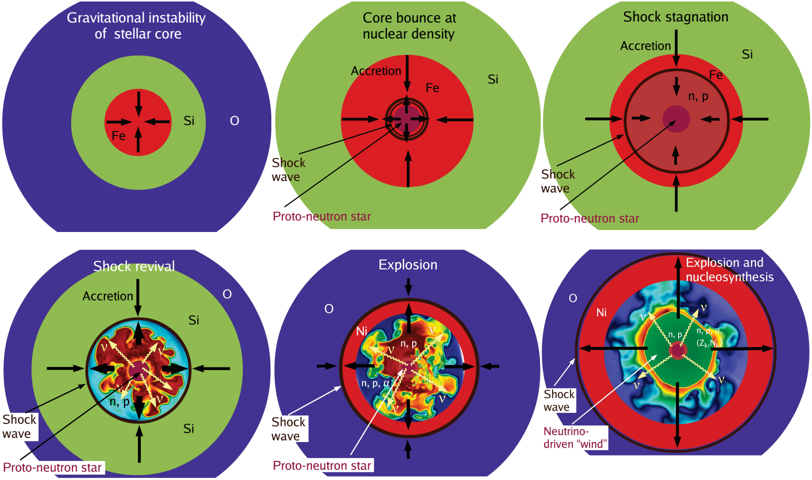
Presupernova Star

- Star has an onion like structure.
- Iron is the final product of the different burning processes.
- As the mass of the iron core grows it becomes unstable and collapses when it reaches around 1.4 $M_{\odot}$.





Schematical evolution

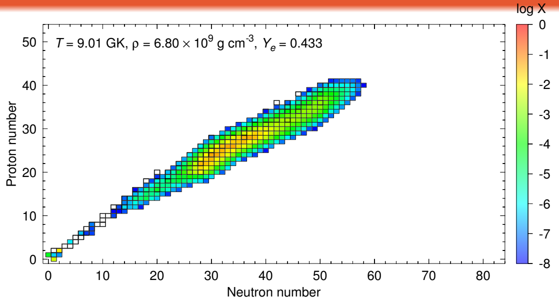


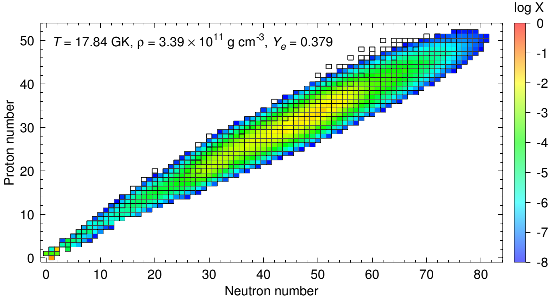
H.-Th. Janka, *et al*, PTEP 01A309 (2012)

Early iron core

- The core is made of heavy nuclei (iron-mass range $A = 45–65$) and electrons. Composition given by Nuclear Statistical Equilibrium. There are Y_e electrons per nucleon.
- The mass of the core M_c is determined by the nucleons ($M_c = nm_u$).
- There is no nuclear energy generation which adds to the pressure. Thus, the pressure is mainly due to the degenerate electrons, with a small correction from the electrostatic interaction between electrons and nuclei.
- As long as $M_c < M_{\rm ch} = 1.44(2Y_e)^2 M_\odot$ (plus slight corrections for finite temperature), the core can be stabilized by the degeneracy pressure of the electrons.

Composition





Onset of collapse

There are two processes that make the situation unstable:

1. Silicon burning is continuing in a shell around the iron core. This adds mass to the iron core increasing M_c.
2. Electrons can be captured by protons (free or in nuclei):

$$e^- + A(Z, N) \rightarrow A(Z-1, N+1) + \nu_e.$$

This reduces the pressure and keep the core cold, as the neutrinos leave. The net effect is a reduction of Y_e and consequently of the Chandrasekhar mass (M_{ch})

Initial conditions

The dominant contribution to the pressure comes from the electrons. They are degenerate and relativistic:

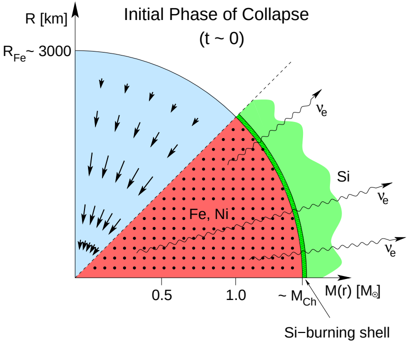
$$P \approx n_e \mu_e = n_e \varepsilon_F$$

μ_e is the chemical potential, fermi energy, of the electrons:

$$\mu_e \approx 1.11(\rho_7 Y_e)^{1/3}\ \mathrm{MeV}, \qquad \frac{\rho Y_e}{m_u} = n_e$$

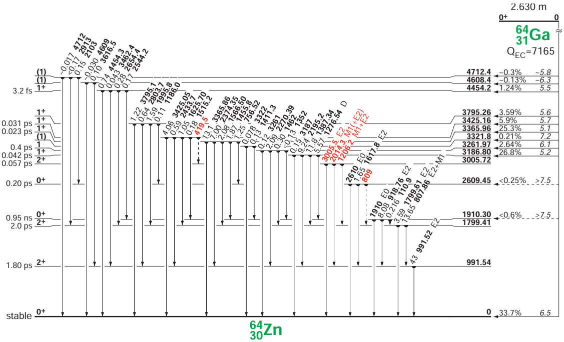
For $\rho_7 = 1$ ($\rho = 10^7$ g cm^{-3}) the chemical potential is 1 MeV, reaching the nuclear energy scale. At this point is energetically favorable to capture electrons by nuclei.

Presupernova evolution



- $T = 0.1\text{–}0.8$ MeV, $\rho = 10^7\text{–}10^{10}$ g cm^{-3}. Composition of iron group nuclei.
- Important processes:
    - electron capture: $e^- + (N,Z) \rightarrow (N+1, Z-1) + \nu_e$
    - β^- decay: $(N,Z) \rightarrow (N-1, Z+1) + e^- + \bar{\nu}_e$
- Dominated by allowed transitions (Fermi and Gamow-Teller)
- Evolution decreases number of electrons (Y_e) and Chandrasekar mass ($M_{\mathrm{ch}} \approx 1.4(2Y_e)^2 M_\odot$)

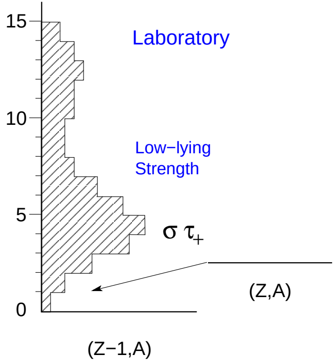
Electron capture on Earth

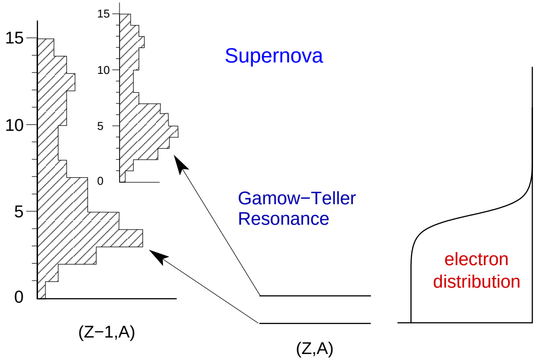


$$\lambda_{\rm ec} = \frac{\ln 2}{K} f(Q)[B(F) + B(GT)], \qquad K = 6147.0 \pm 2.4\ s$$

- $f(Q)$ phase space function.
- $B(F)$ Fermi matrix element.
- $B(GT)$ Gamow-Teller matrix element.

Laboratory vs. stellar electron capture



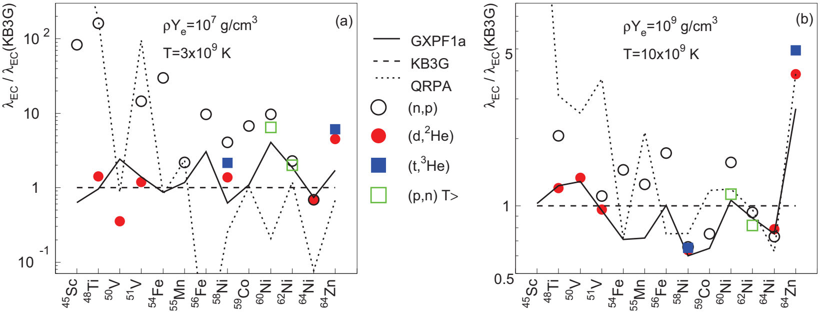


Capture of K-shell electrons to tail of GT strength distribution. Parent nucleus in the ground state

Capture of electrons from the high energy tail of the FD distribution. Capture to states with large GT matrix elements (GT resonance). Thermal ensemble of initial states.

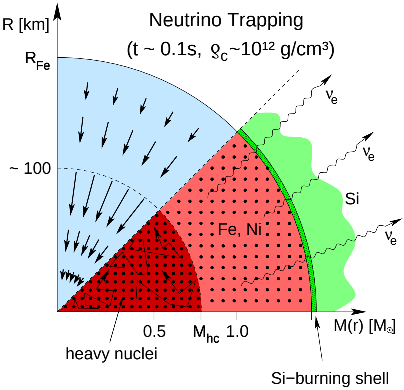
Systematic study measured GT strengths

A. L. Cole *et al.*, PRC **86**, 015809 (2012)



- Rates for iron-group nuclei are under control
- With increasing density, less sophisticated models like QRPA may suffice.

Collapse phase

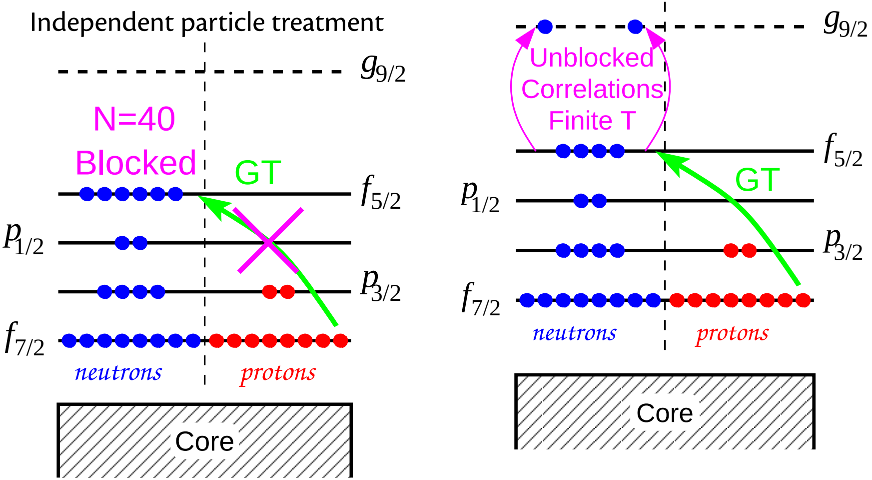


Important processes:

- Neutrino transport (Boltzmann equation):
  $\nu + A \rightleftarrows \nu + A$ (trapping)
  $\nu + e^- \rightleftarrows \nu + e^-$ (thermalization)

  cross sections $\sim E_\nu^2$
- electron capture on protons:
  $e^- + p \rightleftarrows n + \nu_e$
- electron capture on nuclei:
  $e^- + A(Z,N) \rightleftarrows A(Z-1,N+1) + \nu_e$

(Un)blocking electron capture at N=40



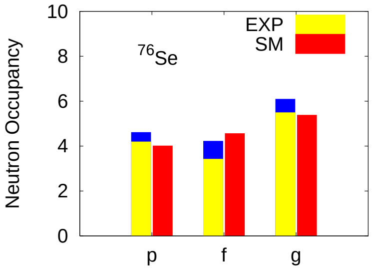
Correlations around N=40: GT+ strength for ^{76}Se

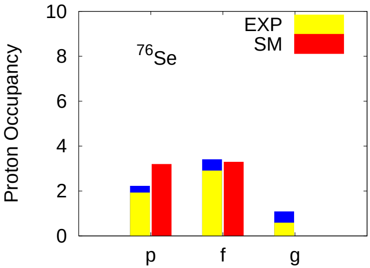
The structure of ^{76}Se ($Z = 34, N = 42$) has been the subject of several studies due to its important for the double beta decay of ^{76}Ge

Measured occupation numbers in transfer reactions

Schiffer *et al*, PRL **100**, 112501 (2008)

Kay *et al*, PRC **79**, 021301(R) (2009)

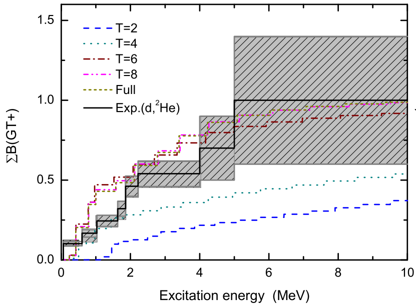


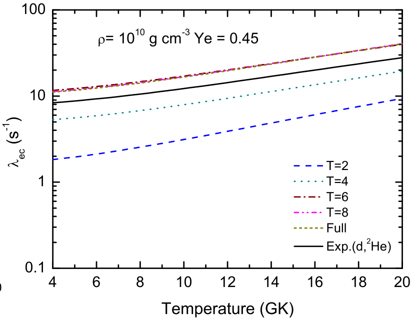


Occupation of $g_{9/2}$ orbital is larger than naive IPM estimates.

Correlations around N=40: GT+ strength for ^{76}Se

Gamow-Teller strength measured in charge-exchange reactions:
$(d, {}^{2}\text{He})$: Grewe *et al.*, PRC **78**, 044301 (2008)



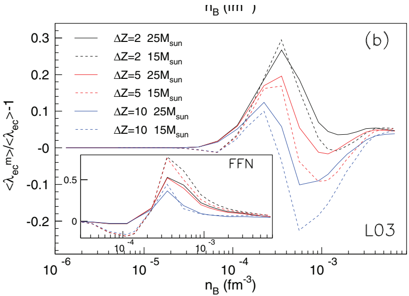


- Slow convergence of cross-shell correlations.
- Thermofield dynamics or finite temperature QRPA models, which consider only 2p-2h (T=2) correlations, do not suffice.
- What is the role of the $N = 40$ ($Z \lesssim 26$) island of inversion on electron capture rates?

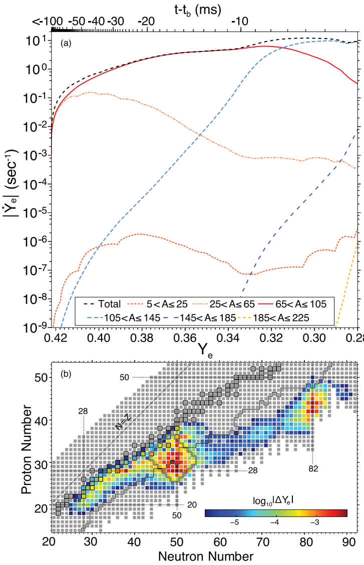
Zhi, Langanke, GMP, Nowacki, Sieja, NPA **859**, 172 (2011)

Most important nuclei

- Most relevant nuclei are those around $N = 50$.
- Shell closure enhances the abundances.
- Results are sensitive to assumptions about shell closure far from stability.

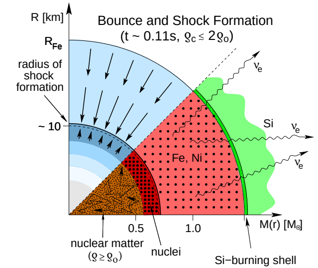


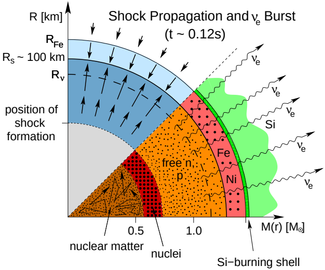
Raduta, *et al*, PRC **93**, 025803 (2016)



Sullivan *et al*, ApJ **816**, 44 (2015).

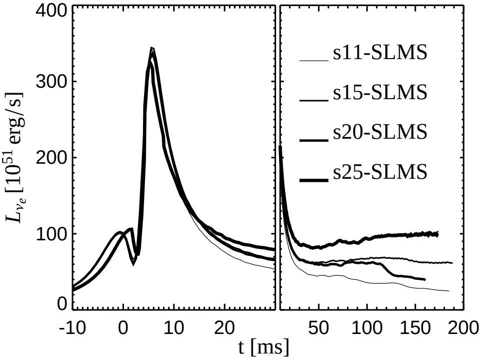
Bounce and ν_e burst





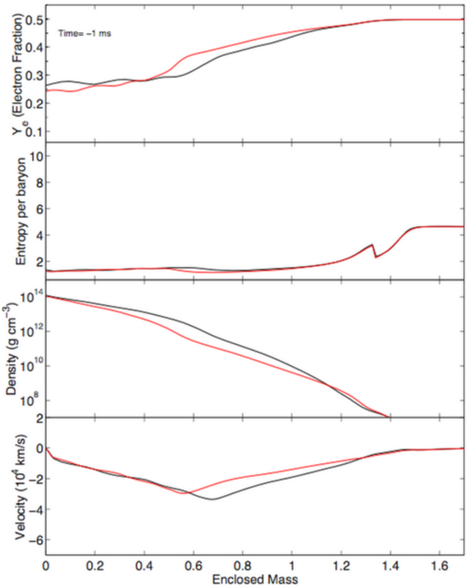
- Collapse continues until central density becomes around twice nuclear matter density.
- Sudden increase in nuclear pressure stops the collapse and a shock wave is launched at the sonic point. The energy of the shock depends on the Equation of State.
- The passage of the shock dissociates nuclei into free nucleons which costs ~ 8 MeV/nucleon. Additional energy is lost by neutrino emission produced by electron capture (ν_e burst).
- Shock stalls at a distance of several 100 km.

Neutrino burst

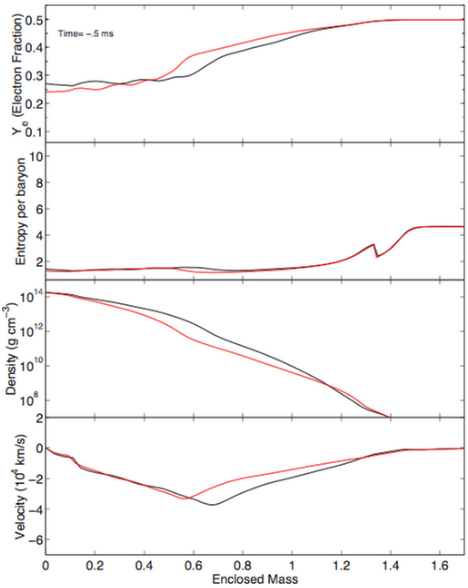


- Burst occurs when shock wave reaches regions with densities low enough to be transparent to neutrinos. It is produced by electron captures on free protons from the dissociation.
- Burst structure does not depend on the progenitor star.
- Future observation by a supernova neutrino detector may test our basic understanding of supernova explosions. Standard neutrino candles.

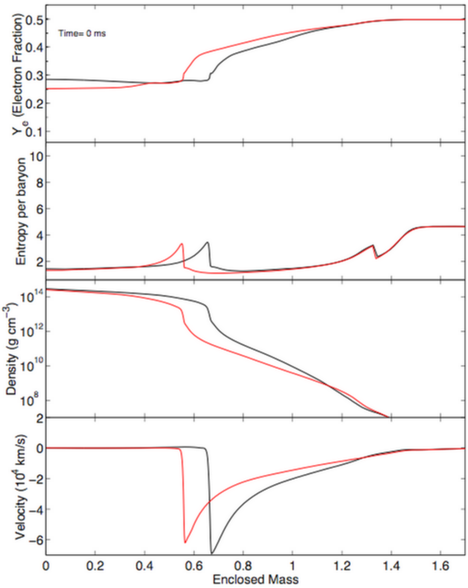
Spherical simulation



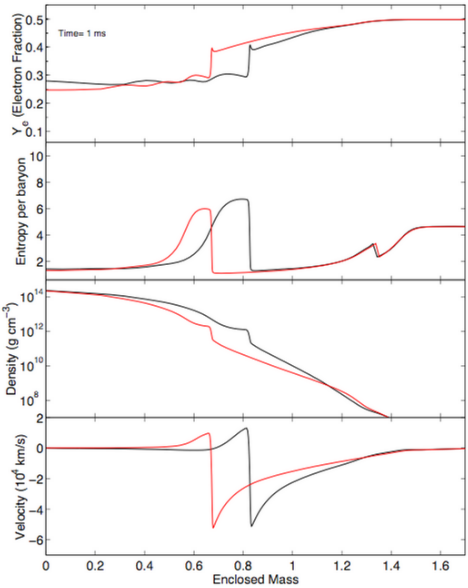
Spherical simulation



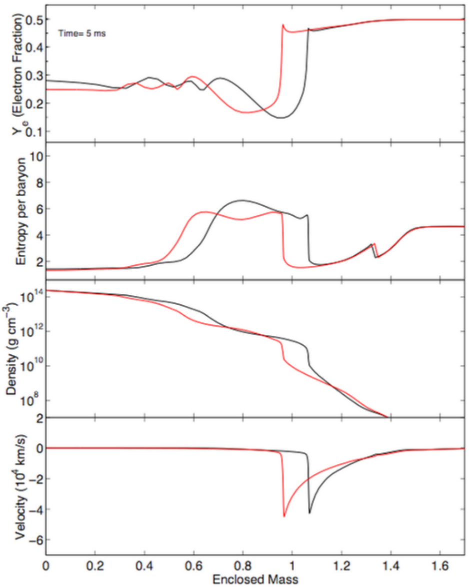
Spherical simulation



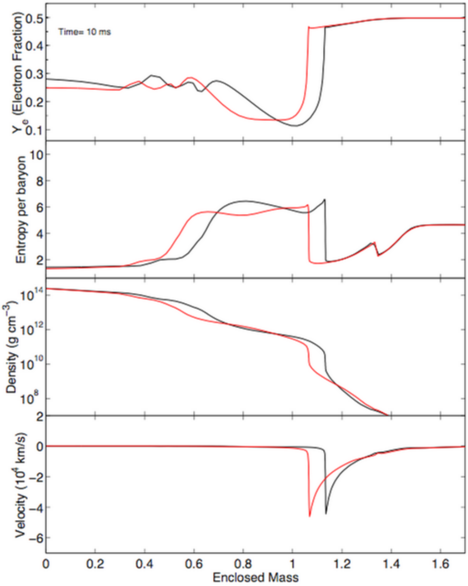
Spherical simulation



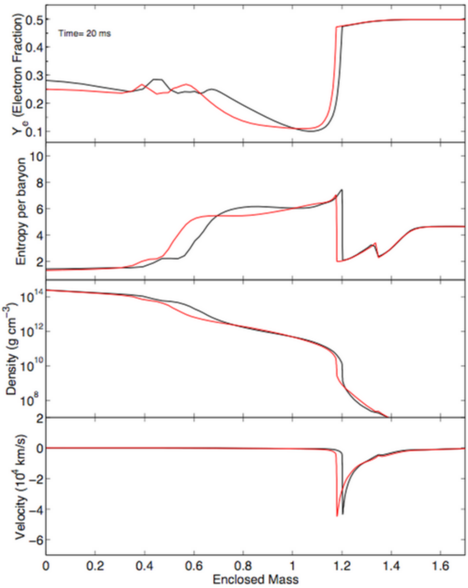
Spherical simulation



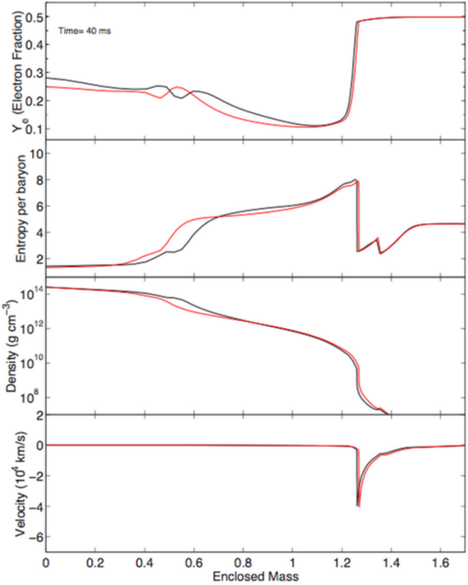
Spherical simulation



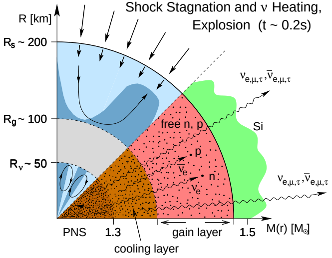
Spherical simulation

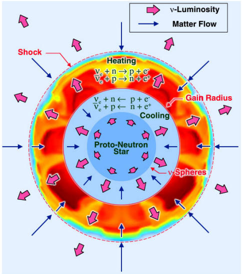


Spherical simulation



Delayed explosion mechanism: neutrino heating





Main processes:

$$\nu_e + n \rightleftarrows p + e^-$$
$$\bar{\nu}_e + p \rightleftarrows n + e^+$$

Concept of gain radius due to Bethe.
Corresponds to the region where cooling (electron positron capture) and heating (neutrino antineutrino absorption) are equal.

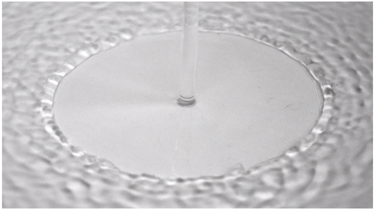
$$\text{Cooling: } 143 \left(\frac{kT}{2\text{ MeV}}\right)^6 \text{ MeV/s}$$

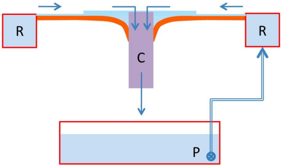
$$\text{Heating: } 110 \left(\frac{L_{\nu_e,52}\epsilon^2_{\nu_e}}{r_7^2} Y_n + \frac{L_{\bar{\nu}_e,52}\epsilon^2_{\bar{\nu}_e}}{r_7^2} Y_p\right) \text{ MeV/s}$$

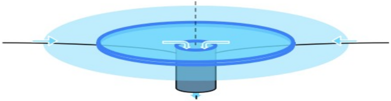
Gravitational energy of a nucleon at 100 km: 14 MeV
Energy transfer induces convection and requires multidimensional simulations.

SWASI : Shallow Water Analogue of a Shock Instability

Kitchen sink hydraulic jump







acoustic waves ↔ surface wave
shock wave ↔ hydraulic jump
pressure ↔ depth

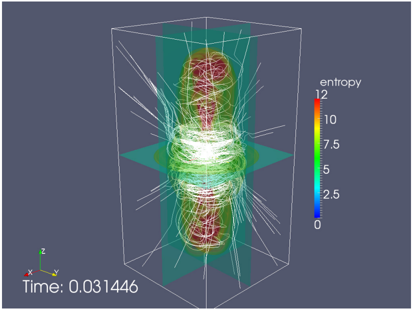
Foglizzo *et al*, PRL **108** 051103 (2012)

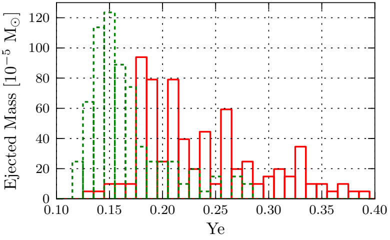
Summary

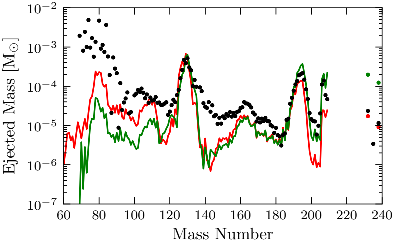
- Multidymensional (3D) simulations of core-collapse supernova are very challenging.
- There may be several mechanism operating
- Important role of microphysics (neutrino reactions consistent with the equation of state) and hydrodynamical instabilities.
- Current exploding 3D models suggest very low explosion energies. A factor ten smaller than 10^{51} ergs.
- Explosion very sensitive to small variations, e.g. neutrino interactions.
- It may suggest that supernova explosions are rare phenomena.
- If explosions are a common outcome of massive star evolution we will need to develop a robust explosion mechanism.

Magnetorotationally Driven Supernovae

Winteller *et al*, ApJ **750**, L22 (2012)







- Rotation and magnetic fields may play an important role in some supernova explosions (relation GRBs?).
- Origin highly magnetized neutron stars (magnetars)
- Site r-process nucleosynthesis.