Nuclear Astrophysics

II. Core-collapse supernovae

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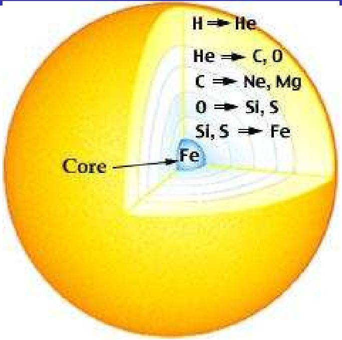
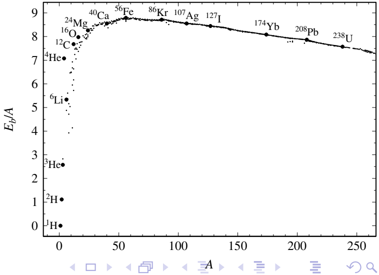
Presupernova star

- 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 once it grows above around 1.4 solar masses.





Onset of collapse

However, there are two processes which make the situation unstable.

1. Silicon burning is continuing in a shell around the iron core. This adds mass to the iron core, thus M_c grows.
2. Electrons can be captured by nuclei.

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

   This reduces the pressure and cools the core, as the neutrinos leave. In other words, Y_e and hence the Chandrasekhar mass M_{ch} is reduced.

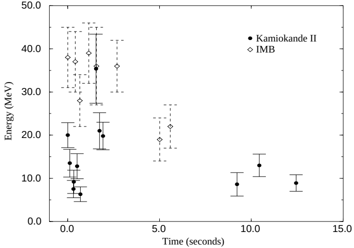
The core finally collapses.

SN1987A

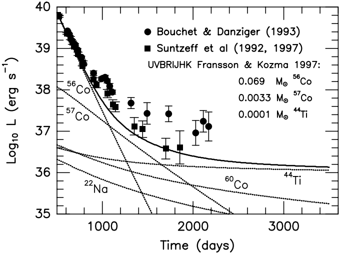
Type II supernova in LMC ($\sim$ 55 kpc)

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

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



light curve

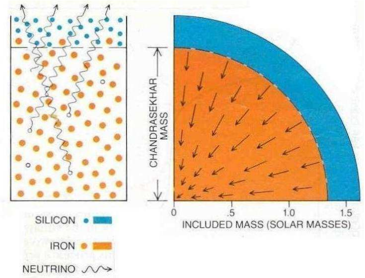


Presupernova and collapse models

Core-collapse supernova simulations are separated into:

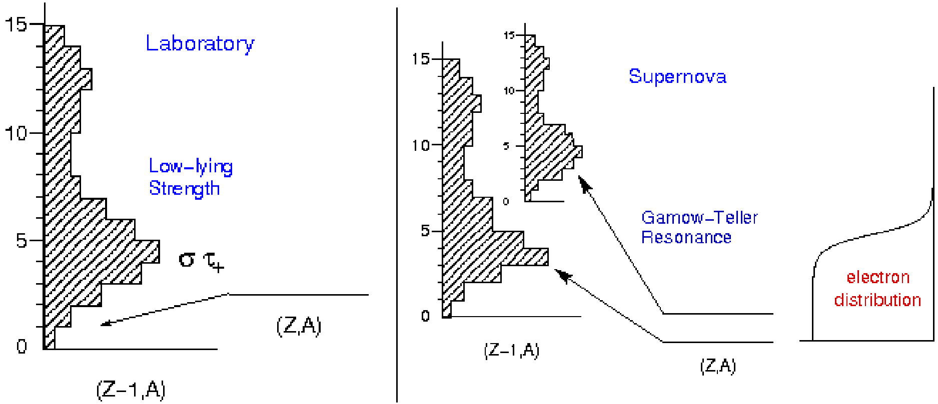
1. **presupernova models**:
   - describes the stellar evolution through the various hydrostatic burning stages (H, He,...,Si) and follows the collapse of the central core until densities of order $\rho_9 = 10$ are reached
   - large nuclear networks are used to include the nuclear energy generation and the changes in composition
   - neutrinos, produced in weak-interaction reactions, can leave the star unhindered and are treated as energy loss
2. **collapse models**
   - describes the final collapse and the explosion phase
   - the temperature during these phases is high enough that all reactions mediated by the strong and electromagnetic interaction are in equilibrium; thus the matter composition is given by Nuclear Statistical Equilibrium (NSE)
   - reactions mediated by the weak interaction are not in equilibrium
   - neutrino interactions with matter have to be considered in details (Boltzmann transport)

Presupernova evolution



- $T = 0.1\text{–}0.8$ MeV, $\rho = 10^7\text{–}10^{10}$ g cm^{-3}. Composition of iron group nuclei (A = 45–65)
- 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)
- Calculated within large-scale shell model, constrained by data from charge-exchange (d,^{2}He), (n,p) experiments

Laboratory vs stellar electron capture

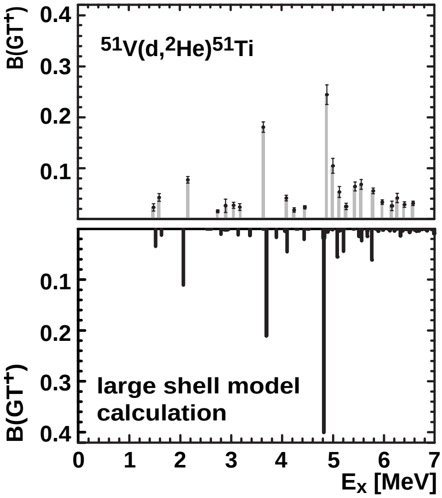


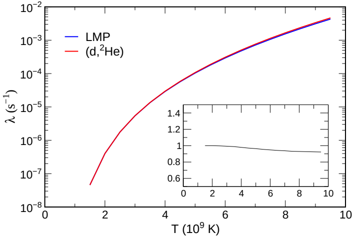
capture of K-shell electrons to tail of GT strength distribution; parent nucleus in ground state

capture of electrons from high-energy tail of FD distribution; capture of strong GT transitions possible; thermal ensemble of initial states

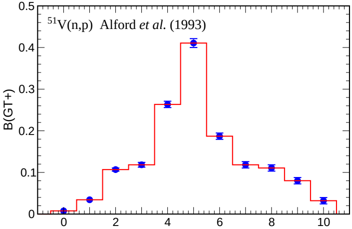
Shell model and (d,^{2}He) GT strengths

C. Bäumer *et al.* PRC **68**, 031303 (2003)

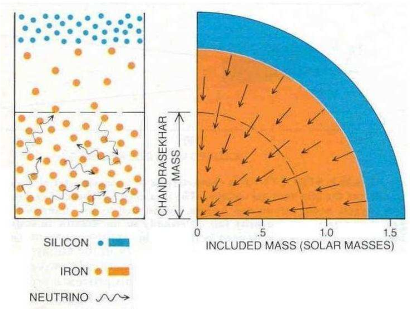




Old (n, p) data



Collapse phase

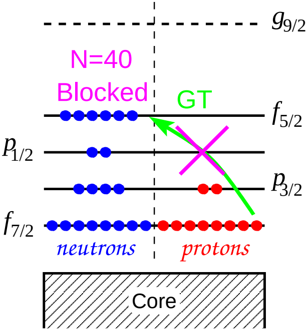


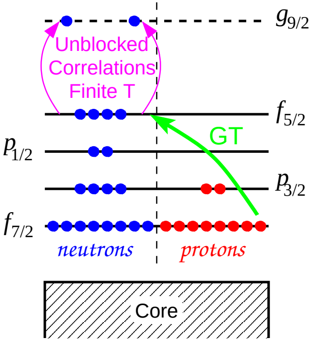
Important processes:

- 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 nuclei and protons:
  $e^- + (N, Z) \rightleftarrows (N+1, Z-1) + \nu_e$
  $e^- + p \rightleftarrows n + \nu_e$
- capture on nuclei dominates

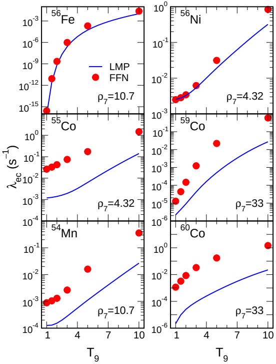
Pauli blocking of Gamow-Teller transition



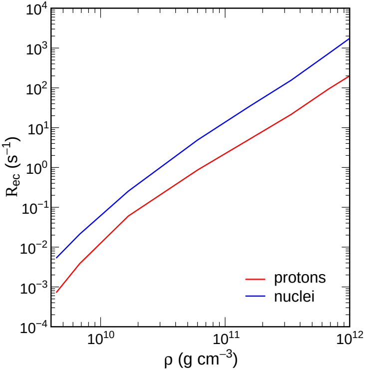


- Unblocking mechanism: correlations and finite temperature
- calculation of rate in SMMC + RPA model

How do shell-model rates compare to previous rates?

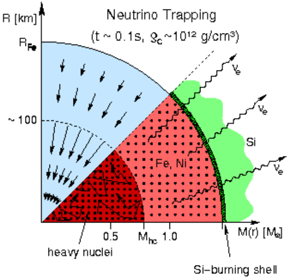


$A < 65$: SM rates smaller



$A > 65$: SM rates larger

Neutrino trapping

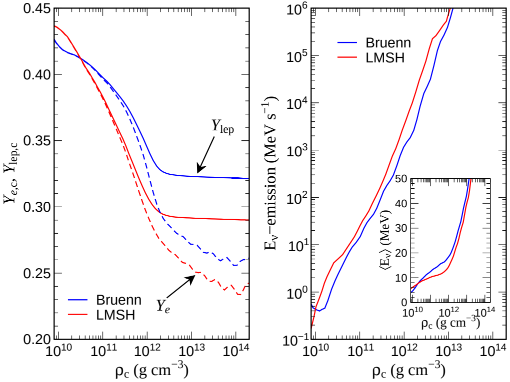


- $\nu + A \rightleftarrows \nu + A$ (trapping)
  elastic process, no energy, but momentum transfer
- $\nu + e^- \rightleftarrows \nu' + e^-$ (thermalization)
  inelastic scattering, energy transfer
- $\nu + (Z, A) \rightarrow \nu' + (Z, A)^*$
  (thermalization)
  inelastic scattering, energy transfer
- cross sections $\sim E_\nu^2$

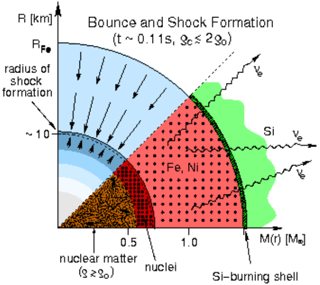
treatment by neutrino transport (Boltzmann equations) which consider all neutrino types and keep track of neutrino fluxes, energies at all space-time points

Effect on improved rates on collapse simulations

With Rampp & Janka (General Relativistic model)
15 $M_\odot$ presupernova model from A. Heger & S. Woosley



Core bounce

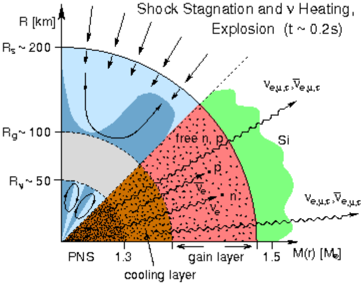


The collapse continues until the central density becomes substantially (by about a factor 2-4) larger than nuclear density ($\rho_{nm} \approx 2 \times 10^{14}$ g/cm^3). Then nuclear pressure slows down the infall and finally stops it. When the inner core has reached its maximum density (*maximum scrunch*), it rebounds and a shock starts.

A decisive quantity for this stage of the collapse is the *Equation of State*. It is assumed that matter consists of nuclear and electron components, while neutrinos have negligible interactions, but are important for the determination of quantities like Y_e or temperature.

In the shock the temperature increases. So the passage of the shock dissociates the nuclei into free nucleons which costs the shock energy (about 8-9 MeV/nucleon). The shock has not enough energy to traverse the iron core. It stalls. No prompt explosion.

Shock revival

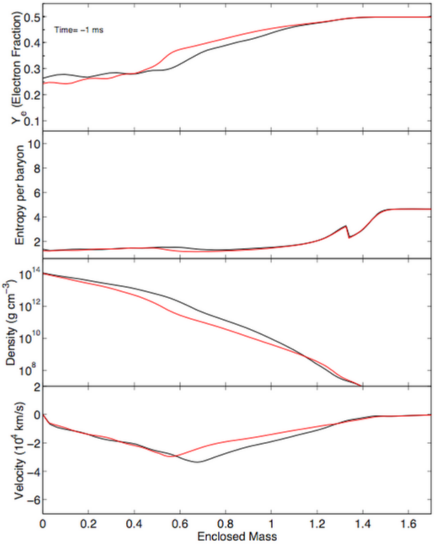


- The important reactions directly behind the shock are:

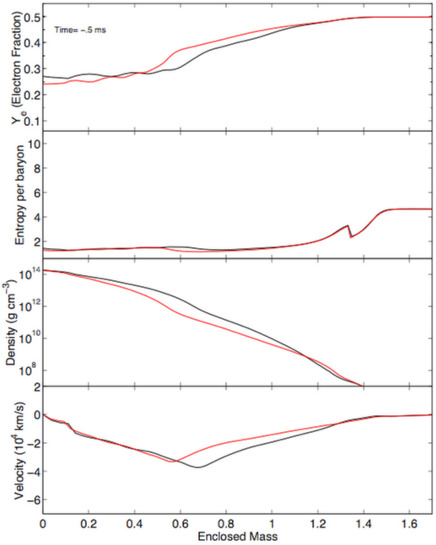
  $$\nu_e + n \leftrightarrow p + e^- ; \quad \bar{\nu}_e + p \leftrightarrow n + e^+$$

- Competition between emission (cooling) and absorption (heating) by neutrinos.
- Thus the material directly behind the shock gets heated.
- This increases the kinetic energy of matter and revives the shock (delayed supernova mechanism).
- However, spherical simulations fail and show no successful explosions.

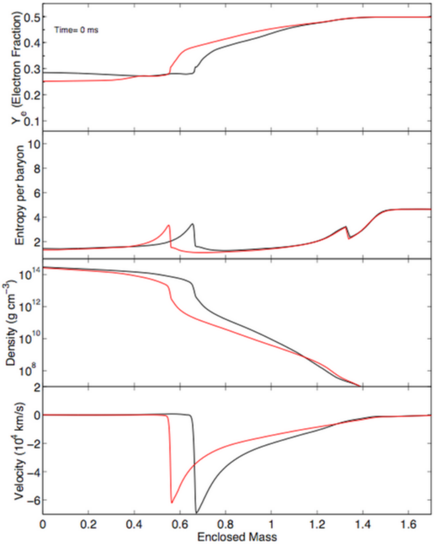
Bounce and shock wave evolution



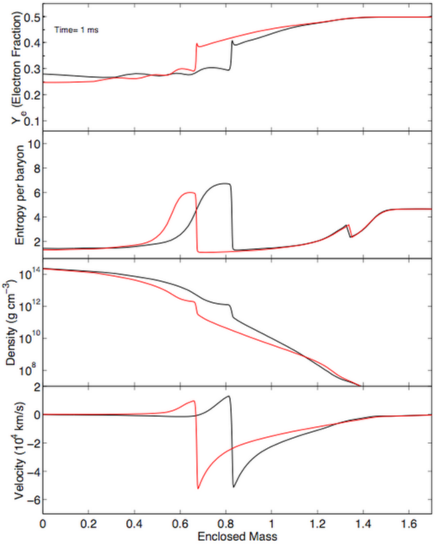
Bounce and shock wave evolution



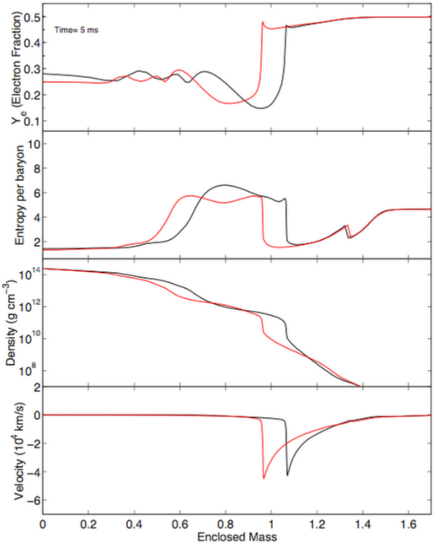
Bounce and shock wave evolution



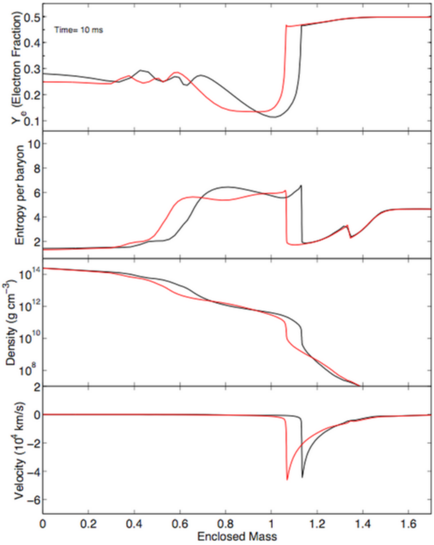
Bounce and shock wave evolution



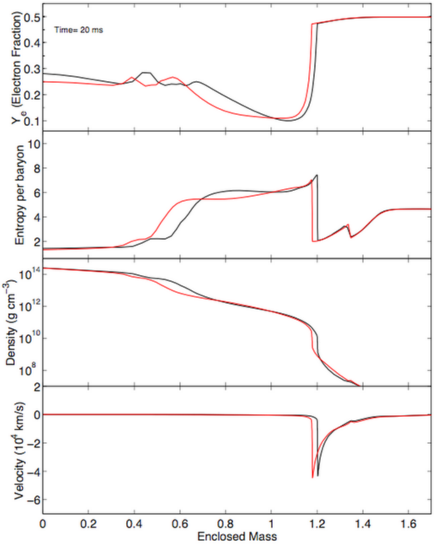
Bounce and shock wave evolution



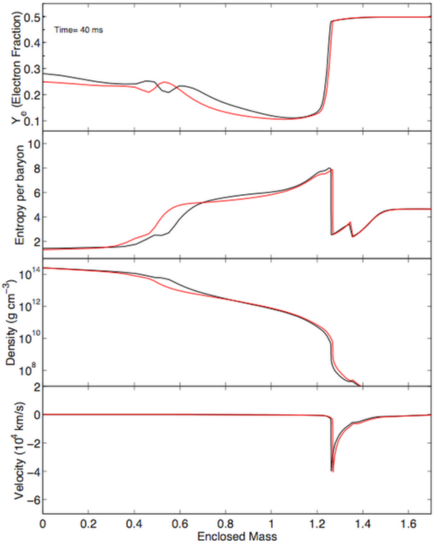
Bounce and shock wave evolution



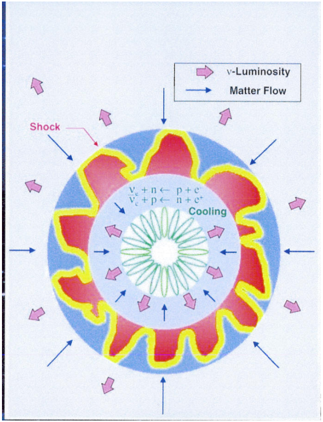
Bounce and shock wave evolution



Bounce and shock wave evolution



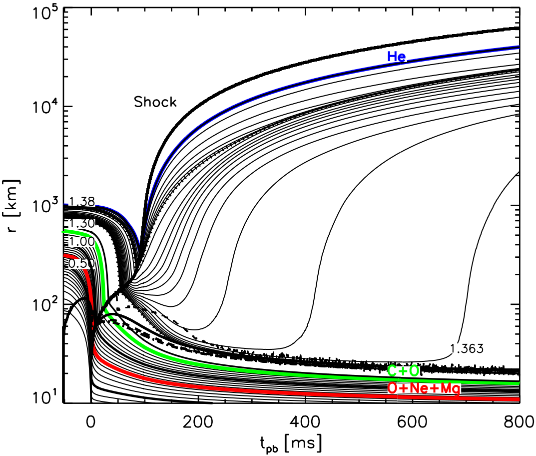
Convection



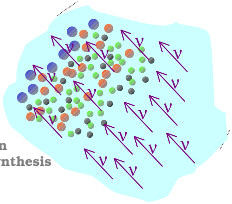
There exist now two-dimensional simulations (with neutrino transport and modern microphysics) which yield successful explosions. Convection brings neutrinos from deeper (hotter) layers to the shock and increase the effectiveness of energy transfer.

Successful two-dimensional supernova

Successful 2-dimensional explosion of $11 M_\odot$ star with ONeMg core (H.-Th. Janka)



Explosive nucleosynthesis in supernova



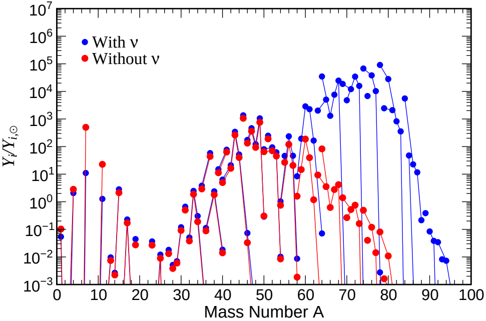
- Consistent treatment of supernova dynamics coupled with a nuclear network.
- Essential neutrino reactions in the shock heated region

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

- early ($\sim$ 1 s): matter protonrich $\rightarrow$ νp-process
- later: matter neutronrich $\rightarrow$ r-process

The νp-process: basic idea

- Protonrich matter is ejected under the influence of neutrino reactions
- Nuclei form at distance where a substantial antineutrino flux is present

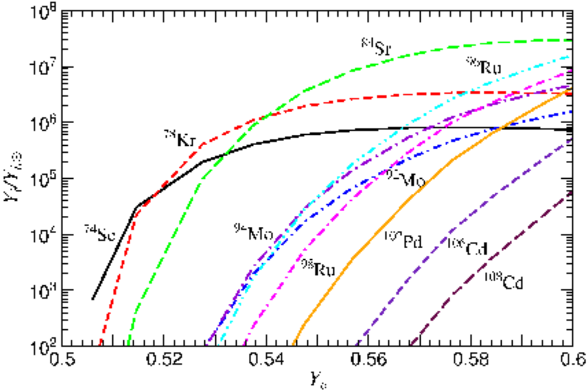


Antineutrinos help to bridge long waiting points via (n,p) reactions

$$\bar{\nu}_e + p \rightarrow e^+ + n; \quad n + {}^{64}\mathrm{Ge} \rightarrow {}^{64}\mathrm{Ga} + p; \quad {}^{64}\mathrm{Ga} + p \rightarrow {}^{65}\mathrm{Ge}; \ldots$$

C. Fröhlich, G. Martinez-Pinedo, et al., PRL 96 (2006) 142502

νp-process: abundance yields of medium-mass nuclei



Y_e: electron-to-nucleon ratio

the larger Y_e, the more protons exist and can be transformed into neutrons by antineutrino capture

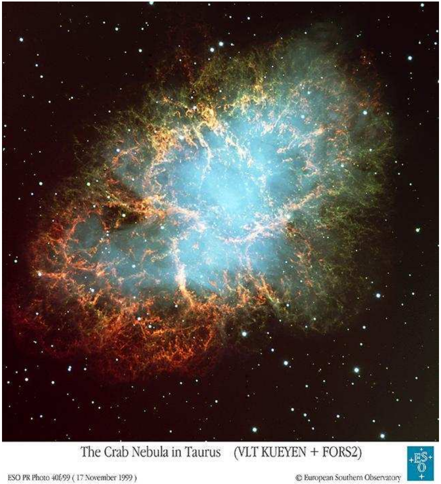
Supernova remnants

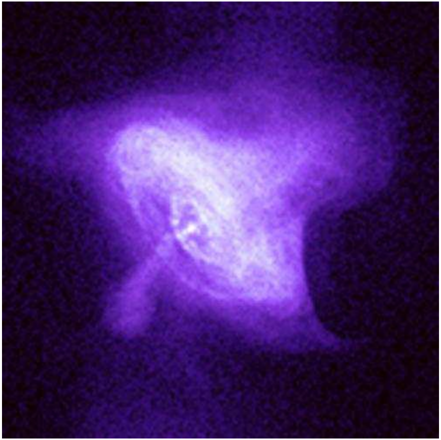
The remnant left over in the explosion depends on the main-sequence mass M_{ms} and on the maximum mass for neutron stars. The later is not quite well known. Most neutron stars, whose masses are well determined (they are in binaries), have masses around 1.4 $M_\odot$, however, recent observations might imply masses up to 2.1 $M_\odot$.

It is generally assumed that the collapse of stars with $M_{ms} > 20 - 25 M_\odot$ leads to a black hole in the center, while stars with $8 M_\odot < M_{ms} < 20 - 25 M_\odot$ yield a supernova with a neutron star remnant.

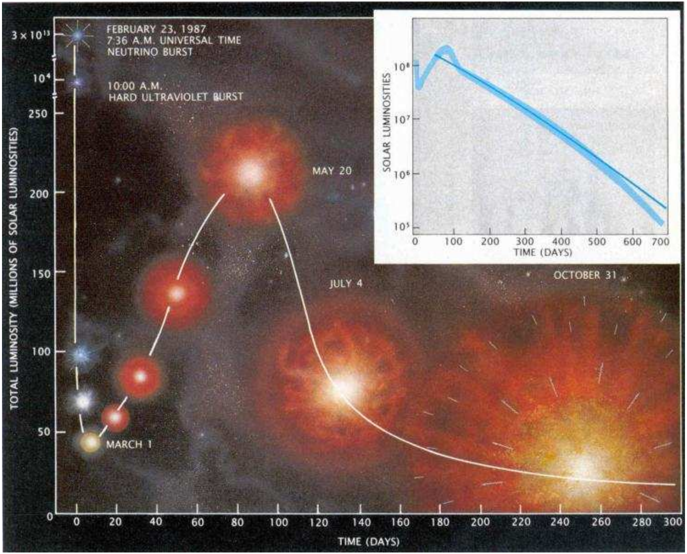
It is also possible that accretion during the explosion might put the remnant over the neutron star mass limit. It is speculated that this happened in the case of the SN87A.

Supernova remnants





Light curve



FEBRUARY 23, 1987
7:36 A.M. UNIVERSAL TIME
NEUTRINO BURST
10:00 A.M.
HARD ULTRAVIOLET BURST
MAY 20
JULY 4
OCTOBER 31
MARCH 1
TOTAL LUMINOSITY (MILLIONS OF SOLAR LUMINOSITIES)
3 × 10¹³
10⁴
250
200
150
100
50
0
0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300
TIME (DAYS)
SOLAR LUMINOSITIES
10⁸
10⁷
10⁶
10⁵
0 100 200 300 400 500 600 700
TIME (DAYS)

Energy from radioactive decays

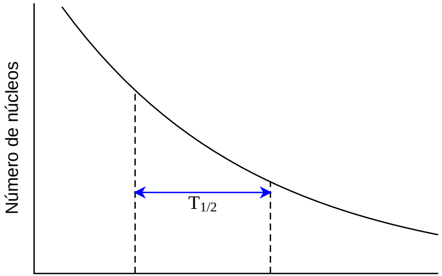
A core-collapse supernova produces about $0.15 - 0.2\ M_\odot$ ^{56}Ni. This is made in the outer layers of the star ($Y_e = 0.5$, mainly ^{16}O) when the shock wave passes through and brings this matter into NSE by fast reactions. Supernova also produce other radioactive nuclides (for example ^{57}Ni and ^{44}Ti). ^{44}Ti is only barely made (about $10^{-4}\ M_\odot$), but has a lifetime of about 60 years. It dominates the lightcurve of SN87A today.

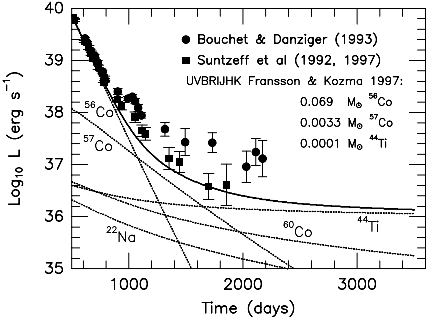
These radiactive nuclides decay, producing γ radiation in the MeV range. By scattering with electrons, these photons are thermalized and then radiated away as infrared, visible, and ultraviolet light.

Radioactive decay

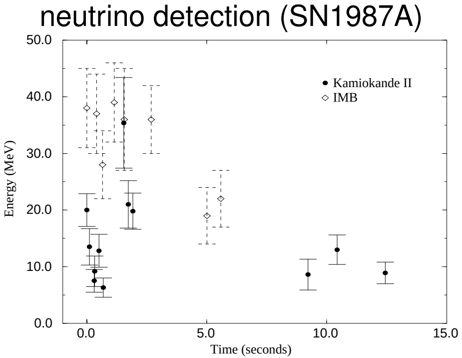
Light curve follows the decay of Nickel.

$$^{56}\mathrm{Ni} \xrightarrow{6\ \text{days}} {}^{56}\mathrm{Co} \xrightarrow{77\ \text{days}} {}^{56}\mathrm{Fe}$$





Supernova neutrino detection

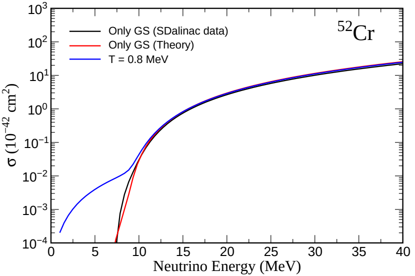


The Kamioka and IMB detectors are water Cerenkov detectors. Observed have been $\bar{\nu}_e$ neutrinos via there interaction on protons (in the water molecule). The detection of the other neutrino types is the main goal for the next nearby supernova to test the predicted neutrino hierarchy.

Inelastic ν-nucleus scattering in supernovae

Potential consequences:

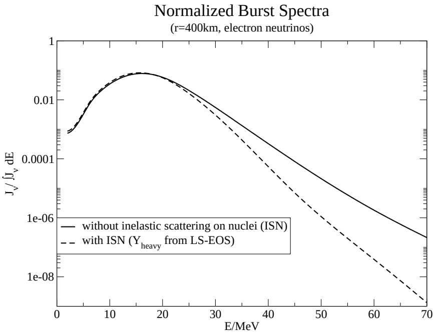
- thermalization of neutrinos during collapse
- preheating of matter before passing of shock
- nucleosynthesis, νp-process
- supernova neutrino signal



- neutrino cross sections from (e, e') data
- validation of shell model
- G.Martinez-Pinedo, P. v. Neumann-Cosel, A. Richter

Supernova neutrino signal

inelastic ν-nucleus scattering adds to the opacity for high-energy neutrin os



B. Müller, H.-Th. Janka, G. Martinez-Pinedo, A. Juodagalvis, J. Sampaio

Consequences for supernova neutrino detectors

Detector	Material	$\langle\sigma\rangle$ (10^{-42} cm^2) With $A(\nu,\nu')A^\star$	$\langle\sigma\rangle$ (10^{-42} cm^2) Without $A(\nu,\nu')A^\star$	Change
SNO	d	5.92	7.08	16%
MiniBoone	^{12}C	0.098	0.17	43%
	^{12}C (N_{gs})	0.089	0.15	41%
S-Kamiokande	^{16}O	0.013	0.031	58%
Icarus	^{40}Ar	17.1	21.5	20%
Minos	^{56}Fe	8.8	12.0	27%
OMNIS	^{208}Pb	147.2	201.2	27%

Change in supernova neutrino spectra reduce detection rates!