Nuclear Astrophysics

Stellar evolution, core-collapse supernova and explosive nucleosynthesis

Karlheinz Langanke

GSI & TU Darmstadt & FIAS

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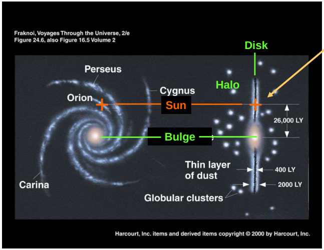
What is nuclear astrophysics?

Nuclear astrophysics aims at understanding the nuclear processes that take place in the universe. These nuclear processes generate energy in stars and contribute to the nucleosynthesis of the elements.

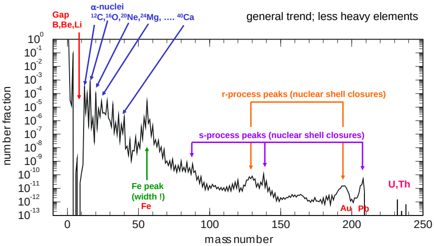
3. The solar abundance distribution



solar abundances:

Elemental (and isotopic) composition of Galaxy at location of solar system at the time of it's formation

Hydrogen mass fraction	X = 0.71
Helium mass fraction	Y = 0.28
Metallicity (mass fraction of everything else)	Z = 0.019
Heavy Elements (beyond Nickel) mass fraction	4E-6



N. Grevesse and A. J. Sauval, Space Science Reviews **85**, 161

Stellar reaction rate

Consider N_a and N_b particles per cubic centimeter of particle types a and b. The rate of nuclear reactions is given by:

$$r = N_a N_b \sigma(v) v$$

In stellar environment the velocity (energy) of particles follows a thermal distribution that depends on the type of particles.

- Nuclei (Maxwell-Boltzmann): $\phi(v) = N 4\pi v^2 \left(\frac{m}{2\pi kT}\right)^{3/2} \exp\left(-\frac{mv^2}{2kT}\right)$

The product σv has to be averaged over the velocity distribution $\phi(v)$

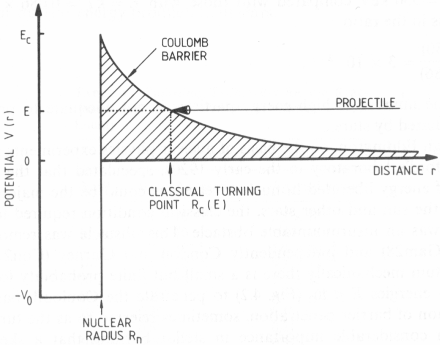
$$\langle \sigma v \rangle = \int_0^\infty \int_0^\infty \phi(v_a)\phi(v_b)\sigma(v) v dv_a dv_b$$

Changing to center-of-mass coordinates, integrating over the cm-velocity and using $E = \mu v^2/2$

$$\langle \sigma v \rangle = \left(\frac{8}{\pi\mu}\right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty \sigma(E) E \exp\left(-\frac{E}{kT}\right) dE$$

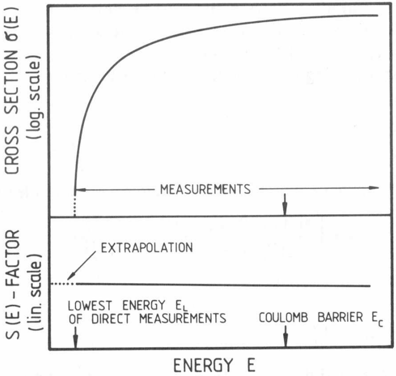
Charged-particle cross section

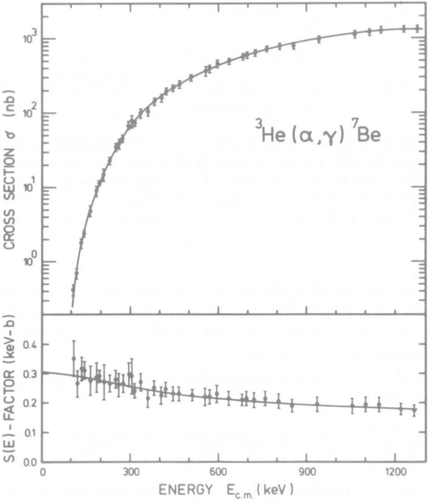
Stars' interior is a plasma made of charged particles (nuclei, electron). Nuclear reactions proceed by tunnel effect. For $p + p$ reaction Coulomb barrier 550 keV, but the typical energy in the sun is only 1.35 keV.



cross section: $\sigma(E) = \frac{1}{E} S(E) e^{-2\pi\eta}; \quad \eta = \frac{Z_1 Z_2 e^2}{\hbar}\sqrt{\frac{\mu}{2E}} = \frac{b}{E^{1/2}}$

S factor allows accurate extrapolations to low energy.

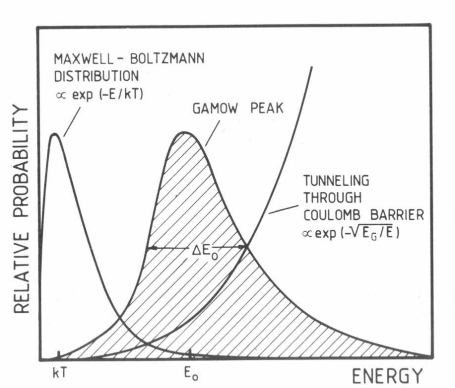




Gamow window

Using definition of S factor:

$$\langle \sigma v \rangle = \left(\frac{8}{\pi\mu}\right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty S(E) \exp\left[-\frac{E}{kT} - \frac{b}{E^{1/2}}\right] dE$$



Gamow window

Assuming that S factor is constant over the Gamow window and approximating the integrand by a Gaussian one gets:

$$\langle \sigma v \rangle = \left(\frac{2}{\mu}\right)^{1/2} \frac{\Delta}{(kT)^{3/2}} S(E_0) \exp\left(-\frac{3E_0}{kT}\right)$$

$$\begin{aligned} E_0 &= 1.22[\mathrm{keV}](Z_1^2 Z_2^2 \mu T_6^2)^{1/3} \\ \Delta &= 0.749[\mathrm{keV}](Z_1^2 Z_2^2 \mu T_6^5)^{1/6} \end{aligned}$$

(T_x measures the temperature in 10^x K.)
Examples for solar conditions:

reaction	E_0 [keV]	$\Delta/2$ [keV]	$I_{\max}$	T dependence of $\langle \sigma v \rangle$
p+p	5.9	3.2	1.1×10^{-6}	$T^{3.9}$
p+^{14}N	26.5	6.8	1.8×10^{-27}	T^{20}
α+^{12}C	56.0	9.8	3.0×10^{-57}	T^{42}
^{16}O+^{16}O	237.0	20.2	6.2×10^{-239}	T^{182}

It depends very sensitively on temperature!

The solar pp chains

$$^1_1\mathrm{H} + {}^1_1\mathrm{H} \longrightarrow {}^2_1\mathrm{H} + e^+ + \nu_e$$

$$^2_1\mathrm{H} + {}^1_1\mathrm{H} \longrightarrow {}^3_2\mathrm{He} + \gamma$$

85%

$$^3_2\mathrm{He} + {}^3_2\mathrm{He} \longrightarrow {}^4_2\mathrm{He} + 2\,{}^1_1\mathrm{H}$$

(PP I)

15%

$$^3_2\mathrm{He} + {}^4_2\mathrm{He} \longrightarrow {}^7_4\mathrm{Be} + \gamma$$

15%

$$^7_4\mathrm{Be} + e^- \longrightarrow {}^7_3\mathrm{Li} + \nu_e$$

$$^7_3\mathrm{Li} + {}^1_1\mathrm{H} \longrightarrow 2\,{}^4_2\mathrm{He}$$

(PP II)

0.02%

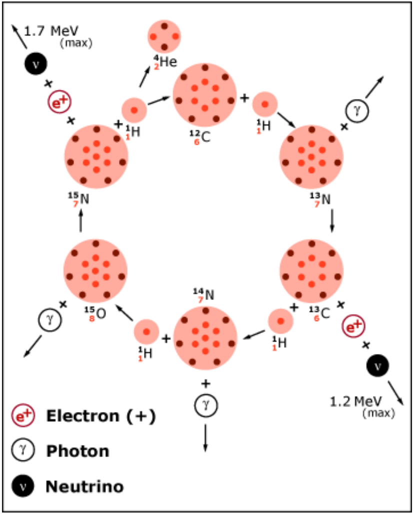
$$^7_4\mathrm{Be} + {}^1_1\mathrm{H} \longrightarrow {}^8_5\mathrm{B} + \gamma$$

$$^8_5\mathrm{B} \longrightarrow {}^8_4\mathrm{Be} + e^+ + \nu_e$$

$$^8_4\mathrm{Be} \longrightarrow 2\,{}^4_2\mathrm{He}$$

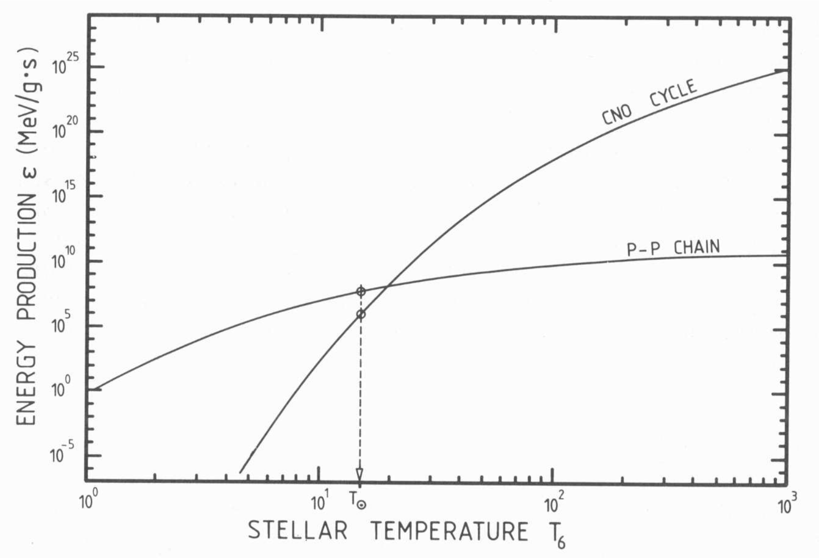
(PP III)

The other hydrogen burning: CNO cycle



requires presence of ^{12}C as catalyst

Energy generation: CNO cycle vs pp-chains

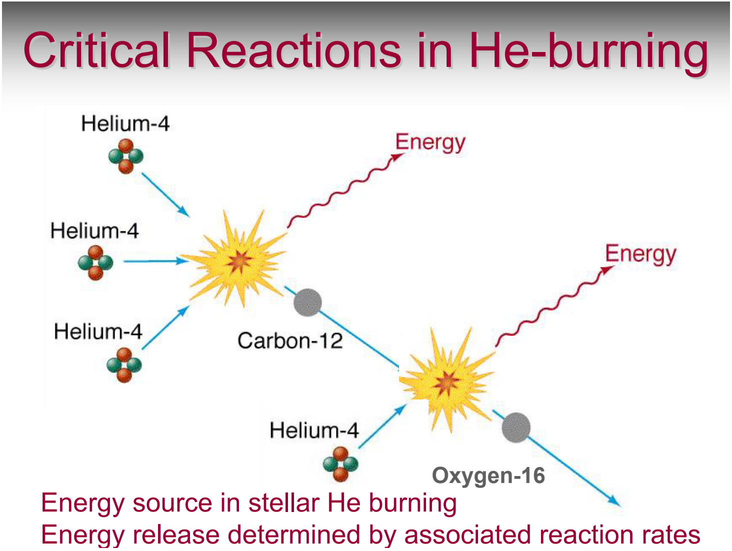


Consequences

- stars slightly heavier than the Sun burn hydrogen via CNO cycle
- this goes significantly faster; such stars have much shorter lifetimes

mass [$M_\odot$]	timescale [y]
0.4	2×10^{11}
0.8	1.4×10^{10}
1.0	1×10^{10}
1.1	9×10^{9}
1.7	2.7×10^{9}
3.0	2.2×10^{8}
5.0	6×10^{7}
9.0	2×10^{7}
16.0	1×10^{7}
25.0	7×10^{6}
40.0	1×10^{6}

hydrogen burning timescales depend strongly on mass. Stars slightly heavier than the Sun burn hydrogen by CNO cycle.



Products of helium burning are carbon and oxygen, the bricks of life!

Carbon Burning

Burning conditions:

for stars > 8 M_o (solar masses) (ZAMS)

T~ 600-700 Mio

$\rho \sim 10^5$-10^6 g/cm^3

Major reaction sequences:

$$
\begin{aligned}
^{12}\mathrm{C} + {}^{12}\mathrm{C} \rightarrow {}^{24}\mathrm{Mg}^* &\rightarrow {}^{23}\mathrm{Mg} + n - 2.62 \text{ MeV} \\
&\rightarrow {}^{20}\mathrm{Ne} + \alpha + 4.62 \text{ MeV} \\
&\rightarrow {}^{23}\mathrm{Na} + p + 2.24 \text{ MeV}.
\end{aligned}
$$

dominates by far

of course p's, n's, and a's are recaptured … ^{23}Mg can b-decay into ^{23}Na

Composition at the end of burning:

mainly ^{20}Ne, ^{24}Mg, with some ^{21,22}Ne, ^{23}Na, ^{24,25,26}Mg, ^{26,27}Al

of course ^{16}O is still present in quantities comparable with ^{20}Ne (not burning … yet) 21

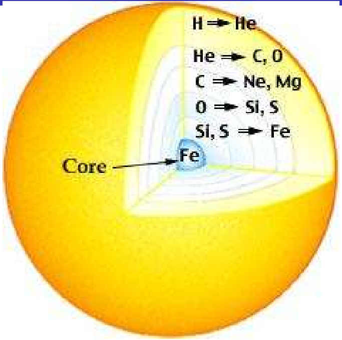
Nuclear burning stages

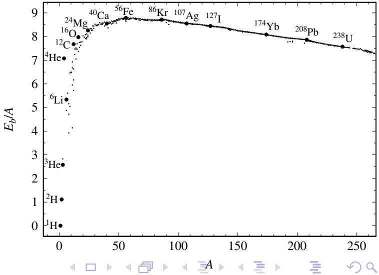
(e.g., 20 solar mass star)

Fuel	Main Product	Secondary Product	T (10^9 K)	Time (yr)	Main Reaction
H	He	^{14}N	0.02	10^7	$4\,H \xrightarrow{CNO} {}^4He$
He	O, C	^{18}O, ^{22}Ne s-process	0.2	10^6	$3\,He^4 \rightarrow {}^{12}C$ $^{12}C(\alpha,\gamma)^{16}O$
C	Ne, Mg	Na	0.8	10^3	$^{12}C + {}^{12}C$
Ne	O, Mg	Al, P	1.5	3	$^{20}Ne(\gamma,\alpha)^{16}O$ $^{20}Ne(\alpha,\gamma)^{24}Mg$
O	Si, S	Cl, Ar, K, Ca	2.0	0.8	$^{16}O + {}^{16}O$
Si	Fe	Ti, V, Cr, Mn, Co, Ni	3.5	0.02	$^{28}Si(\gamma,\alpha)\ldots$

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 solar masses.



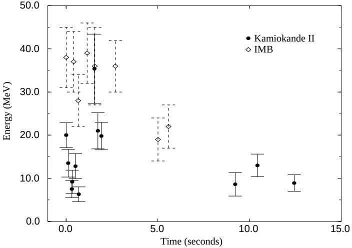


A few facts: SN1987A

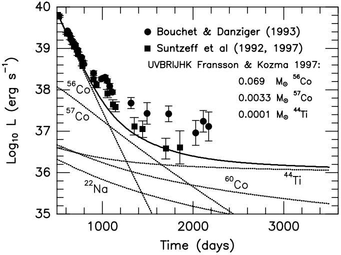
Type II supernova in LMC ($\sim$ 55 kpc)

- $E_{\rm grav} \approx 10^{53}$ 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

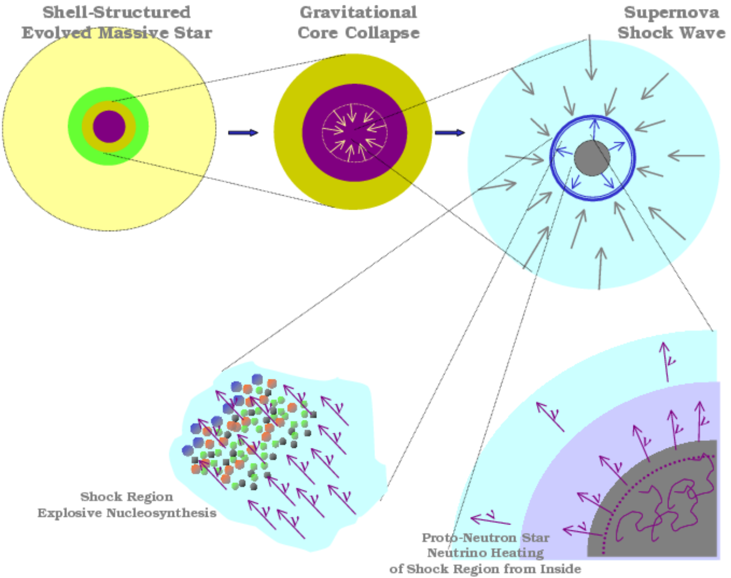


Presupernova and collapse models

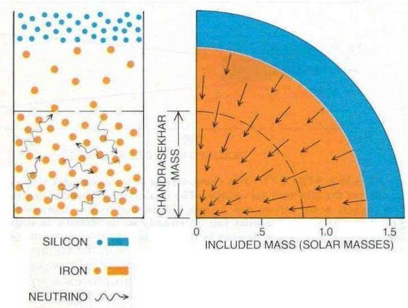
Core-collapse supernova simulations are separated into:

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)

Core-collapse supernova.



Collapse phase



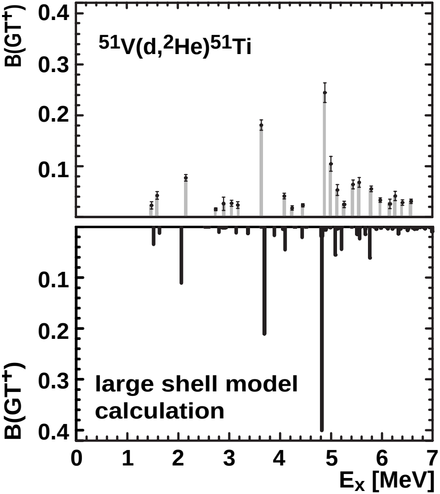
Important processes:

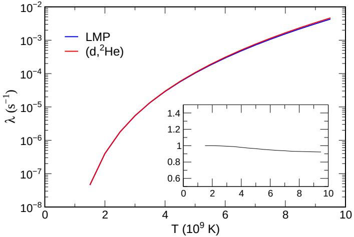
- $T > 10^{10}$ K, $\rho > 10^{10}$ g/cm^3
- Neutrino transport (Boltzmann equation):
  $\nu + A \rightleftarrows \nu + A$ (trapping)
  $\nu + e^- \rightleftarrows \nu + e^-$ (thermalization)

  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

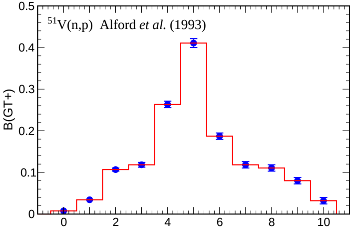
Shell model and $(d,{}^2\mathrm{He})$ GT strengths

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

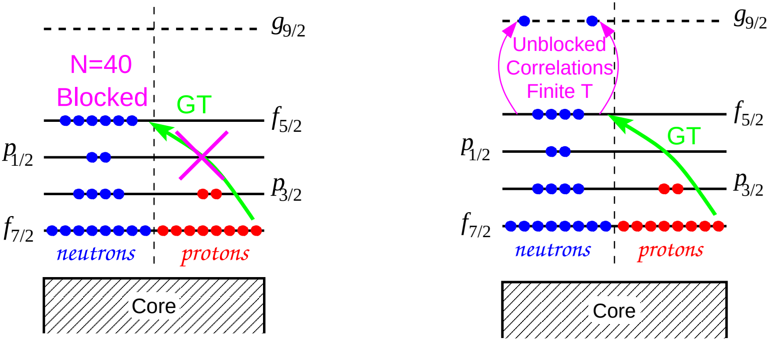




Old (n,p) data

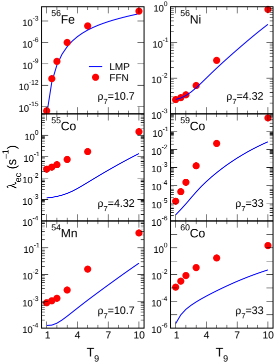


Pauli blocking of Gamow-Teller transition

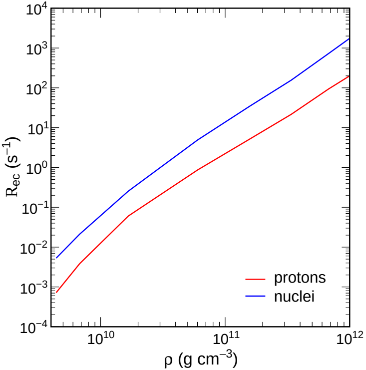


- Unblocking mechanism: correlations and finite temperature
- calculation of rate in SMMC + RPA model

How do shell-model rates compare to previous rates?

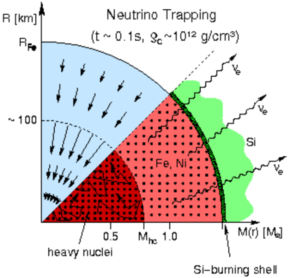


$A < 65$: SM rates smaller



$A > 65$: SM rates larger

Neutrino trapping

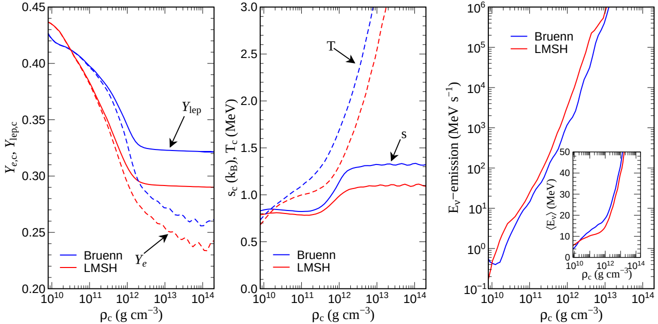


- $\nu + A \rightleftarrows \nu + A$ (trapping)
  elastic process, no energy, but momentum transfer
- $\nu + e^- \rightleftarrows \nu' + e^-$ (thermalization)
  inelastic scattering, energy transfer
- $\nu + (Z, A) \rightarrow \nu' + (Z, A)^*$
  (thermalization)
  inelastic scattering, energy transfer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

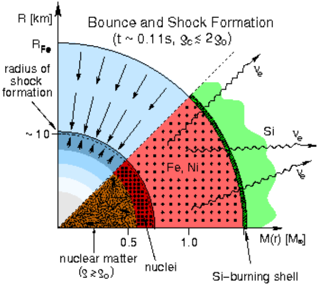
Effect on improved capture rates on collapse

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



For $\rho > 10^{12}$ g/cm^3 fermi sea of neutrinos forms as neutrinos get trapped. Weak interaction is then basically in equilibrium!

Core bounce

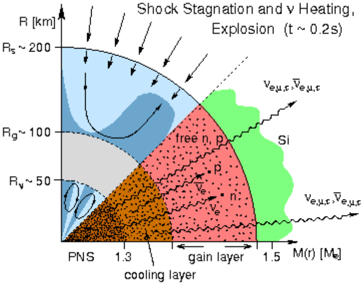


The collapse continues until the central density becomes substantially (by about a factor 2-4) larger than nuclear density ($\rho_{nm} \approx 2 \times 10^{14}$ g/cm^3). Then nuclear pressure slows down the infall and finally stops it. When the inner core has reached its maximum density (*maximum scrunch*),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

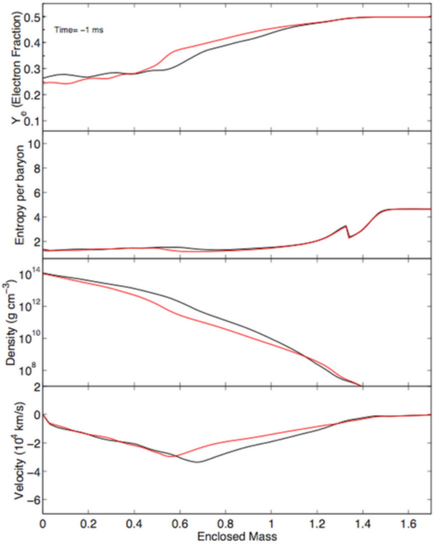


- The important reactions directly behind the shock are:

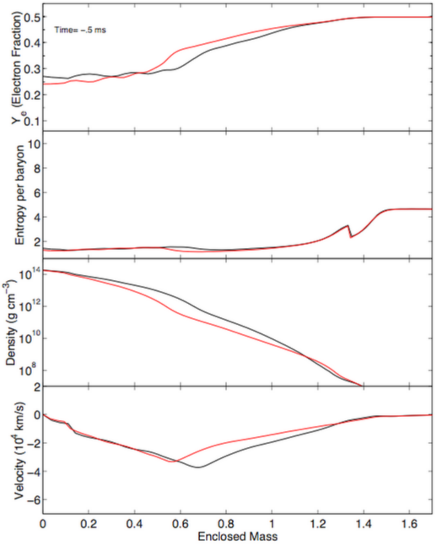
  $$\nu_e + n \leftrightarrow p + e^- ; \quad \bar{\nu}_e + p \leftrightarrow n + e^+$$

- 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



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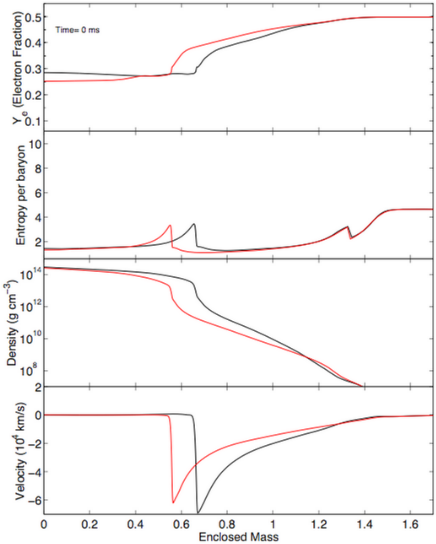
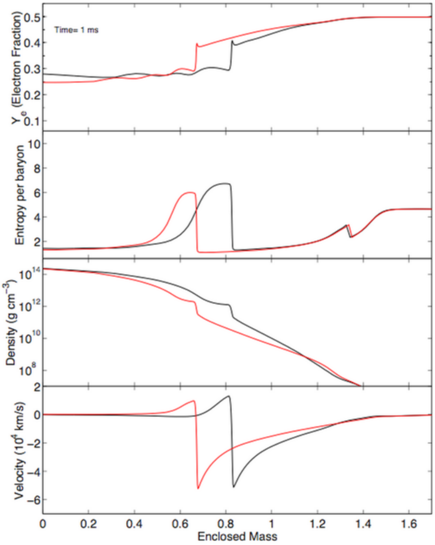


Bounce and shock wave evolution



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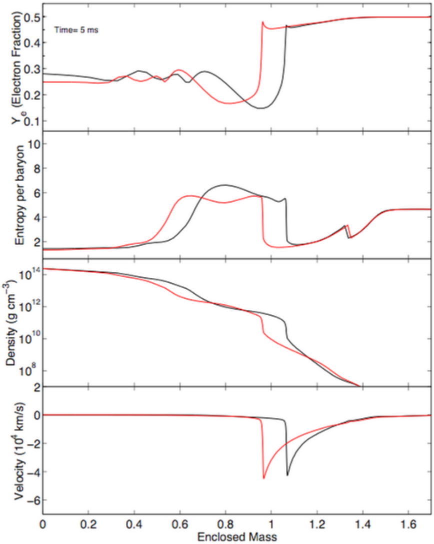

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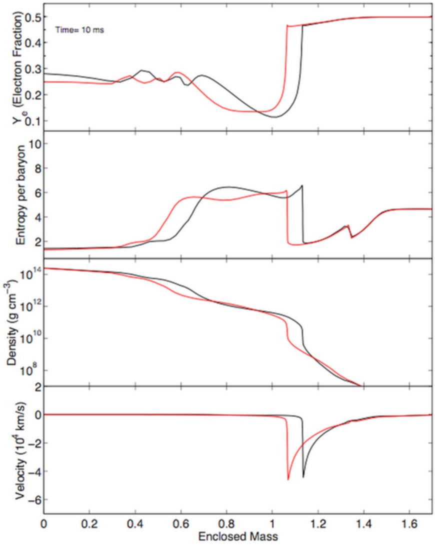
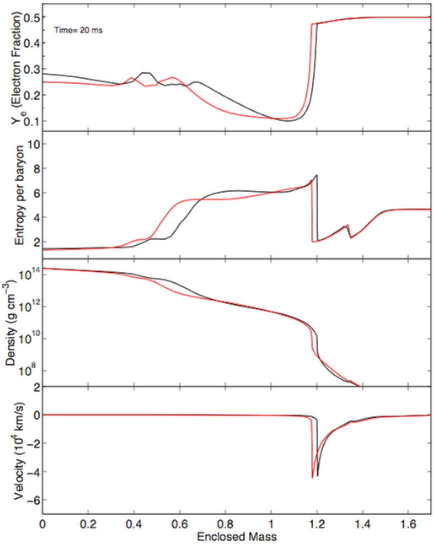
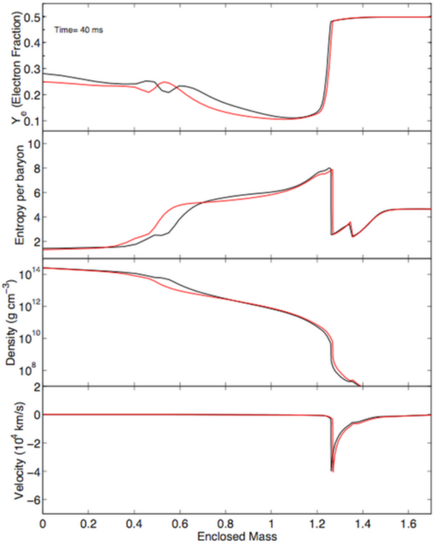


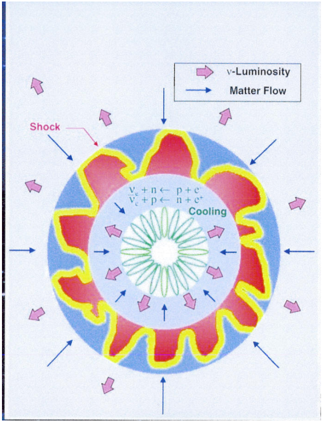
Bounce and shock wave evolution



Bounce and shock wave evolution

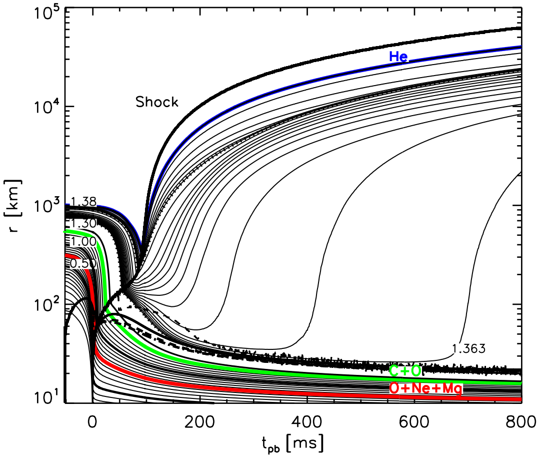


Convection

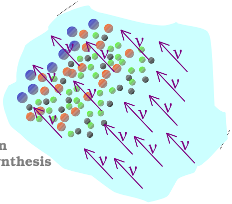


There exist now two-dimensional simulations (with neutrino transport and modern microphysics) which yield successful explosions. Convection brings neutrinos from deeper (hotter) layers to the shock and increase the effectiveness of energy transfer.

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



Explosive nucleosynthesis in supernova



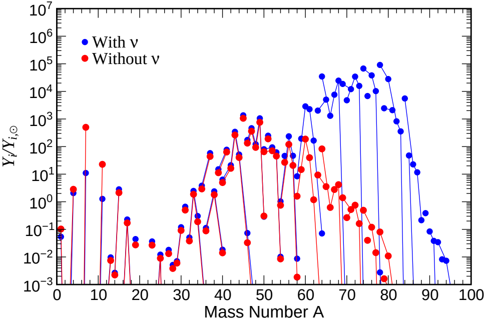
- Consistent treatment of supernova dynamics coupled with a nuclear network.
- Essential neutrino reactions in the shock heated region

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

- 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

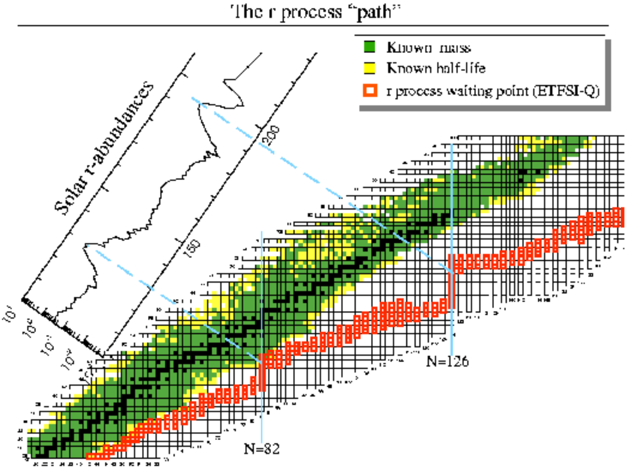


Antineutrinos help to bridge long waiting points via (n,p) reactions

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

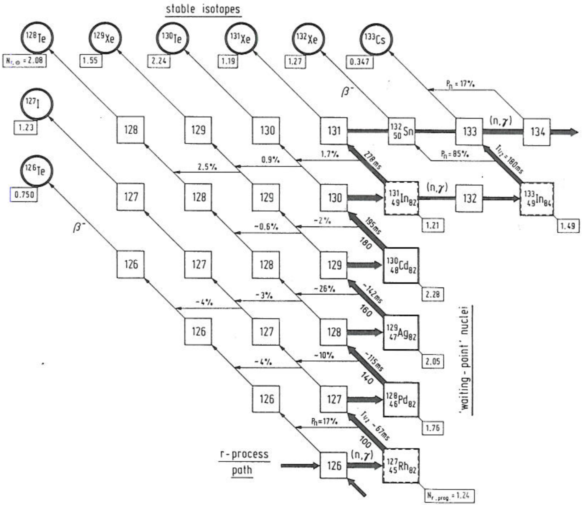
C. Fröhlich, G. Martinez-Pinedo, et al., PRL 96 (2006) 142502

r-process



$T \approx 100$ keV $\quad n \gtrsim 10^{20}$ cm^{-3} implies $\tau_n \ll \tau_\beta$
$(n, \gamma) \rightleftarrows (\gamma, n)$ implies $S_n \approx 2$ MeV

The r-process at magic neutron numbers



Why are there r-process peaks?

Once the path reaches nuclei with magic neutron numbers (Z, N_{mag}), the neutron separation energy for the nucleus $(Z, N_{mag} + 1)$ decreases strongly. Thus, (γ, n) hinders the process to continue and (Z, N_{mag}) *beta*-decays to $(Z + 1, N_{mag} - 1)$, which is followed immediately by n-capture to $(Z + 1, N_{mag})$. This sequence of alternative β-decays and n-captures repeat itself, until n-capture on a magic nucleus can compete with destruction by (γ, n).

Thus, the r-process flow halts at the magic neutron numbers. Due to the extra binding energy of magic nuclei, the Q_β values of these nuclei are usually smaller than those for other r-process nuclei. This makes the lifetimes of the magic nuclei longer than lifetimes of other r-process nuclei. Furthermore, the lifetimes of the magic nuclei increase significantly with decreasing neutron excess. For example, the halflive of the r-process nucleus ^{130}Cd has been measured as 195 ± 35 ms, while typical halflives along the r-process are about 10 ms.

Thus, material is enhanced in nuclei with N_{mag}, which after freeze-out, results in the observed r-process abundance peaks.

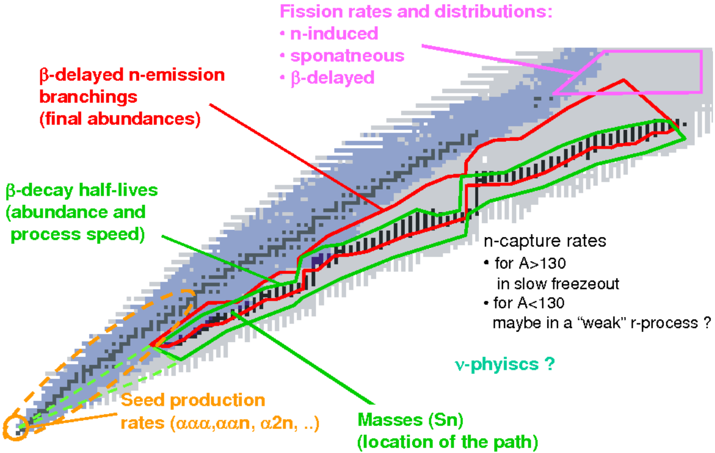
Where does the r-process occur in nature?

This has been named one of the 11 fundamental questions in science. Recent observational evidence in metal-poor (very old) stars point to two distinct r-process sites. One site appears to produce the r-process nuclides above $A \sim 130$; another one has to add to the abundance of r-process nuclides below $A = 130$.

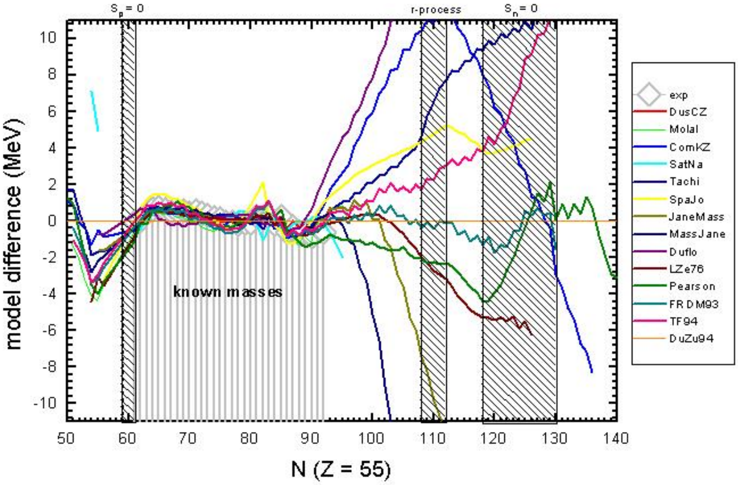
The two favorite sites are:

1. neutrino-driven wind above the proto-neutron star in a core-collapse supernova
2. neutron star mergers

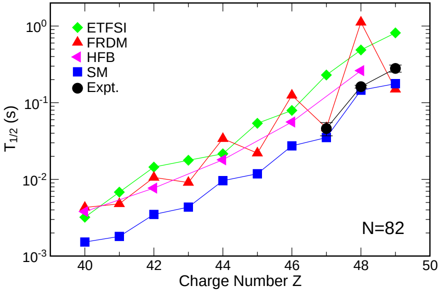
Which nuclear ingredients are needed?

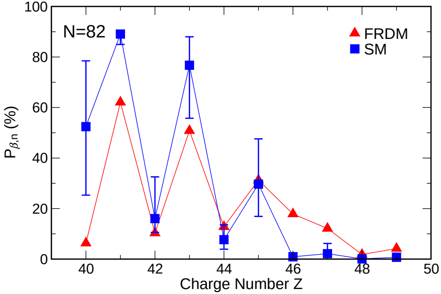


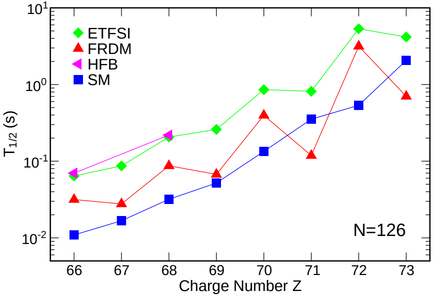
Mass predictions

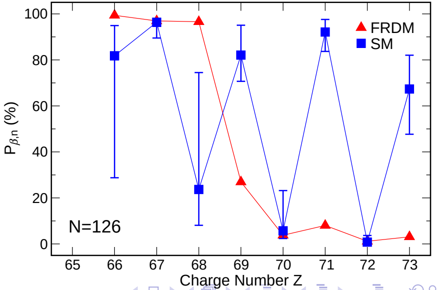


Half-lives for r-process nuclei





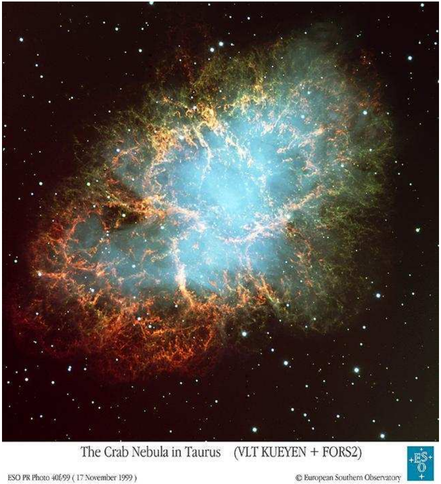


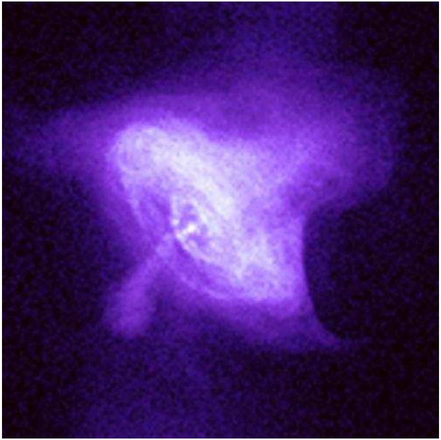


Supernova remnants

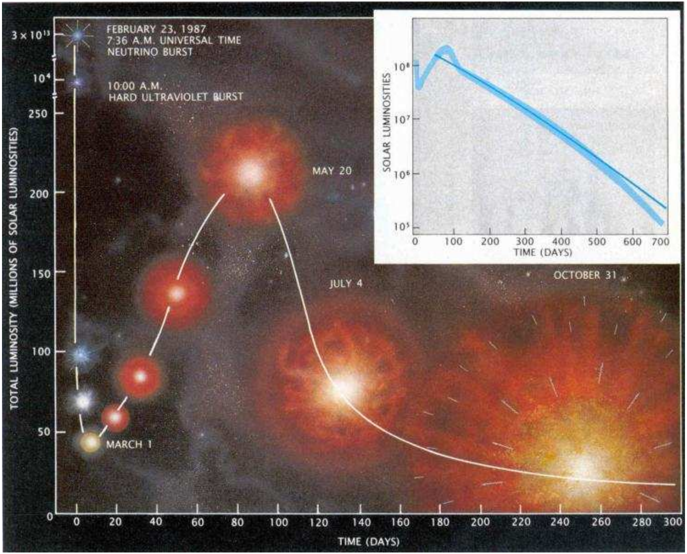
The remnant left over in the explosion depends on the main-sequence mass M_{ms} and on the maximum mass for neutron stars. The later is not quite well known. Most neutron stars, whose masses are well determined (they are in binaries), have masses around 1.4 $M_\odot$, however, recent observations might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



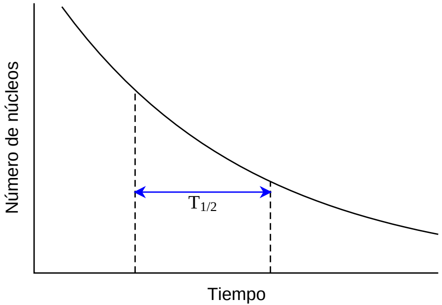
FEBRUARY 23, 1987
7:36 A.M. UNIVERSAL TIME
NEUTRINO BURST
10:00 A.M.
HARD ULTRAVIOLET BURST
MAY 20
JULY 4
OCTOBER 31
MARCH 1
TOTAL LUMINOSITY (MILLIONS OF SOLAR LUMINOSITIES)
3 × 10¹³
10⁴
250
200
150
100
50
0
0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300
TIME (DAYS)
SOLAR LUMINOSITIES
10⁸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

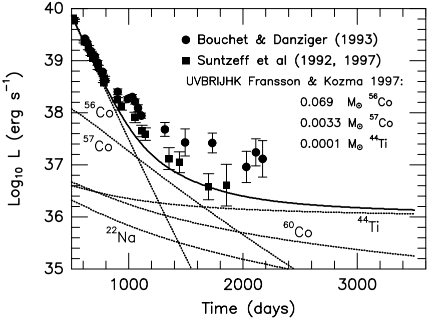
Energy from radioactive decays

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.

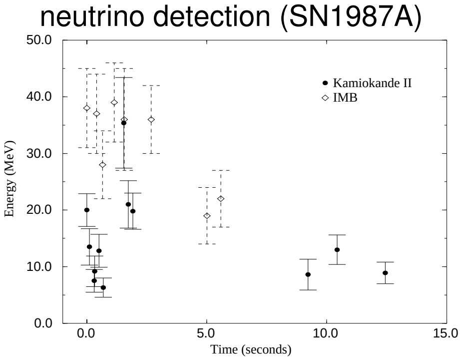
Light curve follows the decay of Nickel.

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





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.