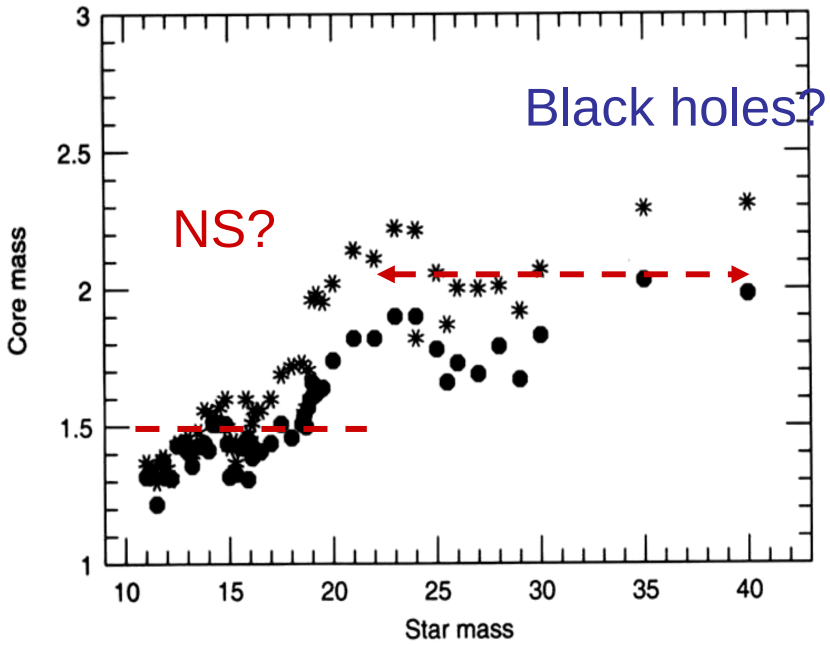
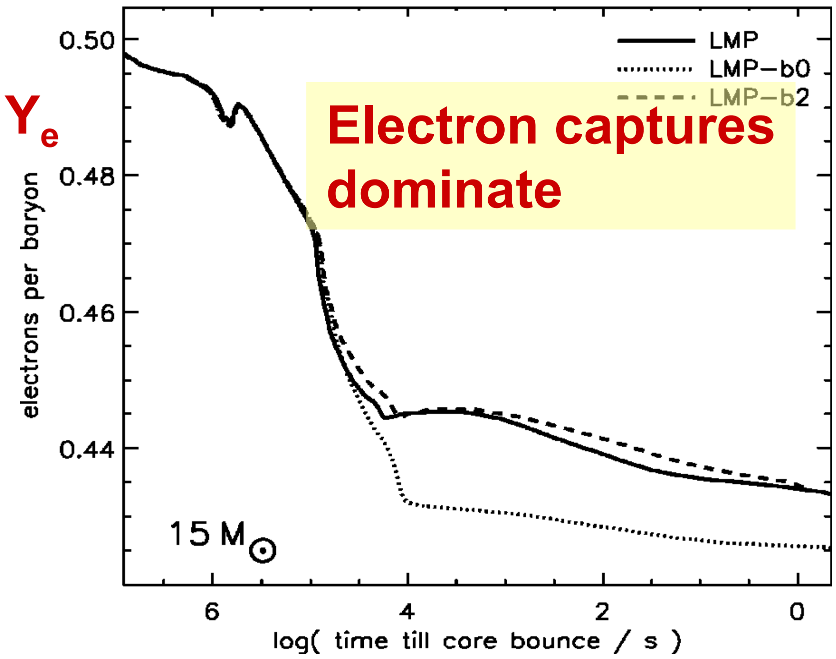
Lecture 6.Core collapse supernovae (type II, type Ibc). Neutrino emission. SN1987A. Classification of supernovae. Formation of neutron stars.

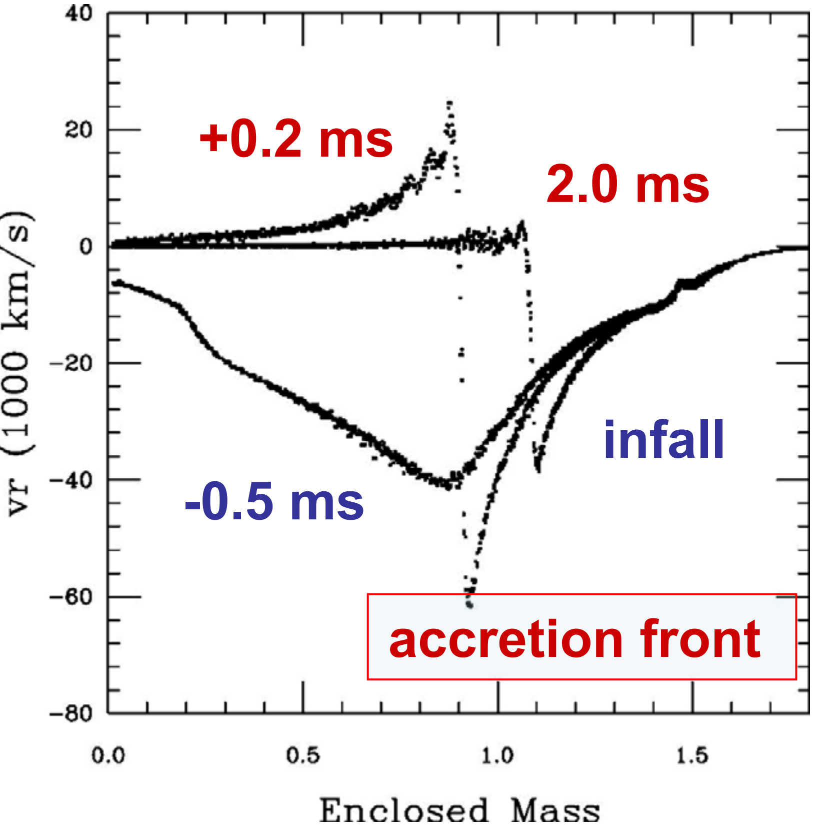
Deleptonized iron core is formed and starts to collapse due to various instabilities





Timmes, Woosley, Weaver 1995

Core collapse and bounce



Herant, Woosley 1996

During collapse, relatively cold heavy bound nuclei persist until they touch and merged at about nuclear density $\rho_n = 2.8 \times 10^{14}$ g/cm^3 forming one huge nucleus. The density overshoots ρ_n by a factor of several. The core rebounds due to hard-core repulsive potential. Shock bounce is formed. BUT DOES NOT LEAD TO THE SN EXPLOSION:

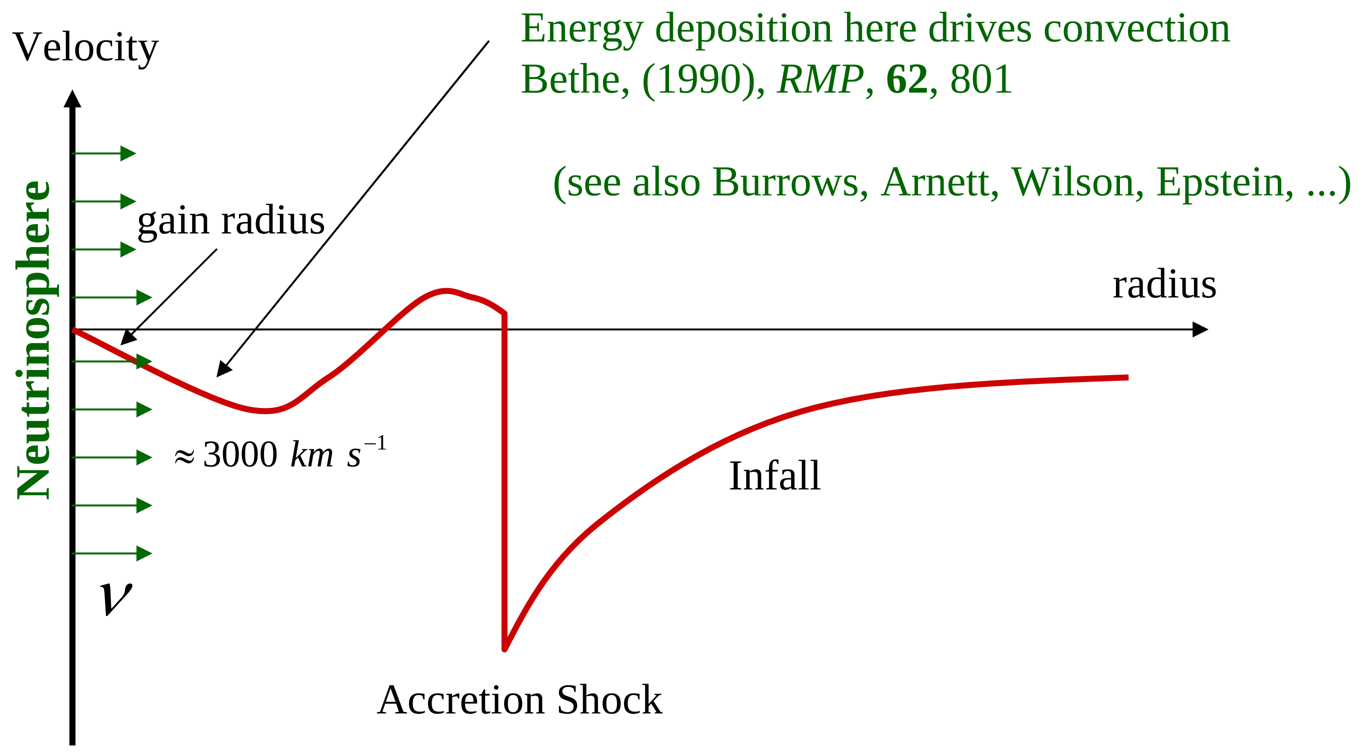
1. Shock spends its energy to disintegrate nuclei (10^{51} ergs per each 0.1 M☉)
2. Neutrino cooling from behind the shock is very effective ➔

10 ms after the core bounce a hot dense proto-NS accretes matter at a rate 1-10 $M_\odot$ per yr!

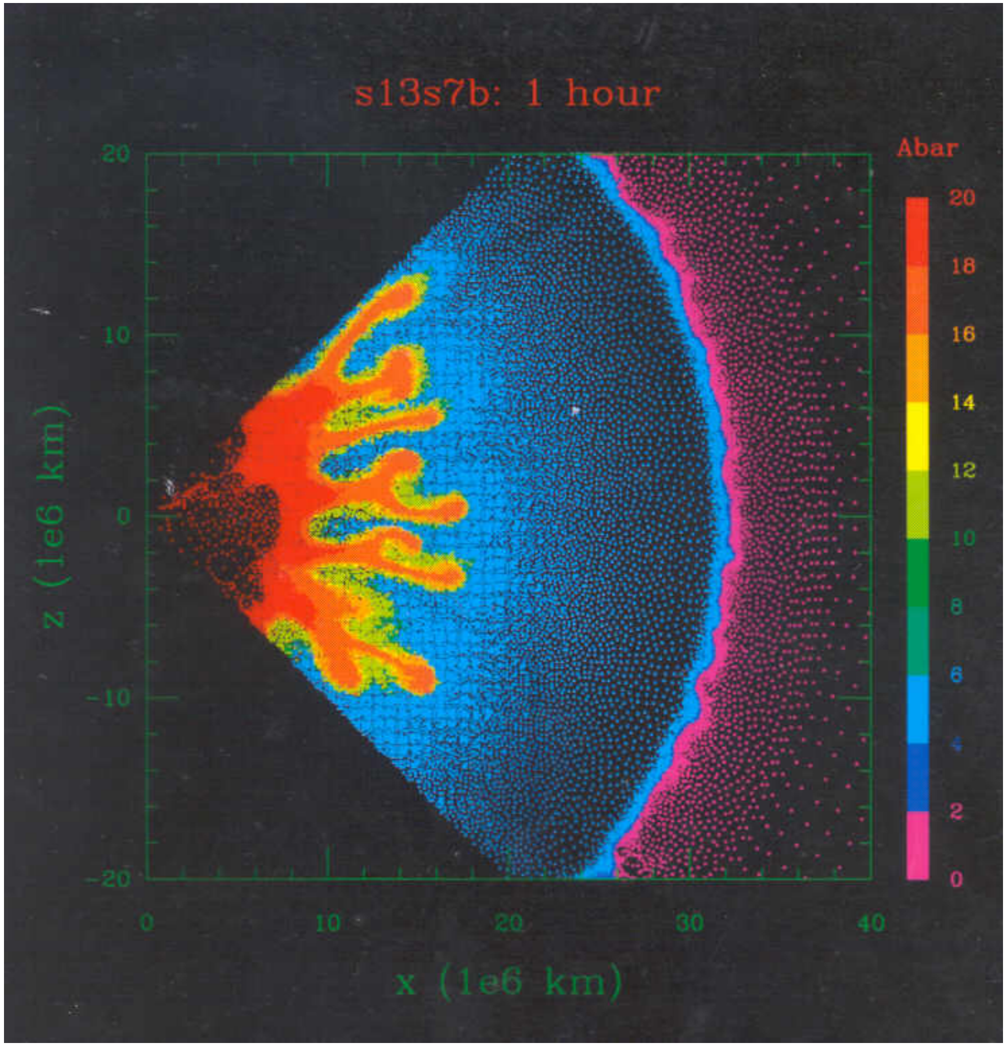
Delayed SN explosions

?

- Neutrino-driven explosions (Colgate & White 1966, Arnett 1966). "Delayed" neutrino mechanism Wilson (1985), Bethe & Wilson (1985)…. Decades of simulations: bounce itself cannot produce explosion by piston action on the mantle
- How to revive the stalled shock? Ideas: neutrino-driven convection (Herant et al 94, Burrows, Hayes, Fryxell 95,… Fryer &Warren 04…)
- Modern best multi-D with neutrino transport (Rampp & Janka 02, Buras et al. 05): Within 200-300ms after bounce, at 150-200 km above proto-NS, the shock stalls. No successful explosions.
- Alternatives: Magneto-rotational mechanism (Bisnovatyj-Kogan 1970, 2D Ardelyan et al. 05 – successful!), Akiyama et al 03, rotation core fragmentation (Imshennik 92, Imshennik & Nadyozhin 92) – *but require rapid rotation of pre-SN core*.
- New ideas (Burrows et al 05, astro-ph/0510687): accretion front instability ➔ acoustic power generates in the core region and drives explosion 500 ms after bounce. Worth further study.

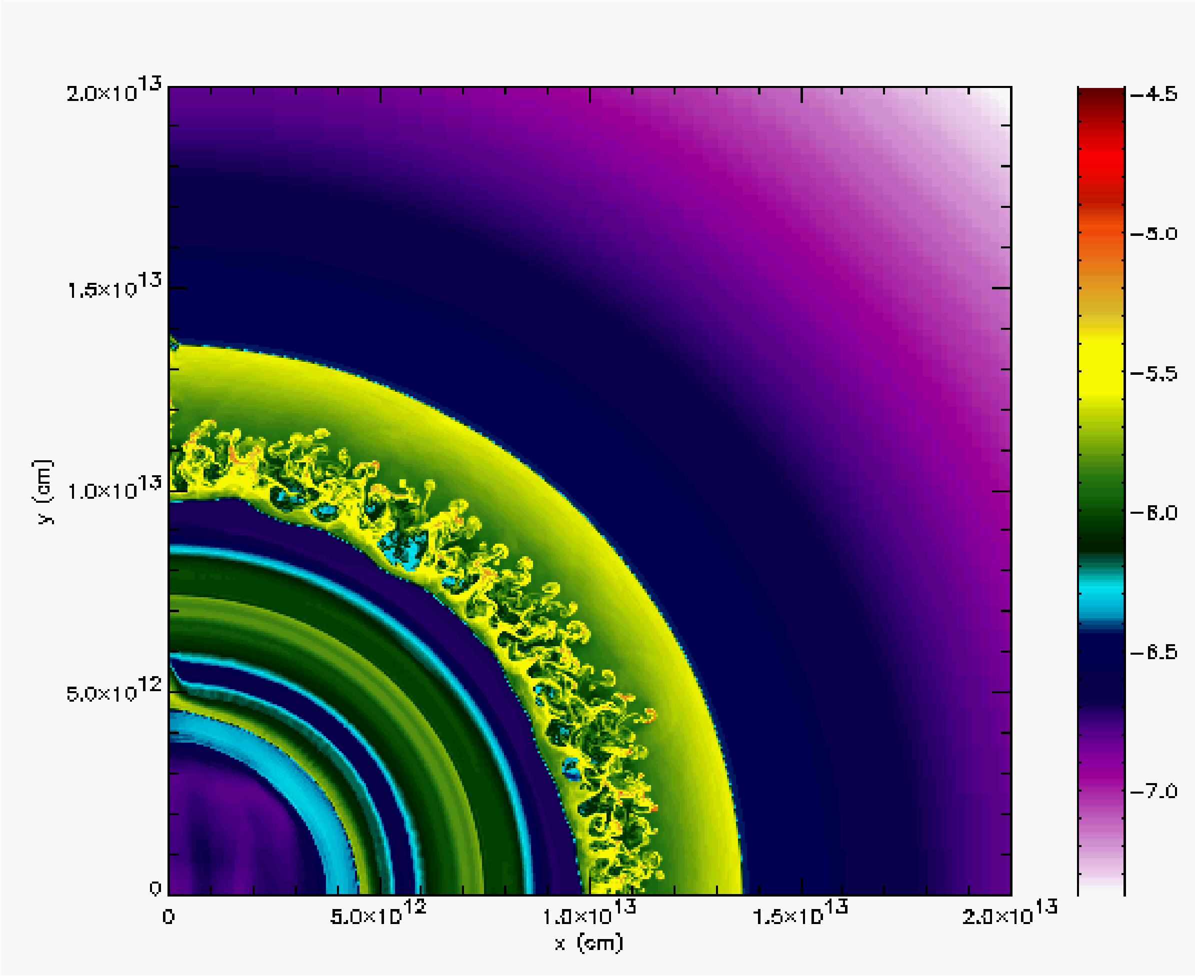


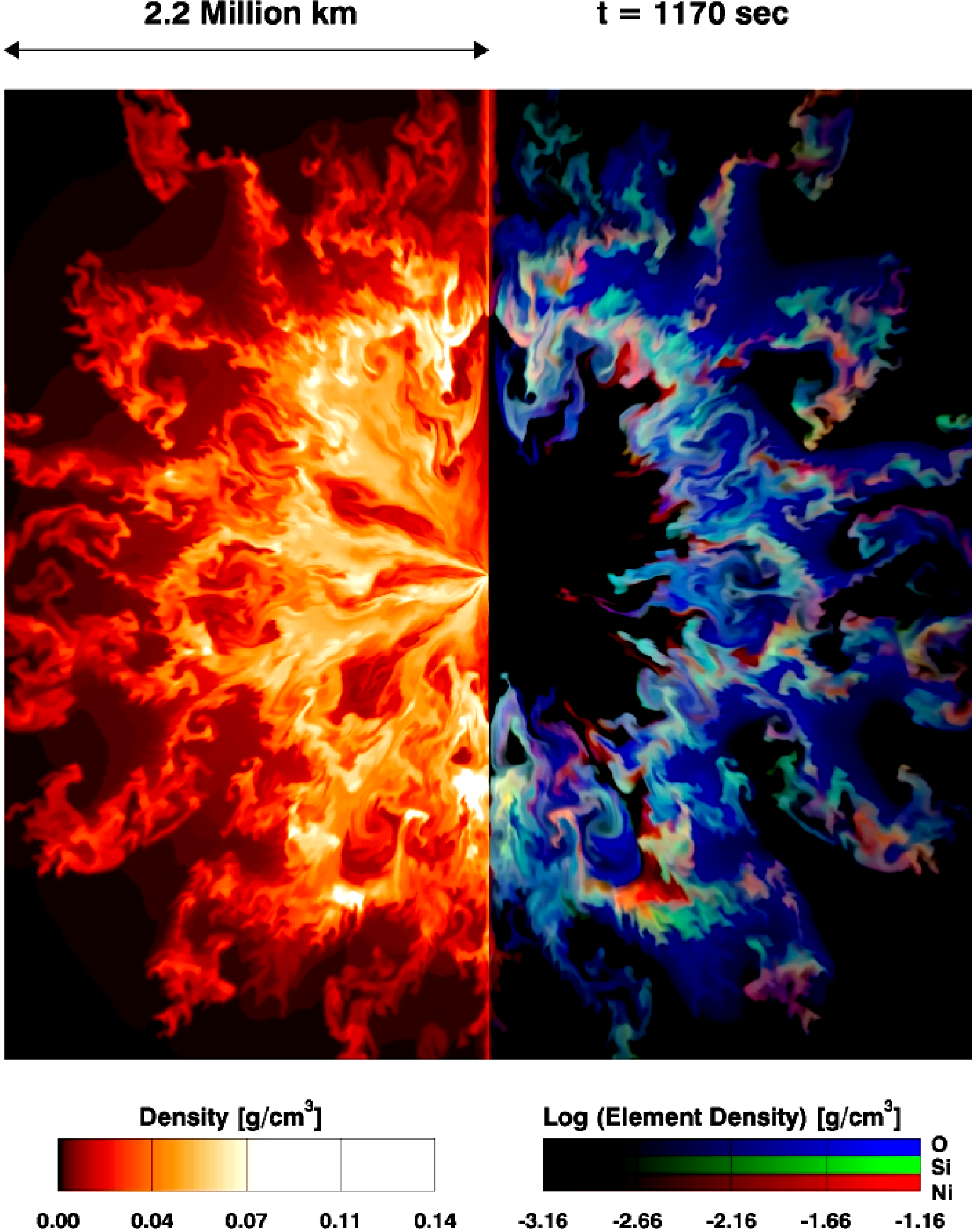
Inside the shock, matter is in approximate hydrostatic equilibrium. Inside the gain radius there is net energy loss to neutrinos. Outside there is net energy gain from neutrino deposition. At any one time there is about 0.1 solar masses in the gain region absorbing a few percent of the neutrino luminosity.



As the shock moves though regions of increasing ρr^3, it slows. The deceleration is communicated back towards the center by pressure waves. The density increases as one goes towards the center. The situation is thus RT unstable.

25 solar mass supernova, 1.2 x 10^{51} erg explosion. Calculation using modified FLASH code - Zingale & Woosley



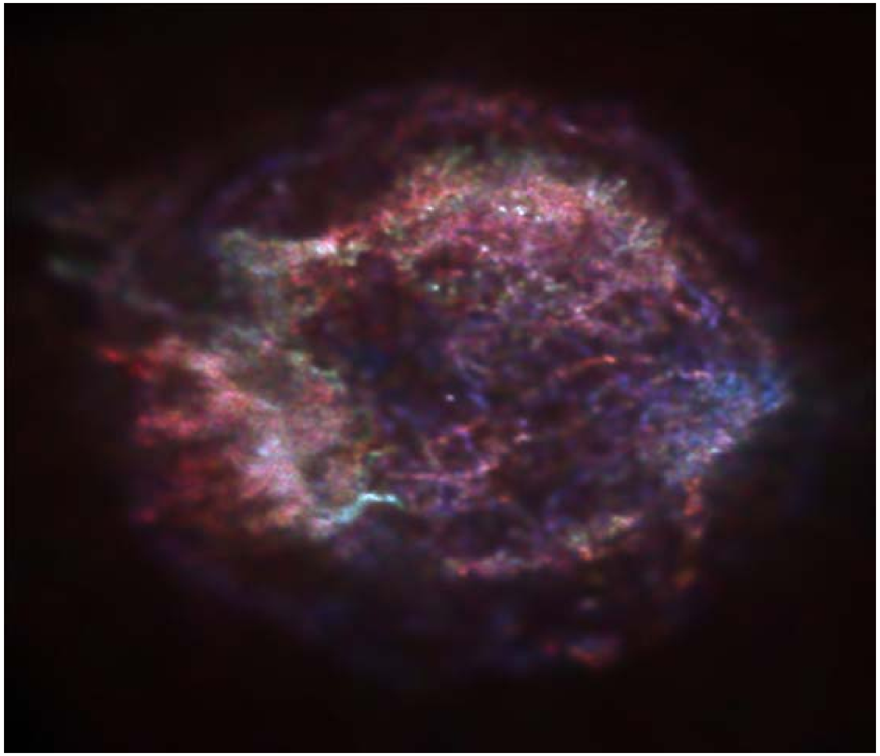


Mixing

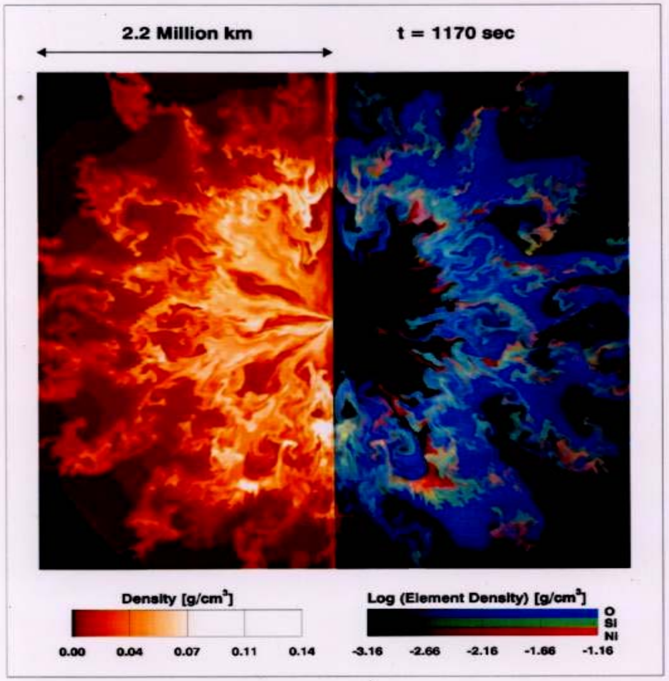
early during the supernova explosion may allow material from the bottom of exploding star come out -- even if most of the core falls back to form a black hole.

(Kifonidis et al. 2000)

Diagnosing an explosion

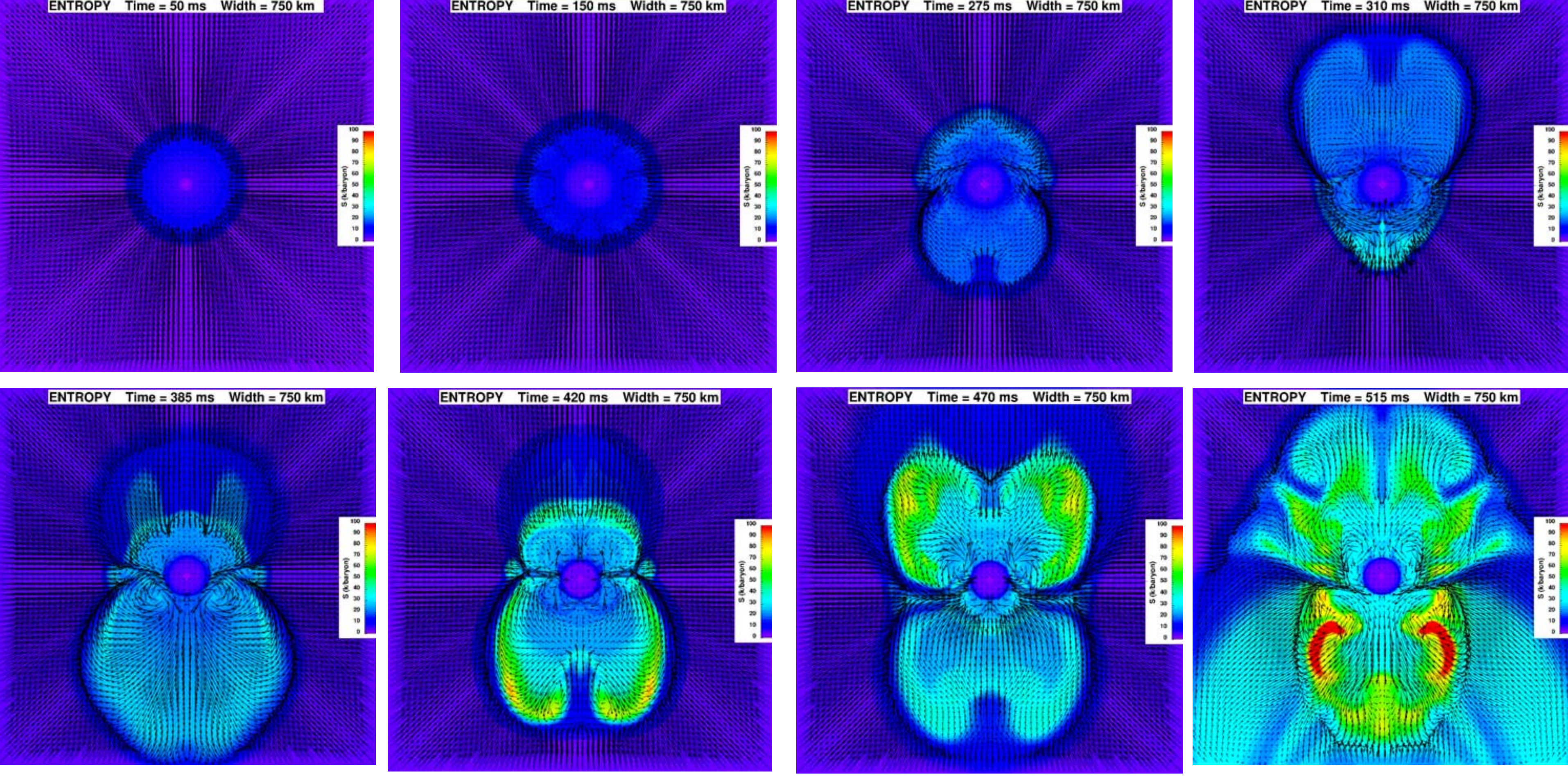


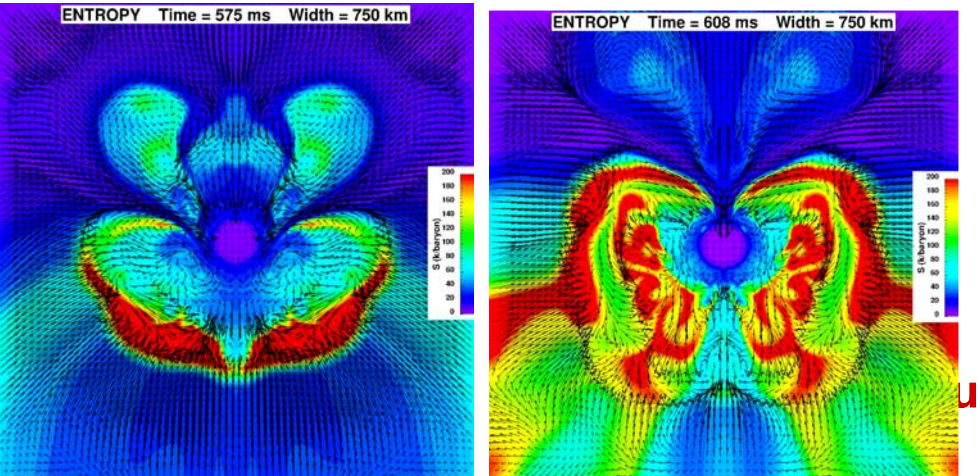
Kifonidis et al. (2001), *ApJL*, *531*, 123



Cas A SNR as seen by the Chandra Observatory.

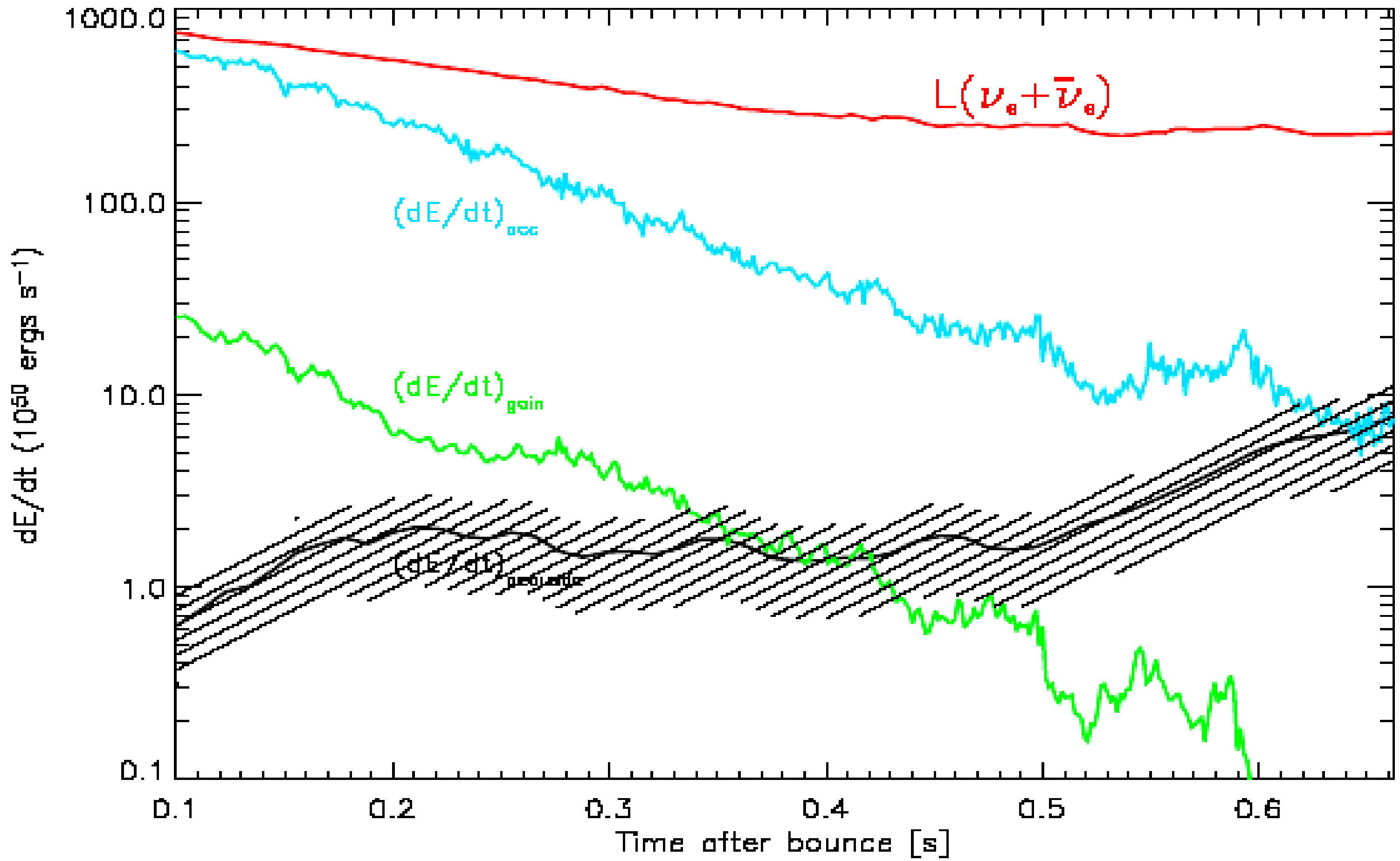
The red material on the left outer edge is enriched in iron. The greenish-white region is enriched in silicon. Why are elements made in the middle on the outside?



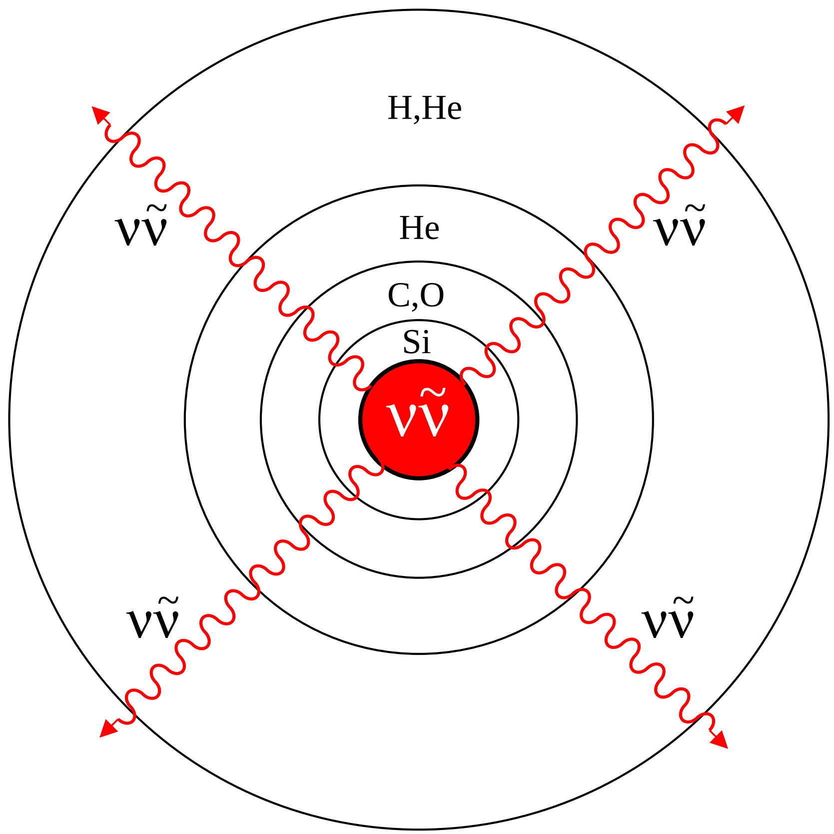


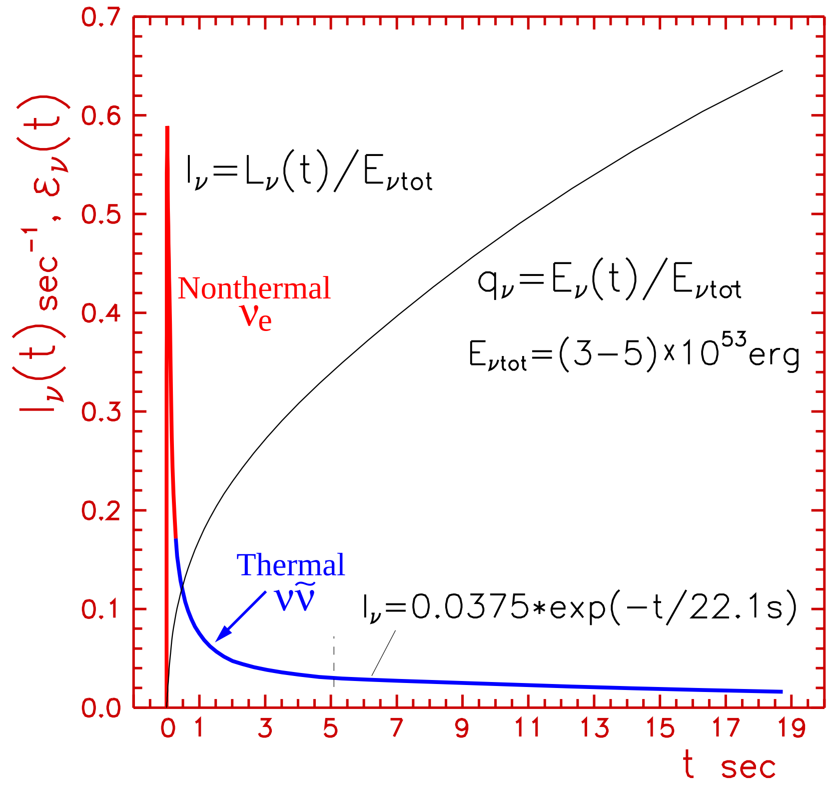
Example of successful acoustic powered SN (11 $M_\odot$ non-rotating progenitor) by Burrows et al ’05.

Acoustic power generation. The PNS acts as a transducer of accretion power GMM'/R to acoustic energy flux



Neutrino emission in SNe





Nadyozhin D.K., 1978

- **Non-thermal** ν-s (mostly ν_e!) are generated in non-equilibrium neutronization of matter during 1 s after the collapse when the core is transparent.

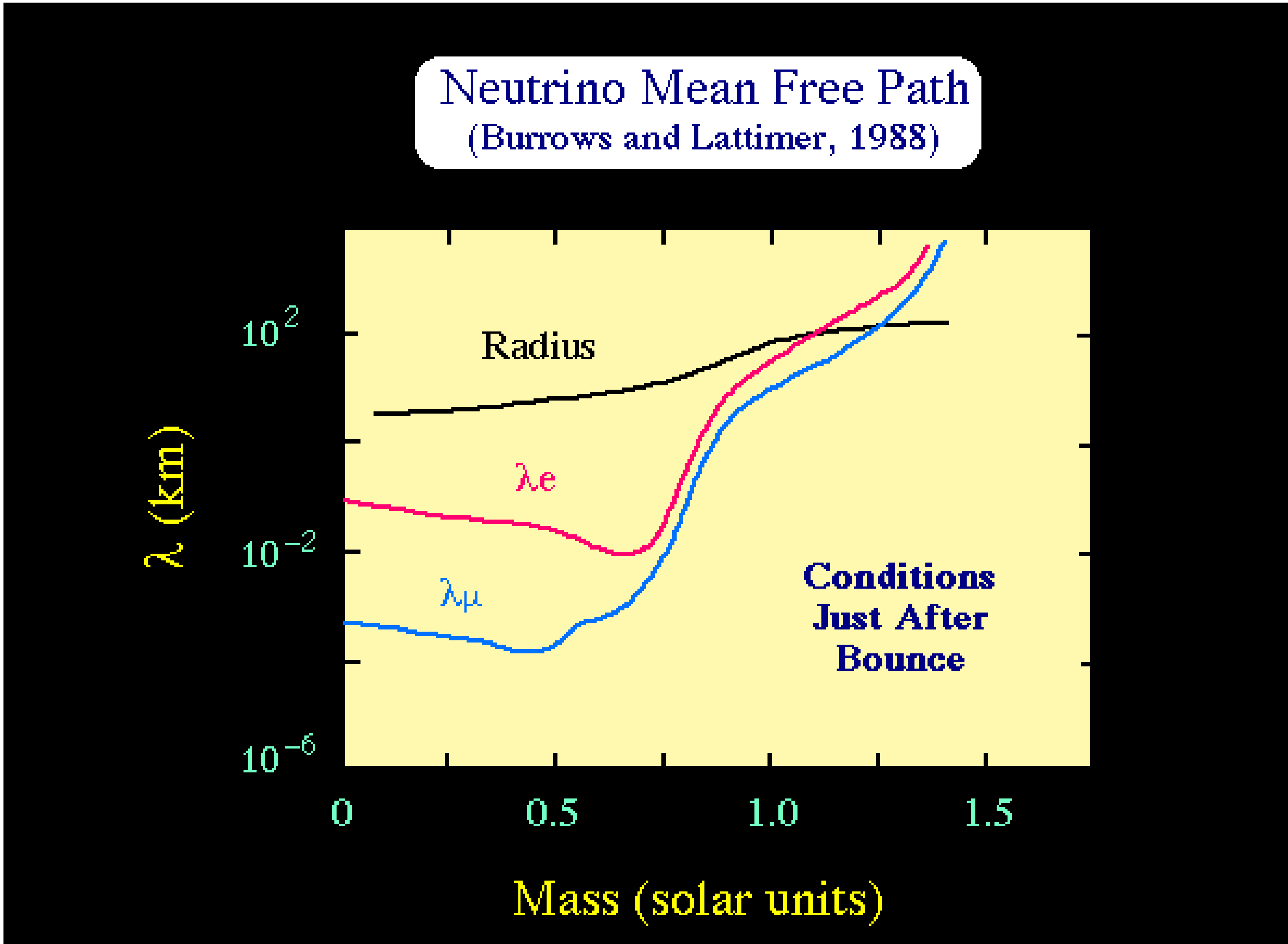
$$\langle \varepsilon_{\nu,e} \rangle \simeq 15-20\ \text{MeV}$$

$\Delta E_{\nu,e} \sim 10\%$ of total neutrino energy losses ($\sim 10^{53} ergs$)

- Neutrino cross-section $\sigma_\nu \sim 10^{-44}\text{cm}^2(\varepsilon_\nu/1\text{MeV})^2$ [times A^2 for coherent scattering on nuclei with atomic weight A]
- Elastic neutrino scattering + inelastic scattering of hot ν-s on degenrate electrons (each inelastic event decreases neutrino energy by a factor of 2) $\Rightarrow$

THERMALIZATION of neutrinos with $T_\nu \sim T_{\text{matter}} \sim 10$ MeV

- **Thermal neutrinos** of all sorts are "captured" at $\rho \sim 3\cdot 10^{11}\,\text{g/cm}^3$ and form optically thick neutrinosphere with $R_\nu \sim 20$ km



Neutrino Mean Free Path
(Burrows and Lattimer, 1988)
Radius
λe
λμ
Conditions
Just After
Bounce
λ (km)
10^2
10^-2
10^-6
0
0.5
1.0
1.5
Mass (solar units)

Thermal Neutrino Burst Properties:

$$E_{tot} \sim \frac{3}{5}\frac{GM^2}{R}$$ $M = 1.5\ M_\odot$

$\sim 3\times10^{53}$ erg

$R = 10$ km

emitted roughly equally in ν_e, $\bar{\nu}_e$, ν_μ, $\bar{\nu}_\mu$, ν_τ, and $\bar{\nu}_\tau$

Time scale

$$\tau_{Diff} \sim \left(\frac{R^2}{l\ c}\right) \qquad l = \frac{1}{\kappa_\nu \rho}$$

$\kappa_\nu \sim 10^{-16}\ \text{cm}^2\ \text{gm}^{-1}$ for $\varepsilon_\nu =$ 50 MeV

$\rho \sim 3\times10^{14}\ \text{gm cm}^{-3} \quad \Rightarrow \quad l \sim$ 30 cm $\qquad R \sim 20$ km

$$\tau_{Diff} \sim \left(\frac{(2\times10^6)^2}{30\bullet3\times10^{10}}\right) \sim 5\ \text{sec}$$

Very approximate

Temperature:

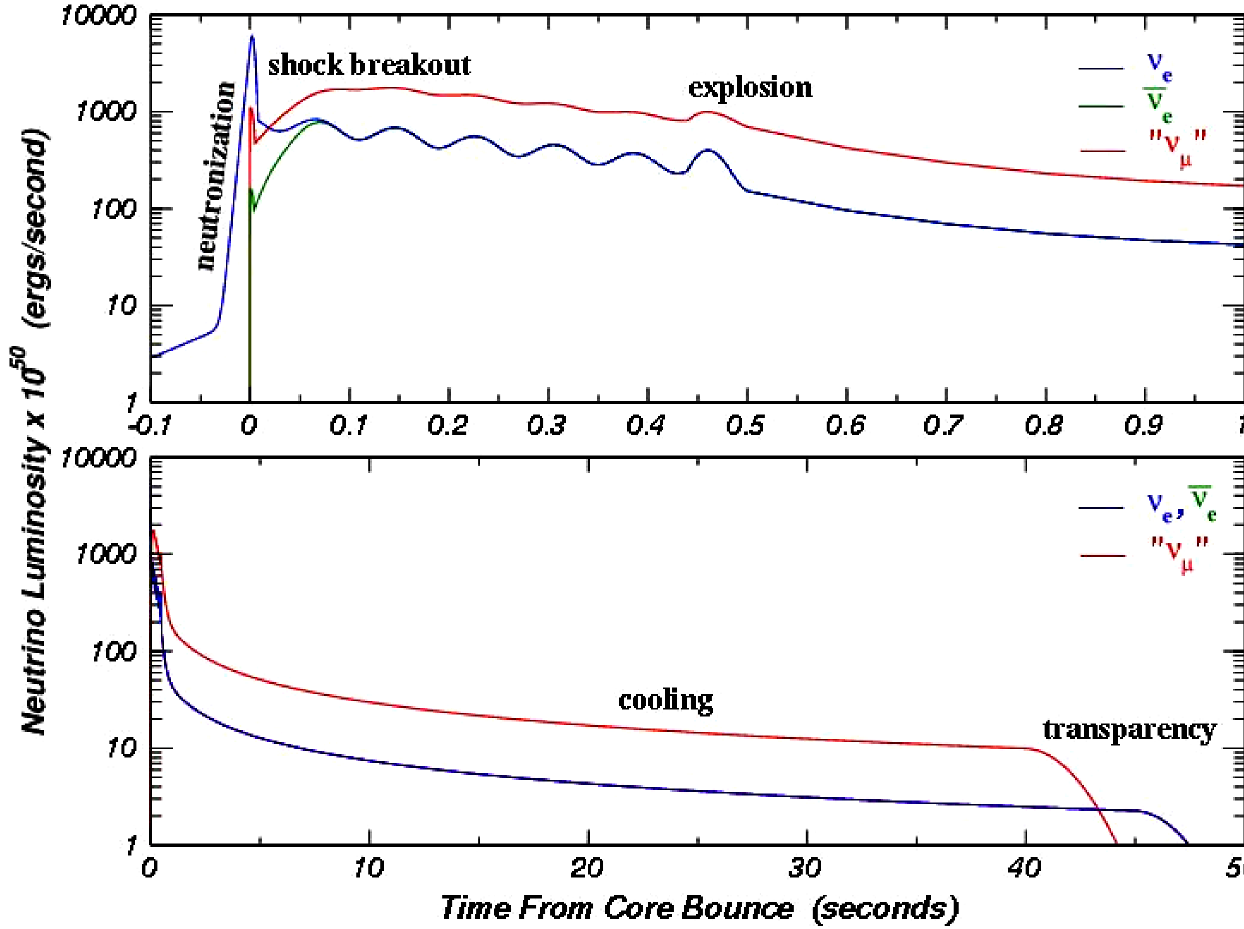
$$L_\nu \approx \frac{E_{tot}}{6\tau_{Diff}} \approx 10^{52}\ \text{erg s}^{-1}\ \text{per flavor}$$

$$\approx \frac{7}{16}\left(4\pi\sigma R_\nu^2 T_\nu^4\right) \quad \Rightarrow \boxed{T_\nu \approx 4.5\ \text{MeV}}$$

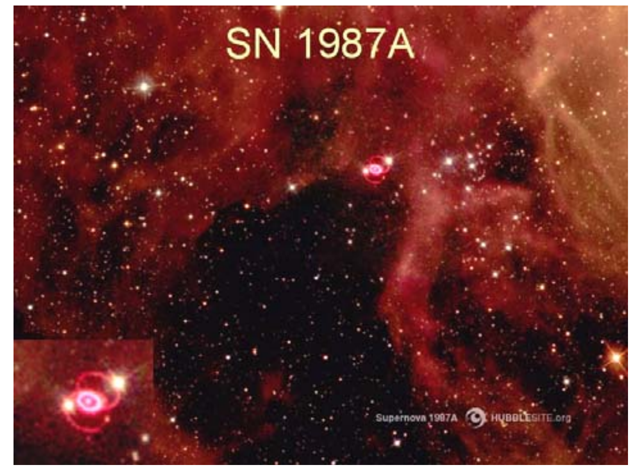
for $R_\upsilon \approx 20$ km and $\tau_\nu = 3$ sec

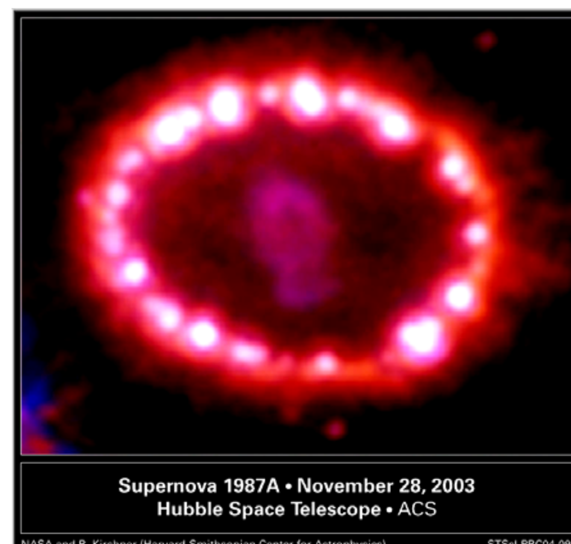
Actually $\bar{R}_\nu$ is a little bit smaller and τ_{Diff} is a little bit longer but 4.5 MeV is about right.

Summary of neutrino luminosity (A.Burrows)

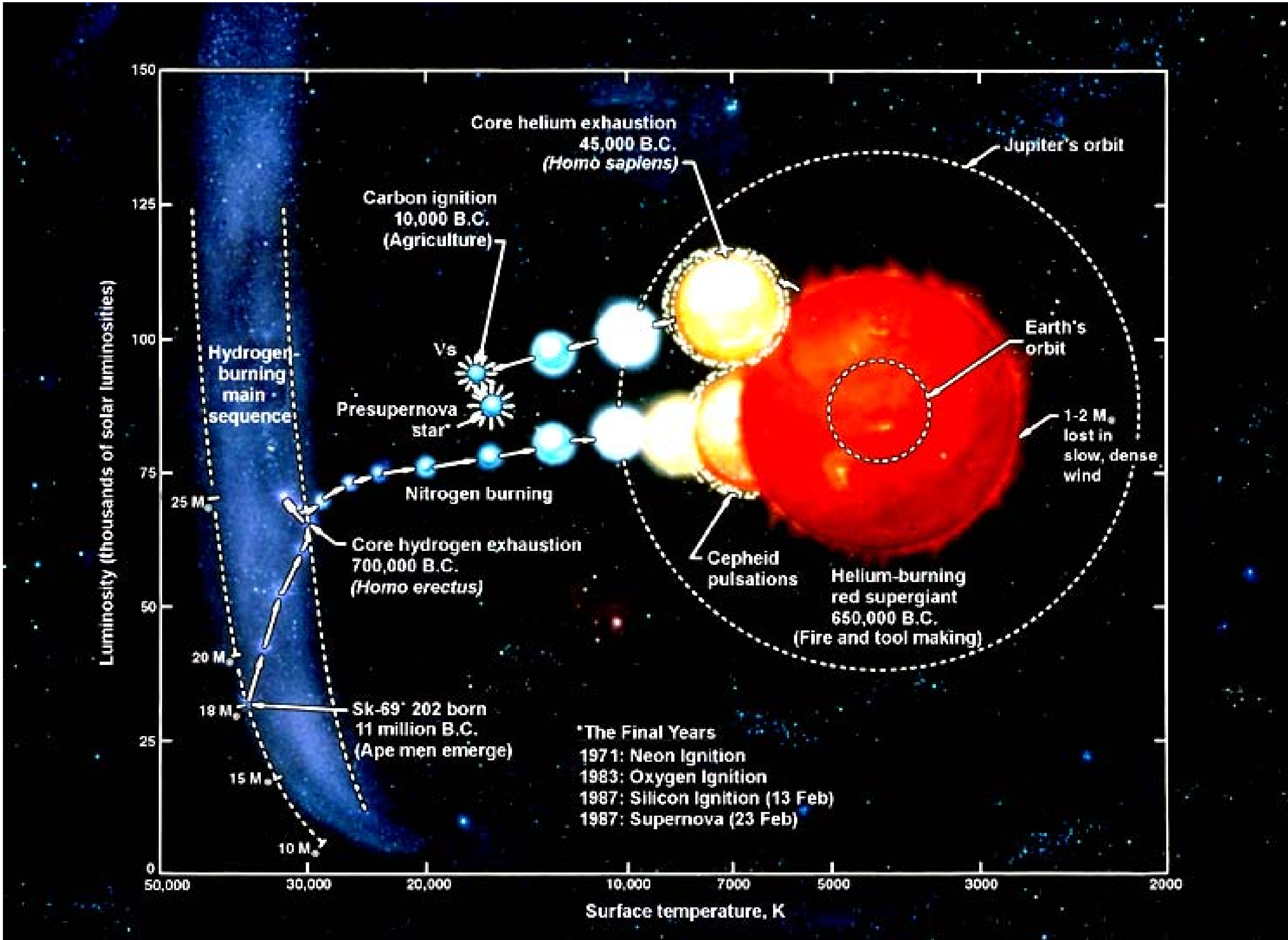


SN1987a in the Large Magellanic Cloud

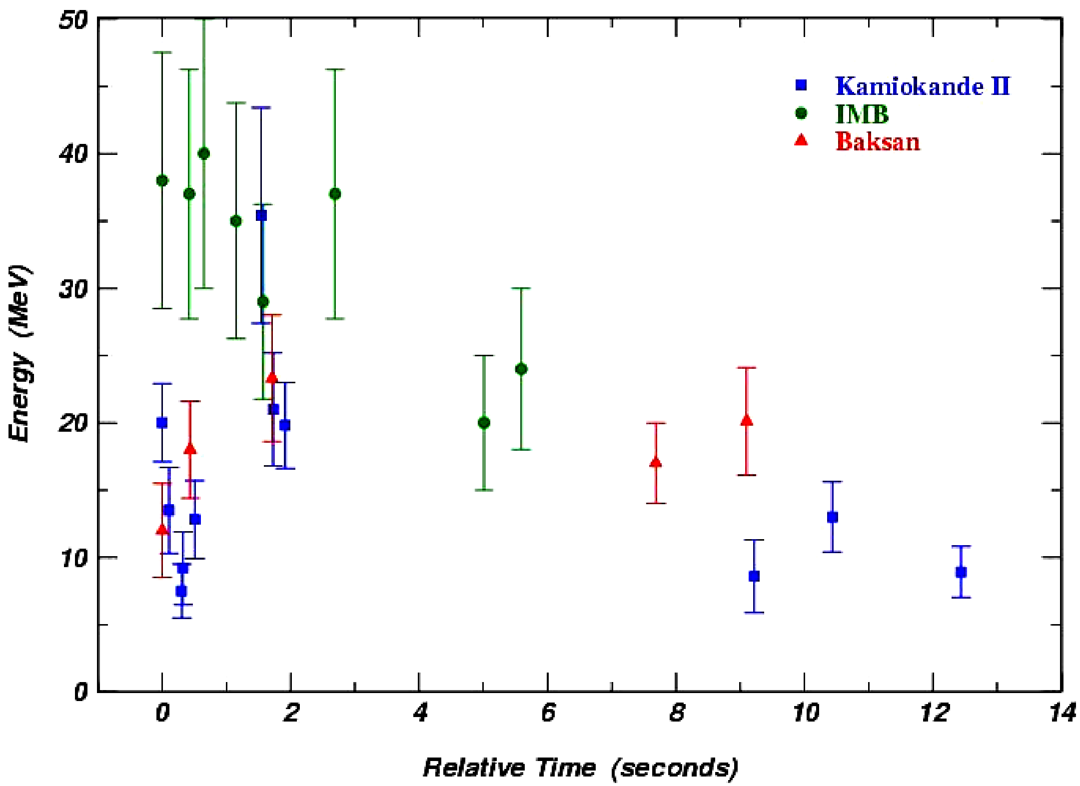


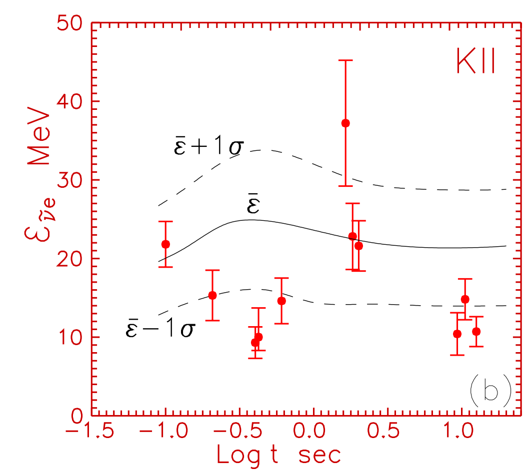


23 Feb 1987
Sk -69 202 disappeared…

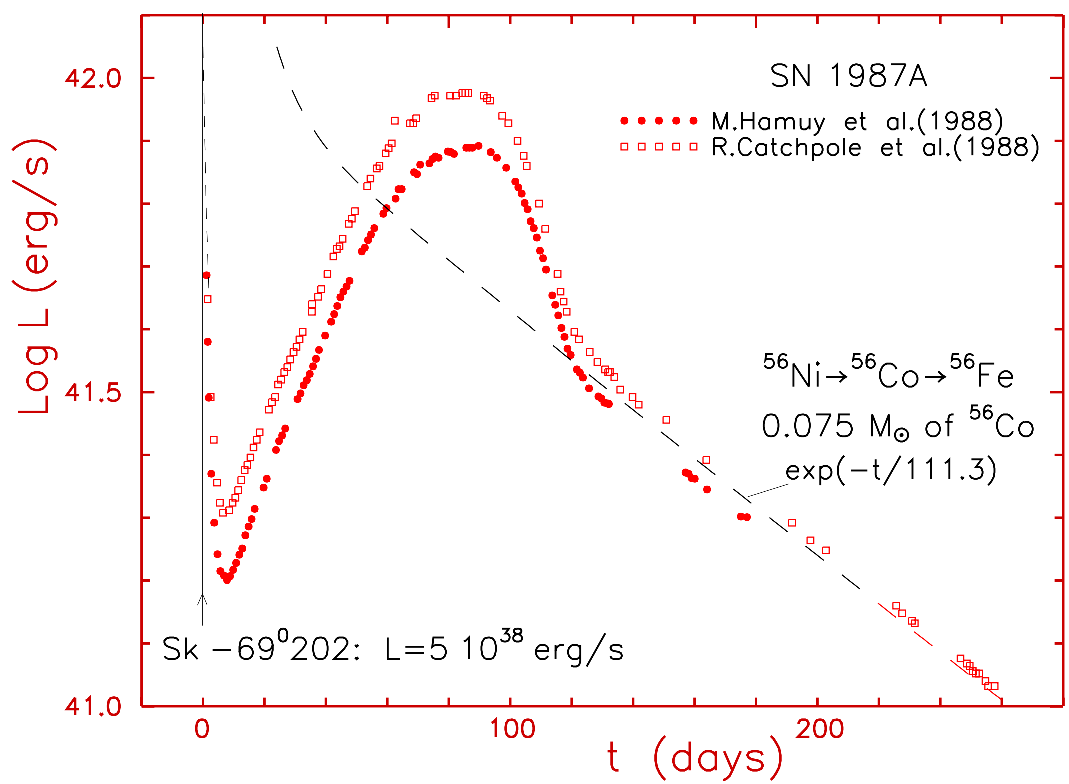

Core helium exhaustion
45,000 B.C.
(Homo sapiens)
Jupiter's orbit
Carbon ignition
10,000 B.C.
(Agriculture)
Vs
Presupernova
star*
Hydrogen-
burning
main
sequence
Earth's
orbit
1-2 M☉
lost in
slow, dense
wind
Nitrogen burning
25 M☉
Core hydrogen exhaustion
700,000 B.C.
(Homo erectus)
Cepheid
pulsations
Helium-burning
red supergiant
650,000 B.C.
(Fire and tool making)
20 M☉
18 M☉
Sk-69° 202 born
11 million B.C.
(Ape men emerge)
15 M☉
10 M☉
*The Final Years
1971: Neon Ignition
1983: Oxygen Ignition
1987: Silicon Ignition (13 Feb)
1987: Supernova (23 Feb)
Luminosity (thousands of solar luminosities)
150
125
100
75
50
25
0
50,000
30,000
20,000
10,000
7000
5000
3000
2000
Surface temperature, K

Neutrinos from SN1987A

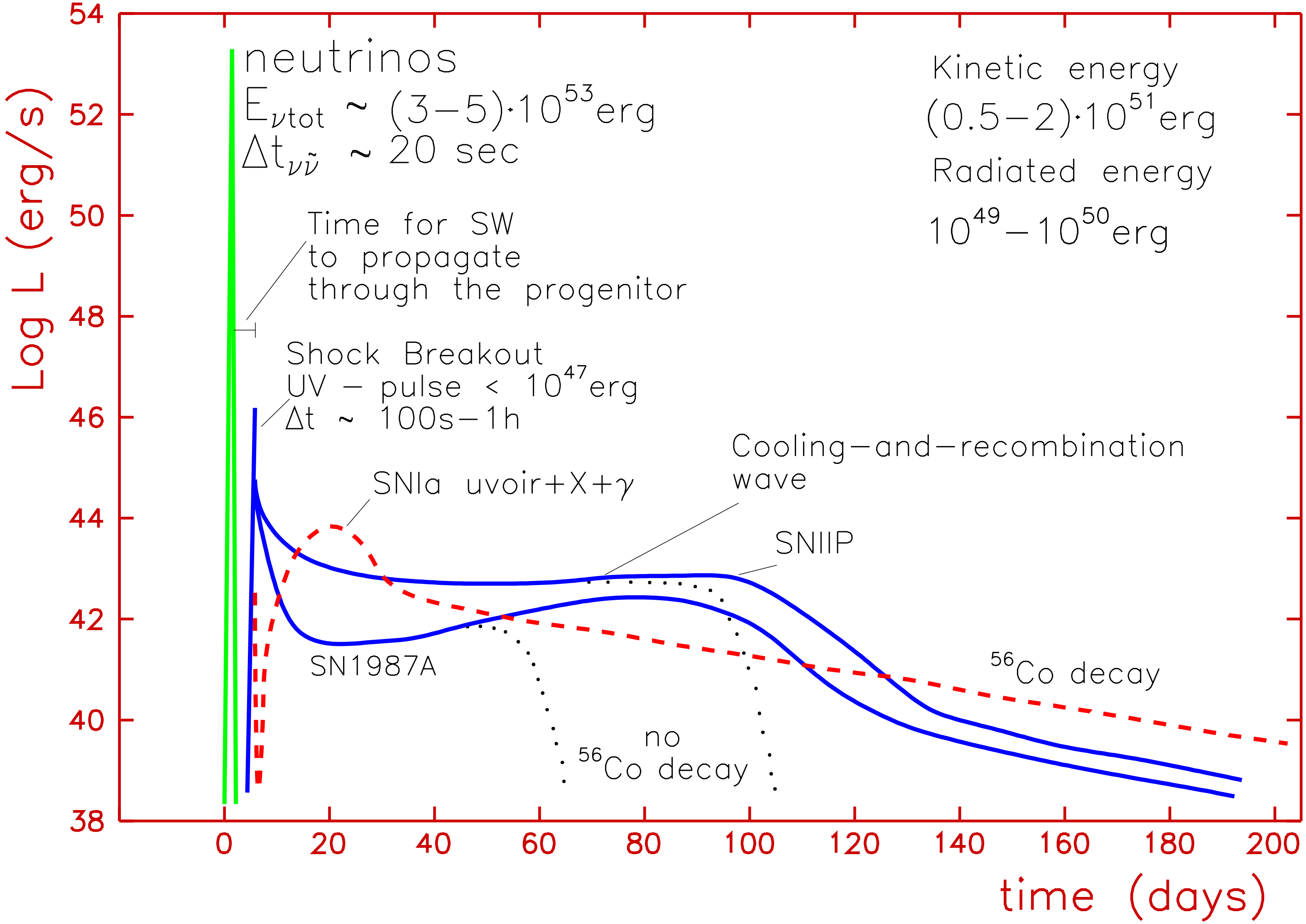




Shock breakout and SN light curve



Summary of SN luminosities



Sources of SN light curve luminosity

- Type II: **Hydrogen recombination** (13.6 eV per H atom) – give 10^{47} ergs for 8-10 $M_\odot$ envelope. Cooling recombination wave in expanding envelope explains the plateau in some type II SNe (IIp).
- Diffusion in expanding shell → $t_{peak} \sim \sqrt{M}$
- Type Ia and late type II: **Radioactive decays:**

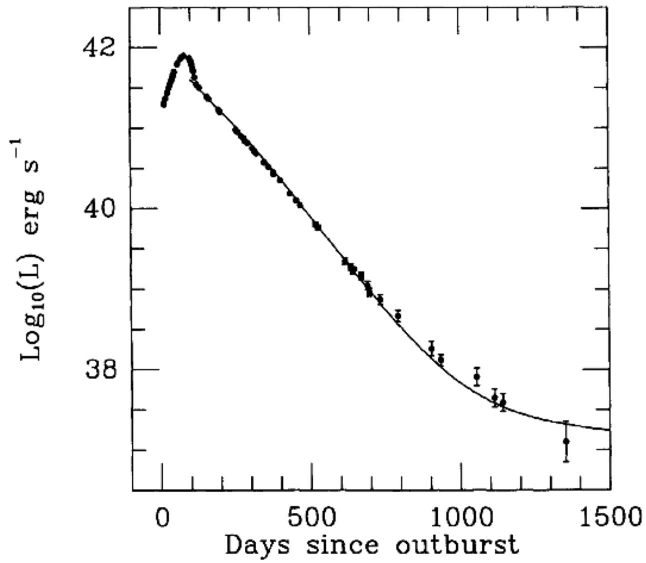
$^{56}Ni \rightarrow {}^{56}Co \rightarrow {}^{56}Fe$, $\tau_{1/2}(Ni) \sim 7.6 \times 10^5$ s

gamma-photons (0.163-1.56 MeV) are emitted, lose energy by Compton scattering and thermalized to give

$$L(t)_{Ni} \approx 9.7 \cdot 10^{42}\,(\mathrm{erg/s}) \left(\frac{M_{Ni}}{0.1 M_\odot} \right) \exp(-t/\tau_{Ni})$$

Late time lc are dominated by radioactive decays of ^{56}Co, ^{44}Ti and other. Confirmed by direct line measurements in SN 1987A.

SN 1987A



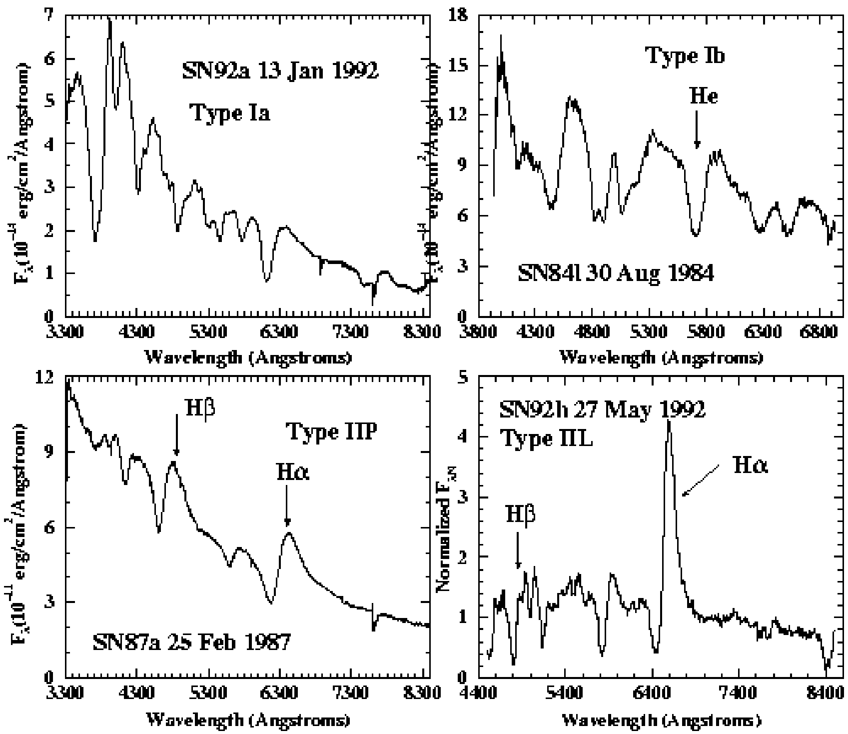
(Co+Ti; Suntzeff et al., 1991, Fig. 9)

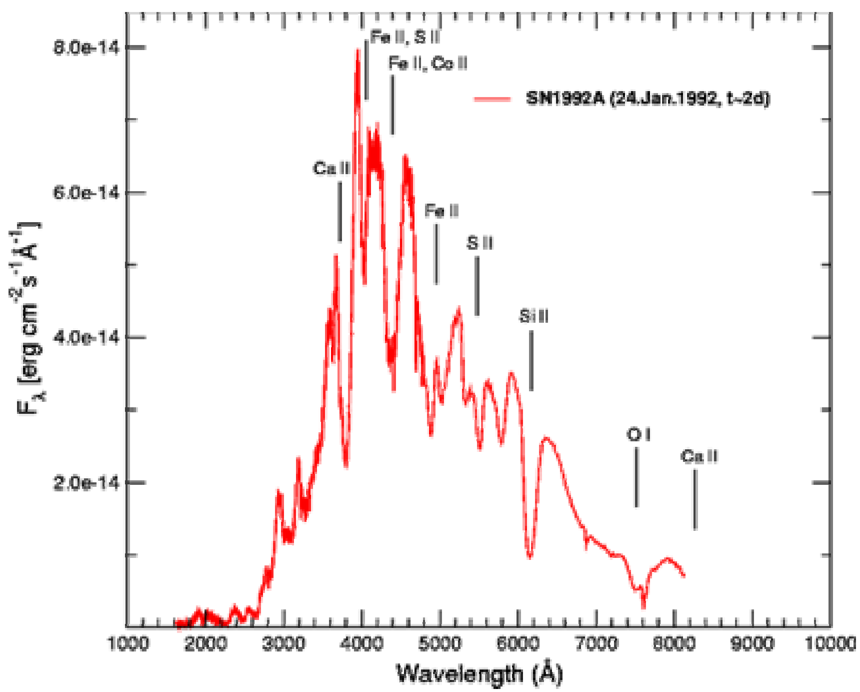
Late time light curve due to radioactive decay of Cobalt.

- Day 125–700: dominated by decay of ^{56}Co
- Around day 1000: radioactive decay of ^{57}Co starts to dominate (e-folding time: 391 d).

Optical light curve well described by enhanced ^{57}Co/^{56}Co ratio (~2.5–4× solar) plus ^{56}Ni and ^{44}Ti (Suntzeff et al., 1991).

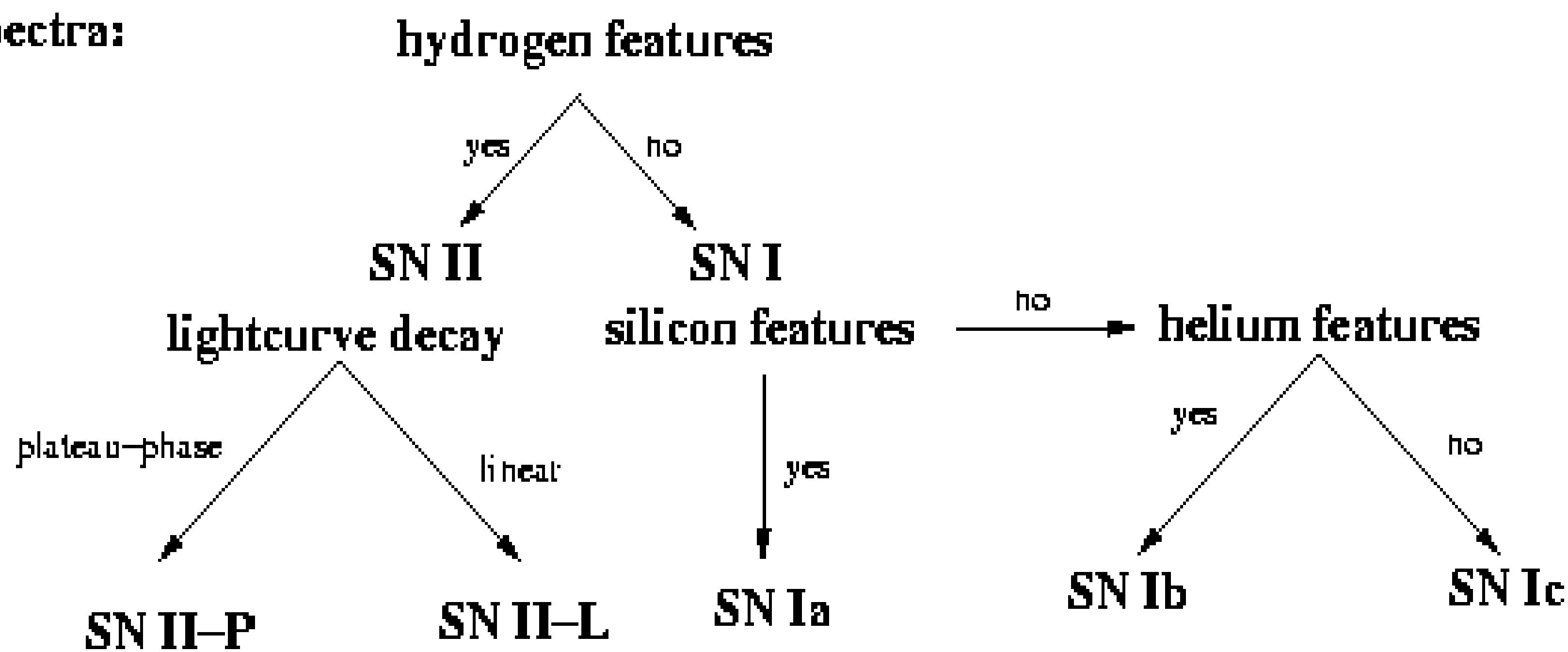
Supernovae: classification

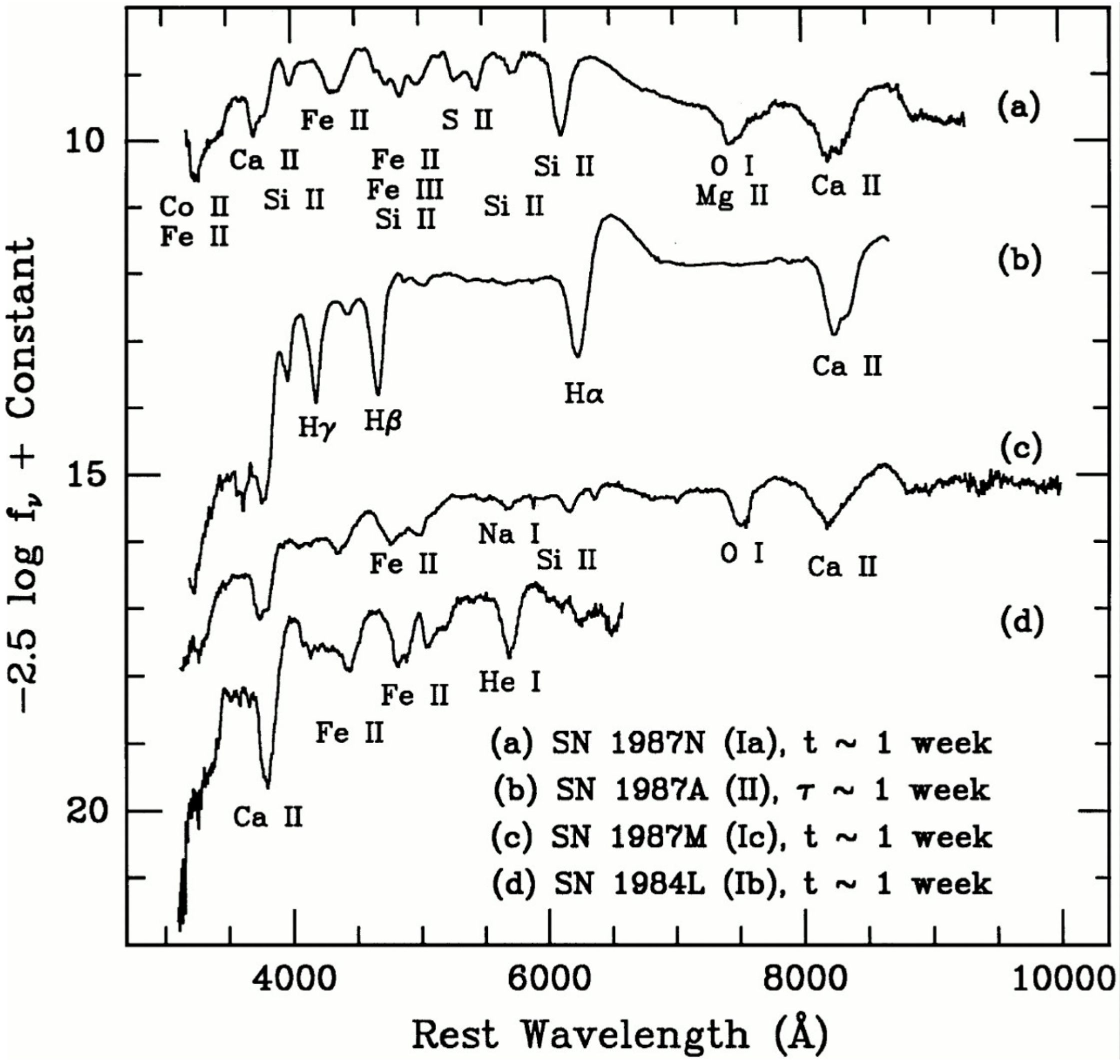




Classification: Early spectra

Early spectra:

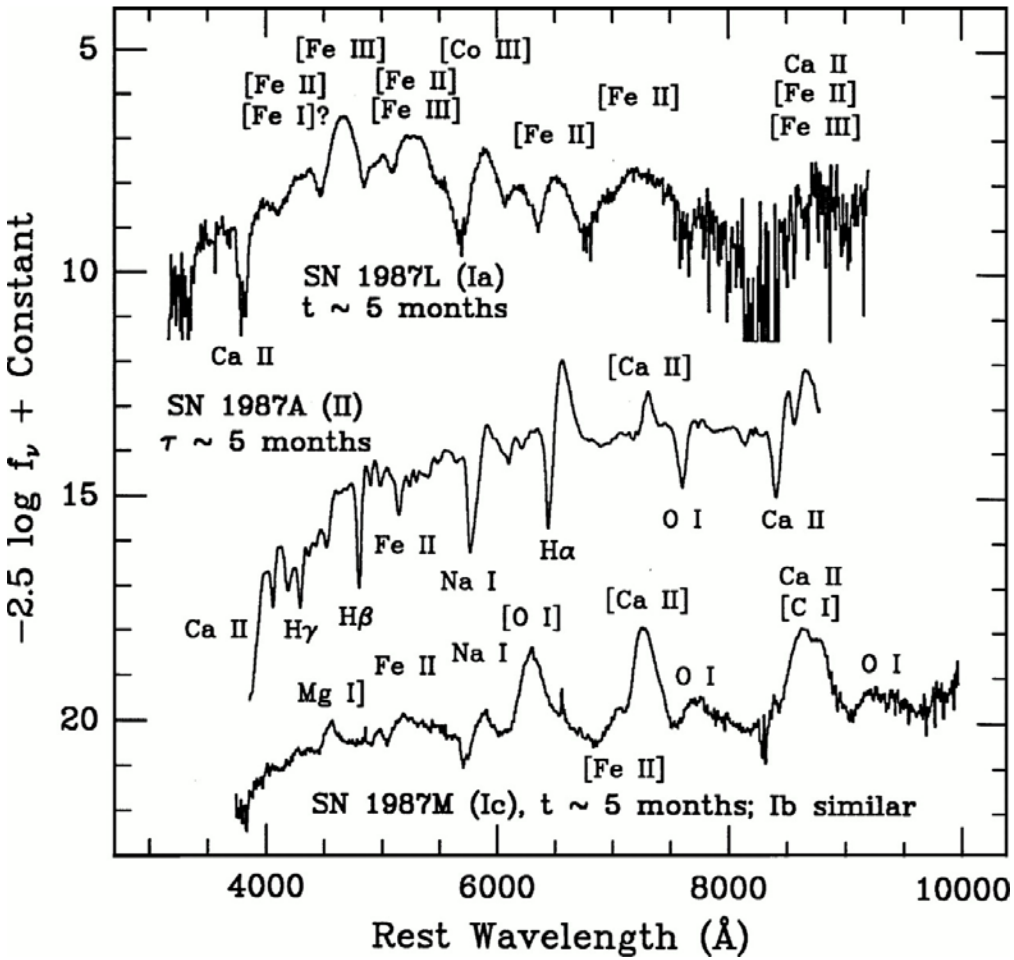




A. Filippenko, ARRA 1997

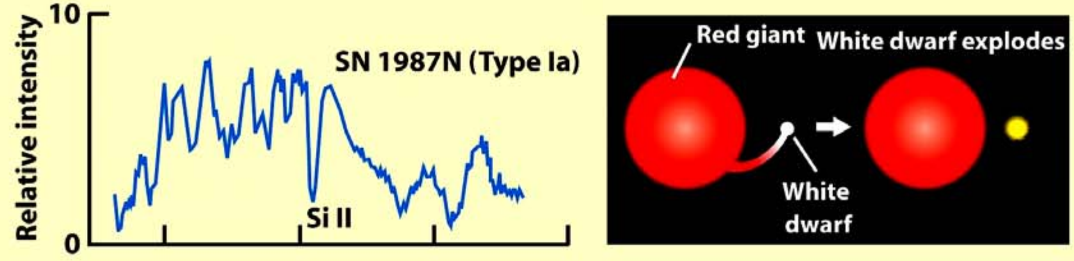
- t – time after maximum light, τ – time after core collapse
- P Cyg profiles give v~10000 km/s

Late spectra



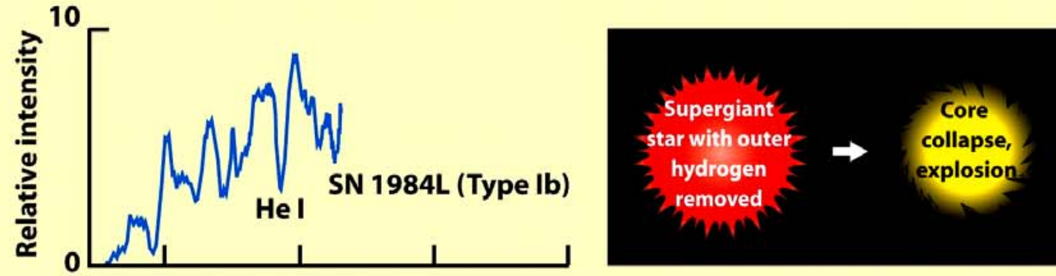
(a) Type Ia supernova

- The spectrum has no hydrogen or helium lines, but does have a strong absorption line of ionized silicon (Si II).
- Produced by runaway carbon fusion in a white dwarf in a close binary system (the ionized silicon is a by-product of carbon fusion).



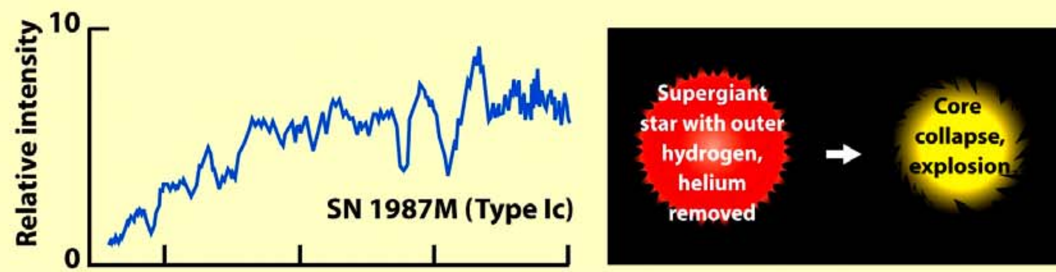
(b) Type Ib supernova

- The spectrum has no hydrogen lines, but does have a strong absorption line of un-ionized helium (He I).
- Produced by core collapse in a massive star that lost the hydrogen from its outer layers.



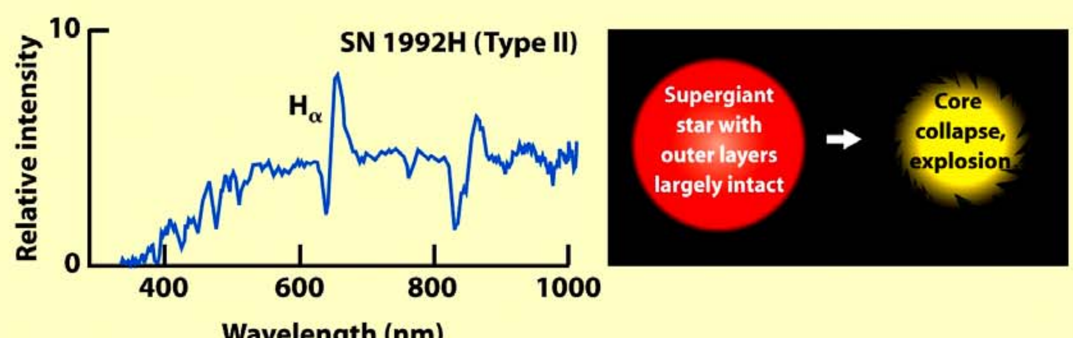
(c) Type Ic supernova

- The spectrum has no hydrogen lines or helium lines.
- Produced by core collapse in a massive star that lost the hydrogen and the helium from its outer layers.

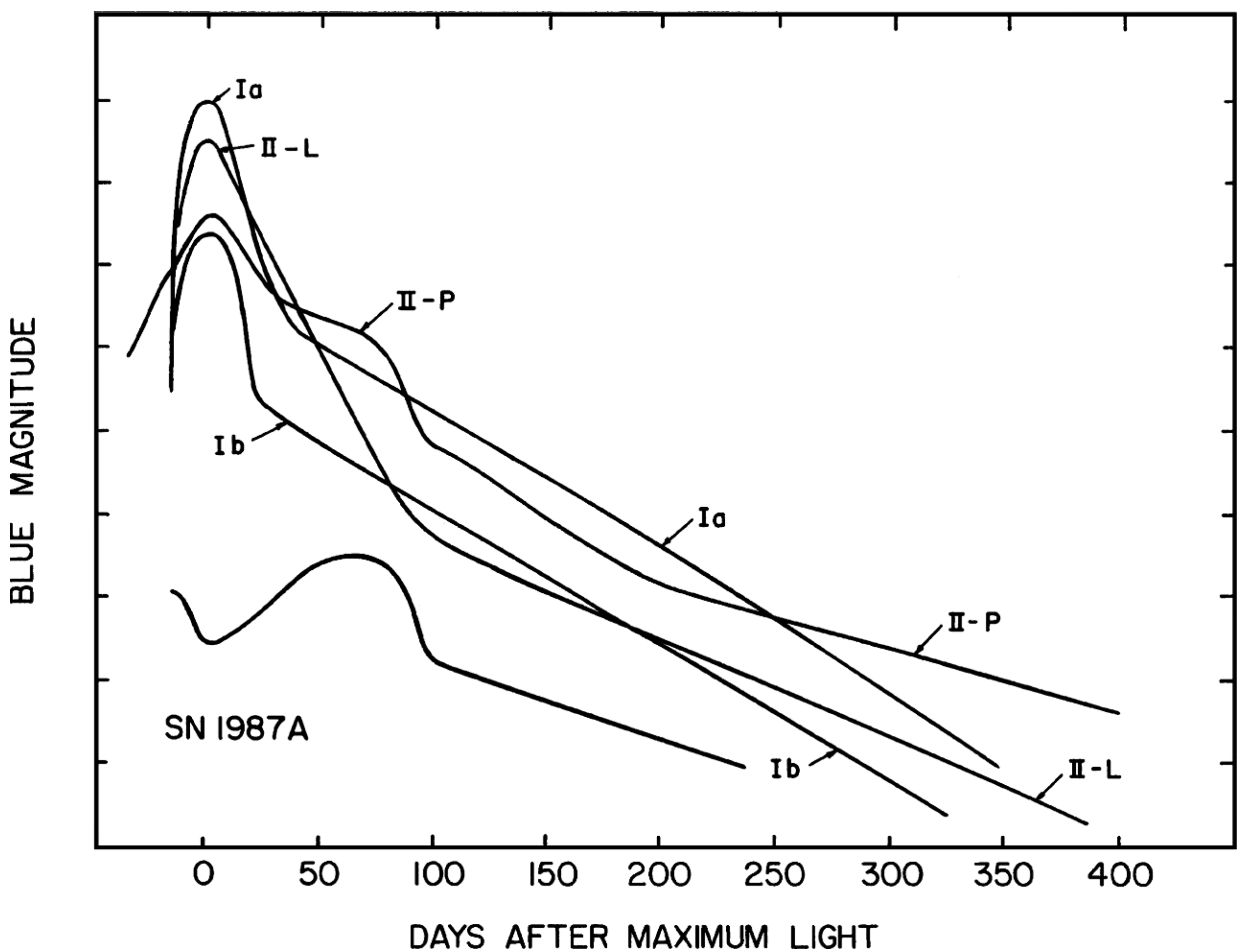


(d) Type II supernova

- The spectrum has prominent hydrogen lines such as H_α.
- Produced by core collapse in a massive star whose outer layers were largely intact.

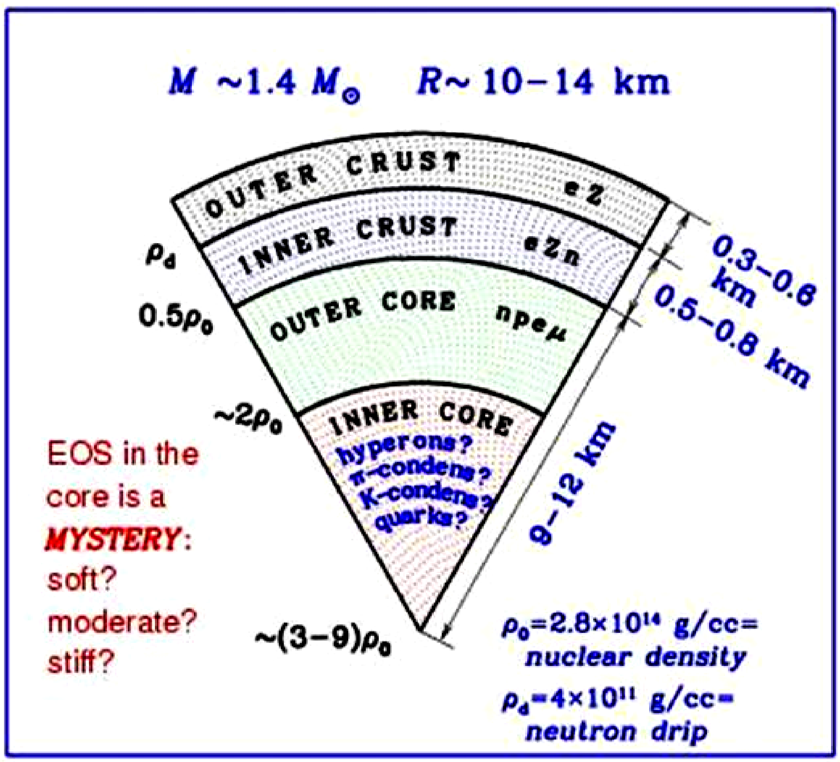


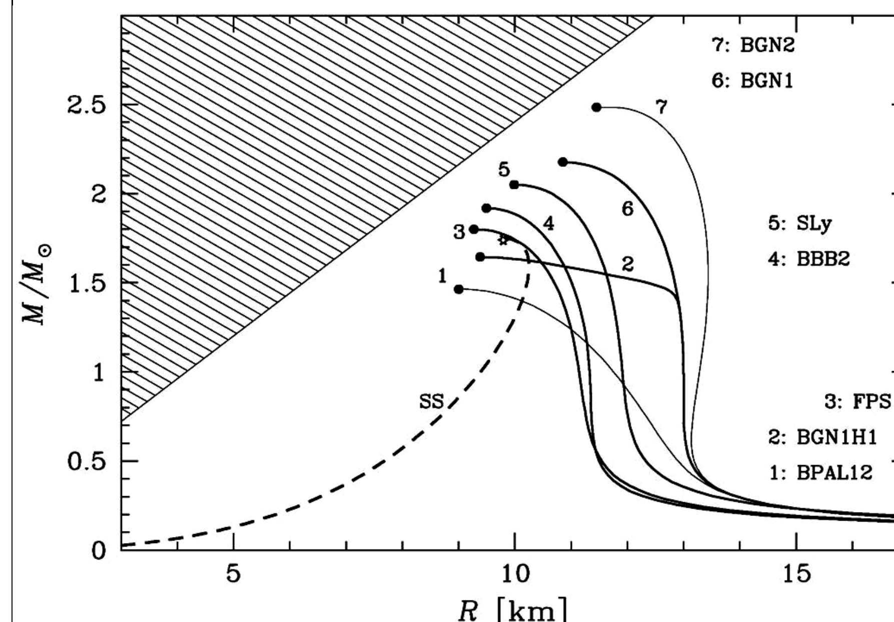
SN: diversity of lightcurves



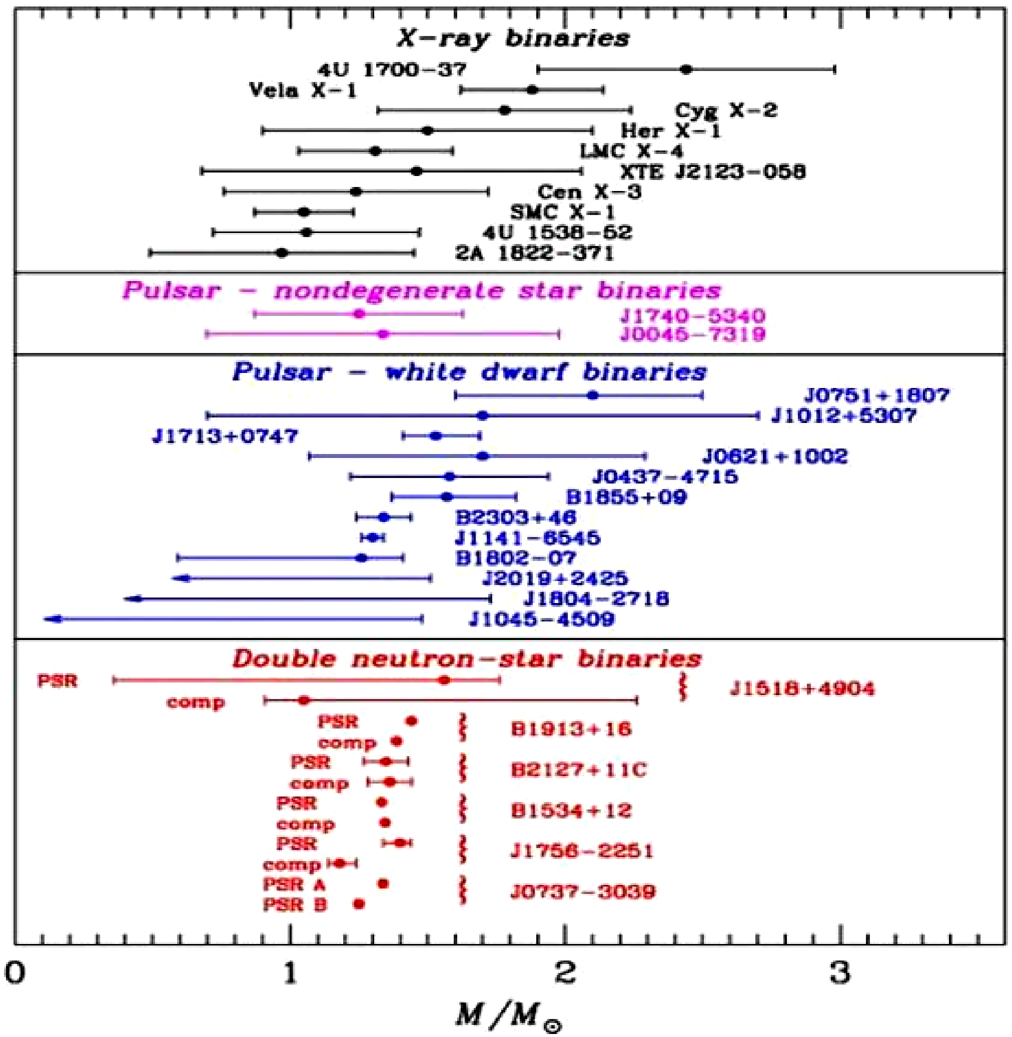
Remnants of the collapse: Neutron stars

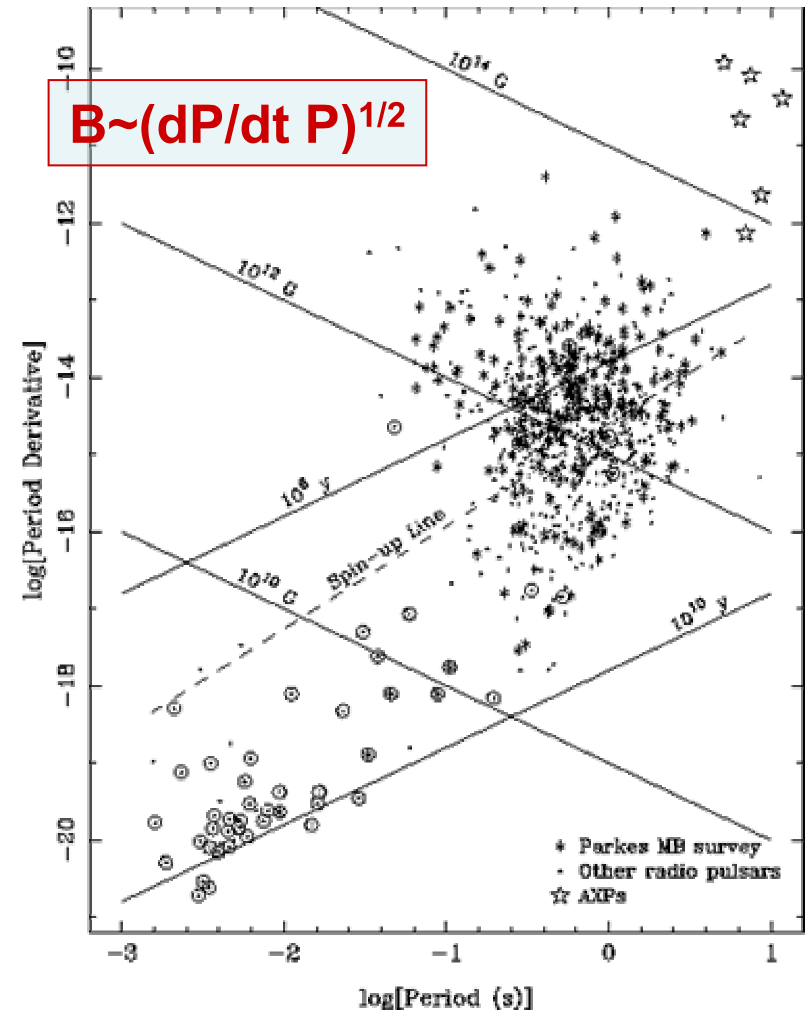
NS internal structure is determined by equation of state which is poorly known





Astrophysical measurements: masses, radii (less secure), surface magnetic fields, space velocities…





Core collapse SNe: Conclusions

- Explosion mechanism is still to be determined. Neutrino delay is still promising, but other energies may be required to revive the shock (acoustic power? Rotation? Magnetic fields?)
- All SNII/Ib/Ibc appear asymmetric (SN 1987a, optical polarimetry, high natal velocities of NSs). Rotation and magnetic field appear to be important ingredients.
- Neutron stars definitely form in core collapse SNe. Do they also form in other SNe (e-capture of O-Ne-Mg cores, accretion induced collapse of WD,…) and what are their properties?
- What physical parameters determine the outcome of the core collapse (mass, metallicity, rotation, magnetic fields, binarity…)? What is the connection of core collapse SNe with GRBs?