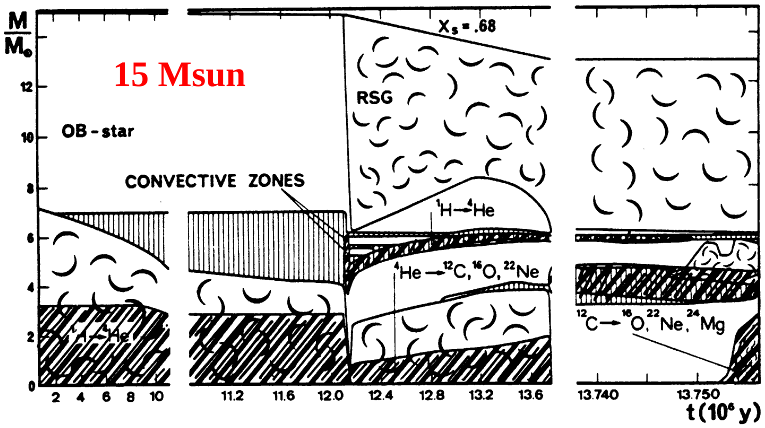
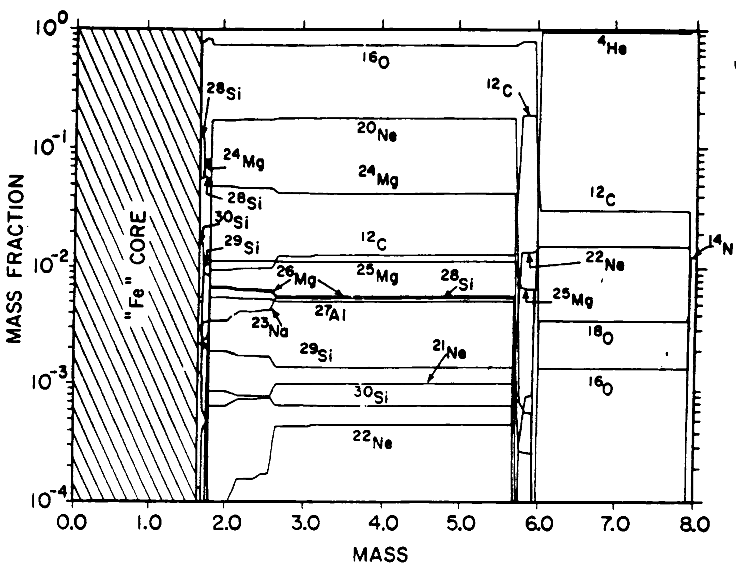
Evolution of Massive Stars



Maeder (1987)

Helium Core (8 Msun)



Itoh and Nomoto (1987)

EVOLUTION OF MASSIVE STARS ($M \gtrsim 13\,M_\odot$)

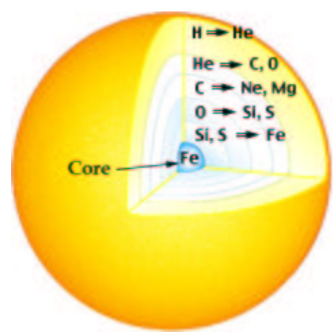
- massive stars continue to burn nuclear fuel beyond hydrogen and helium burning and ultimately form an iron core
- alternation of nuclear burning and contraction phases
  - ▹ carbon burning ($T \sim 6 \times 10^8$ K)

$$
\begin{aligned}
{}^{12}C + {}^{12}C &\rightarrow {}^{20}Ne + {}^{4}He \\
&\rightarrow {}^{23}Na + {}^{1}H \\
&\rightarrow {}^{23}Mg + n
\end{aligned}
$$

  - ▹ oxygen burning ($T \sim 10^9$ K)

$$
\begin{aligned}
{}^{16}O + {}^{16}O &\rightarrow {}^{28}Si + {}^{4}He \\
&\rightarrow {}^{31}P + {}^{1}H \\
&\rightarrow {}^{31}S + n \\
&\rightarrow {}^{30}S + 2\,{}^{1}H \\
&\rightarrow {}^{24}Mg + {}^{4}He + {}^{4}He
\end{aligned}
$$

  - ▹ silicon burning: photodisintegration of complex nuclei, hundreds of reactions → iron



- ▹ form iron core
- ▹ iron is the most tightly bound nucleus → no further energy from nuclear fusion
- ▹ iron core surrounded by onion-like shell structure

EXPLOSION MECHANISMS

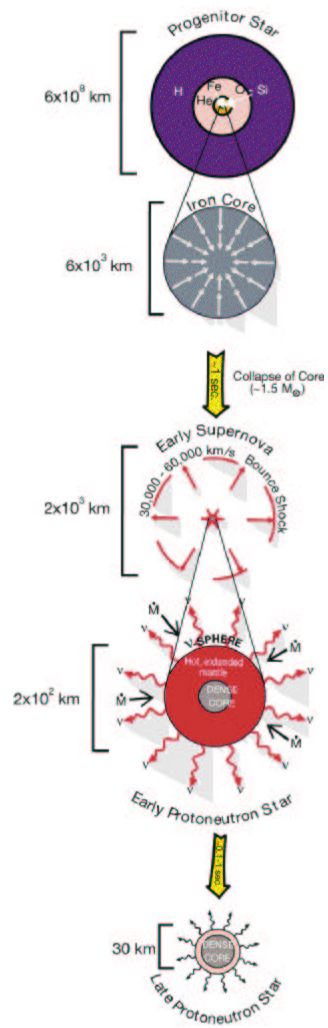
- two main, completely different mechanisms

Core-Collapse Supernovae

- triggered after the exhaustion of nuclear fuel in the core of a massive star, if the iron core mass > Chandrasekhar mass
- energy source is gravitational energy from the collapsing core ($\sim 10\,\%$ of neutron star rest mass $\sim 3 \times 10^{46}\,$J)
- most of the energy comes out in neutrinos (SN 1987A!)
  - ▷ unsolved problem: how is some of this energy in neutrinos deposited ($\sim 1\,\%$) in the envelope to eject the envelope produce the supernova?
- leaves compact remnant (neutron star or black hole)

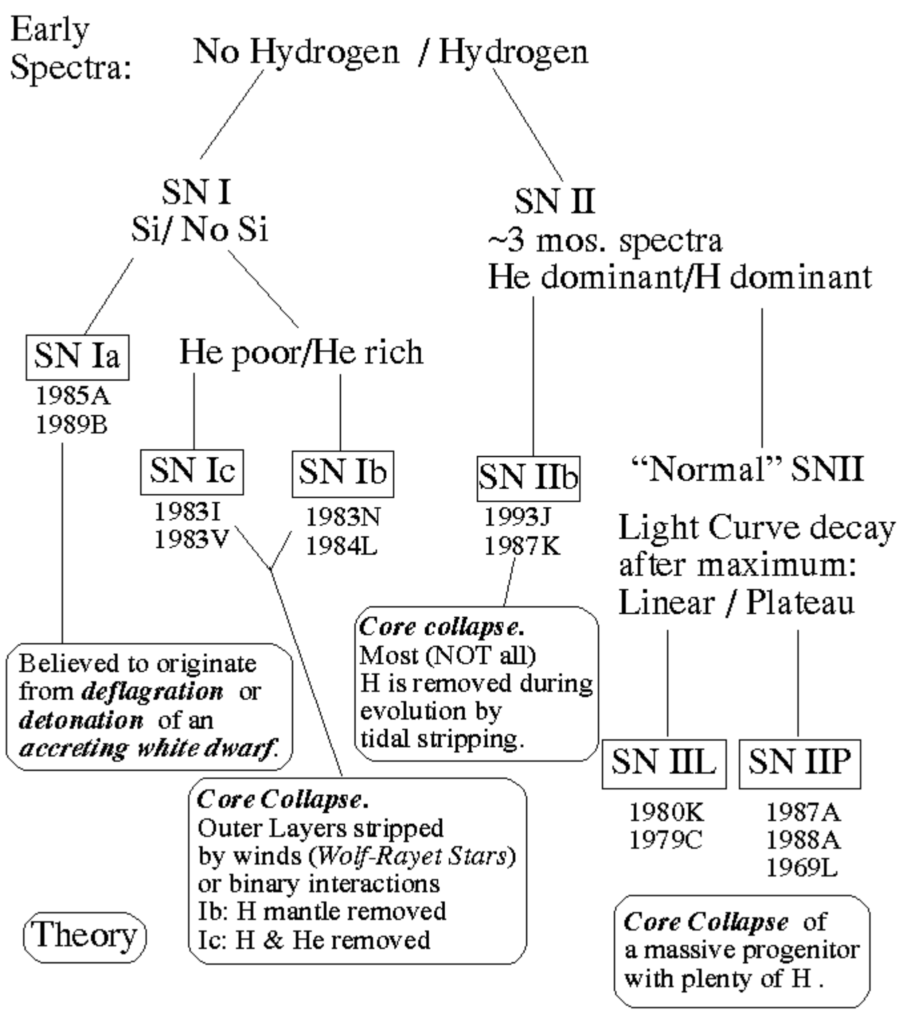
Thermonuclear Explosions

- occurs in accreting carbon/oxygen white dwarf when it reaches the Chandrasekhar mass
  - → carbon ignited under degenerate conditions; nuclear burning raises T, but not P
  - → thermonuclear runaway
  - → incineration and complete destruction of the star
- energy source is nuclear energy ($10^{44}\,$J)
- no compact remnant expected
- main producer of iron
- standard candle (Hubble constant, acceleration of Universe?)



Core Collapse

- central properties at the beginning of core collapse: for $M_{core} = 1.5\,M_\odot$, $T_c \simeq 8 \times 10^9\,$K, $\rho_c \simeq 4 \times 10^{12}\,$kg m^{-3}
- instabilities in the contracting core lead to essentially free-fall collapse
- photodissociation of nuclei
  - ▷ $T_c \sim 10^{11}\,$K : $\gamma + {}^{56}\mathrm{Fe} \rightleftharpoons 13\,\alpha + 4\,n - 124\,$Mev
  - ▷ endothermic reaction (requires heat) → temperature increases less rapidly than pressure → rapid contraction
  - ▷ $T_c \sim 2 \times 10^{11}\,$K : $\gamma + {}^4\mathrm{He} \rightleftharpoons 2\,p + 2\,n - 28\,$Mev
- note: all of these reactions occur in both directions; maximization of entropy favours right-hand sides (larger number of particles)
- these reactions essentially undo all of the previous nuclear fusion reactions
- neutronization
  - ▷ electron capture reactions (reduce the number of electrons and electron degeneracy pressure)
    $e^- + (Z, A) \to \nu_e + (Z-1, A)$
    $e^- + p \to \nu_e + n$ (also: $n \to \bar{\nu}_e + p + e^-$)
- most of the energy is lost by neutrino emission (10 % of the rest mass energy of the neutron star)
- energy source: gravitational energy



SUPERNOVA CLASSIFICATION

observational:

- Type I: no hydrogen lines in spectrum
- Type II: hydrogen lines in spectrum

theoretical:

- thermonuclear explosion of degenerate core
- core collapse → neutron star/black hole

relation no longer 1 to 1 → confusion

- Type Ia (Si lines): thermonuclear explosion of white dwarf
- Type Ib/Ic (no Si; He or no He): core collapse of He star
- Type II-P: "classical" core collapse of a massive star with hydrogen envelope
- Type II-L: supernova with linear lightcurve (thermonuclear explosion of intermediate-mass star? probably not!)

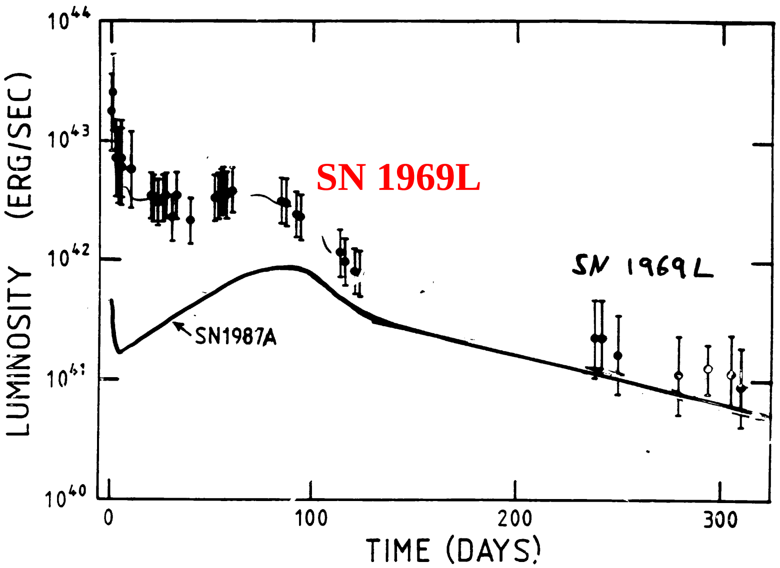
complications

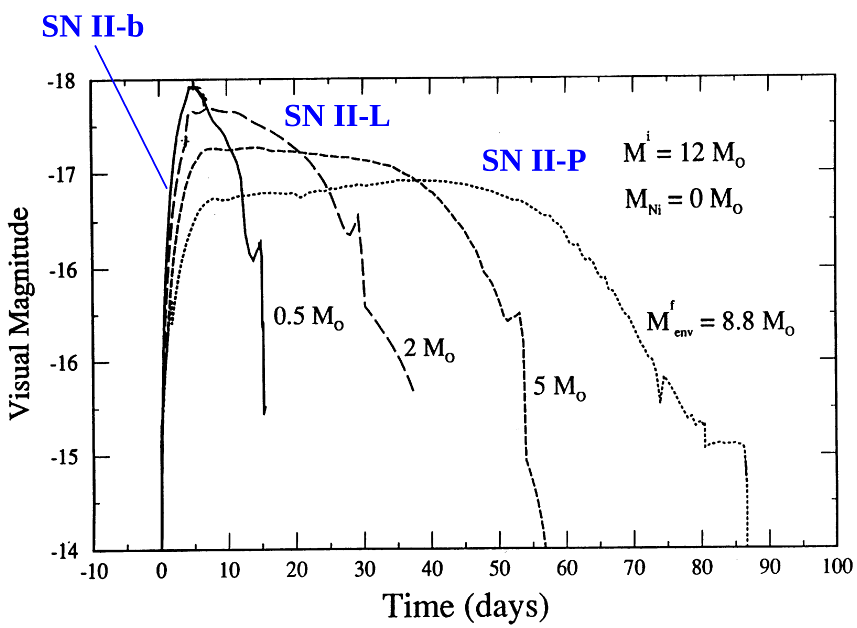
- special supernovae like SN 1987A
- Type IIb: supernovae that change type, SN 1993J (Type II → Type Ib)
- predicted new types: thermonuclear explosion of He star (Type Iab?)

new scheme (in ~ 10 yr?)

- use theoretical classification for primary classification
- use continuous parameter(s) for sub-classification

Supernova lightcurves (core collapse)





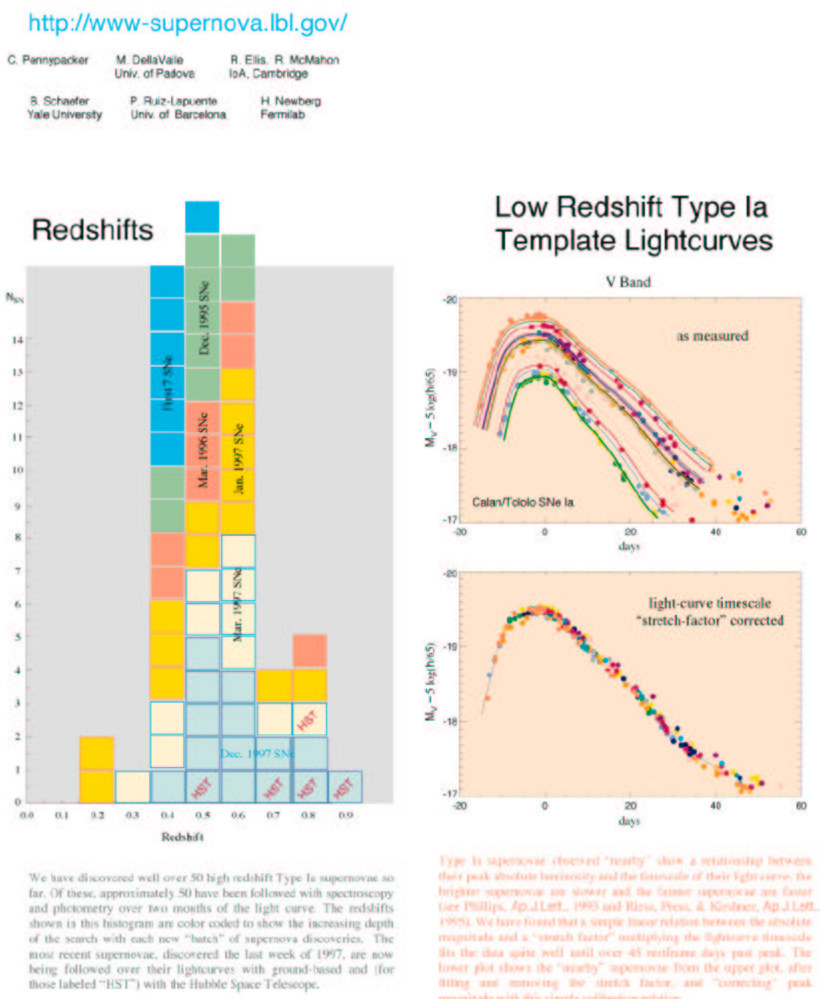
Hsu, Ross, Joss, P.

LIGHTCURVES OF CORE-COLLAPSE SUPERNOVAE

- central explosion may be very similar in all cases (with $E \sim 10^{44}\,J$)
- variation of lightcurves/supernova subtypes mainly due to varying envelope properties
  - ▷ envelope mass: determines thermal diffusion time and length/existence of plateau
  - ▷ envelope radius: more compact progenitor → more expansion work required → dimmer supernova
- binary interactions mainly affect stellar envelopes
- a large fraction of all stars are in interacting binaries

→ binary interactions are, at least in part, responsible for the large variety of supernova (sub-)types

- recent: new-born pulsars (neutron stars) have large space velocities (median: $200 - 300\,\mathrm{km\,s^{-1}}$) → neutron-stars receive a large supernova kick
  - ▷ probably due to asymmetry in neutrino flux (1 %)
- late lightcurve powered by radioactive decay of $^{56}Co \rightarrow ^{56}Fe$ (^{56}Co decay product of ^{56}Ni, produced during Si burning in the explosion)



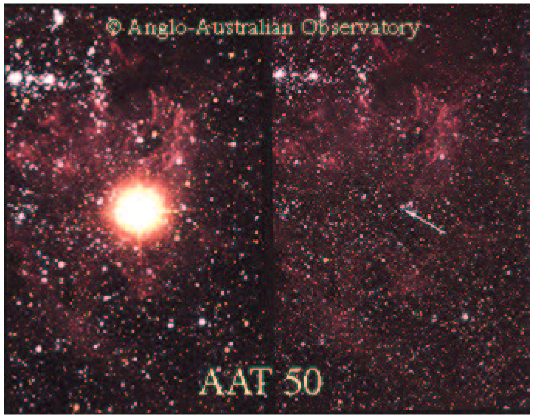
TYPE IA SUPERNOVAE

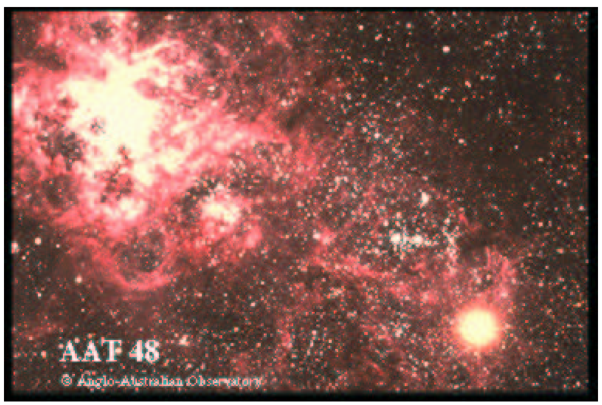
- recently: Type Ia supernovae have been used as standard distance candles to measure the curvature of the Universe → accelerating Universe?
- Type Ia supernovae are no good standard candles! (peak luminosities vary by a factor up to 10)
- but they may be standardizable candles, i.e. there appears to be a unique relation between peak luminosity and the width of the lightcurve which can be used to derive good distances

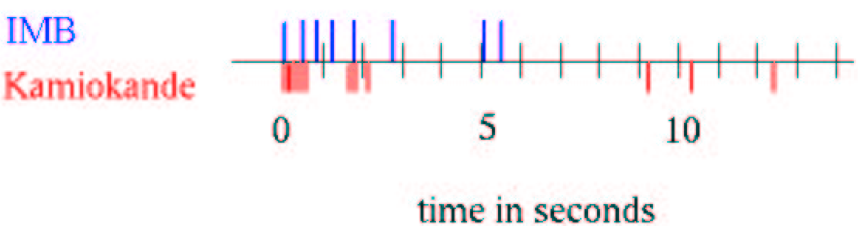
Caveats:

- the relation between lightcurve shape and peak luminosity is not well understood (depends on diffusion time and probably opacity)
- the progenitors of Type Ia supernovae are not known
- many progenitors models
  - ▷ Chandrasekhar white dwarf accreting from a companion star (main-sequence star, helium star, subgiant, giant)
  - ▷ merging of two CO white dwarfs with a total mass > Chandrasekhar mass (probably not!)
  - ▷ sub-Chandrasekhar mass white dwarfs (helium shell flash leading to a detonation of the white dwarf; extremely unlikely!)

SN 1987A (LMC)







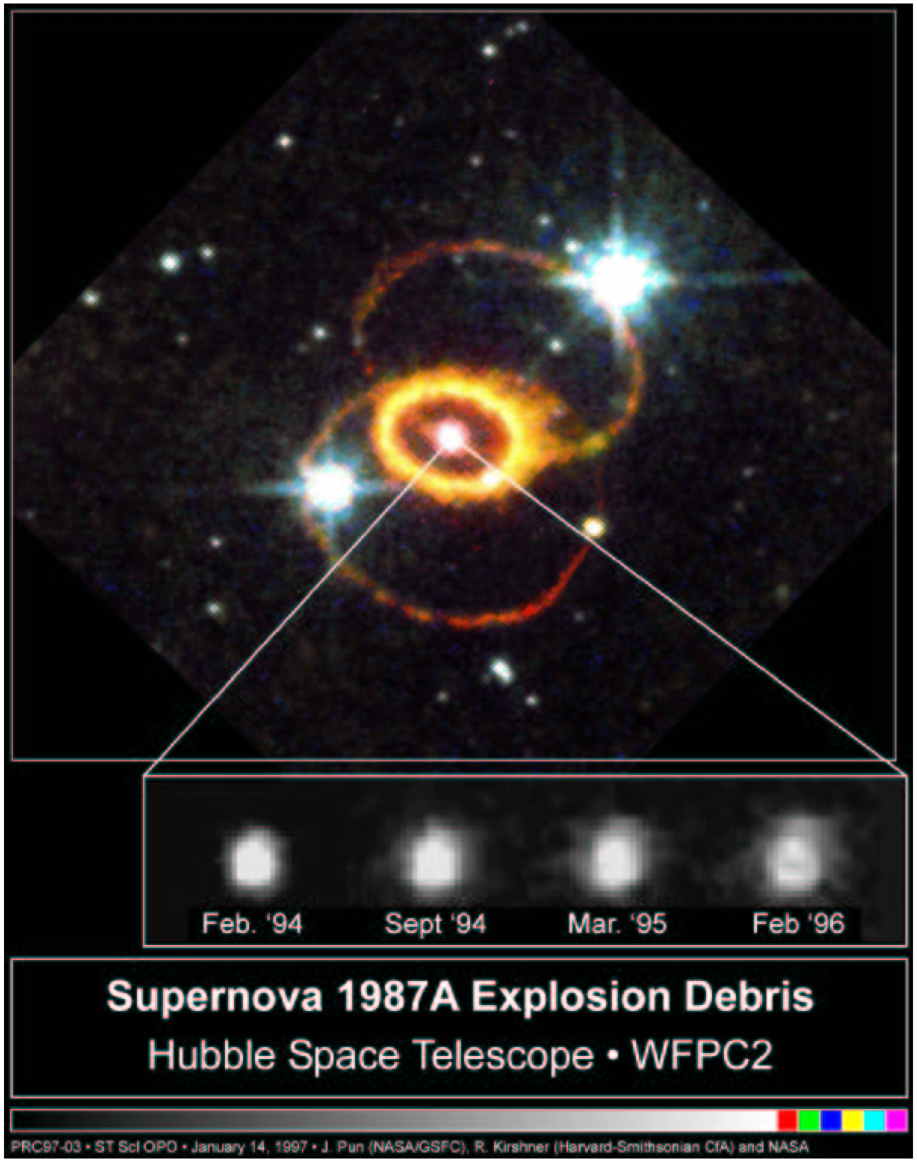
Neutrino Signal

SN 1987A

- SN 1987A in the Large Magellanic Cloud (satellite galaxy of the Milky Way) was the first naked-eye supernova since Kepler's supernova in 1604
- long-awaited, but highly unusual, anomalous supernova
  - ▷ progenitor blue supergiant instead of red supergiant
  - ▷ complex presupernova nebula
  - ▷ chemical anomalies: envelope mixed with part of the helium core

Confirmation of core collapse

- neutrinos ($\bar{\nu}_e + p \rightarrow n + e^+$), detected with Kamiokande and IMB detectors
  - ▷ confirmation: supernova triggered by core collapse
  - ▷ formation of compact object (neutron star)
  - ▷ energy in neutrinos ($\sim 3 \times 10^{46}$ J) consistent with the binding energy of a neutron star



THE TRIPLE-RING NEBULA

- the material in the nebula was ejected by the progenitor $\sim 30,000\,\mathrm{yr}$ before the supernova

→ extremely non-spherical, but approximately axi-symmetric

→ signature of rotation?

- progenitor was a red supergiant in recent past
- any single star would have to be slowly rotating as a red supergiant even if it was rapidly rotating on the main sequence (because there is no source of angular momentum and the star expands by a factor of ~ 100)

→ signature of a binary

Model

- progenitor was a wide binary that merged 30,000 yr ago
  - → source of angular momentum → triple-ring nebula
  - → mixing + addition of mass → blue supergiant
  - → chemical anomalies
- jet-like explosion because of rapidly rotating core?

IMPORTANT STELLAR TIMESCALES

- dynamical timescale: $t_{dyn} \simeq \frac{1}{\sqrt{4G\rho}}$

$$\sim 30\,\text{min}\,\left(\rho/1000\,\text{kg}\,\text{m}^{-3}\right)^{-1/2}$$

- thermal timescale (Kelvin-Helmholtz): $t_{KH} \simeq \frac{GM^2}{2RL}$

$$\sim 1.5\times10^7\,\text{yr}\,(M/M_\odot)^2\,(R/R_\odot)^{-1}\,(L/L_\odot)^{-1}$$

- nuclear timescale: $t_{nuc} \simeq \underbrace{M_c/M}_{\text{core mass}}\;\underbrace{\eta}_{\text{efficiency}}\;(Mc^2)/L$

$$\sim 10^{10}\,\text{yr}\,(M/M_\odot)^{-3}$$

Example	t_{dyn}	t_{KH}	t_{nuc}
main-sequence stars			
a) $M = 0.1\,M_\odot$, $L = 10^{-3}\,L_\odot$, $R = 0.15\,R_\odot$	4 min	10^9 yr	10^{12} yr
b) $M = 1\,M_\odot$, $L = 1\,L_\odot$, $R = 1\,R_\odot$	30 min	15×10^6 yr	10^{10} yr
c) $M = 30\,M_\odot$, $L = 2\times10^5\,L_\odot$, $R = 20\,R_\odot$	400 min	3×10^3 yr	2×10^6 yr
red giant ($M = 1\,M_\odot$, $L = 10^3\,L_\odot$, $R = 200\,R_\odot$)	50 d	75 yr	
white dwarf ($M = 1\,M_\odot$, $L = 5\times10^{-3}\,L_\odot$, $R = 2.6\times10^{-3}\,R_\odot$)	7 s	10^{11} yr	
neutron star ($M = 1.4\,M_\odot$, $L = 0.2\,L_\odot$, $R = 10$ km, $T_{eff} = 10^6$ K)	0.1 ms	10^{13} yr	

END STATES OF STARS

Three (main) possibilities

- the star develops a degenerate core and nuclear burning stops (+ envelope loss) → degenerate dwarf (white dwarf)
- the star develops a degenerate core and ignites nuclear fuel explosively (e.g. carbon) → complete disruption in a supernova
- the star exhausts all of its nuclear fuel and the core exceeds the Chandrasekhar mass → core collapse, compact remnant (neutron star, black hole)

Final fate as a function of initial mass (M_0) for $Z = 0.02$

$M_0 \lesssim 0.08\,M_\odot$	no hydrogen burning (degeneracy pressure + Coulomb forces)	planets, brown dwarfs
$[0.08, 0.48]\,M_\odot$	hydrogen burning, no helium burning	degenerate He dwarf
$[0.48, 8]\,M_\odot$	hydrogen, helium burning	degenerate CO dwarf
$[8, 13]\,M_\odot$	complicated burning sequences, no iron core	neutron star
$[13, 80]\,M_\odot$	formation of iron core, core collapse	neutron star, black hole
$M_0 \gtrsim 80\,M_\odot$	pair instability? complete disruption?	no remnant
also (?) $[6, 8]\,M_\odot$	degenerate carbon ignition possible (but unlikely), complete disruption	no remnant