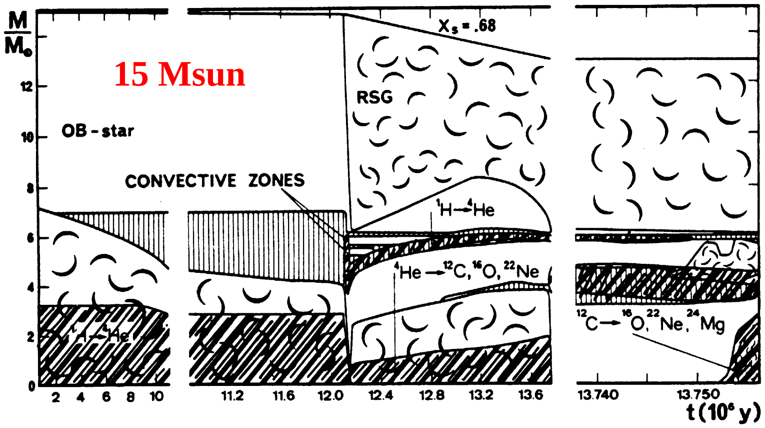
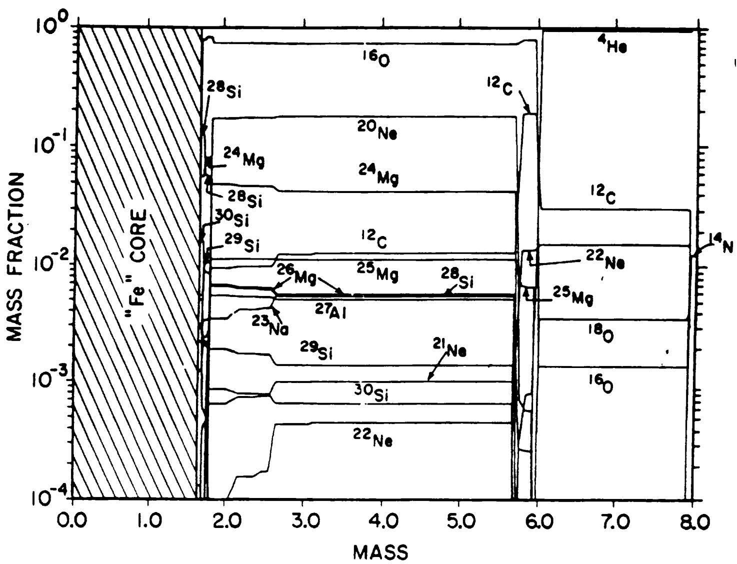
Evolution of Massive Stars



Maeder (1987)

Helium Core (8 Msun)



Itoh and Nomoto (1987)

6.3 EVOLUTION OF MASSIVE STARS ($M \gtrsim 13\,M_\odot$)
(CO: 13.3)

- 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

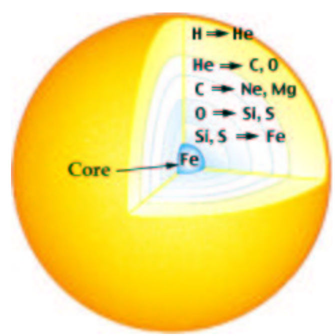
▷ *carbon burning* ($T \sim 6 \times 10^8$ K)

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

▷ *oxygen burning* ($T \sim 10^9$ K)

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

▷ *silicon burning:* photodisintegration of complex nuclei, hundreds of reactions → *iron*



▷ form *iron core*

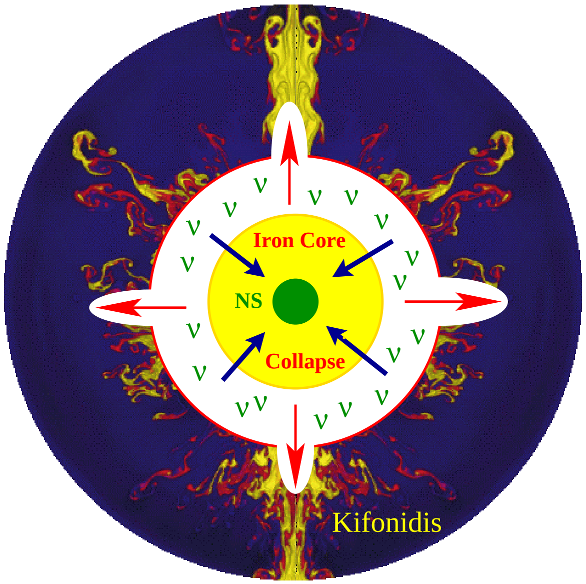
▷ *iron* is the most tightly *bound nucleus* → no further energy from nuclear fusion

▷ iron core surrounded by *onion-like shell structure*

6.4.1 EXPLOSION MECHANISMS (ZG: 18-5B/C/D)

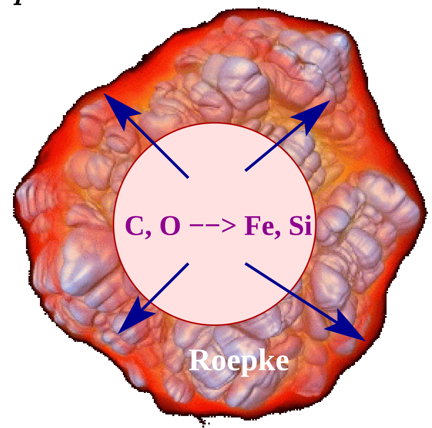
- *two* main, *completely different* mechanisms

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 the neutrino energy *deposited* ($\sim 1\,\%$, 10^{44} J) in the envelope to *eject* the envelope and produce the supernova?
- leaves *compact remnant* (neutron star/black hole)

Thermonuclear Explosions

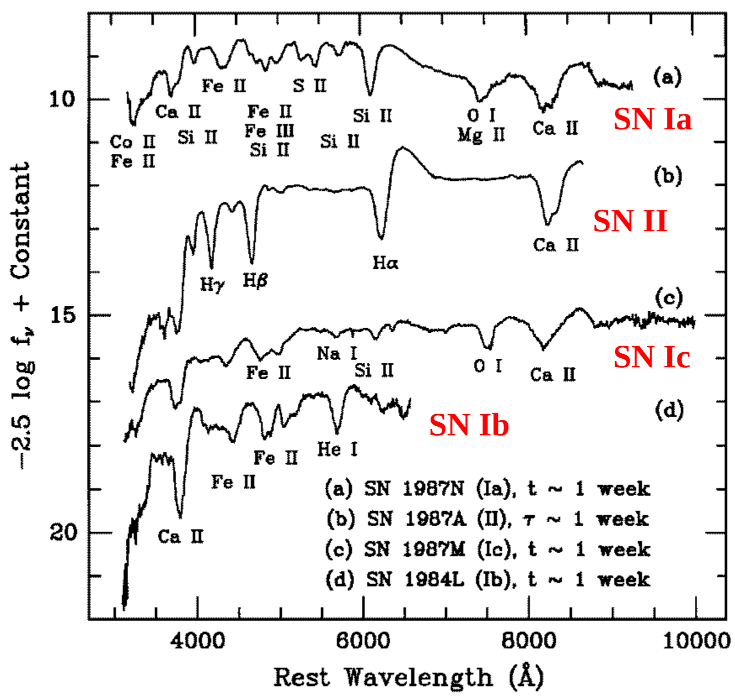


- occurs in *accreting* carbon/oxygen *white dwarf* when it reaches the *Chandrasekhar mass*
  - → *carbon ignited* under *degenerate* conditions; nuclear burning raises T, but not P
  - → *thermonuclear runaway*
  - → incineration and *complete destruction* of the star
- energy source is *nuclear energy*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

but: *progenitor* evolution not understood

- ▷ *single-degenerate channel:* accretion from non-degenerate companion
- ▷ *double-degenerate channel:* merger of two CO white dwarfs

Supernova Classification



6.4.2 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

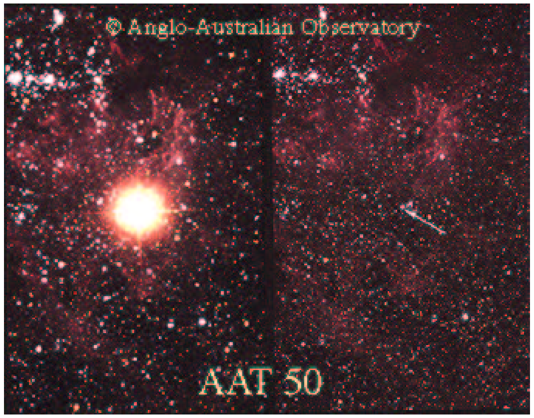
relation no longer 1 to 1 → confusion

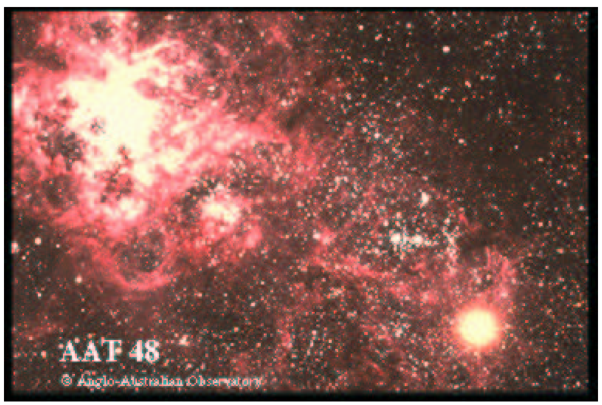
- *Type Ia* (Si lines): thermonuclear explosion of white dwarf
- *Type Ib/Ic* (no Si; He or no He): core collapse of He star
- *Type II-P:* "classical" core collapse of a massive star with hydrogen envelope
- *Type II-L:* supernova with linear lightcurve (thermonuclear explosion of intermediate-mass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

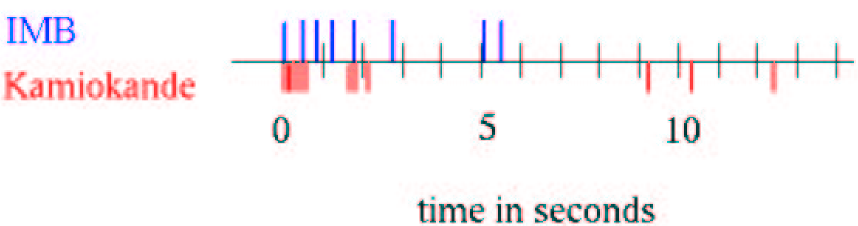
complications

- special supernovae like *SN 1987A*
- *Type IIb:* supernovae that change type, *SN 1993J* (Type II → Type Ib)
- some supernova *"types"* (e.g., IIn) occur for both explosion types (*"phenomenon"*, not type; also see SNe Ic)
- new types: thermonuclear explosion of He star (Type Iab?)

SN 1987A (LMC)







Neutrino Signal

6.4.3 SN 1987A (ZG: 18-5)

- 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

SUMMARY III(B): 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): $t_{KH} \simeq \frac{GM^2}{2RL}$
$$\sim 1.5 \times 10^7\,\text{yr}\,(M/M_\odot)^2\,(R/R_\odot)^{-1}\,(L/L_\odot)^{-1}$$
- *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) $M = 30\,M_\odot$, $L = 2 \times 10^5\,L_\odot$, $R = 20\,R_\odot$	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 ($M = 1\,M_\odot$, $L = 5 \times 10^{-3}\,L_\odot$, $R = 2.6 \times 10^{-3}\,R_\odot$)	7 s	10^{11} yr	
neutron star ($M = 1.4\,M_\odot$, $L = 0.2\,L_\odot$, $R = 10\,\text{km}$, $T_{eff} = 10^6\,\text{K}$)	0.1 ms	10^{13} yr	

SUMMARY V: THE 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 $Z = 0.02$

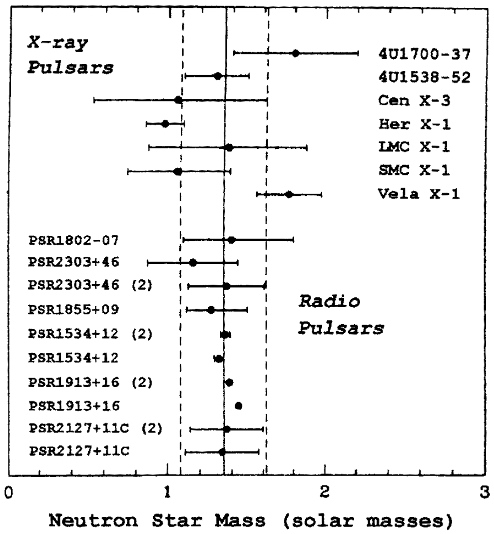
$M_0 \lesssim 0.08\,M_\odot$	*no hydrogen* burning (degeneracy pressure + Coulomb forces)	*planets, brown dwarfs*
$[0.08, 0.48]\,M_\odot$	*hydrogen* burning, *no helium* burning	*degenerate He dwarf*
$[0.48, 8]\,M_\odot$	*hydrogen, helium* burning	*degenerate CO dwarf*
$[8, 13]\,M_\odot$	*complicated* 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*

6.4.4 NEUTRON STARS (ZG: 17-2; CO: 15.6)

- are the end products of the *collapse* of the cores (mainly Fe) of massive stars (between 8 and $\sim 20\,M_\odot$)
- in the collapse, all nuclei are dissociated to produce a very compact remnant mainly composed of *neutrons* and some *protons/electrons*

  Note: this dissociation is *endothermic*, using some of the gravitational energy released in the collapse

  ▷ these reactions *undo* all the previous nuclear fusion reactions
- since neutrons are *fermions*, there is a *maximum mass* for a neutron star (similar to the Chandrasekhar mass for white dwarfs), estimated to be between *1.5* – *3* $M_\odot$
- *typical radii: 10 km* (i.e. density $\sim 10^{18}\,\mathrm{kg\,m^{-3}}$!)



6.4.5 SCHWARZSCHILD BLACK HOLES (ZG: 17-3; CO: 16)

- *event horizon:* (after Michell 1784)

  ▷ the *escape velocity* for a particle of mass m from an object of mass M and radius R is $v_{esc} = \sqrt{\frac{2GM}{R}}$ ($11\,\mathrm{km\,s^{-1}}$ for Earth, $600\,\mathrm{km\,s^{-1}}$ for Sun)

  ▷ assume *photons* have *mass:* $m \propto E$ (Newton's corpuscular theory of light)

  ▷ photons travel with the *speed of light c*

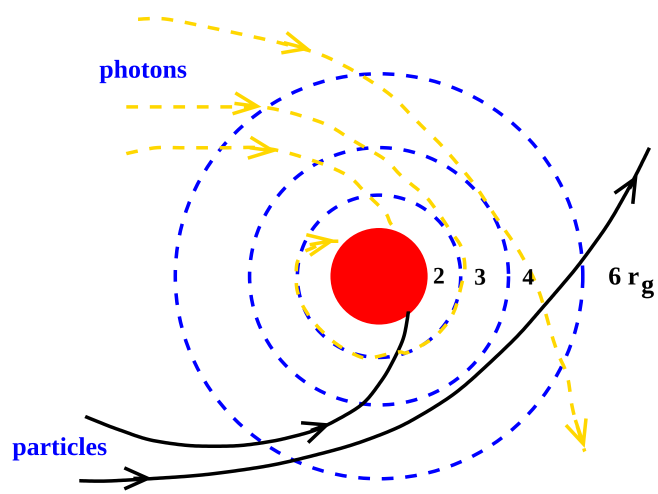
  → photons cannot escape, if $v_{esc} > c$

$$\rightarrow \boxed{R < R_s \equiv \frac{2GM}{c^2}} \quad \textit{(Schwarzschild radius)}$$

  ▷ $R_s = 3\,\mathrm{km}\,(M/M_\odot)$

  Note: for neutron stars $R_s \simeq 5\,\mathrm{km}$; only a factor of 2 smaller than R_{NS} → GR important

Orbits near Schwarzschild Black Holes



gravitational radius: $r_g = \frac{GM}{c^2}$