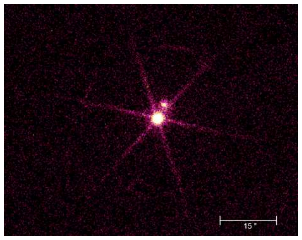
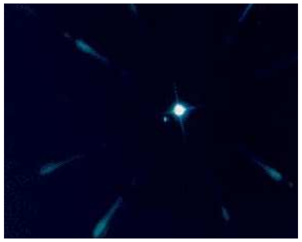
End-Stages of Stellar Evolution

White Dwarfs



Sirius A+B: *Chandra* (X-rays; *WD is bright*)

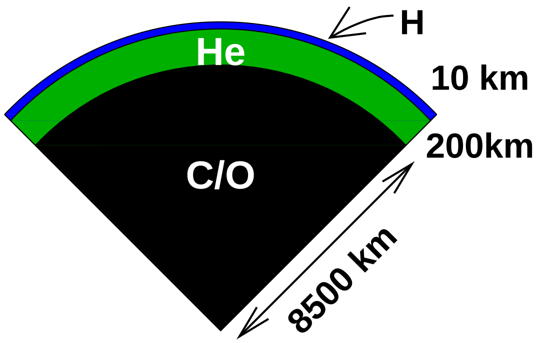


McDonald Observatory (optical; *WD is faint*)

White Dwarfs:

1. End stages of evolution of stars with $M \lesssim 10\,M_\odot$ on main sequence
2. typically $M \sim 0.6 \dots 0.8\,M_\odot$, and always $M < 1.44\,M_\odot$ (Chandrasekhar mass); above that: relativistic degenerate gas ($P \propto \rho^{4/3}$), can show that under these circumstances WD is not stable.
3. mainly consist of C and O
4. Radius $\sim$ Earth
5. Typical density $\rho \sim 10^6\,\mathrm{g\,cm^{-3}}$
6. interior temperature $\sim 10^7$ K, atmosphere $\sim 10^4$ K, slowly cooling down (observable for $\gtrsim 10^9$ years).

White Dwarfs



White dwarfs come in two flavors:

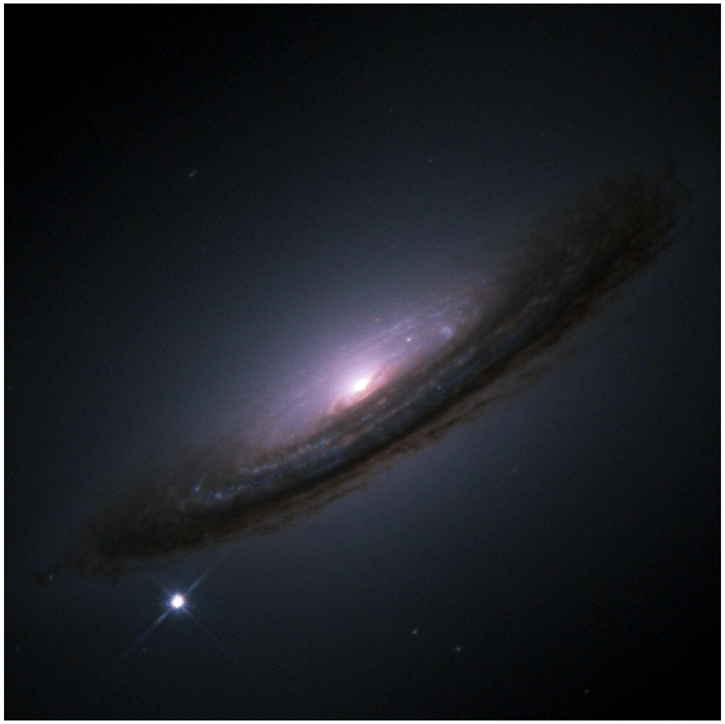
DA: H present in spectrum (~80% of all WD)

DB: He present in spectrum (~ the rest)

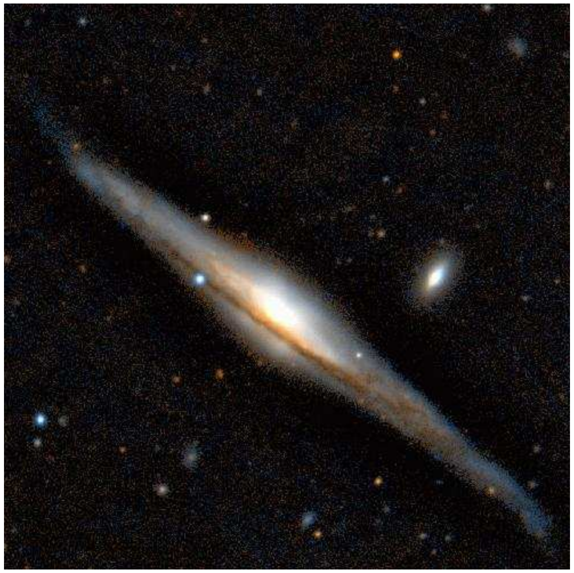
plus a few oddballs

Structure: gravitationally settled, so DB's really do not have any H since it would "swim on top"

$\Longrightarrow$ layered, "onion-like" structure

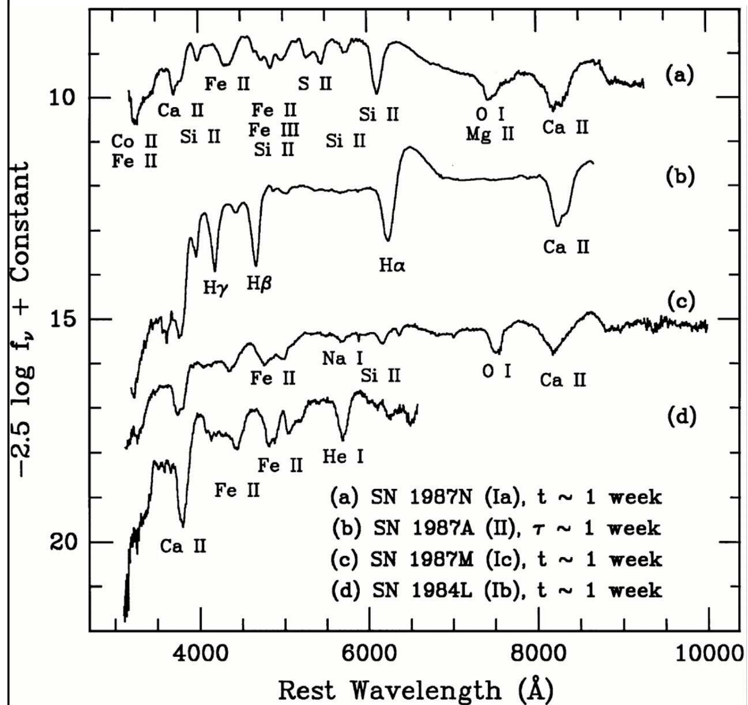


SN1994d (HST WFPC)



Type II SN2001cm in NGC5965 (2.56 m NOT, Håkon Dahle; NORDITA)

Evolution of more massive stars: fusion up to ^{56}Fe, then no energy gain $\Longrightarrow$ no pressure balance in centre $\Longrightarrow$ supernova explosion of type II.
energy release: 10^{46} W ($10^{20} L_\odot$; about 1% in light, rest in neutrinos)



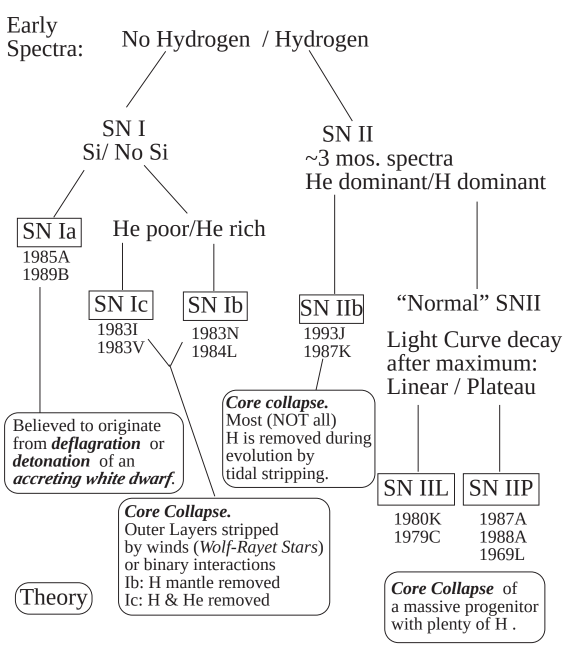
(?, Fig. 1); t: time after maximum light; τ: time after explosion; P Cyg profiles give $v \sim 10000\,\mathrm{km\,s^{-1}}$

Rough classification (Minkowski, 1941):

Type I: no hydrogen in spectra; subtypes Ia, Ib, Ic

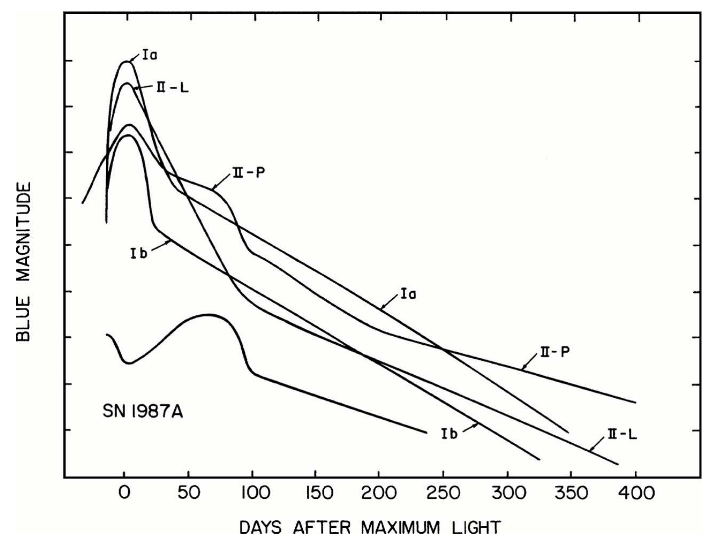
Type II: hydrogen present, subtypes II-L, II-P

Note: pre 1985 subtypes Ia, Ib had different definition than today $\Longrightarrow$ beware when reading older texts.



courtesy M.J. Montes

Supernovae, V



(?, Fig. 3)

Light curves of SNe I all very similar, SNe II have much more scatter.

SNe II-L ("linear") resemble SNe I

SNe II-P ("plateau") have const. brightness to within 1 mag for extended period of time.

Supernova Statistics, I

Clue on origin from supernova statistics:

- SNe II, Ib, Ic: never seen in elliptical galaxies, which are void of gas and have no new star formation; generally associated with spiral arms and H II regions in spiral galaxies, i.e., with star forming regions

$\Longrightarrow$ progenitor of SNe II, Ib, Ic: massive stars ($\gtrsim 8\,M_\odot$) $\Longrightarrow$ “core collapse supernova”

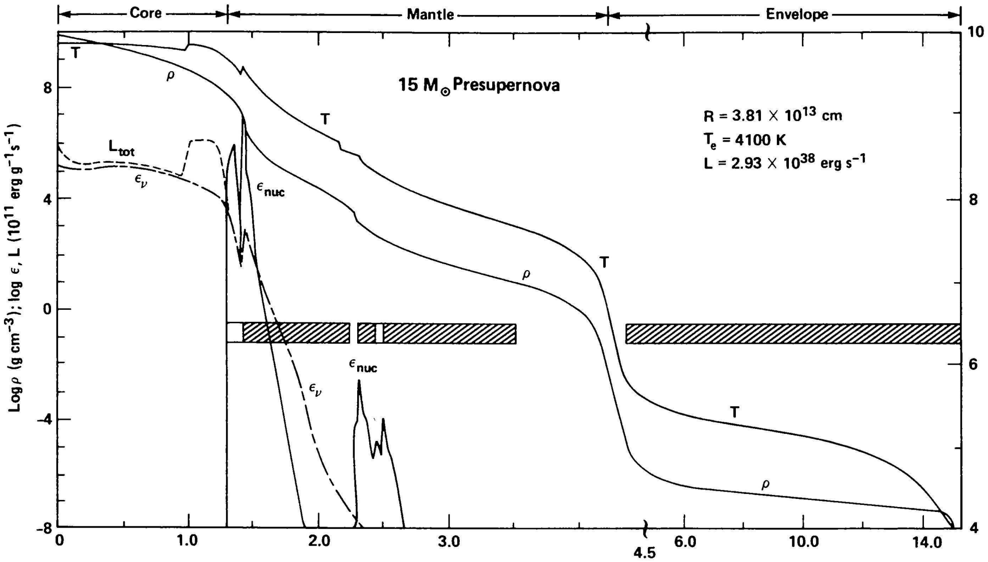
- SNe Ia: all types of galaxies, no preference for arms.

$\Longrightarrow$ progenitor of SNe Ia: accreting carbon-oxygen white dwarfs, undergoing thermonuclear runaway (see later)

Core Collapse SNe

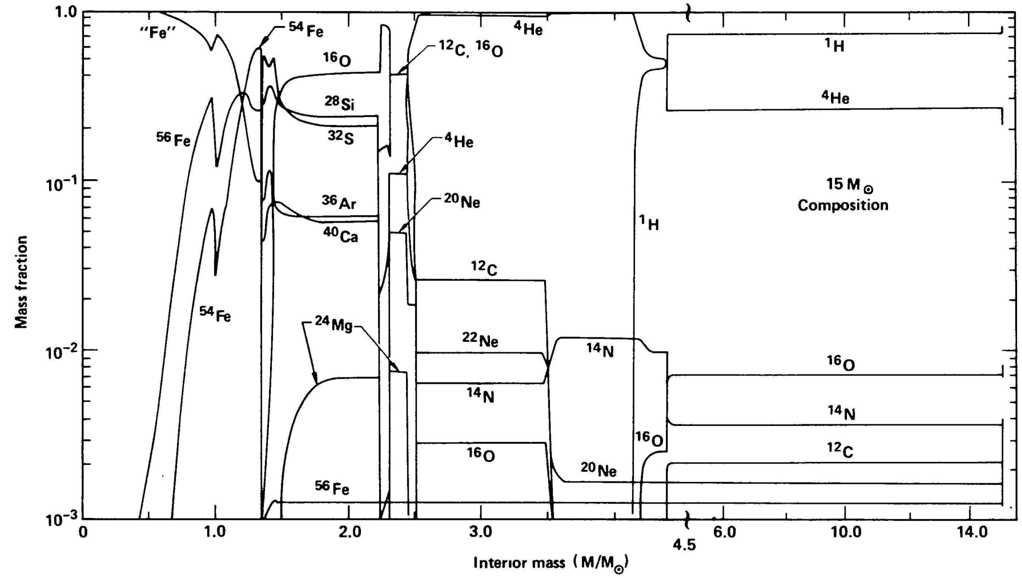
Nuclear reactions in massive ($> 8\,M_\odot$) stars:

Reaction	above T [10^6 K]	Energy gain [MeV]
Hydrogen burning		
$4\,^1\mathrm{H} \longrightarrow {}^4\mathrm{He}$	4	6.55
Helium burning		
$3\,^4\mathrm{He} \longrightarrow {}^8\mathrm{Be} + {}^4\mathrm{He} \longrightarrow {}^{12}\mathrm{C}$	100	<0.61
Carbon burning		
${}^{12}\mathrm{C} + {}^4\mathrm{He} \longrightarrow {}^{16}\mathrm{O}$	600	<0.54
$2\,^{12}\mathrm{C} \longrightarrow {}^4\mathrm{He} + {}^{20}\mathrm{Ne}$		
${}^{20}\mathrm{Ne} +{}^4\,\mathrm{He} \longrightarrow \mathrm{n} + {}^{23}\mathrm{Mg}$		
Oxygen burning		
$2\,^{16}\mathrm{O} \longrightarrow {}^4\mathrm{He} + {}^{28}\mathrm{Si}$	1000	<0.3
$2\,^{16}\mathrm{O} \longrightarrow 2\,^4\mathrm{He} + {}^{24}\mathrm{Mg}$		
Silicon burning		
$2\,^{28}\mathrm{Si} \longrightarrow {}^{56}\mathrm{Fe}$	3000	< 0.18



Woosley & Weaver, 1988, Fig. 1

Structure of a 15 $M_\odot$ pre-supernova star

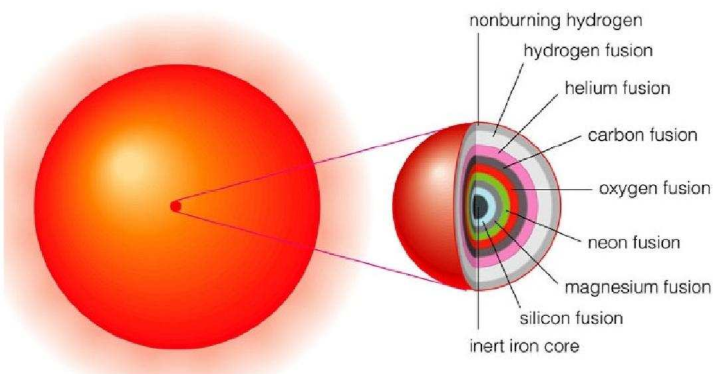


Woosley & Weaver, 1988, Fig. 1

Structure of a 15 $M_\odot$ pre-supernova star

4–16

Core Collapse SNe



Core collapse supernovae:

- SNe II: progenitors are stars with mass 8–40 $M_\odot$ (approximate).
- SNe Ib, Ic: more massive stars, which lost their H shell due to strong stellar winds

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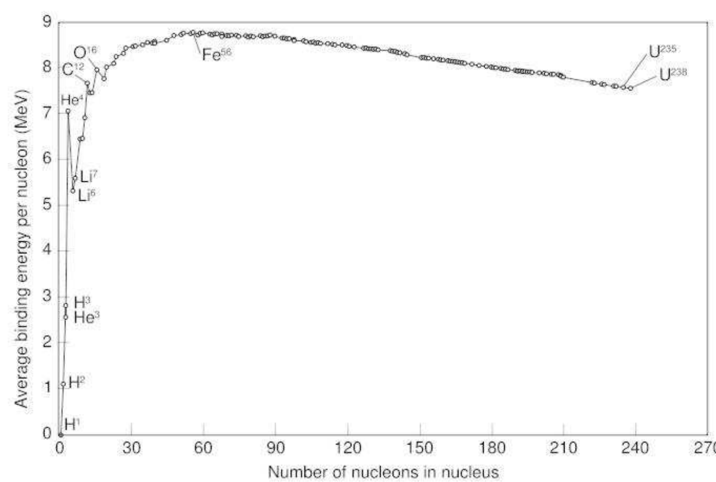
Core Collapse SNe



^{56}Fe is one of the most tightly bound nucleons $\Longrightarrow$ Star has a problem once ^{56}Fe reached: fusion processed become endotherm

Core Collapse SNe

Iron core starts to shrink $\Longrightarrow$ T increases $\Longrightarrow$ ^{56}Fe starts photodisintegration:

$$^{56}\mathrm{Fe} + \gamma \longrightarrow 13\,^{4}\mathrm{He} + 4\mathrm{n}$$
$$^{4}\mathrm{He} + \gamma \longrightarrow 2\mathrm{p} + 2\mathrm{n}$$

Typical core masses are between 1.3 $M_\odot$ (for 10 $M_\odot$ on ZAMS) and 2.5 $M_\odot$ (for 50 $M_\odot$ on ZAMS).

Until now, free electrons have degeneracy pressure and hold star

BUT: once core temperature increases to $T_\mathrm{c} \sim 8 \times 10^9$ K and density to $\rho_\mathrm{c} \sim 10^{10}\,\mathrm{g\,cm^{-3}}$: neutronization:

$$\mathrm{p} + \mathrm{e}^- \rightarrow \mathrm{n} + \nu_\mathrm{e}$$

$\Longrightarrow$ rapid energy loss (for a 20 $M_\odot$ star: $4.4 \times 10^{38}\,\mathrm{erg\,s^{-1}}$ in photons, but $3 \times 10^{45}\,\mathrm{erg\,s^{-1}}$ in neutrinos!) $\Longrightarrow$ COLLAPSE

Core Collapse SNe

Once pressure support is gone:

$\Longrightarrow$ collapse (free fall)

$\Longrightarrow$ speeds are fast (outer core: $\sim$70000 $\mathrm{km\,s^{-1}}$!)

$\Longrightarrow$ supersonic, so outer parts don't realize what's happening

$\Longrightarrow$ inner core compresses further through neutronization

$\Longrightarrow$ once $\rho_\mathrm{c} \sim 8 \times 10^{14}\,\mathrm{g\,cm^{-3}}$: Neutron star forms (degeneracy pressure of neutrons)

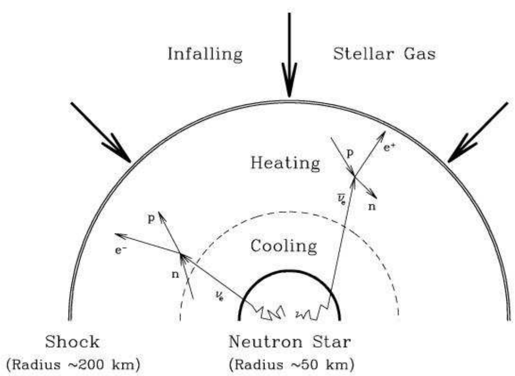
$\Longrightarrow$ "solid surface forms", resulting in bounce back

$\sim$20 msec for shock wave to pass through core

$\Longrightarrow$ further photodesintegration

$\Longrightarrow$ shock moves outwards $\Longrightarrow$ explosion ("prompt hydrodynamic explosion")

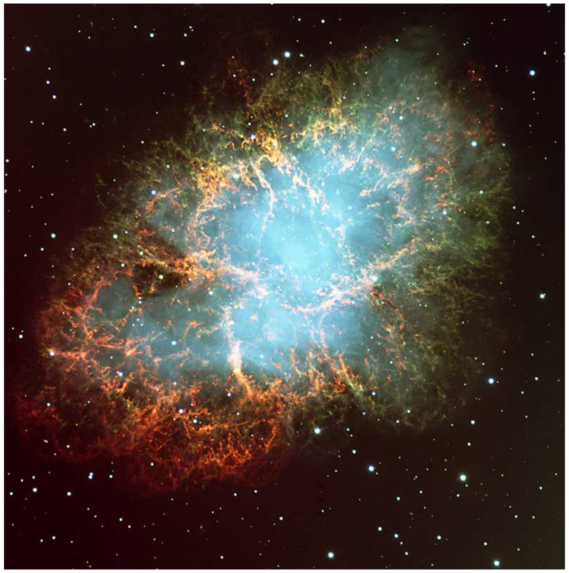
Core Collapse SNe



H.-T. Janka

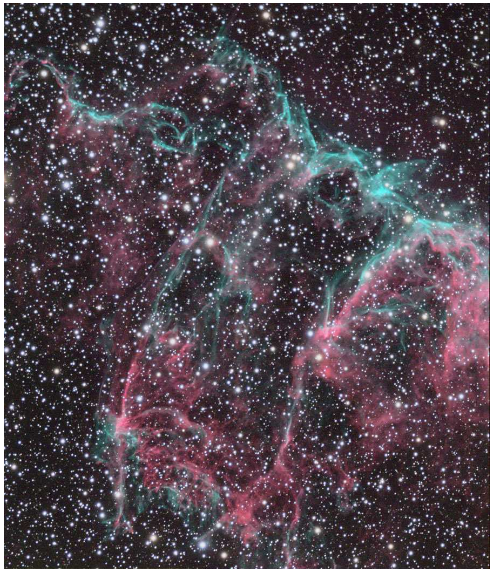
For Fe core mass of $\gtrsim$1.2 $M_\odot$: Infalling gas damps expansion of shock $\Longrightarrow$ need sufficient heating by neutrinos to trigger explosion! (takes $\sim$1 s $\Longrightarrow$ "delayed explosion mechanism")

energy loss $\sim 1.7 \times 10^{51}\,\mathrm{ergs\,s^{-1}}$ per 0.1 $M_\odot$ of Fe



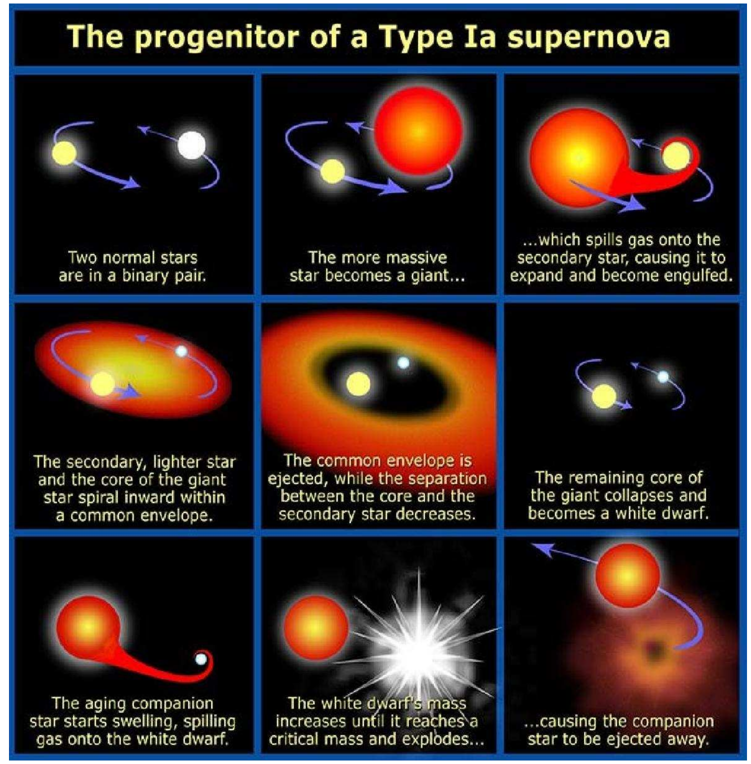
(ESO VLT/FORS 2)

Crab nebula: young remnant of SN of 1054, observed light due to synchrotron radiation (radiation emitted by electrons accelerated in magnetic field)

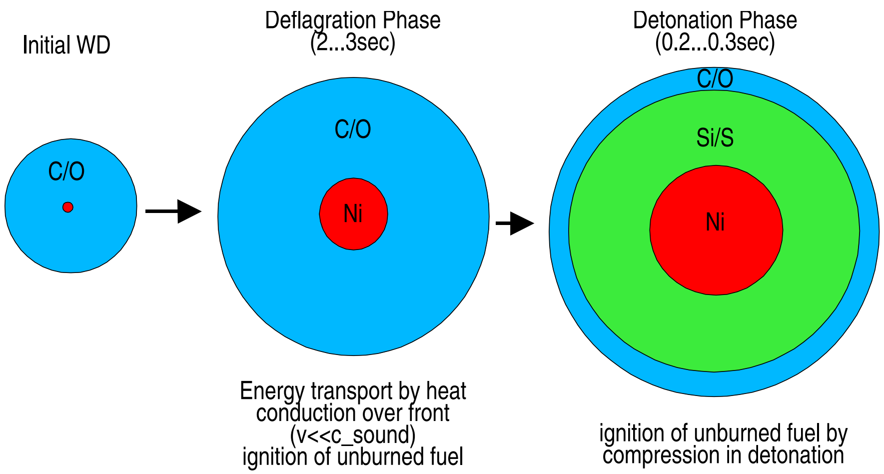


5000–10000 year old IC 1340/Veil Nebula/Cygnus Loop (©Loke Kun Tan)

Older supernova remnants: “wispy structure” due to interaction with interstellar medium, radiation (line emission) mainly caused by heating due to shocks.



Supernova Mechanisms – Ia, II



after P. Höflich

SNe Ia: thermonuclear runaway in carbon-oxygen white dwarfs (See later for details)