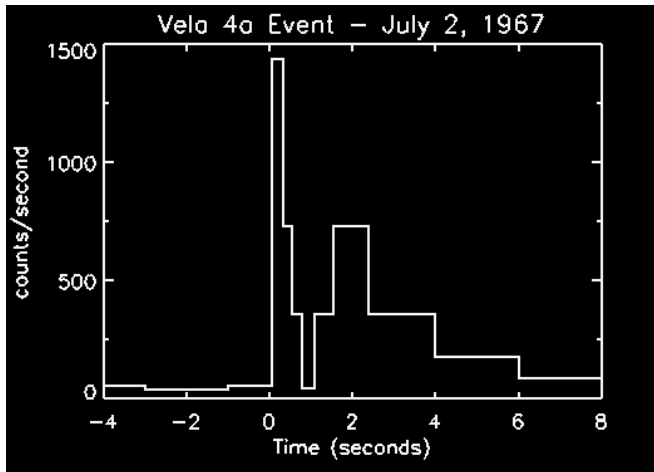


The deaths of high mass stars

Chapter 20



Star Destroyer class ship of the Republic

Evolution of high mass stars

- For stars with initial masses $> 8M_{\odot}$, the fusion process goes beyond C and O.
- Possible because of greater internal pressures and temperatures.
- Here, radiation pressure becomes important, and together with gas pressure the core does not become degenerate: nothing stops the core from contracting $\Rightarrow$ further heating.
- Produces a core that has an "onion layer" structure. Different layers are dominated by different nuclear species.

Onion shell buildup

1. Inert C-O core collapses and heats up, H & He shell burning => red supergiant again.
2. C-O core collapses until $T \sim 6 \times 10^8$ K: igniting C
 $^{12}\text{C} + ^{12}\text{C}$ fuses to O, Ne, Mg. C fusion lasts $\sim 10^3$ yr before out of C.
3. Inert O-Ne-Mg core collapses and heats up, H & He & C shell burning => red supergiant again...
4. Collapses until $T \sim 1.5 \times 10^9$ K: igniting Ne. Ne fuses to O, Mg....

And so on.... Causes evolutionary tracks to move rapidly back and forth on the HR diagram.

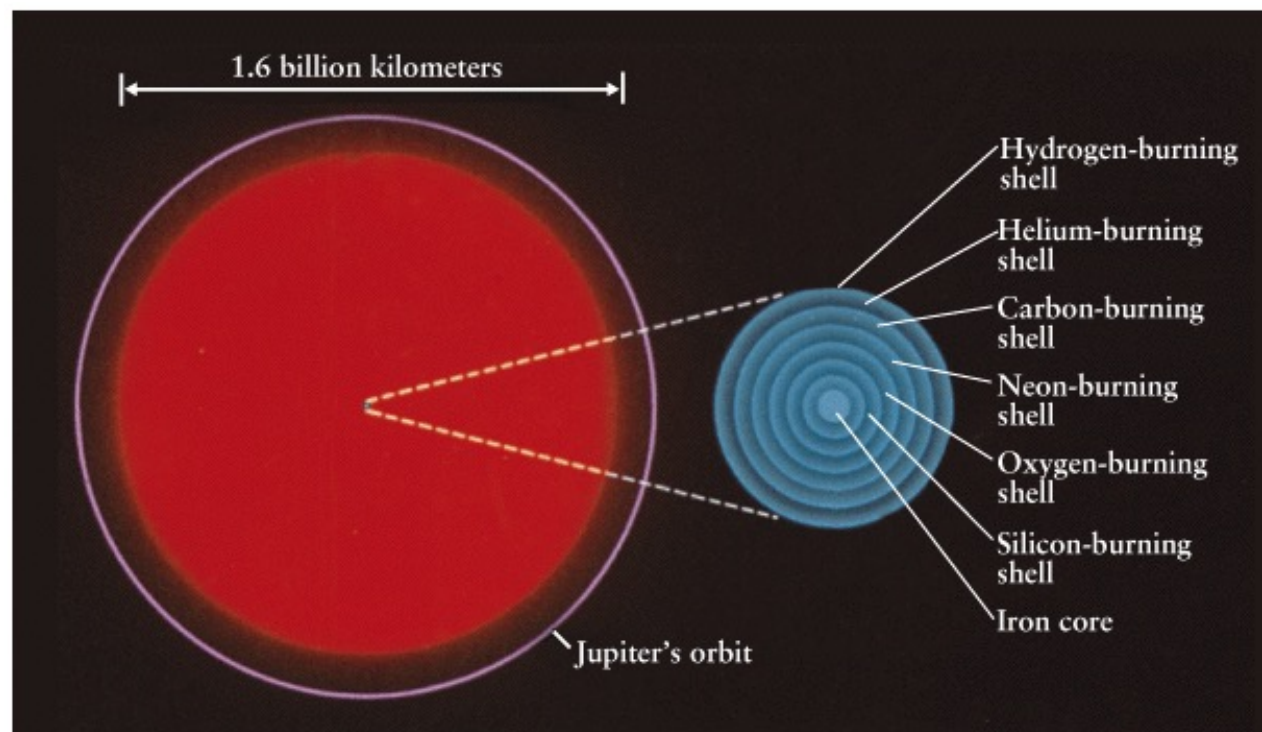
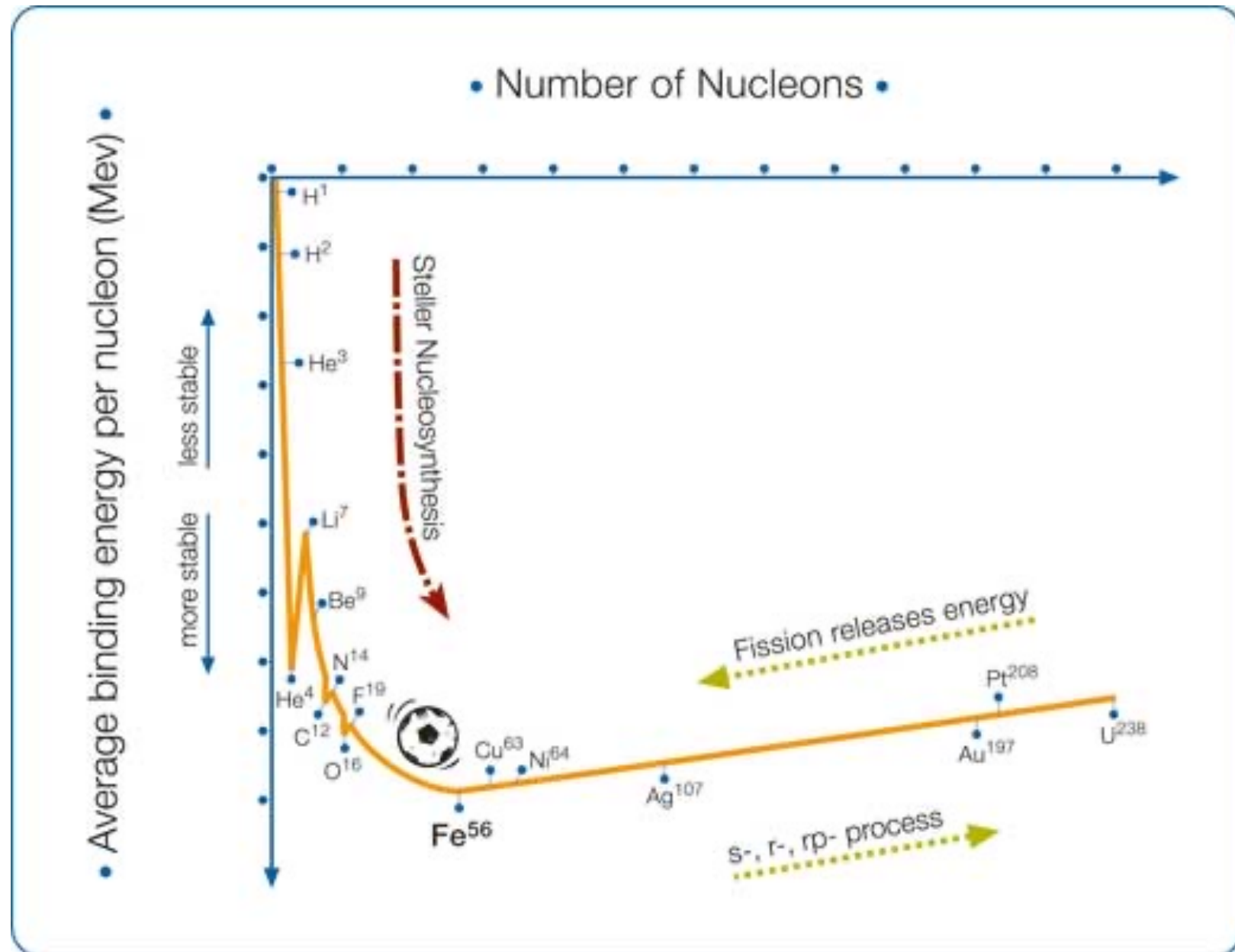


table 22-1 **Evolutionary Stages of a 25- $M_{\odot}$ Star**

Stage	Core temperature (K)	Core density (kg/m^3)	Duration of stage
Hydrogen fusion	4×10^7	5×10^3	7×10^6 years
Helium fusion	2×10^8	7×10^5	7×10^5 years
Carbon fusion	6×10^8	2×10^8	600 years
Neon fusion	1.2×10^9	4×10^9	1 year
Oxygen fusion	1.5×10^9	10^{10}	6 months
Silicon fusion	2.7×10^9	3×10^{10}	1 day
Core collapse	5.4×10^9	3×10^{12}	$\frac{1}{4}$ second
Core bounce	2.3×10^{10}	4×10^{15}	milliseconds
Explosive (supernova)	about 10^9	varies	10 seconds

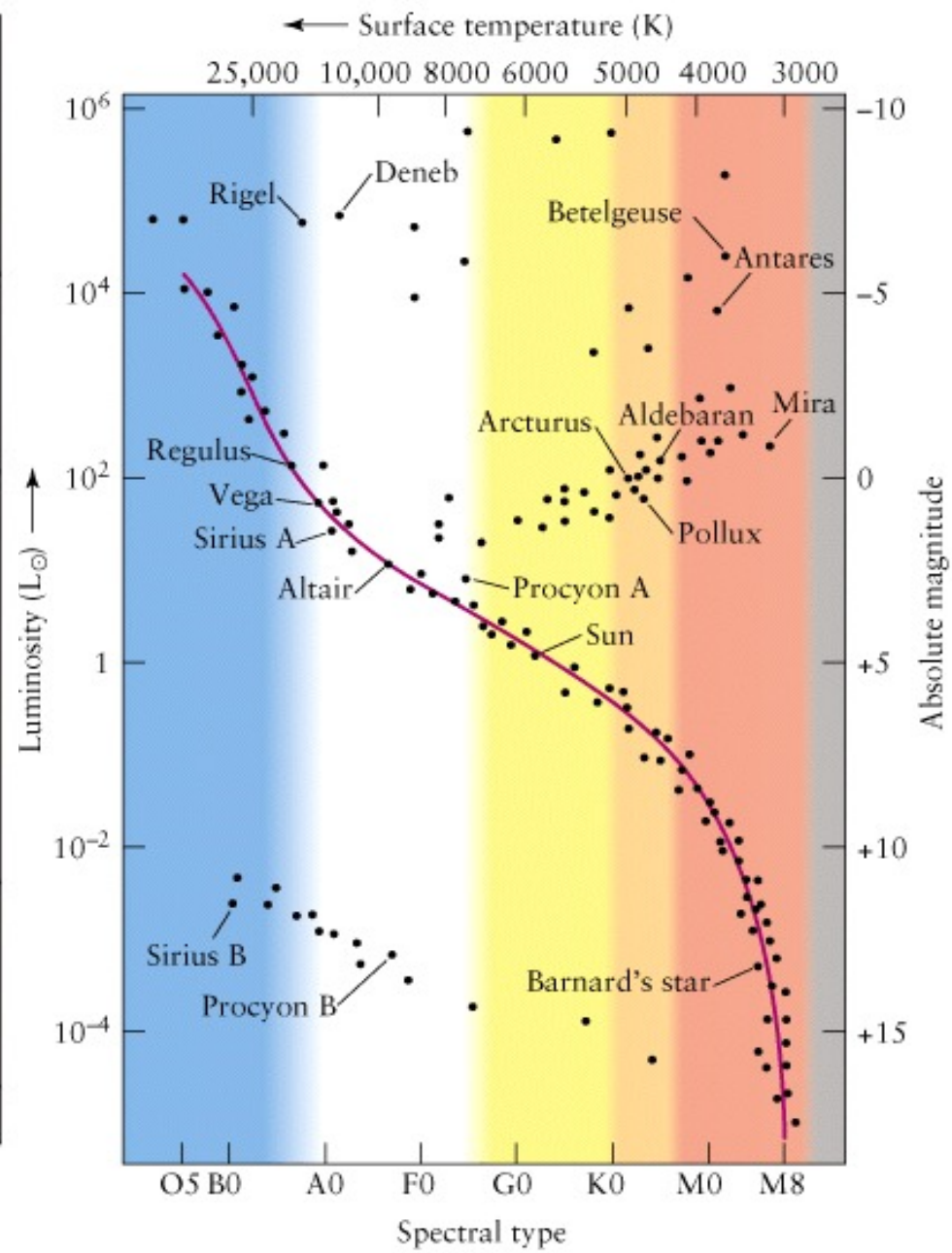
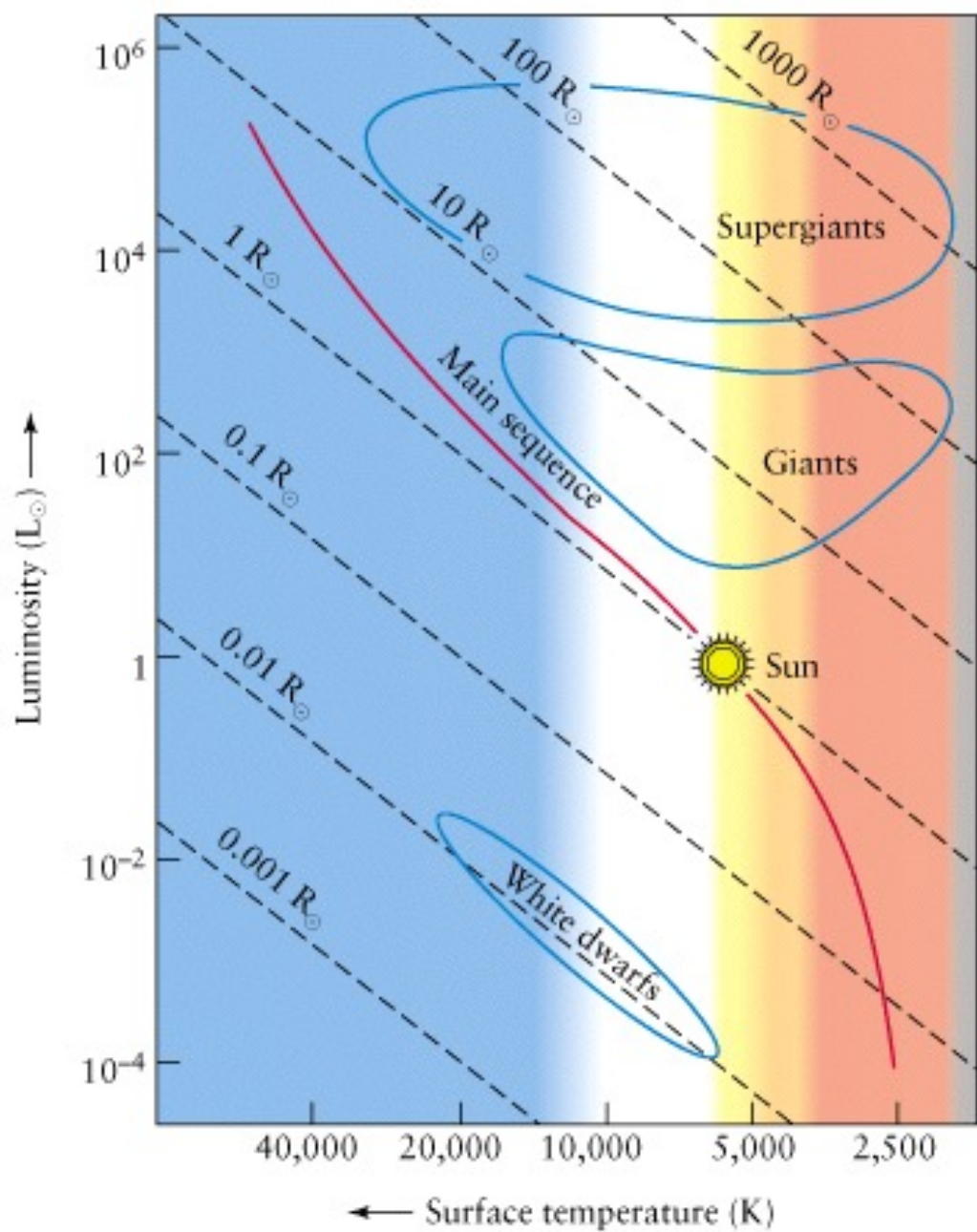
Binding Energy per nucleon

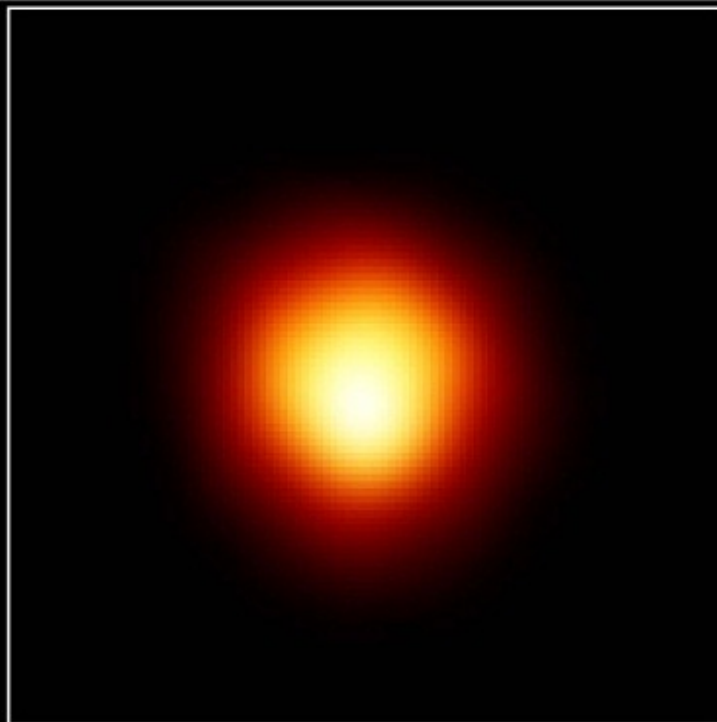


Where does it stop?

- A very high mass star can process all the way to iron (^{56}Fe). Stars will not make bigger nuclei than ^{56}Fe .
- Why? It is not energetically advantageous to make larger nuclei: fusion of nuclei heavier than Fe *absorbs* energy. So, massive stars eventually make iron cores.

Note that these stars are the supergiants.





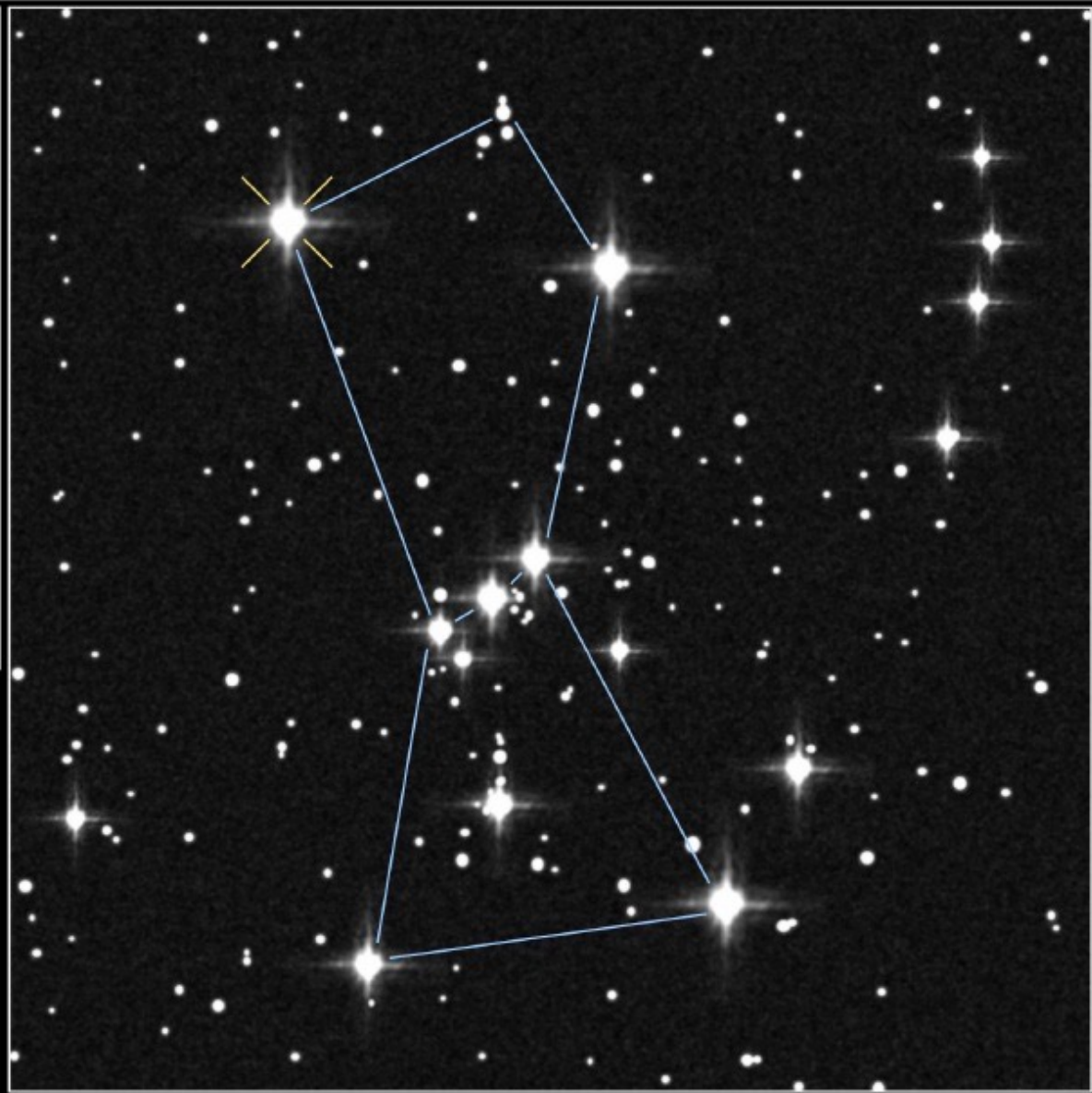
Size of Star



Size of Earth's Orbit

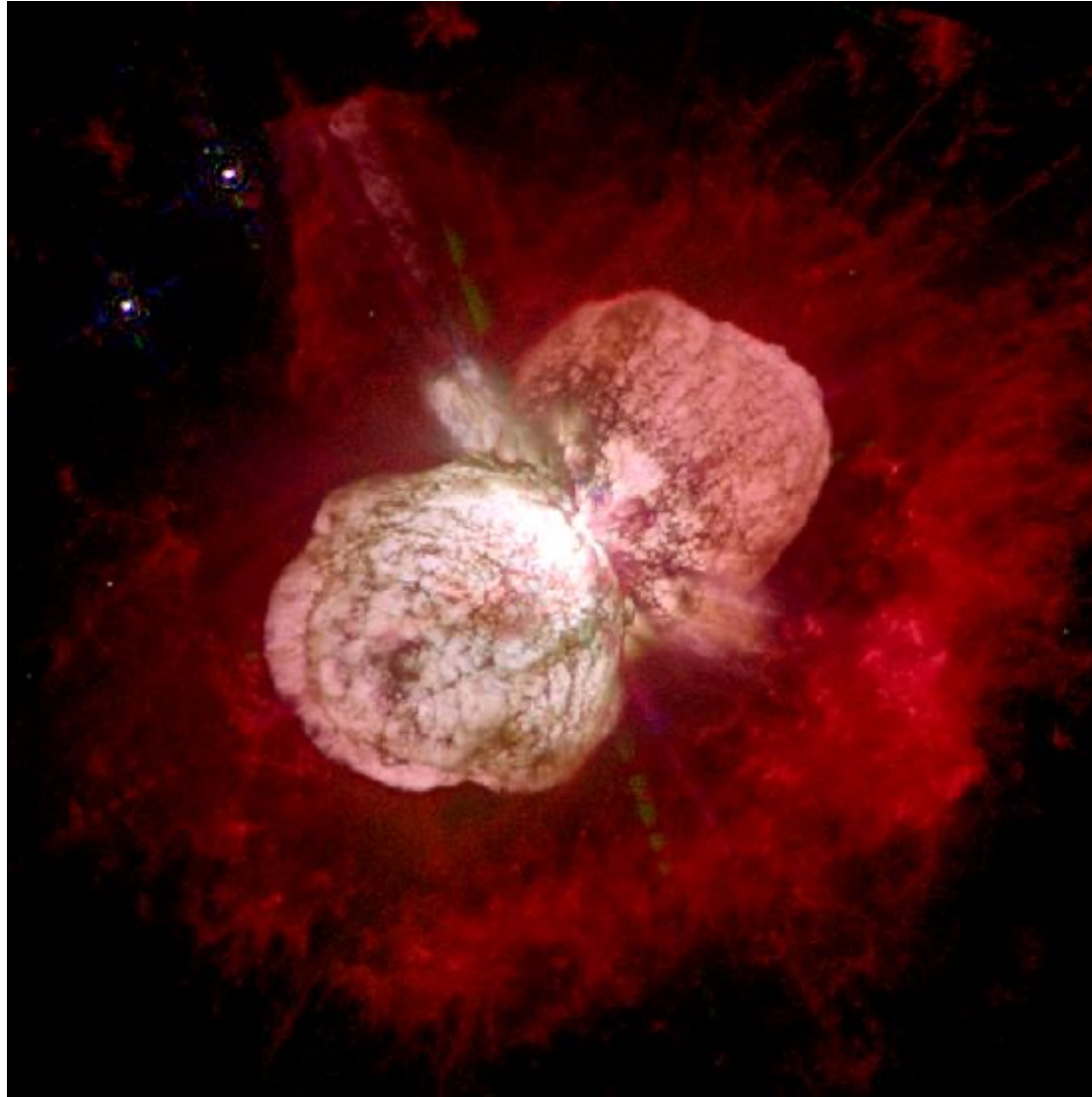


Size of Jupiter's Orbit



Atmosphere of Betelgeuse · Alpha Orionis

Hubble Space Telescope · Faint Object Camera

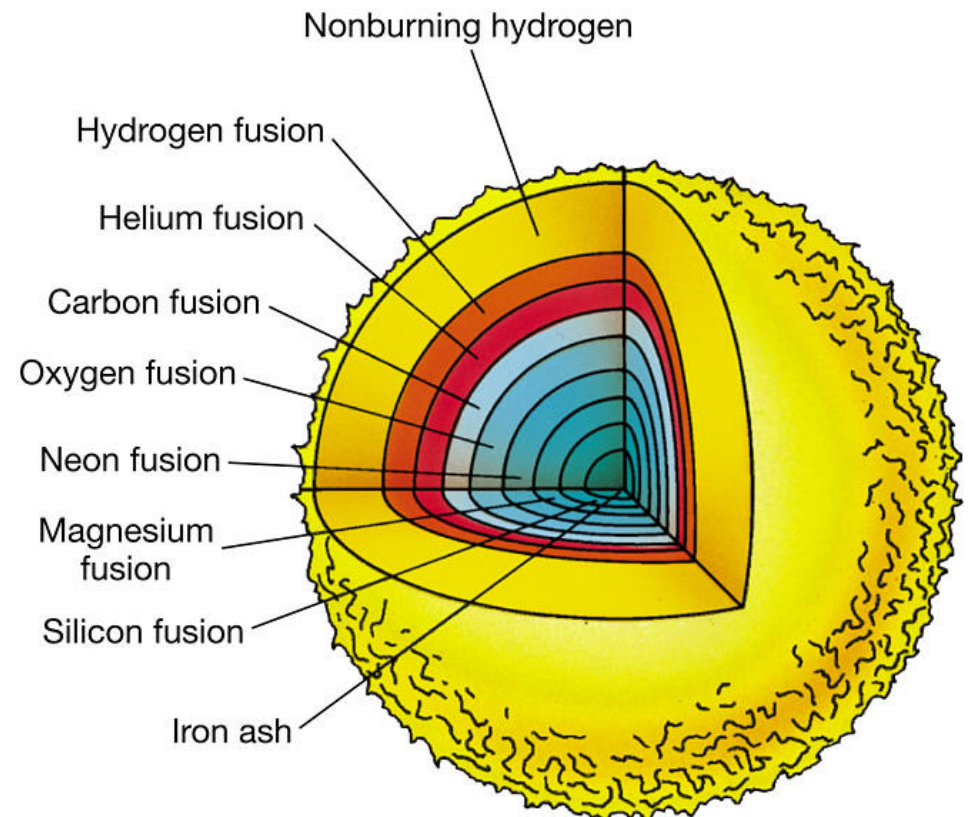


Eta Carinae - a ~~120-150 solar mass~~ supergiant!

Confirmed in 2005 to be a binary system, orbit not yet measured

At the end of the road

- End of Si burning day: inert Fe core, and an onion skin of nested nuclear burning shells.
- 1.2-1.4 $M_{\odot}$ Fe core contracts, heats up: a catastrophic collapse is unavoidable.

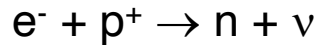


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The energy producing region ~ size of Earth (or 10^{-6} of the stellar radius).

The final collapse

- *Photodisintegration*: For stars with $M > 8 M_{\odot}$, when the core temp reaches 5×10^9 K, γ -rays disintegrate Fe nuclei (1/10 s) $\Rightarrow$ He, p, n
- *Neutronization*: In another 1/10 s, core becomes so dense that electrons are pushed onto protons to create neutrons via



These are energy *consuming* processes!

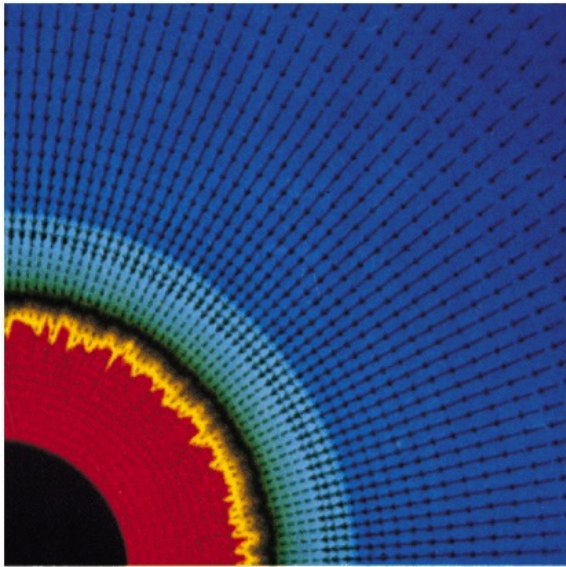
- Neutrons takes energy to create, and neutrinos escape, robbing the core of more energy so it collapses faster.
- After 0.25s, the core reaches the nuclear density $\sim 10^{17}$ kg/m³ (from $\sim 10^{12}$ kg/m³) .
- It becomes incompressible, and the core collapse stops suddenly $\Rightarrow$ overshooting causes a *core bounce* (outwards propagating pressure wave).

At the start of the iron core collapse, the core is ~ 6000 km. A second later it is ~ 50 km!

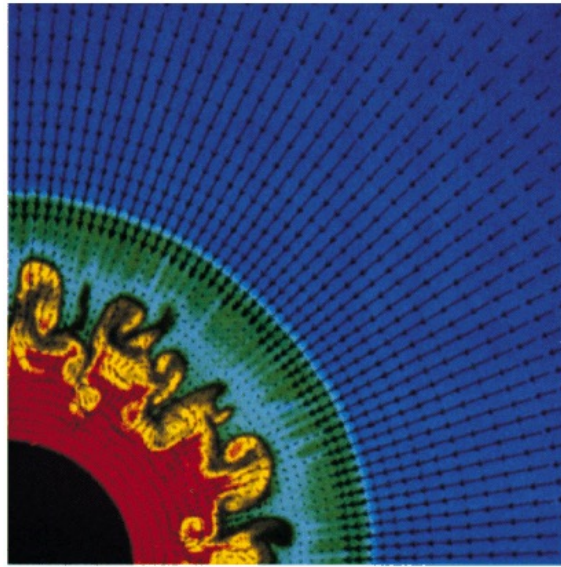
- Outside the core, material is falling inward at about $0.15c$. This is because the cooling of the core (because of loss of energy!) and hence the nearby layers, allowing material to fall back onto core.
- This material crashes onto the outward bouncing core, and blasts outwards. This wave actually speeds up, and will become supersonic: a shock wave!
- In a few hours the shock gets to the outer layers and breaks out from the surface at about $0.1c$.
- Where the layers have thinned out sufficiently, the energy escapes in form of a blast of photons.
- Seen from a distance, the star explodes as a *supernova*. This is a Type II SN (more later).

Simulations of supernova explosions:

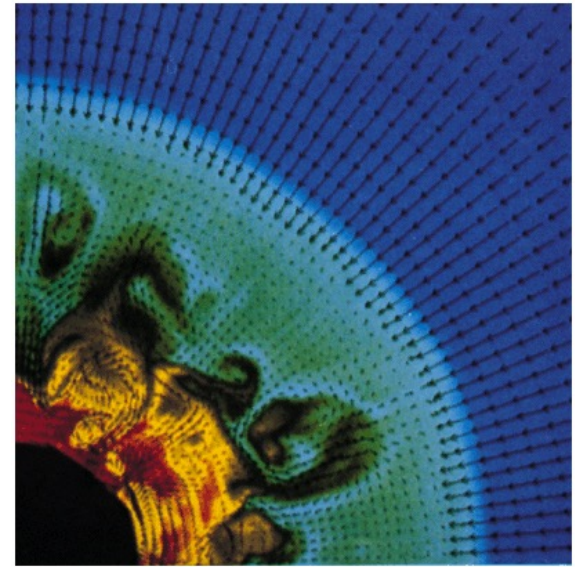
DEMO



5 milliseconds



10 milliseconds



15 milliseconds

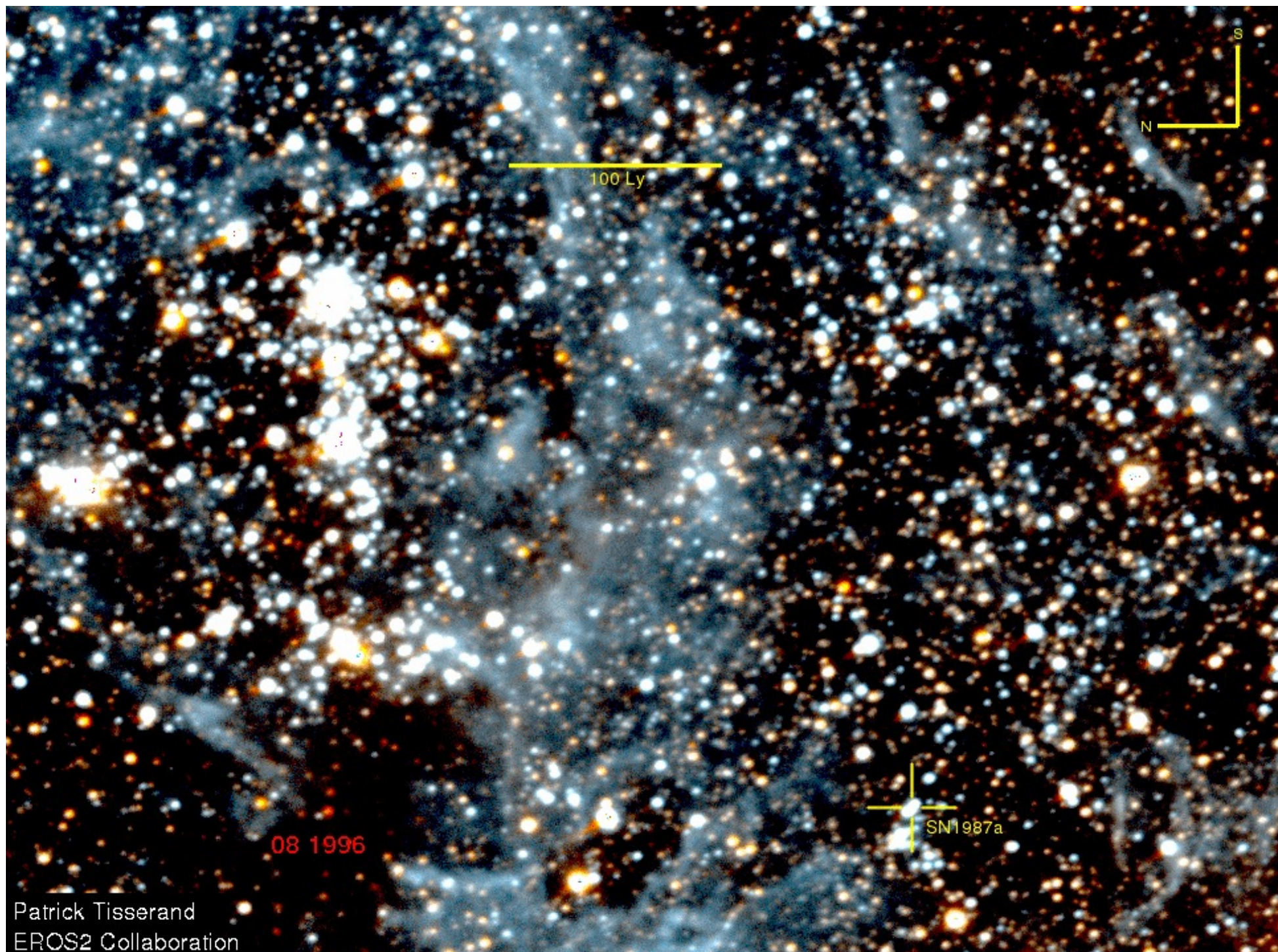
Nucleosynthesis

- Elements beyond iron on the periodic table are created in SN explosions (and also in neutron-star – neutron-star collisions)
- At these enormous pressures and temperatures, neutron reactions can build heavier nuclei (energy release by SN explosion 10^{46} J, needed for these reactions).
- $\Rightarrow$ very heavy elements are created
 $\Rightarrow$ spewed out into space before they can be torn apart.

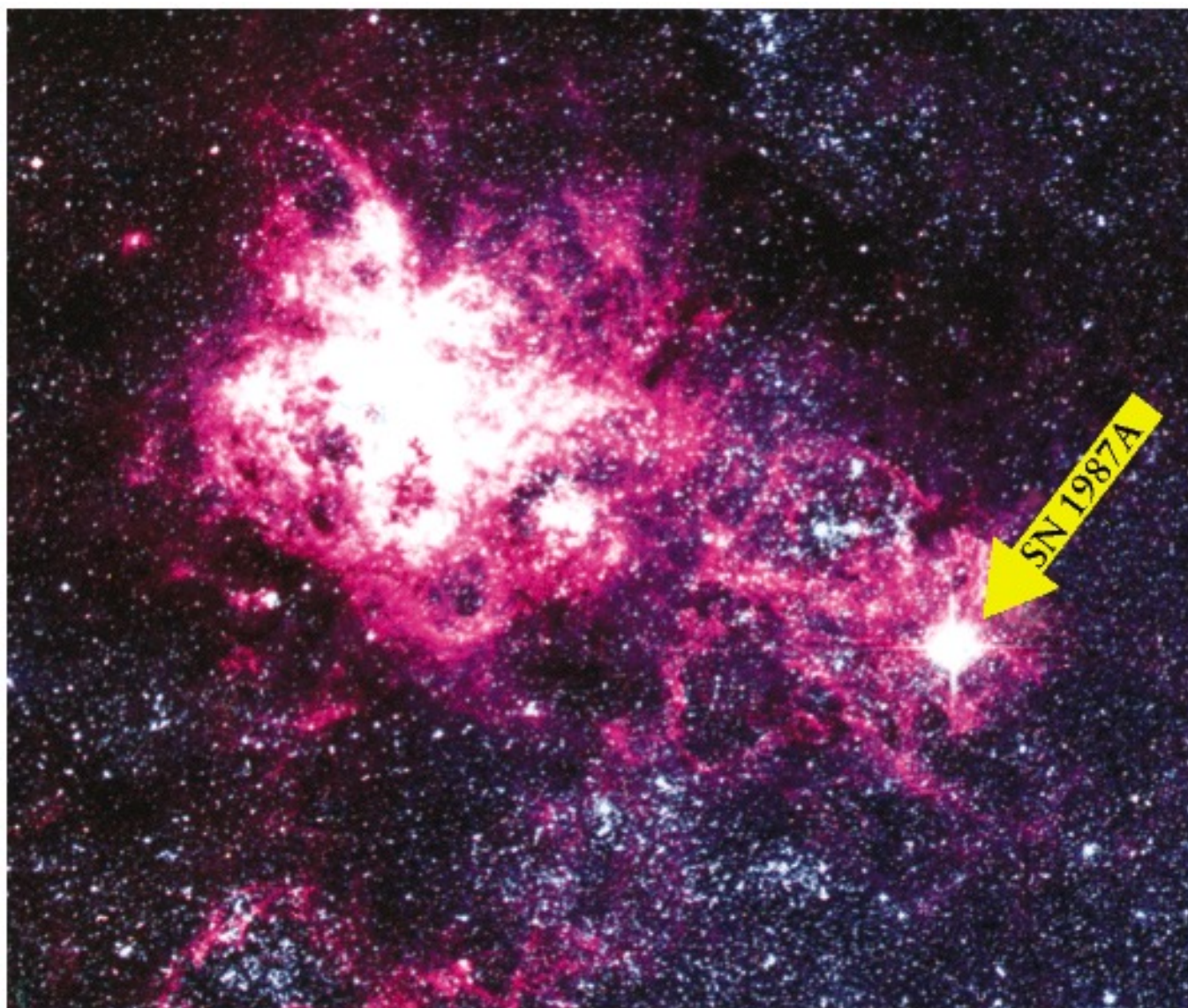
This enriched material is eventually available to the formation of the next generation of stars and planets.

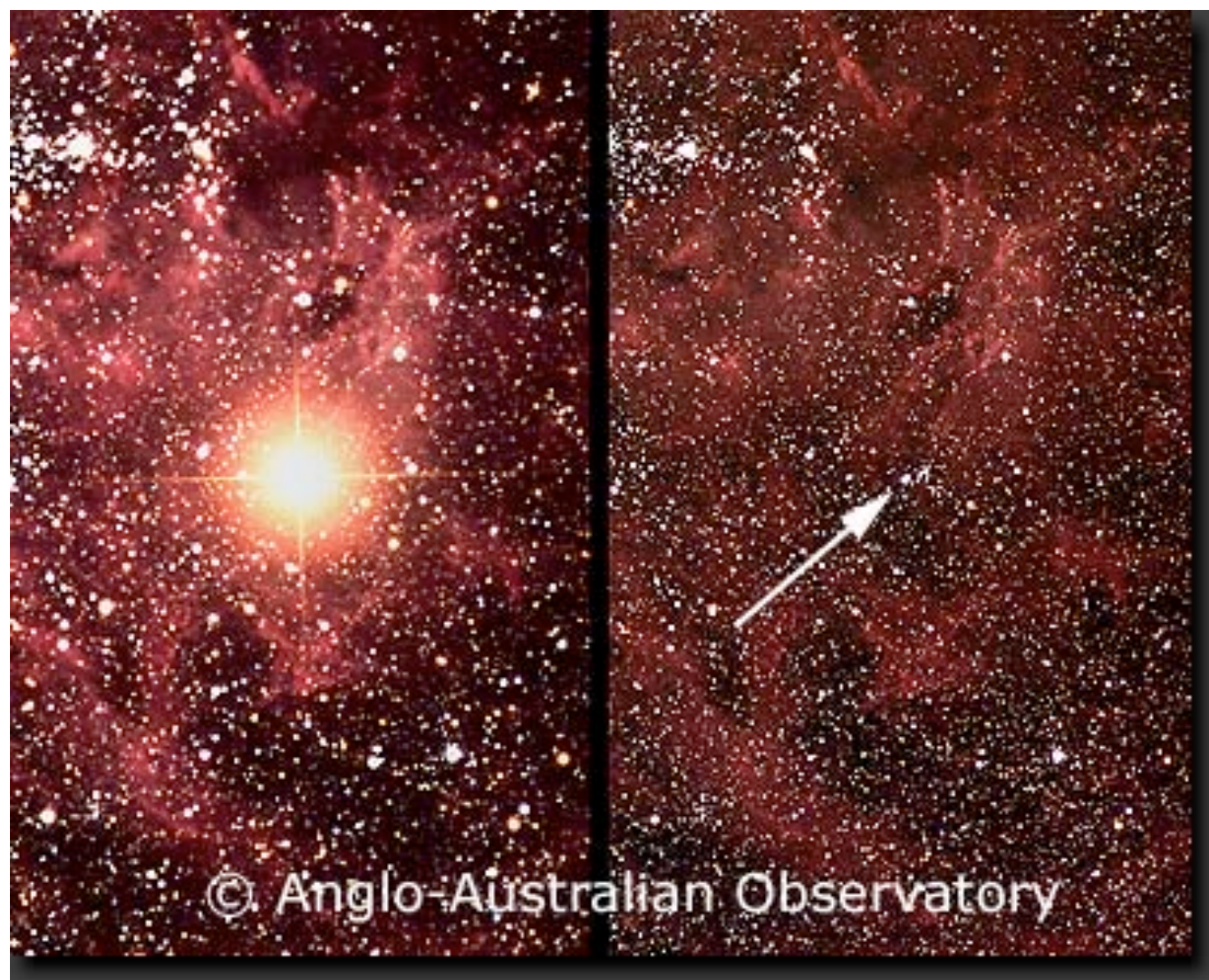
Thus far, theory. We got to test this in 1987 when light from a supernova in Large Magellanic Cloud (dwarf galaxy near Milky Way) reached us.



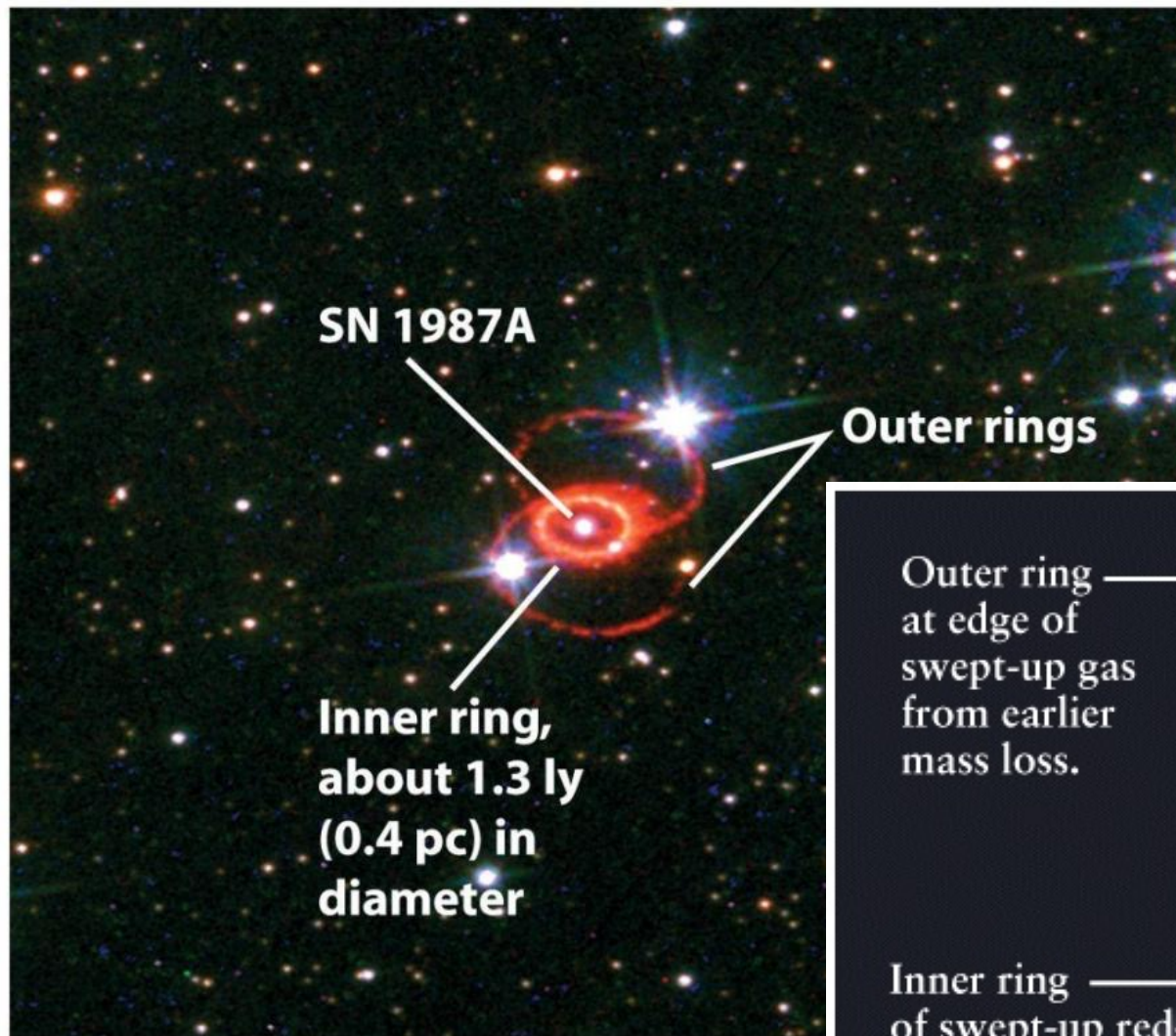


Patrick Tisserand
EROS2 Collaboration



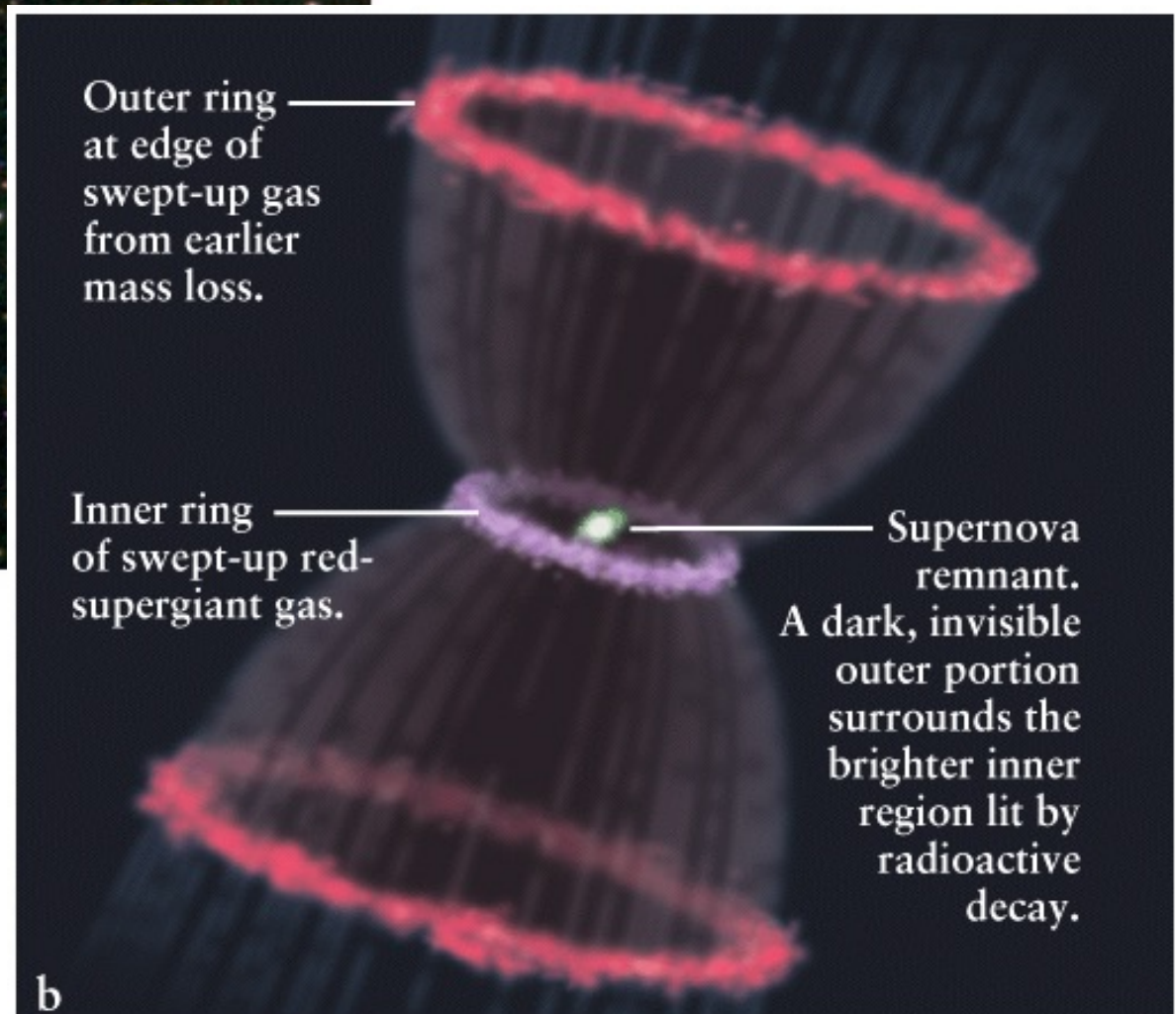


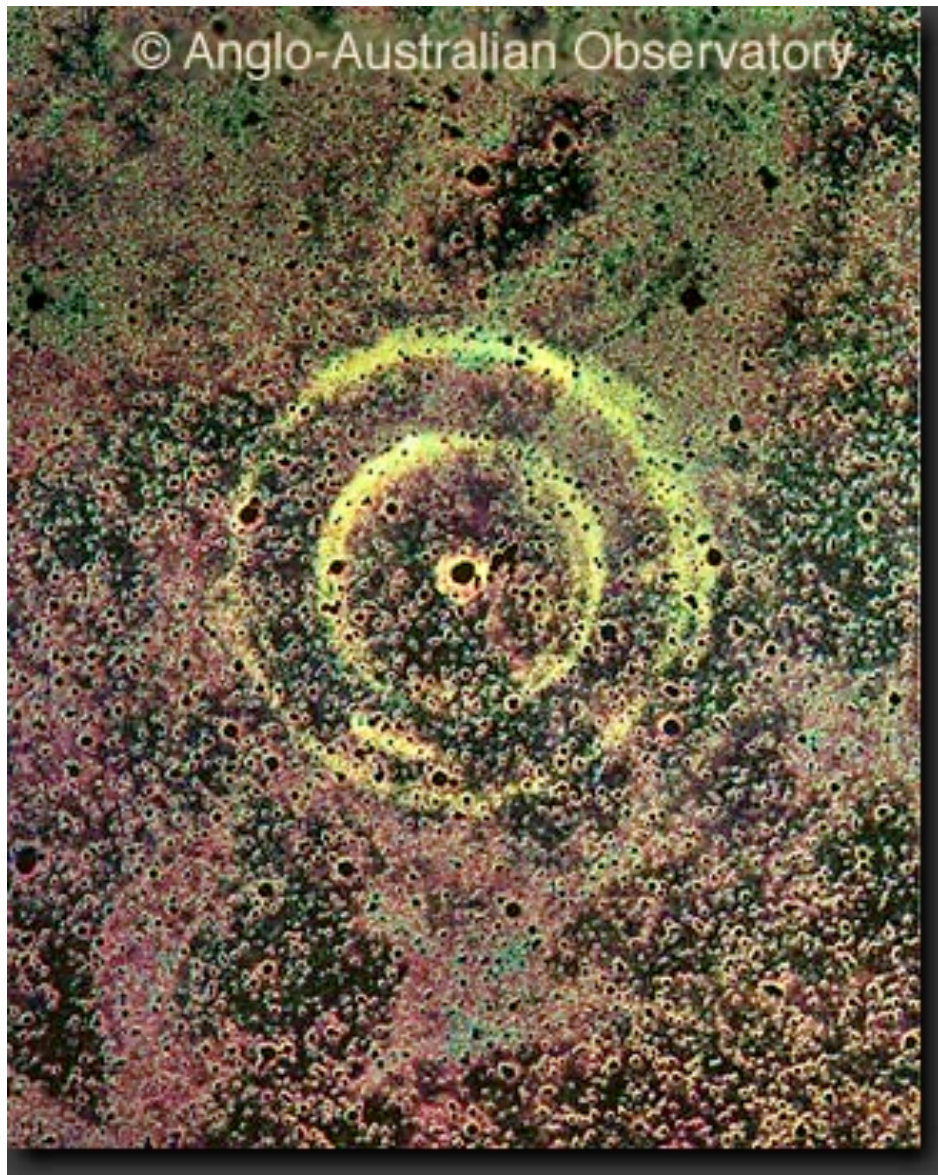
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Supernova 1987A seen in 1996

Outer rings lit by UV radiation from explosion.





Light from SN
bounces off interstellar
dust - "light echoes".

Supernova 1987A Rings

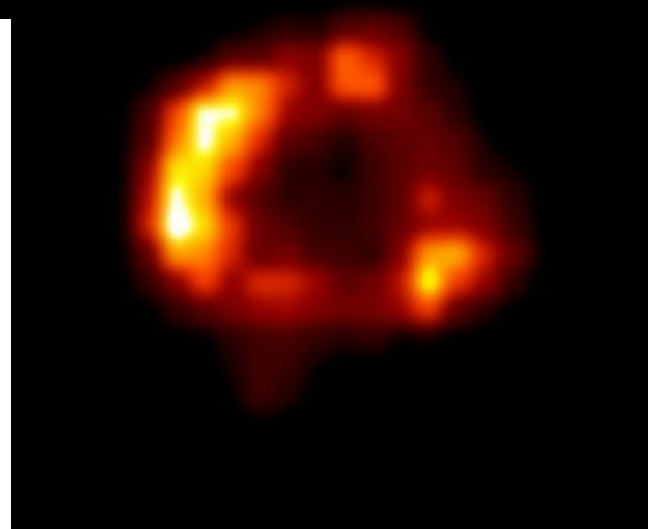


Hubble Space Telescope



Wic

Chandra X-ray image



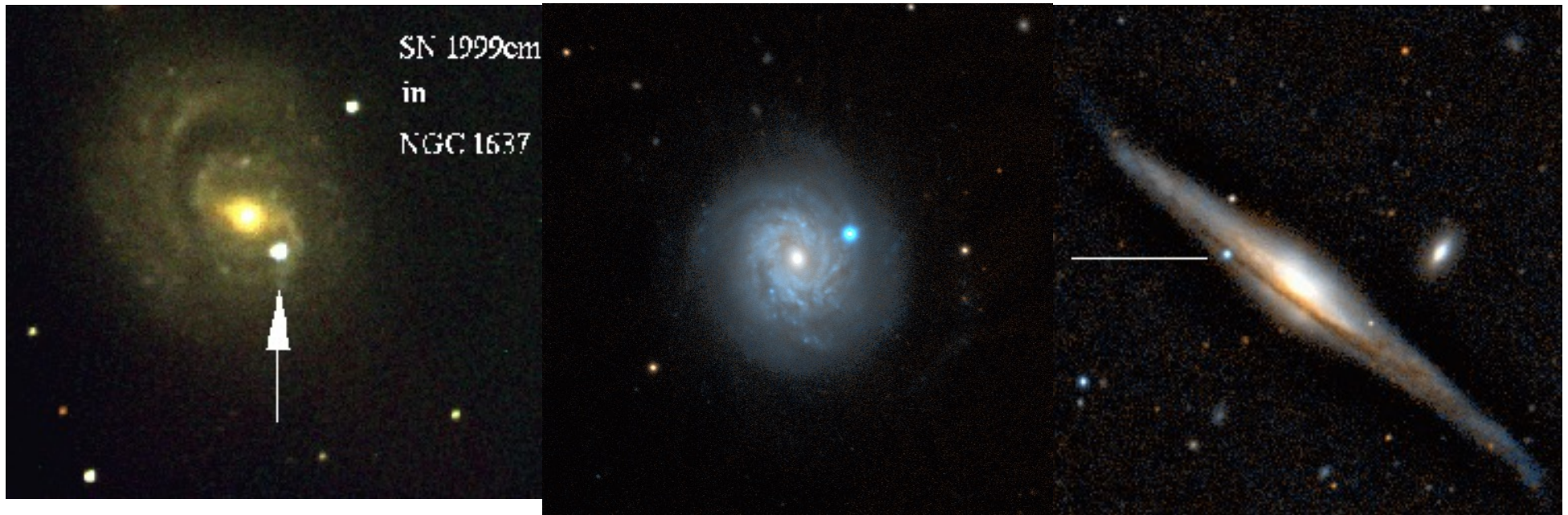
Neutrinos and supernovae

- Most of the energy of a supernova comes out in the form of neutrinos, which are formed in the 'neutronization' process.
- From SN1987A we detected neutrinos at 2 different neutrino detectors. They arrived 3 hours before the visible light.
- Why before?

Neutrinos and supernovae

- Most of the energy of a supernova comes out in the form of neutrinos, which are formed in the 'neutronization' process.
- From SN1987A we detected neutrinos at 2 different neutrino detectors. They arrived 3 hours before the visible light.
- Why before? Light emitted only when shockwave gets out of core, reaches surface layers of star.

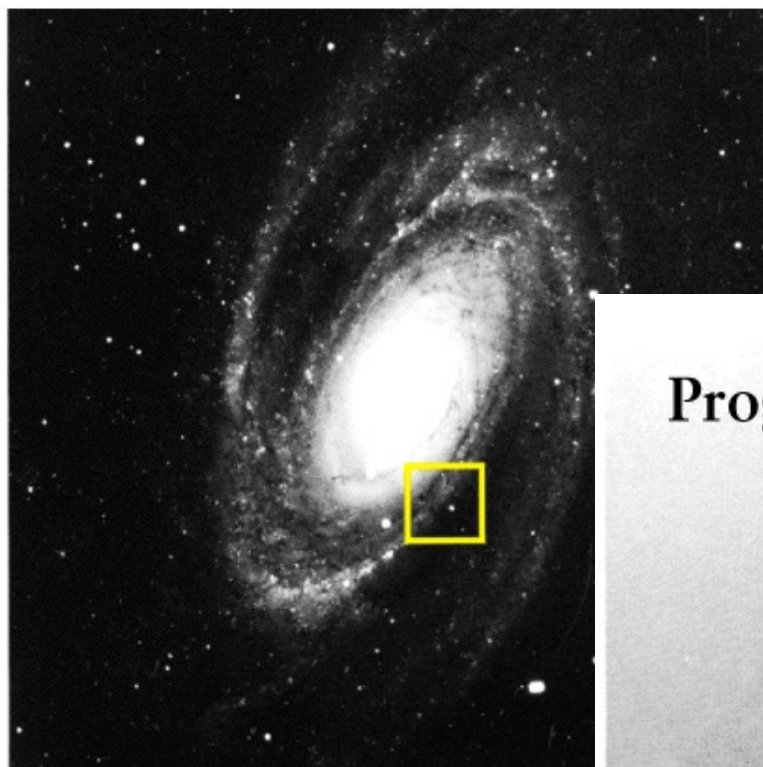
Supernovae are so bright that we can see them across the Universe, and that one supernova can outshine all 10 to 100 billion stars in the galaxy at maximum light.



NGC1637, 1999
(9Mpc)

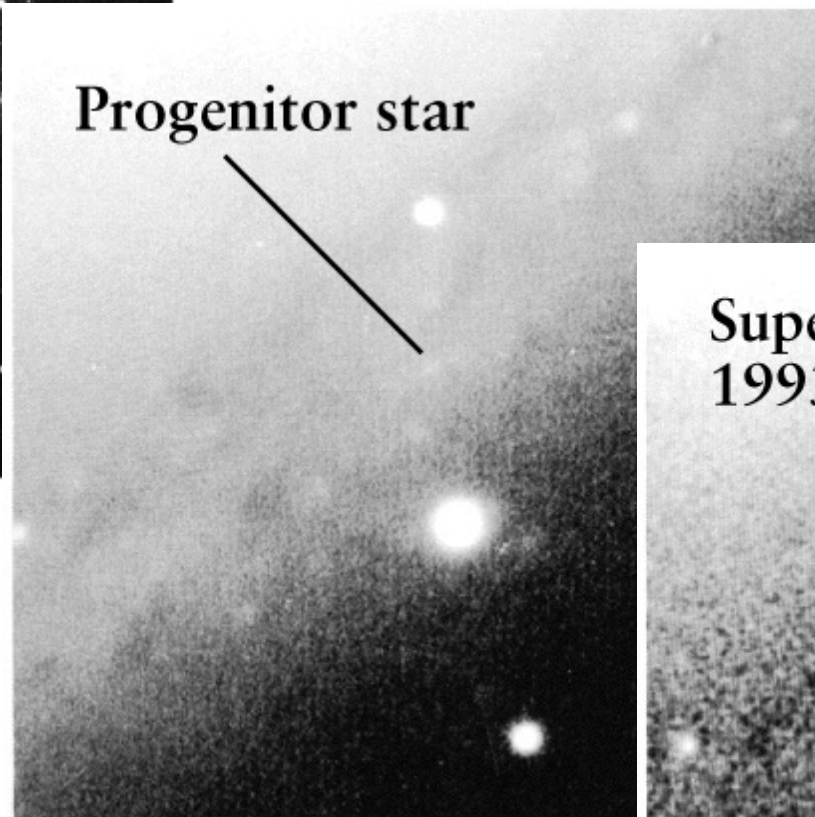
NGC3982, 1998
(23Mpc)

NGC5965, 2001
(50Mpc)



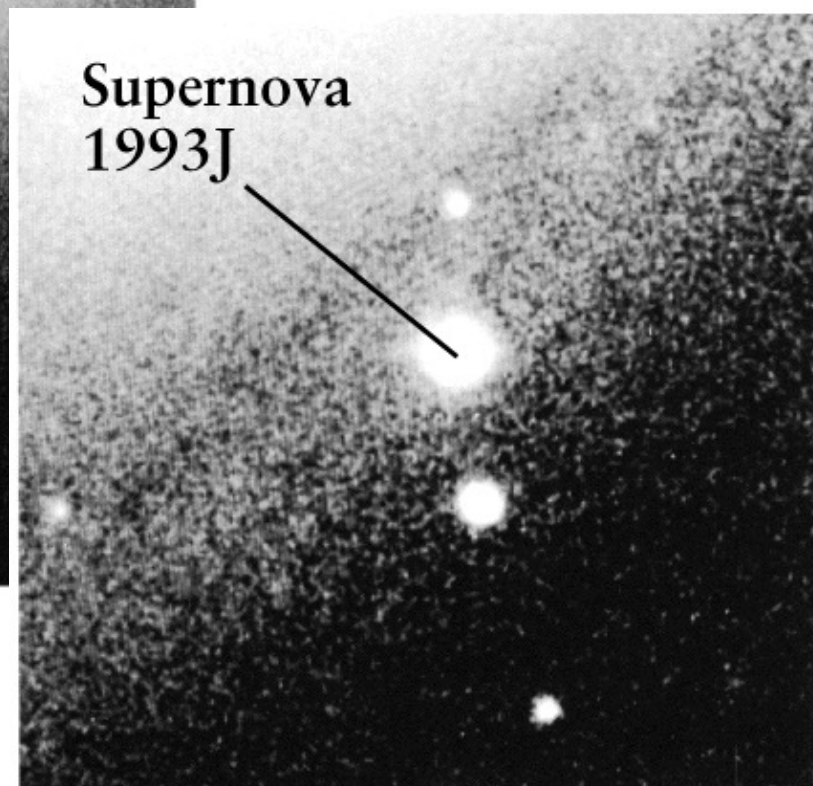
SN in M81 in
1993 (3.6 Mpc)

a



Progenitor star

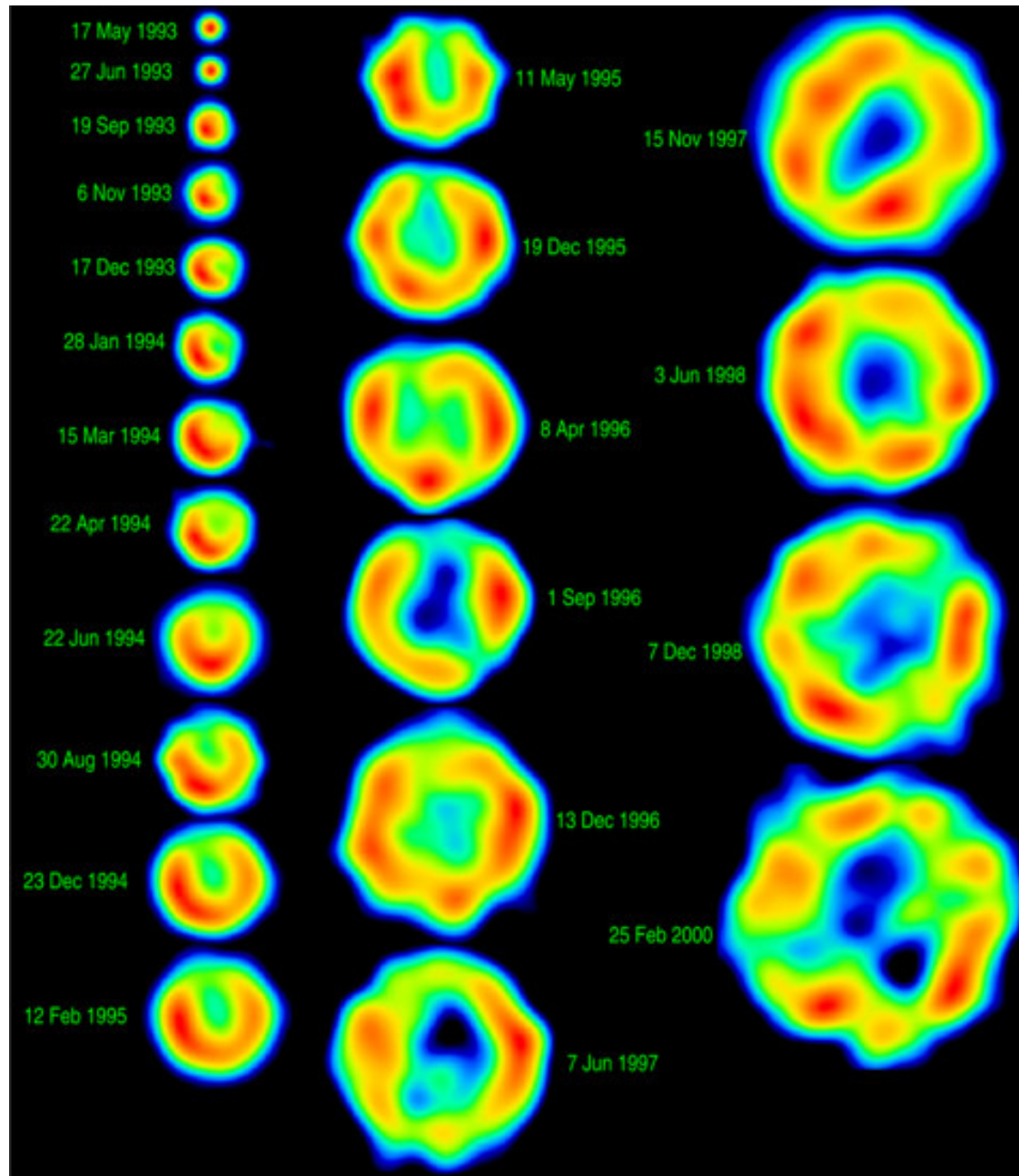
b



Supernova
1993J

c

A Young Supernova

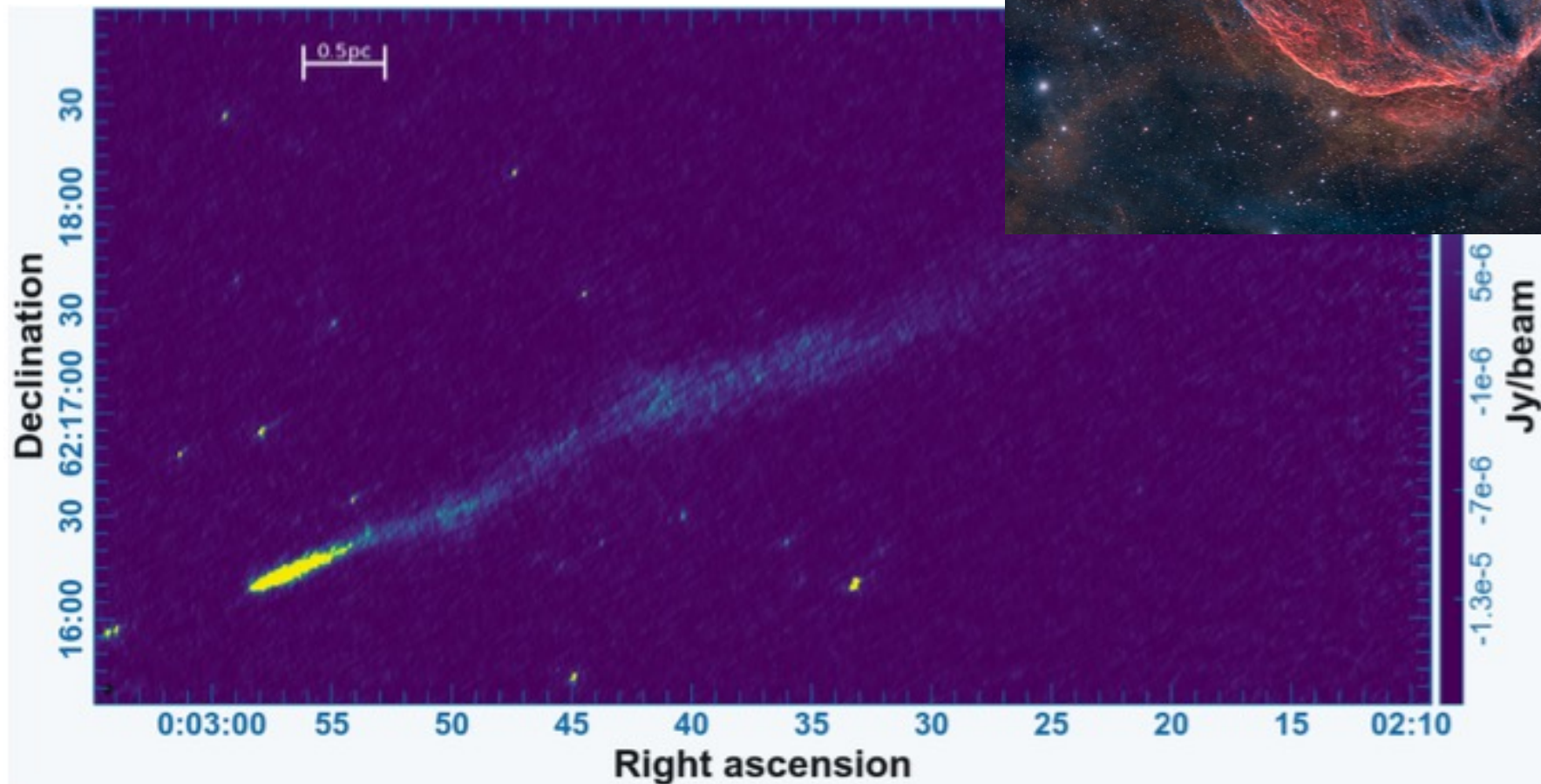


SN 1993J
Rupen et al.

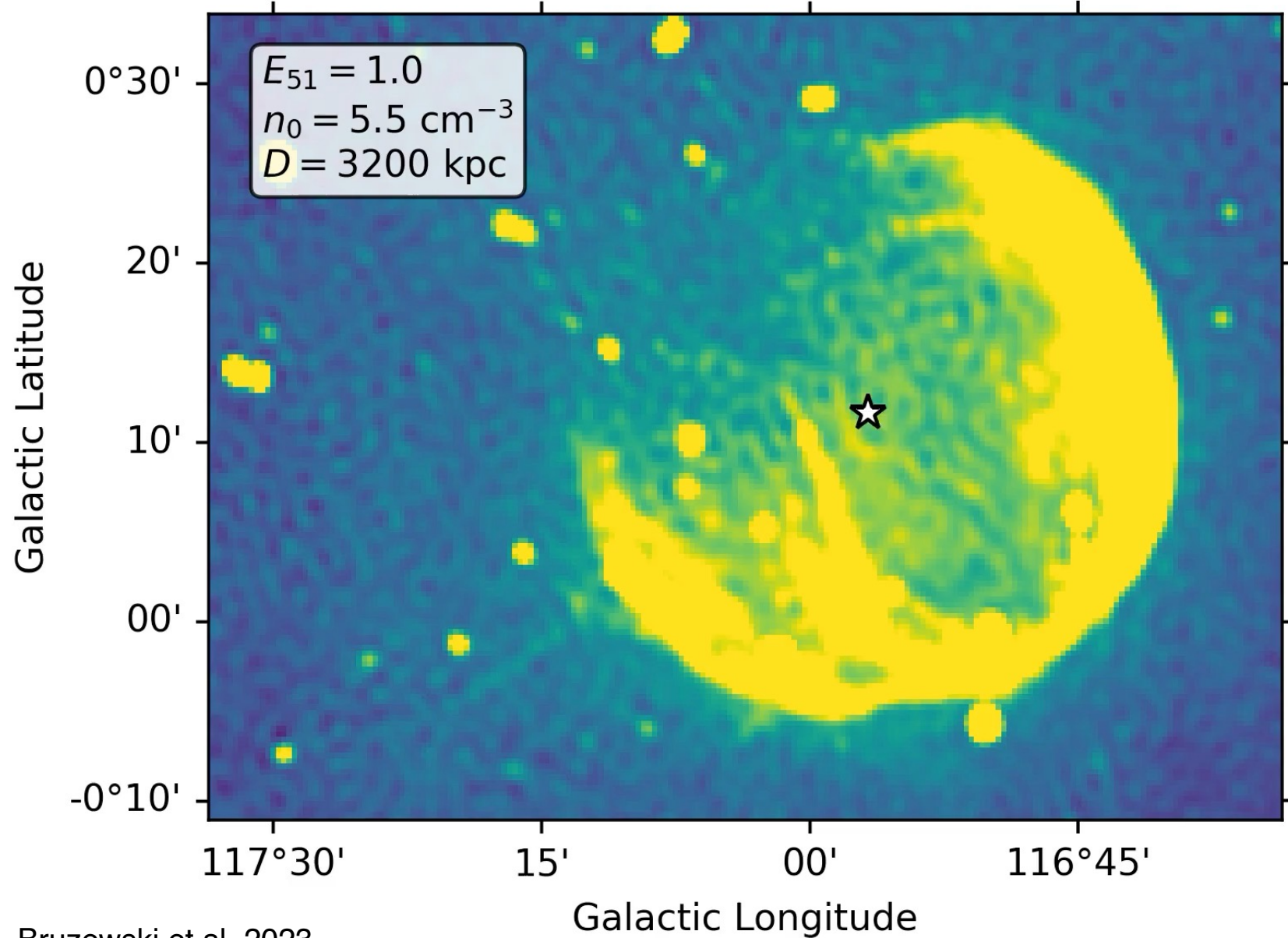
Cannonball J0002+6216 and SNR CTB-1

Kumar et al. 2022 VLA 6 GHz

Optical



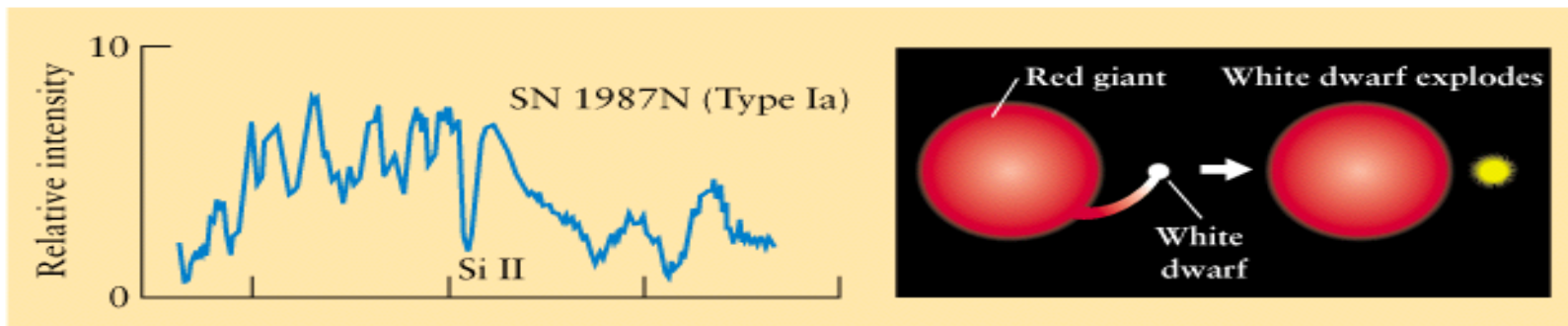
Cannonball J0002+6216 and SNR CTB-1



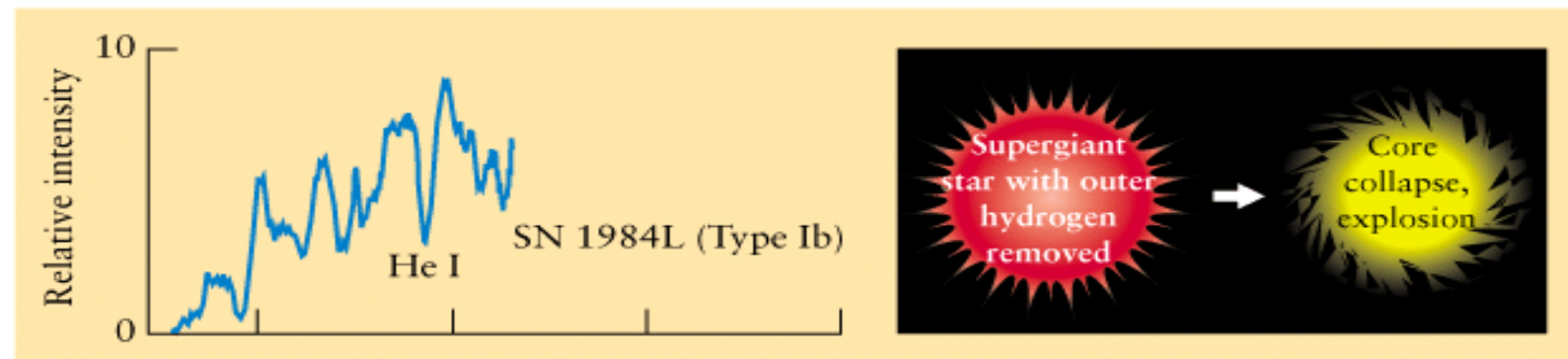
Bruzewski et al. 2023

Types of supernovae

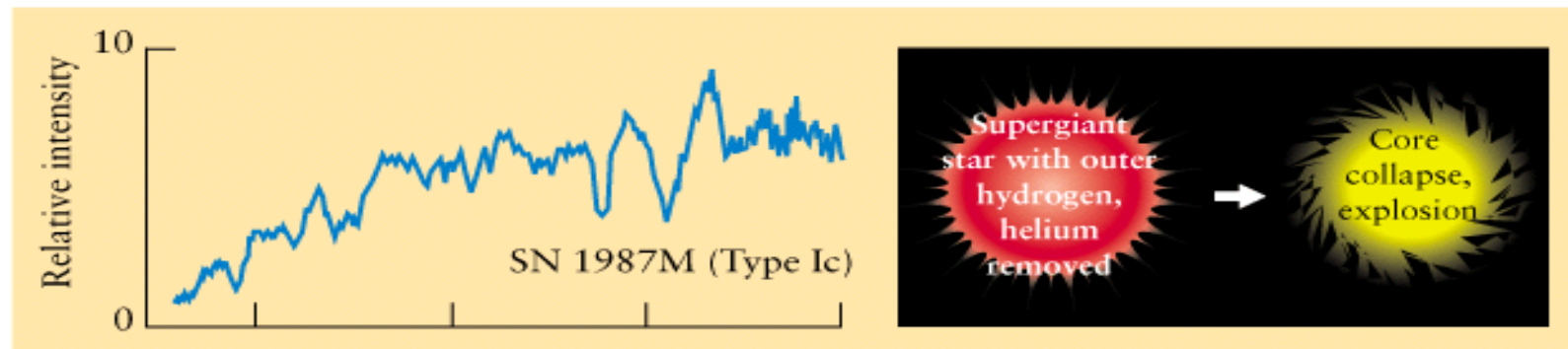
- These were the so called Type II supernovae, and they show hydrogen emission lines in their spectra.
- Why? These highly massive stars still have H in their atmospheres while exploding.
- There are other supernovae with no hydrogen lines: Type Ia, Ib and Ic.



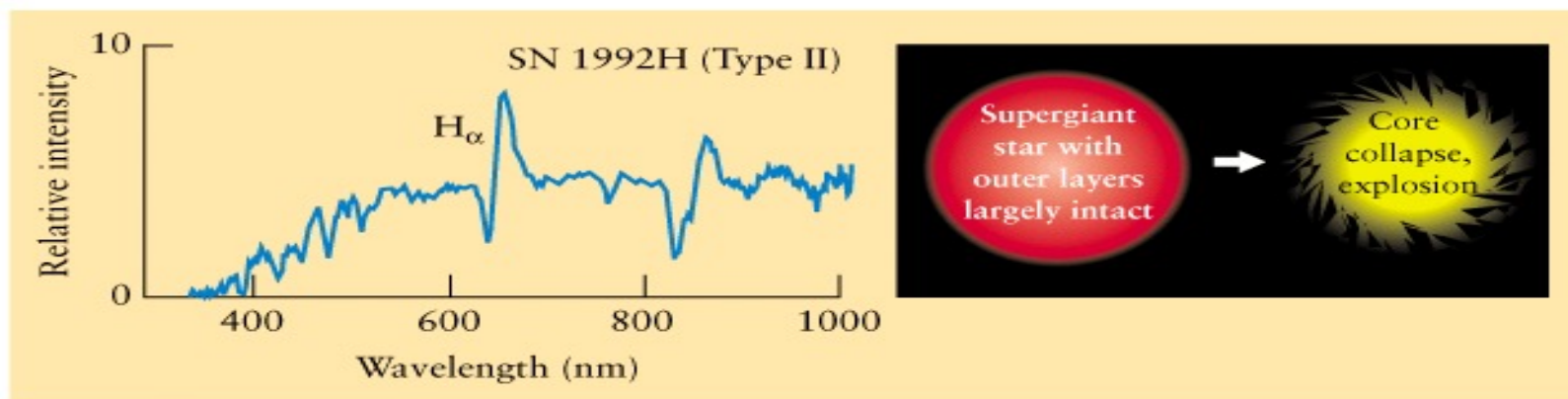
Sill lines



He lines



No H, no He



Lots of H

Types of supernovae cont.

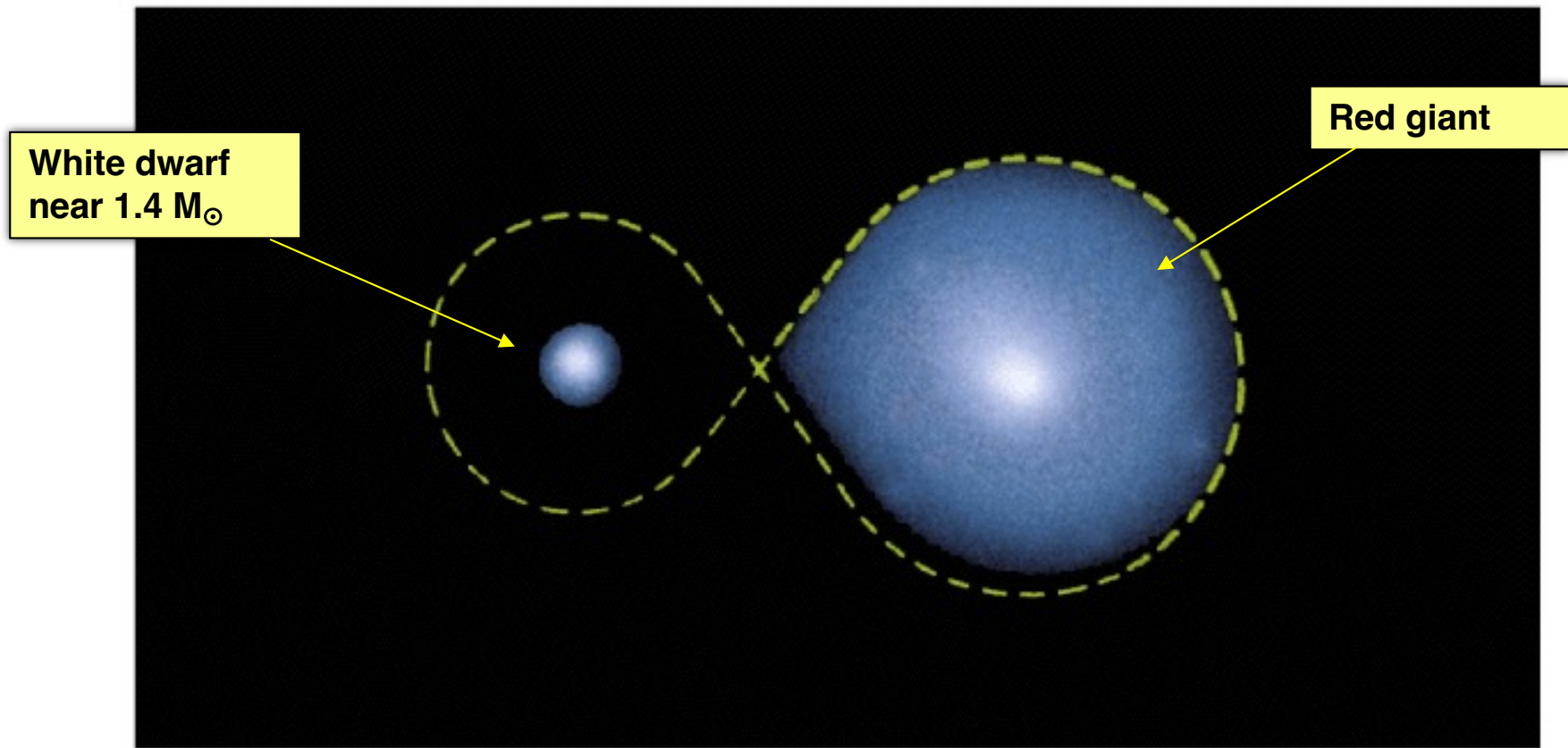
- Types Ib and Ic are exploding massive stars, like Type II, but with outer layers removed.

Gravitational collapse

- Type Ia are different: they are white dwarfs in close binary systems.
- Mass transfer pushes white dwarf toward Chandrasekhar limit ($1.4 M_{\odot}$), and gets very hot.
- Carbon suddenly ignites in core, because it is degenerate the fusion rate increases really fast: the star blows up.

Thermonuclear runaway

Set-up for a Type Ia SN:



b Semi-detached binary

Type Ia supernovae

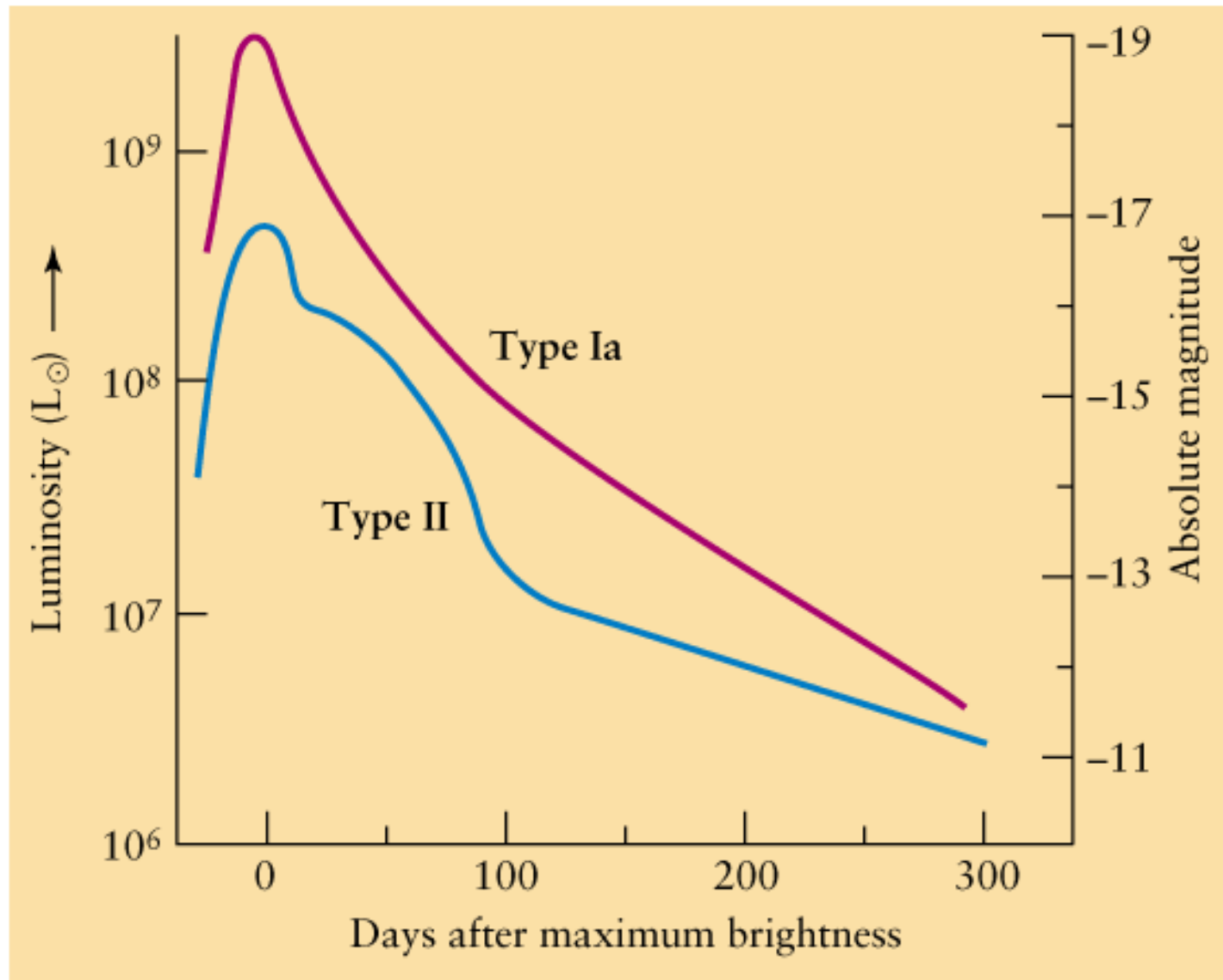
- Type Ia SN have critical importance in understanding the Universe as a whole: they are *standard candles*.
- No matter where in the Universe they happen, they are physically similar: WD with about $1.4 M_{\odot}$ (the Chandrasekhar limit), so they produce similar explosions.

Why is this useful? Would Type II's be as good as standard candles?

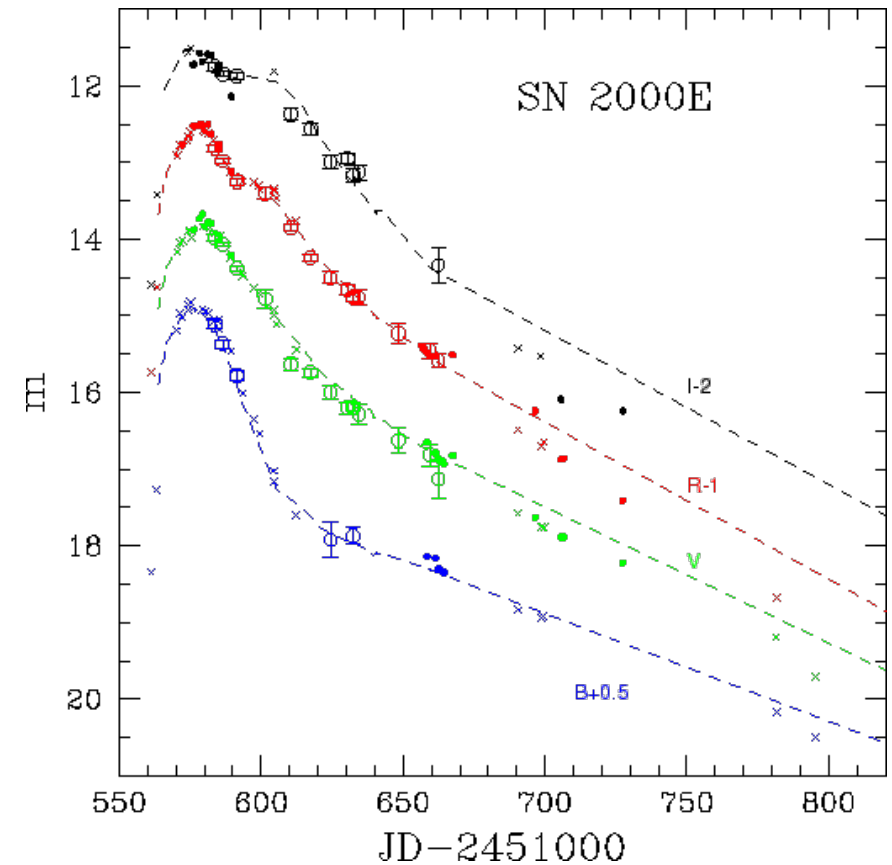
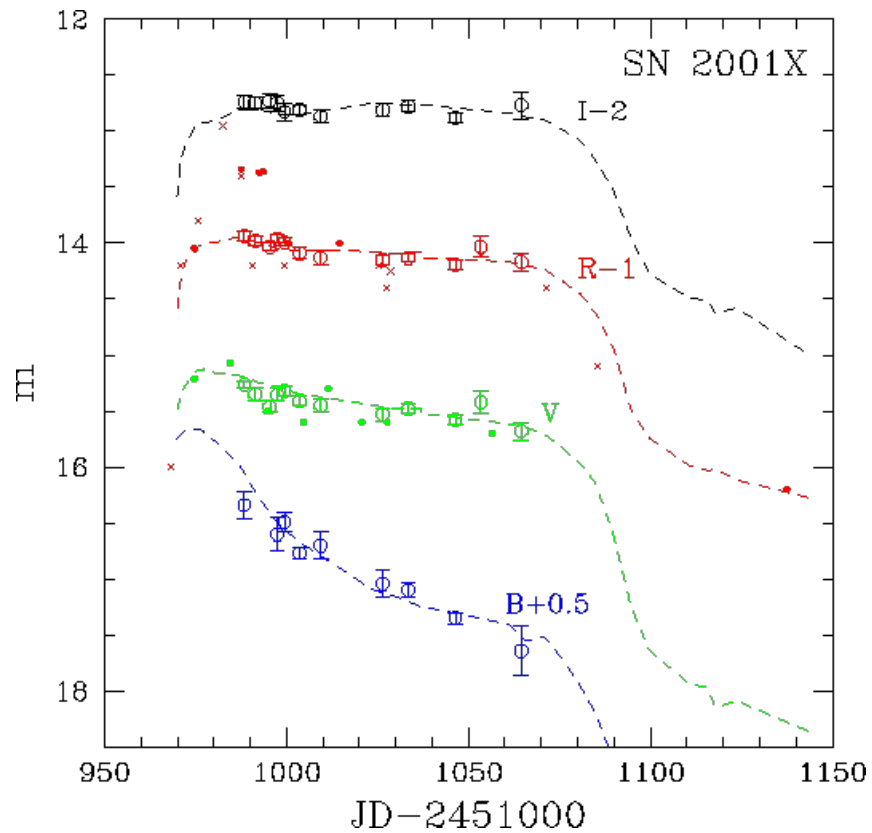
For how long can we see the SN?

- The SN fades out after a few months
- Fade-out is slightly extended due to release of γ rays by the decay of radioactive elements (Ni, Co)
- Thus, the more Ni the slower the fade out

Light curves for Type Ia and Type II supernovae



Lightcurves



- Very diverse for any type (but Type Ia)
- Type II, Ib, Ic have different peak luminosities depending on previous mass ejections etc.

Supernova remnants

- The extreme violence of a supernova blasts the outer layers of the star into the ISM.
- This enriches the ISM with heavy elements and accelerates atomic nuclei (protons and electrons) to speeds near c , travel across the Galaxy and are called *cosmic rays* when they hit the Earth.
- In addition, the collision between the shock and the ISM excites the gas and makes it glow: supernova remnants



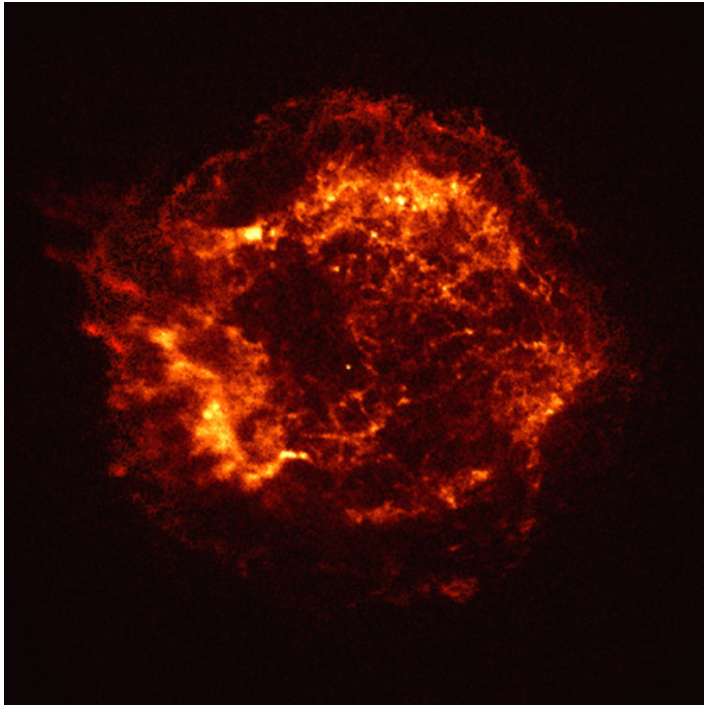
Crab Nebula



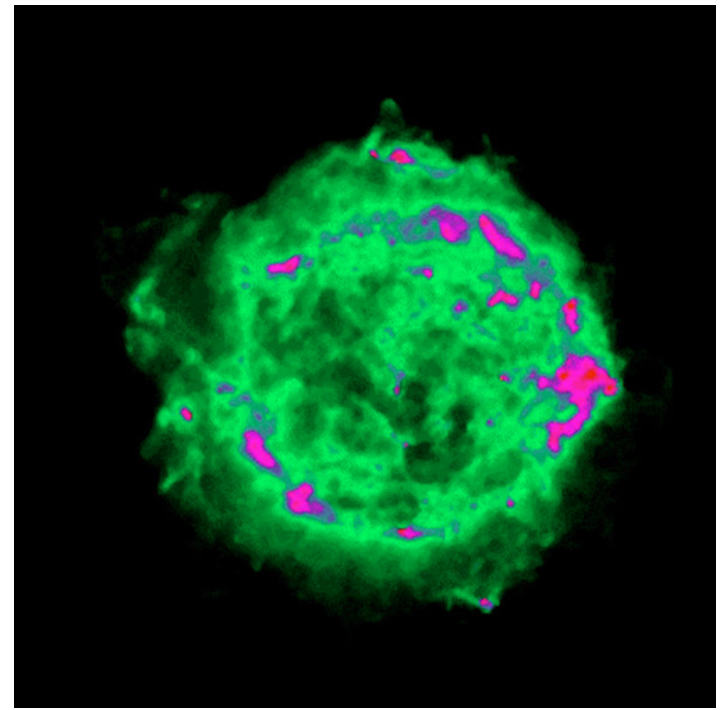
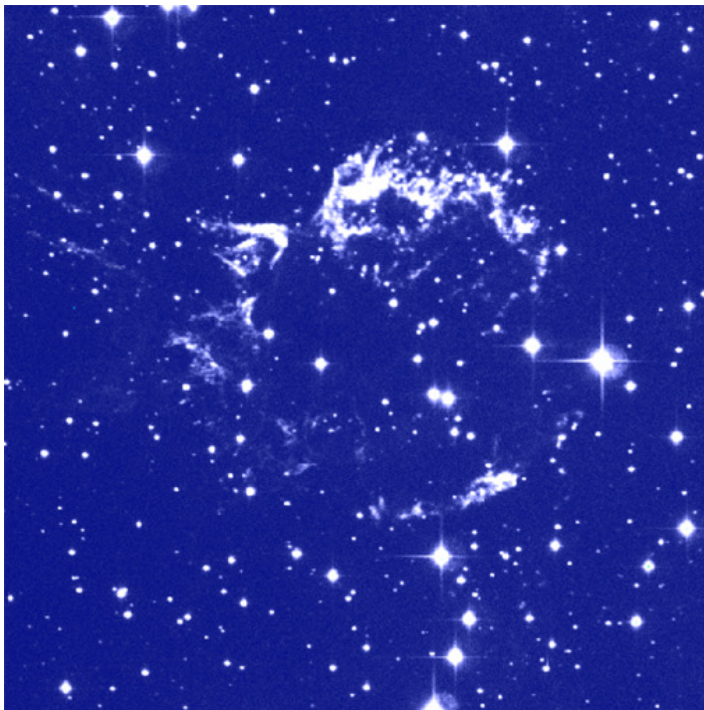
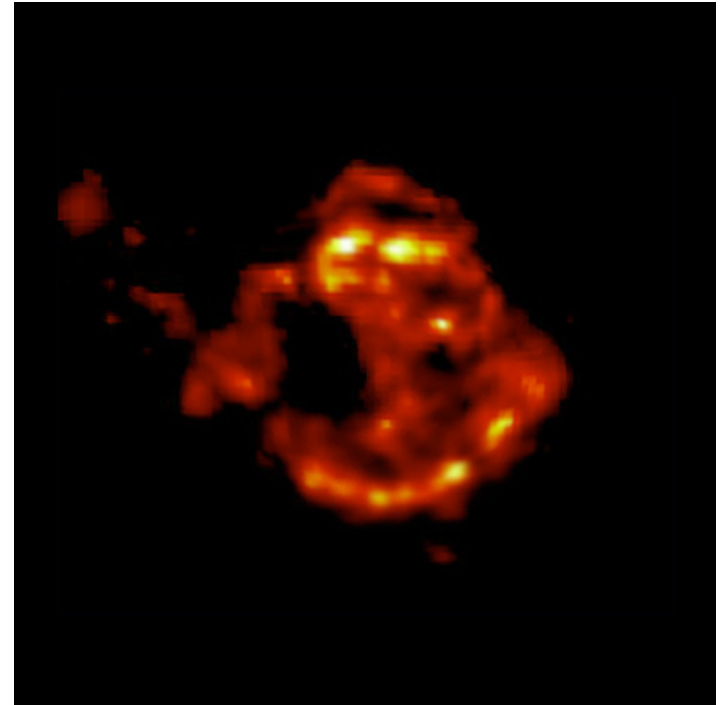
Vela Nebula

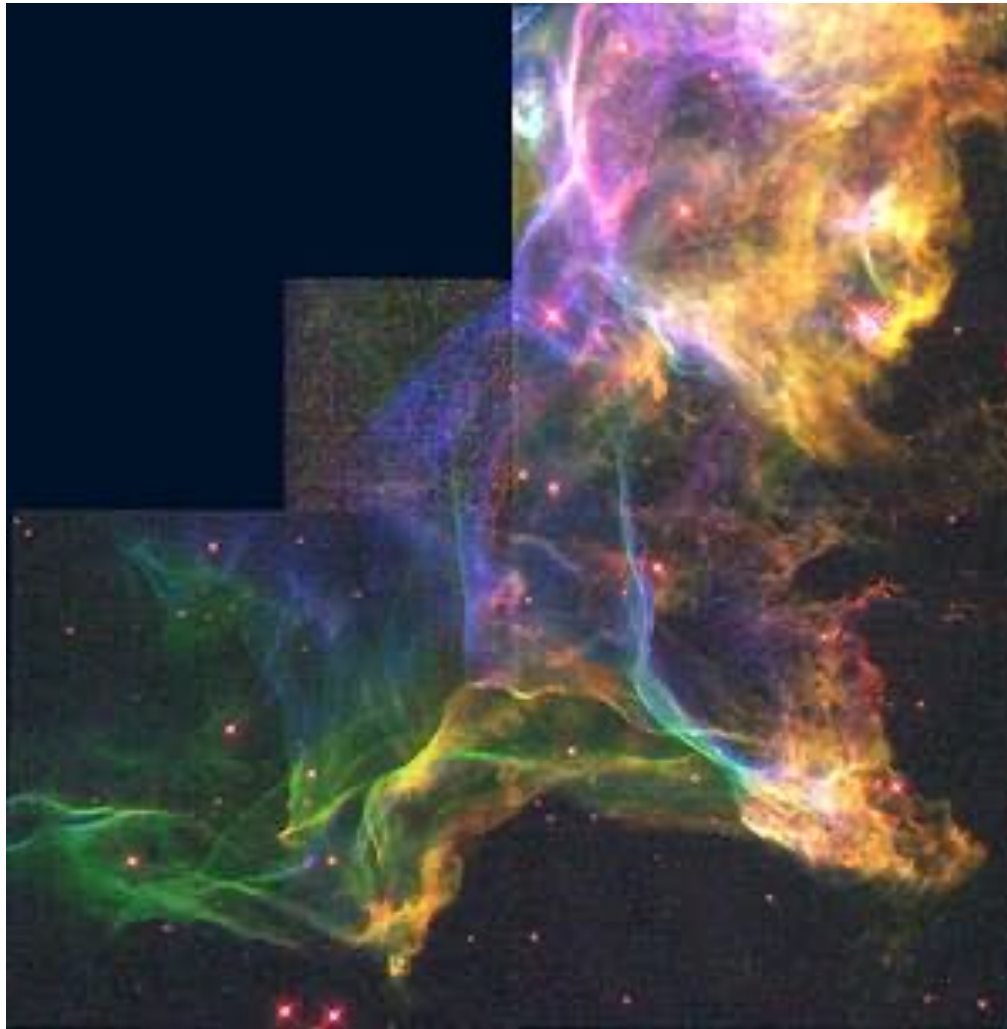


A young SNR seen in X-rays

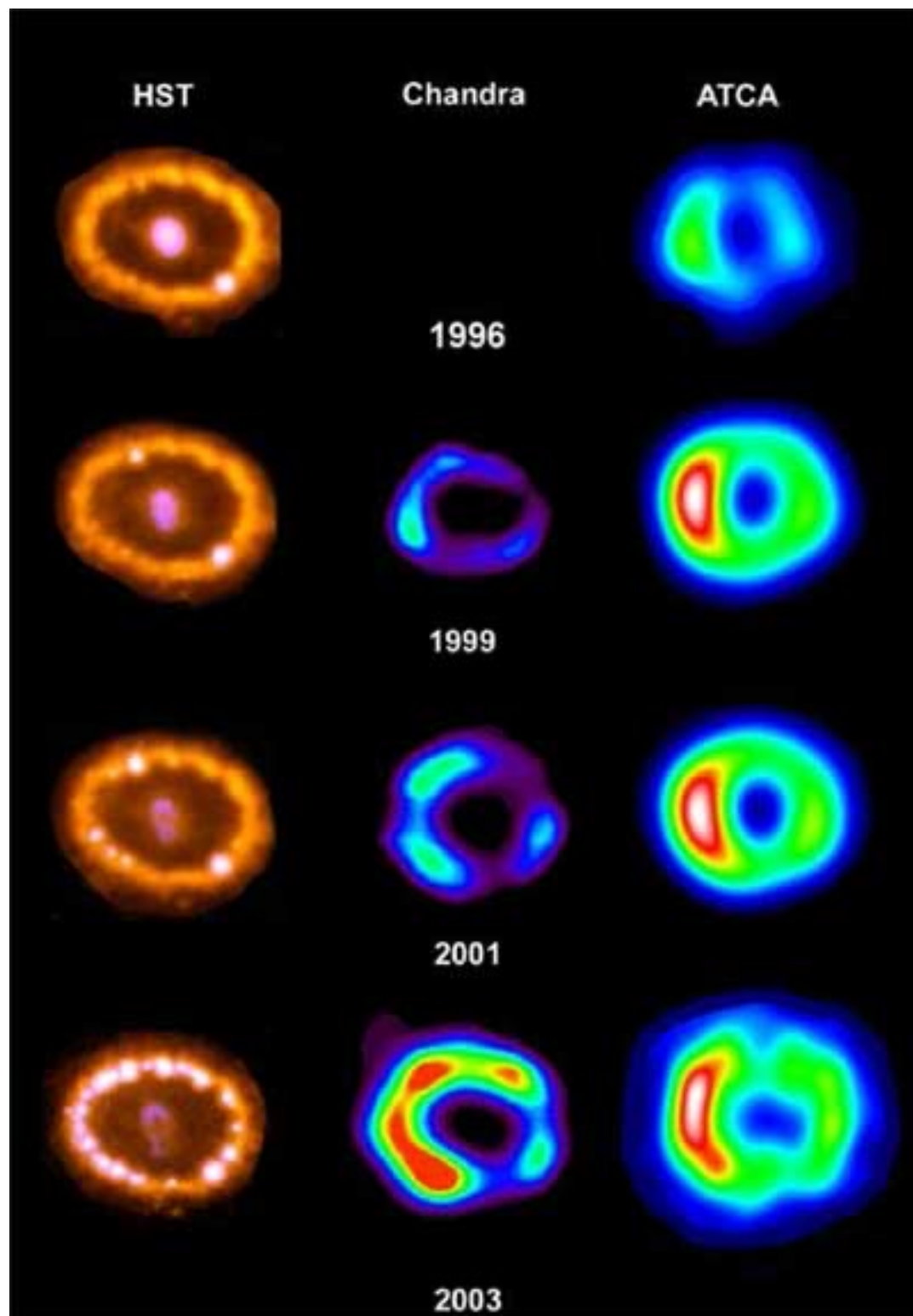


Cas A (300yr) in
X-ray, optical, IR
and radio





Part of the Cygnus Loop, 15,000 yr SNR. Greenish light indicates the presence of oxygen ions.

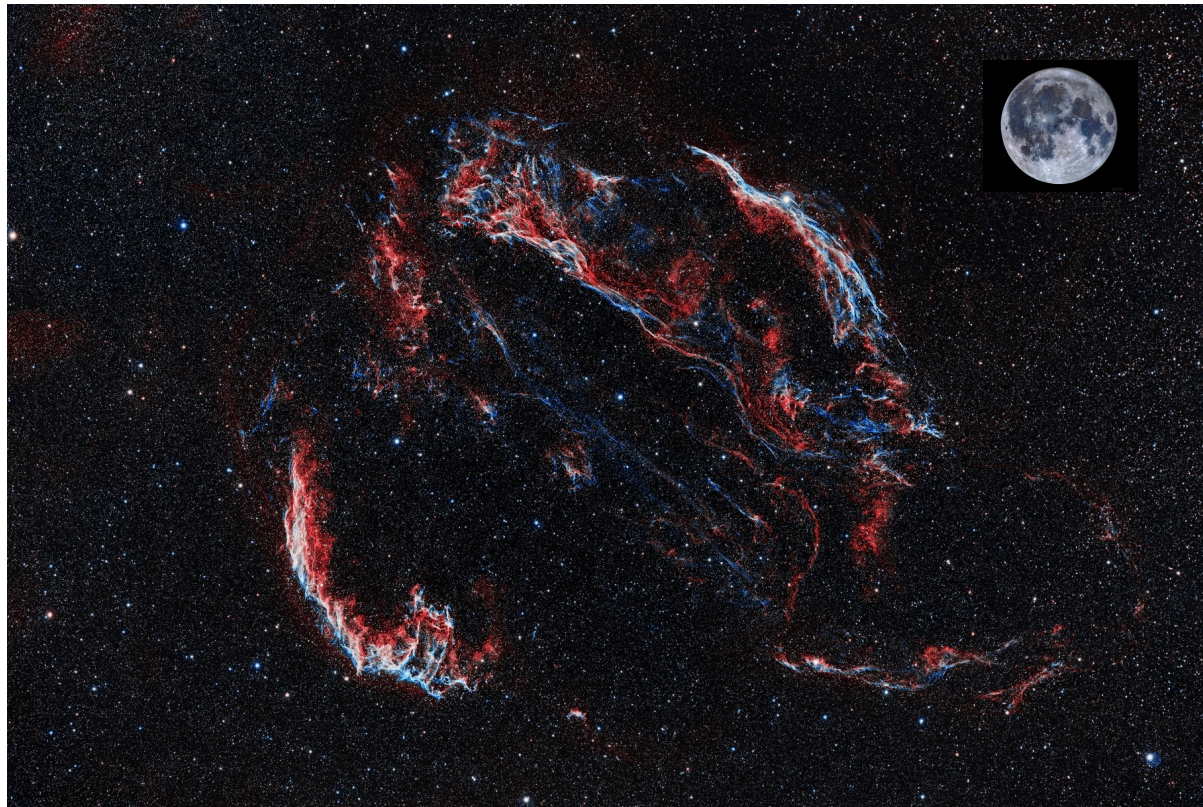


SN 1987A

Direct expansion speed can be measured - a relatively 'fast' event for astronomers.

Veil Nebula

- Fig. 20.22 shows the Veil Nebula in Cygnus. This SNR is a roughly spherical remnant of a SN that exploded about 15000 years ago (the distance to the nebula is about 2400 ly). Calculate the average speed of the material has been moving away from the site of the SN explosion over the past 15000 years. Express in km/s and as a fraction of the speed of light.



Hypernovae

- Collapse of extremely massive stars, producing energy outputs 10-30 times that of a normal SN.
- They release enormous amounts of gamma rays, and are thought to be the sources of Gamma Ray Bursts (GRBs).
- No H or He in their spectra: the star is so massive that it has fused all of it to C and O, or shed the outer layer from strong winds.

Implications of supernovae

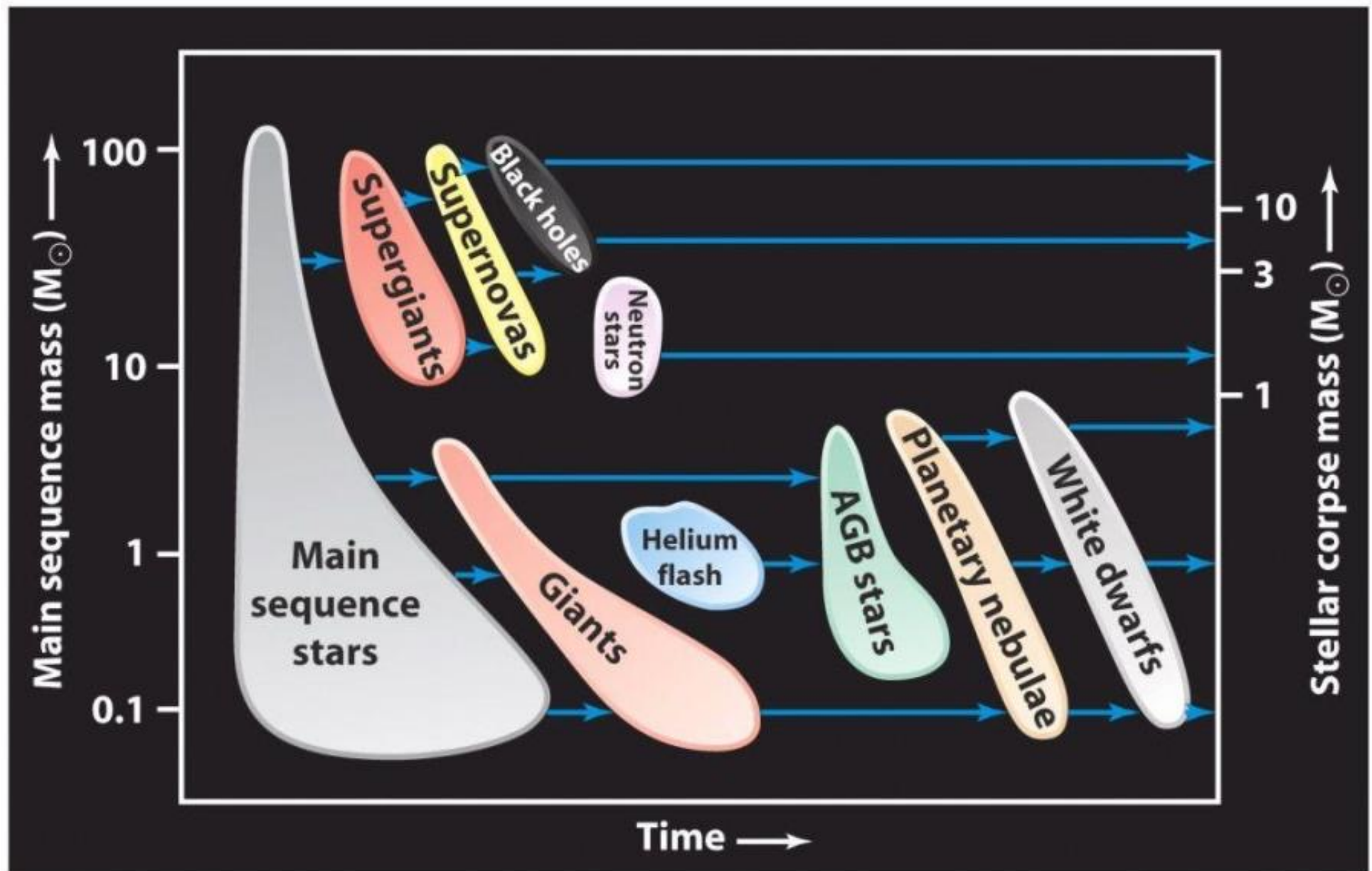
- Provide heavy elements
- Initiate contraction of ISM clouds to form new stars and planetary systems
- Main source of cosmic rays, which in turn are important for understanding evolution.

You wouldn't exist without supernovae!

- Supernovae are so bright that they can be seen to the observable limits of the Universe.
- They are crucial to measuring the size, age, expansion rate, acceleration rate, etc. of the Universe as a whole (more in ch 26).

For Type Ia, $M_{\text{max}} = -19$, comparable to that of a typical galaxy.

Summary of star deaths



Final States of a Star

1. White Dwarf

If initial star mass $< 8 M_{\text{Sun}}$ or so

No Event + PN

2. Neutron Star

If initial mass $> 8 M_{\text{Sun}}$ and $< 25 M_{\text{Sun}}$

Supernova +
ejecta

3. Black Hole

If initial mass $> 25 M_{\text{Sun}}$

GRB +
Hypernova +
ejecta