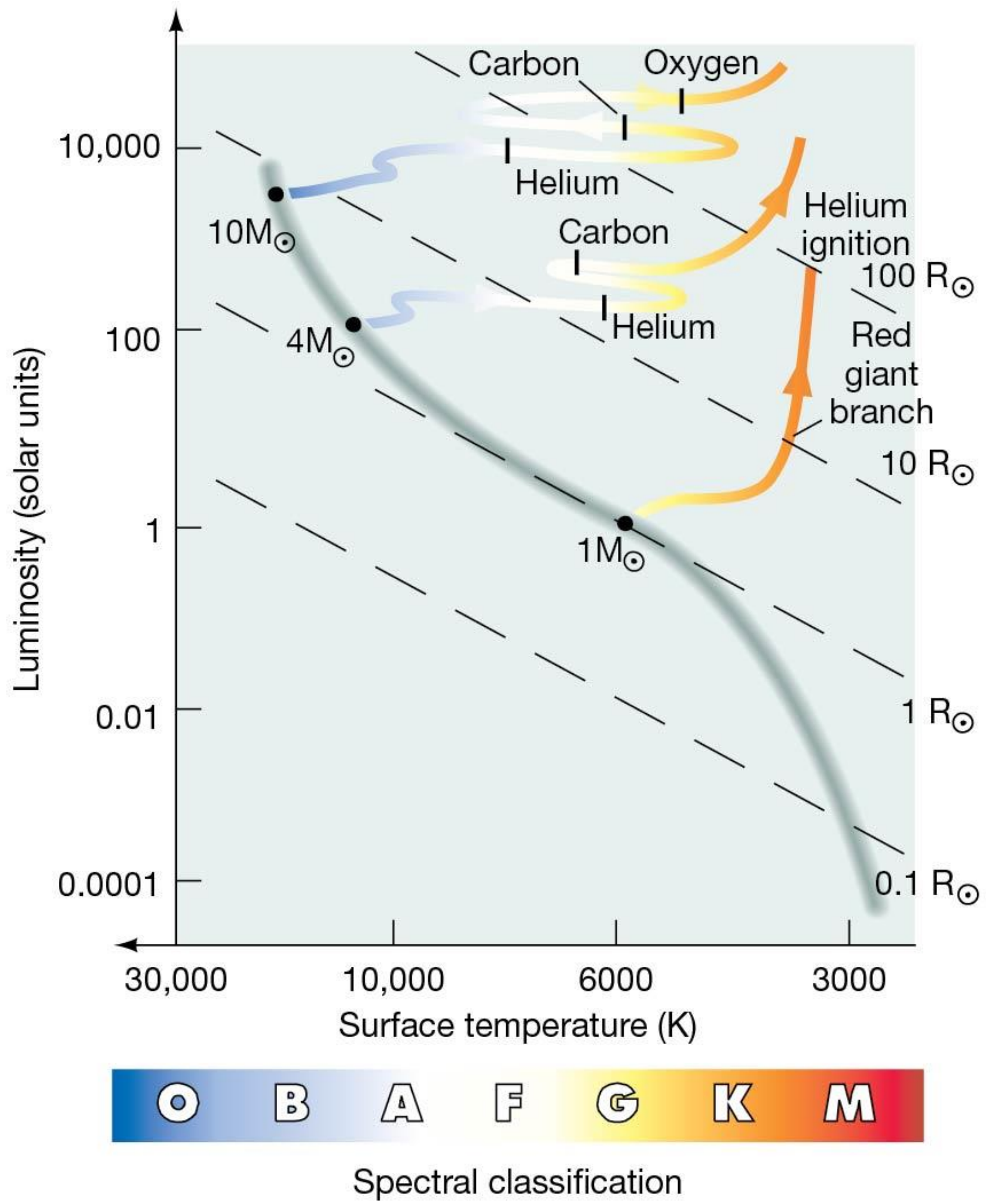
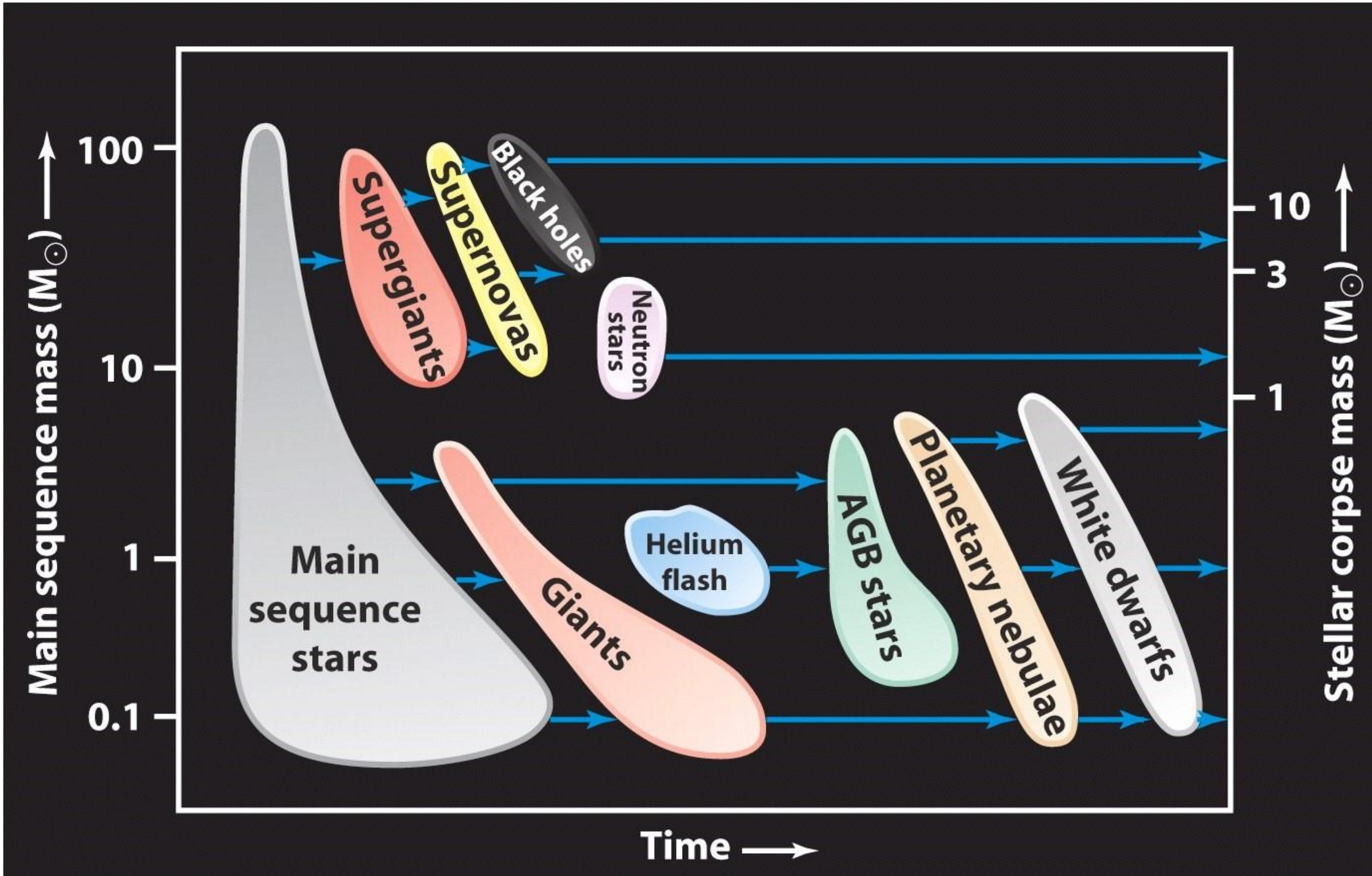
HRD – massive stars

- They follow very different paths when leaving the main sequence
- The temperatures and densities in the cores are much different => different reactions



Evolution – massive stars



Evolution – massive stars

- They leave the main sequence when the hydrogen is depleted in their cores
- The first few events are similar to those in lower-mass stars:
  1. hydrogen shell
  2. core burning helium to carbon, surrounded by helium- and hydrogen-burning shells
- ***Difference***: stars with masses > 2.5 $M_{\odot}$ have ***no helium flash*** but it starts gradually burning
- It becomes a ***supergiant***

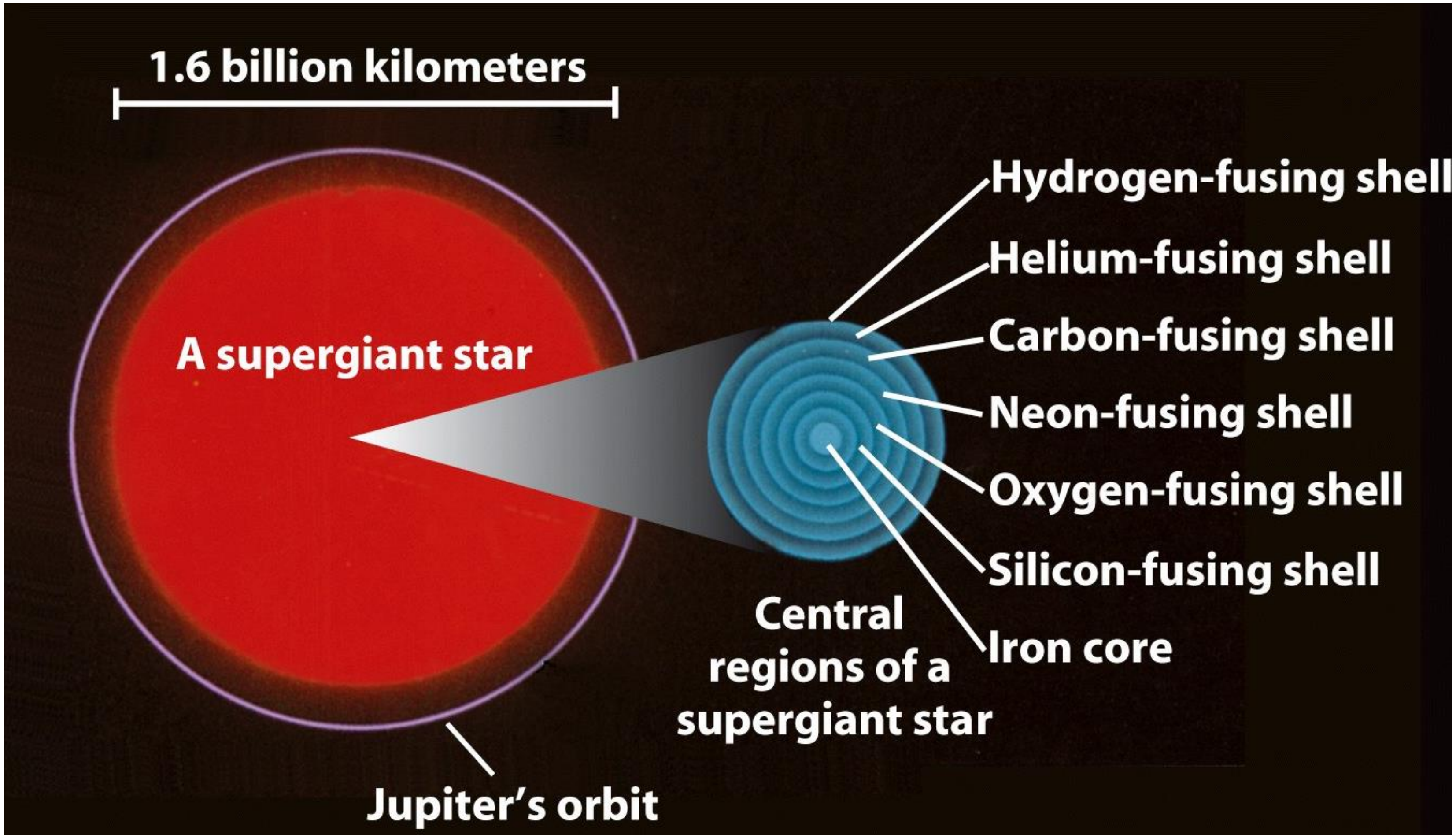
Evolution – core burning

- They undergo an extended sequence of thermonuclear reactions in its core and shells
- These include carbon (^{12}C) fusion, neon (^{20}Ne) fusion, oxygen (^{16}O) fusion, and silicon (^{28}Si) fusion
- See the slides in the lecture “Fusion – Fission”

Evolution – massive stars

Stages for a star with 25 $M_\odot$

Stage	Core temperature (K)	Core density (kg/m³)	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}	¼ second
Core bounce	2.3×10^{10}	4×10^{15}	milliseconds
Explosive (Supernova)	about 10^9	varies	10 seconds



- ***The last stage***: an iron-rich core surrounded by concentric shells hosting the various thermonuclear reactions
- The sequence of thermonuclear reactions stops here, because the formation of elements heavier than iron requires an input of energy rather than causing energy to be released

Evolution – Supernova

- Once the iron core is formed, the core contracts very rapidly and the temperature rises dramatically
- Photodisintegration: high energy photons break the iron nuclei to helium nuclei
- Electron combines with proton to form neutrons, neutrinos transport the energy
- The core ends up as all neutron, with nuclear density (10^{17} kg/m^3)
- The degenerate neutron pressure suddenly halts the core contract
- The outer core bounce back and sends a powerful wave of pressure
- The pressure wave becomes a powerful shock wave as it go outwards, and expel most stellar material outward
- Shock wave produces a series of nuclear reaction, the only place elements heavier than iron are produced in the universe

Supernova: Five Stages in the Death of a Star

1. Just before explosion

A red super-giant star approaches the end of its life. There is no more fuel to burn and make it shine. Soon its massive dense core is bound to collapse under its own weight.

2. The first light flash

The core collapses and sends a shock wave out. For a few hours the shock compresses and heats the envelope, thus producing a very bright flash of light from the inside of the star.

3. The flash has gone

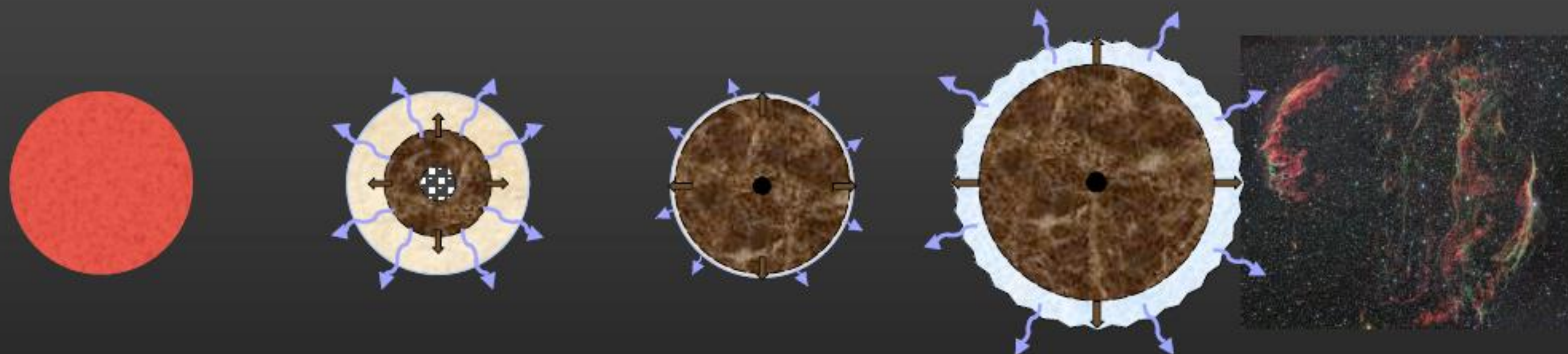
After hitting the surface at 50 million km/h the shock blows the star apart. The core turns into a neutron star, a compact atomic nucleus with the mass of the Sun but 10 km in size.

4. The proper Supernova

The hot glowing surface expands quickly making the fireball brighter again. In a few days it will be 10x the size of the original star and will be discovered by supernova hunters.

5. A long time after

The remains of the former star are spread over light years of space. They keep floating quickly, sweeping up interstellar gas here and there, leaving a faint beautiful glow behind...



Schawinksi, Justham, Wolf, et al.: "Supernova shock breakout from a red supergiant", published in Science 2008

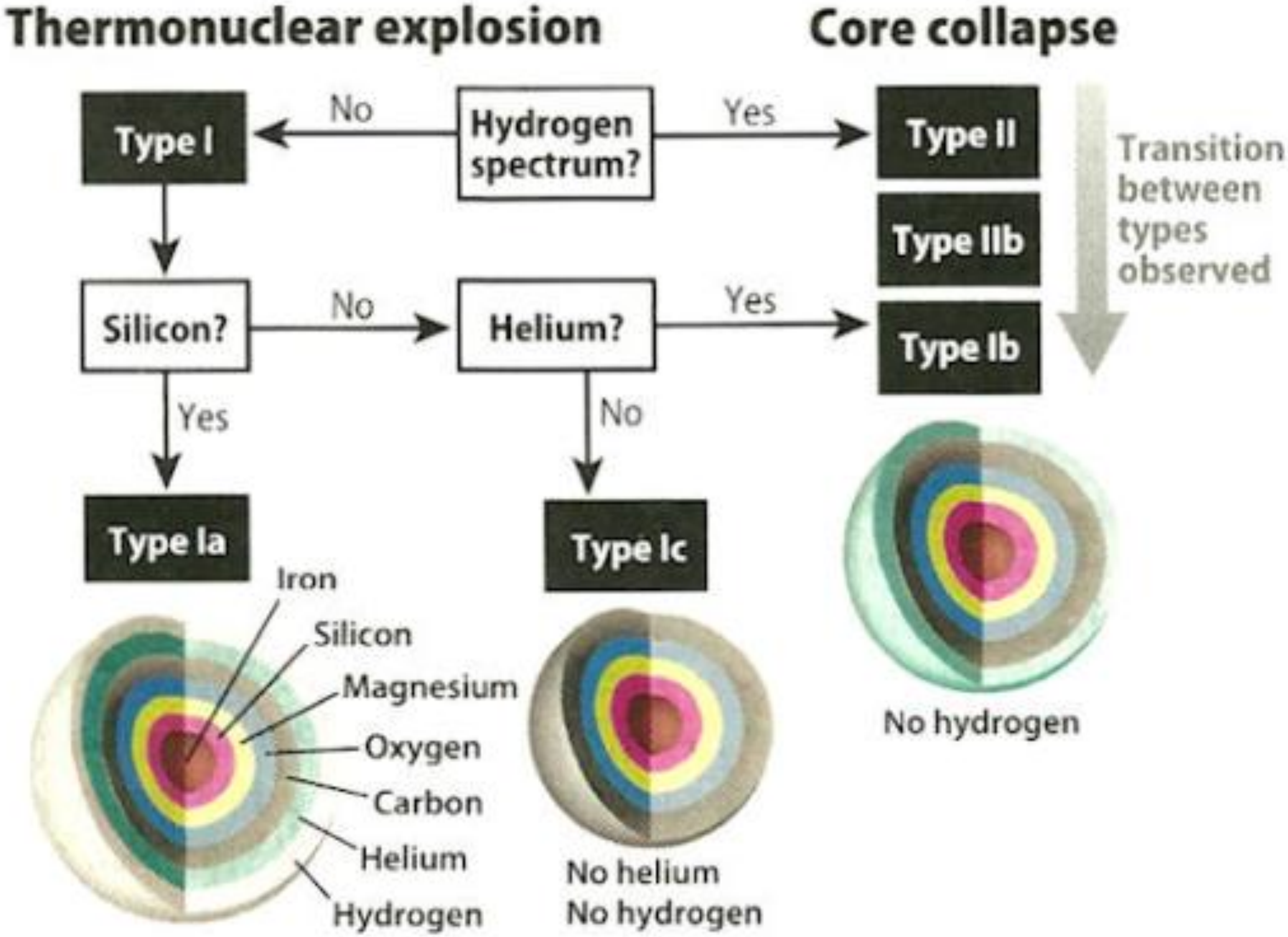
Supernova remnants

X-ray

Different Types of Supernovae

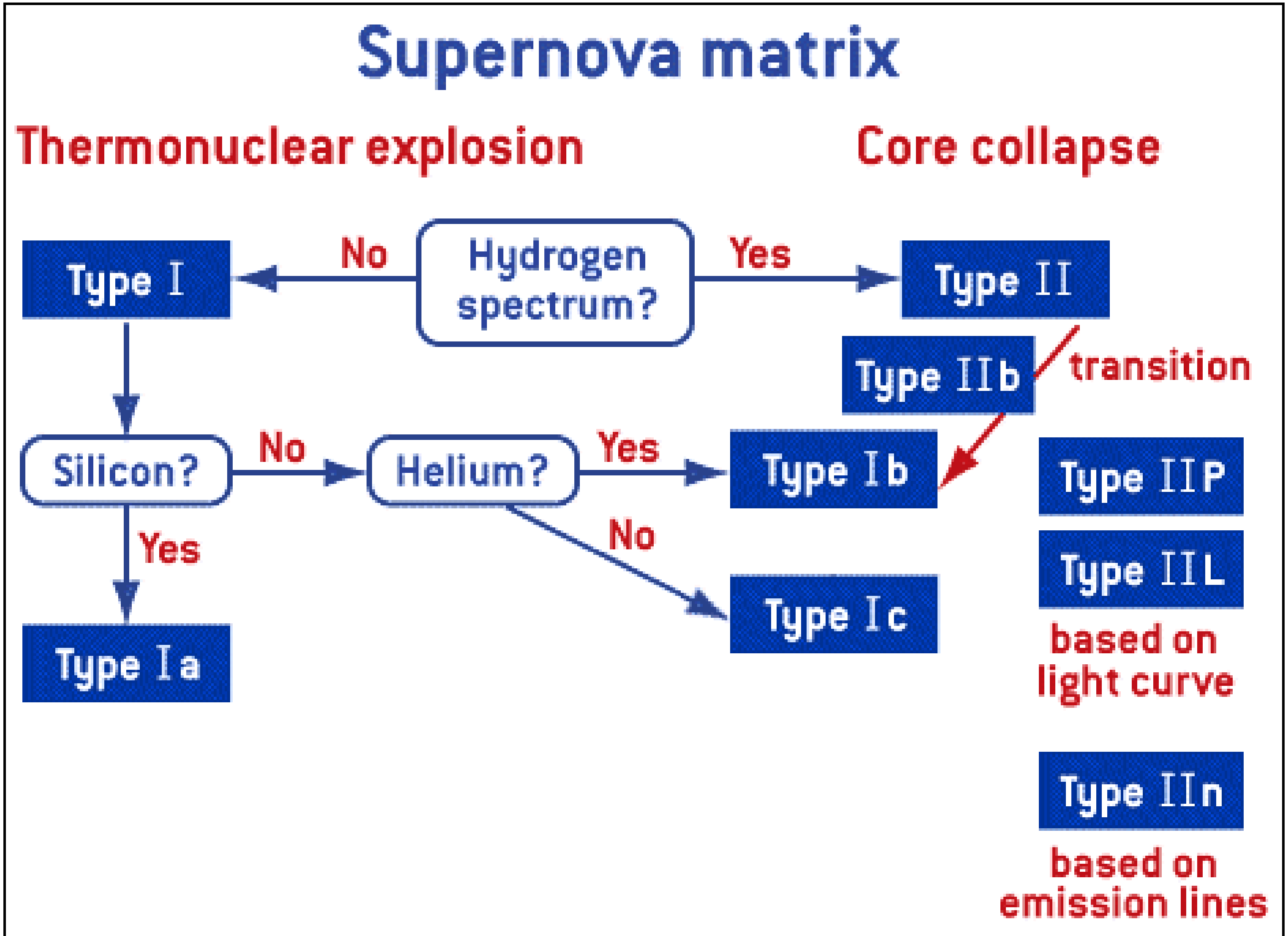
- **Type 1 supernova**: no hydrogen lines
  - **Type 1a supernova**: explosion of white dwarf in a closed binary system; mass accumulation exceeds the critical mass and ignites the carbon fusion at the core
  - **Type 1b supernova**: core collapse of massive star with hydrogen shell lost before
  - **Type 1c supernova:** core collapse of massive star with both hydrogen and helium shells lost before
- **Type 2 supernova**: strong hydrogen lines
  - core collapse of massive star with hydrogen shell largely intact

supernovae spectra



To characterize a supernova, astronomers analyze its spectrum and look for hydrogen, silicon, and helium, as well as how the star's brightness changes over time. This diagram shows how the cores of stars that produce different types of supernovae compare. ASTRONOMY: ROEN KELLY, AFTER MARYAM MODJAZ

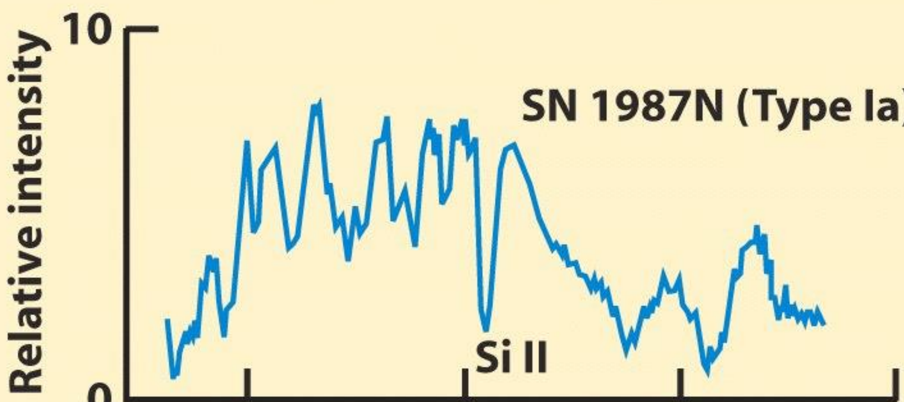
Supernovae – classification scheme

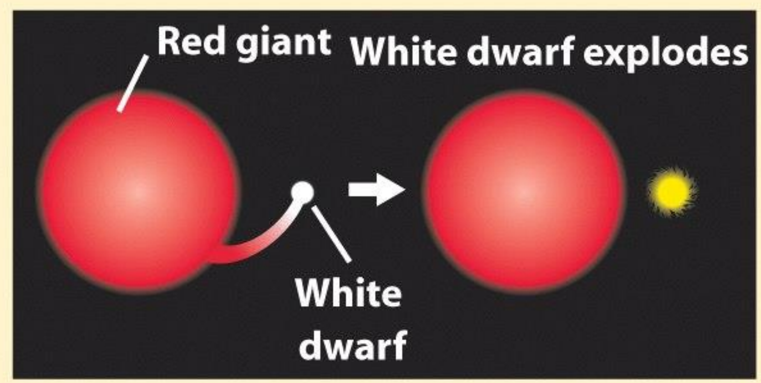


Type Ia supernovae are those produced by accreting white dwarfs in close binaries

(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).

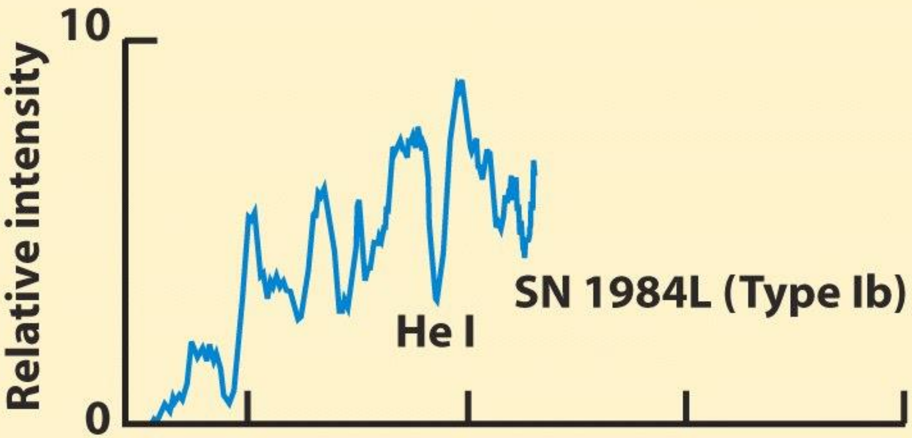


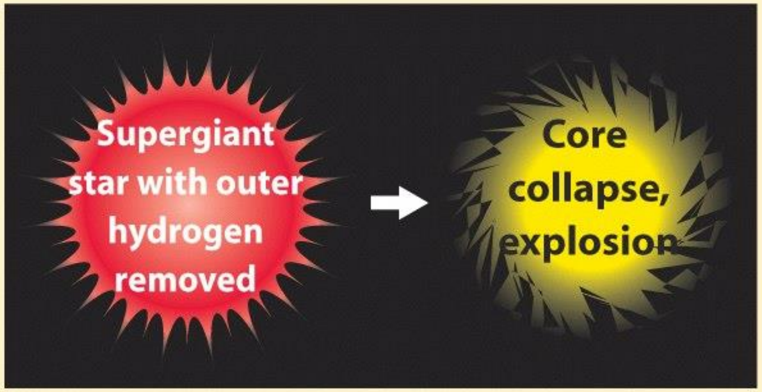


Type Ib supernovae occur when the star has lost a substantial part of its hydrogen shell

(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.**

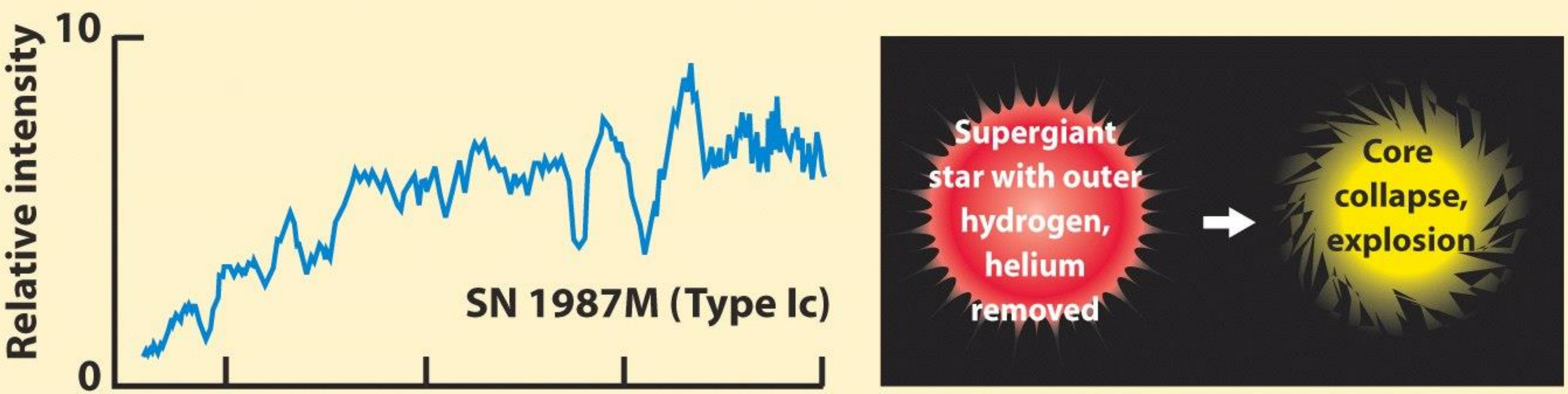




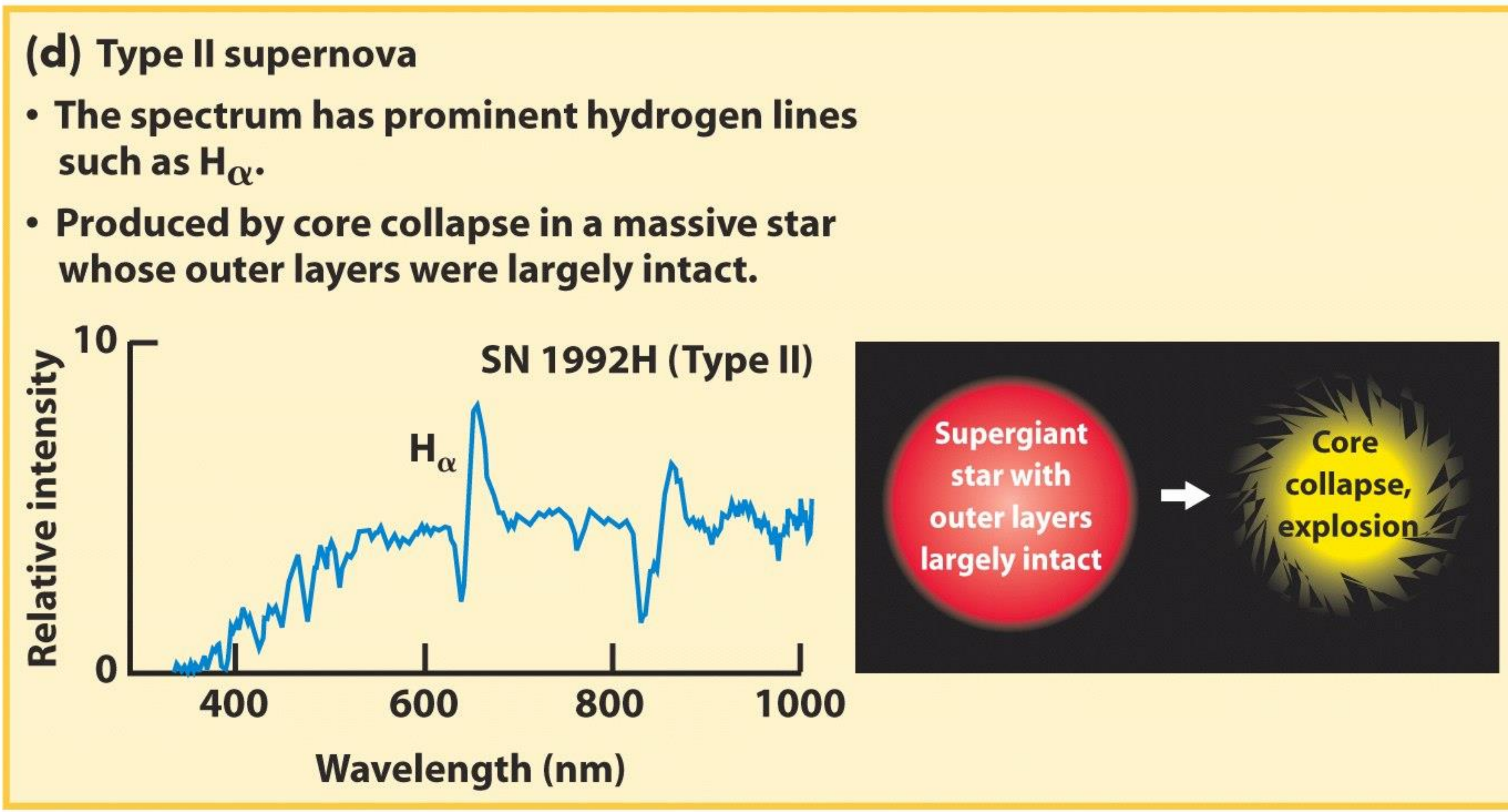
Type Ic supernovae occur when the star has lost a substantial part of both its hydrogen shell and helium shell

(c) Type Ic supernova

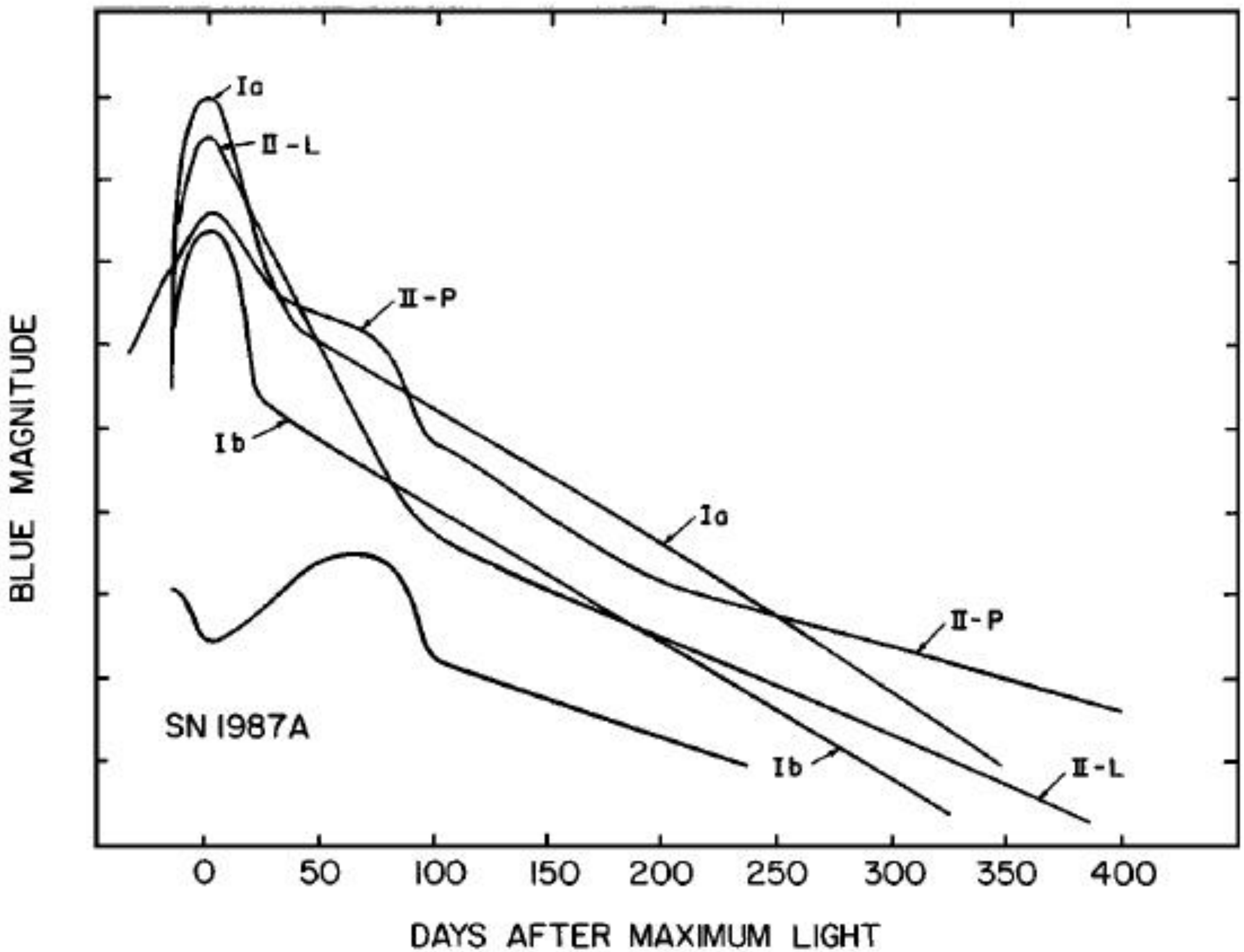
- **The spectrum has no hydrogen lines or helium lines.**
- **Produced by core collapse in a massive star that lost the hydrogen and the helium from its outer layers.**

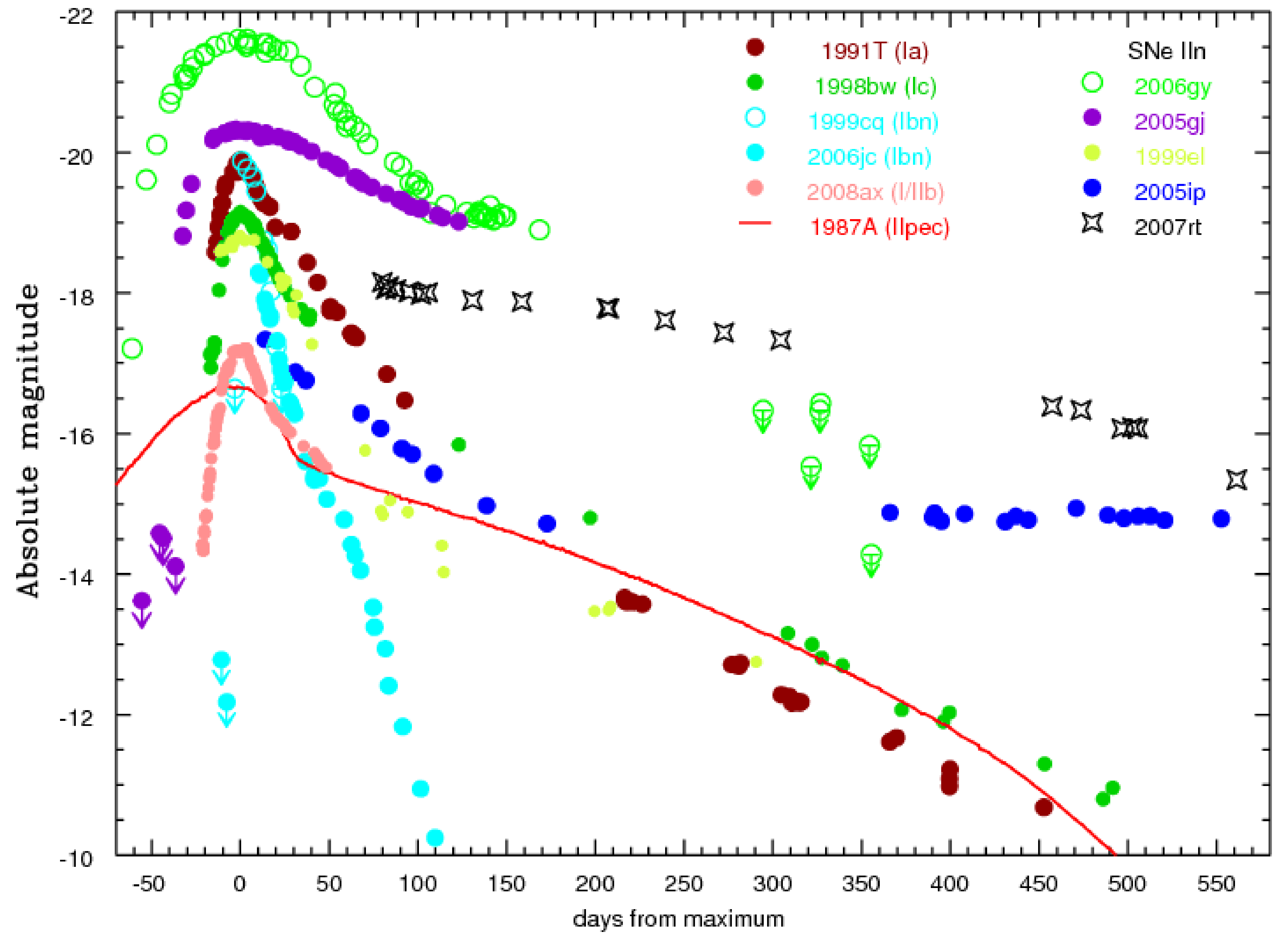


Type II supernovae are created by the deaths of massive stars



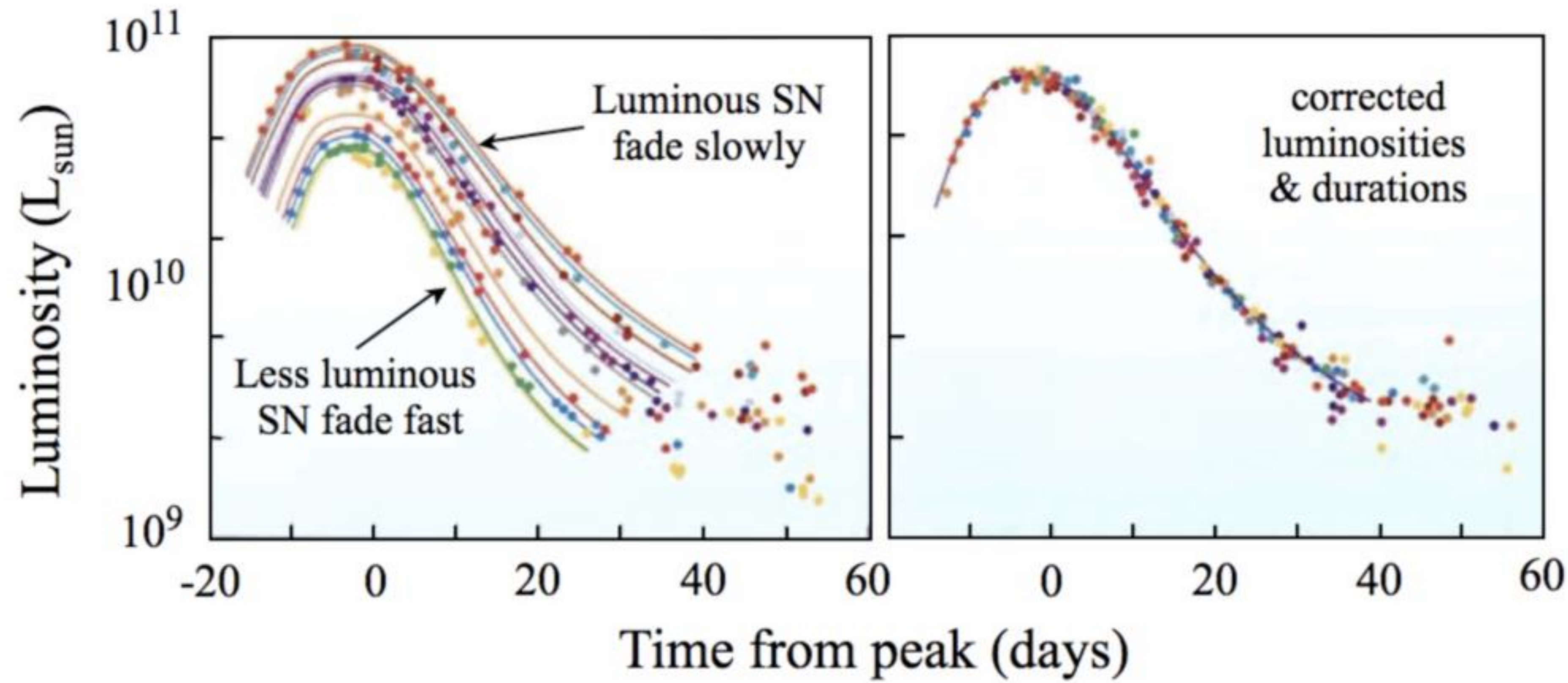
Supernovae – light curves





Absolute magnitude
days from maximum
-22
-20
-18
-16
-14
-12
-10
-50
0
50
100
150
200
250
300
350
400
450
500
550
1991T (Ia)
1998bw (Ic)
1999cq (Ibn)
2006jc (Ibn)
2008ax (I/IIb)
1987A (IIpec)
SNe IIn
2006gy
2005gj
1999el
2005ip
2007rt

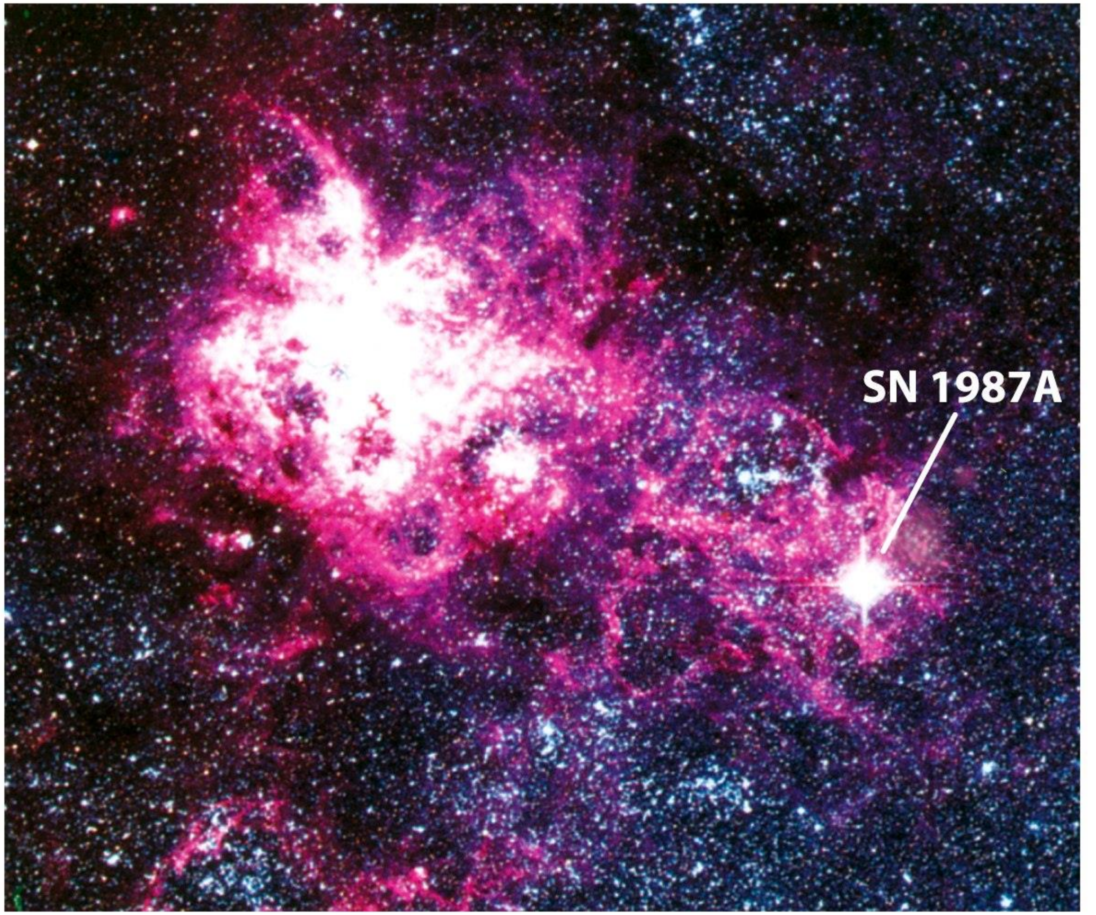
Type Ia Supernovae as Standard Candles



- Absolute magnitude is strongly correlated with rate of decline (faster = fainter)
- Apply “stretch factor” to compensate for this

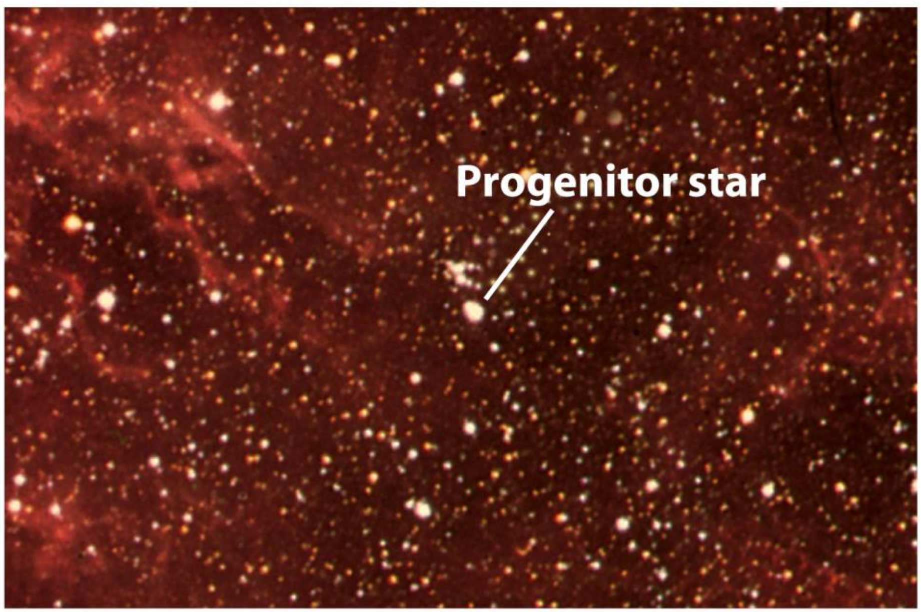
SN 1987A - the best observed SN

- Occurred on 23.02.1987
- In the Large Magellanic Cloud reached V = 2.9 mag

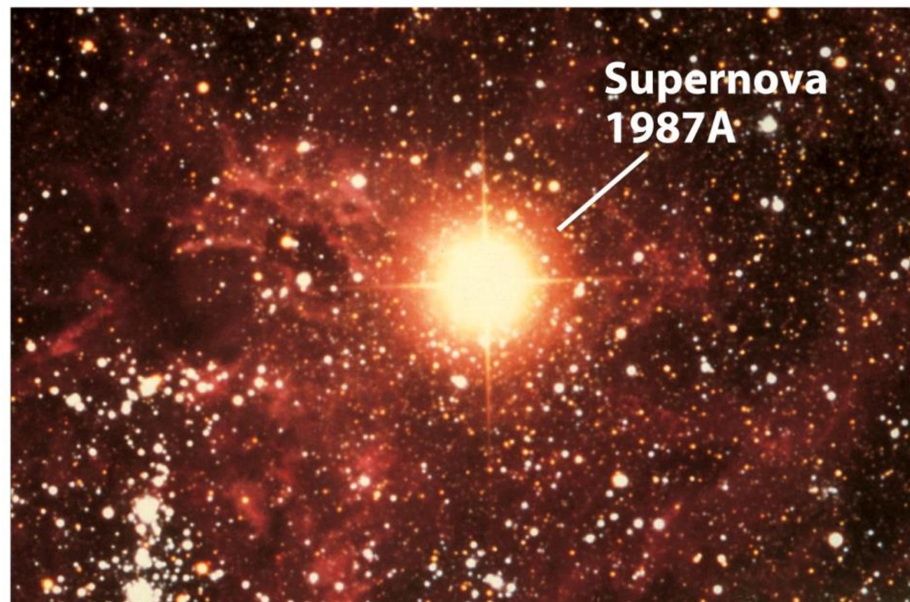


SN 1987A - the best observed SN

- Progenitor star: blue B3 I supergiant



Before the star exploded

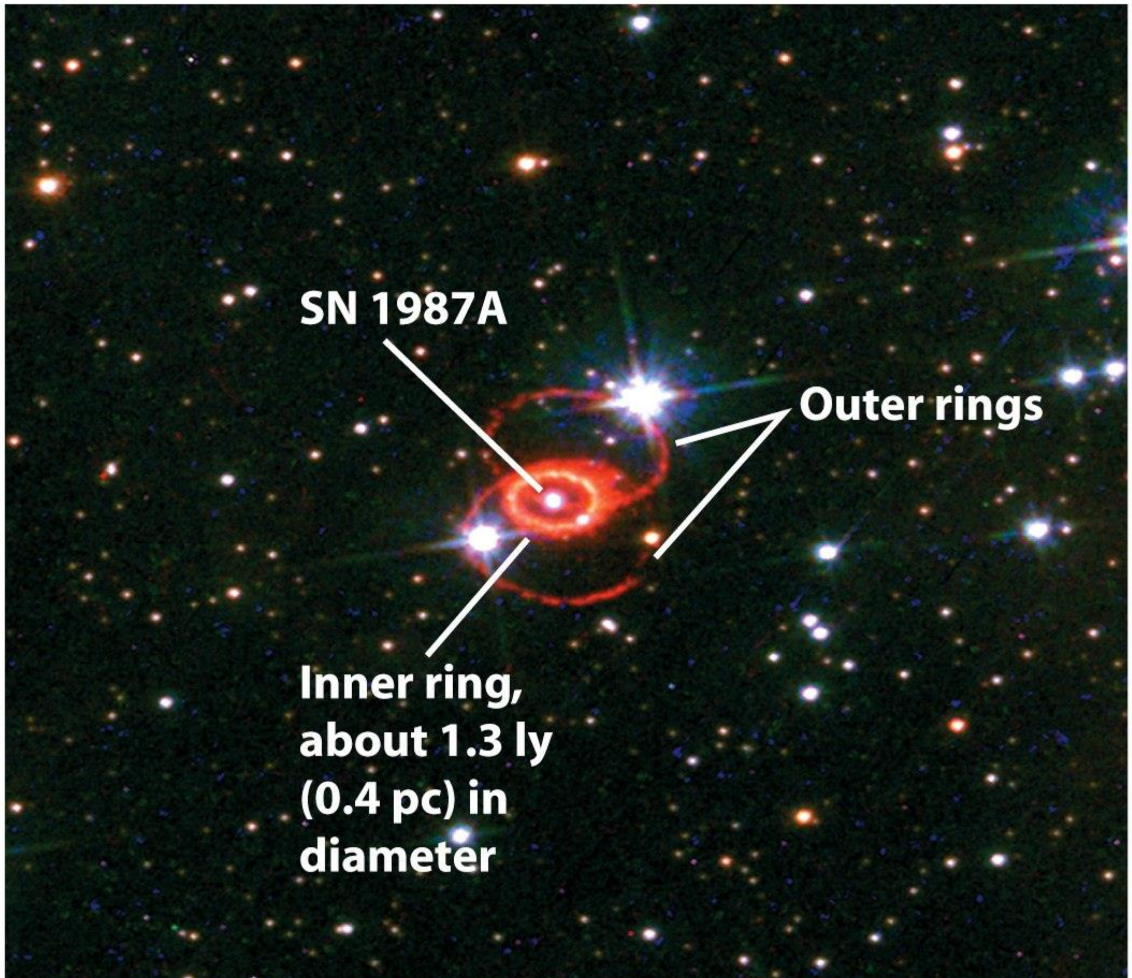


After the star exploded

SN 1987A: Neutrinos were detected

- More than 99% of the energy from such a supernova is emitted in the form of neutrinos from the collapsing core
- Neutrino energy 10^{46} Joules, 100 times as much energy as the Sun has emitted in its entire history
- Neutrinos arrived 3 hours before the first SN light was seen
- **The 3-hour delay was due to the propagation time of the shock wave from the core to the surface of the supergiant**

SN 1987 A - the best observed SN

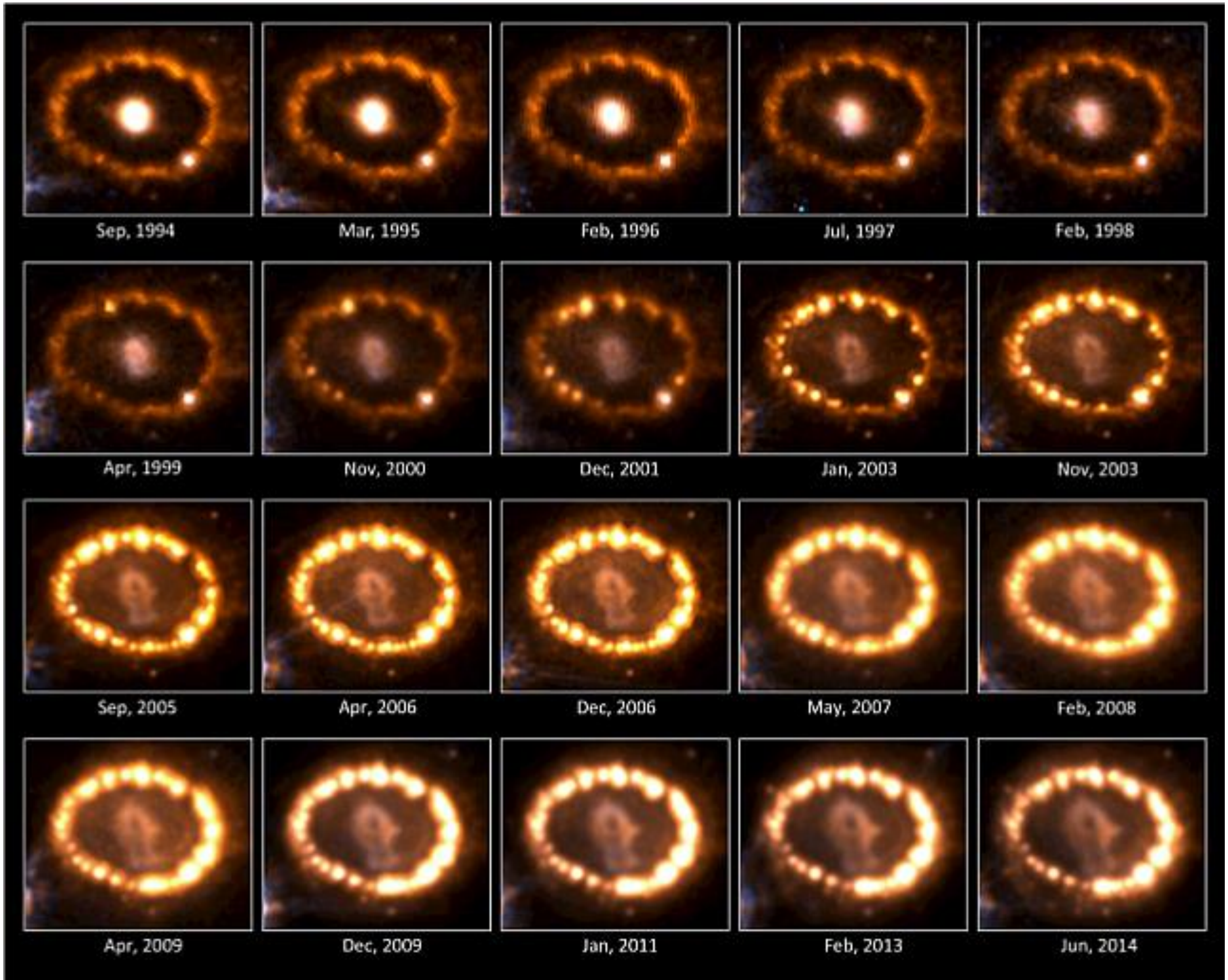


Supernova 1987A seen in 1996

SN 1987A - the best observed SN

HST in 2017

SN 1987A - the best observed SN



SN 1987A - the best observed SN