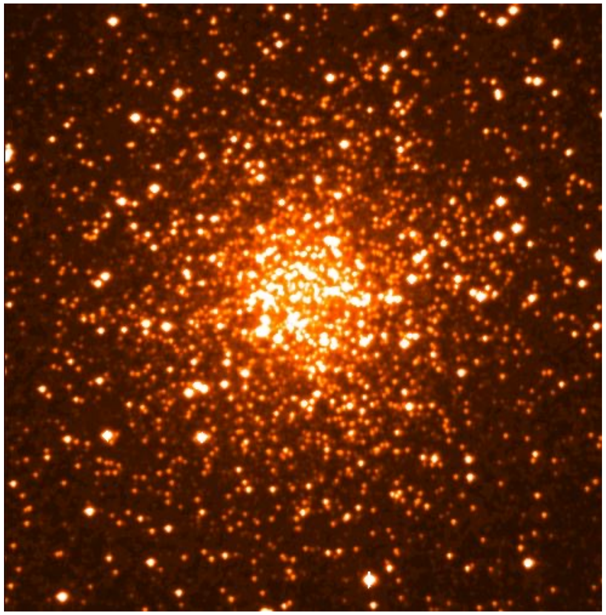
Testing stellar evolution (C+O 13.3)

We've made predictions for the evolution of stars of various mass - how their L, T_{eff} change as fusion sources change, and timescales for changes.

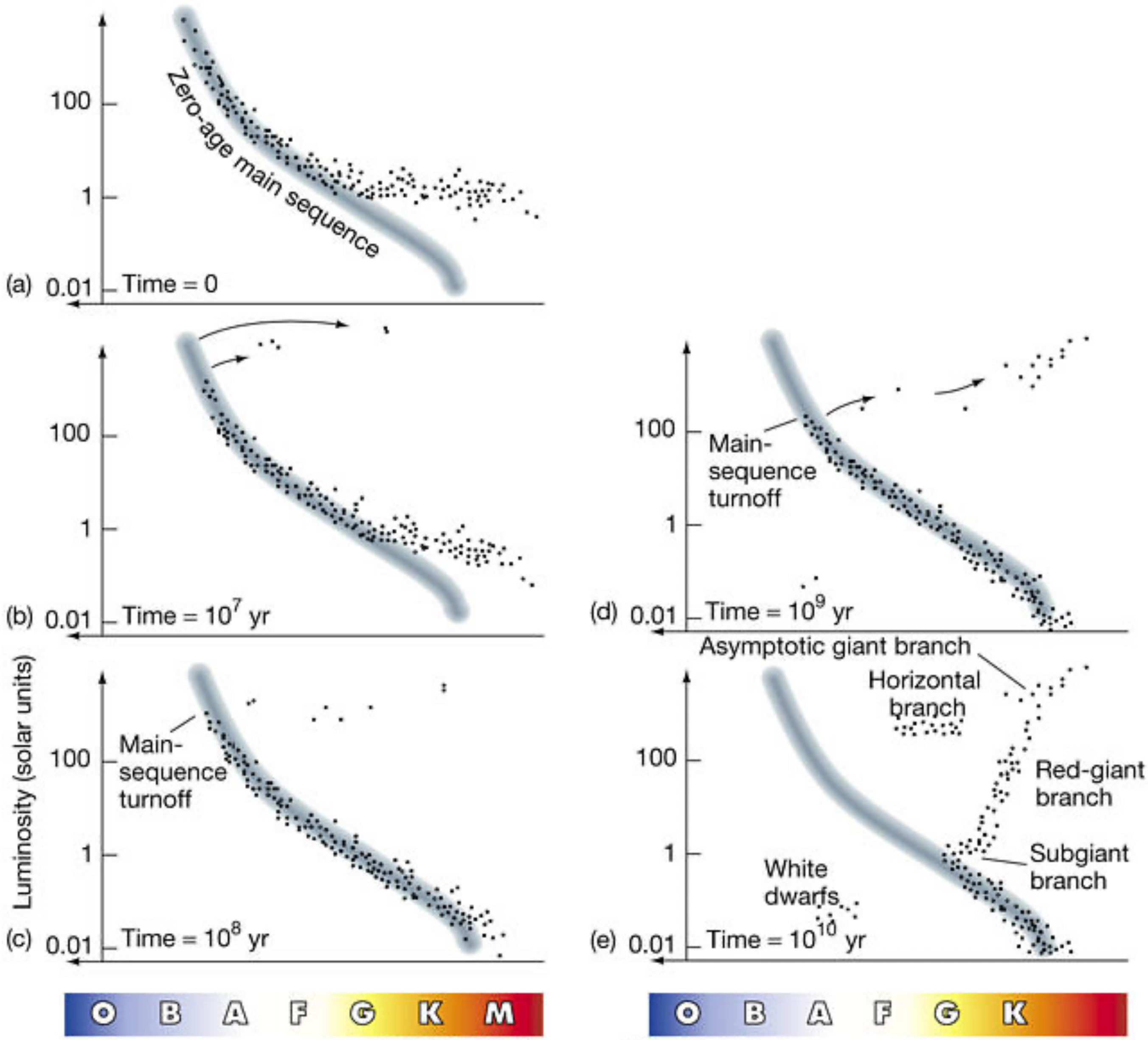
We can test this by studying stellar clusters - all stars formed at same time, all stars at same distance, with same initial abundances.

Globular clusters: Spherical assemblages of 100 000 or more stars

Galactic or Open clusters: About 100-1000 more loosely bound stars

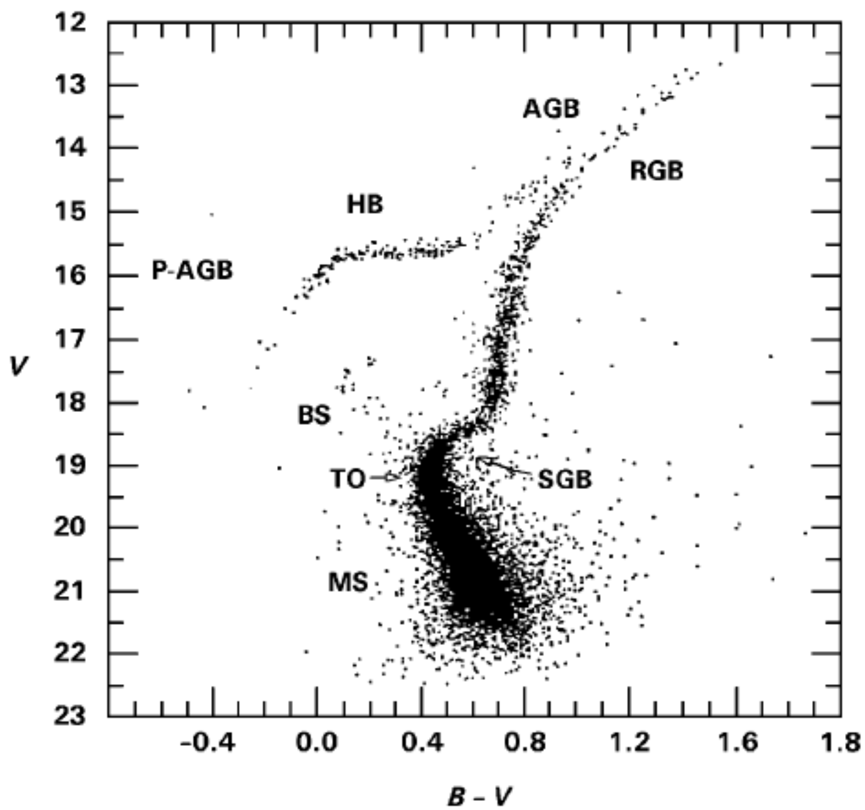


HR evolution of hypothetical cluster

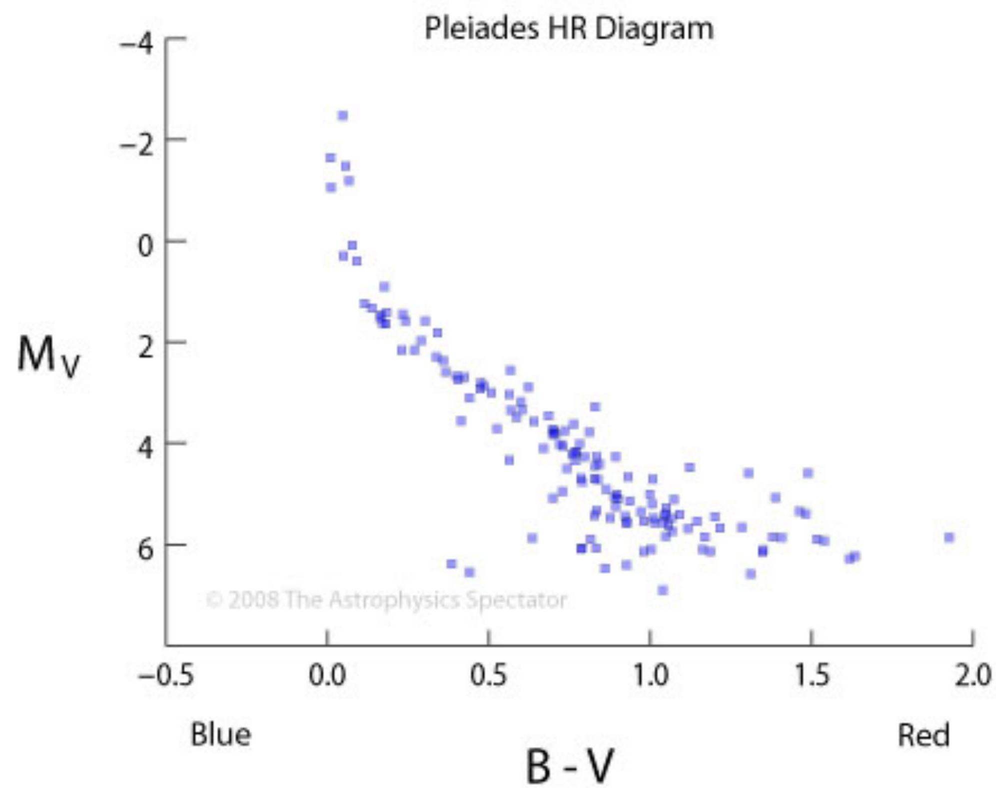


Color-magnitude diagrams

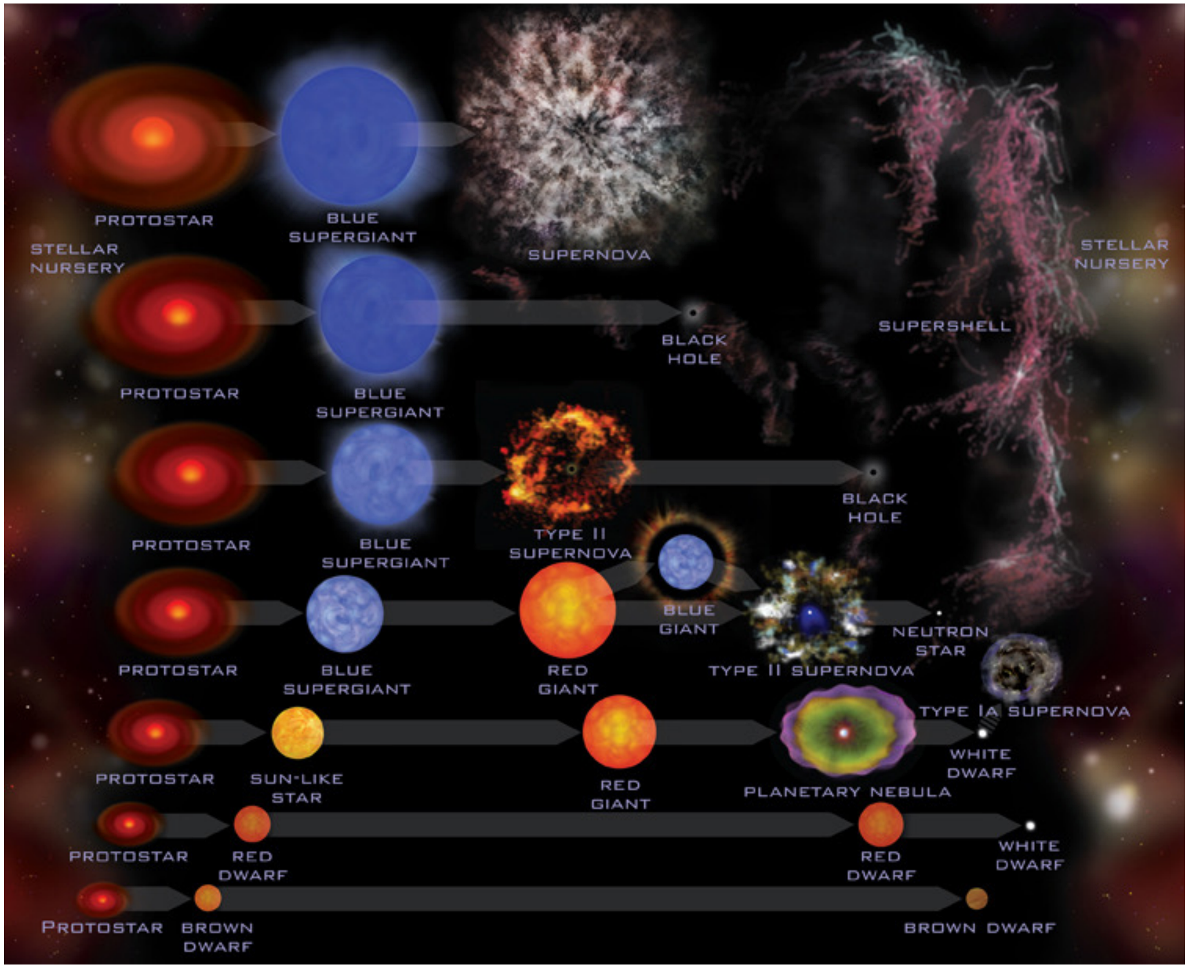
Globular cluster M3



Galactic cluster



Astronomy 421



Lecture 21: Stellar Evolution - Massive Stars
(15.1-15.3)

Final Project

- Look at the example
- Consider using Overleaf

Cosmic Explosions

Flare stars

Novae (detonations on the surface of a star)

[Magnetar Flares and Giant Flares]

Supernovae (detonations of a star)

[Gamma Ray Bursts (formation of a black hole?)]

Post MS stellar evolution - high mass stars $M > 8M_\odot$

Rapid: approximately $\tau \propto M^{-2}$

High mass

=> high gravity

=> high core T

=> rapid burning

=> can burn beyond C,O to Fe, Ni.

And s-process elements too (gold!)

e.g. $^{12}_{6}C + ^{4}_{2}He \rightarrow ^{16}_{8}O + \gamma$

$$^{12}_{6}C + ^{12}_{6}C \rightarrow ^{24}_{12}Mg + \gamma$$

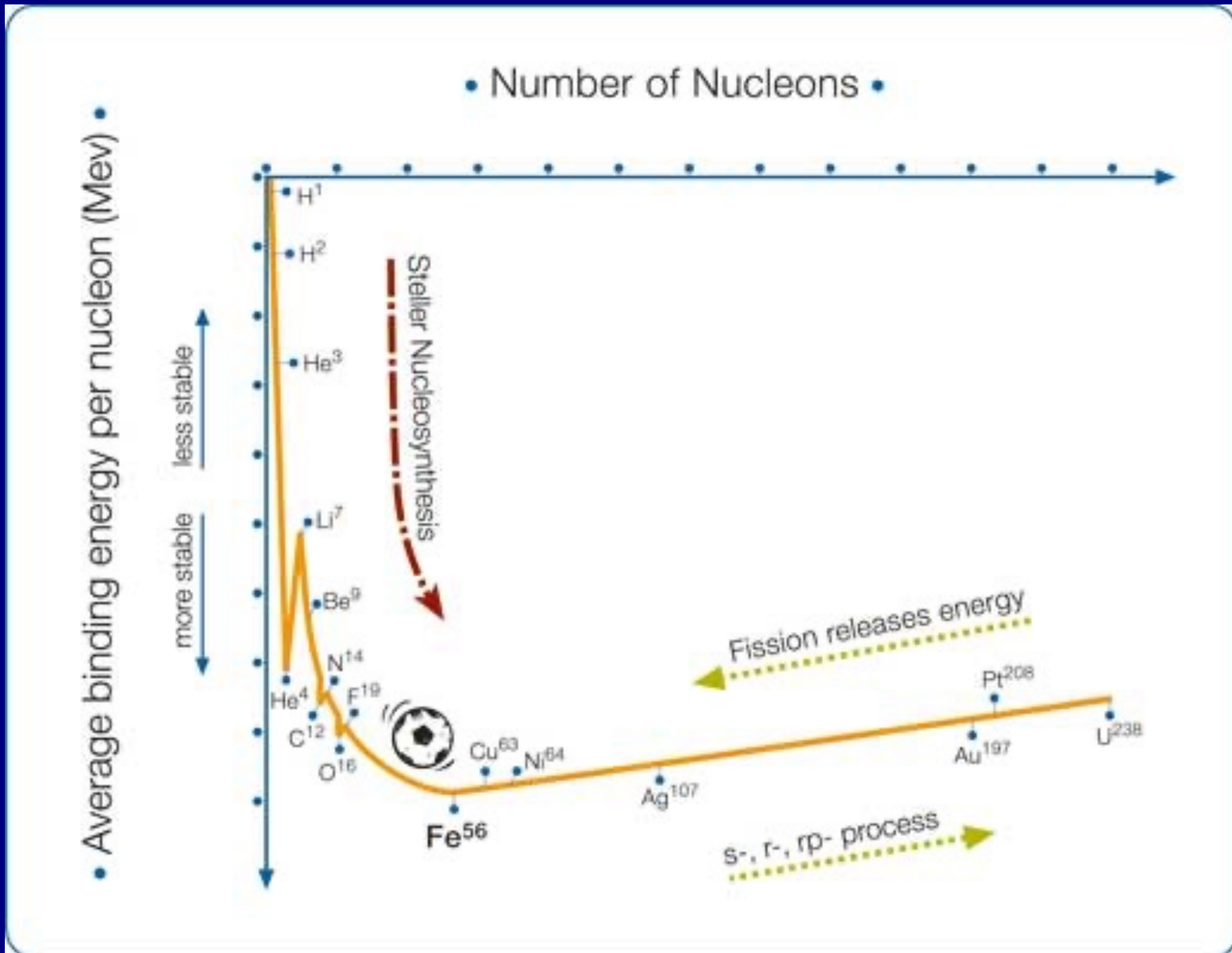
$$^{16}_{8}O + ^{16}_{8}O \rightarrow ^{24}_{14}Si + ^{4}_{2}He$$

$$^{16}_{8}O + ^{16}_{8}O \rightarrow ^{32}_{16}S + \gamma$$

$$^{28}_{14}Si \rightarrow ^{56}_{26}Fe,\ ^{54}_{26}Fe,\ ^{56}_{28}Ni$$

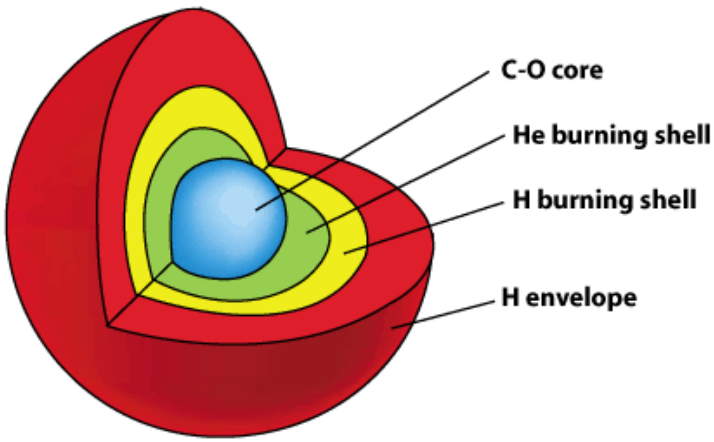
1) Fuel in core exhausts
2) Inert core contracts
3) Shell burning of “previous” element begins
4) Formerly inert core ignites etc….

Binding Energy per nucleon

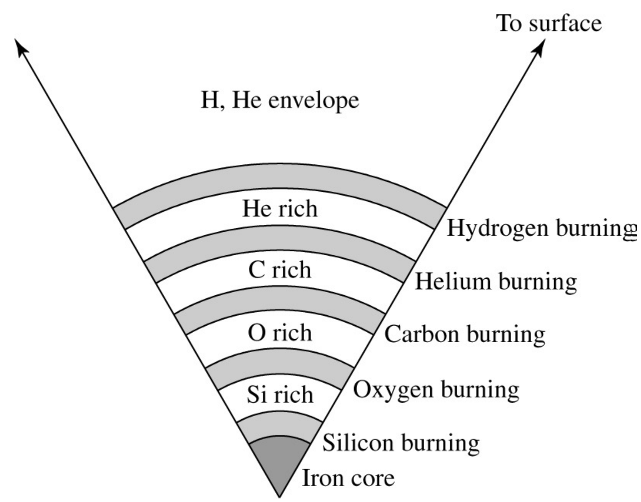


Compare structure of AGB star to that of a massive star:

AGB star



massive star

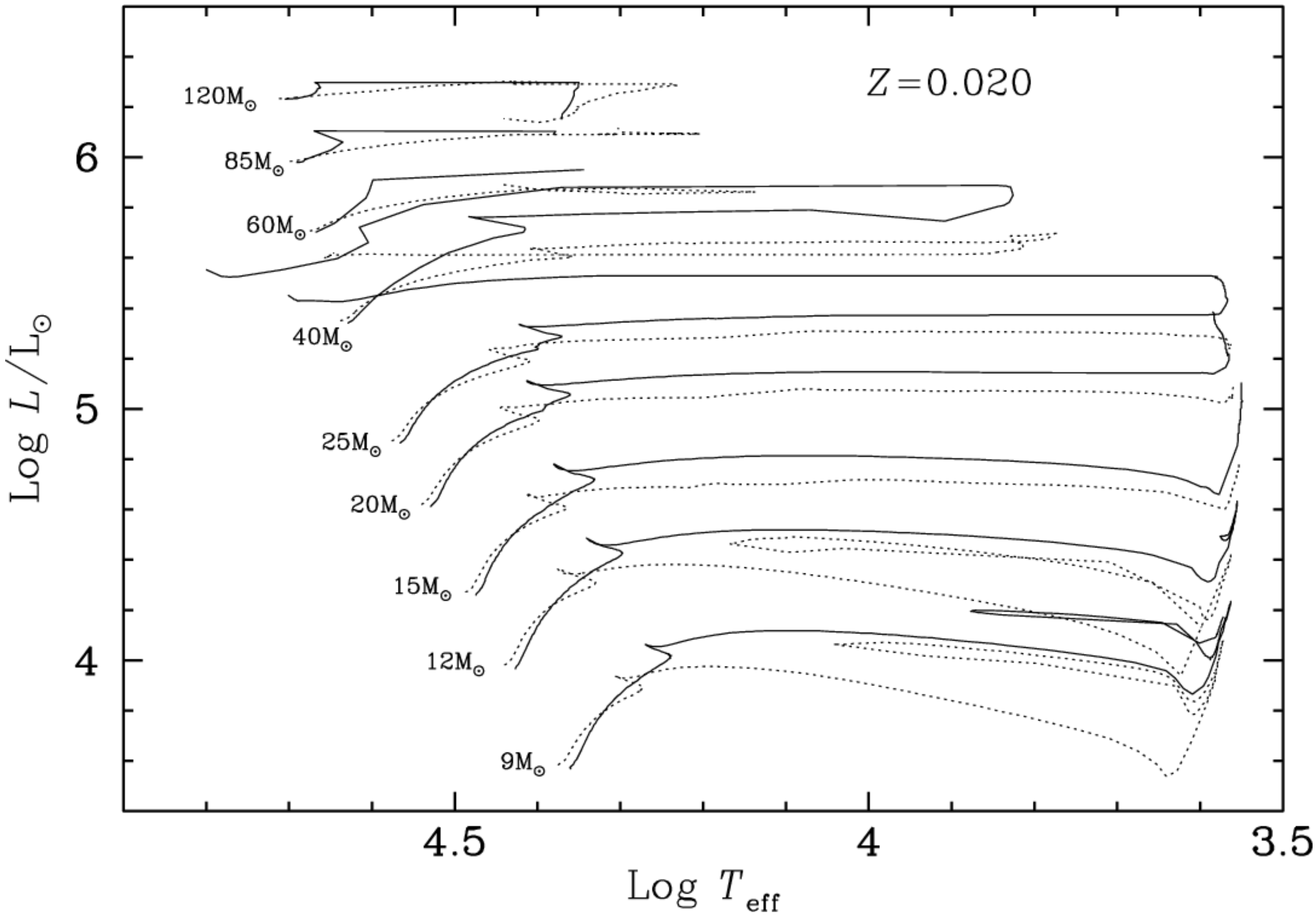


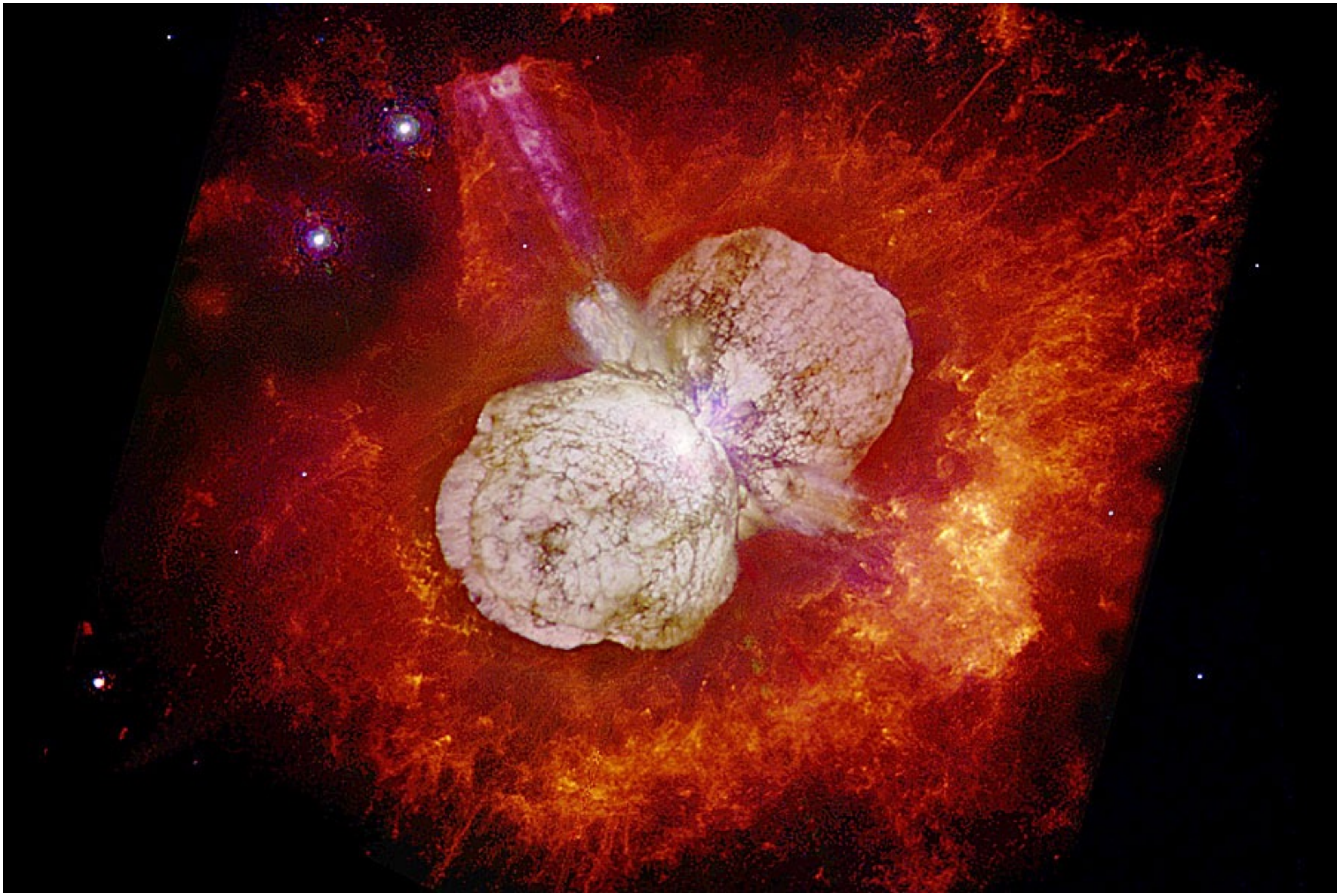
<u>20 $M_\odot$</u>

Core H burning time	10^7 yrs
Core He burning time	10^6 yrs
Core C burning time	300 yrs
Core O burning time	200 days
Core Si burning time	2 days

Core masses range from 1.3 $M_\odot$ for a 10 $M_\odot$ star to 2.5 $M_\odot$ for a 50 $M_\odot$ star.

Evolution in H-R diagram at relatively constant *L*, to higher *R* and lower T_{eff}. Cores generally not degenerate – each stage starts smoothly after previous completed. Winds are significant. These plots are up to end of core He burning.





Eta Carina and the Homunculus Nebula

Wolf-Rayet Stars

NGC 2359 Nebula

Core Collapse Supernovae

Once Fe, Ni made, any further reactions *endothermic,* no energy out, no more source of pressure support.

When T~10^9 K ($\rho = 10^{13}$ kg m^{-3}), gamma-rays destroy nuclei (photodisintegration).

especially
$$^{56}_{26}Fe + \gamma \;\rightarrow\; 13\,^4_2He + 4n$$
$$^4_2He + \gamma \;\rightarrow\; 2p^+ + 2n$$

Nucleosynthesis reversed!

Energy is going into disrupting nuclei, core starts to lose support.
Electron degeneracy pressure becomes important as it contracts.

Next, $p^+ + e^- \rightarrow n + \nu_e$

Core's support now completely removed, because of

1. Enormous energy loss as neutrinos escape
2. *e^-* degeneracy support gone

Core collapses nearly in free-fall in ~1 sec, at speeds up to 70,000 km/s.

In free-fall, collapse is "homologous", i.e. $V_{collapse}$ increases linearly with radius. Loss of pressure support for layers above is communicated at speed of sound, so at some radius $V_{collapse} > V_{sound.}$

=> this defines outer core, which is trying to collapse supersonically => material starts to pile up in a shock. Inner core leaves it behind.

Inner core collapse halted by *neutron degeneracy pressure* when

$$\rho \sim \rho_{nucleus}$$

Sends out pressure waves with $V \gg V_{sound}$ => shock waves. Many details uncertain because things evolve so rapidly, see C+O, e.g. shock may temporarily stall at outer core but gets re-energized by neutrino energy being deposited in the dense, swept up material.

Outer core + envelope explode – "Type II" or core-collapse supernova

Energies involved:

$E_{neutrino} \sim 10^{46}$ J

KE $\sim 10^{44}$ J

$E_{photons} \sim 10^{42}$ J (once expanded enough to be optically thin)

Peak L $\sim 10^{36}$ W $\sim 10^{9}\ L_{\odot}$

What is left:

If $8M_{\odot} \leq M_{ZAMS} \leq 25?M_{\odot}$ *(very uncertain…)*

$1.4M_{\odot} \leq M_{inner\ core} \leq 3M_{\odot}$ => neutron star

If *M* higher, degeneracy pressure less than gravity => black hole

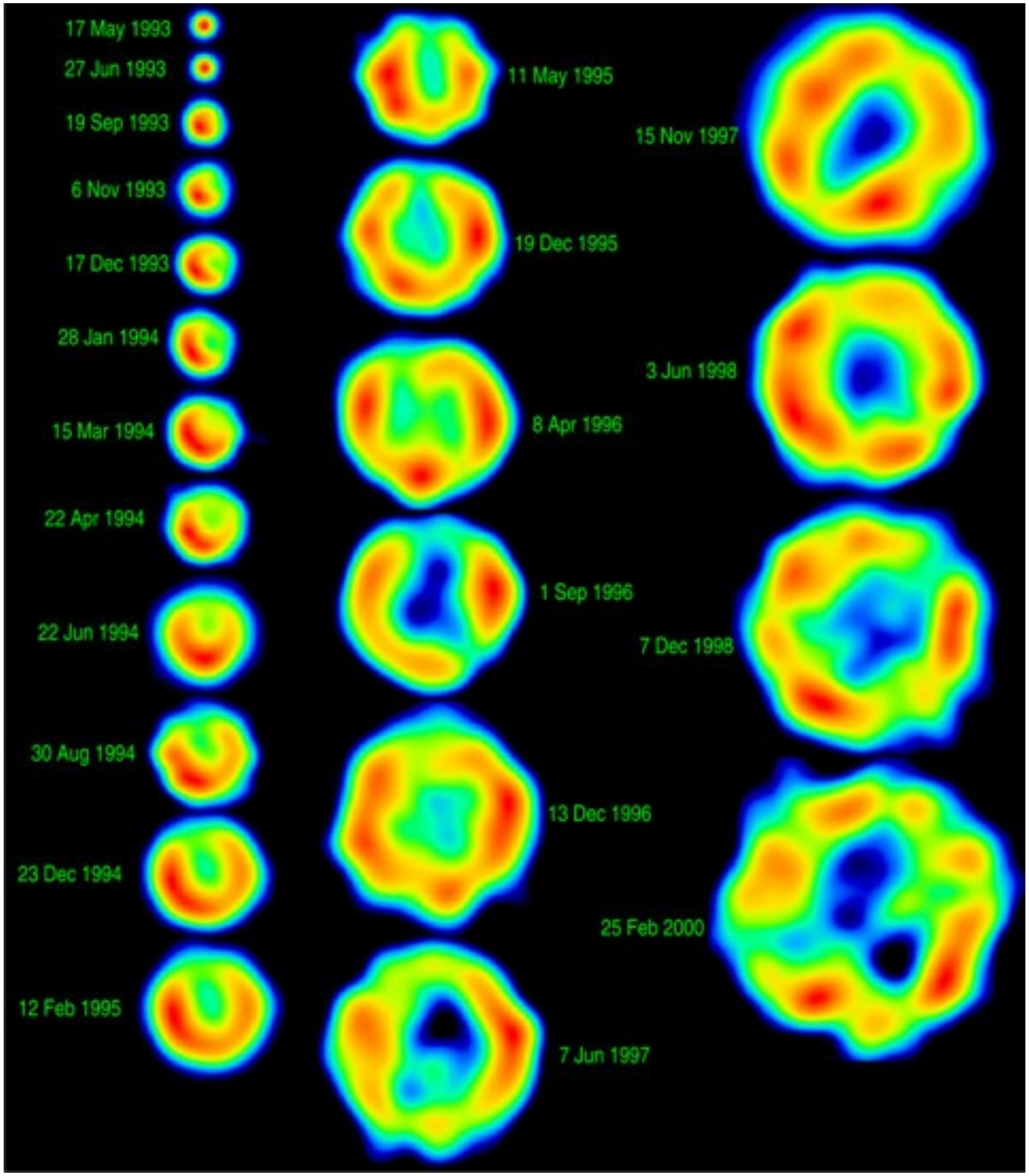
Example Supernova: 1994D in NGC 4526

Example Supernova: 1998bw

SN 1998bw in Spiral Galaxy ESO184-G82

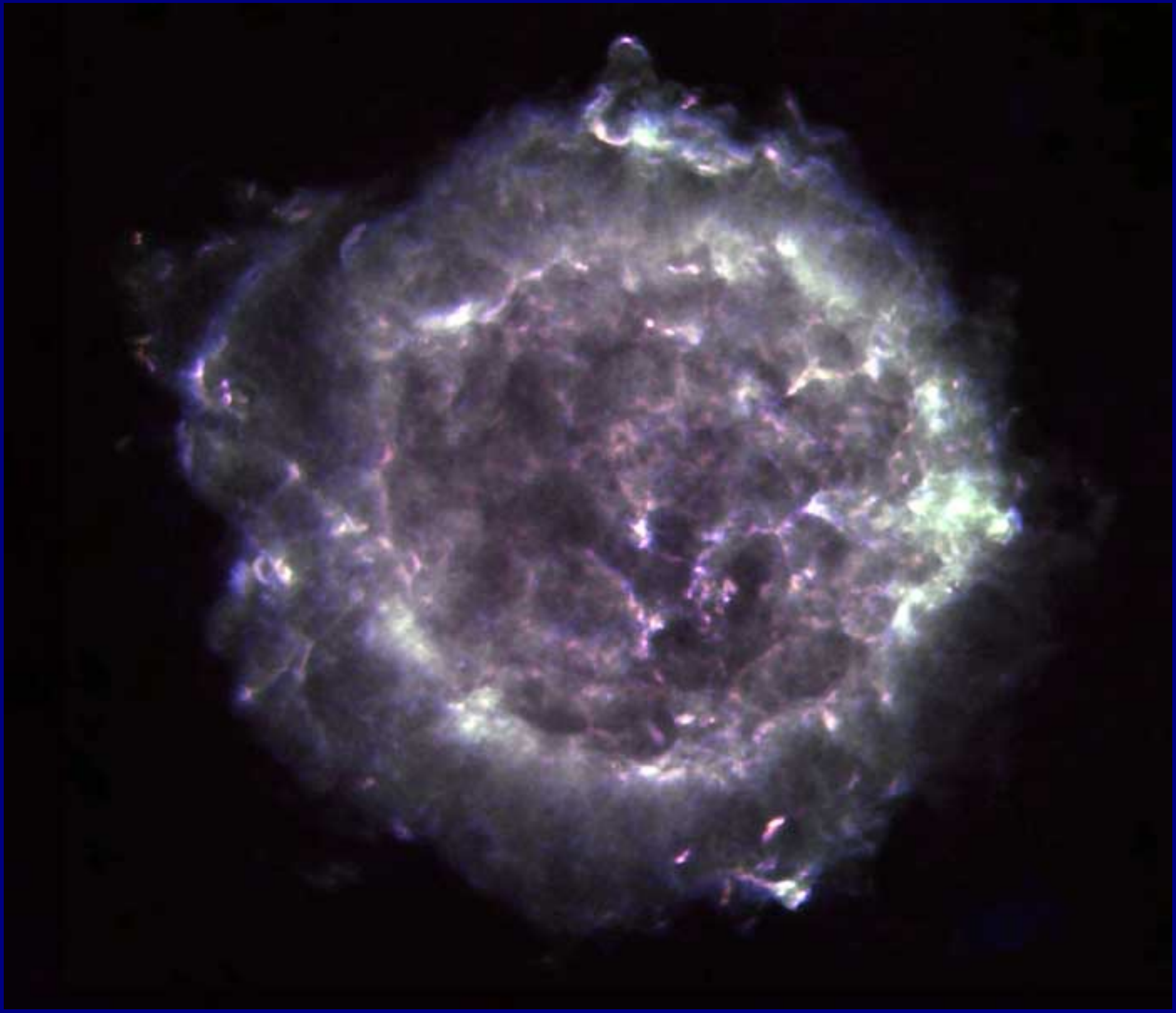
ESO PR Photo 39a/98 (15 October 1998)

A Young Supernova

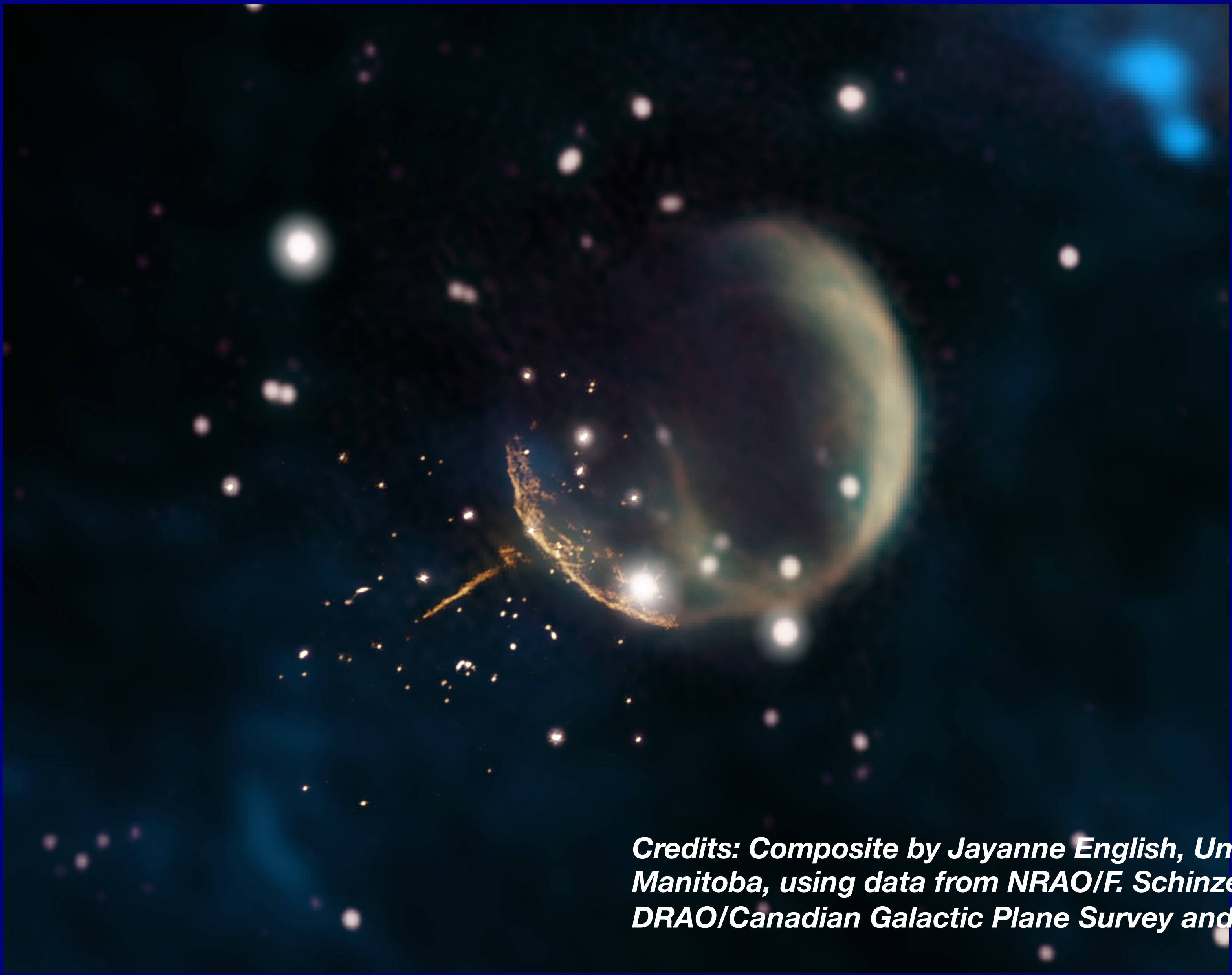


SN 1993J
Rupen et al.

Cassiopeia A: Supernova Remnant

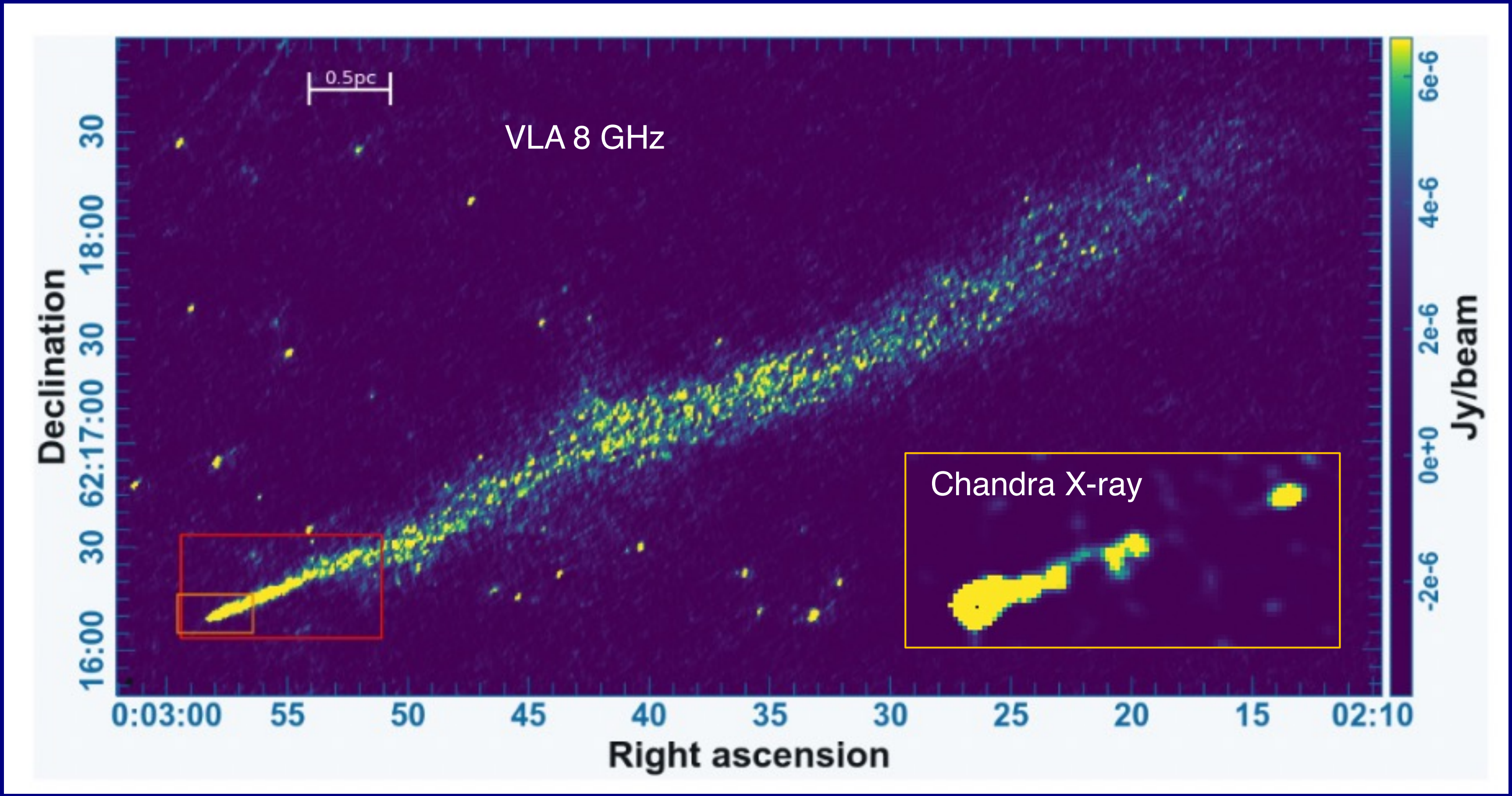


Cannonball Supernova Remnant



Credits: Composite by Jayanne English, University of Manitoba, using data from NRAO/F. Schinzel et al., DRAO/Canadian Galactic Plane Survey and NASA/IRAS

Cannonball Supernova Remnant



Worksheet 12

Kumar et al. 2022

In 1000 years, the exploded debris might look something like this:

2 pc

Crab Nebula: debris from a stellar explosion observed in 1054 AD.

Or in 10,000 years:

50 pc

Vela Nebula: debris from a stellar explosion in about 9000 BC.

Types of Supernovae

Supernova are classified by the optical lines in the spectra of the debris. Must then go back to figure out what explosive processes can produce such spectra.

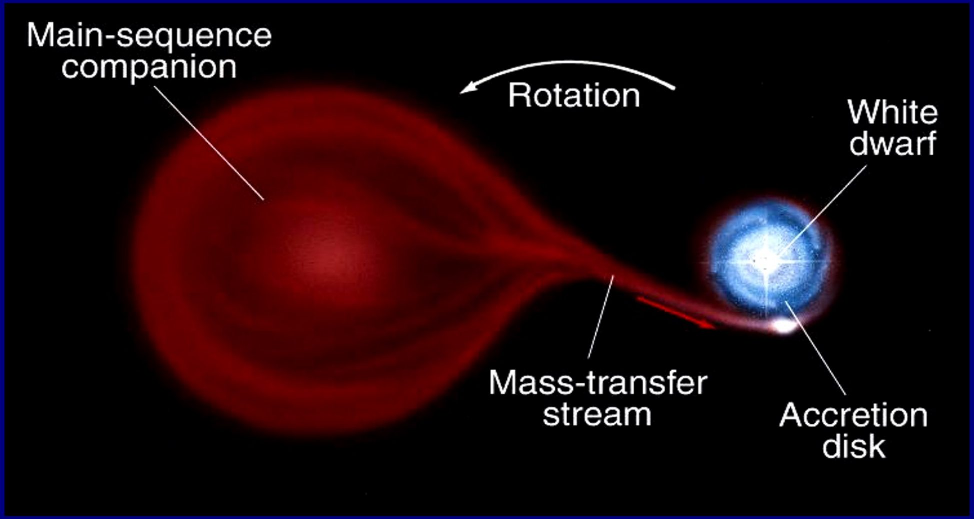
Type I – No H lines in spectrum →
- Type Ia – a strong Si II line at 615 nm
- Type Ib – weak Si II, but He lines
- Type Ic – weak Si II, no He lines

Type II – H lines

Type II's are core-collapse SNe, with H from envelope
Type Ib's are as well, but H envelope previously completely lost through winds (see Wolf-Rayet stars in C+O 15.1)
Type Ic's are as well, but also lost He shell
Type Ia's are due to accretion-induced collapse of a white dwarf in a close binary.

A Carbon-Detonation or “Type Ia” Supernova

Despite novae, mass continues to build up on White Dwarf.

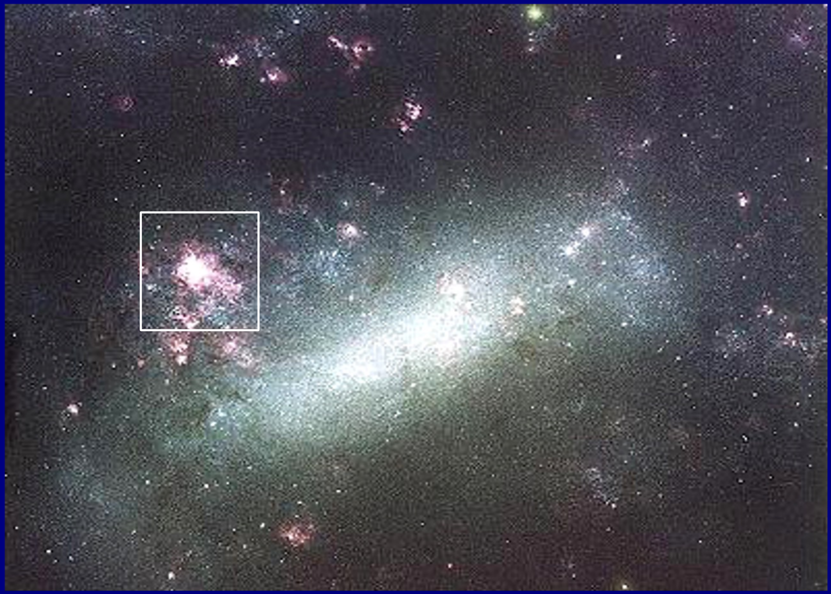


If mass grows to 1.4 M_{Sun} (the "Chandrasekhar limit"), gravity overwhelms the Pauli exclusion pressure supporting the WD, so it contracts and heats up.

This starts carbon fusion everywhere at once.

Tremendous energy makes star explode. No core remnant.

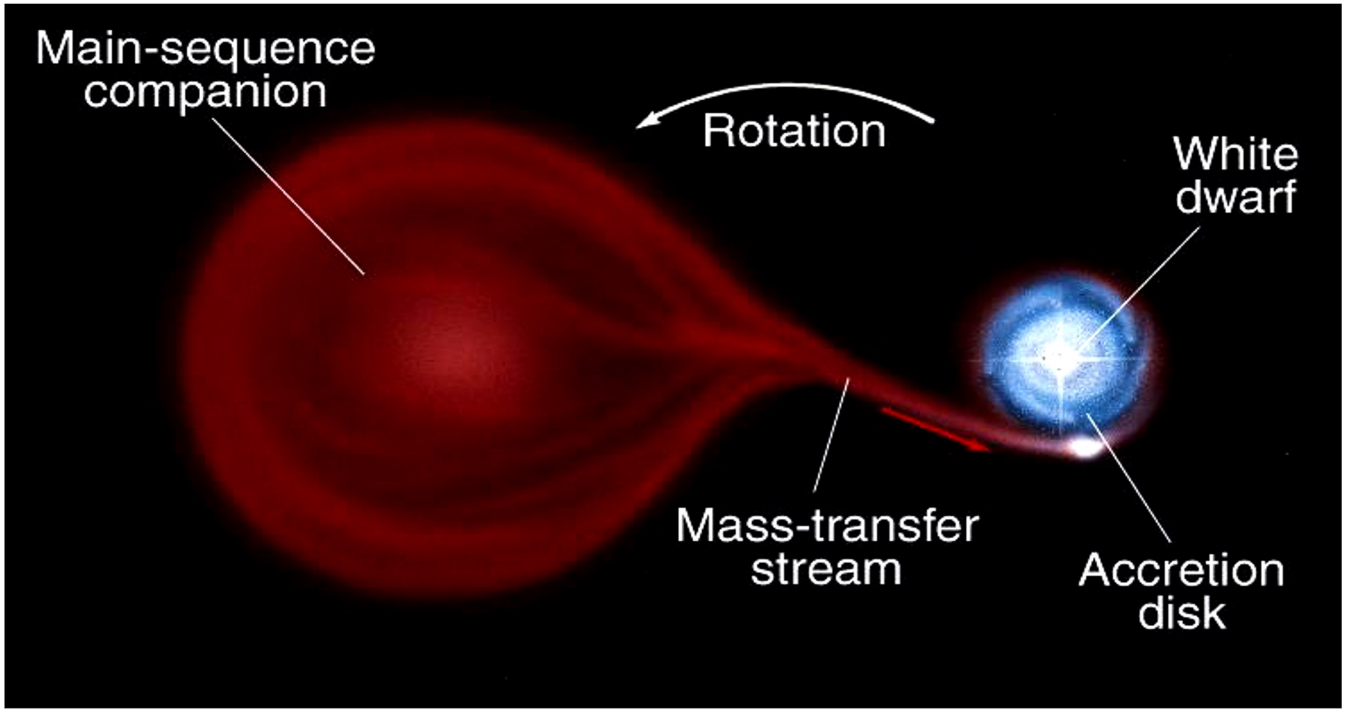
Supernova 1987A in the Large Magellanic Cloud



Stellar Explosions

Novae

White dwarf in
close binary system

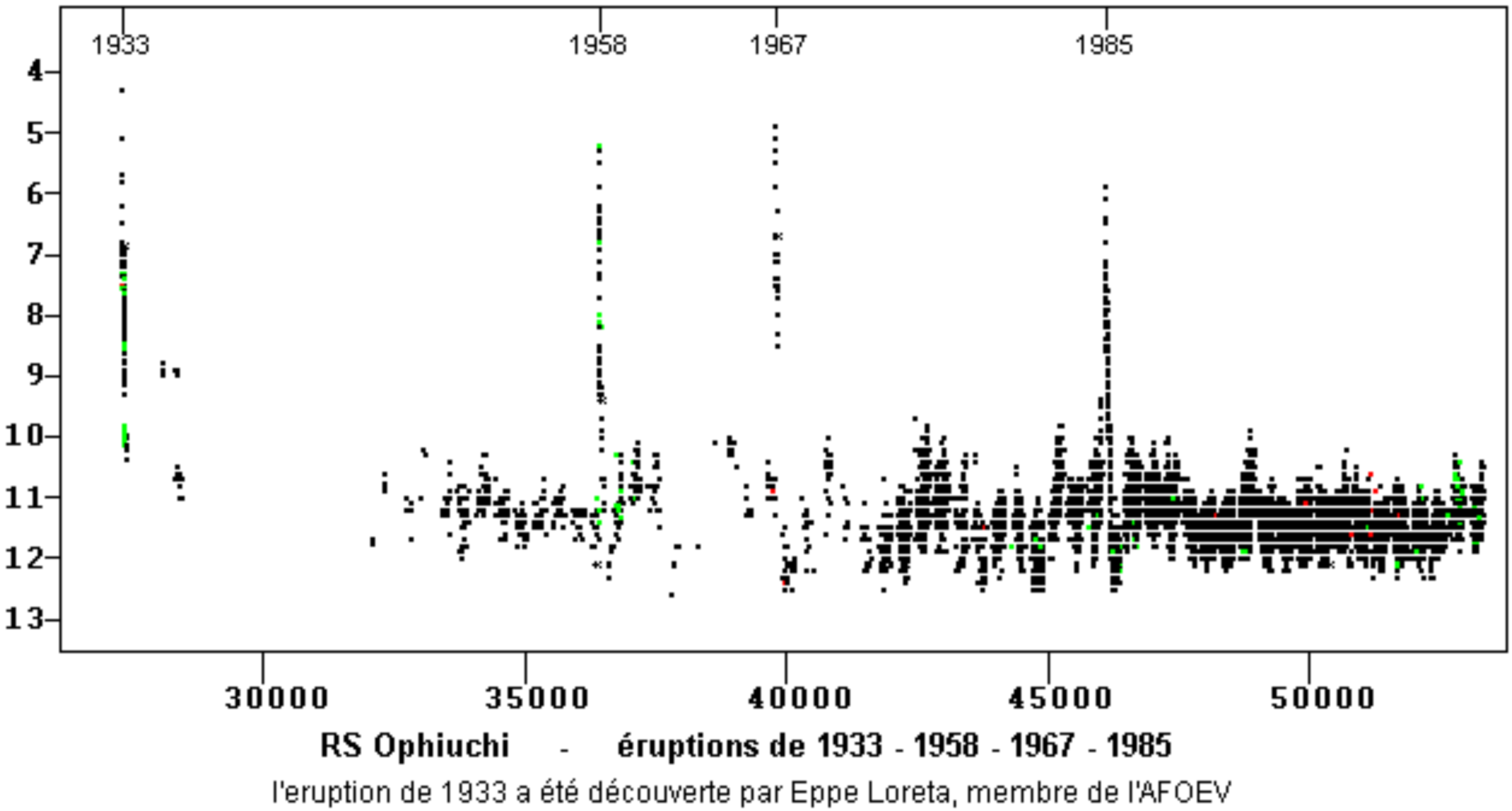


WD's tidal force stretches out companion, until parts of outer envelope spill onto WD. Surface gets hotter and denser. Eventually, a burst of fusion. Binary brightens by 10'000's! Some gas expelled into space. Whole cycle may repeat every few decades => recurrent novae.

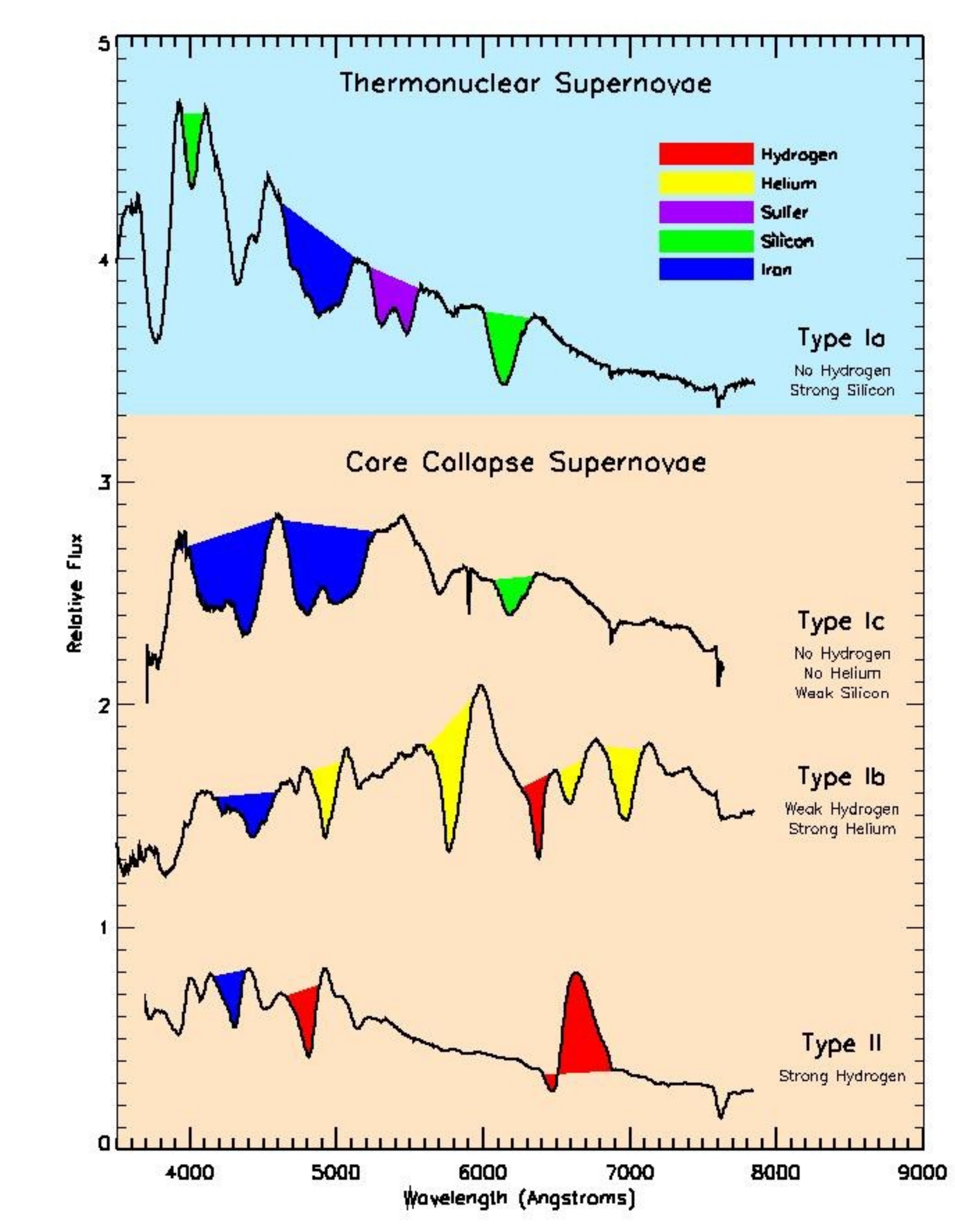
Nova V838Mon with
Hubble, May – Dec 2002

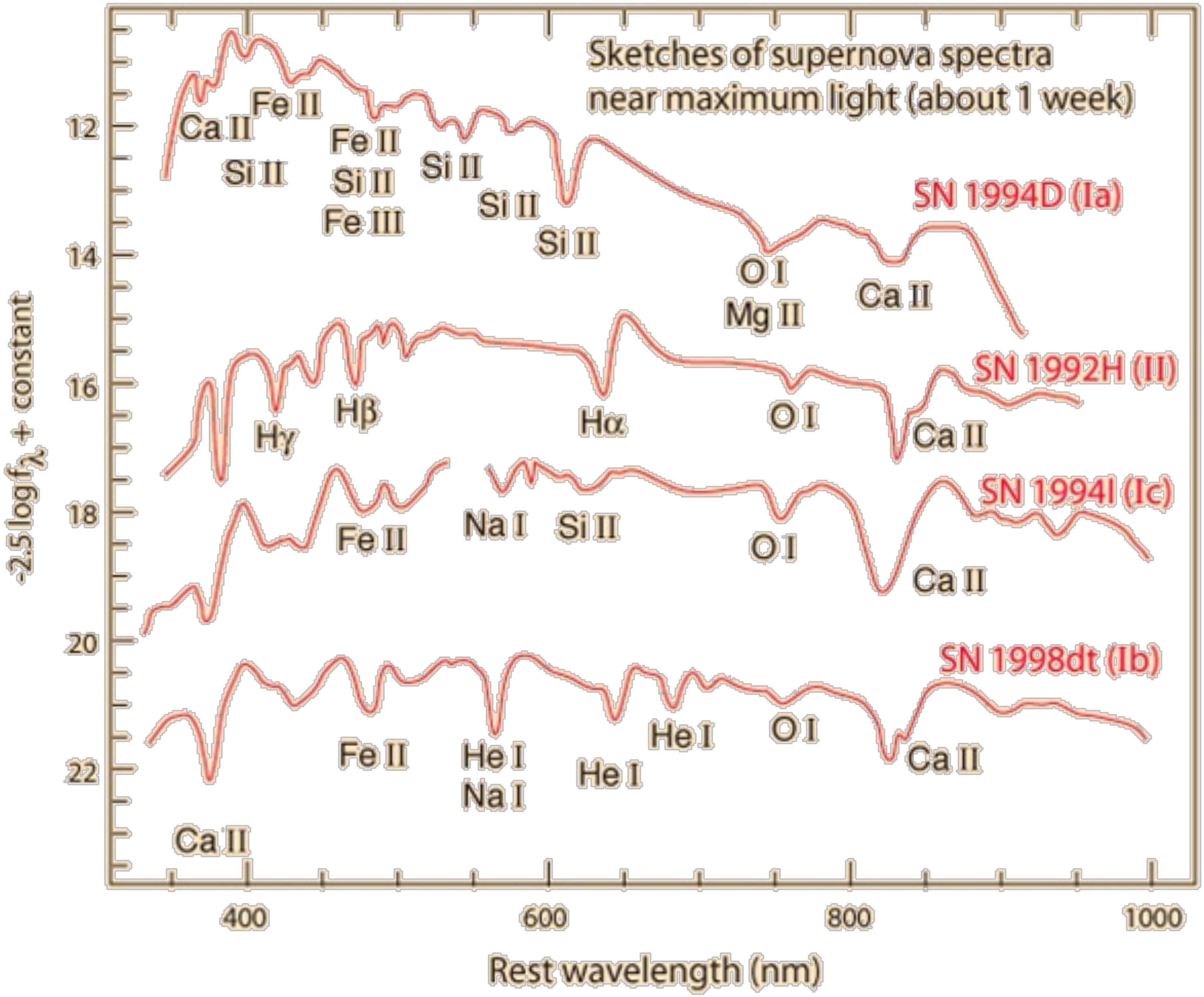
4.2 pc

RS Ophiuchi – recurrent nova



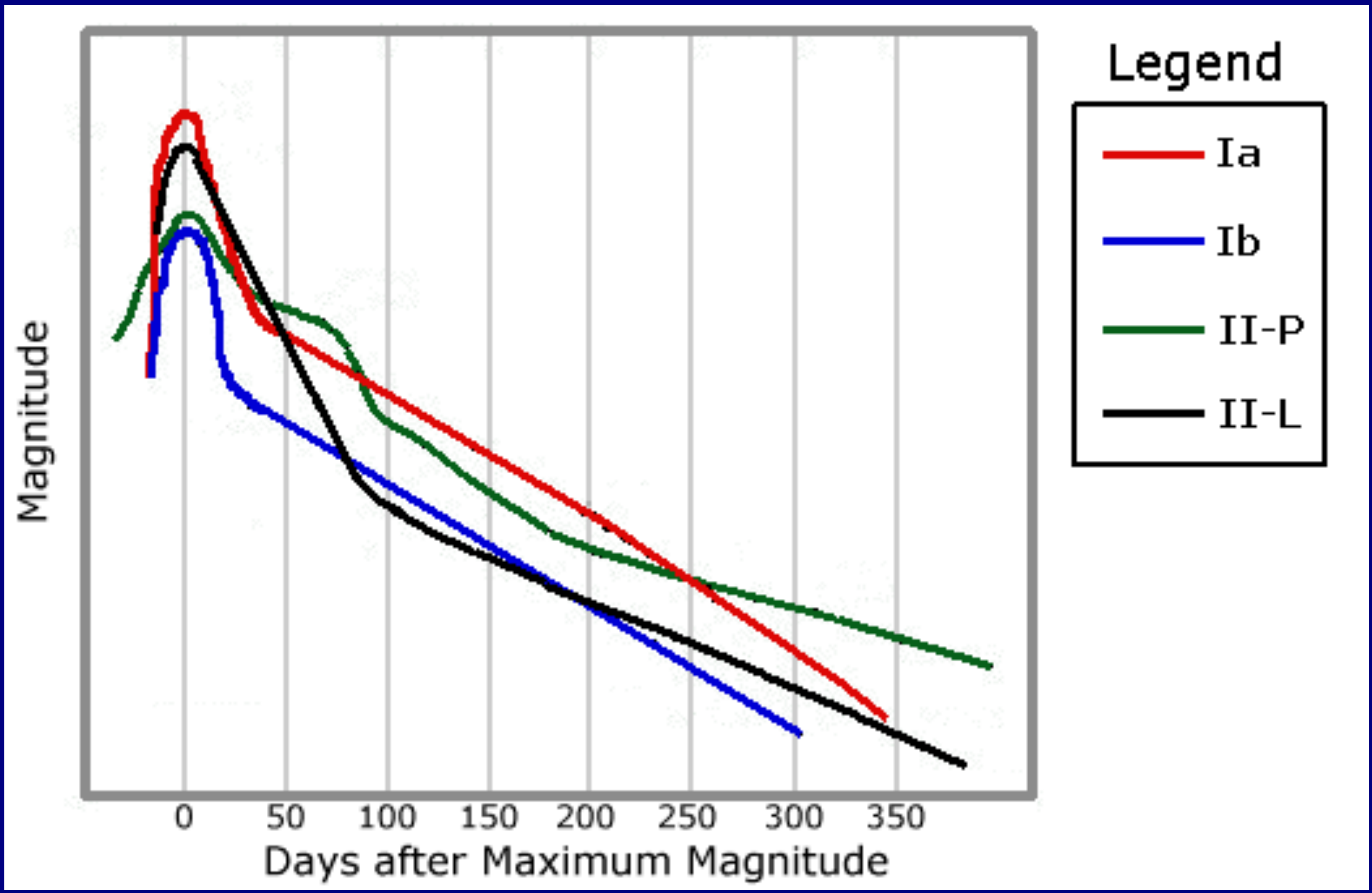
Supernova Spectra





Sketches of spectra from Carroll & Ostlie, data attributed to Thomas Matheson of National Optical Astronomy Observatory.

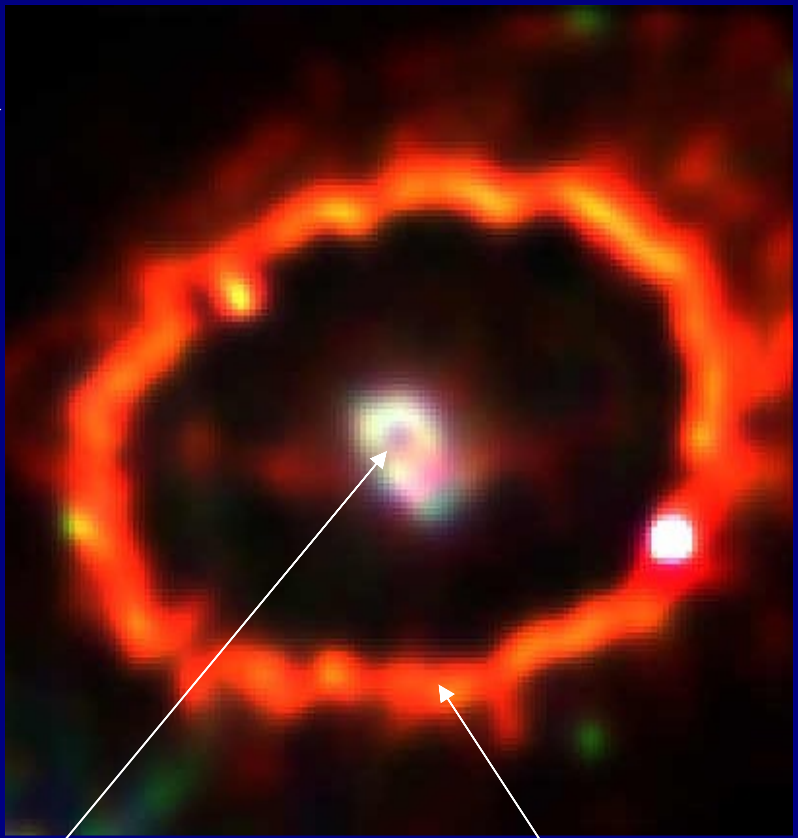
Supernova light curves



SN 1987A is evolving quickly!

1994

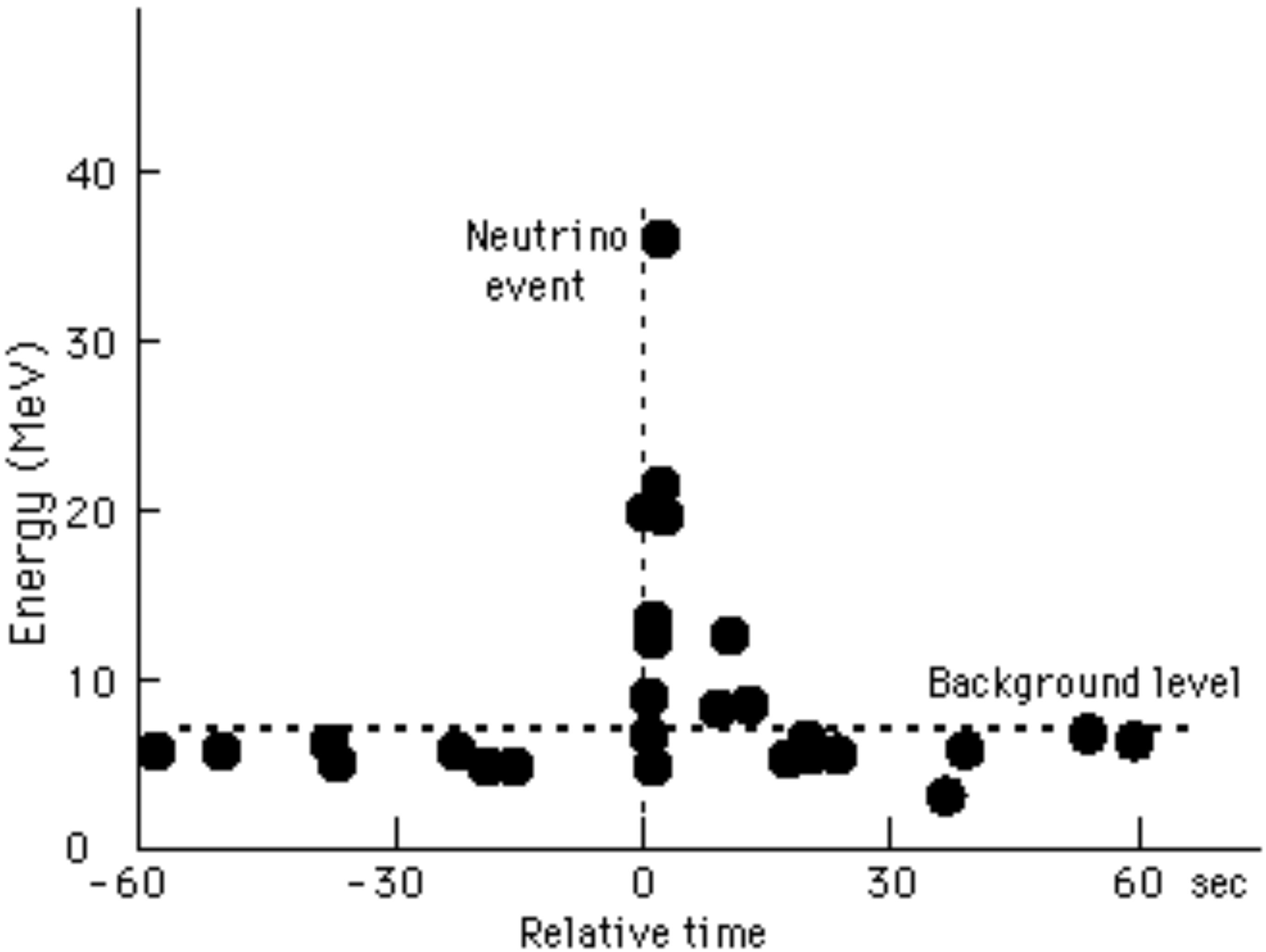
1998



Expanding debris from star. Speed almost 3000 km/sec!

Light from supernova hitting ring of gas, probably a shell from earlier mass loss event.

Neutrinos from SN1987A



Kamiokande II: 11
IMB: 8
Baksan: 5

All in 13 seconds
Arriving ~2 hours
Before optical light

Making elements beyond iron – neutron capture

If stellar nucleosynthesis creates elements with atomic weights up to iron, where do heavier elements come from?

In supernovae, we create plenty of free neutrons, while in normal stellar evolution, some reactions also create them. This makes possible:

$$ {}^{A}_{Z}X + n \rightarrow {}^{A+1}_{Z}X + \gamma \quad \text{(no Coulomb barrier)} $$

New nucleus is either stable (=> new isotope) or unstable and undergoes "β-decay"

$$ n \rightarrow p + e^{-} + \bar{\nu}_e $$

If unstable, two limits:

1) If β-decay time << n-capture timescale, β-decay occurs first:

$$ {}^{A}_{Z}X \rightarrow {}^{A+1}_{Z+1}X + e^{-} + \overline{\nu_e} + \gamma $$

"s process". Happens during stellar evolution.

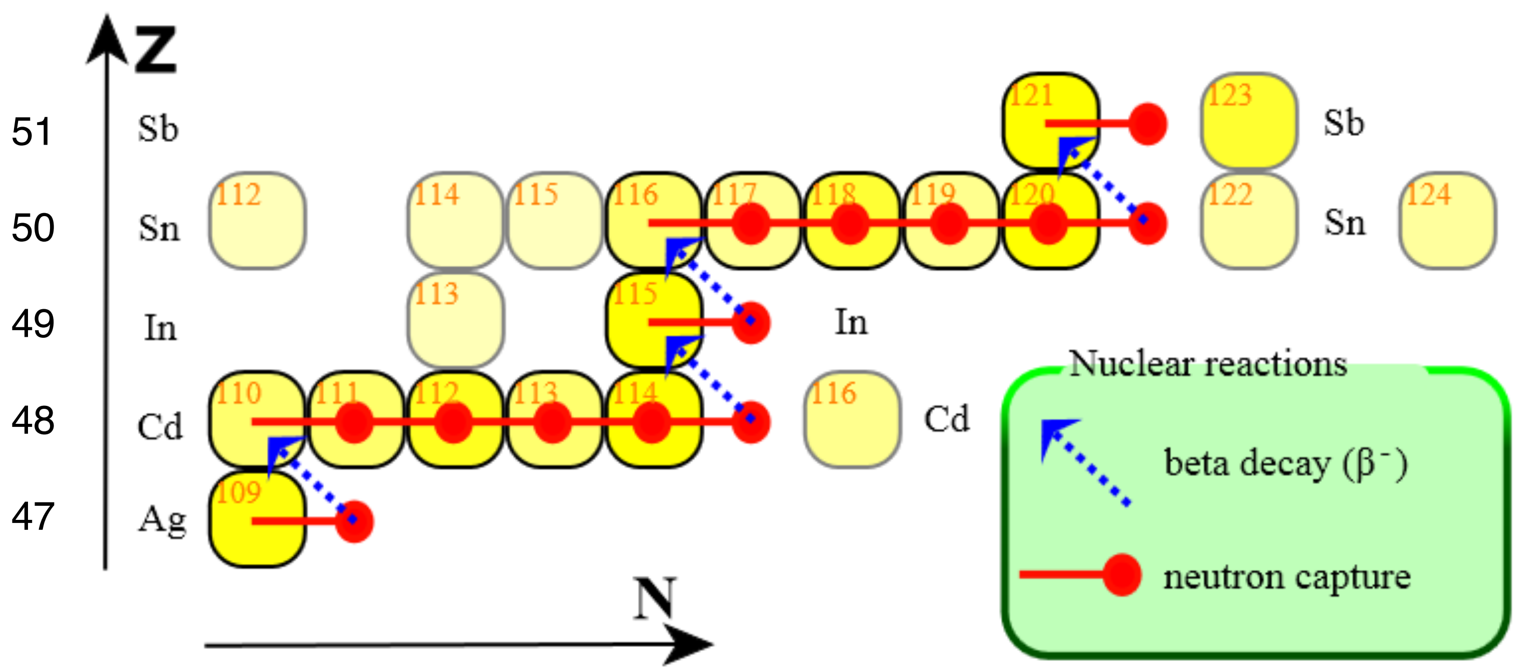
2) If n-capture timescale << β-decay time, add more n's until isotope with short decay time reached, and then it will undergo β-decay:

$$^{A+i}_{Z}X \rightarrow \, ^{A+i}_{Z+1}X + e^{-} + \bar{\upsilon}_e$$

until a stable isotope is reached

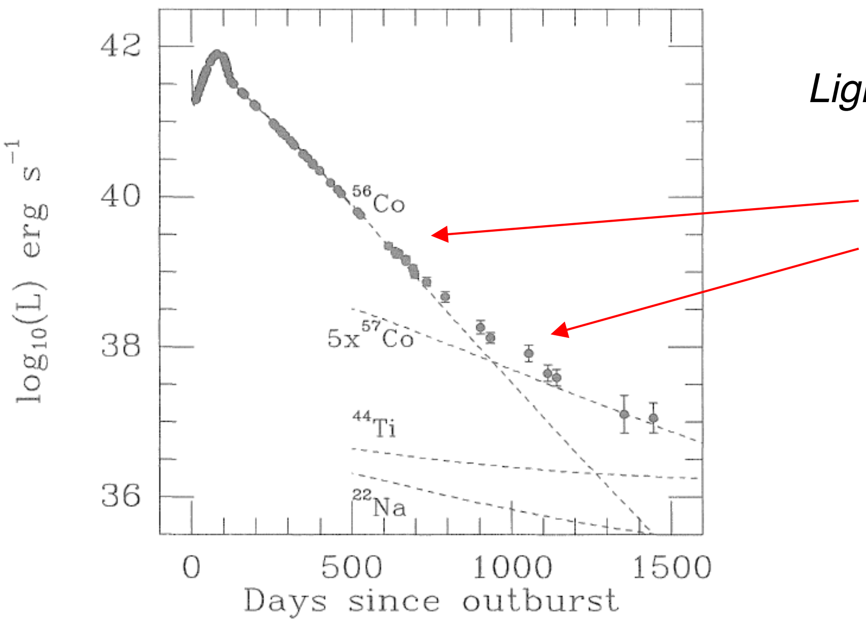
"r process" => n-rich but stable isotopes. Happens in supernovae.

Example of some elements and isotopes produced by s-process:



but, e.g. $^{122}_{50}Sn$, $^{124}_{50}Sn$ can only be made by r-process

Supernova light curves and radioactive decay



Light curve of SN 1987a

Eventually, envelope cooled and dimmed, so that light was dominated by exponential decay of other radioactive isotopes

Radioactive elements produced by fusion in the shock front. Decay:

$$^{56}_{28}Ni \rightarrow {}^{56}_{27}Co + e^+ + \nu_e + \gamma$$ Half life: 6 days

$$^{56}_{27}Co \rightarrow {}^{56}_{26}Fe + e^+ + \nu_e + \gamma$$ Half life: 78 days

$$^{57}_{27}Co \rightarrow {}^{57}_{26}Fe + e^+ + \nu_e + \gamma$$ Half life: 272 days

etc. Shape of light curve depends on abundances, so we can identify responsible elements => can work out how much produced.

Cosmic rays

Discovered by Victor Hess in 1912

Cosmic rays are high energy particles producing radiation when interacting with the atmosphere of the Earth.

What are they?

Solar particles

Supernova accelerated particles

AGN???