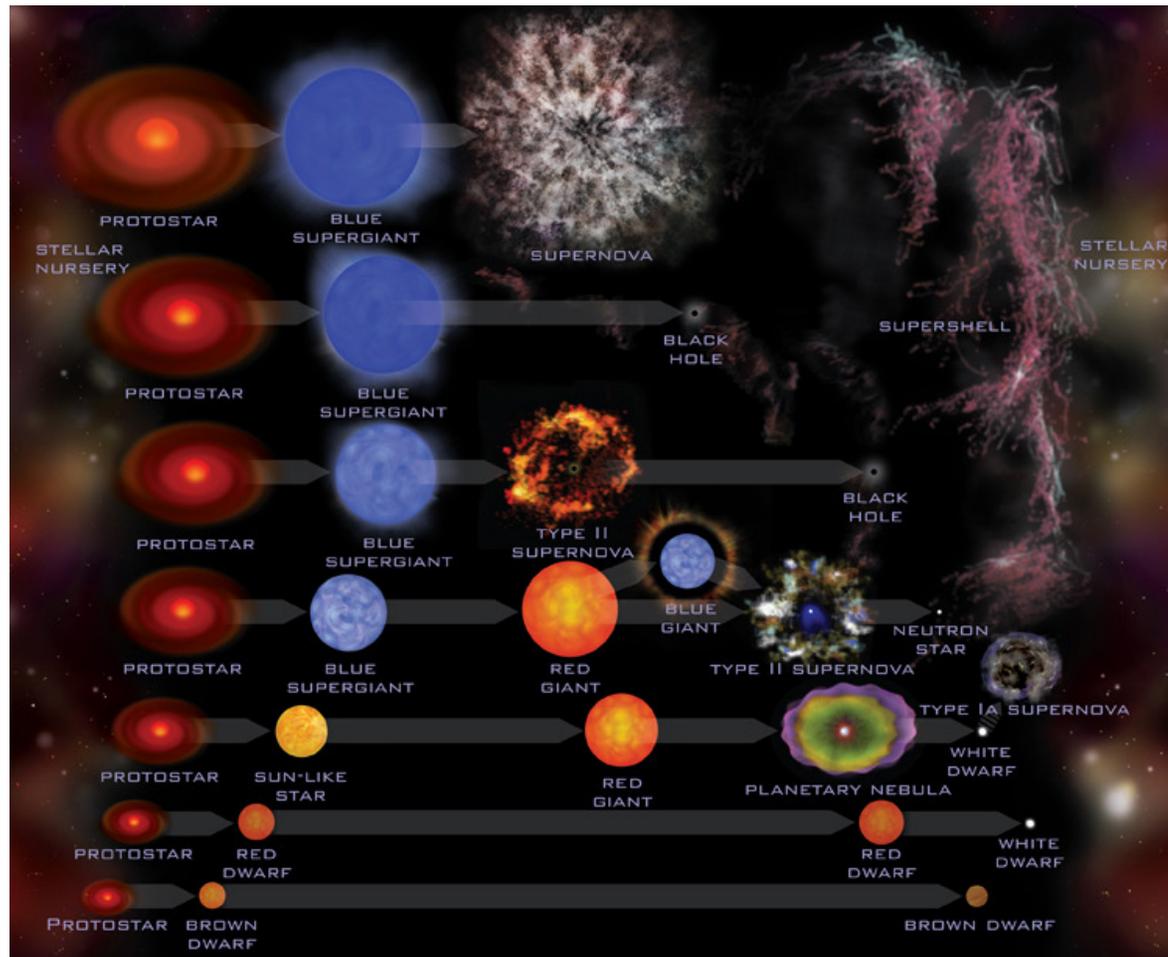# Astronomy 421

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

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

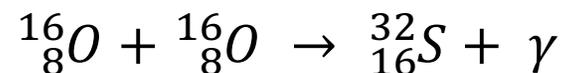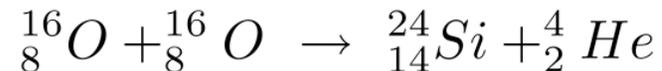   => high core T
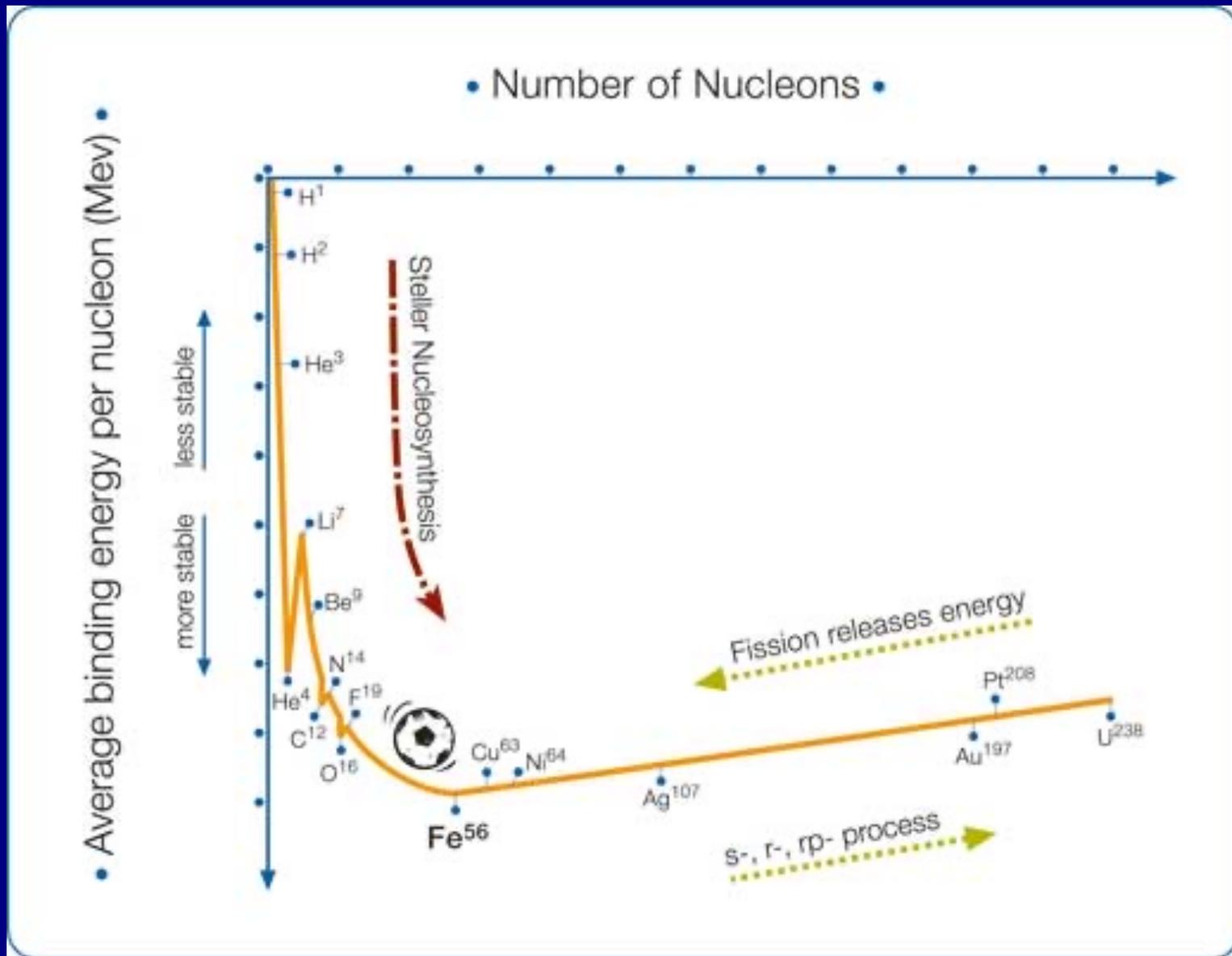
                        => rapid burning

                                => can burn beyond C,O to Fe, Ni.
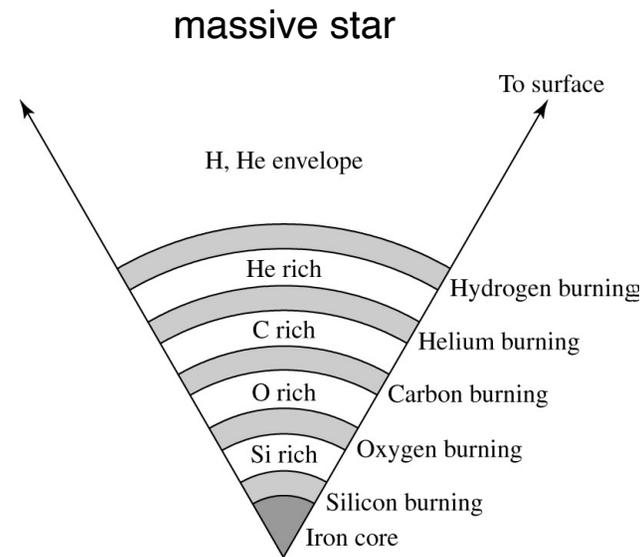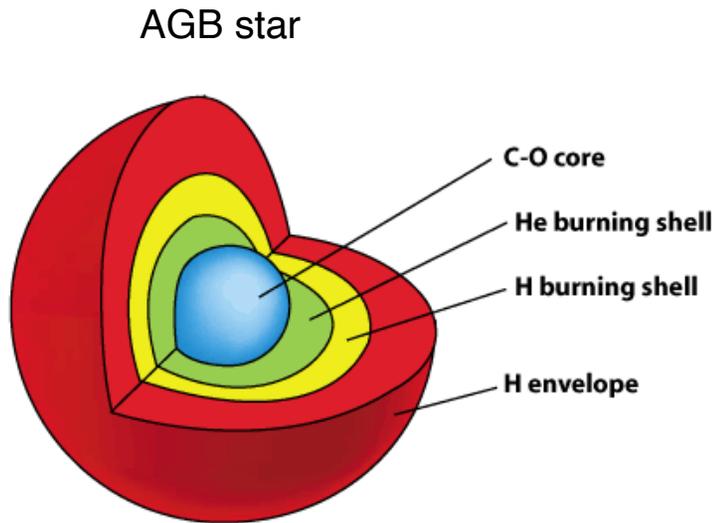
And s-process elements too (gold!)

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

20 $M_\odot$

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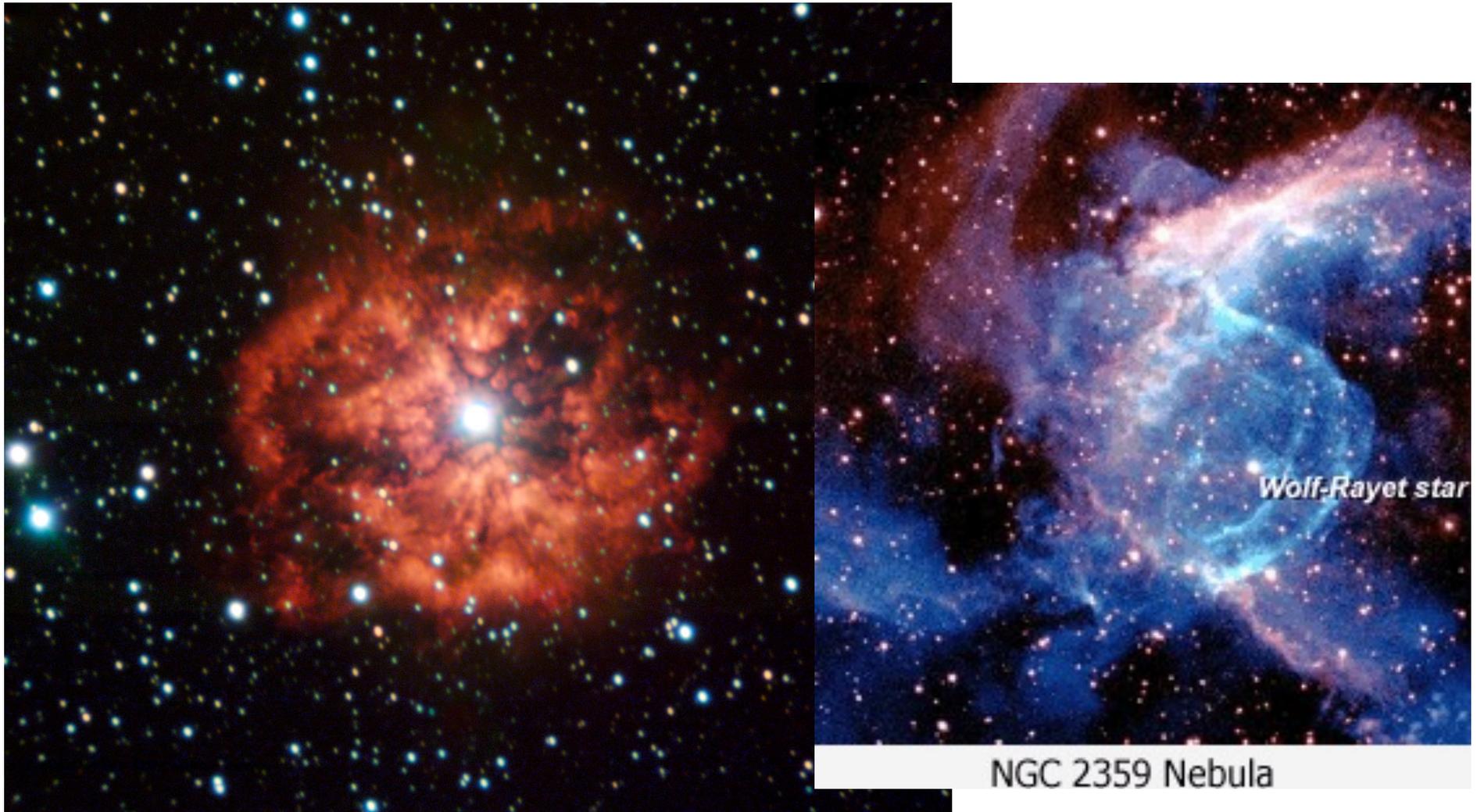
Evolution in H-R diagram at relatively constant L, to higher R and lower T_{eff}. Cores generally not degenerate – each stage starts smoothly after previous completed. Winds are significant. These plots are up to end of core He burning.
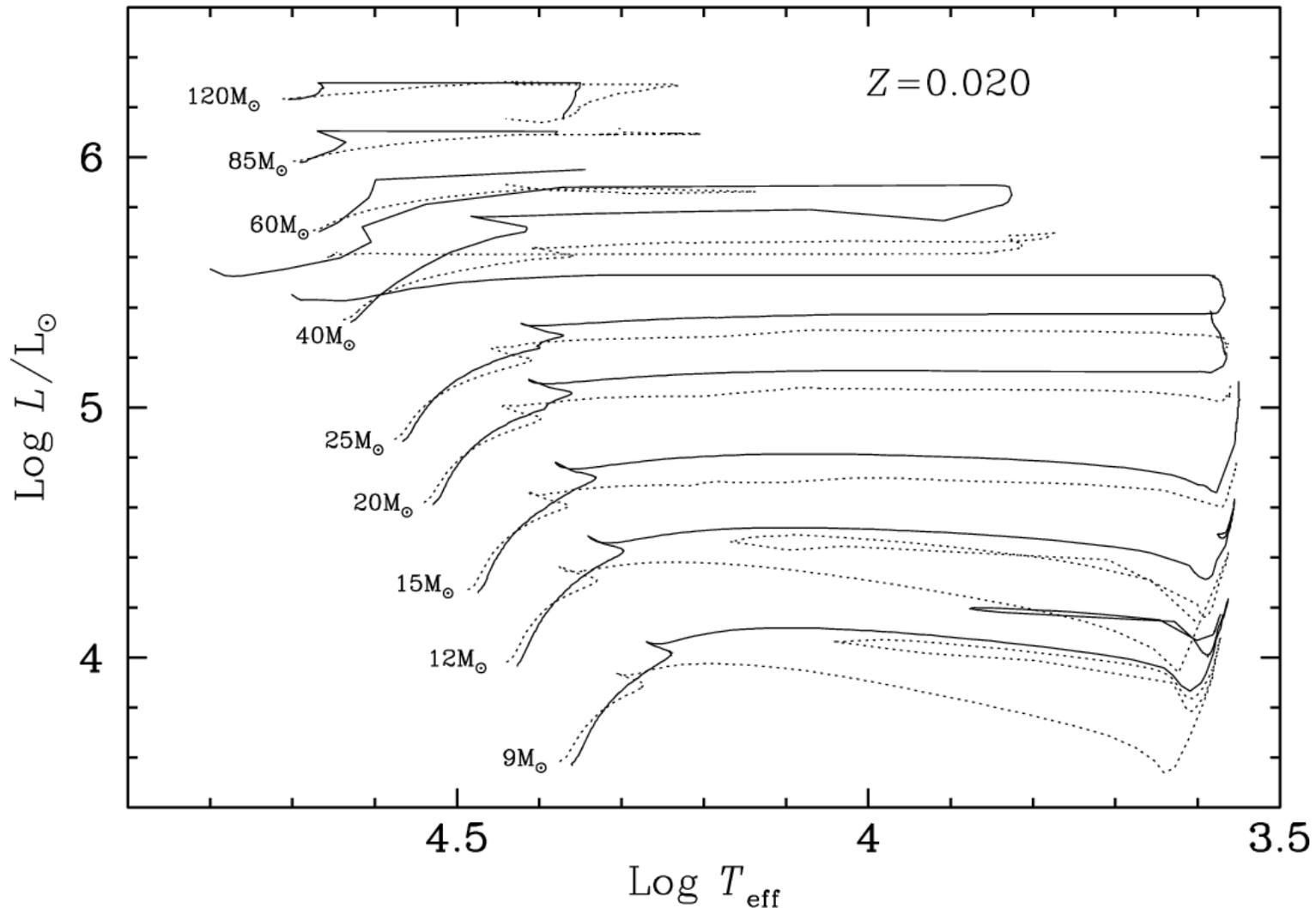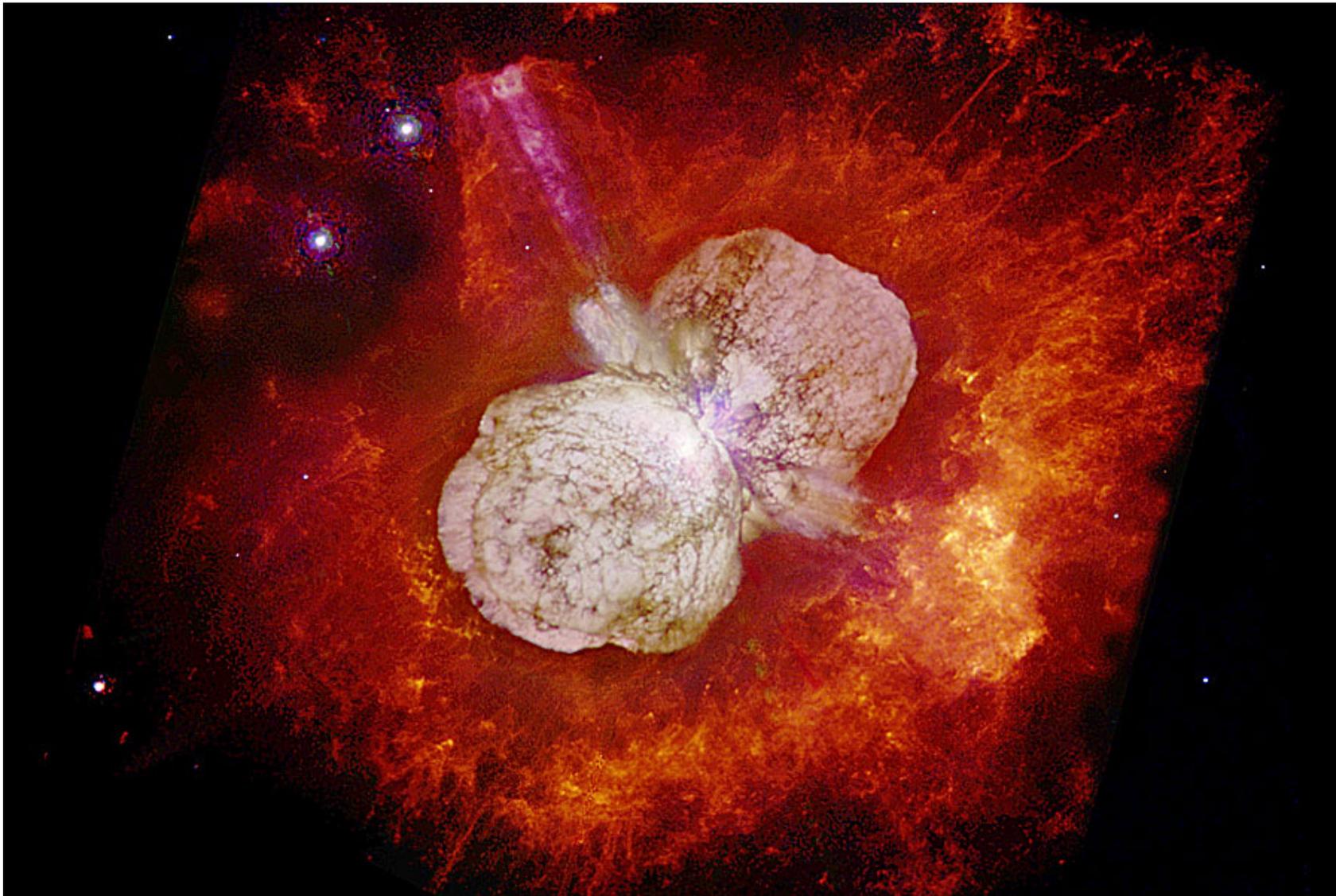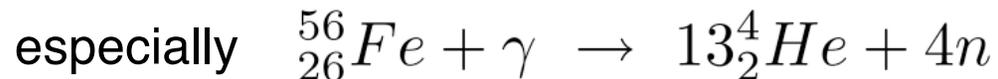
Eta Carina and the Homunculus Nebula

Wolf-Rayet Stars

Wolf-Rayet star

NGC 2359 Nebula

Core Collapse Supernovae

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

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

especially $\quad {}^{56}_{26}Fe + \gamma \;\rightarrow\; 13{}^{4}_{2}He + 4n$

$\qquad\qquad {}^{4}_{2}He + \gamma \;\rightarrow\; 2p^{+} + 2n$

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:

$E_{neutrino}$ ~ 10^{46} J

KE ~ 10^{44} J ~ 10^{51} erg ~ 1 FOE

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

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

What is left:

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

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

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

Example Supernova: 1994D in NGC 4526
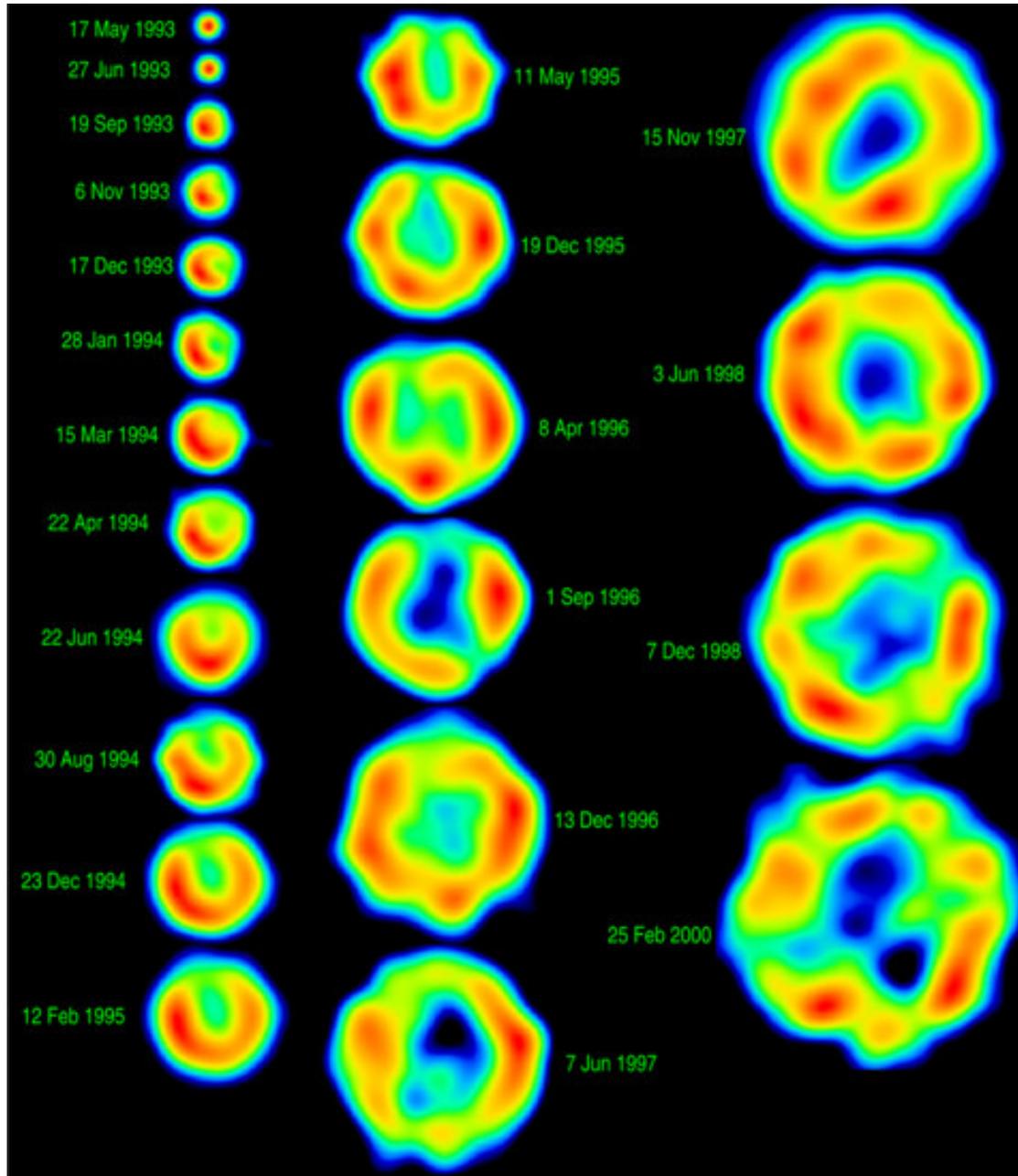
Example Supernova: 1998bw

SN 1998bw in Spiral Galaxy ESO184-G82

ESO PR Photo 39a/98 (15 October 1998)
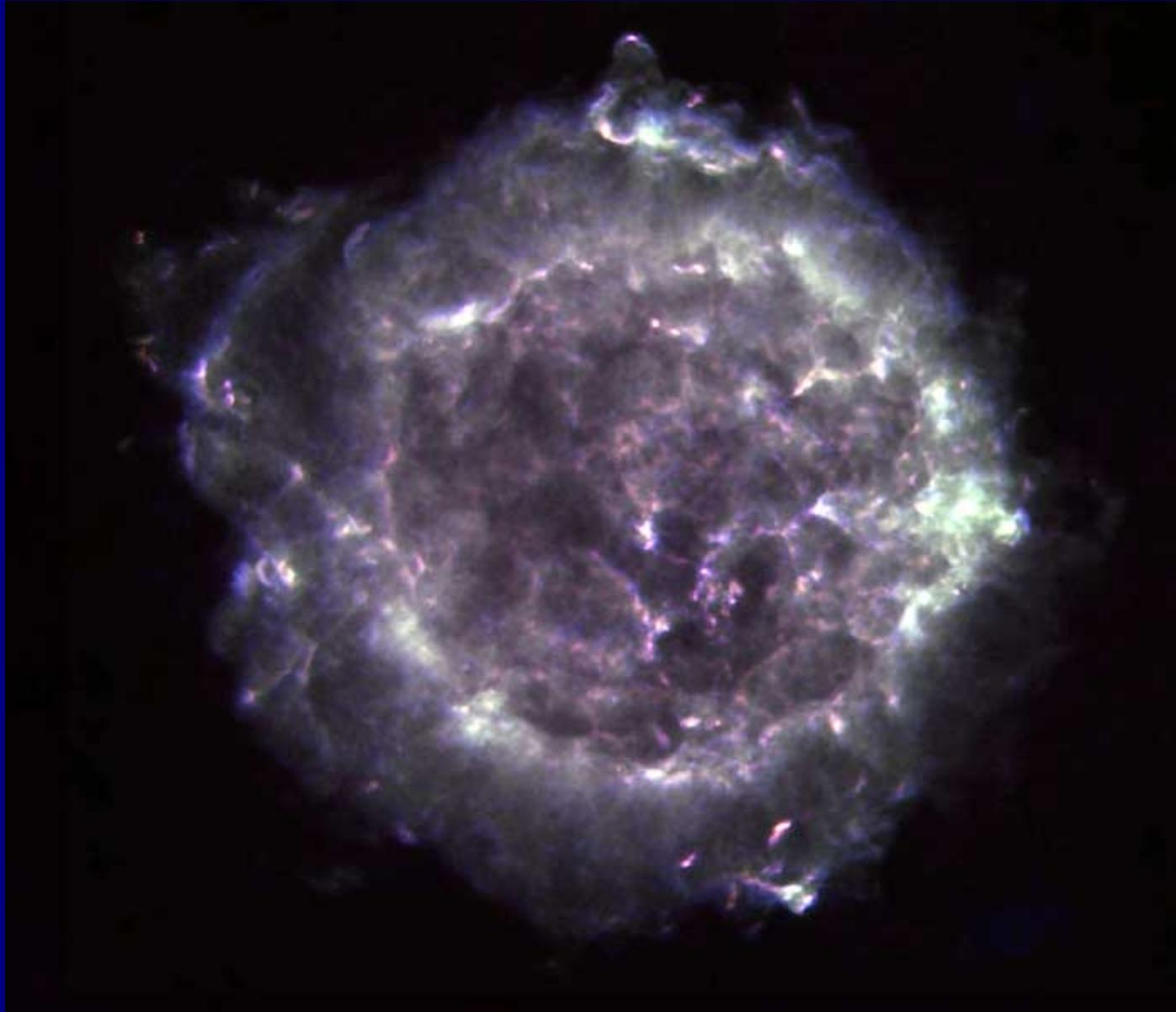
© European Southern Observatory
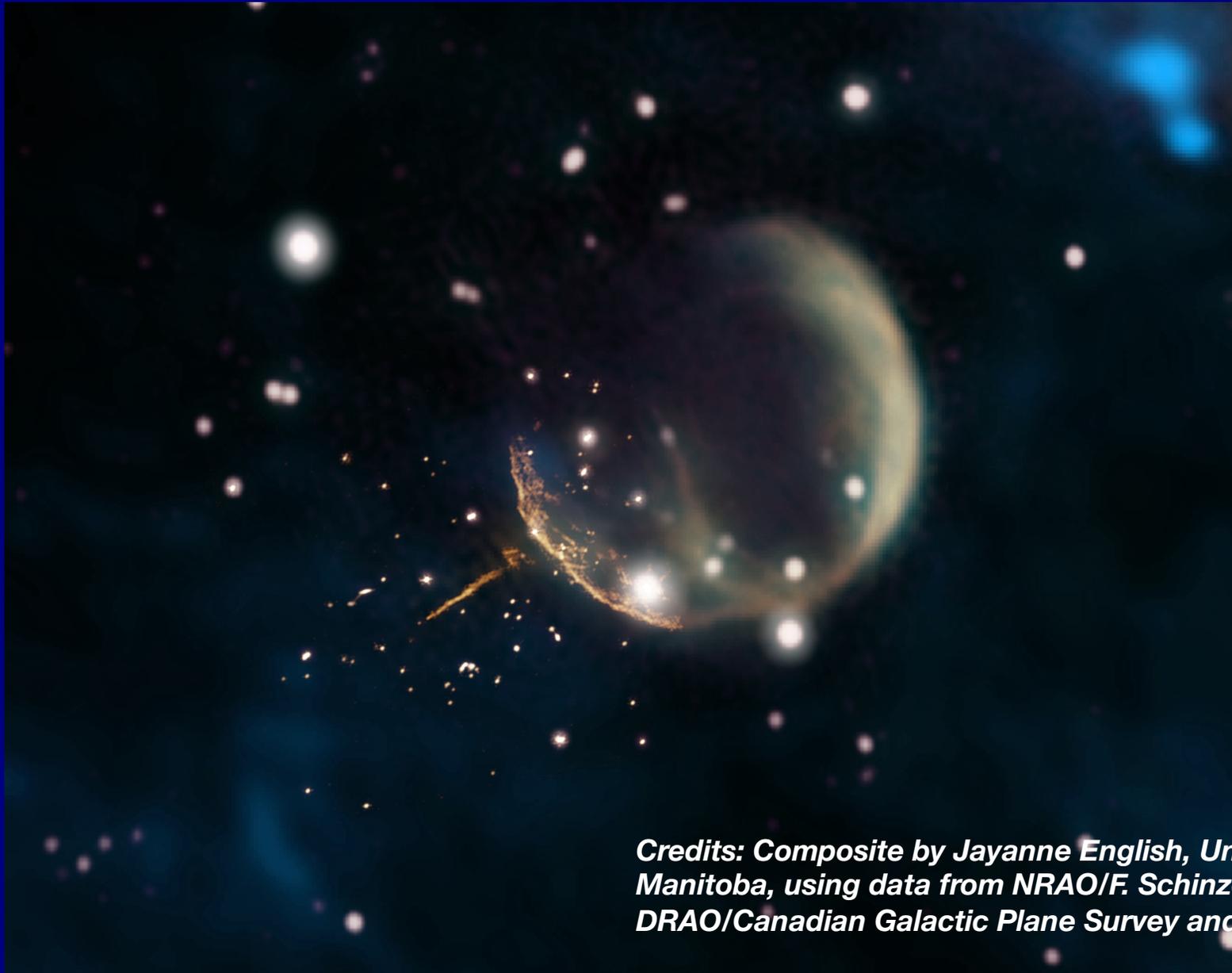
A Young Supernova
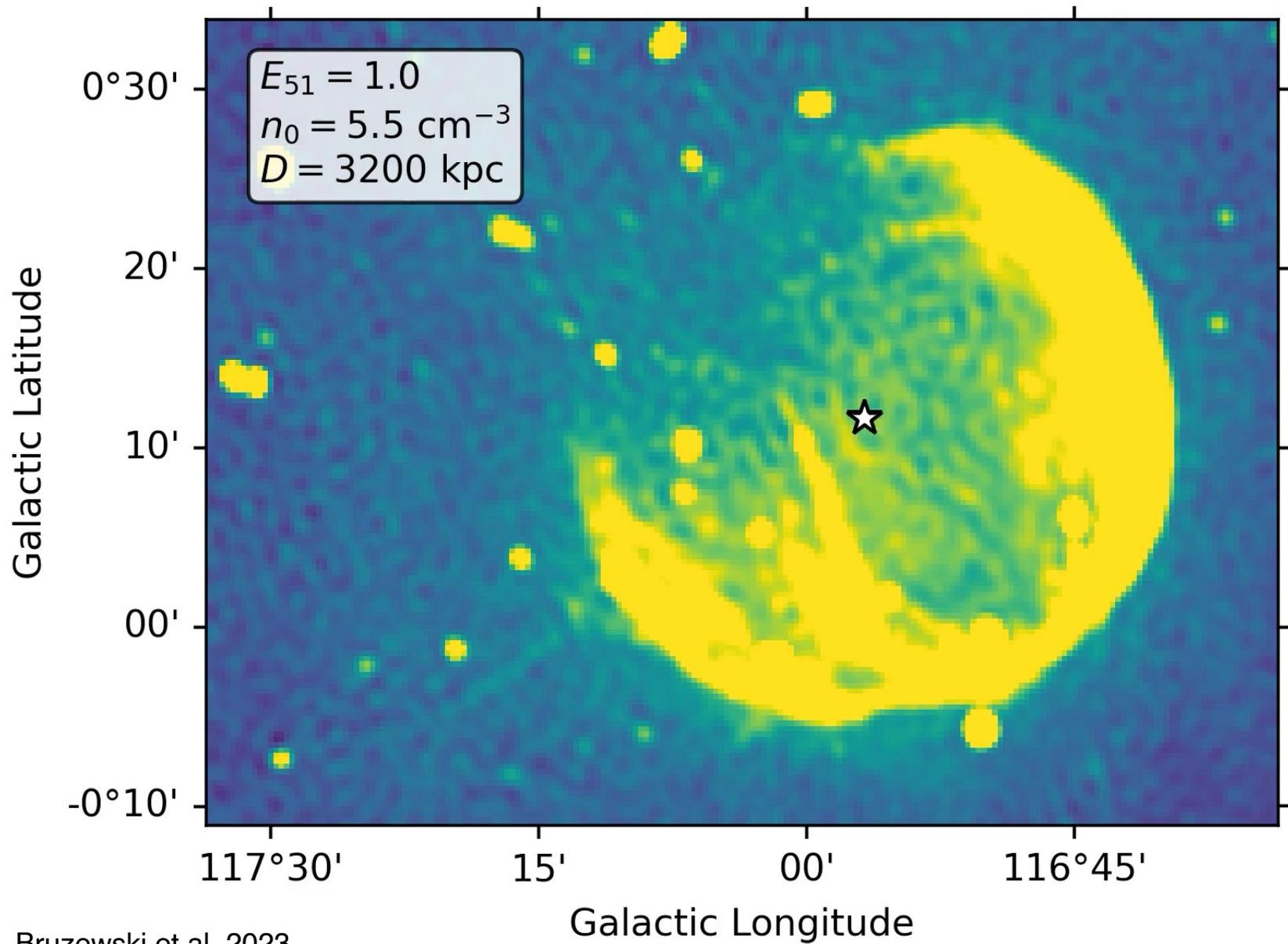

SN 1993J
Rupen et al.

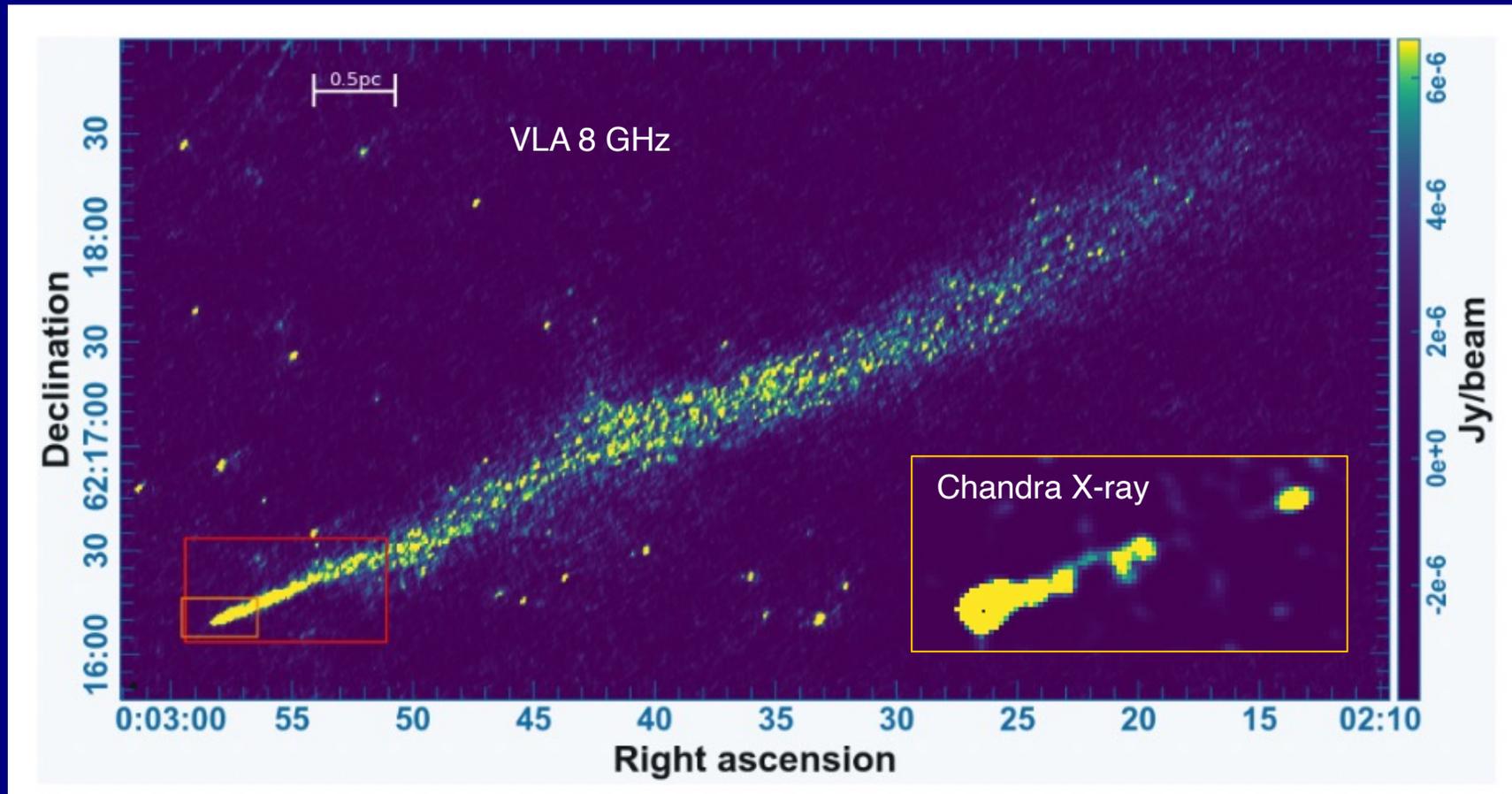# Cassiopeia A: Supernova Remnant

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

$E_{51} = 1.0$
$n_0 = 5.5 \ \mathrm{cm}^{-3}$
$D = 3200 \ \mathrm{kpc}$

Bruzewski et al. 2023

Cannonball Supernova Remnant

VLA 8 GHz

Chandra X-ray

Kumar et al. 2022

Worksheet 17

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

2 pc

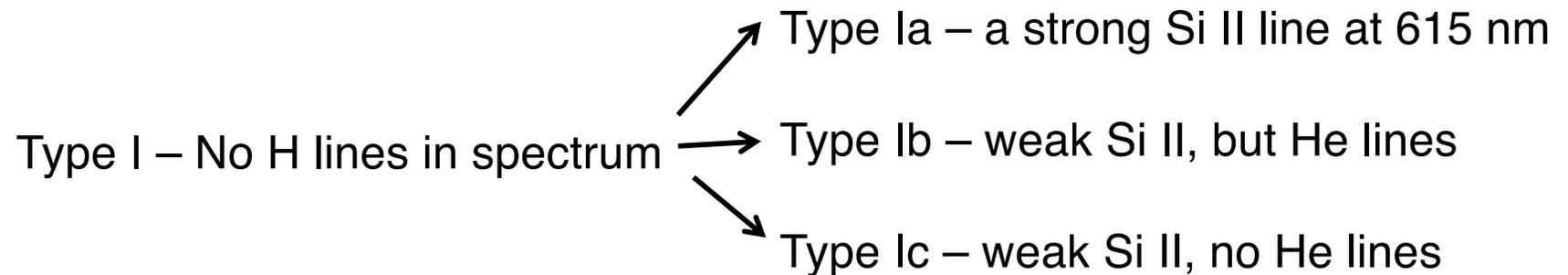Crab Nebula: debris from a stellar explosion observed in 1054 AD.

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 Ia – a strong Si II line at 615 nm

Type I – No H lines in spectrum → 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
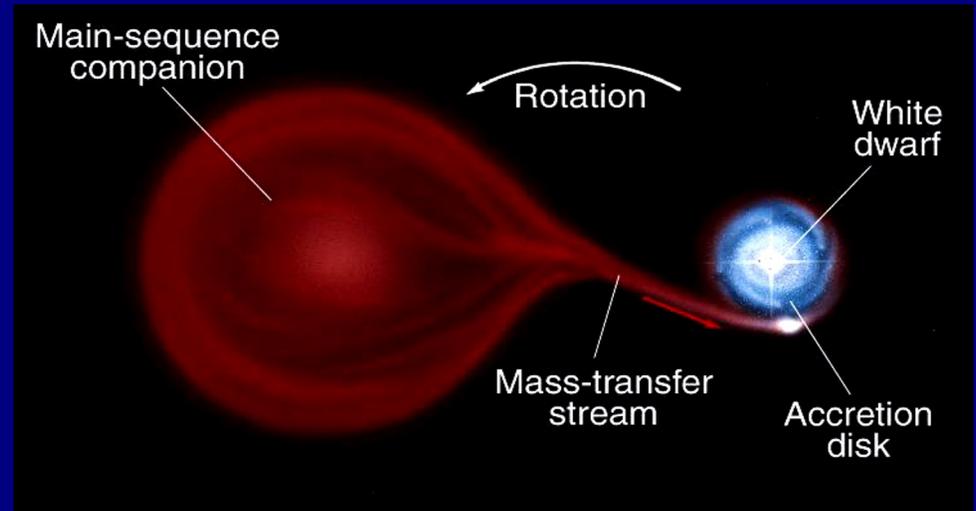Type Ib's are as well, but H envelope previously completely lost through
        winds (see Wolf-Rayet stars in C+O 15.1)
Type Ic's are as well, but also lost He shell
Type Ia's are due to accretion-induced collapse of a white dwarf in
        a close binary.

A Carbon-Detonation or "Type Ia" Supernova

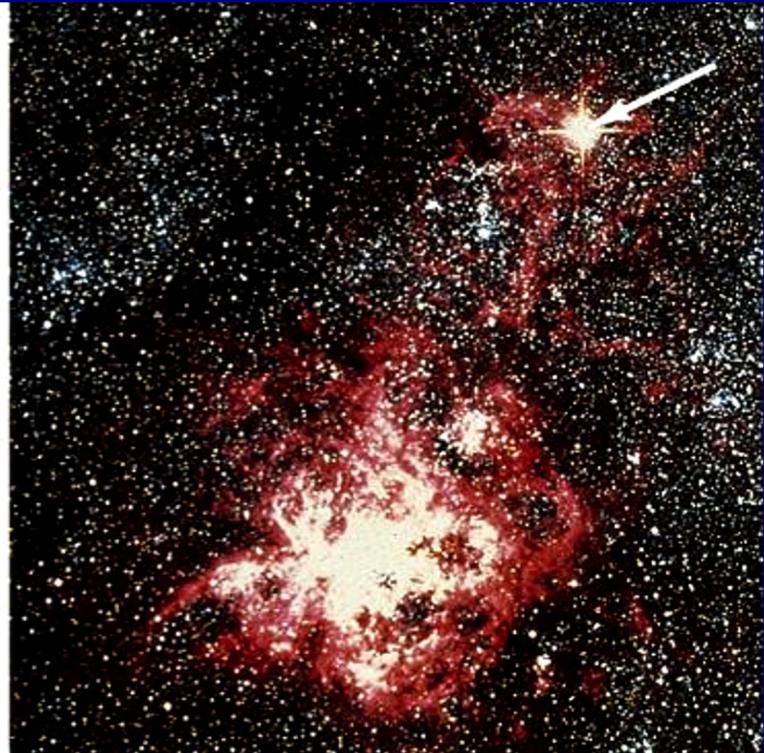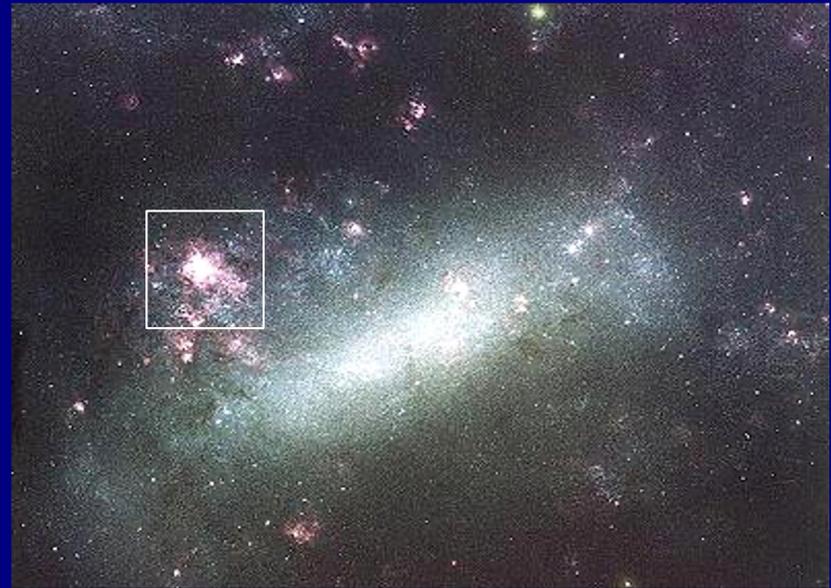Despite novae, mass continues to build up on White Dwarf.

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.

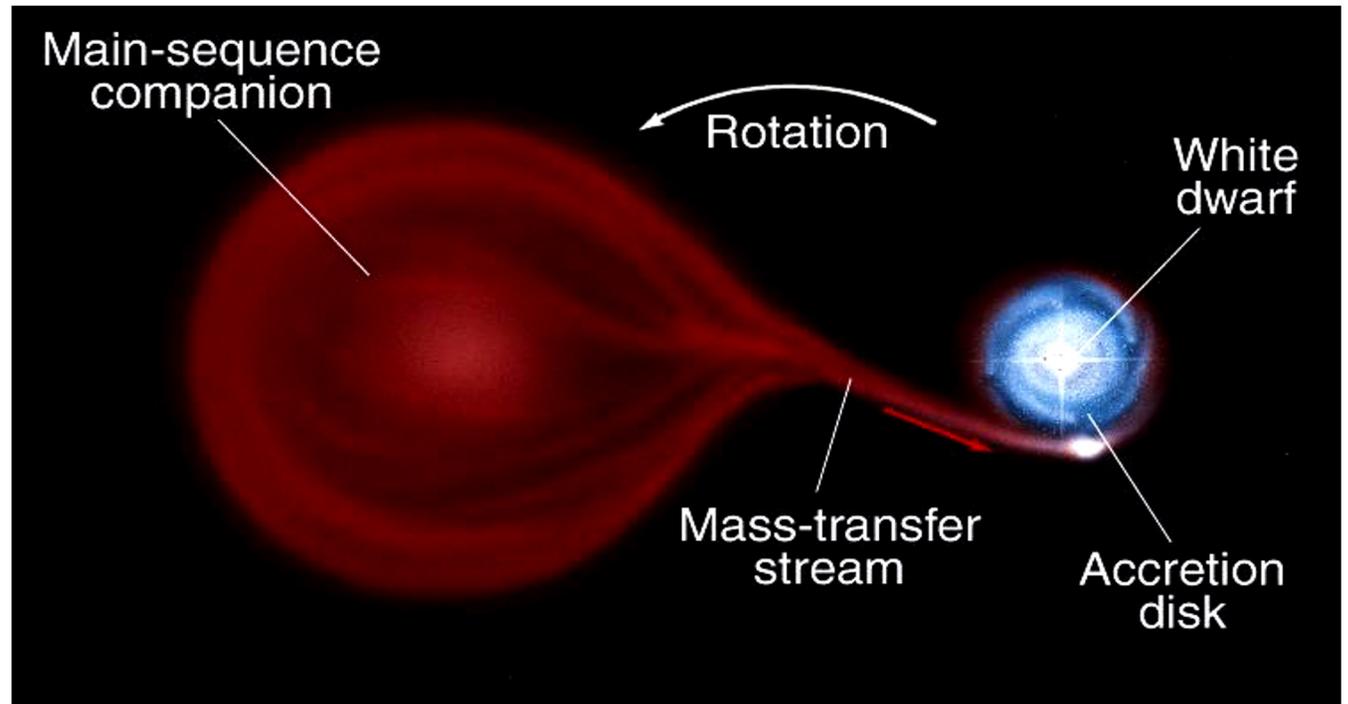Tremendous energy makes star explode. No core remnant.

Supernova 1987A in the Large Magellanic Cloud

Stellar Explosions

Novae

White dwarf in
close <u>binary</u> system

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

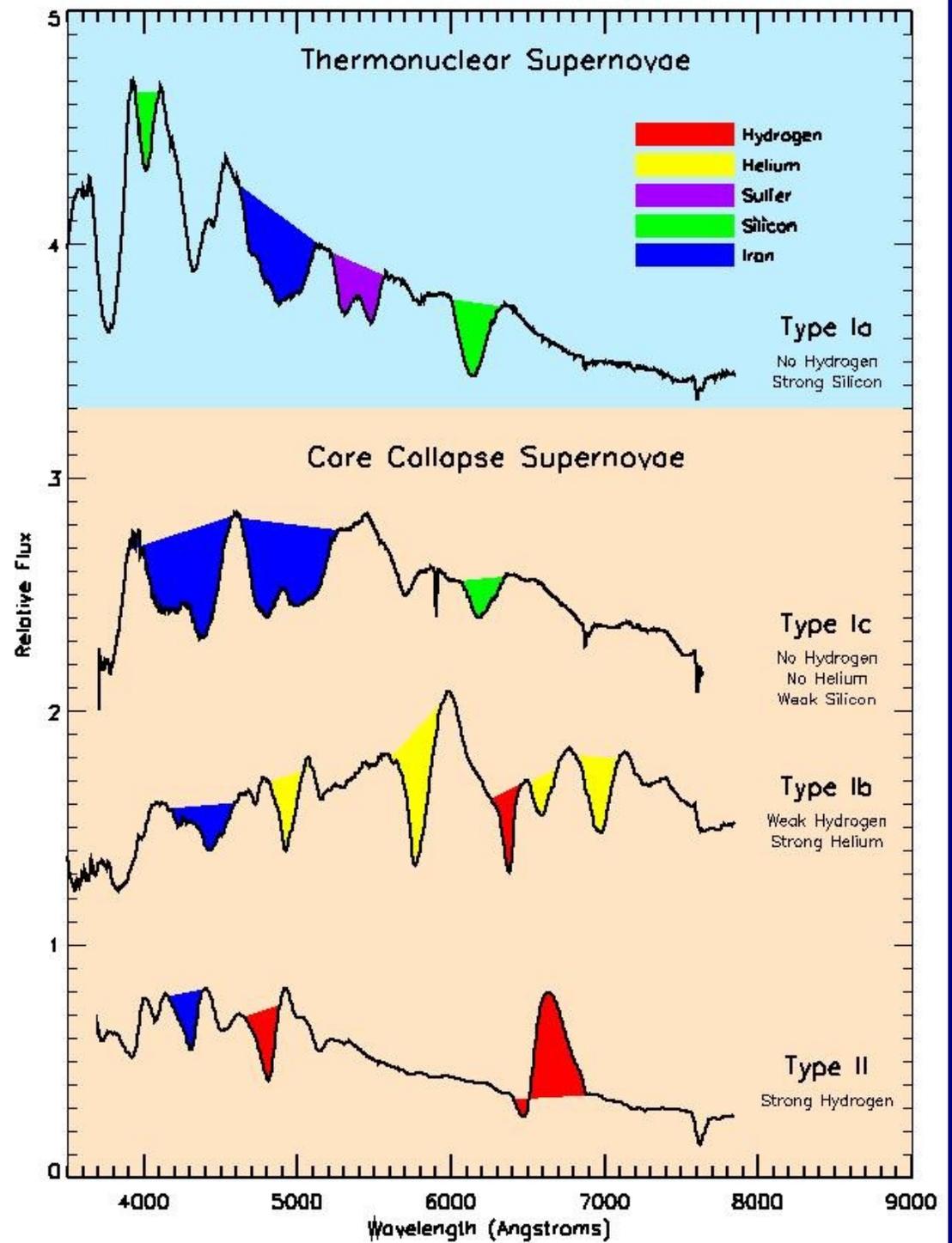Nova V838Mon with
Hubble, May – Dec 2002

4.2 pc
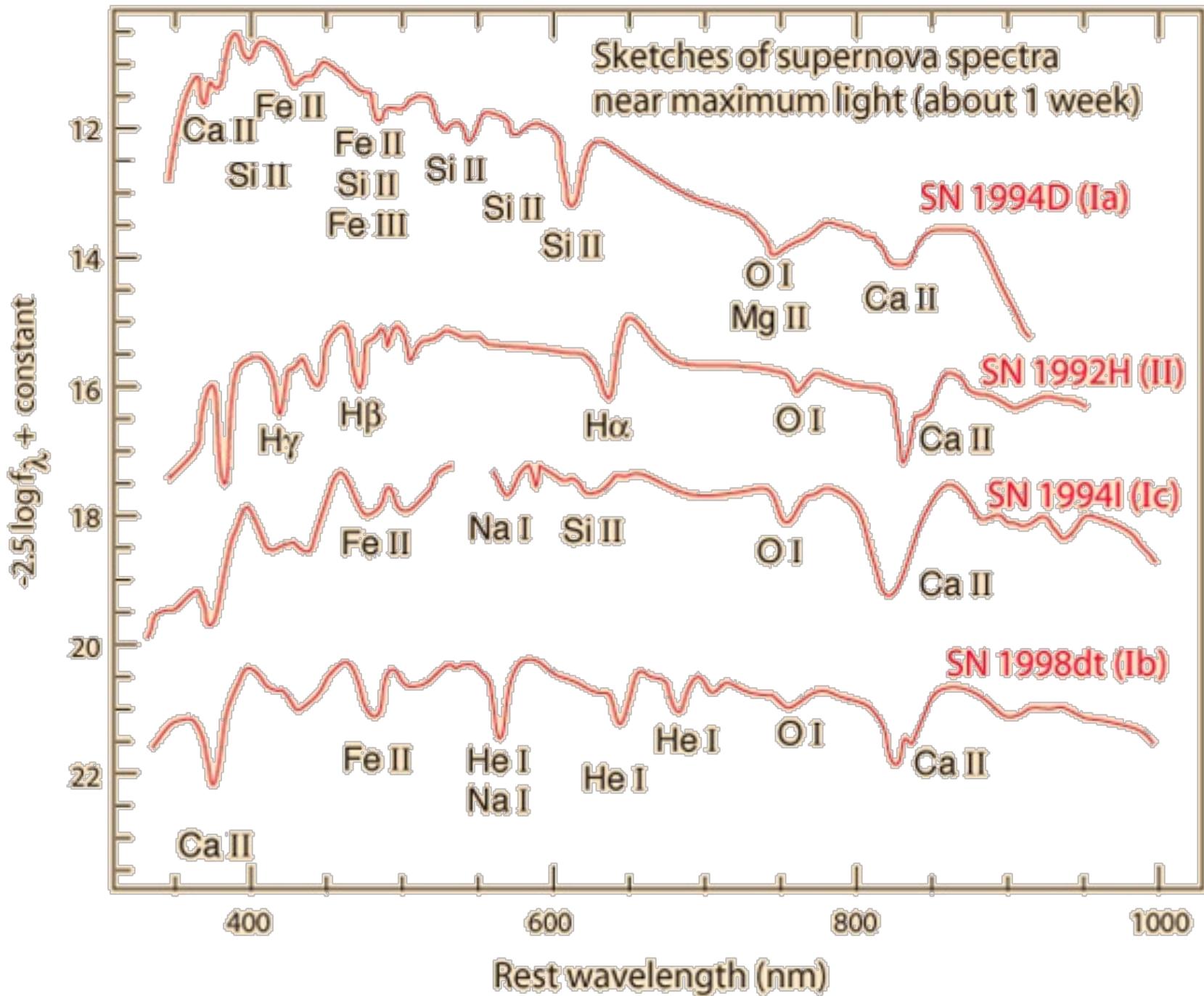
RS Ophiuchi – recurrent nova
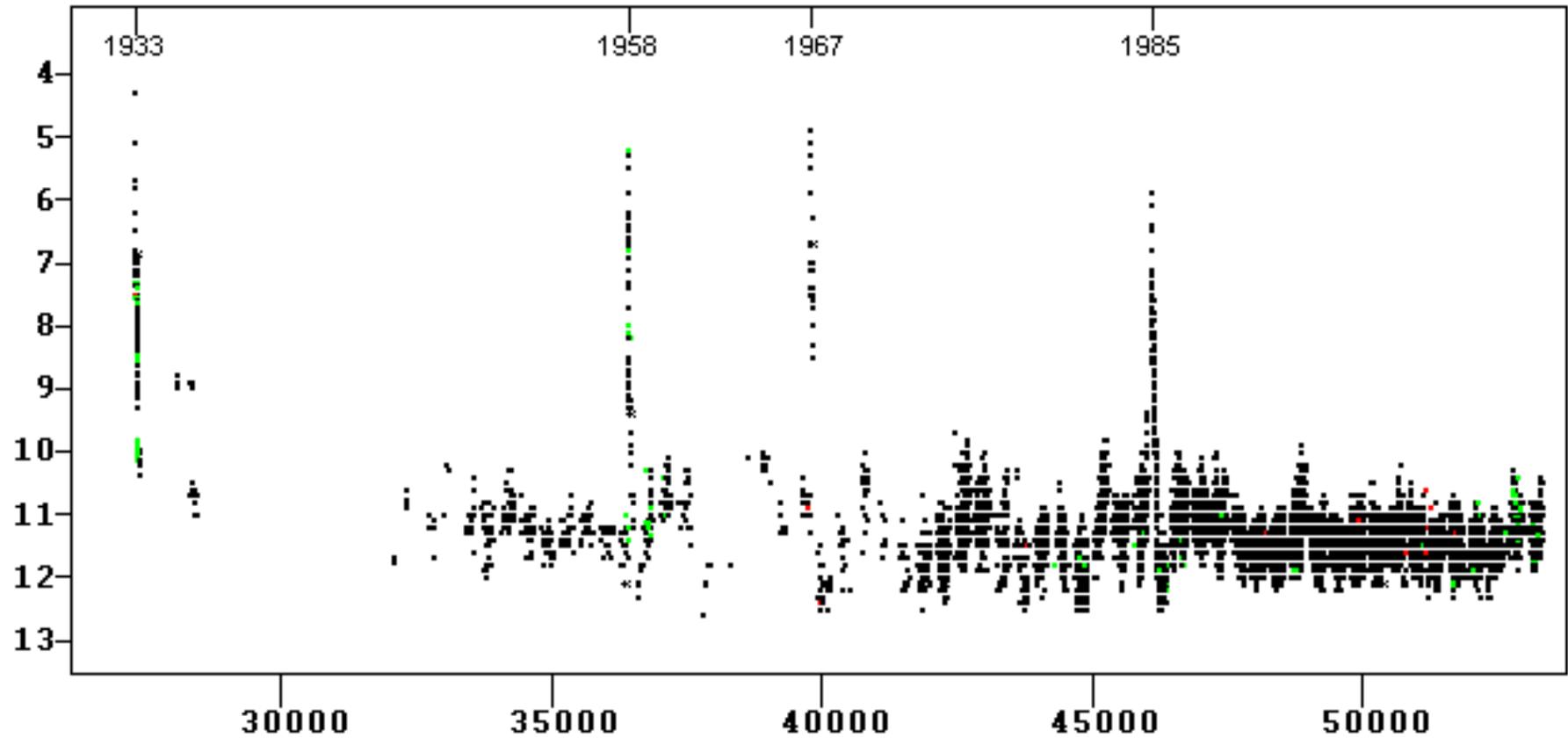
RS Ophiuchi - éruptions de 1933 - 1958 - 1967 - 1985

l'eruption de 1933 a été découverte par Eppe Loreta, membre de l'AFOEV

Supernova Spectra

Sketches of supernova spectra near maximum light (about 1 week)

SN 1994D (Ia)

Ca II · Fe II · Si II · Fe II · Si II · Fe III · Si II · Si II · Si II · O I · Mg II · Ca II

SN 1992H (II)

Hγ · Hβ · Hα · O I · Ca II

SN 1994I (Ic)

Fe II · Na I · Si II · O I · Ca II

SN 1998dt (Ib)

Fe II · He I · Na I · He I · He I · O I · Ca II · Ca II

x-axis: Rest wavelength (nm)
y-axis: $-2.5 \log f_\lambda$ + constant

Sketches of spectra from Carroll & Ostlie, data attributed to Thomas Matheson of National Optical Astronomy Observatory.
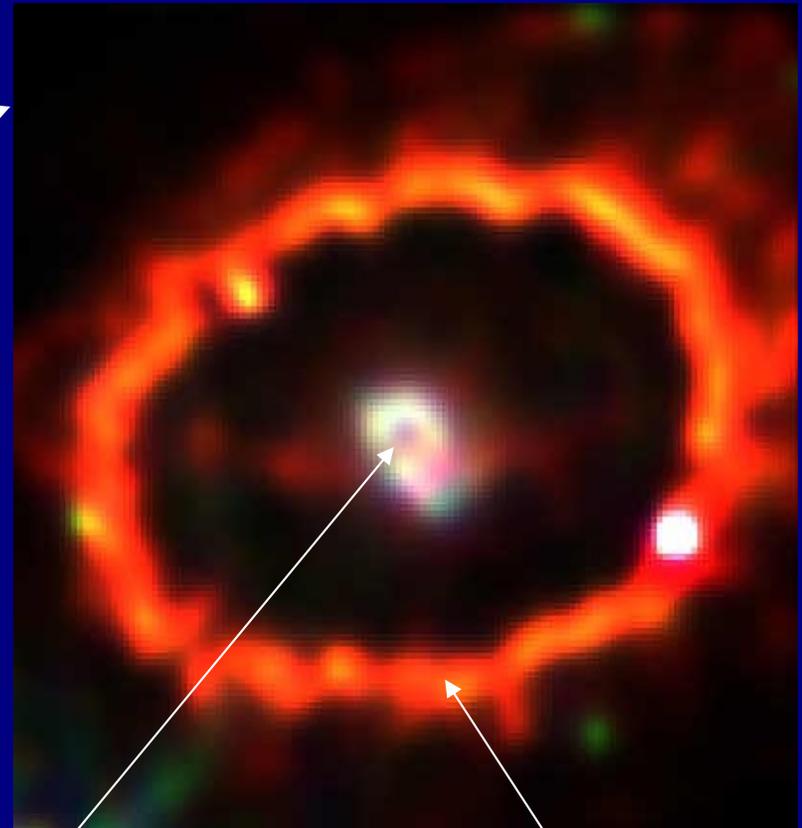
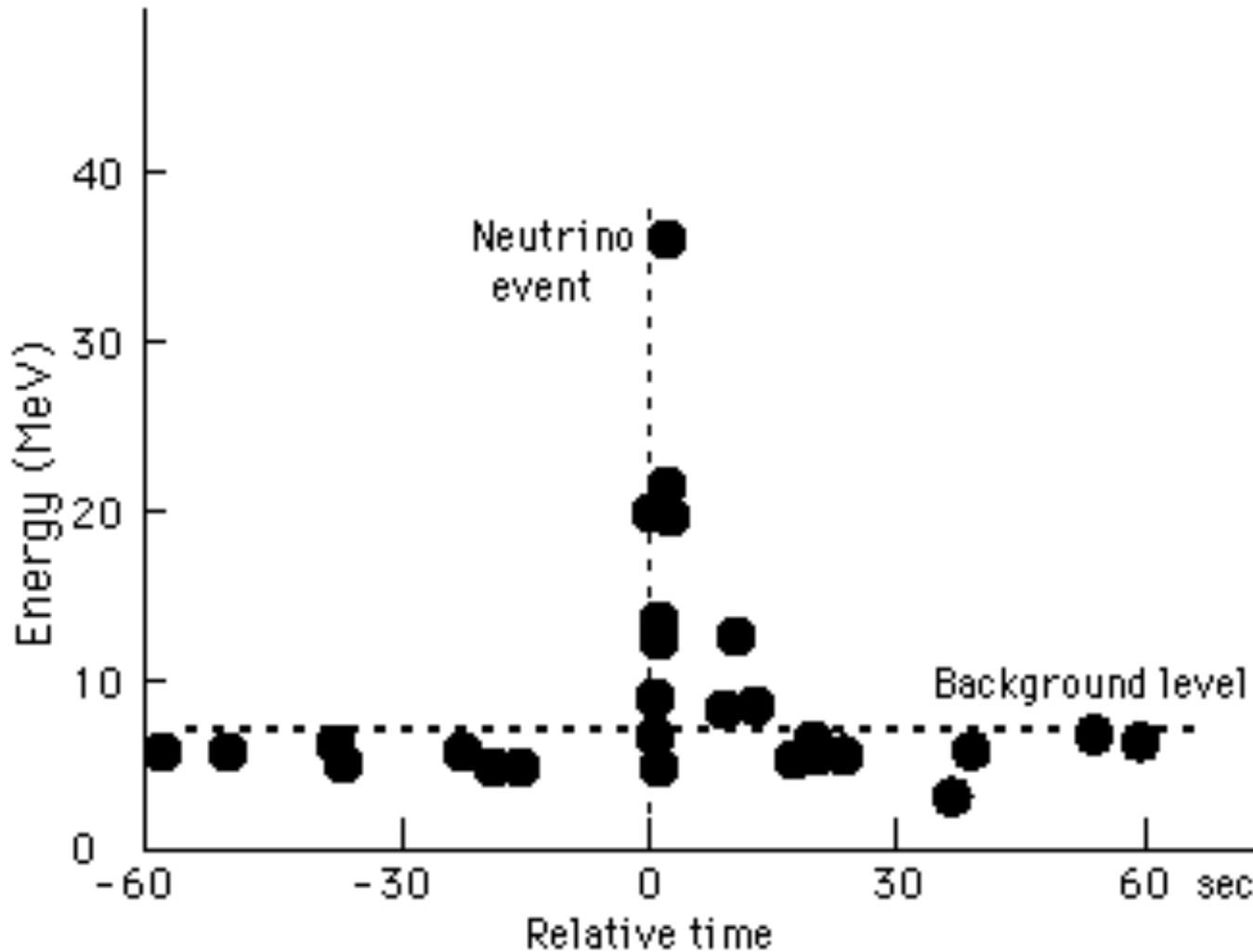# Supernova light curves
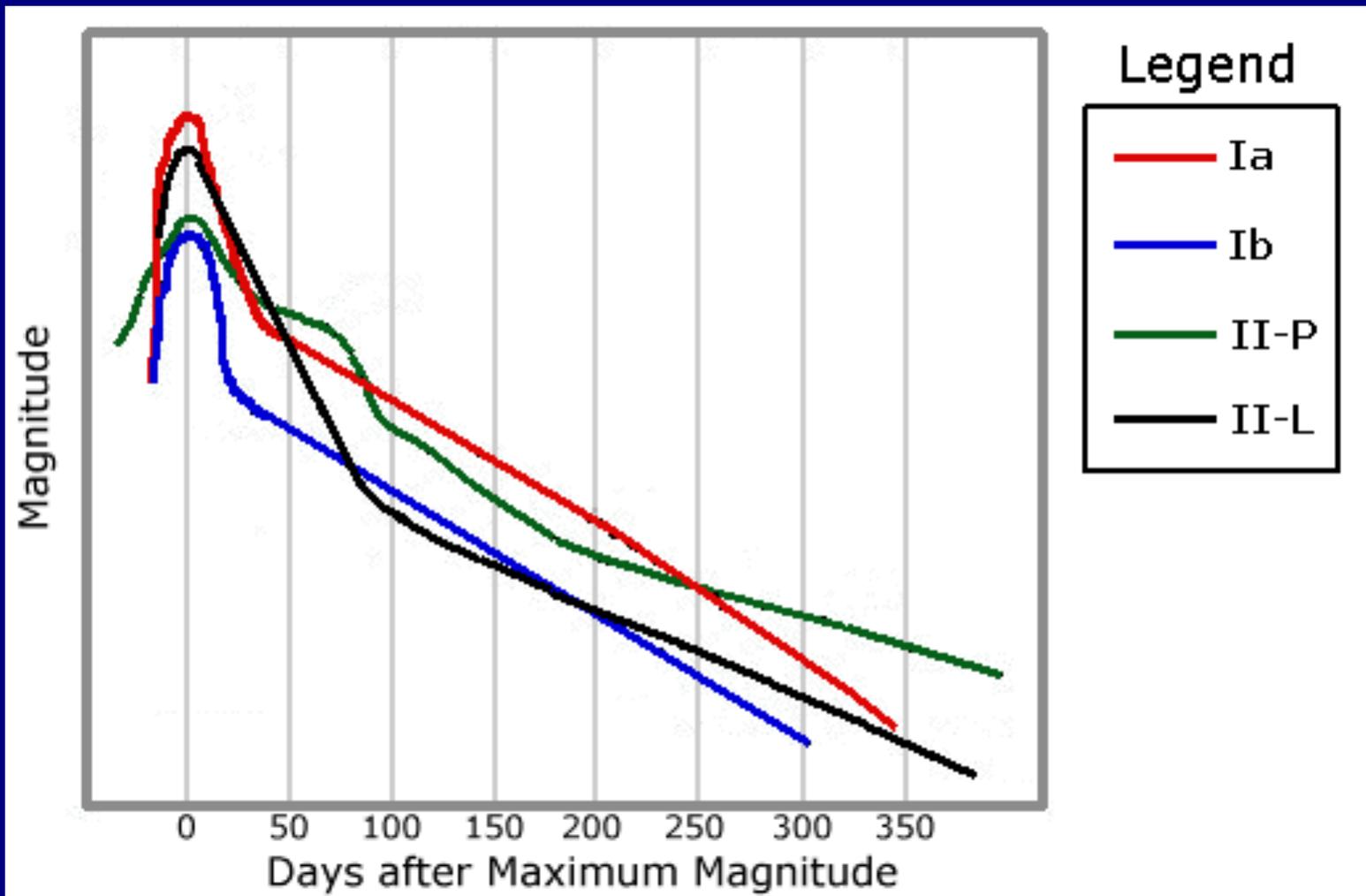
SN 1987A is evolving quickly!

1994
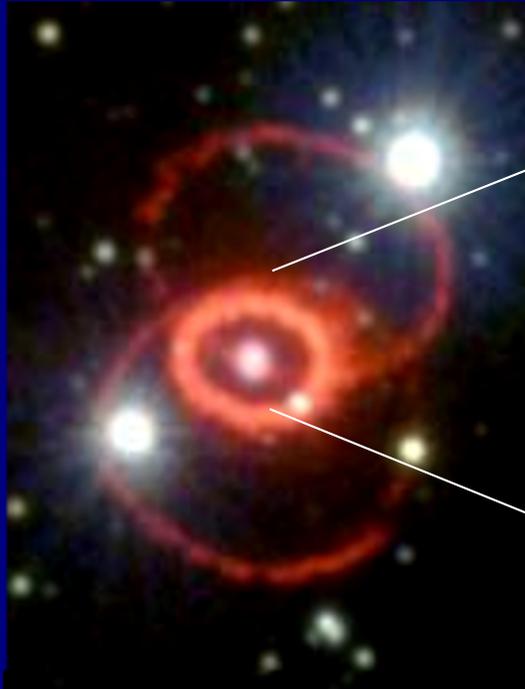
1998

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:
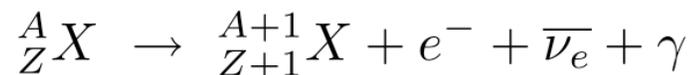
$$^{A}_{Z}X + n \ \rightarrow \ ^{A+1}_{Z}X + \gamma \quad \text{(no Coulomb barrier)}$$
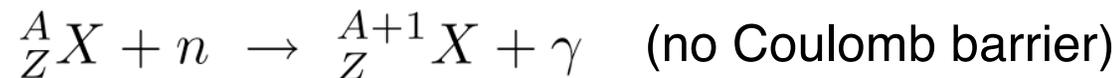
New nucleus is either stable (=> new isotope) or unstable and undergoes "β-decay"

$$n \rightarrow p + e^- + \bar{\nu}_e$$
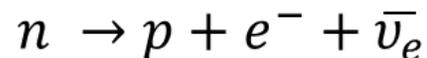
If unstable, two limits:

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

$$^{A}_{Z}X \ \rightarrow \ ^{A+1}_{Z+1}X + e^- + \bar{\nu}_e + \gamma$$
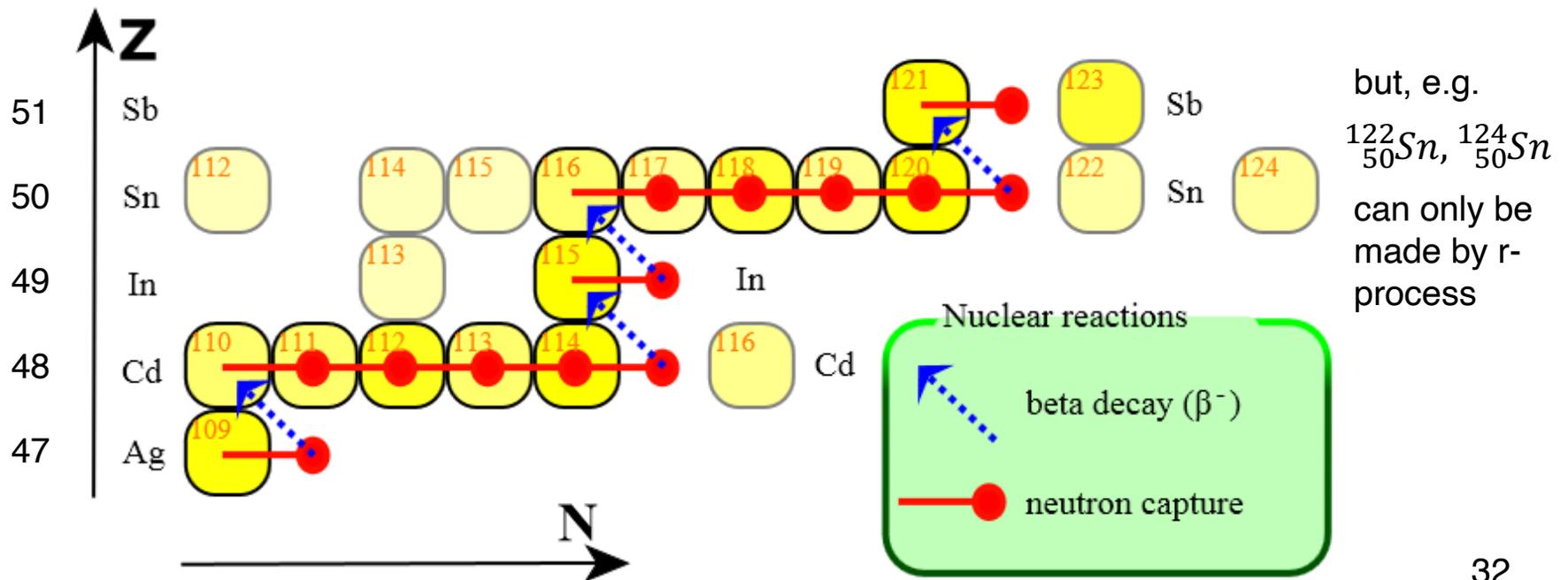
   "s process". Happens during stellar evolution.

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:
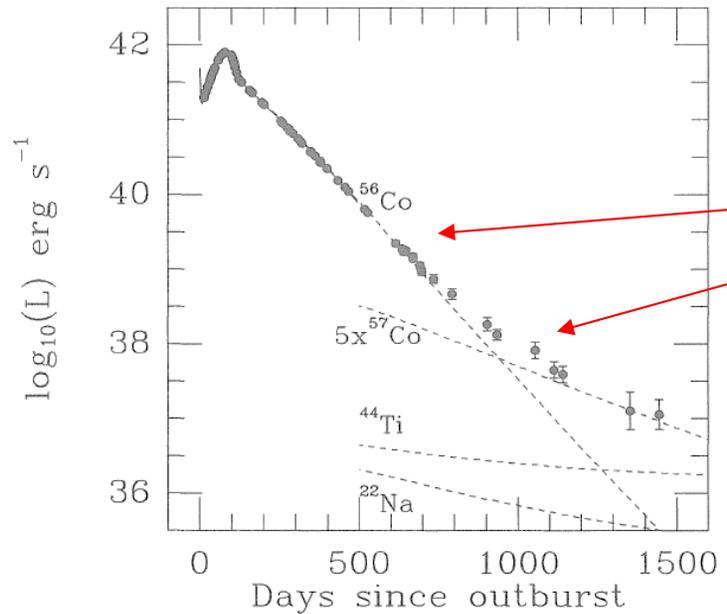
$$^{A+i}_{Z}X \rightarrow \, ^{A+i}_{Z+1}X + e^- + \bar{\nu}_e$$
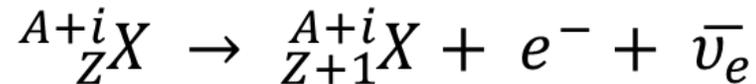
until a stable isotope is reached

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

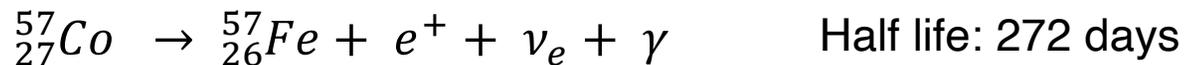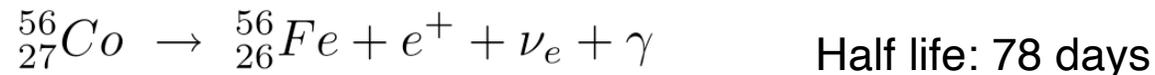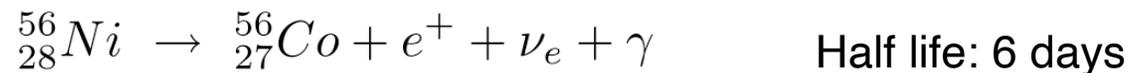Example of some elements and isotopes produced by s-process:

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:

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

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

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

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???

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