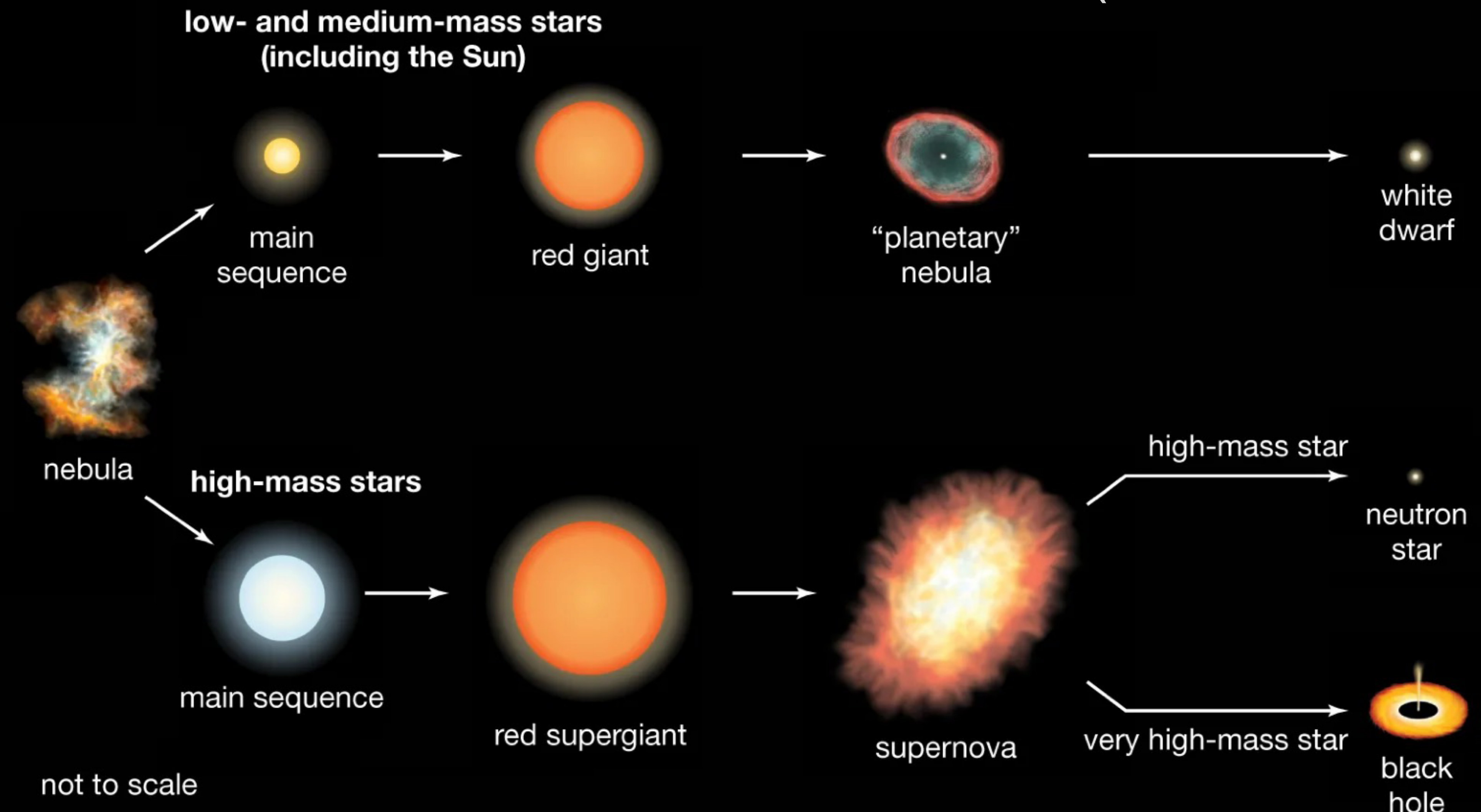
Chap 17: The Evolution of High-Mass Stars

Chap 17: The Evolution of High-Mass Stars

- CNO Cycles
- Convective cores
- Consecutive fusion shells
- End of fusion - Binding Energy
- Core collapse supernovae
- Neutron stars and Pulsars
- Supernova Remnants (SNR)
- The Origin of Elements: six primary astrophysical sources
- Periodic variables: L-P relations (distance measure)



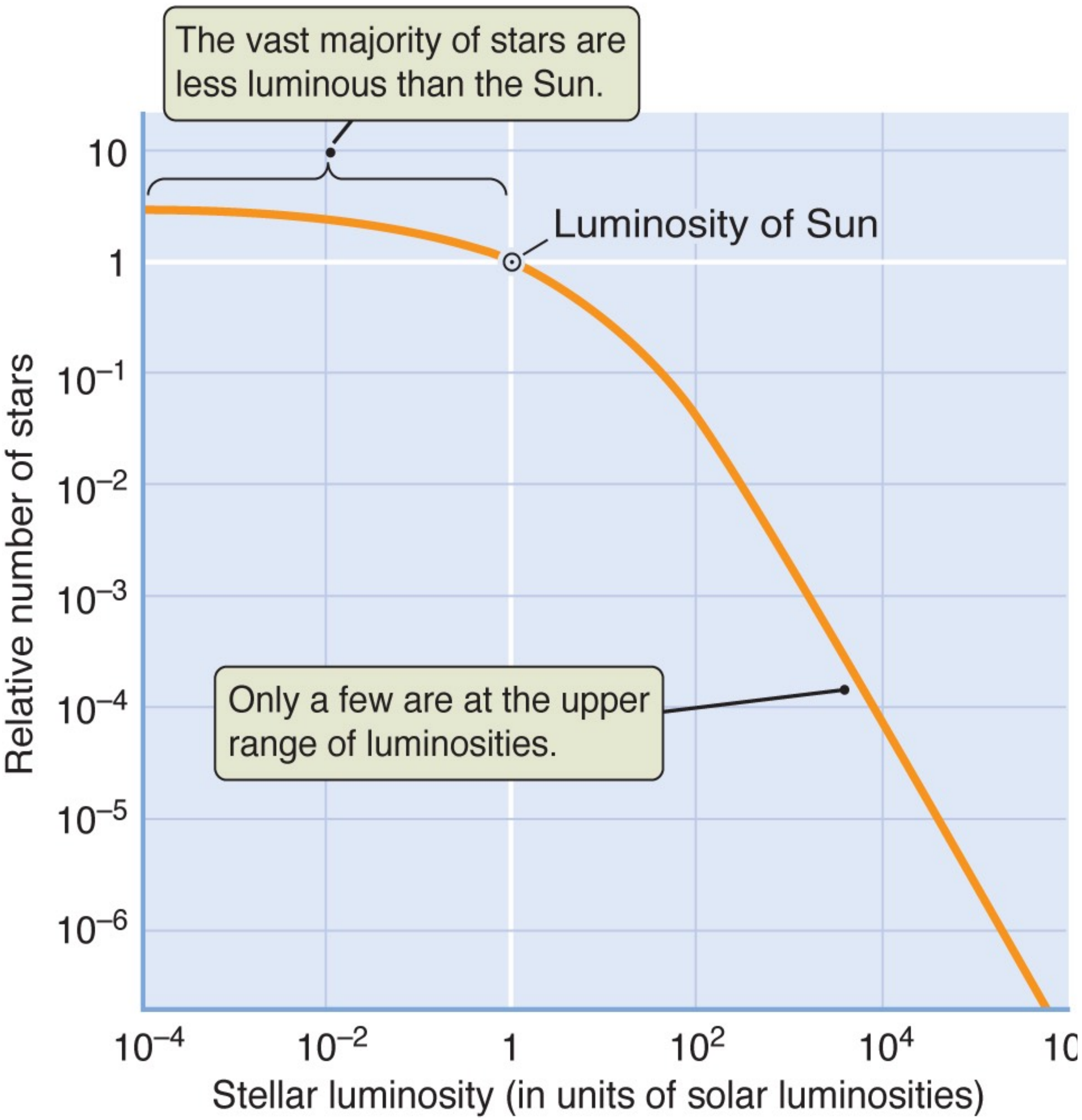
Chap 17 deals with stars of initial masses greater then 3 M_{sun}

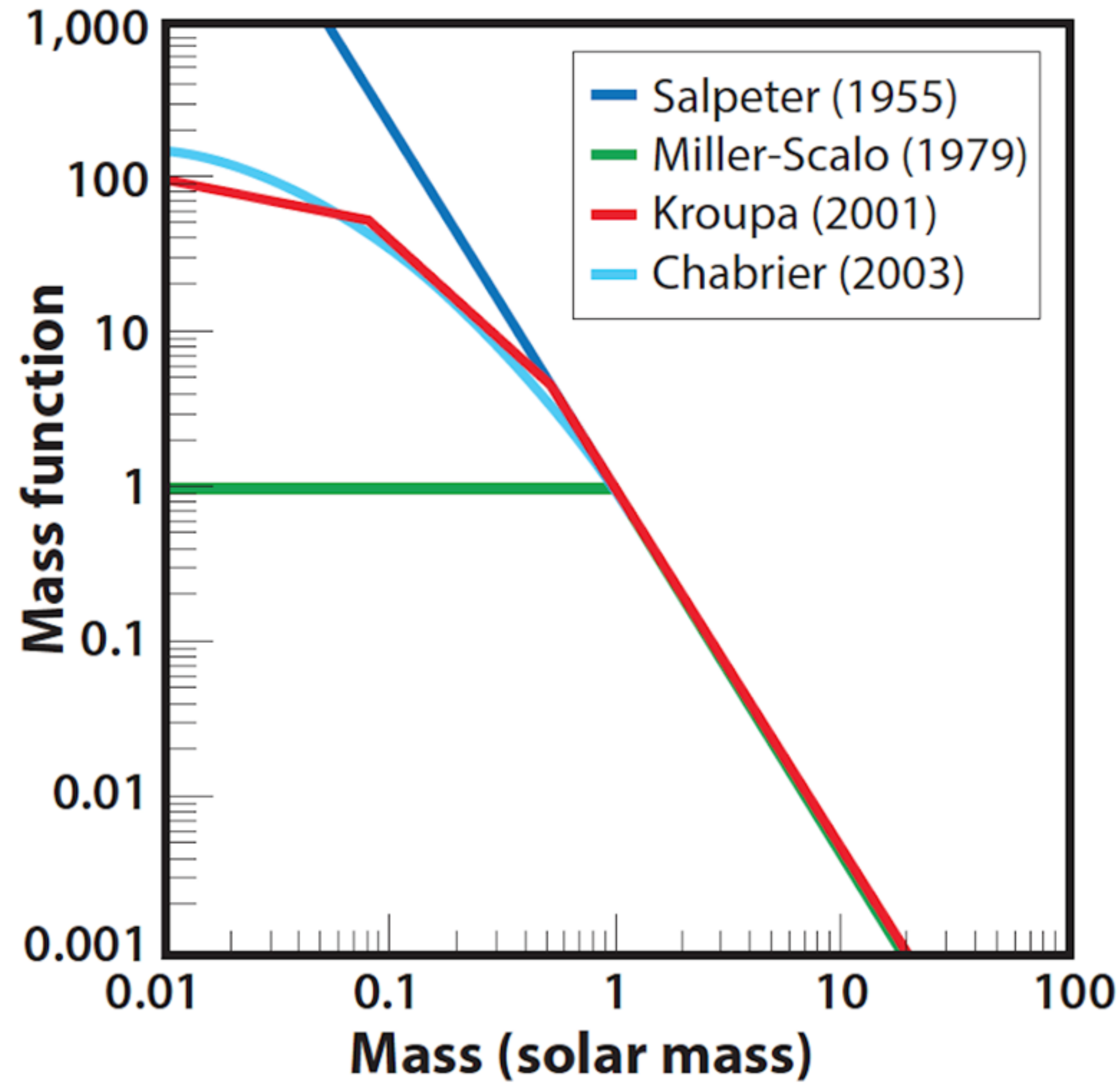
- A star's life depends on mass and composition because the rates and types of fusion depend on the star's mass.
- Stars of different masses evolve differently. There are three categories of stars:
  - **low-mass stars** (Mass < 3 M_{Sun})
  - **intermediate-mass stars** (Mass between 3 M_{Sun} and 8 M_{Sun})
  - **high-mass stars** (Mass > 8 M_{Sun})

Name	High-mass stars	Medium-mass stars	Low-mass stars	Very low-mass stars	Brown dwarfs
Spectral type	O, B	B	A, F, G, K	M	M, L, T, Y
Minimum mass	8 M_{Sun}	3 M_{Sun}	0.5 M_{Sun}	0.08 M_{Sun}	~0.01 M_{Sun} (~13 $M_{Jupiter}$)

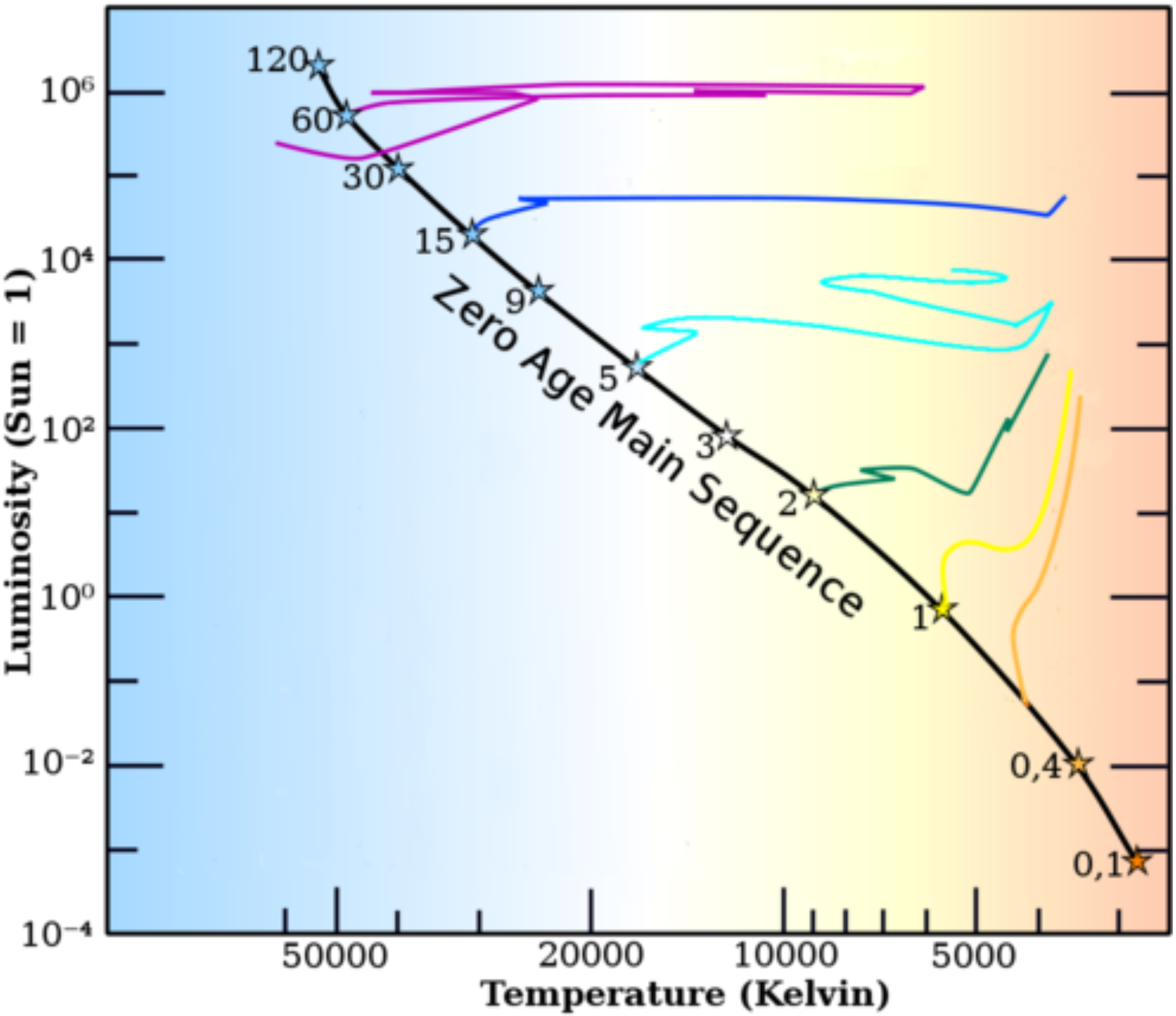
Massive stars are rare, not only because of their short lifespan

- *Initial Mass Function* shows the distribution of stellar masses at birth





The division at 3 M_{sun} marks an rough transition in the shape of the computed evolutionary tracks

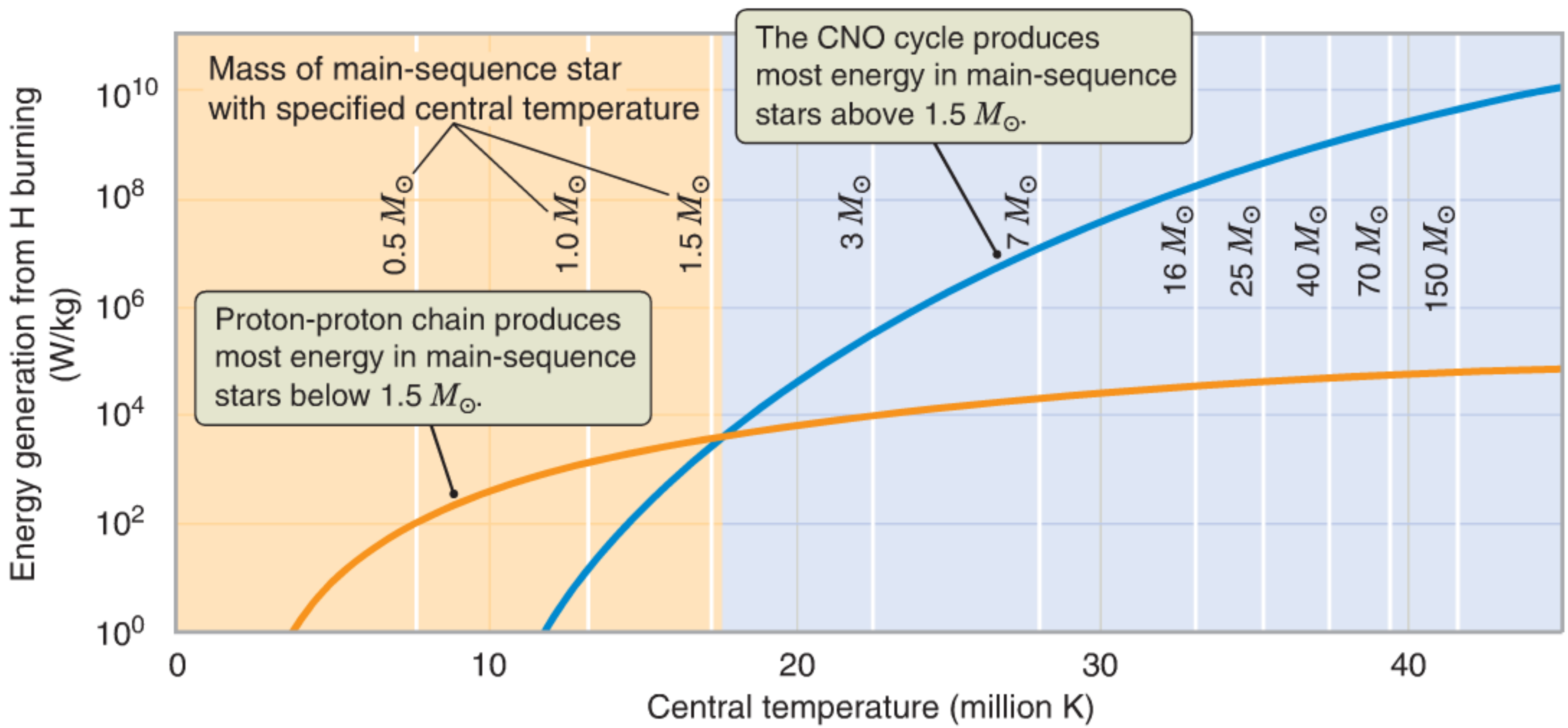


High-mass stars on the main sequence:

CNO cycle and convective core

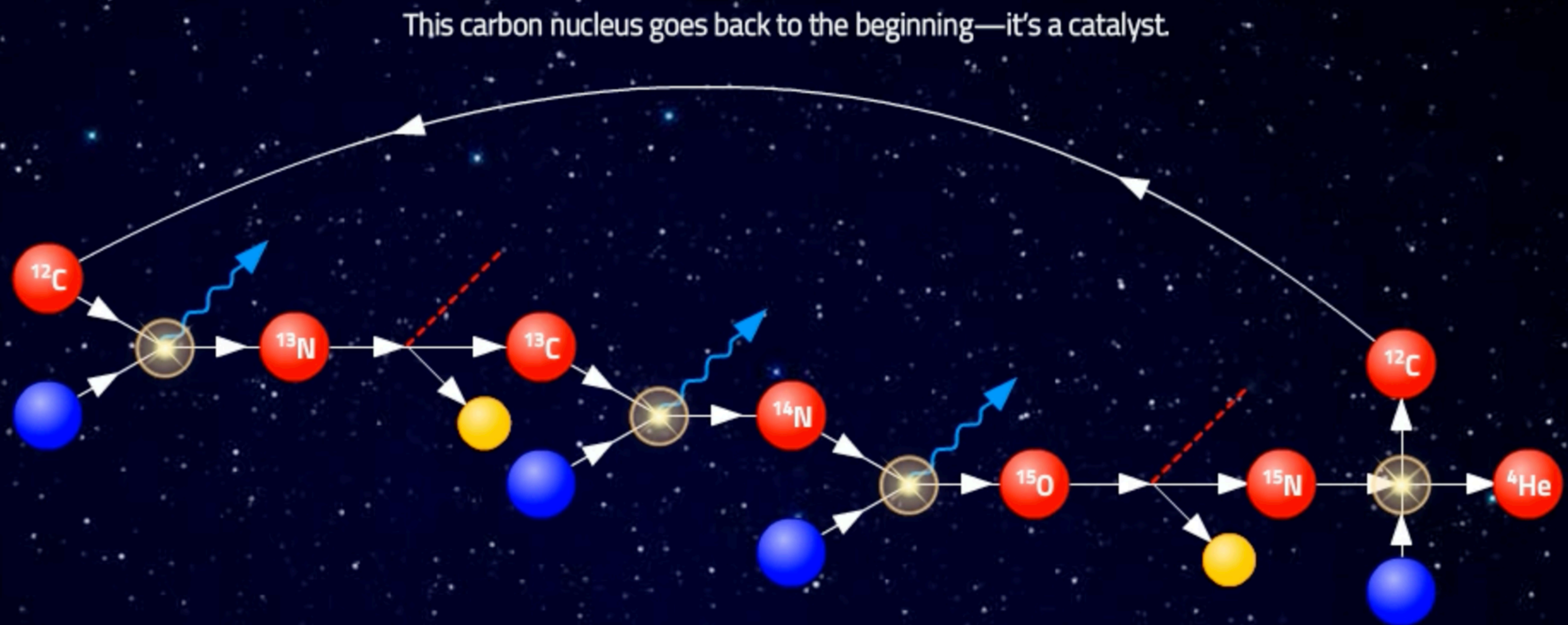
Massive MS stars have higher core temperature but lower core pressure

- Core temperature can be estimated using the **virial theorem**:
$$kT_c \approx GM\mu m_H / R$$
- Core pressure can be estimated from a **force balance**:
$$4\pi R^2 P_c \approx GM^2/R^2 \Rightarrow P_c \approx GM^2/(4\pi R^4)$$
- Main sequence stars show a **mass-radius relation** of:
$$R \propto M^{0.8}$$
- Therefore, $T_c \propto M^{0.2}$ and $P_c \propto M^{-1.2}$



The CNO Cycle: step-by-step

CNO Cycle



Legend: Proton | Nucleus | Positron | Neutrino | Gamma ray

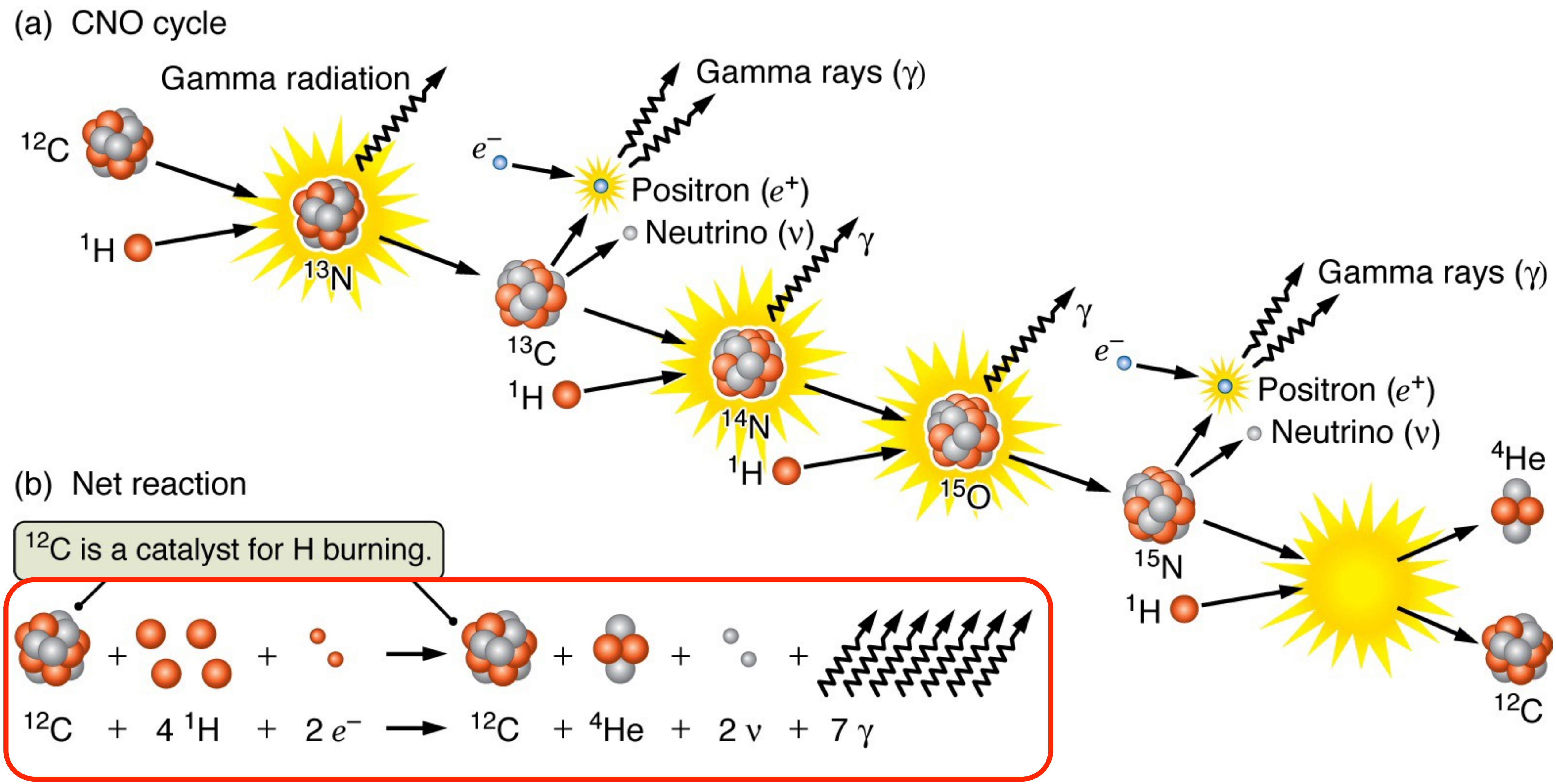
The net result is that four hydrogen nuclei were turned into a helium nucleus, two neutrinos, and seven gamma rays.

Play Reset

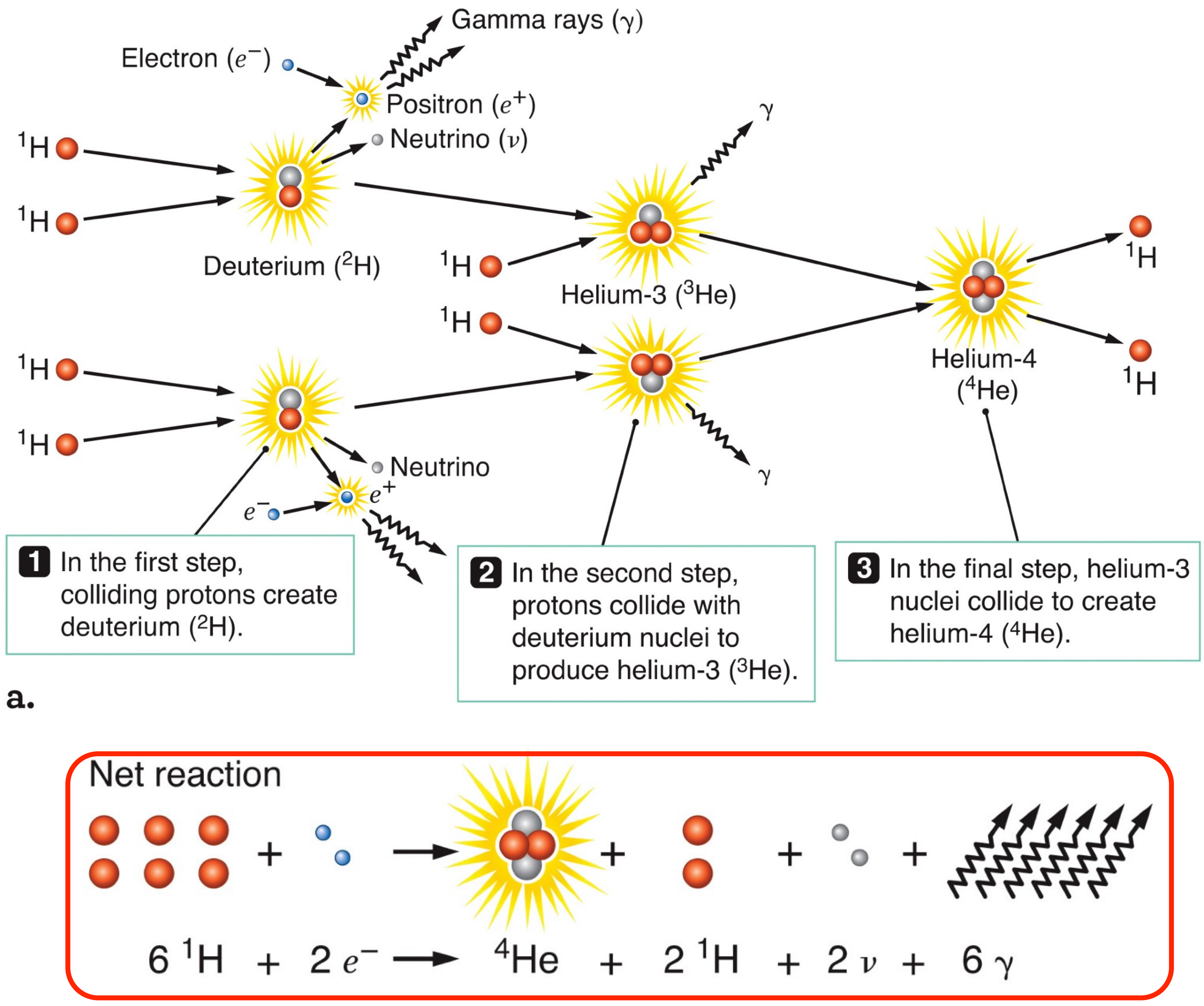
PREVIOUS NEXT

Net reaction of the CNO cycle

- In high-mass stars and the midlife Sun, hydrogen burning proceeds in the CNO cycle instead of the pp chain, due to higher core temperatures.
- The net result is the same as the pp chain: 4 H -> 1 He

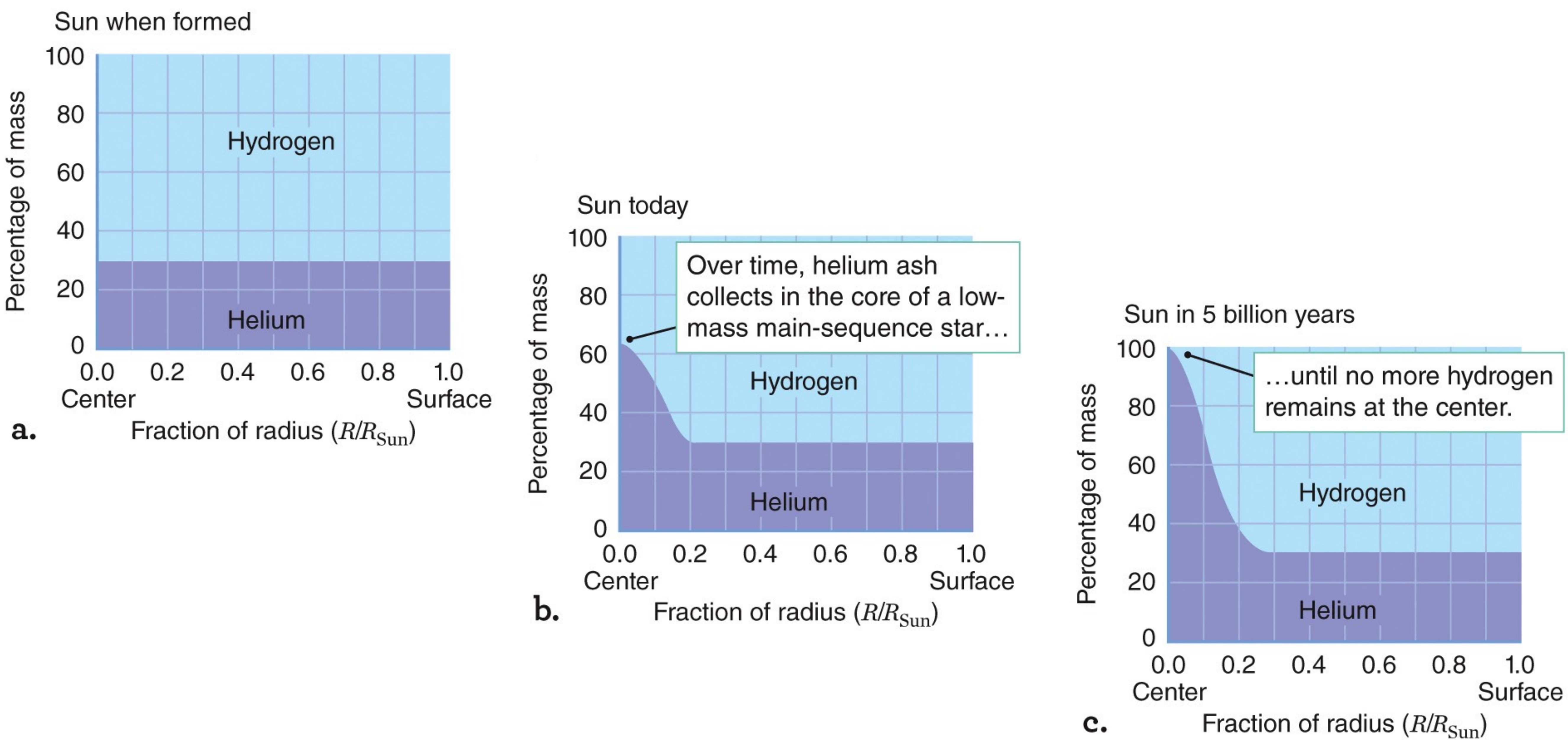


Net reaction of the Proton-Proton chain



Changes on the Main Sequence due to Fuel Exhaustion

- The chemical composition inside a star changes over time as hydrogen is fused into helium.
- The Sun started with 70 percent hydrogen by mass, but now contains only 35 percent hydrogen in the core.
- What will happen when the hydrogen is exhausted in the core?

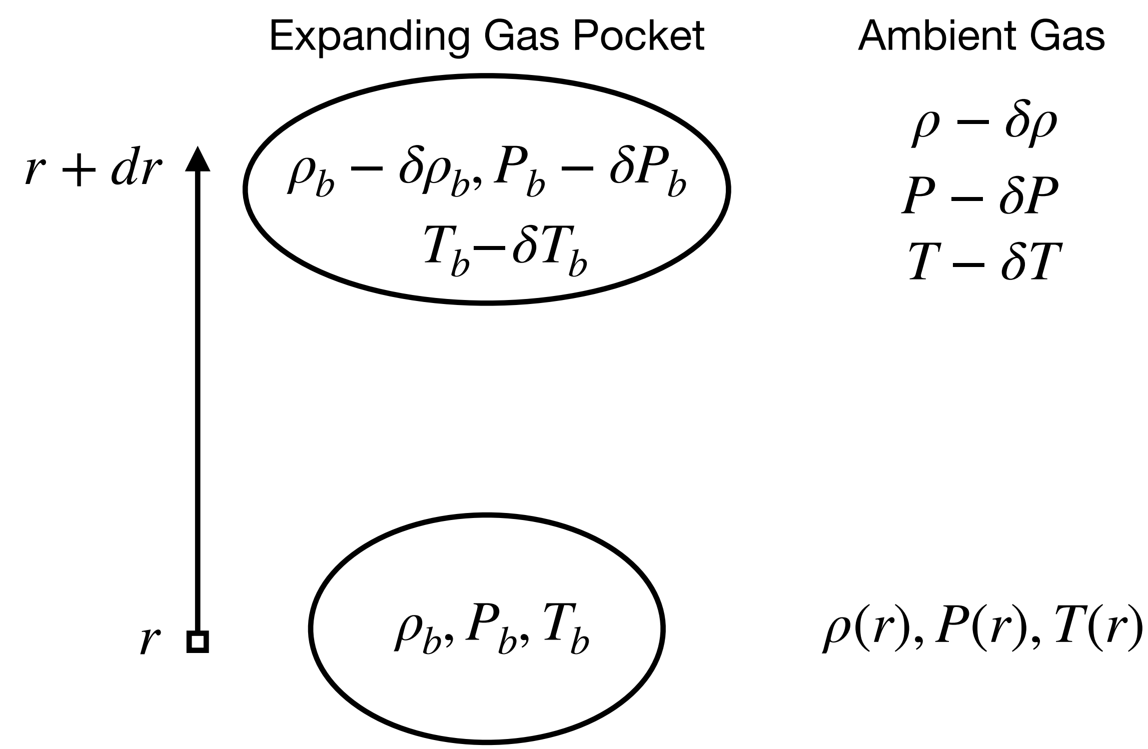


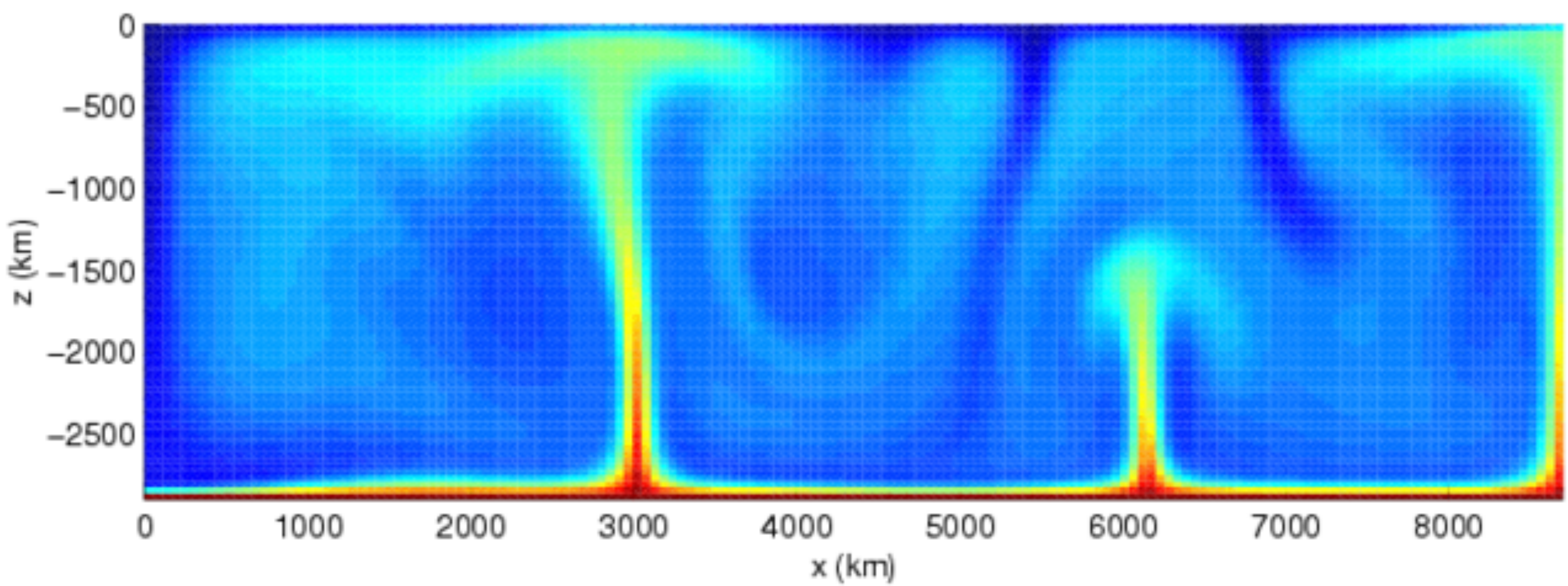
Condition for Convection: Large Temperature Gradients

- When **adiabatic expansion** of a gas pocket causes its temperature to drop ***less*** than that of the ambient gas, **convection** ensues:

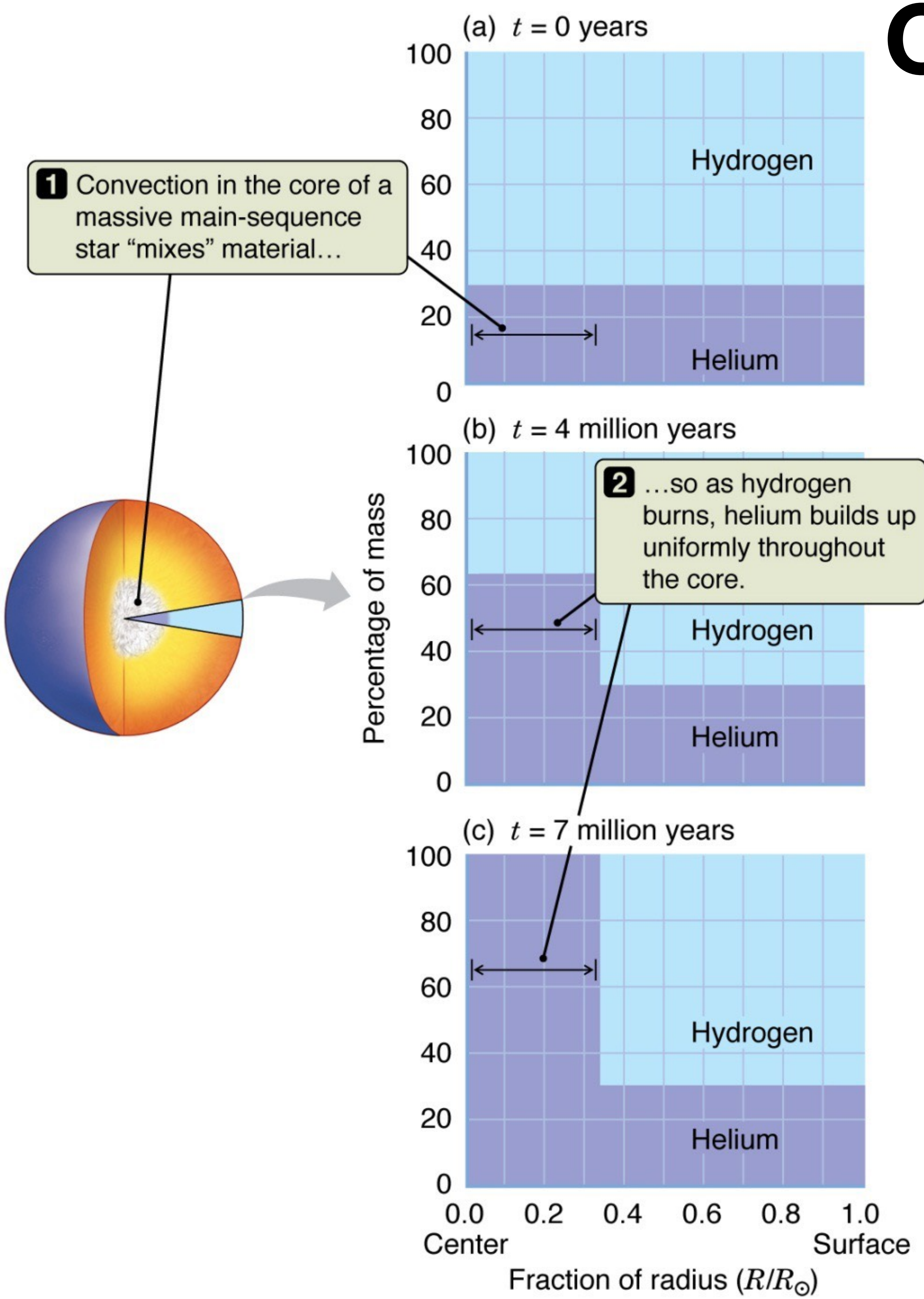
$$-\left(1-\frac{1}{\gamma}\right)\frac{T}{P}\frac{dP}{dr} < -\frac{dT}{dr}$$

- **Why**? *P = nkT*, warmer gas at the same pressure as colder gas will have lower density. So the pocket will continue to rise due to buoyancy





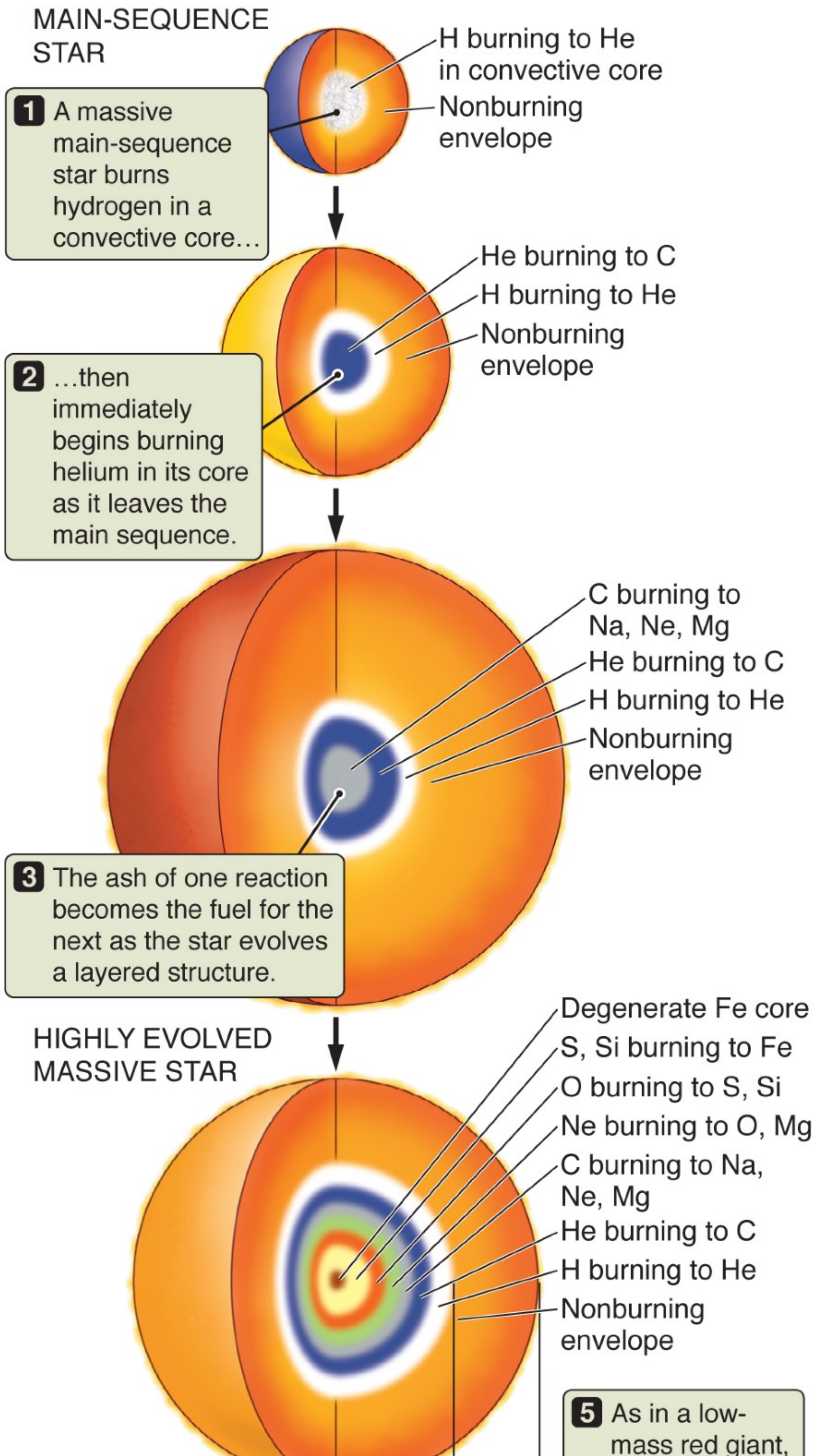
Convective Cores



- High-mass stars have large T gradient, so convection mixes the core effectively.
- Increases the amount available for fusion, but still cannot sustain the high luminosity very long
- High-mass stars live faster lives (3 Myr for 25 M_{sun}).
- Once H is exhausted from the core, the star leaves the MS and expands and cools

High-mass stars’ post-MS evolution:

Onion layers of burning shells, nearly horizontal evolution on the HRD

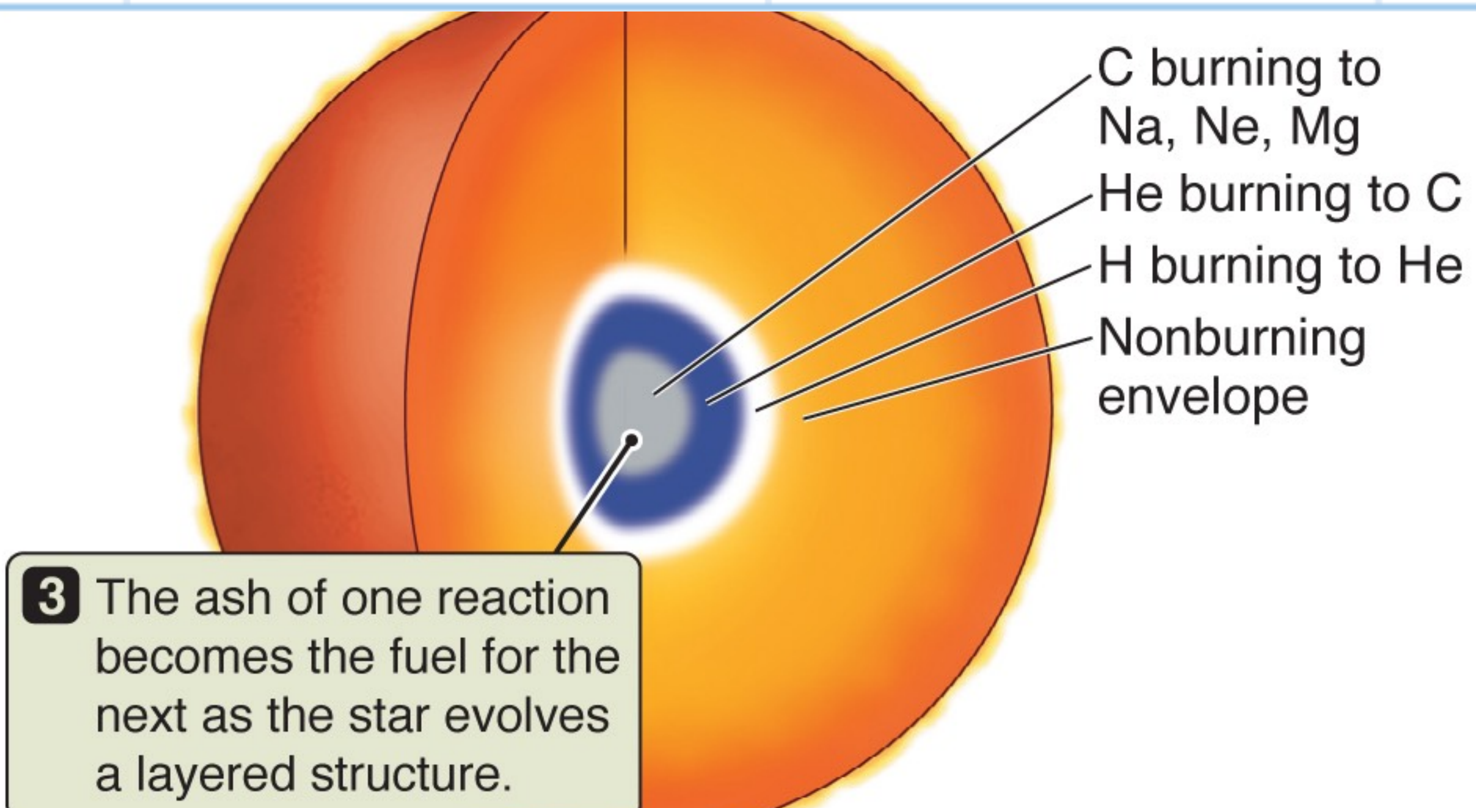


Fusion Shells

- The compression of the core ignite **He-burning** before it becomes degenerate, unlike low-mass stars.
- The fusion shells build up like the layers of an onion.
- The more massive the star, the heavier the elements that can fuse.
- Cores of high-mass stars will fuse elements up until iron (Fe).

Burning Stages in High-Mass Stars

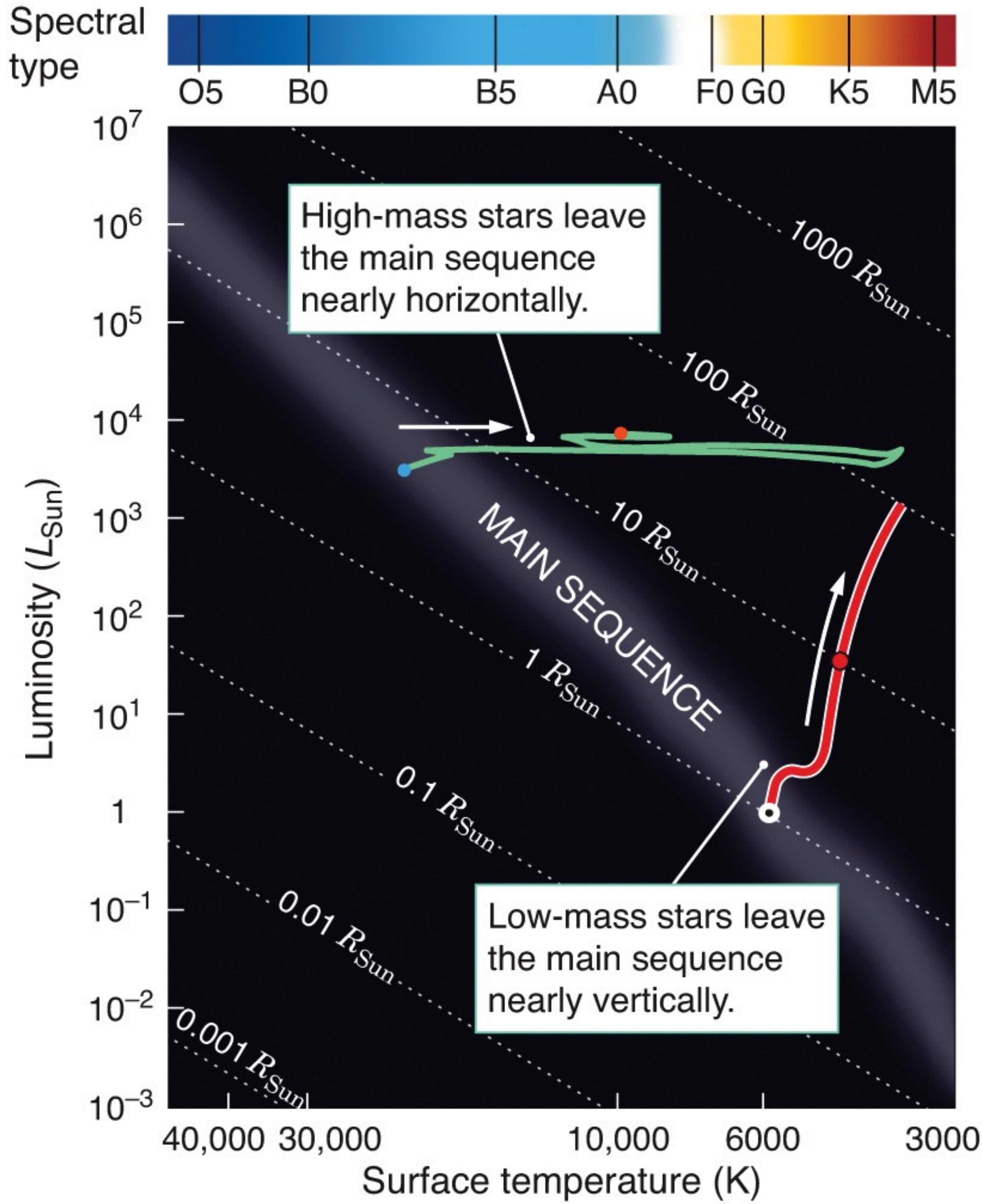
Core Burning Stage	9-$M_\odot$ Star	25-$M_\odot$ Star	Typical Core Temperatures
Hydrogen (H) burning	20 million years	7 million years	$(3\text{–}10) \times 10^7$ K
Helium (He) burning	2 million years	700,000 years	$(1\text{–}7.5) \times 10^8$ K
Carbon (C) burning	380 years	160 years	$(0.8\text{–}1.4) \times 10^9$ K
Neon (Ne) burning	1.1 years	1 year	$(1.4\text{–}1.7) \times 10^9$ K
Oxygen (O) burning	8 months	6 months	$(1.8\text{–}2.8) \times 10^9$ K
Silicon (Si) burning	4 days	1 day	$(2.8\text{–}4) \times 10^9$ K



Evolution Tracks on H-R Diagram

Once leaving the main sequence, the star starts to expand to a supergiant, while keeping almost constant luminosity

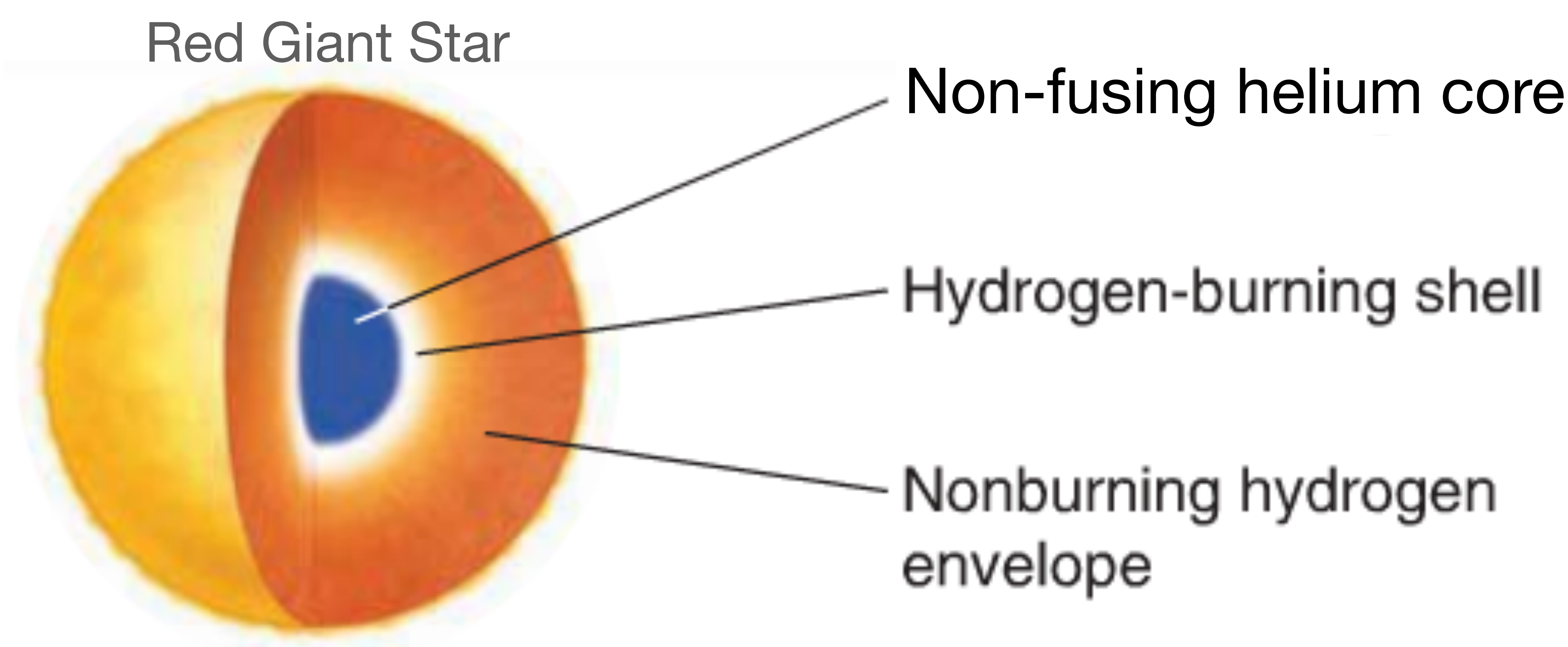
The reason of the expansion is the same as the red giant stars — **the fusion shell**



Copyright © 2022 W. W. Norton & Company, Inc.

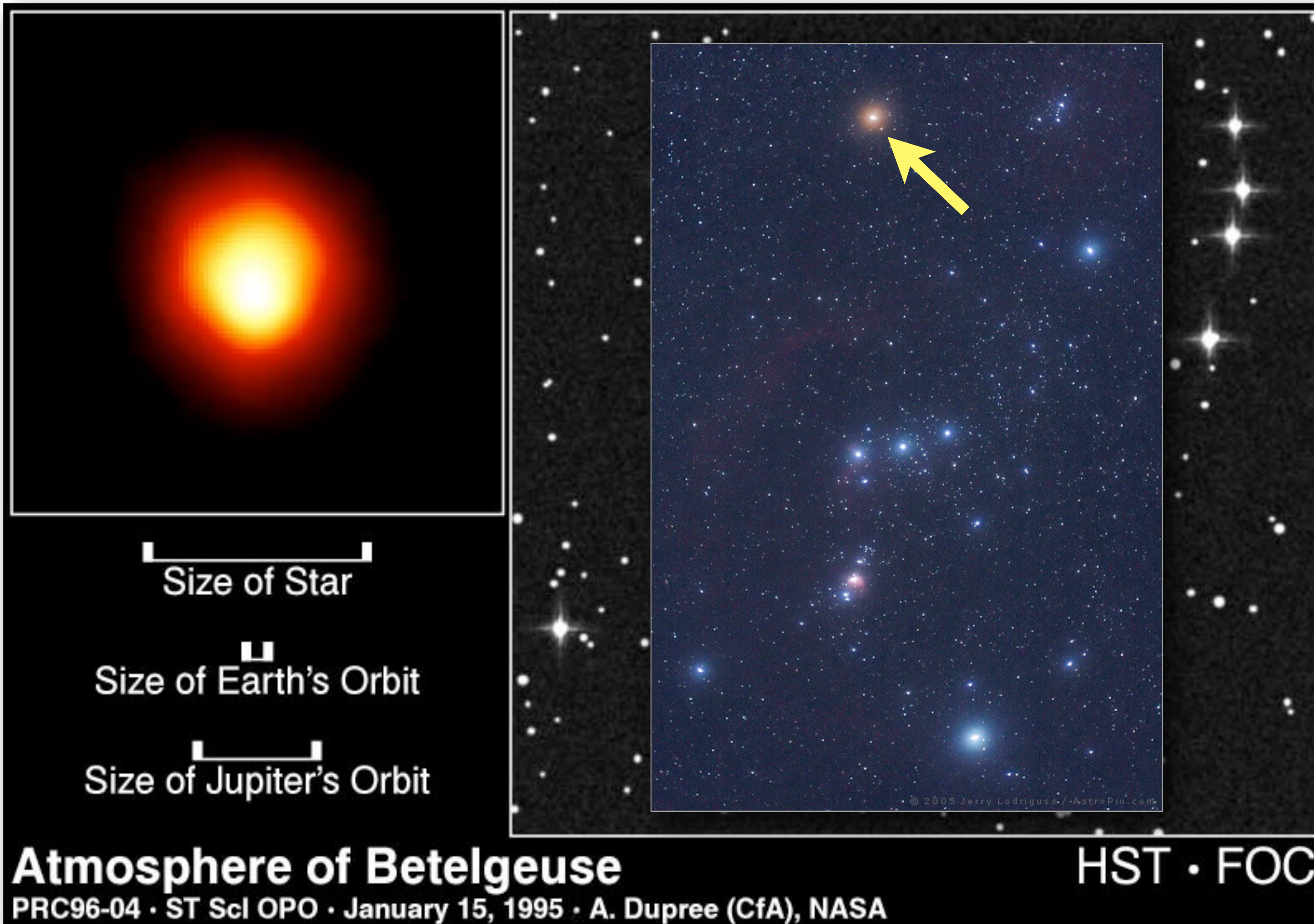
The mirror principle of a fusion shell: when one side contracts, the other side expands

- While the **gravitational thermostat** works well to control the **burning core**'s temperature, it cannot control the temperature of a **burning shell**
- When fusion stops in the **core**, it **contracts**. Gravitational potential energy heats up the core and it conducts its heat to the surrounding shell.
- As the **shell's temperature rises**, its fusion reaction rate increases rapidly
- To avoid a thermonuclear runaway, the shell must decrease its temperature by dumping its energy to the **non-burning envelope**, causing the star to expand to a giant.



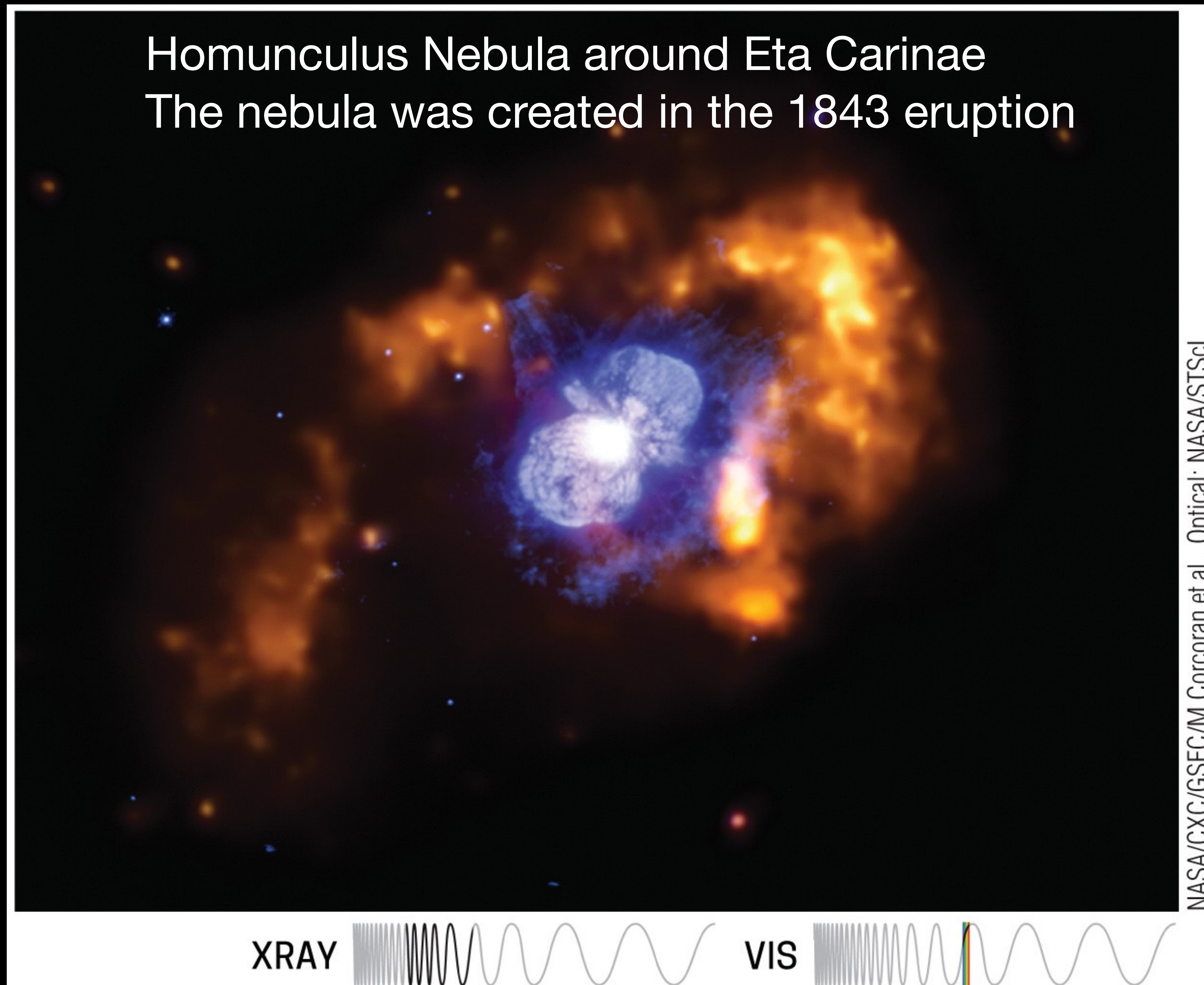
Betelgeuse

The familiar red star in Orion constellation. Betelgeuse is a red supergiant.



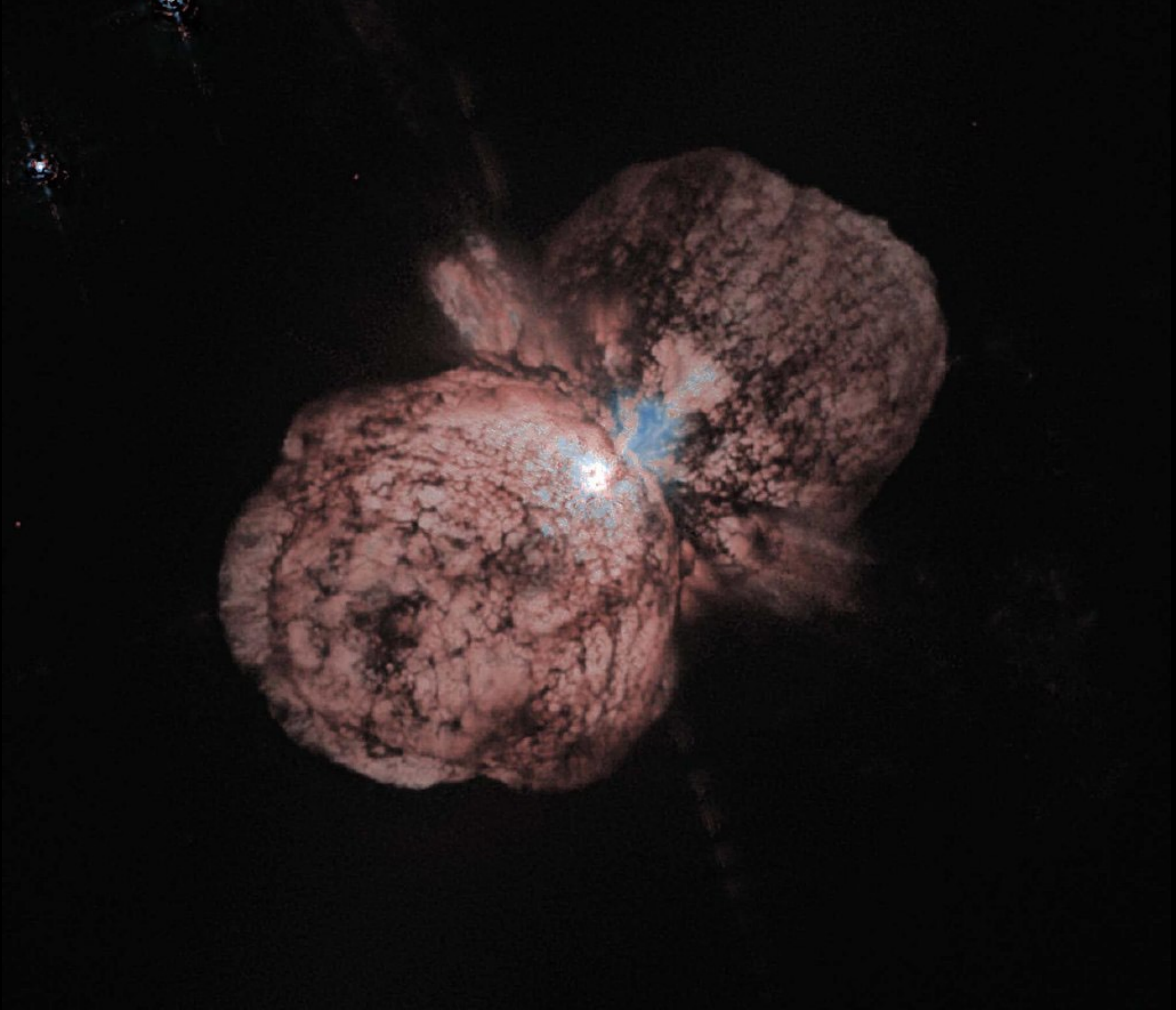
distance = 640 light years, $M = 7.7\ M_{sun}$, $R = 1{,}200\ R_{sun}$

Severe Mass Loss of High Mass Stars



- Stars with 20 M_{sun} could lose > 50% of their mass.
- Mass loss rates are large: 10^{-7} to 10^{-5} M_{sun}/yr because of low gravity and radiation pressure, and occasional erruptions

- Eta Carinae: 150 M_{sun} primary + 80 M_{sun} secondary
- The primary may have already lost 30 M_{sun} by now.

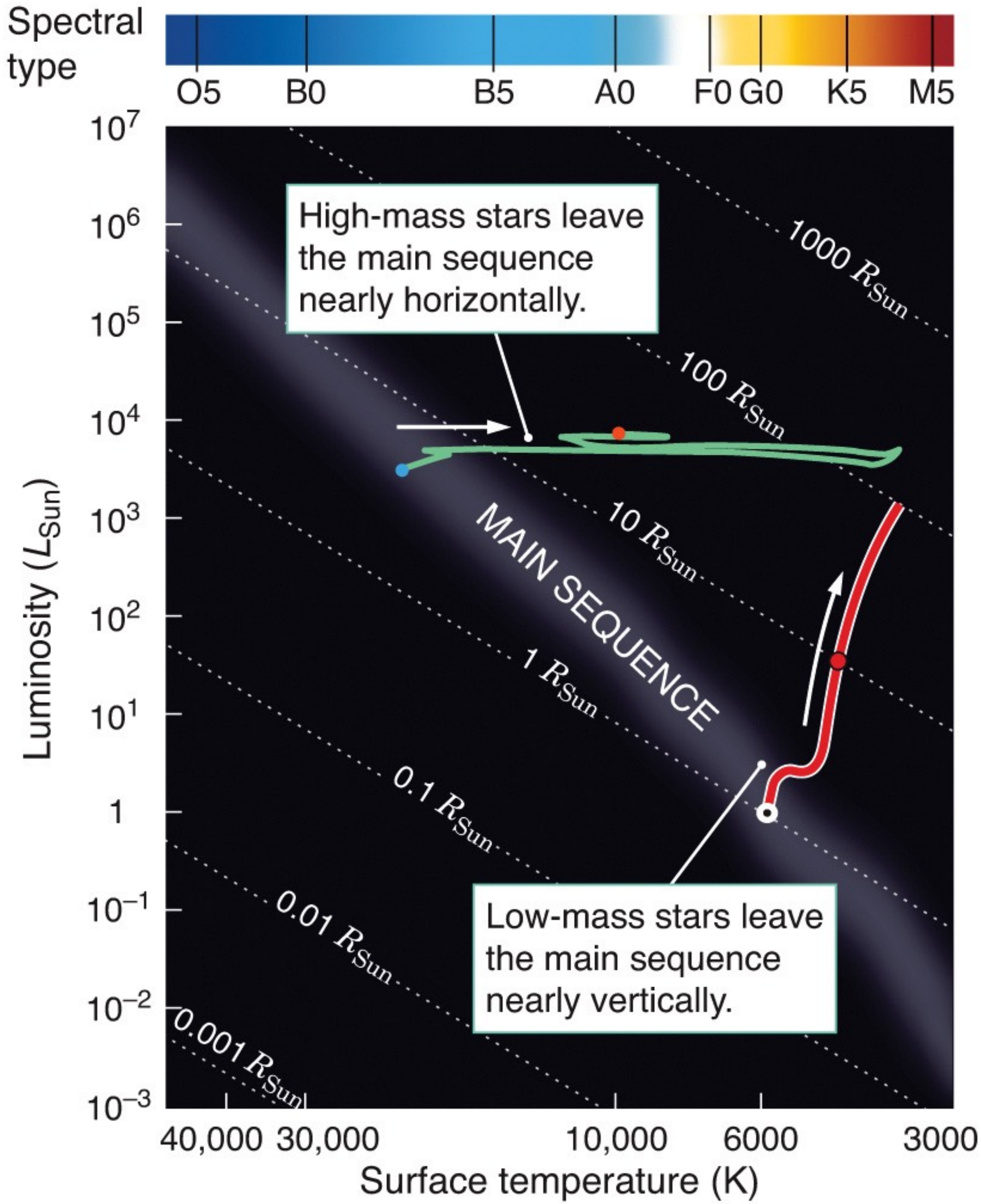


Recap: Massive Star Post-Main-Sequence Evolution

Evolution Tracks on H-R Diagram

Once leaving the main sequence, the star starts to expand to a supergiant, while keeping almost constant luminosity

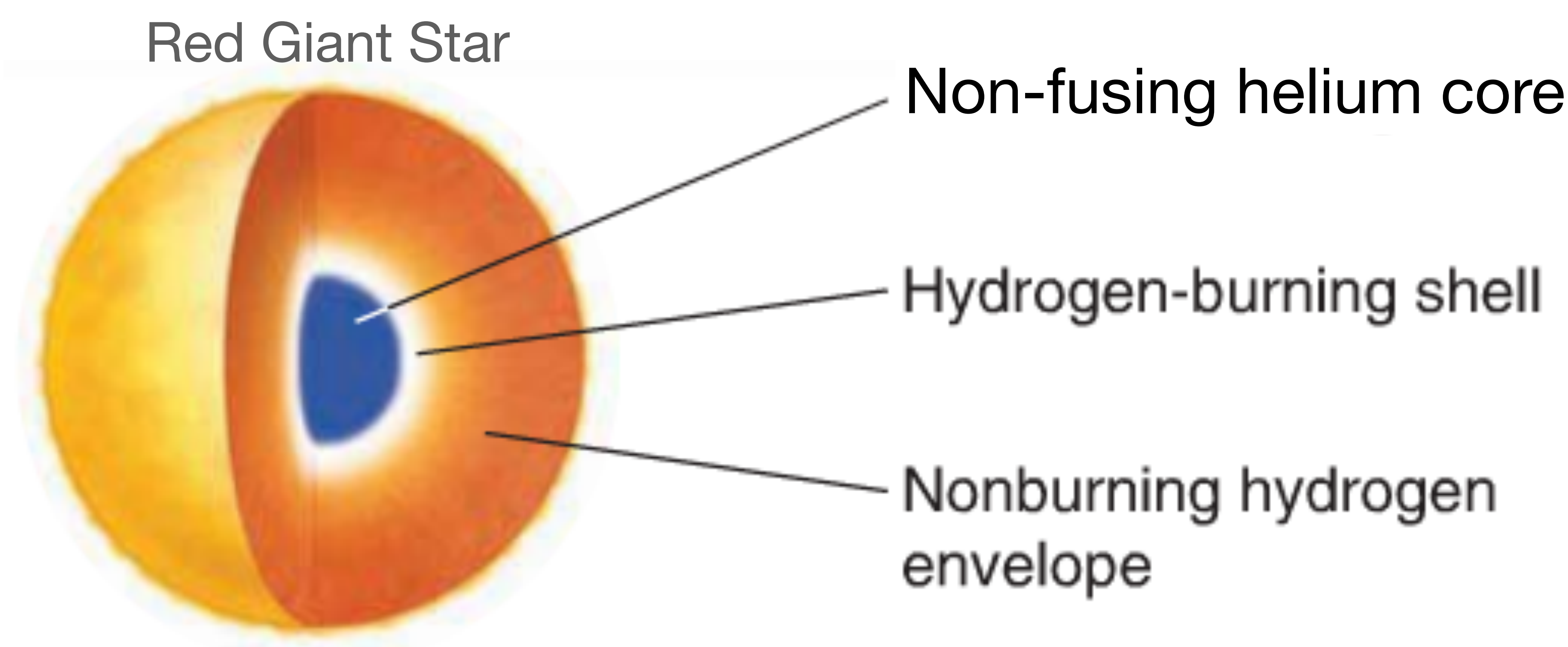
The reason of the expansion is the same as the red giant stars — **the fusion shell**



Copyright © 2022 W. W. Norton & Company, Inc.

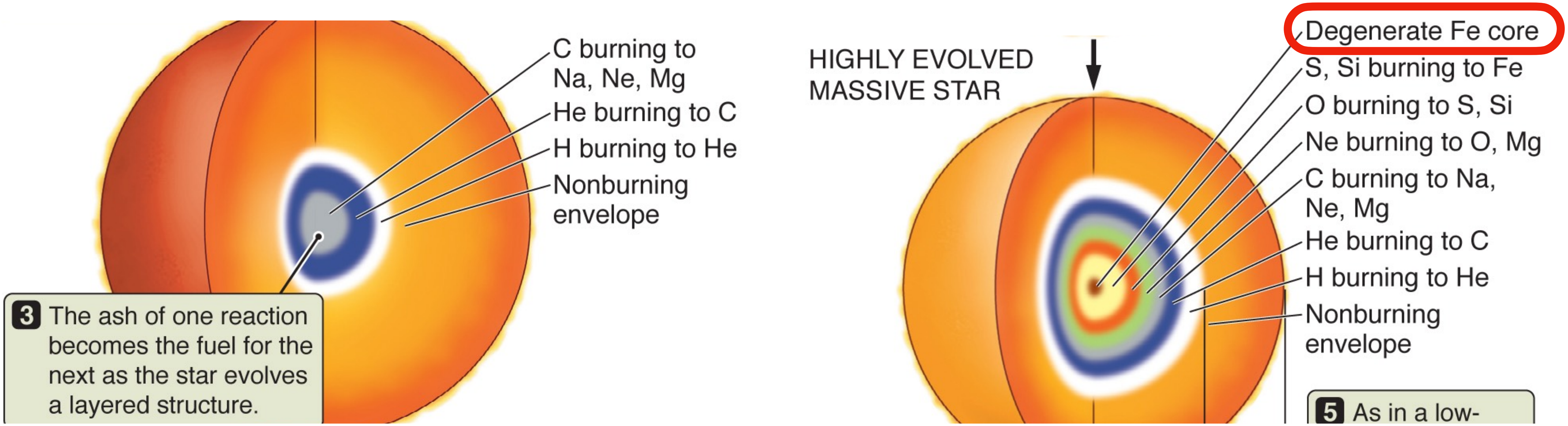
The mirror principle of a fusion shell: when one side contracts, the other side expands

- While the **gravitational thermostat** works well to control the **burning core**'s temperature, it cannot control the temperature of a **burning shell**
- When fusion stops in the **core**, it **contracts**. Gravitational potential energy heats up the core and it conducts its heat to the surrounding shell.
- As the **shell's temperature rises**, its fusion reaction rate increases rapidly
- To avoid a thermonuclear runaway, the shell must decrease its temperature by dumping its energy to the **non-burning envelope**, causing the star to expand to a giant.



Burning Stages in High-Mass Stars

Core Burning Stage	9-$M_\odot$ Star	25-$M_\odot$ Star	Typical Core Temperatures
Hydrogen (H) burning	20 million years	7 million years	$(3–10) \times 10^7$ K
Helium (He) burning	2 million years	700,000 years	$(1–7.5) \times 10^8$ K
Carbon (C) burning	380 years	160 years	$(0.8–1.4) \times 10^9$ K
Neon (Ne) burning	1.1 years	1 year	$(1.4–1.7) \times 10^9$ K
Oxygen (O) burning	8 months	6 months	$(1.8–2.8) \times 10^9$ K
Silicon (Si) burning	4 days	1 day	$(2.8–4) \times 10^9$ K

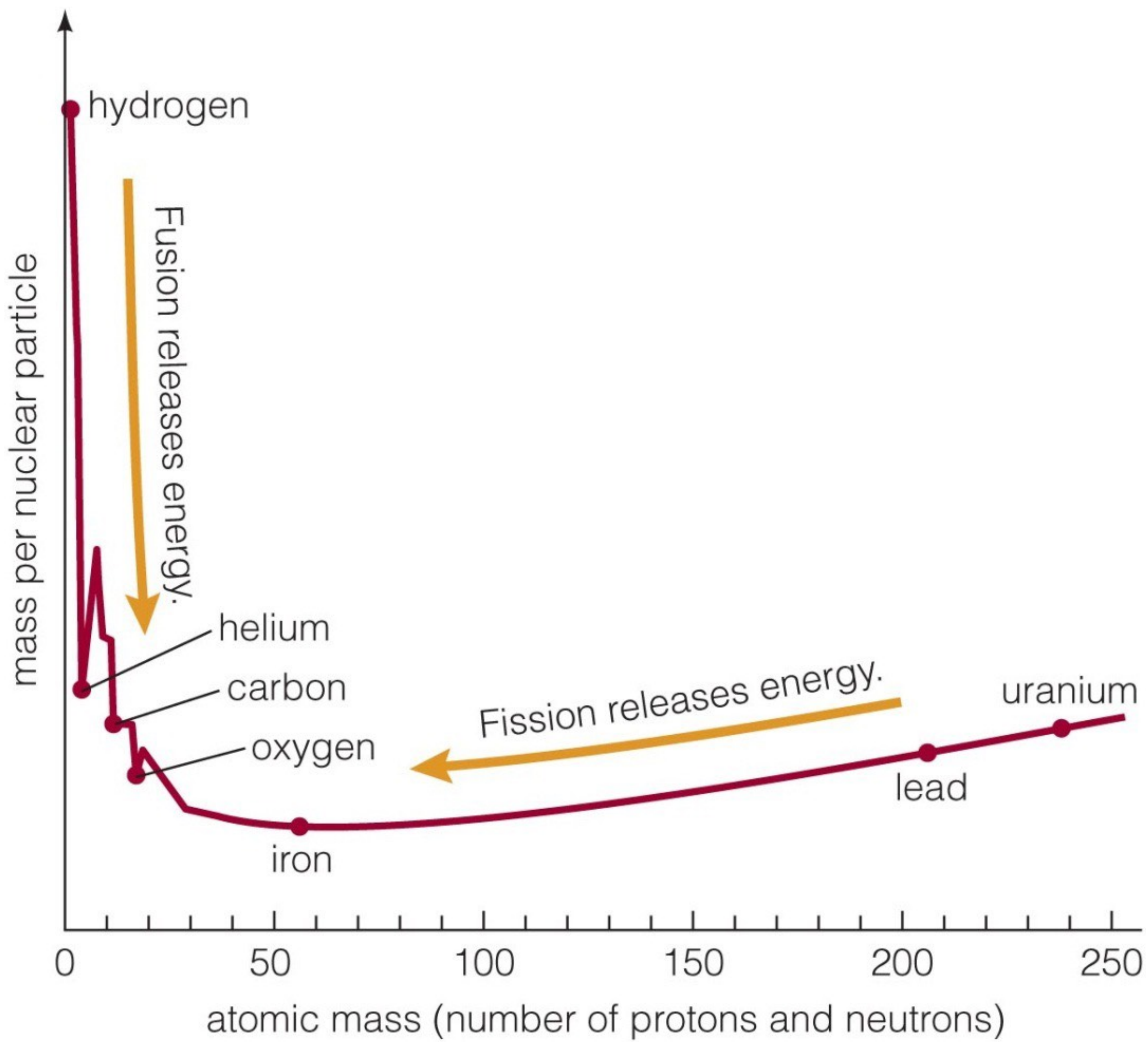


The End of Nuclear Fusion:

Nuclear Binding Energy

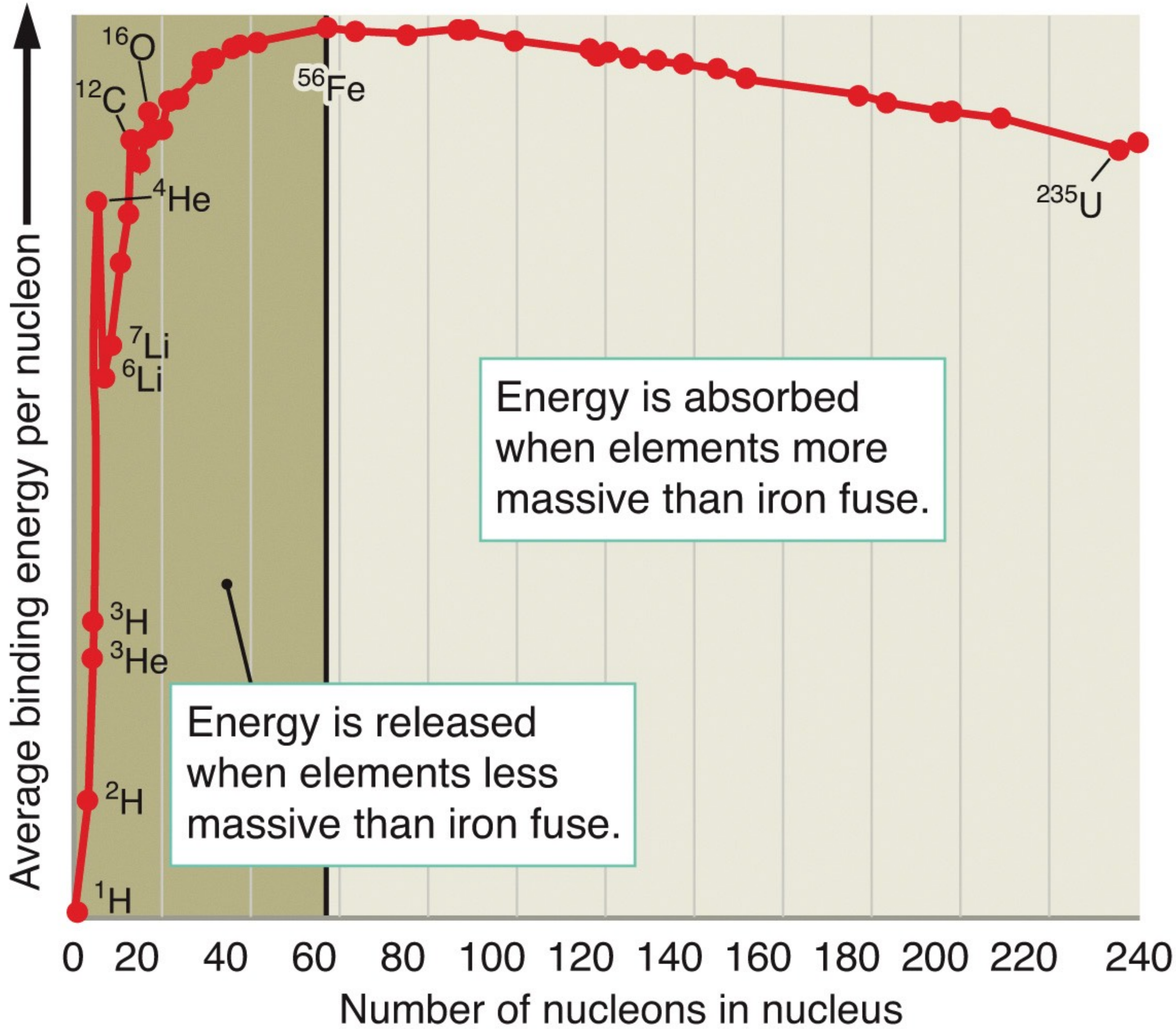
Fusion Energy: the mass per nucleon decreases from H to Fe

- Nuclear fusion produces energy from the mass loss occurred when fusing lighter elements into heavier elements ($E = \Delta m \cdot c^2$). This works from Hydrogen (H), to Helium (He-4), up to **Iron (Fe-56)**, which has the *lowest* mass per nucleon.



An alternative way to understand fusion energy: nuclear binding energy

- **Binding Energy** is the minimum energy required to **disassemble** the nucleus of an atom into its constituent nucleons.
- **Fusion energy** is produced from **the difference in binding energy** between products and reactants.
- **Fe-56** has the highest binding energy per nucleon, so it marks **the end of both fusion and fission.**



Working It Out 17.1: Binding Energy of Atomic Nuclei

- The net energy released by a nuclear reaction is the difference between the **binding energy** of the products and the binding energy of the reactants.
- For the triple-alpha process:

$$\begin{pmatrix}\text{Net energy from}\\ \text{fusing 1 kg of He}\end{pmatrix} = \begin{pmatrix}\text{Binding energy}\\ \text{of C formed}\end{pmatrix} - \begin{pmatrix}\text{Binding energy}\\ \text{of He fused}\end{pmatrix}$$

$$= (7.402 \times 10^{14}\ \text{J}) - (6.824 \times 10^{14}\ \text{J})$$

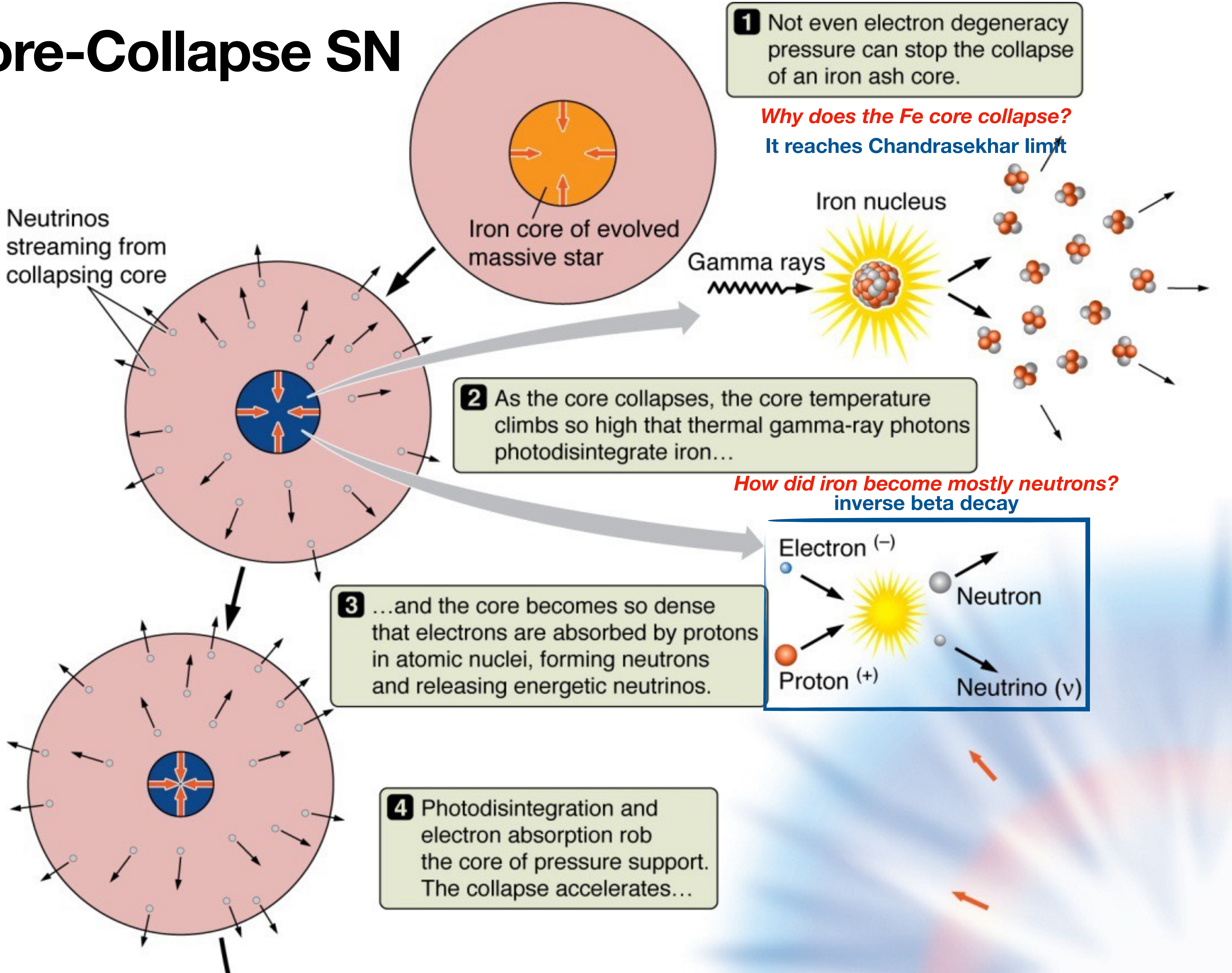
$$= 5.780 \times 10^{13}\ \text{J}$$

- For the fusion of iron, the binding energy of the products is less than that of the reactants, so the net energy is negative.

Core-Collapse Supernovae

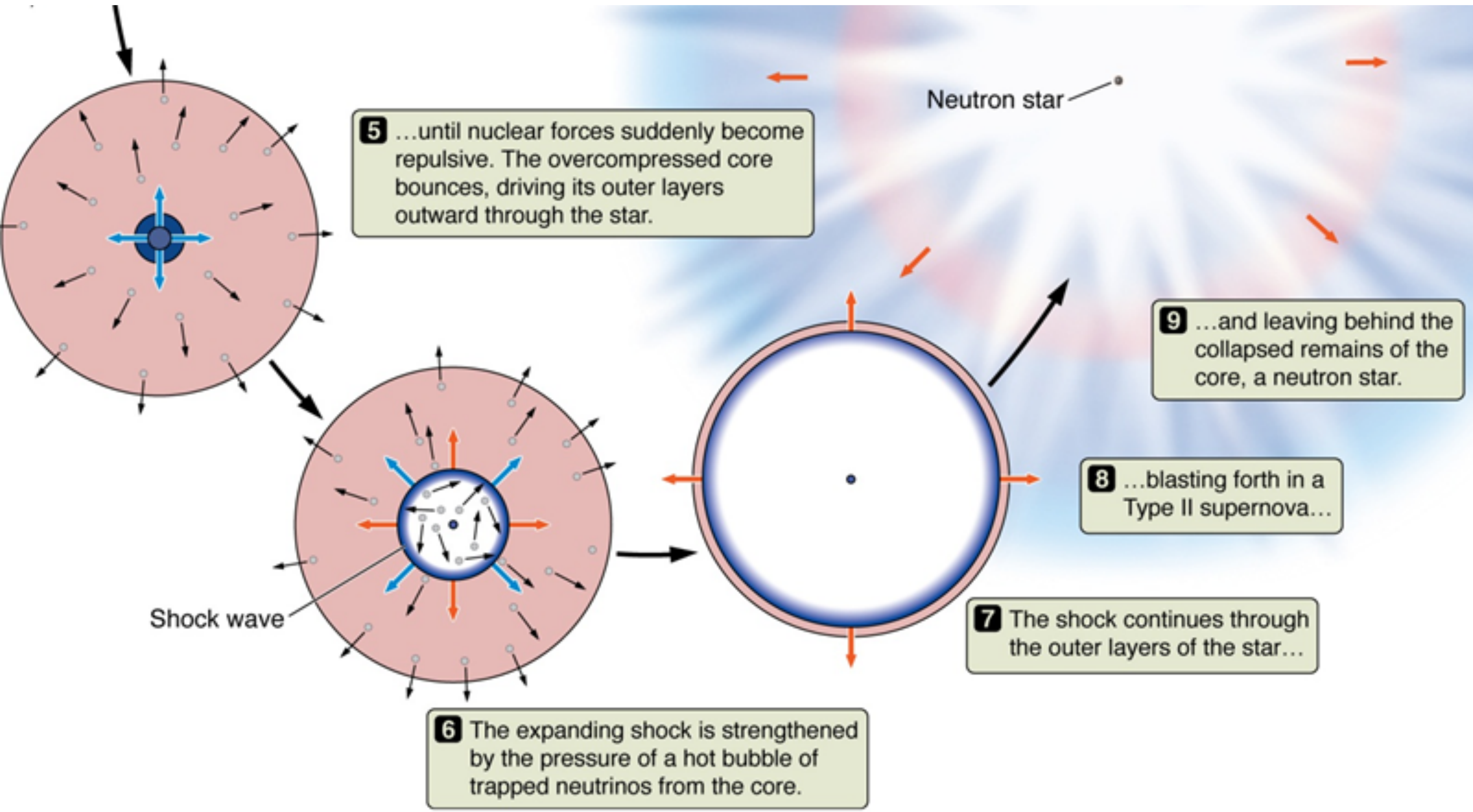
Type II SNe

Core-Collapse SN



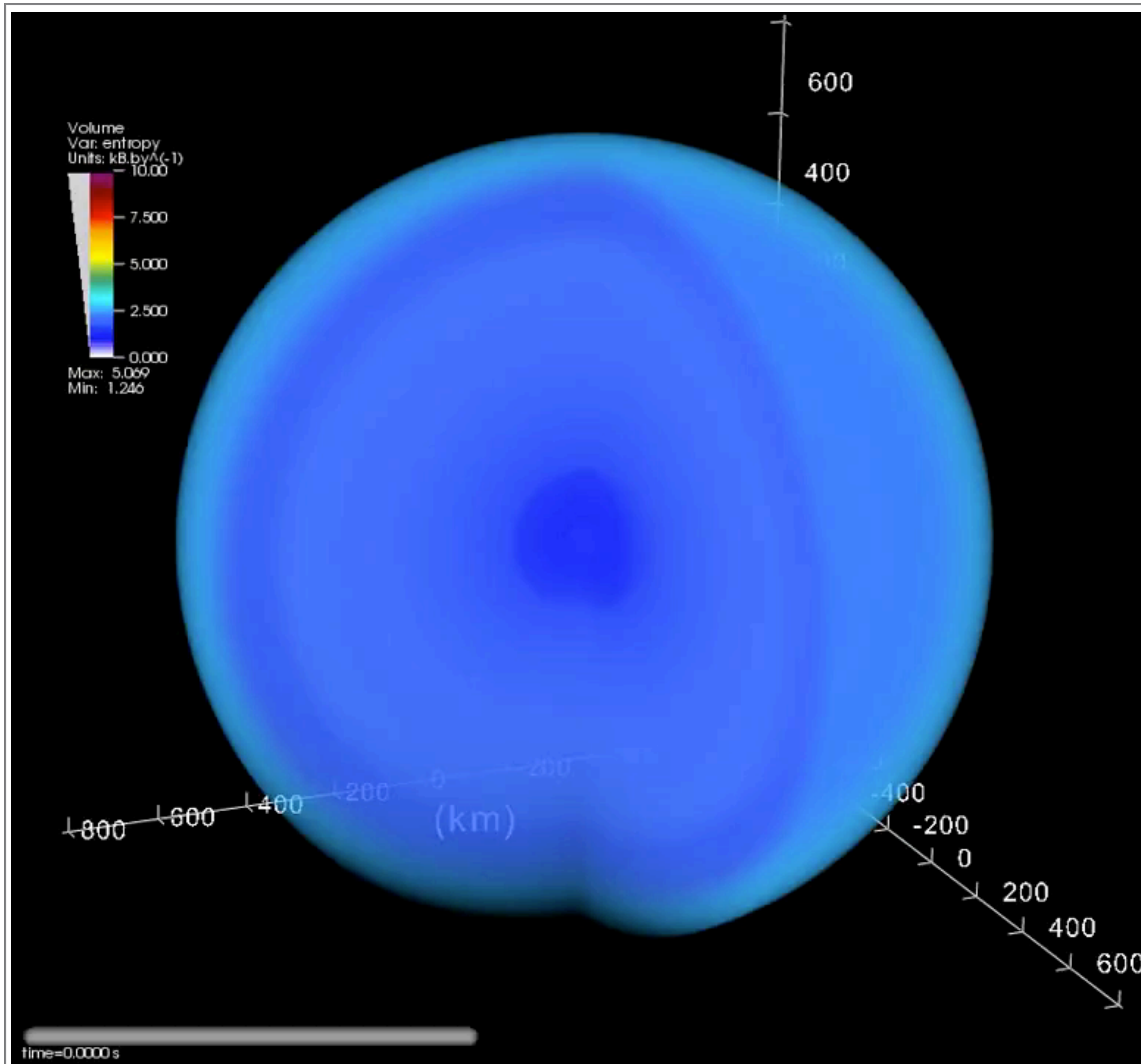
Core Bounce and Explosion

leaving behind a blast nebula and a neutron star



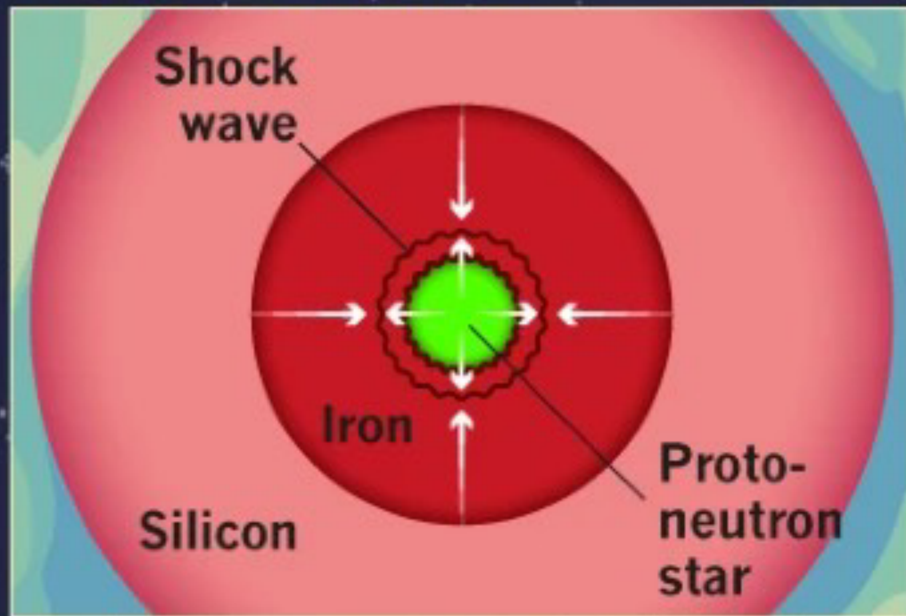
Simulation of a Core-Collapse SN explosion

- e- degenerate iron core collapses
- *P* surpasses e$^-$ degenerate
- Fe -> He, *photodisintegration*
- $p^+ + e^- = n + \nu$
- core collapse accelerates
- strong nuclear force becomes repulsive
- core **bounces** and send shock waves outwards
- trapped **neutrinos** further accelerate shock waves
- 0.1*c* shocks reach surface and heat it to 500,000 K



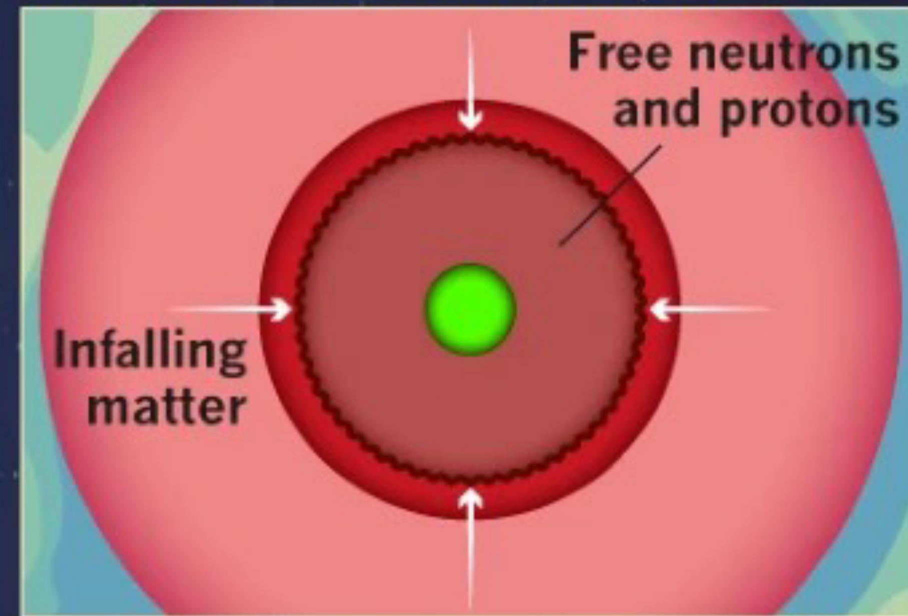
HOW TO BLOW UP A STAR

1. CORE BOUNCE



The growing iron core collapses under gravity, forming a neutron star. Infalling material bounces off the neutron star, creating a shock wave.

2. SHOCK STAGNATION

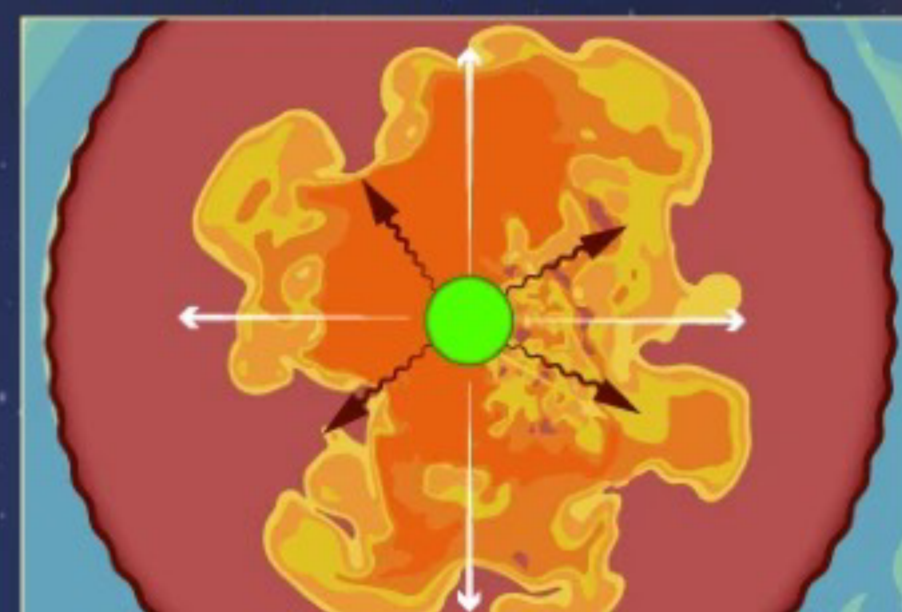


The outward-travelling shock wave collides with still-falling iron in the outer layers of the iron core and stalls.

3. NEUTRINO HEATING

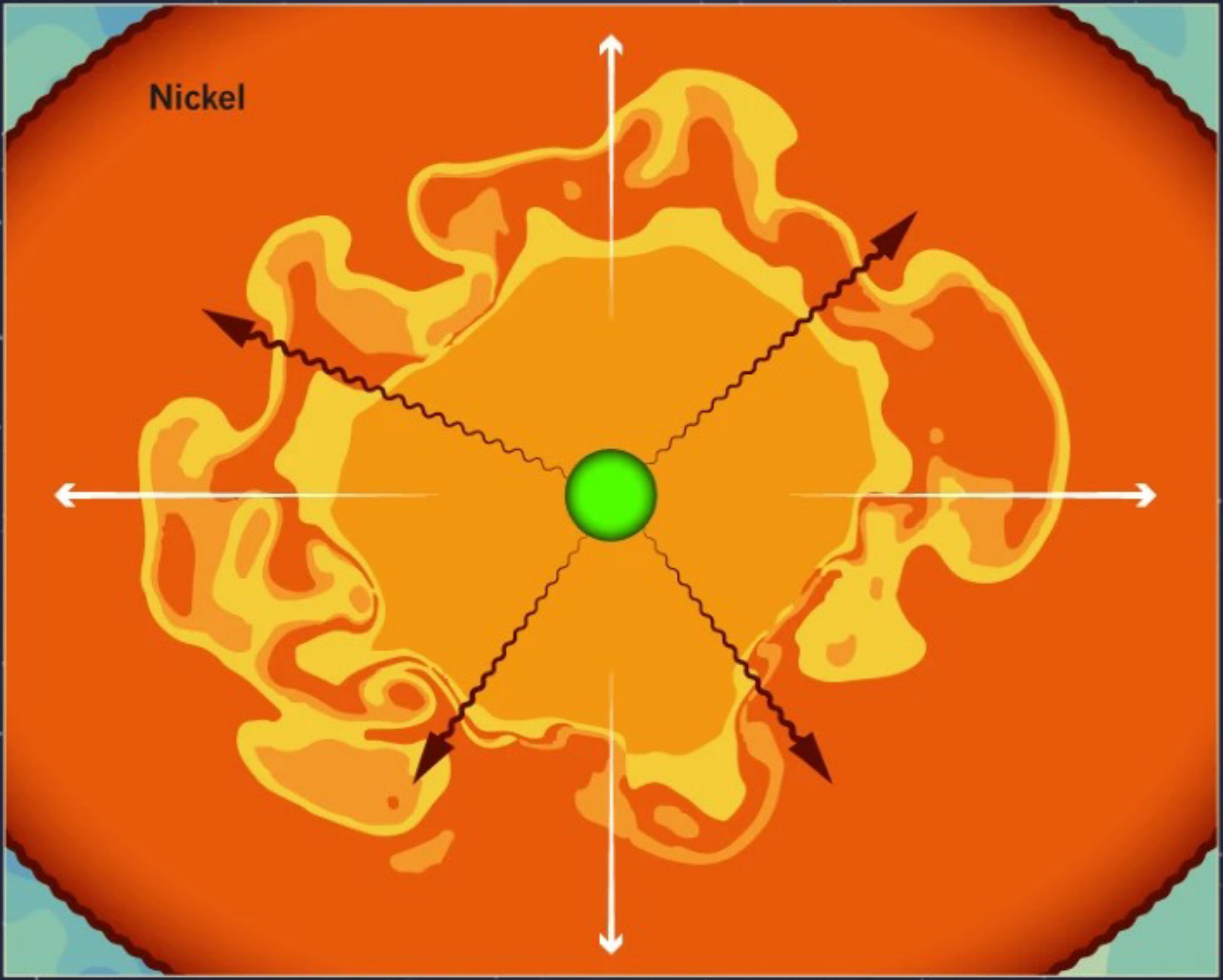
Neutrinos emerge from the neutron star and heat up surrounding matter. The heat creates violent sloshing motions and bubbling convection.

4. SHOCK REVIVAL



The ferocious motions in the hot core create a pressure that helps to revive the shock wave and drive it out.

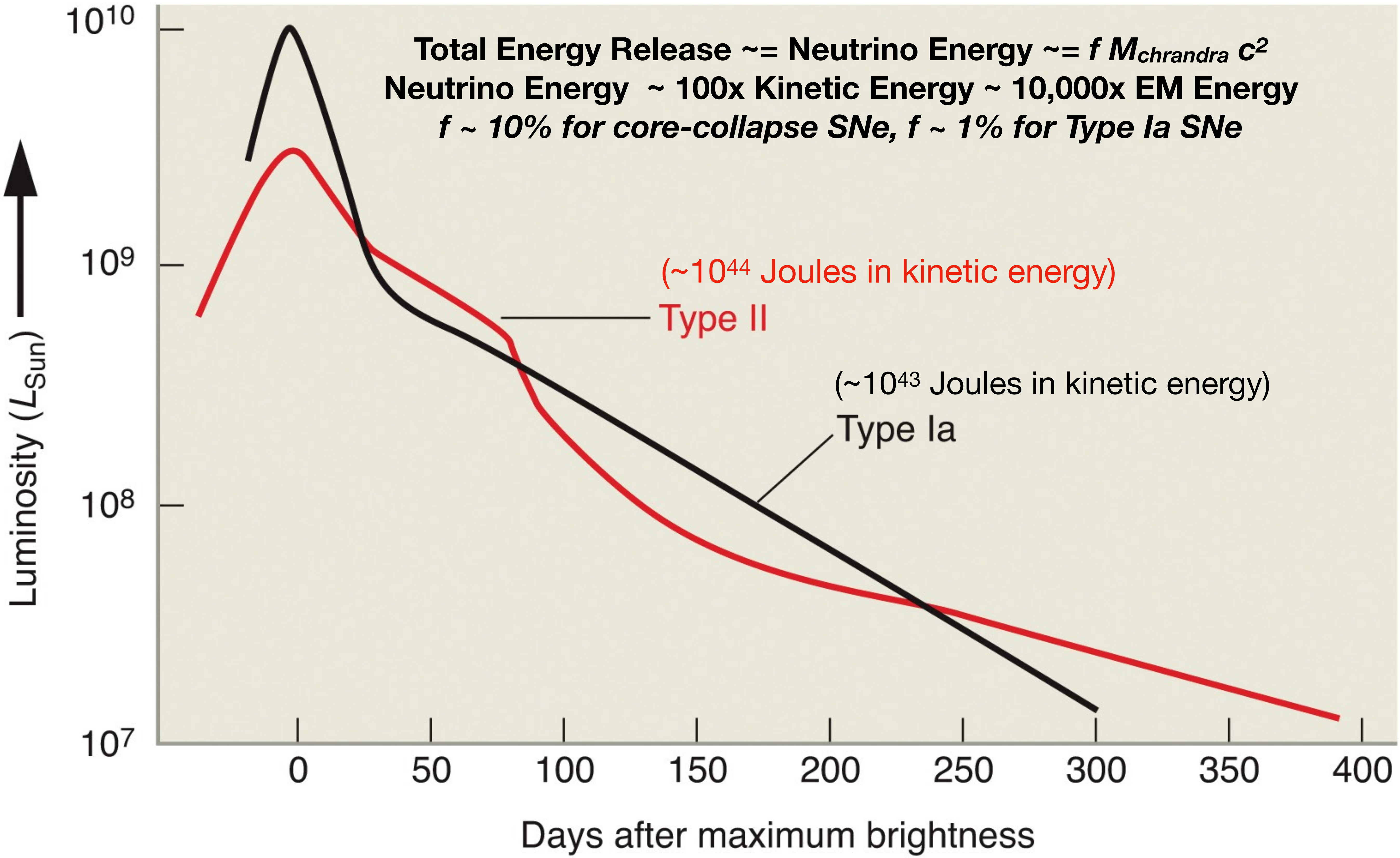
5. EXPLOSION AND NUCLEOSYNTHESIS



Just a few hundred milliseconds after the shock wave first forms, it accelerates out of the core — although it can take as long as a day to reach the star's surface. The energy of the shock wave creates new elements, such as radioactive nickel. In the neutrino-heated, inner part of the explosion, nuclei also capture free neutrons or protons to form elements heavier than iron.

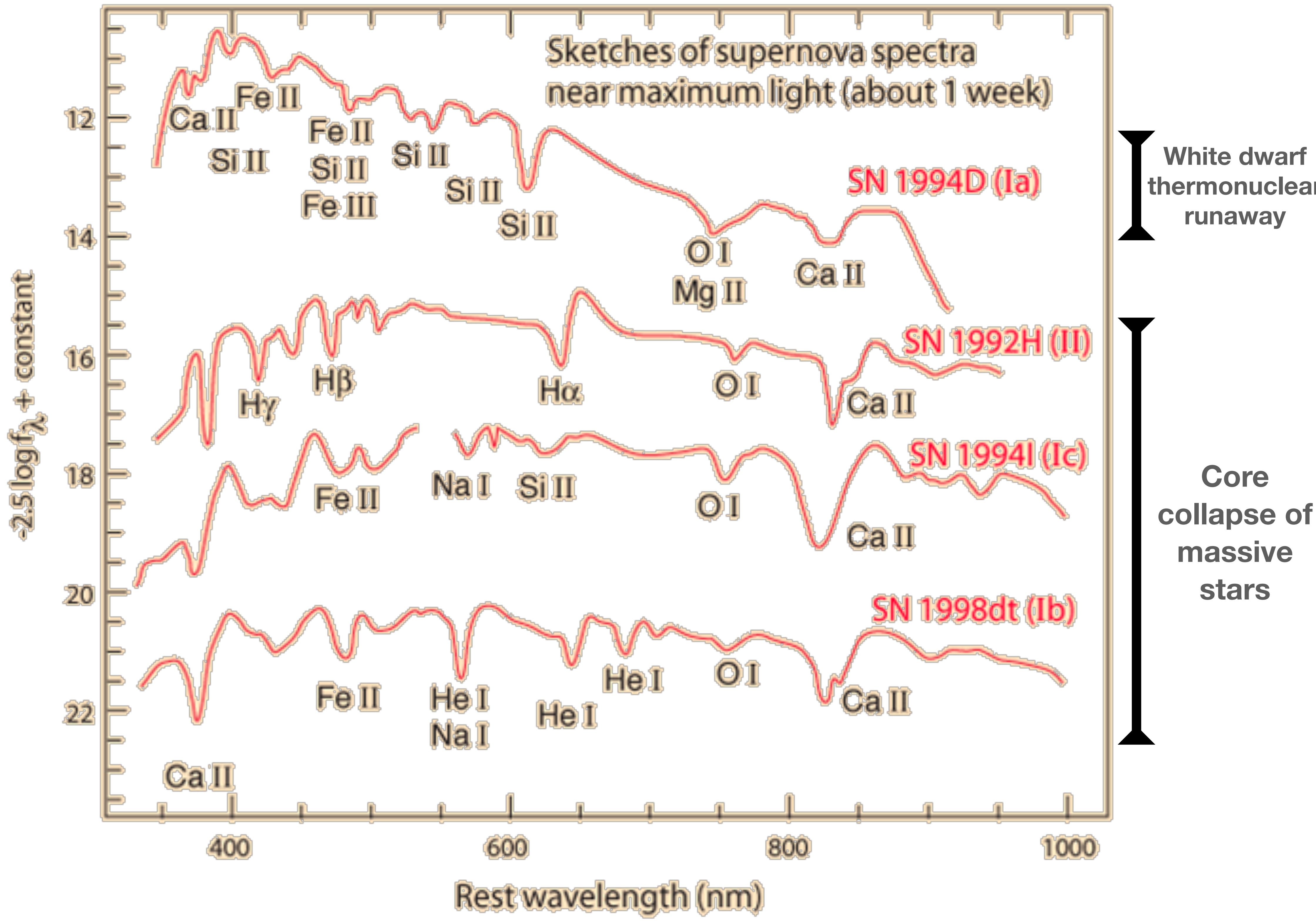
©nature

Light Curves & Energy Output: Type Ia vs. Type II Supernovae



Copyright © 2022 W. W. Norton & Company, Inc.

Spectra: Type I (No Hydrogen lines) vs. Type II (Hydrogen lines)

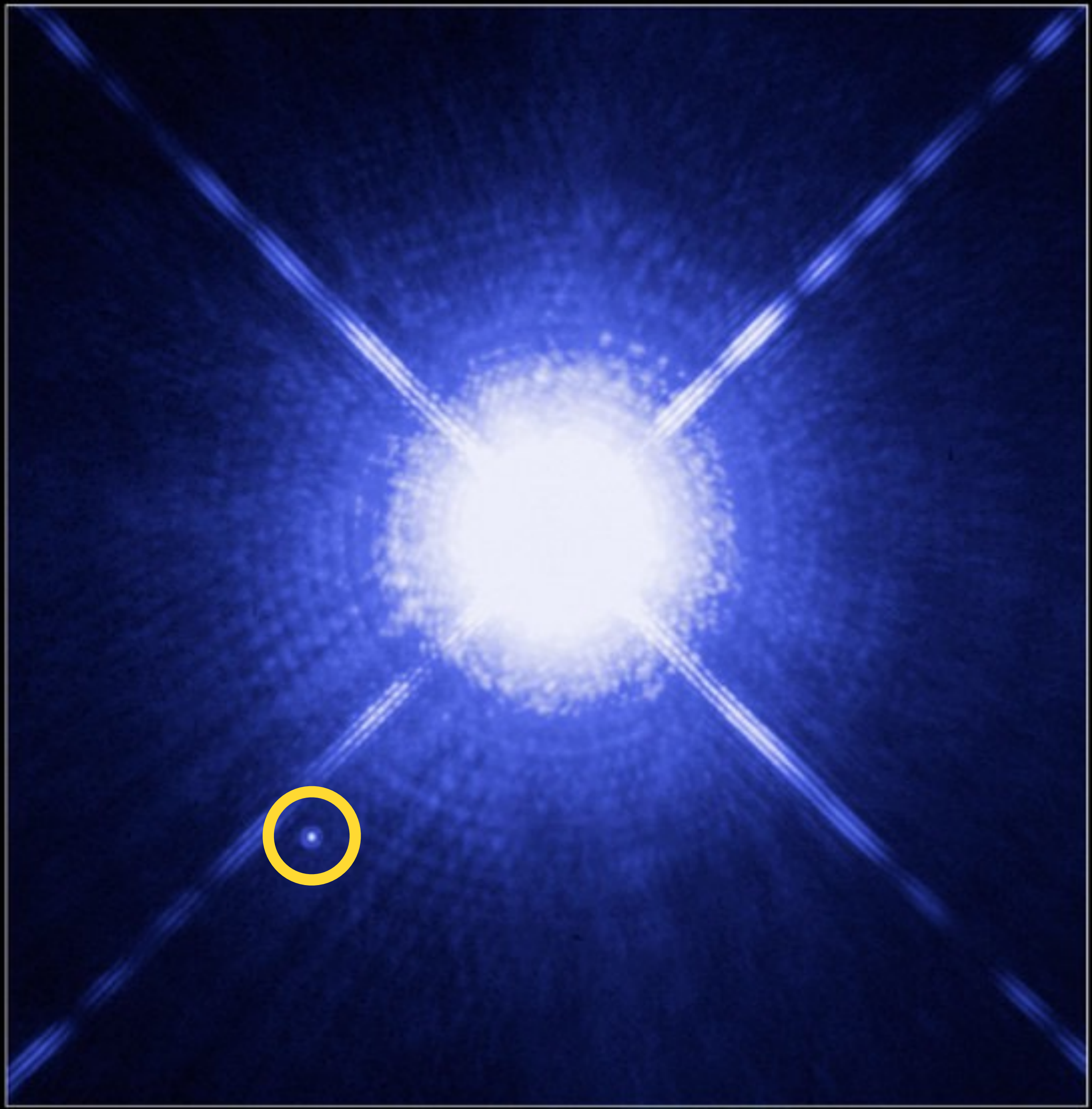


Sketches of spectra from Carroll & Ostlie, data attributed to Thomas Matheson of National Optical Astronomy Observatory.

Properties of Neutron Stars:

Theoretical Models

Sirius B - the white dwarf companion of the Dog Star



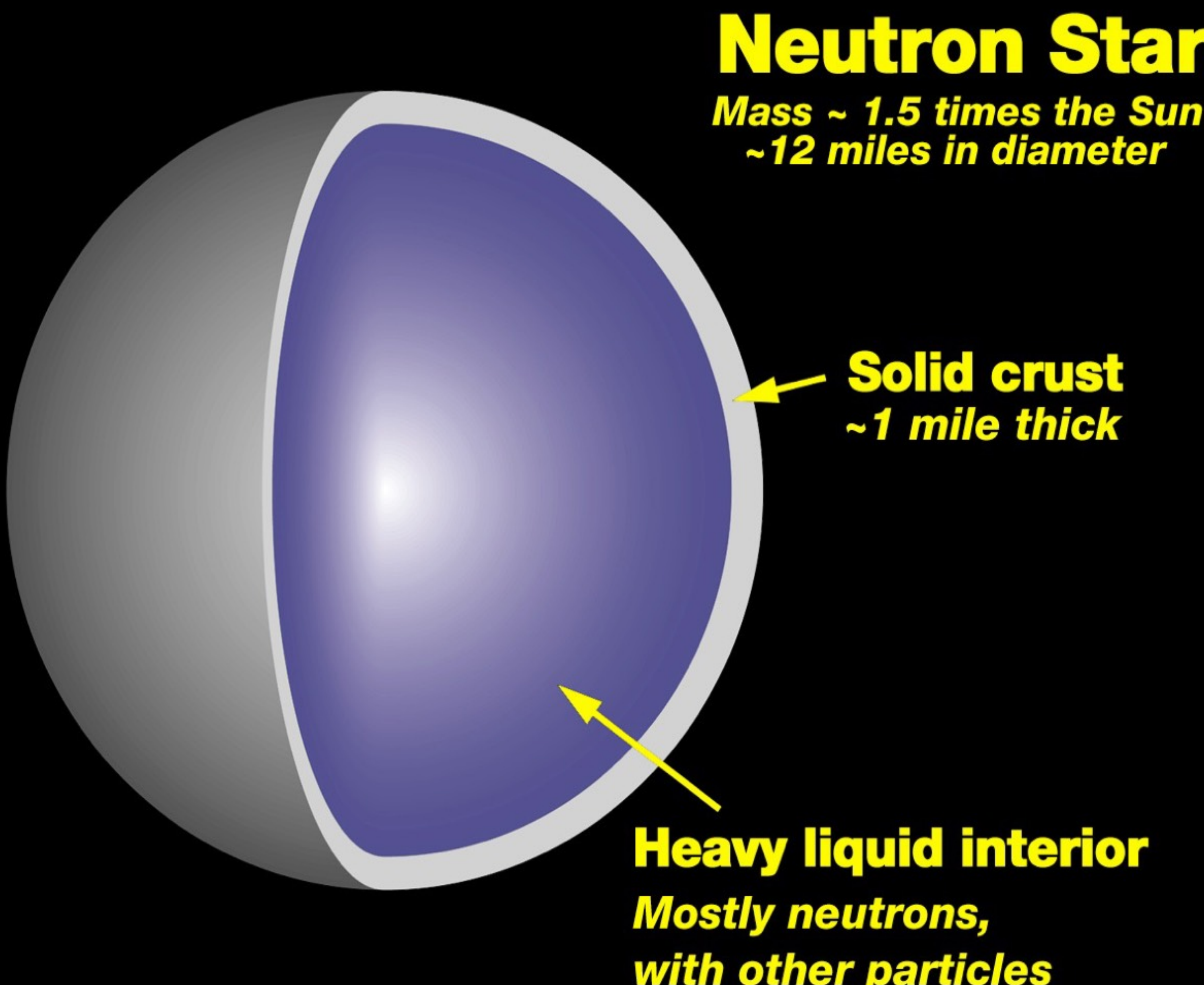
Sirius A and Sirius B
Hubble Space Telescope • WFPC2

NASA, ESA, H. Bond (STScI), and M. Barstow (University of Leicester) STScI-PRC05-36a

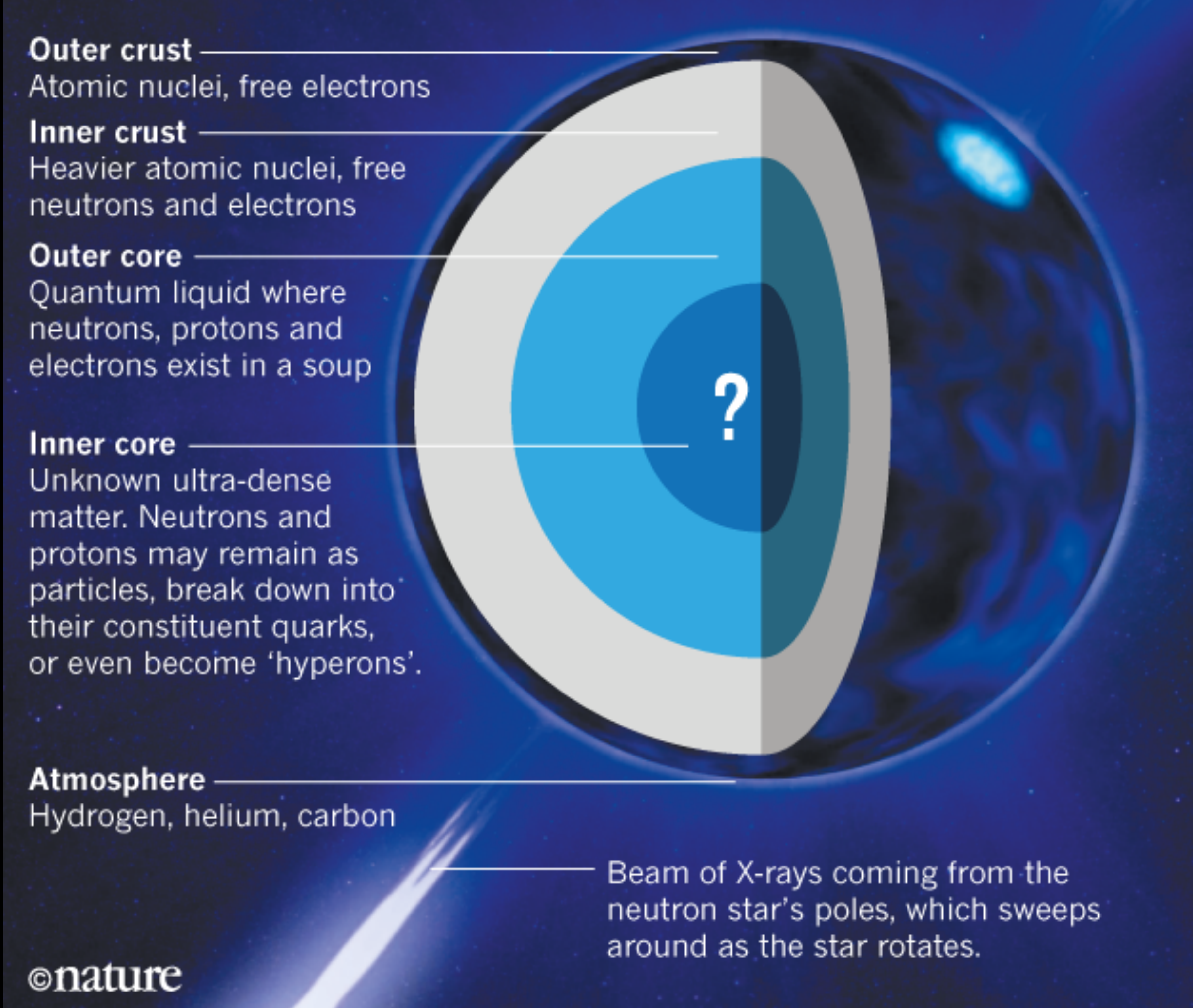
- Inferred properties of Sirius B:
  - 1 Solar Mass
  - 0.03 Solar Luminosity
  - 27,000 K surface temperature
  - 5500 km radius (Earth-size)
- Sirius B represent a class of objects called **White Dwarfs (WDs)**

- The physical conditions of WDs are extreme:
  - extreme density ($\rho \approx$ 3e9 kg/m^3) ($n_e \sim$ 1e36 /m^3)
  - extreme surface gravity (HW)
  - extreme pressure at the center

Neutron stars are extremely compact and dense, even compared to white dwarfs



- packing a solar mass into a ball of ~10 km in radius results in a density of ~10^9 tons per teaspoon (compared to ~10 tons on a white dwarf)
- surface gravitational field – 300,000 times that of Earth ($g = GM/R^2$)
- To escape from a neutron star, an object would have to reach 50% the speed of light!


Outer crust
Atomic nuclei, free electrons
Inner crust
Heavier atomic nuclei, free neutrons and electrons
Outer core
Quantum liquid where neutrons, protons and electrons exist in a soup
?
Inner core
Unknown ultra-dense matter. Neutrons and protons may remain as particles, break down into their constituent quarks, or even become ‘hyperons’.
Atmosphere
Hydrogen, helium, carbon
Beam of X-rays coming from the neutron star’s poles, which sweeps around as the star rotates.
©nature

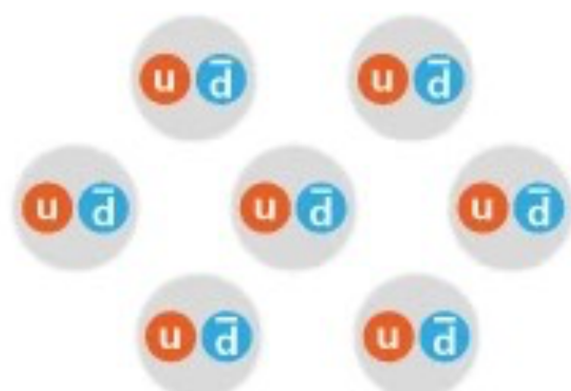
Core scenarios

A number of possibilities have been suggested for the inner core, including these three options.

- u Up quark
- d Down quark
- s Strange quark
- d̄ Anti-down quark

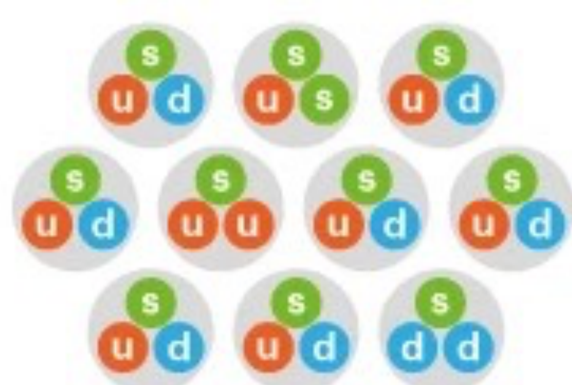
Quarks

The constituents of protons and neutrons — up and down quarks — roam freely.



Bose–Einstein condensate

Particles such as pions containing an up quark and an anti-down quark combine to form a single quantum-mechanical entity.



Hyperons

Particles called hyperons form. Like protons and neutrons, they contain three quarks but include 'strange' quarks.

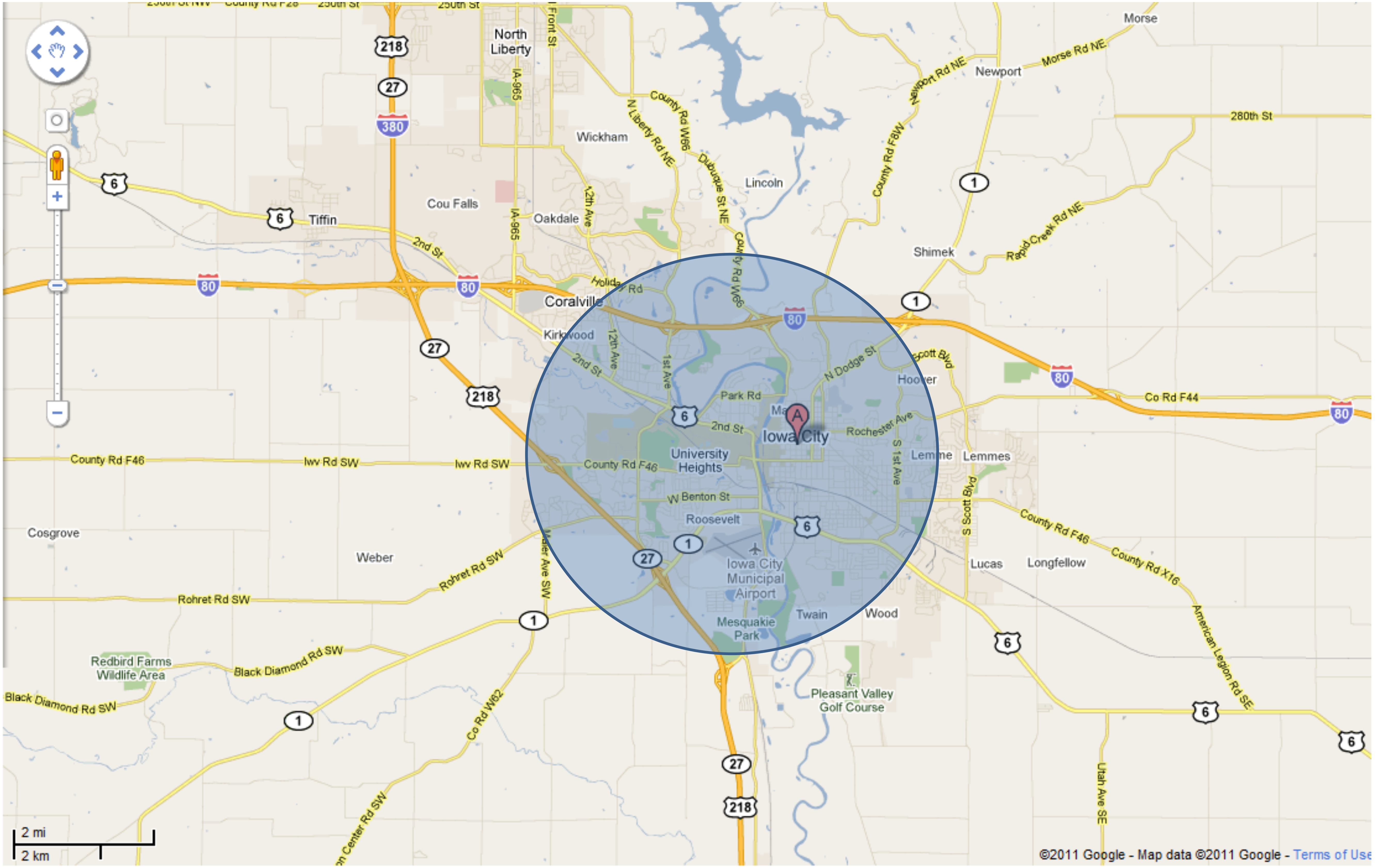
©nature

X-ray hotspots rotate in two scenarios for the pulsar J0030+0451, based on analysis of NICER data (Neutron Star Interior Composition Explorer)

Observable Neutron Stars I:

Pulsars

Neutron star has a size of a small city - How can we find them?



What are the unique observational properties of neutron stars?

- How can we tell if any of the objects in the image is a neutron star?

Contact (1997): Jodie Foster - Detecting the signal at the VLA

The Discovery of Pulsars in 1967

1967: Jocelyn Bell Burnell
PhD student of Anthony Hewish
at Cambridge University, England

Helped build a radio telescope to study the solar wind by looking at "twinkling" of background radio sources as their emission passes through the solar wind

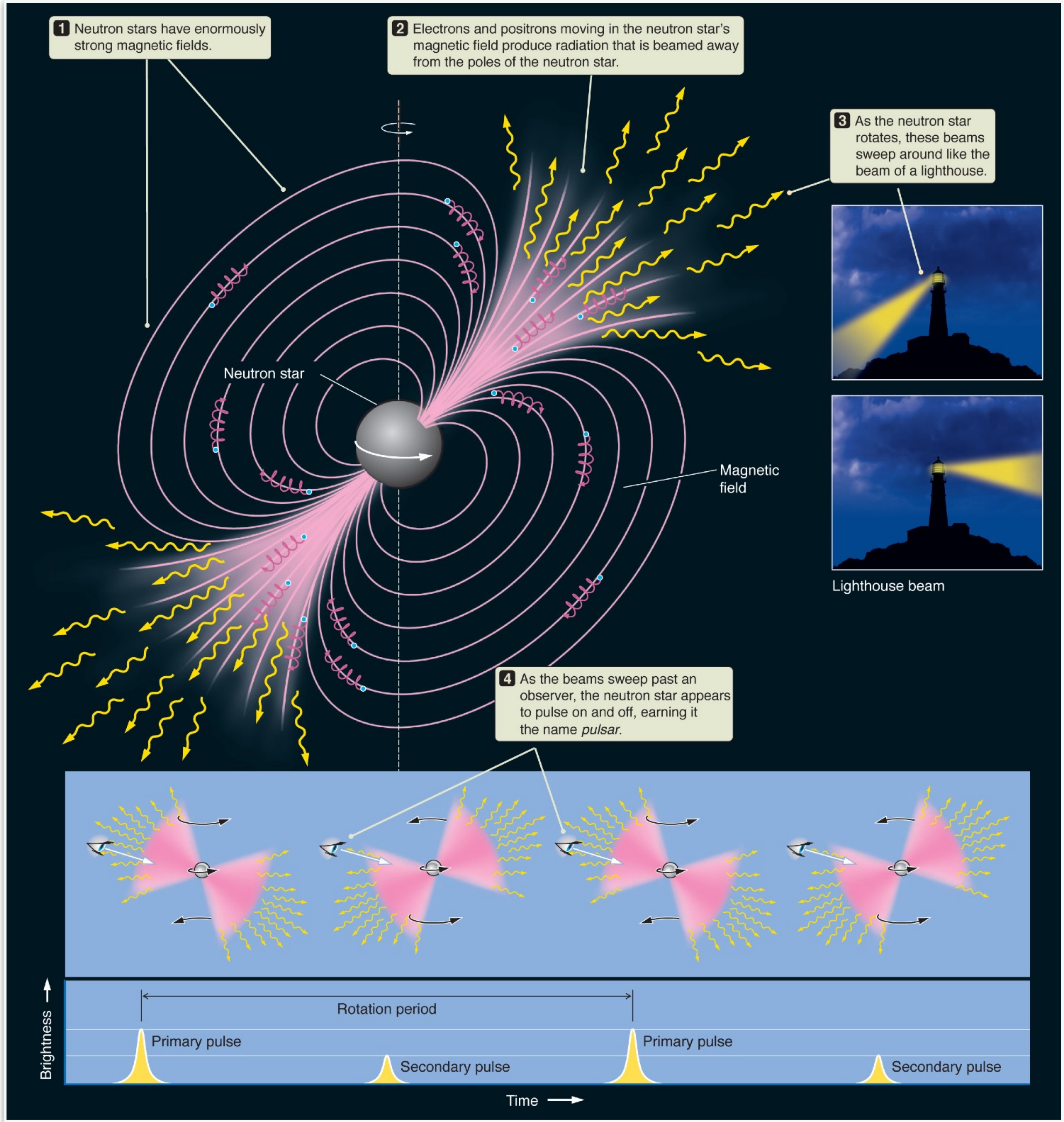
In Nov 1967, she discovered a repeating radio signal with P ~ 1s

Thought it could be detection of ET – "LGM1"
extraterrestrial (ET)
little green men (LGM)

Now known as PSR 1919+21

Pulsars

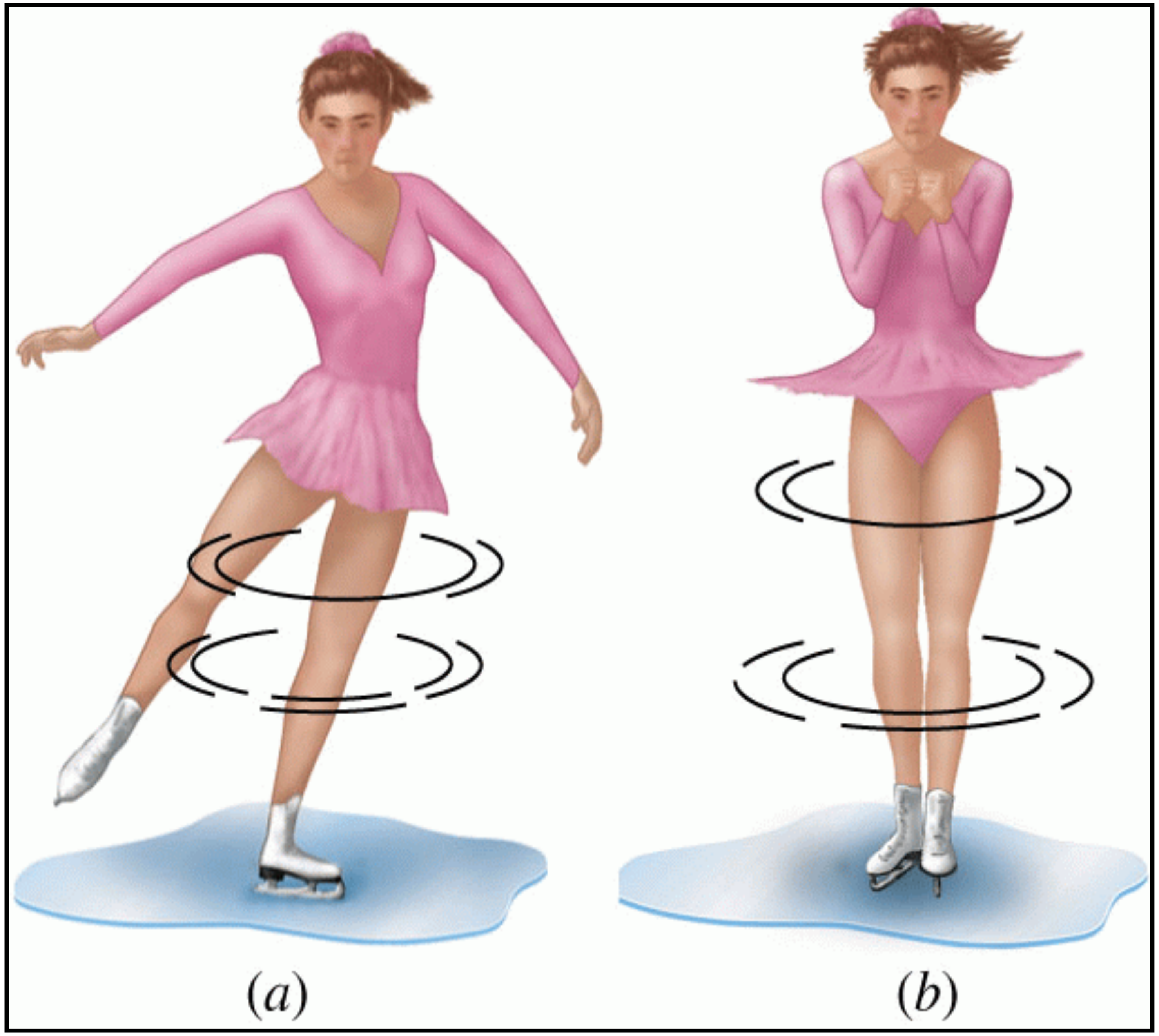
- Charged particles around rapidly rotating, highly magnetized *object* produce beam of **synchrotron radiation**
- The beams sweep by Earth like a lighthouse beam.



Neutron stars are expected to spin very fast!

Angular momentum of a uniform sphere, and L is conserved during collapse

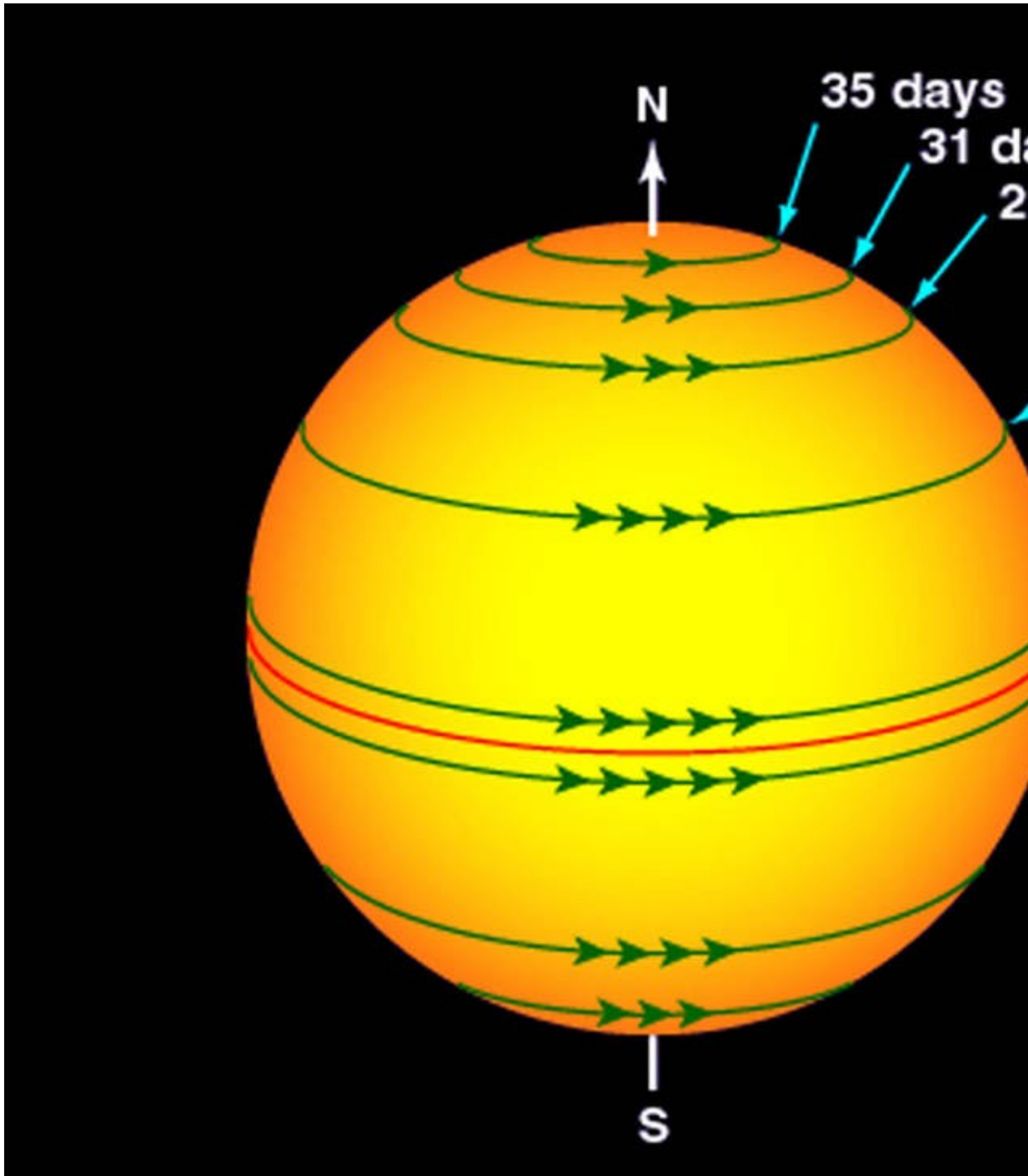
$$L = I\omega = \frac{2}{5}Mr^2\omega \Rightarrow \omega \propto r^{-2} \Rightarrow P \propto r^2$$



When the Sun (R = 7e5 km) collapses into a neutron star (R = 10 km):

What's the current angular velocity?
What will be the rotating period?

$$\omega_\odot = \frac{2\pi}{P} = 14 \text{ deg/day for } P = 25 \text{ days}$$



When it collapses to 10 km radius, its rotation period will be P = 0.44 milliseconds.

Conservation of magnetic flux: Neutron stars are expected to have strong magnetic fields

The collapse of a star concentrates the magnetic field on the surface

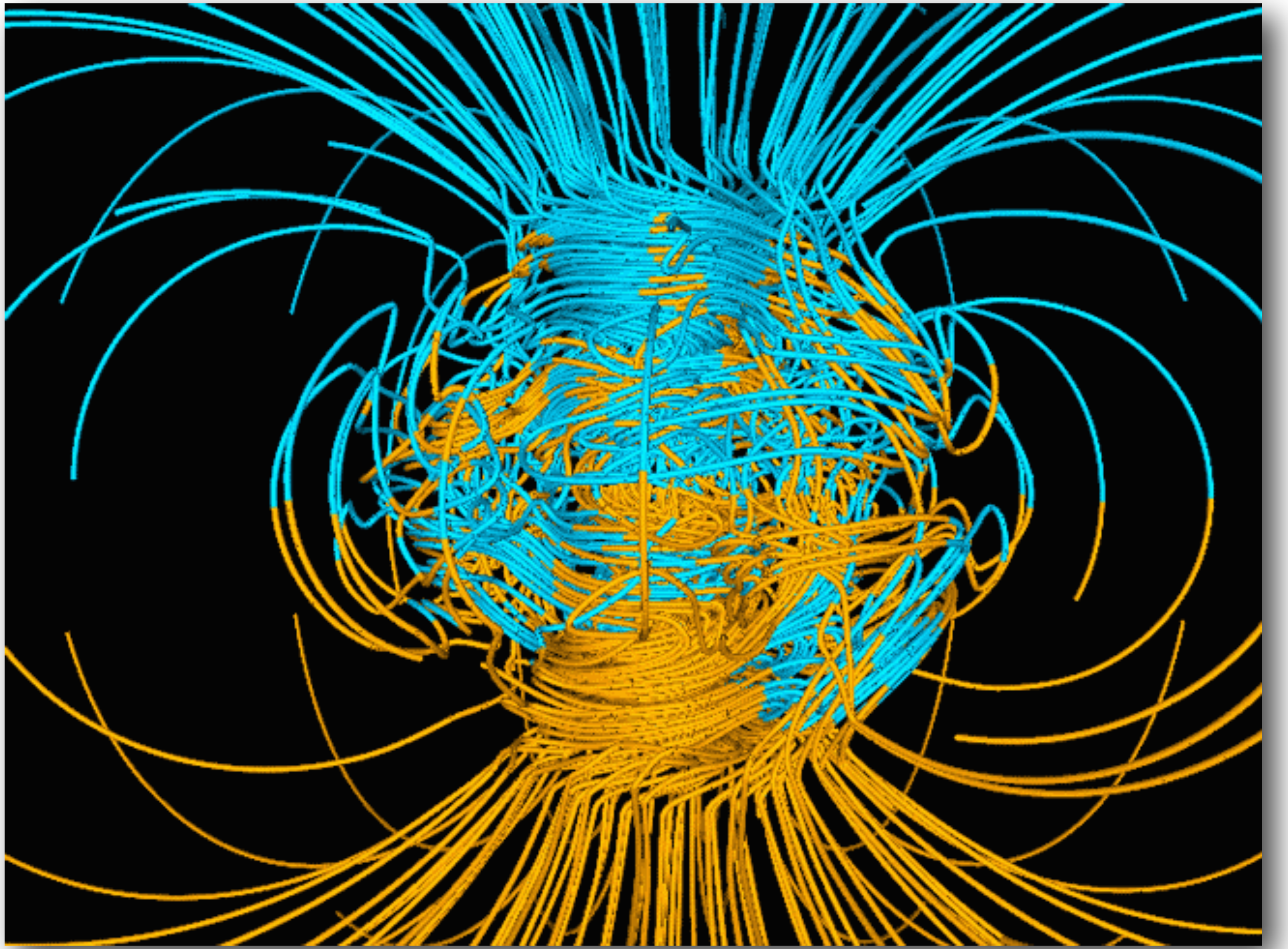
Similar to angular velocity, $B \propto R^{-2}$

shrinking to a radius of 10 km, the Sun's magnetic field would be 10^{10} times as strong!

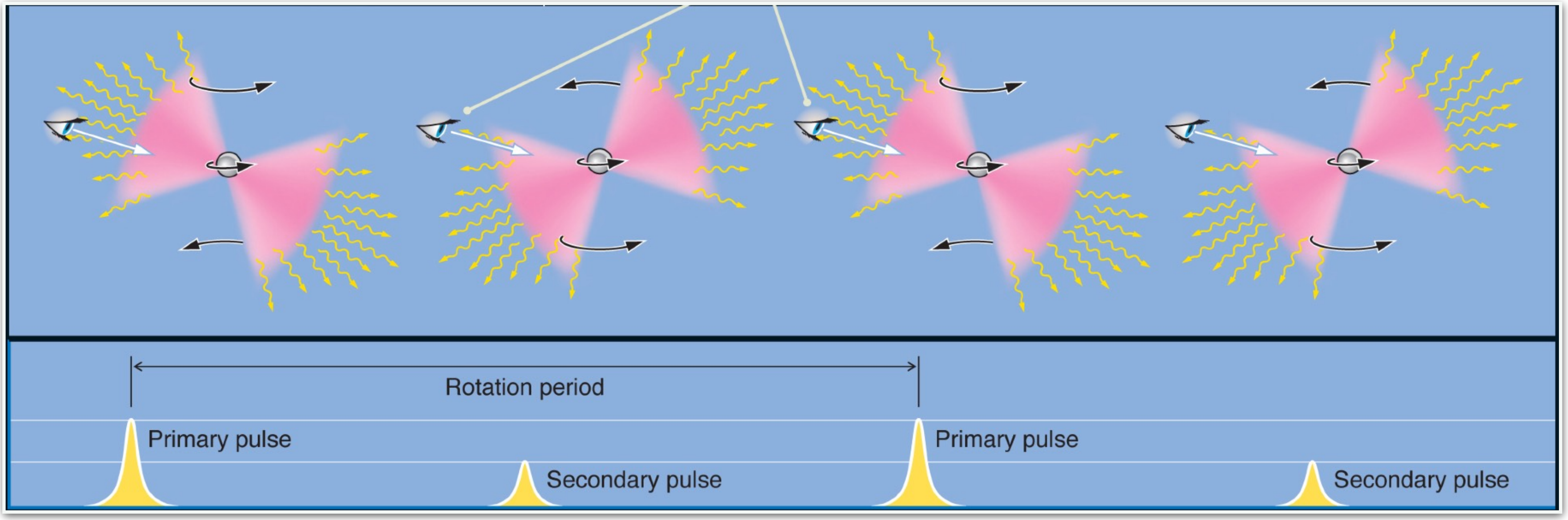
Magnetic field for normal star (e.g. Sun): a few Gauss (G)

Magnetic field for neutron star: up to 10^{15} G

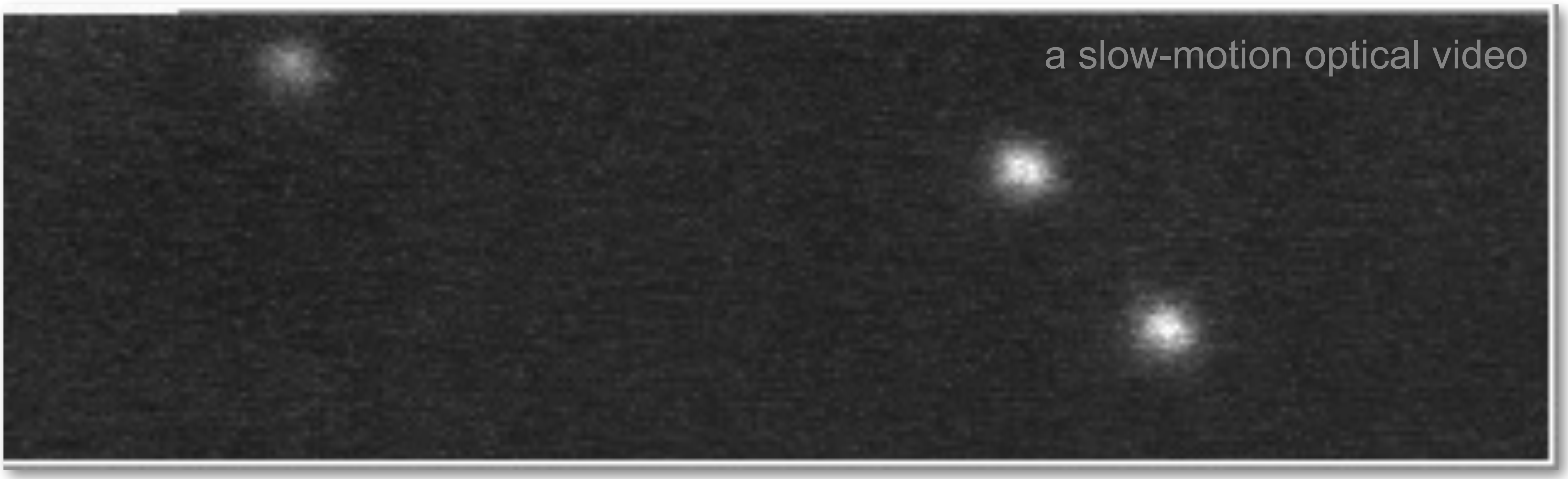
Strongest magnetic field produced in a laboratory (for a few seconds): 10^{6} G



Optical Pulsars and Primary vs. Secondary Pulses



The pulsar near the center of the Crab Nebula

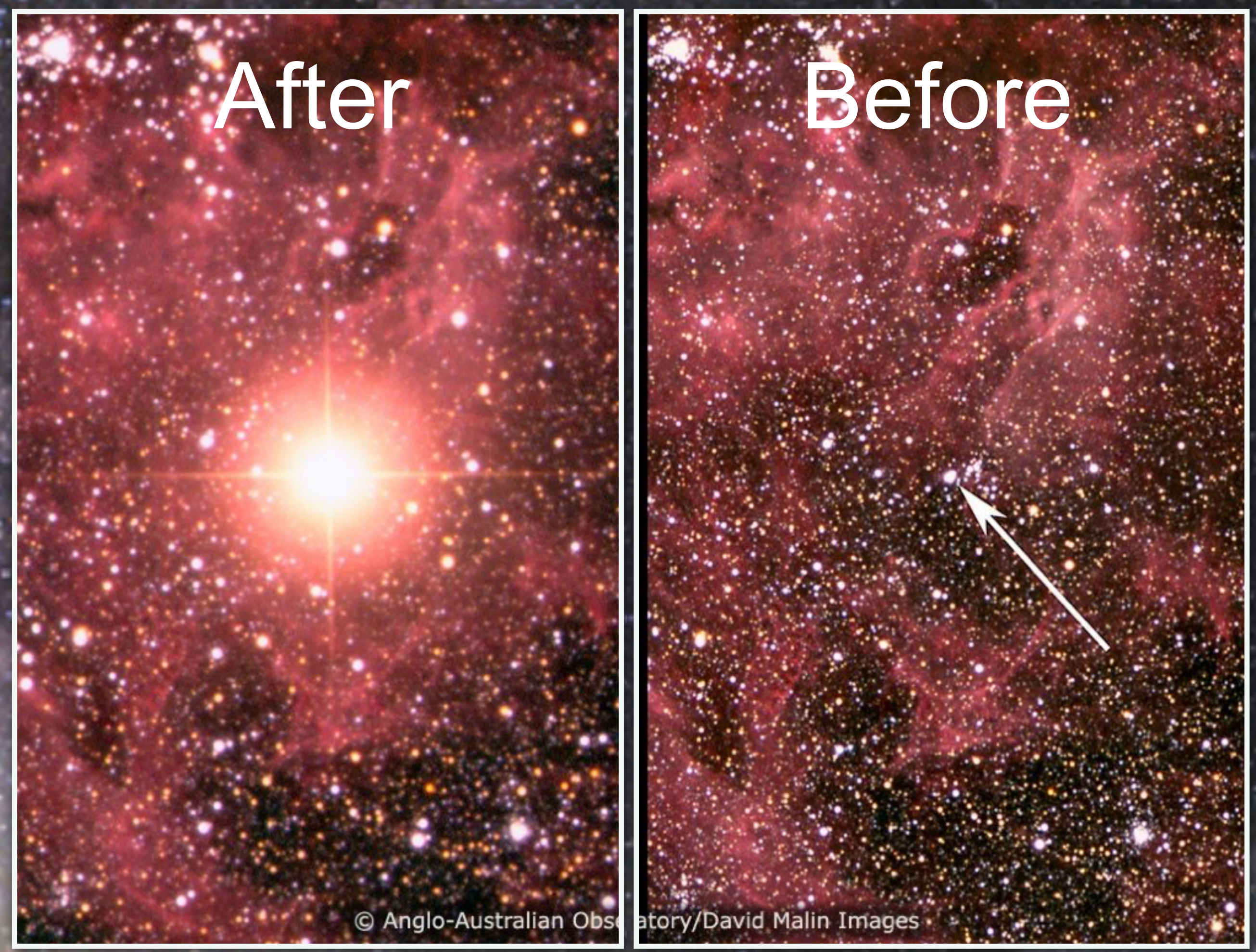


Pulsars animation

Witnessing the formation of a Supernova Remnant (SNR)

SN 1987A

SN 1987A



LMC

d = 50 kpc

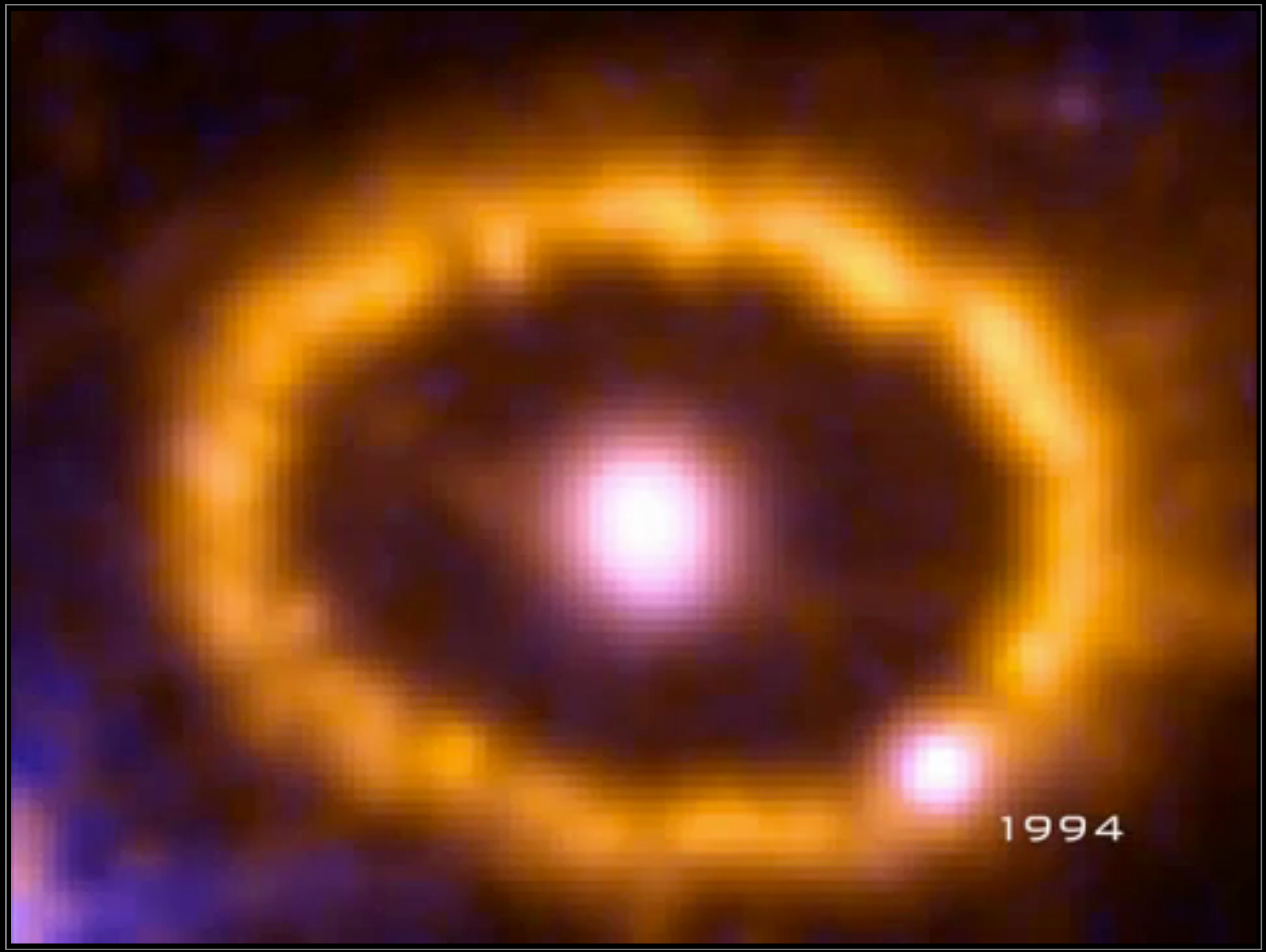
Dec = -70d

$M^* = 1e10\ M_{sun}$

Zoom in onto SN 1987A

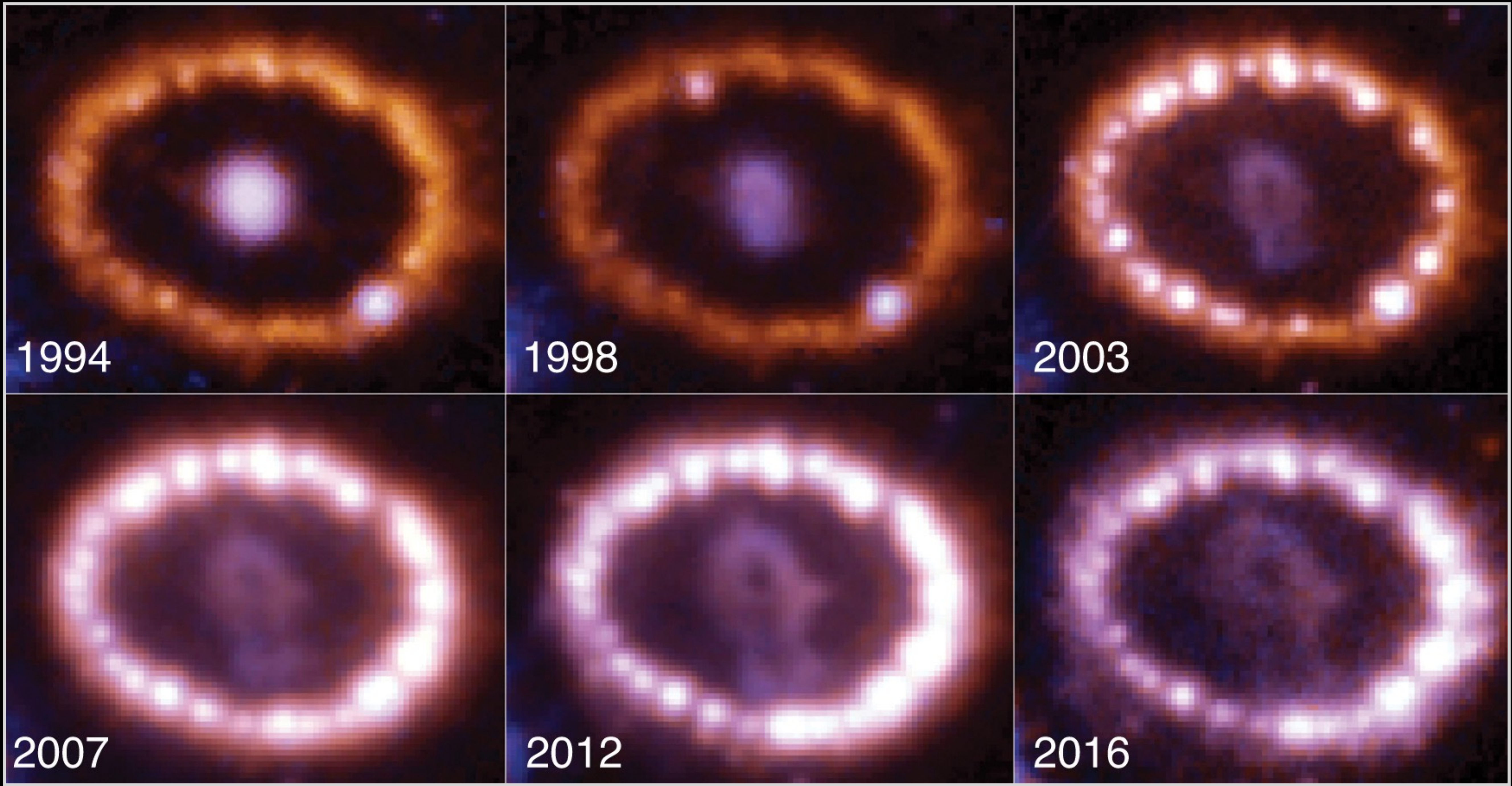
The firework after the explosion

SN ejecta catching up with the mass loss from stellar winds



The firework after the explosion

SN ejecta catching up with the mass loss from stellar winds



Neutrinos from SN 1987A

19 neutrinos were detected
(in Japan & Ohio)
the day ***before*** the
optical explosion was seen

Detection of neutrinos supports the core-collapse model: neutrinos are released when protons and electrons combine to form neutrons

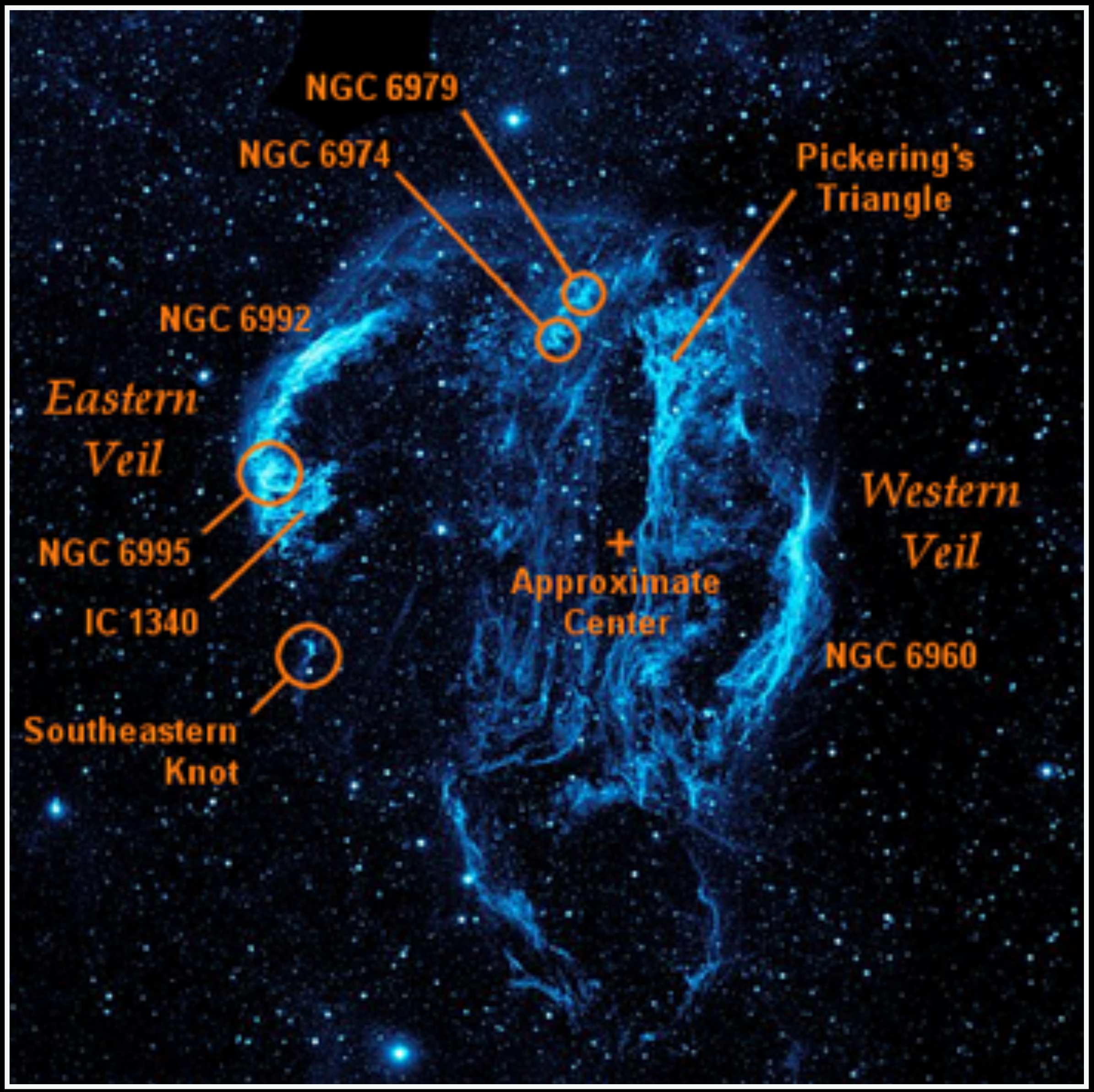
How to Measure the Age and Distance of a Supernova Remnant?

e.g., the Crab SNR’s association w/ SN 1054

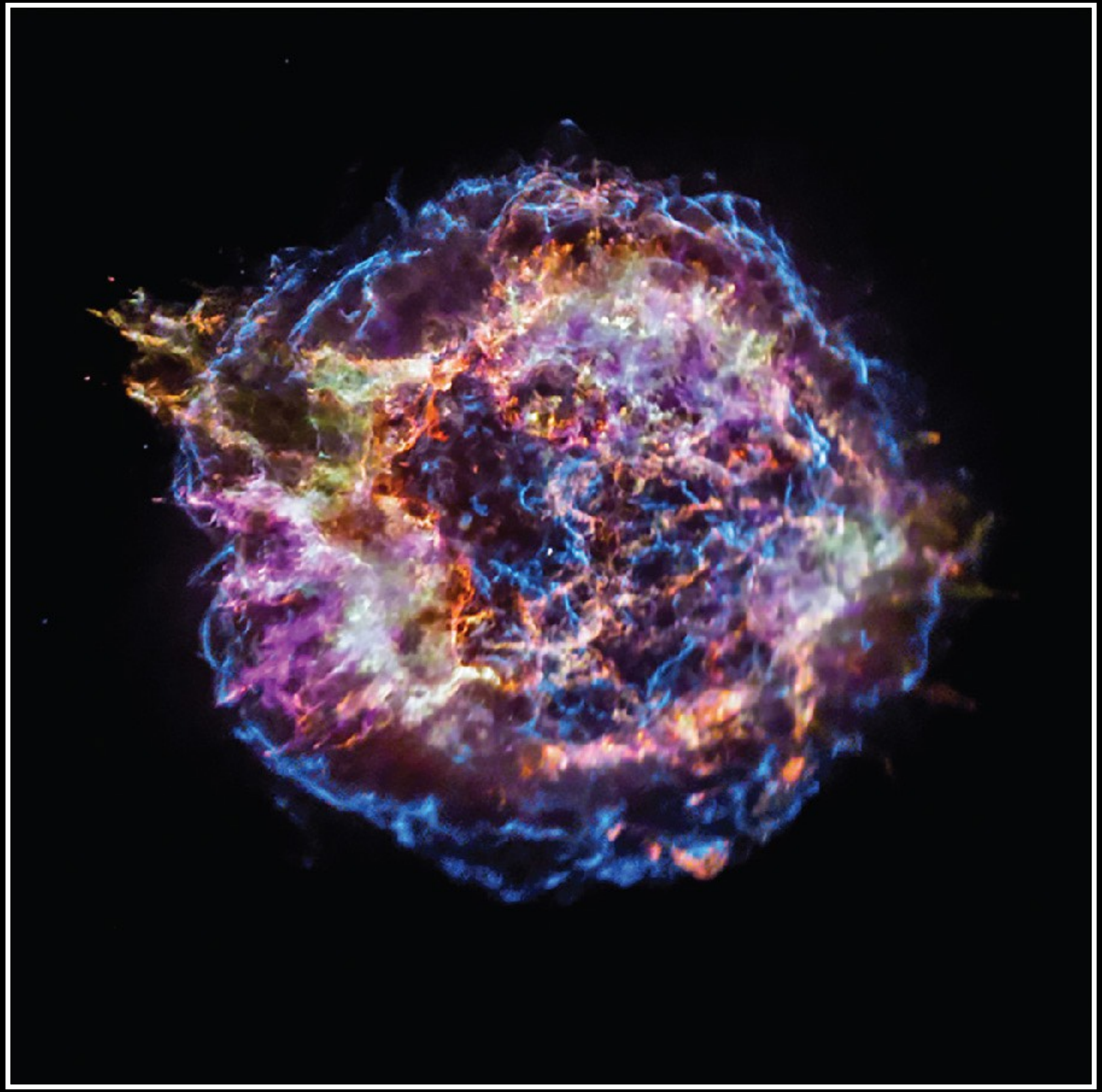
Zoom into Veil Nebula (a SN remnant formed 10,000 yrs ago)

When you see a SN remnant, how would you measure the age of it and thus estimate when the SN exploded?

Veil Nebula



Cassiopeia A



The Crab SN remnant is still *visibly* expanding

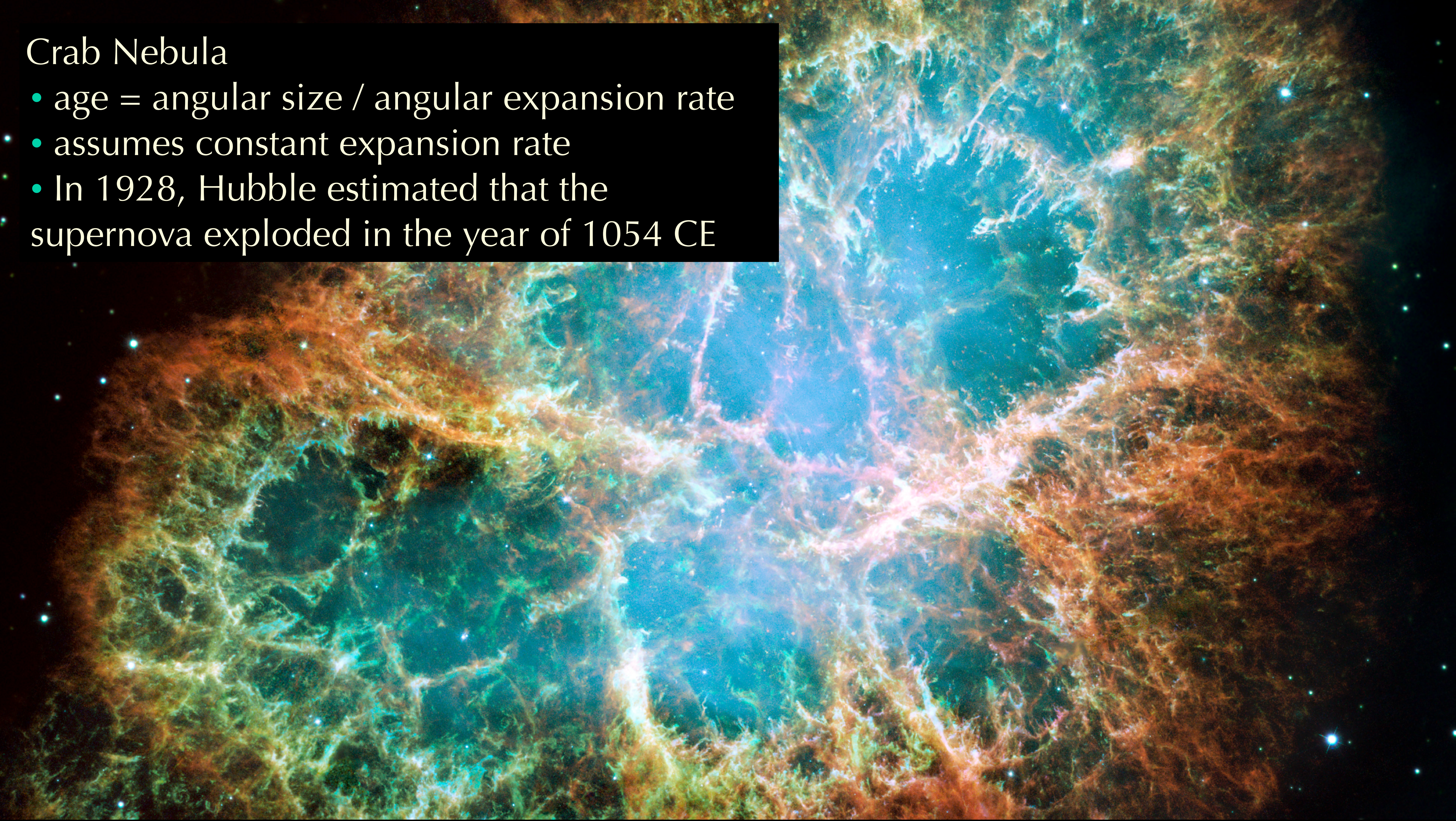
How to associate a remnant with a supernova in the past?

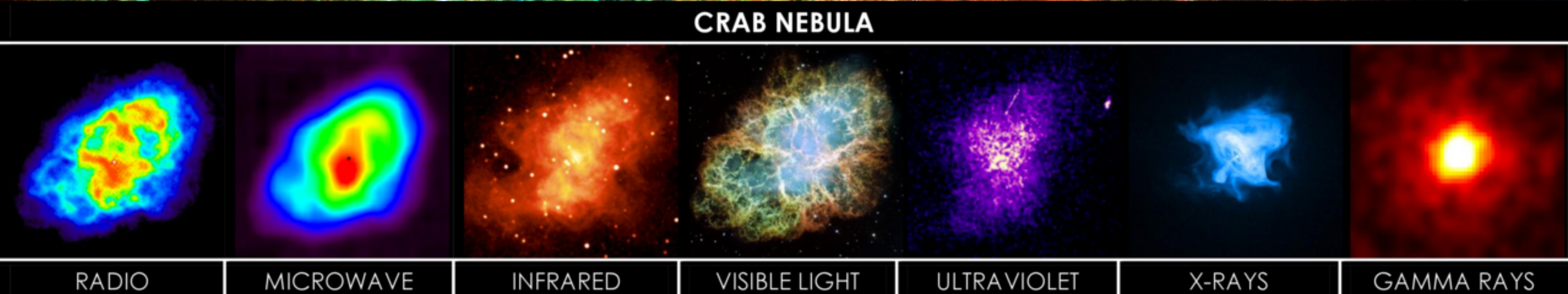
Expansion of the Crab Nebula

Years 1999 and 2012

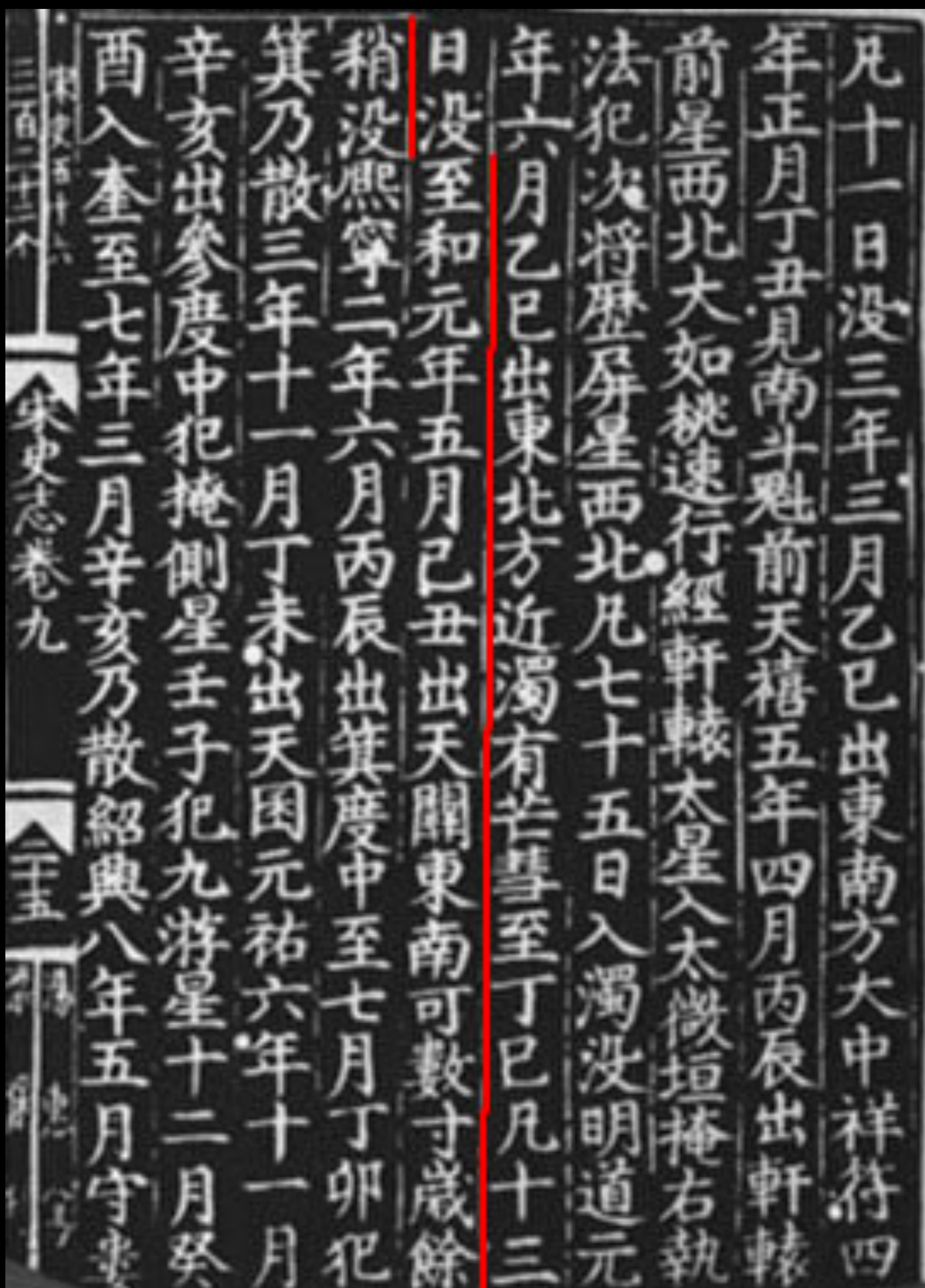
Crab Nebula

- age = angular size / angular expansion rate
- assumes constant expansion rate
- In 1928, Hubble estimated that the supernova exploded in the year of 1054 CE





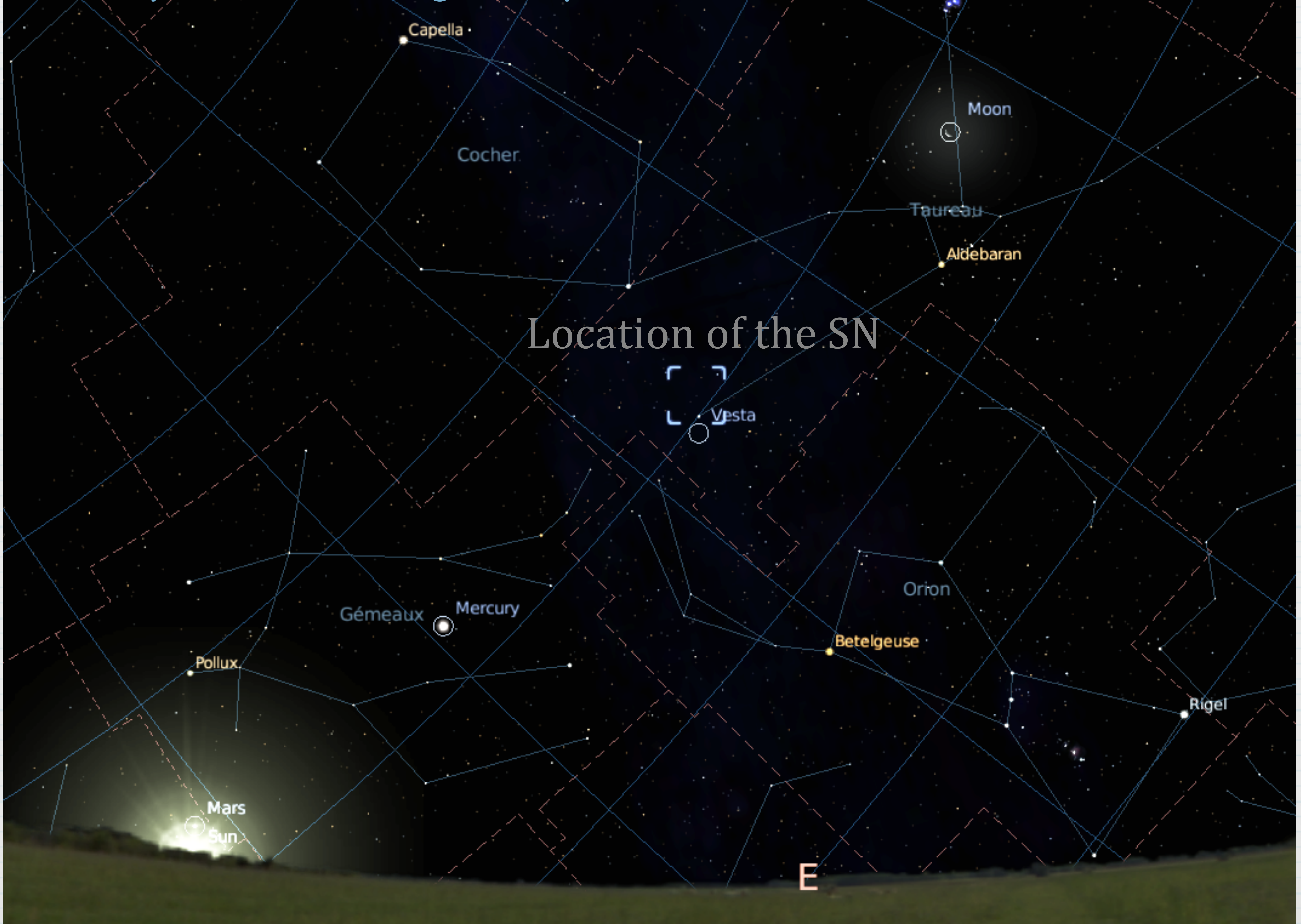
- The supernova was seen by the entire world in July 1054 CE.
- Peak magnitude between -7 and -4.5 (brighter than Venus)
- The event was documented by astronomers in Song Dynasty
- There is also some drawing evidence in Native American ruins in New Mexico, Chaco Canyon



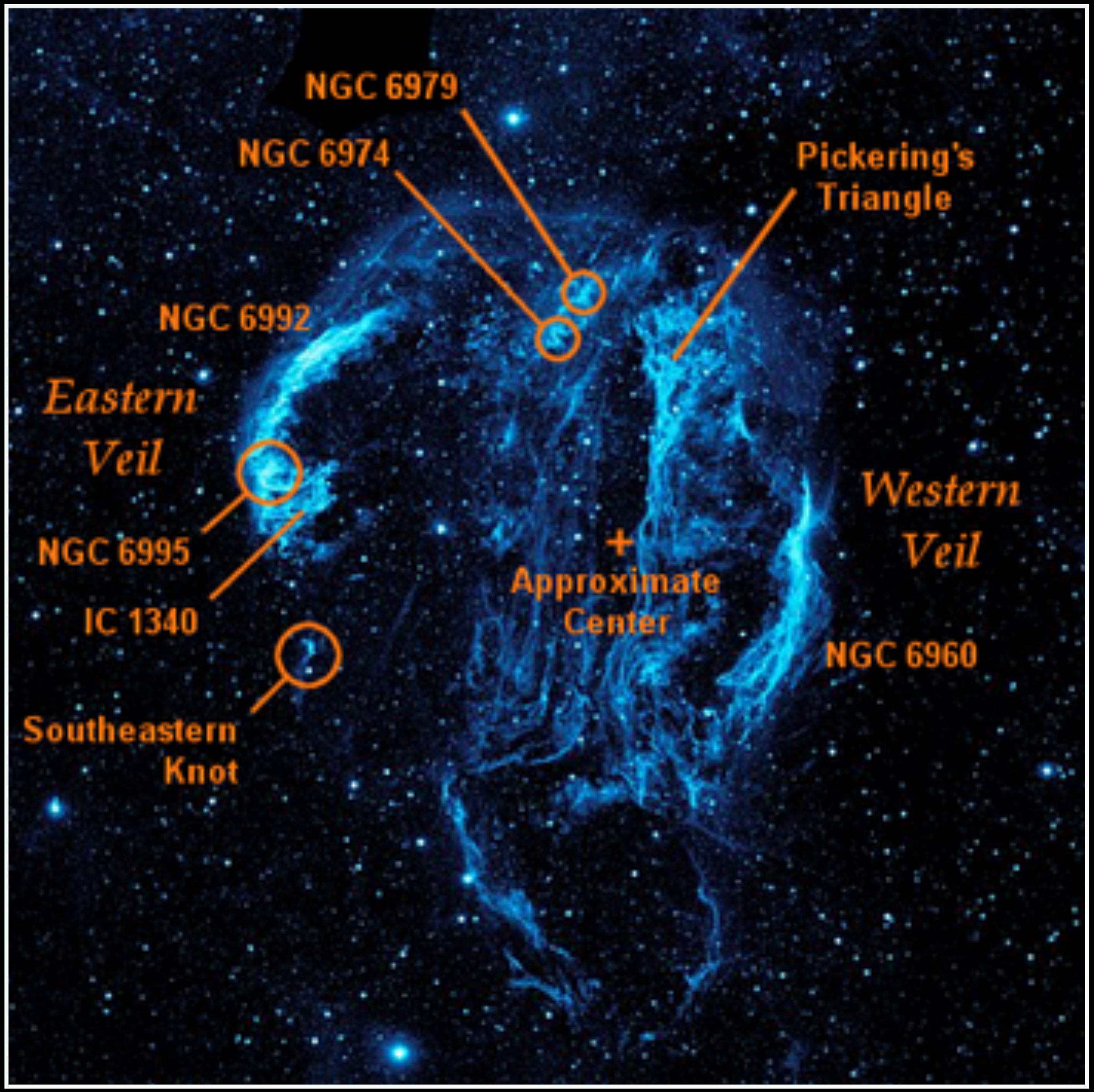
凡十一日沒三年三月乙巳出東南方大中祥符四年正月丁丑見南斗魁前天禧五年四月丙辰出軒轅前星西北大如桃速行經軒轅大星入太微垣掩右執法犯次將歷屏星西北凡七十五日入濁沒明道元年六月乙巳出東北方近濁有芒彗至丁巳凡十三日沒至和元年五月己丑出天關東南可數寸歲餘稍沒熙寧二年六月丙辰出箕度中至七月丁卯犯箕乃散三年十一月丁未出天囷元祐六年十一月辛亥出參度中犯掩廁星壬子犯九斿星十二月癸酉入奎至七年三月辛亥乃散紹興八年五月守婁

宋史志卷九

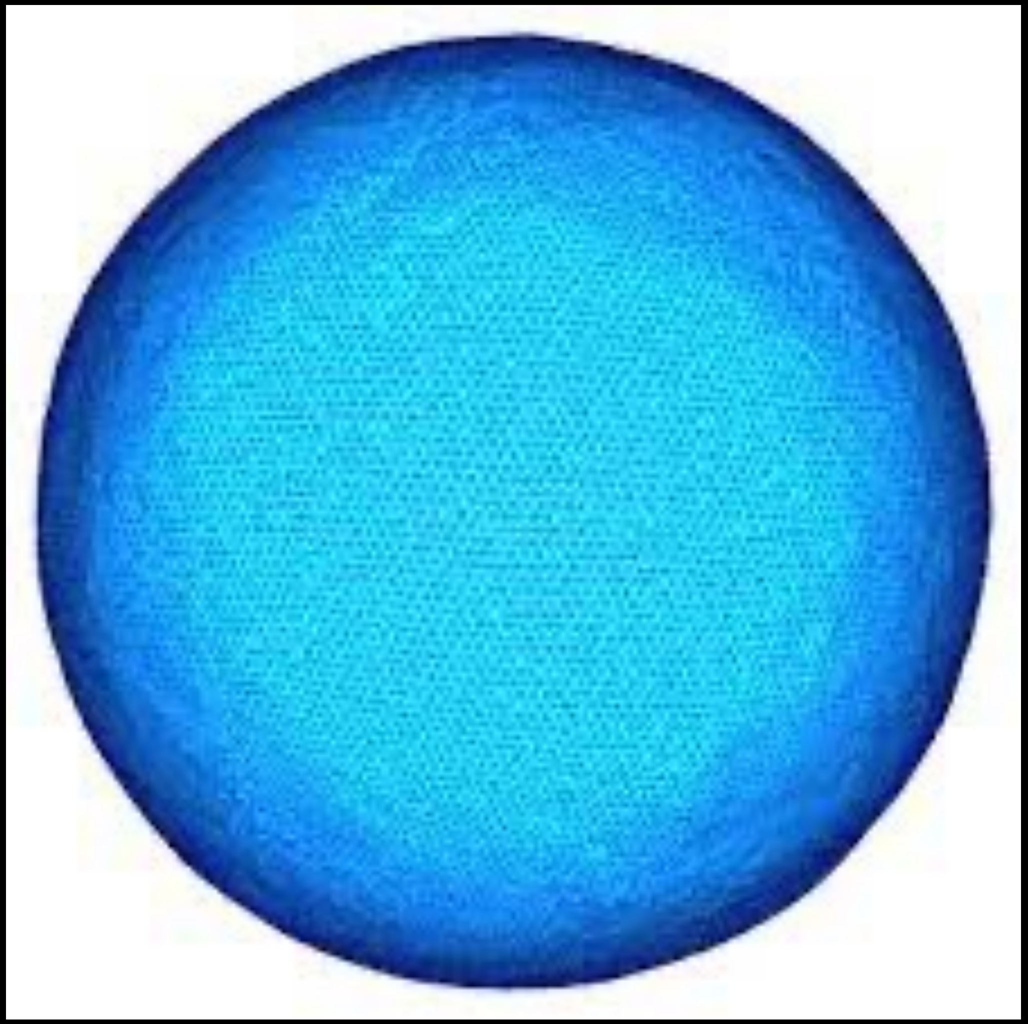
The Sky in the morning of July 4, 1054

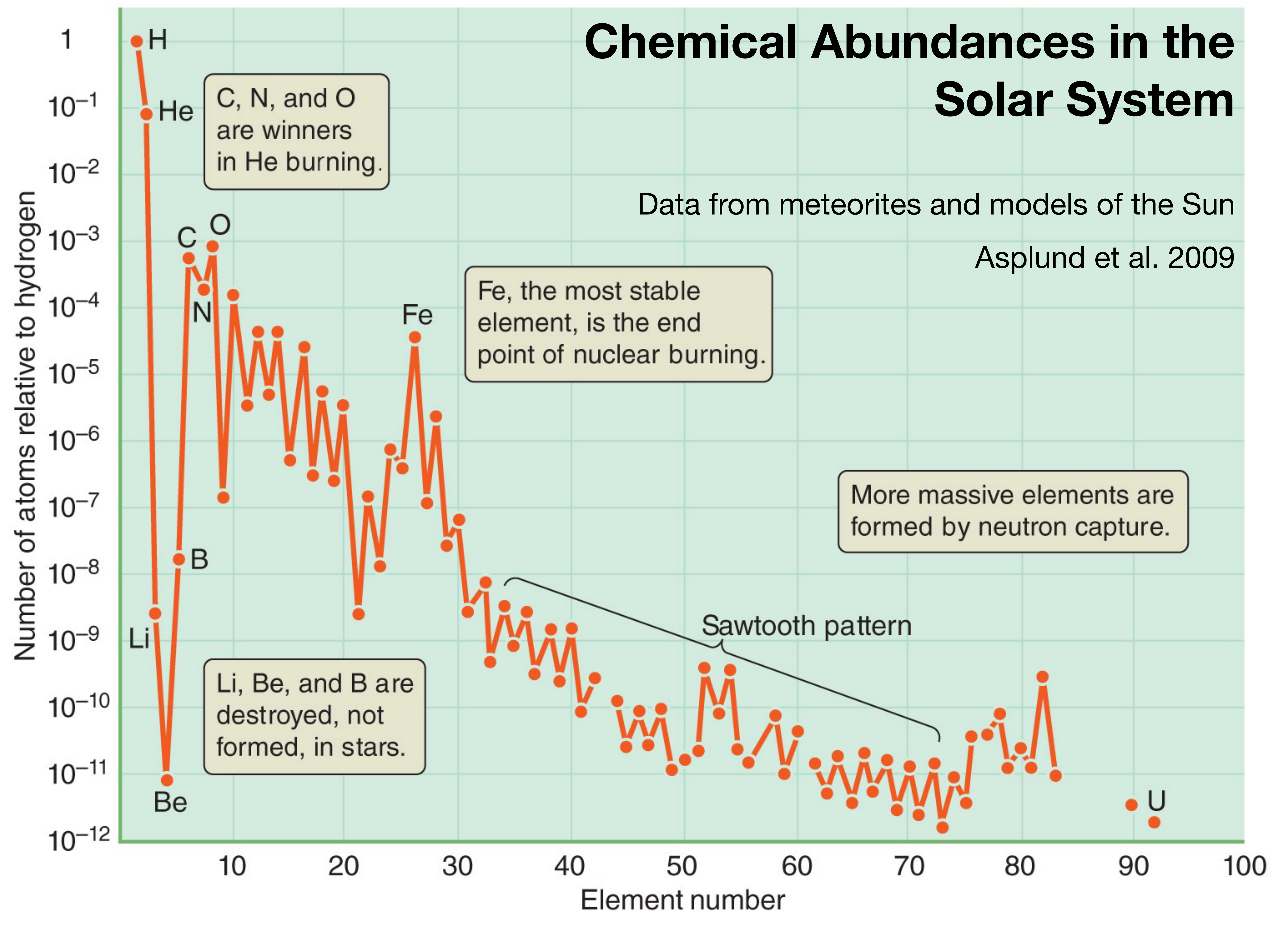


When you see a SN remnant, how would you measure its distance? So that we know how large it is in physical units (e.g., AU)?



Imagine the spherical expansion of a shell of gas



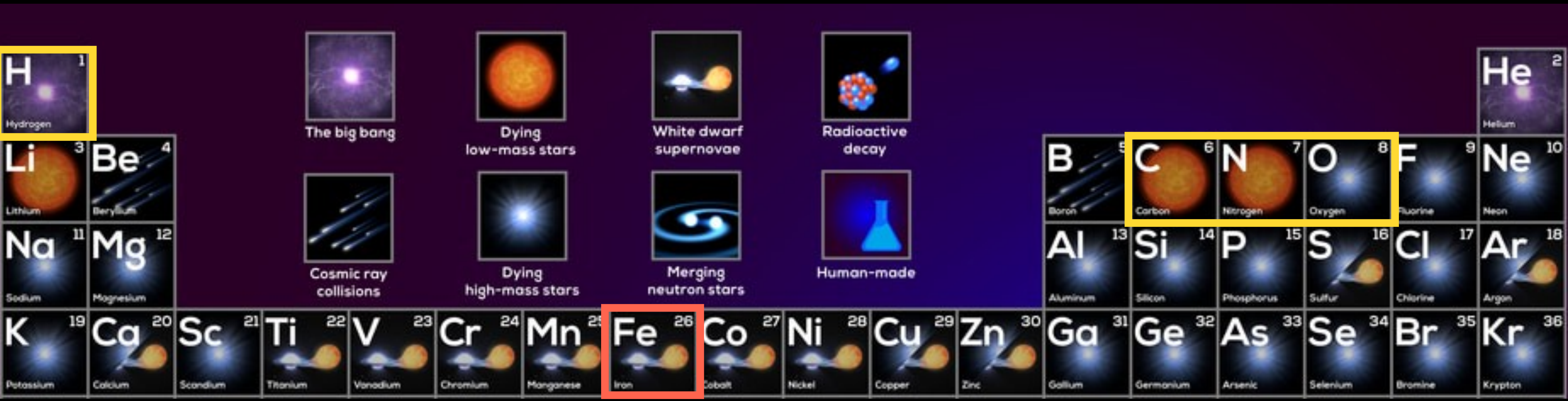


Chemical Abundances in the Solar System
Data from meteorites and models of the Sun
Asplund et al. 2009
C, N, and O are winners in He burning.
Fe, the most stable element, is the end point of nuclear burning.
More massive elements are formed by neutron capture.
Li, Be, and B are destroyed, not formed, in stars.
Sawtooth pattern
H
He
C
N
O
Fe
B
Li
Be
U
Number of atoms relative to hydrogen
Element number

The Origin of Elements: from H to Fe

Nucleosynthesis in the Big Bang, stellar cores, and supernovae explosions

The Primary Origin of Each Element
(up to two main contributors are shown for each element)

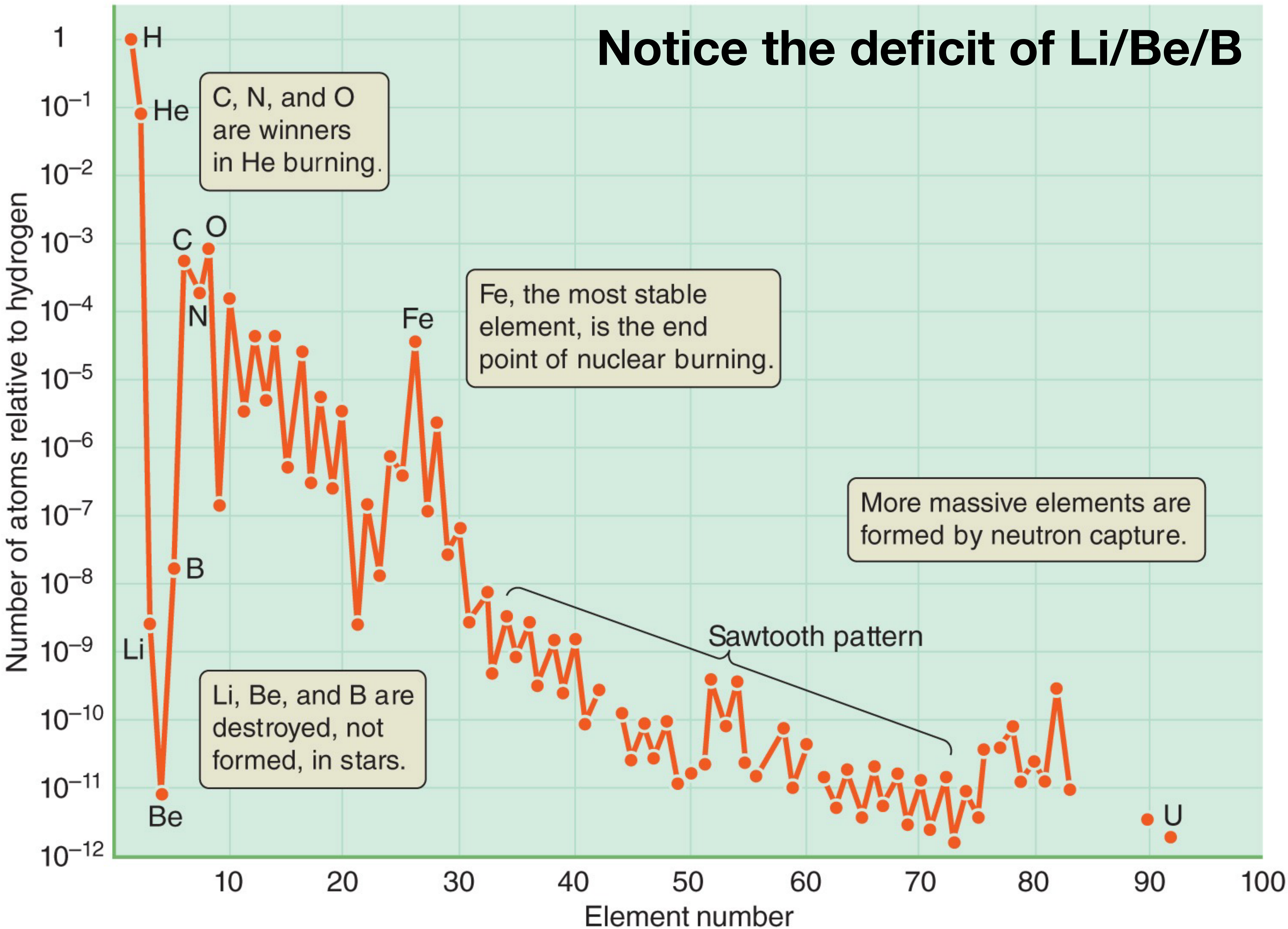


- The **hydrogen** atoms in water were created 13.7 billion years ago in the Big Bang (t = 3 min, *T = 1e9 K, density = 1e5 kg/m*^{3})
- The **oxygen** atoms in the air you breathe and the water you drink were created by nucleosynthesis in the cores of high mass stars and released into the ISM via type II SNe.
- The **carbon** atoms were formed in the cores of low mass stars and released into the ISM in the Post-AGB phase.
- The **iron** atoms that are a key element of hemoglobin, which makes up the red blood cells that carry oxygen from your lungs to the rest of your body, formed in the explosion of white dwarfs (type Ia SNe).

The Origin of Elements: Li, Be, and B

Classical Nova, AGB stars, and Cosmic Ray Spallation

Notice the deficit of Li/Be/B



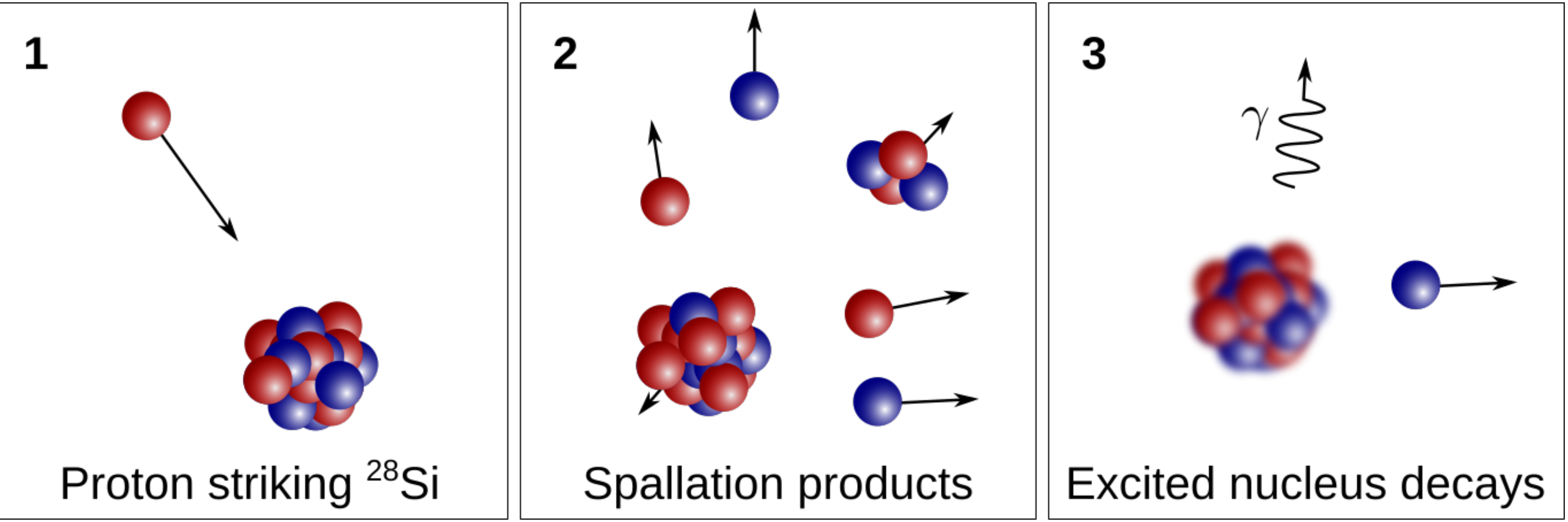
Lithium Production in AGB and Classical Nova (Cameron & Fowler 1971)

- *As part of the triple-alpha process in Helium burning, Beryllium forms:*
  - $^{3}\text{He} + {}^{4}\text{He} \rightarrow {}^{7}\text{Be}$ + photon
- *if Be is transported to cooler regions (10^{6} K) by convection, it can form Lithium:*
  - $^{7}\text{Be} + e^{-} \rightarrow {}^{7}\text{Li}$ + neutrino
- *Otherwise, Beryllium fuses with hydrogen to form Boron:*
  - $^{7}\text{Be} + p \rightarrow {}^{8}\text{B}$ + photon

Illustration by David A. Hardy

Cosmic Ray Spallation (x-process): Be and B

- **Cosmic rays** are high energy particles emitted by astrophysical sources like our Sun, supernovae, and active galactic nuclei (1936 Nobel Prize)
- Cosmic rays can hit other nuclei and cause them to split. This process is called **Cosmic Ray Spallation** or **x-process**
- Lithium, Beryllium, and Boron are *destroyed* in stars, the x-process is responsible for their abundances:
  e.g., $n + {}^{14}N \rightarrow p + {}^{4}He + {}^{10}Be$, then ${}^{10}Be \rightarrow {}^{10}B + e^-$ (beta decay)

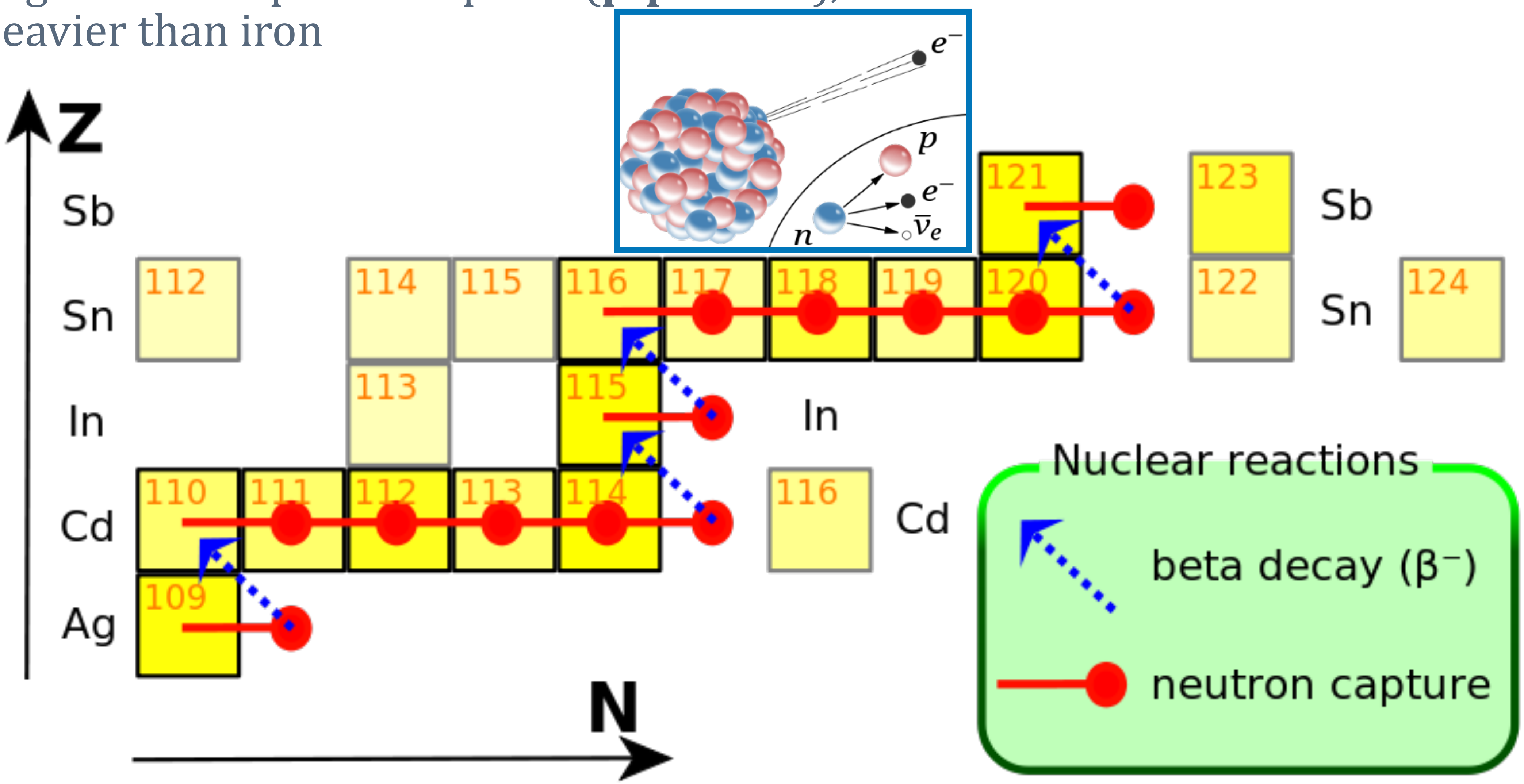


The Origin of Elements: beyond Fe

Neutron star mergers and AGB Stars

Rapid and Slow Neutron Capture Processes (r- / s-process)

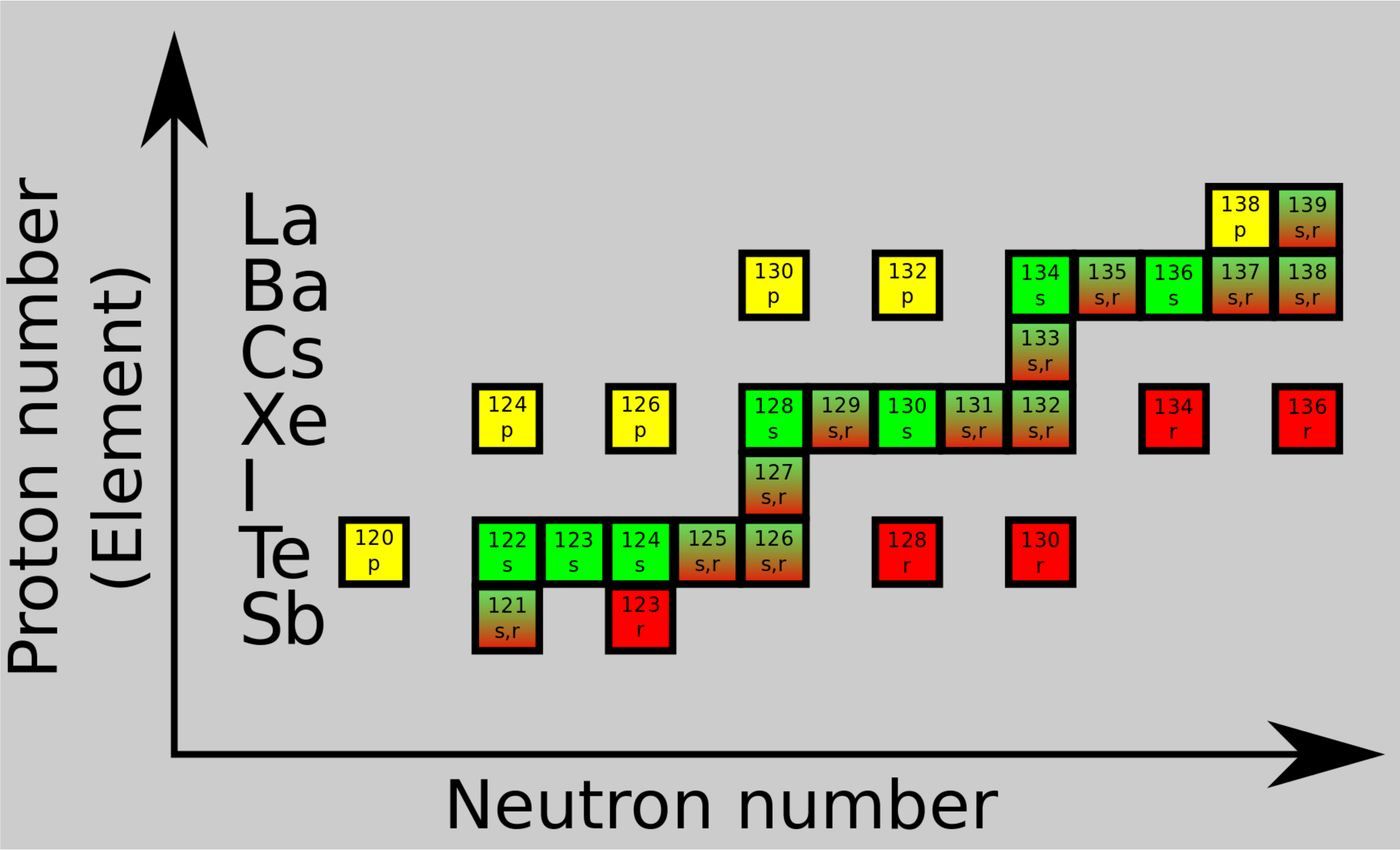
- ***Rapid*** neutron capture: the nuclei can capture multiple neutrons before the **beta decay** (emission of an electron)
  - Important in **neutron star mergers (short GRB)**, given the high neutron fluxes
  - Makes half of the nuclei heavier than iron (mostly **neutron-rich isotopes**)
- ***Slow*** neutron capture: the nuclei undergo **beta decay** before another neutron can be captured.
  - Important in **AGB stars**, neutron flux comes from $^{13}C(\alpha, n)^{16}O$ & $^{22}Ne(\alpha, n)^{25}Mg$
  - Together with proton capture (**p-process**), makes the other half of the nuclei heavier than iron



Neutron Star Merger: Gravitational Wave & Gamma-Ray Burst

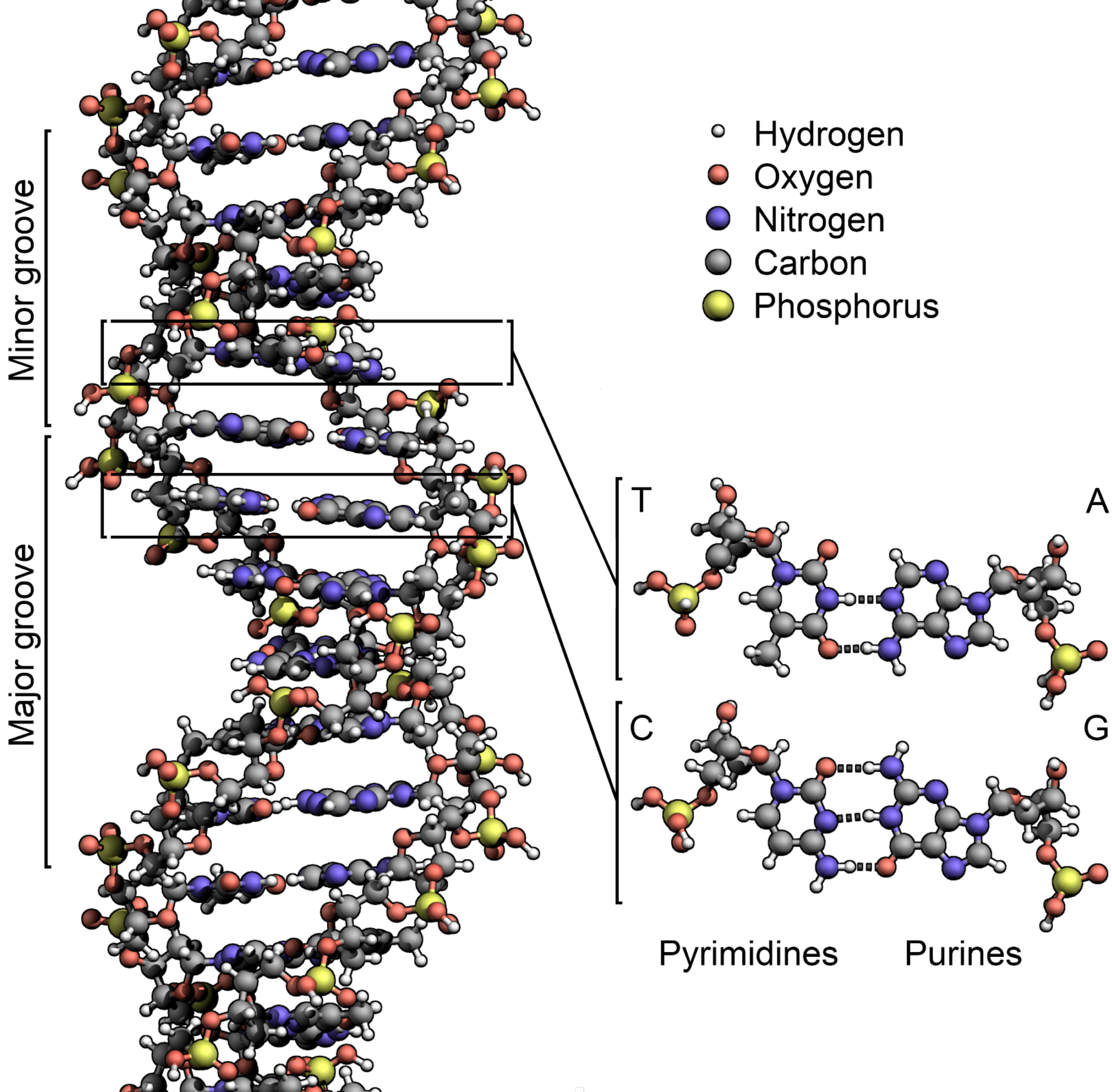
The Proton Capture Process (p-process)

- makes **neutron-deficit** isotopes from selenium (Se-34) to mercury (Hg-80)

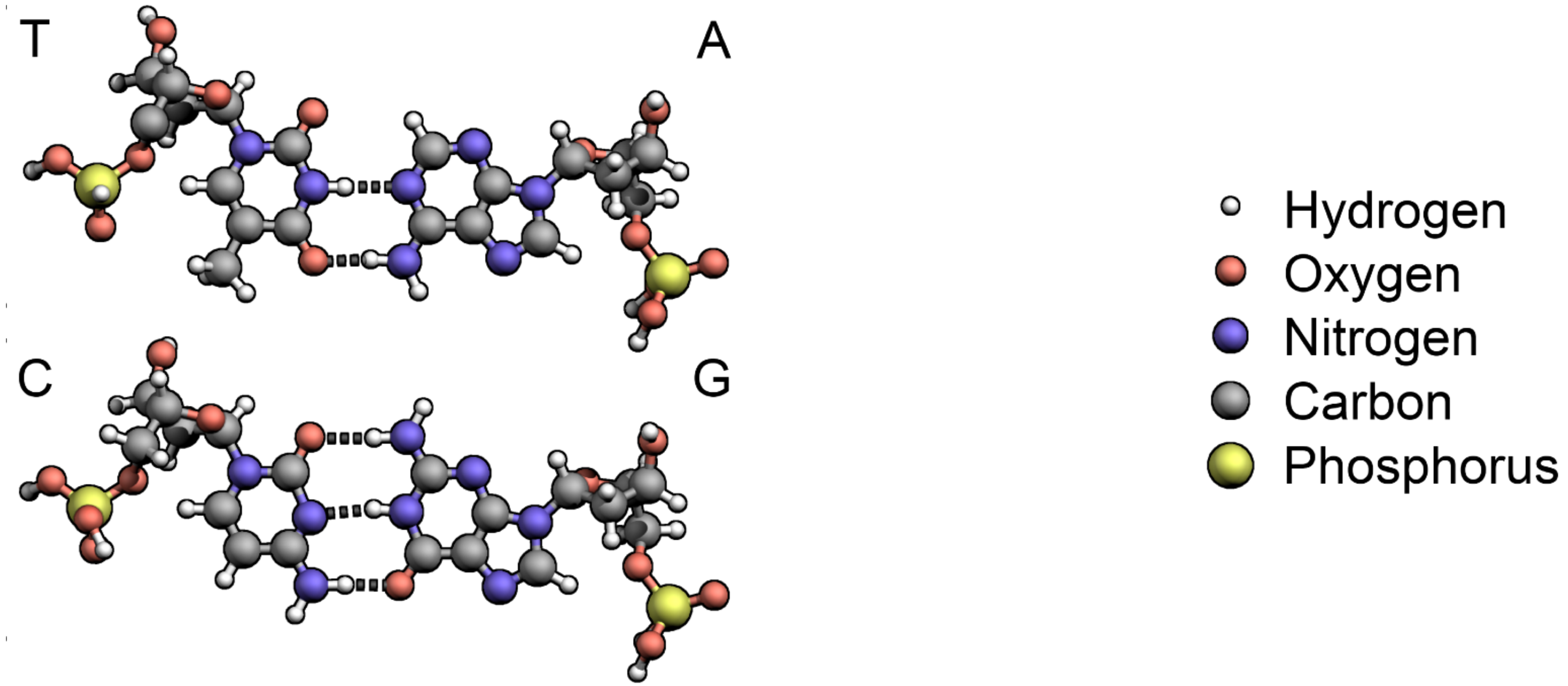


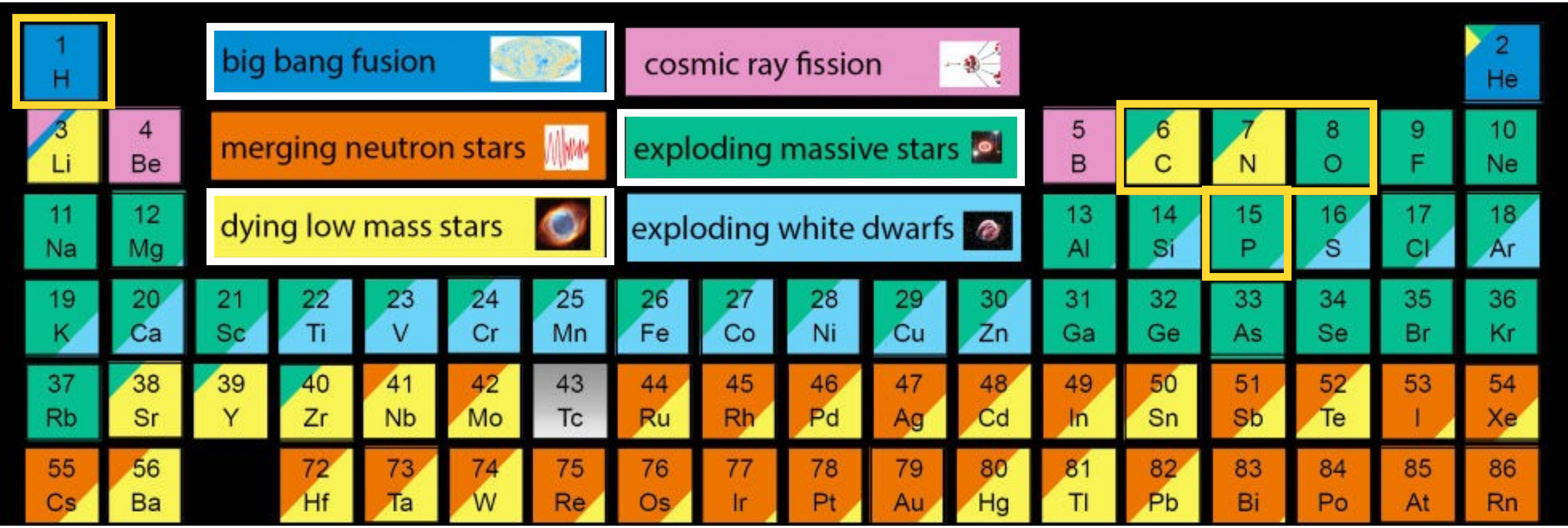
Summary: The Six Astrophysical Sources of Elements

(top two/three main contributors are shown foreach element)

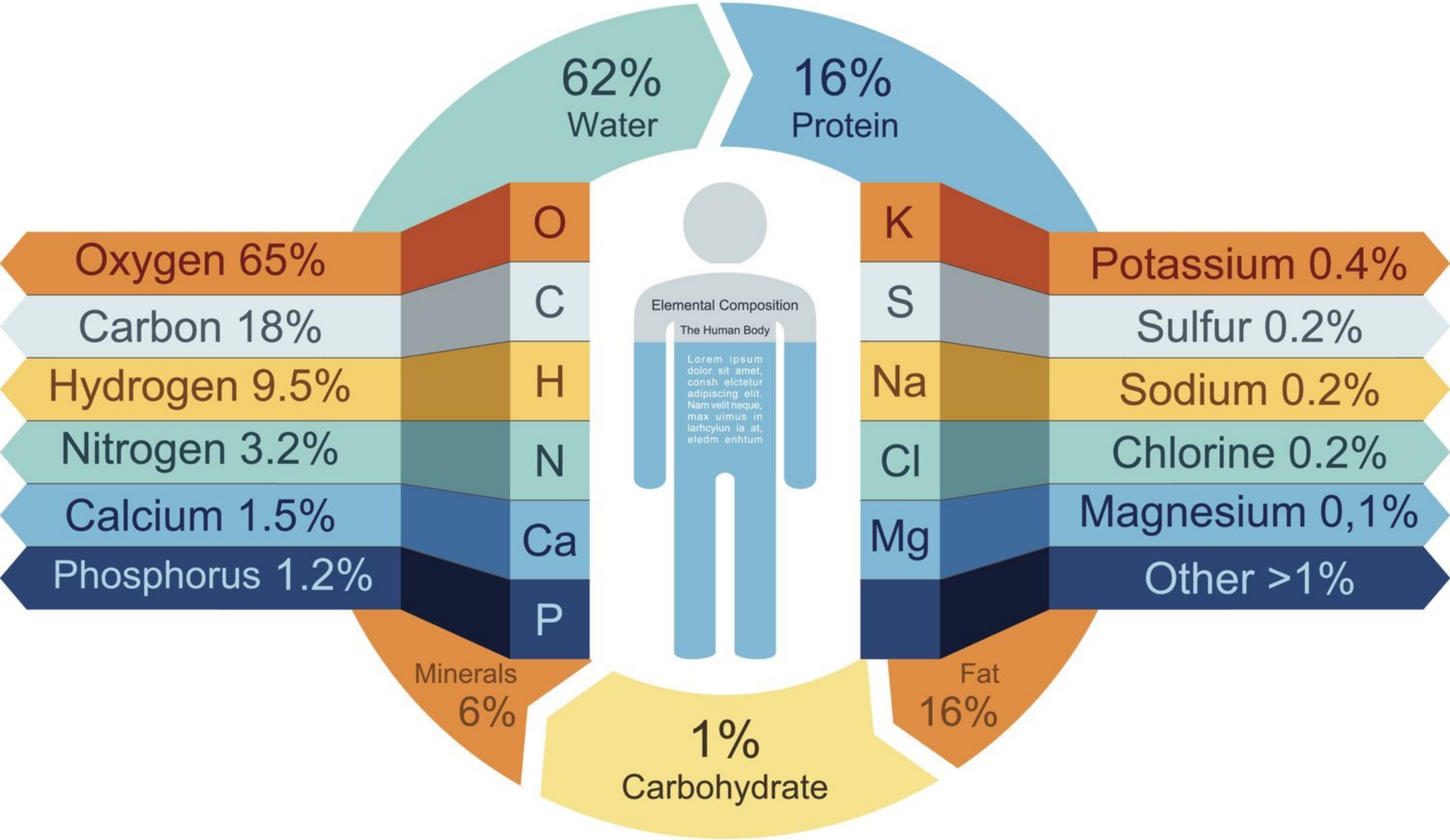


Hydrogen
Oxygen
Nitrogen
Carbon
Phosphorus
Minor groove
Major groove
T
A
C
G
Pyrimidines
Purines

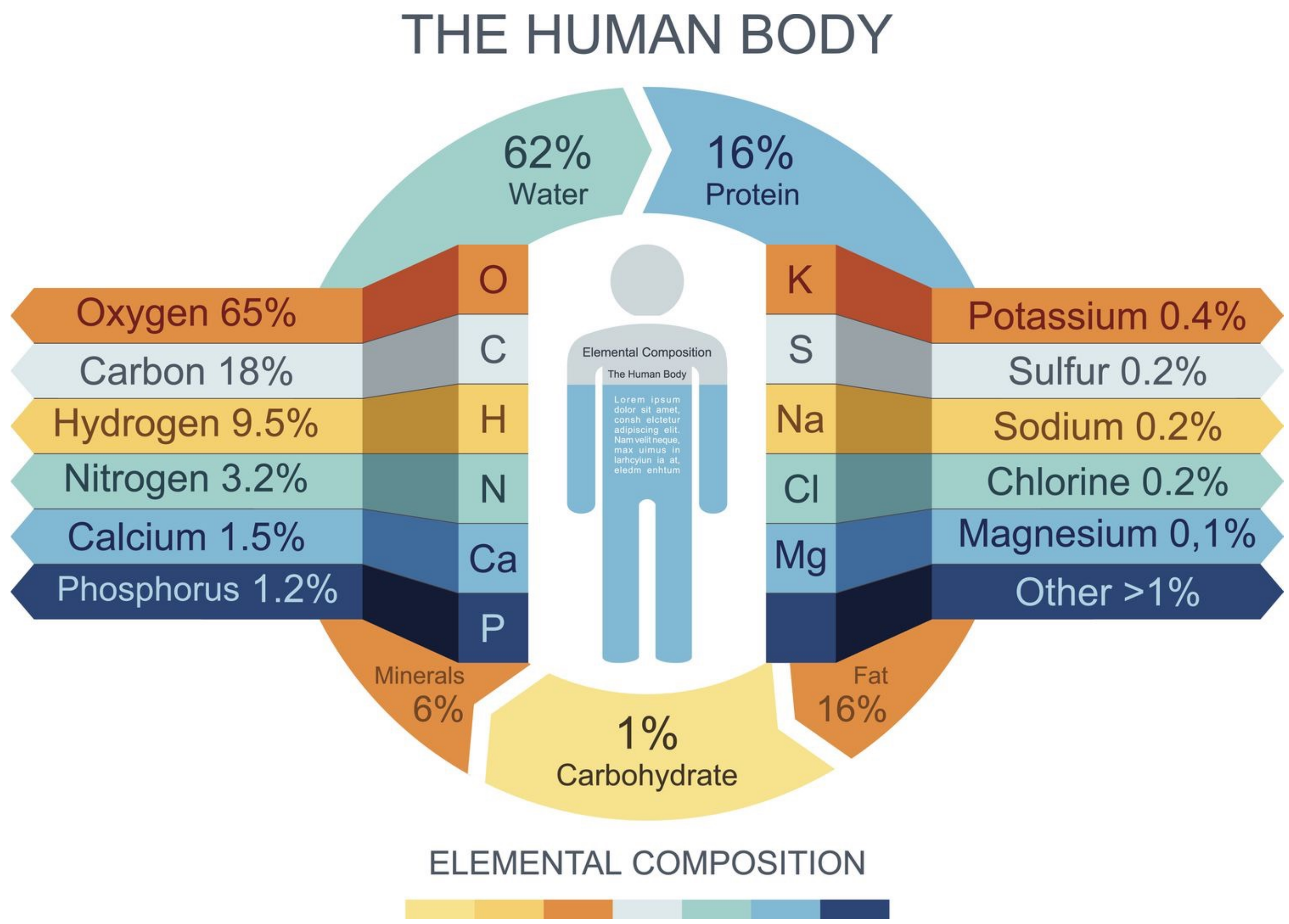

T
A
C
G
Hydrogen
Oxygen
Nitrogen
Carbon
Phosphorus


big bang fusion
cosmic ray fission
merging neutron stars
exploding massive stars
dying low mass stars
exploding white dwarfs
1 H
2 He
3 Li
4 Be
5 B
6 C
7 N
8 O
9 F
10 Ne
11 Na
12 Mg
13 Al
14 Si
15 P
16 S
17 Cl
18 Ar
19 K
20 Ca
21 Sc
22 Ti
23 V
24 Cr
25 Mn
26 Fe
27 Co
28 Ni
29 Cu
30 Zn
31 Ga
32 Ge
33 As
34 Se
35 Br
36 Kr
37 Rb
38 Sr
39 Y
40 Zr
41 Nb
42 Mo
43 Tc
44 Ru
45 Rh
46 Pd
47 Ag
48 Cd
49 In
50 Sn
51 Sb
52 Te
53 I
54 Xe
55 Cs
56 Ba
72 Hf
73 Ta
74 W
75 Re
76 Os
77 Ir
78 Pt
79 Au
80 Hg
81 Tl
82 Pb
83 Bi
84 Po
85 At
86 Rn

THE HUMAN BODY



ELEMENTAL COMPOSITION


THE HUMAN BODY
62% Water
16% Protein
Oxygen 65%
Carbon 18%
Hydrogen 9.5%
Nitrogen 3.2%
Calcium 1.5%
Phosphorus 1.2%
O
C
H
N
Ca
P
K
S
Na
Cl
Mg
Potassium 0.4%
Sulfur 0.2%
Sodium 0.2%
Chlorine 0.2%
Magnesium 0,1%
Other >1%
Elemental Composition
The Human Body
Minerals 6%
1% Carbohydrate
Fat 16%
ELEMENTAL COMPOSITION

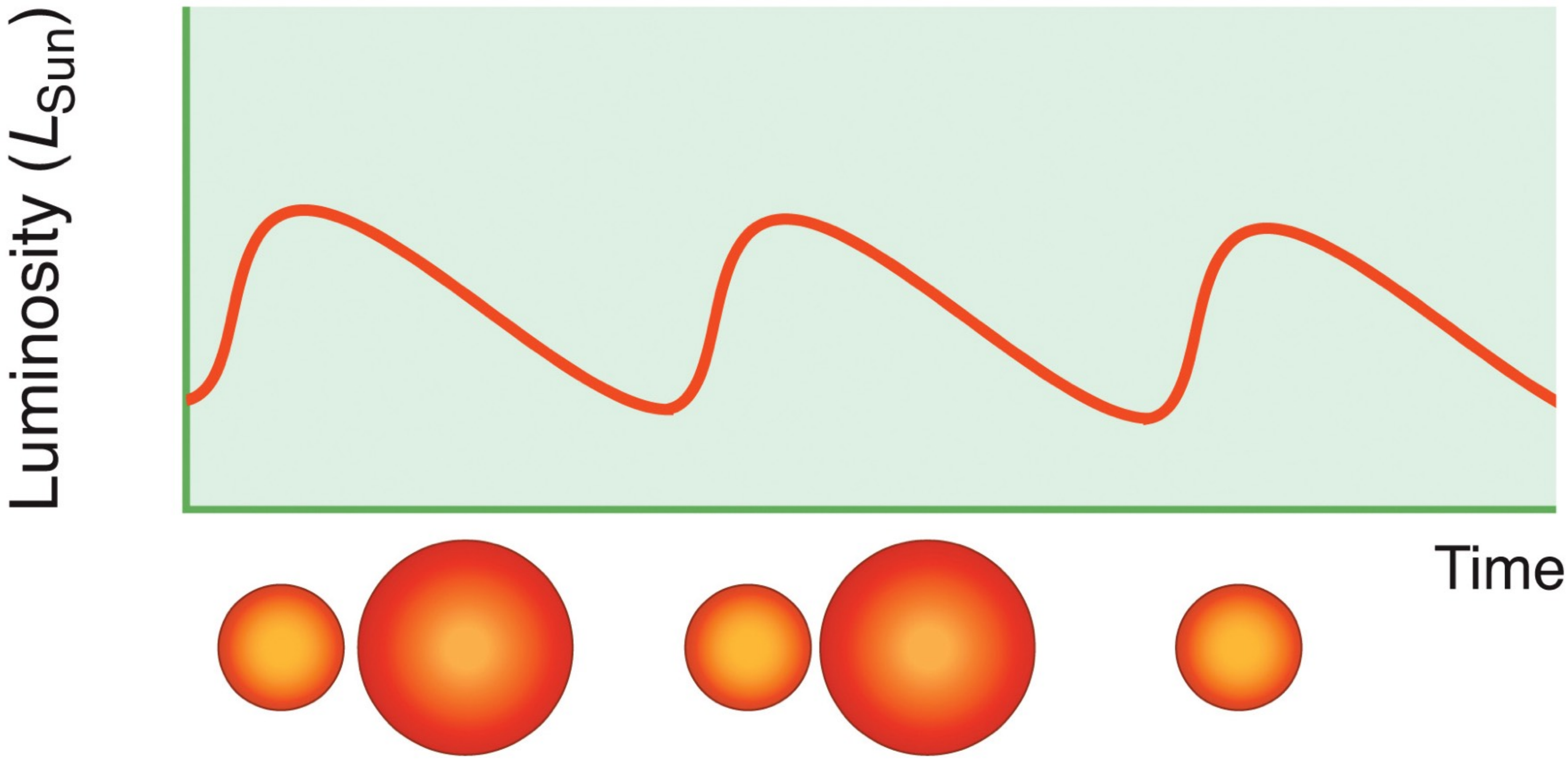

big bang fusion
cosmic ray fission
merging neutron stars
exploding massive stars
dying low mass stars
exploding white dwarfs
1 H
2 He
3 Li
4 Be
5 B
6 C
7 N
8 O
9 F
10 Ne
11 Na
12 Mg
13 Al
14 Si
15 P
16 S
17 Cl
18 Ar
19 K
20 Ca
21 Sc
22 Ti
23 V
24 Cr
25 Mn
26 Fe
27 Co
28 Ni
29 Cu
30 Zn
31 Ga
32 Ge
33 As
34 Se
35 Br
36 Kr
37 Rb
38 Sr
39 Y
40 Zr
41 Nb
42 Mo
43 Tc
44 Ru
45 Rh
46 Pd
47 Ag
48 Cd
49 In
50 Sn
51 Sb
52 Te
53 I
54 Xe
55 Cs
56 Ba
72 Hf
73 Ta
74 W
75 Re
76 Os
77 Ir
78 Pt
79 Au
80 Hg
81 Tl
82 Pb
83 Bi
84 Po
85 At
86 Rn


Even through your hardest
days, remember we are all
made of stardust.
Carl Sagan
quotefancy

The Instability Strip on the H-R Diagram:
Pulsating Variable Stars and P-L Relations

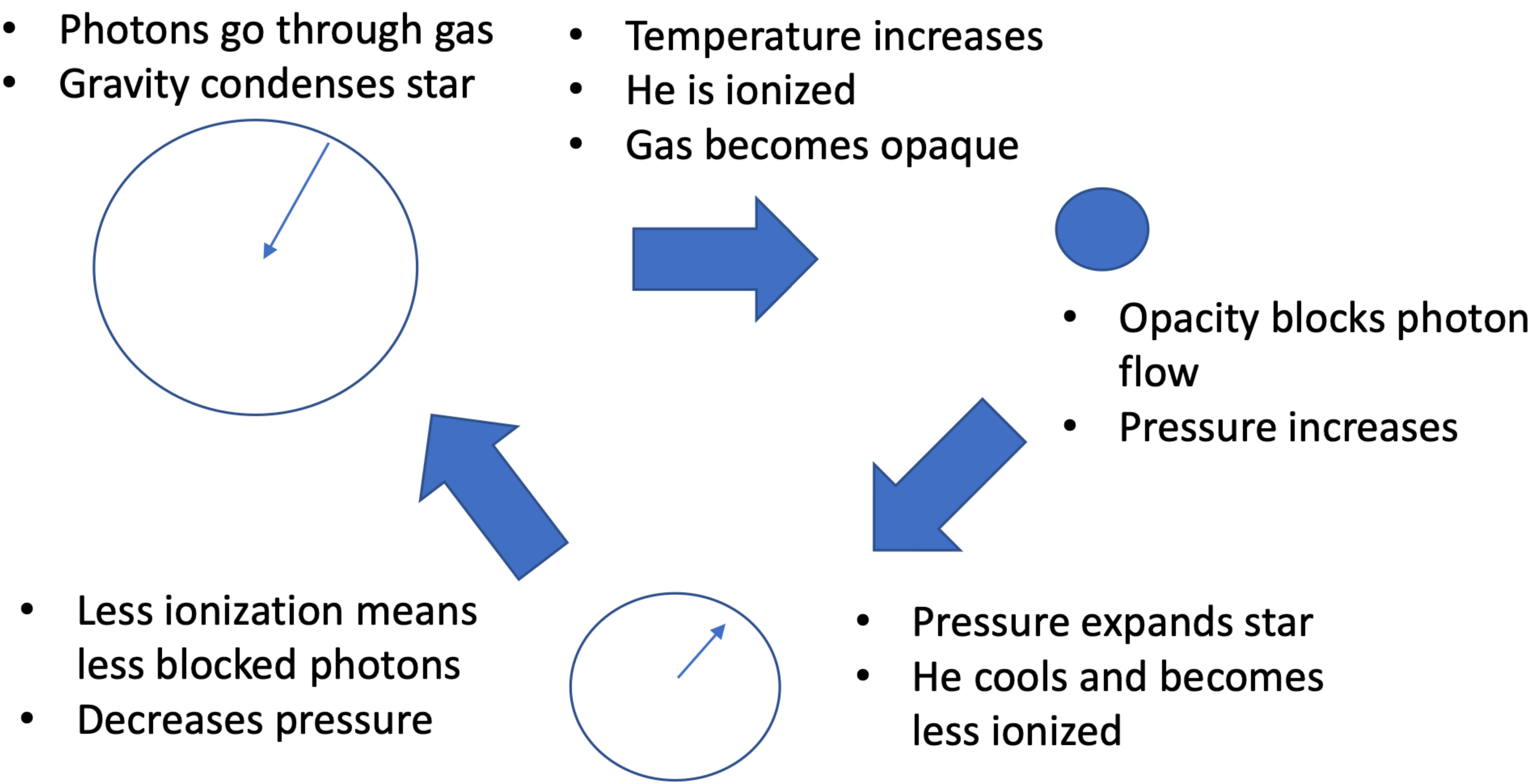
Pulsating Variable Stars

- A star can evolve into a **pulsating variable star when its interior fails to** achieve a steady balance between pressure and gravity (i.e., it overshoots).
- The star's **luminosity** changes as their **radius** and **temperature** changes at a regular period. Note that although the amount of emitted light changes, the *nuclear fusion rate is unaffected.*



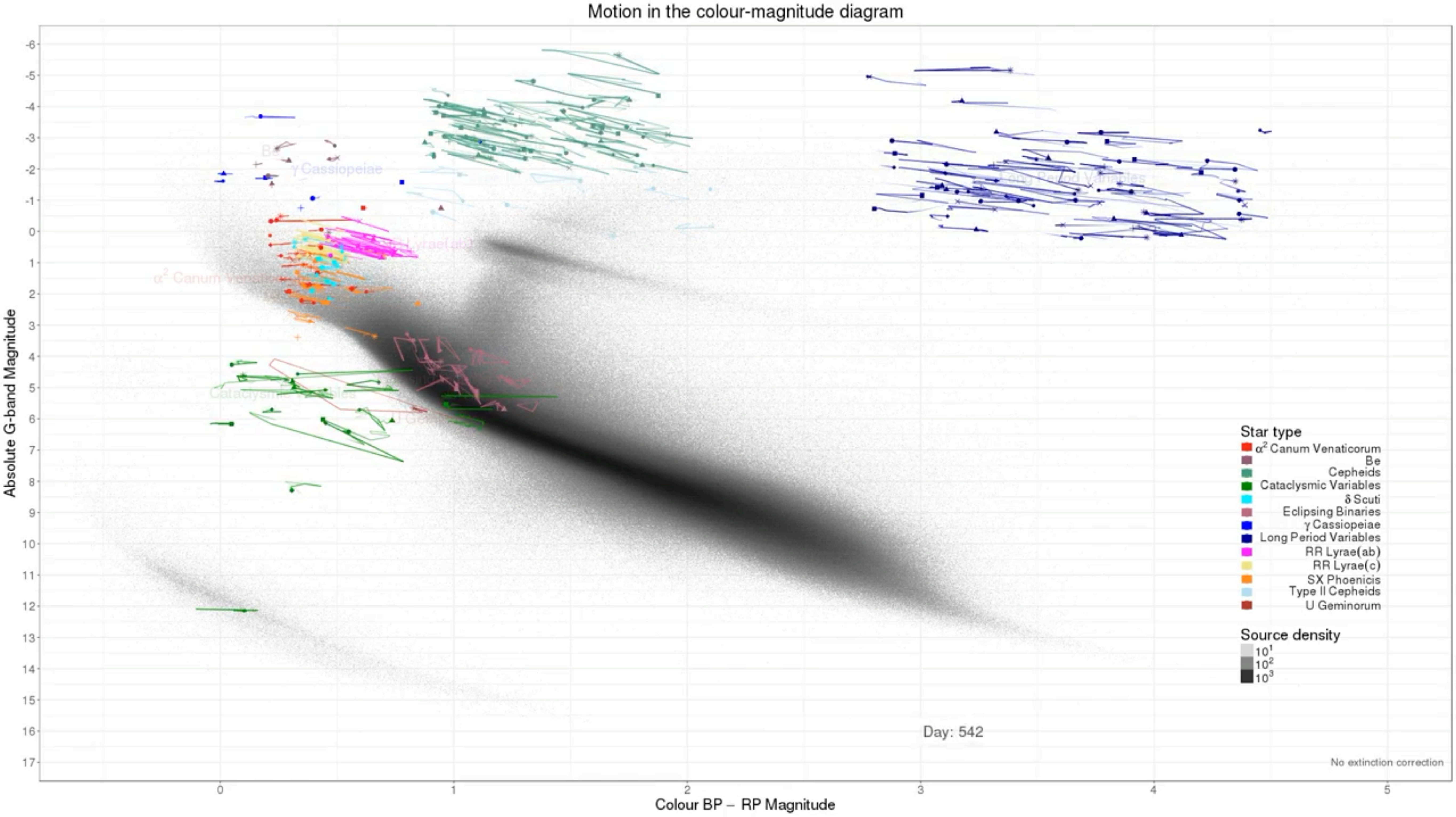
Pulsation Caused by Gas Ionization and Recombination

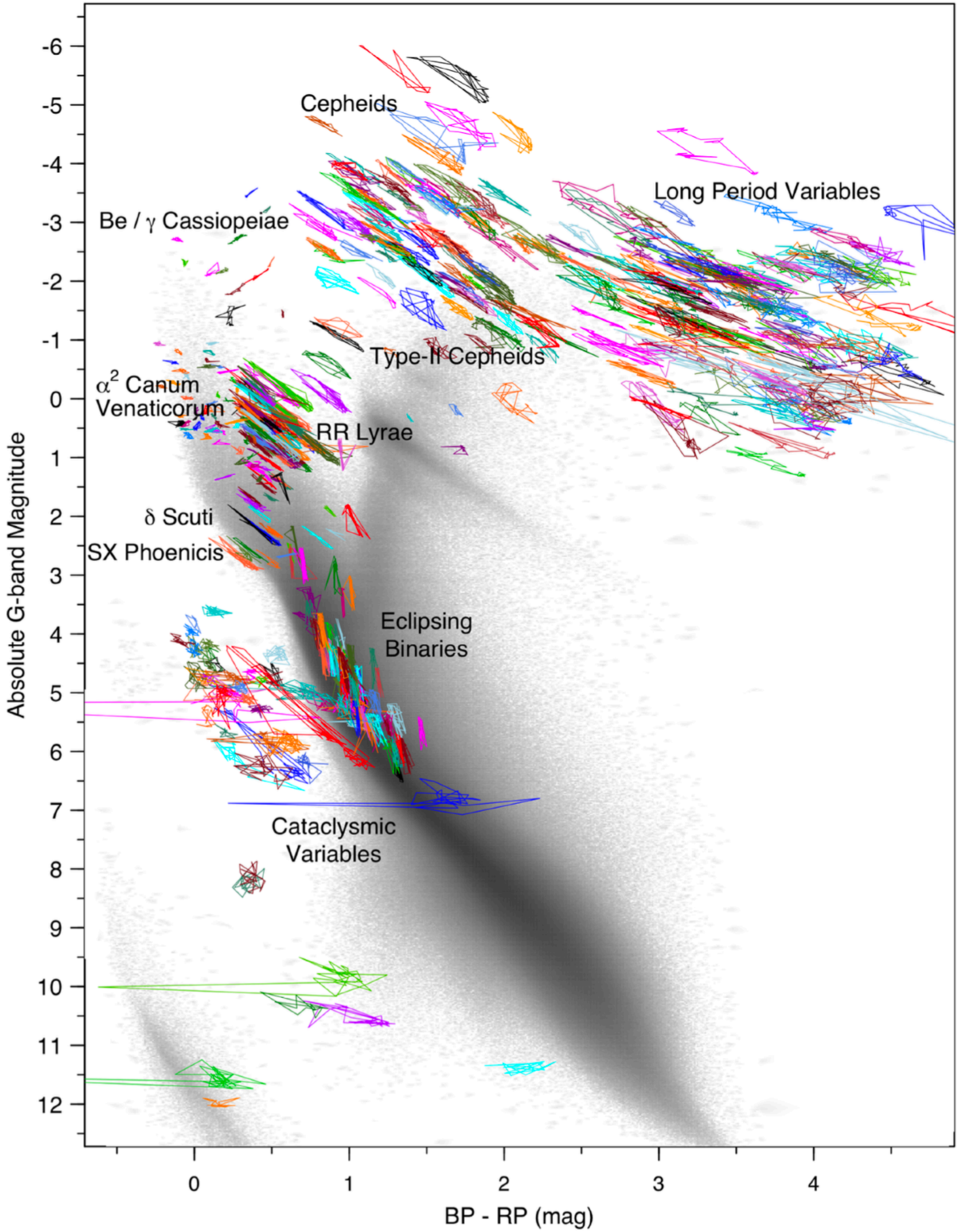
- **Pulsations** are caused by the atmosphere oscillating between **ionized (more opaque)** and **neutral (more transparent)** phases.



Peter Wysocki

GAIA data release 2: Variable Stars on the HR Diagram

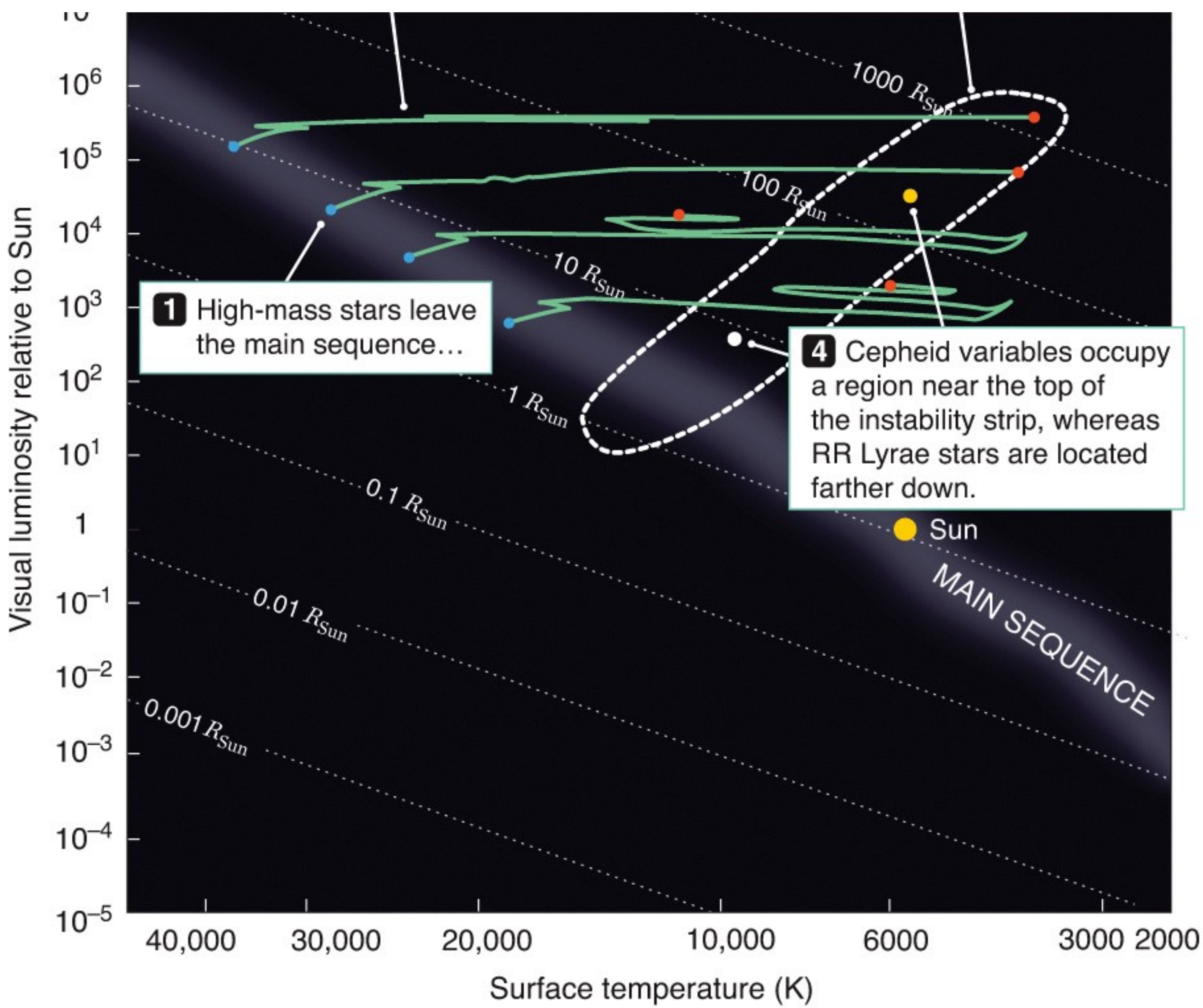




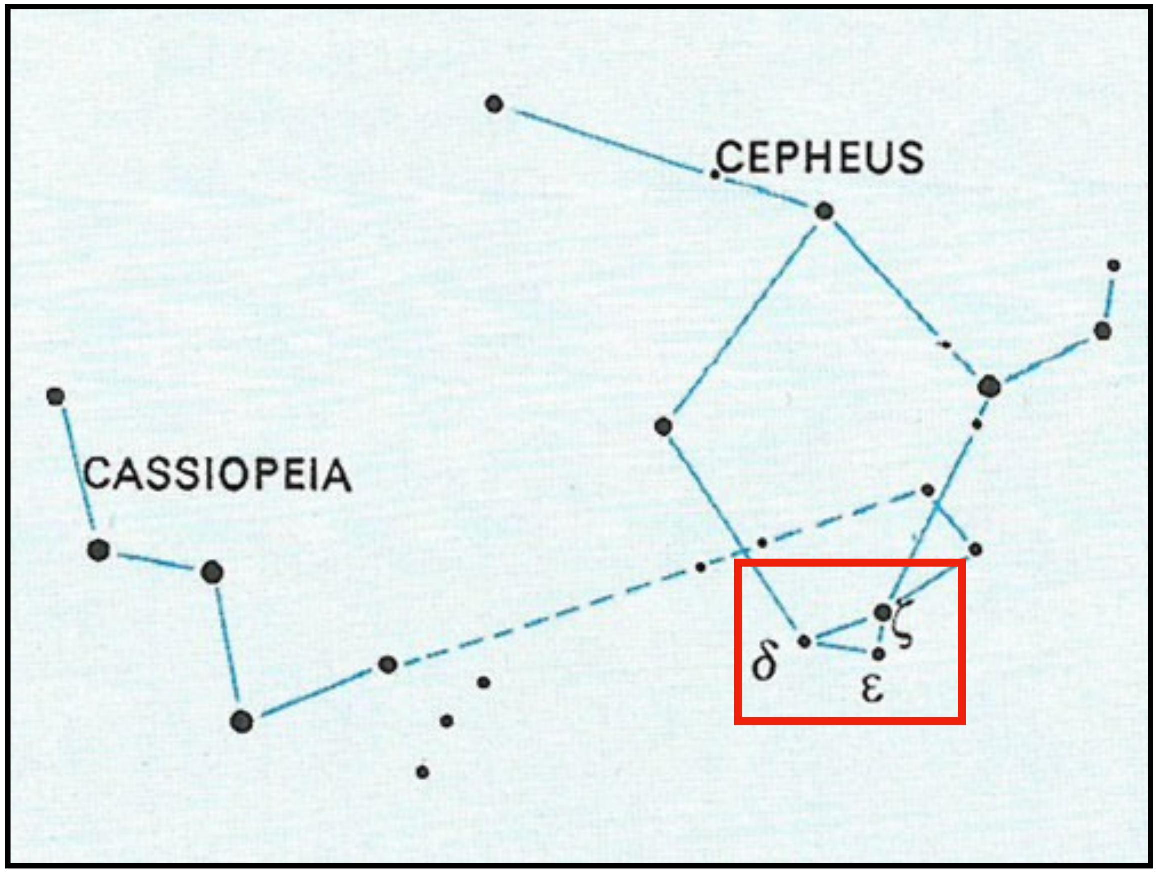
Cepheids
Long Period Variables
Be / γ Cassiopeiae
Type-II Cepheids
α² Canum Venaticorum
RR Lyrae
δ Scuti
SX Phoenicis
Eclipsing Binaries
Cataclysmic Variables
Absolute G-band Magnitude
-6
-5
-4
-3
-2
-1
0
1
2
3
4
5
6
7
8
9
10
11
12
0
1
2
3
4
BP - RP (mag)

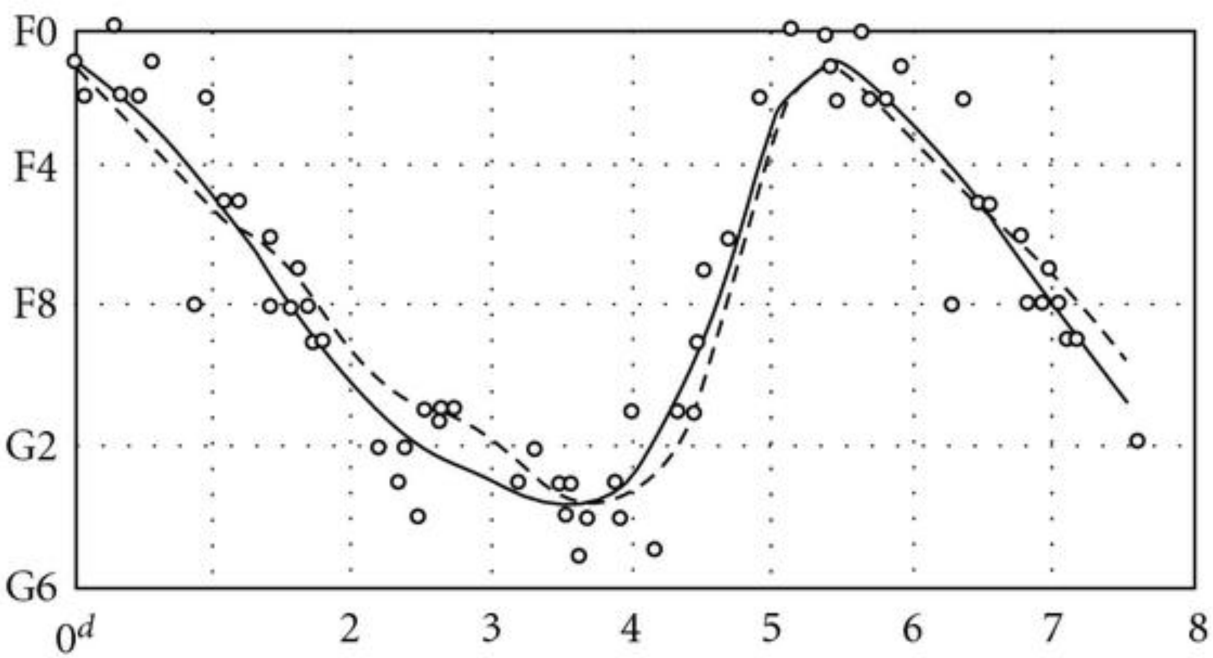
The Instability Strip on the HR Diagram

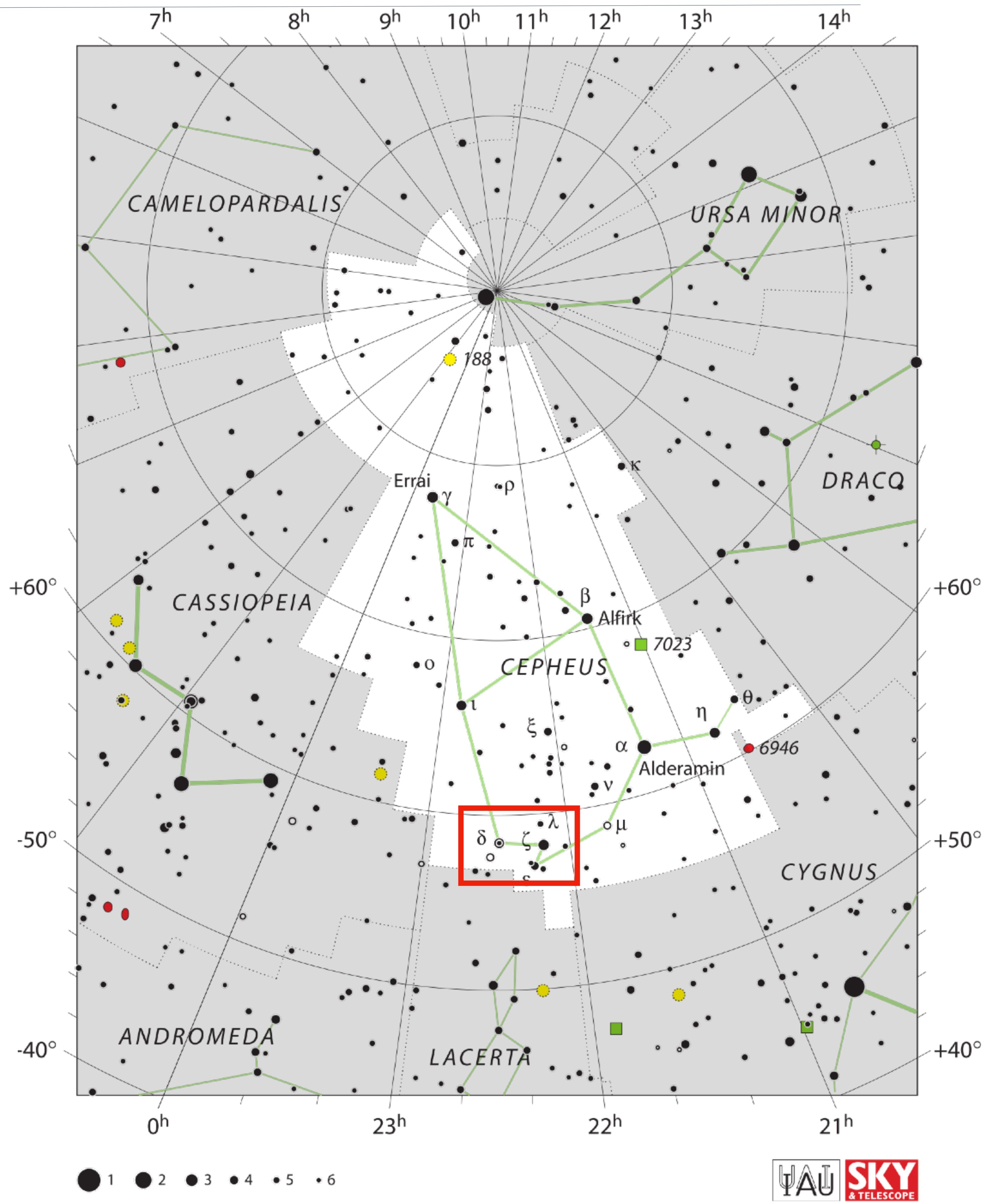
- **Pulsating variables** populate the **instability strip** on the HR diagram.



Delta Cephei - the Prototype Cepheid Variable Star

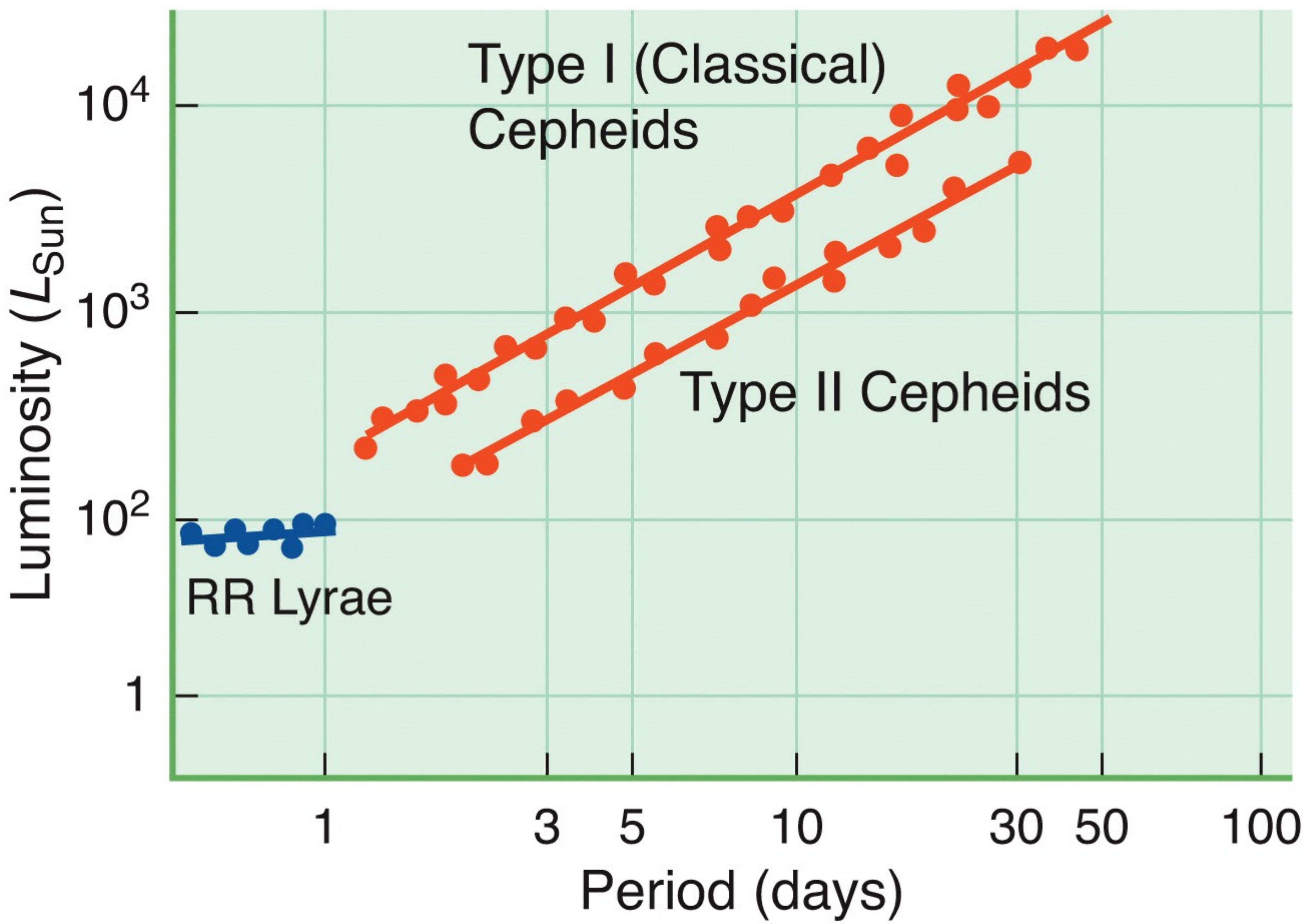






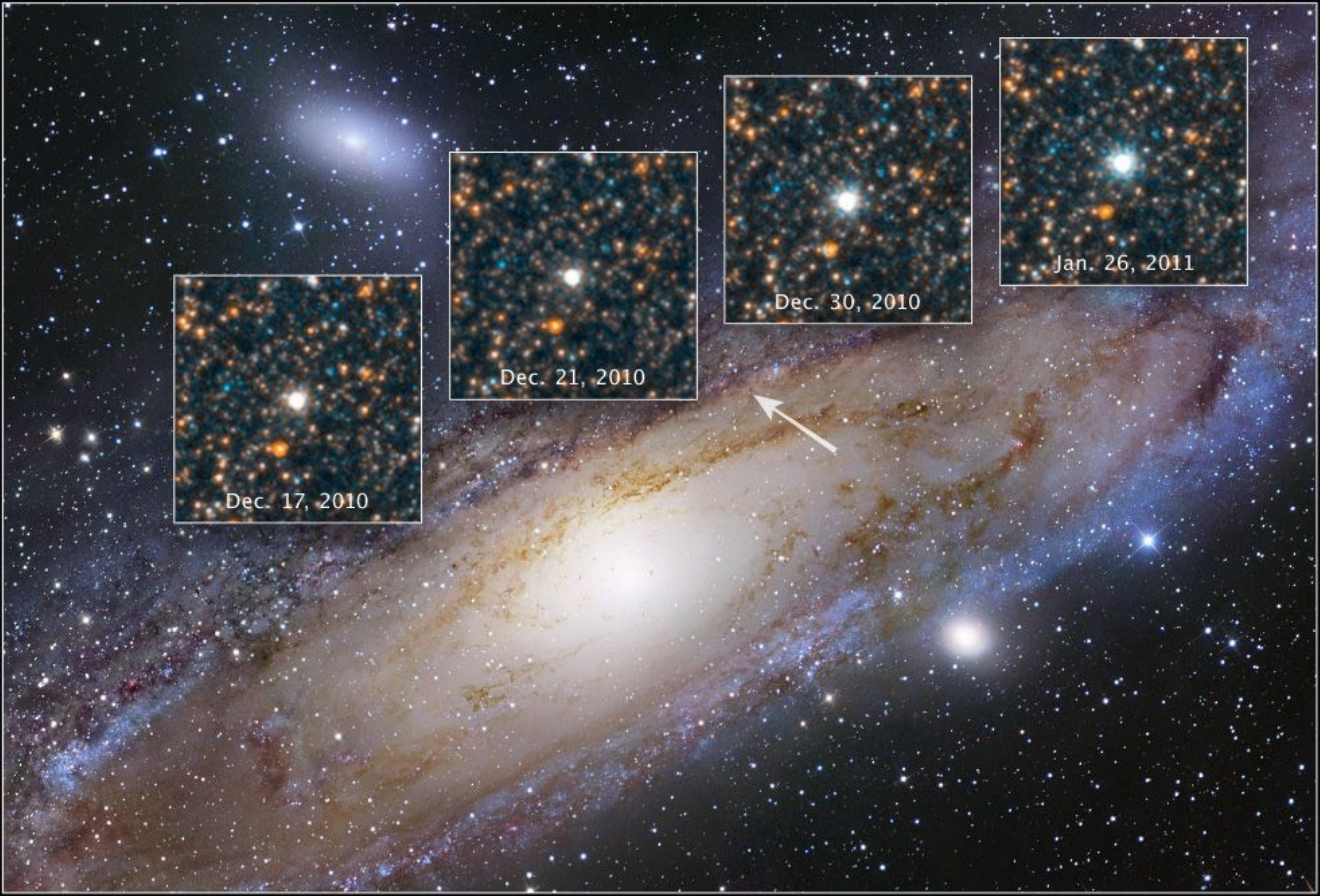
Period-Luminosity Relations (Leavitt 1912)

- $M_V = -2.43\log(P_{\text{day}}) - 1.62$ (Classical Cepheids, Fritz et al. 2007)
- This period-luminosity relationship is important for determining distances to other galaxies: *Measuring period gives luminosity (absolute magnitude), which combined with apparent magnitude, gives the distance modulus (thus distance):* $m - M = 5\log(d_{\text{pc}}) - 5$



Cepheid Variable Star V1 in M31

Hubble Space Telescope ▪ WFC3/UVIS

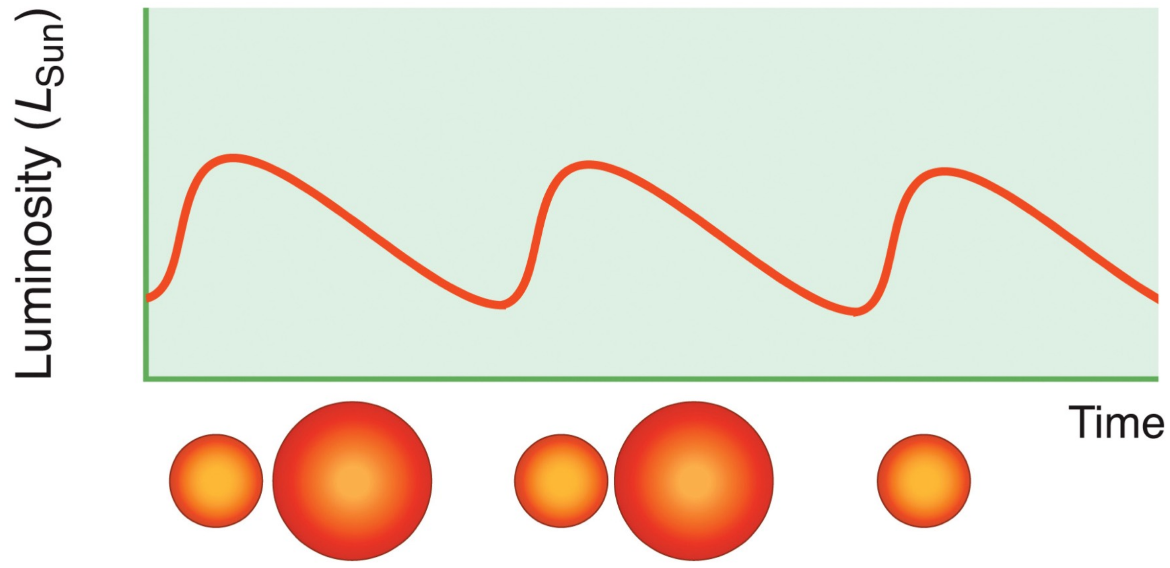


NASA, ESA, and the Hubble Heritage Team (STScI/AURA)

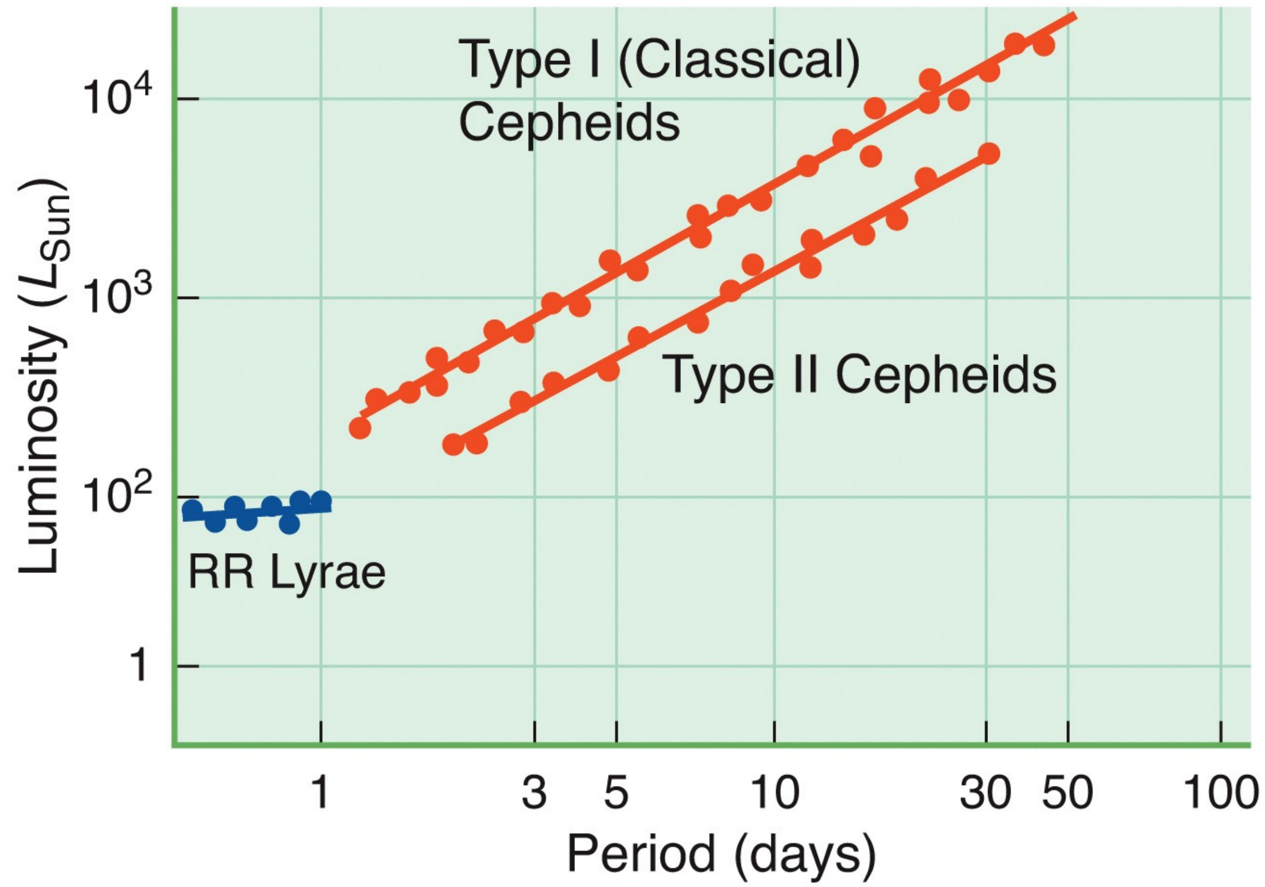
STScI-PRC11-15a

How to Tell Apart the Different Types of Pulsating Variable Stars?

- **Type I Cepheid variables**
  - Cepheid variables are high-mass stars becoming supergiants.
  - They have periods from 1 to 100 days.
  - More luminous stars have longer periods.
- **RR Lyrae variables and Type II Cepheid variables**
  - These are low-mass stars on the horizontal branch.
  - They are less luminous than Cepheid variables.

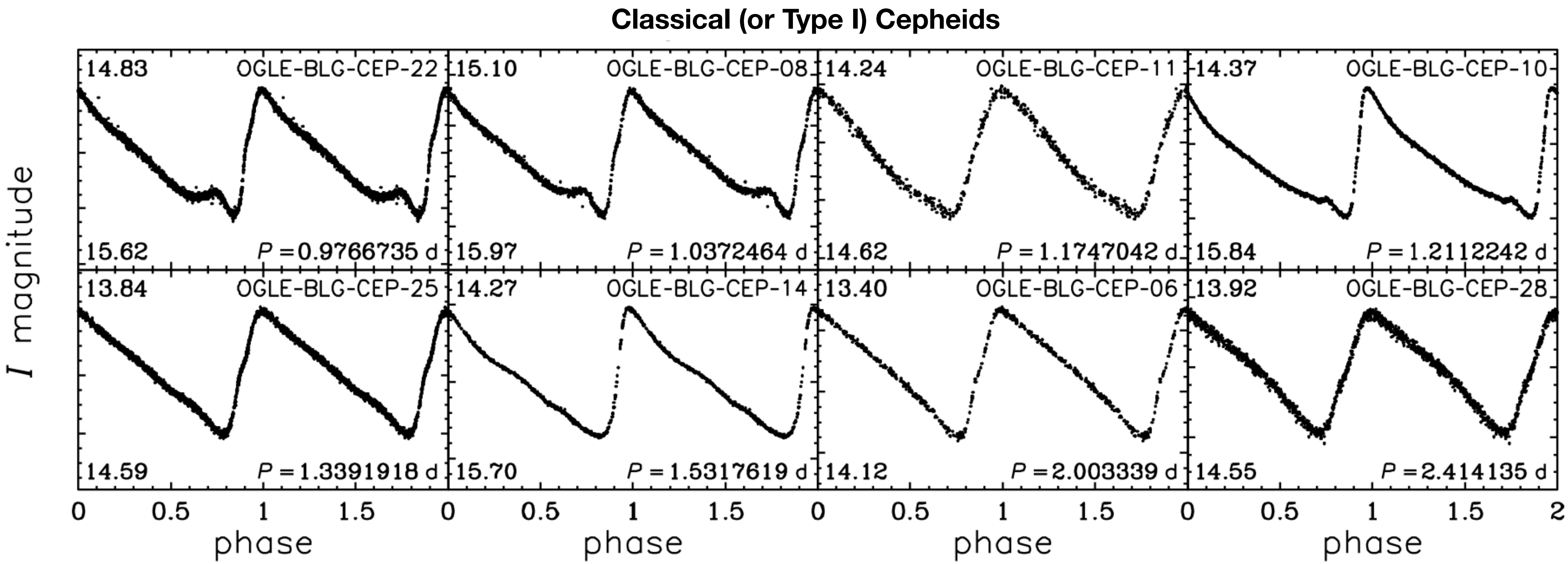


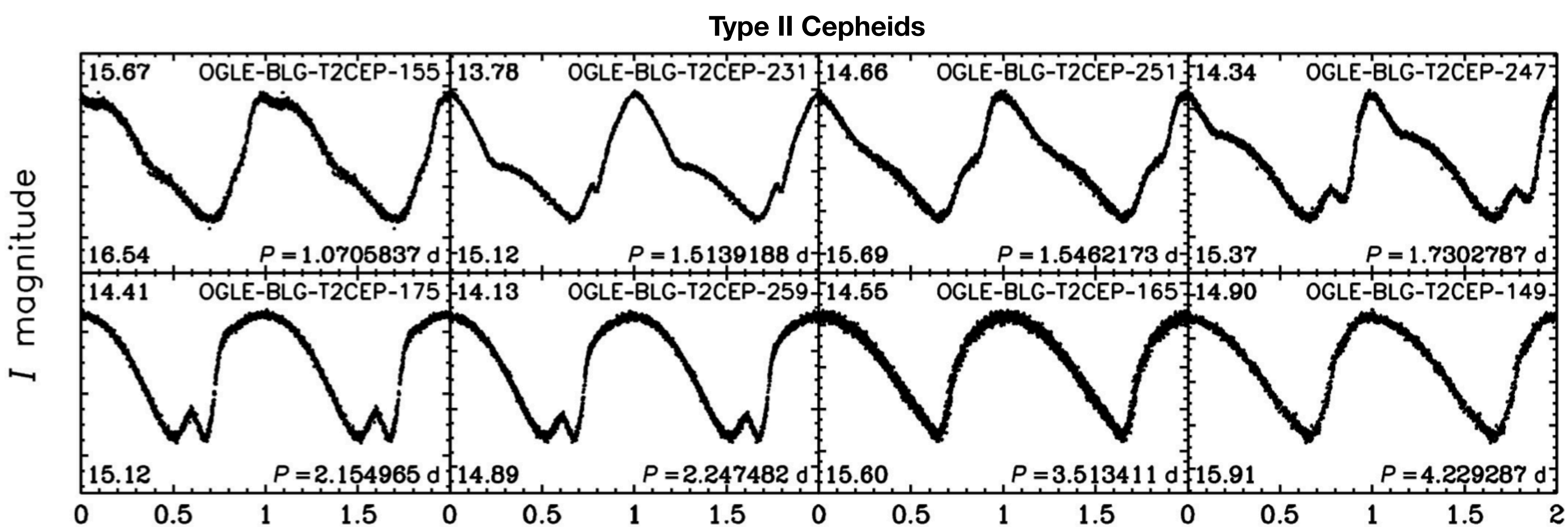
Luminosity vs. time



Period-luminosity relationship

Cepheids Light Curves - Type I vs. Type II Cepheids

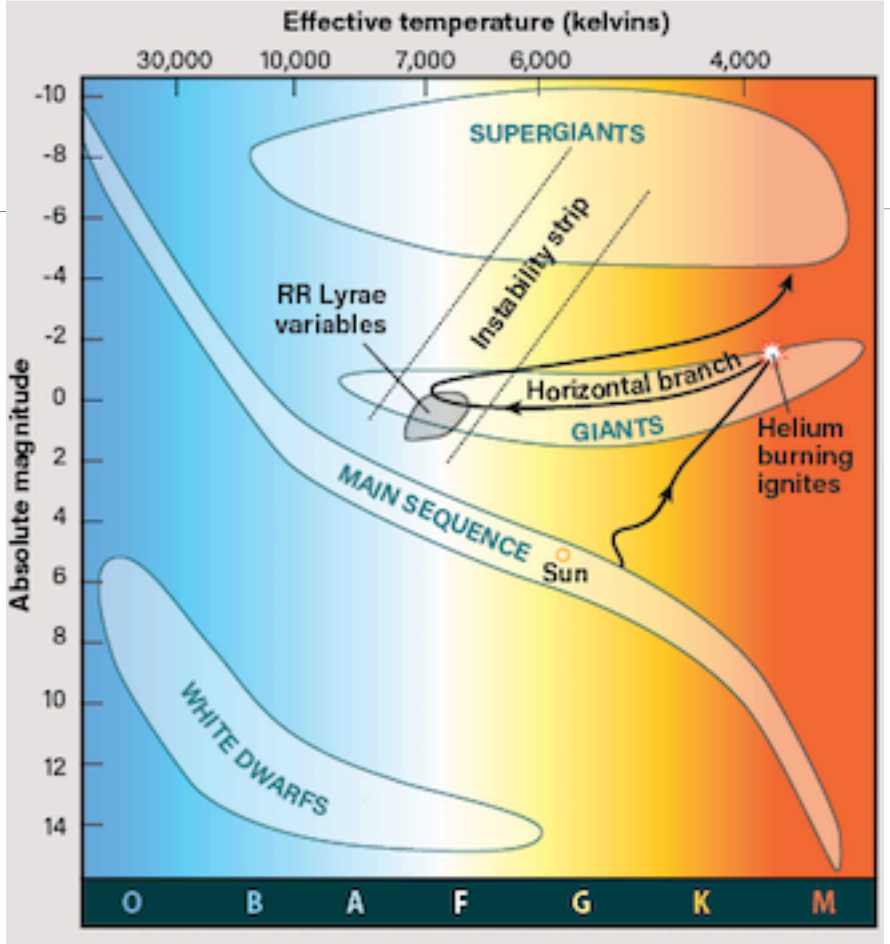




https://arxiv.org/abs/1112.1406

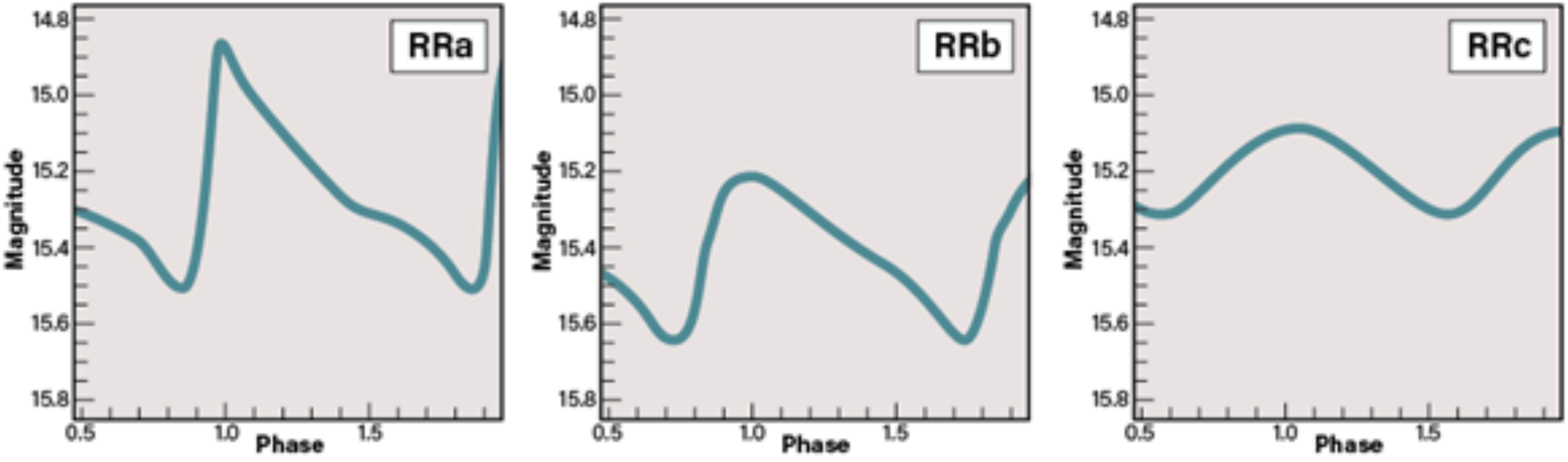
RR Lyrae - Shorter Periods

- RR Lyrae variables have periods shorter than one day.
- Like Cepheids, their light curves show a variety shapes.
- They are low-mass stars in the horizontal branch phase.



RR LYRAE LIGHT CURVES

There are two major classes of RR Lyrae stars, based on the shape of their light curve, which measures a star's brightness over time: RRab- (left, middle) and RRc-type stars. ASTRONOMY: ROEN KELLY



https://astronomy.com/magazine/news/2020/07/how-pulsating-stars-unlock-our-universe

Chap 17: The Evolution of High-Mass Stars

- CNO Cycles
- Convective cores
- Consecutive fusion shells
- End of fusion - Binding Energy
- Core collapse supernovae
- Neutron stars and Pulsars
- Supernova Remnants (SNR)
- The Origin of Elements: six primary astrophysical sources
- Periodic variables: L-P relations (distance measure)