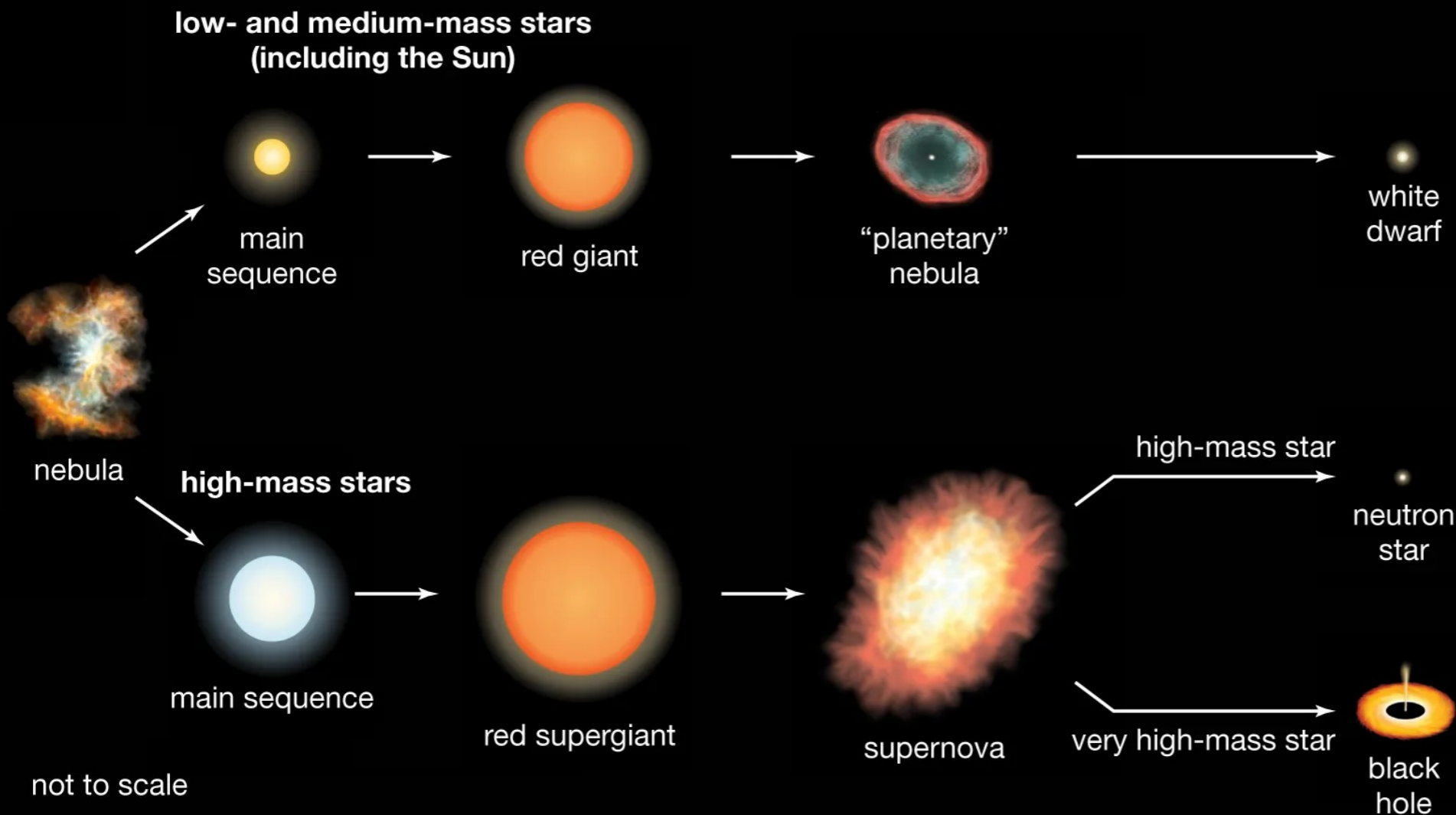


Chap 4: The Evolution of High-Mass Stars



Chap 4: The Evolution of High-Mass Stars

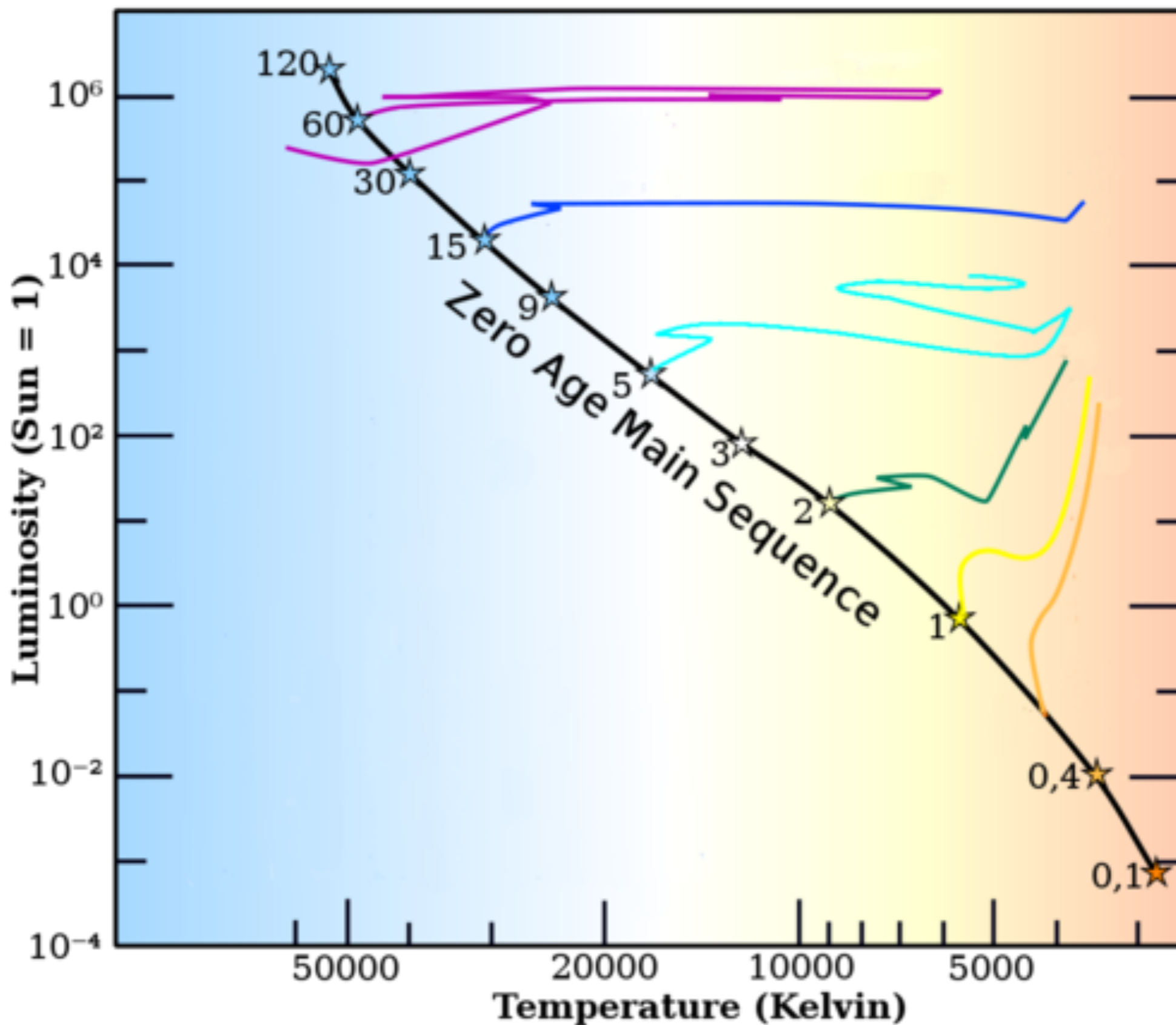
- CNO Cycles
- Convective cores
- Consecutive fusion shells
- End of fusion - Binding Energy
- Core collapse supernovae
- Neutron stars and Pulsars
- Supernova Remnants (SNR): expansion parallax method
- The Origin of Elements: six primary astrophysical sources
- Periodic variables: L-P relations (distance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



• Mass-Transfer Binaries

- Roche Lobe, Lagrange Points
- Novae, Type Ia SNe, Blue Stragglers

The division at $3 M_{\text{SUN}}$ marks an rough transition in the shape of the computed evolutionary tracks



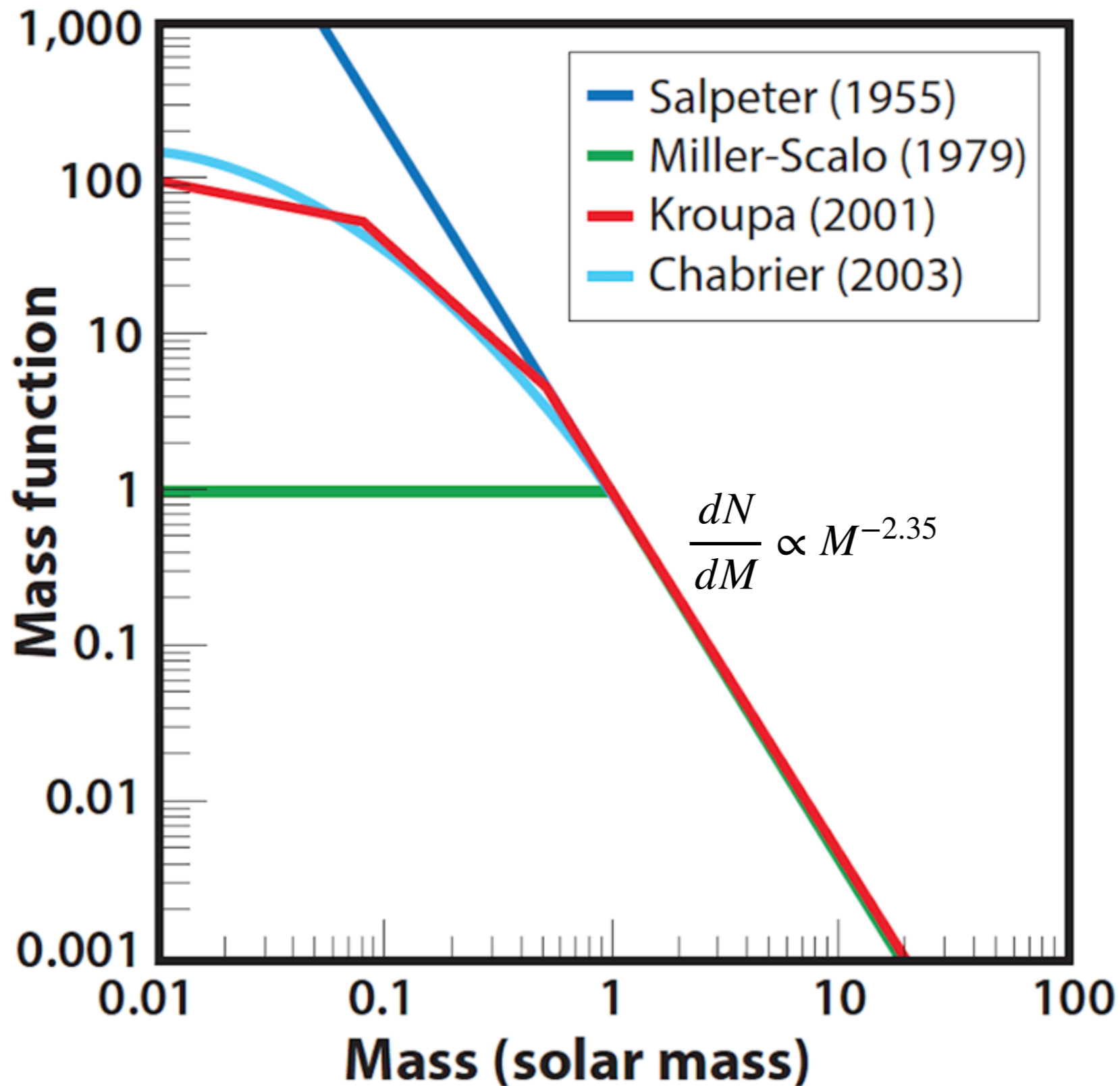
Chap 4 deals with stars of initial masses greater than $3 M_{\text{Sun}}$

- 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 $< 3 M_{\text{Sun}}$)
 - **intermediate-mass stars** (Mass between $3 M_{\text{Sun}}$ and $8 M_{\text{Sun}}$)
 - **high-mass stars** (Mass $> 8 M_{\text{Sun}}$)

| 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 | $8 M_{\text{Sun}}$ | $3 M_{\text{Sun}}$ | $0.5 M_{\text{Sun}}$ | $0.08 M_{\text{Sun}}$ | $\sim 0.01 M_{\text{Sun}}$ ($\sim 13 M_{\text{Jupiter}}$) |

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

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



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**:

$$kT_c \approx GM\mu m_H/R$$

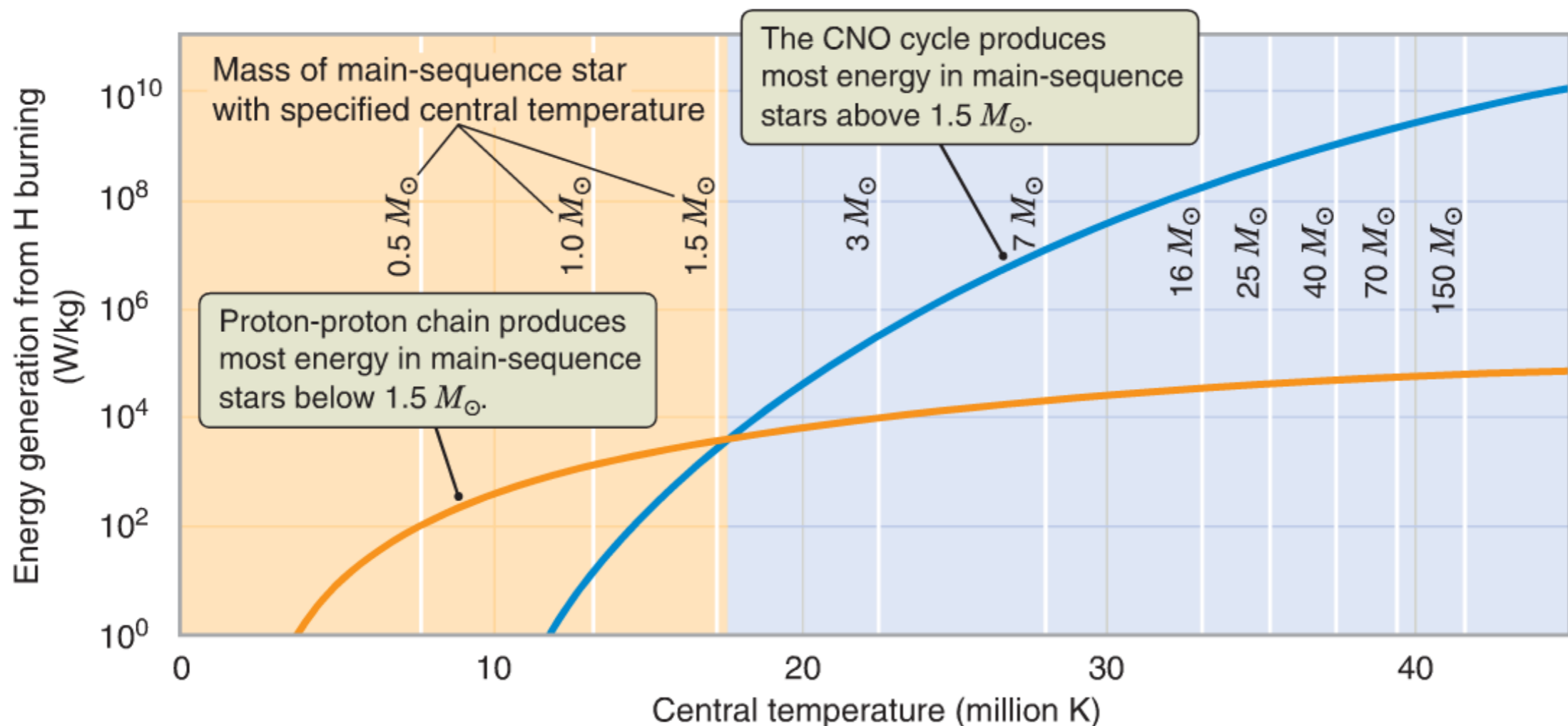
- Core pressure can be estimated from a **force balance**:

$$4\pi R^2 P_c \approx GM^2/R^2 \Rightarrow P_c \approx GM^2/(4\pi R^4)$$

- Main sequence stars show a **mass-radius relation** of:

$$R \propto M^{0.7}$$

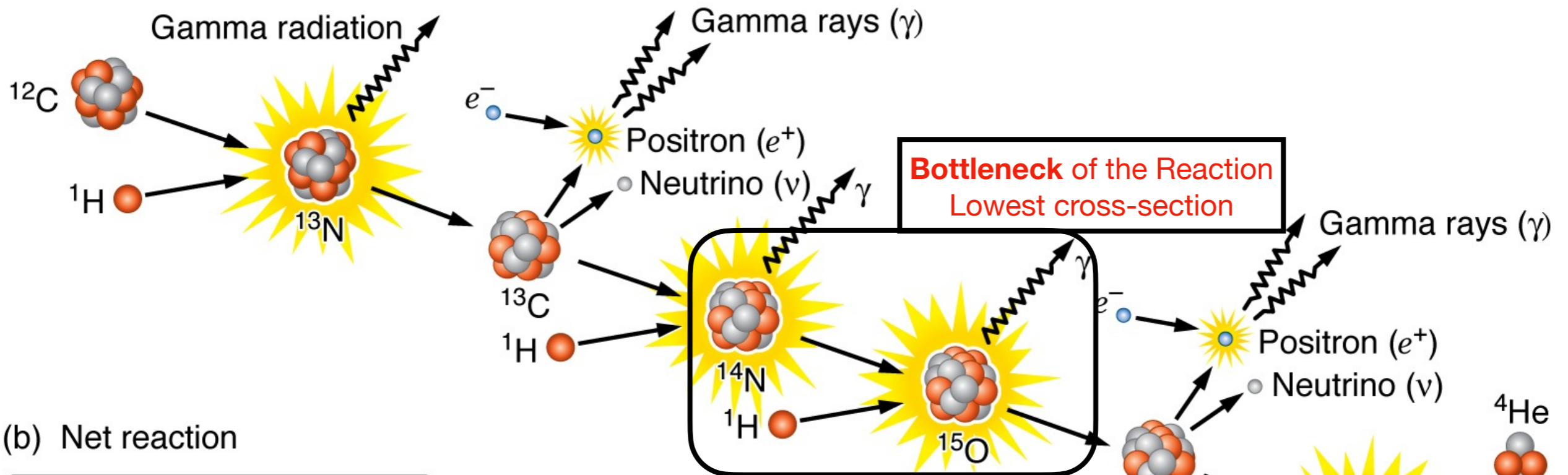
- Therefore, $T_c \propto M^{0.3}$ and $P_c \propto M^{-0.8}$



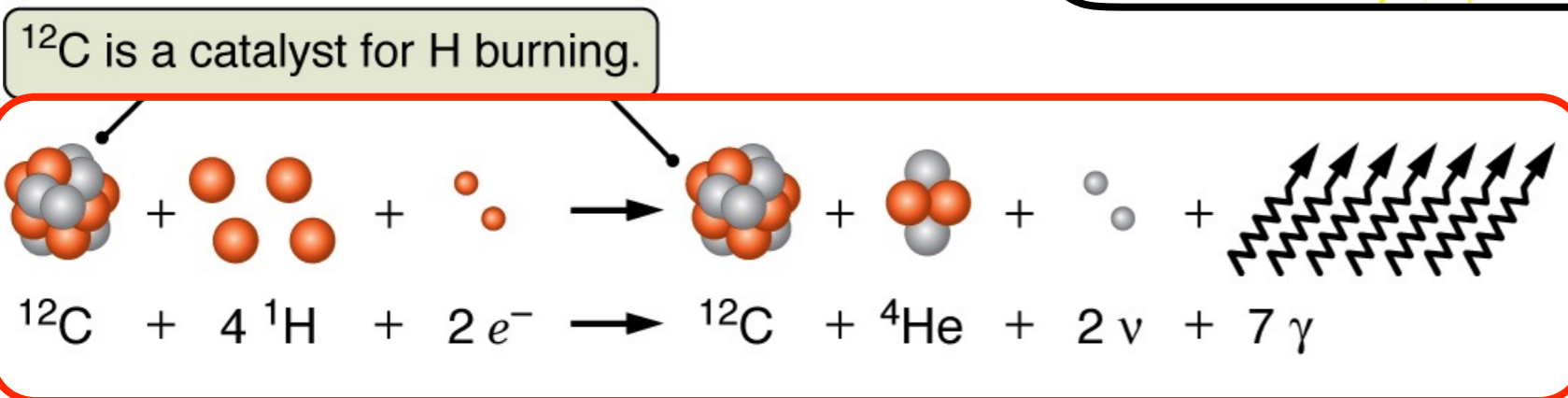
Net reaction of the CNO cycle and the Origin of Nitrogen

- 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.
- Due to the **bottleneck** of the reaction chain ($^{14}\text{N} \rightarrow ^{15}\text{O}$), **Nitrogen** accumulates to high levels in the core while depleting **Carbon** (this is the origin of N)

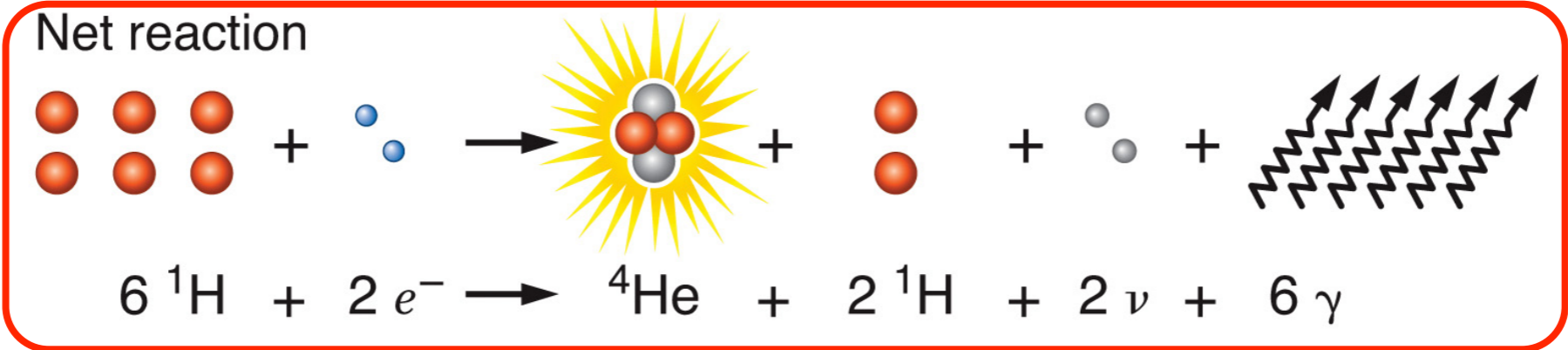
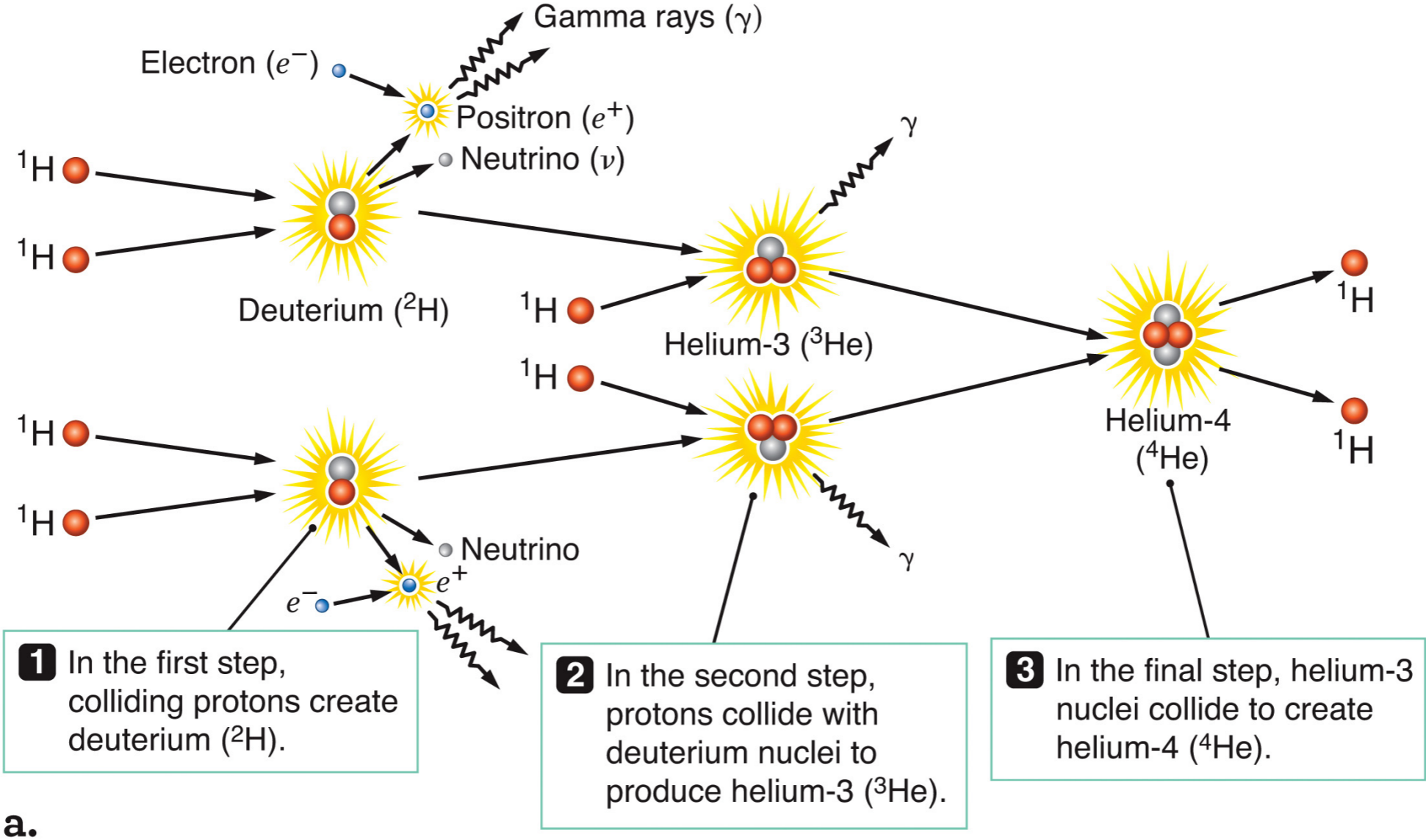
(a) CNO cycle



(b) Net reaction

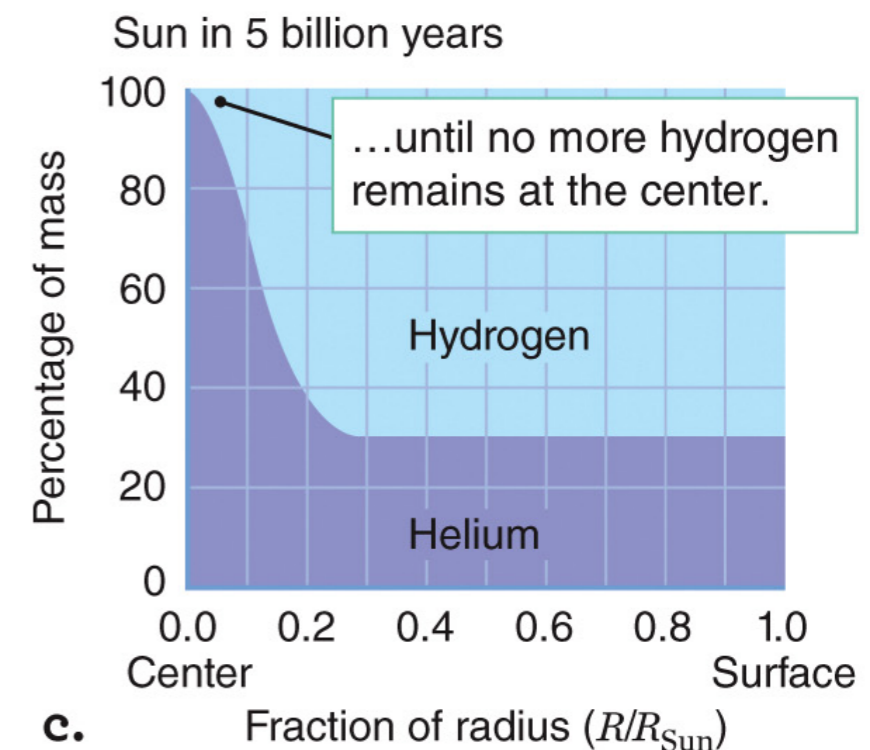
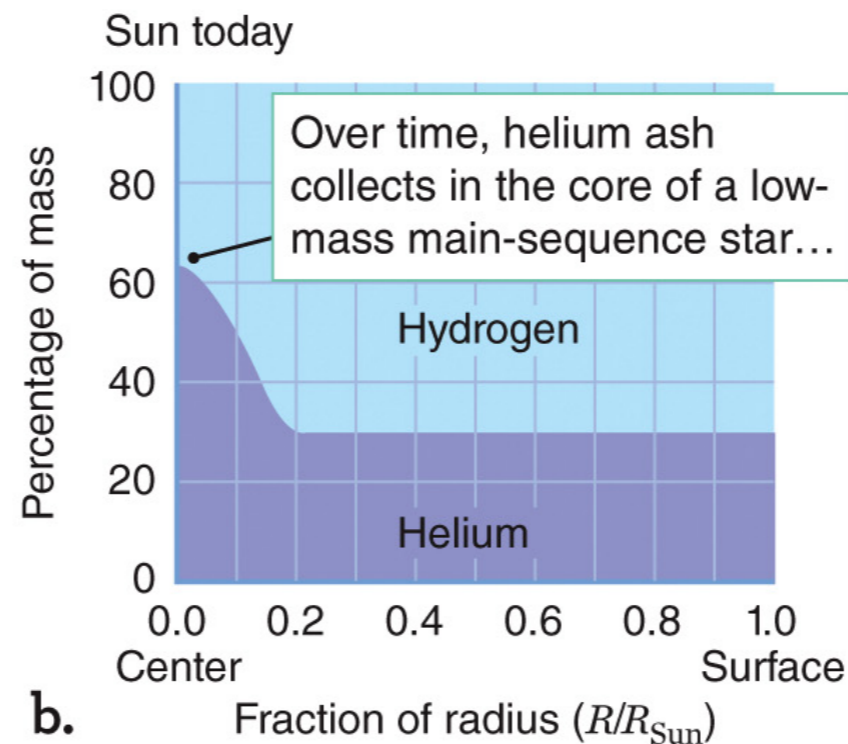
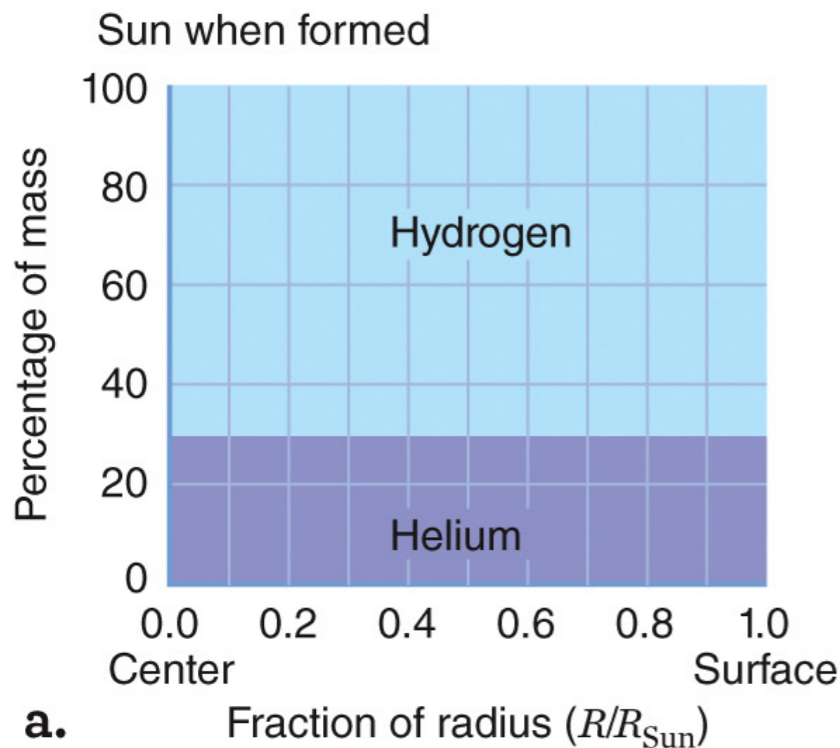


Net reaction of the Proton-Proton chain



Changes on the Main Sequence due to Fuel Exhaustion

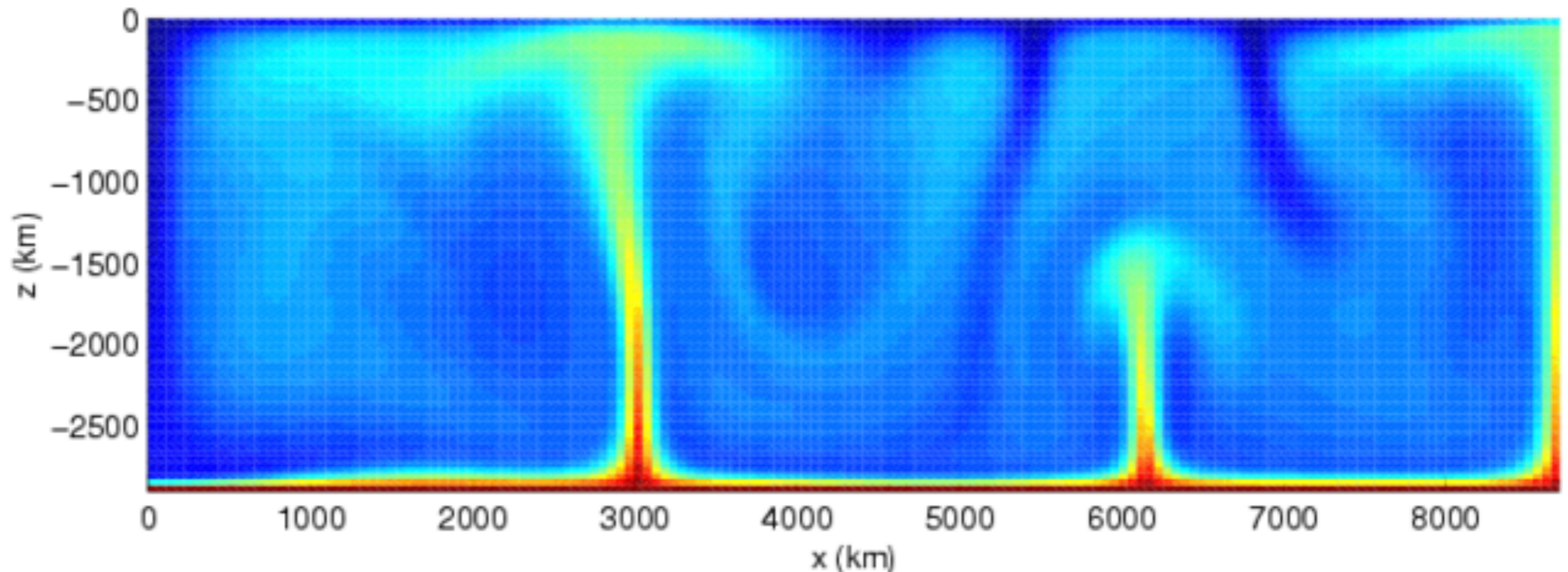
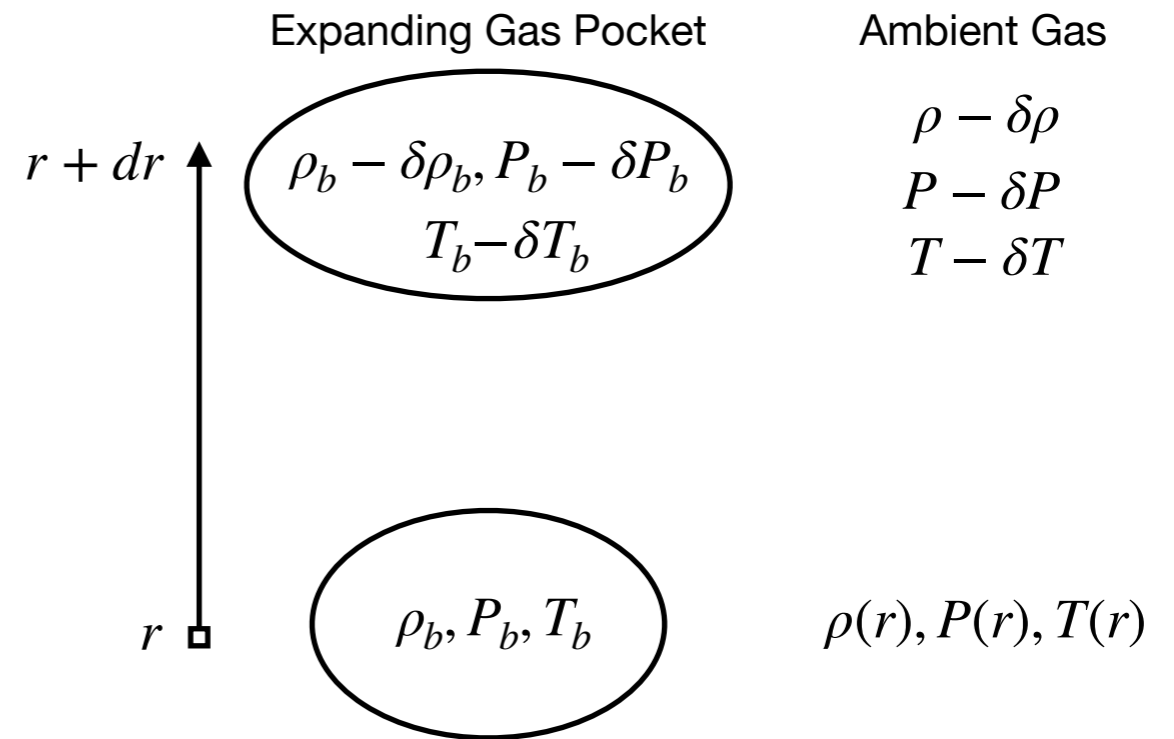
- The chemical composition inside a star changes over time as hydrogen is fused into helium.
- The Sun started with 70 percent hydrogen by mass, but now contains only 35 percent hydrogen in the core.



Condition for Convection: Steep Temperature Gradients

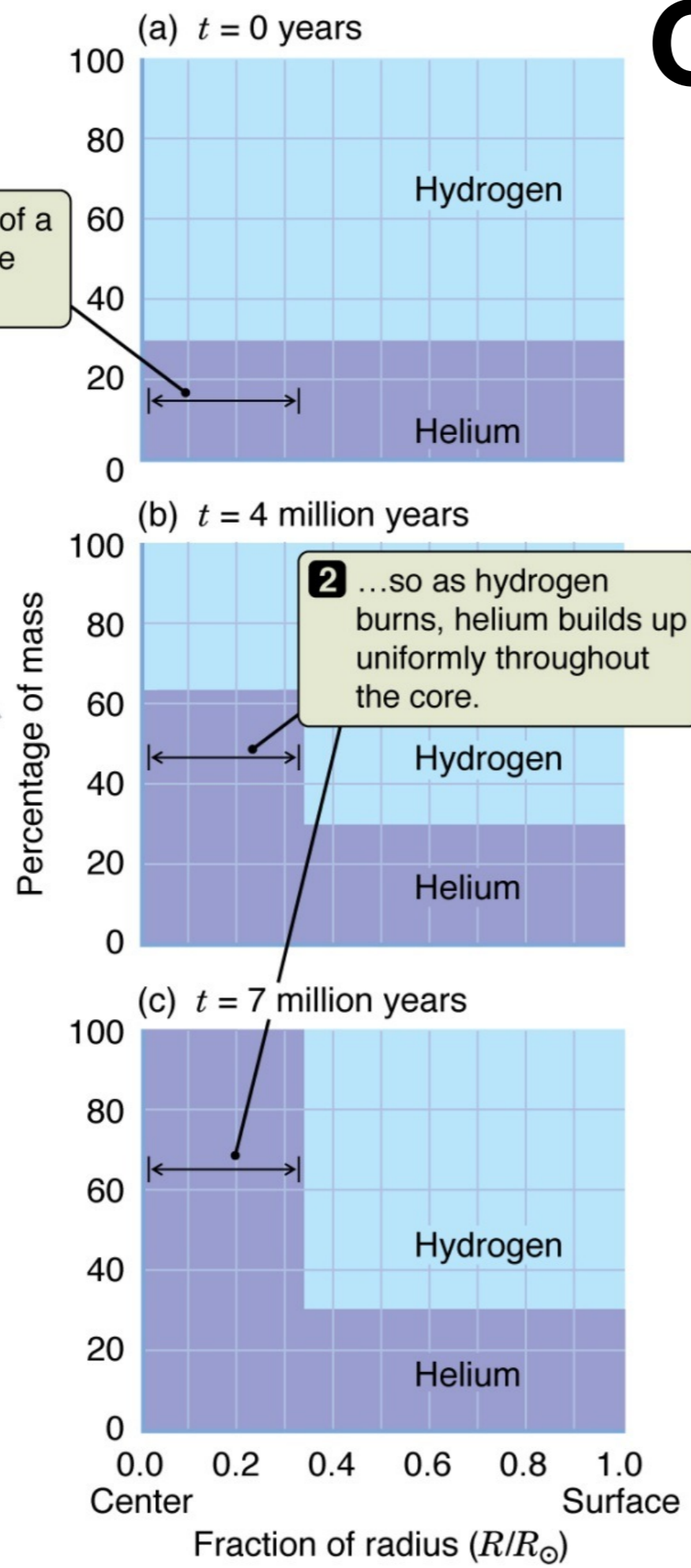
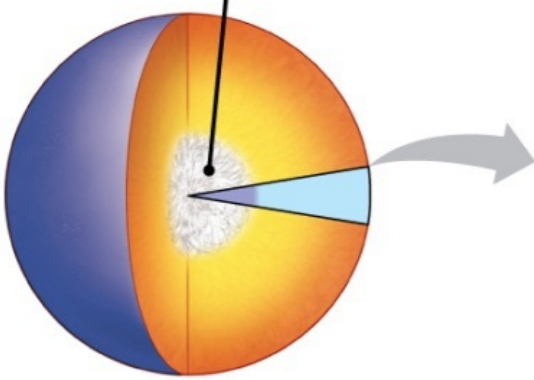
- When **adiabatic expansion** of a gas pocket causes its temperature to drop *less* than that of the ambient gas, **convection** ensues:

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

1 Convection in the core of a massive main-sequence star "mixes" material...

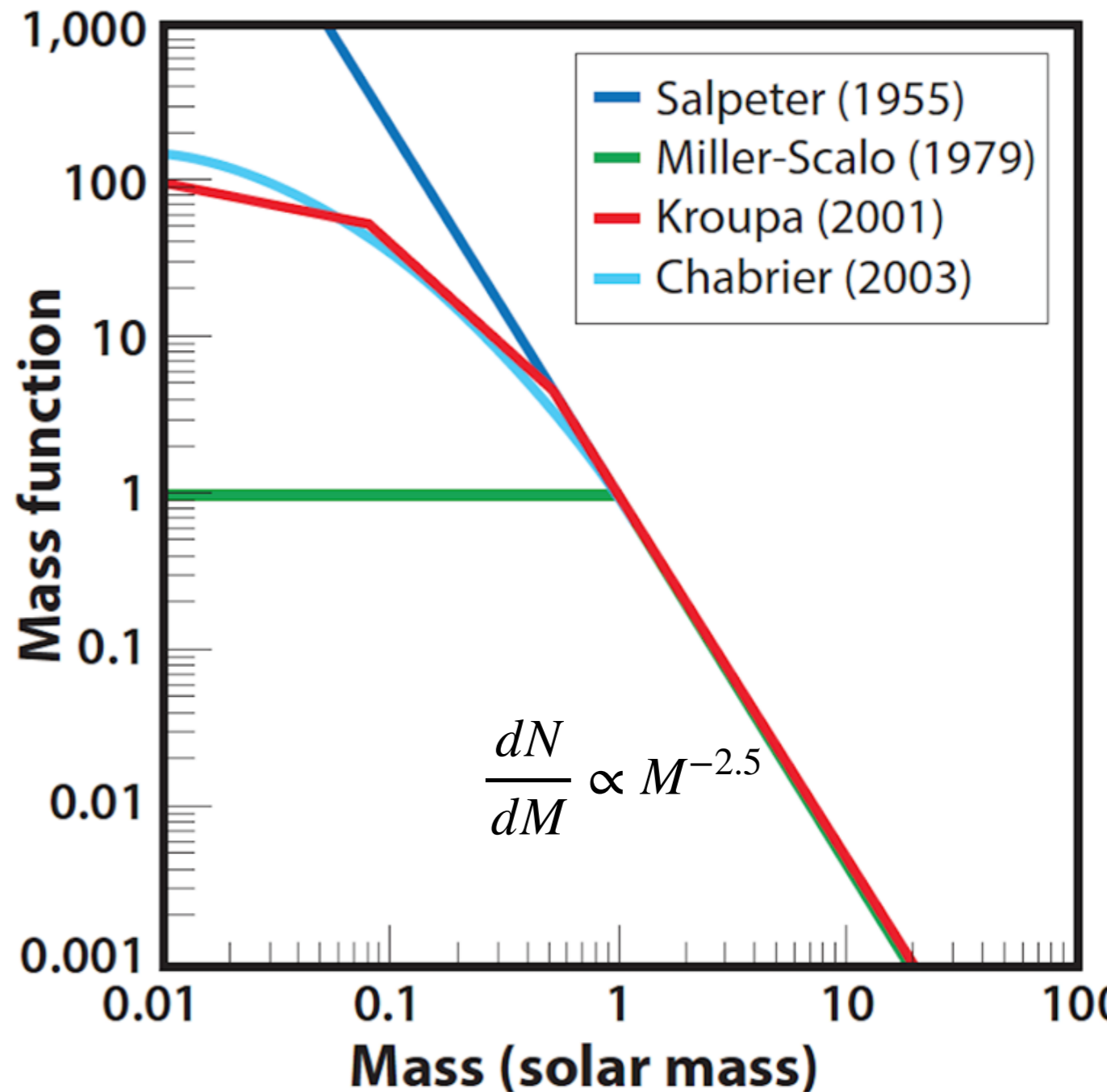
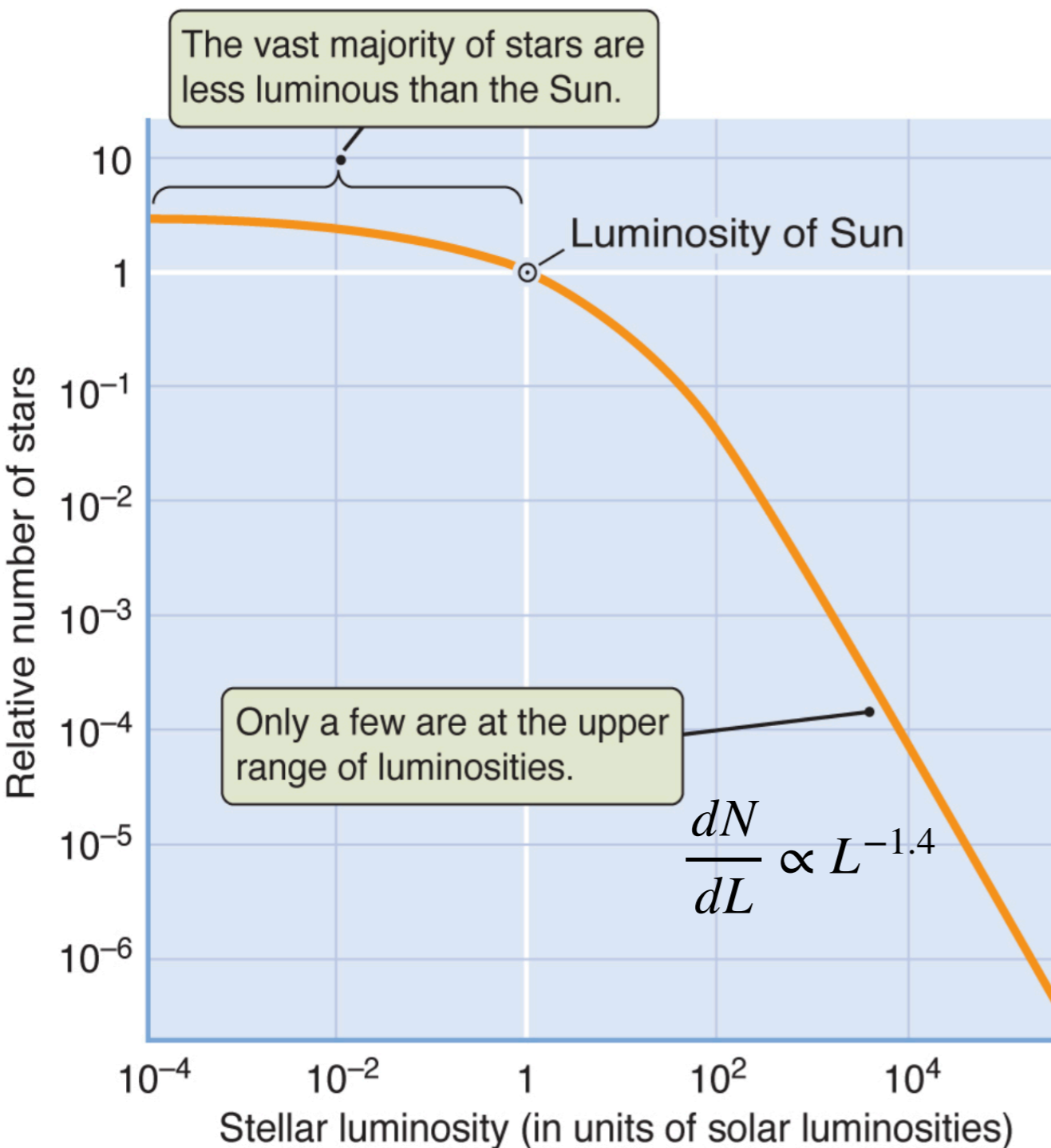


2 ...so as hydrogen burns, helium builds up uniformly throughout the core.

- CNO cycle's extreme temperature sensitivity (T^{17}) causes a **steep T gradient**, causing **convections** that mix H & Helium effectively.
- This increases the available fuel for H-He fusion, and makes a nearly **uniform chemical composition** across the core
- High-mass stars live shorter lives (e.g., ~ 3 Myr for $25 M_{\text{sun}}$) due to high luminosity: $L \propto M^{3.5}$.
- *Is the core of a Horizontal Branch star radiative or convective?*

Correction: Luminosity Distribution vs. Mass Distribution

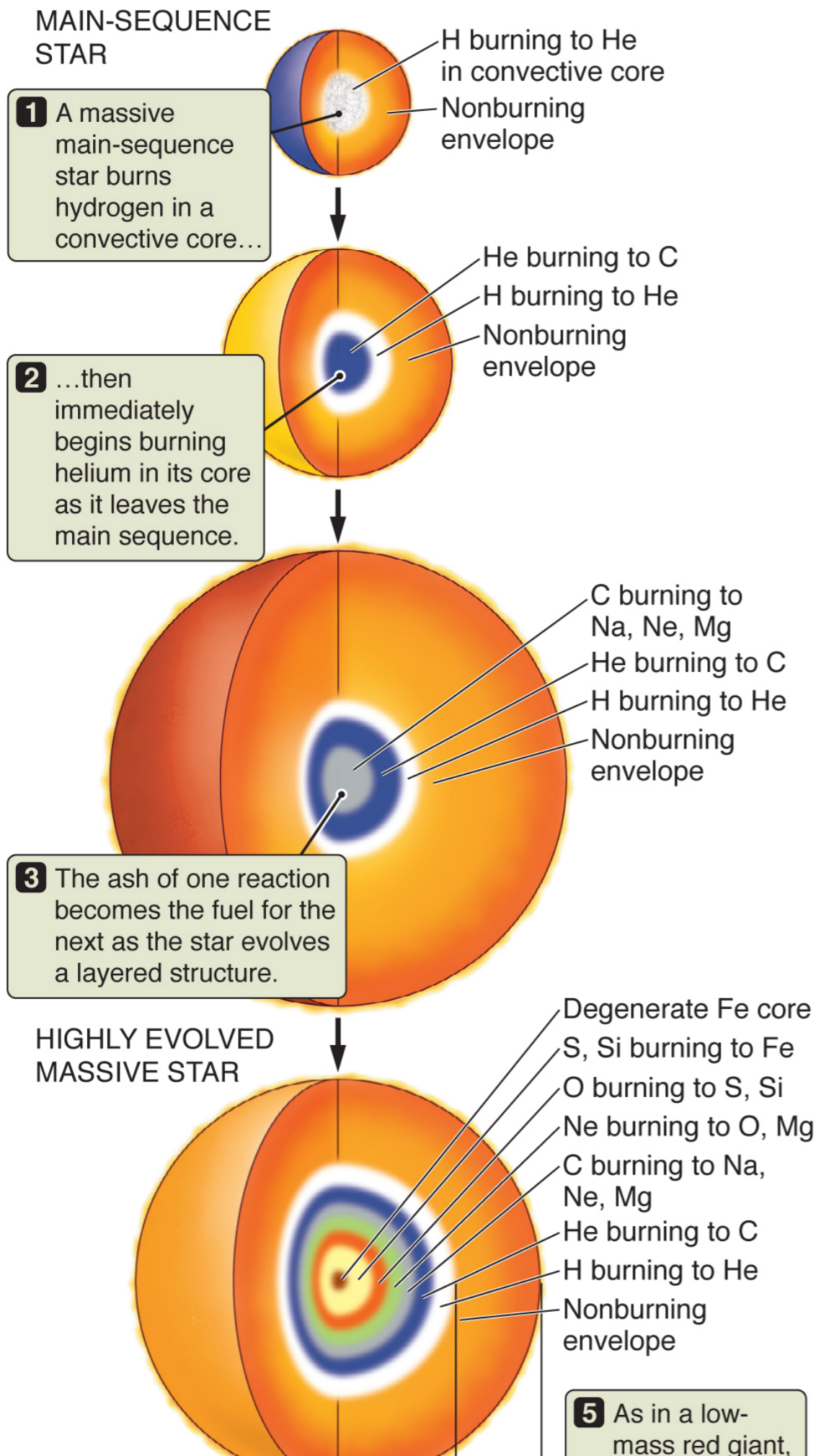
When the mass distribution follows $\frac{dN}{dM} \propto M^{-2.5}$, we expect $\frac{dN}{dL} \propto L^{1.4}$, because $L \propto M^{3.5}$



Post-MS evolution:

**Onion layers of burning shells,
& the end of fusion**

Burning Core and Burning Shells

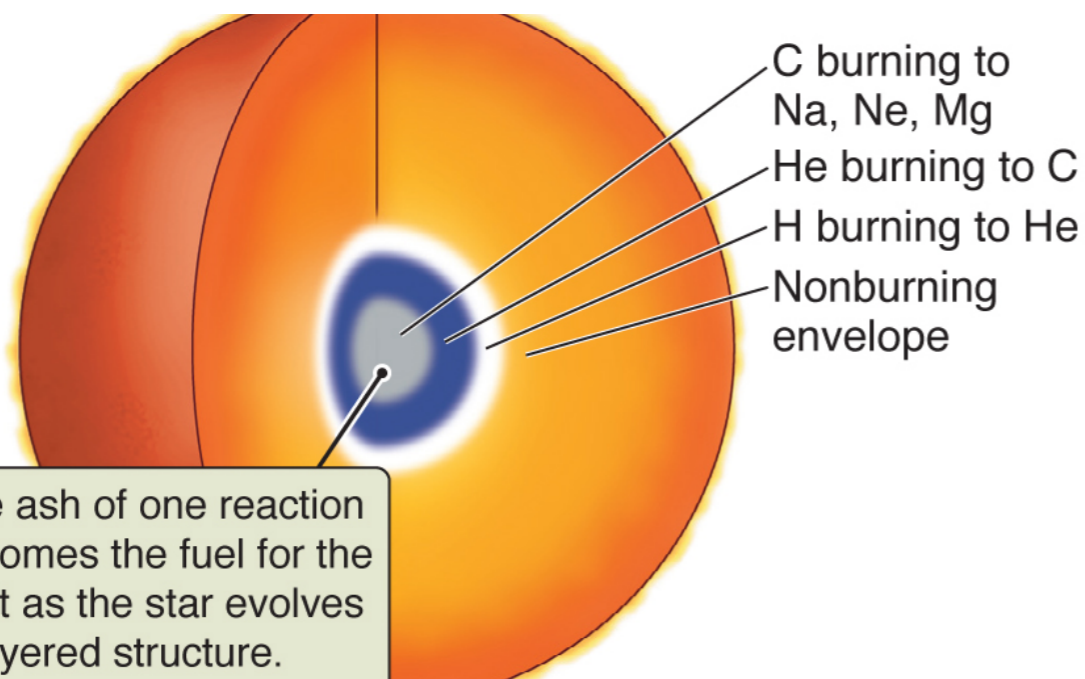


- The compression of the **core** ignites **He-burning before it becomes degenerate**, unlike low-mass stars.
- The fusion shells build up like the **layers of an onion**.
- The more massive the star, the heavier the elements that can fuse.
- Cores of high-mass stars will **fuse elements up until iron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

Burning Stages in High-Mass Stars

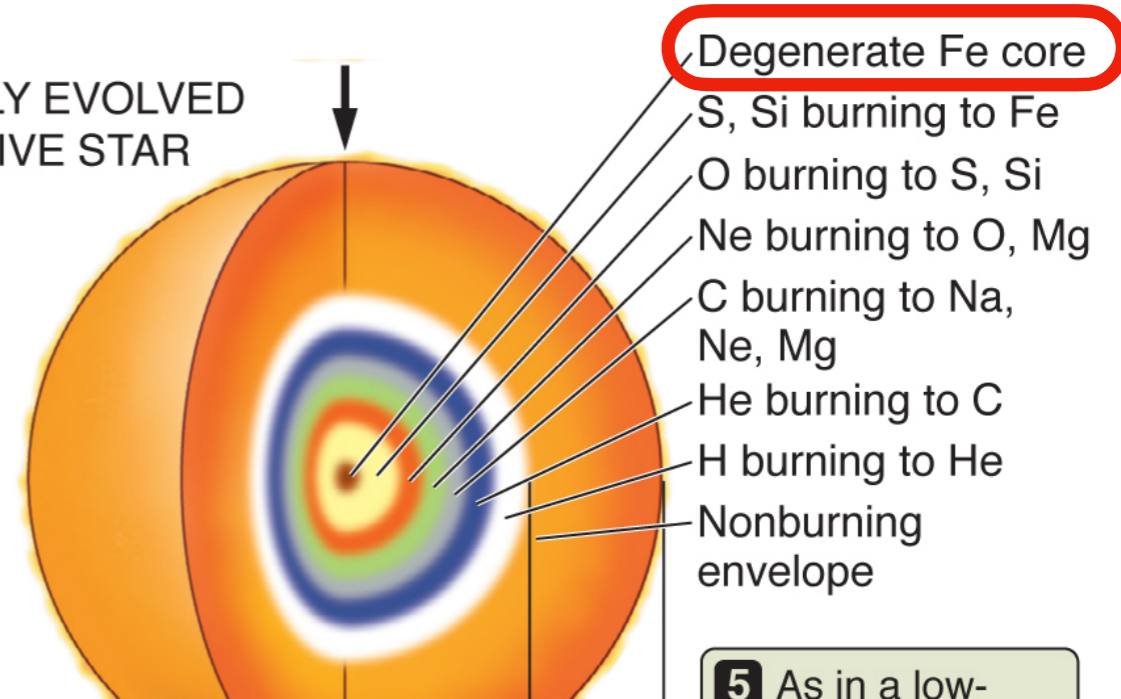
Harder to fuse heavier elements, with diminishing returns

| 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 |



3 The ash of one reaction becomes the fuel for the next as the star evolves a layered structure.

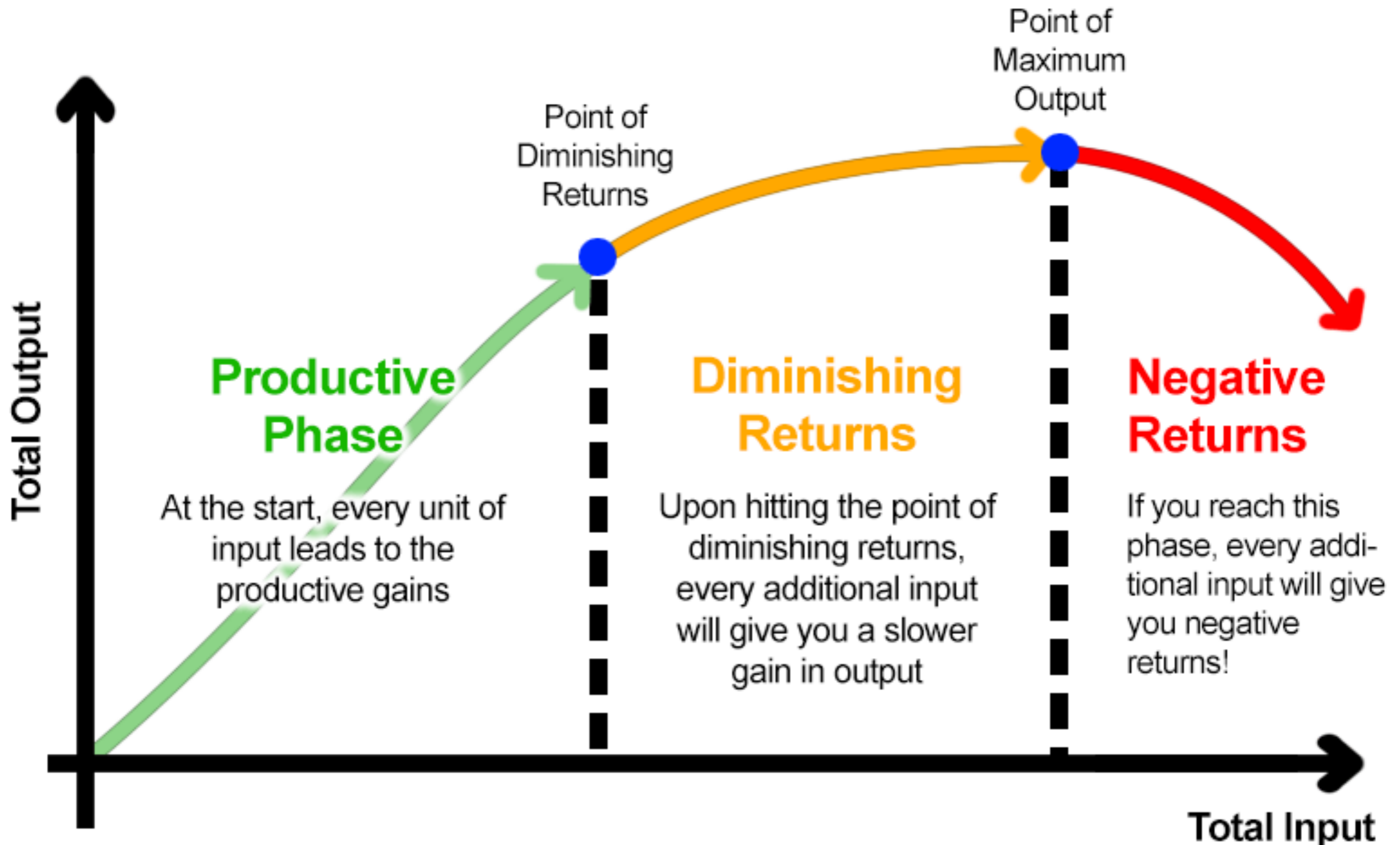
HIGHLY EVOLVED MASSIVE STAR



5 As in a low-

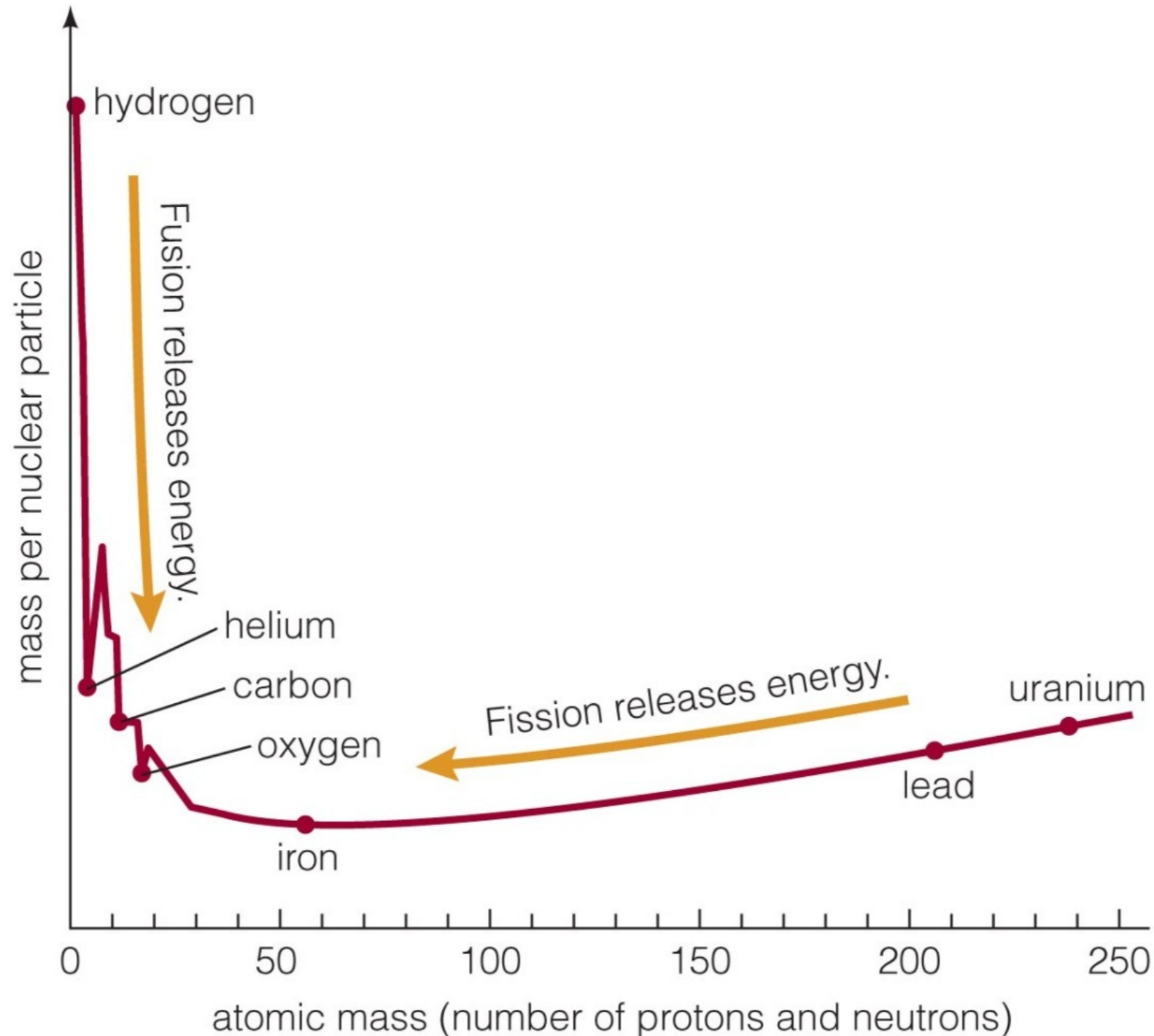
The Law of Diminishing Returns

In Economics, the law of diminishing returns states that in productive processes, increasing a factor of production by one, while holding all others constant, **will at some point return lower output per incremental input unit**



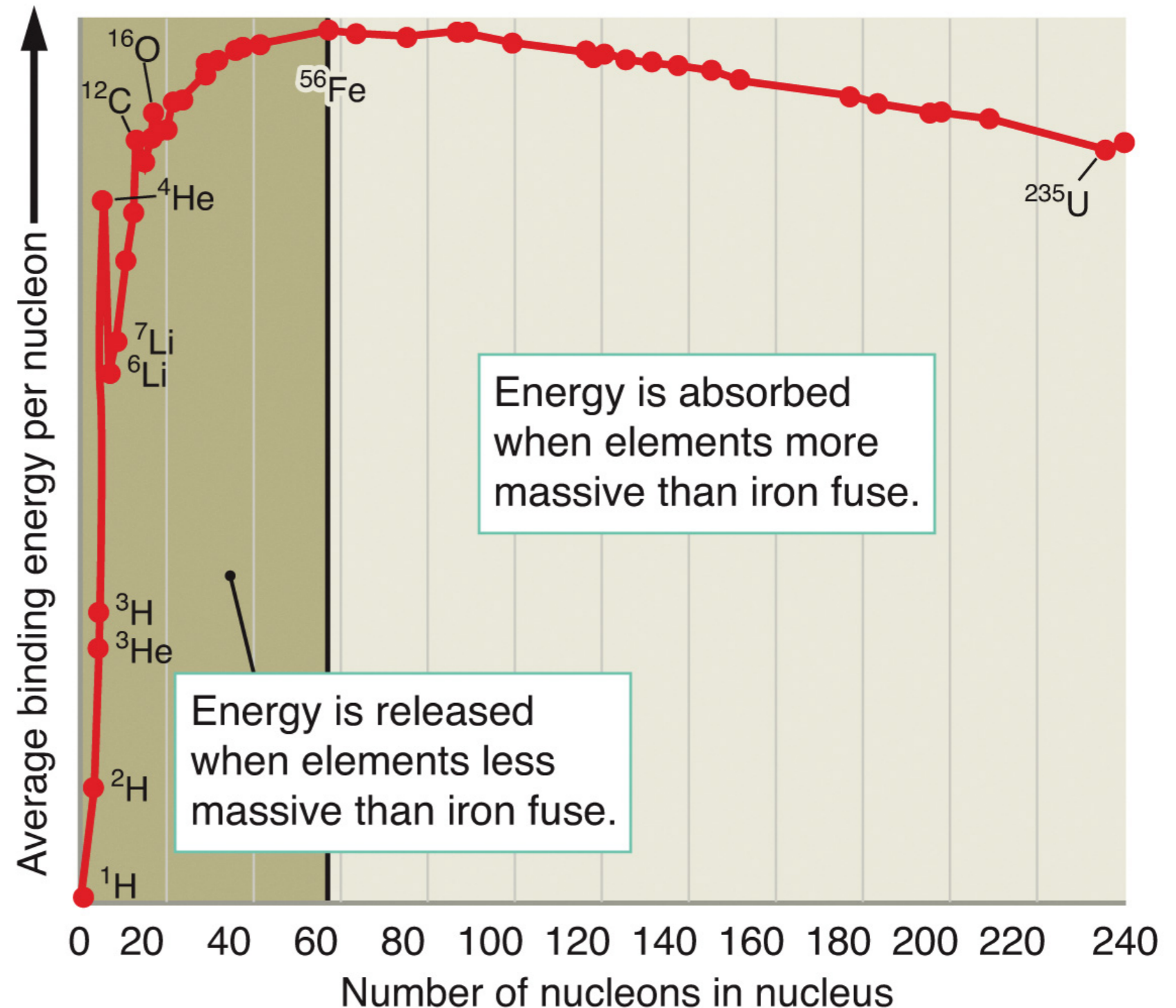
Fusion Energy: the mass per nucleon decreases from H to Fe

- **Fusion** produces energy from the mass loss occurred when fusing lighter elements into heavier elements because the **mass per nucleon decreases** ($E = \Delta m \cdot c^2$) from H-He-C-Ne-O-Si, up to Fe. **Fusion ends** when the *lowest* mass per nucleon is reached at Fe.



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.**



Example: 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:

$$\begin{aligned} \left(\text{Net energy from} \right) &= \left(\text{Binding energy} \right) - \left(\text{Binding energy} \right) \\ \left(\text{fusing 1 kg of He} \right) &= \left(\text{of C formed} \right) - \left(\text{of He fused} \right) \\ &= (7.402 \times 10^{14} \text{ J}) - (6.824 \times 10^{14} \text{ J}) \\ &= 5.780 \times 10^{13} \text{ J} \end{aligned}$$

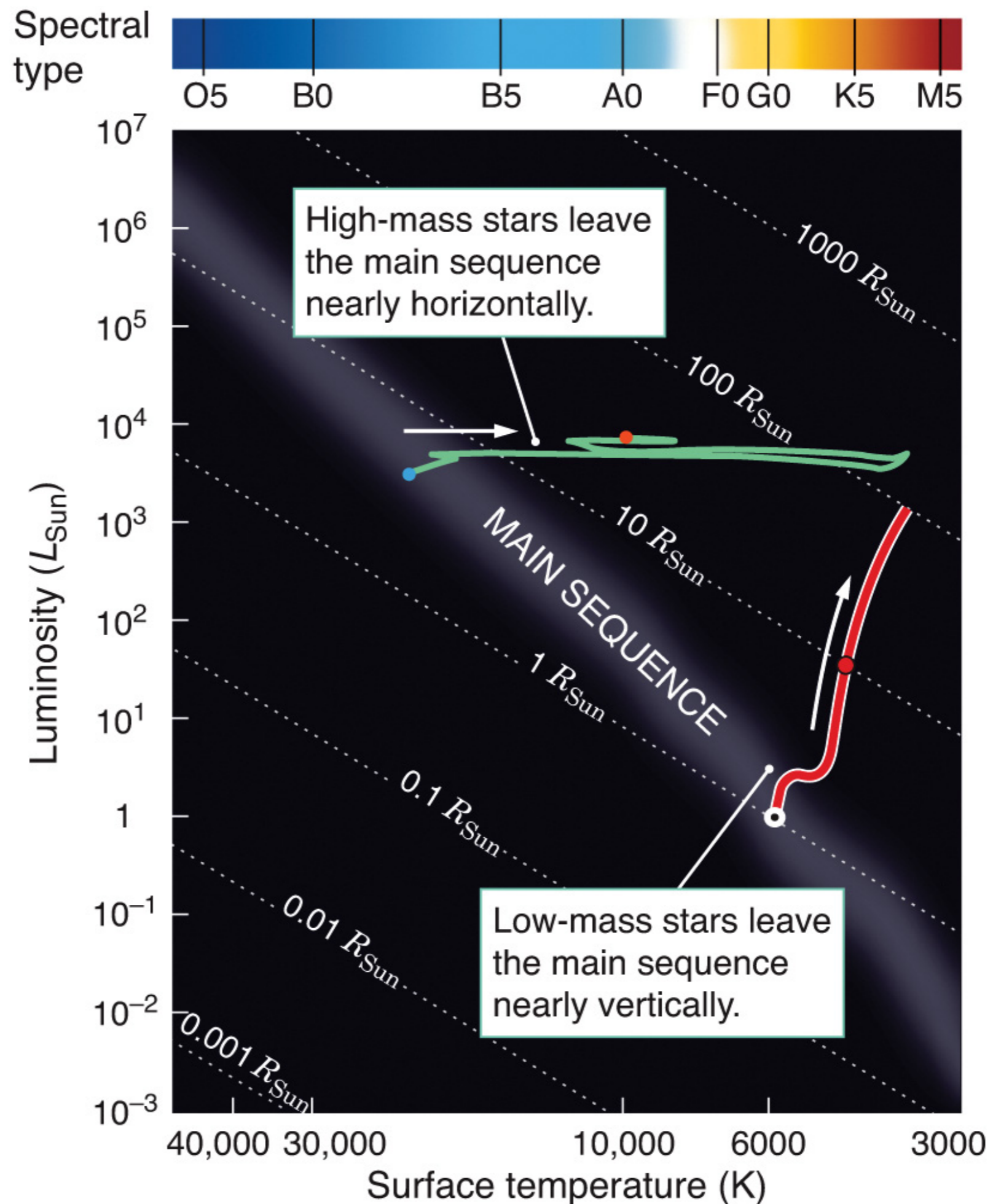
- For the fusion of **iron**, the binding energy of the products is less than that of the reactants, so the net energy is **negative**.

Post-MS evolution:

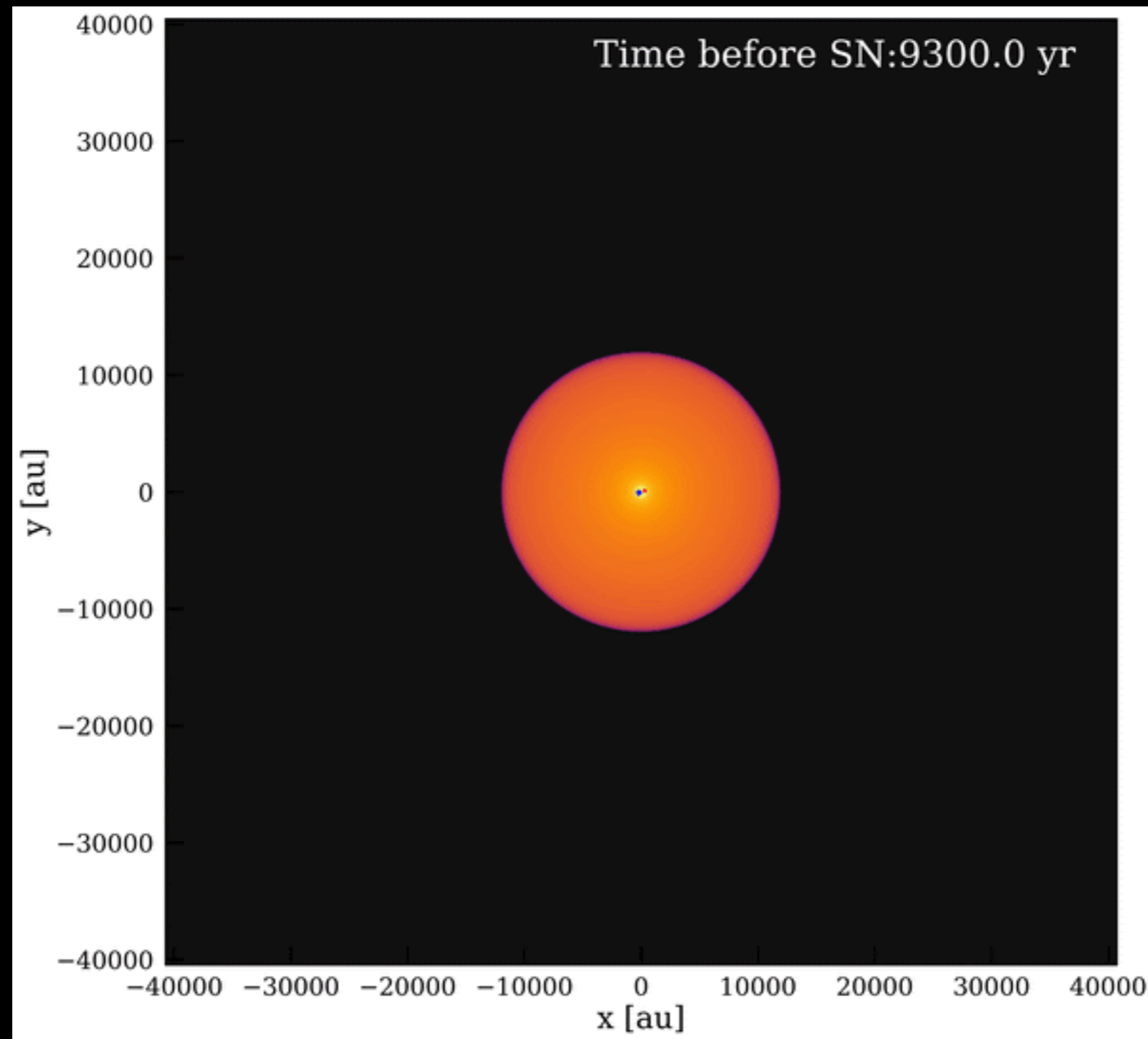
Mass Losses and Eruptions

Evolution Tracks on H-R Diagram

Once leaving the MS, the star starts to expand to a supergiant. While keeping almost constant luminosity, its temperature varies by $\sim 10x$



Severe Mass Loss of High Mass Stars

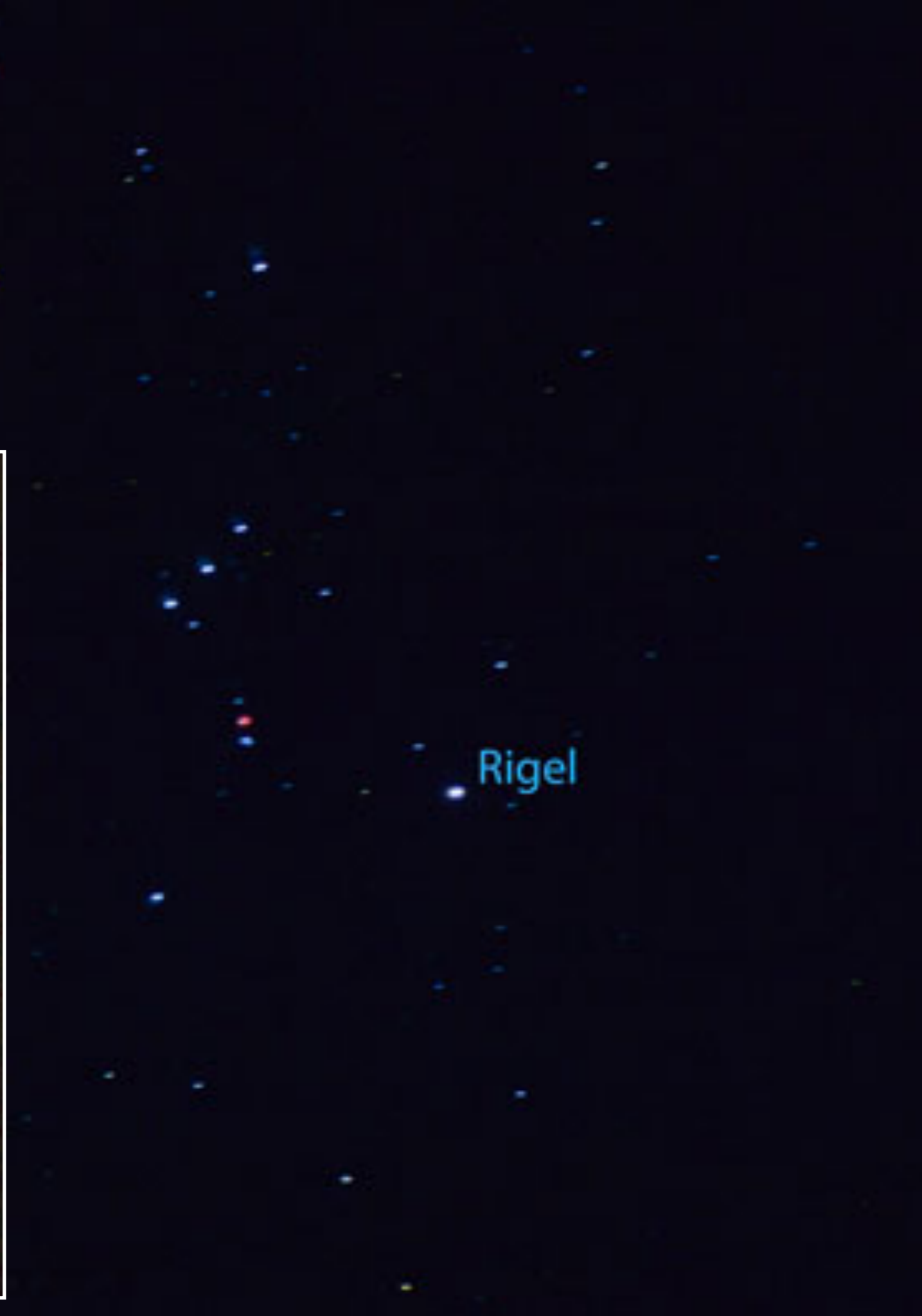
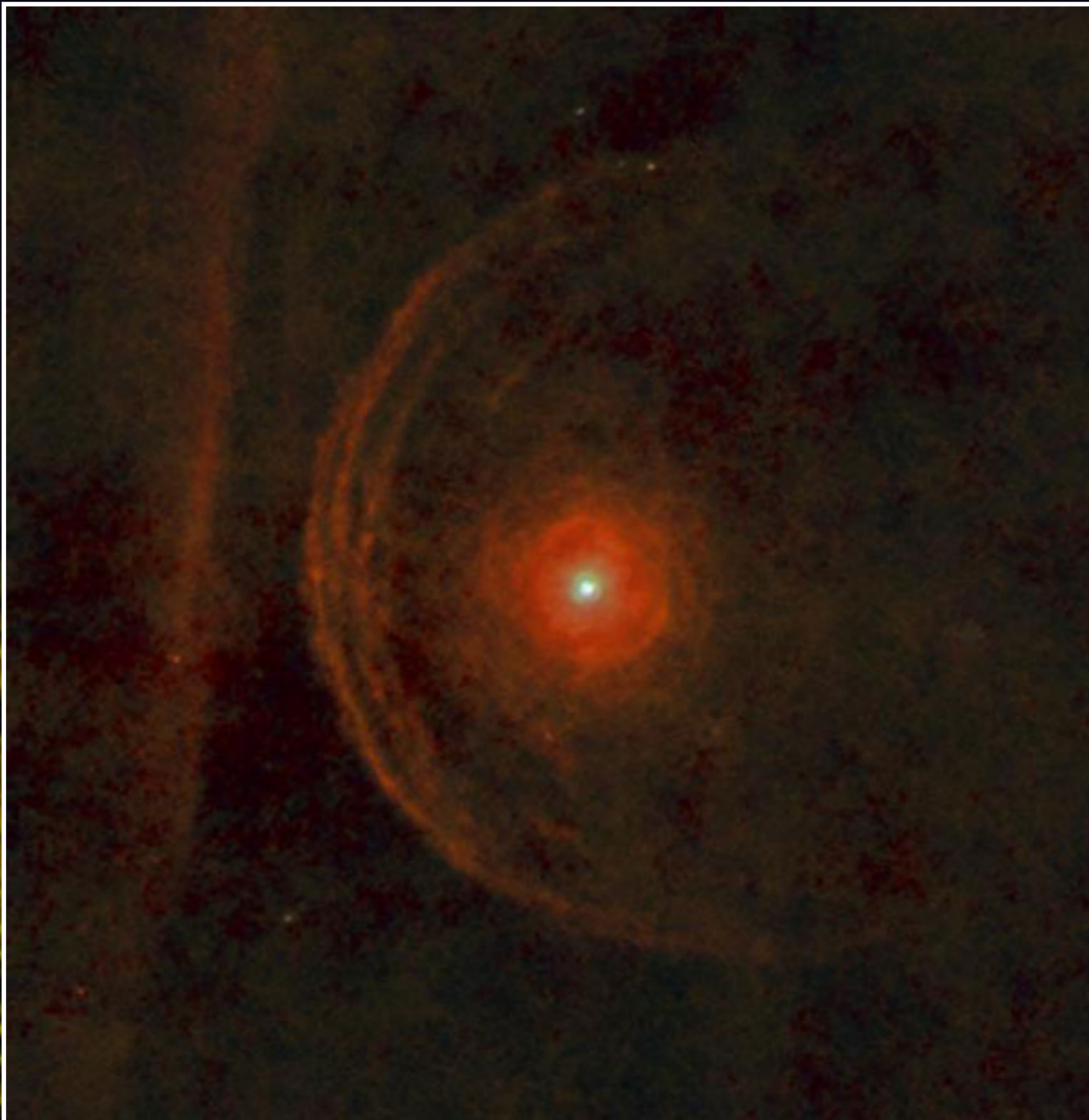


- Stars with $20 M_{\text{sun}}$ loses its mass quickly: 10^{-7} to $10^{-5} M_{\text{sun}}/\text{yr}$ because of low gravity and radiation pressure, and occasional eruptions (the Sun loses 10^{-14} to $10^{-13} M_{\text{sun}}/\text{yr}$ to wind)

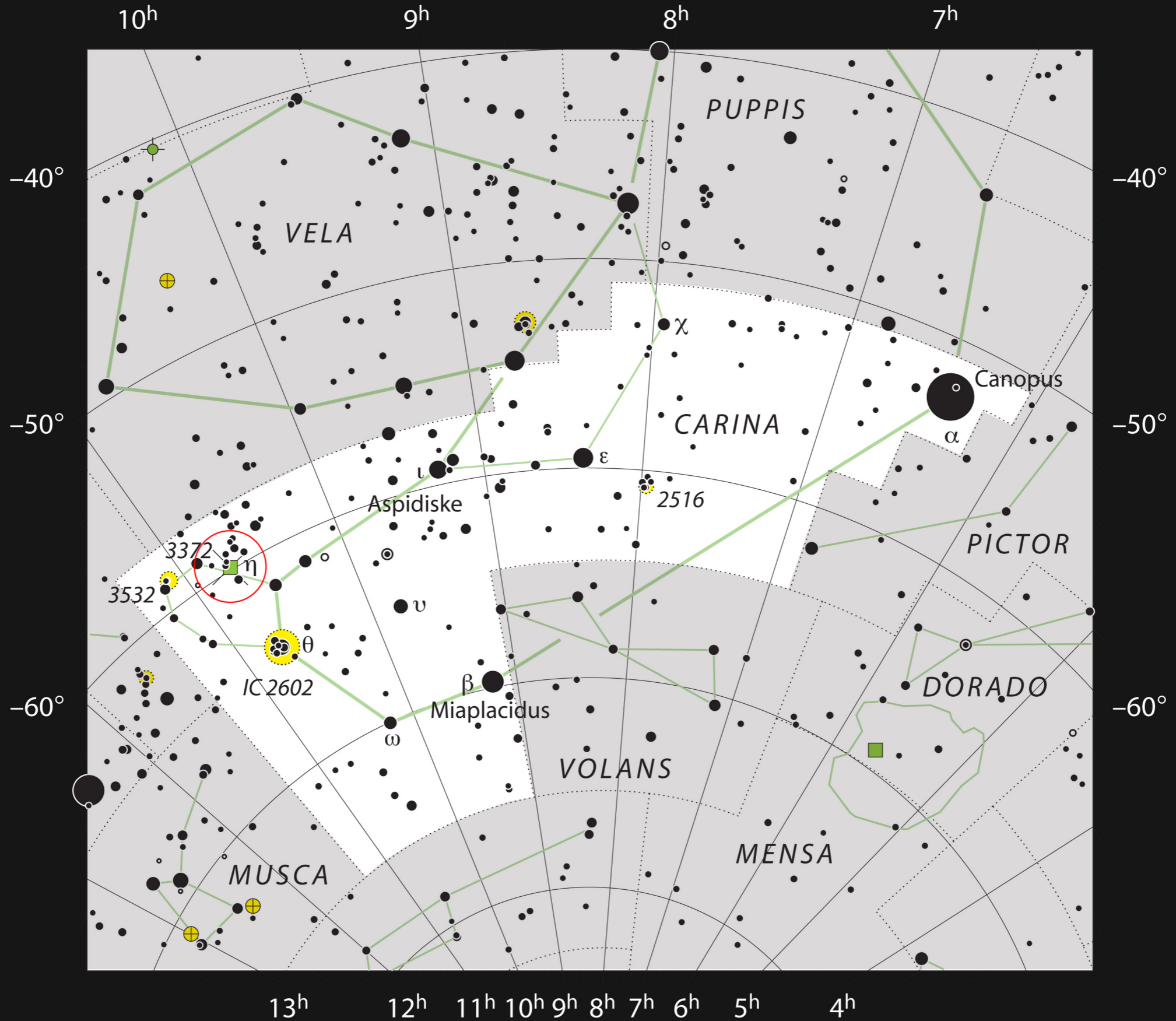
Mass Loss of Supergiant Stars

Betelgeuse

Rigel

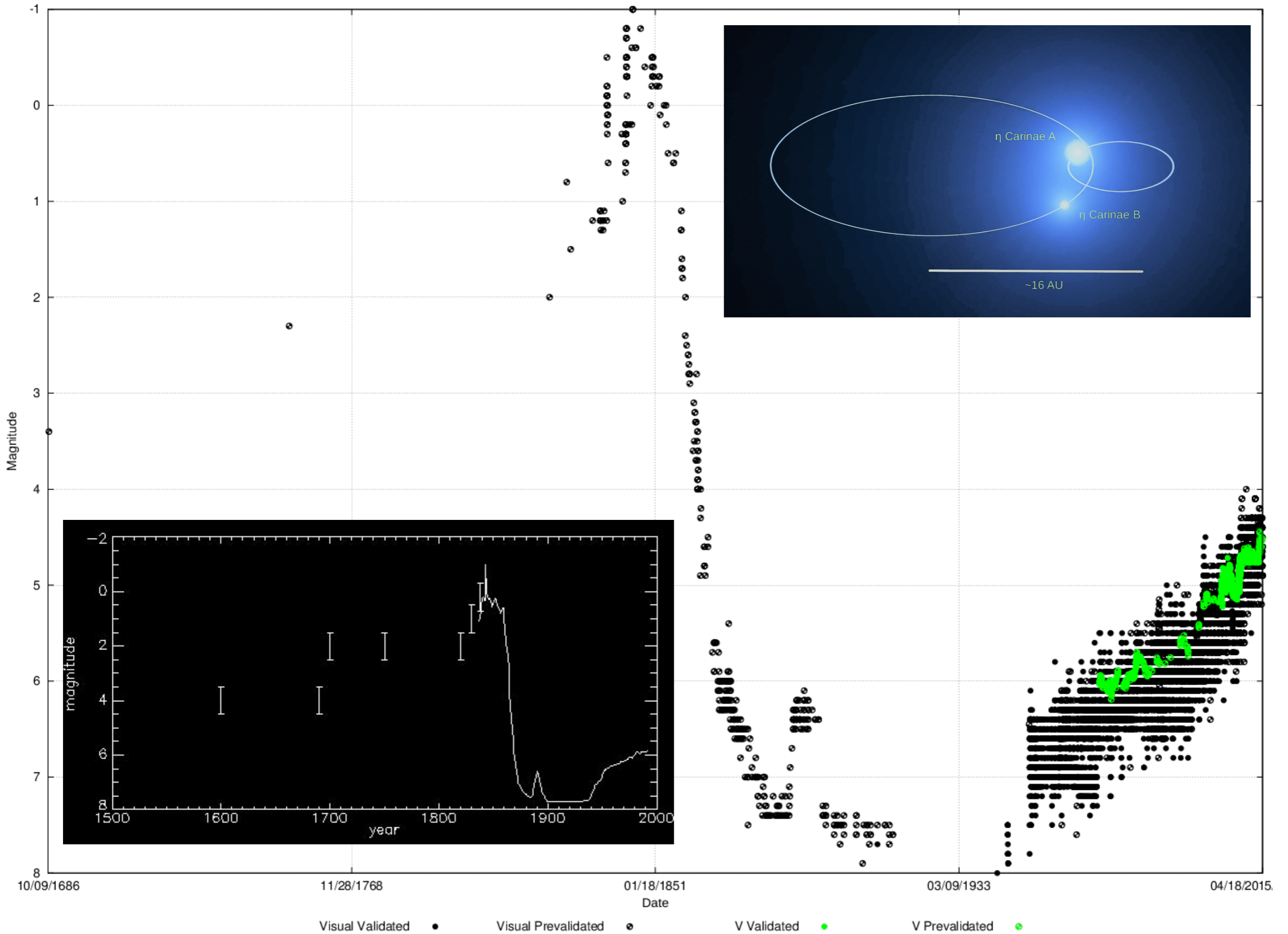


Eta Carinae (η Car): currently a 4th magnitude star

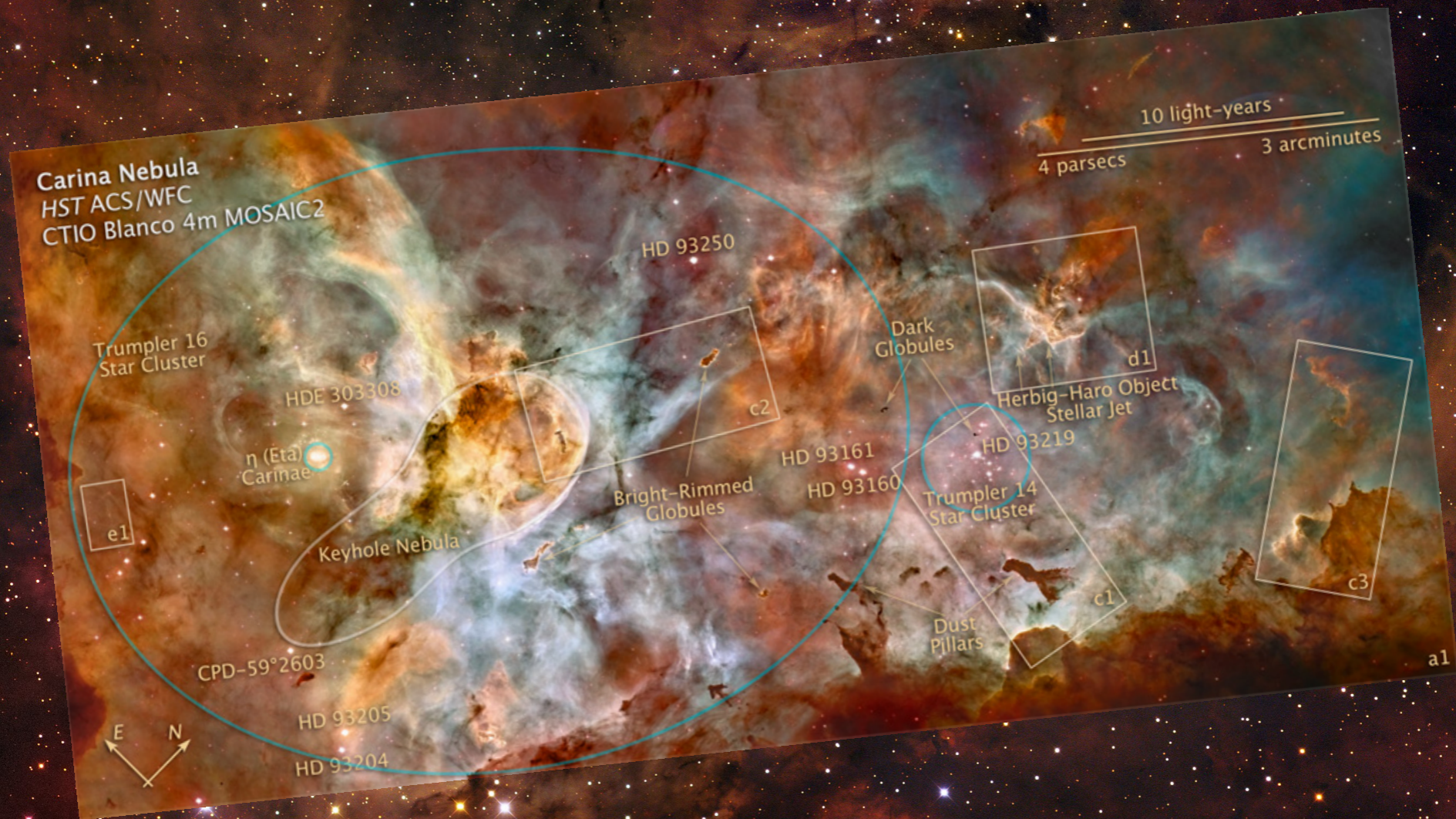


Eta Carinae (η Car): the Great Eruption around 1840 (a SN imposter)

AAVSO DATA FOR ETA CAR - WWW.AAVSO.ORG



Carina Nebula around Eta Carinae



Light Echos of the 1840 Eruption



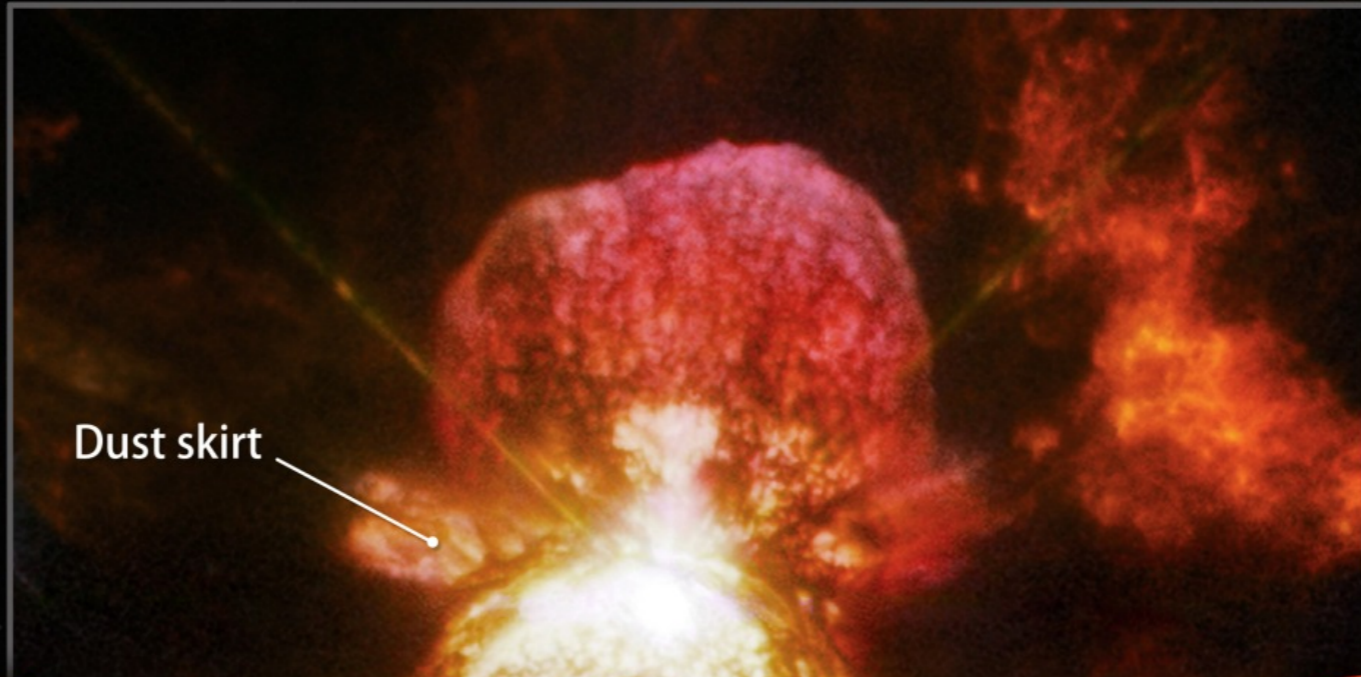
Homunculus Nebula:

22,000 AU in radius (bipolar lobes), likely formed in the 1840 outburst.

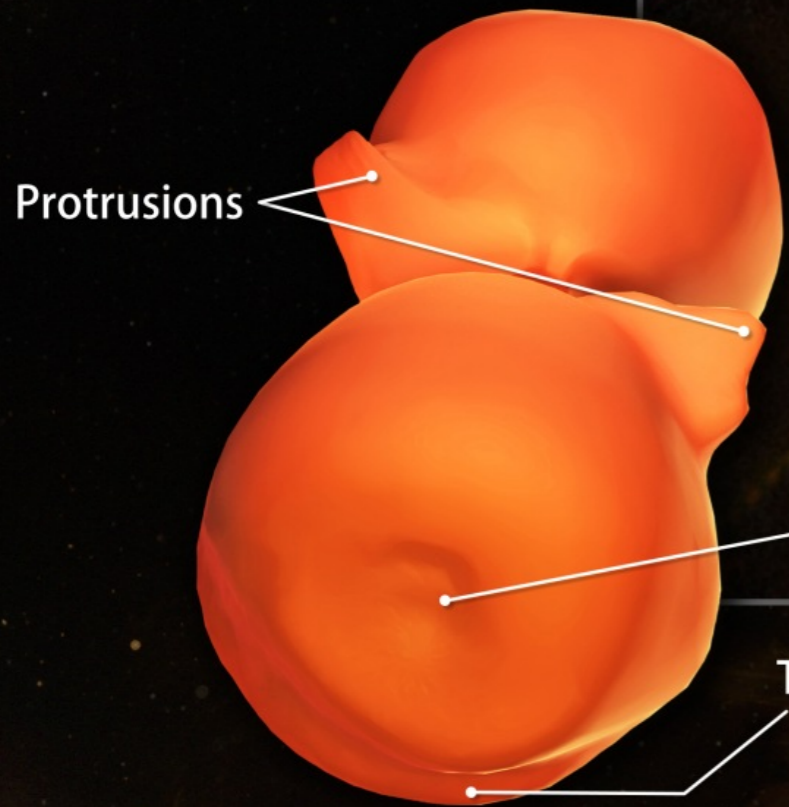


- Eta Carinae (dis \sim 2.4 kpc): $150 M_{\text{sun}}$ primary + $80 M_{\text{sun}}$ secondary
- The primary may have already lost at least $30 M_{\text{sun}}$.

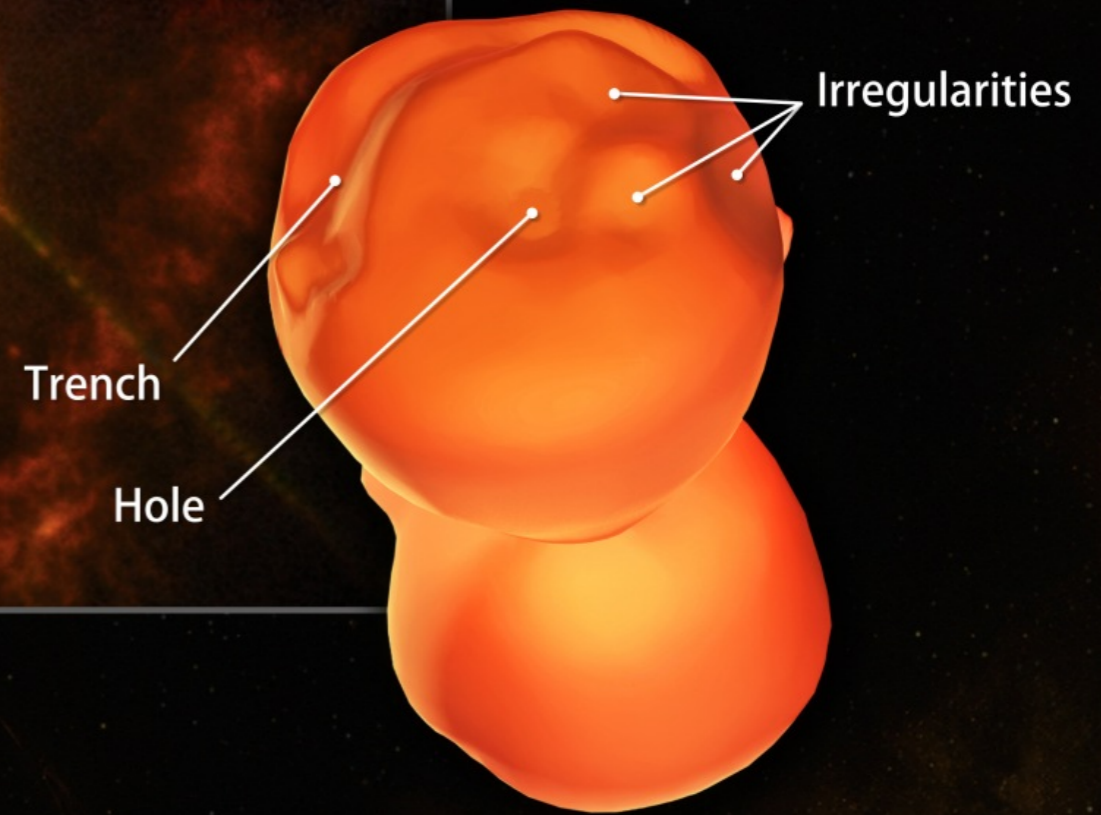
Eta Carinae Homunculus Nebula



Model
Side facing toward Earth



Model
Side facing away from Earth



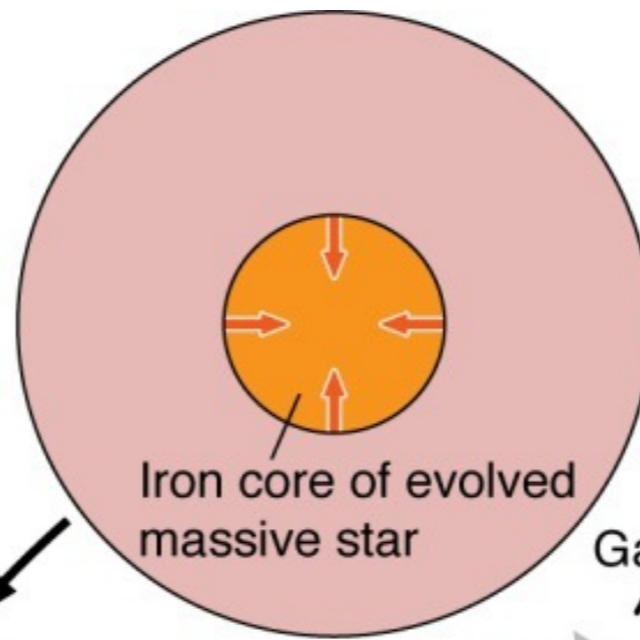
Core-Collapse Supernovae

Type II SNe

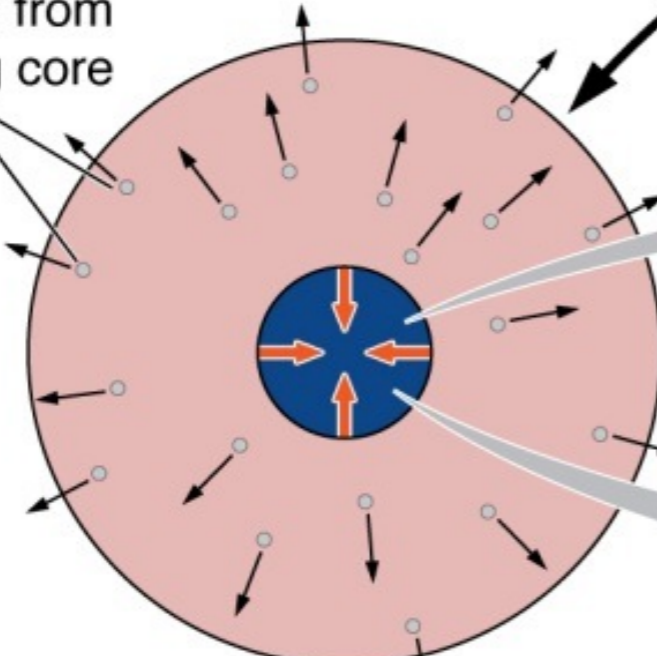
Core-Collapse SN

1 Not even electron degeneracy pressure can stop the collapse of an iron ash core.

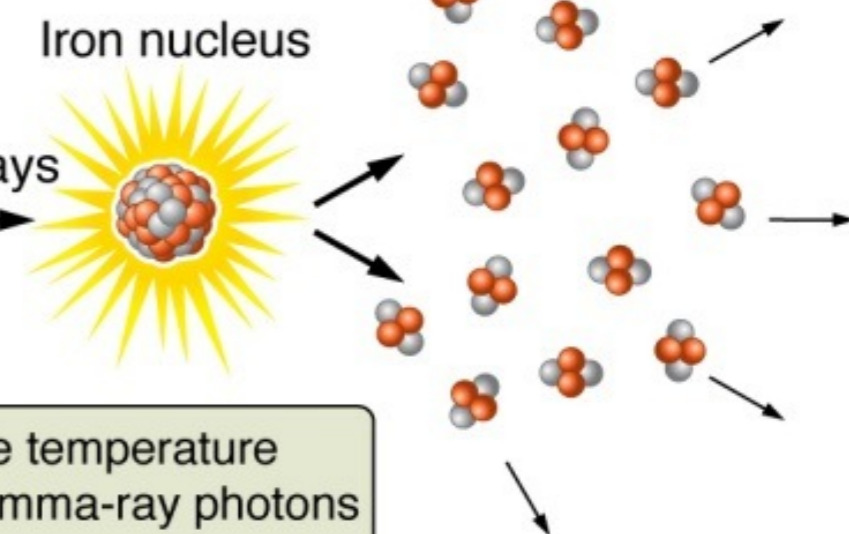
Why does the Fe core collapse?
It reaches Chandrasekhar limit



Neutrinos streaming from collapsing core

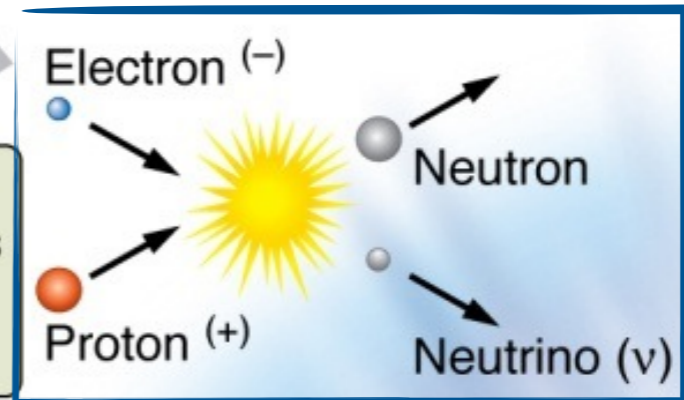


Gamma rays

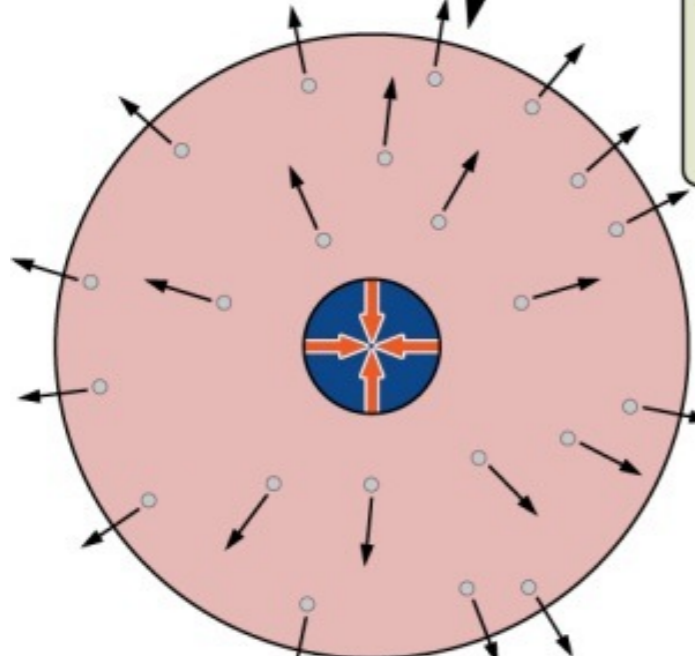


2 As the core collapses, the core temperature climbs so high that thermal gamma-ray photons photodisintegrate iron...

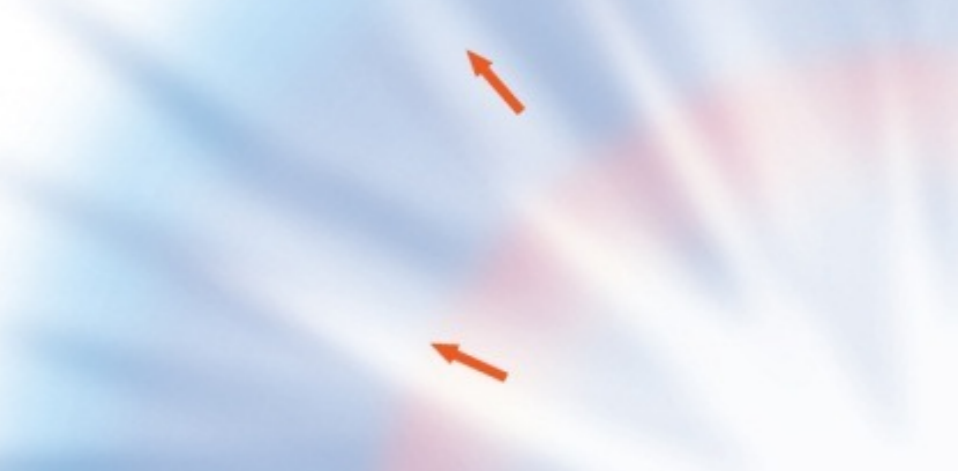
How did protons become mostly neutrons?
inverse beta decay



3 ...and the core becomes so dense that electrons are absorbed by protons in atomic nuclei, forming neutrons and releasing energetic neutrinos.

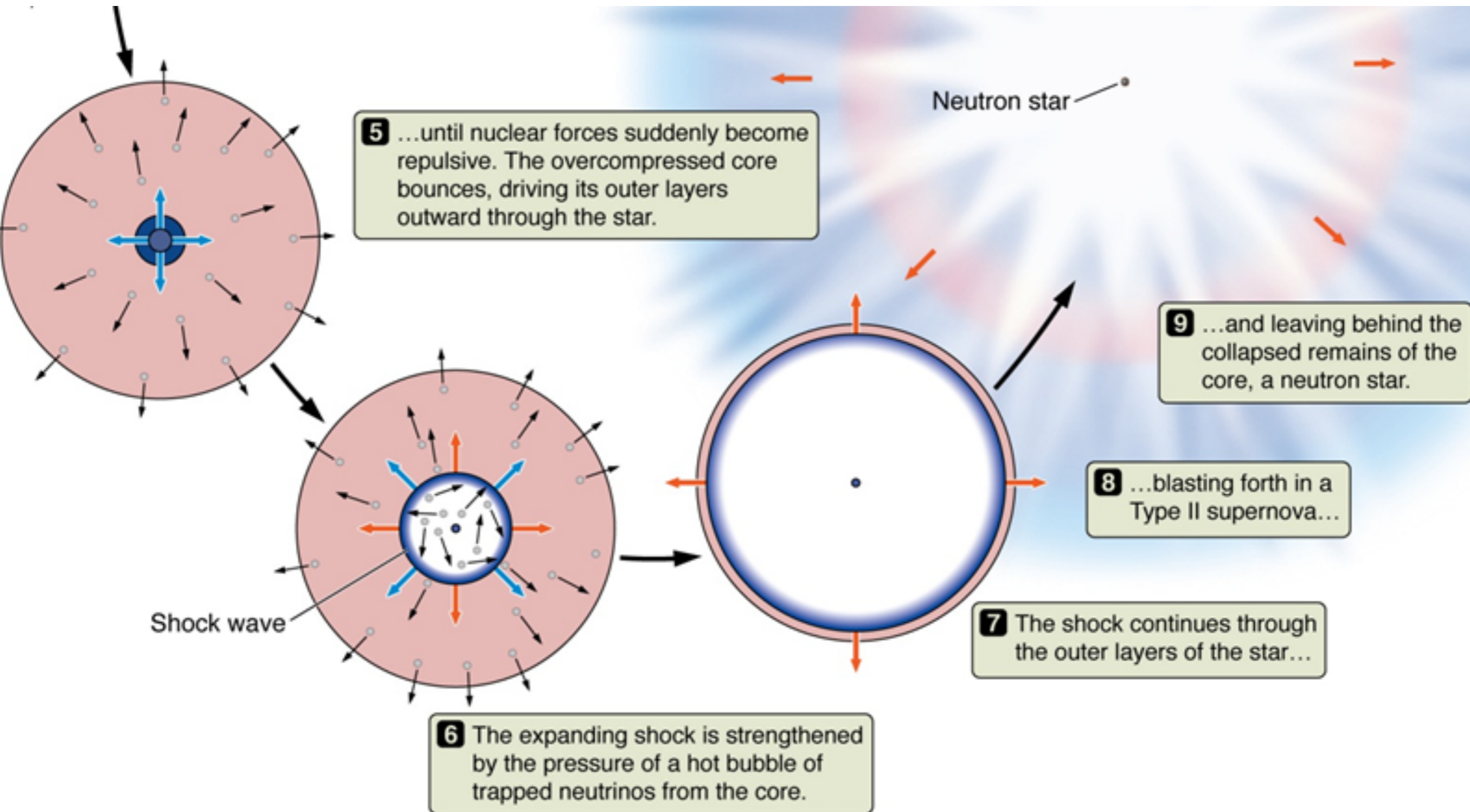


4 Photodisintegration and electron absorption rob the core of pressure support. The collapse accelerates...



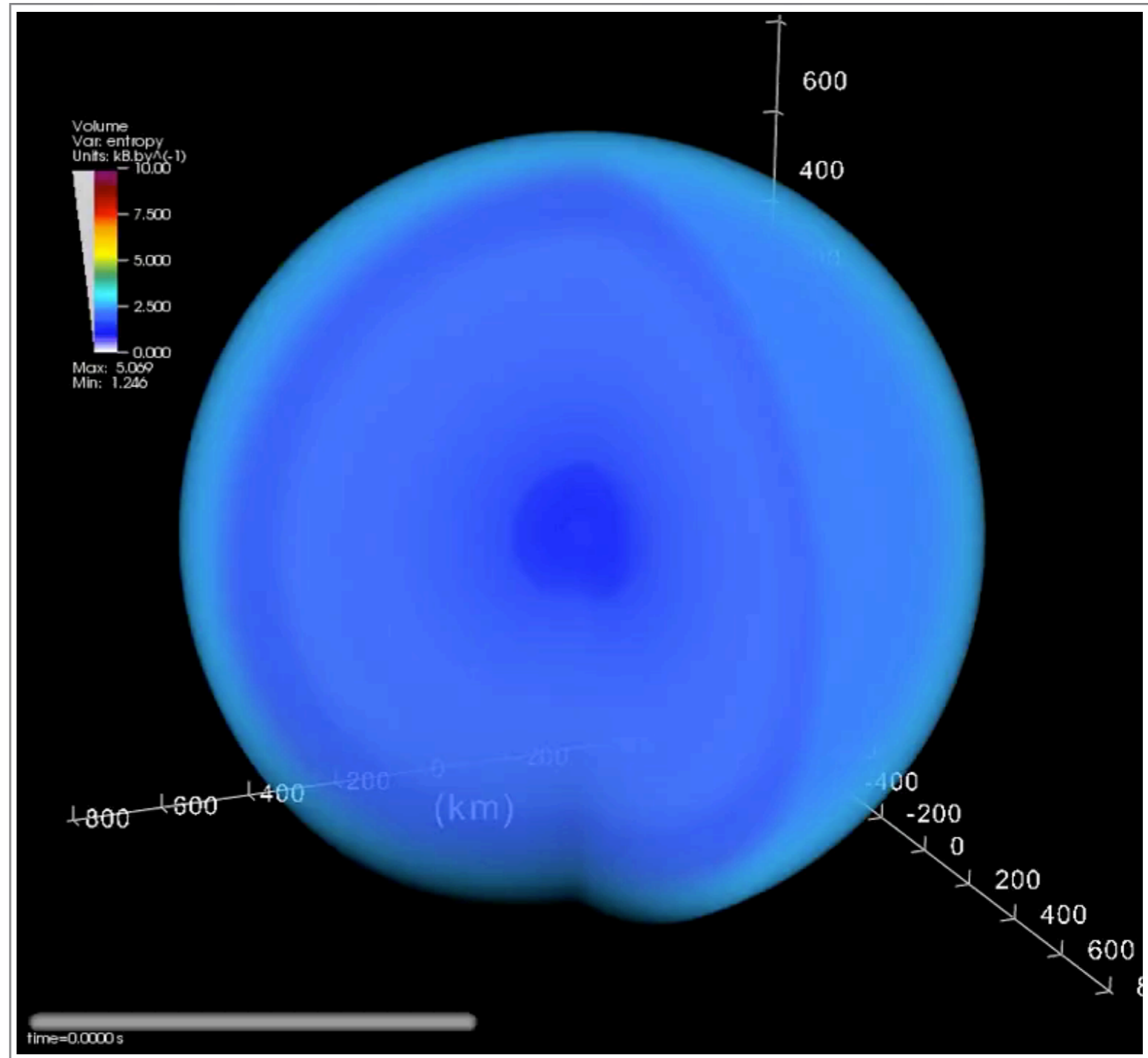
Core Bounce and Explosion

leaving behind a blast nebula and a neutron star



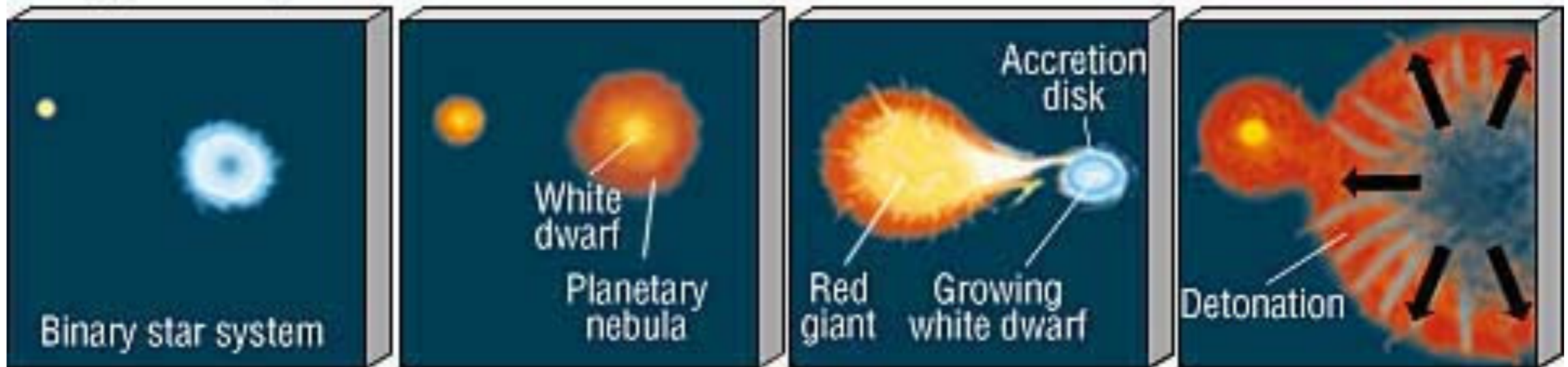
Simulation of a Core-Collapse SN explosion

- The **Fe-core** initially contracts and becomes **e-degenerate (Earth-size)**, but it eventually collapses as required P surpasses degenerate pressure
- **Fe \rightarrow He, photo-disintegration**
- **$p^+ + e^- = n + \nu$**
- core collapse accelerates
- **strong nuclear force becomes repulsive**
- core **bounces** and send shock waves outwards
- trapped **neutrinos** further accelerate shock waves
0.1c shocks reach surface and heat it to 500,000 K

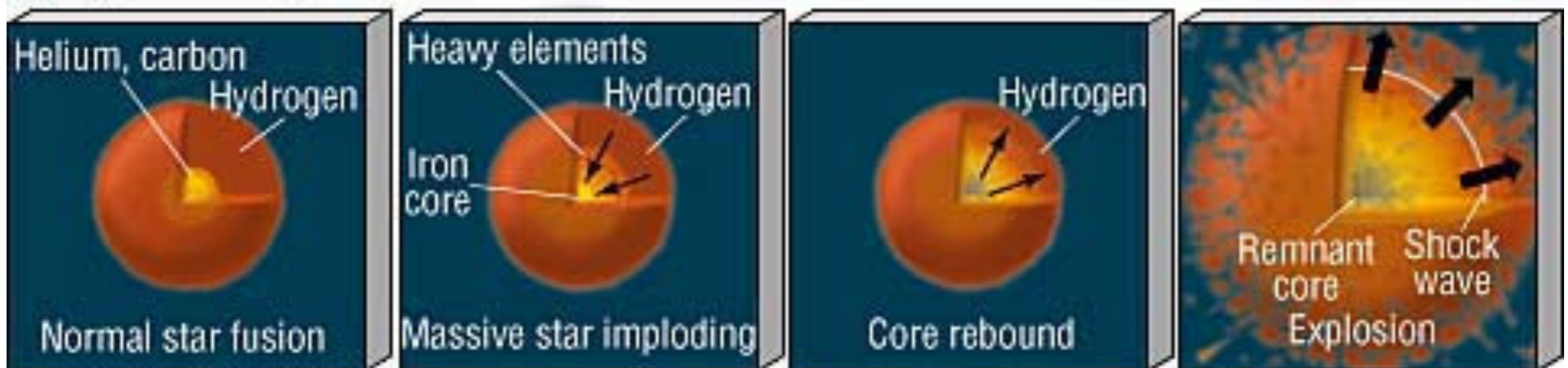


How to distinguish between the two main types of SNe?

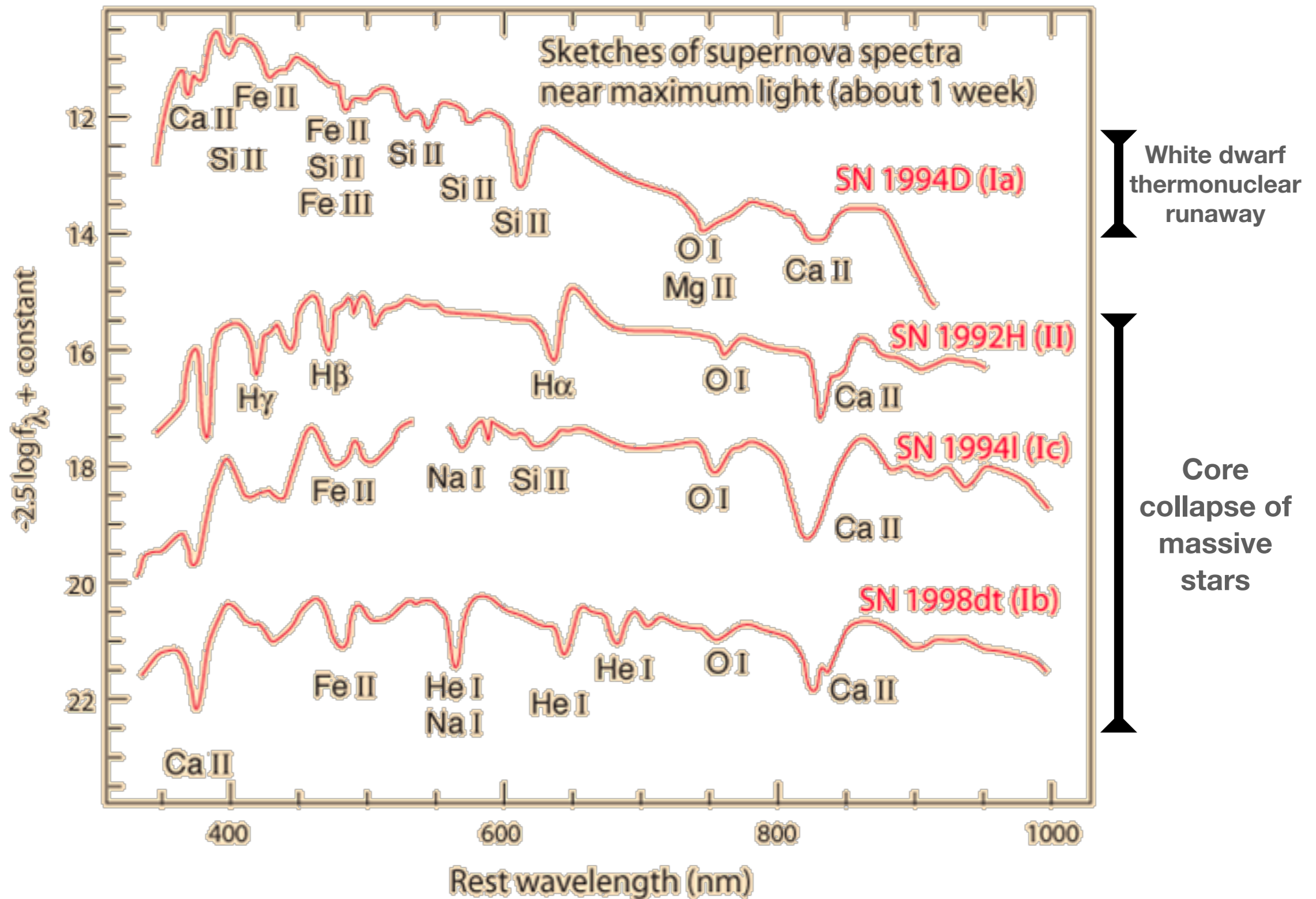
(a) Type- I Supernova



(b) Type- II Supernova

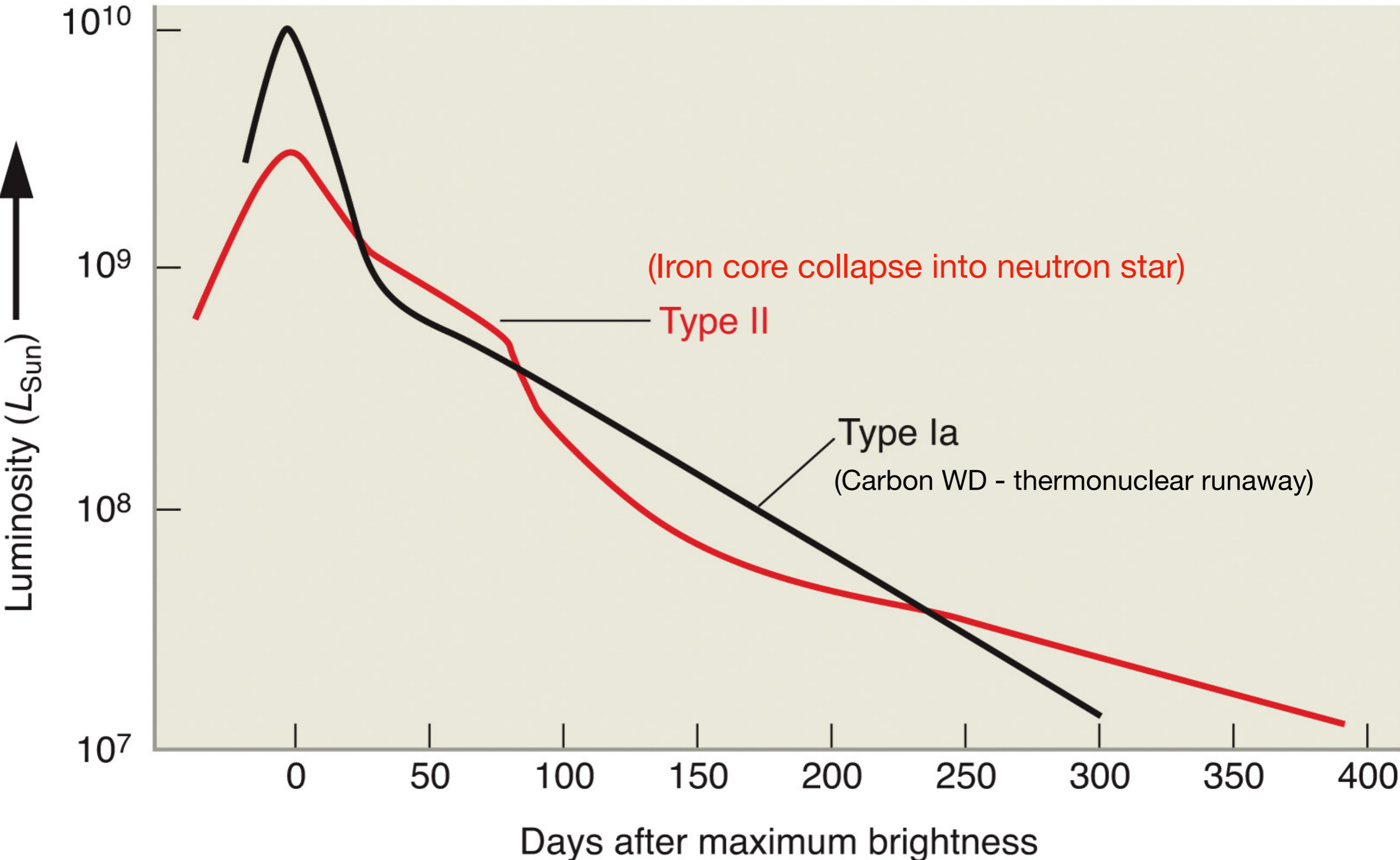


Optical Spectra of Supernovae near Peak: Type I (No Hydrogen lines) vs. Type II (Hydrogen lines)



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

Light Curves: Type Ia vs. Type II Supernovae



(Iron core collapse into neutron star)

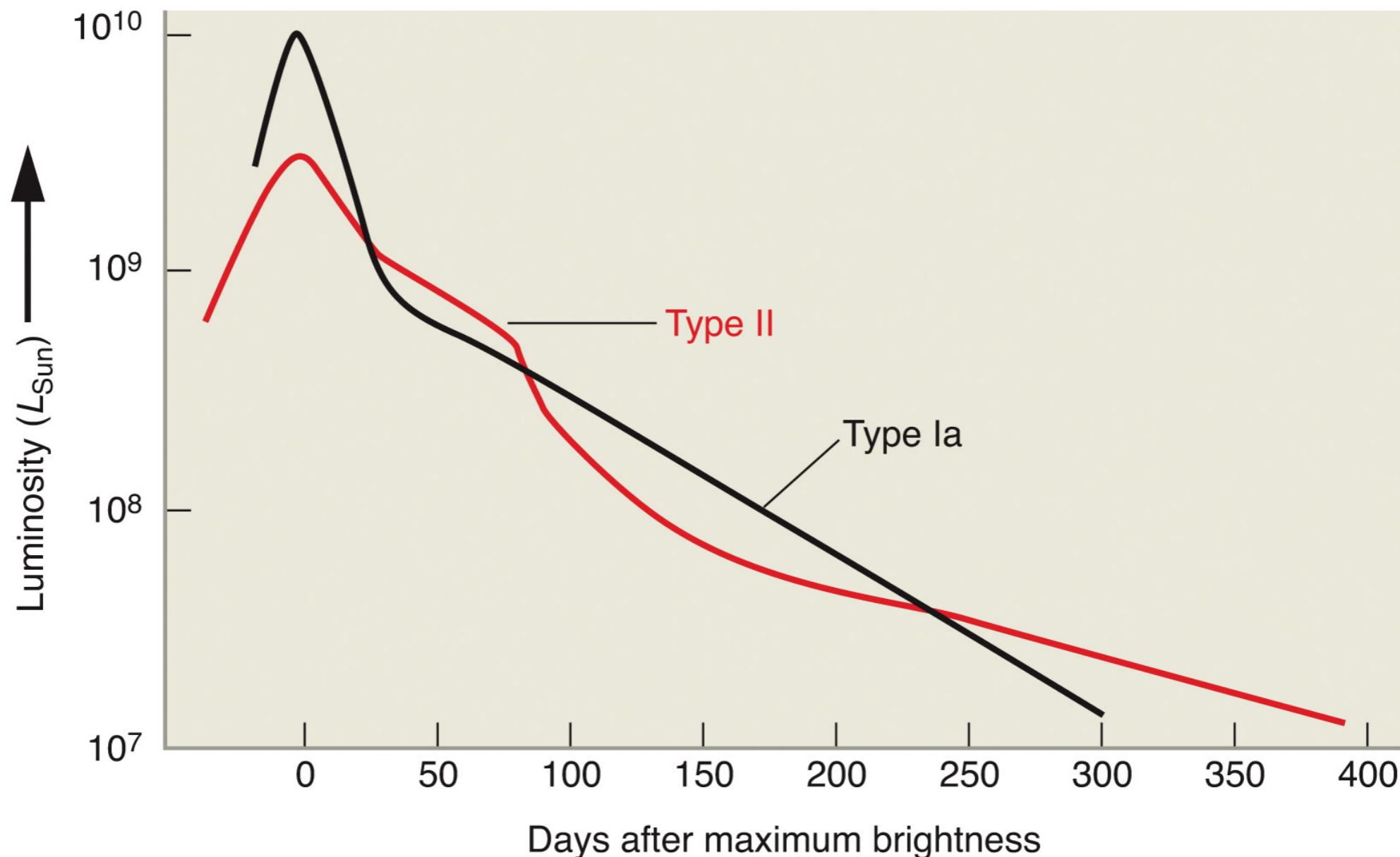
Type II

Type Ia

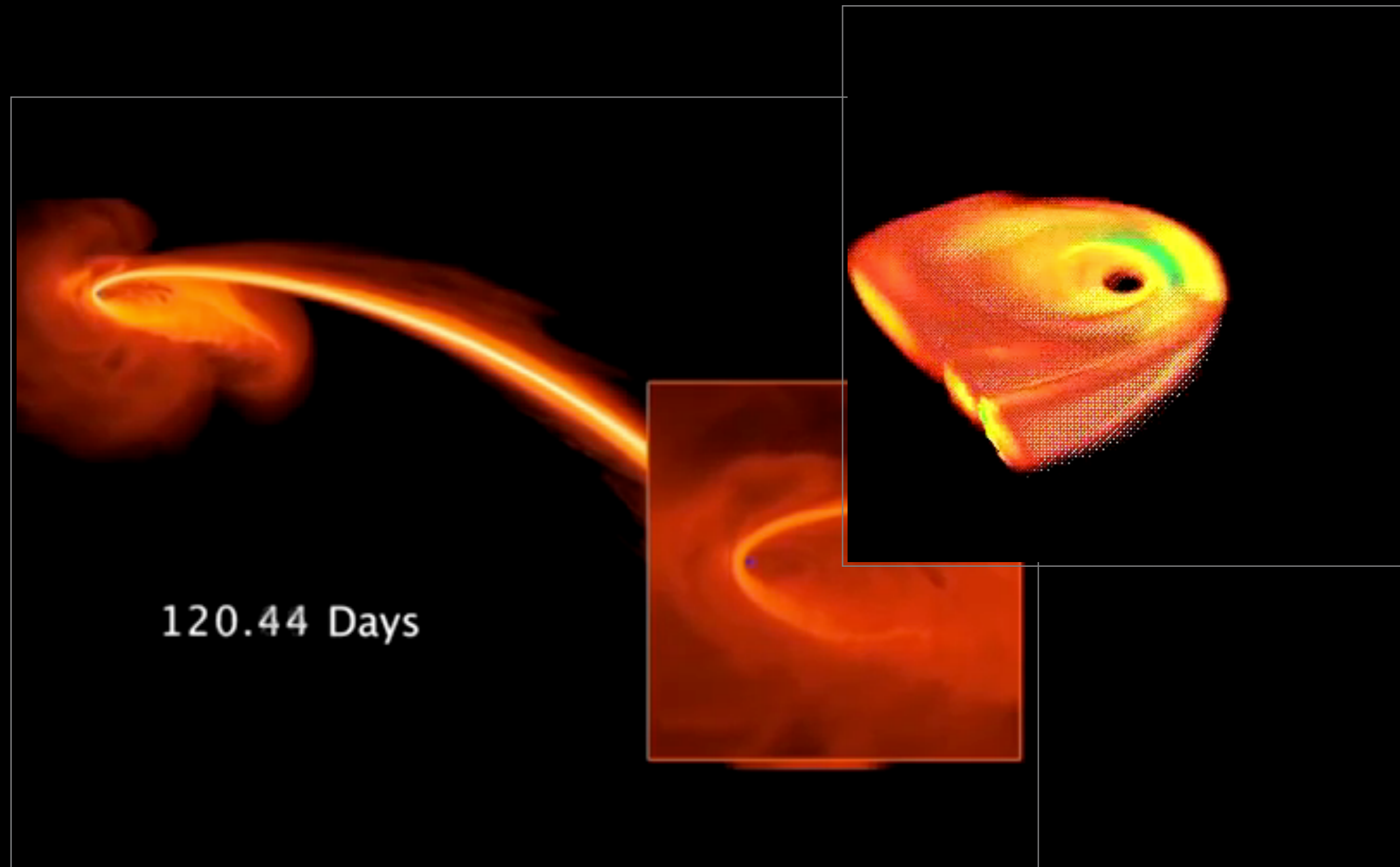
(Carbon WD - thermonuclear runaway)

Total Energy Output: Core Collapse = 100x Thermal Nuclear

- **Type II:** $1e46$ J (99% in **neutrino** energy), $1e42$ J in **light** (0.01%)
- **Type Ia:** $1e44$ J (99% in **kinetic** energy), $1e42$ J in **light** (1%)
- Both are produced by e- degenerate cores of 1.4 Msun.
Why 100x different in the total energy budget?



Simulation of the formation of an accretion disk

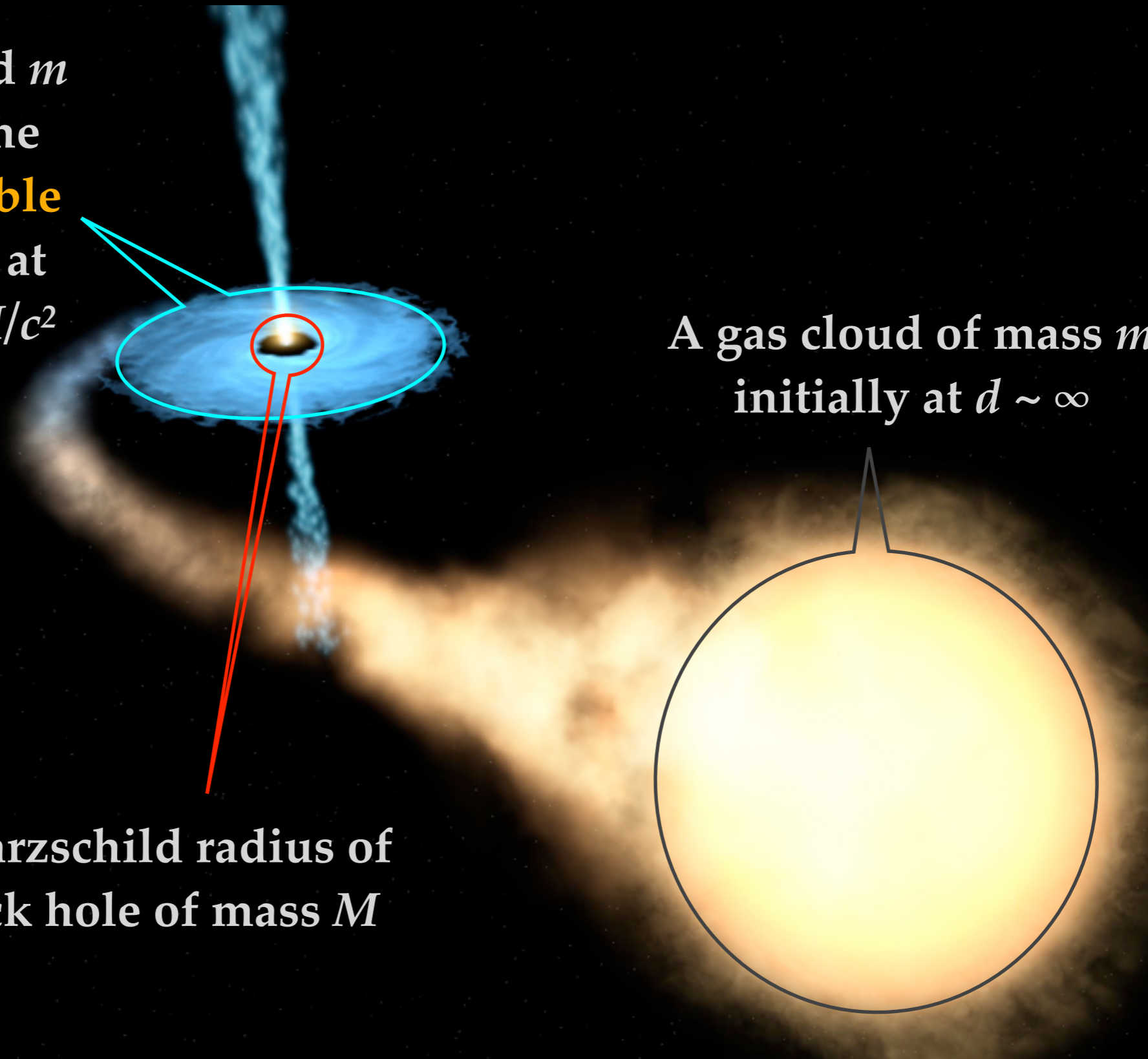


The accretion disk around a black hole has an inner edge

the same cloud m
ends up on the
**innermost stable
circular orbit** at
 $d = 3 r_s = 6GM/c^2$

Schwarzschild radius of
a black hole of mass M

A gas cloud of mass m
initially at $d \sim \infty$



Energy Release from Black Hole Accretion

- **Initial energy** of a gas cloud m before accretion:

$$K + U = mv^2/2 - GMm/d = 0$$

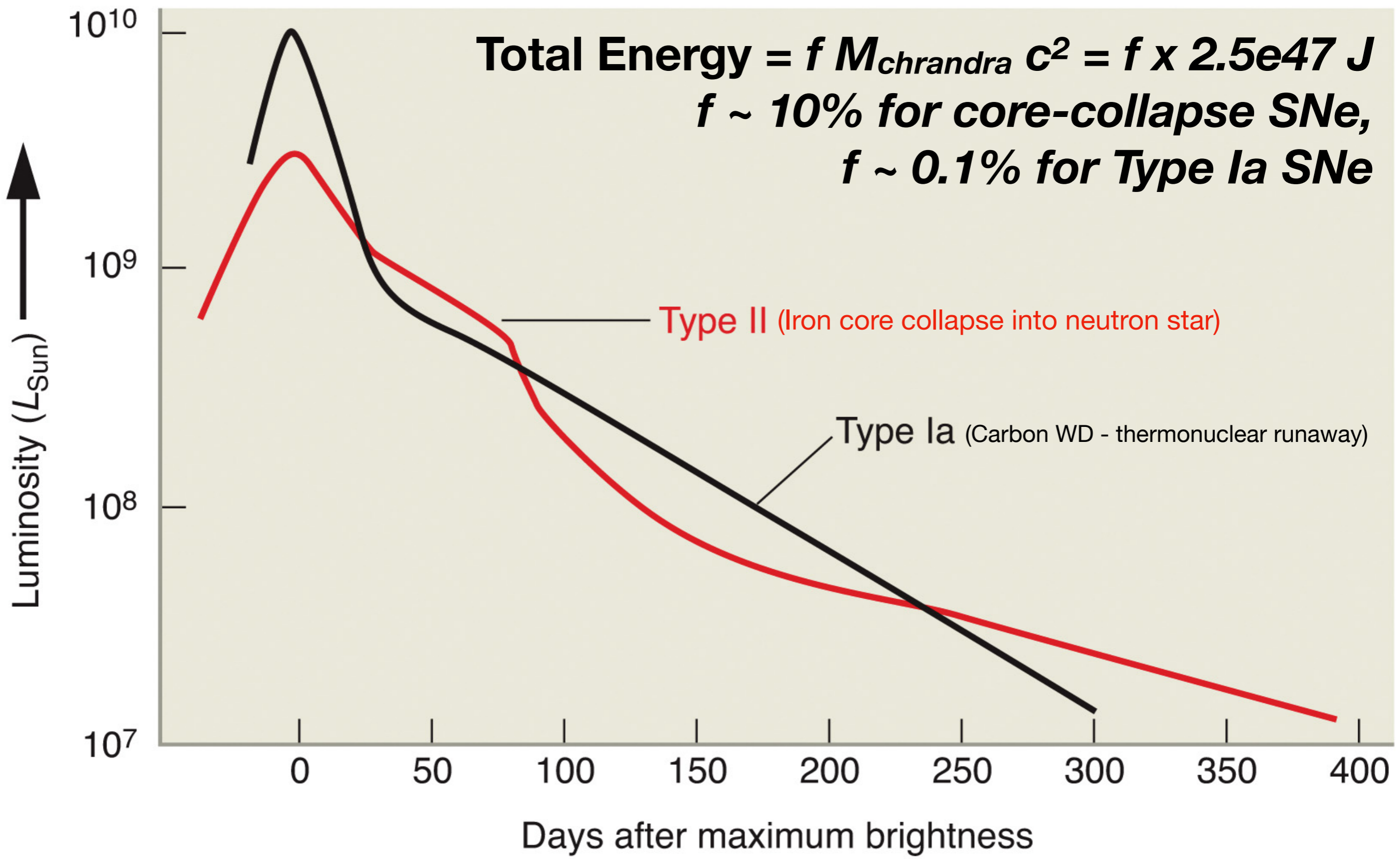
because $v = 0$ at $d = \infty$.

- **Final energy** at the **last stable orbit** at $d = 3 r_s = 6GM/c^2$:
We can use either **Virial Theorem** ($2K + U = 0$) to obtain the following:

$$K + U = U/2 = -GMm/2d = -mc^2/12$$

- The difference between the initial energy and the final energy must be released to allow accretion to occur. So the amount of energy released is $mc^2/12$ during the accretion of mass m .
- This shows that roughly **10% (~1/12) of the rest mass** is converted into energy. For comparison, the pp chain converts **0.7%** of the rest mass into energy (because $\delta m/m = 0.7\%$ between 4xH and 1xHe).
- This is huge! Just **1 Solar mass is accreted in a year**, the released energy would be as luminous as **10^{12} Suns combined!**

Core-Collapse has 100x greater mass-energy conversion factor



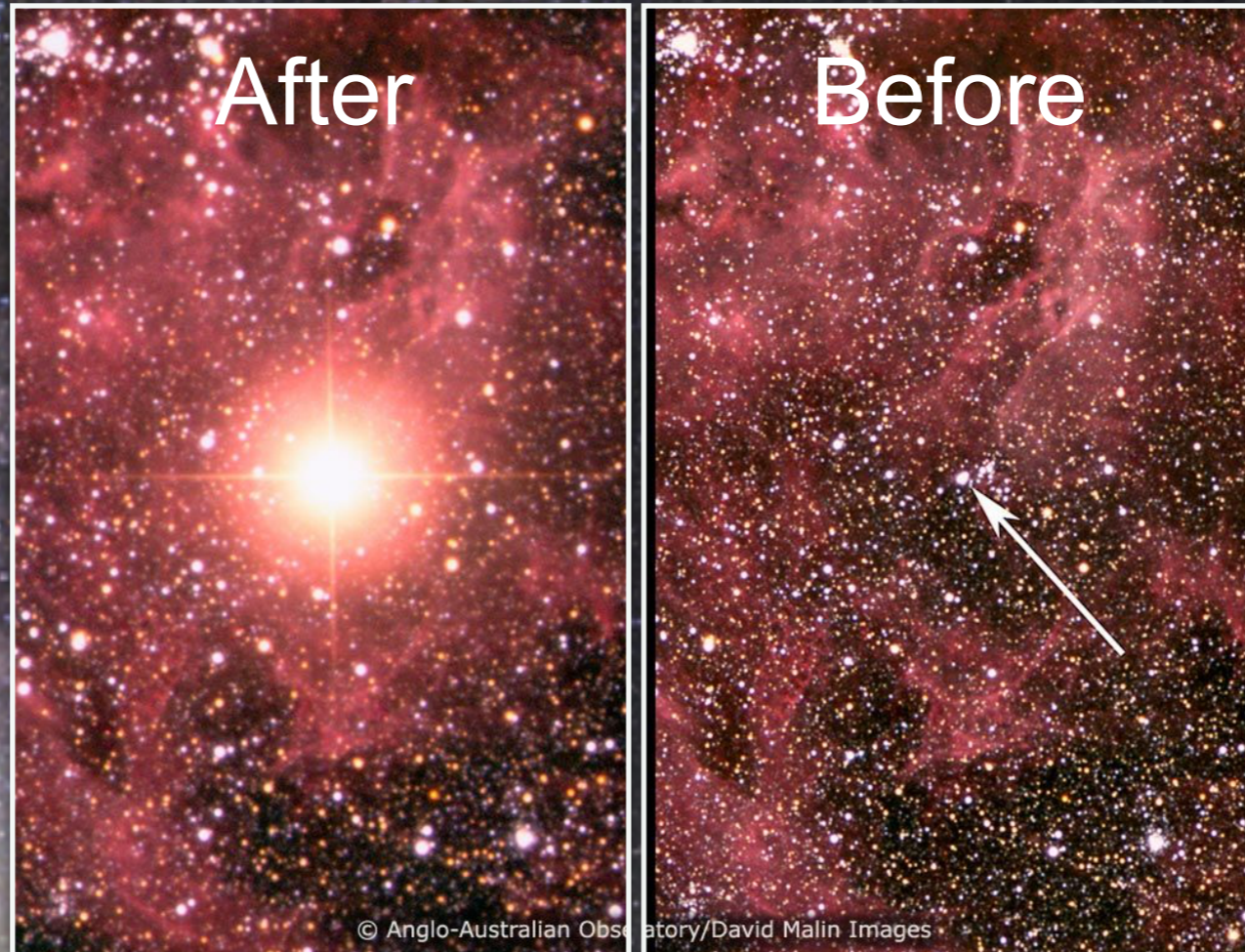
Zoom into Veil Nebula (a SN remnant formed ~10,000 yrs ago)



Witnessing the formation of a Supernova Remnant (SNR)

SN 1987A

SN 1987A



LMC
d = 50 kpc
Dec = -70d
 $M^* = 1e10 M_{\text{sun}}$

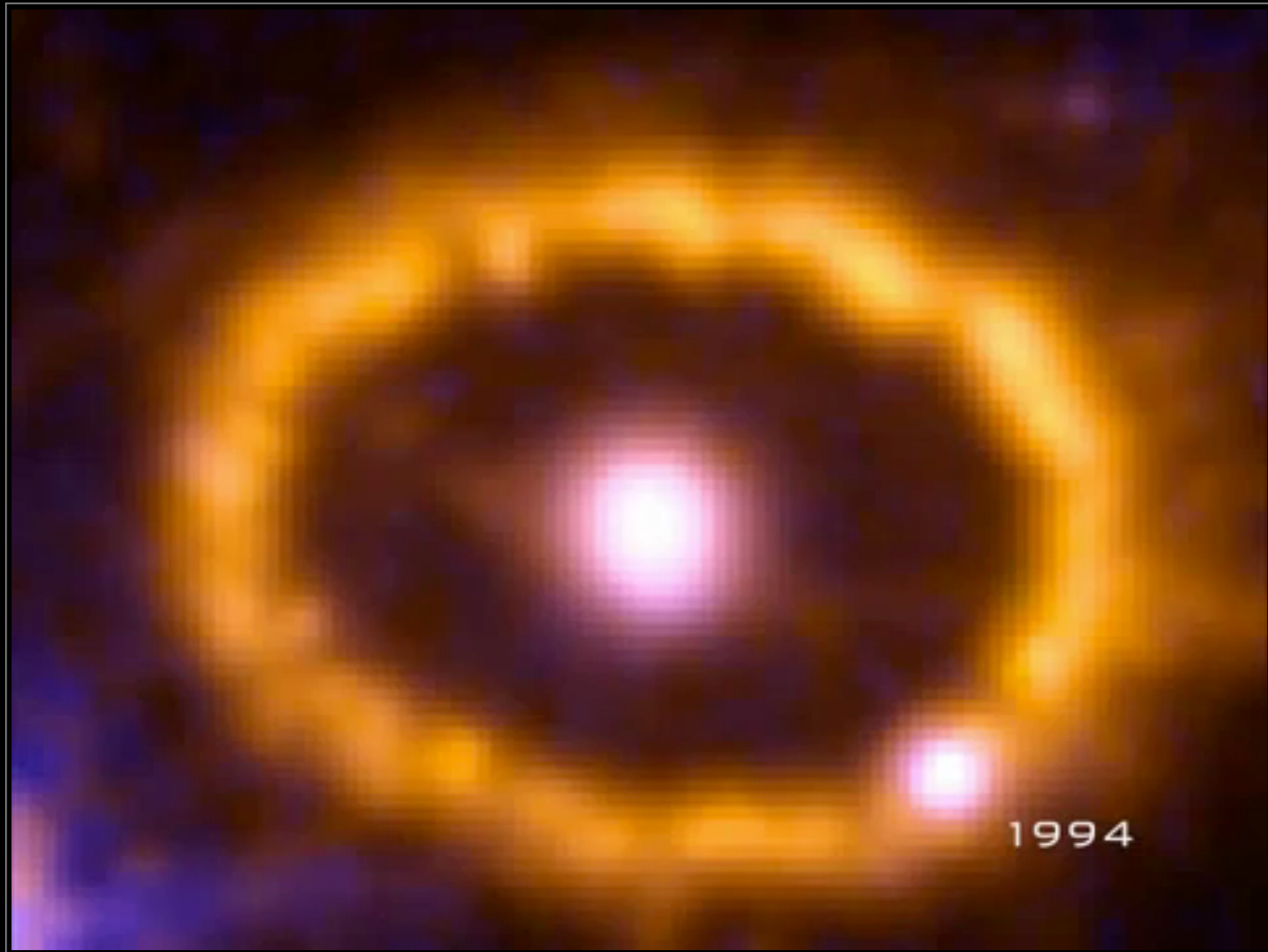
Zoom in onto SN 1987A



Hubble Space Telescope

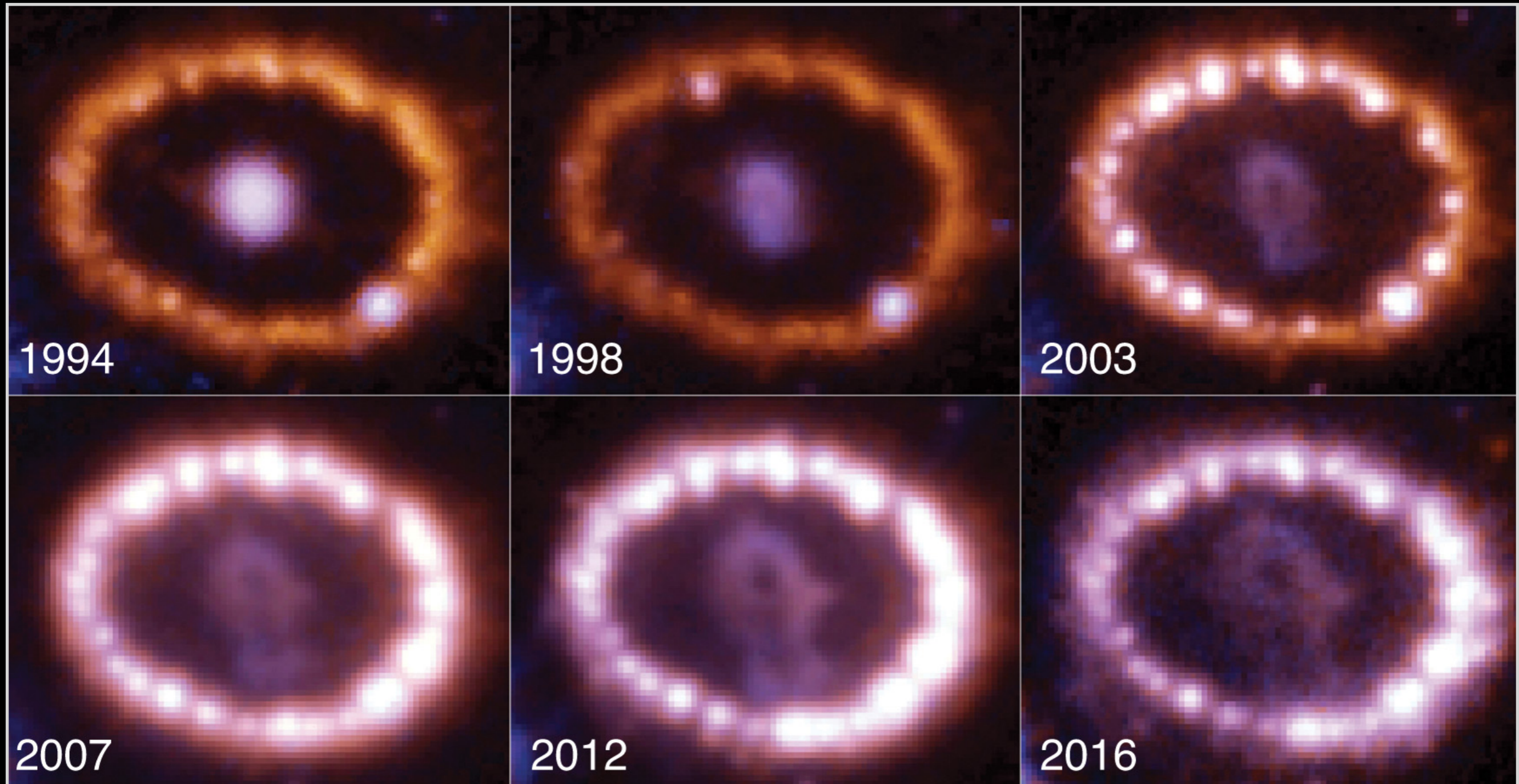
The firework after the explosion

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



G X U V I R



G X U V I R

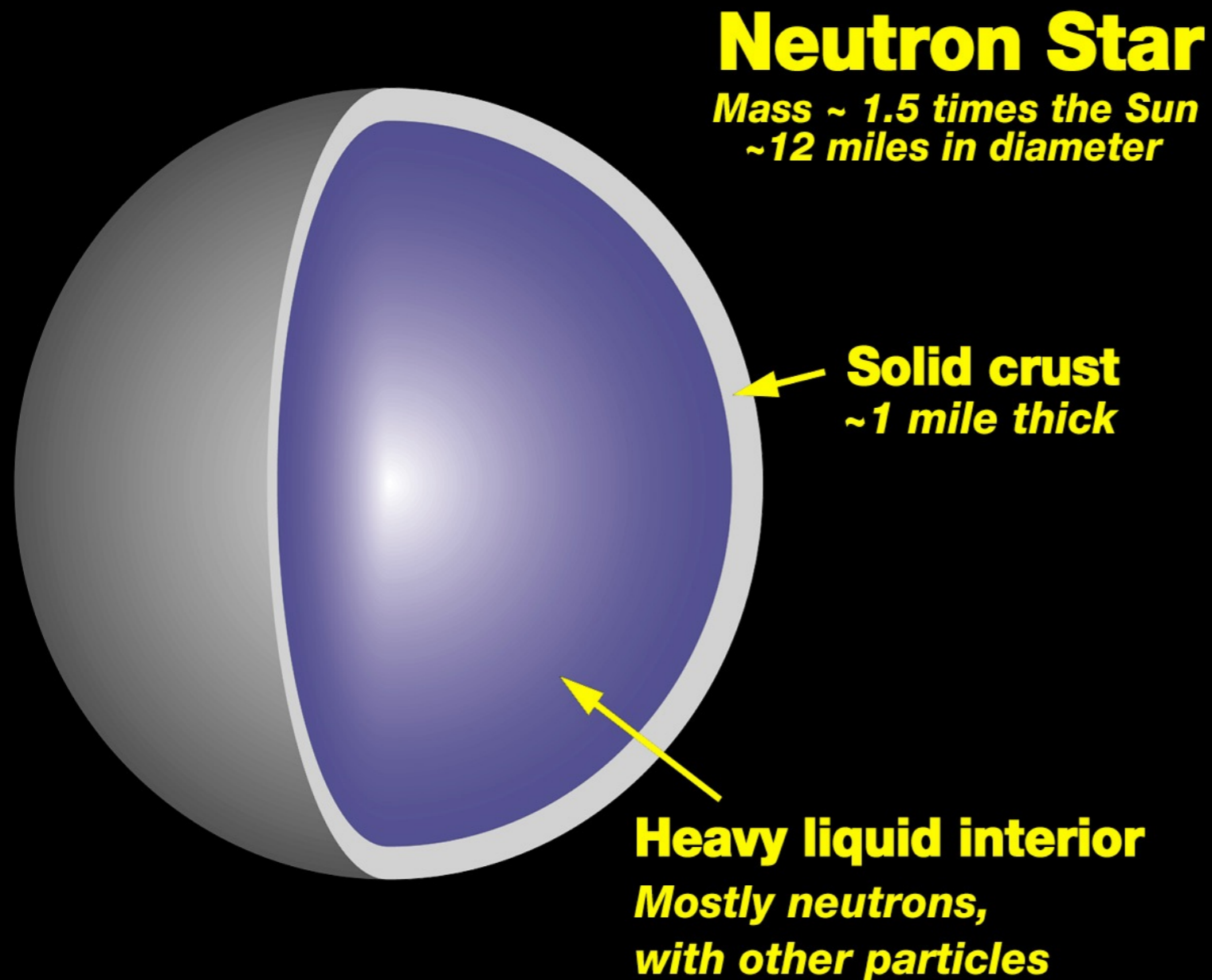
19 neutrinos were detected
(in Japan & Ohio)
the day *before* the
optical explosion was seen

In a core-collapse SN (i.e., type II), neutrinos are produced when protons and electrons combine to form neutrons

**At the center of the SN explosion,
a Neutron Star is born**

Theoretical Models

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 $\sim 10^9$ 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!

INSIDE A NEUTRON STAR

A NASA mission will use X-ray spectroscopy to gather clues about the interior of neutron stars — the Universe's densest forms of matter.

Outer crust

Atomic nuclei, free electrons

Inner crust

Heavier atomic nuclei, free neutrons and electrons

Outer core

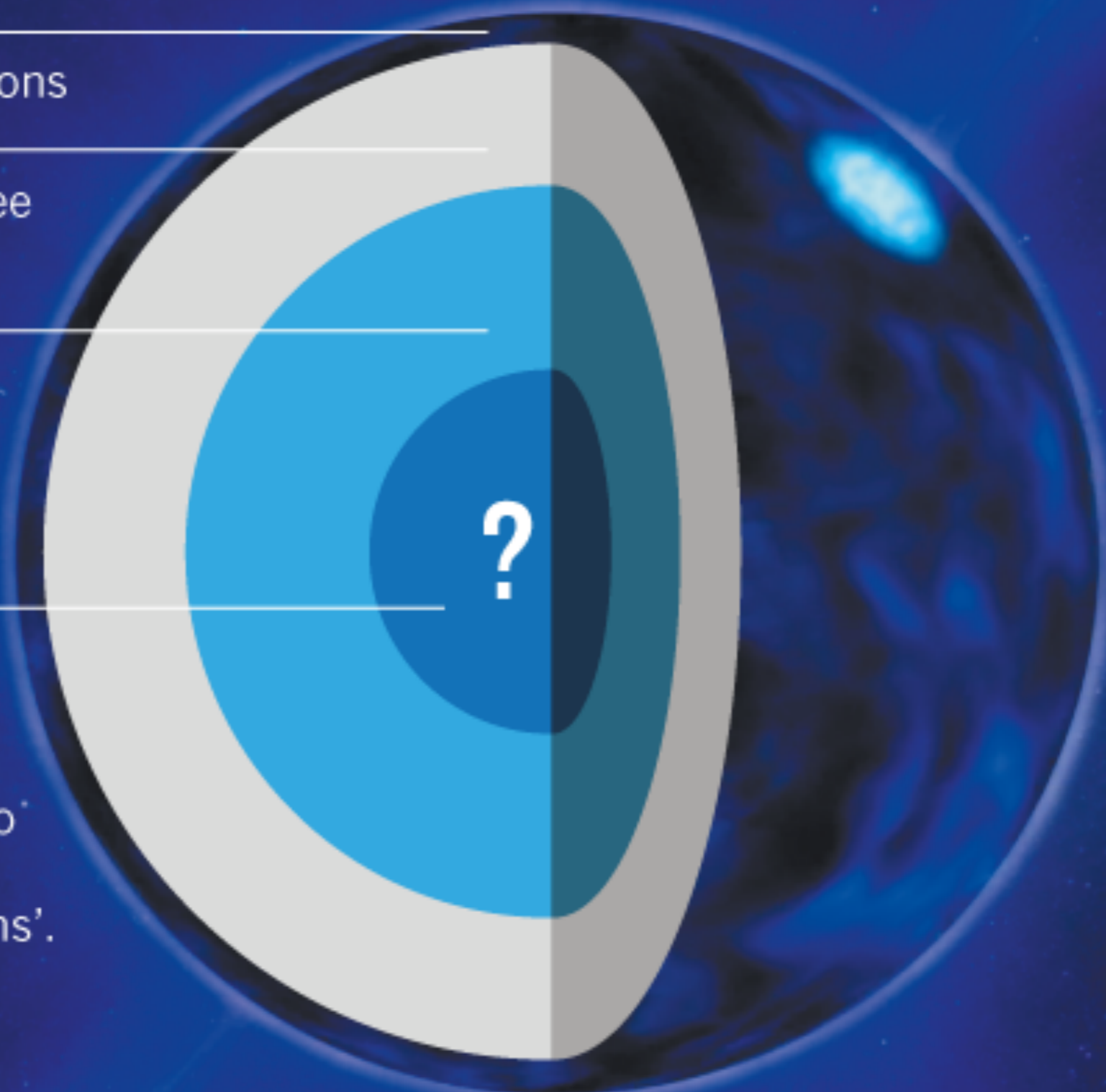
Quantum liquid where neutrons, protons and electrons exist in a soup

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



Core scenarios

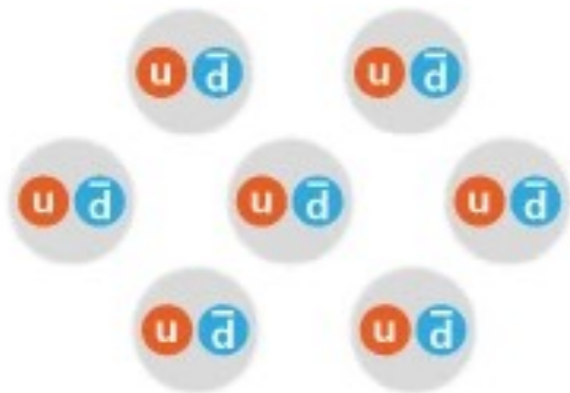
A number of possibilities have been suggested for the inner core, including these three options.

- u** Up quark
- s** Strange quark
- d** Down quark
- \bar{d}** 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

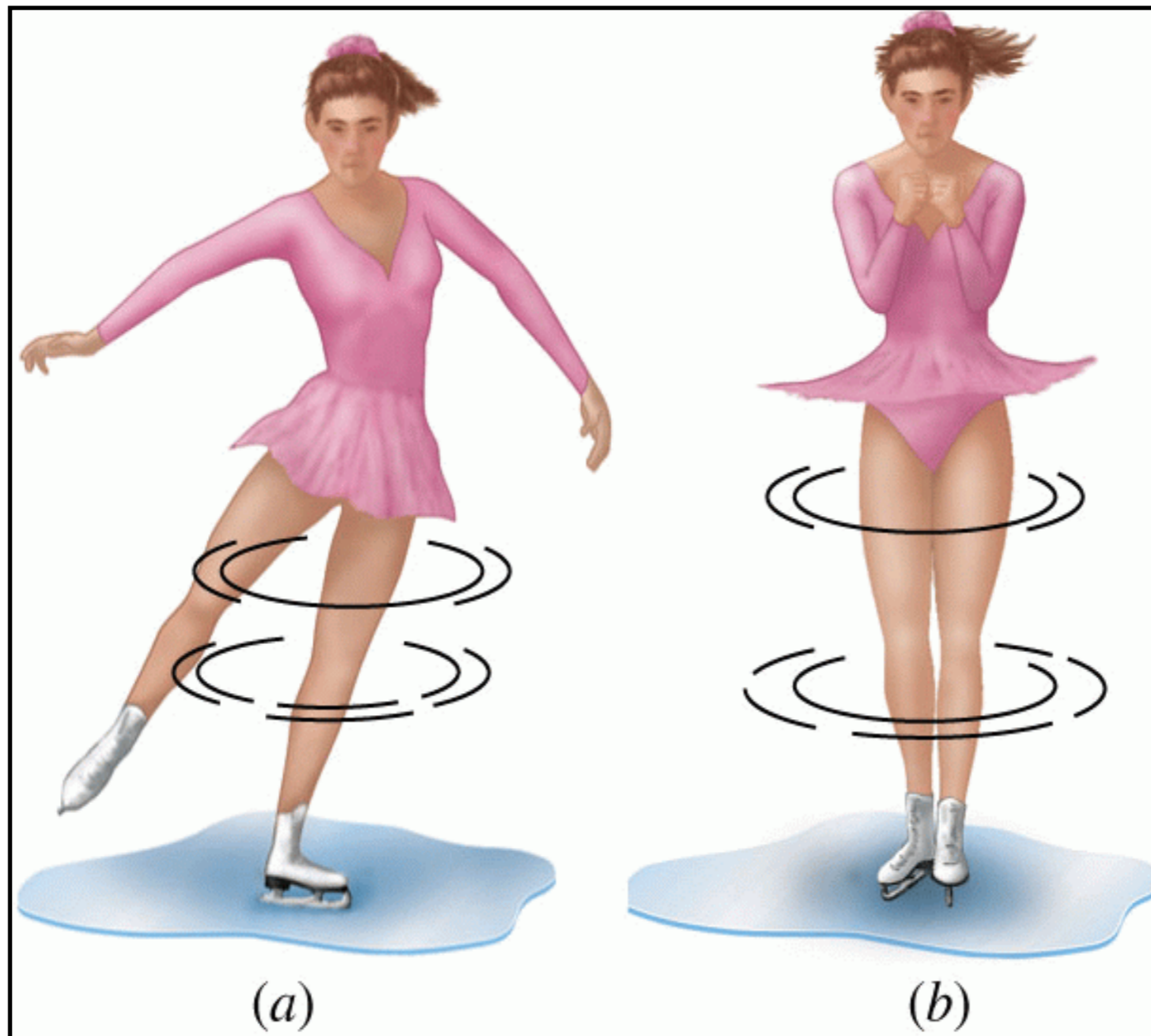
Particles called hyperons form. Like protons and neutrons, they contain three quarks but include 'strange' quarks.

Neutron stars are expected to spin very fast!

Angular momentum is conserved. For a uniform sphere, we have:

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

where I is the moment of inertia, and ω the angular velocity.

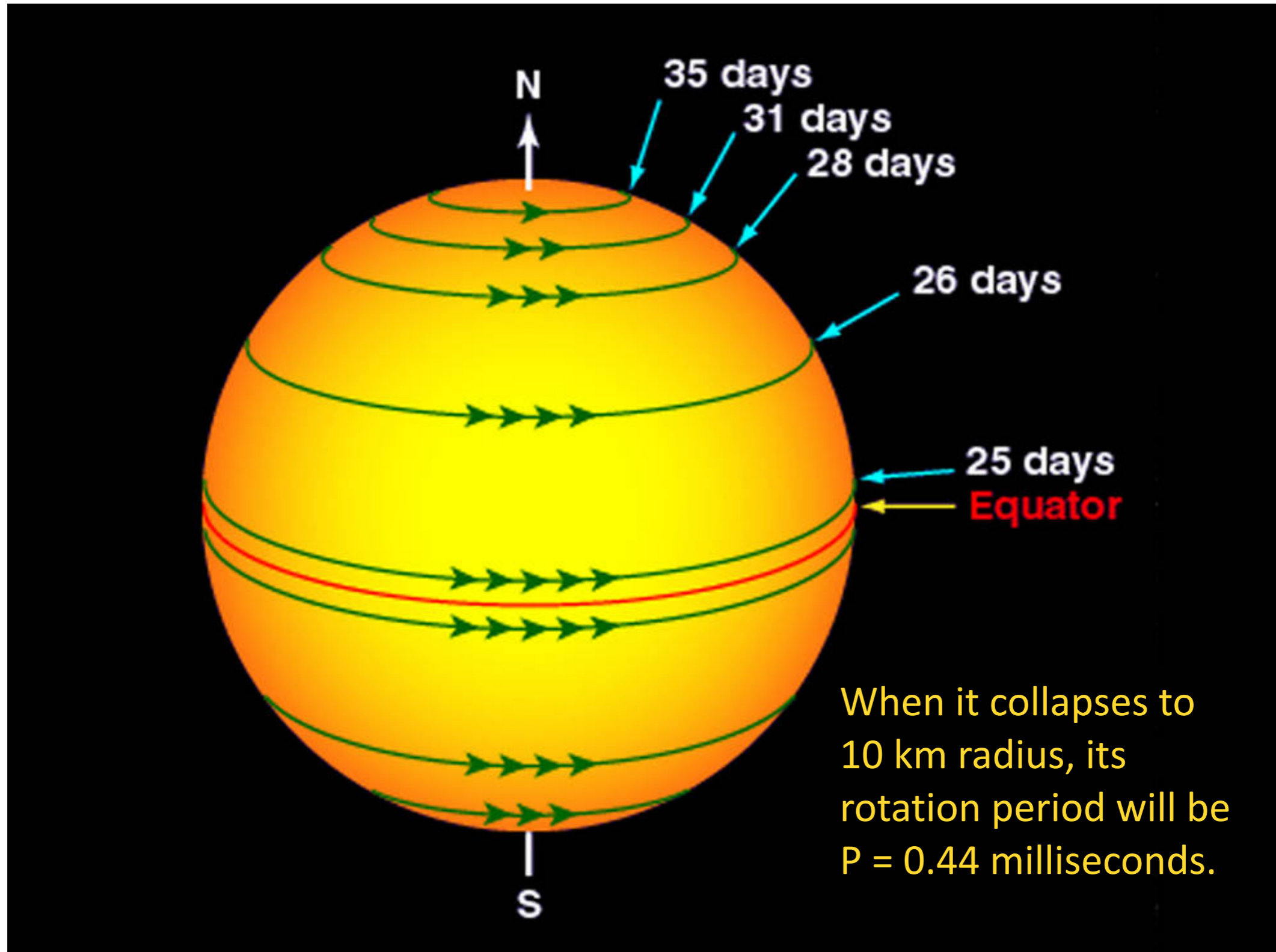


When the Sun ($R = 7e5$ km) collapses into a neutron star ($R = 10$ km):

What's the current angular velocity?

What will be the rotating period?

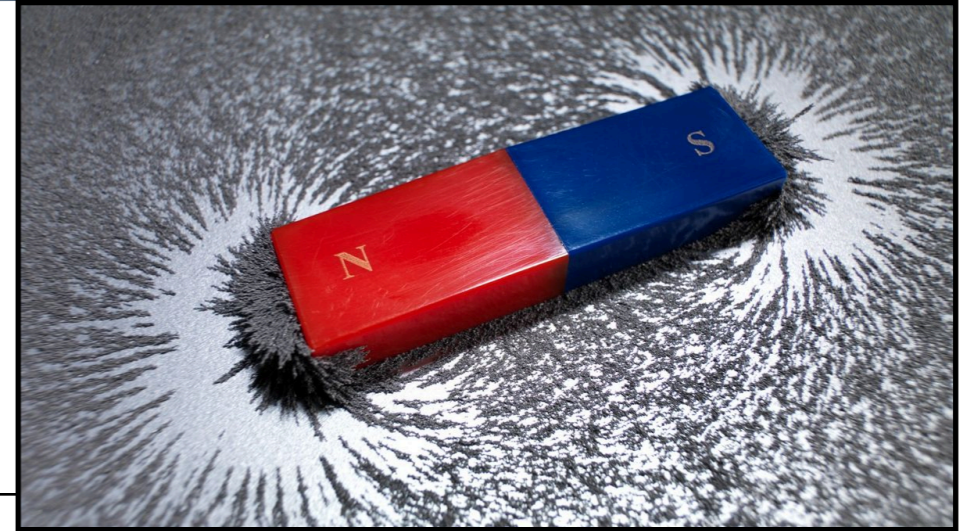
$$\omega_{\odot} = \frac{2\pi}{P} = 14 \text{ deg/day for } P = 25 \text{ days}$$



Neutron stars are expected to have strong magnetic fields

The **tesla** (symbol: **T**) is the SI unit of **magnetic flux density** (also called **magnetic B-field strength**). **1 T = 1e4 Gauss**

A particle, carrying a charge of one **coulomb** (C), and moving perpendicularly through a magnetic field of one tesla, at a speed of one meter per second, experiences a force with magnitude one **newton** (N), according to the **Lorentz force law**: $\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$.



| | | |
|--|------------------------------|-------------------------|
| Smallest value in a magnetically shielded room | 10 ⁻¹⁴ Tesla | 10 ⁻¹⁰ Gauss |
| Interstellar space | 10 ⁻¹⁰ Tesla | 10 ⁻⁶ Gauss |
| Earth's magnetic field | 0.00005 Tesla | 0.5 Gauss |
| Small bar magnet | 0.01 Tesla | 100 Gauss |
| Within a sunspot | 0.15 Tesla | 1500 Gauss |
| Small NIB magnet | 0.2 Tesla | 2000 Gauss |
| Big electromagnet | 1.5 Tesla | 15,000 Gauss |
| Strong lab magnet | 10 Tesla | 100,000 Gauss |
| Surface of neutron star | 100,000,000 Tesla | 10 ¹² Gauss |
| Magstar | 100,000,000,000 Tesla | 10 ¹⁵ Gauss |

Conservation of magnetic flux

The collapse of a star also concentrates the magnetic field on the surface, because **magnetic flux** is conserved:

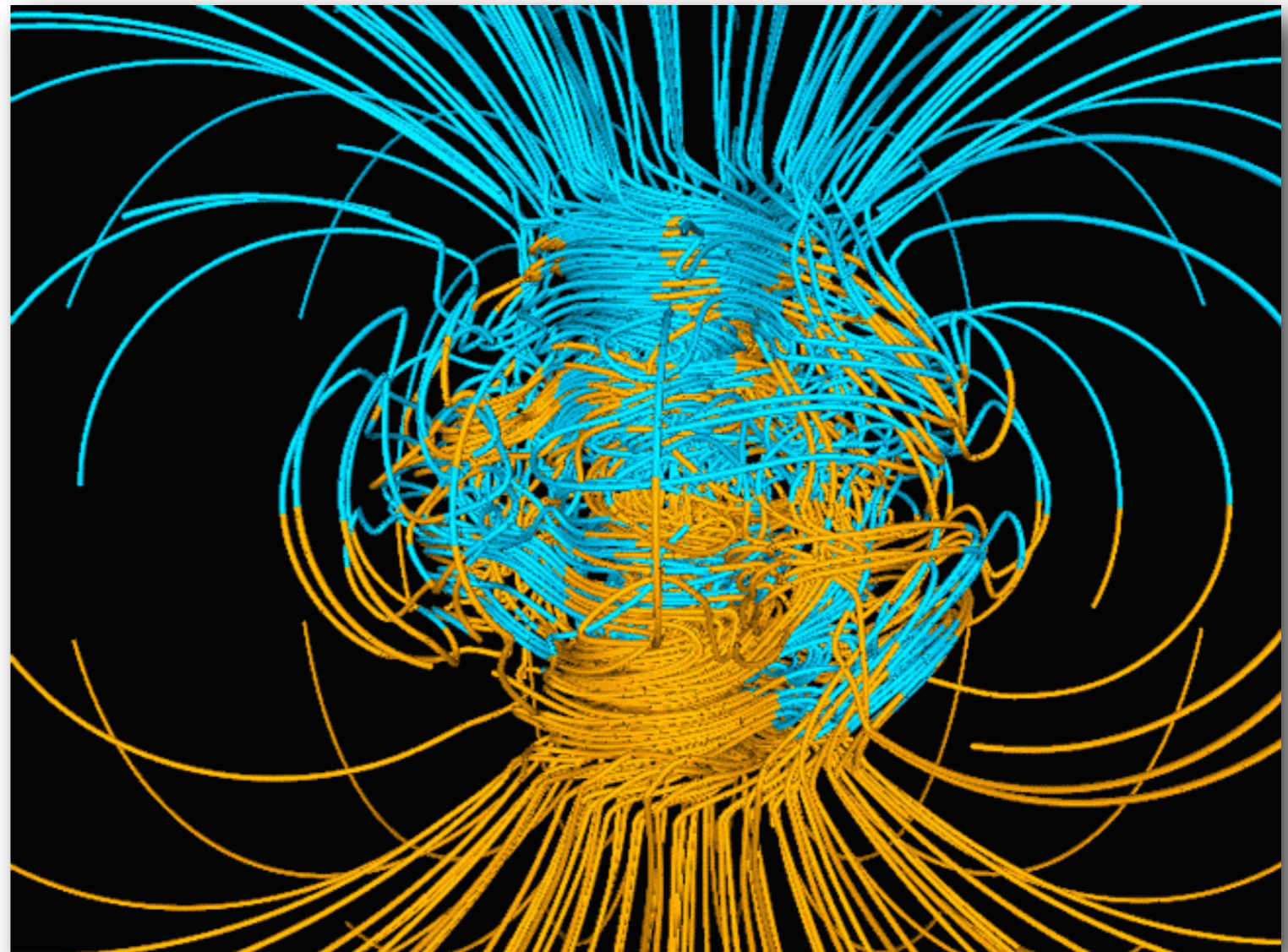
$$\bar{B} \times 4\pi r^2 = \text{const.} \Rightarrow \bar{B} \propto r^{-2}$$

e.g., 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; $1e-4$ T)**

Magnetic field for neutron star: up to **10^{15} G ($1e11$ T)**

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



Observable Neutron Stars I:

Pulsars

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?



The Discovery of Pulsars in 1967



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

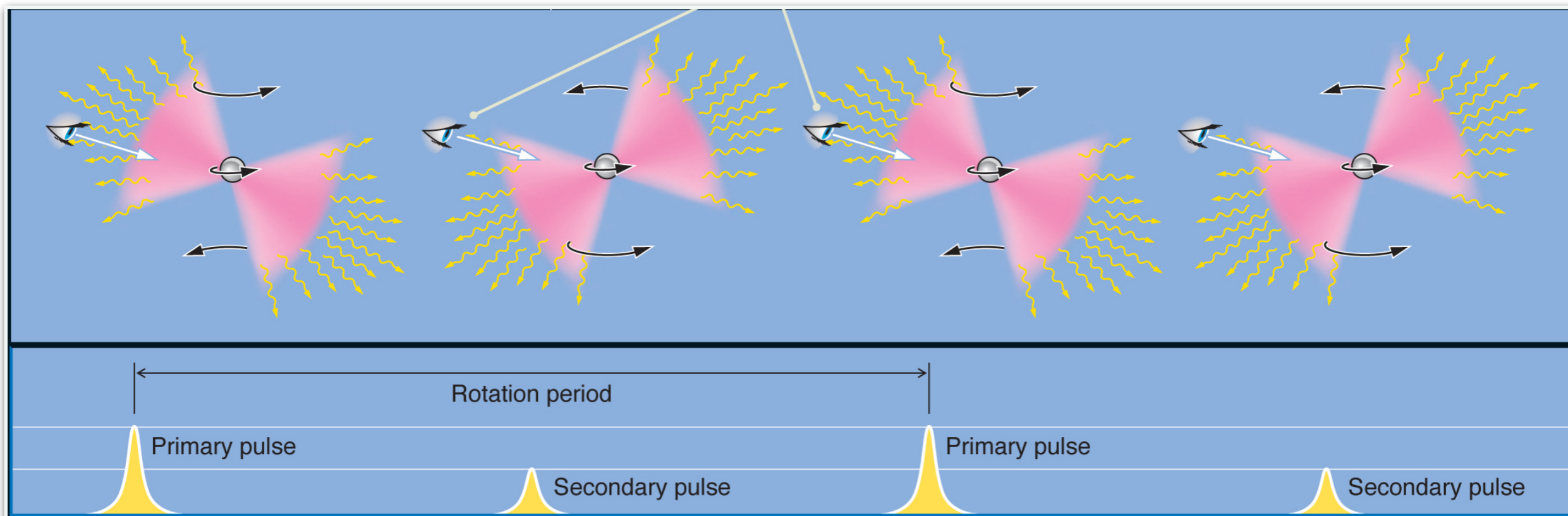
Helped build a radio telescope to study
the solar wind by looking at
“twinkling” of background radio
sources as their emission passes
through the solar wind

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

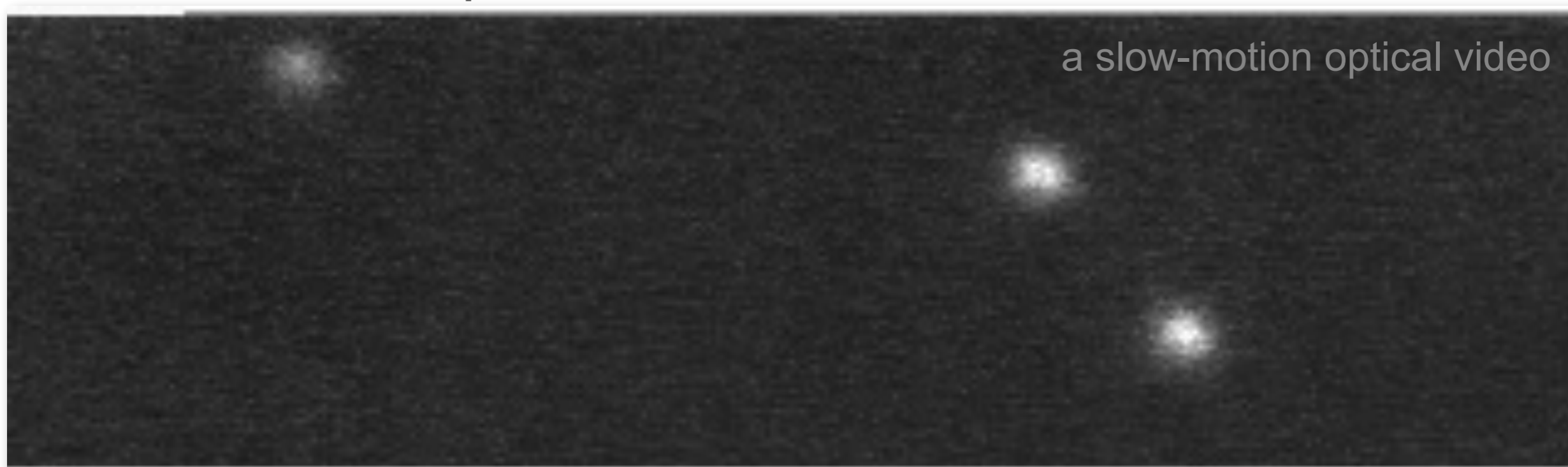
Thought it could be
detection of ET – “LGM1”
extraterrestrial (ET)
little green men (LGM)

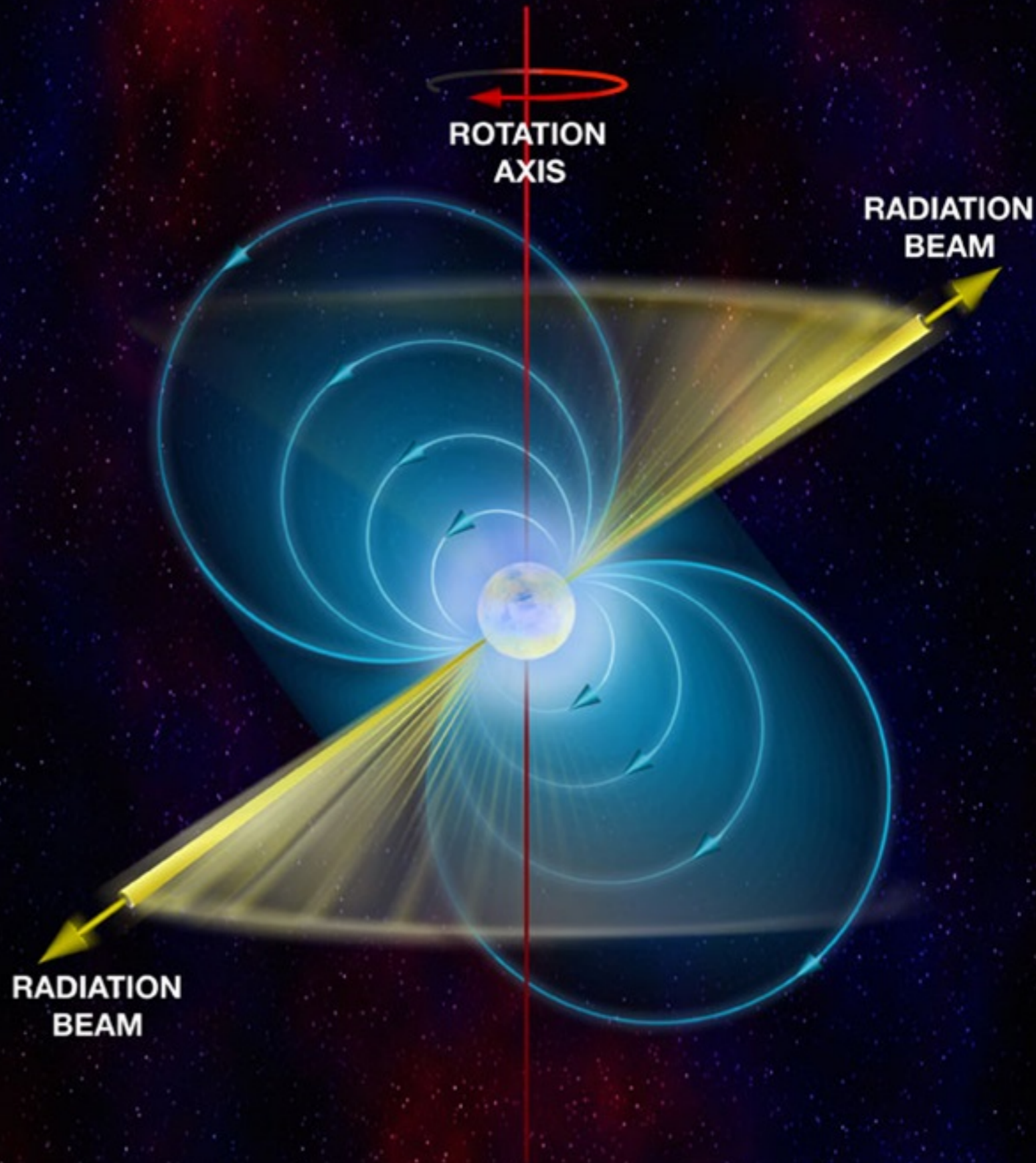
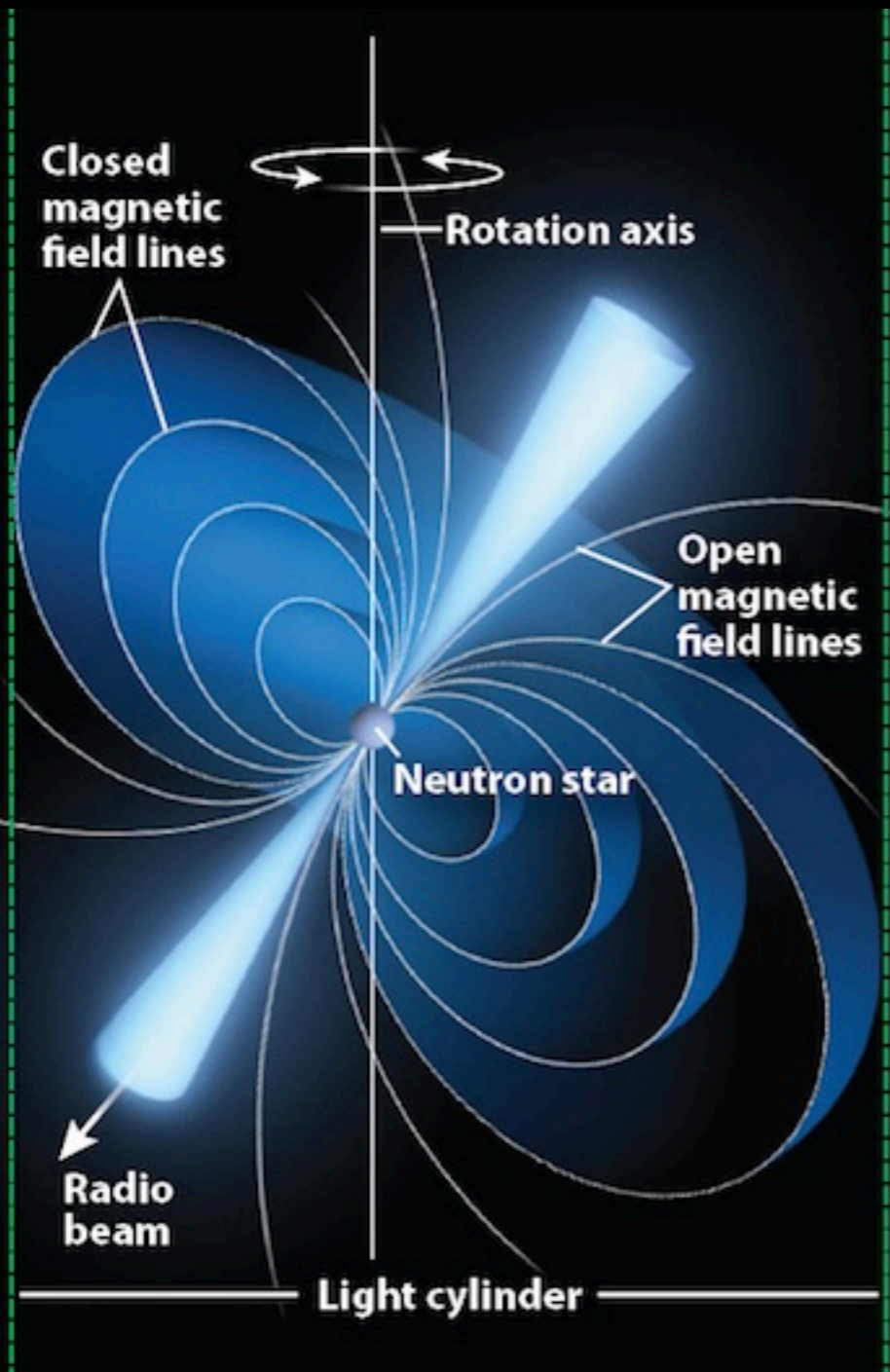
Now known as PSR 1919+21

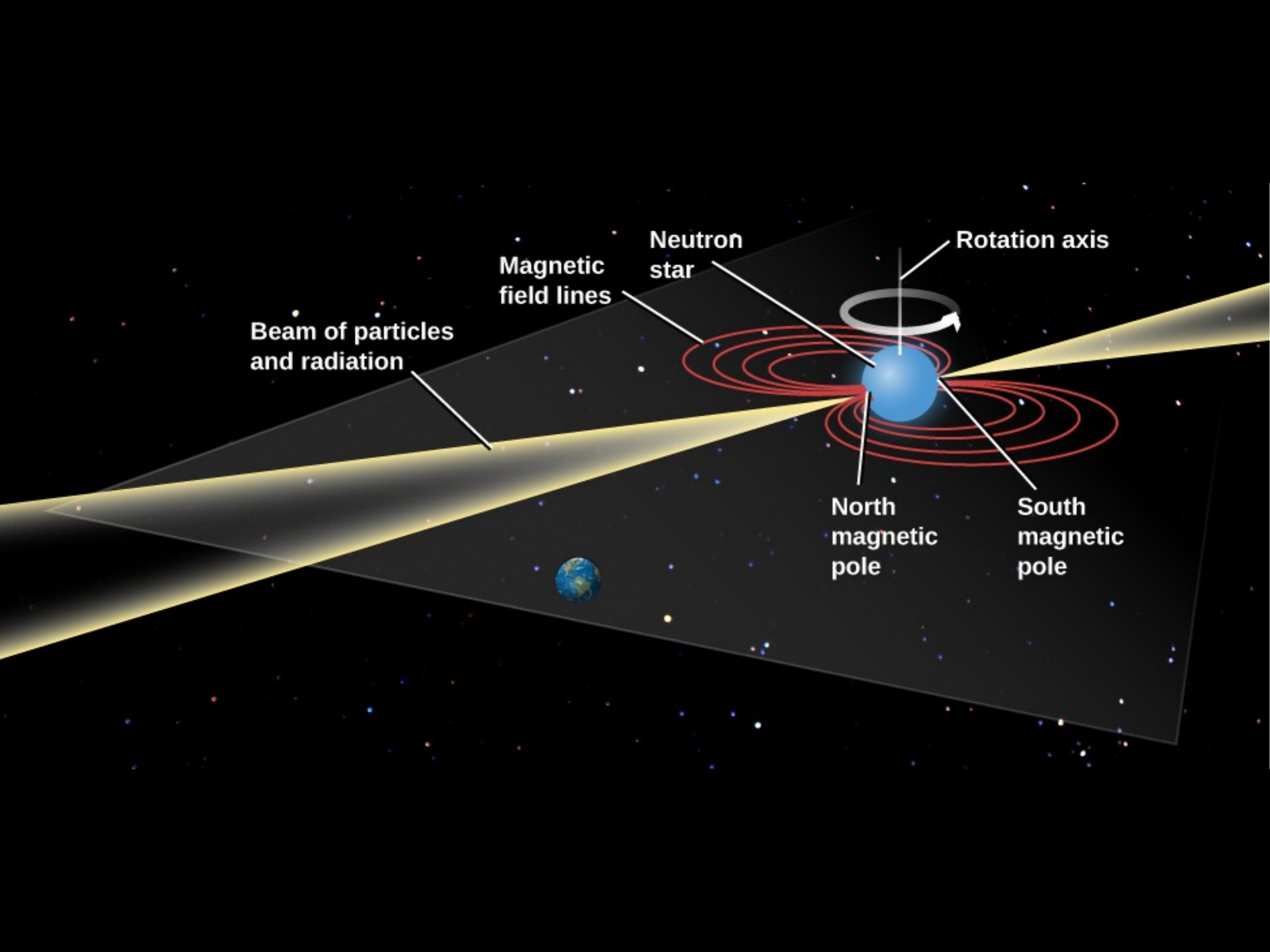
Optical Pulsars and Primary vs. Secondary Pulses



The pulsar near the center of the Crab Nebula







Beam of particles and radiation

Magnetic field lines

Neutron star

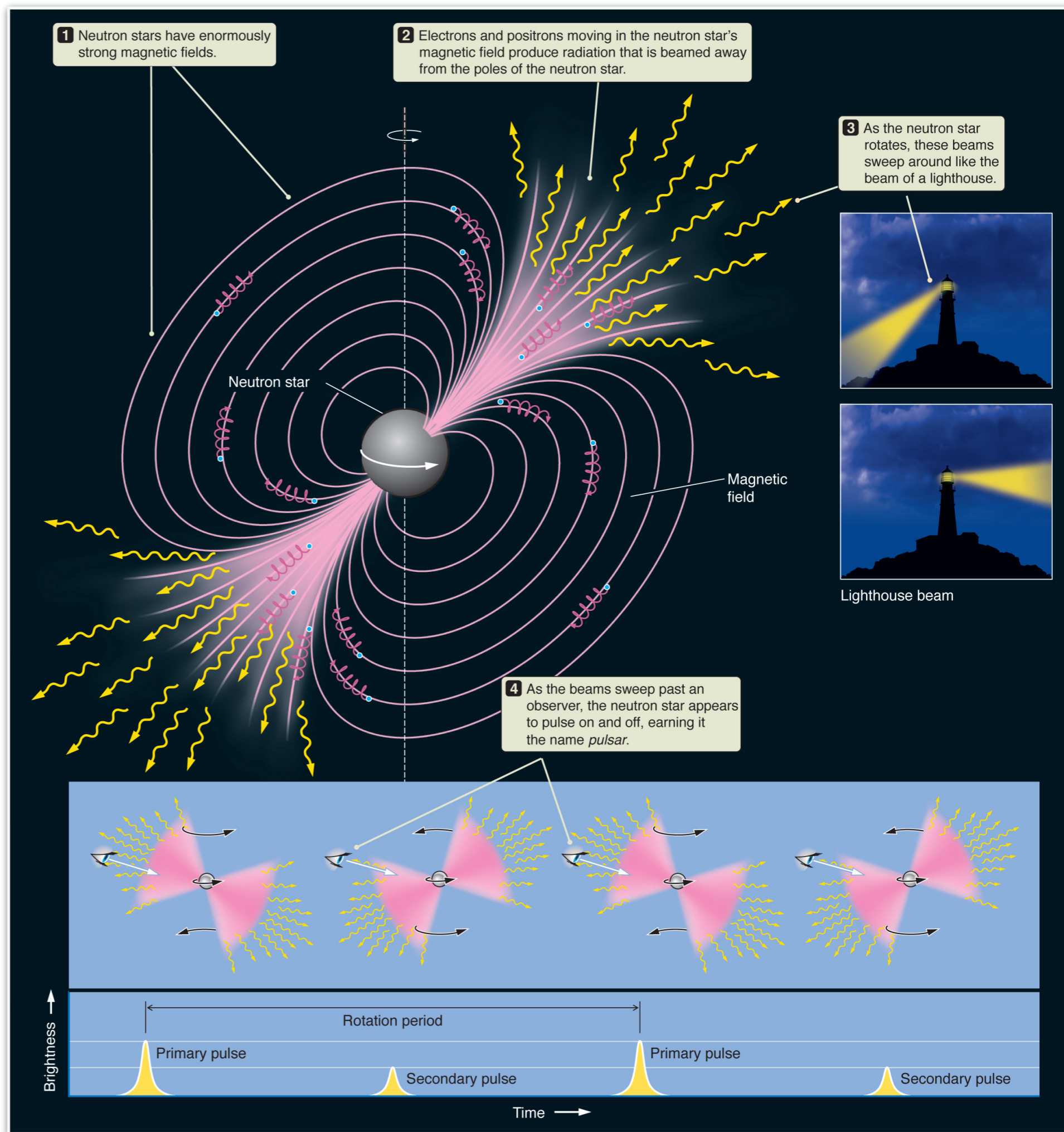
Rotation axis

North magnetic pole

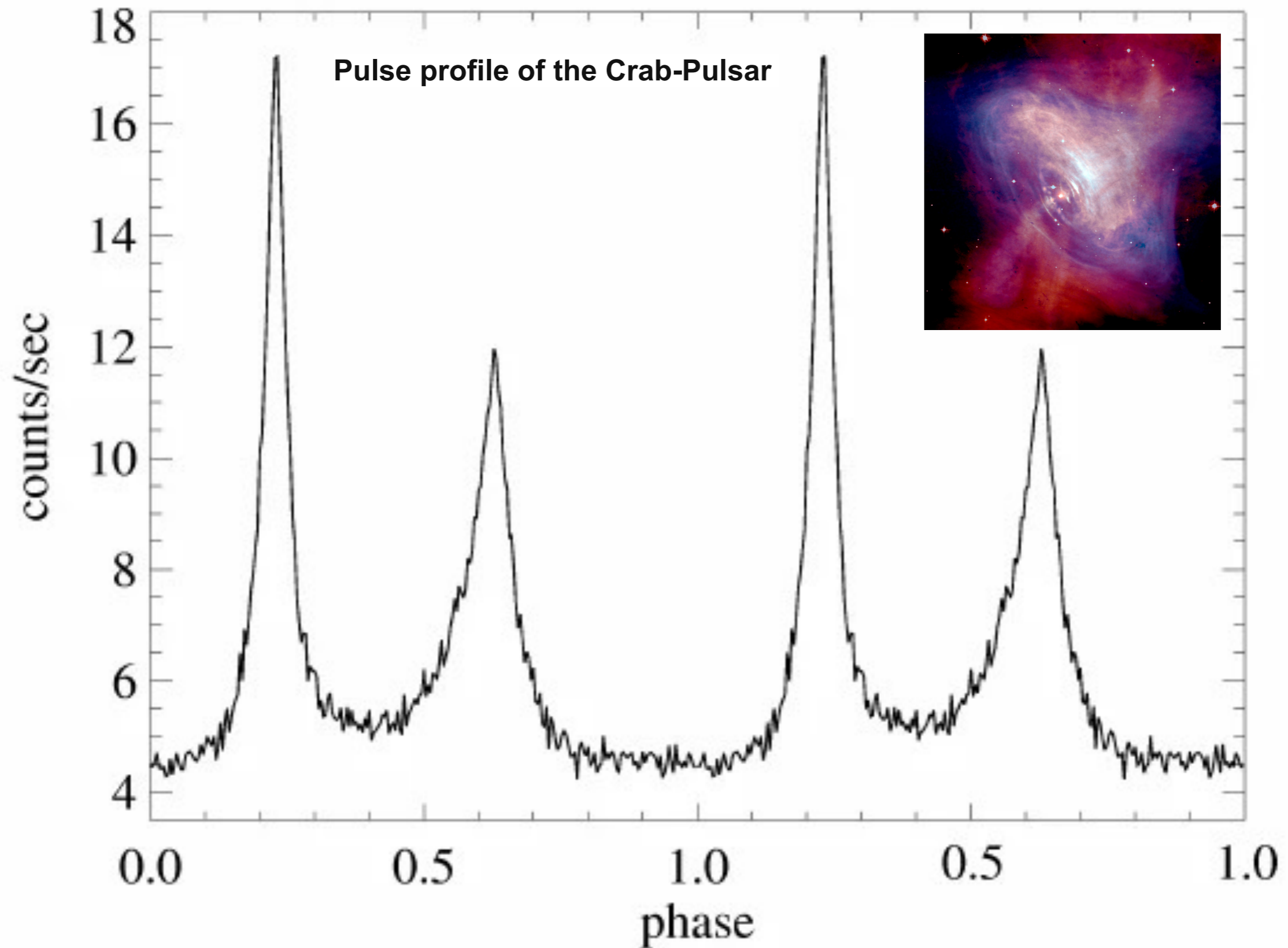
South magnetic pole

Pulsars

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



Not exactly 180deg phase offset



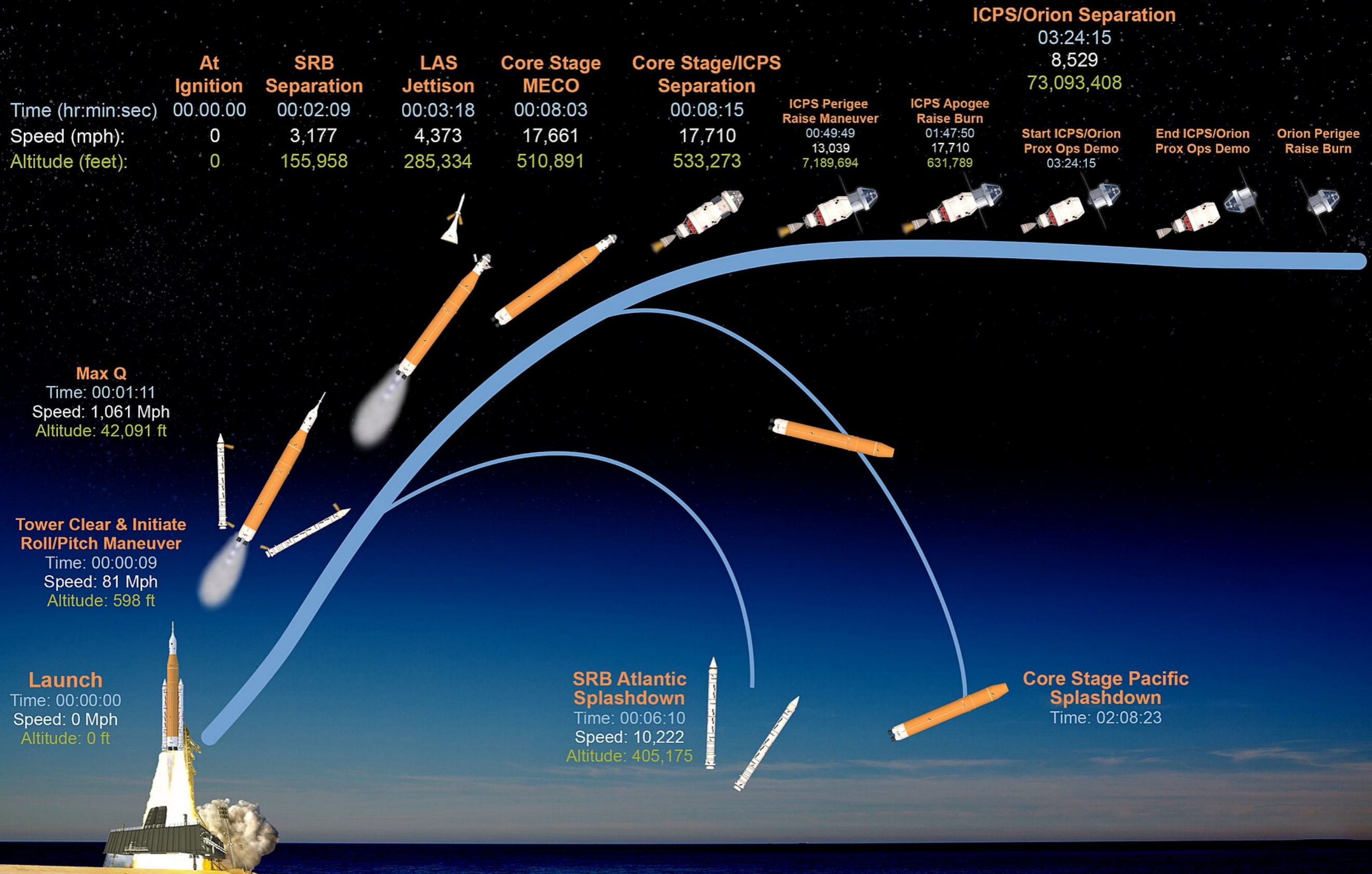
Pulsars animation



NASA's Artemis II Mission to the Moon (2026 04)



Separations of rocket stages



Trajectory in Earth-Moon Co-Rotating Frame



ARTEMIS II

First Crewed Test Flight to the Moon Since Apollo

- 1 LAUNCH**
Astronauts lift off from pad 39B at Kennedy Space Center.
- 2 JETTISON SOLID ROCKET BOOSTERS, FAIRINGS, AND LAUNCH ABORT SYSTEM**
- 3 CORE STAGE MAIN ENGINE CUT OFF**
With separation.
- 4 PERIGEE RAISE MANEUVER**
- 5 APOGEE RAISE BURN TO HIGH EARTH ORBIT**
Begin 23.5 hour checkout of spacecraft.
- 6 ORION SEPARATION FROM INTERIM CRYOGENIC PROPULSION STAGE (ICPS) FOLLOWED BY PROX OPS DEMO**
Plus manual handling qualities assessment for up to 2 hours.
- 7 ORION UPPER STAGE SEPARATION (USS) BURN**
Begins high Earth orbit checkout. Life support, exercise, and habitation equipment evaluations.
- 8 PERIGEE RAISE BURN**
- 9 TRANS-LUNAR INJECTION (TLI) BY ORION'S MAIN ENGINE**
Lunar free return trajectory initiated with European service module.
- 10 OUTBOUND TRANSIT TO MOON**
Outbound Trajectory Correction (OTC) burns as necessary for Lunar free return trajectory; travel time approximately 4 days.
- 11 LUNAR FLYBY**
6,479 miles / 10,427 km (mean) lunar farside altitude.
- 12 TRANS-EARTH RETURN**
Return Trajectory Correction (RTC) burns as necessary to aim for Earth's atmosphere; travel time approximately 4 days.
- 13 CREW MODULE SEPARATION FROM SERVICE MODULE**
- 14 ENTRY INTERFACE (EI)**
Enter Earth's atmosphere.
- 15 SPLASHDOWN**
Ship recovers astronauts and capsule.

| PROXIMITY OPERATIONS DEMONSTRATION SEQUENCE | |
|---|----|
| 1 | 9 |
| 2 | 10 |
| 3 | 11 |
| 4 | 12 |
| 5 | 13 |
| 6 | 14 |
| 7 | 15 |
| 8 | 16 |
| | 17 |

Trajectory in Geocentric Inertial Reference Frame

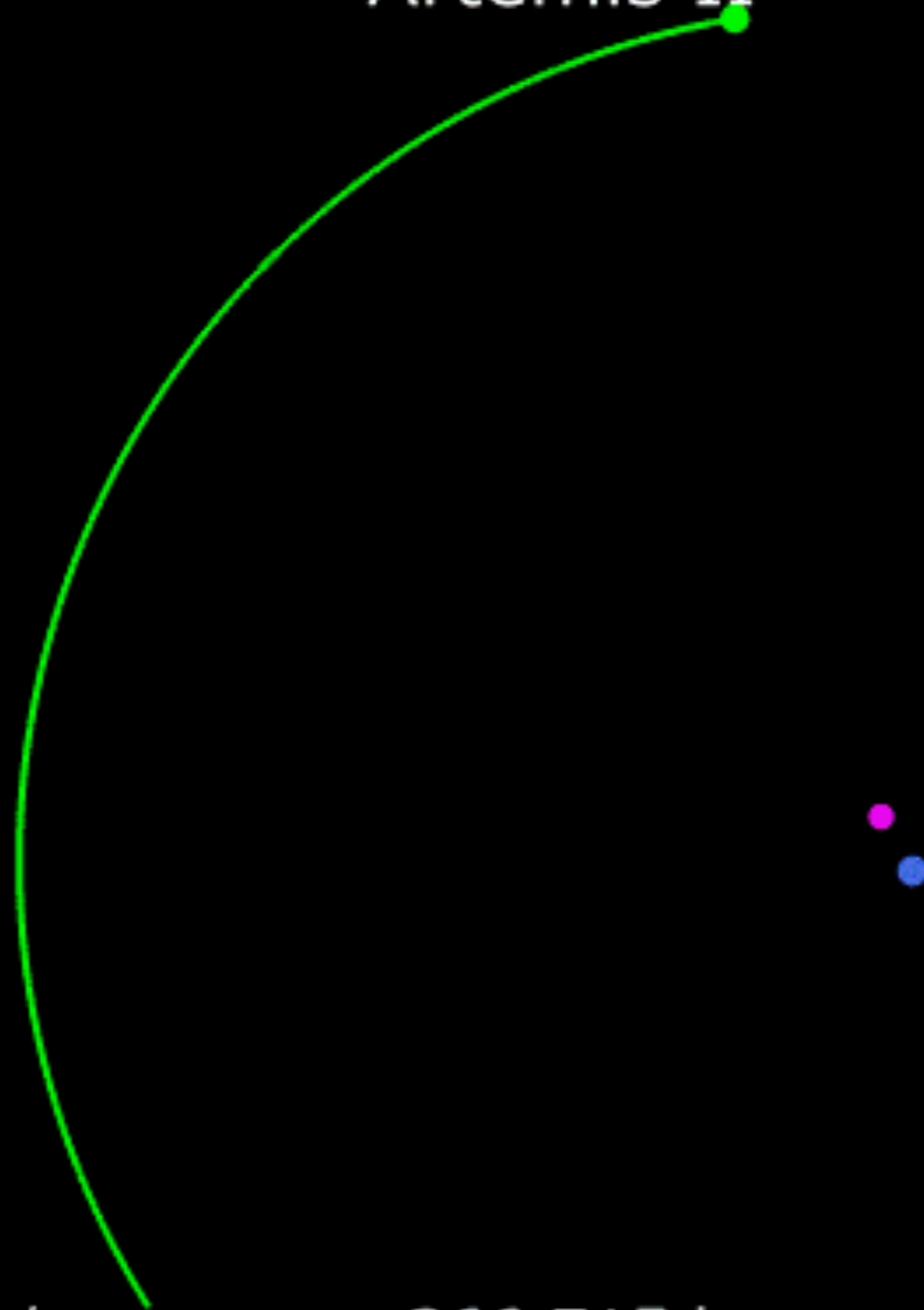
2026-04-02 01:48

Artemis II

0.000 km/s

366,715 km

(88.4°, 0.0°)



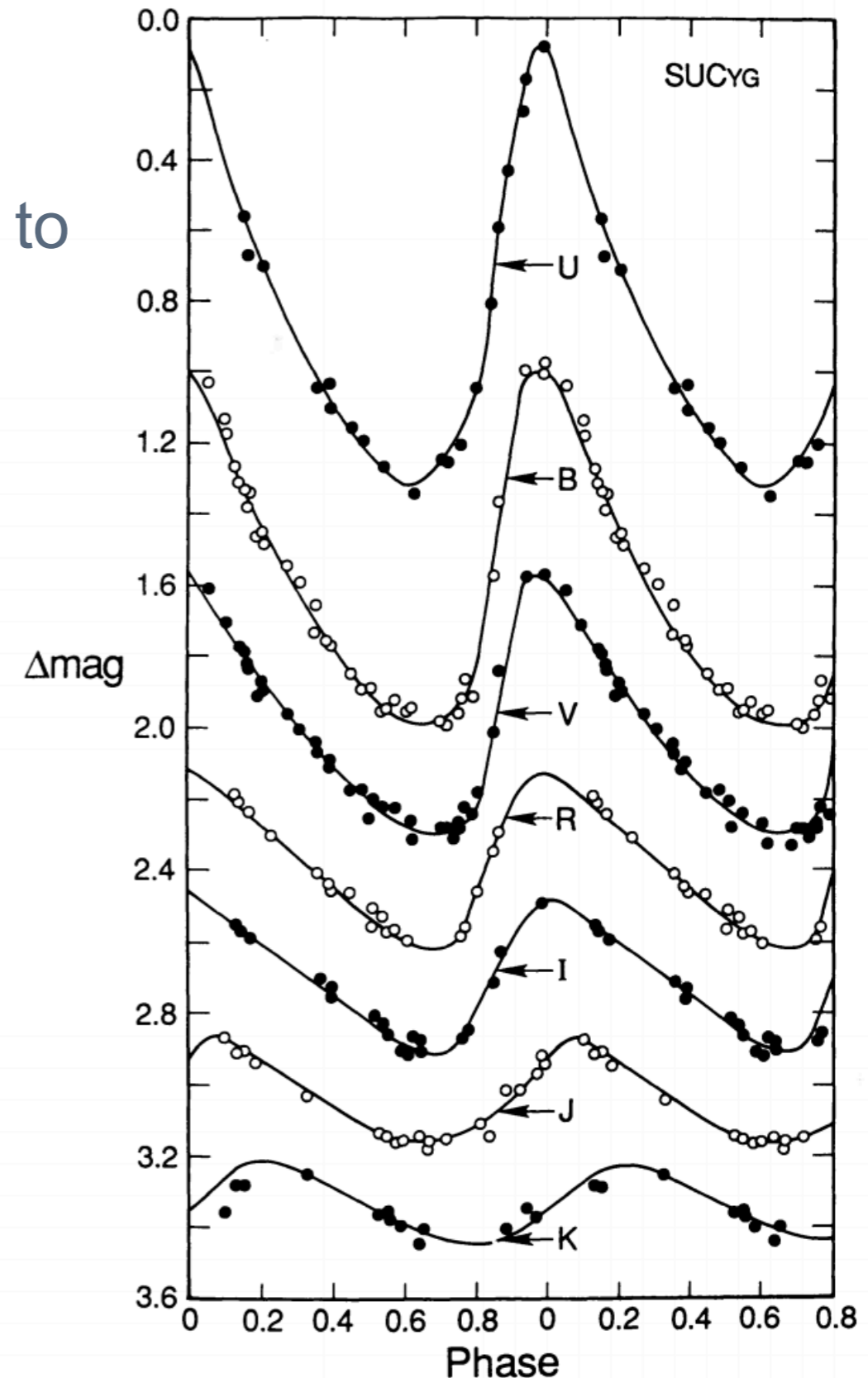
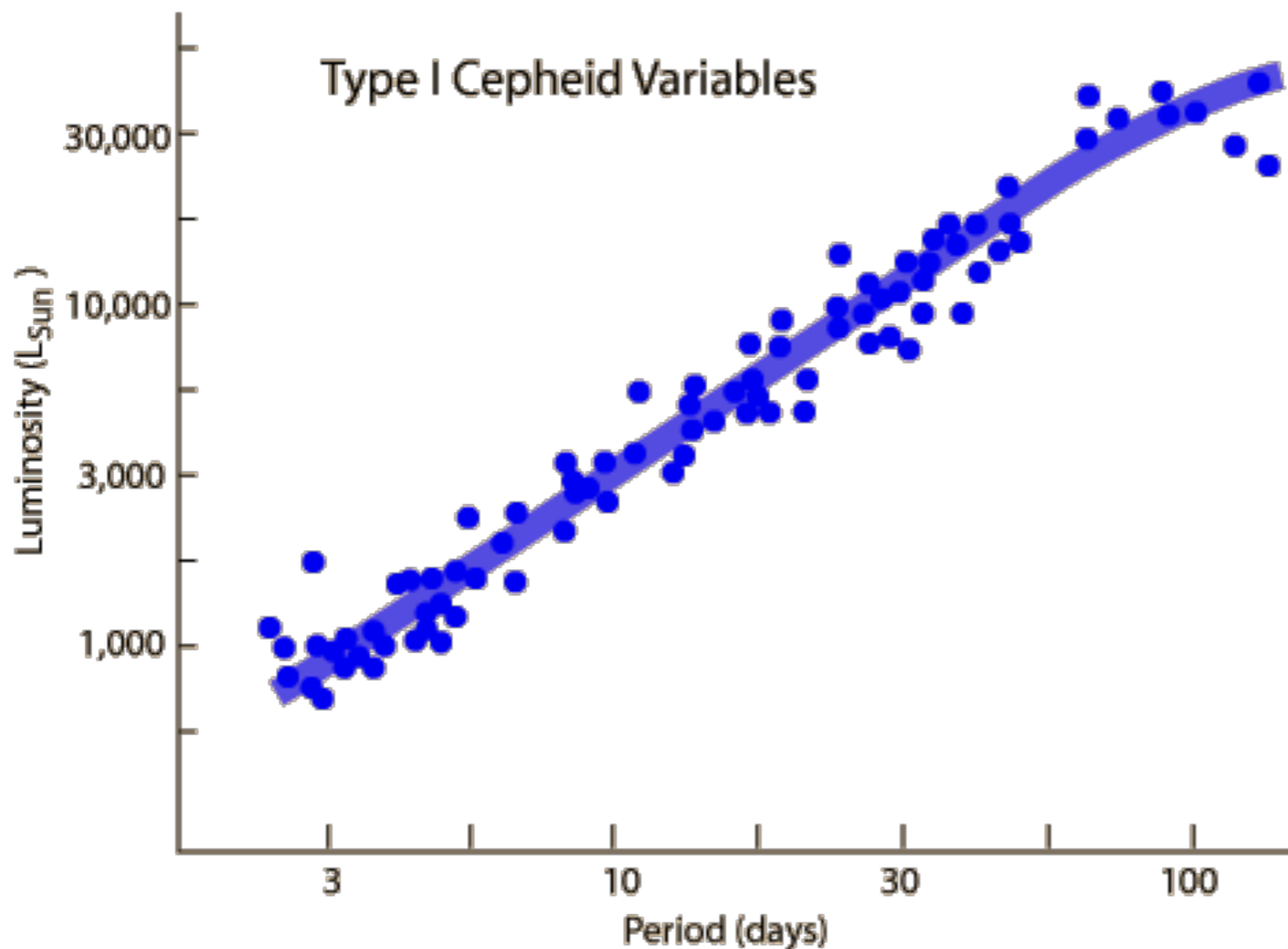
Well, let's not forget about the people inside :)



Cepheid Variables

Cepheids as standard candles: Period-Luminosity Relation

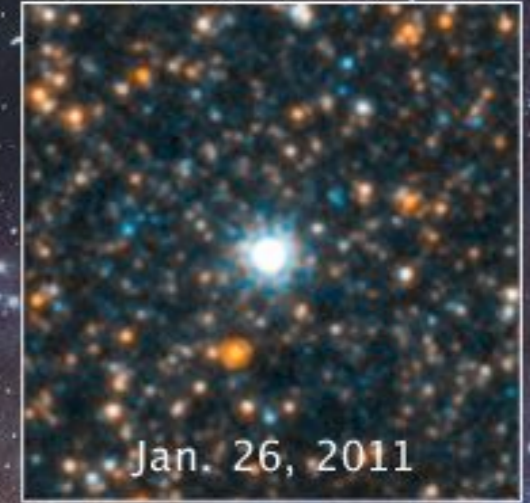
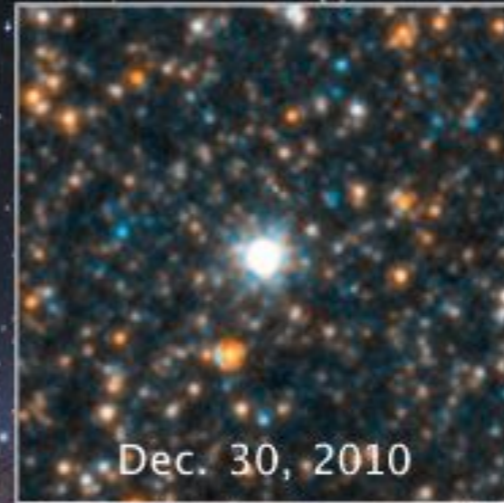
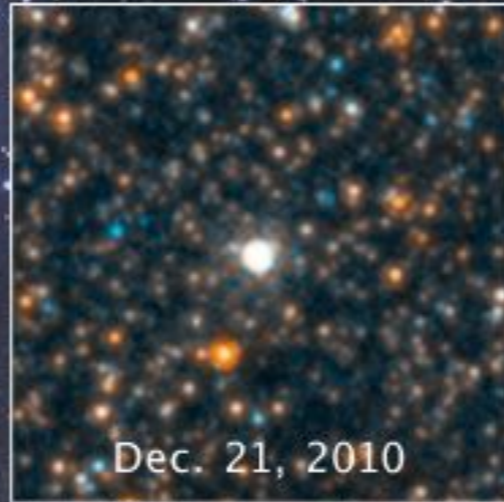
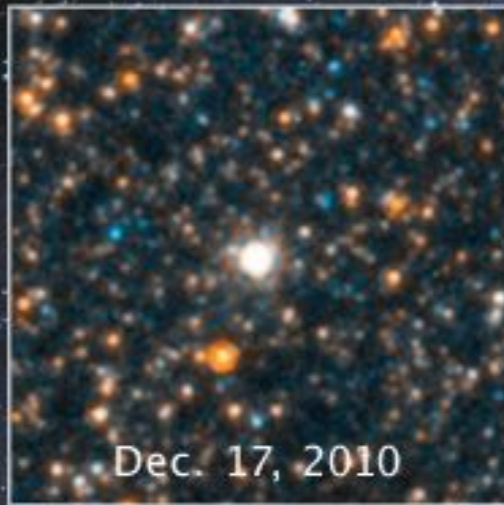
- $M_V = -2.43 \log(P_{\text{day}}) - 1.62$
(Type I Cepheids, Fritz et al. 2007)
- This is critical for determining distances to other galaxies: $d_{\text{pc}} = 10^{\frac{(m - M) + 5}{5}}$



Cepheid Variable Star V1 in M31

Hubble Space Telescope ■ WFC3/UVIS

The First Cepheid discovered by Edwin Hubble in M31
($P = 31.41$ days and a peak magnitude of 18.2)

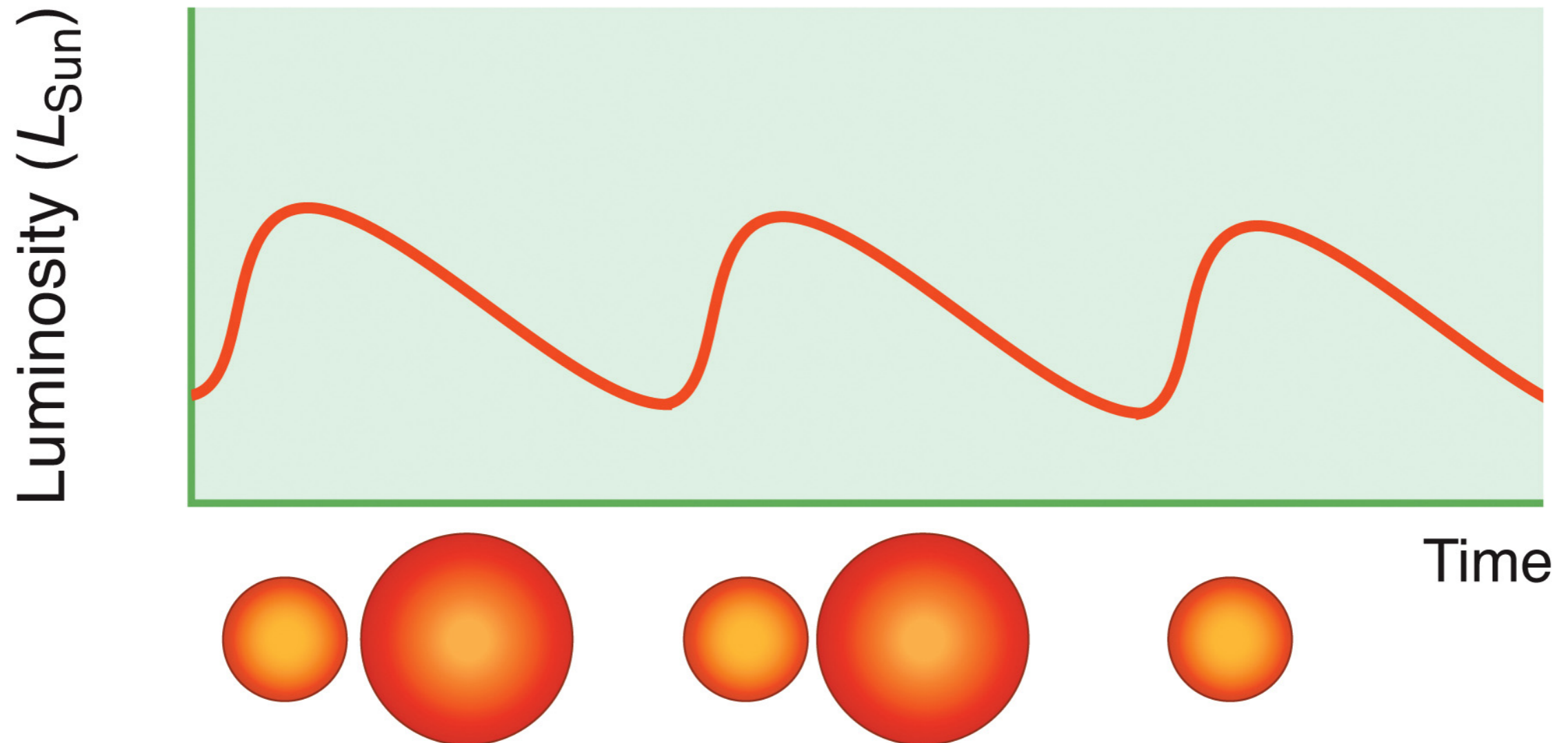


$$M_V = -2.43 \log(P_{\text{day}}) - 1.62$$

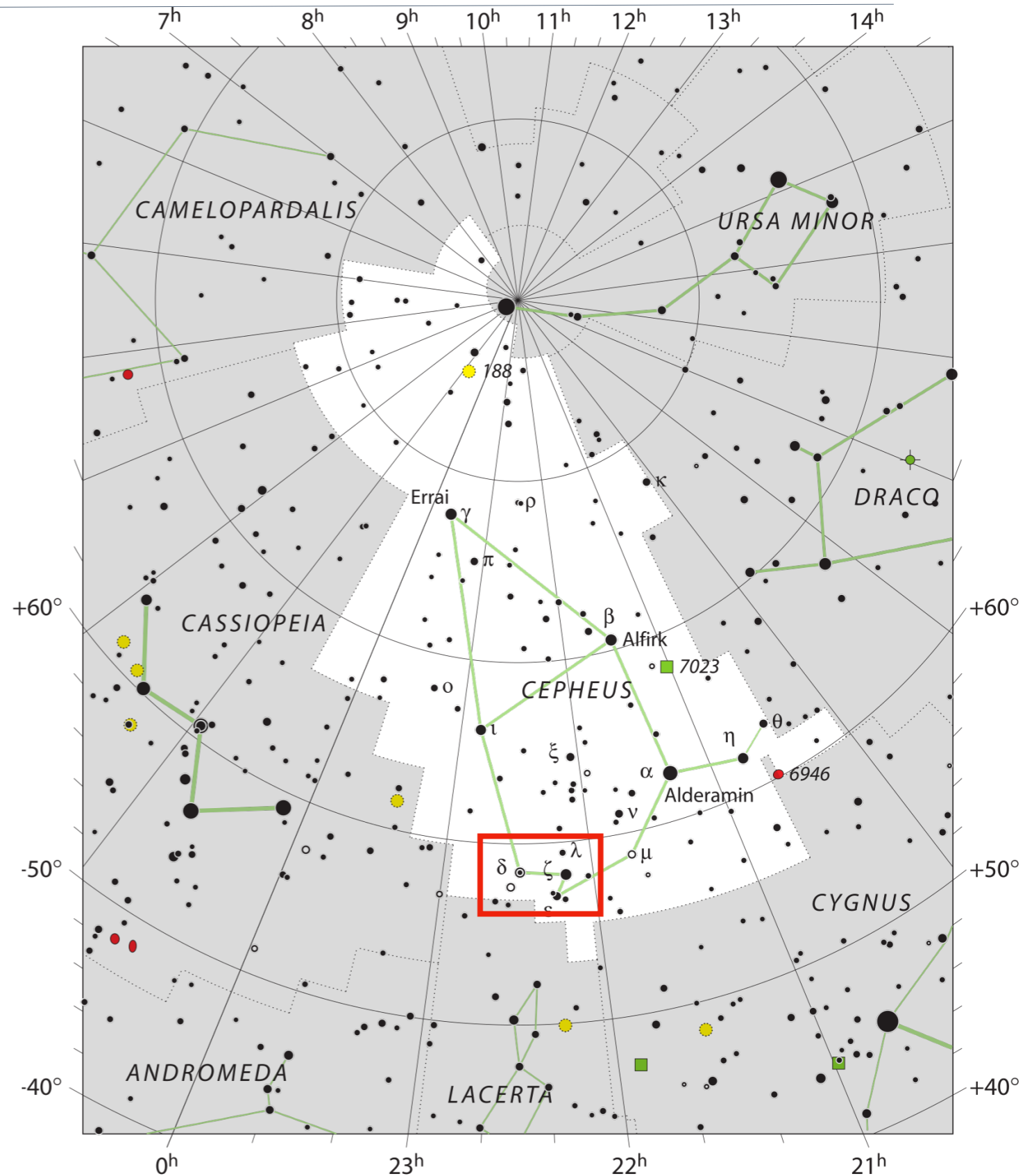
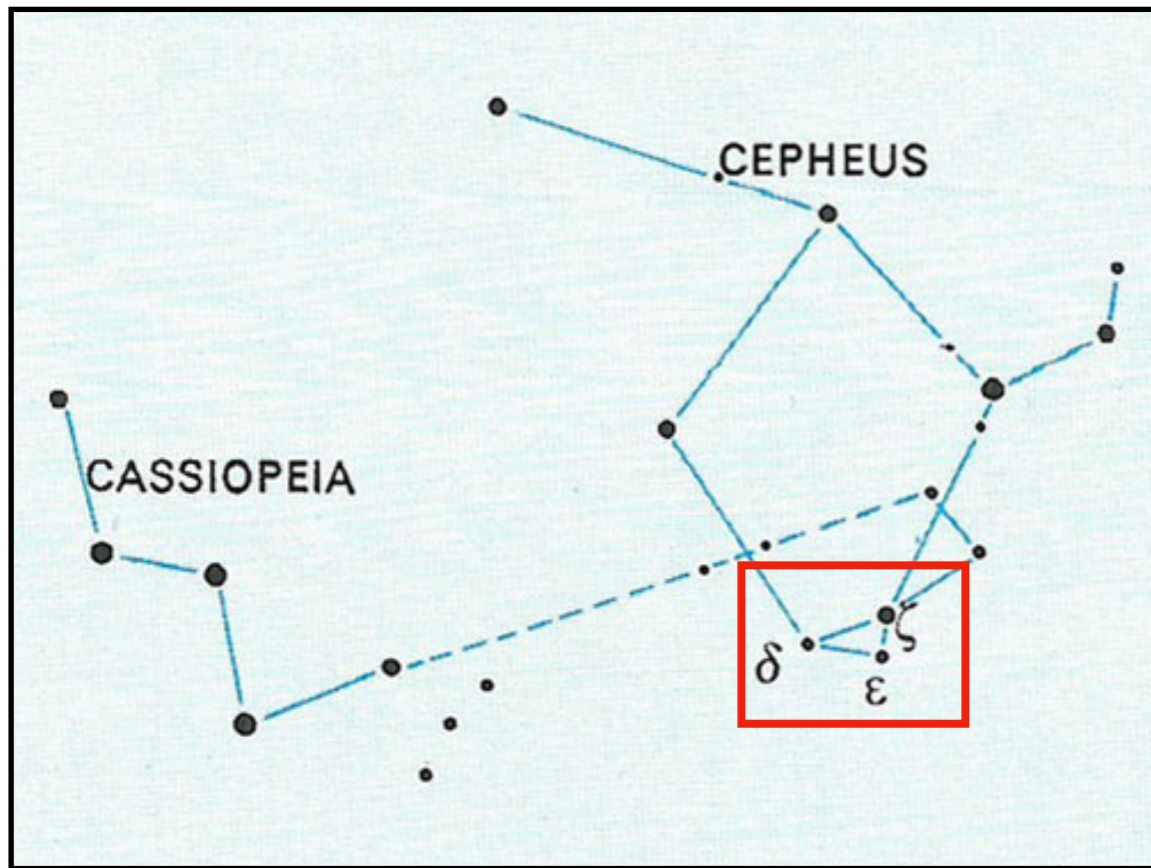
$$d_{\text{pc}} = 10^{\frac{(m - M) + 5}{5}}$$

Pulsating Variable Stars Change in Size and Temperature

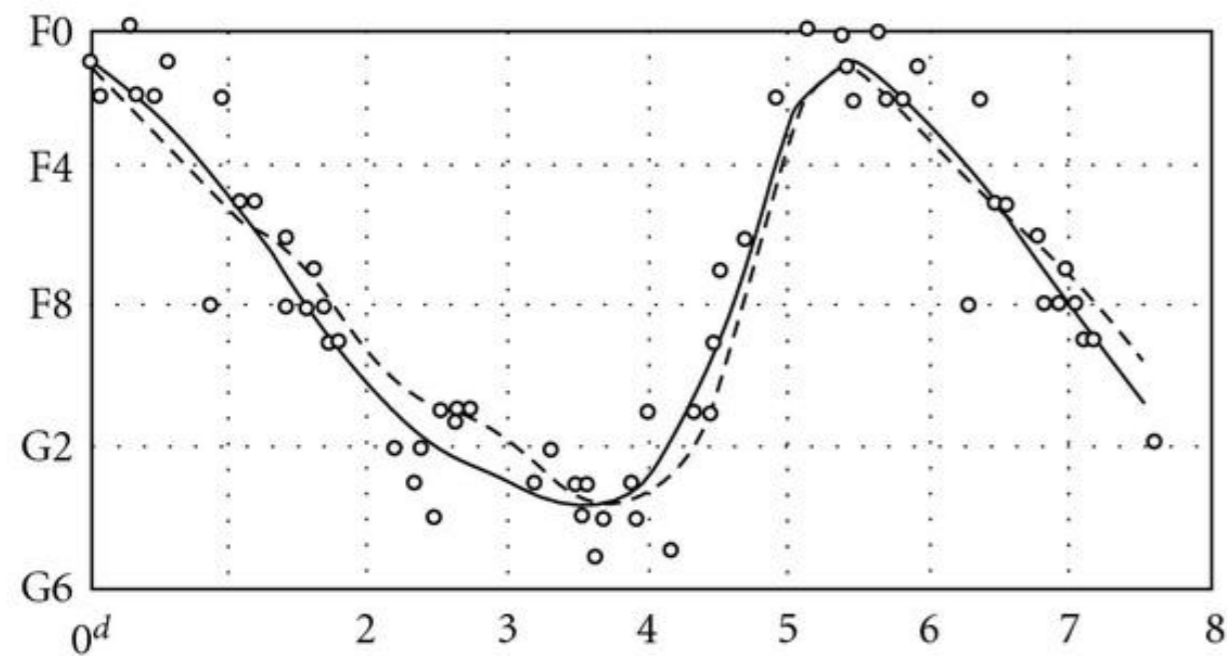
- The star's **luminosity** changes as their **radius** and **temperature** changes at a regular period.
- A star can evolve into a **pulsating variable star** when its **interior fails to** achieve a steady balance between pressure and gravity (i.e., it overshoots and undershoots).



Temperature Phase Diagram of Delta Cephei

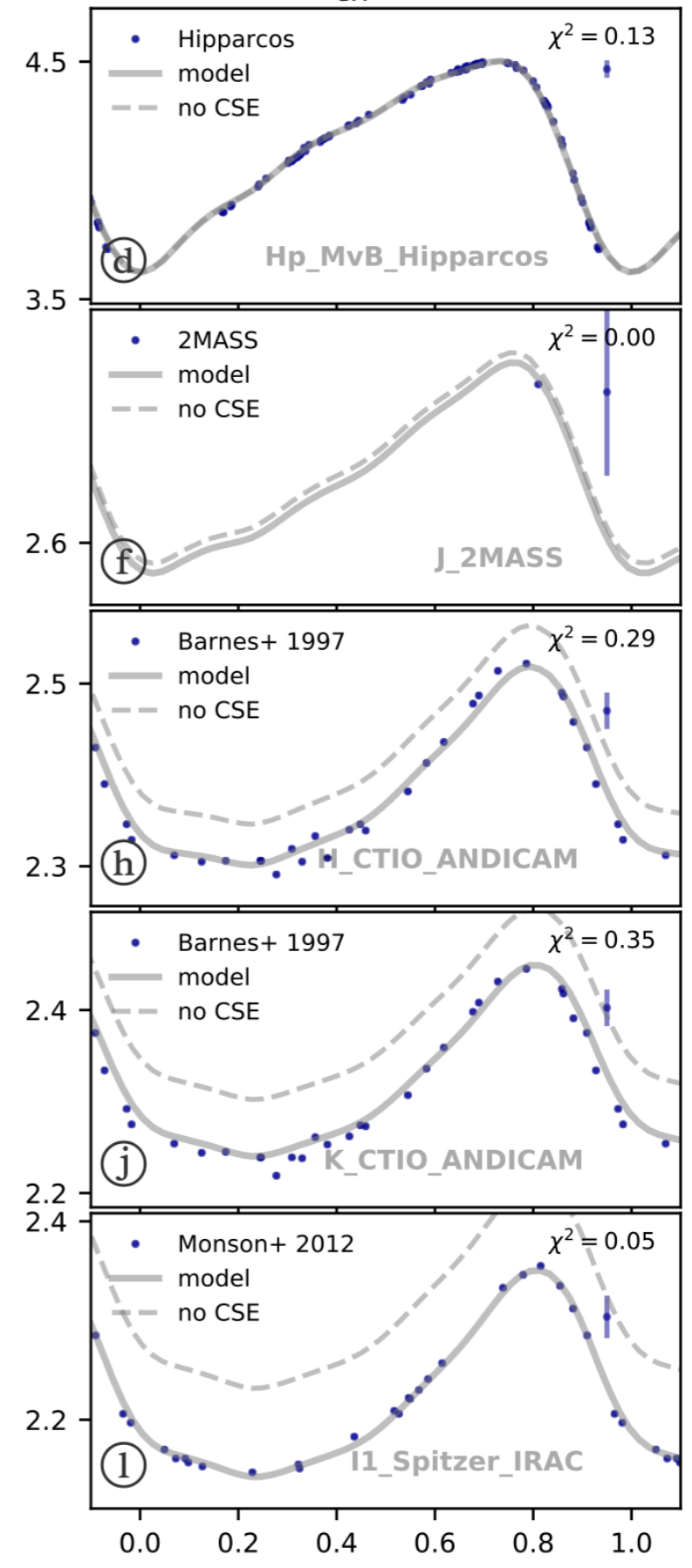
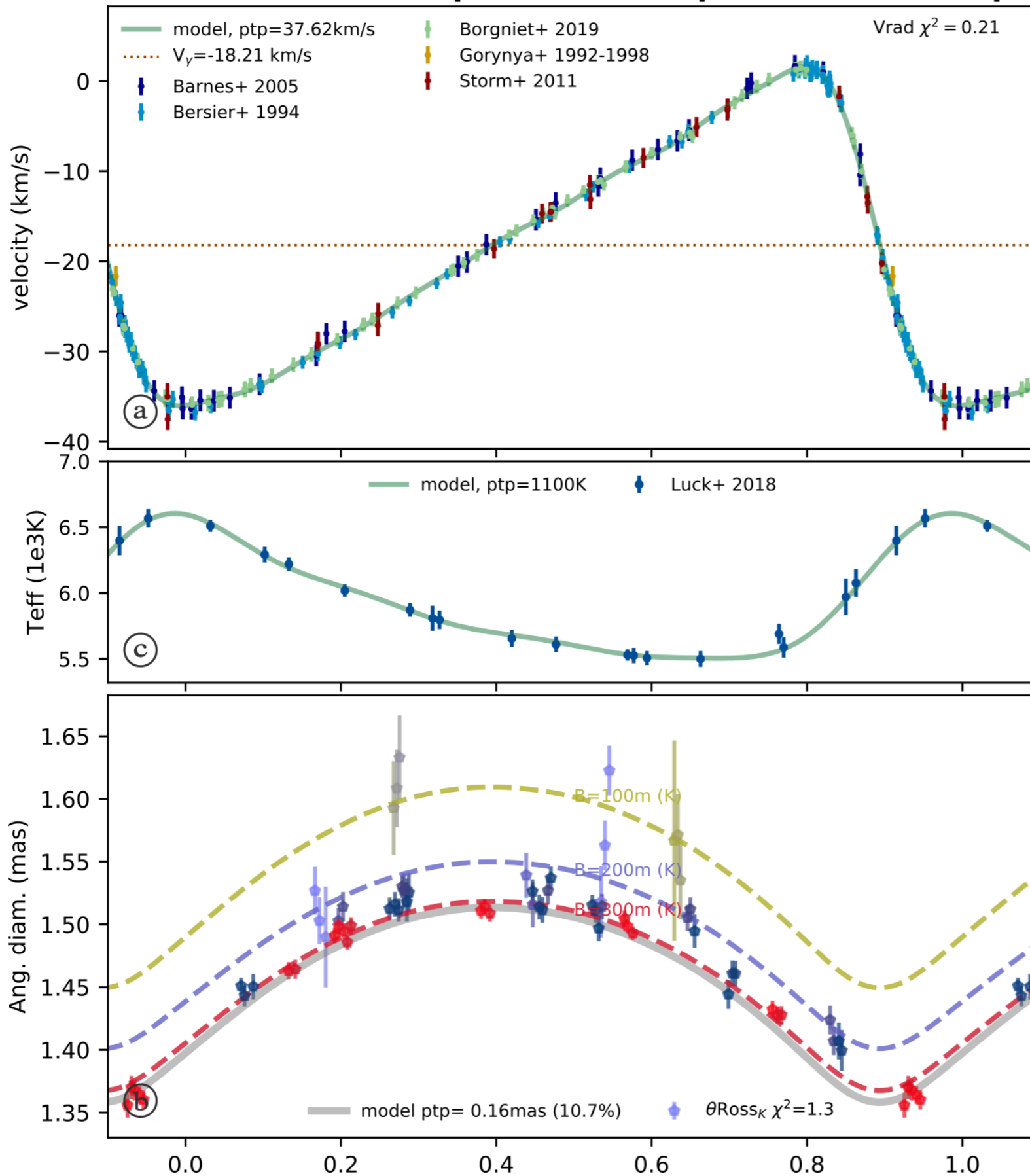


● 1 ● 2 ● 3 ● 4 ● 5 ● 6



Phase Diagrams of *Velocity, Temperature, Size, and Magnitude*

Delta Cep (P~ 5.366d) p=1.317 d=279.5pc E(B-V)=0.092; IR_{ex} = 0.064(λ - 1.2



**What's the physical mechanism
that drives the pulsation?**

4C50.30 - Critical Temperature - Sulfur Hexafluoride



Sulfur hexafluoride (SF₆) is an odorless, colorless, and inert synthetic gas heavily used as an electrical insulator in high-voltage switchgear and equipment. While **non-toxic**, it is the **most potent greenhouse gas**.

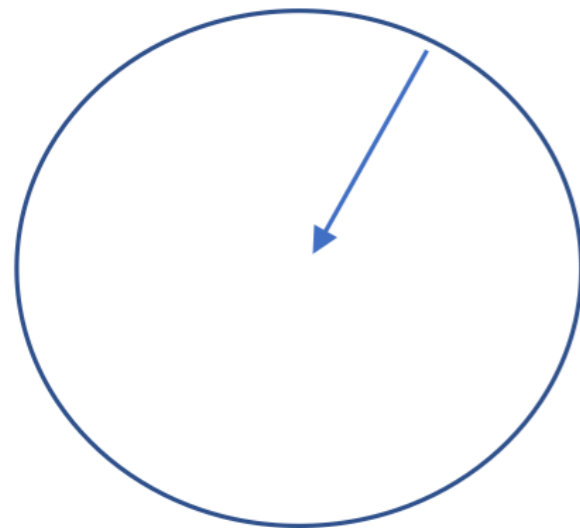
Code Number: 4C50.30

Demo Title: Critical Temperature - Sulfur Hexafluoride

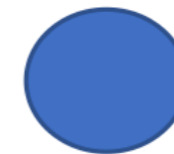
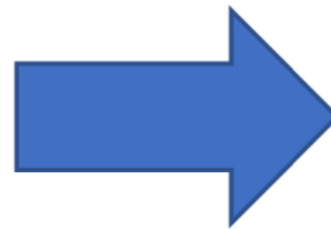
Pulsation Caused by Helium Ionization and Recombination

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

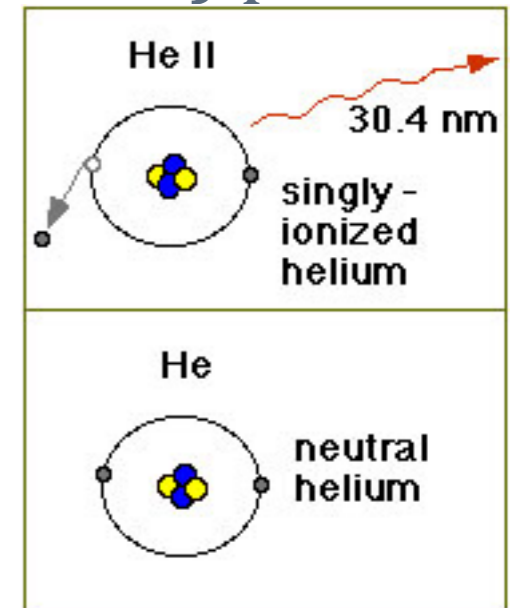
- Photons go through gas
- Gravity condenses star



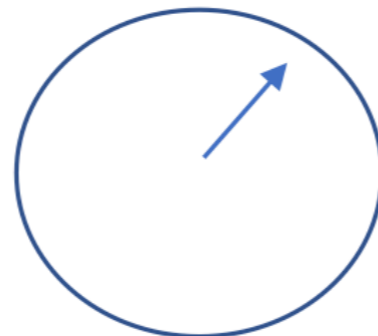
- Temperature increases
- He is ionized
- Gas becomes opaque



- Opacity blocks photon flow
- Pressure increases



- Less ionization means less blocked photons
- Decreases pressure



- Pressure expands star
- He cools and becomes less ionized

Pulsation Caused by the Opacity-Mechanism

The **kappa(opacity)-mechanism** works as follows:

- As the star **contracts**, its **temperature rises**, causing the outer layers to become **more ionized**.
- **The increased ionization leads to a corresponding increase in opacity in these layers.**
- This increase in opacity inhibits the outward flow of radiation, leading to a **buildup of pressure**.
- The increased pressure causes the outer layers to **expand**, which in turn causes the **temperature to decrease**.
- **As the temperature decreases, the outer layers become less ionized, reducing the opacity.**
- With reduced opacity, radiation can escape more easily, leading to a **decrease in pressure**.
- The decreased pressure allows the outer layers to **contract** again, starting the cycle anew.

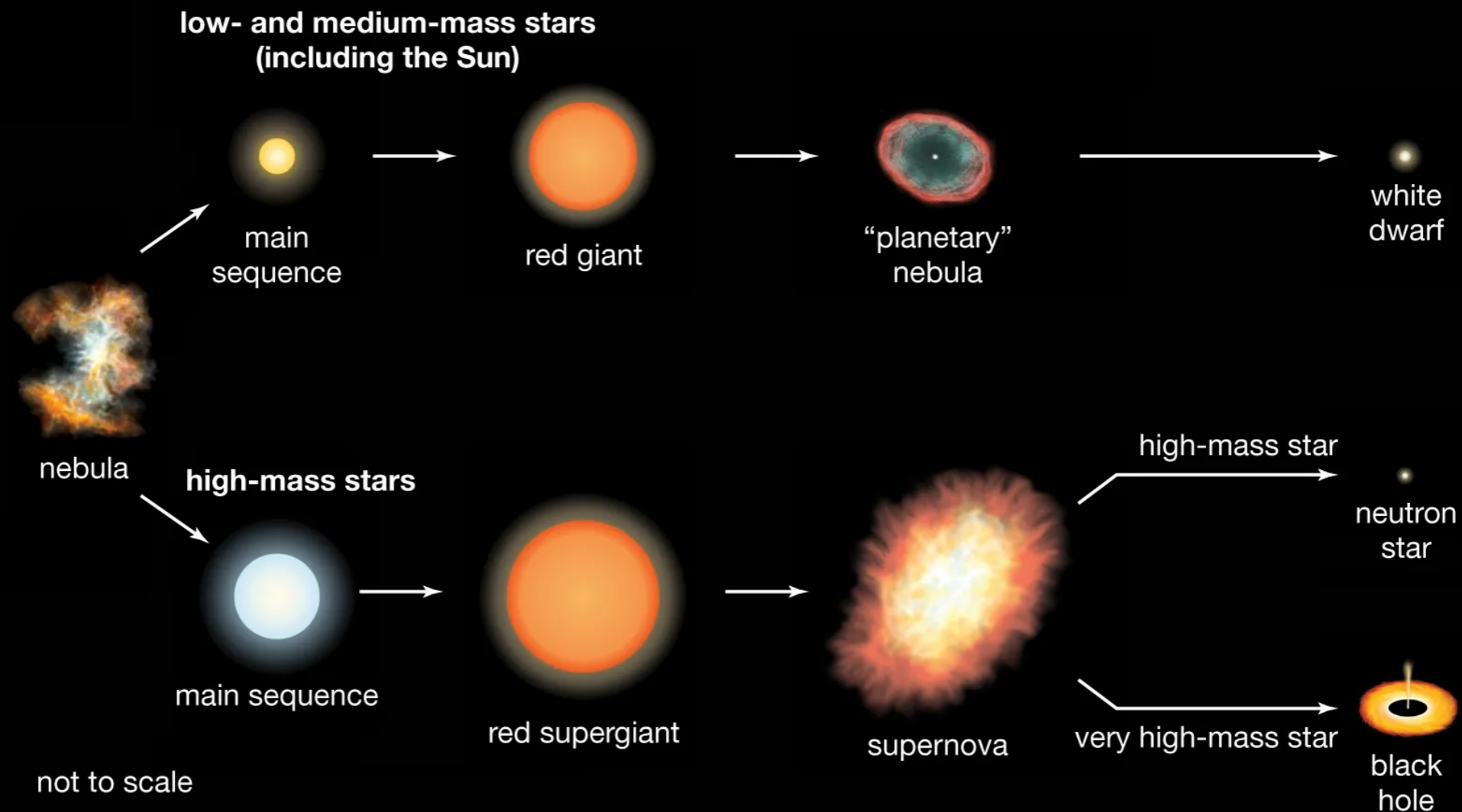
Pulsation Caused by the Opacity-Mechanism

The **Period-Luminosity Relation** arises because:

- * This cyclical process results in periodic expansions and contractions of the star's outer layers, which manifest as changes in color and magnitude.
- * The **period** of these pulsations is related to the time it takes for a pressure wave to travel through the star's interior and back to the surface
- * The period is approximately the **free-fall time, which is inversely proportional to initial density:**
$$\sqrt{3\pi/(32G\rho_0)}.$$

Chap 4: The Evolution of High-Mass Stars

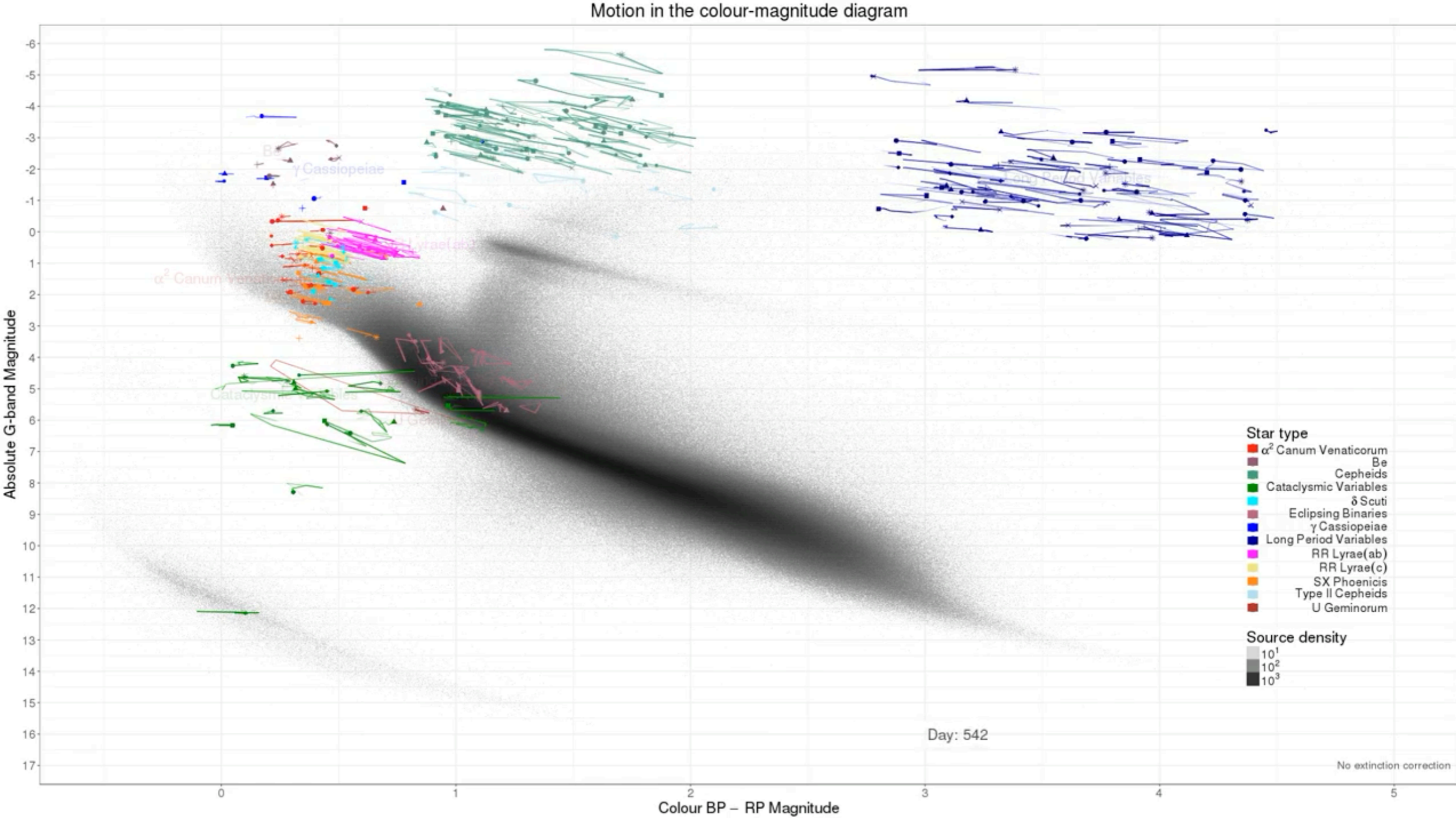
- CNO Cycles
- Convective cores
- Consecutive fusion shells
- End of fusion - Binding Energy
- Type I vs. II supernovae
- Neutron stars and Pulsars
- Periodic variables: Leavitt's law (standard candles)
- The origins of elements: six primary sources

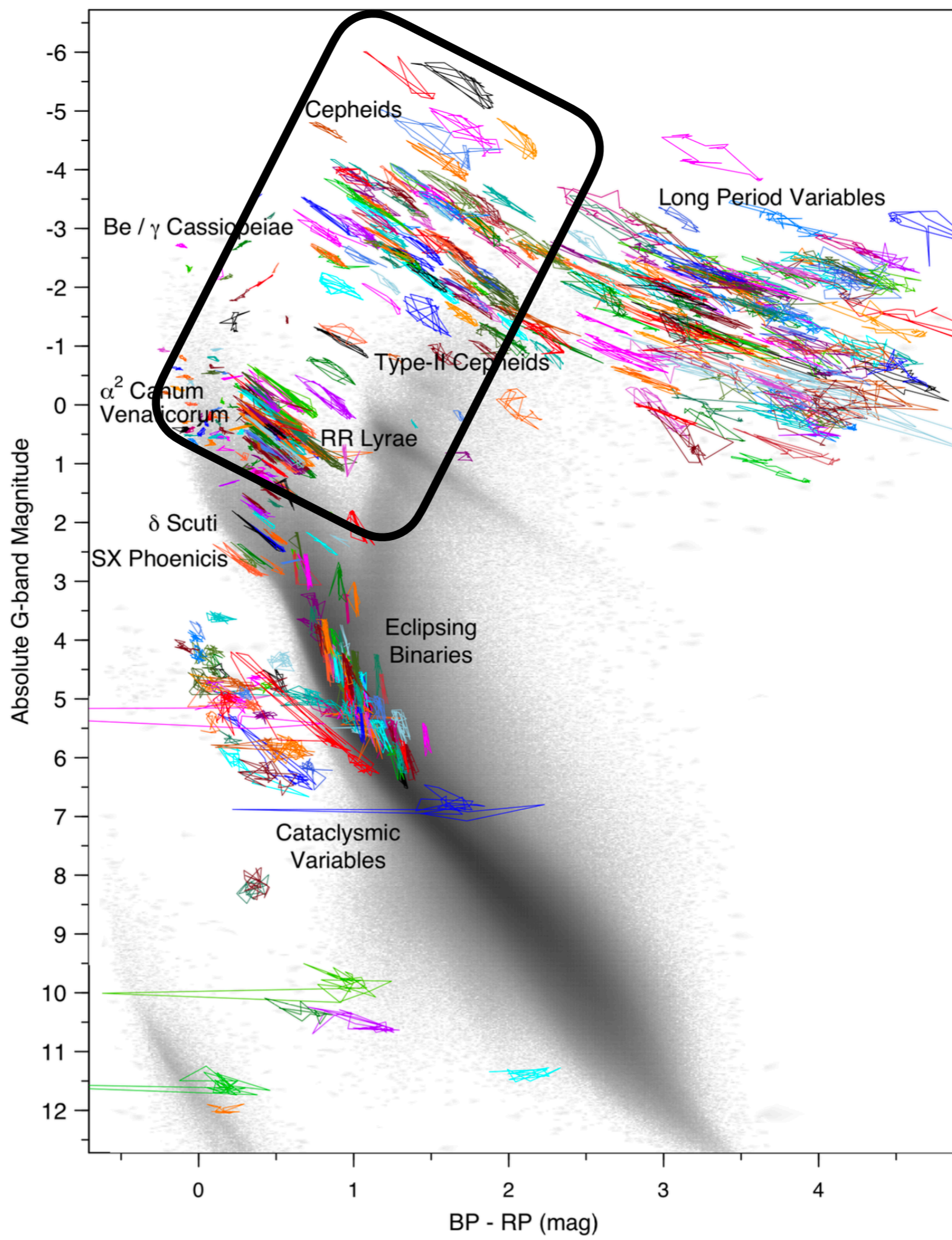


Additional Topics

Various Types of Pulsating Variable Stars from high-mass and low-mass progenitors

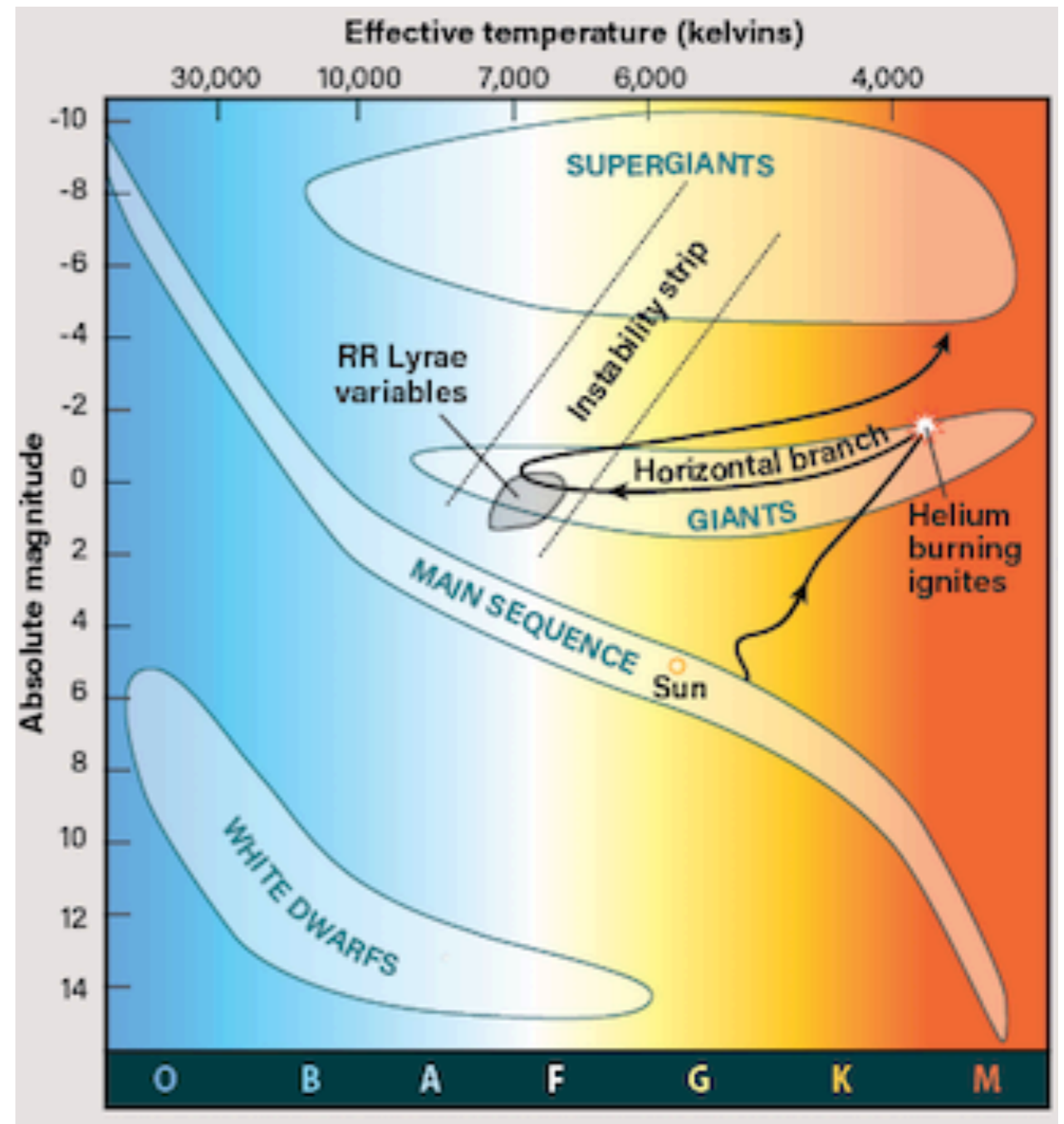
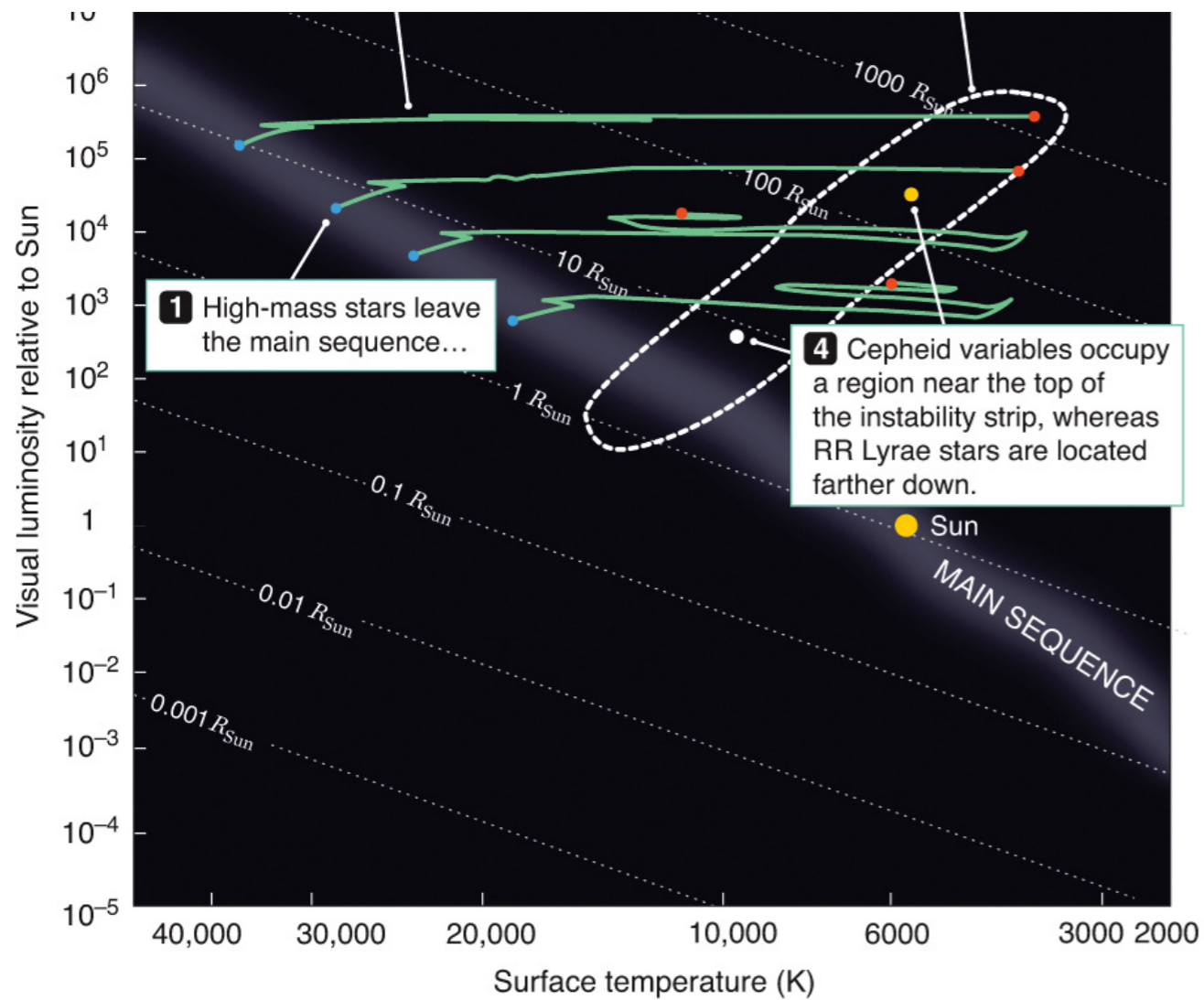
GAIA data release 2: Variable Stars on the HR Diagram





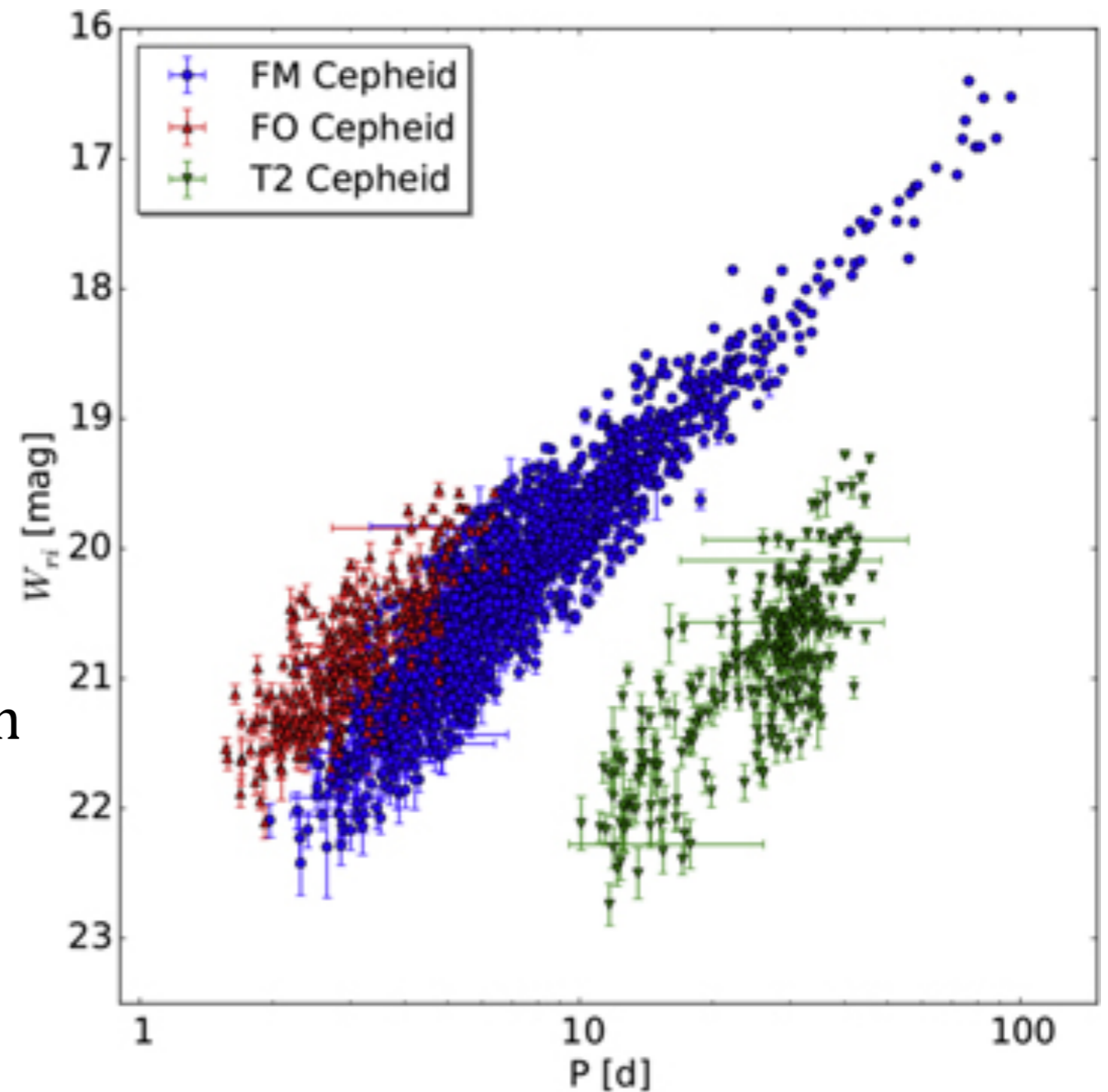
The Instability Strip on the HR Diagram

- Pulsating variables populate the **instability strip** on the HR diagram.
- During the pulsation, the stars change in both **radius** and **temperature**



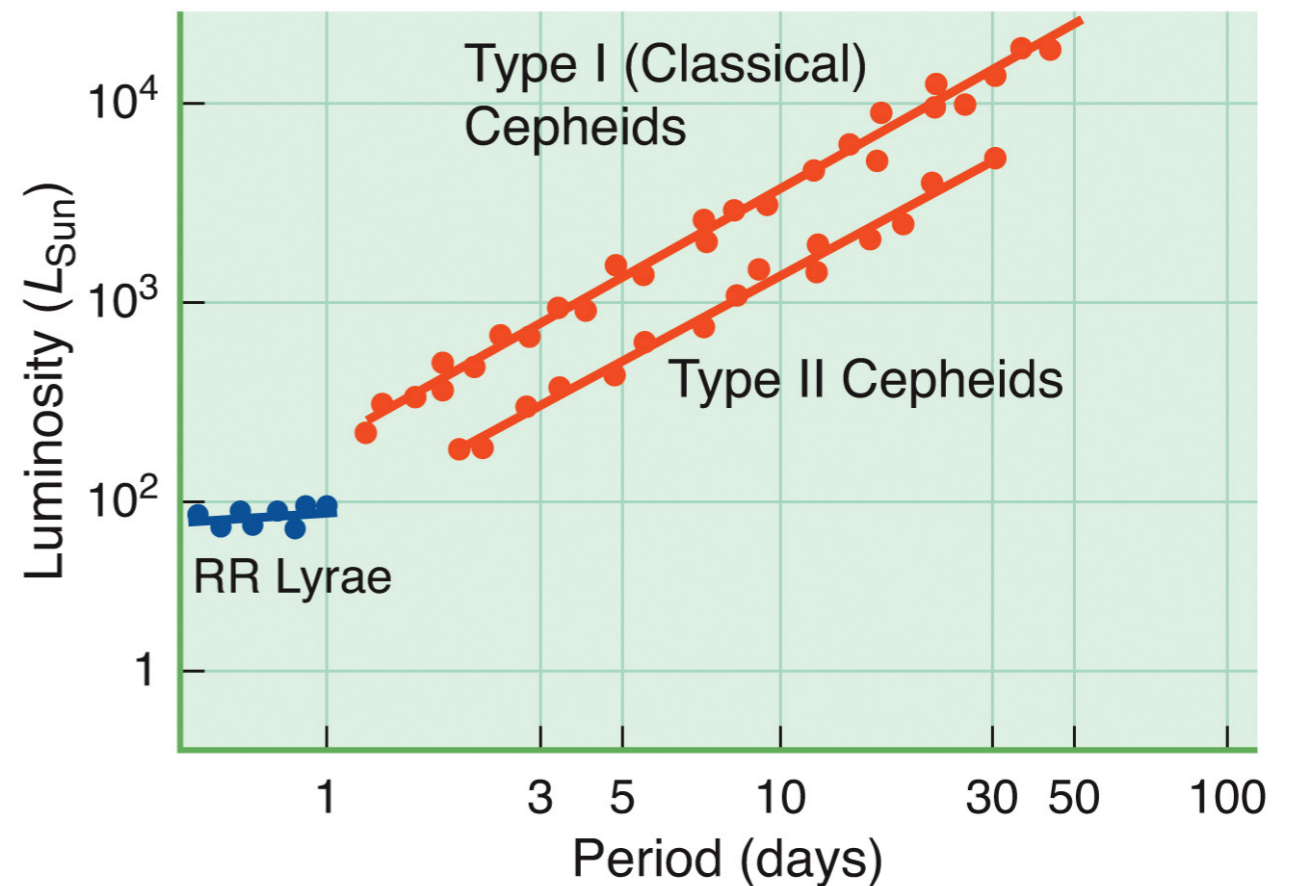
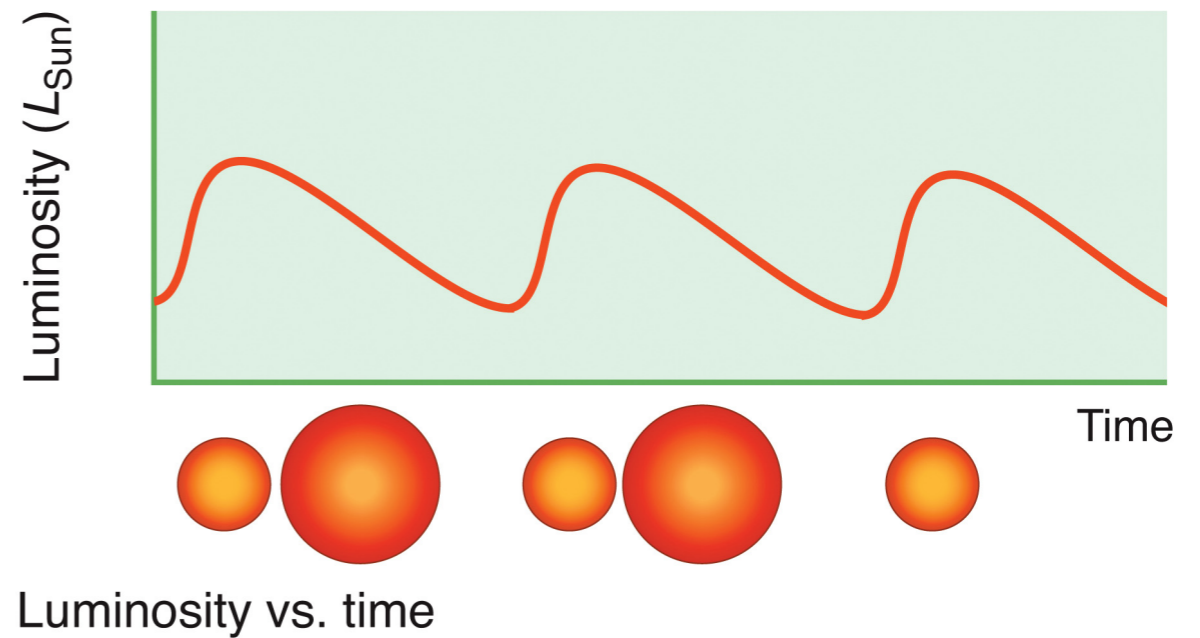
Period-Luminosity Relation of Different Types of Cepheids

- Based on the shape of the light curve, astronomers have classified three main types of Cepheids:
 - FM - Fundamental Mode
 - FO - First Overtone
 - T2 - Type II
- The P-L relations of the three types differ from each other, as illustrated on the diagram using ~ 2000 Cepheids in M31 (Kodric+2018; Fig 10).



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

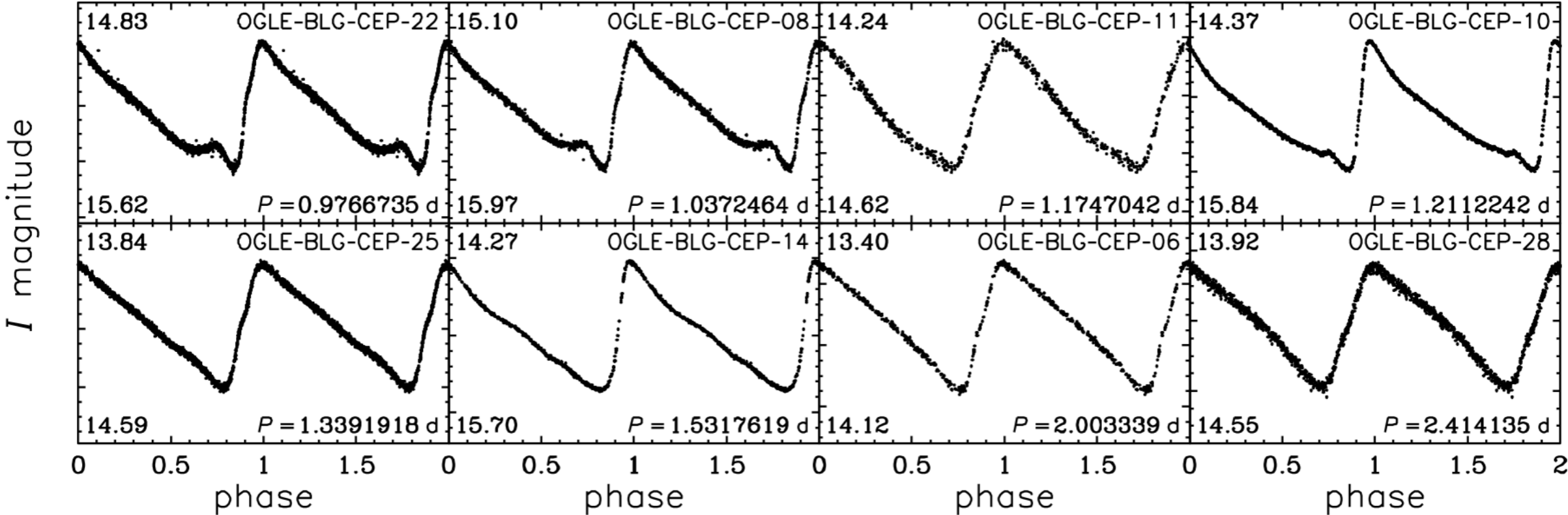
- **Type I Cepheid variables**
 - Classic Cepheid variables are **high-mass stars** becoming **supergiants**.
 - They have periods from 1 to 100 days.
- **RR Lyrae variables & Type II Cepheid variables**
 - These are **low-mass stars** on the **horizontal branch**.
 - They are less luminous than Cepheid variables.
 - They follow different L-P relations



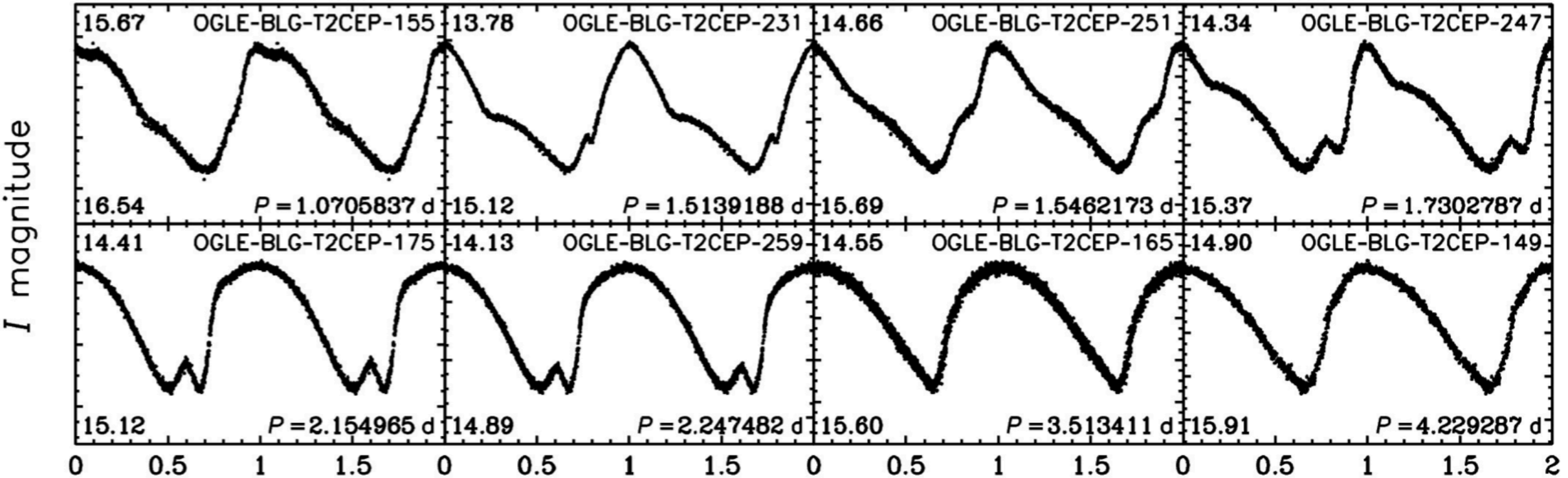
Period-luminosity relationship

Cepheids Light Curves - Type I vs. Type II Cepheids

Classical (or Type I) Cepheids

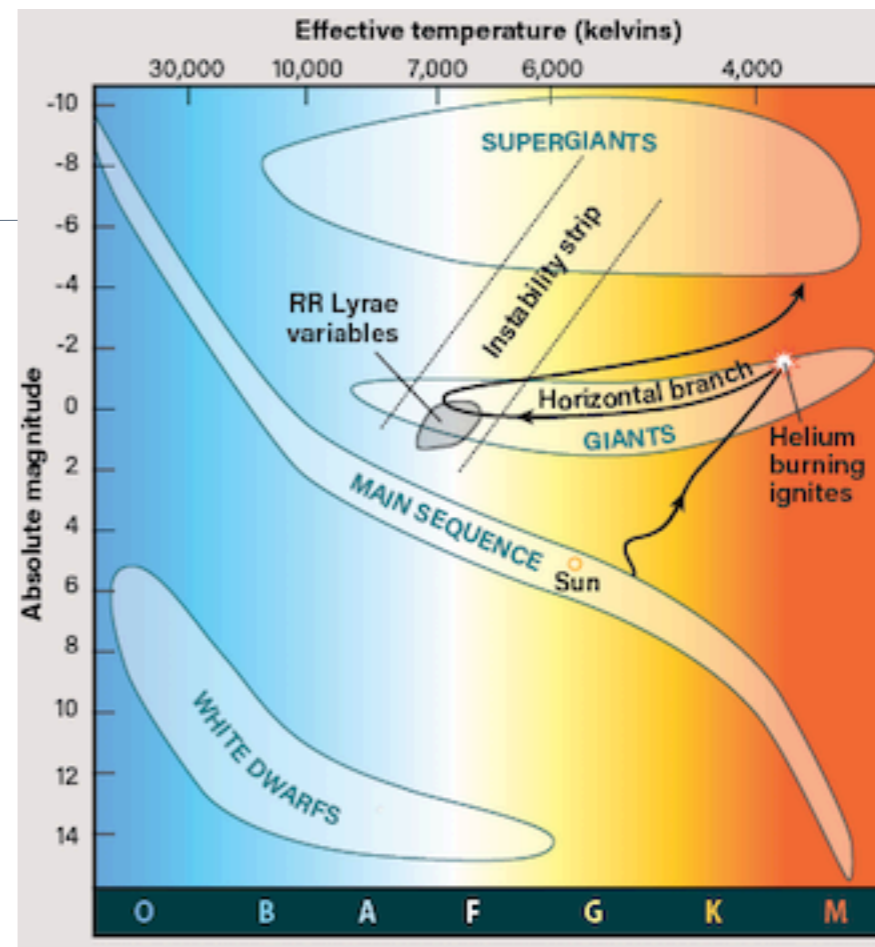


Type II Cepheids



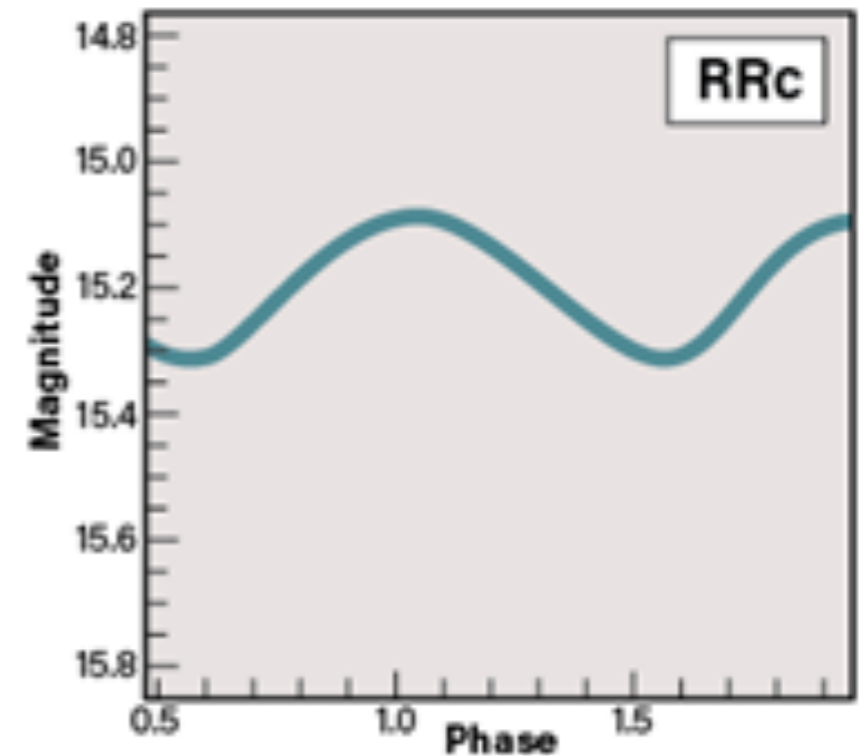
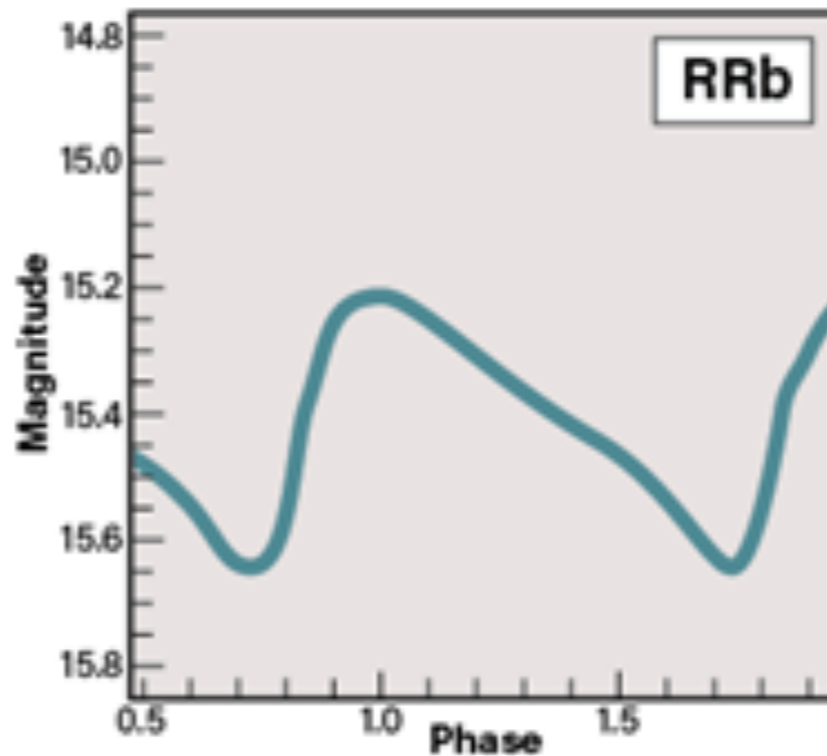
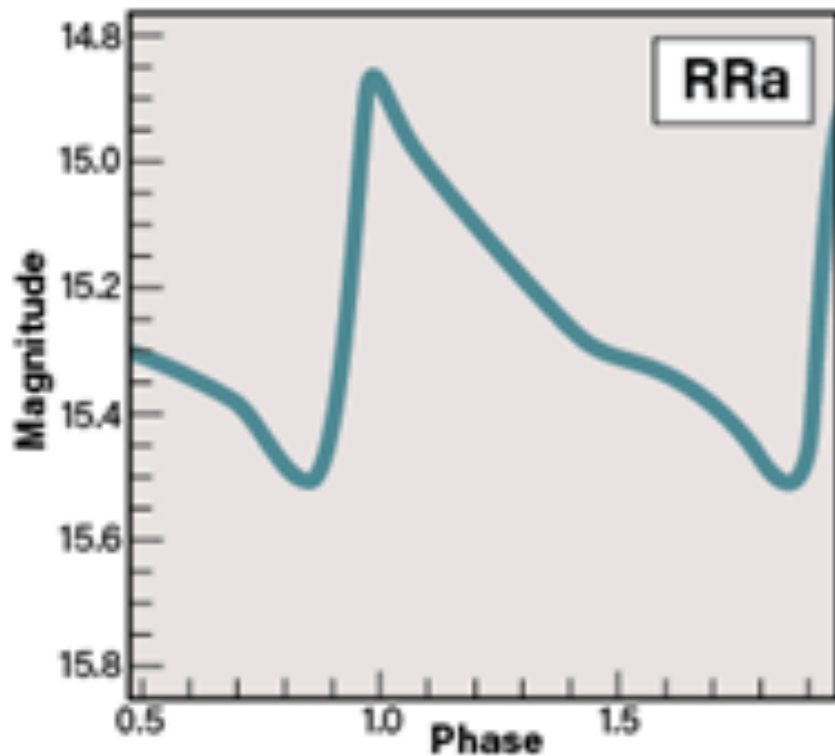
RR Lyrae - Shorter Periods

- 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: BOB KELLY



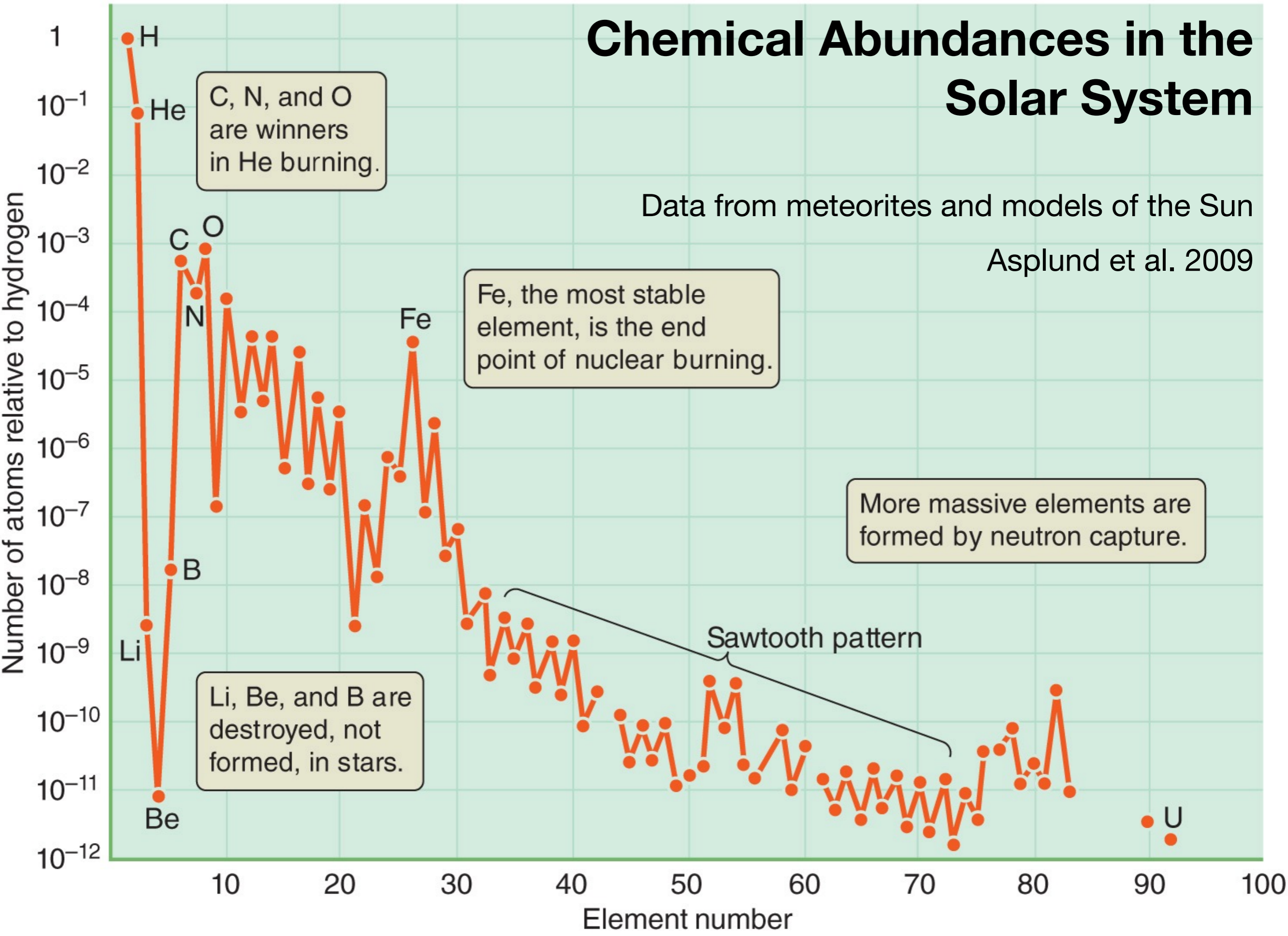
The Origin of Elements: from H to Fe

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

Chemical Abundances in the Solar System

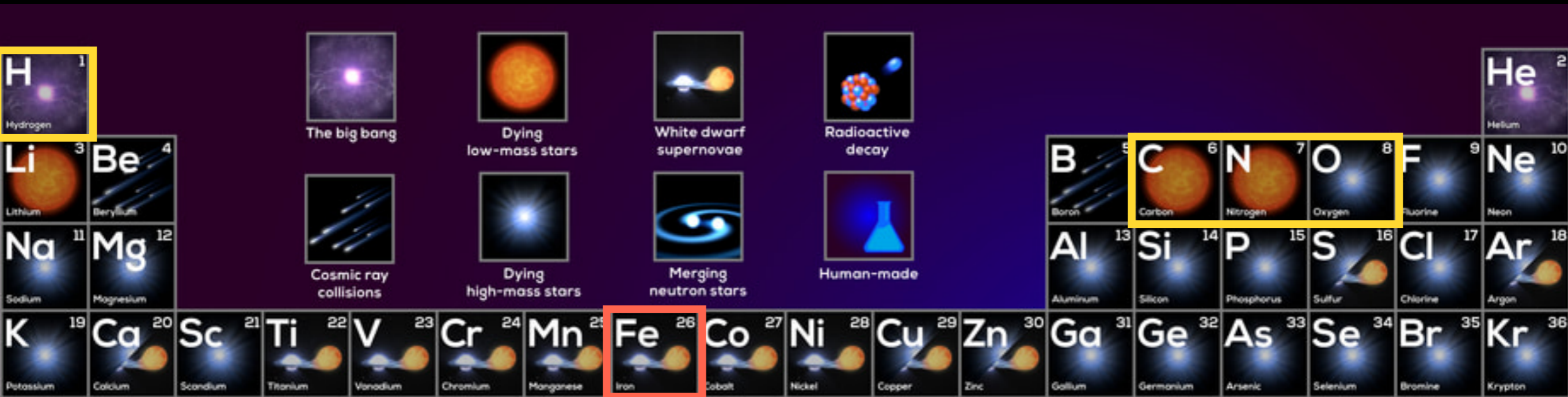
Data from meteorites and models of the Sun

Asplund et al. 2009



The Primary Origin of Each Element

(up to two main contributors are shown for each element)

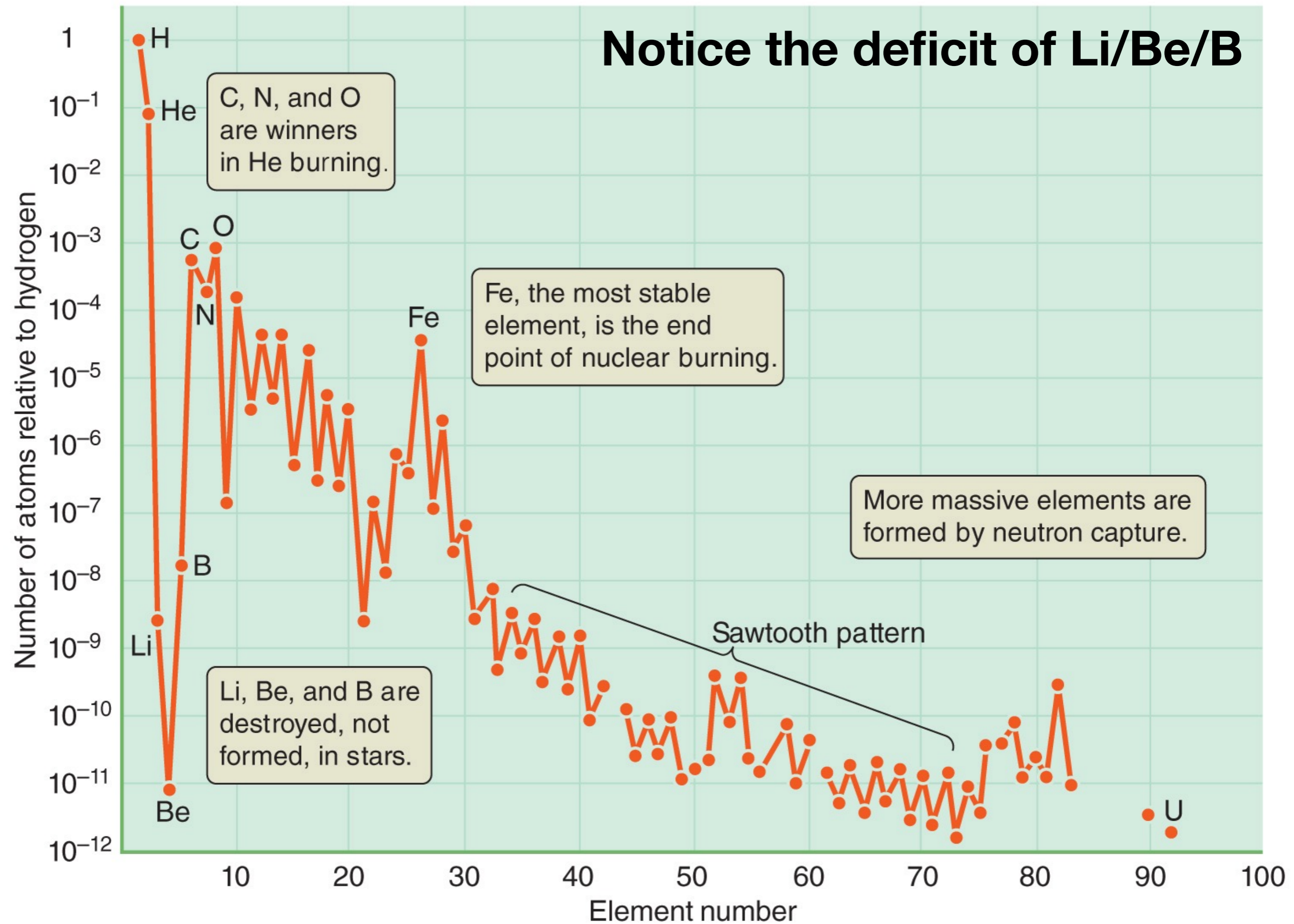


- The **hydrogen** atoms in water were created 13.7 billion years ago in the **Big Bang** ($t = 3 \text{ min}$, $T = 1e9 \text{ K}$, $\text{density} = 1e5 \text{ kg/m}^3$)
- The **oxygen** atoms in the air you breathe and the water you drink were created by nucleosynthesis in the cores of high mass stars and released into the ISM via **type II SNe**.
- The **carbon** atoms were formed in the cores of low-to-intermediate 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

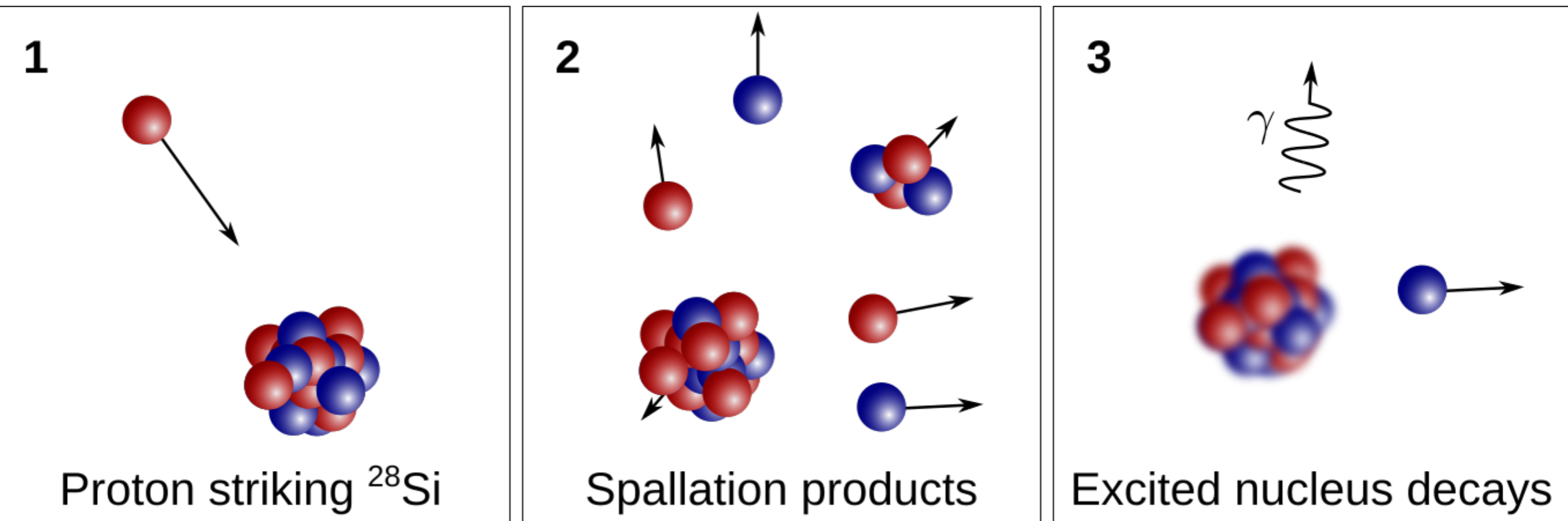
Classical Nova, AGB stars, and
Cosmic Ray Spallation

Notice the deficit of Li/Be/B



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., $n + {}^{14}\text{N} \rightarrow p + {}^4\text{He} + {}^{10}\text{Be}$, then ${}^{10}\text{Be} \rightarrow {}^{10}\text{B} + e^-$ (beta decay)



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

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

Classical Novae are powered by thermonuclear runaway on the surface of C/O White Dwarfs.

Helium burning shell in
an AGB star

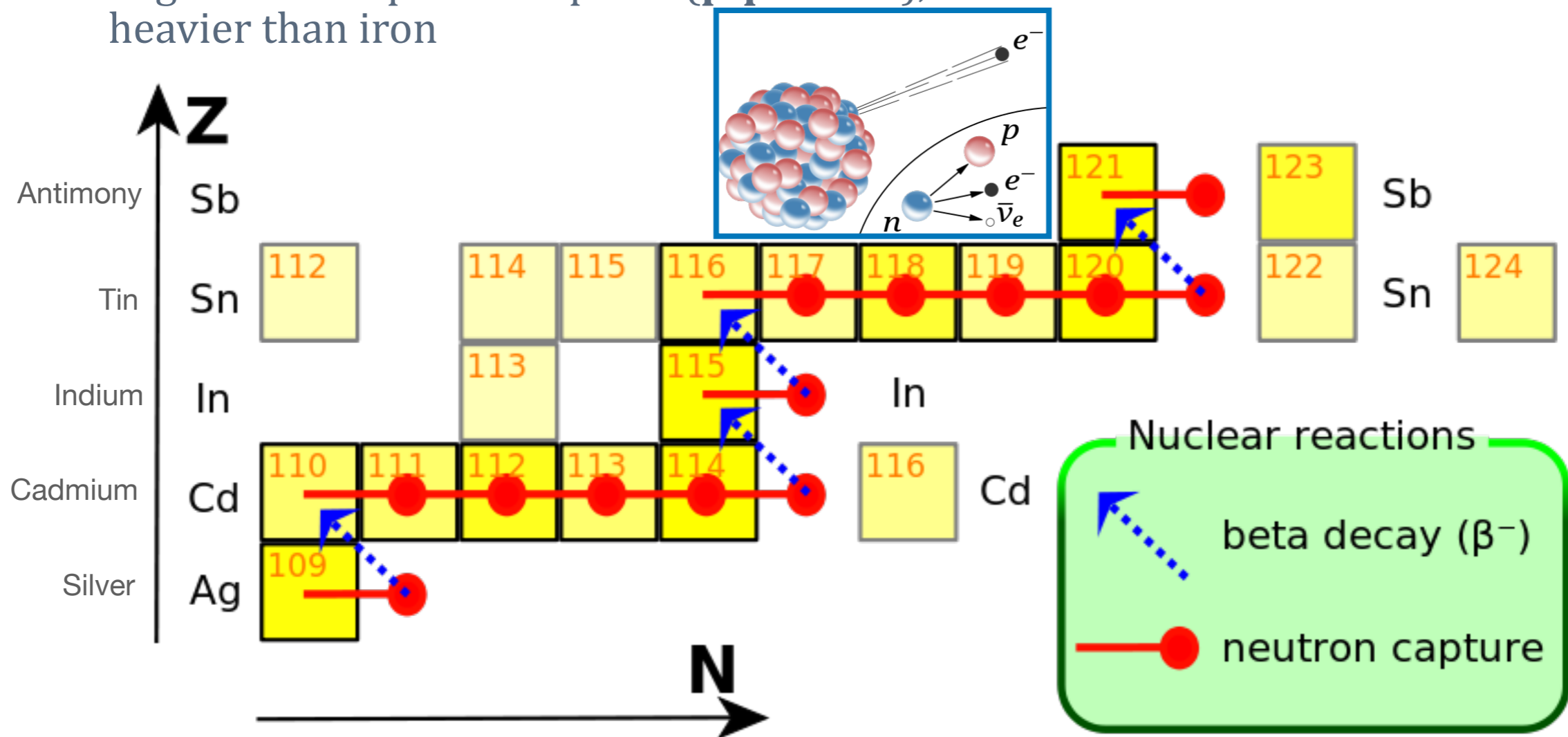
HARDY

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)
 - **neutron star mergers** (short Gamma-ray bursts), 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 $^{13}\text{C}(\alpha, n)^{16}\text{O}$ & $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$
 - Together with proton capture (**p-process**), makes the other half of the nuclei heavier than iron

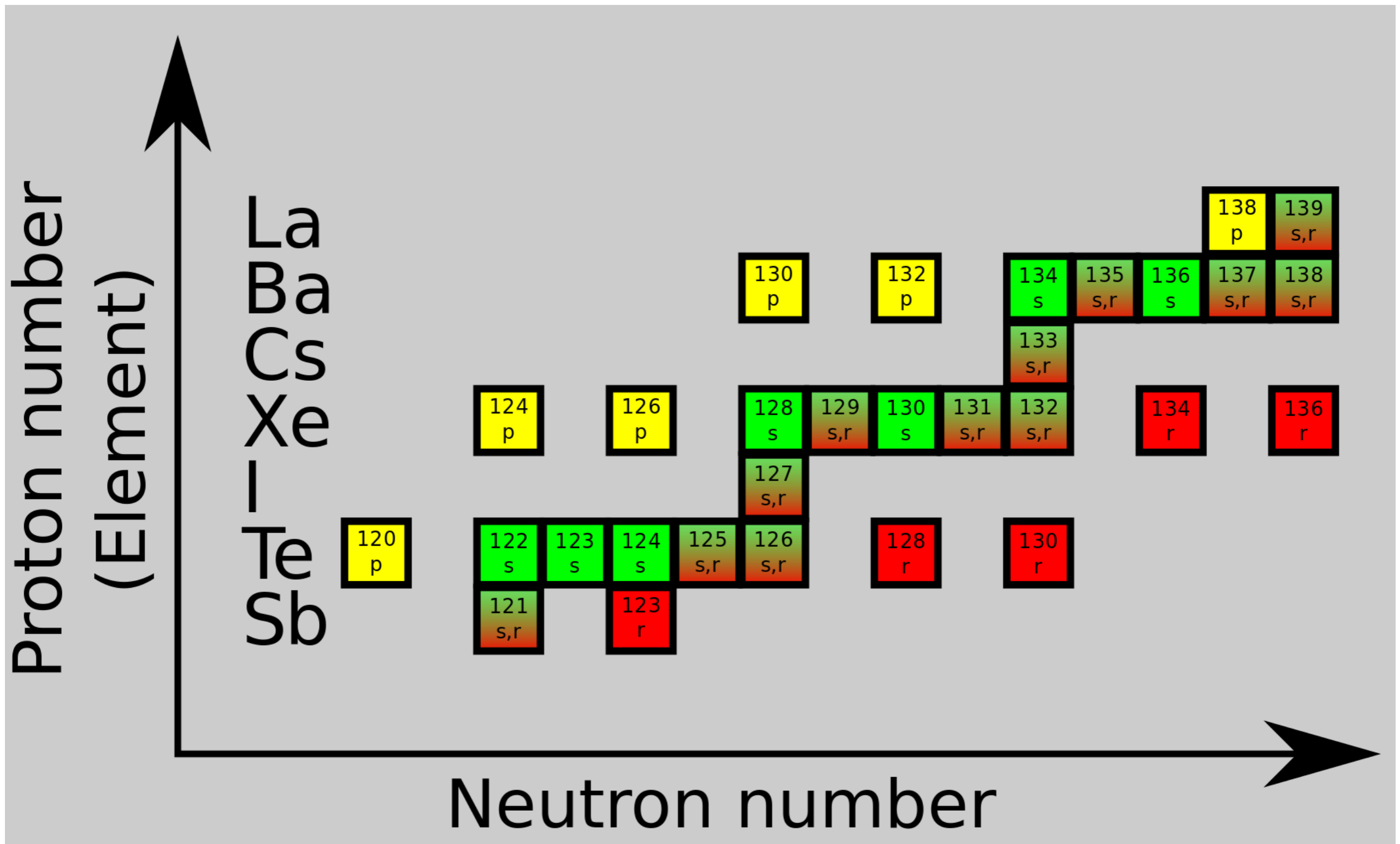


Neutron Star Merger: Gravitational Wave & Gamma-Ray Burst



The Proton Capture Process (p-process)

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

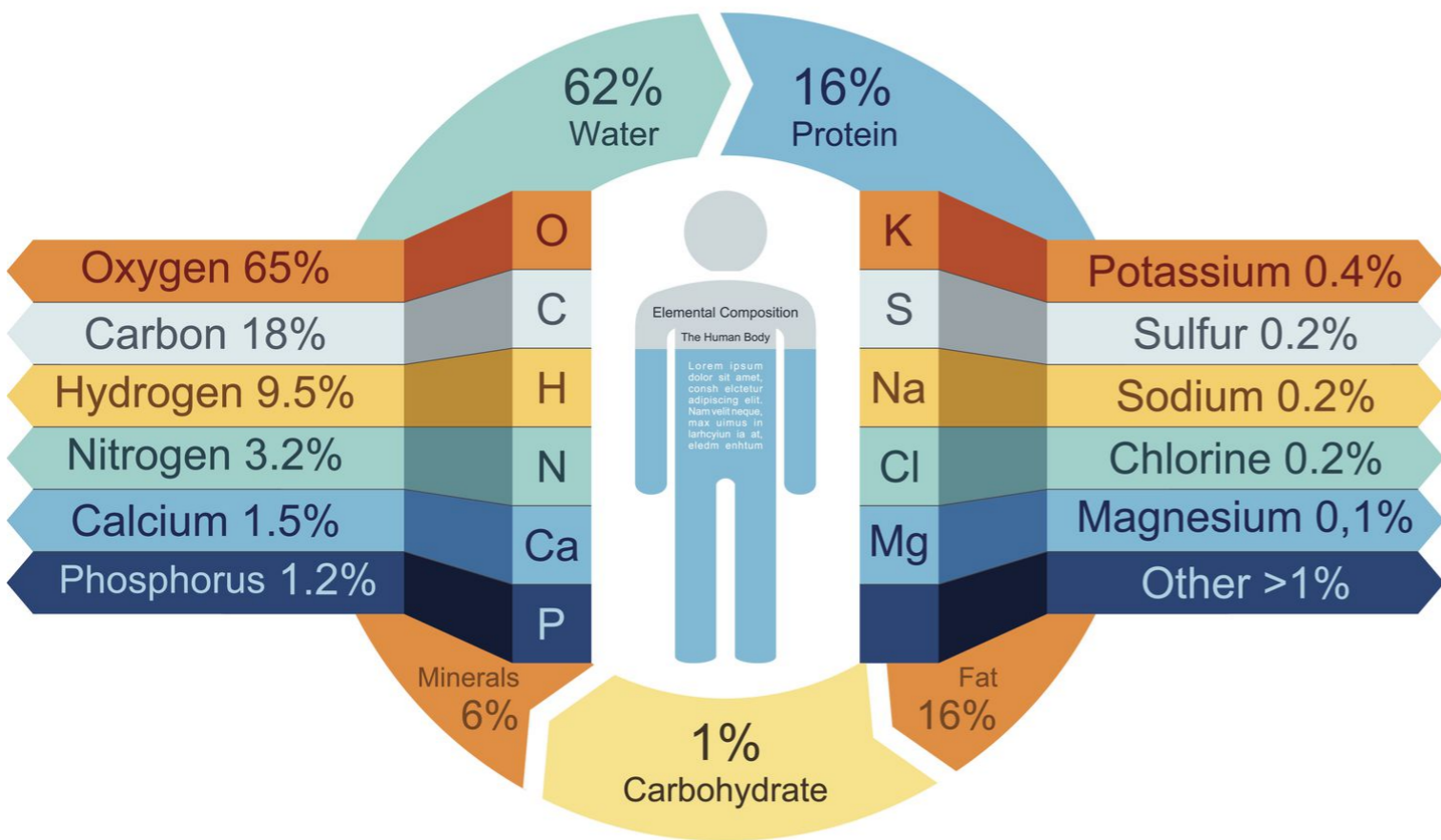


Summary: The Six Astrophysical Sources of Elements

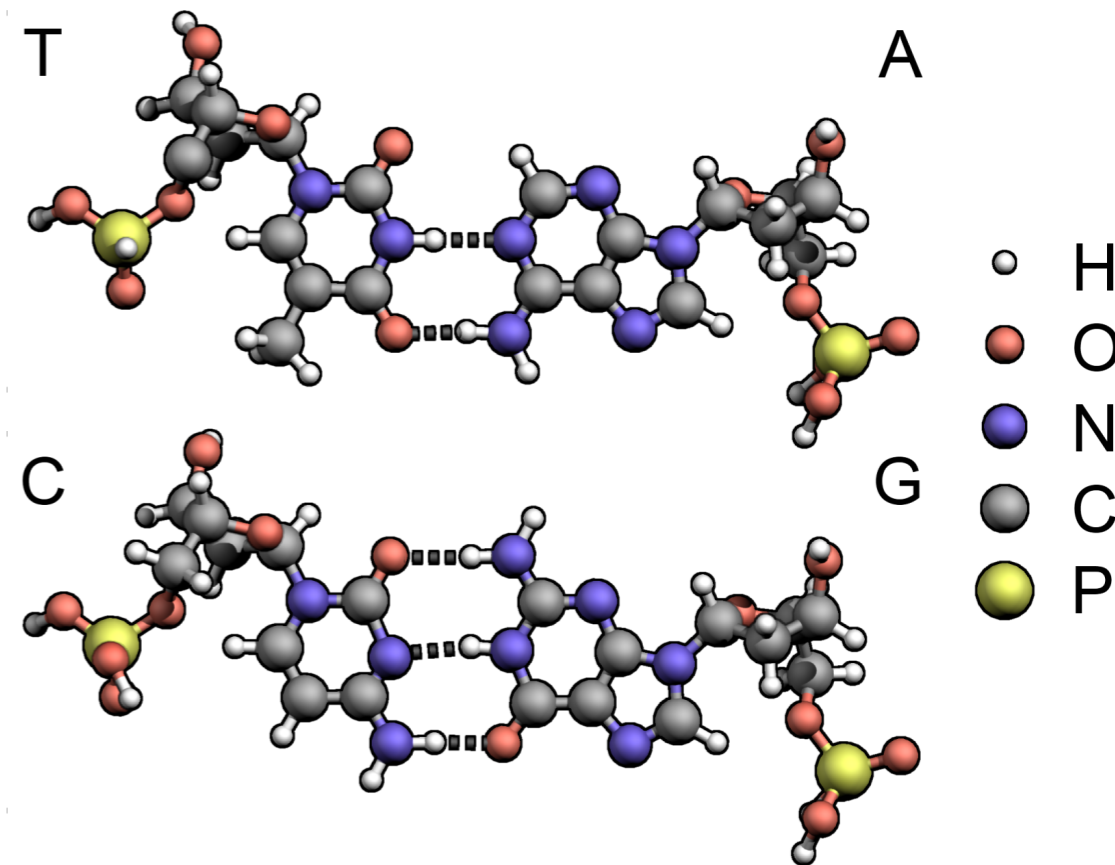
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|----------|--|--|----------|----------|----------|----------|--|---|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| 1 H | big bang fusion  | | | | | | cosmic ray fission  | | | | | | 2 He | | | | | | |
| 3 Li | 4 Be | merging neutron stars  | | | | | | exploding massive stars  | | | | | | 5 B | 6 C | 7 N | 8 O | 9 F | 10 Ne |
| 11 Na | 12 Mg | dying low mass stars  | | | | | | exploding white dwarfs  | | | | | | 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 | | | |

(top two/three main contributors are shown for each element)

THE HUMAN BODY



DNA



“We are all made of stardust” — Carl Sagan

Chemical Abundances in the Solar System

Data from meteorites and models of the Sun

Asplund et al. 2009

