ASTR20A:
Introduction to Astrophysics I

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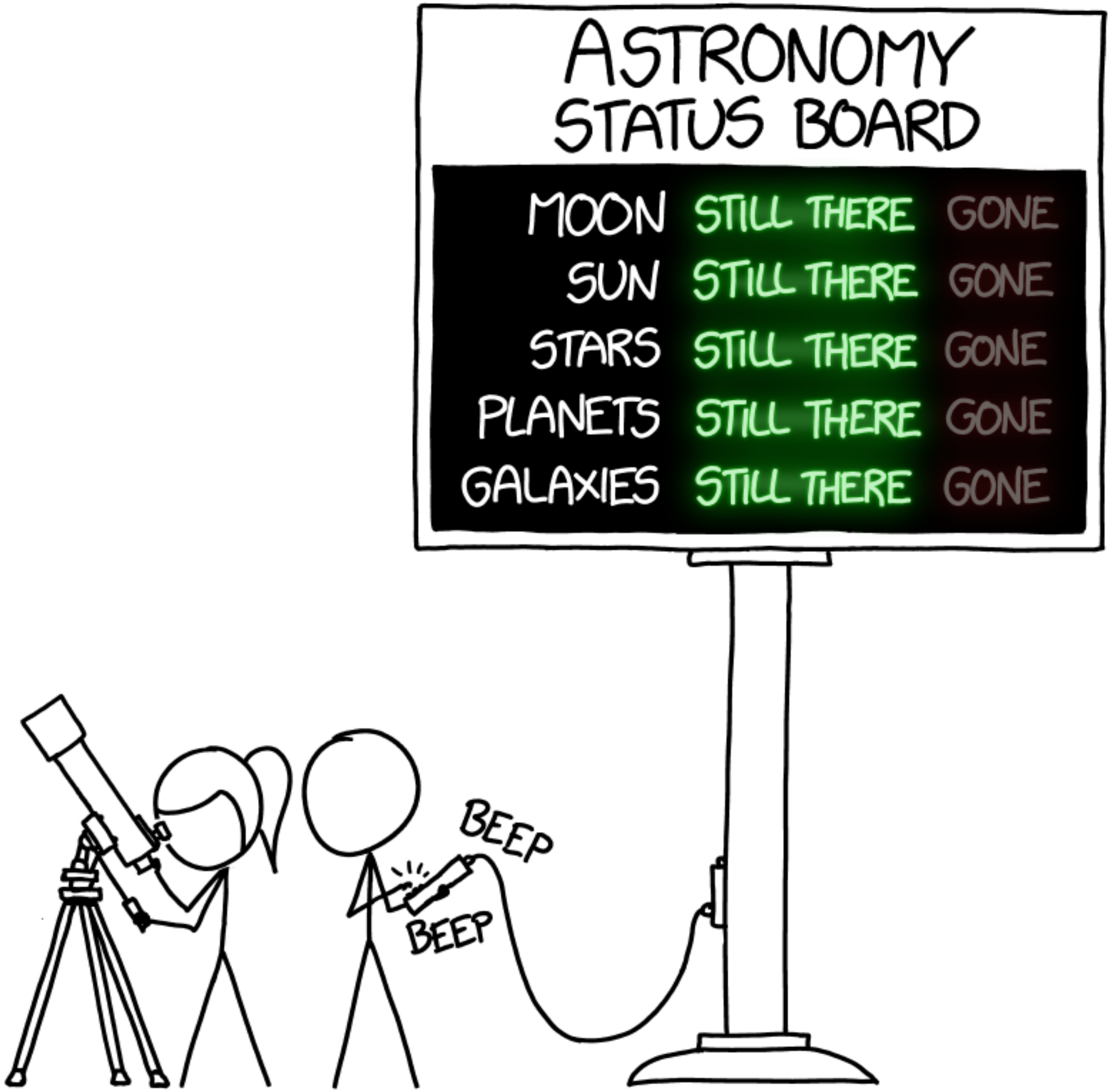
Lecture 17 | Stellar Interiors

Thursday, December 04, 2025

Announcements

- HW #8 will be due **tonight, 12/04 by 11:59 pm.**
- Final Exam is **Thursday, 12/11 from 3:00pm-5:59pm.**
- **Student Evaluation of Teaching Survey** is available until **Saturday, December 6 at 8:00 AM.**



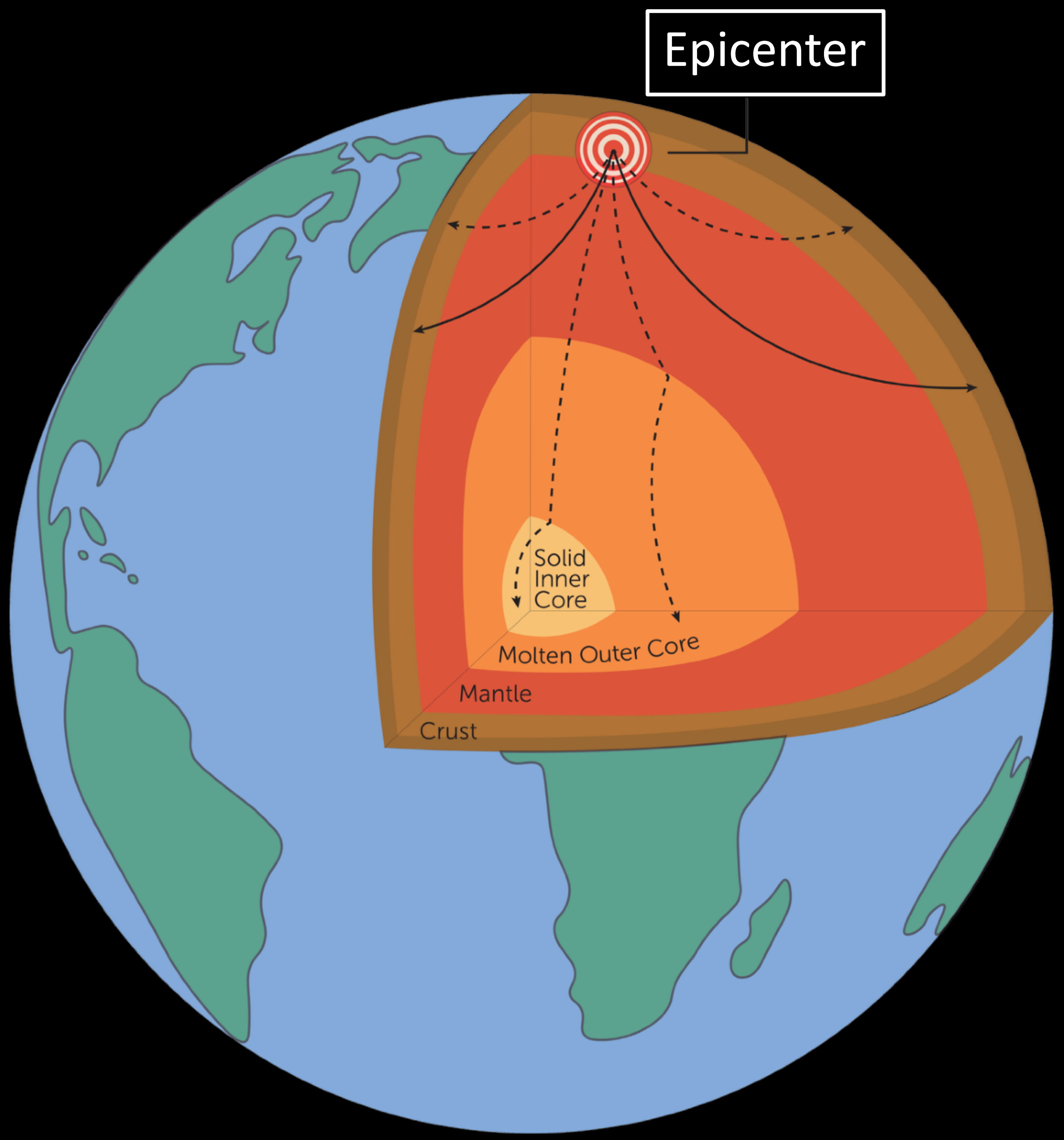
Learning Objectives

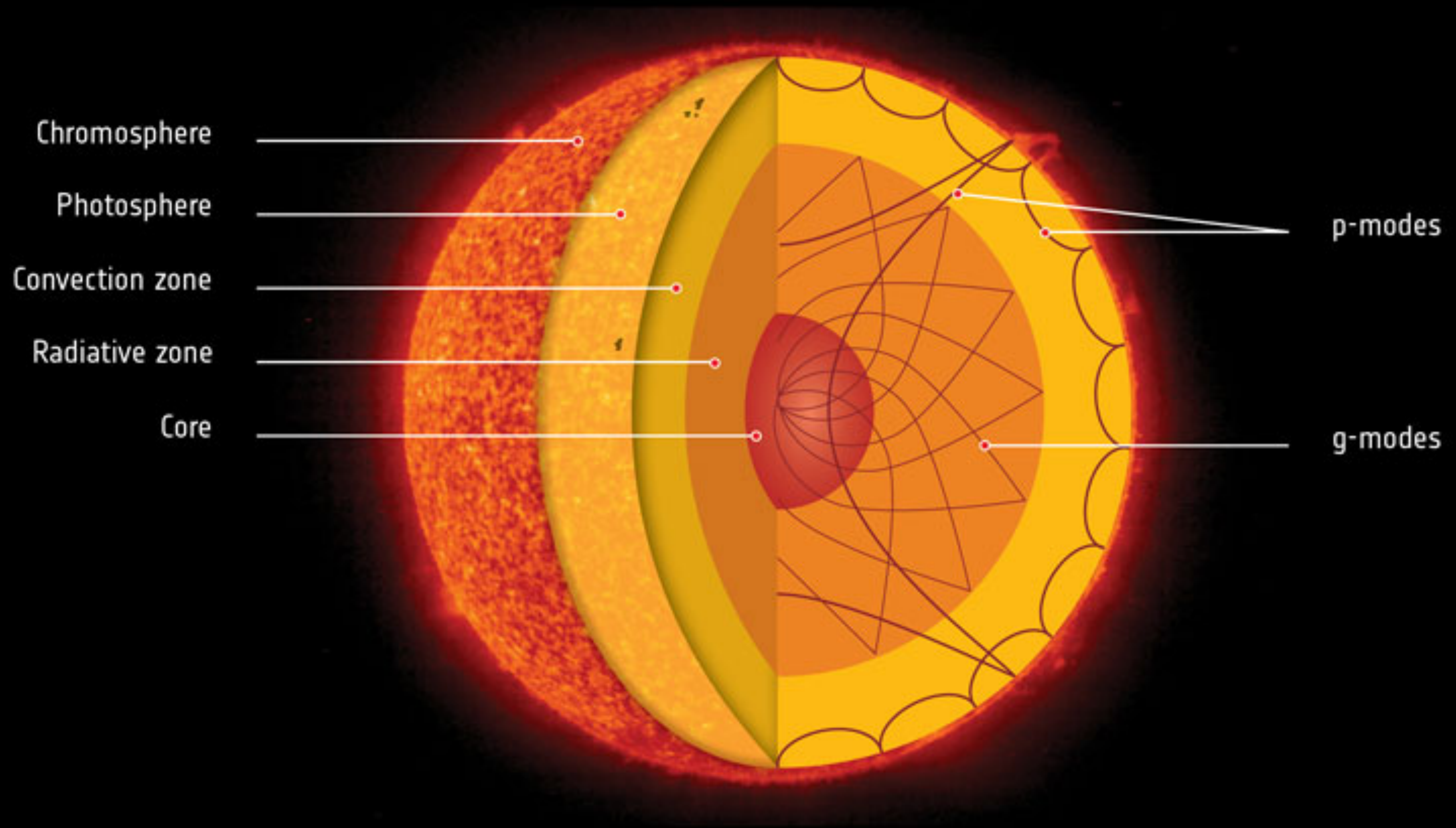
By the end of today's lecture you will be able to:

- Explain the differences between *radiative* and *convective* energy transport and identify the stellar conditions where each mechanism dominates.
- Describe the dominant fusion process in *Sun-like stars* and the conditions under which it occurs.
- Describe the dominant fusion process in stars *more massive than the Sun* and the conditions under which it occurs.
- Explain the *triple-alpha process* and its role in helium fusion in evolved stars.

Probing the Sun’s Interior

Similar to how *seismologist* study the interior of Earth by analyzing seismic waves, *helioseismologists* study the interior of the Sun from observations of the vibrations of the surface.





How is energy transported in stars?

Photons are created primarily in the cores of stars, *but* they have to traverse outwards to be observed.

Energy is transported through a few different methods depending on the structure of the star at a given layer/radius.

In general, how energy is transported within a star comes down to one simple question,

"What is *most efficient way to transport the energy at any given layer?"**

*leads to the smaller temperature gradient.

Radiative Transport

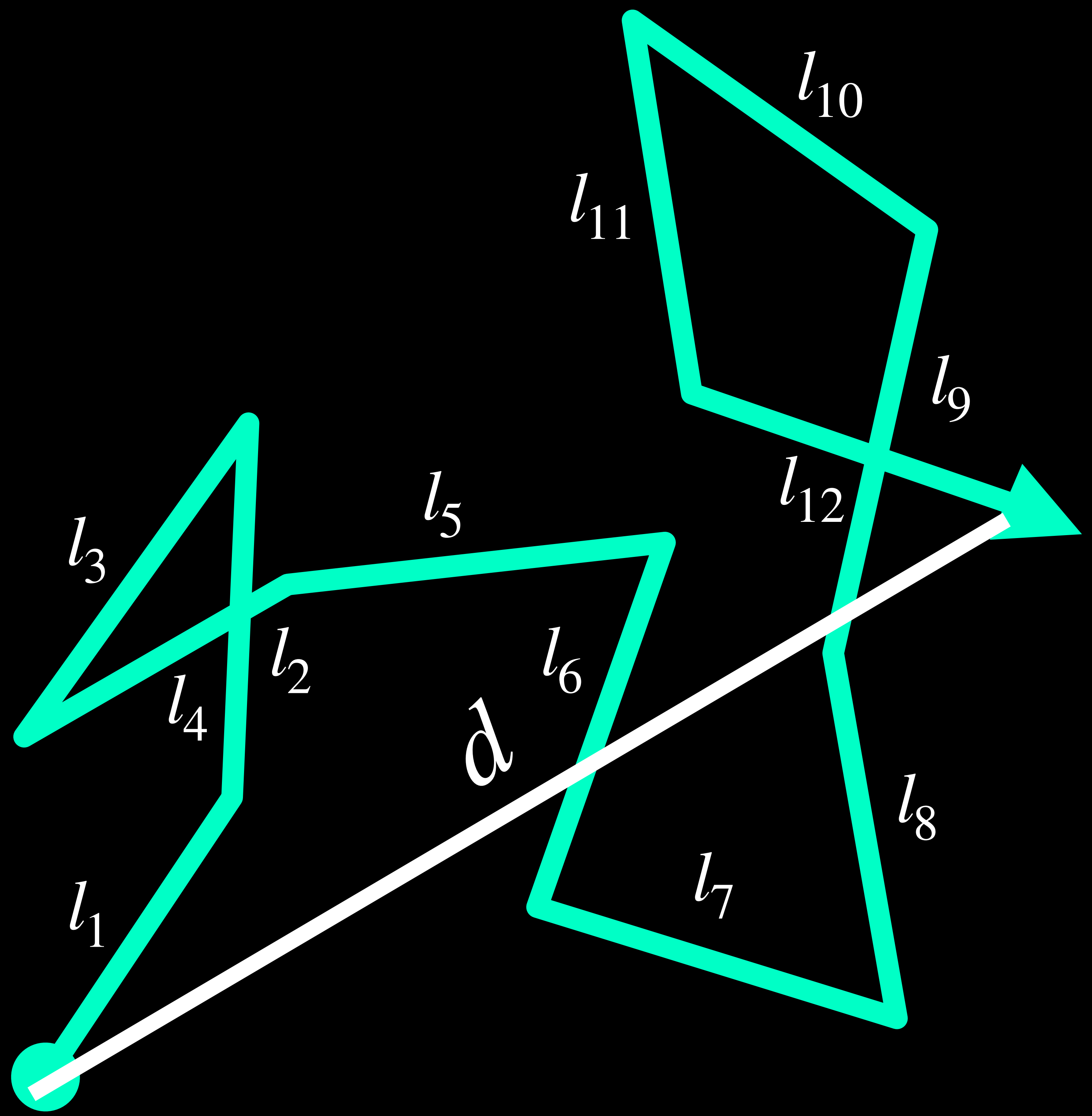
A photon created in the Sun's core does a "**random walk**", repeatedly being absorbed and re-emitted, until they eventually escape at the photosphere."

If we consider that the photon will take N steps, each of length l, then the *mean-squared displacement* d is

$$d = l\sqrt{N}$$

where l can be approximated as the *mean free path of the photon.*

Illustration of Random Walk



The efficiency of this process is linked to the number density of absorbers. If a photon is frequently absorbed (i.e., if opacity is high), the efficiency of radiative transport is low.

A photon must travel from the center of the Sun to the photosphere ($R_{\odot} = 7 \times 10^{10}$ cm). Each step is 1.5 cm before being absorbed and re-emitted. Approximately how many steps does it take for the photon to escape?

10^{12}

0%

10^{21}

0%

10^{18}

0%

10^{16}

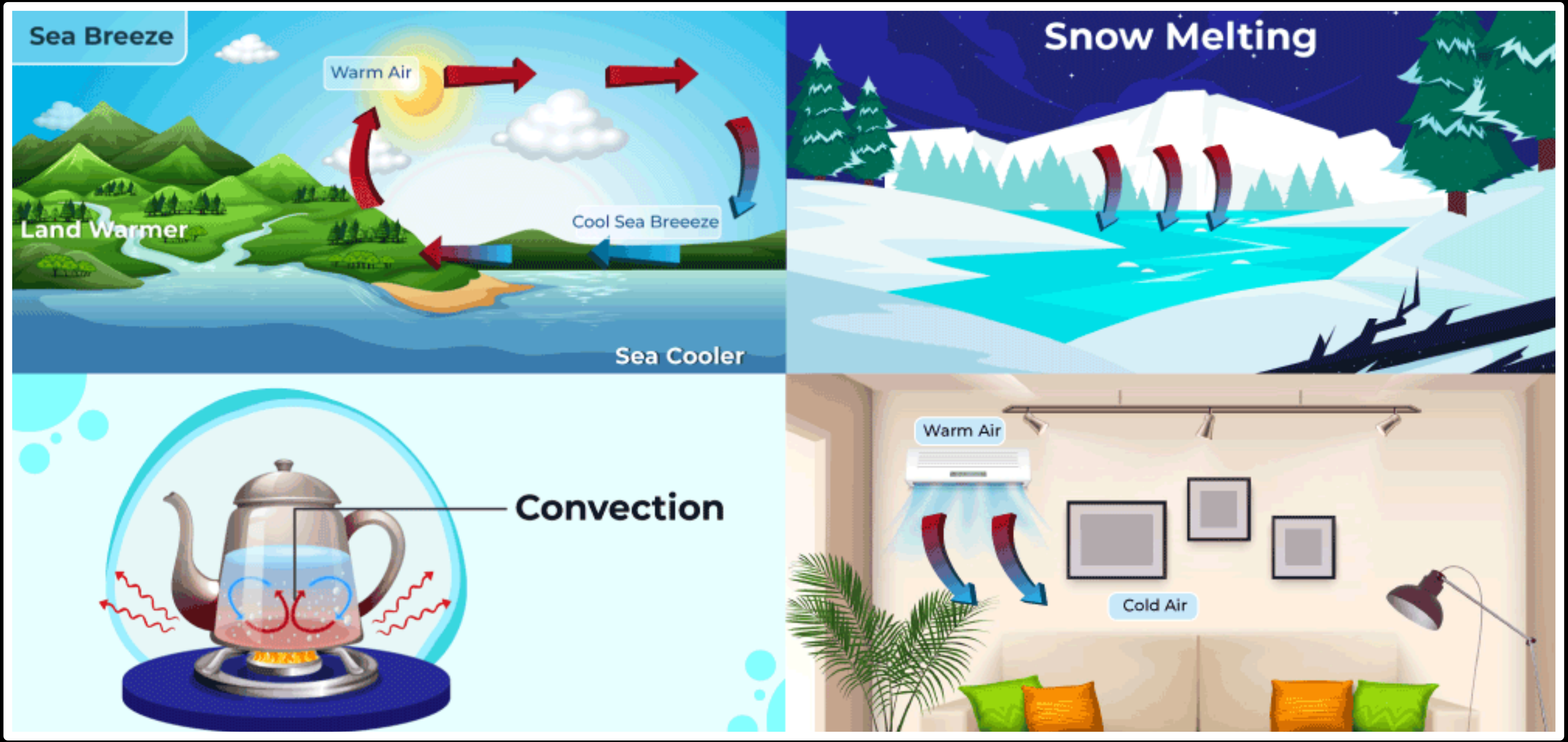
0%

A photon must travel from the center of the Sun to the photosphere ($R_\odot = 7 \times 10^{10}$ cm). Each step is 1.5 cm before being absorbed and re-emitted. Approximately how many steps does it take for the photon to escape?

10^{12}	0%
10^{21}	100%
10^{18}	0%
10^{16}	0%

Convective Transport

Convection occurs when **hot material rises, cools, and sinks back down.**

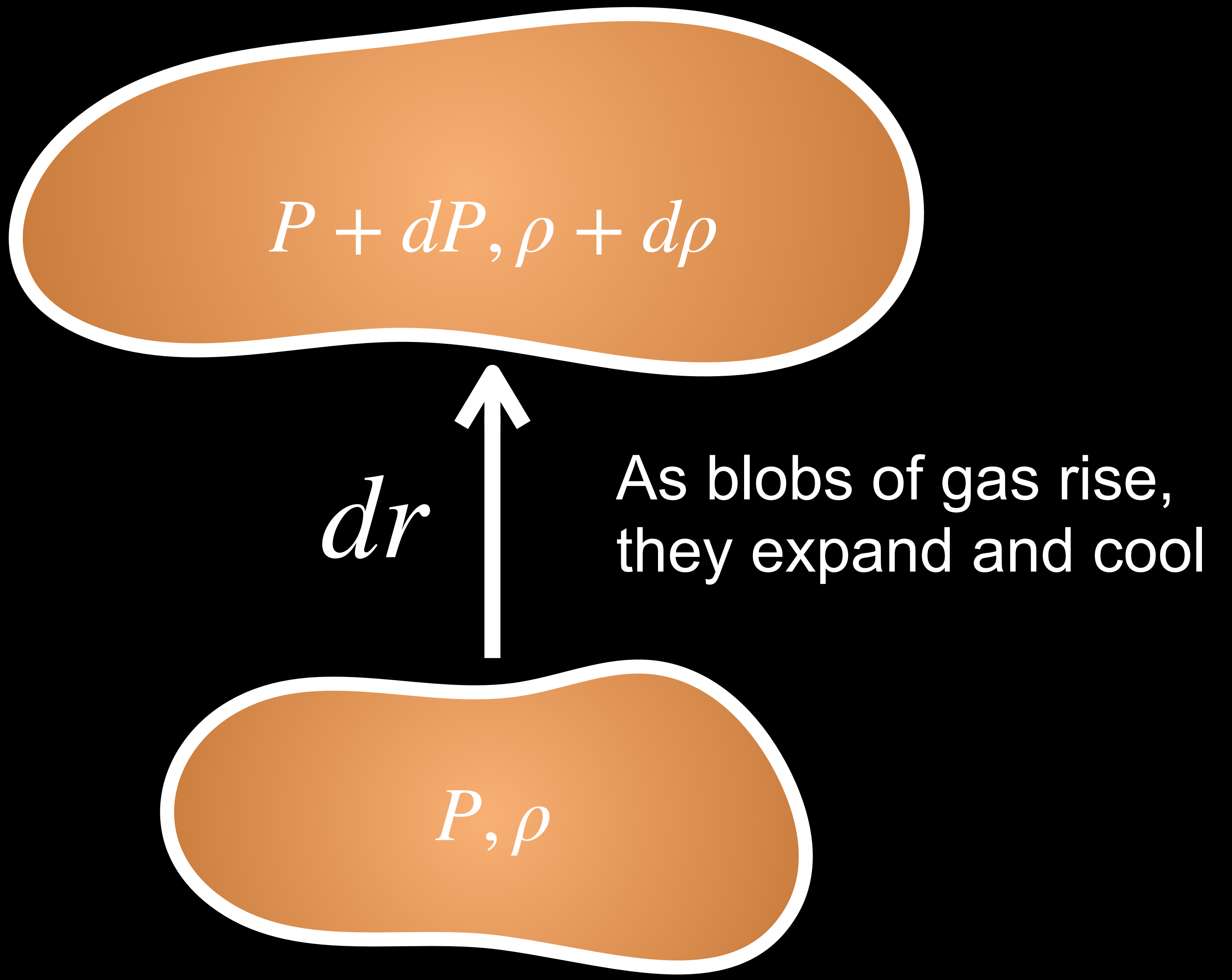


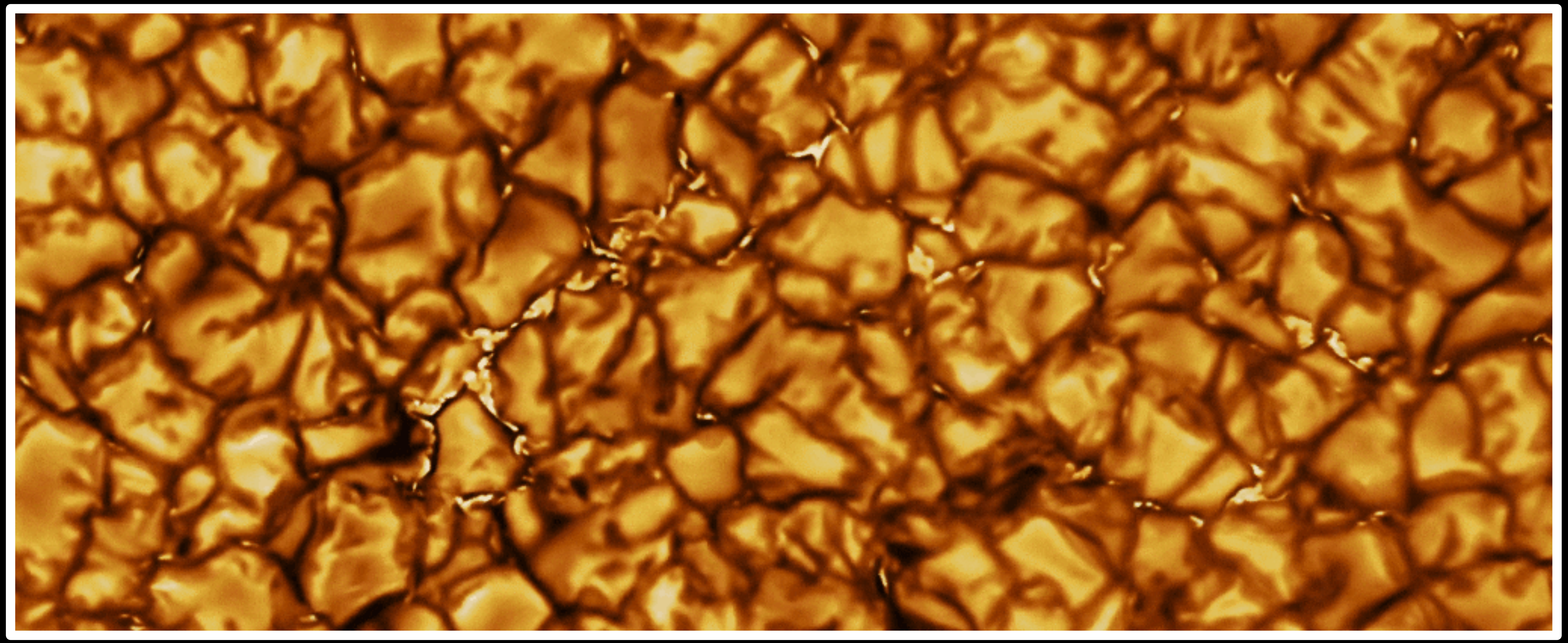
This is a driving force between many processes we see every day

Convective Transport

At some point the Sun becomes almost completely opaque (optical depth tends toward infinity). In this case, it is not possible for energy to move outwards through radiative transfer in these layers.

Instead, the energy is transferred through **convection**.



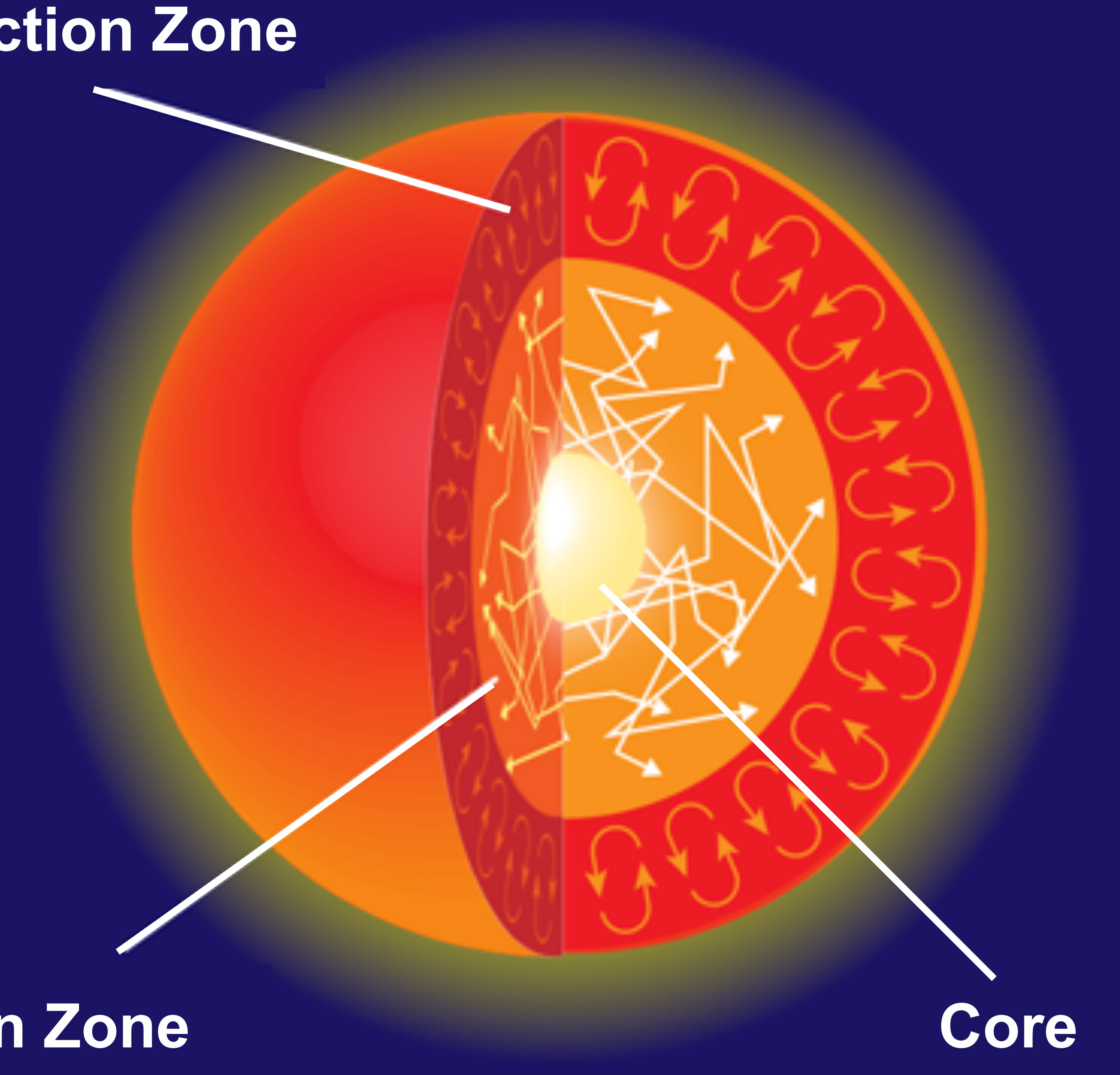


Convection - cells of hot gas move up, cells of cool gas move down

Structure of the Sun's Interior

In the Sun, energy transport is divided into regions where it is the most efficient method.

- **Core:** The innermost region of the Sun where nuclear fusion occurs, extending from the center out to $0 - 0.2\ R_\odot$
- **Radiation zone:** the layer where energy is transported primarily by radiation because the opacity is low enough, extending roughly from $0.2 - 0.7\ R_\odot$
- **Convection zone:** The outer layer where opacity is high and energy is transported by convection, extending from $0.7 - 1.0\ R_\odot$

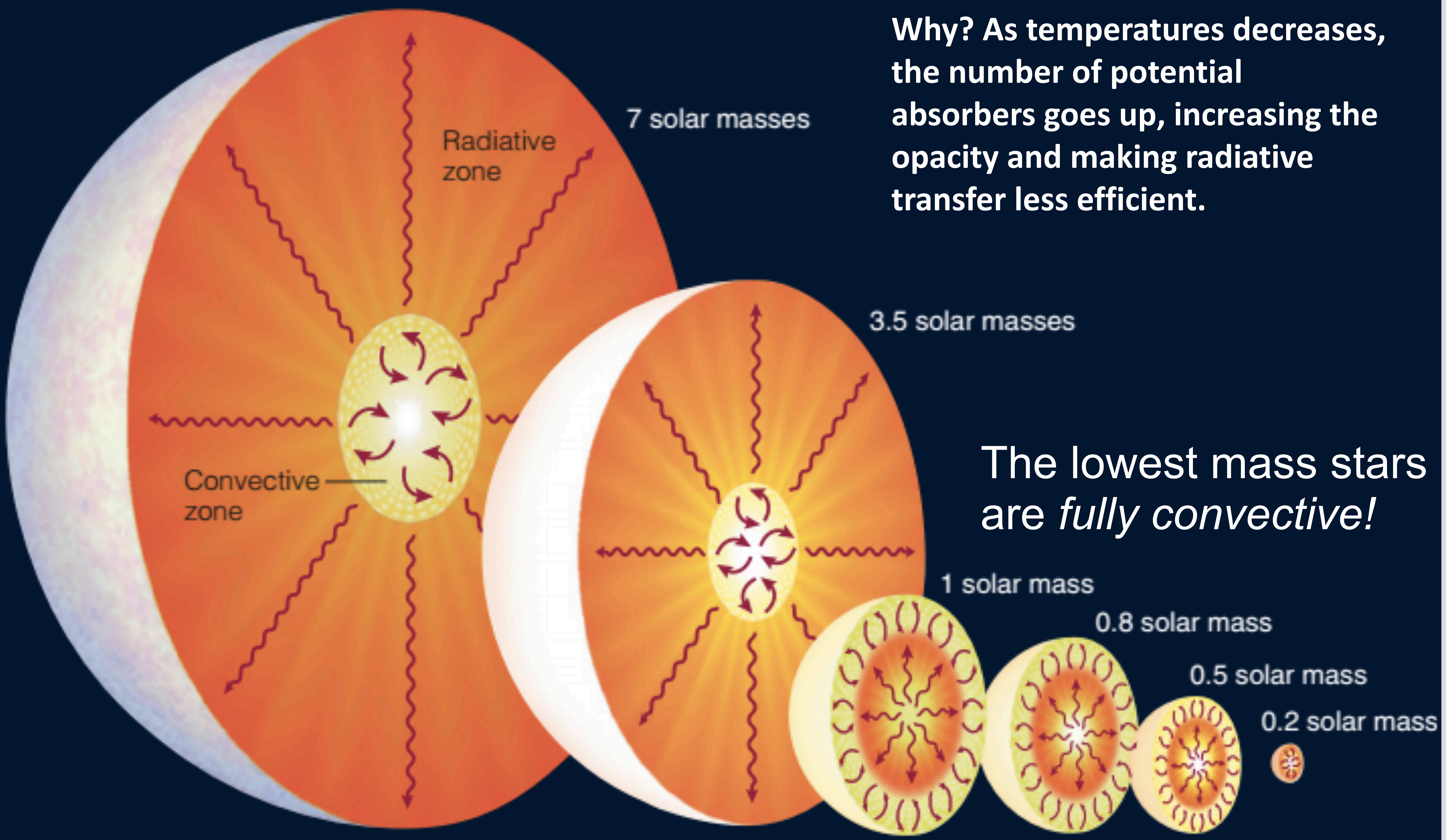


Most of the energy in the Sun is transported through radiation.

Structure of the Sun's Interior

The efficiency of energy transport depends on stellar mass.

The most massive stars have *convective interiors* and *radiative envelopes.*



Why? As temperatures decreases, the number of potential absorbers goes up, increasing the opacity and making radiative transfer less efficient.

The lowest mass stars are *fully convective!*

As we'll see, high mass stars are

Pause

The Proton-Proton Chain

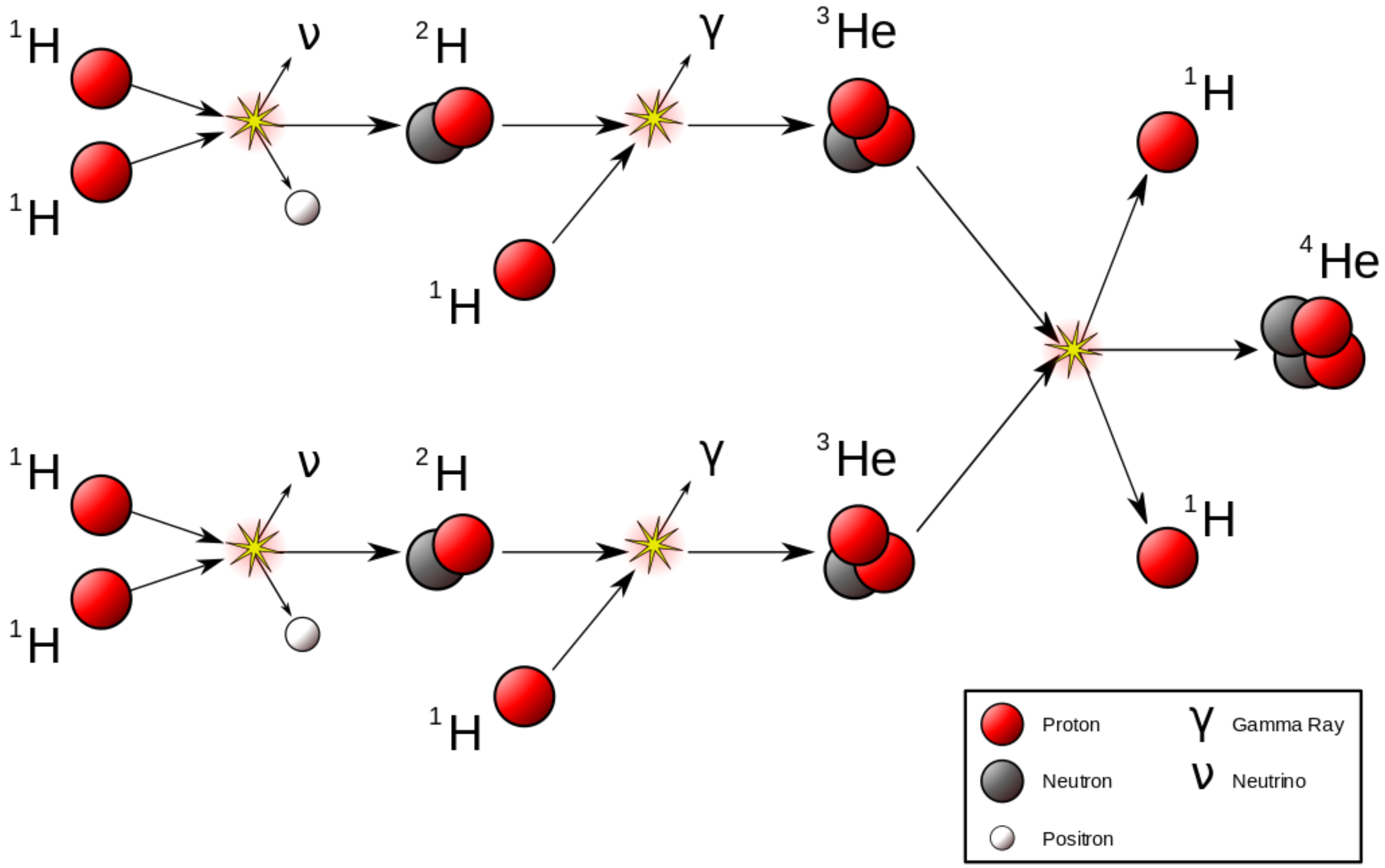
This is the dominant fusion process in *stars like the Sun,* where core temperatures are ***less* than 18 million Kelvin.**

$$\boxed{p} + \boxed{p} \longrightarrow {}^2\mathrm{H} + e^+ + \nu_e \text{ (twice)}$$

$$ {}^2\mathrm{H} + p \longrightarrow {}^3\mathrm{He} + \gamma \text{ (twice)}$$

$$ {}^3\mathrm{He} + {}^3\mathrm{He} \longrightarrow \boxed{{}^4\mathrm{He}} + p + p$$

Net result: $4p \rightarrow {}^4\mathrm{He} + 2e^+ + 2\nu_e + 2\gamma$



Terminology:

Positron (e^+)**:** *antiparticle* of the electron, having the same mass but the opposite positive charge.

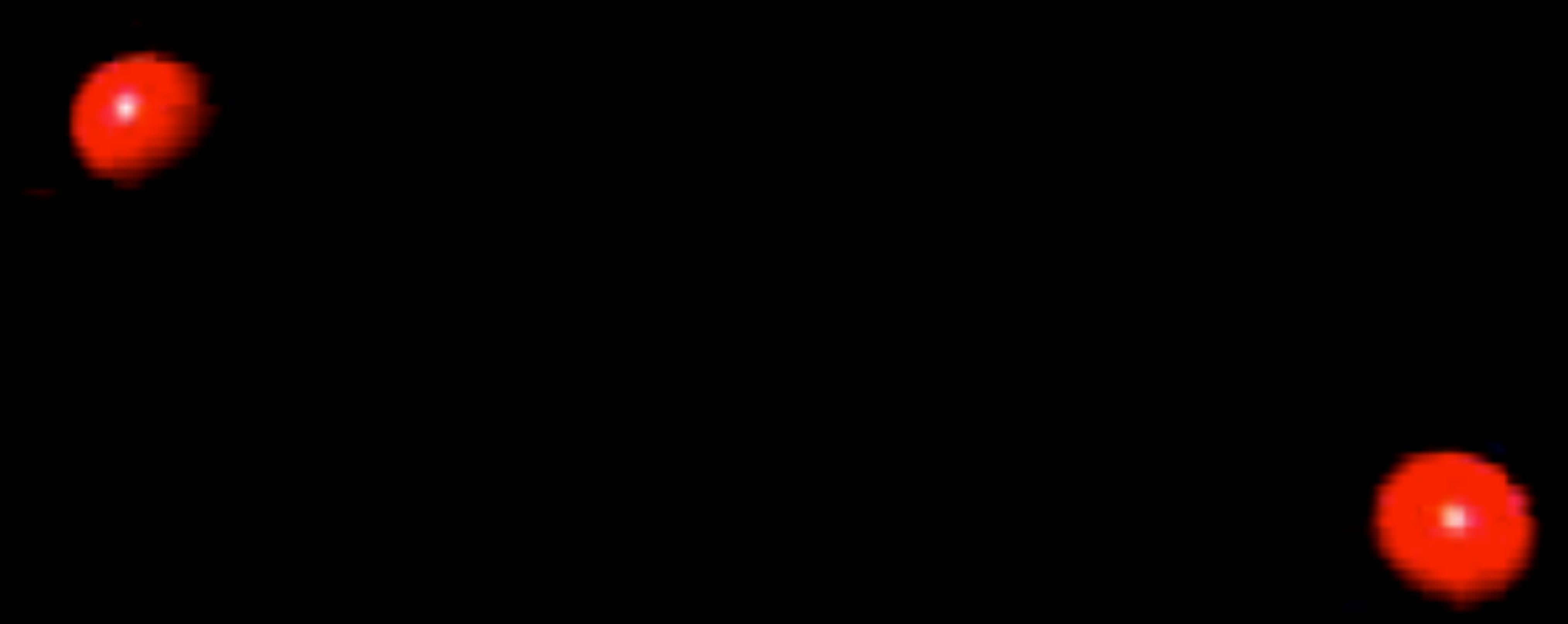
Electron neutrino (ν_e)**:** very light, electrically neutral particle that *rarely* interact with matter.

Gamma ray (γ): very high energy photon created from annihilation of electron with positron.

Deuterium $({}^2\mathrm{H})$: a stable isotope of hydrogen with a nucleus containing one proton and one neutron.

The Proton-Proton Chain

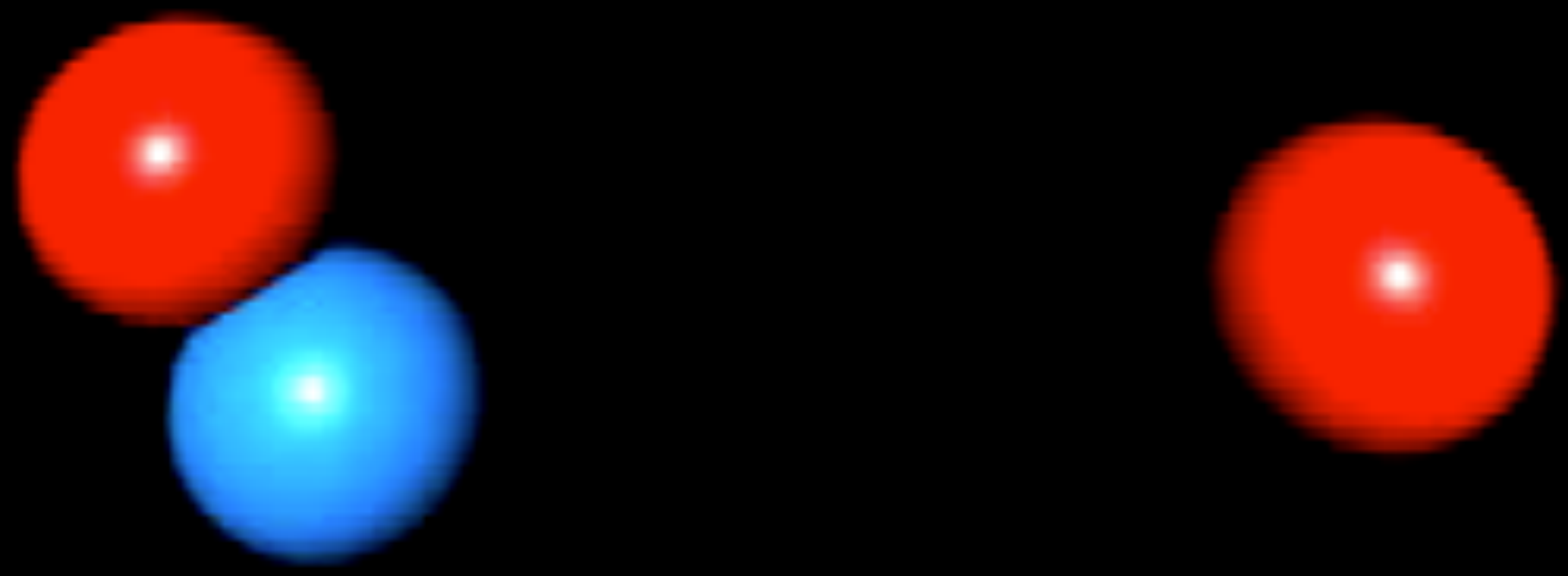
Step 1: Smash two protons together to make deuterium



$$p + p \rightarrow {}^{2}\mathrm{H} + e^{+} + \nu_{e}$$

The Proton-Proton Chain

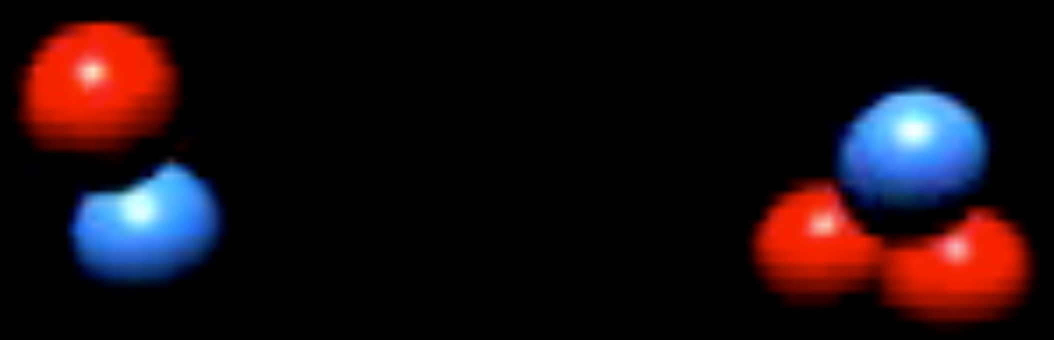
Step 2: A proton slams into a deuterium nucleus, making helium-3



$$^{2}\mathrm{H} + \mathrm{p} \rightarrow {}^{3}\mathrm{He} + \gamma$$

The Proton-Proton Chain

Step 3: Smash two helium-3 nuclei together to make helium-4



$$^{3}\mathrm{He} + {}^{3}\mathrm{He} \rightarrow {}^{4}\mathrm{He} + \mathrm{p} + \mathrm{p}$$

The Proton-Proton Chain

The former reaction is known as the **PPI reaction**. It is the *most common pathway* for producing helium in the Sun (occurring 69% of the time), but it is not the only one.

PPII Chain

$$^{3}\mathrm{He} + {}^{4}\mathrm{He} \rightarrow {}^{7}\mathrm{Be} + \gamma$$

$$^{7}\mathrm{Be} + e^{-} \rightarrow {}^{7}\mathrm{Li} + \nu_e$$

$$^{7}\mathrm{Li} + {}^{1}\mathrm{H} \rightarrow 2\,{}^{4}\mathrm{He}$$

Occurs ~31% of the time

PPIII Chain

$$^{7}\mathrm{Be} + {}^{1}\mathrm{H} \rightarrow {}^{8}\mathrm{B} + \gamma$$

$$^{8}\mathrm{B} \rightarrow {}^{8}\mathrm{Be} + e^{+} + \nu_e$$

$$^{8}\mathrm{Be} \rightarrow 2\,{}^{4}\mathrm{He}$$

Occurs ~0.3% of the time.

Carbon-Nitrogen-Oxygen (CNO) Cycle

This is the dominant fusion process in stars more massive than the Sun, where core temperatures are ***greater*** **than 18 million Kelvin.**

$$\boxed{{}^{12}\mathrm{C}} + p \rightarrow {}^{13}\mathrm{N} + \gamma$$

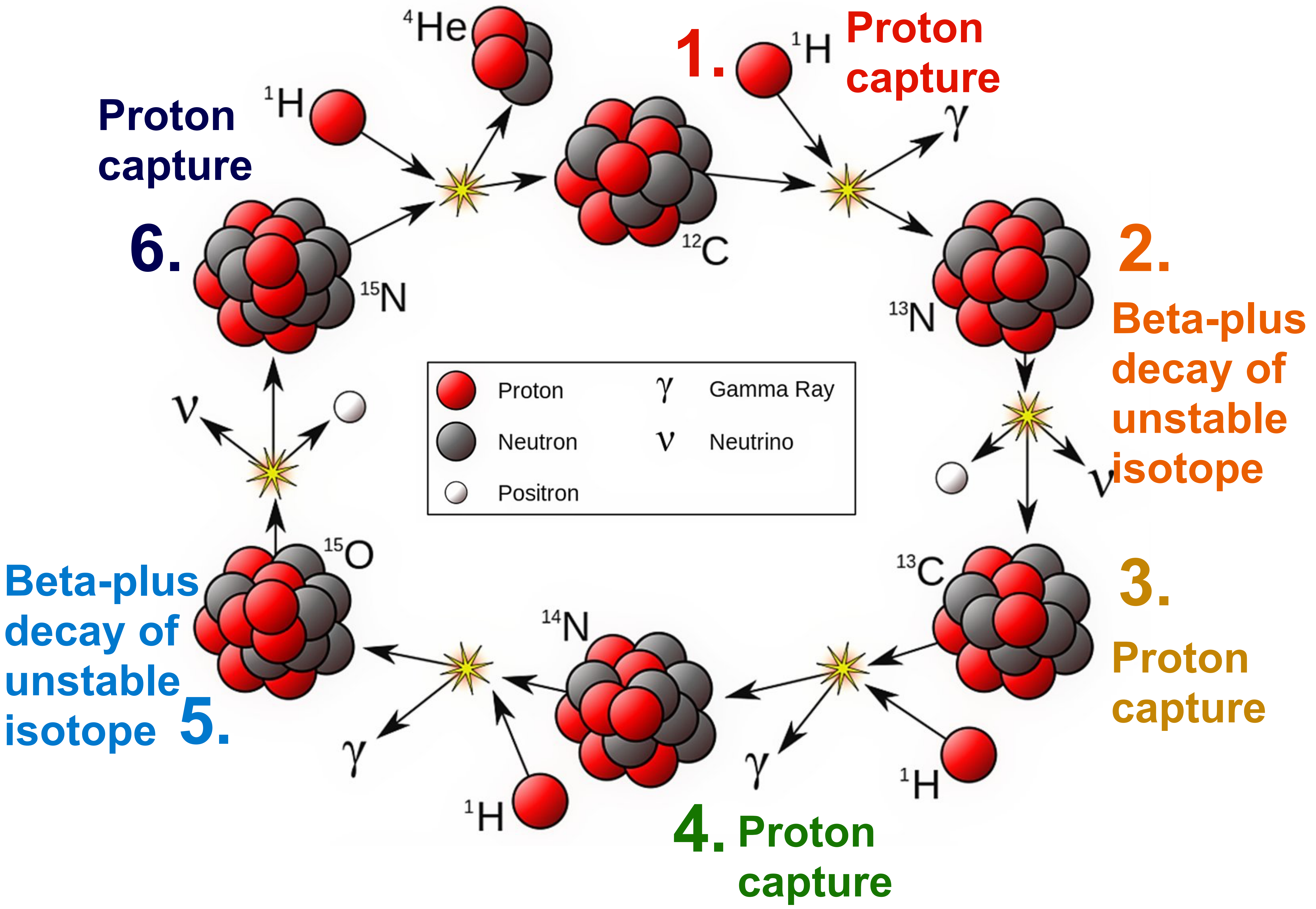
$${}^{13}\mathrm{N} \rightarrow {}^{13}\mathrm{C} + e^{+} + \nu_e$$

$${}^{13}\mathrm{C} + p \rightarrow {}^{14}\mathrm{N} + \gamma$$

$${}^{14}\mathrm{N} + p \rightarrow {}^{15}\mathrm{O} + \gamma$$

$${}^{15}\mathrm{O} \rightarrow {}^{15}\mathrm{N} + e^{+} + \nu_e$$

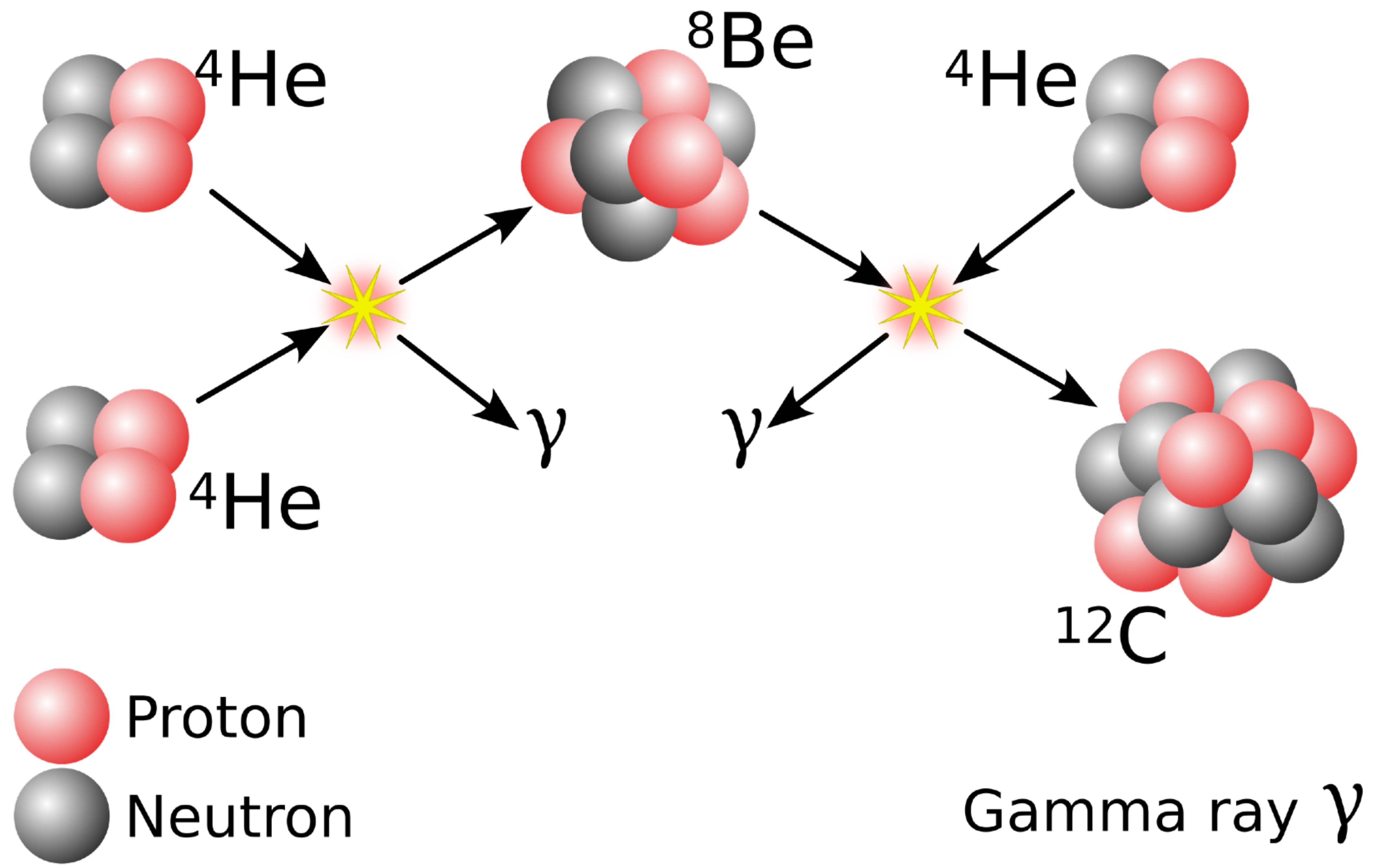
$${}^{15}\mathrm{N} + p \rightarrow \boxed{{}^{12}\mathrm{C}} + {}^{4}\mathrm{He}$$

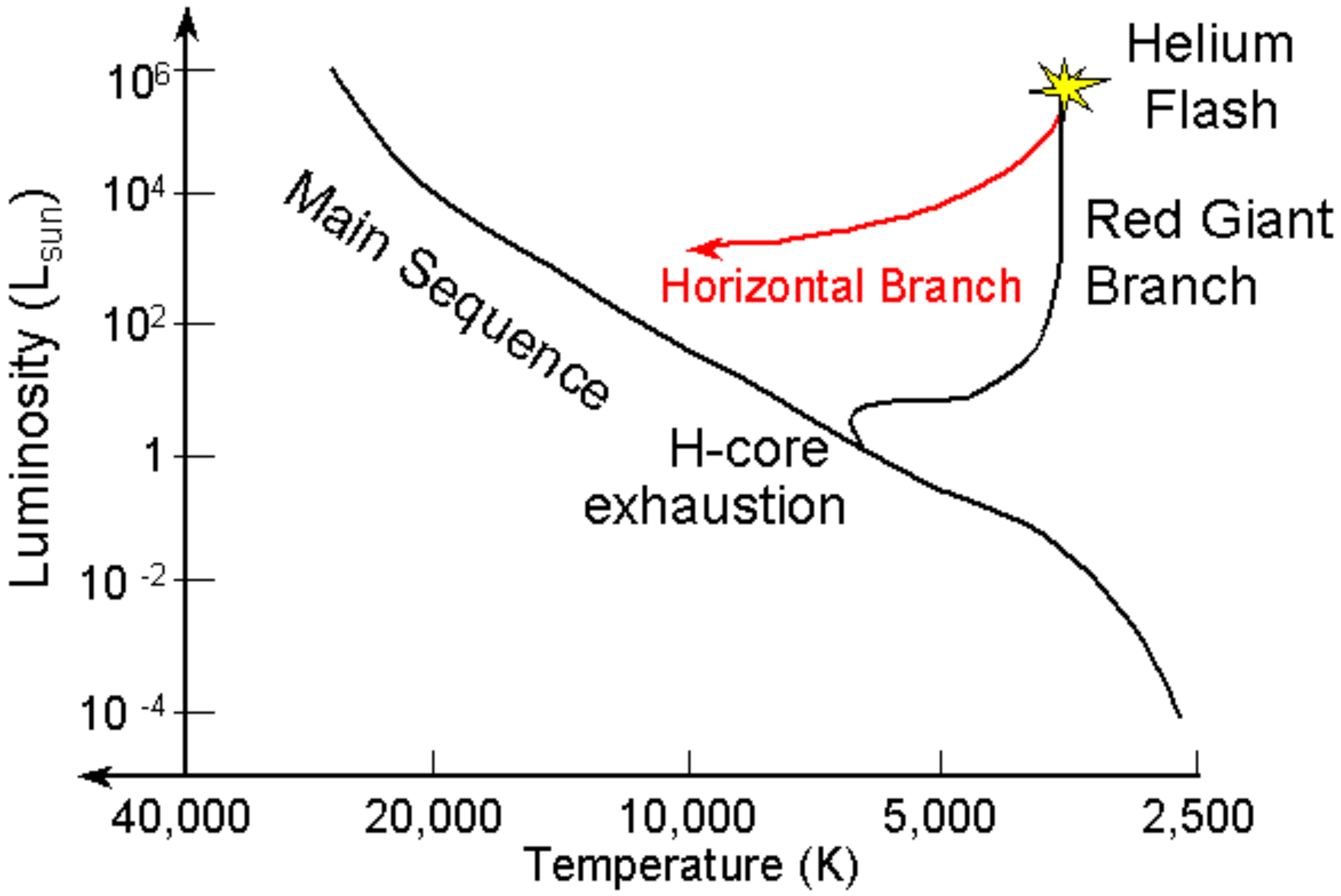


The net result: $4p \rightarrow {}^{4}\mathrm{He} + 2e^{+} + 2\nu_e + 3\gamma$

Triple Alpha Process

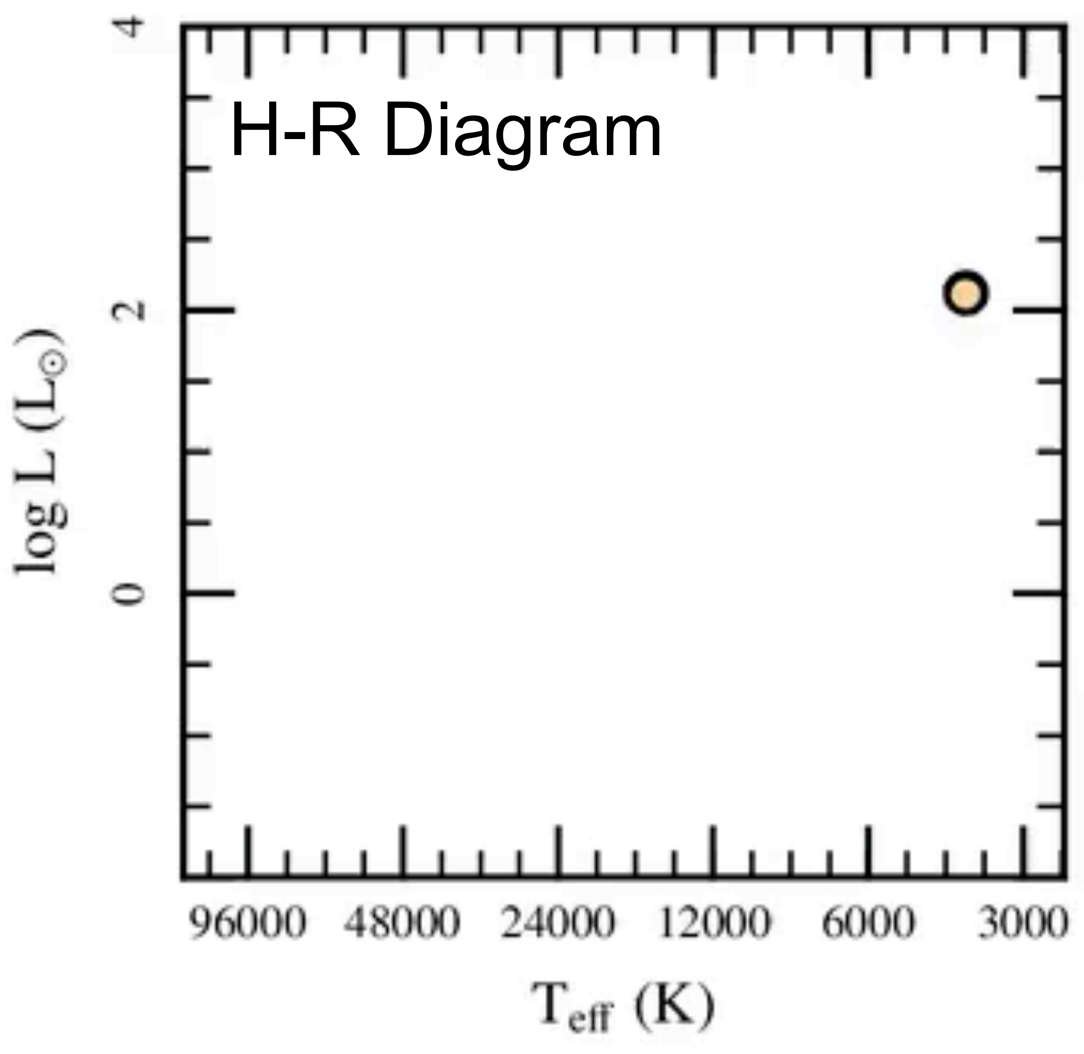
At 100 Million K, a new fusion source ignites: the Triple-alpha process.
This is the fusion of **three** $^{4}\mathrm{He}$ **nuclei into one** $^{12}\mathrm{C}$ **nucleus.**

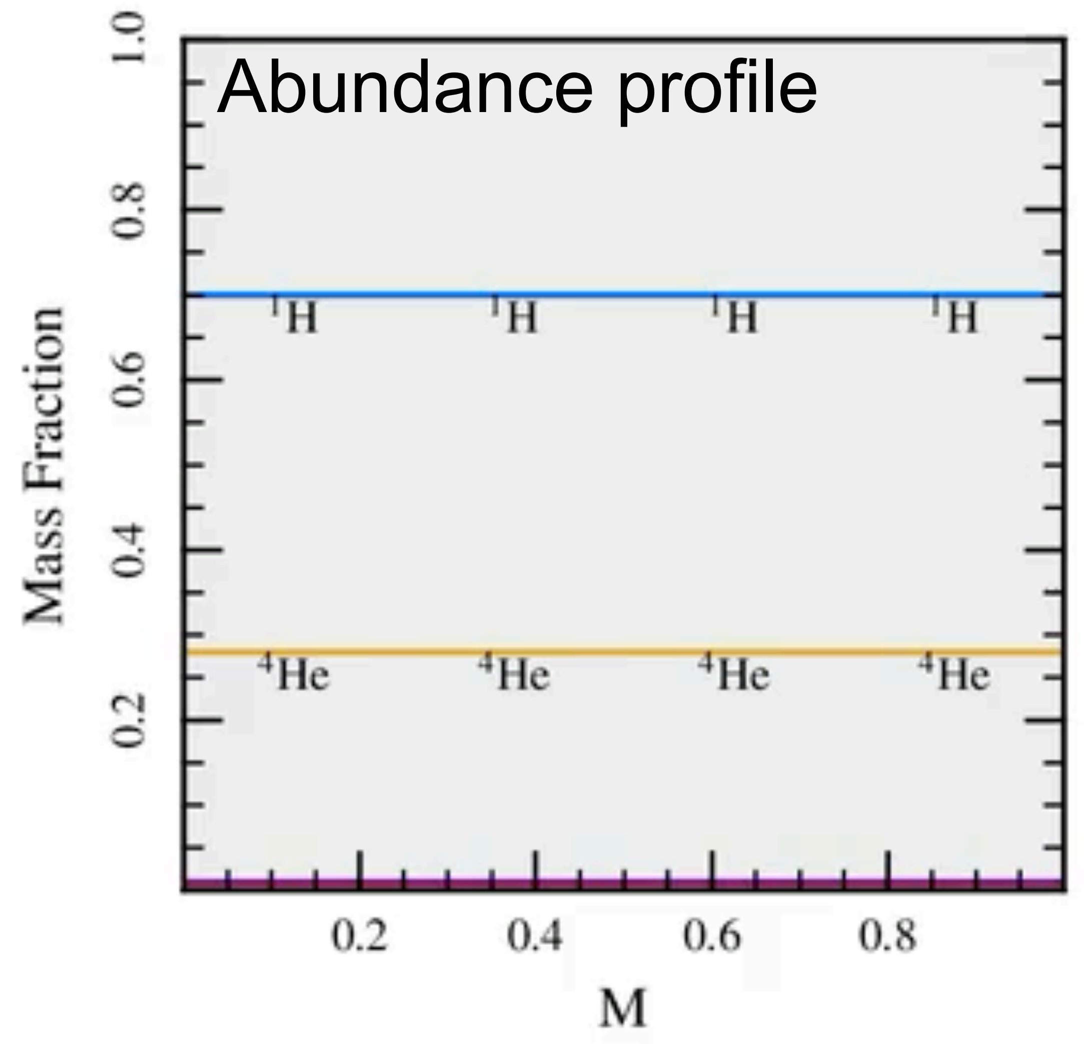


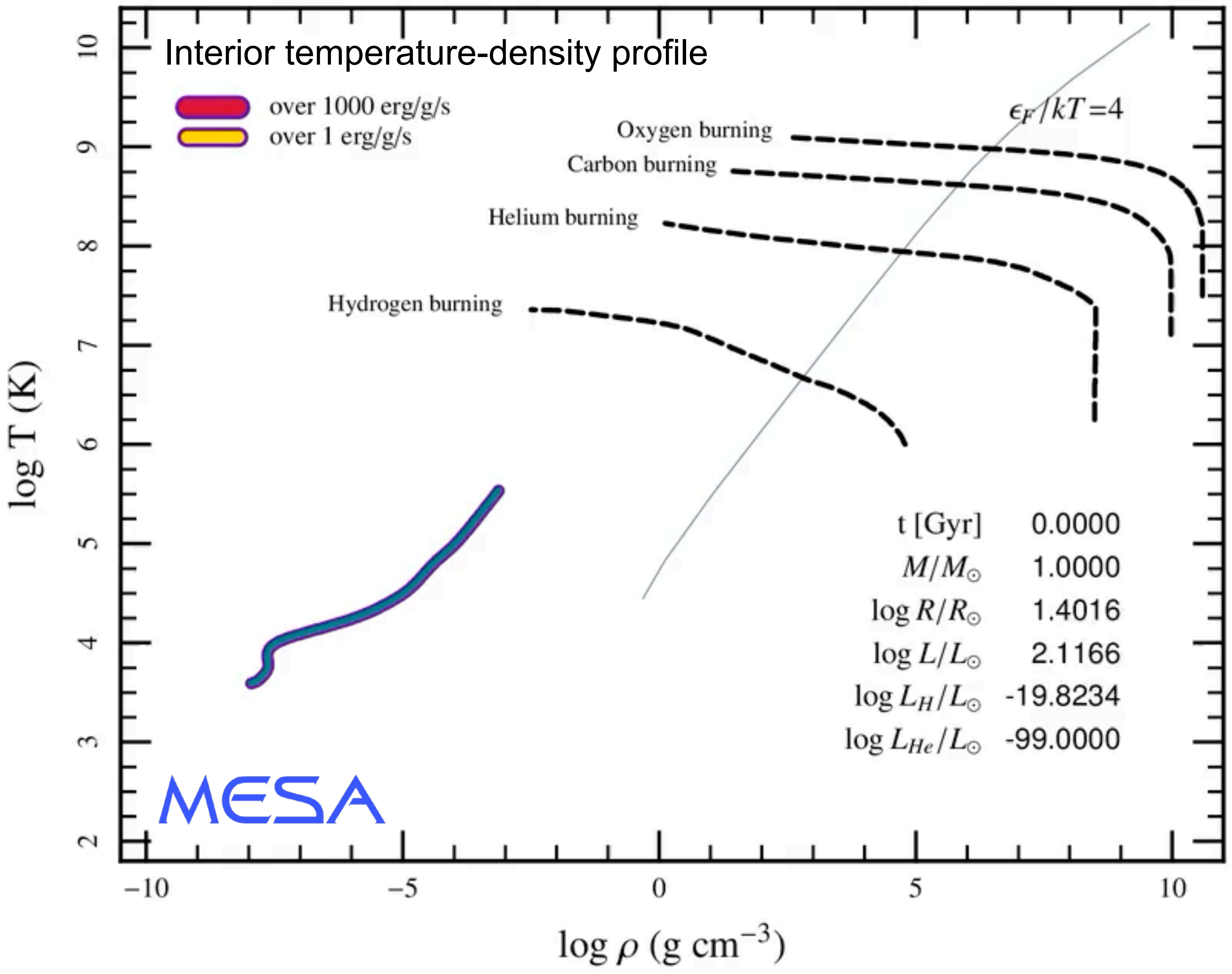


Occurs in the core of **red giant stars** near the end of their lives.

Modeling the evolution of a Sun-like star







Computational astrophysicists “radiative transfer” codes to models stellar evolution.

Pause

Brain Break – Think-pair-share

1. Reflect on your experience in this class. What were your **favorite lectures or topics?** What concepts did you find most **challenging to understand?**

2. Share your experiences with a neighbor and discuss which concepts you found confusing. If possible, work together to identify potential sources of confusion.

Final Review

Join at www.kahoot.it
or with the Kahoot! app
Game PIN:
426 0670
Kahoot!
Start
Waiting for participants
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Student Evaluation of Teaching (SET)

- The Student Evaluation of Teaching Survey is available until **Saturday, December 6 at 8:00 AM.**
- Please provide comments and <u>constructive</u> feedback before the deadline.
- Your response are *anonymous*
  – *I can only see the percentage of students who have completed it.*

Reminders

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Additional Slides

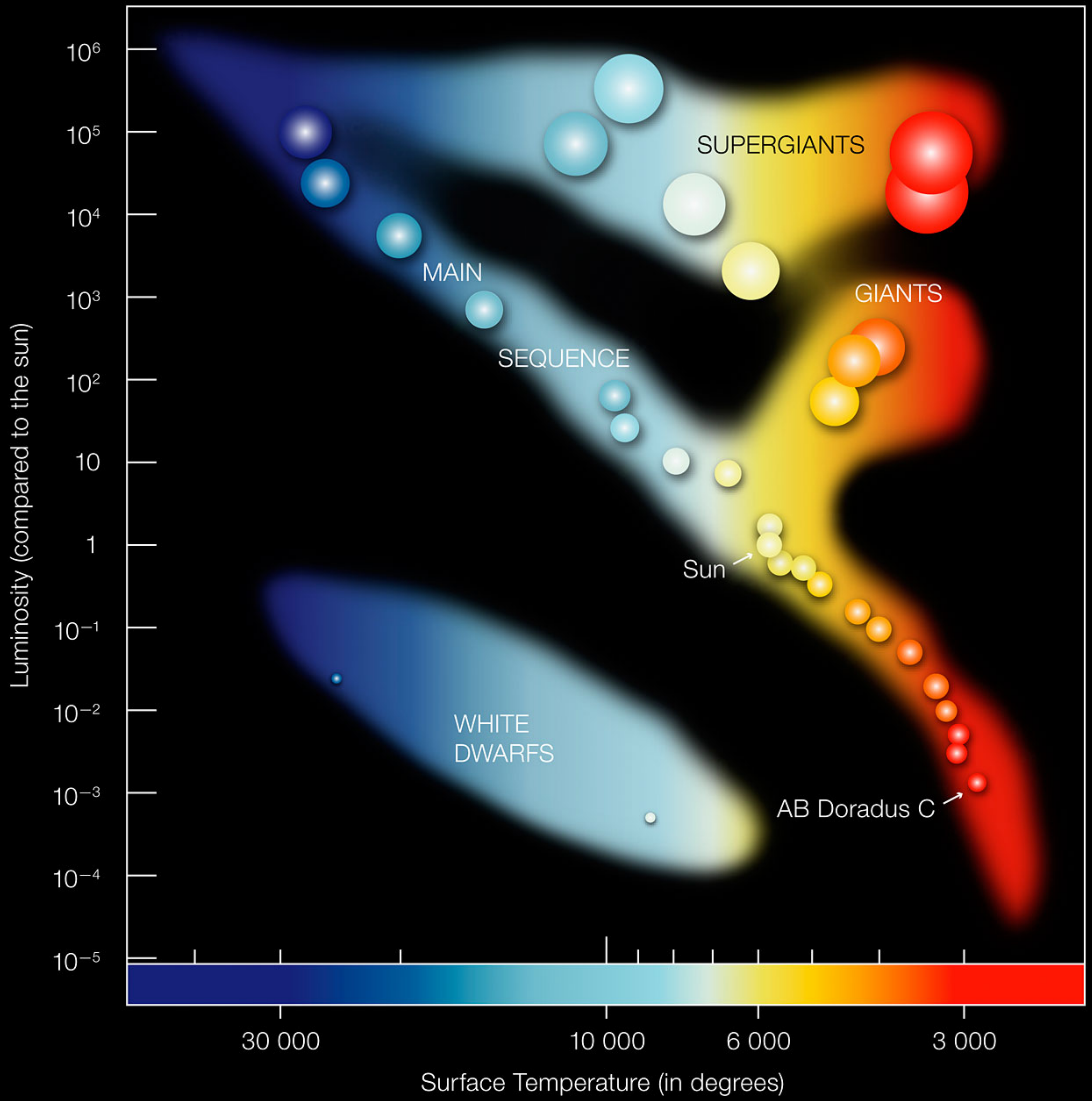
H-R Diagram

1. What is being plotted?

- Stars' intrinsic brightness versus temperature or color.
- Can be shown as luminosity vs. surface temperature or absolute magnitude vs. color index

2. Key features to recognize:

- **Main sequence:** Where stars spend most of their lives fusing hydrogen in their cores
- **Giants and supergiants:** Evolved, luminous stars with expanded envelopes
- **White dwarfs:** Hot but faint remnants of low- and intermediate-mass stars



Radiative Transport

Consider the layers of the Sun as a series of thin shells starting from the core.

At each layer a photon has some probability to be absorbed and reemitted.

The total rate at which photons carry energy through each shell is just the luminosity (energy in = energy out)

Setting radiation forces equal for adjoining shells we would get the **equation of radiative energy transport**

$$\frac{dT}{dr} = -\frac{3\rho(r)\kappa(r)L(r)}{64\pi\sigma_{\mathrm{SB}}T(r)^3r^2}$$

which describes the temperature gradient of a star.

Radiative Transport

We can make an approximation using this formula for how temperatures changes throughout the Sun

$$\frac{\Delta T}{\Delta R} \approx \frac{T_{\text{phot}} - T_c}{R_\odot - 0} = \frac{5800\ \text{K} - 1.47 \times 10^7\ \text{K}}{6.96 \times 10^5\ \text{km}} \approx -20\ \text{K/km}$$

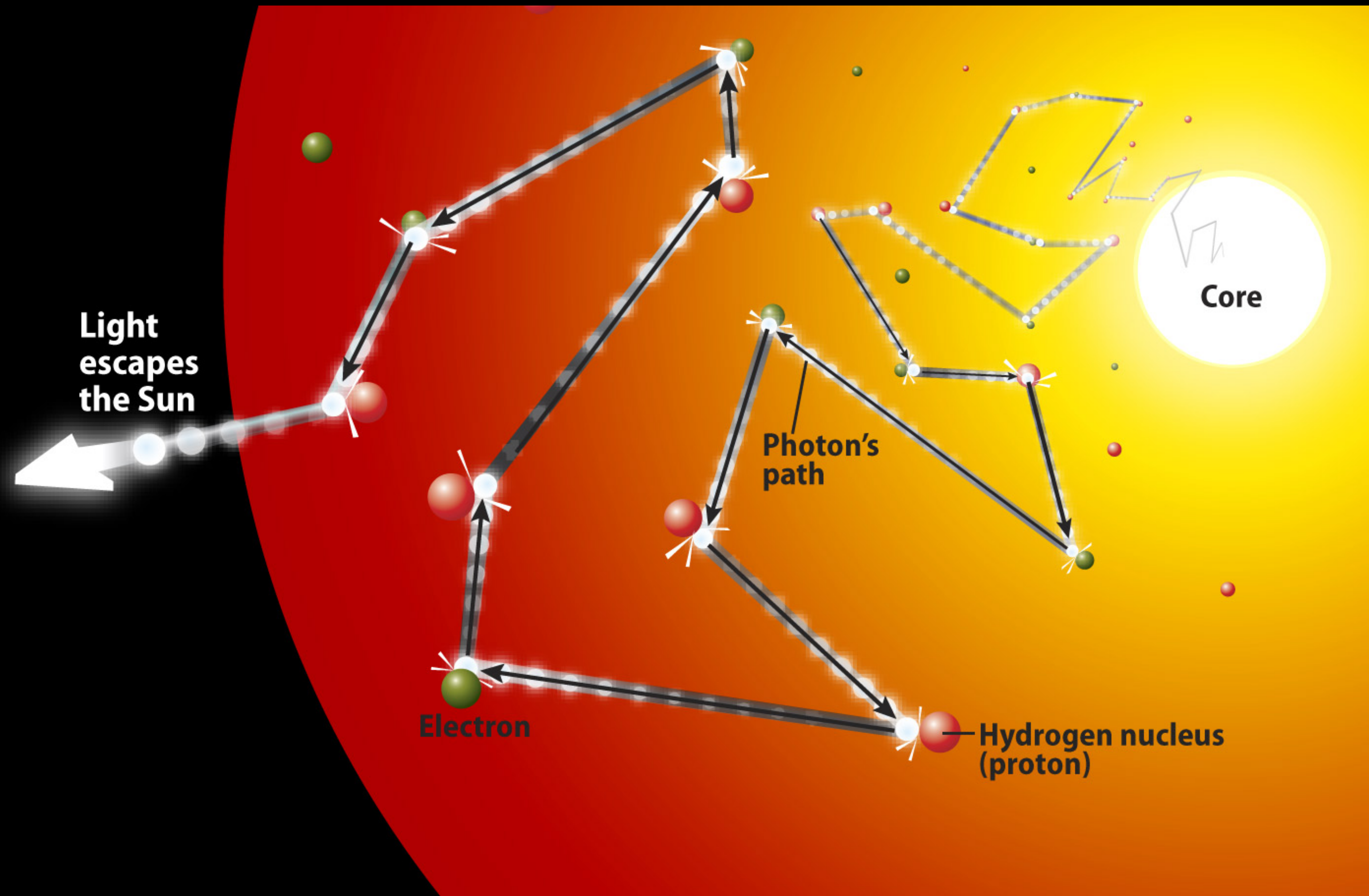
On average, every kilometer you move outwards in the Sun you cool down 20 K.

Bonus Brain Break – Think-pair-share

A photon must make an arduous trek from the center of the Sun to the top of the photosphere. Each step is approximately 1-2 cm before it is absorbed and reemitted. Considering this, how many “steps” will it take to get out of the Sun?

Considering this, how many “steps” will it take to get out of the Sun?

We can approximate the time it takes to get out of the Sun by multiplying the number of steps (N) by the length of each step (l) and dividing by the speed of light (c). How long does it take to escape?



Sustained Energy

"How does the Sun sustains its energy?"

Initially, it was thought that the Sun's gravitational energy was converted into radiative energy. Let's fact check this.

Start with the **gravitational potential energy**

$$U_\odot = -\,q\,\frac{GM_\odot^2}{R_\odot} \qquad (q \sim 1)$$

Plugging in we get $U_\odot$ is approximately -5.7×10^{41} Joules

Sustained Energy

Plugging in we get,

$$U_\odot = -\, q\,\frac{GM_\odot^2}{R_\odot} \approx 5.7 \times 10^{41}\ \text{Joules}$$

We can calculate how long the Sun would last converting this energy using the present-day value of the luminosity (the **Kelvin-Helmholtz time**)

$$t_{\text{KH}} = \frac{|\,U_\odot\,|}{L_\odot} \approx 1.5 \times 10^{15}\ \text{s} \approx 50\ \text{Myr}$$

Fusion Reactions

If the Sun was made entirely of Hydrogen, it would have N_H atoms

$$N_H = \frac{M_\odot}{m_p} \approx 1.2 \times 10^{57}$$

Fusing all those H atoms into He would release an amount of energy

$$E_{\text{fusion}} = \frac{N_H}{4} \Delta E \approx 1.2 \times 10^{45}\,\text{J}\,.$$

Under this assumption, the time to run out of fuel would be:

$$t_{KH} = \frac{E_{\text{fusion}}}{L_\odot} \approx 3.3 \times 10^{18}\,\text{s} \approx 100\ \text{Gyr}\,.$$

However, the Sun isn’t pure Hydrogen and the Sun doesn’t convert all H into He.

Fusion Reactions

The Sun sustains its energy by fusing Hydrogen into Helium.

We can compute the energy released in each reaction using the mass-energy equivalence equation ($E = mc^2$).

Mass of 4 H nuclei = 6.6905×10^{-27} kg

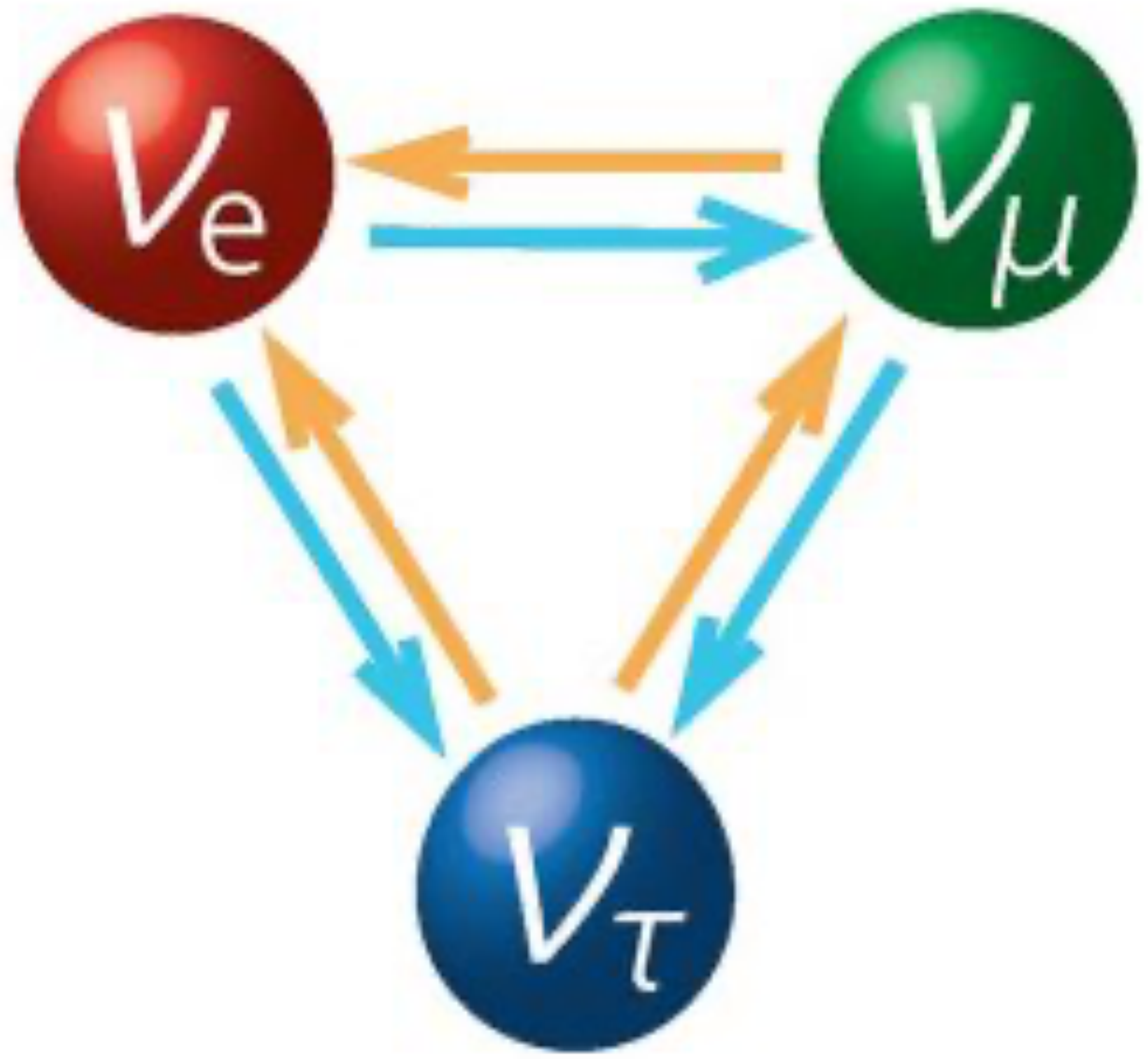
Mass of 1 He nucleus = 6.6447×10^{-27} kg

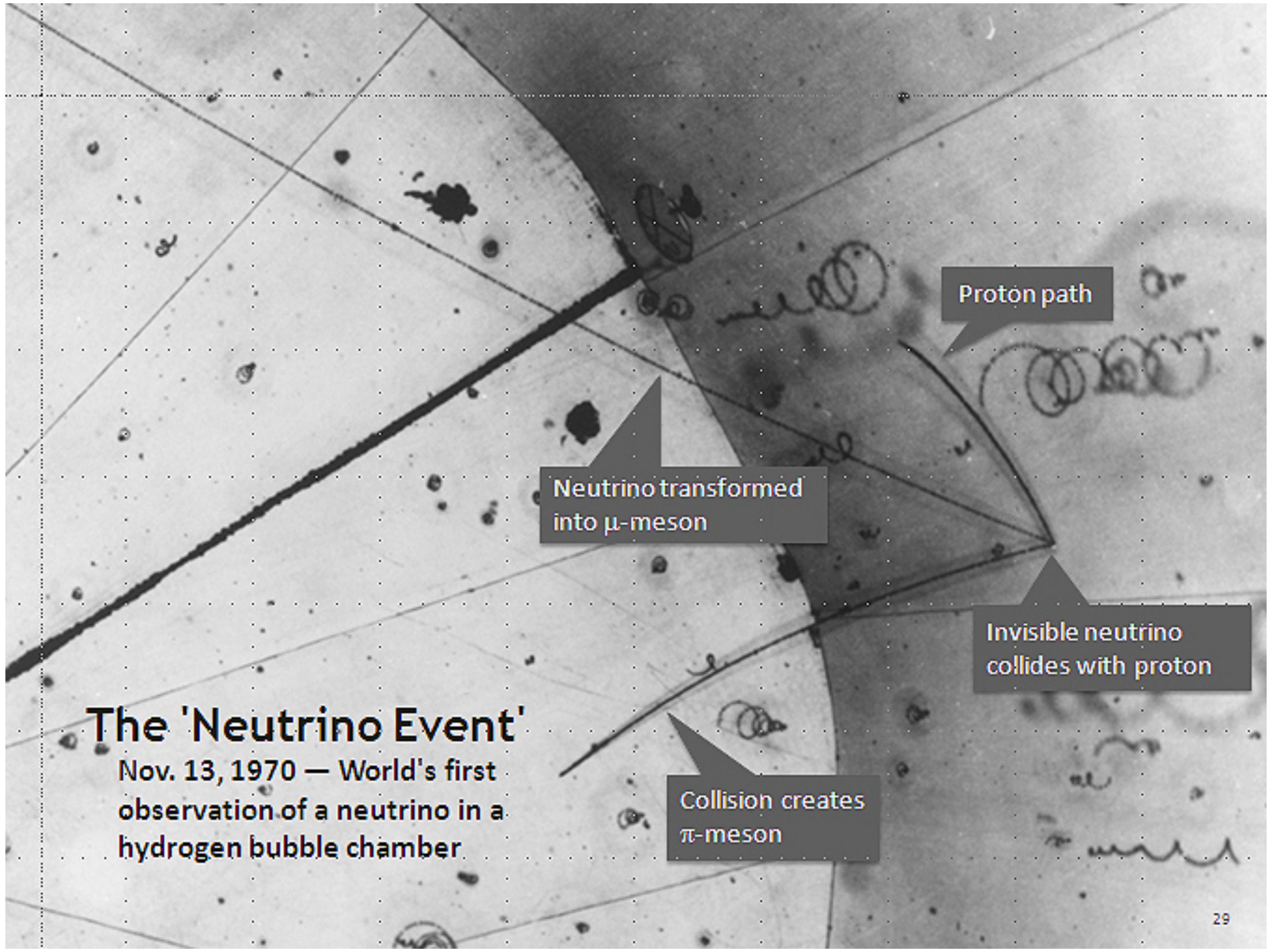
$$\Delta m = 0.0458 \times 10^{-27} \text{ kg}$$

$$\Delta E = |\Delta m| c^2 = 4.1 \times 10^{-12} \text{ J}$$

Solar Neutrino Problem

The PPI chain predicts a yield of *electron* neutrinos from the Sun, however, early experiments detected about 1/3 of the predicted *electron* neutrinos.





Solution: Neutrinos “oscillate” and change flavors.