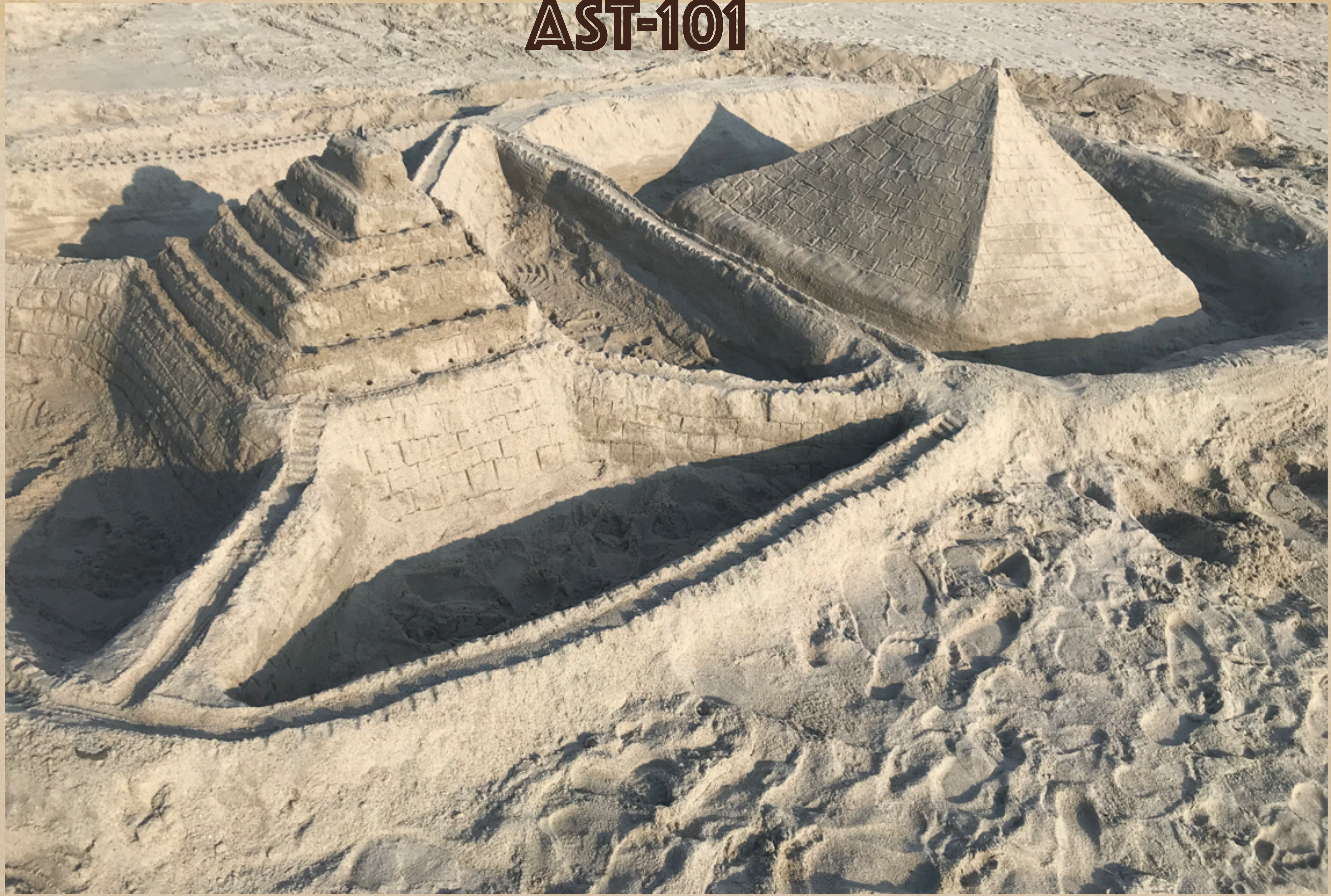
AST-101



Life cycle of the Sun

Luis Anchordoqui

- Stars appear unchanging
- Night after night heavens reveal no significant variations
- On human time scales ☛ majority of stars change very little

- We cannot follow any but tiniest part of star life cycle

Star formation

- Stars are born when gaseous clouds (mostly hydrogen) contract due to pull of gravity
- Huge gas cloud fragments into numerous contracting masses
- Each mass is centered in area where density is only slightly greater than @ nearby points
- Once such "globules" formed gravity would cause each to contract in towards its center
- As particles of such protostar accelerate inward their kinetic energy increases
- When kinetic energy is sufficiently high Coulomb repulsion ☛ not strong enough to keep ^{1}H nuclei appart and nuclear fussion can take place
- In star like our Sun "burning" of ^{1}H occurs when 4p fuse to form ^{2}He nucleus with release of: γ, e^{+}, ν_e

Star Birth

- We start with clouds of cold, interstellar gas:

- Molecular clouds - cold enough to form molecules; T=10-30K
- Often dusty
- Collapses under its own gravity

Recurring theme: conservation of energy

1.- Collapse due to gravity increases the temperature (gravitational energy! thermal energy)

If thermal energy can escape via radiation (glowing gas), collapse continues

2.- If thermal energy is contained, or more energy is generated due to fusion, collapse is slowed (by thermal pressure)

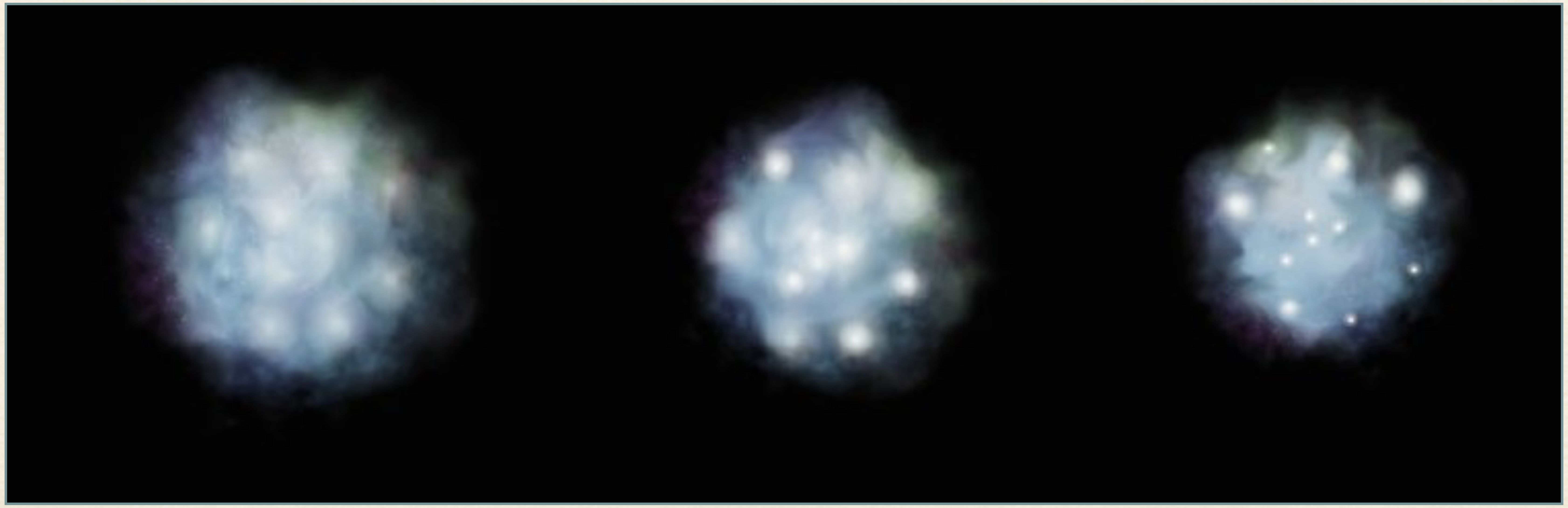
Collapse from Cloud to Protostar

- First collapse from very large, cold molecular clouds

  - cloud is turbulent and clumpy -

- Fragments into star-sized masses

- Temperature increases in each fragment as it continues to collapse



Multiple Protostars Can Form From a Single Cloud

Starting point: turbulent gas cloud 1.2 ly across and with 50 Msun of gas

What is the energy source that heats a contracting protostar?

A. Friction of the gas molecules rubbing against each other

B. Pressure, as the gas and dust are compressed

C. Gravitational energy that is released as the cloud compresses

D. Fusion

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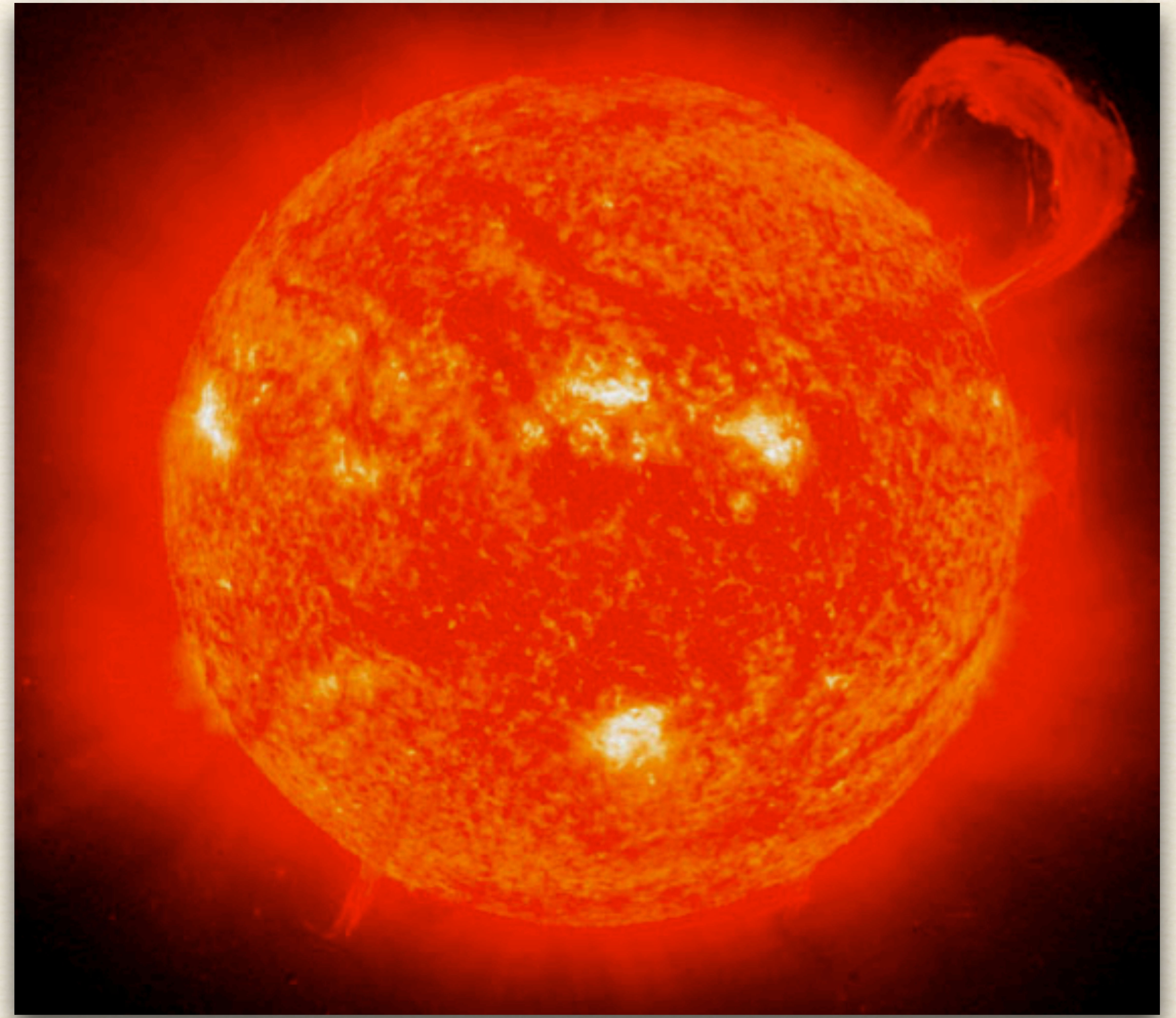
M16 a.k.a. Eagle Nebula located ≈ 7,000 ly away

HSTs pillars of creation

How does the Sun produce its energy?



Could it be chemical burning?

1.- Energy released by burning oil ~10^7 joules/kg

2.- Solar energy output (Luminosity) = 3×10^{26} joules/sec (mostly in visible light)

3.- Need (3×10^{26} joules/sec) / (10^7 joules/kg) = 3×10^{19} kg of burning oil per second

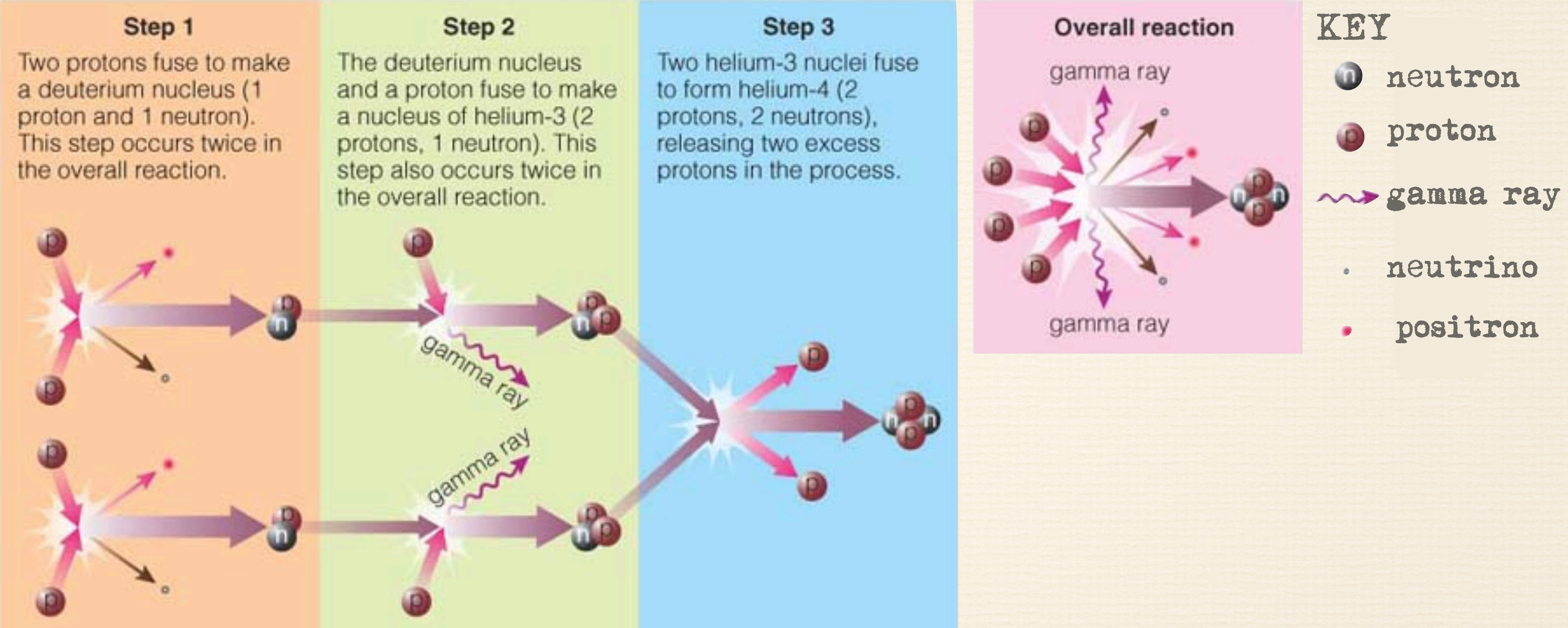
4.- How long will the Sun last?

$\Rightarrow M_{Sun}$/(amount burning per second) = (2×10^{30} kg)/ 3×10^{19} kg/s

= 6.6×10^{10} seconds = 2,000 years!!

Energy generated by FUSION!

Hydrogen Fusion by the Proton-Proton chain



Proton-Proton chain

$E = mc^2$

Suns energy output

- pp cycle due to following sequence of fusion reactions

$$ {}^1_1\mathrm{H} + {}^1_1\mathrm{H} \rightarrow {}^2_1\mathrm{H} + 2\,e^+ + 2\,\nu_e $$

$$ {}^1_1\mathrm{H} + {}^2_1\mathrm{H} \rightarrow {}^3_2\mathrm{He} + \gamma $$

$$ {}^3_2\mathrm{He} + {}^3_2\mathrm{He} \rightarrow {}^4_2\mathrm{He} + {}^1_1\mathrm{H} + {}^1_1\mathrm{H} $$

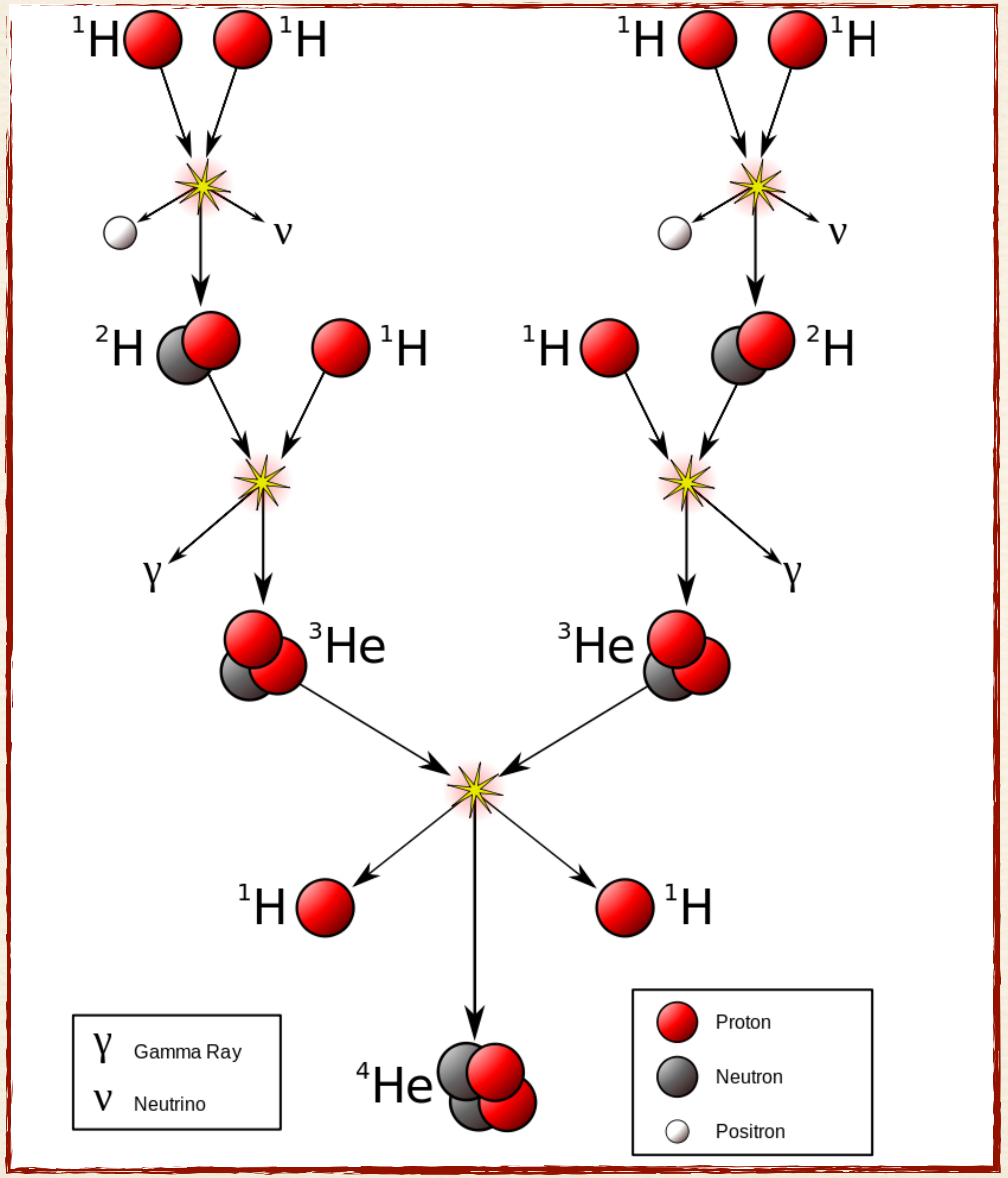
- Released energy
  - mass difference between initial & final states
  - carried off by outgoing particles
- Net effect

$$ 4\,{}^1_1\mathrm{H} \rightarrow {}^4_2\mathrm{He} + 2e^+ + 2\nu_e + 2\gamma $$

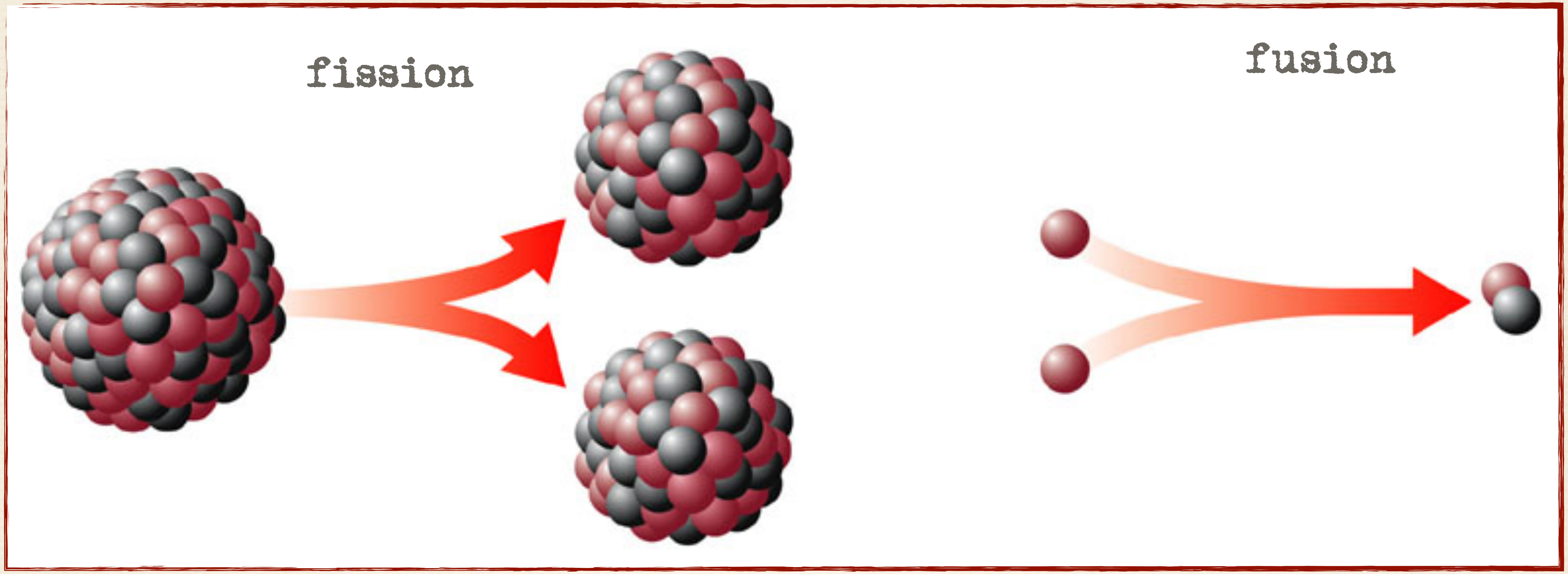
- Takes 2 of each of first 2 reactions to produce two ${}^3_2\mathrm{He}$
- Deuterium formation has very low probability

infrequency of reaction limits rate at which Sun produces energy

Nuclear Burning



Fusion NOT fission as energy source



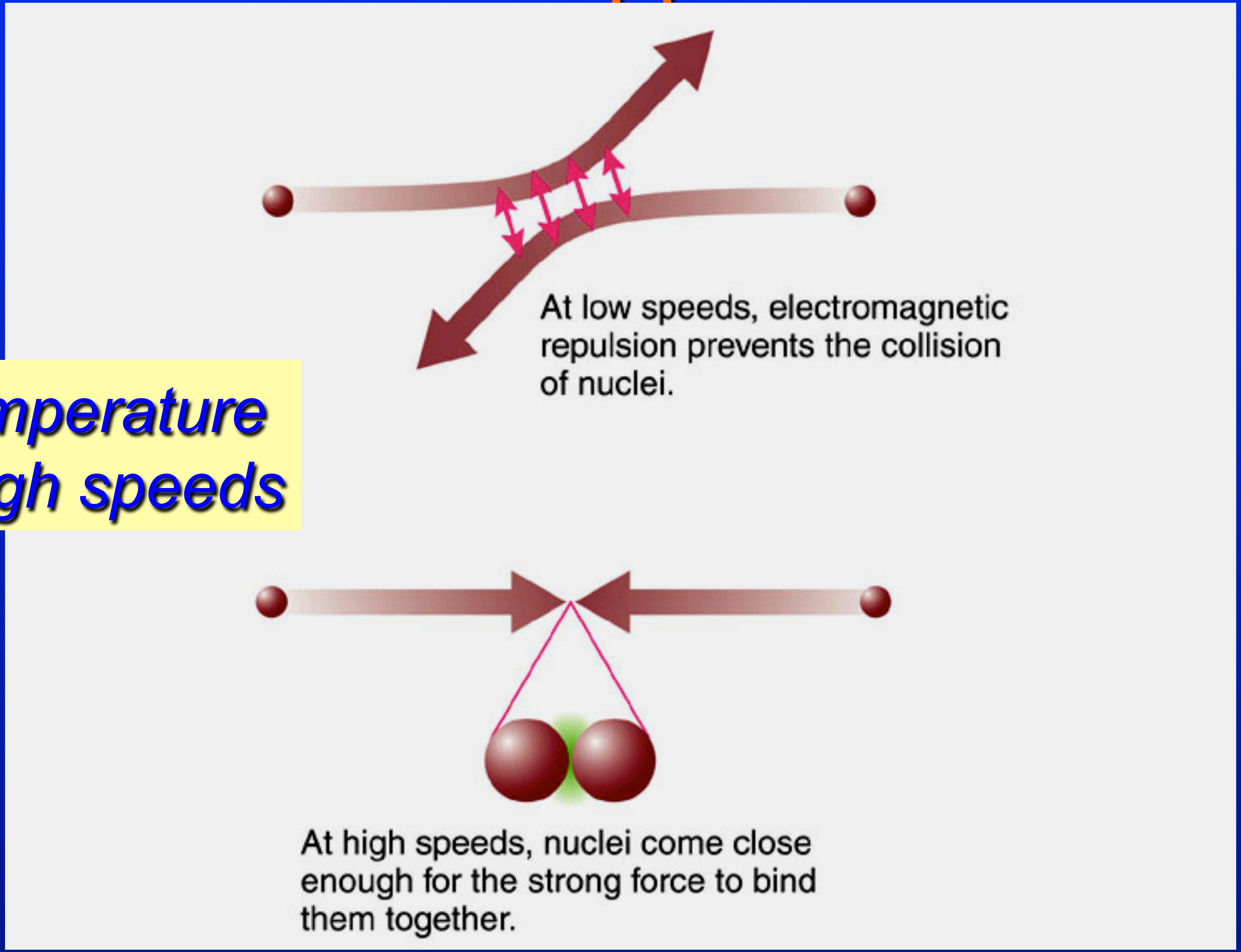
Fission
Big nucleus splits into smaller pieces
(Nuclear power plants)

Fusion
Small nuclei stick together to make a bigger one
(Sun, stars)

Sun's energy budget

- Helium has atomic mass 3.97 times that of hydrogen, NOT exactly 4 times
- Tiny amount of the protons' mass is lost to energy
- *$E = mc^2$ (a little mass makes a lot of energy!)*
- 600 million tons of H every second is converted to 596 million tons of He…4 million tons of mass are converted into energy each second!

Need high temperatures to make fusion happen



High temperature gives high speeds

The Sun is made up of (mostly) hydrogen. Yet the P-P chain starts with two protons. Why are they not with their electrons?

A. The material is very hot so the nuclei and electrons are all free.
B. The electrons have all moved to the outer layers of the Sun.
C. The Sun is electrically positive (thus the magnetic fields) so all that exists are hydrogen ions.
D. Neutral hydrogen only consists of one proton and one neutron in the first place.

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Do we have direct evidence for fusion in the Sun?

- YES! Neutrinos

Those Mysterious Neutrinos

MADE BY HYDROGEN FUSION IN CORE

- *Very small masses,* travel close to speed of light
- *Don’t interact (almost) with other matter:* requires lead wall 1 light year thick to stop a neutrino!
- *Lots of them:* 10^{38} neutrinos/sec from the Sun, 10^{15} coming through YOU each sec !
- But we can still catch some, using massive underground “detectors”

Could the neutrinos flowing through our bodies be a cause of cancer or other cellular damage?

A. YES, because there are so many and they carry a lot of energy
B. NO, because they don't interact with anything and just flow through
C. MAYBE, it depends on if they are electron, muon or tau neutrinos.

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How does the number of neutrinos passing through your body at night compare with the number passing through during the day?

A. About the same.
B. Much smaller during the night.
C. Much larger during the night.
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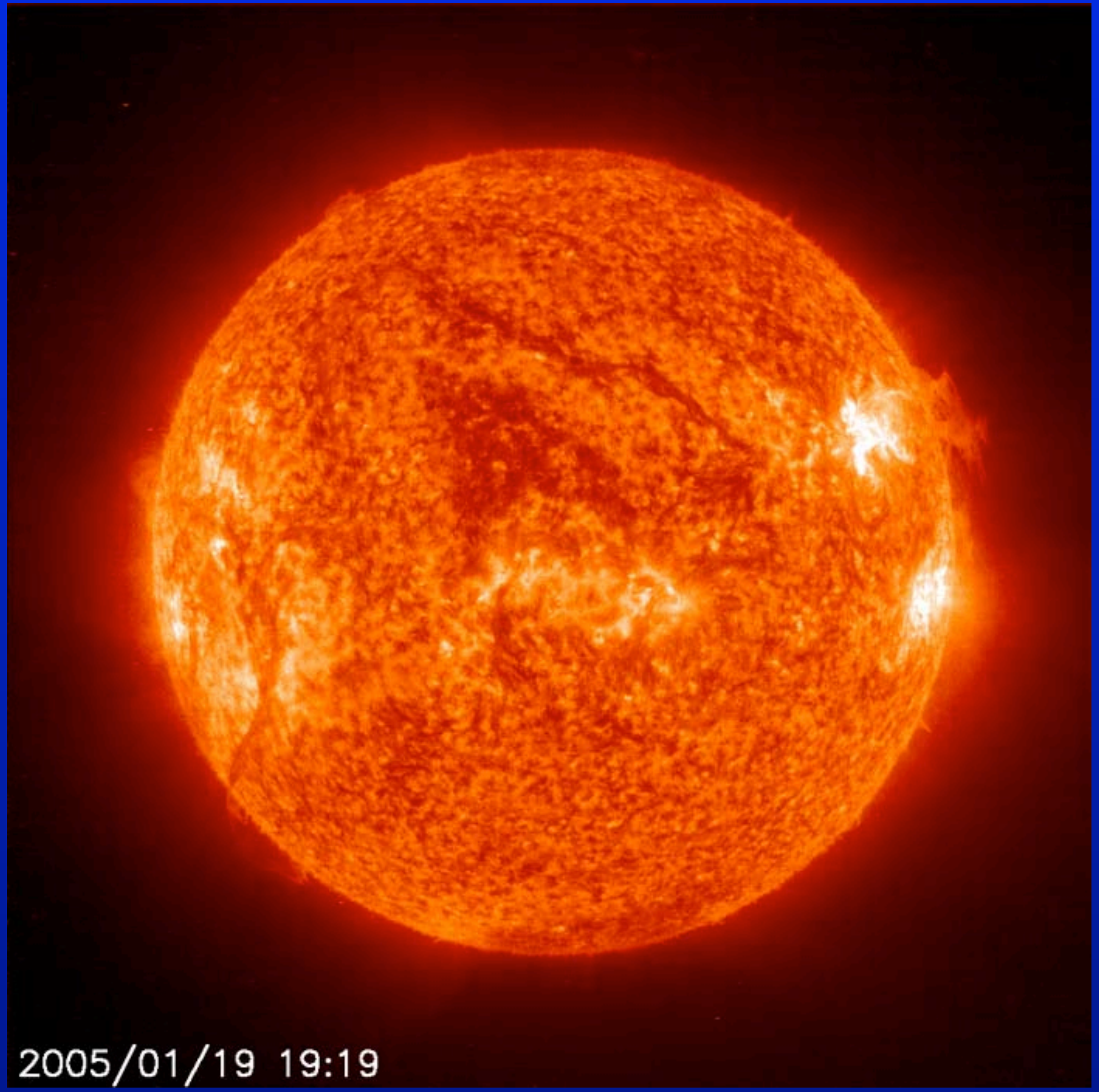
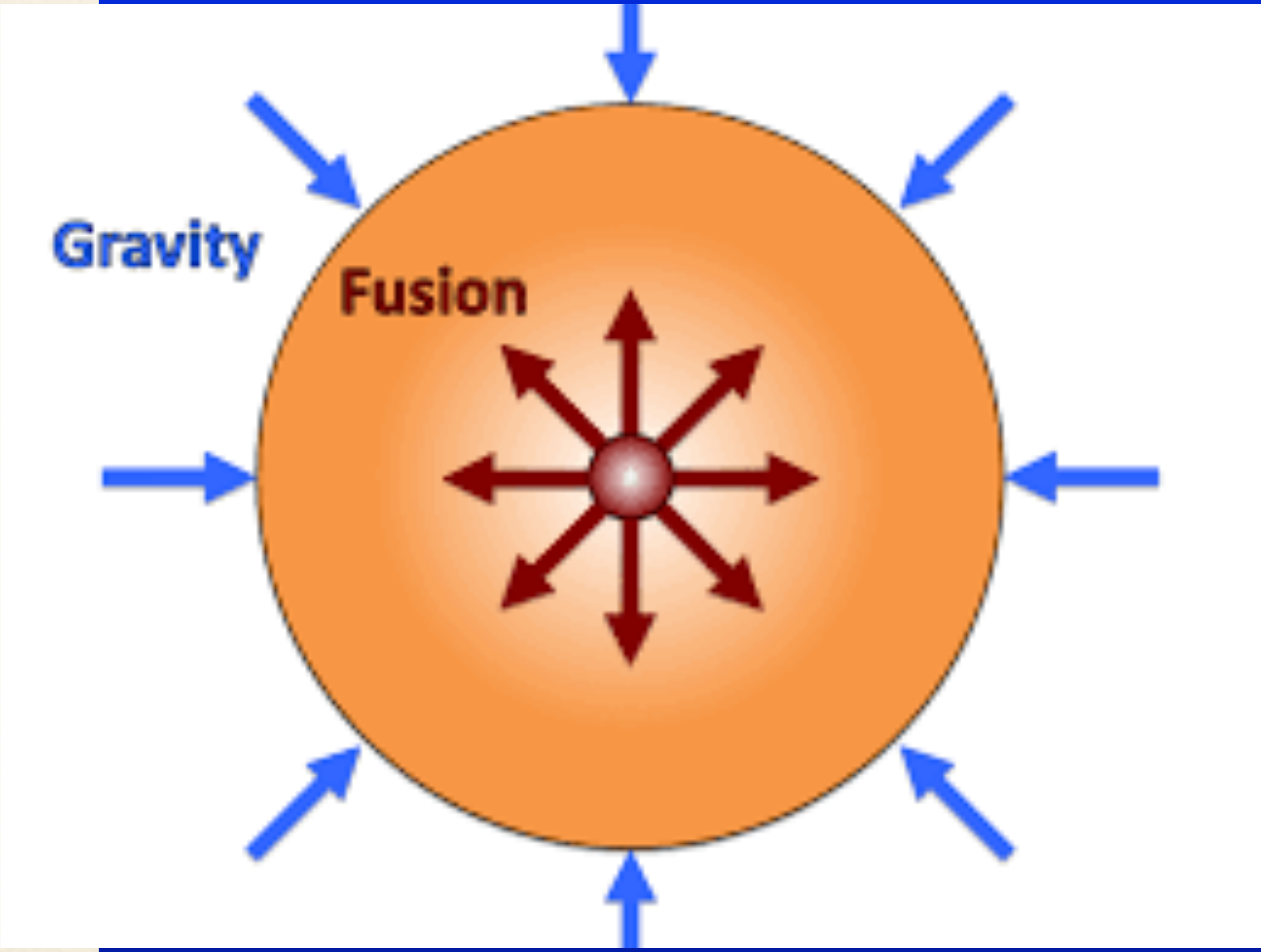
What makes the Sun stable?

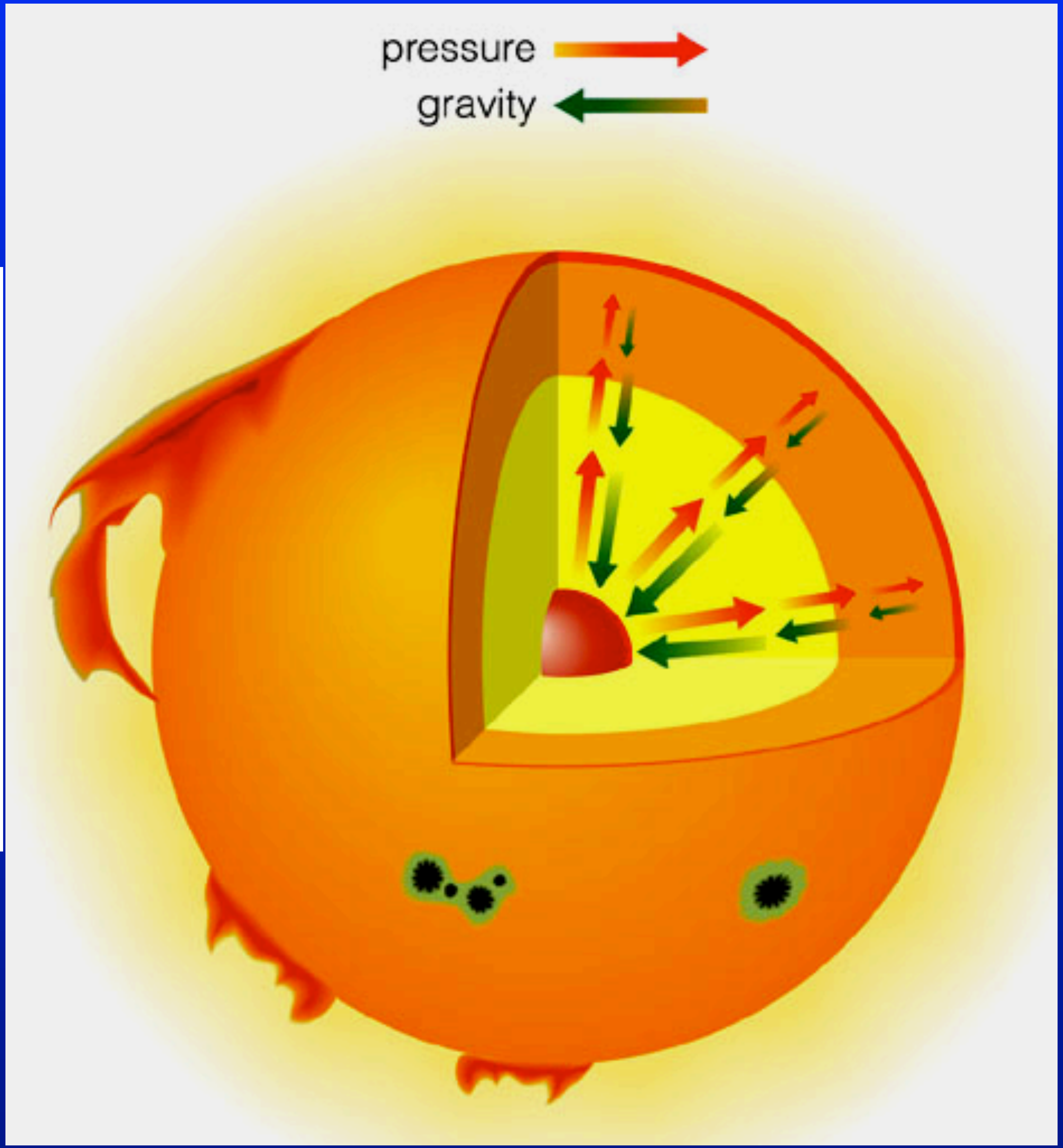
- To understand this, we have to look into the forces at work on the Sun.



Hydrostatic Equilibrium

Pull of gravity = Push of pressure





High PRESSURE at CENTER

In gases, we have, roughly:

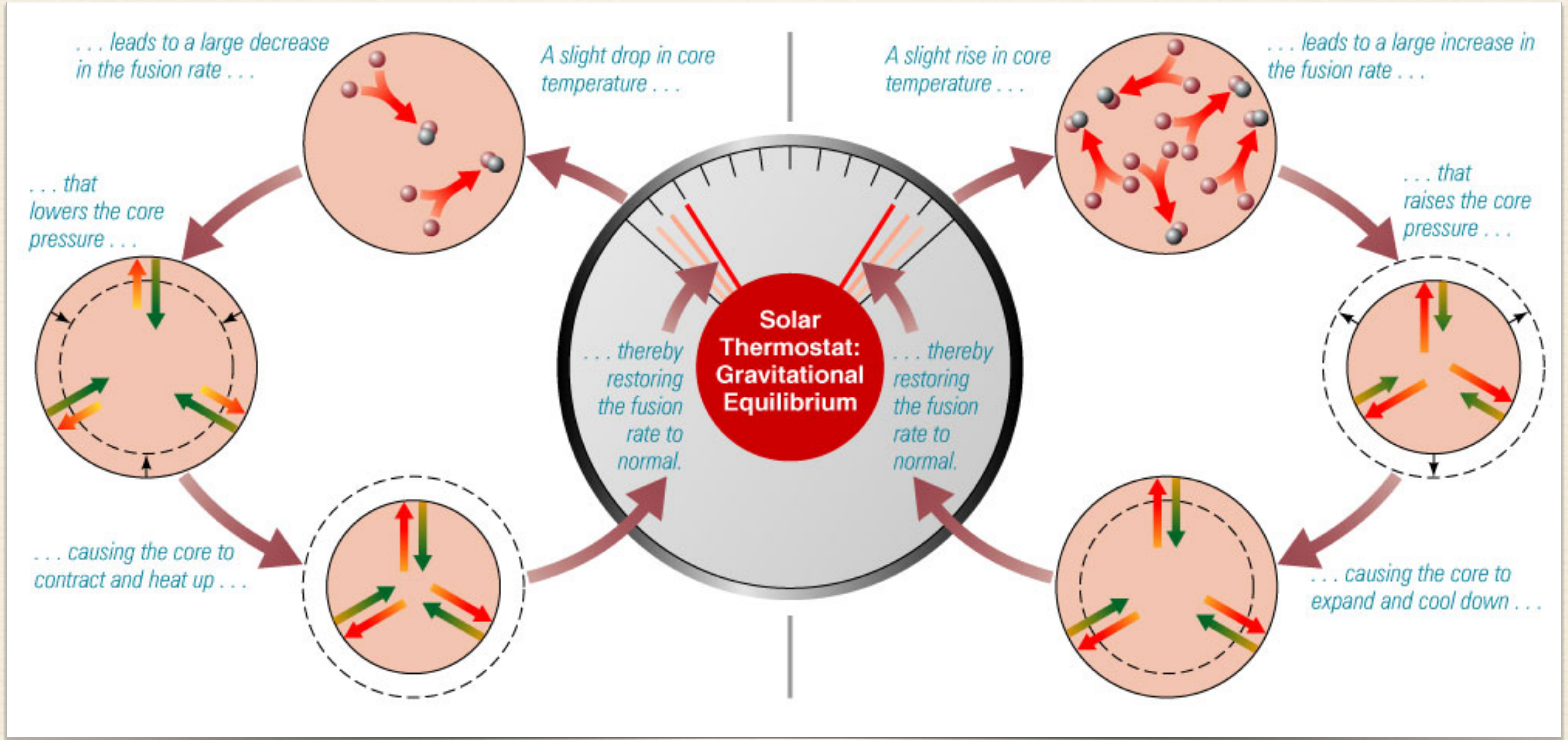
PRESSURE = DENSITY x TEMPERATURE

1. *A high pressure in the center results in a high temperature.*

2. *If really hot, NUCLEAR BURNING can supply more energy*

- *Why don't we get a runaway reaction?*

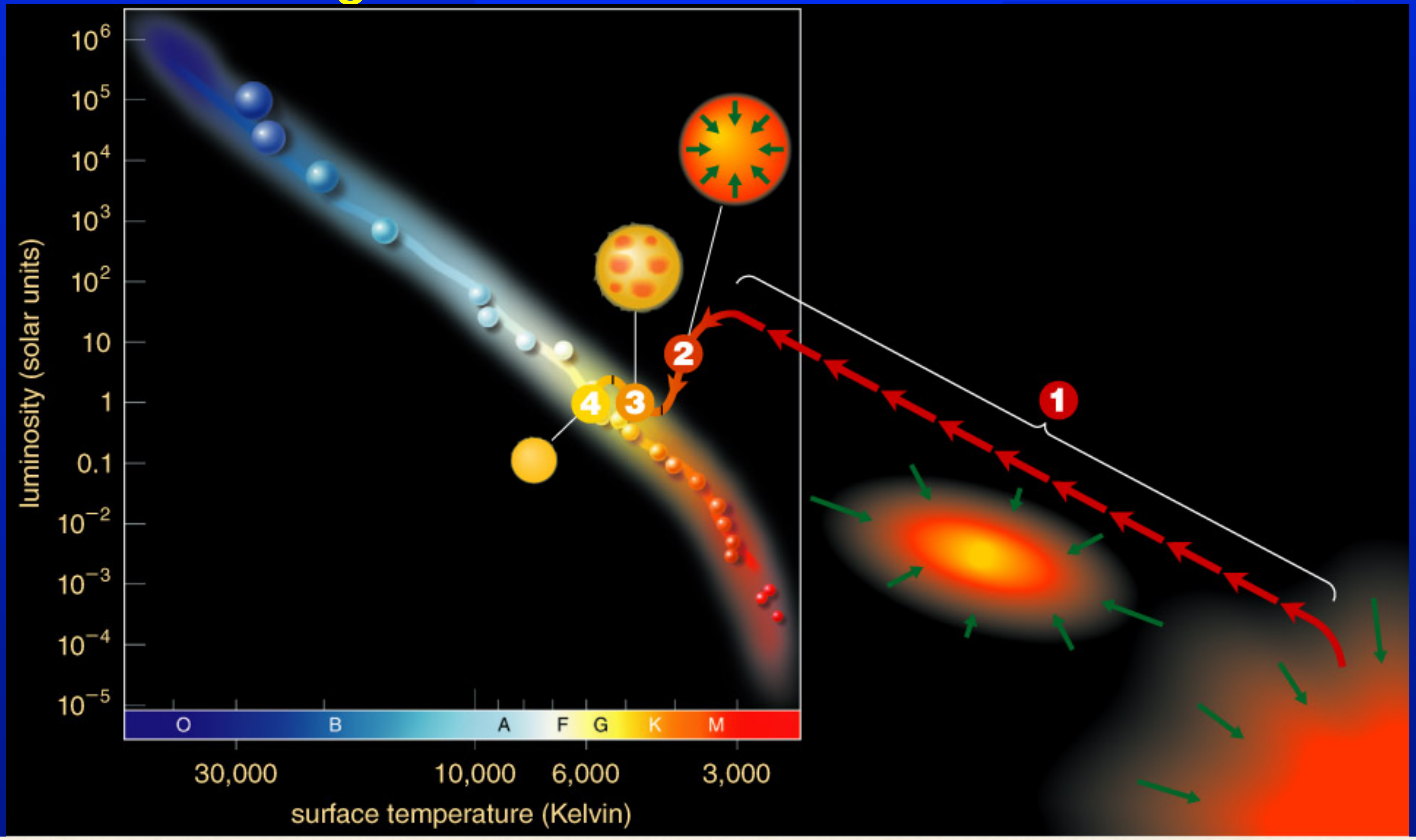
The solar thermostat



Nuclear fusion rate very sensitive to temperature

1. Our cloud collapses to form one or more protostars, heating up as it shrinks.
2. Collapse continues, temperature stabilizes as convection circulates **energy outwards**

- On HR Diagram



Protostars start out relatively cool and dark. On the HR diagram, a protostar appears at the:

A. Upper left corner
B. Upper right corner
C. Lower right corner
D. Lower left corner

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B. Upper right corner
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What kind of pressure opposes the inward pull of gravity during <u>most</u> of a star's life:

A. Thermal pressure.
B. Barometric pressure.
C. Degeneracy pressure.
D. Sound wave pressure.

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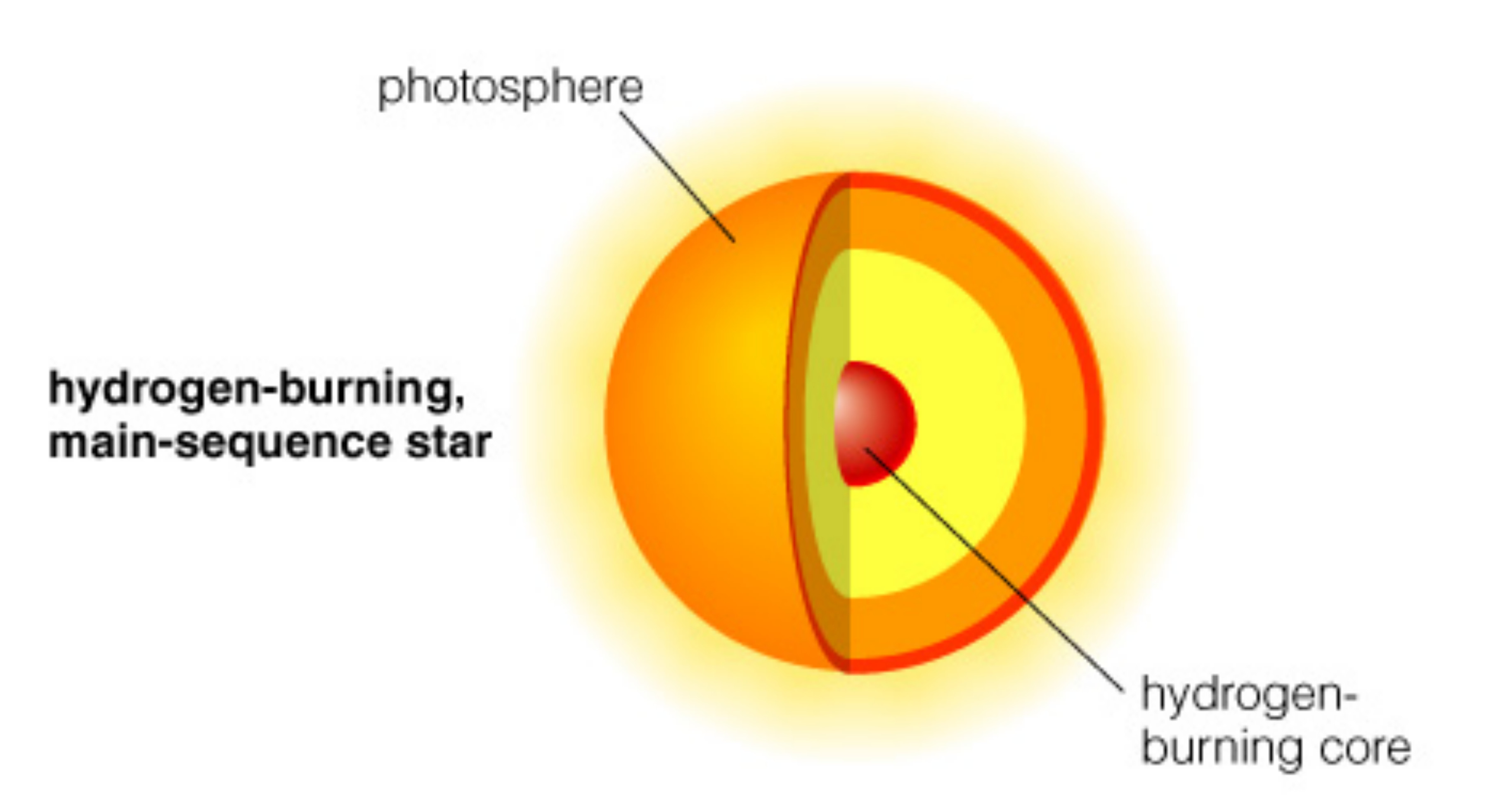
Evolution of Low Mass Stars (less than ~2 x Sun's mass)

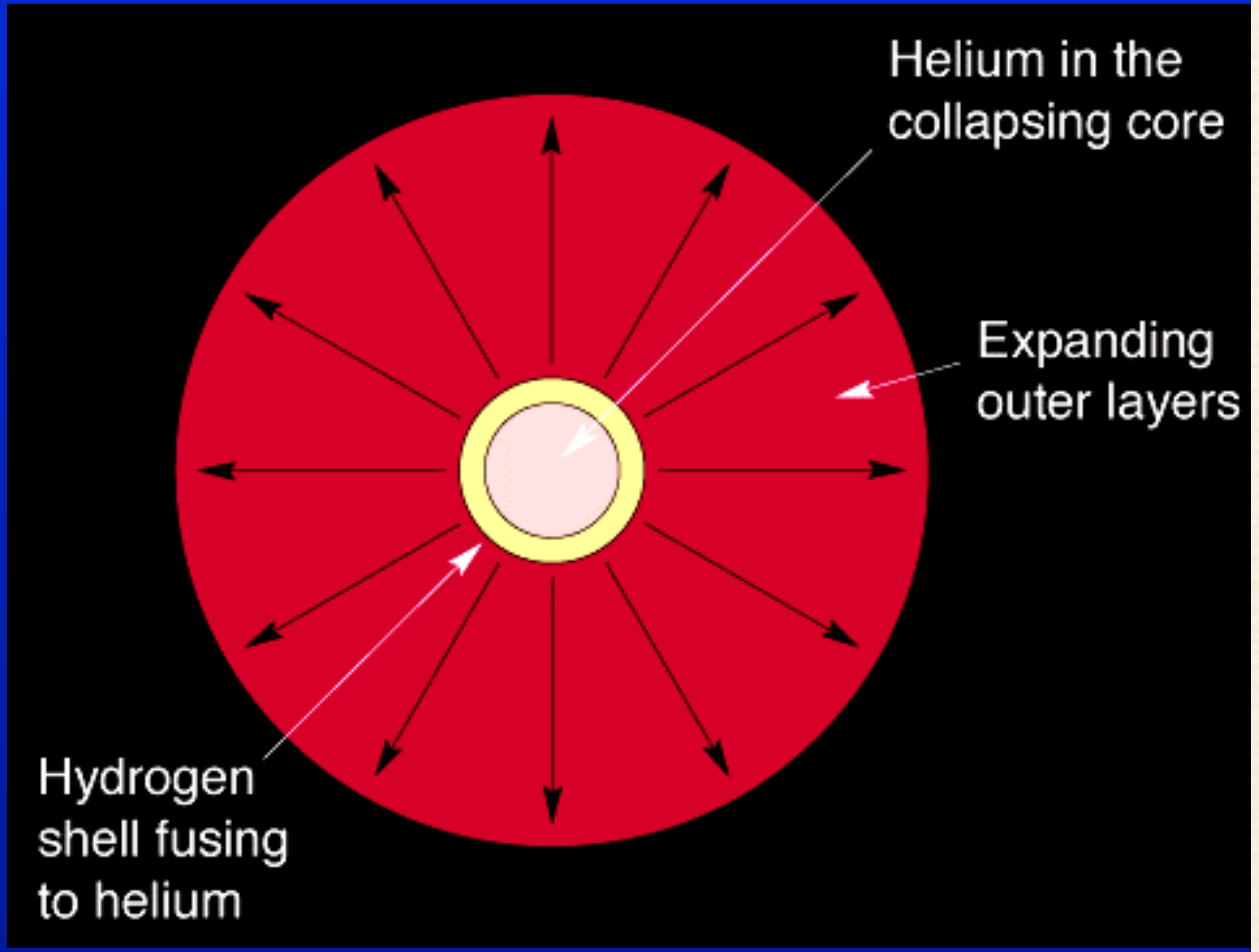
- Protostars → Main sequence
- Most of its life on Main sequence (billions of years)
- What happens when it runs out of hydrogen?



When The Core Runs Out Of Hydrogen, All That is Left in the Center is Helium

- But the temperature is not hot enough to fuse helium.
- With fusion no longer occurring in the core, gravity causes core collapse ← *key theme*
  - Core temperature starts to heat up
- Now Hydrogen fusion has moved to shells surrounding the core
  - Pushes outer layers of the star out.

RED GIANT

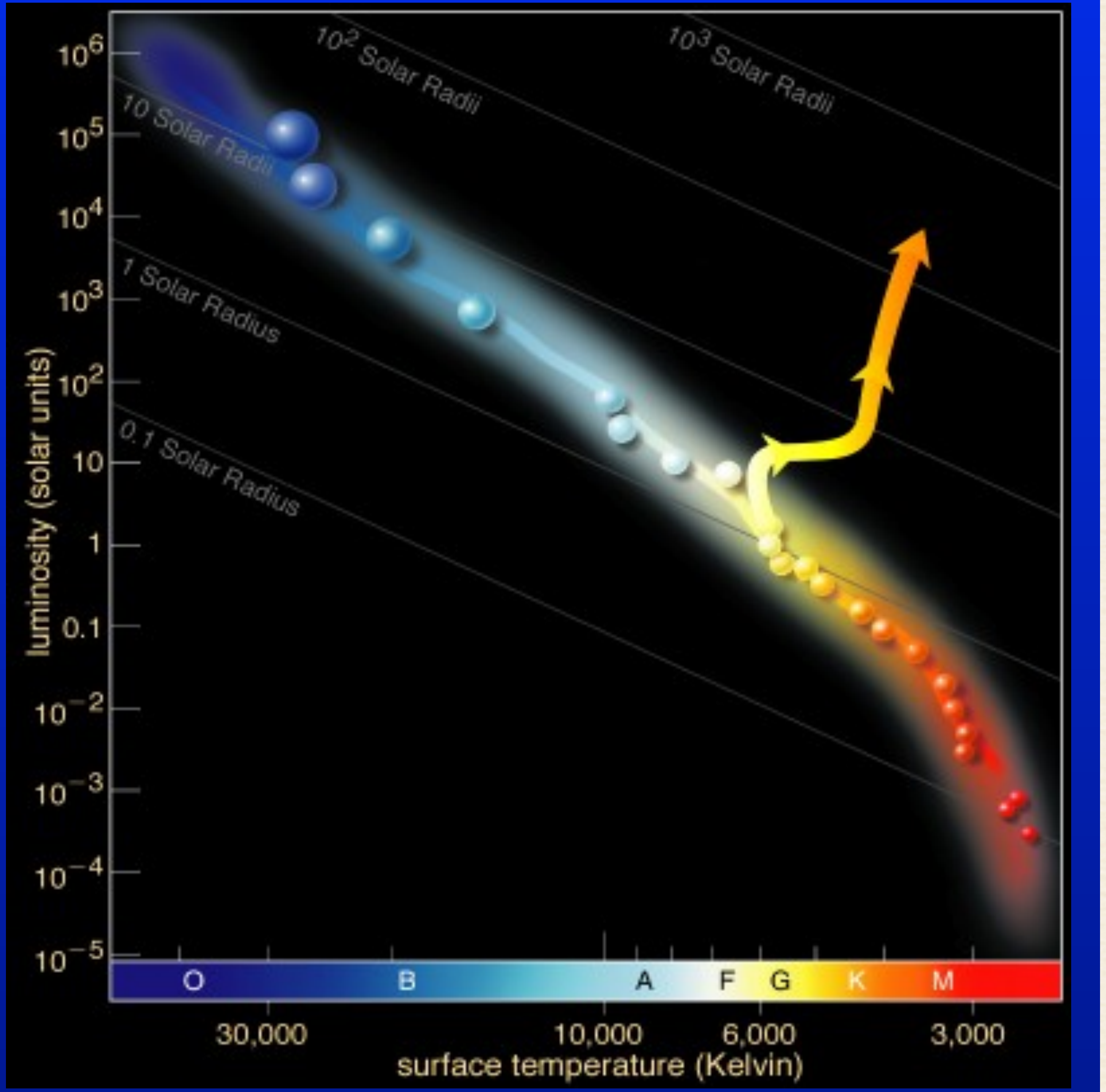


- As core collapses, hydrogen SHELL burns faster and faster – more energy created

- Luminosity increases, lifts outer parts of star

- Star becomes brighter, larger and cooler!!

- All the while, the core is continuing to shrink and is heating up.



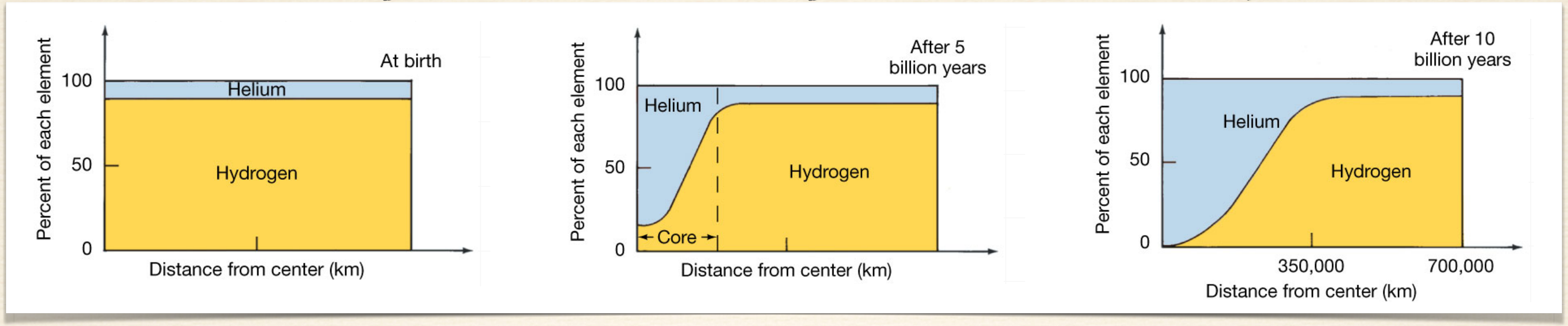
- As hydrogen fuses to form helium @ star's core
  helium formed is denser and tends to accumulate in central core
- As core of helium grows
  hydrogen continues to fuse in a shell around it
- When much of hydrogen within core has been consumed
  production of energy decreases at center and . . .
  cannot prevent gravitational force to contract and heat up core
- Hydrogen in shell around core fuses more fiercely
  as T rises causing outer envelope to expand and cool
- Surface T reduces ☞ spectrum peaks at longer wavelength
  (reddish)
- By this time the star has left the main sequence:
  - It has become redder
  - It has grown in size
  - It has become more luminous
  - It enters red giant stage
- Model explains origin of red giants as step in stellar evolution

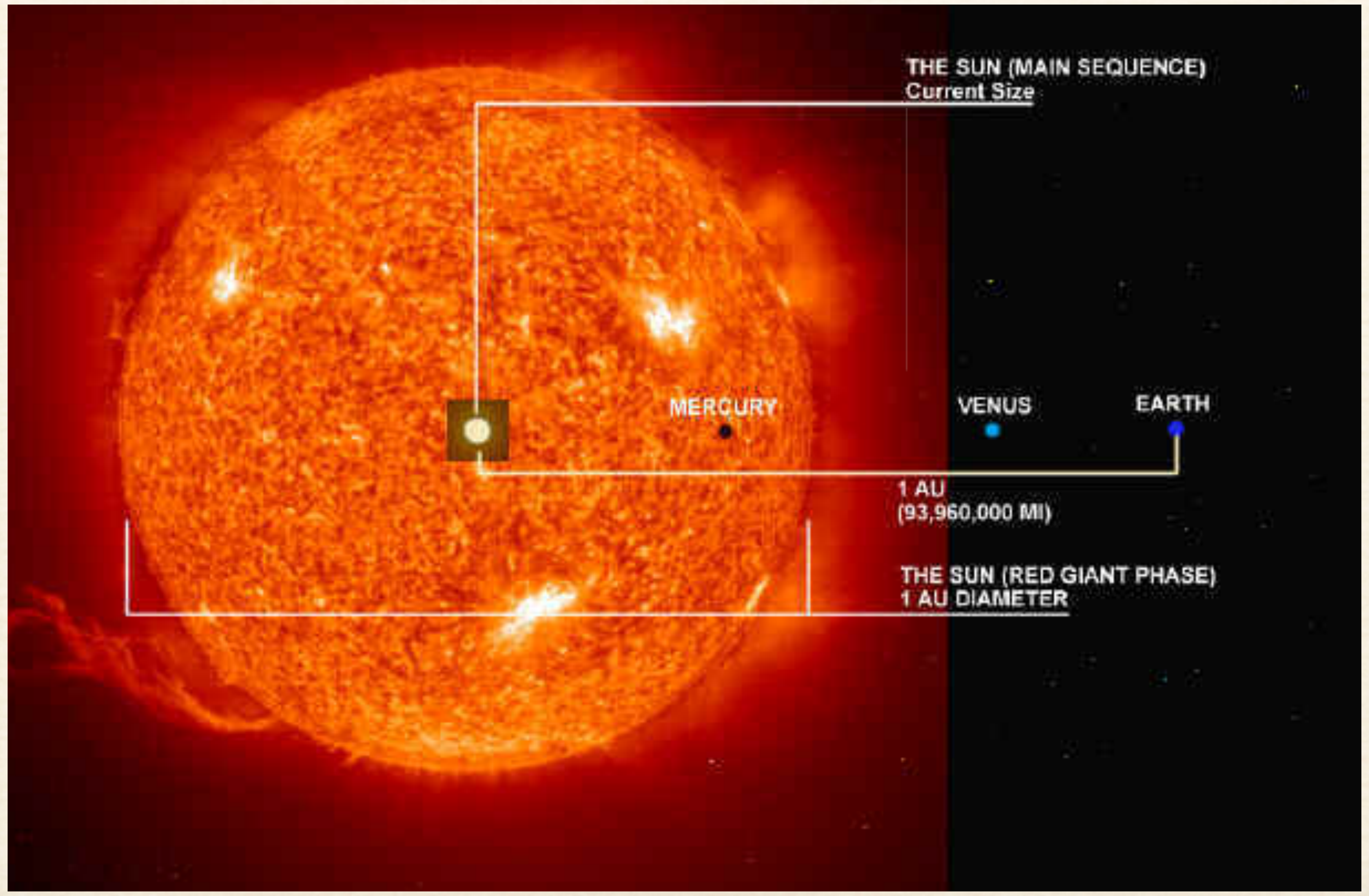
EXAMPLE

Sun has been on main sequence for ~ four and a half billion years

It will probably remain there another 4 or 5 billion years

As becomes red giant expected to grow out to Mercury's orbit





What happens to the Earth?

- Red giants have sizes up to 100 x the Sun's radius, 1000 times the luminosity

- Sun will swallow Mercury, Venus… EARTH!!!

In 5-7 billion years, we will be toast.

Putting Doom into Perspective

- 65 million years ago, the dinosaurs died
- Present-day mammals (like us) evolved from small rodents alive at that time
- In the next 5 billion years, we have about 80 equal sized time intervals - enough time to re-evolve over and over again if necessary

A star moves upwards and to the right on the HR diagram. What is probably happening in the core?

A. The core has just started to burn a new element
B. All nuclear burning is slowing down
C. The inner core temperature is cooling
D. The inner core is collapsing and heating up; shell burning is increasing

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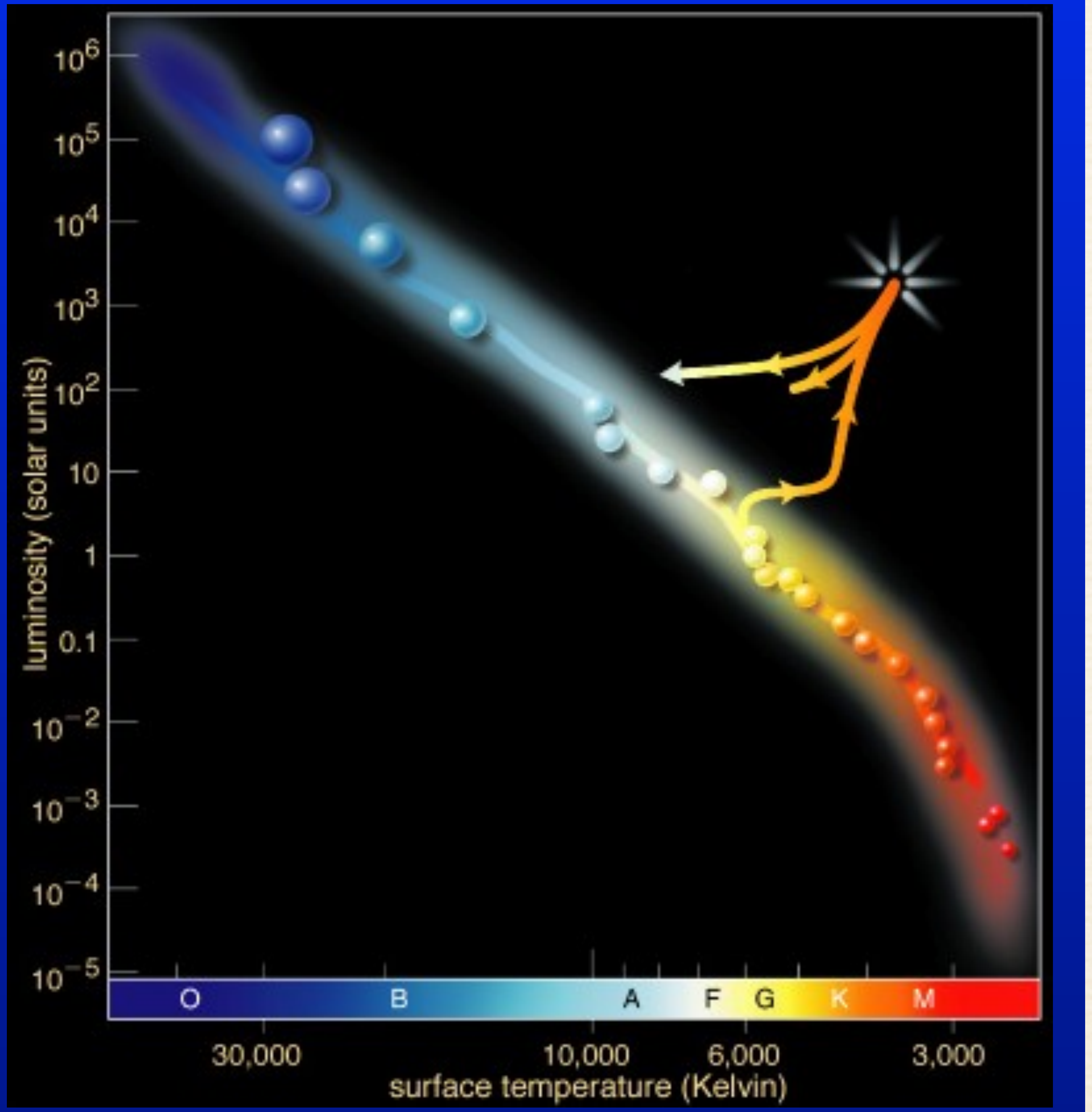
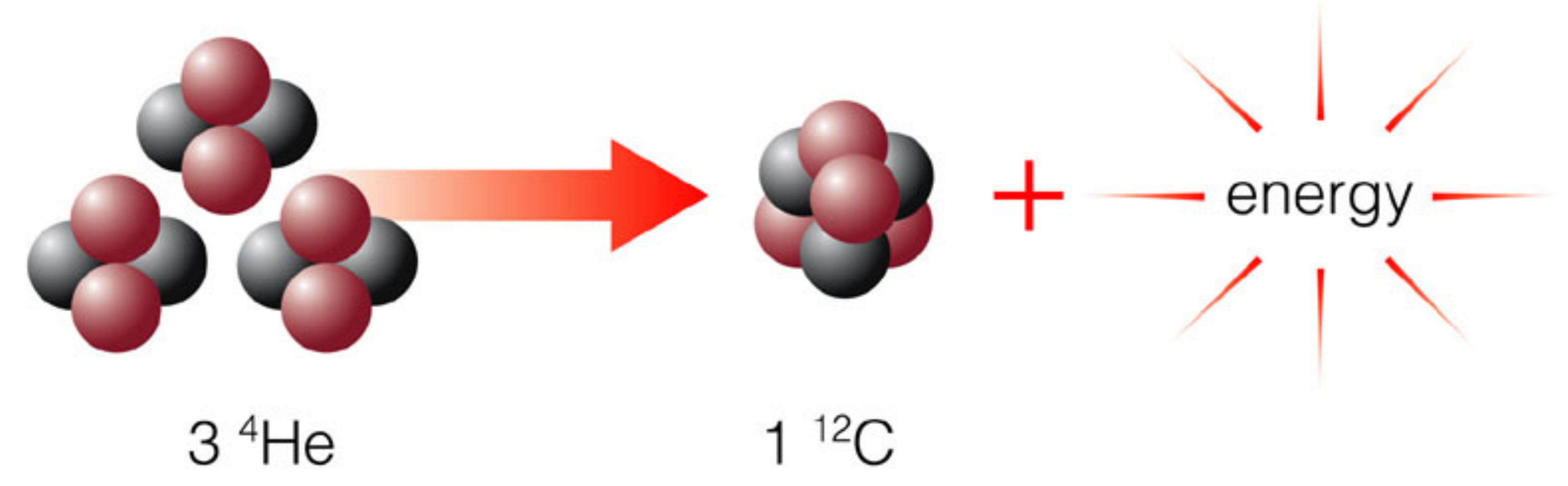
Eventually, The Core Is Hot Enough To Burn Helium

- At Temp >10^8 K – helium flash occurs and helium ignites.
- Hydrostatic equilibrium has been restored and the core is now balanced again… happily burning helium to carbon as a Horizontal Branch Star



Helium Fusion

- Temperatures ~ 100 million K
- He + He + He → C + energy
  - Triple-alpha process



What Will Happen When There Is No More Helium in the Core?

A. The core will cool down.
B. The core will start to collapse.
C. Carbon fusion will start immediately.
D. The star will explode.

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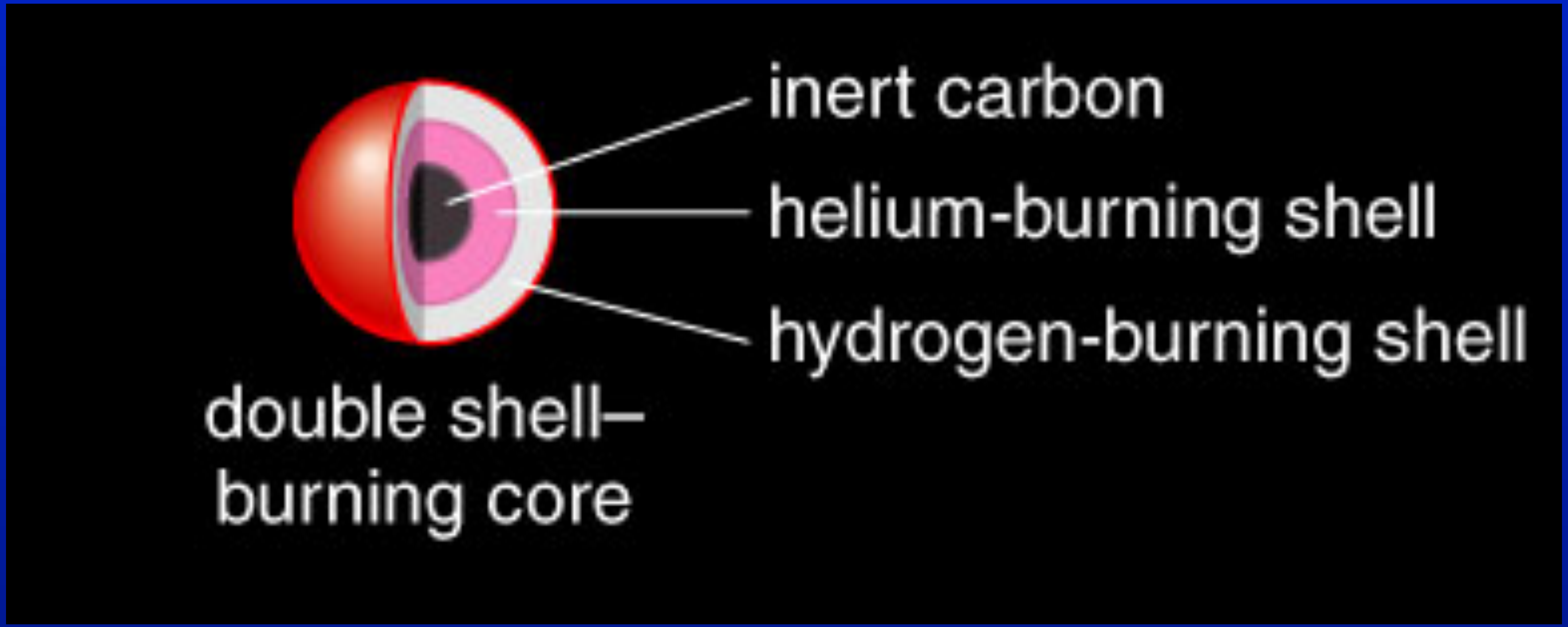
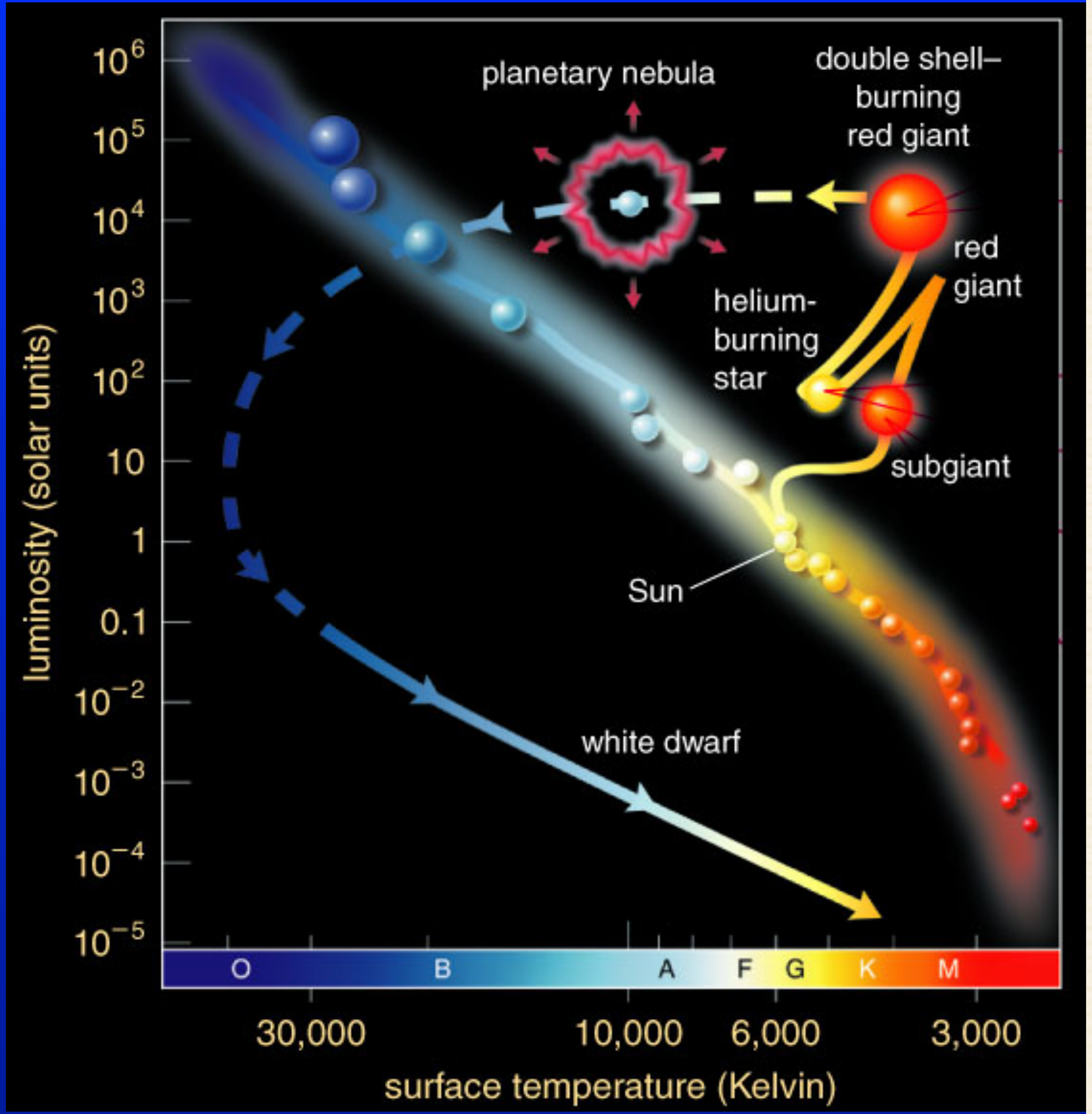
When helium runs out….

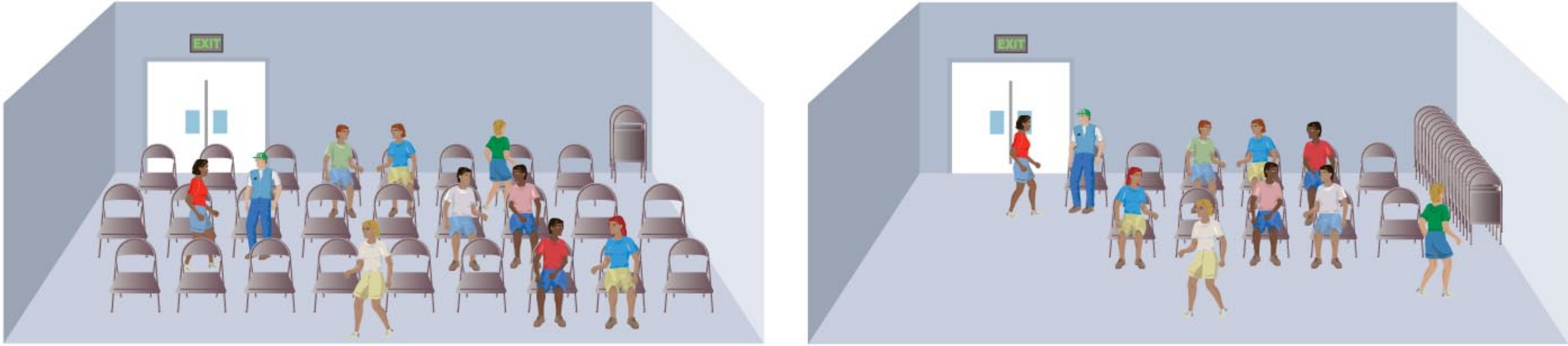
- Carbon core collapses and heats up
- Triggers burning in helium AND hydrogen shells
  - Shell burning now unstable = Thermal Pulses



- Energy generation becomes much higher *again*
- Outer layers lift and cool *again*
- Star becomes very luminous red giant
  - Class II



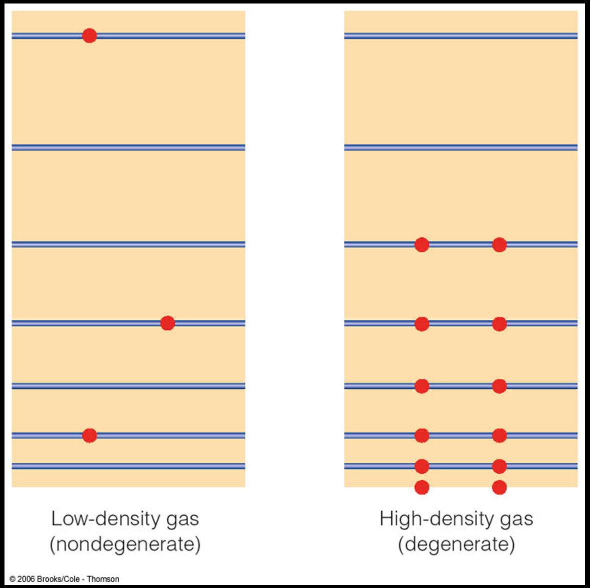
Degeneracy Pressure



a When there are many more available quantum states (chairs) than electrons (people), an electron is unlikely to try to enter the same state as another electron. The only pressure comes from the temperature-related motion of the electrons, which is thermal pressure.

b When the number of electrons (people) approaches the number of available quantum states (chairs), finding an available state requires that the electrons move faster than they would otherwise. This extra motion creates degeneracy pressure.

Q: The Helium core contracts and heats the star enough to induce a hydrogen-burning shell… so what stops the helium core from contracting to zero radius (keep in mind that He fusion has not set in yet….)?



A: Degeneracy pressure!

The core becomes very dense… and two laws of quantum mechanics become important:

1. Energy is quantized
2. Pauli exclusion principle

All energy levels below the "Fermi energy" are filled.

The electrons are not free to change their energy.

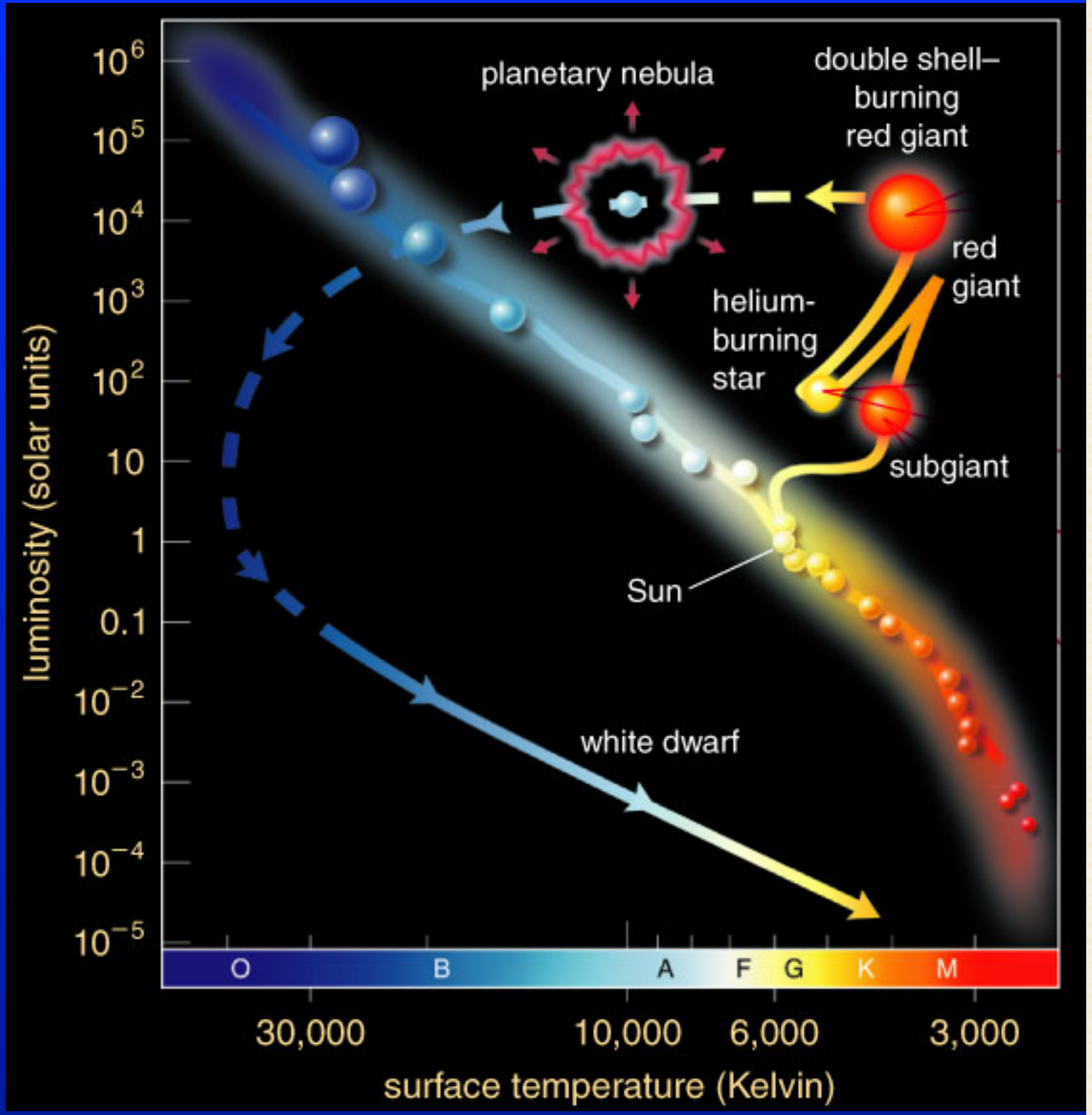
Q: What happens when we "push" on this gas?

A: Nothing! To compress it requires tremendous energy because we would have to change the electron's energy state. It resists compression!

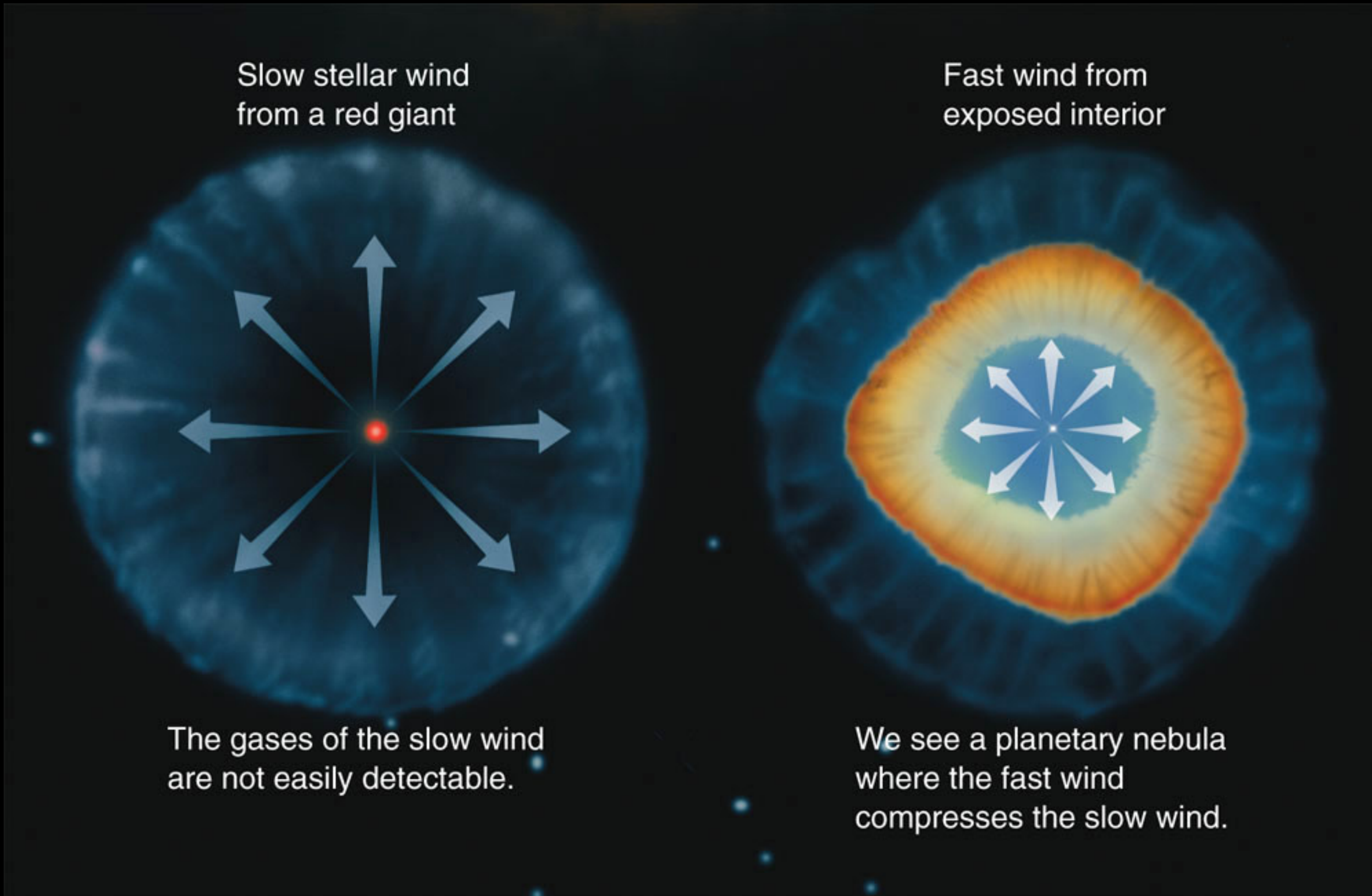
Q: What if we increase the temperature?

A: This temperature mostly goes into speeding up the nuclei… *not* the electrons.

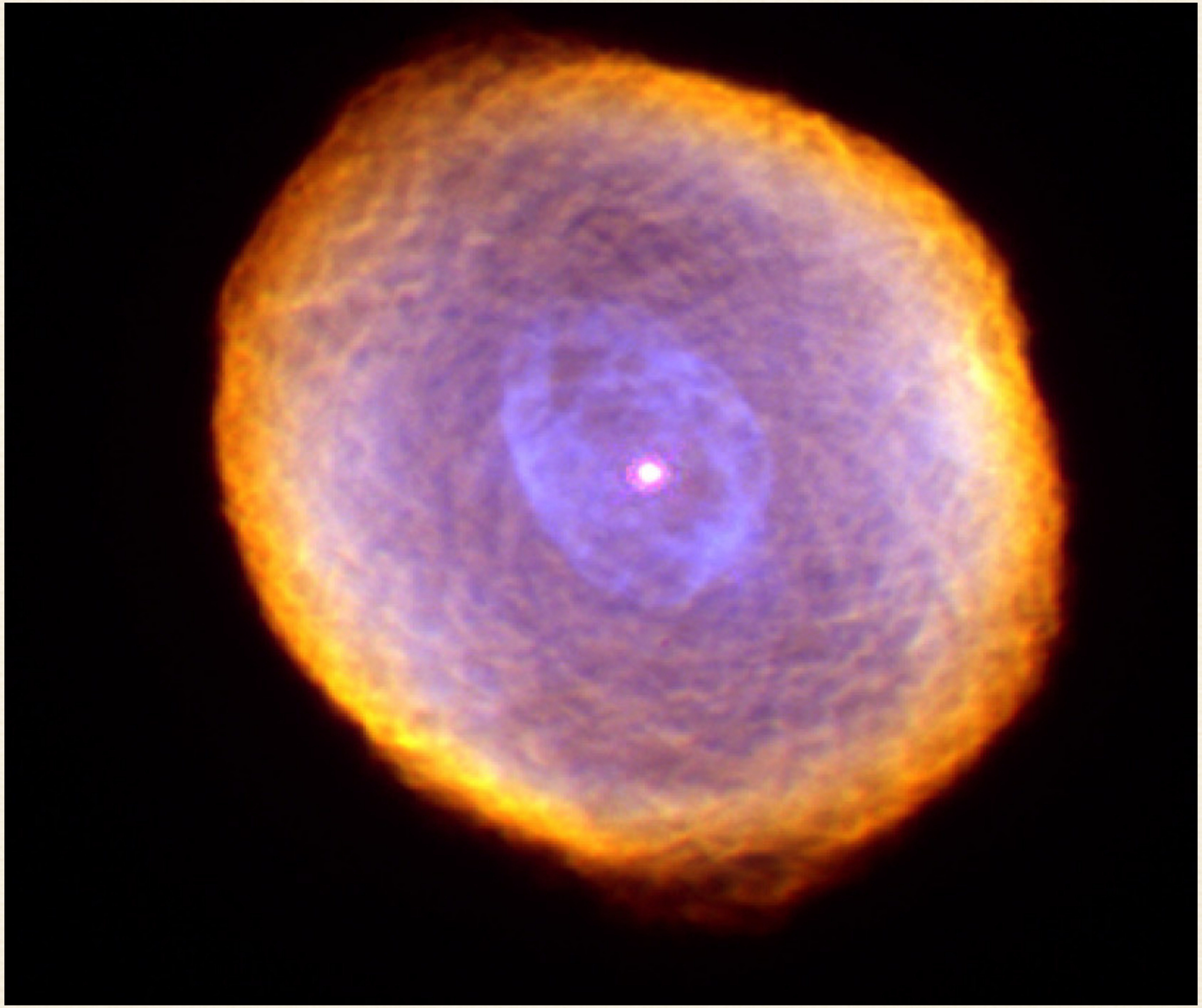
- Degeneracy pressure halts gravitational collapse before T=600 million K is reached
  - No carbon fusion
- Stellar winds blow material from the outside
  - including some carbon that gets to the outer layers via convection
- Outer layers thrown off in a **big puff** around the inert carbon core
  - Big puff = Planetary Nebula
  - Inert carbon core = White Dwarf
    - Slowly cools and fades until it becomes a nearly invisible "black dwarf"



Planetary nebulae:

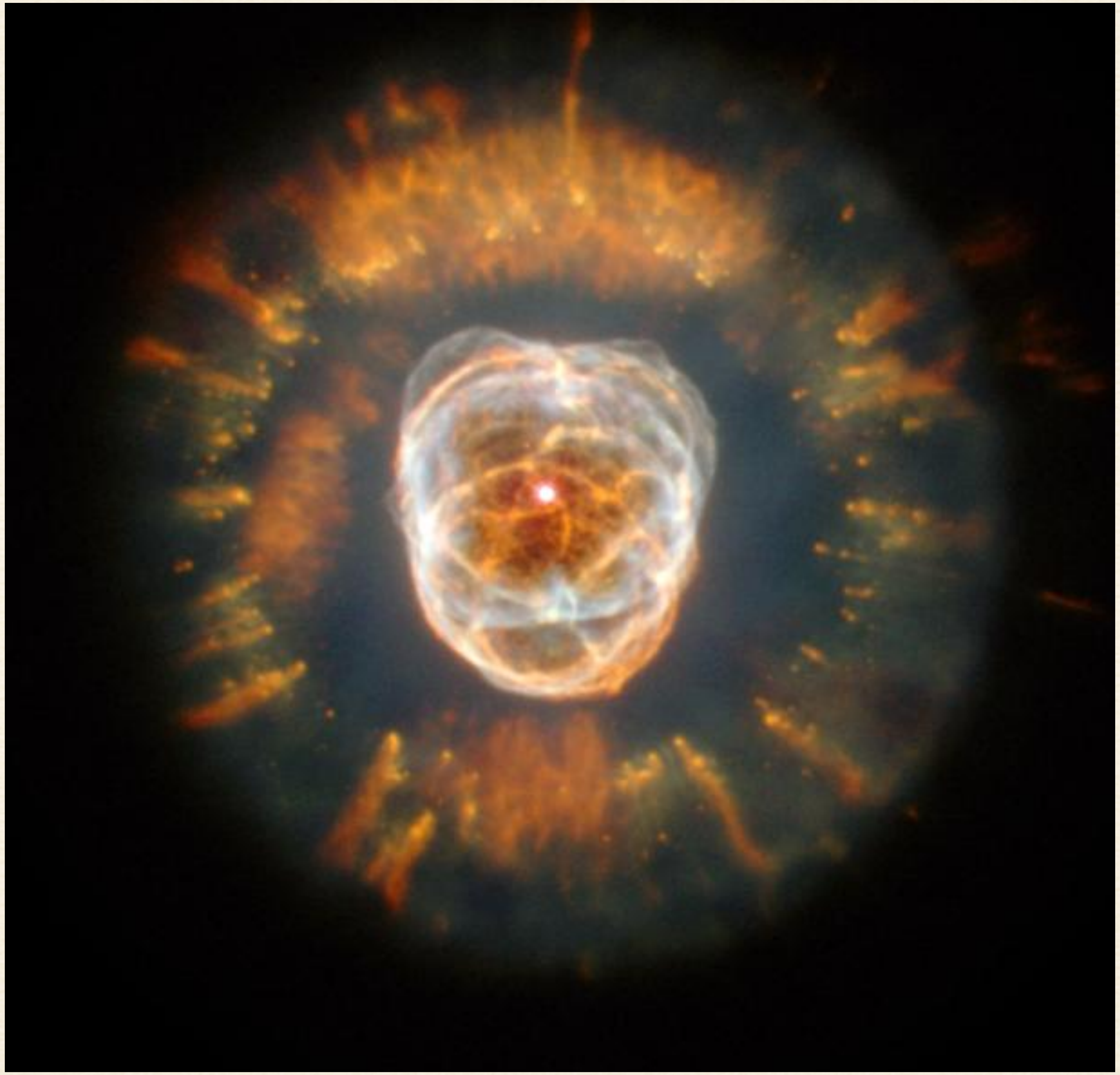


IC 418: The Spirograph nebula



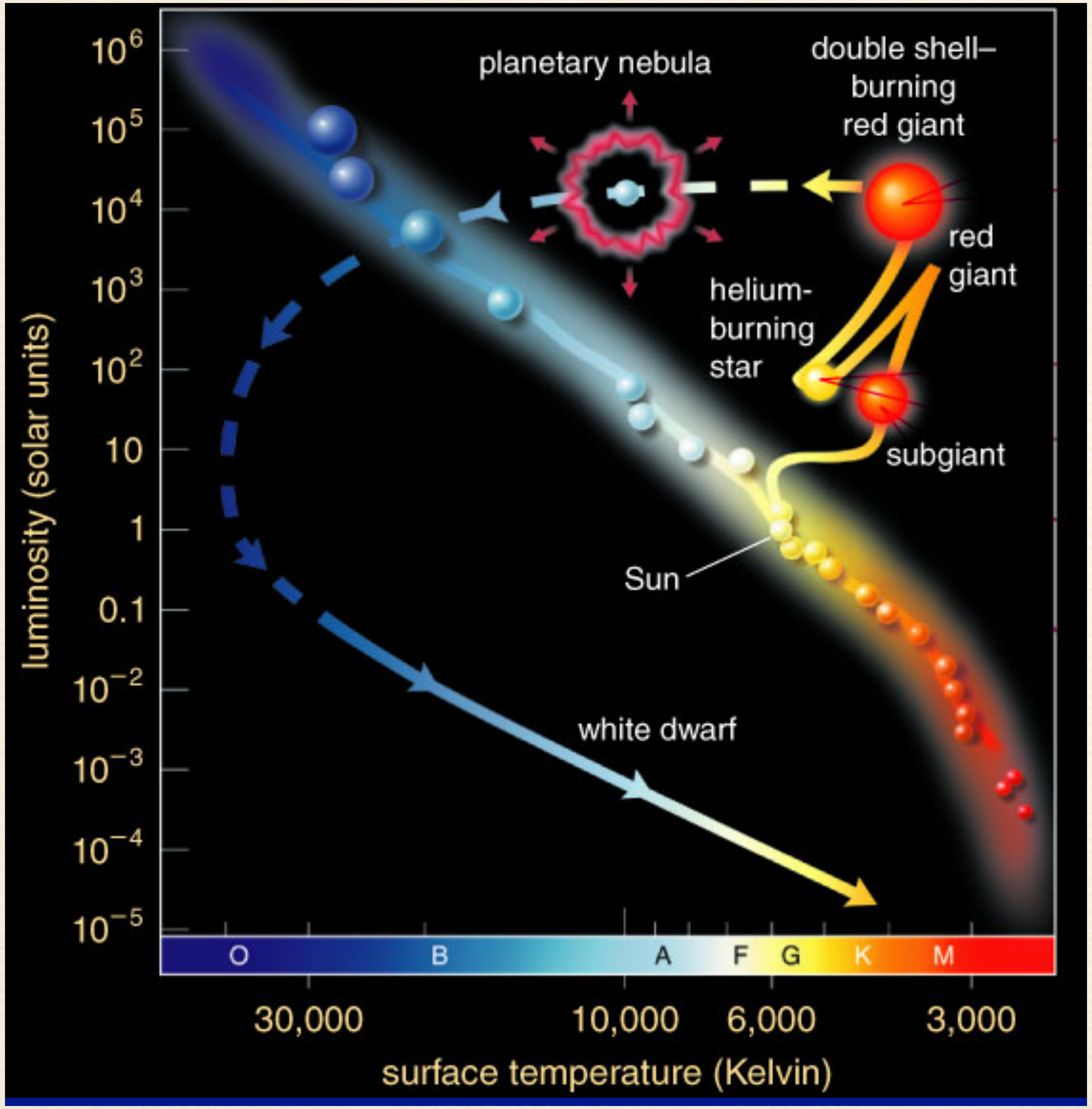
NGC 6826: The Blinking Eye Nebula

NGC 2392: The Eskimo Nebula



NGC 7293: The Helix Nebula

Life of a Low-Mass Star



End State

Planetary Nebula

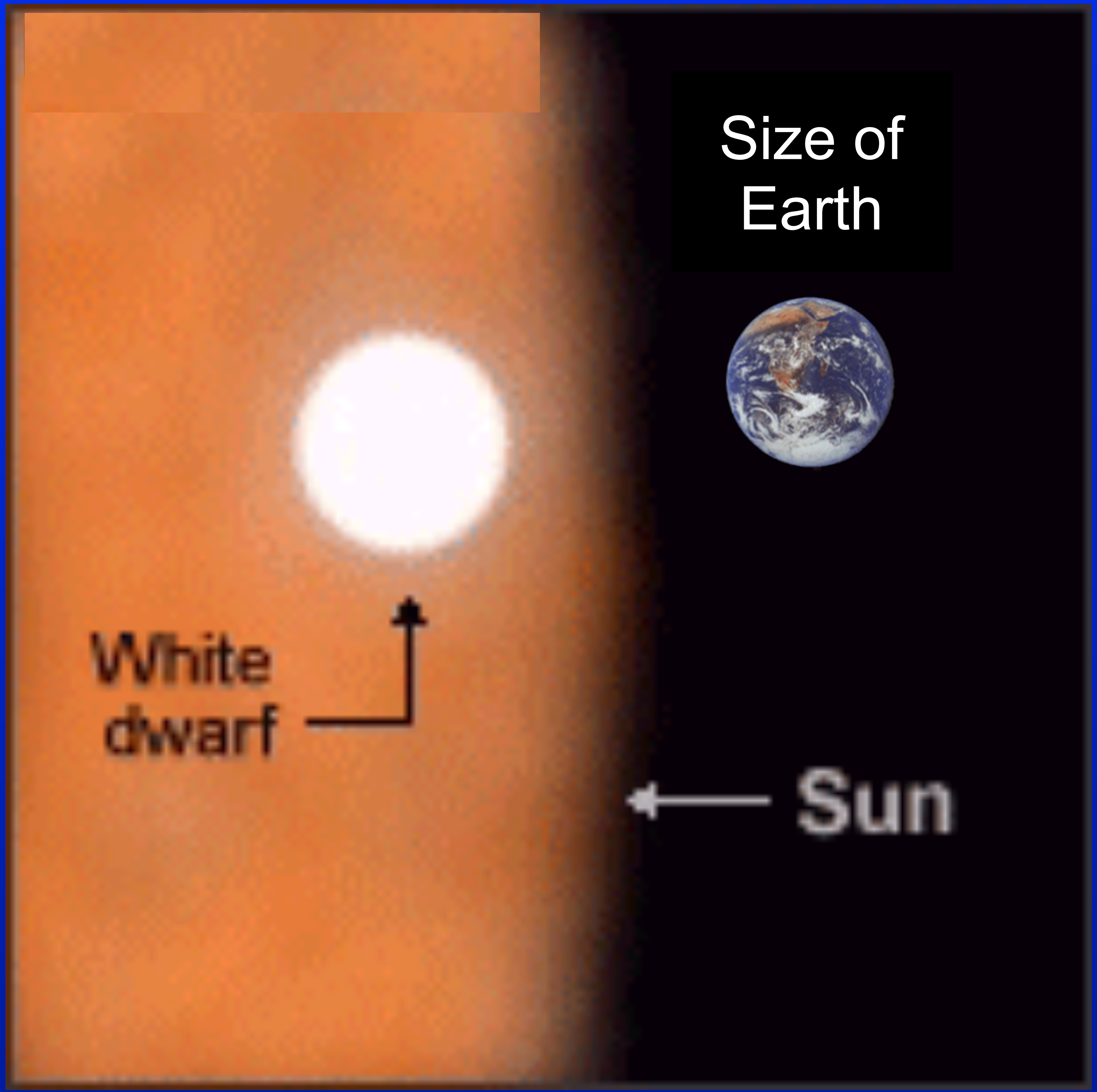
+

White Dwarf

Sirius

- Sirius @ 2.6 pc ☞ fifth closest stellar system to Sun
- Analyzing motions of Sirius Bessel concluded
  it had an unseen companion with an orbital period $T \sim 50$ yr
- In 1862 ☞ Clark discovered this companion ☞ Sirius B
- Following-up observations showed that for Sirius B $M \approx M_\odot$
- Sirius B's peculiar properties were not established until 1915
- Adams noted high temperature of Sirius B ☞ $T \simeq 25,000$ K
  which together with its small luminosity ☞ $L = 3.84 \times 10^{26}$ W
  requires extremely small radius and thus large density of this star

Size Of A White Dwarf



Which is correct order for some stages of life in a low-mass star?

A. protostar, main-sequence star, red giant, planetary nebula, white dwarf
B. main-sequence star, white dwarf, red giant, planetary nebula, protostar
C. protostar, main-sequence star, planetary nebula, red giant
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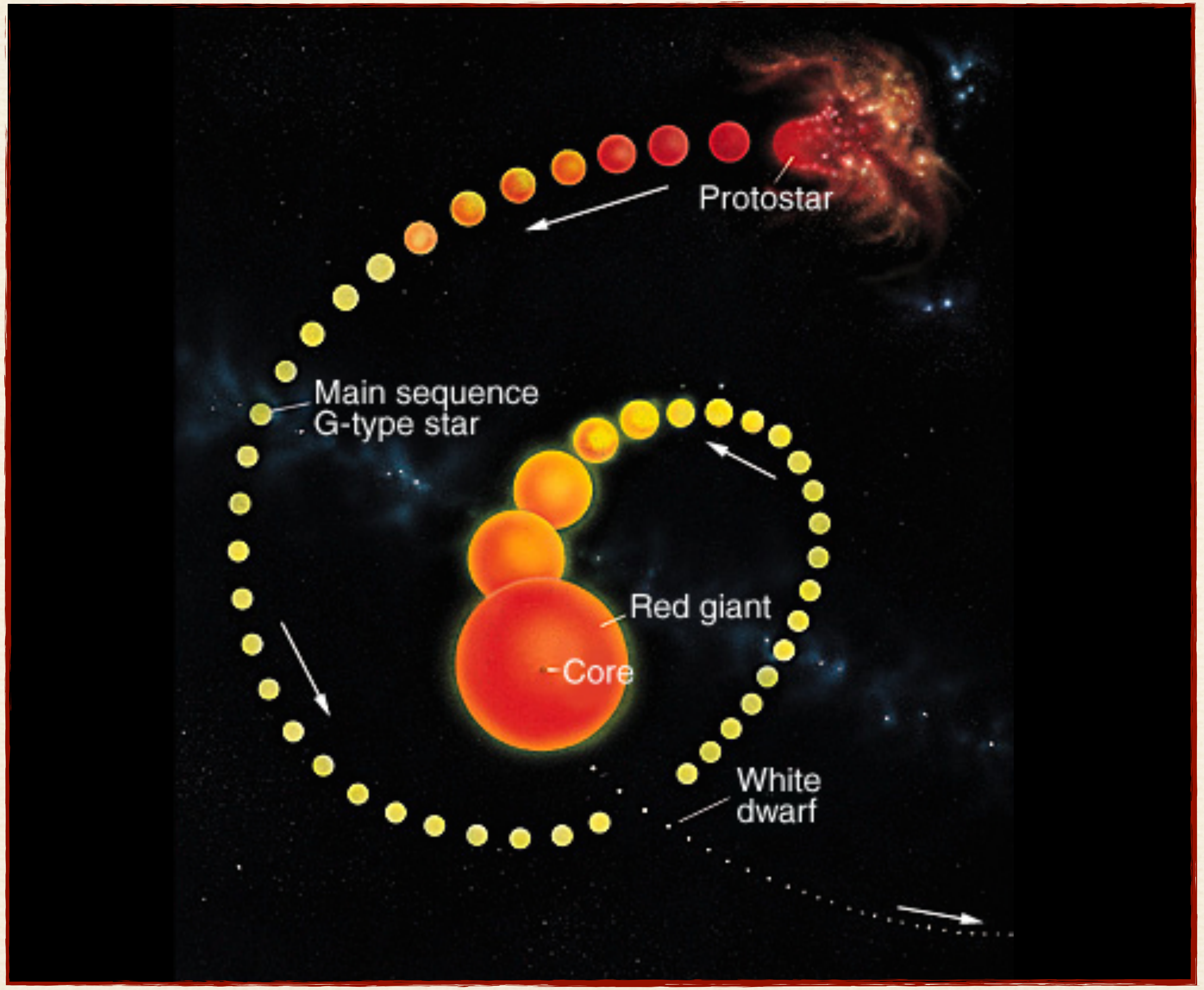
Time scales for Evolution of Sun-like Star

H core burning	Main Sequence	10^{10} yr 10 billion years
Inactive He core, H shell burning	Red Giant	10^{8} yr 100 million years
He core burning (unstable)	Helium Flash	Hours
He core burning (stable)	Horizontal Branch	10^{7} yr 10 million years
C core, He + H shells burning	Bright Red Giant	10^{4} yr 10 thousand years
Envelope ejected	Planetary Nebula	10^{5} yr 100 thousand years
Cooling C/O core	White Dwarf	-
Cold C/O core	Black Dwarf	∞

Life cycle of the Sun



QUERY 20

Einstein showed that mass (m) and energy (E) are interchangeable: $E = mc^2$, where **c** is the speed of light

This implies, for instance, that 1 kilogram of matter is equivalent to an energy $E = (1\ kg) \times (3 \times 10^8\ m/s)^2 = 9 \times 10^{16}\ kg\ m^2/s^2$

An energy of $1 kg\ m^2/s^2$ is known as 1 joule, for short

The Sun actually does convert mass into energy; it does this by nuclear fusion

During one second, the Sun produces an energy $E = 3.9 \times 10^{26}$ joules, which then is carried away by photons

How much mass m must the Sun convert into energy E each second?

QUERY 20

The amount of mass required to create E = 3.9 × 10^{26} joules = 3.9 × 10^{26} kg m^2 / sec^2 is

$$M = \frac{E}{c^2} = \frac{3.9 \times 10^{26}\,\mathrm{kg\,m^2/sec^2}}{(3 \times 10^8\,\mathrm{m/sec})^2} = 4.33 \times 10^9\mathrm{kg}$$

In other units, this is nearly 900,000 elephant-masses

QUERY 21

The mass of the Sun is $M_\odot = 2 \times 10^{33}$ grams

The mass of a hydrogen atom is $m_H = 1.7 \times 10^{-24}$ grams

If the Sun consisted entirely of hydrogen atoms, how many atoms would it contain?

Dividing this number of atoms by the volume of the Sun, show how many hydrogen atoms there would be, on average, per cubic meter of the Sun

QUERY 21

The total number of hydrogen atoms in the Sun is the mass of the Sun divided by the mass of a single hydrogen atom:

$$N_{\mathrm{H}} = \frac{M_\odot}{M_{\mathrm{H}}} = \frac{2 \times 10^{33} \text{ grams}}{1.7 \times 10^{-24} \text{ grams}} = 1.176 \times 10^{57}$$

The radius of the Sun is

$$R_\odot = 7 \times 10^5 \text{km} \left(\frac{1000 \text{ m}}{1 \text{ km}} \right) = 7 \times 10^8 \text{ m}$$

The volume of the Sun then is

$$V_\odot = \frac{4}{3} \pi R_\odot^3 = \frac{4}{3} \pi (7 \times 10^8 \text{ m})^3 = 1.437 \times 10^{27} \text{ m}^3$$

The number of hydrogen atoms per cubic meter of the Sun is then

$$\frac{N_{\mathrm{H}}}{V_\odot} = \frac{1.176 \times 10^{57}}{1.437 \times 10^{27} \text{ m}^3} = 8.18 \times 10^{29} \text{ m}^{-3}$$

QUERY 22

Consider a source which emits energy at a rate of L units per second (the type of source, and the units of L are actually irrelevant for this discussion)

This situation is shown in the diagram of Fig. 1

Consider a sphere centered on the source, and surrounding it at a radius r

If we assume the energy flows out isotropically (this means the flux is the same in all directions) from the source, then the energy received at any point on the sphere should be the same

It is easy to calculate the flux on the sphere, which is the energy as it passes through the sphere (energy/ unit area)

It is just the total energy divided by the surface of the sphere

Now, extend this idea to spheres at different radii: the surface area of each sphere increases as r^2, so the flux of the energy (energy per unit area) must reduce as $1/r^2$

This is known as the inverse square law

QUERY 22

Approximately 1.6×10^{38} neutrinos are produced by the pp chain in the Sun every second

Using the inverse square law calculate the number of neutrinos from the Sun that are passing through your brain every second

Imagine your brain as a circle with a diameter of 15 cm

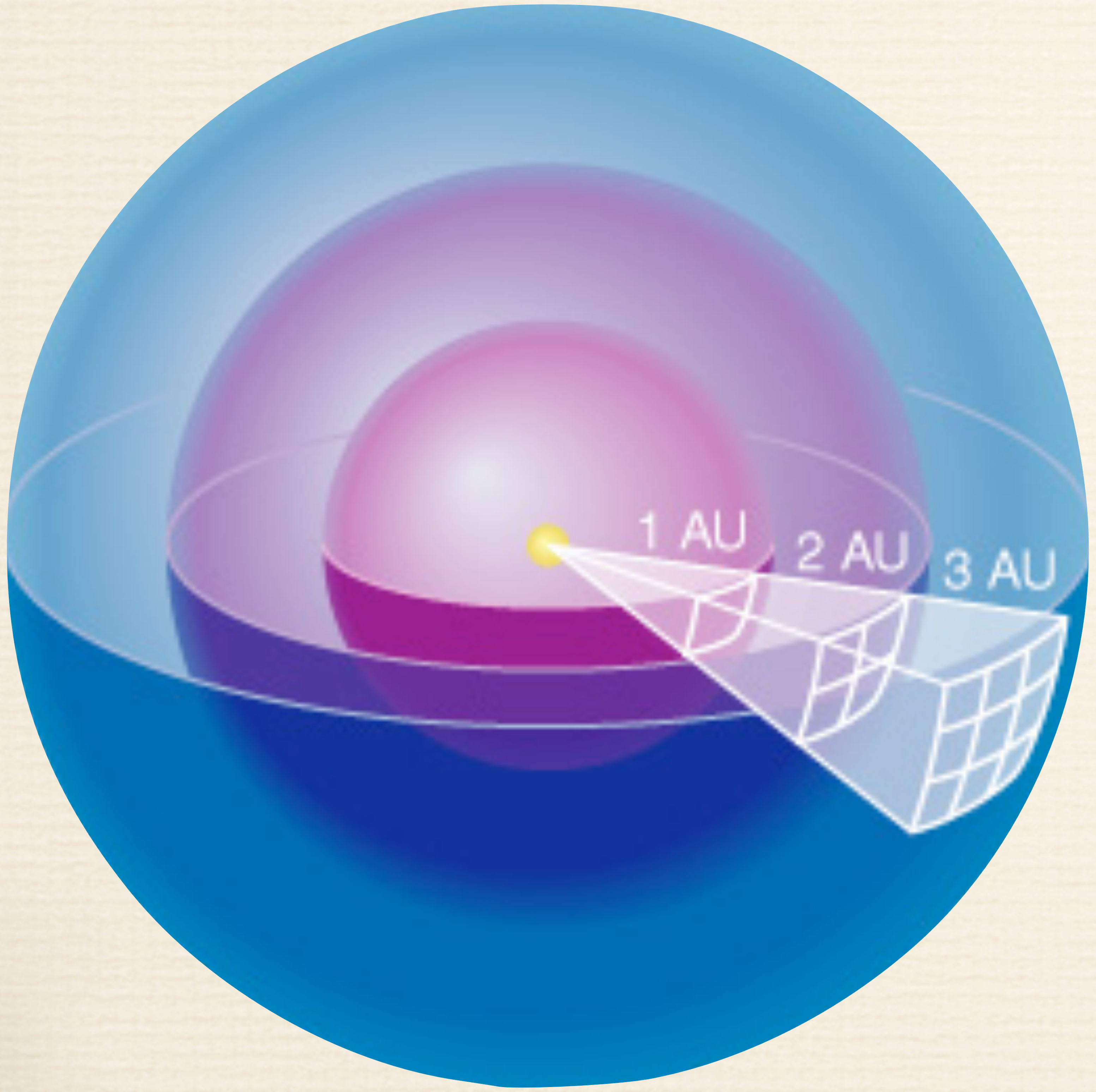


Fig 1: Inverse square law

The energy twice as far from the source is spread over four times the area, hence one-fourth the flux

QUERY 22

The flux density of neutrinos at Earth is

$$\mathscr{F}_\nu = \frac{1.6 \times 10^{38} \text{ neutrinos/s}}{4\pi d^2} = 6 \times 10^{10} \, \frac{\text{neutrinos}}{\text{cm}^2 \text{ s}}$$

where d is the Sun-Earth distance

Thus, the flux of neutrinos passing through the brain per second is

$$\frac{\Delta N_\nu}{\Delta t} = \mathscr{F}_\nu \, A_{\text{brain}} = 6 \times 10^{10} \, \frac{\text{neutrinos}}{\text{cm}^2 \text{ s}} \frac{\pi D^2_{\text{brain}}}{4} \approx 10^{13} \, \frac{\text{neutrinos}}{\text{s}}$$

where we have assumed that the diameter of the brain is $D_{brain} \simeq 15$ cm