ASTR 1120
:: Star and Galaxies ::

The Sun

A mass of incandescent gas.

(or a miasma of incandescent plasma?)

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July 2010

Learning Goals

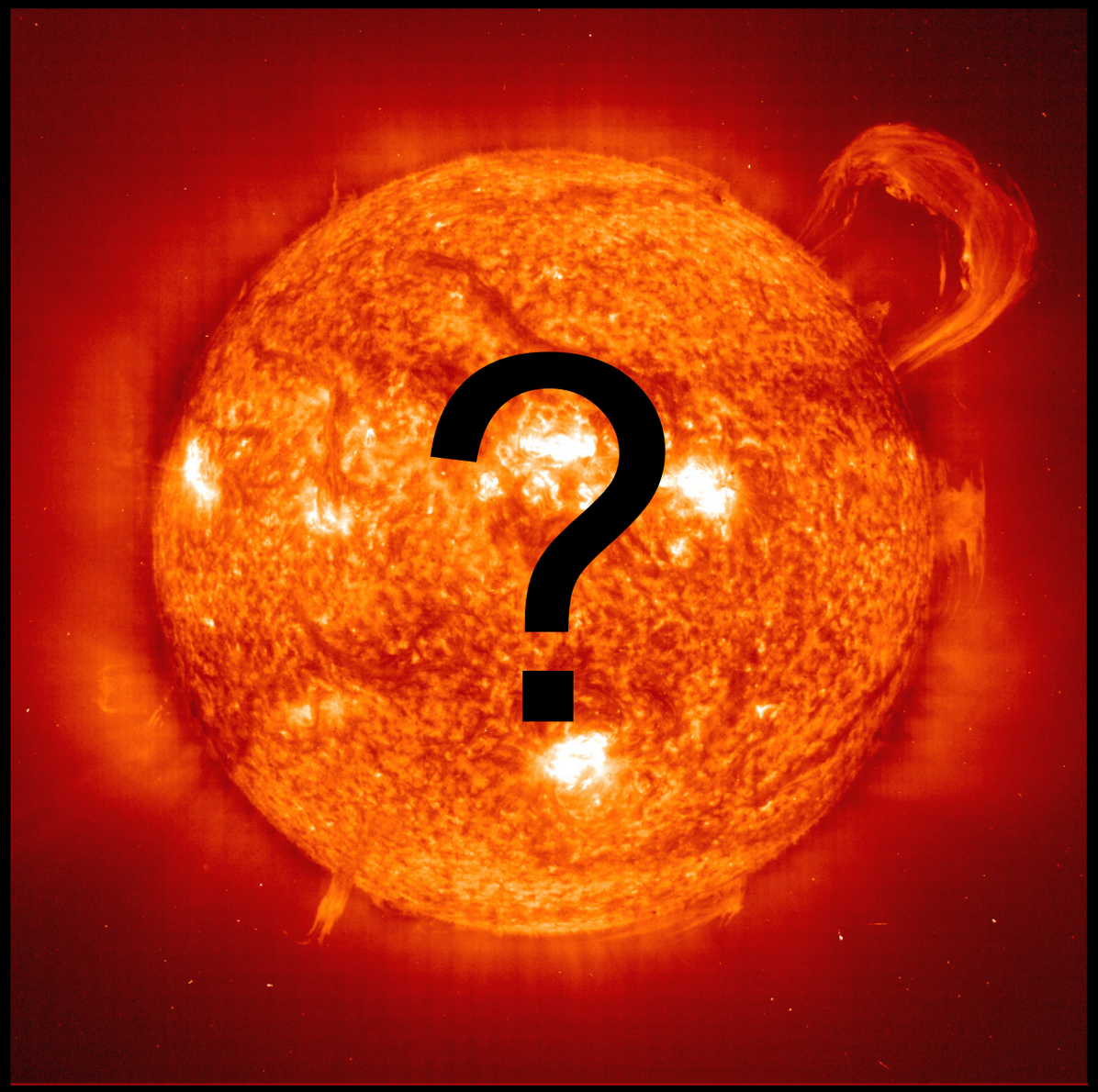
- Nail down basic facts about the sun.
- Understand:
  - What powers the Sun? Early theories and the current model
  - The details of fusion.
  - The structure of the Sun’s interior
  - Observable properties of the Sun

Unlocking the mysteries of our nearest star, the sun.

- If you were an ancient thinker, what might you wonder about the sun? What might you want to know?

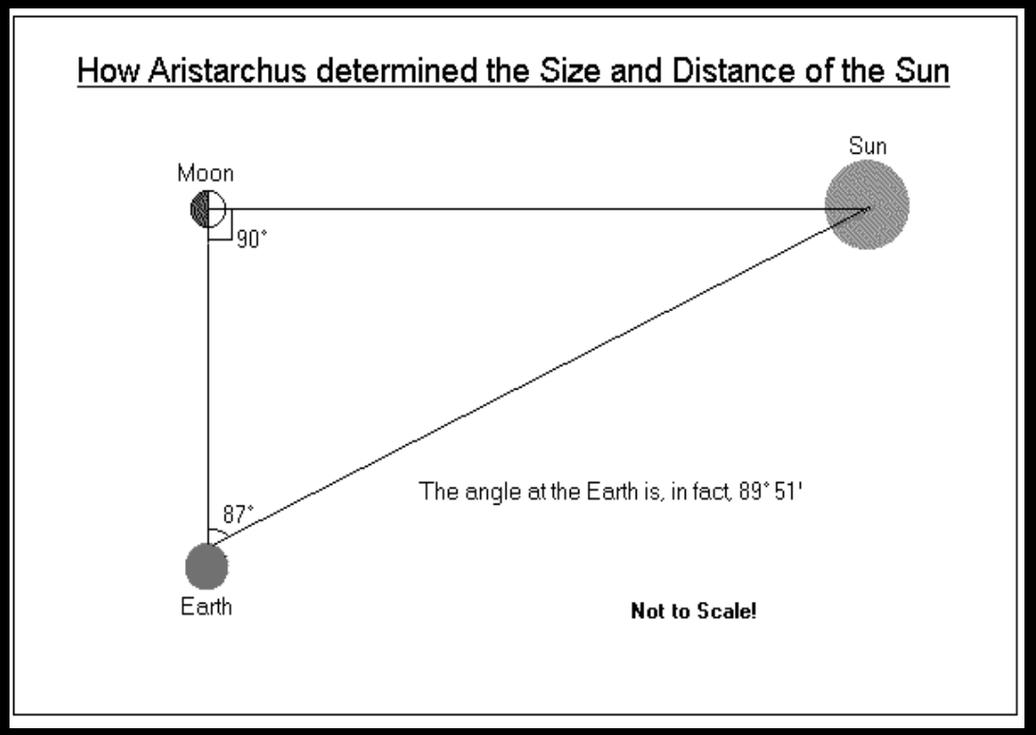
Unlocking the mysteries of our nearest star, the Sun.

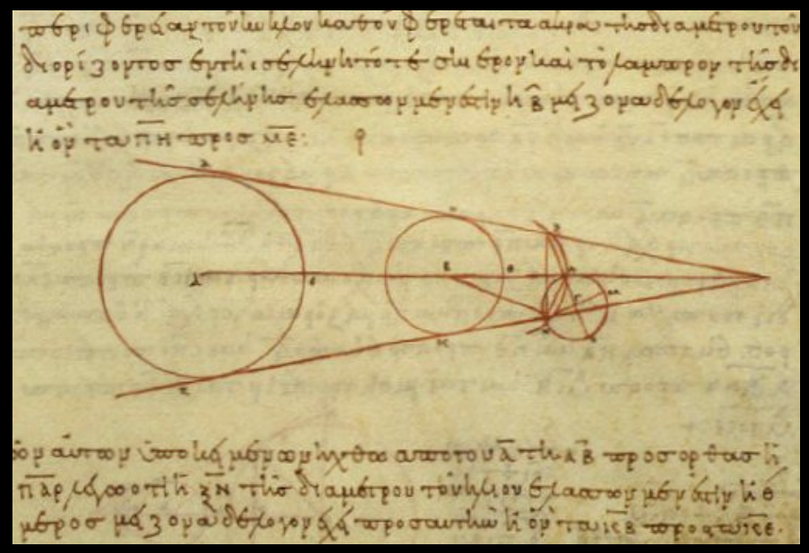
- How far away is the Sun?
- What is the Sun made of?
- What is the relationship between the Sun and the Earth, which body revolves around the other?
- How does the Sun produce its energy?
- How old is the Sun?
- Why is the Sun round?
- What’s the inside of the Sun like?
- What will be the end of the Sun?
- How massive is the Sun?



How far away is the Sun?

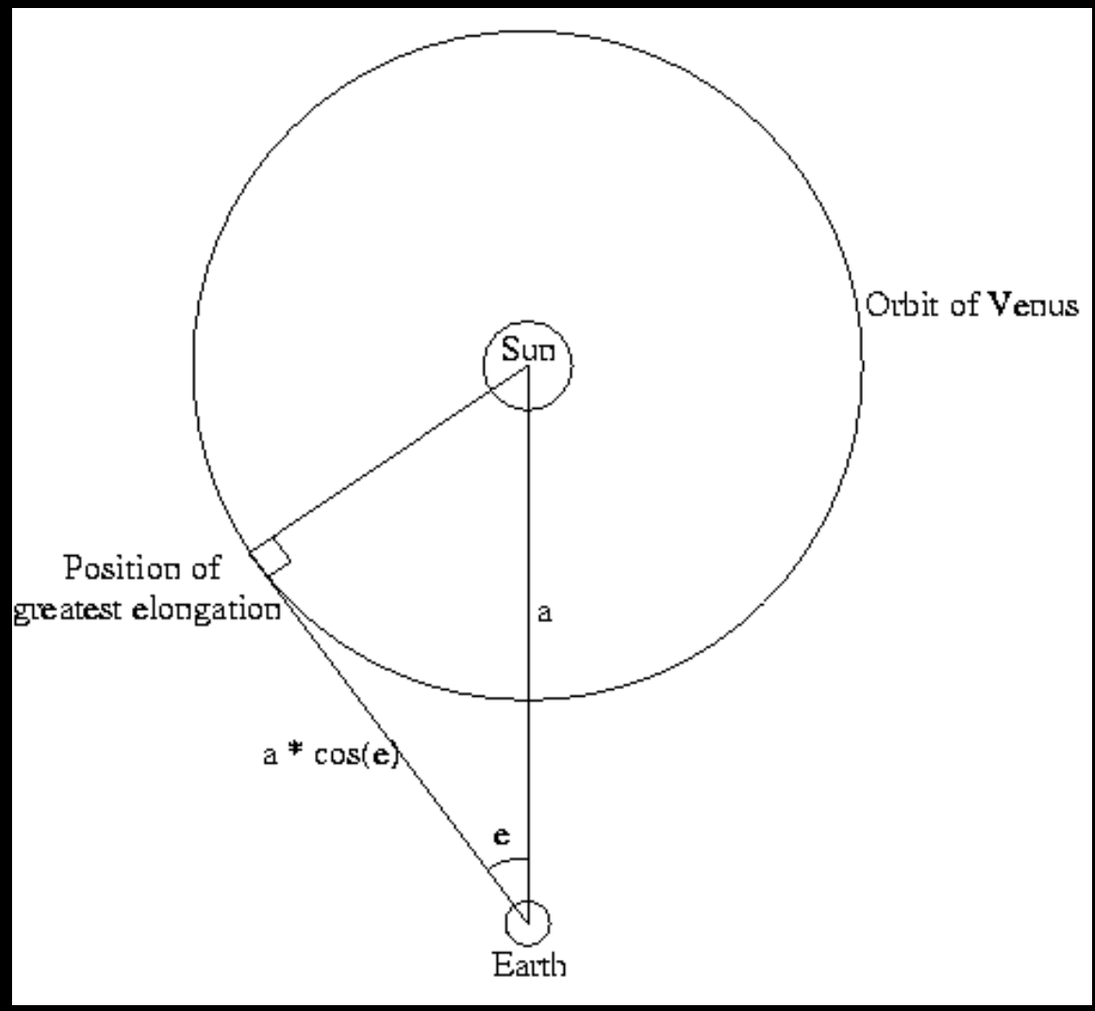
- Aristarchus of Samos (310-230 BC)
- Measured angle between Moon and Sun from Earth
- Estimated Sun is 19x further away than the Moon, and 19x bigger (why?)
- Estimated size and distance to the Moon by comparing size of the Moon to Earth's shadow during a lunar eclipse
- More accurate value of this angle is close to 89° 50', and the Sun is actually about 390 times farther away than the Moon, and 390 times larger





How far away is the Sun?

- Find the distance to an inner planet in Astronomical Units (AU) by direct radar ranging of that object.
- Calculate distance to Sun using trigonometry (like the Greeks)



Modern measurements indicate the Sun is at a mean distance of 150 million km (1 AU), with a diameter equal to 109 times that of the Earth, or 696,000 km

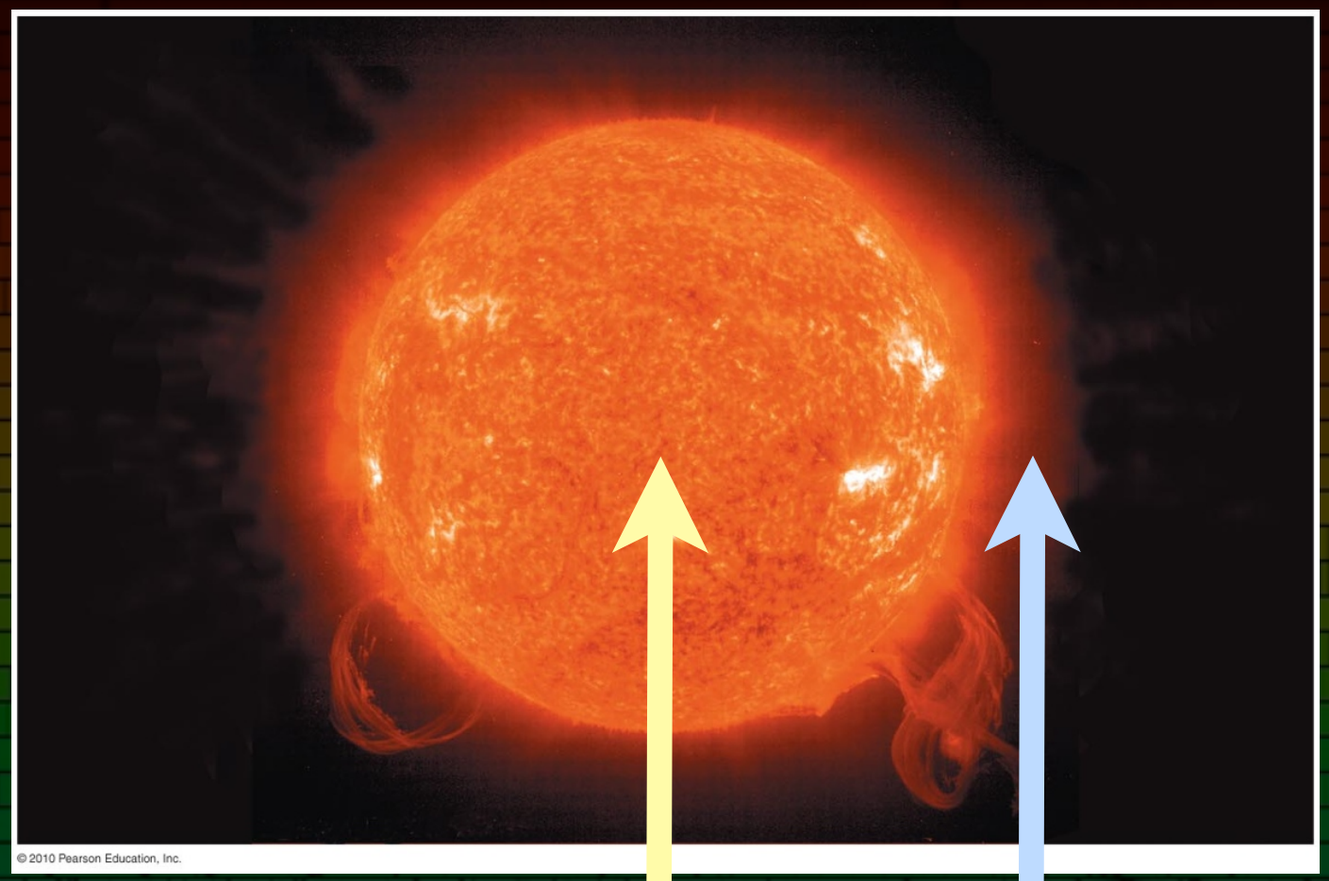
What is the Sun made of?

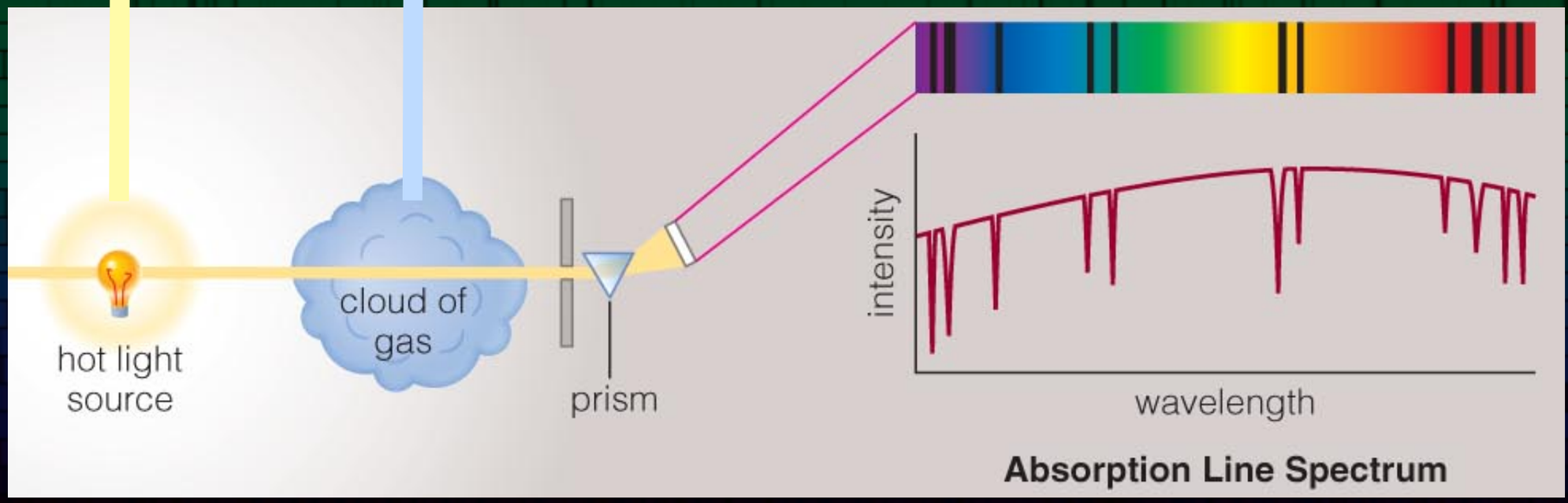
If only we had a means of sorting this out...

What is the Sun made of?

Our favorite spectrum!

What is the Sun made of?

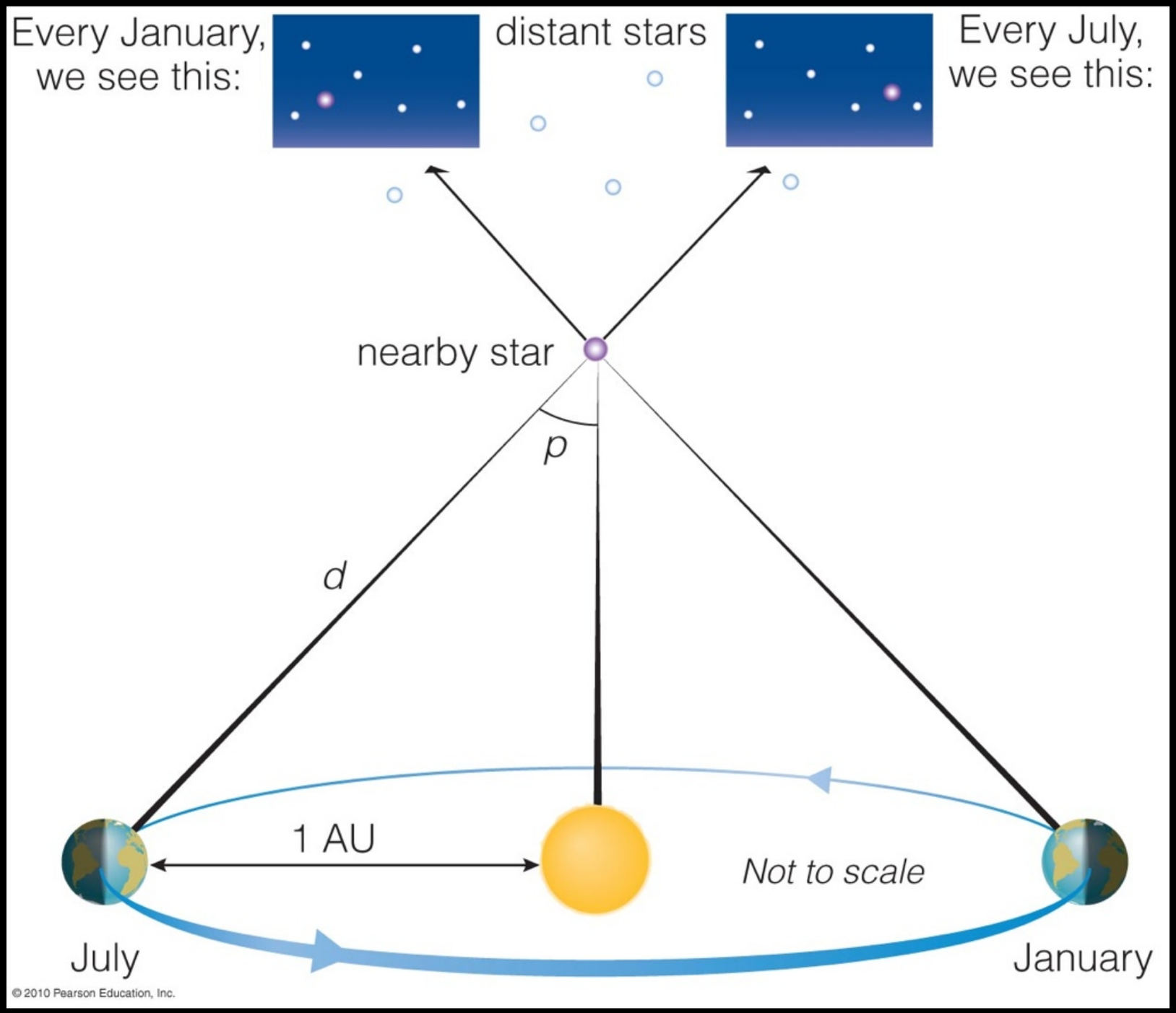




What is the relationship between the Sun and the Earth, which body revolves around the other?

- We need to find a way to determine if the Earth is moving. How might we do that?

Remember from yesterday: Parallax!

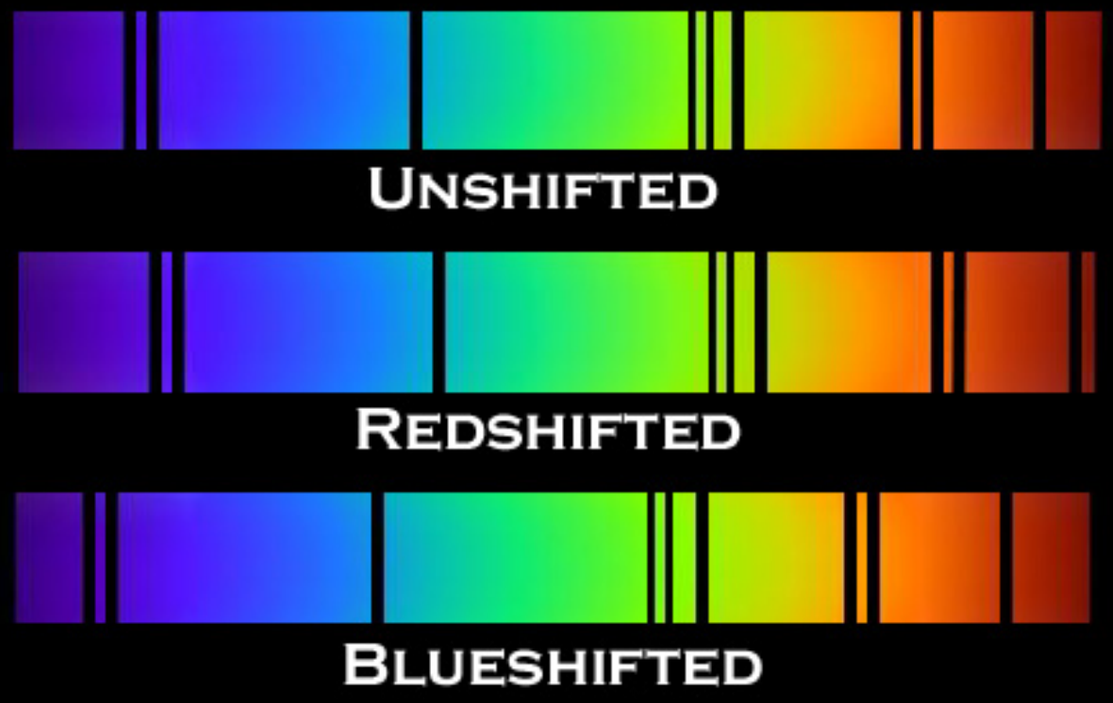


But ancient greeks couldn't resolve the shifts with enough accuracy!

What would a lack of shifts mean?

- The stars are way too far away to observe parallax with the naked eye
- The Earth doesn’t move, it’s the center of the universe!

Direct proof that we are moving:
Doppler Shift!

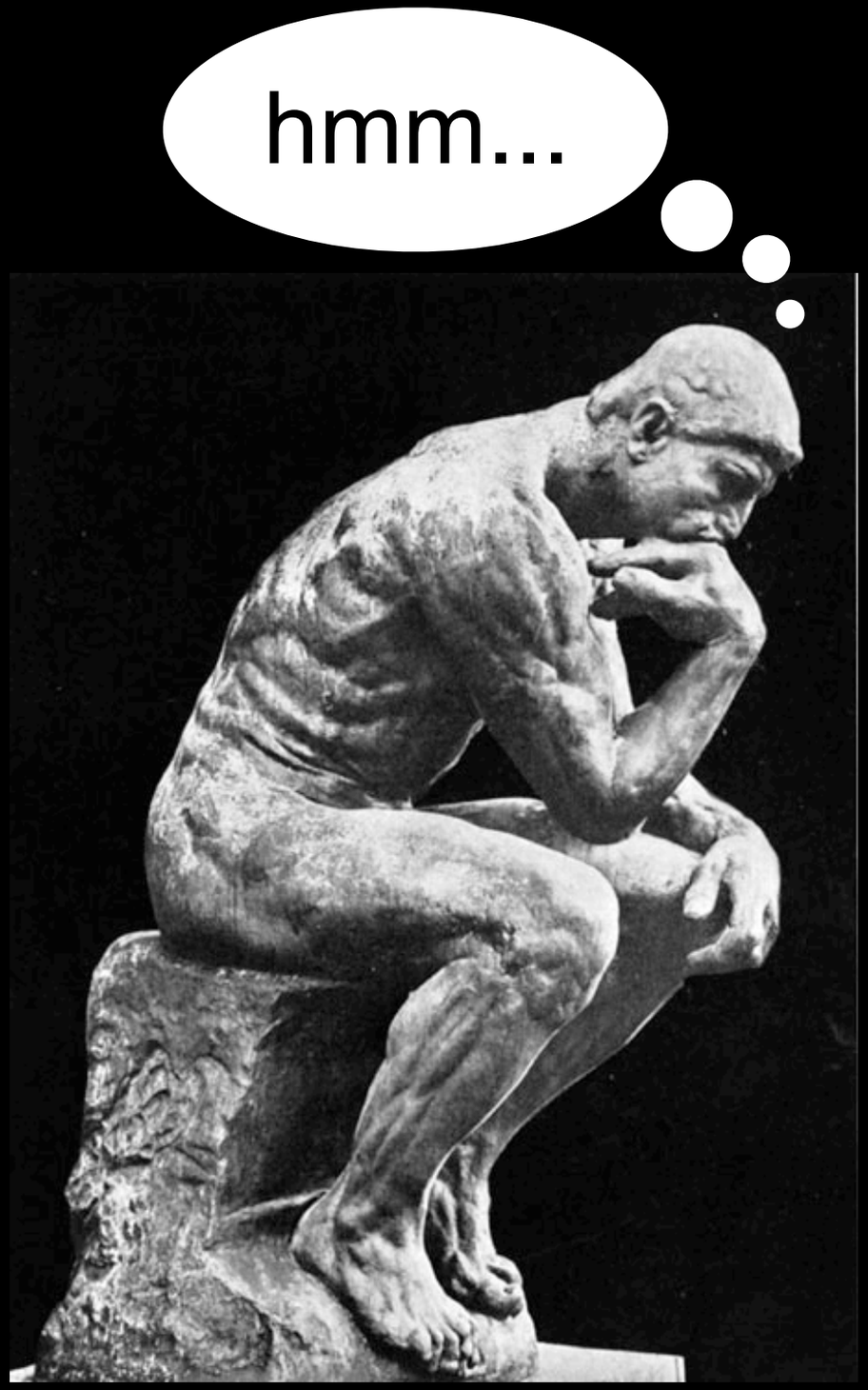


As we move through the seasons, we will observe shifts the lines in stellar spectra.

How does the Sun produce its energy? How old is the Sun?

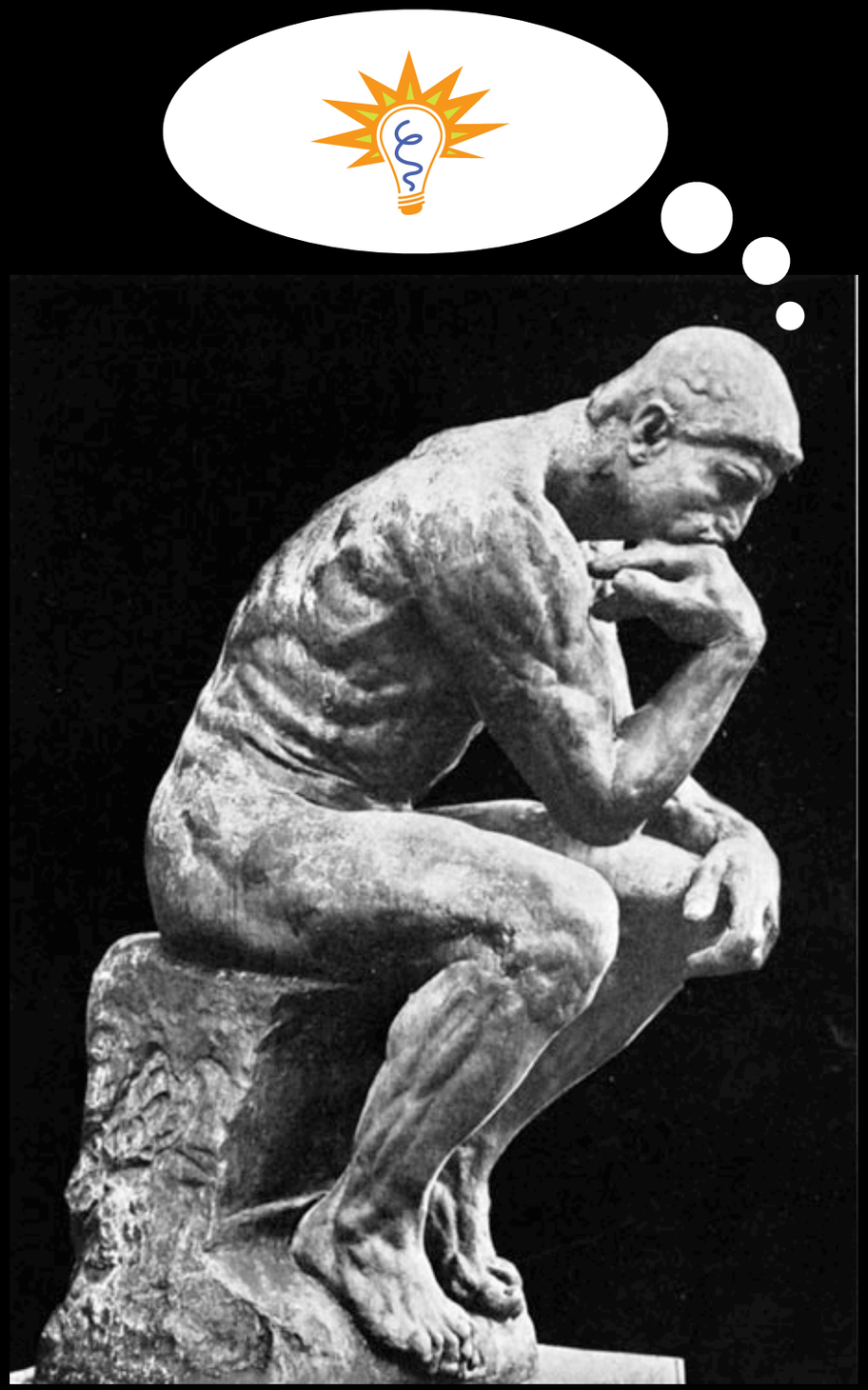
- Topics of extensive debate
- Geology/Evolution (Darwin) vs. Physics (Kelvin)
- Not solved until the 20th Century (Einstein)

Ancient thoughts



- The sun keeps earth warm, fire keeps us warm...

Ancient thoughts

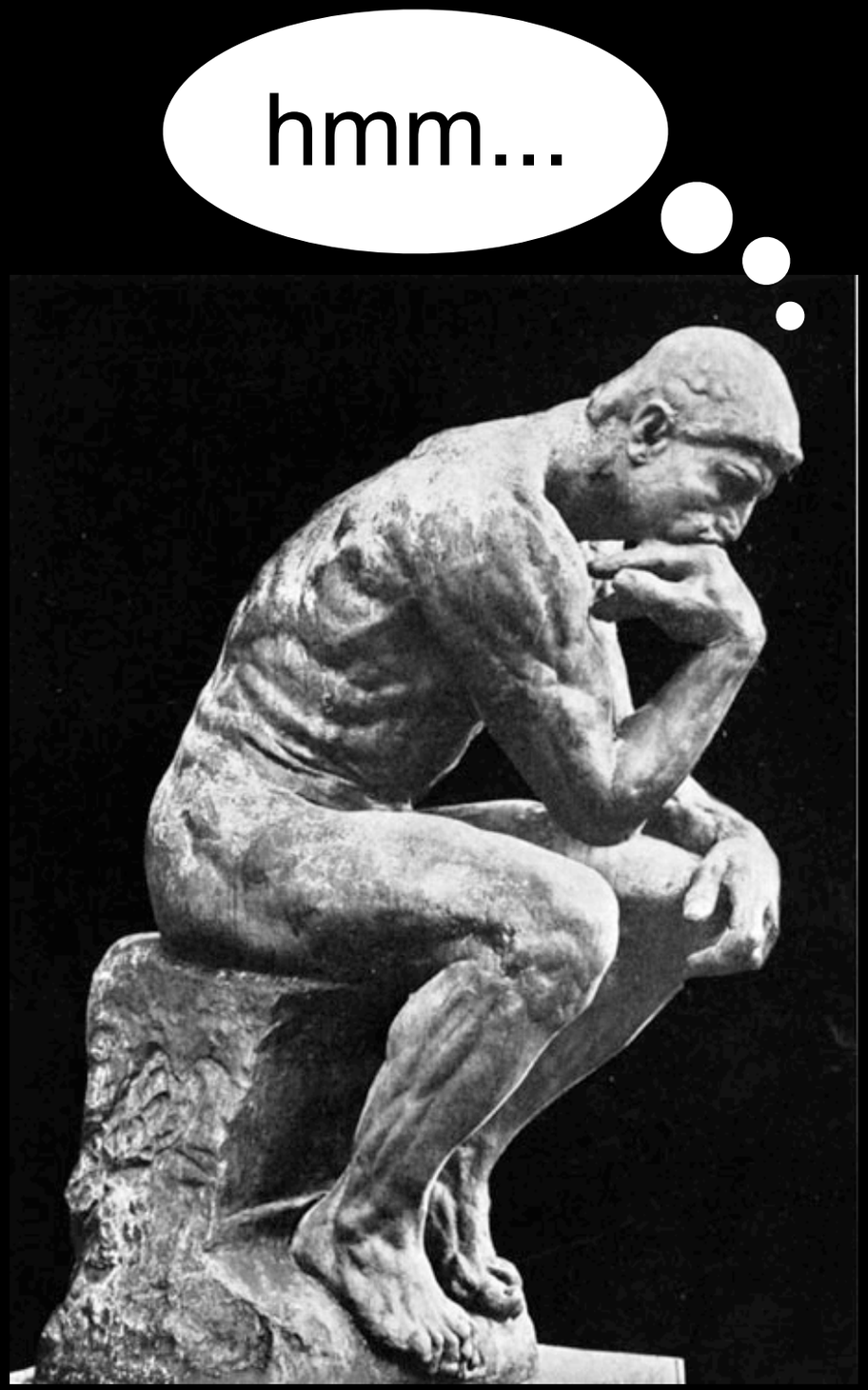


- The sun keeps earth warm, fire keeps us warm...

... the Sun must be burning!

(maybe coal, wood, oil, etc.)

Ancient thoughts



- The sun keeps earth warm, fire keeps us warm...

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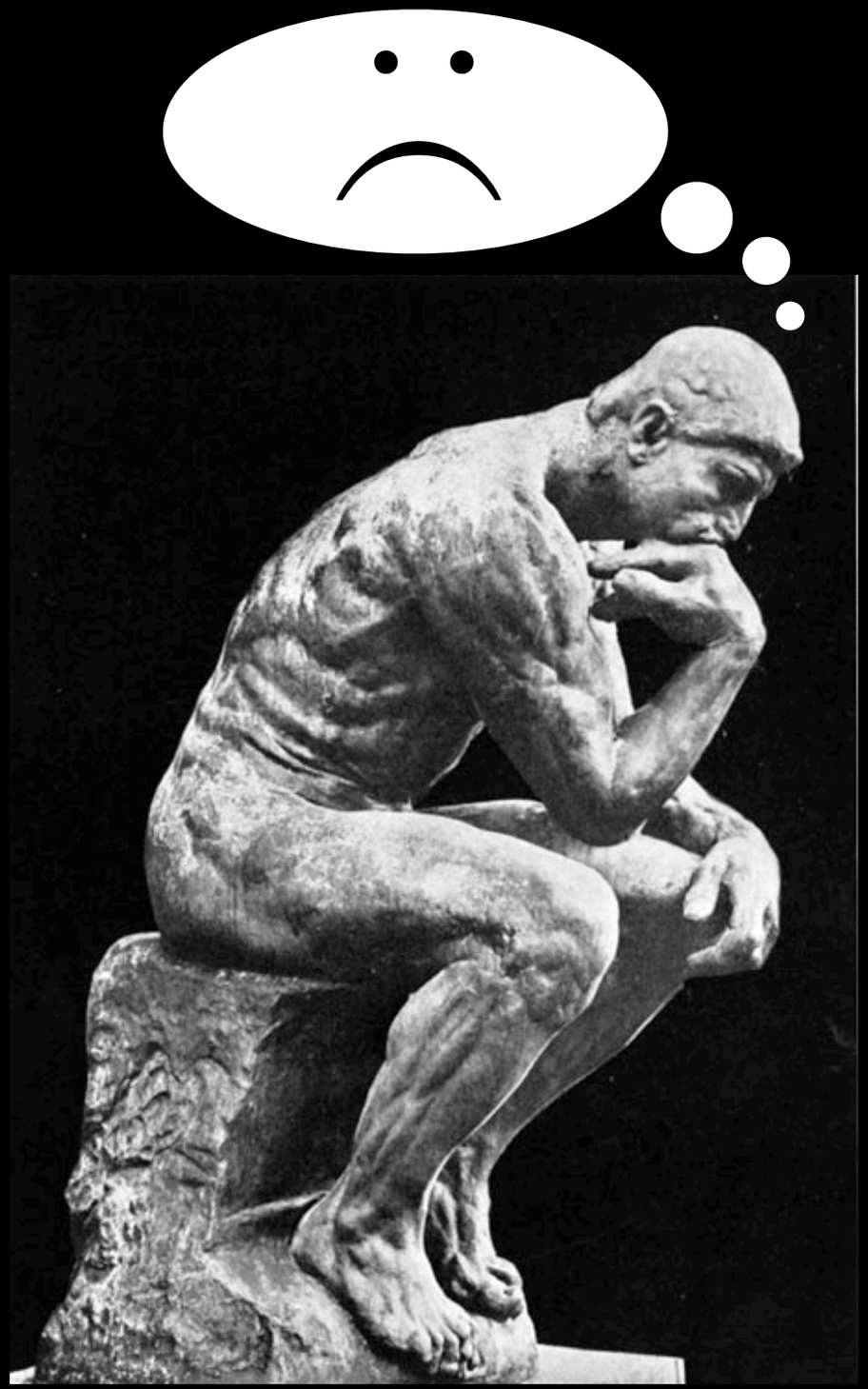
  (maybe coal, wood, oil, etc.)

- How long would that last?

Ancient thoughts



- The sun keeps earth warm, fire keeps us warm...

  ... the Sun must be burning!

  (maybe coal, wood, oil, etc.)

- How long would that last?

  Using the energy output of the Sun, and the energy produced from burning oil, the sun would only last ~2,000 years!

So maybe something else...

- Gravitational Contraction (*Kelvin-Helmholtz contraction*)
  - As a cloud of gas collapses, the gas heats up
    - If the Sun were gradually shrinking, it would always have a source of energy
    - ~10,000 times more energy than chemical reactions from burning
- The Sun could last for ~25 million years!

But geological record showed age > 150 million years!

- Gravitation
  (*Kelvin*
  - A
    of gas collapse
    gas
    s up
  - he Sun w
    radually shri
    g, it
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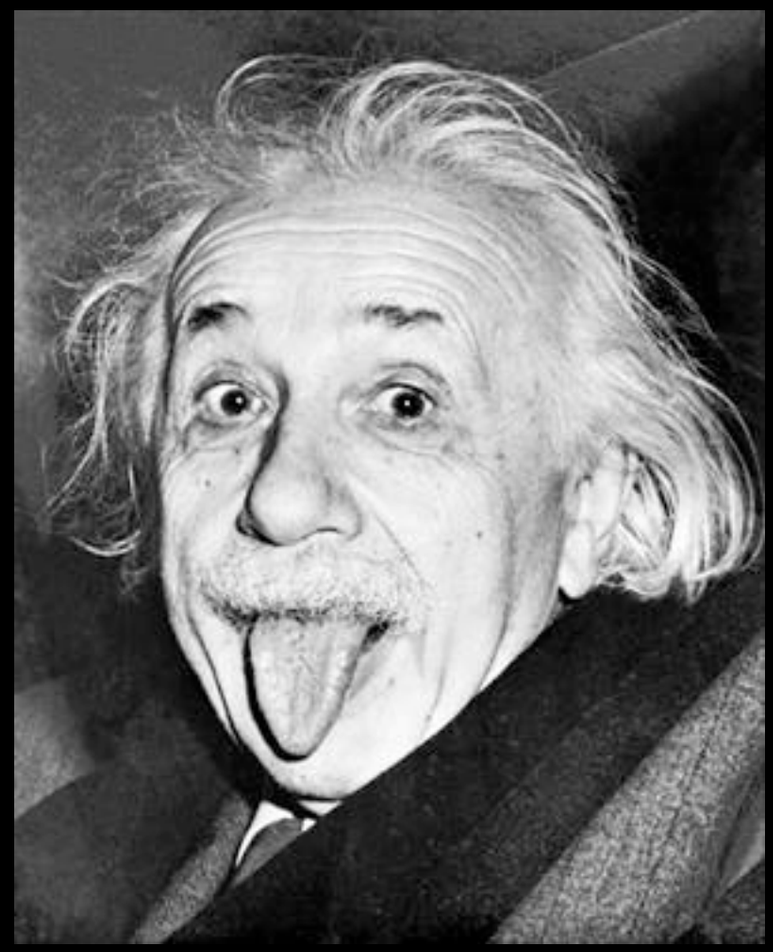
What’s the solution?

What's the solution?

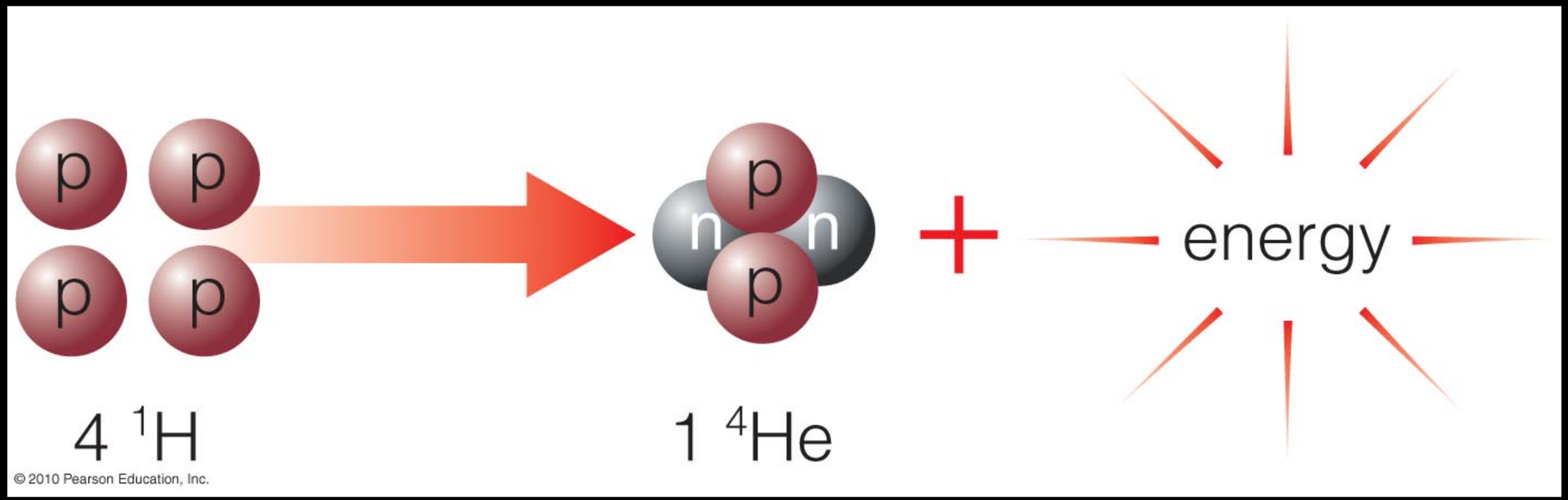
$E = mc^2$



Mass can be converted to Energy!

The Sun is powered by FUSION

In a nut shell:



Which has more mass, 4 individual protons, or a helium nucleus (2 protons plus 2 neutrons)?

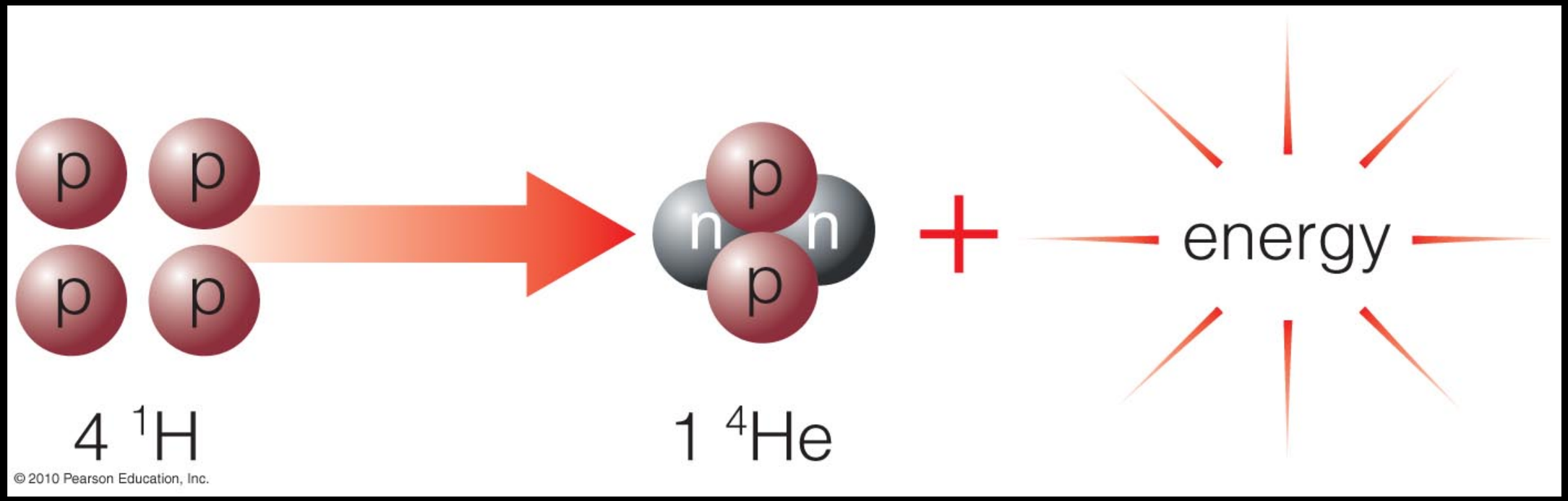
A. The 4 individual protons

B. The helium nucleus

C. Huh? Well... 2 + 2 = 4... so...

The Sun is powered by FUSION

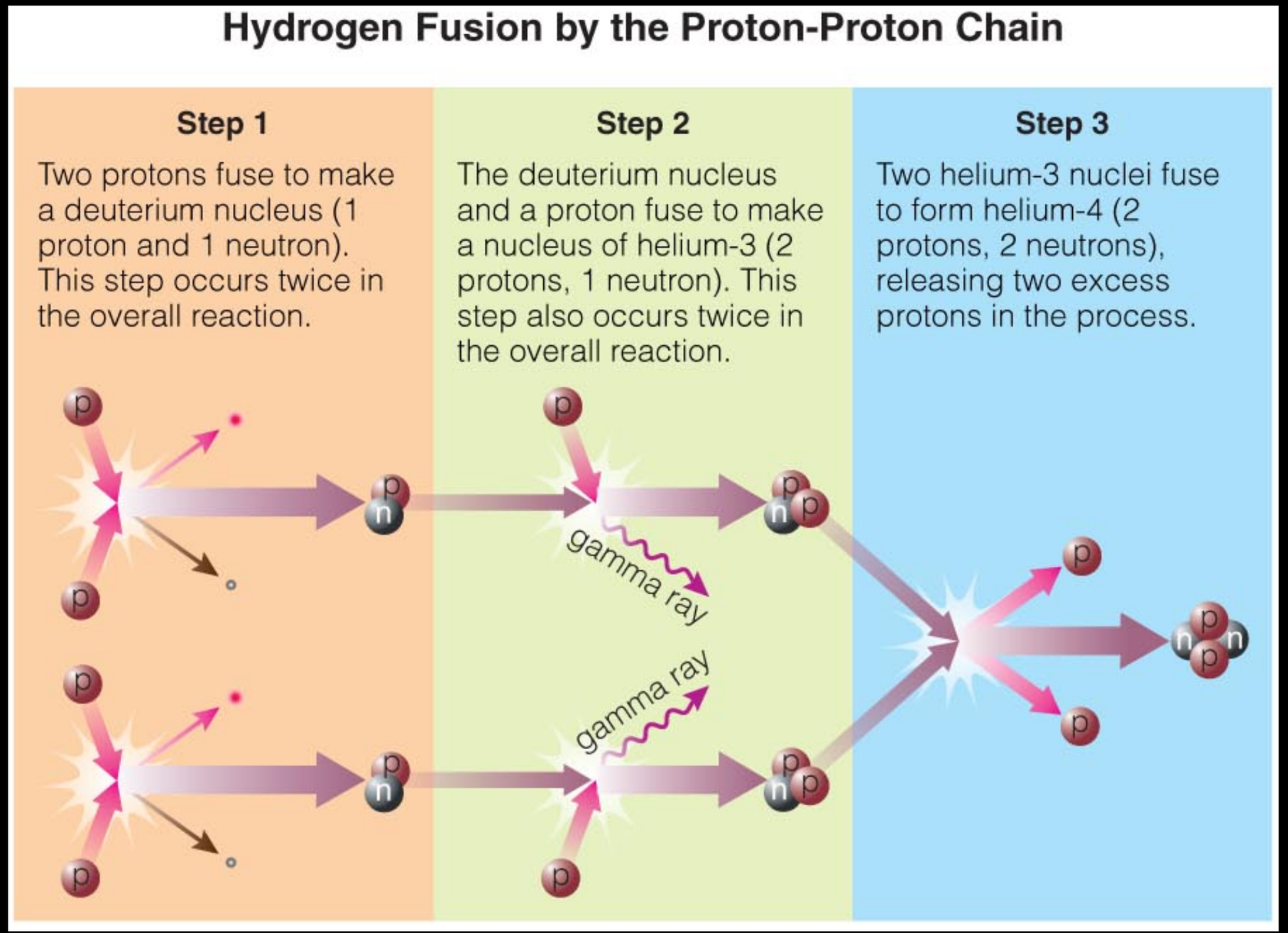
In a nut shell:



4 hydrogen nuclei (protons) have slightly more mass than a helium nucleus. The extra mass is released as energy!

Every second, 600 million tons of H is converted into 596 million tons of He -- 4 million tons of mass are converted into energy each second!

The Proton-Proton (P-P) Chain



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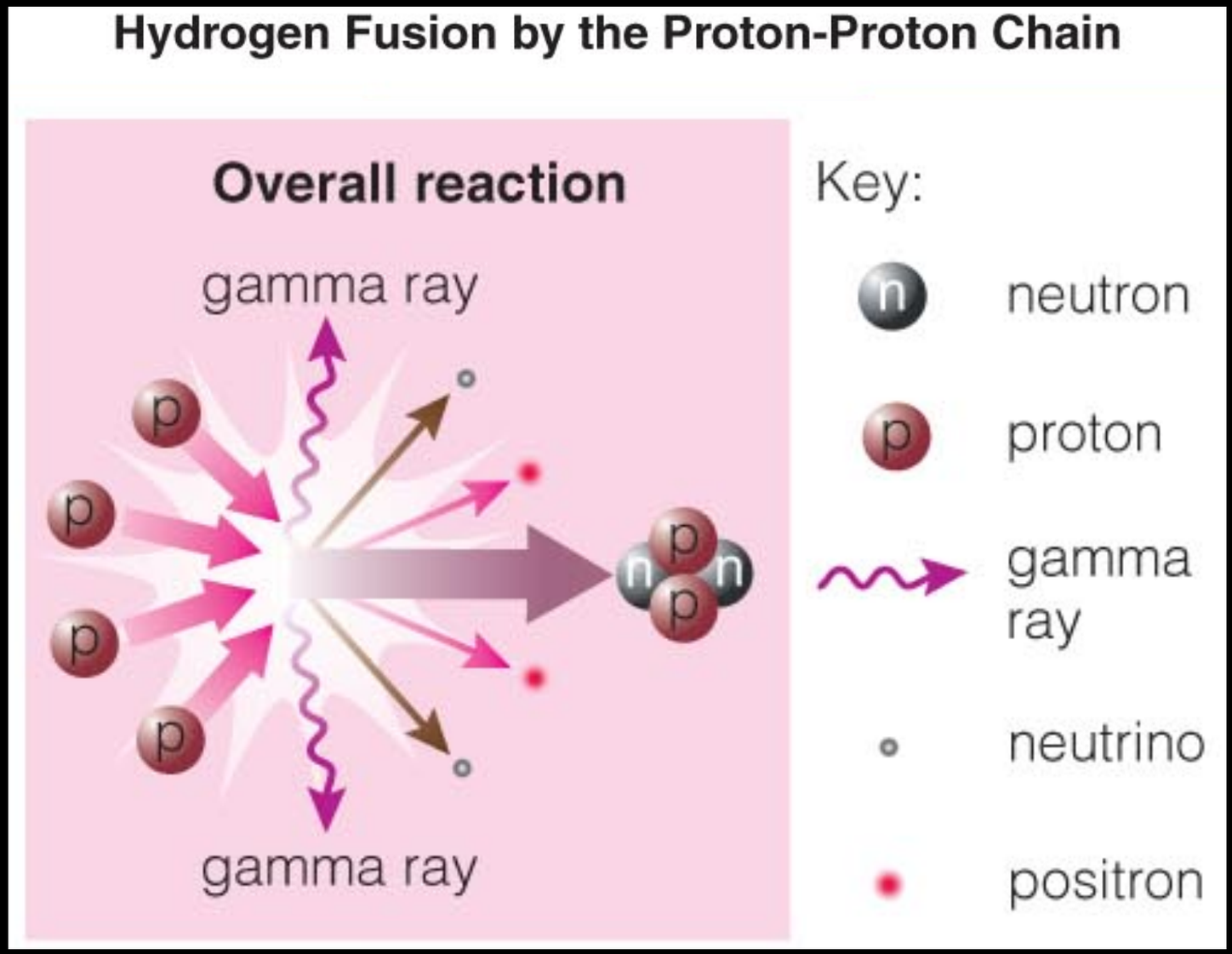


The Sun is made up of (mostly) hydrogen. Yet the P-P chain starts with two protons. Why are they separated from their electrons?

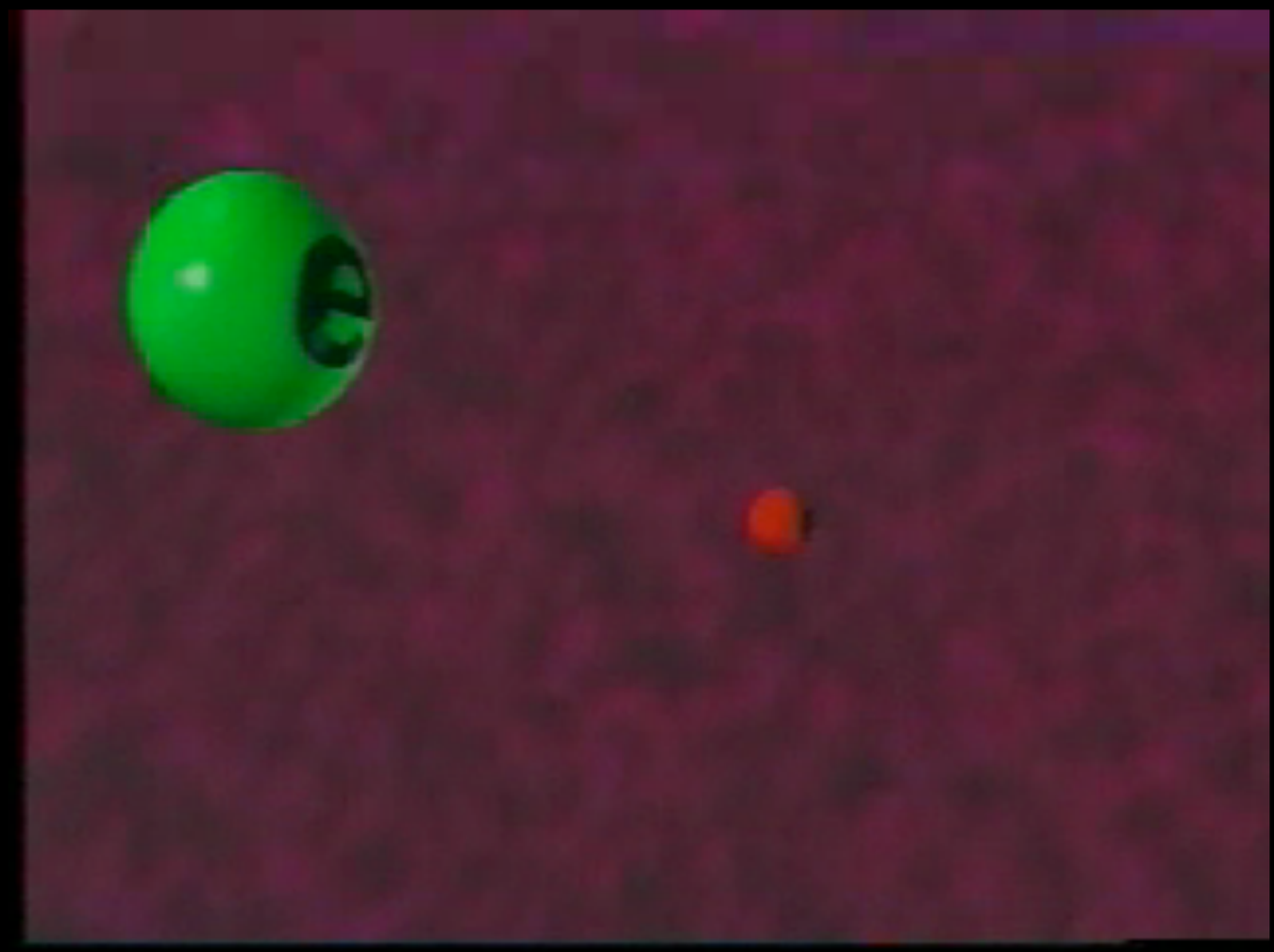
A. The core is very hot so the electrons are all ionized.

B. The electrons have all moved to the outer layers of the Sun.

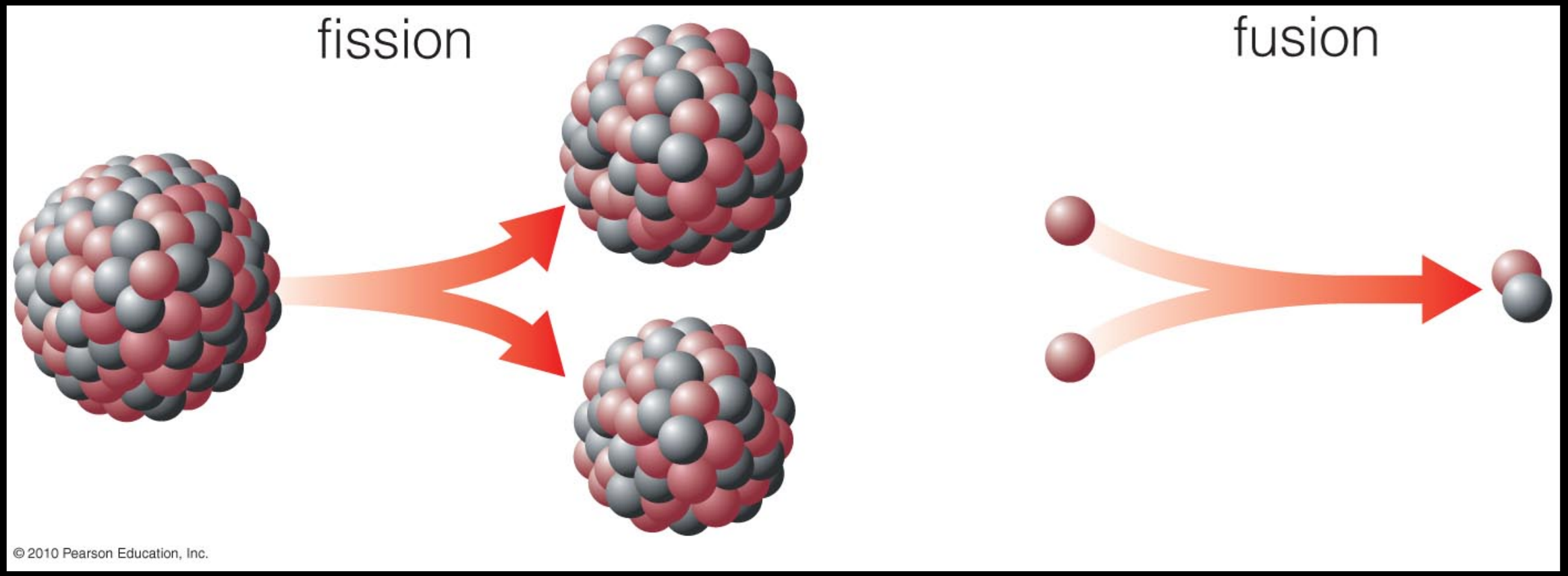
C. The Sun is electrically positive (thus the magnetic fields) so all that exists are hydrogen ions.

D. Neutral hydrogen only consists of one proton and one neutron in the first place.

What's happening to all those extra electrons?



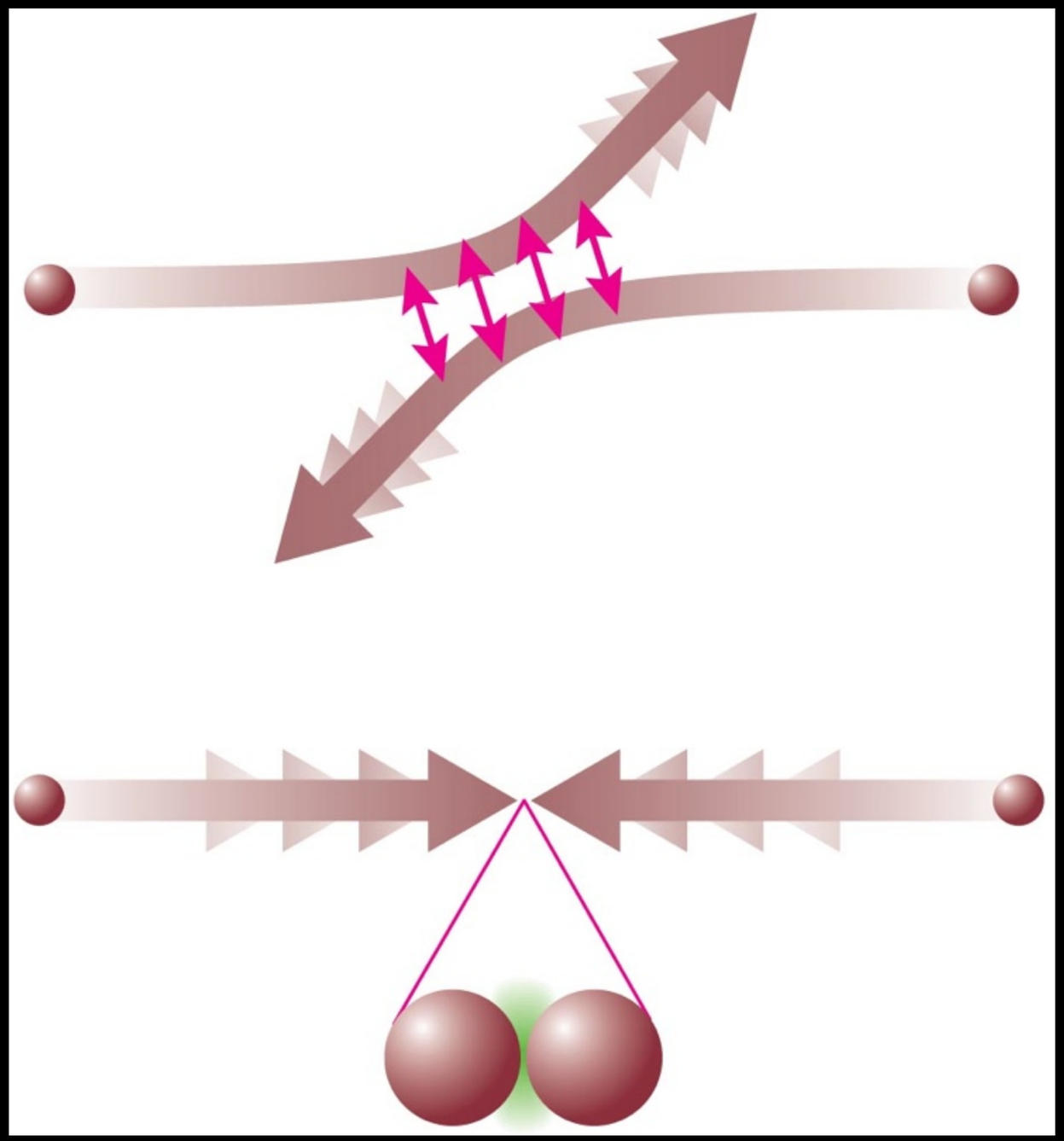
Fission vs. Fusion



Big Nucleus splits into smaller pieces
Example: Nuclear power plants, atomic bombs

Small nuclei stick together to form a larger one
Example: Stars

What Makes Fusion Possible?



Electromagnetic forces normally prevent protons from colliding

But! If density and temperature are high enough... protons can get close enough for strong force to take over

It's a nice idea, but how can we know for sure?

- Proof of fusion: Neutrinos!
  - Extremely small masses
  - Travel at nearly the speed of light
  - Rarely interact with matter
  - Reactions in the Sun produce 10^{38} neutrinos per second -- 10^{15} passing through you each second

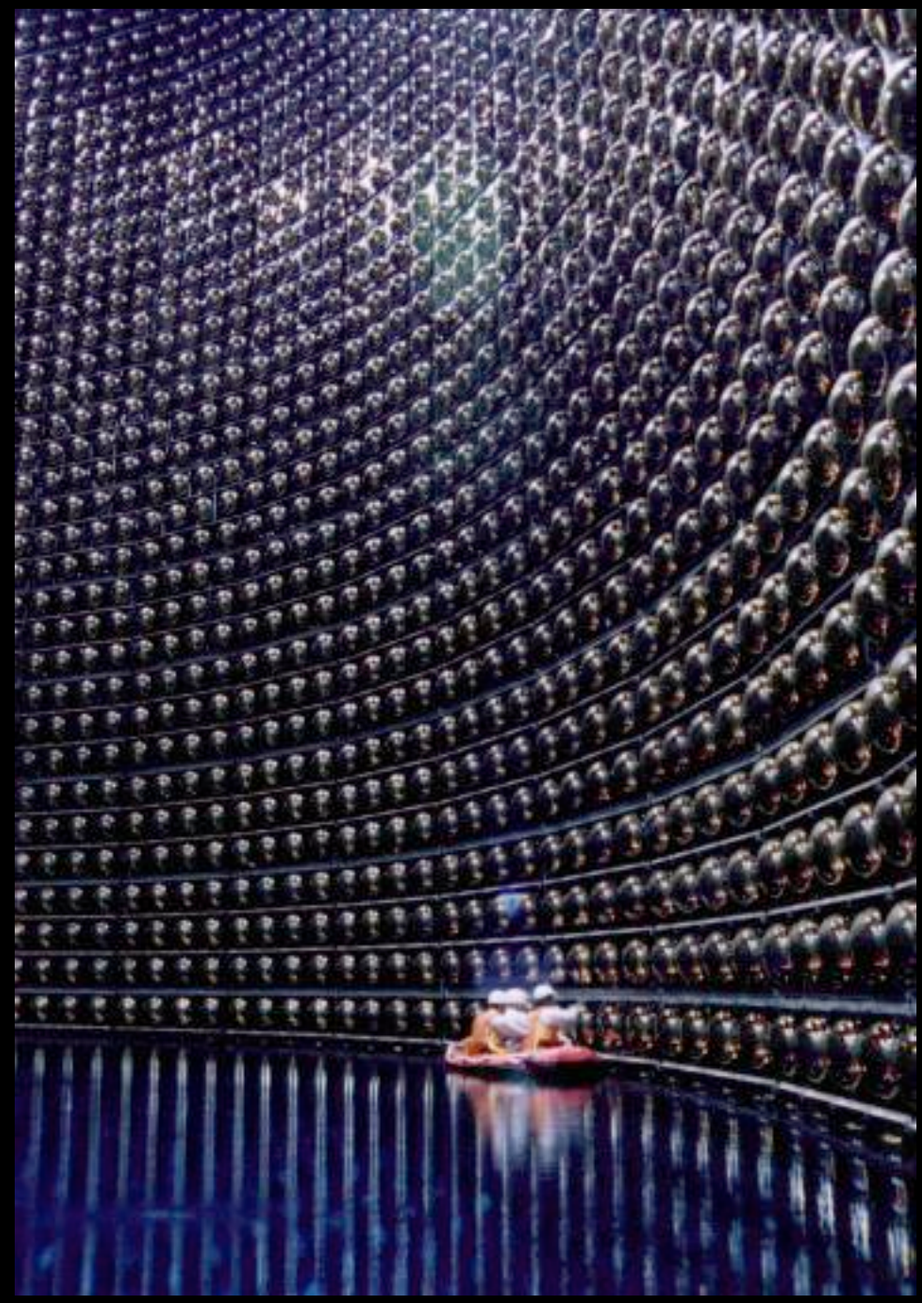
Can we detect them?

Homestake Experiment
(~1 neutrino detection every 3 days)

- Yes. But it's not easy.
- Detectors must built deep underground (why?)
- First one was a huge vat containing 500 tons of dry cleaning fluid -- neutrinos occassionally hit chlorine and make radioactive argon.
- Only detected 1/3 of the expected neutrino count
- Solar Neutrino Problem!

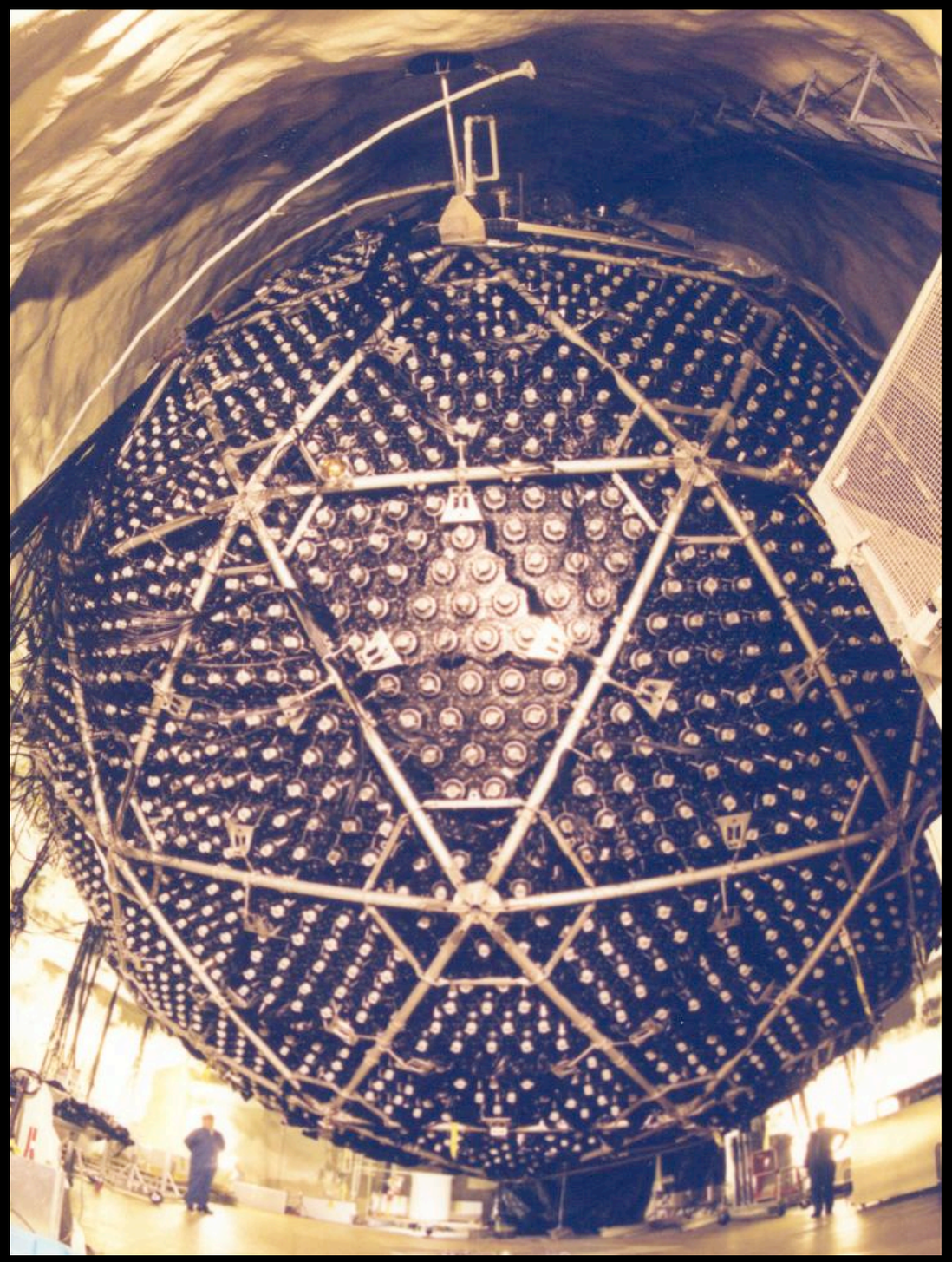
Seeking the solution

- Super-Kamiokande built with 50,000 tons of water
- Interactions with the water produces small flashes of light
- Flashes are detected by giant photo-multiplier tubes that surround the tank
- Results suggest that neutrinos change their type on their way to earth
  - Neutrino oscillations!



Super-K

Success!



SNO

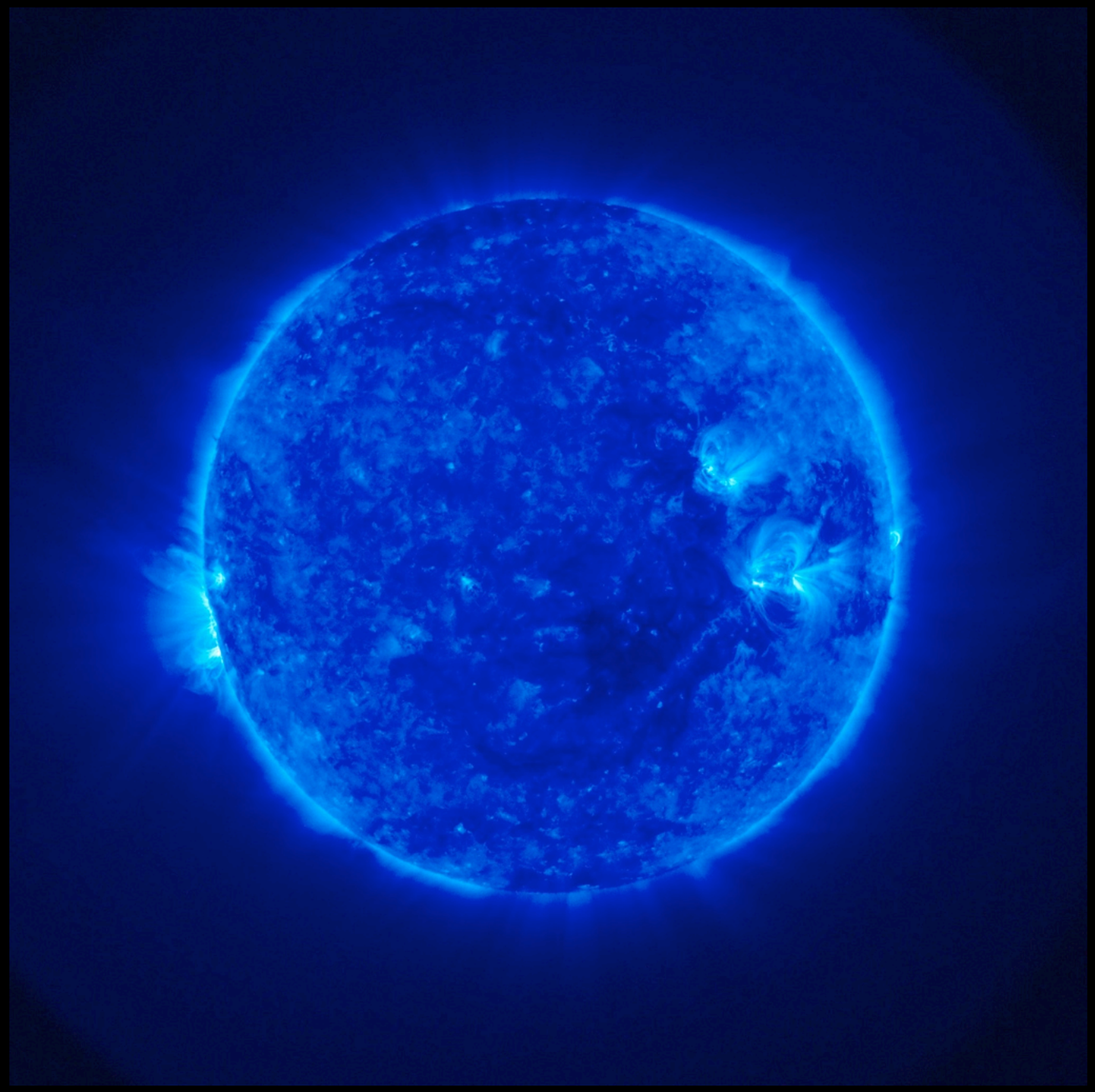
- Sudbury Neutrino Observatory (SNO) made use of “heavy water”
- 6800 feet below ground
- Capable of detecting all three types of neutrinos
- Results matched theory, problem solved!

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

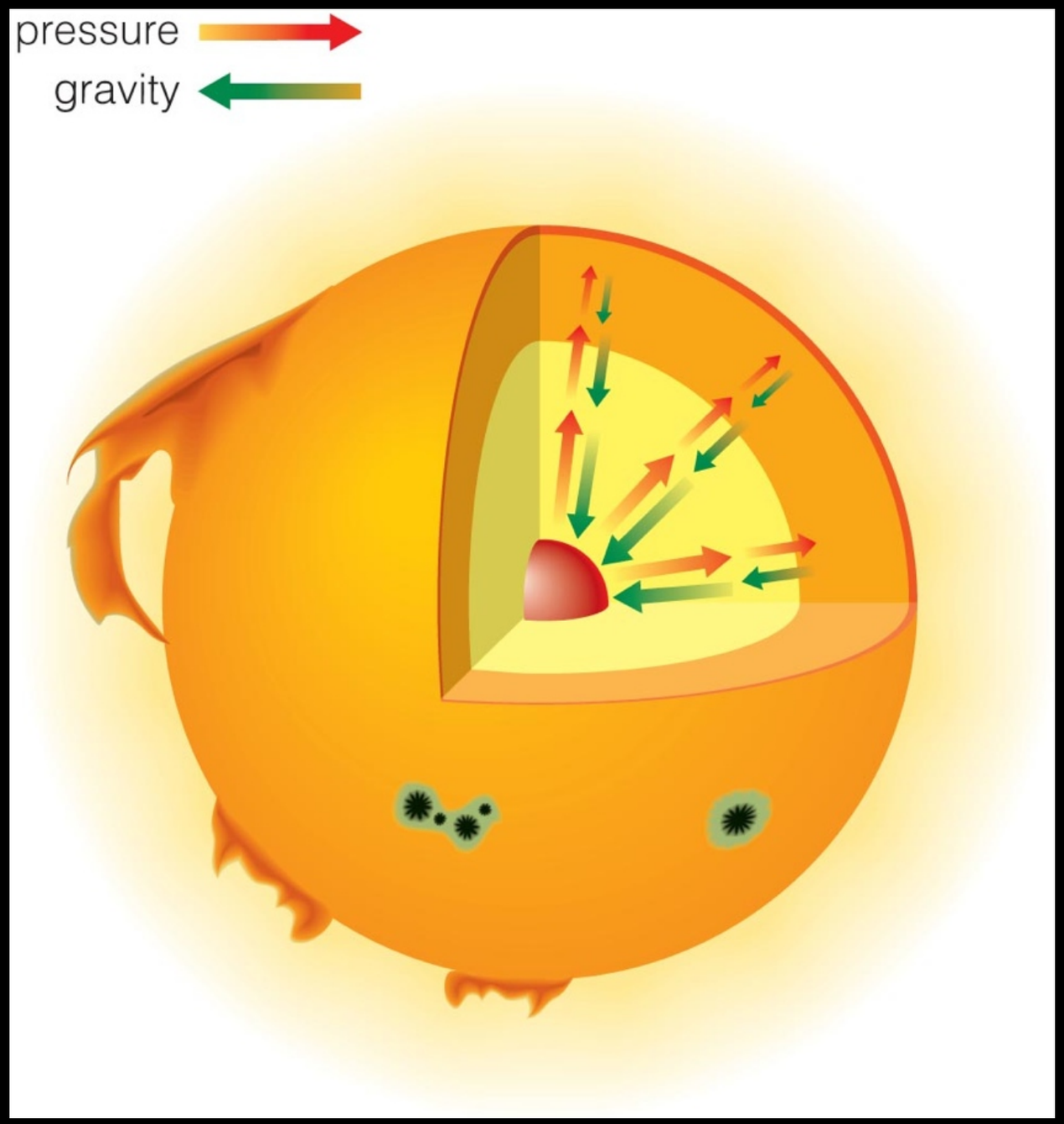
A. About the same.
B. Much smaller during the night.
C. Much larger during the night.
D. Neutrinos don’t pass through our bodies.
E. Wait, are we talking about those hot-rodding teenagers from Teenage Mutant Ninja Turtles?

Why is the Sun round?

- What are the forces at work that shape and support the Sun?



Gravitational Equilibrium (hydrostatic equilibrium)

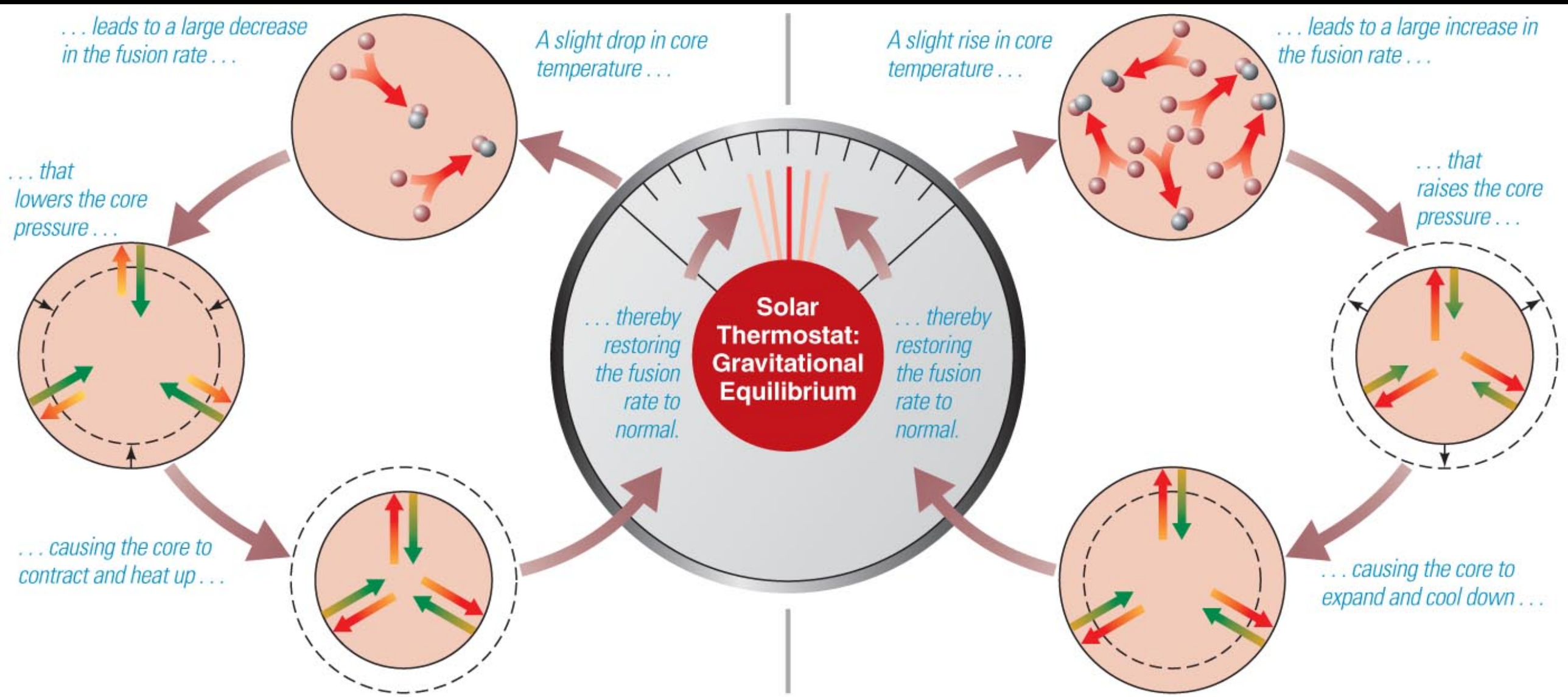


- Inward force of gravity is balanced by outward force of pressure
- Gravity will force the sun into the most compact shape possible: a sphere
- Pressure and temperature are highest in the core

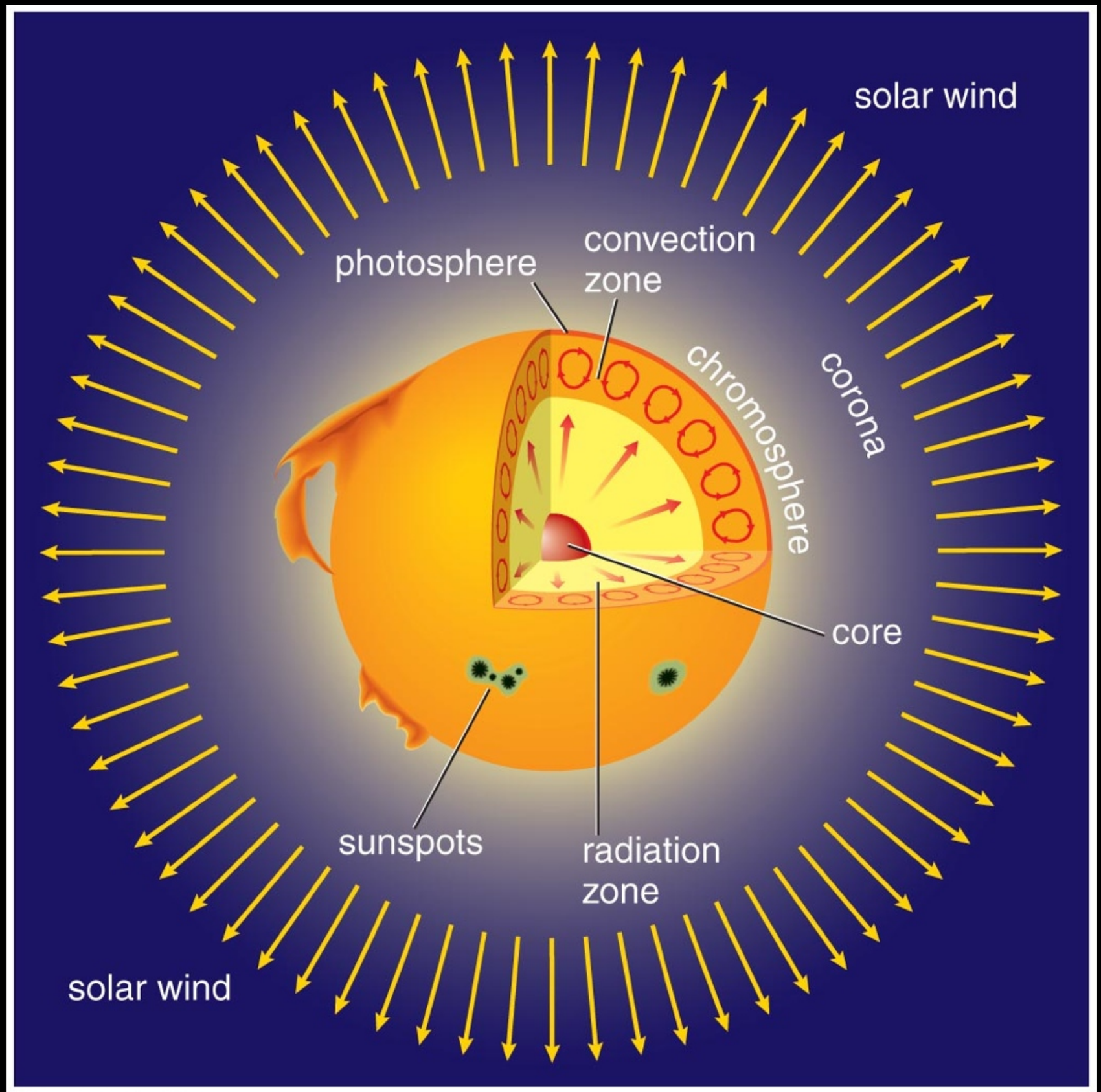
Where does the pressure come from?

- When you compress a gas without leaking heat away, the temperature goes up. Pressure goes up.
  - Pressure ~ Density x Temperature
- If pressure is great enough, you initiate fusion
- Fusion creates energy, keeps gas hot
- But couldn’t this get horribly out of control?

Solar Thermostat

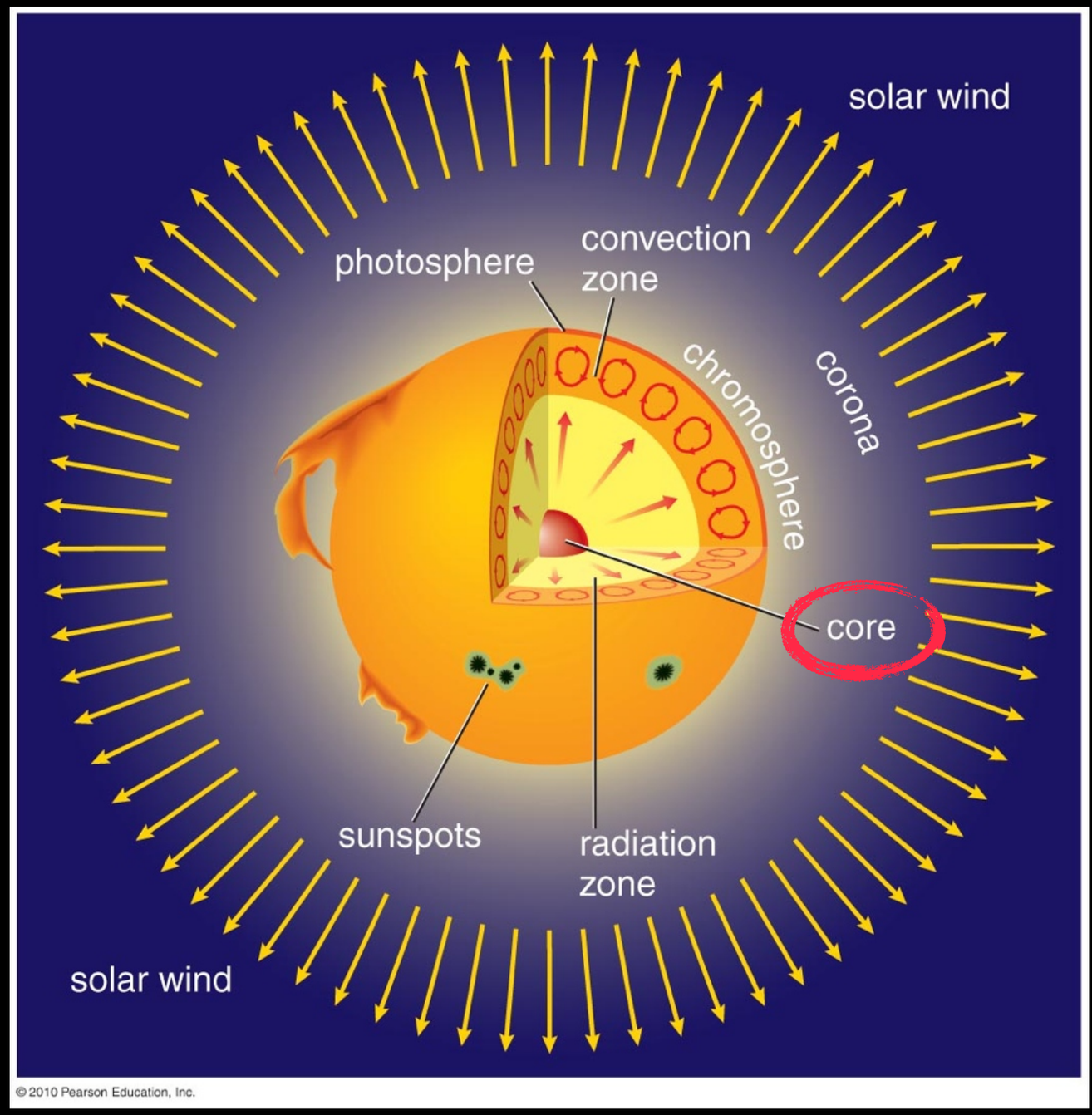


What's the inside of the Sun like?



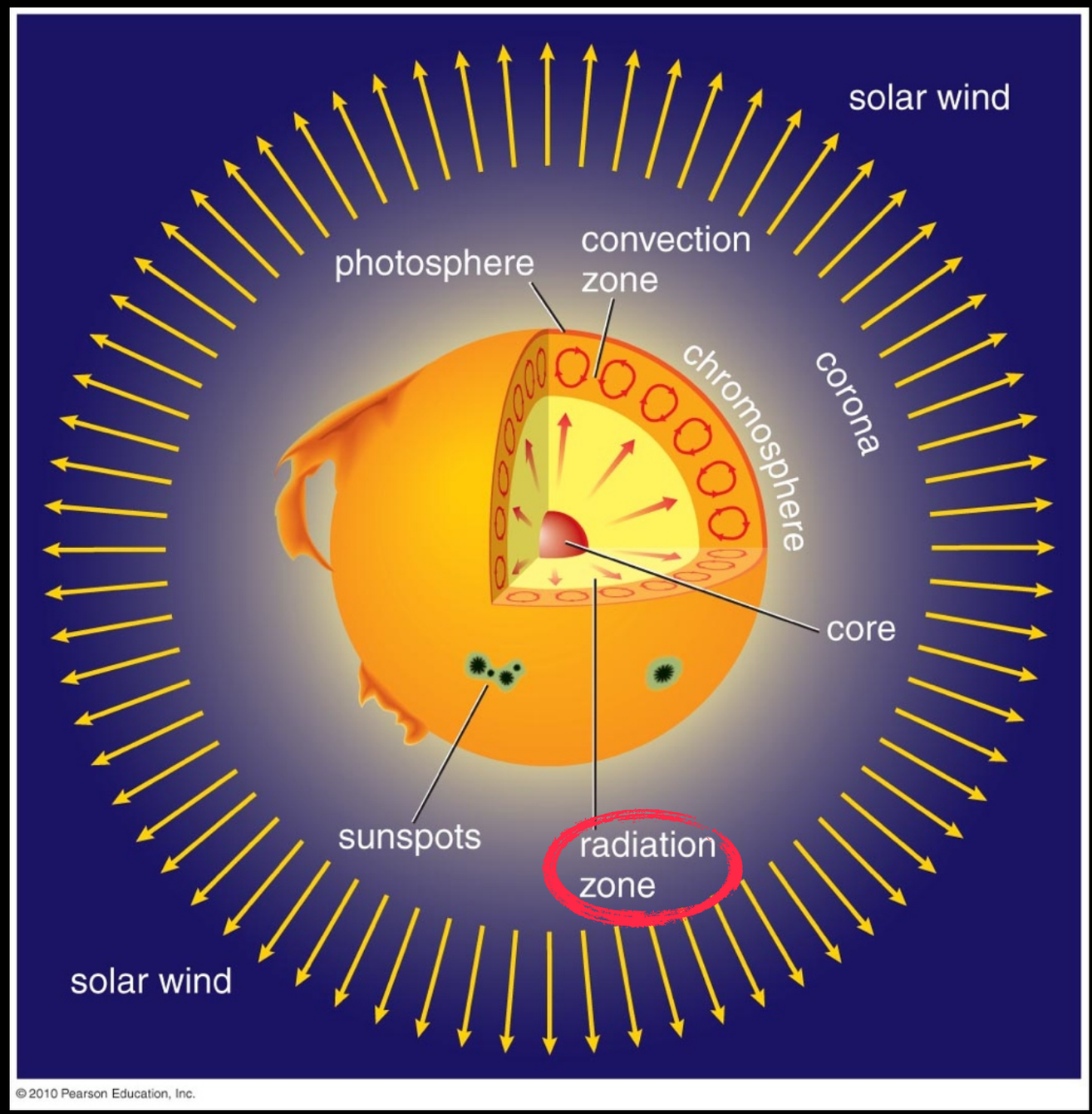
Let’s start at the center

- The core
  - Hydrogen is fusing into helium
  - Temperature is ~15 million K
  - Energy is produced in the form of gamma rays, positrons and neutrinos

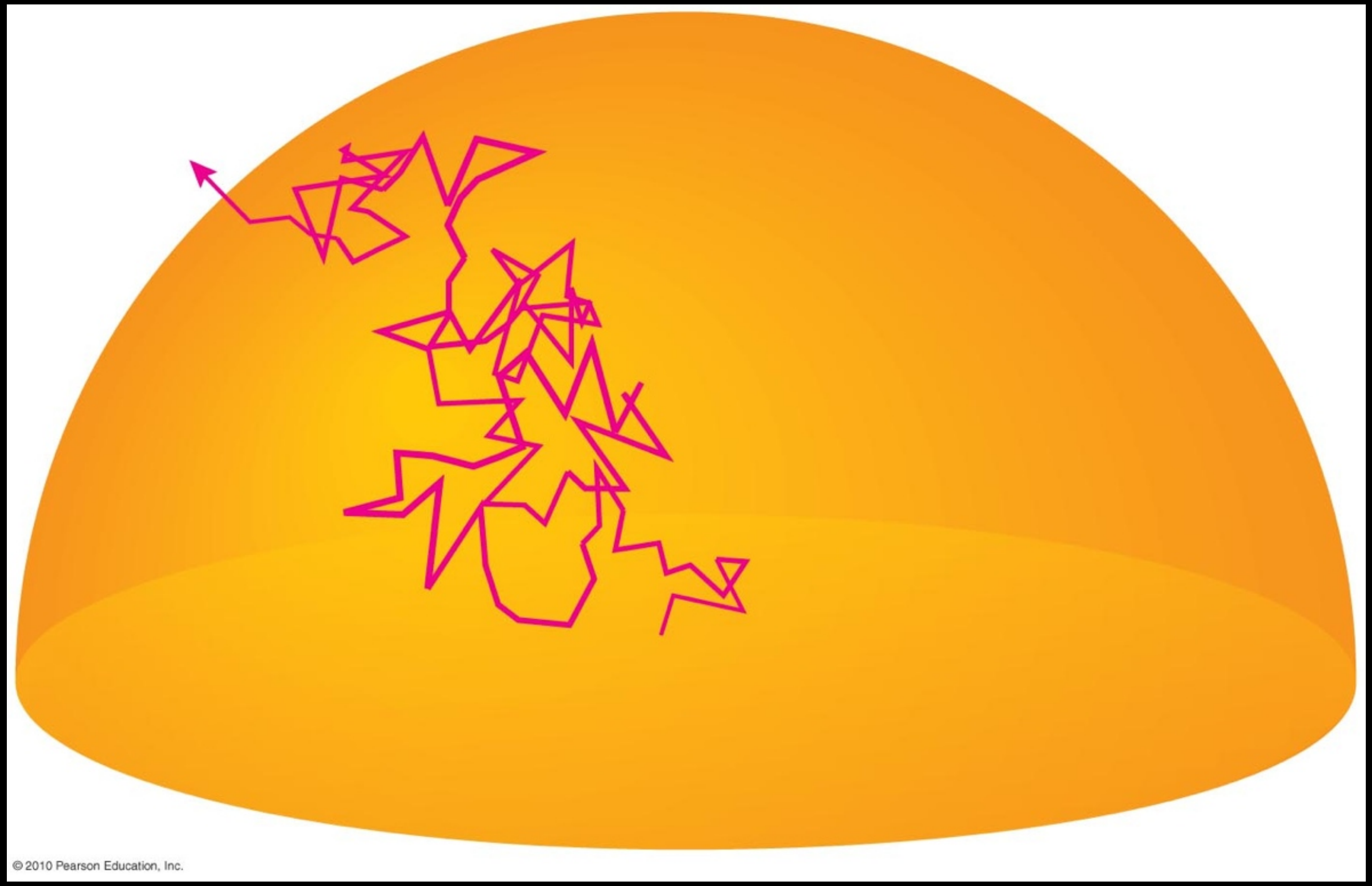


Then we come to...

- The radiation zone
  - Gamma rays leave the core and begin to work their way out
    - High density of radiation zone makes this difficult
- Neutrinos go whizzing out freely
- Positrons annihilate with electrons in the core



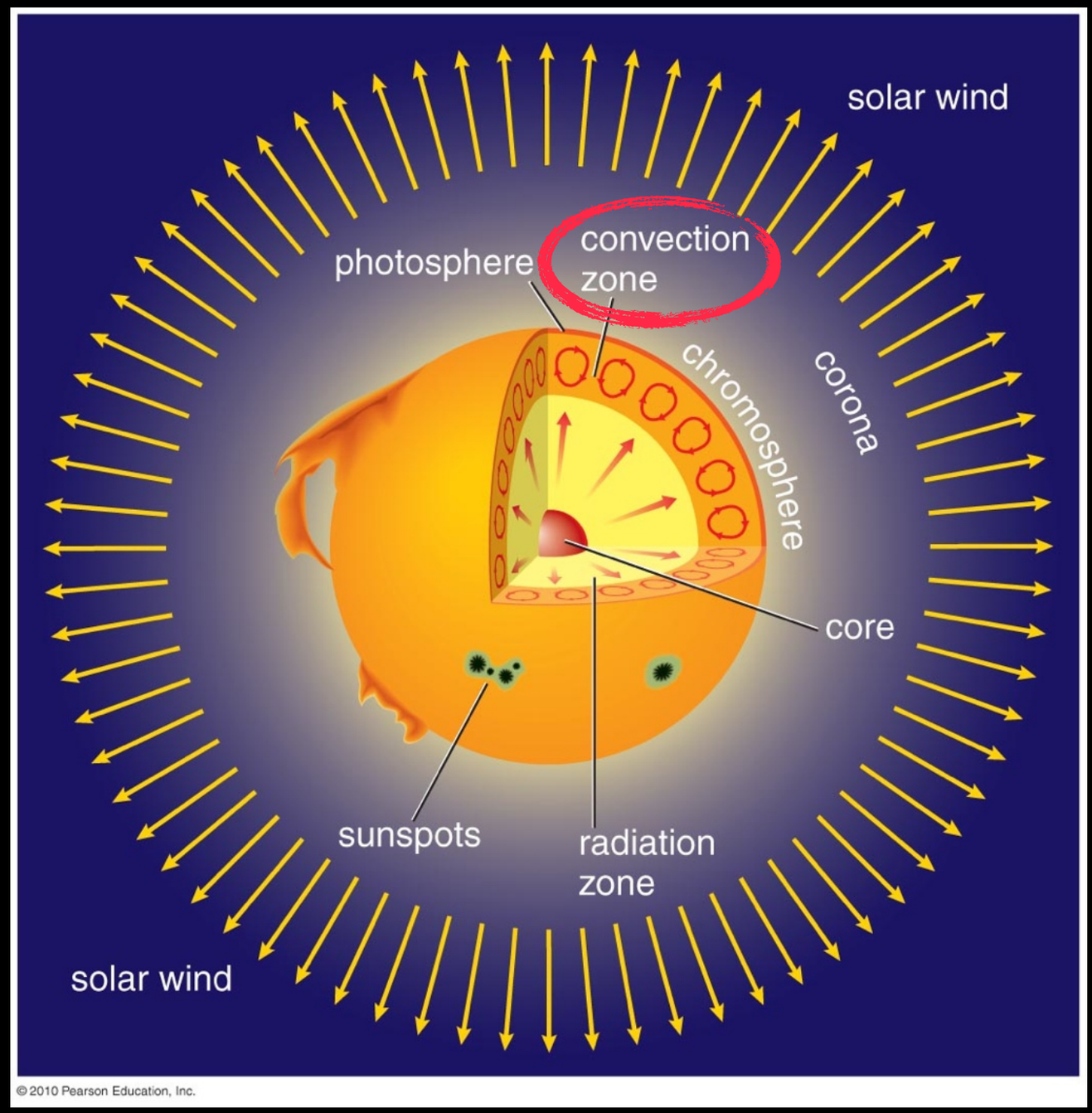
Radiative Diffusion



Photons take a “random walk” out of the radiative zone (takes hundreds of thousands of year to make it out)

Next up…

- The convection zone
  - Gas has cooled to roughly 2 million K
  - Photons are no longer redirected, they are absorbed
  - Gas at the bottom of the convection zone gets hot and rises
  - Gas at the top of the convection zone cools and sinks



It's a long and winding road

- Energy has to work it's way out from the core to the top of the convection zone before streaming into space
- This can take nearly 1 million years!

At the base of the convection zone (2 million K), what is the main wavelength of photons present?

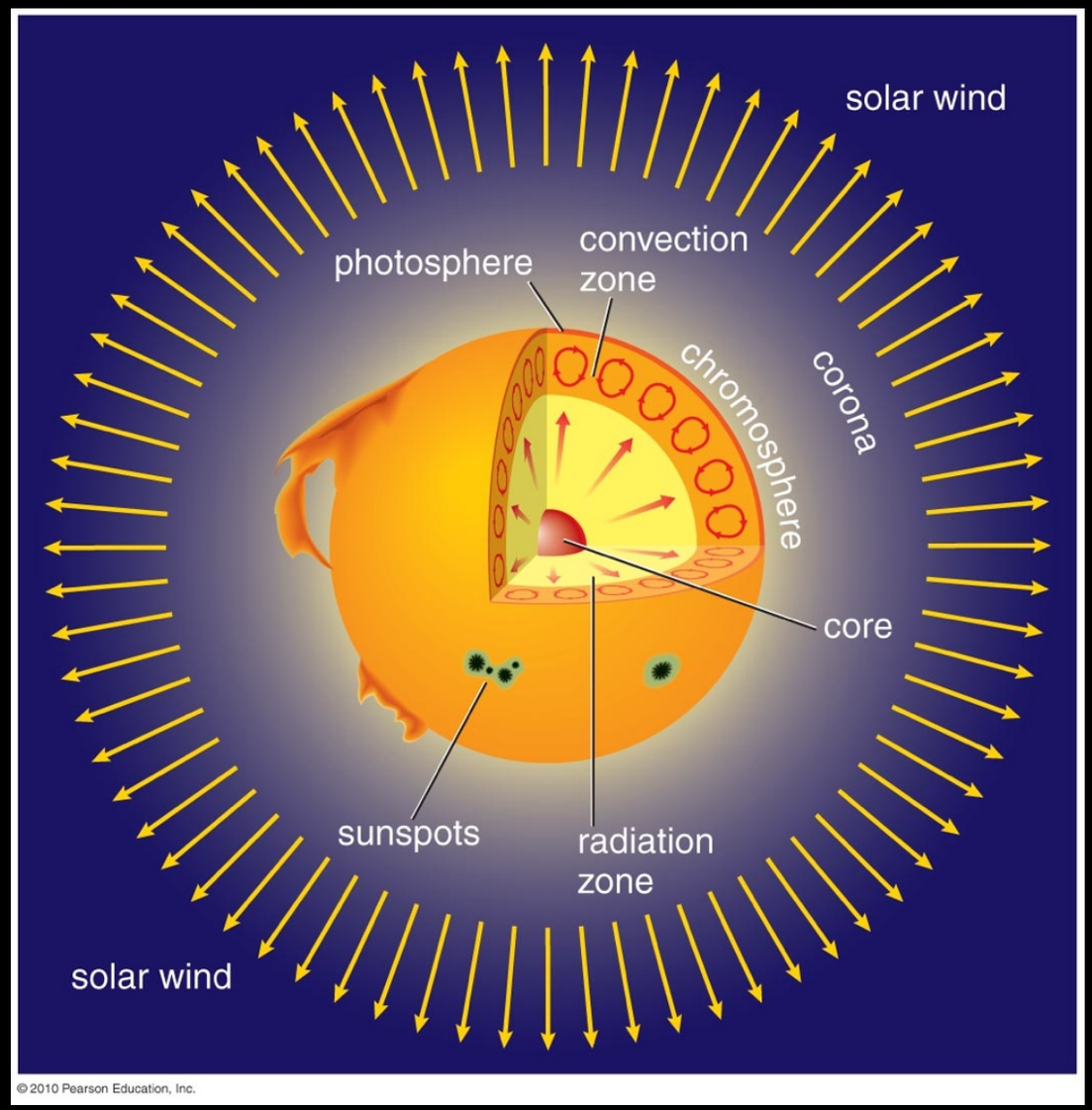
A. Radio waves

B. Ultra violet

C. Visible

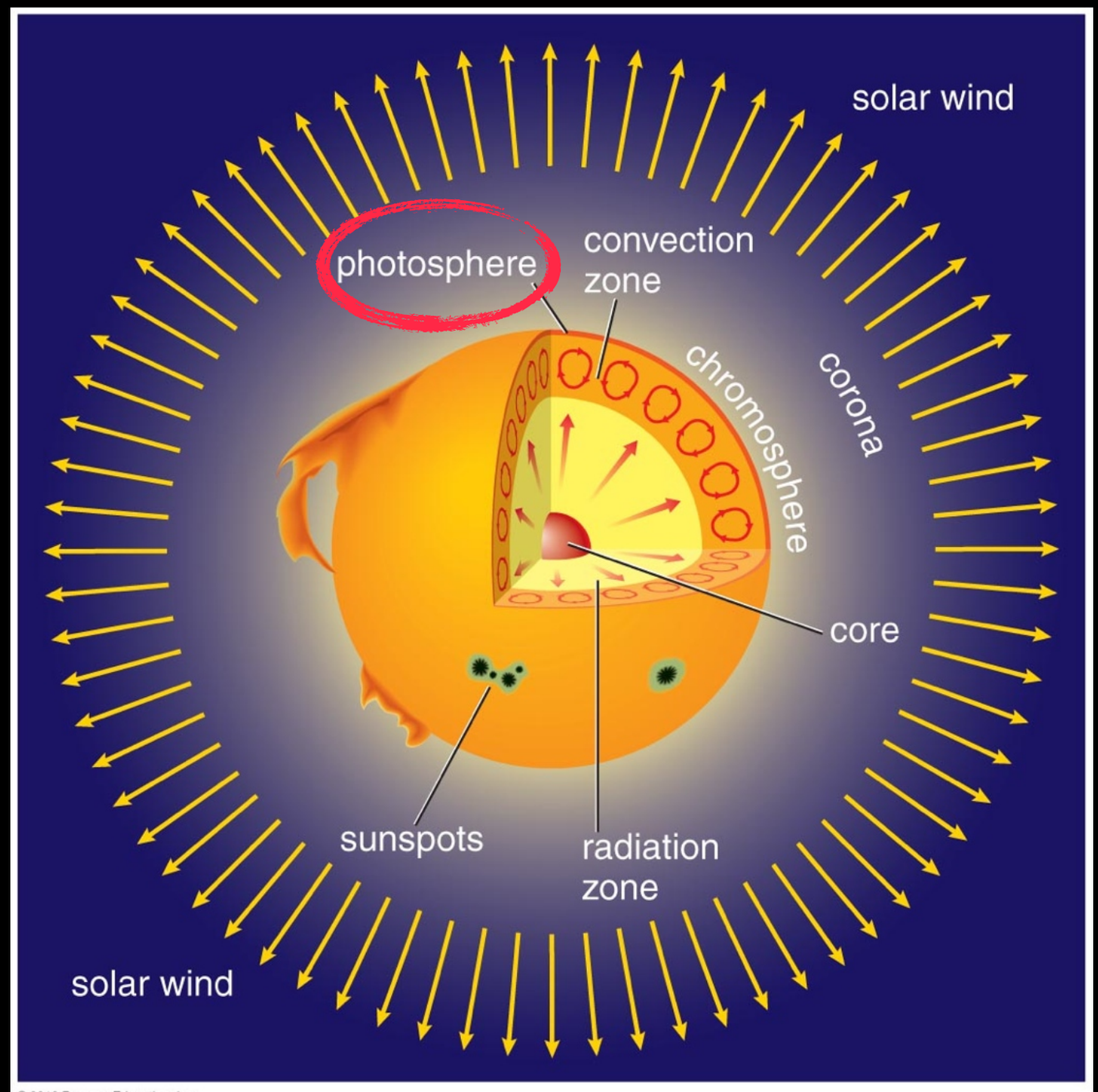
D. Infrared

E. X-rays



The part we see

- The photosphere
  - Gas has cooled to roughly 5800 K



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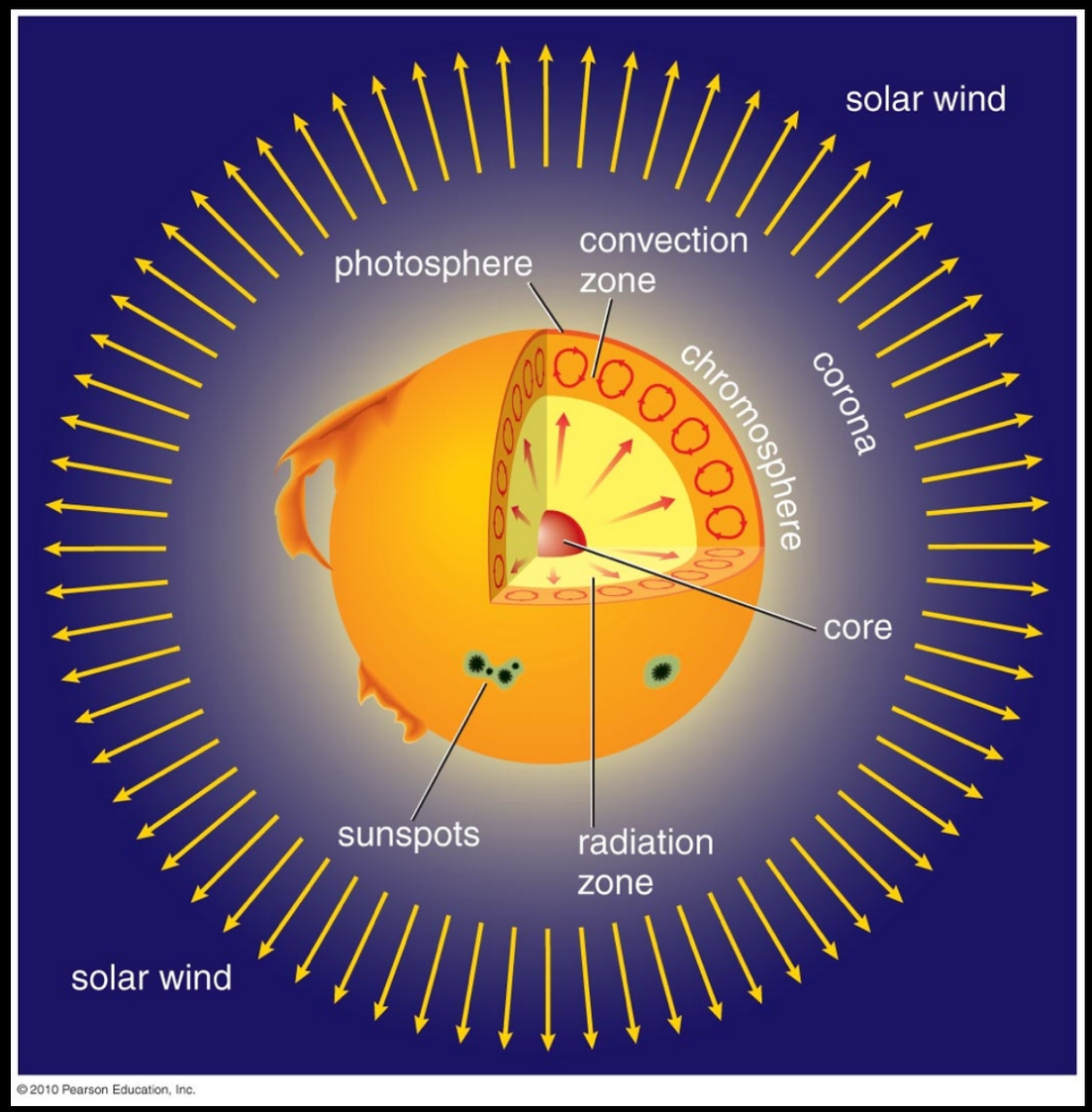
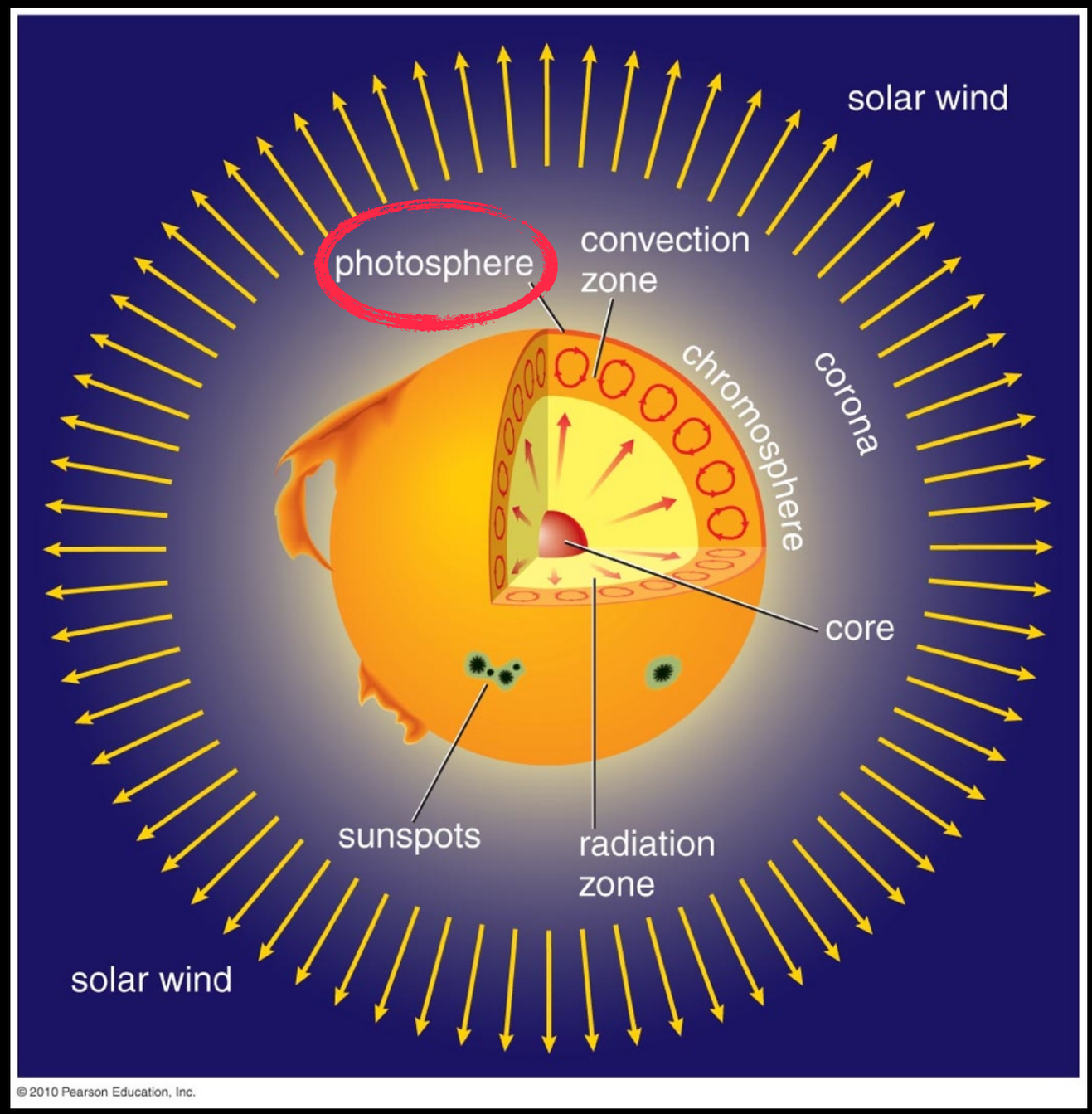


The part we see

- The photosphere
  - Gas has cooled to roughly 5800 K
  - Photons can finally leave the sun
  - Energy of photons has dropped to visible wavelengths
  - It's the "visible surface"



What does the surface of the Sun look like?