HW tip

13.52: calculating orbits around other stars. Which version of Kepler's third law to use?

Full version? $P^2 = 4\pi^2 a^3 / G(M_1+M_2)$

With P measured in seconds, a in meters, M in kilograms, and $G=6.67x10^{-11}$ $m^3/kg/s^2$

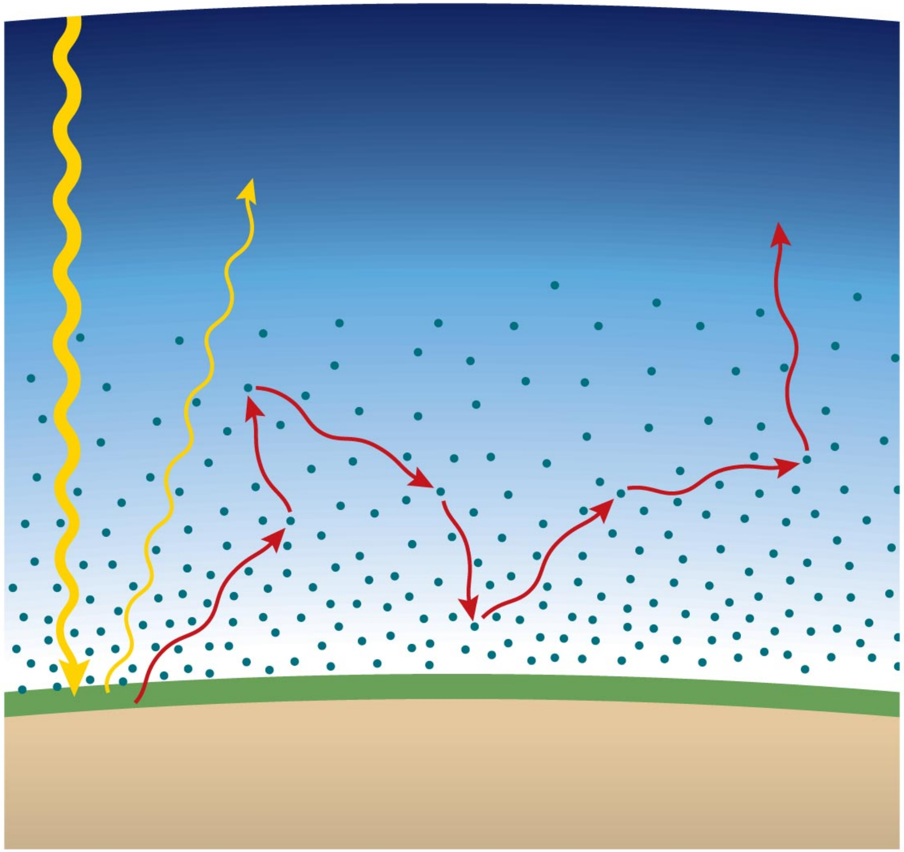
Or simpler version?

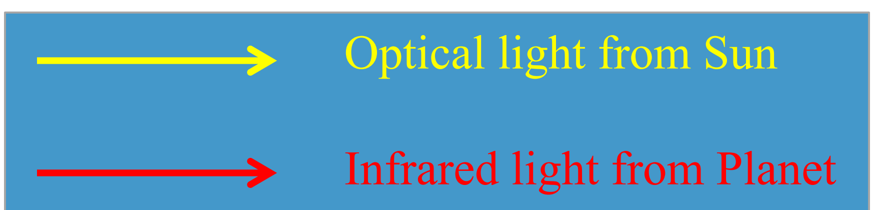
If P is measured in years, a in AU, and M in solar masses:

$$P^2 = a^3 / (M_1+M_2)$$

(because $G=4\pi^2$ $AU^3/M_{sun}/yr^2$)

Greenhouse Effect

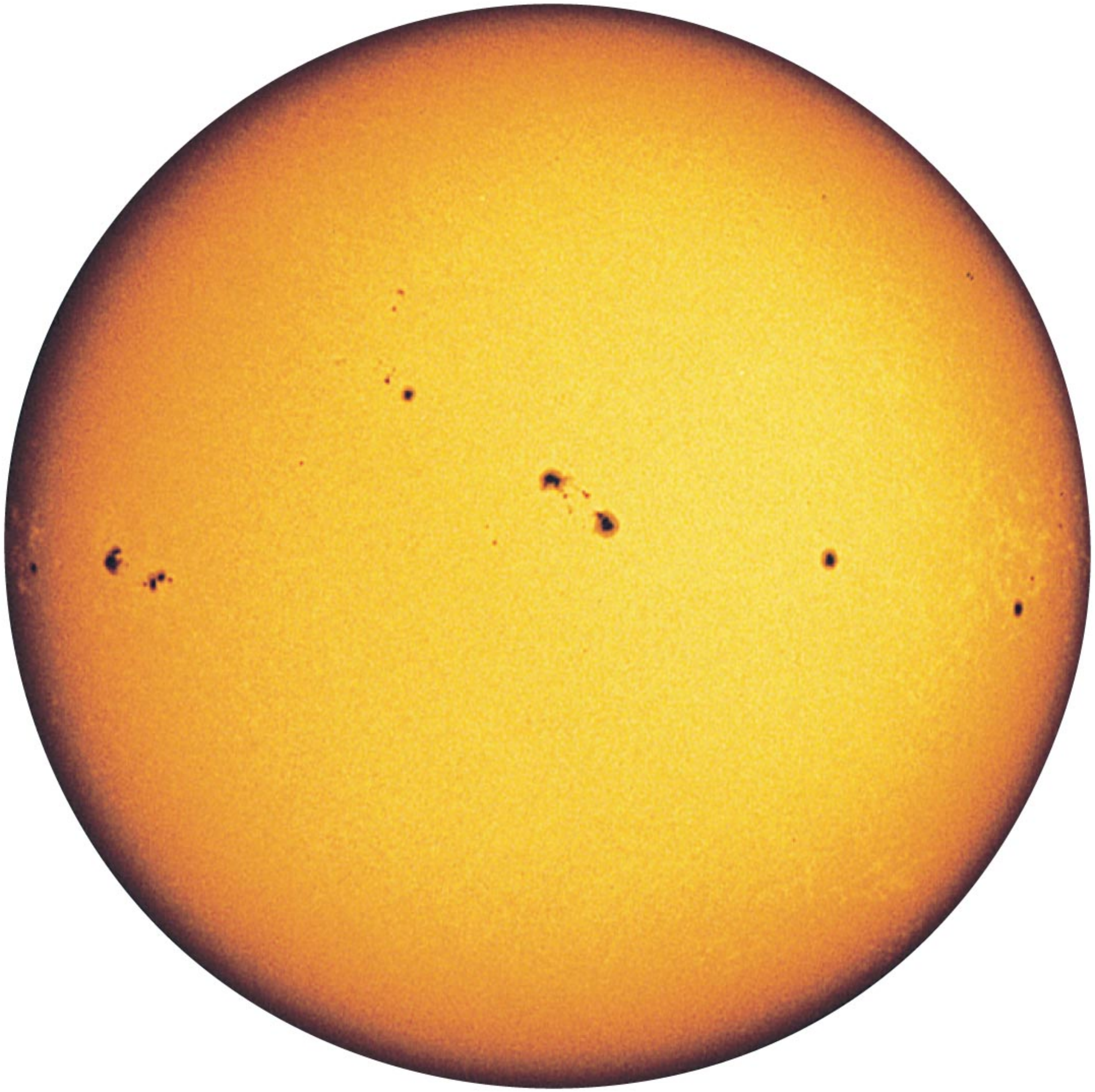




- Greenhouse gases let visible light through, but absorb infrared light.
- Visible light from the Sun passes through the atmosphere and warms a planet's surface.
- The planet's warm surface emits infrared light.
- The atmosphere absorbs the infrared light from the surface, trapping heat.
- Water vapor (H_2O) and carbon dioxide (CO_2) strongest absorbers.

14.1 A Closer Look at the Sun

- Our goals for learning:
  - **Why does the Sun shine?**
  - **What is the Sun's structure?**



Radius:

6.9×10^8 m

(109 times Earth)

Mass:

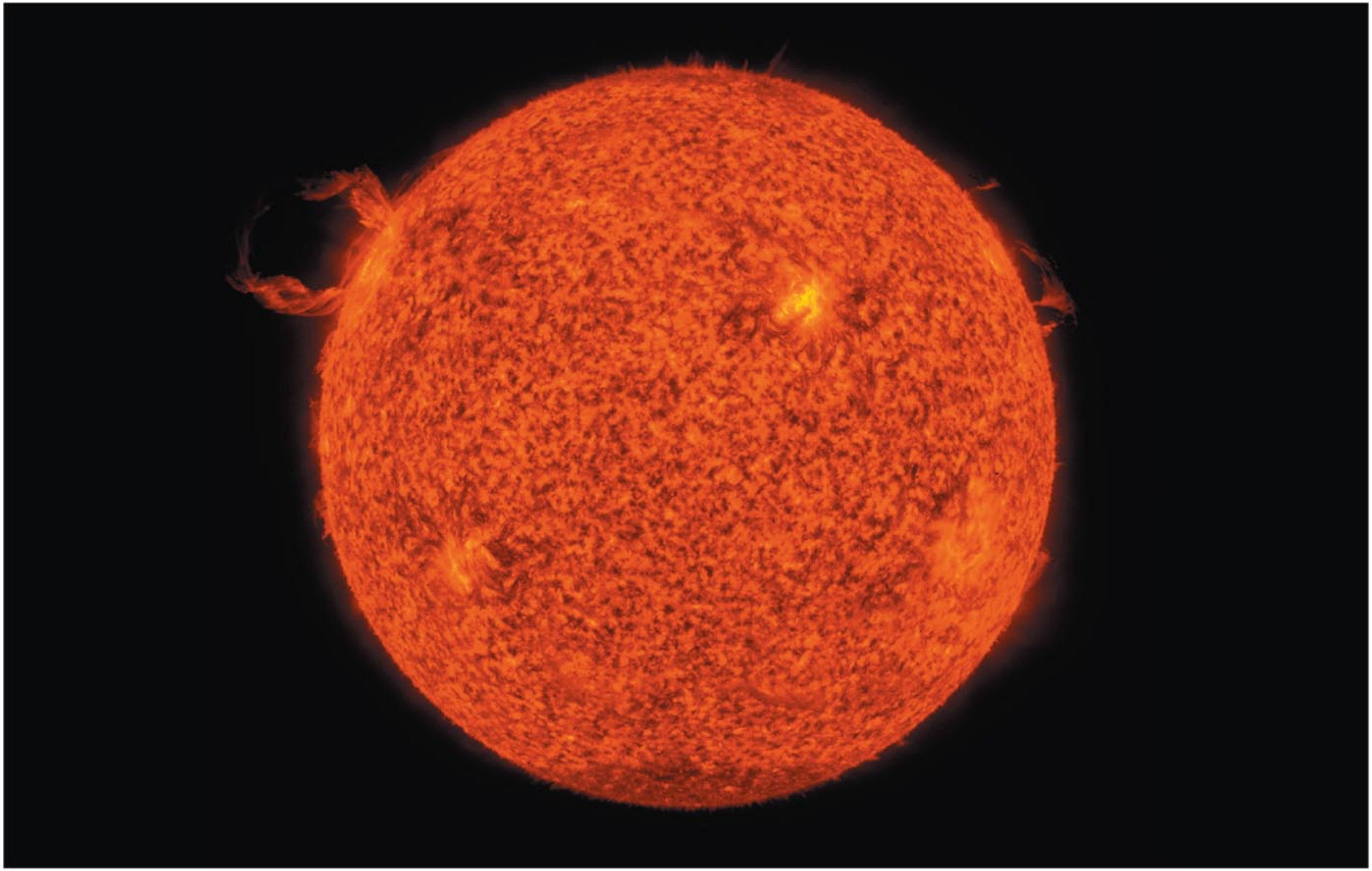
2×10^{30} kg

(300,000 Earths)

Luminosity:

3.8×10^{26} watts

Why does the Sun shine?



Why does the Sun shine?

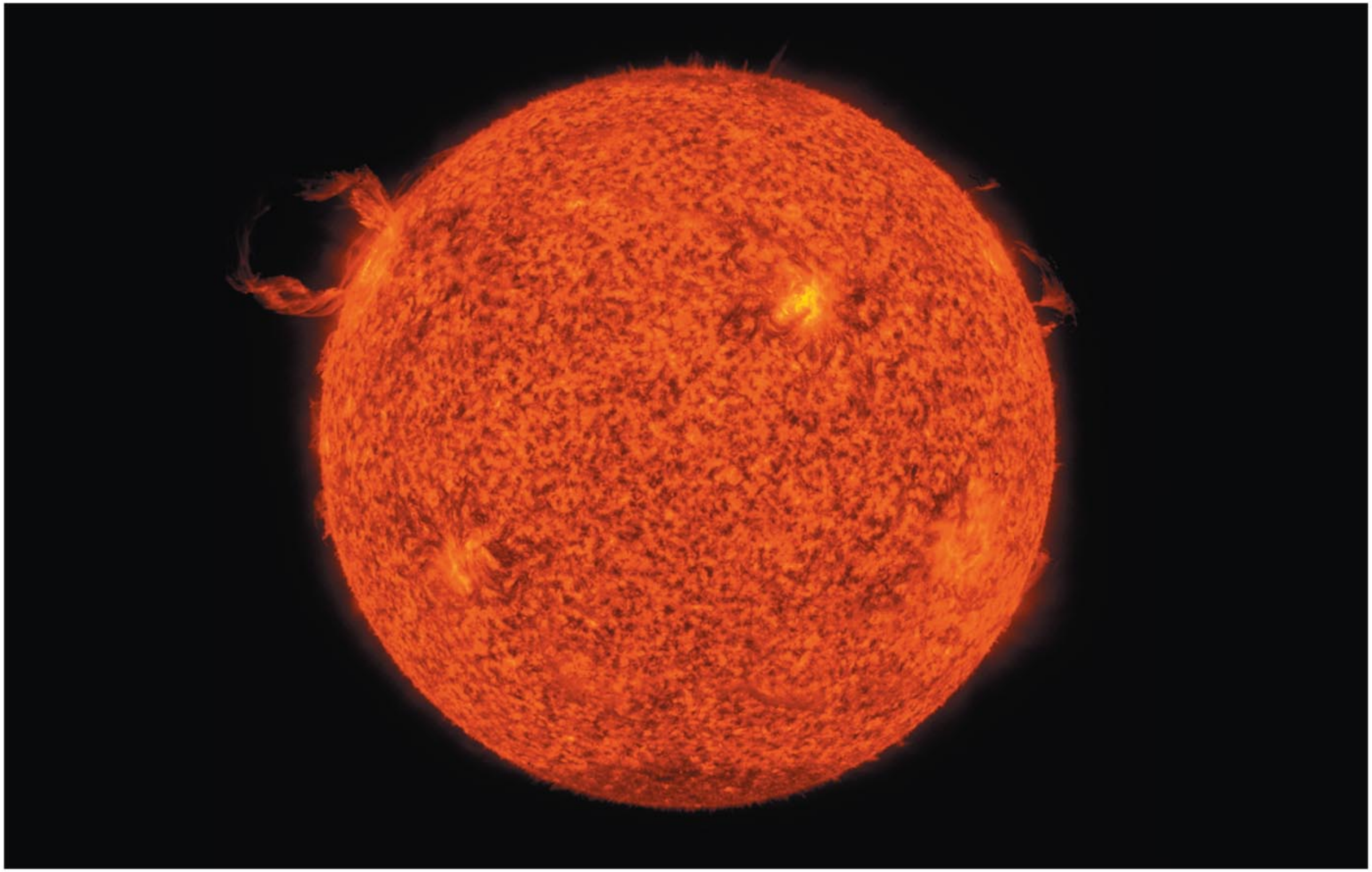
“Fuel tank” argument:

Luminosity = how much energy the Sun releases each second

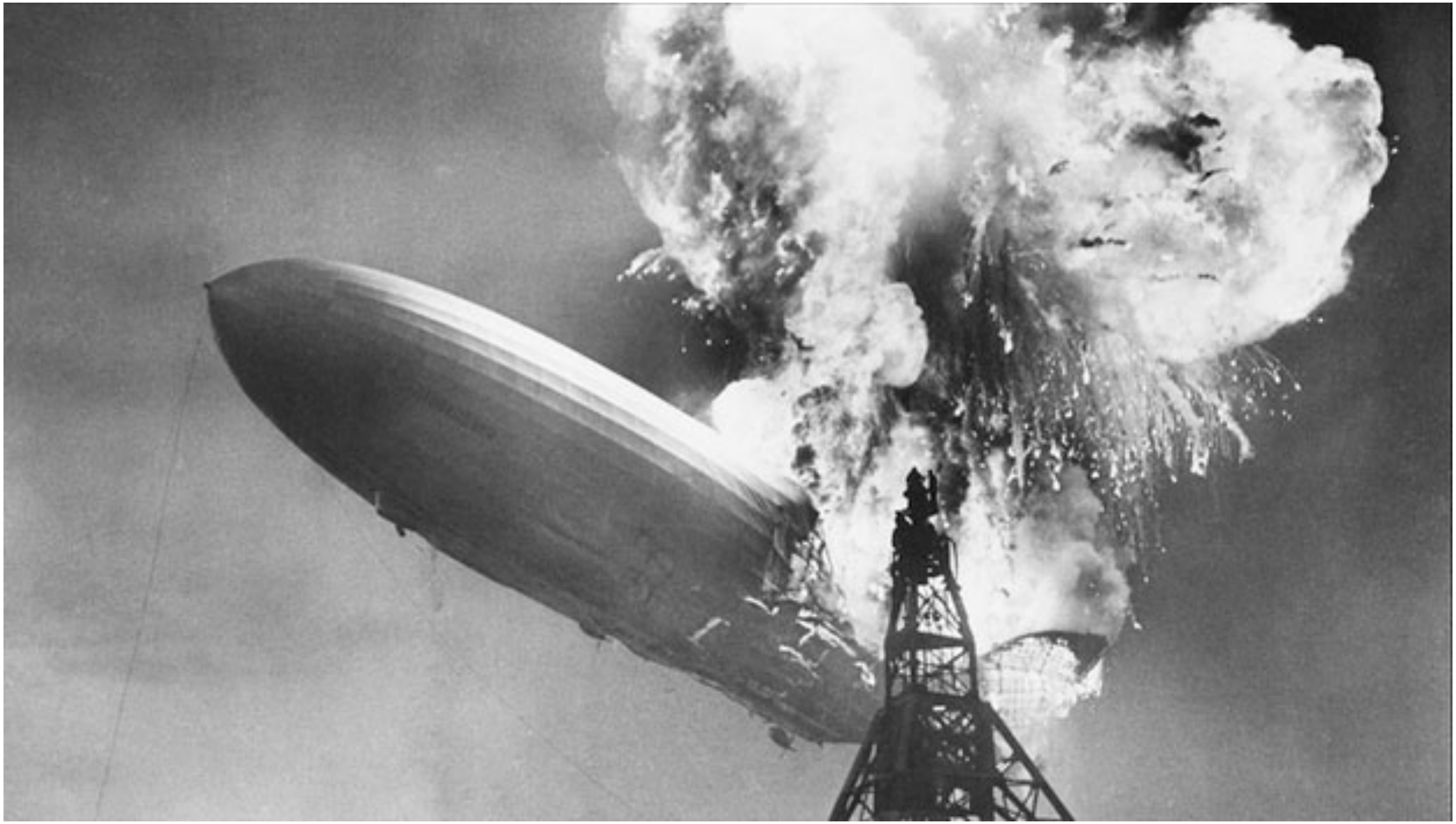
So…

Sun’s lifetime = Total Energy Stored / Luminosity

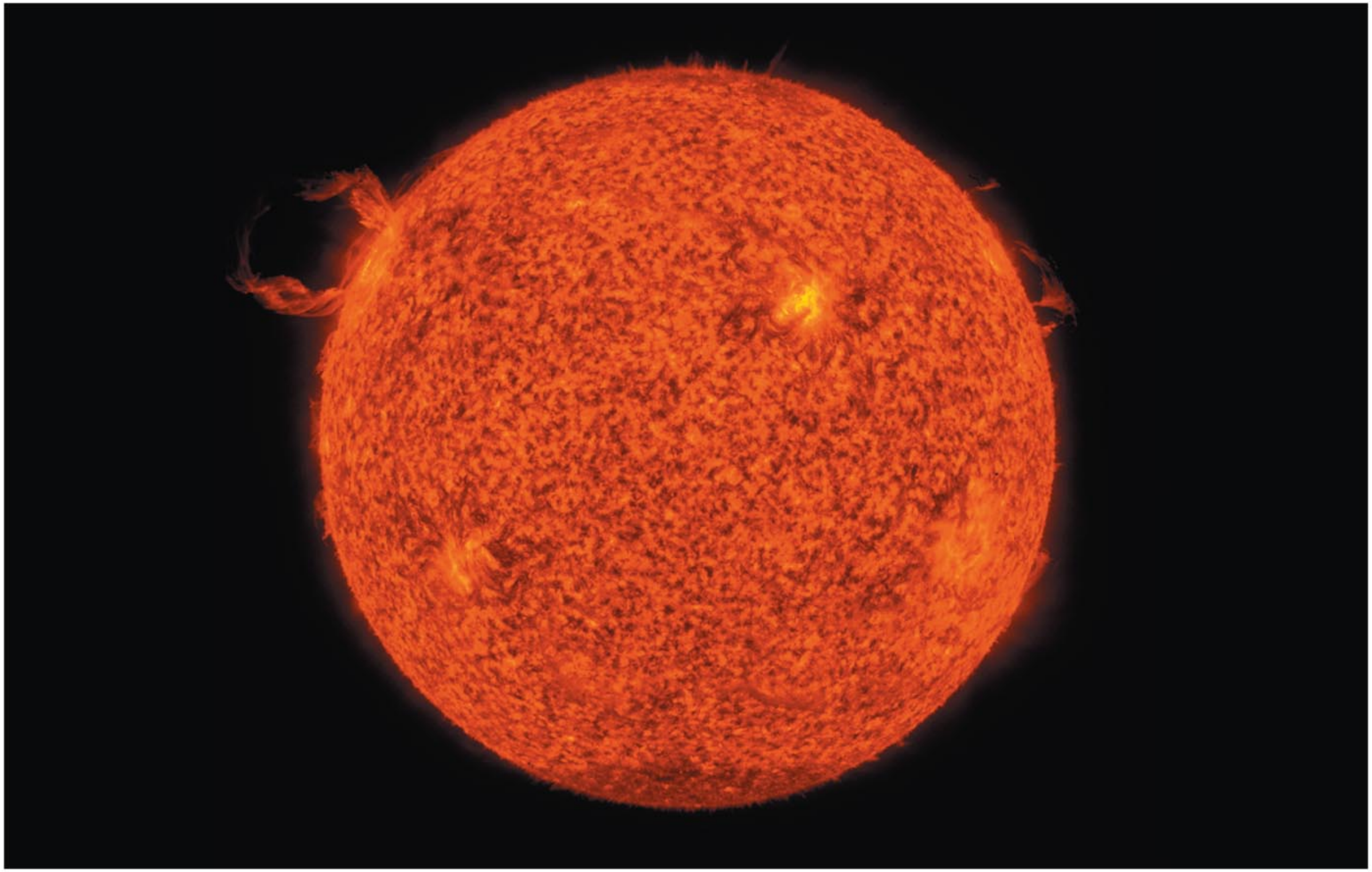
And we know that the Earth is at least 4.5 billion years old. So the Sun’s lifetime has to be at least that long.



Is it on FIRE?

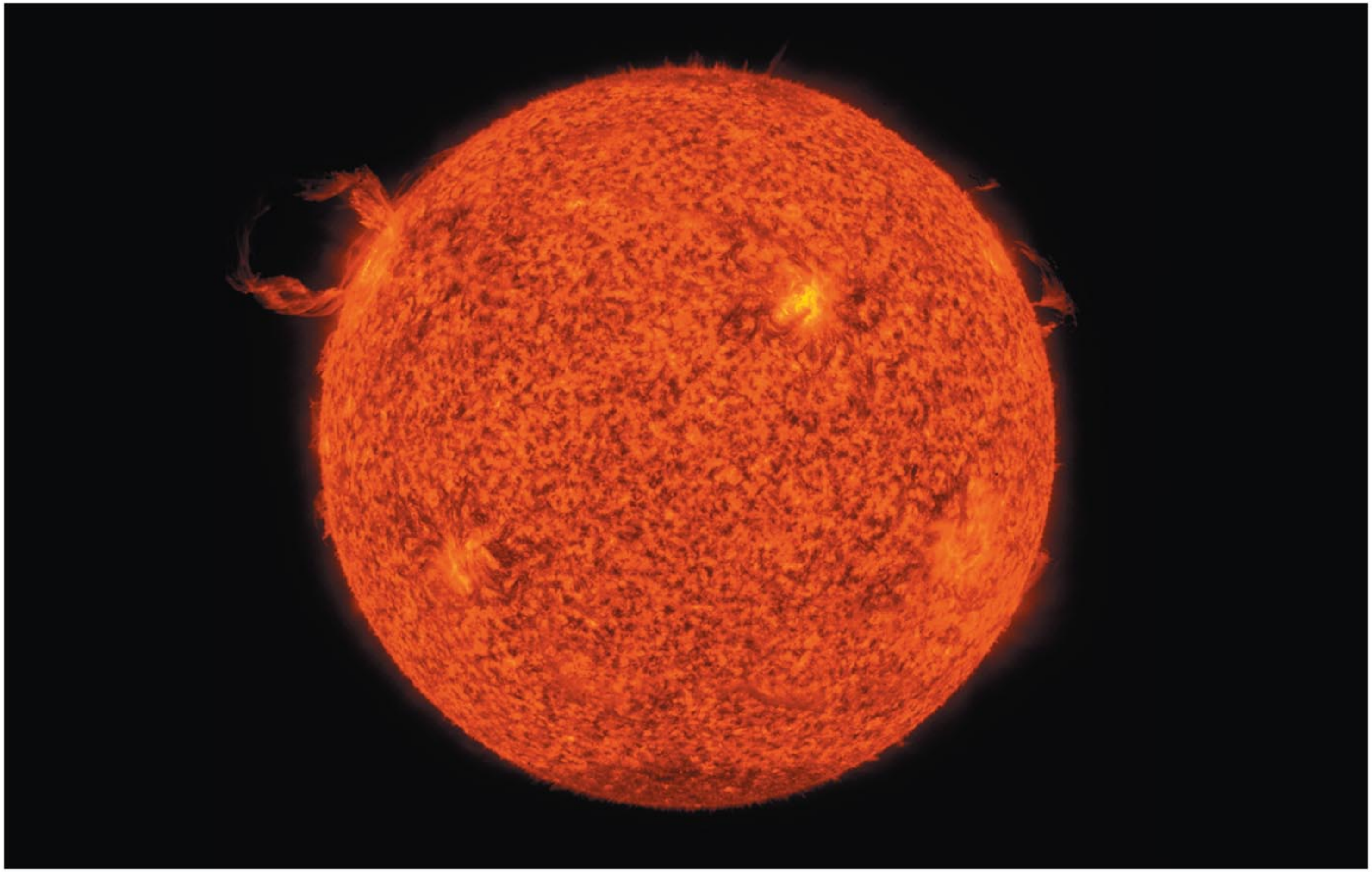


Fire: Chemical reaction involving breaking of atomic bonds that releases energy. Sun is mostly hydrogen….

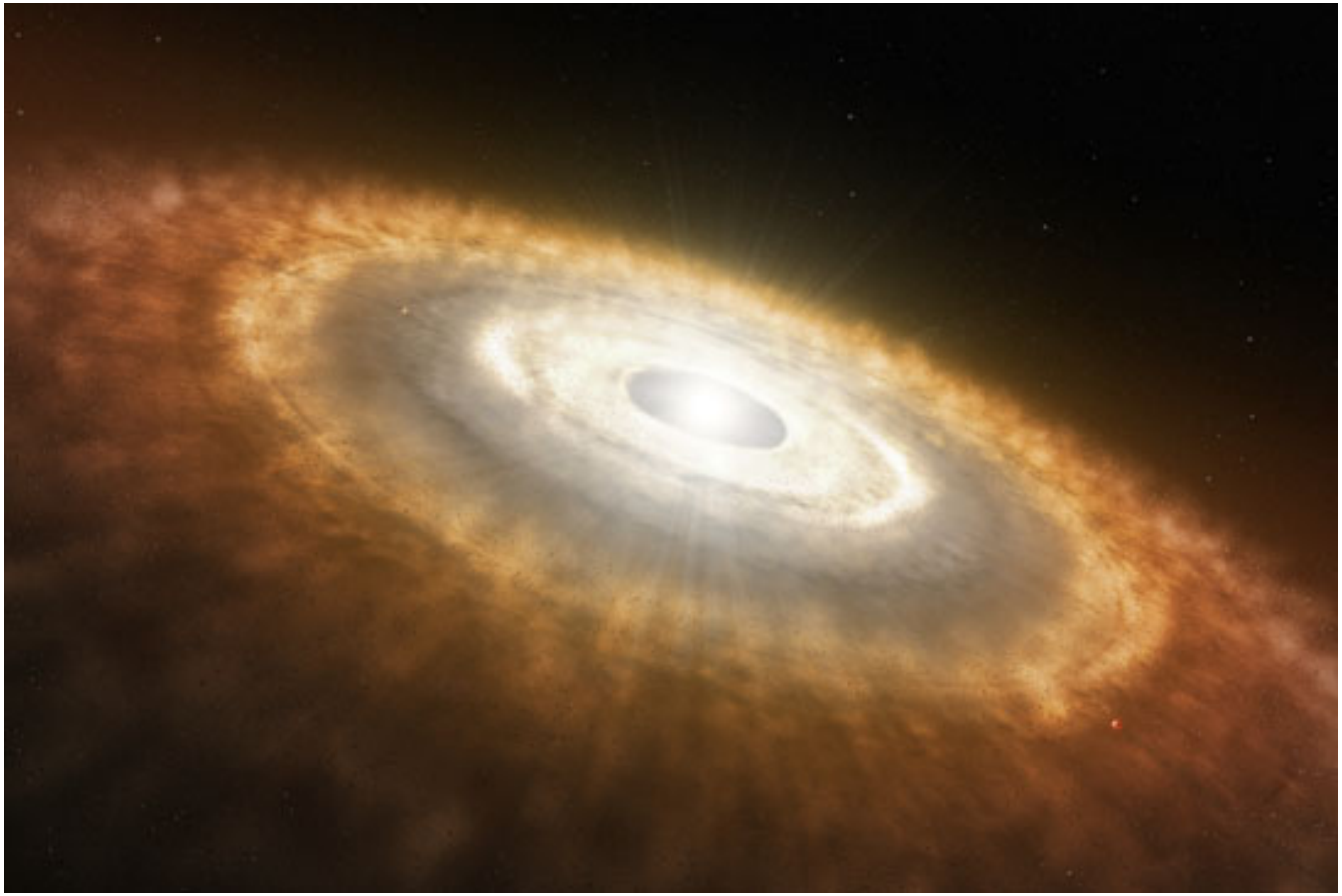


Is it on FIRE? … NO!

$$\frac{\text{Chemical energy content}}{\text{Luminosity}} \sim 10{,}000 \text{ years}$$

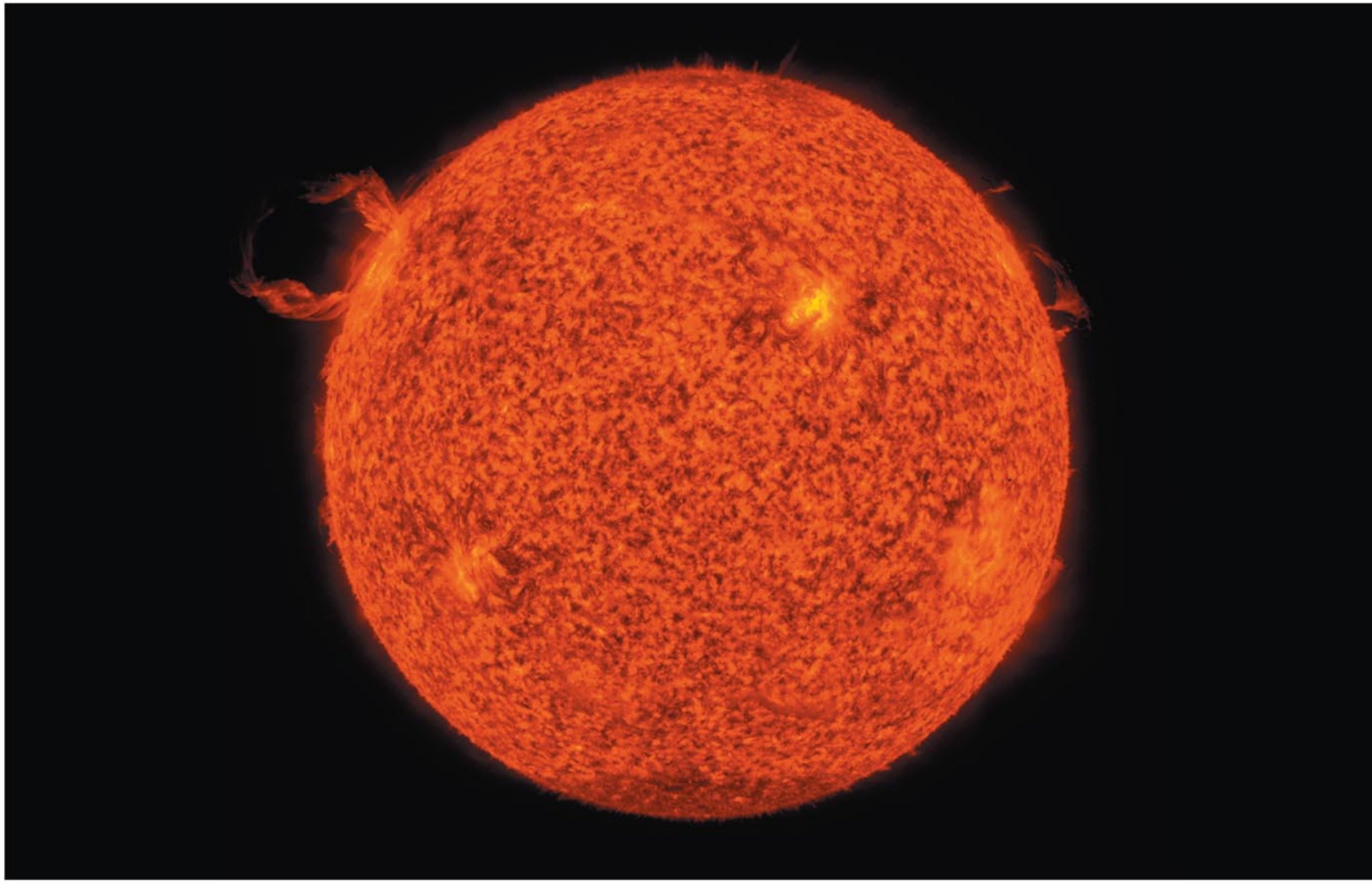


Is it CONTRACTING?



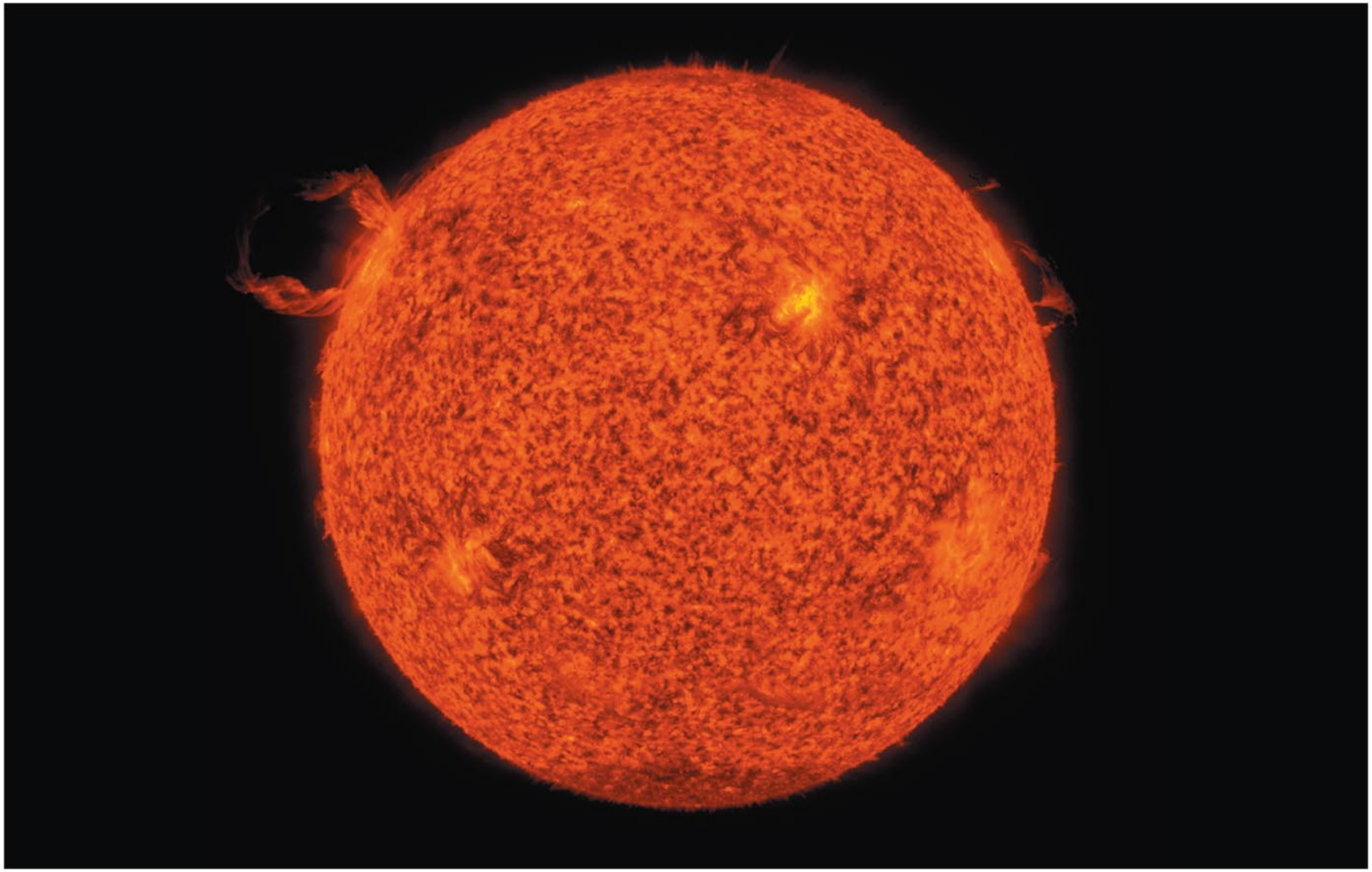
Contraction converts gravitational potential energy into heat:

- Formation of solar system
- Formation of Jupiter

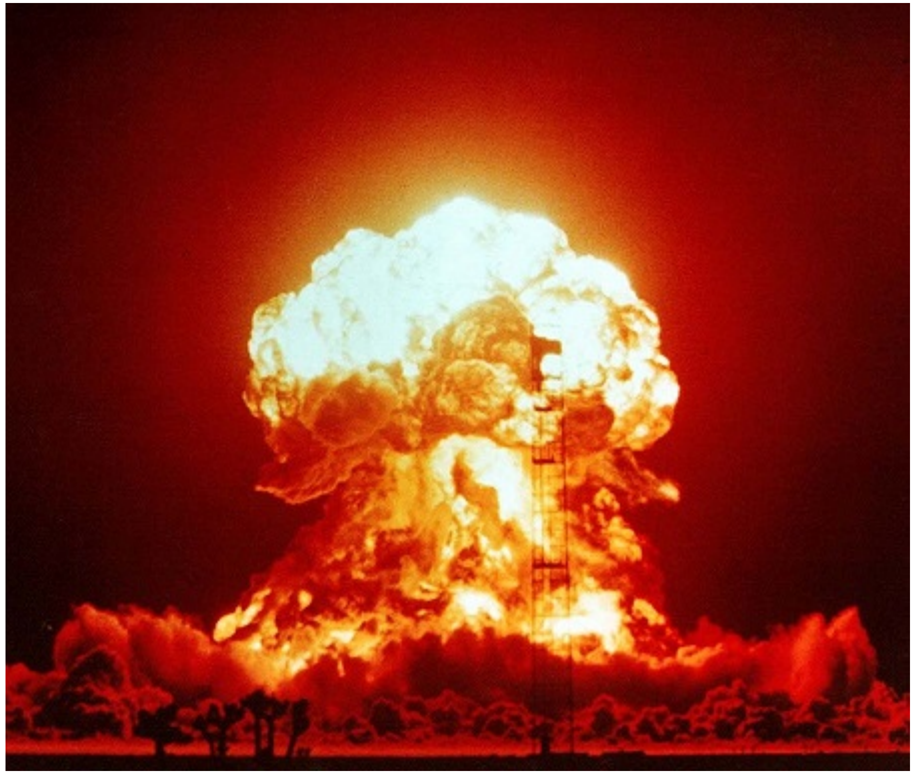


Is it CONTRACTING? … NO!

$$\frac{\text{Gravitational potential energy}}{\text{Luminosity}} \sim \text{ 25 million years}$$



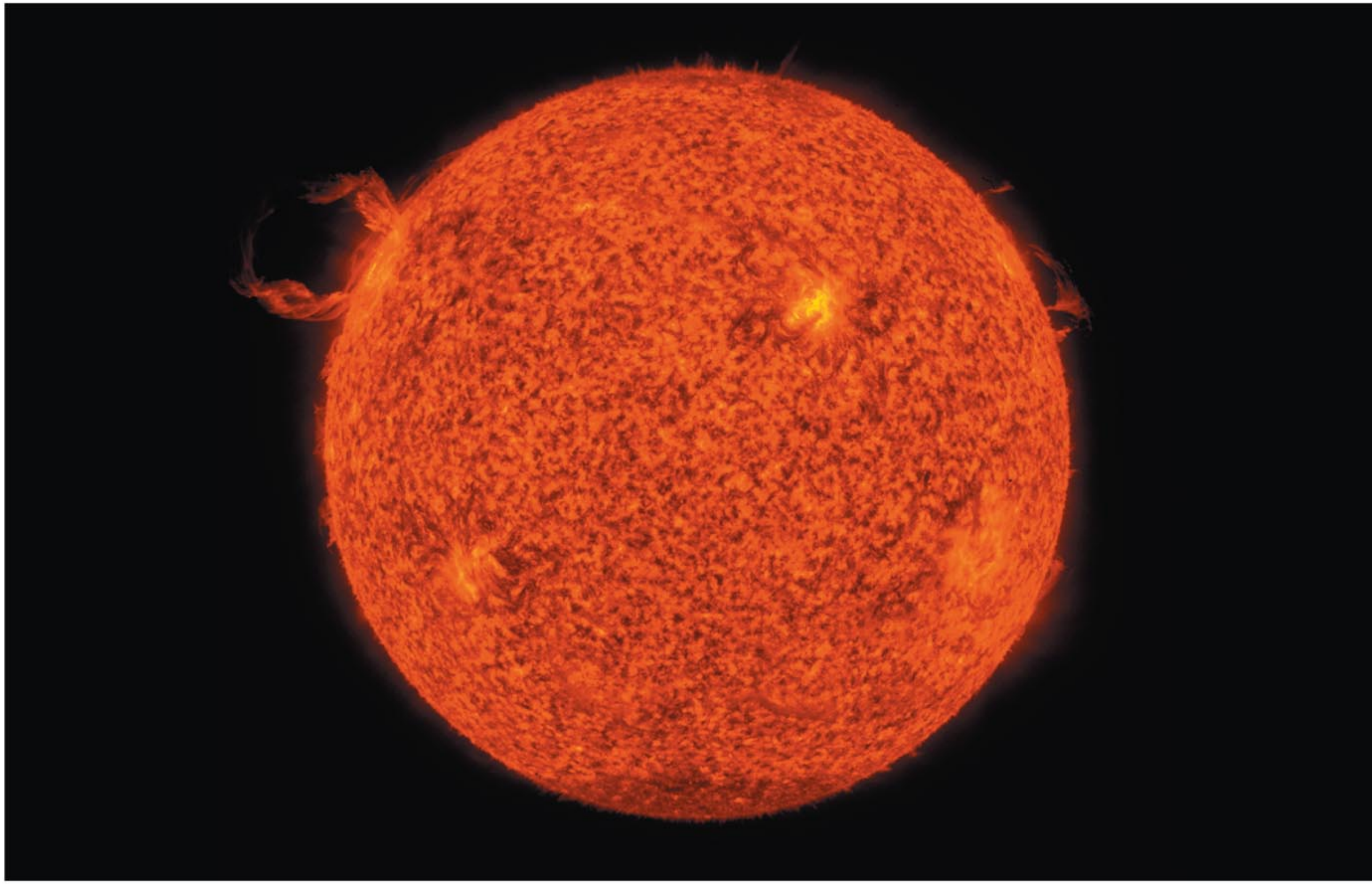
Can it be powered by NUCLEAR ENERGY?



Nuclear energy: $E=mc^2$

Two ways:

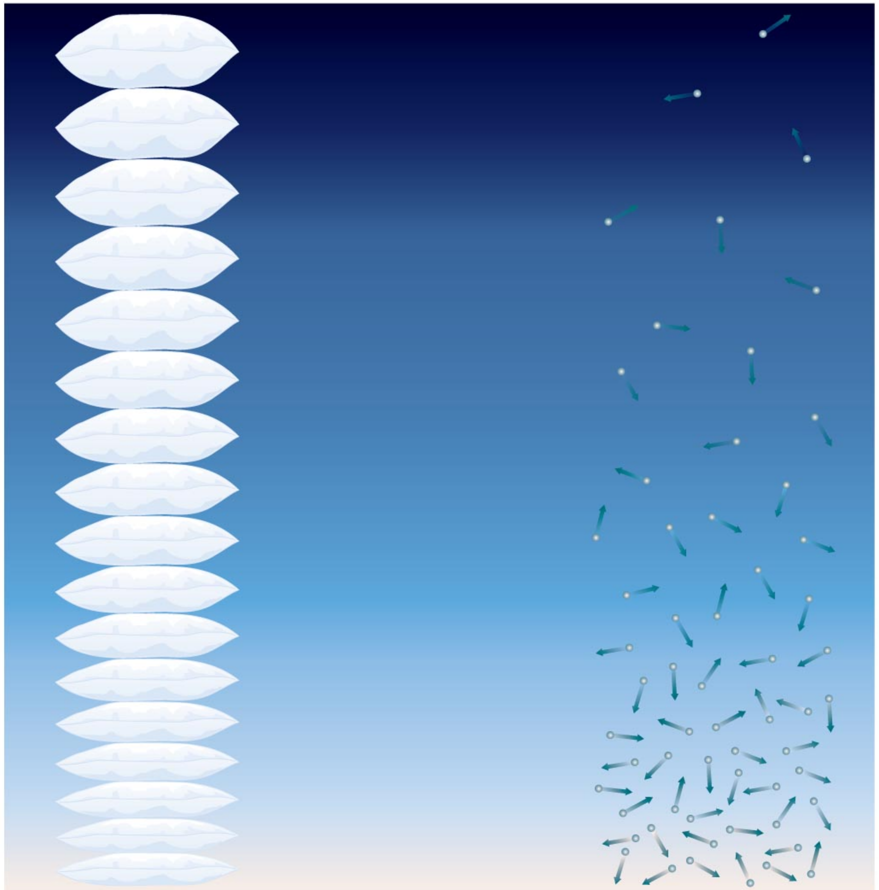
- Nuclear fission: splitting an atomic nucleus
- Nuclear fusion: fusing two atomic nuclei



Can it be powered by NUCLEAR ENERGY? …Yes!

$$\frac{\text{Nuclear potential energy (core)}}{\text{Luminosity}} \sim \text{10 billion years}$$

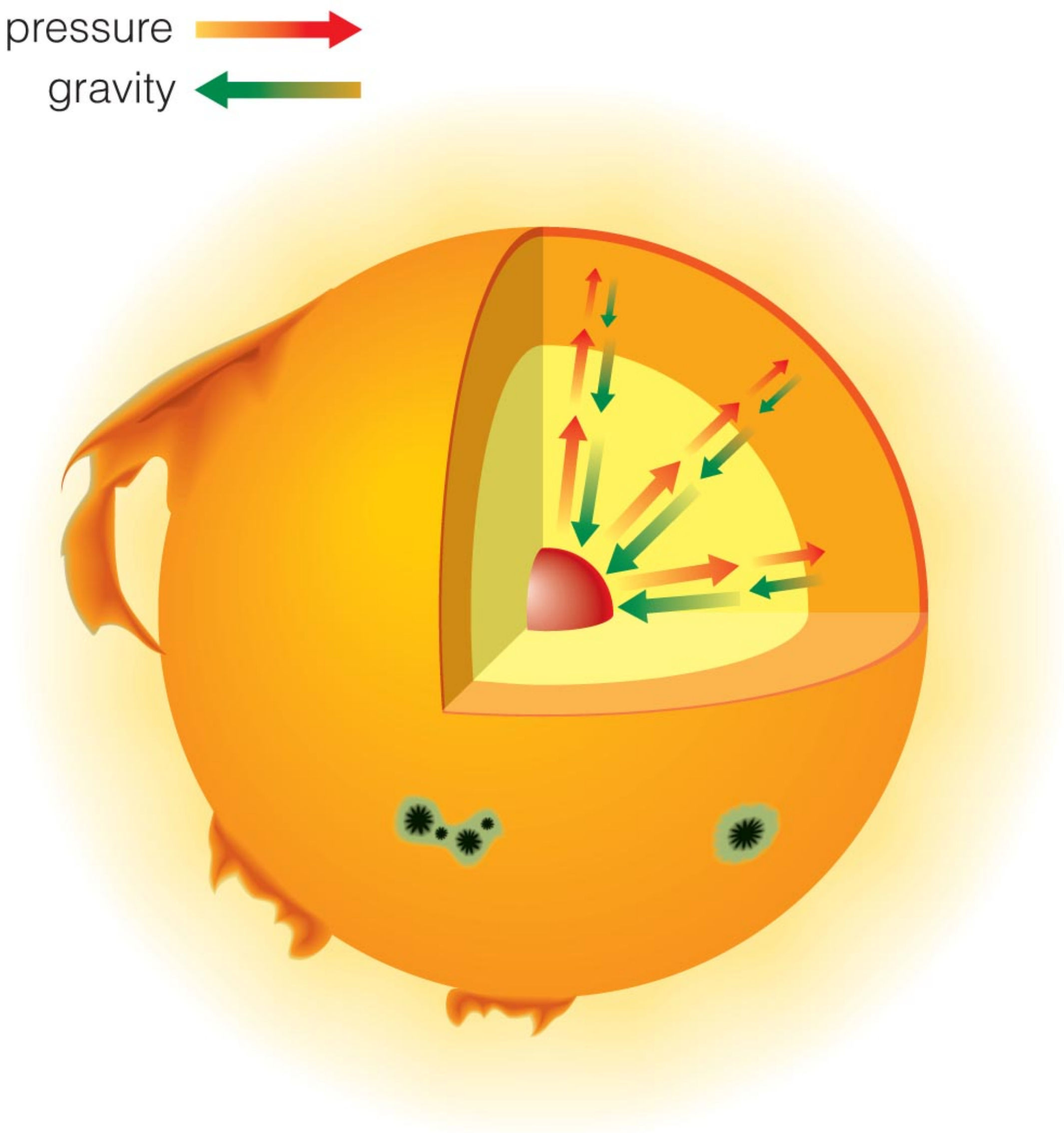
The Sun's core



Weight of the Sun's outer layers compress and heat up the inner layers.

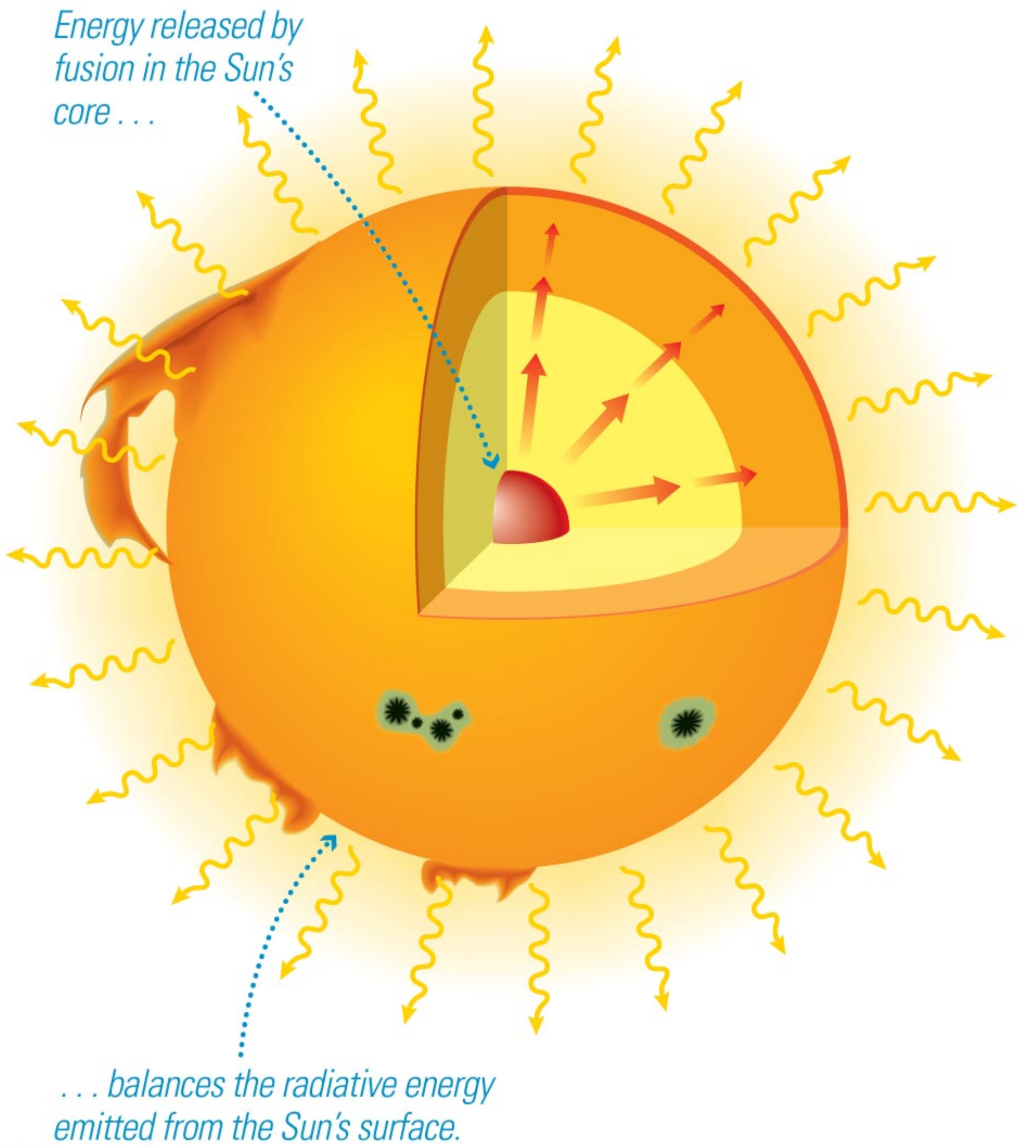
The Sun is so massive that the core temperature is very dense and hot: 15 million degrees.

The conditions are right for fusing hydrogen into helium.



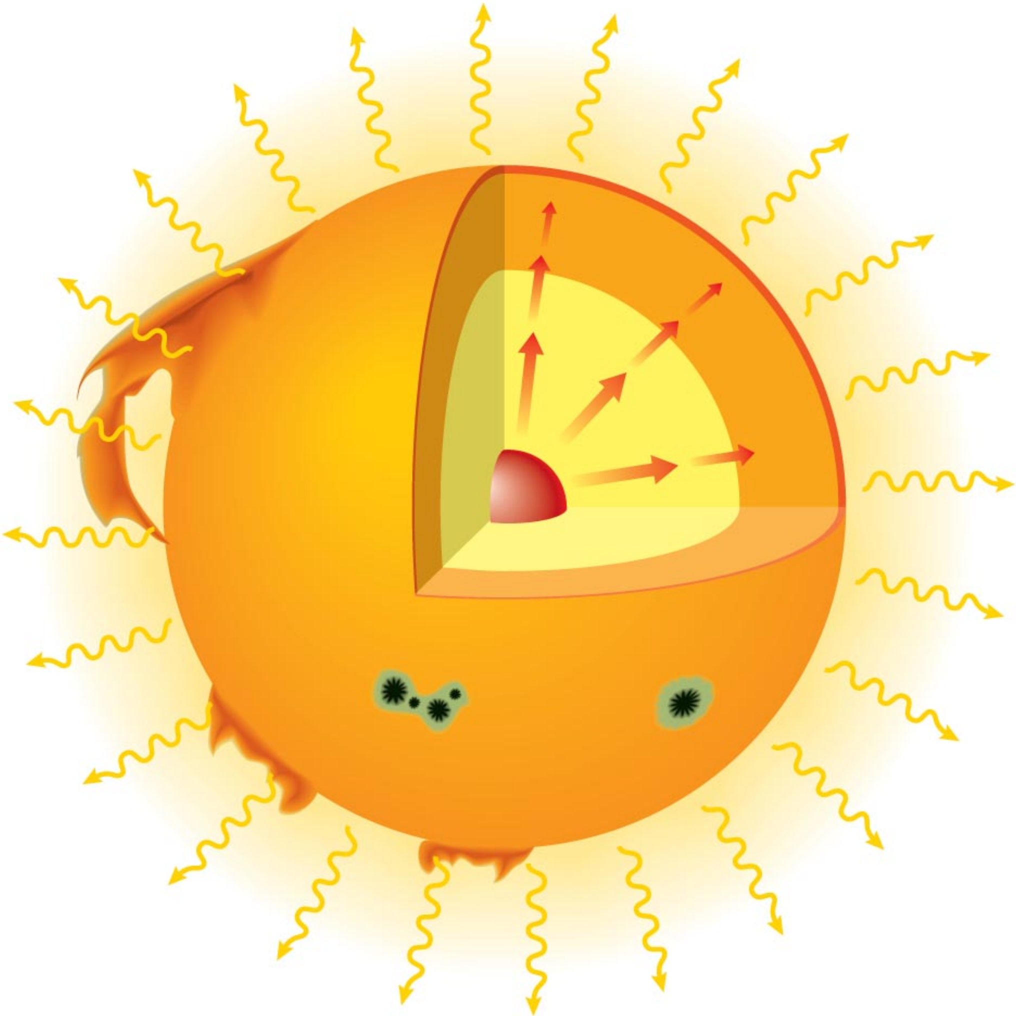
Gravitational equilibrium:

Energy supplied by fusion maintains the pressure that balances the inward crush of gravity.



Energy Balance:

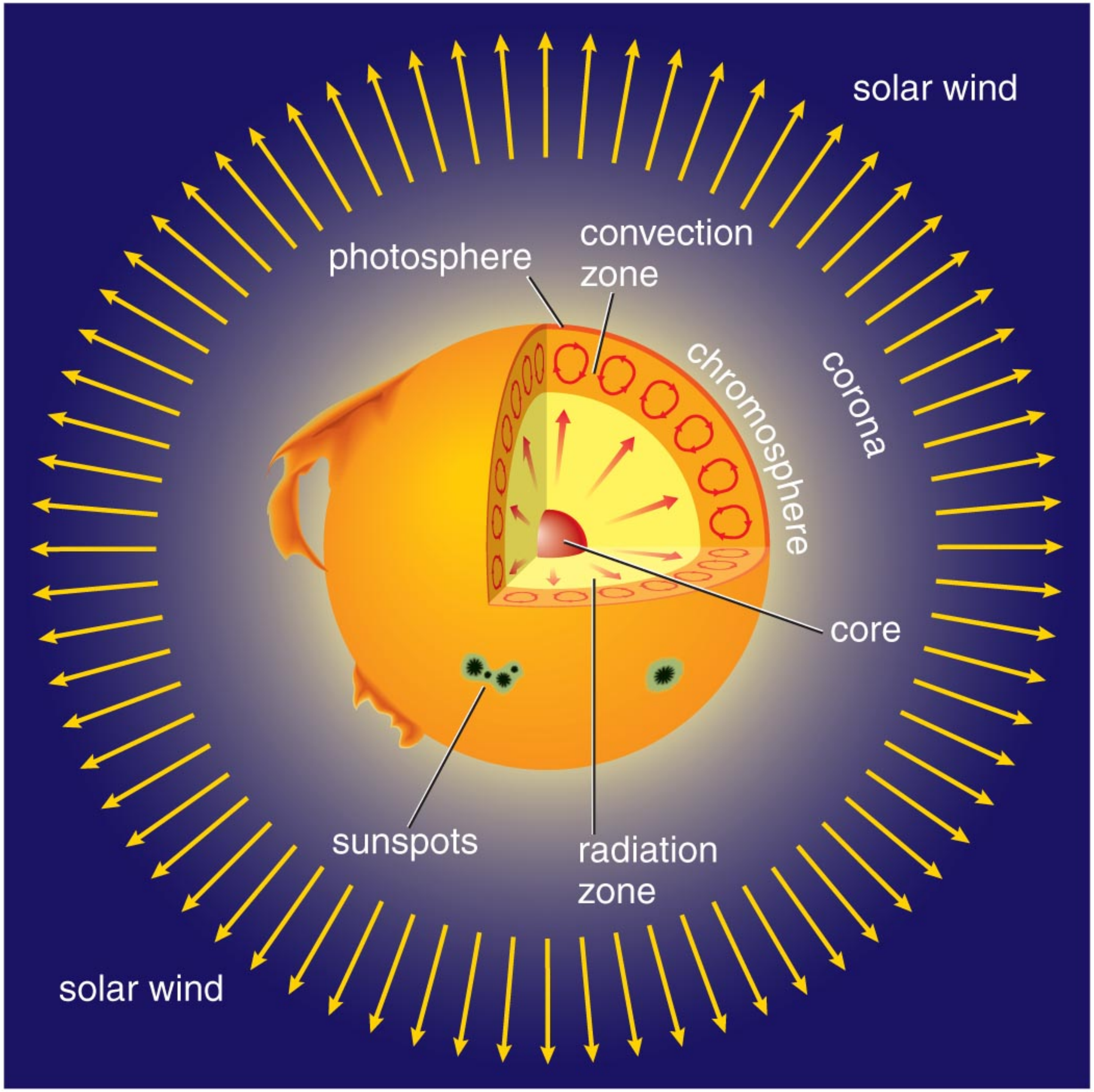
The rate at which energy radiates from the surface of the Sun must be the same as the rate at which it is released by fusion in the core.

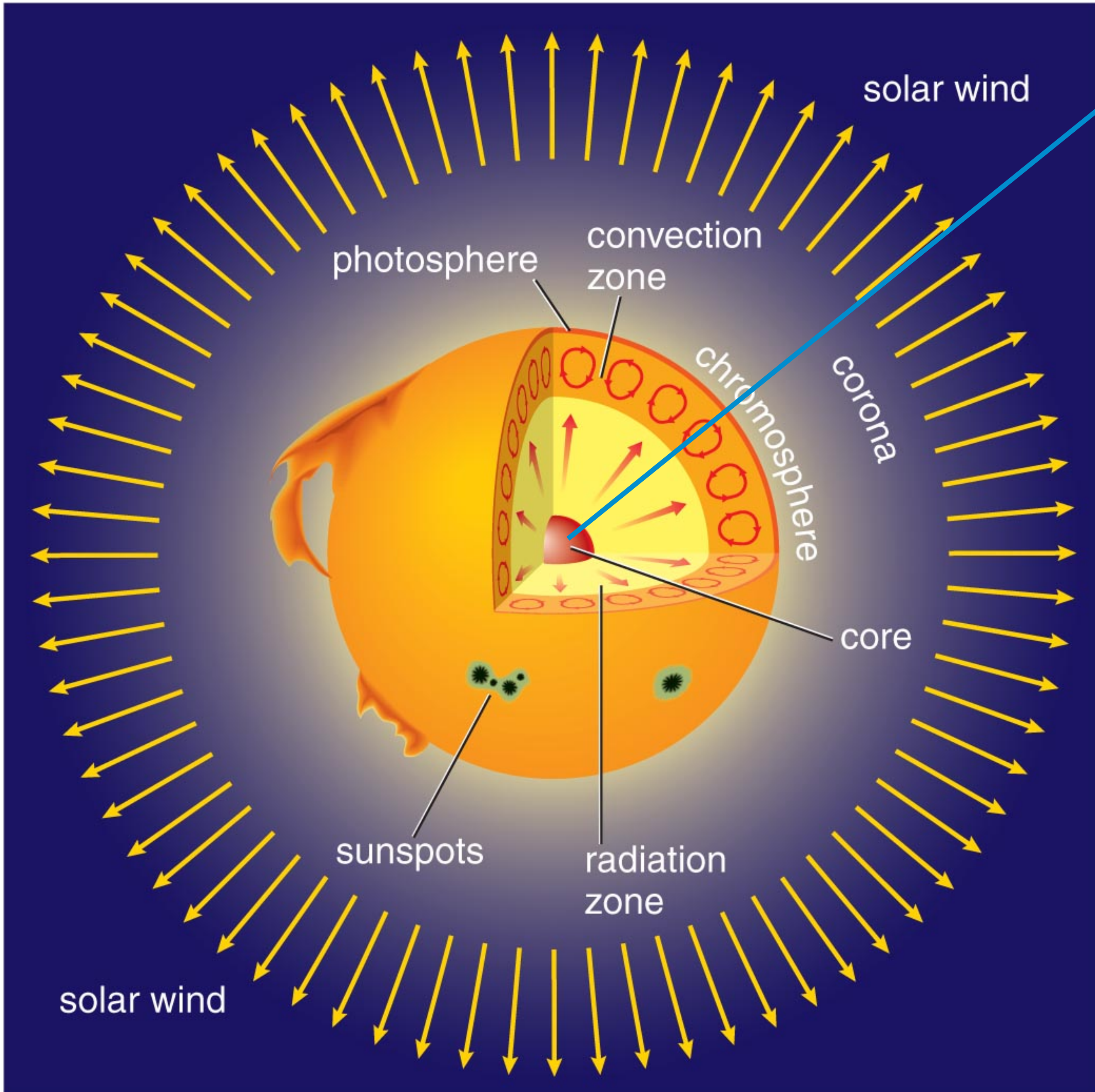


Gravitational contraction:

- Provided the energy that heated the core as Sun was forming
- But contraction stopped when fusion began.

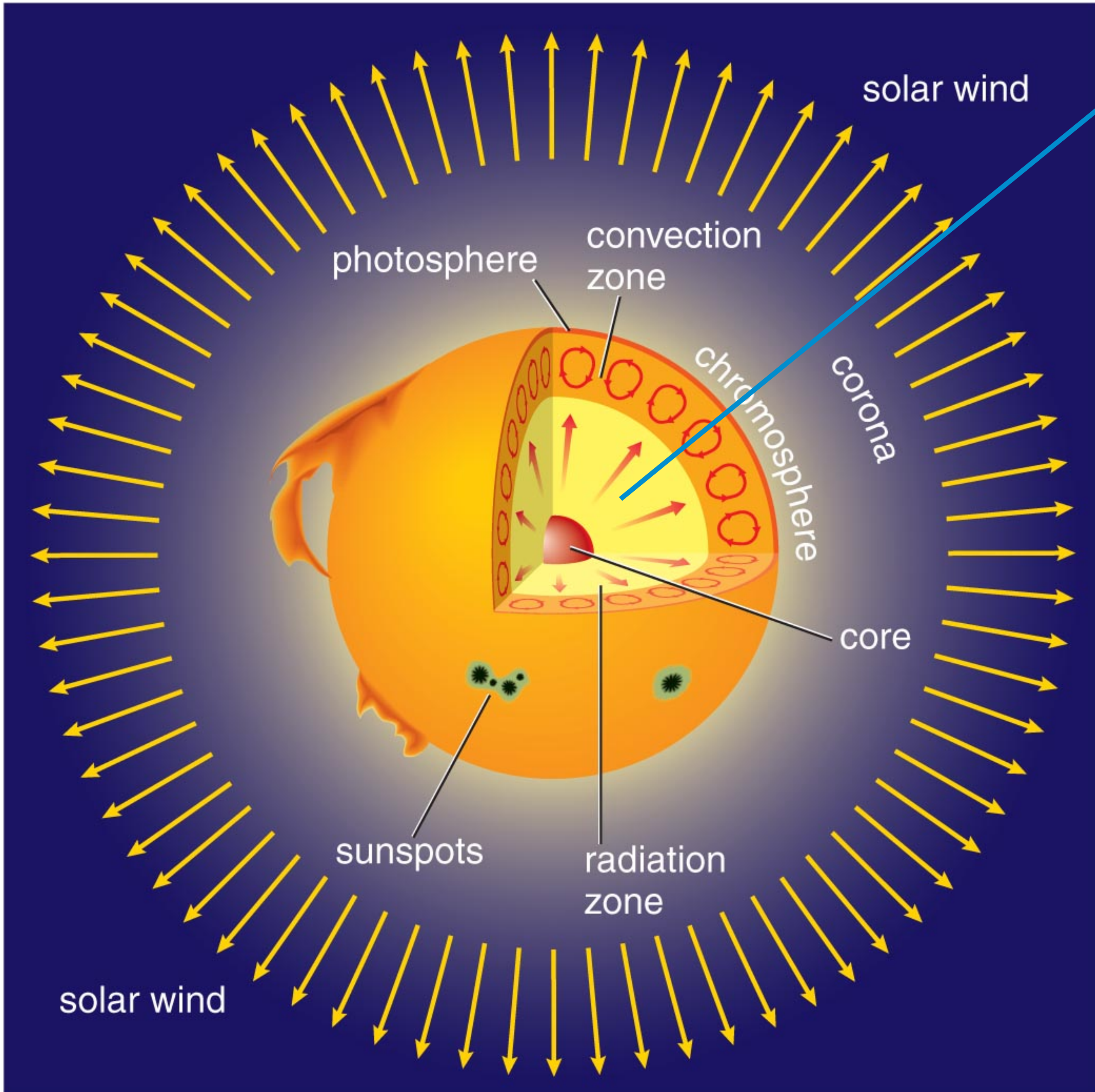
What is the Sun's structure?





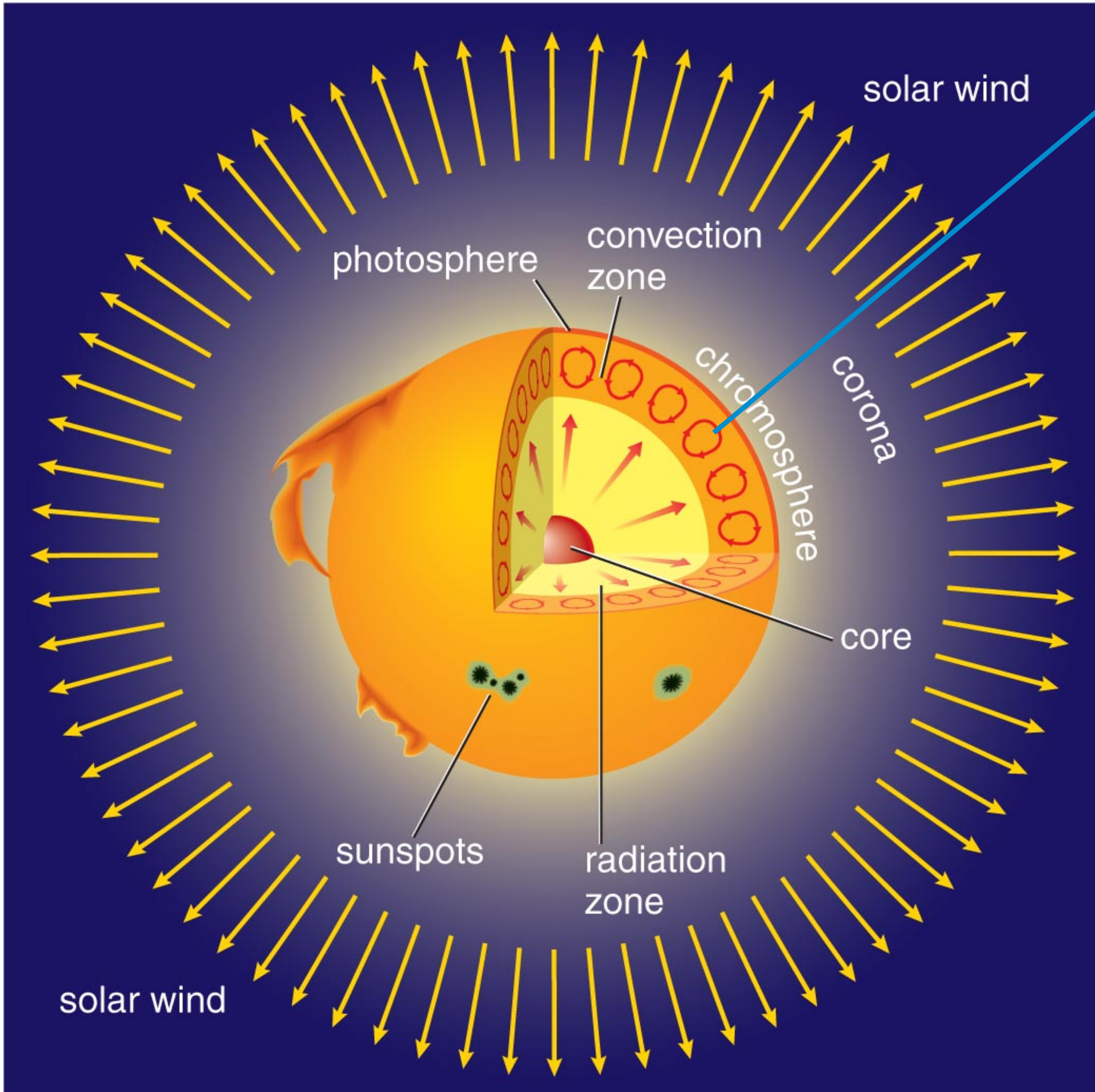
Core:

- Energy generated by nuclear fusion ~ 15 million K



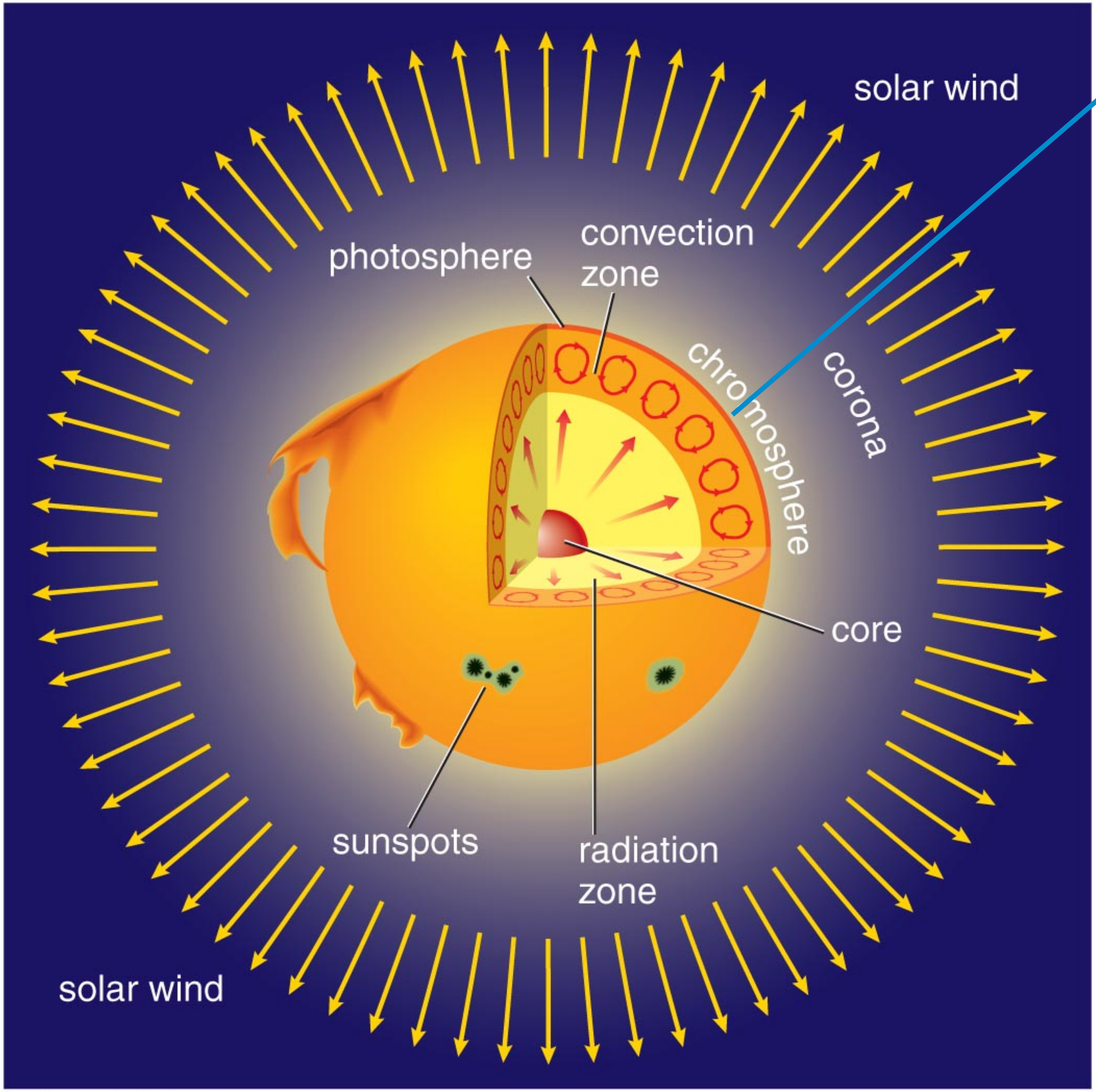
Radiation Zone:

- Energy transported upward by photons



Convection Zone:

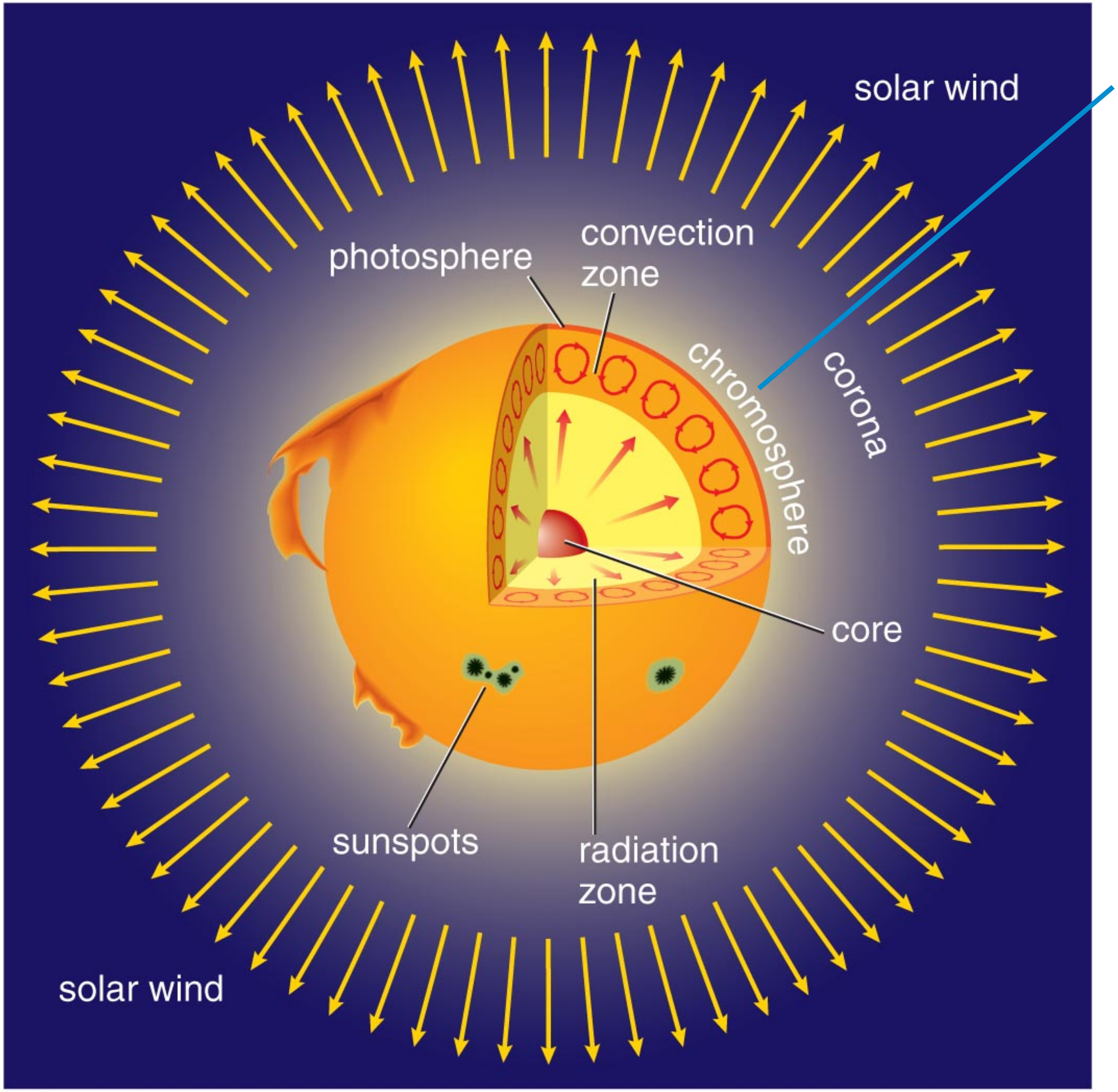
- Energy transported upward by rising hot gas



Photosphere:

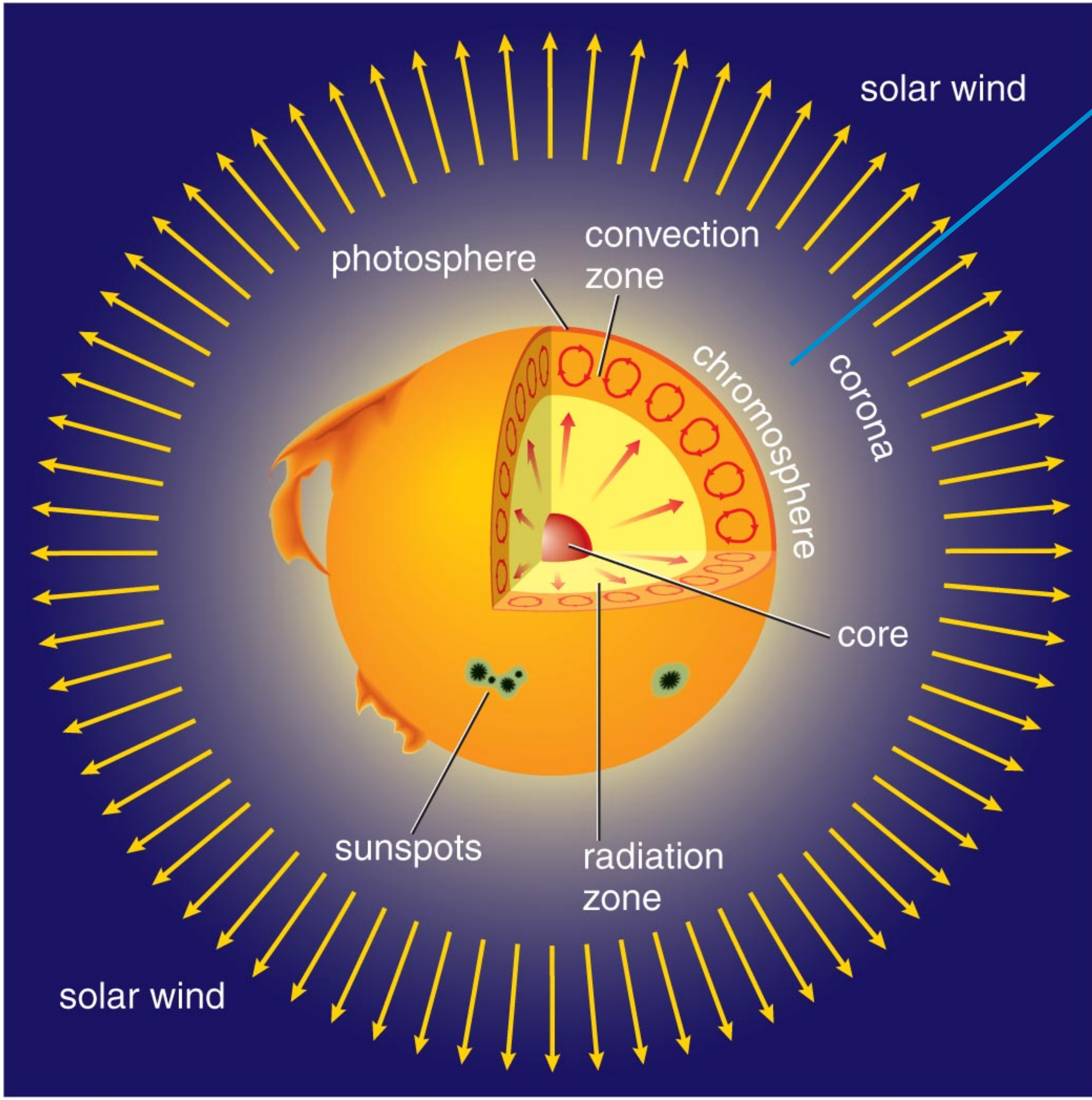
- Visible surface of Sun

  ~ 6000 K



Chromosphere:

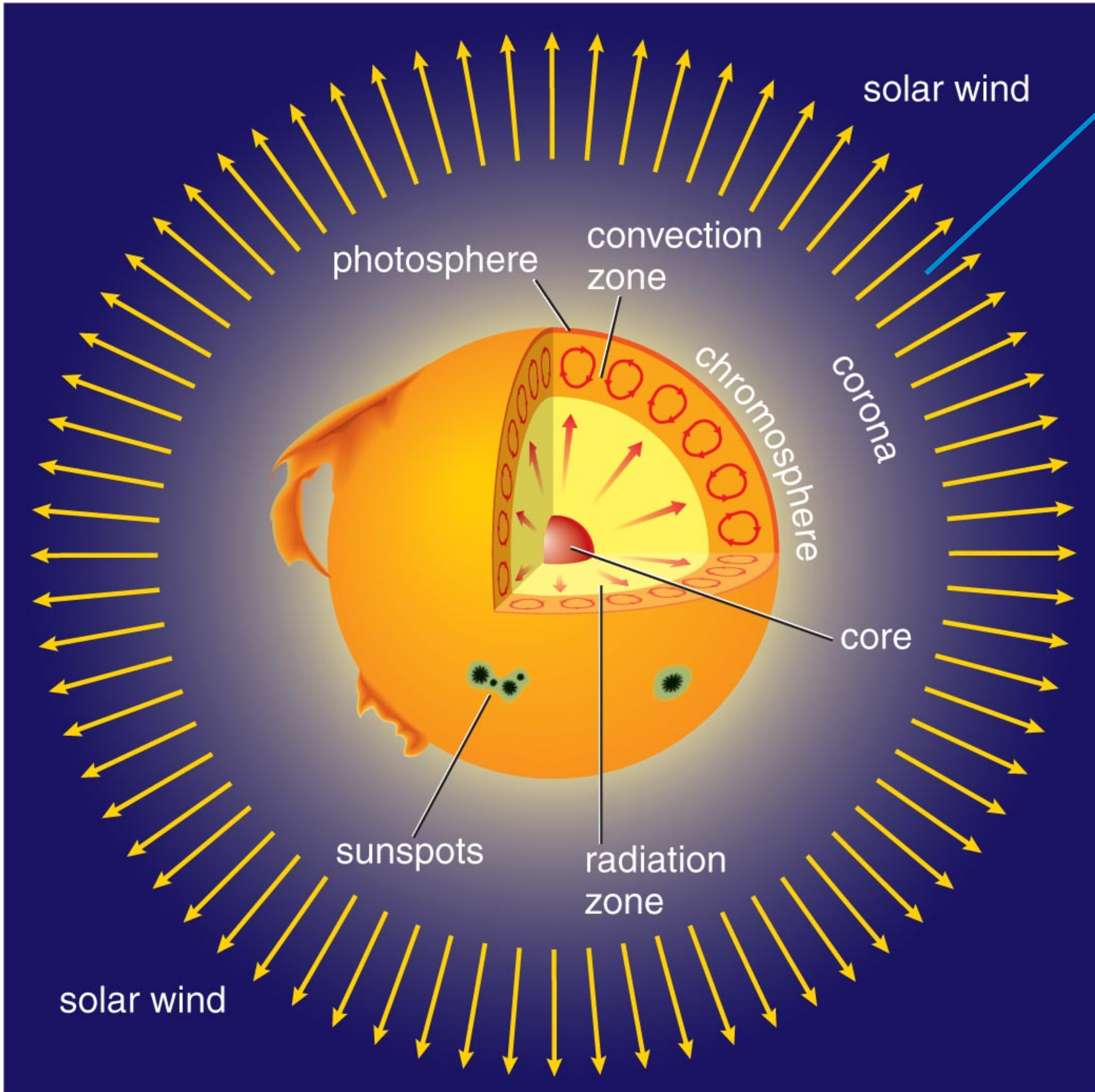
- Middle layer of solar atmosphere
- Very hot: 10,000 K – 100,000 K



Corona:

- Outermost layer of solar atmosphere

~1 million K



Solar wind:

- A flow of charged particles from the surface of the Sun

What have we learned?

- **Why does the Sun shine?**
  - Chemical and gravitational energy sources could not explain how the Sun could sustain its luminosity for more than about 25 million years.
  - The Sun shines because **gravitational equilibrium** keeps its core hot and dense enough to release energy through nuclear fusion.

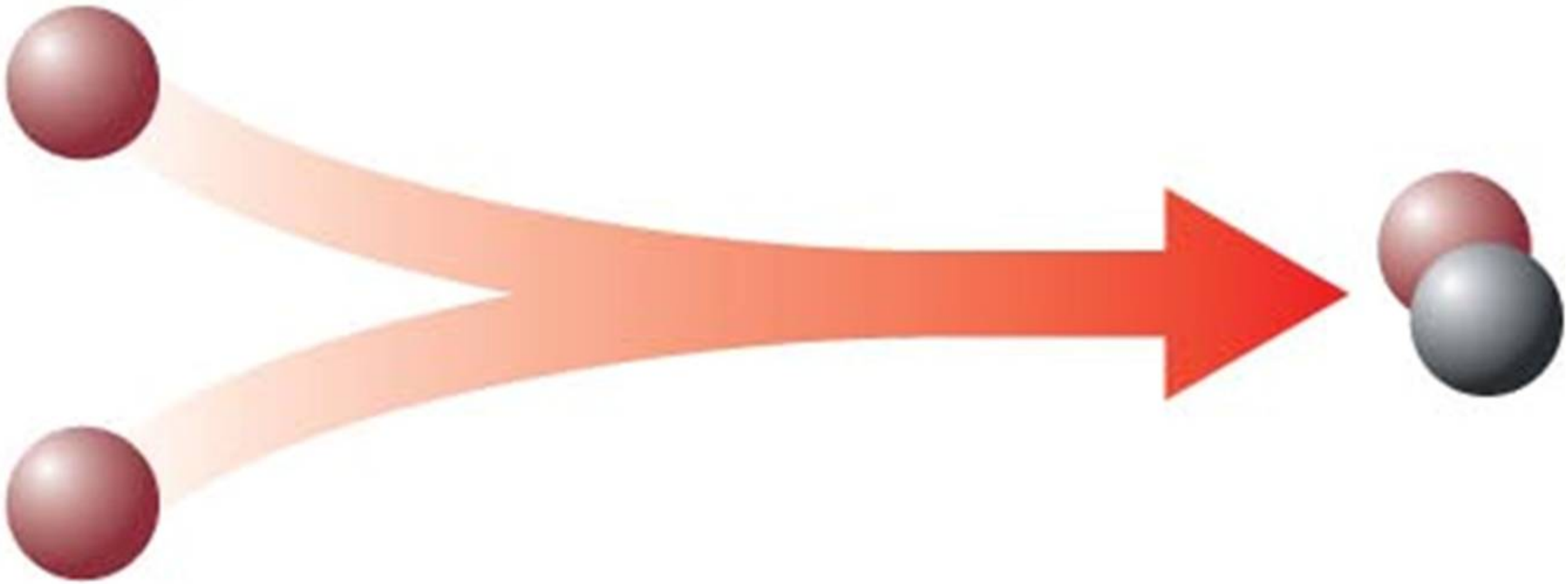
What have we learned?

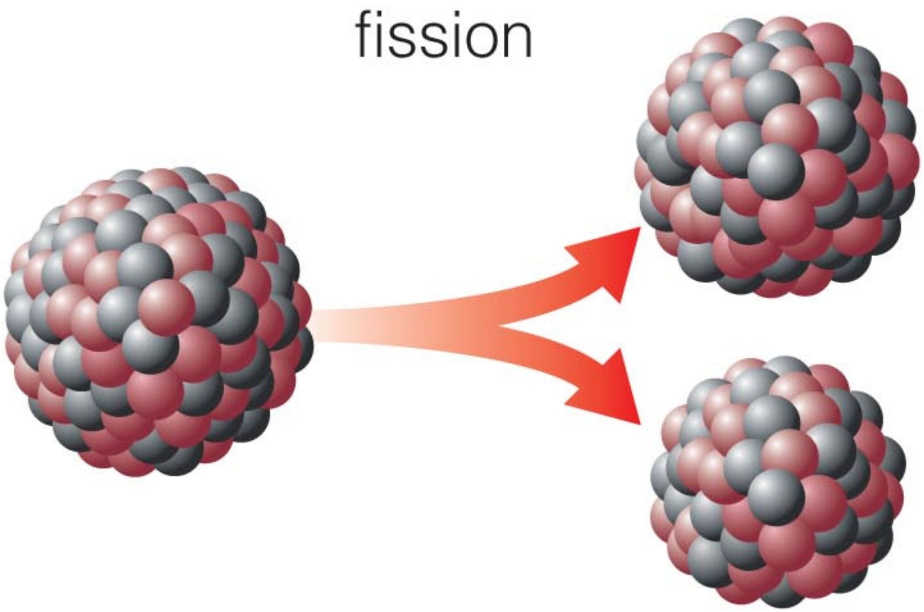
- **What is the Sun's structure?**
  - From inside out, the layers are:
    - Core
    - Radiation zone
    - Convection zone
    - Photosphere
    - Chromosphere
    - Corona

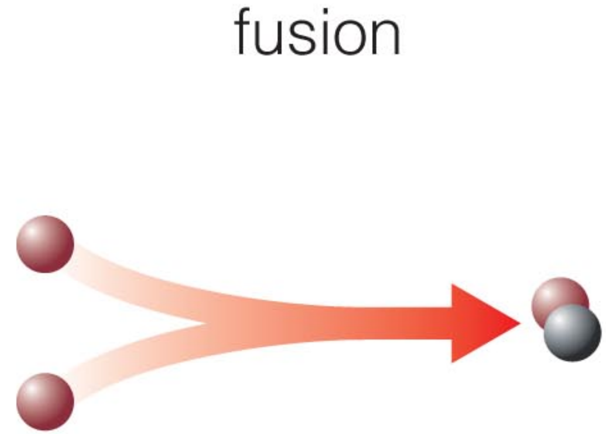
14.2 Nuclear Fusion in the Sun

- Our goals for learning:
  - **How does nuclear fusion occur in the Sun?**
  - **How does the energy from fusion get out of the Sun?**
  - **How do we know what is happening inside the Sun?**

How does nuclear fusion occur in the Sun?







Fission

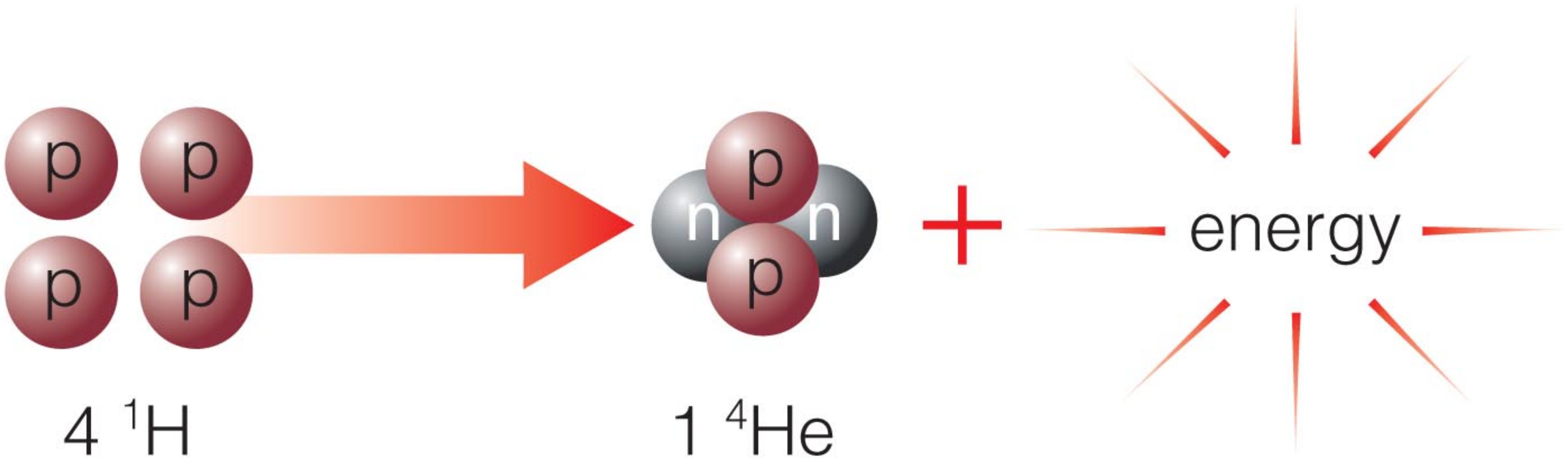
- Big nucleus splits into smaller pieces.

•Example: nuclear power plants

Fusion

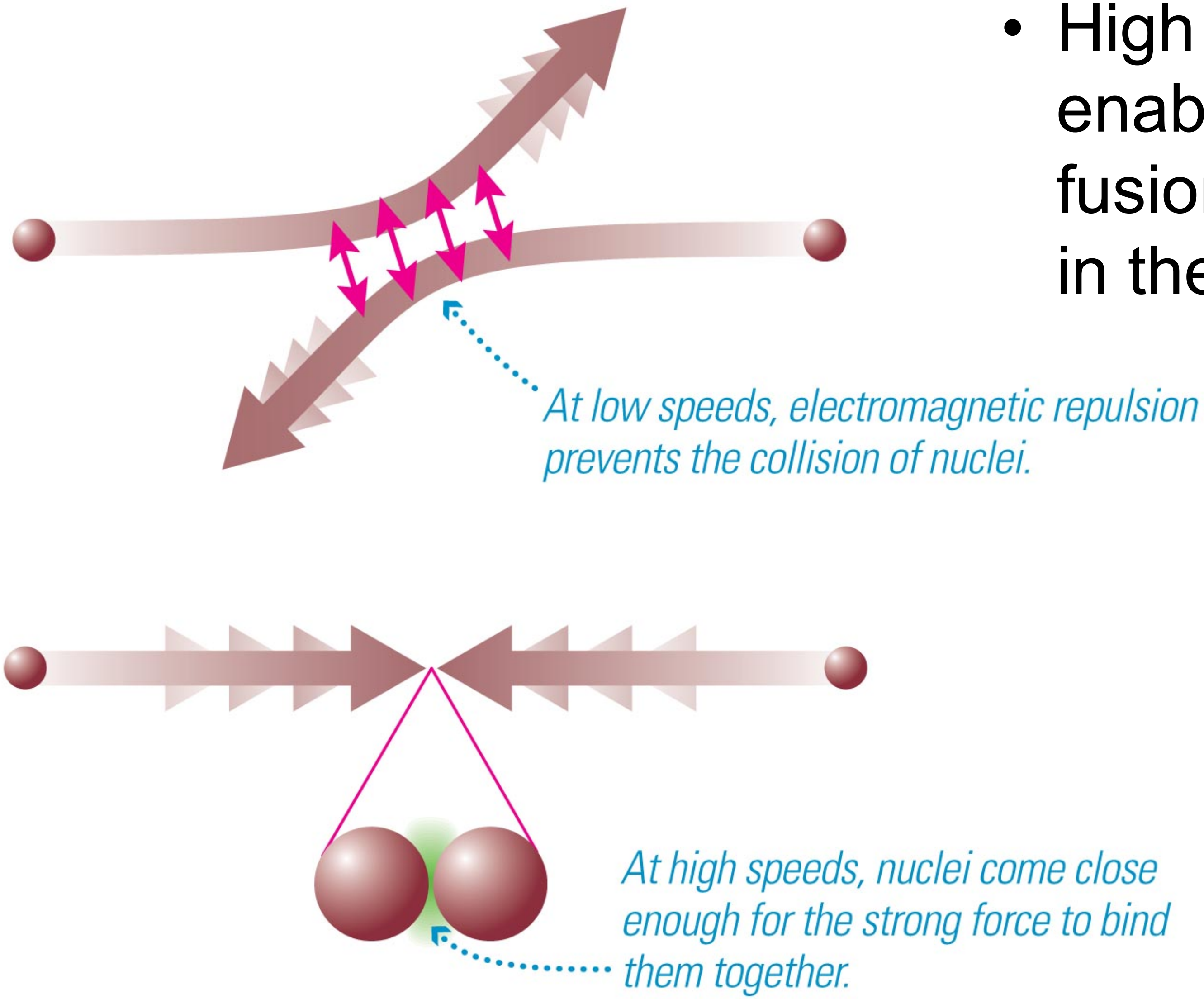
- Small nuclei stick together to make a bigger one.

- Example: the Sun, stars



- The Sun releases energy by fusing four hydrogen nuclei into one helium nucleus.

- High temperatures enable nuclear fusion to happen in the core.



The Proton-Proton Chain

Proton
Neutron
Positron
Neutrino
Gamma Ray

Step 1: proton + proton = deuterium (^{2}H) + positron + neutrino

The Proton-Proton Chain

Proton
Neutron
Positron
Neutrino
Gamma Ray

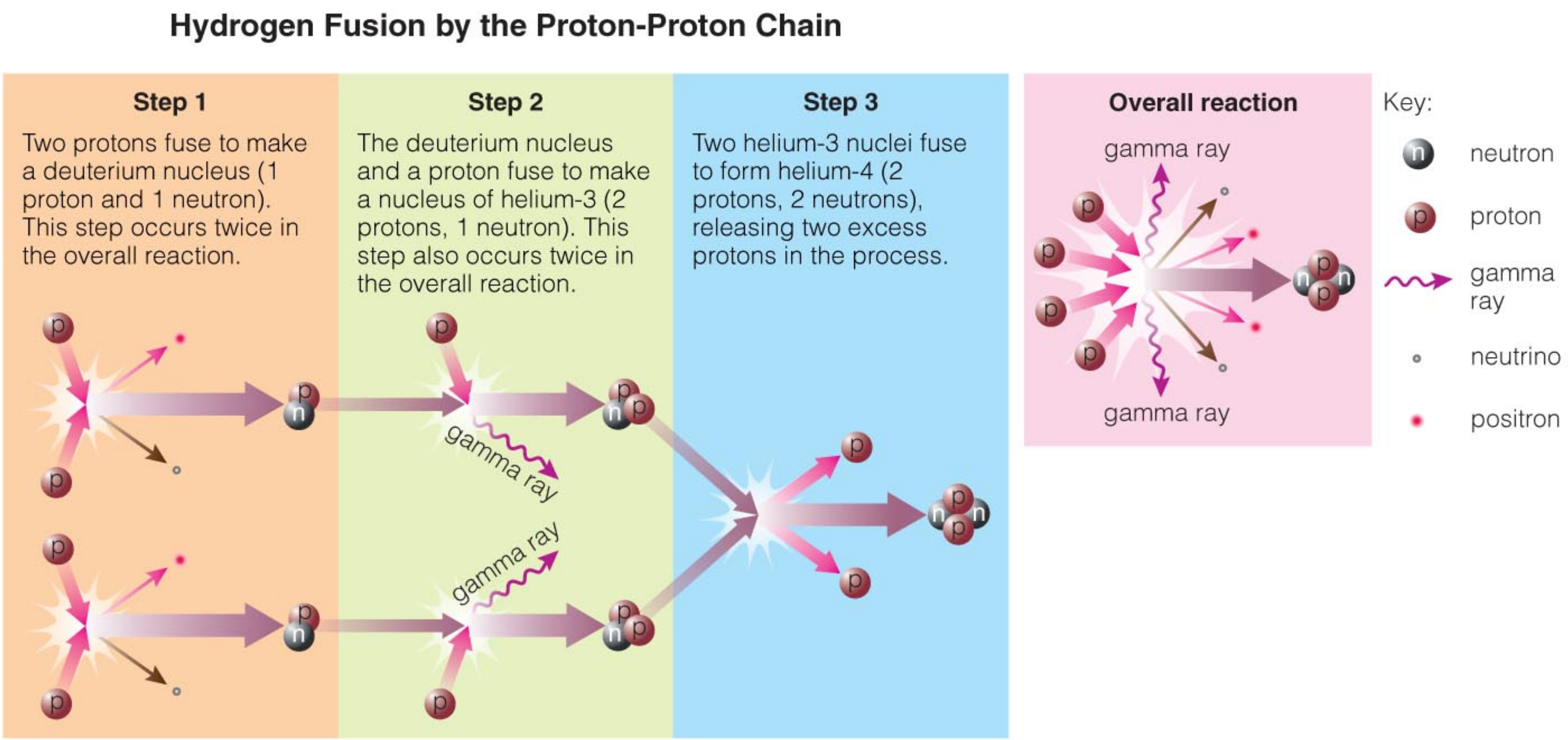
Step 2: deuterium (^{2}H) + proton = light helium (^{3}He) + gamma ray

The Proton-Proton Chain

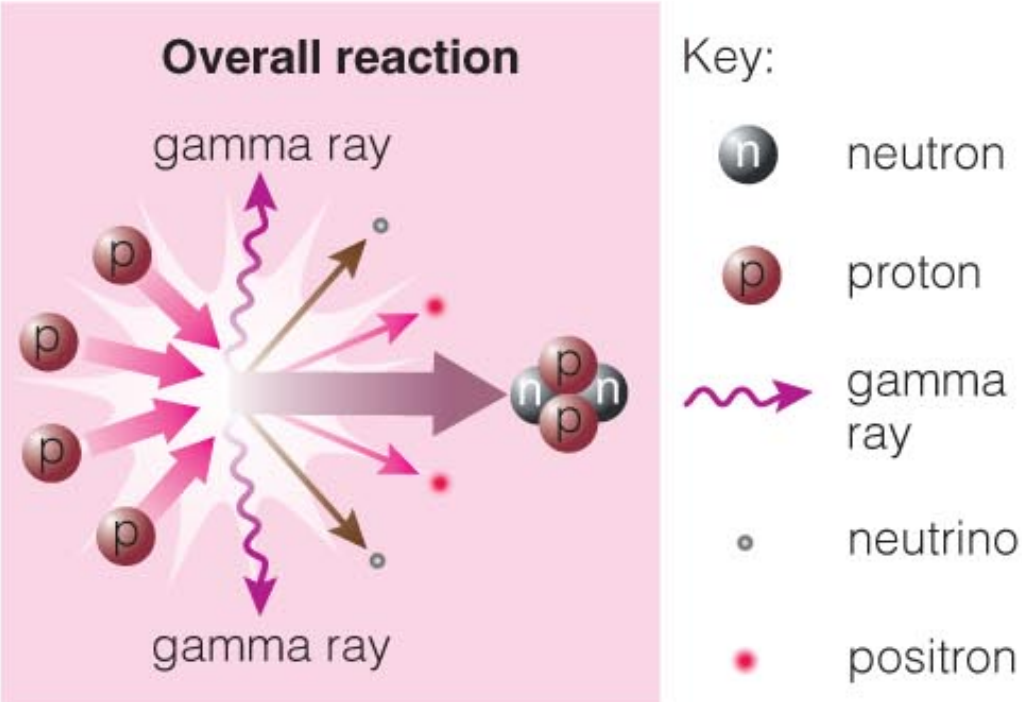
Proton
Neutron
Positron
Neutrino
Gamma Ray

Do steps 1 and 2 twice, so you have two ^{3}He nuclei, then

Step 3: light helium (^{3}He) + light helium (^{3}He) =
regular helium (^{4}He) + two protons



- The **proton–proton chain** is how hydrogen fuses into helium in Sun.



IN

4 protons

OUT

^{4}He nucleus

2 gamma rays

2 positrons

2 neutrinos

The mass of a Helium nucleus is 0.7% smaller than the mass of four protons (Hydrogen nuclei). That extra mass was converted to energy: a lot of it.

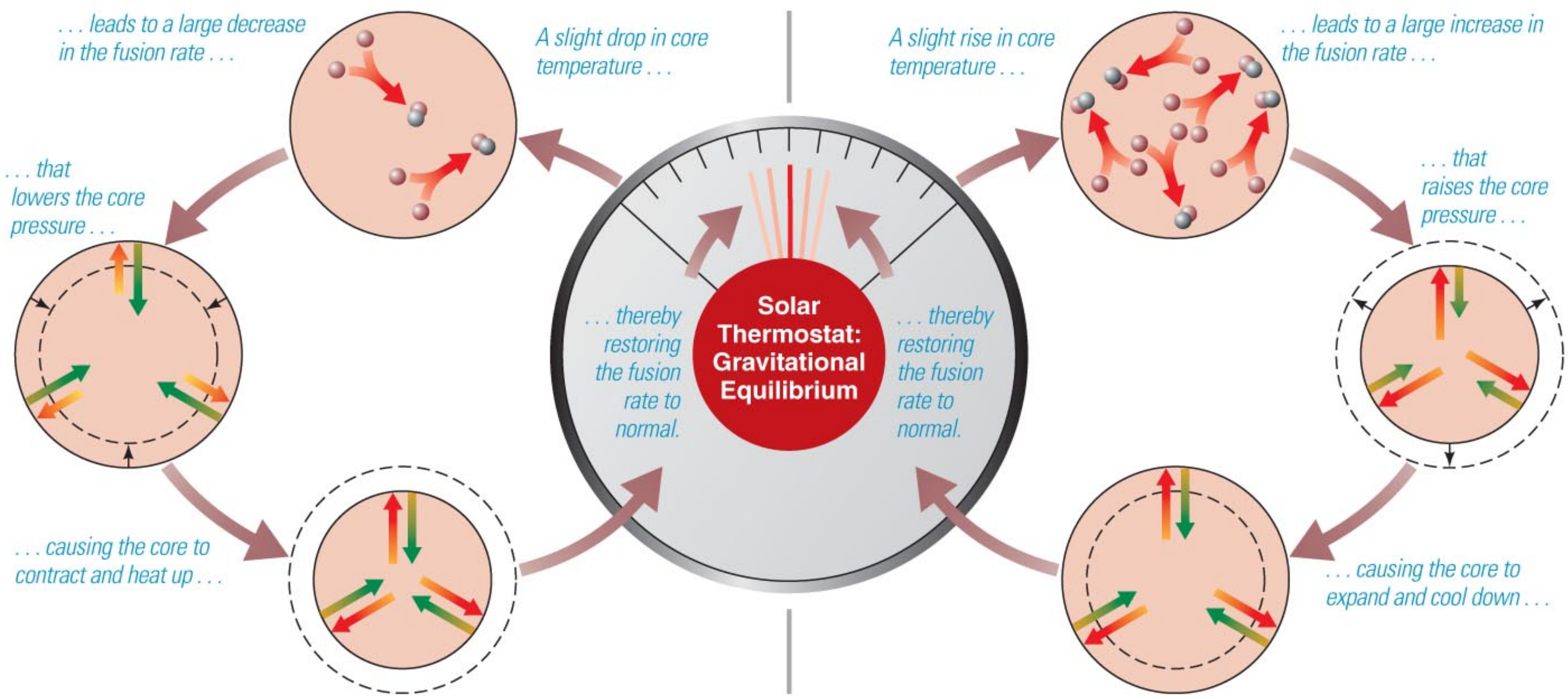
Thought Question

What would happen inside the Sun if a slight rise in core temperature led to a rapid rise in fusion energy?

Remember, the nuclear reactions in the core provide the energy that balances the pressure from the layers of gas on top.

If you change the reaction rate, you change that balance.

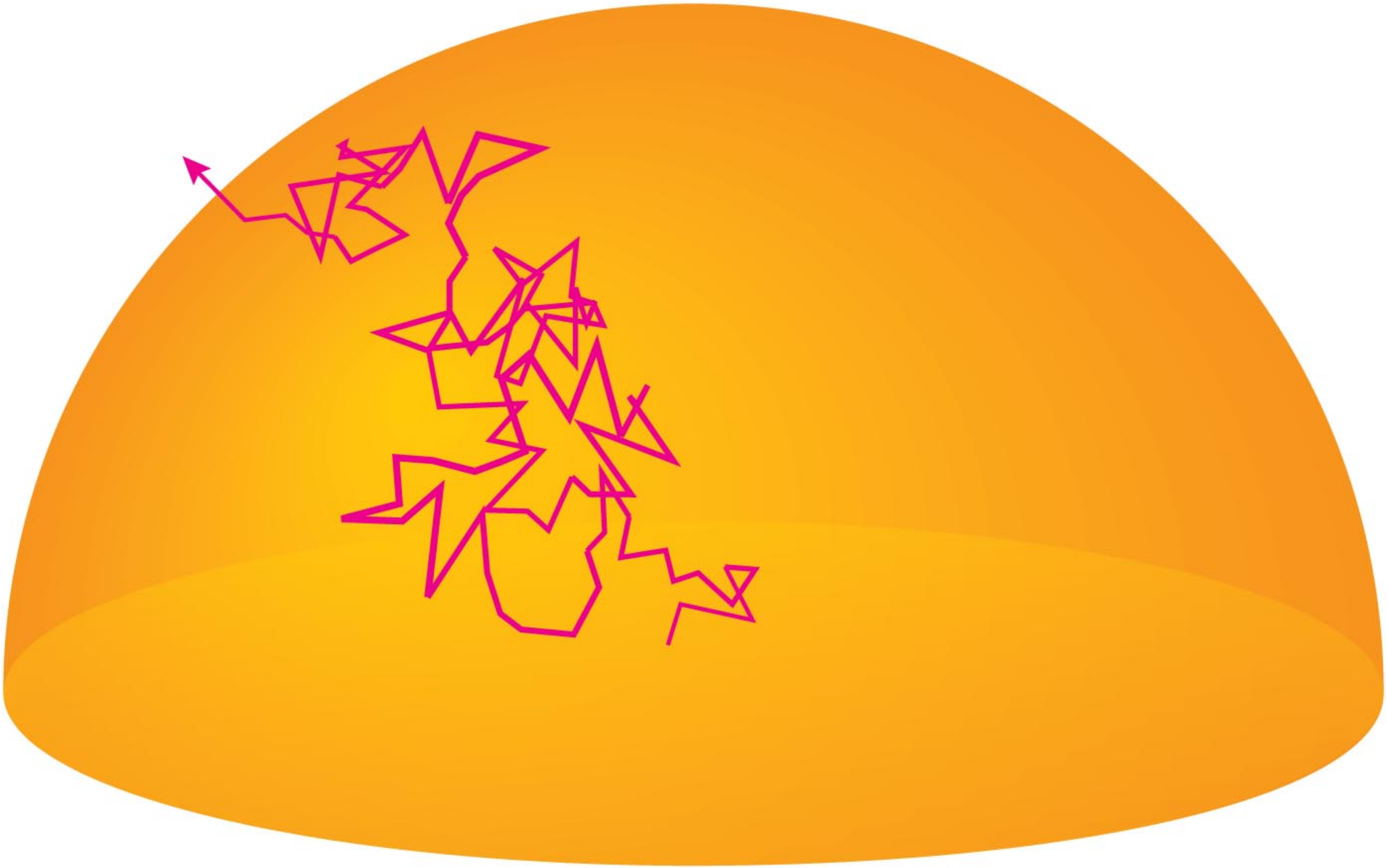
Solar Thermostat

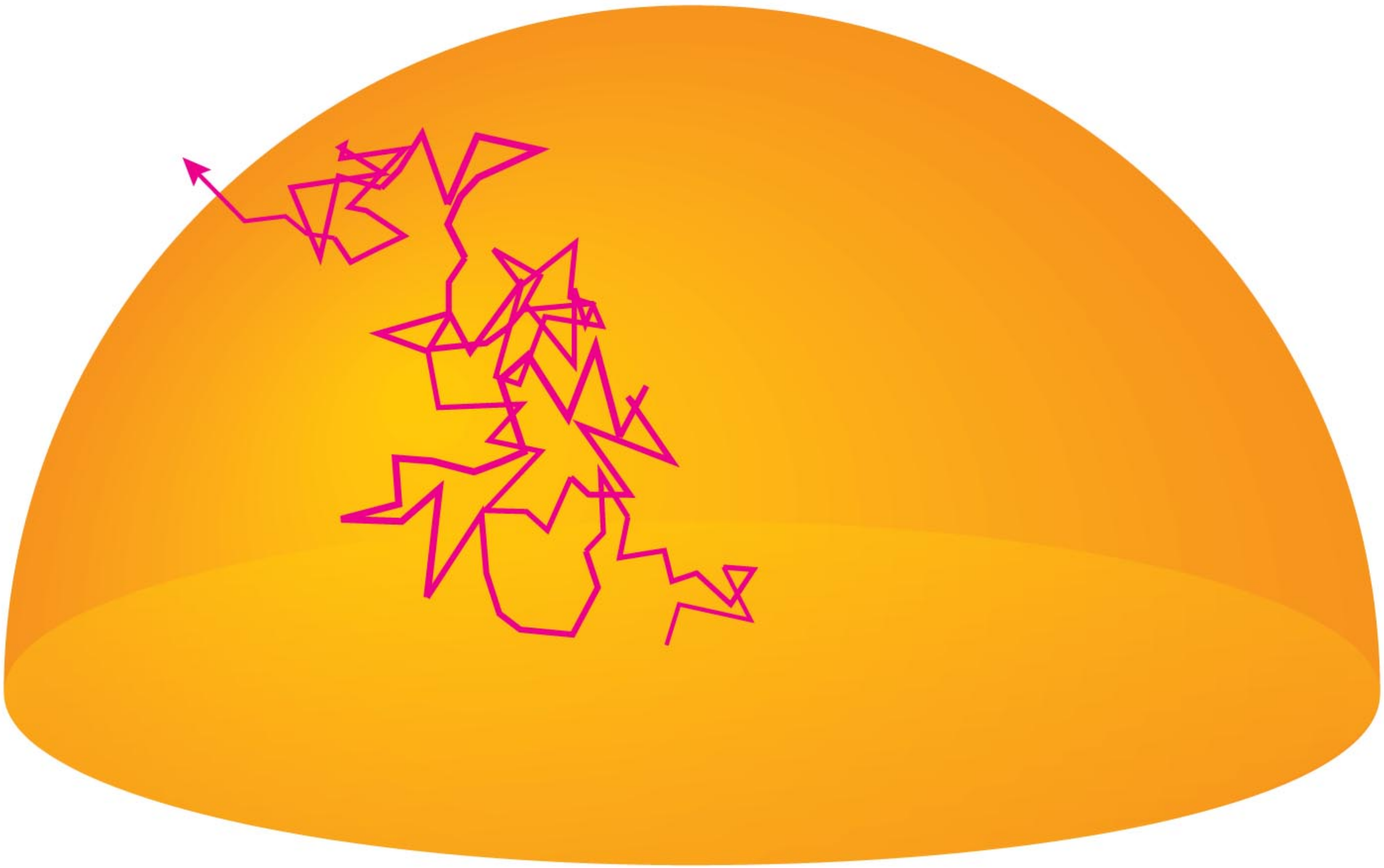


- Decline in core temperature causes fusion rate to drop, so core contracts and heats up.
- Rise in core temperature causes fusion rate to rise, so core expands and cools down.

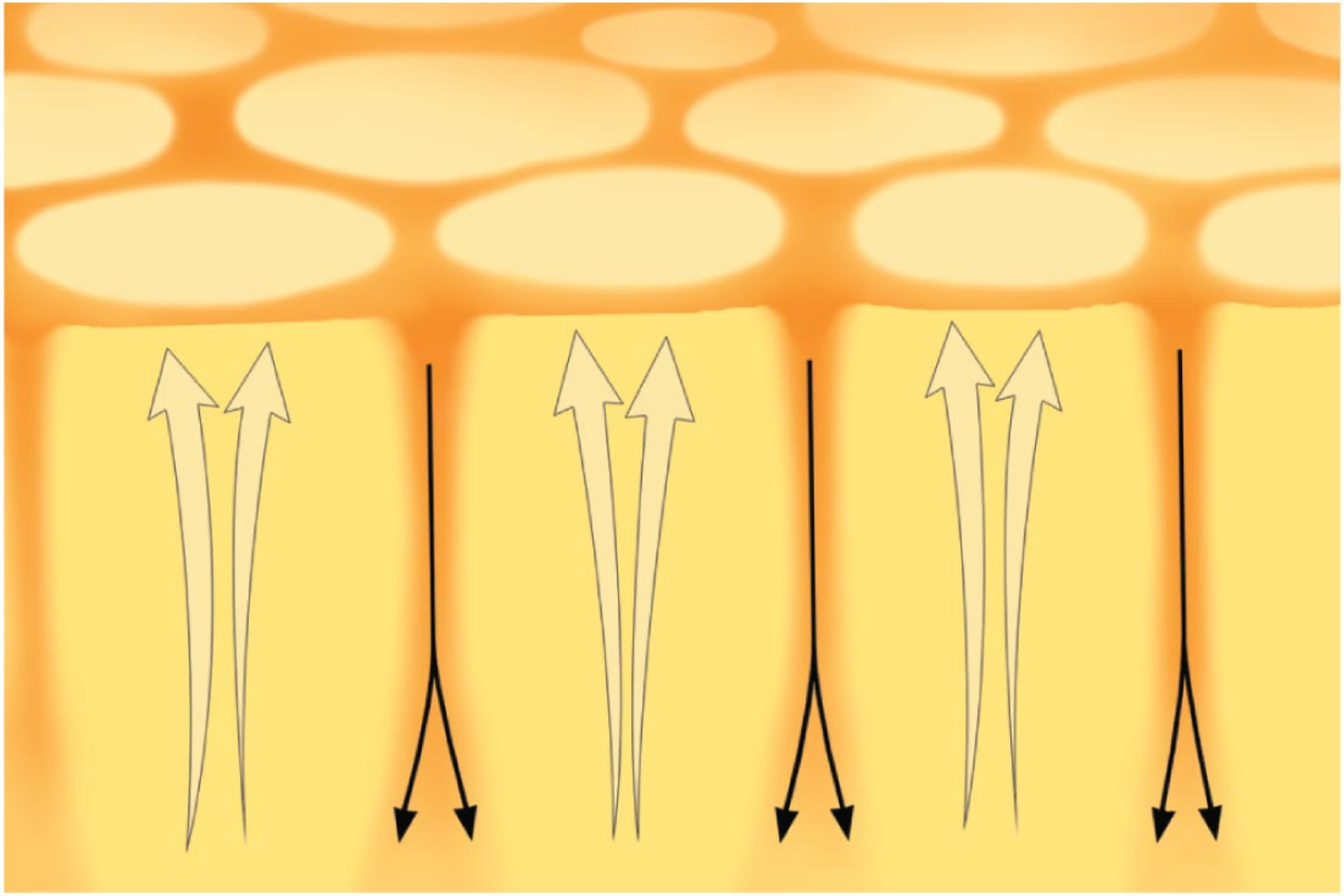
Sun maintains a balance!

How does the energy from fusion get out of the Sun?

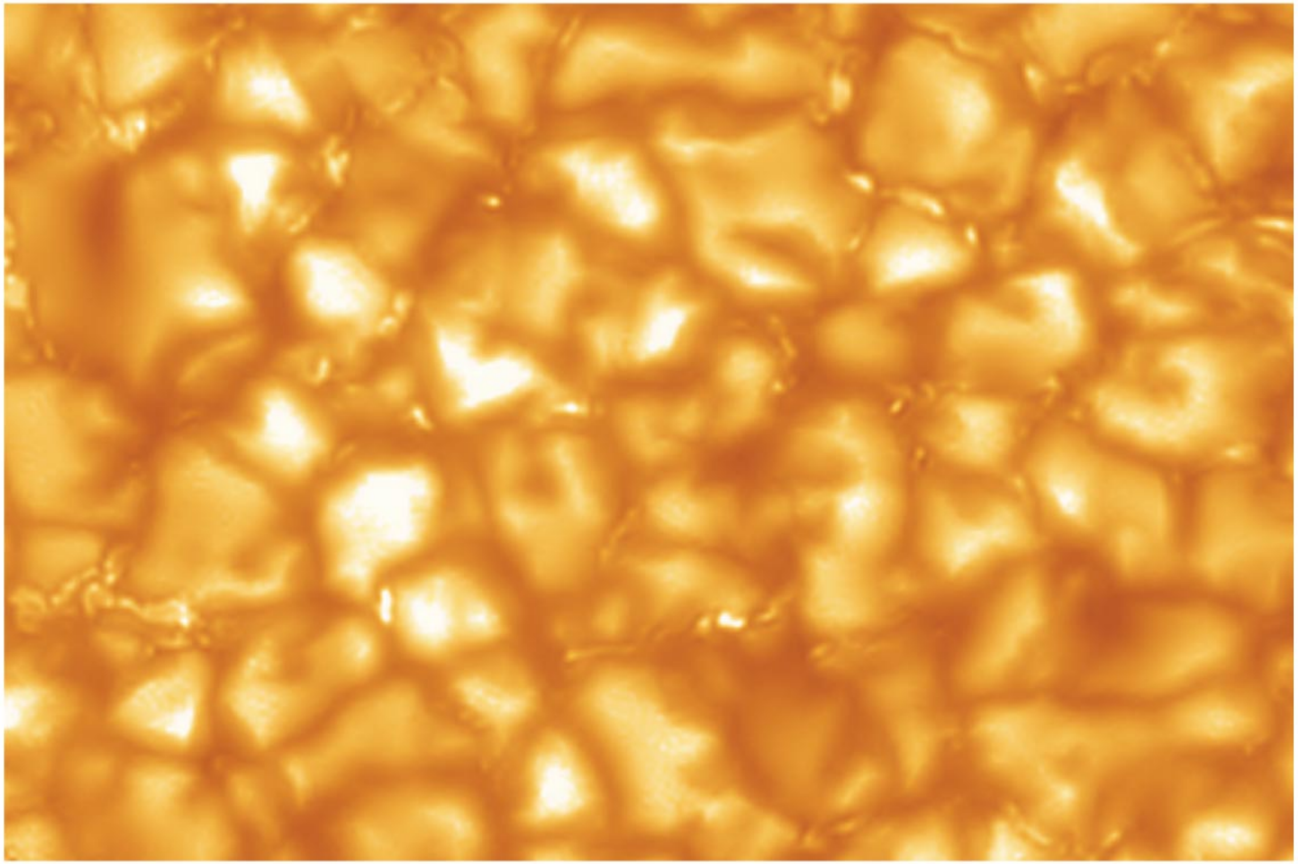




Energy gradually leaks out of radiation zone in form of photons randomly being scattered and slowly moving outwards. Takes about 50,000 years for energy to get out!



When the energy gets to the convection zone, it moves outwards in pockets of hot rising gases.



b This photograph shows the mottled appearance of the Sun's photosphere. The bright spots, each about 1000 kilometers across, correspond to the rising plumes of hot gas in part a.

Bright blobs on photosphere ("granulation") show where hot gas is reaching the surface. [Movie of granulation.]

How we know what is happening inside the Sun?

We learn about the inside of the Sun by …

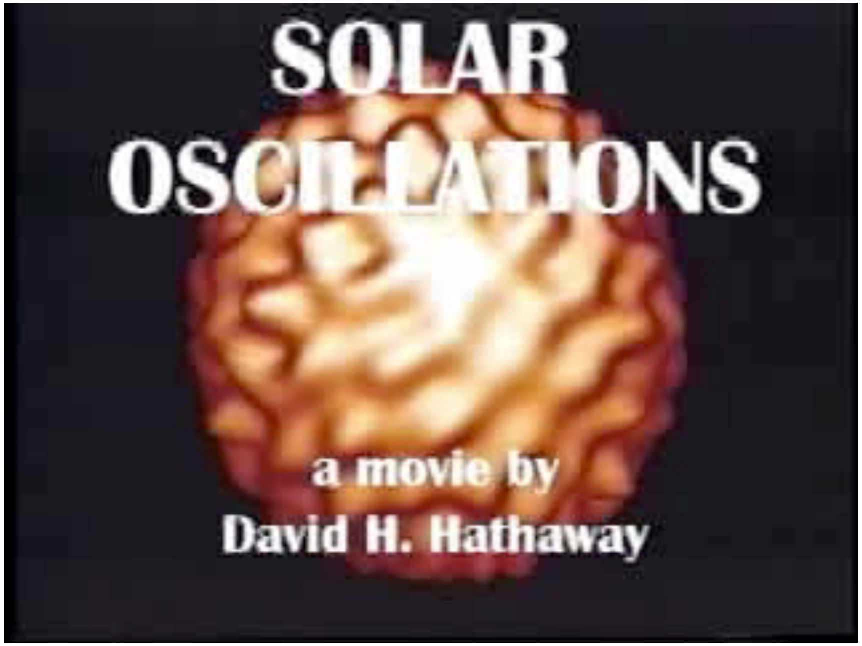
- making mathematical models based on physical laws
- observing solar vibrations
- observing solar neutrinos

Solar vibrations (helioseismology)

Think of a church organ.

The air inside a pipe vibrates with a frequency that depends on the length of the pipe, but also the pressure and density of the air.

Solar vibrations (helioseismology)



Simulation of solar vibration (motion is very exaggerated compared to reality!)

A similar thing happens with the Sun, where the vibrations depend on the pressure and density of the Sun's interior.

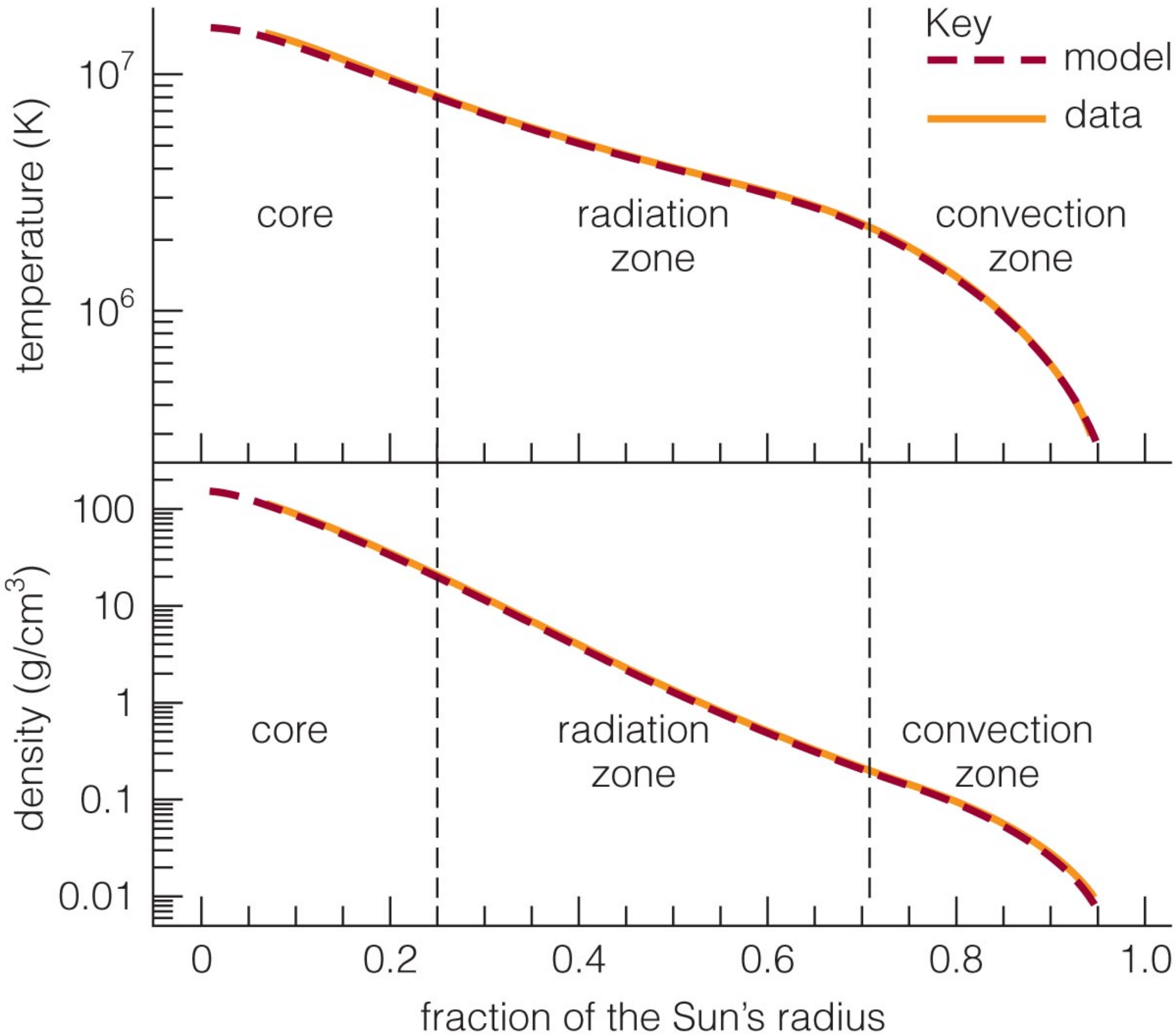
Patterns of vibration on the surface tell us about what the Sun is like inside.

Solar vibrations (helioseismology)

Patterns of vibration on the surface tell us about what the Sun is like inside.

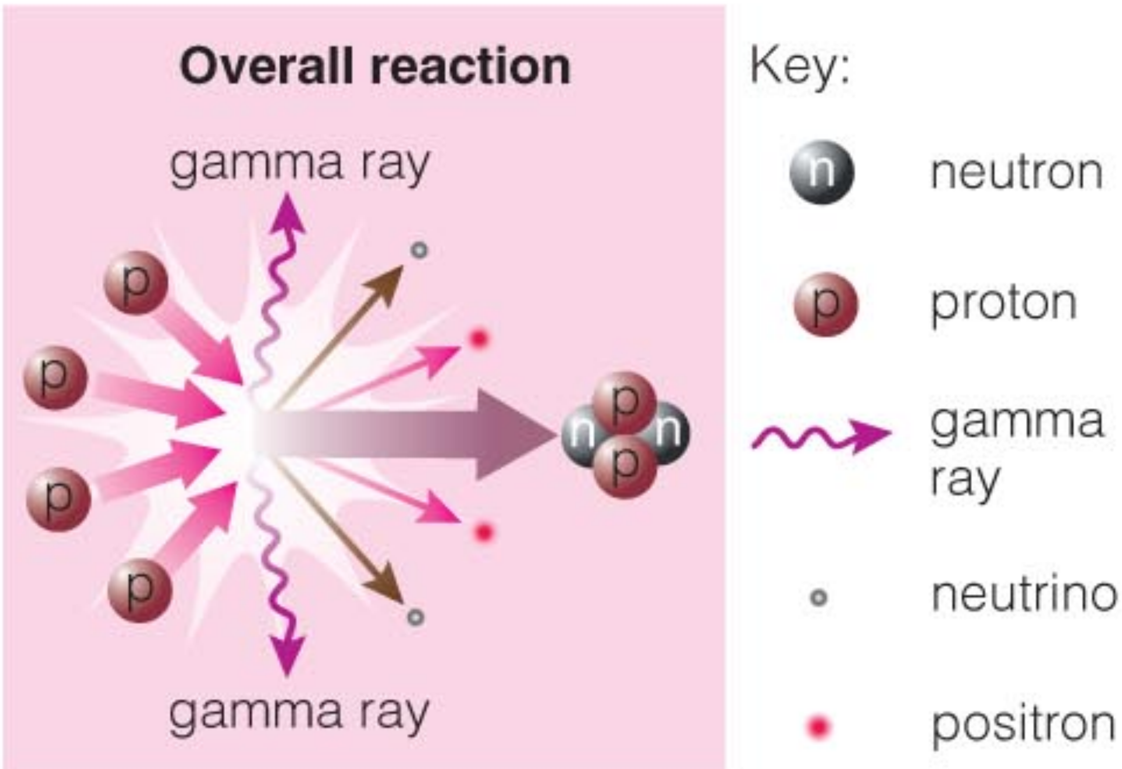
Actual solar vibrations measured by the Doppler shift of the sun's photosphere.

Solar vibrations (helioseismology)



Data on solar vibrations agree very well with **mathematical models** of solar interior.

Solar neutrinos

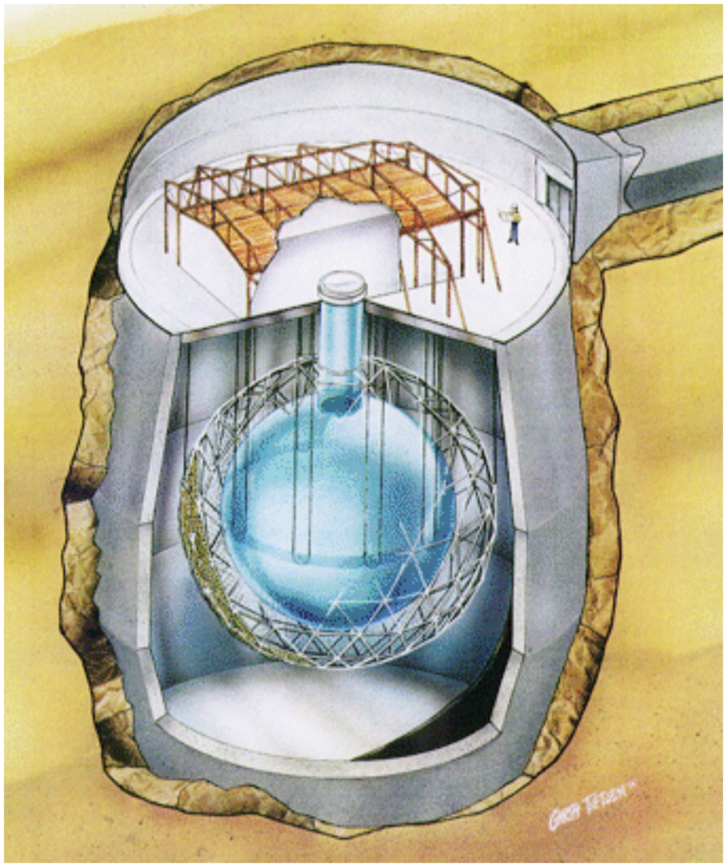


Neutrinos created in the core by nuclear fusion. They don't interact strongly with matter and can fly directly out from the Sun.

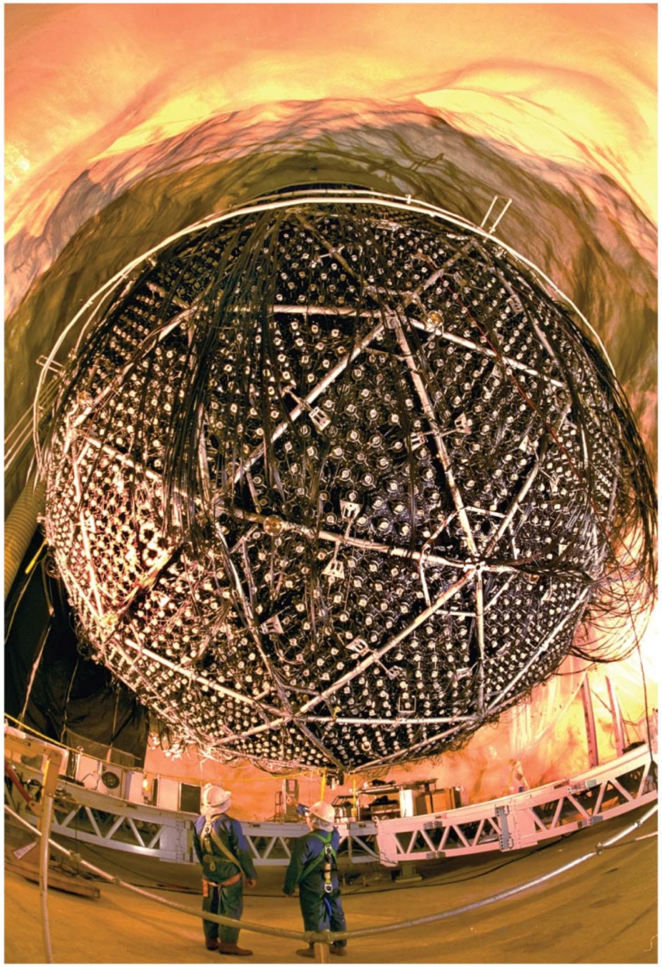
Observations of these solar neutrinos can tell us directly what's happening in core.

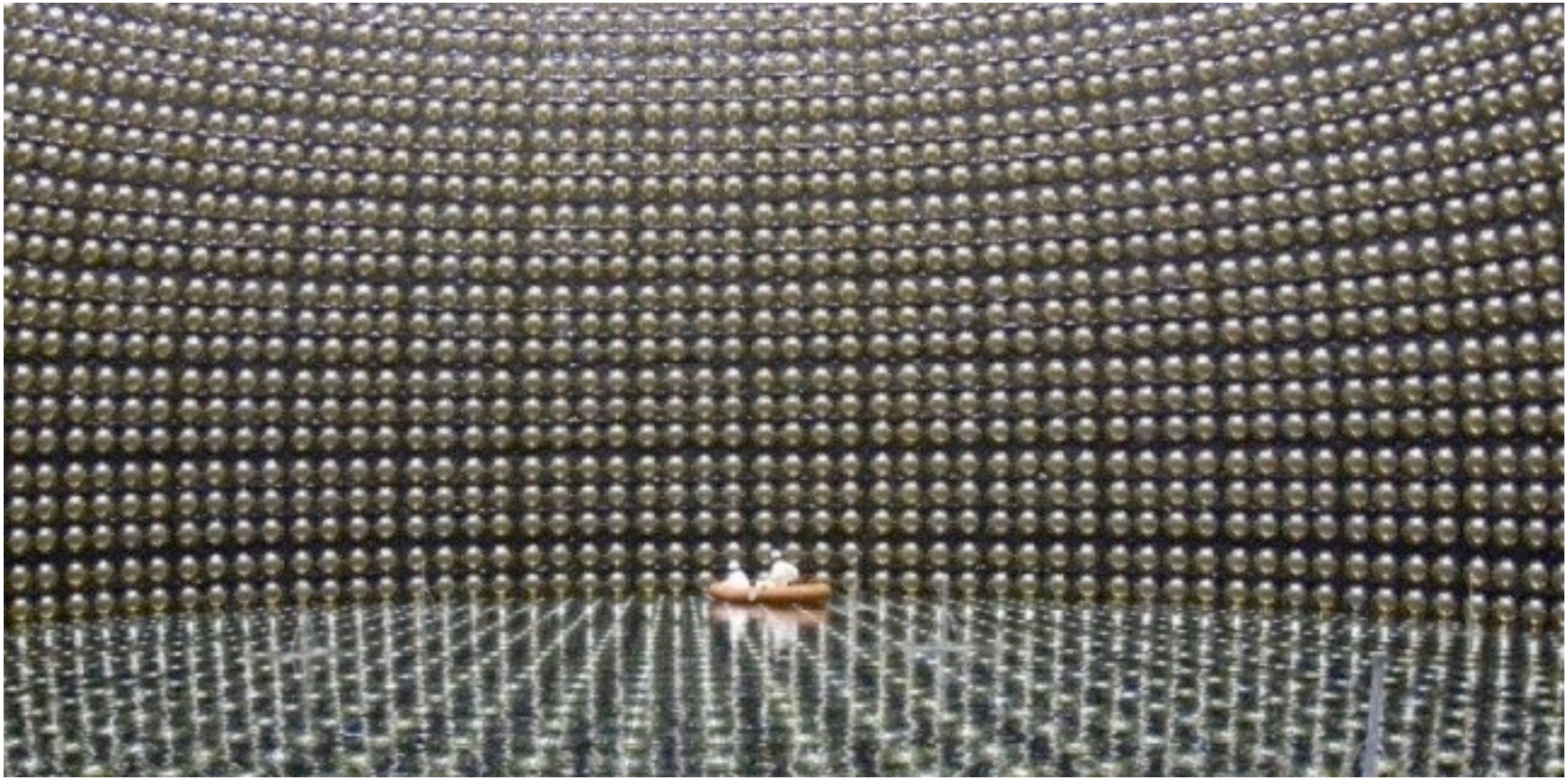
Solar neutrinos

How do you detect a particle that almost never interacts with matter?



Sudbury Neutrino Observatory





Super Kamiokande

Early experiments detected too few neutrinos: solar neutrino problem.

More recent experiments have found them all!

What have we learned?

- **How does nuclear fusion occur in the Sun?**
  - The core's extreme temperature and density are just right for nuclear fusion of hydrogen to helium through the proton–proton chain.
  - Gravitational equilibrium acts as a thermostat to regulate the core temperature because fusion rate is very sensitive to temperature.

What have we learned?

- **How does the energy from fusion get out of the Sun?**
  - Randomly bouncing photons carry energy through the radiation zone.
  - Rising of hot plasma carries energy through the convection zone to photosphere.
- **How do we know what is happening inside the Sun?**
  - Mathematical models agree with observations of solar vibrations and solar neutrinos.