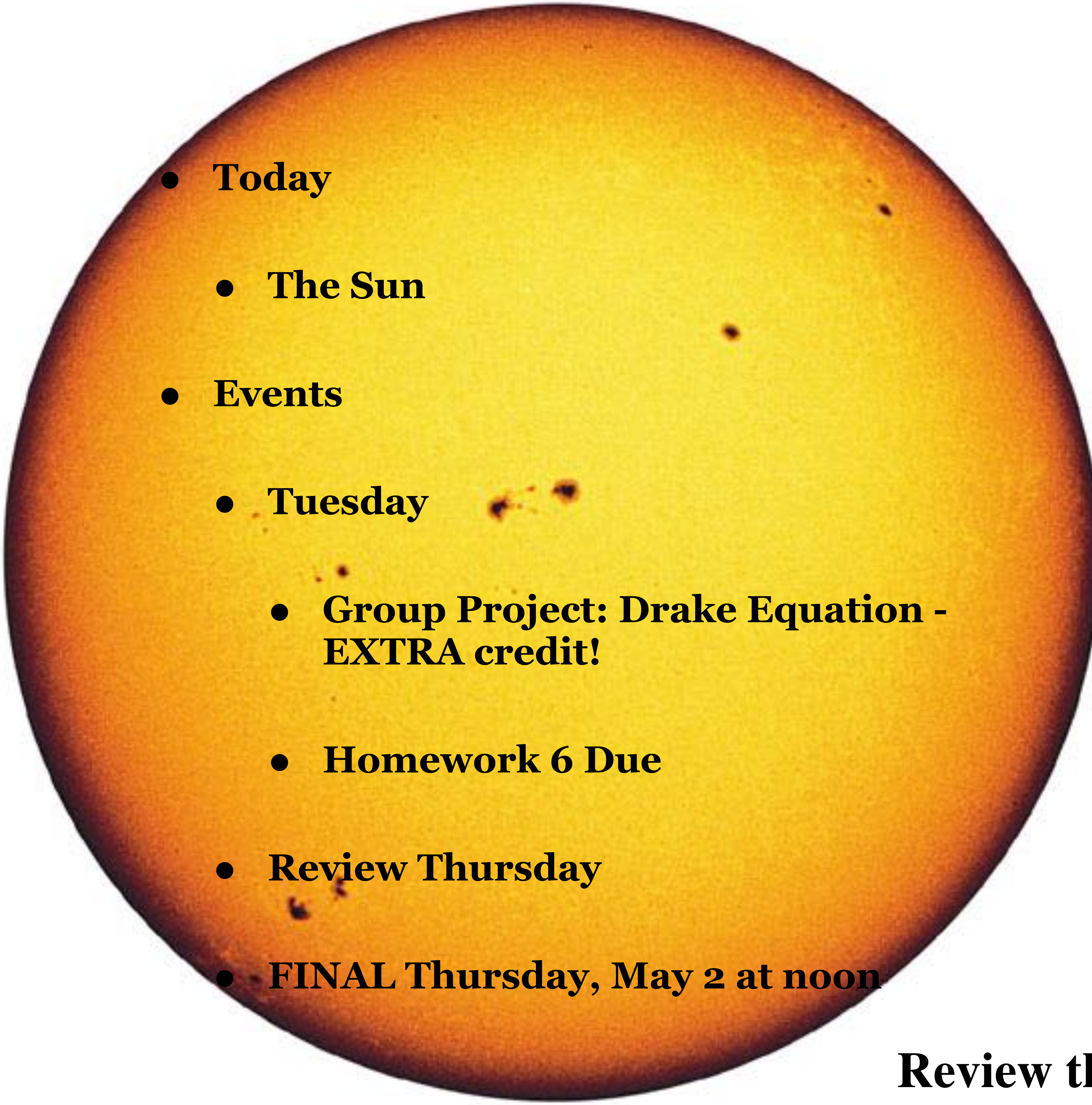


- Today
  - The Sun
- Events
  - Tuesday
    - Group Project: Drake Equation - EXTRA credit!
    - Homework 6 Due
  - Review Thursday
  - FINAL Thursday, May 2 at noon

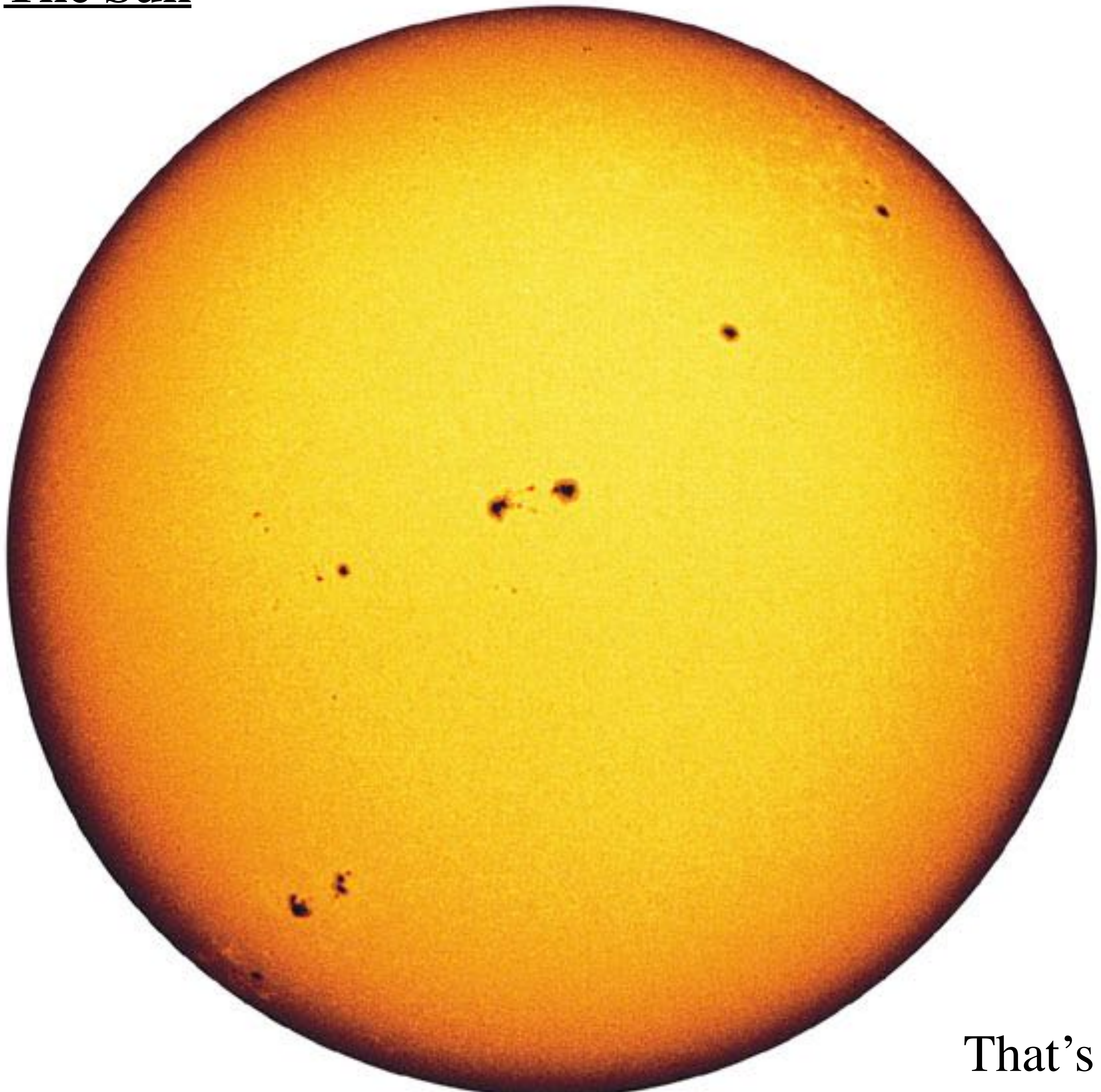
Review this Course!

https://webapps.case.edu/courseevals/

The Sun

- the main show in the solar system
  - 99.8% of the mass
  - 99.9999...% of the energy

The Sun



Radius:

6.9×10^8 m

(109 times Earth)

Mass:

2×10^{30} kg

(1,000 Jupiters;

300,000 Earths)

Luminosity:

3.8×10^{26} watts

That's about a billion big nuclear bombs every second

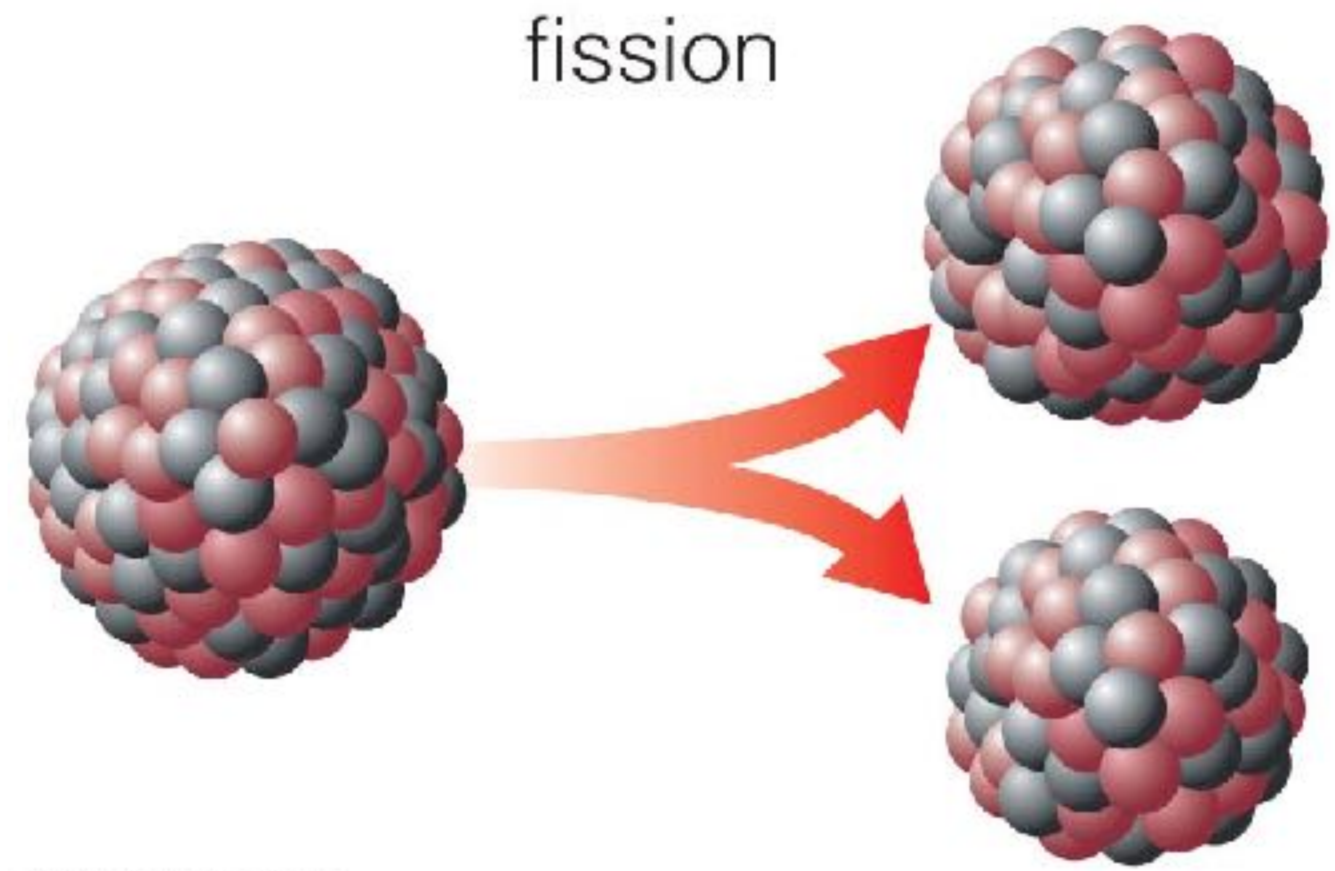
- Why the Sun shines
  - Chemical and gravitational energy sources can not explain how the Sun could sustain its luminosity for more than about 25 million years.
  - The Sun shines because gravitational equilibrium keeps its core hot and dense enough to release energy through nuclear fusion.
    - Hydrogen fuses into Helium in a 3-step process called the proton-proton chain.

0.7% of the rest mass of hydrogen is converted to energy via fusion

$E=\alpha mc^2$	$\alpha=1$	for **matter-antimatter annihilation**
	$\alpha=0.007$	for **nuclear fusion**
	$\alpha\sim0.000000001$	for **chemical reactions**

Four fundamental forces

- **Gravity**
  - e.g, planetary orbits
  - falling objects
- **Electromagnetism**
  - attraction and repulsion of electric charges, magnets
  - light; all forms of electromagnetic radiation
- **Strong nuclear force**
  - **fusion**: binds protons together in atomic nuclei
- **Weak nuclear force**
  - **fission**; radioactive decay

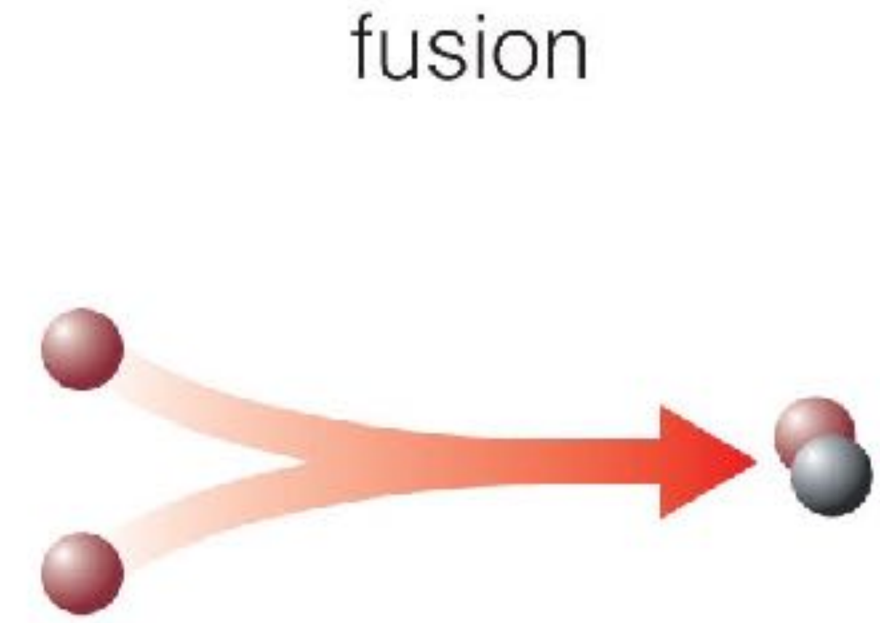


Fission

- Weak nuclear force

- Big nucleus splits into smaller pieces.

- (Example: nuclear power plants)

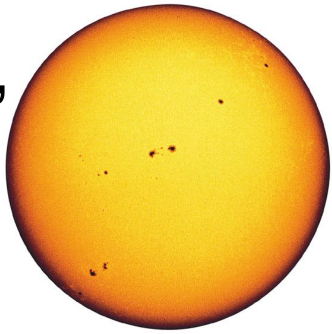


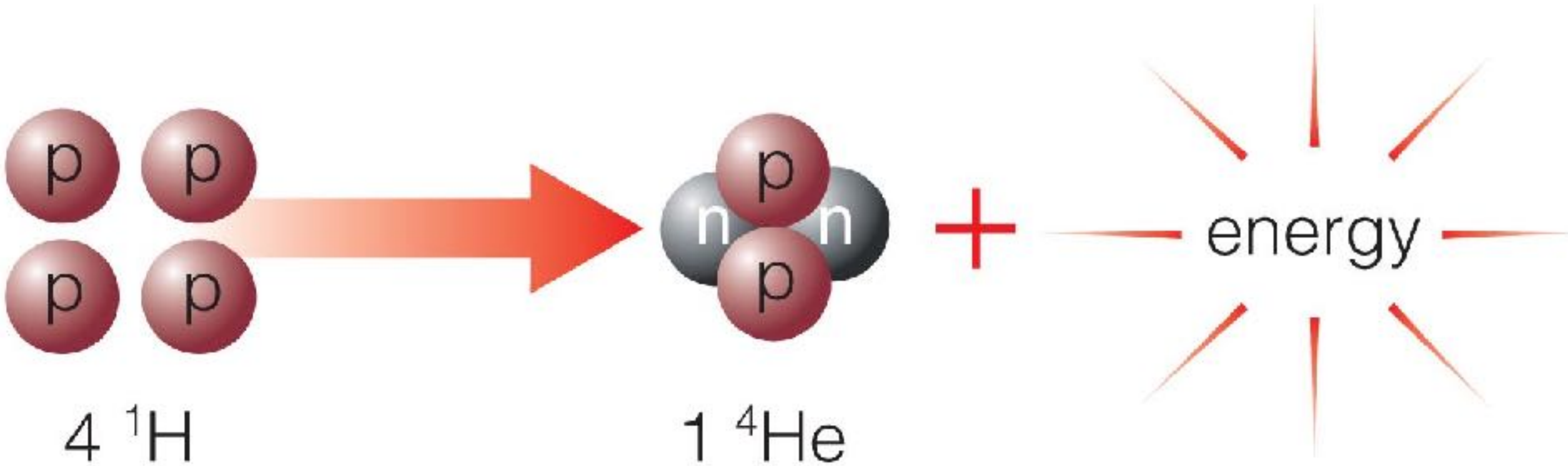
- Strong nuclear force

Fusion

- Small nuclei stick together to make a bigger one.

- (Example: the Sun, stars)



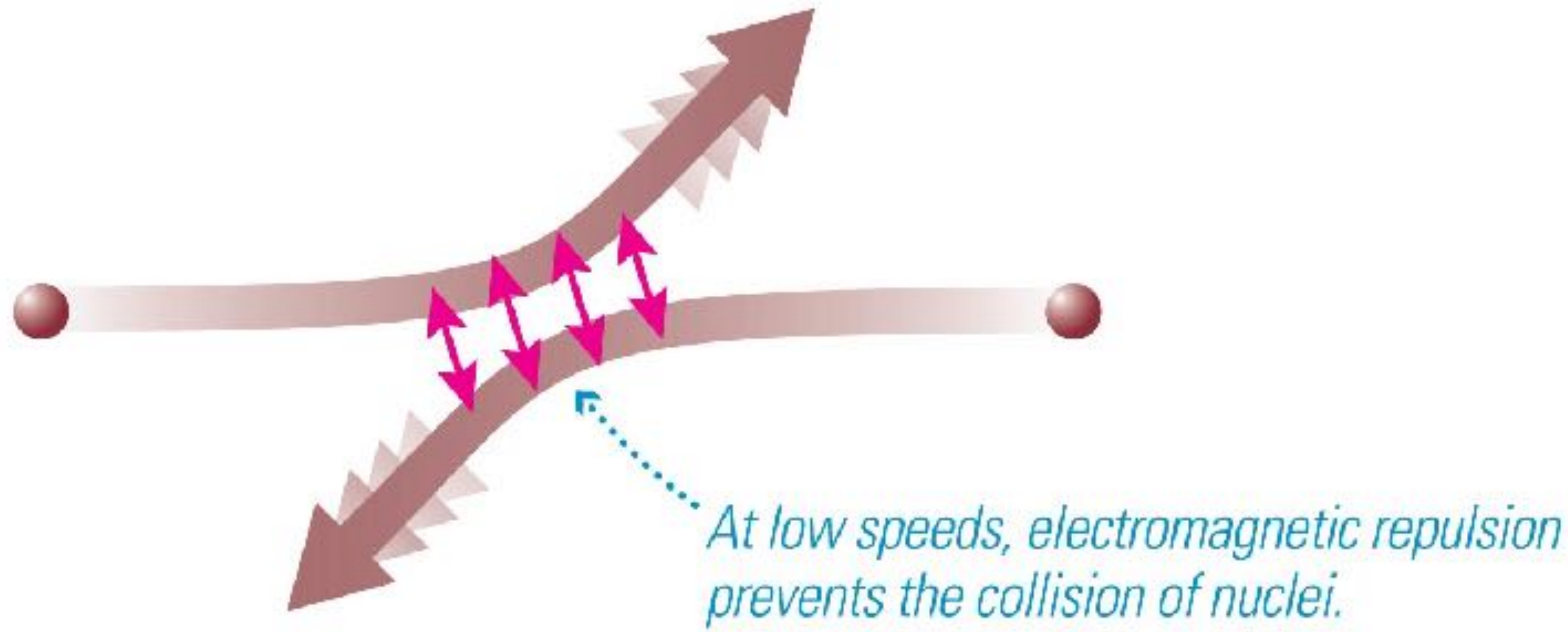


- The Sun releases energy by fusing four hydrogen nuclei into one helium nucleus.

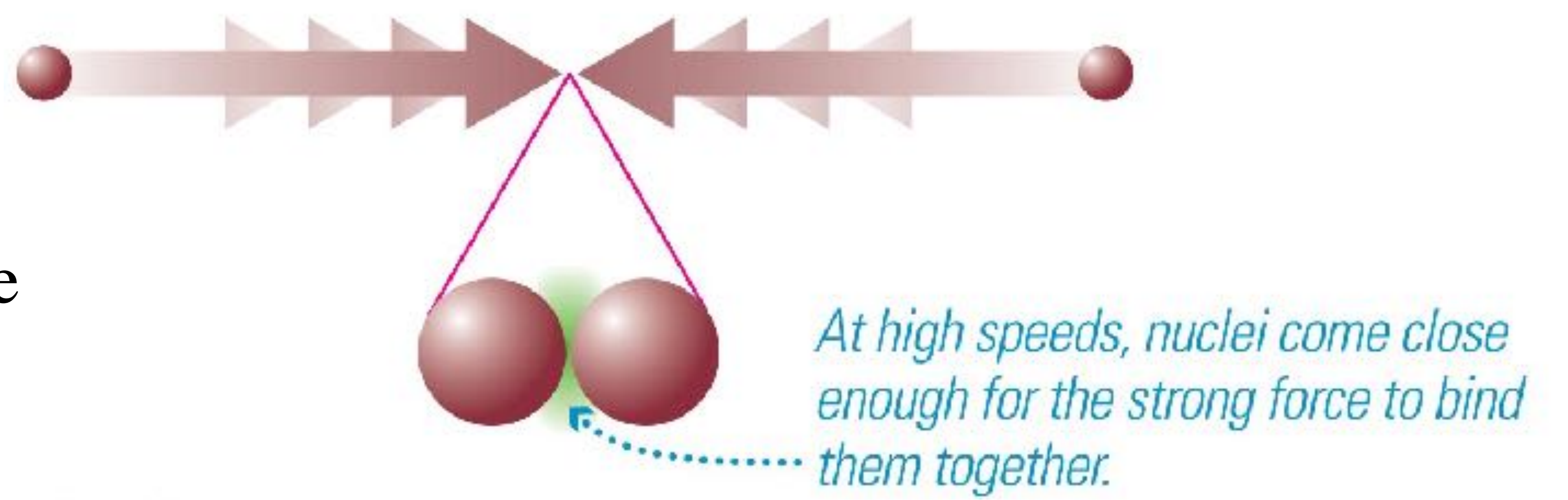
- Fusion is driven by the strong nuclear force after gravity heats a star’s core enough to overcome the electrostatic repulsion of protons.

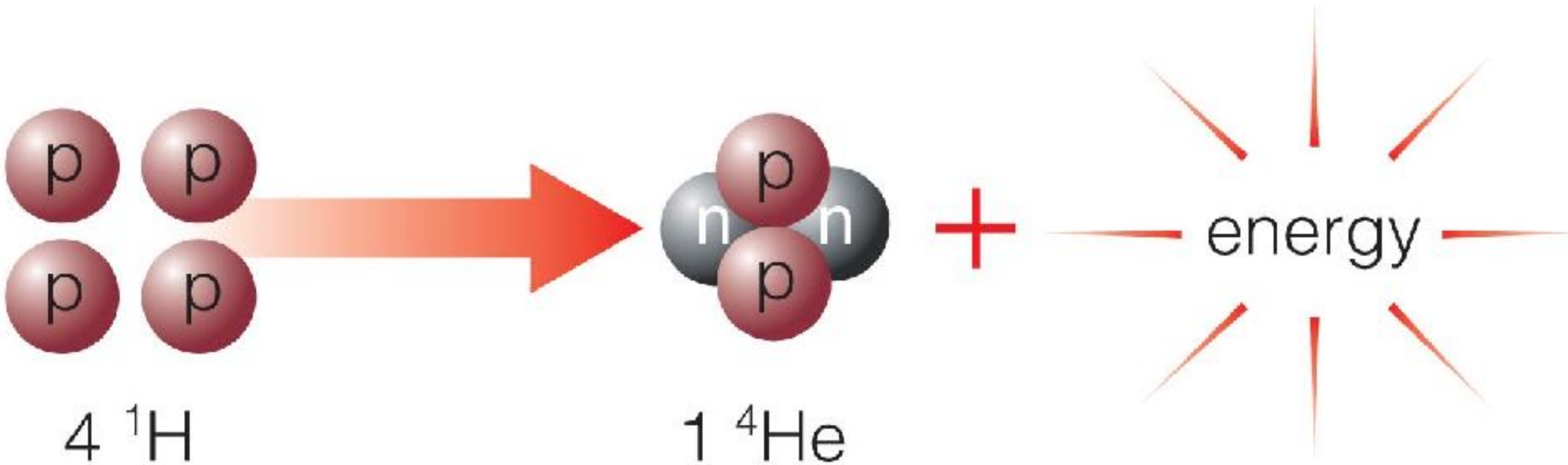
High temperatures enable nuclear fusion to happen in the core.

Positively charged protons repel each other.



Fusion only happens when the strong nuclear force is stronger than this repulsion, which only happens at very small separations. High temperatures are required to move fast enough to get that close.

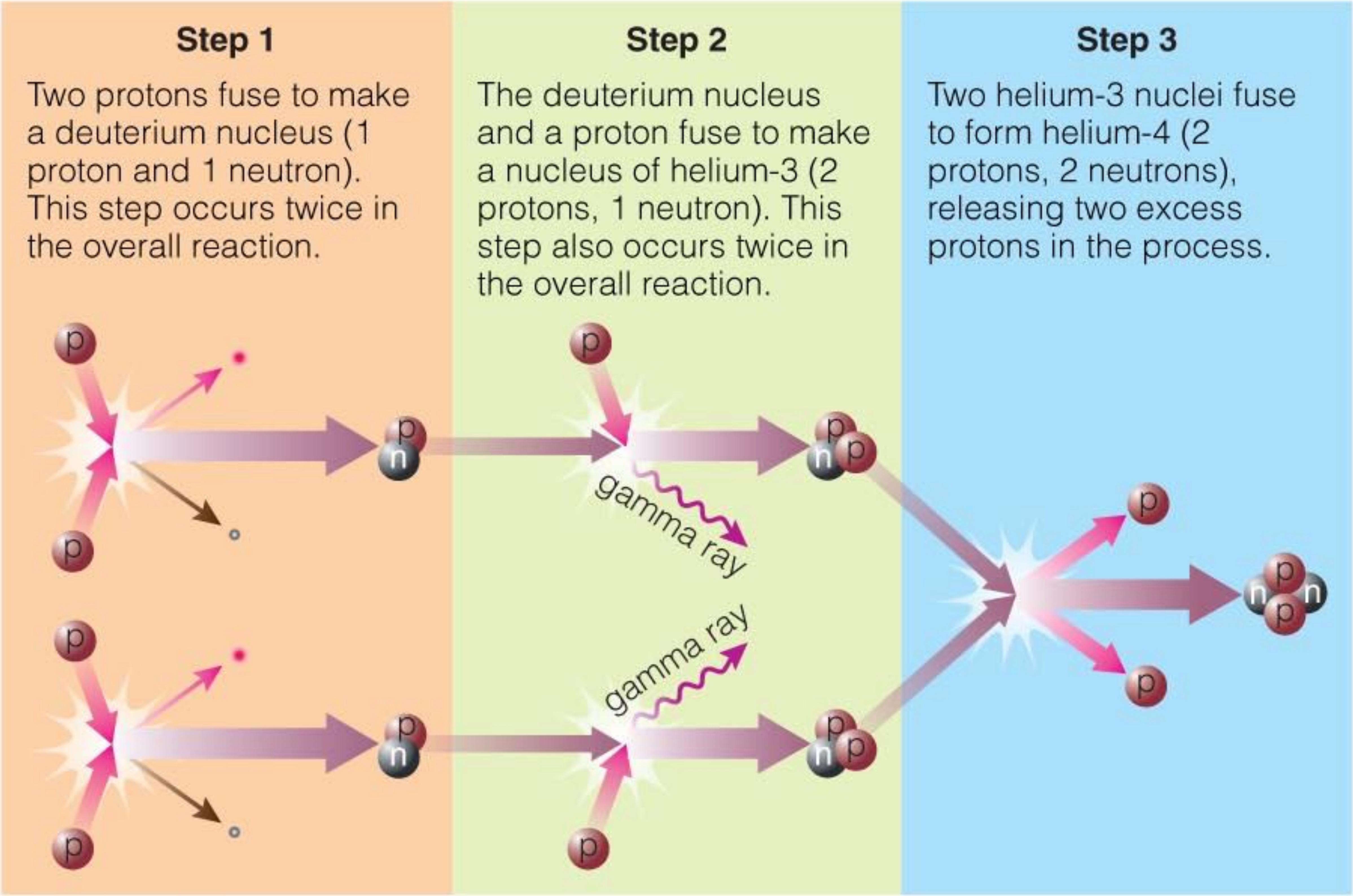




Sun releases energy by fusing four hydrogen nuclei into one helium nucleus.

Starting point is 4 protons.
End point is 2 p + 2 n (a helium nucleus) + energy
There are several steps required to make this happen.

Hydrogen Fusion by the Proton-Proton Chain



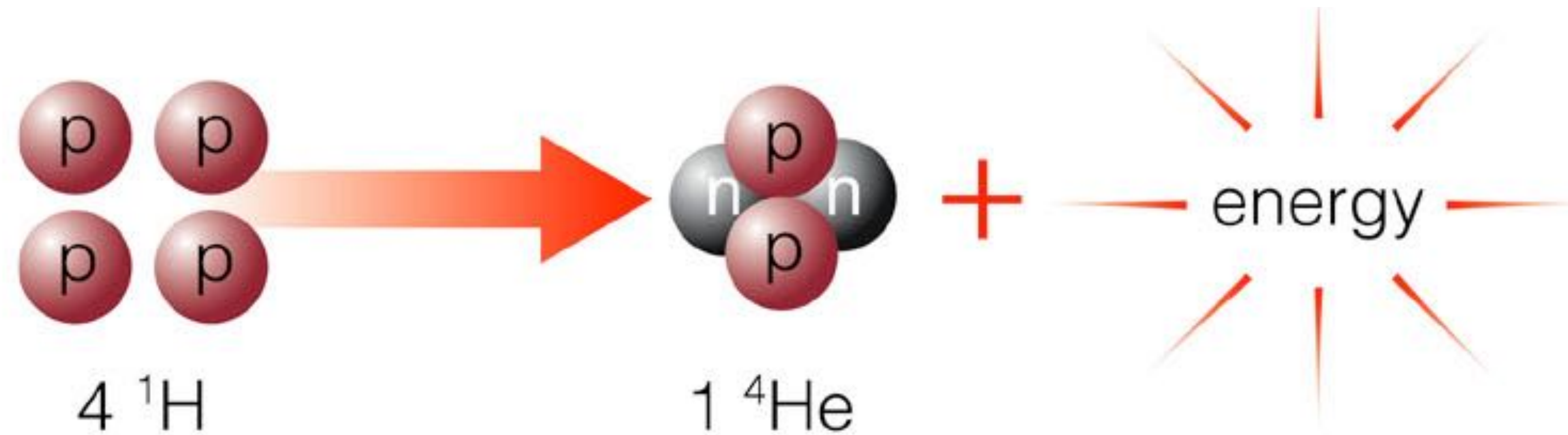
https://www.youtube.com/watch?v=LpUB8iMbNw0

Proton–proton chain is how hydrogen fuses into helium in Sun

Deuterium is the extra weight in heavy water

- step 1: p + p makes D (deuterium)
- step 2: p + D makes ^{3}He (helium 3)
- step 3: ^{3}He + ^{3}He makes ^{4}He (helium 4)
  – plus energy plus 2 spare protons and neutrinos.

Overcoming electrostatic repulsion makes the first step is the hardest - on average, it takes 8 billion years to happen to one proton in the sun.



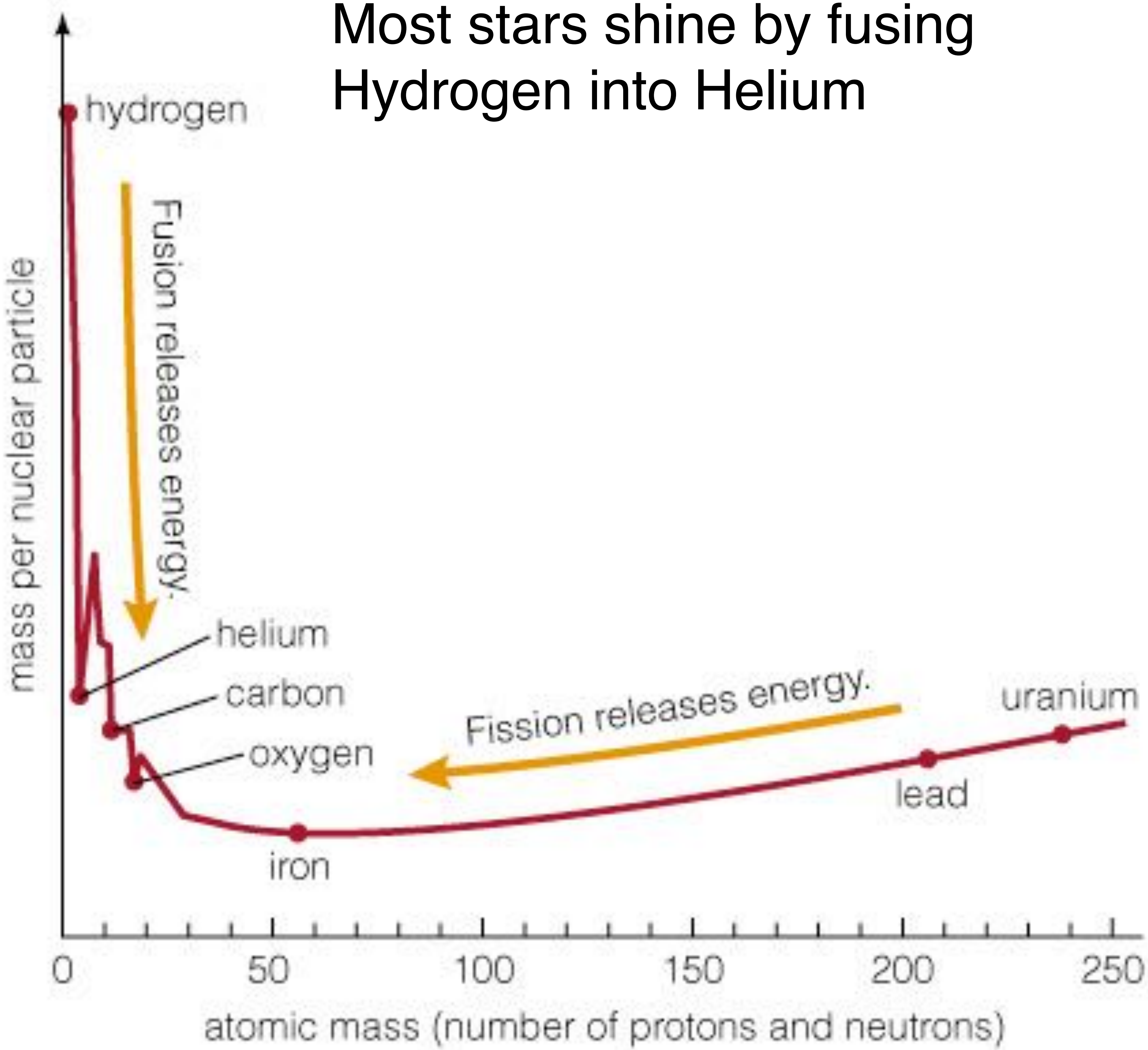
Net Result:

IN
4 protons

OUT
^{4}He nucleus
2 gamma rays
2 positrons
2 neutrinos

$E = mc^2$: ***Total mass is 0.7% lower.***

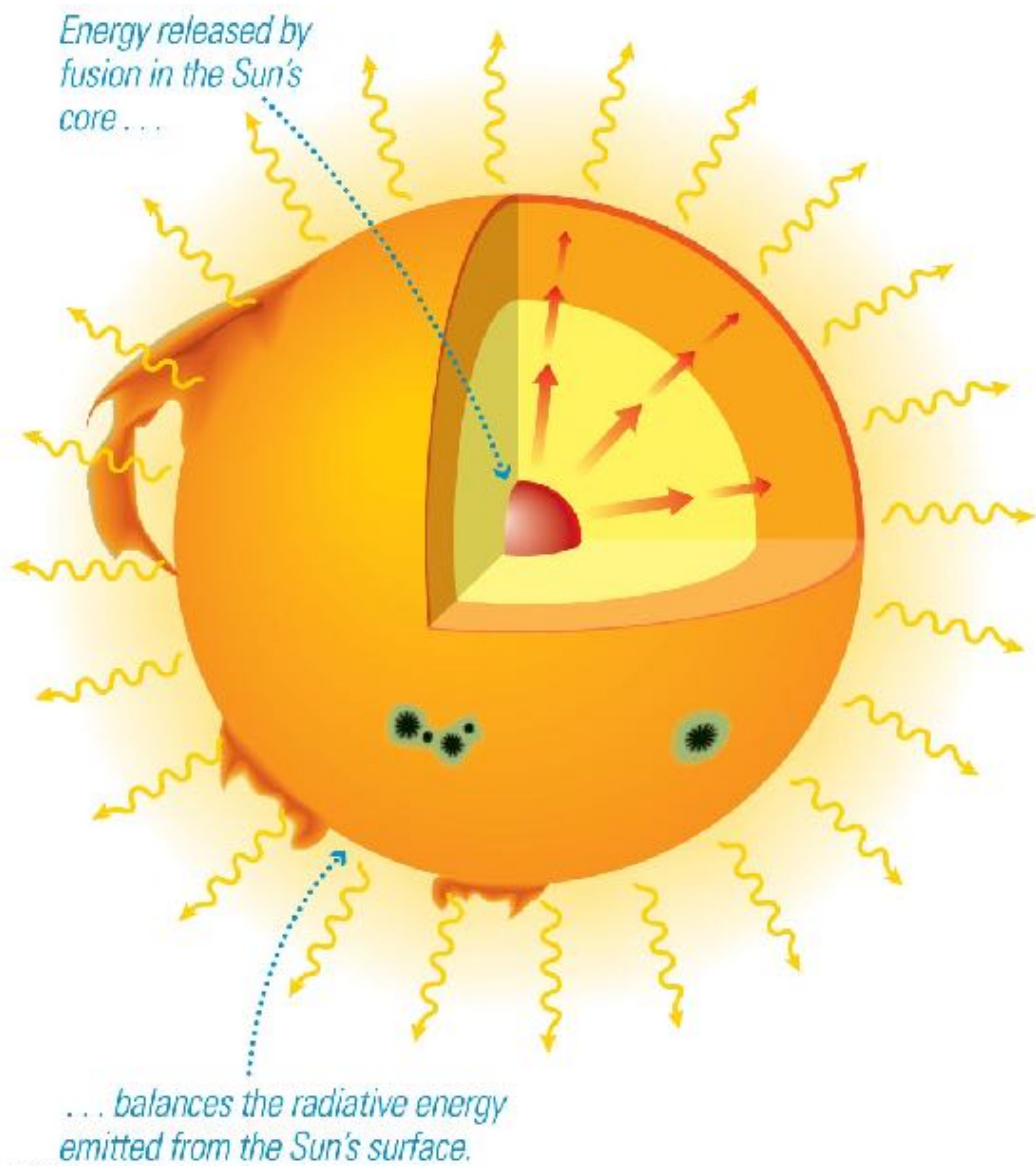
Most stars shine by fusing Hydrogen into Helium



Iron has the most stable nucleus.

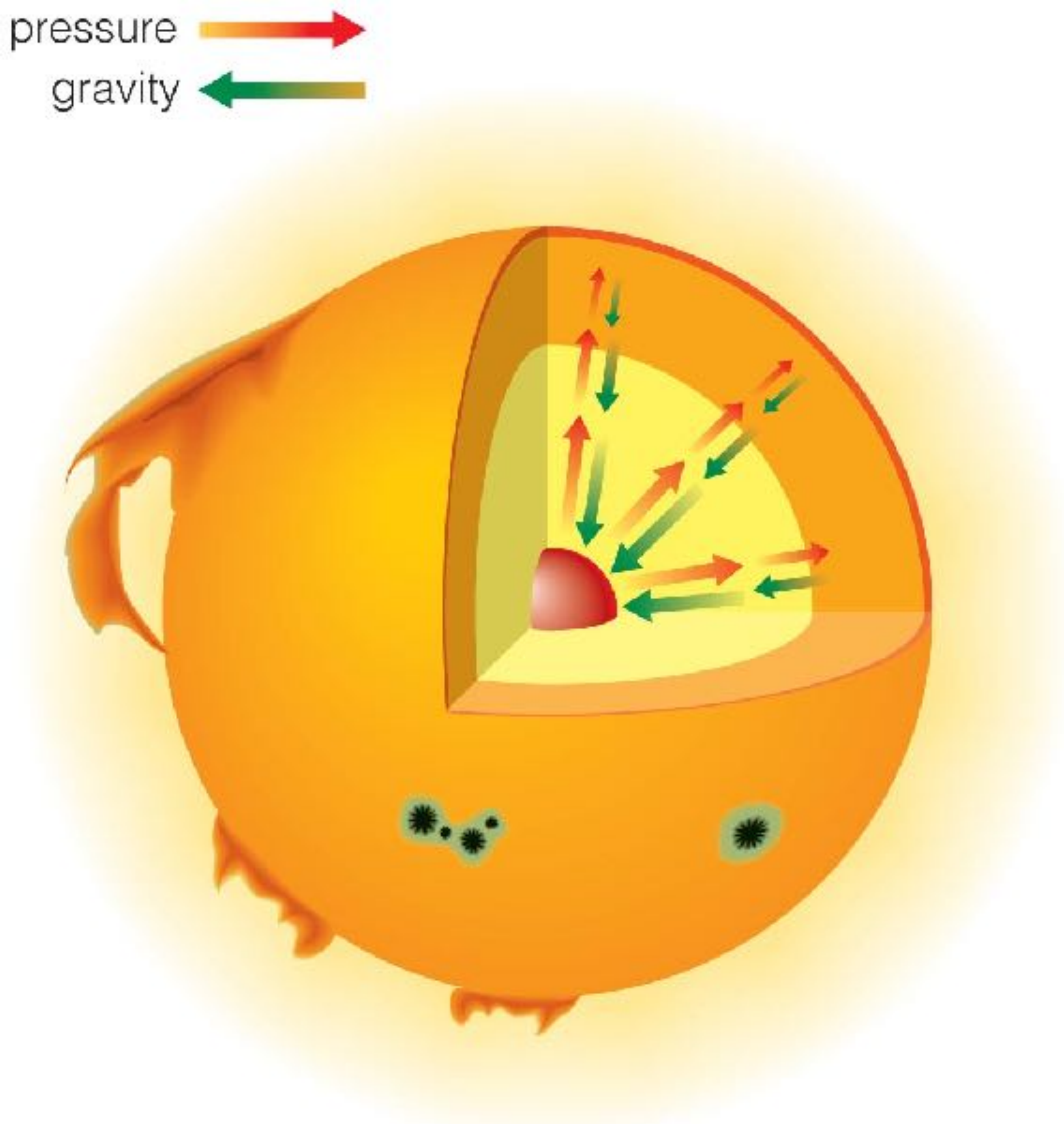
Fusion up to iron releases energy.

For elements heavier than iron, Fission releases energy.



Energy Balance:

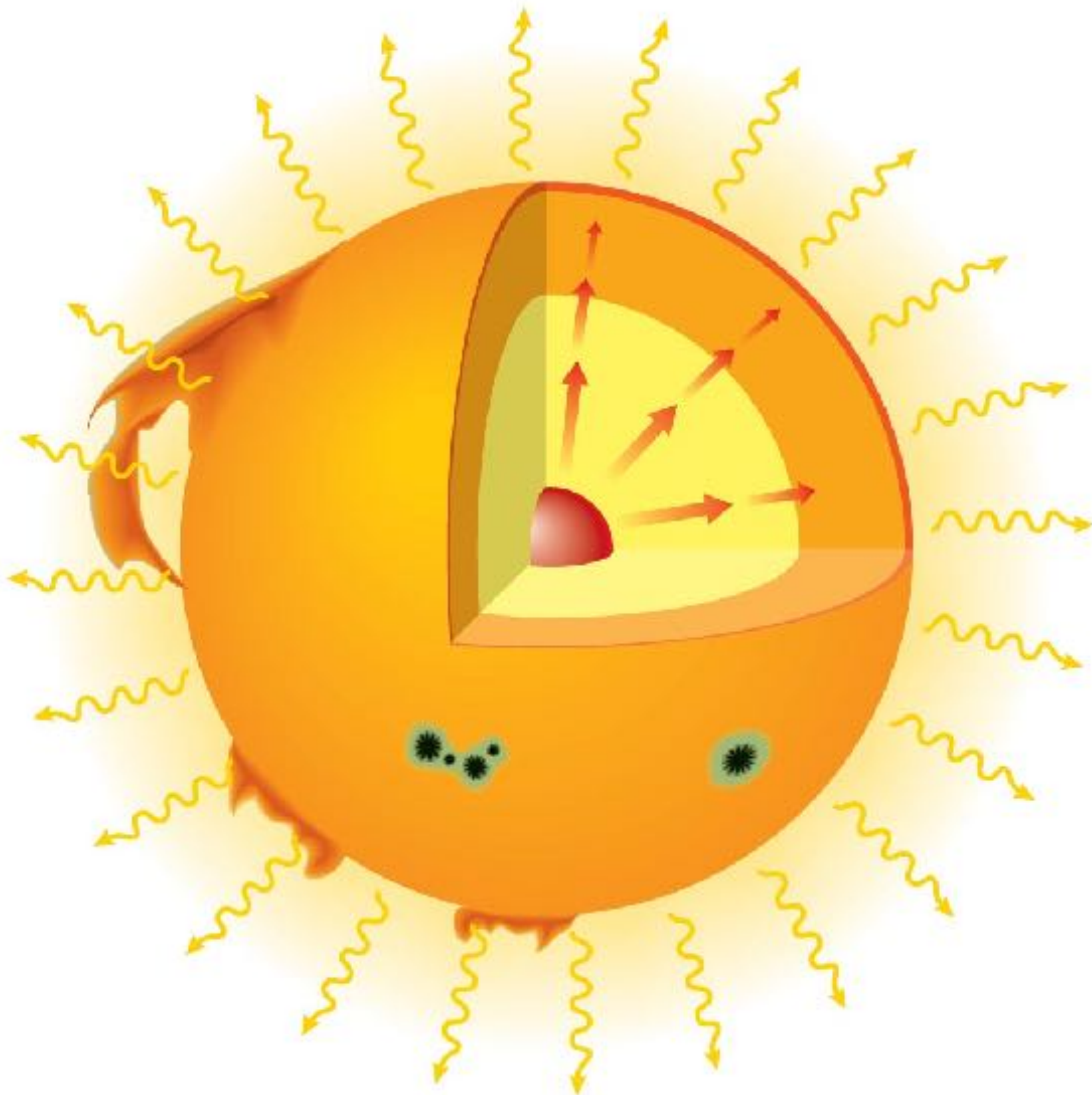
- The rate at which energy radiates from the surface of the Sun must be the same as the rate at which it is released by fusion in the core.



Stars are stable: pressure balances gravity.

Hydrostatic equilibrium:

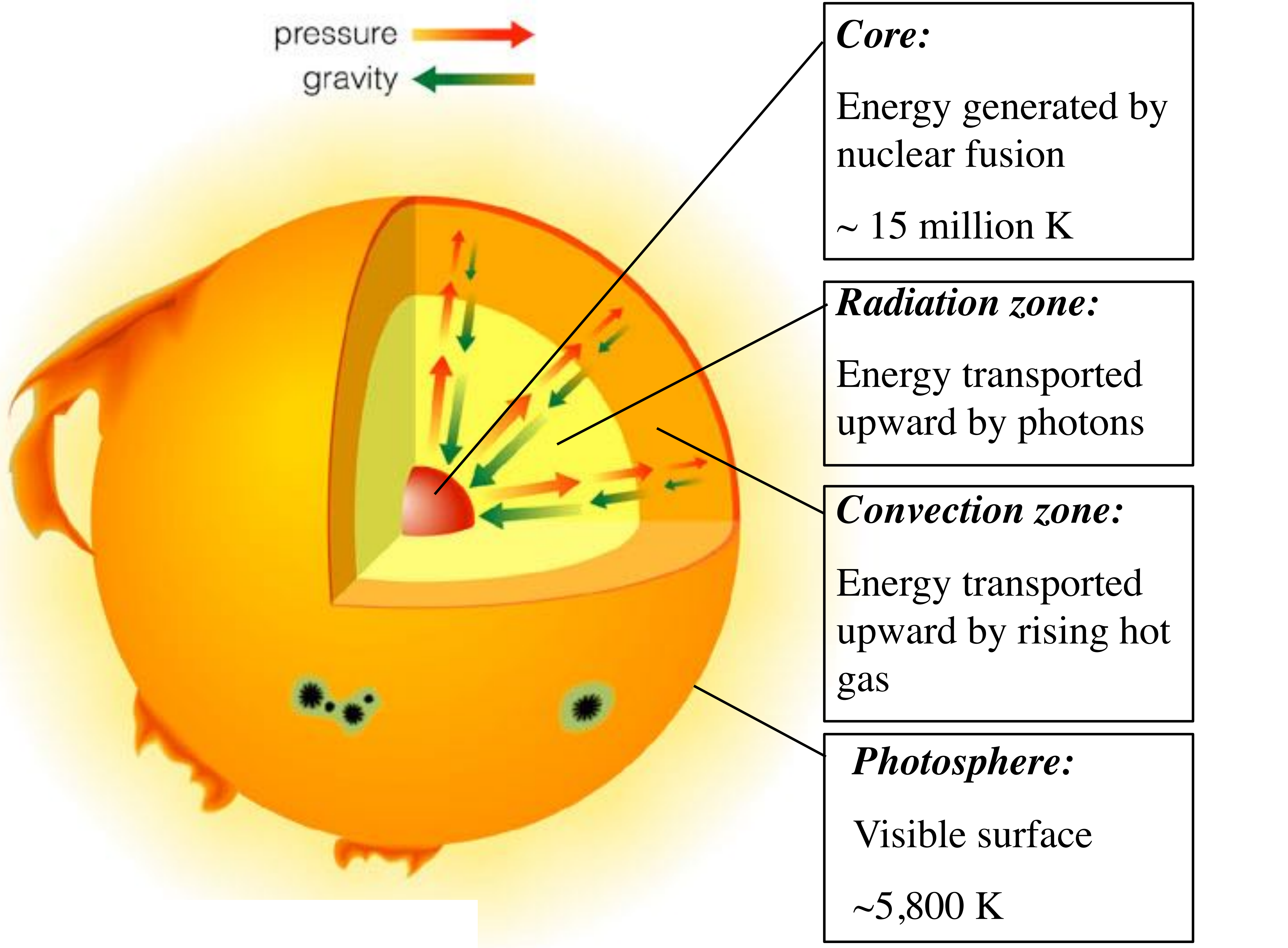
Energy released by nuclear fusion in the core of the sun heats the surrounding gas. The resultant pressure balances the relentless crush of gravity.



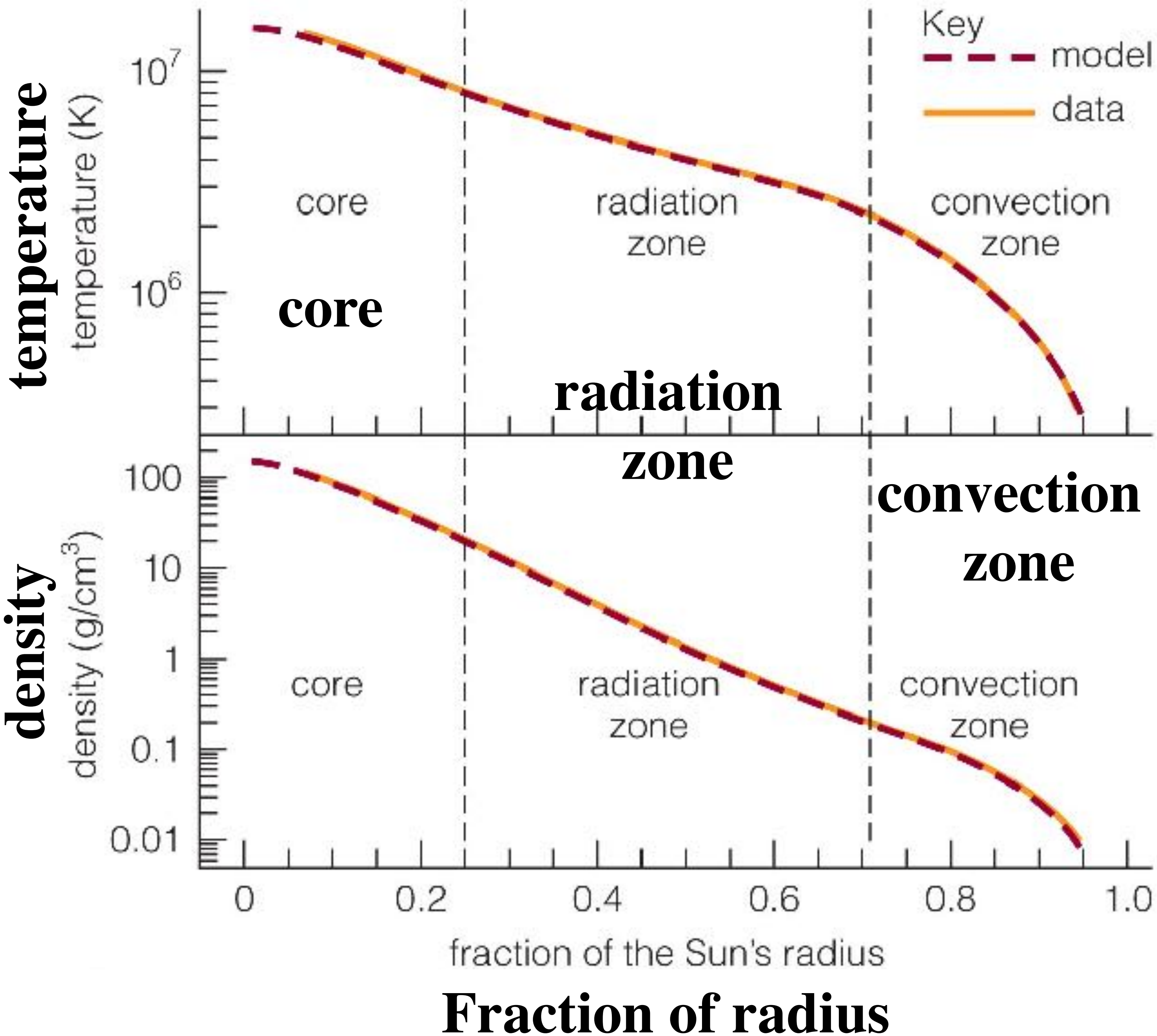
initial gravitational contraction:

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

Need a minimum of ~70 Jupiter masses to ignite fusion and to make a star

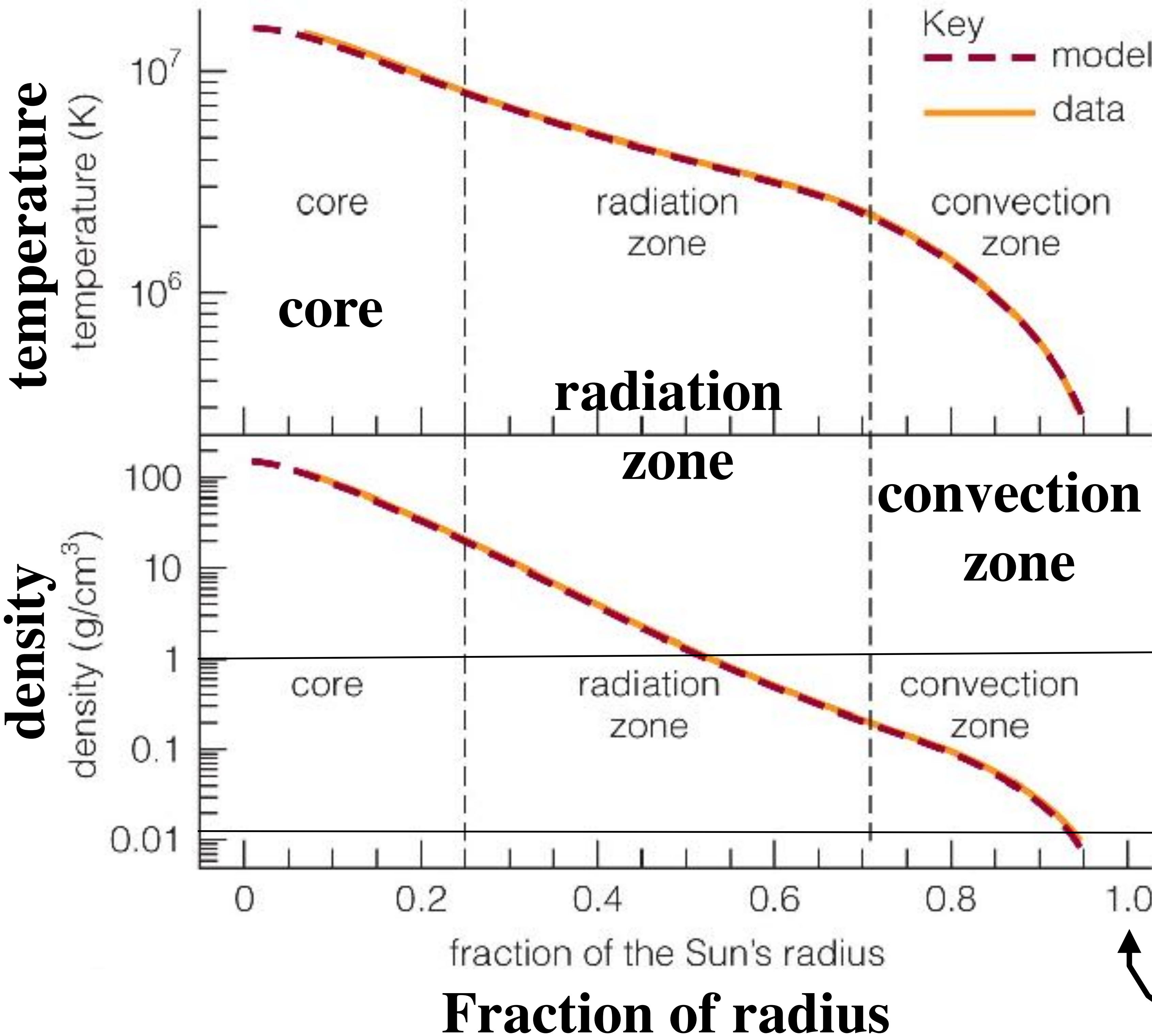

pressure
gravity
Core:
Energy generated by nuclear fusion
~ 15 million K
Radiation zone:
Energy transported upward by photons
Convection zone:
Energy transported upward by rising hot gas
Photosphere:
Visible surface
~5,800 K

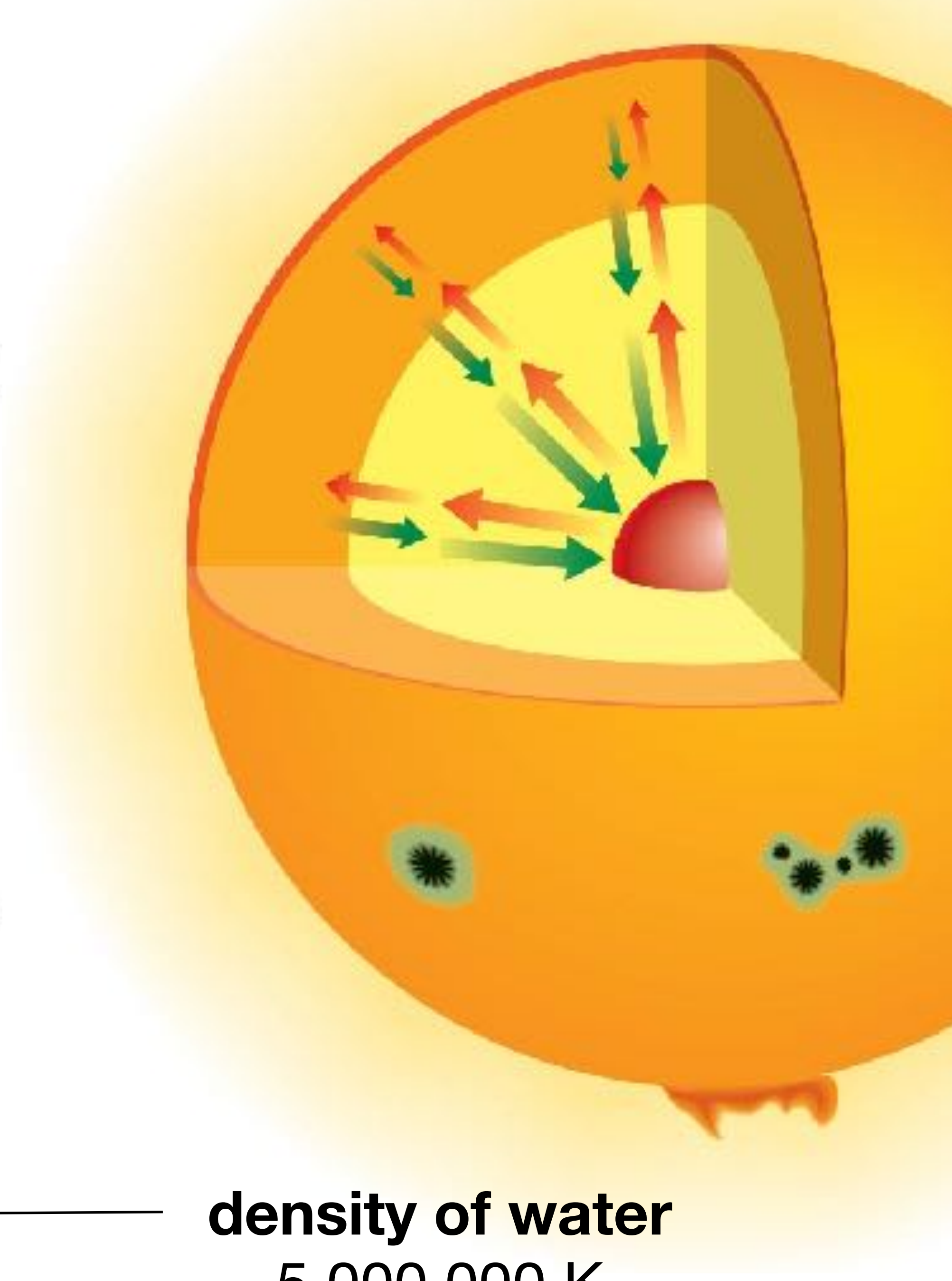
Interior Structure of the Sun



- Gravity causes the density and temperature to increase towards the center.
- Ave. density about 1 g/cc (water)
- but
  - much denser in core
  - much thinner at surface

Interior Structure of the Sun





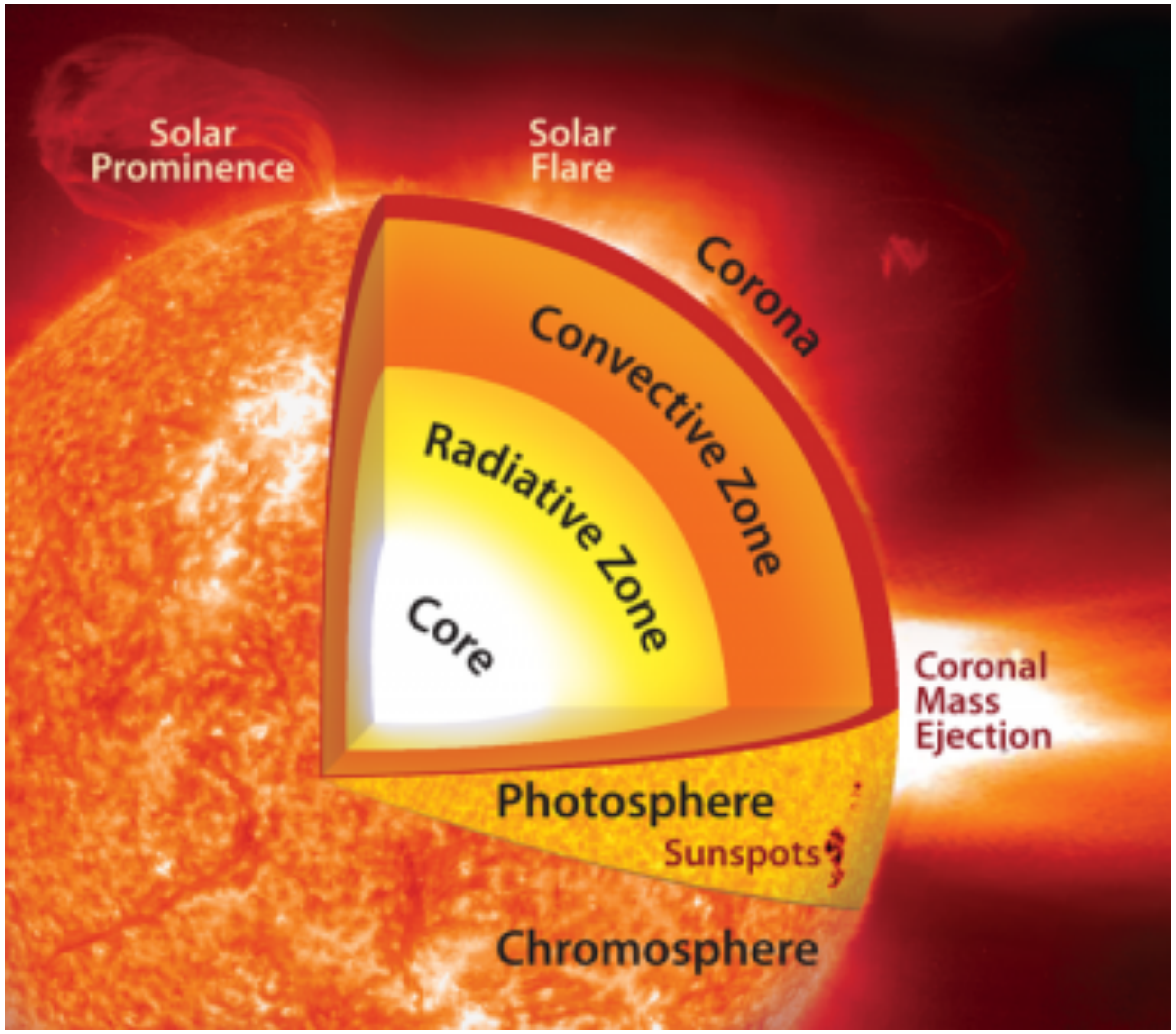
density of water
5,000,000 K

density of air
300,000 K

photosphere (visible surface)
5,800 K

Energy transport through the Sun

- Energy is produced in the core
- Transported through
  - Radiative Zone by photons
  - Convective Zone by gas motions
  - Nature chooses whichever is more efficient



Fusion occurs only in the core

- Solar structure
  - From inside out, the layers are:

INTERIOR

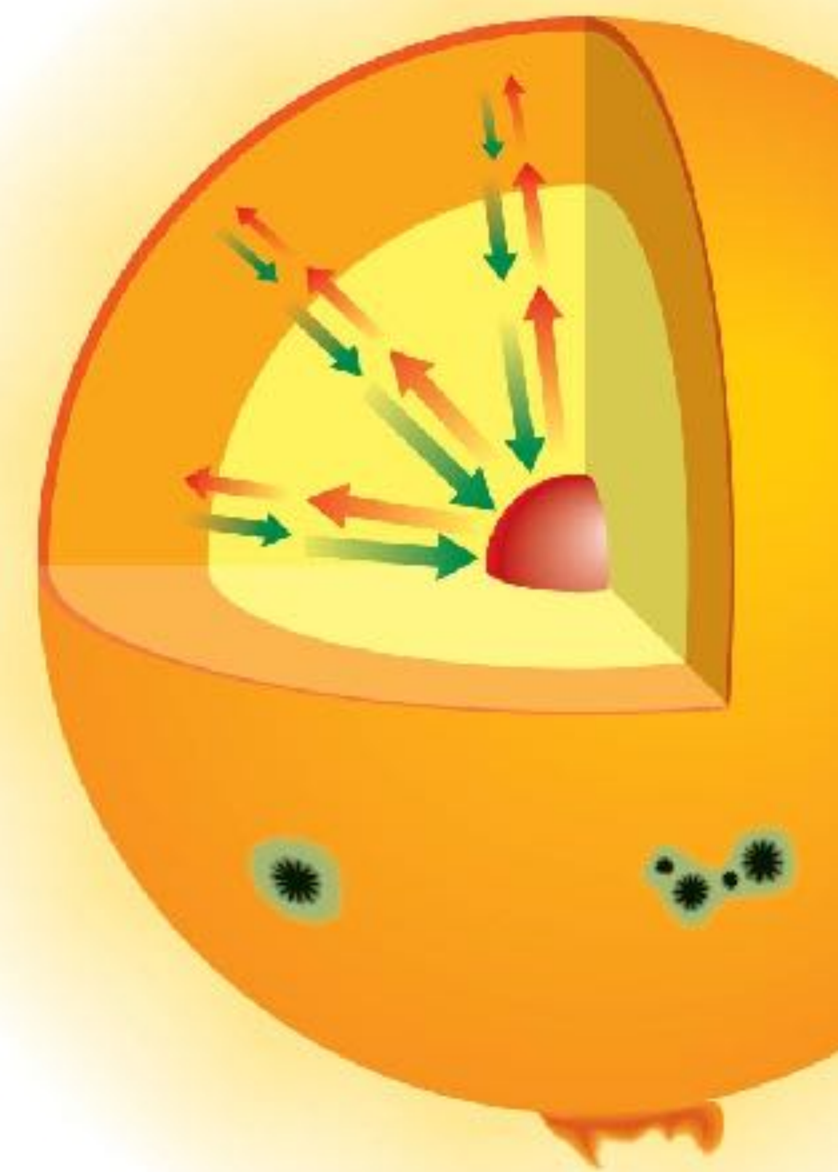
- Core
  - Energy generation by fusion reactions
- Radiation zone
  - Outward energy transport by photons
- Convection zone
  - Outward energy transport by gas motions

SURFACE

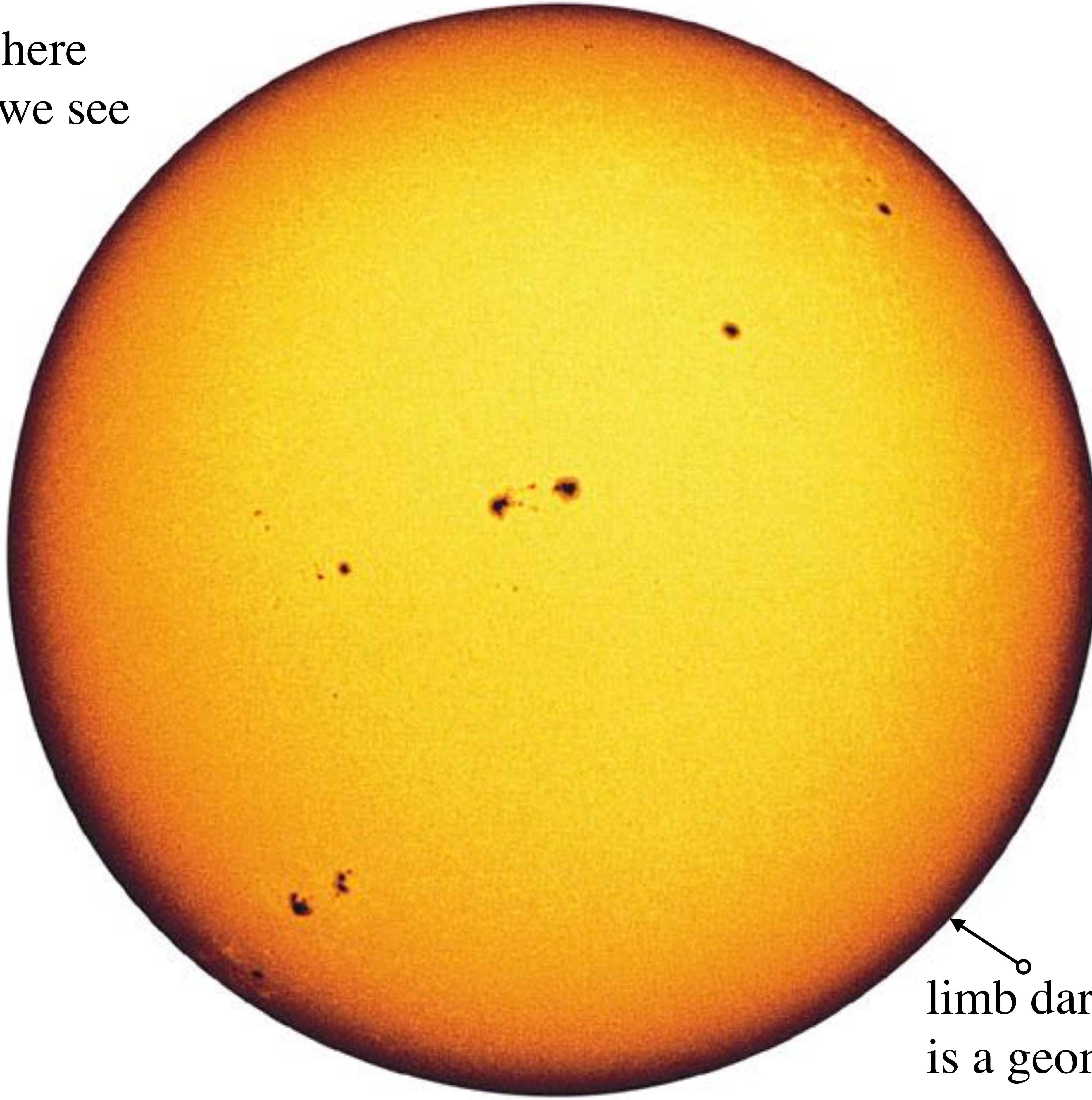
- Photosphere
  - Luminous surface (energy emitted to space)
    - » absorption spectrum

EXTERIOR

- Chromosphere
  - low density upper atmosphere
    - » emission spectrum, but much fainter than photosphere
- Corona
  - very hot, low density plasma tailing off into space

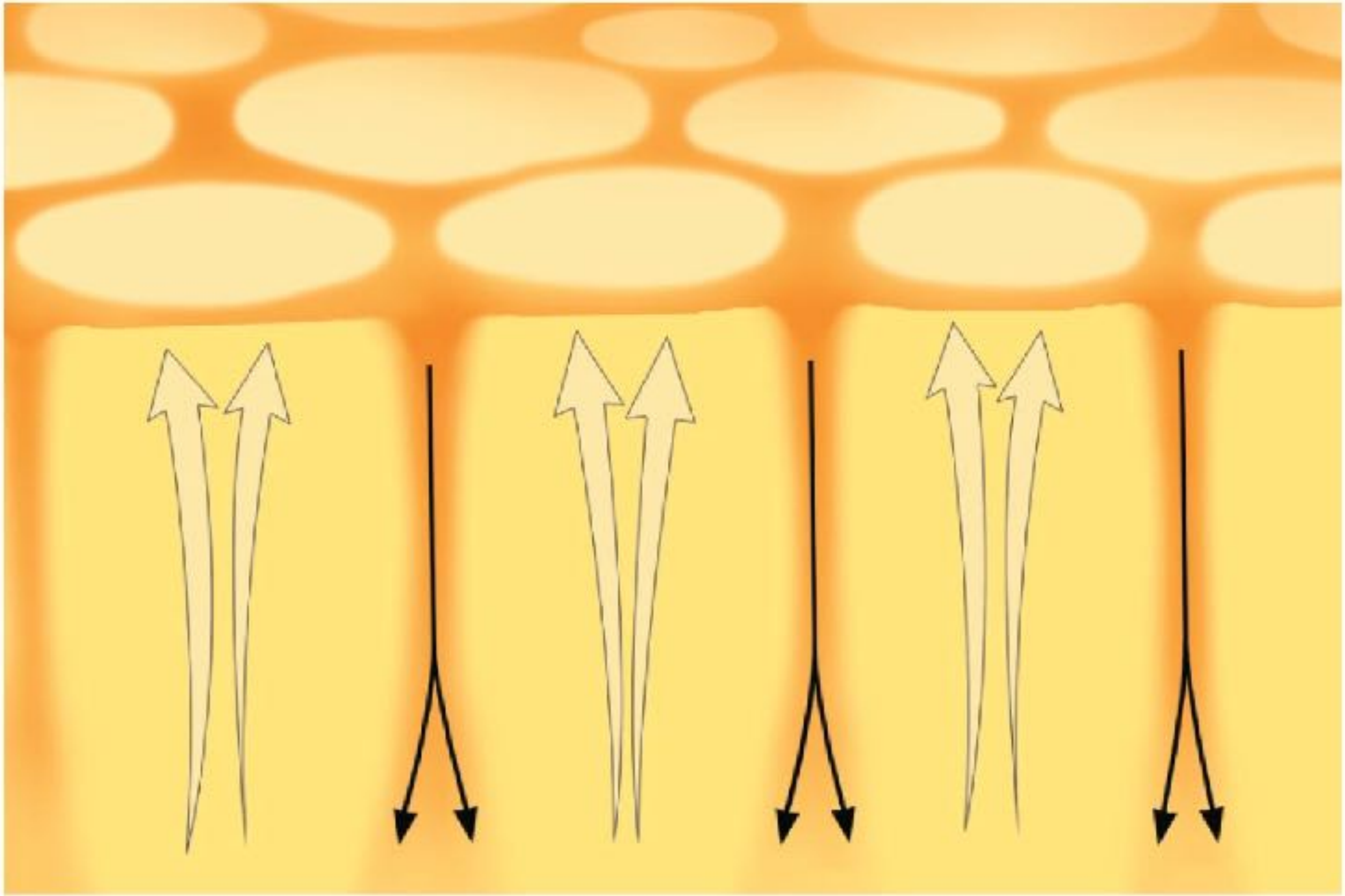


Photosphere
is what we see



Energy transport through the Sun: Convective Zone

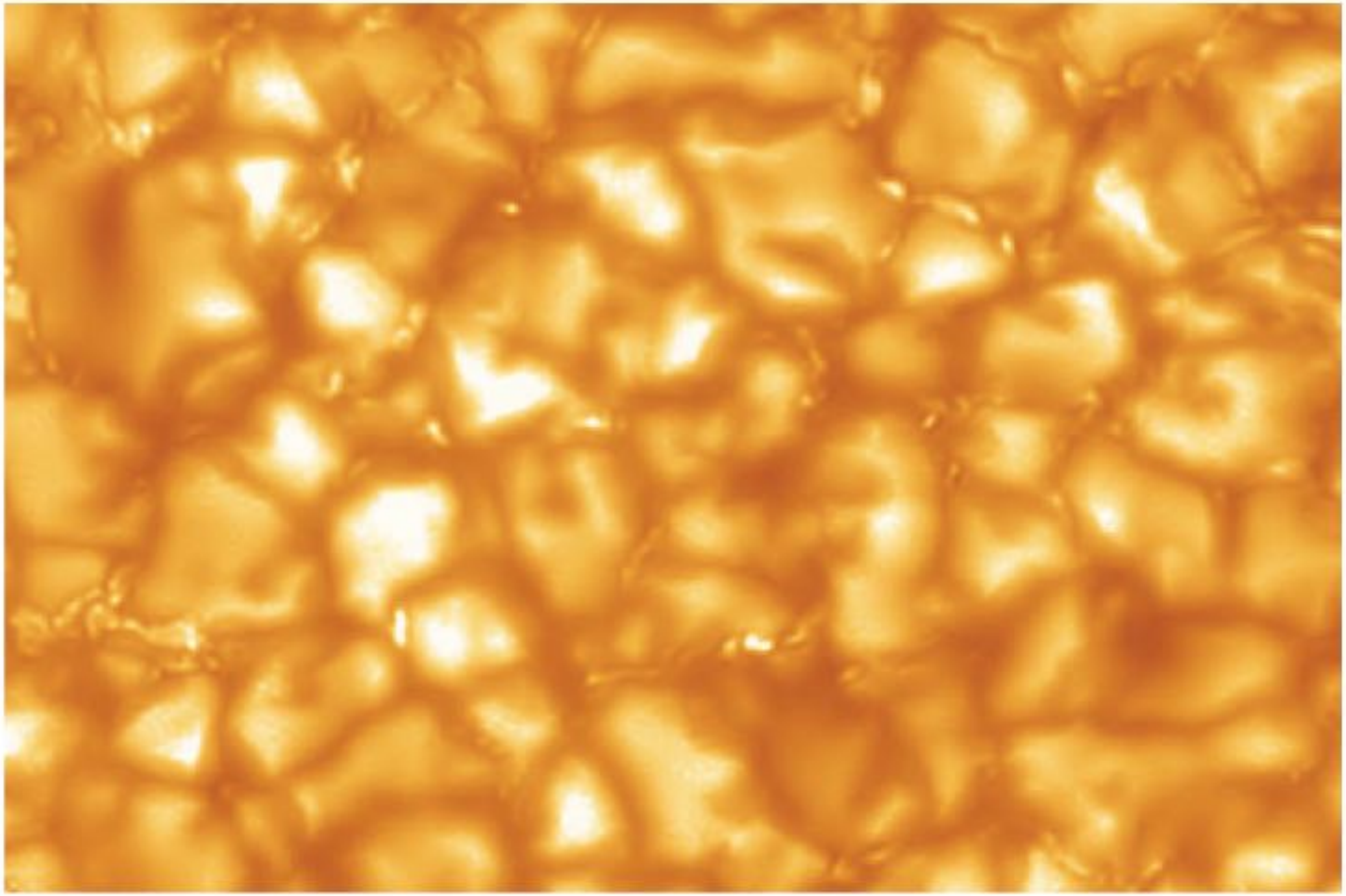
just under the photosphere



a This diagram shows convection beneath the Sun's surface. Hot gas (light yellow arrows) rises while cooler gas (black arrows) descends around it.

- Convection (rising hot gas) takes energy to surface.

https://www.youtube.com/watch?v=W_Scoj4HqCQ

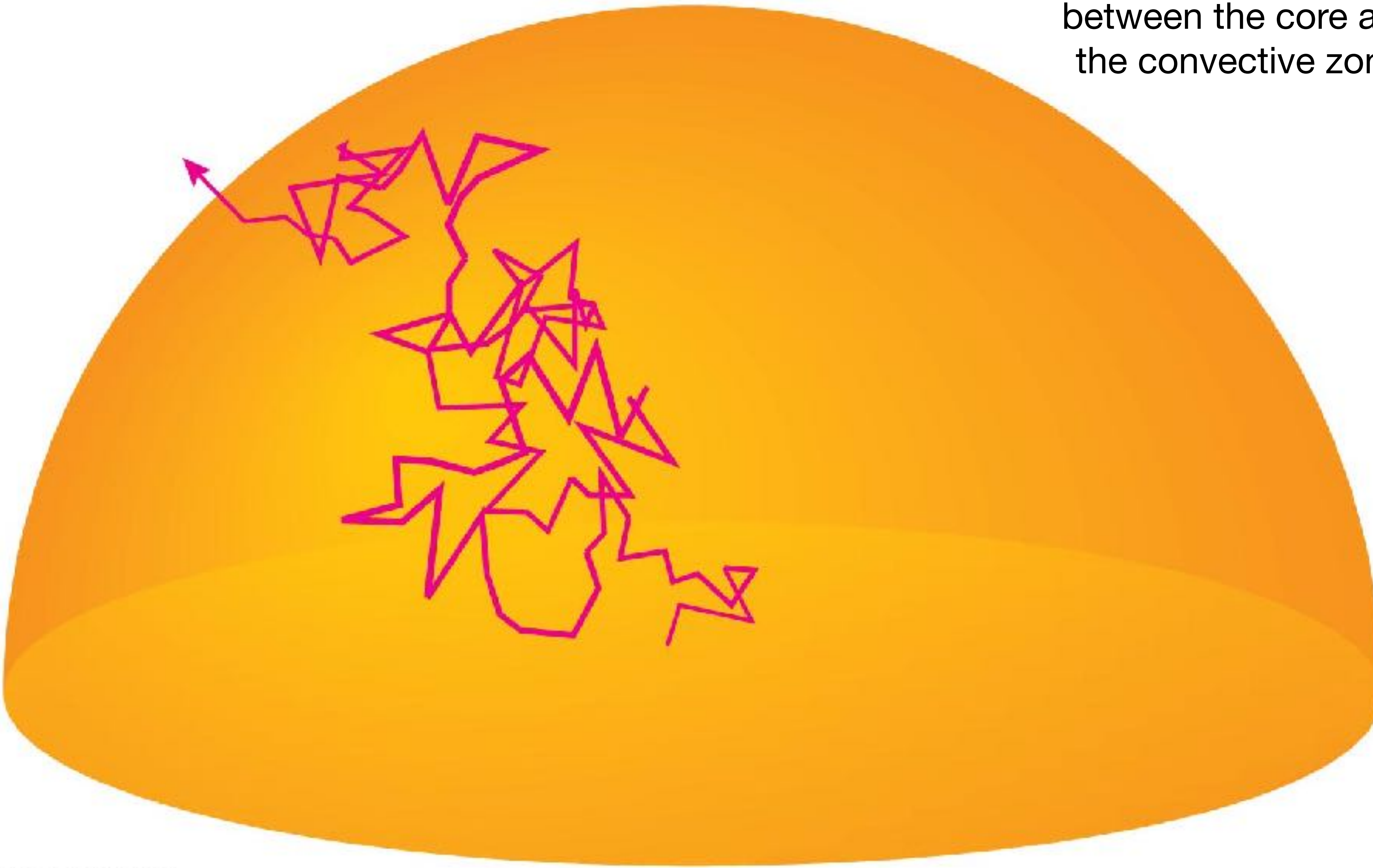


b This photograph shows the mottled appearance of the Sun's photosphere. The bright spots, each about 1000 kilometers across, correspond to the rising plumes of hot gas in part a.

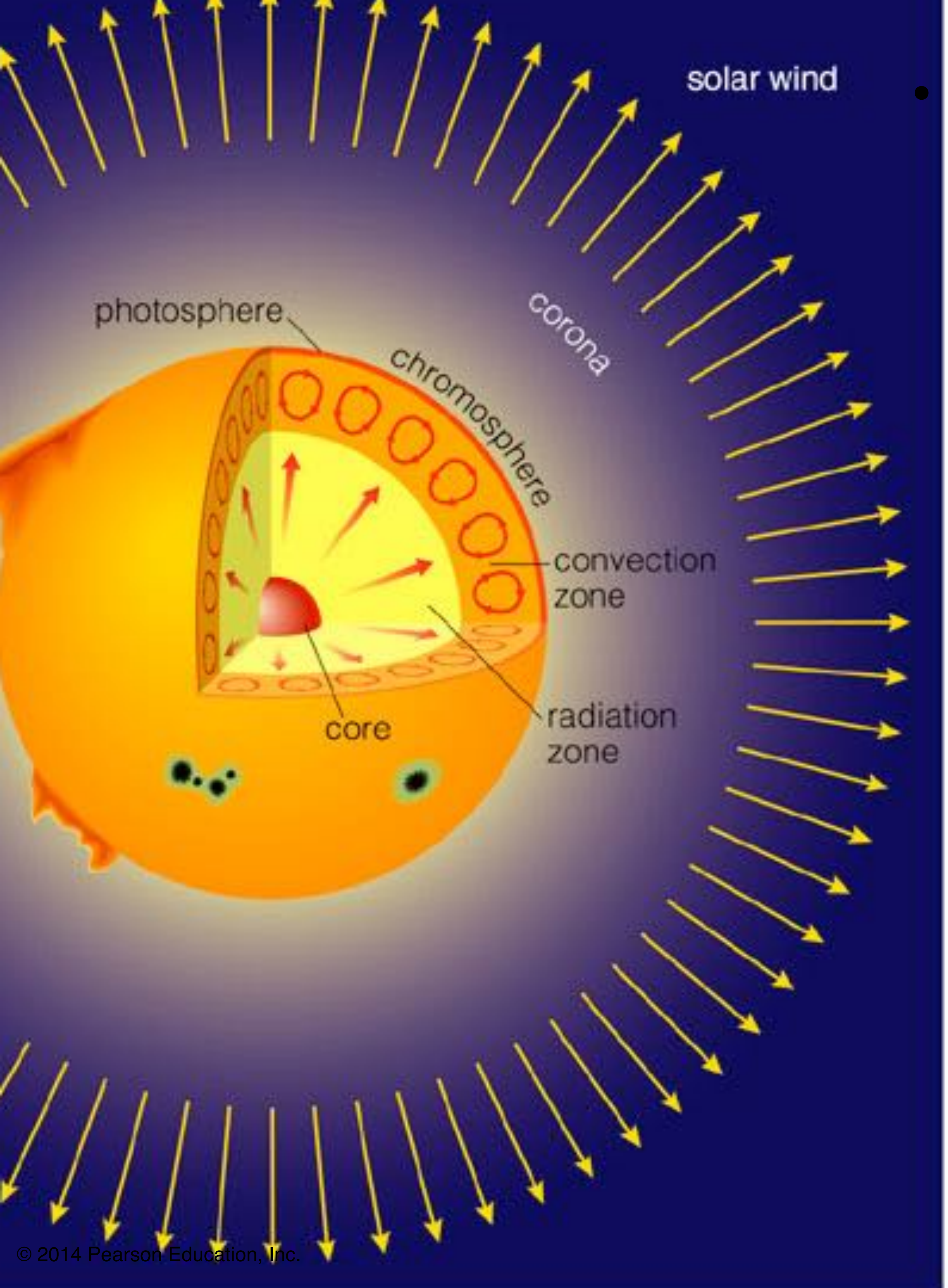
- Bright blobs on photosphere show where hot gas is reaching the surface: energy transport by **convection**.

Energy transport through the Sun: Radiative Zone

between the core and
the convective zone



- Energy gradually leaks out of radiation zone in form of randomly bouncing photons.

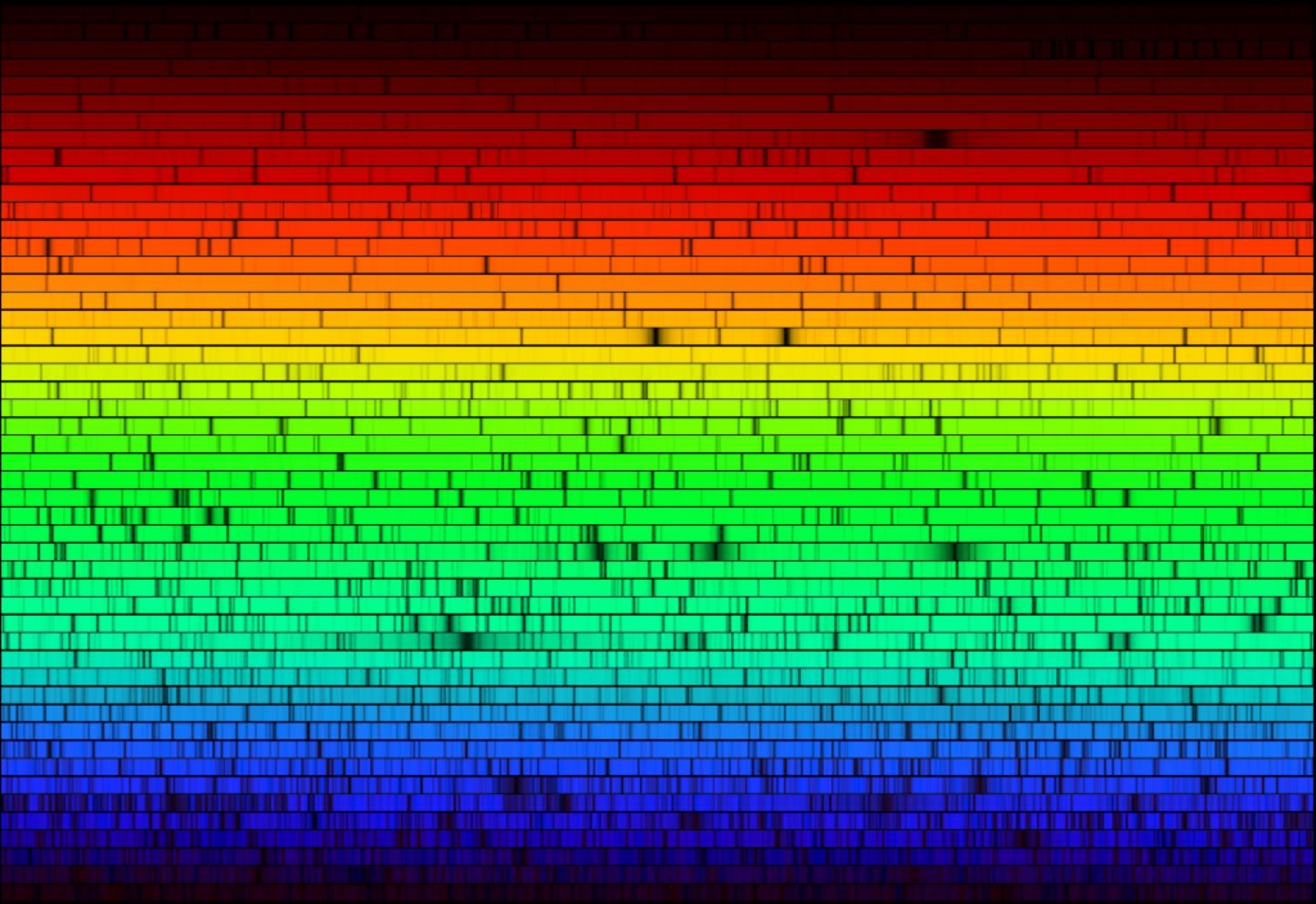


- Solar structure
  - above the photosphere:
    - Chromosphere
      - low density upper atmosphere
        - » emission spectrum, but much fainter than photosphere
    - Corona
      - very hot, low density plasma tailing off into space
    - Solar wind
      - thin plasma blown into space

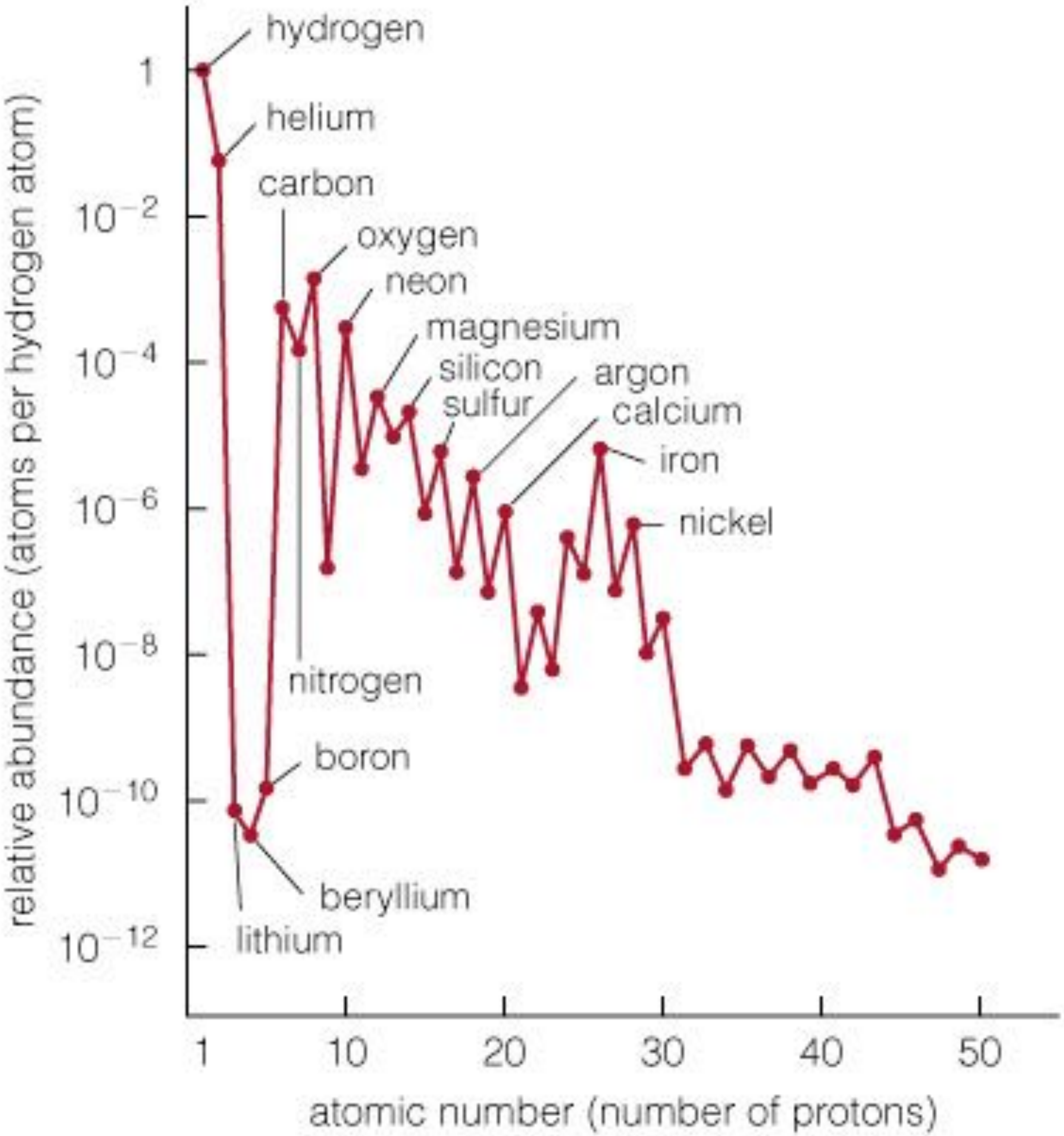
Little mass in these components


solar corona
only visible during eclipse -
photosphere vastly
outshines the corona
solar chromosphere
seen in Hα emission

The photosphere produces an absorption spectrum



Composition determined from absorption lines



Abundance (by number relative to Hydrogen)

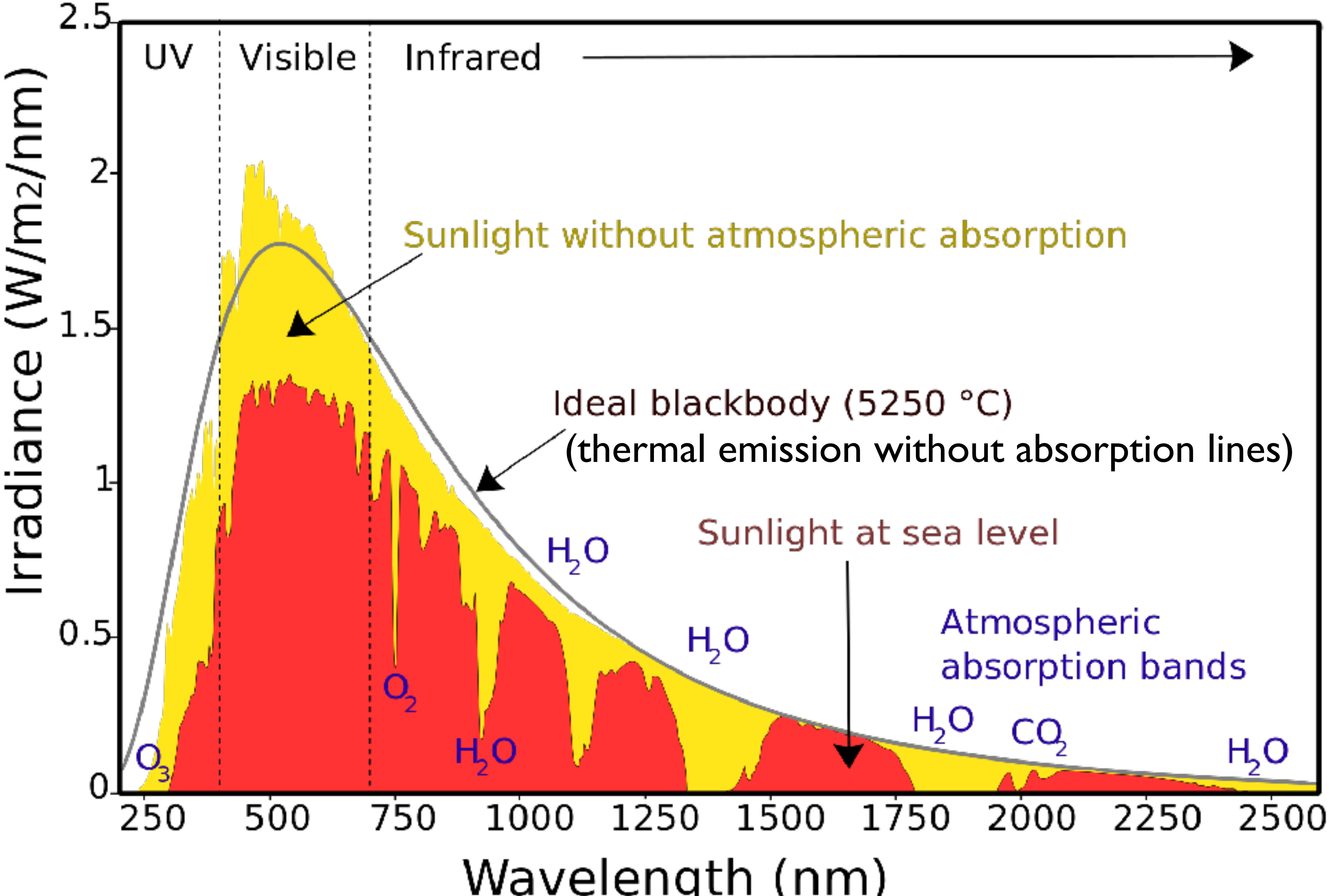
Atomic number (number of protons)

By mass, the sun is
3/4 Hydrogen
1/4 Helium
< 2% everything else

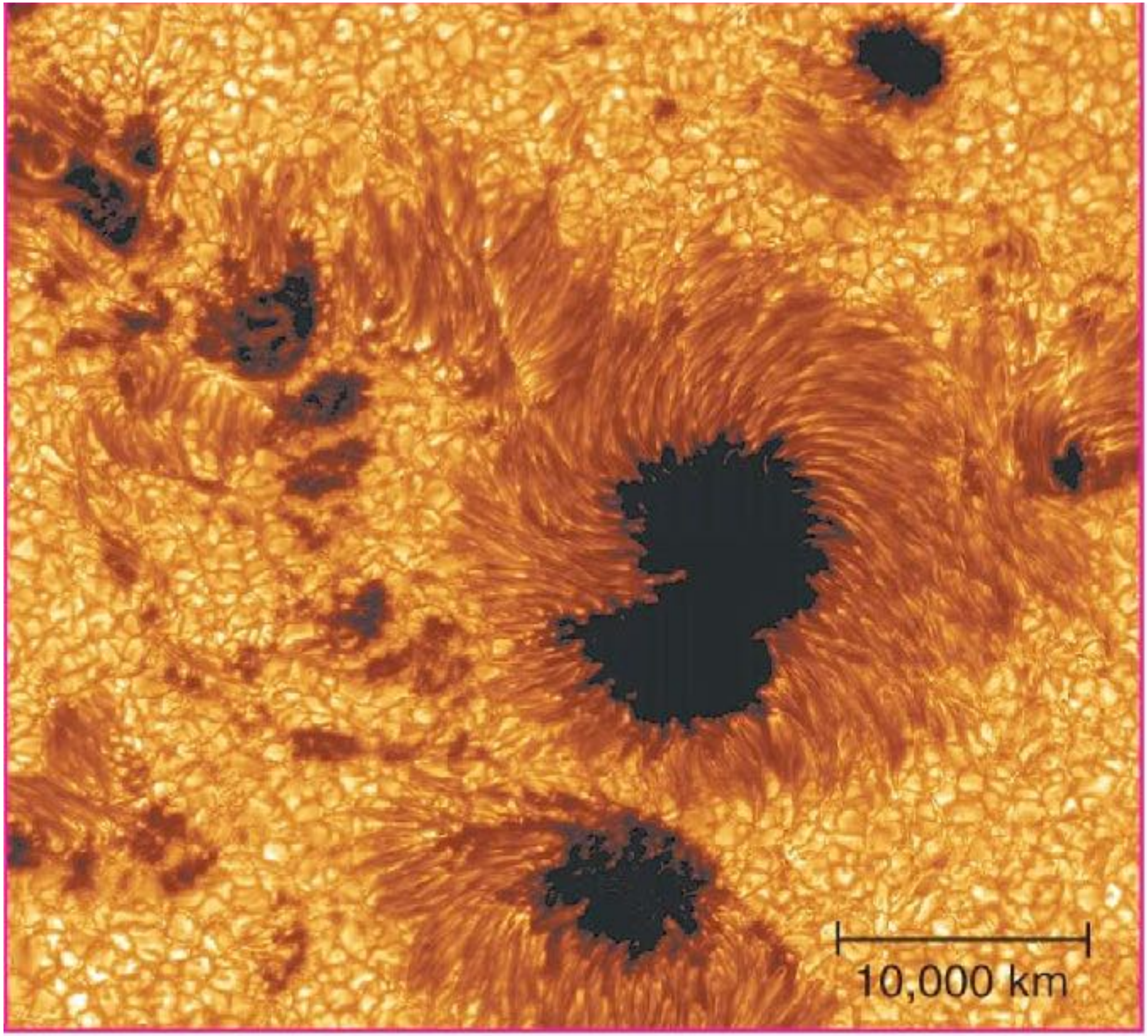
This is typical of the universe; Earth is an exception.

Helium *discovered* in the spectrum of the sun (hence the name)

Spectrum of Solar Radiation (Earth)



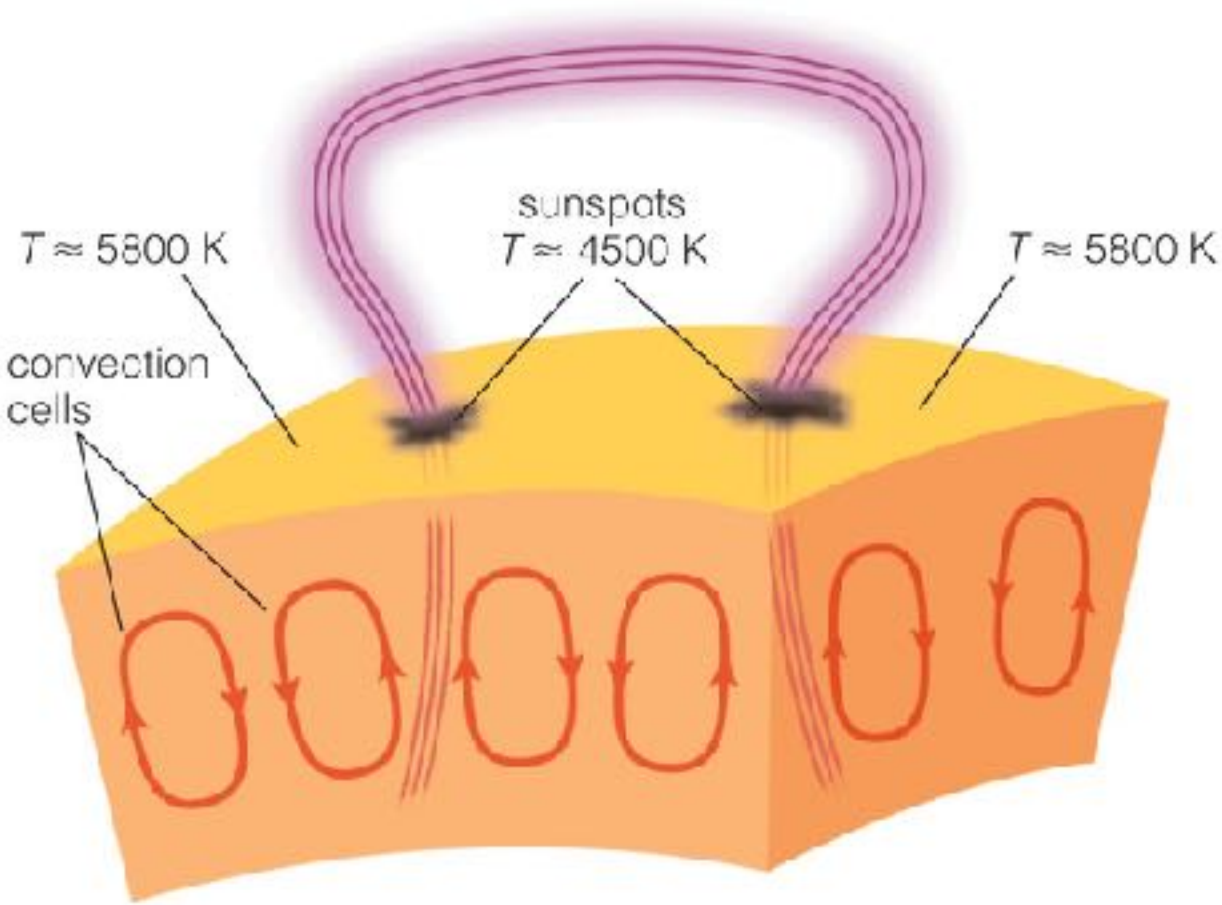
Sometimes see spots on the photosphere



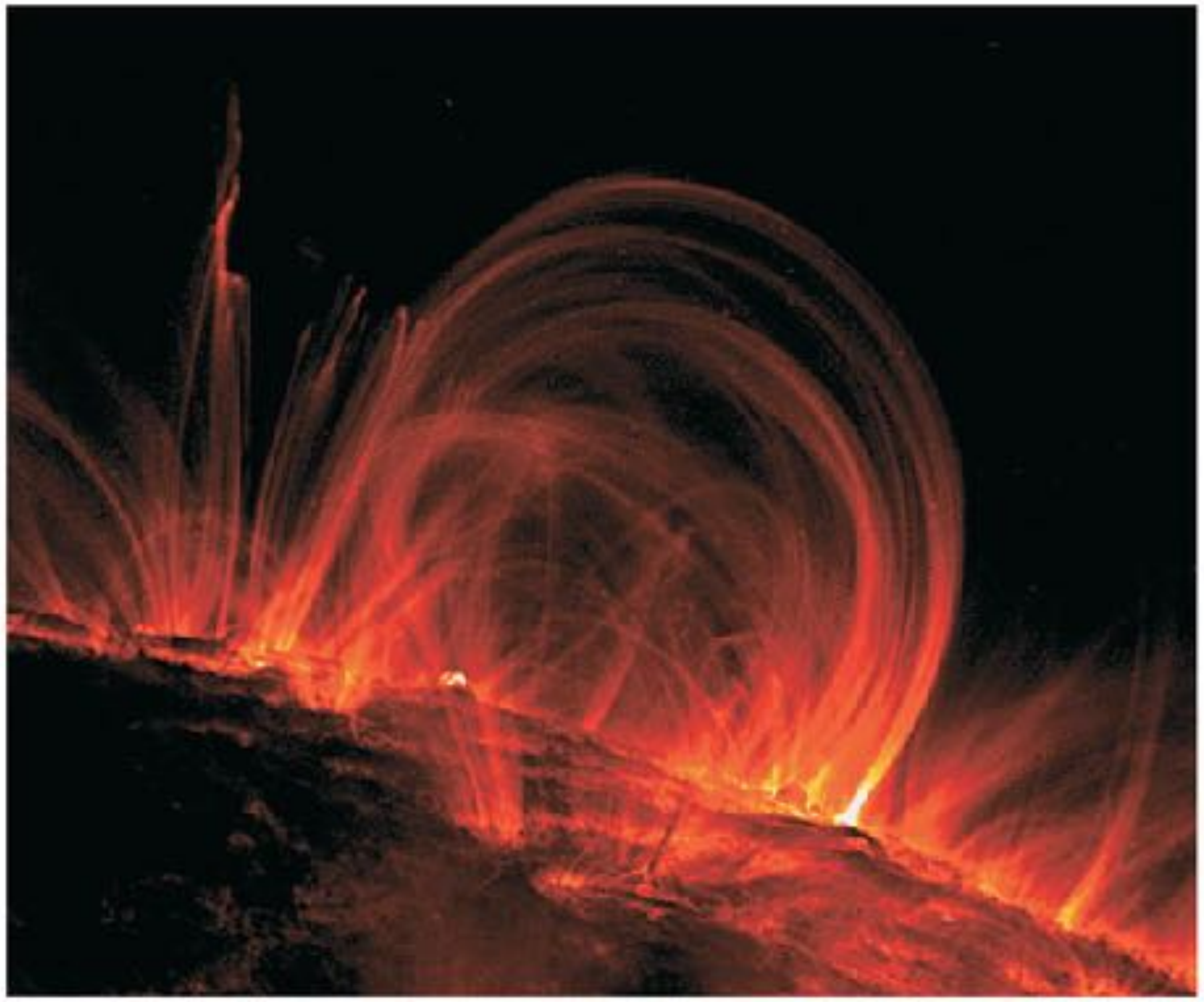
Sunspots

- Are cooler than other parts of the Sun's surface (4000 vs 5800K)
- Are regions with strong magnetic fields

Magnetic fields associated with sunspots sometimes lead to solar storms



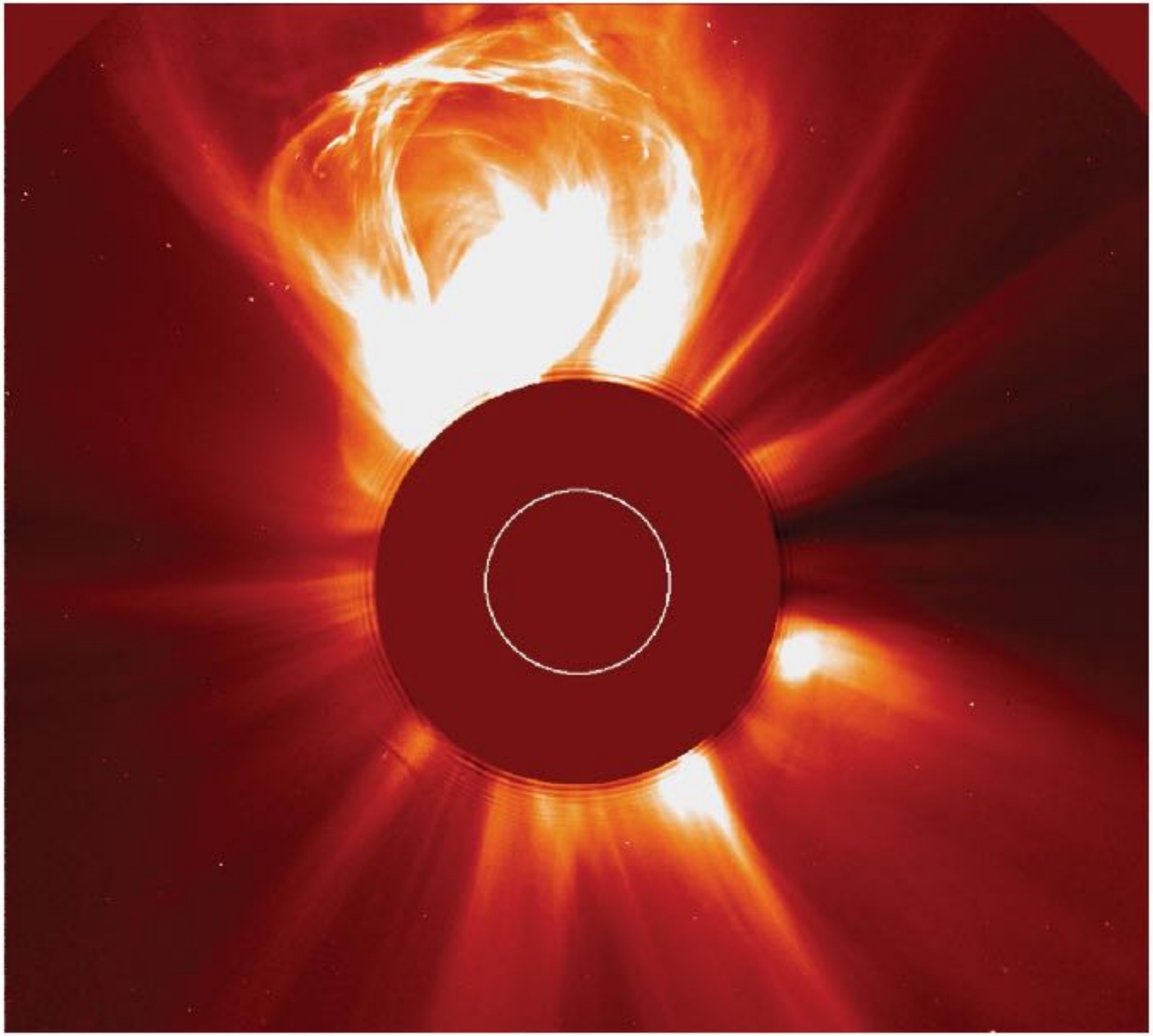
a Pairs of sunspots are connected by tightly wound magnetic field lines.



b This X-ray photo (from NASA's *TRACE* mission) shows hot gas trapped within looped magnetic field lines.

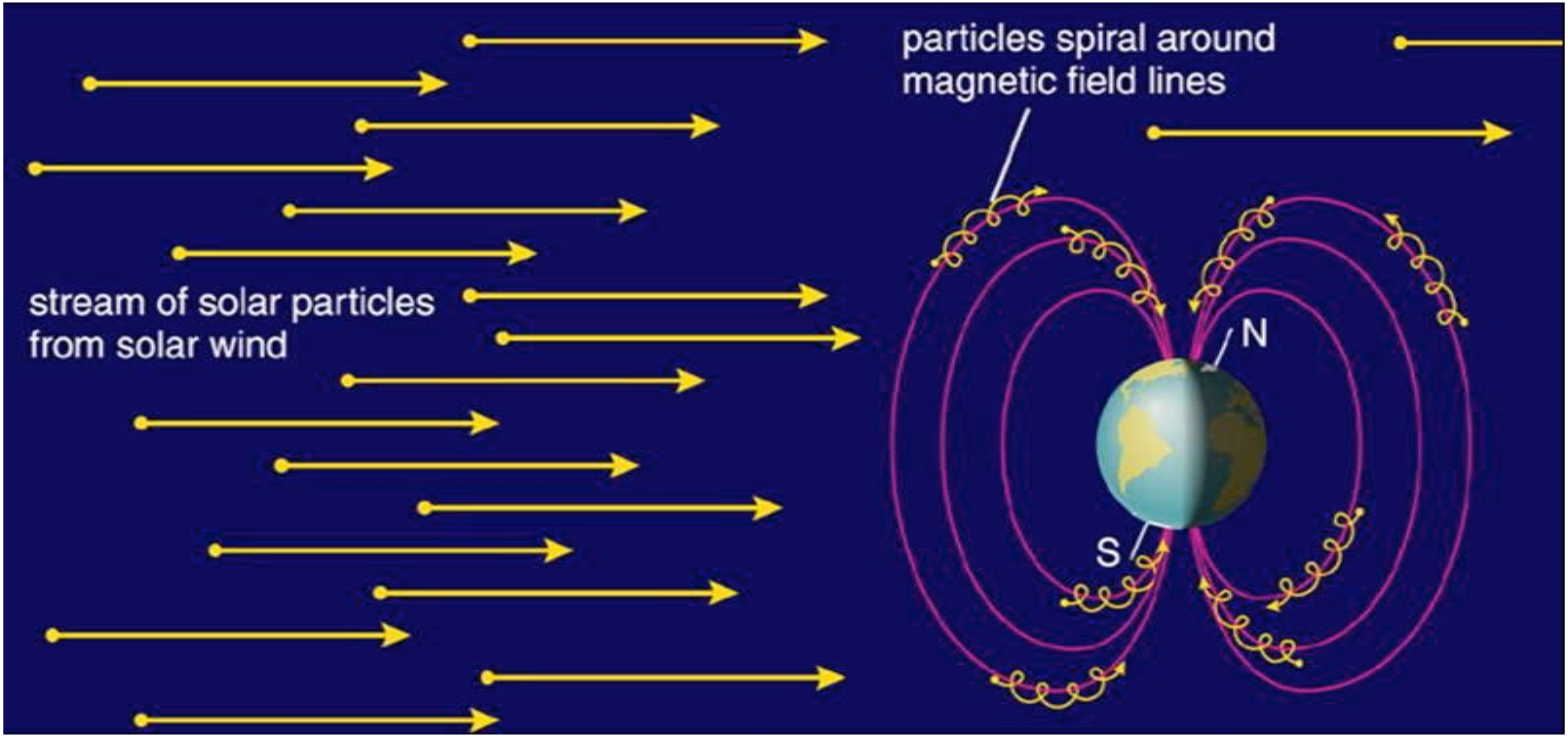
- Loops of bright gas often connect sunspot pairs.

Magnetic fields associated with sunspots sometimes lead to solar storms



https://www.youtube.com/watch?v=LHAQj86iVIo

- Coronal mass ejections send bursts of energetic charged particles out through the solar system.
- Poses a risk to the power grid & would-be space travelers



- Charged particles streaming from the Sun cause aurora near poles
- Can sometimes disrupt electrical power grids and can disable communications satellites.

aurora - “northern lights”