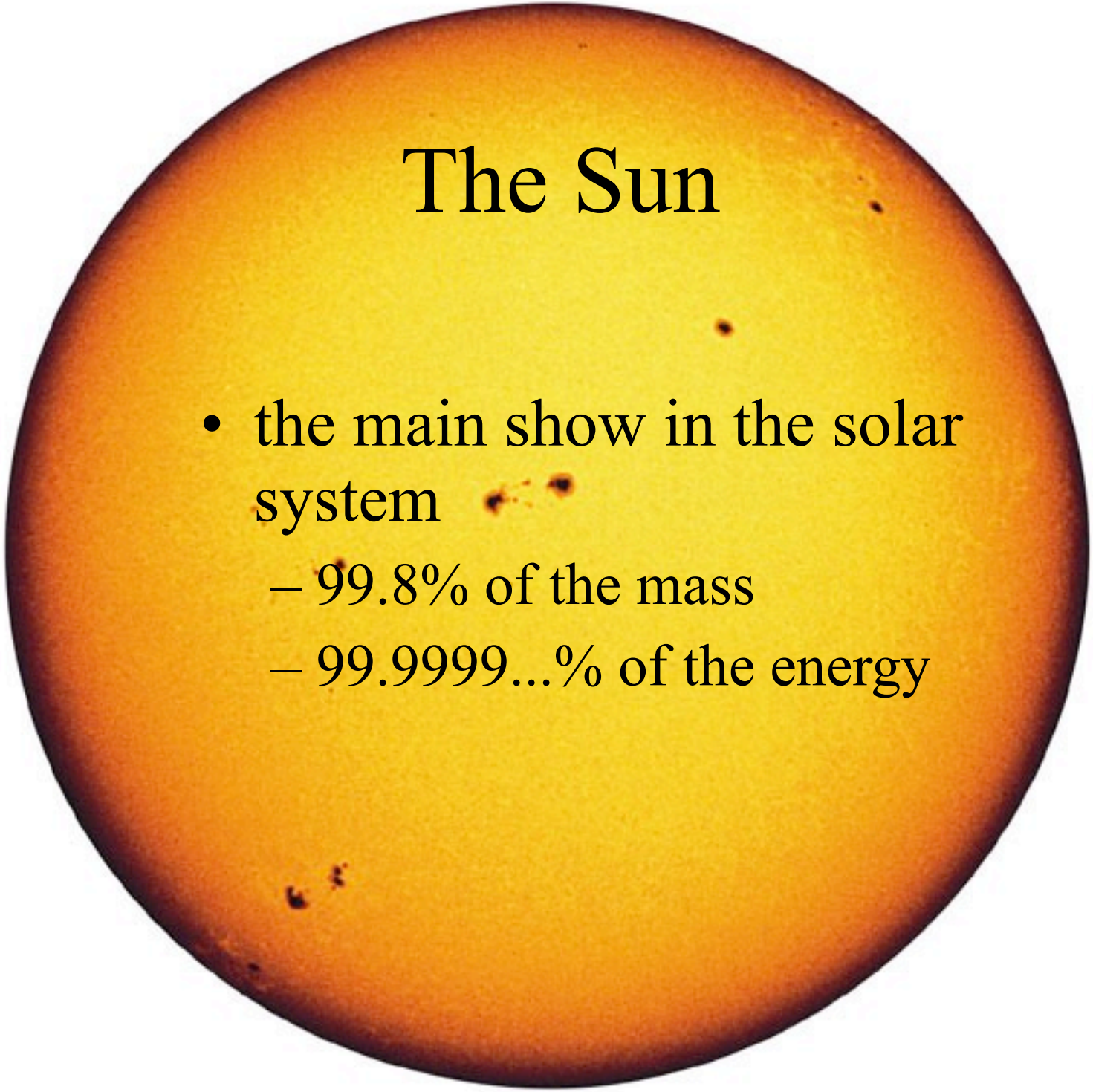
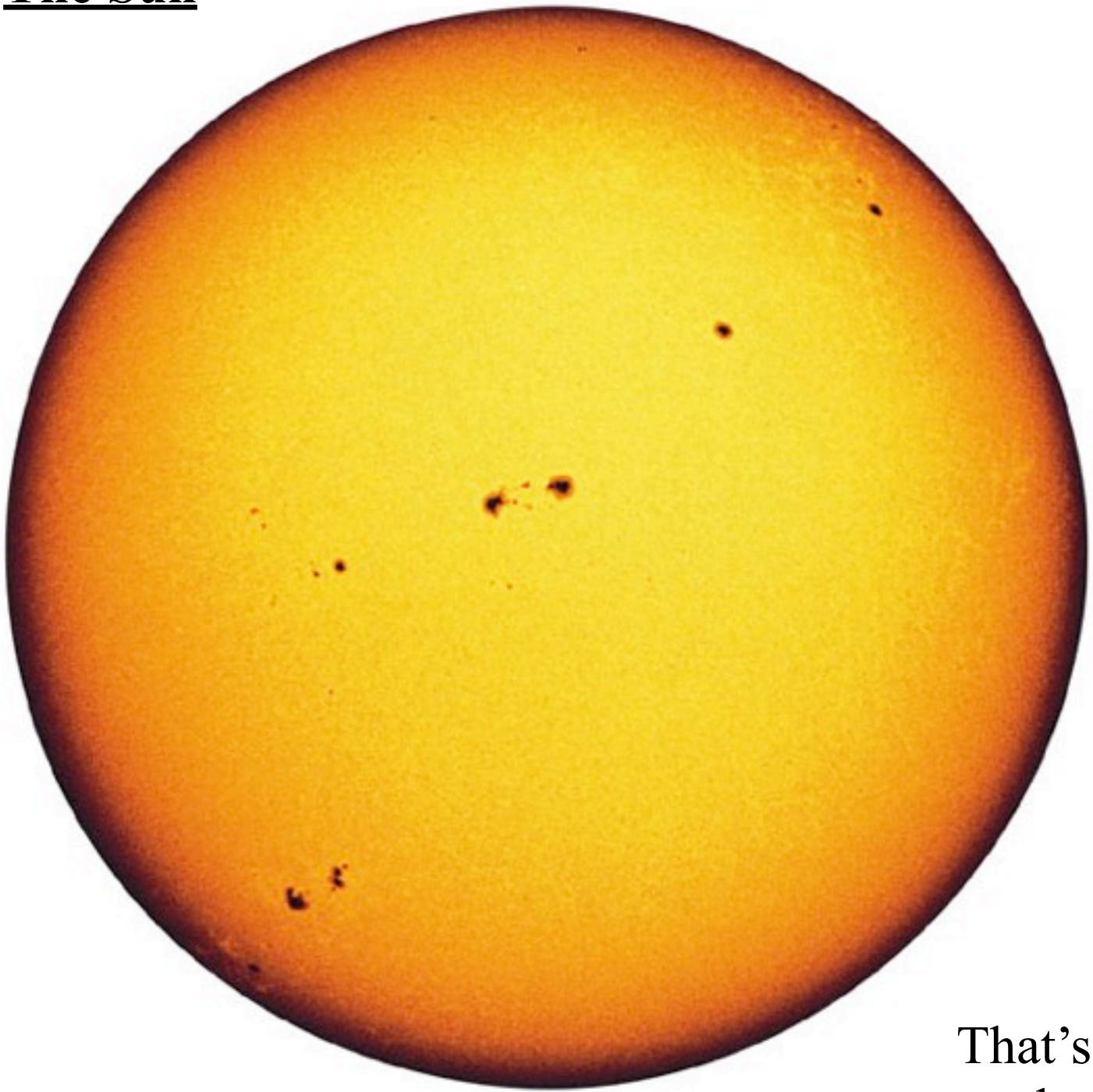
The Sun



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

Homework due next time - will count best 5 of 6

The Sun



Radius:

6.9×10^8 m

(109 times Earth)

Mass:

2×10^{30} kg

(1,000 Jupiters;

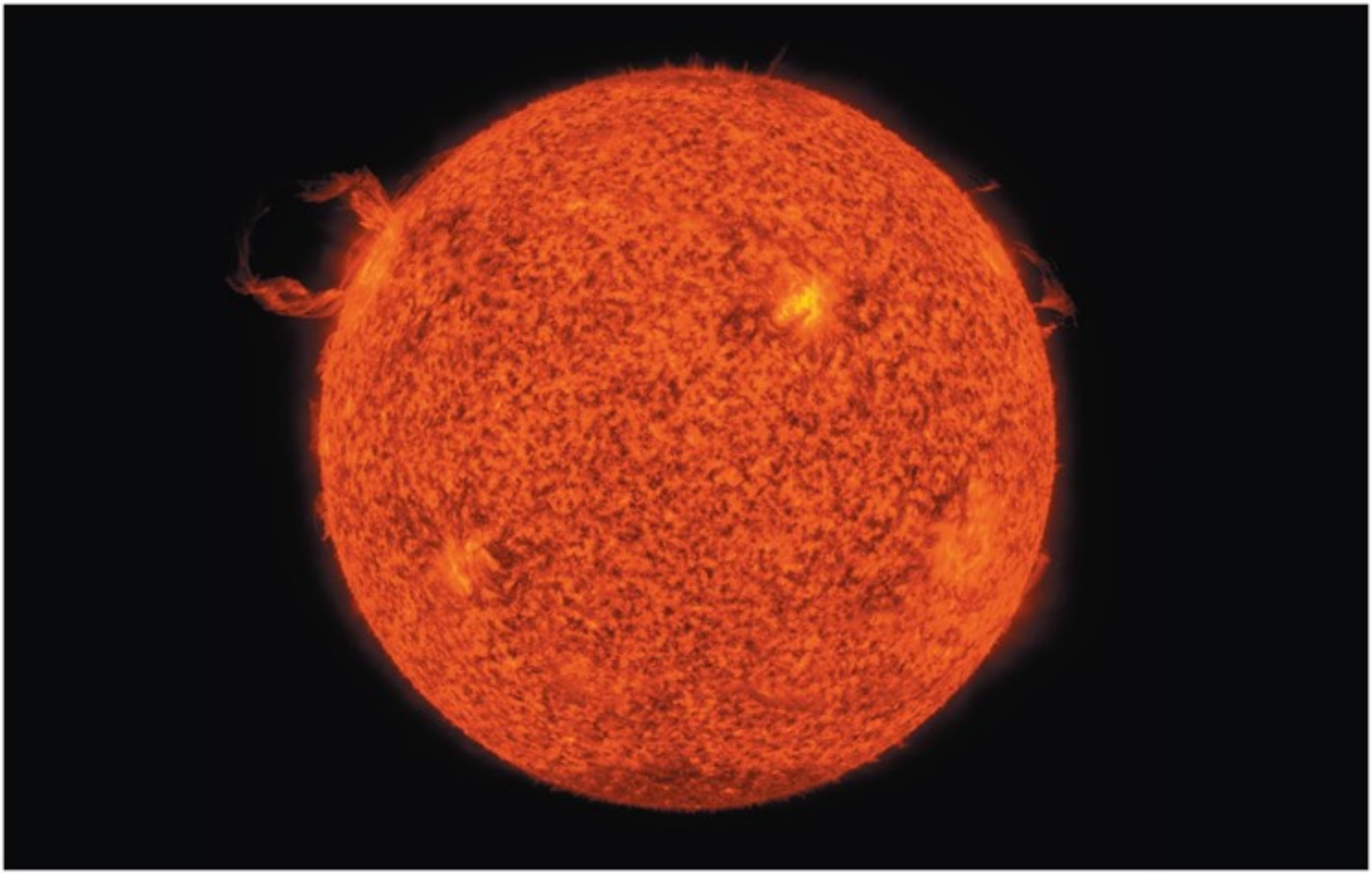
300,000 Earths)

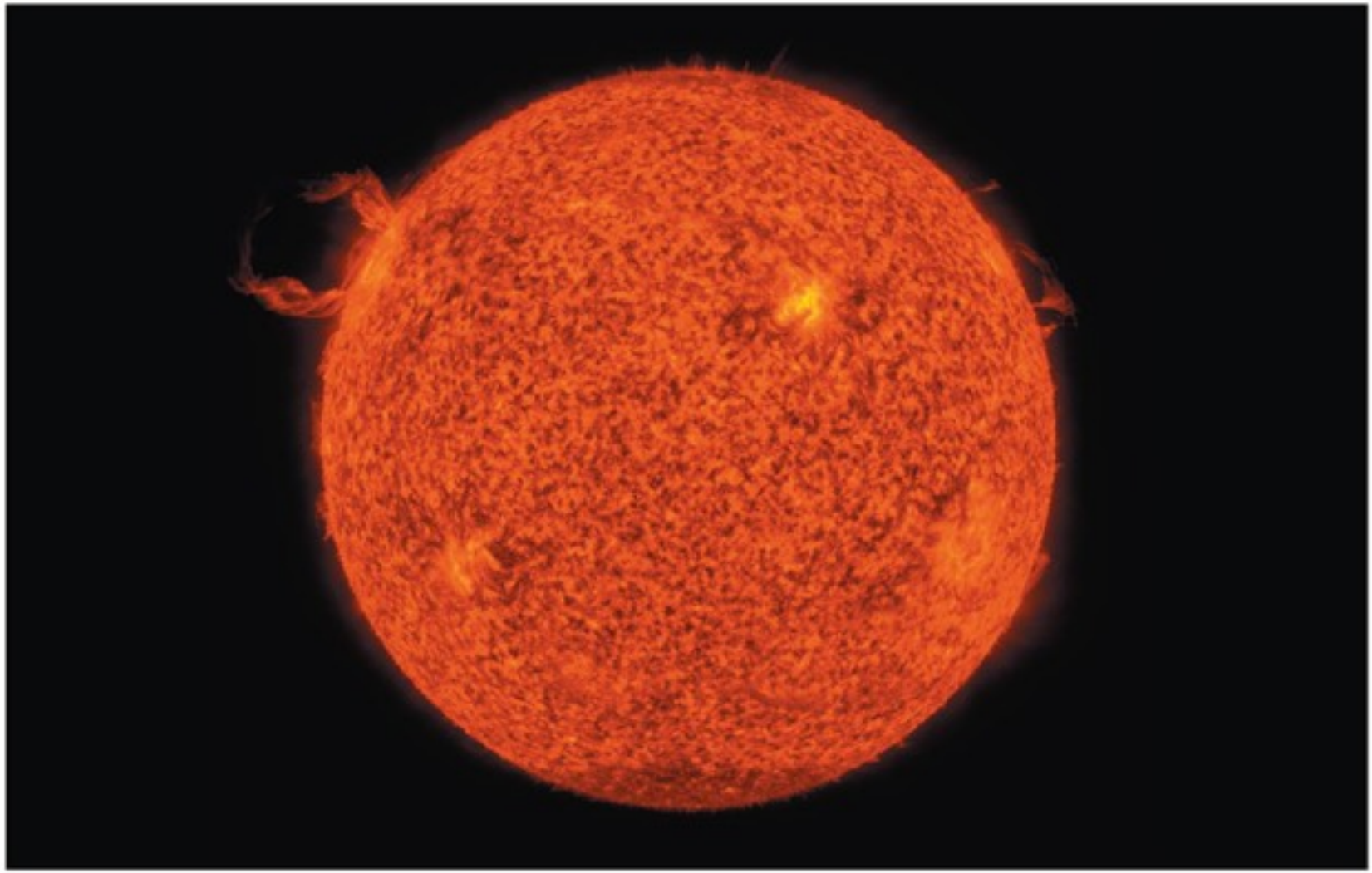
Luminosity:

3.8×10^{26} watts

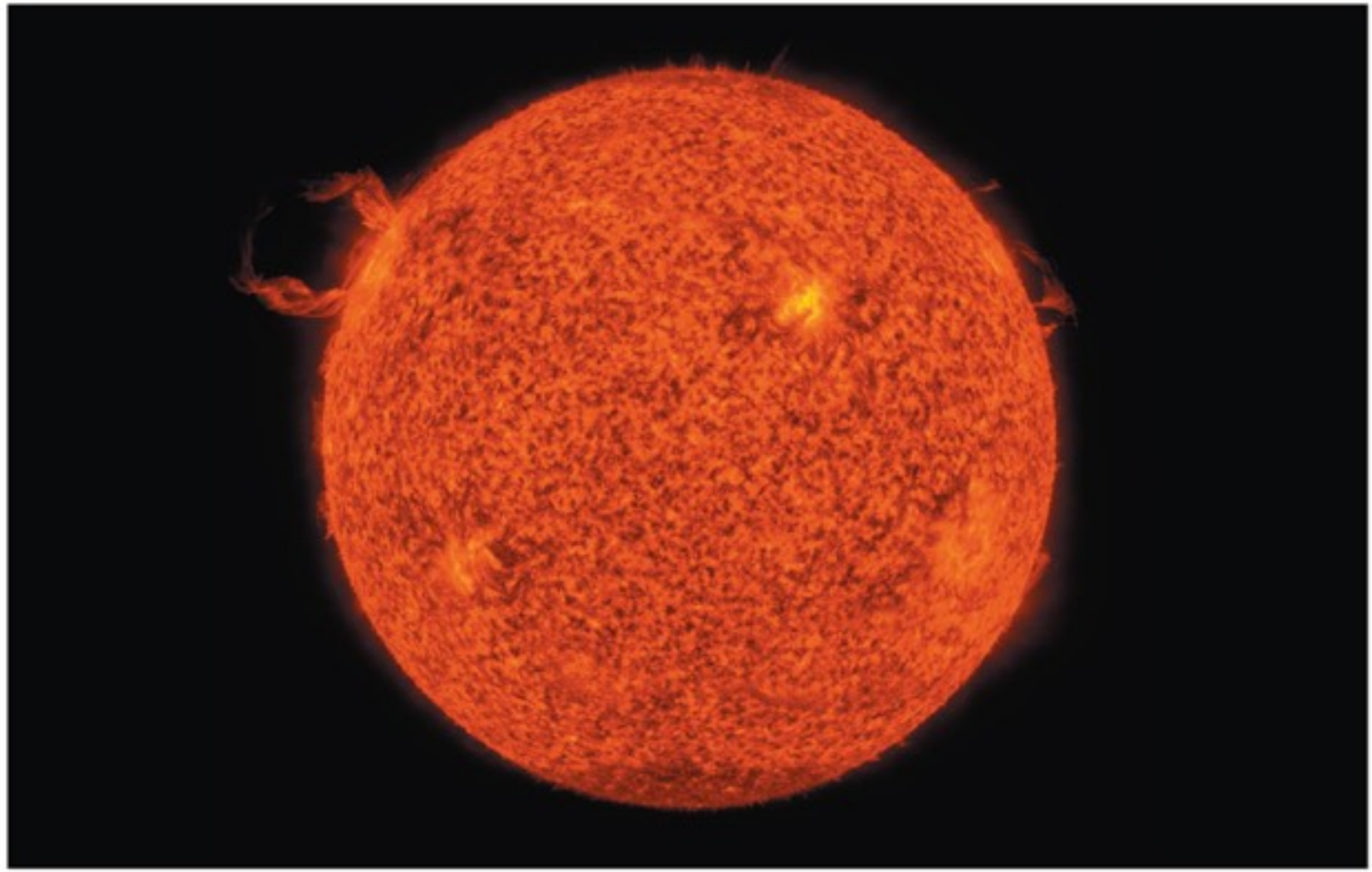
That's about a billion big nuclear bombs every second

Why does the Sun shine?



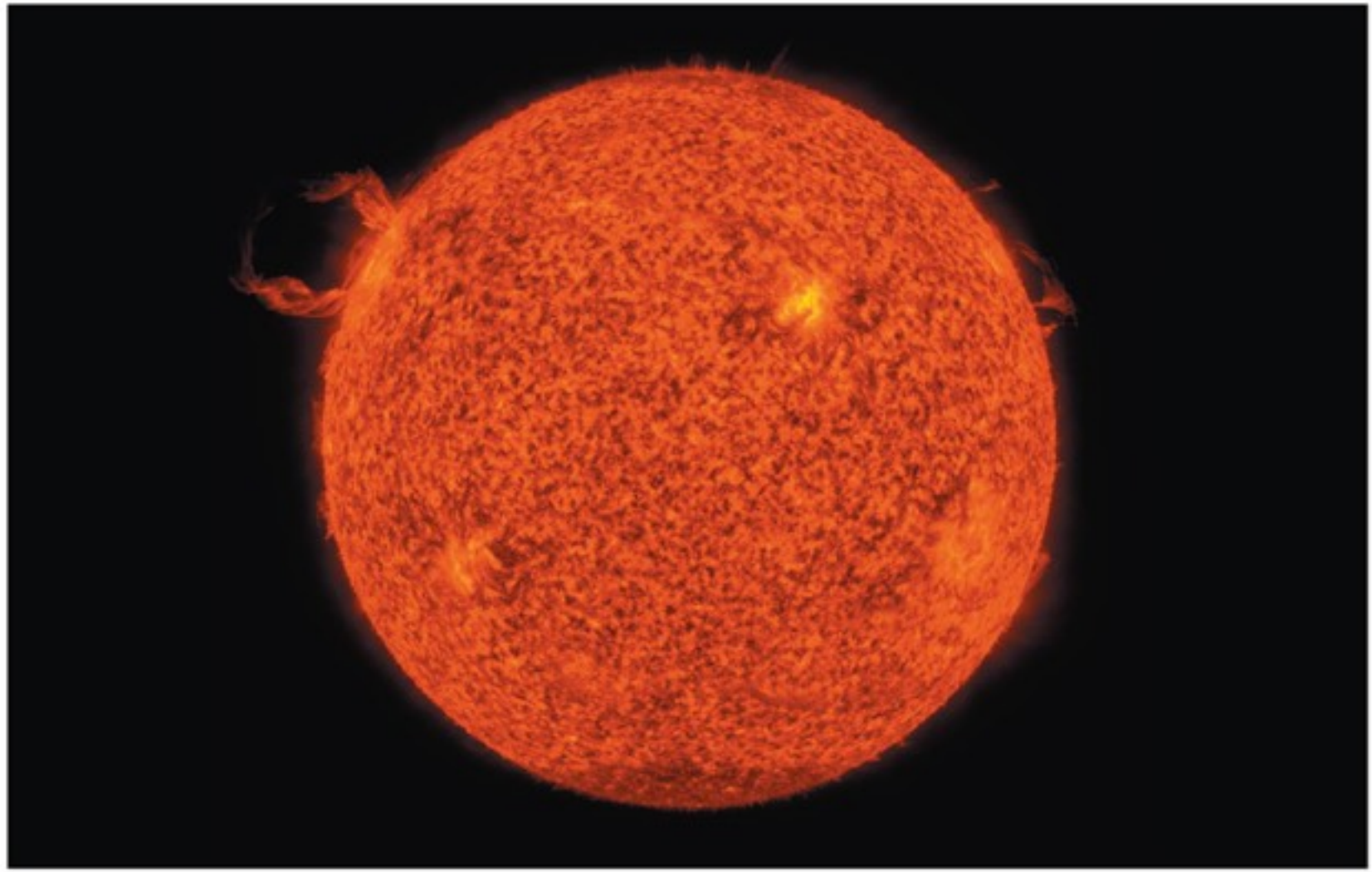


Is it on FIRE?



Is it on FIRE?

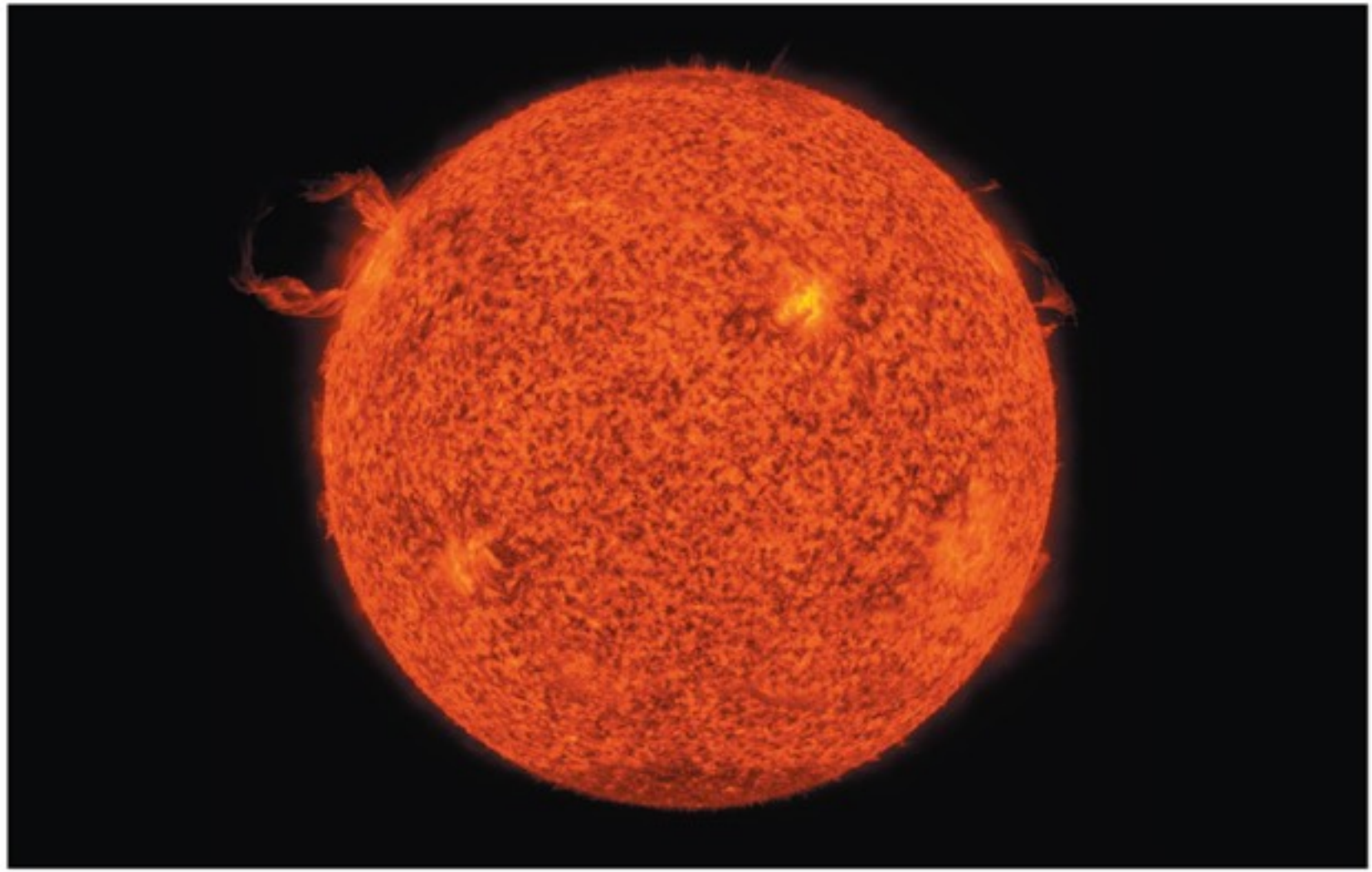
$$\frac{\text{Chemical energy content}}{\text{Luminosity}} \sim 10{,}000 \text{ years}$$



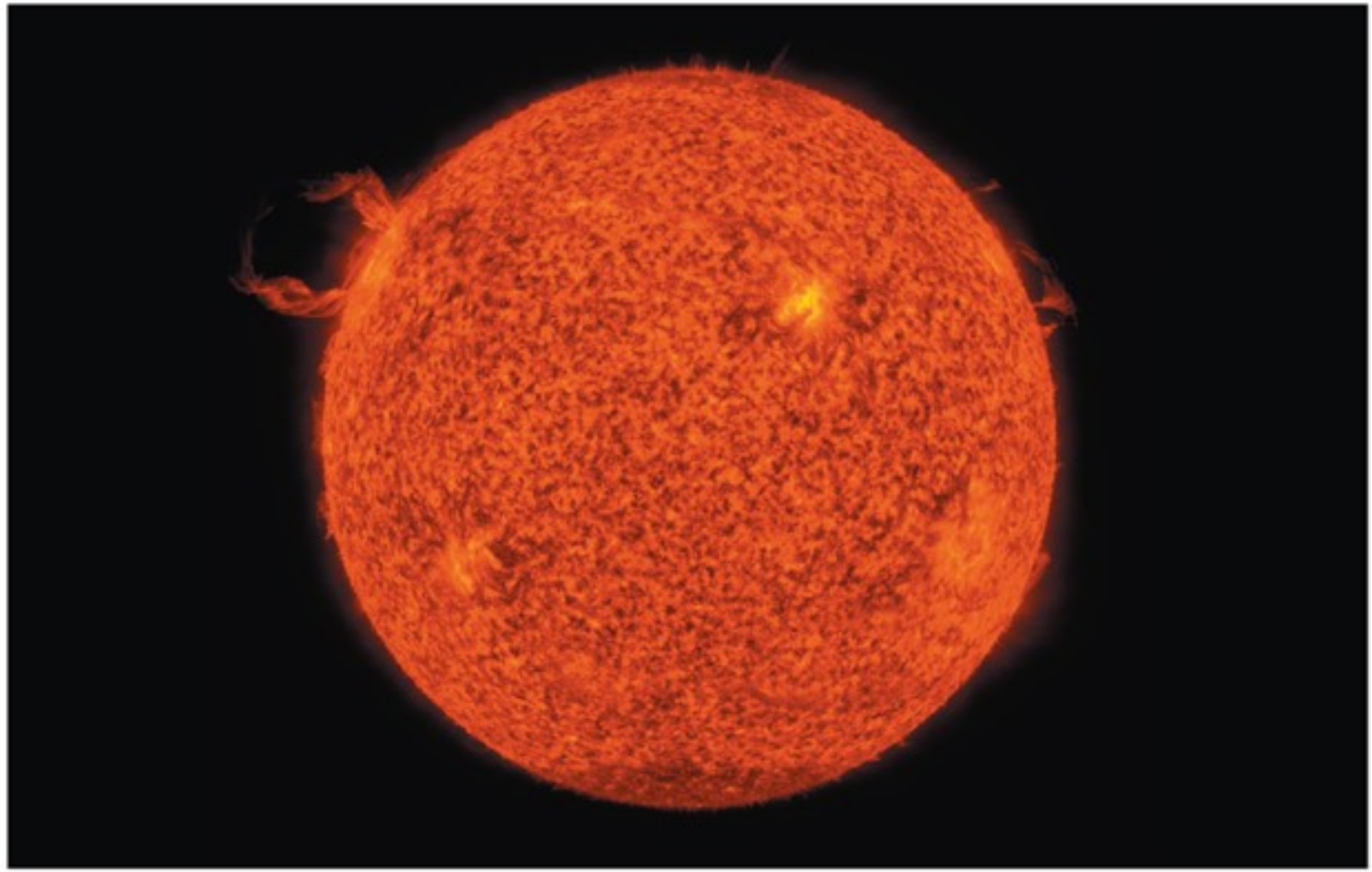
Is it on FIRE? … NO!

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

$$\text{Rate of Energy Use} \triangleright$$

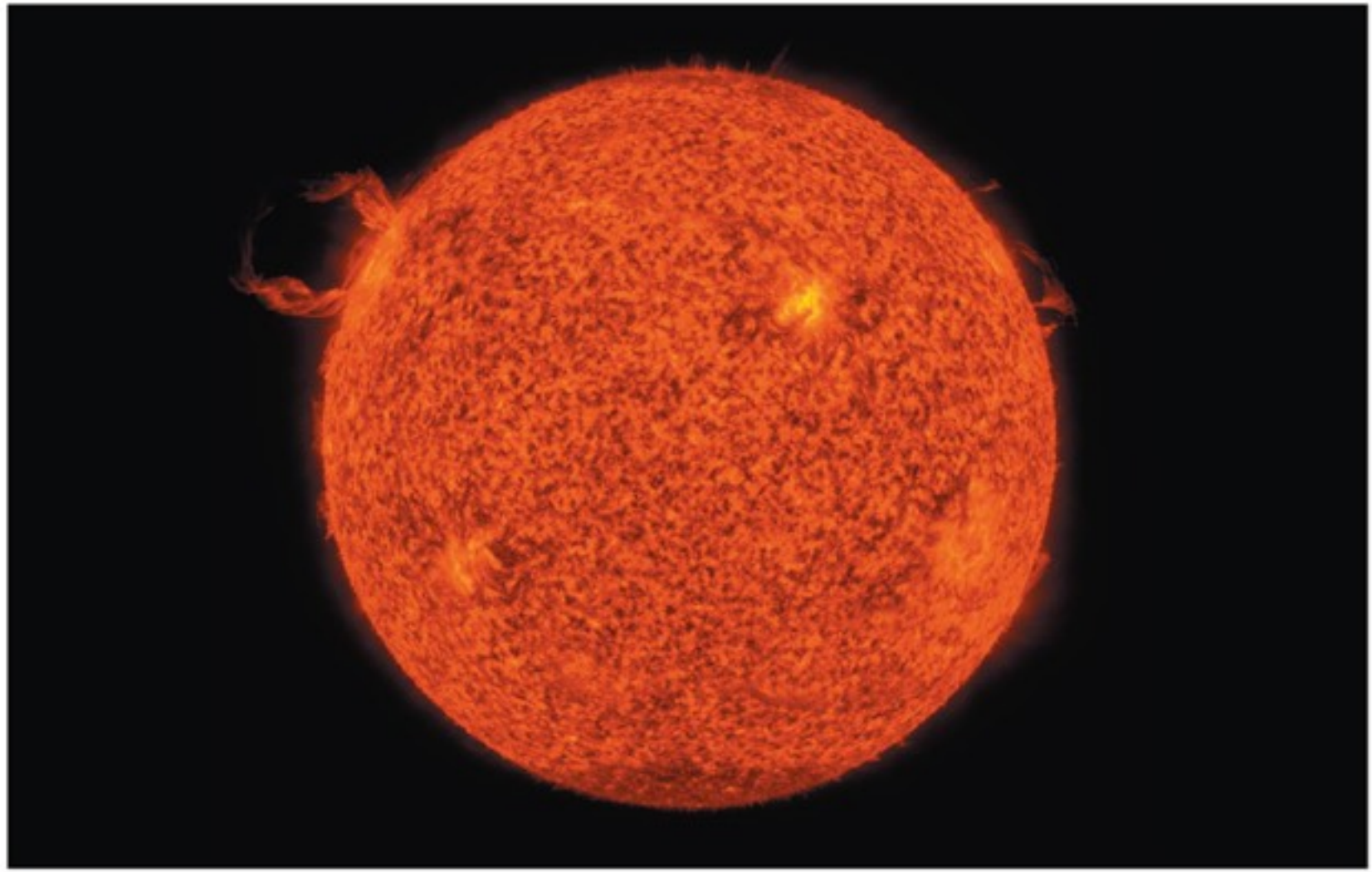


Is it CONTRACTING?



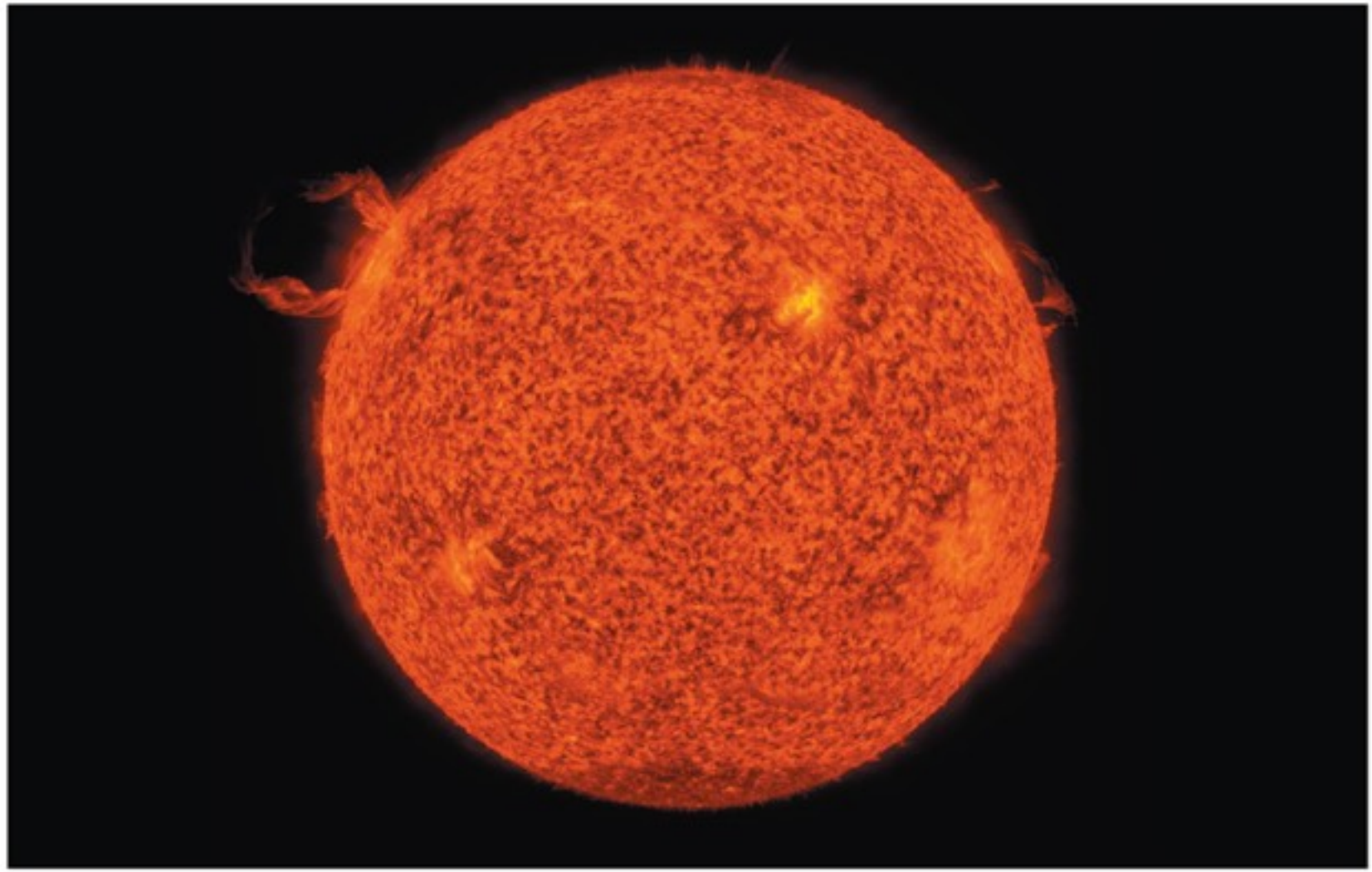
Is it CONTRACTING?

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



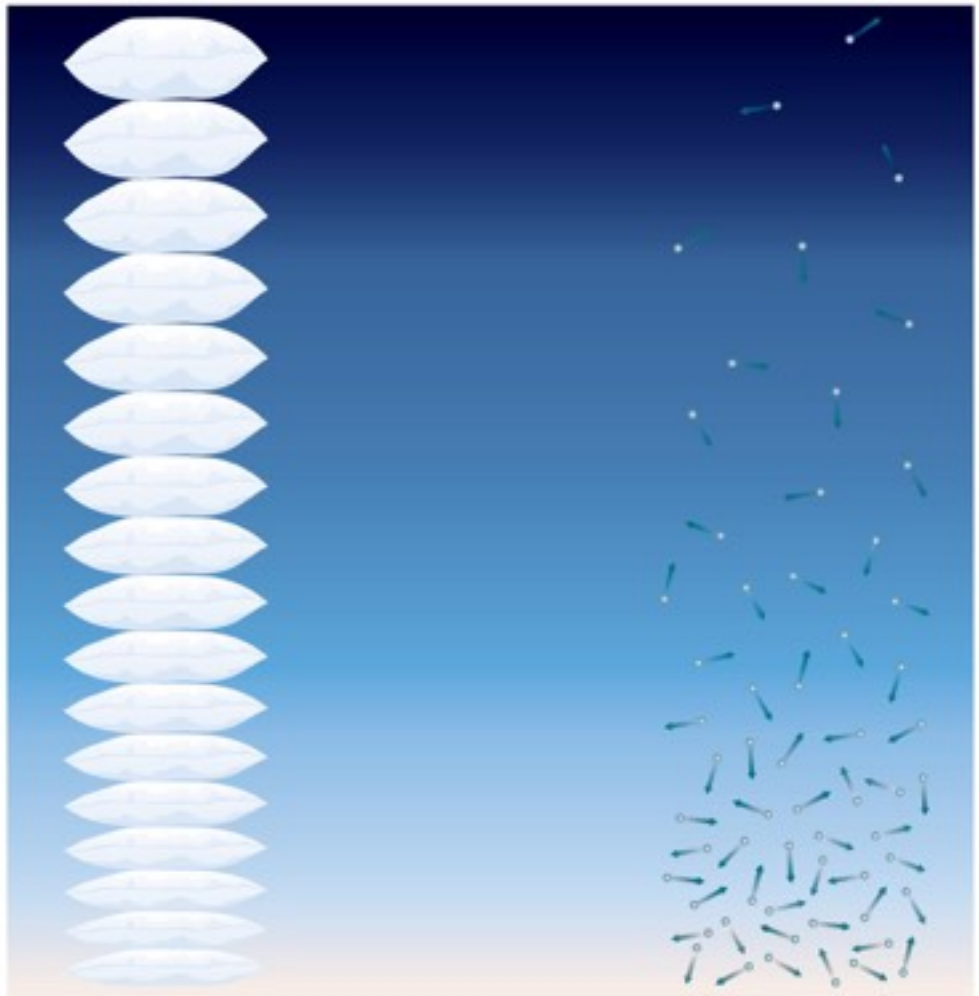
Is it CONTRACTING? … NO!

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

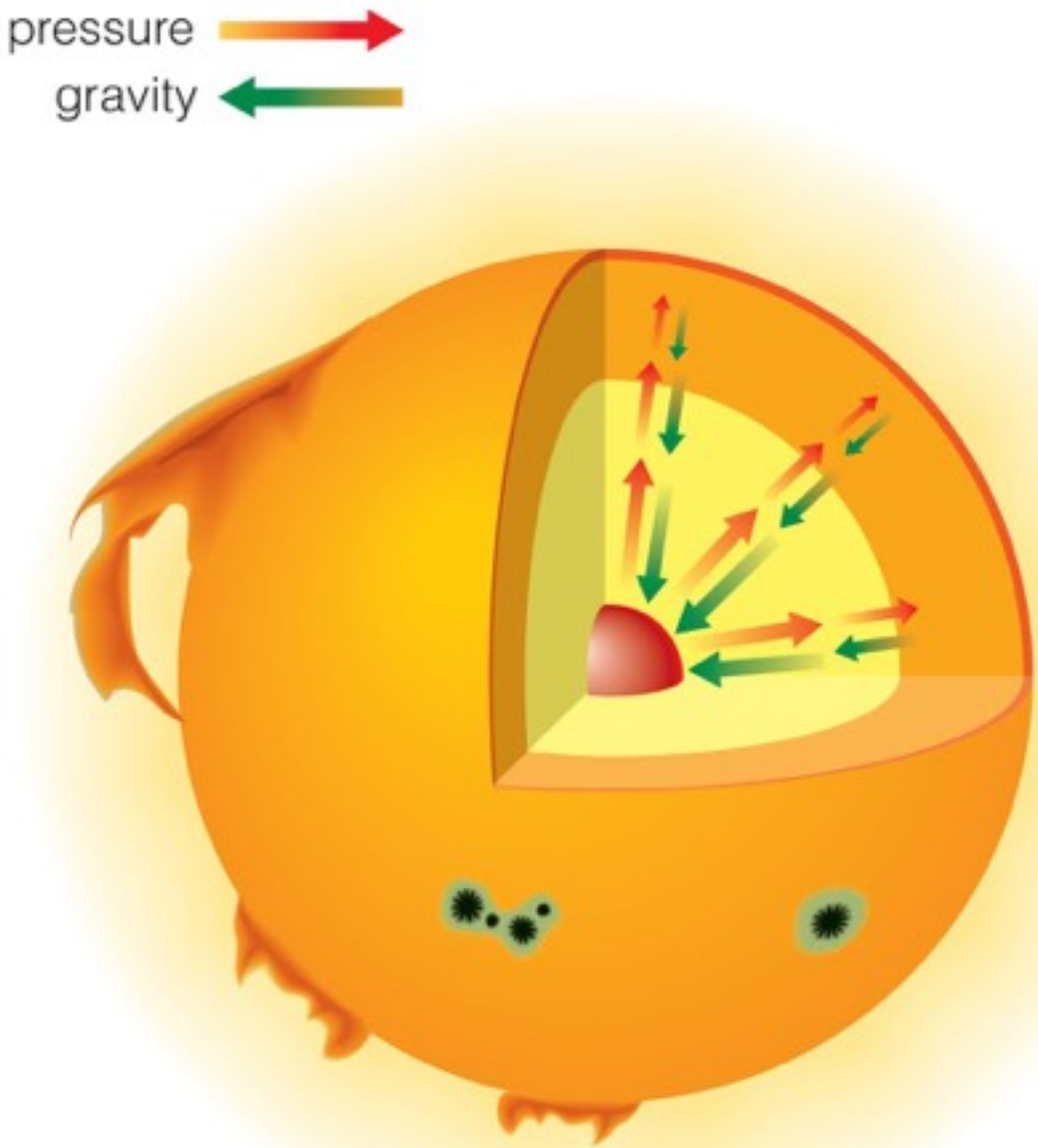


It can be powered by NUCLEAR ENERGY! ($E = mc^2$)

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



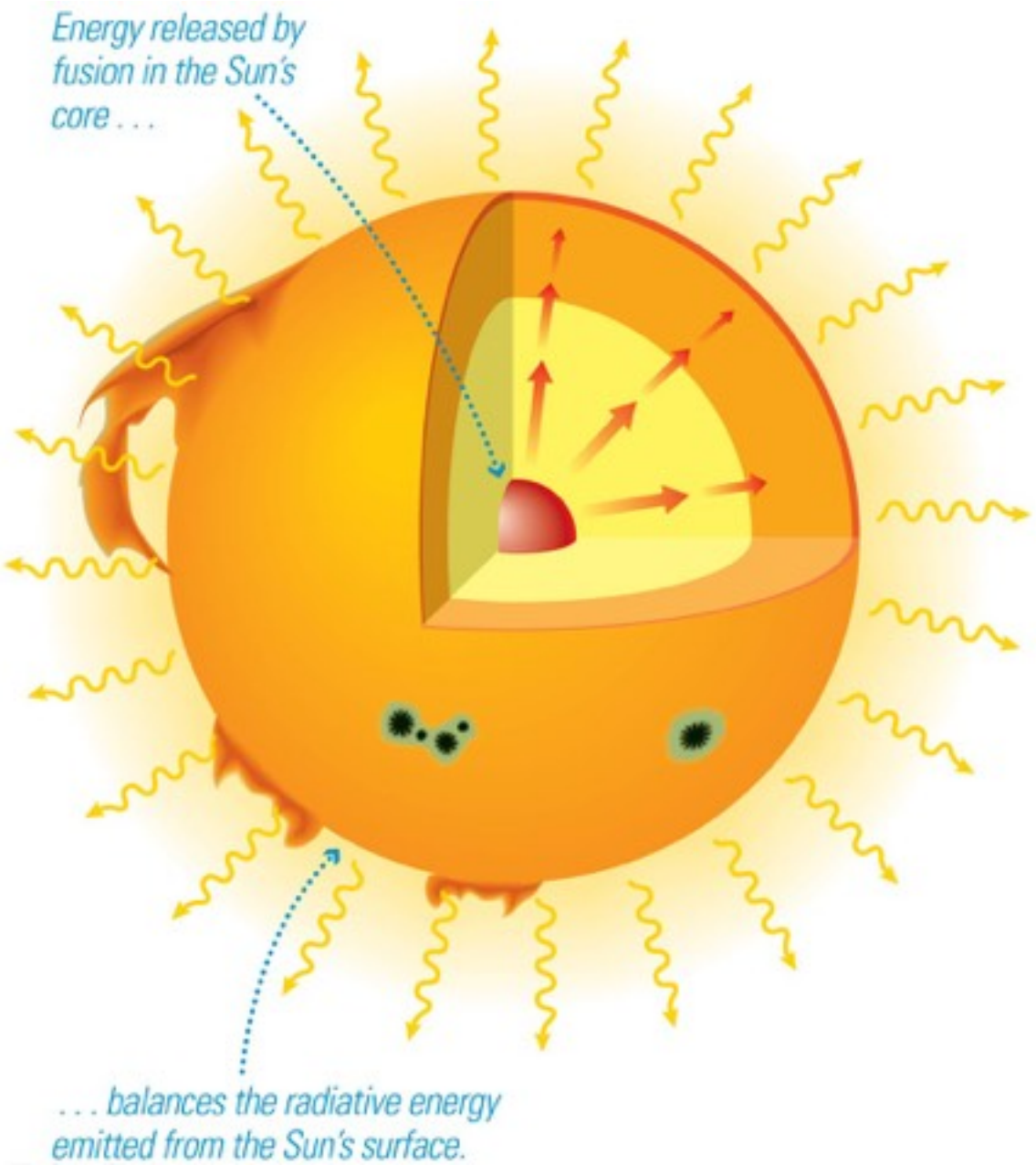
- Weight of upper layers compresses lower layers.



Stars are stable: pressure balances gravity.

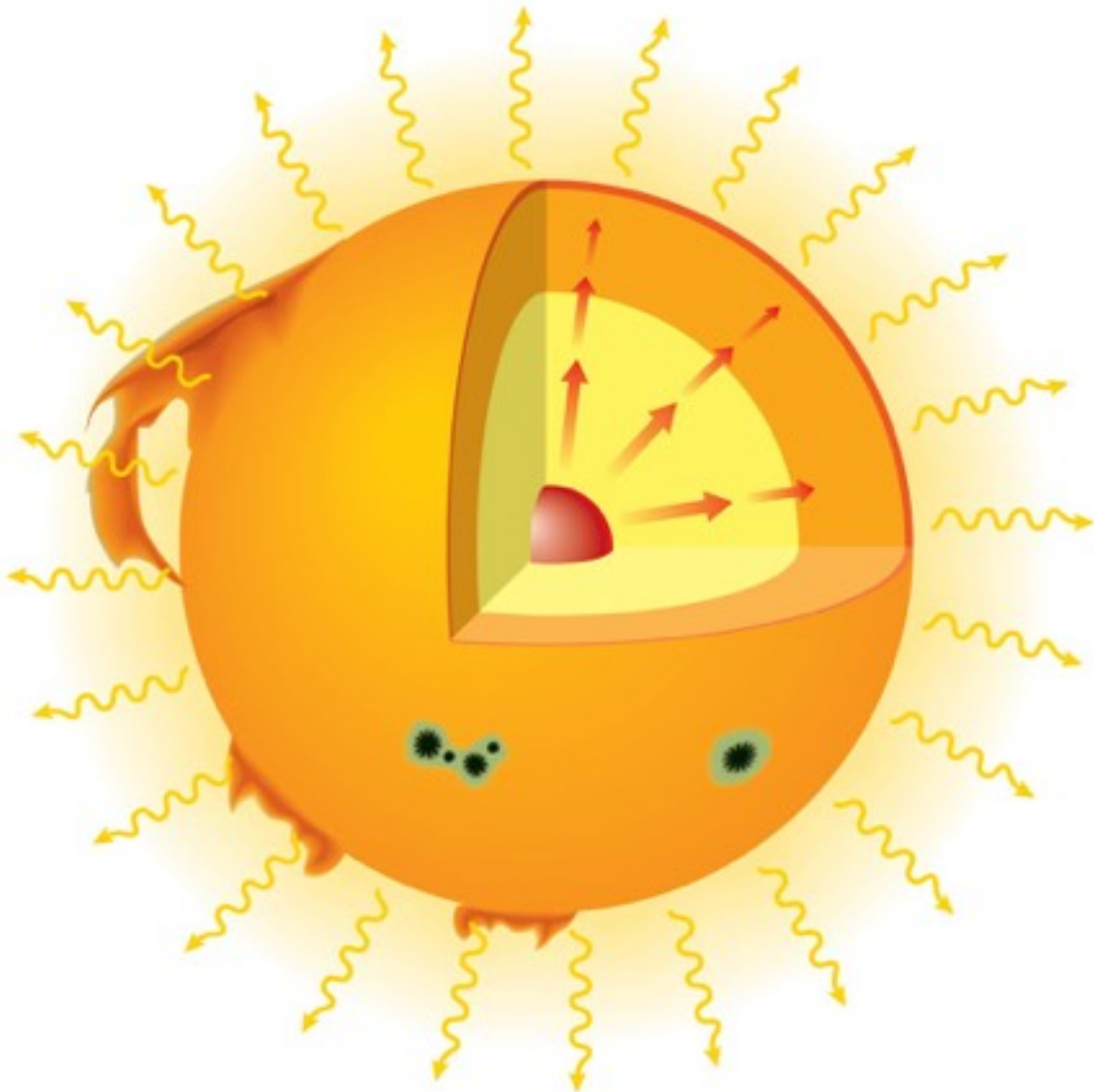
Hydrostatic equilibrium:

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



Energy Balance:

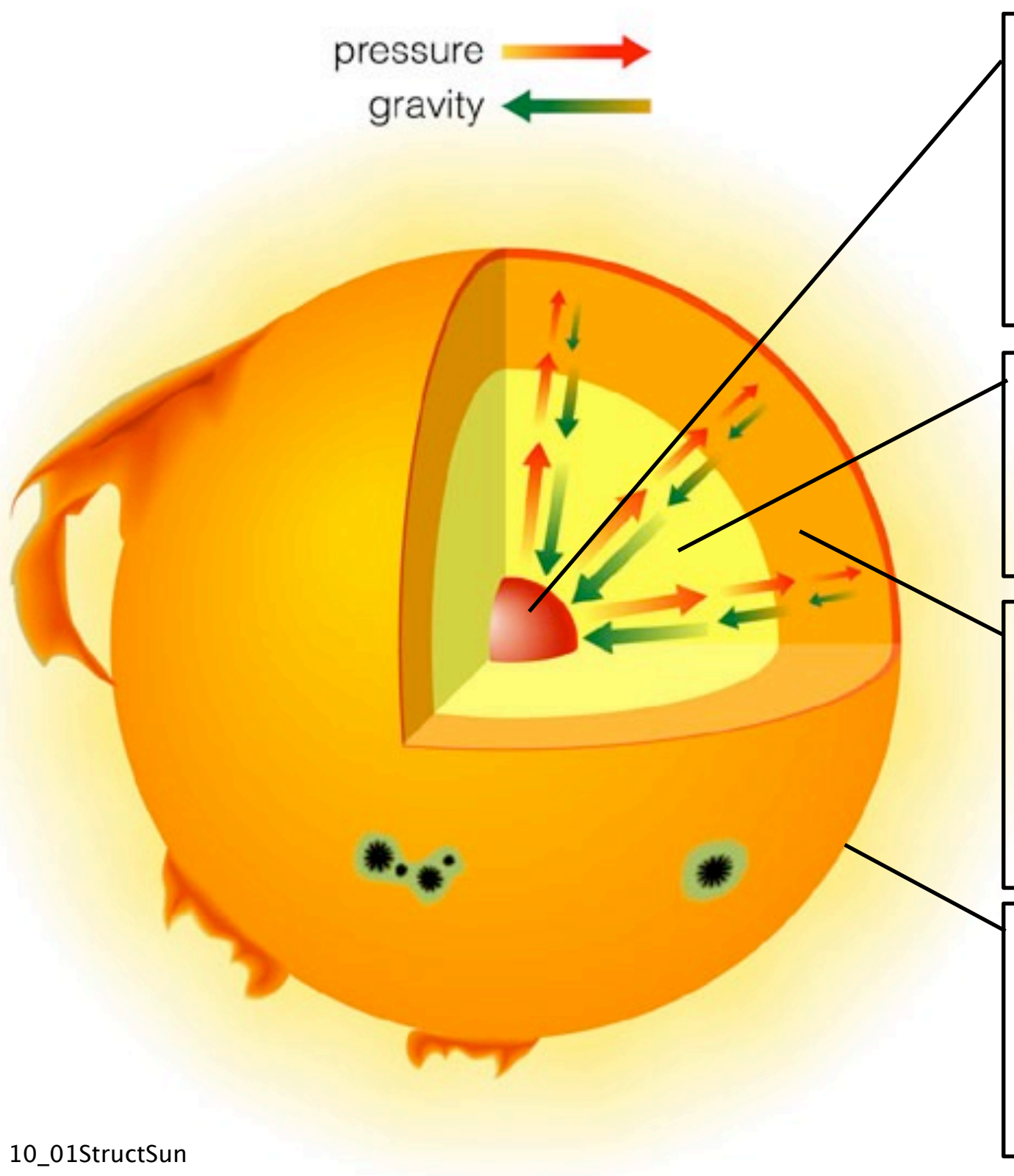
- The rate at which energy radiates from the surface of the Sun must be the same as the rate at which it is released by fusion in the core.



initial gravitational contraction:

- Provided the energy that heated the core as Sun was forming

- Contraction stopped when fusion began.



Core:

Energy generated by nuclear fusion

~ 15 million K

Radiation zone:

Energy transported upward by photons

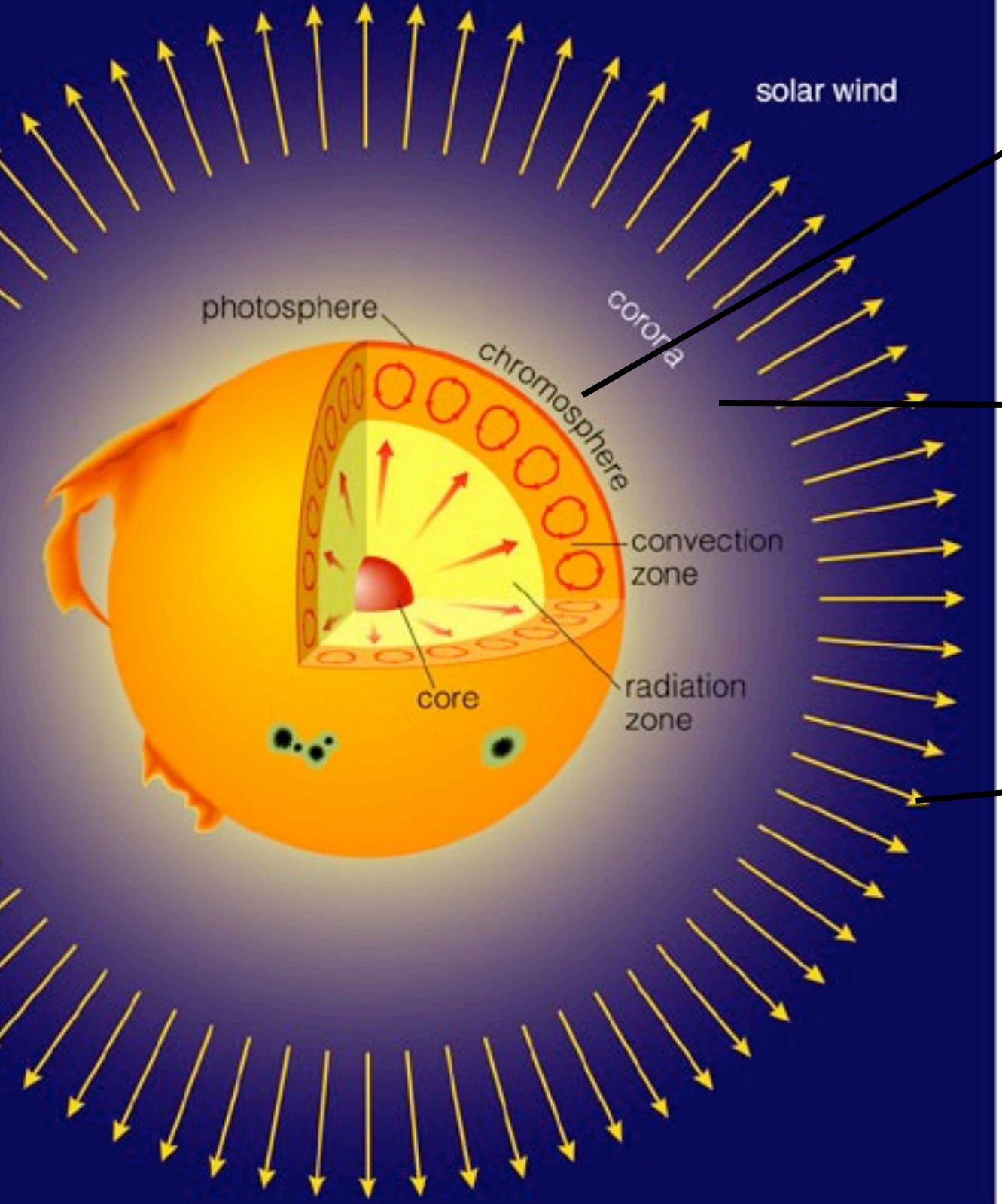
Convection zone:

Energy transported upward by rising hot gas

Photosphere:

Visible surface

~5,800 K



Chromosphere:

Middle layer of solar atmosphere

Corona:

Outermost layer of solar atmosphere

Solar wind:

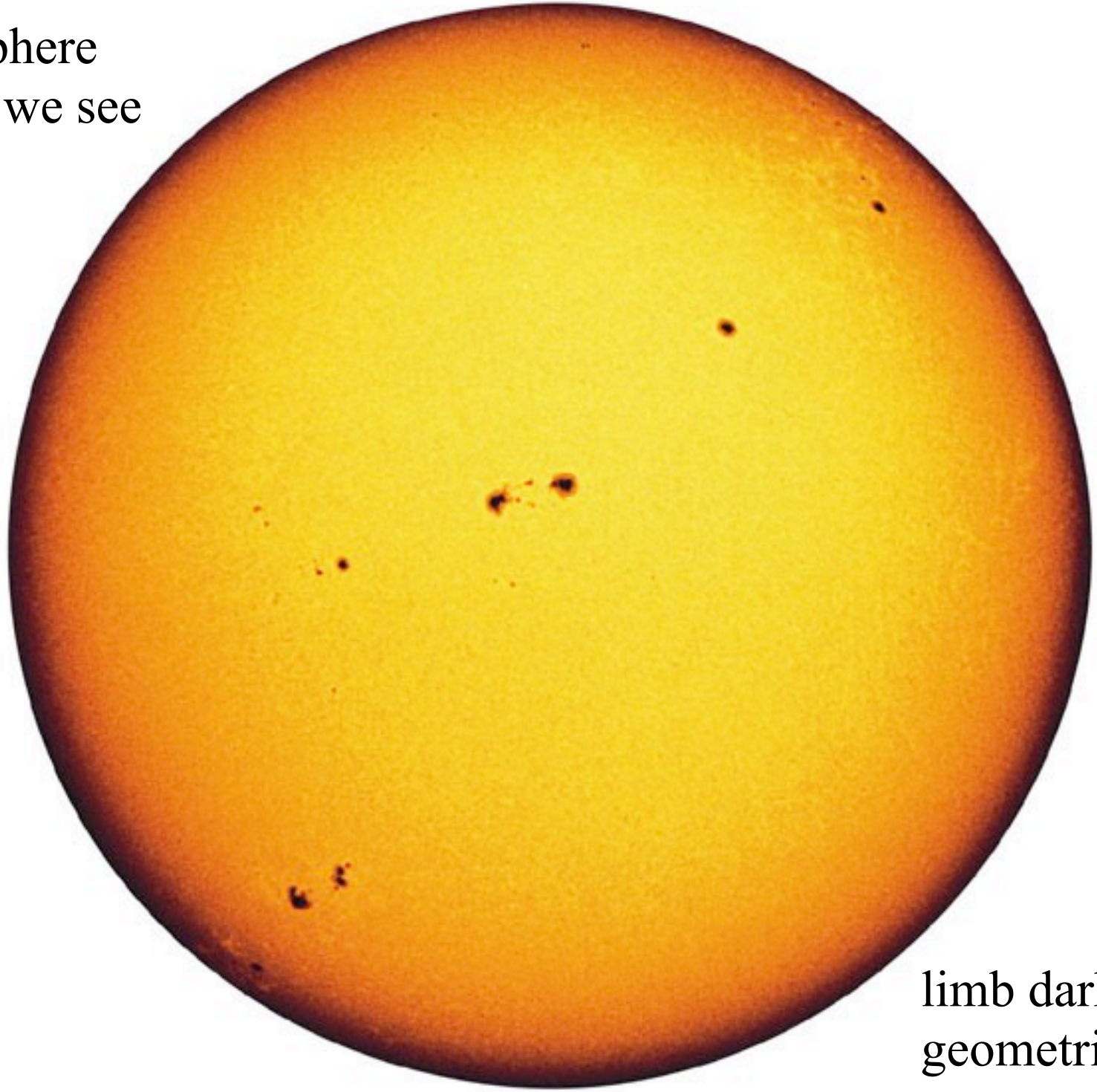
A flow of charged particles from the surface of the Sun

Little mass in these components

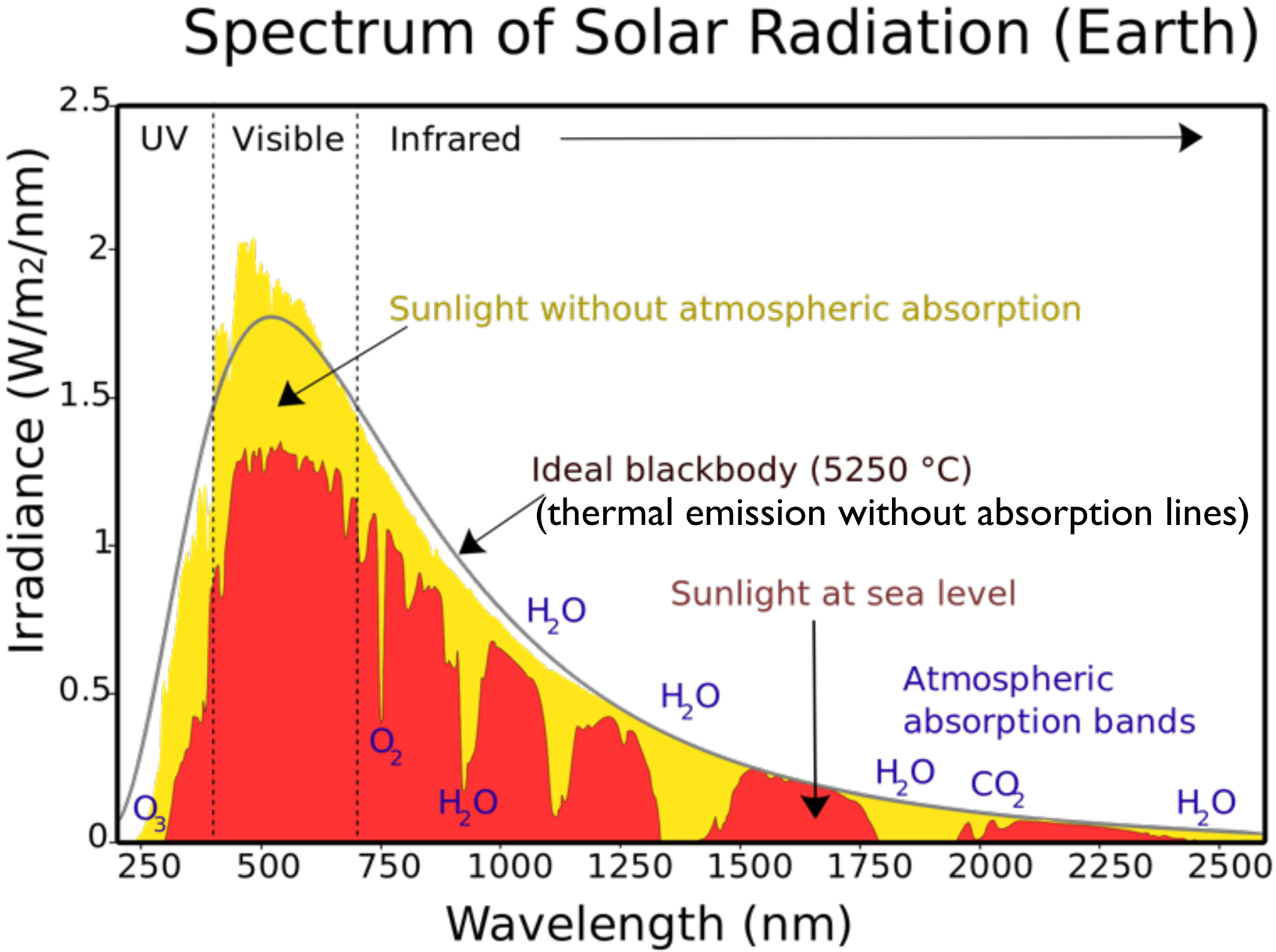
- **Why the Sun shines**
  - Chemical and gravitational energy sources could not explain how the Sun could sustain its luminosity for more than about 25 million years.
  - The Sun shines because **gravitational equilibrium** keeps its core hot and dense enough to release energy through nuclear fusion.

- **Solar structure**
  - From inside out, the layers are:
    - Core
      - Energy generation by fusion reactions
    - Radiation zone
      - Outward energy transport by photons
    - Convection zone
      - Outward energy transport by gas motions
    - Photosphere
      - Luminous surface (energy emitted to space)
        - » absorption spectrum
    - Chromosphere
      - low density upper atmosphere
        - » emission spectrum, but much fainter than photosphere
    - Corona
      - very hot, low density plasma tailing off into space

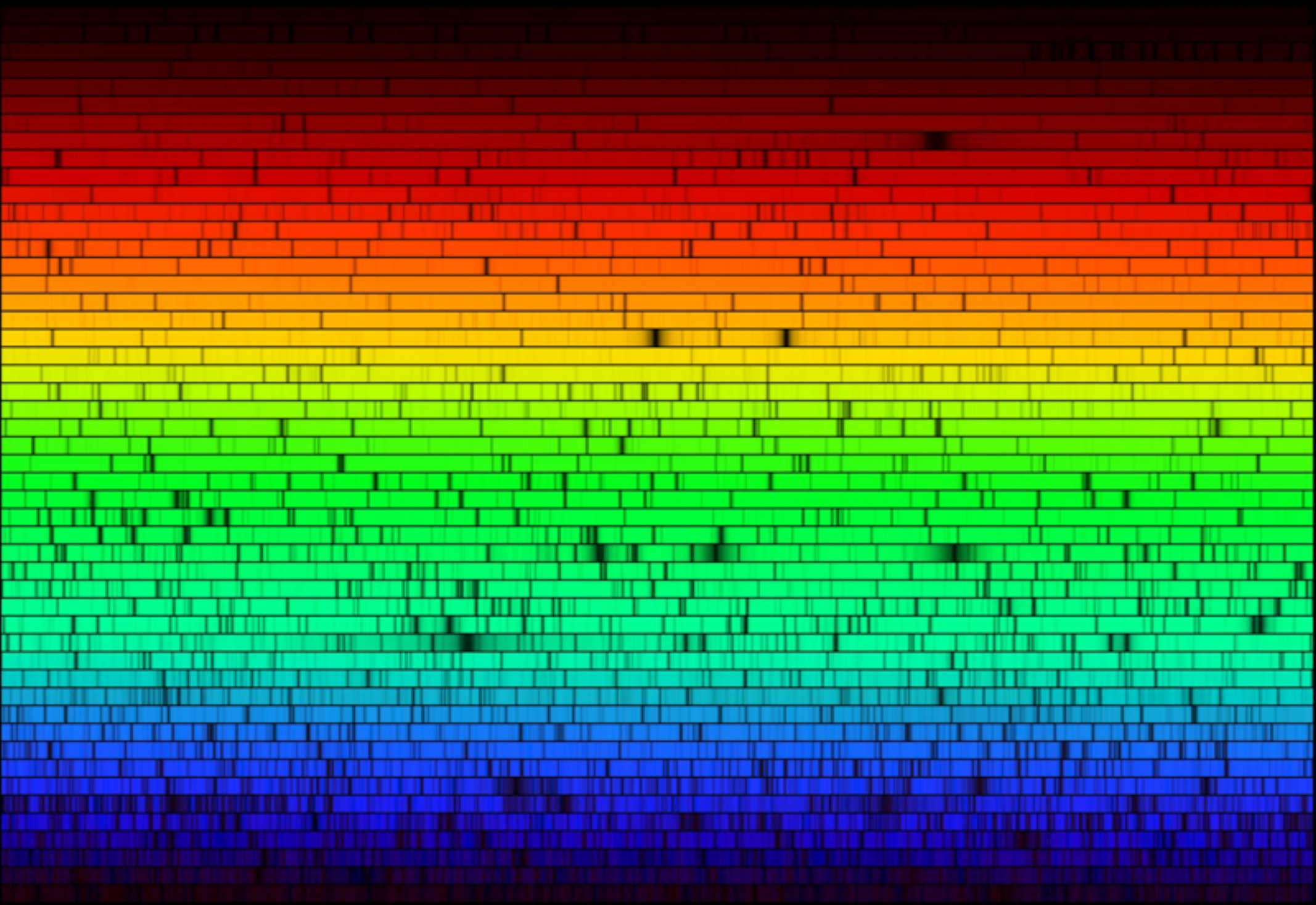
Photosphere
is what we see



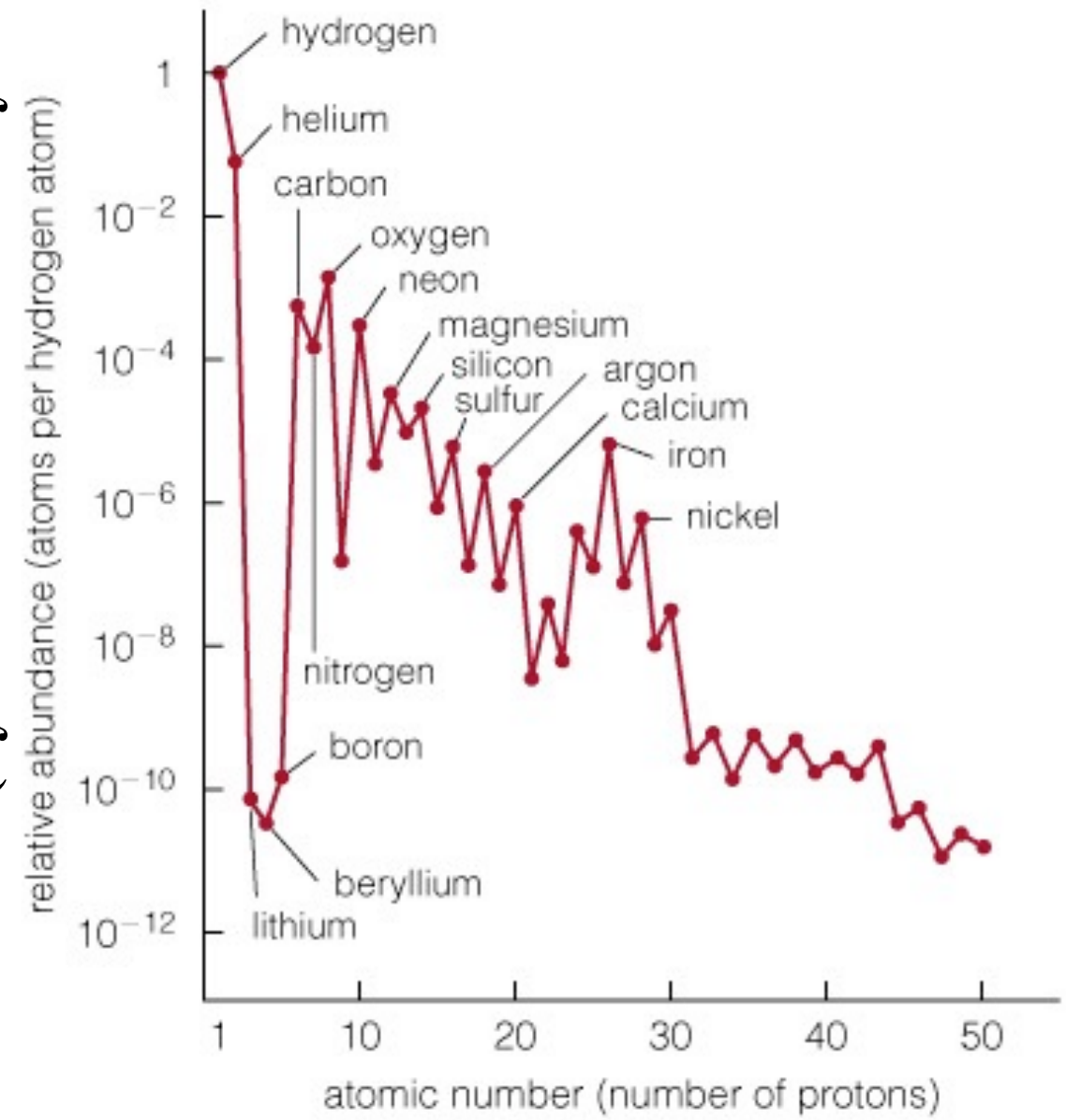
limb darkening is a
geometric effect


Spectrum of Solar Radiation (Earth)
UV
Visible
Infrared
Sunlight without atmospheric absorption
Ideal blackbody (5250 °C)
(thermal emission without absorption lines)
Sunlight at sea level
Atmospheric absorption bands
O_3
O_2
H_2O
H_2O
H_2O
H_2O
CO_2
H_2O
Irradiance (W/m2/nm)
Wavelength (nm)
2.5
2
1.5
1
0.5
0
250
500
750
1000
1250
1500
1750
2000
2250
2500

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

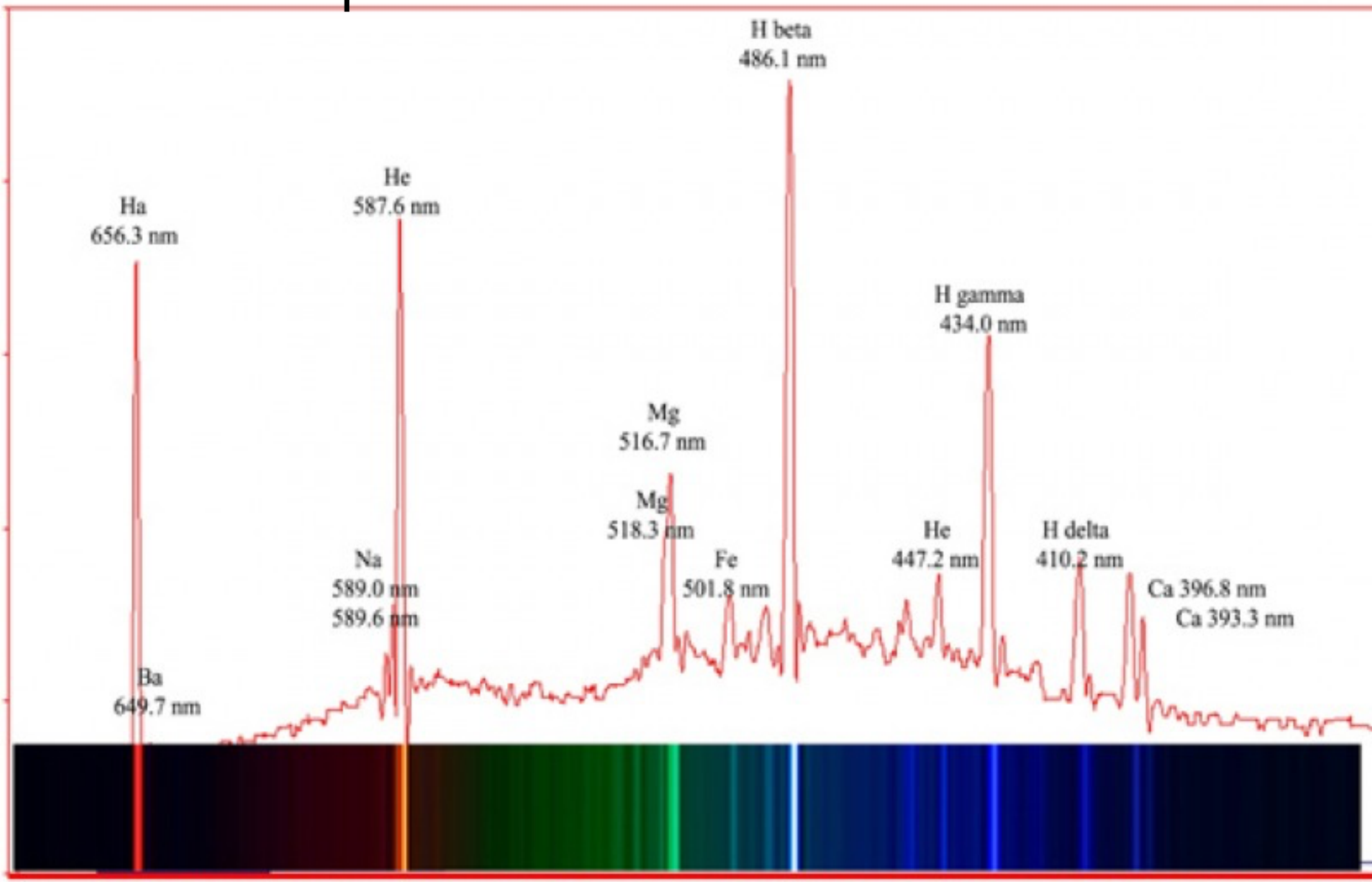
This is typical of the universe; Earth is an exception.

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

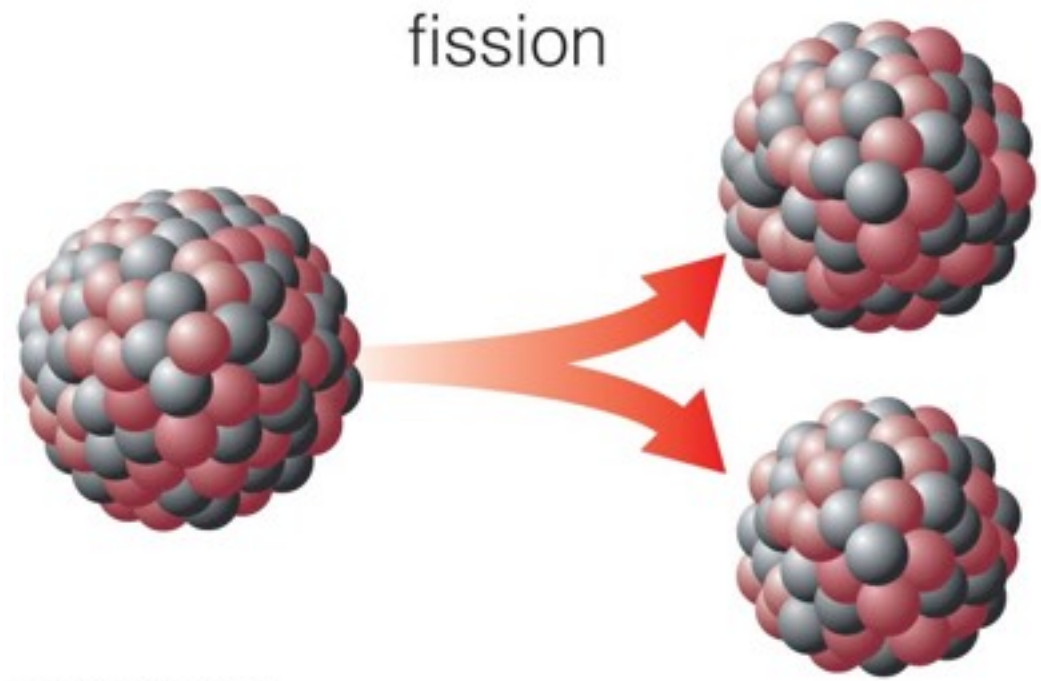

solar corona
only visible during eclipse - greatly outshown by photosphere normally
solar chromosphere
seen in Hα emission

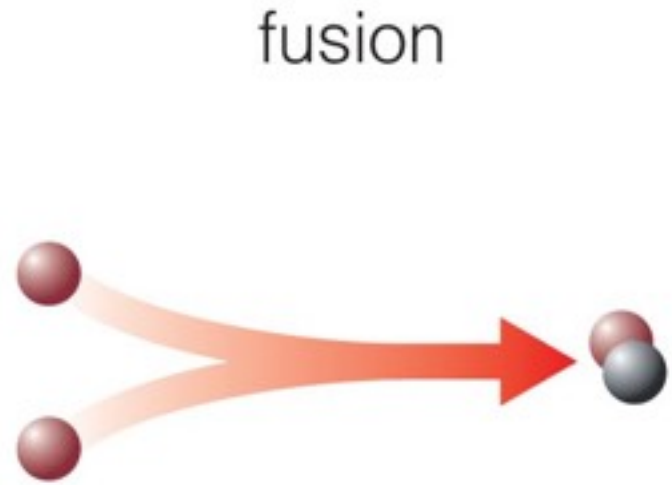
he Solar Chromosphere Spectrum (Flash Spectrum

emission line spectrum



Nuclear fusion powers the Sun





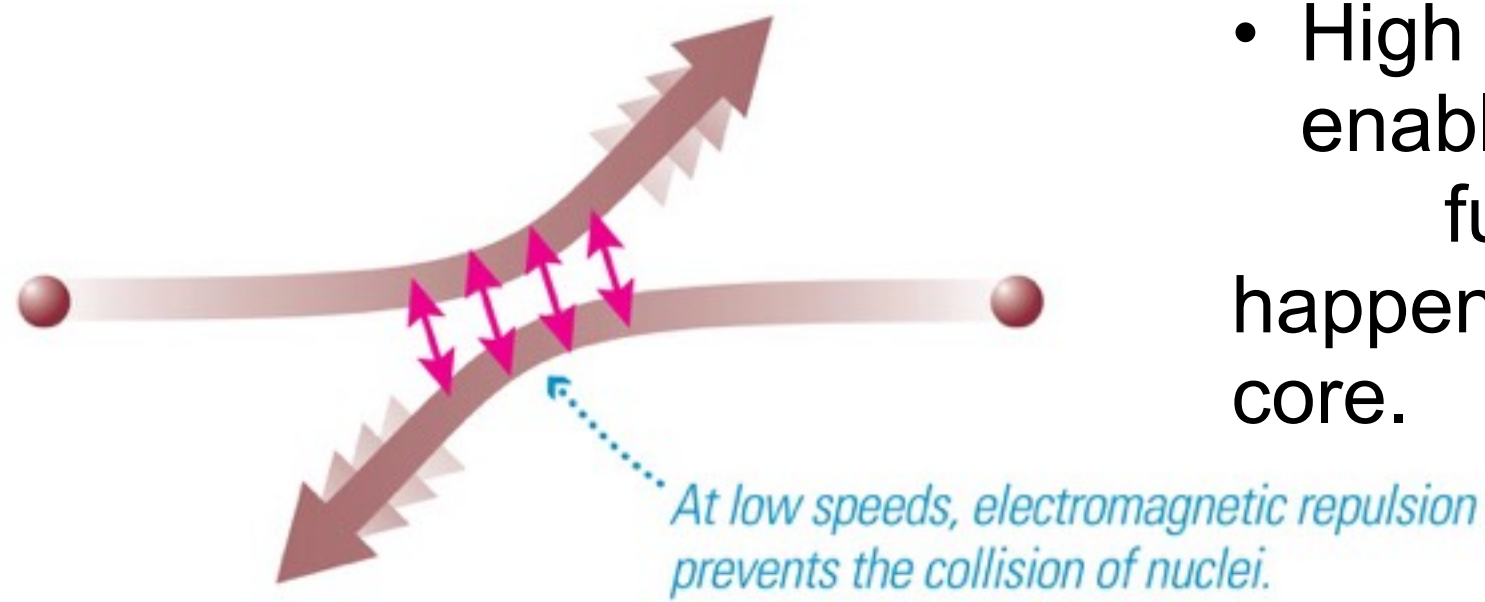
Fission

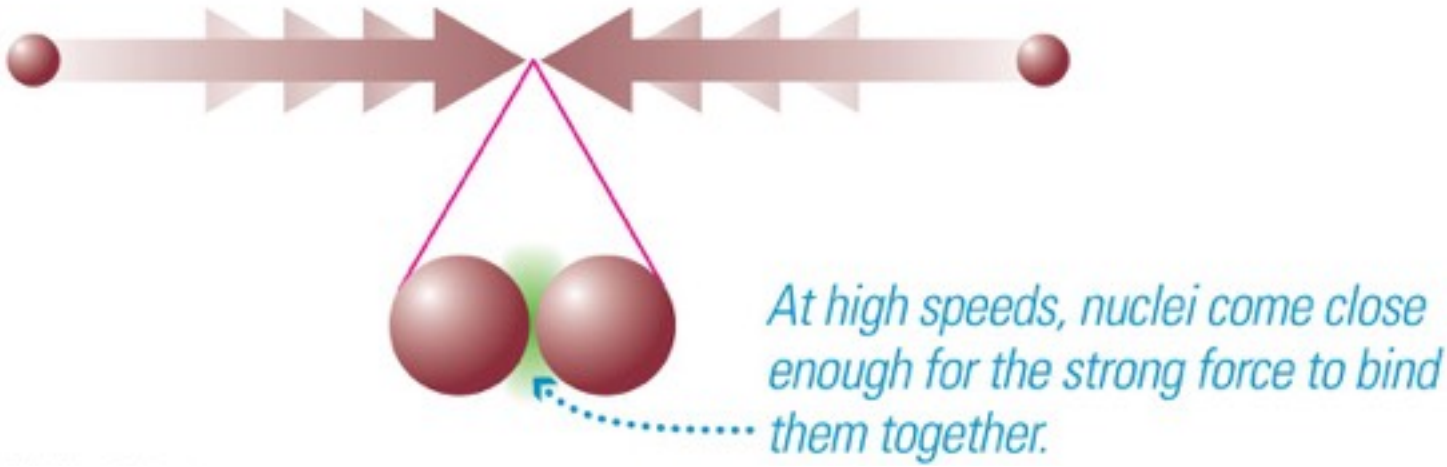
- Big nucleus splits into smaller pieces.
- (Example: nuclear power plants)

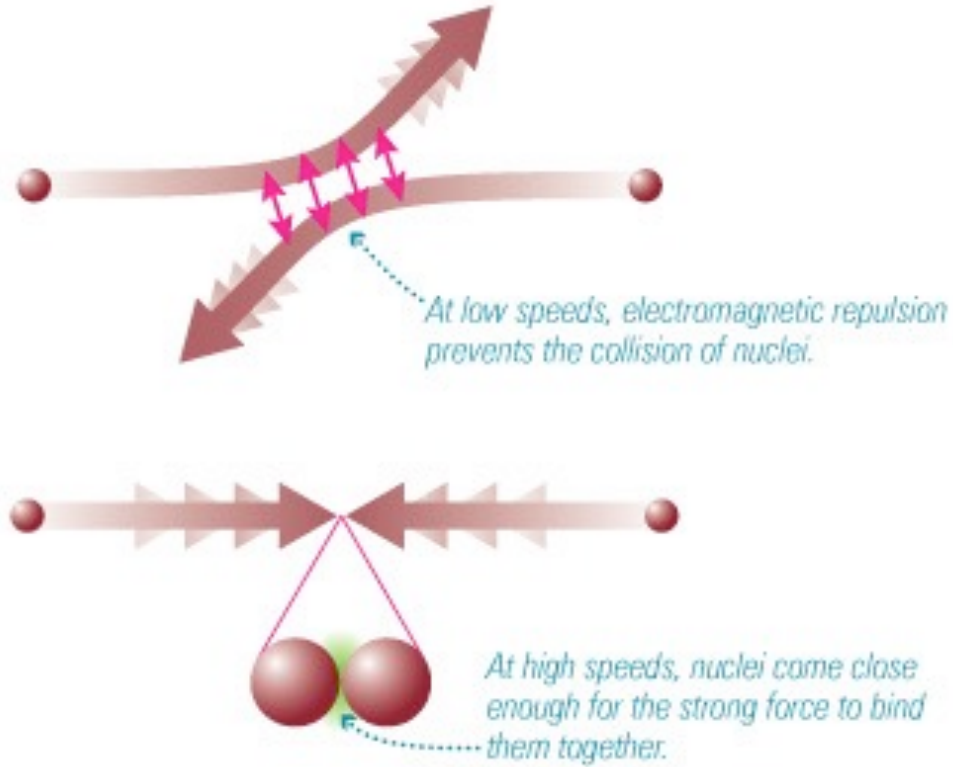
Fusion

- Small nuclei stick together to make a bigger one.
- (Example: the Sun, stars)

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







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.

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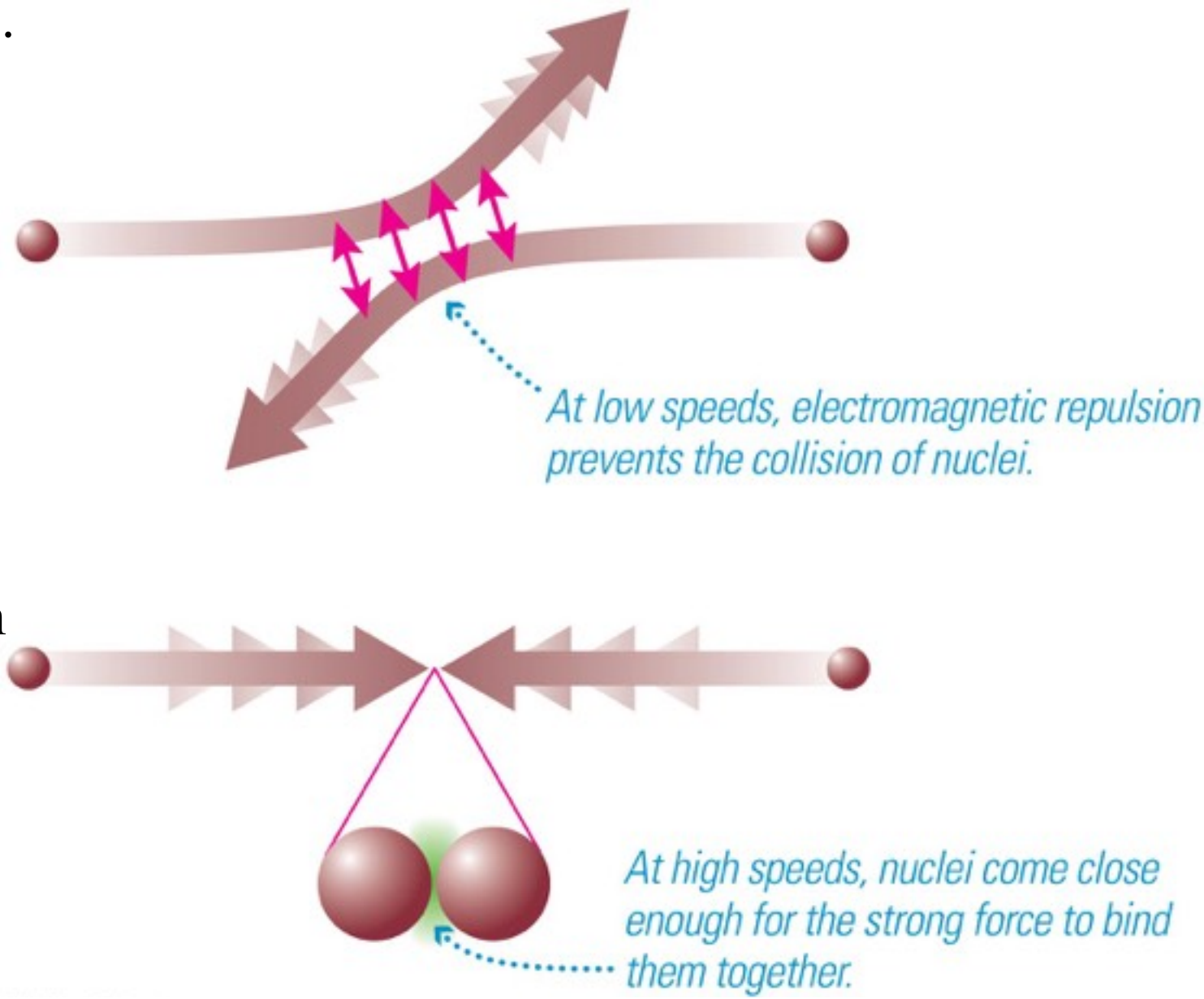
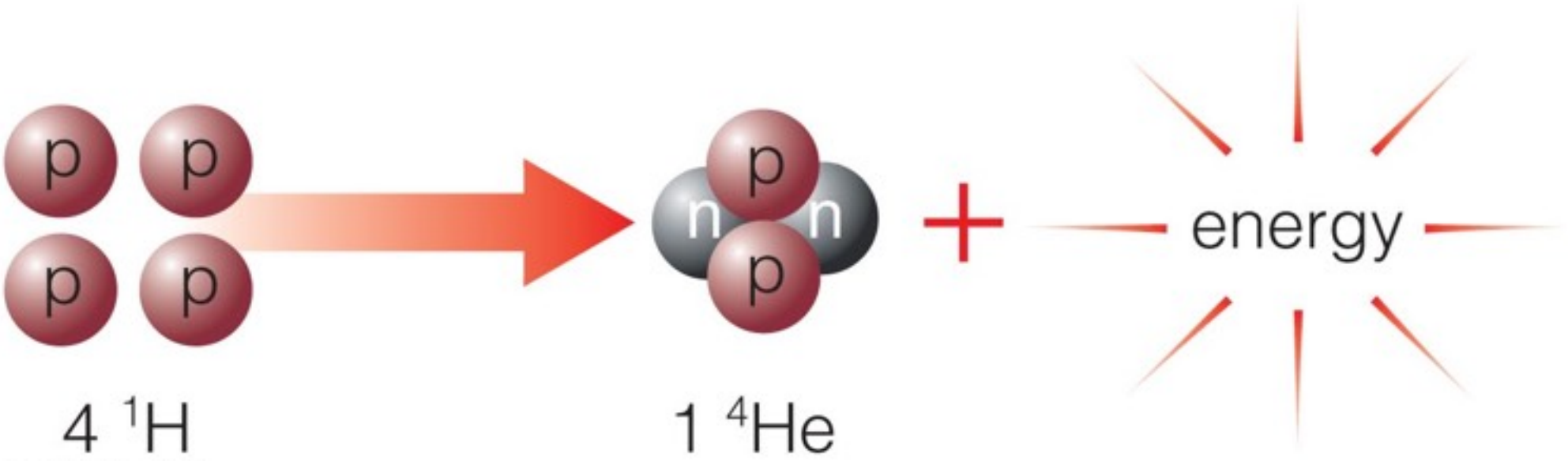
Fusion only happens when the strong nuclear force is stronger than this repulsion, which only happens at very small separations. High temperatures are required to move fast enough to get that close.



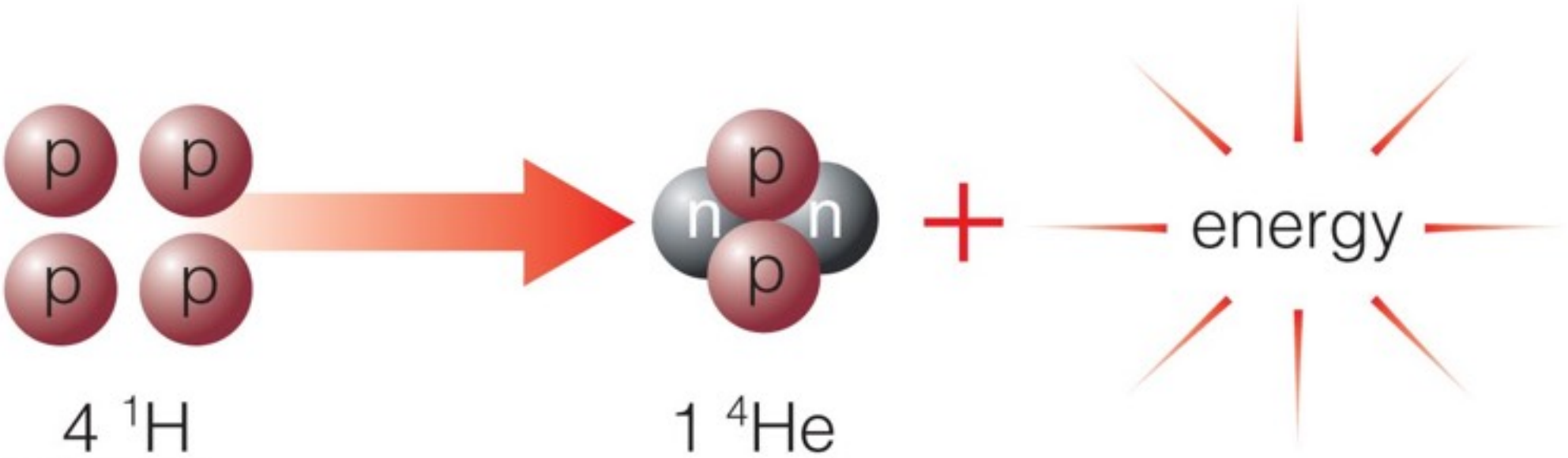
Four fundamental forces

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



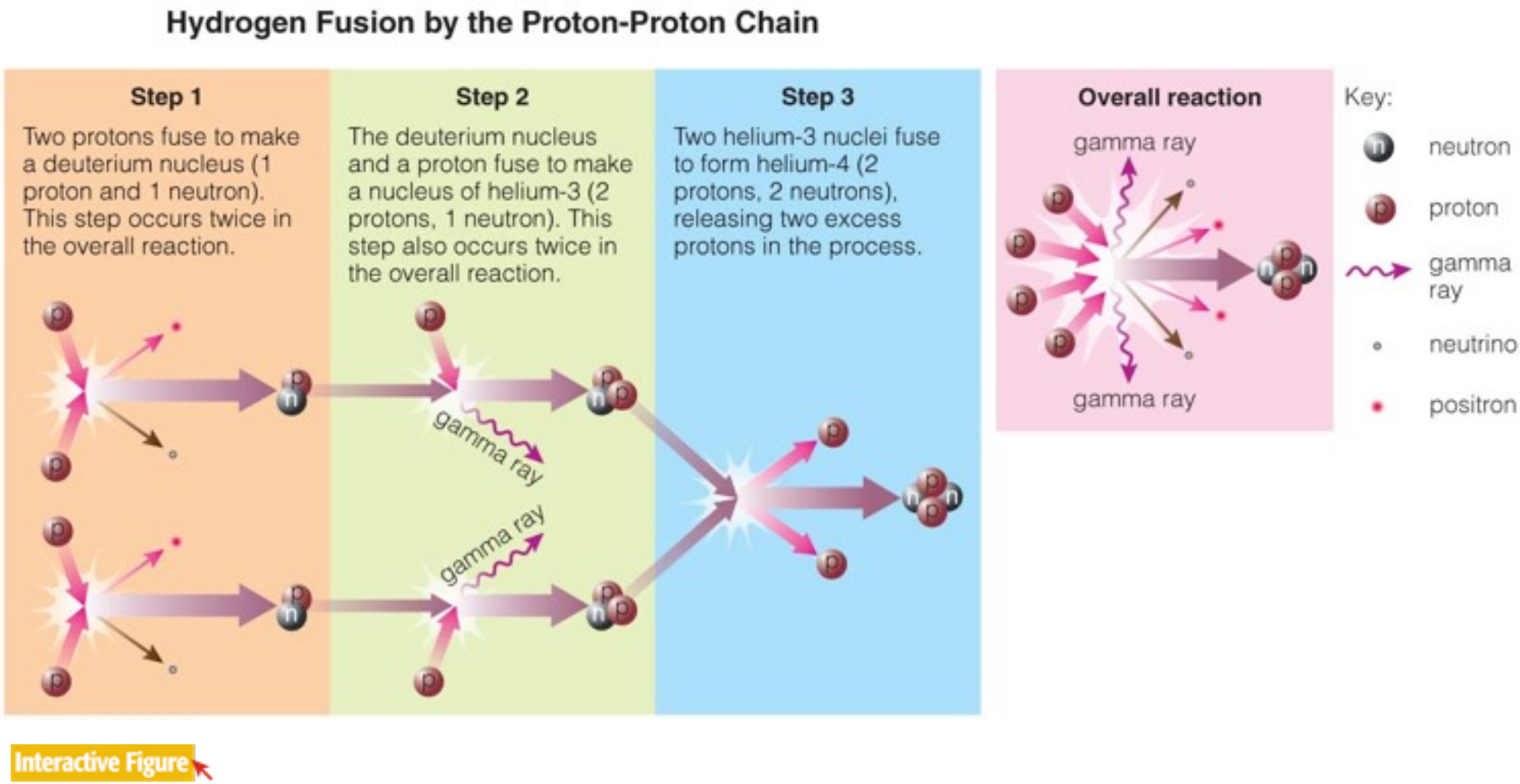
- The Sun releases energy by fusing four hydrogen nuclei into one helium nucleus.

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



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.

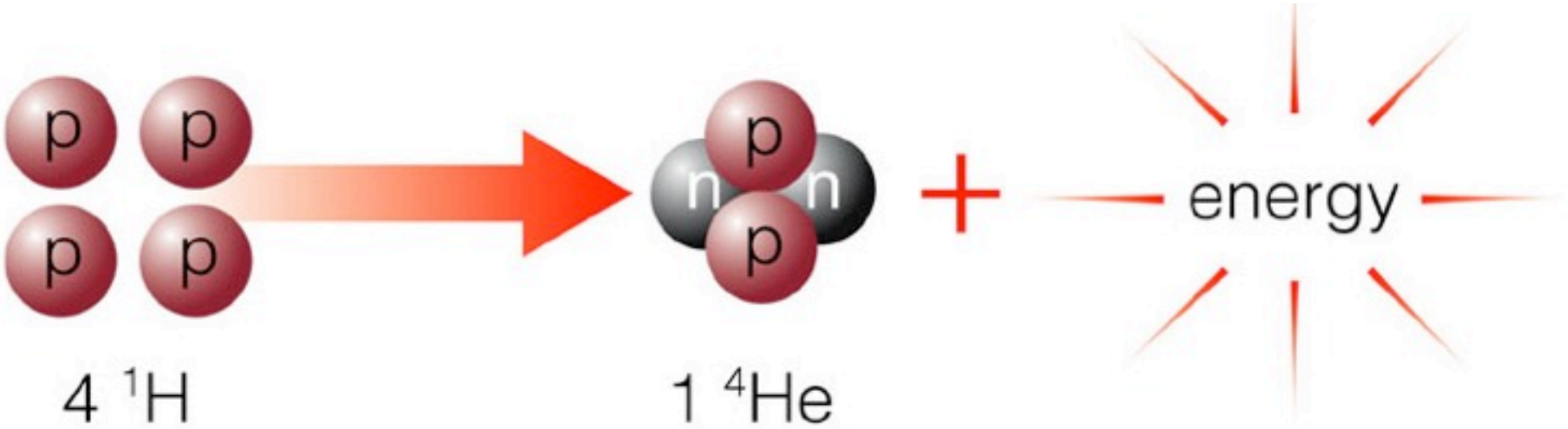


- The **proton–proton chain** is how hydrogen fuses into helium in Sun.

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

- step 1: p + p makes D (deuterium)
- step 2: D + 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.

The first step is the hardest -
on average, takes 10,000,000 years to occur in the sun.



Net Result:

IN

4 protons

OUT

^{4}He nucleus

2 gamma rays

2 positrons

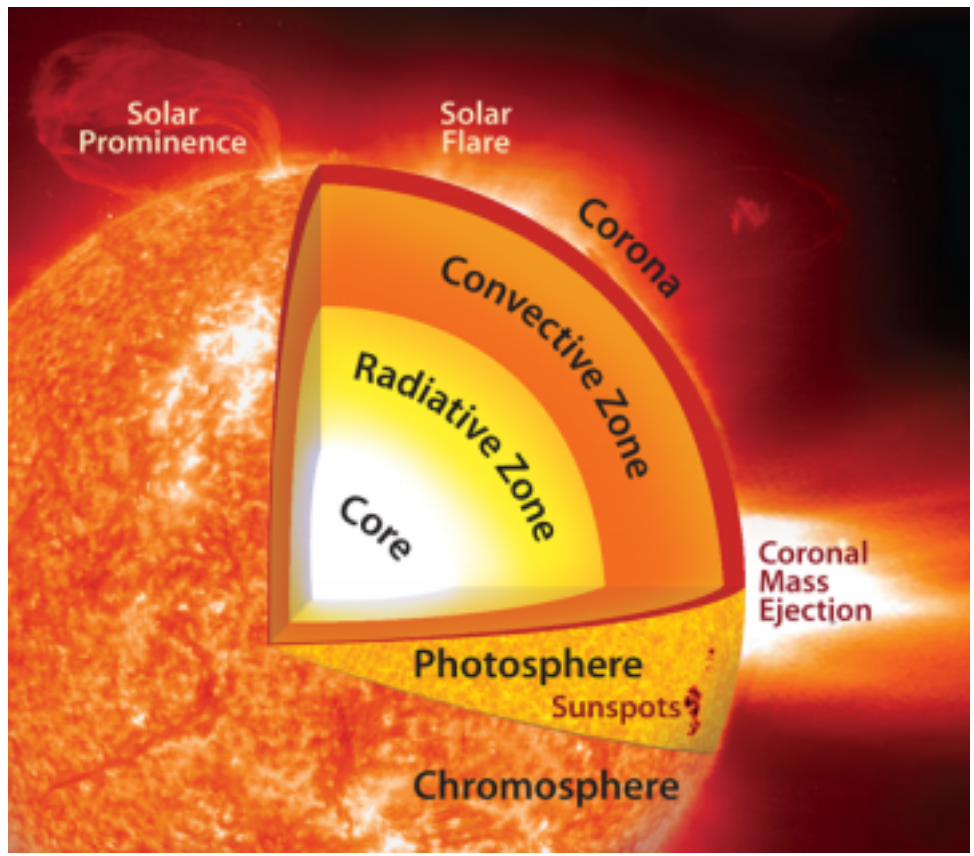
2 neutrinos

$E = mc^2$:

Total mass is 0.7% lower.

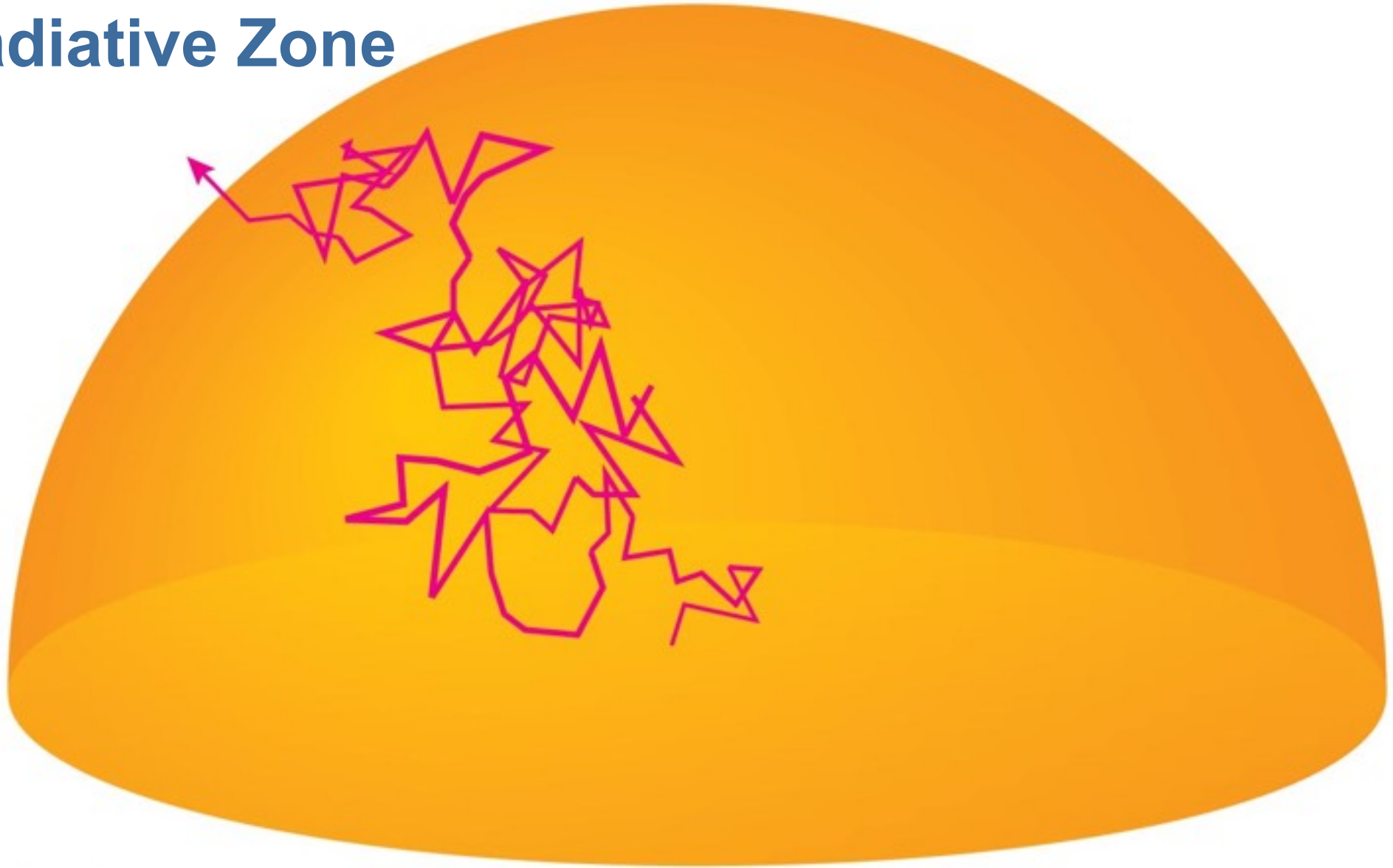
Energy transport through the Sun

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



Energy transport through the Sun

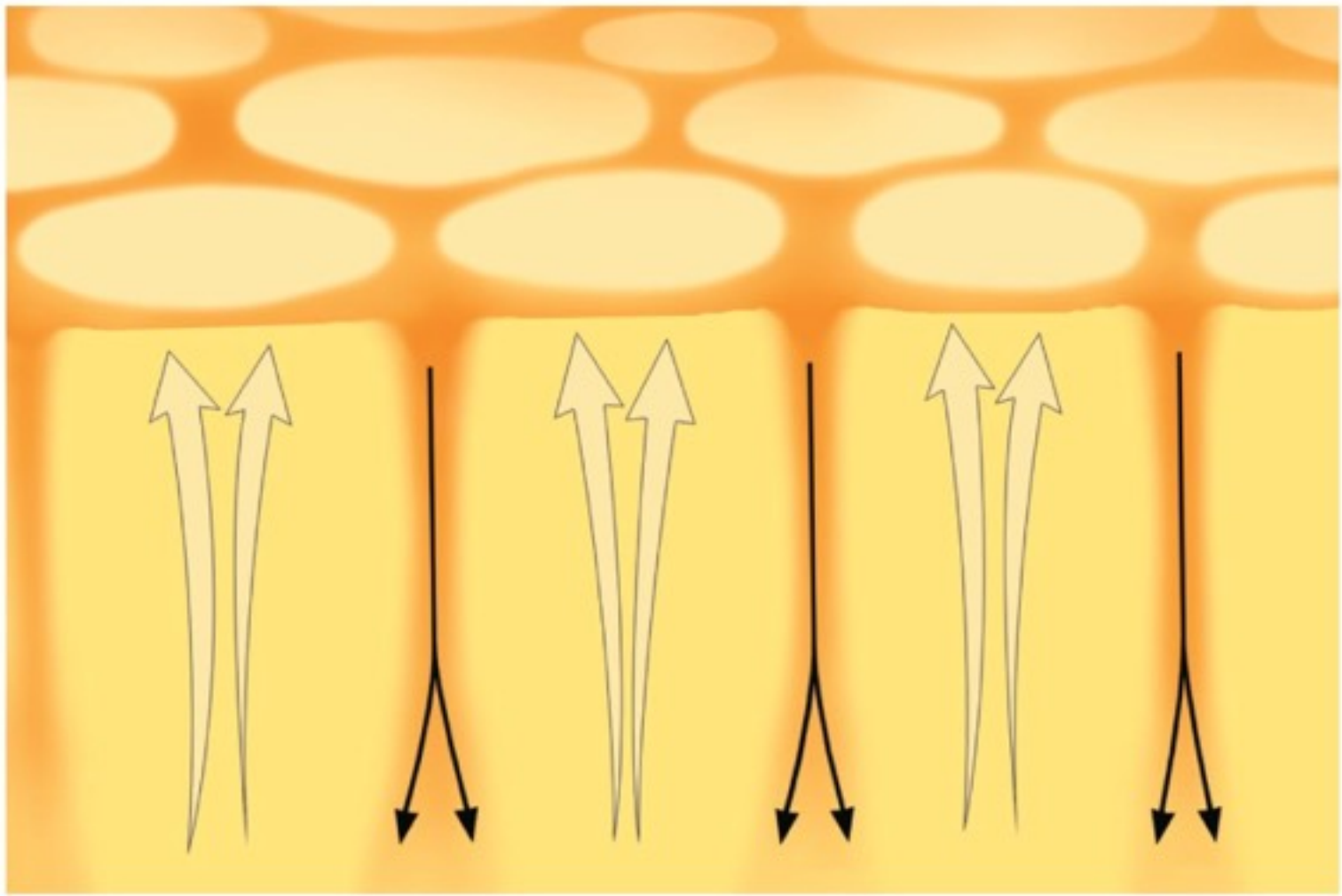
Radiative Zone



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

Energy transport through the Sun

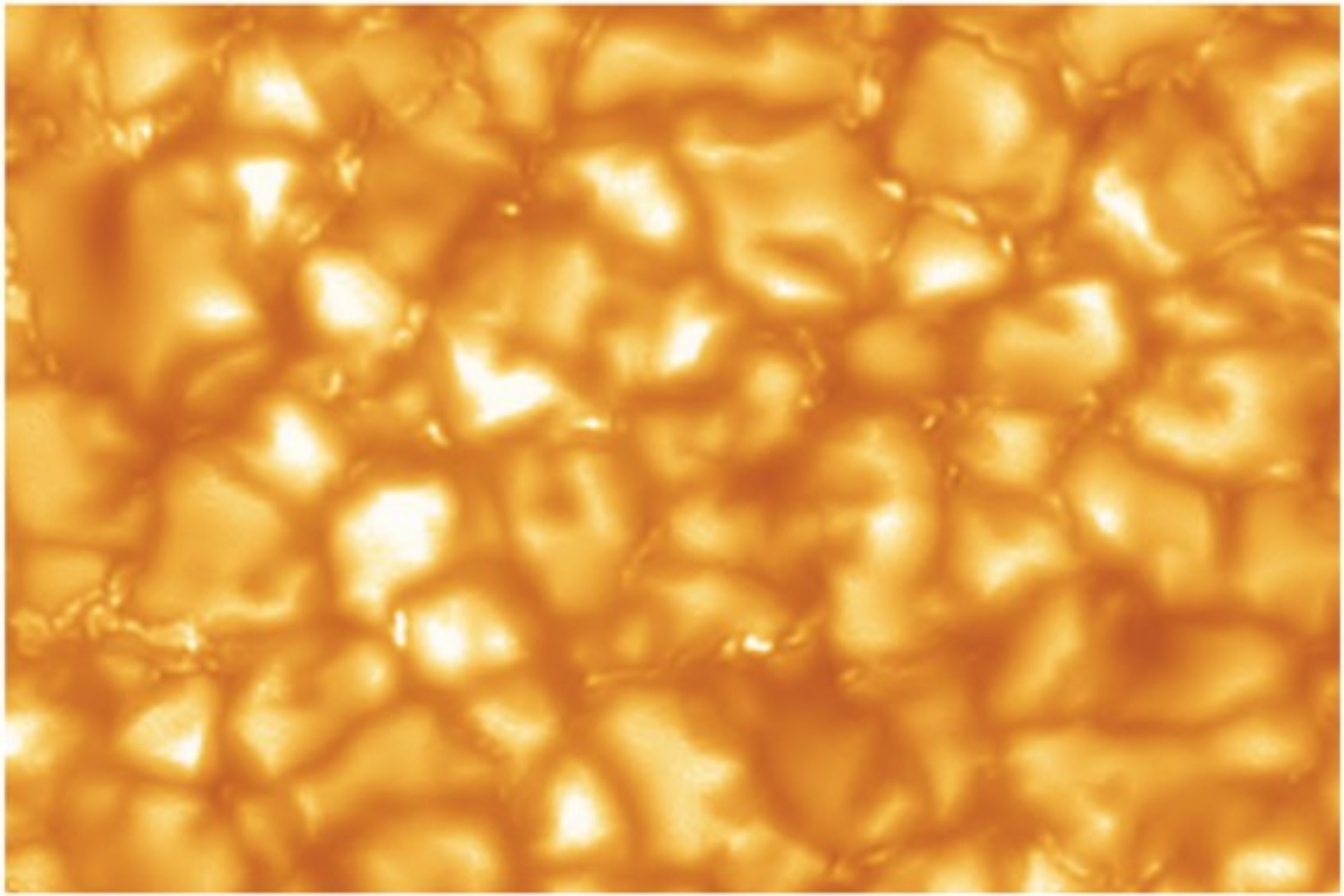
Convective Zone



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.

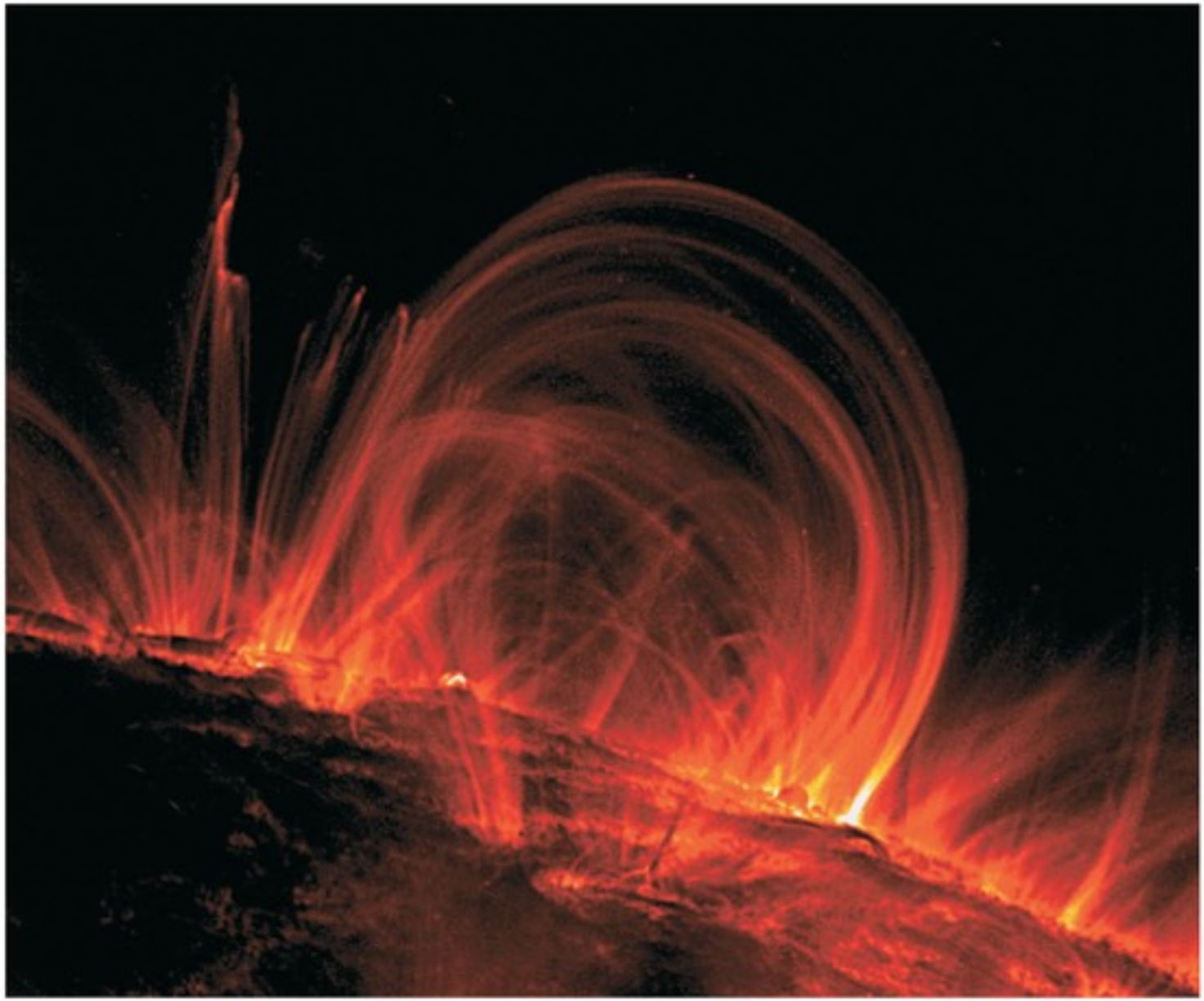
https://www.youtube.com/watch?v=W_Scoj4HqCQ



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.

Solar activity

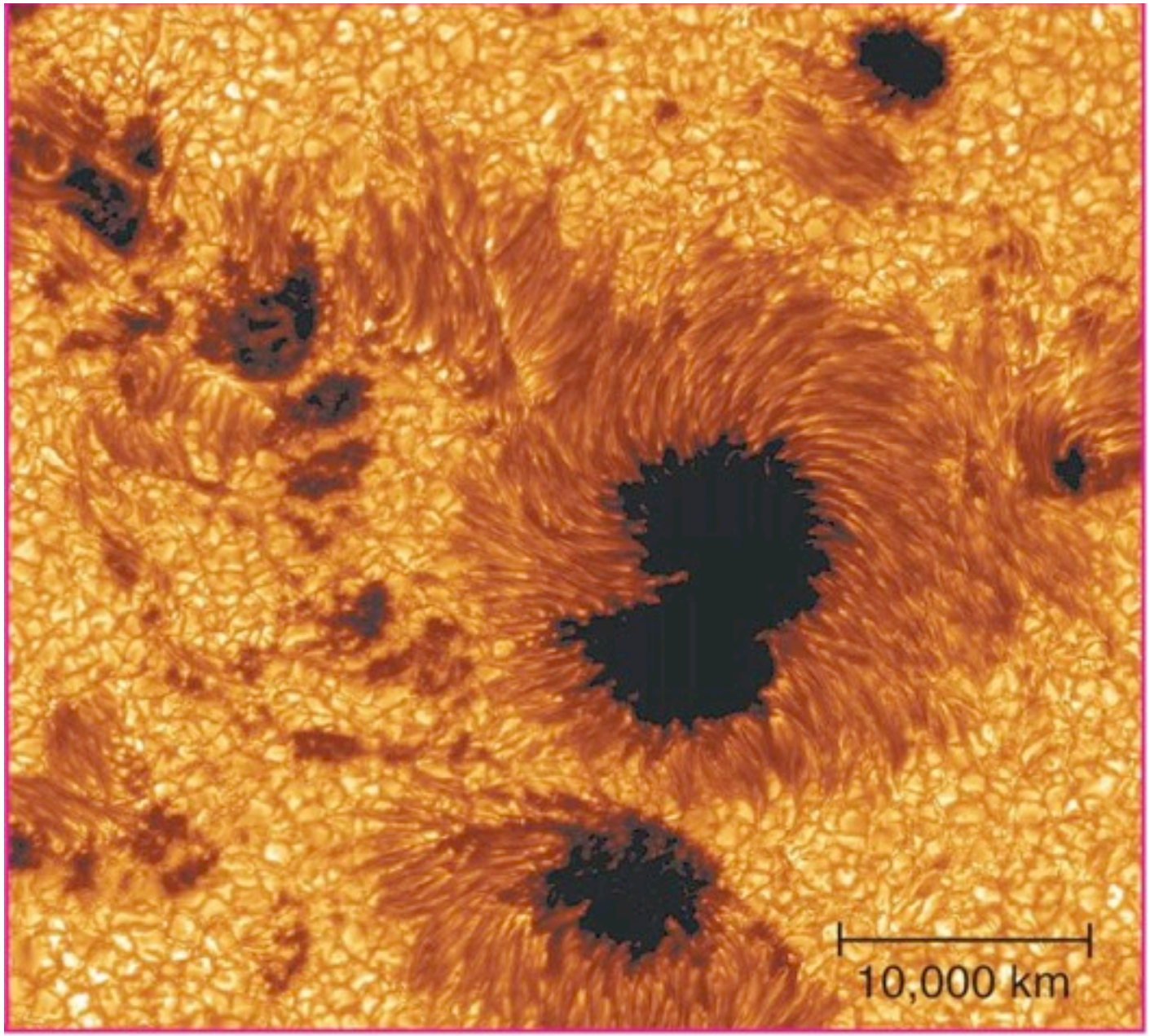


b This X-ray photo (from NASA's *TRACE* mission) shows hot gas trapped within looped magnetic field lines.

Solar activity is like "weather".

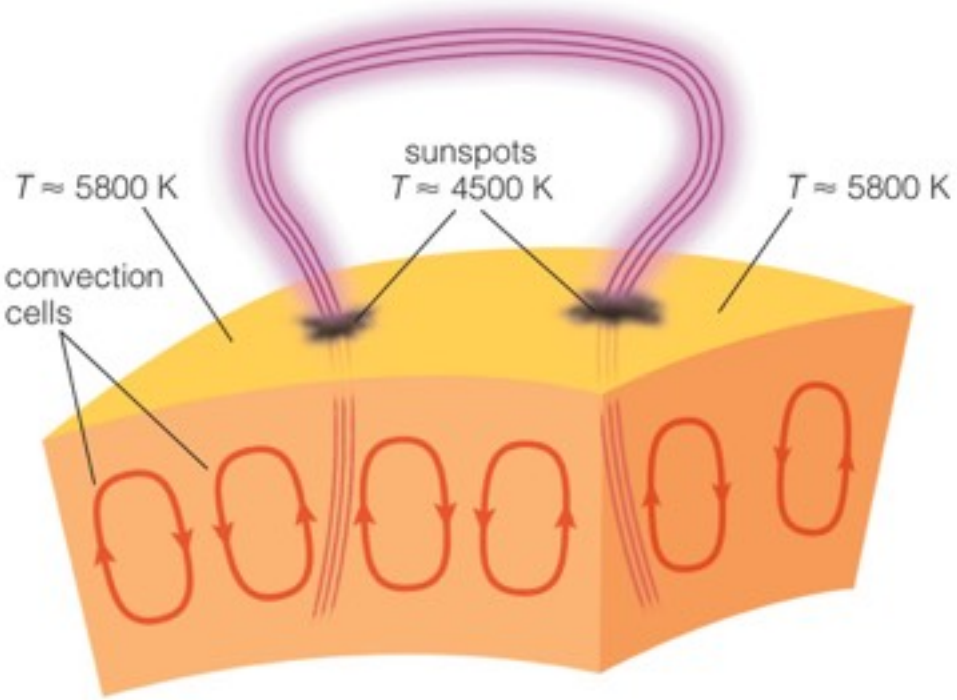
- Sunspots
- Solar flares
- Solar prominences

- All these phenomena are related to magnetic fields.

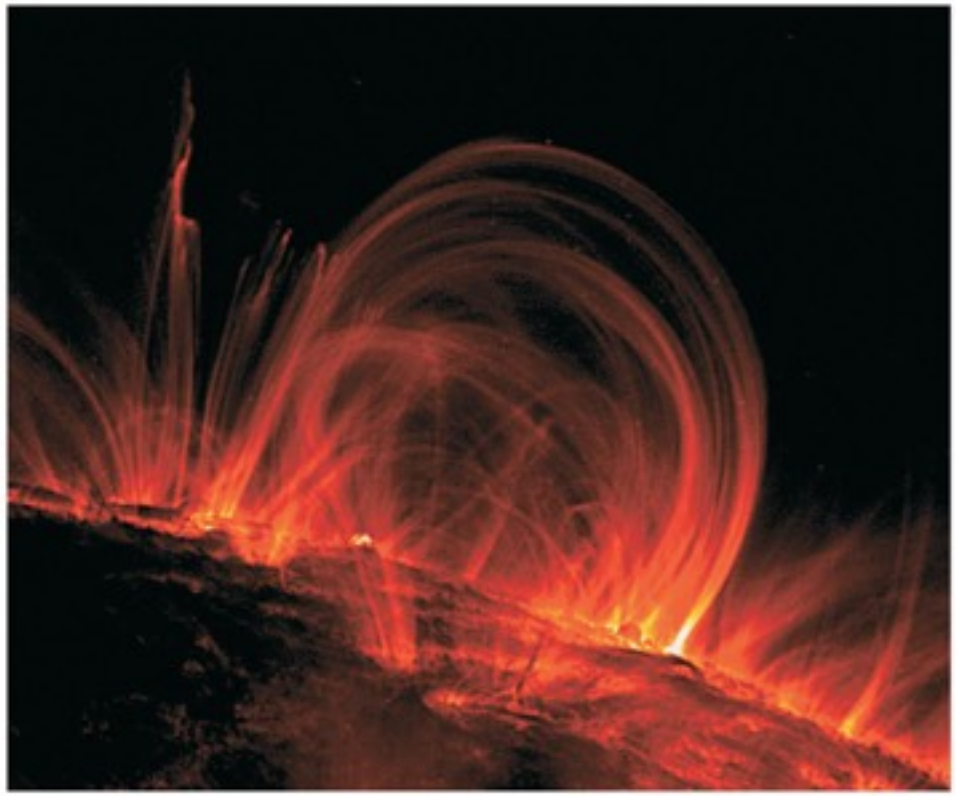


Sunspots

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



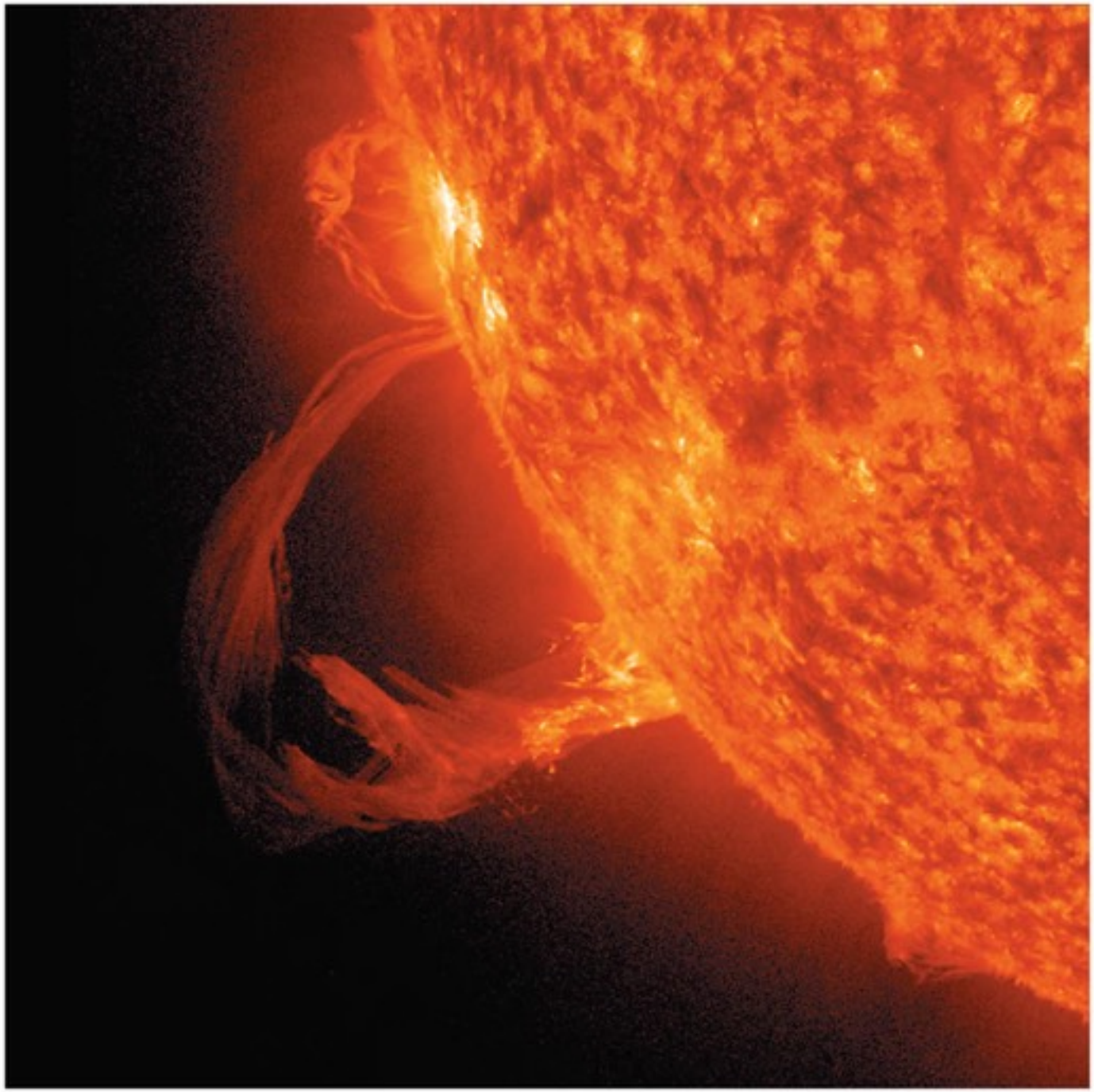
a Pairs of sunspots are connected by tightly wound magnetic field lines.



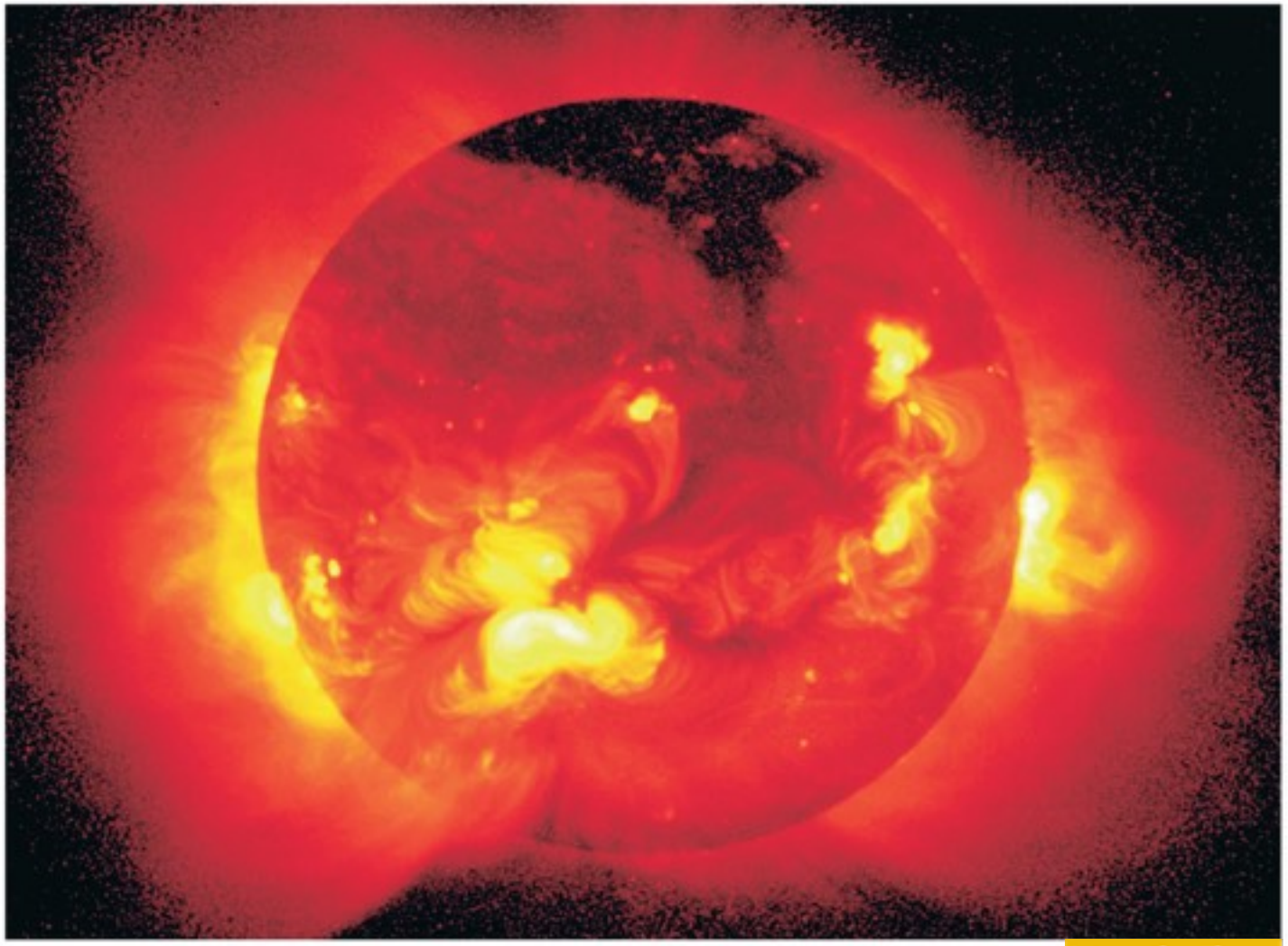
b This X-ray photo (from NASA's *TRACE* mission) shows hot gas trapped within looped magnetic field lines.

- Loops of bright gas often connect sunspot pairs.

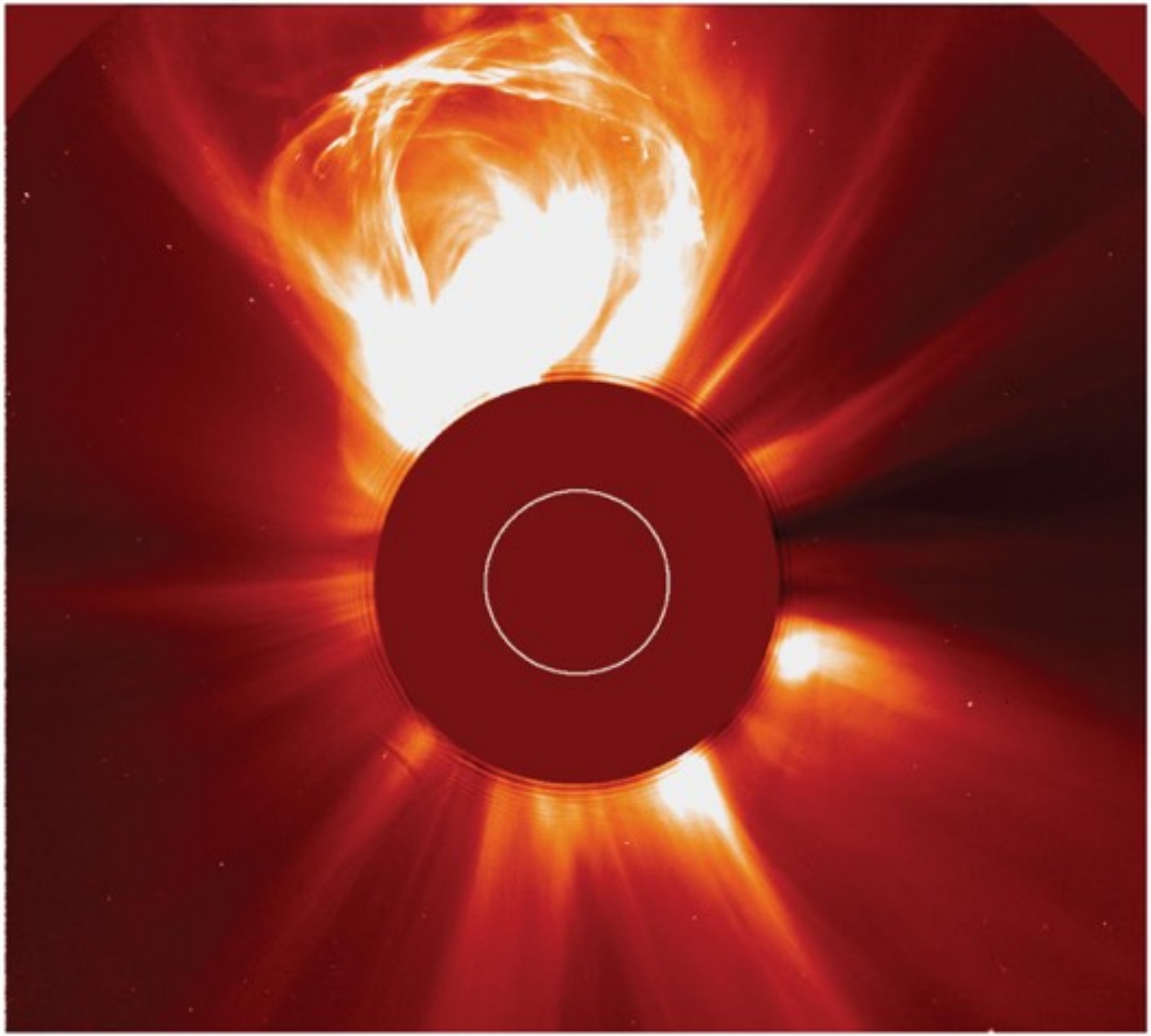
- Magnetic activity causes ***solar flares*** that send bursts of X rays and charged particles into space.



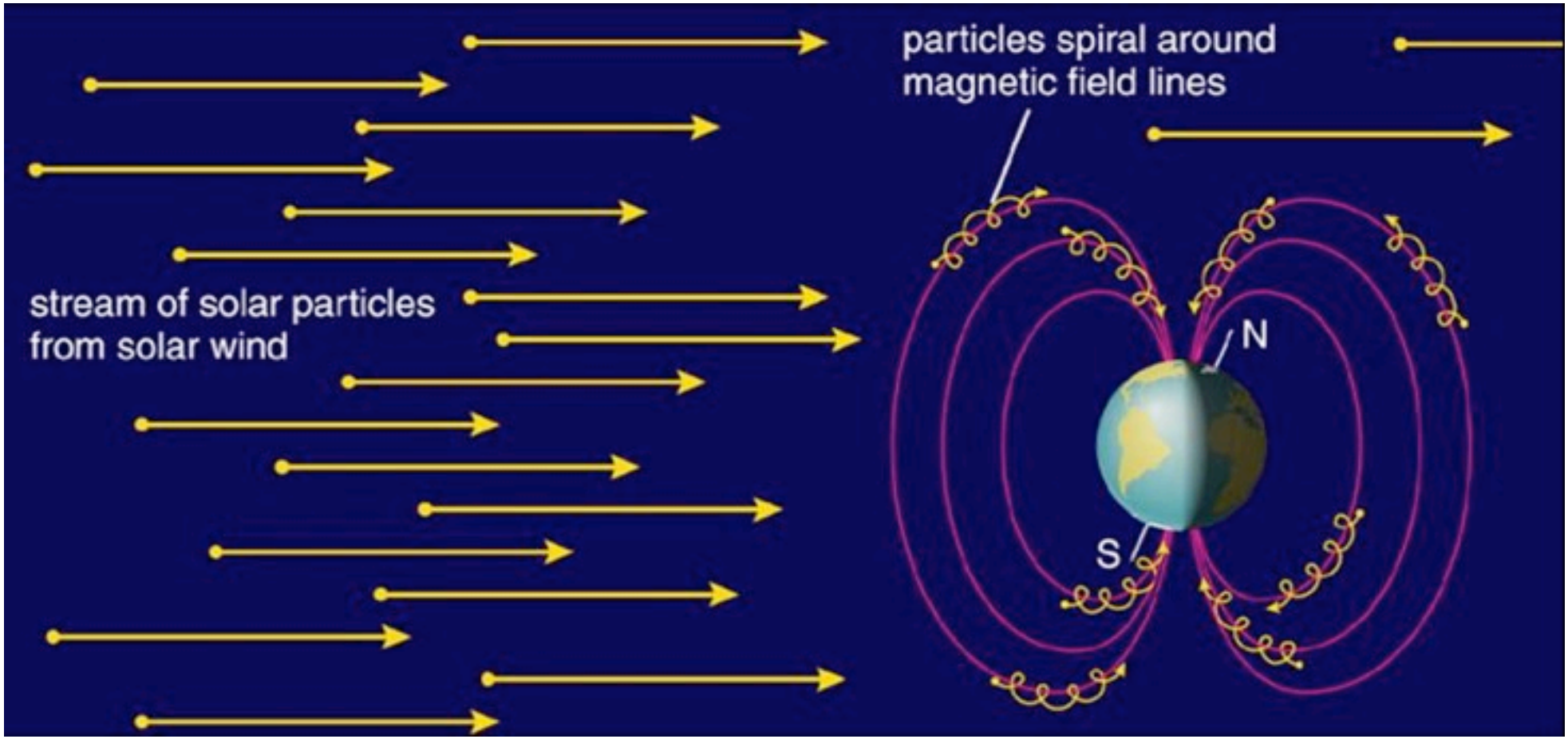
- Magnetic activity also causes ***solar prominences*** that erupt high above the Sun's surface.



- The corona appears bright in X-ray photos in places where magnetic fields trap hot gas.

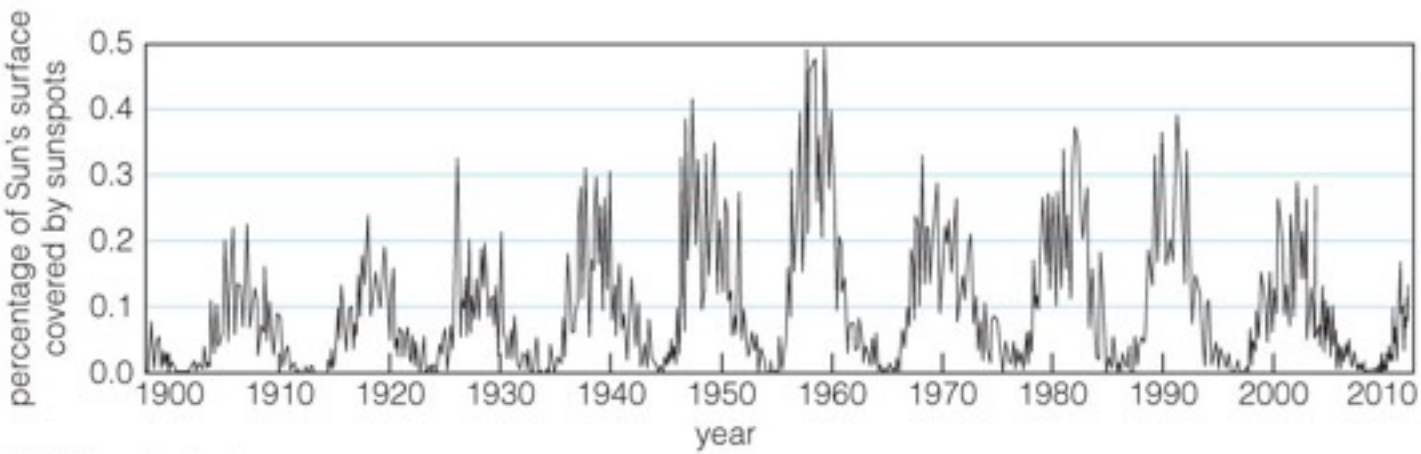


- ***Coronal mass ejections*** send bursts of energetic charged particles out through the solar system.

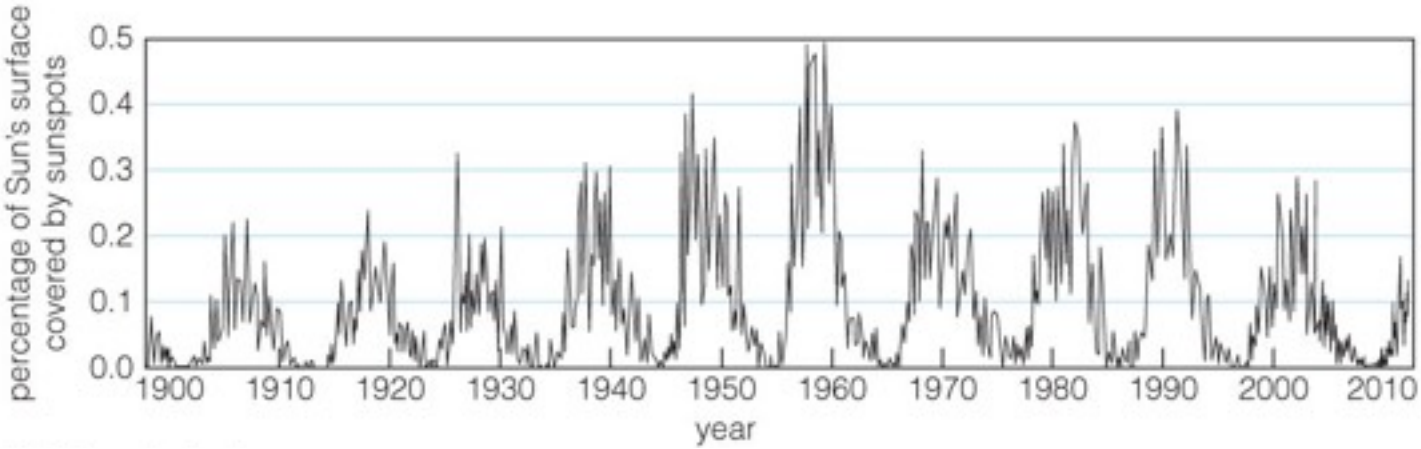


- Charged particles streaming from the Sun can disrupt electrical power grids and can disable communications satellites.

How does solar activity vary with time?

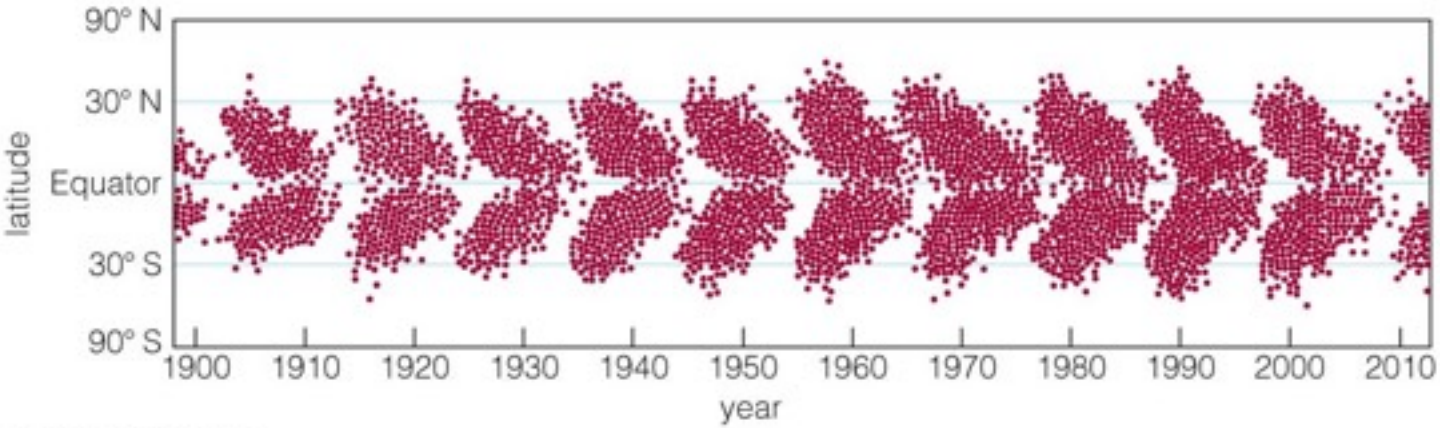


a This graph shows how the number of sunspots on the Sun changes with time. The vertical axis shows the percentage of the Sun's surface covered by sunspots. The cycle has a period of approximately 11 years.

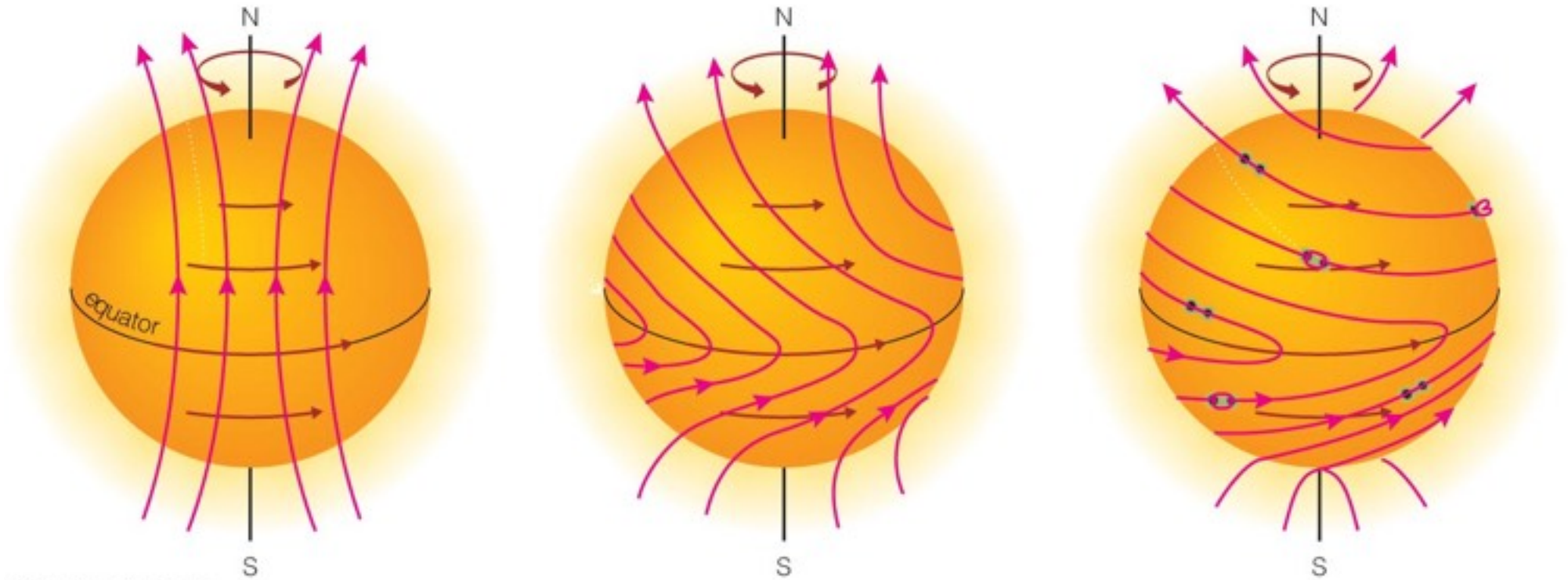


a This graph shows how the number of sunspots on the Sun changes with time. The vertical axis shows the percentage of the Sun's surface covered by sunspots. The cycle has a period of approximately 11 years.

- The number of sunspots rises and falls in an 11-year cycle.



b This graph shows how the latitudes at which sunspot groups appear tend to shift during a single sunspot cycle.



- The sunspot cycle has something to do with winding and twisting of the Sun's magnetic field.

Probing the Solar Interior

We learn about the inside of the Sun by …

- making mathematical models
- observing solar vibrations
- observing solar neutrinos