Today
The Sun

Events

Last class!

Homework due now

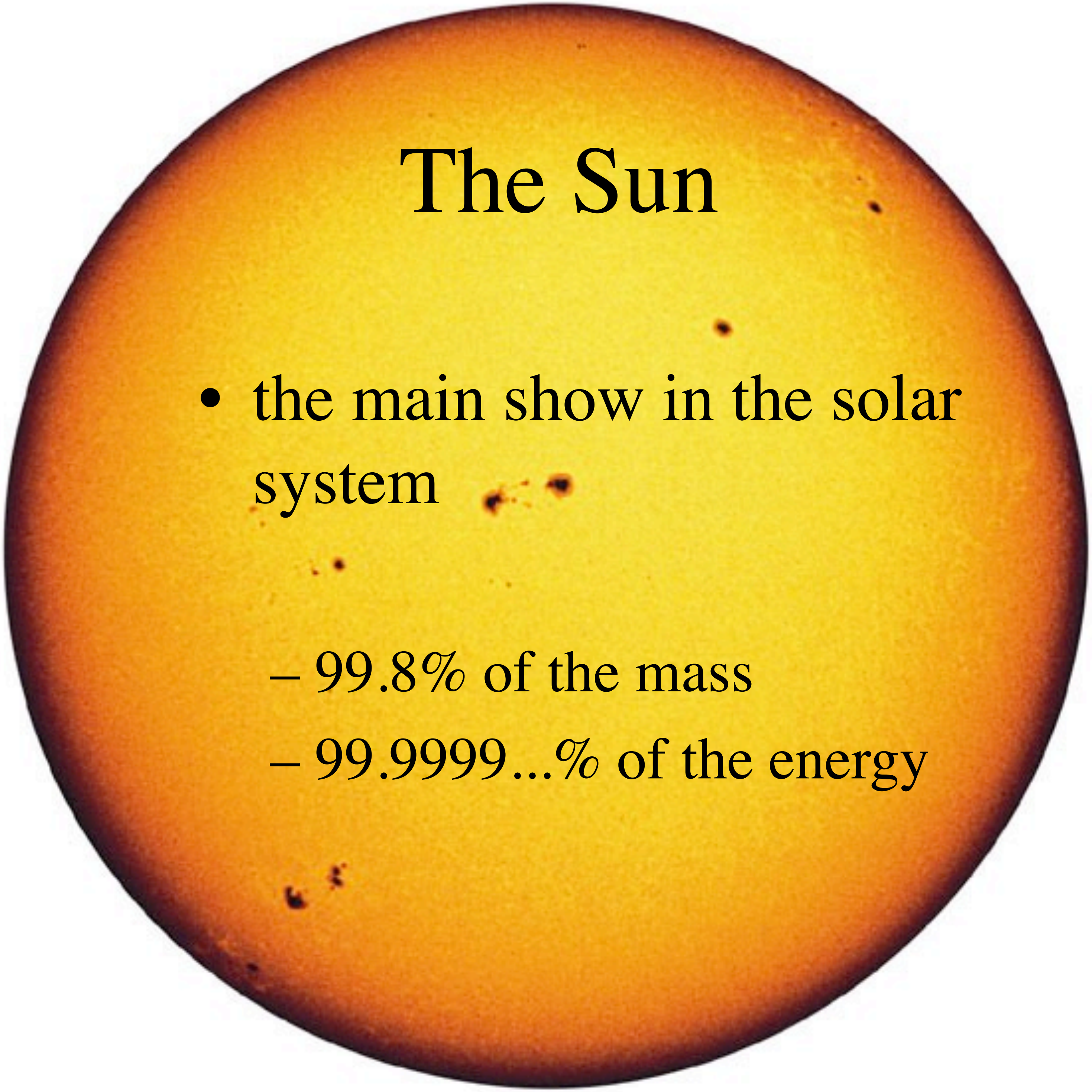
- will count best 5 of 6

Final exam Dec. 20 @ 12:00 noon here

Review this Course!

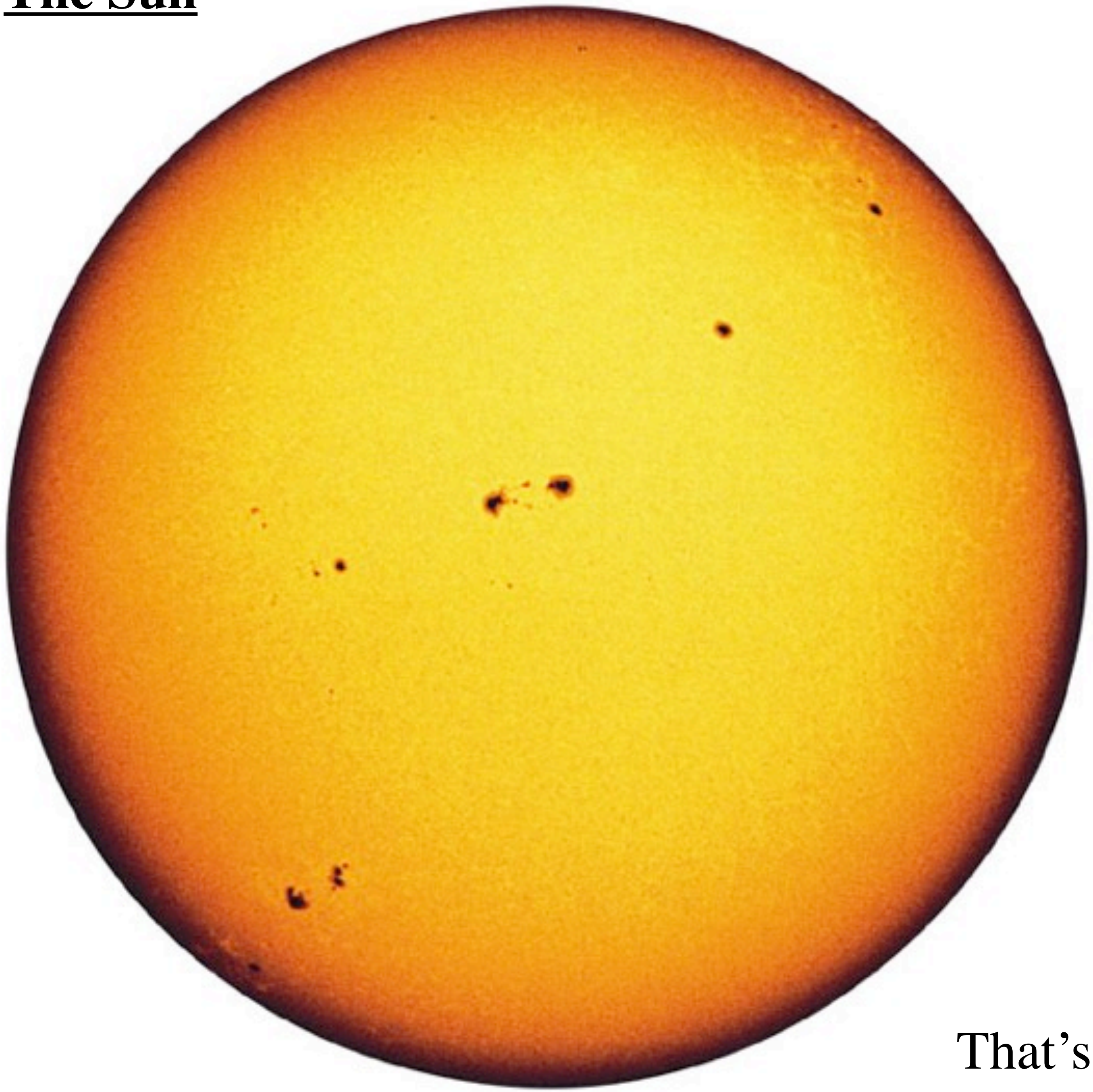
www.case.edu/utech/course-evaluations/

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

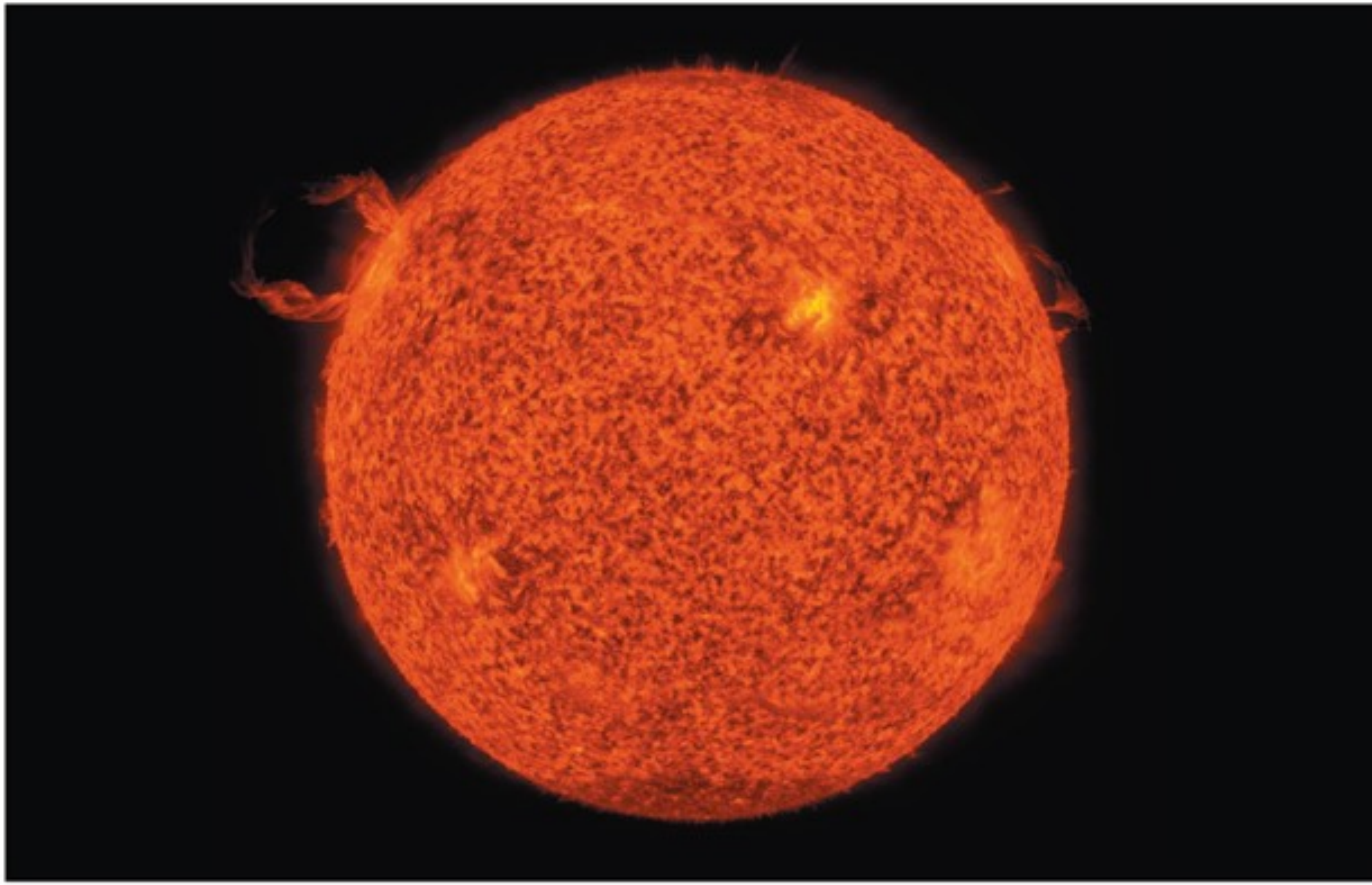
(1,000 Jupiters;

300,000 Earths)

Luminosity:

3.8×10^{26} watts

That's about a billion big nuclear bombs every second



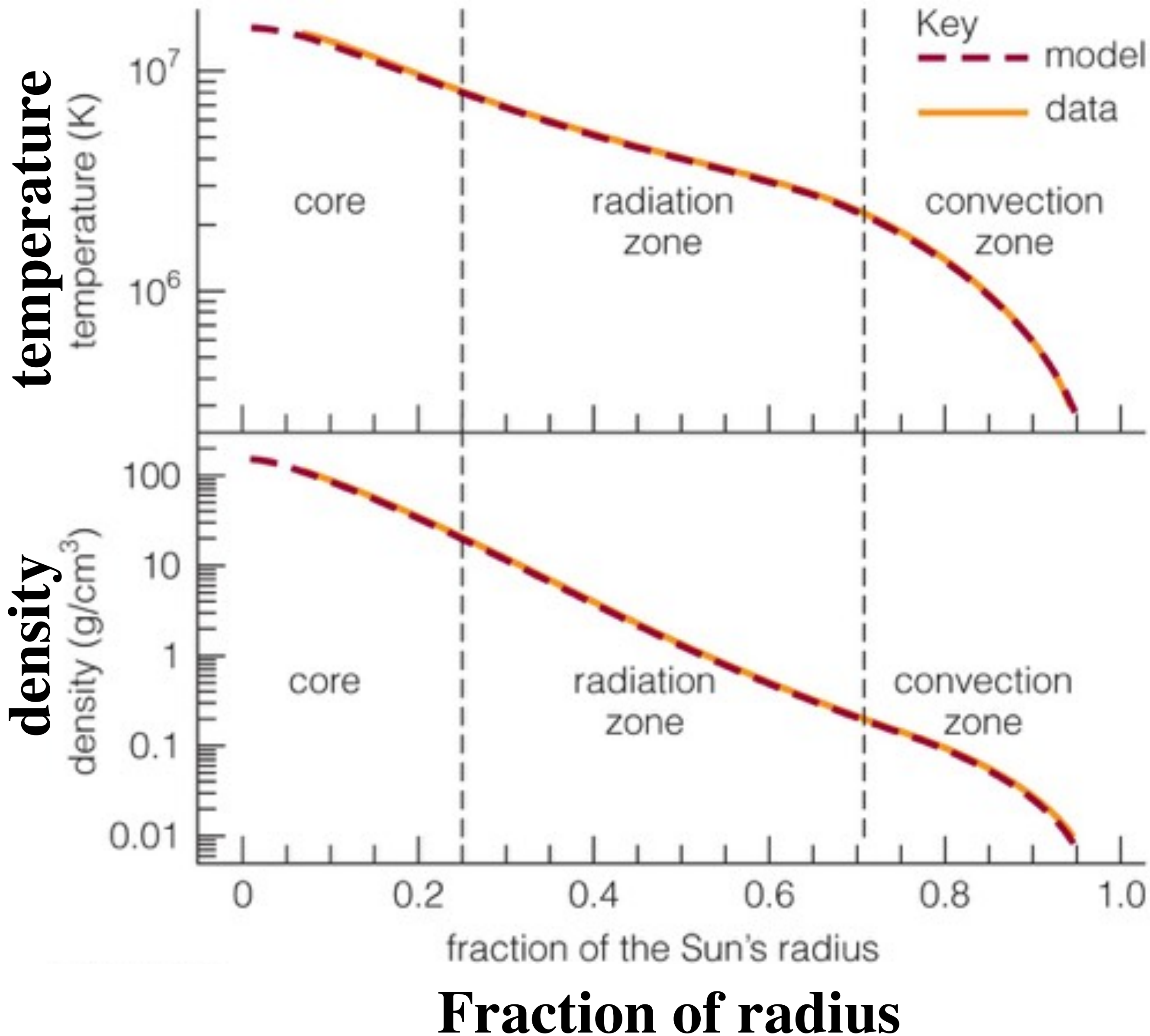
It can be powered by NUCLEAR ENERGY! ($E = mc^2$)

with 0.7% efficiency

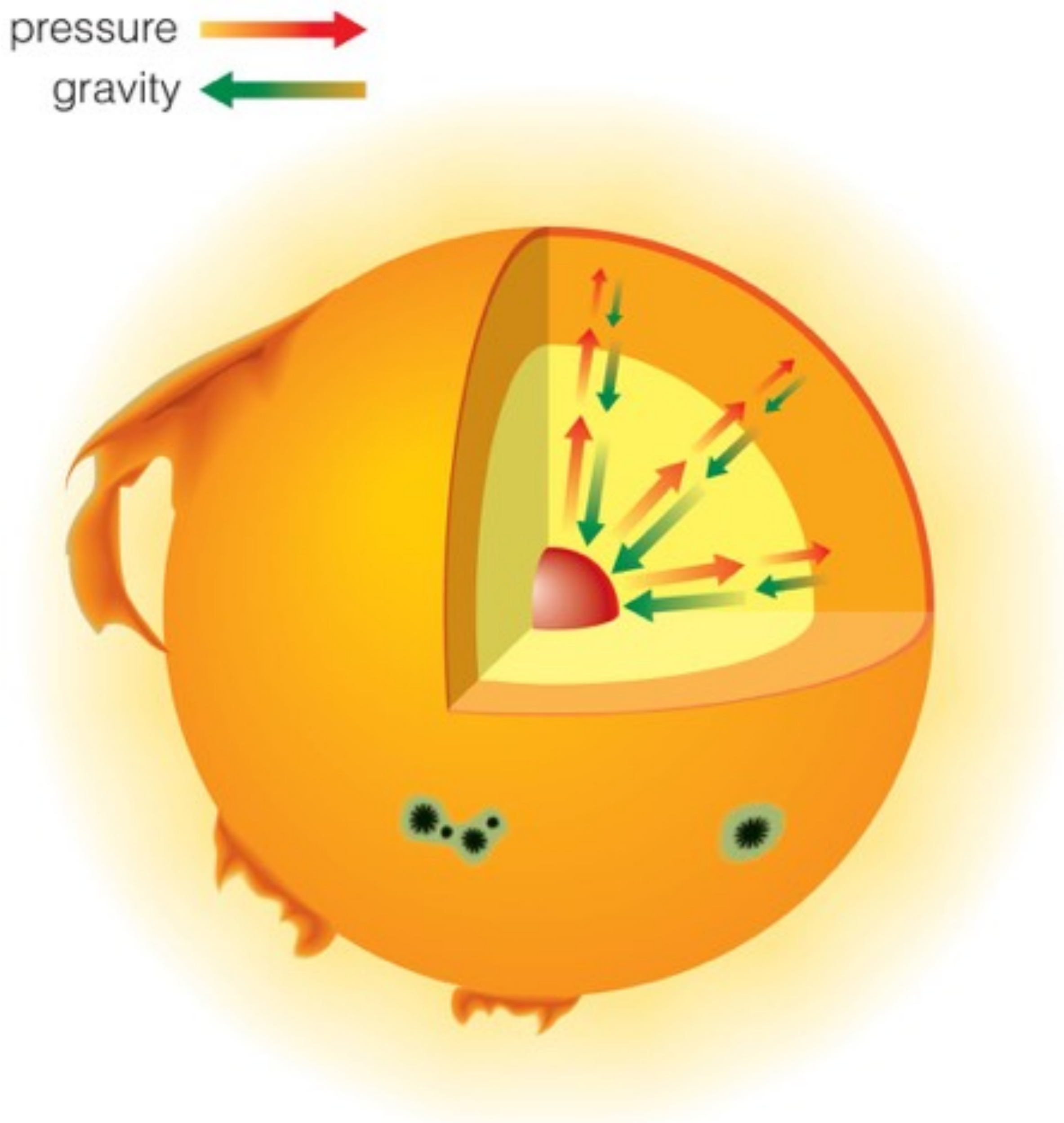
$$\frac{\text{Nuclear potential energy (core)}}{\text{Luminosity}} \sim \text{10 billion years}$$

- 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.
    - Hydrogen fuses into Helium in a 3-step process called the proton-proton chain.

Interior Structure of the Sun



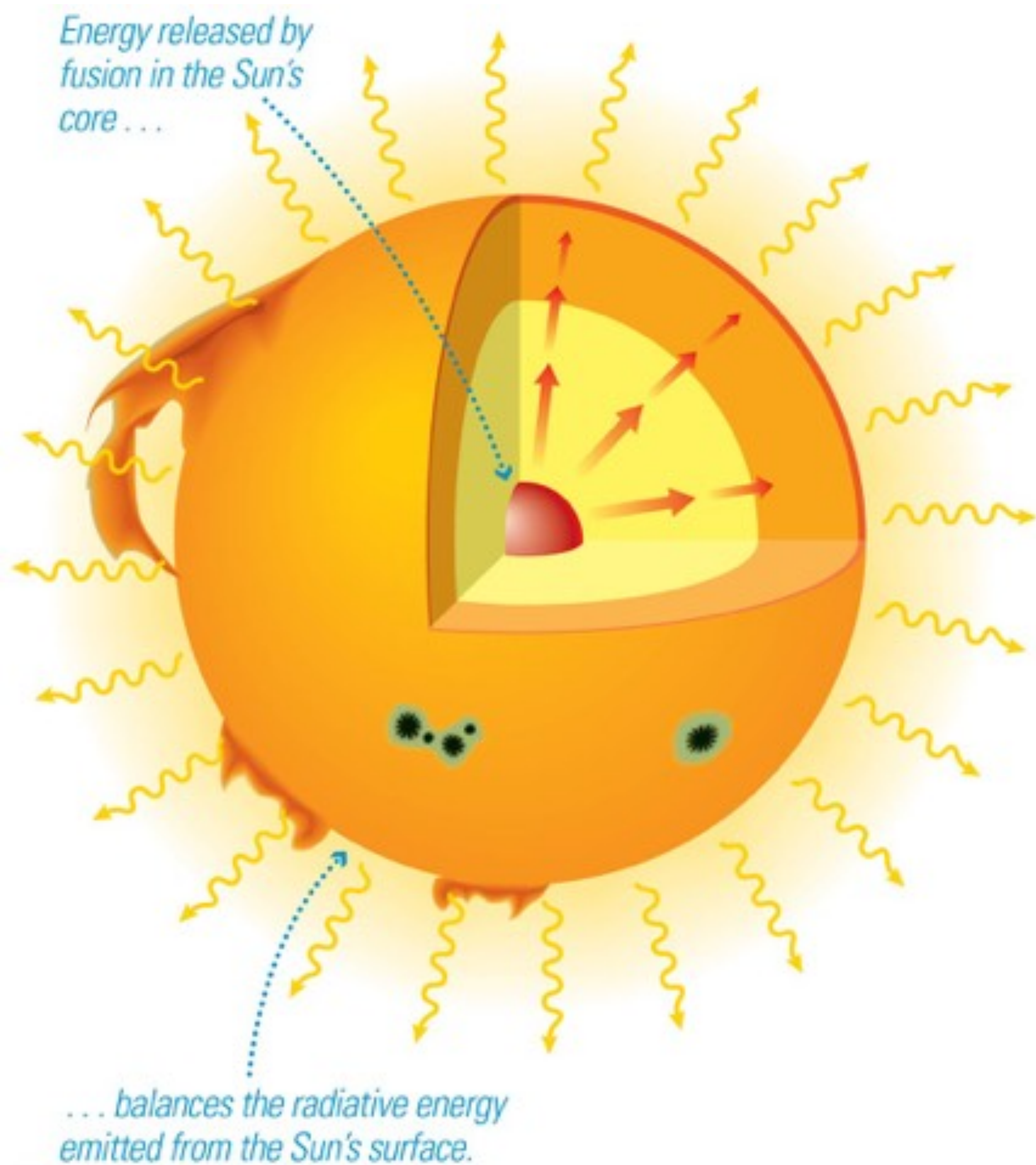
- Gravity causes the density and temperature to increase towards the center.
- Ave. density about 1 g/cc (water)
- but
  - much denser in core
  - much thinner at surface



Stars are stable: pressure balances gravity.

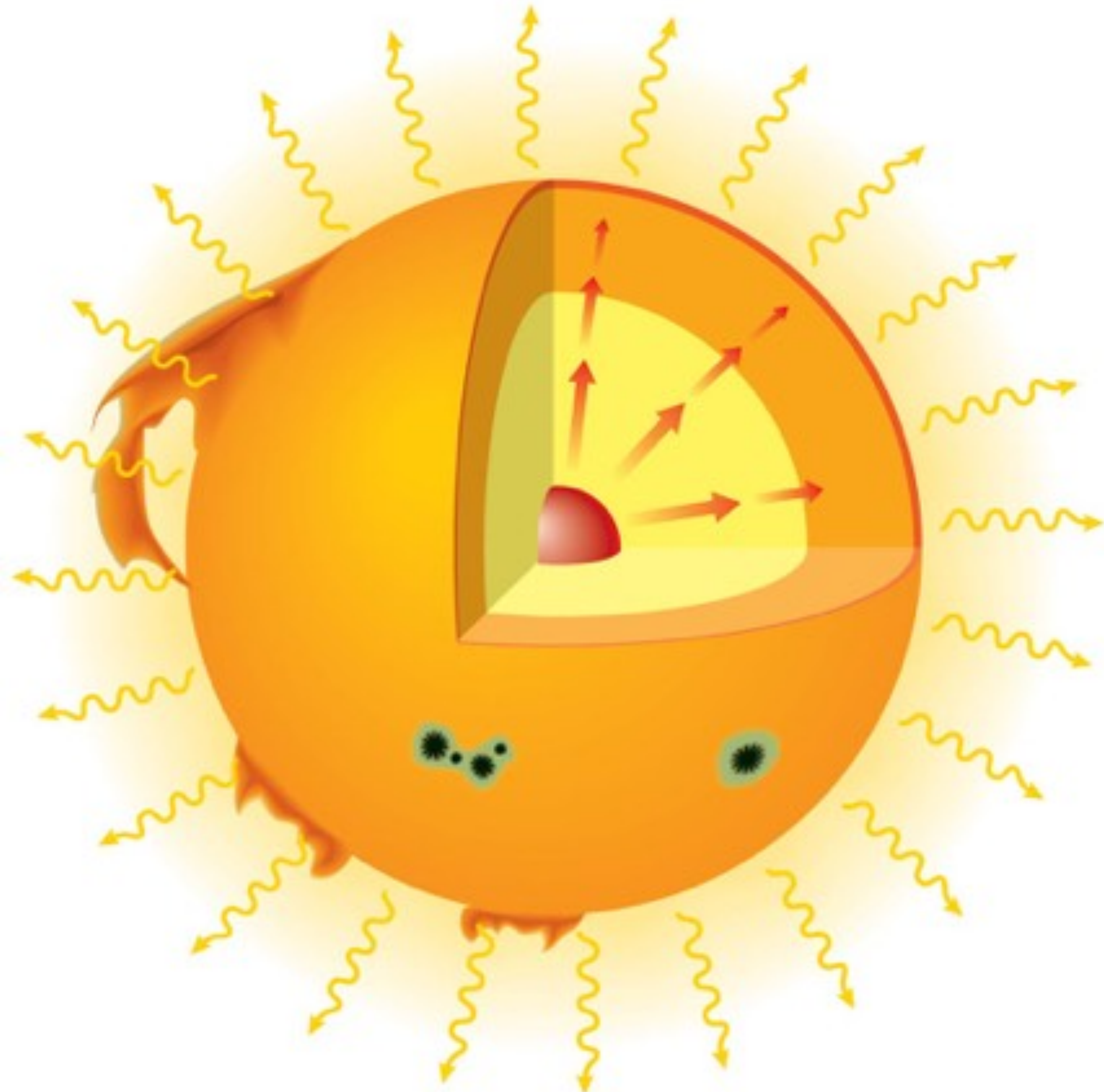
Hydrostatic equilibrium:

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:

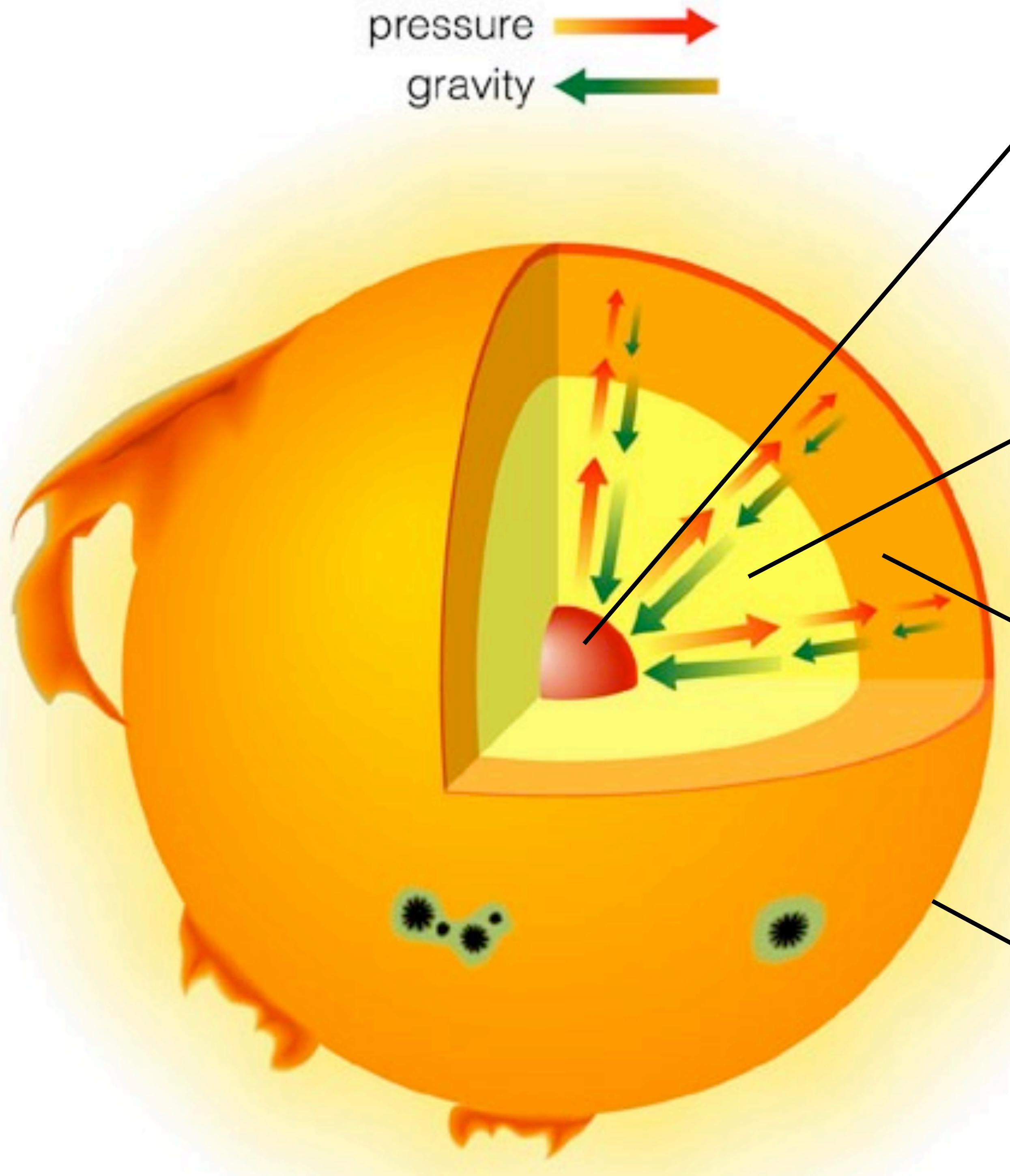
- The rate at which energy radiates from the surface of the Sun must be the same as the rate at which it is released by fusion in the core.



initial gravitational contraction:

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

Need a minimum of 70 Jupiter masses to make a star



10_01StructSun

Core:

Energy generated by nuclear fusion

~ 15 million K

Radiation zone:

Energy transported upward by photons

Convection zone:

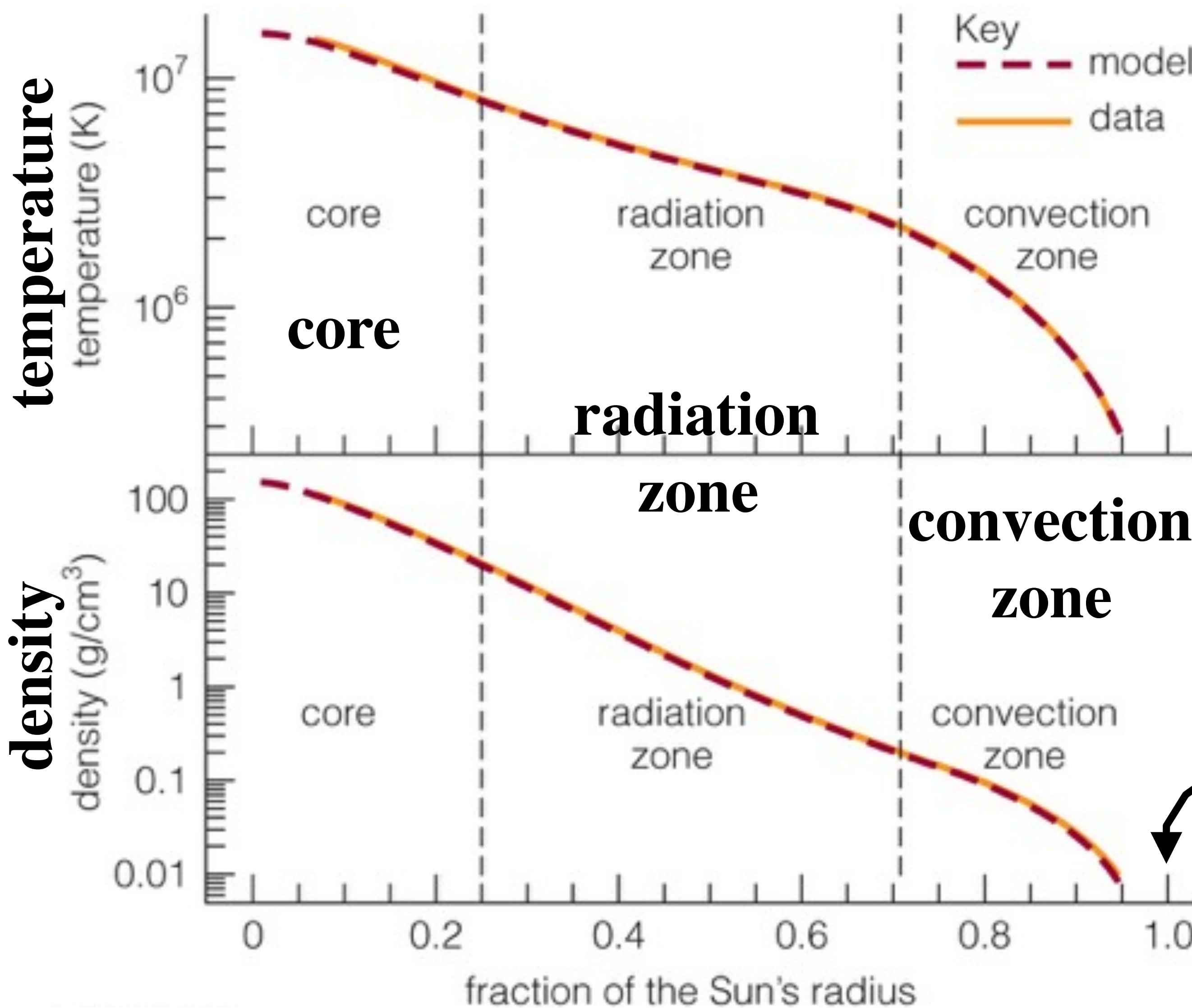
Energy transported upward by rising hot gas

Photosphere:

Visible surface

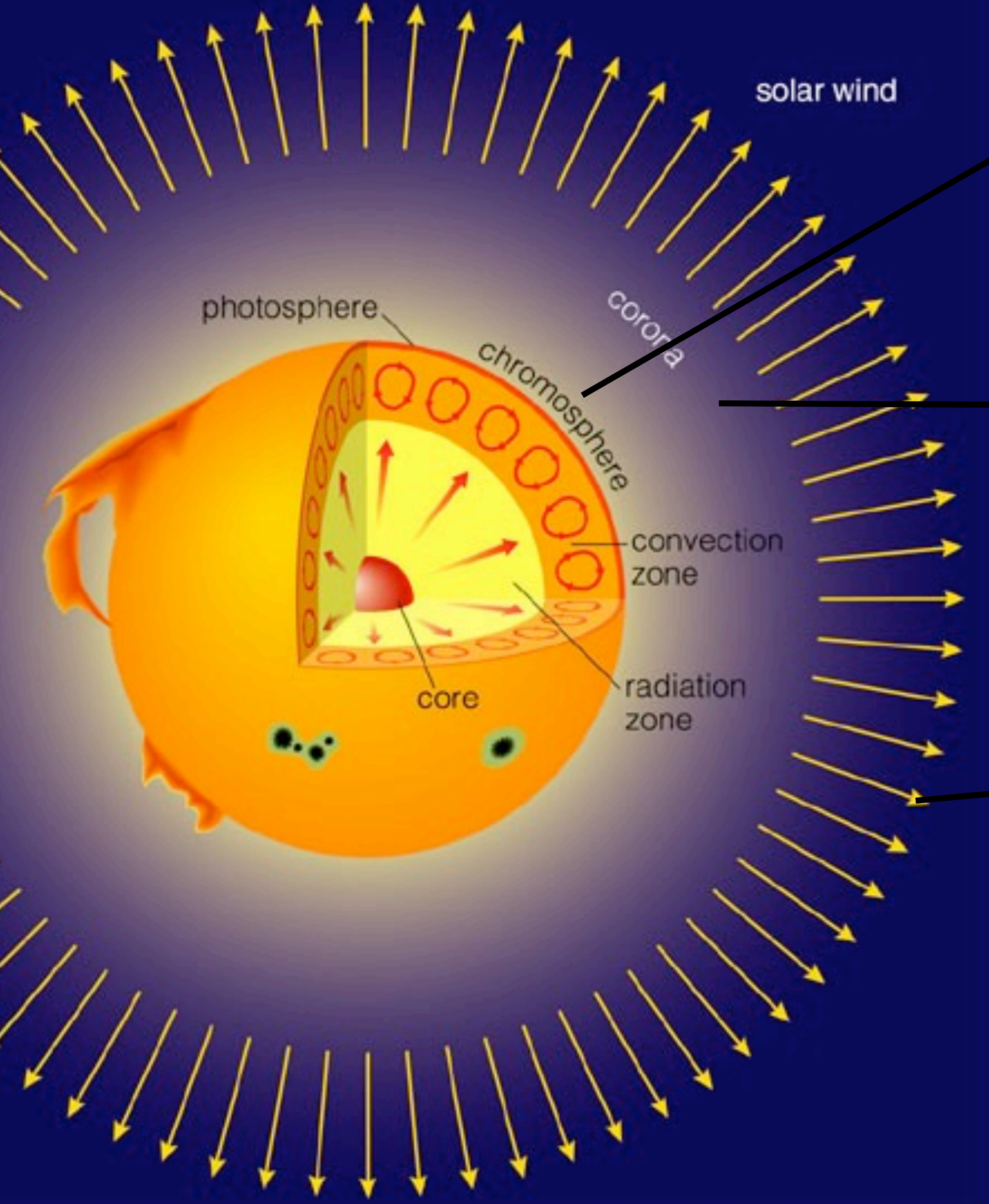
~5,800 K

Interior Structure of the Sun



photosphere (visible surface)

Fraction of radius



Chromosphere:

Middle layer of solar atmosphere

Corona:

Outermost layer of solar atmosphere

Solar wind:

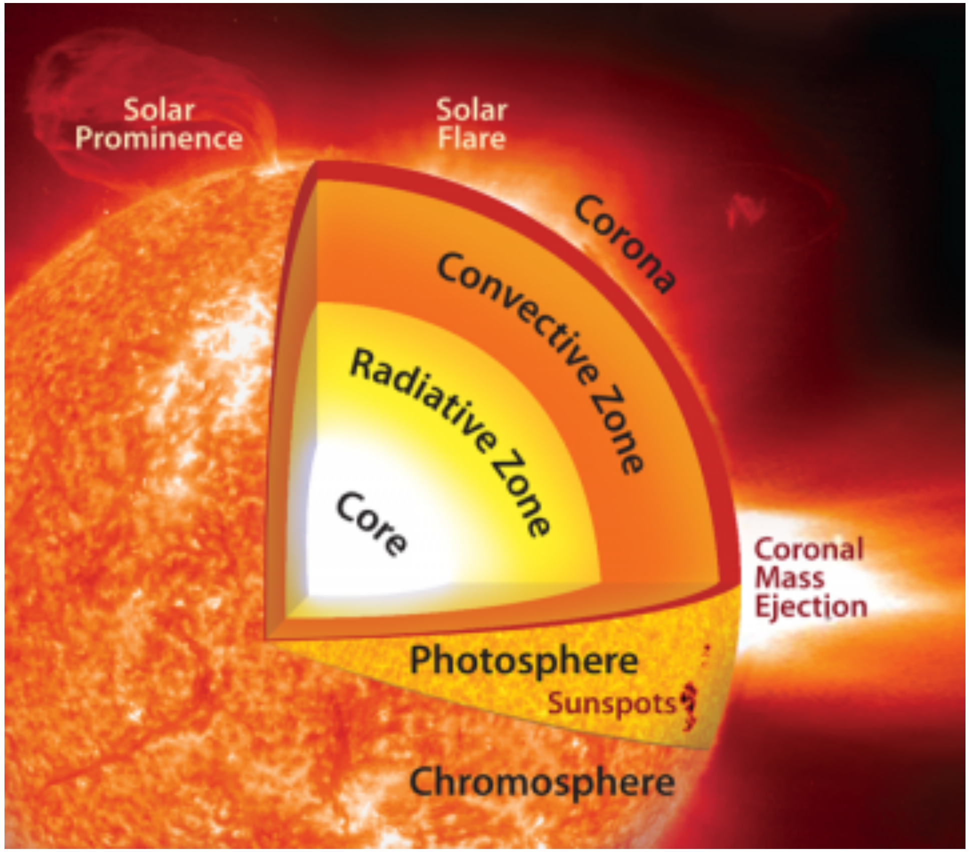
A flow of charged particles from the surface of the Sun

Little mass in these components

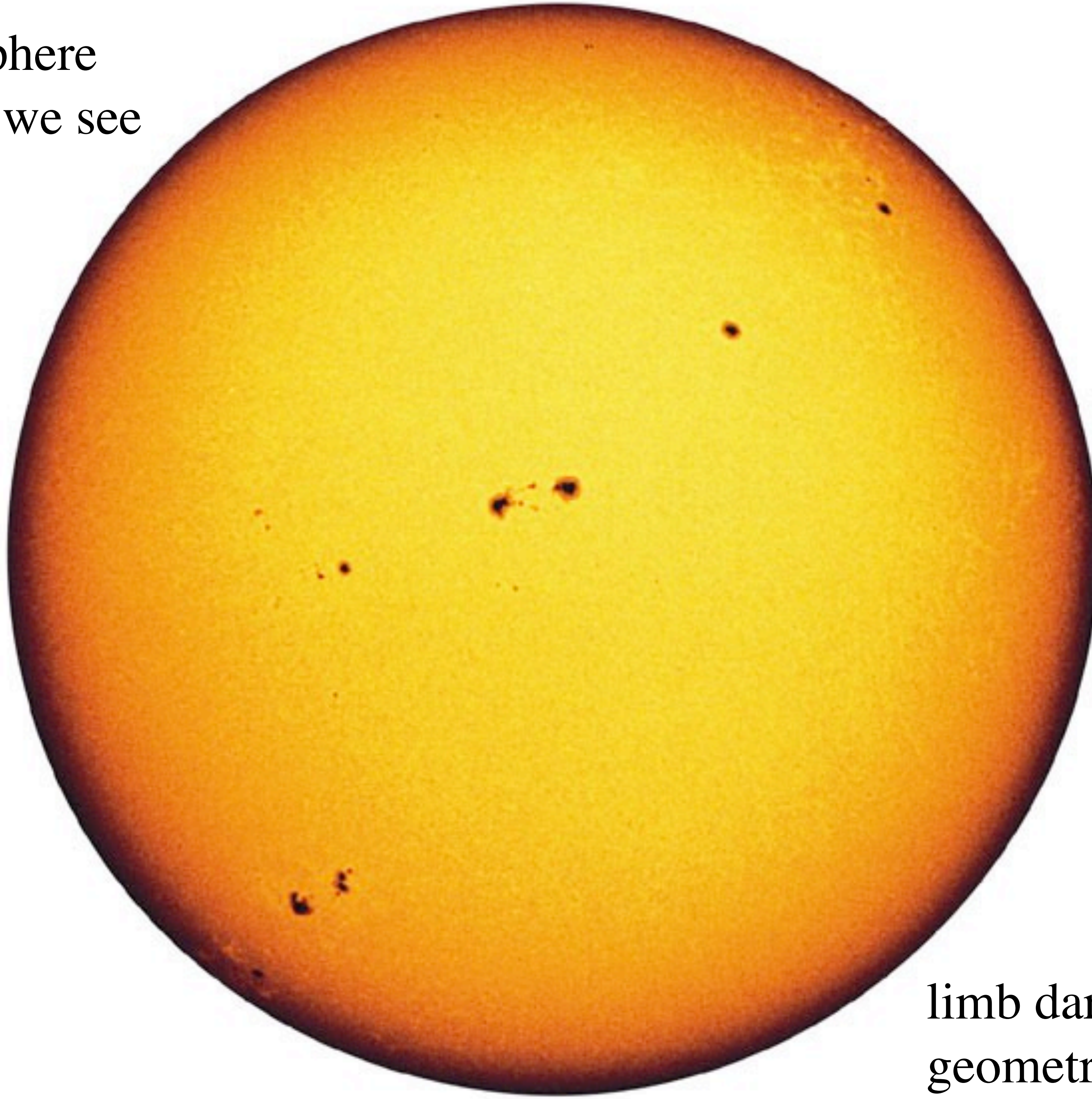
- Solar structure
  - From inside out, the layers are:
    - Core
      - Energy generation by fusion reactions
    - Radiation zone
      - Outward energy transport by photons
    - Convection zone
      - Outward energy transport by gas motions
    - Photosphere
      - Luminous surface (energy emitted 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

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

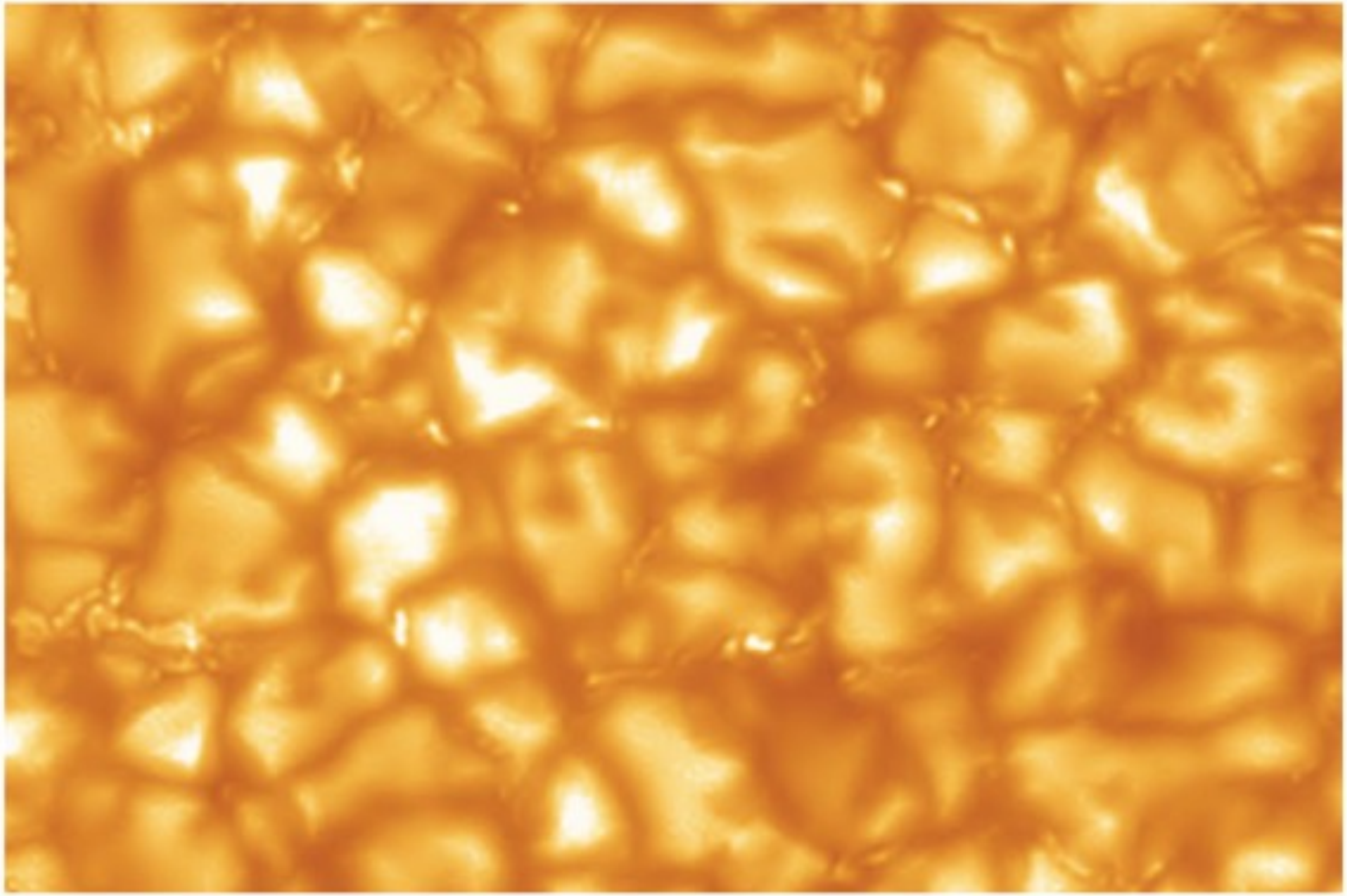


Photosphere
is what we see



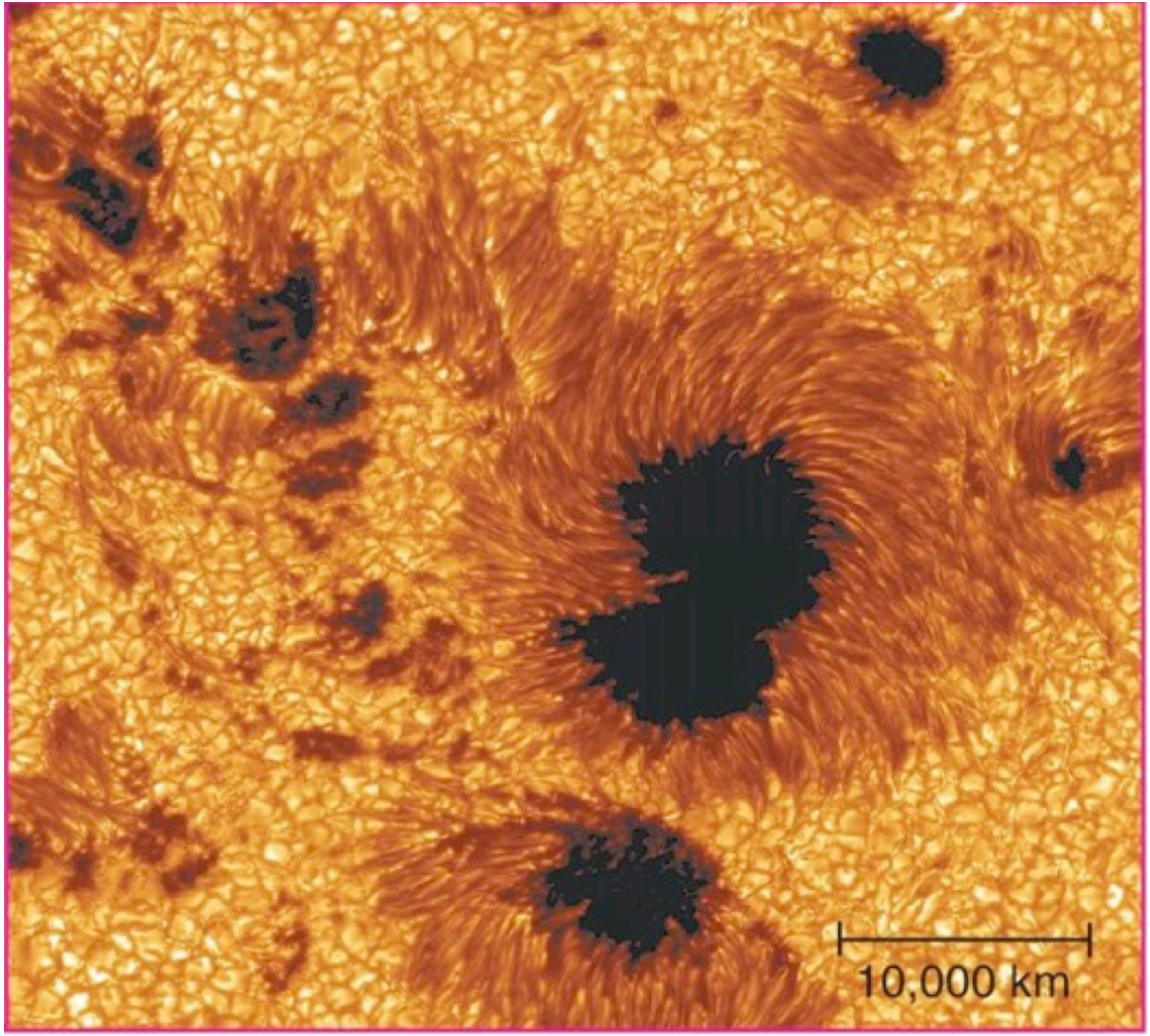
limb darkening is a
geometric effect

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.

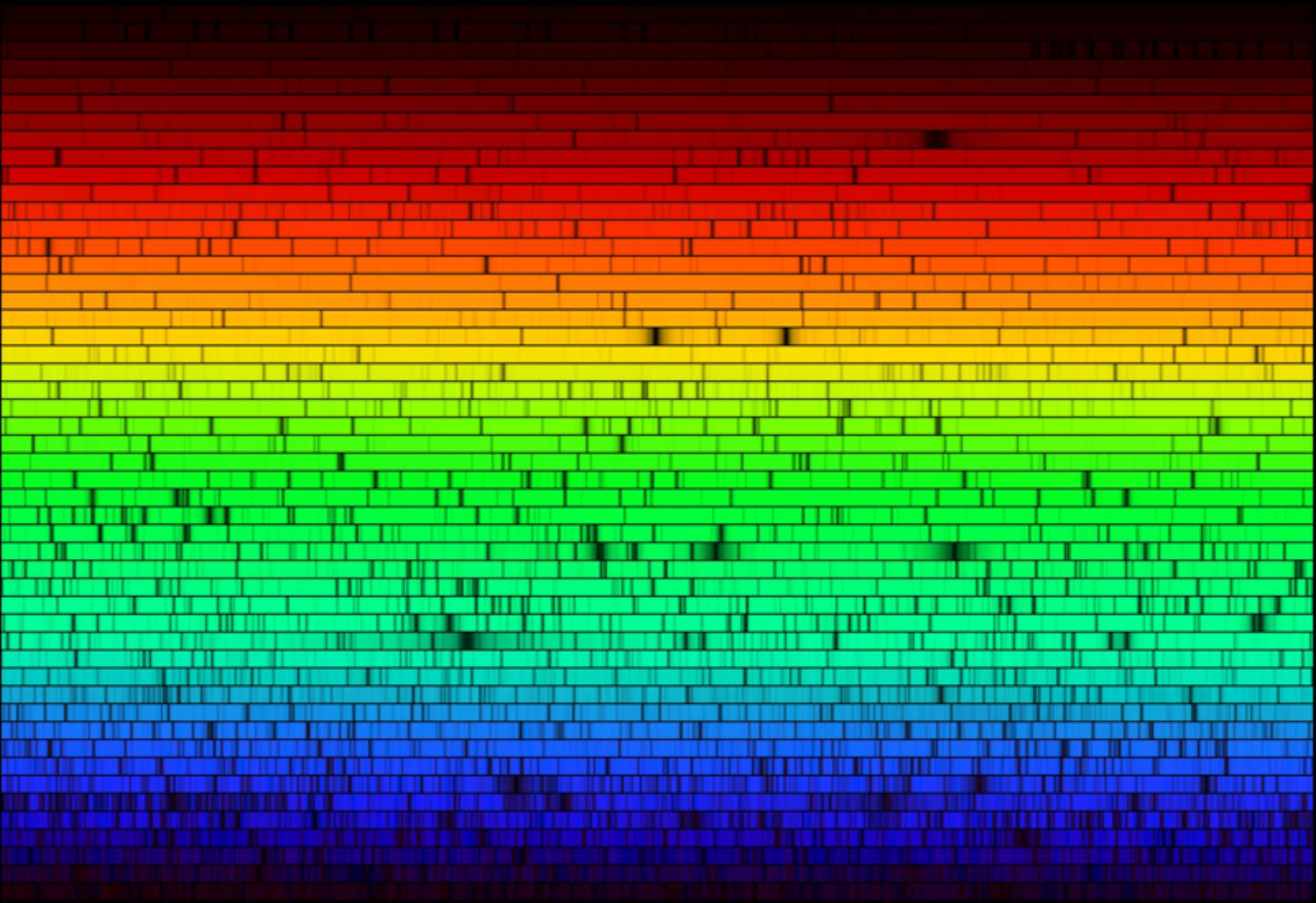
- Bright blobs on photosphere show where hot gas is reaching the surface.



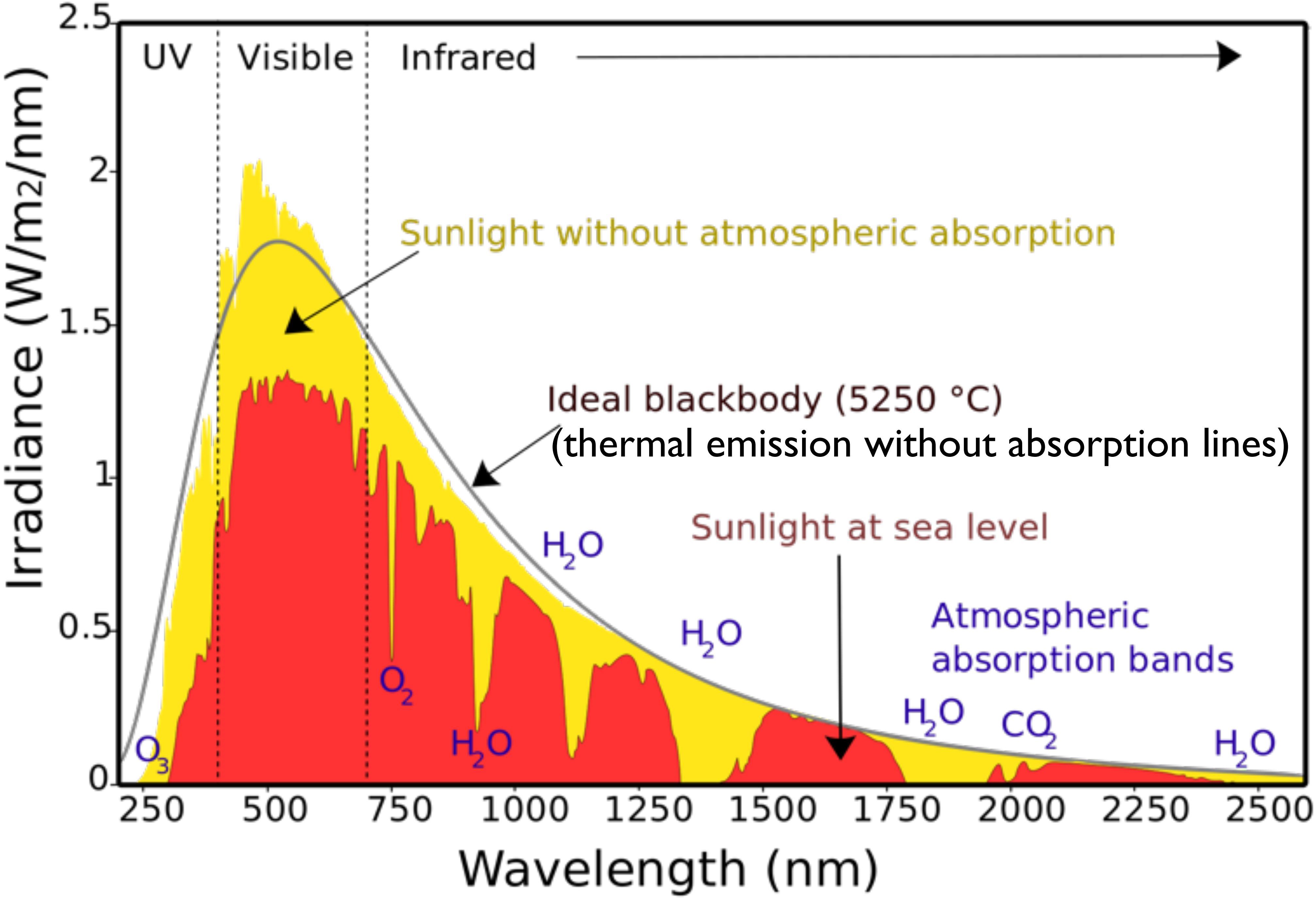
Sunspots

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

The photosphere produces an absorption spectrum

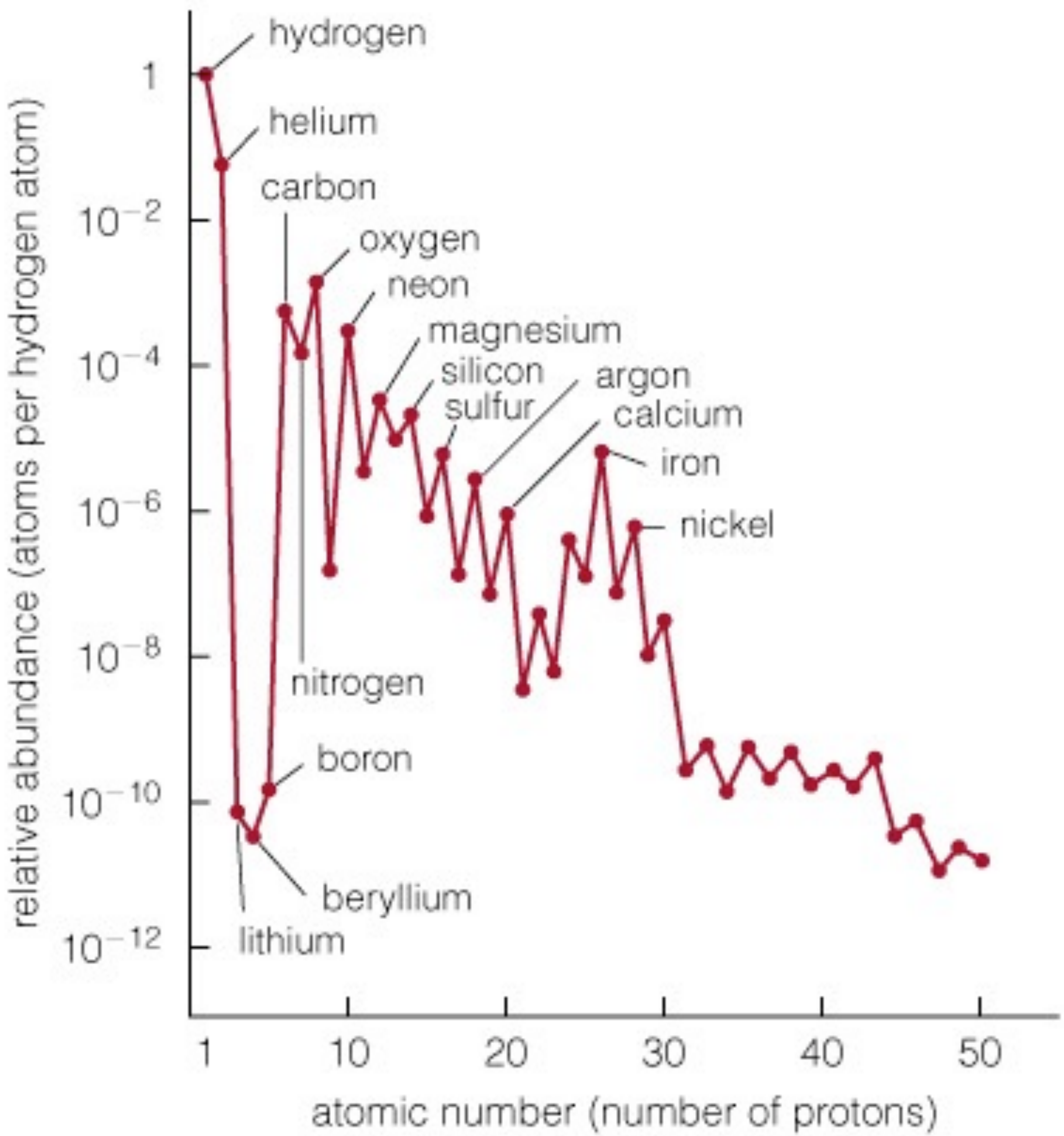


Spectrum of Solar Radiation (Earth)



Composition determined from absorption lines

Abundance (by number relative to Hydrogen)



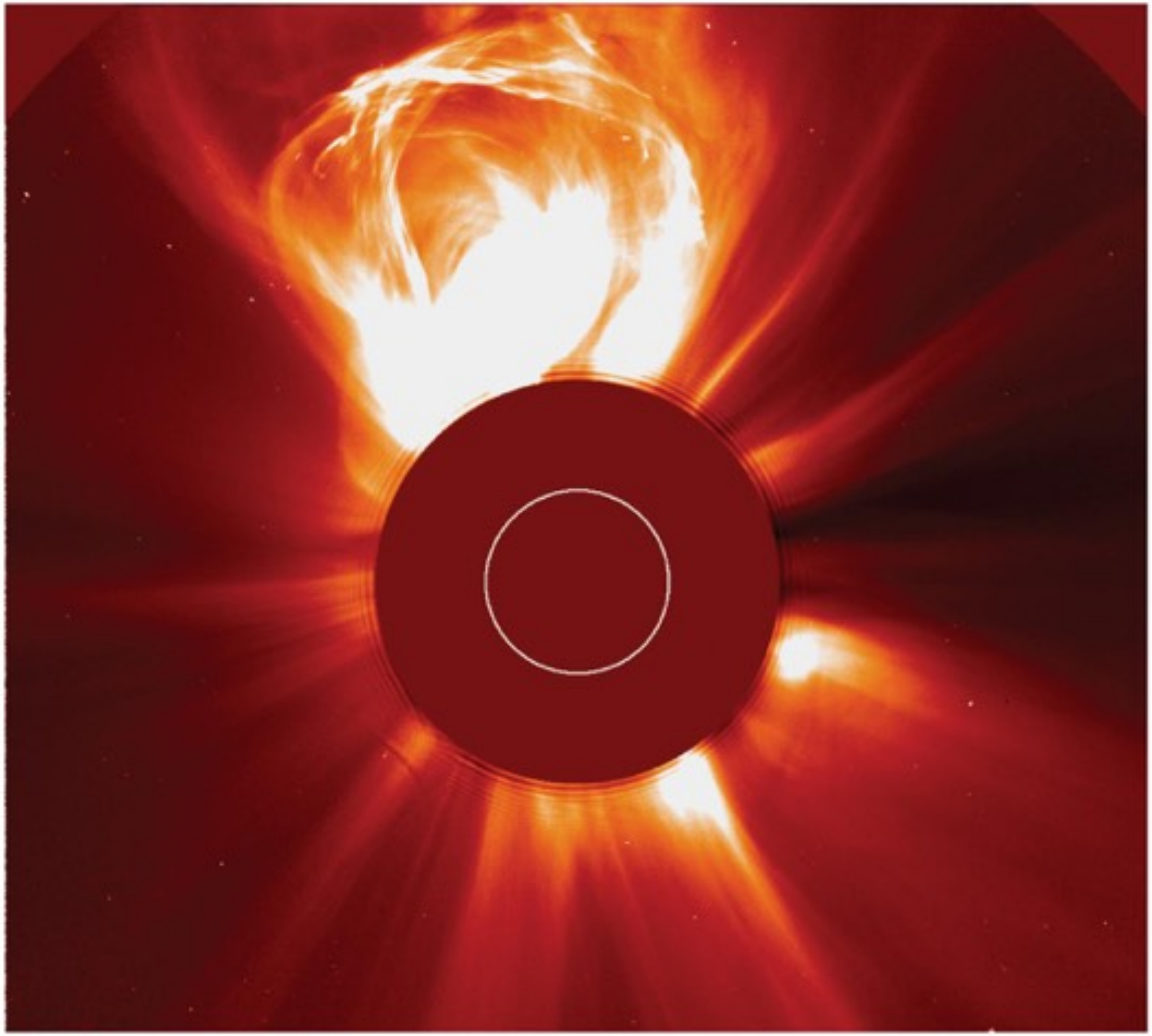
Atomic number (number of protons)

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

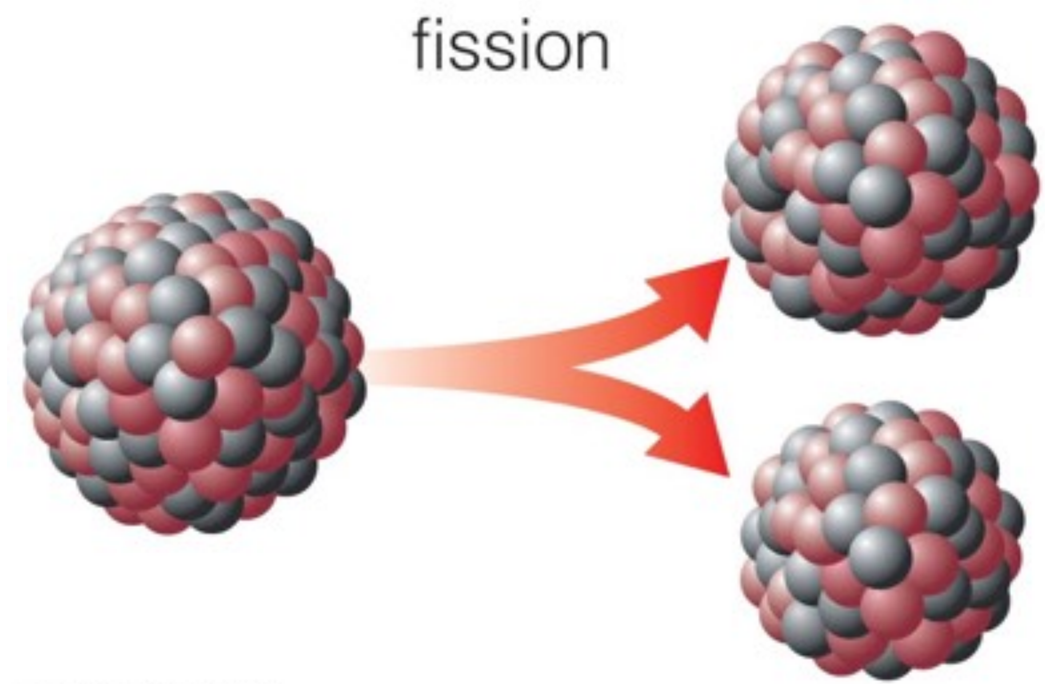


- Coronal mass ejections send bursts of energetic charged particles out through the solar system.
- Poses a risk to the power grid & would-be space travelers

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

Nuclear fusion powers the Sun

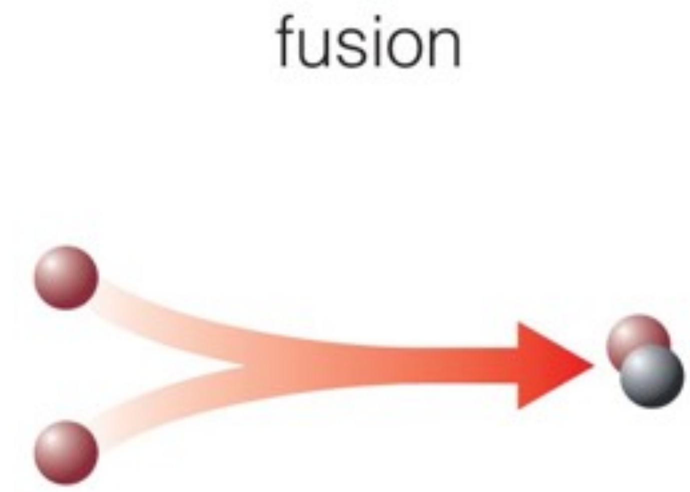


Fission

- Weak nuclear force

- Big nucleus splits into smaller pieces.

- (Example: nuclear power plants)



- Strong nuclear force

Fusion

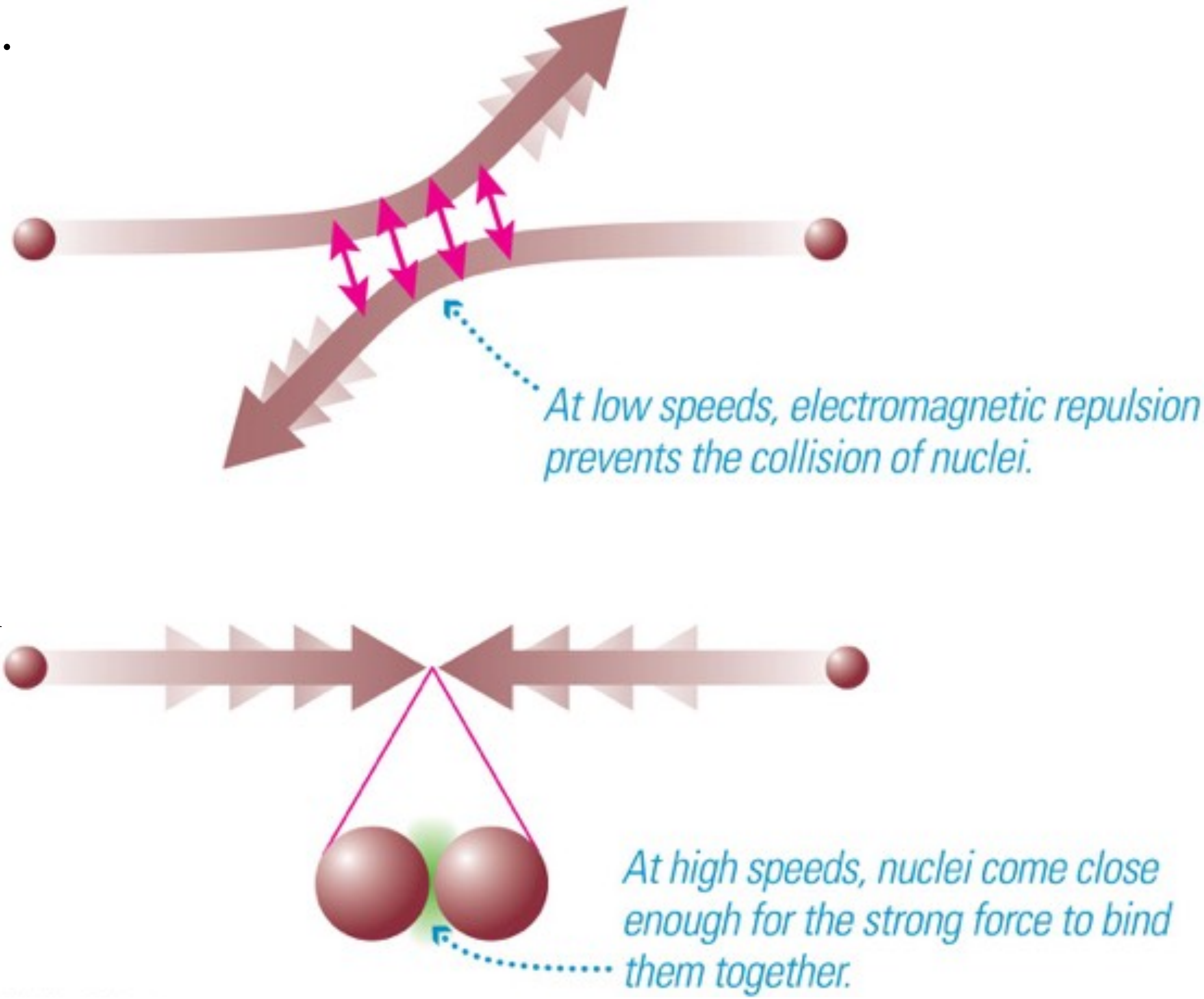
- Small nuclei stick together to make a bigger one.

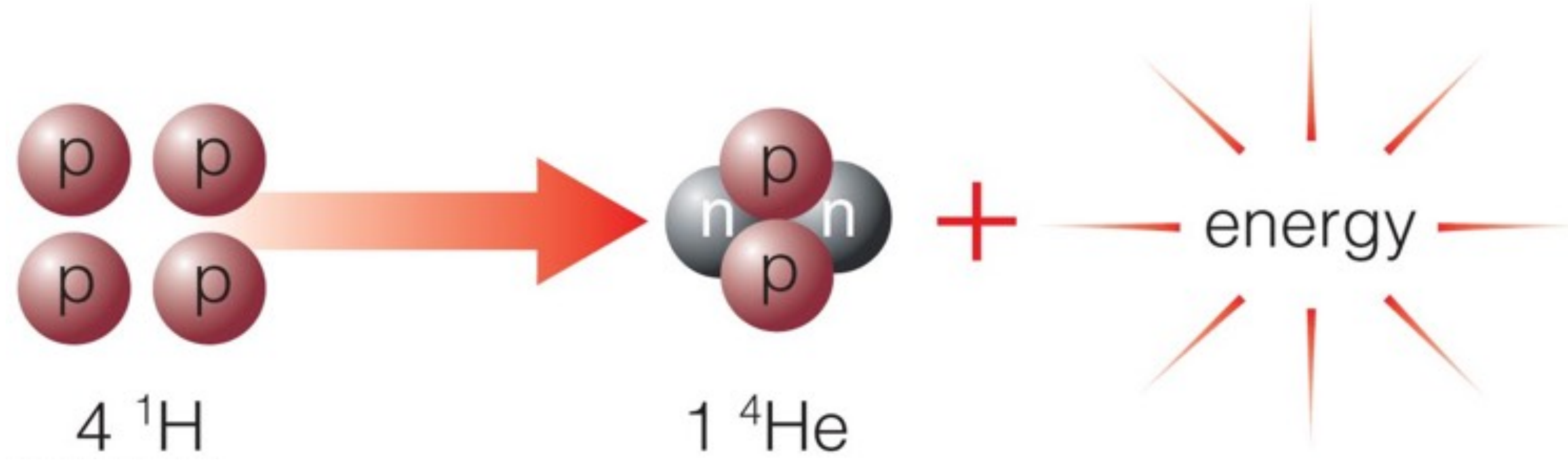
- (Example: the Sun, stars)

High temperatures enable nuclear fusion to happen in the core.

Positively charged protons repel each other.

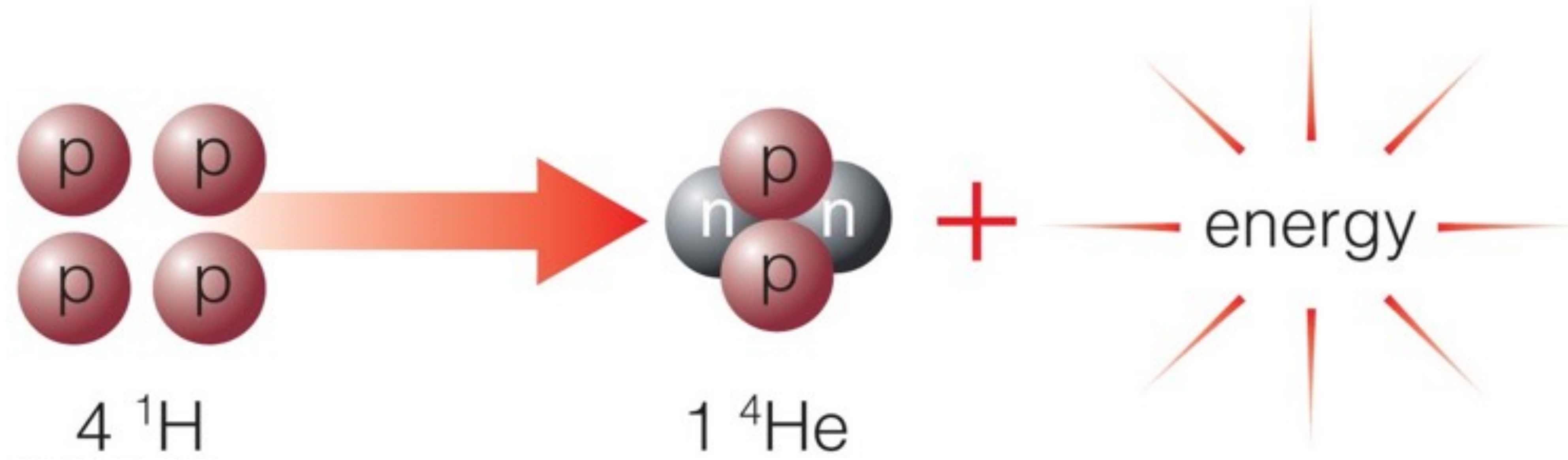
Fusion only happens when the strong nuclear
force is stronger than this repulsion, which only happens at very small separations. High temperatures are required to move fast enough to get that close.





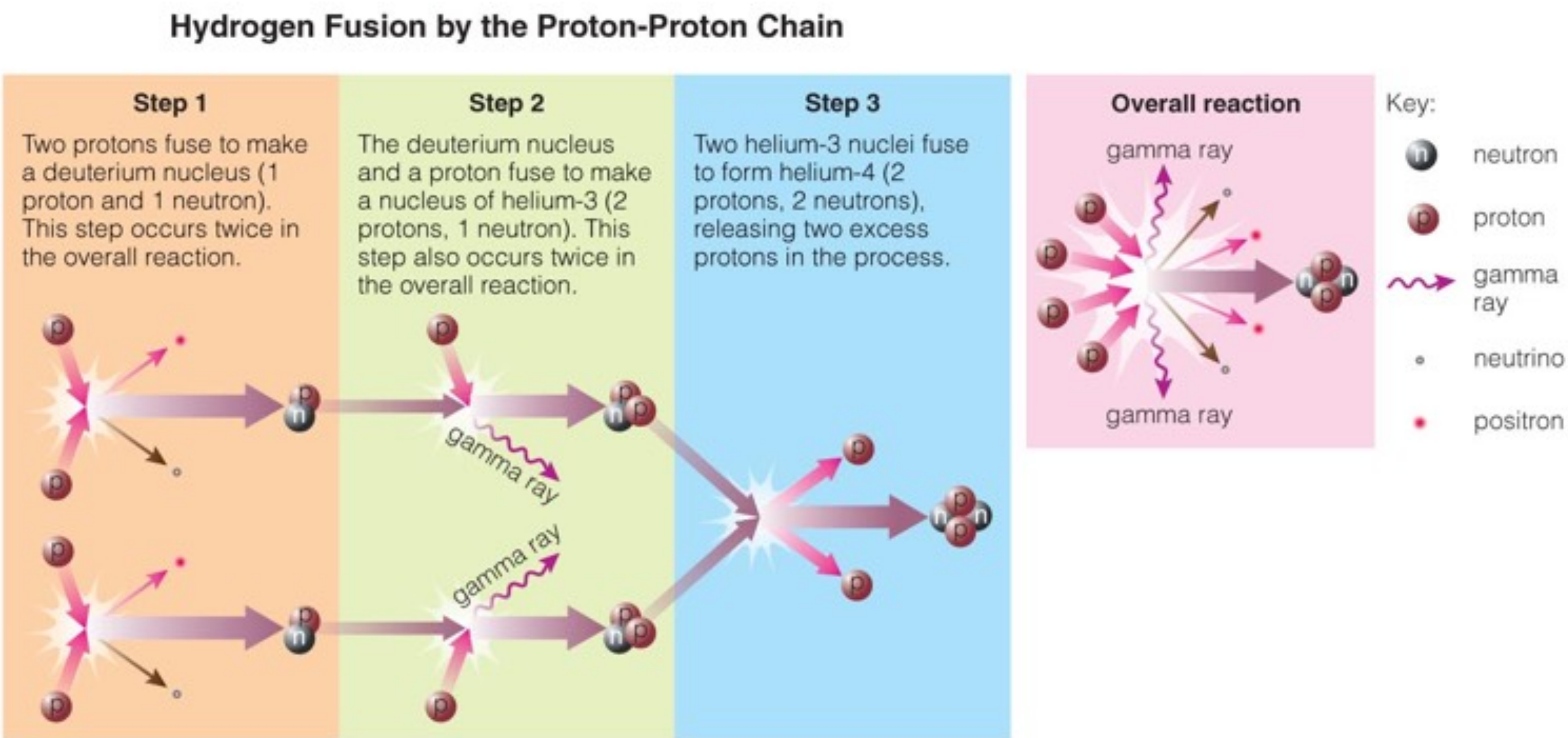
- The Sun releases energy by fusing four hydrogen nuclei into one helium nucleus.

- 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.



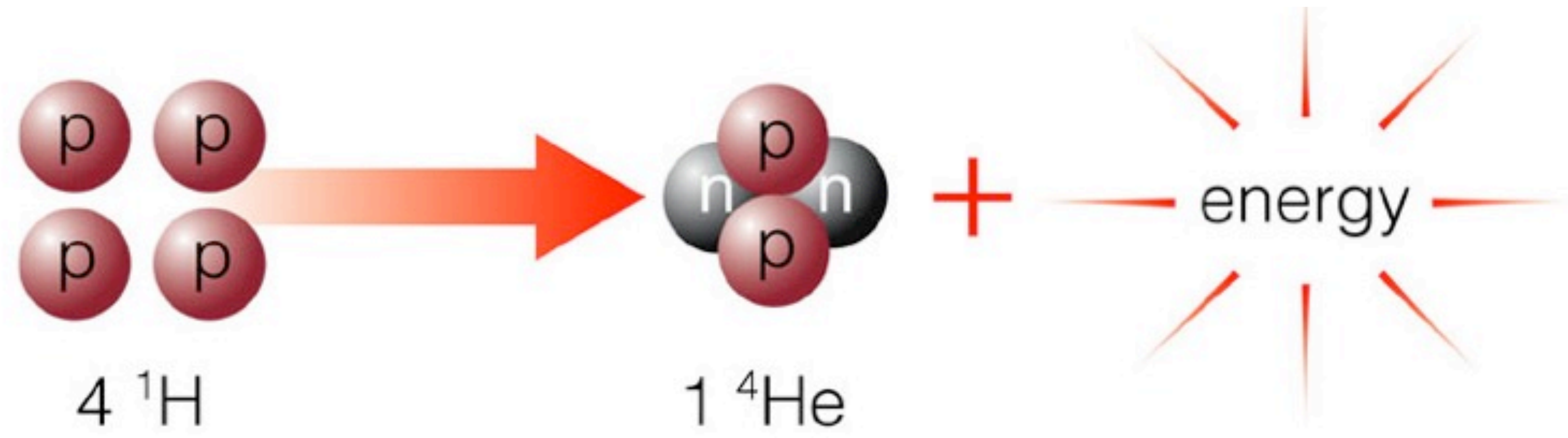
Interactive Figure

- 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

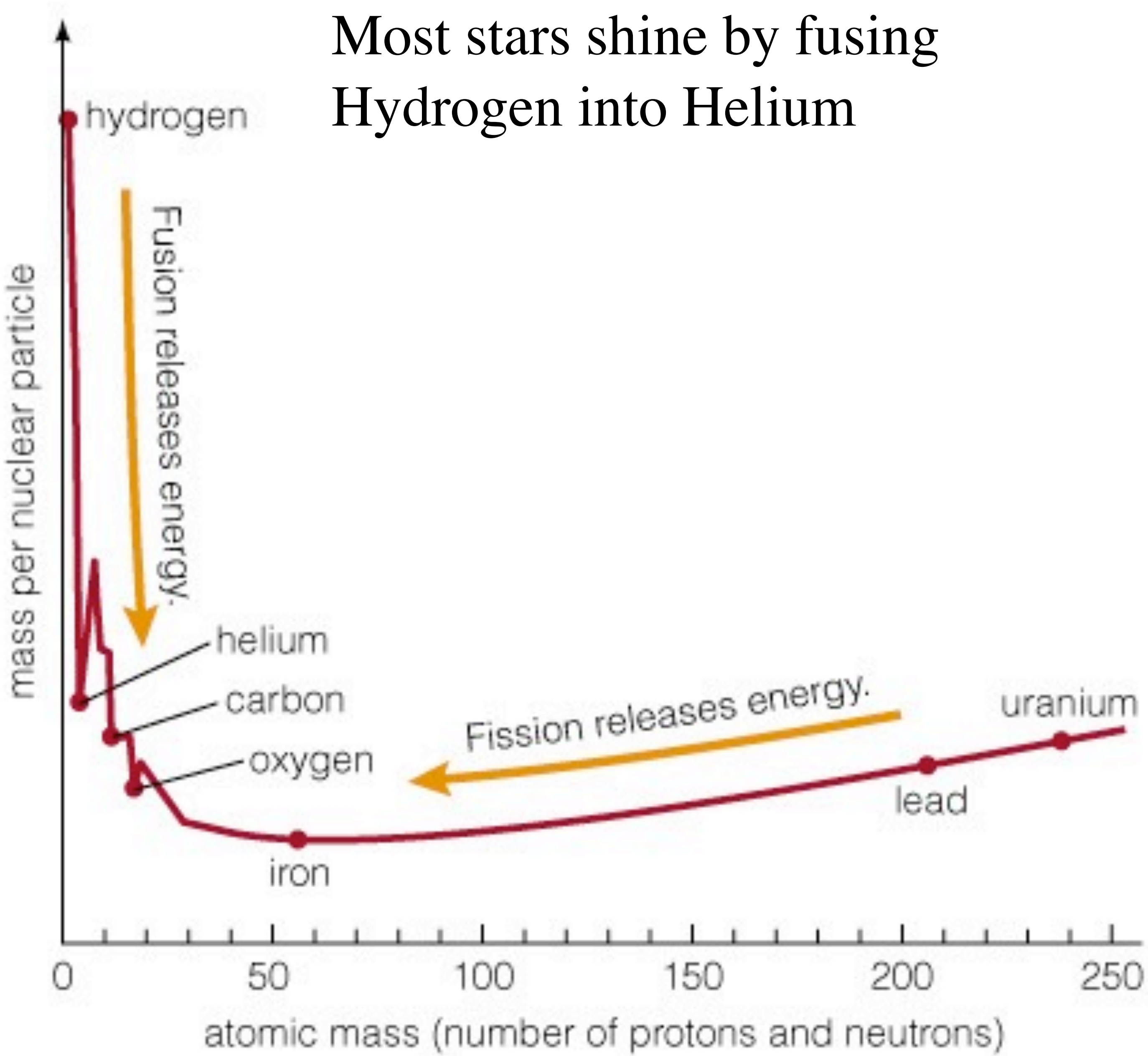
2 gamma rays

2 positrons

2 neutrinos

$$E = mc^2 :$$

Total mass is 0.7% lower.



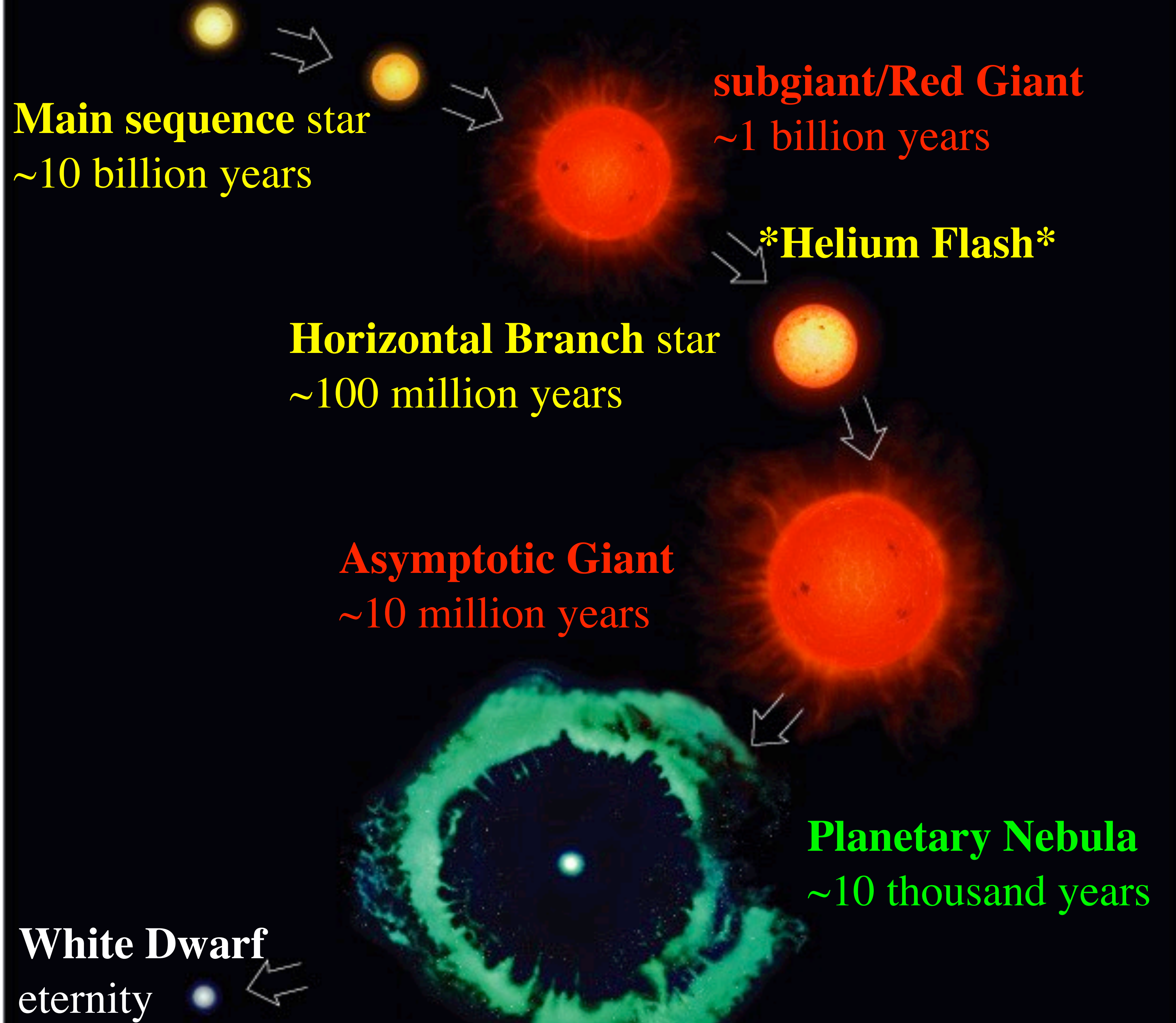
Most stars shine by fusing Hydrogen into Helium

Iron has the most stable nucleus.

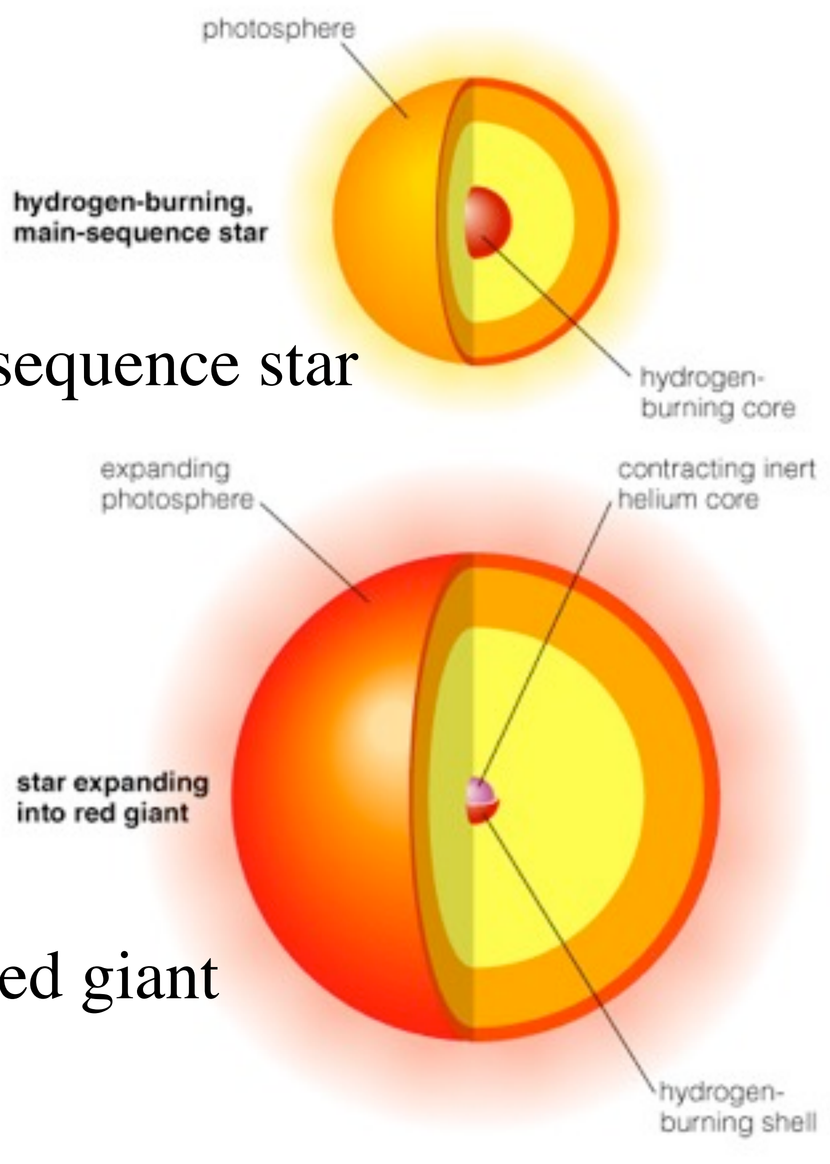
Fusion up to iron releases energy.

For elements heavier than iron, Fission releases energy.

The life stages of the sun



Red Giant: after hydrogen fuel is spent



main sequence star

red giant

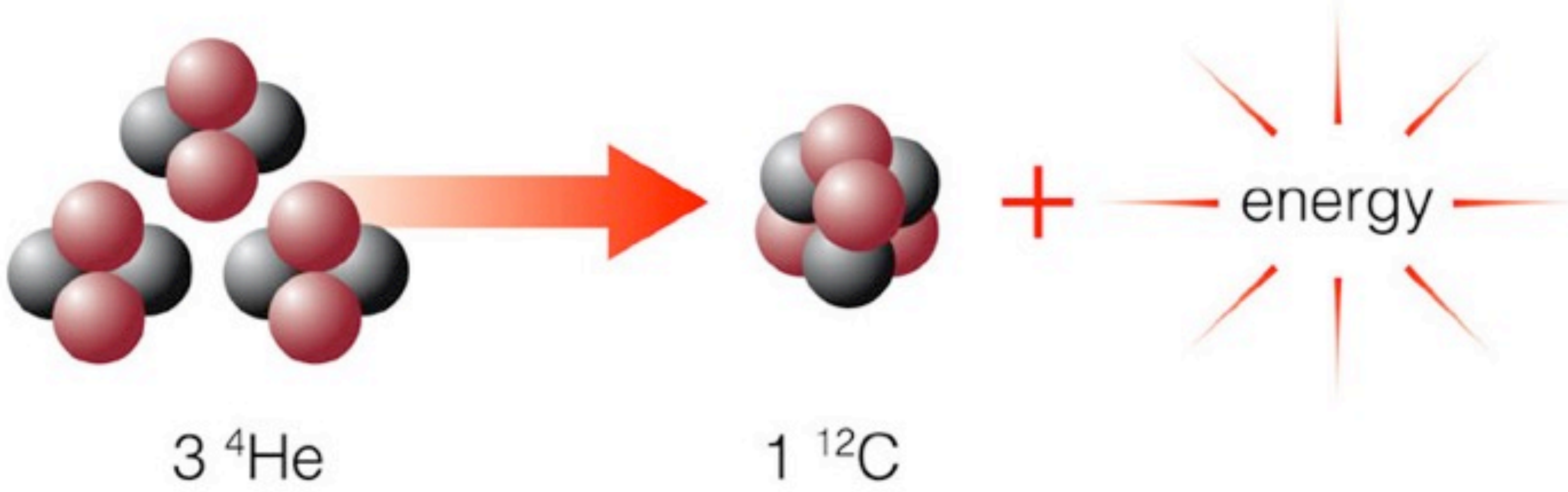
- The sun will eventually exhaust the H fuel in its core
- Without further fusion, the core contracts. H begins fusing to He in a shell around the core.
- As the core contracts, temperature increases, nuclear reaction rates increase (in the shell), and the Radius and Luminosity increase.

Helium Flash

- The core continues to shrink and heat as the rest of the star expands and becomes more luminous.
  - Ascends giant branch for a billion years

- At a critical temperature and density, helium fusion suddenly begins.
  - The Helium Flash

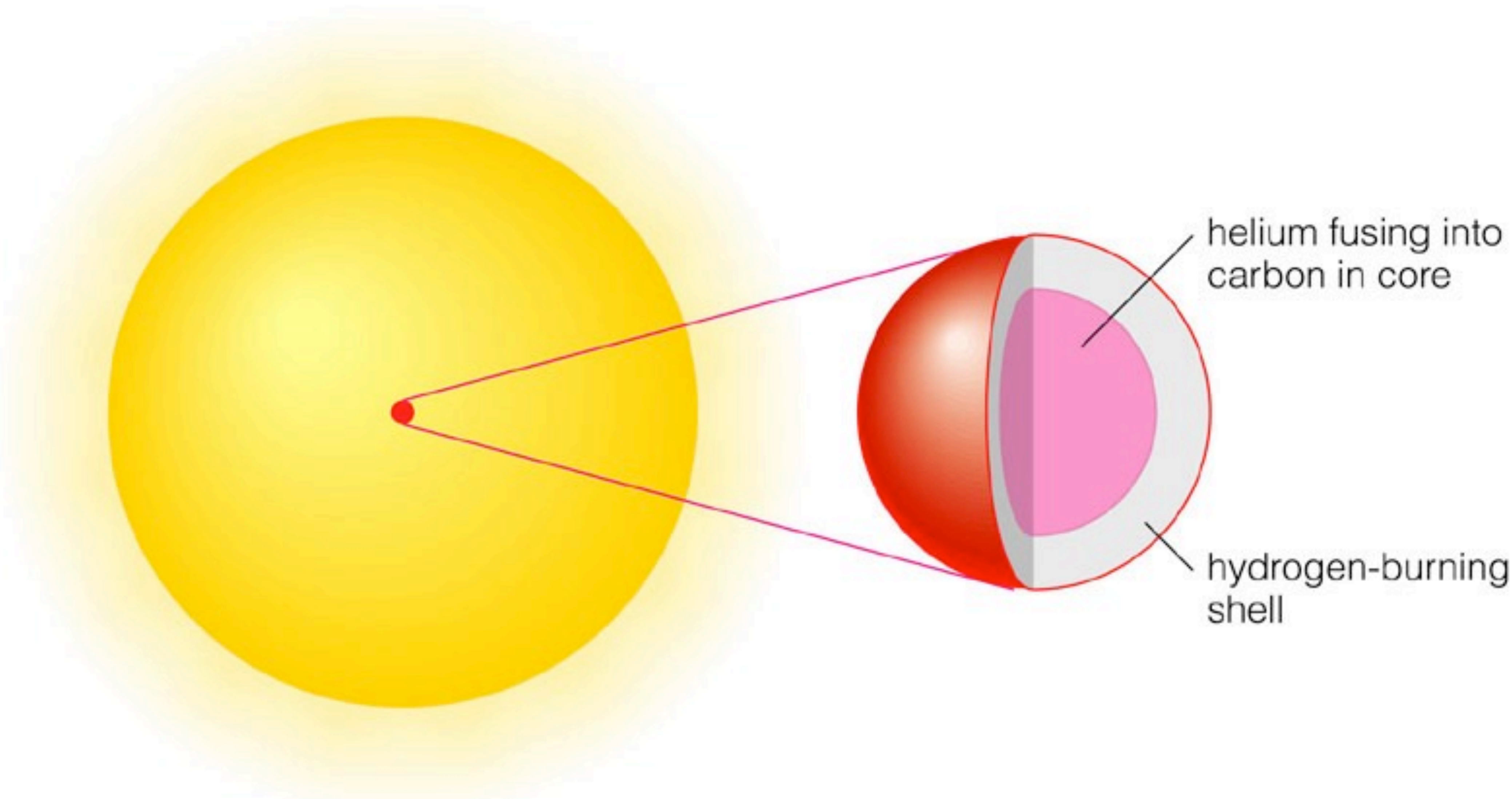
- The star evolves rapidly, finding a new equilibrium with He burning in core and H burning in a shell surrounding the core.



Helium fusion tough—larger charge leads to greater repulsion. Worse, the fusion of two helium nuclei doesn't work; ^{4}He more stable than Beryllium (^{8}Be).

Need three ^{4}He nuclei to make carbon (^{12}C).

Only works because of resonant state of carbon predicted by Fred Hoyle.



Helium burning stars line for a brief time fusing Helium in the core and Hydrogen in a shell.

Double-Shell Burning

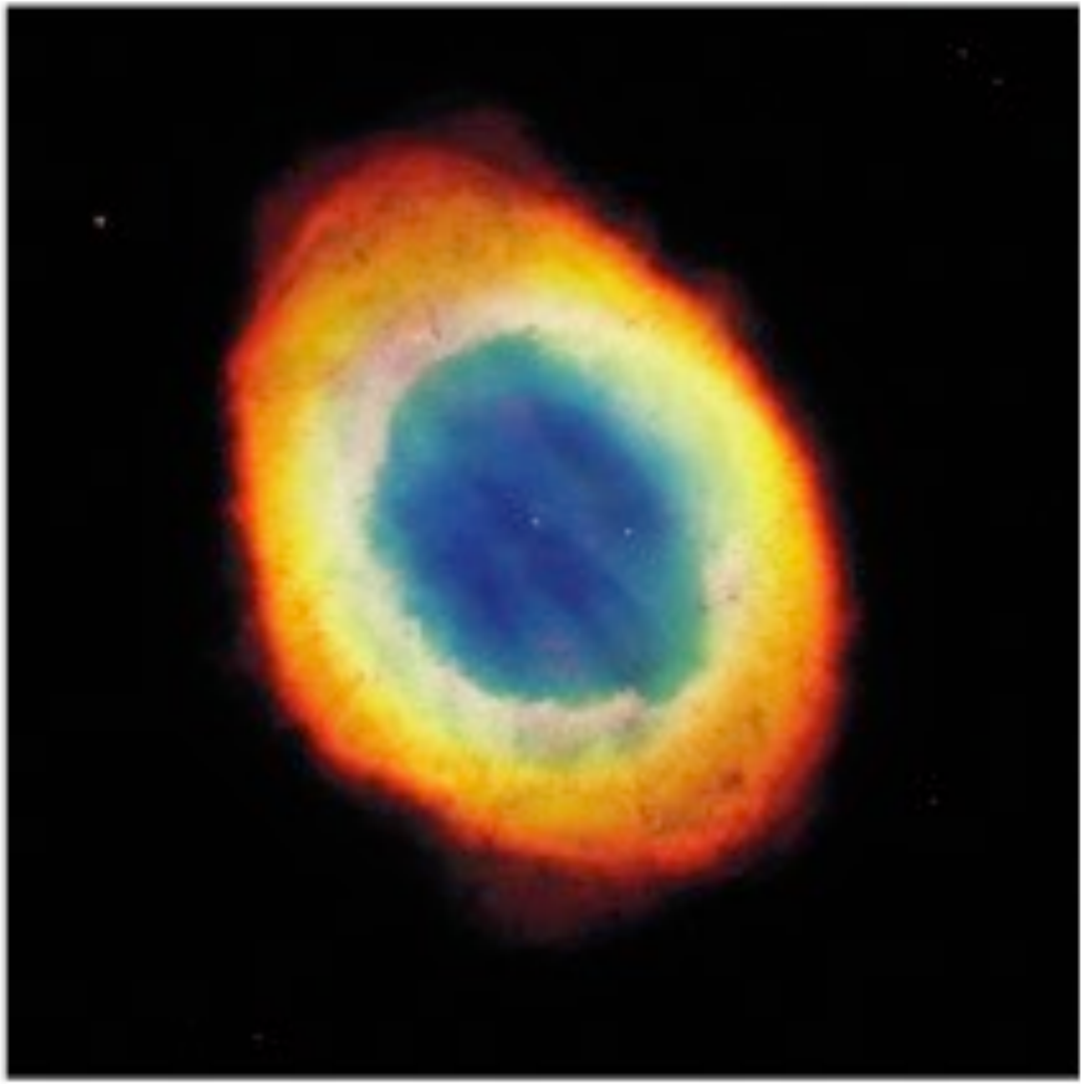
- Helium also gets used up. He continues to fuse into carbon in a shell around the carbon core, and H fuses to He in a shell around the helium layer.

- The star expands again, ascending the **Asymptotic Giant Branch**

- This double-shell-burning stage never reaches equilibrium—the fusion rate periodically spikes upward in a series of *thermal pulses*.

- With each spike, some of the outer layers may be lost to space.

Planetary Nebulae

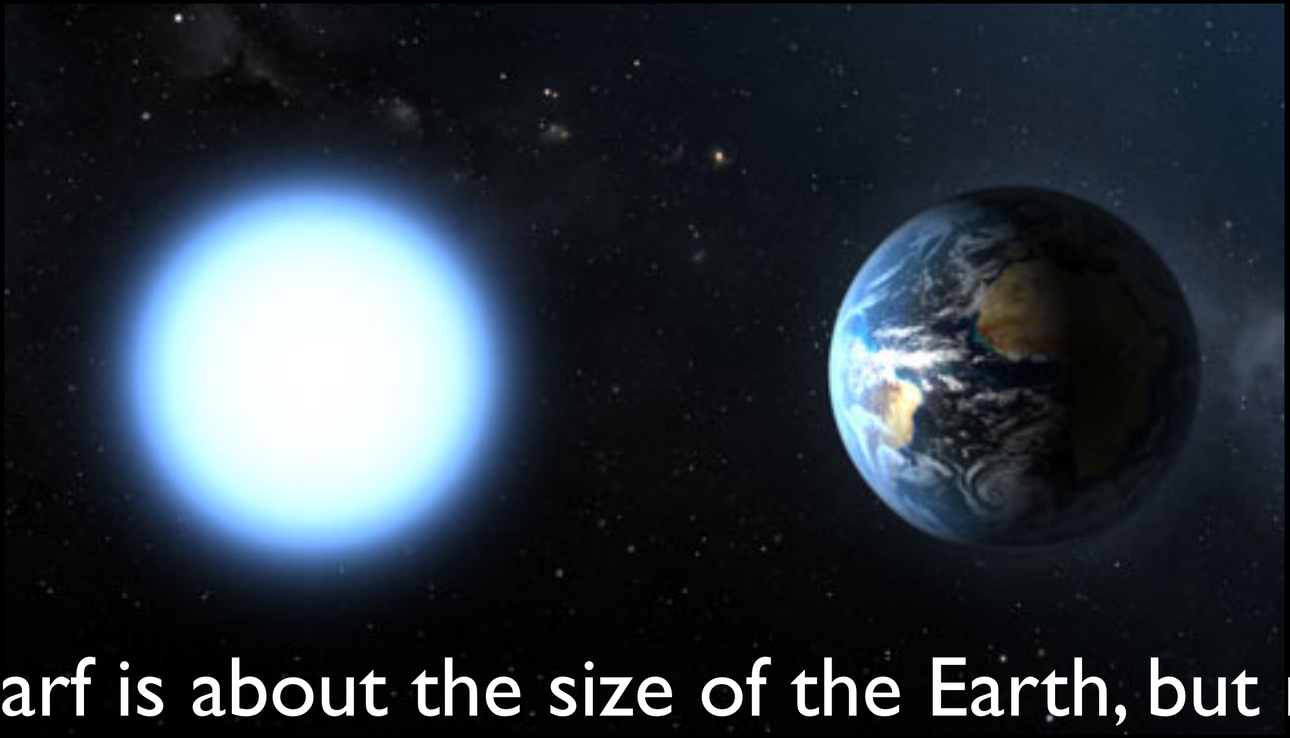


- Double-shell burning ends with a pulse that ejects the H and He into space as a *planetary nebula*.
- The core left behind becomes a white dwarf.

End of Fusion

- Fusion progresses no further in a low-mass star because the core temperature never grows hot enough for fusion of heavier elements (some He fuses to C to make oxygen).
- Degeneracy pressure supports the white dwarf against gravity.
- White dwarf spend eternity cooling off, eventually going dark entirely.

Ultimately, the sun will lose about half its mass to space, leaving the other half in a dense core called a white dwarf.



A white dwarf is about the size of the Earth, but much more massive, being a million times more dense.
It is the cinder left over when a star dies.
It shines by residual heat, but after billions of years will fade into oblivion. This is the ultimate fate of our sun.