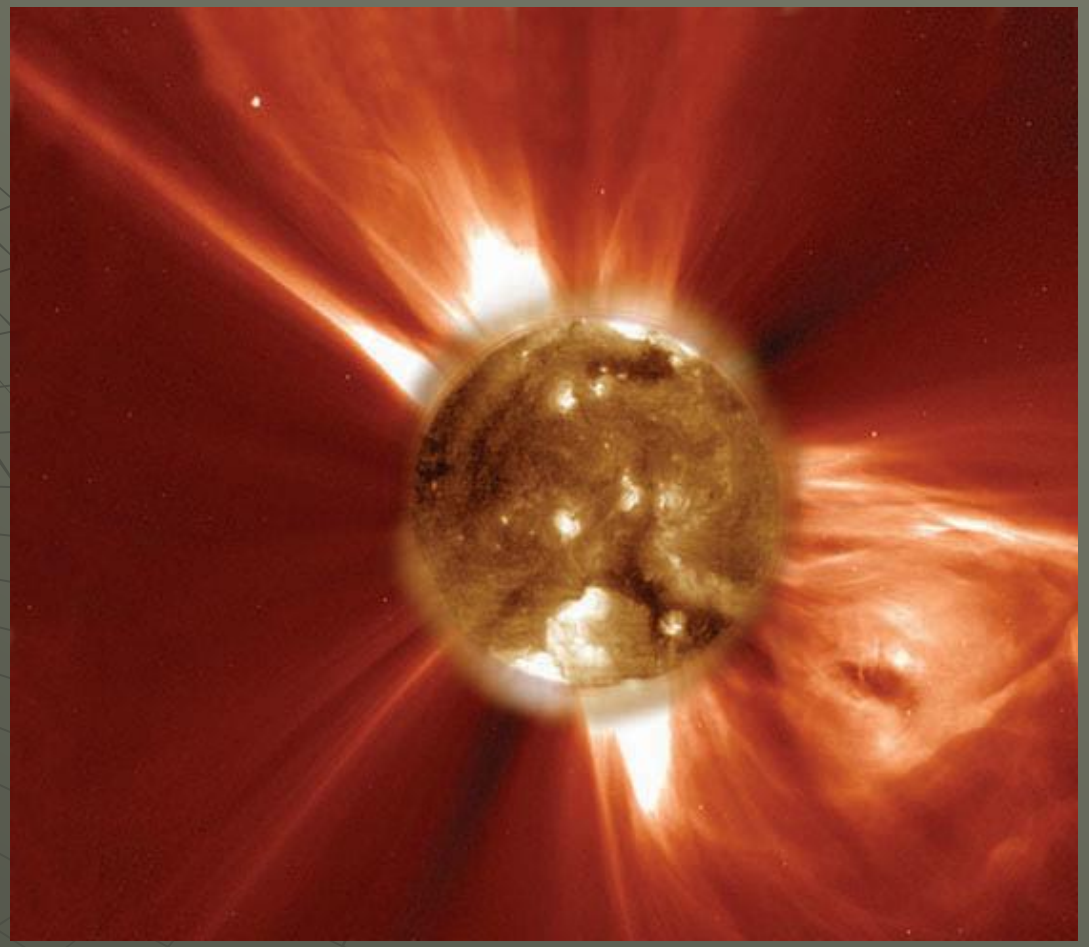
The Sun

- Objective
  - Energy source
  - Structure
  - Magnetic field

The Sun

- The Sun is the only SS object that emits significant amounts of light
- It's spectrum is close to that of a blackbody with a temperature of 5800 K
- This high temperature leads to a high flux
  - ($F=\sigma T^4$)
  - the large size leads to a high *luminosity*
  - $L_\odot=4 \times 10^{26}$ (J/s)
  - all H are ionized (p^+ and e^-)
- What is the energy source!?!?!?
  - Sun is about 4.5 billion years old
  - what process could sustain it so long?



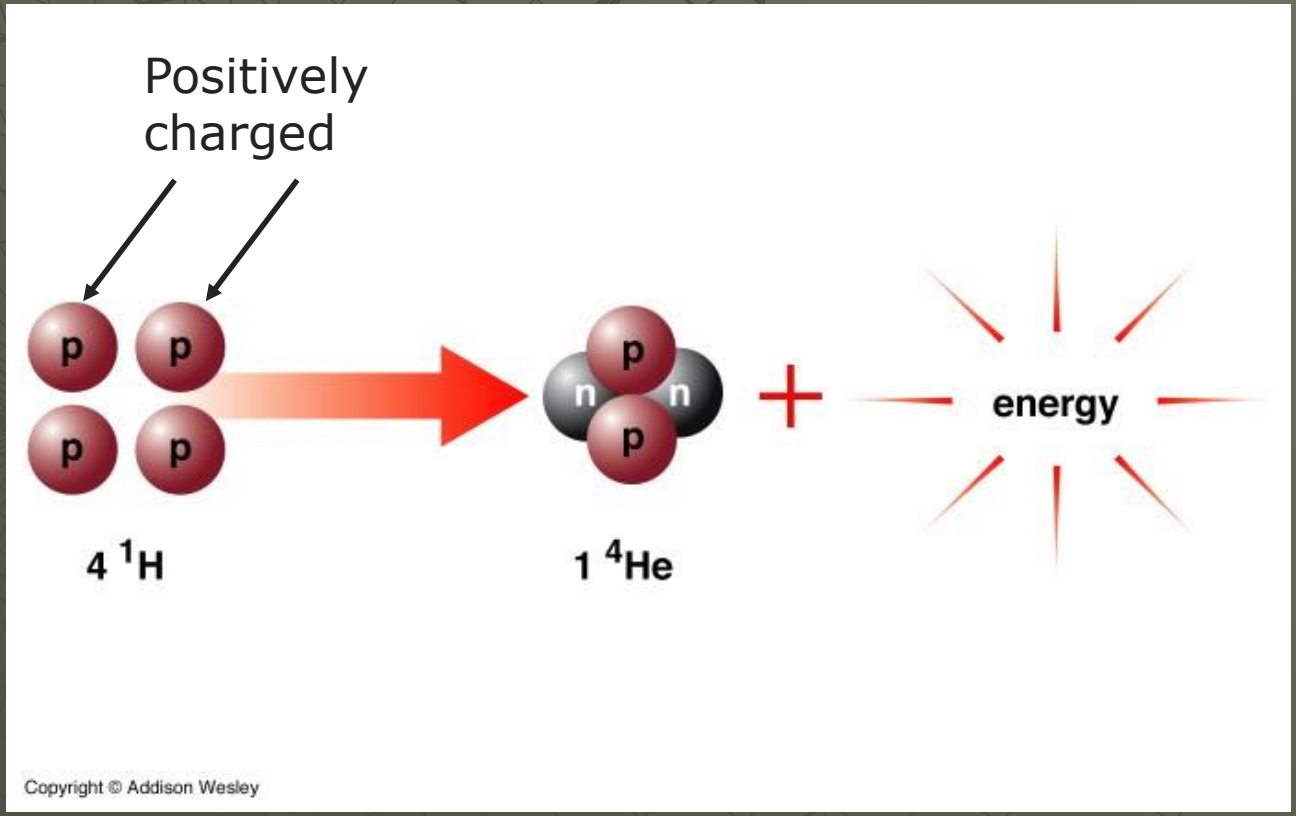
How does the sun "burn"?

- Geologic evidence shows Earth ≈ 4.5 billion years old
- What energy source could fuel sun for this time?
  - Chemical energy (fossil fuels)? 5×10^7 J/kg
    - 5×10^7 J/kg * 2×10^{30} kg = 1×10^{38} J total
    - 1×10^{38} J/4×10^{26} J/s = 5000 years!
  - Gravitational contraction?
    - 1×10^{41} J (complicated) → 8 million years
  - Fission? 1×10^{14} J/kg
    - Only 25% hot enough → 1 billion years

What's the answer?

- Only process that can provide the necessary energy for so much time: NUCLEAR FUSION

- Fusion: conversion of lighter elements into heavier ones



EXAMPLE

- 4 hydrogen atoms combine to make 1 helium
  - Hydrogen: 1 proton, 1 electron
  - Helium: 2 protons, 2 neutrons, 2 electrons
- A great deal of energy given off... WHY?!?!

Energy Production in Stars

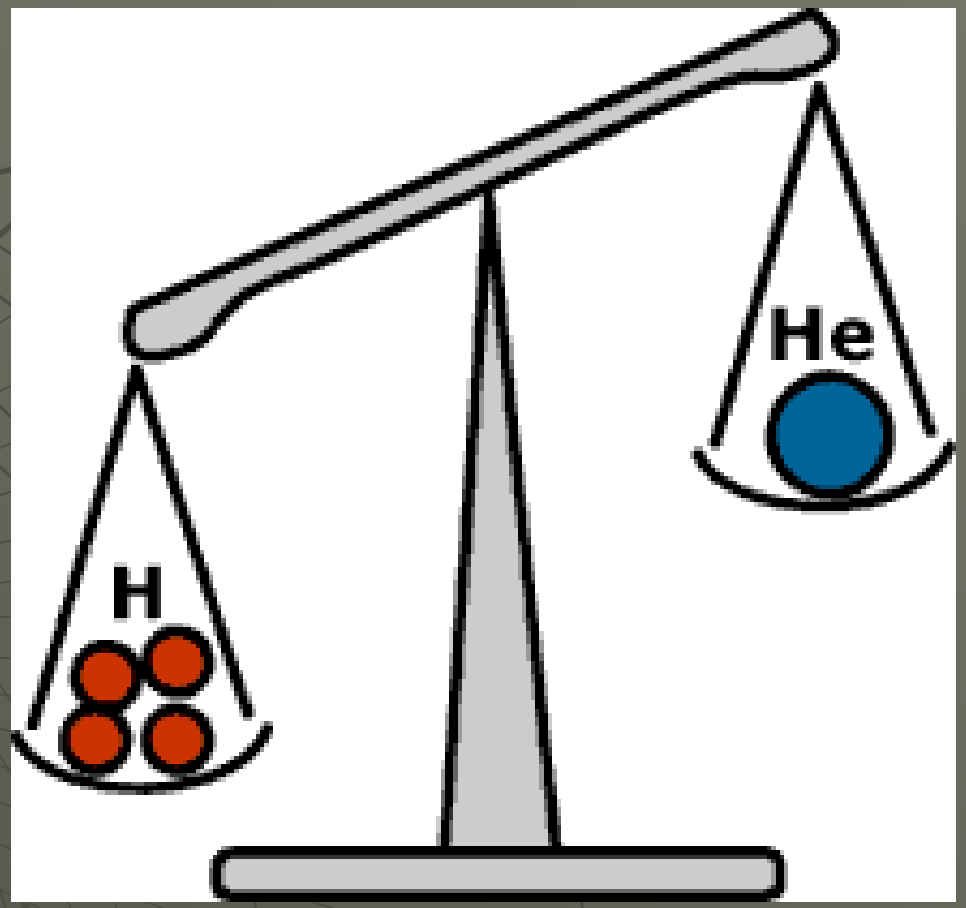
In 1905, a young patent clerk
changed the way we saw the world…forever.

What happened to the mass?

- Einstein: $E = mc^2$
- Mass & energy are different forms of same thing
- This energy is given off in sun's core, in form of heat & neutrinos

IMAGINARY DEMO

- 4 H = 4.0313 amu
- 1 He = 4.0026 amu
- Δm = 0.03 amu
- $4H/\Delta m$ = 0.007 = 0.7%
  - Of mass is turned into energy



Sun's lifetime

- Sun's mass: 2×10^{30} kg
  - 75% of the Sun is Hydrogen
  - Only 25% of the sun is hot enough for fusion
  - Only 0.7% (0.007) of mass is turned into E
- How long could sun "burn" hydrogen fuel?
  - 2×10^{30} kg * 0.25 * 0.75 * 0.007 = 2×10^{27} kg
  - $E = mc^2 = 2 \times 10^{27}$ kg * $(3 \times 10^8)^2 = 2 \times 10^{44}$ J
  - Time = 2×10^{44} J/4×10^{26} J/s = 6×10^{17} seconds
    - 10 billion years!

The Sun- Neutrinos

- *Neutrinos* are particles that are almost massless, have no charge, and interact only very weakly with matter

- Neutrinos are formed in great numbers during fusion (10^{38} per second in the Sun!)

- We have detected these coming from the Sun in large numbers, strongly supporting that there is nuclear fusion going on in the core

DISCUSSION QUESTIONS

- It’s not all that easy to fuse 4 hydrogen atoms into a helium atom. Why might it be difficult to get the process started by bringing two hydrogen atoms together?
- How could stars overcome this difficulty?
- Take 5 mins to discuss

We already know the sun's "surface temp"

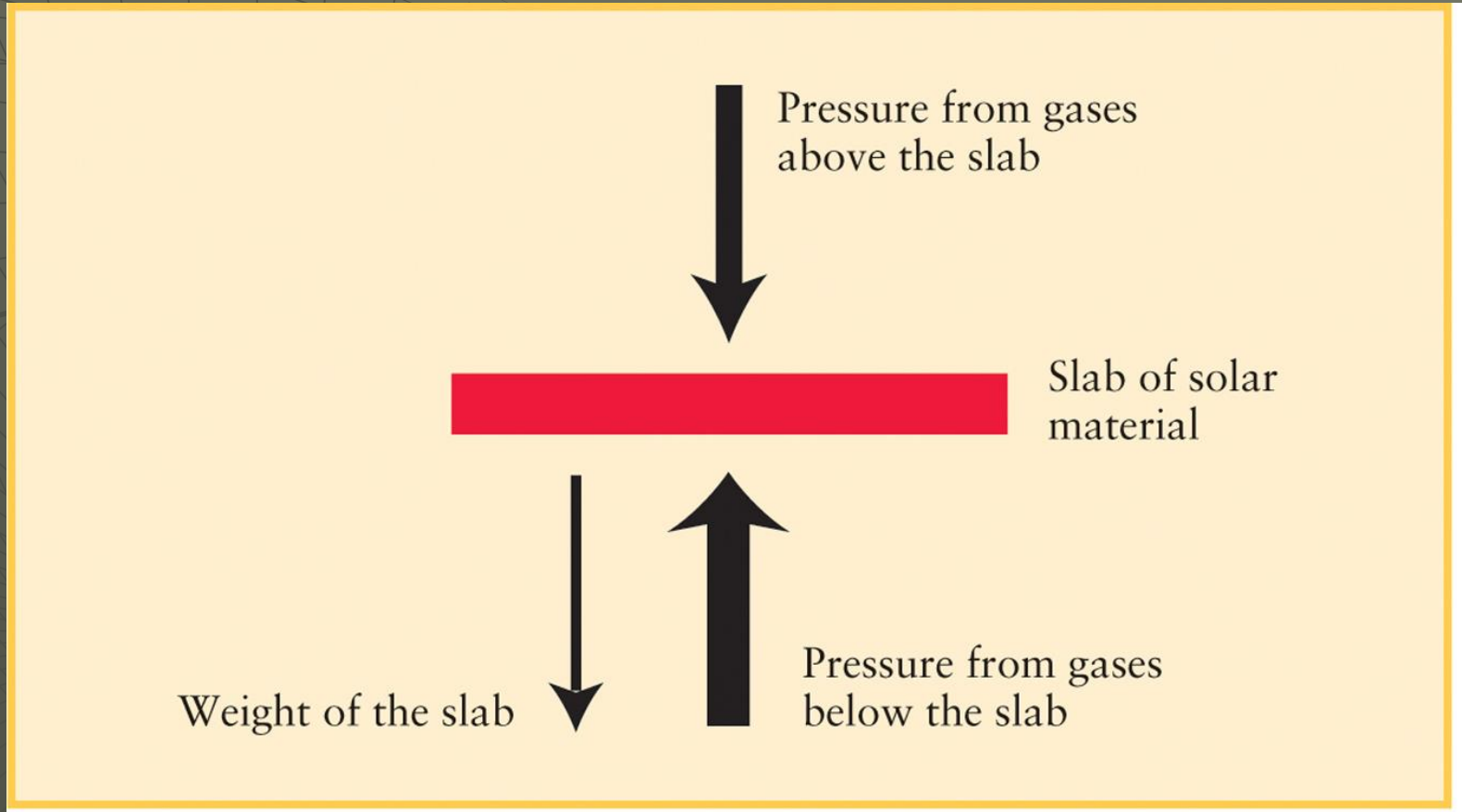
- At core: In order to generate nuclear fusion, density must be **extreme**
  - Gravity & pressure take care of this
- Temperature must exceed 10^6 Kelvin!
  - Sun's core temperature: 15,000,000 K.
- Density: 160,000 kg/m^3
  - Density of water = 1000 kg/m^3

TPS

Structure

- All of that energy being produced in the core of the Sun
- Why doesn’t the Sun blow itself apart?

Hydrostatic Equilibrium

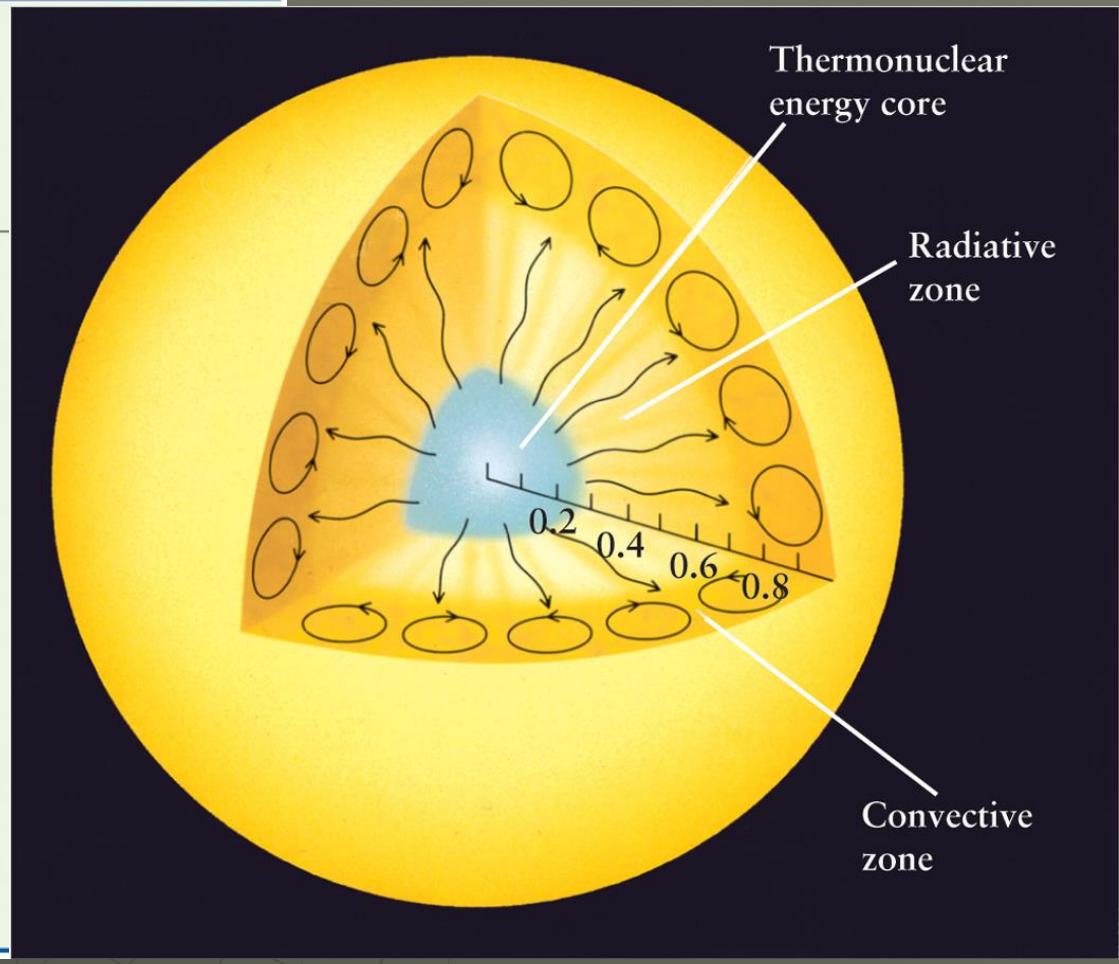


(a) Material inside the Sun is in hydrostatic equilibrium, so forces balance

Energy Transport

TABLE 9-1 A Theoretical Model of the Sun

Distance from the Sun's center (solar radii)	Fraction of luminosity	Fraction of mass	Temperature ($\times 10^6$ K)	Density (kg/m^3)
0.0	0.00	0.00	15.5	160000
0.1	0.42	0.07	13.0	90000
0.2	0.94	0.35	9.5	40000
0.3	1.00	0.64	6.7	13000
0.4	1.00	0.85	4.8	4000
0.5	1.00	0.94	3.4	1000
0.6	1.00	0.98	2.2	400
0.7	1.00	0.99	1.2	80
0.8	1.00	1.00	0.7	20
0.9	1.00	1.00	0.3	2
1.0	1.00	1.00	0.006	0.00030

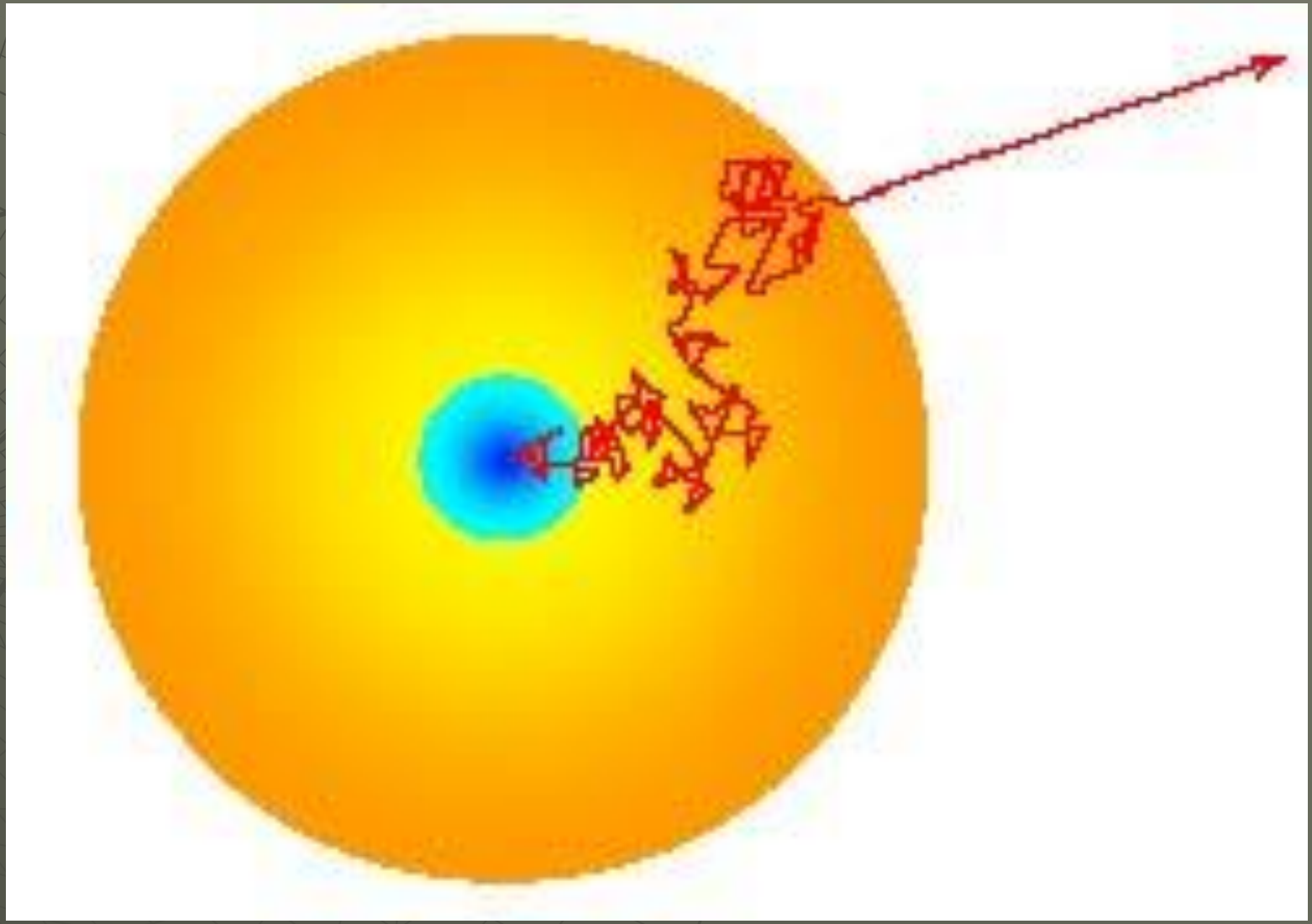


170,000 years !!!

Sun's density = 10^5 kg/m^3

Even photons take a
Long time to escape

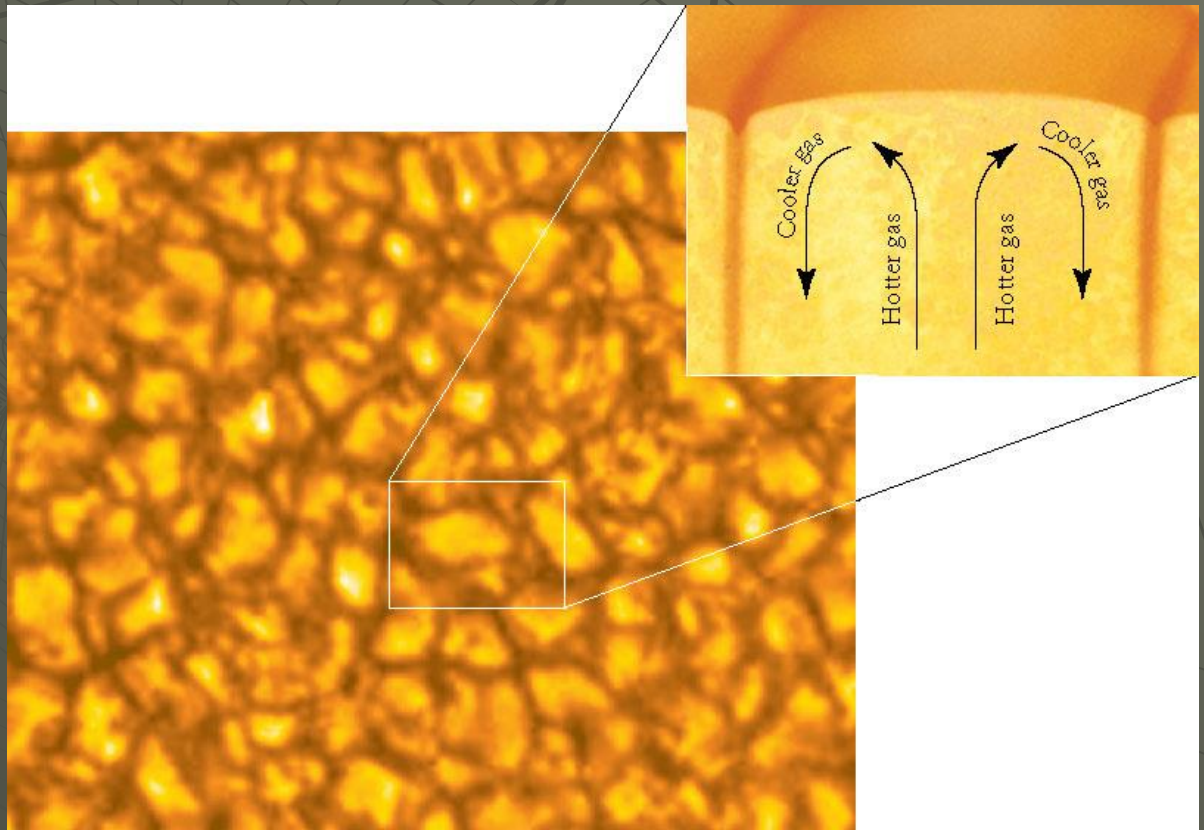
Kind of a drunk walk…



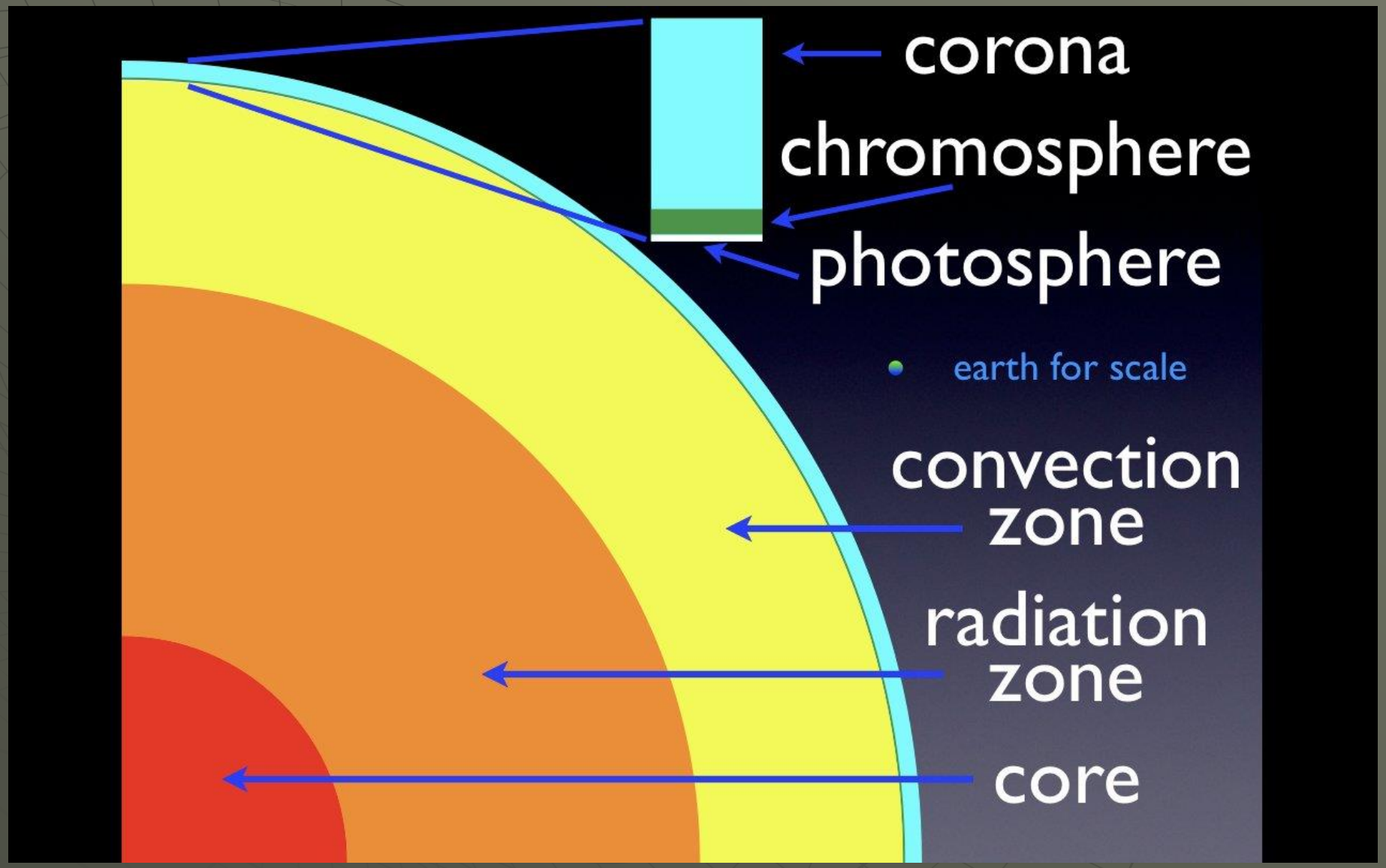
The Sun- Granulation

- Convection in the outer layers of the Sun causes *granules* to form

- These are just convection cells with cooler (fainter) gas sinking at the edges and hotter (brighter) gas rising in the center. Each cell is about 1000 km wide

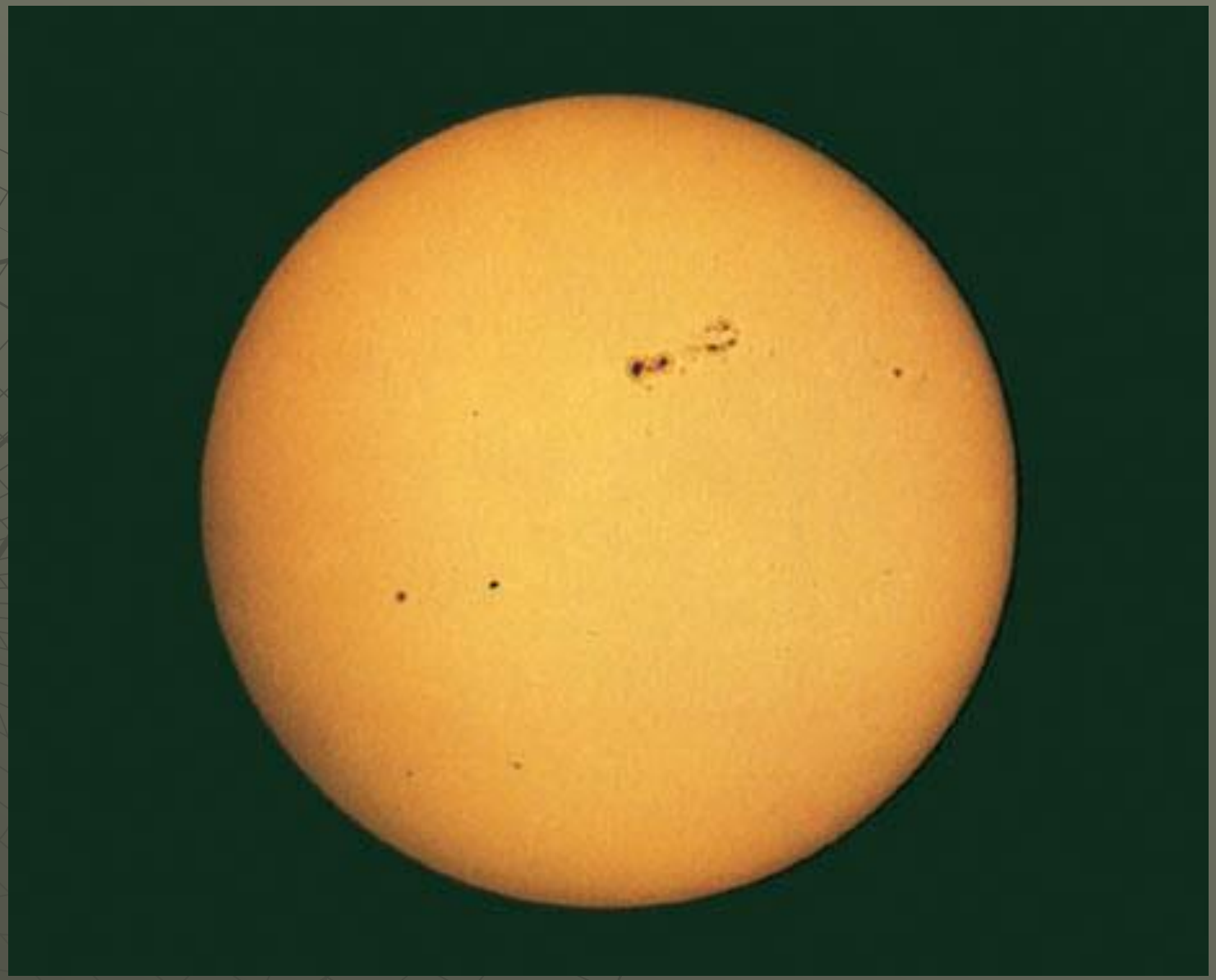


Sun's Layers


corona
chromosphere
photosphere
earth for scale
convection zone
radiation zone
core

Photosphere

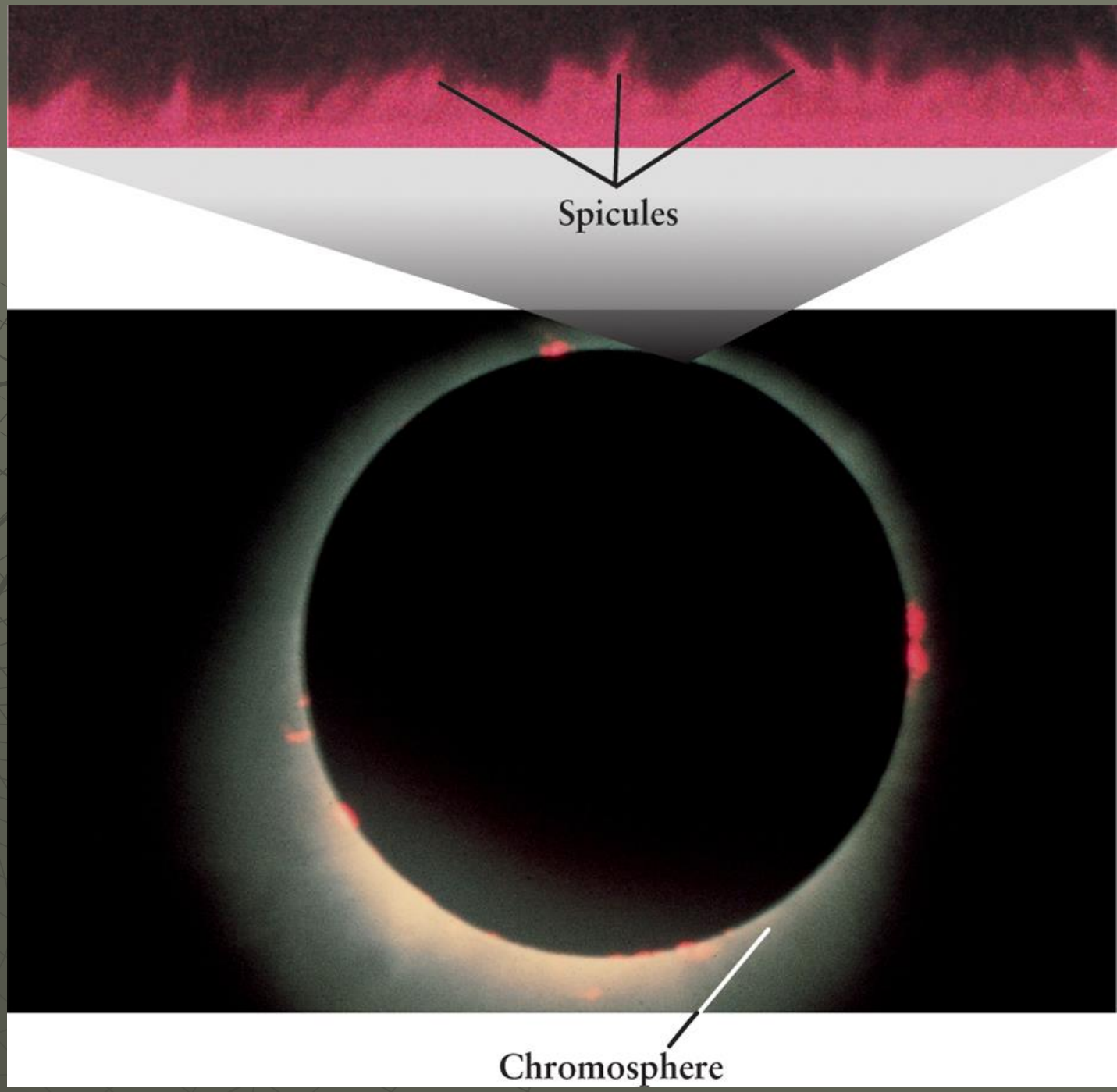
- Layer where the density is low enough to allow photons to escape
  - I'm free of my drunk walk!!! (sober)
  - Temp = 5800 K
- It makes the Sun appear as a solid disk, even though it is gaseous



Chromosphere

- Hotter than the photosphere!!!
  - 25,000 K
- Less dense than photosphere

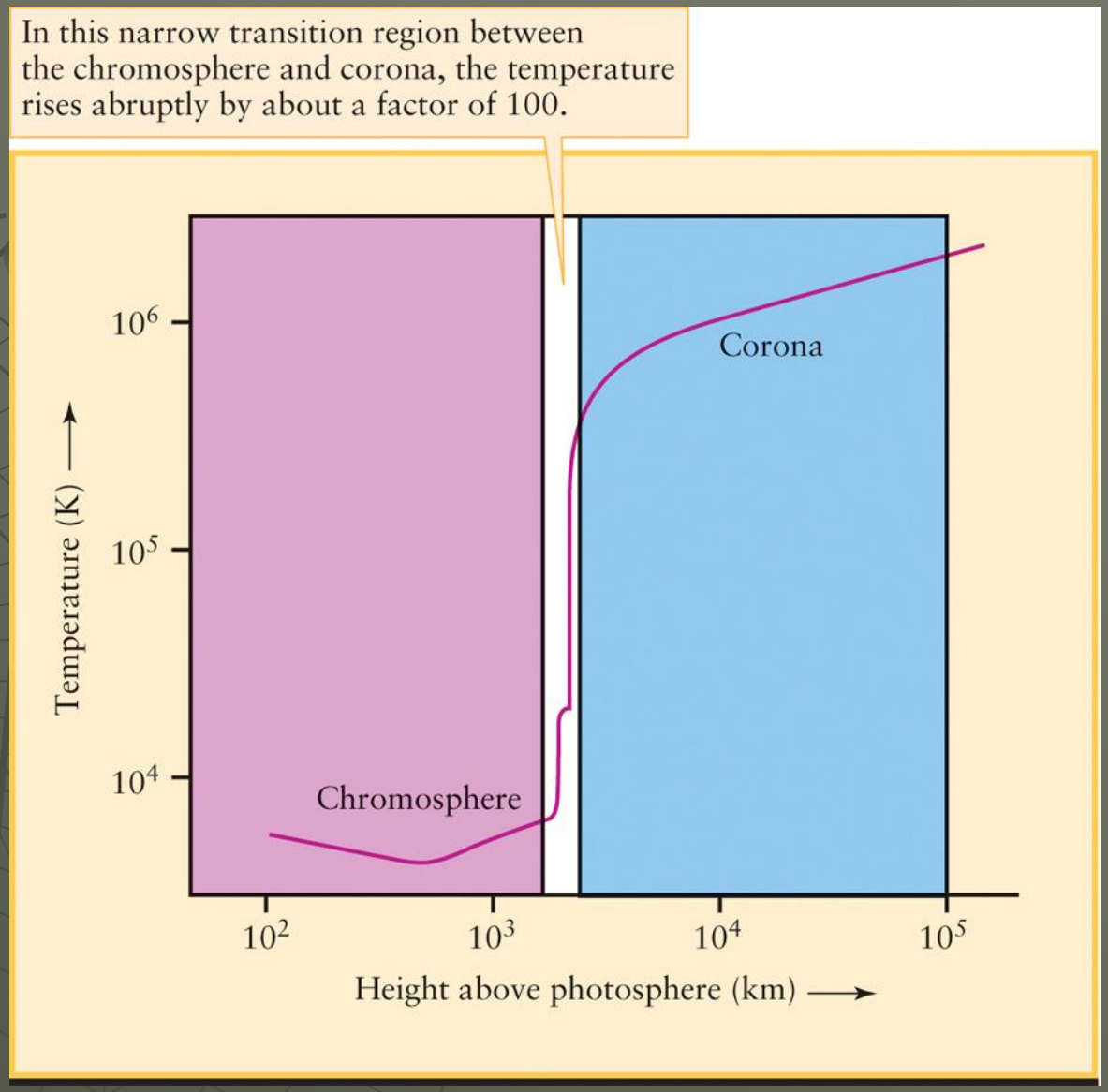
- Why???



Corona

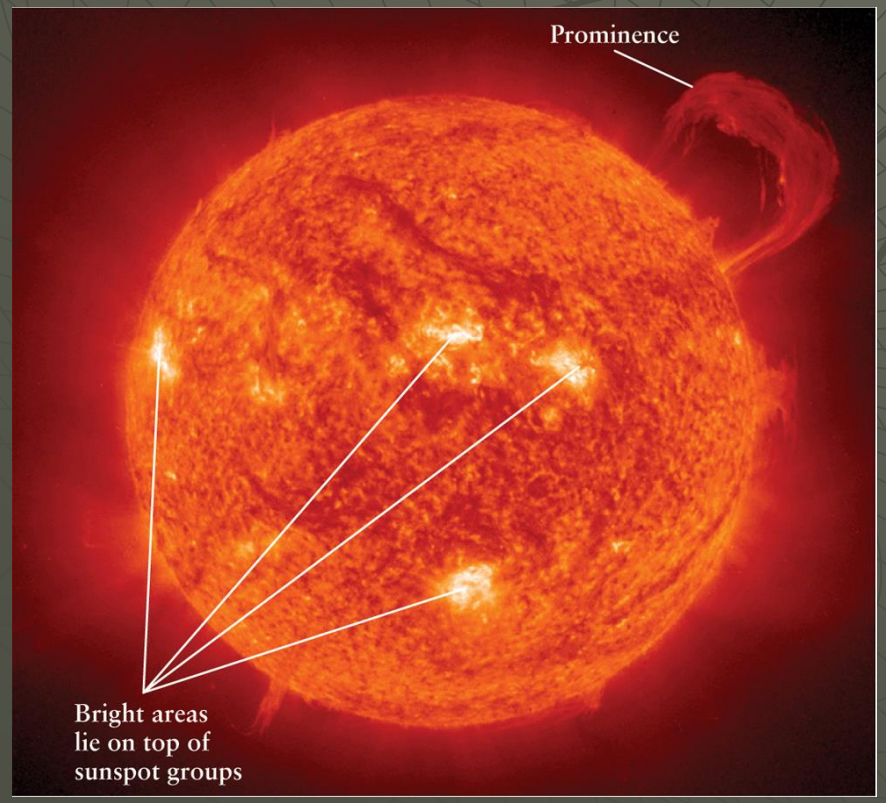
- Has an even higher temperature than the chromosphere!!!
  - 2 x 10^6 K!!!
- Less dense than chromosphere

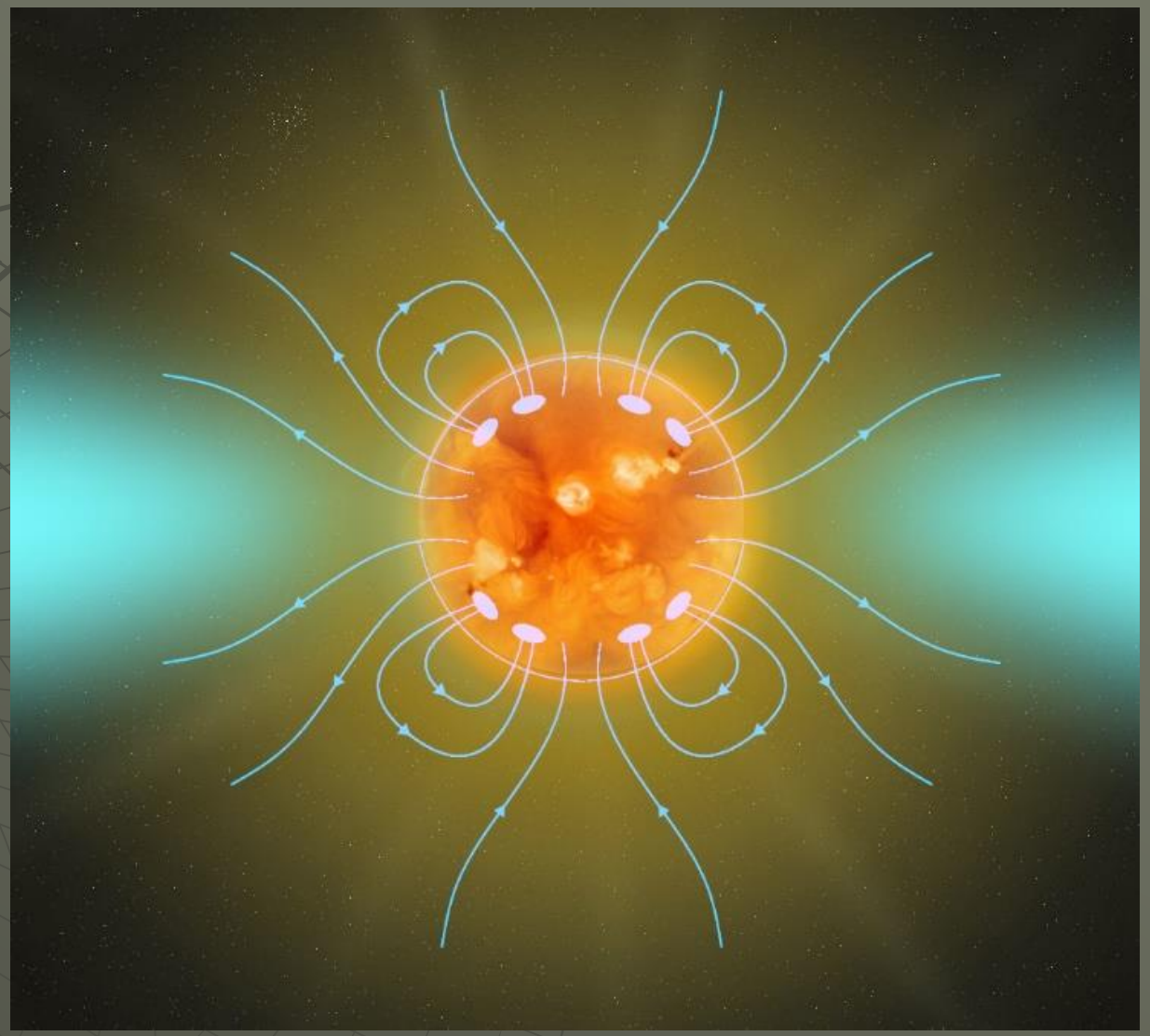
- Seriously, what is going on?
  - Any guesses???



Sun's Magnetic Field

- Almost the entire Sun is liquid charged particles
  - HUGE magnetic field!
  - Complicated magnetic field…

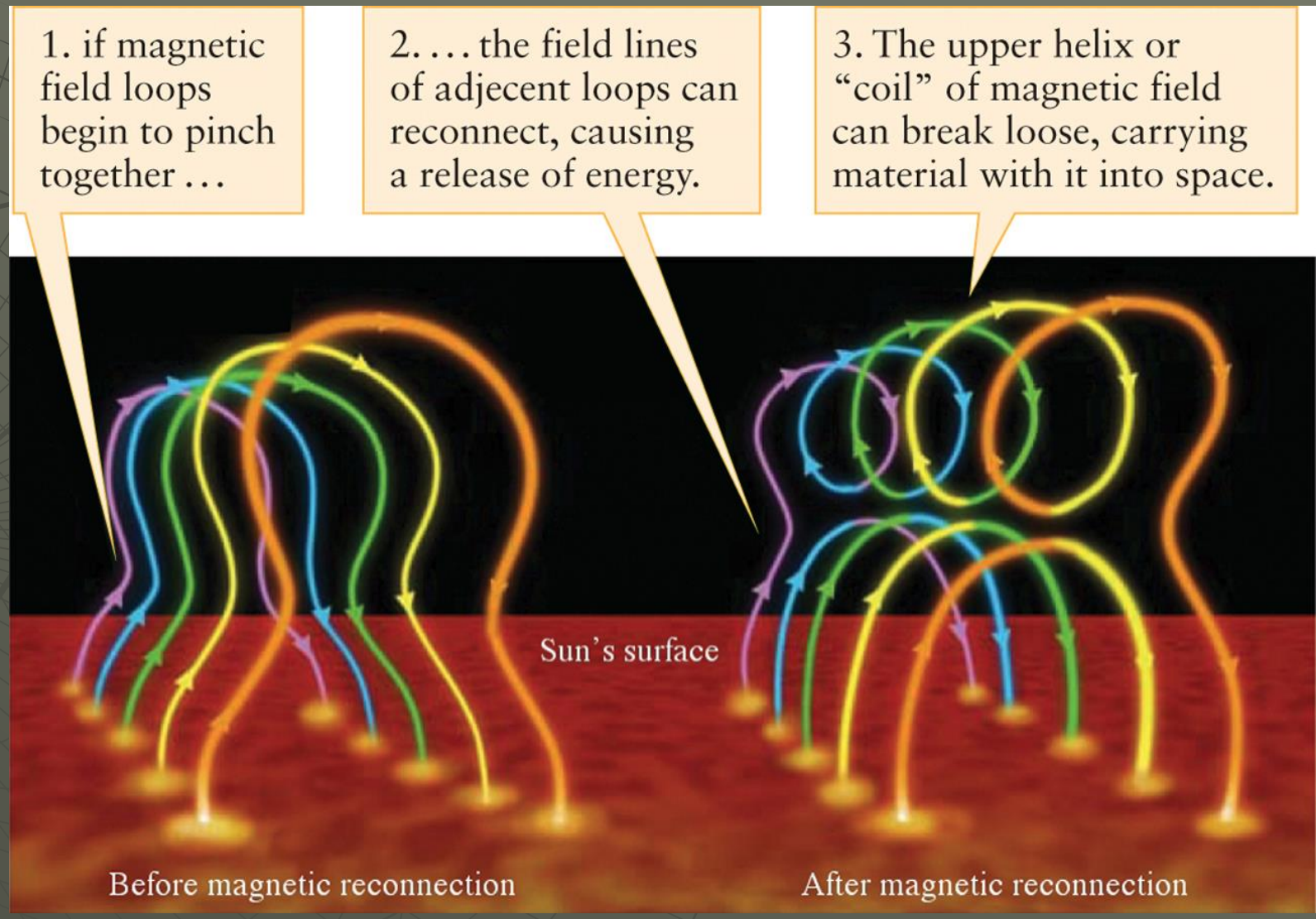




Mag Field Lines

- What happens if the field lines break or meet another line???
- Magnetic fields of this magnitude hold a lot of energy
  - As much as an energy plant in a million years.

Plasma follows the magnetic field lines

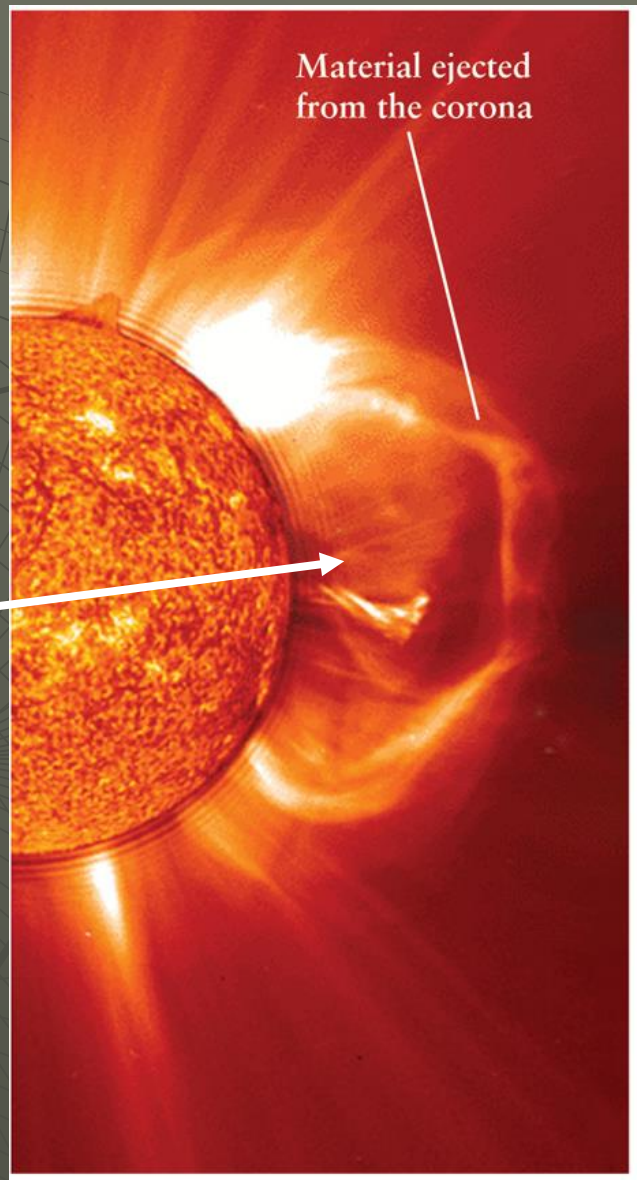


Coronal Mass Ejections!

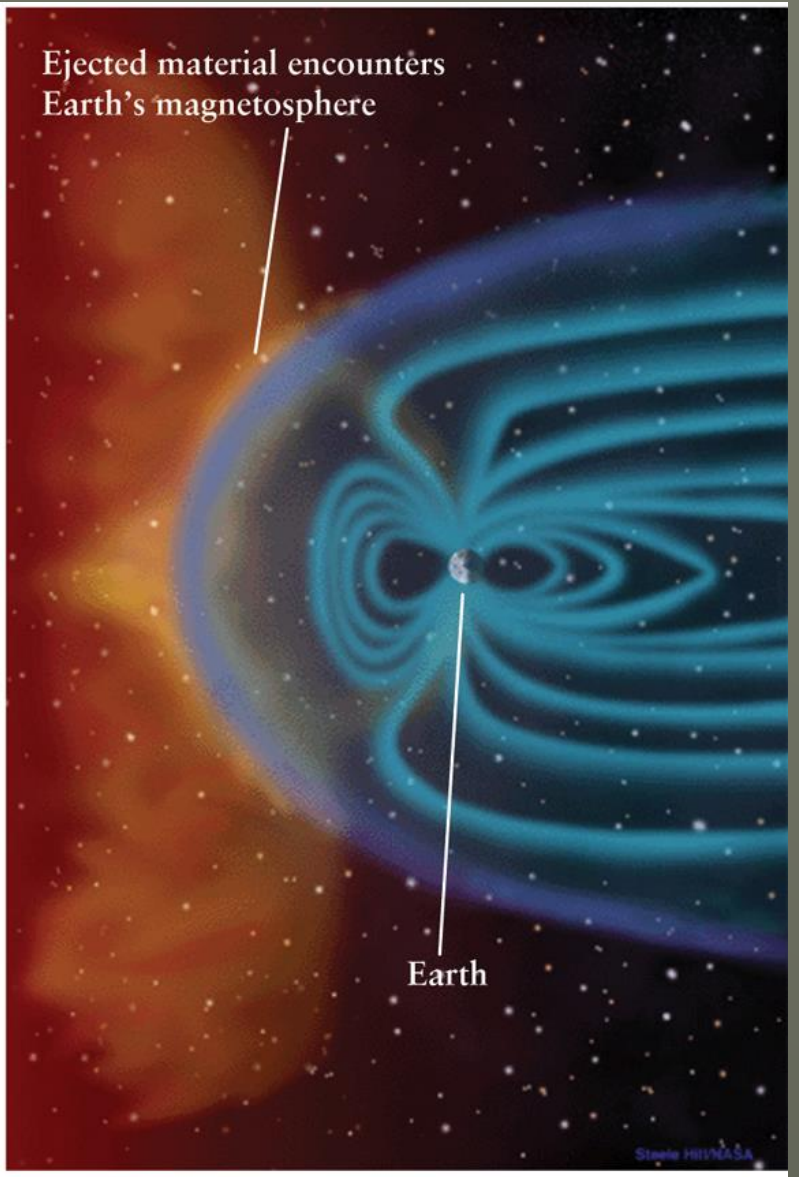
- Mag lines break and eject plasma into space

- Some are small
  - Flares

- Some are HUGE!
  - Coronal Mass Ejection

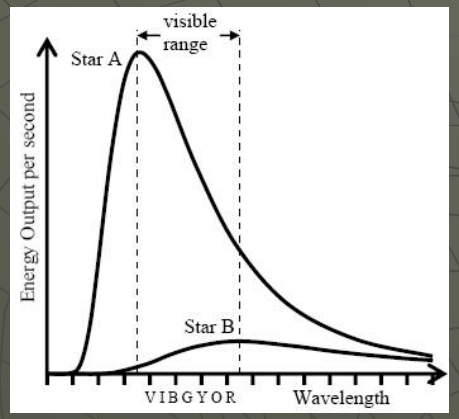


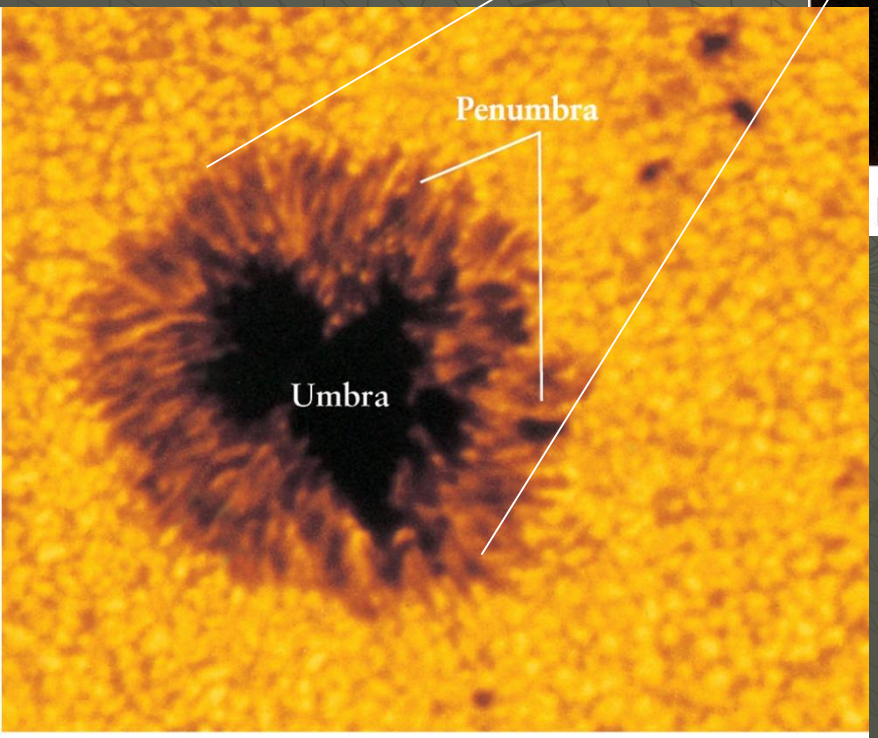
(a) A coronal mass ejection



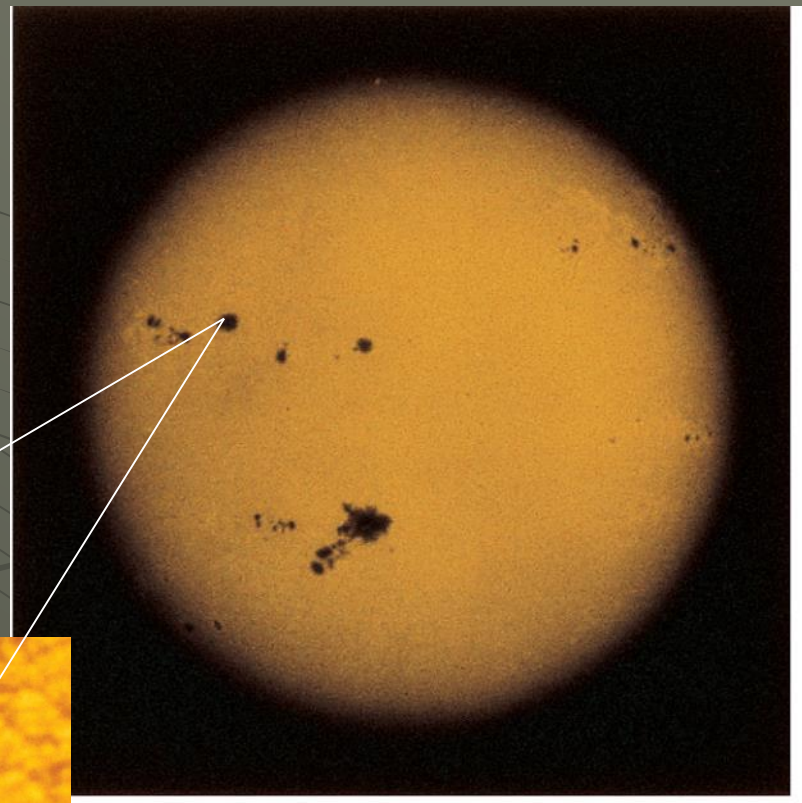
(b) Two to four days later

Sunspots

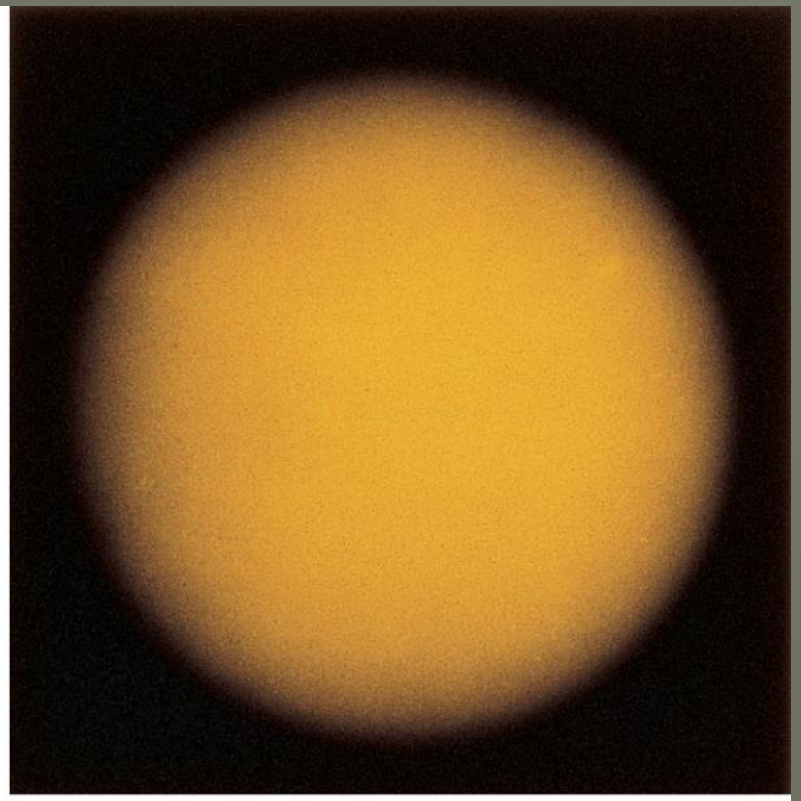




(a)



Near sunspot maximum



(c) Near sunspot minimum

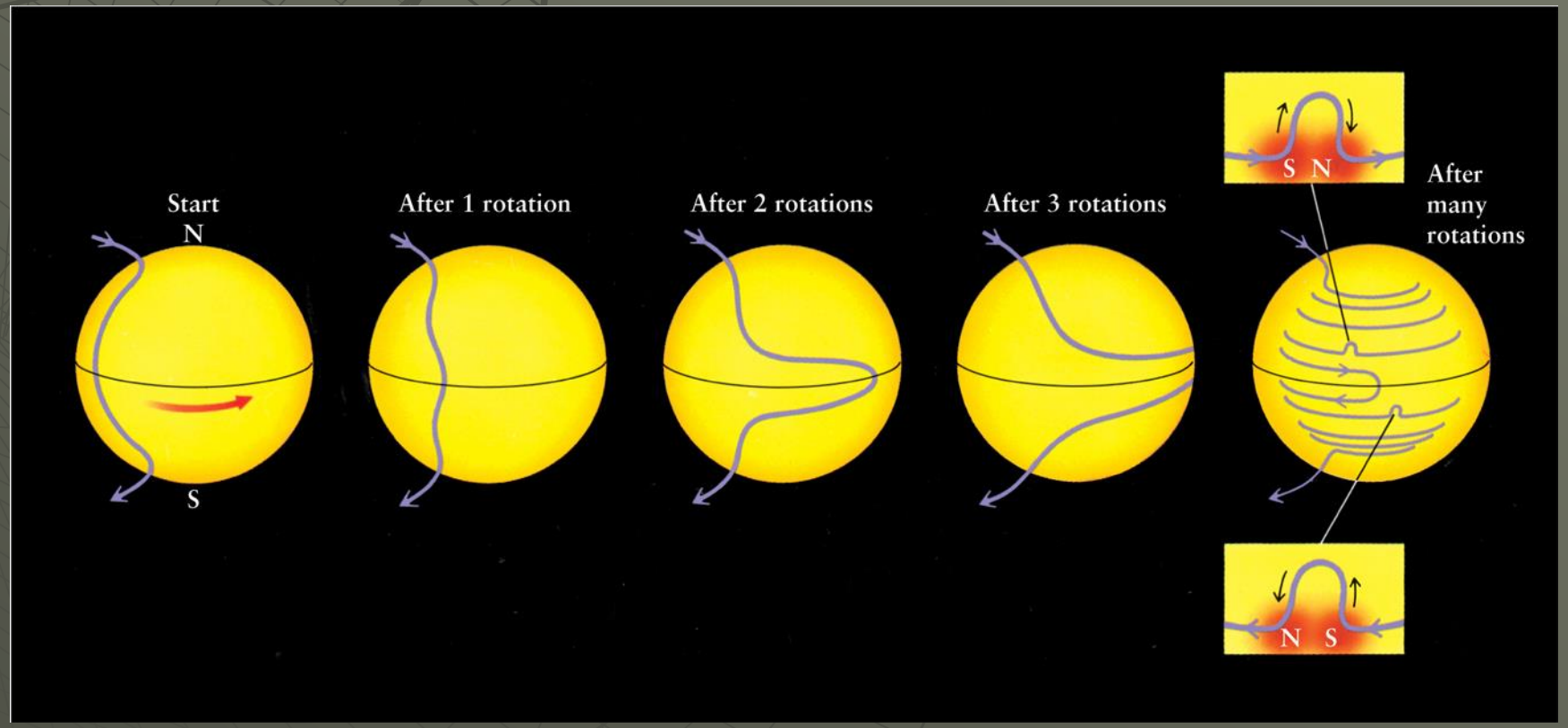
- Astronomers noticed dark spots appear and vanish
- Every 11 years

- Through spectroscopy
  - Lines were slightly different in a Sunspot
  - Sunspots are related to the magnetic field!

Differential Rotation

- Rotates faster at the equator
- Slower at the poles

- The Sun winds up like a rubber band
- Rubber band breaks
- Polarity is switched!



TPS

- The photosphere of the Sun gives off a(n) _____ spectrum.

A. Absorption
B. Continuous
C. emission

Hint: photosphere is cool enough for atoms not to be ionized

- Typically, hotter objects emit more intensely than cooler objects. Why, then, is the photosphere more luminous than the corona?

A. The photosphere is denser.
B. The photosphere is closer to the core of the Sun.
C. The photosphere is thicker.
D. The photosphere is more transparent.

- . The solar wind is composed mostly of

A. electrons and protons.
B. gamma ray radiation.
C. neutrinos.
D. the nuclei of heavy elements like iron.

- A solar flare occurs when

A. nuclear fusion originates close to the surface of the Sun.
B. energy is released from an intense magnetic field associated with a sunspot group.
C. convective material tries to rise up through the photosphere but is blocked by a sunspot.