The Sun

Basic Facts

- Mass = 2×10^{30} kg
  - 300,000 times more massive than Earth
  - Most massive member of solar system
    - More massive than all planets, moons, asteroids, comets, & meteoroids combined
- Radius = 7×10^{5} km
  - more than 100 times larger than Earth
  - largest member of solar system
- Distance from Earth to Sun = 1AU = 1.5×10^{8} km
  - light travel time = 500 s = 8 min

Basic Facts

- Composition
  - 74% Hydrogen, 25% Helium, 1% all other elements
- Temperatures
  - Surface = 5800 K
  - Core = 1.5×10^7 K
- Distance from center of galaxy = 26,000 ly
  - Orbital period about center of galaxy = 2.2×10^8 yr
  - Orbital speed about center of galaxy = 220 km/s = 500,000 mi/hr

Sun is a Star

- Star emits its own light
  - Most light from Moon and planets is reflected
  - Light is made of tiny packets of energy
  - Can measure how much energy is given off by the Sun
- ***Luminosity*** – measure of how much energy is given off per unit time

$$L = 4\pi R^2 F = 3.9 \times 10^{26}\,\mathrm{J/s} = 3.9 \times 10^{26}\,\mathrm{W}$$

That's a LOT of energy every second! Where does it come from?

Energy Production in Sun

- Chemical Reactions (burning)
  - burning coal releases 10^{-19} J/atom
  - Sun contains 10^{57} atoms
    - based upon mass and chemical composition

$$E = \left(10^{-19}\mathrm{J/atom}\right)\left(10^{57}\mathrm{atoms}\right) = 10^{38}\mathrm{J}$$

$$\mathrm{Lifespan} = \frac{E}{L} = \frac{10^{38}\mathrm{J}}{3.9 \times 10^{26}\mathrm{J/s}} = 3 \times 10^{11}\mathrm{s} = 10^{4}\mathrm{yr}$$

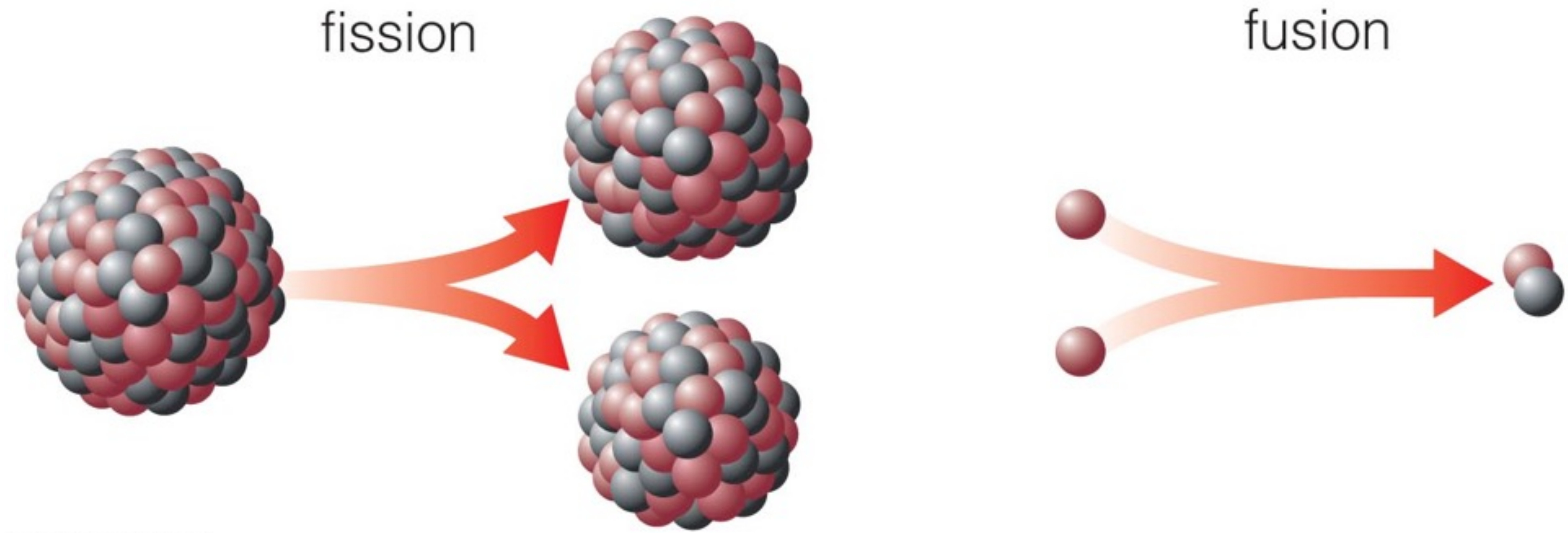
Energy Production in Sun

- Gravitational Contraction
  - As an object shrinks (or contracts), it's gravitational energy is converted into thermal energy (heat)
  - Gravitational energy released in forming the Sun:

$$E = \frac{3}{5}\frac{GM^2}{R} = 2.2 \times 10^{41}\,\mathrm{J}$$

$$\mathrm{Lifespan} = \frac{E}{L} = \frac{2.2 \times 10^{41}\,\mathrm{J}}{3.9 \times 10^{26}\,\mathrm{J/s}} = 5.6 \times 10^{14}\mathrm{s} = 1.8 \times 10^{7}\mathrm{yr}$$

Energy Production in Sun



Fission

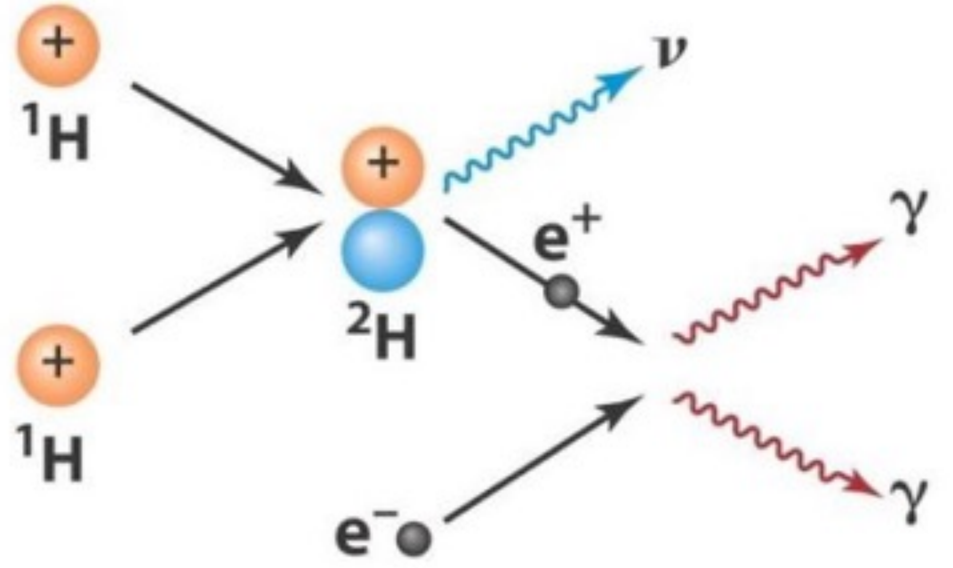
- Big nucleus splits into smaller pieces.
- (Example: nuclear power plants)

Fusion

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

Energy Production in Sun

- Thermonuclear Fusion

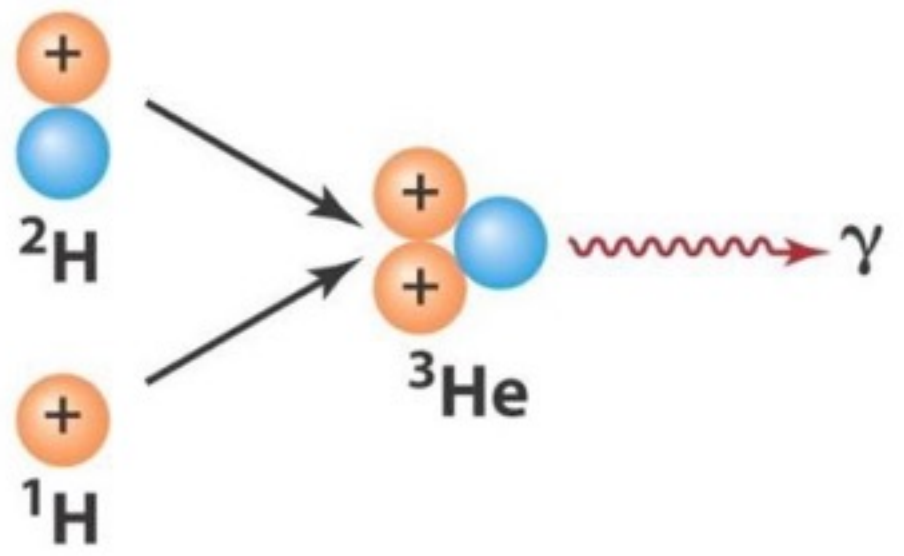


Step 1:

- Two protons (hydrogen nuclei, ^{1}H) collide.
- One of the protons changes into a neutron (shown in blue), a neutral, nearly massless neutrino (ν), and a positively charged electron, or positron (e^{+}).
- The proton and neutron form a hydrogen isotope (^{2}H).
- The positron encounters an ordinary electron (e^{-}), annihilating both particles and converting them into gamma-ray photons (γ).

Energy Production in Sun

- Thermonuclear Fusion

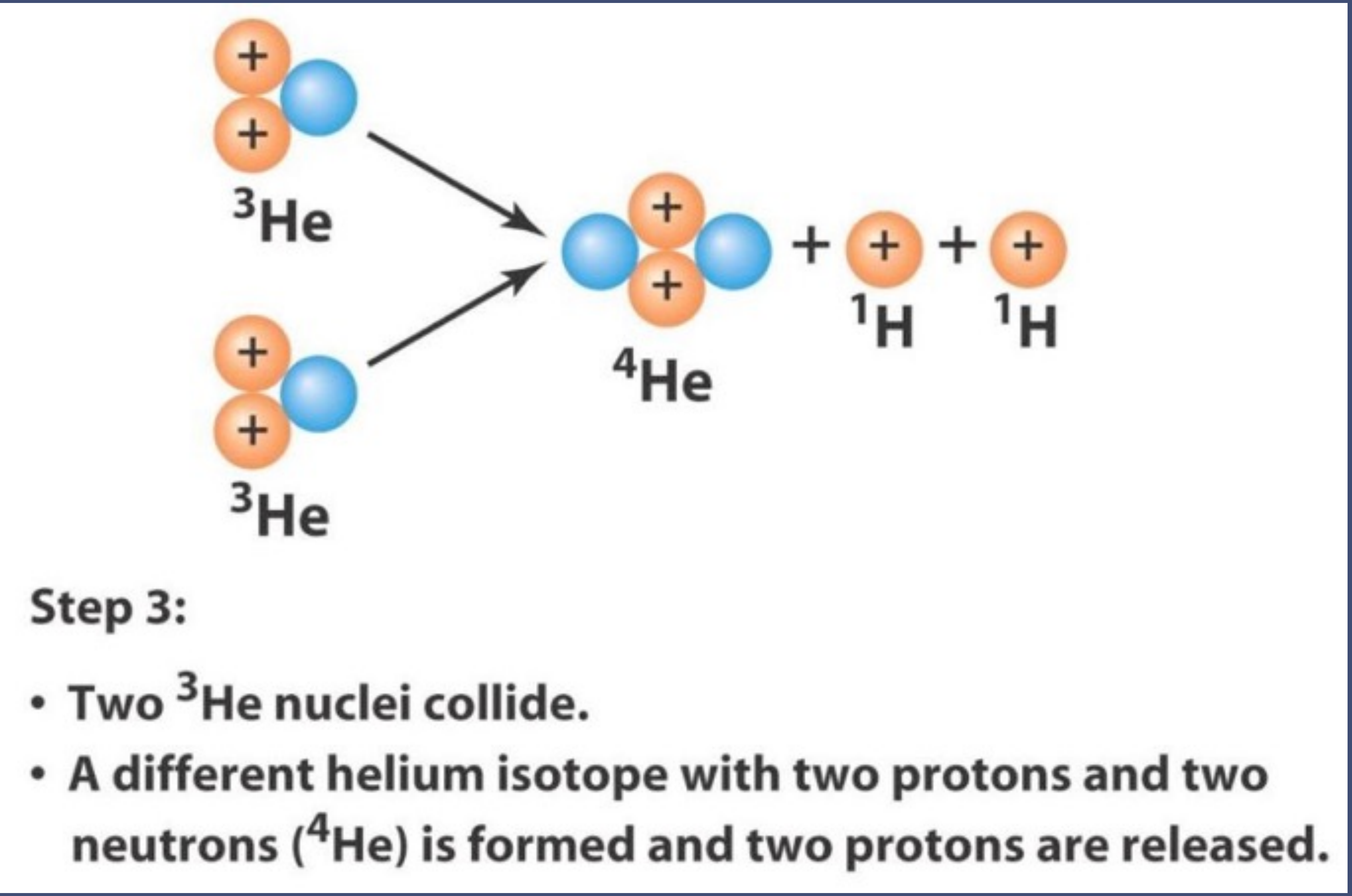


Step 2:

- **The ^2H nucleus from the first step collides with a third proton.**
- **A helium isotope (^3He) is formed and another gamma-ray photon is released.**

Energy Production in Sun

- Thermonuclear Fusion



Energy Production in Sun

- Thermonuclear Fusion

$$4\text{H} \rightarrow \text{He} + \text{neutrinos} + \boxed{\text{photons}}$$

Energy

- Where did the energy come from?
  - –Einstein's mass-energy equation

$$E = mc^2$$

E – energy

m – mass

c – speed of light

Energy Production in Sun

- Thermonuclear Fusion

$$\text{mass of 4H} = 6.693 \times 10^{-27}\text{kg}$$

$$\text{mass of He} = 6.645 \times 10^{-27}\text{kg}$$

$$(\text{mass of 4H}) - (\text{mass of He}) = \boxed{0.048 \times 10^{-27}\text{kg}}$$

Amount of mass converted to energy

$$E = \left(0.048 \times 10^{-27}\text{kg}\right)\left(3 \times 10^{8}\text{m/s}\right)^2 = 4.3 \times 10^{-12}\text{J/reaction}$$

$$E = \frac{4.3 \times 10^{-12}\text{J/reaction}}{4\text{atoms/reaction}} = 10^{-12}\text{J/atom}$$

10,000,000 times more efficient than burning coal

Energy Production in Sun

- Thermonuclear Fusion
  - –fusion releases 10^{-12} J/atom
  - –Sun contains 10^{57} atoms

$$E = \left(10^{-12}\mathrm{J/atom}\right)\left(10^{57}\mathrm{atoms}\right) = 10^{45}\mathrm{J}$$

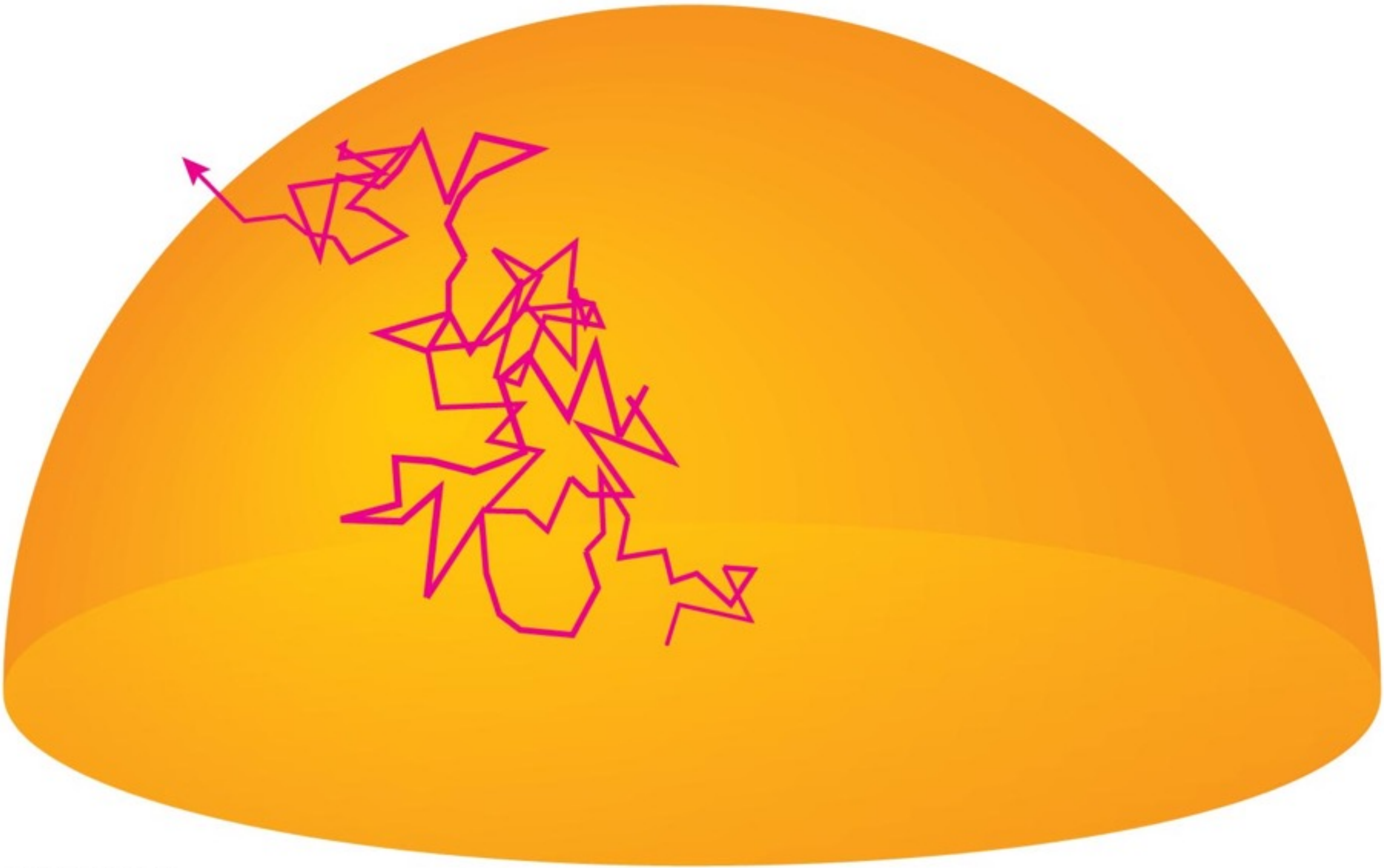
$$\mathrm{Lifespan} = \frac{E}{L} = \frac{10^{45}\mathrm{J}}{3.9\times 10^{26}\mathrm{J/s}} = 3\times 10^{18}\mathrm{s} = 10^{11}\mathrm{yr}$$

In reality, the Sun won’t be able to fuse all of its hydrogen into helium. It will most likely die at about 10^{10} yr old.

Energy Production in Sun

- Thermonuclear Fusion

$$4H \rightarrow He + \text{neutrinos} + \boxed{\text{photons}}$$

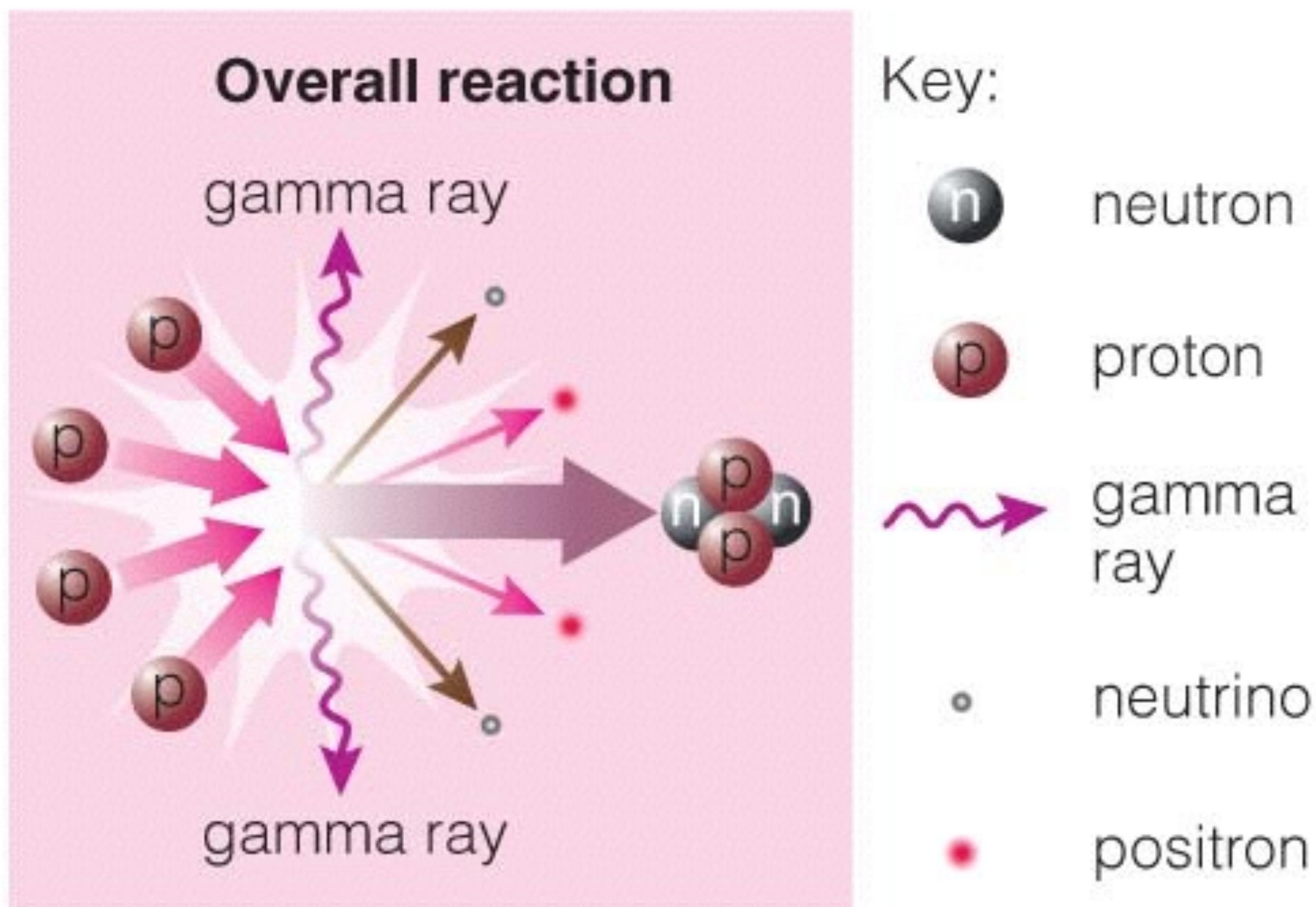


- Energy gradually leaks out of radiation zone in form of randomly bouncing photons.

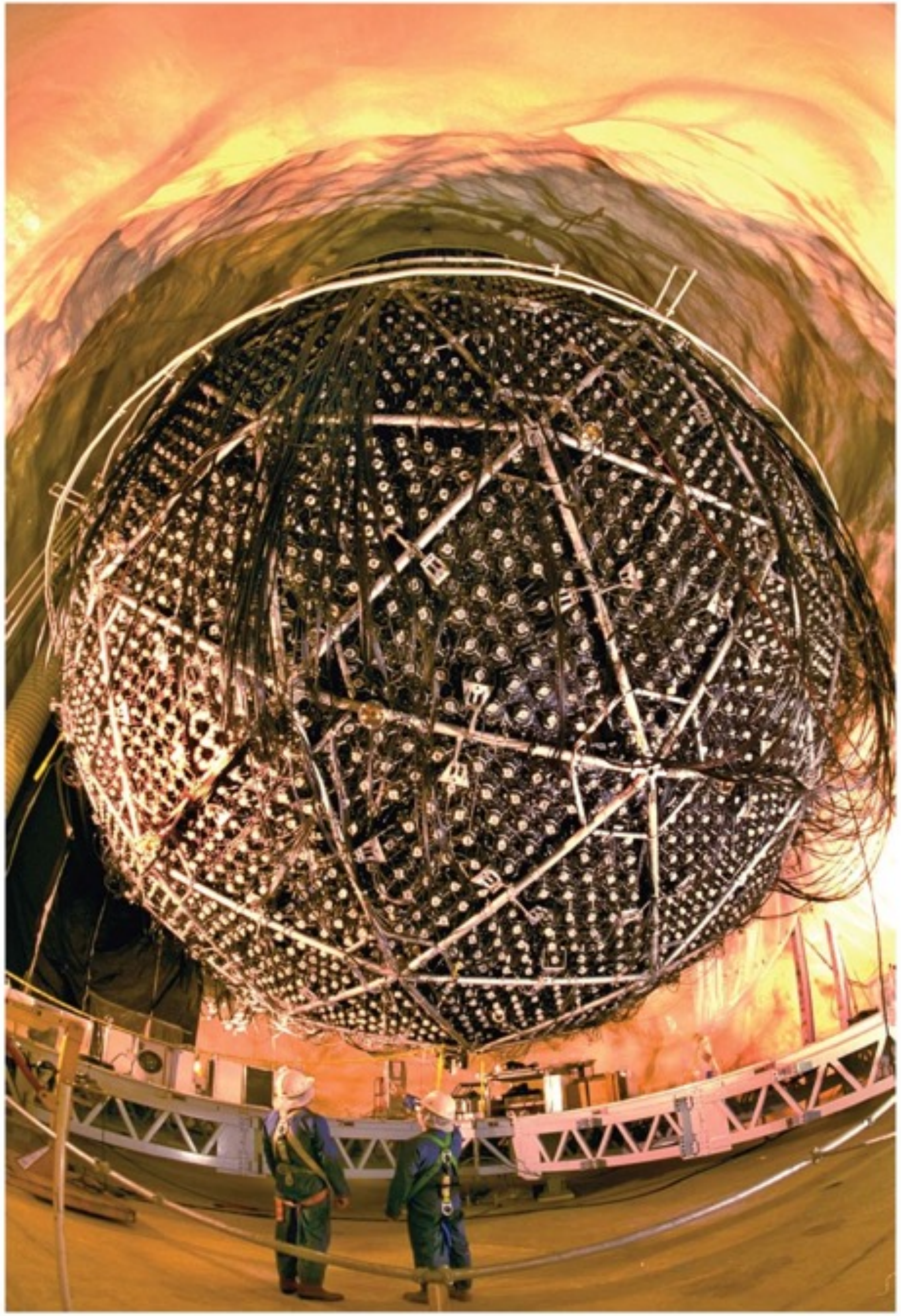
Energy Production in Sun

- Thermonuclear Fusion

$$4H \rightarrow He + \boxed{\text{neutrinos}} + \text{photons}$$



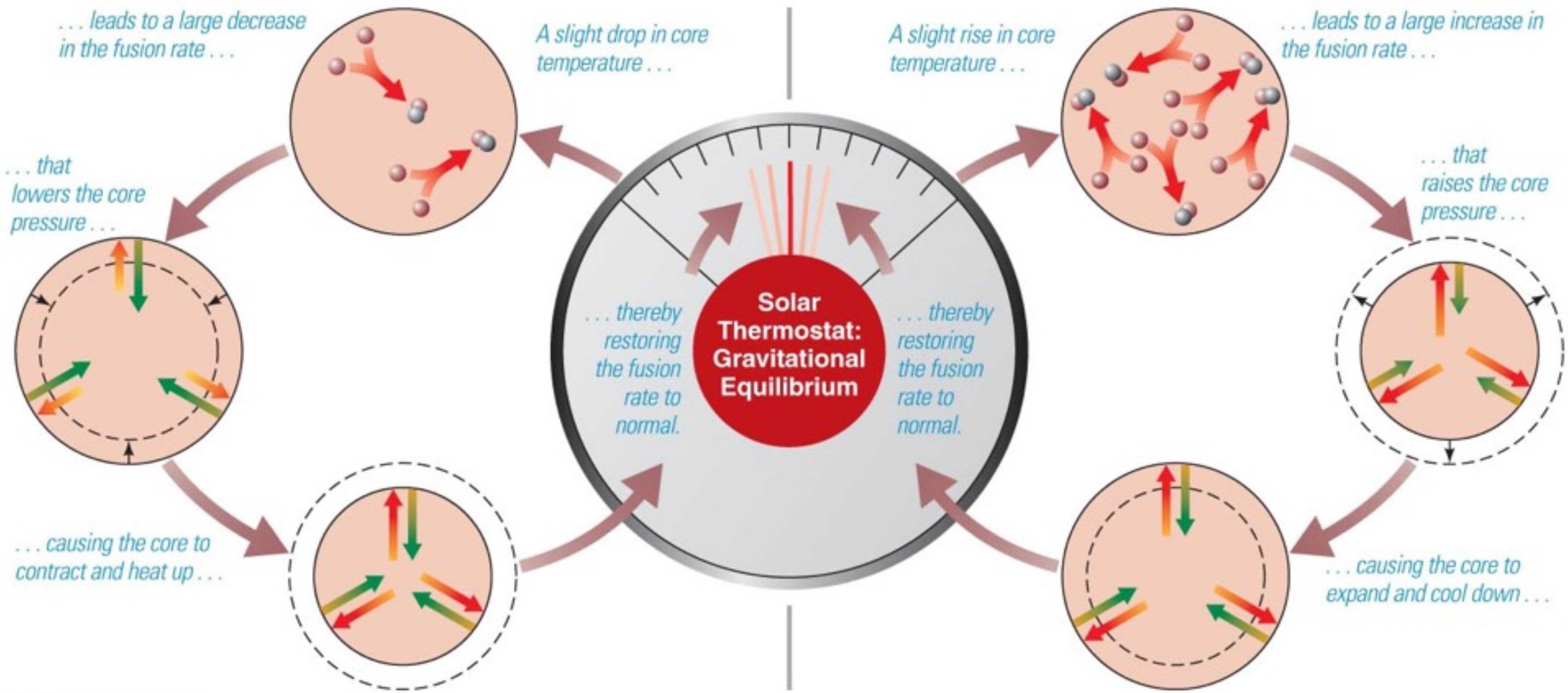
- Neutrinos created during fusion fly directly through the Sun.
- Observations of these solar neutrinos can tell us what's happening in core.



Solar neutrino problem:

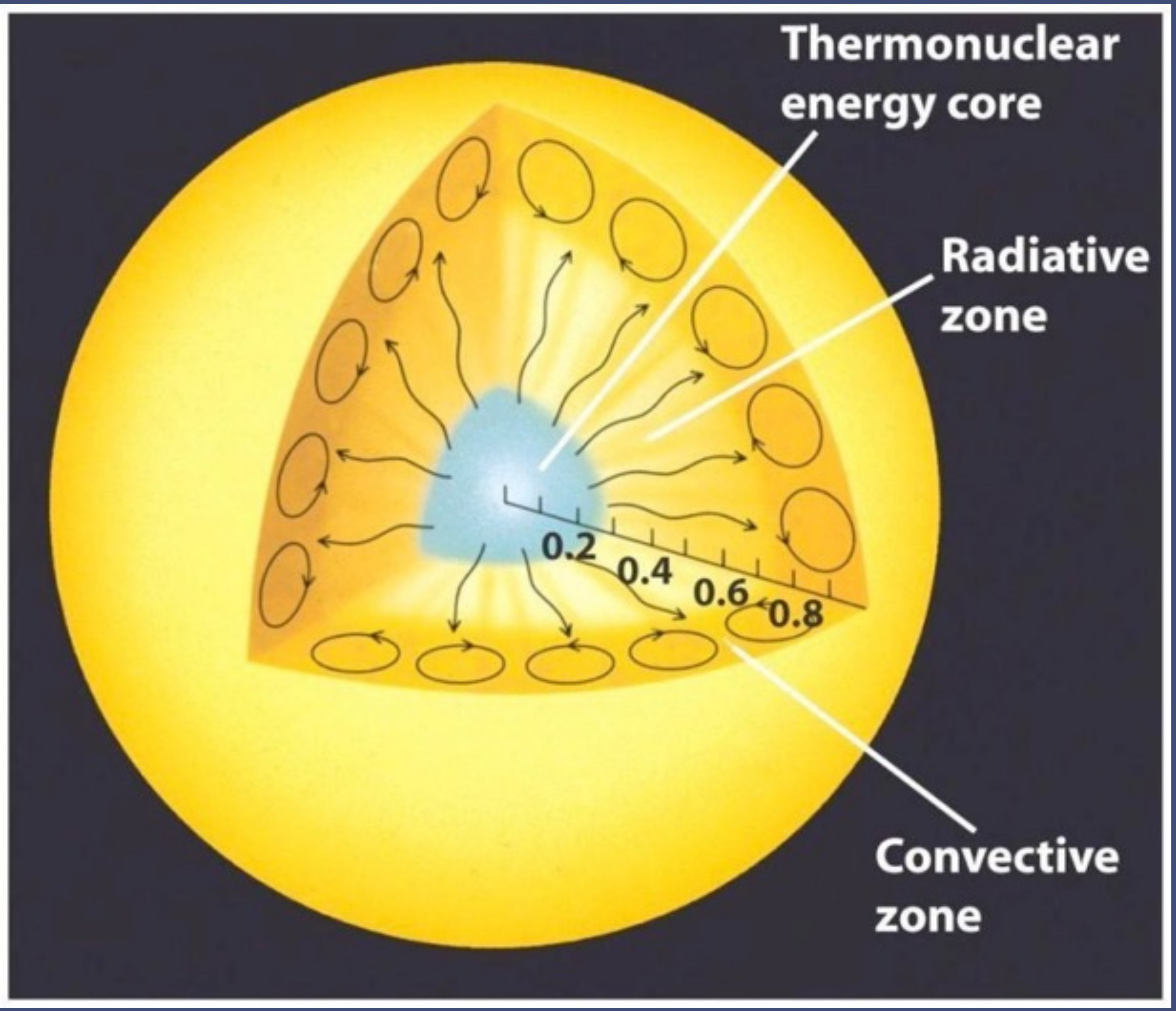
- Early searches for solar neutrinos failed to find the predicted number.
- More recent observations find the right number of neutrinos, but some have changed form.

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.

Solar Interior

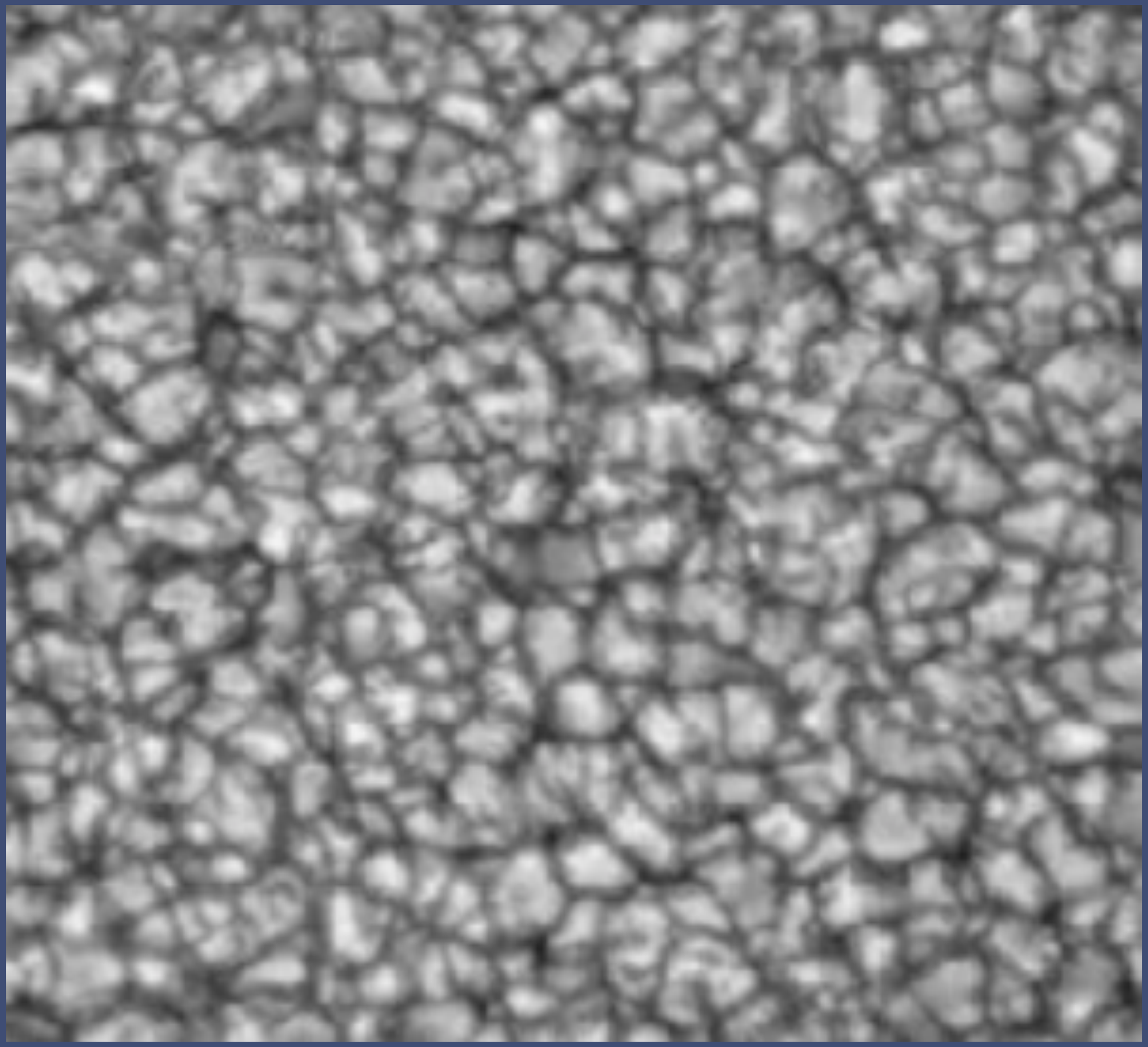


- Core
  - –site of thermonuclear fusion
  - –this is where photons are produced
  - –inner 25% of Sun
- Radiative zone
  - –energy carried toward surface by photons
  - –0.25-0.71 x solar radius
- Convective zone
  - –energy carried toward surface by convection
    - large-scale motion of fluid within Sun

Solar Surface

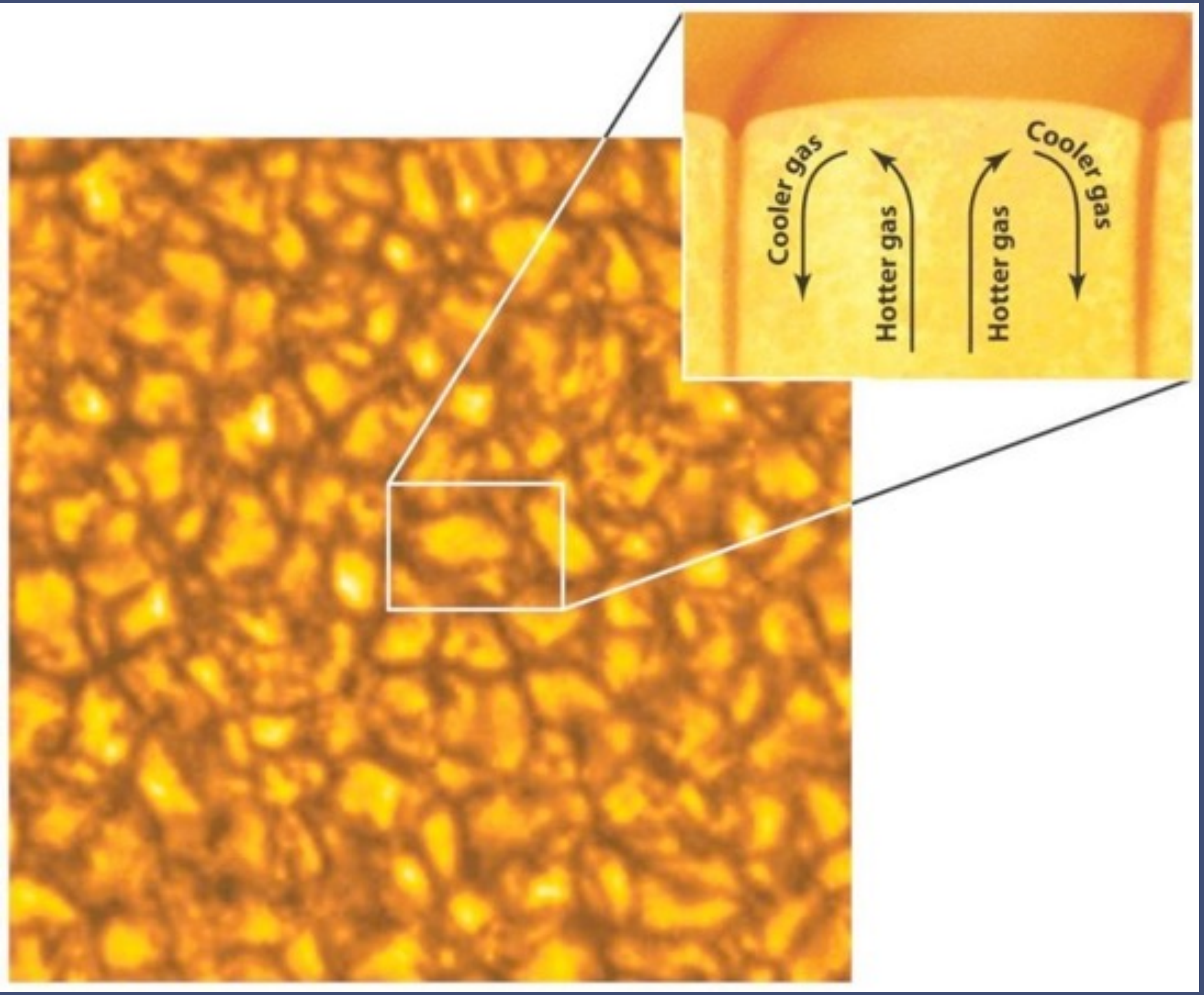
- Photosphere
  - this is the "surface" we see
  - thin layer of Sun where photons produced in Sun's interior are finally able to escape
    - takes an average photon 170,000 years to get from Sun's core to surface
  - 400 km thick
    - radius of Sun = 696,000 km

Solar Surface



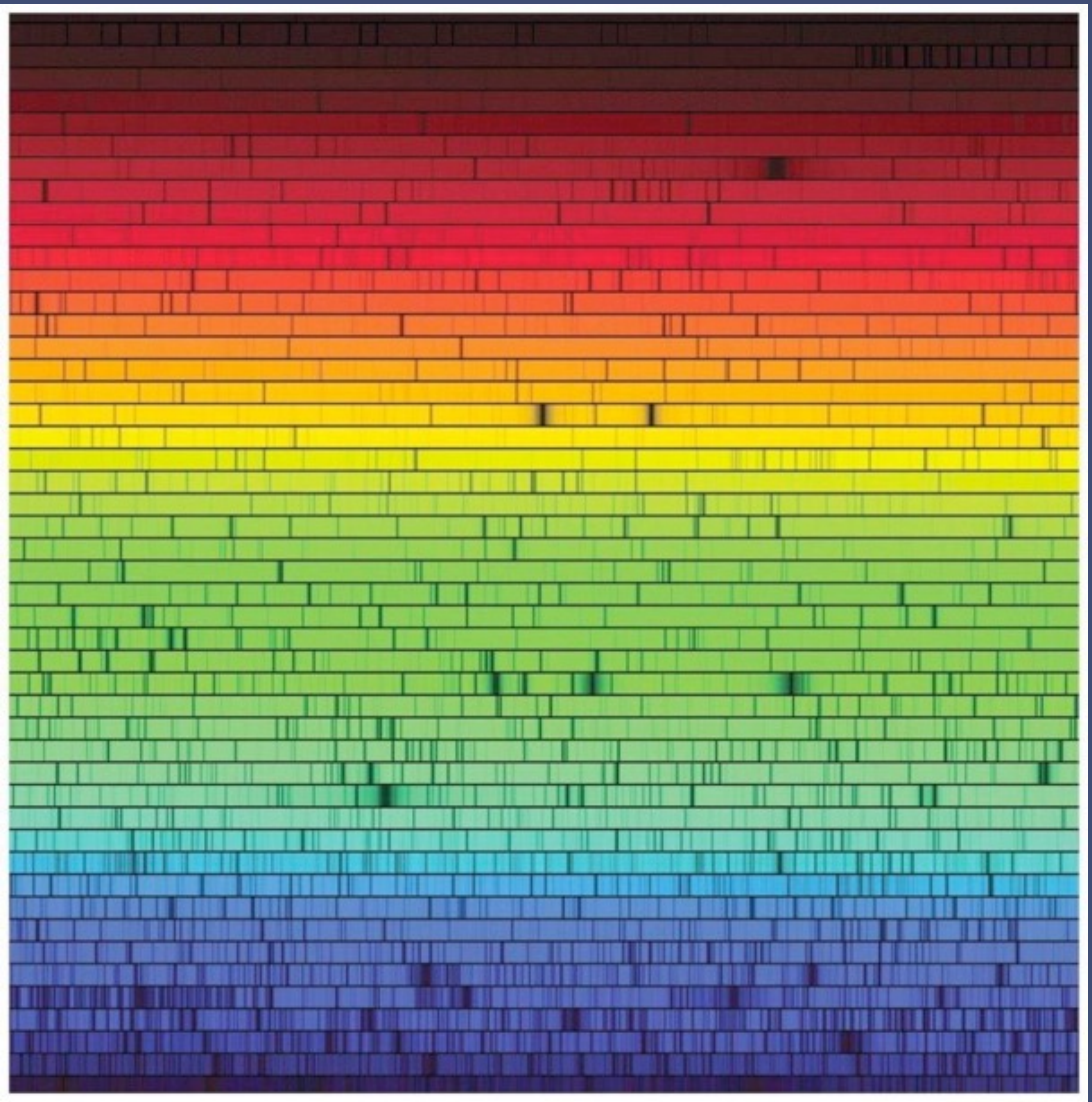
- Photosphere
  - –patchy appearance
    - "granules"
    - typical size = 1000 km
  - –What causes these bright patches with dark edges?

Solar Surface



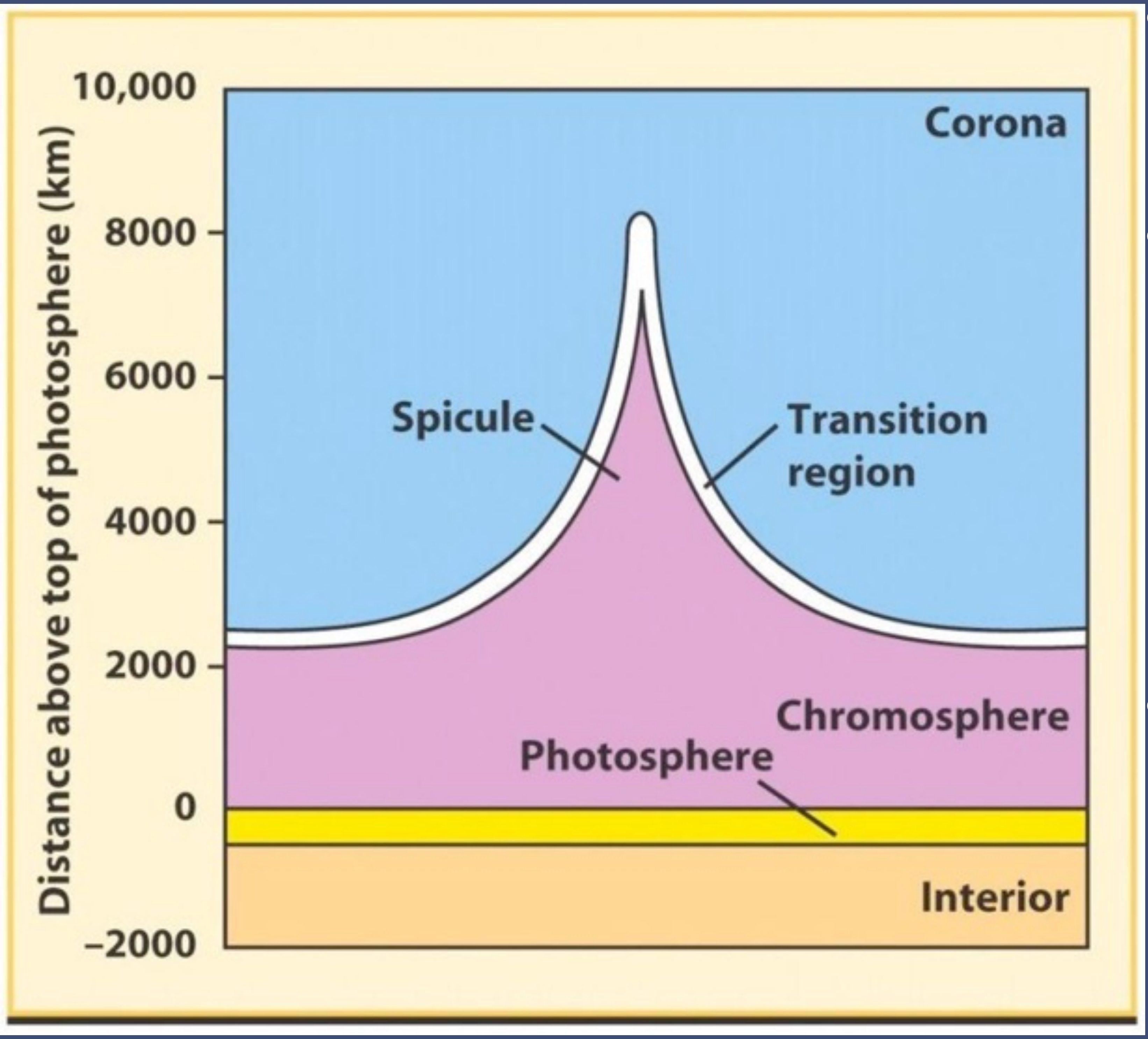
- Photosphere
  - –granule
    - hot gas rising in the center
    - cooler gas sinking on the edges
    - hotter gases produce more radiation (brighter)

Solar Spectrum



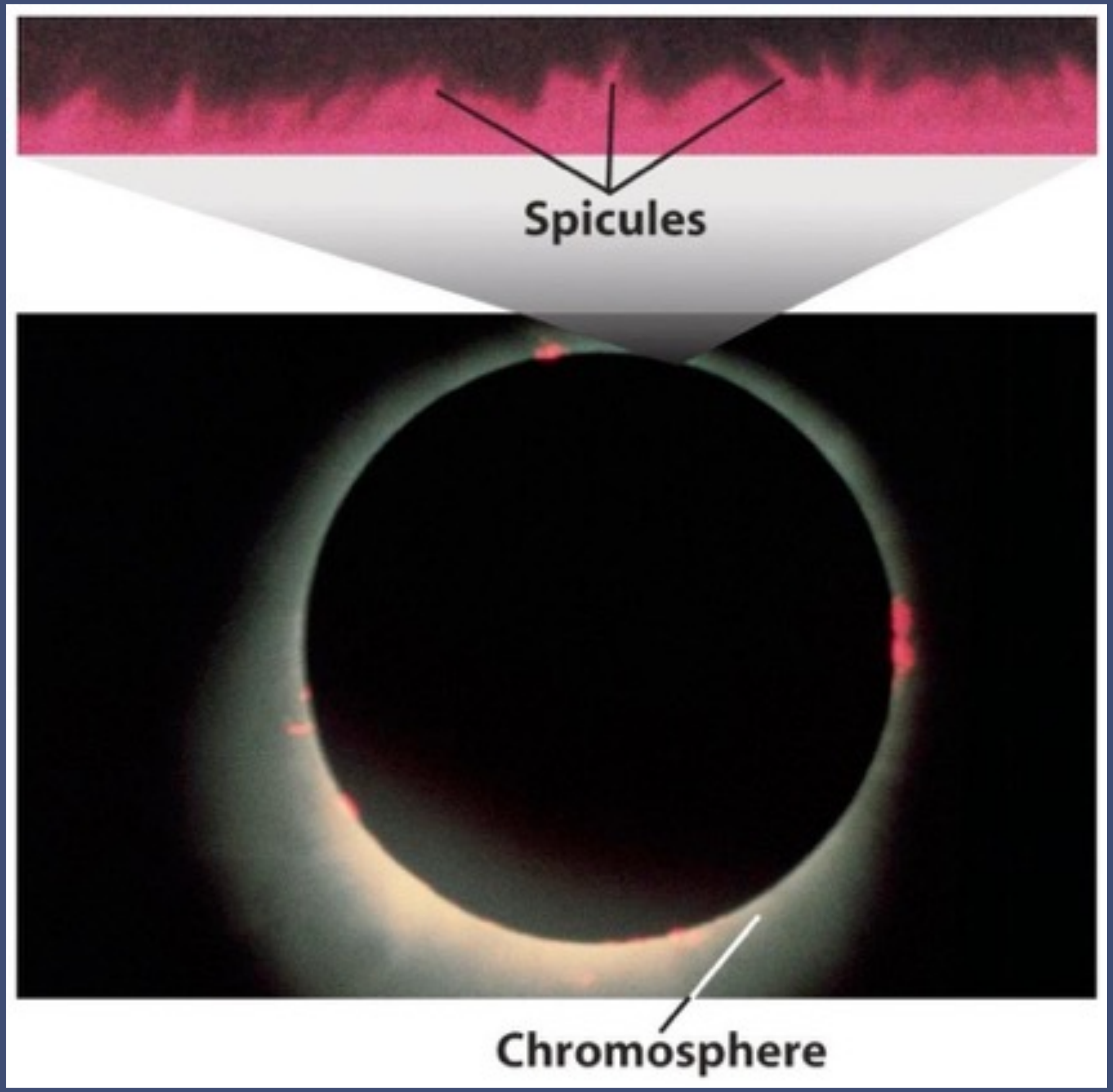
- What kind of spectrum is this?
  - –absorption line spectrum
- What does this tell us about the Sun?
  - –there is an atmosphere above the surface of the Sun

Solar Atmosphere

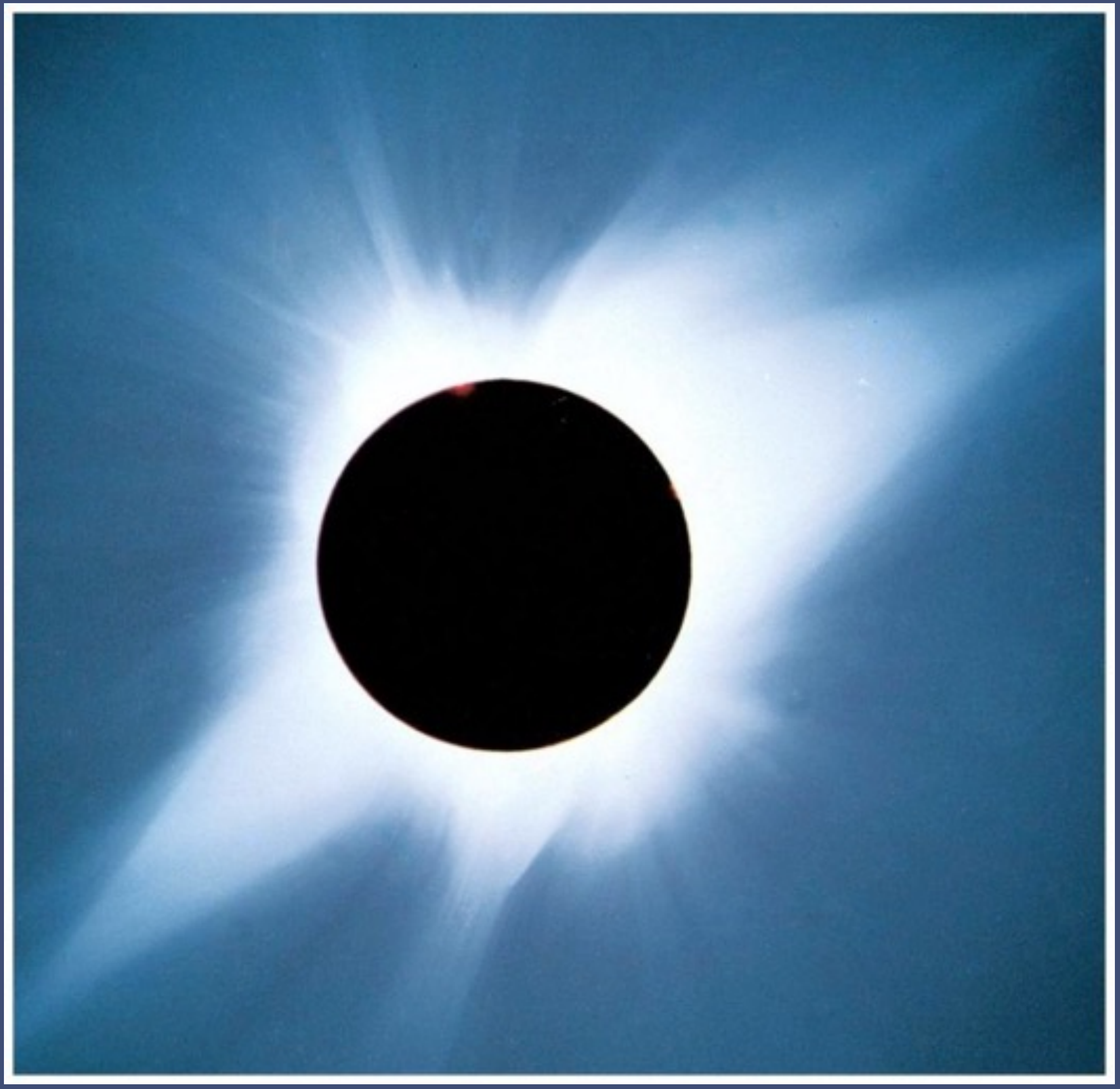


- Photosphere
  - –base of solar atmosphere
- Chromosphere
  - –relatively hot, transparent layer above the photosphere
  - –can be seen through emission lines
- Corona
  - –extremely hot, tenuous outer layer of solar atmosphere
  - –origin of solar wind

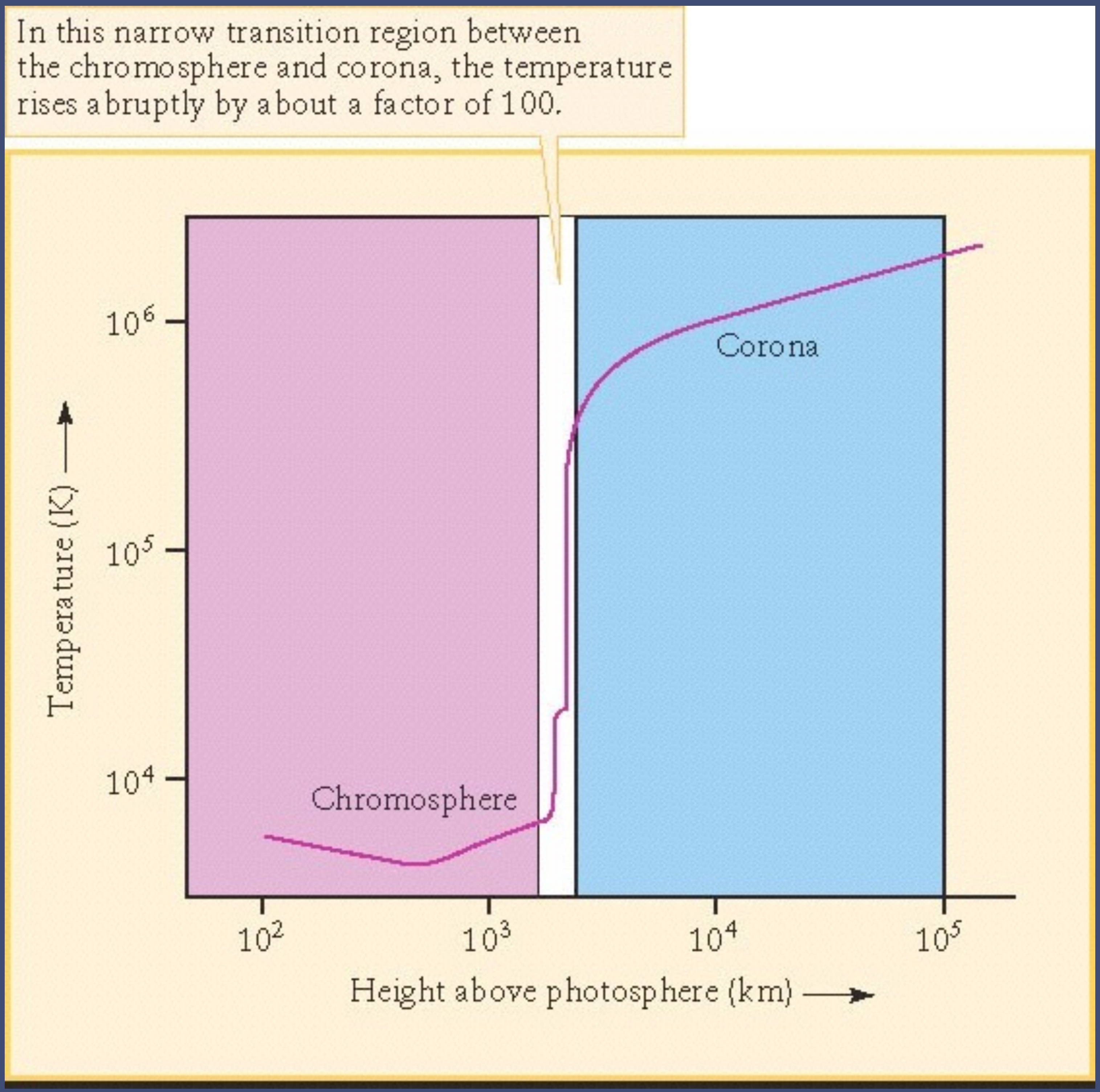
Solar Atmosphere



Corona



Solar Atmosphere



- Photosphere
  - –base of solar atmosphere
- Chromosphere
  - –relatively hot, transparent layer above the photosphere
  - –can be seen through emission lines
- Corona
  - –extremely hot, tenuous outer layer of solar atmosphere
  - –origin of solar wind

Solar Wind

- Temperature of corona is over 10^6 K
- Particles in corona are moving at about 10^6 km/hr (on average)
- Escape velocity in corona:

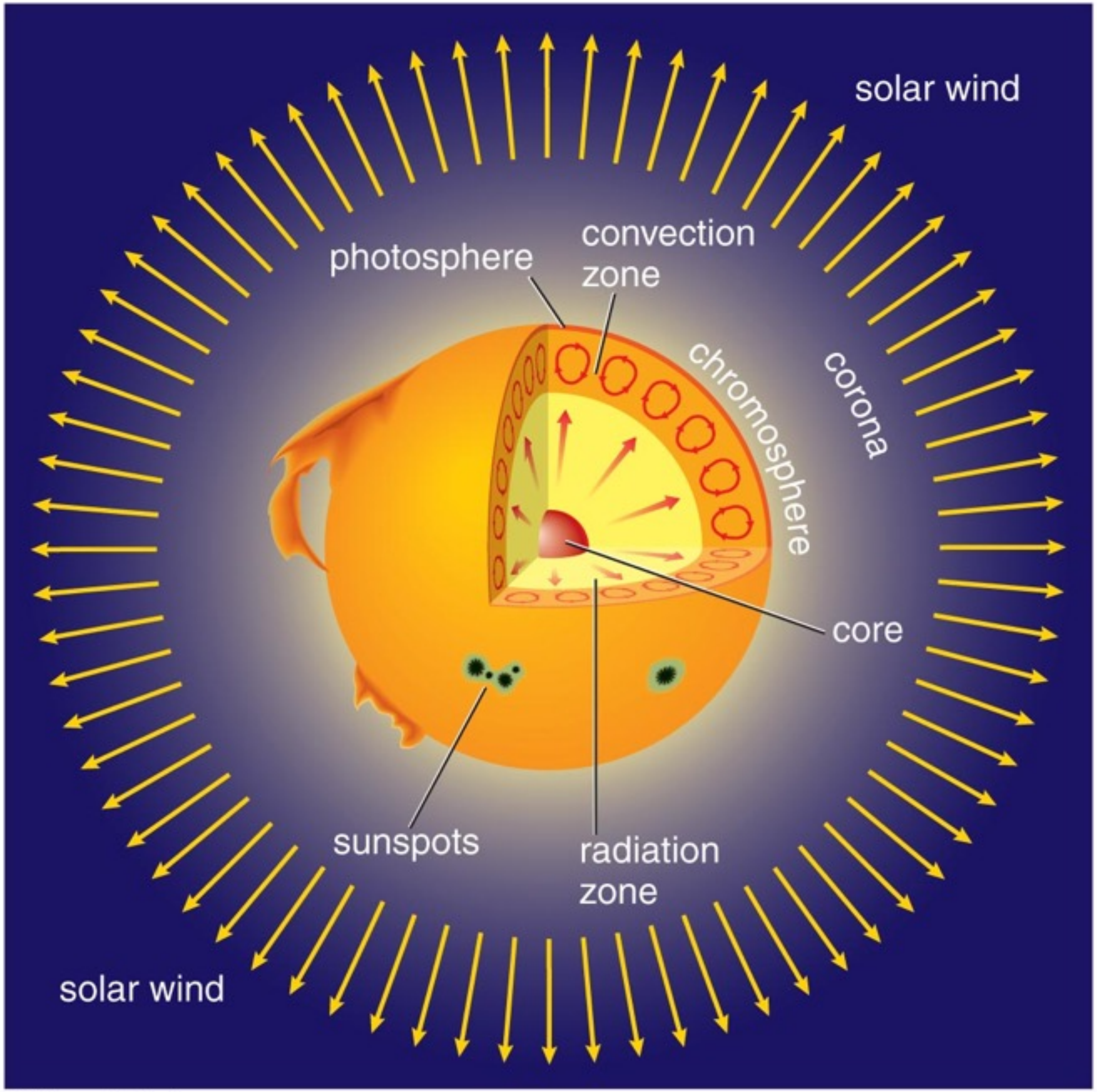
$$v_{\mathrm{escape}} = \sqrt{\frac{2GM}{r}} \approx 2 \times 10^6 \mathrm{km/hr}$$

A substantial fraction of the particles in the corona can escape the Sun's gravity! These become the solar wind.

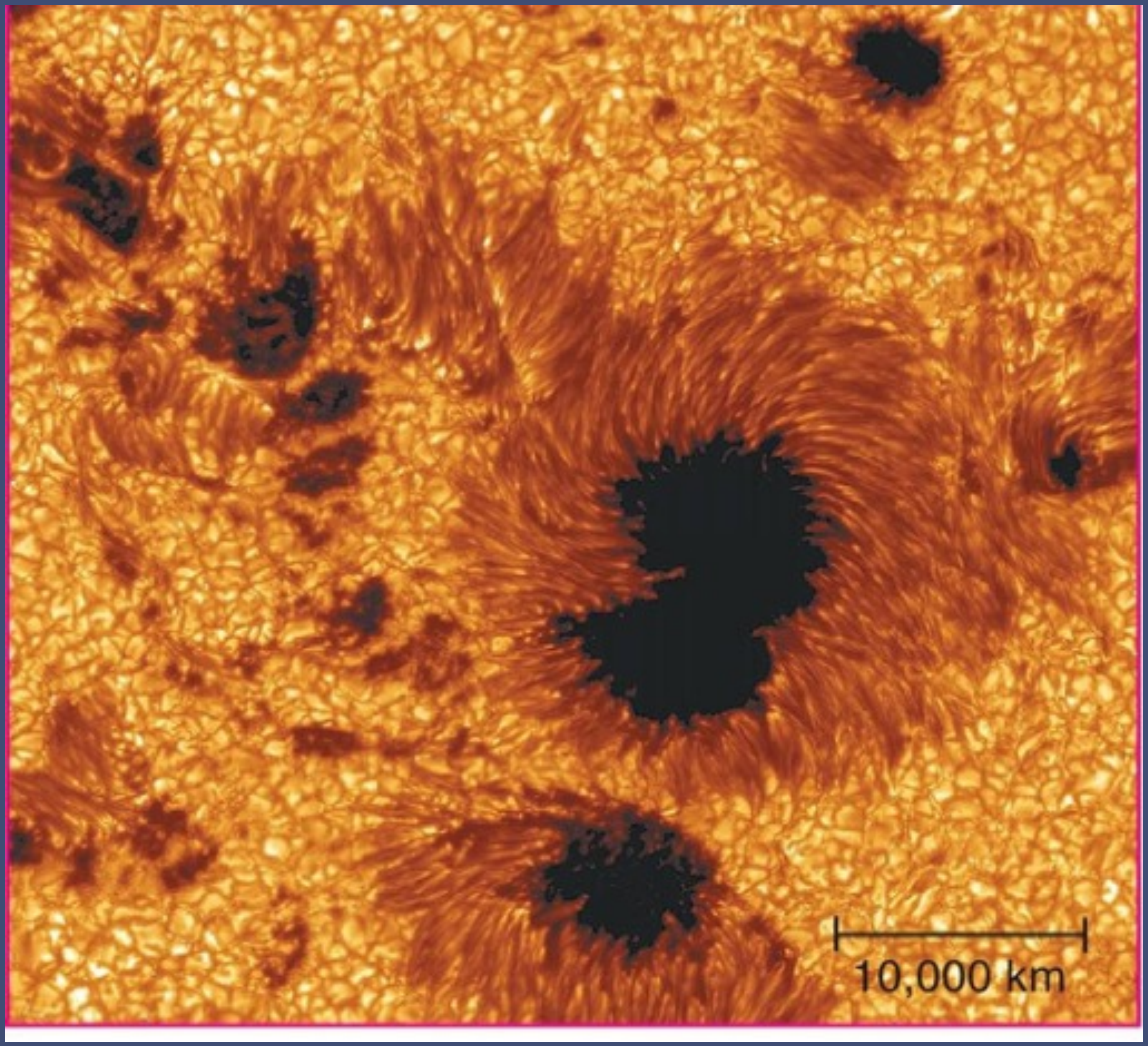
Solar Wind

- Carries off about 10^9 kg (10^6 tons) of material each second!
  - only a tiny fraction of the mass of the Sun, even over its entire lifetime

What is the Sun's structure?

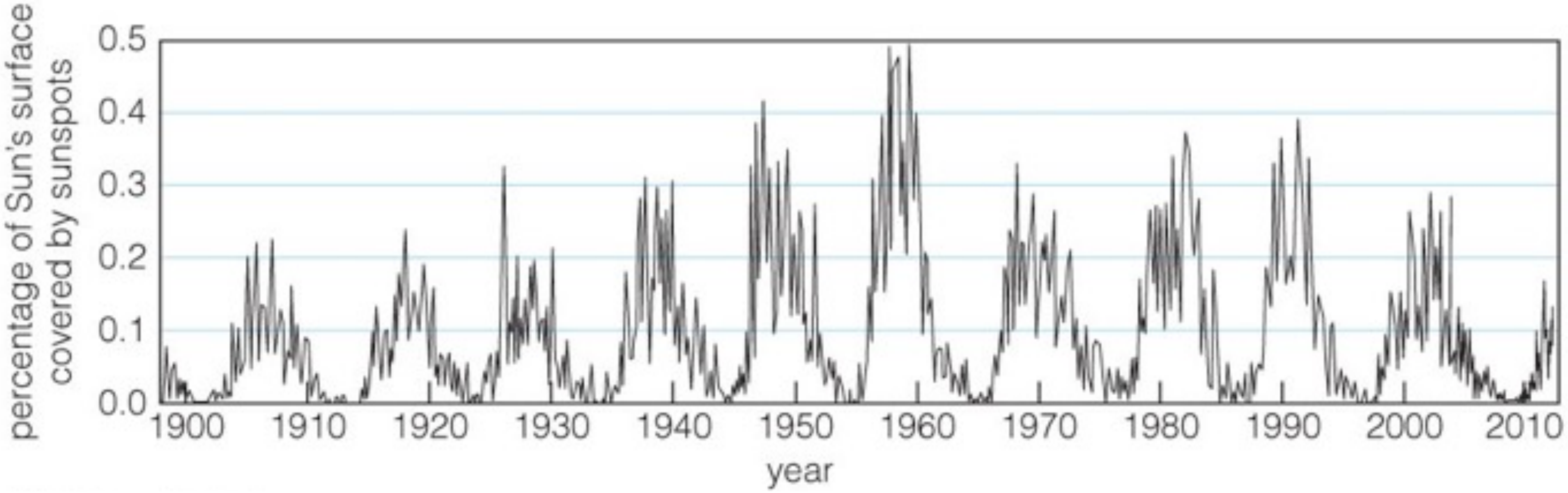


Sunspots



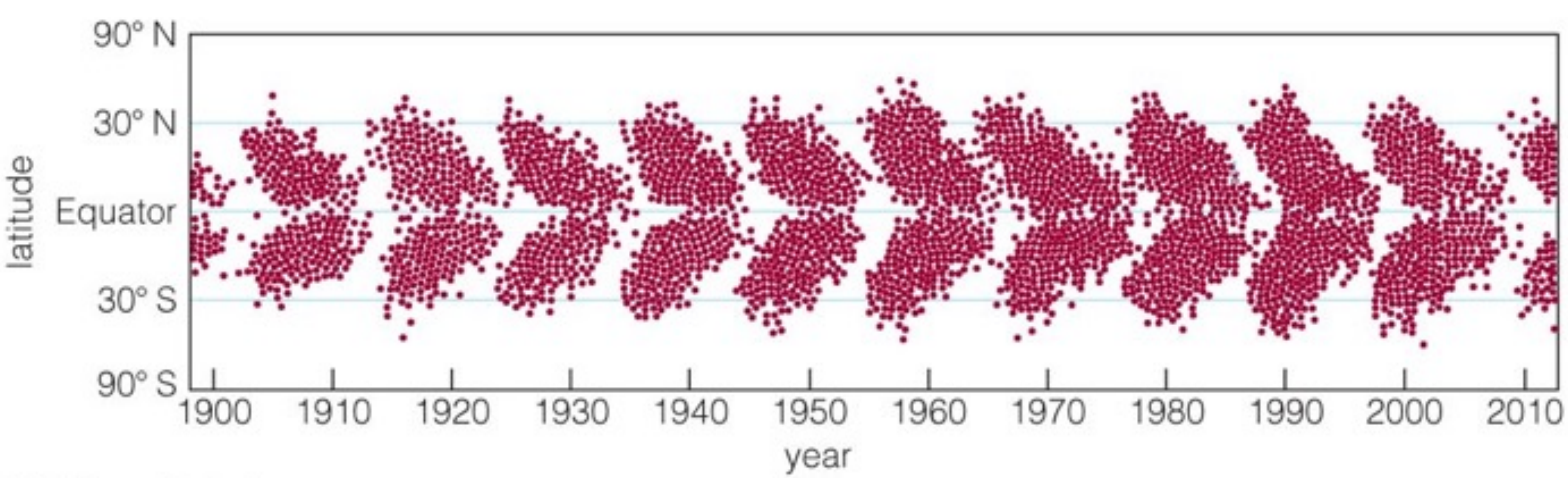
- Large, dark blotches or spots in photosphere
- What does the fact that they appear dark tell us?
  - –Cooler than surrounding photosphere
    - 4300 K vs 5800 K
- Regions of intense magnetic fields
  - –strong fields prevent hot material from rising up in these regions
  - –associated with flares and coronal mass ejections

Sunspot cycle



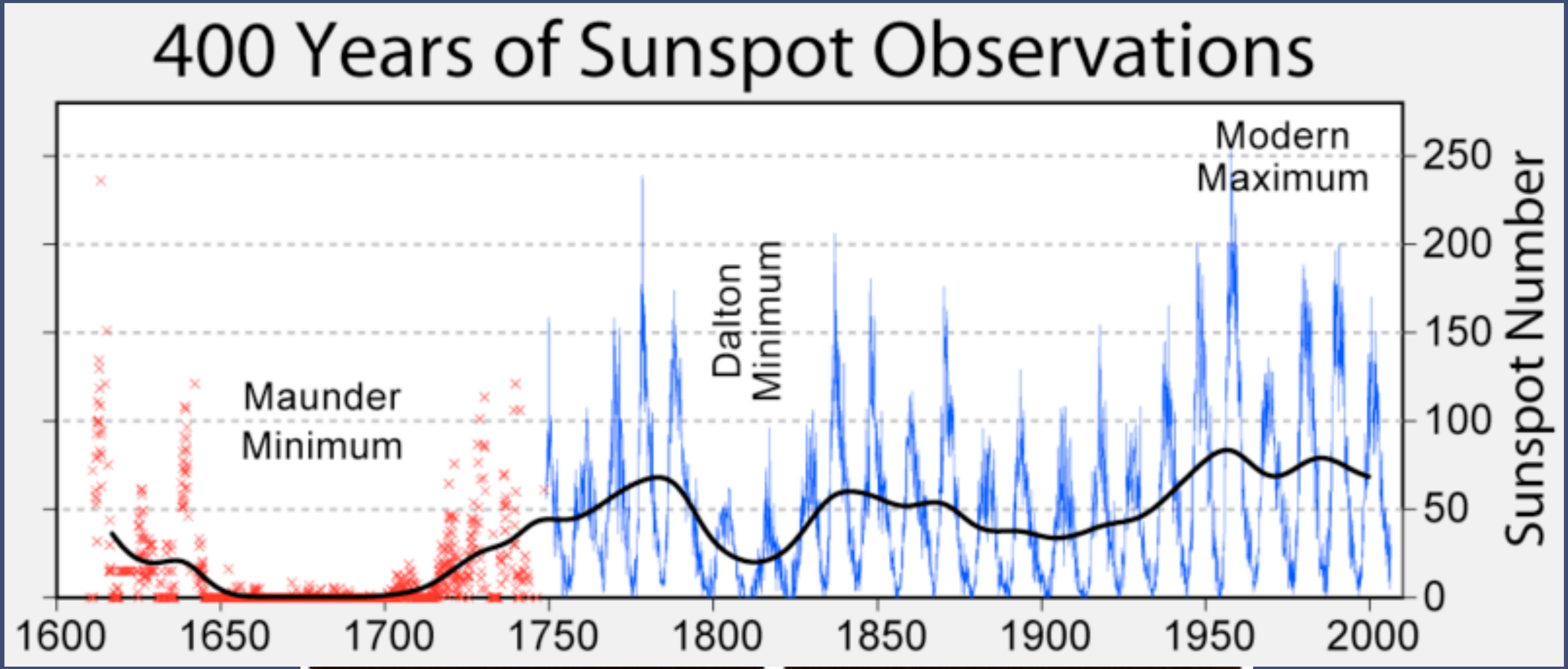
a This graph shows how the number of sunspots on the Sun changes with time. The vertical axis shows the percentage of the Sun's surface covered by sunspots. The cycle has a period of approximately 11 years.

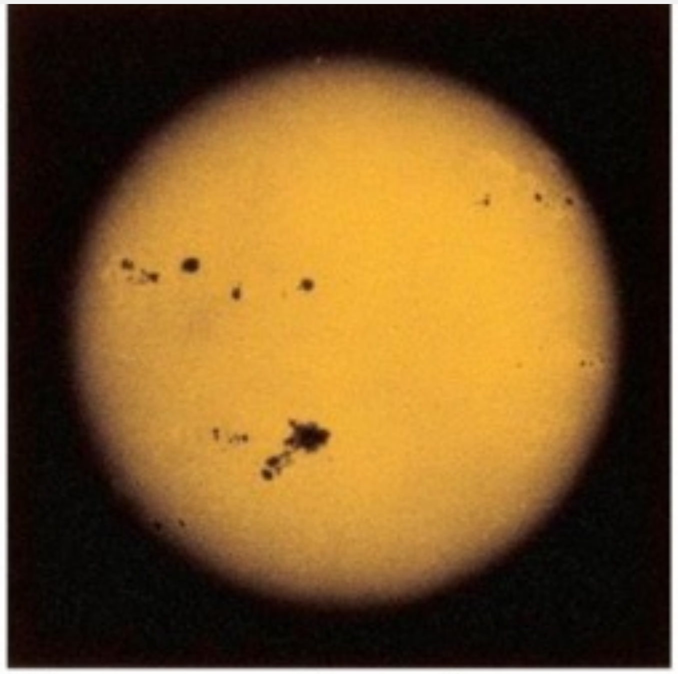
- The number of sunspots rises and falls in an 11-year cycle.



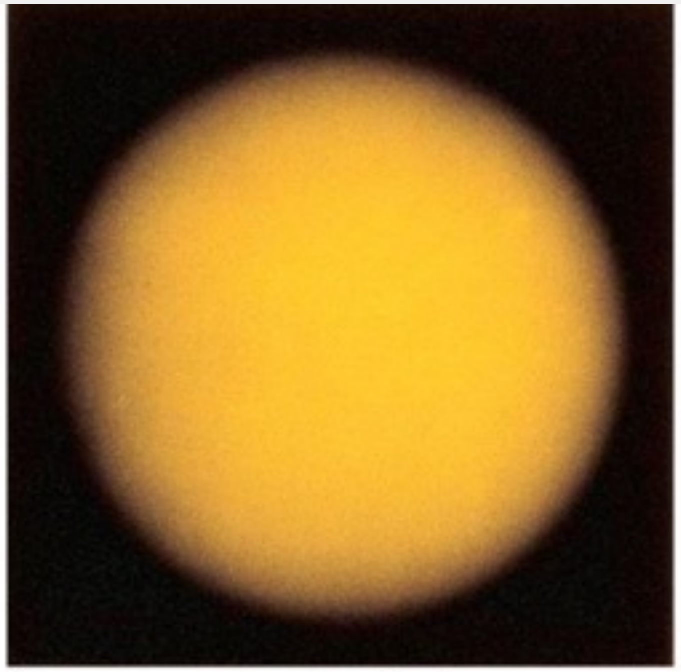
b This graph shows how the latitudes at which sunspot groups appear tend to shift during a single sunspot cycle.

Sunspot Cycle





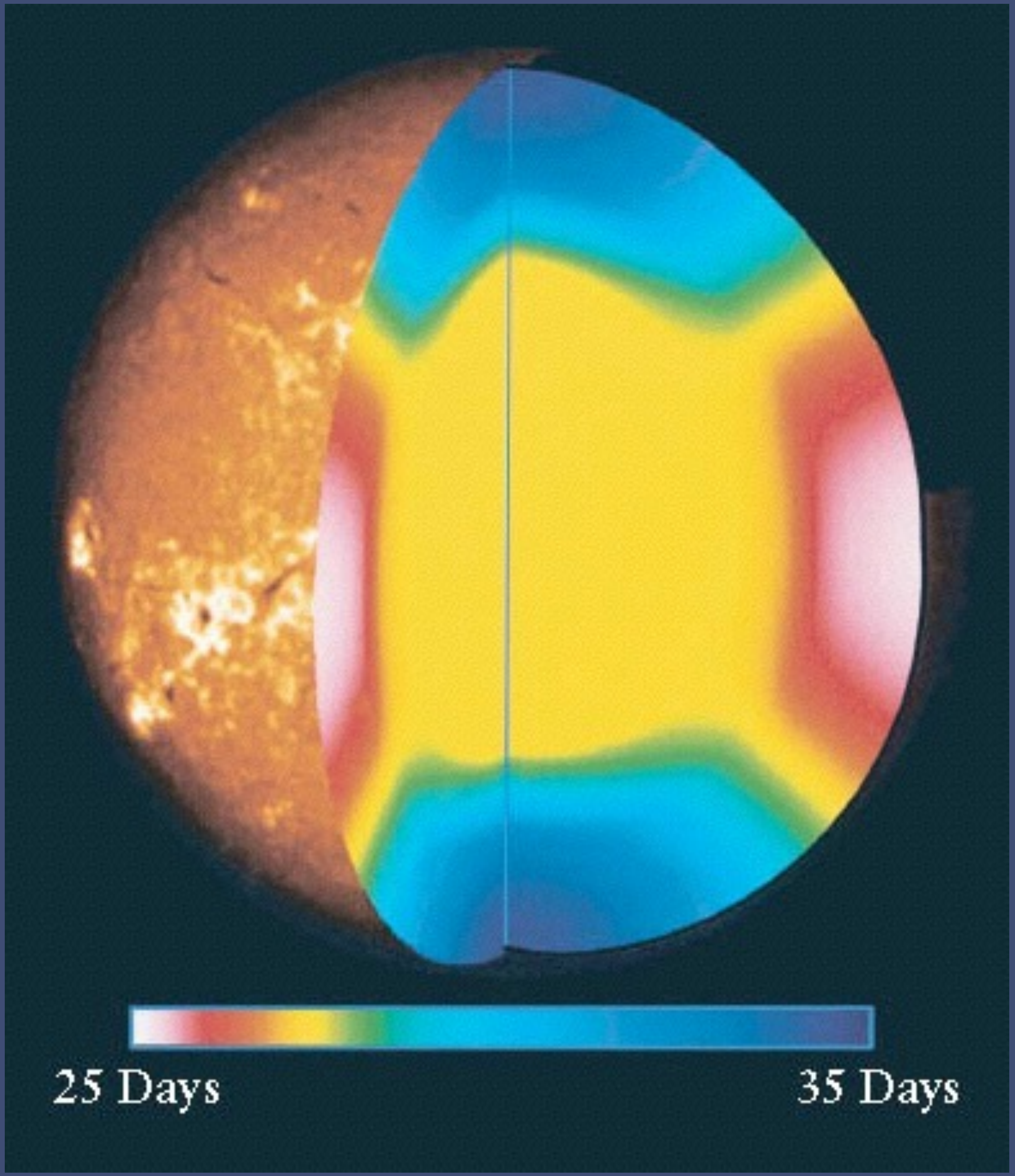
Near sunspot maximum

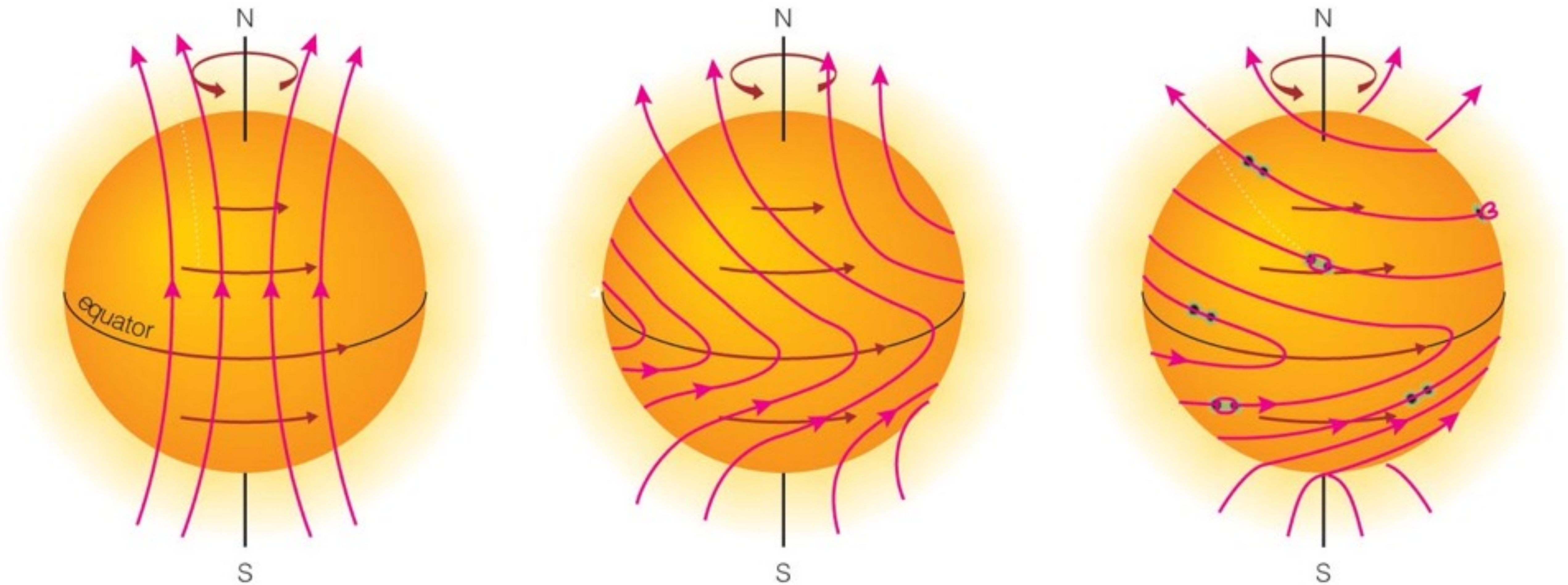


Near sunspot minimum

Solar Rotation

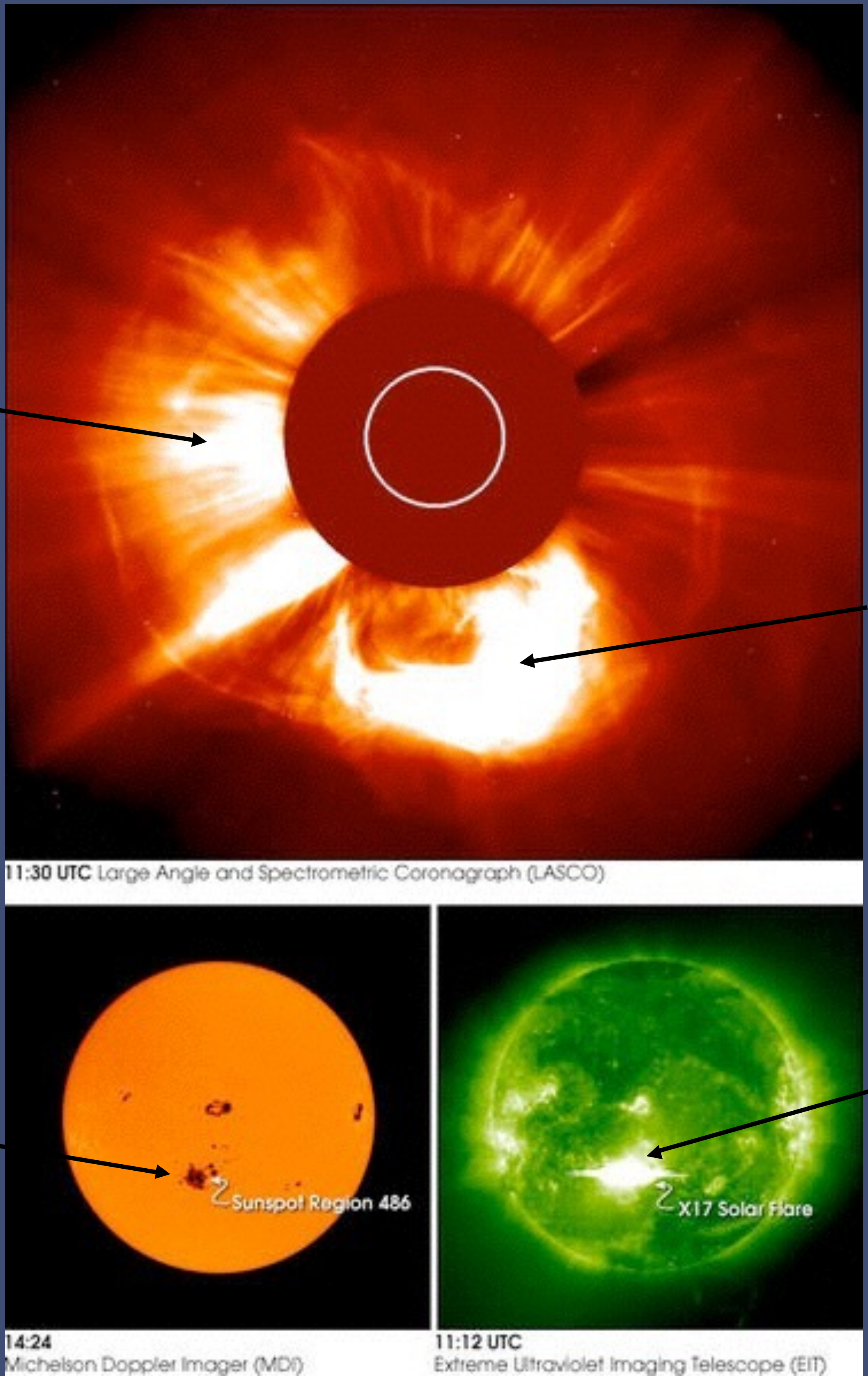
- Galileo used sunspots to measure Sun's rotation
- Sun undergoes ***<u>differential rotation</u>***
  - –25 days at equator
  - –27.5 days at 30°
  - –33 days at 75°
  - –35 days near poles





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

Active Sun



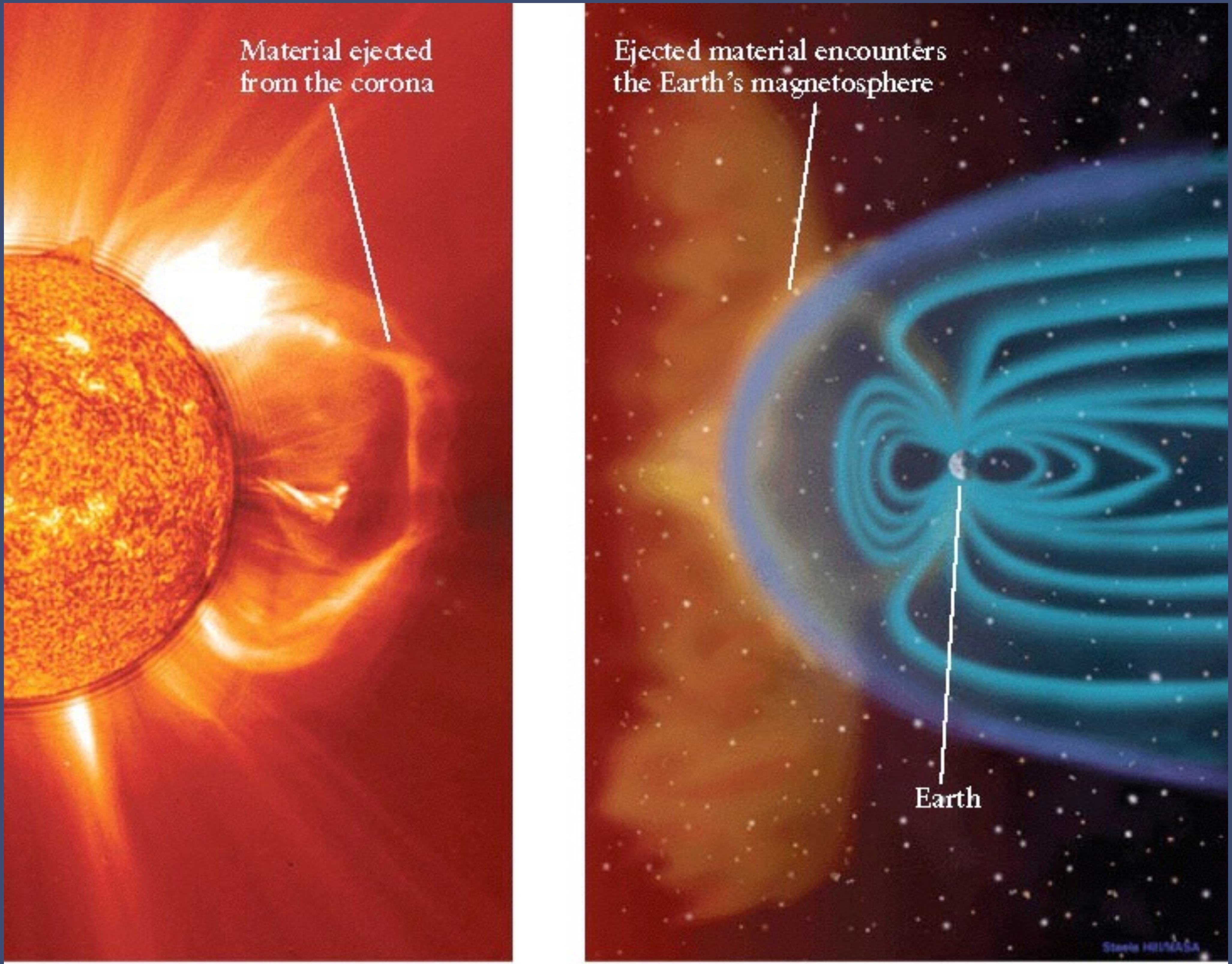
Coronal mass ejection

Prominence

Sunspot

Flare

Coronal Mass Ejection



(a) A coronal mass ejection

(b) Two to four days later