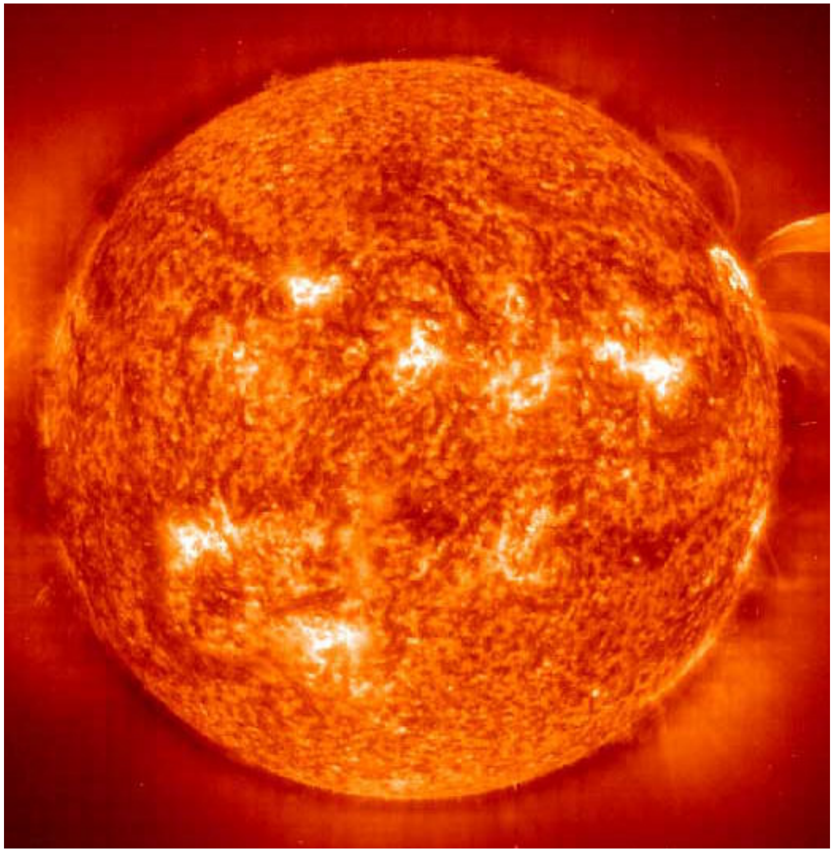
[22] Solar Structure (11/16/17)

Upcoming Items

1. Homework #10 due on Tuesday.
2. Read Ch. 14.3 by next class and do the self-study quizzes.
3. Homework #11 due **Thursday** Nov 30.

https://www.universetoday.com/wp-content/uploads/2014/09/sun1.jpg



LEARNING GOALS

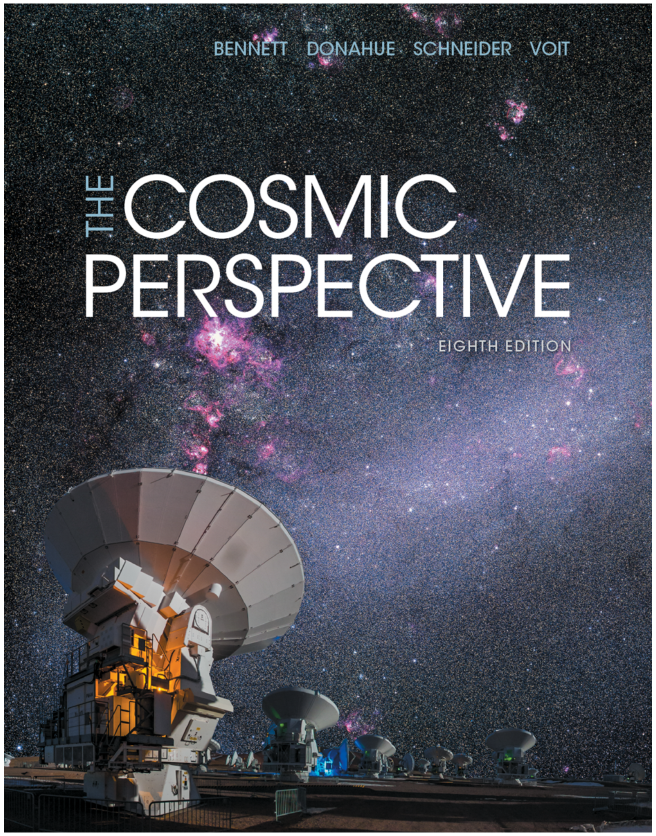
Ch. 14.1–14.2

By the end of this lecture, you should be able to…

… *rank the principal layers of the Sun, from the core to the corona, based on their relative temperature, density, and distance from the center, and group them by dominant energy transport type;*

… *using the solar thermostat concept, predict how the Sun reacts to a small change in internal conditions;*

… *understand what powers the Sun*



Tomorrow: JSI Research Expo!

- 12:30-2:30 PM, Friday, Nov 17, PSC 1136
- Joint Space-Science Institute scientists will give 5-minute research pitches, followed by informal interaction
- Will involve UMd Astronomy, UMd Physics, and NASA-Goddard scientists
- NASA/GSFC has undergraduate summer research opportunities
- Refreshments will be provided ☺

Any astro questions?

In-Class Quiz

1. Which statement about solar structure is true?

A. The corona is hotter and denser than the photosphere.
B. The corona is hotter but less dense than the photosphere.
C. The corona is cooler but denser than the photosphere.
D. The corona is cooler and less dense than the photosphere.

2. What would happen inside the Sun if a slight rise in core temperature led to a rapid rise in fusion energy?

A. The core would expand and heat up slightly.
B. The core would expand and cool.
C. The Sun would blow up like a hydrogen bomb.

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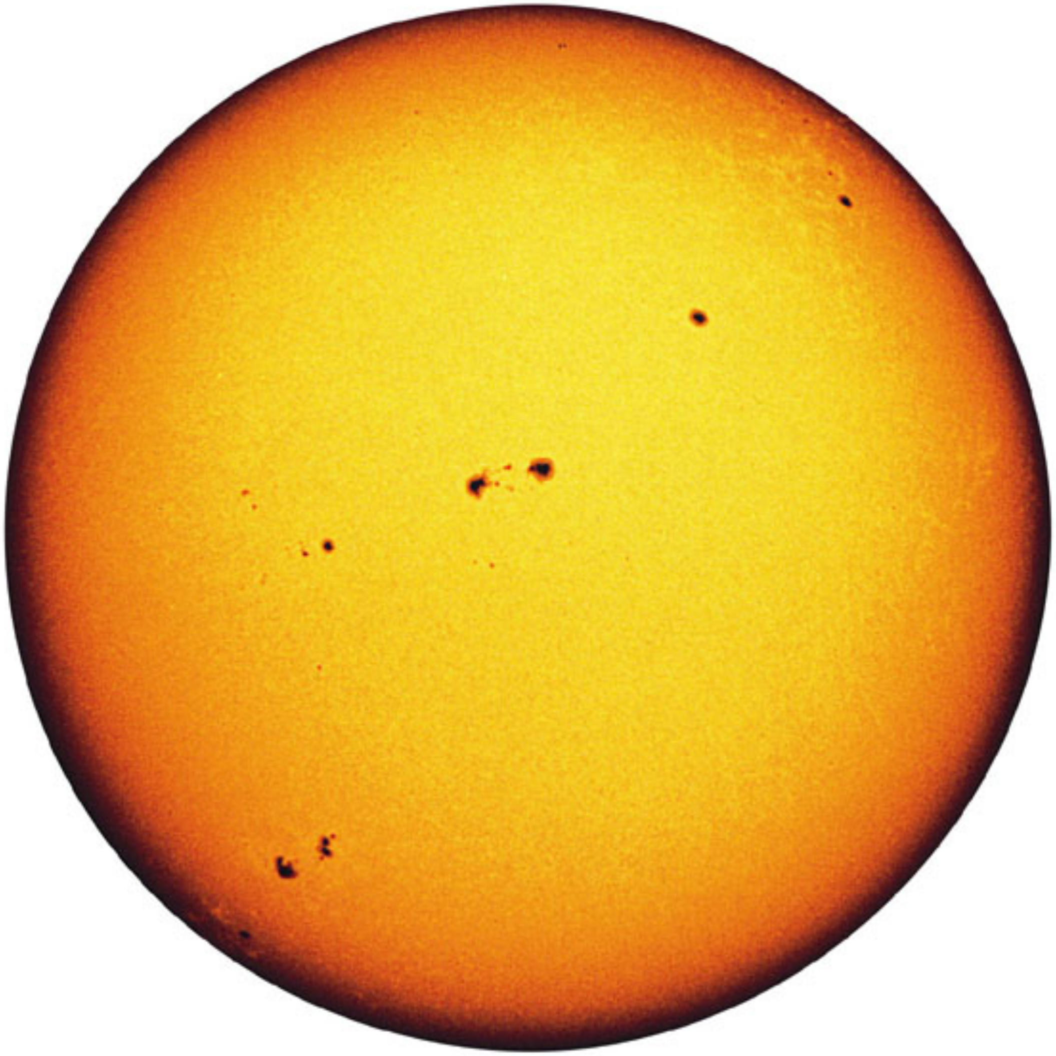
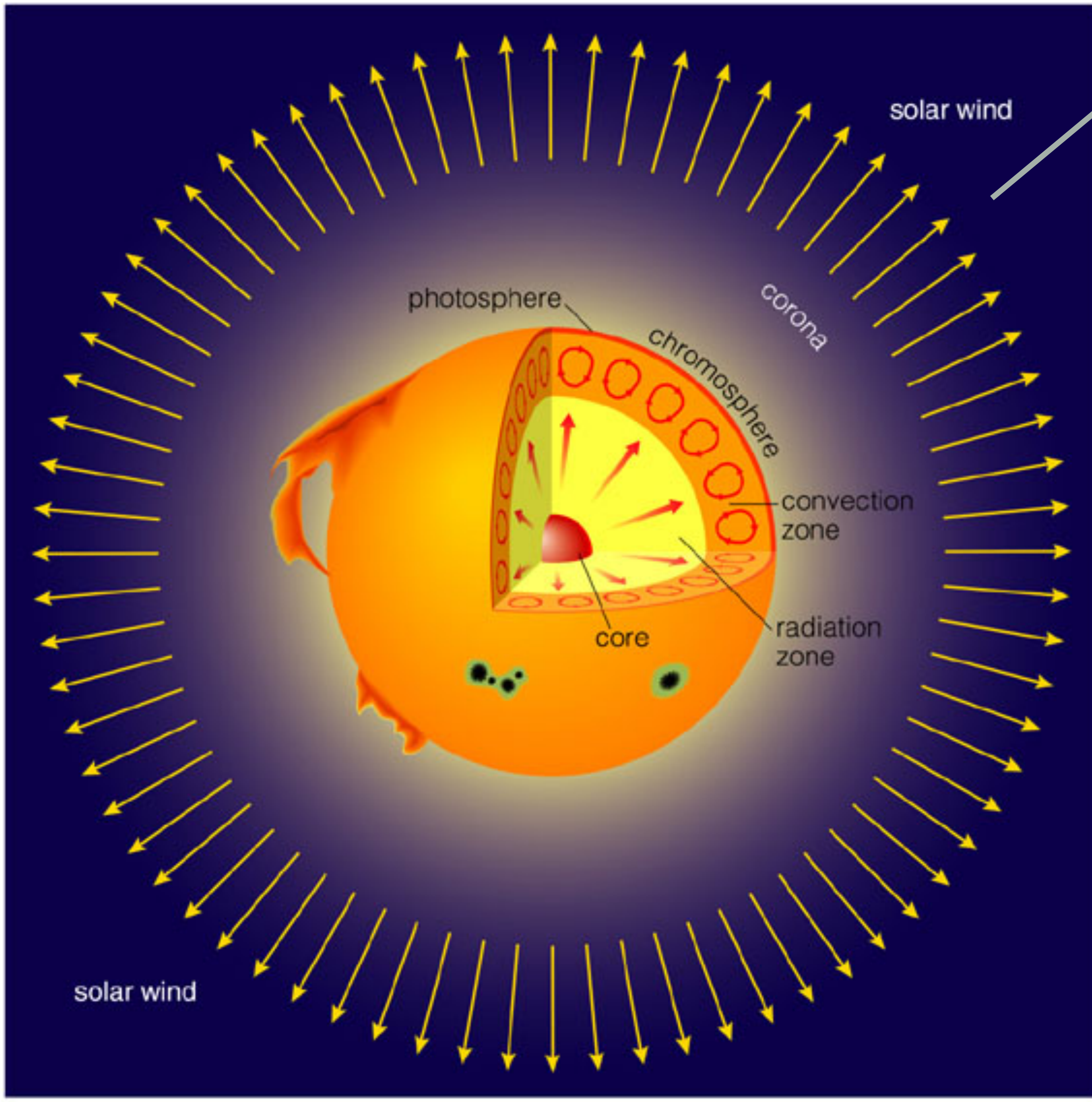


- Radius:
  6.955×10^{8} m
  (~100 times Earth).
- Mass:
  1.989×10^{30} kg
  (~300,000 Earths).
- Luminosity:
  3.846×10^{26} W.
- Rotation Period:
  ~26 d (at equator).

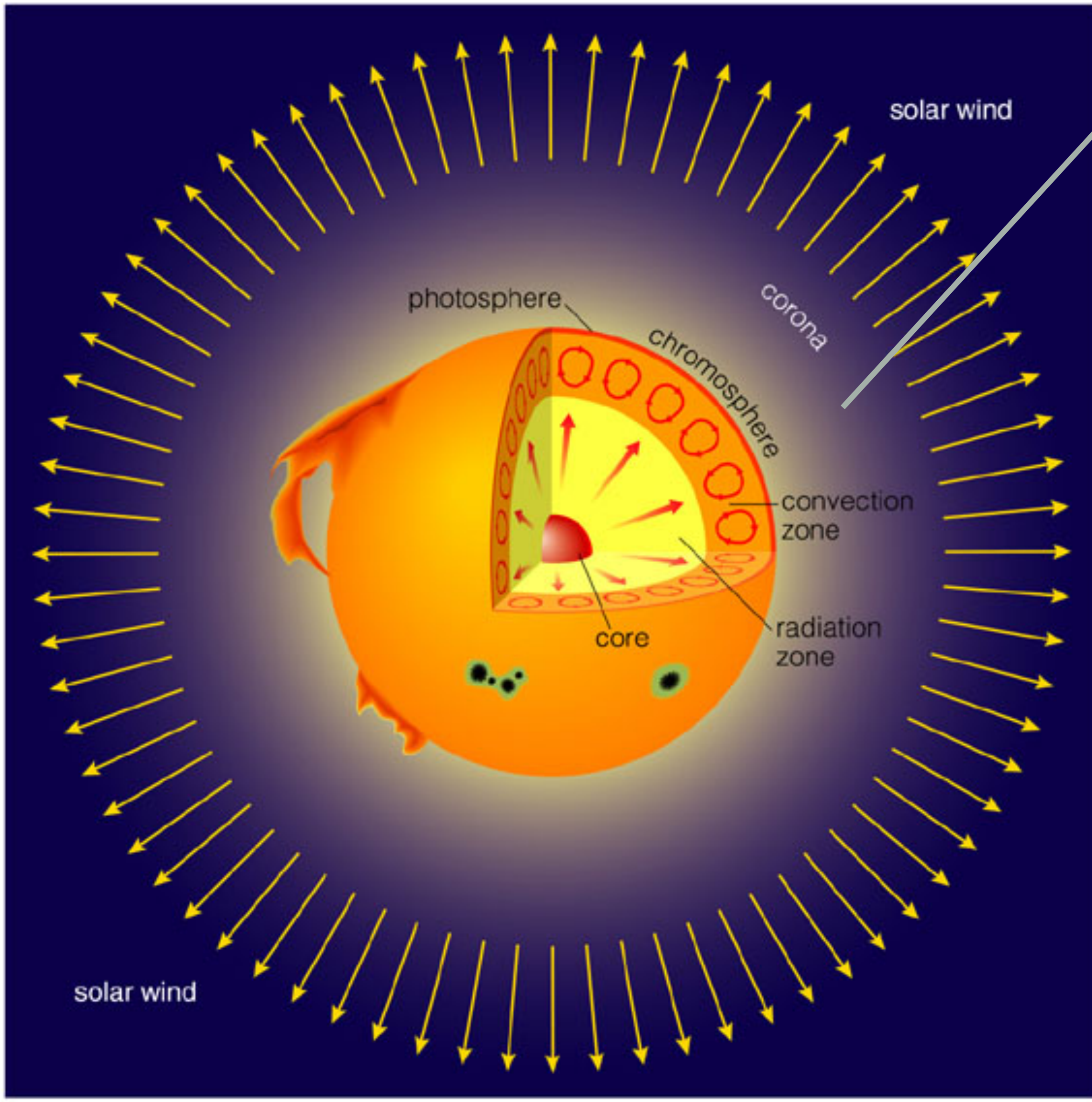
Solar Structure

- Layers based on temperature, density, and transport type.
  - Solar wind, corona, chromosphere, photosphere, convection zone, radiation zone, core.
- The Sun is in gravitational equilibrium: outward (thermal) pressure gradients balance inward (gravity) acceleration.
  - An increase in core temperature (outward pressure) causes the core to expand and cool, reducing pressure, and vice versa.
- The Sun gets its energy from fusion of hydrogen to helium (proton-proton chain).
  - $4H \rightarrow {}^4He$ + energy + neutrinos, needs high T & P to start (why?).
- Dominant energy transport depends on layer.



Solar wind:

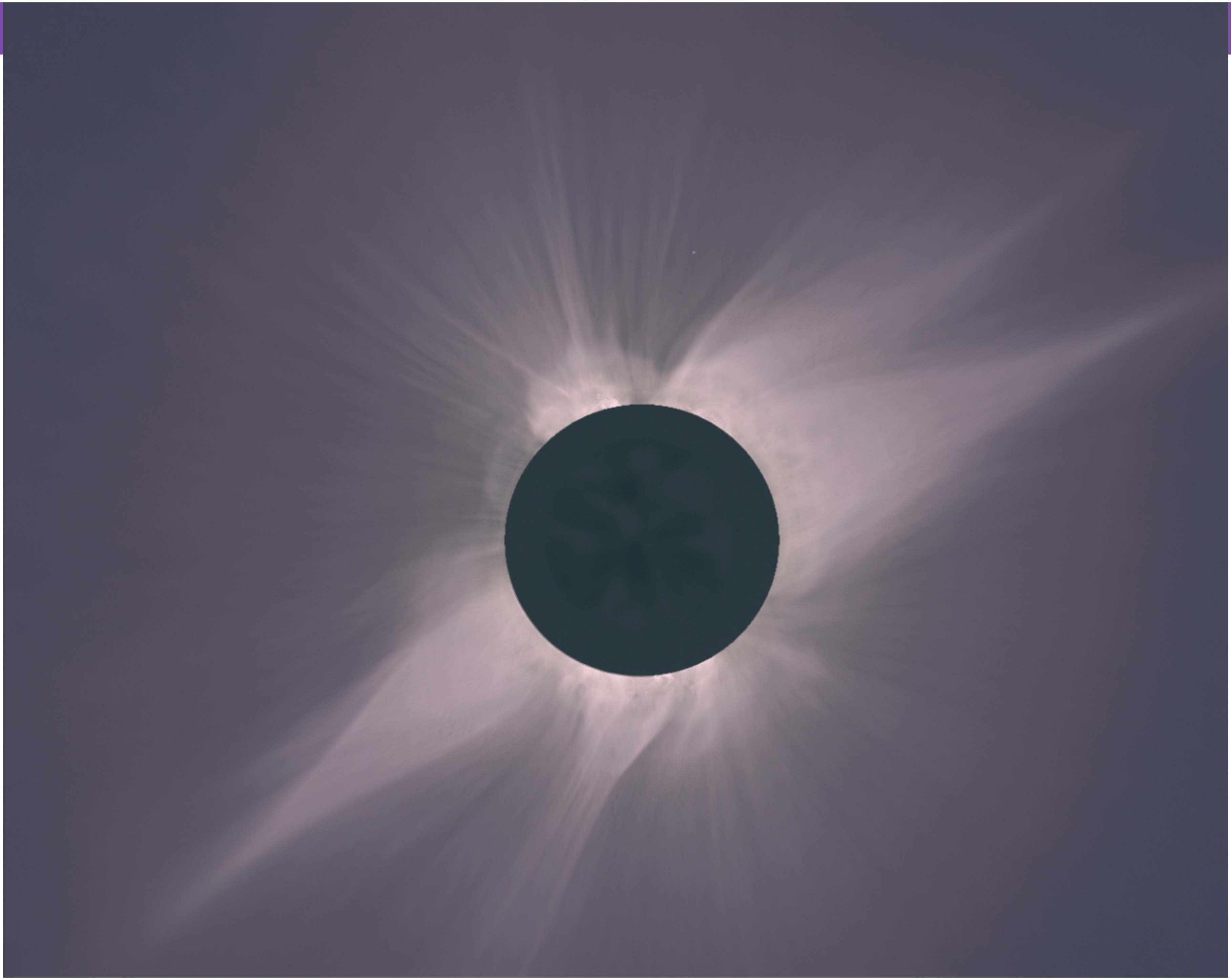
A flow of charged particles (electrons and ions, mostly protons) from the surface of the Sun, moving at ~500 km/s.

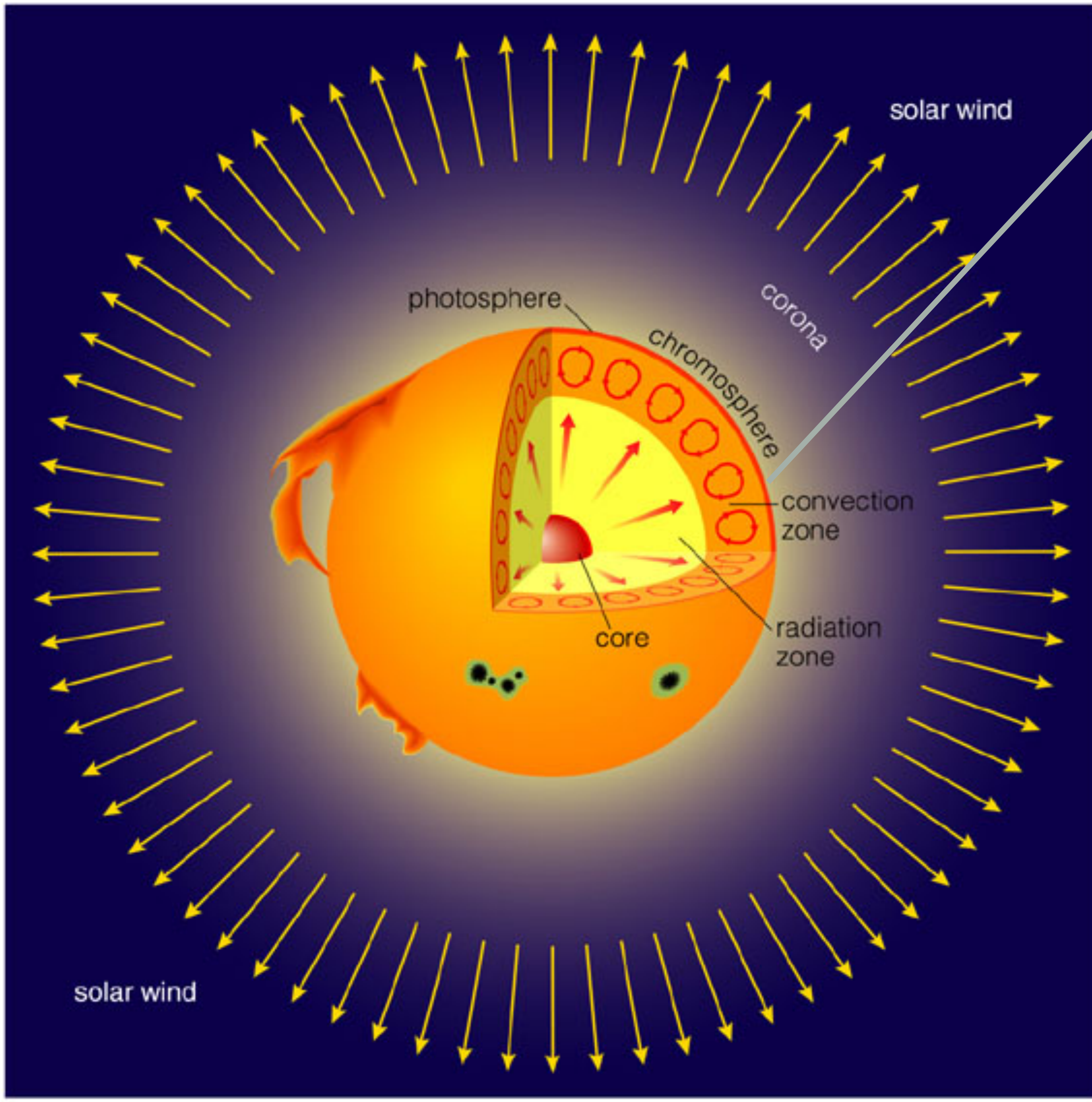


Corona:

Outermost layer of solar atmosphere: tenuous gas extending far into space, heated by magnetic fields.

~1 million K, emits X rays.

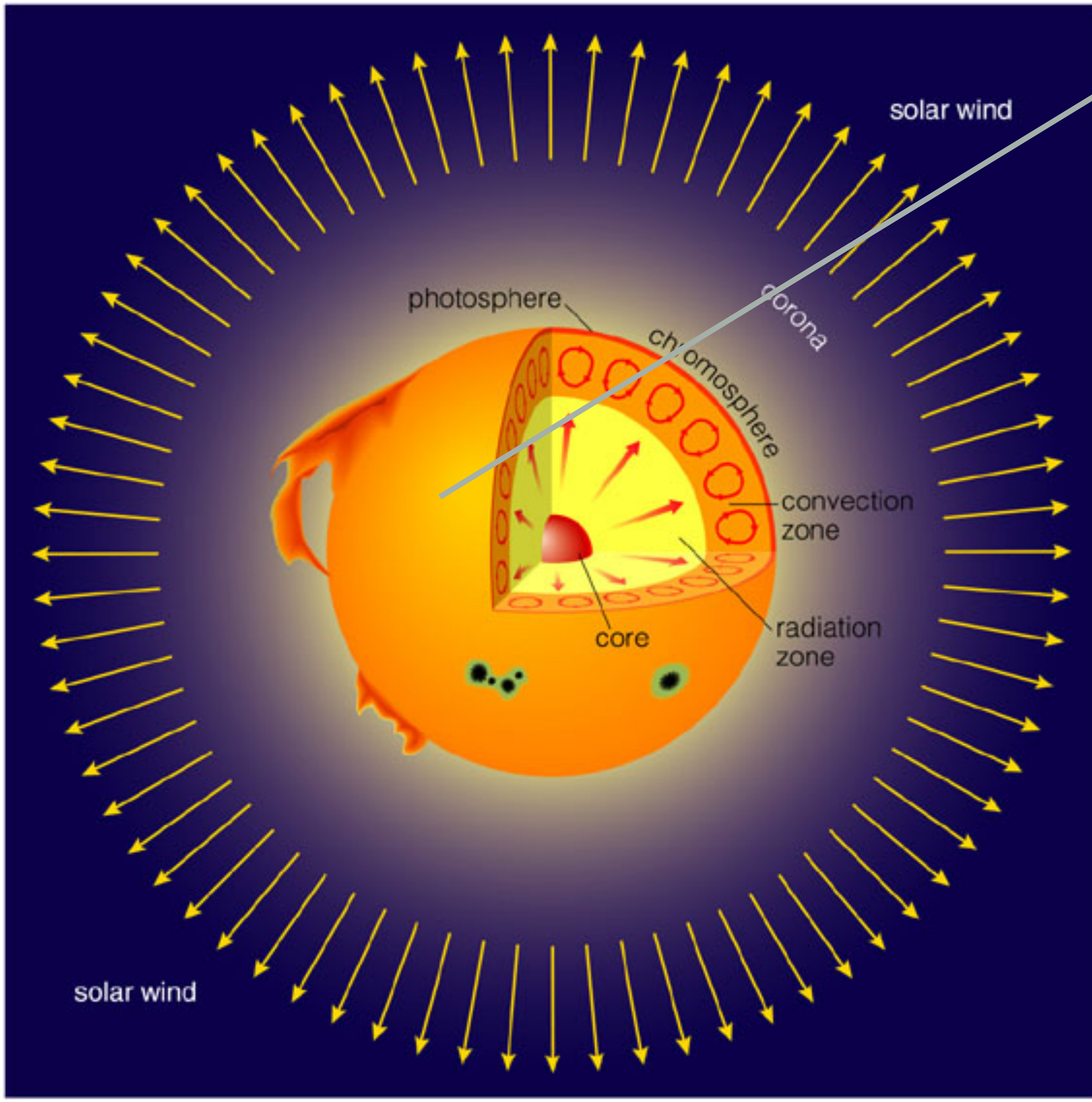




Chromo-sphere:

Middle layer of atmosphere, ~10^6× denser than corona (still very tenuous!), only 1000 km thick.

~10^4–10^5 K, produces emission lines, especially of hydrogen ➔ pink glow.

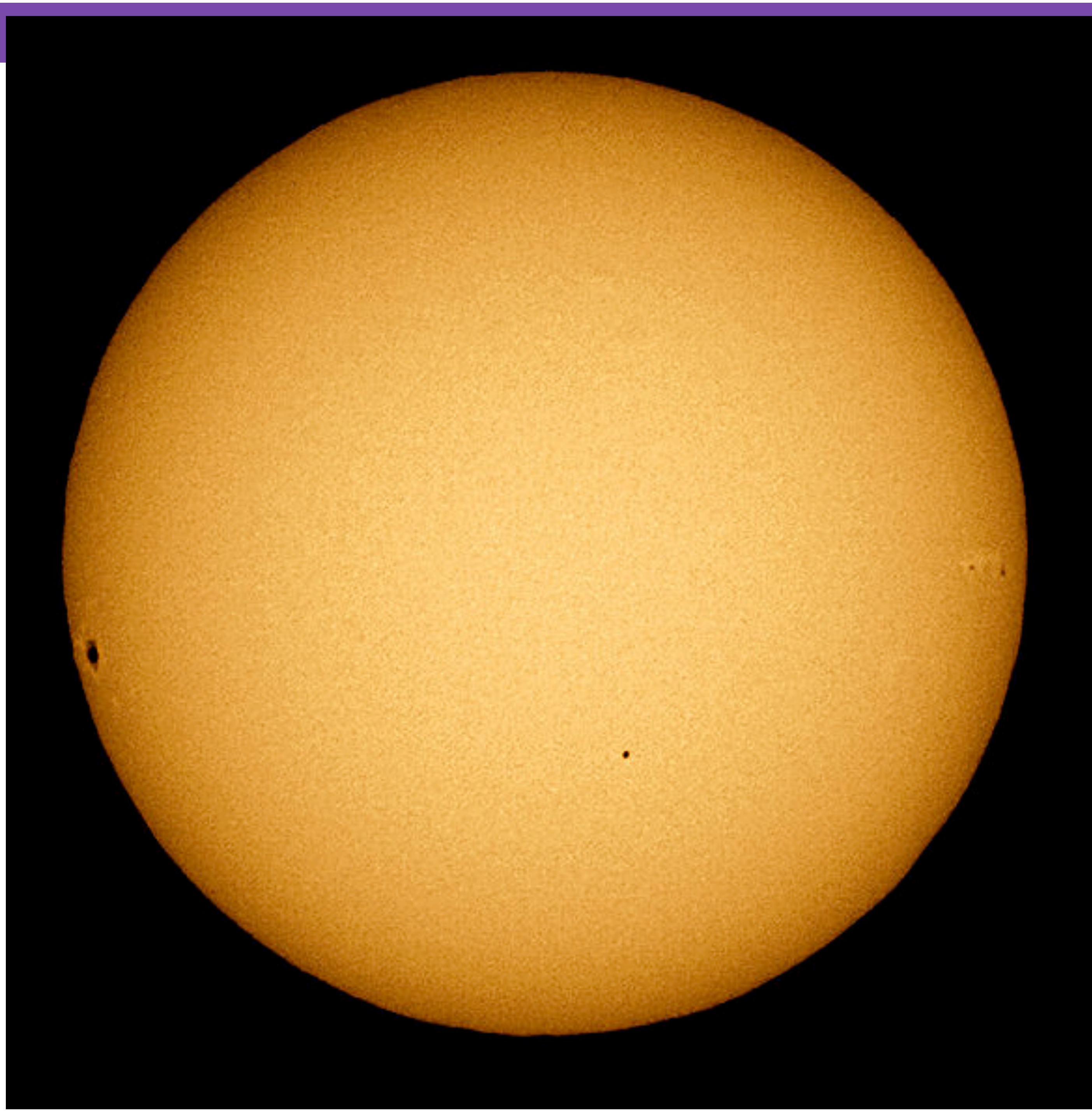


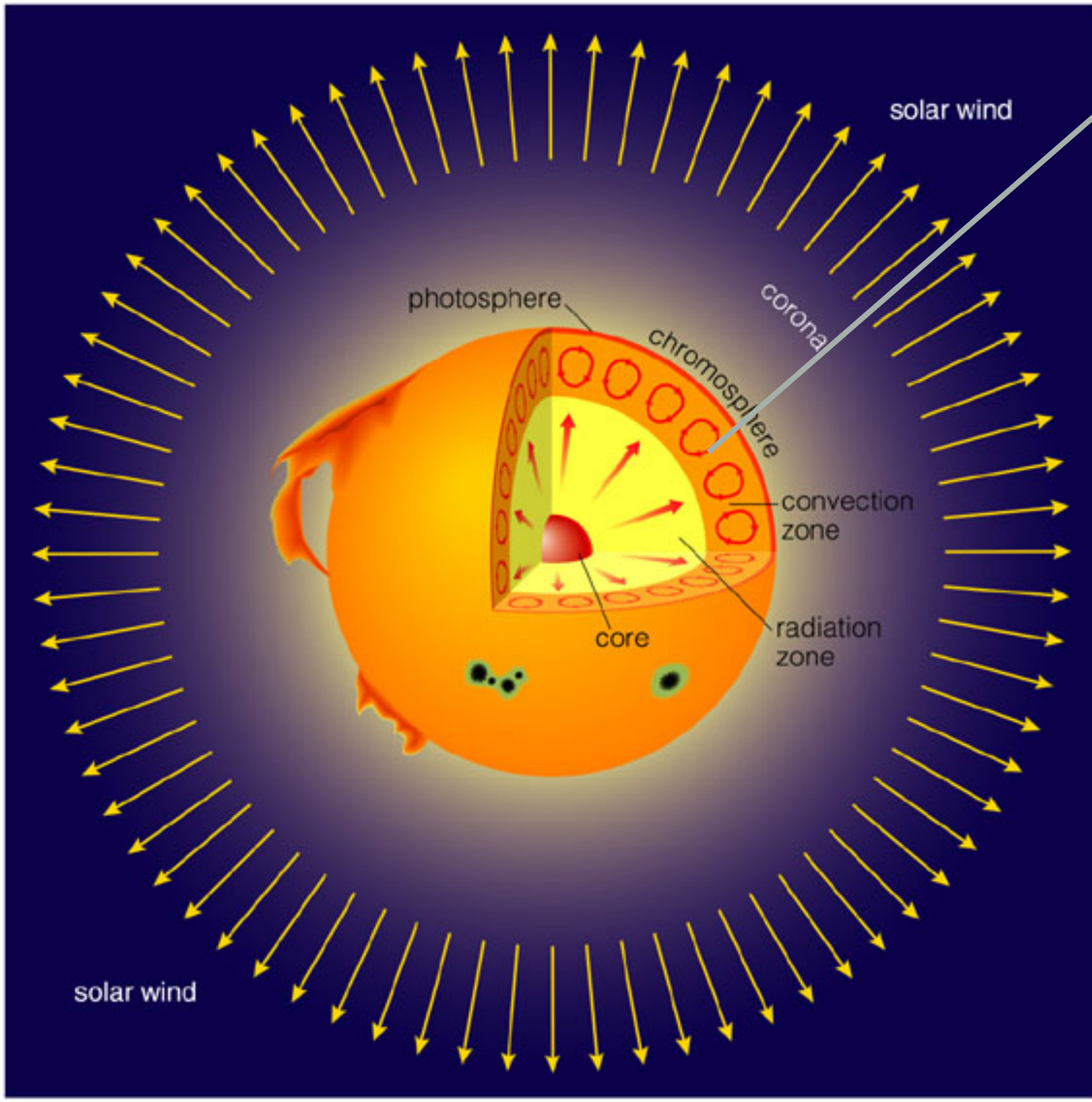
Photosphere:

Visible surface of Sun, density ~10^{-4} kg/m^3 (~10,000× chromosphere).

~6,000 K, upper layer cooler ➔ absorption lines, limb darkening.

Why absorption lines here, versus emission in chromosphere?

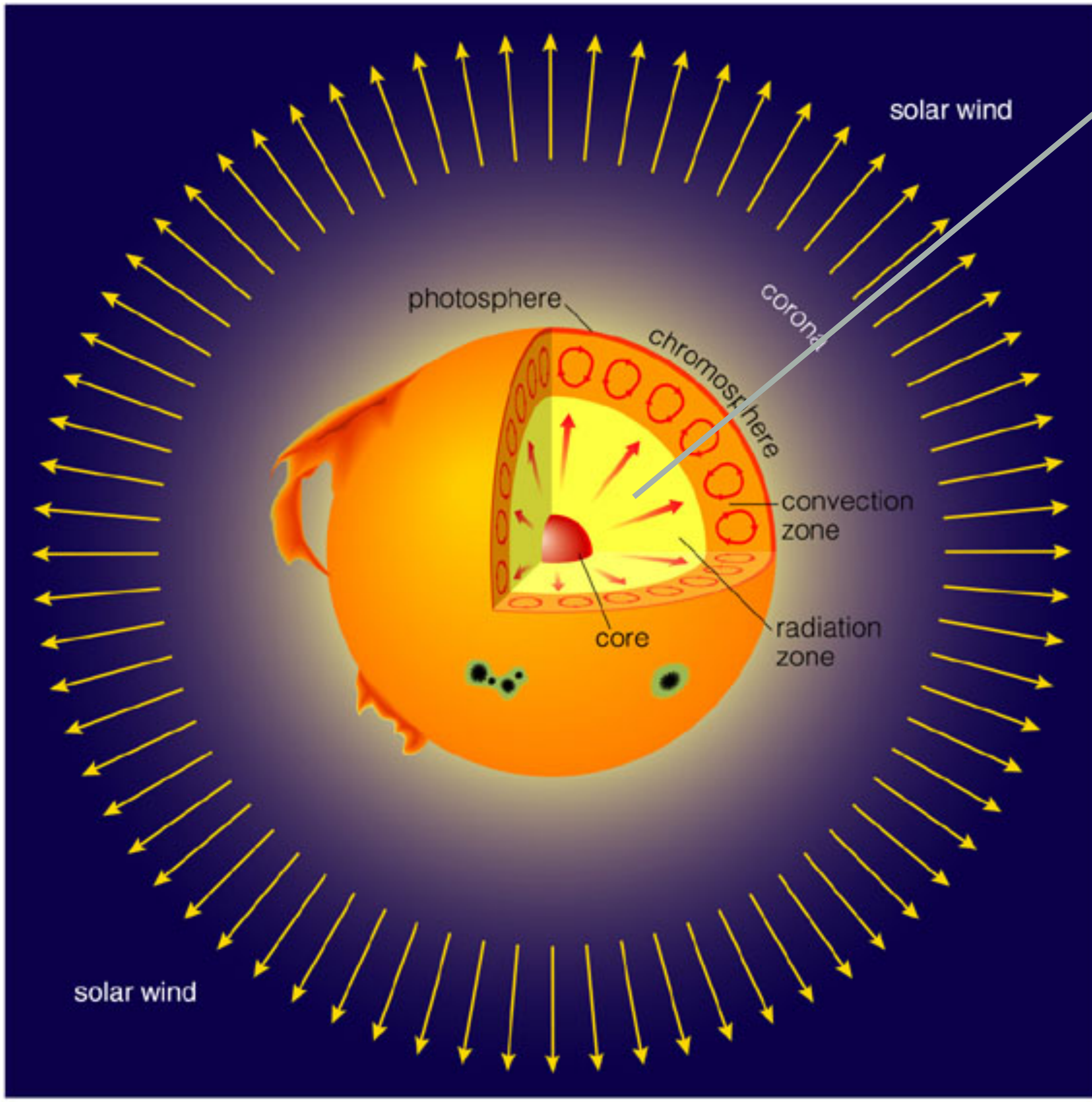




Convection Zone:

Energy transported upward by rising hot gas.

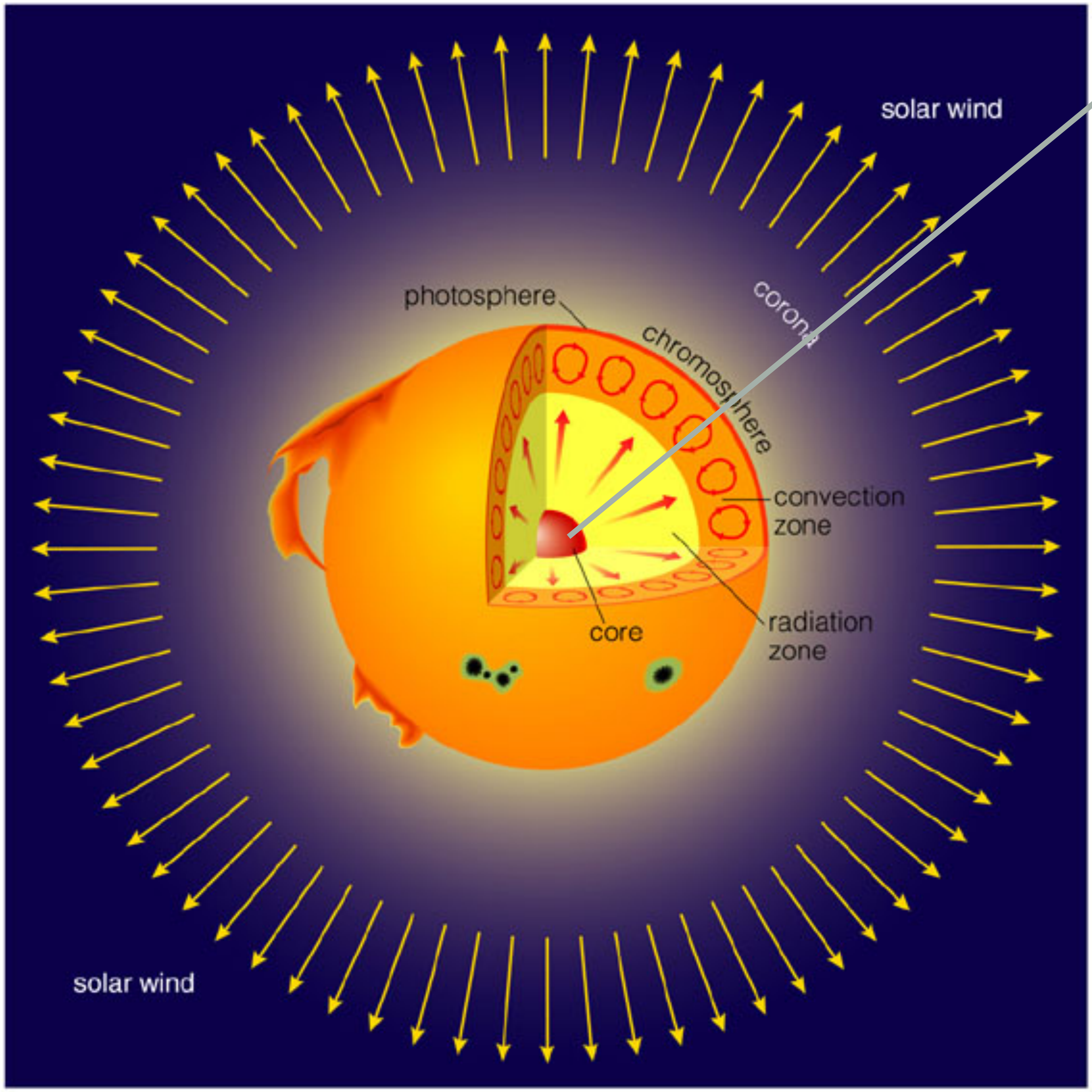
Temperature cool enough ($< 2\times10^6$ K) and gradient steep enough for convection to dominate energy transport.



Radiation Zone:

Energy transported upward by photons (light).

High density (~10× lead near core) ➔ radiative diffusion: photons random walk their way out—takes >100,000 years!



Core:

Energy generated by nuclear fusion.

~15 million K, $1.6{\times}10^5$ kg/m^3.

Using the Ideal Gas Law

- The ideal gas law works pretty well for normal stars:

$$\boxed{P = nk_B T.}$$

- Here P is the pressure, n is the number of atoms per unit volume, and T is the temperature.
- Consider a slab of material of mass m and thickness h:

$$P = \frac{\text{force}}{\text{area}} = \frac{mg}{A} = \frac{mgh}{V} = \rho gh.$$

- If we apply this to the entire star, $g = GM/R^2$, $h = R$, so

$$P_{\text{core}} \sim \rho gh \sim \left(M/\tfrac{4}{3}\pi R^3\right)\left(GM/R^2\right)R \approx \underline{3\times10^{14}\ \text{Pa}}.$$

- Then from the ideal gas law, with $n = (M/m_{\text{H}})/(\text{volume})$:

$$T_{\text{core}} = P_{\text{core}}/nk_B \approx \underline{2\times10^{7}\ \text{K}}.$$

Where does the Sun get its energy?

- Group exercise
- Pretend that you don’t know that fusion powers the Sun
- Come up with as many fundamental power sources as possible, so that we can assess them
- Not all have to be serious; have fun!

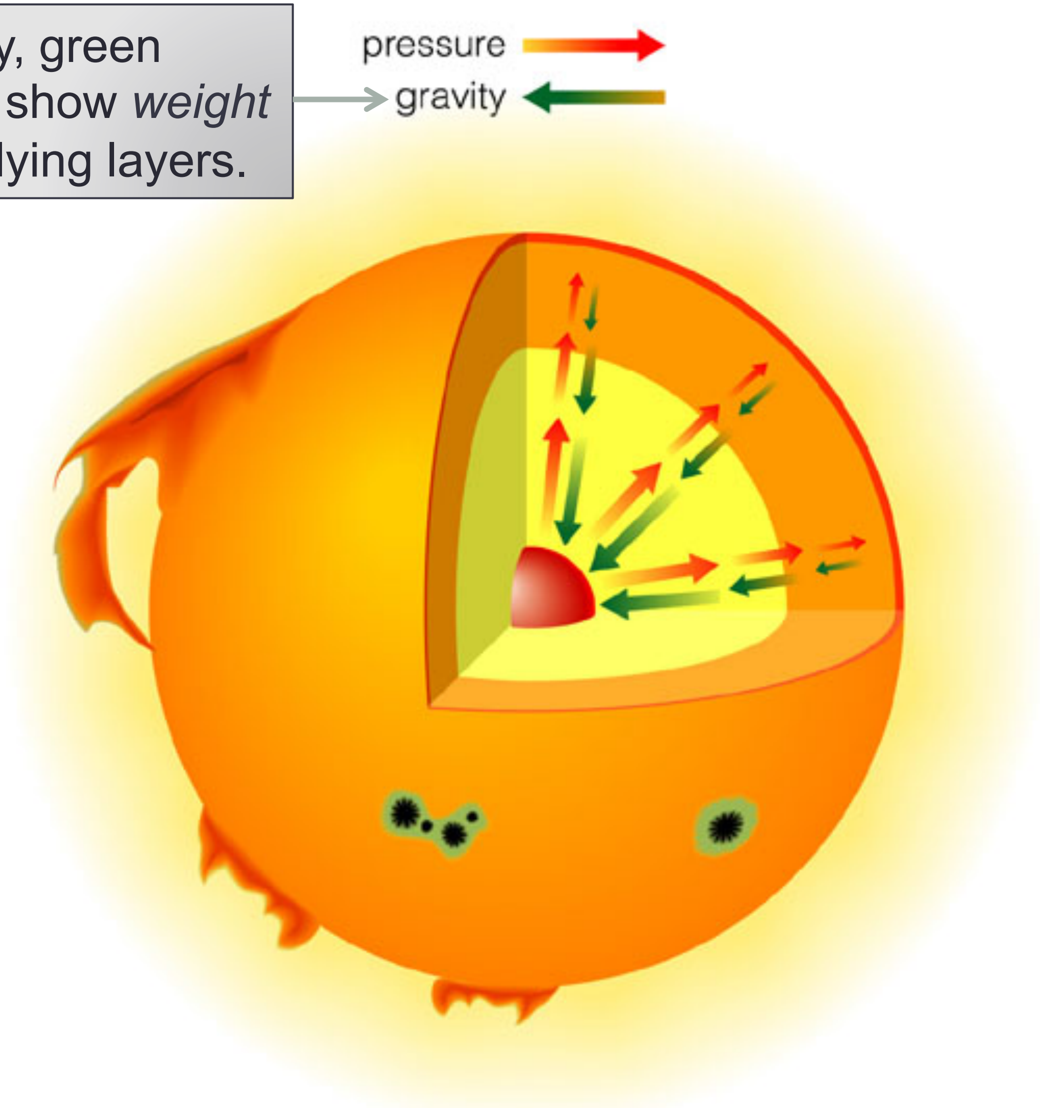
List of Fundamental Power Sources

- Alien light bulbs, 5th dim being, Hell, fireflies, belief, self-motivated, terrapins all the way down, computer program, giant baby head, gravitational contraction, rotation of dense core, hamsters, POTUS hair, Ra, neurons, monsters scaring children, triboluminescence, Pixar lamp, Santa, good vibes, white hole, batteries, volcano, simulation, 17 baked potatoes, fire, crystal reflecting light, dark energy, burning metal, tidal forces, explosions, fission, gasoline, photon collisions, neutrinos

How would we narrow down the list?

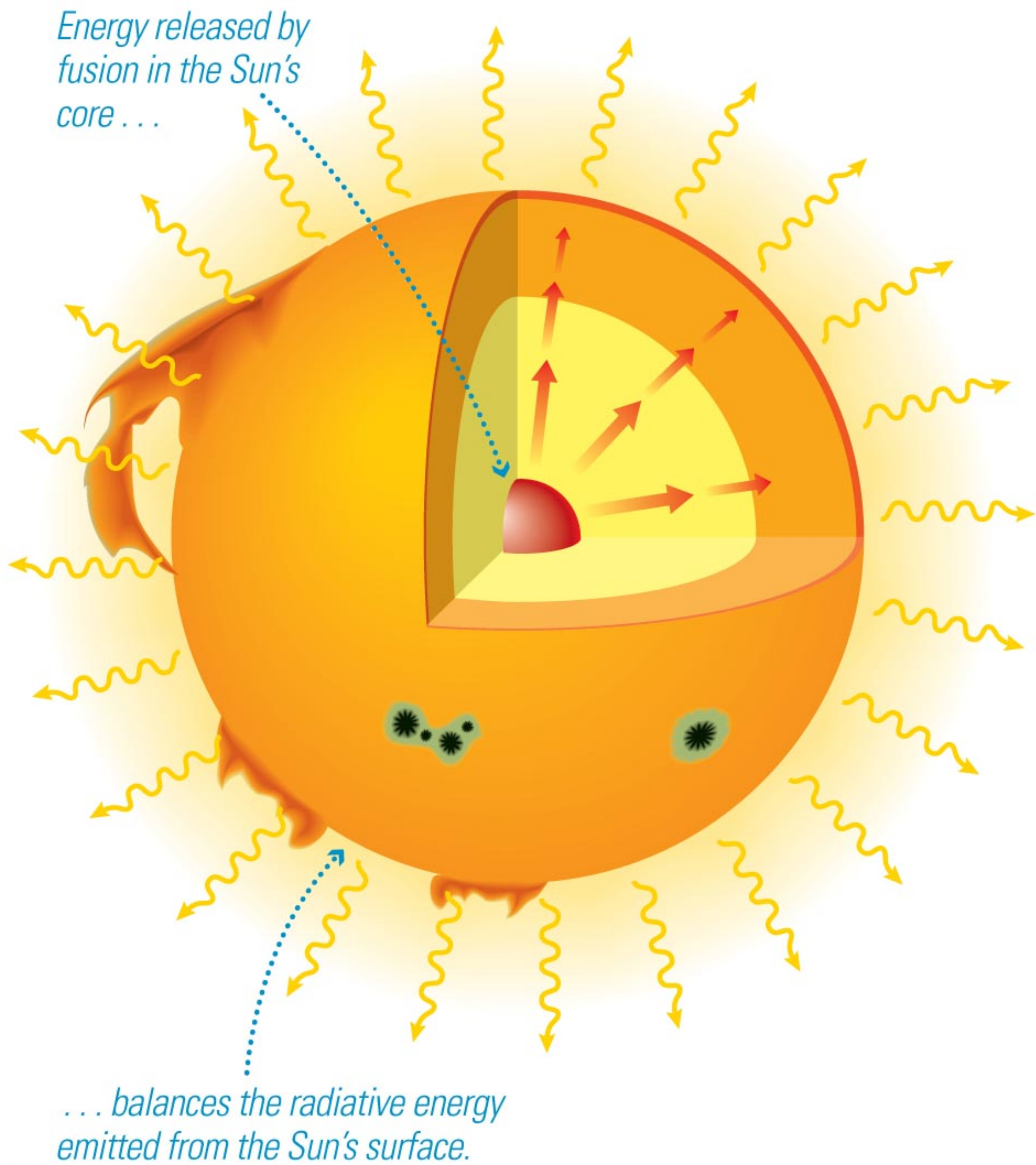
- What are the major constraints we would apply?
- Ideal is to have ***clean*** kills of ideas; nothing complicated, because those arguments can go wrong
- So what are the major aspects of the Sun's luminosity and energy that we would use to cull models?
- Ockham's razor, sustainability, life, energy conservation, age of the Sun, energy density, composition

Actually, green arrows show *weight* of overlying layers.



Gravitational equilibrium…

Energy provided by *fusion* (heat) maintains the pressure that balances the inward crush of gravity.

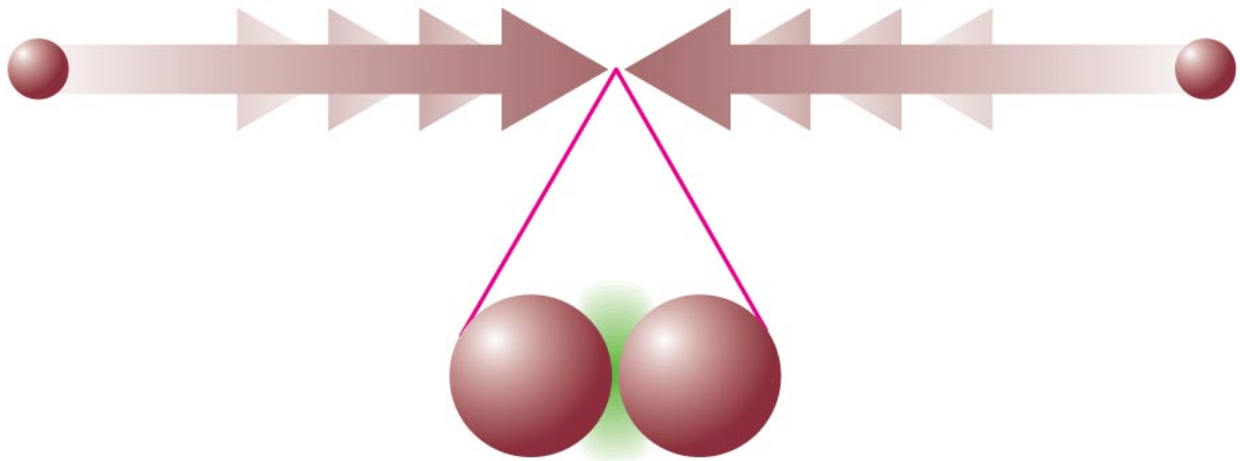


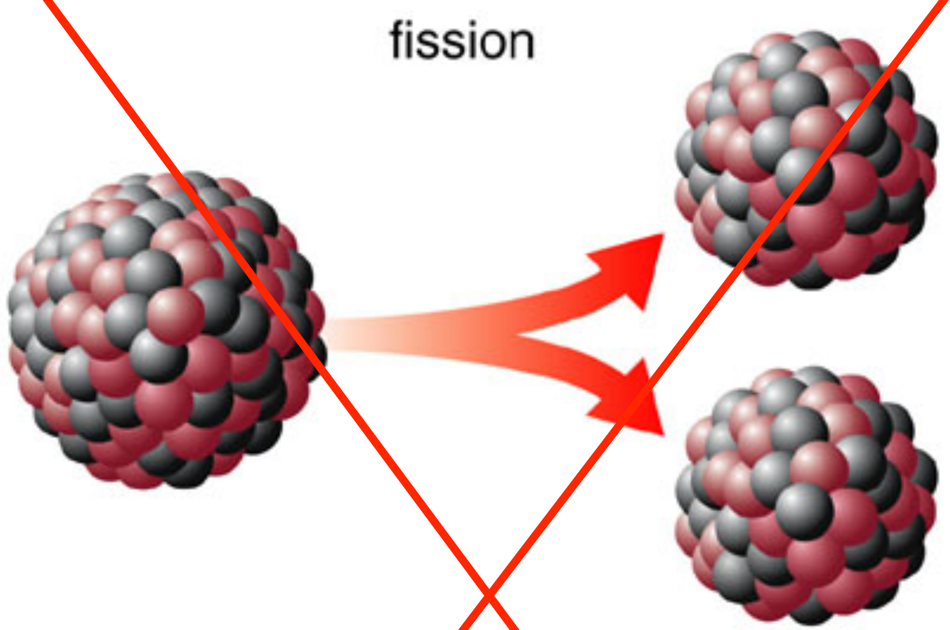
Energy balance…

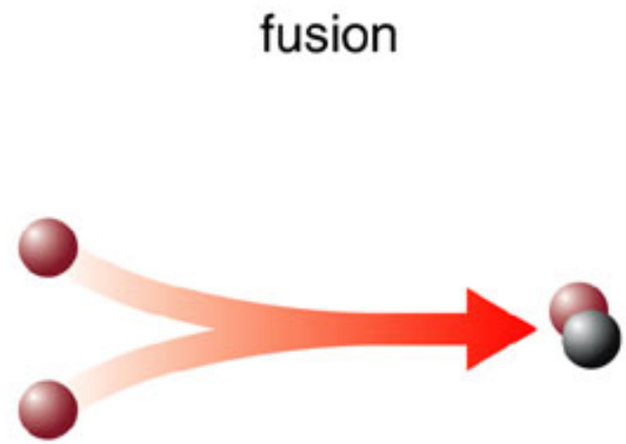
The rate at which energy radiates from the surface of the Sun must be the same as the rate at which it is released by fusion in the core.

What if the rates did not balance?

How does nuclear fusion occur in the Sun?







Fission

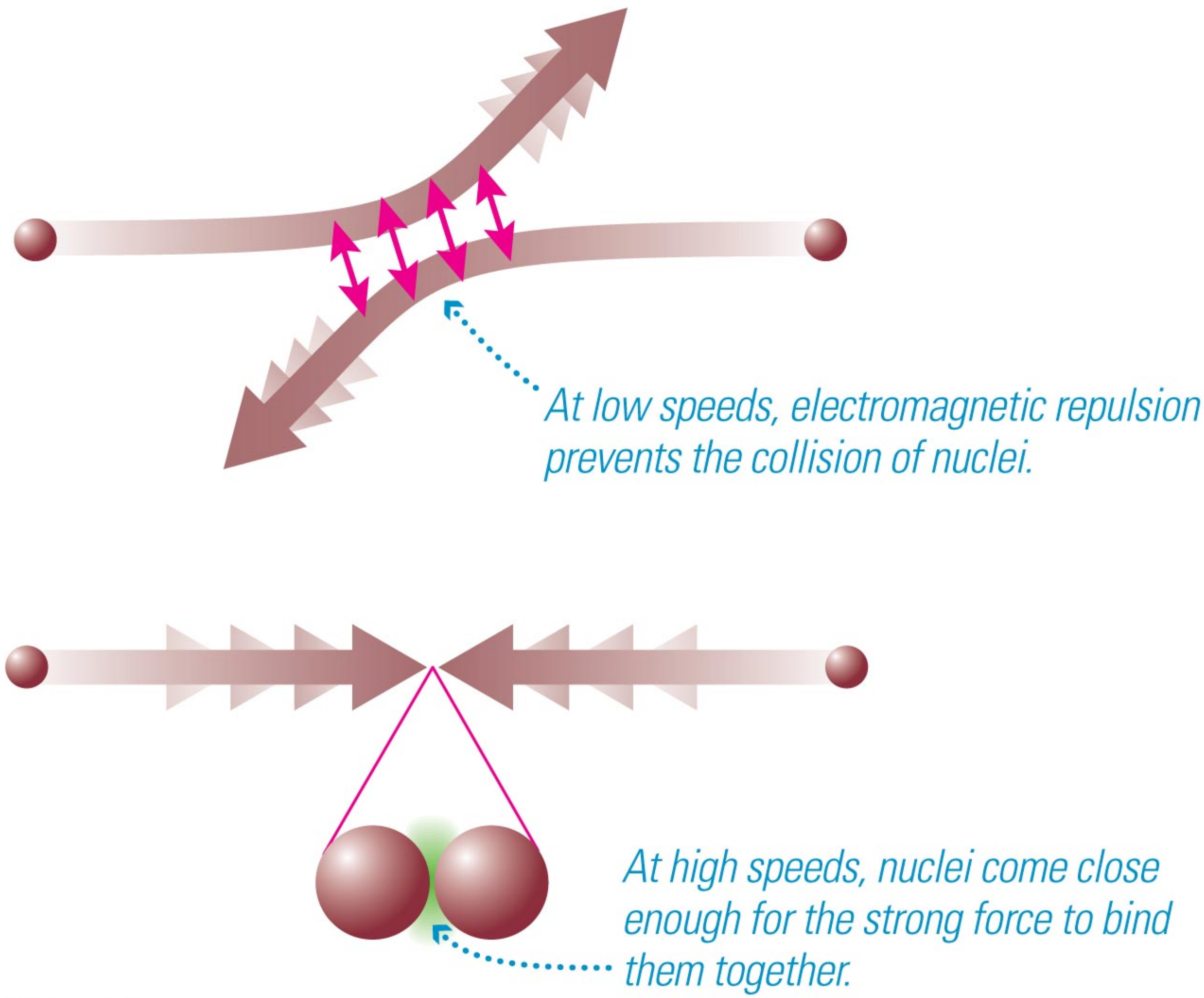
Big nucleus splits into smaller pieces.

(Nuclear power plants.)

Fusion

Small nuclei stick together to make a bigger one.

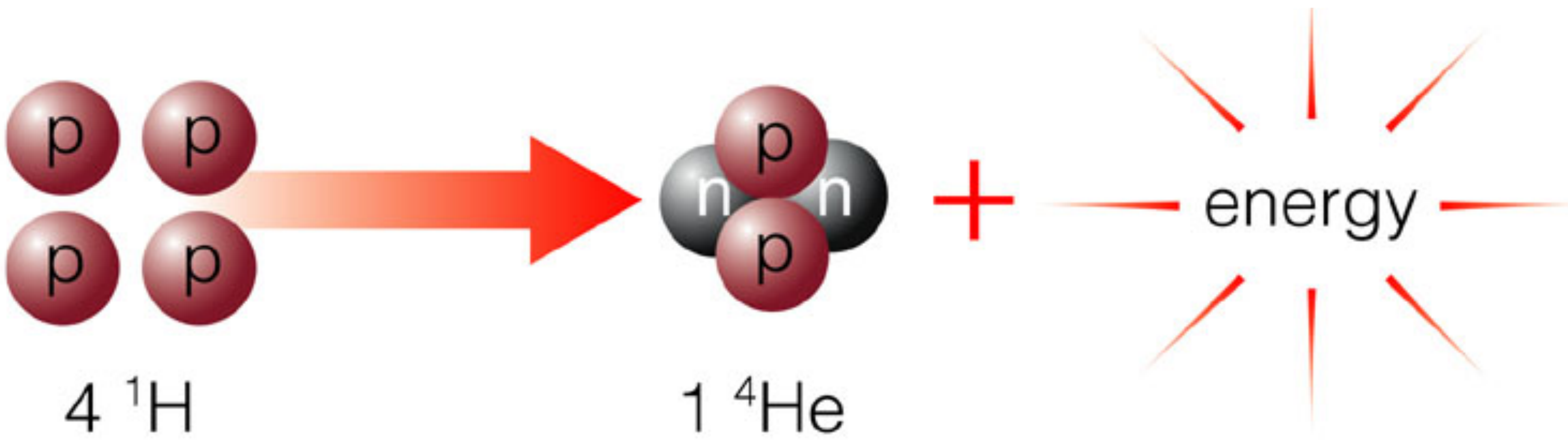
(Sun, stars.)



High temperature enables nuclear fusion to happen in the core.

(Atoms move faster when they're hotter.)

Also need high density (number) of atoms because reactions are so rare.



The Sun releases energy by fusing four hydrogen nuclei into one helium nucleus in several steps.

The sequence of steps is called the *proton-proton chain*. We won't focus on the details, but note that two protons have to convert to neutrons somewhere along the way. How?

A Couple of Comments

- The Sun has a long lifetime, so the conversion of hydrogen to helium is siooooow... a typical proton takes billions of years to become incorporated into a helium nucleus
- To overcome electrostatic repulsion, need enough energy
  Typical energy barrier for H fusion is ~2×10^{-13} J
  E=kT, so typical temperature would be ~$2\times10^{-13}/k$, or ~$2\times10^{-13}/1.38\times10^{-23}$, or >$10^{10}$ K
  But actual temperatures for H fusion are ~$1\text{-}2\times10^{7}$ K
- Why is there such a huge difference???

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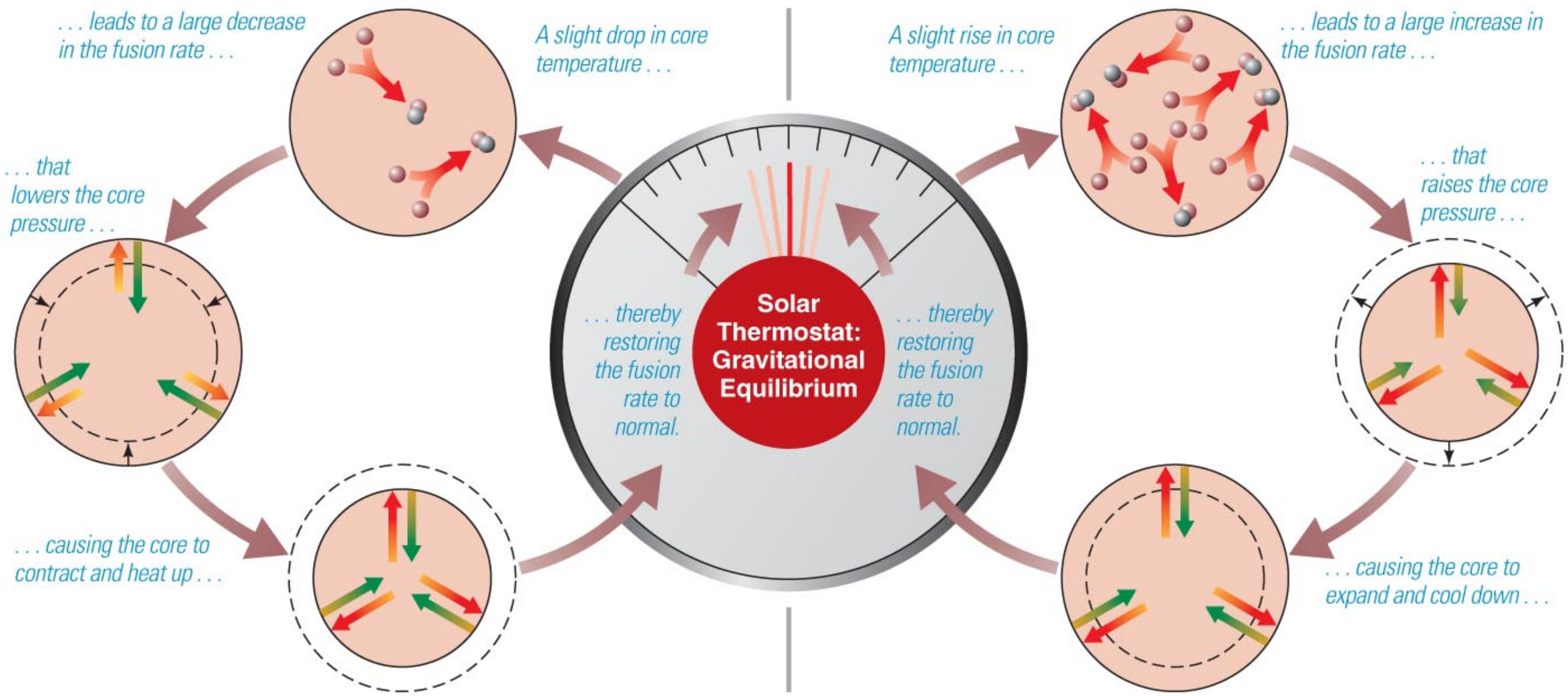
  But actual temperatures for H fusion are $\sim 1\text{-}2\times10^{7}$ K
- Why is there such a huge difference???
- Key turns out to be "quantum tunneling", by which a particle can get through a barrier with less energy

Solar Thermostat



- Drop 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.