Announcements

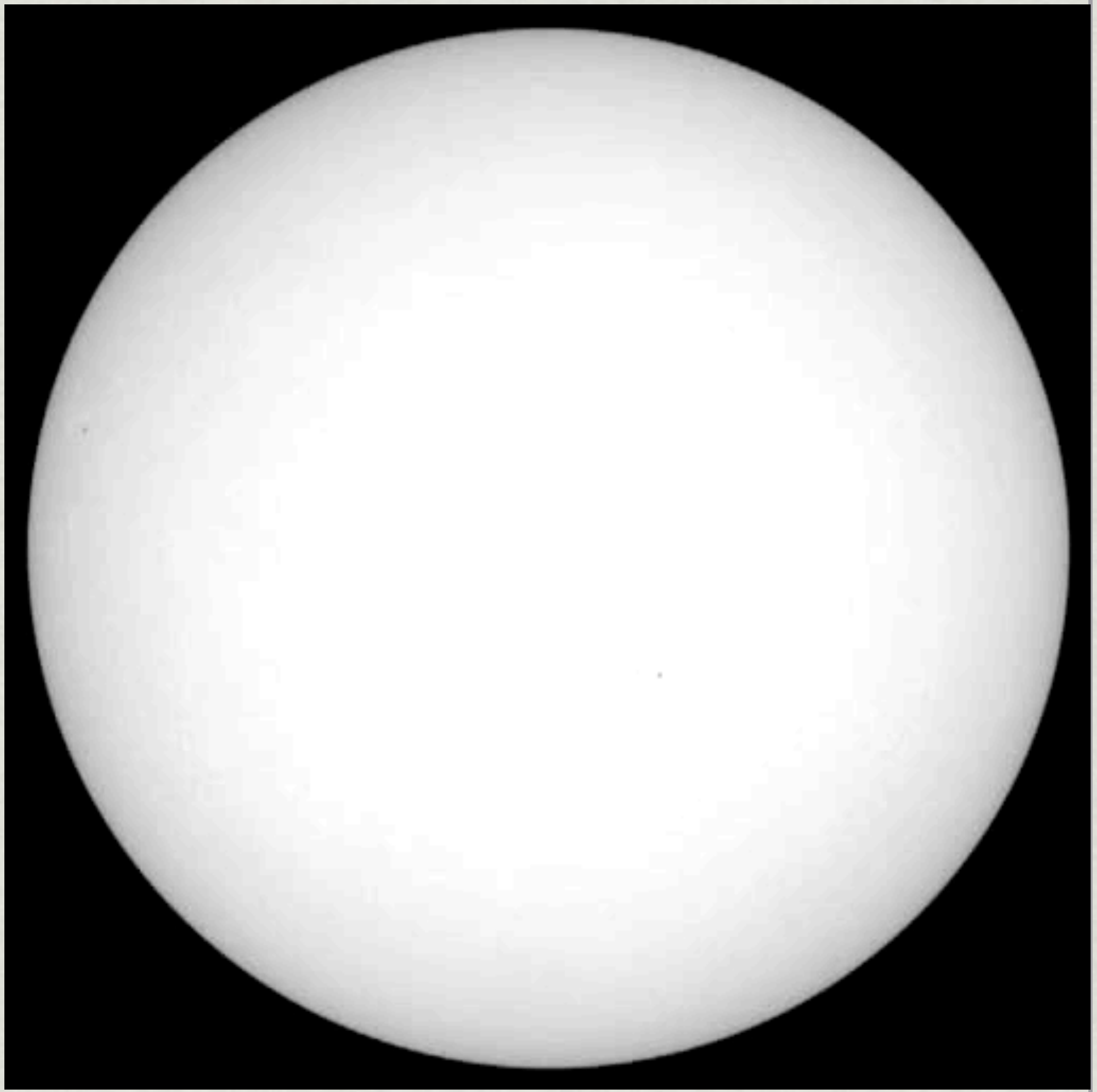
- Midterm in-class Tuesday, 2/14
  - Content: everything through lecture 2/7, homework due 2/9 (Chapters 1,2,3,4)
  - You will get a formula sheet and all numbers you need
  - Closed book and notes.
  - Bring a pencil and a non-web-enabled calculator
  - Best practice is to review the homework problems and reading assignments
- Midterm review sessions: TBD
- About that homework problem: you will never have a test problem that uses mass in lbs (pounds).

Movie: highlights of data from the SOHO (Solar and Heliospheric Observatory) satellite.

A NASA+European Space Agency (ESA) space mission to study the sun and the solar wind.

Launched in 1995, still working today.
www.nasa.gov/mission_pages/soho

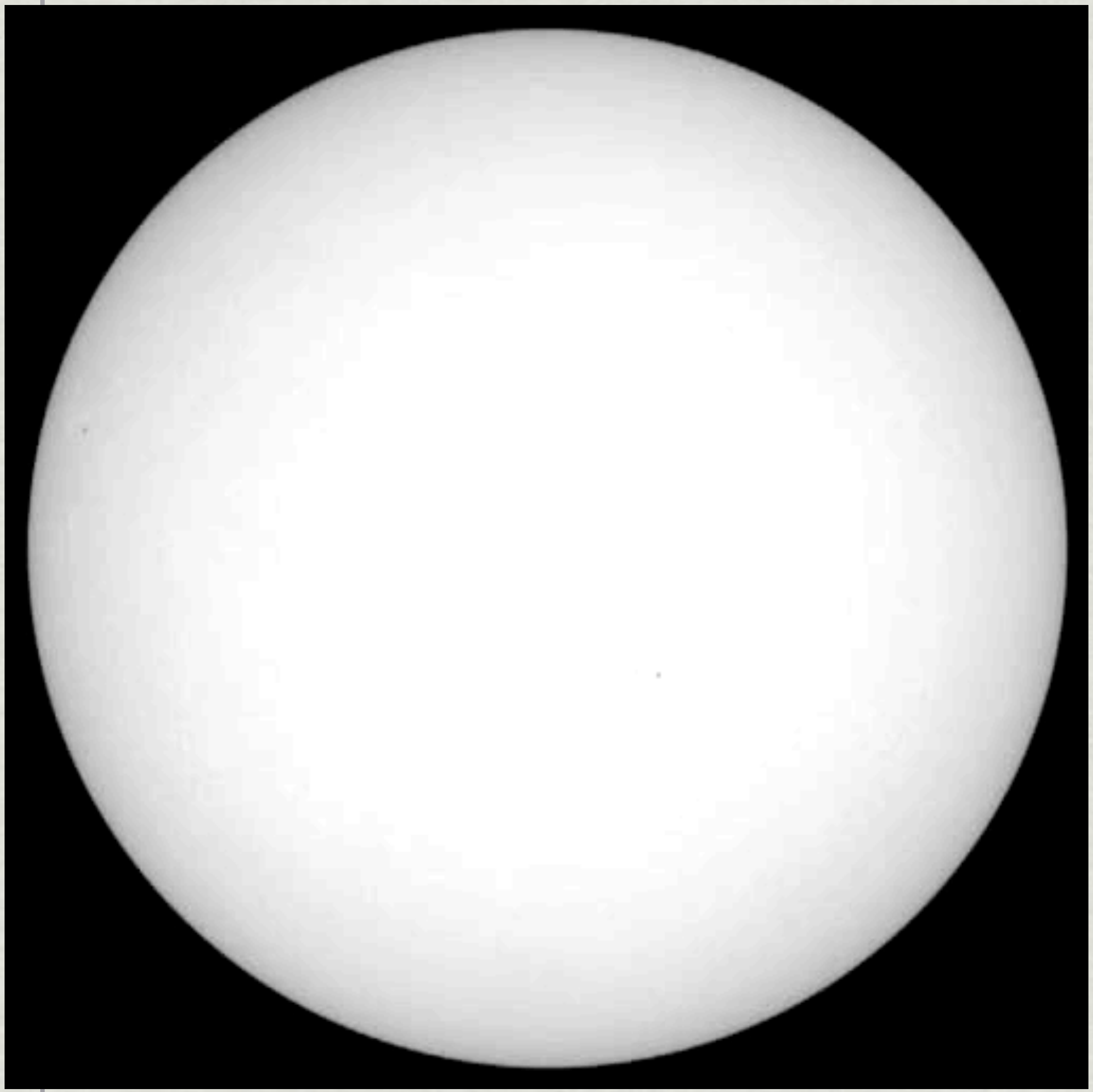
Saving SOHO and engineering problem-solving:
http://sohowww.nascom.nasa.gov/about/spacecraft.html
("Recovery" links)



Radius: 7 x 10^8 m
~100 times bigger than Earth's radius

Mass: 2 x 10^{30} kg
3 x 10^5 times Earth's mass

The Sun: an average star

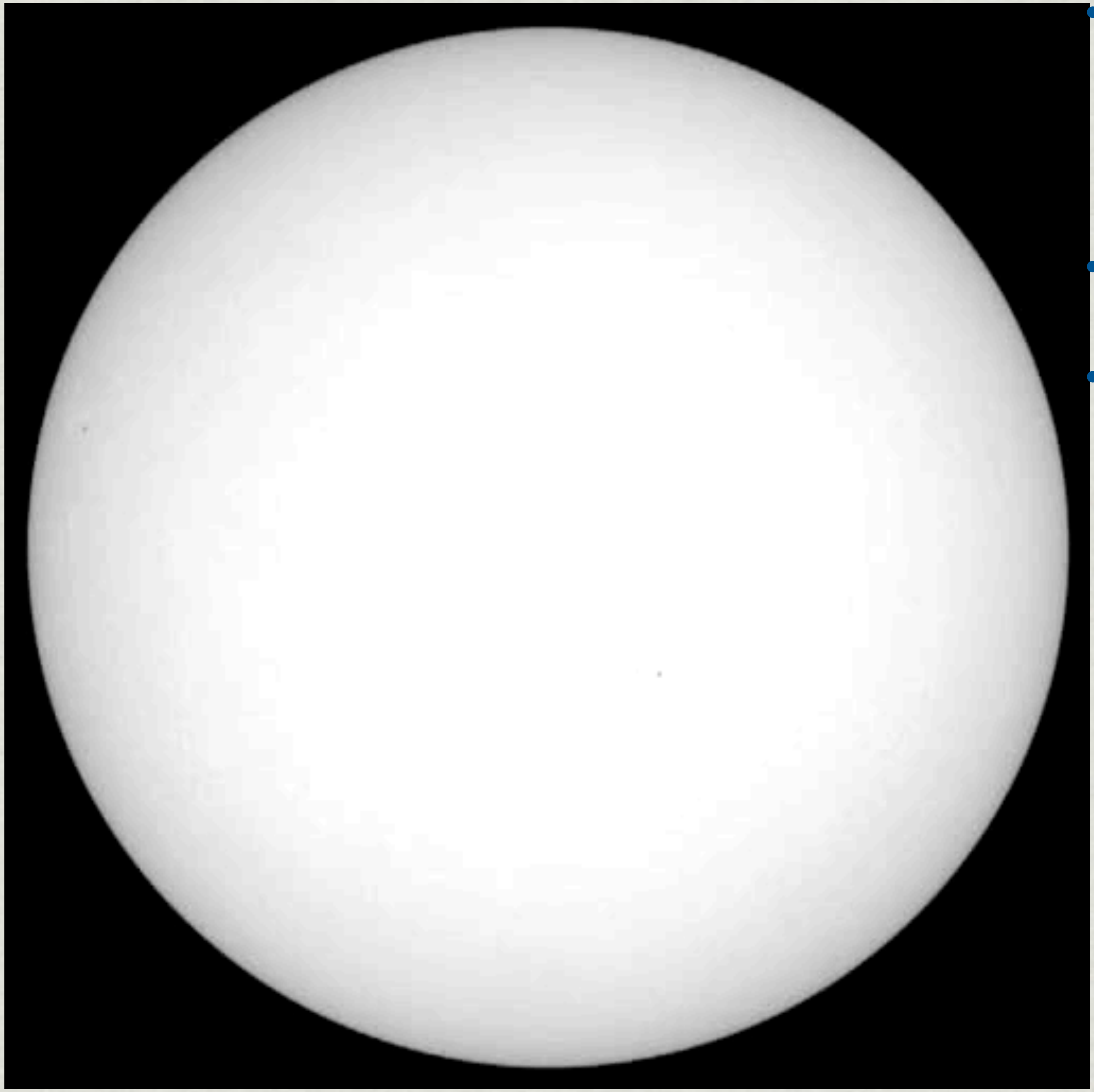


Luminosity: 4 x 10^{26} Watts (Joules/sec)

The sun is made of gas, mostly hydrogen and helium.

- 71% hydrogen
- 27% Helium
- The remaining 2% of the atoms are of other elements

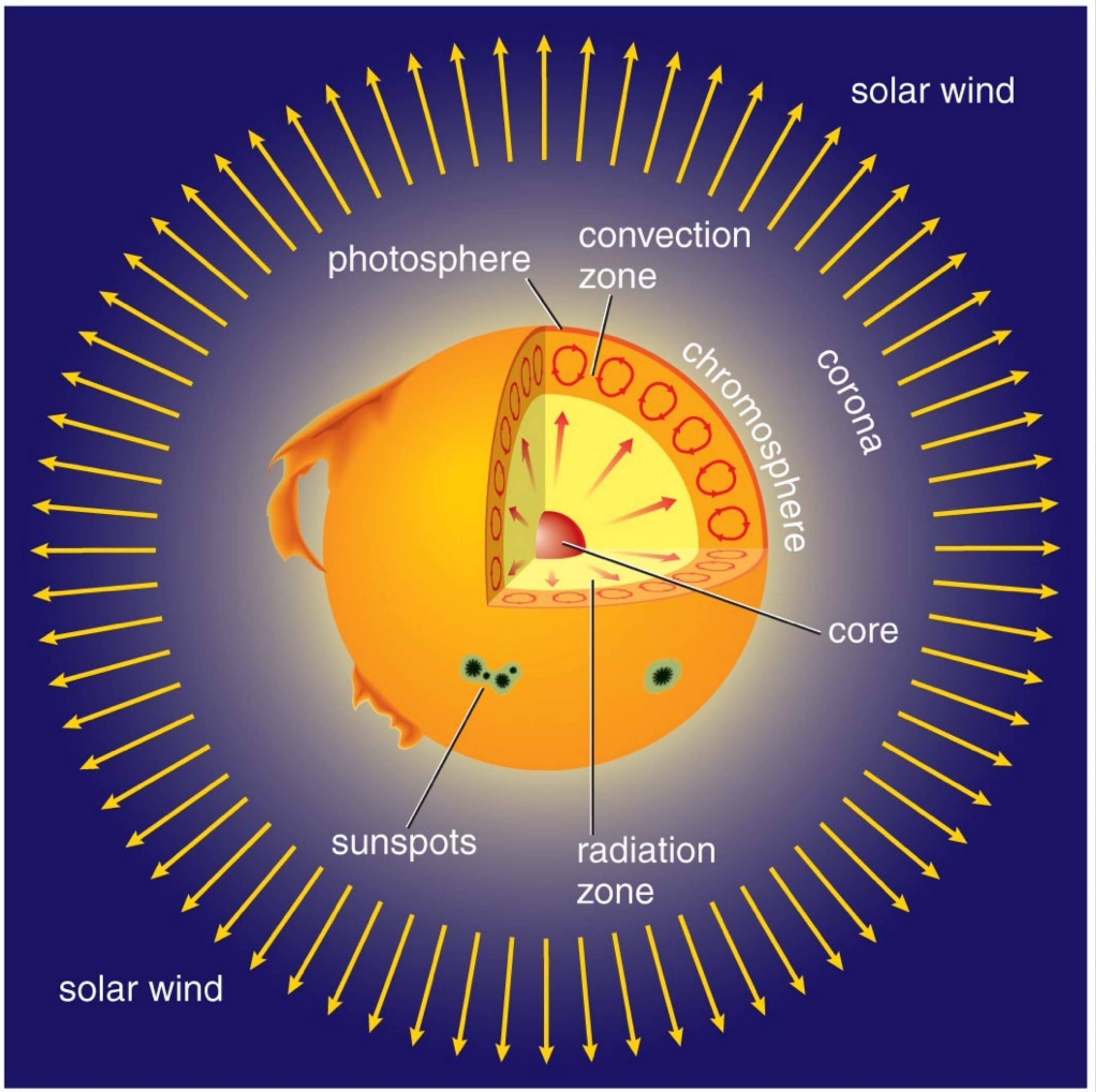
The Sun: an Average Star



- Structure: names and descriptions of layers
- Held up by Hydrostatic Equilibrium: balance between gravity and pressure
- Energy source: nucleosynthesis
- The sun and magnetic fields: flares and sunspots

Movie: highlights of data from the SOHO satellite. A NASA+ESA space mission to study the sun

The Sun: an average star



Interior of the sun is very high density, but so hot that the atoms remain a gas

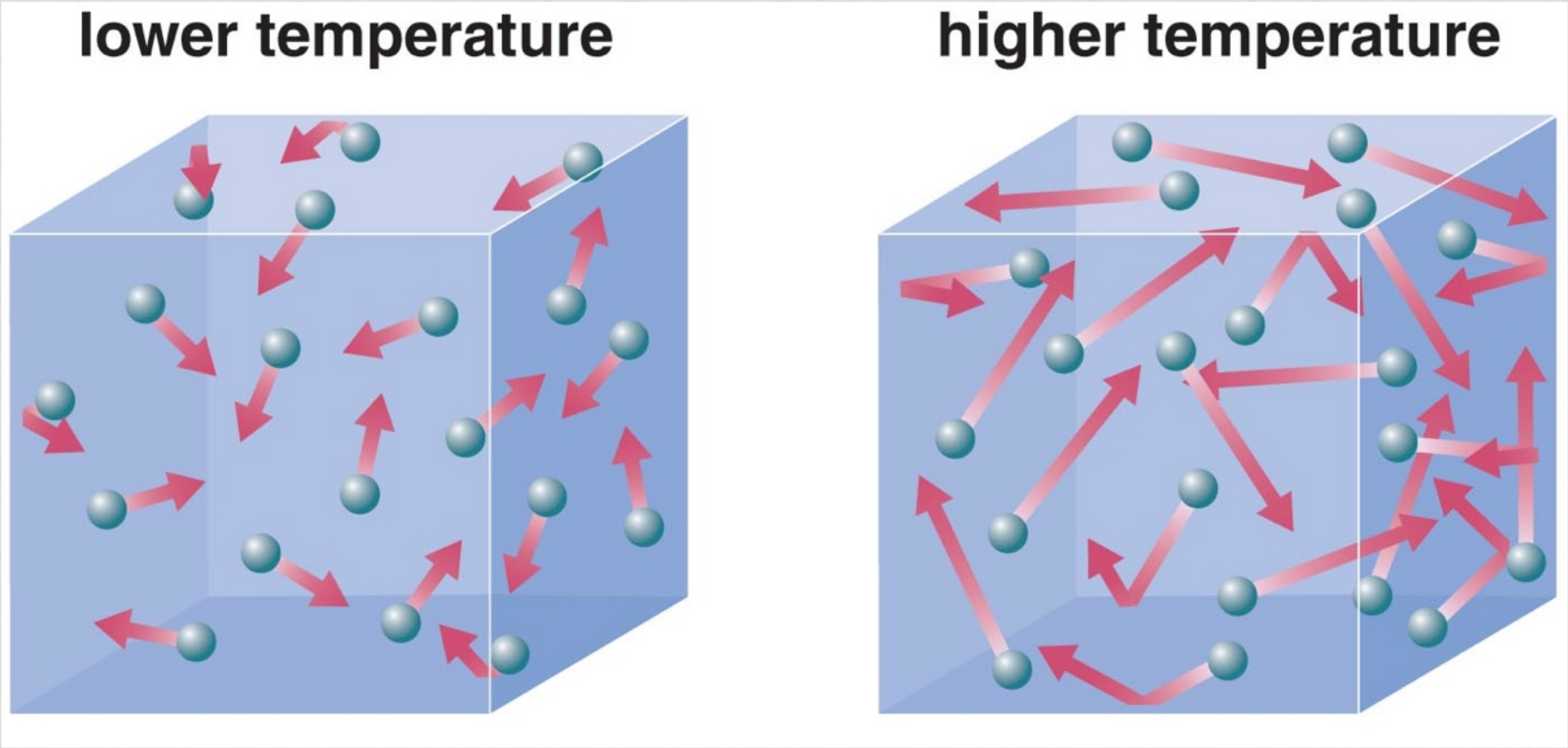
Can't form bonds to form a solid or a liquid: too much kinetic energy

They Might be Giants: "The sun is a mass of incandescent gas...."

"incandescent" = glowing
A thermal spectrum!

Temperature: average kinetic energy of each particle in some object or system

For one particle: $E_{kinetic} = \frac{m\,v^2}{2}$



More thermal energy

20 particles

...also 20 particles

The interior of the sun is so hot that the thermal energy of the electrons is too high to stay bound to the positive charge of the nucleus.

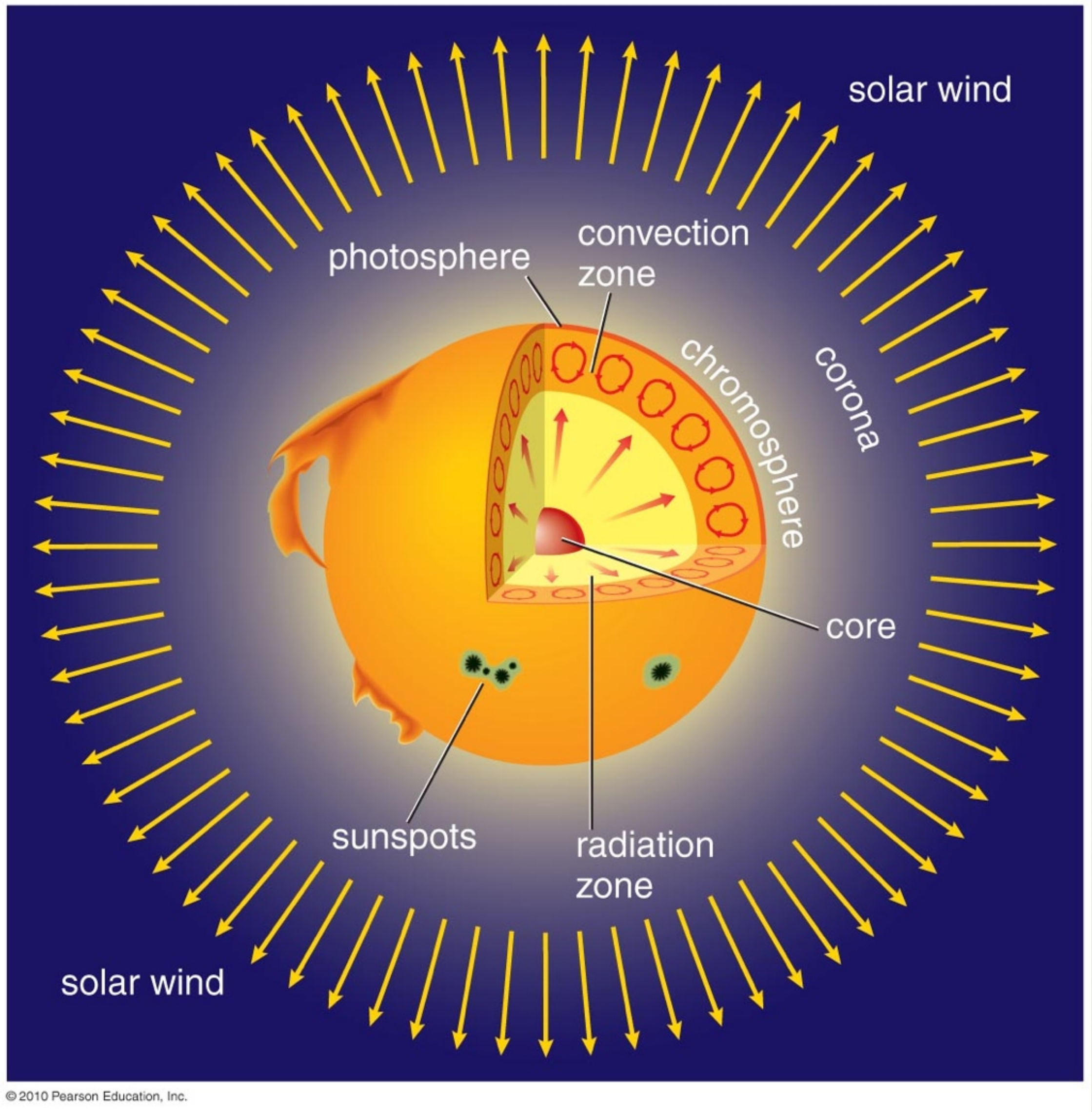
The thermal energy causes the atoms to collide with enough force to overcome the electromagnetic force holding the electrons to the nucleus.

Gas in the sun is ***ionized:*** the electrons and nuclei are no longer bound by the electromagnetic force

- like a rocket accelerating to the escape speed and no longer being bound to the gravitational pull of the earth

A plasma: a gas of charged (positive or negative) particles

Structure of the Sun



Interior of the sun
(core, radiative and convective zones):

dense, opaque

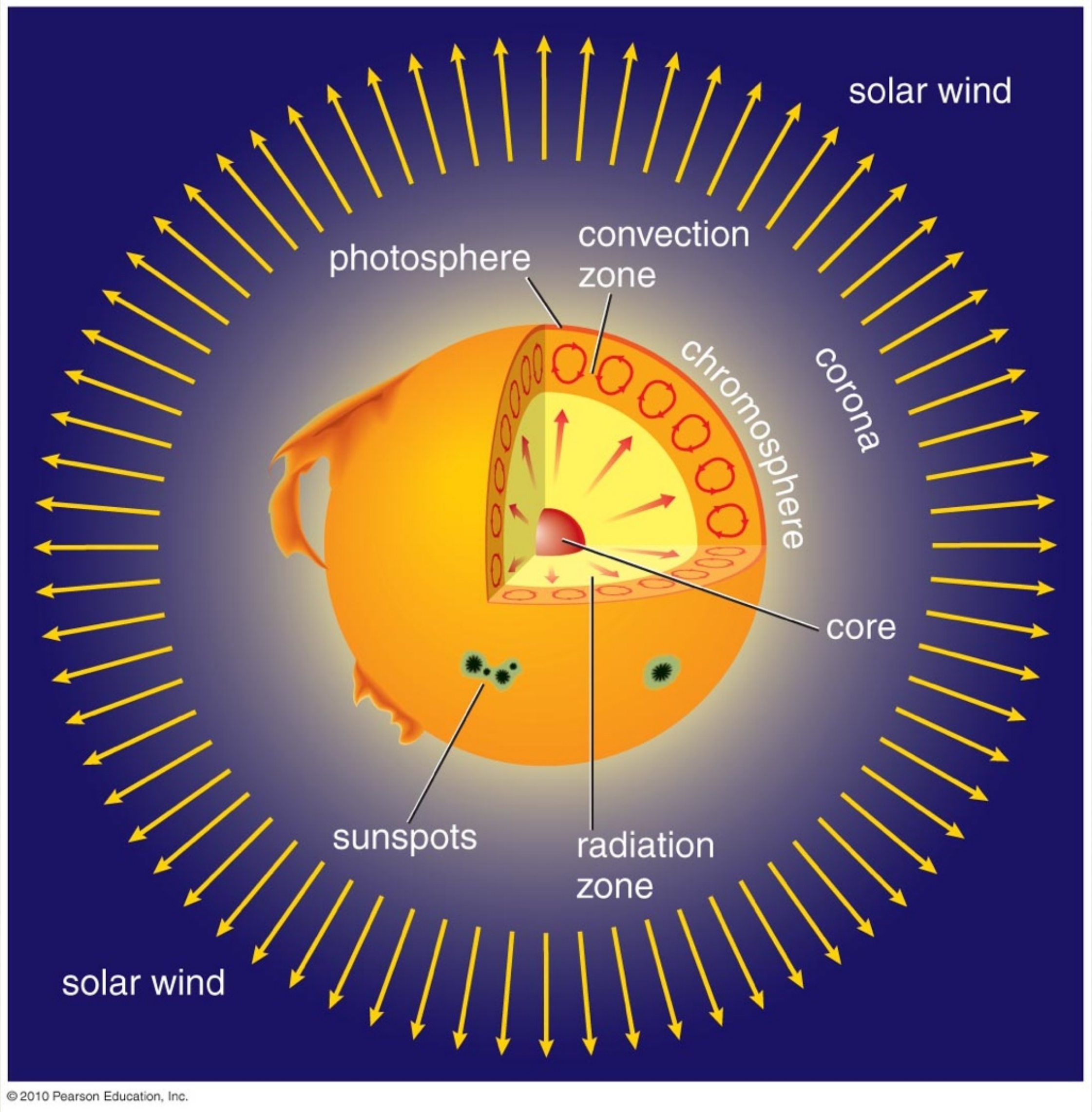
So dense, photons are absorbed and re-emitted by atoms, gain and loose energy from the thermal motion of the atoms, spread out photon energies to create a thermal spectrum

Emission line spectrum: chemical fingerprints of the atoms

➜

Continuous, thermal spectrum

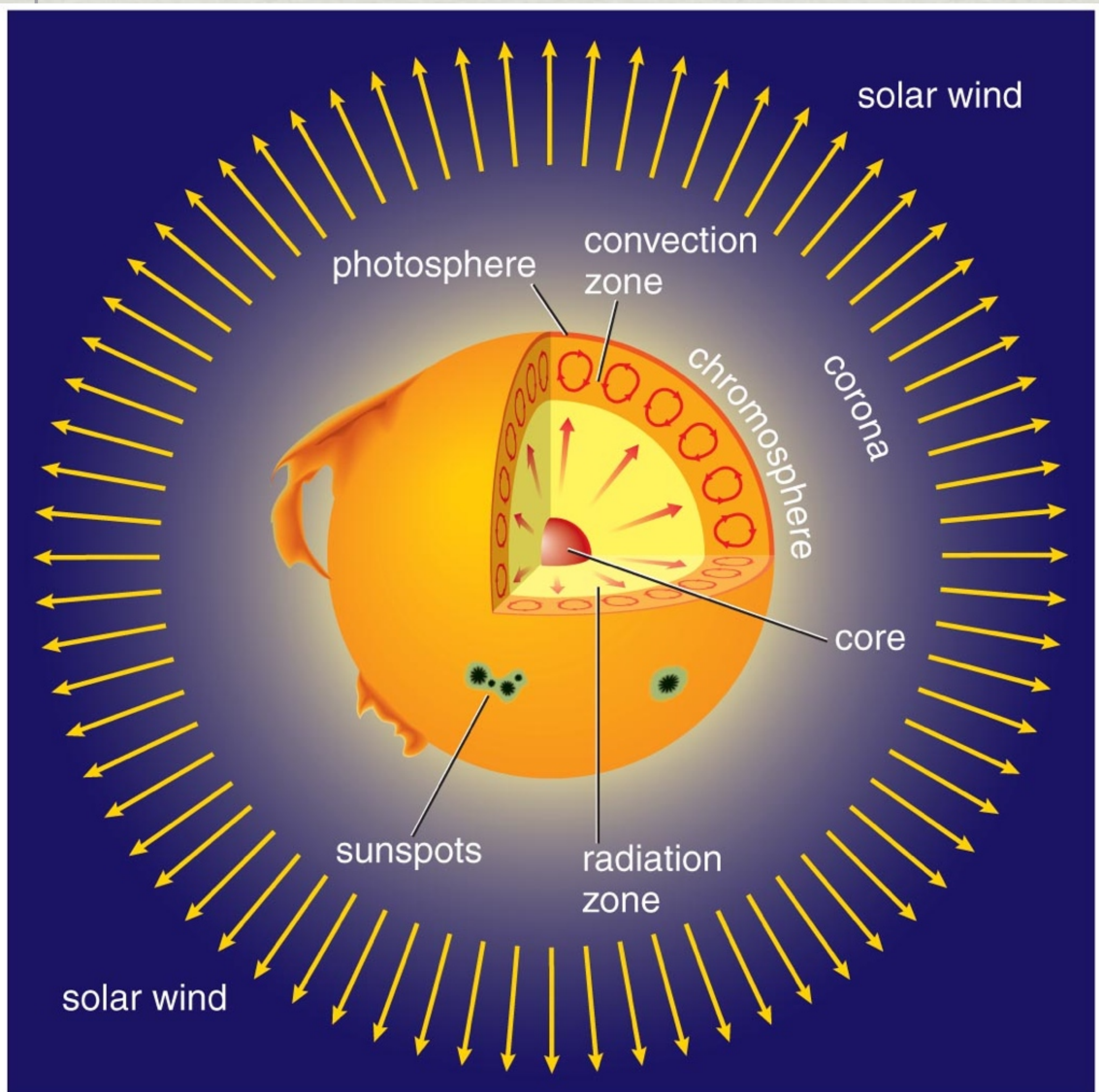
Structure of the Sun



Heat flows from hot to cold. Energy (photons) generated in the core, flow to the outer layers and eventually escape, reach places like earth

How dense is dense? It takes a photon ***16 million years*** for a photon produced in the core to get to the surface of the sun

Structure of the Sun



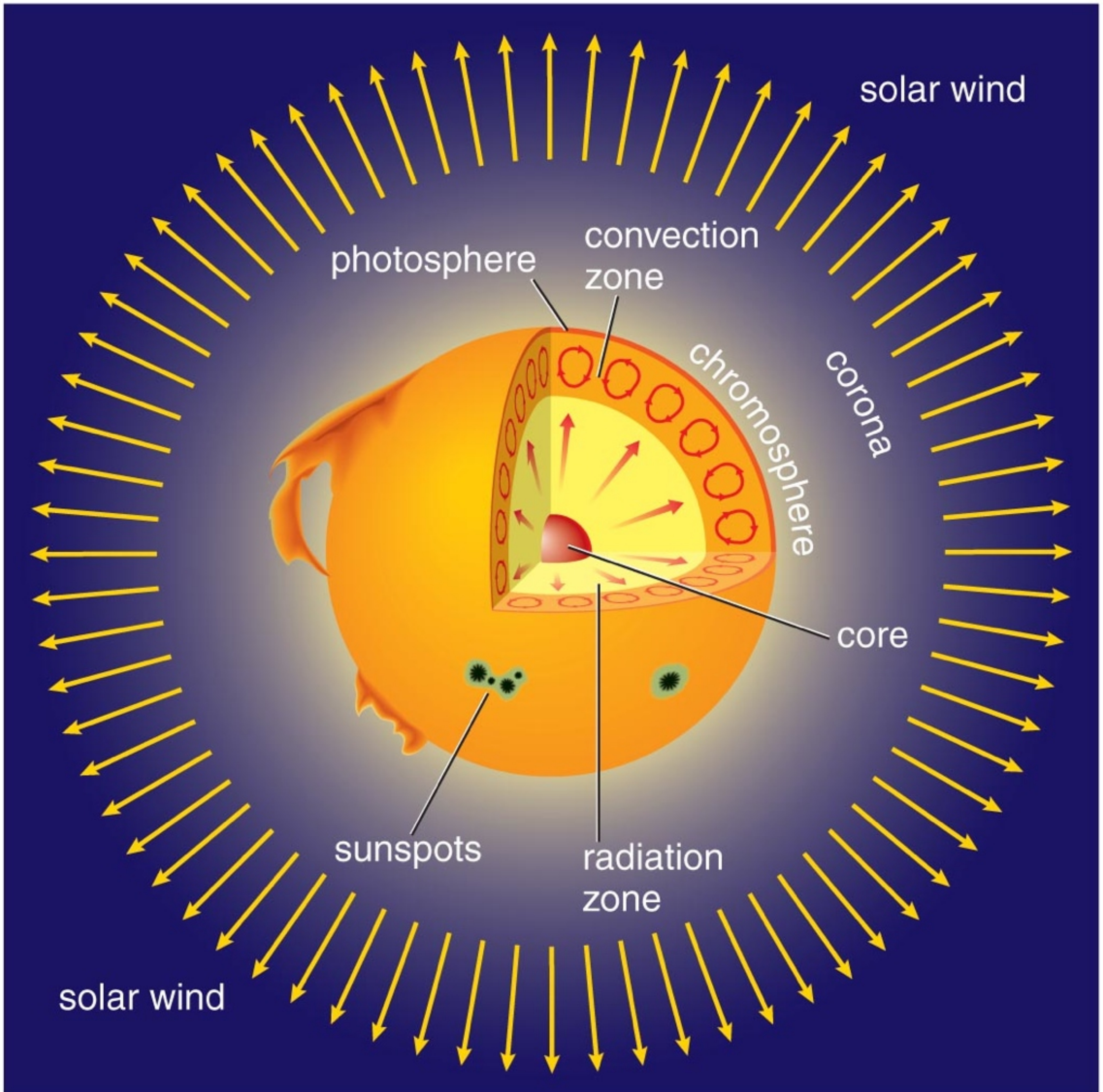
Core

Energy generated by nuclear fusion

~15,000,000 K

Compare:
photosphere (surface) temperature
"only" 6000 K

Structure of the Sun

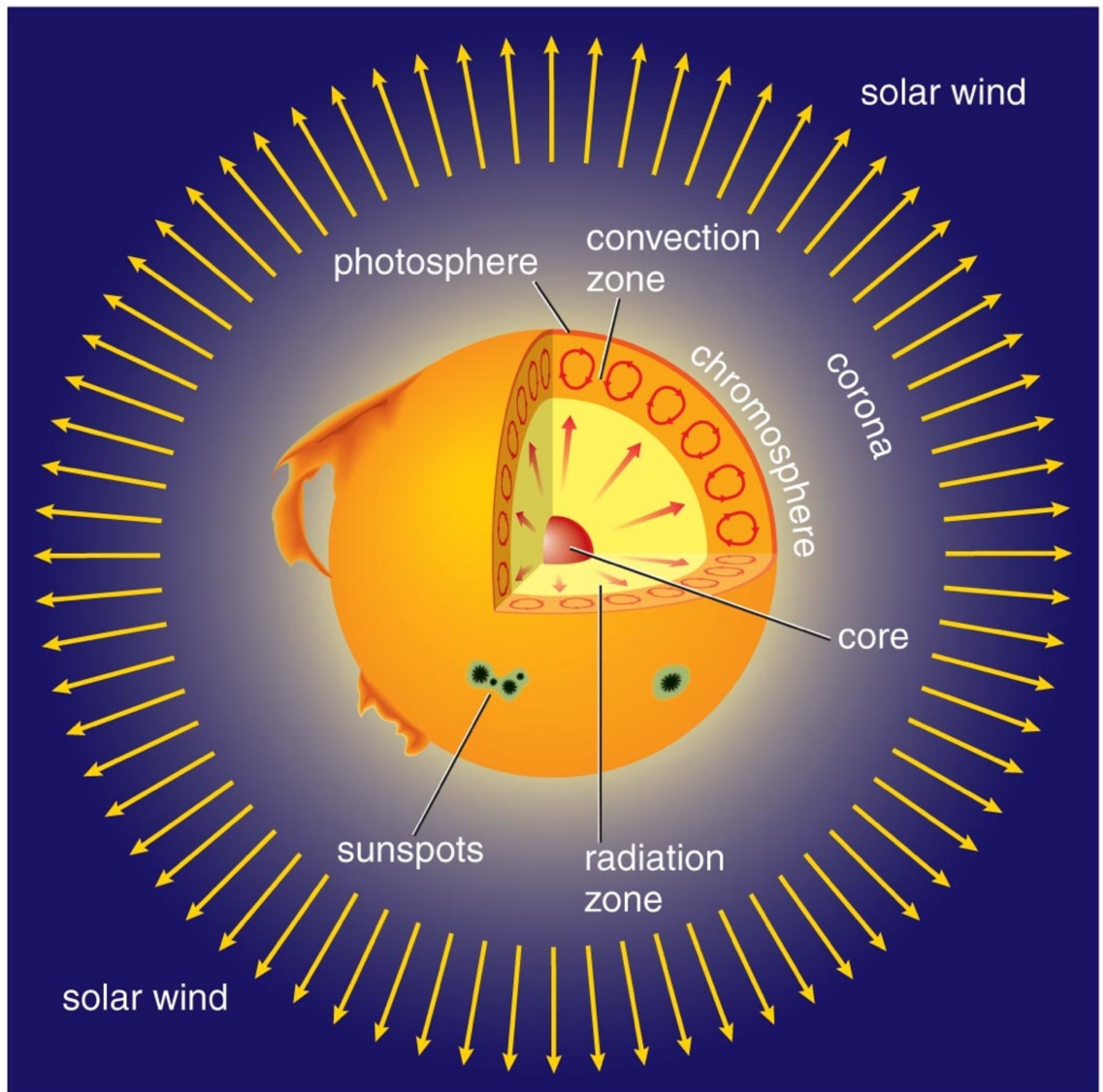


Radiation zone

Energy gradually comes out from the core as photons generated in the core bounce around through the dense matter, interacting with atoms

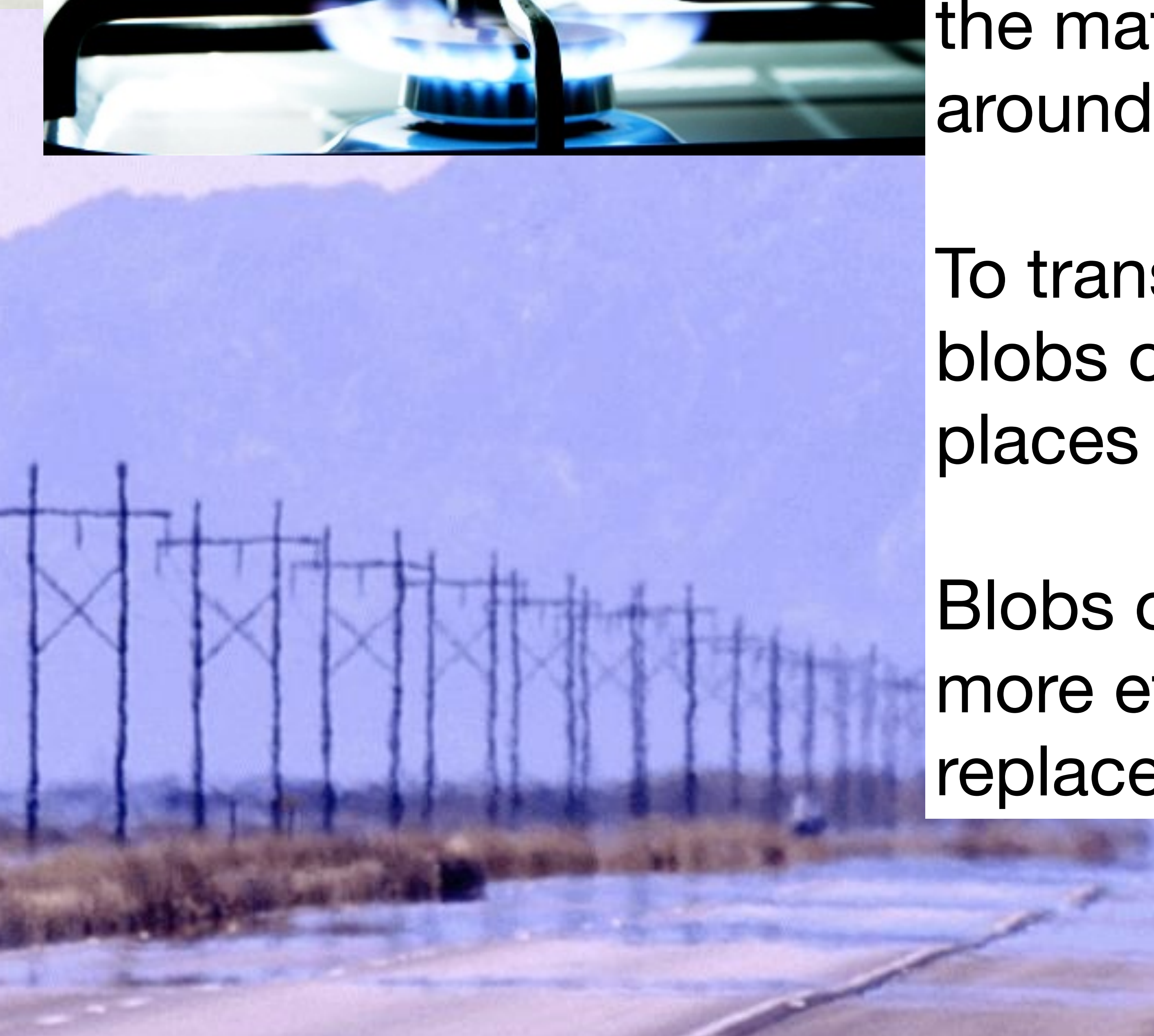
Energy from the sun has a thermal radiation spectrum

Structure of the Sun



Convection zone

Energy transported to surface by rising bubbles of hot gas



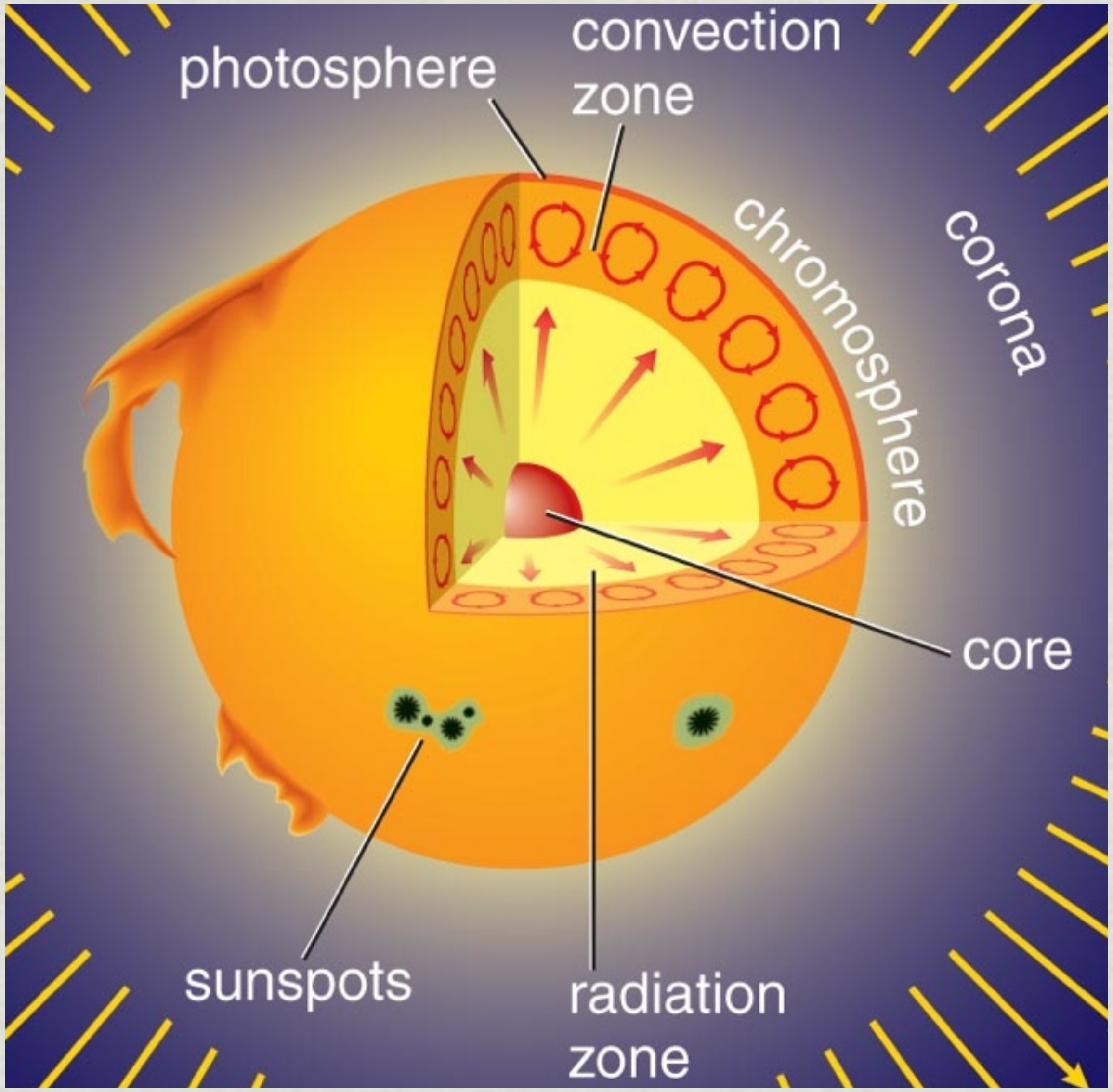
Everyday examples of convection:
Air next to a hot road, water at the bottom of a pot on the stove.

A gas or liquid is hottest at the bottom where it is heated, can't pass along the thermal energy fast enough to the rest of the material just by atoms bouncing around.

To transfer thermal energy faster, big blobs of the hot material exchange places with blobs of cooler stuff

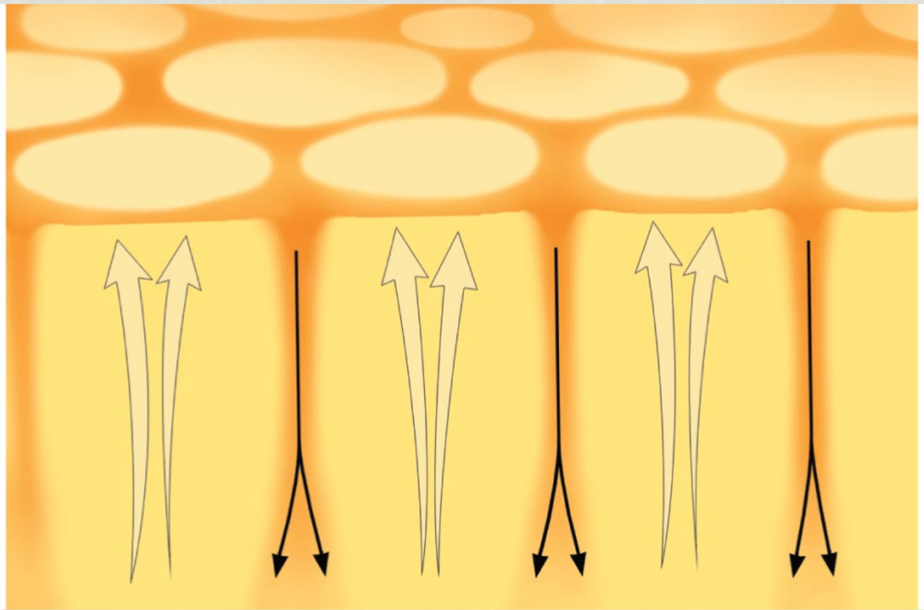
Blobs of cooler stuff then absorb heat more efficiently that the hot stuff they replaced

Structure of the Sun



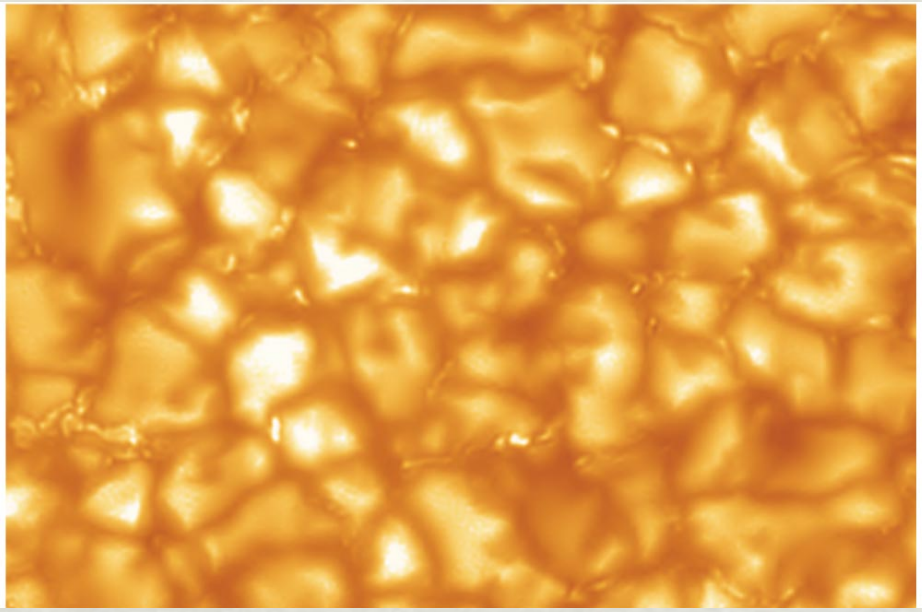
Convection zone

Energy transported toward surface by rising bubbles of hot gas



Cartoon of convection at the sun's surface

The bright spots are blobs of hot gas that reach the surface by convection.

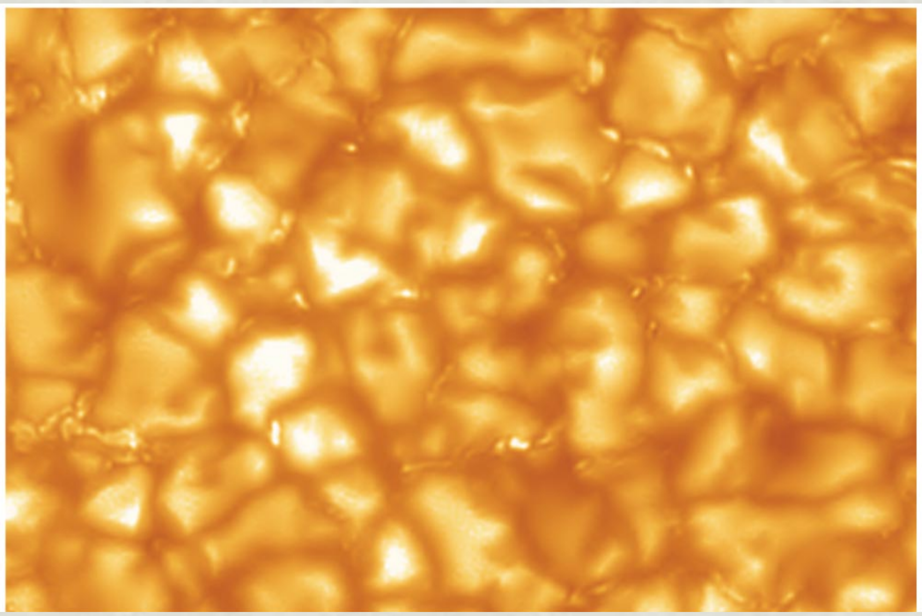


Real image of the sun's surface

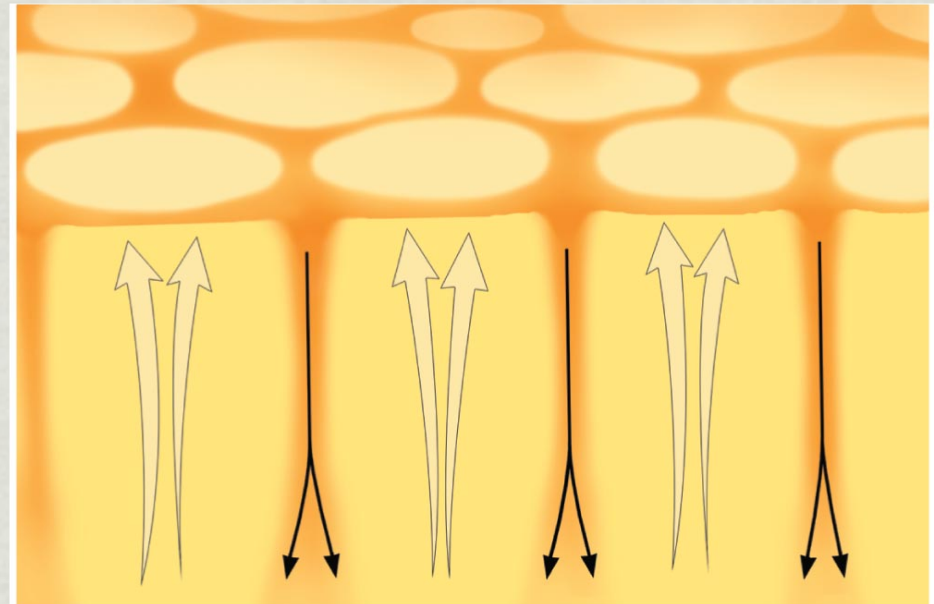
Structure of the Sun

Convection zone

Energy transported toward surface by rising bubbles of hot gas



Real image of the sun's surface



Cartoon of convection at the sun's surface

The bright spots are blobs of hot gas that reach the surface by convection.

Why are those spots bright?

Why do those spots look white compared to neighboring regions?

The bright spots:

A have higher mass
B are moving faster
C are cooler than the rest of the sun's surface
D are warmer than the rest of the sun's surface

Structure of the Sun

Convection zone

Energy tra

The blobs of gas are rising because they are hot

Thermal spectrum:

- hotter things are brighter
- hotter things have a spectrum with a bluer peak wavelength: more blue photons

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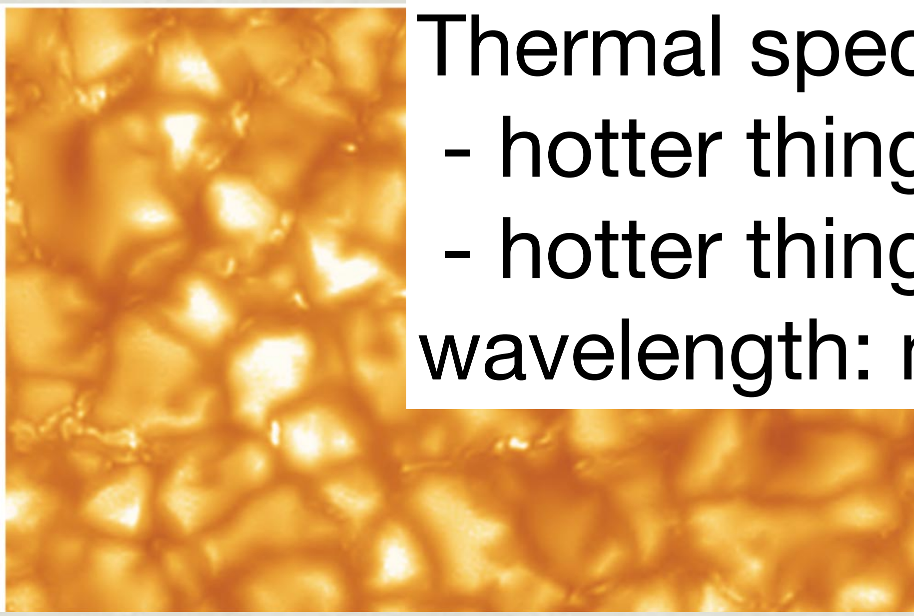

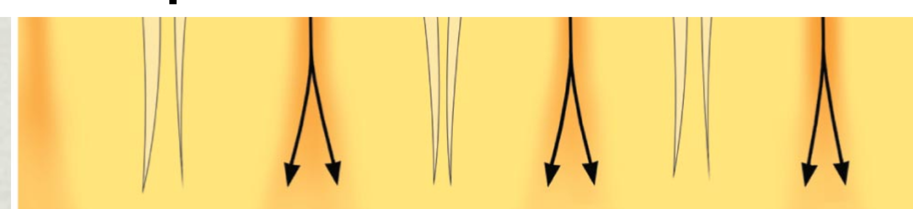

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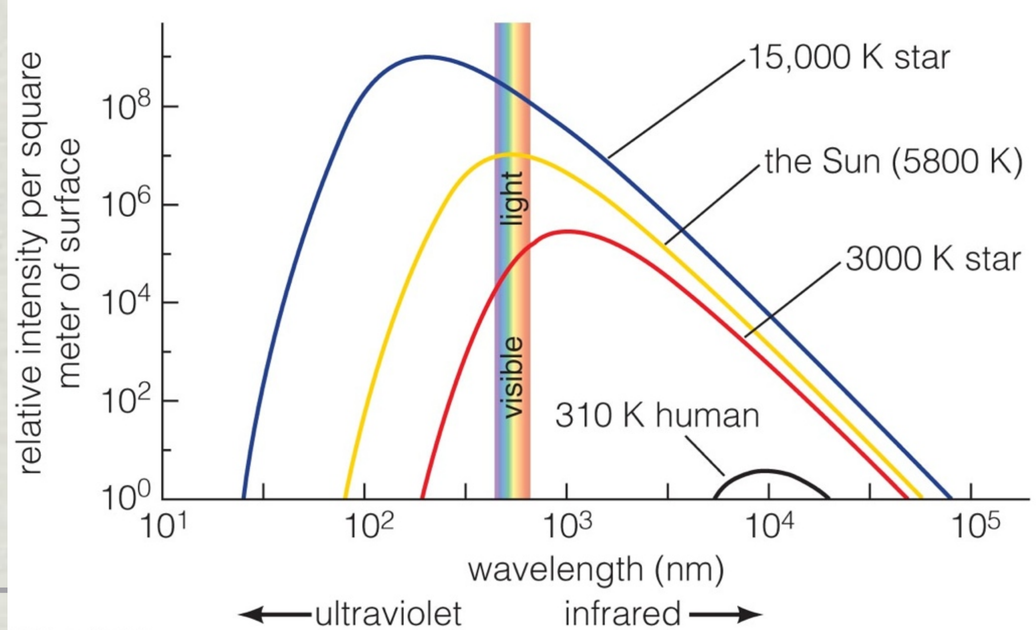
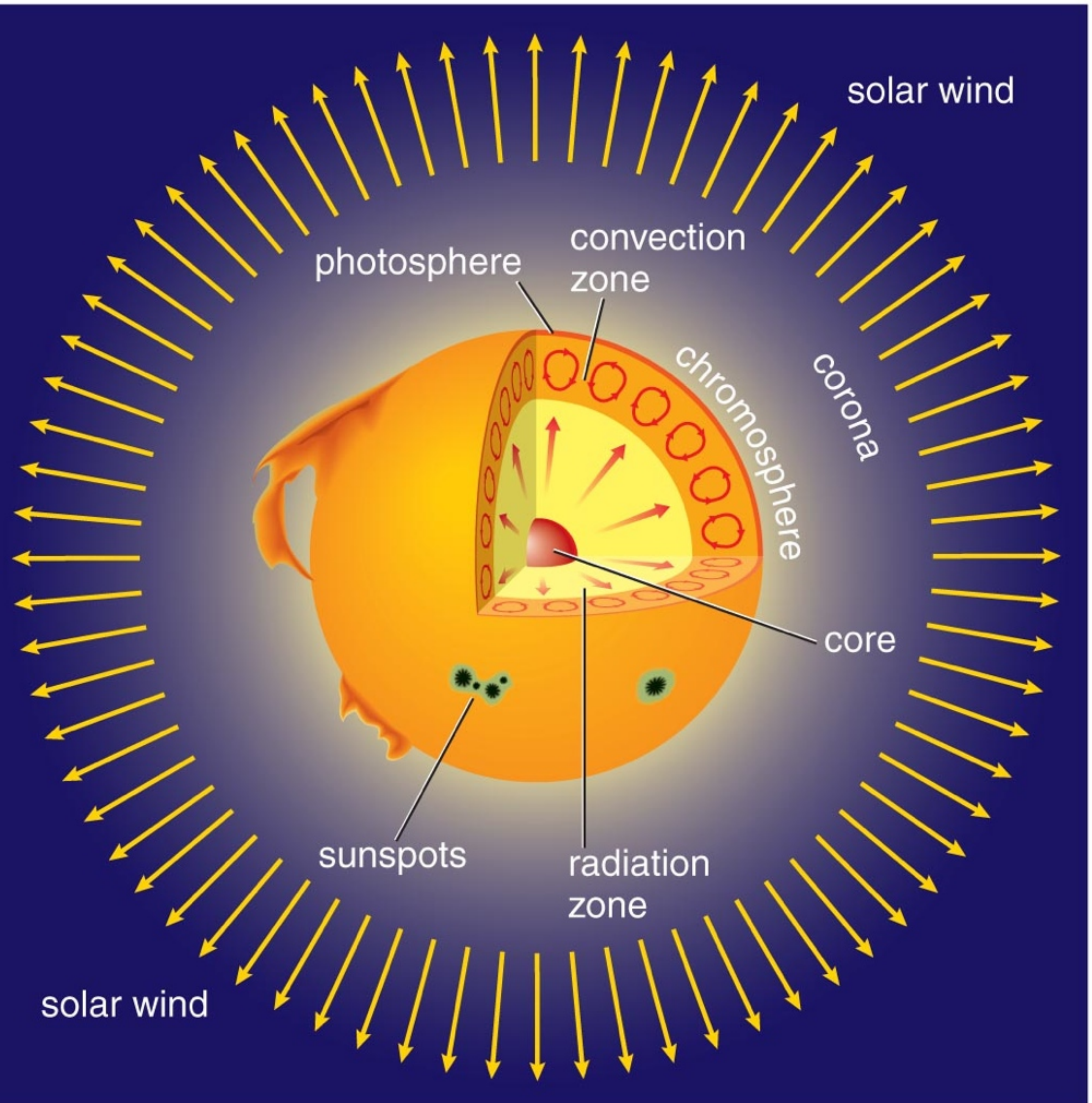


Structure of the Sun



Sun's Atmosphere:

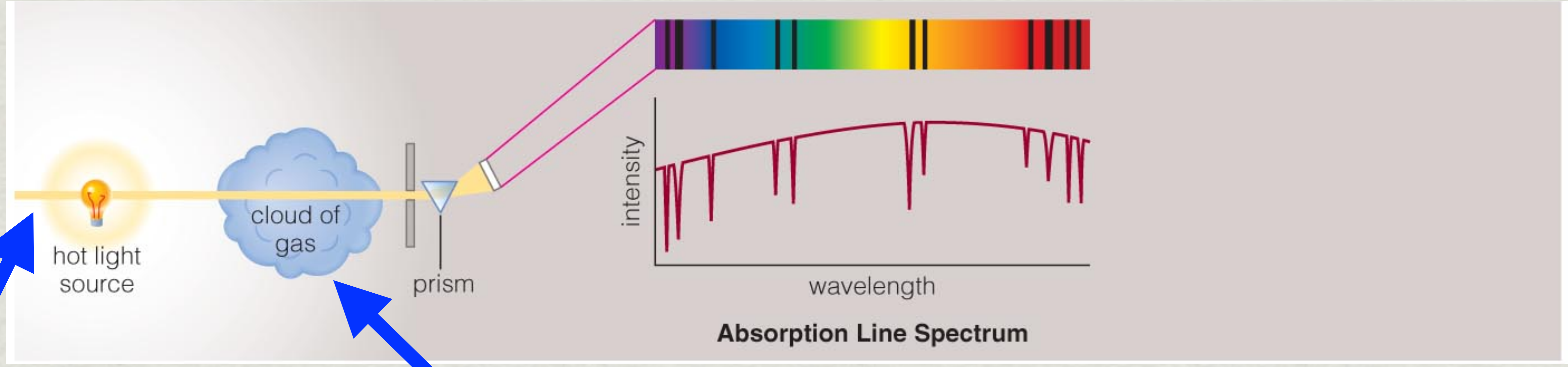
Photosphere:
Layer where the photons get out.
~6000 K

Density of atoms is low enough that photons can flow out freely

Sun changes from being dense (opaque) to being transparent (low density)

Solar Spectrum

- Gas at the photosphere is cooler than the lower layers of the sun.
  - Looks like this cartoon



Thermal source, the inner, opaque layers of the sun

Cooler gas, the photosphere

We see an absorption line spectrum from the sun

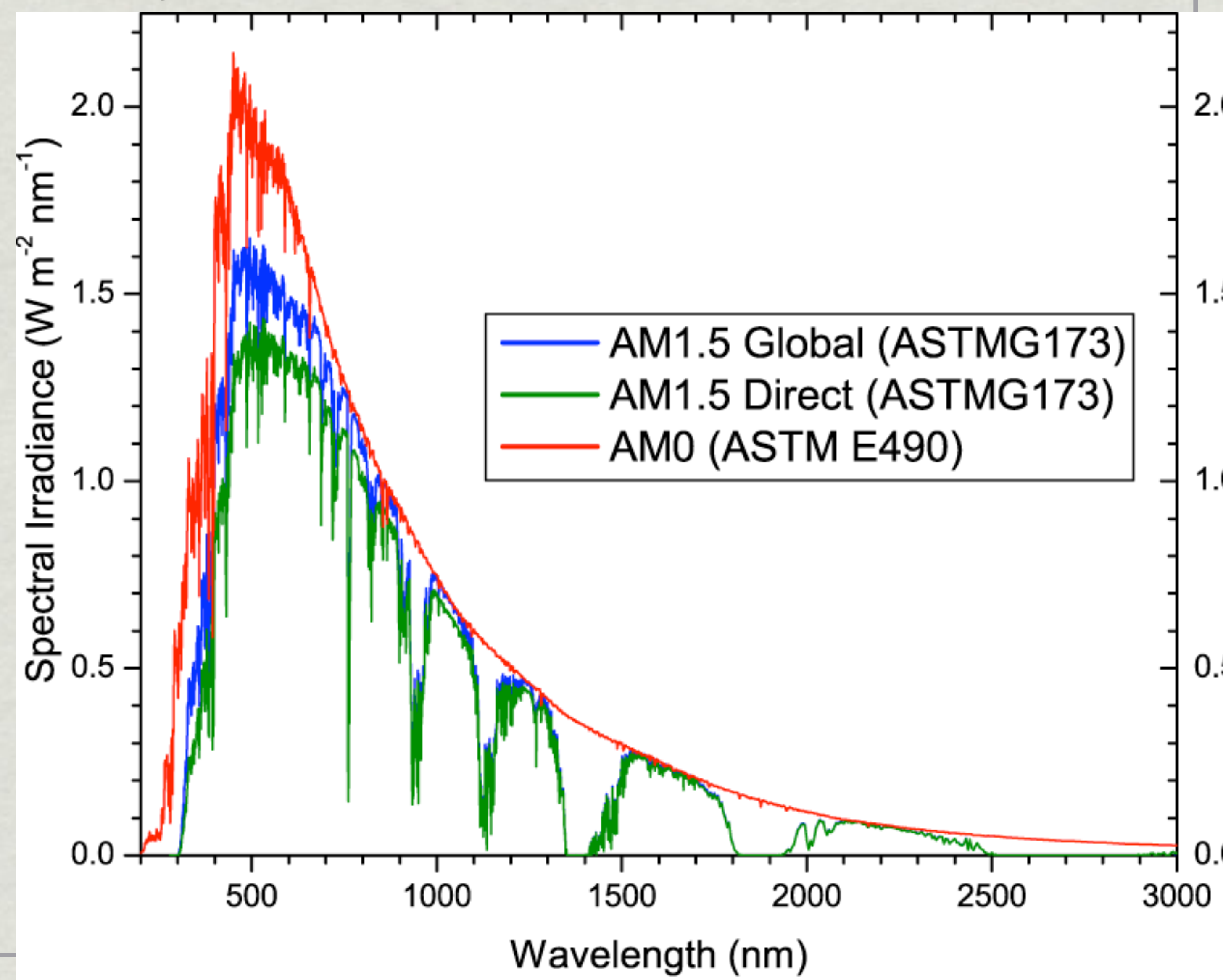
Solar Spectrum

A more compact view of the solar spectrum:

<- Wavelength ->

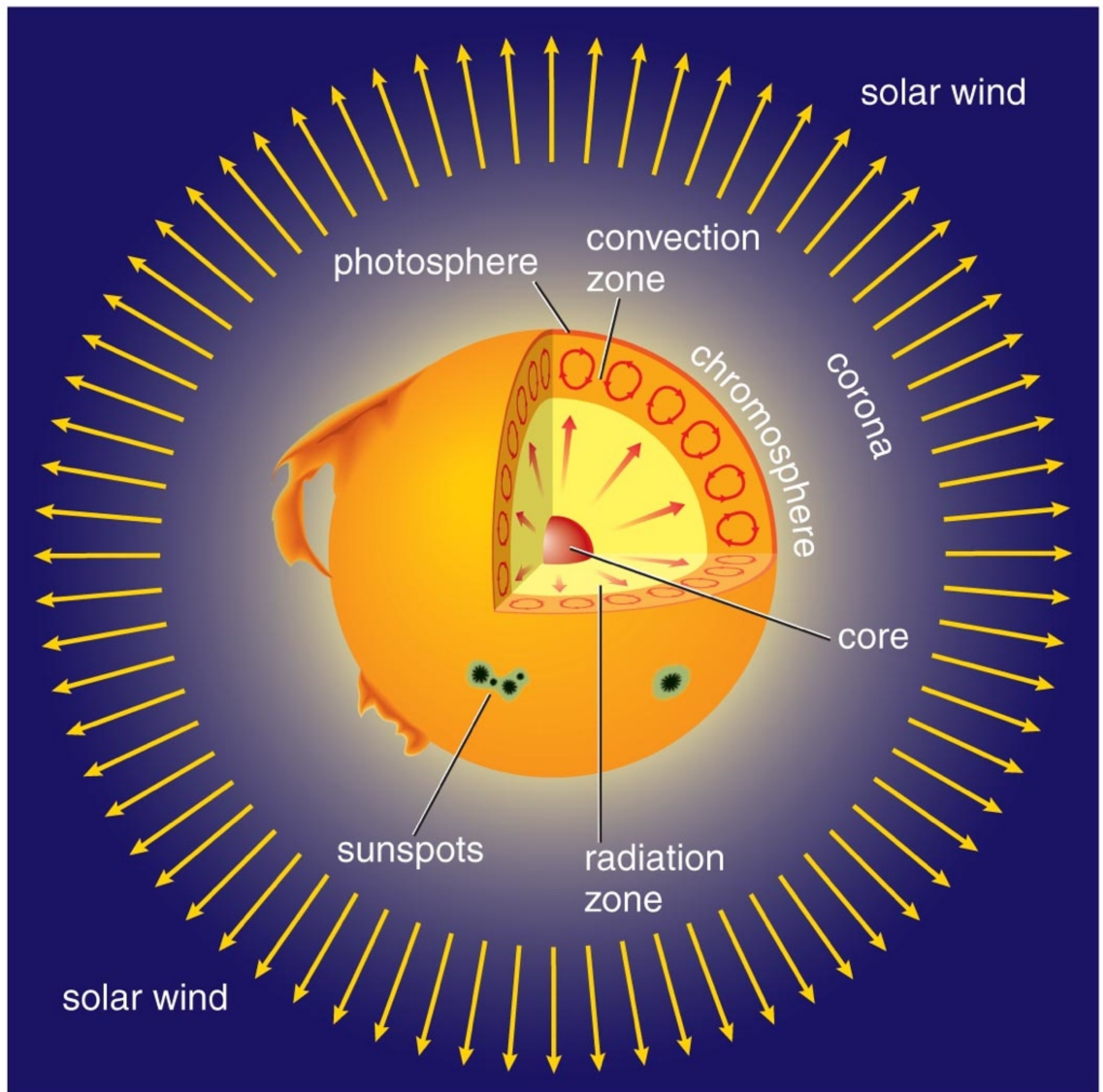
Very cool interactive plot of the solar spectrum:

http://bass2000.obspm.fr/solar_spect.php



A solar spectrum showing the amount of energy at each wavelength.
A thermal spectrum with absorption lines.

Structure of the Sun



Atmosphere:

Above the photosphere, there are layers of very hot, very low density gas.

Extra energy comes from the sun's magnetic field

Chromosphere:
Middle layer, 10^4 - 10^5 K

Corona:
Outer layer, 10^6 K

Solar wind:
Flow of charged particles from the sun

Solar Corona Spectrum

Solar Corona: Transparent, low-density matter, too hot to re-absorb photons: emission line spectrum.

From last time:

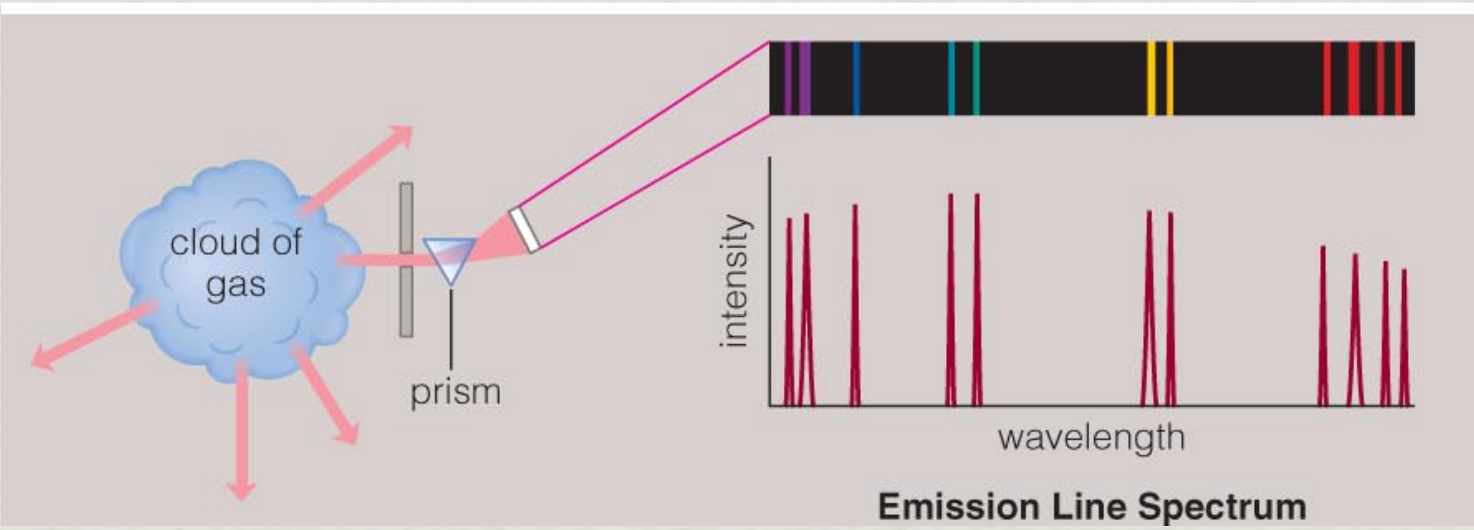
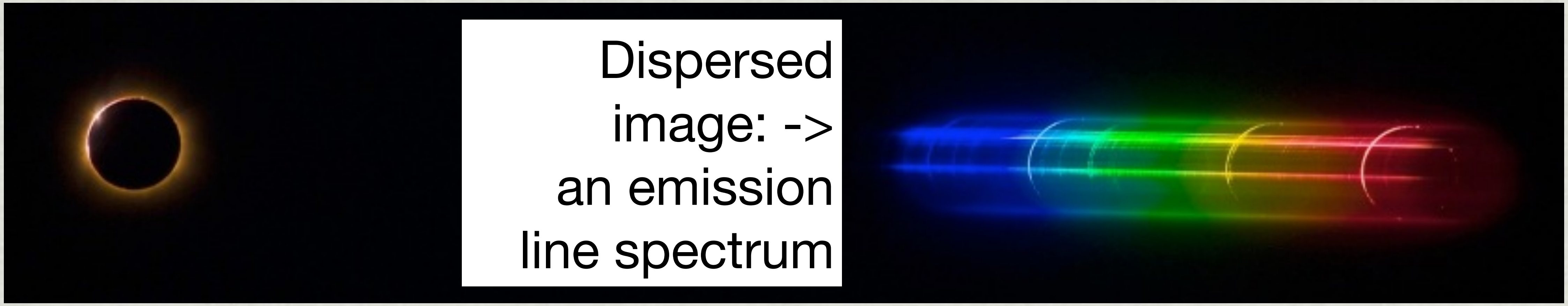


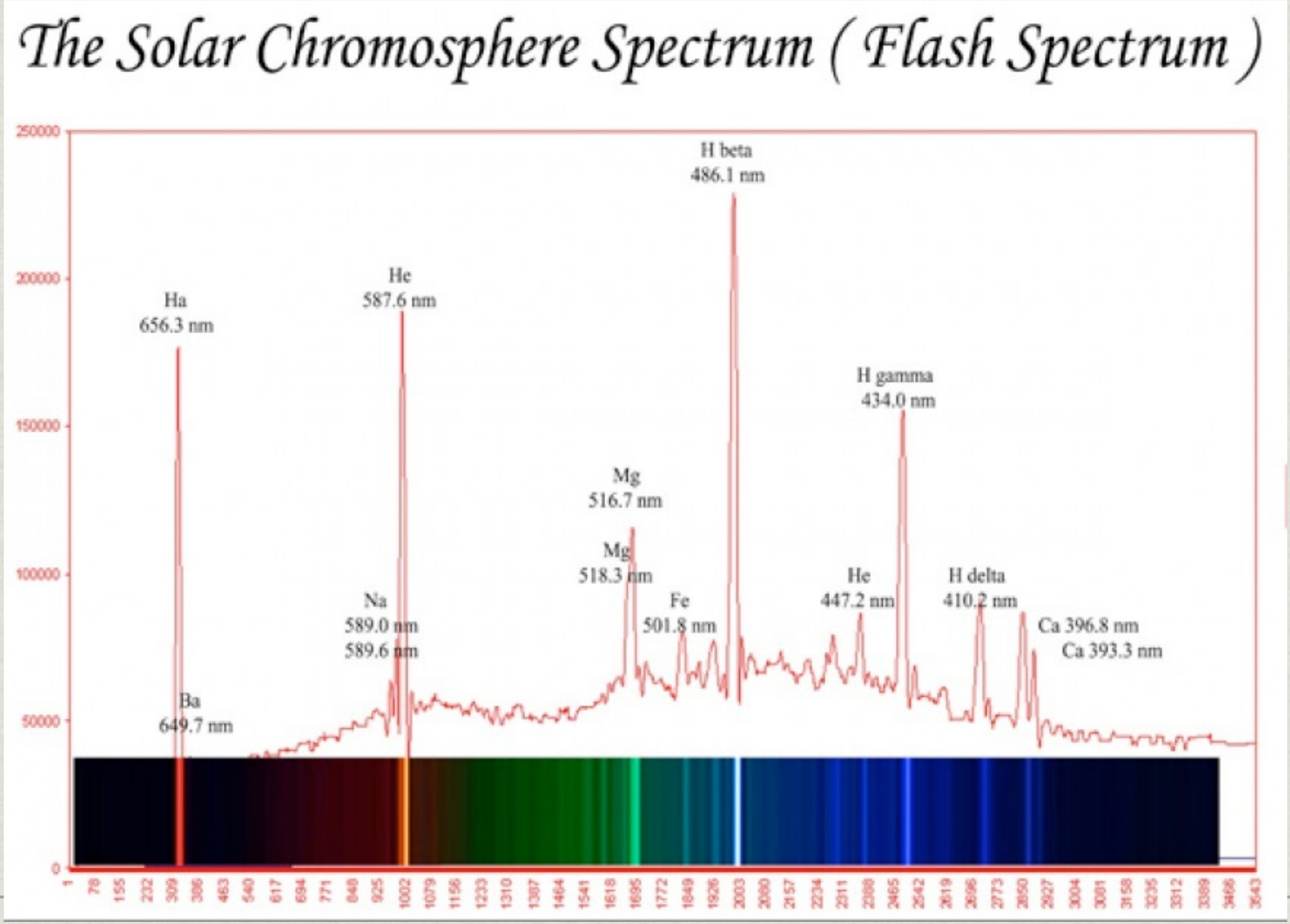
Image of solar eclipse



Dispersed image: -> an emission line spectrum

Solar corona emission line spectrum.
Taken during a solar eclipse, thermal spectrum from photosphere is blocked.

Solar Corona Spectrum



Solar Spectrum

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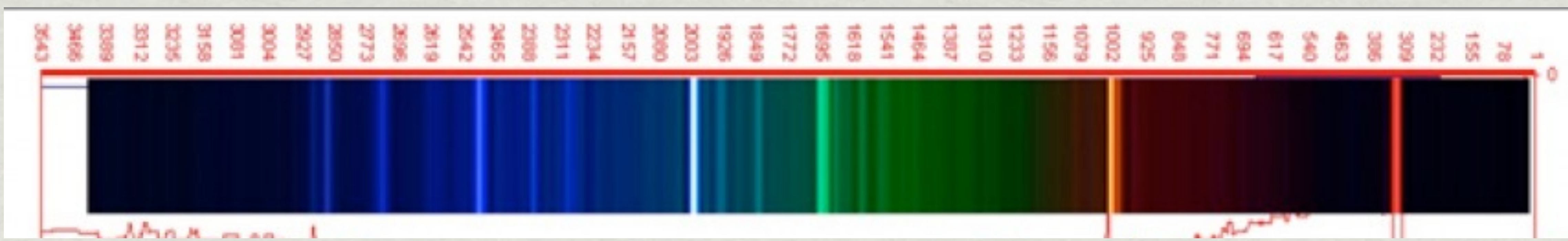


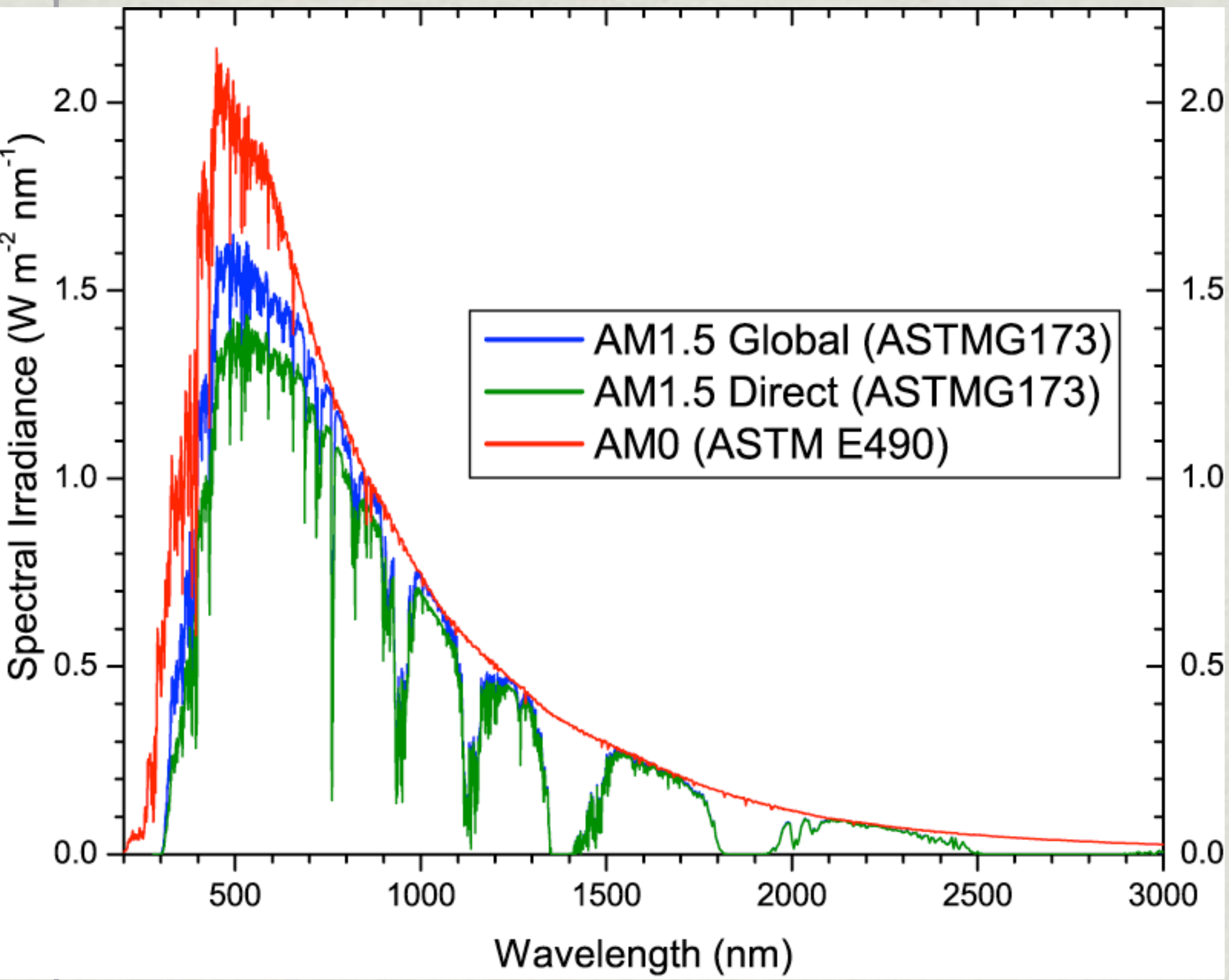
Observe all light: see mostly thermal spectrum

- Your eye looking through eyepiece, at projection screen

Observe just in small wavelength range of a bright emission line: most of the light is from the emission line, see coronal features

- H-alpha filter (that will be the little telescope)

Solar Spectrum



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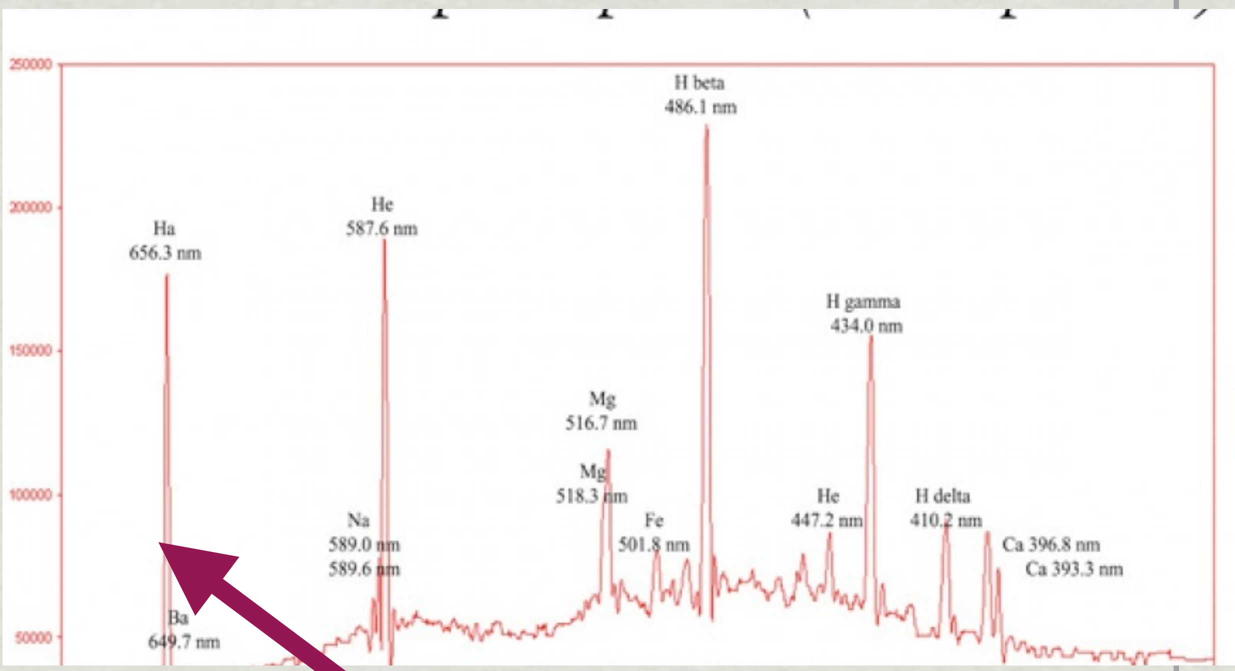


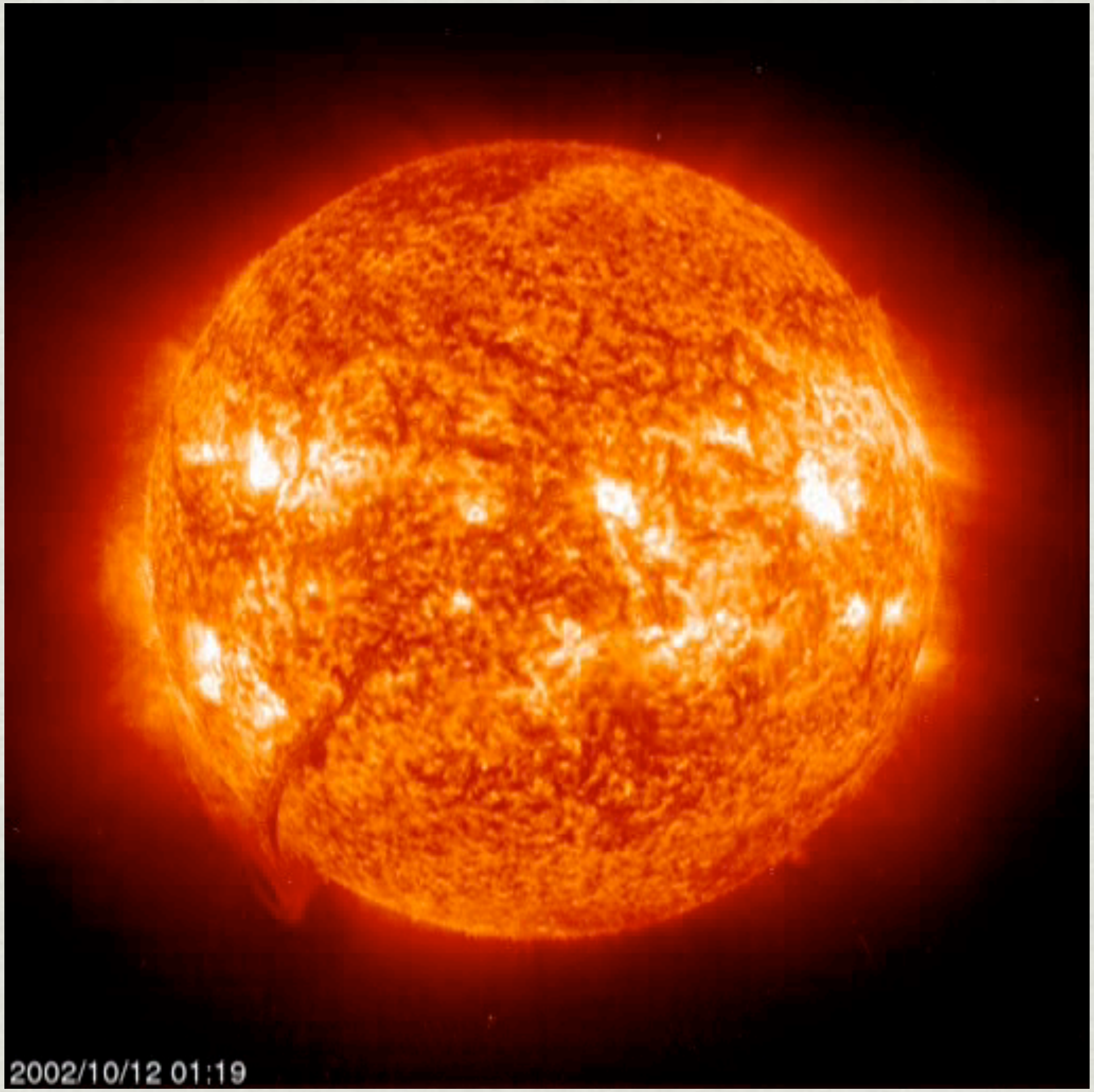
Observe all light: see mostly thermal spectrum
- Your eye looking through eyepiece, at projection screen

Observe just in small wavelength range of a bright emission line: most of the light is from the emission line, see coronal features
- H-alpha filter

Solar Activity

What causes all this excitement at the surface of the sun?

More cool stuff from SOHO

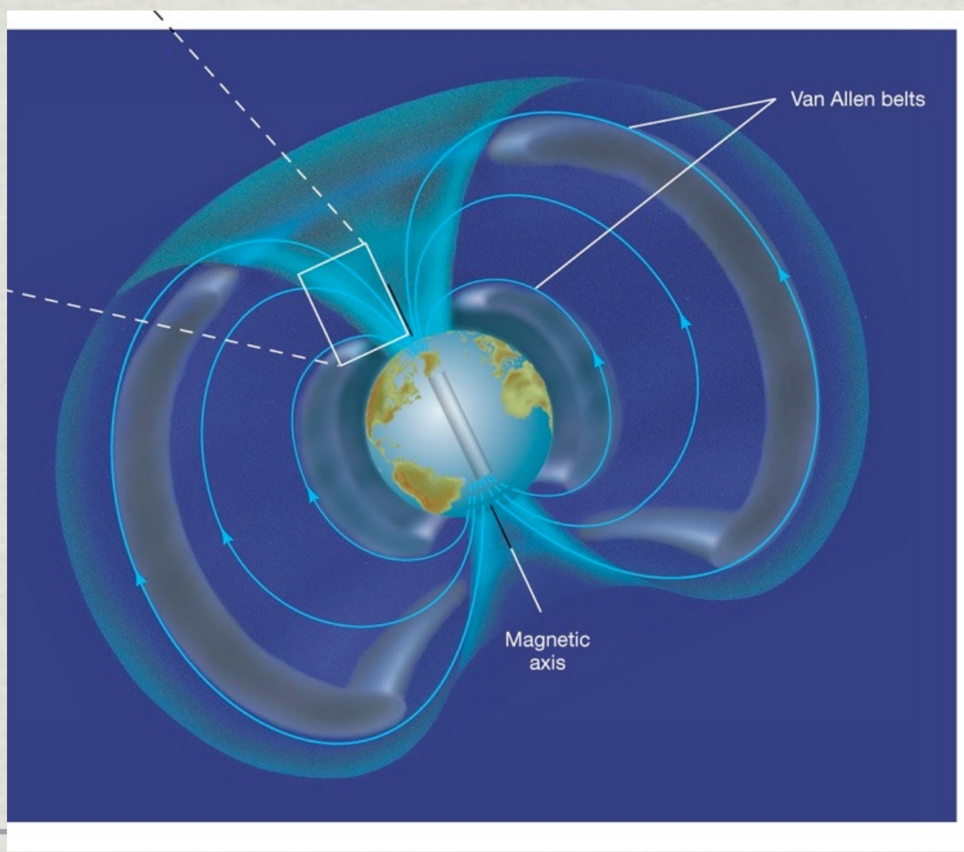


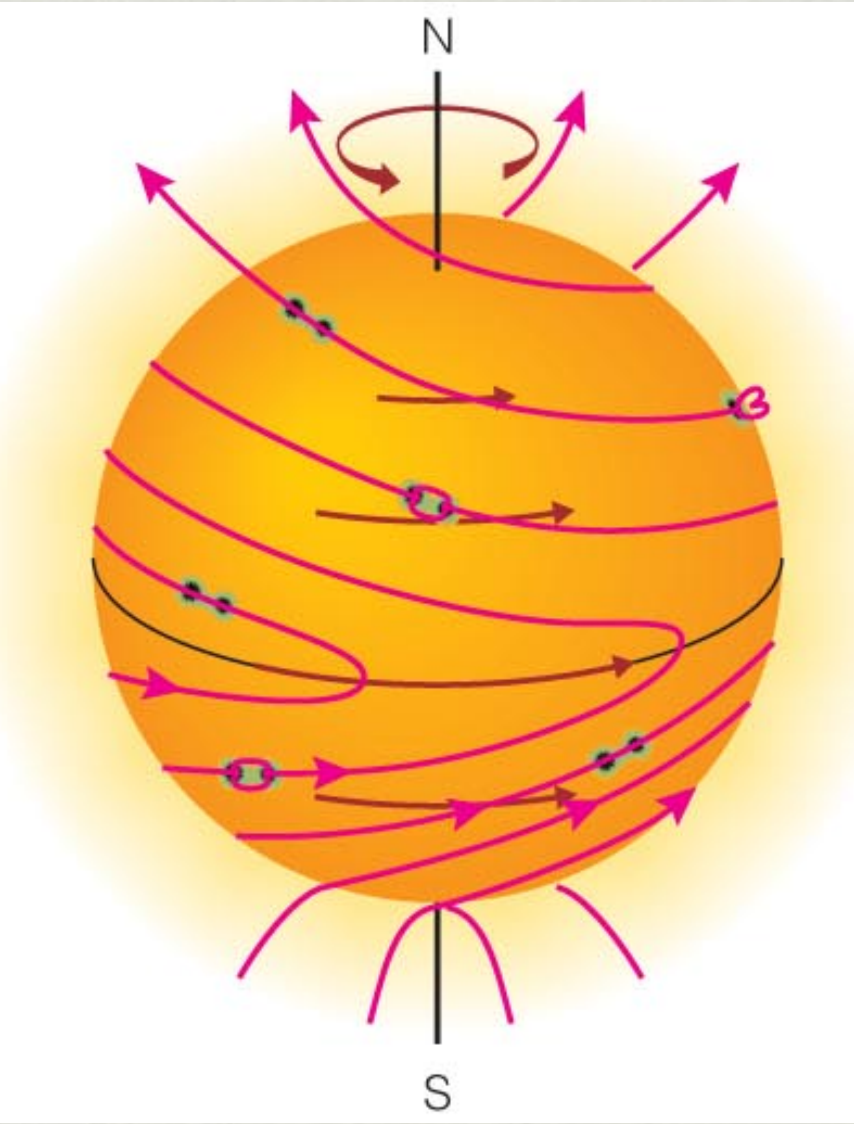
Solar Activity

Magnetic fields explain all of those things.

The sun has a magnetic field that gets more irregular and twisted up than the Earth's

Earth's magnetic field





Sun's magnetic field

Both of these pictures are cartoons!

Solar Activity

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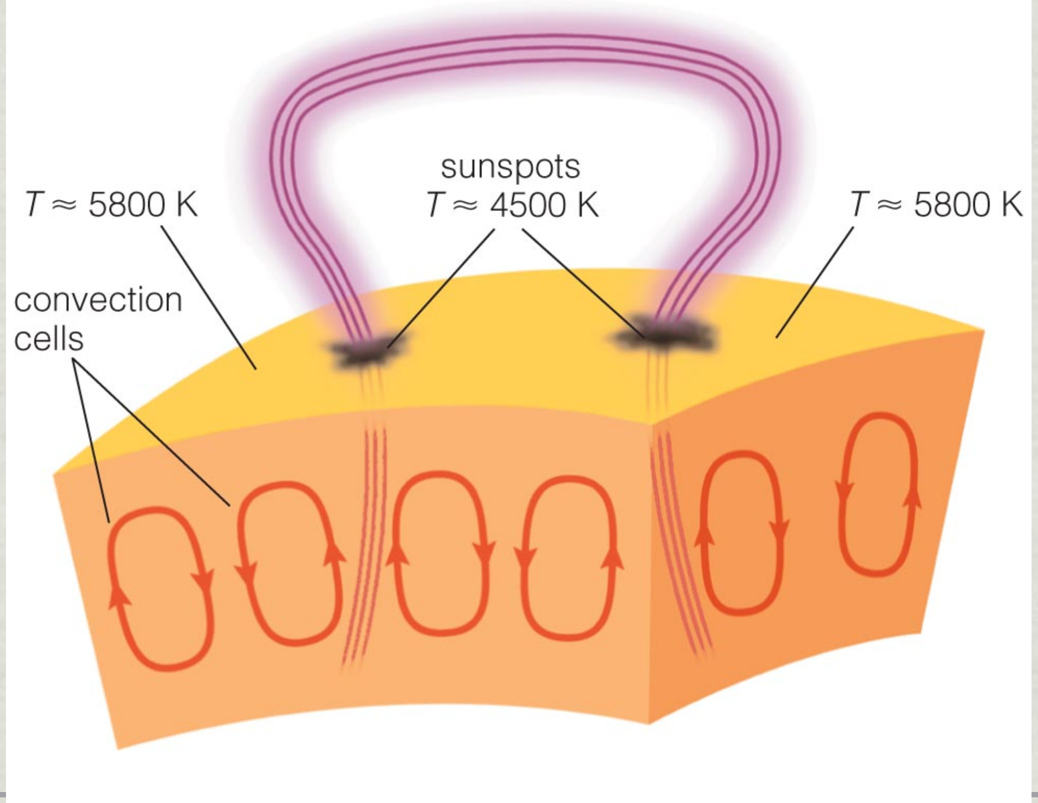
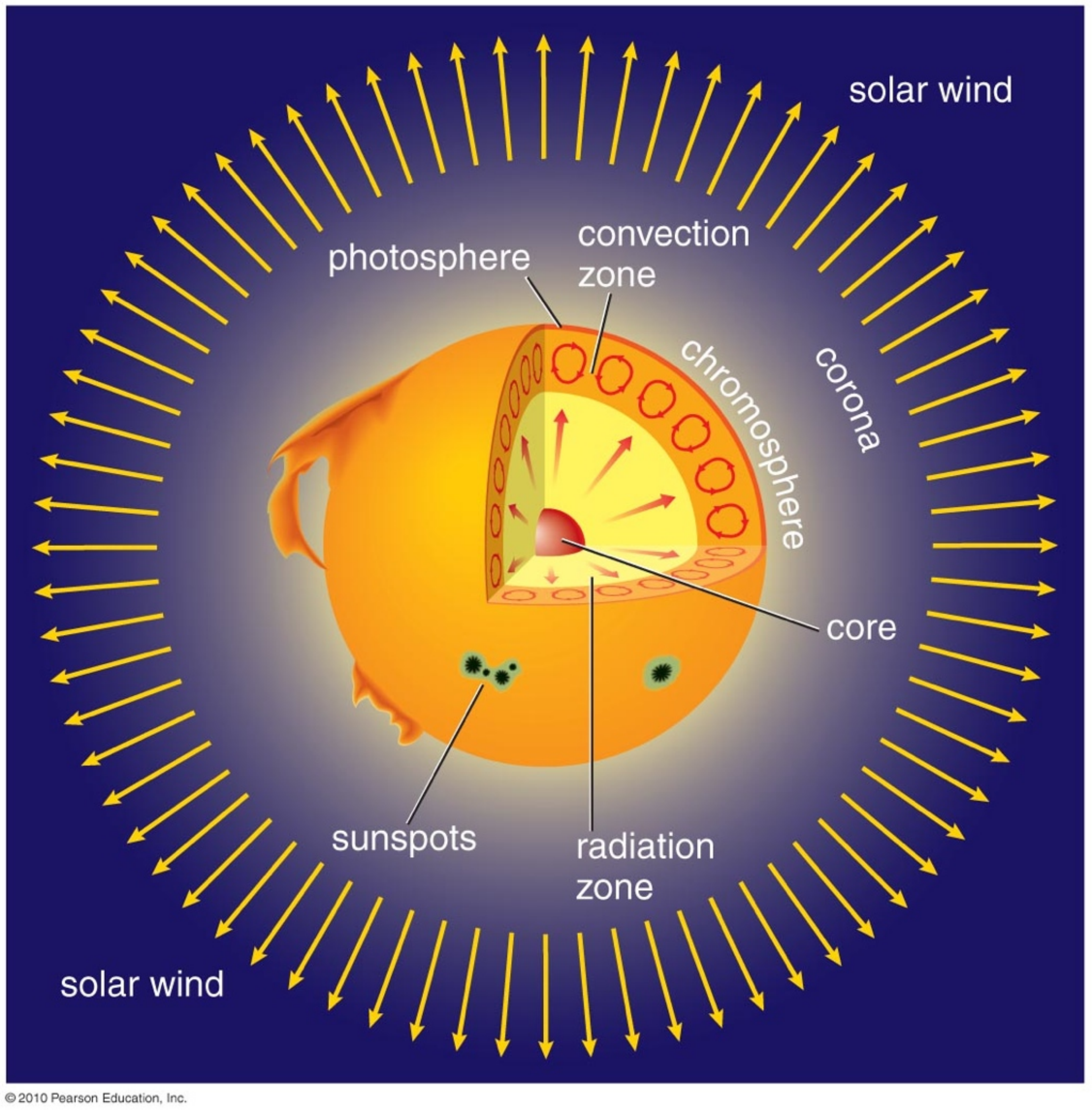
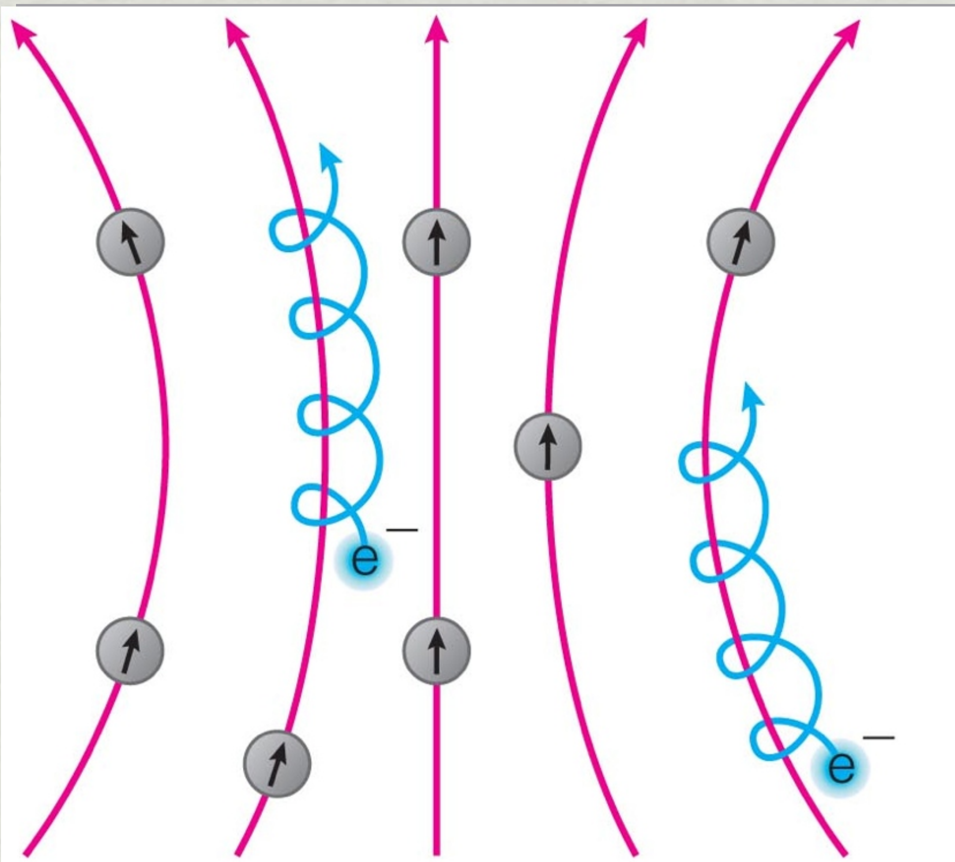




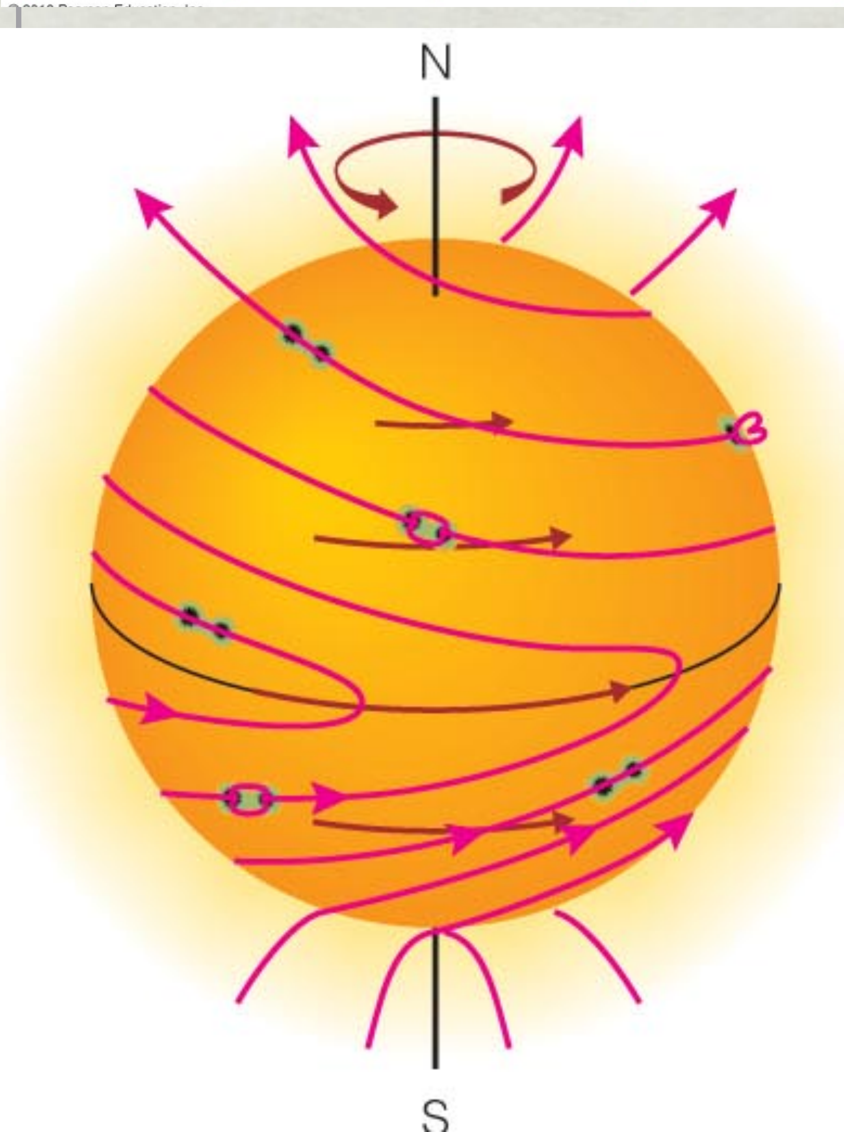
Solar Activity



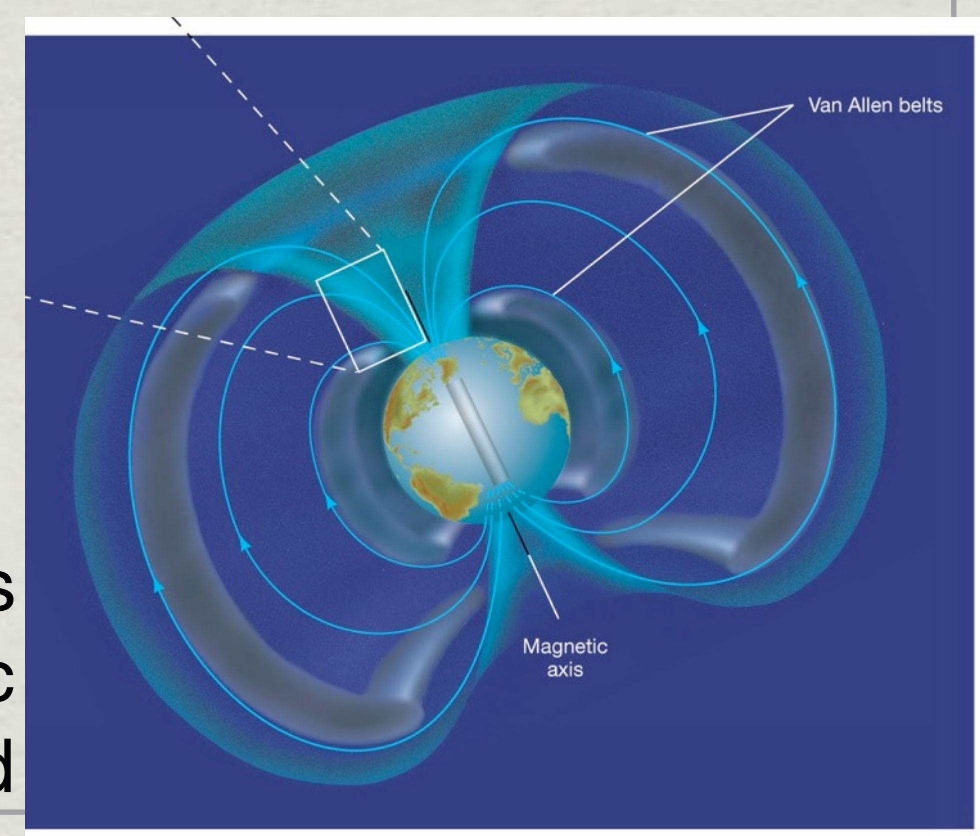
Charged particles “stick” to magnetic fields. Can move freely in the direction of the “field lines” but not across them

If the field lines twist, particles are dragged along

Sun is made entirely of ionized gas, so this is a big effect in the sun, much bigger than earth



Sun’s magnetic field



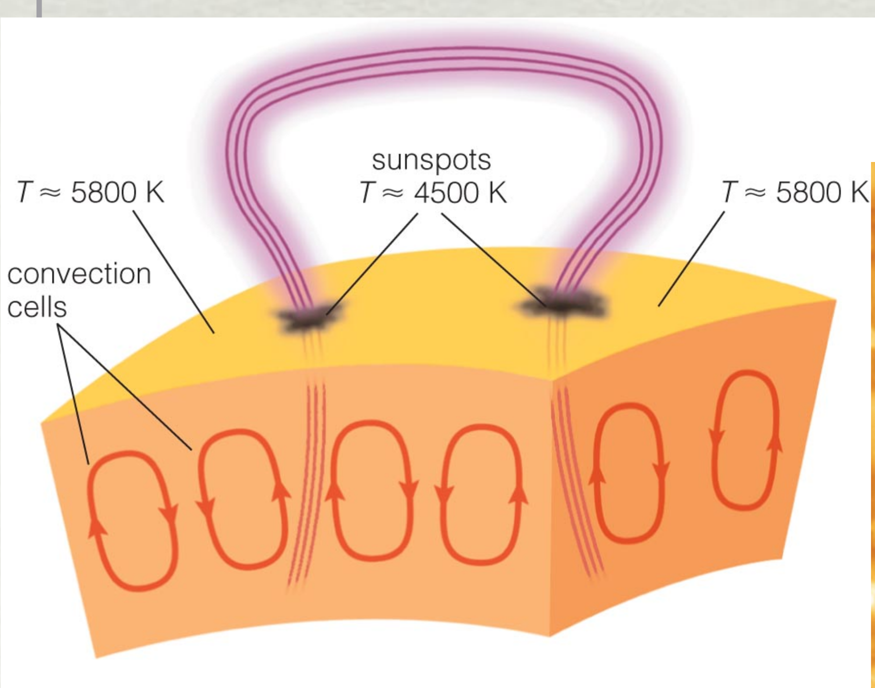
Earth’s magnetic field

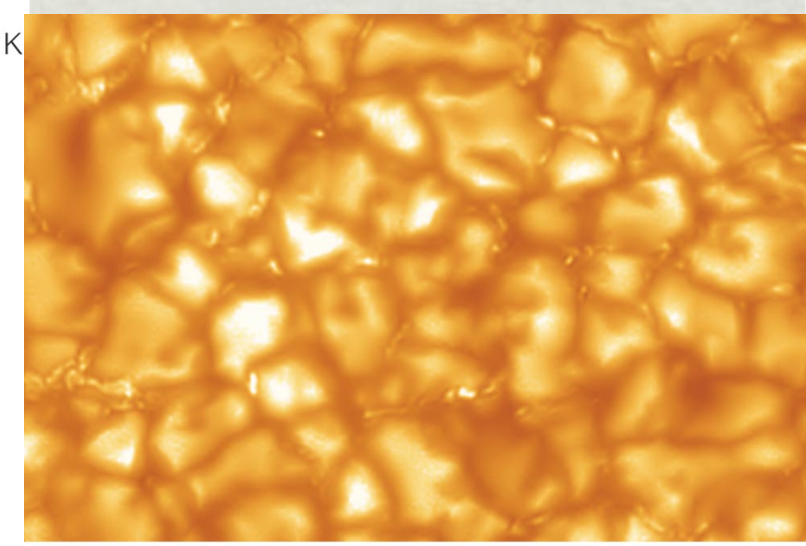
Solar Activity

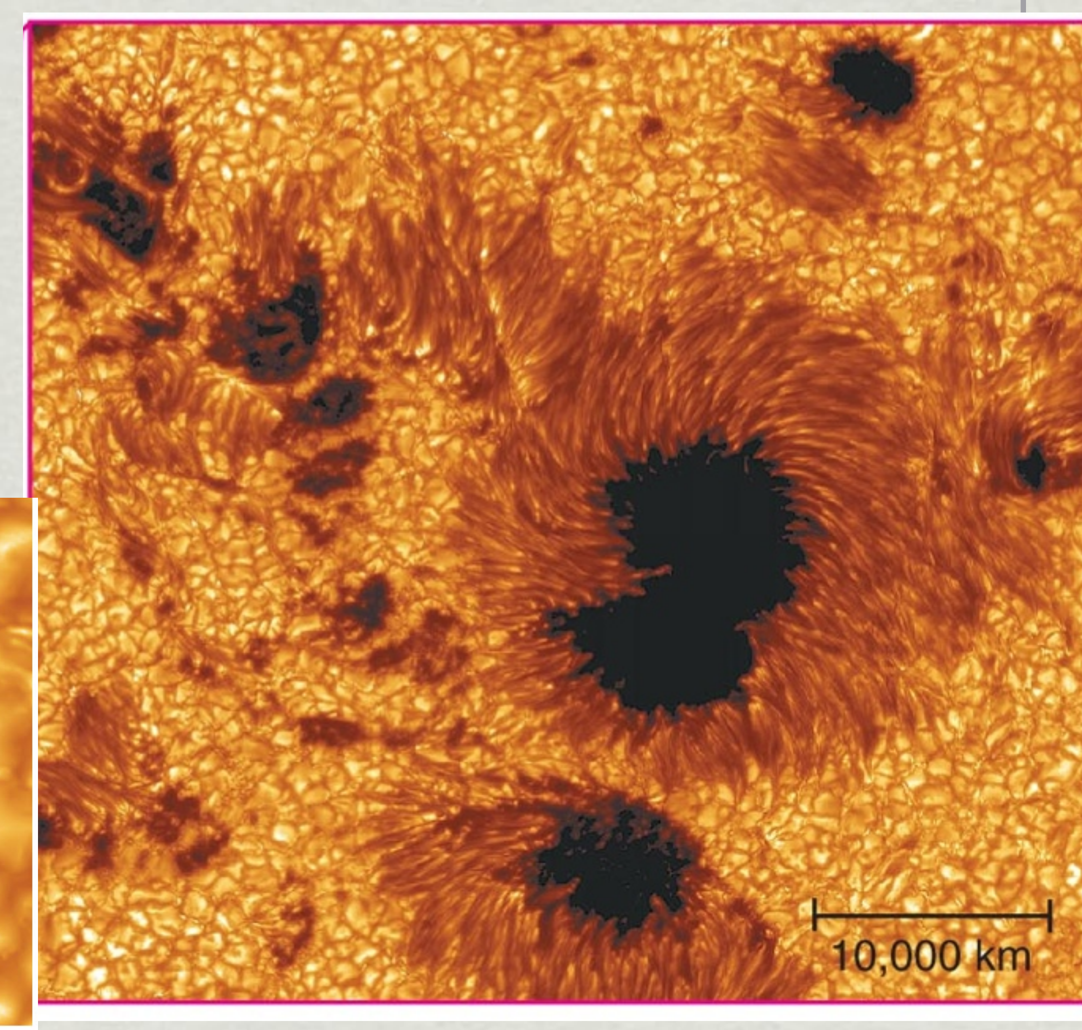
Magnetic field stops convection where it comes up through the photosphere.
Where field lines bunch up, get dark patches = sunspots

Sunspots are cooler than the rest of the surface of the sun: 4000 K in the sunspots vs. 5800 K everywhere else.

Why cooler? Convection is not carrying blobs of hot gas to the surface.





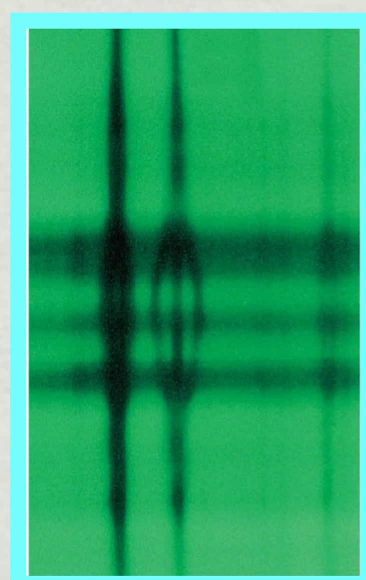


Solar Activity

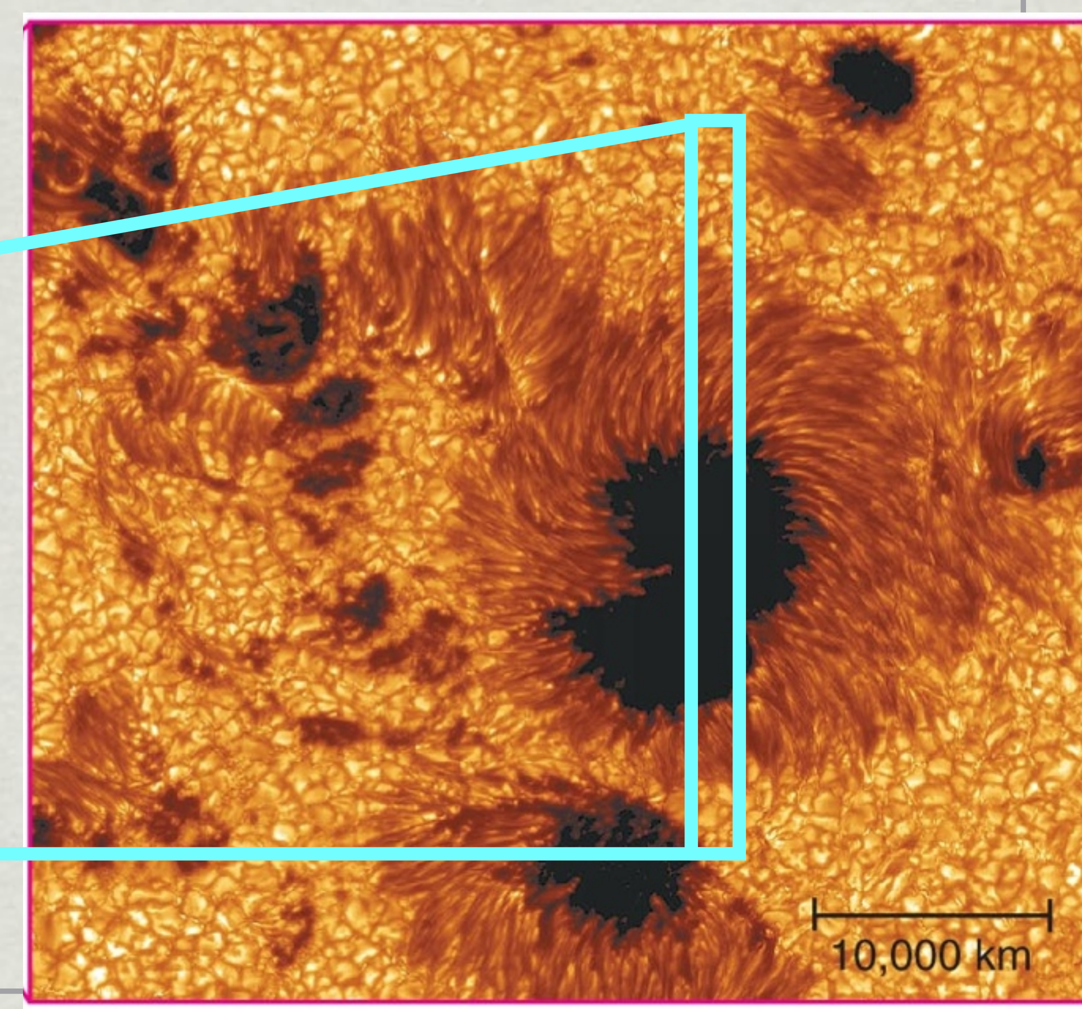
Magnetic field stops convection where it comes up through the photosphere.
Makes dark spots = sunspots

We know the magnetic field is strong in sunspots because we can measure the Zemann effect: strong magnetic fields split spectral lines.

A spectrum: dark = high intensity of light, lots of photons

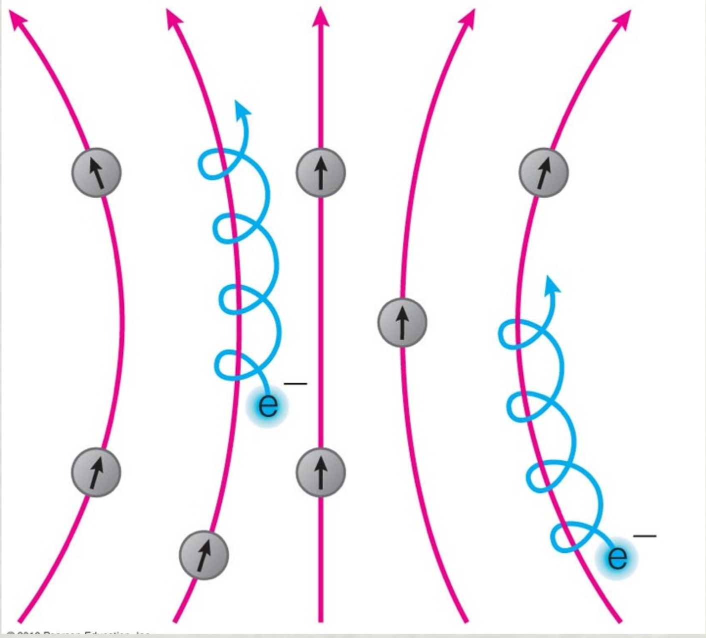


←wavelength→



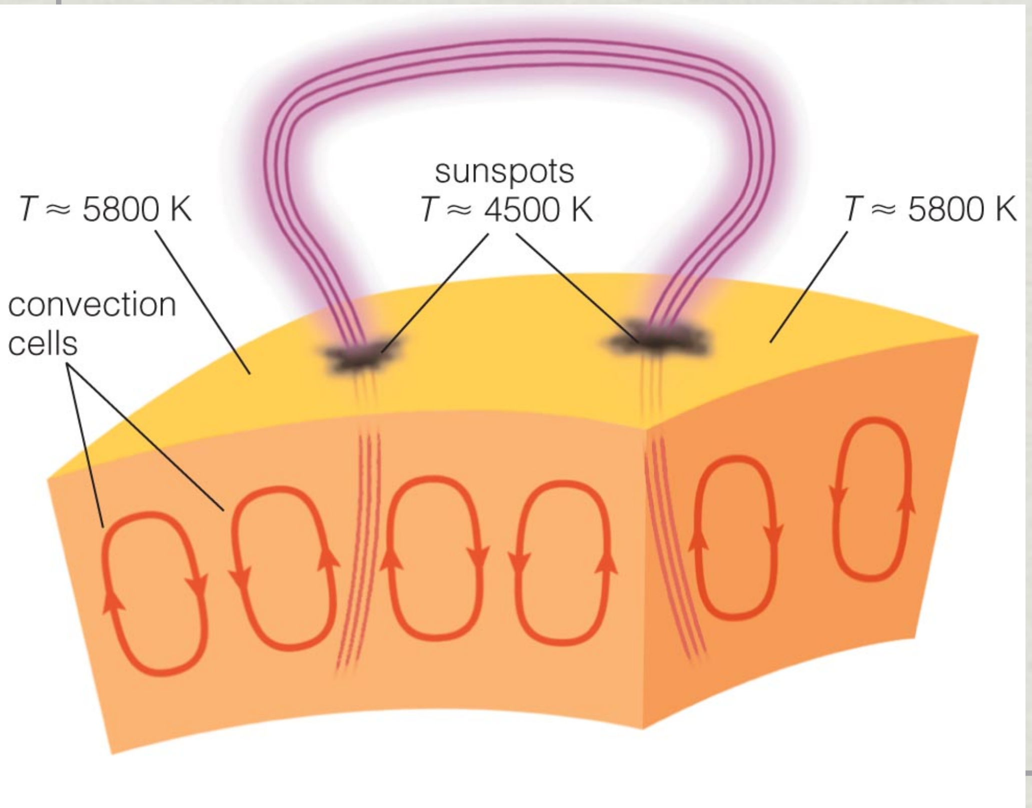
Solar Activity

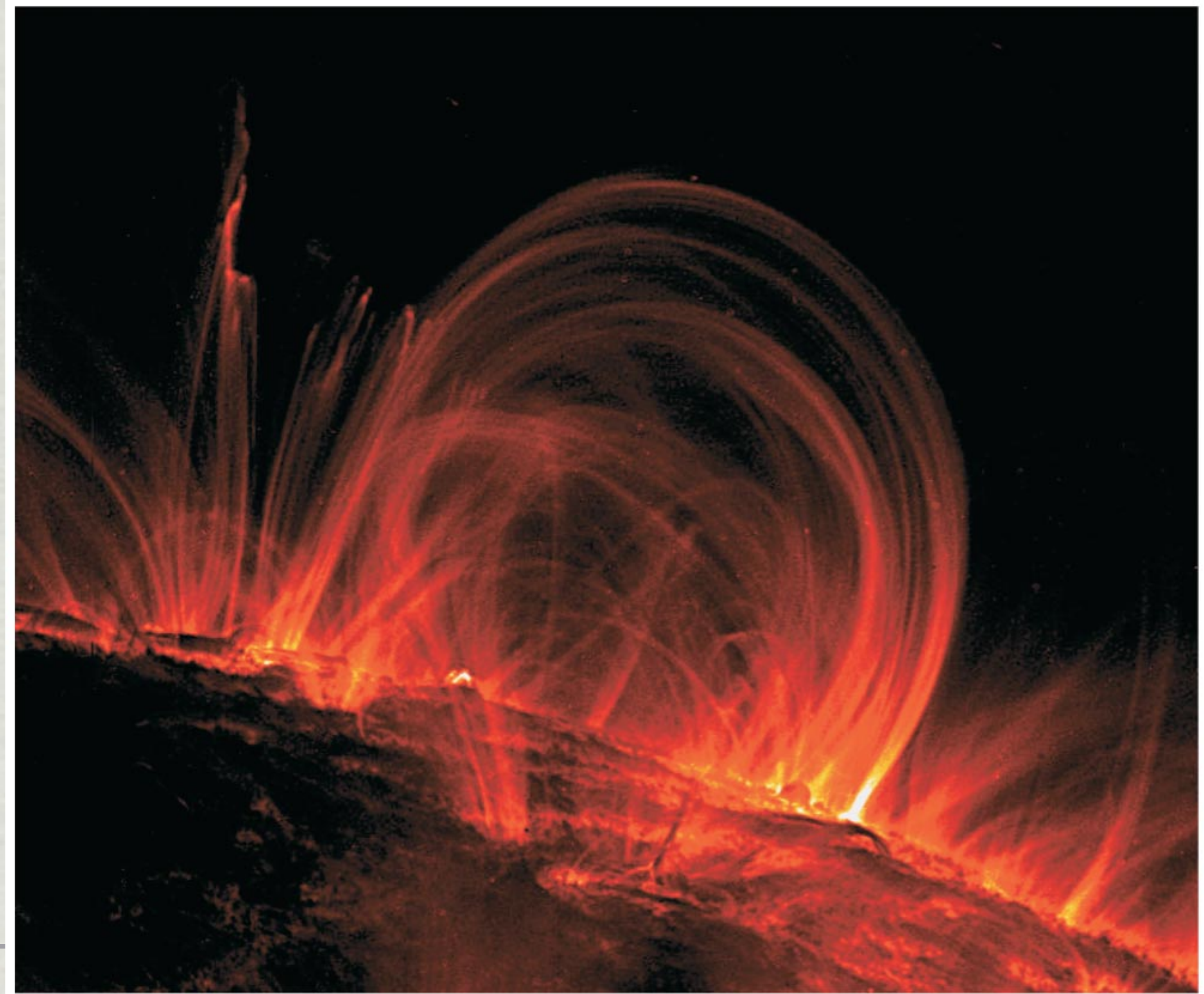
Charged particles stick to magnetic fields. Gas is cooler above sunspots, “bottled up” by surrounding higher pressure.



Charged particles = hot gas

Emits photons, we see loops of magnetic fields (sort of like strings of christmas lights)





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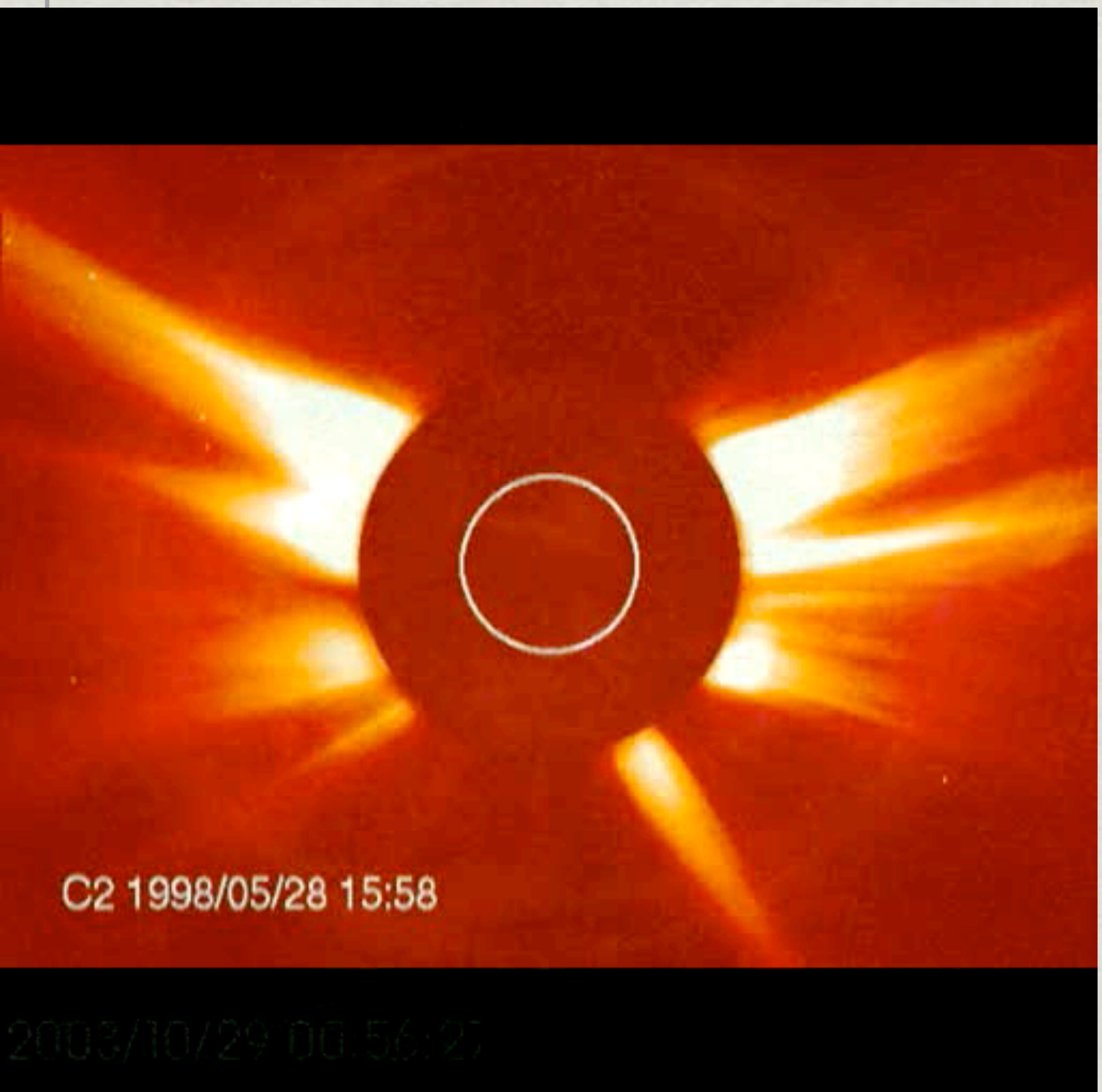
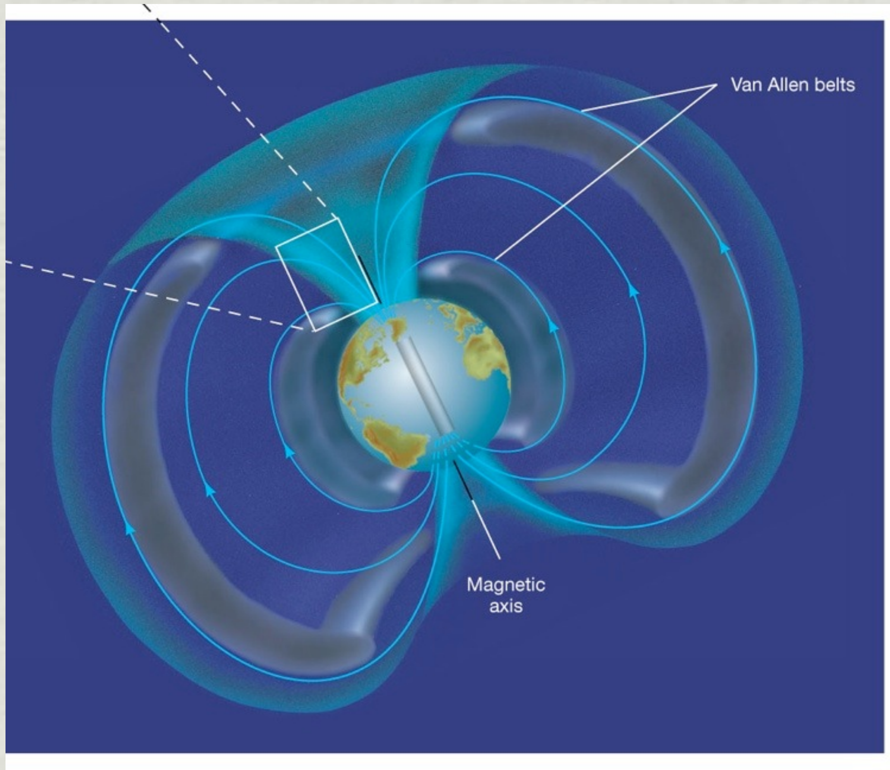


Solar flares: big, fast changes in the magnetic field

Like a storm on the sun: sends bursts of charged particles out into the solar system.



Solar Activity

Solar flares: big, fast changes in the magnetic field.
Send bursts of charged particles out into the solar system...

...get caught in Earth's magnetic field just like they were caught in the Sun's magnetic field.

Cause aurora: emission from charged particles in our atmosphere.

Can also disrupt electrical power grids and disable communications satellites.

The sun formed when a cloud of gas "collapsed" due to the mutual gravitational attraction of each part of the cloud on the rest

Gravity: $F = ma = \frac{G M m}{d^2}$

Cloud becomes smaller and denser

What happens to the gravitational force each part of the cloud feels from the rest as the cloud gets smaller and denser?

A stays the same

B gets weaker

C gets stronger

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Gravity: $F = ma = \frac{G M m}{d^2}$

Cloud becomes smaller and denser

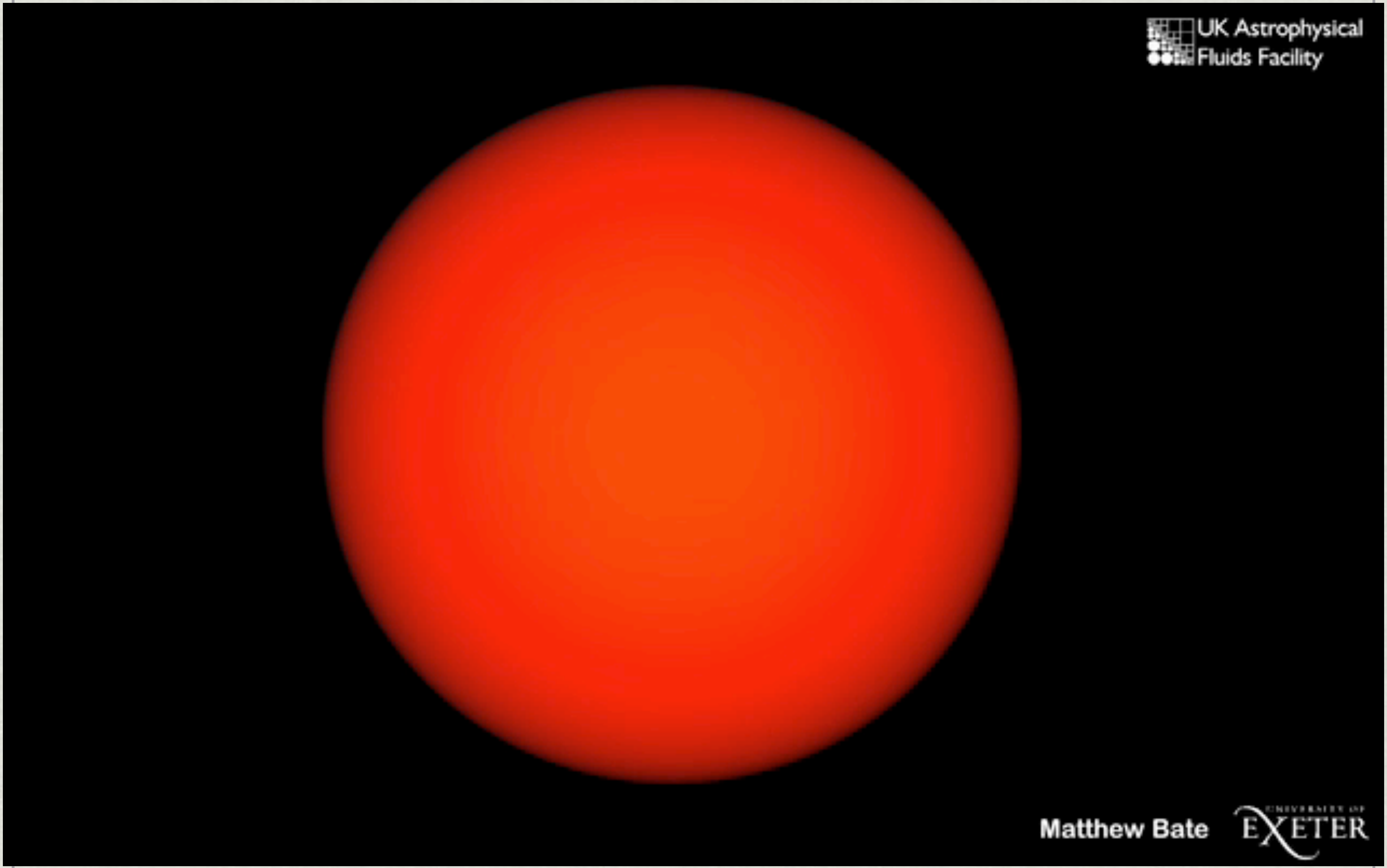
Gravitational force of each part of the gas cloud on the rest becomes stronger

Cloud becomes even smaller and denser

Gravitational force pulling the parts of the cloud together becomes even stronger

…you get the idea

As the cloud shrinks and compresses the force causing it to shrink and compress becomes stronger. It “runs away”: gravitational collapse


UK Astrophysical
Fluids Facility
Matthew Bate
UNIVERSITY OF
EXETER

- Why would a gas cloud start to collapse?
  - Gravitational disturbance, like passing star
  - Gas is squished by shock waves: outflows from a nearby hot, young star or a supernovae, the explosive end of a massive star’s life. Then gravity takes over.

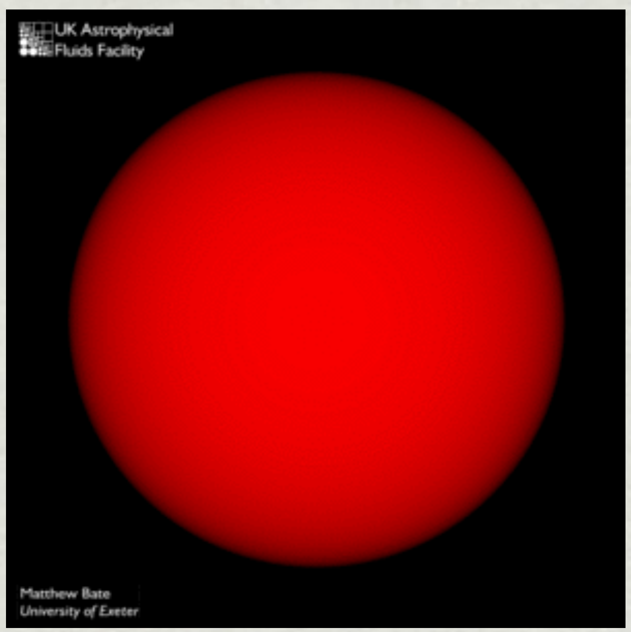
30 Doradus, a giant star-forming region in the Large Magellanic Cloud

Lots of hot, bright young stars.

Transparent gas excited by photons from hot young stars, visible as an emission line spectrum

Bubbles and filaments of hot gas in shock waves from young stars and supernovae explosions, including one in 1987

- Remember: gravitational potential energy is energy stored by working against gravity
- Gravitational force: mass particles (like gas atoms) attract
- When the atoms fall together as they collapse, it's like letting the piano fall back down the stairs: release stored gravitational potential energy



Gravitational collapse releases gravitational potential energy

- like dropping your couch off the roof

Conservation of energy: gravitational potential energy converted to thermal energy of gas particles

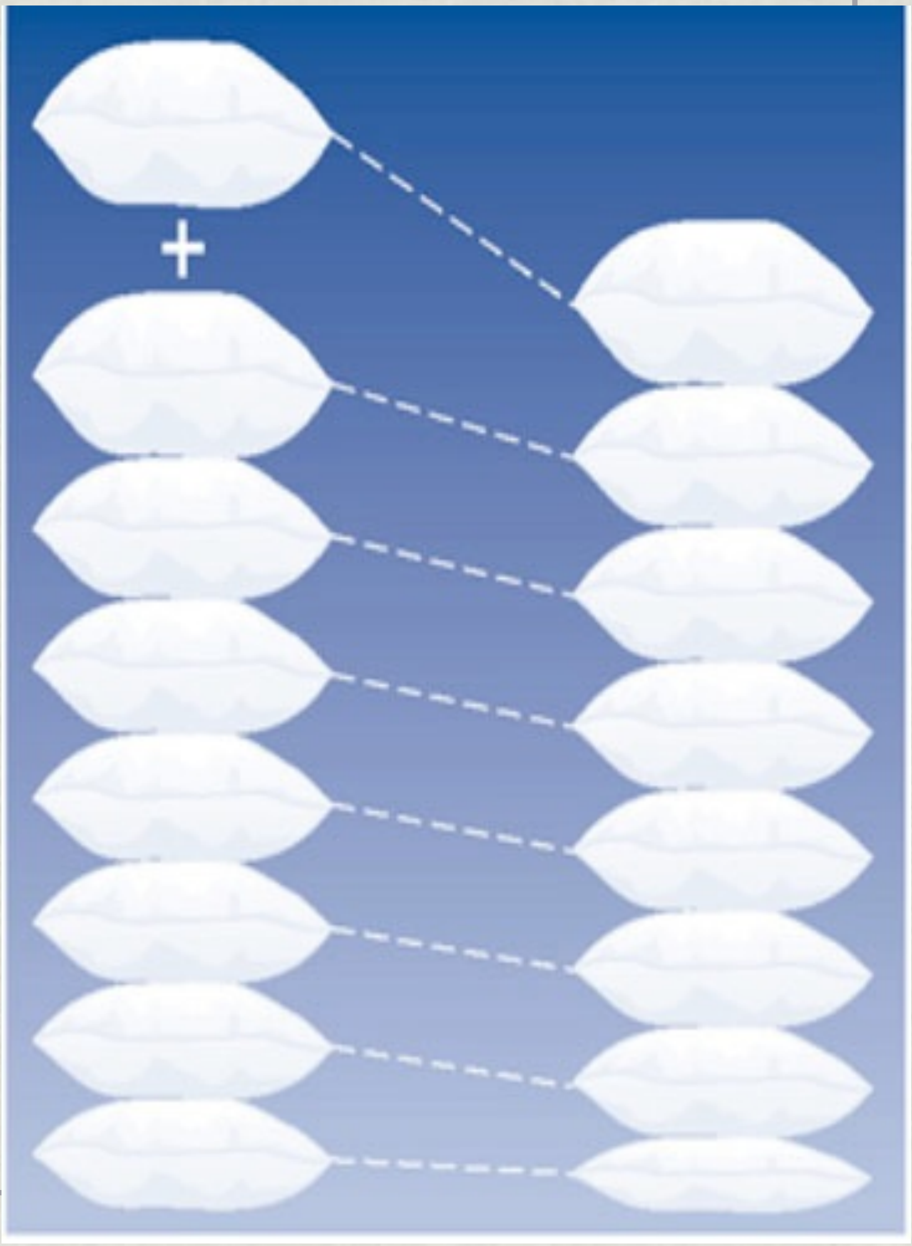
The atoms heat up as the cloud shrinks and compresses

Gravitational (Hydrostatic) Equilibrium in the Sun

What holds the sun together? Gravity!

Weight of the outer layers exerts a huge force pushing down on the deeper layers.

So why doesn't the sun collapse all the way?
What pushes back?



Gravitational Equilibrium in the Sun

$$\text{Pressure} = \frac{\text{Force}}{\text{Area}}$$

Which would you rather lean on?

or

?

Same force: (some of) your weight!
But smaller area = higher pressure

Gravitational Equilibrium in the Sun

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If you have to walk in the mud:

or

?

Gravitational Equilibrium in the Sun

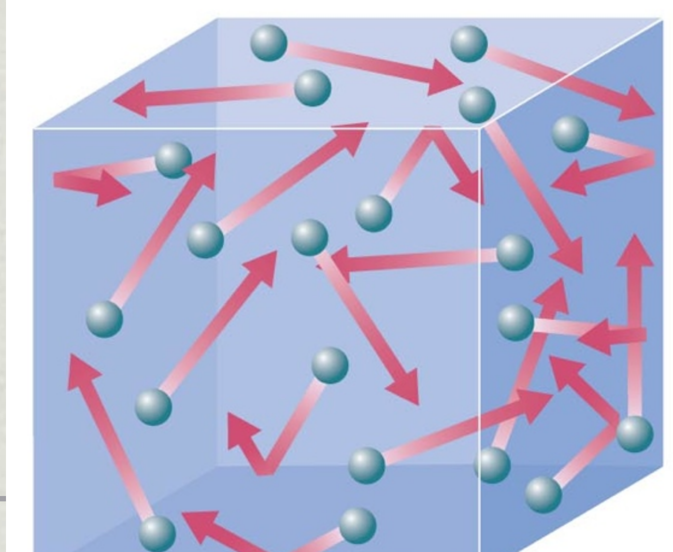
$$\text{Pressure} = \frac{\text{Force}}{\text{Area}}$$

Which would you rather lean on?  or  ?

Same force: (some of) your weight!
But smaller area = higher pressure

That force can come from gravity, or from atoms and molecules bouncing off a boundary. When they change direction, they accelerate → Force!

The boundary exerts force on the molecules (to change their direction), the molecules exert force on the boundary (Newton's 3rd law).



Lots of molecules bouncing off a boundary (like the wall of a balloon) and exerting force on its area → Pressure!

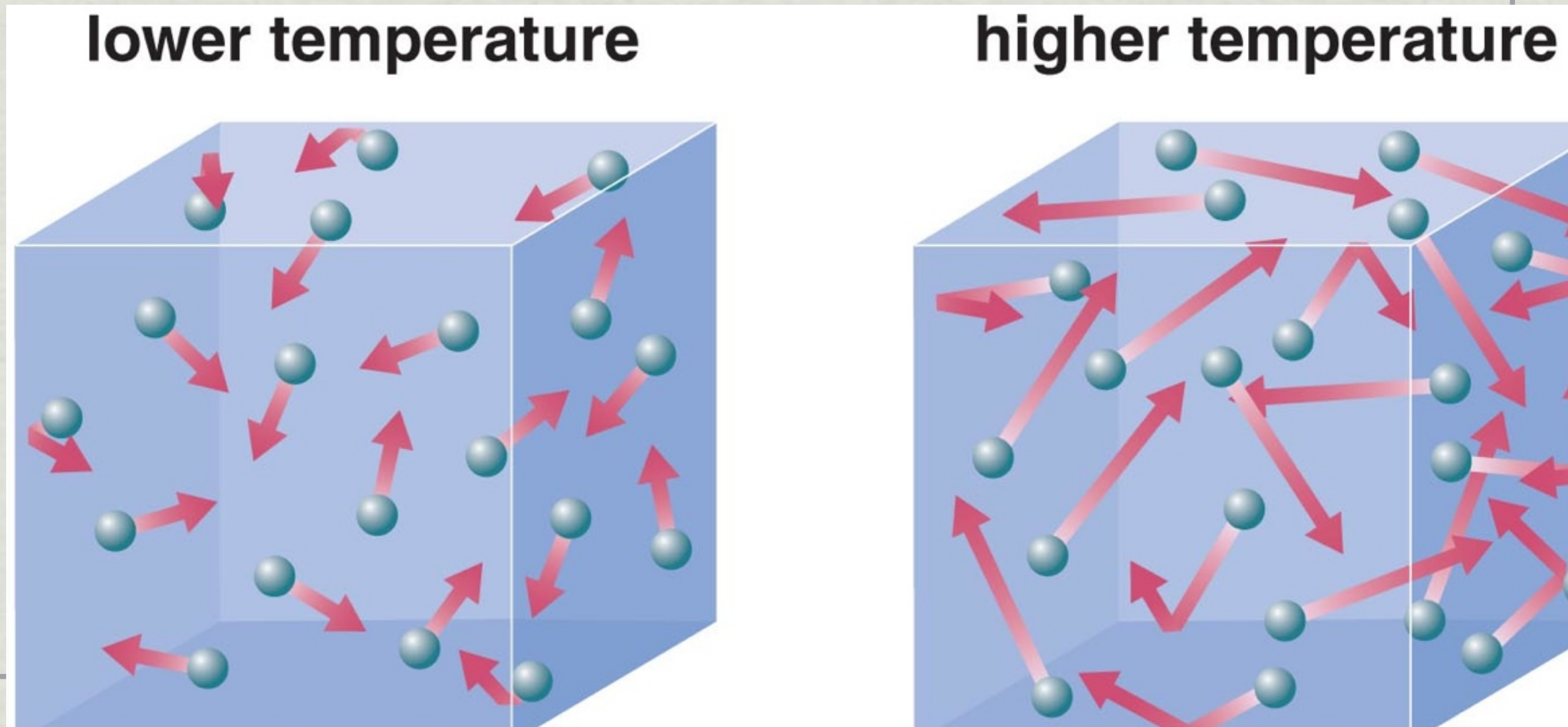
Gravitational Equilibrium in the Sun

$$\text{Pressure} = \frac{\text{Force}}{\text{Area}}$$

For a gas (like the earth's atmosphere or the inside of the sun) two things matter for pressure: density and temperature

High temperature (hot):
molecules and atoms have lots of kinetic energy ($1/2\ mv^2$), so every time an atom changes direction it gets a big acceleration. Lots of force per bounce → high pressure.

Low temperature (cool):
less kinetic energy, less acceleration from every bounce → lower pressure



Gravitational Equilibrium in the Sun

$$\text{Pressure} = \frac{\text{Force}}{\text{Area}}$$

For a gas (like the earth's atmosphere or the inside of the sun) two things matter for pressure: density and temperature

Many molecules (high density): many collisions = high pressure

Few molecules (low density): few collisions = low pressure

Gravitational Equilibrium in the Sun

$$\text{Pressure} = \frac{\text{Force}}{\text{Area}}$$

Perfect Gas Law:

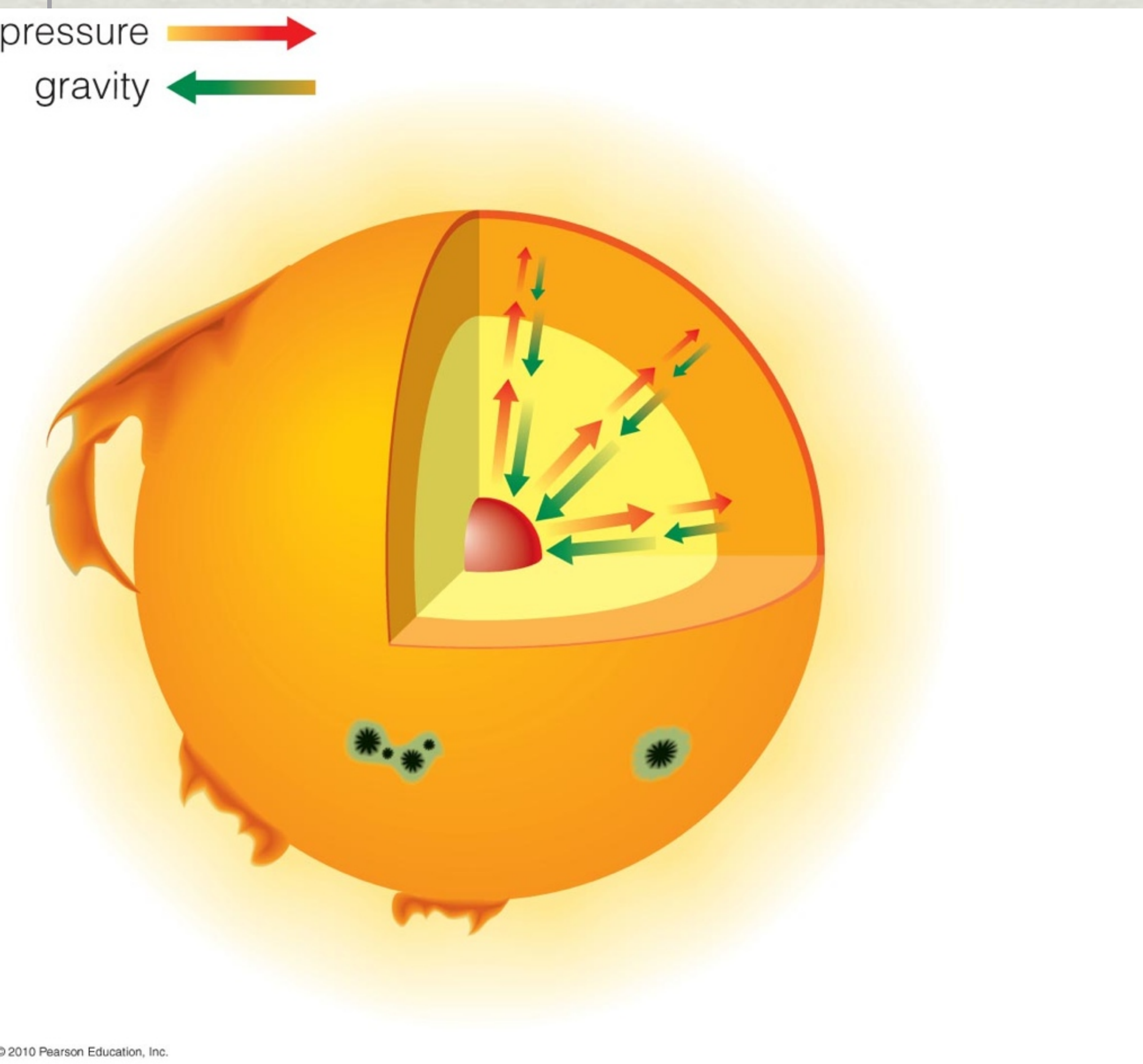
Pressure = k × density x temperature

k is a universal constant (yes, another one), like G

“perfect”: assumes molecules and atoms bounce perfectly in every collision. Chemistry tells us that doesn’t always happen: sometimes they stick together and make molecules! In AY2, you can always assume a gas is “perfect”

Gravitational Equilibrium in the Sun

- Energy produced near the center (in the core) by nuclear fusion: actually fusing two atoms to make a heavier atom. Get energy out, heat atoms in the sun interior. This maintains the pressure in the core of the sun.



  - We'll get to fusion next
  - Key point: more energy generated at higher temperature and pressure.

- Pressure at the deepest layers, near the core, is highest: that's where the most mass above is pushing down

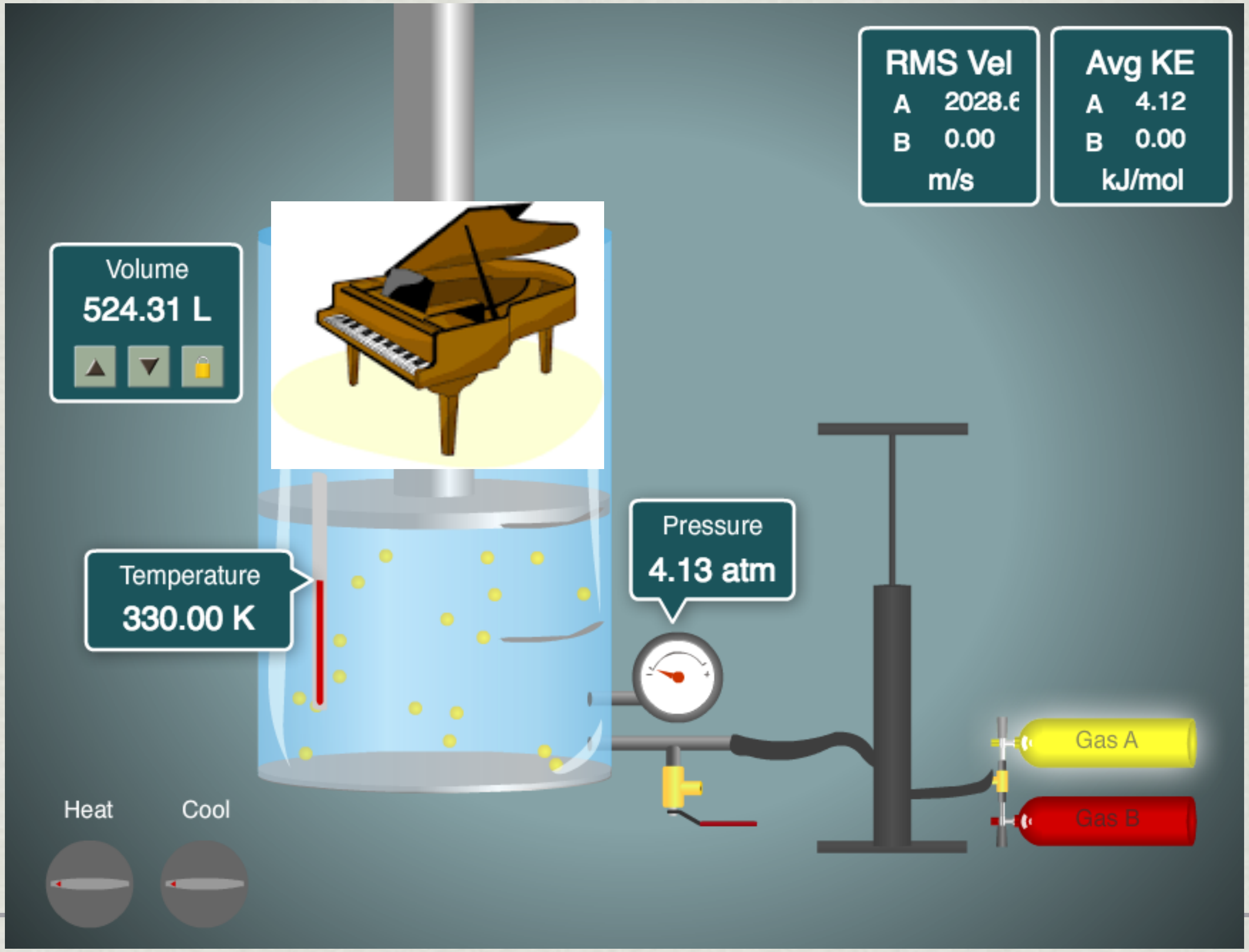
- Pressure is balanced everywhere by the weight (gravitational force) of the layers above.

- If it weren't, the sun would collapse!

If I add another piano what happens to the piston?

A Falls
B Rises
C Stays the same

Perfect Gas Law:
Pressure = k × density x temperature



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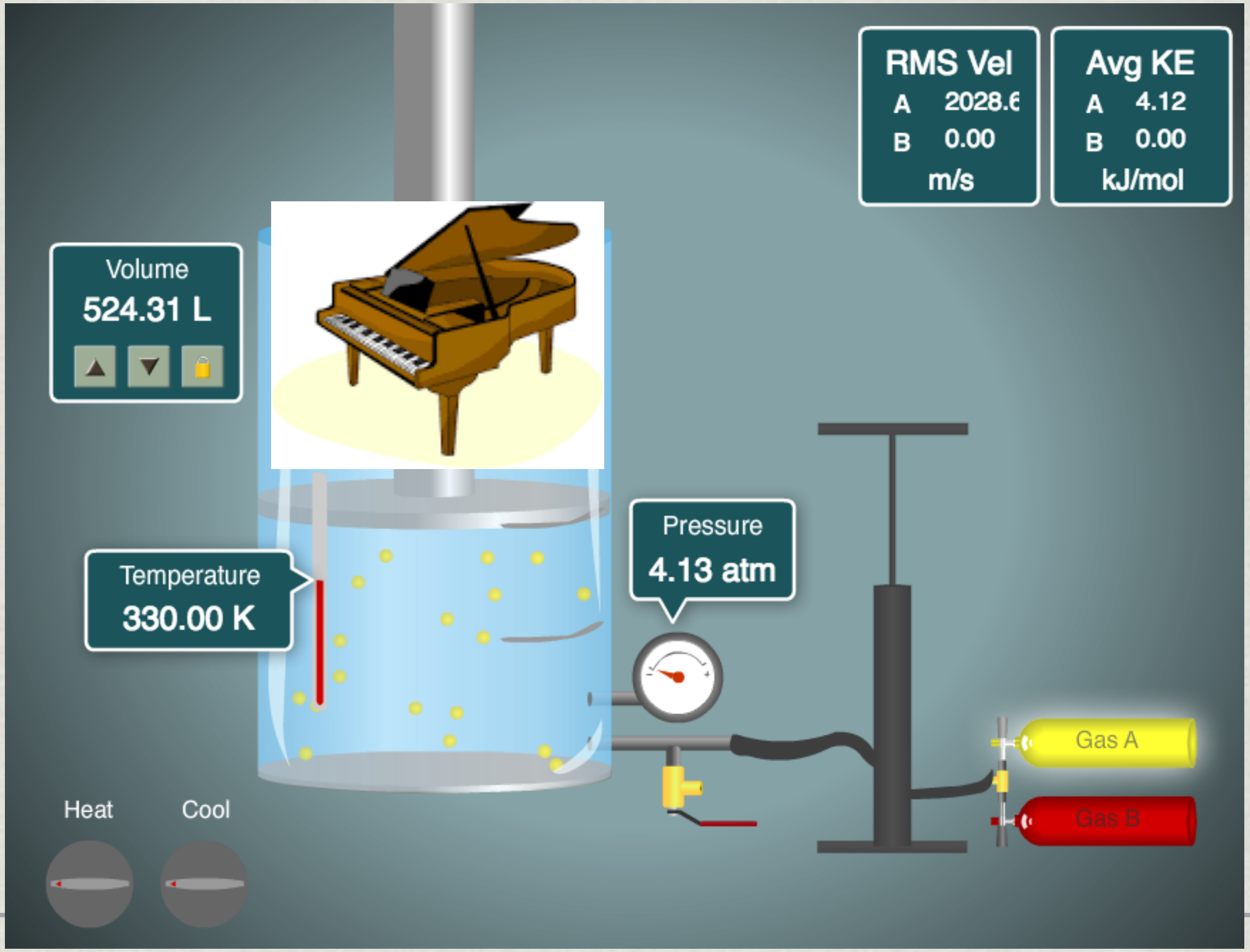


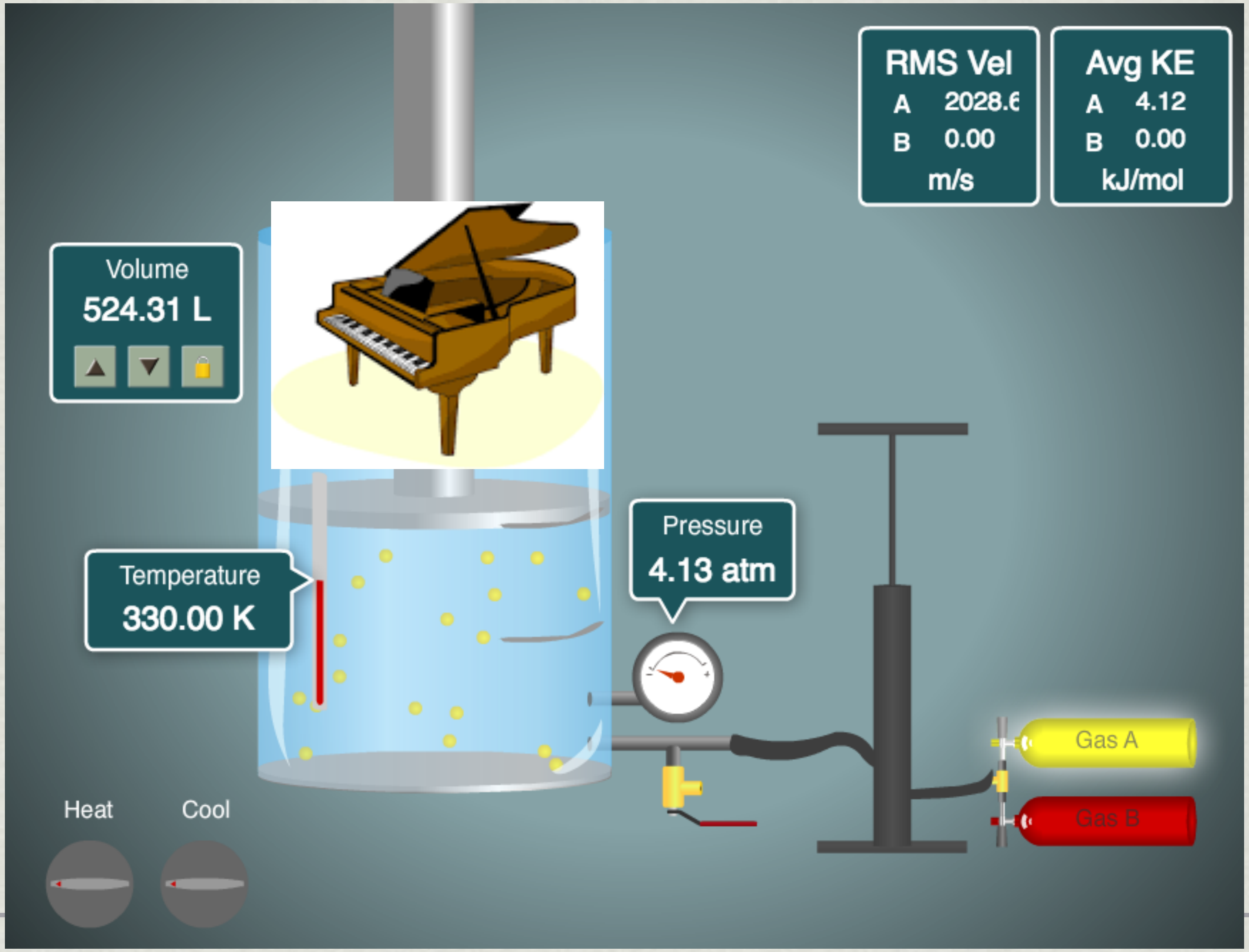
If I add another piano and I want the piston to stay in the same place I have to:

A Heat the gas

B Cool the gas

Perfect Gas Law:

Pressure = k × density x temperature



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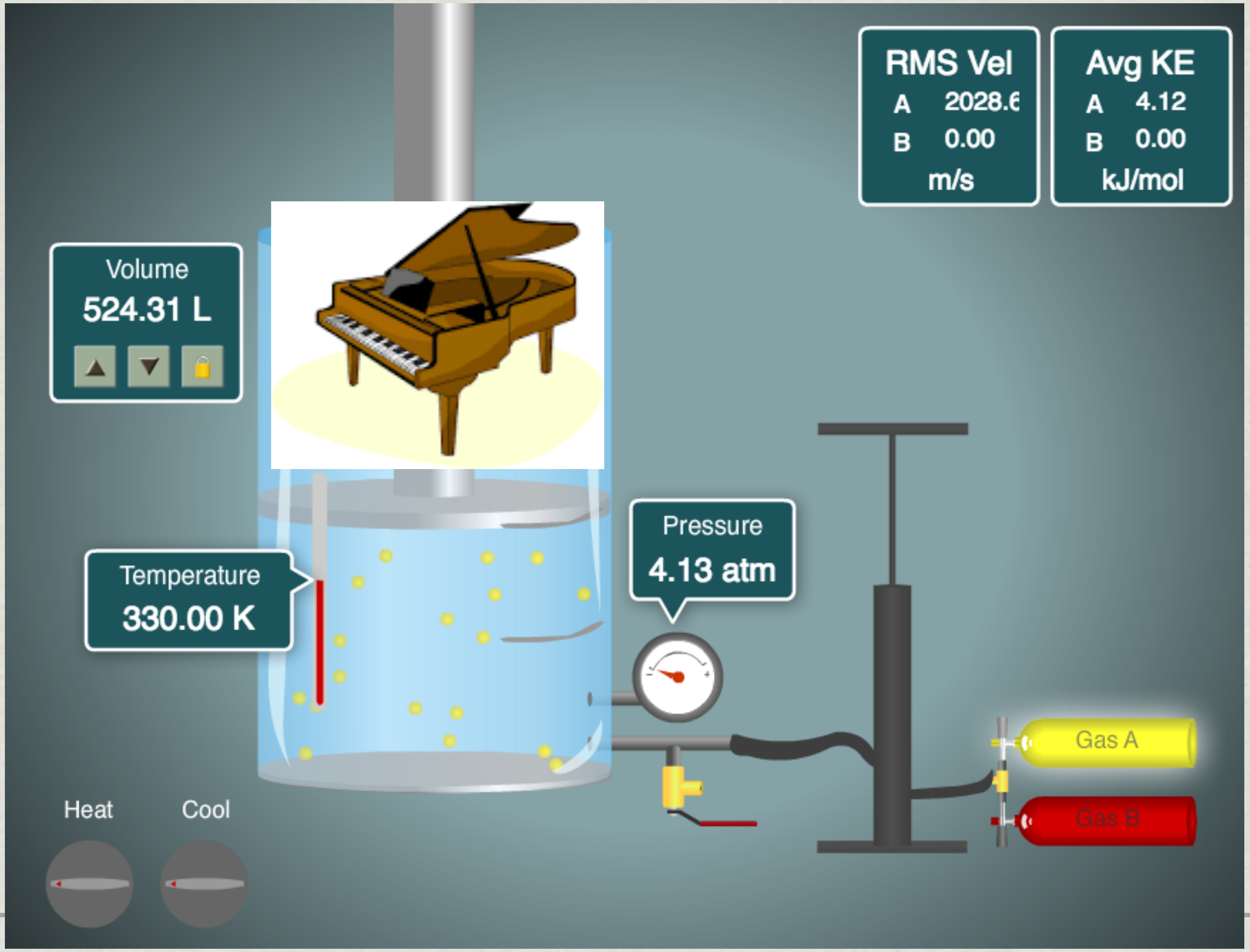
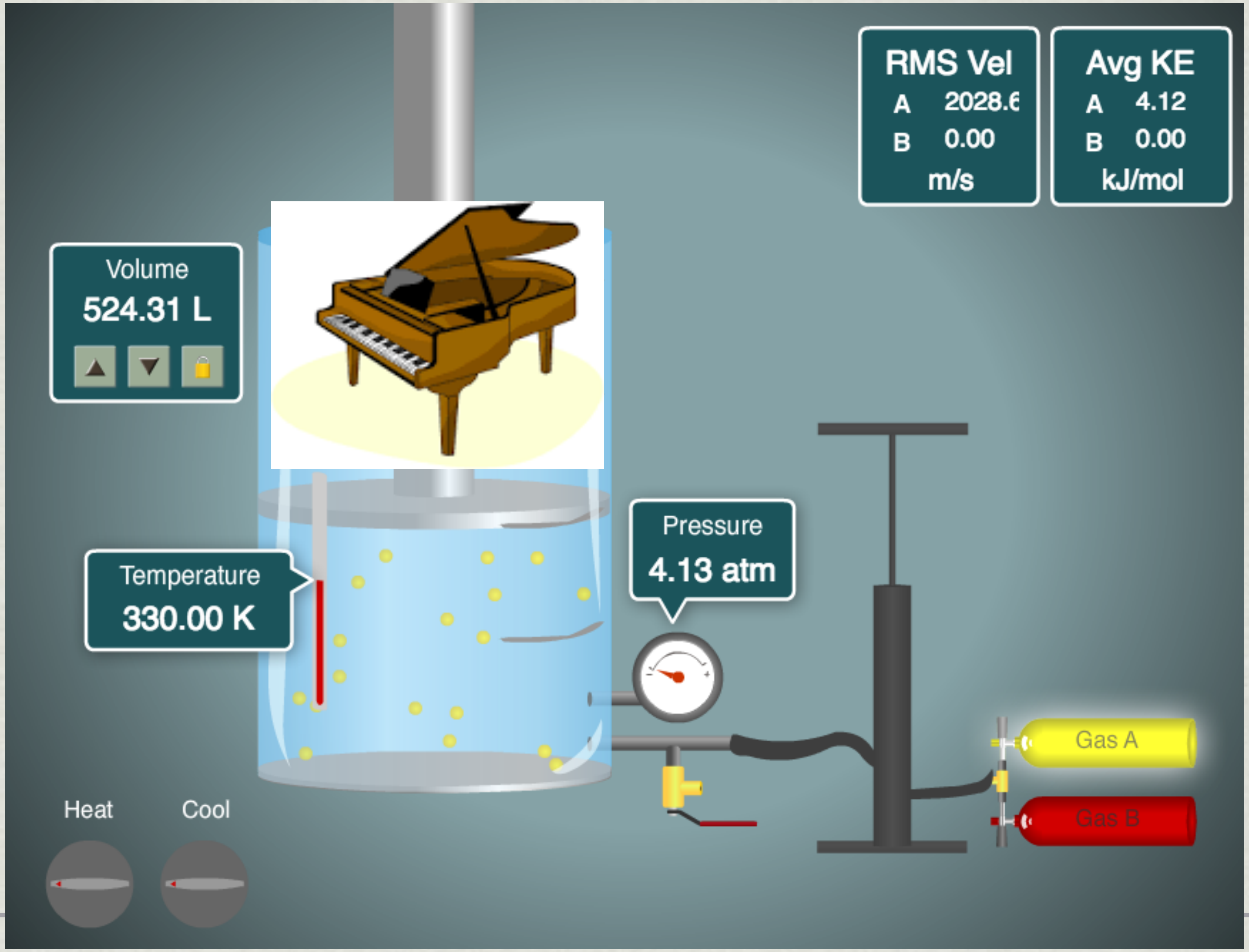


If I add another piano and I want the piston to stay in the same place and my heater is broken I need to:

A Add more gas
B Let some gas out

Perfect Gas Law:
Pressure = k × density x temperature



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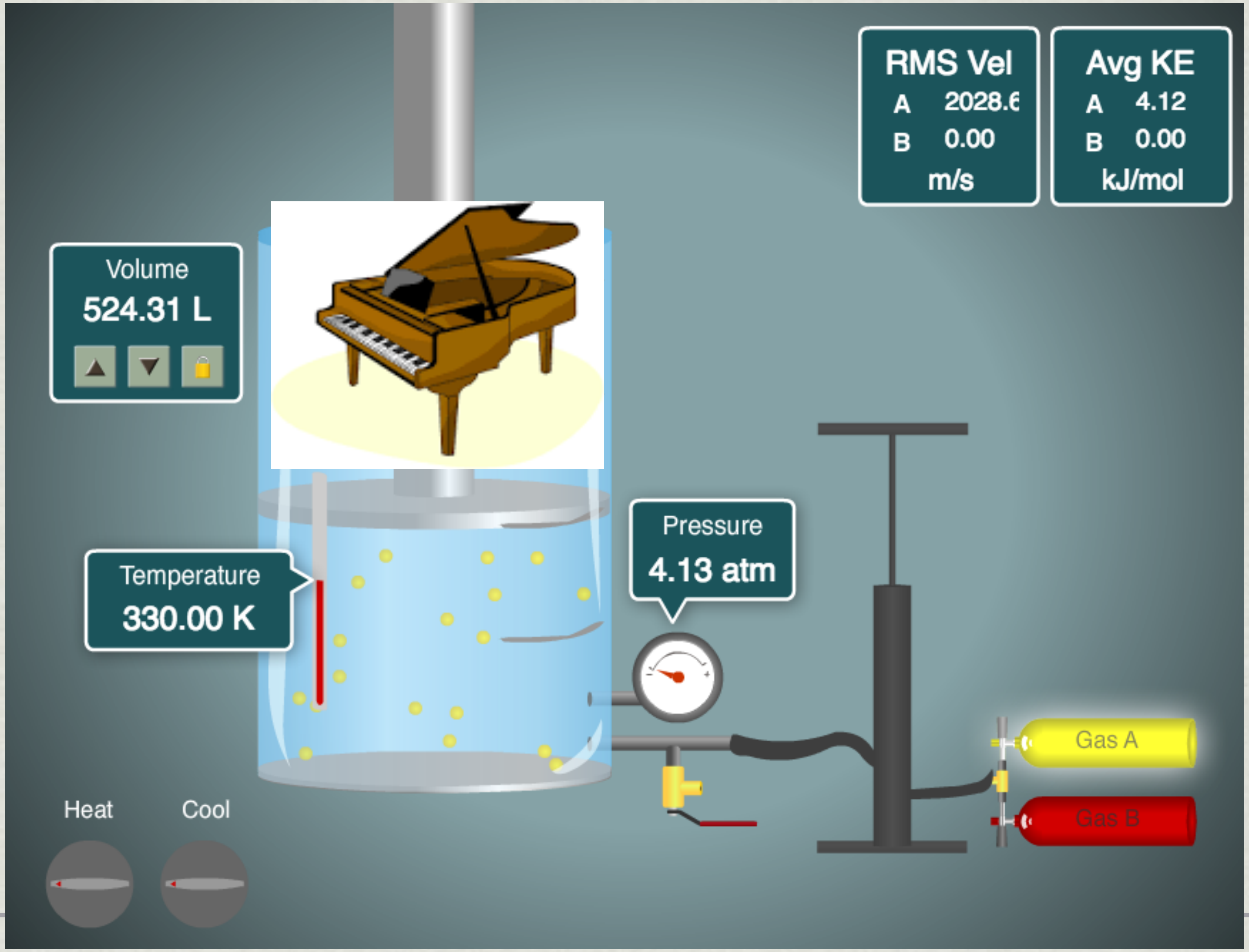
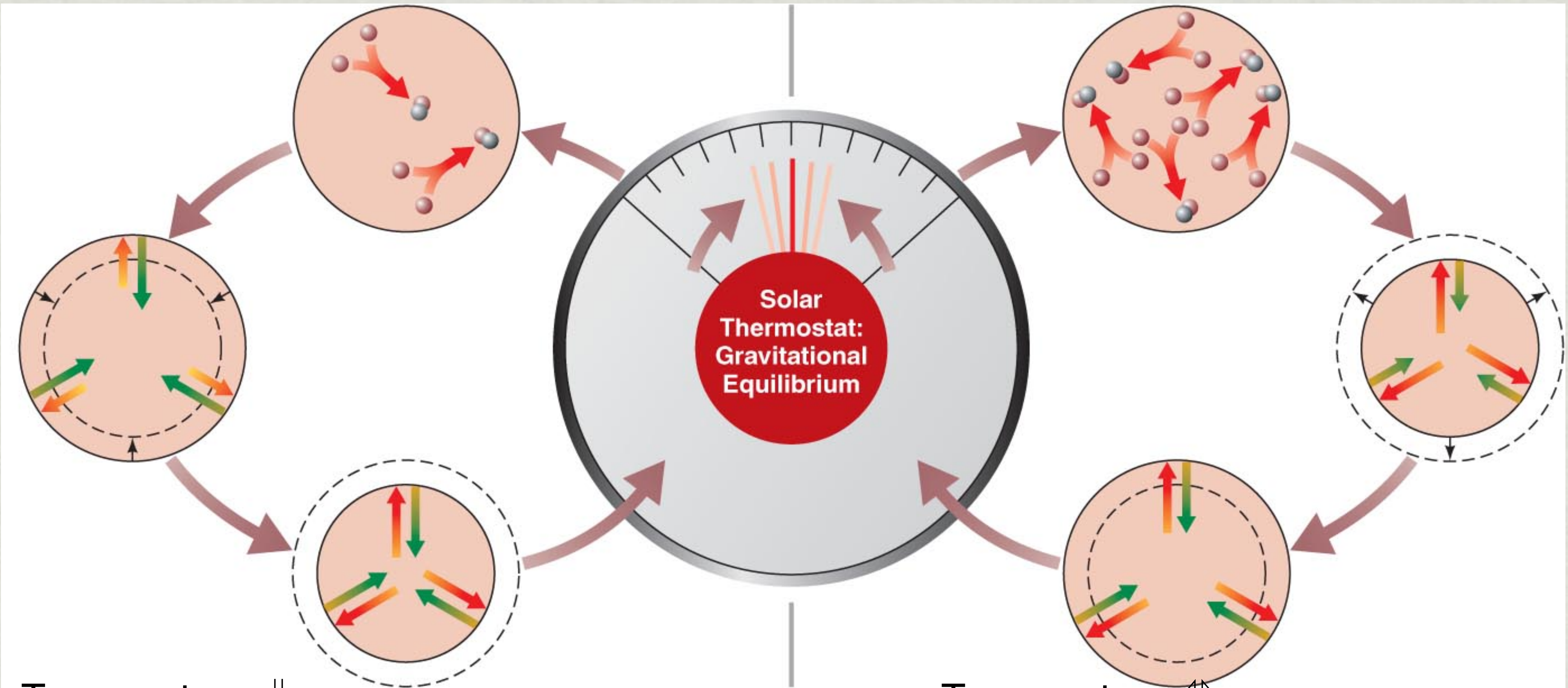


Gravitational Equilibrium in the Sun

Gravitational equilibrium:

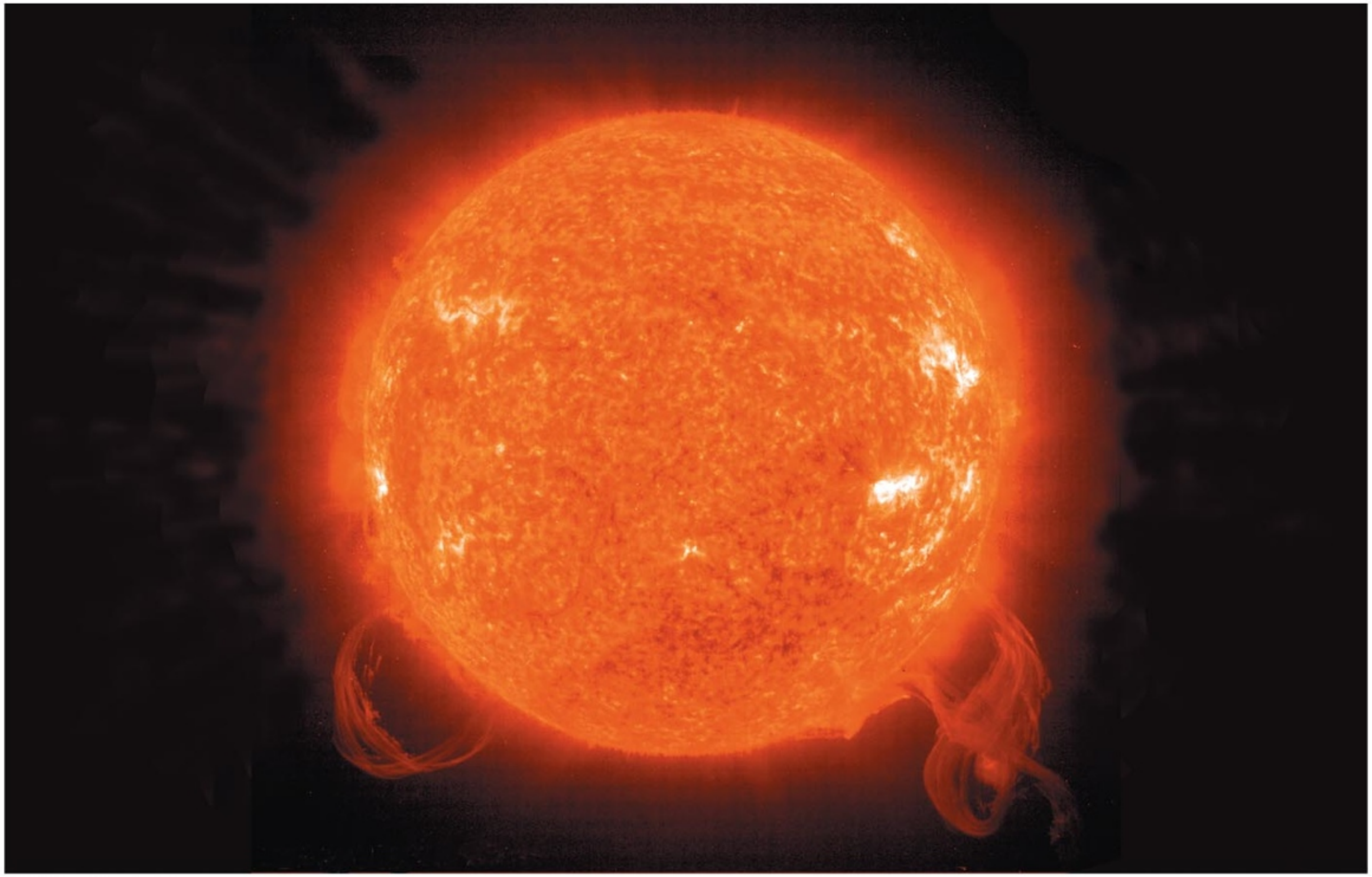
allows sun to regulate it's temperature and pressure, a kind of "solar thermostat"



Temperature ⇓
Pressure ⇓
Core contracts. This increases the rate of energy generation from nuclear fusion

Temperature ⇑
Pressure ⇑
Core expands, reduces rate of nuclear energy generation, cools down

Powering the Sun: Nucleosynthesis



What powers the sun? Is it a big lump of burning stuff (coal, natural gas, etc.)?

Powering the Sun: Nucleosynthesis

What's the fuel? Is it a big lump of burning stuff (coal, natural gas, etc.)?

How long would the fuel last?

Lifespan of sun: $\dfrac{\text{Total energy available in fuel}}{\text{Energy generated per second}}$

= number of seconds that the fuel can power the sun

Powering the Sun: Nucleosynthesis

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Lifespan of sun: $\dfrac{\text{Total energy available in fuel}}{\text{Energy generated per second}}$ = number of seconds that the fuel can power the sun

Just like: how far can I drive on a full tank of gas?

"Lifespan" of one take of gas:

$\dfrac{\text{Total amount of fuel in my gas tank (gallons)}}{\text{Gallons of fuel I use every hour}}$

= how many hours I can drive before I have to stop for more gas

Powering the Sun: Nucleosynthesis

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Lifespan of sun: $\dfrac{\text{Total energy available in fuel}}{\text{Energy generated per second}}$ = number of seconds that the fuel can power the sun

Just like: how long can my phone battery last?

Lifespan of battery charge: $\dfrac{\text{Total amount of energy stored in battery (Joules)}}{\text{Rate my phone uses energy (Joules/sec = Watts)}}$

How can I increase battery lifetime?

- Reduce rate my phone uses energy (use fewer Watts)
  turn down screen
  put in airplane mode (stop using cell antenna)

- Buy a phone with bigger battery: more storage capacity (more Joules)

Powering the Sun: Nucleosynthesis

What's the fuel? Is it a big lump of burning stuff (coal, natural gas, etc.)?

Is it coal? Burning **1 kg of coal** gives **3×10^7** Joules of energy

How long would the coal last?

Lifespan of sun: $\dfrac{\text{Total energy available in fuel}}{\text{Energy generated per second}}$

Numerator:
Total energy available in fuel: Mass of sun (in kg) × energy per kg of fuel

Mass of the sun: **2×10^{30} kg**

Total energy available in fuel if the sun were made of coal:

$$2 \times 10^{30}\ \text{kg} \times \frac{(3 \times 10^7\ \text{Joules})}{(1\ \text{kg coal})} = 6 \times 10^{37}\ \text{Joules}$$

Powering the Sun: Nucleosynthesis

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How long would the coal last?

Lifespan of sun: $\dfrac{\text{Total energy available in fuel}}{\text{Energy generated per second}}$

Denominator:
Energy generated per second = Luminosity of sun, energy output per second
(energy out has to = energy generated; it has to come from somewhere!)

4×10^{26} Joules/sec

Powering the Sun: Nucleosynthesis

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Powering the Sun: Nucleosynthesis

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Energy generated per second: Luminosity of sun = **4×10^{26} J/s**

Lifetime of sun: $\frac{6 \times 10^{37}\ \text{Joules}}{4\text{x}10^{26}\ \text{Joules/sec}} = 1.5 \times 10^{11}\ \text{sec} \times \frac{(1\ \text{year})}{(3.15 \times 10^{7}\ \text{sec})}$

= 4800 years.

Powering the Sun: Nucleosynthesis

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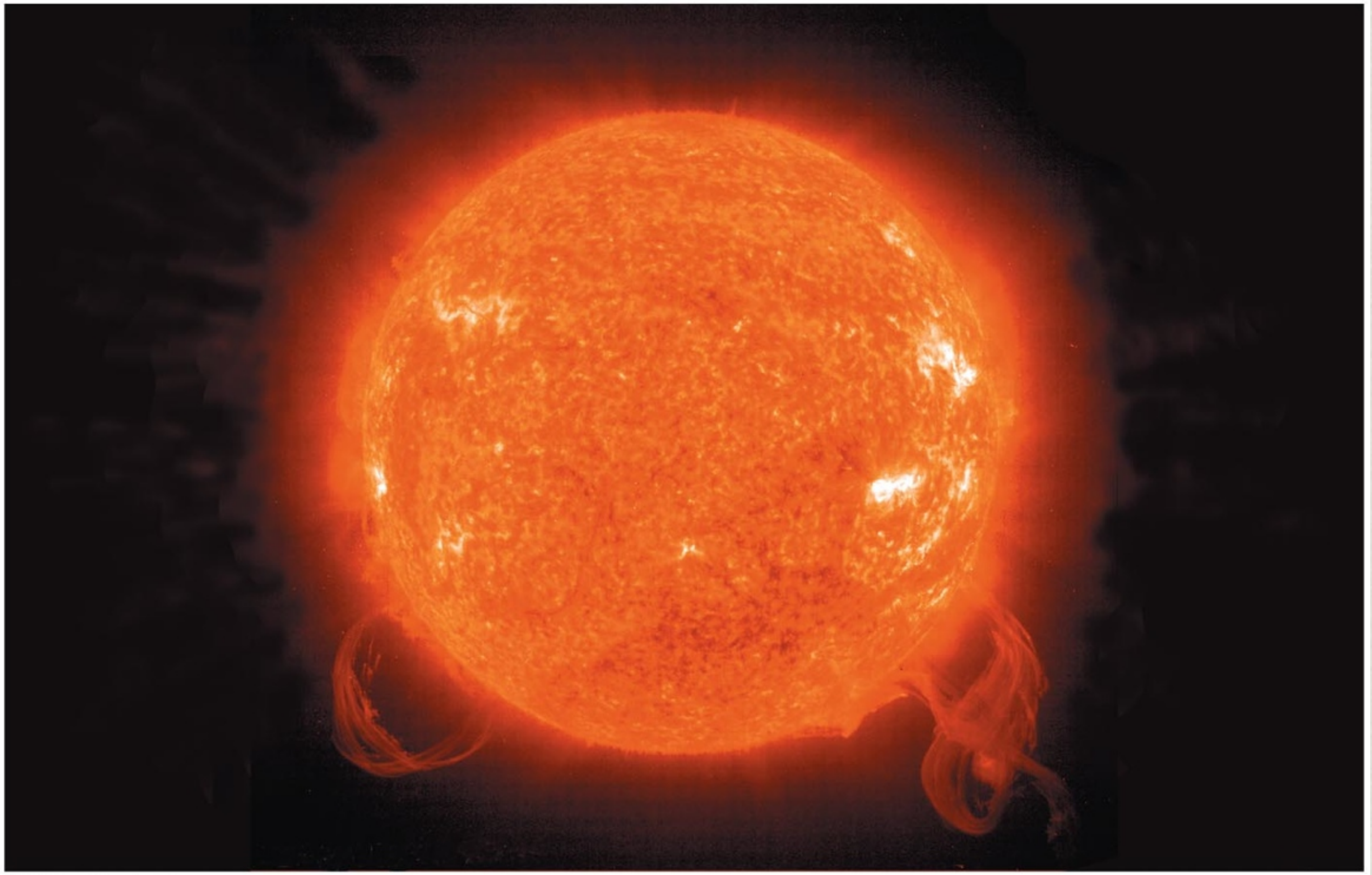
Does this make sense as a way to power the sun?

Powering the Sun: Nucleosynthesis



What powers the sun? What about gravity? Maybe the sun ***is*** still collapsing and releasing gravitational potential energy?

Powering the Sun: Nucleosynthesis

Fuel: Gravitational potential energy?

Energy released as each atom falls to the center

Total gravitational potential energy: $\frac{G M^2_{sun}}{\text{Radius of sun}}$ = **4 x 10^{41} Joules**

That's the total energy available if the fuel for the sun is gravitational potential energy

What would that mean? The sun is still in gravitational collapse

Powering the Sun: Nucleosynthesis

Fuel: Gravitational potential energy?

Energy released as each atom falls to the center

Total gravitational potential energy: $\frac{G\,M^2_{sun}}{\text{Radius of sun}}$ = **4 x 10^{41} Joules**

That's the total energy available if the fuel for the sun is gravitational potential energy

How long would this energy last?

Lifespan of sun: $\frac{\text{Total energy available in fuel}}{\text{Energy generated per second}}$

Energy generated per second: Luminosity of sun = **4 x 10^{26} J/s**

Does this make sense as a way to power the sun?

Polling question: approximately how long will this power the sun?

A) 10^6 seconds C) 10^{12} seconds

B) 10^9 seconds D) 10^{15} seconds

Powering the Sun: Nucleosynthesis

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Lifetime of sun: $\frac{\mathbf{4 \times 10^{41}\ Joules}}{\mathbf{4 \times 10^{26}\ Joules/sec}}$ = 1.0×10^{15} sec x $\frac{(1\ \text{year})}{(3.15 \times 10^{7}\ \text{sec})}$

= 3×10^{7} years, 30 million years.

Better, but we have evidence that the earth existed with sun-powered life a lot longer than that.

Powering the Sun: Nucleosynthesis

What the sun has is a lot of Hydrogen.

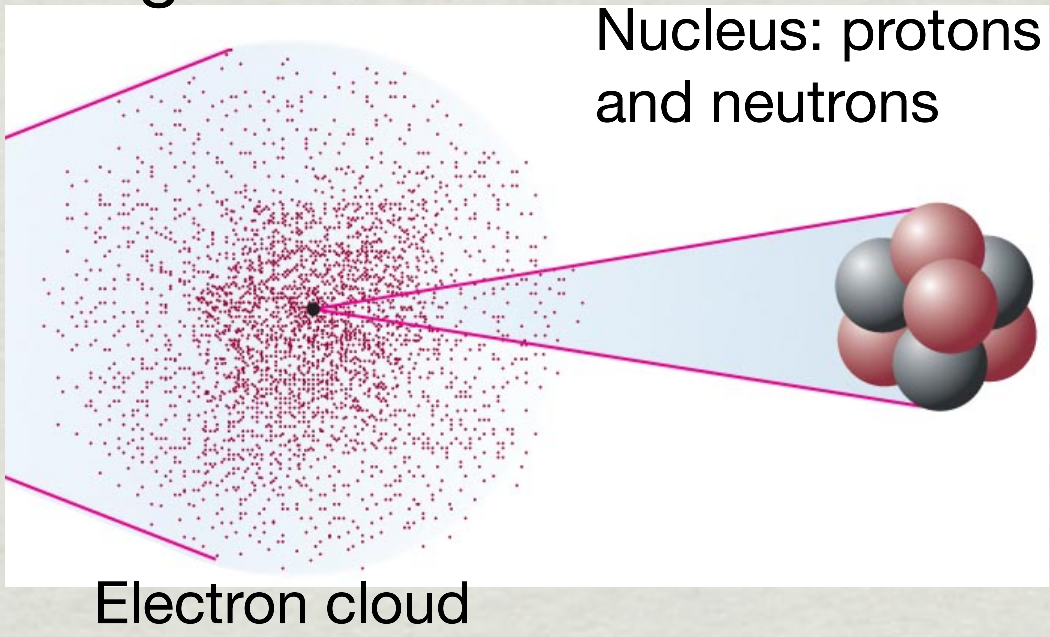
How do you make energy out of 2 x 10^{30} kg of Hydrogen?

We need to solve two puzzles:

Puzzle #1: What holds the nucleus of an atom together?

Is it the Electromagnetic force?

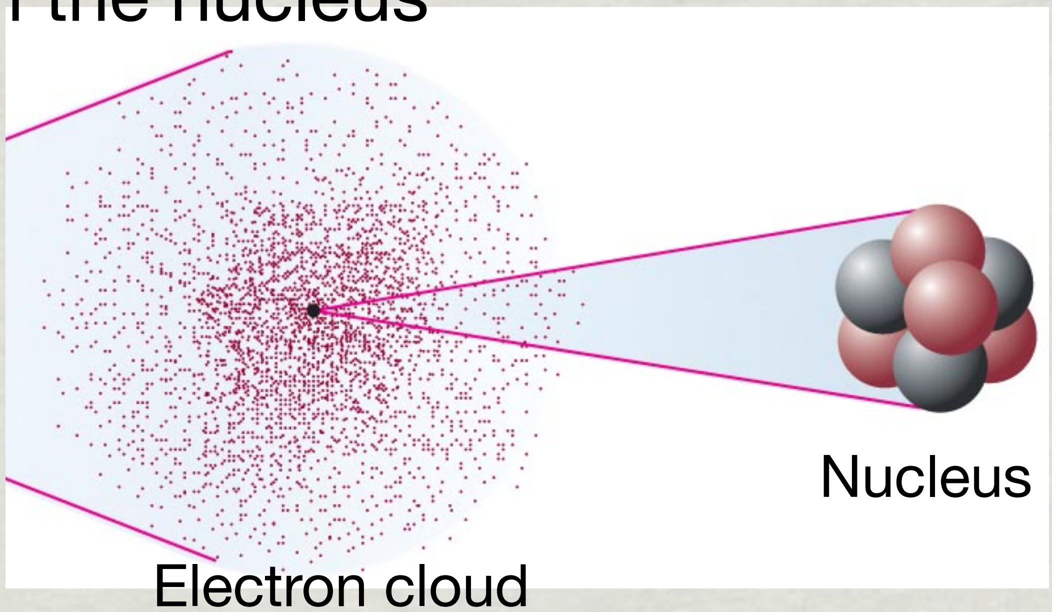
$$F_{EM} = \frac{K\, q_1\, q_2}{r^2}$$



Remember from Lecture 6:

Atoms are made of protons, neutrons and electrons

The protons and neutrons are concentrated in the nucleus



Protons and electrons have charge:

- Proton +1
- Electron -1
- Neutron 0 (no charge)

Atoms are neutral: equal numbers of protons and electrons

Electromagnetic Force: $F_{EM} = \frac{K q_1 q_2}{r^2}$

- q = charge
- r = distance between the particles
- K = a number

(You don't need to know this formula, but notice it is a lot like the formula for gravitational force)

- ✤ Opposite charges (proton-electron) attract
- ✤ Two particles with the same charge repel each other: proton-proton or electron-electron push each other apart
- \- Different from Gravity. Gravity always attracts

Powering the Sun: Nucleosynthesis

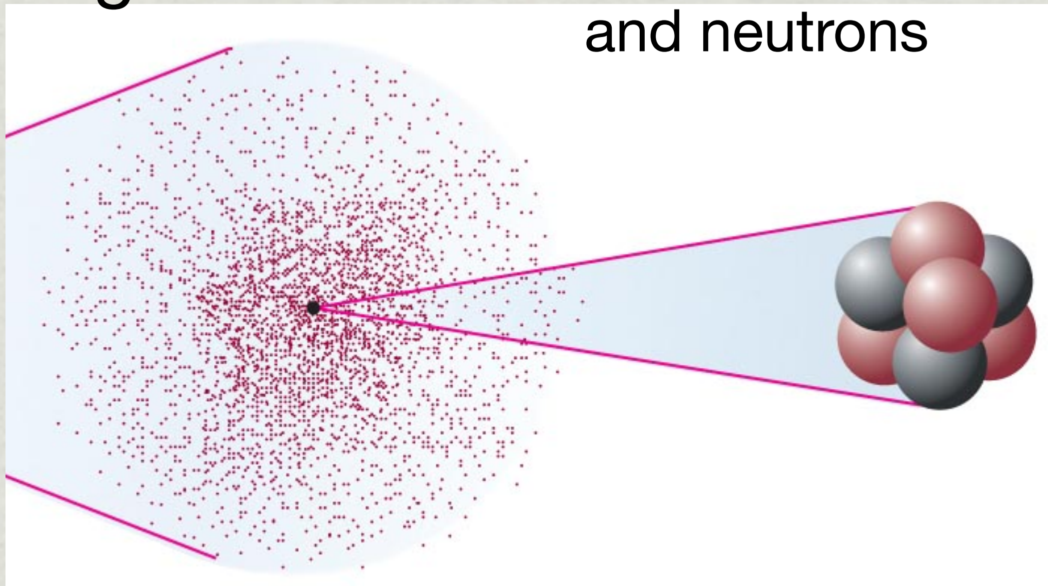
How do you make energy out of 2 x 10^{30} kg of Hydrogen?

Puzzle #1: What holds the nucleus of an atom together?

Is it the Electromagnetic force?

$$F_{EM} = \frac{K\, q_1\, q_2}{r^2}$$

No: particles with same charge repel, and a nucleus contains particles with only positive or zero charge



It's the strong nuclear force:

Works like velcro.

Really strong, way stronger than the electromagnetic force

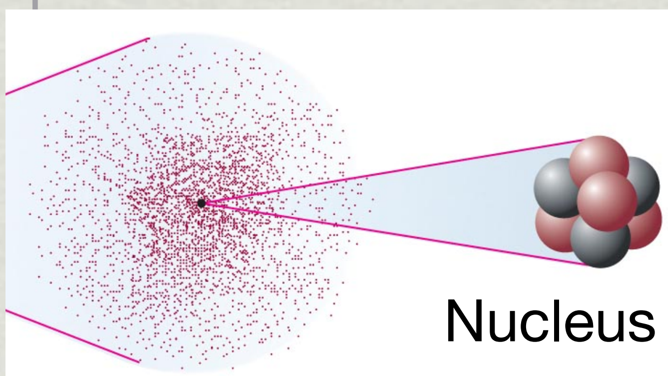
But works ***only*** at very close range.

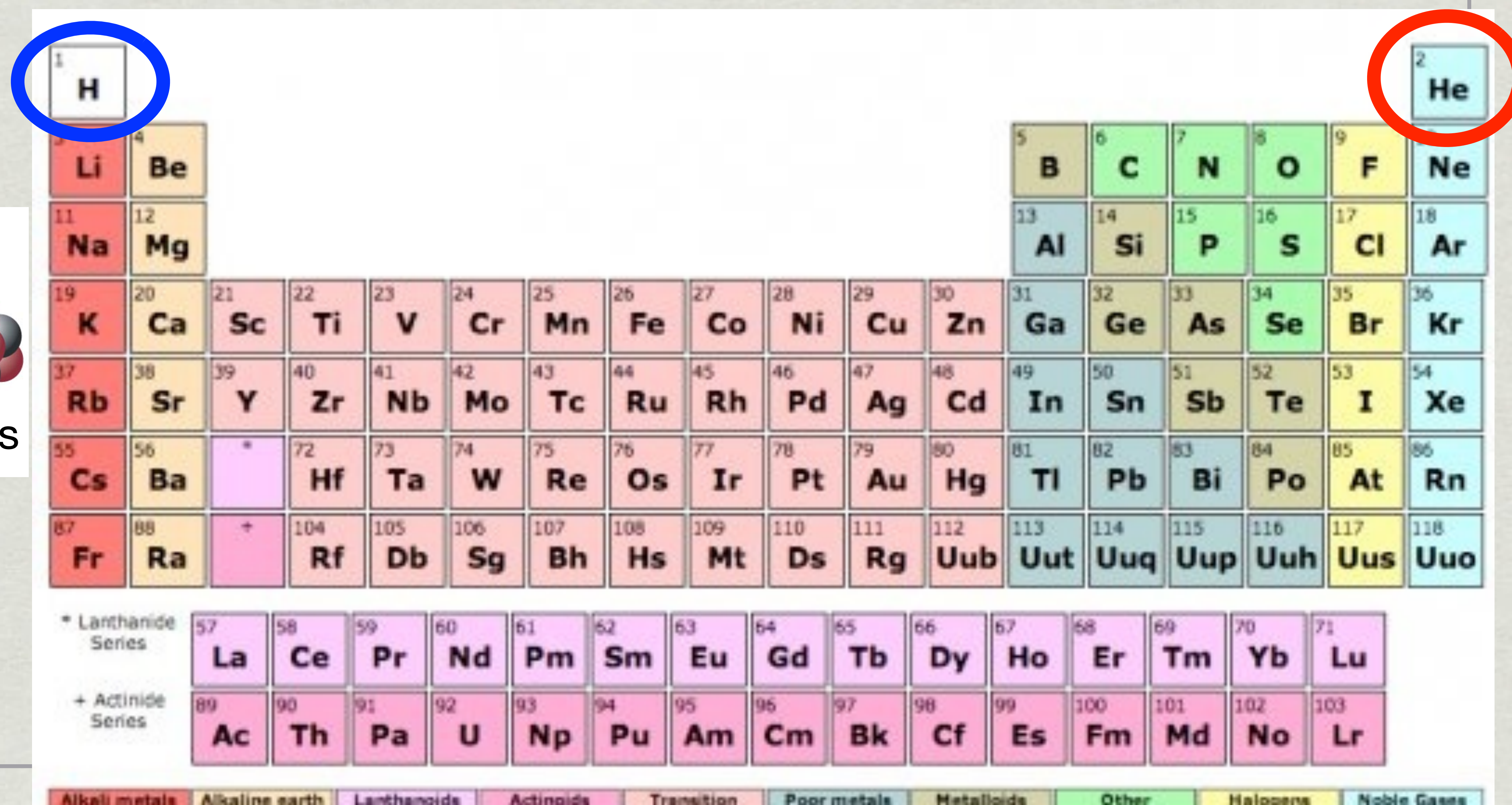
Powering the Sun: Nucleosynthesis

How do you make energy out of 2 x 10^{30} kg of Hydrogen?

Puzzle #2: Why is a Helium atom ***less*** massive than 4 Hydrogen atoms?

Electron cloud



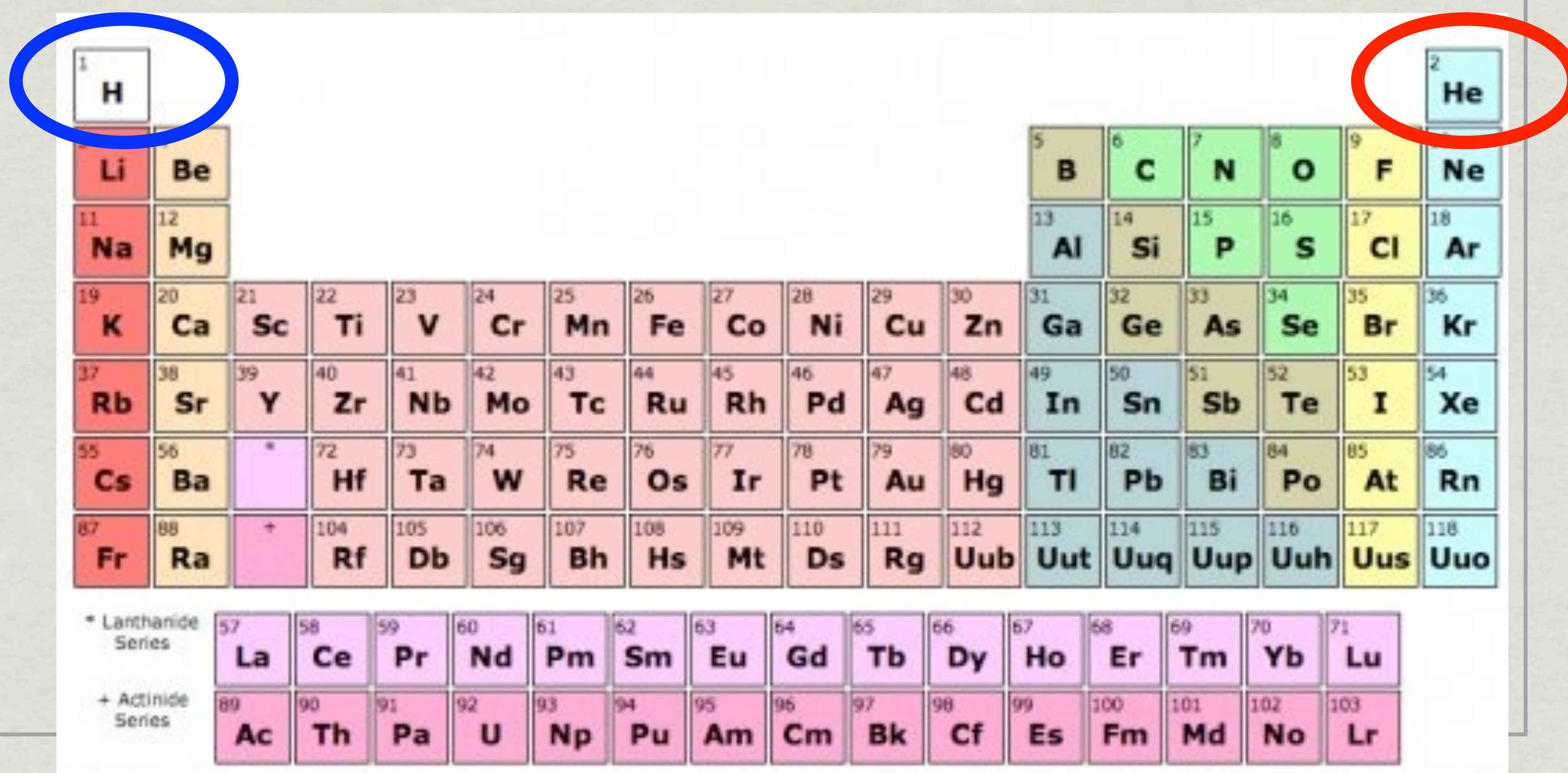


Powering the Sun: Nucleosynthesis

How do you make energy out of 2 x 10^{30} kg of Hydrogen?

Puzzle #2: Why is a Helium atom ***less*** massive than 4 Hydrogen atoms?

4 H atoms = 4 protons: 6.693 x 10^{-27} kg
1 He atom = 2 protons + 2 neutrons: 6.645 x 10^{-27} kg (less massive! by 0.7%)



Powering the Sun: Nucleosynthesis

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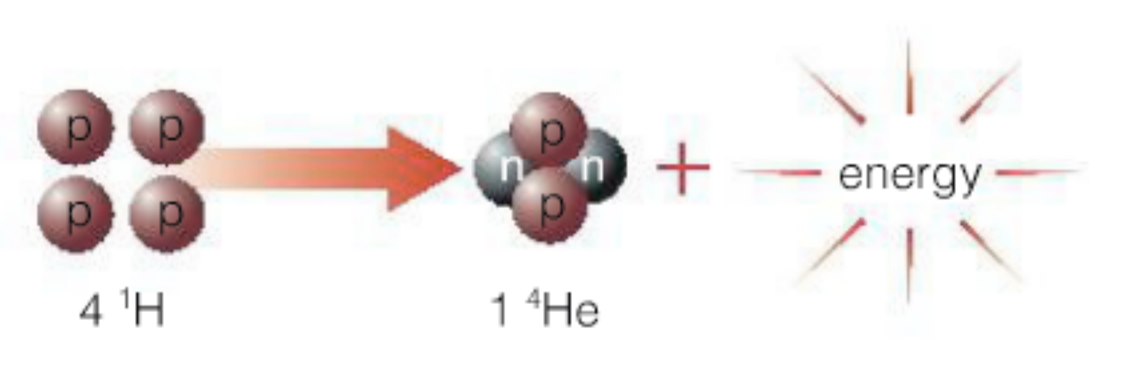
If you stick together Hydrogen atoms to make Helium, the extra mass has to go somewhere.

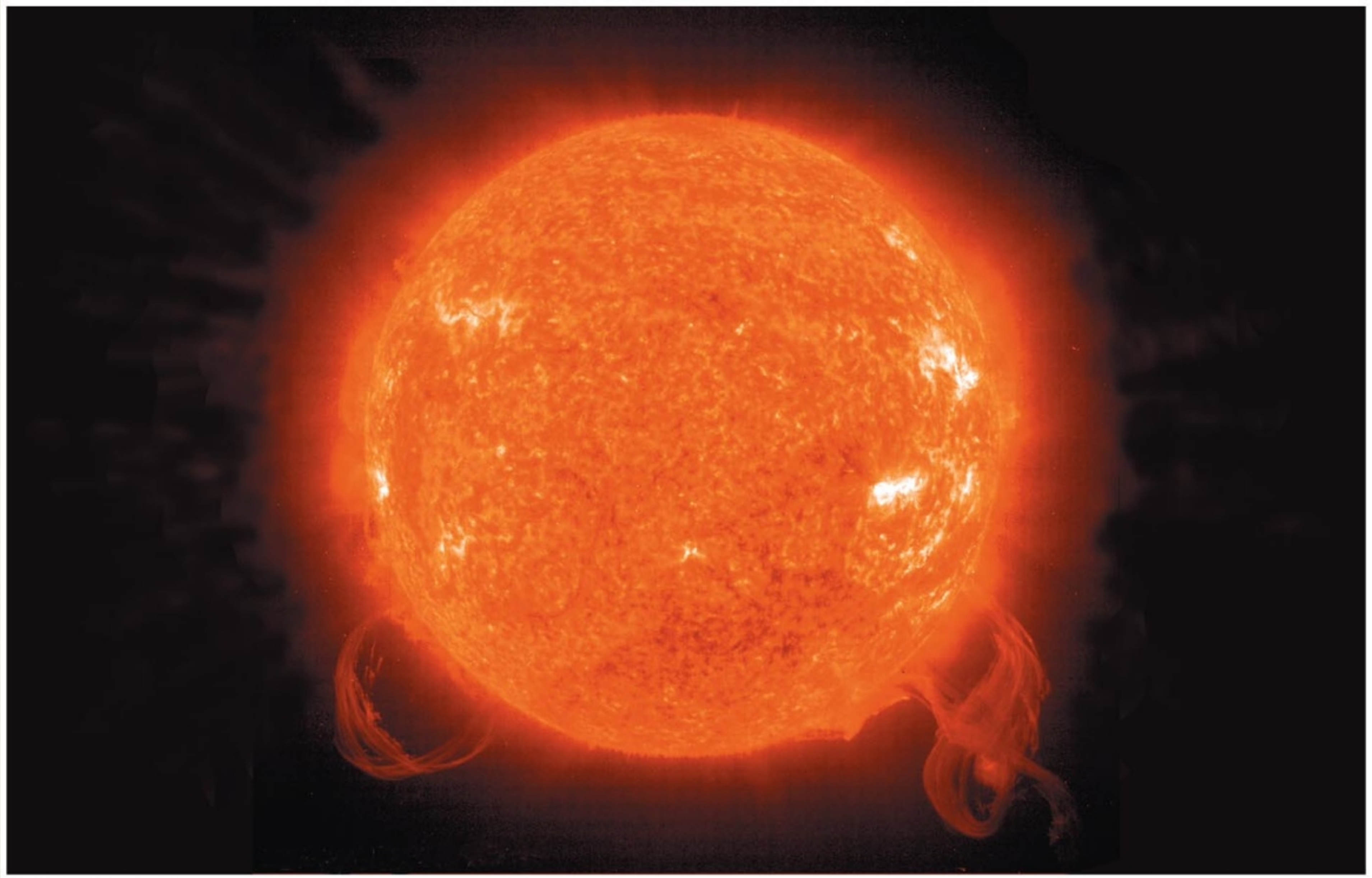


It becomes energy: **$E = mc^2$**

Mass and energy are the same thing, and transform back and forth using this equation.

Fusing Hydrogen into Helium must release energy

Powering the Sun: Nucleosynthesis



What powers the sun? Nuclear fusion!

Powering the Sun: Nucleosynthesis

Energy released per 1 kg of Hydrogen fused into Heluim:
0.7% of the Hydrogen mass is released: **$0.007 * M_{Hydrogen}$**

$E = mc^2 =$ **0.007×1 kg** $\times (3 \times 10^8 \text{ m/s})^2$
$=$ **6.3×10^{14} Joules for 1 kg** Hydrogen → Helium

Total energy available in fuel: Mass of sun (kg) × energy per kg of fuel

Mass of the sun: **2×10^{30} kg**

Total energy available: M_{sun} x (Energy/kg) = **2×10^{30} kg** x **6.3×10^{14} Joules/kg**
$=$ **1.3×10^{45} Joules**

Powering the Sun: Nucleosynthesis

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= **1.3×10^{45} Joules**

Lifespan of sun: $\dfrac{\text{Total energy available in fuel}}{\text{Energy generated per second}}$

Energy generated per second: **Luminosity of sun**, energy output per second
= **4×10^{26} Joules/sec**

Powering the Sun: Nucleosynthesis

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Energy generated per second: **Luminosity of sun**, energy output per second

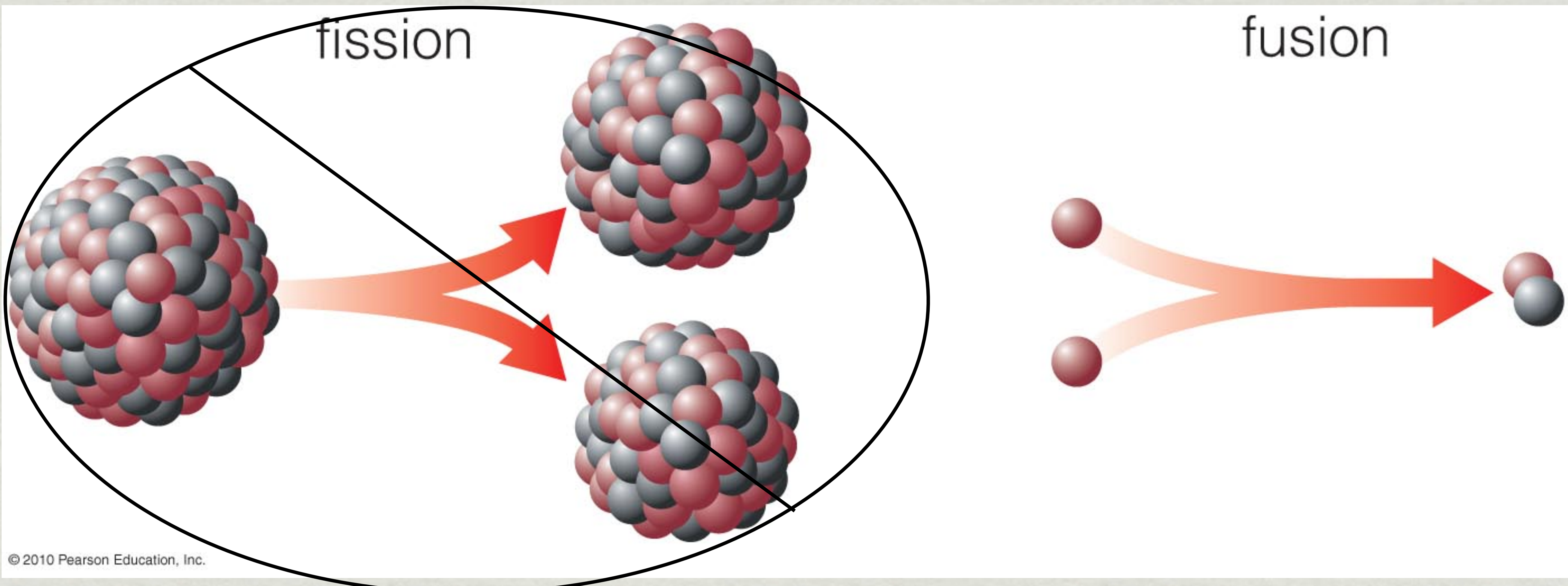
Lifetime of sun: $\dfrac{1.3 \times 10^{45} \text{ Joules}}{4 \times 10^{26} \text{ Joules/sec}} = 3.25 \times 10^{18} \text{ sec} \times \dfrac{(1 \text{ year})}{(3.15 \times 10^7 \text{ sec})}$

$= 1.0 \times 10^{11}$ years. That's 100 billion years. The Universe is "only" 13.7 billion years old. That will do it!

Powering the Sun: Nucleosynthesis

The sun is powered by nuclear ***fusion***

nucleosynthesis: make nuclei



Big nuclei split to make smaller ones, release energy.
This is how nuclear power plants work.

Small nuclei stick together to make bigger ones, release energy.
This is how the sun works.

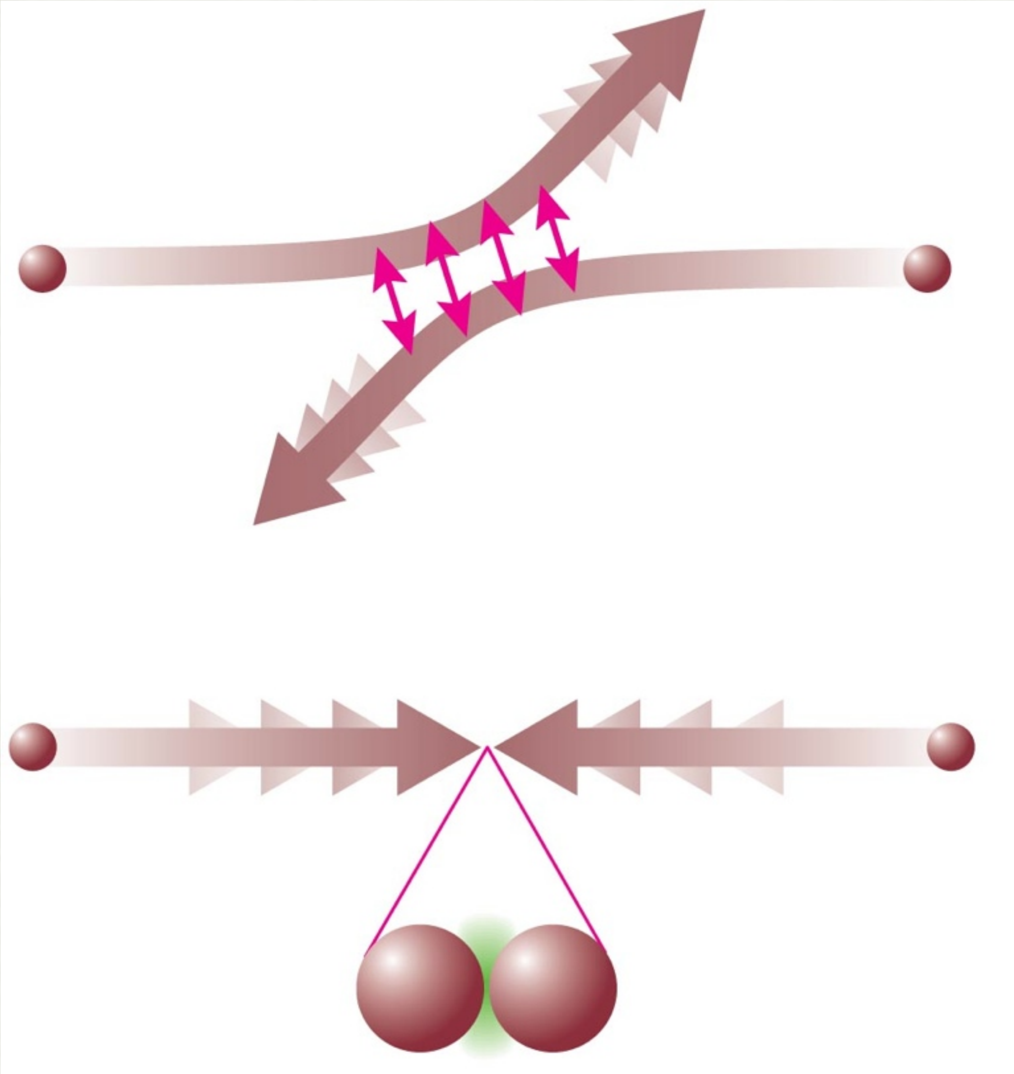
Coming up: energy released by splitting big nuclei or fusing small nuclei. Where is the switch between small and big? Iron!

Powering the Sun: Nucleosynthesis

Fusion works at high pressure: high temperature and density.

At low pressure (low temperature and density):
Electromagnetic force takes over → repulsion

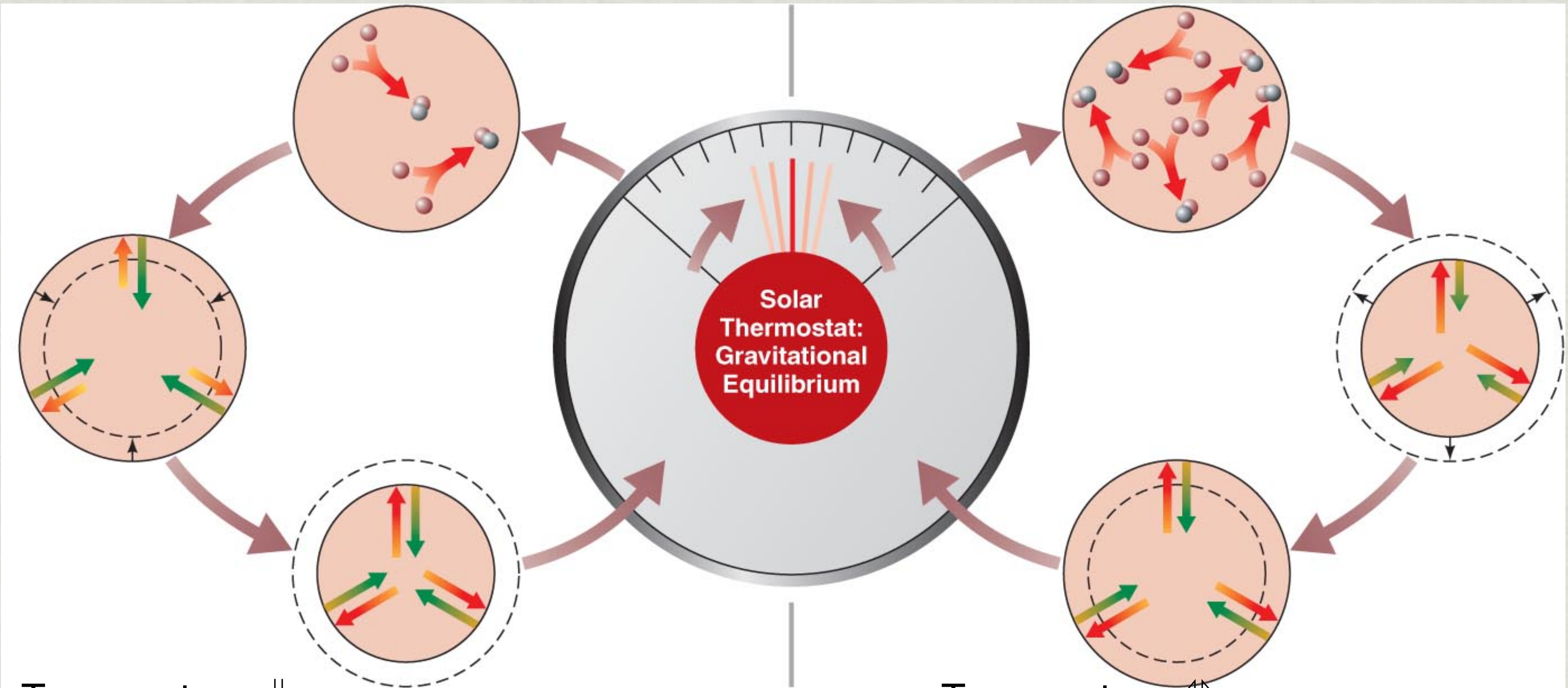
At high pressure (high speeds and density): particles get close enough together for the “velcro” effect of the strong nuclear force to win. Particles with same change can stick together → fusion



Gravitational Equilibrium in the Sun

Gravitational equilibrium:

allows sun to regulate it's temperature and pressure, a kind of "solar thermostat"

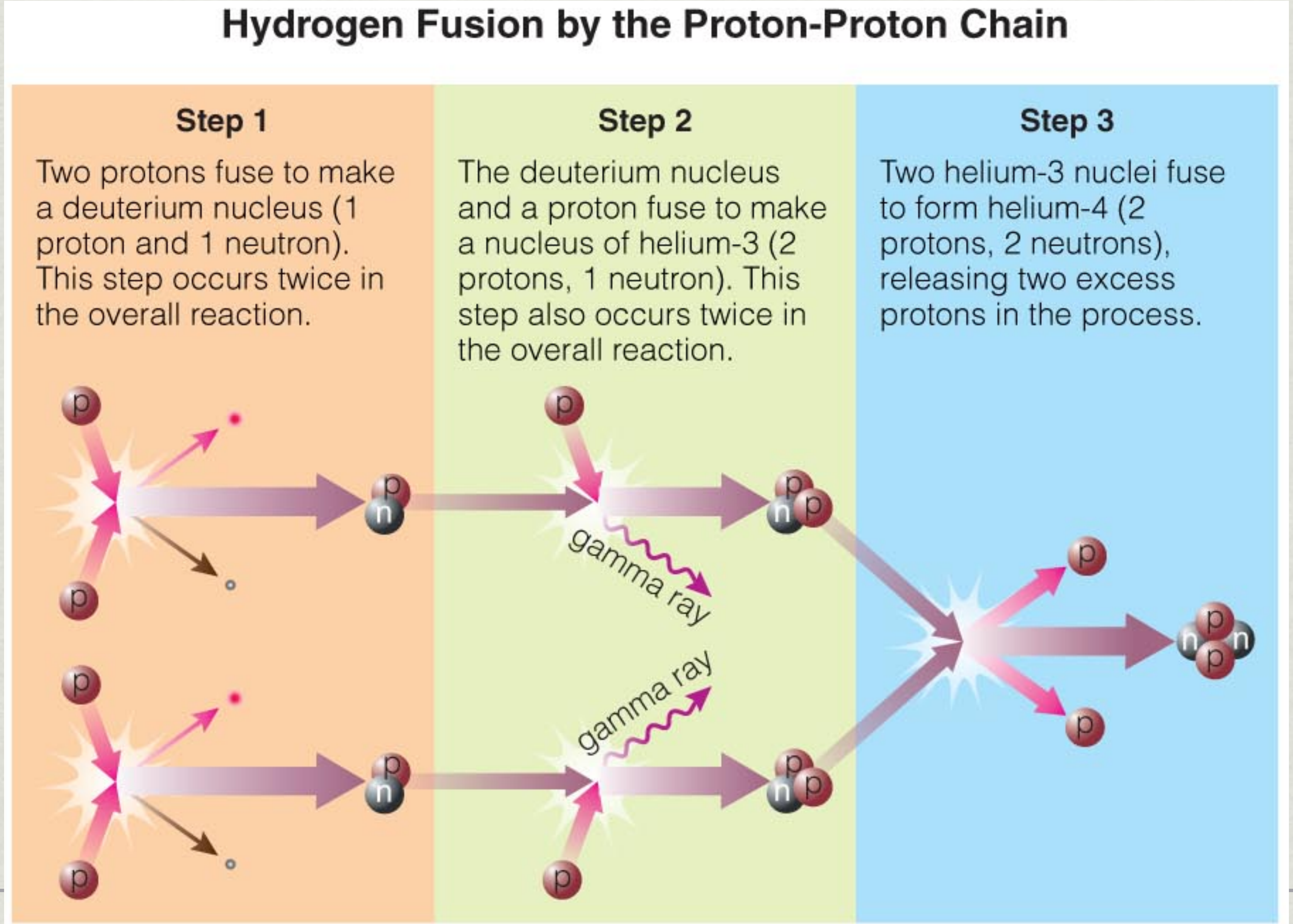


Temperature ⇓
Pressure ⇓
Core contracts to increase rate of energy generation from nuclear fusion

Temperature ⇑
Pressure ⇑
Core expands, reduces rate of nuclear energy generation, cools down

Powering the Sun: Nucleosynthesis

The Hydrogen-to-Helium fusion process is called: the Proton-Proton Chain



Powering the Sun: Nucleosynthesis

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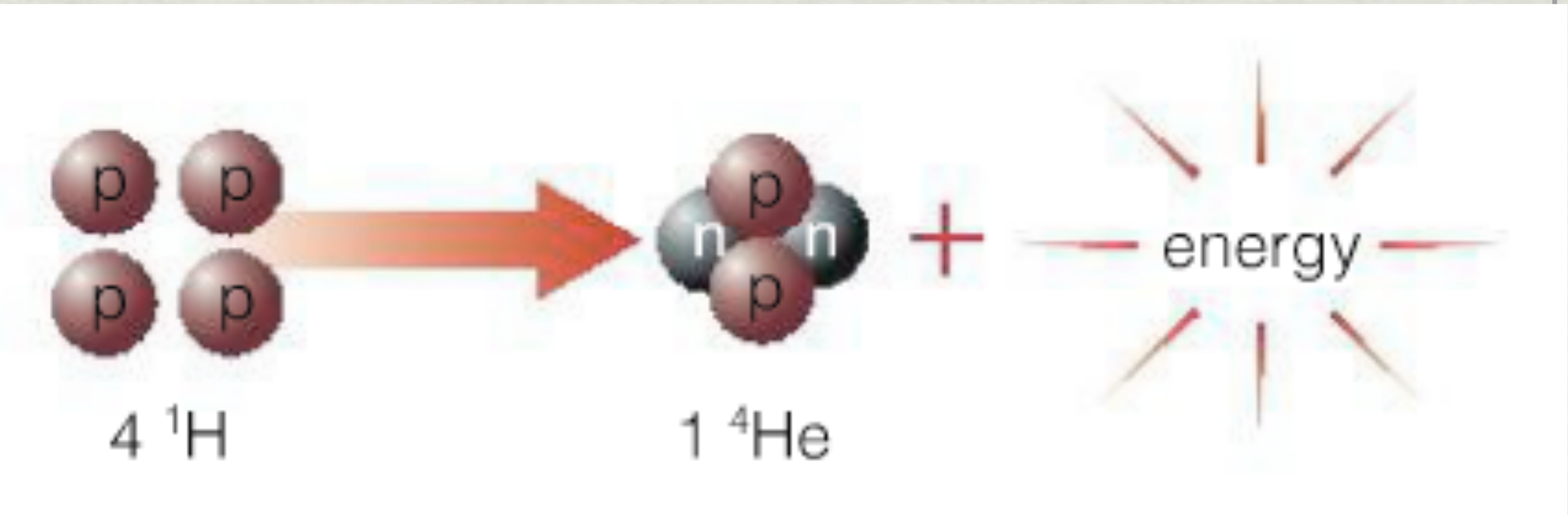

In: 4 protons

Out: 1 ^4He nucleus
2 gamma rays (photons)
2 neutrinos (particles with no charge, lots of energy)
2 positrons (like electrons, but positive charge)

Total mass (He nucleus + positrons + neutrinos) is 0.7% lower