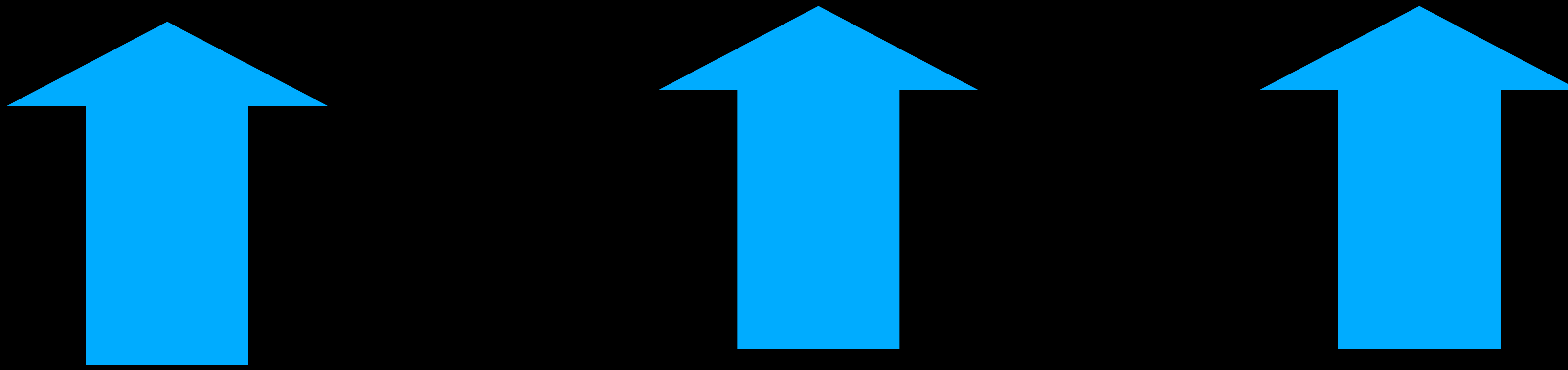
Astr 102

Lec 7: Classification of Stars, the Sun

- What prevents stars from collapsing under the weight of their own gravity?
- Why is the center of the Sun hot?
- What is the source of the Sun's energy?
- What are neutrinos & why do we care
- How does energy get from the inside to the outside of a star?

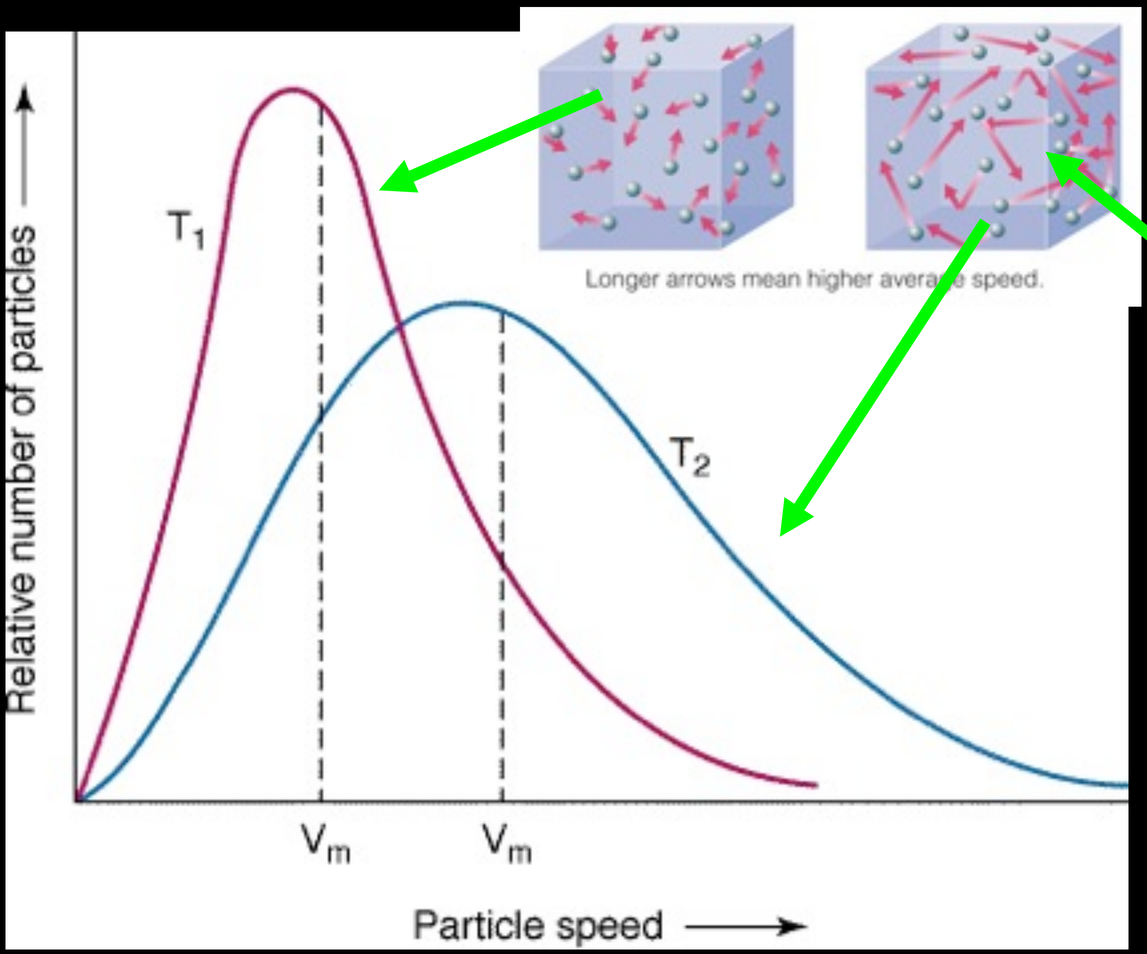
In general, for normal gases, if one increases, the others increase as well.

Pressure **Temperature** **Density**



Increasing the pressure increases the **DENSITY** of the gas.

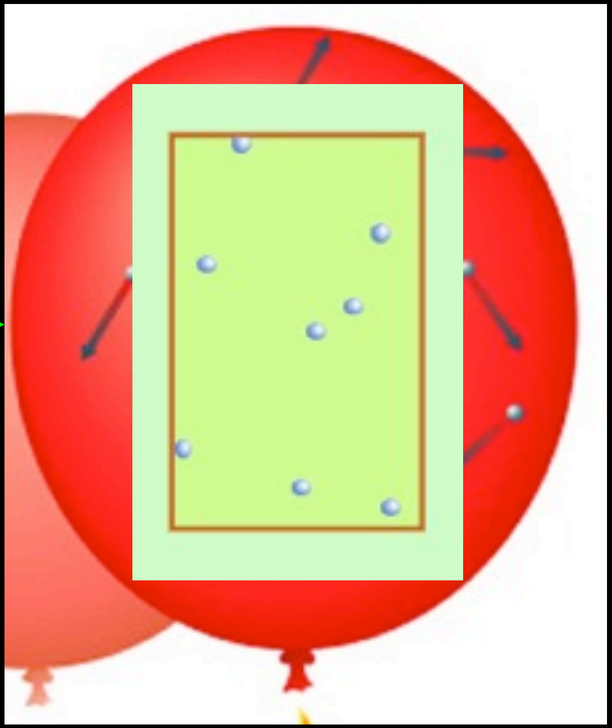
Temperature is also closely related to pressure.



Hits harder, more often!

Boltzmann distribution of particle speeds

A balloon dipped in liquid

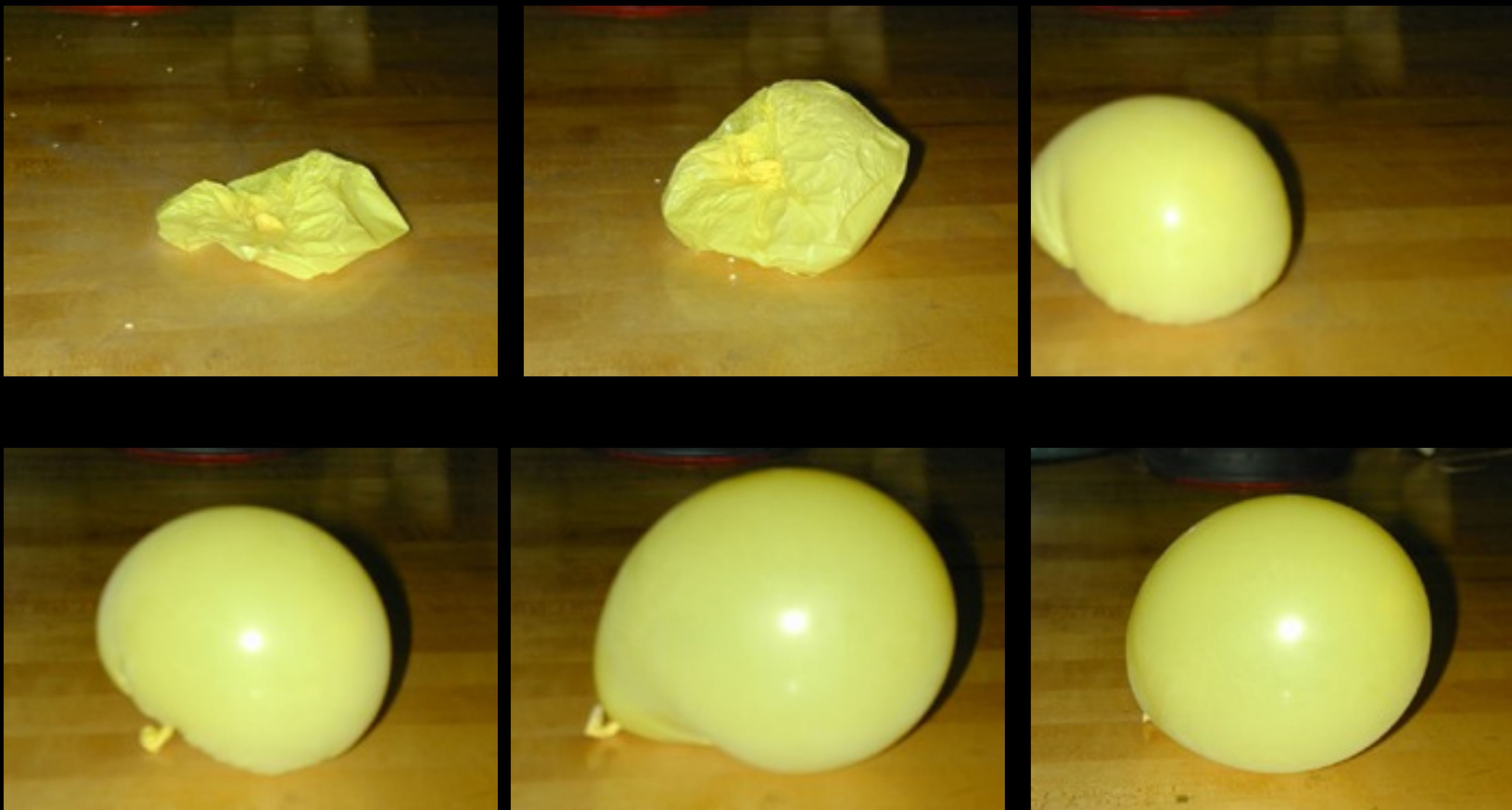


What happens?

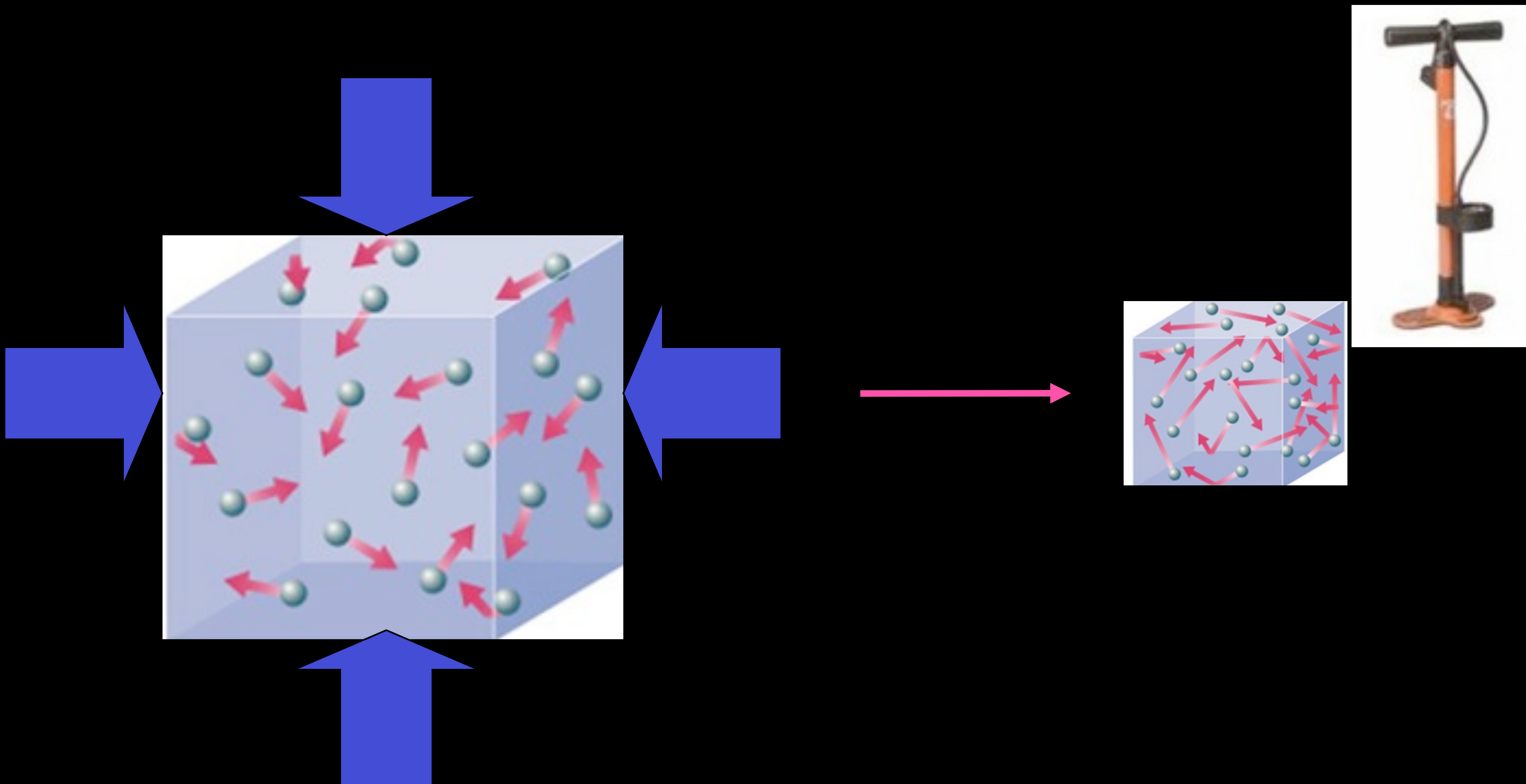
Blue: Nothing
Purple: Balloon shrinks
Green: Balloon expands

A balloon dipped in liquid

A previously frozen balloon,

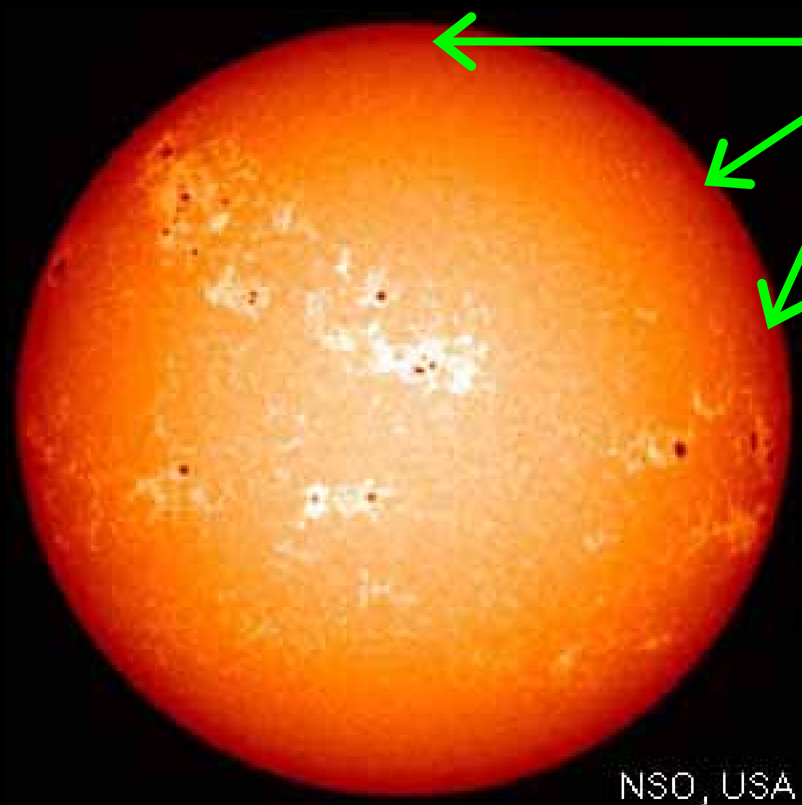


Even Density is related to Temperature:



If you squeeze something, you are pushing the particles within it, which speeds them up

What about temperatures, pressures, & densities in the Sun?

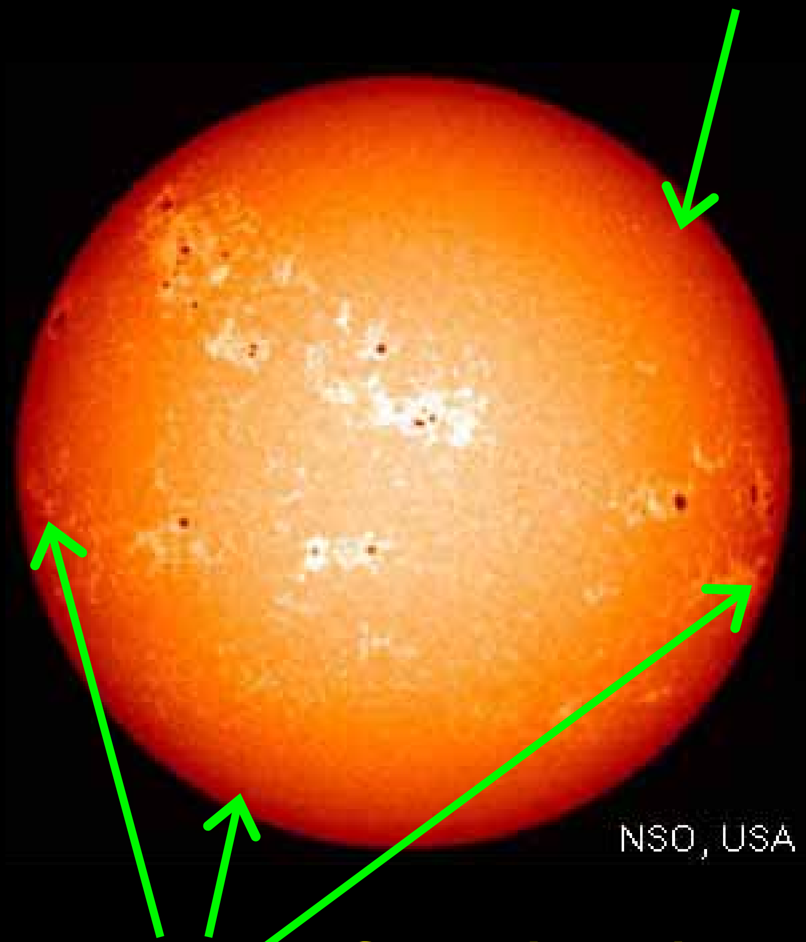


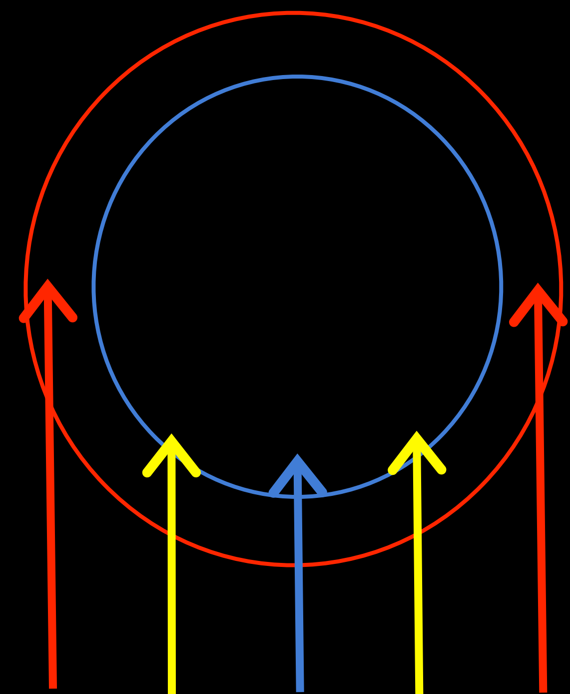
Why are the outer edges darker?

A. (yellow) Lower density
B. (blue) Lower temp
C. (green) Less Hydrogen
D. (pink) I have no idea

Hint: Most of the Sun's light is thermal radiation

"Limb darkening": Outer layers are cooler





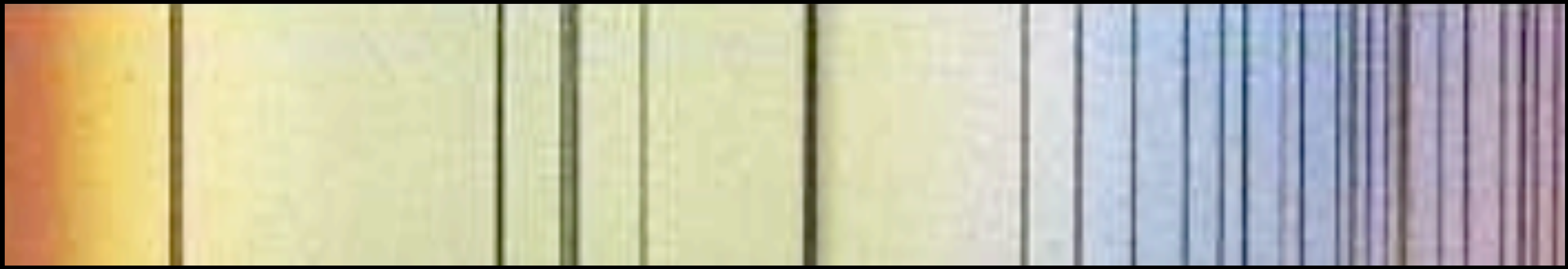
Sees into hotter inner layers

Sees only cooler outer layers

Lower surface brightness=Cooler

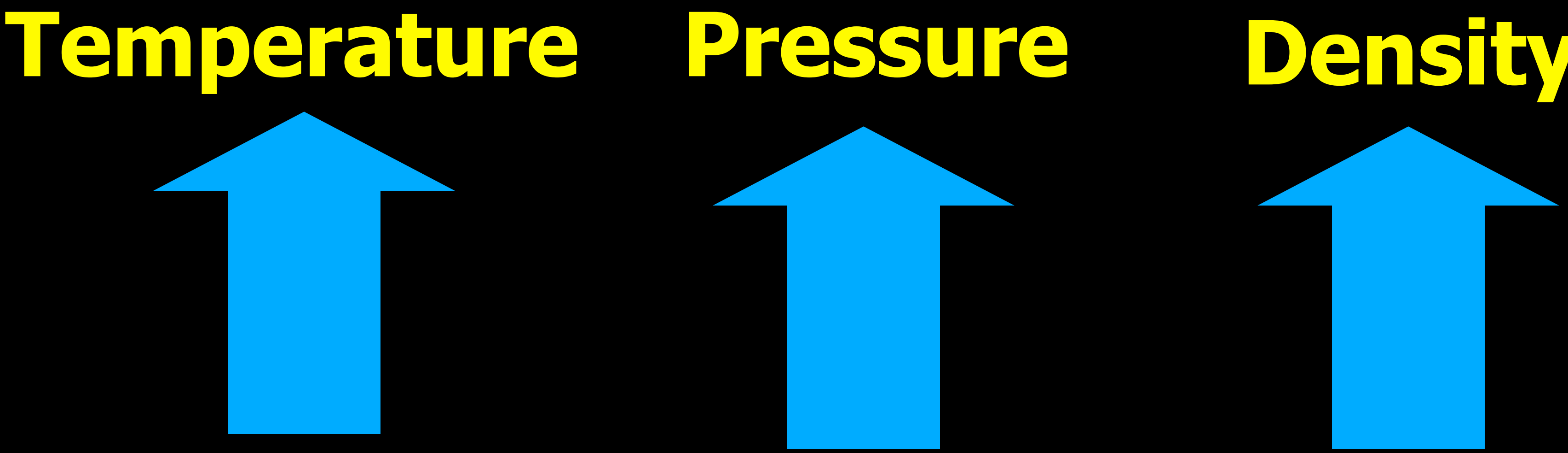
Absorption lines also suggest the outer regions are cooler

Absorption lines = cool gas on surface



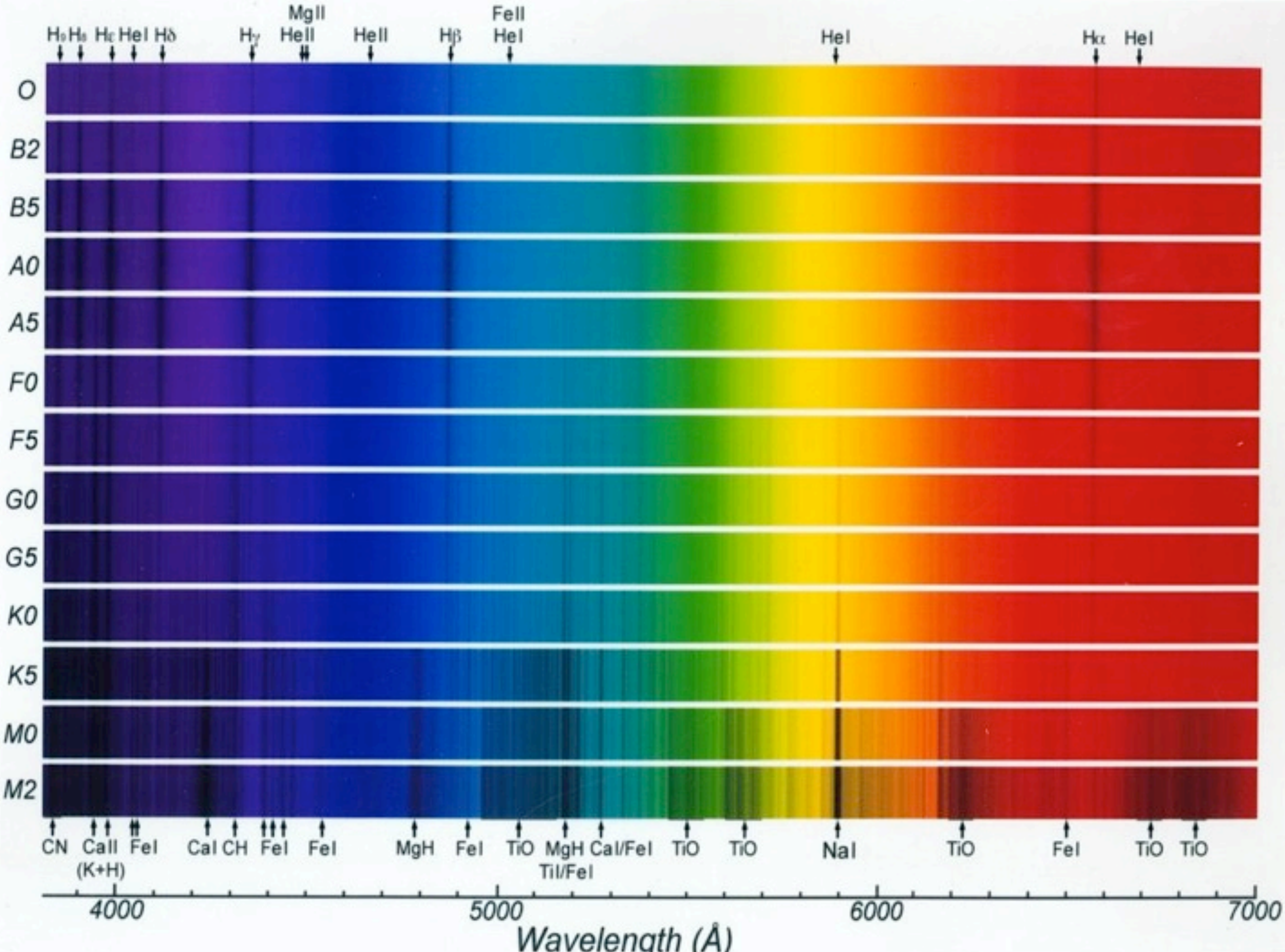
"Temperature Gradient"

(Energy source is probably in the center)



For the Sun:

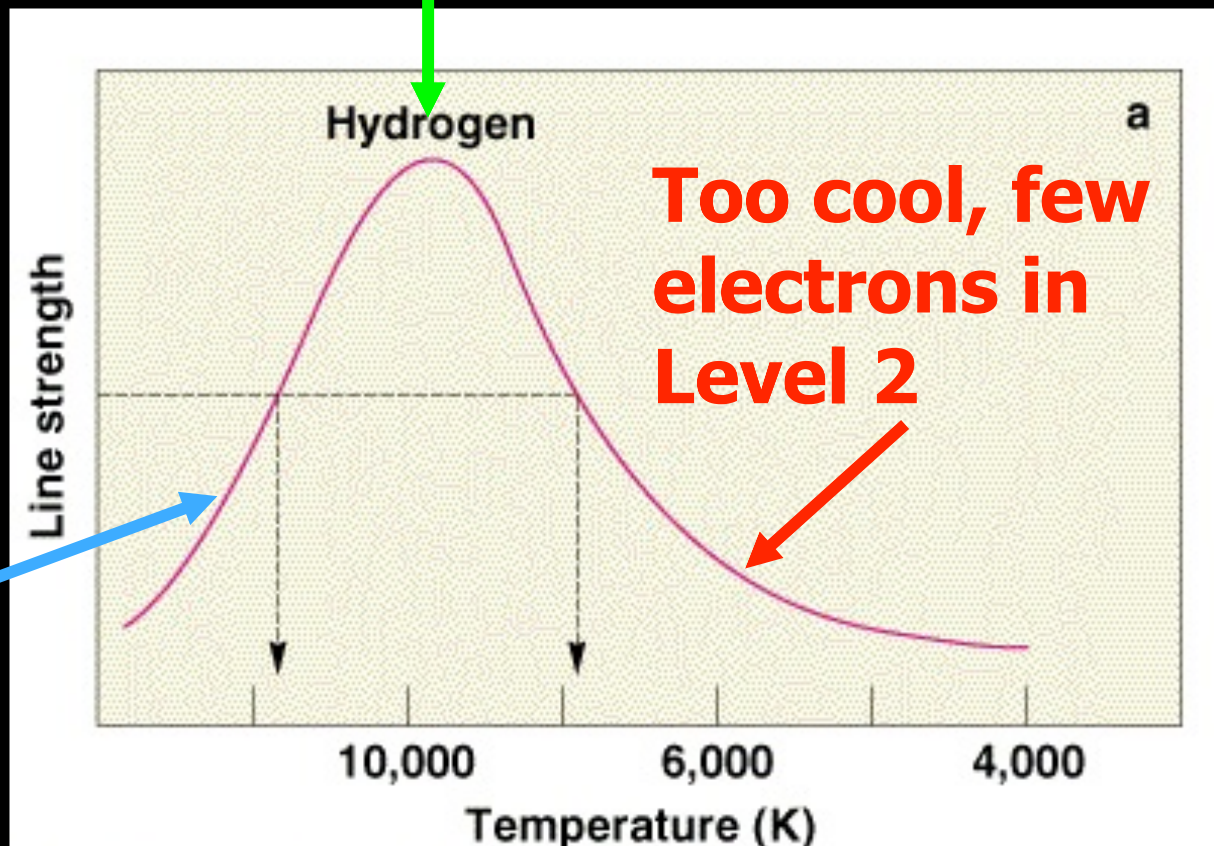
- Temperature increases inwards, so…
  - Density must increase inwards!
  - Pressure must increase inwards!



Hη Hζ Hε HeI Hδ
Hγ
MgII HeII
HeII
Hβ
FeII HeI
HeI
Hα
HeI
O
B2
B5
A0
A5
F0
F5
G0
G5
K0
K5
M0
M2
CN
CaII (K+H)
FeI
CaI
CH
FeI
FeI
MgH
FeI
TiO
MgH TiI/FeI
CaI/FeI
TiO
TiO
NaI
TiO
FeI
TiO
TiO
4000
5000
6000
7000
Wavelength (Å)

"Line Strength" depends upon

Line is Strongest at this Temperature



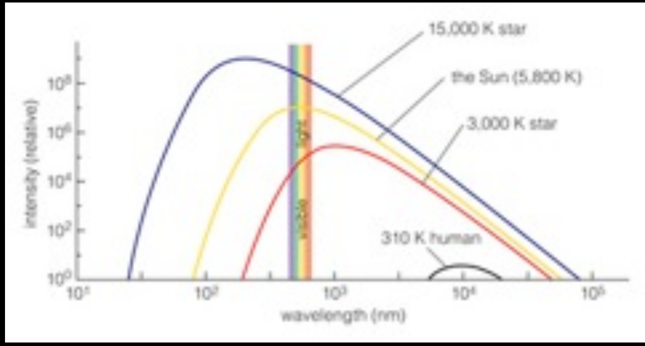
Too cool, few electrons in Level 2

Too hot, few bound electrons

When the temperature of a star varies:

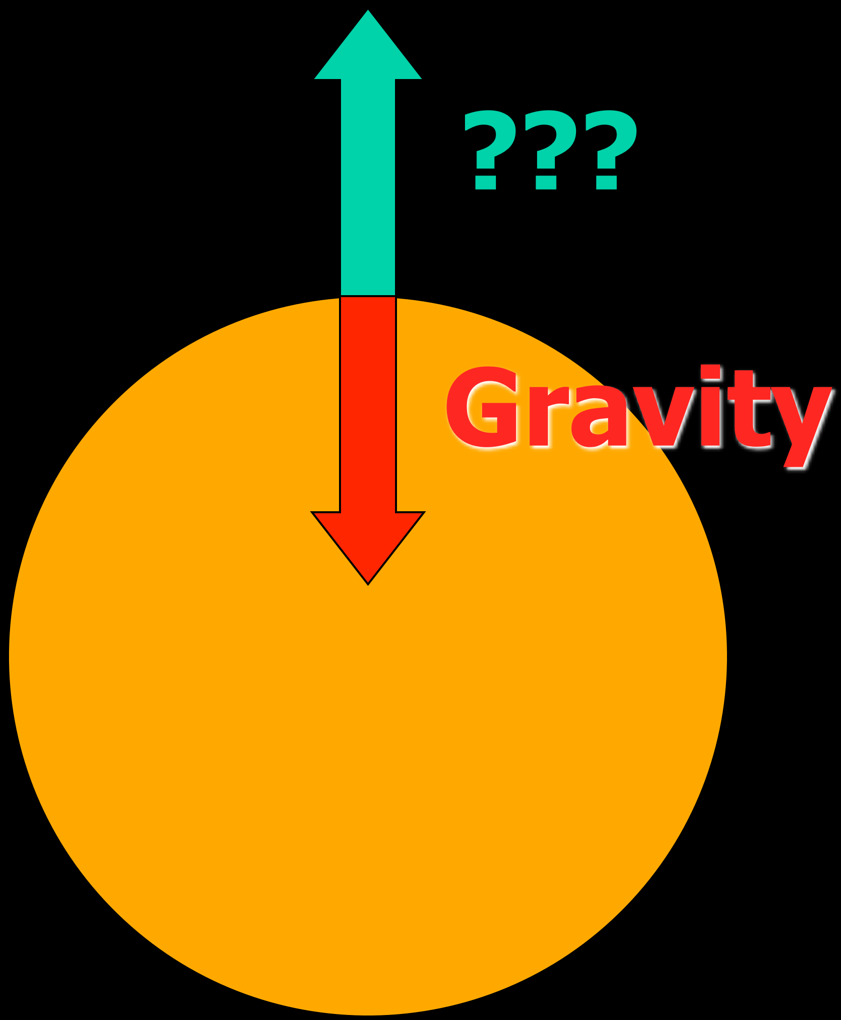
SPECTRAL CLASS	APPROX TEMP (K)	HYDROGEN BALMER LINES	OTHER SPECTRAL FEATURES	NAKED-EYE EXAMPLE
O	40,000	Weak	Ionized helium	Meissa (O8)
B	20,000	Medium	Neutral helium	Achernar (B3)
A	10,000	Strong	Ionized calc weak	Sirius (A1)
F	7,500	Medium	Ionized calc weak	Canopus (F0)
G	5,500	Weak	Ionized calc med	Sun (G2)
K	4,500	Very weak	Ionized calc strong	Arcturus (K2)
M	3,000	Very weak	TiO strong	Betelgeuse (M2)

- "Spectral Type" (OBAFGKM) varies
- Color varies
- Surface brightness varies



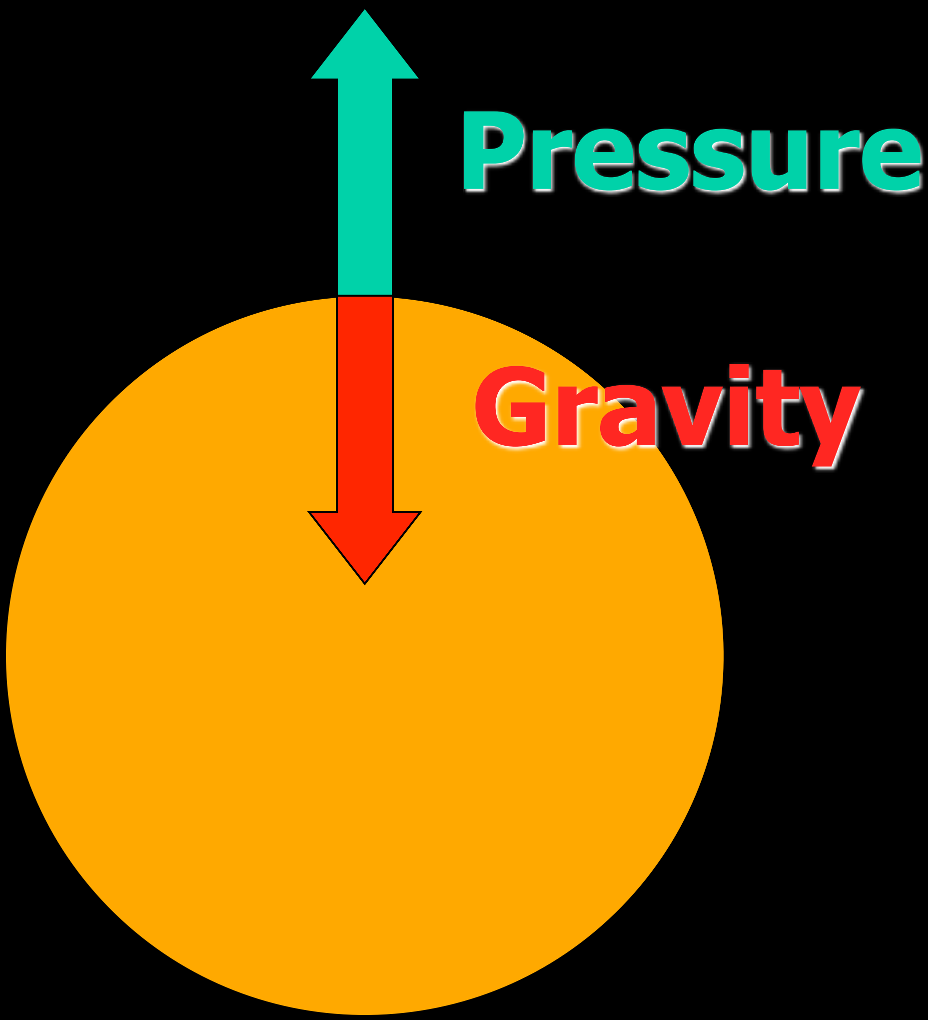
$$\Sigma \propto T^4$$

Why doesn’t the Sun collapse?

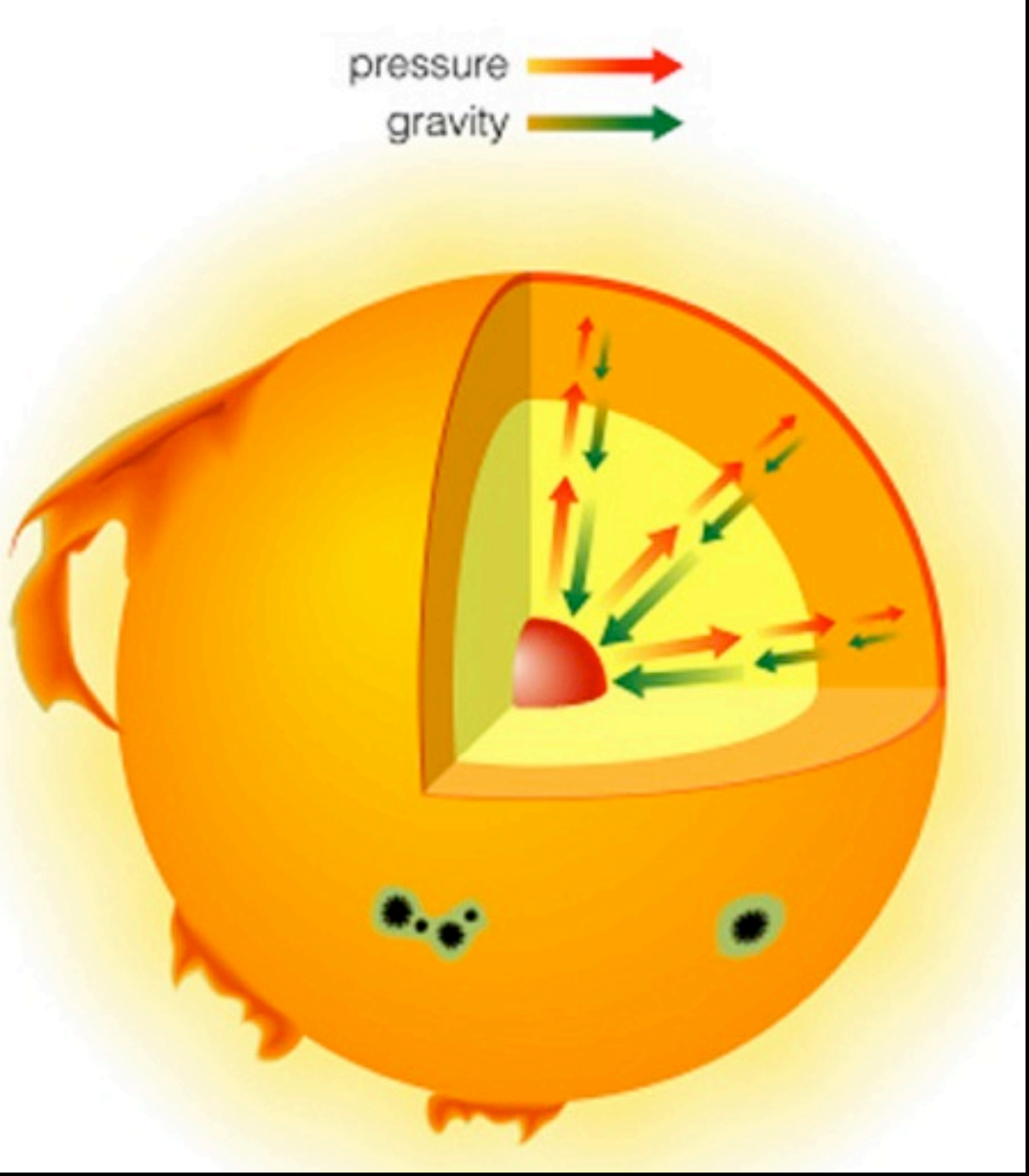


The pressure of the gas layers below.

Gas Pressure keeps the Sun



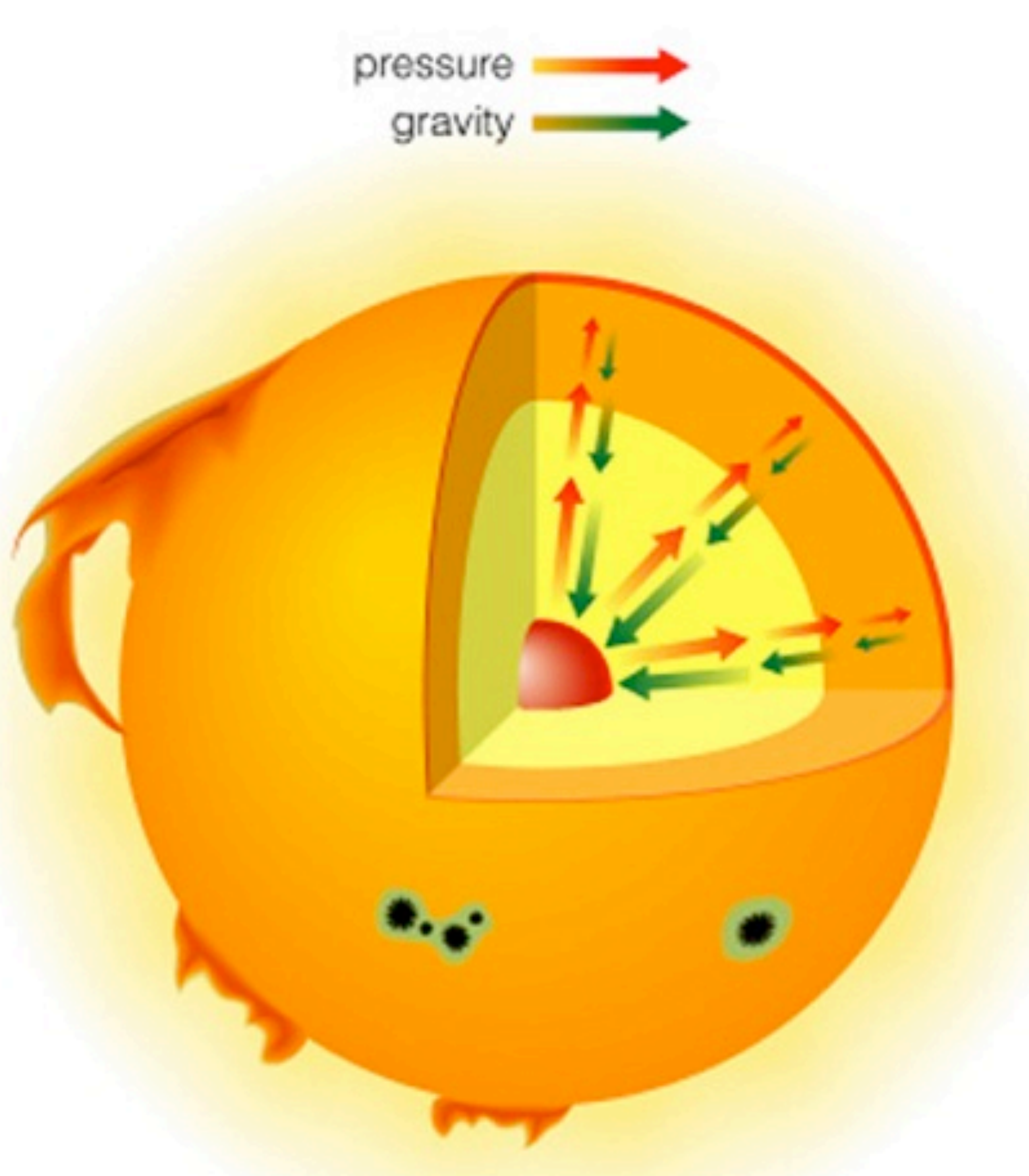
This applies to <u>all</u> layers of the Sun.



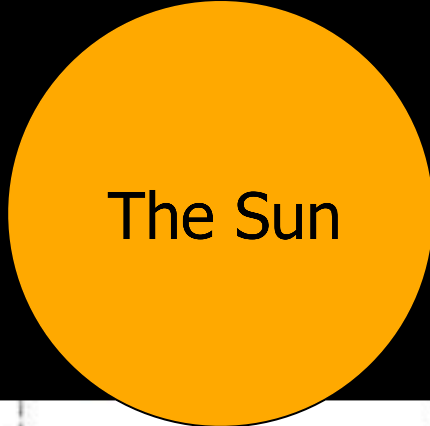
“Hydrostatic Equilibrium”

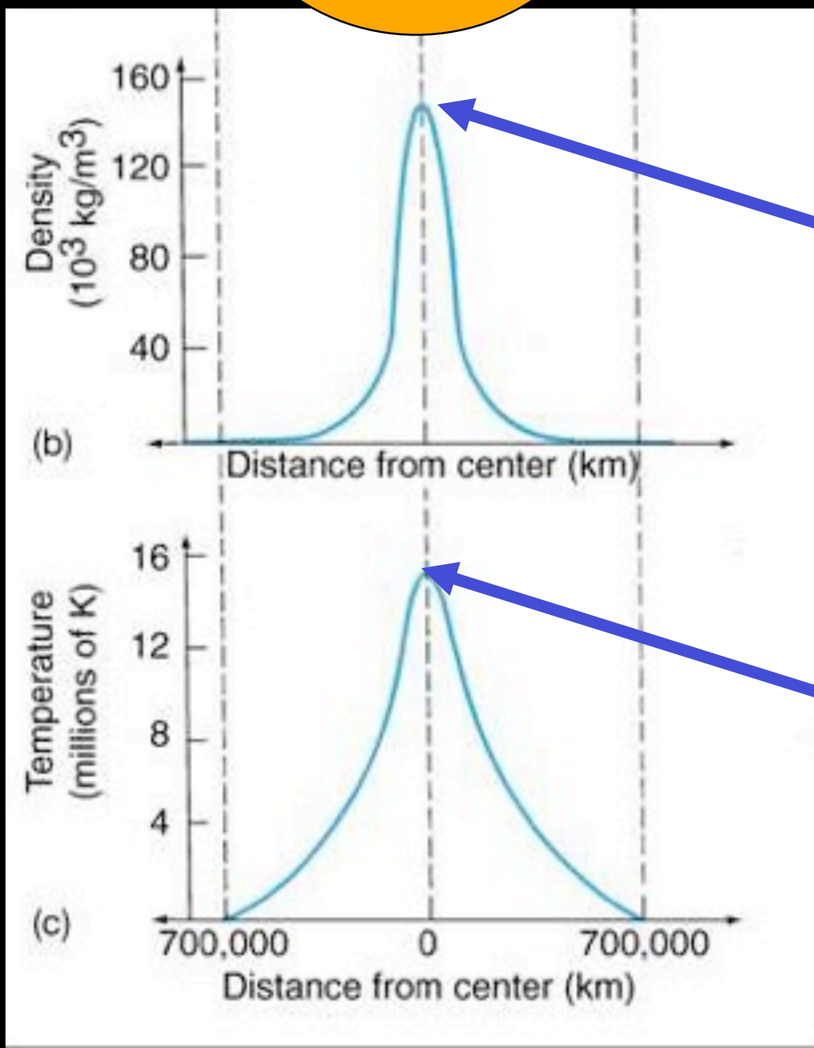
Central pressures are HUGE!!!!

Supports the whole weight of the star!



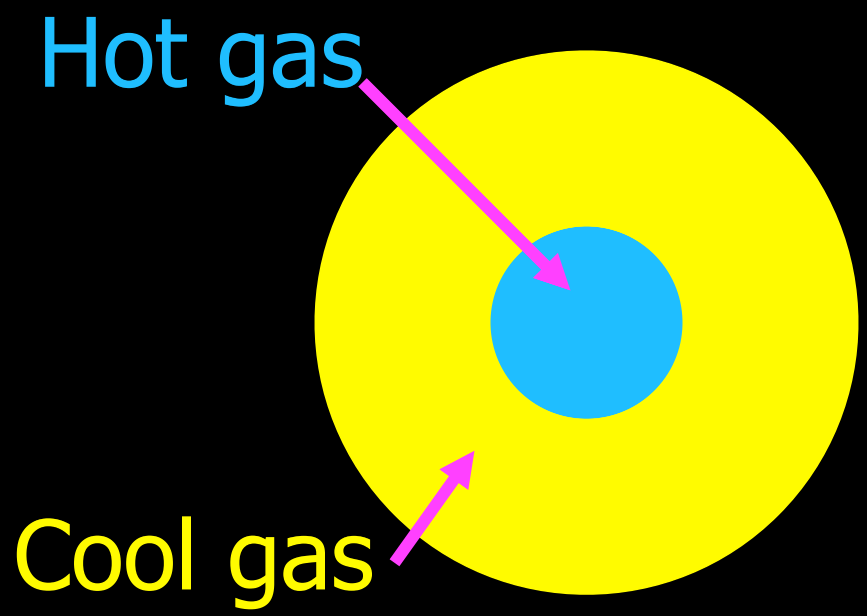
Density & Temperature increase towards the center of a star.





15 times denser than a lead brick!

>10 million degrees! Fully ionized!

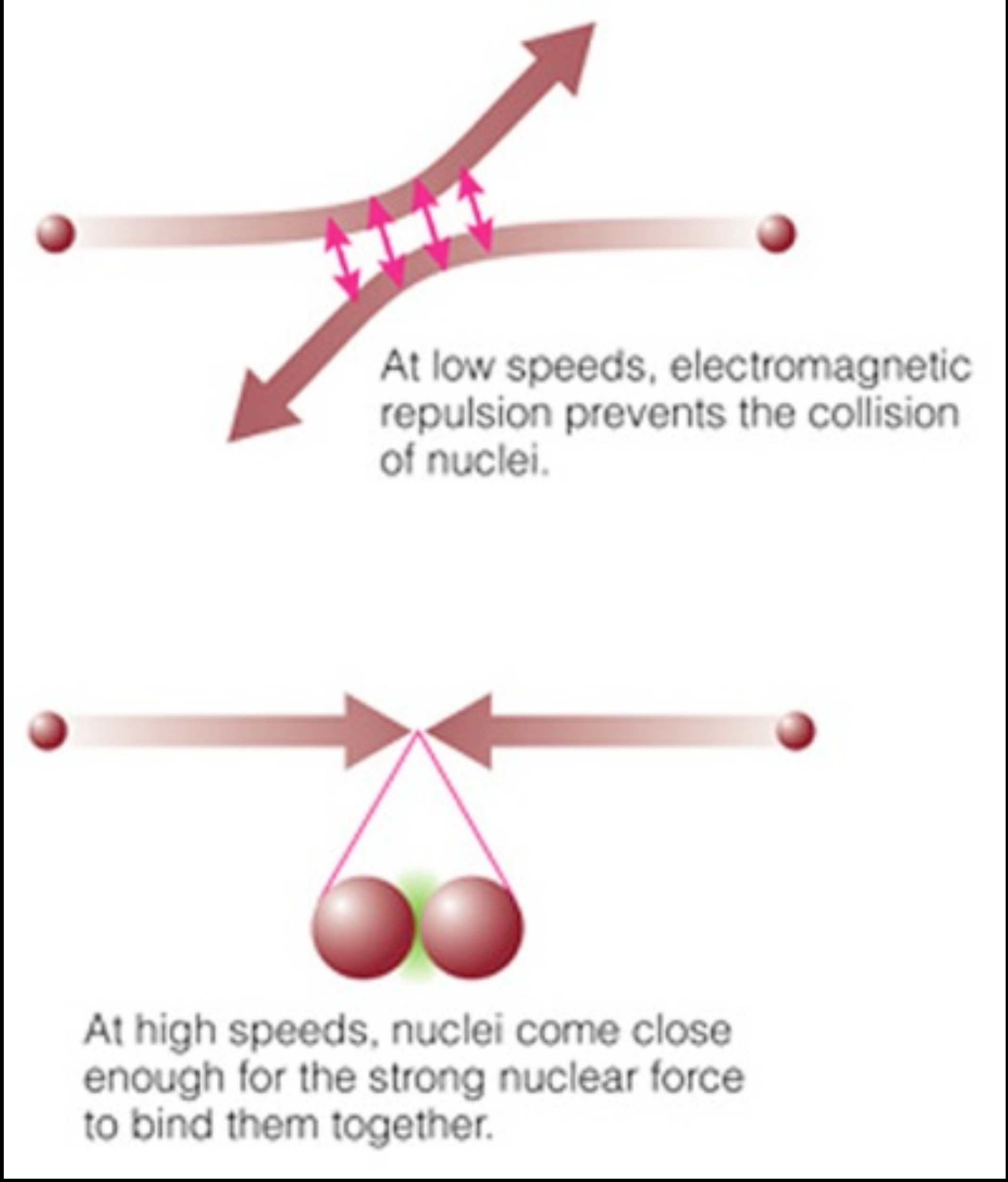


Energy leaks out of the surface all the time, due to thermal radiation

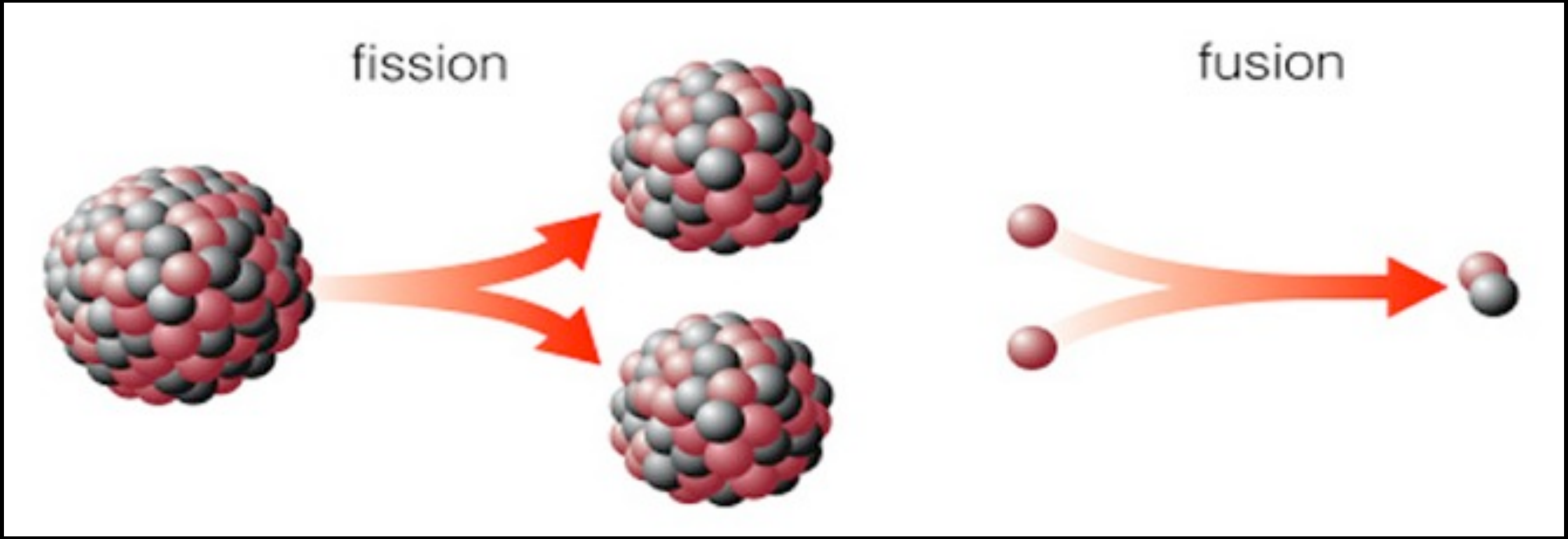
There must be an energy source that continually replaces the heat lost from the surface

High Temperature and Density allows nuclei to interact!

Nuclei can FUSE together:
"Nuclear Fusion"



Nuclear Fission is not



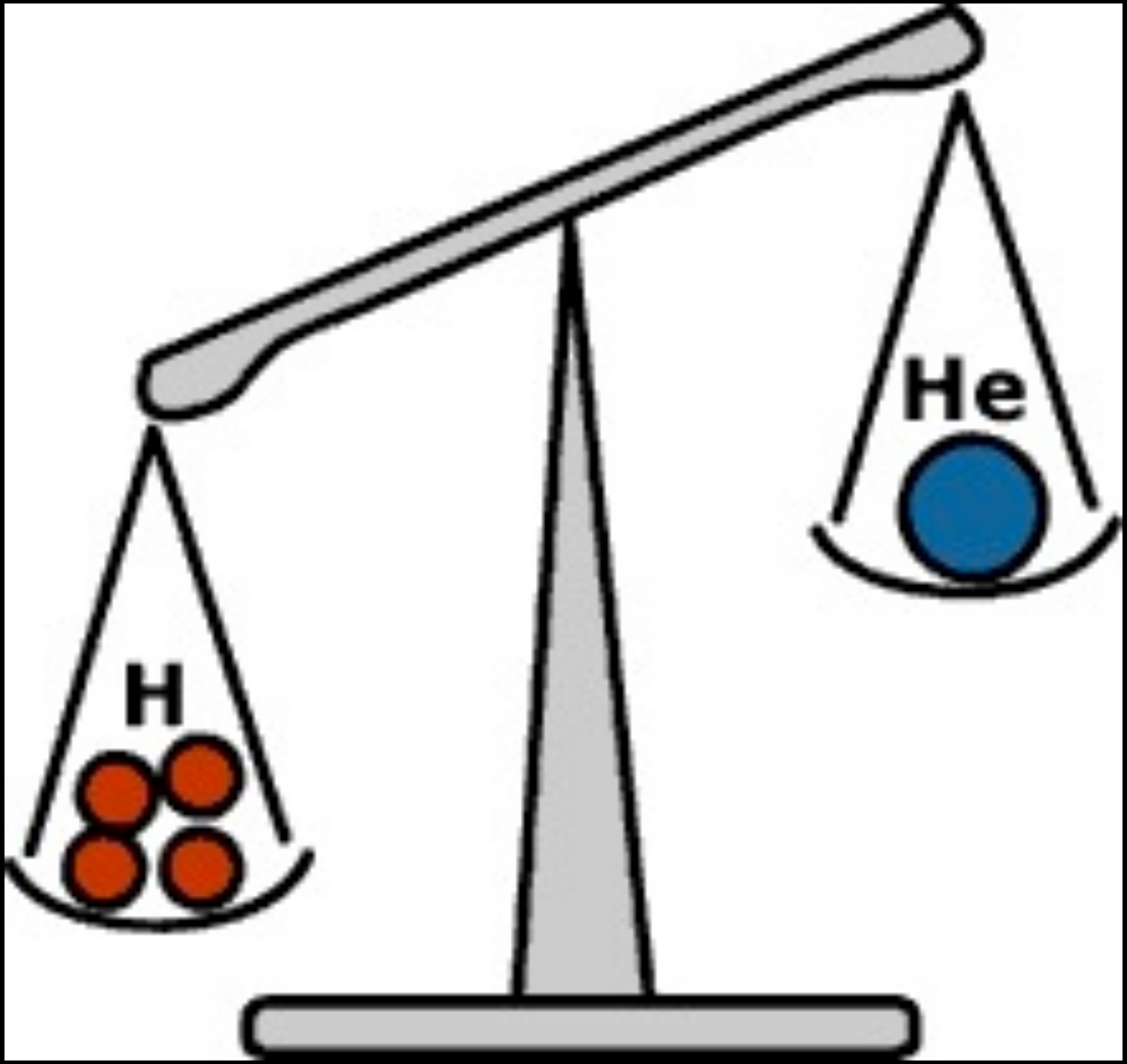
- Messy (i.e. radioactive!)
- Atomic bombs & power plants.
- Requires large complex nuclei to split apart.

- Clean.
- Future power plants?
- Requires only Hydrogen atoms.

Energy Production in Stars: The short form.

4 Hydrogen Atoms fuse to make 1 Helium Atom and a bunch of energy.

Why extra energy at the end?

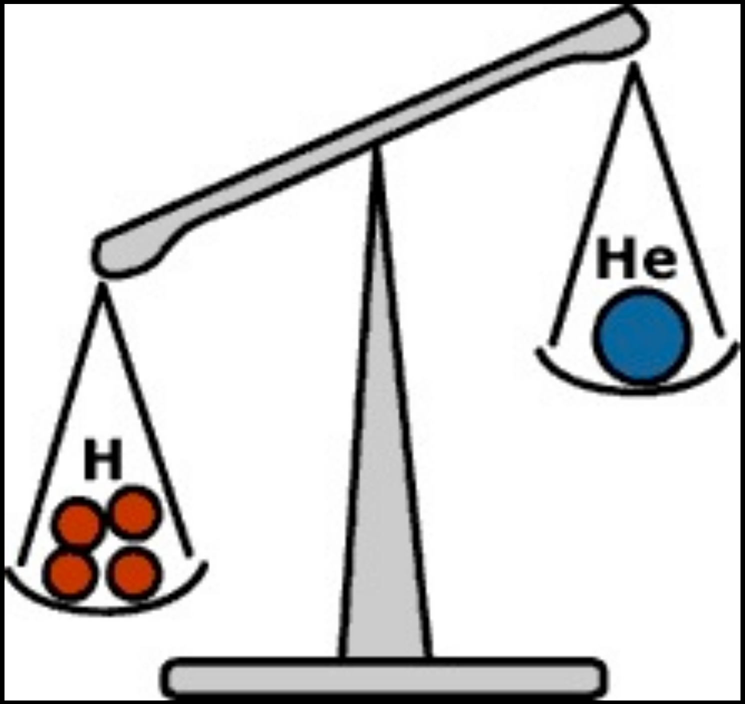


$E = Mc^2$!!

Some mass converts to energy!

How much mass?

6.643×10^{-27} kg



6.690×10^{-27} kg

Mass Difference = 0.047×10^{-27} kg
(0.7% of the original mass)

How much mass?

- Doesn’t take much!

200lb 102 TA

Releases 10% of the entire US energy consumption per year.

$$E = Mc^2$$

Energy released each second…

…must be due to mass destroyed each second

$$\text{Mass Destroyed per second} = \frac{\text{1 Solar Luminosity}}{c^2}$$

4 Billion kg Every Second!

This sounds like a lot, but it isn't…

Sun's Total Mass: 2×10^{30} kg

Every second: 4×10^{9} kg destroyed

Tiny fraction!

It would take 10^{11} years to fuse 0.7% of the Sun's mass. Whew.

Q: Why can't the Sun burn more than 0.7% of its mass?

Suppose there is a momentary drop in the rate of fusion in the center of the Sun.

The temperature:

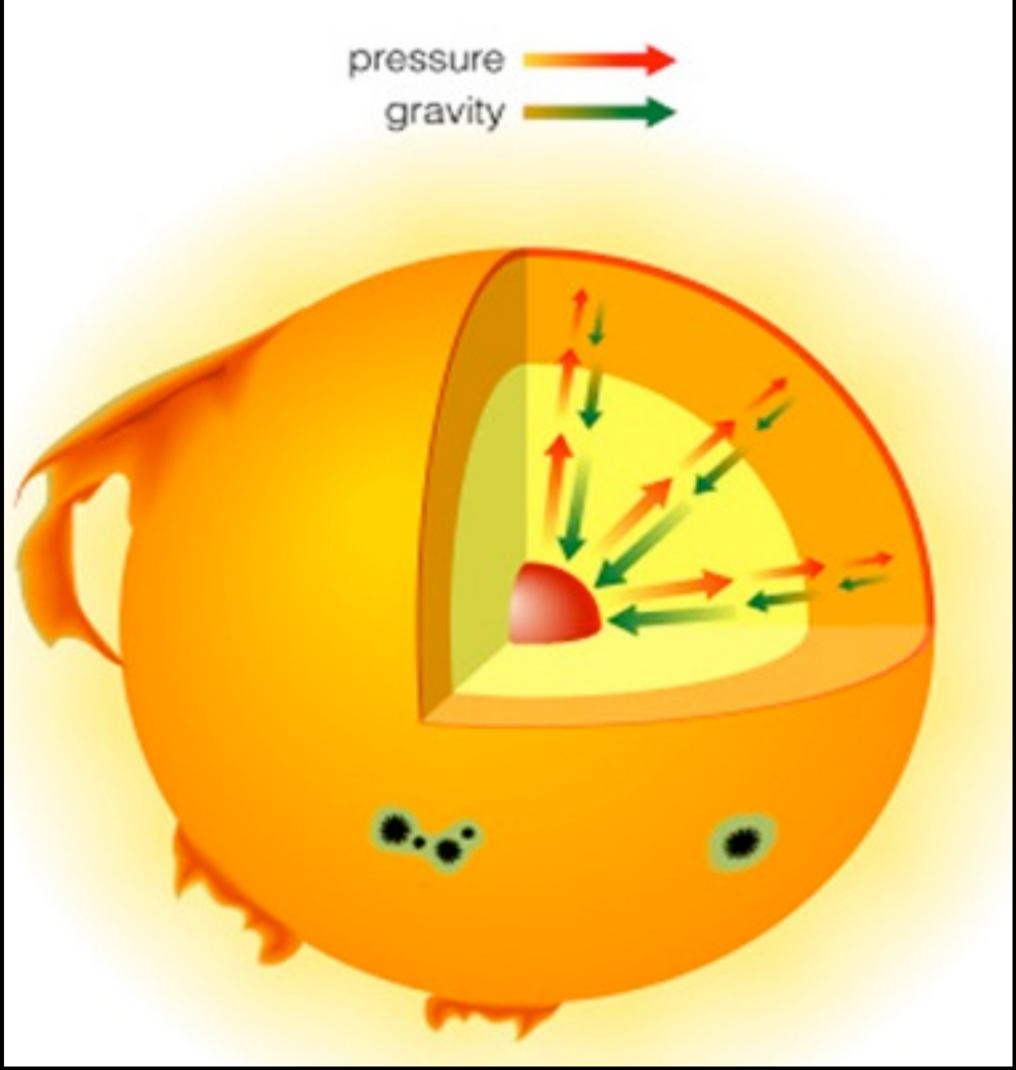
A. Drops

B. Increases

The central Pressure:

A. Decreases

B. Increases



What happens if the central pressure drops?

The star:

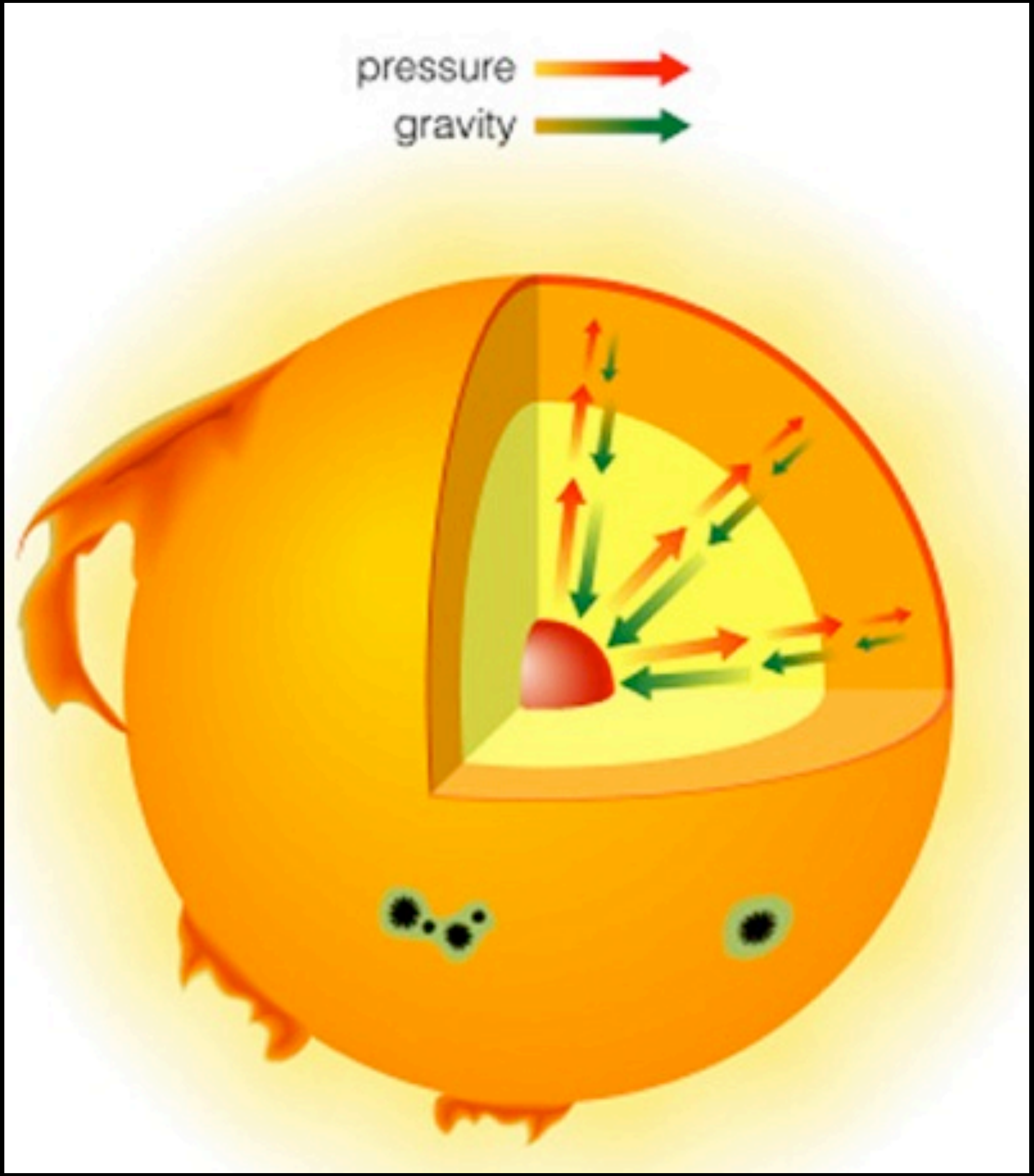
A. Shrinks

B. Expands

The central density:

A. Decreases

B. Increases



What happens if the central density increases?

The rate of fusion:

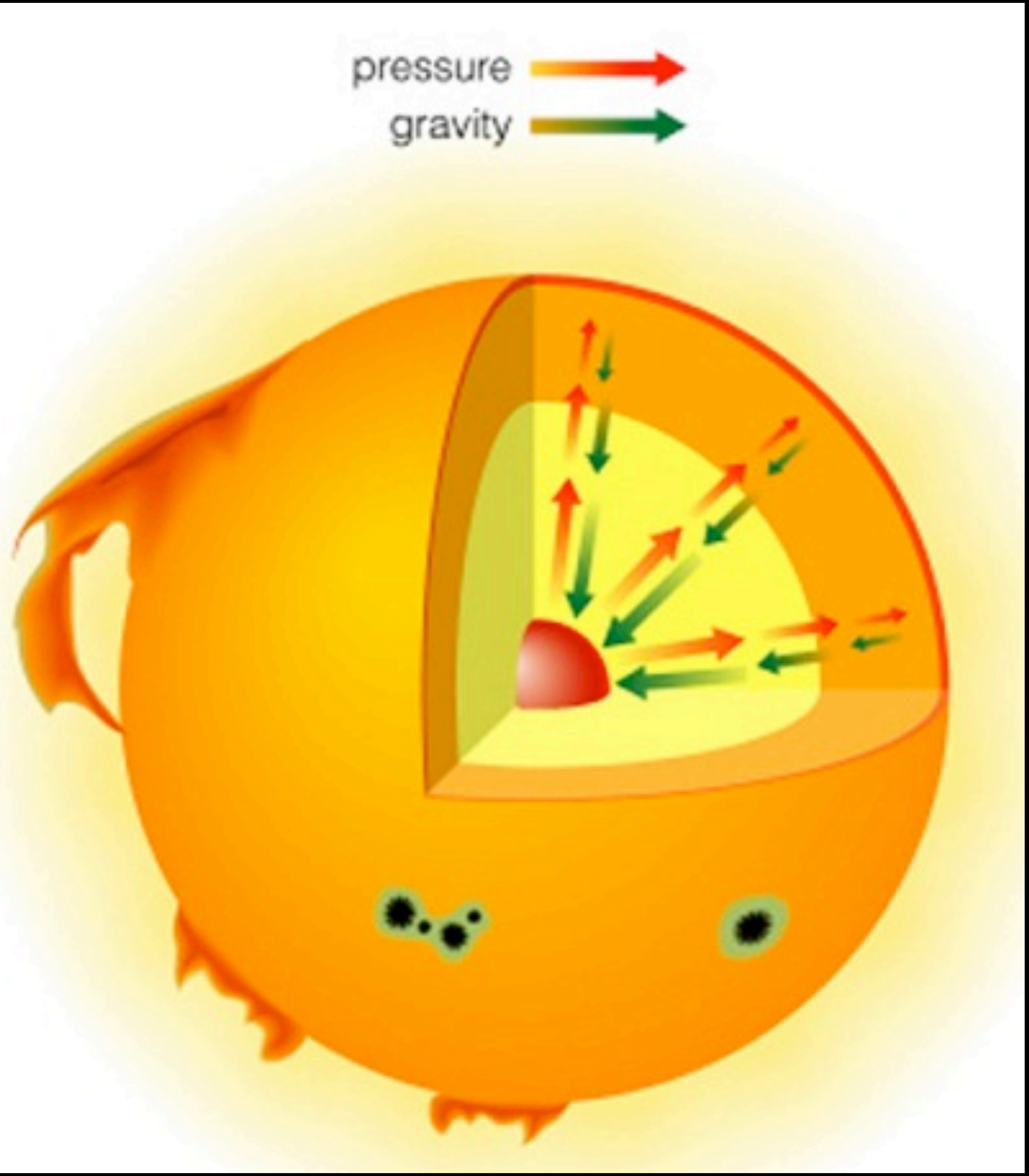
A. Decreases

B. Increases

The central temperature:

A. Decreases

B. Increases



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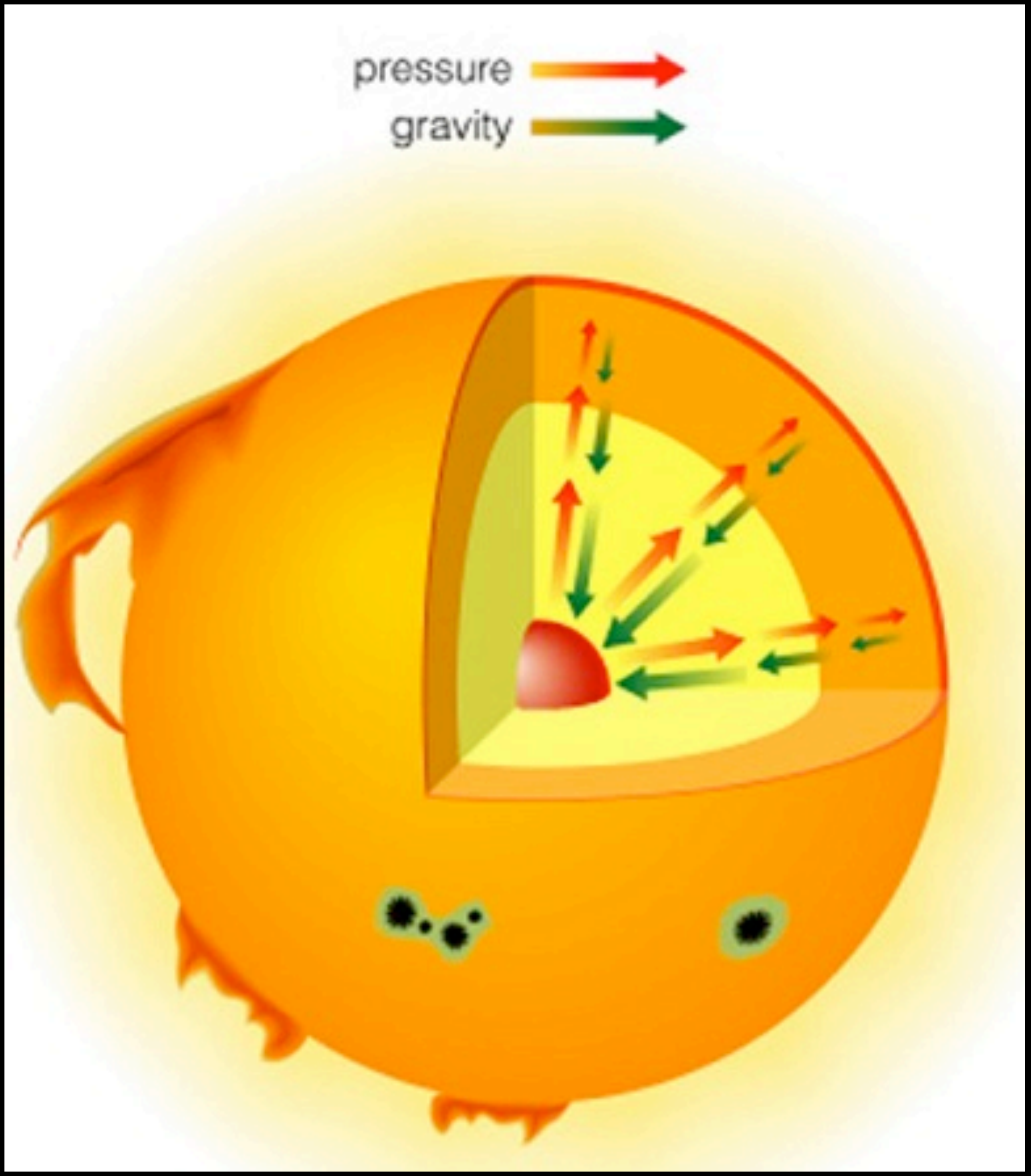
A. Decreases

B. Increases

The star:

A. Shrinks

B. Expands



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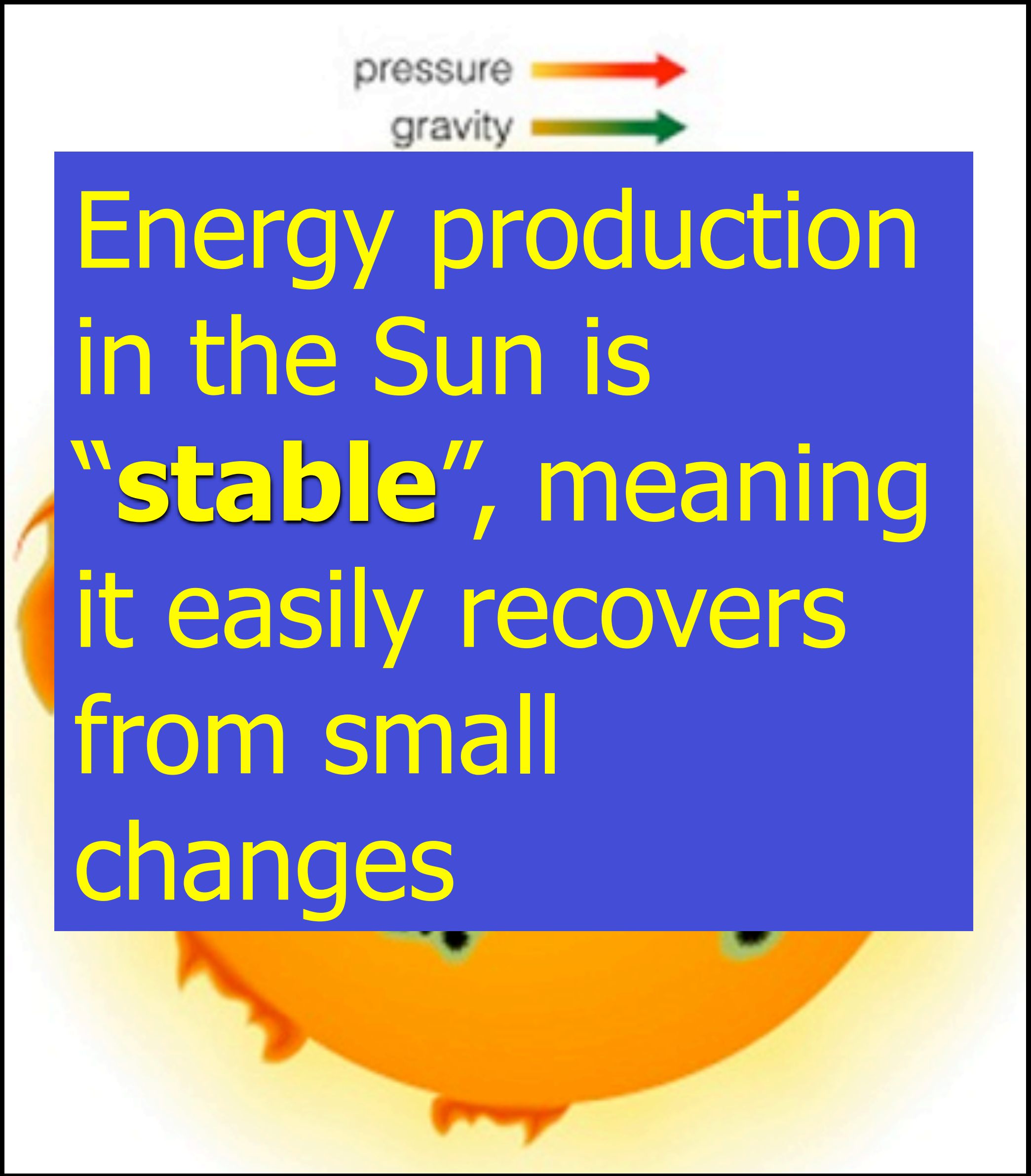
The pressure:
A. Decreases
B. Increases

The star:
A. Shrinks
B. Expands

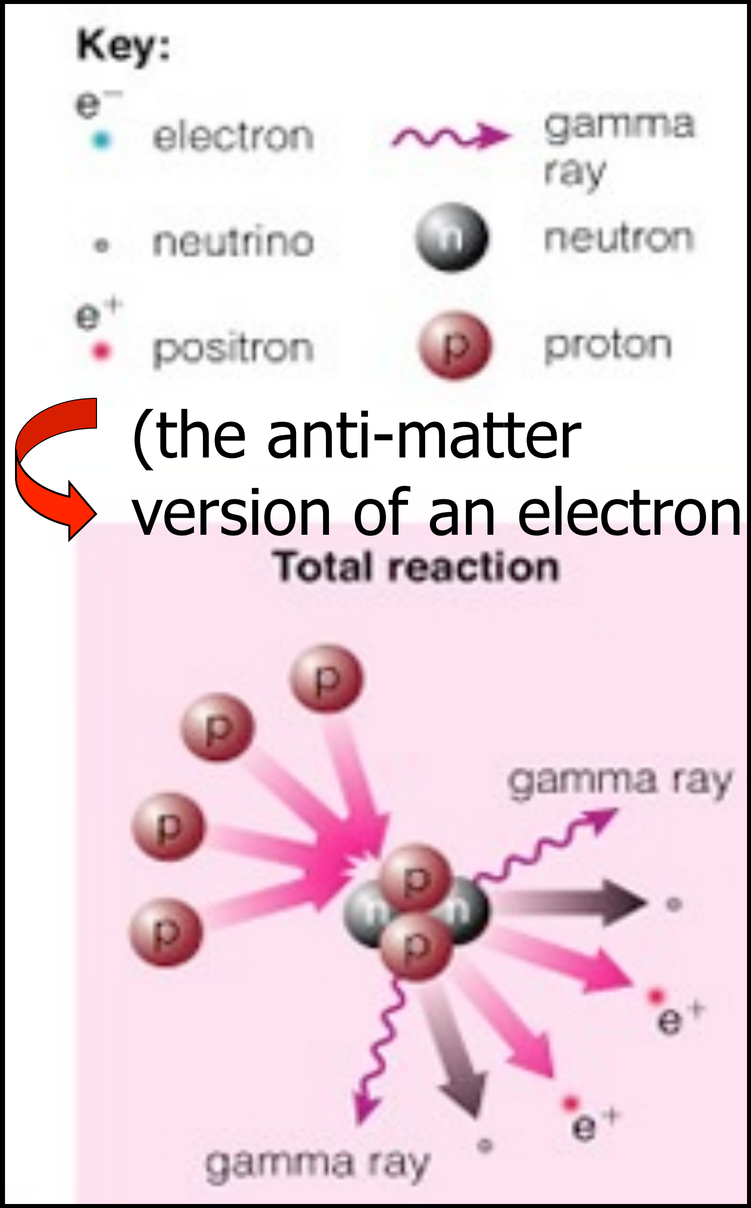


Energy production in the Sun is "**stable**", meaning it easily recovers from small changes

A Recap:

- Stars get denser and hotter towards the center!
- They are entirely gaseous & ionized.
- High density and temperature allows nuclei to collide and interact! → **FUSION**!!!!

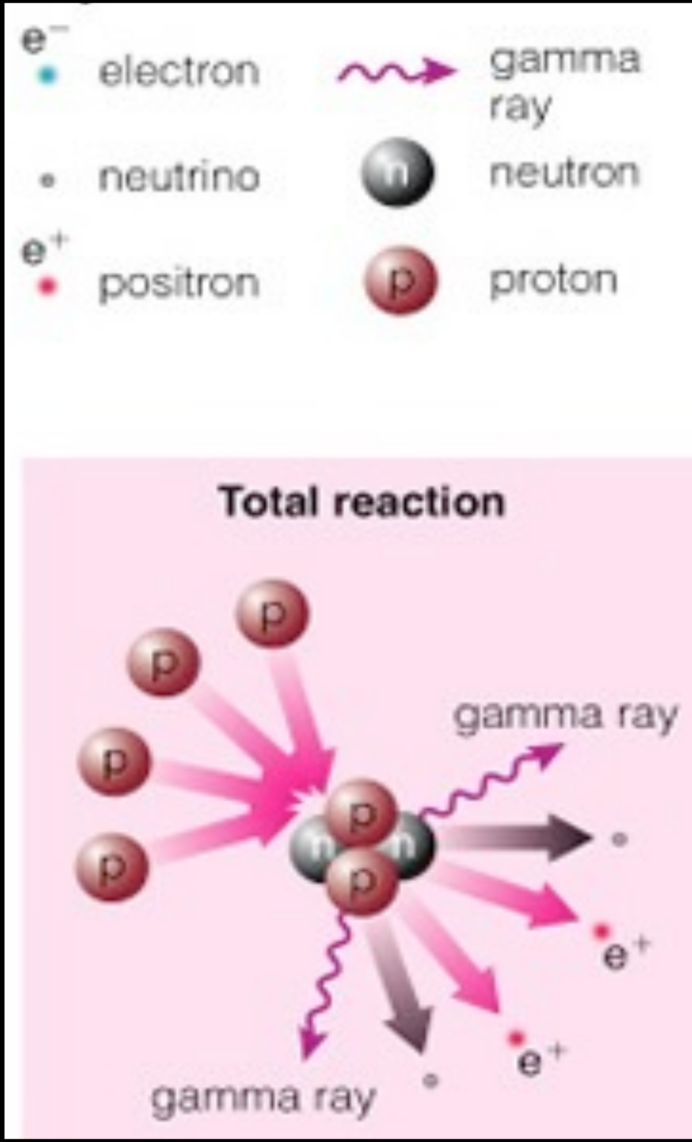
The Recipe for Fusion



- Some energy is carried off in the kinetic energy of the positrons.
- Some is carried off by the energetic gamma ray photons.
- 2% is carried off by "neutrinos"

What are neutrinos?

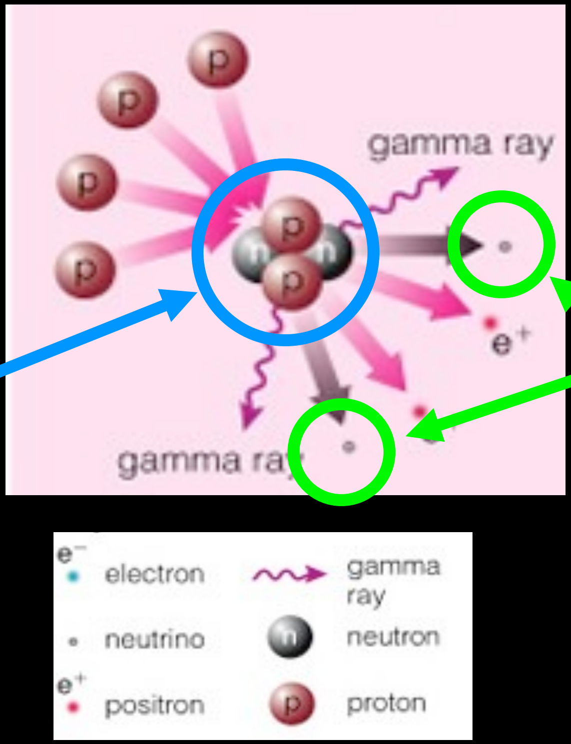
- Nearly massless.
- Chargeless.
- Interacts only by the very short range weak force.



Predicted in 1930.
Detected in 1956!

Neutrinos are a critical signal that we understand energy generation in the Sun

We <u>think</u> we know how much He is made every second



So we'd better get 2x as many neutrinos out every second!

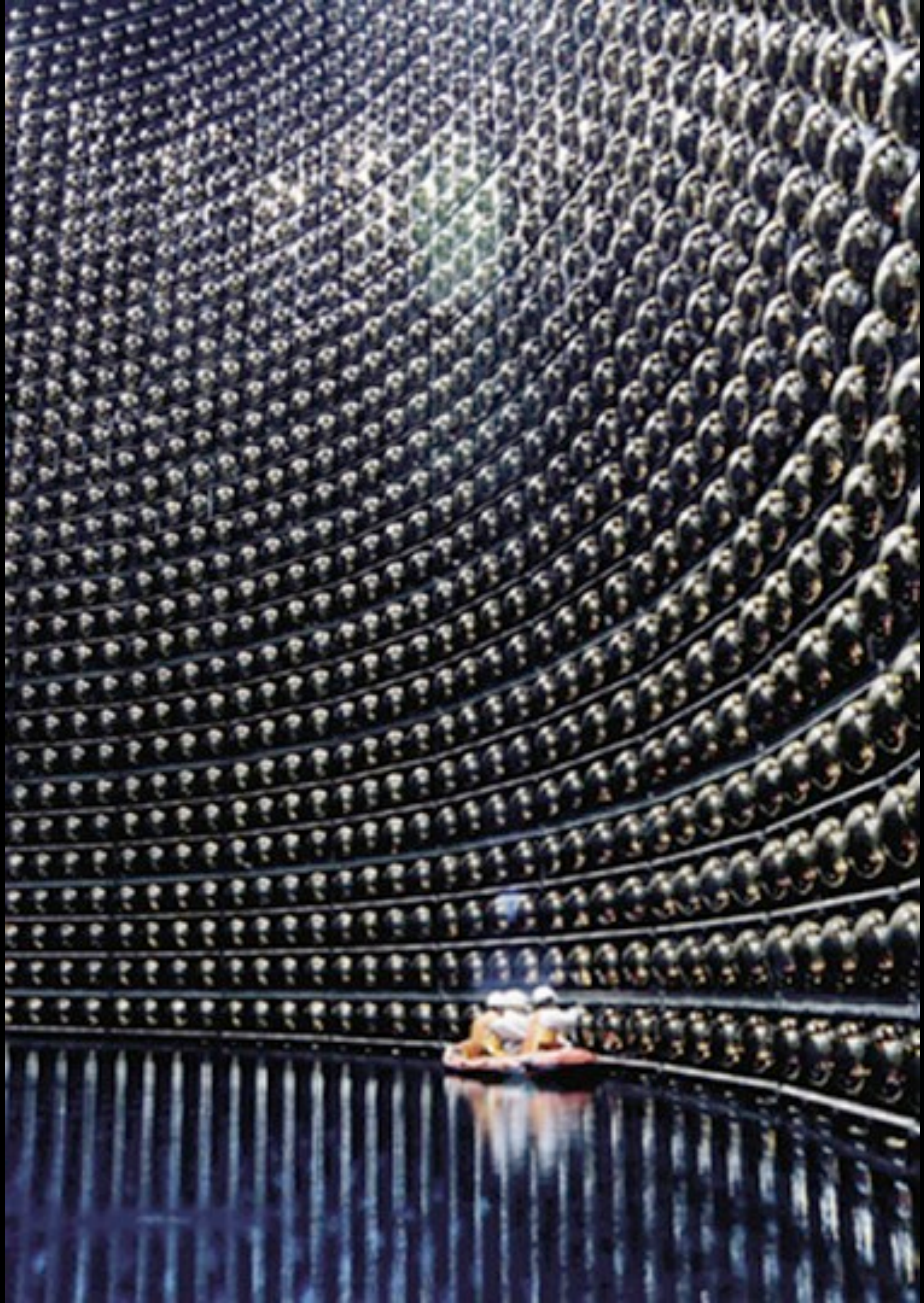
Neutrinos rarely interact with anything!

- Nearly massless.
- Chargeless.
- Interacts only by the very short range weak force.
- Moves fast
- No electromagnetic force
- Needs to run smack dab into a tiny nucleus for anything to happen!

It would take a light-year of lead to be sure of stopping a neutrino!

"Super K", a big honking neutrino detector

- Deep underground.
- Detects neutrinos which have burrowed **THROUGH** the Earth!



Sudbury Neutrino Observatory

- 12m across!
- 6800 ft underground!
- Filled with 1000 tons of "heavy water" (D_20)

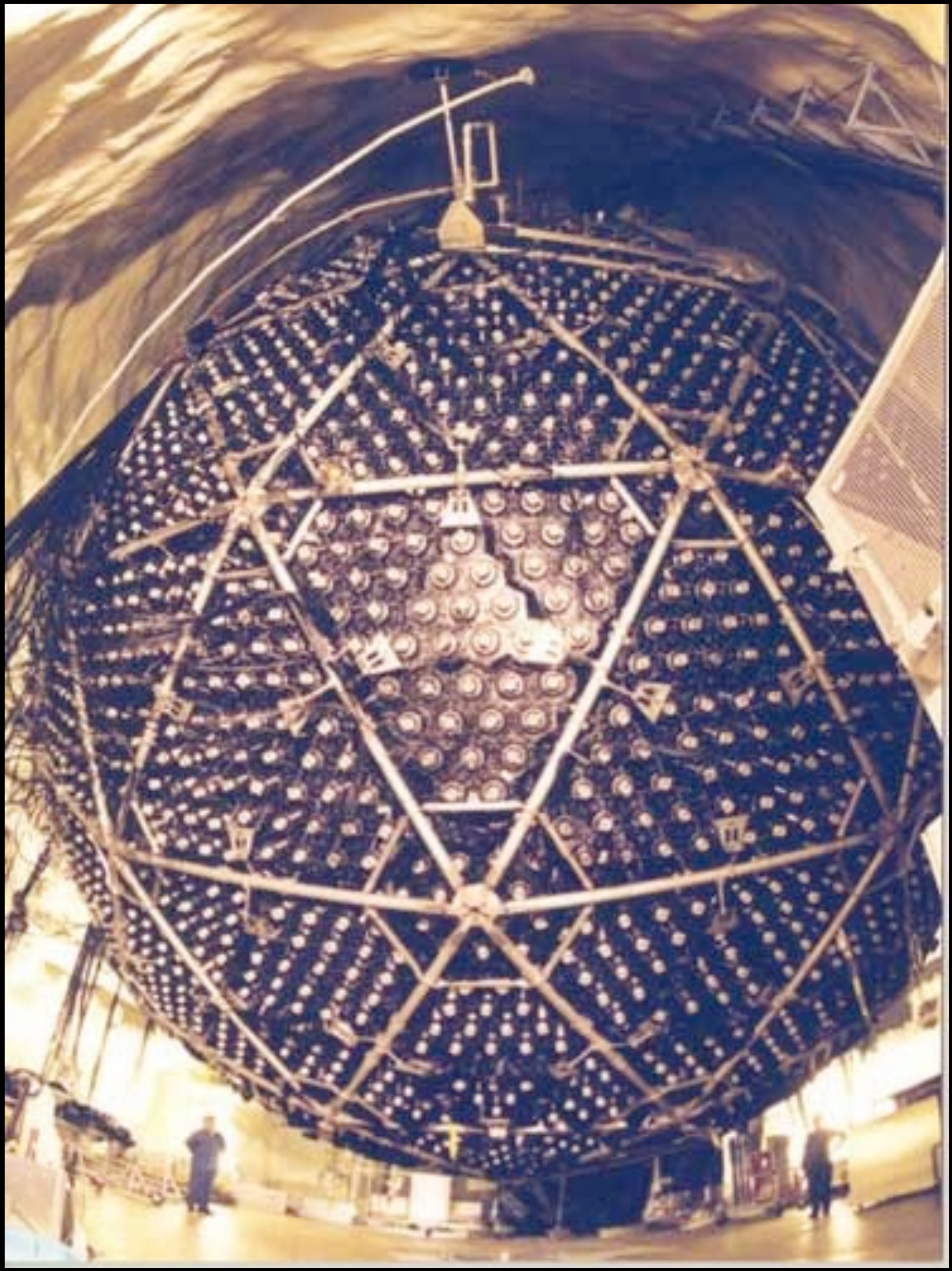
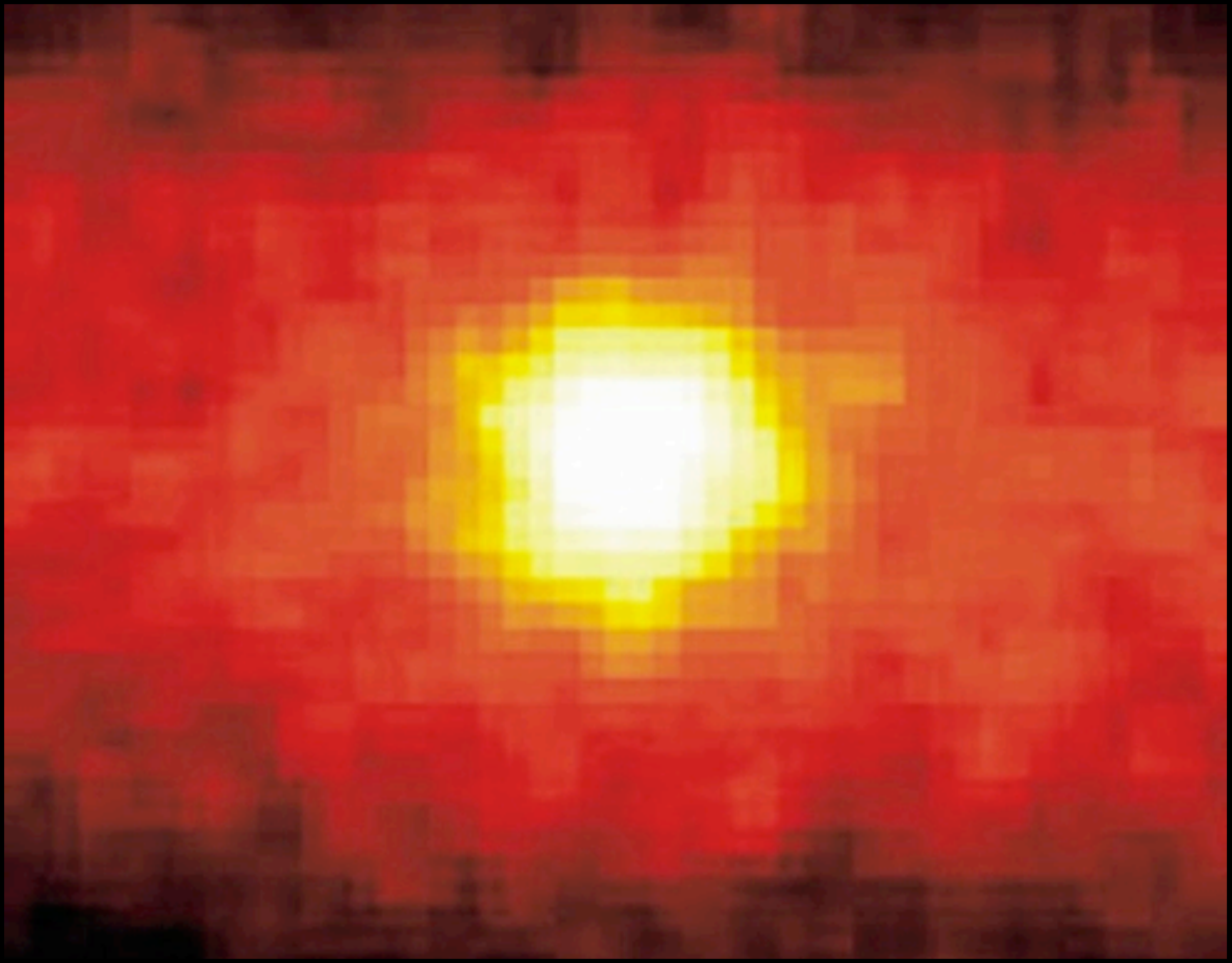


Image of the Sun in neutrinos!

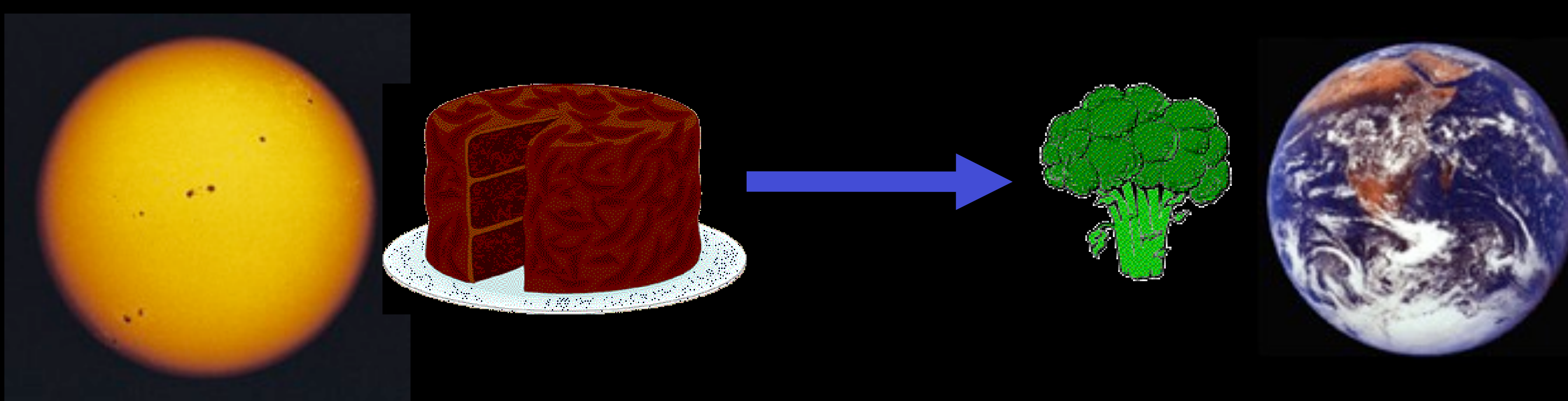


BUT.....

Experiments like Super-K only detect a fraction of the neutrinos expected!

Points to new neutrino physics!

Neutrinos are changing "flavor"!



So, we think we know how energy is produced…

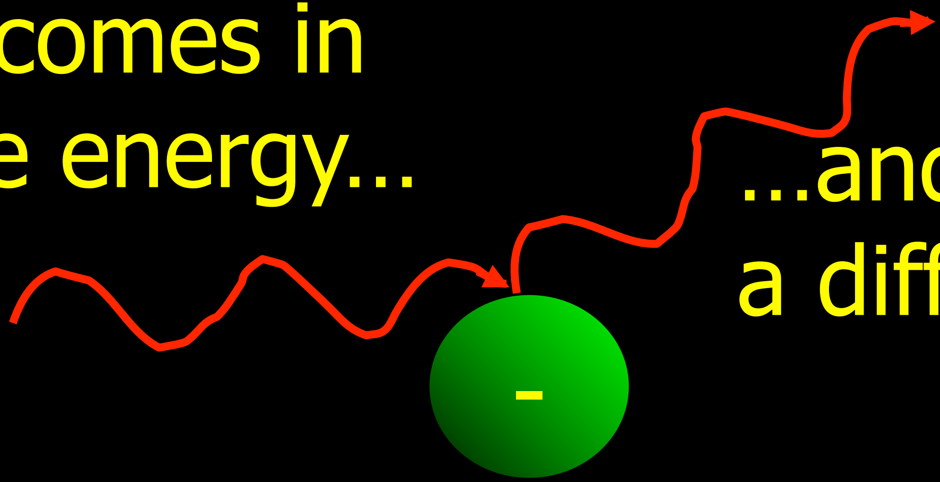
How does the energy get out????

So how does the energy get out?

1. “radiative diffusion”
2. “convection”

Radiative Diffusion:

Photon comes in with one energy…



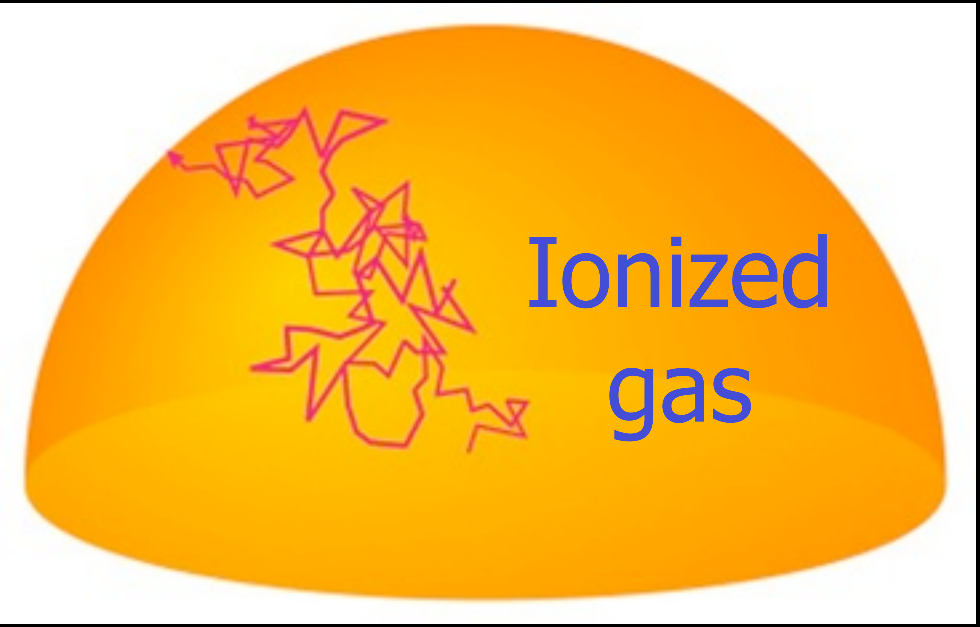
…and leaves with a different energy

…scatters off a free electron…

“Photon Scattering”

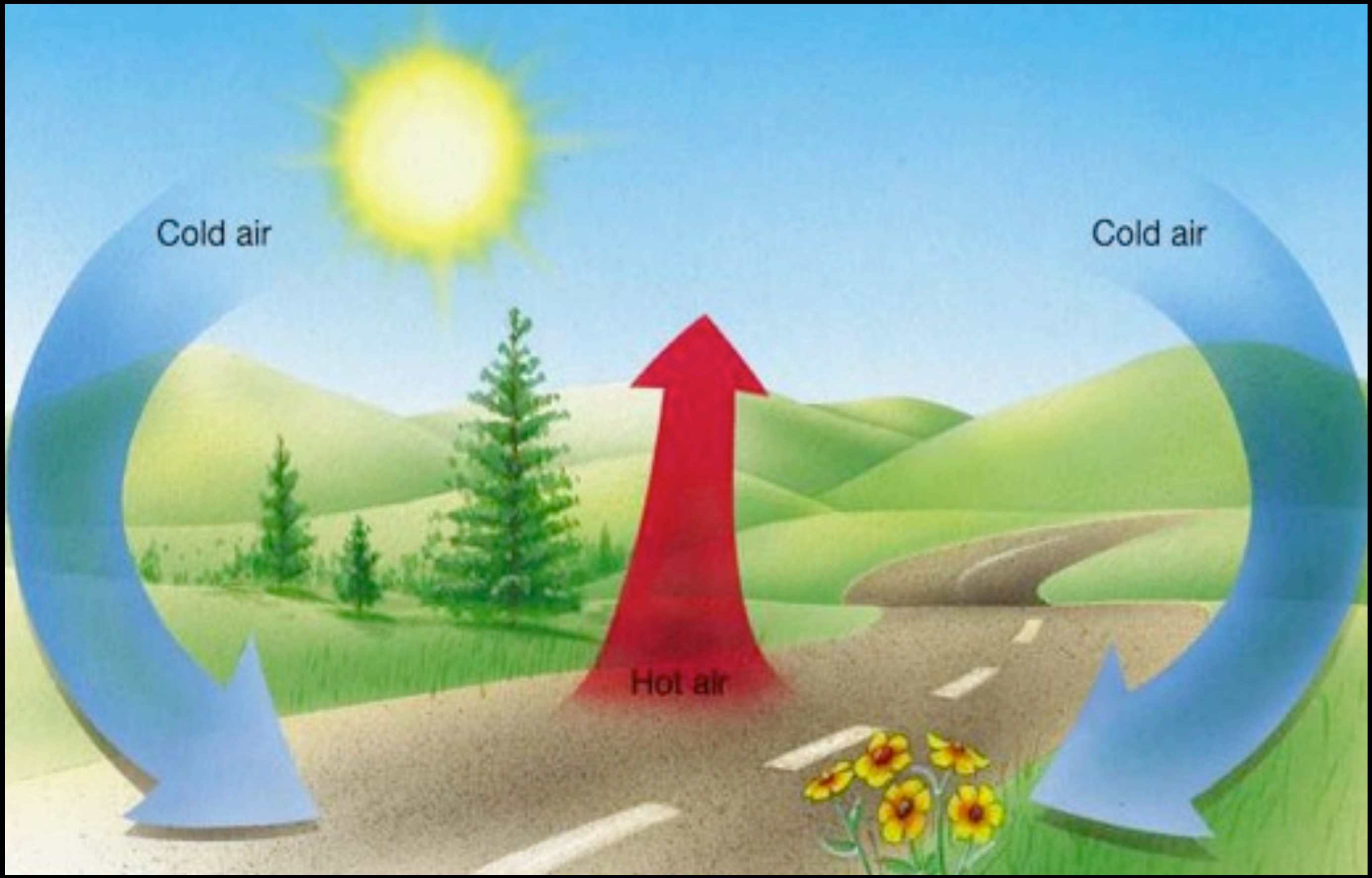
Radiative Diffusion

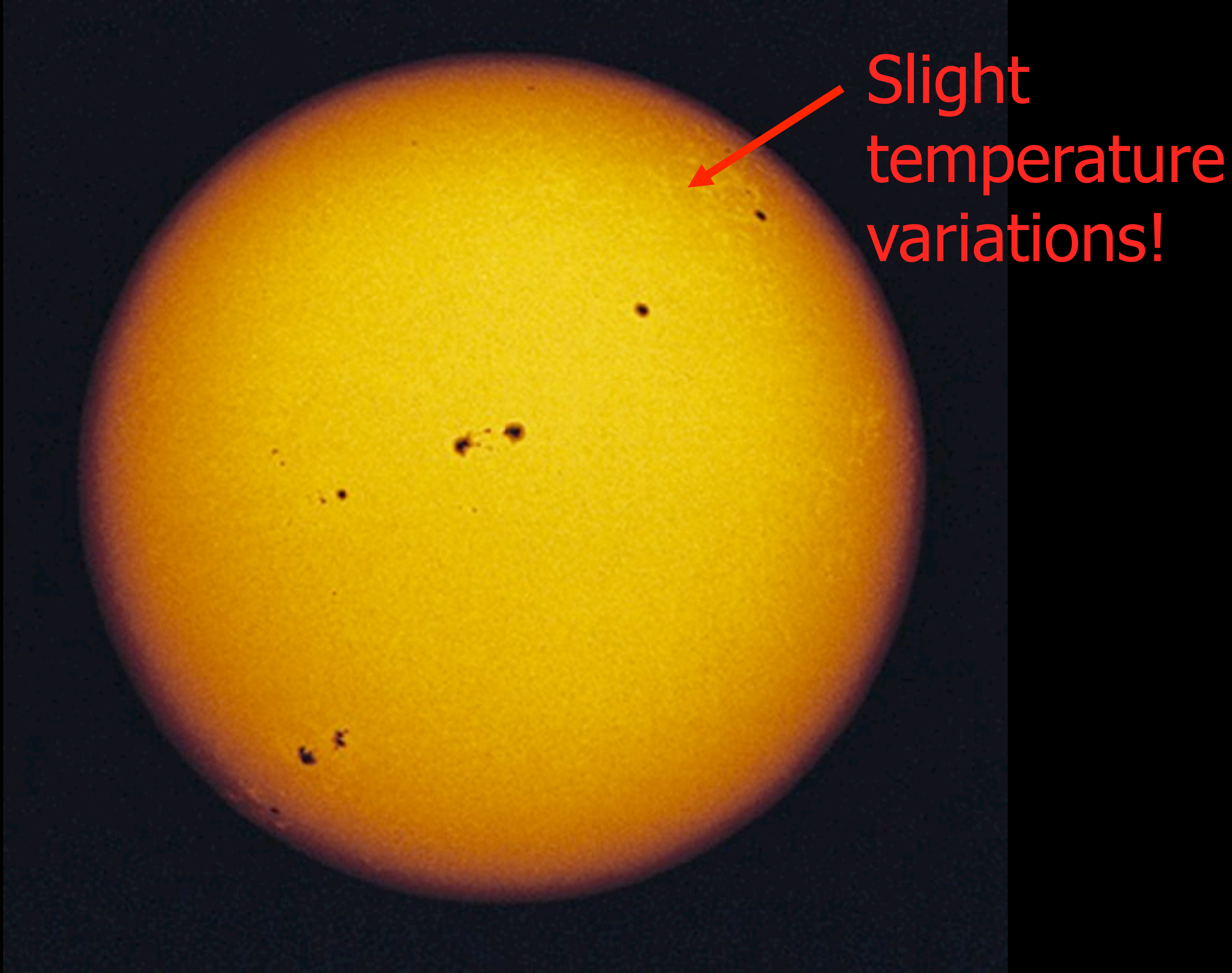
The photons "diffuse" outwards, heating the gas as they go.



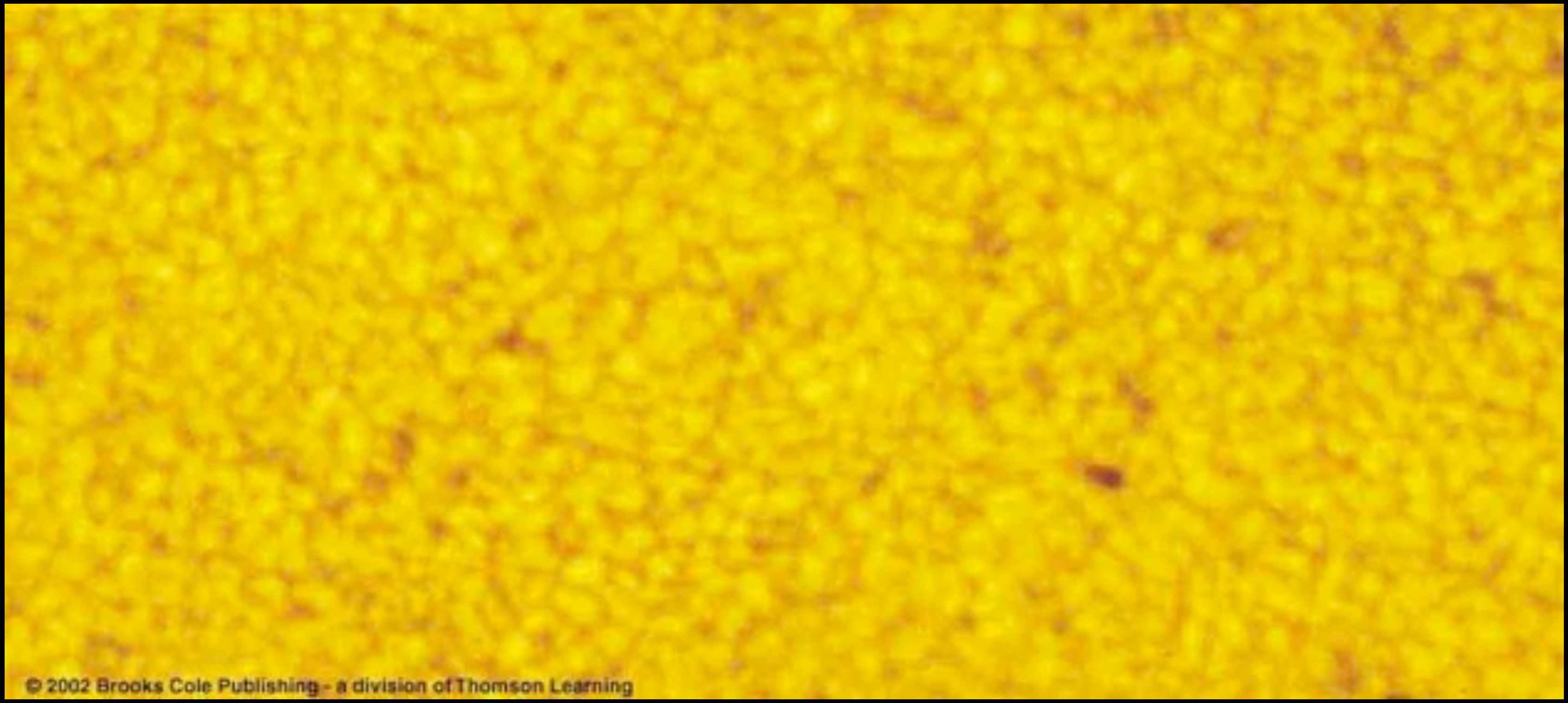
Convection

- Hot stuff floats.
- Cool stuff sinks.



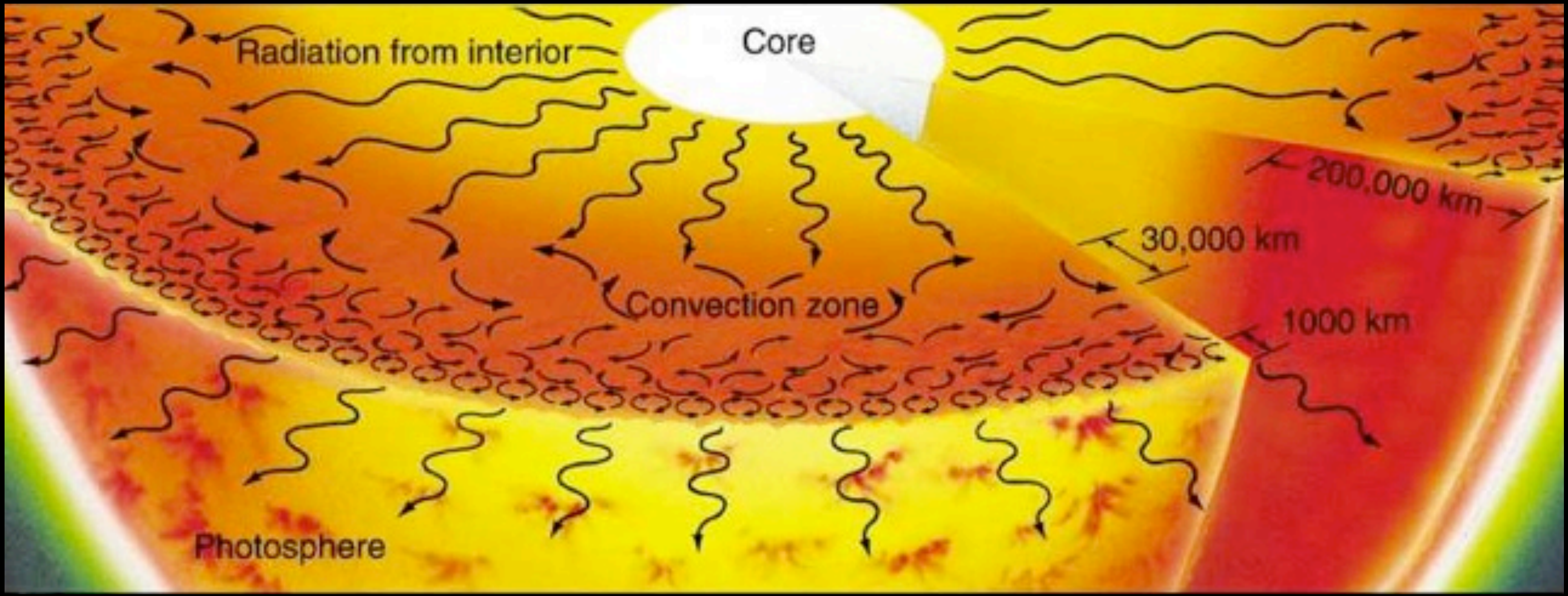

Slight
temperature
variations!

Granules up close.

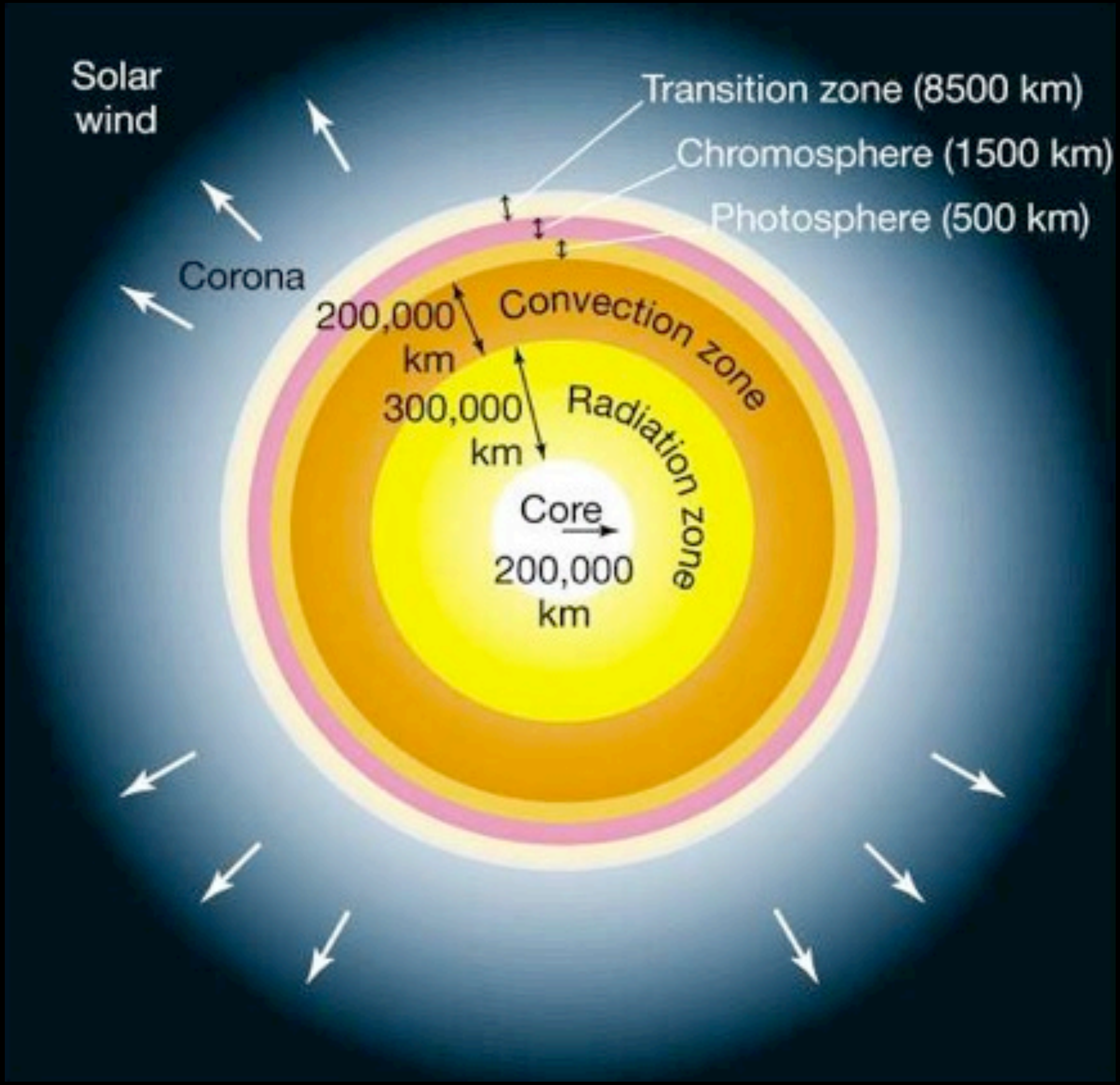


These are regions where hot gas is floating up, cooling, and then sinking back down.

The sun is "convective" near the surface, "radiative" near the center.



Cross section of the Sun:



We only "see" the outer 2000 km of the sun!

The "Core" is the region where Hydrogen is fusing into Helium

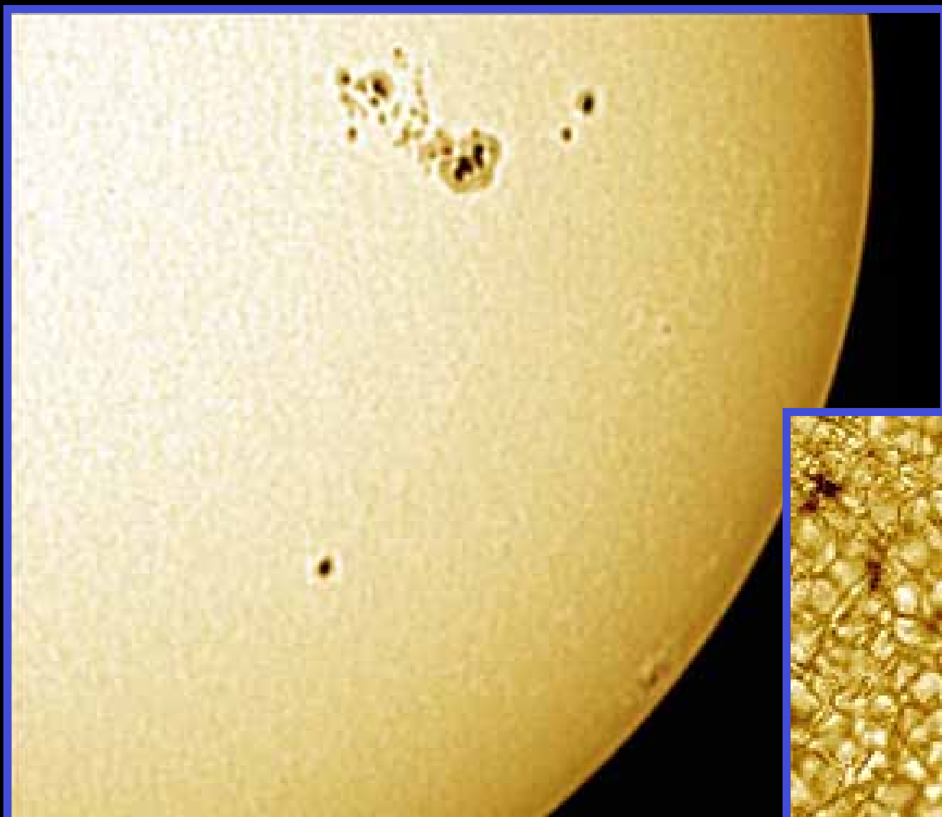
The Corona:

Very hot halo of gas surrounding the Sun.

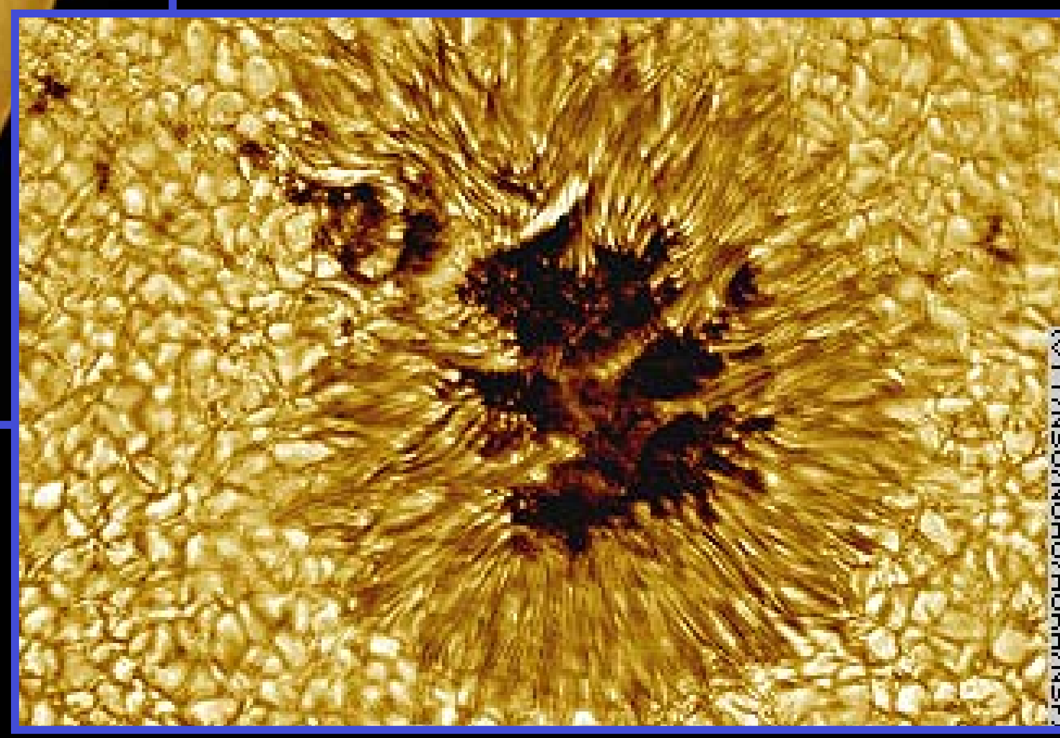
$T > 10^6$ K!

(really only visible optically during a solar eclipse)

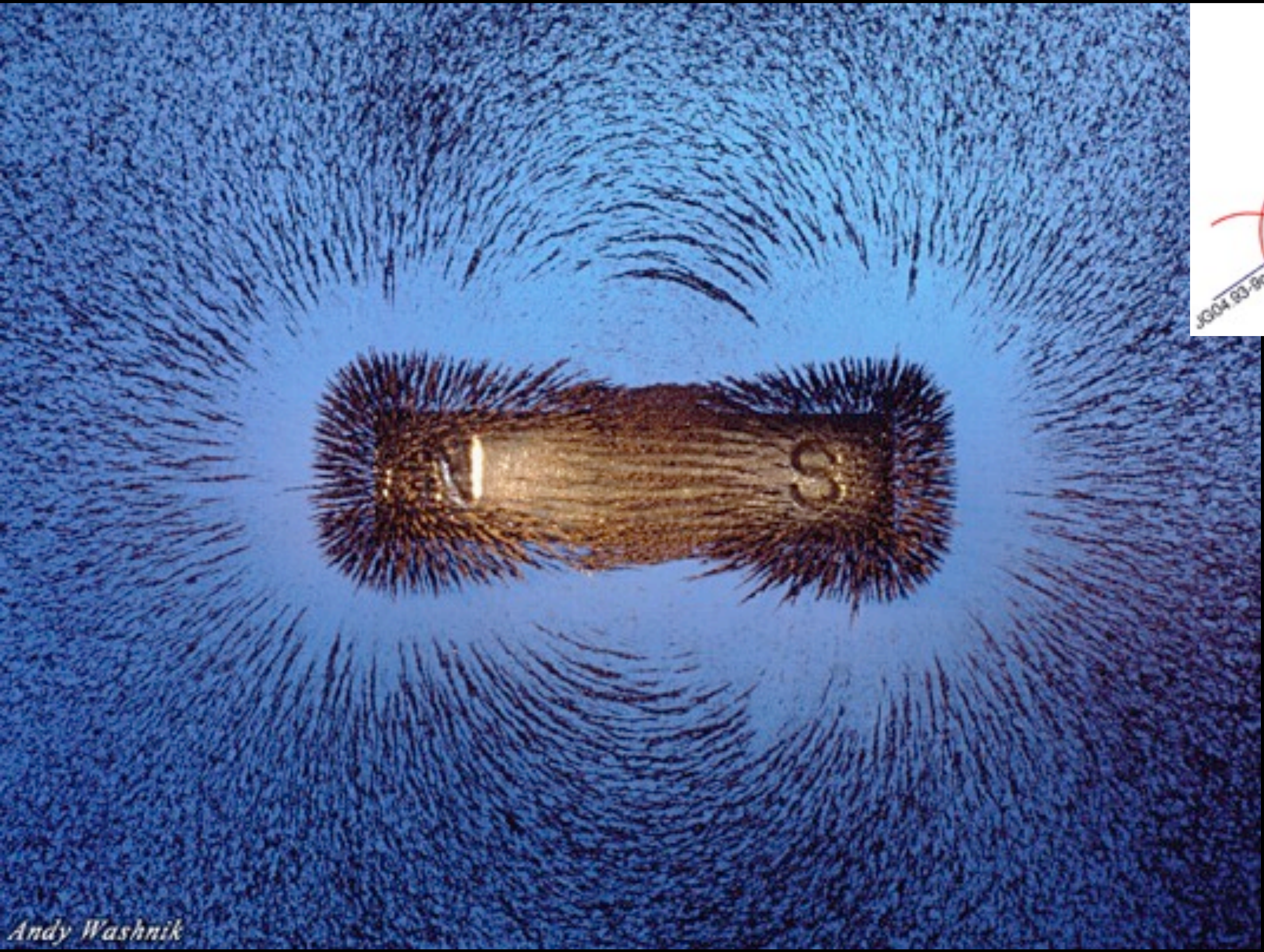
Sunspots: magnetic fields!

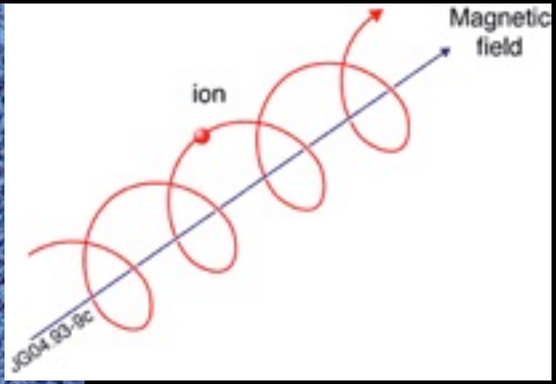


Sunspots are regions of high magnetic field strength.



Stuff that interacts with magnetic fields tends to align along "magnetic field lines"

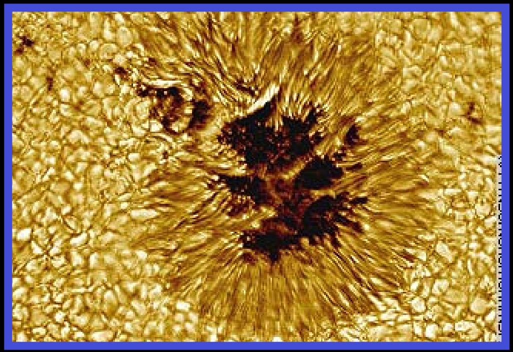




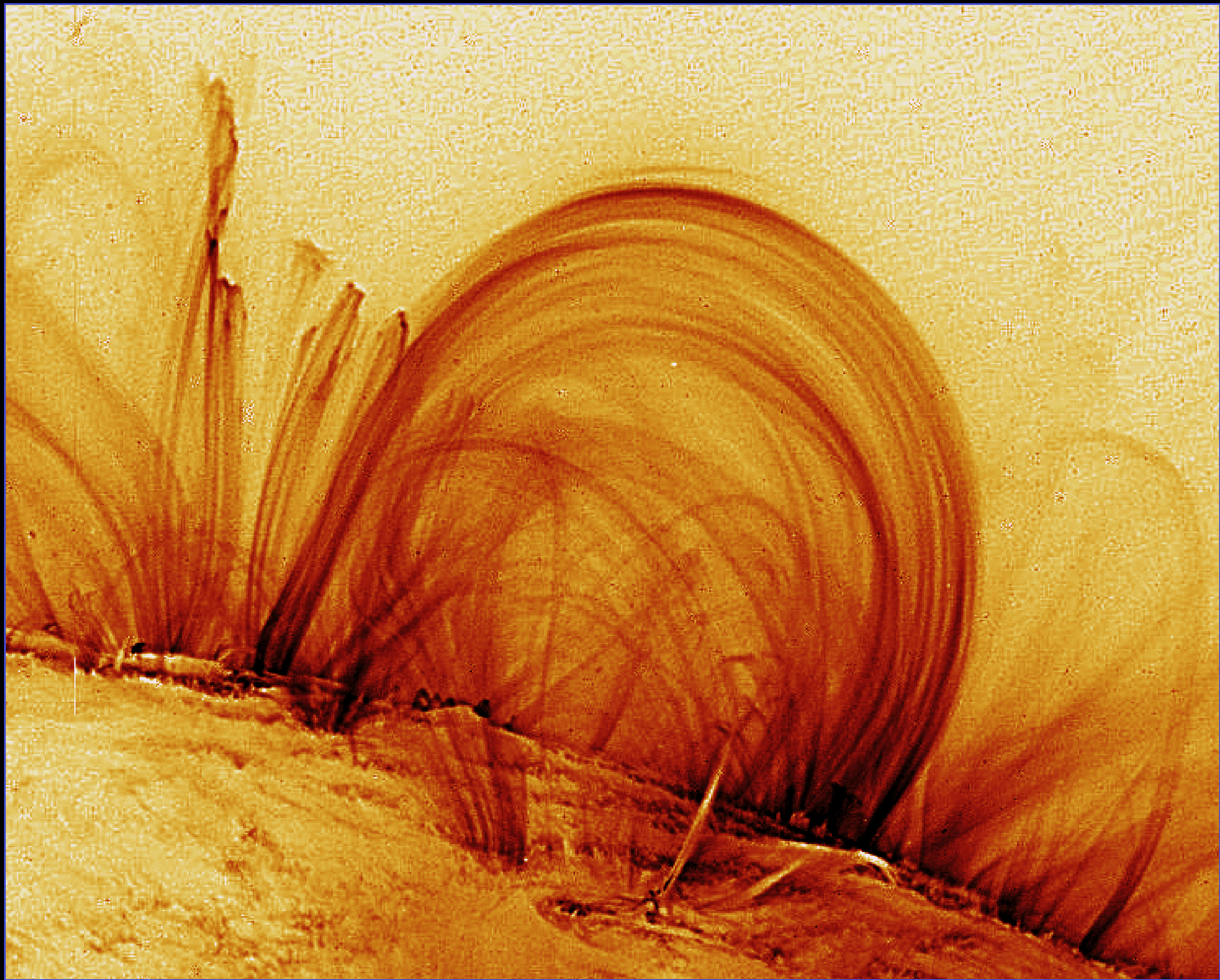
- Iron
- Charged particles

Powerful eruptions: dynamic Sun!

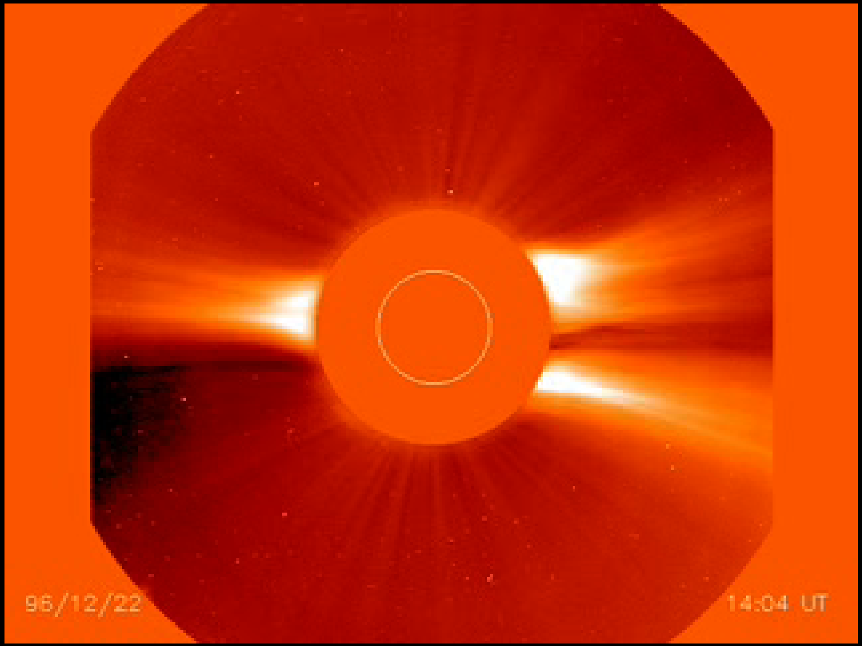
Overhead view



Side view



Coronal Mass Ejections:



"Solar Storms"
Affects telecommunications!