Announcements

I hope everyone has handed in homework 1 !

Homework 2 is posted on UNM Learn:
- due next Thursday (Feb. 4)

Circumference of a circle: $$C = 2\pi r$$

Small-angle formula: $$D = \frac{\alpha d}{206265}$$

Photon energy: $$E = \frac{hc}{\lambda} = h\nu$$

Planck's law: $$I_\nu = \frac{2h\nu^3}{c^2}\left[\frac{1}{e^{h\nu/kT} - 1}\right]$$ OR $$I_\lambda = \frac{2hc^2}{\lambda^5}\left[\frac{1}{e^{hc/\lambda kT} - 1}\right]$$

Wien's law: $$\lambda_{max} = \frac{0.0029}{T}$$

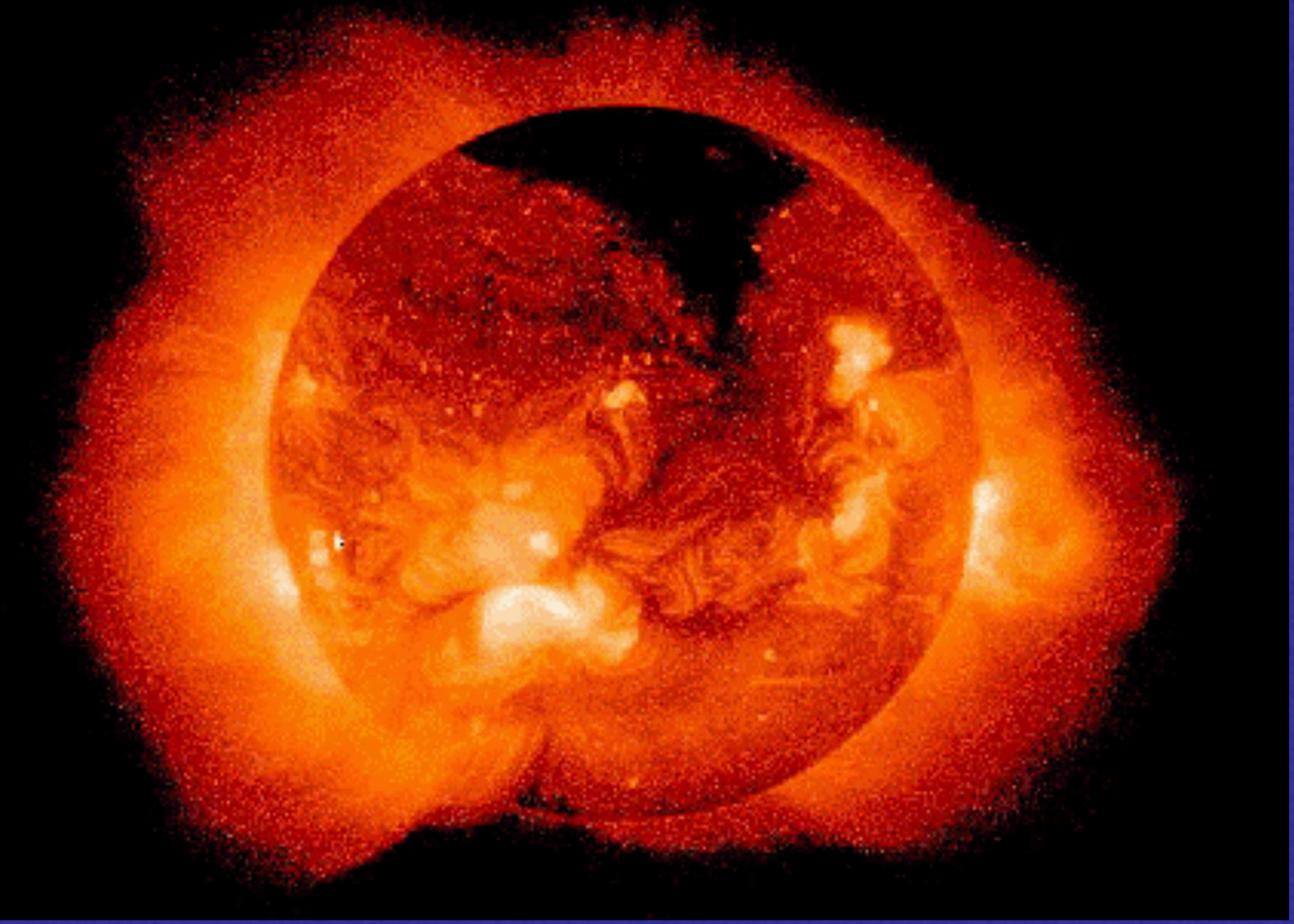
Stefan-Boltzman law: $$F = \sigma T^4$$

Mass-energy relation: $$E = mc^2$$

Doppler shift: $$V_{rad} = \frac{\lambda_{observed} - \lambda_{emitted}}{\lambda_{emitted}} c = \frac{\Delta\lambda}{\lambda_{emitted}} c$$

Discussion Topic

- Why do astronomers build new telescopes?
  - Breakout rooms
  - Discuss (5 minutes)
  - Pick somebody to present ideas



Key concepts:

Energy production

Stability

Basic data

Diameter	1.4×10^6 km	$= 109\ D_{earth}$
Mass	2×10^{30} kg	$= 333{,}000\ M_{earth}$
Composition (by mass)	74% H, 25% He	
Density	$1.4\ g/cm^3$	
Light travel time to Earth	8.32 min	
Orbital period (MW)	220×10^6 years	
Temperature	5800 K to 1.55×10^7 K	
Luminosity	3.86×10^{26} W	

Luminosity - intrinsic property

- Total energy radiated per second.
- How does this relate to flux? Recall flux (flux density) is energy radiated per area per second.
- For the Sun (a sphere):

$$L_\odot = \text{Area x Flux} = (4\pi R_\odot^2)(\sigma T_\odot^4)$$

The energy source

- How long can the Sun shine?

  Lifetime = internal heat (J)/luminosity (J/s)

- Burning as a possible source of energy

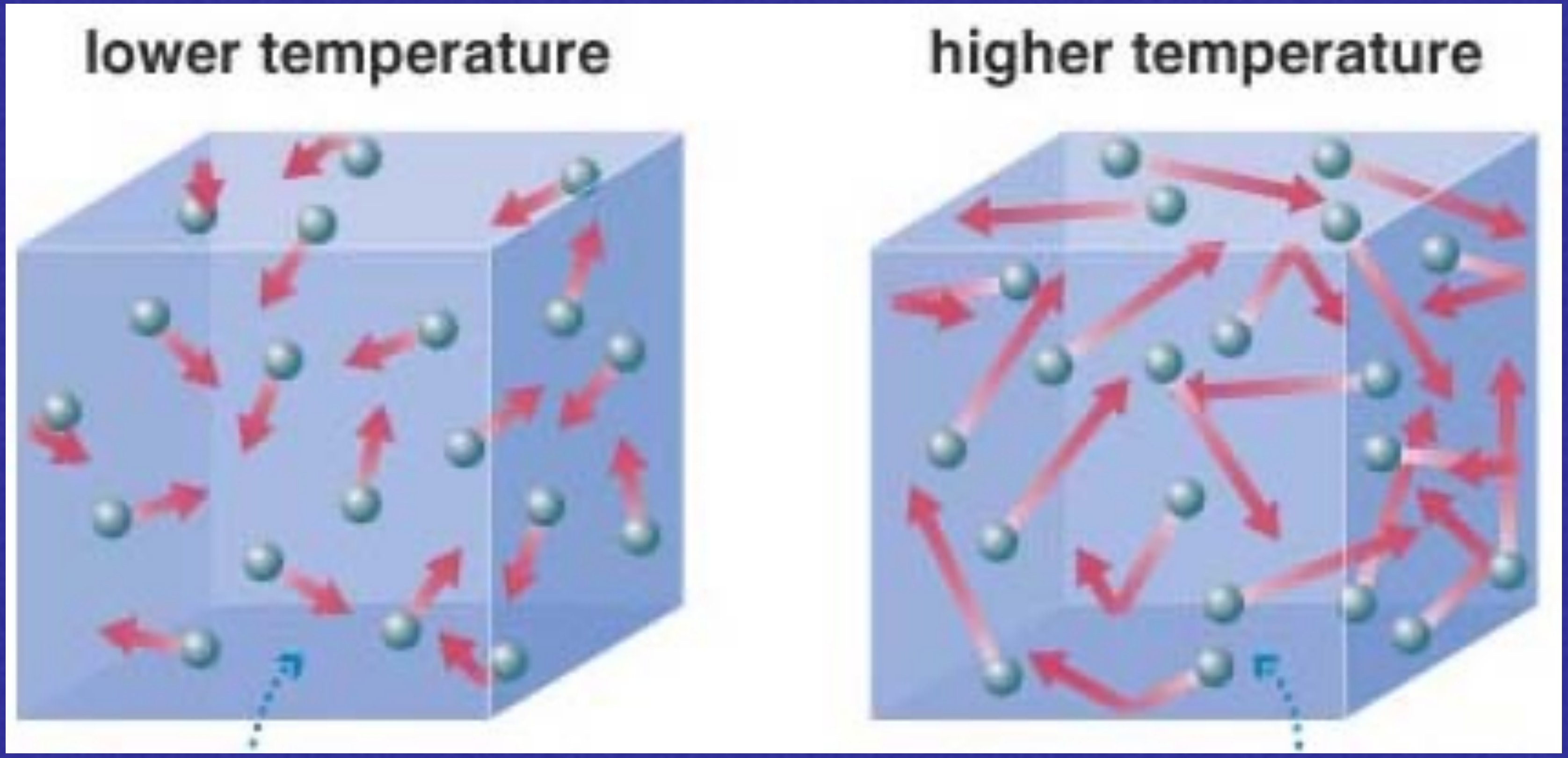
- But chemical reactions can only keep the Sun active for ~10,000 years… so how can the Earth be older than the Sun?

The ideal gas law

- Particles in hot gas move faster, and collide with more force than those in a cooler gas

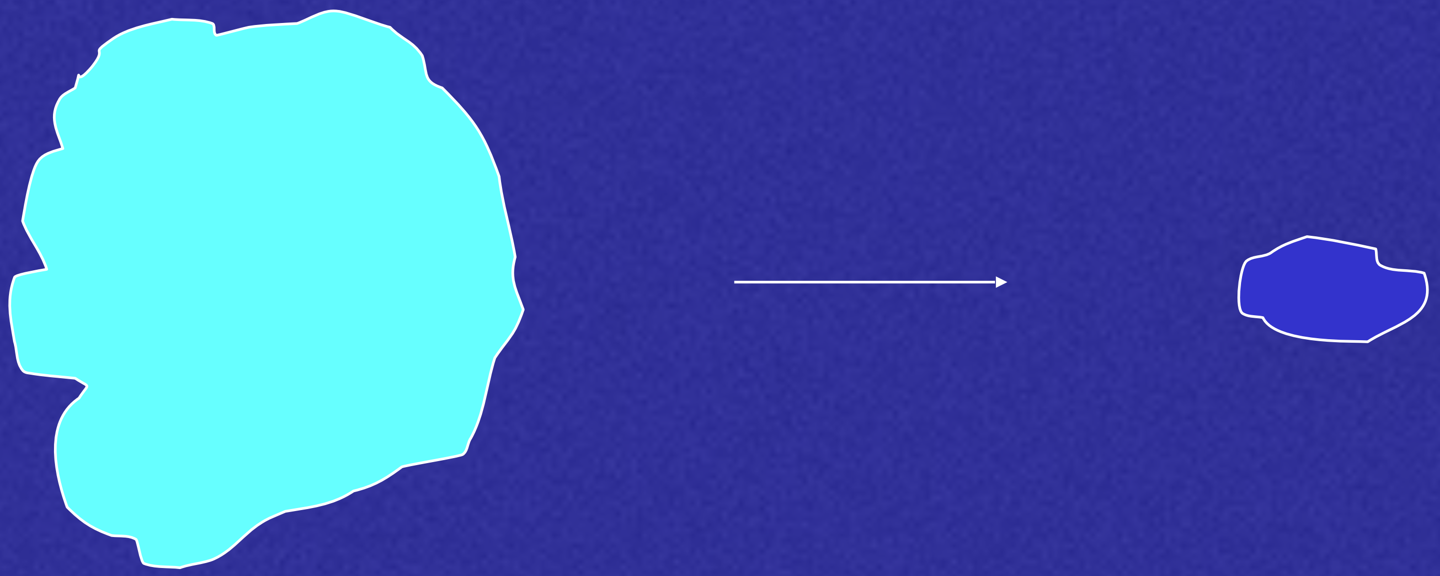
  => hot gas exerts higher pressure on any neighboring surface (P=F/A)

$P = nkT$



Kevin-Helmholtz mechanism

- First try: Kelvin-Helmholtz contraction
  - A contracting gas cloud heats up because of the gravitational potential energy of particles at large radii being converted into thermal energy
  - Some energy escapes as radiation (luminosity)



More gravitational energy

More thermal energy

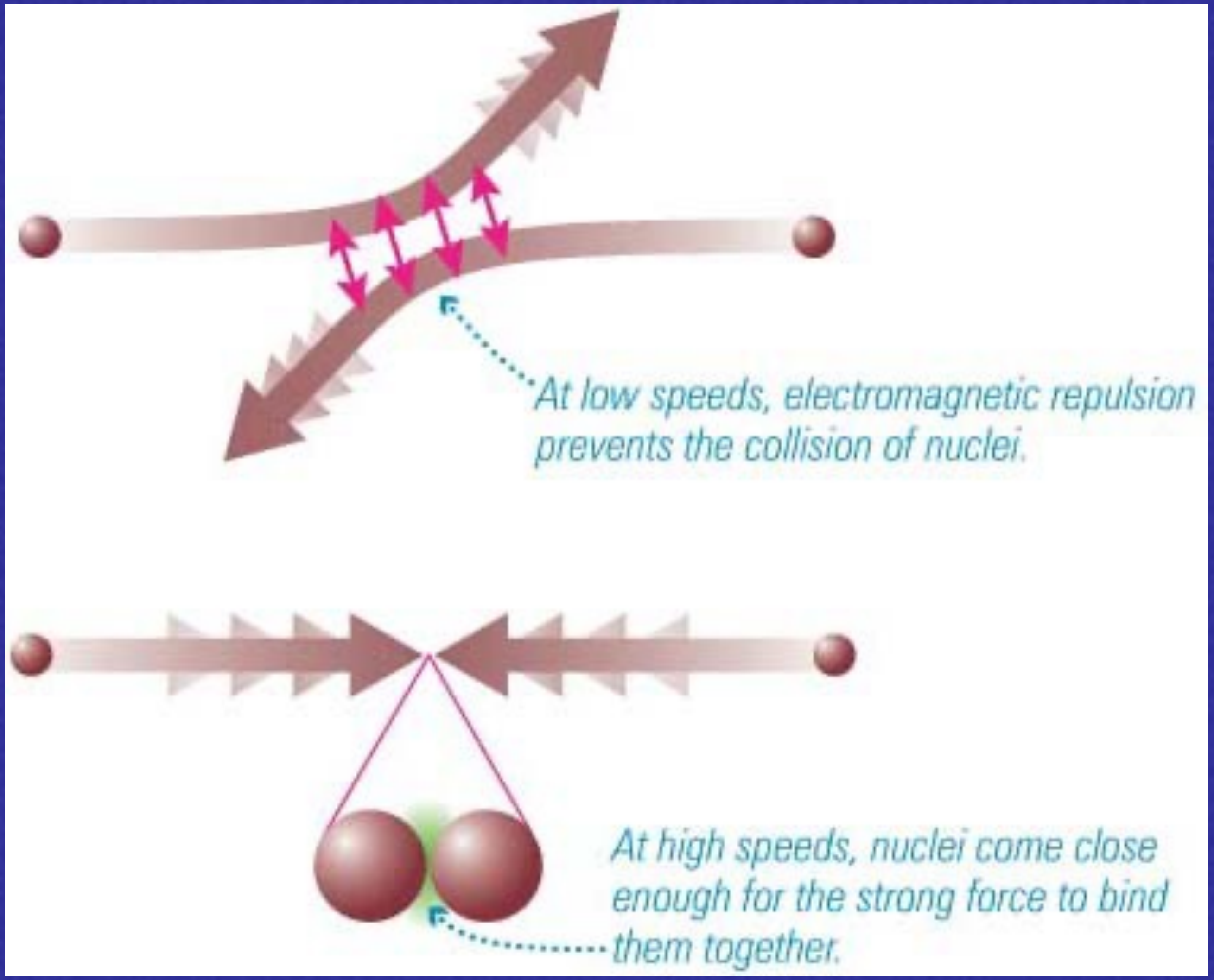
- Luminosity => heat radiates away, cools off the Sun
- Lower internal pressure => gravity compresses the Sun
- Pressure and internal heat increases => hydrostatic equilibrium restored
- … and over again, but now the Sun is slightly smaller!

Nuclear physics: early 1900s

- Einstein discovered that $E=mc^2$
- Eddington discovered that 4 protons have 0.7% more mass than 2p+2n (1 He) nucleus.
- Fusion: build up large nuclei from small ones
- Fission: break down large nuclei into small ones

Hydrogen fusion

- How to fuse 4 ^{1}H (p) into a ^{4}He (2p+2n)?
  - Unlikely 4 protons are colliding at once
  - Must turn 2 protons into 2 neutrons
  - Must be > 10^7 K to get protons close enough for fusion



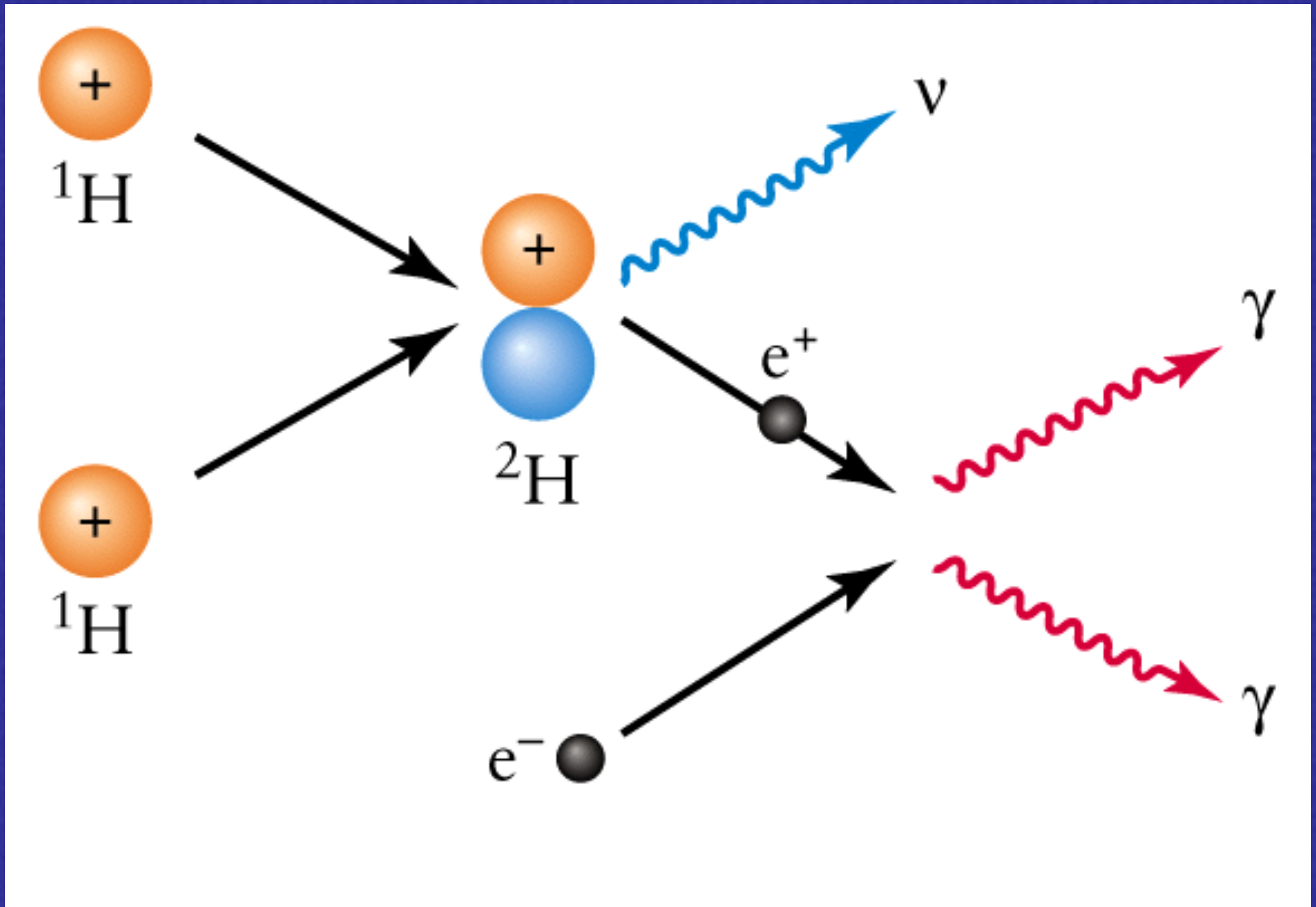
$$4H \rightarrow He + \text{energy}$$

Key: bring nuclei sufficiently close for the strong force to dominate over the electromagnetic force.

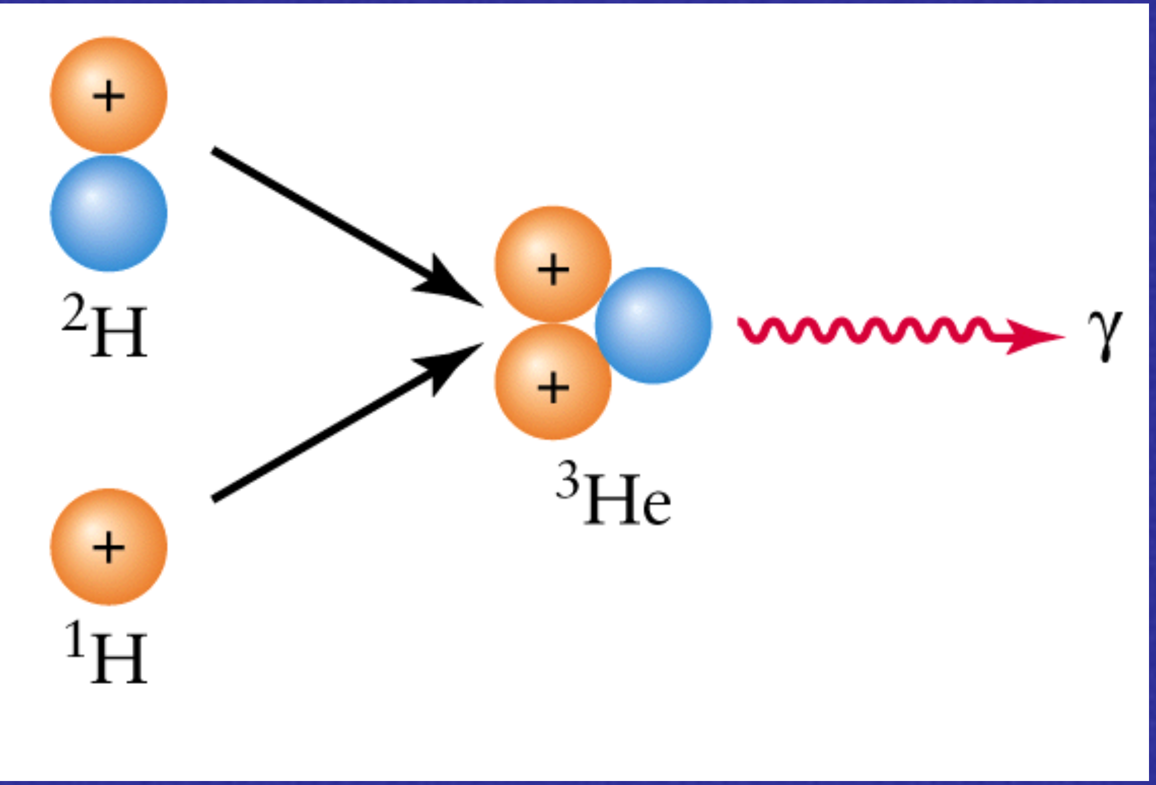
The proton-proton chain in pictures

- Starting point: at 1.5x10^7 K, hydrogen in the core of the Sun is completely ionized, thus a mixture of free electrons and protons (plasma)

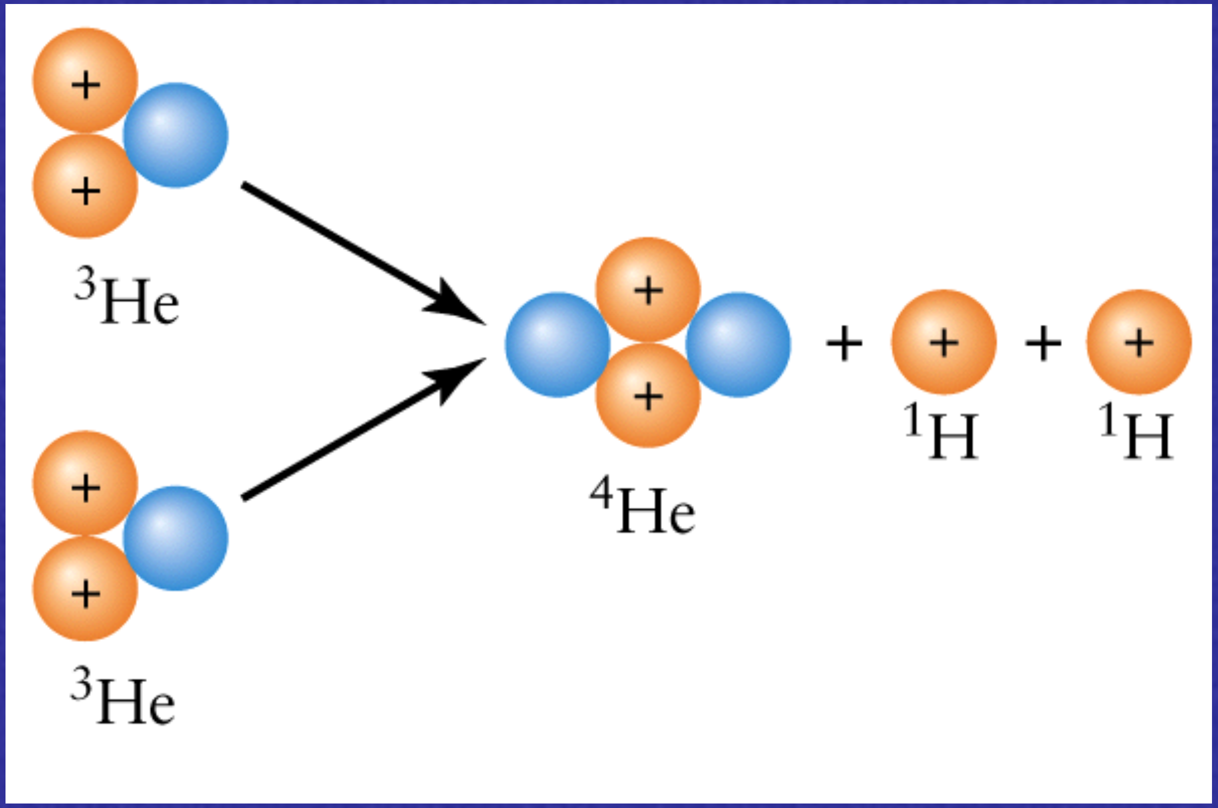
- Step 1:



Once the deuterium has been created, step 2 happens:



In step 3 common helium is formed:



Proton-proton chain

$p + p \rightarrow {}^2H + e^+ + \nu_e$ (twice)

$p + {}^2H \rightarrow {}^3He + \gamma$ (twice)

${}^3He + {}^3He \rightarrow {}^4He + p + p$

Note the six important byproducts: 2e+, 2 neutrino, 2 photons

Calorimetry

- The 4 protons have 4.8×10^{-29} kg more mass than the He nucleus (0.7% of the total mass has disappeared).
- $E=mc^2$ => 4.3×10^{-12} J is released by the formation of a single He nucleus.
- $L_{\odot} = 3.9 \times 10^{26}$ J/s => 6×10^{11} kg of H is converted to He every second.

- About 4×10^9 kg converted to energy per second
- Sun contains 21×10^{24} kg H (but only the inner 10% of the Sun is hot enough for fusion to take place)
- => fusion lifetime about 10 Gyrs.

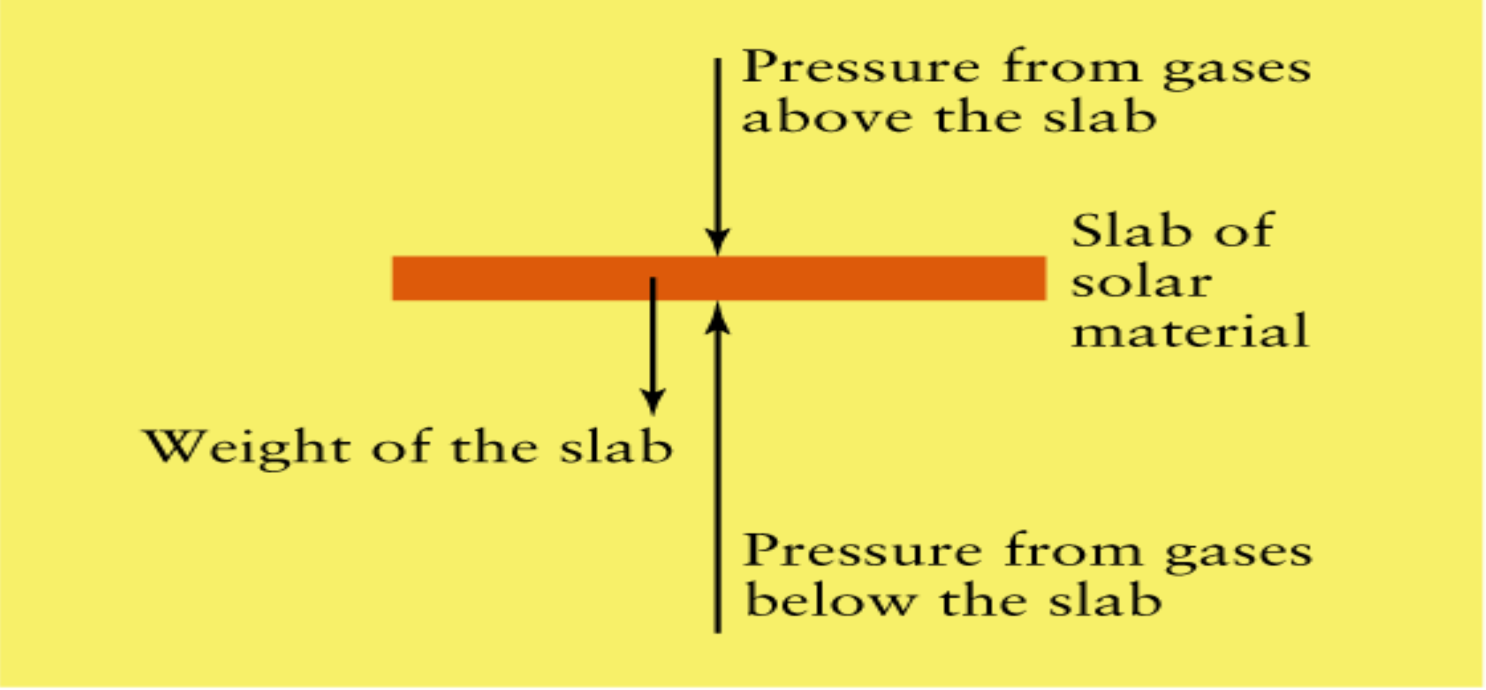
Radioactive dating of oldest rocks gives age of Earth to 4.4 Gyrs - no age crisis!

- The fusing together of nuclei is also called thermonuclear fusion, because it can only happen at very high temperatures

What is the Sun powered by?

Models of the Sun’s interior

- The Sun's interior is a gas (actually, a plasma = ionized gas)
- Hydrostatic equilibrium keeps it stable



(a) In hydrostatic equilibrium, forces balance

- Using ideas of hydrostatic equilibrium and thermal equilibrium (all energy generated by thermonuclear reactions in the Sun's core must be transported to the surface and radiated into space) we can create models of the Sun's interior.

- Models are created by solving equations, such as for hydrostatic equilibrium:

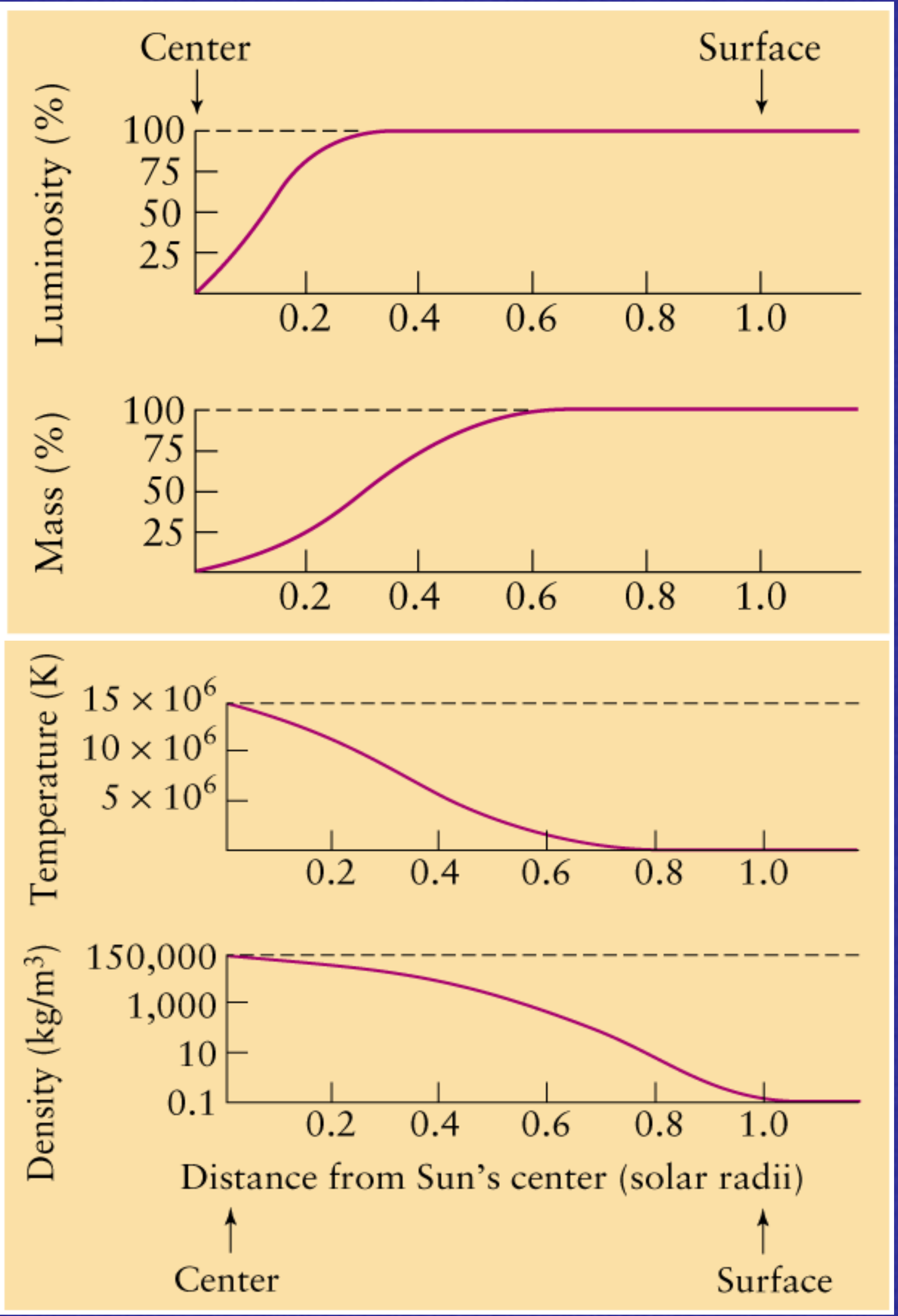
$$\frac{dP}{dr} = -\rho g$$

where *g* is local gravitational acceleration at radius *r*, and

table 18-2 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)	Pressure (relative to pressure at center)
0.0	0.00	0.00	15.5	160,000	1.00
0.1	0.42	0.07	13.0	90,000	0.46
0.2	0.94	0.35	9.5	40,000	0.15
0.3	1.00	0.64	6.7	13,000	0.04
0.4	1.00	0.85	4.8	4,000	0.007
0.5	1.00	0.94	3.4	1,000	0.001
0.6	1.00	0.98	2.2	400	0.0003
0.7	1.00	0.99	1.2	80	4×10^{-5}
0.8	1.00	1.00	0.7	20	5×10^{-6}
0.9	1.00	1.00	0.3	2	3×10^{-7}
1.0	1.00	1.00	0.006	0.00030	4×10^{-13}

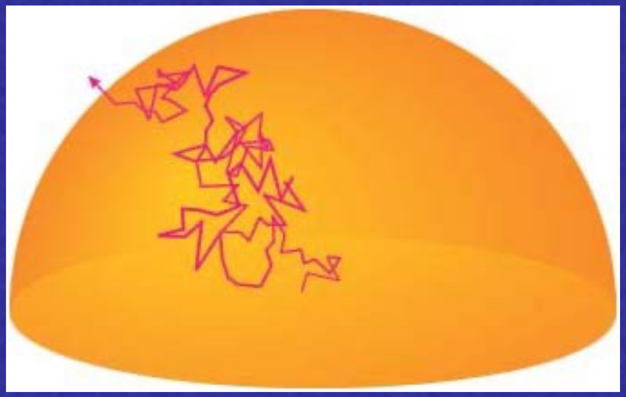
Note: The distance from the Sun's center is expressed as a fraction of the Sun's radius ($R_\odot$). Thus, 0.0 is at the center of the Sun and 1.0 is at the surface. The fraction of luminosity is that portion of the Sun's total luminosity produced within each distance from the center; this is equal to 1.00 for distances of 0.25 $R_\odot$ or more, which means that all of the Sun's nuclear reactions occur within 0.25 solar radius from the Sun's center. The fraction of mass is that portion of the Sun's total mass lying within each distance from the Sun's center. The pressure is expressed as a fraction of the pressure at the center of the Sun.



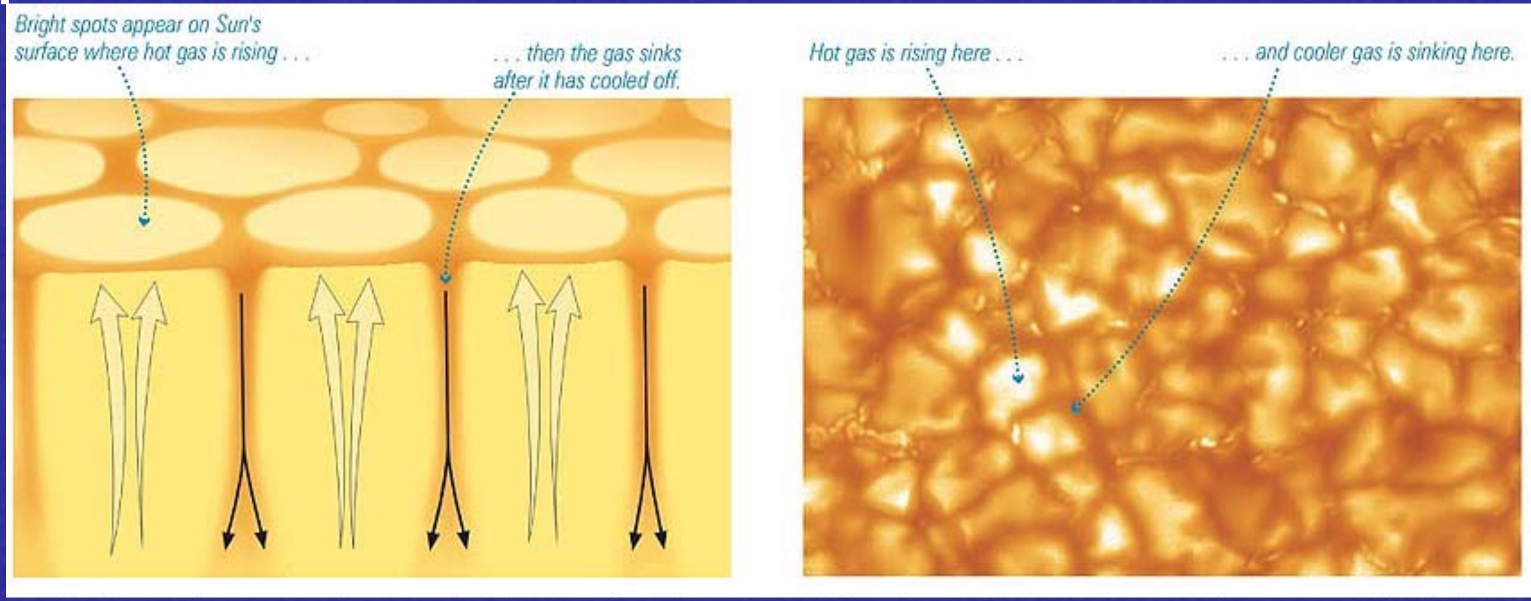
Center
Surface
Luminosity (%)
100
75
50
25
0.2
0.4
0.6
0.8
1.0
Mass (%)
100
75
50
25
0.2
0.4
0.6
0.8
1.0
Temperature (K)
15×10^6
10×10^6
5×10^6
0.2
0.4
0.6
0.8
1.0
Density (kg/m^3)
150,000
1,000
10
0.1
0.2
0.4
0.6
0.8
1.0
Distance from Sun's center (solar radii)
Center
Surface

How does energy get to the surface

- Radiation, or "radiative diffusion"
  - Photons created in core diffuse outward toward surface. Individual photons are quickly absorbed and reemitted by atoms and electrons in the Sun.

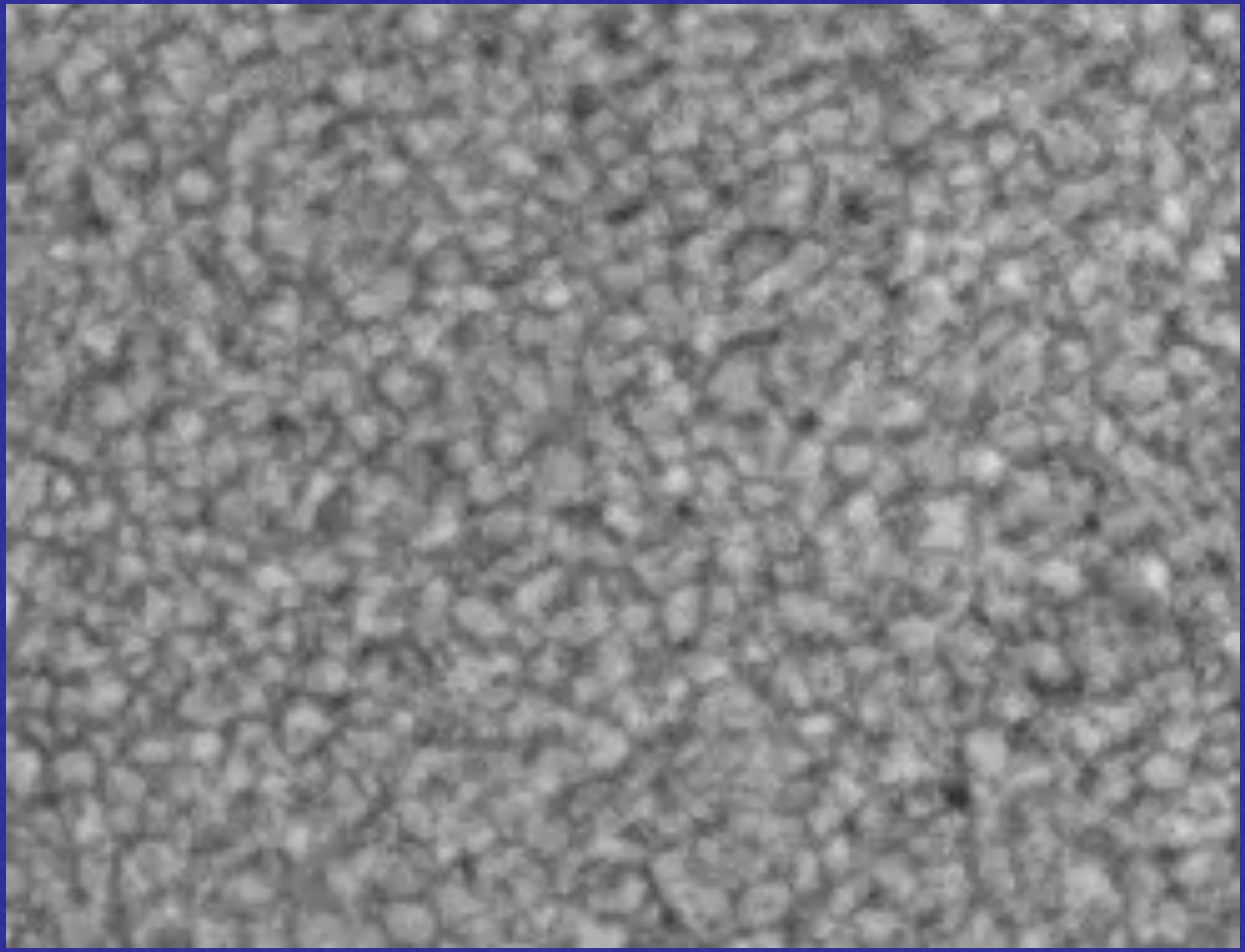


- Convection
  - Mass motion of gas, takes over where the Sun is too opaque for radiation to work well.

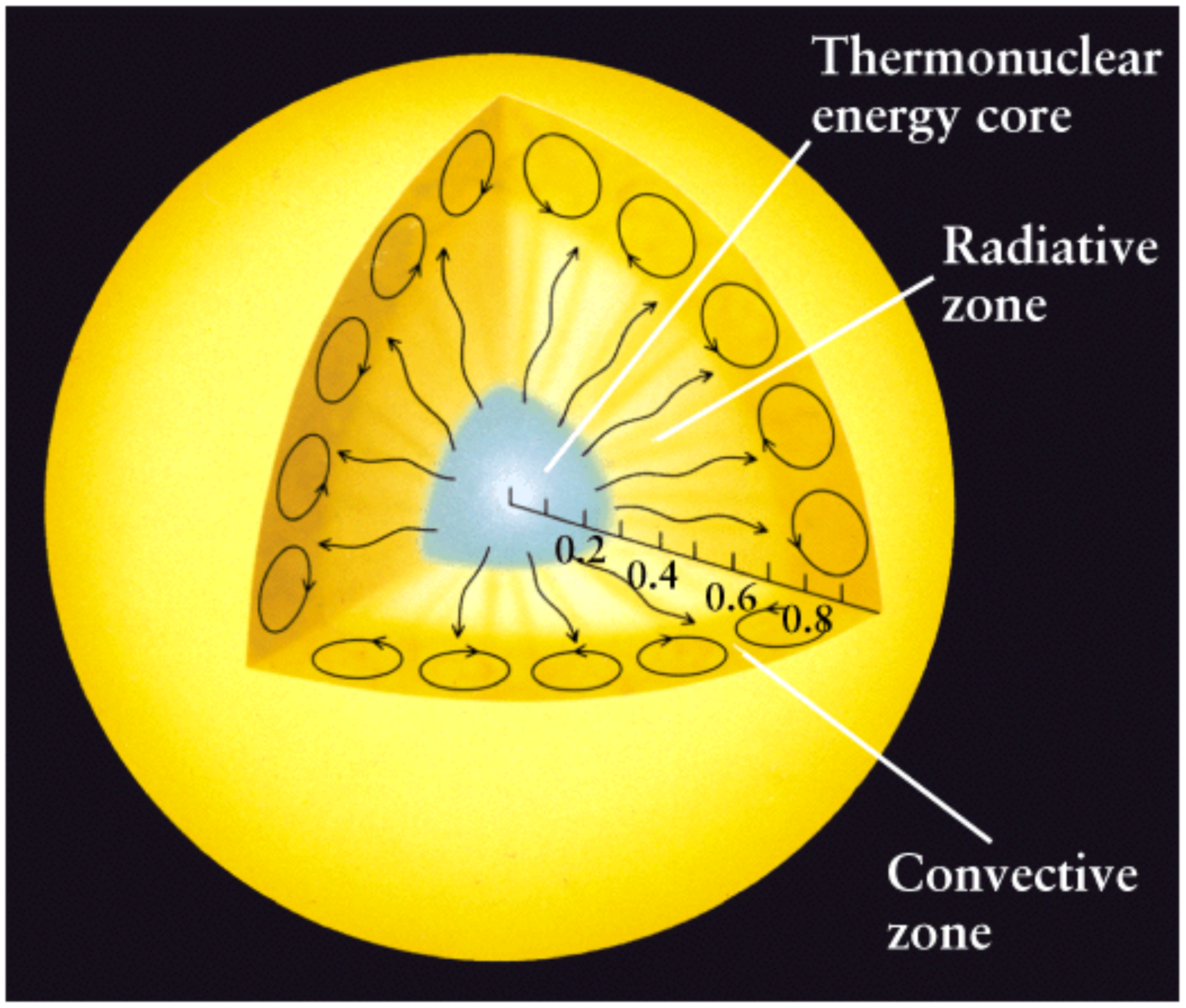


Can see rising and falling convection cells => granulation. Bright granules hotter and rising, dark ones cooler and falling. (Remember convection in Earth's atmosphere, interior and Jupiter).

Granules about 1000 km across



Why are cooler granules dark? Stefan-Boltzman's Law: flux = αT^4



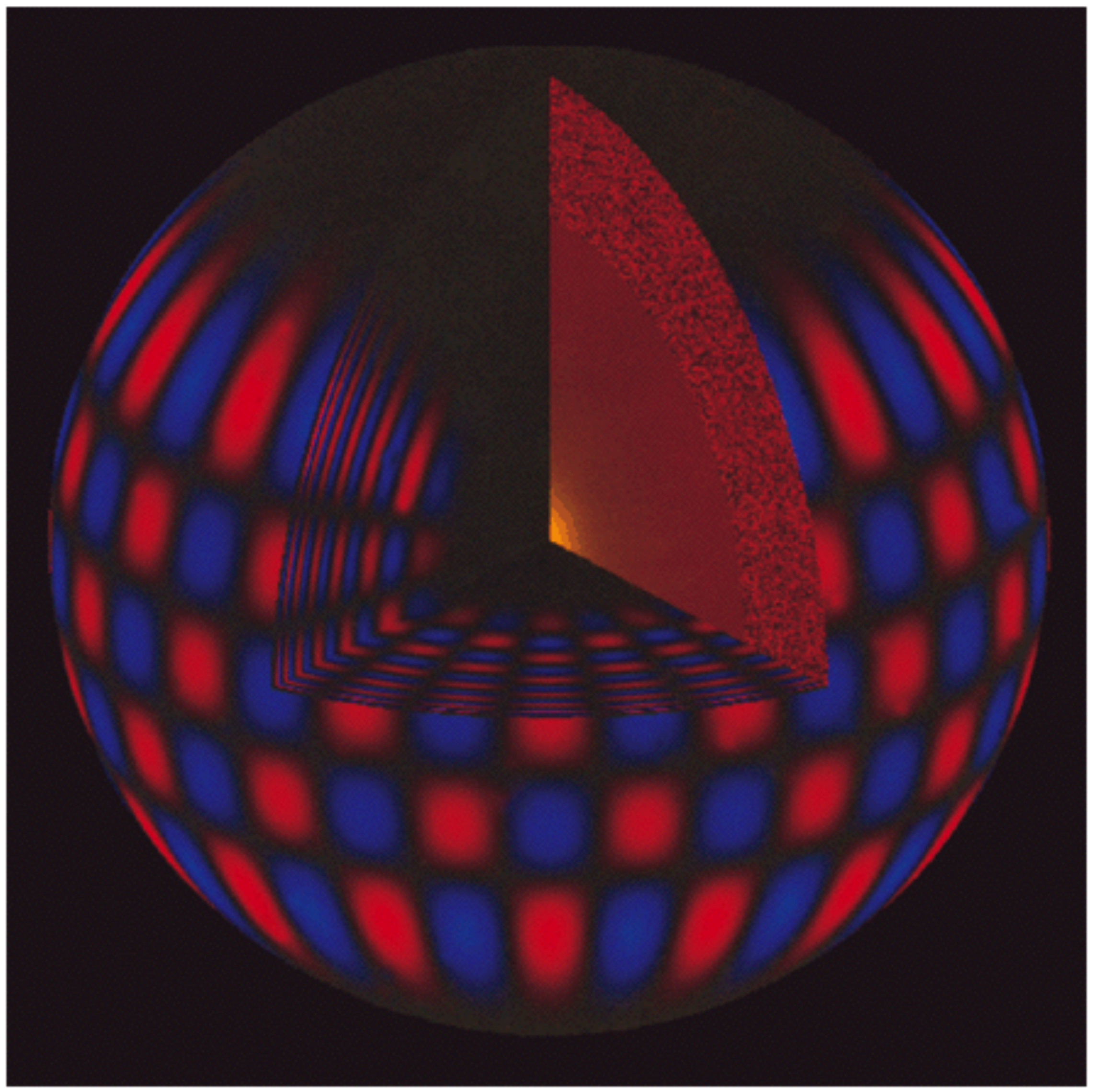
Gas is transparent

Gas is opaque (atoms and molecules can form here)

It takes about 170,000 years for energy created in the Sun’s core to get out, but it takes only about 8 minutes for light to travel from the photosphere to us.

Helioseismology

- A check on our models - sound waves probe the interior of the Sun, and generally confirm our theoretical understanding.



>10^7 modes seen by Doppler shifting at surface.

Periods depend on depth of resonant cavities and propagation speeds => probes temperature, composition and motions down to the core.

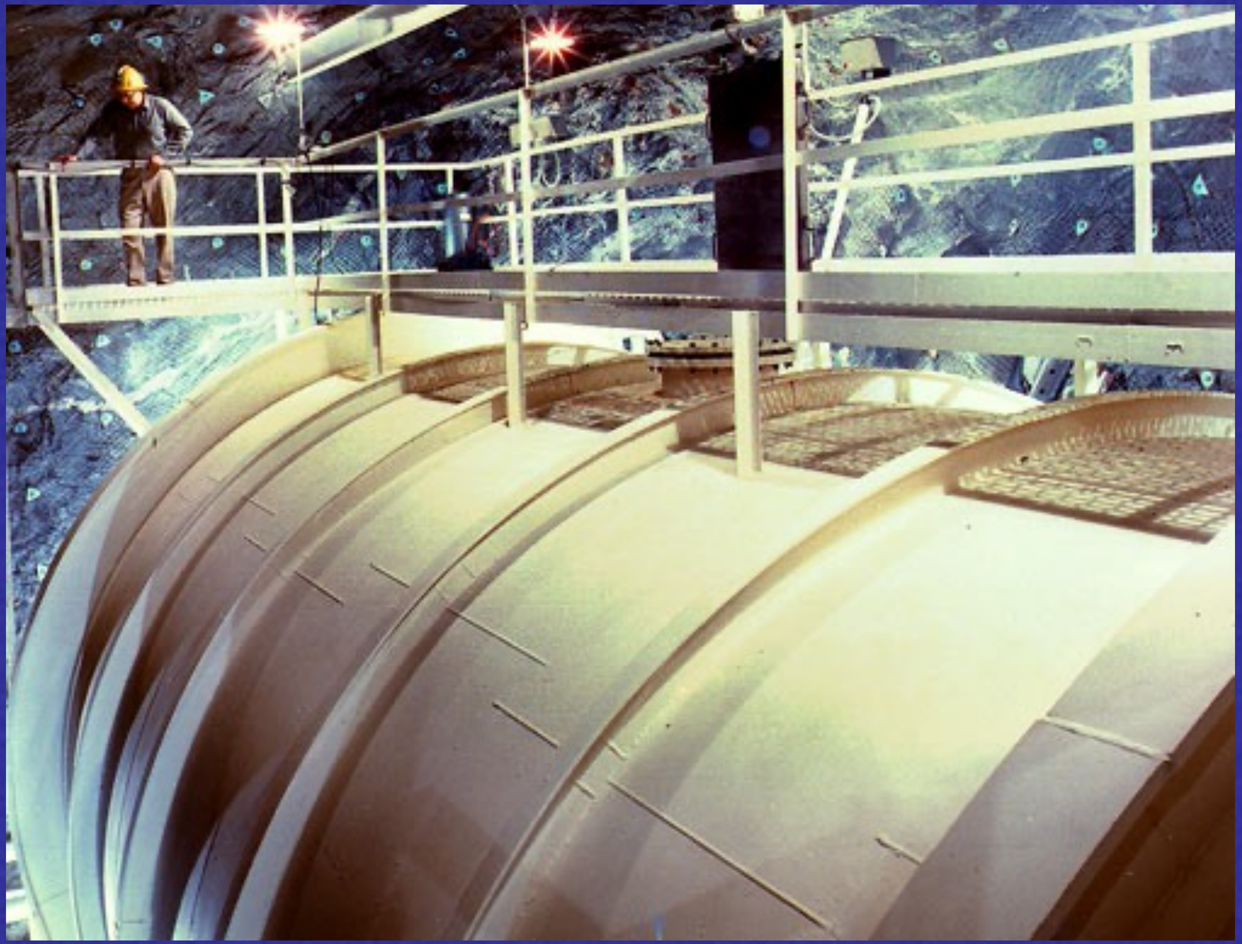
Does nuclear fusion really occur?

- Test: look for the neutrinos produced in the proton-proton chain: $p + p \rightarrow {}^2H + e^+ + \nu_e$
- Neutrinos are weakly interacting subatomic particles
  - Nearly mass less, traveling near *c*
  - Interact with matter via the weak nuclear force
  - Can pass undisturbed through a slab of lead of thickness 1 pc
- Detected via Cherenkov radiation: when a particle is moving at speeds larger than the speed of light in a medium.

Solar neutrino problem

In 1960s Ray Davis and John Bahcall measured the neutrino flux from the Sun and found it to be lower than expected (by 30-50%)

Confirmed in subsequent experiments
Theory of p-p fusion well understood
Solar interior well understood



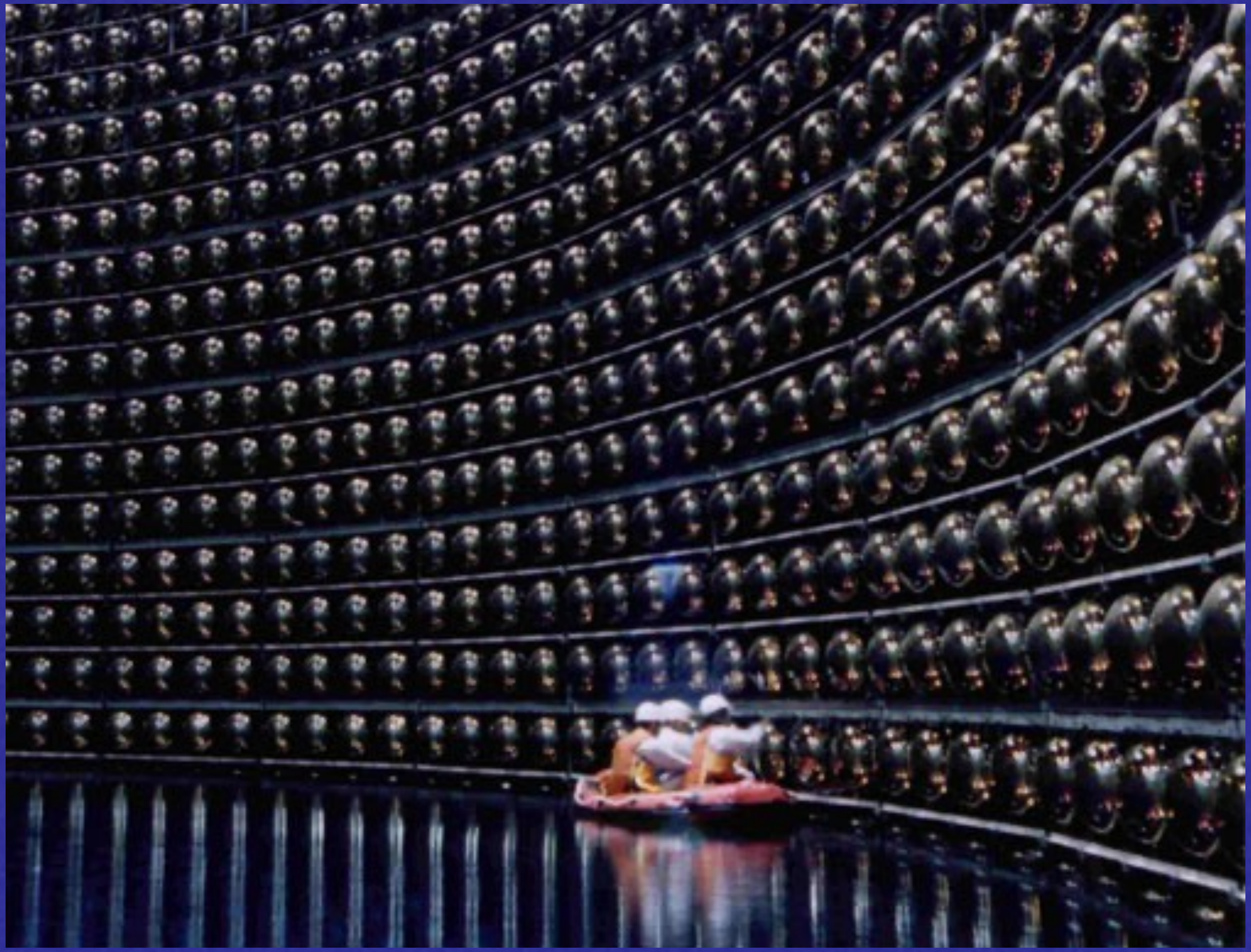
Answer to the Solar neutrino problem

Theoriticians like Bruno Pontecorvo realized

There was more than one type of neutrino

Neutrinos could change from one type to another

Confirmed by Super-Kamiokande experiment in Japan in 1998



50,000 gallon tank

Total number of neutrinos agrees with predictions

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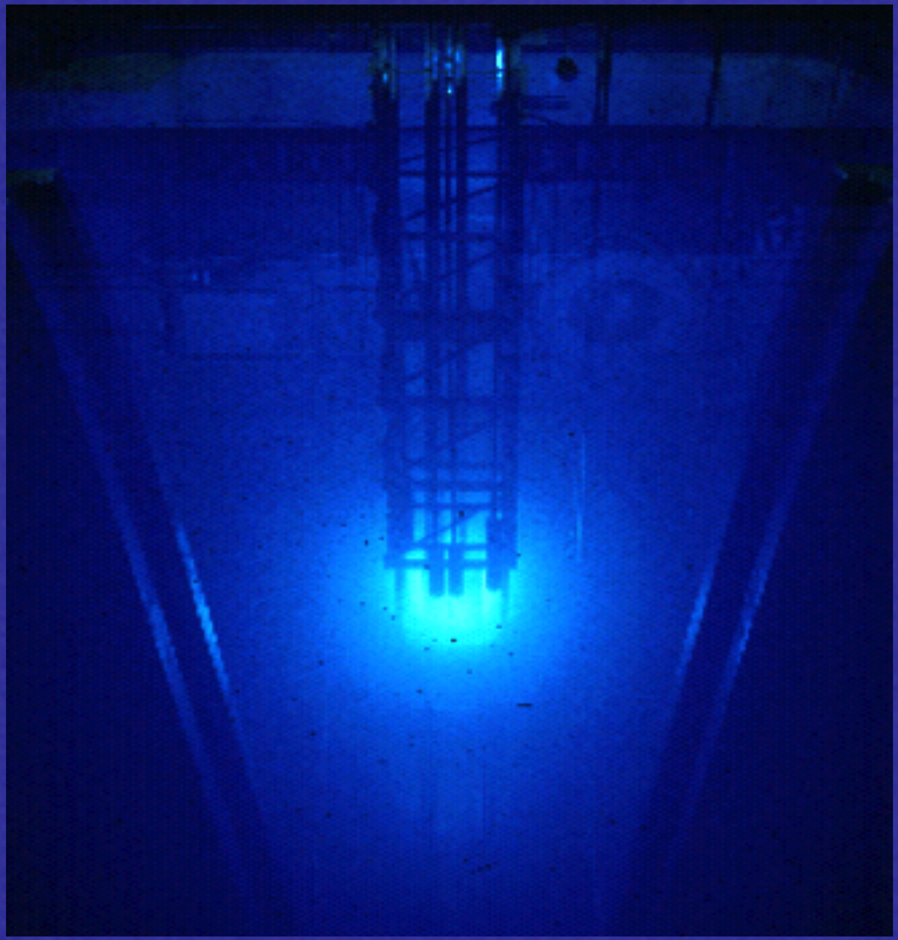
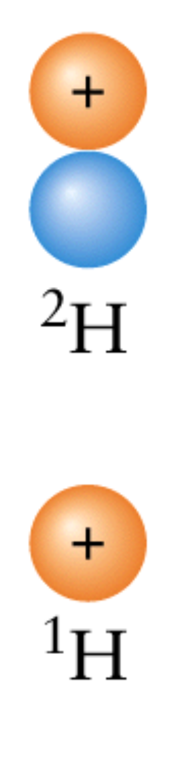
Examples of neutrino detectors: Kamiokande and Super-Kamiokande (Japan), Sudbury Neutrino Observatory (Canada), AMANDA/IceCube (South pole), GALLEX (Italy)

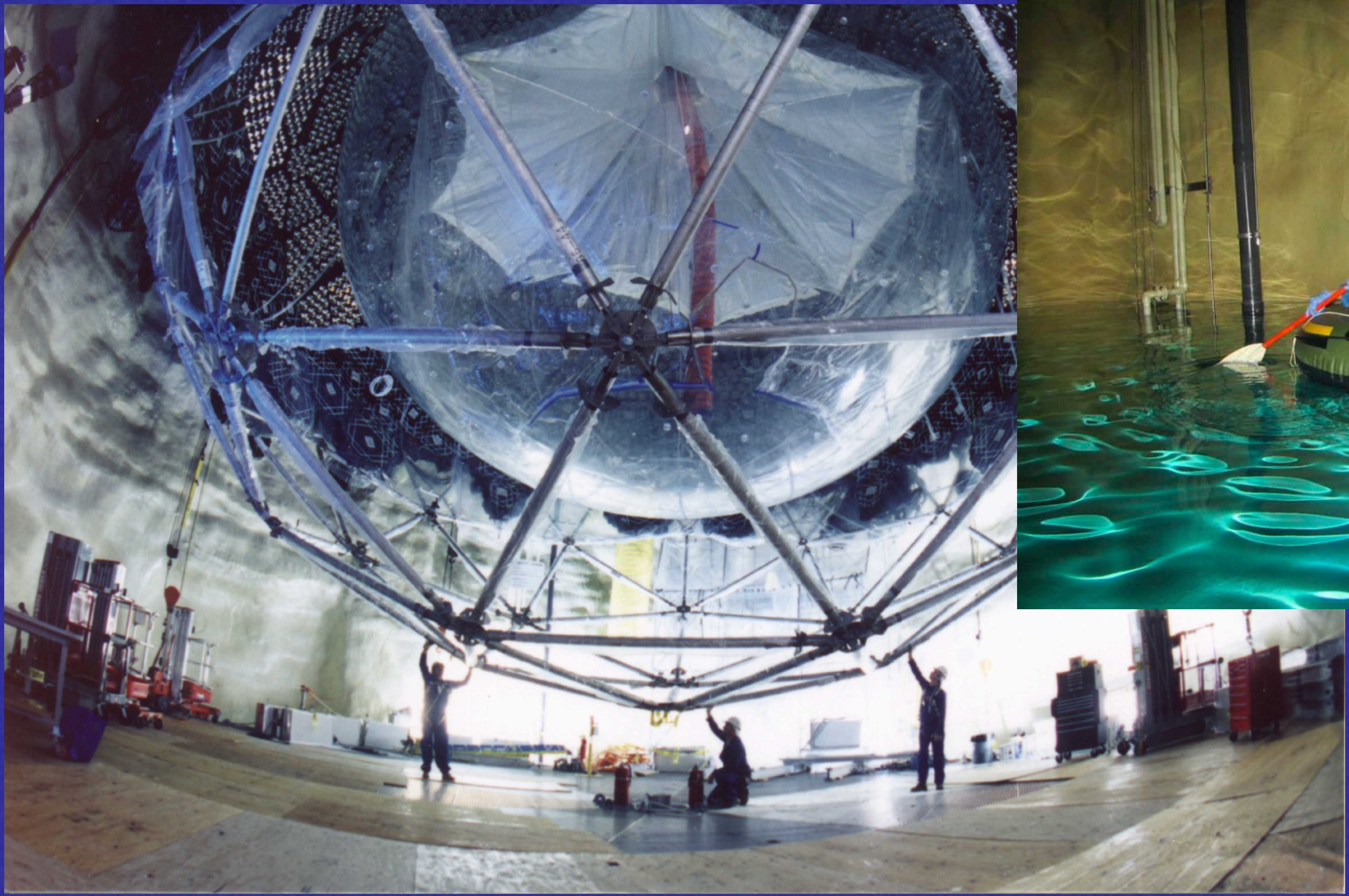


Sudbury Neutrino Observatory (SNO)

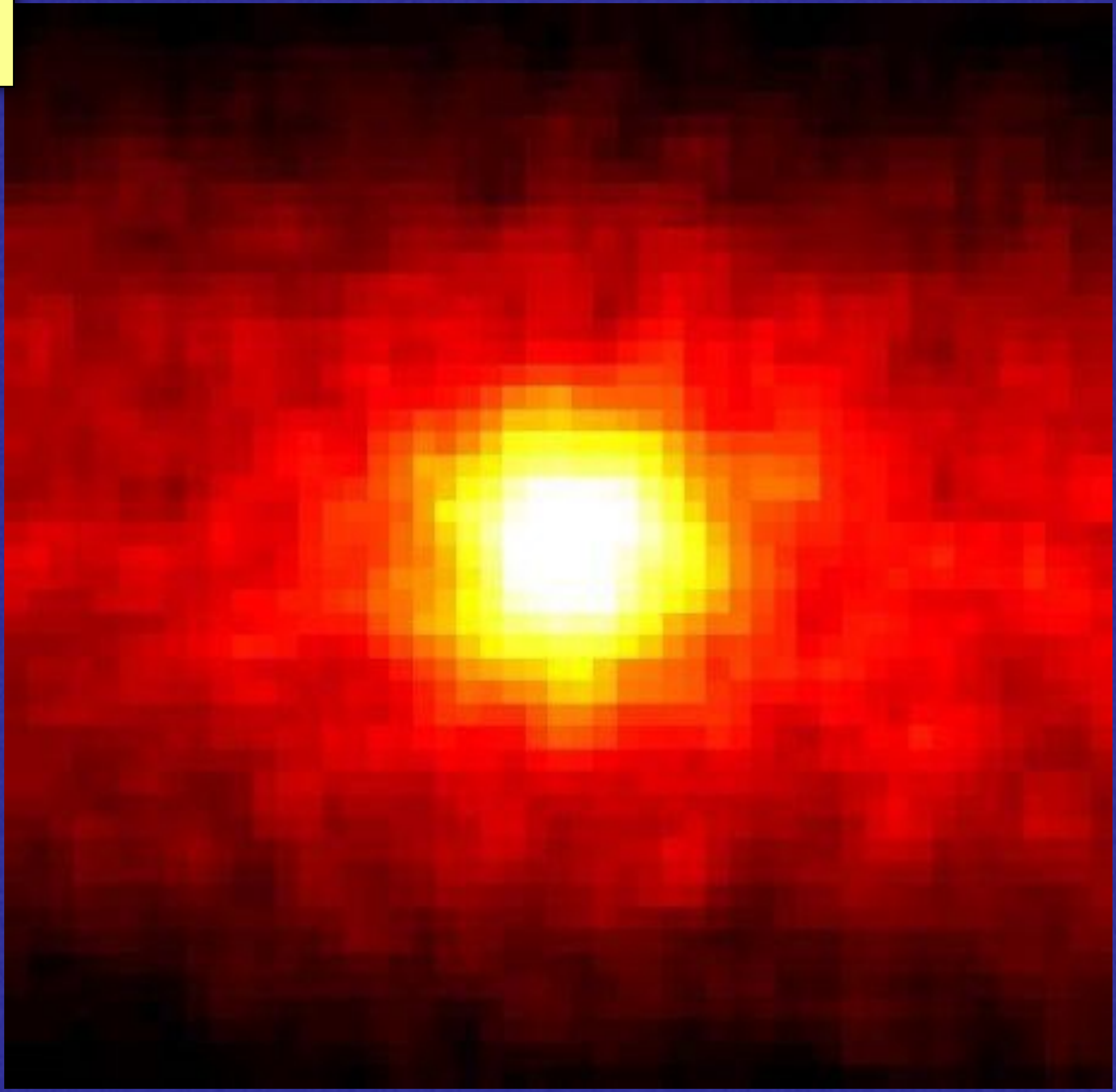
Detection hard, since enormous amount of detector material needed (heavy water in the case of SNO), and must be underground to be shielded from other cosmic radiation



Sudbury Neutrino Observatory (SNO)

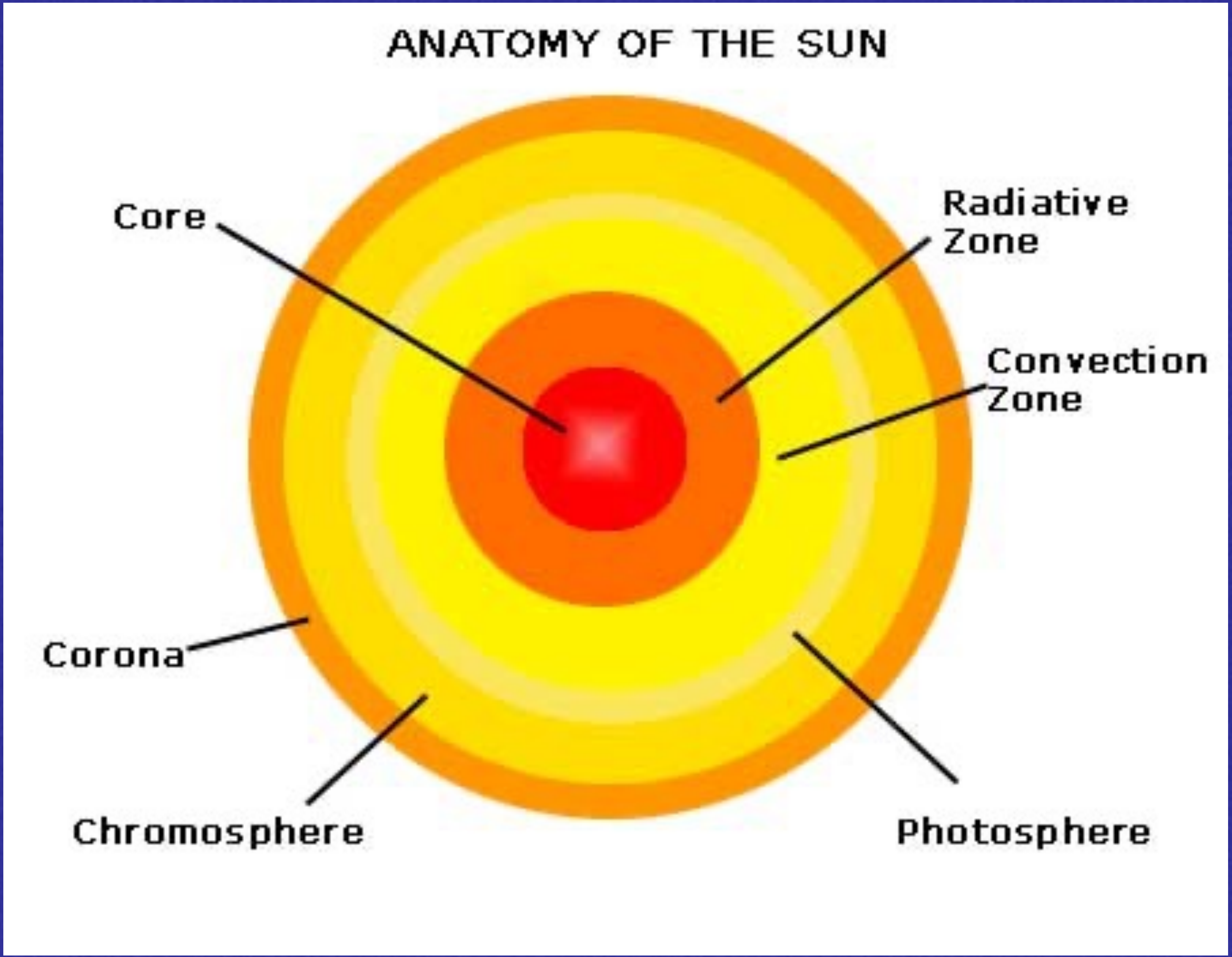


90 x 90 degree neutrino image in direction of Sun



Neutrinos detected at expected energies confirm that the energy source in stars is nuclear fusion.

Overall structure



The Sun's atmosphere

- Photosphere: yellowish color. The part we see, T=5800 K.
- The Sun is a giant sphere or gas - so it doesn't have a well defined surface
- Talking about the surface: we mean the photosphere
- The point where atmosphere becomes completely opaque is the photosphere (defines diameter of the Sun)

- For something not having a well defined surface, it doesn't look very fuzzy, it looks well defined?
- We see about 400 km into photosphere - a tiny distance (0.06%) compared to radius (696,000 km) so looks sharp ("unresolved" to eyes).

Solar photosphere as a function of depth

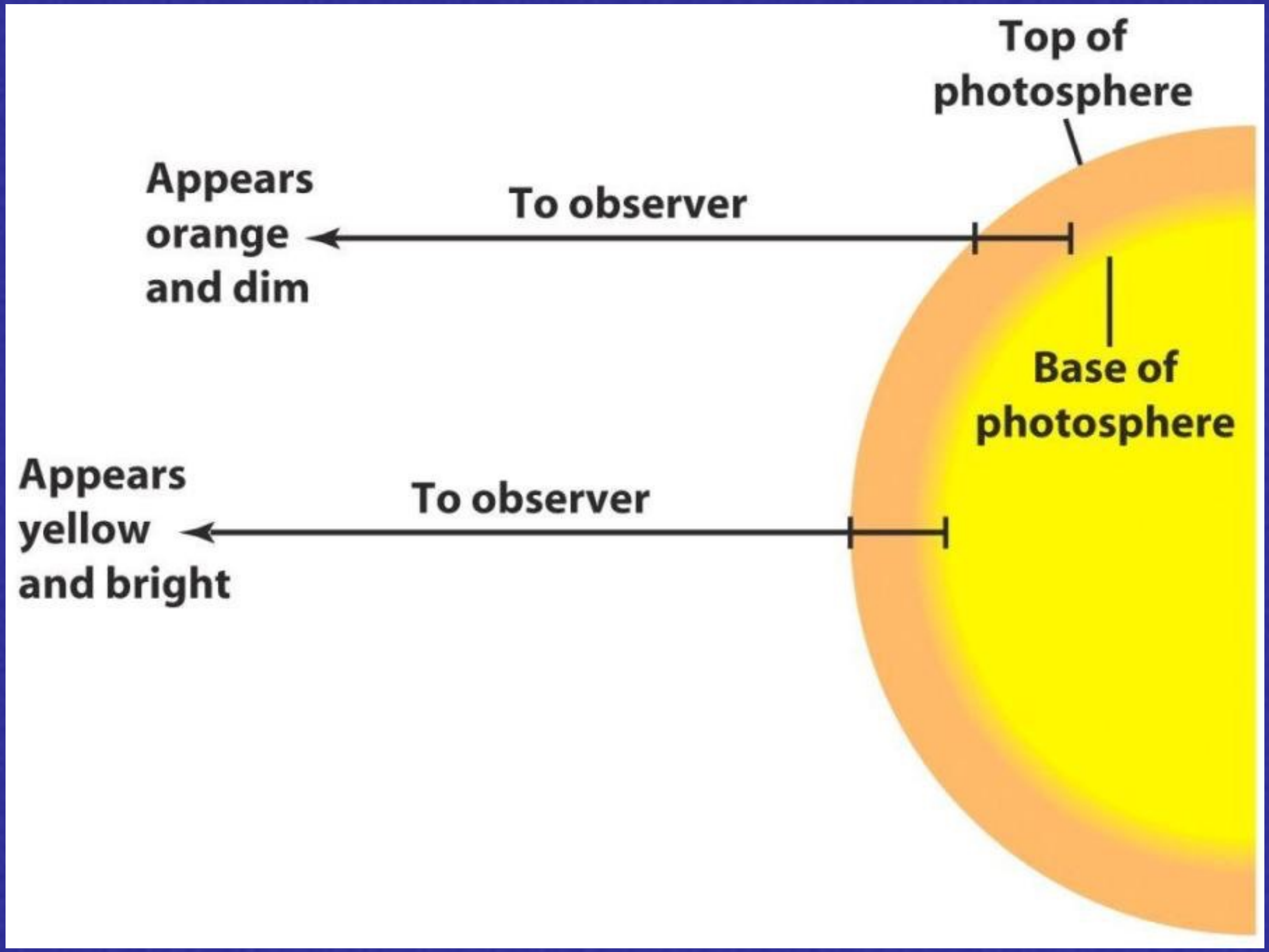
Depth (km)	% Light	Temp (K)	Pressure(bars)
0	99.5	4465	6.8×10^{-3}
100	97	4780	1.7×10^{-2}
200	89	5180	3.9×10^{-2}
250	80	5455	5.8×10^{-2}
300	64	5840	8.3×10^{-2}
350	37	6420	1.2×10^{-1}
375	18	6910	1.4×10^{-1}
400	4	7610	1.6×10^{-1}

Limb darkening

- Outer portions of photosphere being cooler
- Photons travel about the same path length

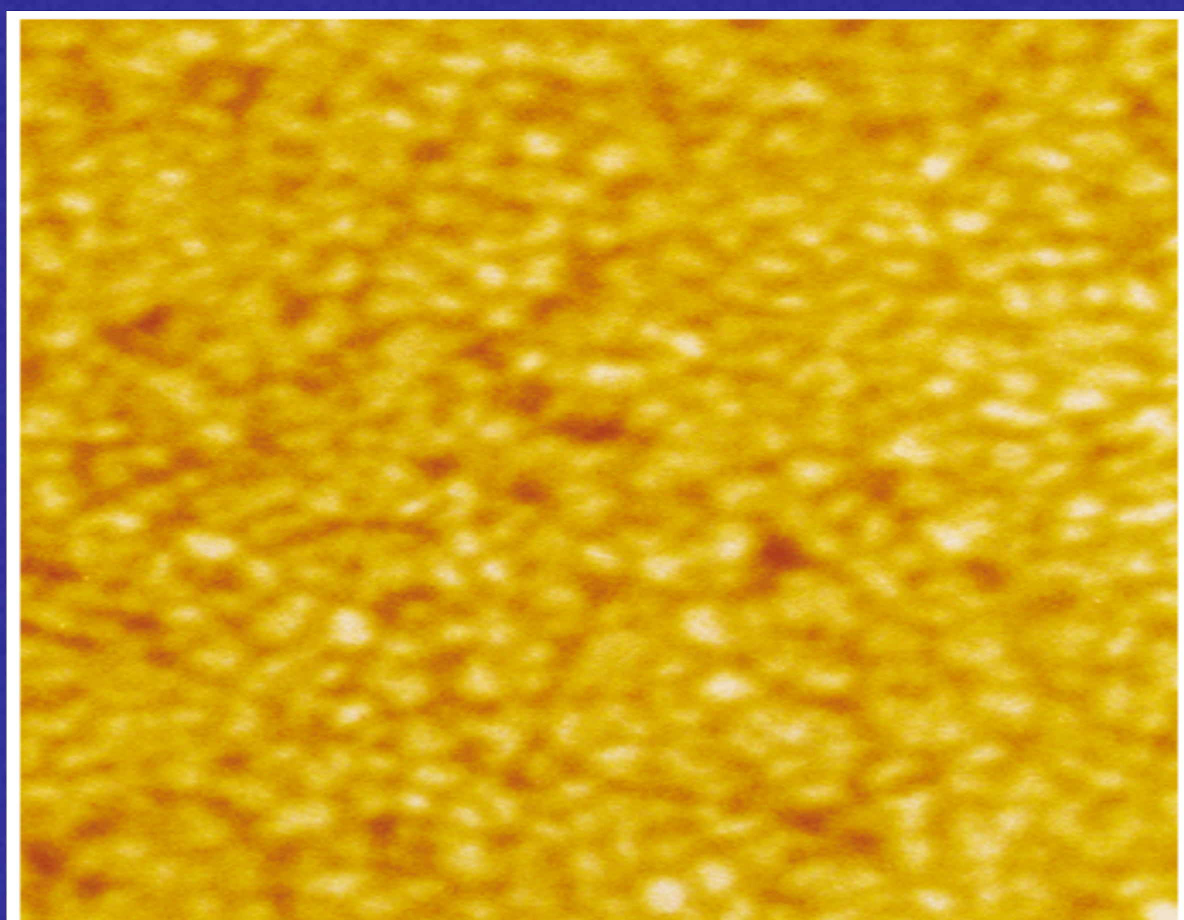
Dimmer light comes from higher, relatively cool layer within the photosphere

Bright light comes from low-lying, hot layer within the photosphere

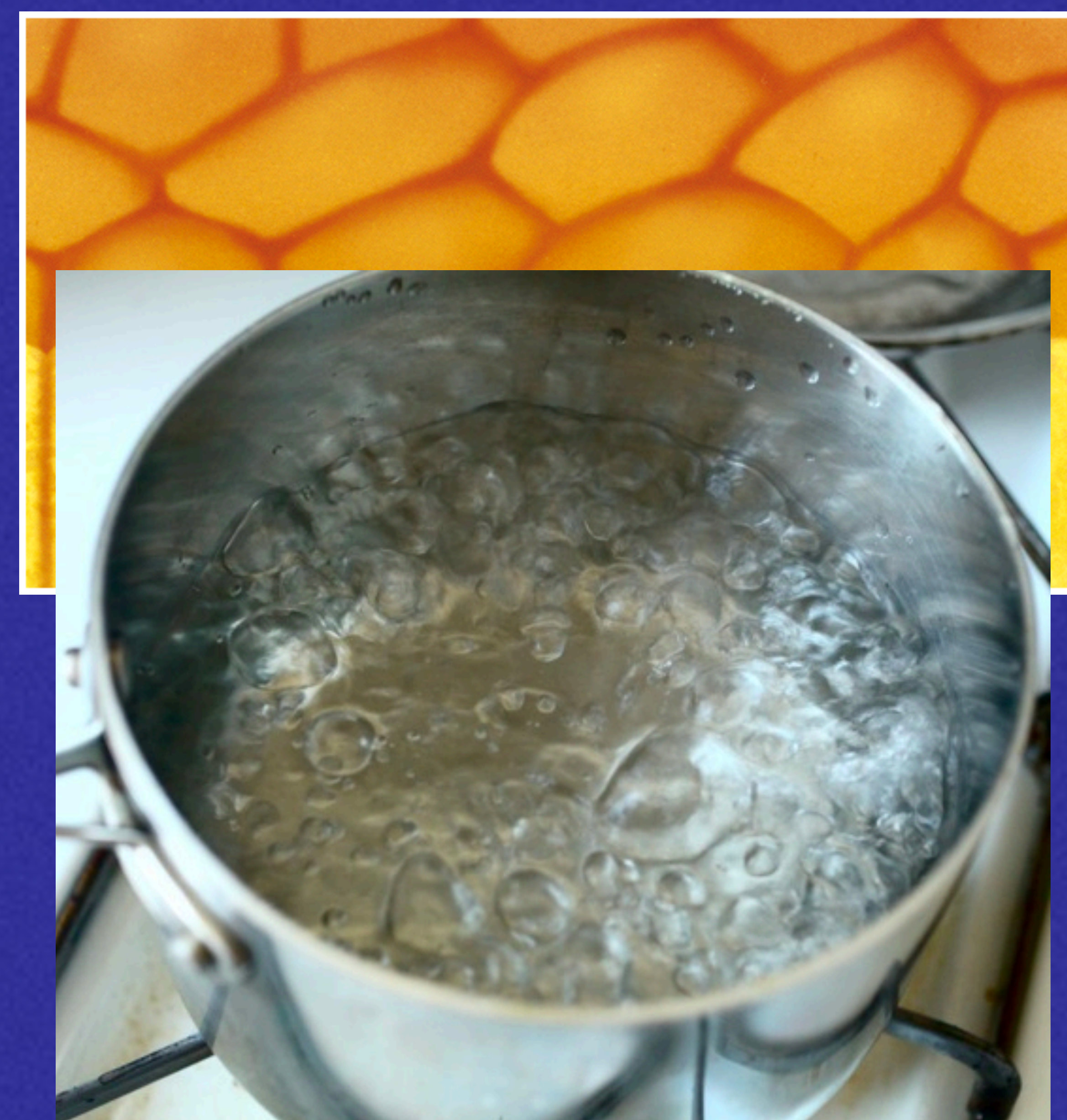


Granulation

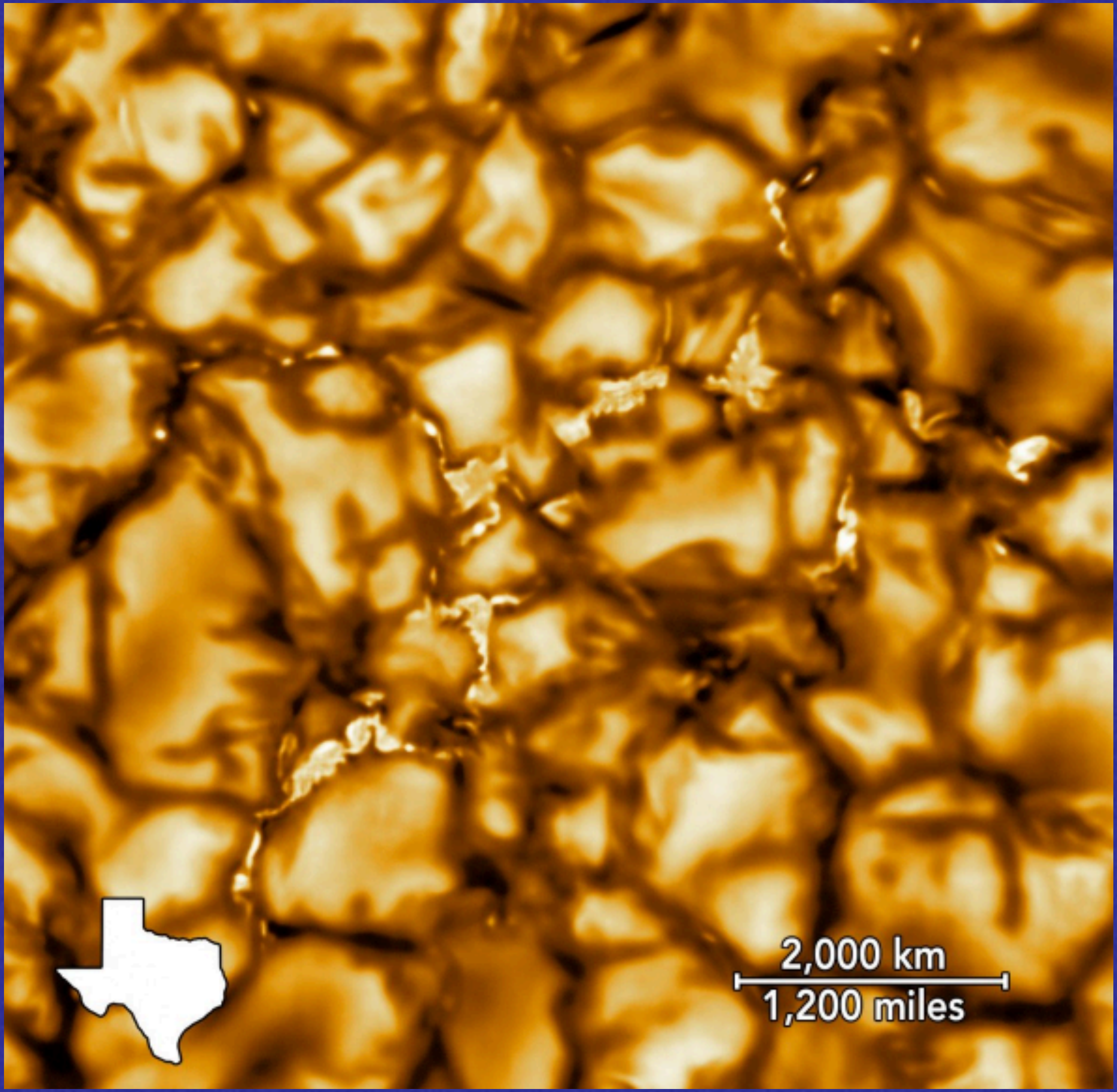
- Photosphere is lowest of 3 atmospheric layers
- Granulation due to convection

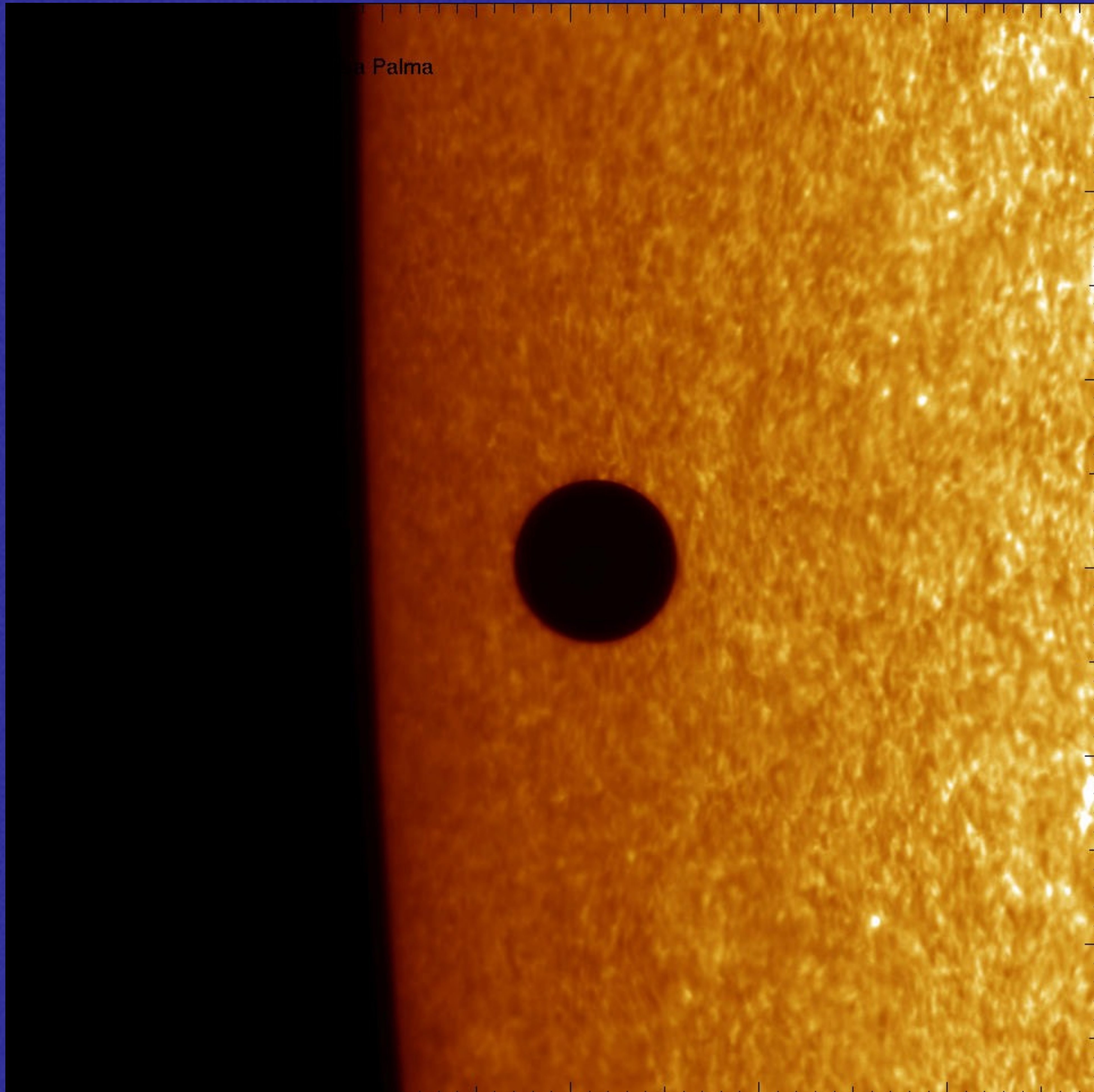


This picture shows blobs ~1000 km across



- Image from DKIST (4m) on Maui, ~30 km resolution

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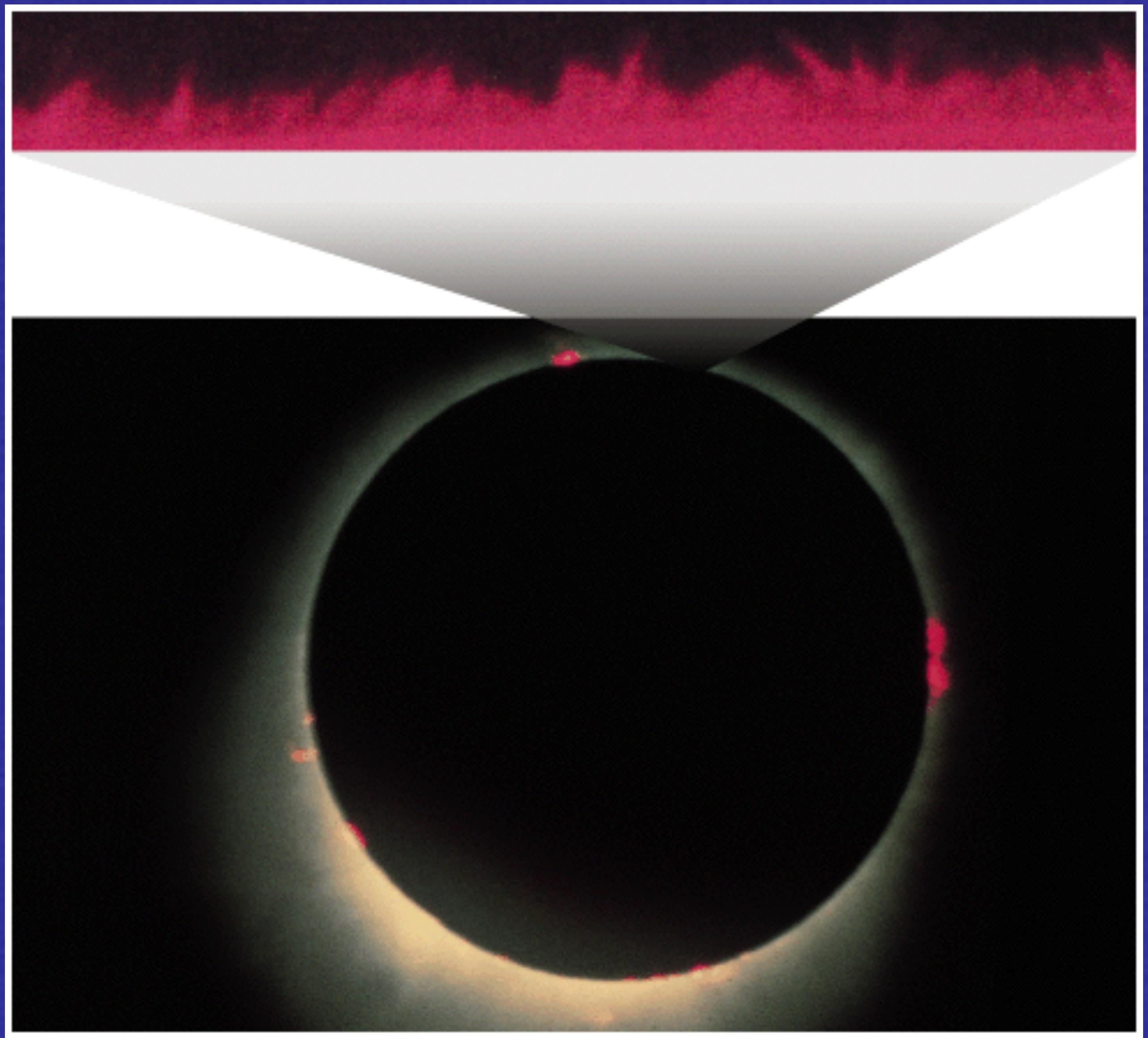
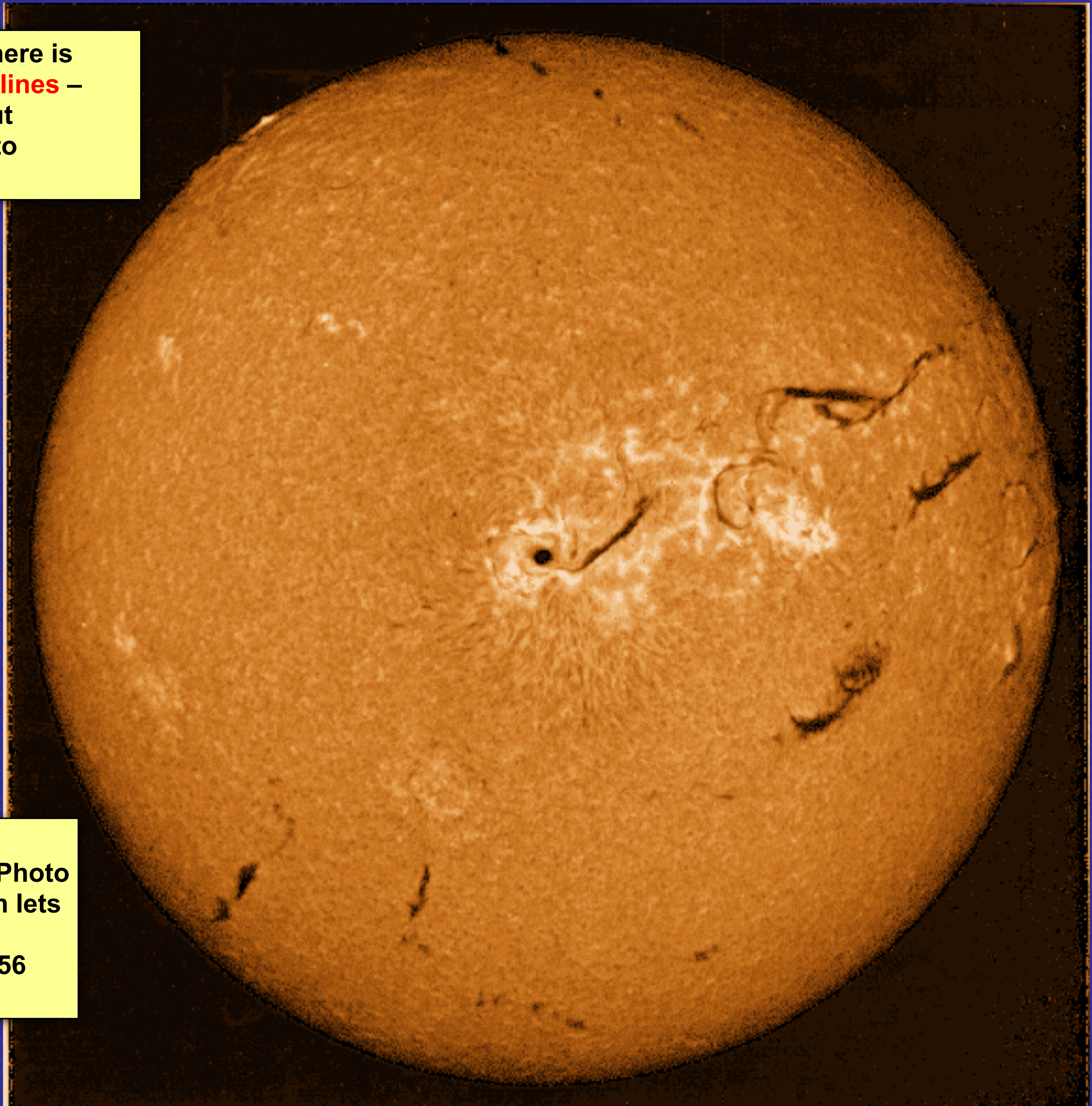
Chromosphere

- Middle layer, characterized by Hα emission: red color.
- The gas is very rarefied (10^{-4} density of photosphere).
- Also featured are gas plumes jutting upward.



Spectrum of chromosphere is dominated by emission lines – what does this say about temperature compared to photosphere?



H alpha image showing chromospheric activity. Photo taken through filter which lets through only light of wavelength of H-alpha (656 nm).