

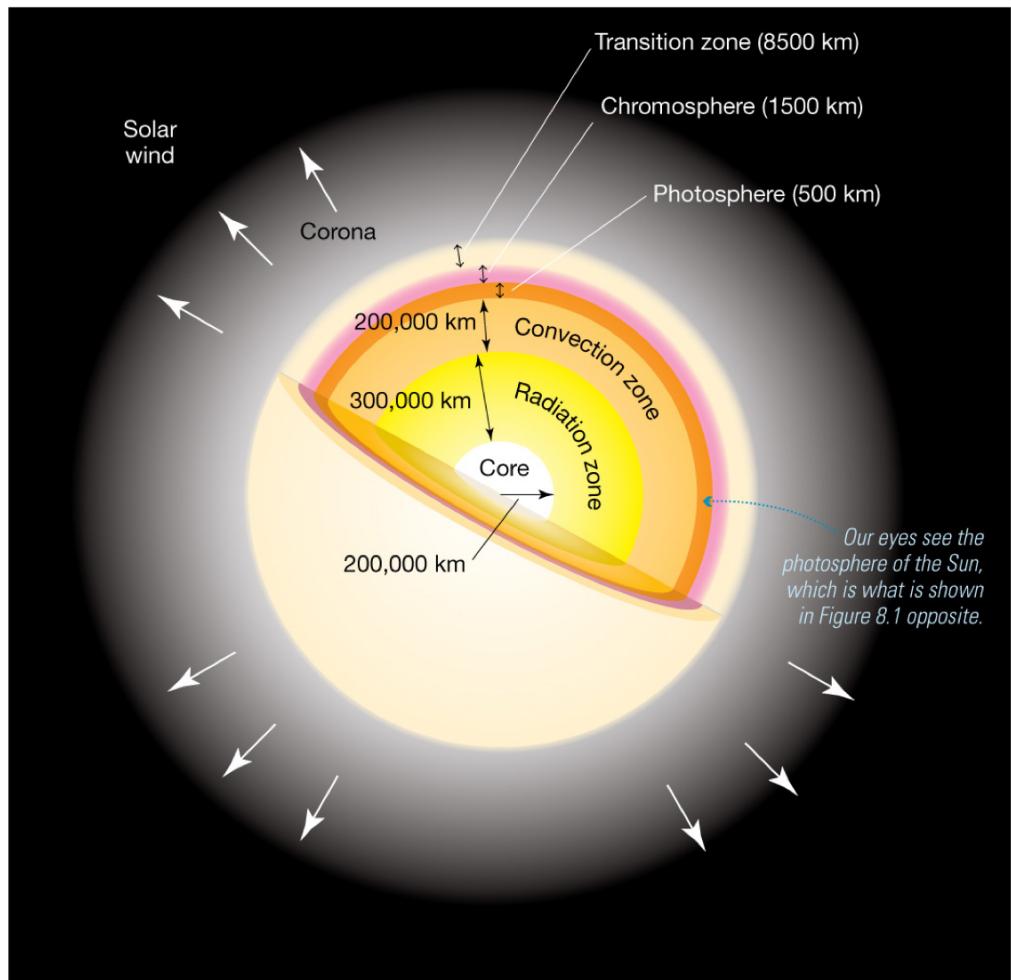
# Chapter 16: The Sun

Prof. Douglas Laurence

AST 1004

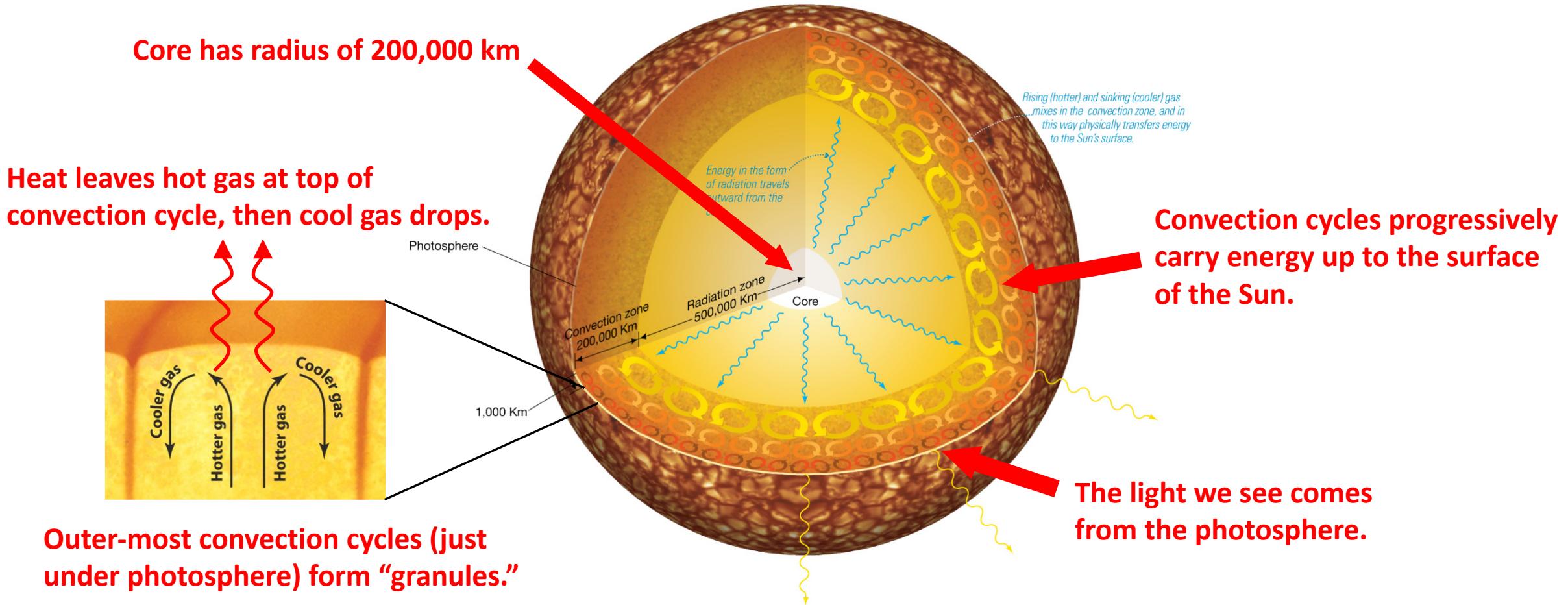
Summer 2018

# Properties of the Sun



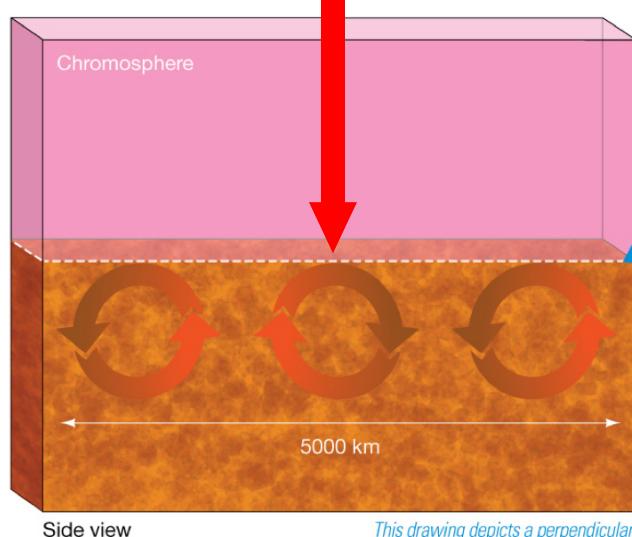
- The Sun is a **star**: a collection of hot gas, mostly hydrogen, which emits light like a blackbody. The Sun is a fairly typical star for our solar system.
- The Sun rotates, but unlike the Earth, it orbits differently between the equator and the poles.
- The Sun has several layers to it:
  - The innermost layer, the **core**, is where the Sun produces its power via nuclear fusion.
  - The **radiation zone**, a transparent gas (one that light can pass through) that allows light to move towards the surface.
  - The **convection zone**, an opaque gas (which light cannot pass through), which moves energy towards the surface via convection currents.
  - The **photosphere**, where the light we see is physically generated.
  - The 3 outer layers – the photosphere, chromosphere, and corona – form the **solar atmosphere**.

# Radiation vs. Convection Zones



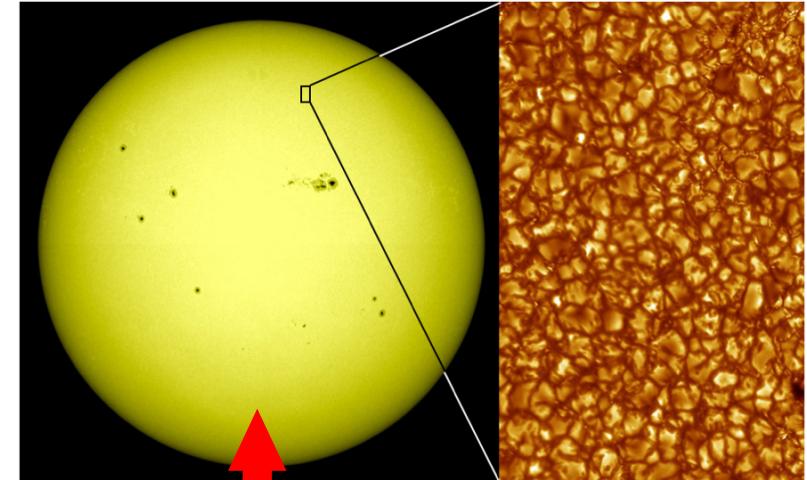
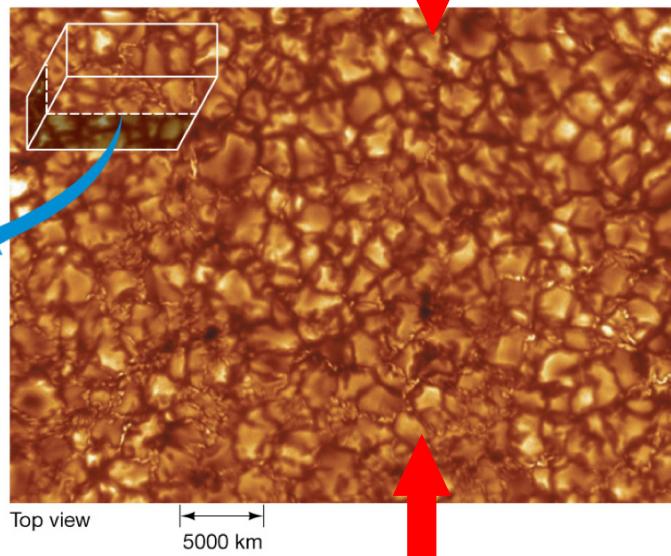
# Granules

The boundary is the photosphere.



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Bright parts are slightly bluer than dark parts



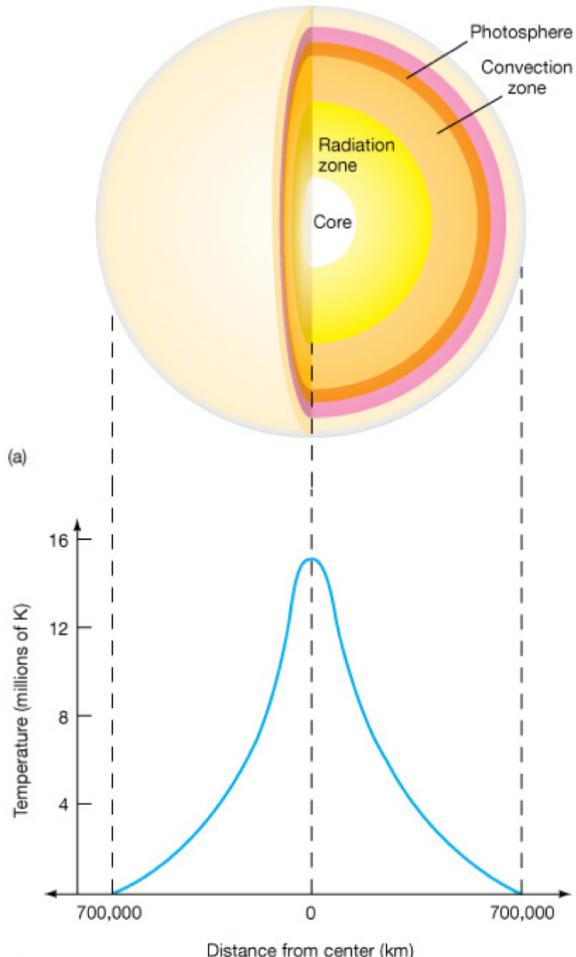
Diameter of the Sun  
is 1.4 million km

Granules are 1000km in size

Granules are produced by convection, the same as bubbles in boiling water.

[https://www.youtube.com/watch?v=W\\_Scoj4HqCQ](https://www.youtube.com/watch?v=W_Scoj4HqCQ)

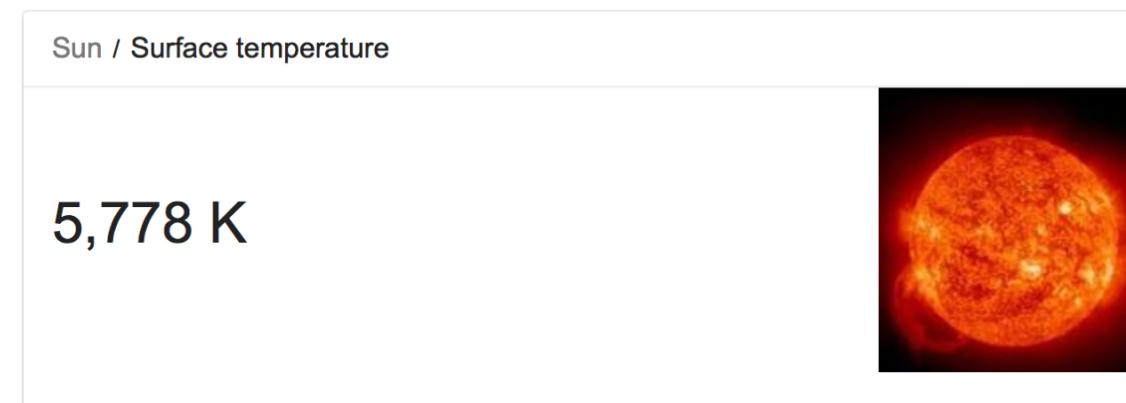
# Temperature of the Sun



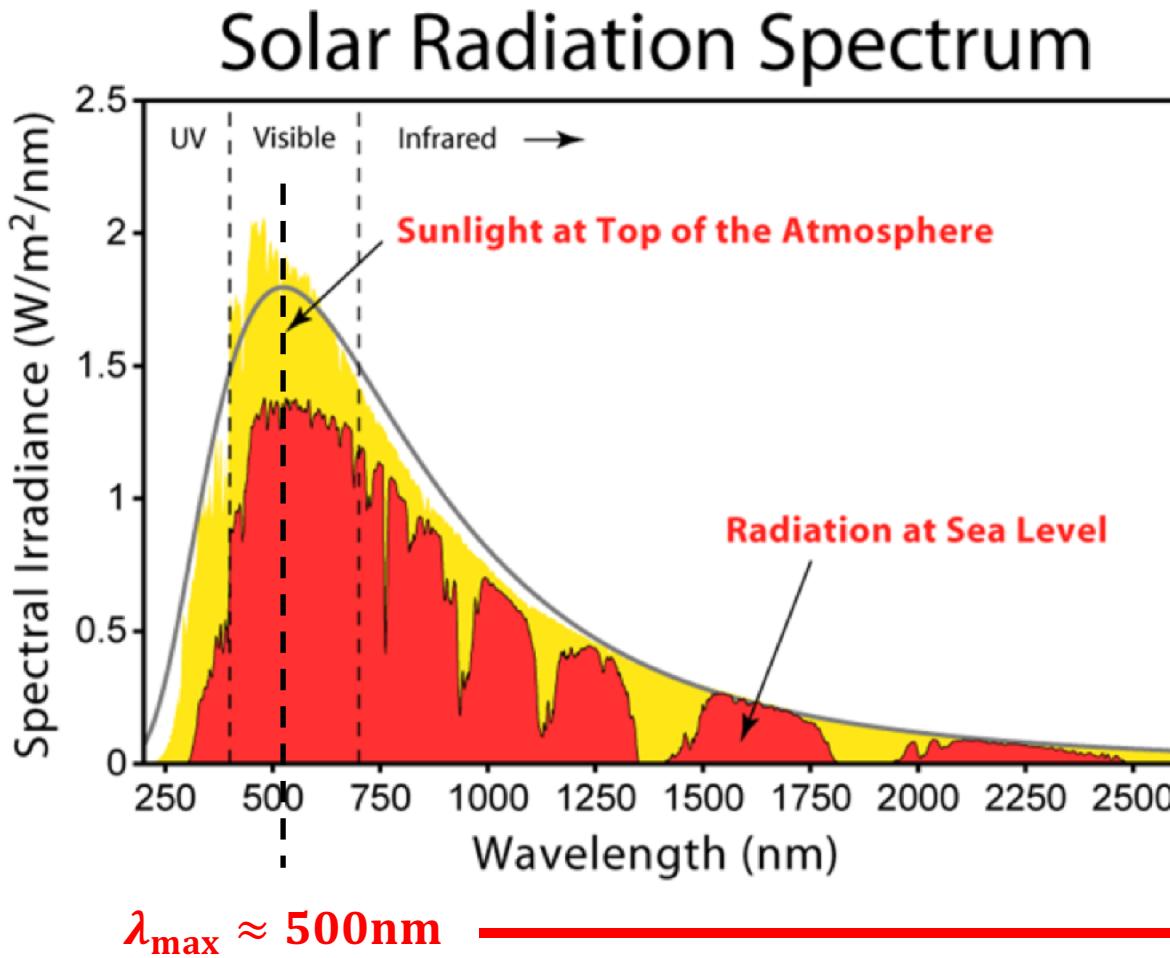
The Sun is a blackbody, so the brightness and color of light we see is determined by temperature.

The photosphere is the visible part of the Sun, which is what acts as the blackbody.

The “temperature of the Sun” is the temperature of the photosphere! This is around 5800K.



# The Sun as a Blackbody



$$b = 2.9 \times 10^6 \text{ nm} \cdot \text{K}$$

Wein's Law:

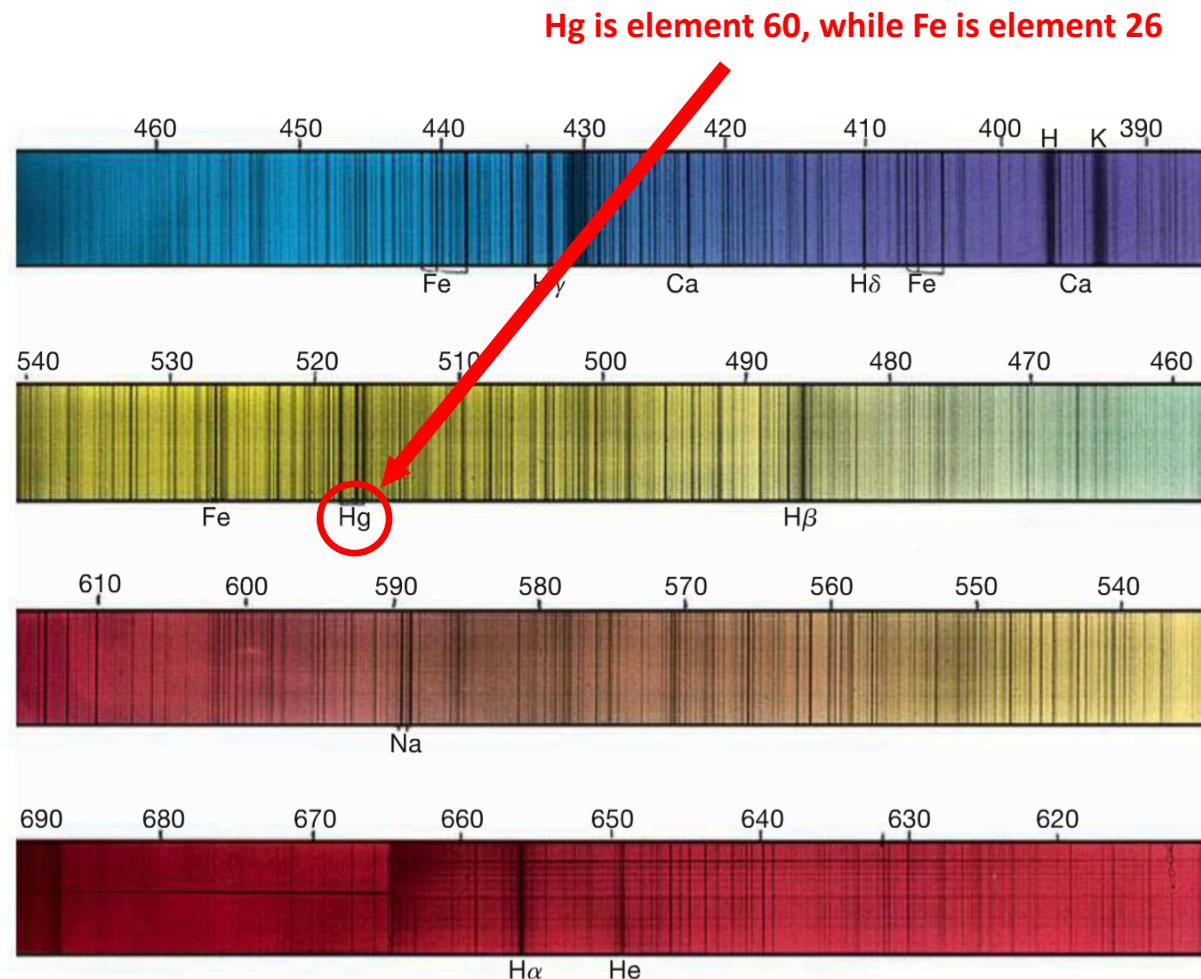
$$\lambda_{\text{max}} = \frac{b}{T}$$

$$T = \frac{b}{\lambda_{\text{max}}} = 5800\text{K}$$

Temperature of the blackbody, and therefore temperature of the photosphere, which we call the **surface temperature**.

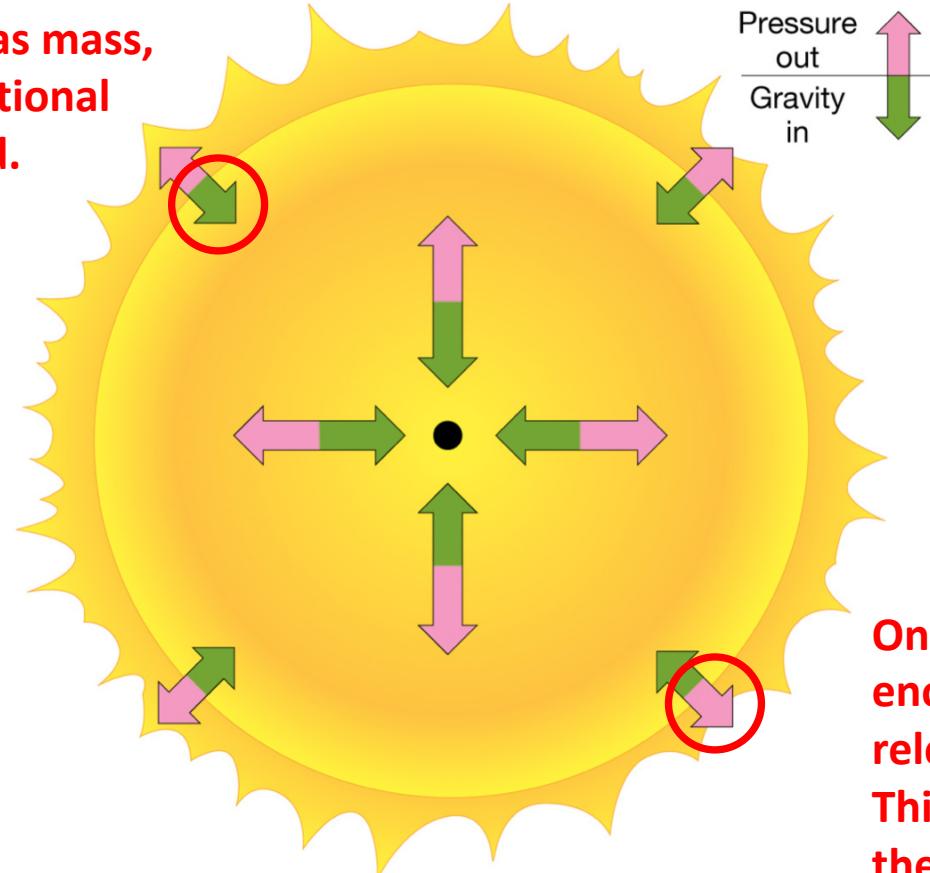
# Chemical Composition of the Sun

- In the emission spectrum, we can see the signatures of over 60 elements.
- By weight, the Sun is made of:
  - Hydrogen, 71.0%
  - Helium, 27.1%
  - Oxygen, 0.97%
  - Carbon, 0.4%
  - Nitrogen, 0.01%
  - Other elements



# Equilibrium in the Sun

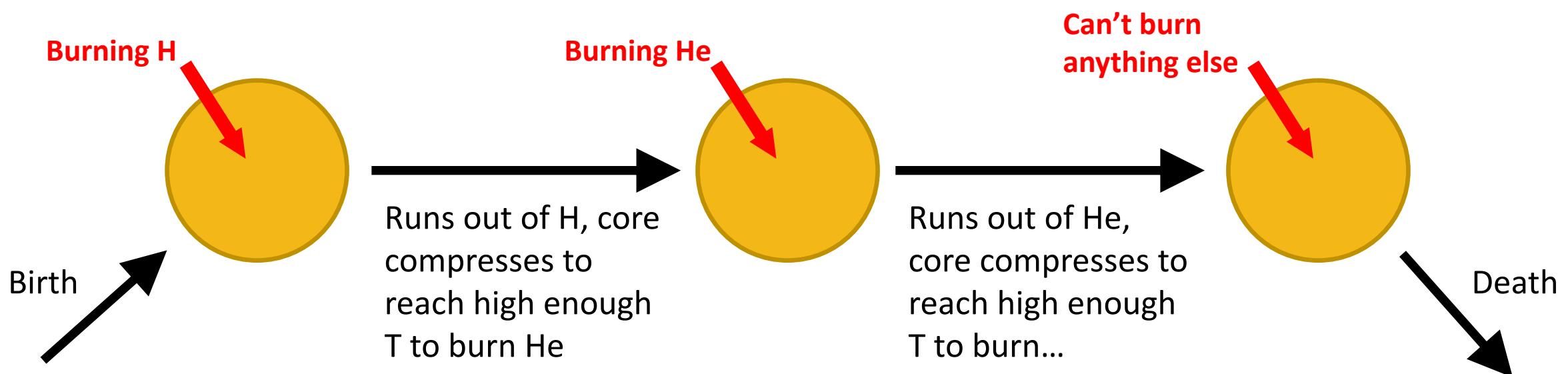
The hydrogen gas in the sun has mass, and all that mass has a gravitational attraction, pulling itself inward.



Once the hydrogen gets packed tightly enough, it can undergo fusion, releasing massive amounts of energy. This counteracts the gravity, keeping the Sun in equilibrium.

# (Very Basics of) Stellar Evolution

- Evolution is a fight to maintain equilibrium. Whenever the environment within the star changes, it's no longer in equilibrium and has to change to return to equilibrium.
- An important rule to remember: As gas gets pulled closer together – as it gets more dense – the temperature rises.



# Mass Controls all characteristics

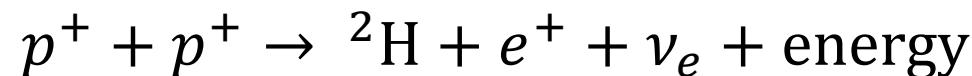
Remnant, as in what's left when the star dies.

Lifetime on the main sequence (i.e. while it's burning hydrogen).

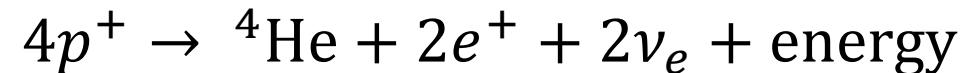
Core temperature.

Stellar Remnant	Evolution Process	Mass	Typical Lifetime	Typical Temperature
Brown Dwarf	It doesn't evolve; it's too cold to ever undergo fusion.	$M < 0.08M_{\odot}$	100 trillion years	100,000 K
Red/Black Dwarf	Slowly burns all its hydrogen, becoming less and less bright.	$M < 0.5M_{\odot}$	16 trillion years	600,000 K
White Dwarf	Planetary nebula (gentle) or nova (somewhat violent).	$M < 8M_{\odot}$	10 billion years	15 million K
Neutron Star	Supernova (violent)	$M < 25M_{\odot}$	10 million years	85 million K
Black Hole	Supernova (violent) or "hypernova" (extremely violent).	$M > 25M_{\odot}$	500,000 years	200 million K

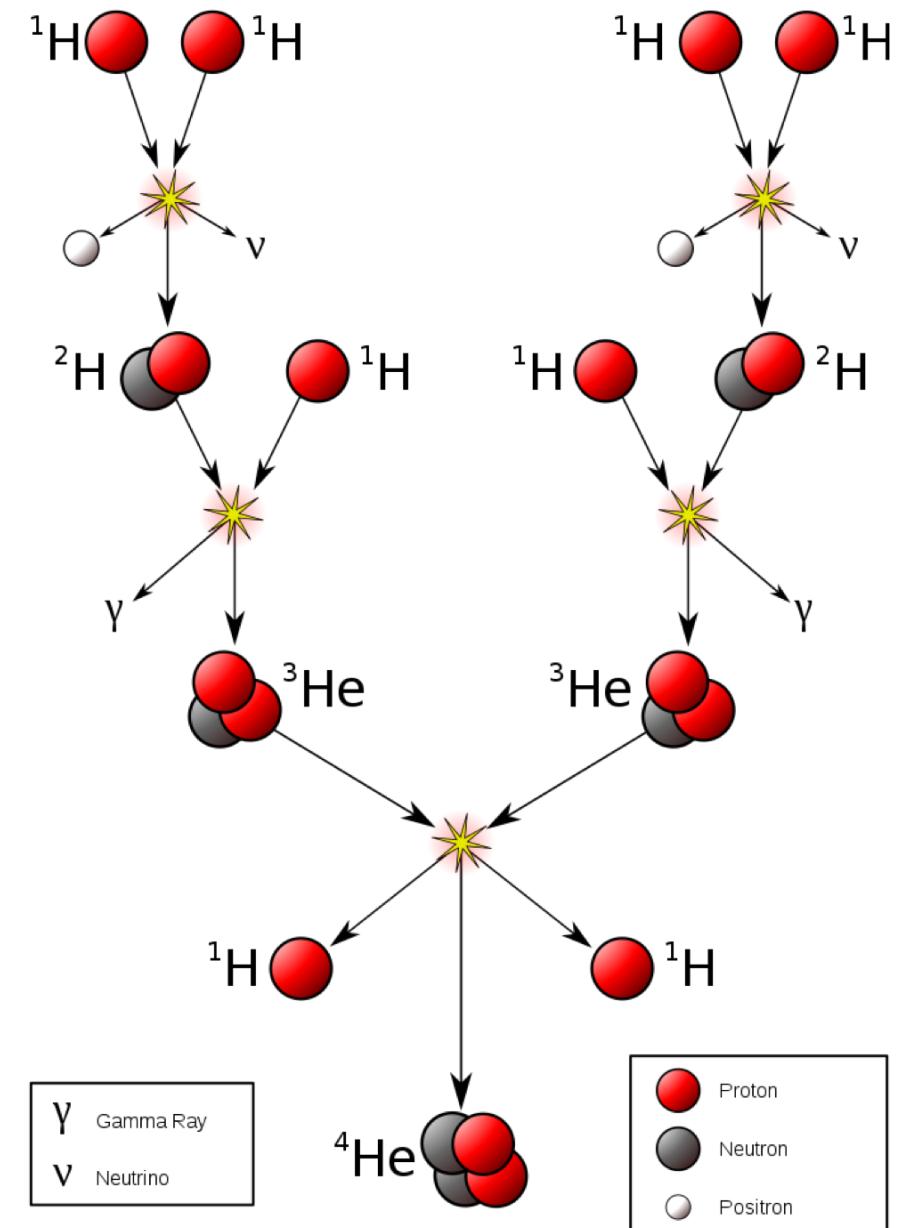
# Nuclear Fusion (pp Process)



Overall:



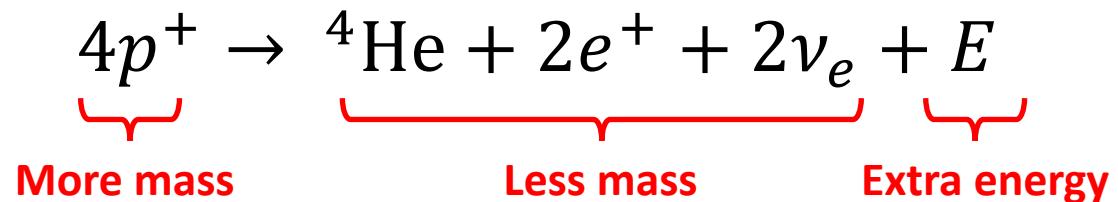
**pp process occurs when the core temperature is >14 million K**



# pp Process Calculations

$$m_p = 1.6726 \times 10^{-27} \text{ kg}$$
$$m_{^4\text{He}} = 6.6442 \times 10^{-27} \text{ kg}$$
$$m_e = 9.11 \times 10^{-31} \text{ kg}$$
$$m_{\nu_e} = 0 \text{ (approximately)}$$

**Step 1:** Overall:



**Step 2:**  $\Delta m = 4m_p - (m_{^4\text{He}} + 2m_e + 2m_{\nu}) = 4.438 \times 10^{-29} \text{ kg}$

$\Delta$  = "Change in"

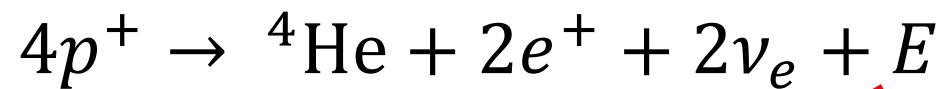
Extra mass

**Step 3:**  $E = (\Delta m)c^2 = 3.994 \times 10^{-12} \text{ J}$

Extra energy      Extra mass

Speed of light:  
 $c = 3 \times 10^8 \text{ m/s}$

# pp Process Calculations (cont'd)



Luminosity,  $L$

Reactions per second

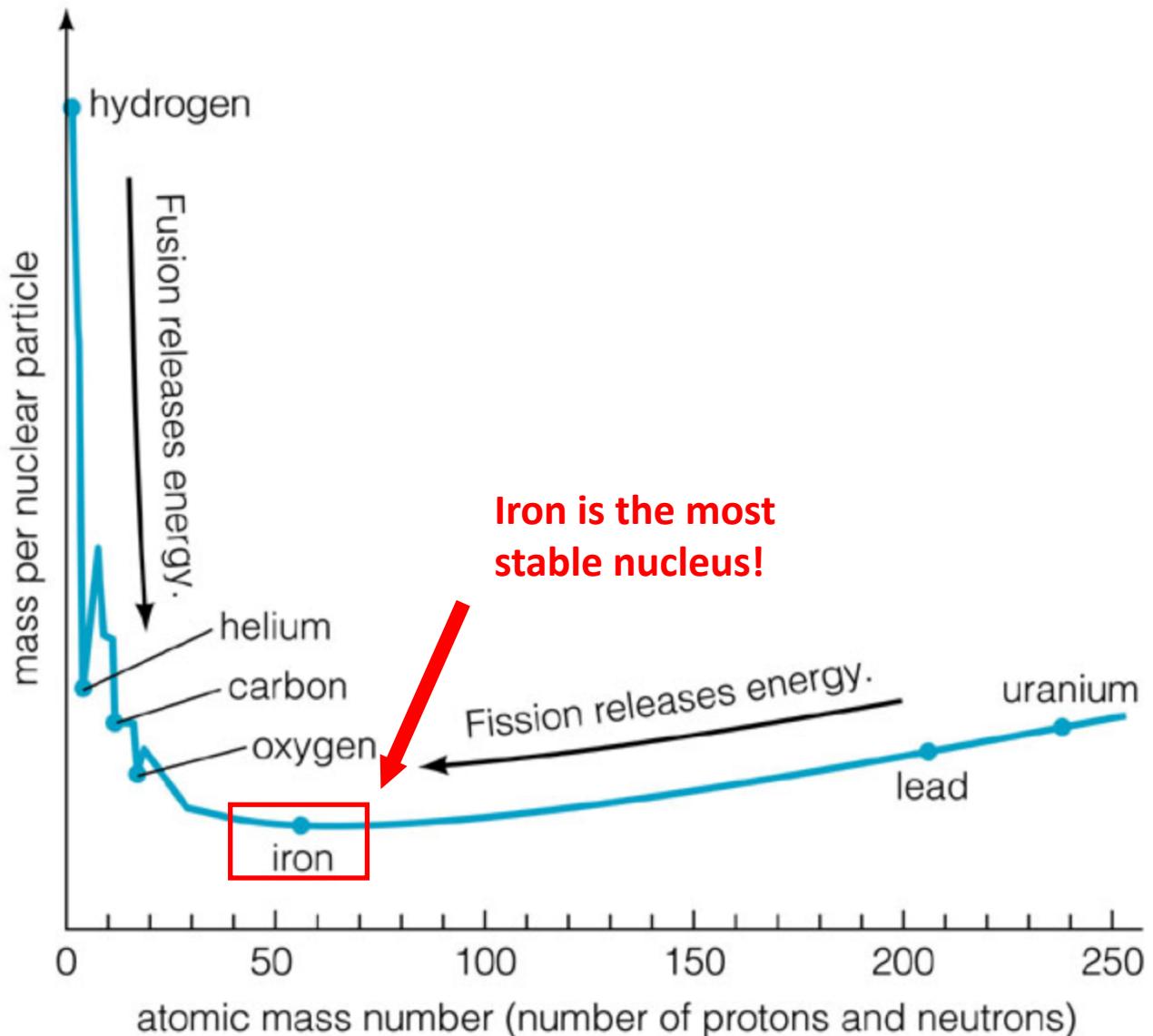
$$\frac{\text{Energy}}{\text{second}} = N * E \Rightarrow N = \frac{E}{L} = 9.58 \times 10^{37} \text{ reactions per second}$$

$$L_\odot = 3.83 \times 10^{26} \text{ J/s}$$

$$E = 3.994 \times 10^{-12} \text{ J}$$

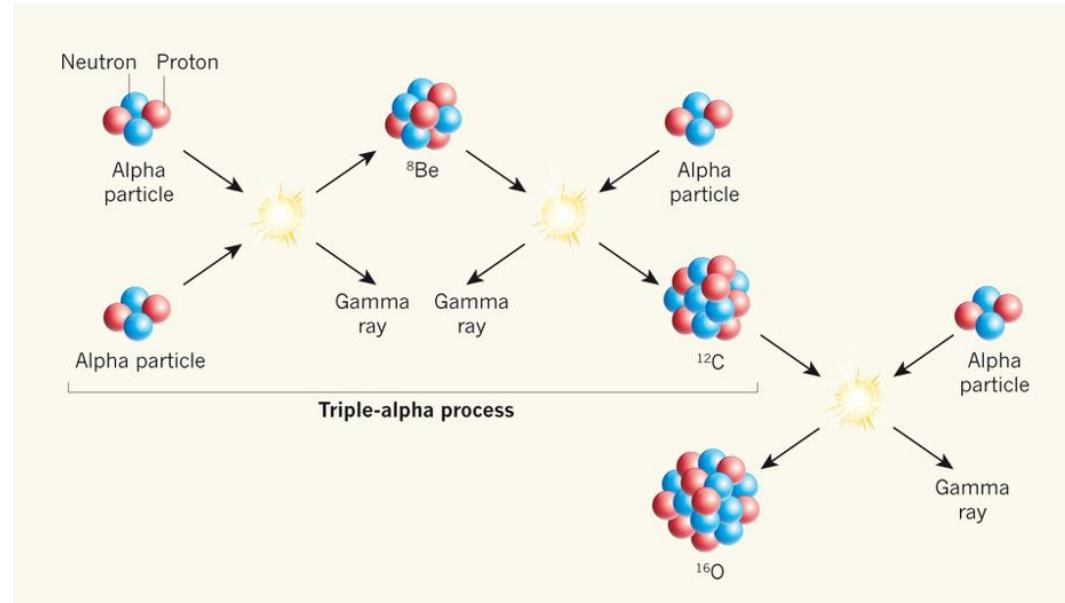
# Fission vs. Fusion

- Fusion will occur in the core of stars, if they have a high enough mass, until they produce **iron**.
- Iron is the most stable nucleus, so there is no energetically *favorable* reaction to produce elements heavier than iron.
  - **Energetically favorable** means a process releases energy.
  - There are **energetically unfavorable** processes, which require energy, and these lead to the production of heavier elements like lead that we see on Earth.

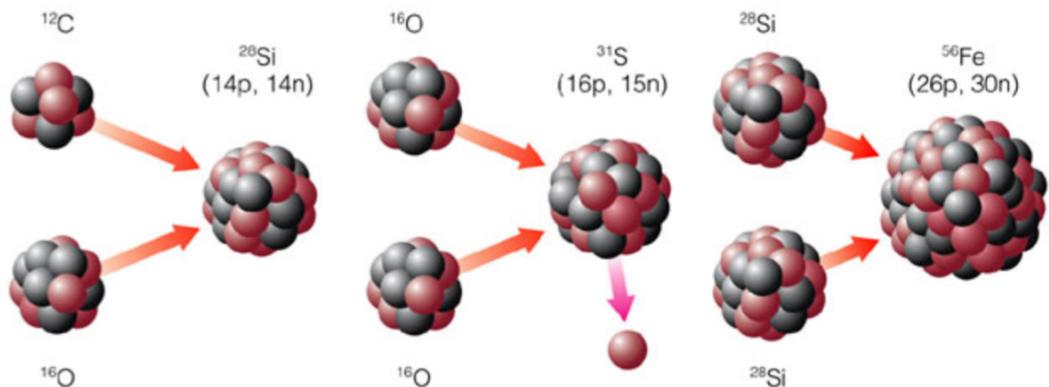


# Burning Heavier Elements

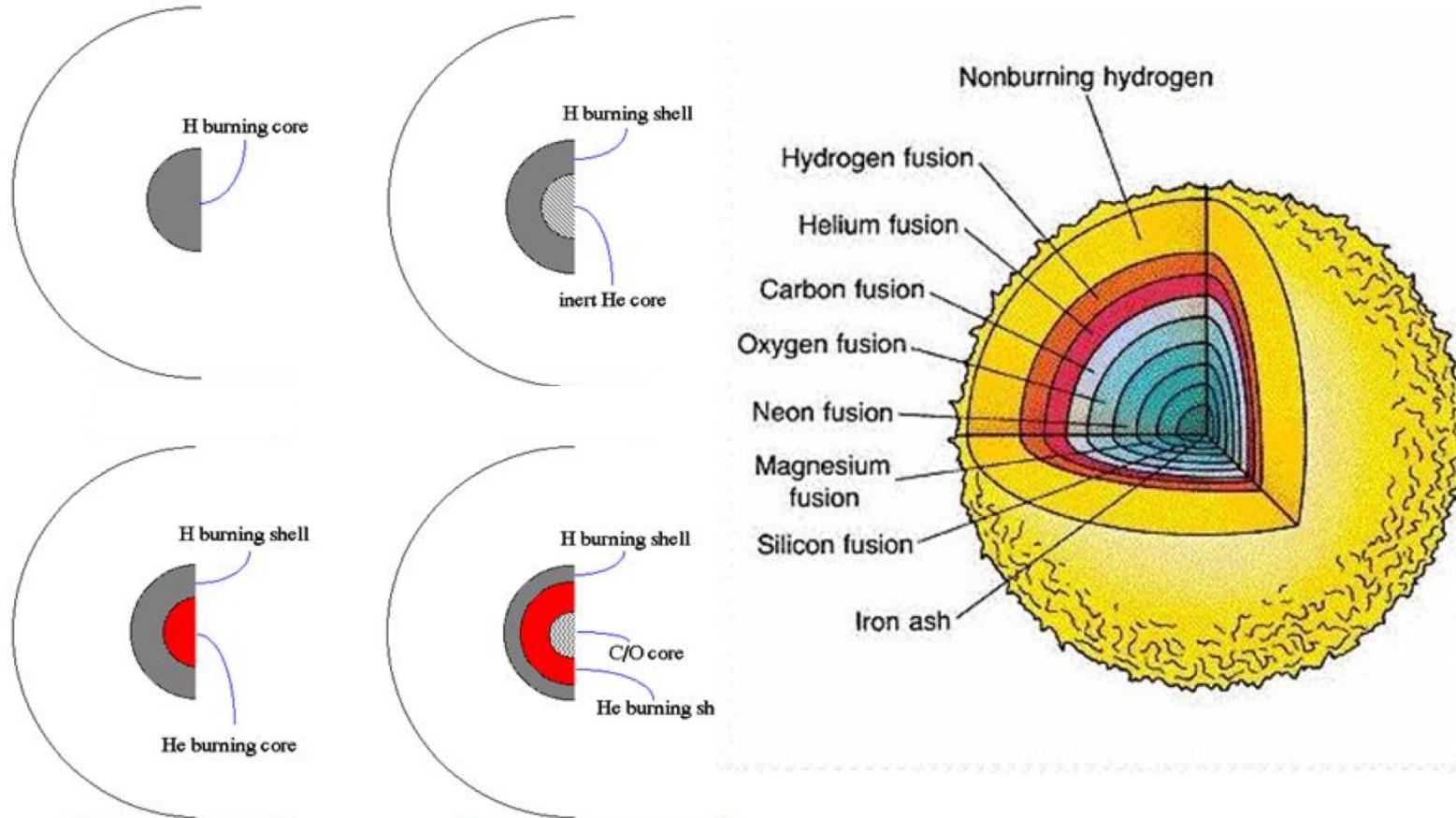
**Triple- $\alpha$  process**, burns He into C.  
Secondary process burns C into O.  
Requires a temperature  $> 100$  million K.



**Other processes** burn C+O into Si (**oxygen burning**), requiring temperatures  $> 1.5$  billion K, and Si into Ni (**silicon burning**), which decays into Fe, requiring temperatures  $> 3$  billion K.

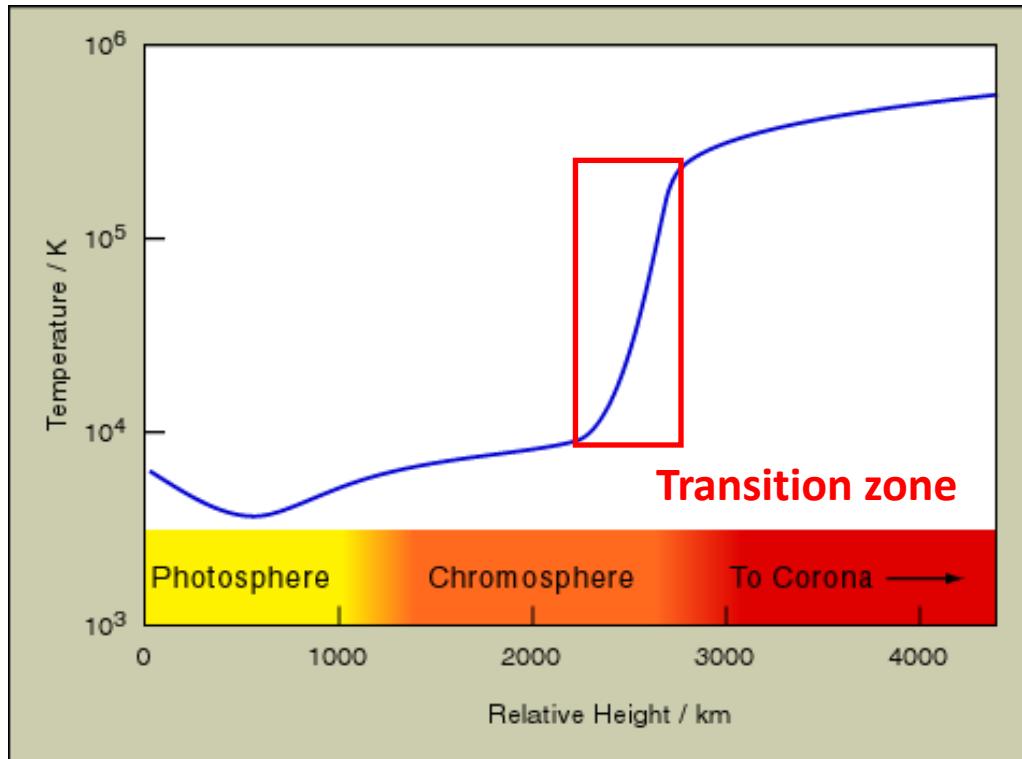


# Summary of Evolution of Stellar Core



# Solar Atmosphere

Atmosphere contradicts temperature trend

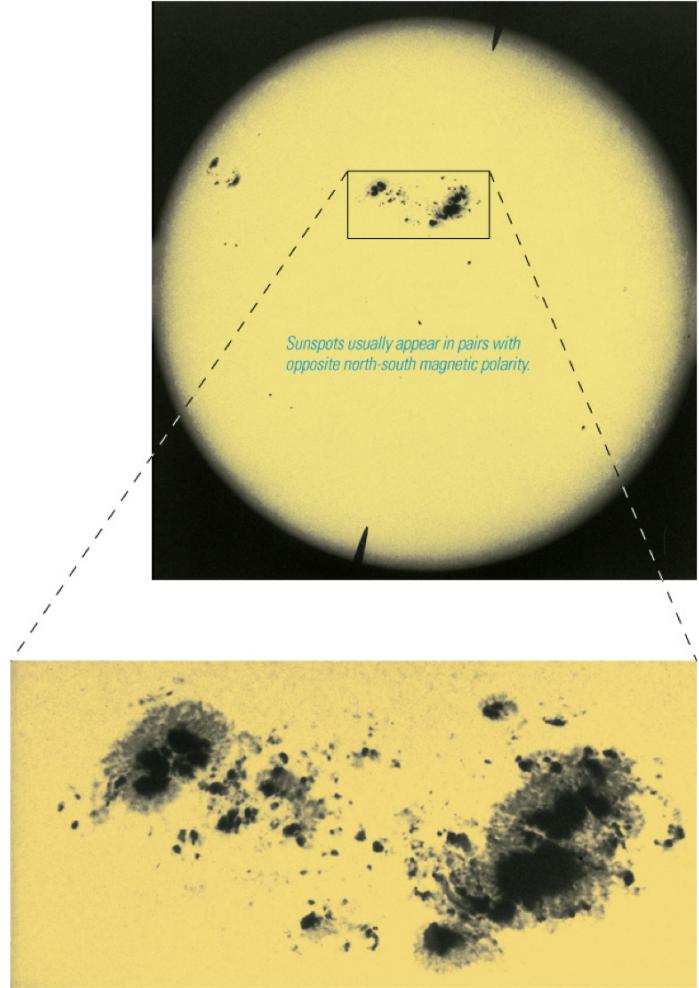


2<sup>nd</sup> Law of Thermodynamics:  
Heat flows from hot to cold, never from cold to hot.

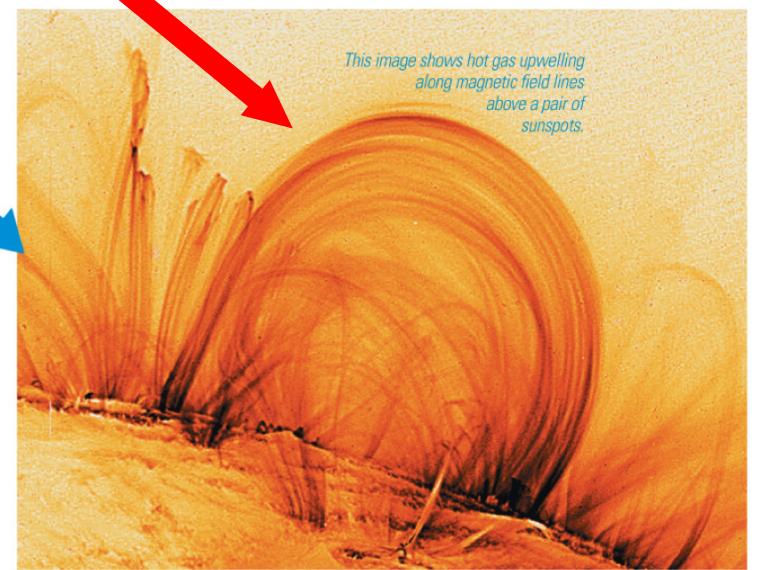
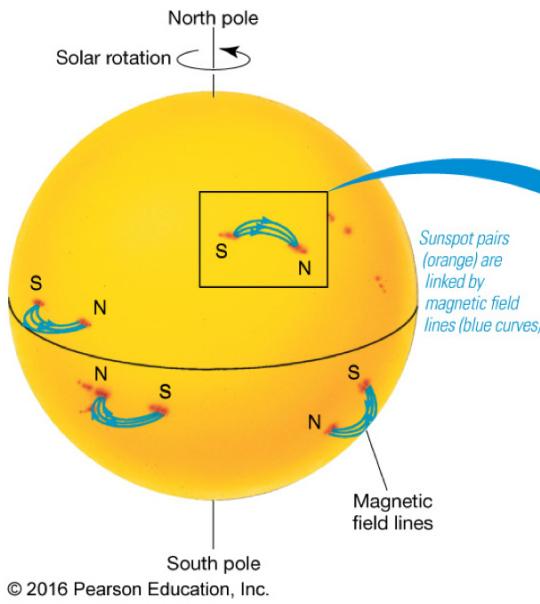


Coronal heating problem!  
Possible solution: magnetic recombination

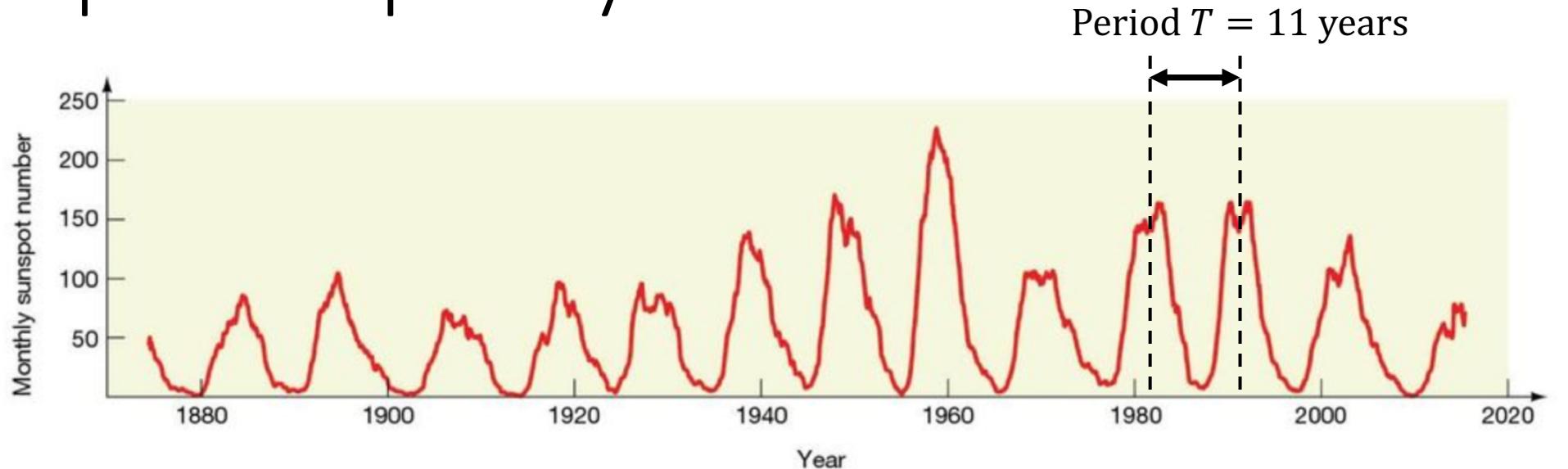
# Sunspots



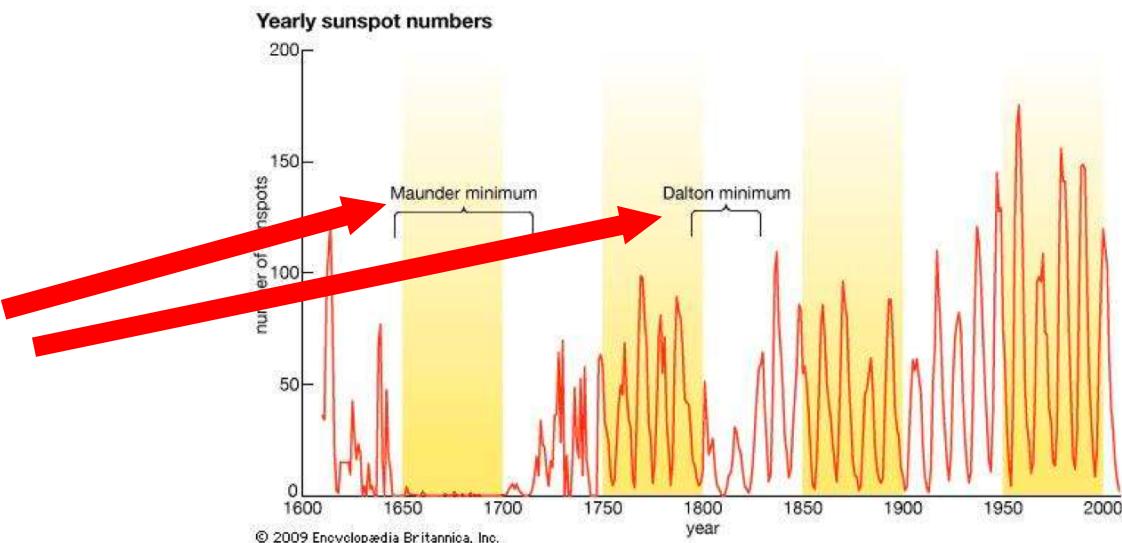
These looping magnetic fields are known as “prominences”



# Sunspot Frequency is Periodic

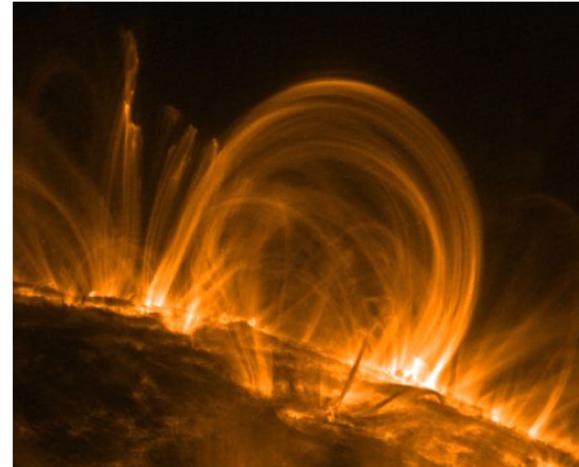
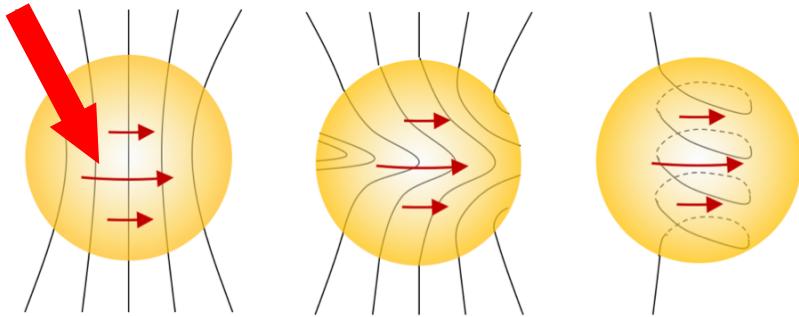


Periods of unusually low sunspot activity are called “minima”

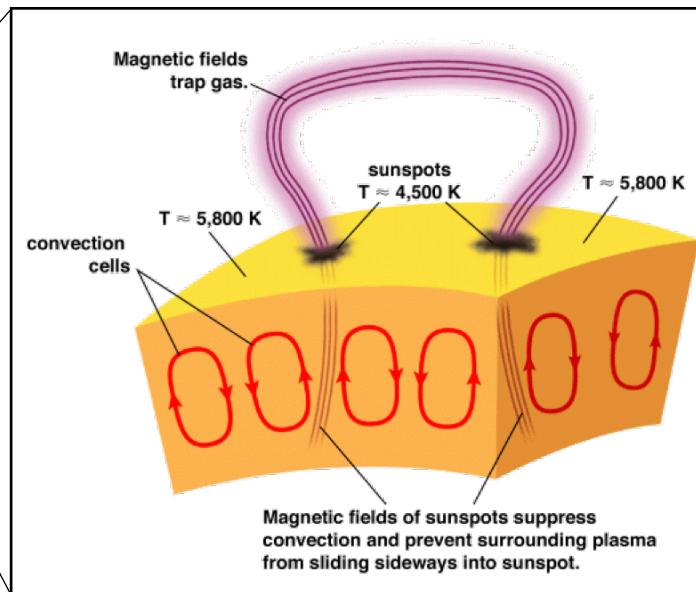


# Magnetic Reconnection

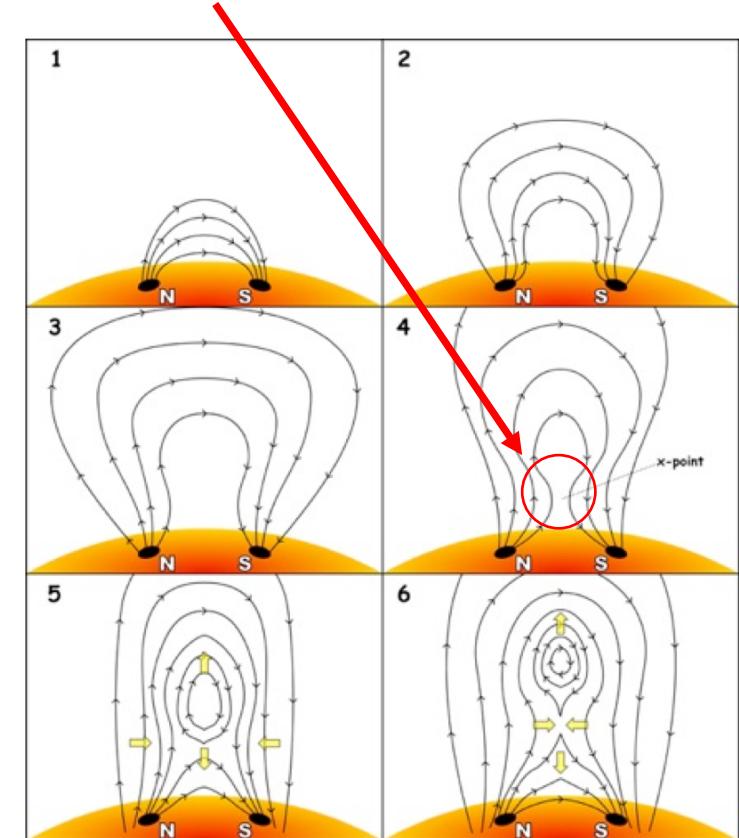
Equator rotates faster than poles



Magnetic loops develop kinks that poke out of Sun's surface

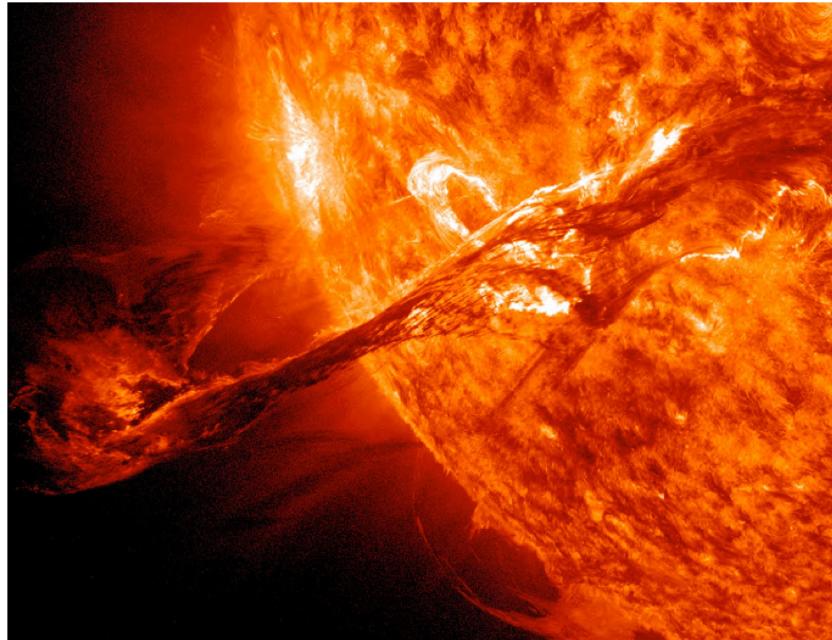


Reconnection point

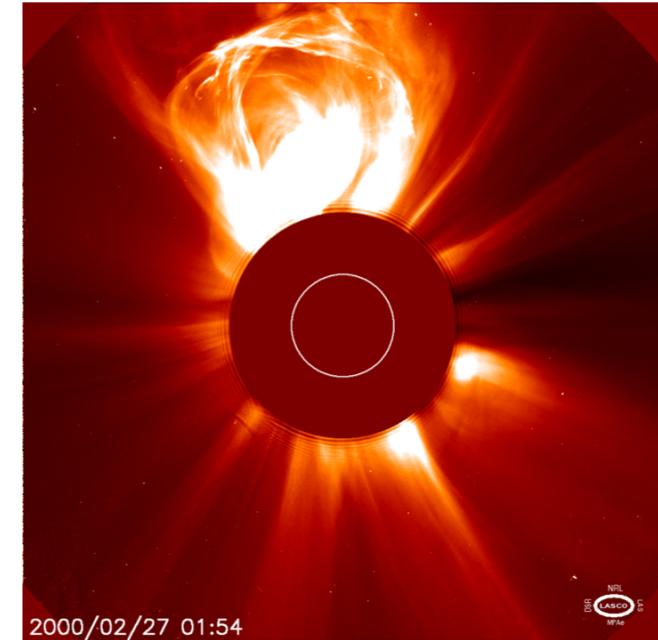


Massive energy released when magnetic fields reconnect, carried to corona to heat it.

# Solar Flares vs. Coronal Mass Ejections



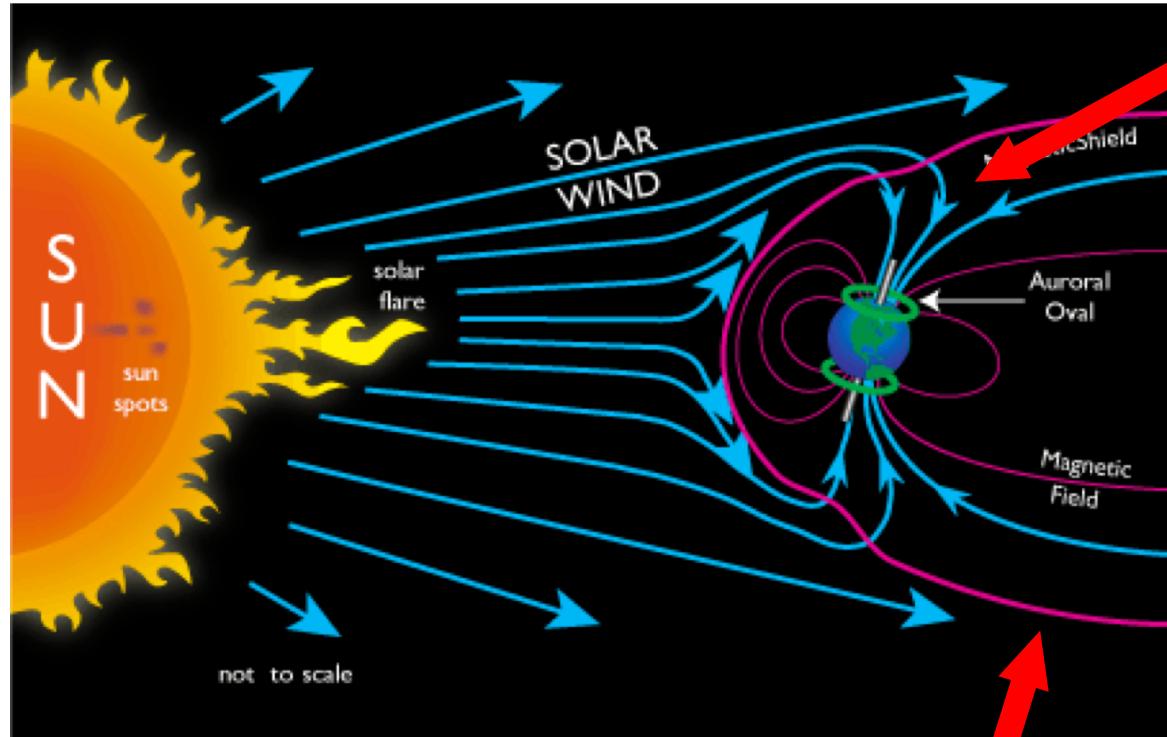
In a solar flare, prominence is still trapped by Sun's magnetic field



In a coronal mass ejection, prominence is energetic enough to escape Sun's magnetic field

Difference between flares and CME's: <https://www.youtube.com/watch?v=TWjtYSRIOUI>

# Magnetosphere and Aurora



Earth's magnetic field creates a "magnetosphere," which protects us from solar radiation, called solar wind.

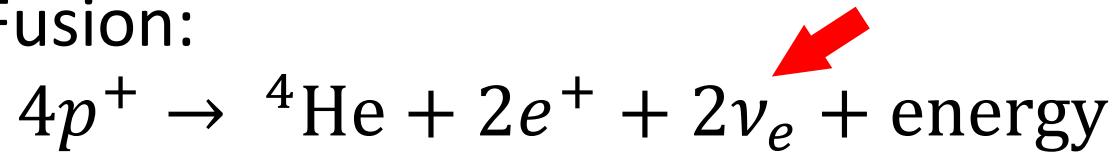
The magnetic field lines guide the charged particles in the solar wind to the poles, creating the Auroras.

Charged particles from solar wind collide with particles in the atmosphere, creating the light seen in the Auroras.

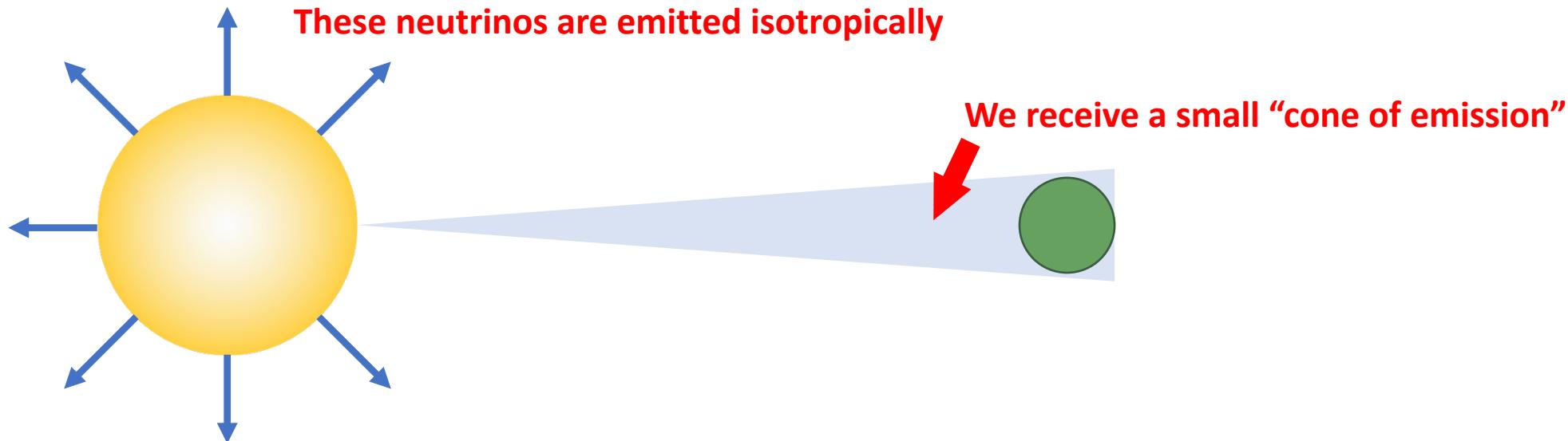


# Solar Neutrinos

Fusion:



Specific type of neutrino, known as “electron neutrino.”  
Recall,  $9.58 \times 10^{37}$  are made every second.



**Solar neutrino problem:**

We can predict how many neutrinos per second we should receive.  
However, we only observe 1/3 of them.