Our Star...
the Sun

Chapter 10

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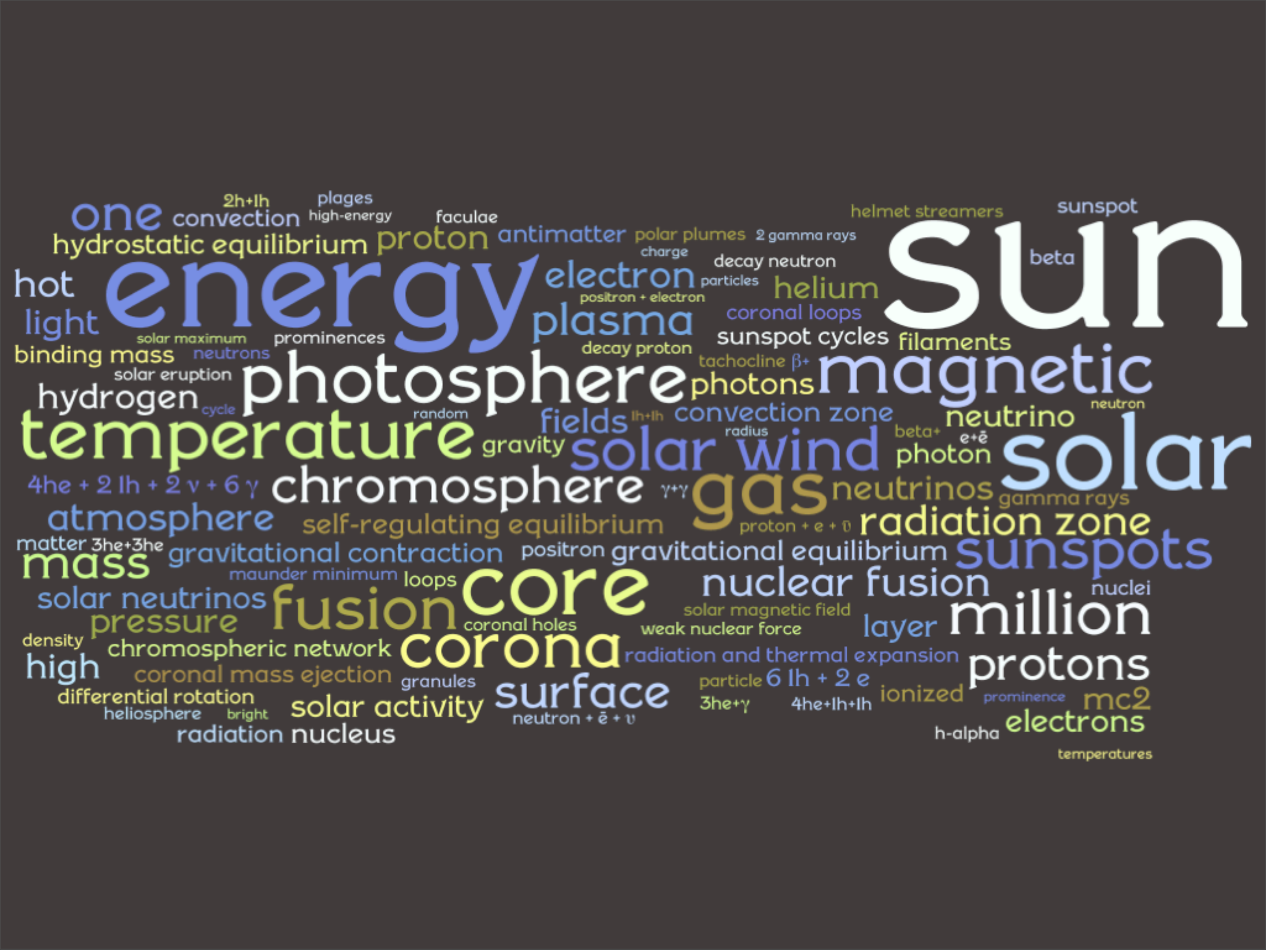
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differential rotation
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heliosphere
bright
solar activity
neutron + ē + υ
electrons
h-alpha
radiation
nucleus
temperatures

Energy Source

- The Sun is virtually the source of all energy in the Solar System
- Without the Sun, there would be
  - no Solar System,
  - no Earth,
  - no life,
  - and, of course, no us

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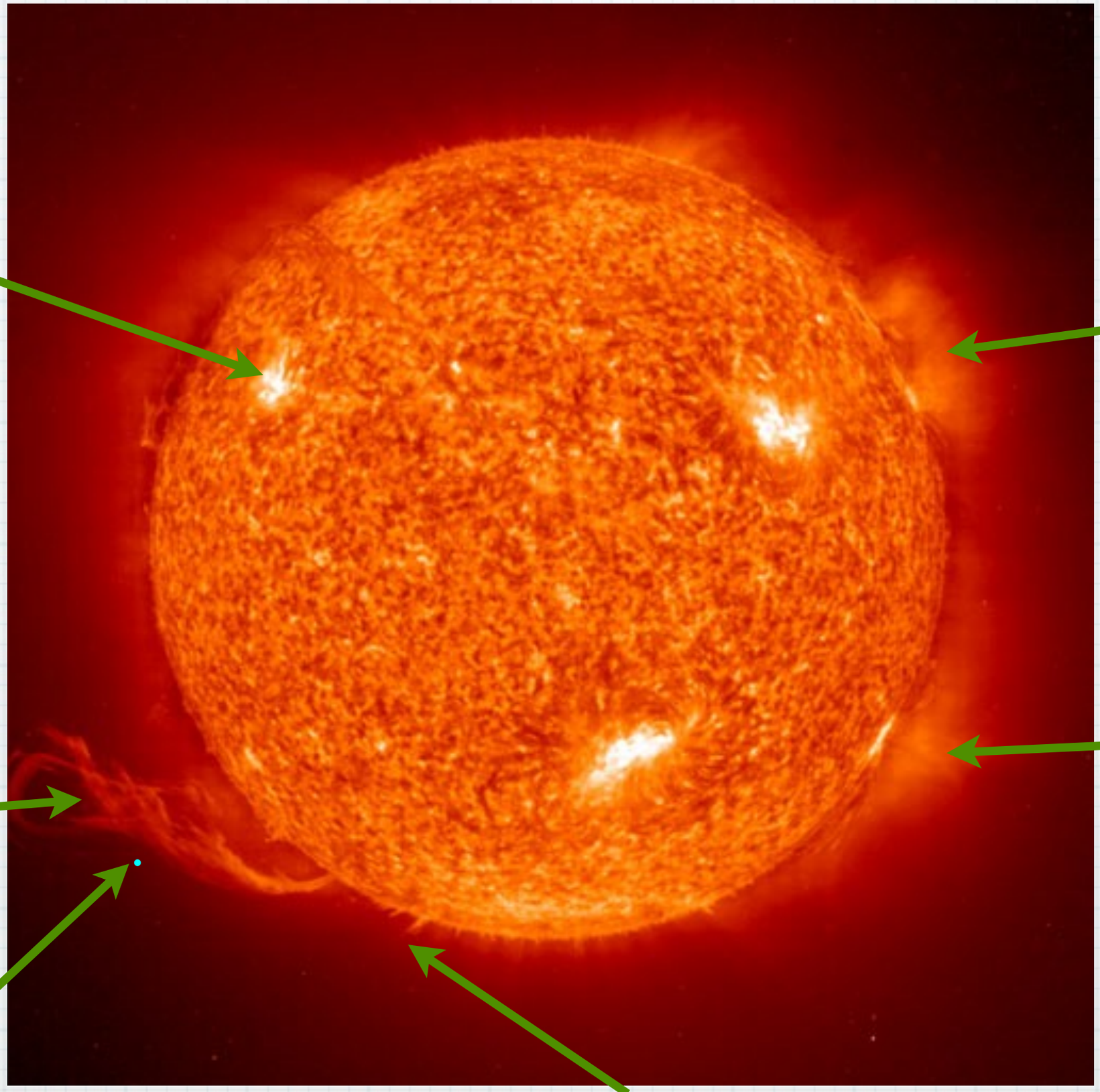
The Sun seen in H-alpha light (n=3→2)



plage

prominence

solar flare

plume

Earth (to size-scale)

polar plume

Solar Composition

About 67 elements are present in the Sun

Most abundant are the following

data obtained via spectrography

Element	By number %	By mass %
Hydrogen	91.2	71.0
Helium	8.7	27.1
Oxygen	0.078	0.97
Carbon	0.043	0.40
Nitrogen	0.0088	0.096
Silicon	0.0045	0.099
Magnesium	0.0038	0.076
Neon	0.0035	0.058
Iron	0.0030	0.14
Sulfur	0.0015	0.040

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A Great Ball of Fire?

* We know the Sun is a giant ball of very hot gas
* In the 19th century people started to investigate how it was generating power
* Was it made of coal or wood?

➡ Not possible: Sun's energy output was too high for these two combustibles

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What is burning?

* Was it burning some other chemical?

$$\frac{\text{Chemical Processes}}{\text{Luminosity}} = 10{,}000 \text{ years}$$

* Was it generating power by slowly contracting in size?

$$\frac{\text{Gravitational Contraction}}{\text{Luminosity}} = 25 \text{ million years}$$

* Geologists said Earth was older than that!

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How is the Sun Shining?

* No one knew until **Einstein** came up with $E = mc^2$ in 1905
* So mass was being converted in energy But how?
* By the end of the 1930's **nuclear fusion** was understood

➡ $$\frac{\text{Nuclear Fusion}}{\text{Luminosity}} = 10 \text{ billion years}$$

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Hot & Dense

* Nuclear fusion requires extremely high temperatures and densities
* Long lived nuclear fusion require a stable environment
* The Sun provides this environment because it is made of gas (which compresses easily) and it is huge and massive

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High Internal Pressures and Temperatures...

* As we have previously seen, a cloud of gas will contract on itself due to the force of gravity

➡ As the gas contracts, its internal pressure increases (outward force)

➡ An increasing internal pressure also increases the local temperature

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...Lead to Fusion

- If there is enough gas, at some point, the gravitational contraction forces the gas to reach a temperature and density where the environment is favorable for fusion to happen

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Gravity vs. Radiation & Thermal Pressure

* When fusion happens, the immense energy created pushes back (radiation pressure) on the gravitational contraction

* A steady shining Sun exists because two sets of forces oppose one another equally:

1. gravity pulls the gas inward
2. radiation & thermal pressure push the gas outward

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Gravitational Equilibrium

* This balance is called
  * gravitational equilibrium, or
  * hydrostatic equilibrium
  * In the Sun (made of gas), this equilibrium is reached at every point in it (core to surface)

➡ This is why the Sun is stable

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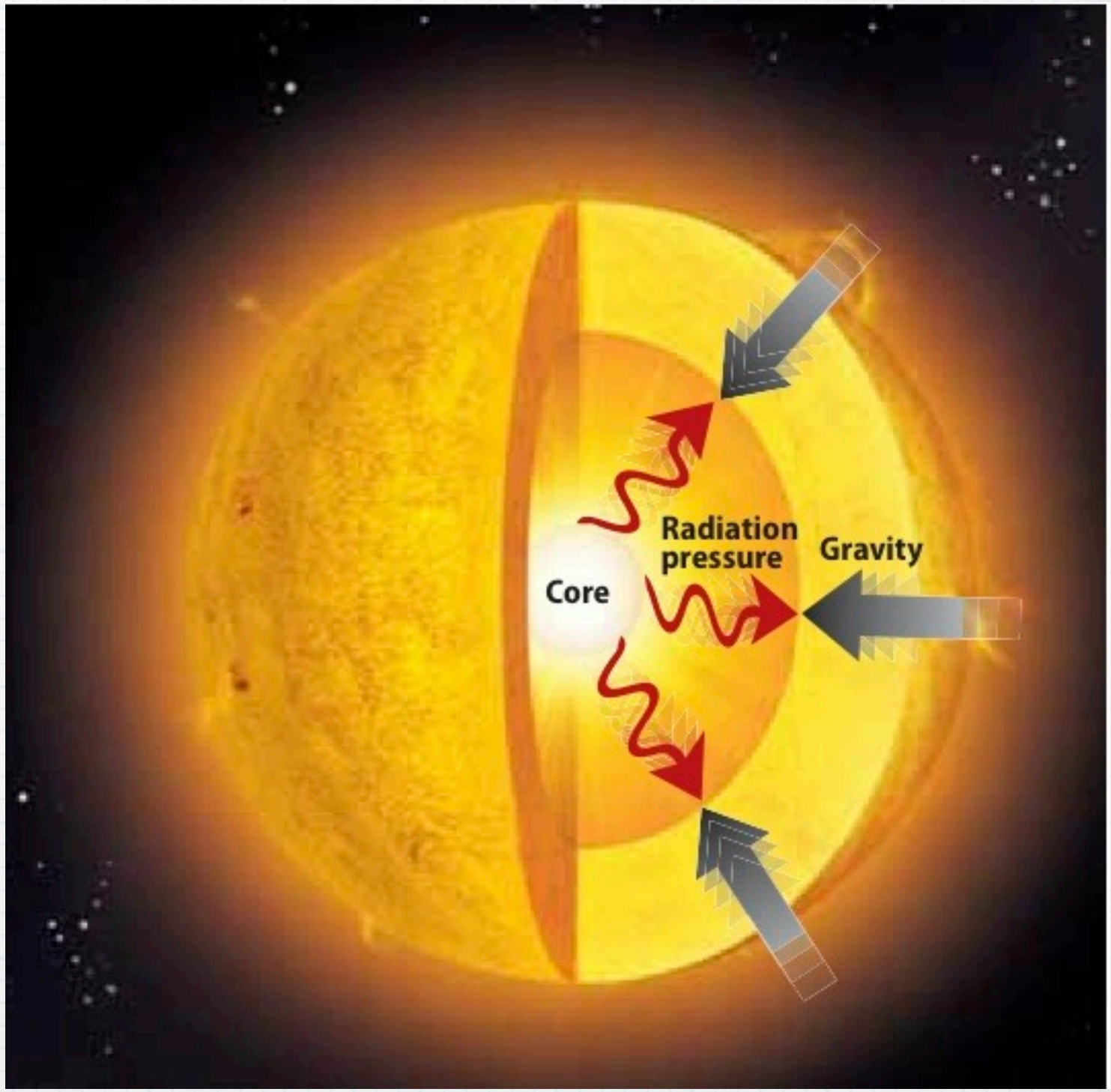
At each point inside the Sun, the radiation and thermal pressures pushing outward are balanced with the weight of the overlying layers (pushing inward)

As depth increases, there is more overlying weight, hence the pressures and temperature increases with depth

Deep in the Sun, it is hot and dense enough to ignite fusion



Gravity is One-Way

* When the solar nebula originally contracted, it got hotter and denser in the center as pressure and density rose
* But hydrostatic equilibrium was not reached until the nuclear fusion rate got constant

➡ When nuclear fusion stops in the core of the Sun (about 5 billion years from now, the core will then resume its contraction

* It is only a matter of time

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Radius: 696,000 km or 109 times the Earth's

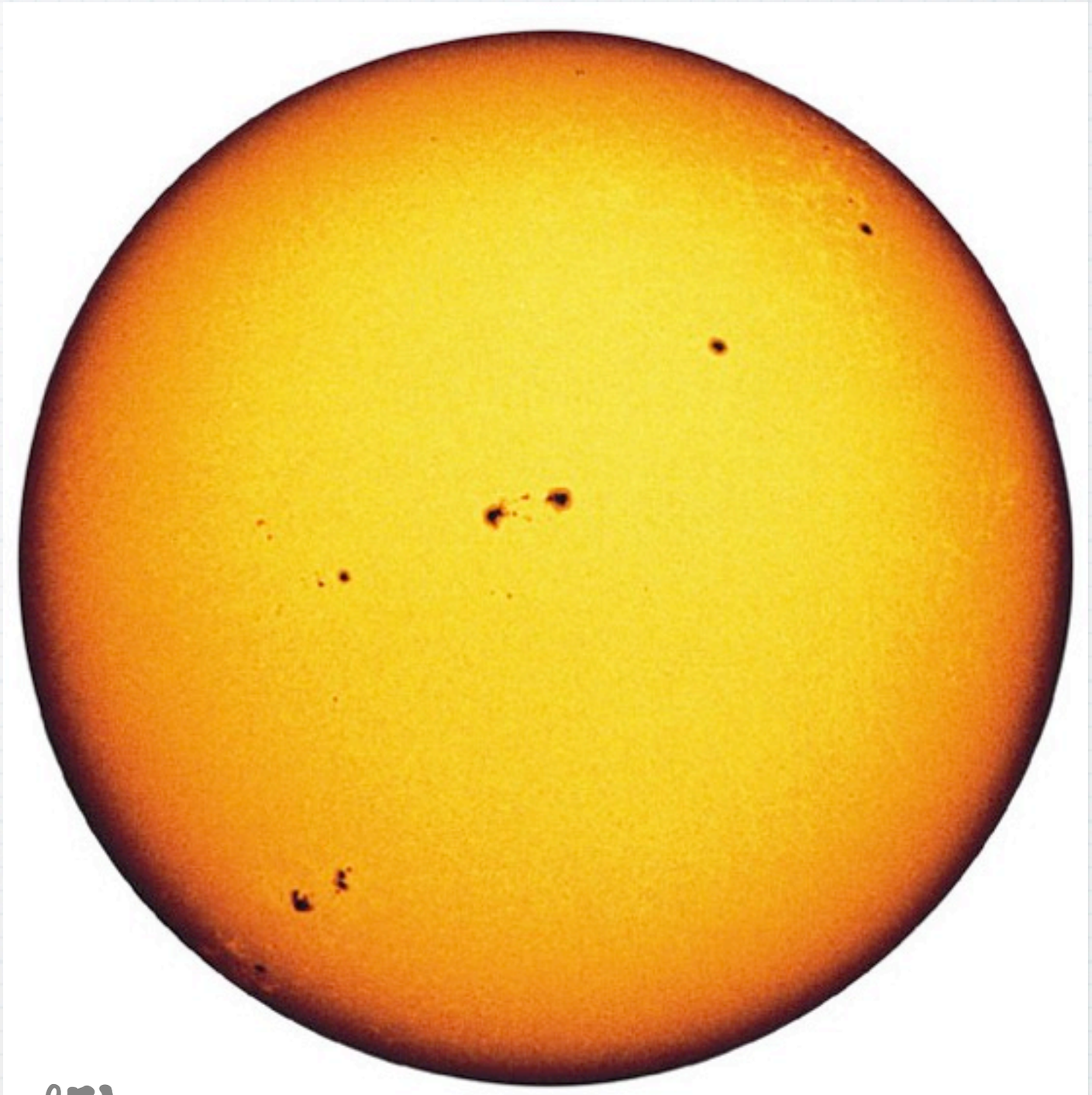
Mass: 332,800 Earths

Surface Temperature:
5,800 K (10,000 °F)

Luminosity:
3.8×10^{26} Watts

Core Temperature:
15 million K (27 million °F)

The Sun in visible light



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The Structure of the Sun

* It is not a giant ball of fire
* It is a giant ball of hot gas
* A ball of plasma to be exact
* Remember plasma?
  * Fourth form of matter? (chapter 5)

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What is Plasma?

* Plasma is a high-temperature gas where its atoms or molecules have lost electrons as they have too much energy to stay bound to their atoms/molecules

➡ The kinetic energy of the electrons is bigger than the binding electrostatic force

* When an atom or molecule has lost one or more electrons, it is in an ionized state (it has an electrical charge)

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Types of Plasma

Found in Sun

1. cold: gas is partially ionized ("cold" is 1000's K)
2. hot: gas is fully ionized
3. hotter still: the gas is only made of atomic nuclei and electrons (no molecules)

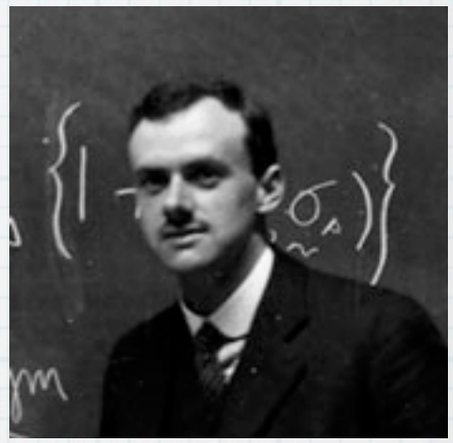
Not found in the Sun

4. hotter yet: the protons and neutrons fly off from their atoms (the first three minutes of the Big Bang at about 10^9K)
5. hottest: quarks and gluons fly off the protons and neutrons: (the first millisecond of the Big Bang: Quark-Gluon plasma at 2×10^{12}K)

Physics Corner
Fusion

* Within the core, temperatures are near 15 million Kelvin
* All atoms are fully ionized: no electron is bound to an atom, so the medium is a soup of electrons and atomic nuclei (mostly hydrogen and helium)
* High speed collisions occur (just like in a particle accelerator) and nuclei will merge

Physics Corner
What is antimatter?



* Antimatter was predicted theoretically by Paul Dirac in 1931
* Antimatter has the same gravitational property as matter (same mass) but...
* it has an opposite electric charge as well as opposite nuclear force charges

Physics Corner
What is a positron?

* positron: it is an anti-electron

* also called the antimatter counterpart of the electron

* it has the same mass as an electron but its charge is +1 (like a proton)

Physics Corner
What is antimatter?

* When one particle meets its antiparticle counterpart, they annihilate themselves into other particles (which may be short-lived)
* When a positron and an electron meet, their combined mass is turned into 2 gamma rays
* For every type of particle (electron, quark, proton, neutron, ...), there is an antiparticle

Physics Corner
What is a neutrino?

* A neutrino is an elementary particle
  * it has no charge (like a neutron) and almost no mass
  * it travels almost at the speed of light

Physics Corner
What is a neutrino?...

* A neutrino barely interacts with matter
* A one light-year thick wall made of lead is needed to stop a solar neutrino on average!
* neutrinos are affected only by the weak nuclear force (particle stability) and gravity

Physics Corner
What is beta decay?

* How are electrons/positrons and neutrinos/antineutrinos related?

1. Beta$^-$ (β^-) decay

* neutron $\rightarrow$ proton + e + $\bar{\upsilon}$

electron

antineutrino

2. Beta$^+$ (β^+) decay

* Energy + proton $\rightarrow$ neutron + $\bar{e}$ + υ

neutrino

positron

The Structure of the Sun

1. Body

   core, radiation layer, tachoclyne, convection layer

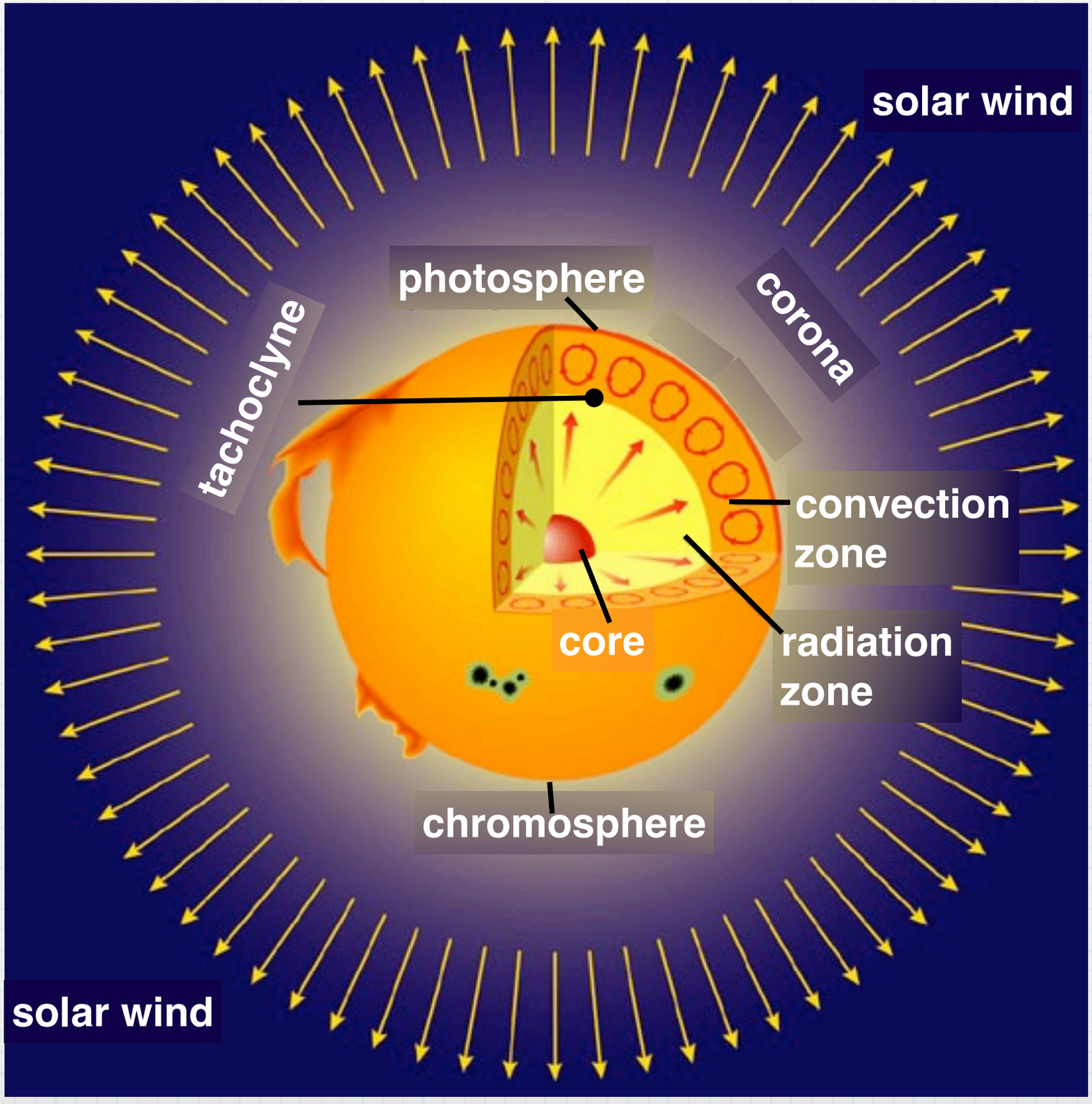
2. Atmosphere

   photosphere, chromosphere, corona

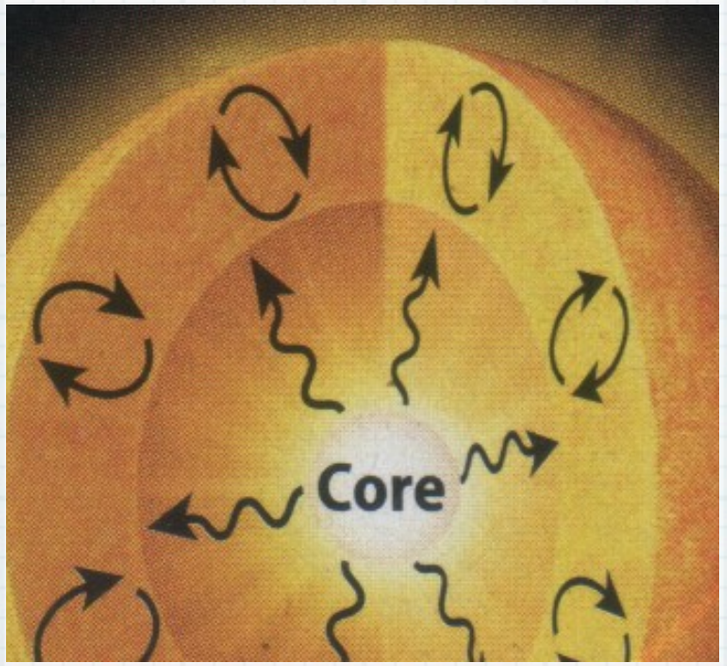
3. Heliosphere (where the solar wind rules)

   termination shock, heliosheath, heliopause, bow shock

The Structure of the Sun



The Core



a. nuclear fusion happens here

b. hydrogen is transformed into helium

c. temperature: 15 million K (27 million °F)

d. 200 billion times the Earth surface pressure

Nuclear Fusion Explained

* The core of the Sun fuses hydrogen into helium

* This is not what happens in a nuclear plant where energy is created by fission (splitting uranium or plutonium into smaller atoms)

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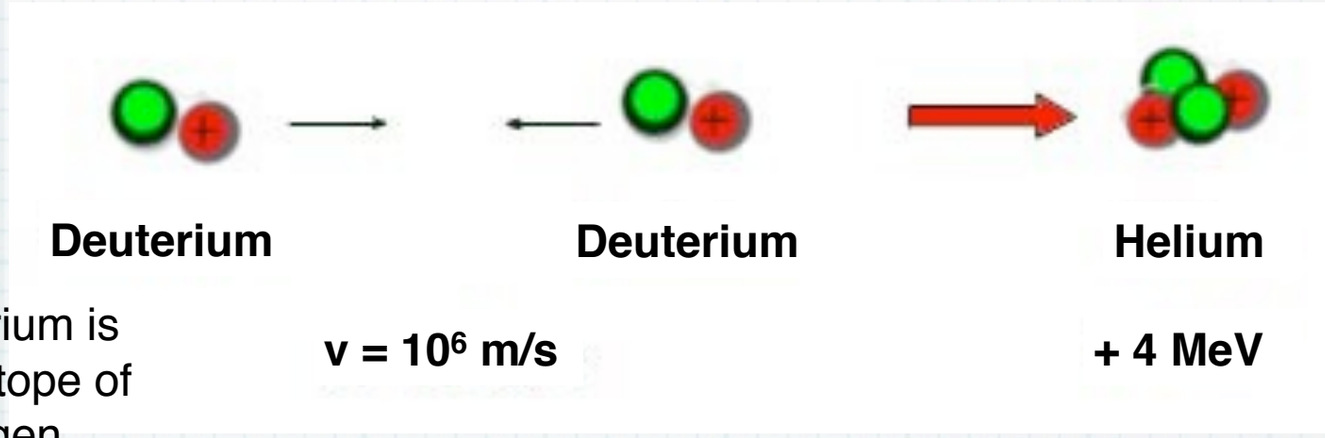
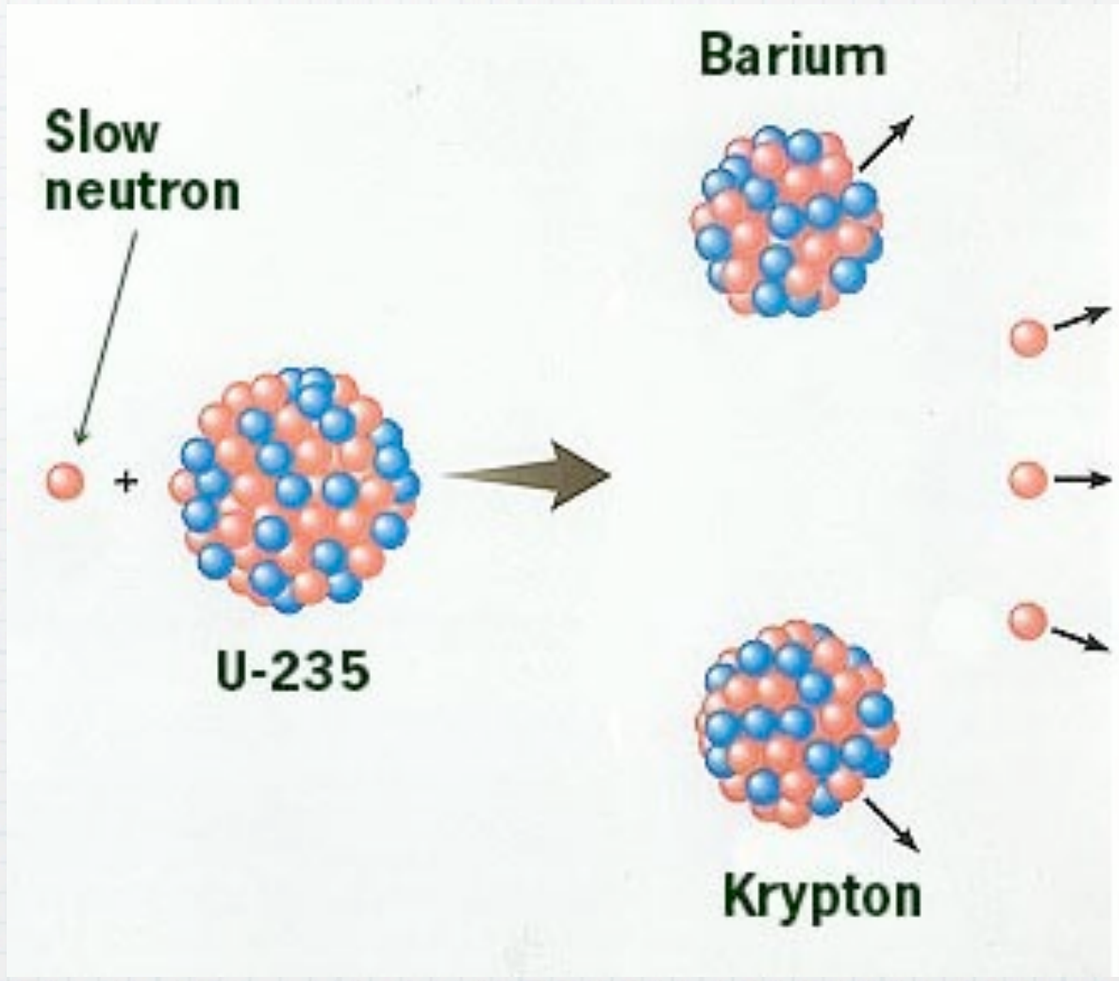
Difference between Fusion and Fission

Fusion



deuterium is an isotope of hydrogen

Fission



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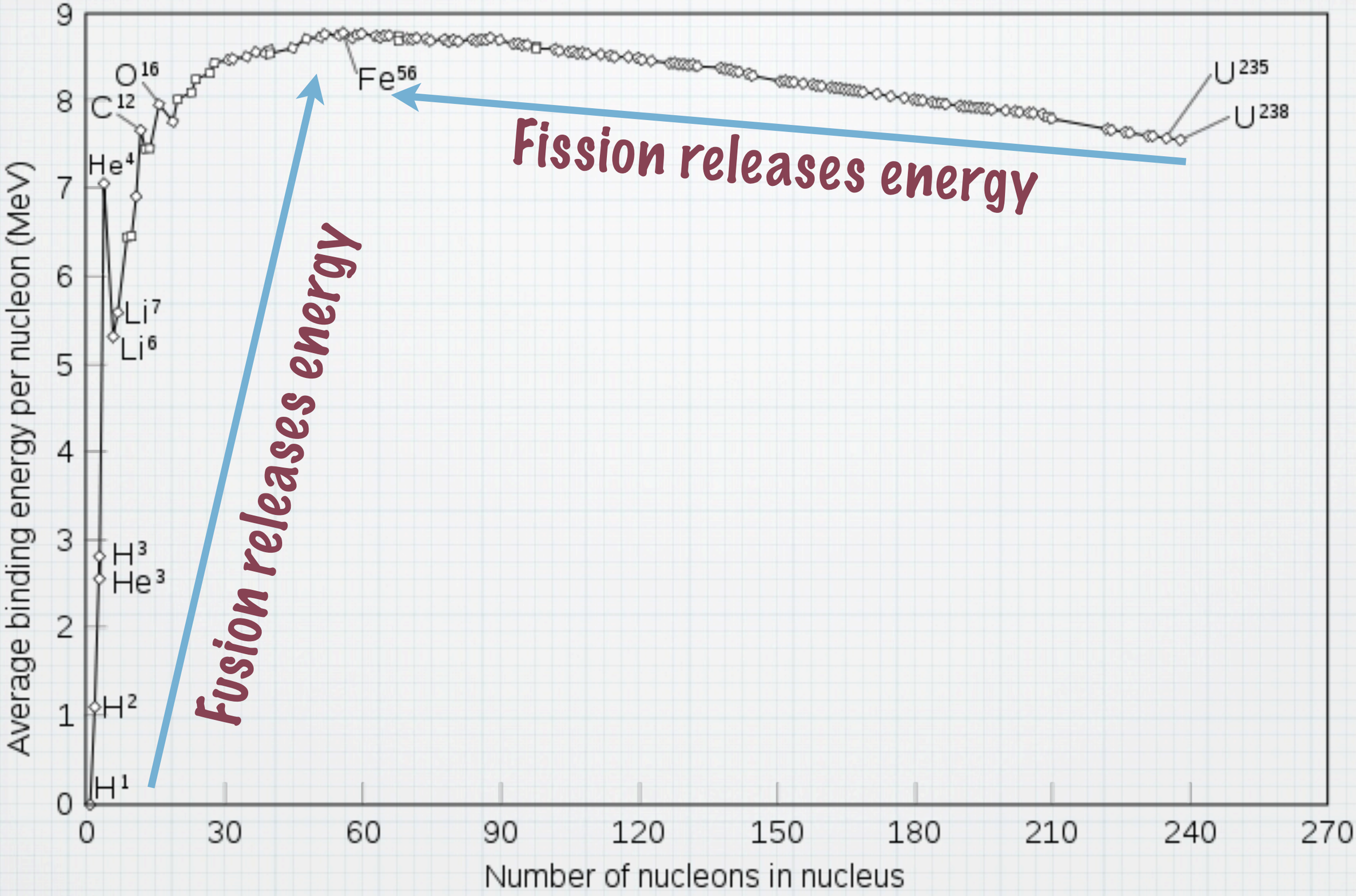

Iron is dead end for fusion because nuclear reactions involving iron do not release energy

Fusion in the Core

* At 15 million K, the plasma is fully ionized

➡ No electron is found bound to a hydrogen nucleus

➡ Every element (H, He, ...) is positively charged

* Electrons, protons & neutrons move with a very high speed (but over extremely small distances due to density of collisions)

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Fusion in the Core...

* The electromagnetic force prevents most head-to-head collisions
* The strong force's range is that of an atomic nucleus

➡ For two protons to "join", or **fuse**, their electromagnetic force repulsion has to be overpowered: this can be done only if they go fast enough

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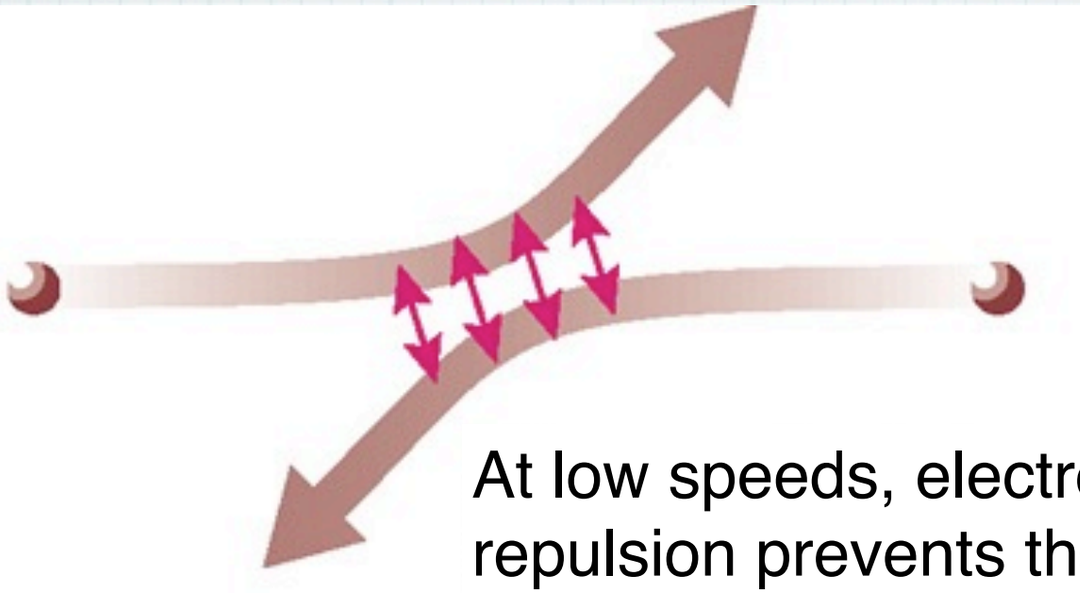
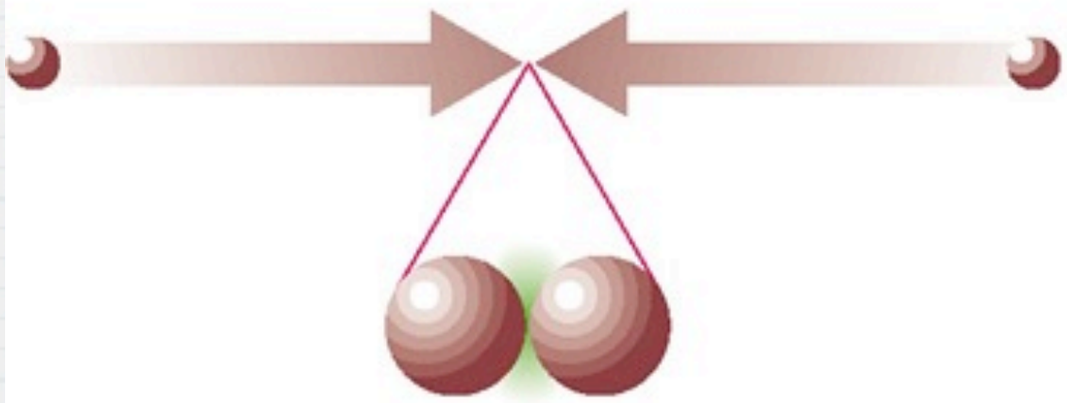
protons naturally repulse one another



At low speeds, electromagnetic repulsion prevents the collision of nuclei



At high speeds, nuclei come close enough for the strong force to bind them together

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Fusion in the Core...

* Positively charged nuclei fuse together if they pass close enough for the strong force to overpower their electromagnetic repulsion
* The higher the temperature, the harder the collisions

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Fusion in the Core...

* The high pressure all around is necessary to contain the resulting energy from blowing the surrounding plasma away - which would shut the nuclear reactions off

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The Proton-Proton Chain Reaction

* A hydrogen atom is a proton and an electron
* A helium atom is 2 protons, 2 neutrons and 2 electrons
* In the core of the Sun, everything is ionized, all electrons and singular protons are "free" (unattached)

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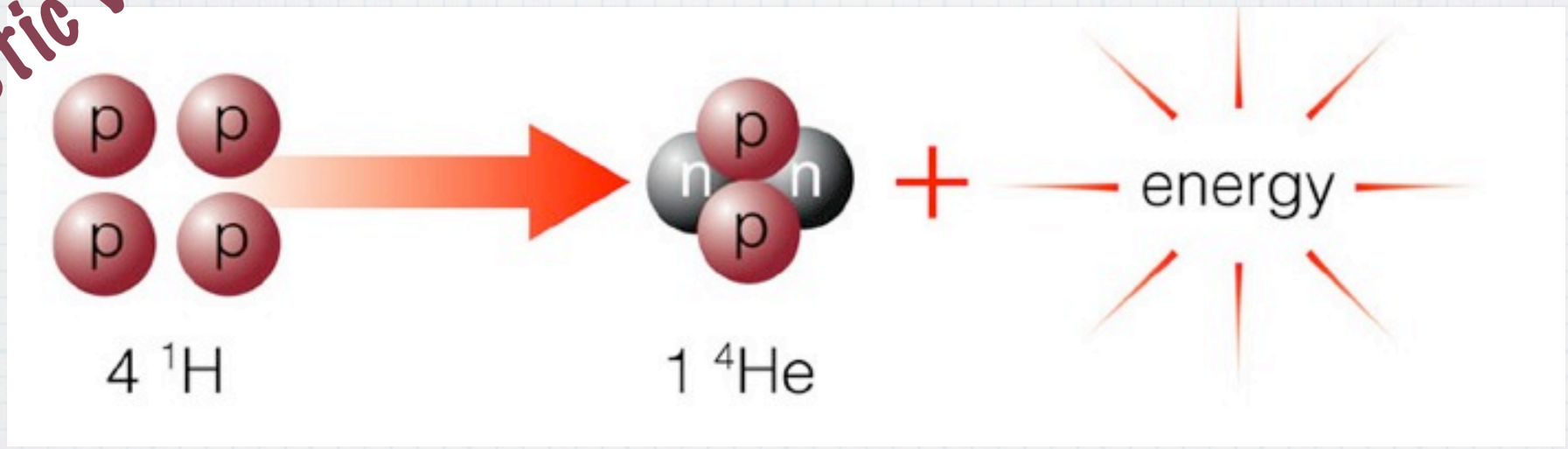
The Proton-Proton Chain...

* So somehow 4 protons (4 hydrogen nucleus) will get together to form a helium nucleus and produce energy
* Let's detail this reaction which is called the **proton-proton chain reaction**

Simplistic view



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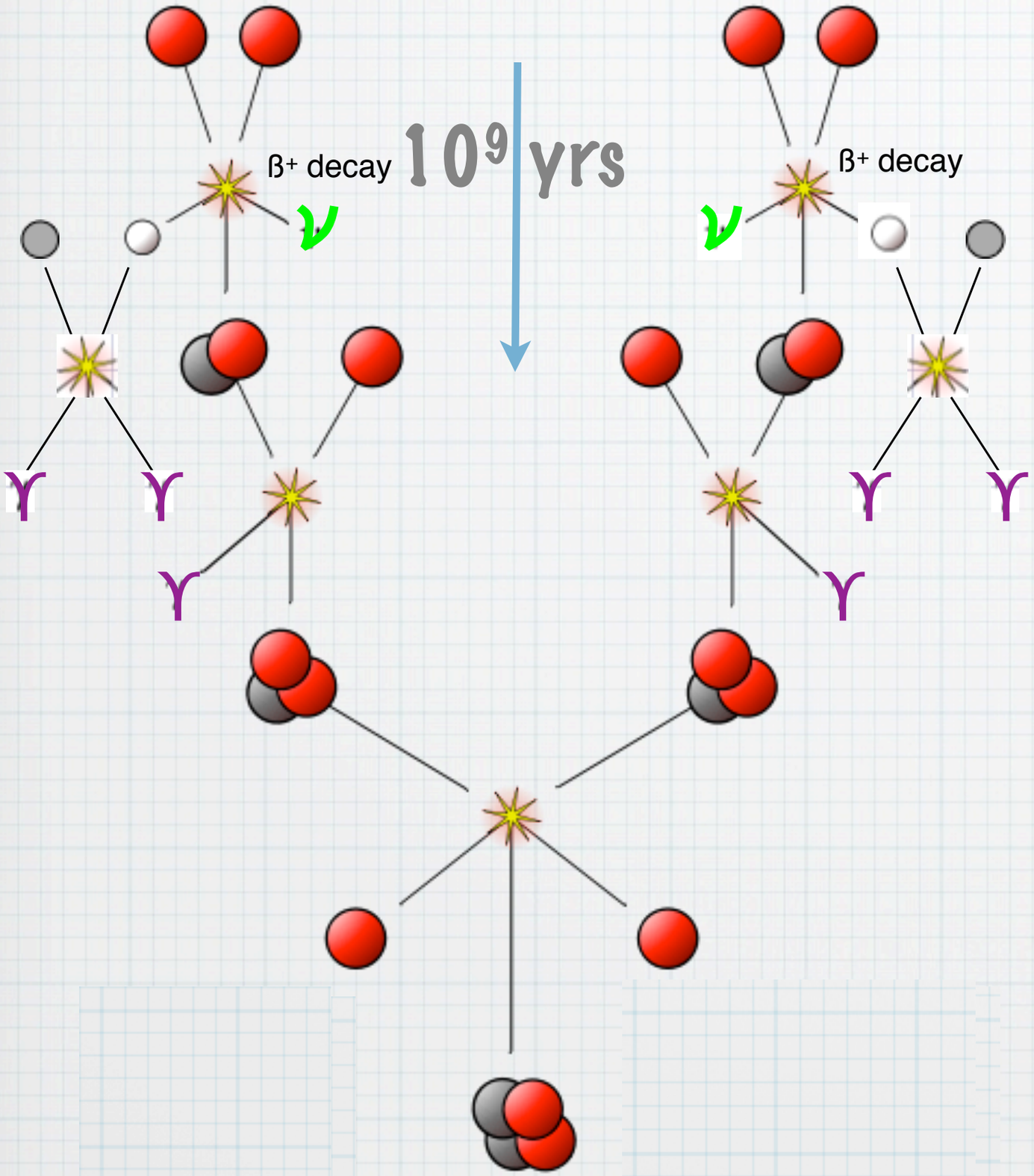
The Proton-Proton Chain...

* The overall reaction:
  * incoming:
    * 6 protons, 2 electrons
    note: a proton is a nucleus of Hydrogen
  * outgoing:
    * 1 nucleus of ^4He, 2 protons, 2 neutrinos and 6 gamma rays

More complete view

proton-proton chain



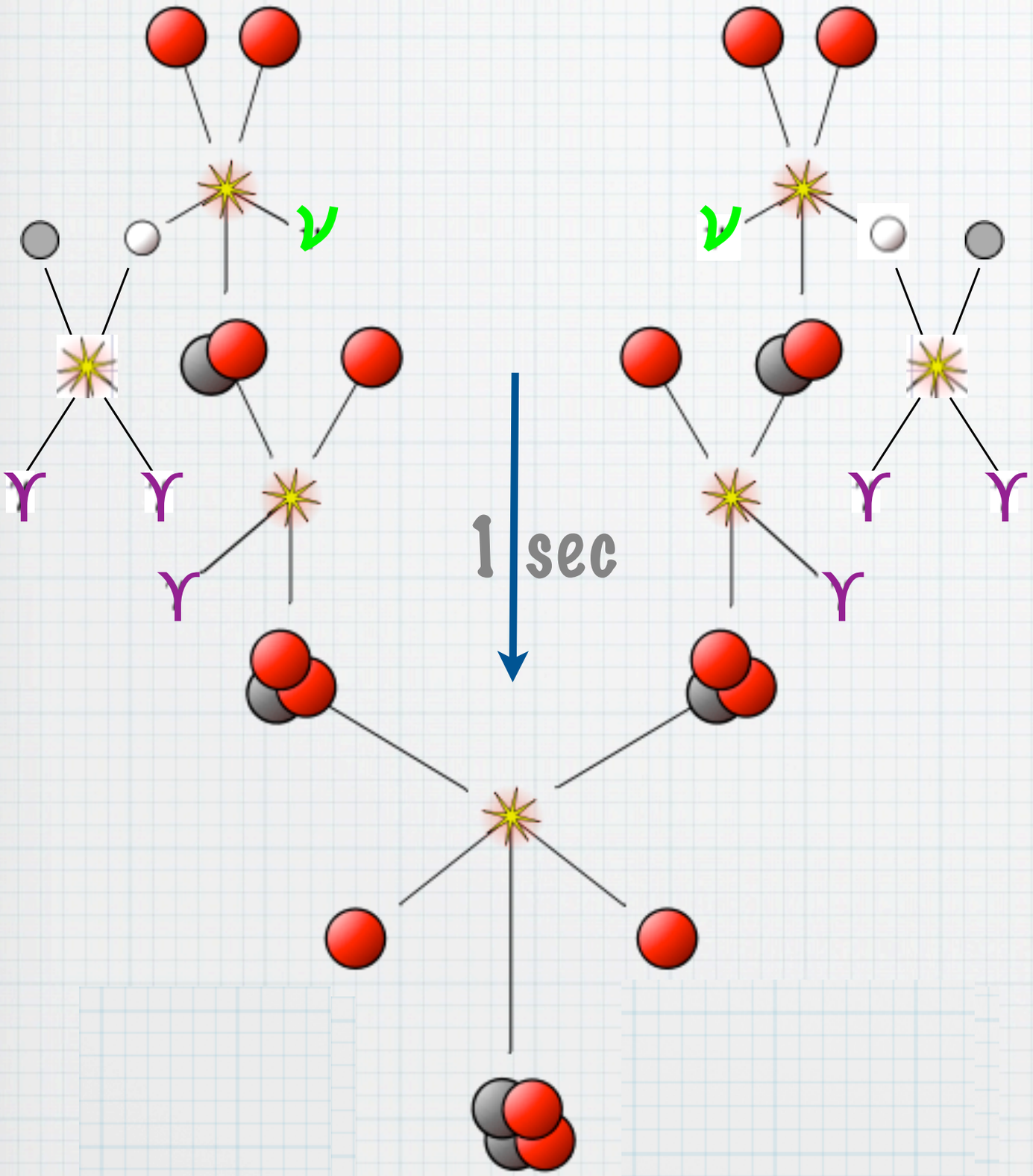
i. 2 protons fuse to form 1 deuterium nucleus (^2H), 1 positron and 1 neutrino

ii. positron + electron = 2 gamma rays

Electron
Proton
Neutron
Positron
Gamma Ray
Neutrino

deuterium is an isotope of hydrogen

proton-proton chain



iii. The **deuterium** fuses with **1 proton** to form **^{3}He** and **1 gamma ray**

Electron

Proton

Neutron

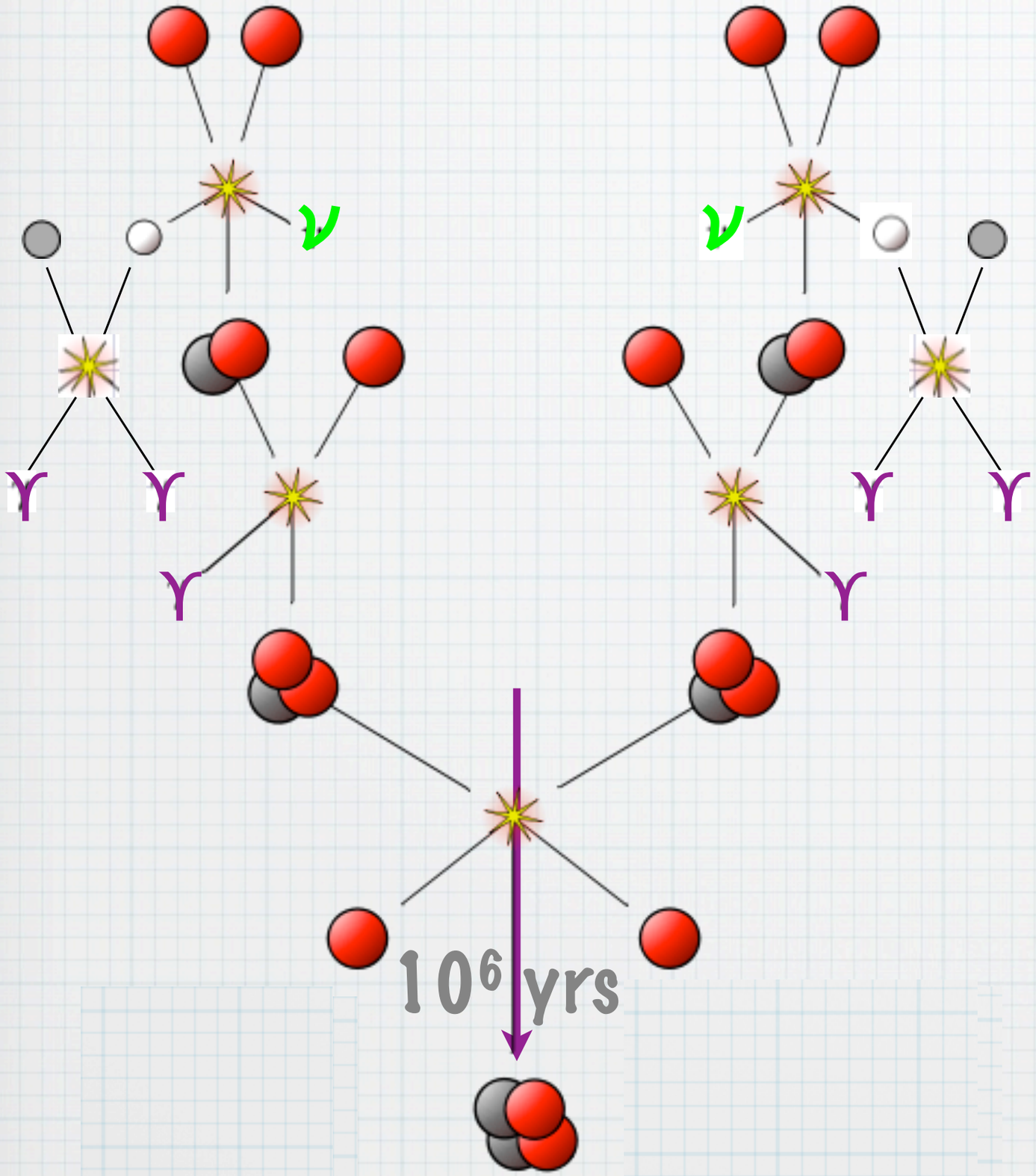
Positron

Gamma Ray

Neutrino

deuterium is an isotope of hydrogen

proton-proton chain



Electron

Proton

Neutron

Positron

Gamma Ray

Neutrino

deuterium is an isotope of hydrogen

iv. 2 ^{3}He nuclei fuse to form ^{4}He and release 2 protons

In English! Well... sort of

i. $2 \times ({}^{1}H + {}^{1}H \rightarrow {}^{2}H + \bar{e} + \nu)$ β+ decay

ii. $2 \times (e + \bar{e} \rightarrow \gamma + \gamma)$ matter - antimatter collision

iii. $2 \times ({}^{2}H + {}^{1}H \rightarrow {}^{3}He + \gamma)$

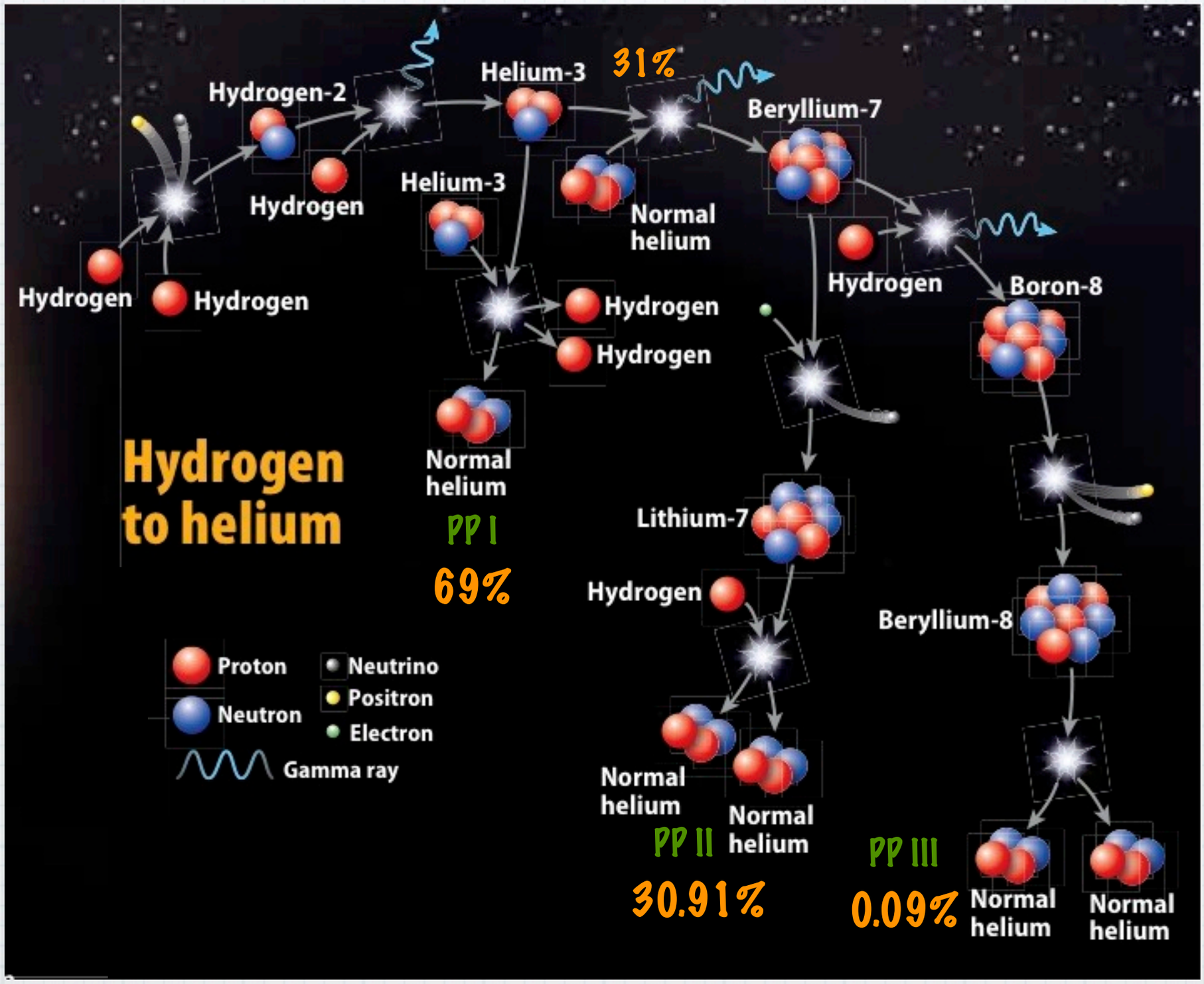
iv. ${}^{3}He + {}^{3}He \rightarrow {}^{4}He + {}^{1}H + {}^{1}H$

➡ $6\ {}^{1}H + 2\ e \rightarrow {}^{4}He + 2\ {}^{1}H + 2\ \nu + 6\ \gamma$

➡ simplified $4\ {}^{1}H + 2\ e \rightarrow {}^{4}He + 2\ \nu + 6\ \gamma$

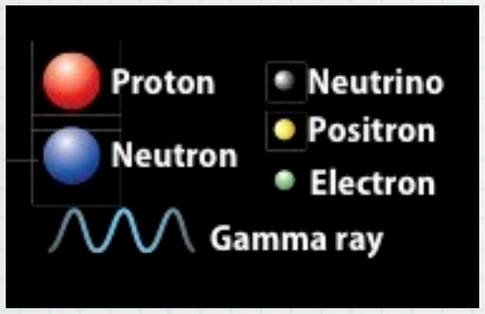
Complete Proton-Proton Chain

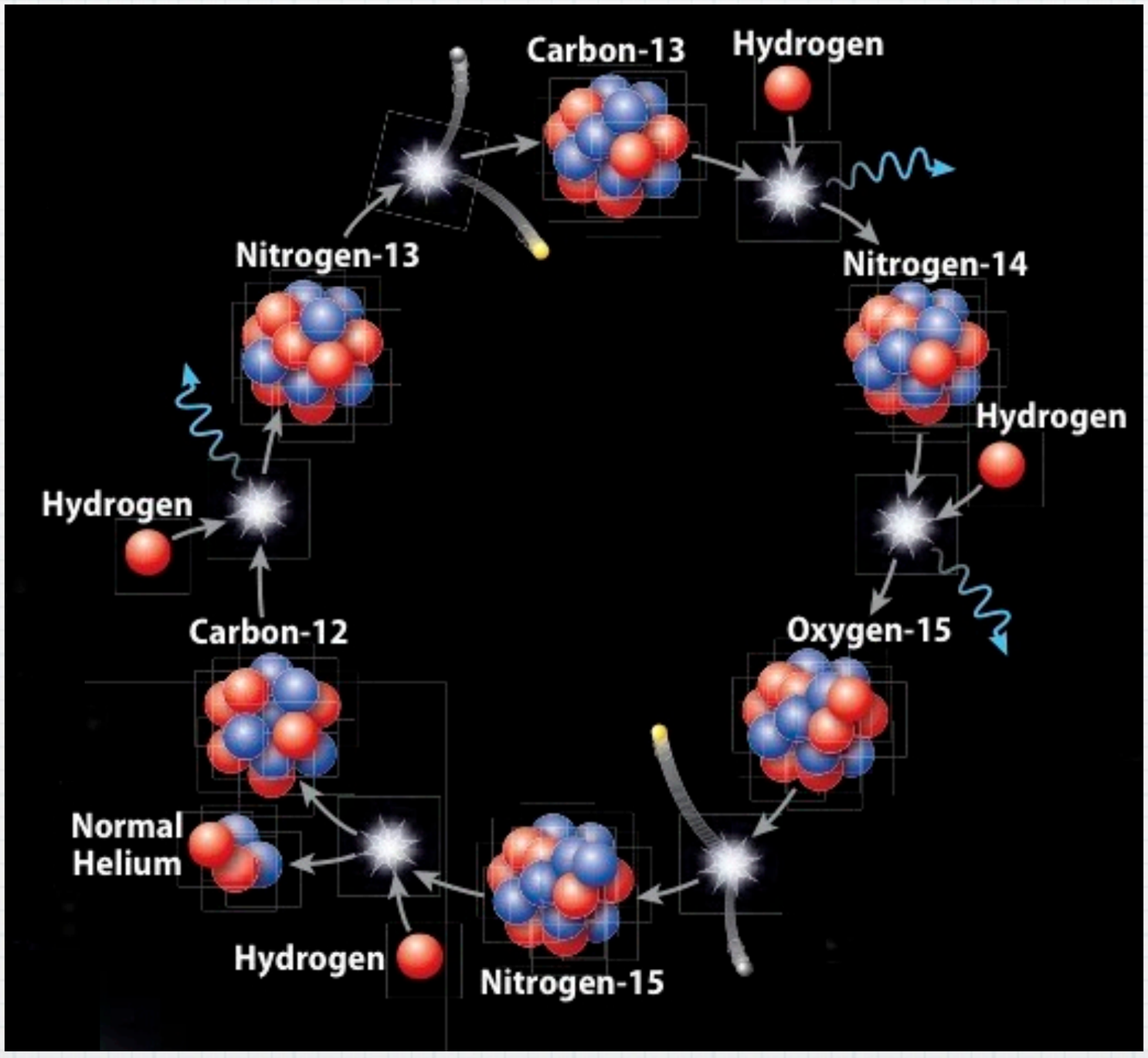
There is more than one way to get Helium



The CNO chain

There is more than one way to get Helium

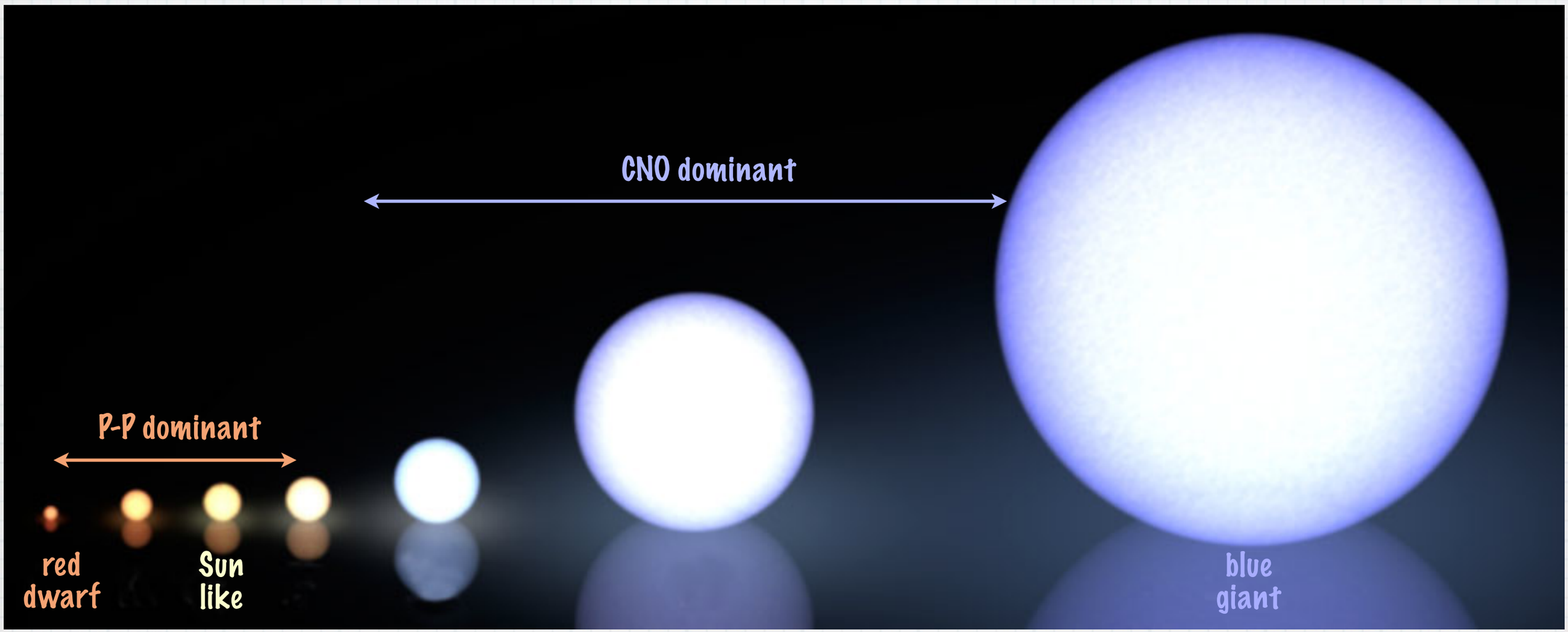




1% importance for the Sun

For stars 20% to 30% more massive than the Sun, this is the primary chain

Type of Stars & fusion method



How the Sun transforms Energy

* Mass energy is transformed into radiation energy ($E = mc^2$) and 2 exotic particles (neutrinos) in this chain
* This energy is carried off by 6 gamma rays (high-energy photons) and 2 neutrinos

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Released Energy

* Every second, 600 million tonnes of proton mass is turned into 596 million tonnes of Helium nuclei mass

➡ 4 million tonnes of matter is turned into radiation every second in the Sun driven by an electron-positron energy conversion

* This is a matter-antimatter reaction
* This has been going for 5 billion years with 5 billion more years to go

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Released Energy

* The "missing" mass (4 million tonnes) is due to the nucleus of helium (2 protons and two neutrons) being lighter than 4 protons (by 0.7%)
* It is also called the **binding mass**

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Self-Regulating Equilibrium

* The Sun fuses hydrogen at a steady rate
* It is a self-regulated process with an auto-feedback
  * gravity against pressure
* Nuclear fusion is very sensitive to temperature

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Solar Thermostat

slight Temperature

Decrease

high Fusion Rate

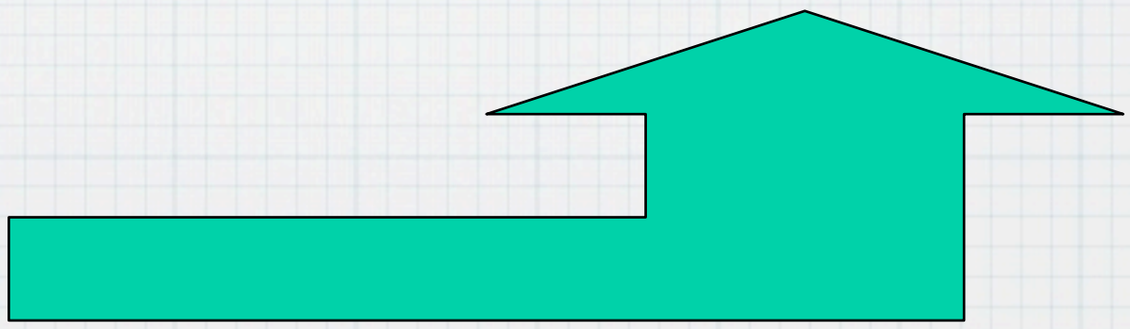
Decrease

Gravity

Compresses Core

Temperature

Increases



Solar Thermostat

slight Temperature

Increase

high Fusion Rate

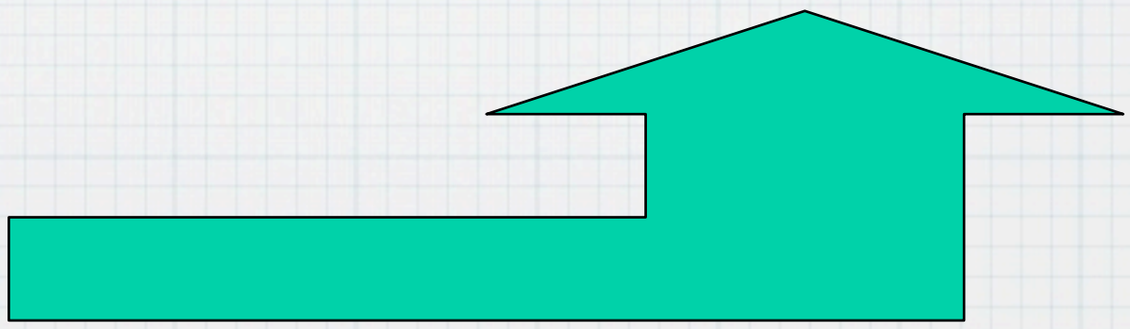
Increase

Energy

Expands Core

Temperature

Decreases



Getting Out of the Sun

* 98% of the energy released by fusion is in the form of high-energy (γ-ray) photons
* The rest is via neutrinos (2%)
* The only speed a photon knows is the speed of light as a photon cannot exist with a different speed

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Amazing, but true!

* A photon of light produced by nuclear fusion inside the core of the Sun can take up to **how many years?** to reach the photosphere

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Amazing, but true!

* A photon of light produced by nuclear fusion inside the core of the Sun can take up to **one million year (or even longer!)** to reach the photosphere

* **200,000 years on average**

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Getting Out of the Sun...

* The core is so dense that the photons are constantly interacting with the free electrons in the plasma
* They are deflected from one electron to another and get out of the core in a random walk pattern
  * deflected here means absorbed and re-emitted with some energy given to the electron (temperature!)
* The **mean free path** is a fraction of a millimeter

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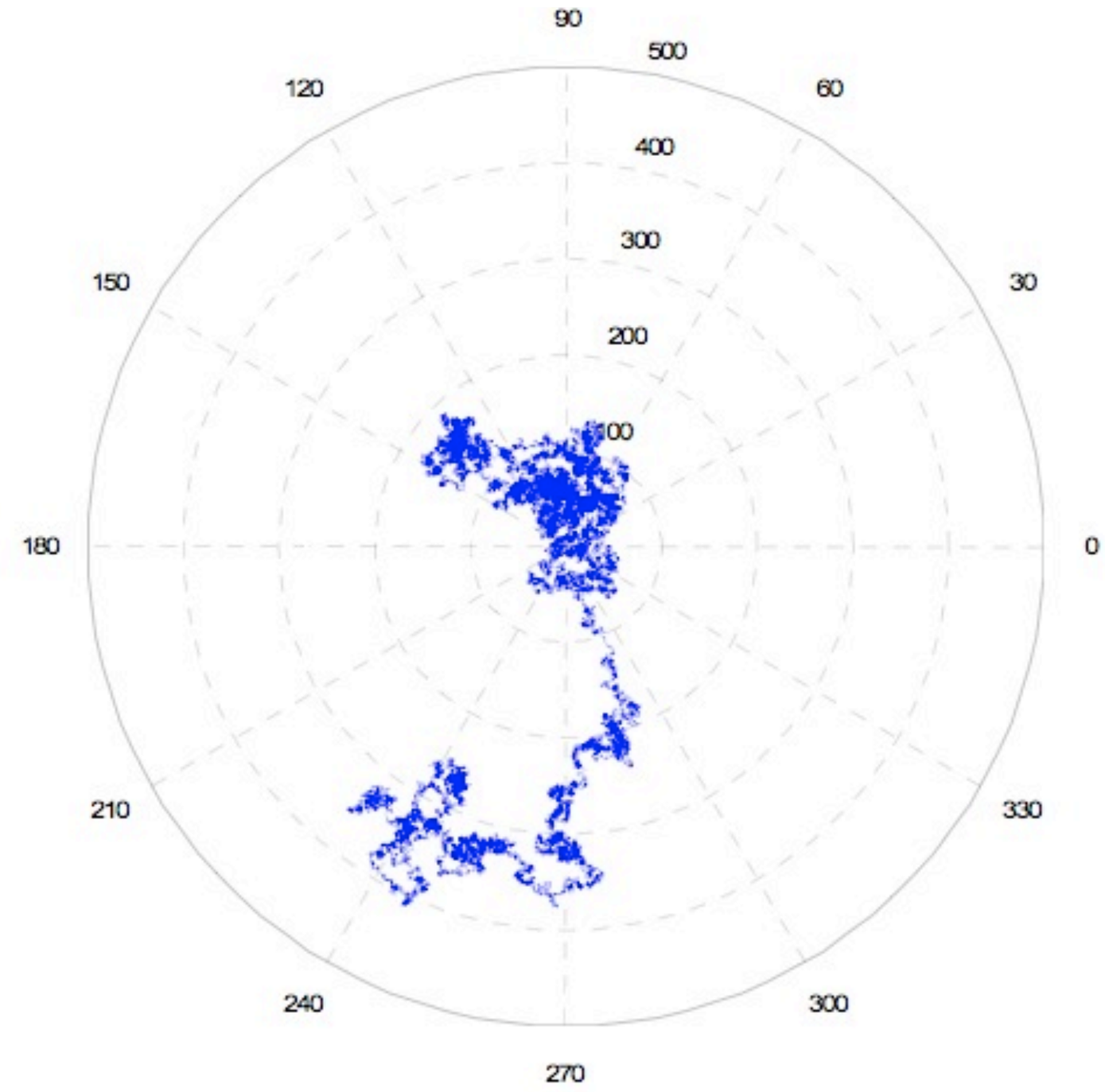
It can take up to **one million years** (or more) before a photon finds its way out of the core!

Average is about 200,000 years

Random Walk from the Solar Core



100000 Interactions, Average Distance = 321.98 cm

Getting Out of the Sun...

* With so many interactions, an original gamma ray's energy will be converted to one thousand lower-energy photons when they leave the Sun
* All of these interactions give off a little energy to the plasma as kinetic energy which increases temperature
* Most of the solar energy leaving the surface will be visible light and infrared photons

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Solar Neutrinos

* About 2% of the fusion energy is passed on to creating neutrinos
* Neutrinos are strange particles (there are 3 types)
* They are **almost massless**
* They travel at **almost the speed of light**
* The **mean free path** of a solar neutrino is about **one light year of solid lead**

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Solar Neutrinos...

* So while it can take hundreds of thousand of years for a photon to escape the Sun...
* It takes a newly created neutrino about 8 minutes to reach us from the center of the core
* About one thousand trillion solar neutrinos pass through us every second

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Solar Neutrinos...

* If we could easily detect them, they might tell us what is happening at the core - eight minutes ago!
* Neutrino detectors need to be built one mile or deeper in the ground to limit "noise"
* What we have found is that neutrinos change "type" as they travel - something theoretical particle physicists had never envisioned (until recently)

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Solar Neutrinos...

* A newly built solar neutrino detector which can detect all three types of neutrinos confirm our theoretical solar model

  * electron neutrino
  * muon neutrino
  * tau neutrino

3 neutrino types, one of each family of matter

each family has its own temperature range

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Getting Out of the Sun...

* After leaving the **core**, the photons go through the **radiative zone** (via the random walk)
* Then comes the **convecting zone** where the energy moves in columns of hot gas toward the photosphere (random walk inside)
* Once a photon has reached the **photosphere**, it finally escapes the Sun, energy is lost by the rising gas which cools and sinks back down the convecting zone

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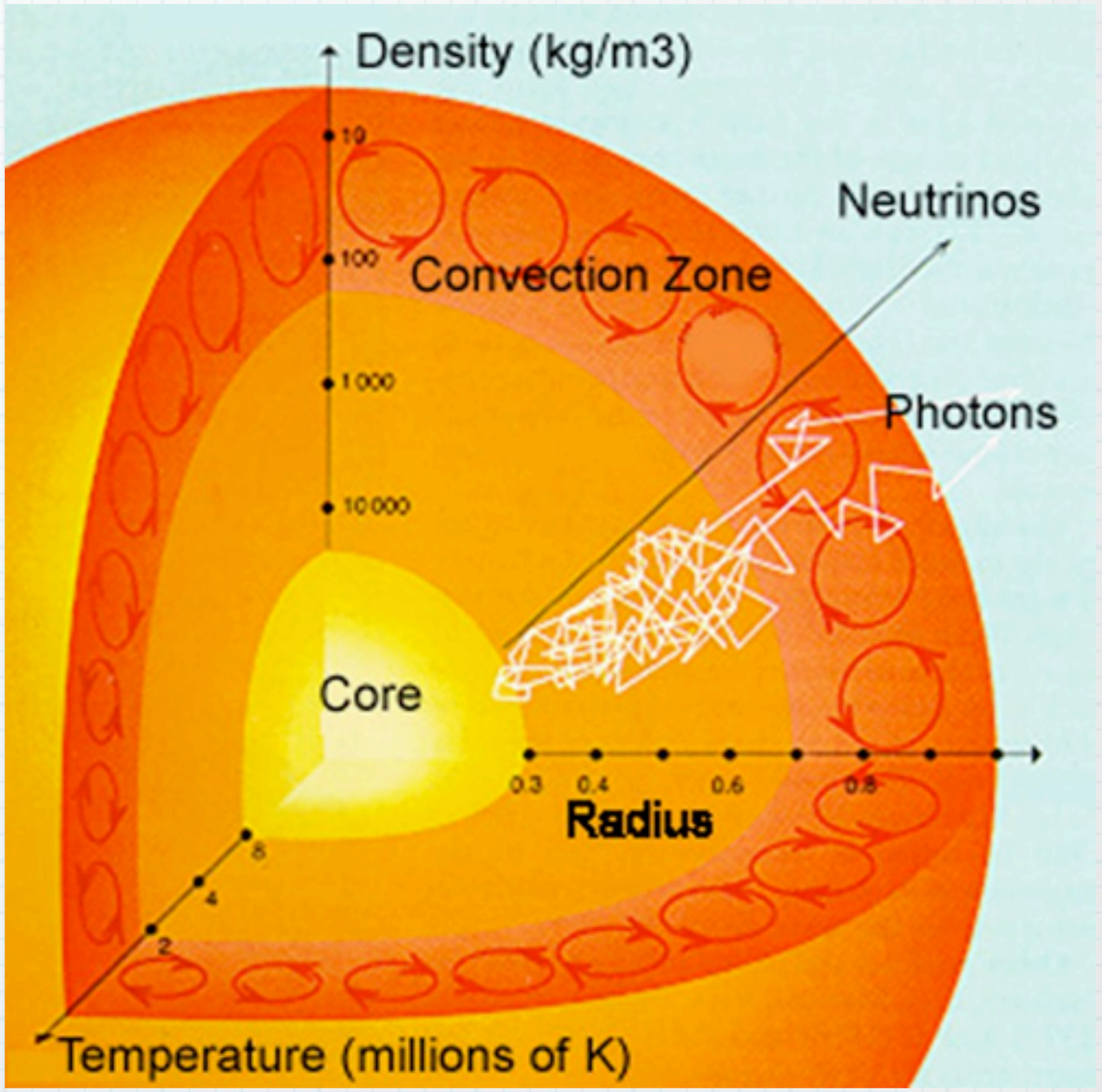
Solar Interior

Core: energy generation (inner 25-30%)

Radiation zone: energy diffusion mostly by gamma-rays and x-rays

Convection zone: energy motion by convective fluid flows (boiling motion) the outermost 30%



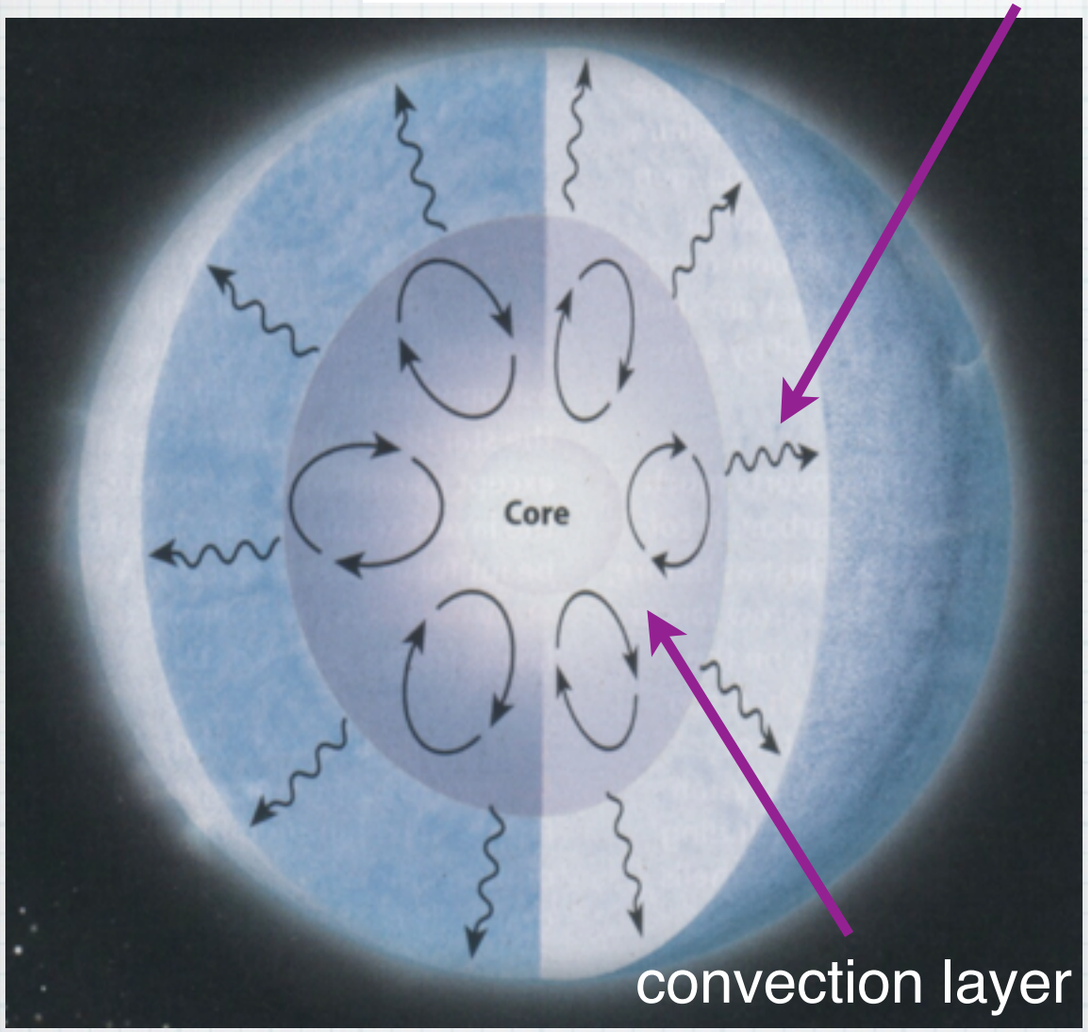
Photon: about 200,000 years to reach the surface
Neutrino: about 4.6 seconds

Star Internal Structures and Mass

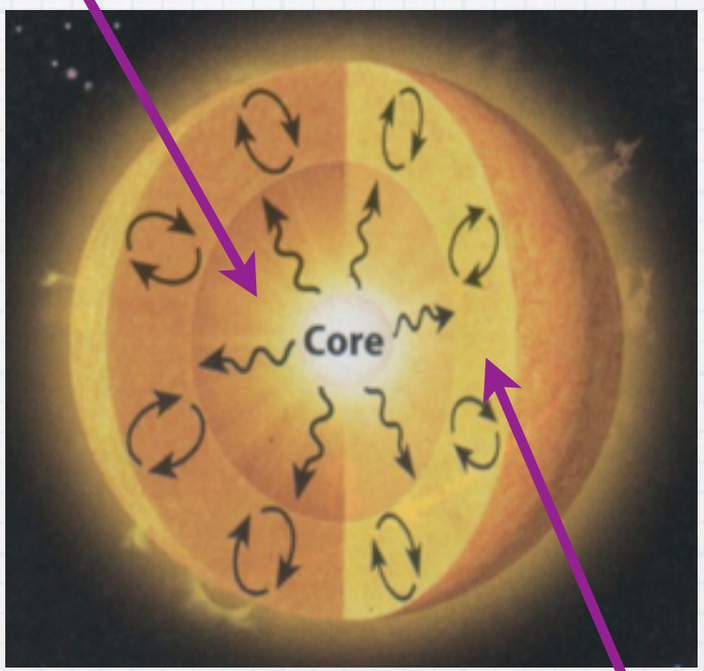
Not all stars have a radiation layer followed by a convection layer: it is mass dependent

massive star
> 1.3 M_{Sun}

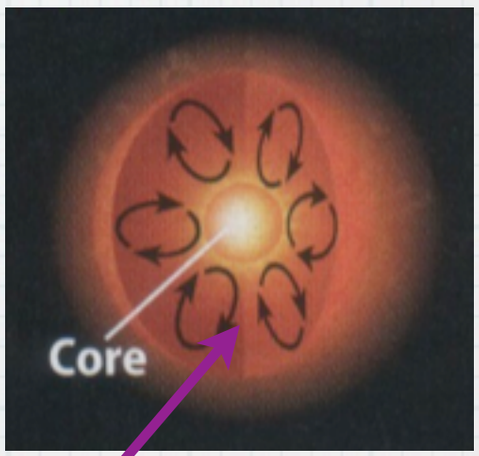
radiation layer



Sun-like star
0.25 to 1.2 M_{Sun} star

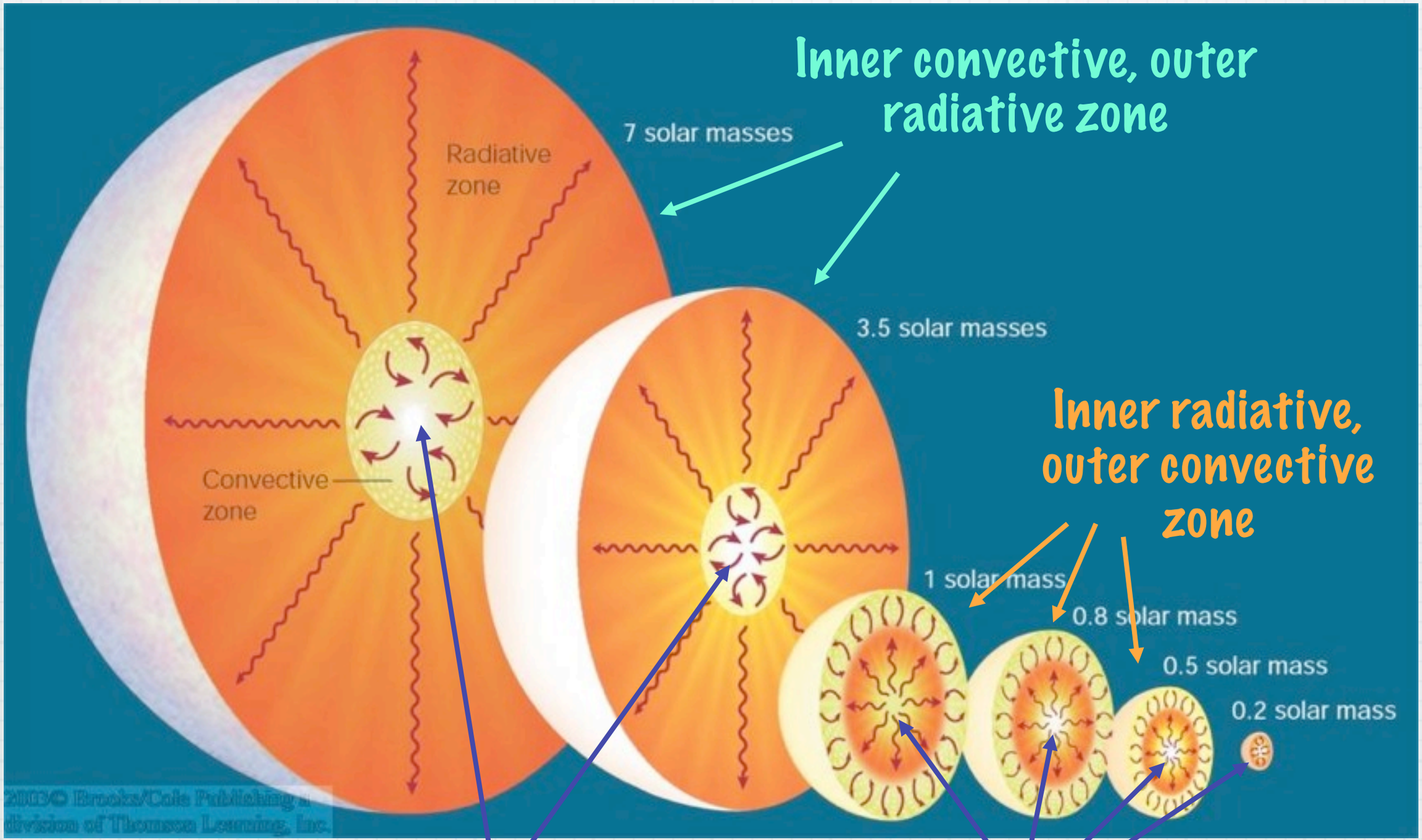


very low mass star
< 0.25 M_{Sun}

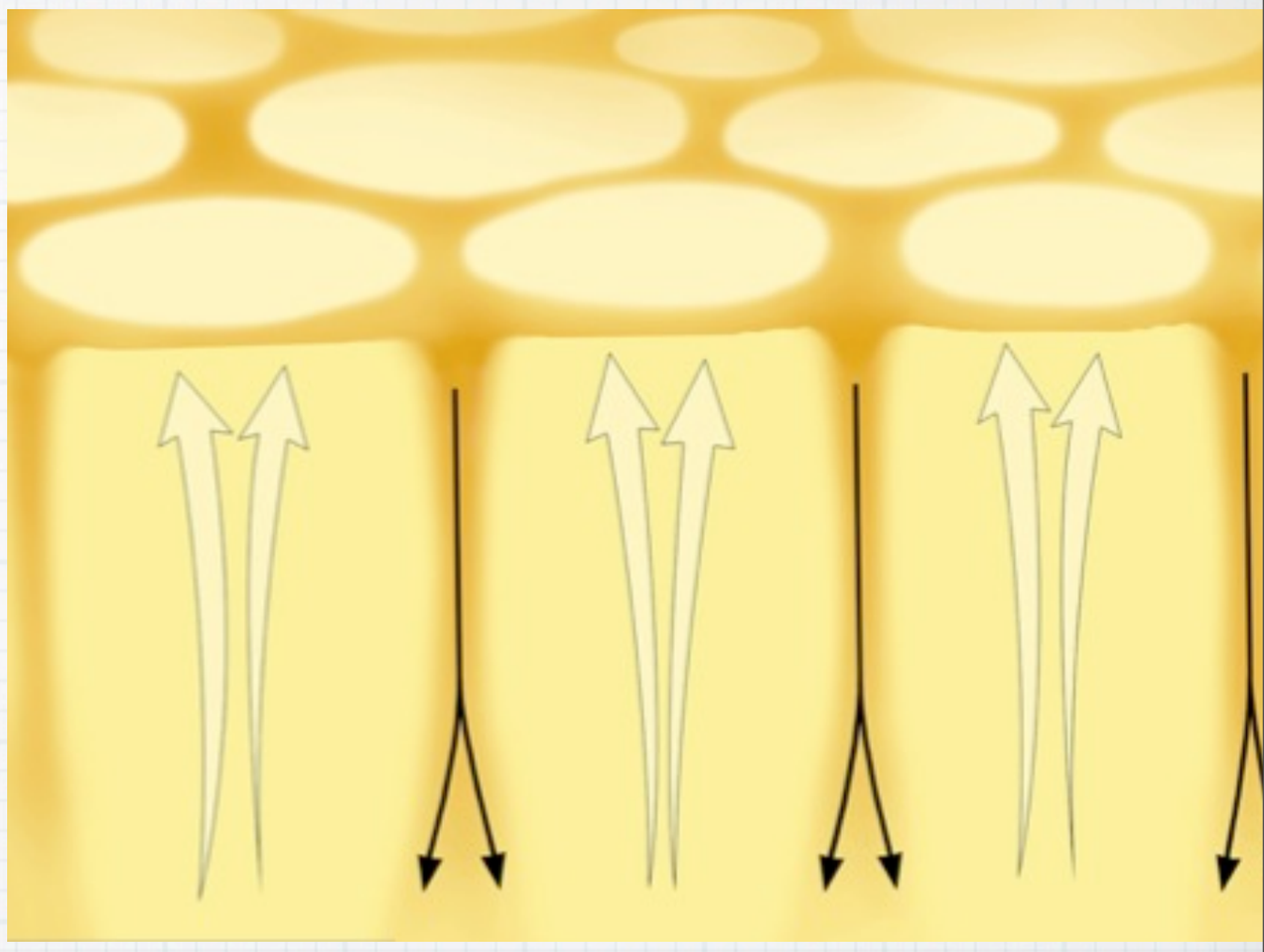


convection layer

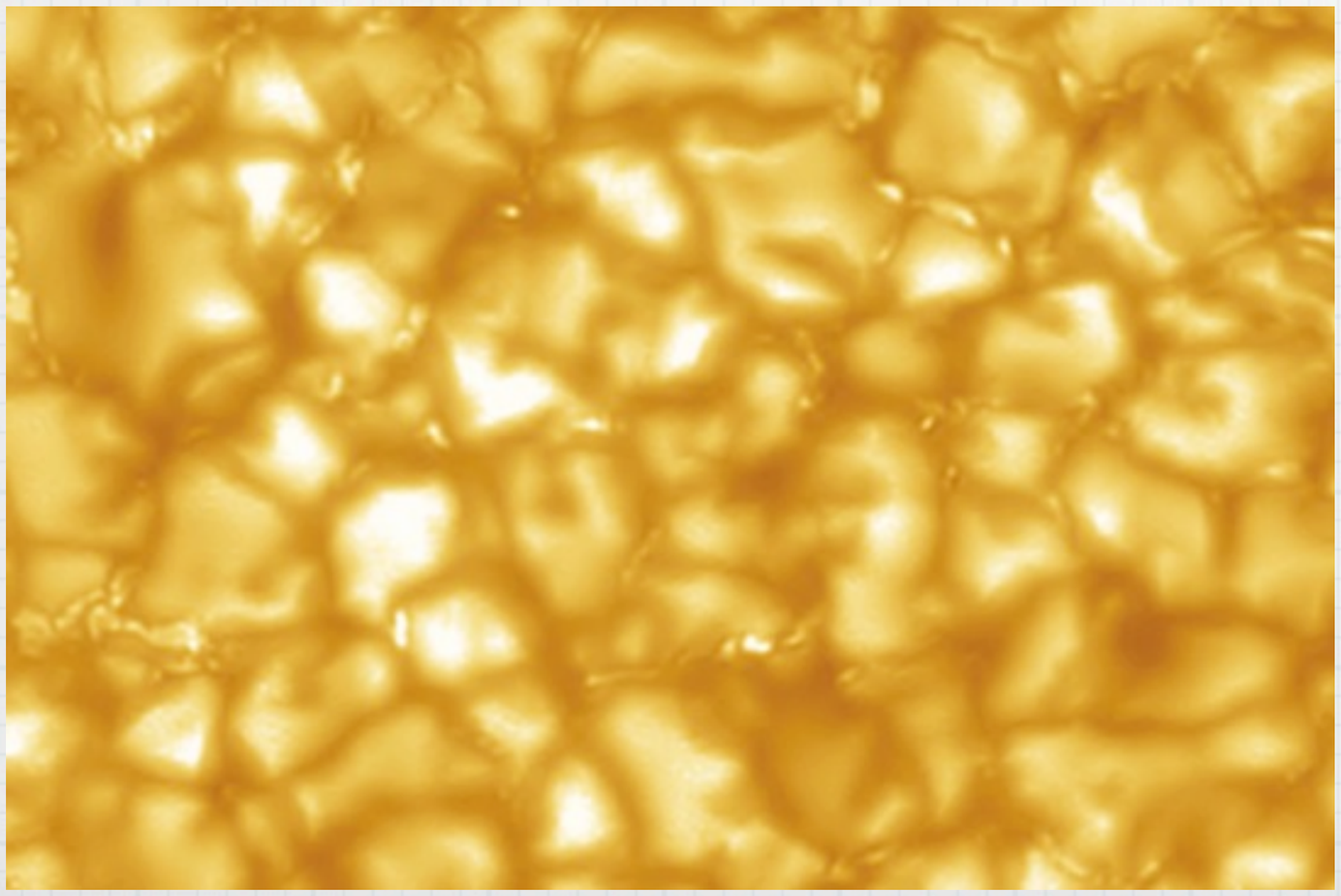
Energy Transport Structure



Convection Zone



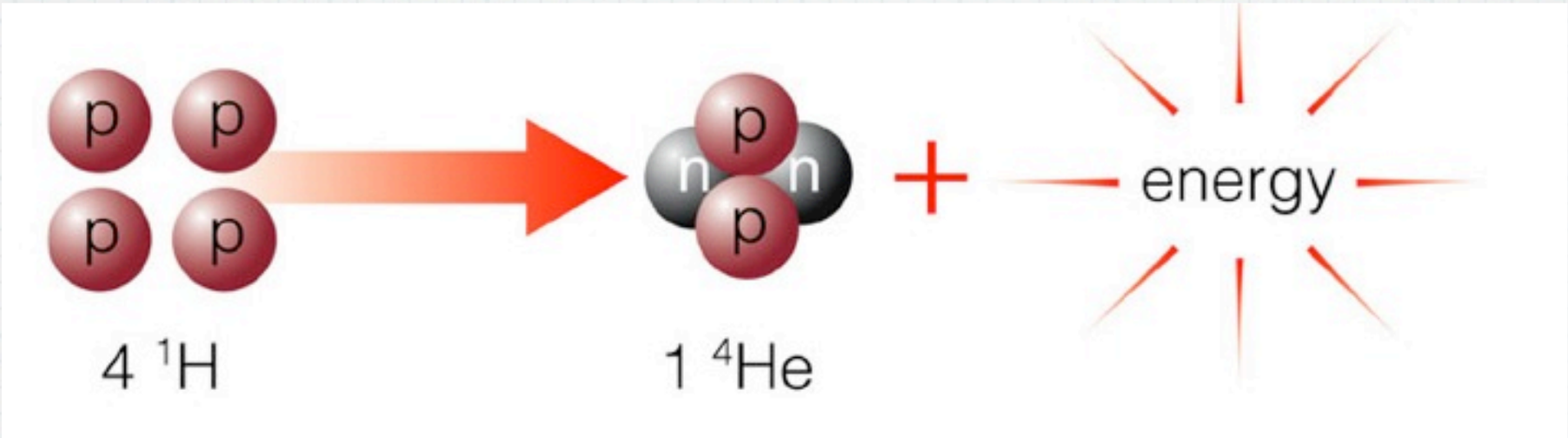
Convection cells



As seen from the surface (photosphere) the cells look like granules

Snapshot

* How does nuclear fusion occur in the Sun?
* Fusion of hydrogen into helium, which occurs via the proton-proton chain is a matter-antimatter process. Gravitational equilibrium acts as a thermostat that keeps the fusion rate steady



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Snapshot

* How does the energy from fusion get out of the Sun?
* Energy moves through the deepest layers of the Sun - the core and the radiation zone - in the form of randomly bouncing photons
* After energy emerges from the radiation zone, convection carries it the rest of the way to the photosphere, where it is radiated into space as sunlight and infrared radiation

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Getting Out of the Sun...

* At the photosphere level, it is said that the medium becomes transparent for a photon
* That is why it can escape
* That is why the solar "surface" looks like a solid sphere
* But those photons have been created tens of thousands of years earlier

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How do we know this stuff?

* Mathematical models
* Sun quakes
* Solar neutrinos capture

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Mathematical Models

Input: - Solar observed composition

- Its mass

Equations: - Gravitational equilibrium

- Solar energy motion within

Output: - Temperature, pressure & density

- Rate of nuclear fusion in the core

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Sun Quakes

* Solar gas movements generates surface vibrations
* We can observe and measure them
* We can deduce (more math!) internal solar structure from them
* Geophysicists do the same with earthquakes on our planet

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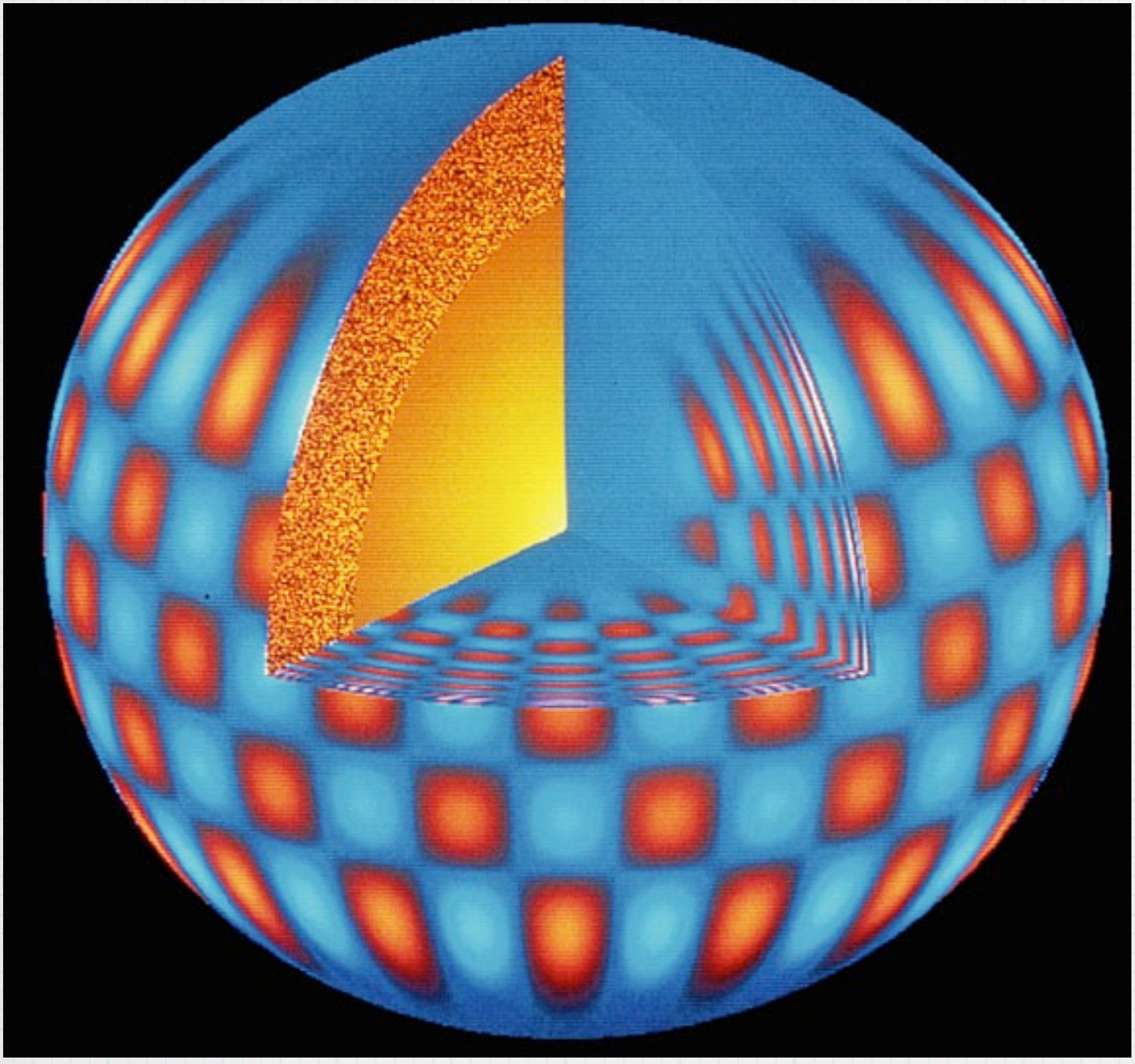


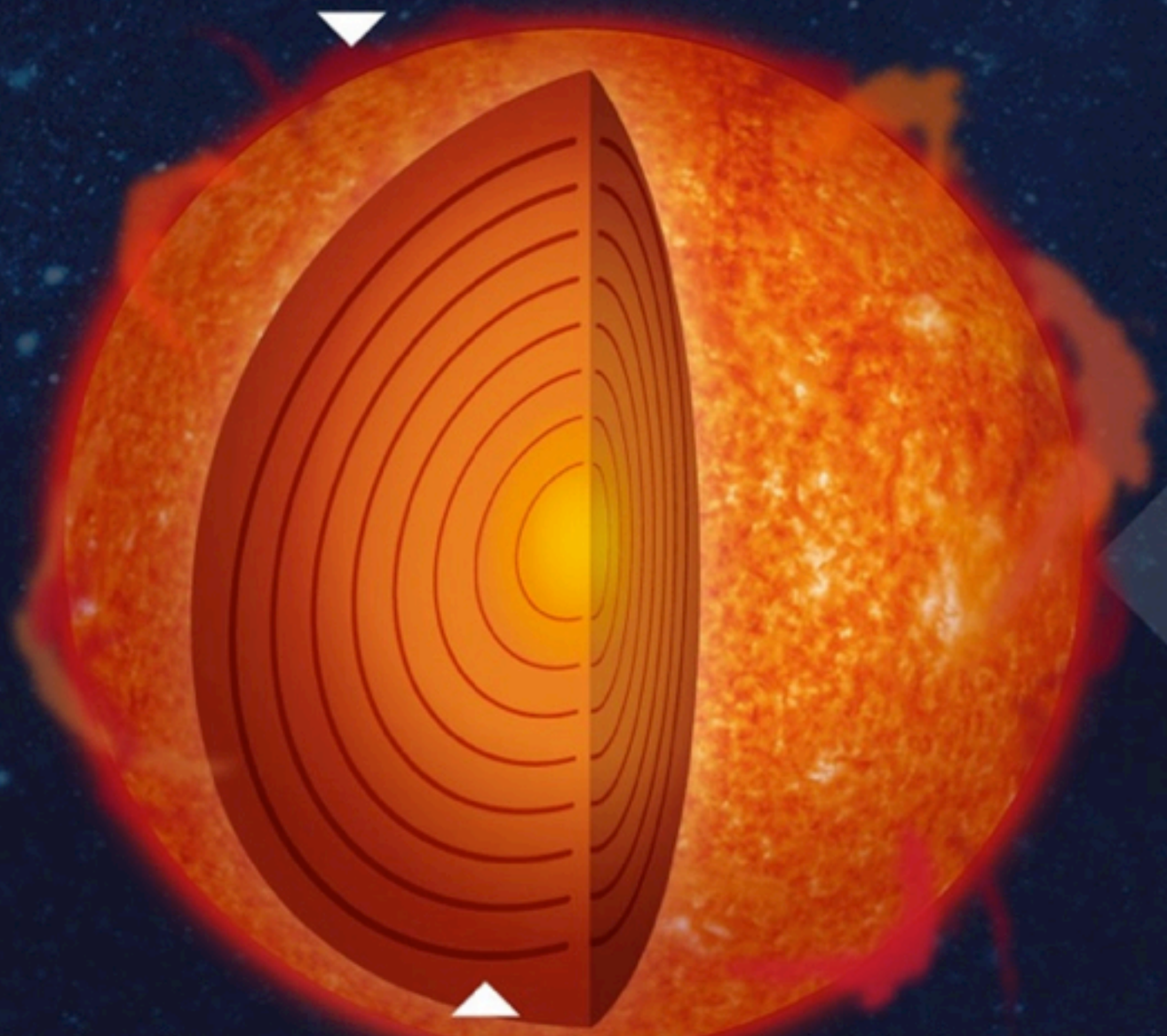
Patterns of vibration on surface tell us about what Sun is like inside

Results agree very well with mathematical models of solar interior

Celestial music

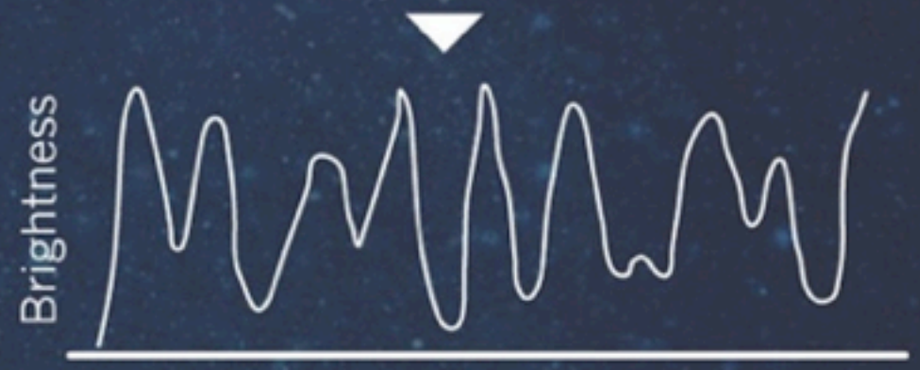
In the same way as a sound wave resonates inside an organ pipe to create a musical tone, sound waves on a far vaster scale can resonate inside a star. By measuring the frequencies of these waves, astronomers can learn about the star's internal structure.

Vibrations are generated by turbulence on the star's surface.

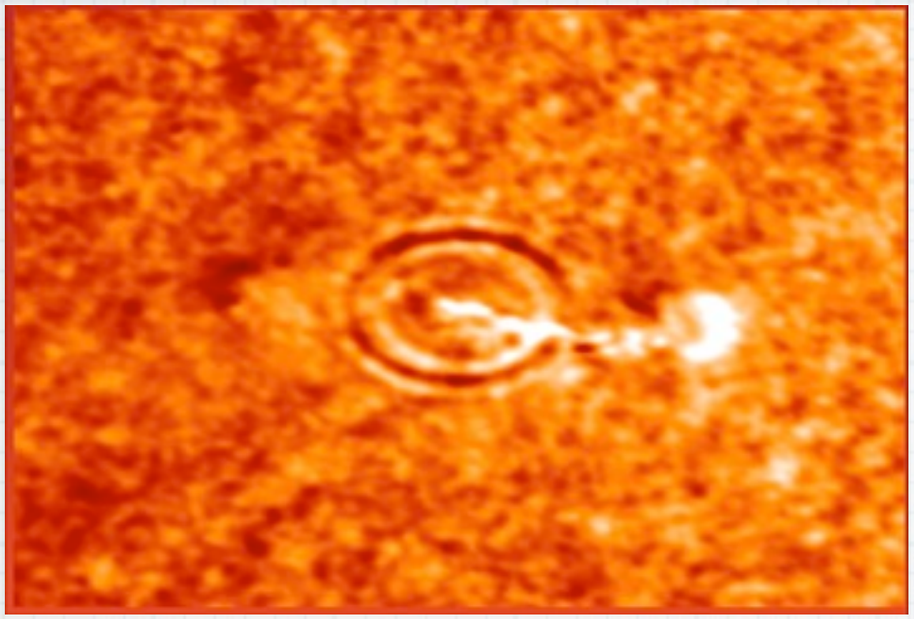


The vibrations penetrate deep into the star's interior, setting up resonant oscillations at frequencies depending on the star's size, density and rotation.

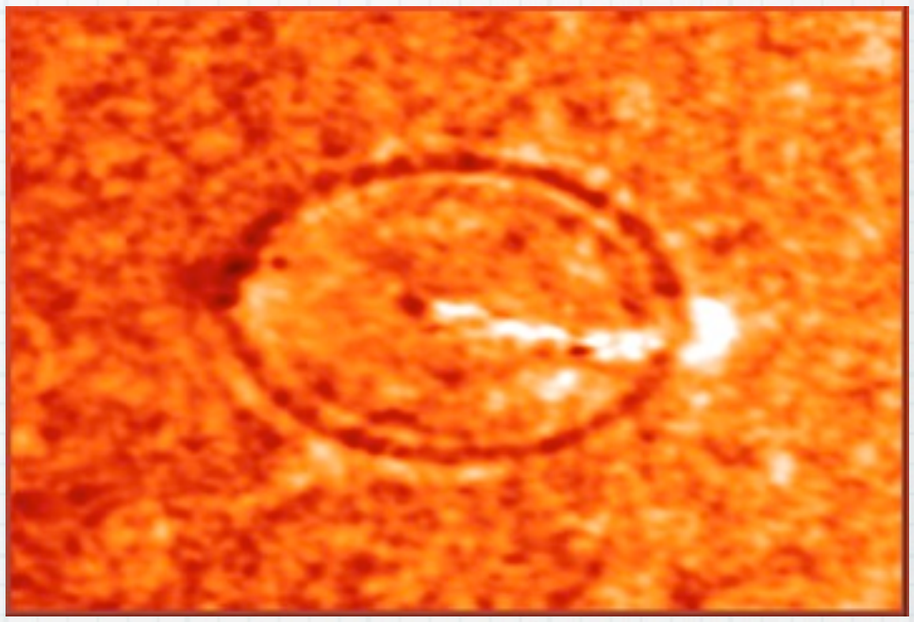
Astronomers see these oscillations as subtle, rhythmic changes in the star's brightness.



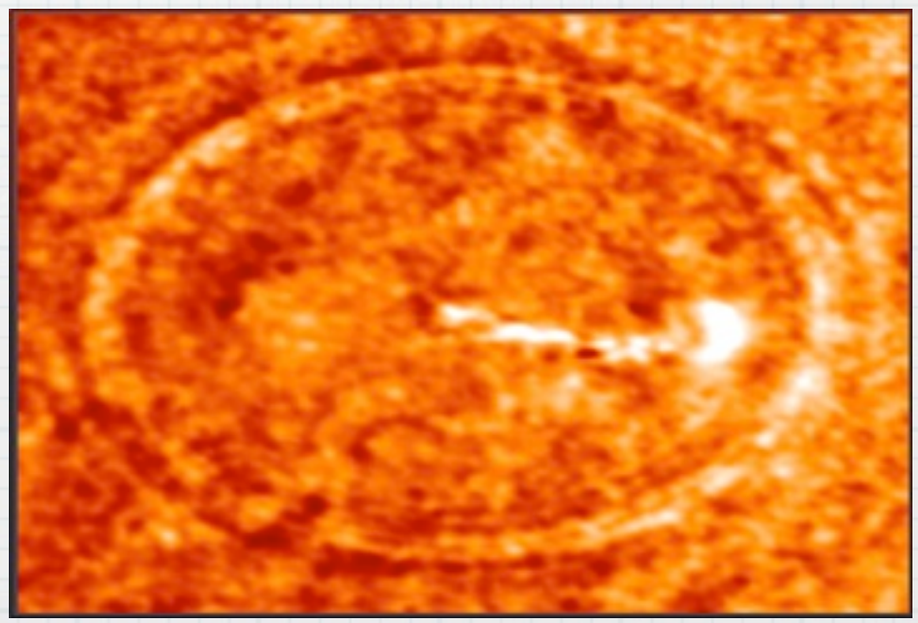
Resonant frequencies can vary from one every few minutes in Sun-like stars to one every few hundred days in red giants.



An 11th magnitude solar quake has been recorded on the Sun, immediately following a moderate solar flare



The magnitude and evolution of these quakes gives information about the physical nature of solar flares, the surface of the Sun, and even the Sun's interior



Solar Activity

* Solar activity, also called solar weather refers to events appearing in the three layers of the Sun's atmosphere
  * photosphere: sunspots, faculae, granules & supergranules
  * chromosphere: chromospheric network, filaments, plage, prominences & spicules
  * corona: flares, plumes, loops, holes & mass ejections

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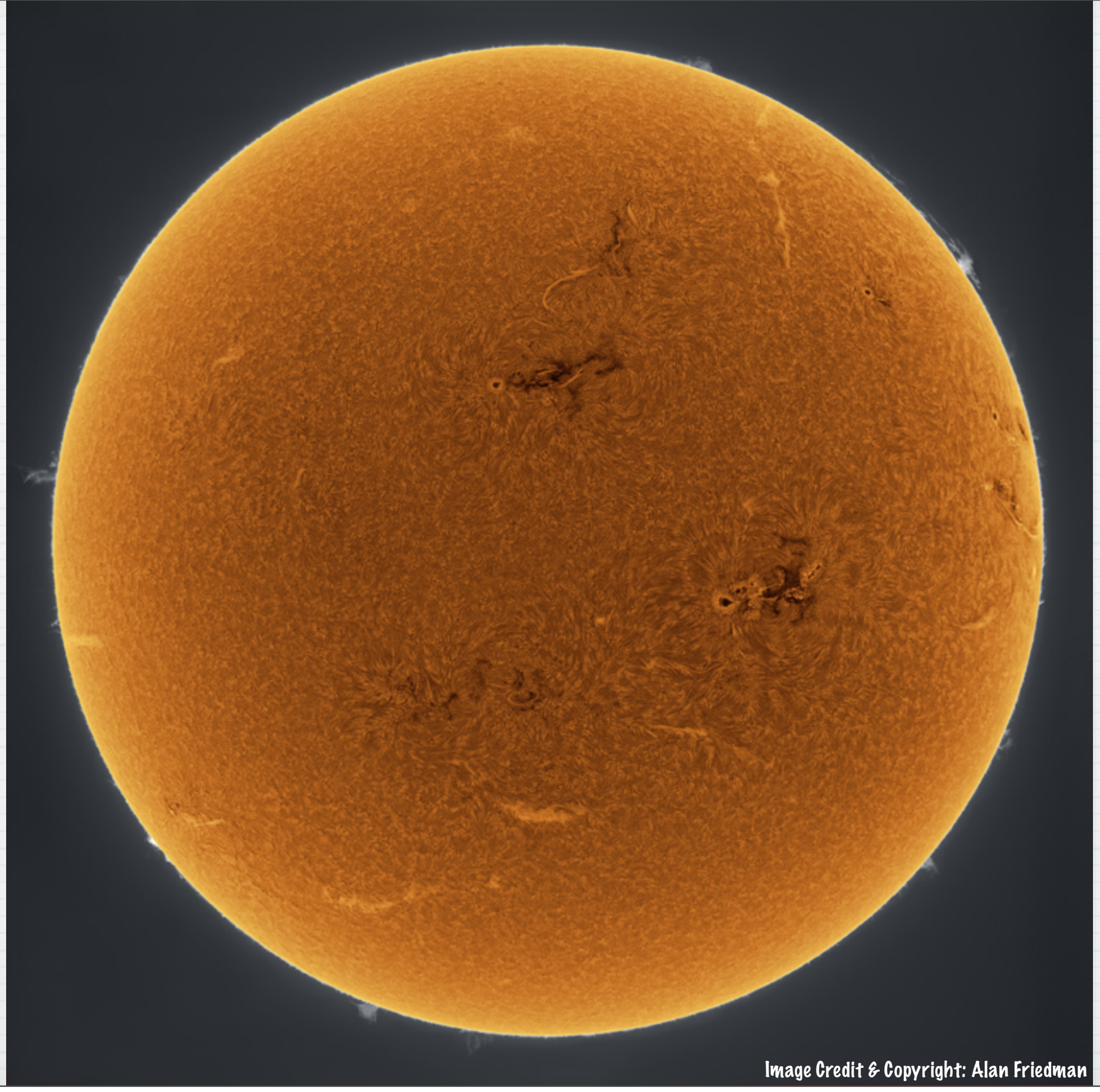


Image Credit & Copyright: Alan Friedman

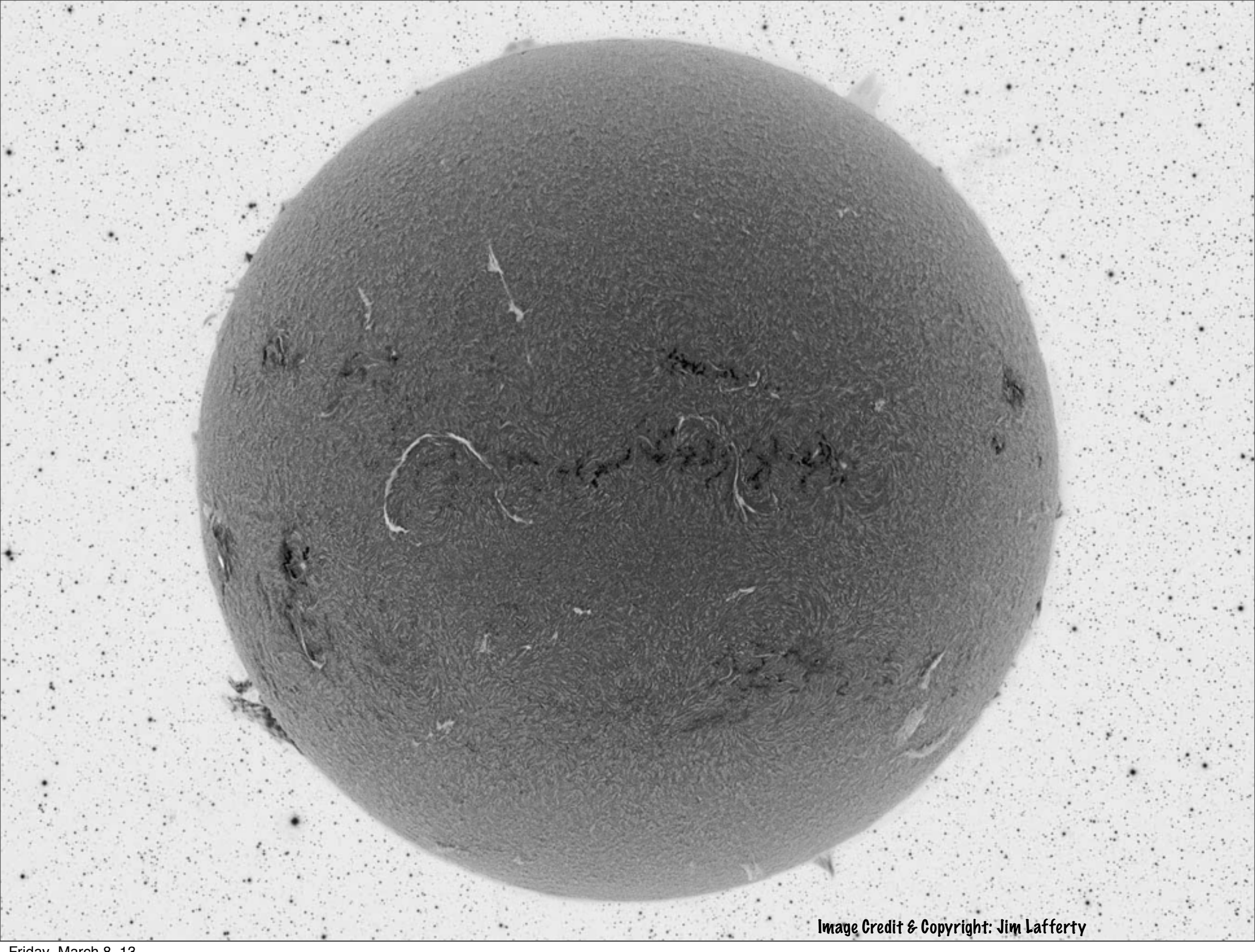
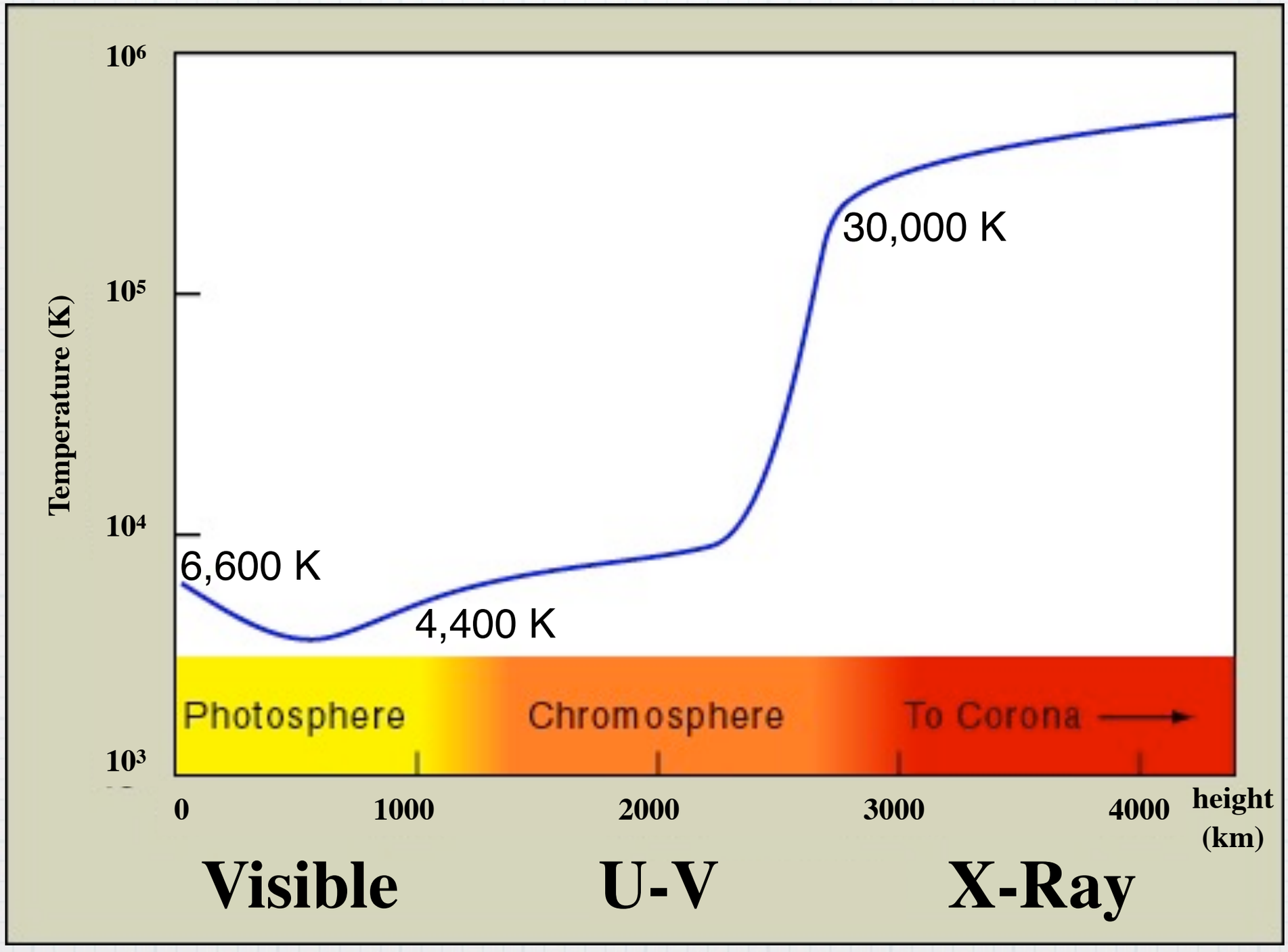


Image Credit & Copyright: Jim Lafferty

Temperature Ranges



Solar Activity...

* The solar activity does not stop at the upper atmosphere but continue much further due to the solar wind
* This activity bubble extends far beyond the Oort cloud

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Solar Magnetic Field

* The solar activity is driven by its **magnetic field**
* The magnetic fields are generated by electric currents moving within the convective layer (plasma)
* **The Sun is a "Magnetic Variable" type star**

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Solar Magnetic Field...

* It is thought that the solar magnetic field is started in a thin layer transitioning the radiative and convective zones (called the Tachocline)
* The radiative zone rotates as a solid and the convective zone rotates differentially
* There is a large shear in the transition

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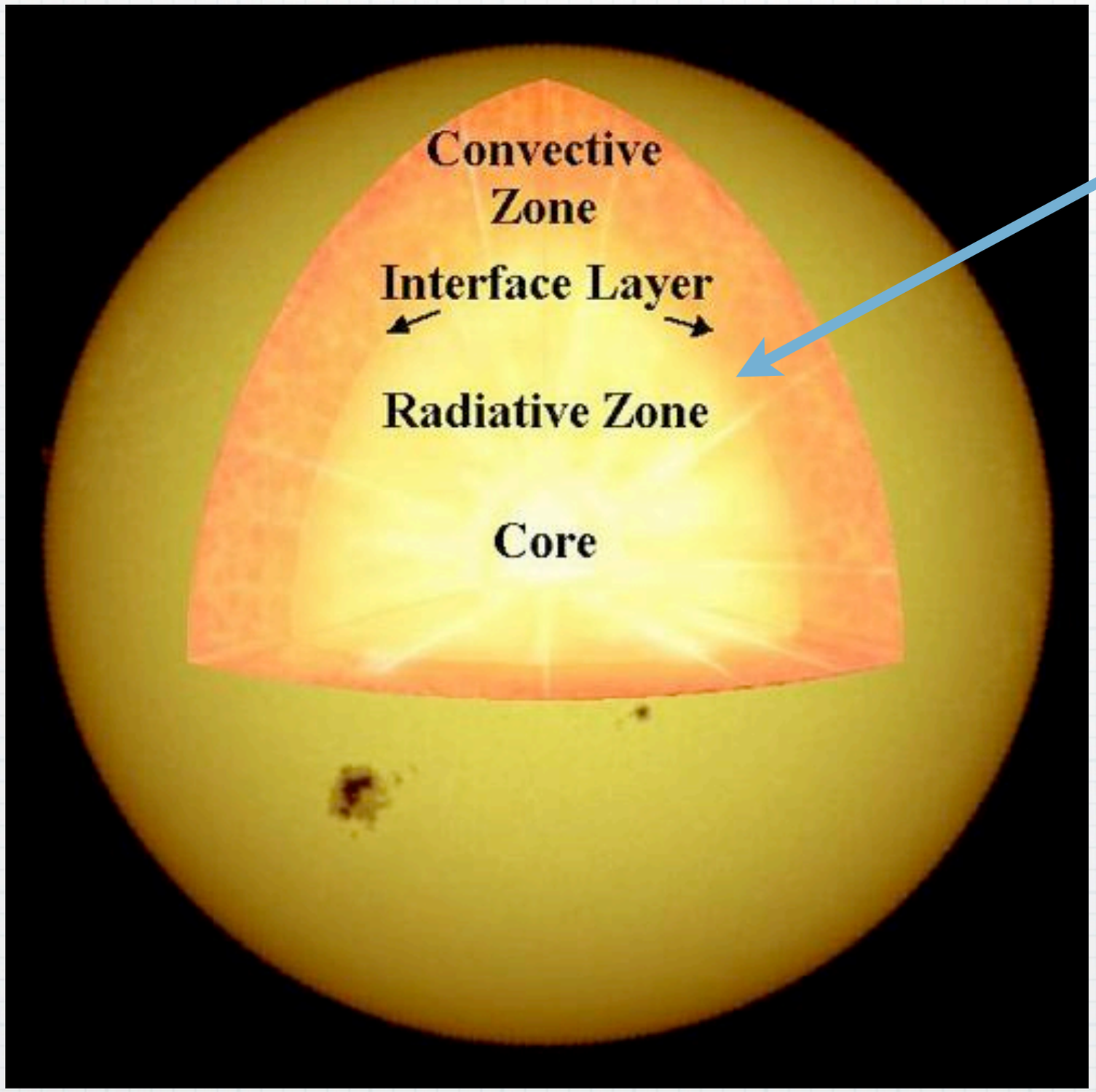
The Tachocline



The tachoclyne is located between the radiation zone and the convection zone

The Photosphere

* The lower atmosphere of the Sun is called the photosphere and is akin to its "surface"
* It is not a solid zone at all but looks like a pot of boiling water (400 km thick)
* Its average temperature drops to about 5,800 K
* This region emits the visible light and infrared

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Sunspots

* Sunspots are caused by intense magnetic fields exiting and re-entering the Sun
* Without special tools, sunspots are the most obvious features that we can see on the solar "surface" (the photosphere)
* Their size, their shapes, their orientations, and their numbers change with time

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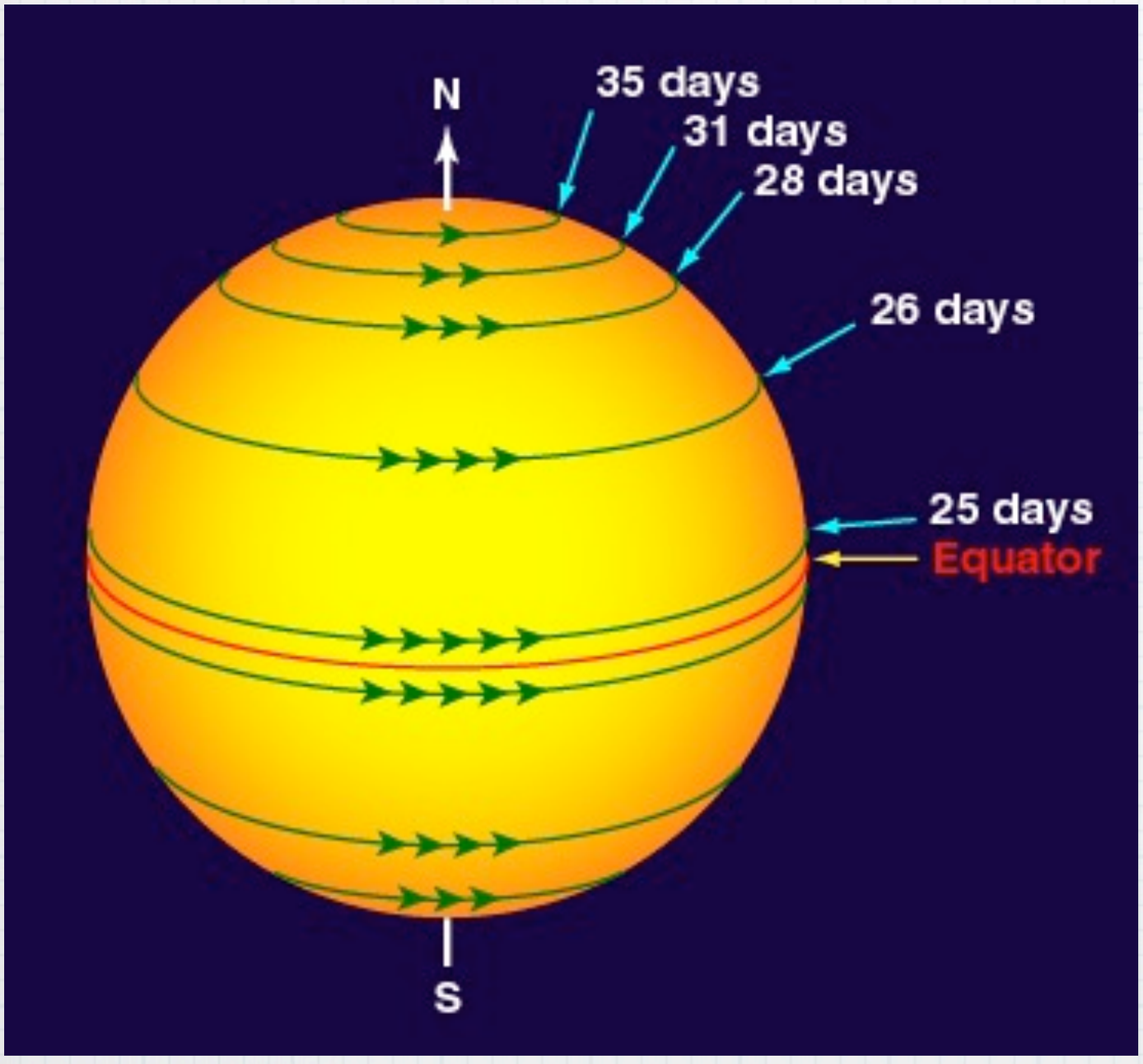
Differential Rotation

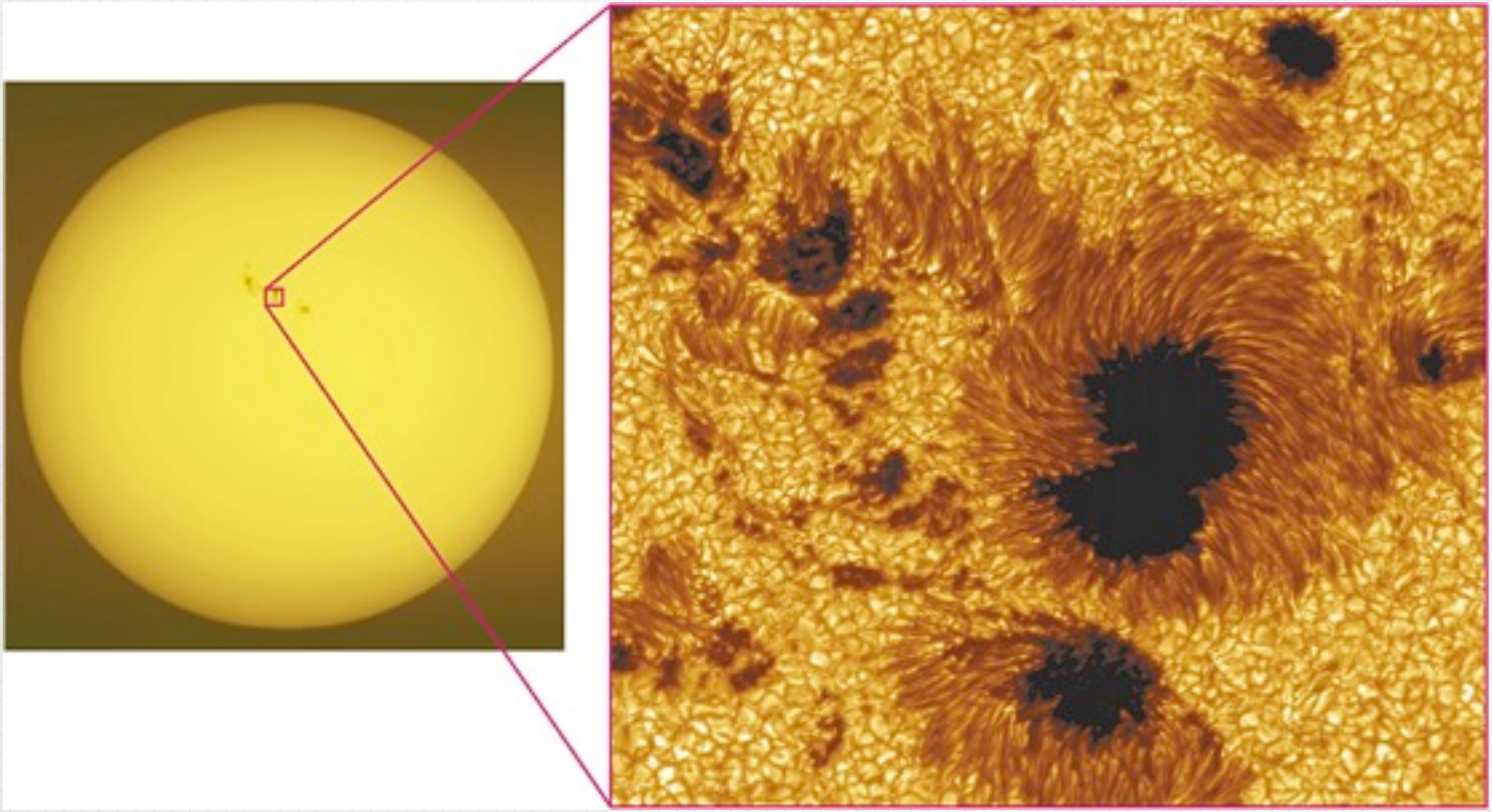


The Sun does not rotate as a rigid sphere: the equator regions rotate faster than the polar ones. This is called "differential rotation"

This rotation twists and folds the Sun's magnetic field lines

Two large sunspots and several smaller ones

The larger ones are about the size of the Earth



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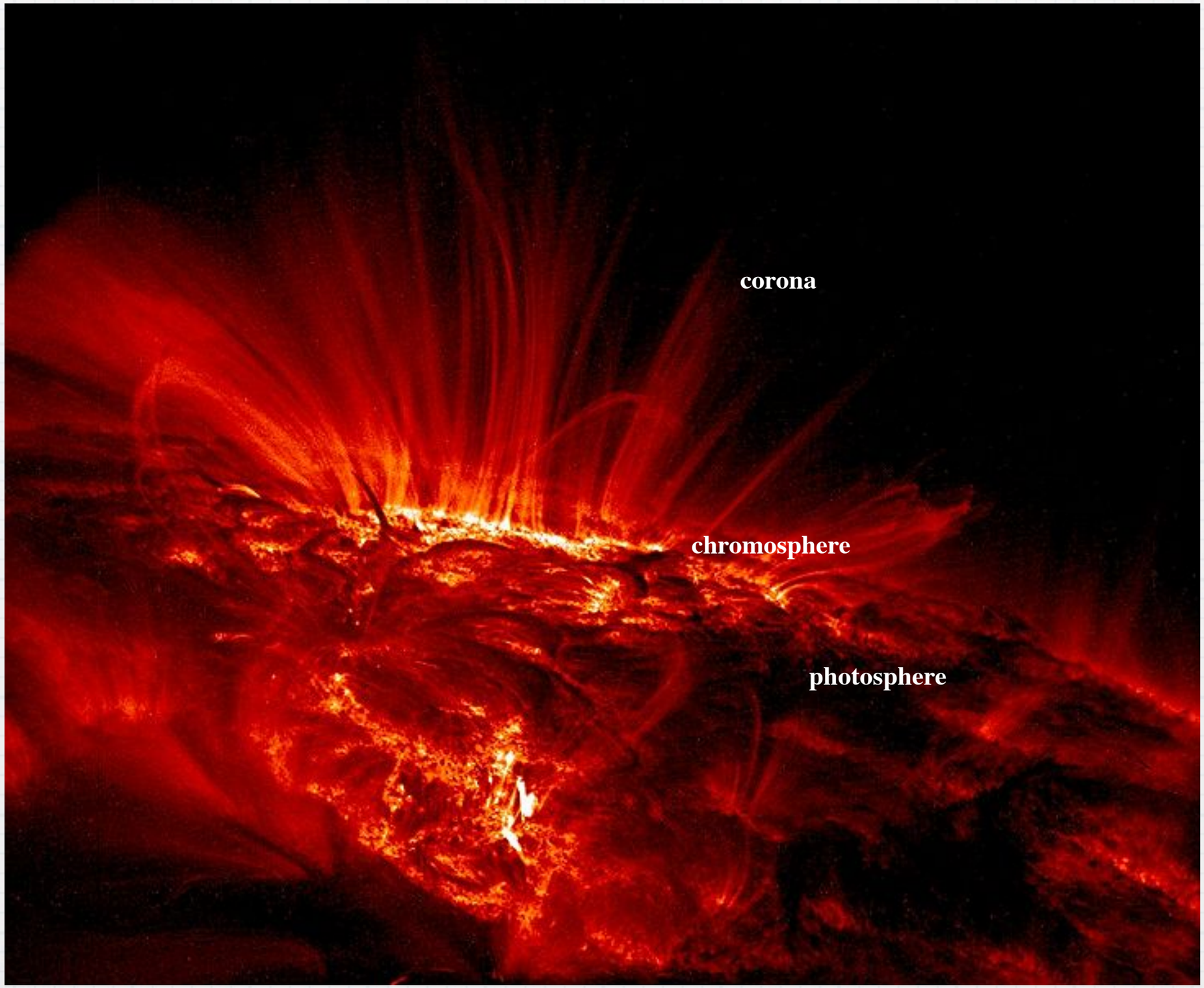
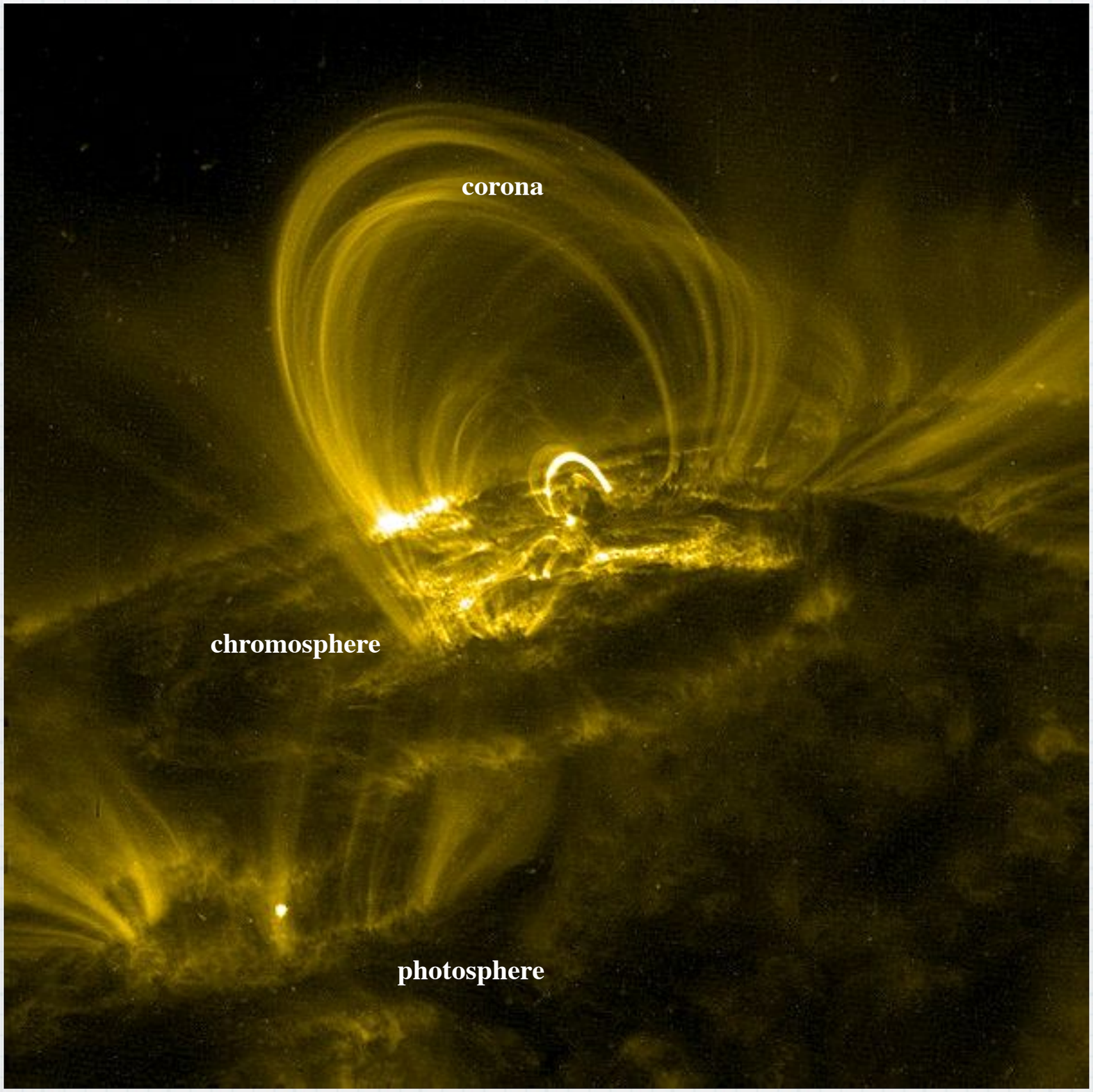
A sunspot viewed close-up in ultraviolet light



Picture: NASA via the TRACE spacecraft

A sunspot and magnetic (coronal) loops viewed close-up in X-ray light



Picture: NASA via the TRACE spacecraft

Sunspot cycles

* Long term observations reveal that there are patterns to solar activity
* The most obvious one is the sunspot cycle where the number of sunspots increases and decreases with time

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Sunspot cycles...

* A solar maximum occurs when sunspots are the most numerous
* A solar minimum occurs when sunspots are the least numerous (there may be none)
* The average length of time between a maximum to a minimum cycle is 11 years
* The full cycle is then about 22-year long

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Sunspot cycles...

* But it has been observed as short as 14 years and as long as 30 years
* Between 1645 and 1715, no sunspots were seen (the Maunder Minimum) - Little Ice Age on Earth
* When the solar minimum begins, sunspots form at mid-latitudes (30 to 40°)
* As the solar maximum approaches, they form mostly at the equator

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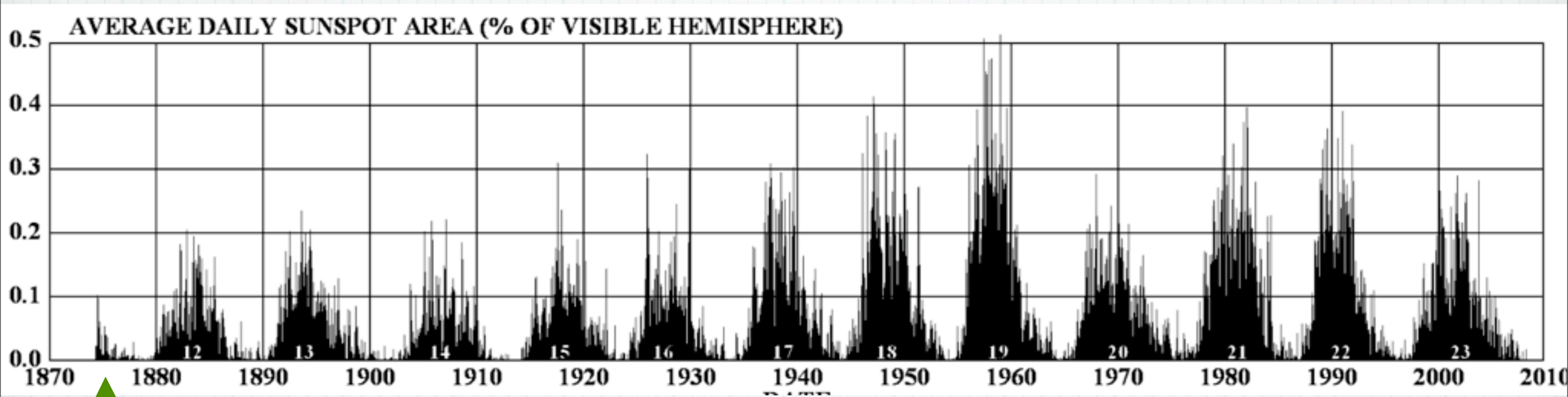
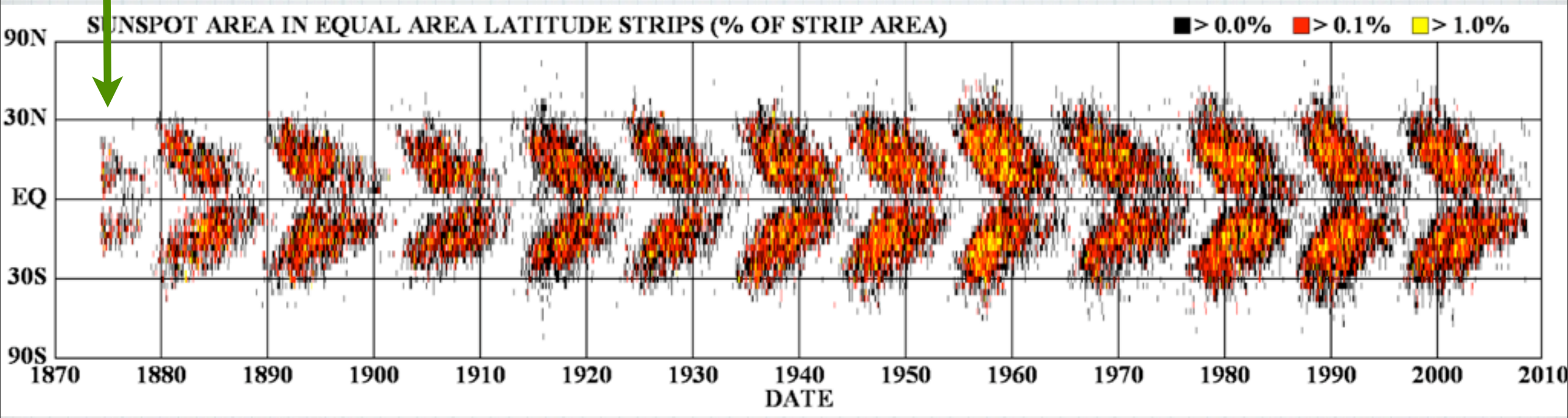
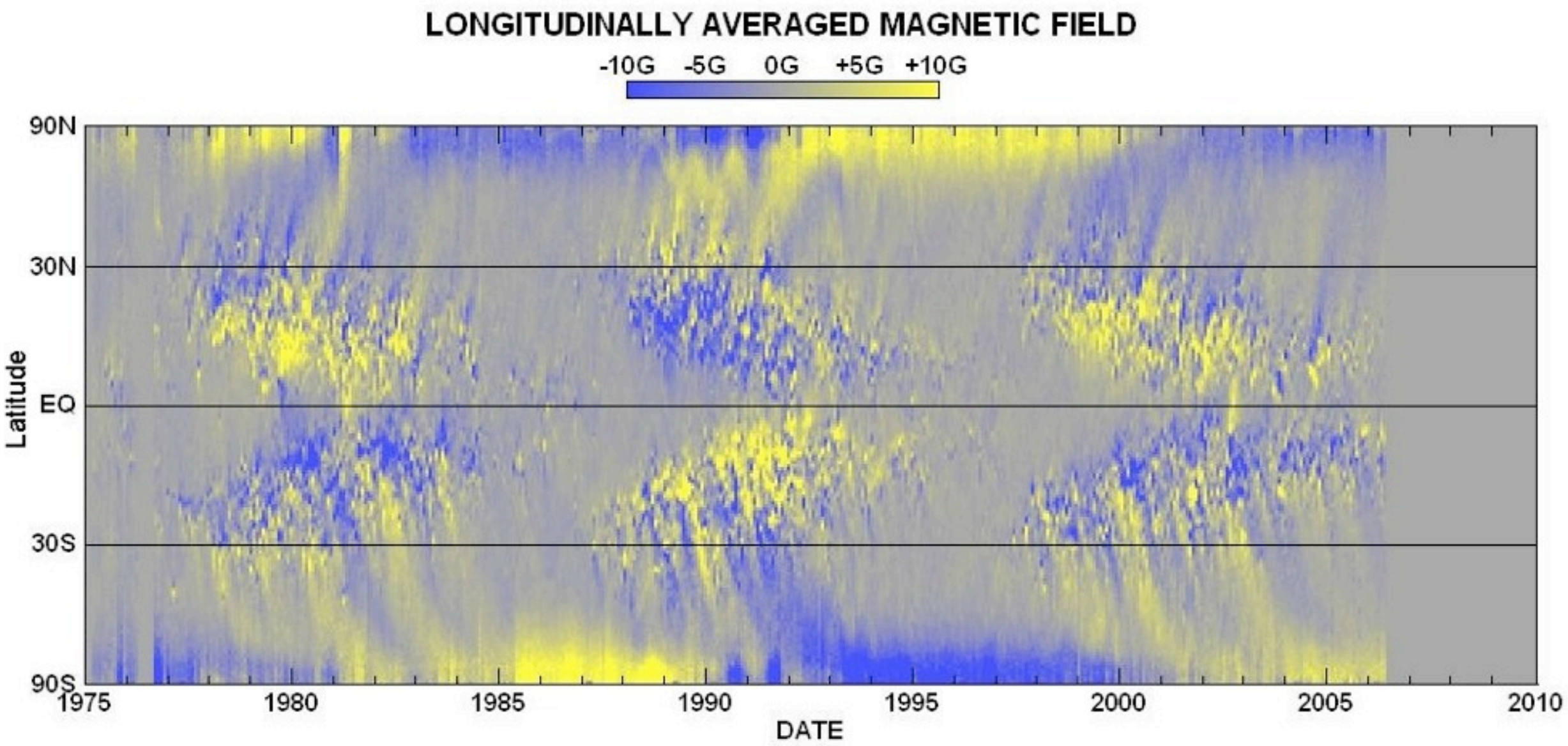
Daily Sunspot Area Averaged over Individual Solar Rotations



the Maunder Minimum



Notice the polarity reversal between the Sun NH and SH between cycles



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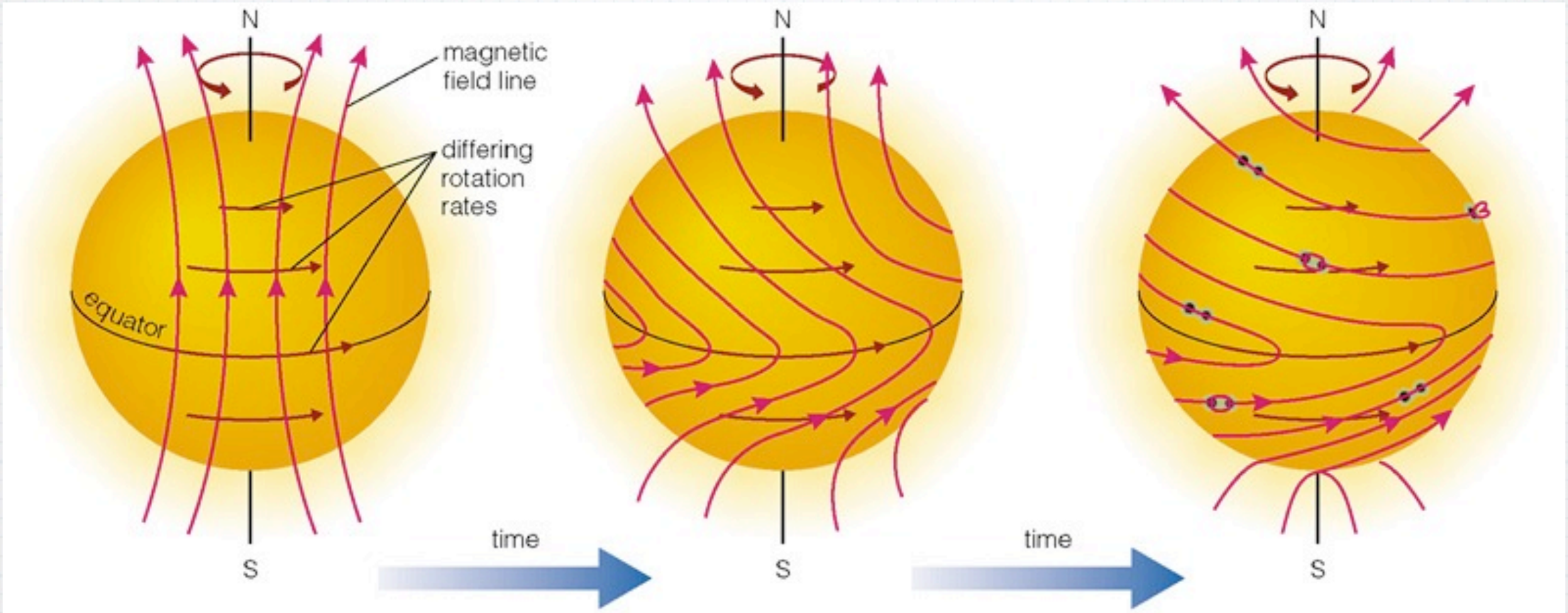
Solar rotational differences and magnetic lines impact



The magnetism is wound into a toroidal field of "flux ropes" that become wrapped around the star

The fields can become highly concentrated, producing activity when they emerge on the surface

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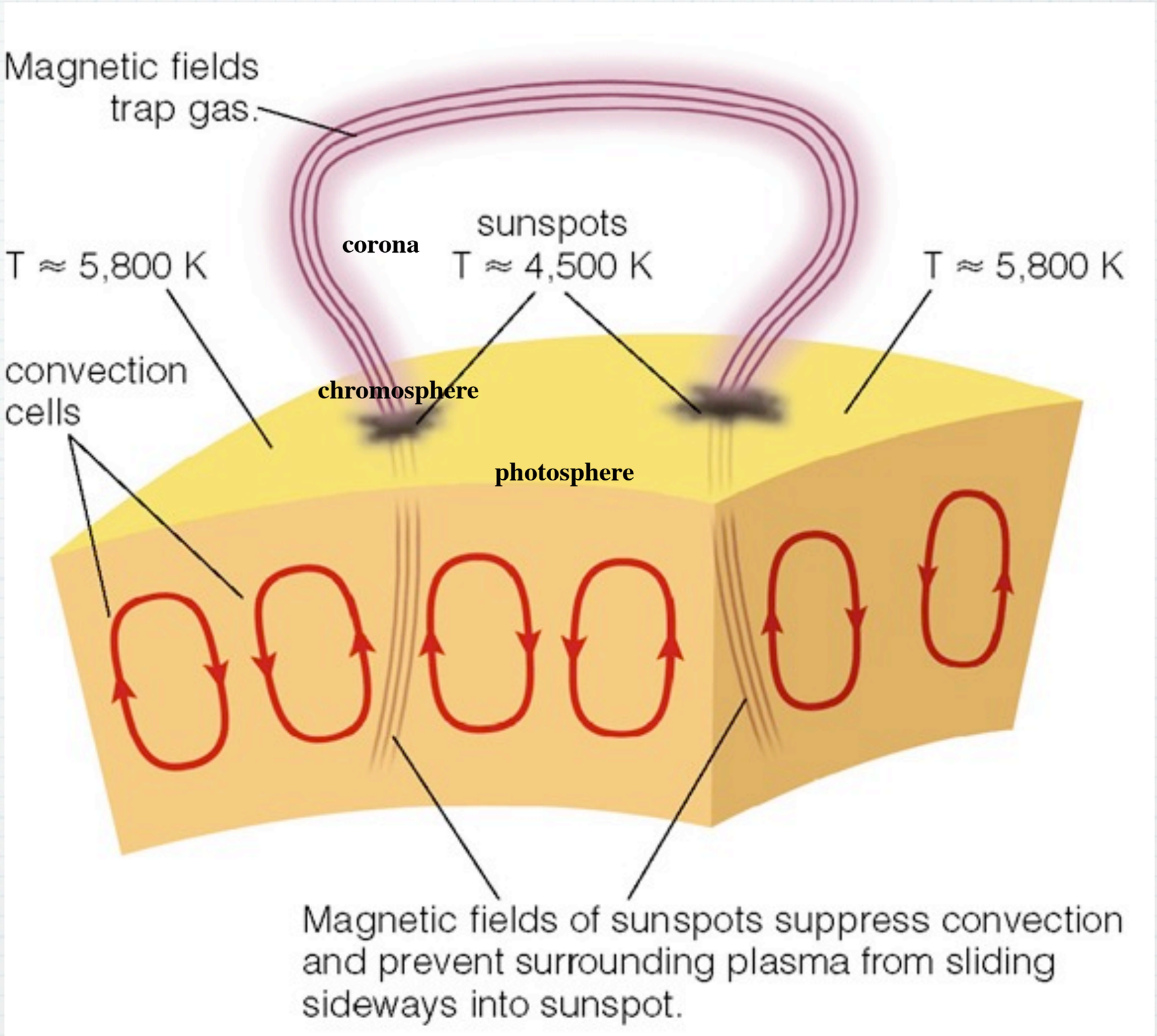
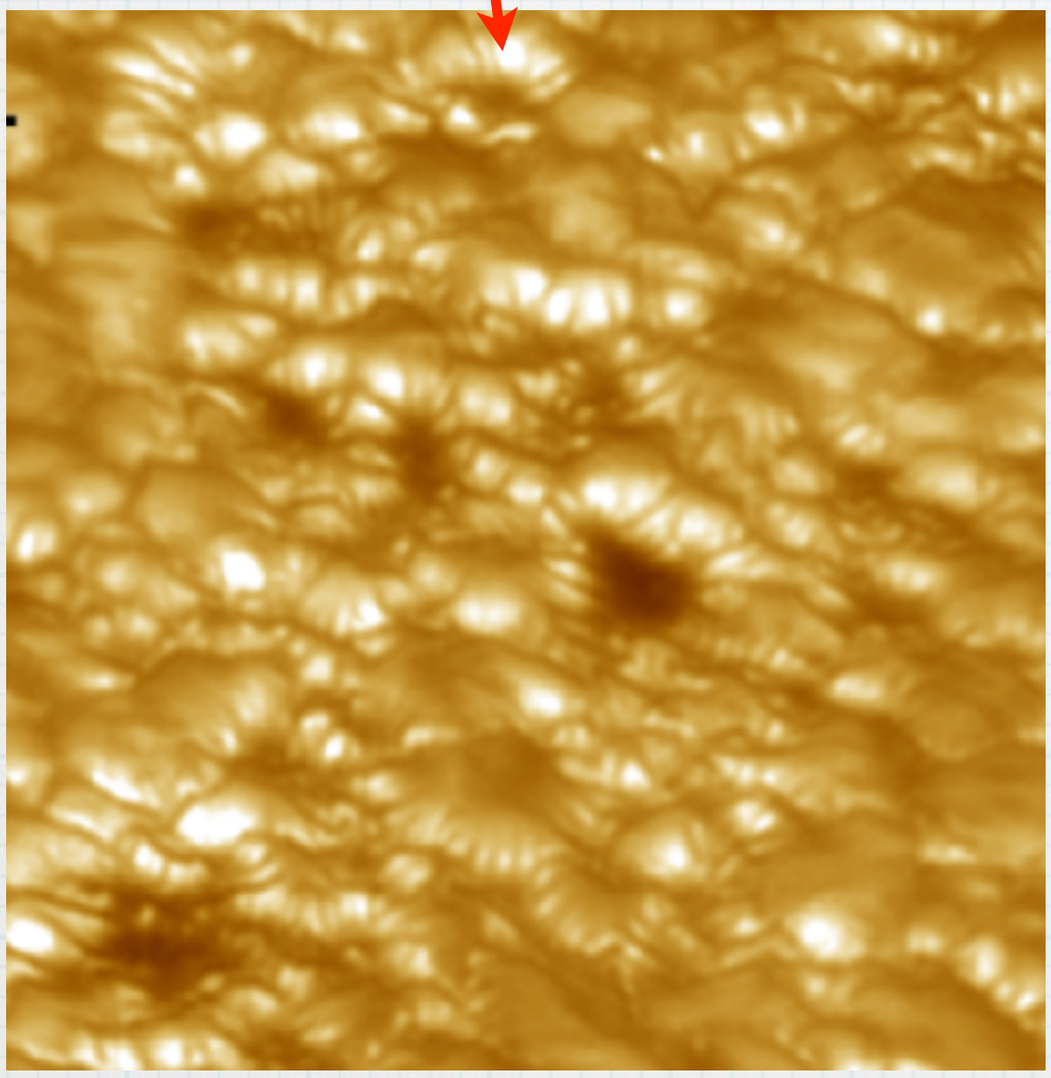
Pairs of sunspots are connected by tightly wound magnetic lines

The magnetic fields explain why sunspots are cooler than their surroundings

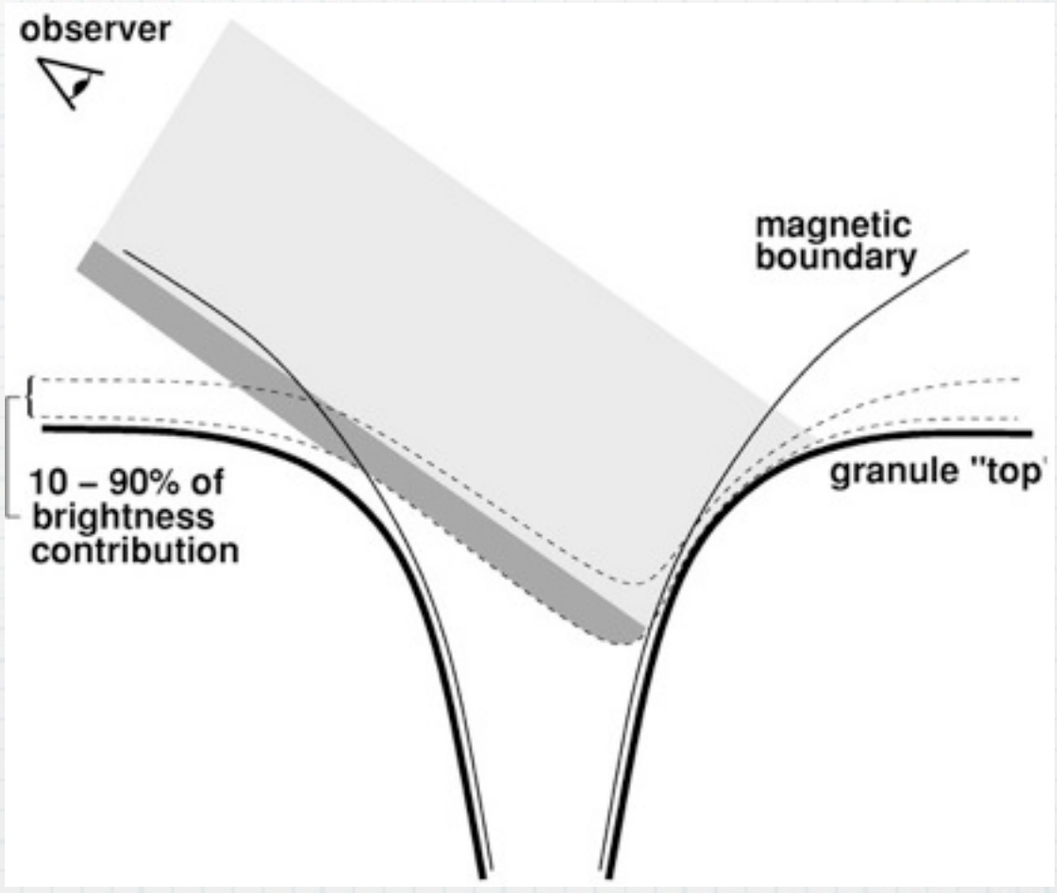
Sunspots last for a few weeks



Faculae
(photosphere)

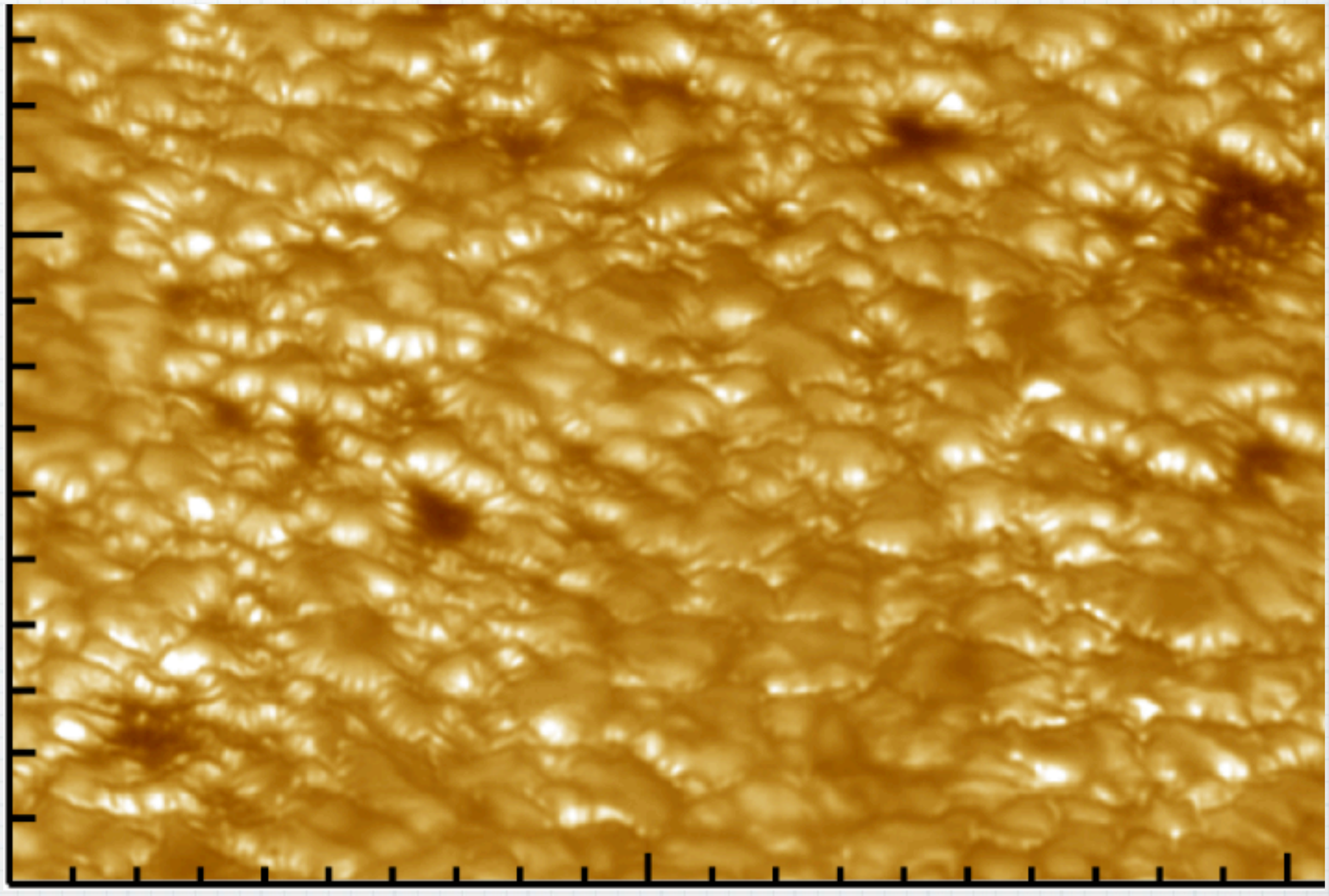


Faculae are bright areas resulting from the presence of strong magnetic fields

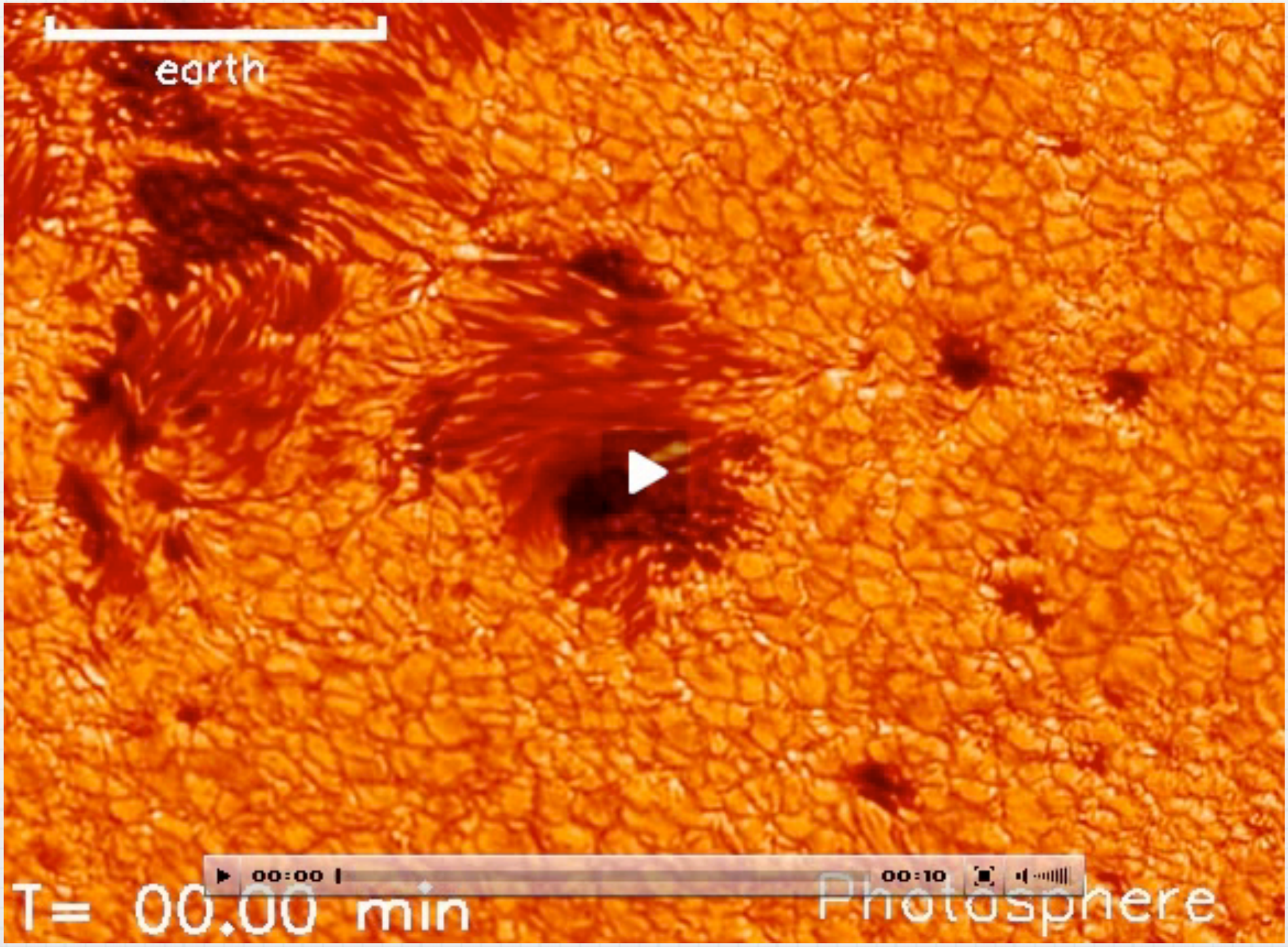


Granules
(photosphere)

Small (1000 km across) cellular features.
They are the tops of convection cells.
Granules last about 20 minutes



Granule Evolution
(one hour)



The Chromosphere

* Nearer the surface, the Sun's middle atmosphere is called the chromosphere
* Its average temperature is about 15,000 K
* This region emits most of the Sun's UV
* Its thickness is about 2,500 km

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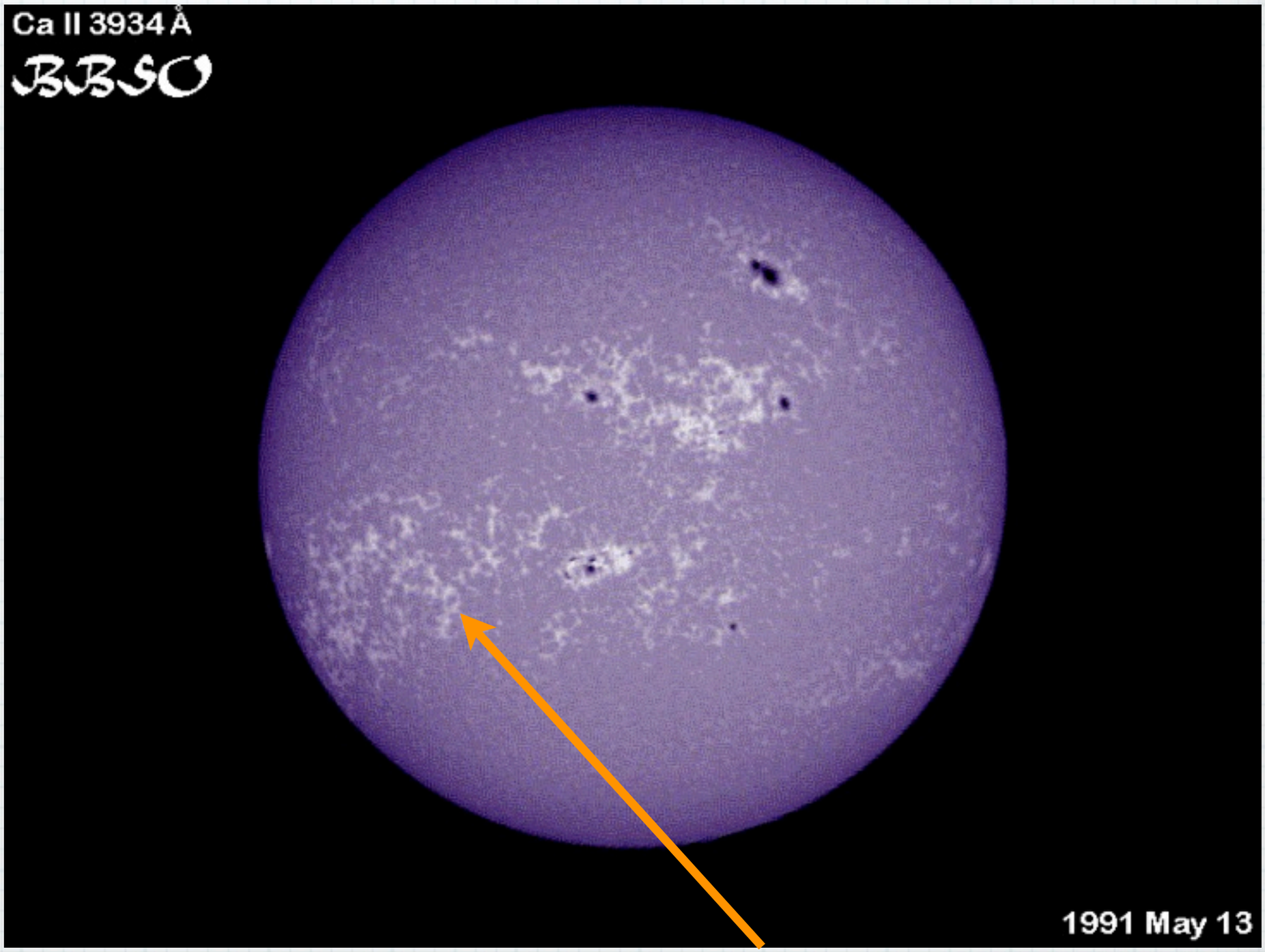
Chromospheric Network

(chromosphere)

Web-like pattern

This picture was taken in the ultraviolet line of Calcium K-line



chromospheric network

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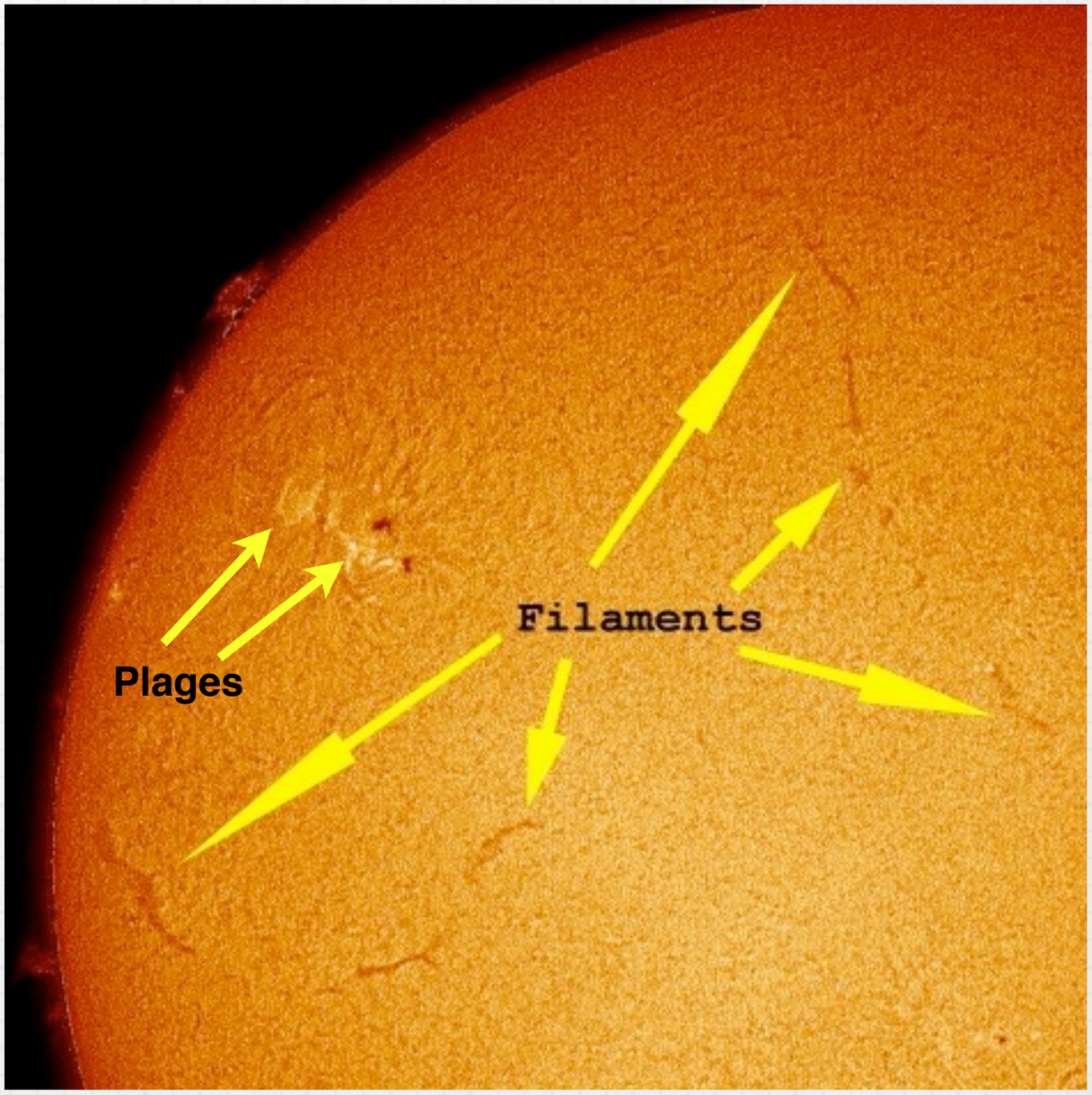
Filaments & Plages

(chromosphere)

~ 10,000 - 100,000 K

Filaments are **dense clouds of material suspended above the photosphere by loops of magnetic fields**

Plages are associated with **concentrations of magnetic fields** which form a part of the network of bright emissions that characterize the chromosphere



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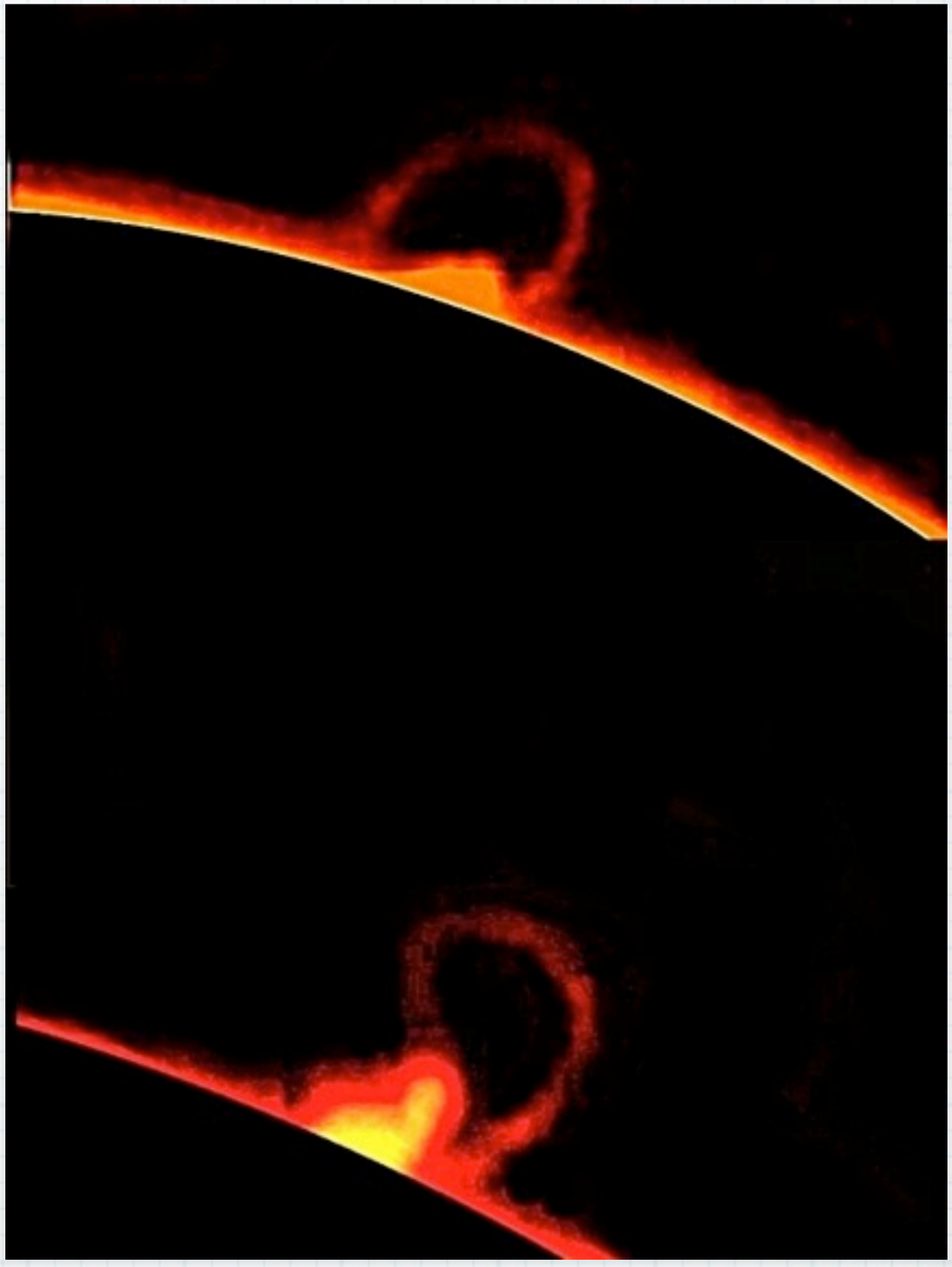
H-alpha picture

Prominences

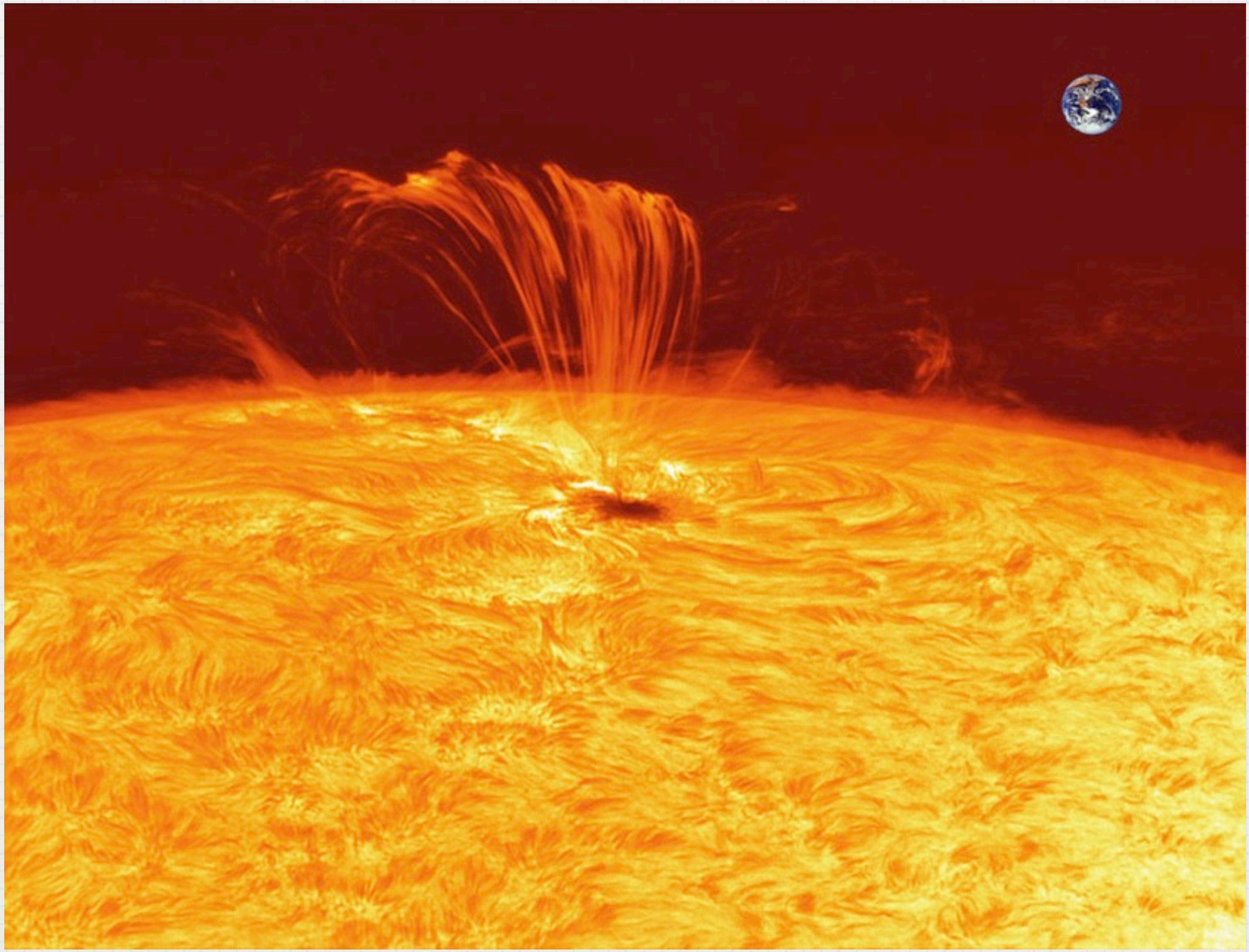
(chromosphere)

A prominence is a filament but it is seen projecting out above the edge of the Sun

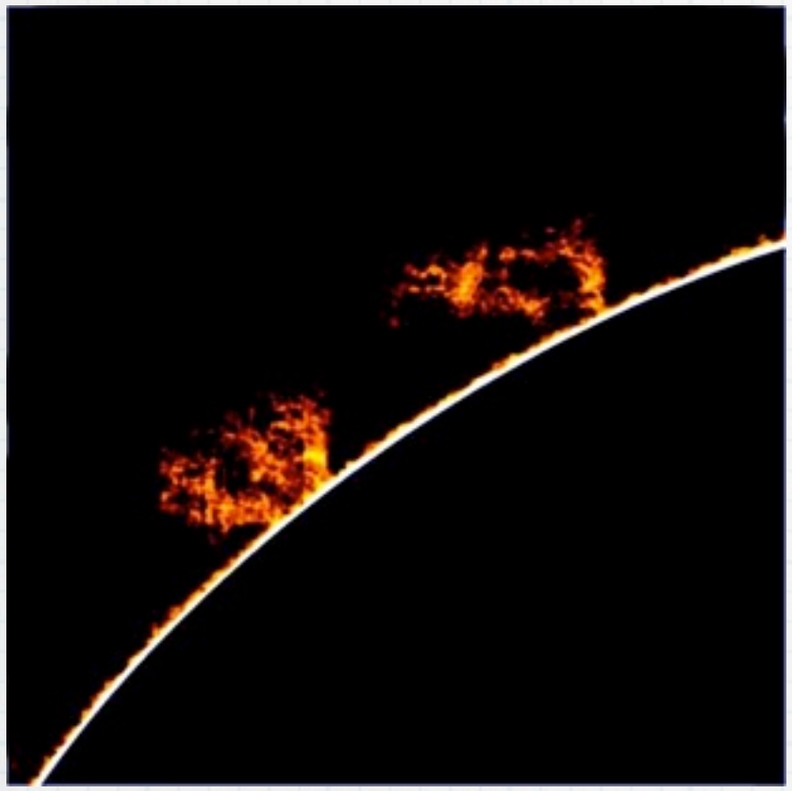


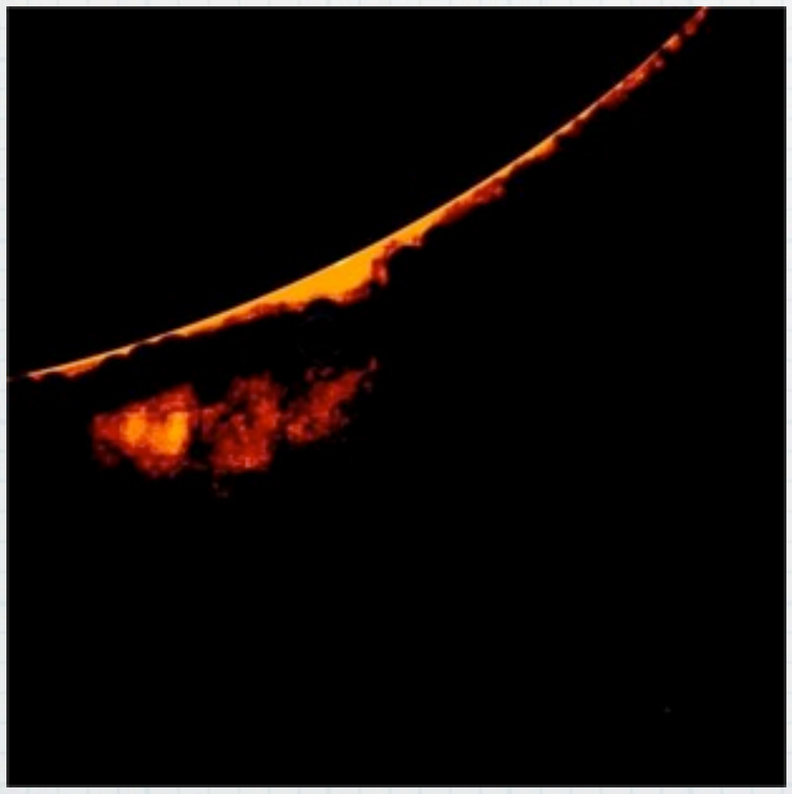
Prominences are anchored in the photosphere and can extend outwards into the corona. They are dense clouds of material suspended by loops of magnetic fields

Solar Prominence and the Earth & the Moon
(shown for scale)



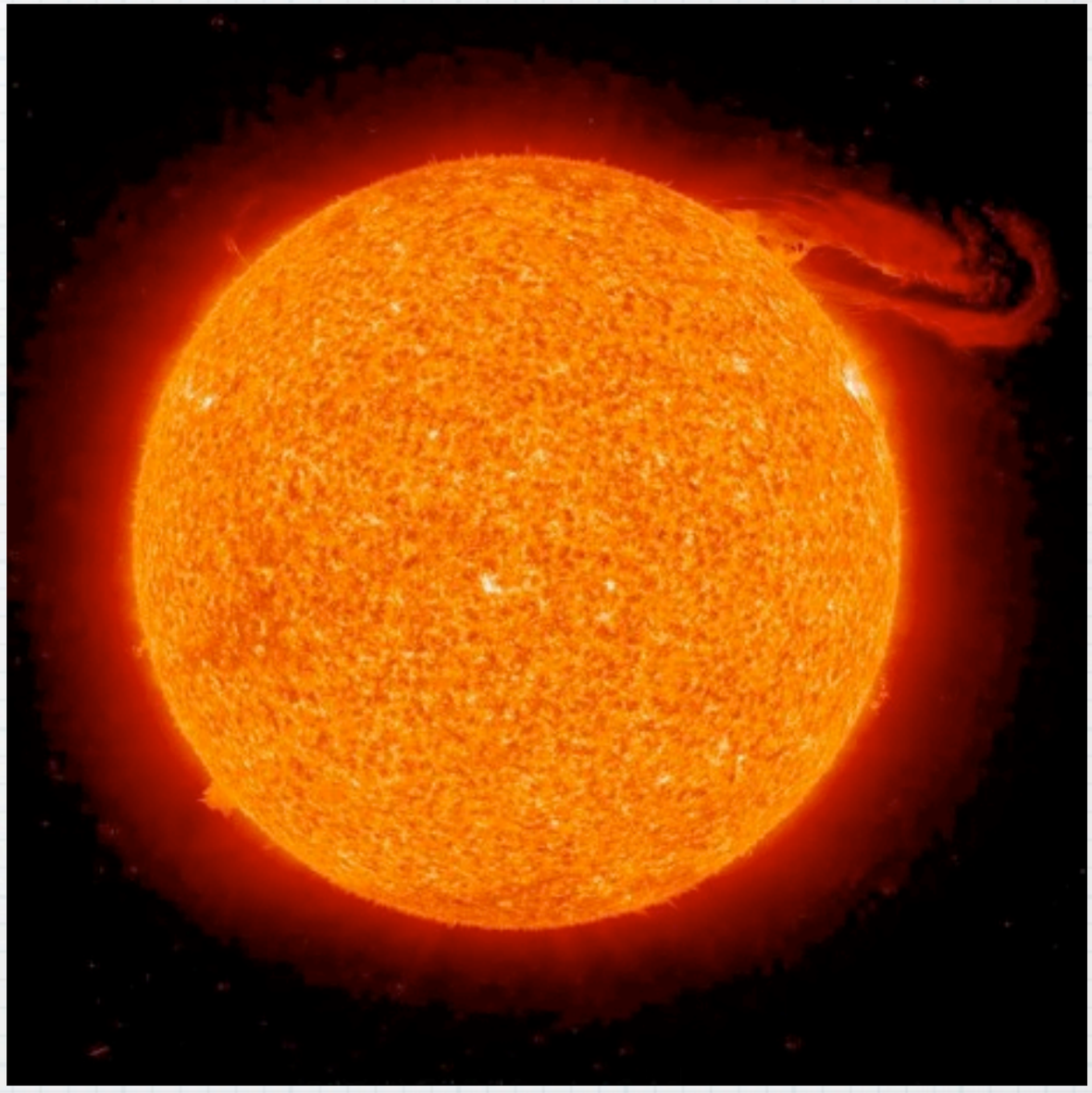
Examples of prominences





some can
be detached

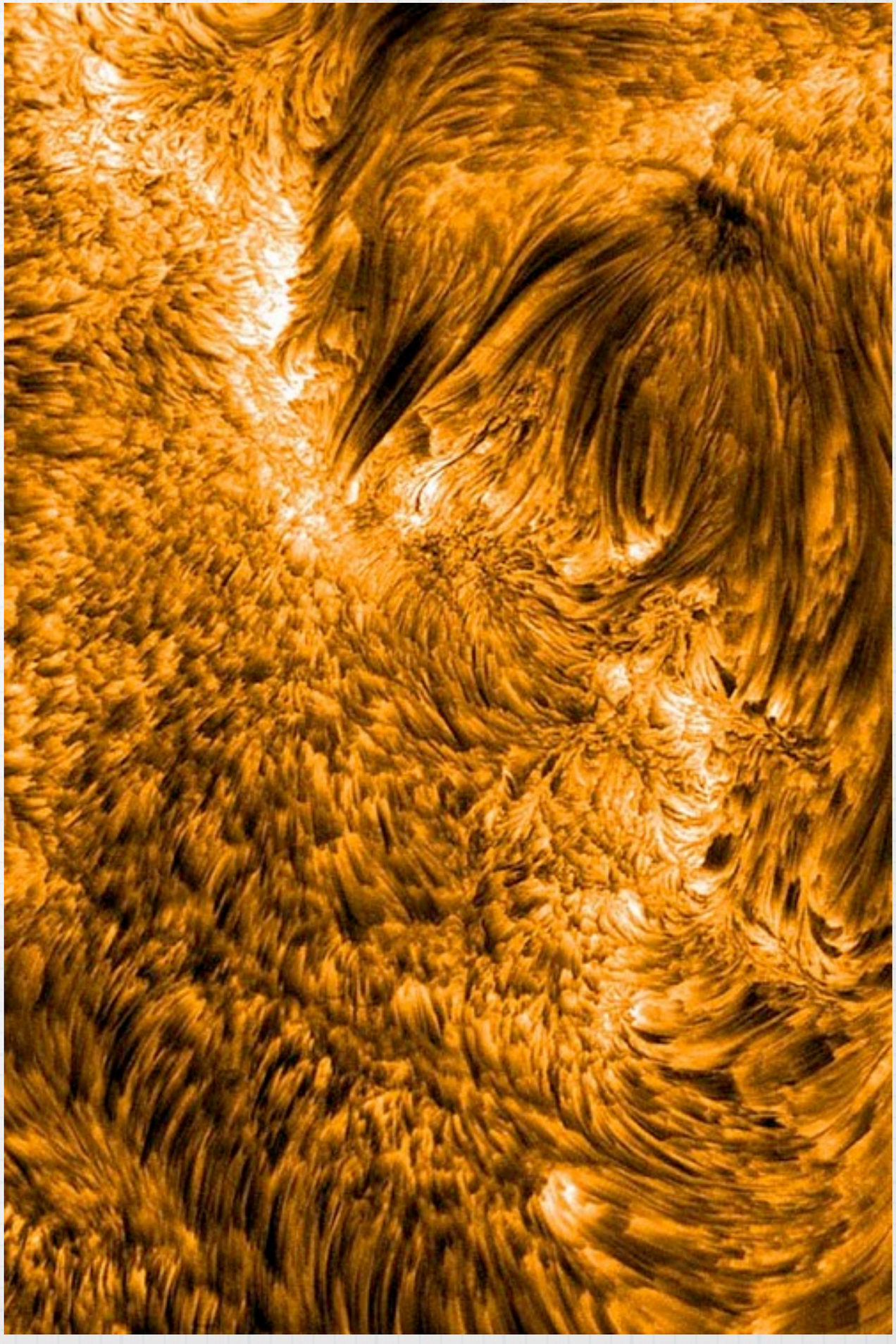
major eruptive prominence:
can rise to a coronal mass ejection



Spicules
(chromosphere)

Spicules are small jet-like eruptions

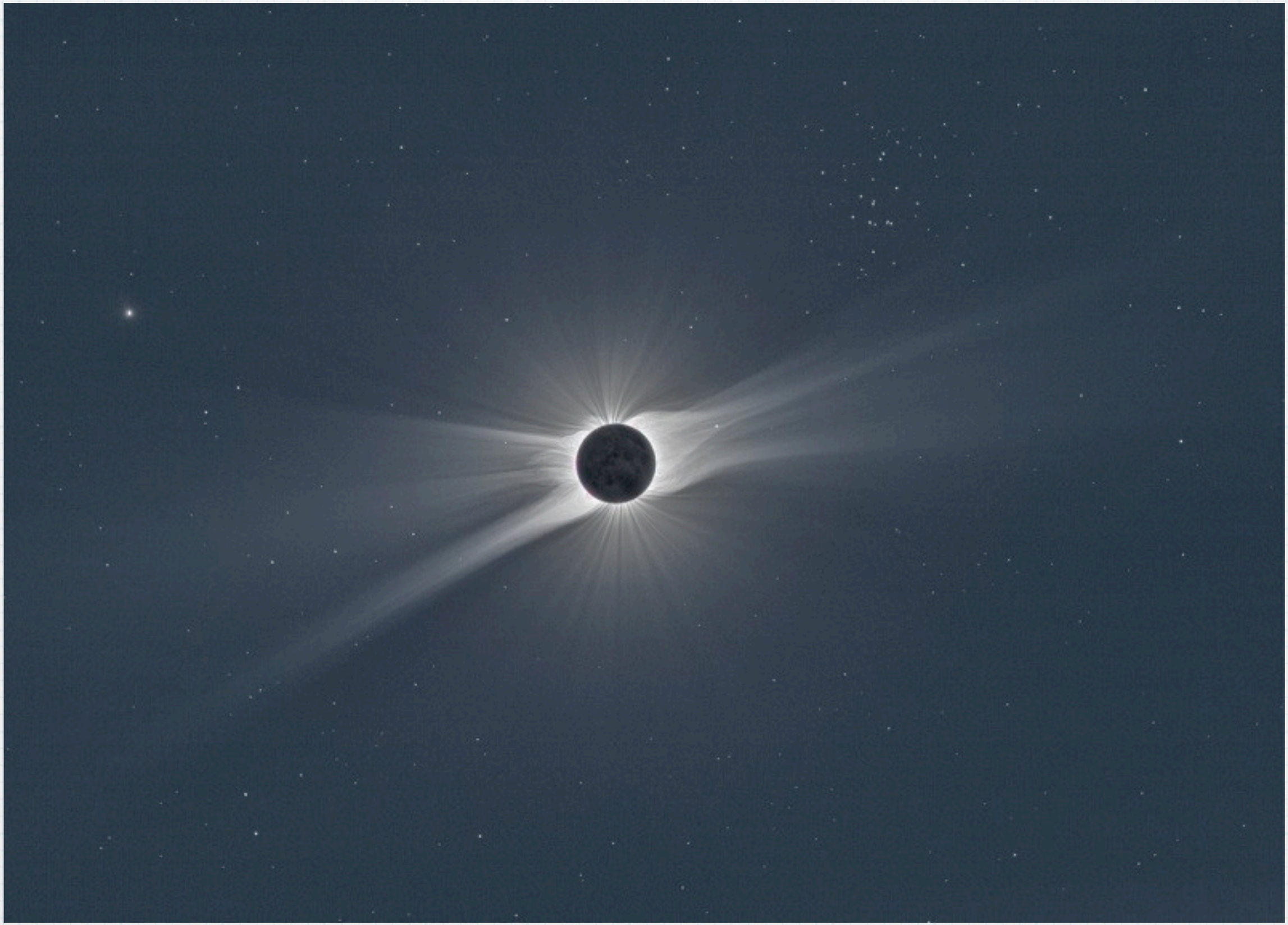
They last for a few minutes but they eject material off the photosphere and toward the hot corona



The Corona

* The outermost gas layer (upper atmosphere) is called the corona
  * it extends several millions of km above the visible surface of the Sun
  * its temperature is amazingly high: about 1 million K
  * it has a very low density
* This region emits most of the Sun's X-rays

Solar Corona - total solar eclipse, 2008-08-20



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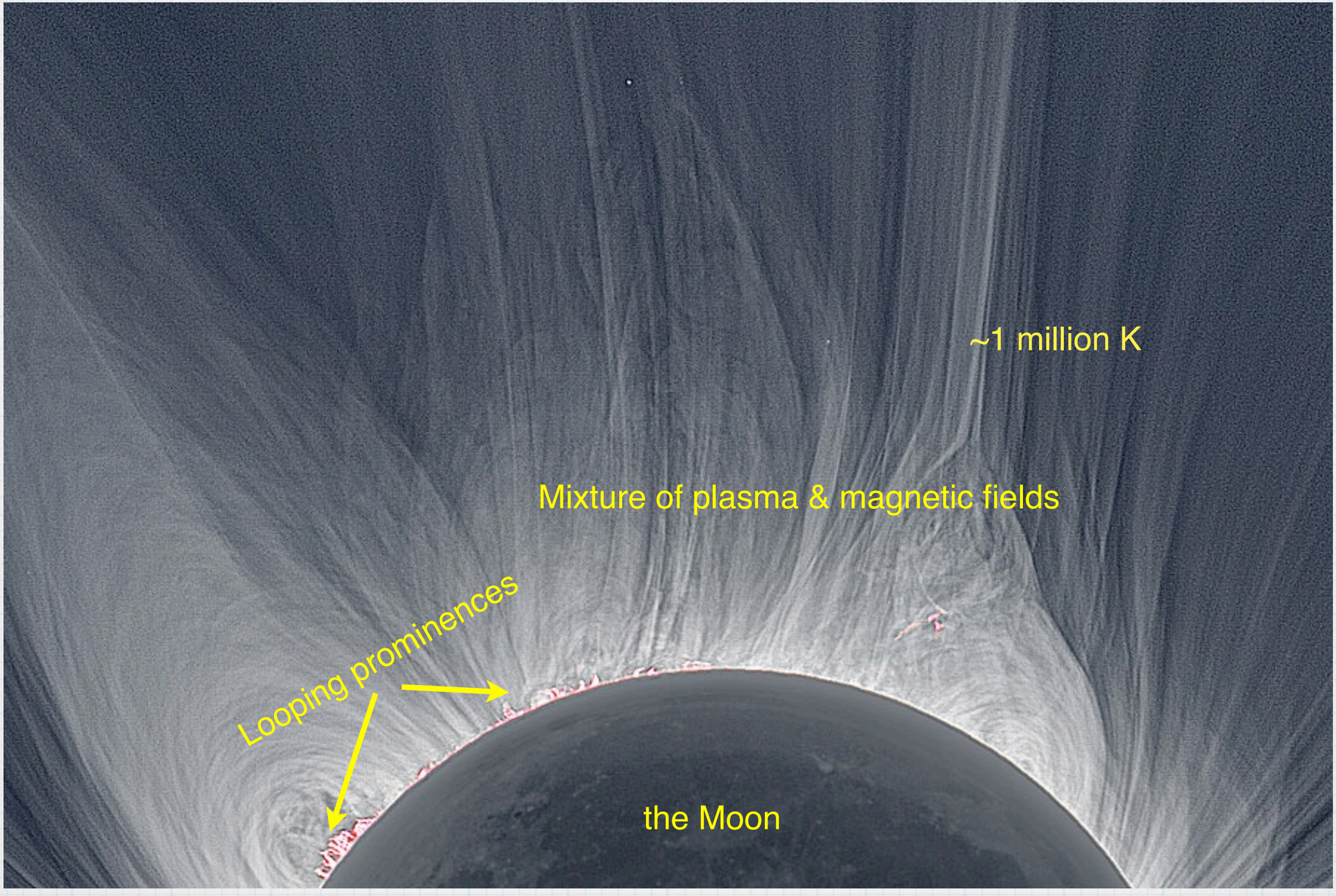
Solar Corona - total solar eclipse, 2008-08-20



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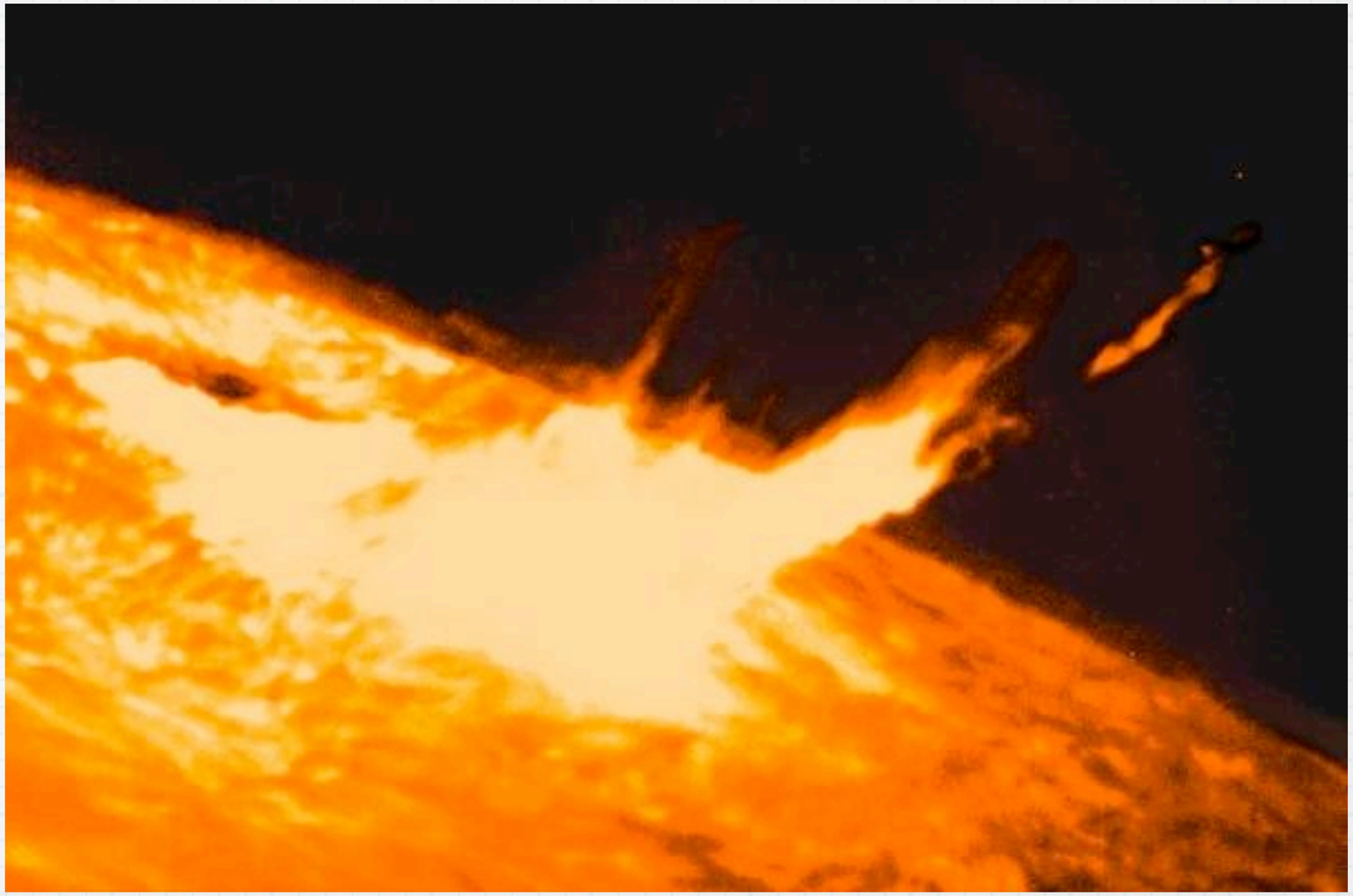
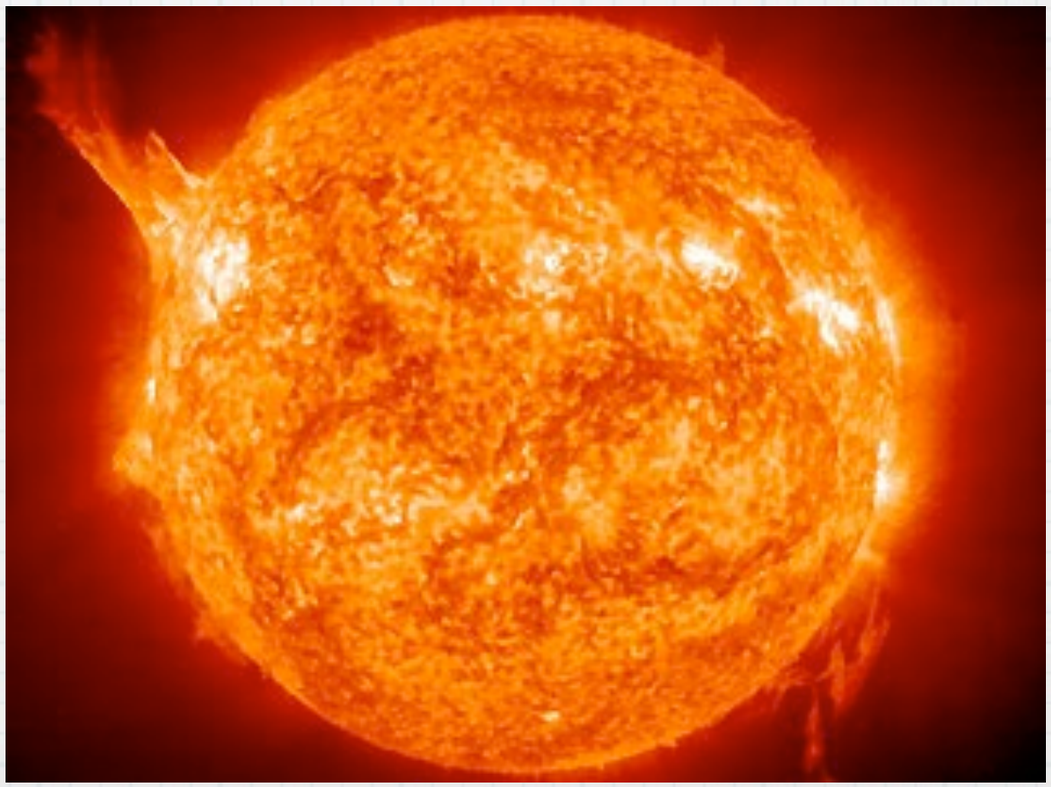
Flares
(corona)

A **solar flare** occurs when magnetic energy that has built up in the solar atmosphere is suddenly released





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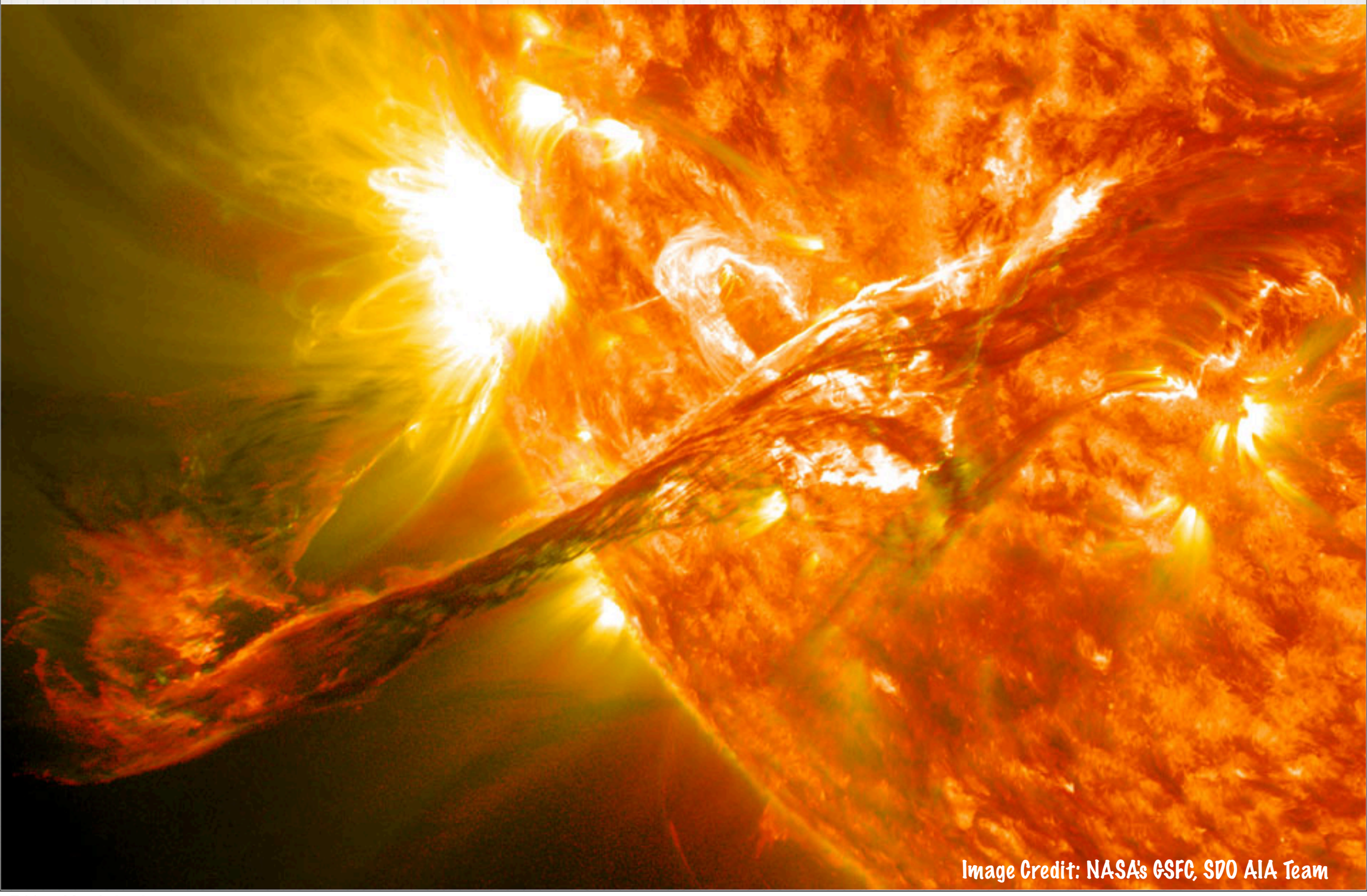
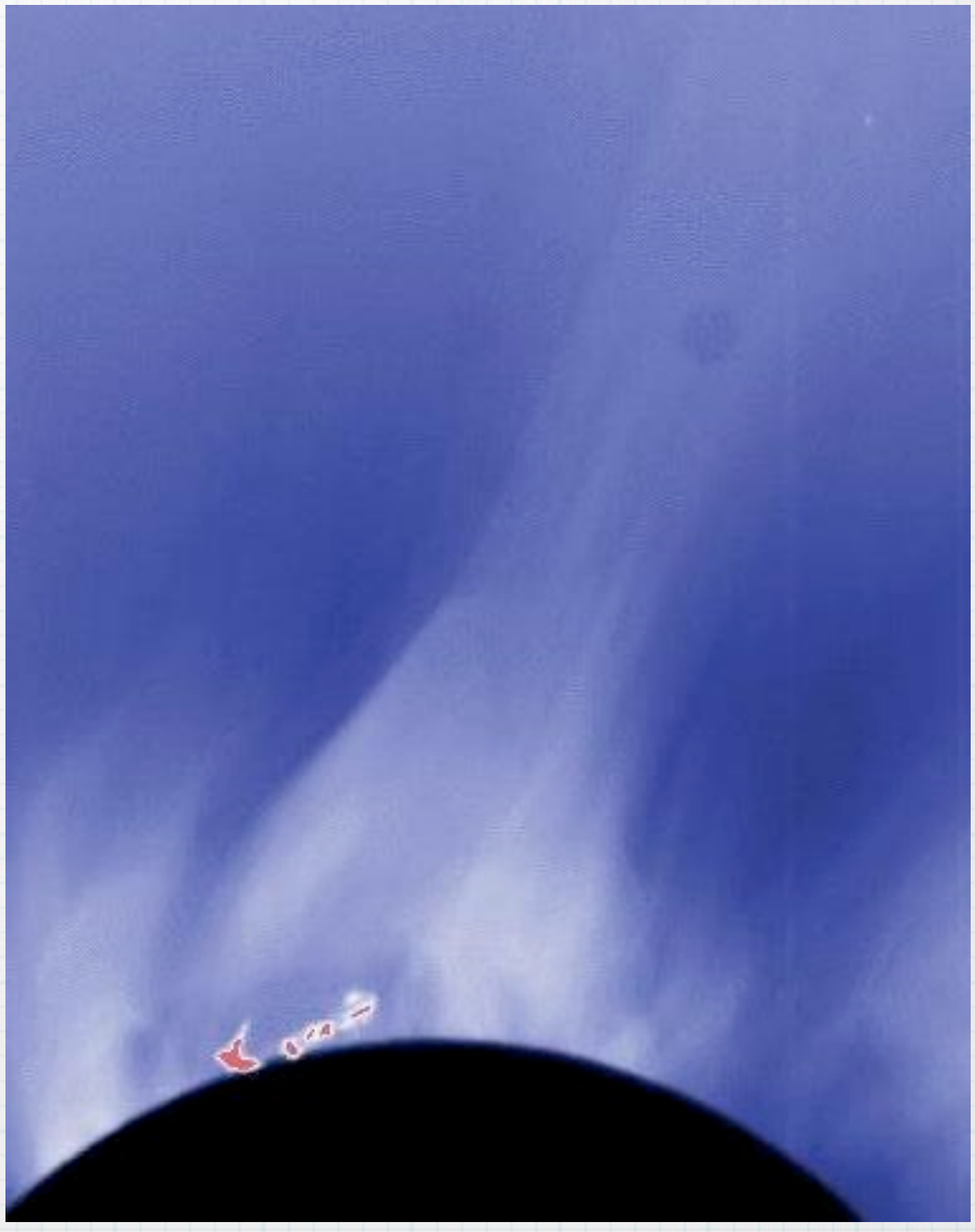
Prominence activity



Helmet Streamers

(corona)

Helmet streamers are large cap-like coronal structures with long pointed peaks and usually overlie sunspots and active regions



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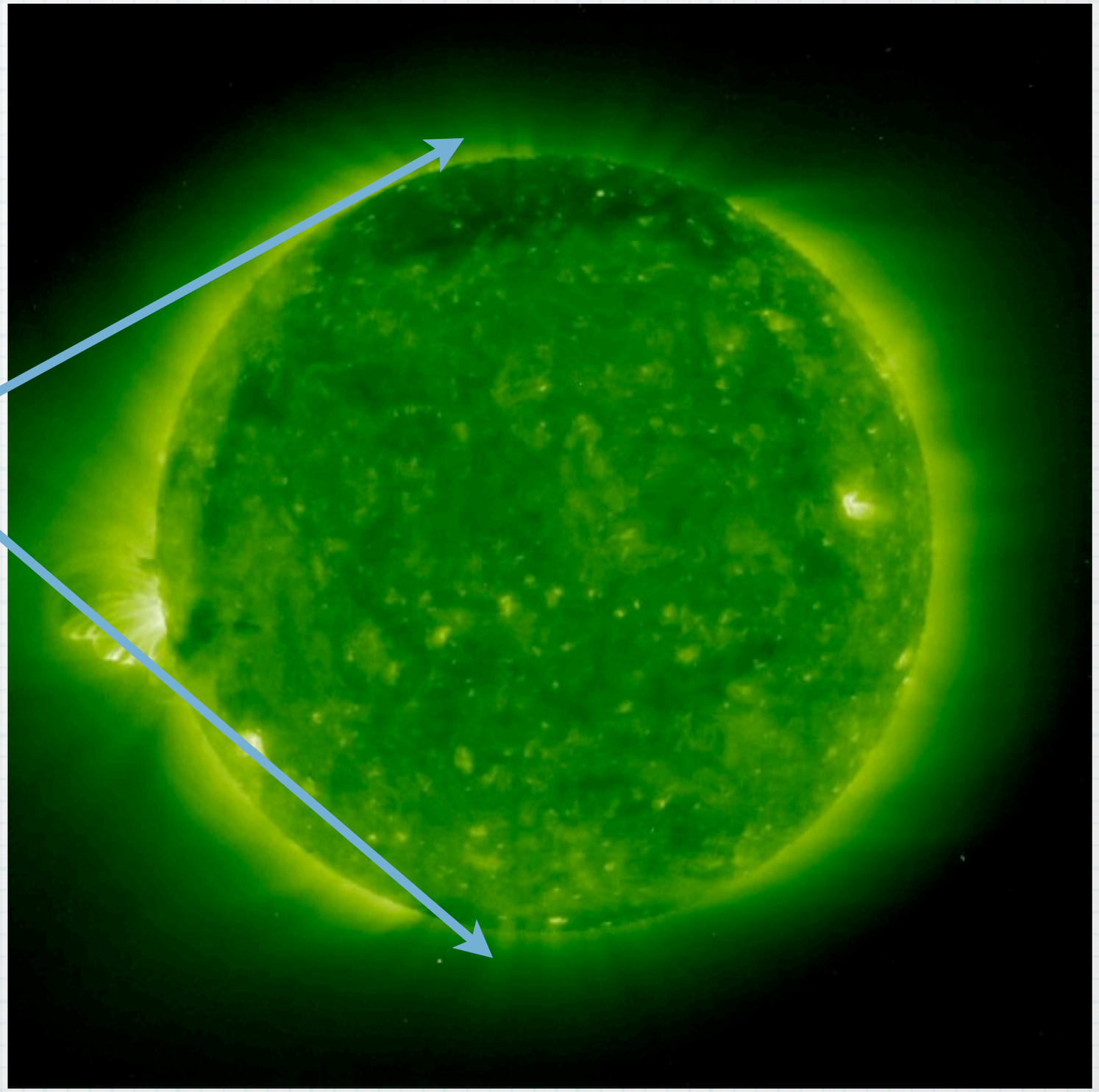
Polar Plumes

(corona)

Polar plumes are long thin streamers that project outward from the Sun's north and south poles



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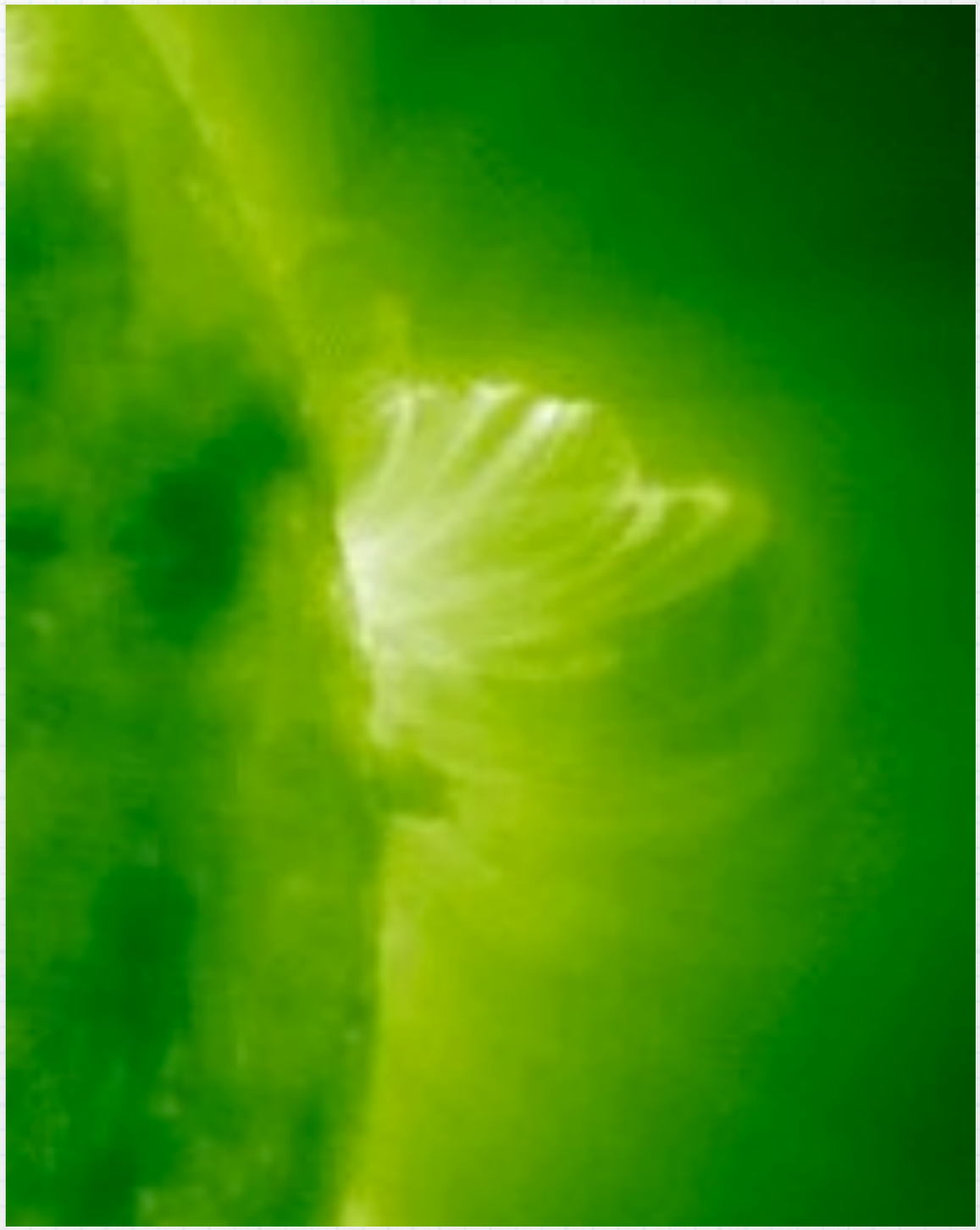
Coronal Loops

(corona)

Coronal loops are found above sunspots and other active regions

These structures are associated with the closed magnetic field lines that connect magnetic regions on the solar surface

They last for days but change quite rapidly



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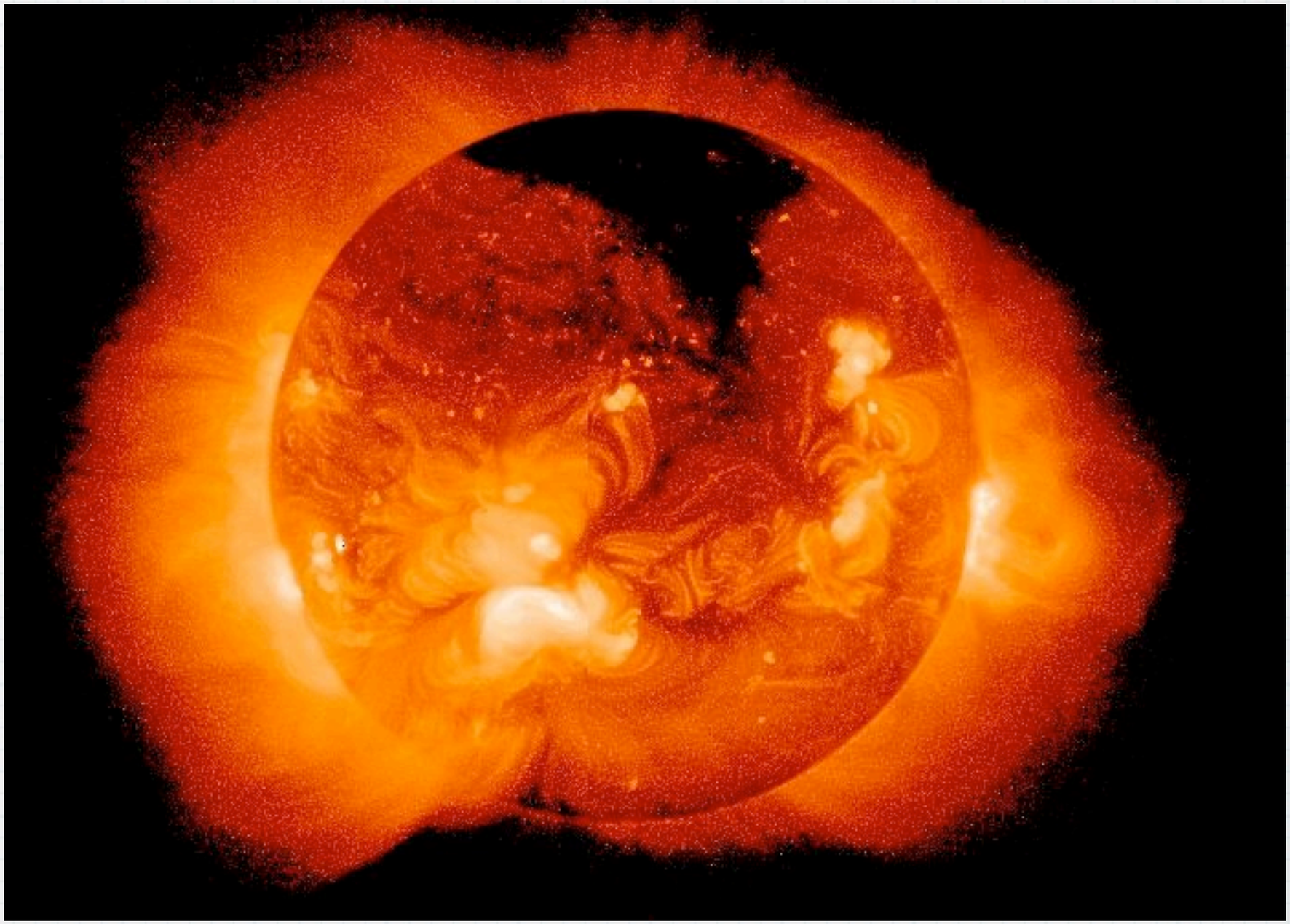
Coronal Holes

(corona)

Coronal holes were only discovered with X-ray telescopes

They are associated with "open" magnetic field lines and often found at the poles



The high-speed solar wind originates in these holes

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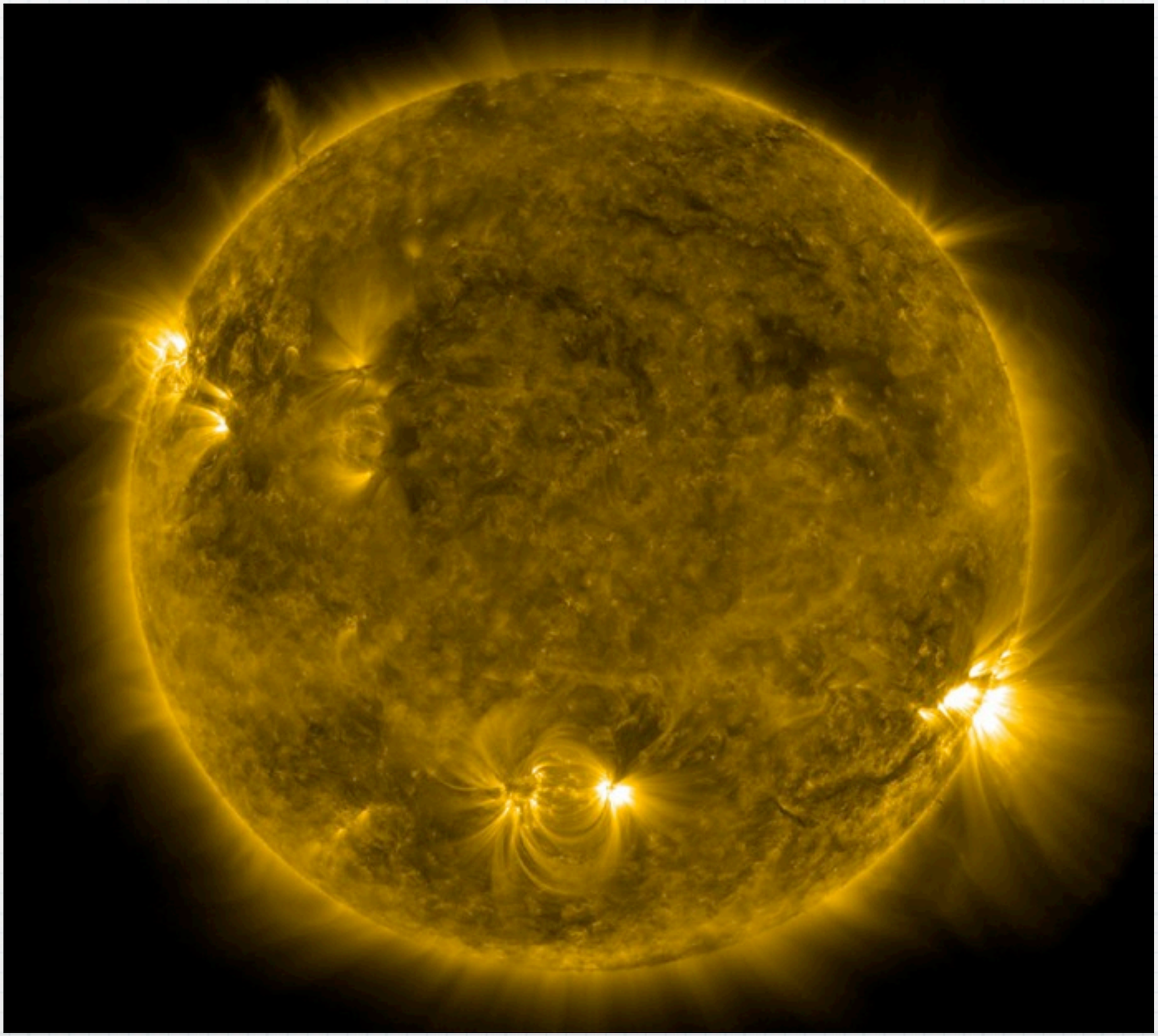
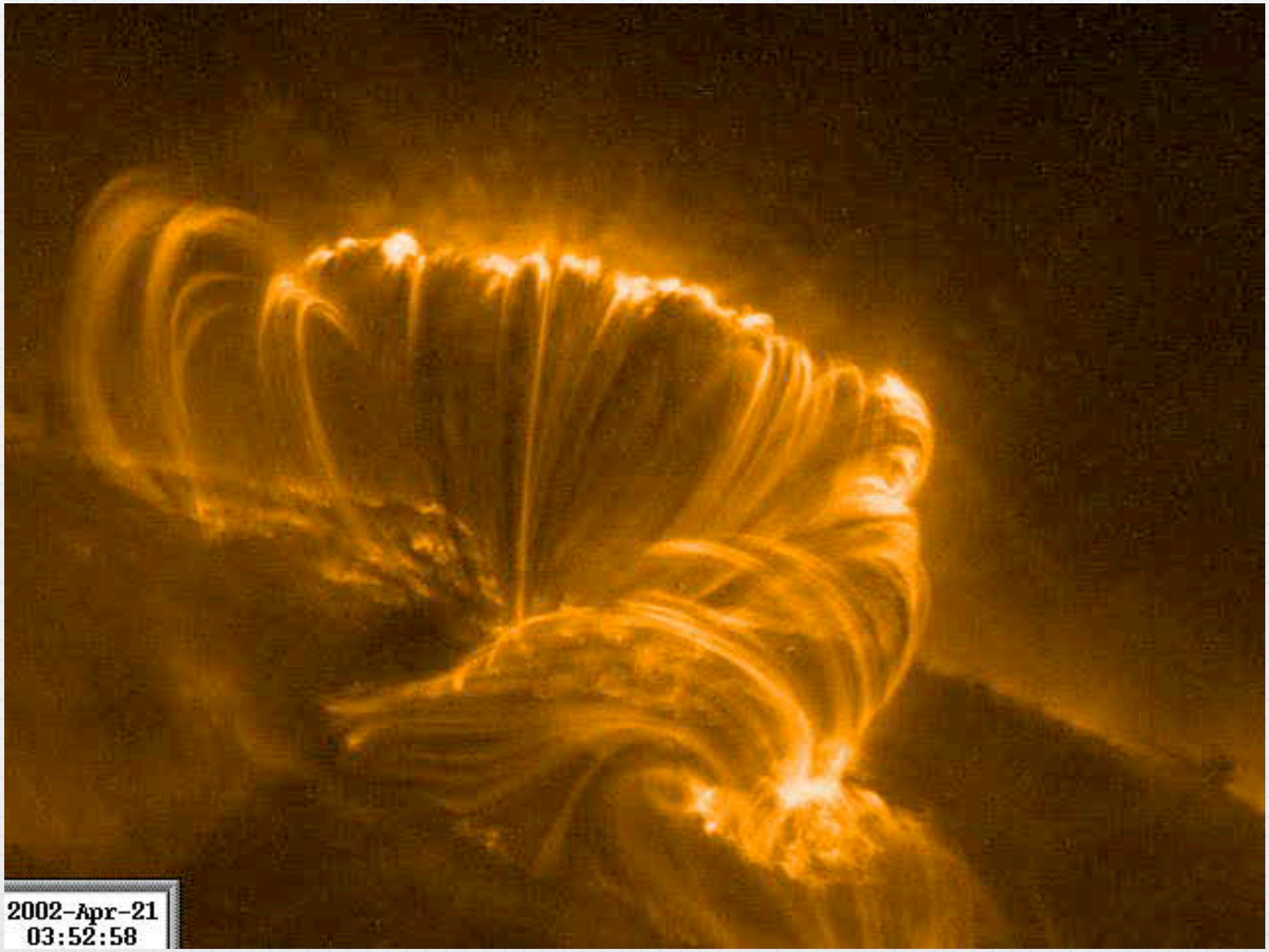
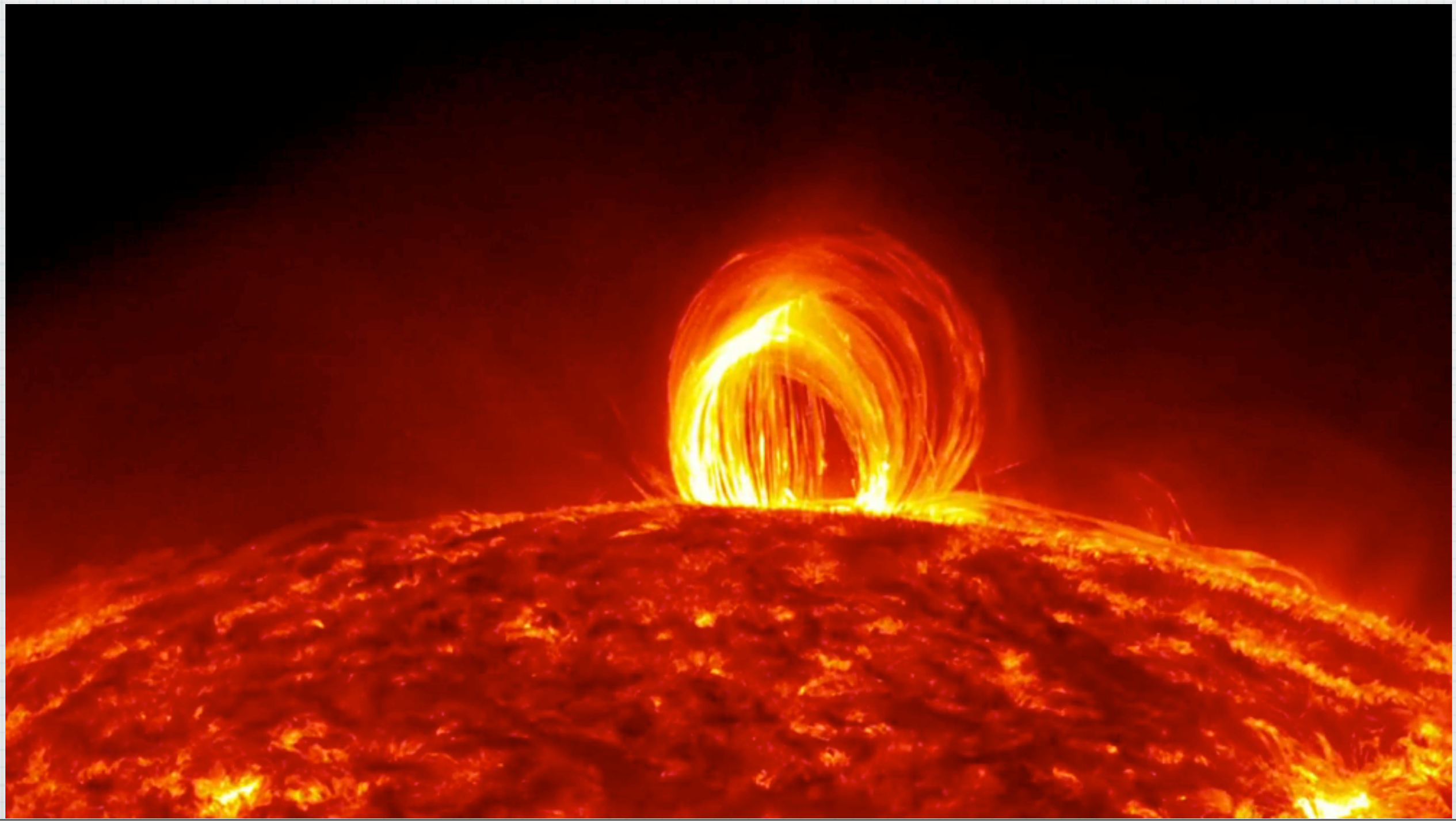
Solar ionized iron line shows coronal activity



Solar Eruption
(X-Ray light)



Coronal Rain
(UV light)



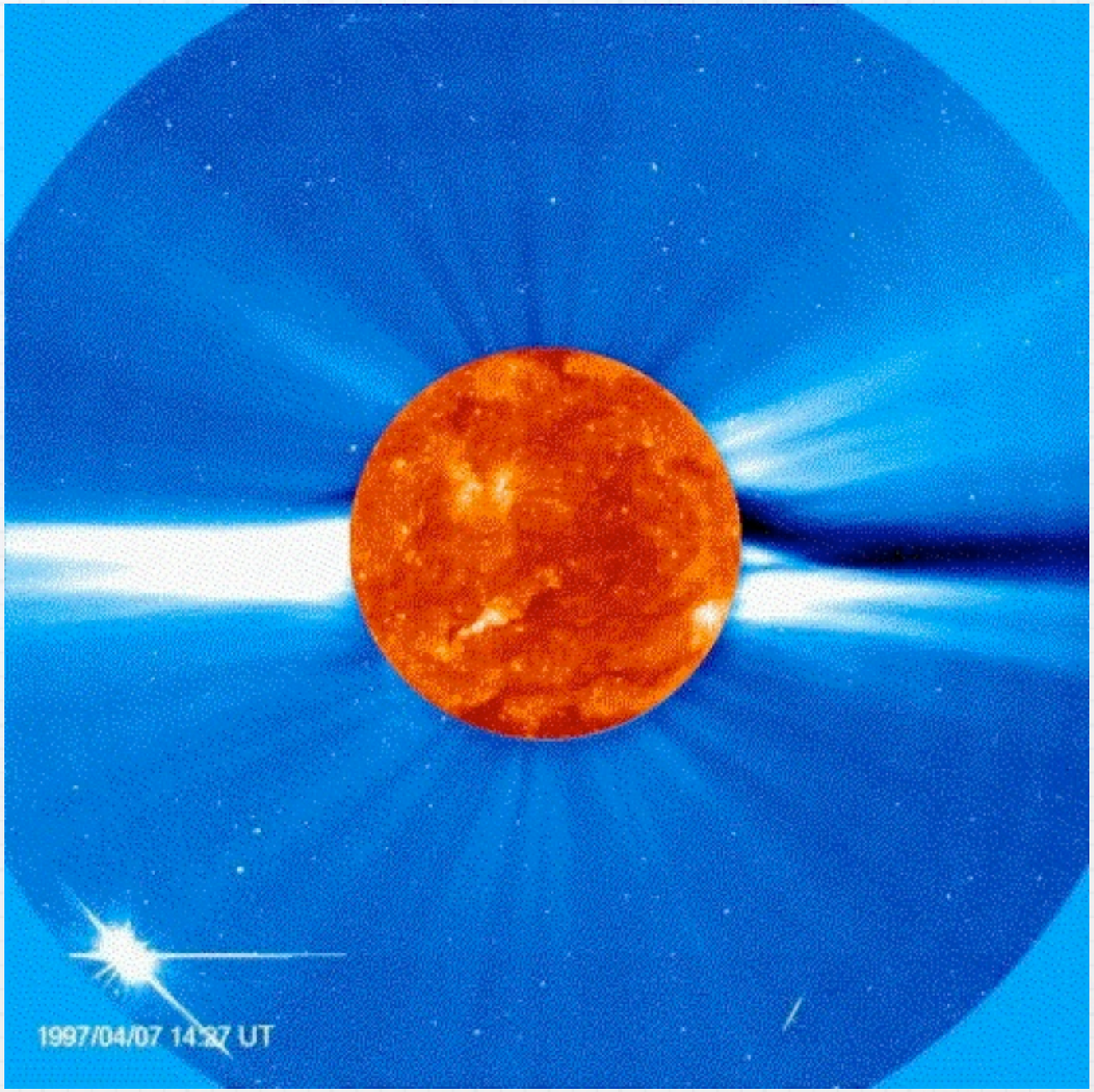
Coronal Mass Ejections

(corona)

CMEs are huge bubbles of gas that are ejected from the Sun

They turn the solar wind into a violent solar storm

Space walking astronauts would be killed if they met such a storm



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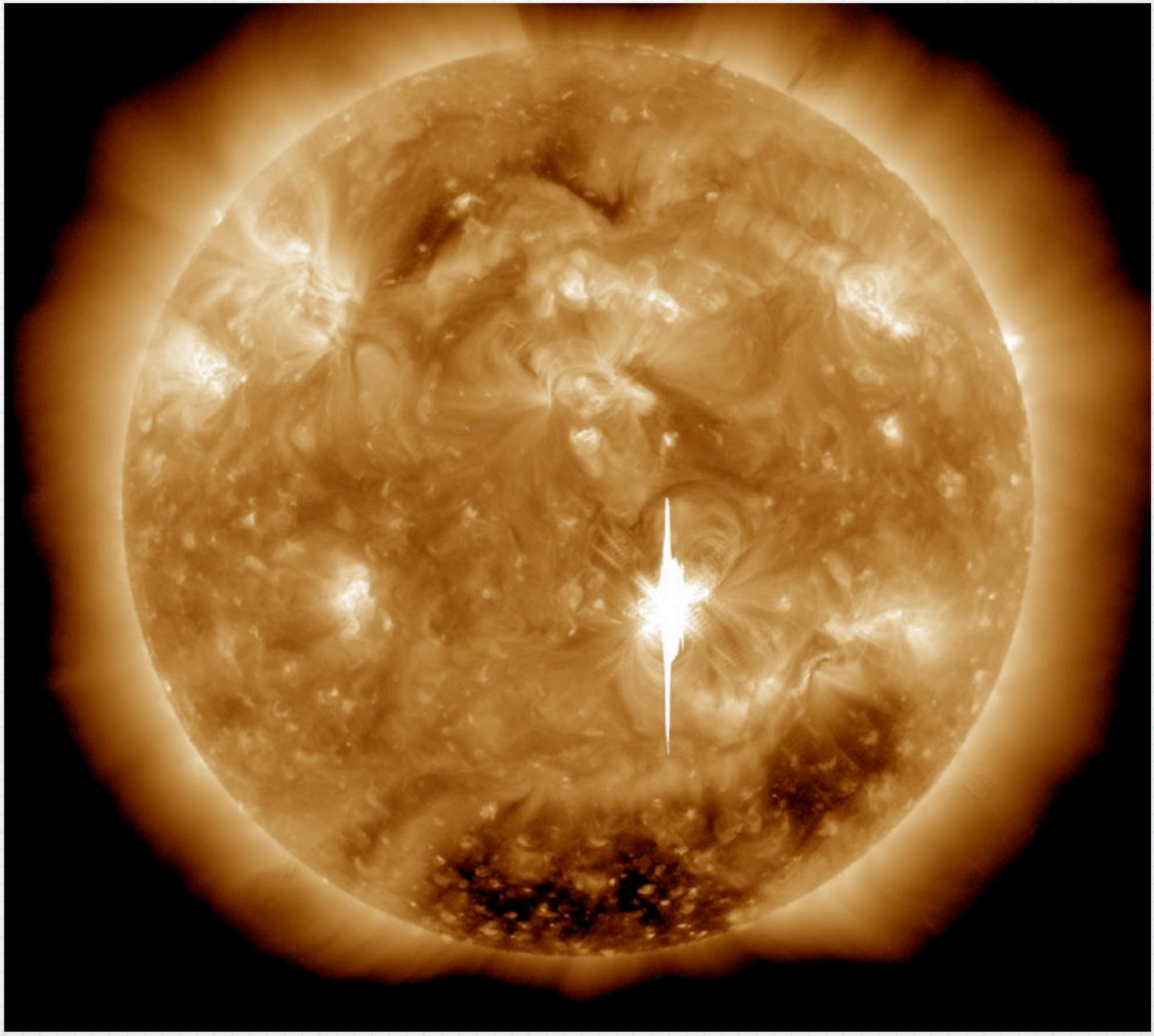
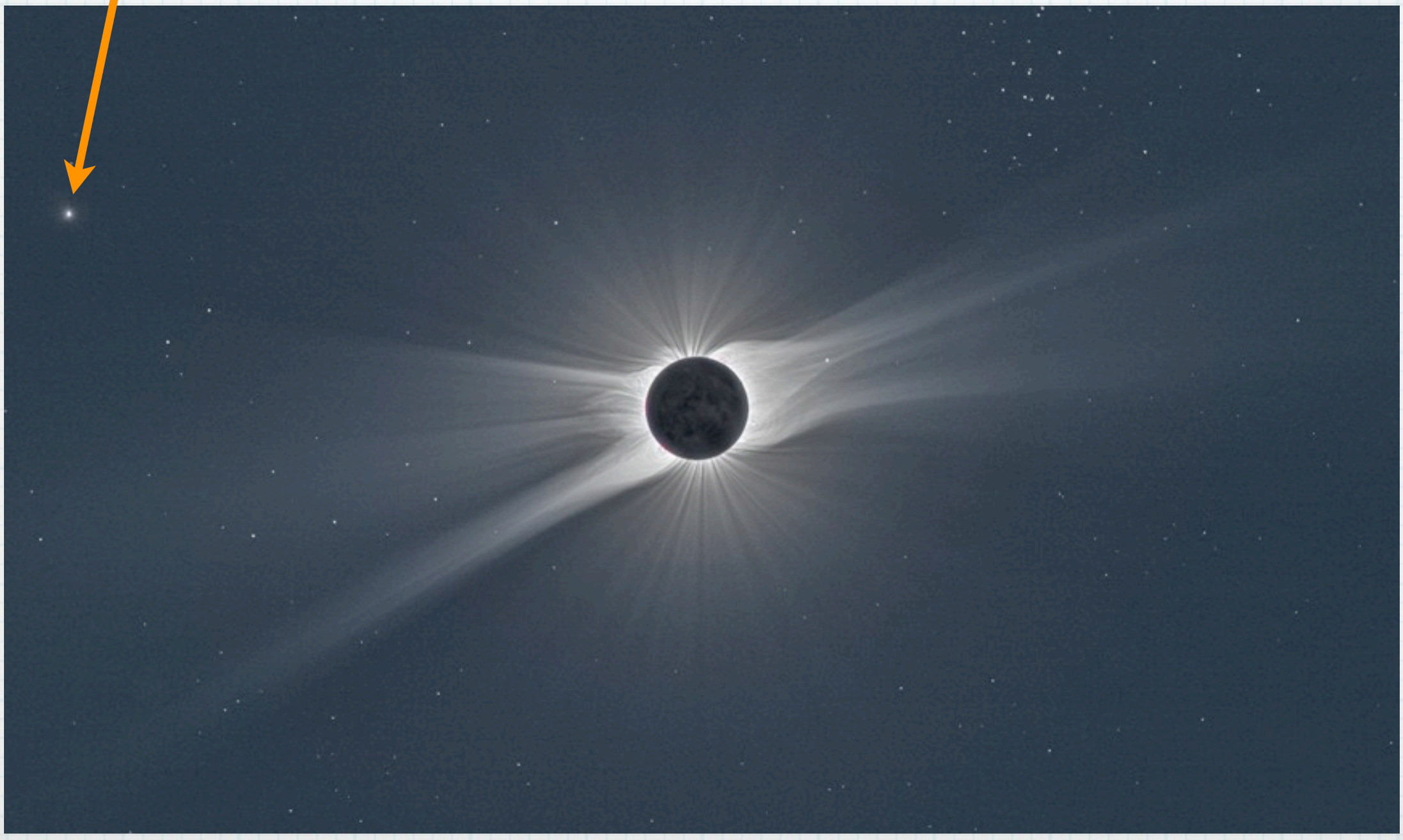
X-ray flare Feb 14, 2011

Has the potential of destroying man-made satellites and disrupt electrical power lines

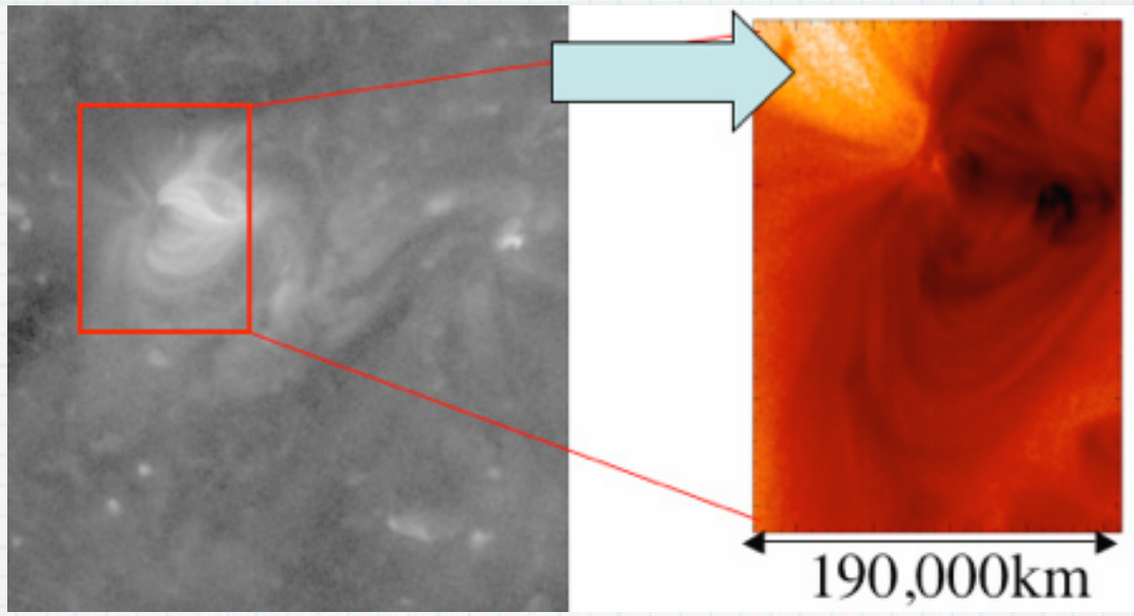


August 1, 2008: Total solar eclipse

The solar corona can be seen out to a distance of nearly 20 times the radius of the Sun



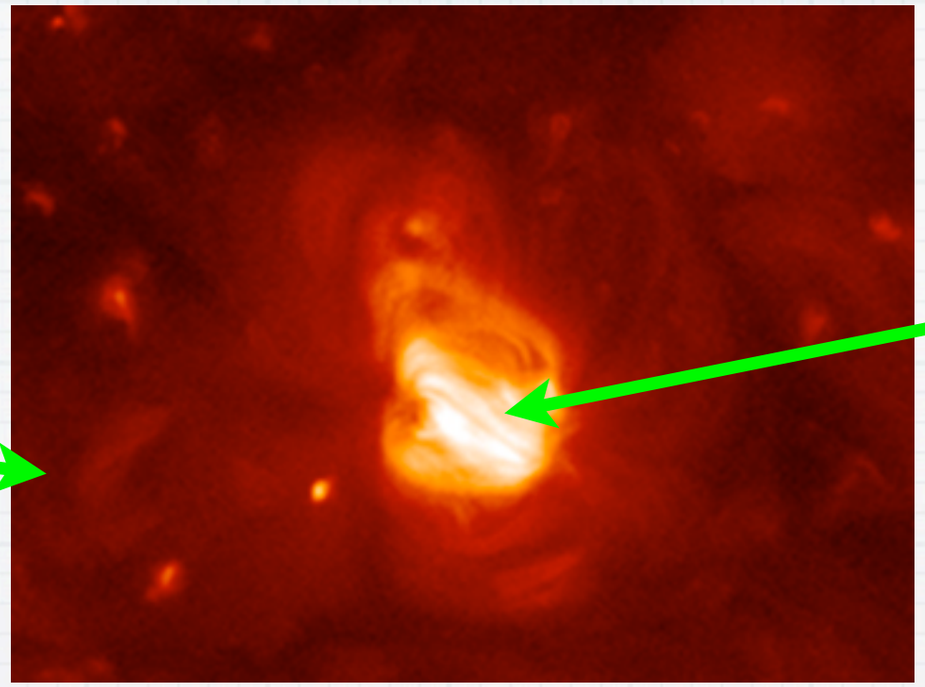
The Solar Wind



* The solar wind consists of electrically charged particles that flow out from the solar corona in all directions
* When magnetic fields from two bright region of activity collide (photosphere) they allow hot gas to escape from the Sun
* this material flows out as the solar wind

Speed of the Solar Wind

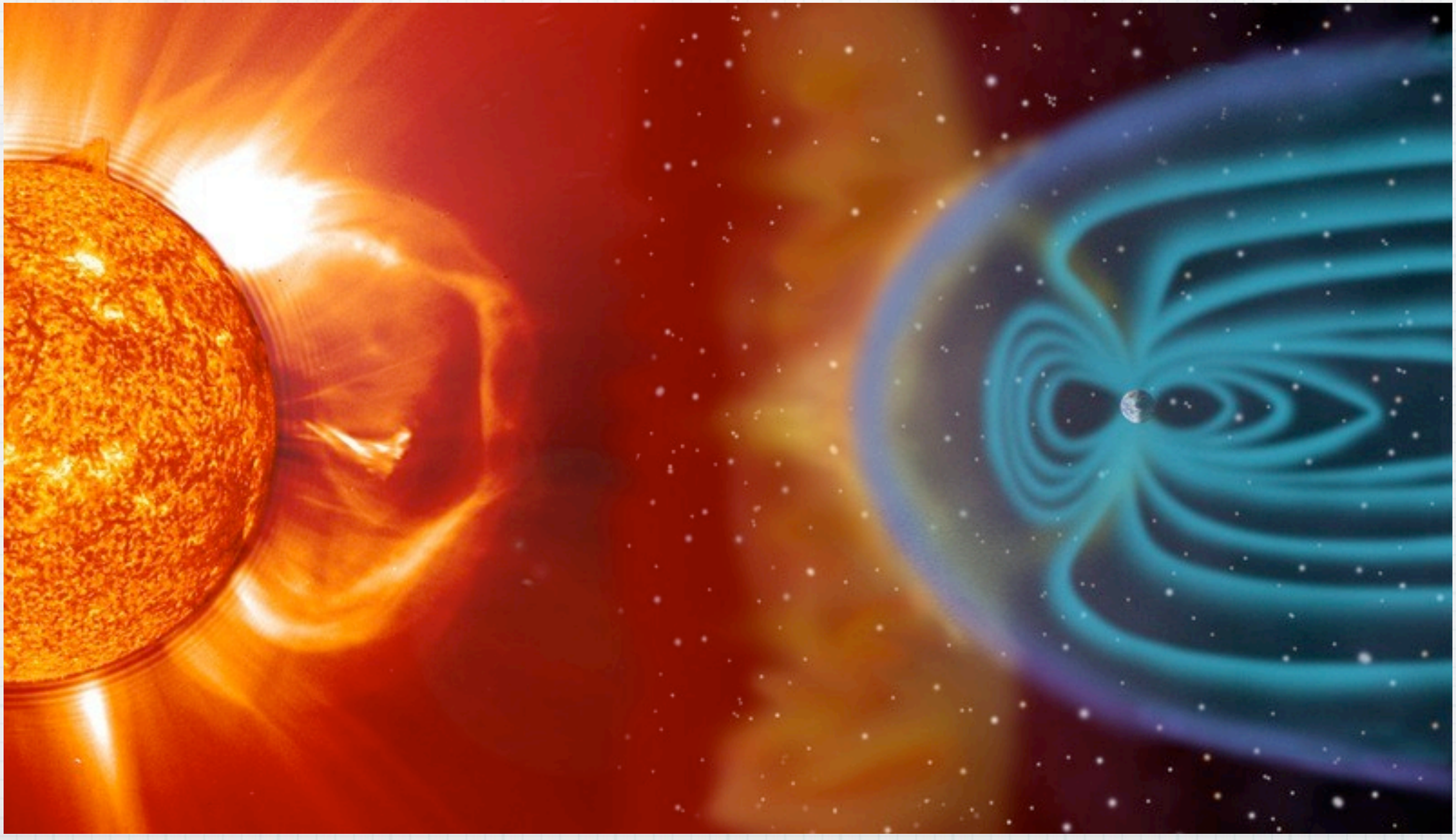
low-speed, low energy solar wind



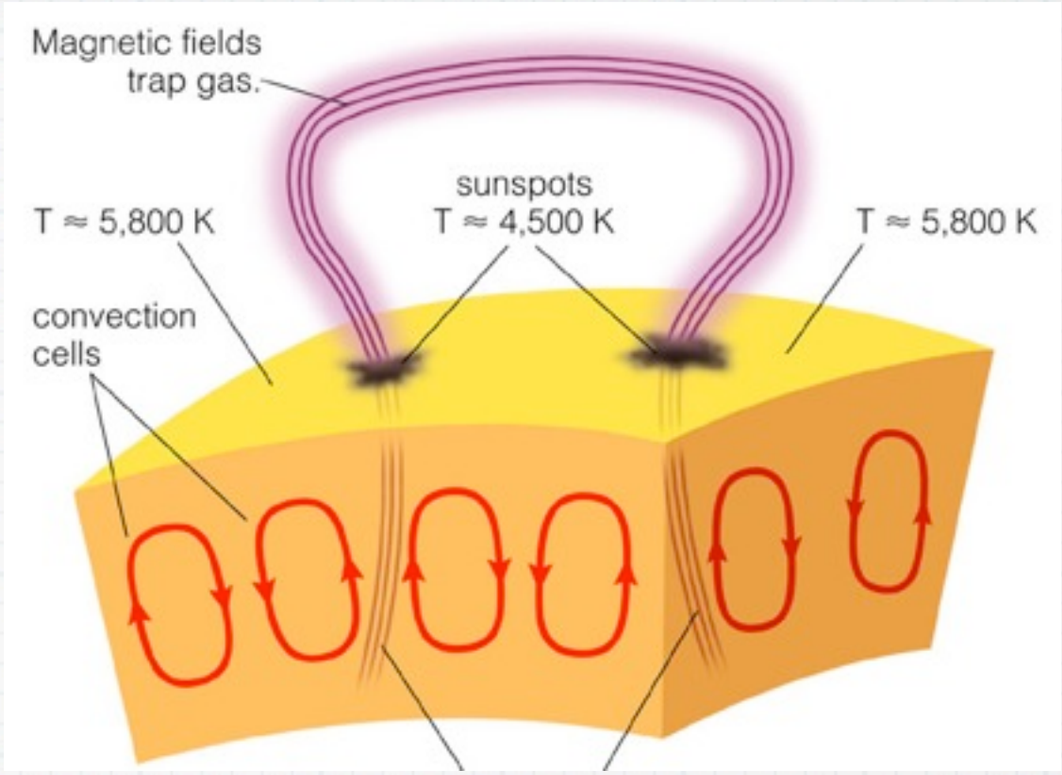
high-speed, high energy solar wind

* The solar wind flows at different speeds: from 300 km/s to up to 1,000 km/s
* Scientists concluded that magnetic reconnection, a process where two oppositely charged magnetic fields collide and release energy, is responsible for the high-speed solar wind

Sun Flares & Earth's Magnetic Field



Snapshot



* What causes solar activity?
* Convection combined with the rotation pattern of the Sun - faster at the equator than at the poles - causes solar activity because these gas motions stretch and twist the Sun's magnetic field

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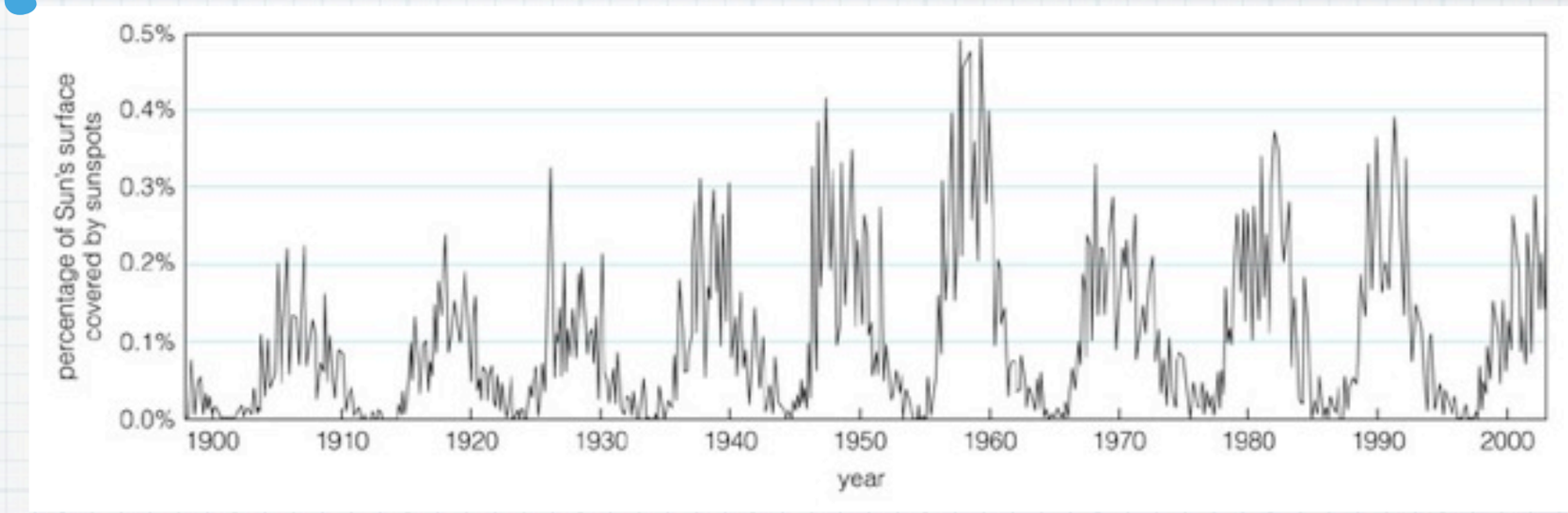
Snapshot



* How does solar activity vary with time?
* The sunspot cycle, or the variation in the number of sunspots on the Sun's surface, has an average period of 11 years. The magnetic field flip-flops every 11 years or so, resulting in a 22-year magnetic cycle

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The Heliosphere

* The farthest reaches of the Sun is called the heliosphere (helios: Greek for Sun)
* It is the volume of space where the solar wind is dominant as compared to stellar winds from other stars
* Its effective "radius" is many many times the radius of the Solar System

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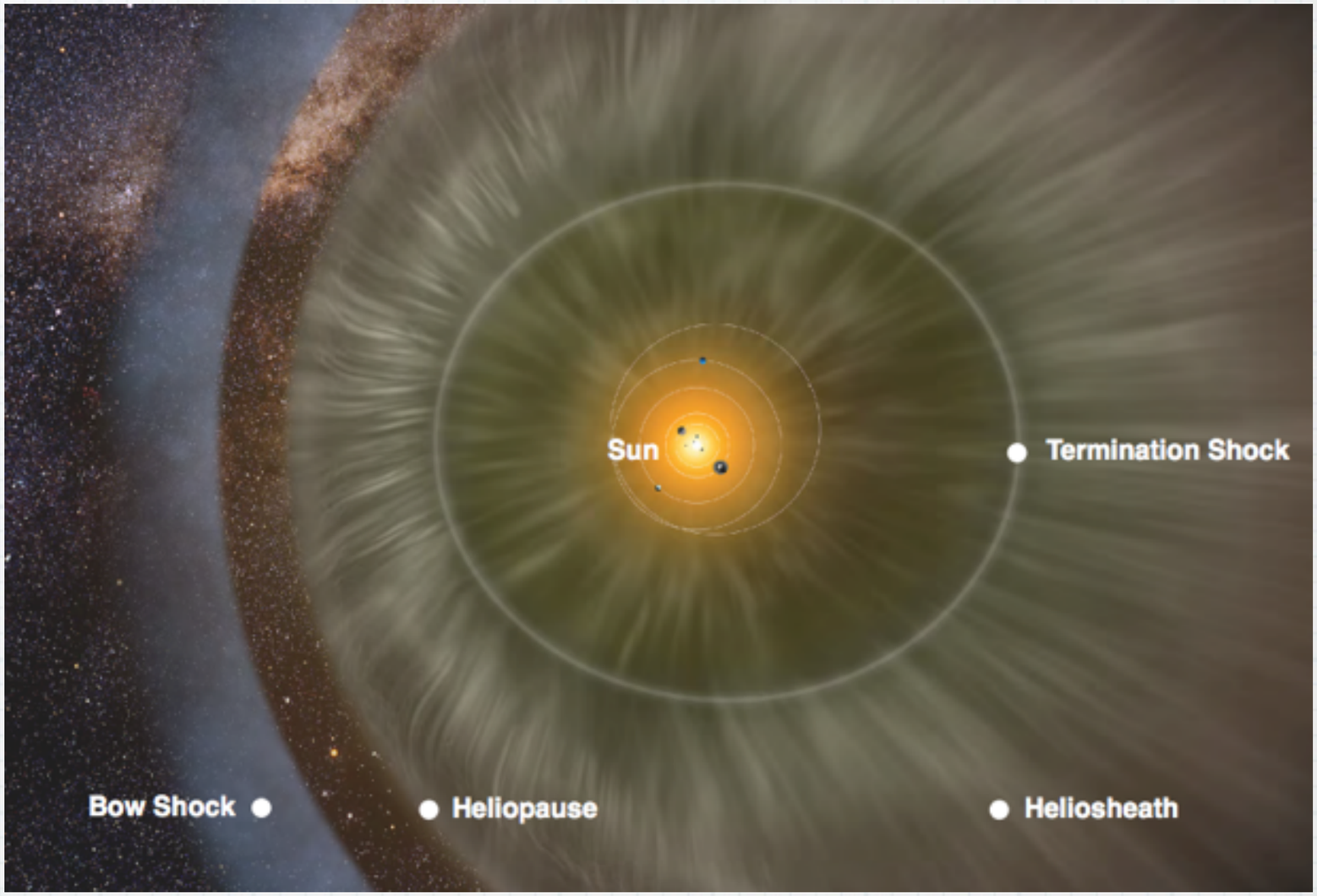
Heliosphere: a bubble of charged particles blown by the solar wind

The heliosphere protects against galactic cosmic rays (high-energy particles from black holes and supernovae)



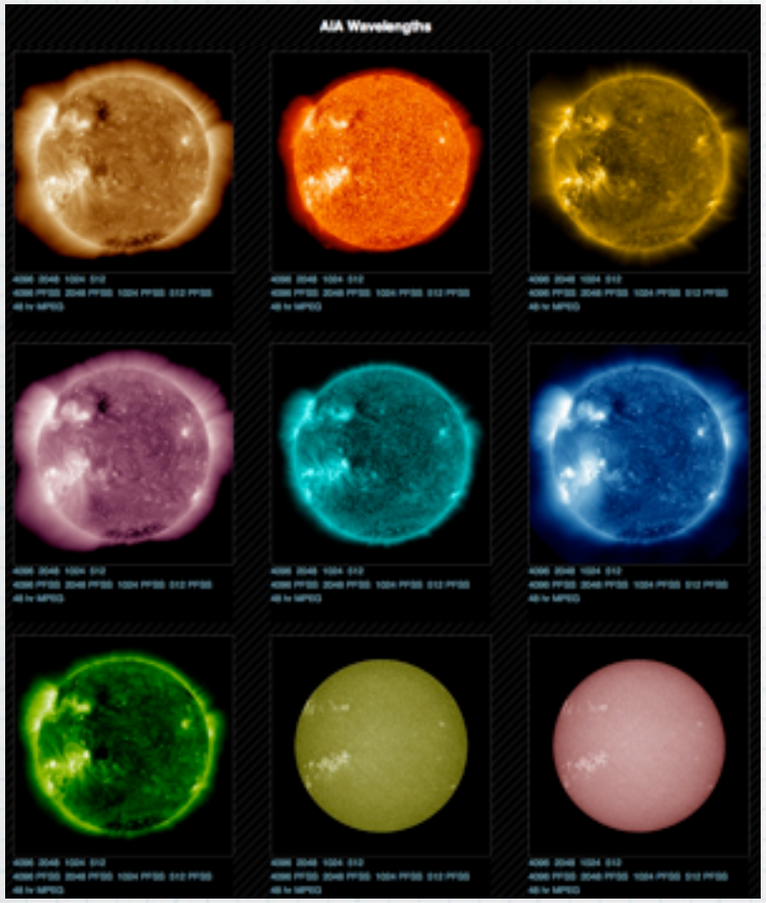
Termination Shock: where the solar wind begins to slow down as it interacts with the interstellar medium

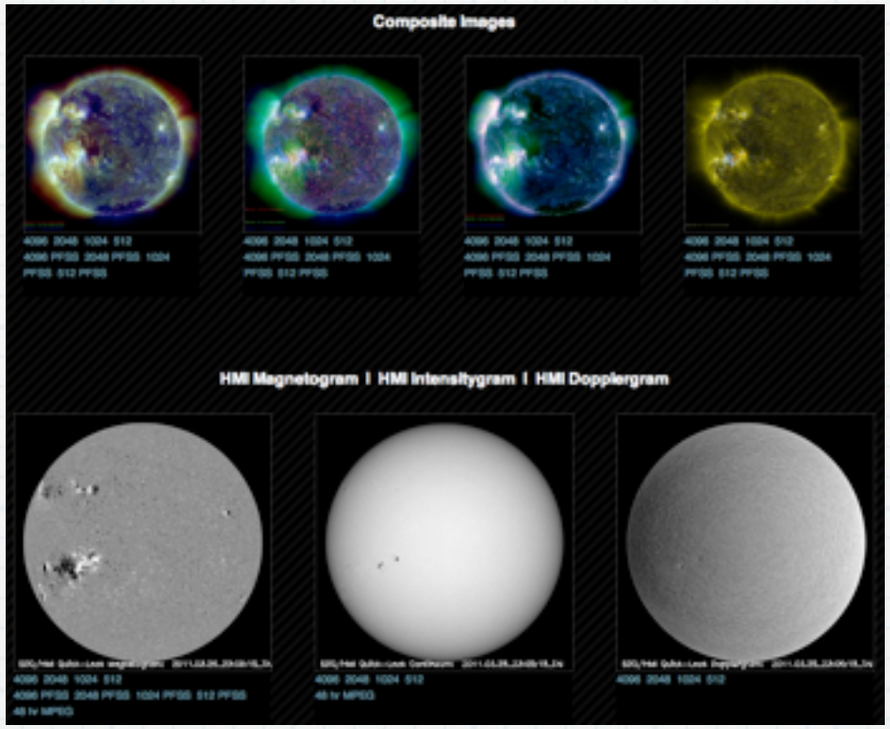
Bow Shock: region where stellar winds hit the heliosphere

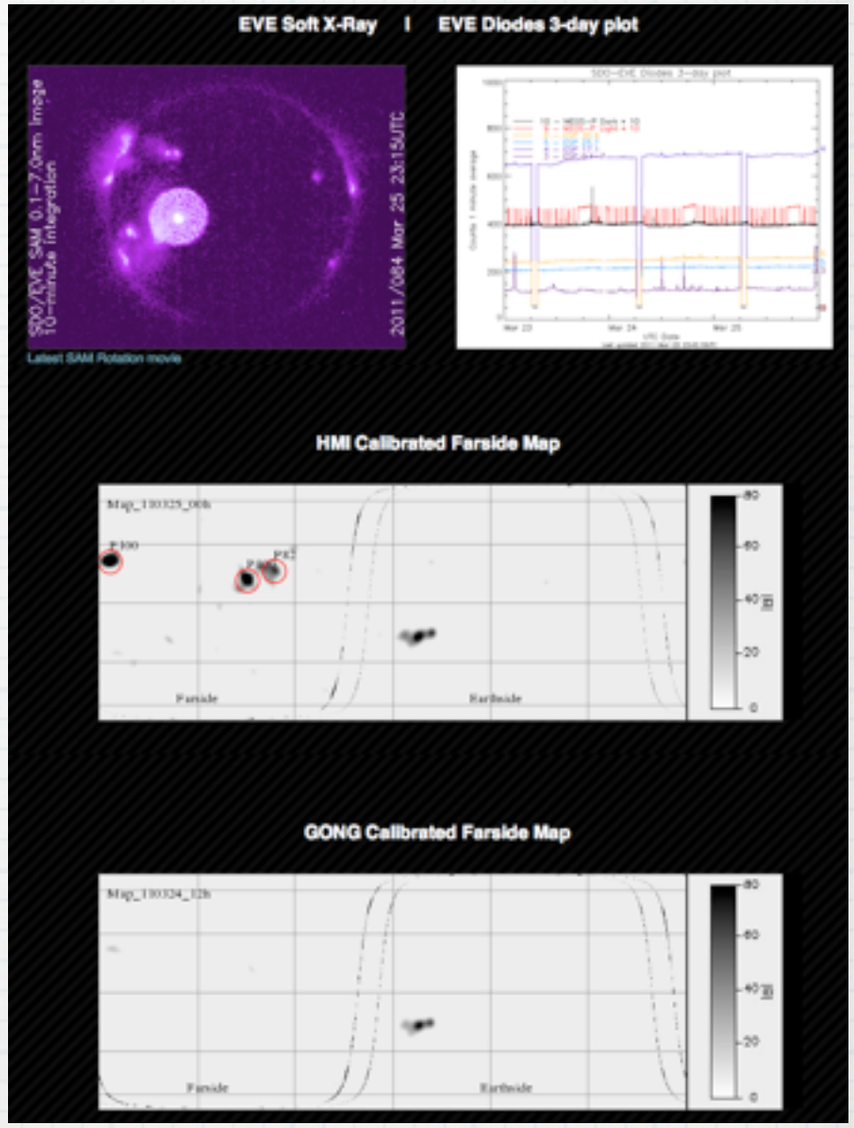
Heliosheath: past the Termination Shock, the solar wind continues to slow and this eventually leads to a boundary where the interstellar medium and solar wind pressures balance called the **Heliopause**

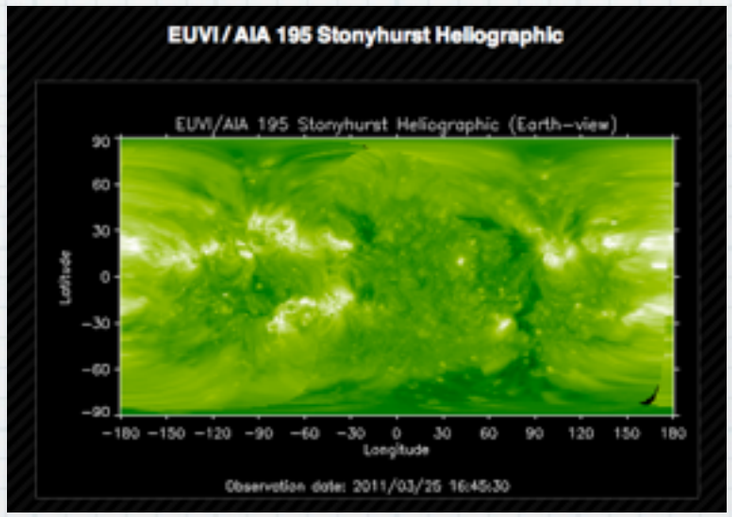
The Current Sun

The current Sun can alway be seen here: http://sdo.gsfc.nasa.gov/data/









Interesting Material

* http://solarscience.msfc.nasa.gov/feature1.shtml
* http://www.youtube.com/watch?v=sASbVkK-p0w
* http://www.youtube.com/watch?v=oOXVZo7KikE
* http://www.wired.com/wiredscience/2012/03/strange-neutrinos-experiments/
* http://www.youtube.com/watch?v=3Ghaf2du-XM