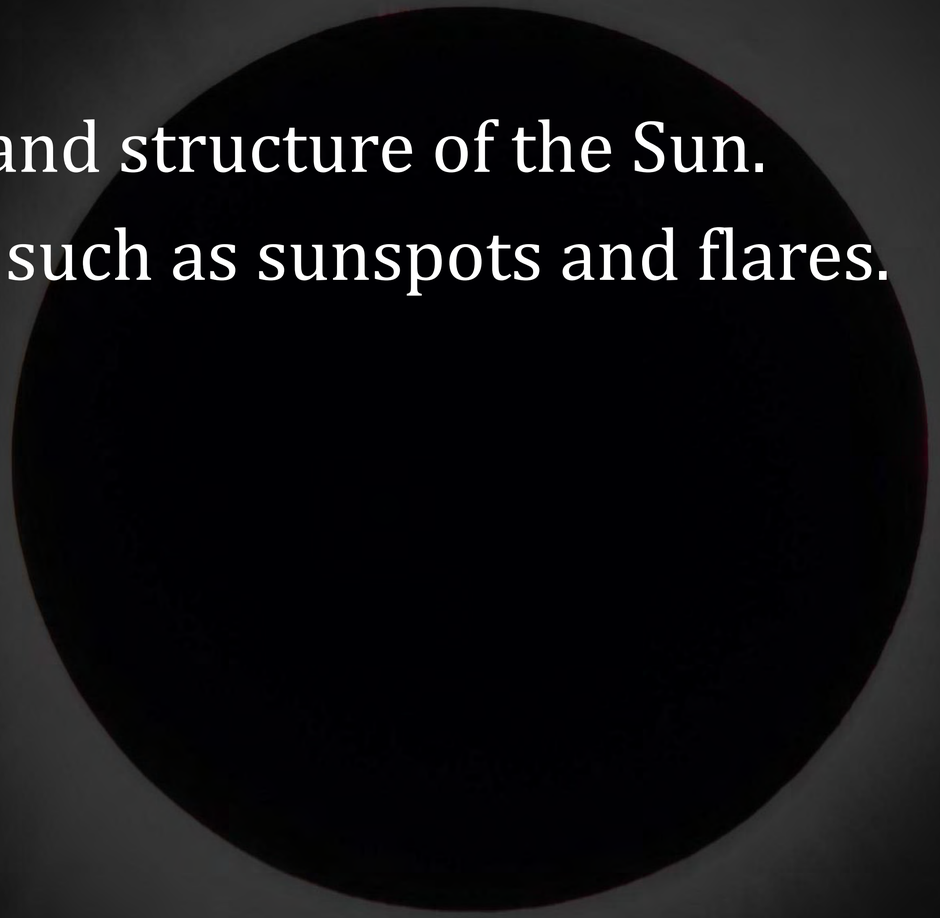
ASTR 1P01
Brock University
Prof. Barak Shoshany

Lecture 9: The Sun

We will learn about…

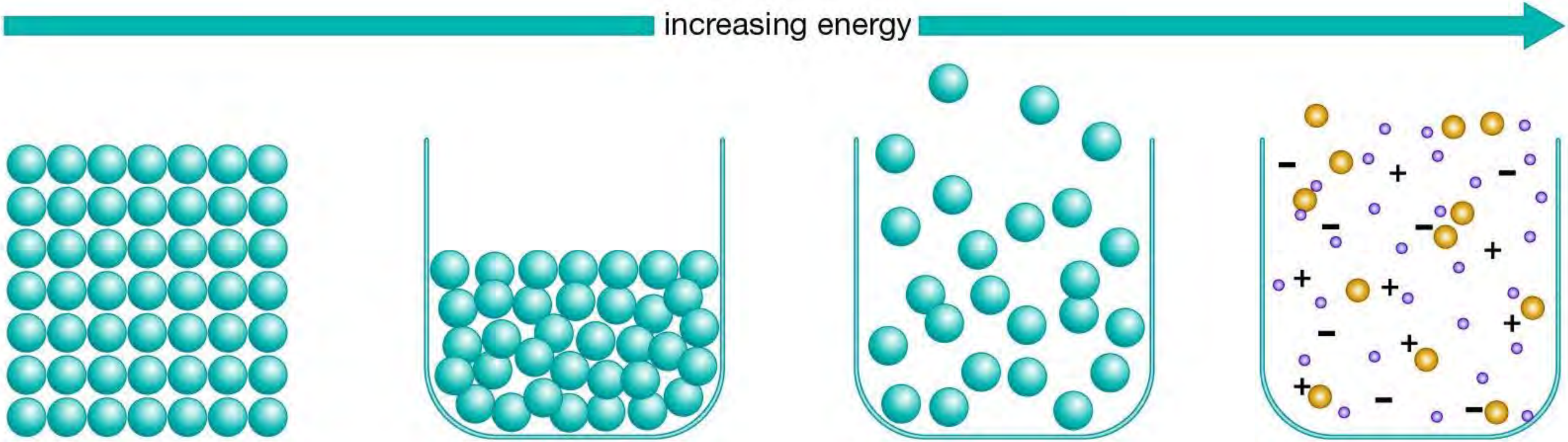
- The composition and structure of the Sun.
- Solar phenomena such as sunspots and flares.



The Sun’s corona as seen during a total solar eclipse
Credits: NASA/Aubrey Gemignani

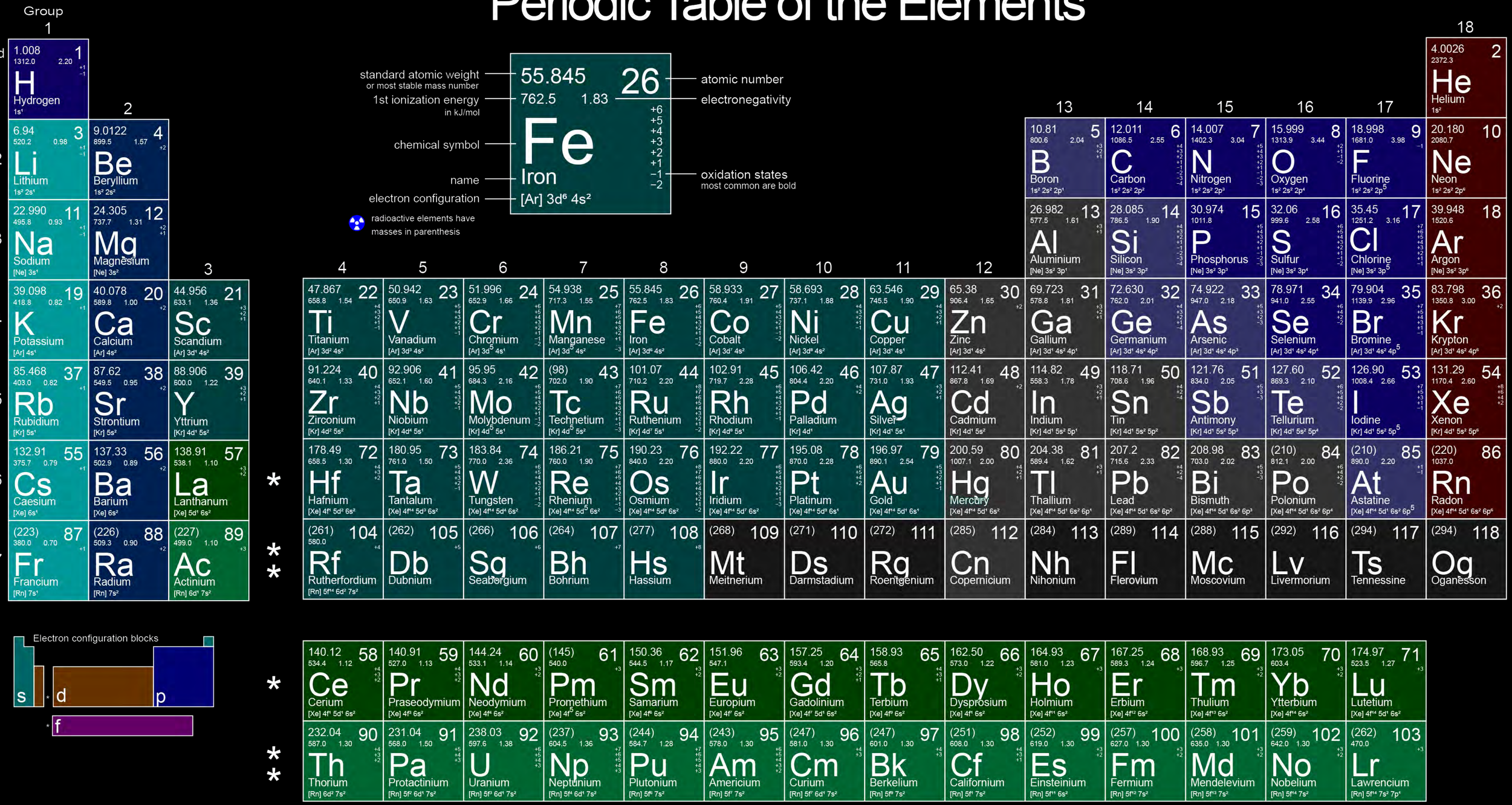
The Sun

- The Sun is composed mainly of the two lightest elements: ~73% hydrogen (H) and ~25% helium (He).
- The other ~2% are heavier elements like oxygen (O), carbon (C), iron (Fe), and neon (Ne).
- These elements in the Sun are in the form of plasma.
  - Plasma is the 4th fundamental state of matter, after solid, liquid, and gas.
  - It's similar to gas, but it's so hot that atoms break down into individual electrons and nuclei.



The 4 fundamental states of matter
Credits: Encyclopaedia Britannica

Periodic Table of the Elements



The Periodic Table of Elements

Credits: Modification of work by Robert Campion

The Sun

- The Sun is basically a huge ball of plasma.
- It has no solid parts, like a surface or core, and no liquid parts like oceans either.
- However, it is divided into several layers.

The Sun

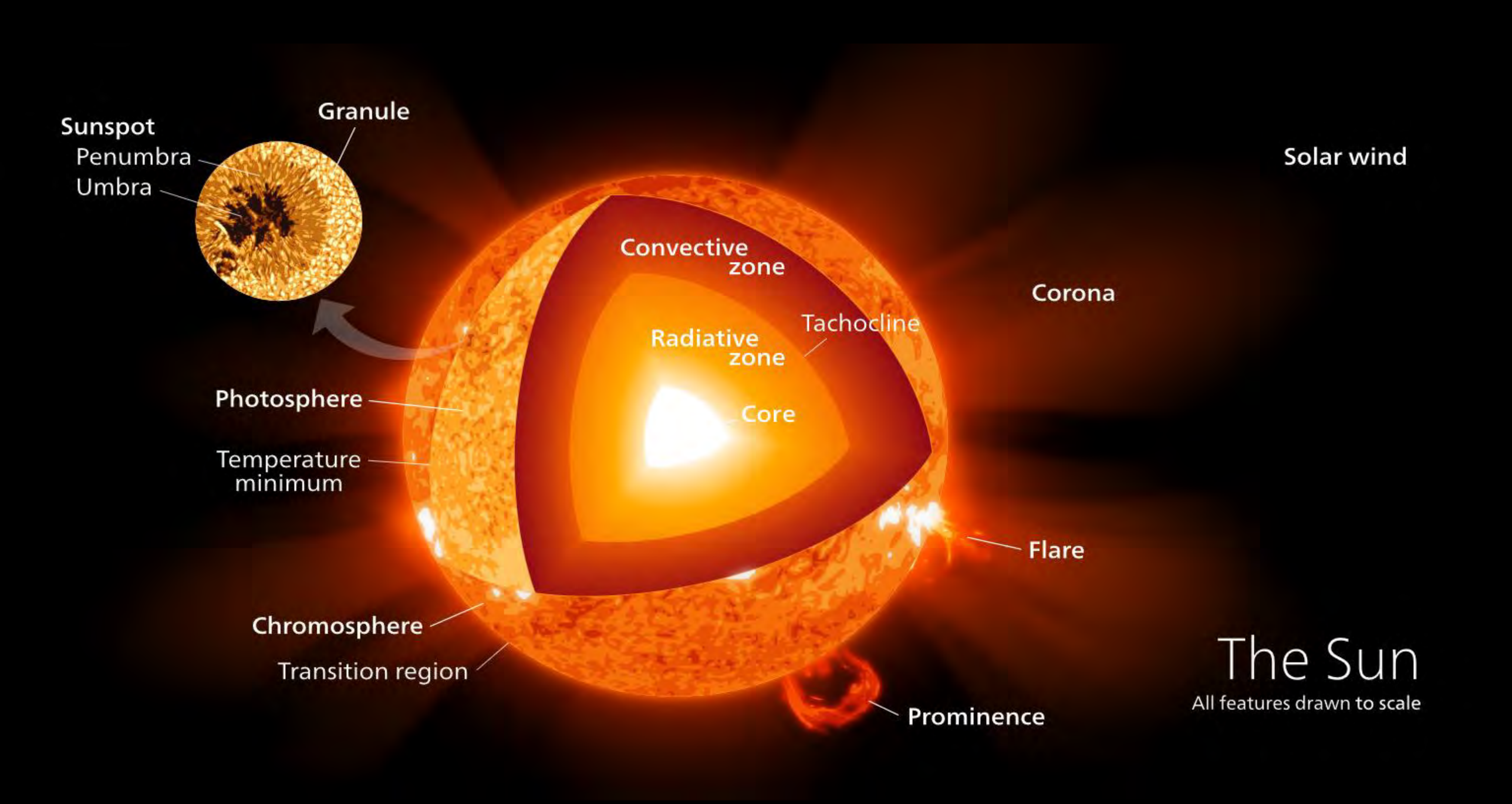
- The first layer, the core, extends from the center to ~20-25% of the solar radius.
- The core is where the Sun's energy (and light) is produced via nuclear fusion reactions.
  - We will learn more about how this works when we learn about stars.
- It is extremely dense, and its temperature is ~15.7 million K.
  - This is compared to the surface temperature of ~5,800 K.

The Sun

- The next layer is the radiative zone, extending up to 45% of the solar radius.
- It transports energy from the core outwards via radiation (in the form of photons, or particles of light).
- It is also very dense, so energy is transported very slowly.
  - The photons keep bumping into other particles on the way, changing direction, and losing energy in the process.
- The temperature drops across the radiative zone, down to ~2 million K at the largest distance from the core.

The Sun

- Next we have the convective zone, the outermost layer of the solar interior, extending up to the surface.
  - It is separated from the radiative zone by the tachocline.
- The convective zone is not dense or hot enough to transfer heat outward via radiation.
- Instead, heat is transferred via convection, or the movement of fluid (in this case plasma).



Layers of the Sun
Credits: Kelvinsong (Wikipedia)

The Sun

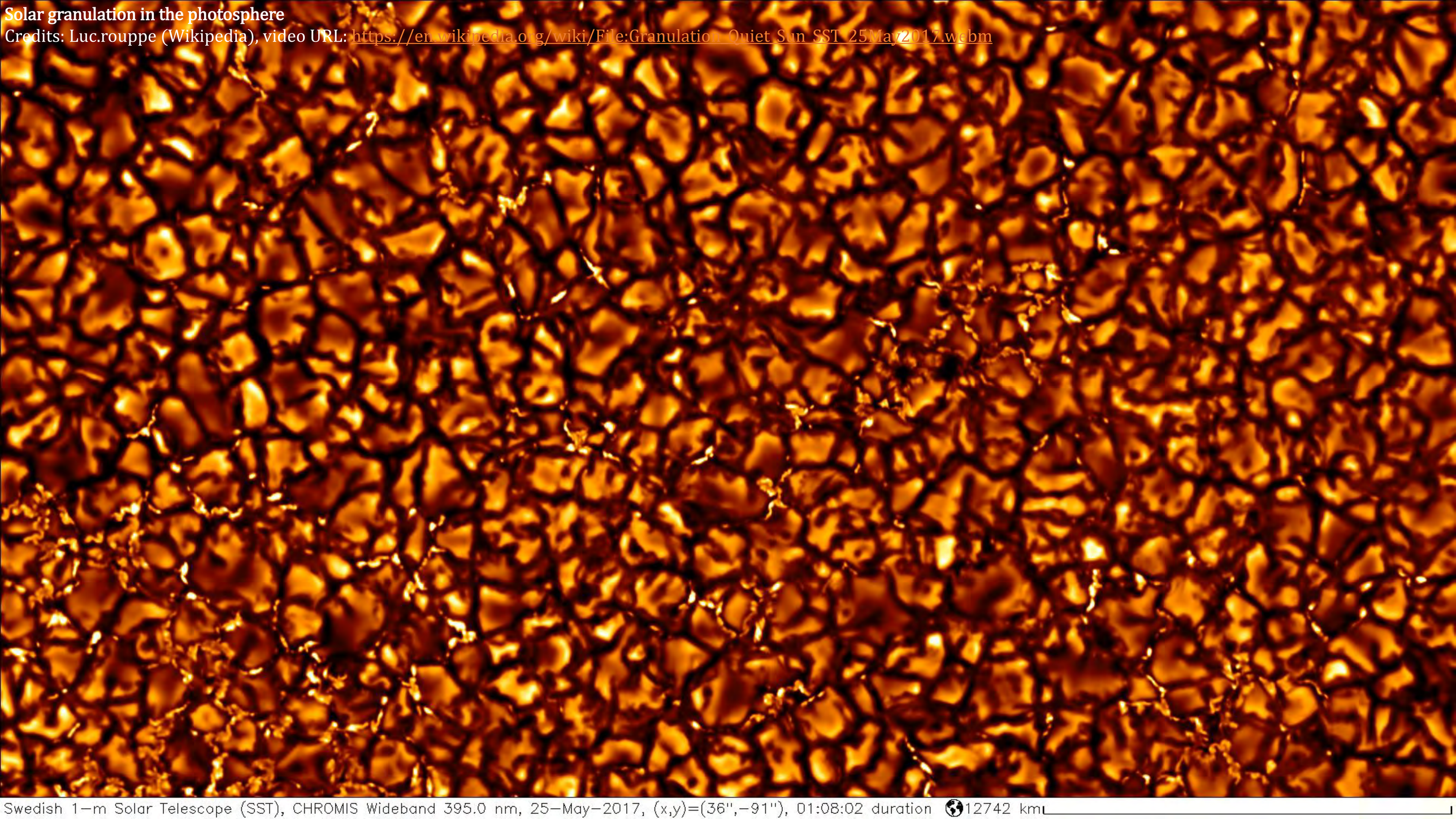
- The visible and opaque surface of the Sun is the photosphere.
- It's where we actually see the photons that originated in the core.
- This layer is only a ~400 km thick. The diameter of the Sun is defined as the size of the region surrounded by the photosphere.
- The temperature of the photosphere is ~5,800 K.
- The photosphere is not a solid surface. If you fell through it (and didn't mind the heat) it would be like falling through air.
- In fact, its density is 1/10,000 the density of Earth's atmosphere at sea level.

The Sun

- The photosphere is composed of granules, ~700-1000 km in diameter (roughly the size of Alberta).
- They appear as bright areas surrounded by narrow, darker, and cooler regions.
- The lifetime of an individual granule is only 5 to 10 minutes.
- Supergranules are ~35,000 km across (about the size of two Earths) and last about 24 hours.
- The granules are a result of convective motion of bubbles that rise from the solar interior, like in boiling soup.

Solar granulation in the photosphere

Credits: Luc.rouppe (Wikipedia), video URL: https://en.wikipedia.org/wiki/File:Granulation_Quiet_Sun_SST_25May2017.webm

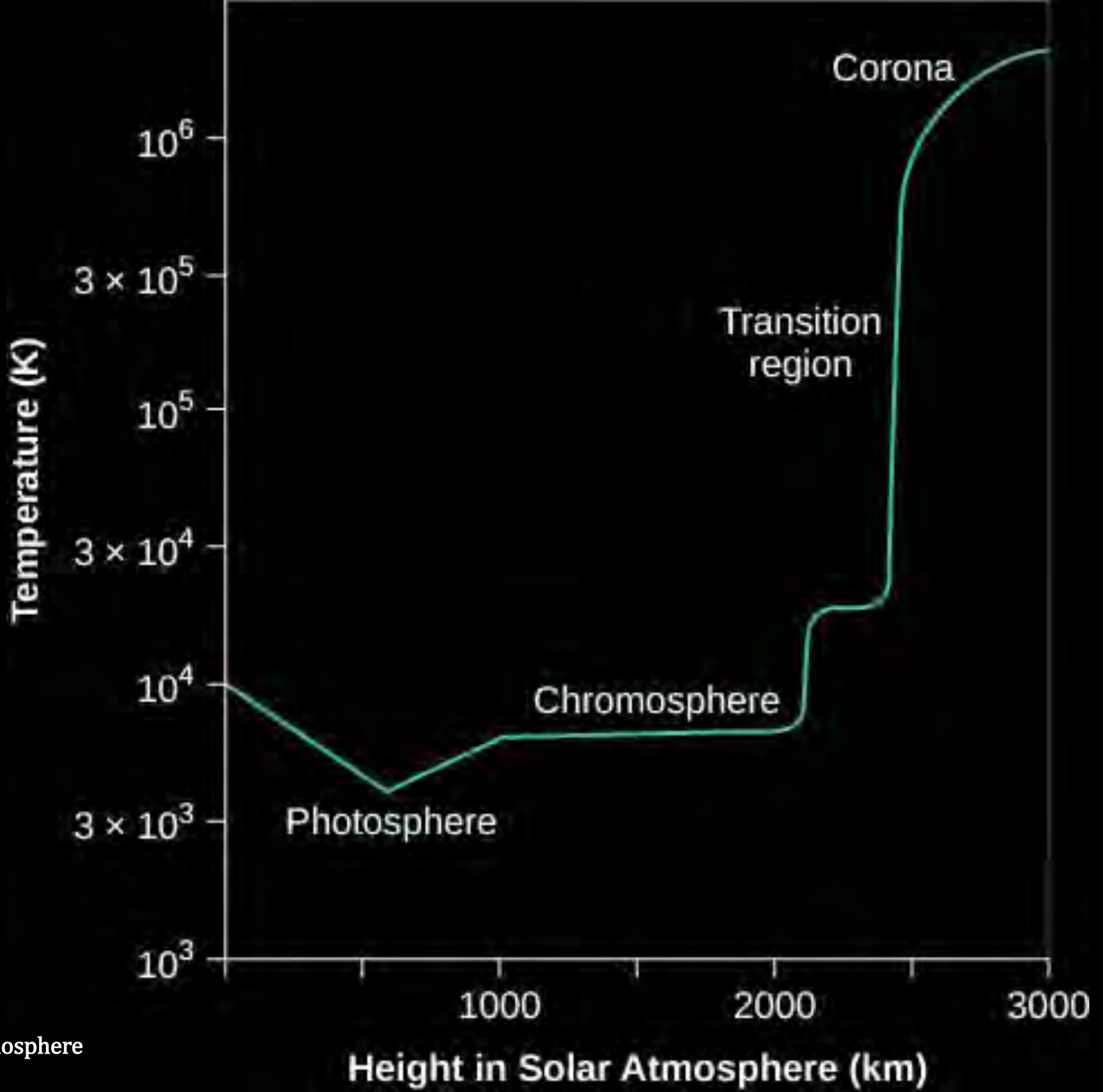


The Sun

- The region of the Sun's atmosphere immediately above the photosphere is called the chromosphere.
- It is ~2,000-3,000 km thick and ~10,000 K hot.
- Note that it is hotter than the photosphere (~5,800 K). This is surprising, since it is farther from the core.
- The chromosphere is visible when the photosphere is concealed by the Moon during a total solar eclipse.

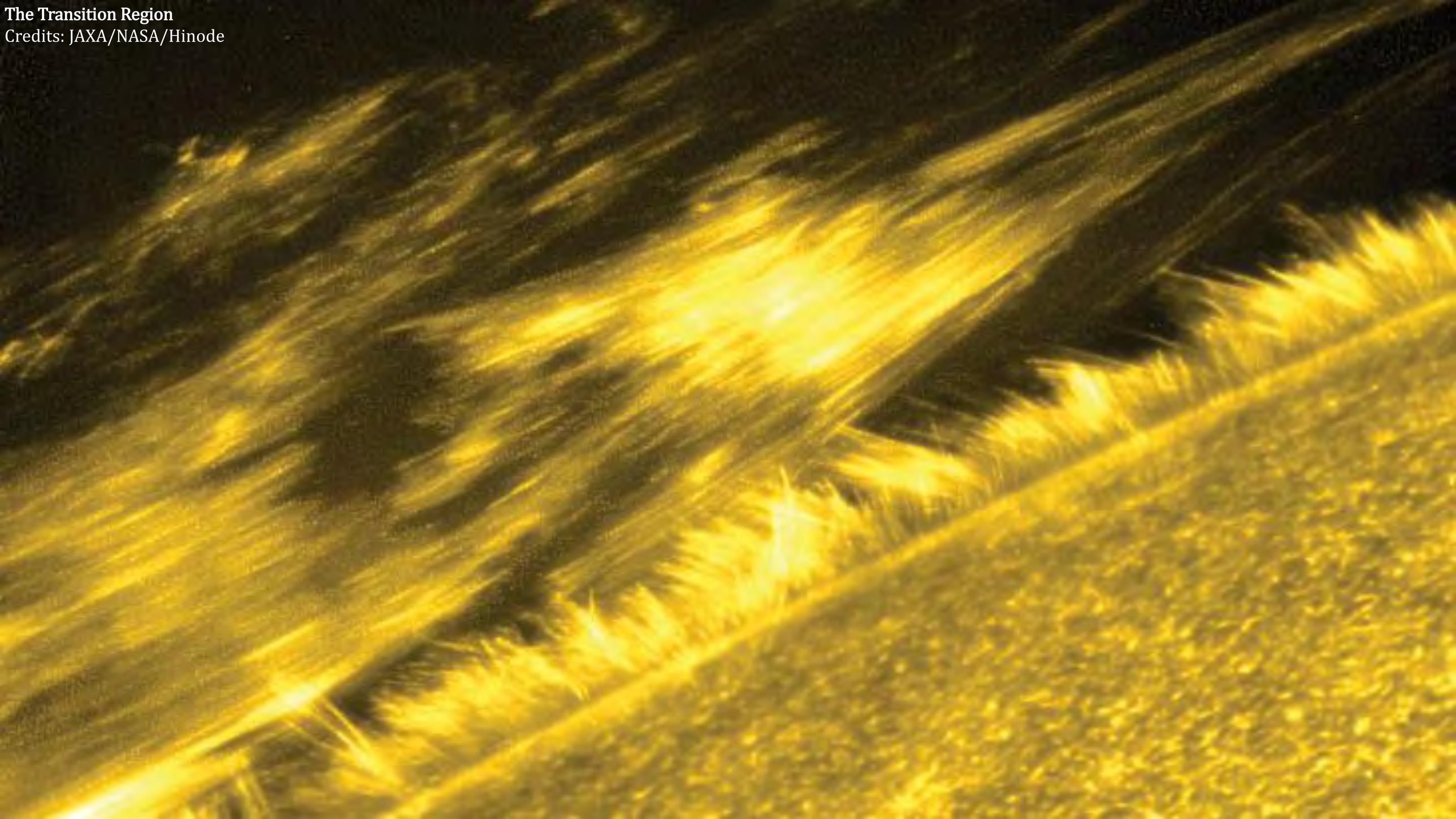
The Sun

- Above the chromosphere is a region called the corona where the temperature increases rapidly from ~10,000 K to ~1 million K!
- The part of the Sun where the rapid temperature rise occurs is called the transition region. It is only a few tens of km thick.



Temperature differences in the Solar Atmosphere
Credits: OpenStax Astronomy

The Transition Region
Credits: JAXA/NASA/Hinode



The Sun

- The corona is the outermost part of the Sun's atmosphere.
- Like the chromosphere, the corona can be seen during total eclipses.
- The corona extends millions of km above the photosphere and emits about half as much light as the full moon.
- The reason we don't see this light until an eclipse occurs is that it is much fainter compared to the photosphere.
- The corona can also be photographed with a special instrument called a coronagraph that removes the Sun's glare from the image with a circular piece of material held in front of the Sun.

The Sun’s corona as seen during a total solar eclipse
Credits: NASA/Aubrey Gemignani

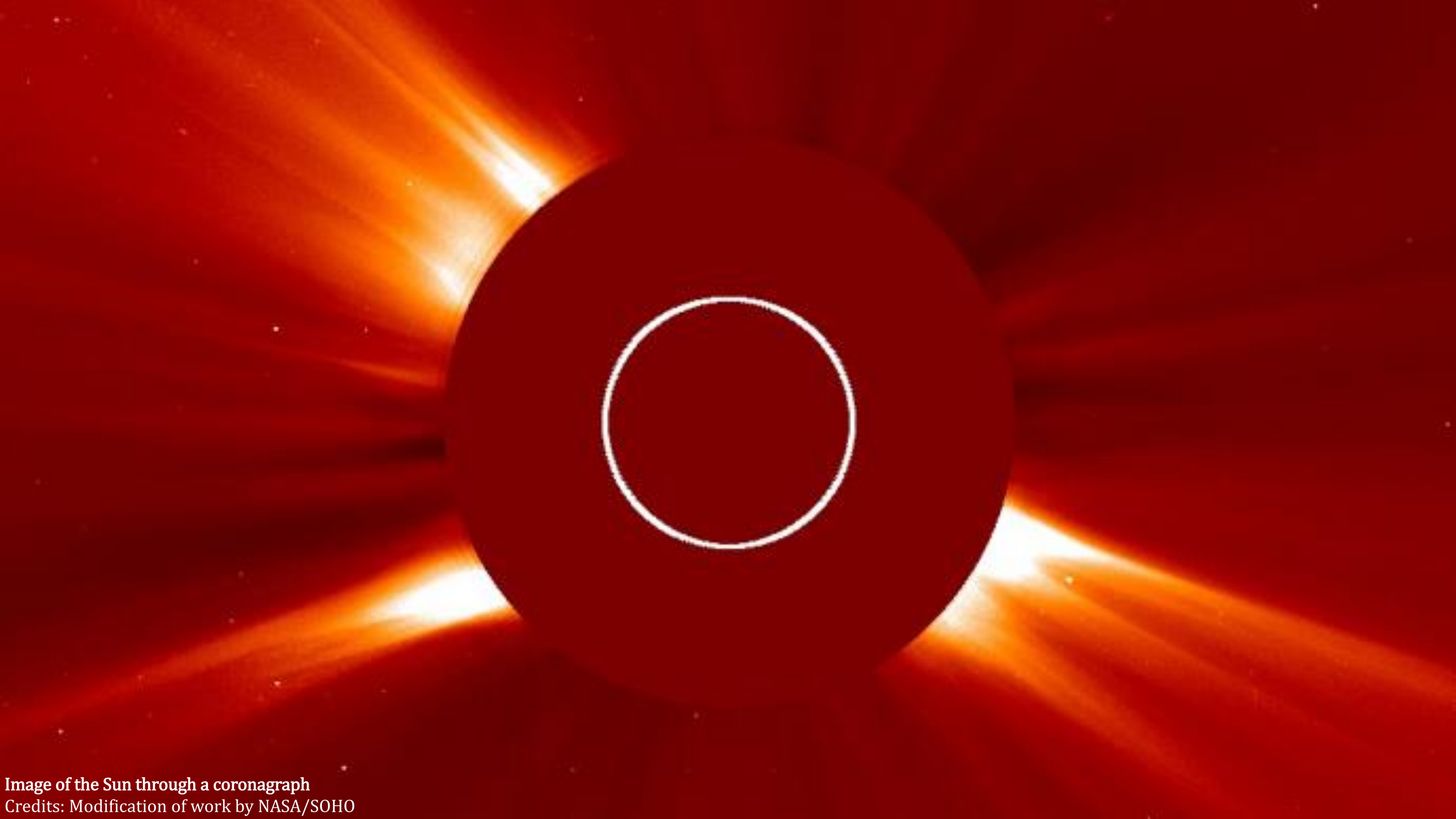


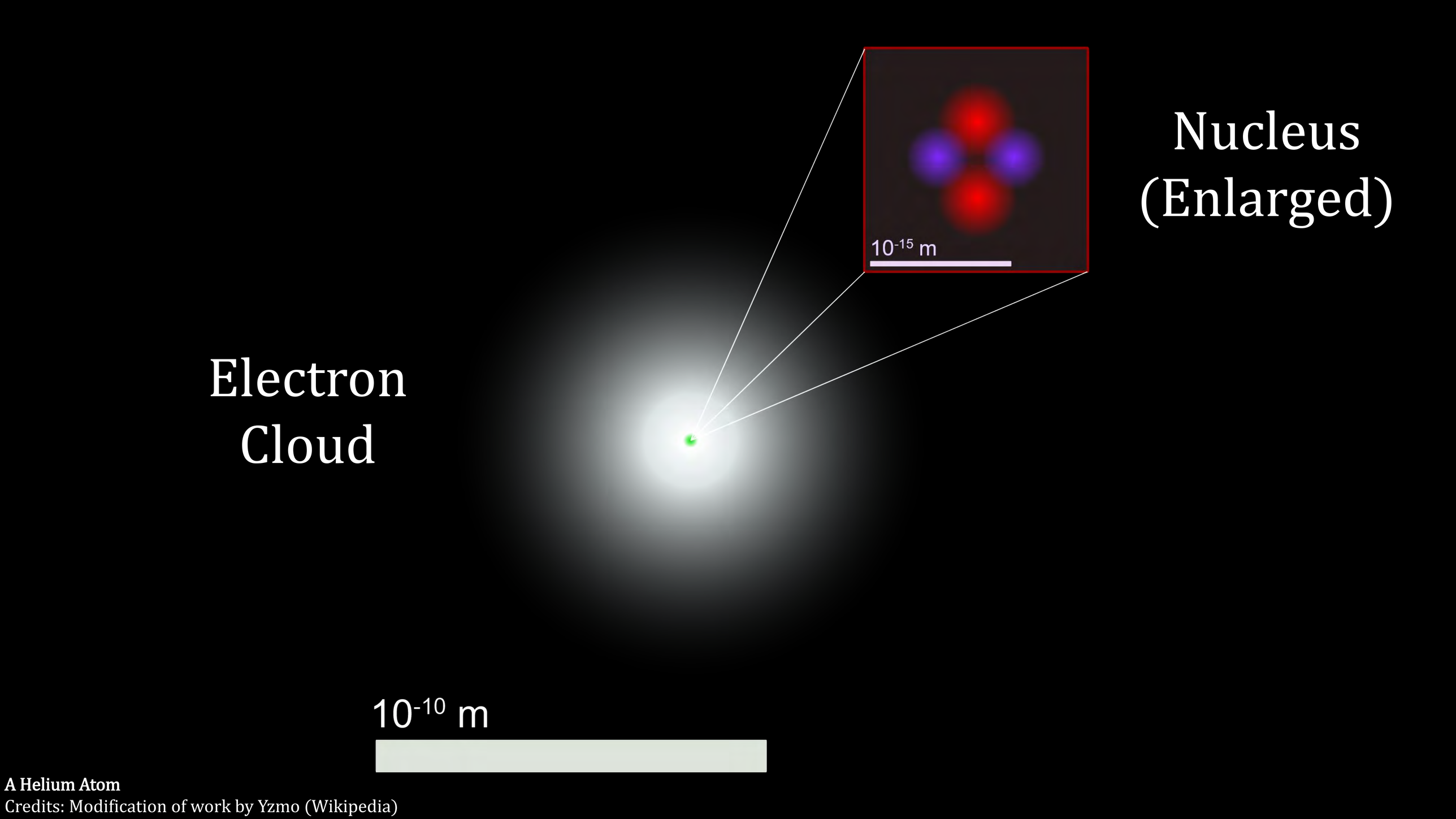
Image of the Sun through a coronagraph
Credits: Modification of work by NASA/SOHO

The Sun

- The corona has very low density and thins out very rapidly at greater heights.
- At the bottom of the corona, there are only $\sim 10^{15}$ atoms/m^3.
- Compare with:
  - $\sim 10^{22}$ atoms/m^3 in the upper photosphere.
  - $\sim 10^{25}$ molecules/m^3 at sea level in Earth's atmosphere.
- The corona extends far past Earth – we are technically living inside the Sun's atmosphere!

The Sun

- The Sun's atmosphere produces a stream of charged particles, mainly protons and electrons, called the solar wind.
  - Recall: an atom is made from a nucleus containing protons and neutrons, surrounded by a cloud of electrons.
- These particles flow outward from the Sun at ~400 km/s.



A Helium Atom
Credits: Modification of work by Yzmo (Wikipedia)

The Sun

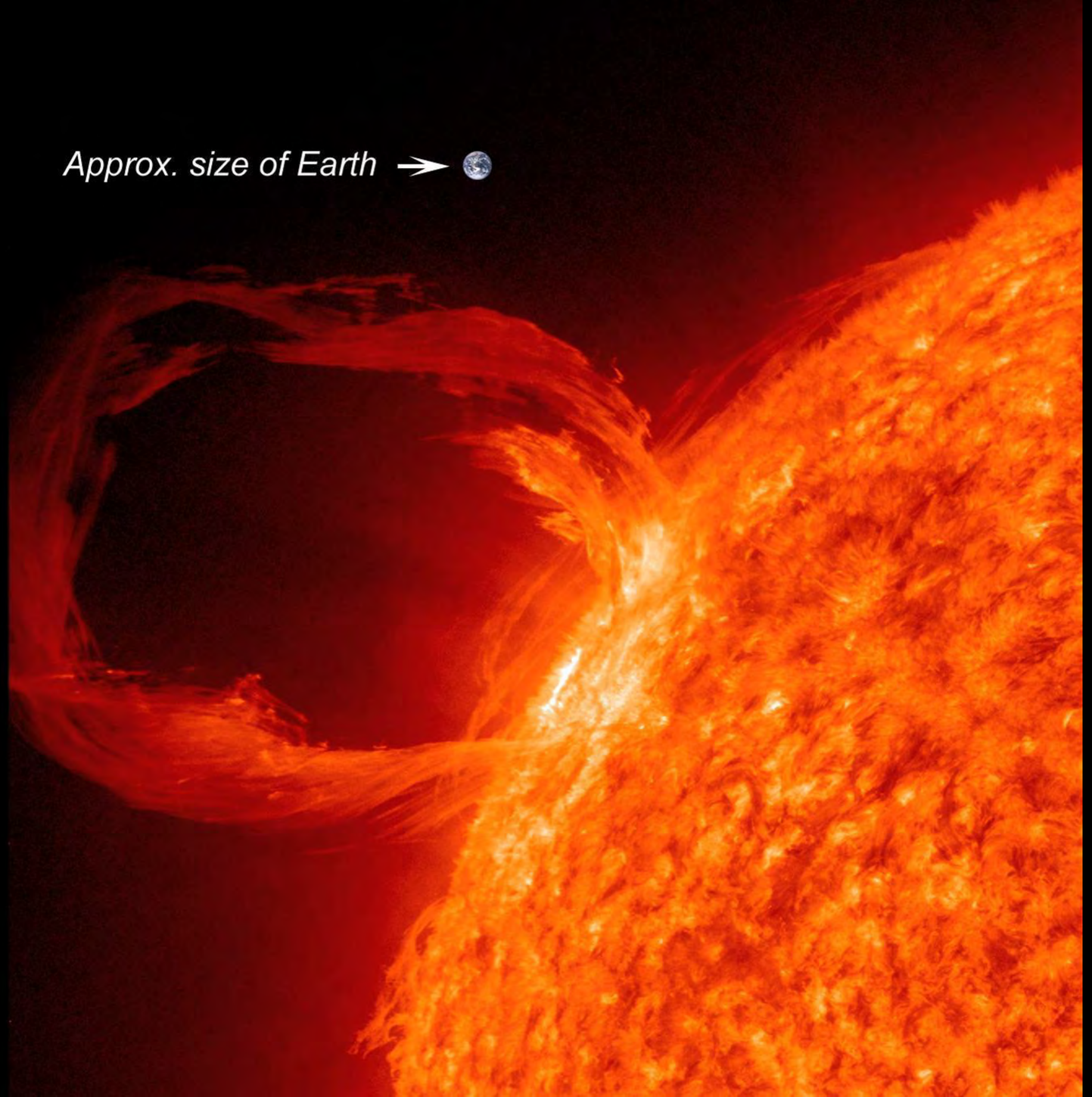
- The solar wind exists because the gases in the corona are so hot and moving so rapidly that they cannot be held back by gravity.
- The Sun is losing ~1–2 million tons of material each second through the solar wind.
- This sounds like a lot, but it’s so small compared to the enormous mass of the Sun that it doesn’t affect it in a noticeable way.

Stellar wind from the star LL Orionis generating a bright arc (called a bow shock), about half a light-year across, as it collides with flowing material in the surrounding Orion Nebula.
Credits: NASA

The Auroras, or polar light, result from charged particles in the solar wind interacting with Earth's magnetic fields
Credits: Moyan Brenn

The Sun

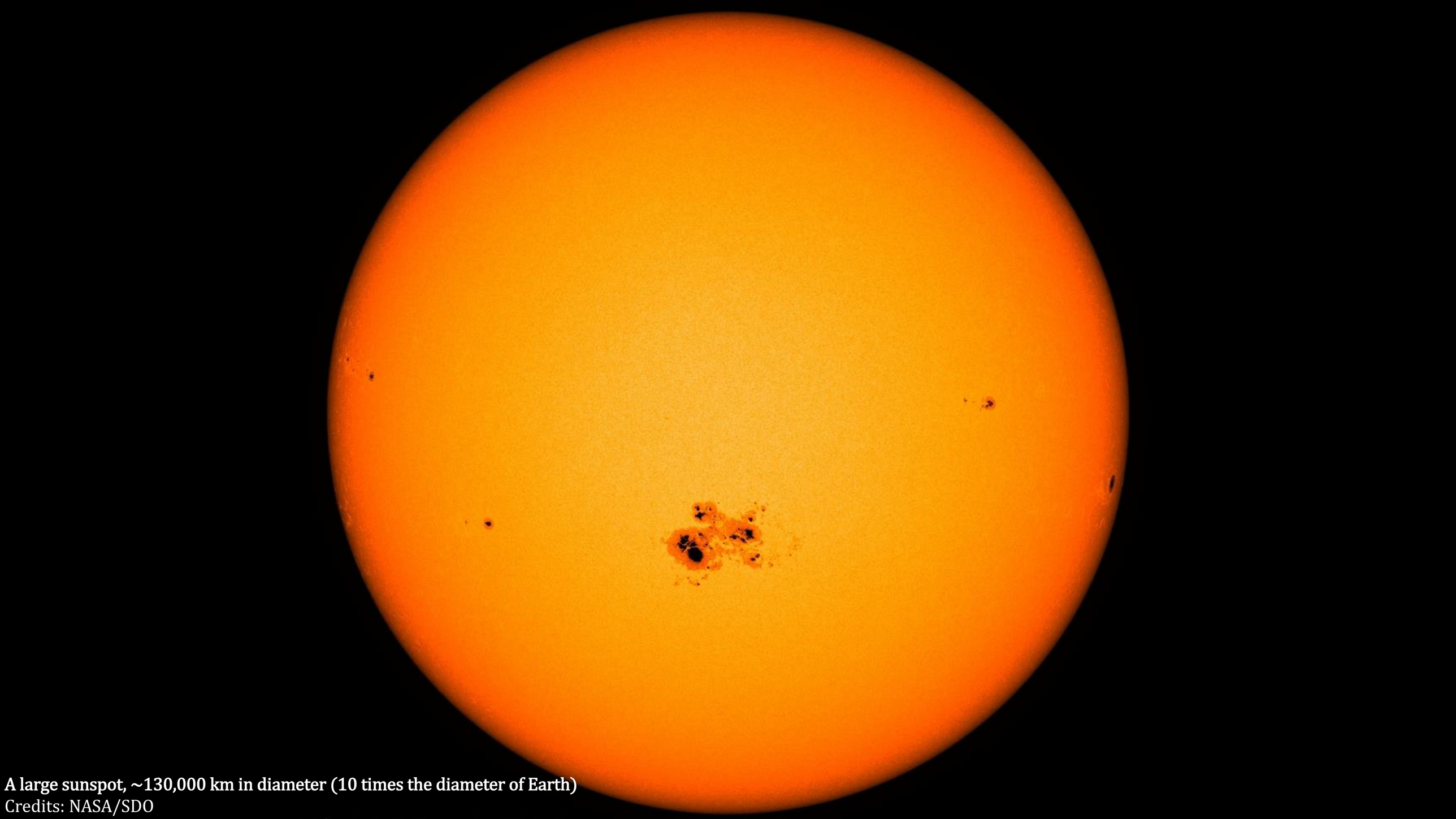
- Prominences are large and bright eruptions from the surface of the Sun, often in the shape of a loop.
- They can extend over thousands of km, sometimes hundreds of thousands.



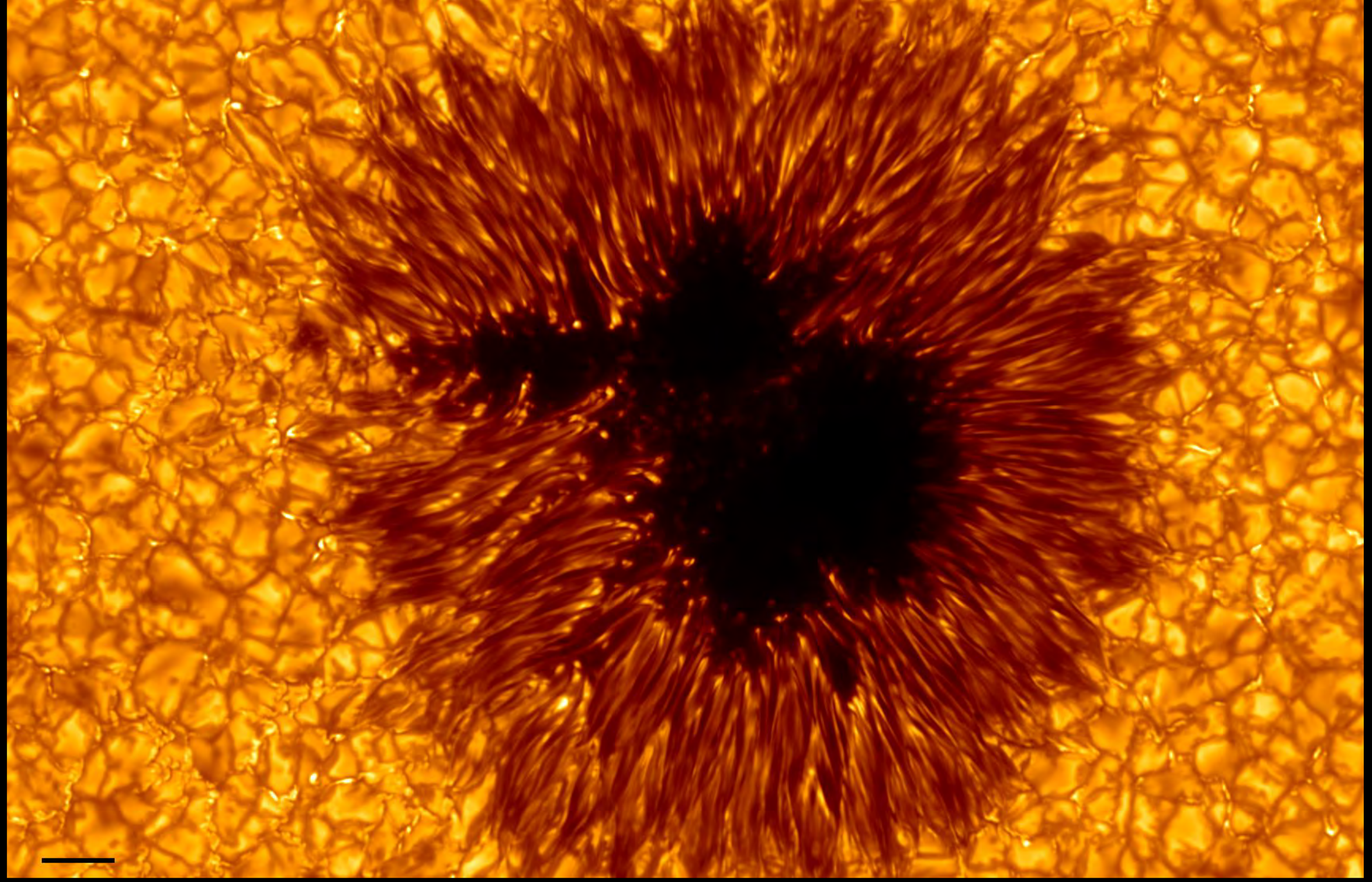
A solar prominence
Credits: NASA/SDO

The Sun

- Sunspots are dark “spots” on the Sun’s photosphere. They are places where the magnetic field is stronger.
- This inhibits heat transport from the solar interior to the surface. This means sunspots are colder, and hence appear darker.
- The central and darkest part of the sunspot is called the umbra. It is where the magnetic field is the strongest.
- The outer and brighter part is called the penumbra.
- The temperature of the umbra (~3,000-4,500 K) is much colder than the penumbra and the surrounding regions (~5,800 K).



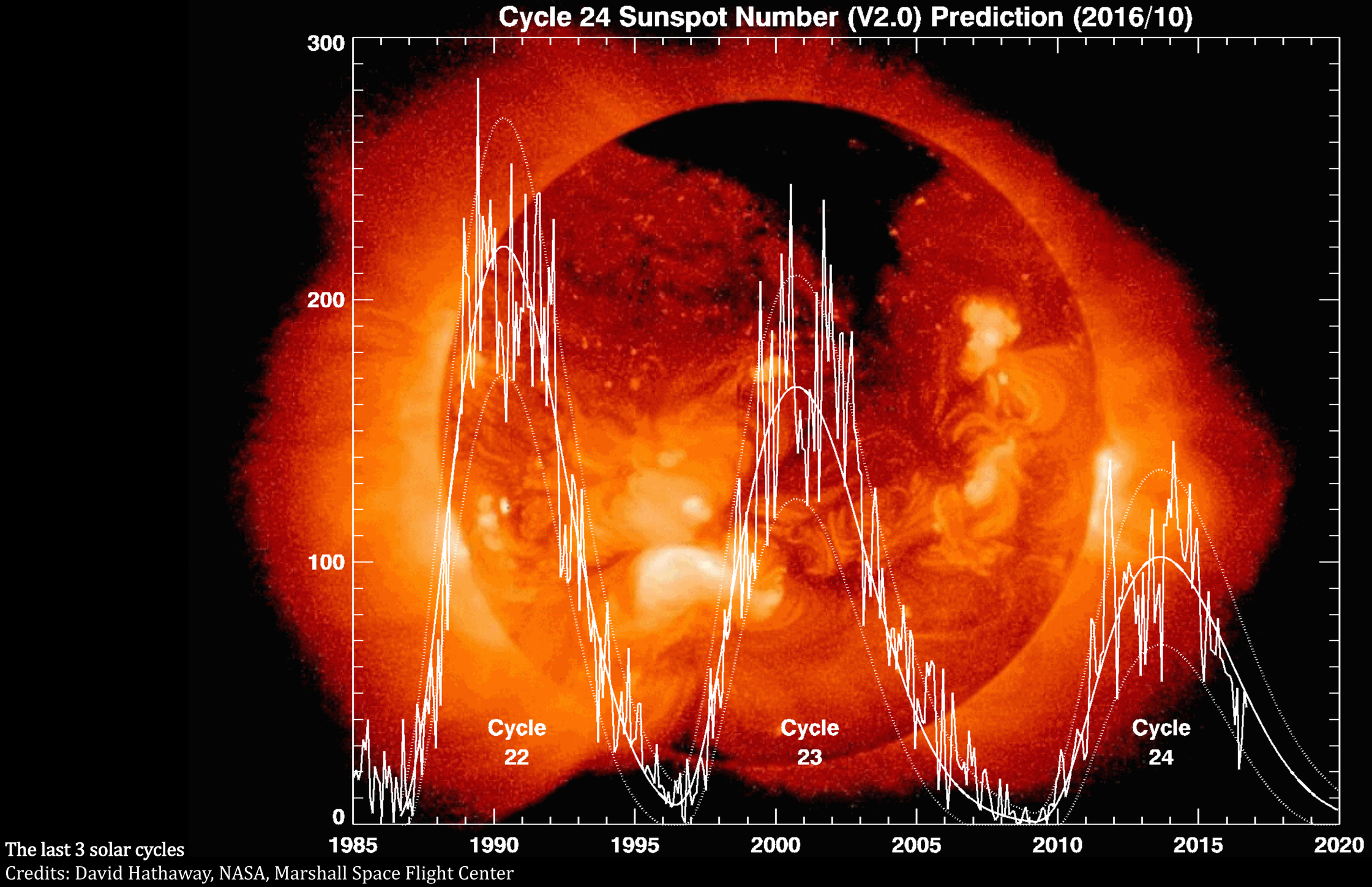
A large sunspot, ~130,000 km in diameter (10 times the diameter of Earth)
Credits: NASA/SDO



A sunspot observed by the Swedish Solar Telescope. The black line on the lower left is 2,500 km long.
Credits: Luc Rouppe van der Voort and Shahin Jafarzadeh

The Sun

- Many solar phenomena change periodically over ~11 years on average. This is called the solar cycle (or the sunspot cycle).
- During a solar cycle, the number of sunspots observed on the Sun's surface varies.
- A solar maximum/minimum is the time with most/least sunspots.
- Each solar cycle starts and ends with a solar minimum.
- We are currently (2022) in cycle 25, which began December 2019 and is expected to end around 2030.
- The previous cycle, number 24, started in January 2008.



The last 3 solar cycles

Credits: David Hathaway, NASA, Marshall Space Flight Center

The Sun

- Several other phenomena vary during a solar cycle.
- A solar flare is a rapid eruption lasting minutes to hours and releasing an enormous amount of energy.
- Near solar maximum, solar flares occur several times per day. Near solar minimum, they can occur less than once per week.
- More powerful flares are less frequent than weaker ones.

A solar flare bursts from the sun on August 9, 2011, as seen by NASA's Solar Dynamics Observatory (SDO) satellite.
Credits: NASA/Goddard Space Flight Center; video URL: https://svs.gsfc.nasa.gov/vis/a010000/a010800/a010833/

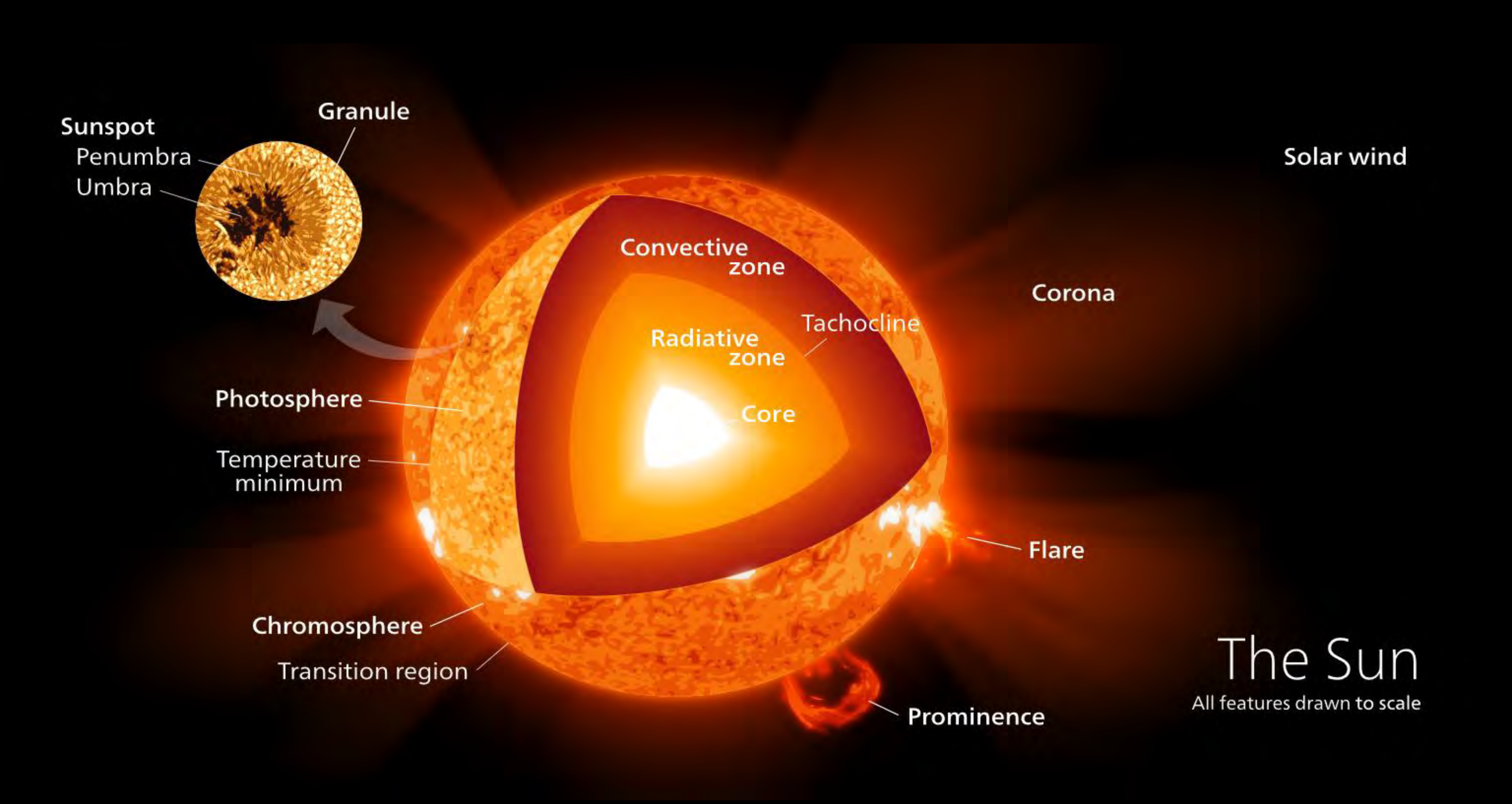
The Sun

- A coronal mass ejection (CME) is a massive burst of solar wind and magnetic fields rising above the solar corona.
- The Sun produces 3 CMEs every day during a solar maximum, but only 1 CME every 5 days during a solar minimum.
- CMEs are often associated with solar flares, but the exact relationship is not understood.
- Some CMEs can reach Earth and even damage electrical power grids (but this only rarely happens).

Video

- This video shows a coronal mass ejection recorded by the Solar Dynamics Observatory on June 18, 2015.
- The video is available at this URL:

https://youtu.be/icitZubDmFI



Layers of the Sun
Credits: Kelvinsong (Wikipedia)

The Sun

- The radius of the Sun (at the Equator) is $\sim 696{,}000$ km.
  - This is called the solar radius and denoted $R_\odot$.
  - It is 109 times the radius of Earth.
- The mass of the Sun is $\sim 2 \times 10^{30}$ kg.
  - This is called the solar mass and denoted $M_\odot$.
  - It is 333,000 times the mass of Earth.
- The average density of the Sun is ~ 1400 kg/m^3.
  - It is about 1/4 of the average density of Earth.

Video

- I will show a video with some nice animations and illustration of the composition of the Sun and relevant phenomena from National Geographic.
- The video is available at this URL:

https://youtu.be/2HoTK_Gqi2Q

Conclusions

- In this lecture, we learned about the Sun, the star at the center of our solar system.
- The Sun isn't just a yellow ball in the sky. There's a lot going on there, both inside and outside!

- Reading: OpenStax Astronomy, chapter 15.
- Exercises: Practice questions will be posted on Teams.