AFG-216 - Introduction to the Sun

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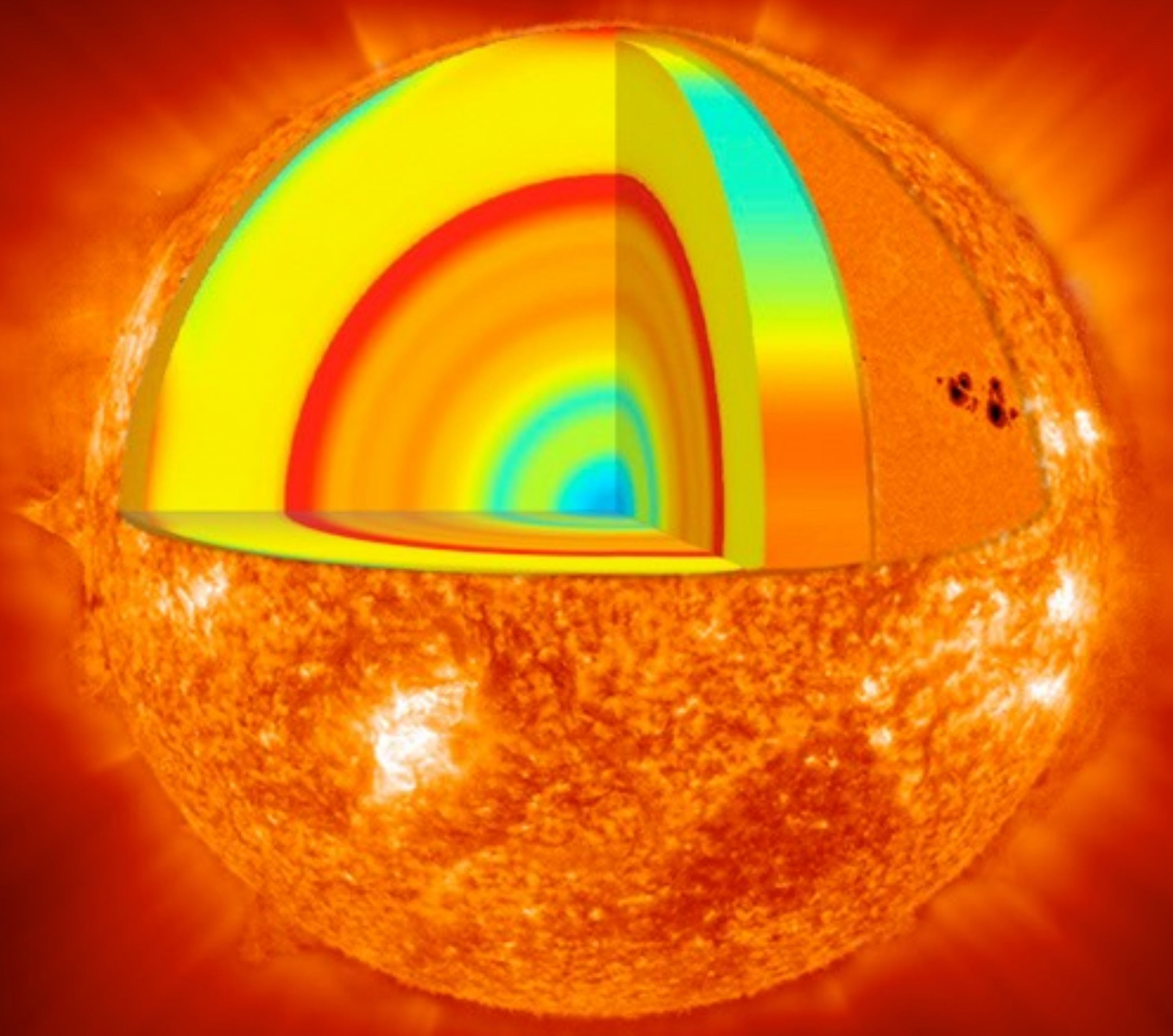
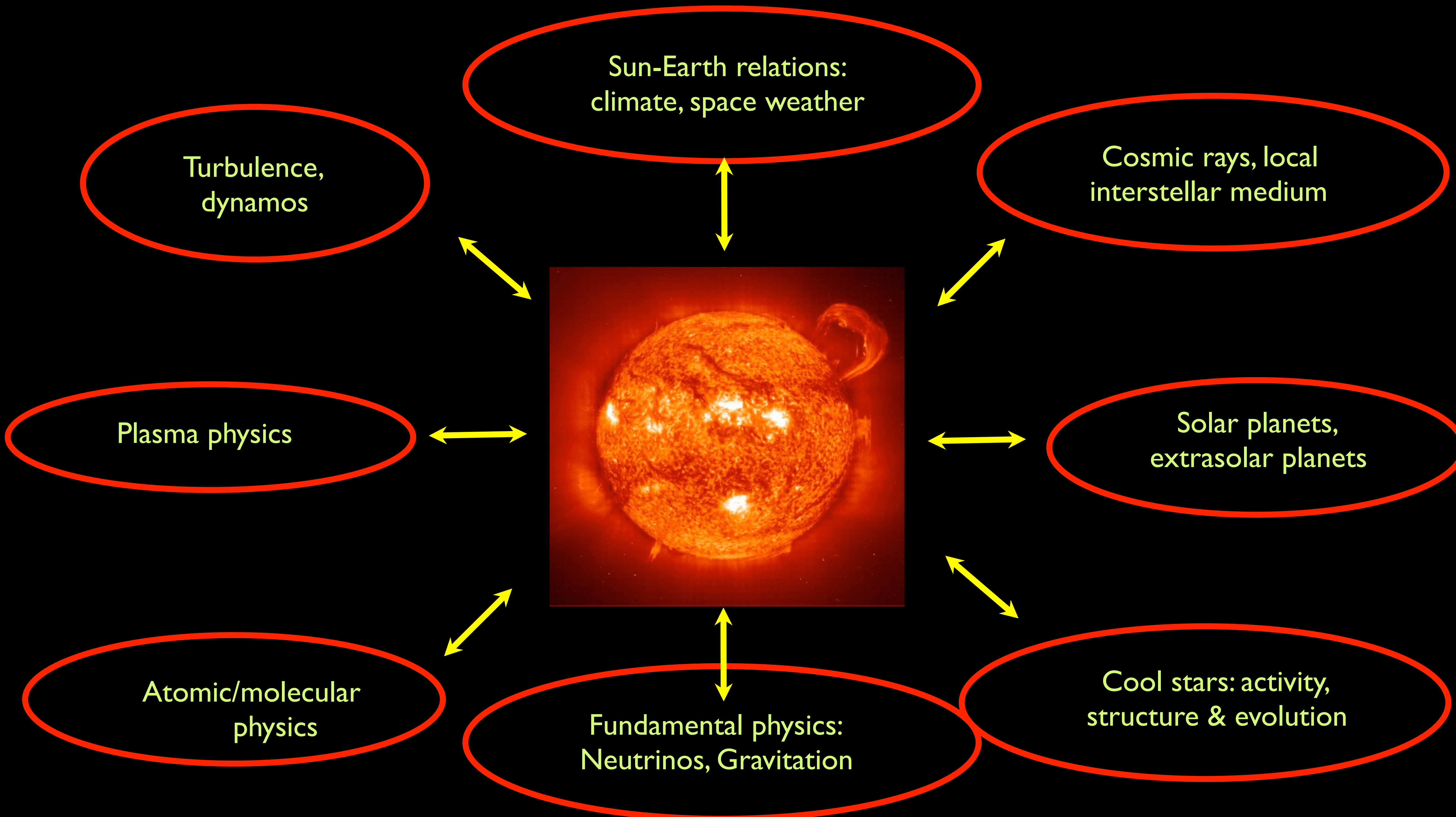
Norwegian Space Centre/UNIS



The Sun

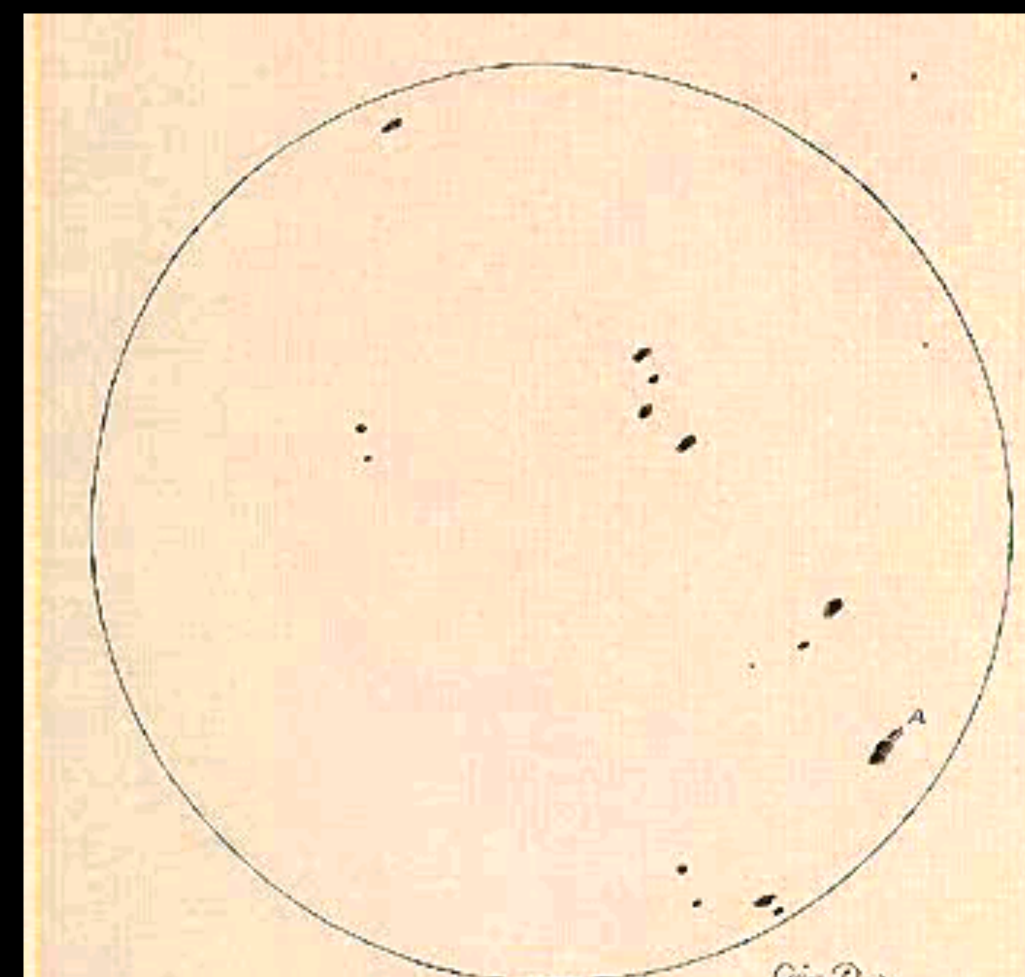
- The Sun is a normal star: middle aged (4.5 Gyr) main sequence star of spectral type G2
- The Sun is a special star: it is the only star on which we can resolve the spatial scales on which fundamental processes take place.
- The Sun is a special star: it provides almost all the energy to the Earth
- The Sun is a special star: it provides us with a unique laboratory in which to learn about various branches of physics.

Solar Physics in Relation to Other Fields



Early Western science

- Aristotle (300 B.C.) -- believed that the Earth was the center of the universe
- Ptolemy (150 A.D.) -- concluded that Earth was the center of the solar system; the planets revolved around it--this belief lasted through the Middle Ages
- <u>**Copernicus (1500s)**</u> -- the father of modern astronomy, first to proclaim that the Sun was at the center of the solar system, a major advance in astronomical thinking
- <u>**Galileo (1600s)**</u> -- agreed with Copernicus and was one of the first scientists to systematically observe and keep records of the Sun and sunspots. He correctly identified sunspots as part of the Sun and determined the Sun's rotation.



More modern solar science

- Sir Isaac Newton (late 1600s) - concluded that stars were tremendously far away and that they gave light like the Sun
- William Herschel (1780s) – infrared light
- **Heinrich Schwabe (1843)** - determined the appearance of sunspot cycles
- Robert Bunsen (1860s) - invented the spectroscope to determine the elements found in the Sun
- George Hale (1908) - discovered the magnetic fields of sunspots
- Albert Einstein (1920s) - proposed that sunlight was made of particles (or had particle characteristics). No one believed himself until it was proven 10 years later.

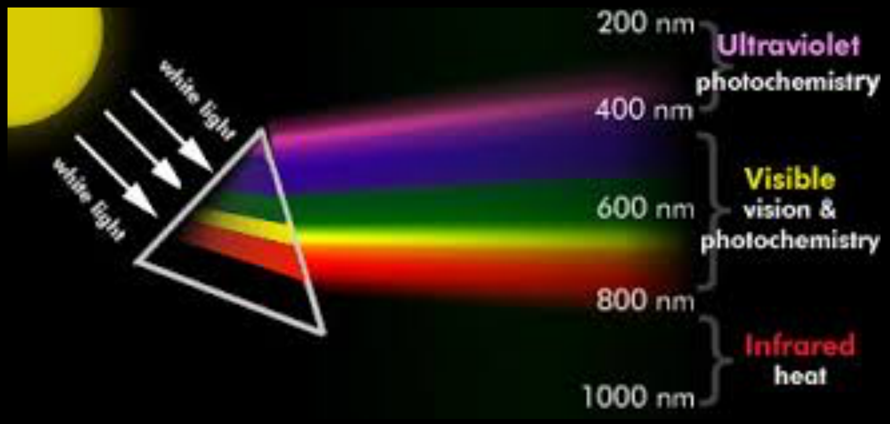
Sir Isaac Newton

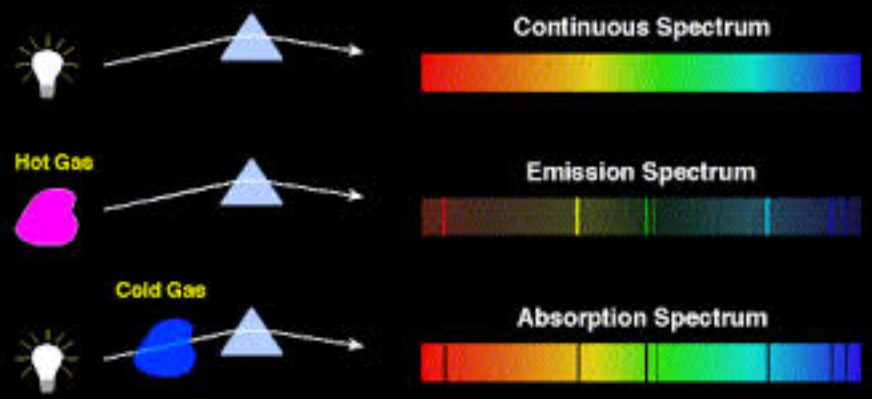
William Herschel

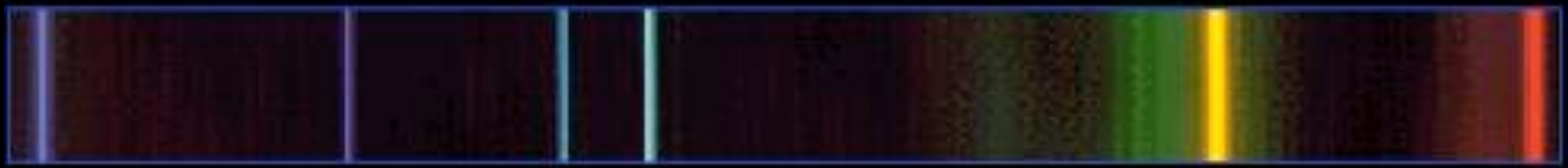
Albert Einstein

Solar Spectrum

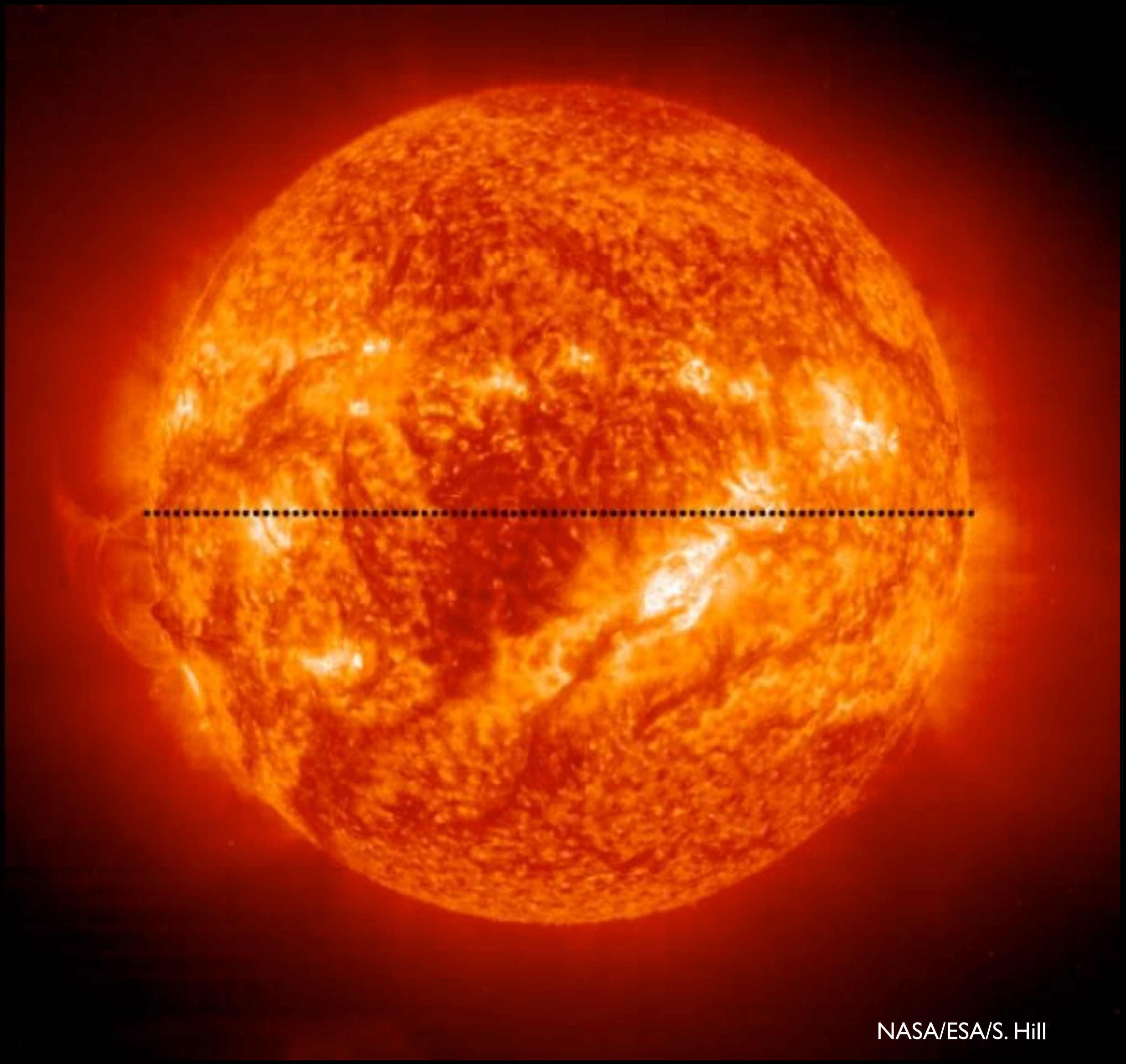
- Huygens (1690): light travels as waves, just likes ocean waves
- Sir Isaac Newton (1704): light from the Sun can be split into a rainbow by shining it through a prism.
- Bunsen and Kirchhoff: devised the first spectroscope to measure the colour of light given off by elements heated by a flame
  - They found that each kind of atom has a special "fingerprint" I.e. a unique set of spectral lines when the electrons are excited at high temperatures
- In 1868 during a solar eclipse Janssen observed the solar spectrum and found "fingerprints" (spectral lines) he did not recognise.
  - This new element was named HELIUM after Helios, the Greek word for Sun







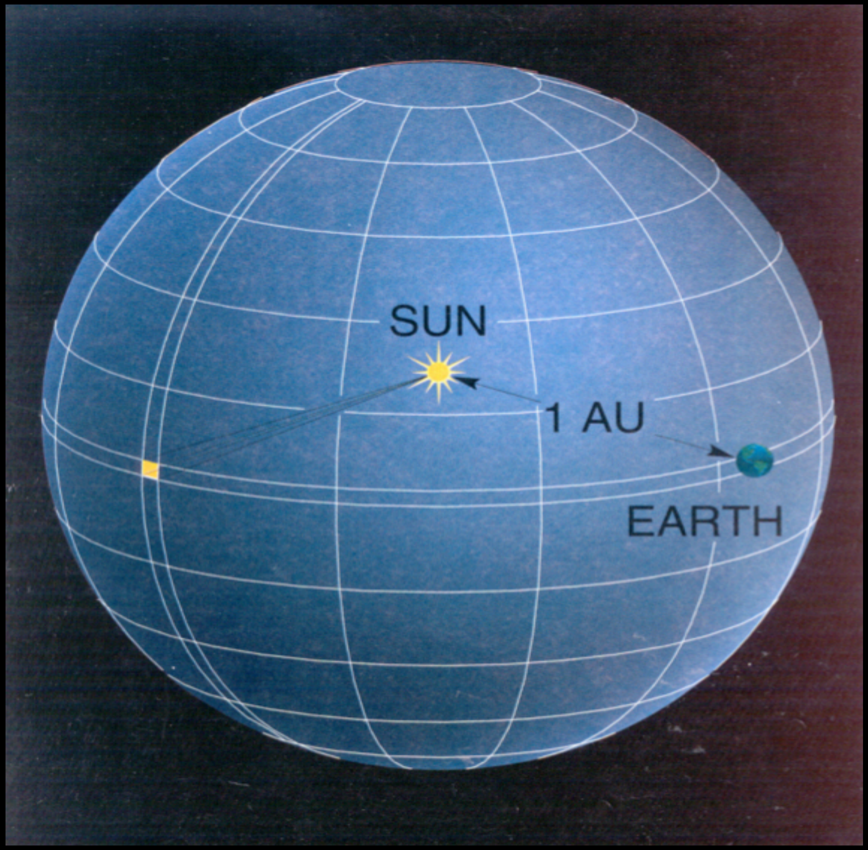
The Sun



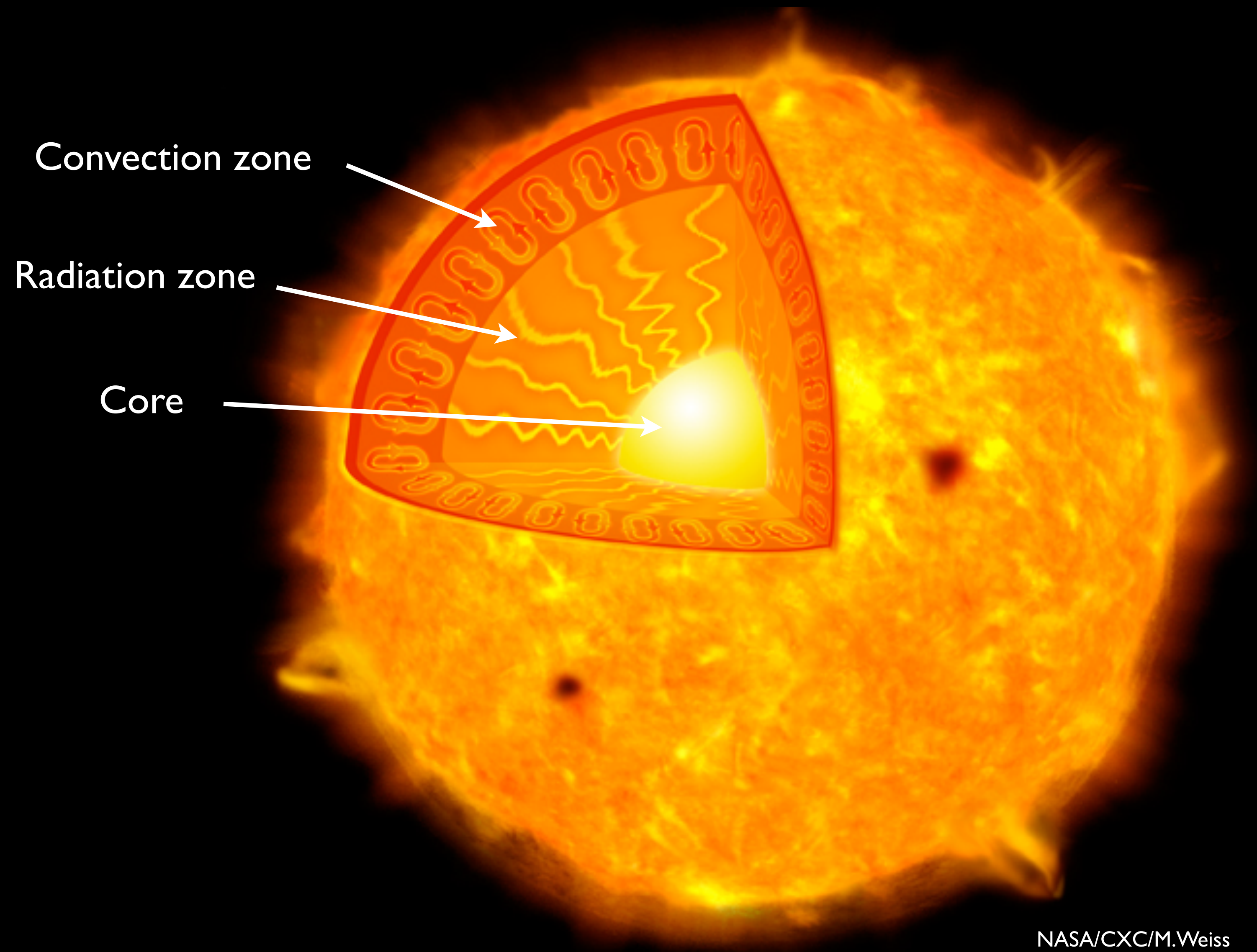
- The Sun is 333,400 times massive than the Earth.
- The Sun contain 99.86% of the total mass in the solar system
- The diameter is 109 times the Earth – 1.3 million Earths can fit inside the Sun
- Consist of 78% Hydrogen and 20% Helium and 2% other elements.

Energy from the Sun

- Energy production: 3.86×10^{26} watt (386 million billion billion watts)
  - Norwegian energy consumption over 600 million years!
- Even if only a small fraction of this energy hits the Earth it is far enough energy to cover the energy need of the entire world - if only we could extract it efficiently.
- The solar energy that hits the Earth in 1 minute could power the entire world in 1 year!



THE STRUCTURE OF THE SUN



The hot compact core of the Sun – where the energy is created – has a radius of about 175,000 km. Outside the core is a layer where the energy is transported by electromagnetic radiation or photons. This layer is called the radiation zone.

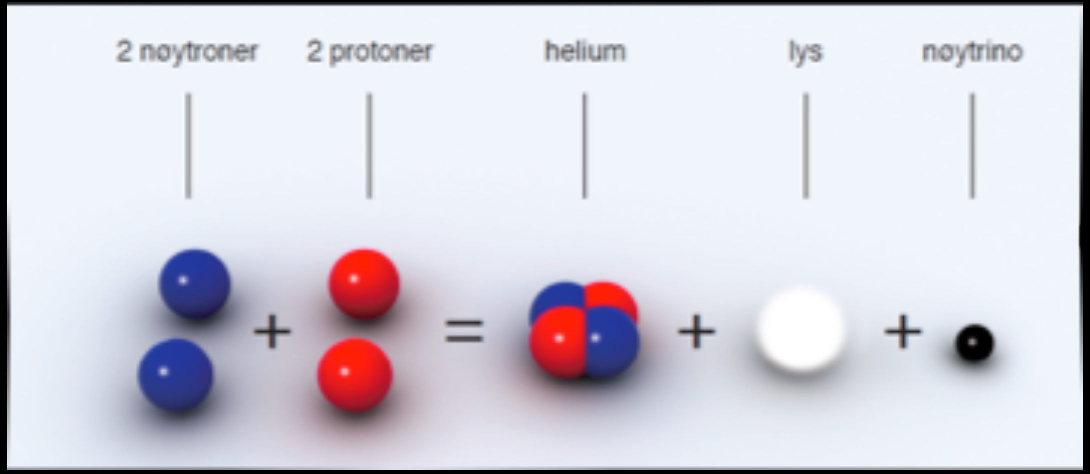
Further out we find the convection zone where the energy is transported as a turbulent churning motion similar to a pot of boiling soup.
The visible surface, the photosphere, is only about 400 km thick. Above the photosphere we find the chromosphere, a layer of thin hot gas extending to a few thousand kilometres. Above the chromosphere is the corona, the Sun´s outermost part of the solar atmosphere.

THE ENERGY PRODUCTION

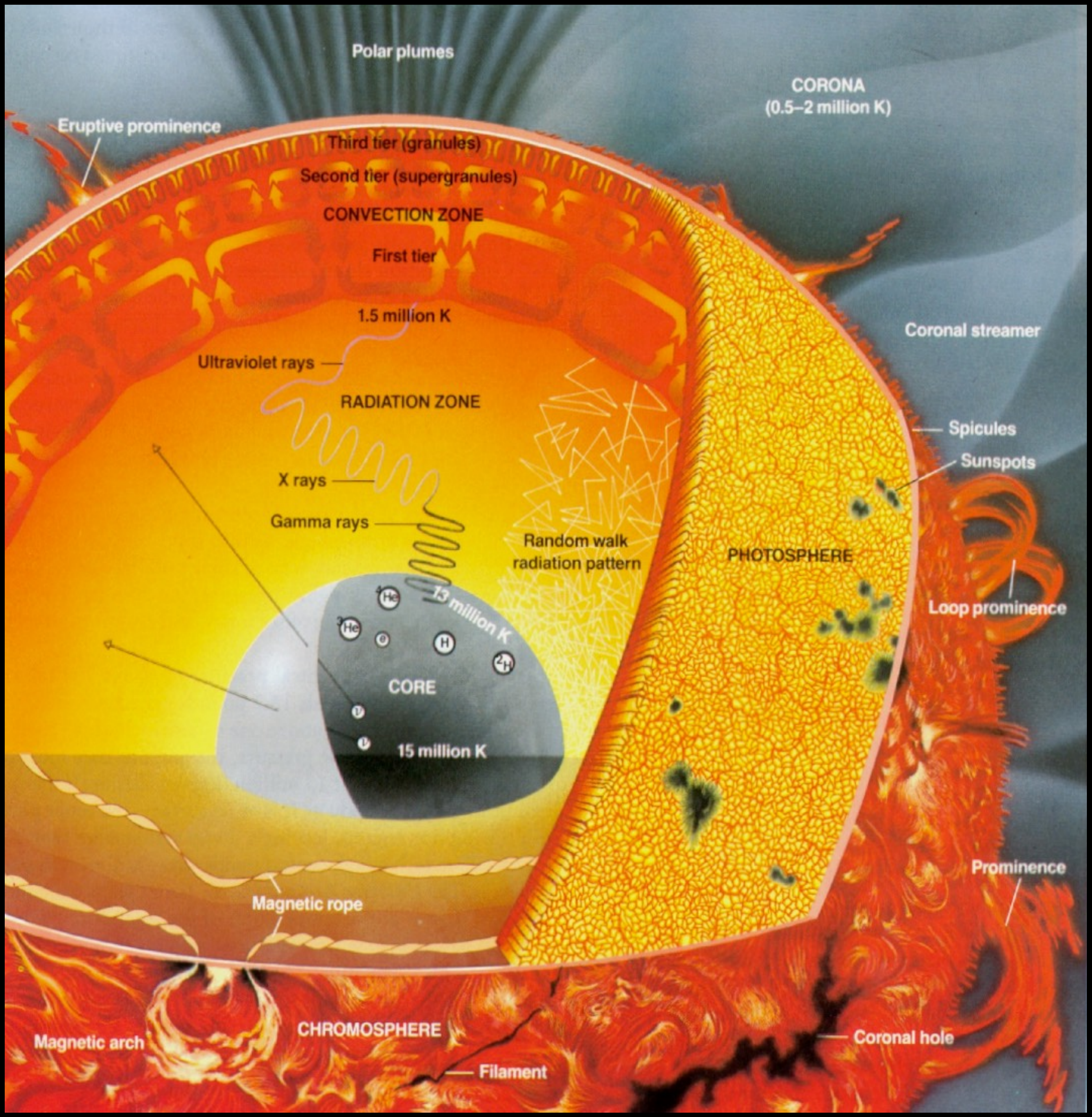
The conditions in the solar core are extreme and this area is kind of like a nuclear power plant. The temperature is over 15 million degrees C, and the enormous pressure is pushing the atoms very close together causing them to collide with each other all the time.

Sometimes hydrogen nucleus combines to form helium nucleus. In this process some of the mass is converted to light particles we call gamma rays. This is the energy that keeps the Sun shining. This process also creates particles called neutrinos.

Each second about 700 million tons of hydrogen is converted into helium, and about 4 million tons of mass is converted into radiation (gamma rays) and neutrinos. The question, is of course: will the Sun run out of hydrogen? Yes, but luckily the Sun has enough hydrogen to shine another 5 billion years.

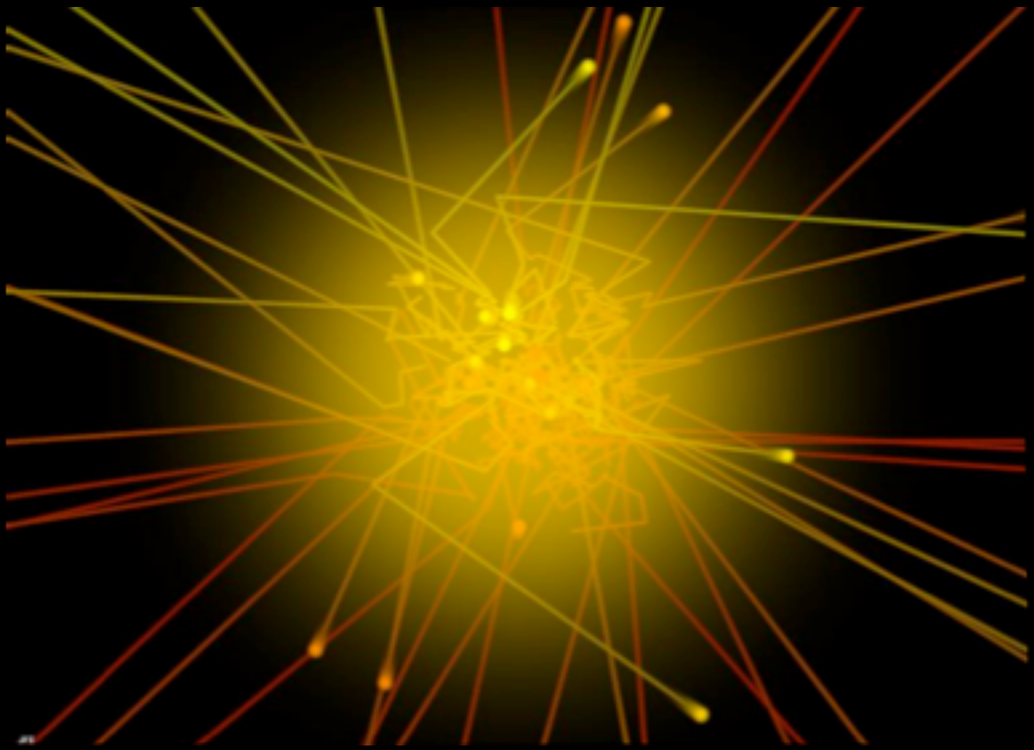


T.Abrahamsen/ARS

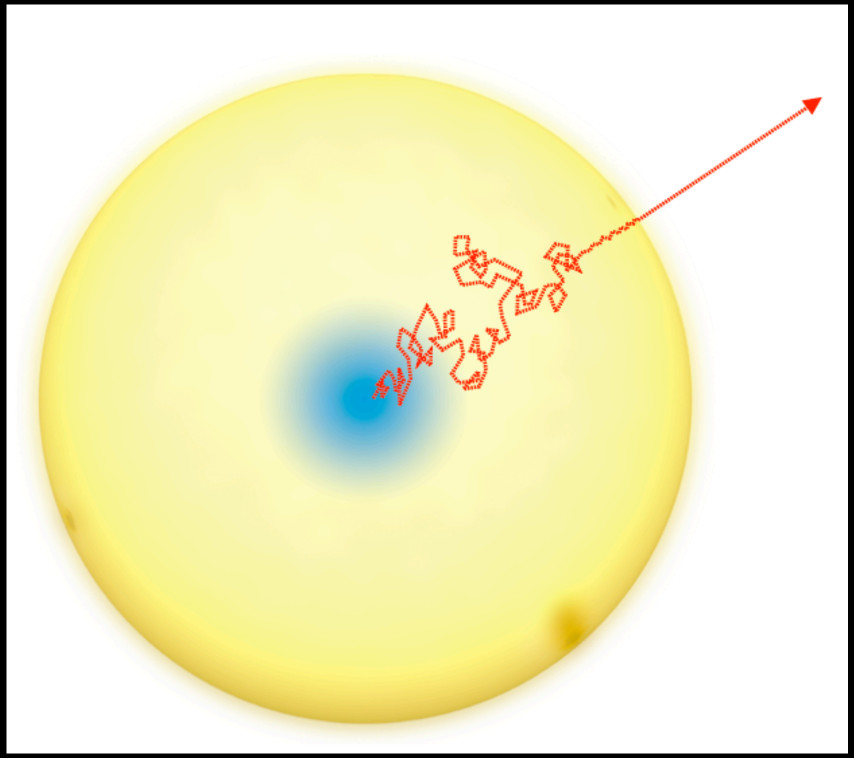


Friedman/NRL

THE JOURNEY OF LIGHT OUT OF THE SUN



Jean-Francois Colonna



T.Abrahamsen/ARS

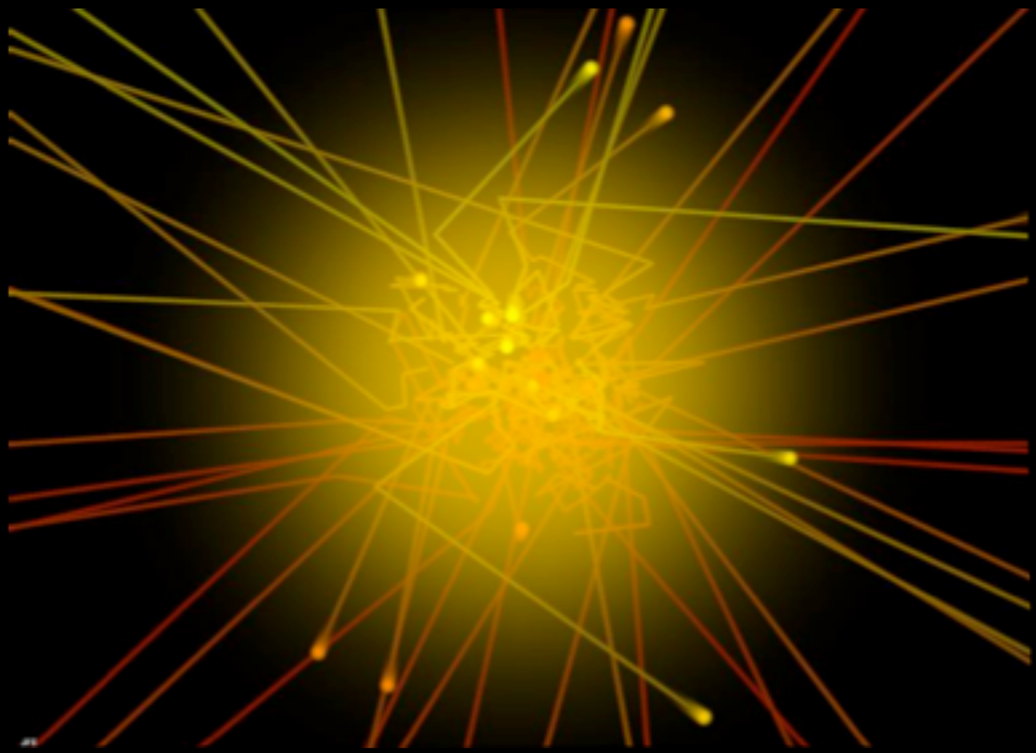
The nuclear reactions in the core of the Sun produces gamma rays. Gamma rays are electromagnetic radiation, just like microwaves, radio and light waves, which means they travel at the speed of light: 300,000 kilometers per second.

The sun has a radius of about 700,000 kilometers. So you could reasonably expect a gamma ray to get outside the sun about 2.3 seconds after it is created. But that doesn't happen.

In the core of the sun the protons and helium nuclei are so thick that an emitted gamma ray can't get very far before it is absorbed. When it crashes into a proton the result of the collision is a proton with extra energy. The proton gives up that extra energy by emitting another gamma ray photon. But this one could head in any direction.

The gamma-ray photons make their way through the particles in the sun, losing some energy along the way and finally making their way out of the sun as x-rays, infrared and visible light.

THE JOURNEY OF LIGHT OUT OF THE SUN



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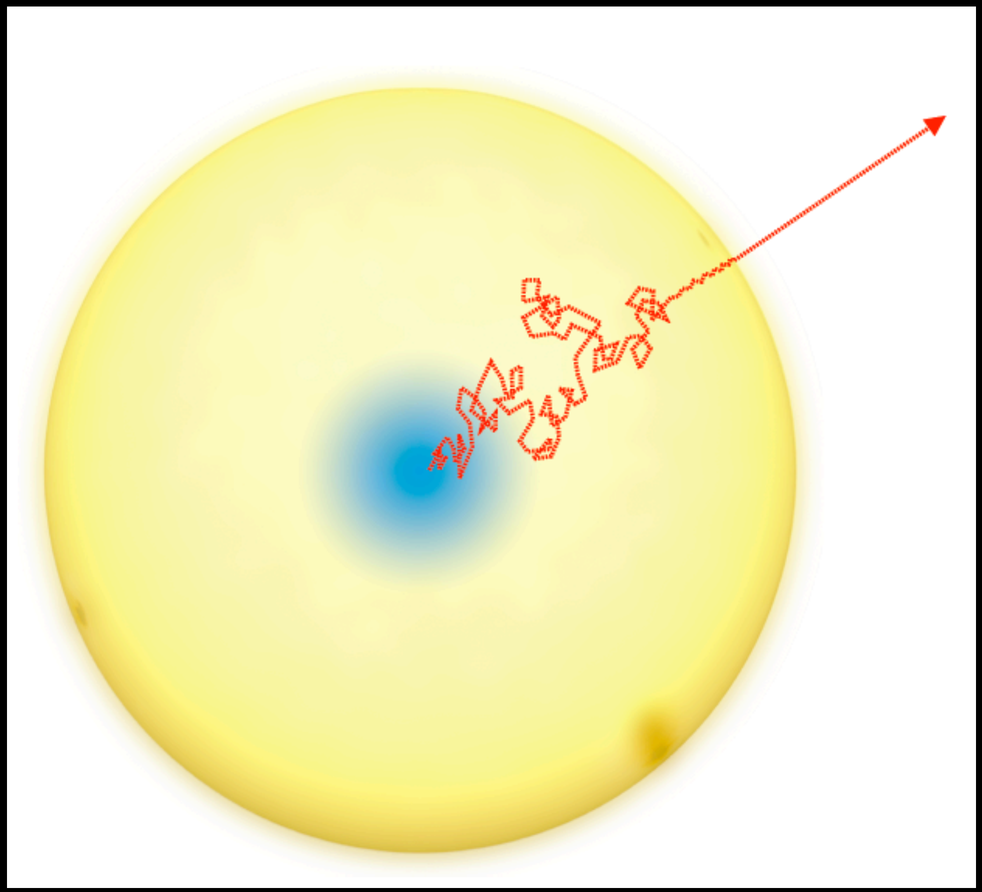


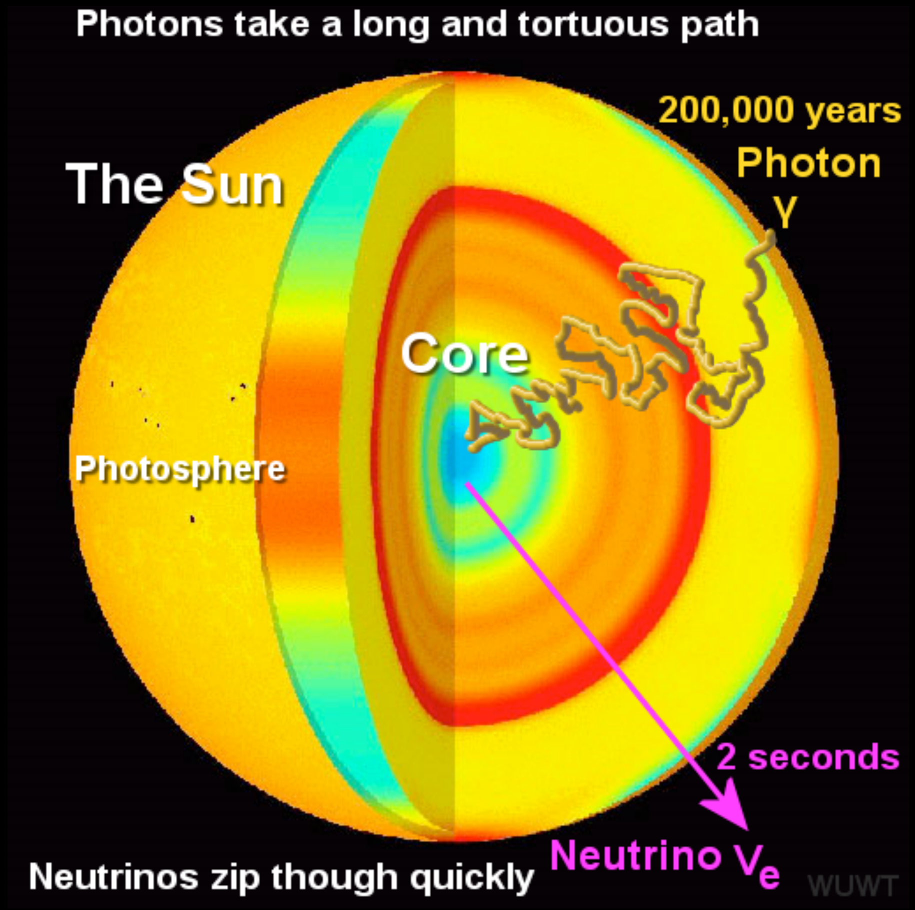
T.Abrahamsen/ARS

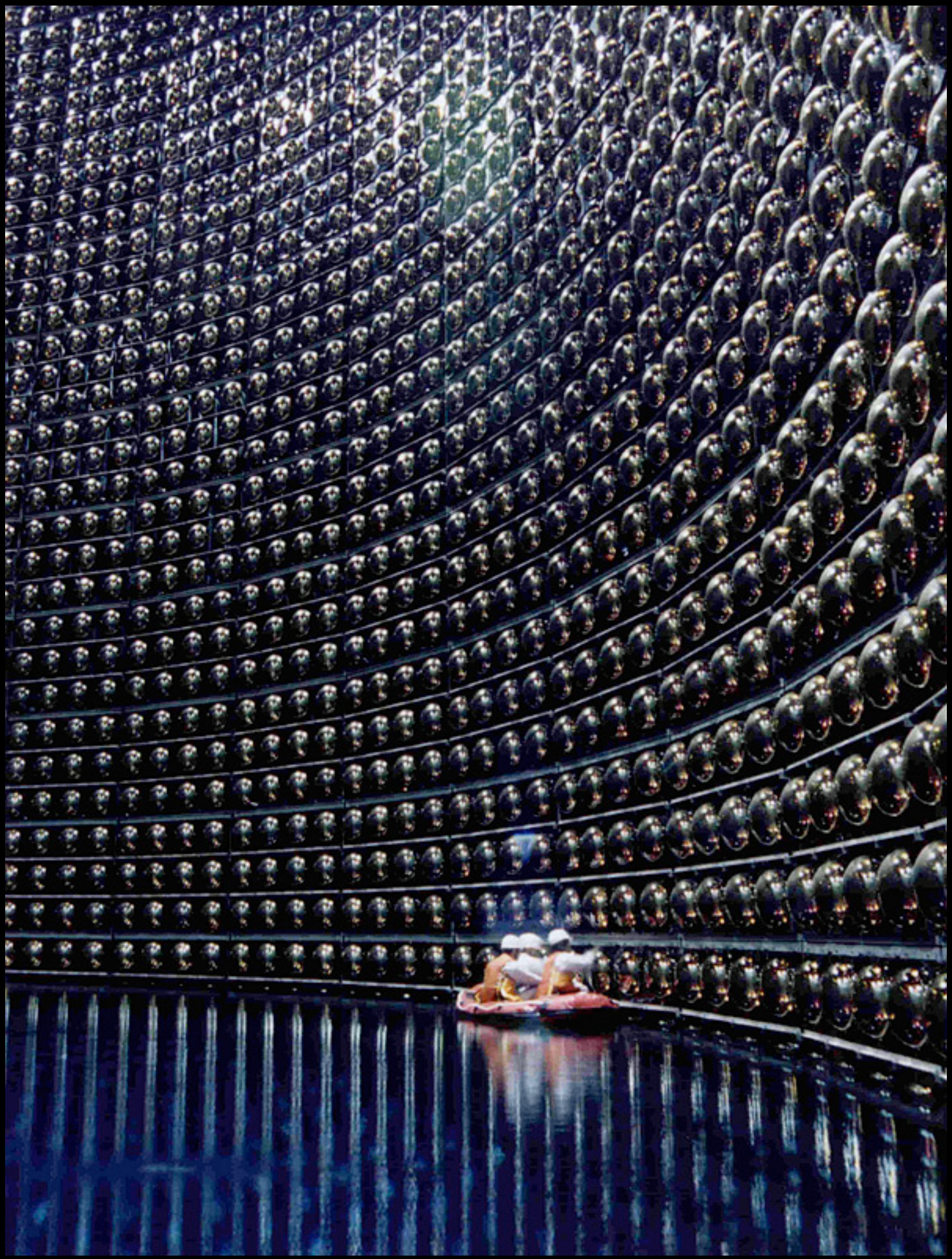
On its way out of the solar core the light particles collide with other atoms, which changes their directions all the time, like a ball in a pin ball game. In this way they zig-zag in a random pattern inside the radiation zone. It can take as much as 200,000 years before the light particles manage to push their way out of the radiation zone that reaches 2/3 of the way out of the Sun.

Outside this region the energy is transported up towards the surface by currents of hot gases. Here the gas bubbles up just like warm soup in a pan. Then, the light can escape freely out in space. Eight minute and 20 seconds later the light reaches the Earth and we feel the heat on our body. It’s odd to think that this is “old” energy that originated inside the Sun 200,000 years ago – when the Neanderthals walked the Earth.

Solar Neutrinos

- 30 billion neutrinons passes your fingernail each second
- Neutrino-detectors has measured about 1/3 of the expected number derived from solar models.
- This has been called the «Solar Neutrino problem»
- Was the temperature in the solar core much lover than 15 million C?
- Or does some of the neutrinos change identity?





Super- Kamiokande Neutrino Detector in Japan

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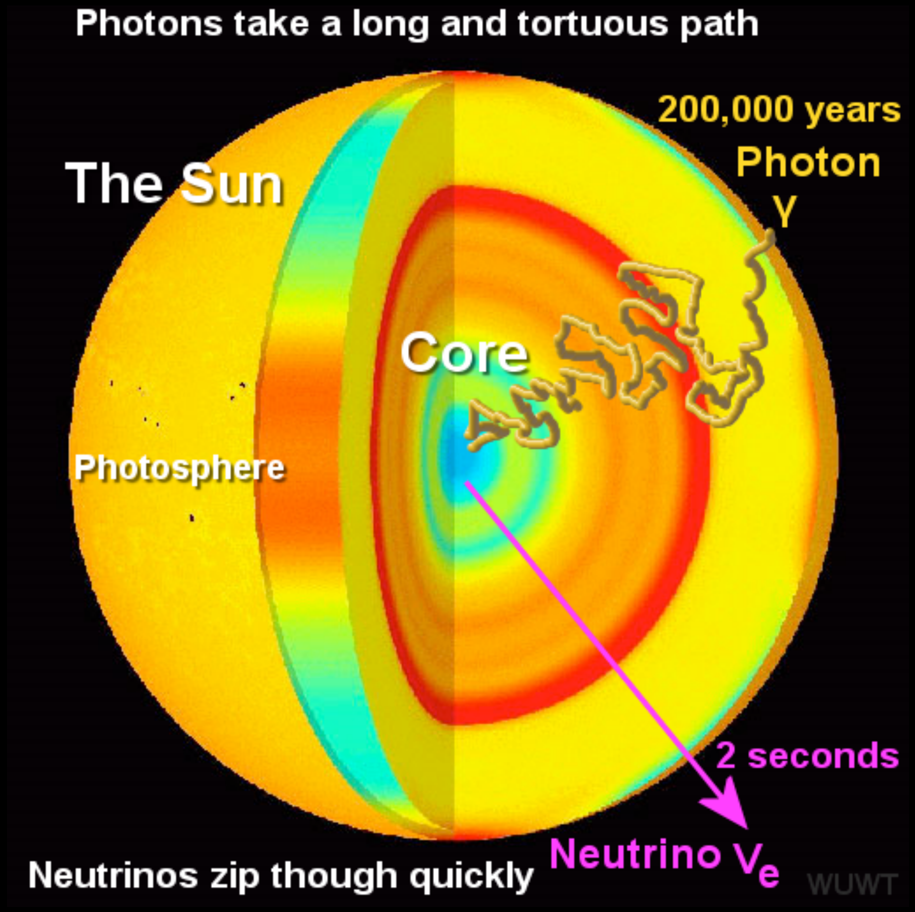
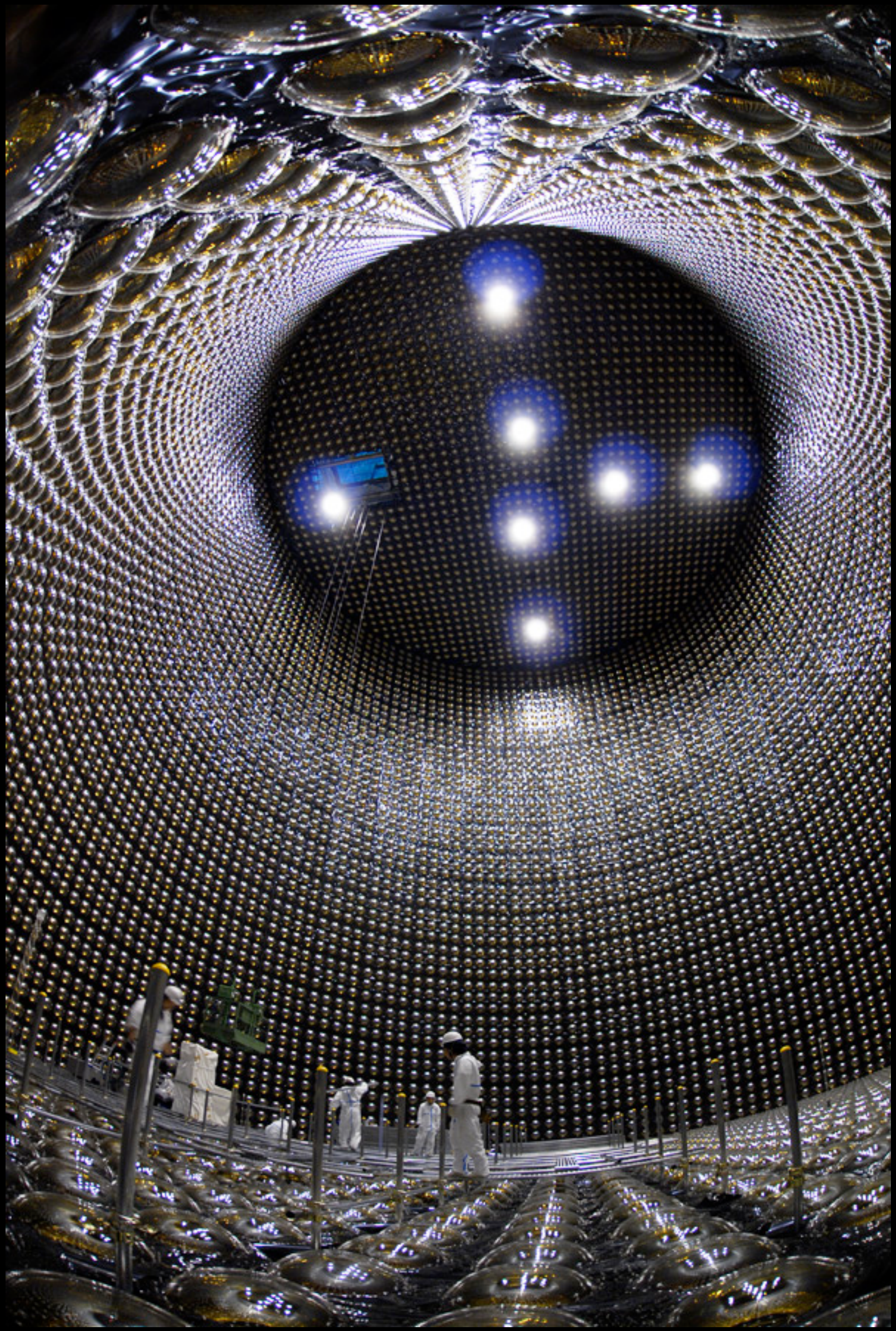


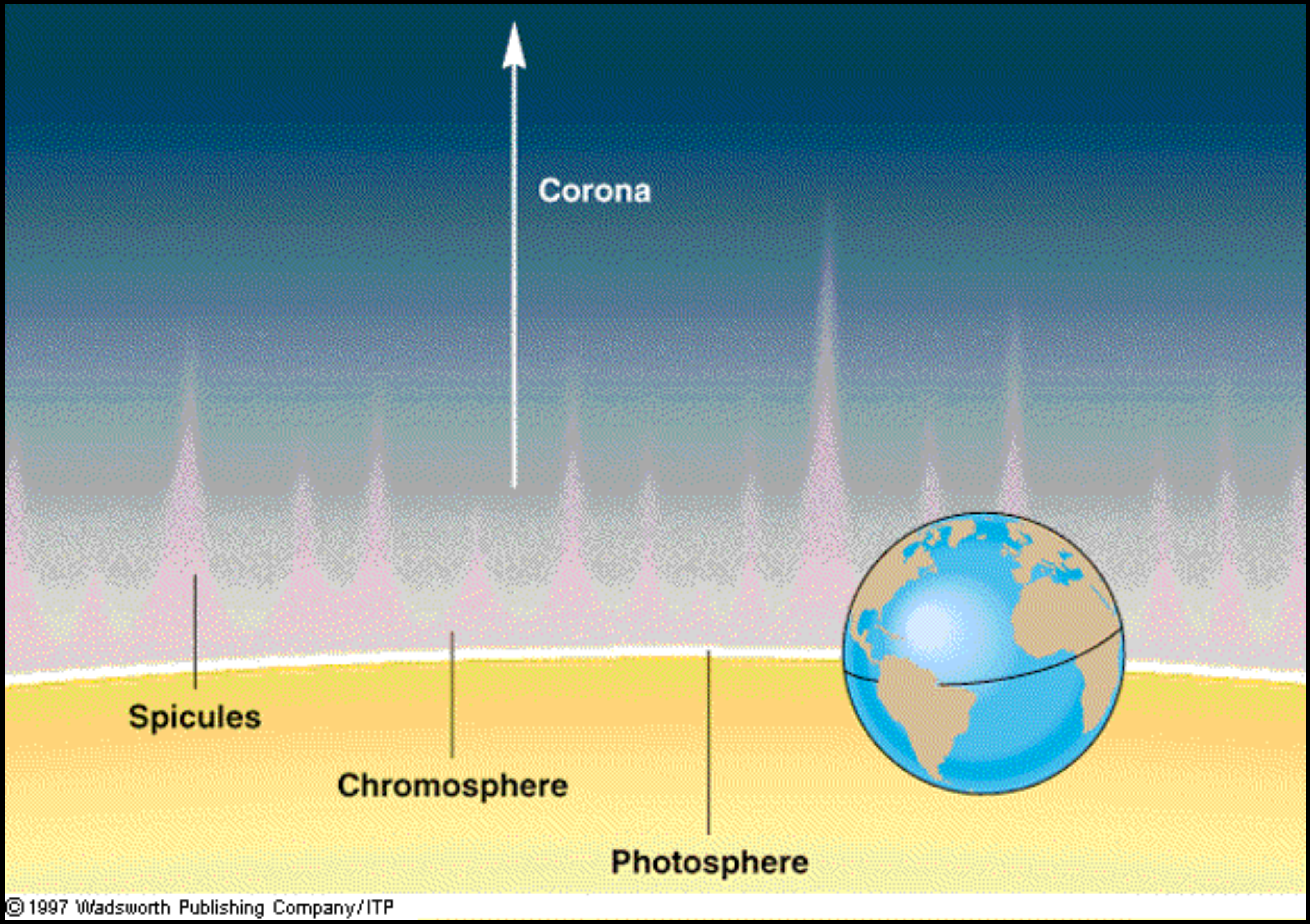


Super- Kamiokande Neutrino Detector in Japan 1000 m under ground, Ca 40 x 40 meter, 50,000 tons of ultra-pure water

The Sun’s atmosphere

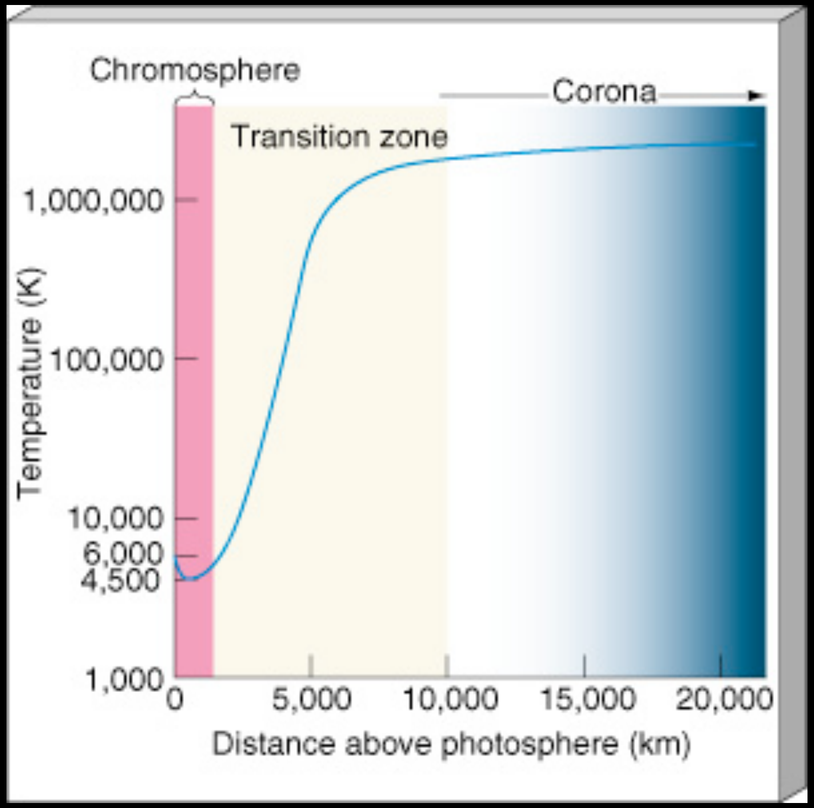
- The solar atmosphere is generally described as being composed of multiple layers, with the lowest layer being the photosphere, followed by the chromosphere, the transition region and the corona.

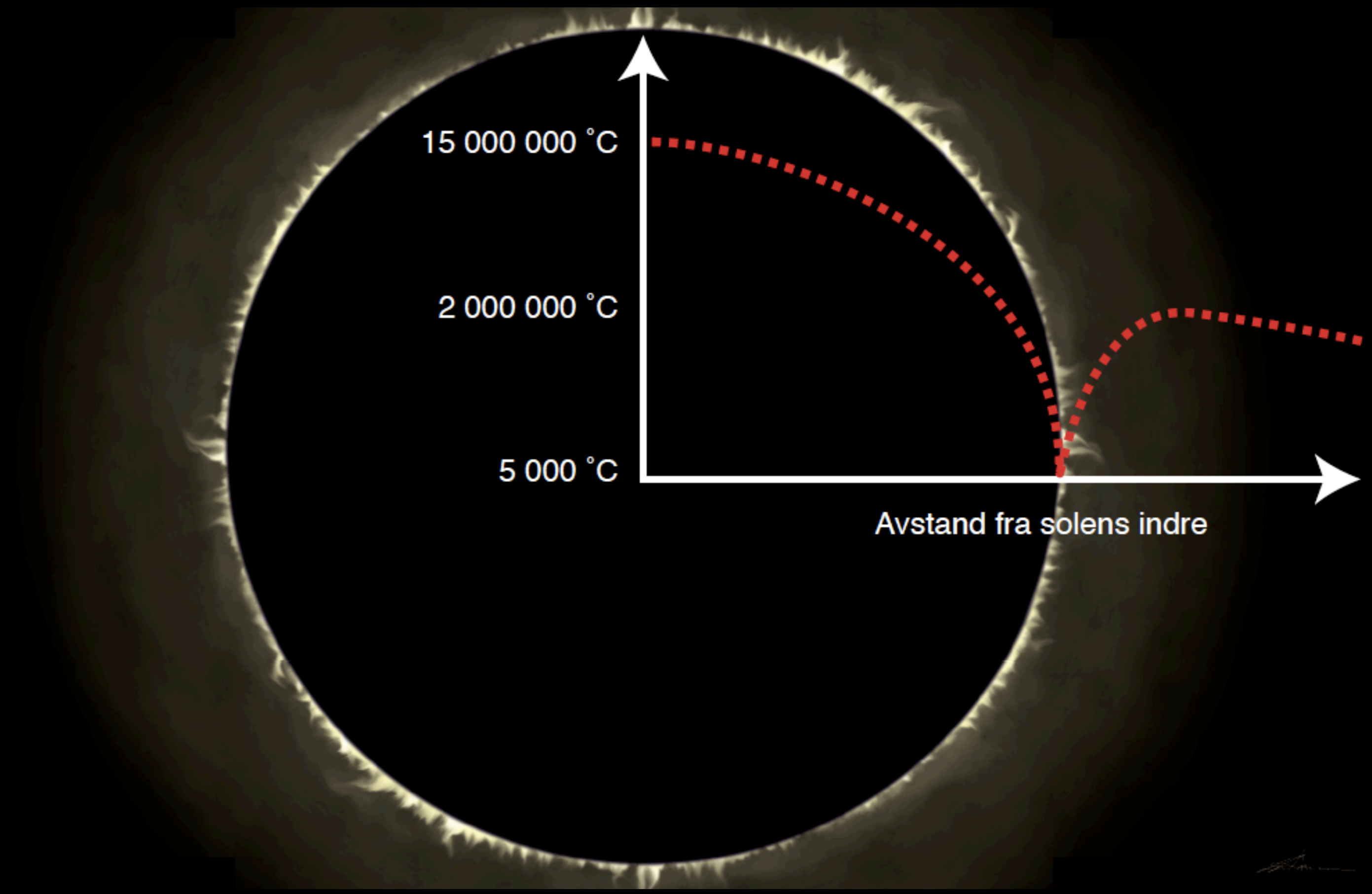
- In its simplest form it is modelled as a single component plane-parallel atmosphere.



The Sun's hot atmosphere

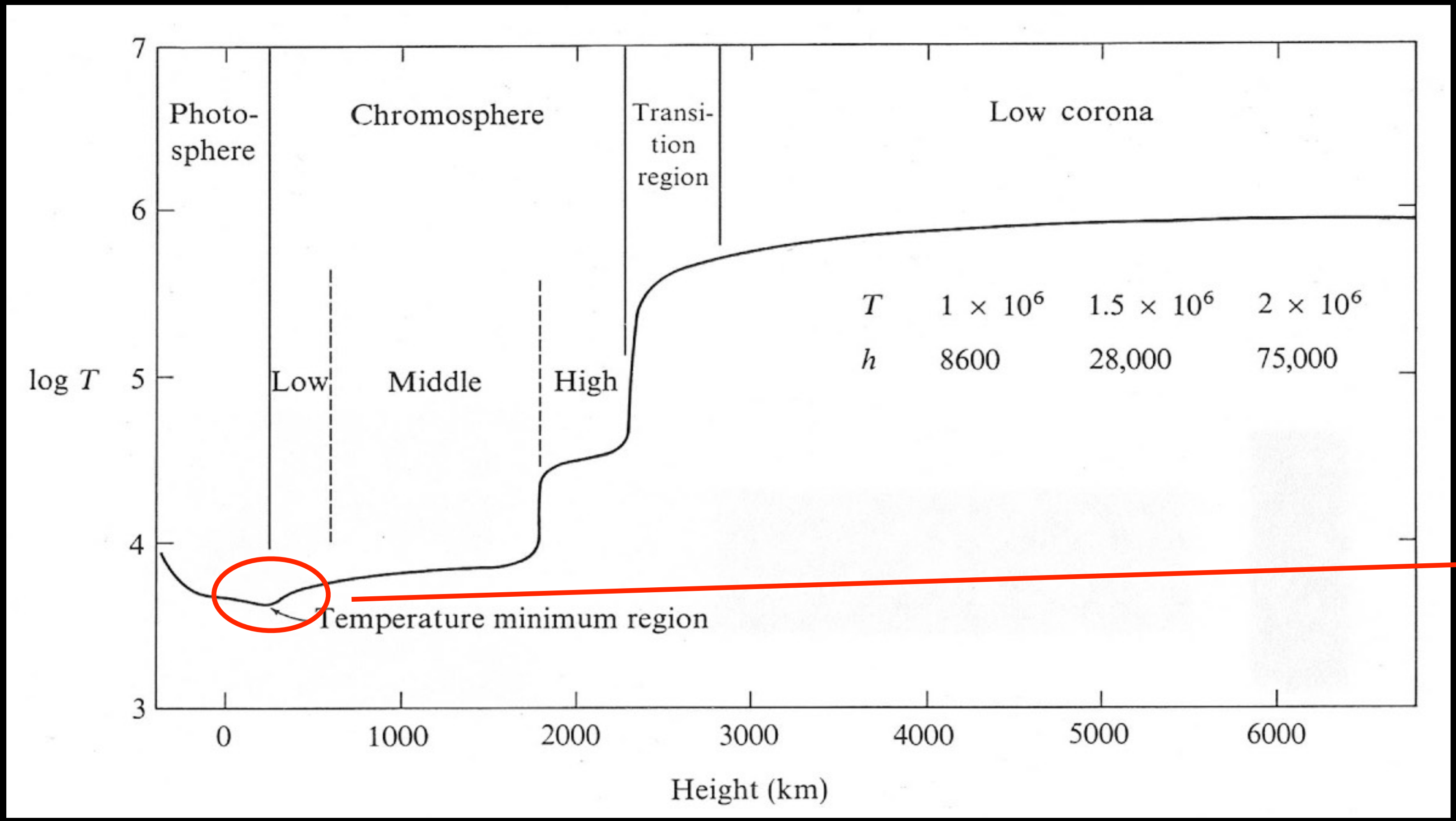
- Surprisingly the solar atmosphere is hotter than the surface/photosphere
- How can that be?

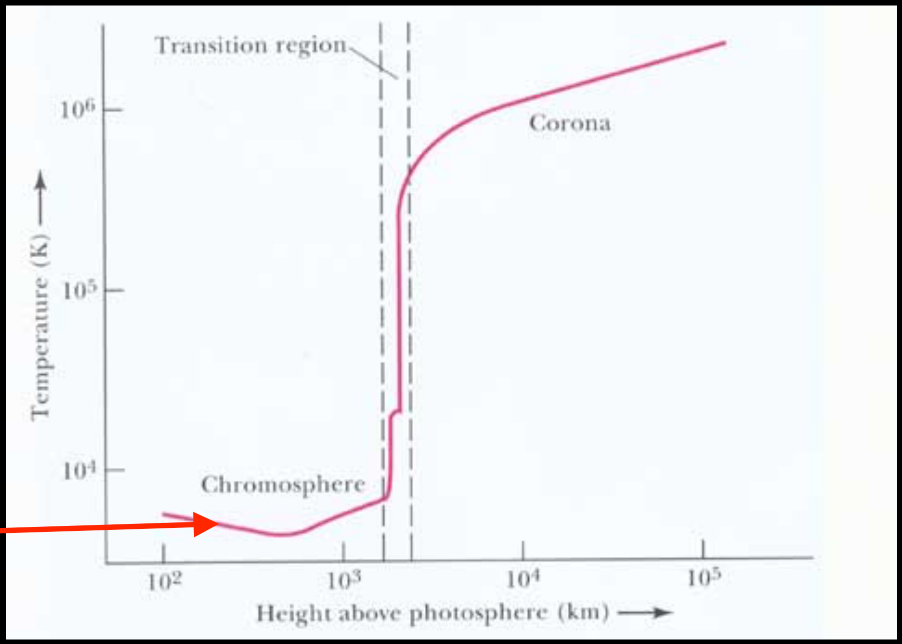




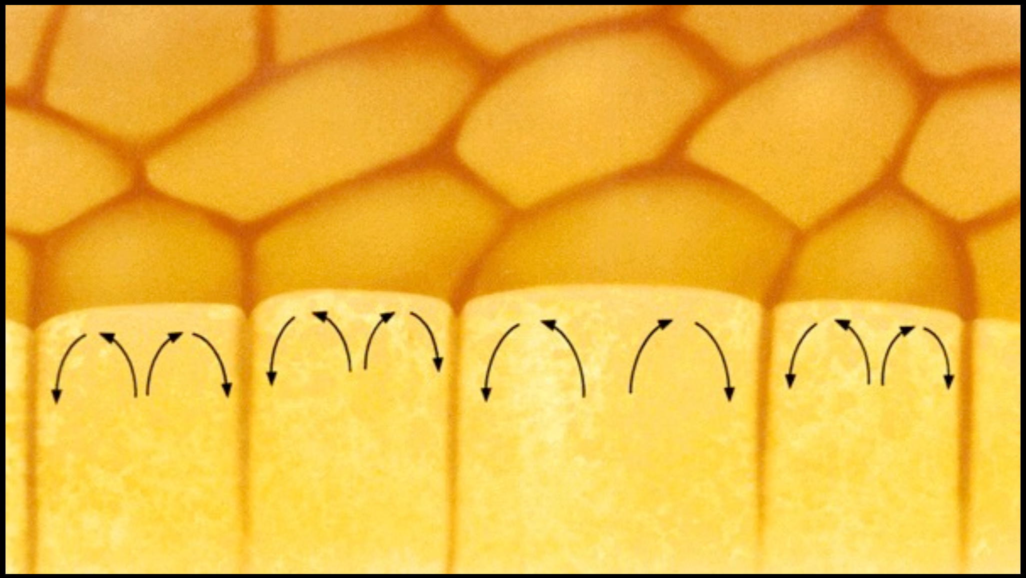
Temperature structure

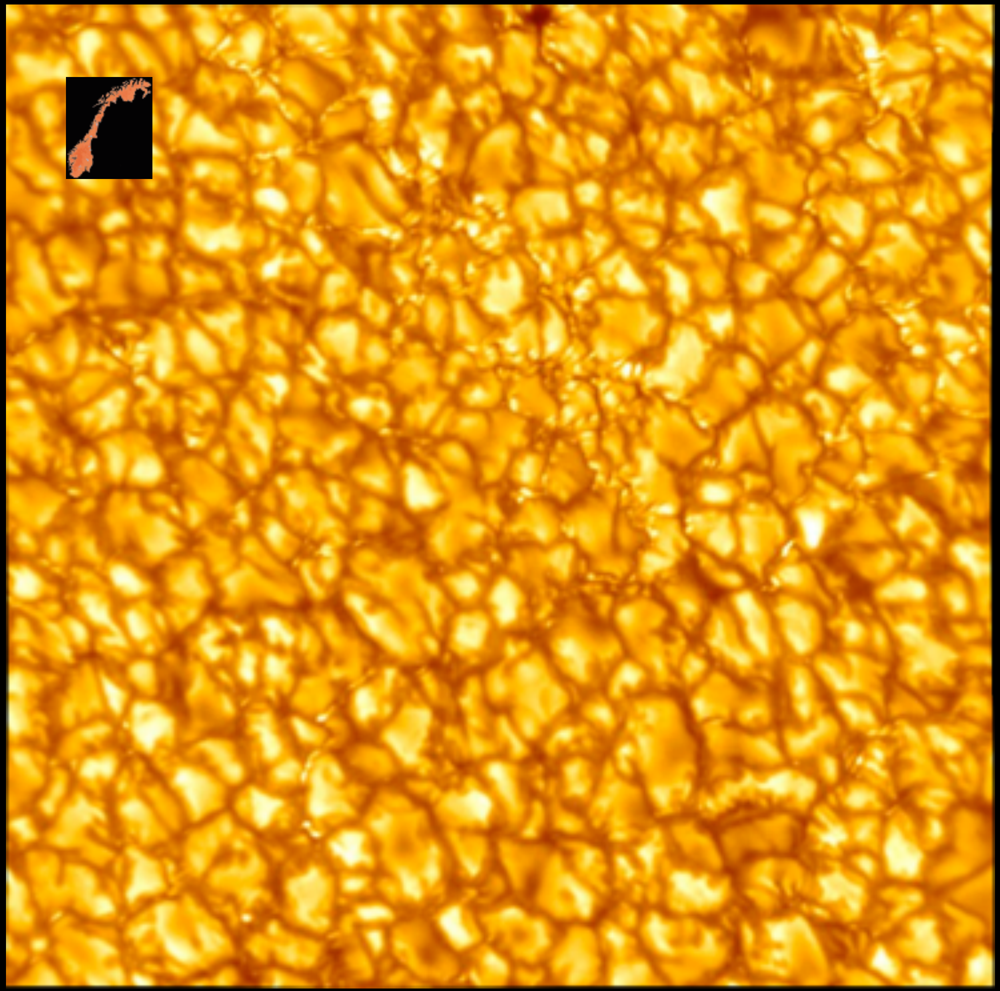
- Photosphere: Temperature decreases outwards.
  - At bottom: T = 6400 K
  - At top: T = 4000 K
- Chromosphere: Temperature decrease and then increases outwards.
  - At top: T = 10,000 K
- Transition Zone: Temperature shoots up to near 1 million K
- Corona: Temperatures increase to about 2 million K





THE SOLAR SURFACE – THE PHOTOSPHERE


NASA


Hinode/NAOJ

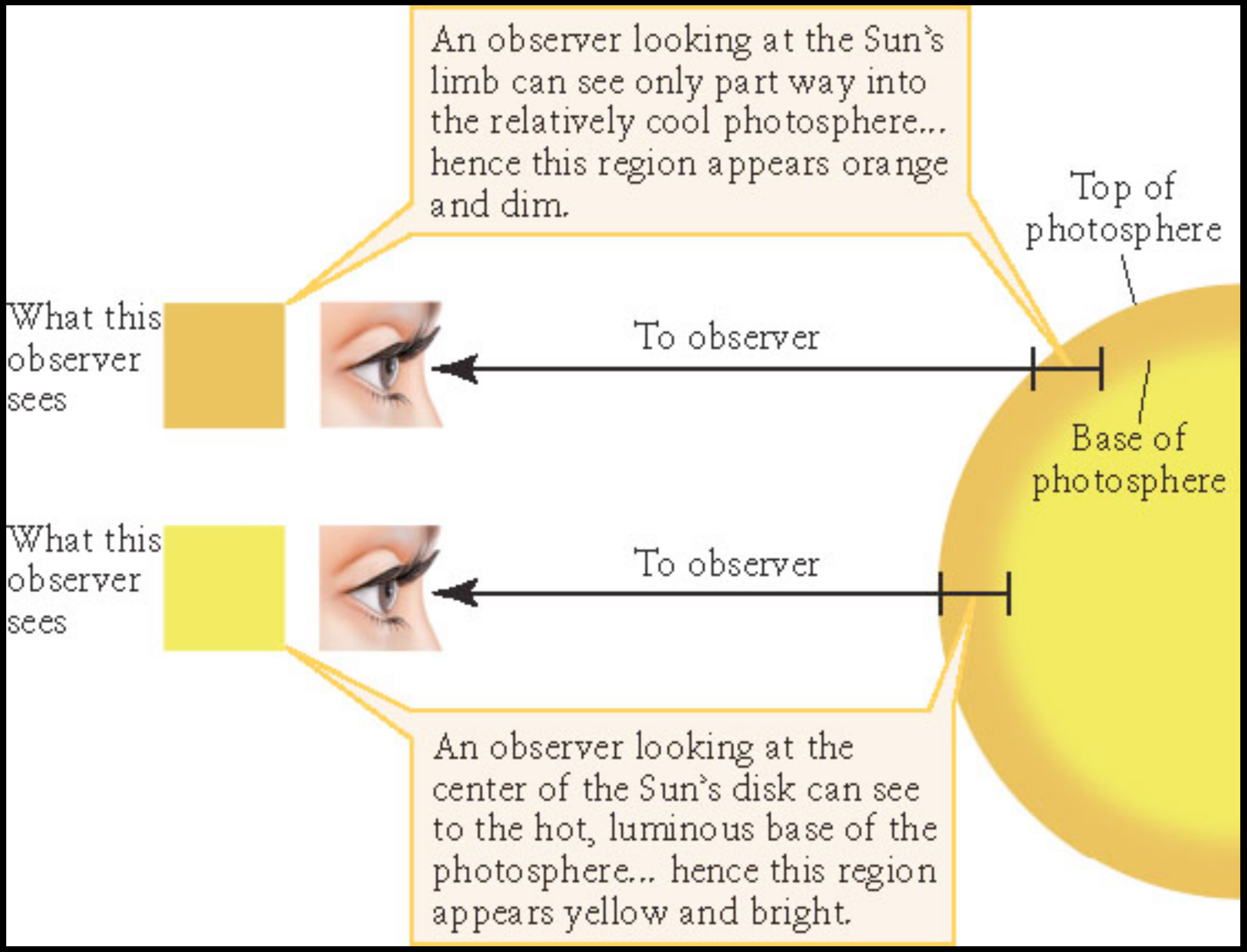
Most of the energy from the Sun is radiation out from the surface, which we call the photosphere. This is the part of the Sun we actually can see from the Earth with the naked eye (see picture on the right). The photosphere is not a solid surface but a layer of gas and part of the Sun's atmosphere.

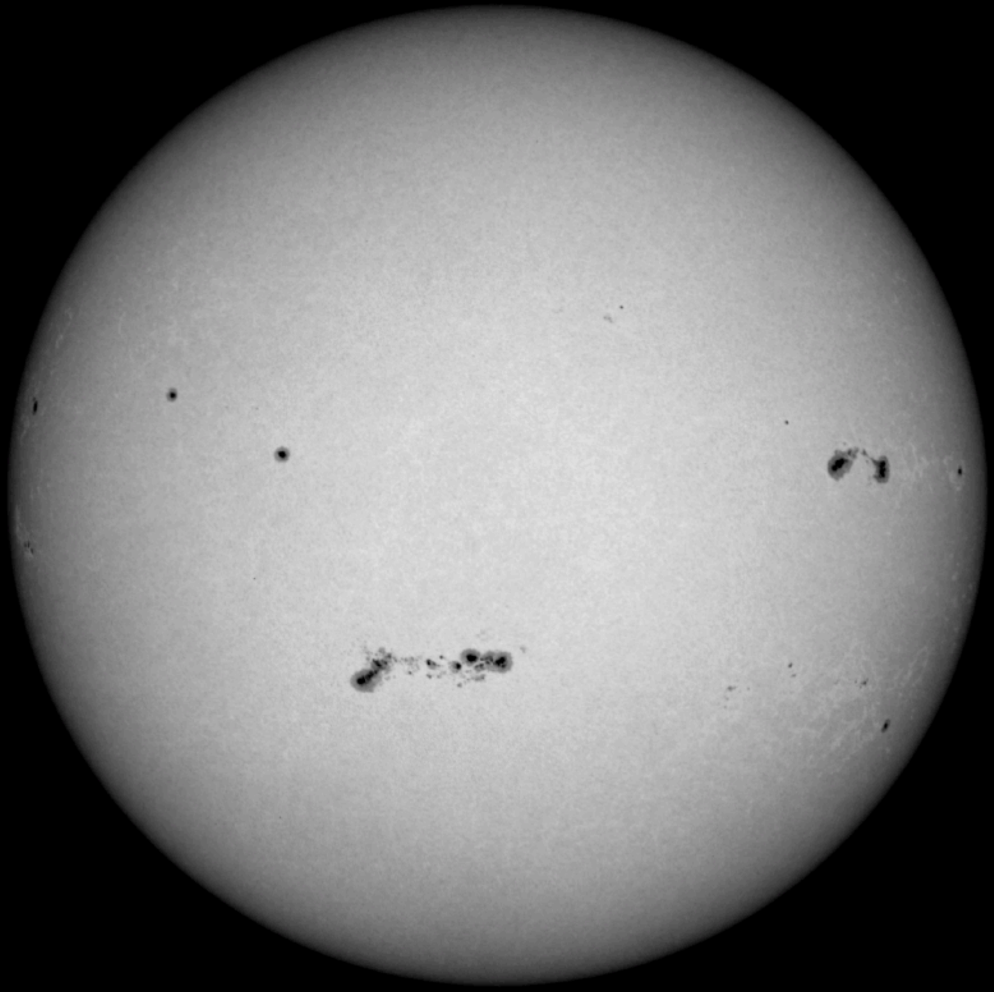
We still call this layer for the surface. It is about 400 kilometres thick and holds a temperature of about 5000 C. It is covered by a cell-like pattern we call granulation and shows how hot gas bubbles up from deeper layers, cools down at the surface and sinks down again in thin darker lanes. This is similar to what you can see in a pot of simmering soup.

The granules are about 1000 km in diameter with a lifetime of about 8 minutes. In recent years one has also discovered that the photosphere moves up and down about 15 km with different periods.

Visible light: Limb darkening

- In the visible, the Sun's limb is darker than the centre of the solar disk (Limb darkening)
- Due to grazing incidence we see higher layers near limb: T decreases outward





Visible ligh: Limb darkening

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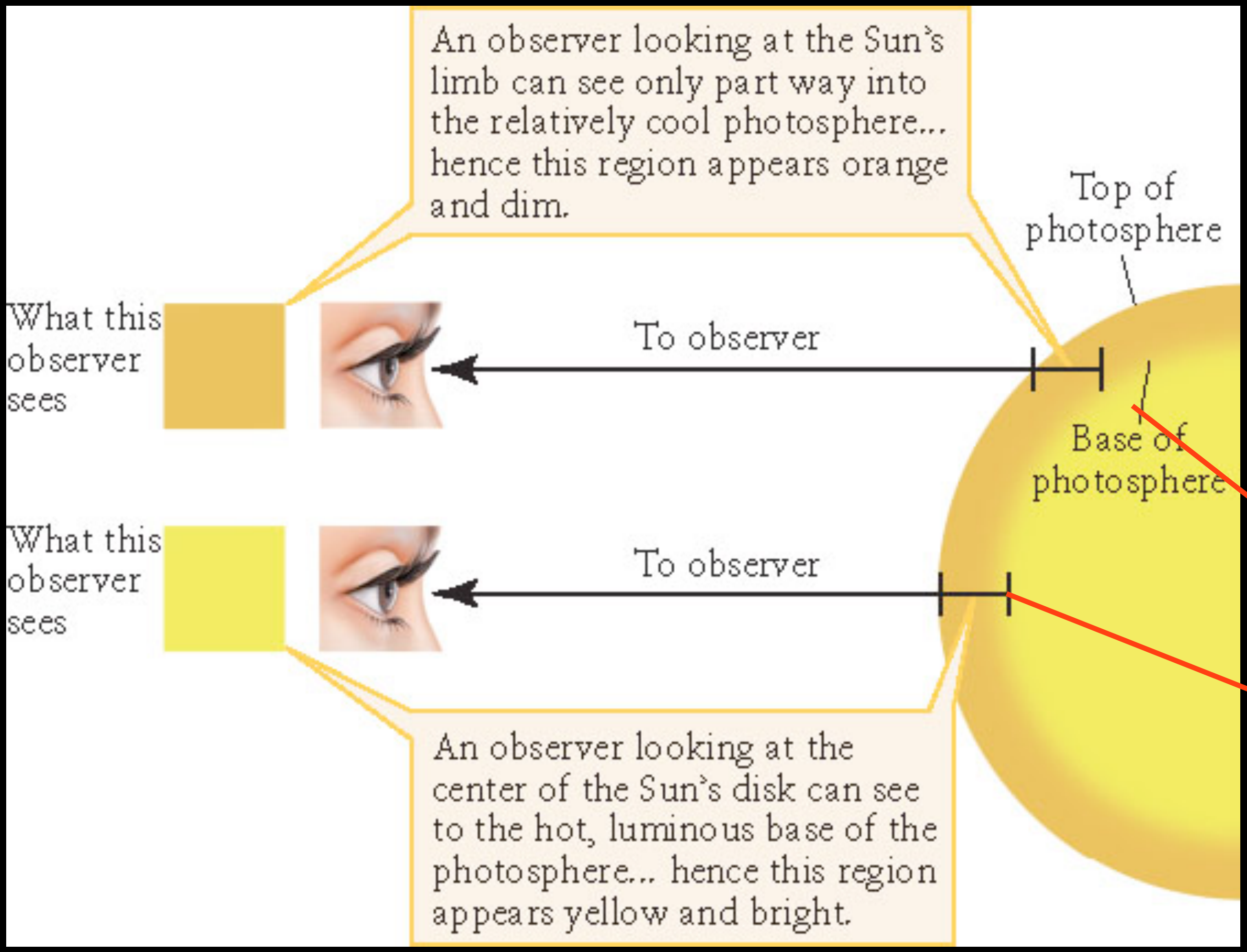
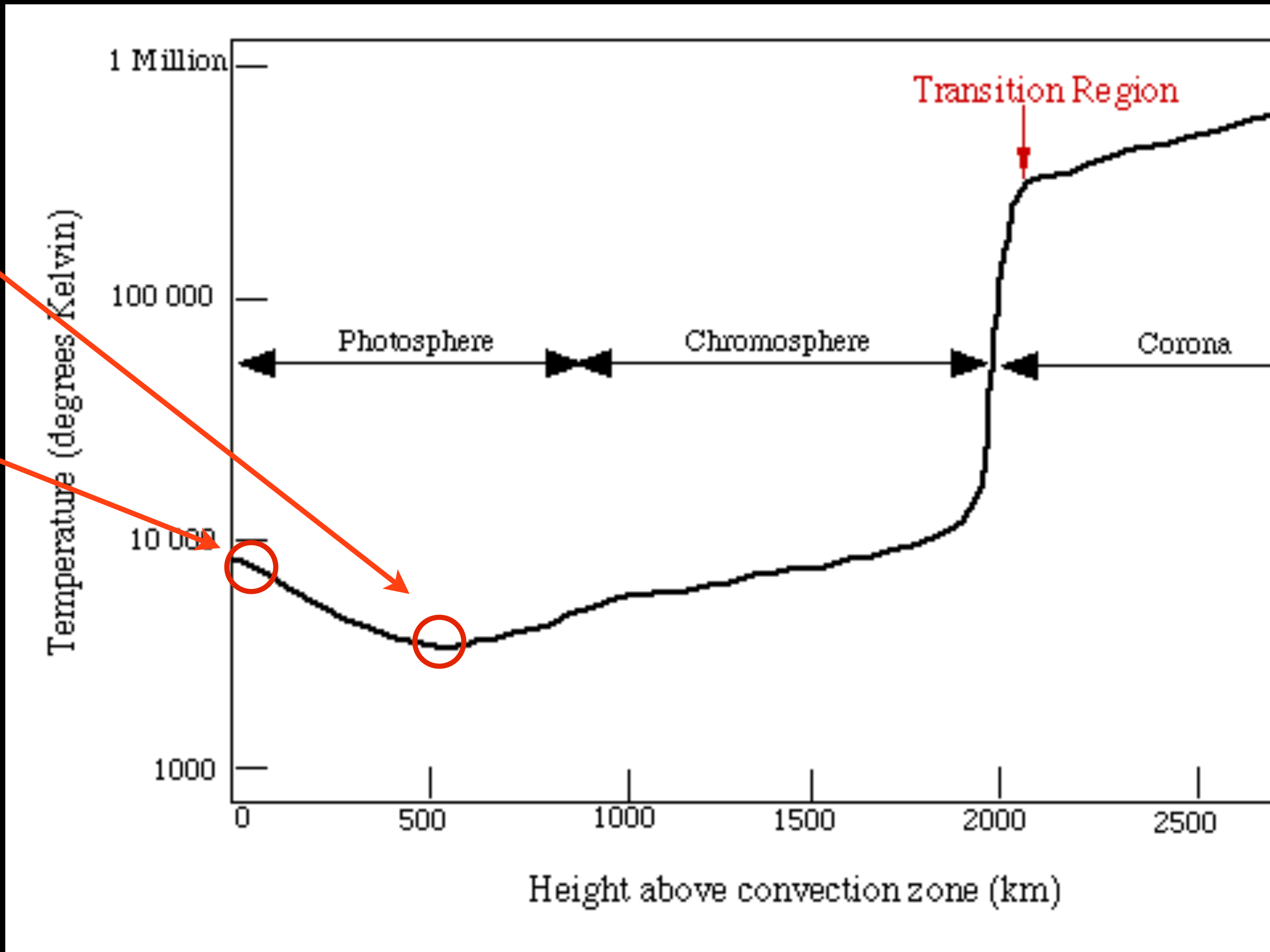




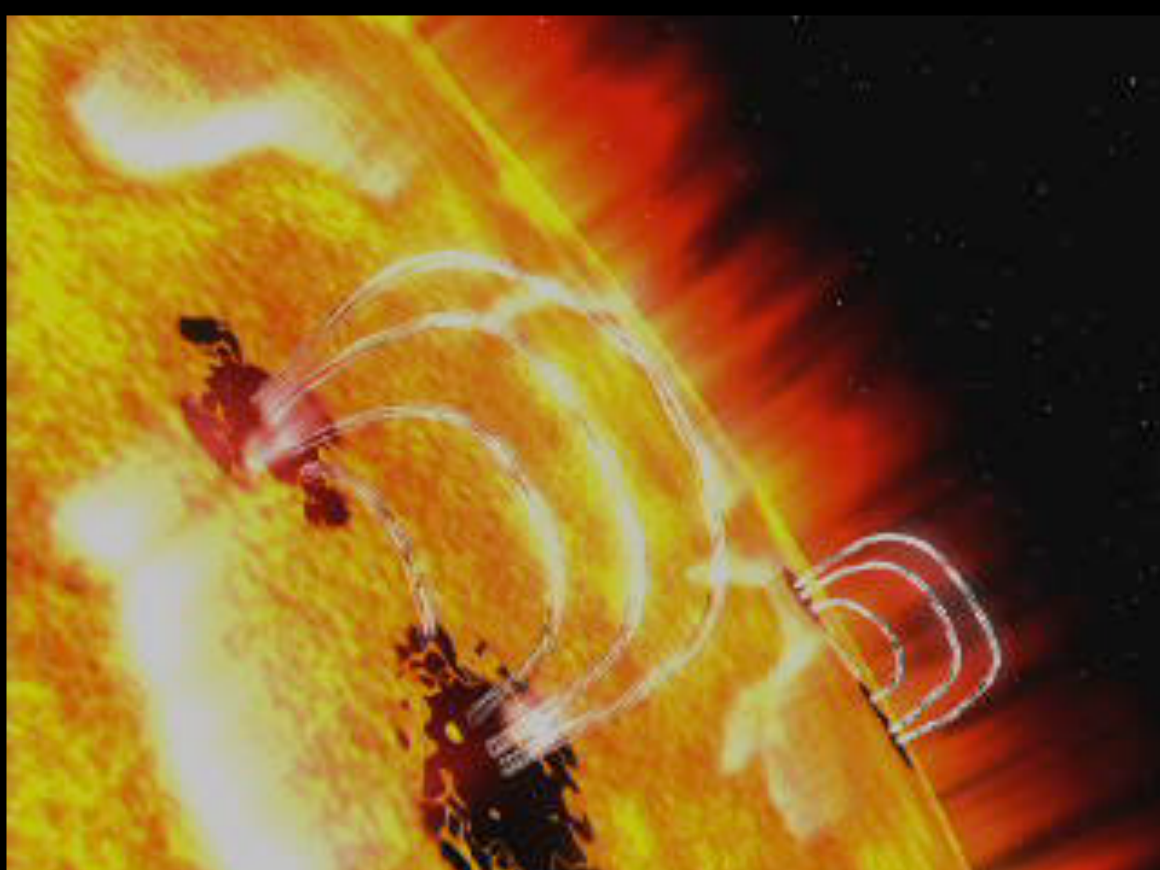
SUNSPOTS

SUNSPOTS

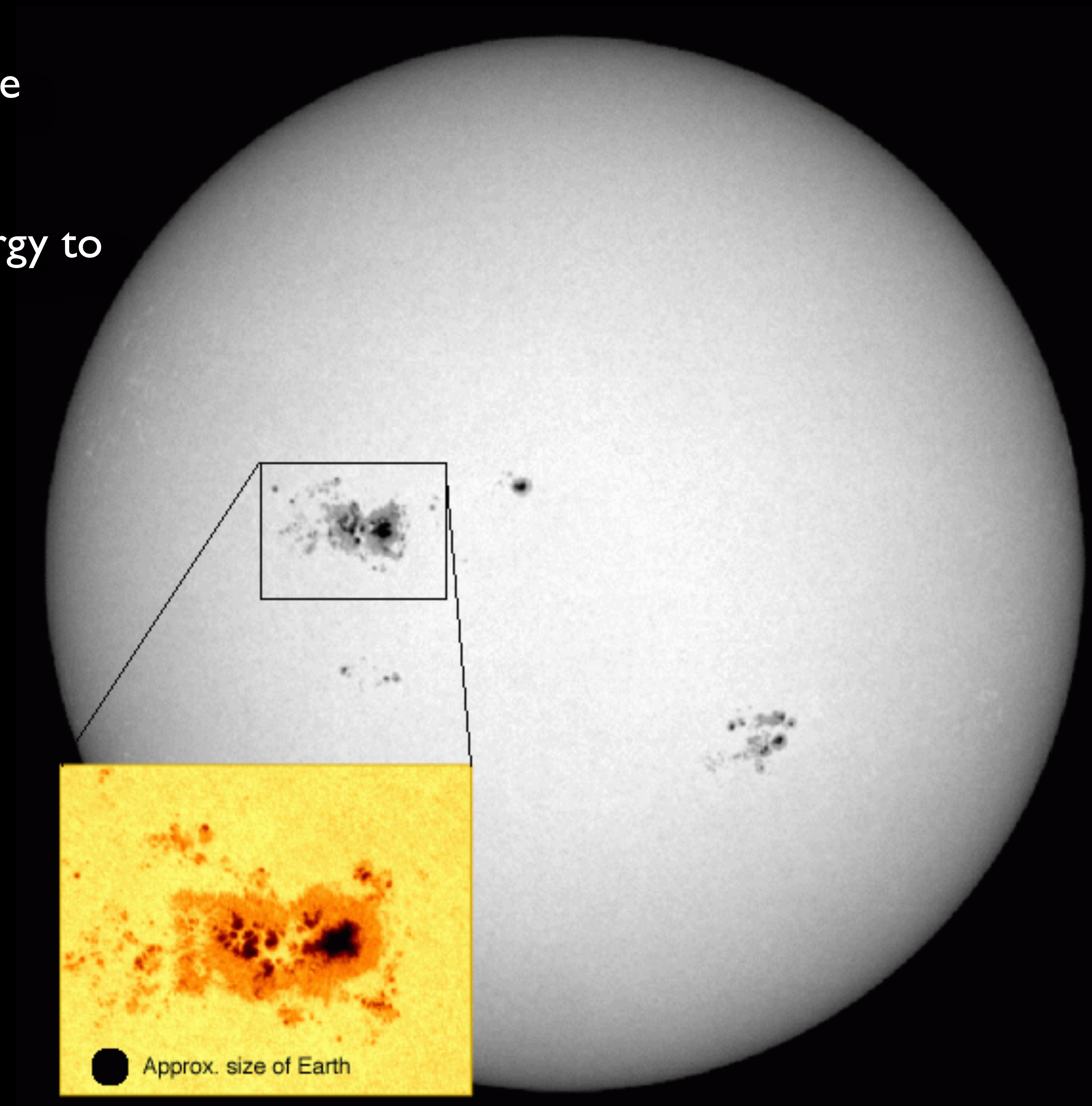
Dark features on the solar surface

Caused by strong magnetic fields emerging from the solar interior.

The strong magnetic fields blocks some of the energy to emerge from these regions.

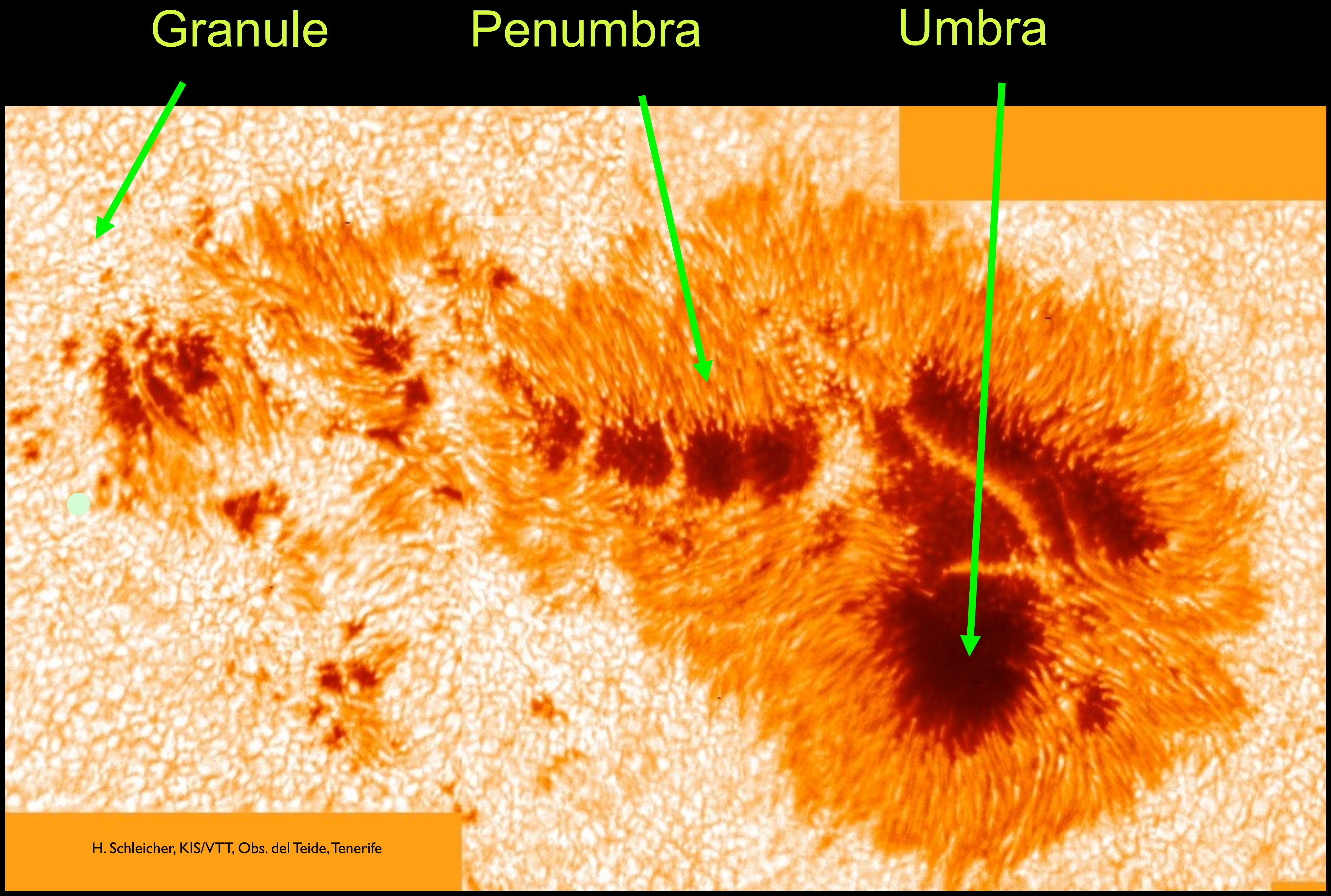


NASA



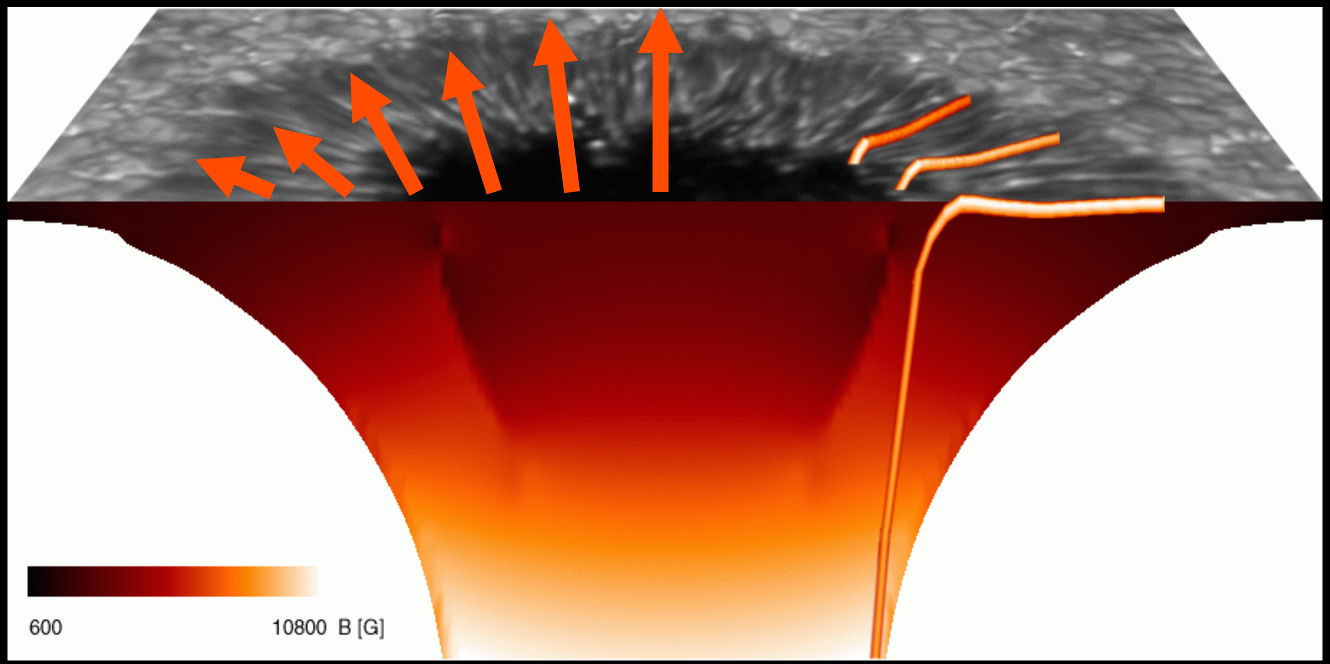
NASA/ESA/S. Hill

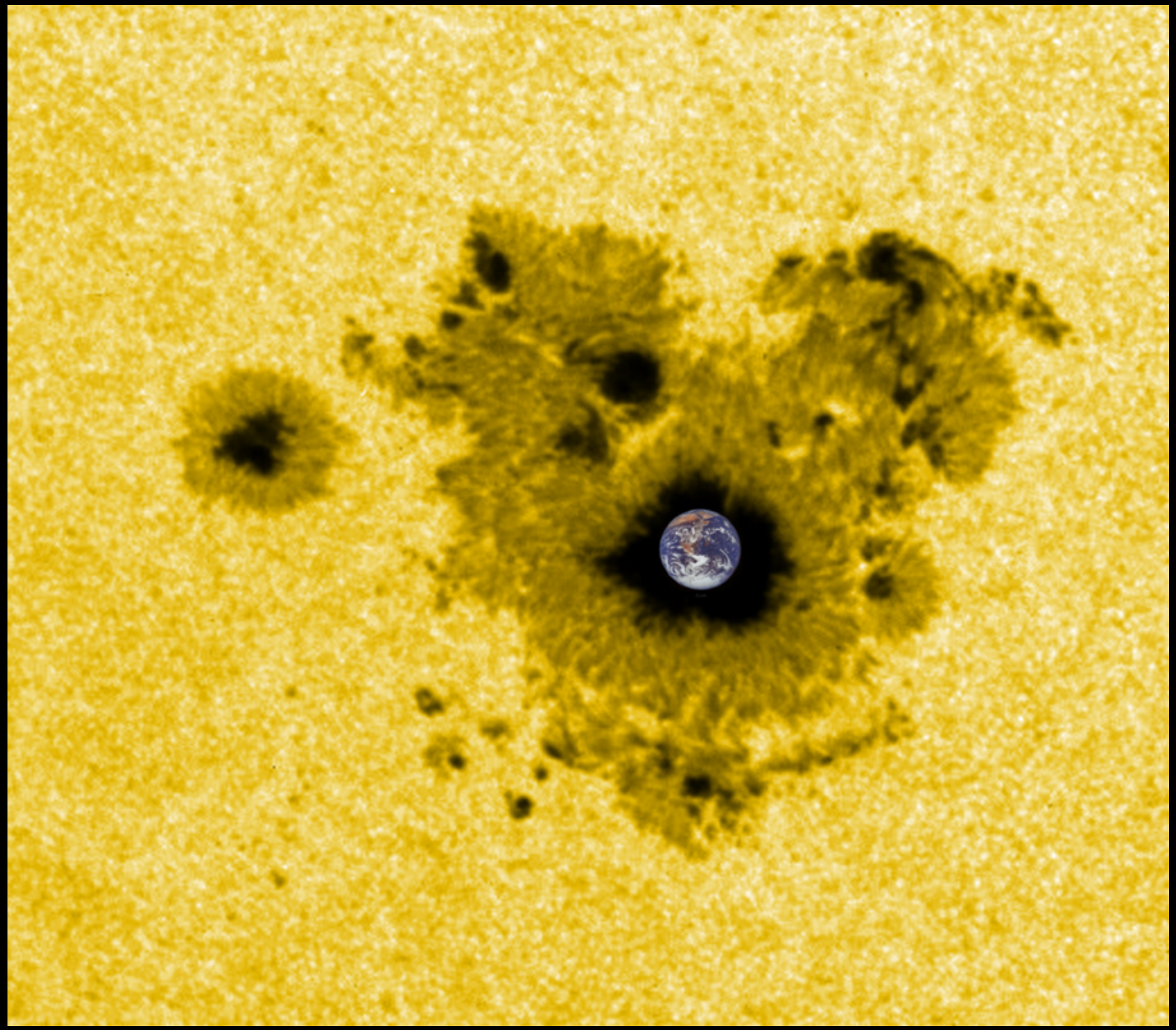
Sunspot structure



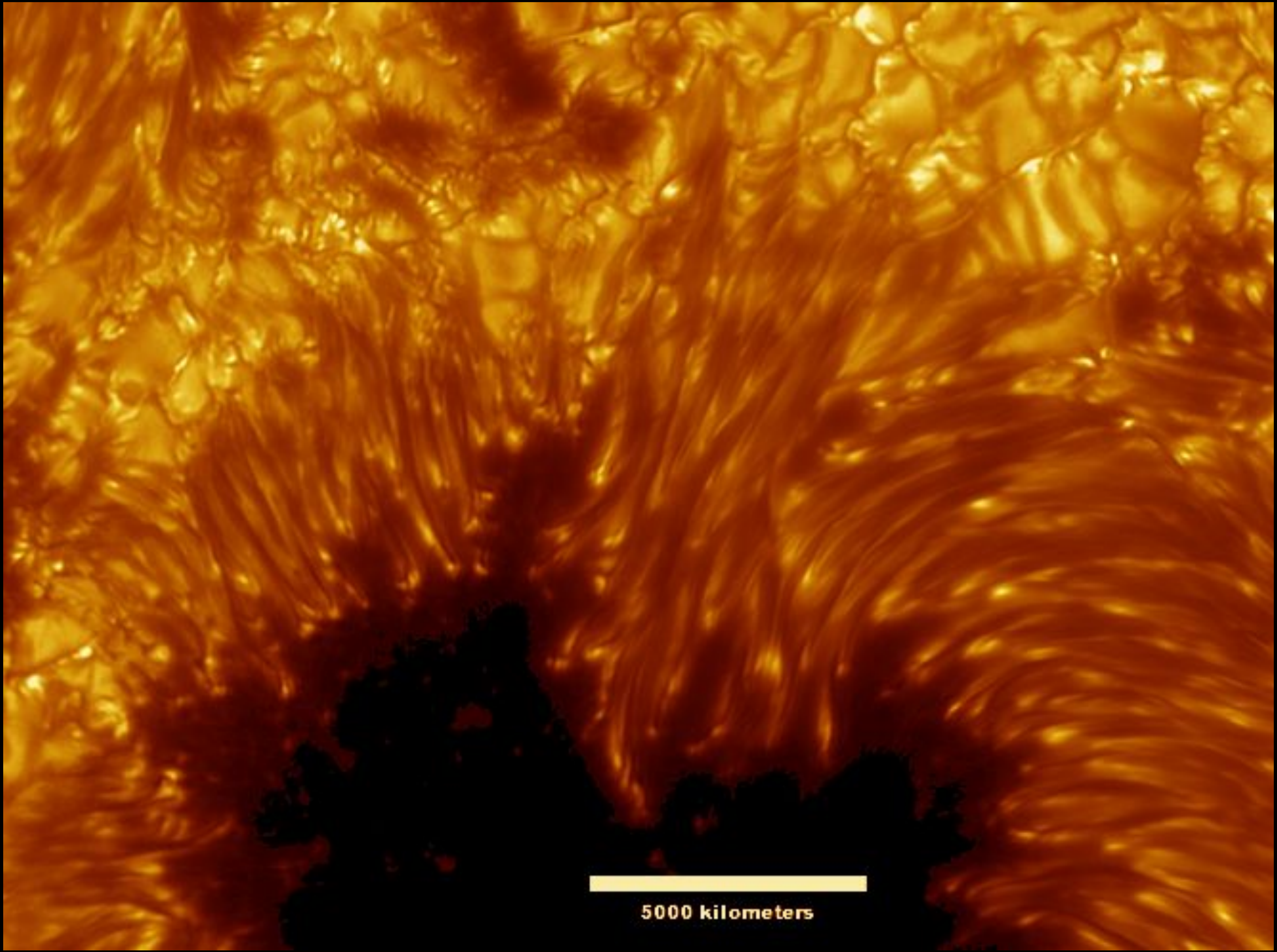
Sunspots, some properties

- Field strength: Peak values 2000-3500 G (Earth < 1 Gauss)
- Brightness: umbra: 20% of quiet Sun, penumbra: 75%
- Sizes: thousands of km's to 10 times the Earth
- Lifetimes: between hours & months:.





Highest resolution

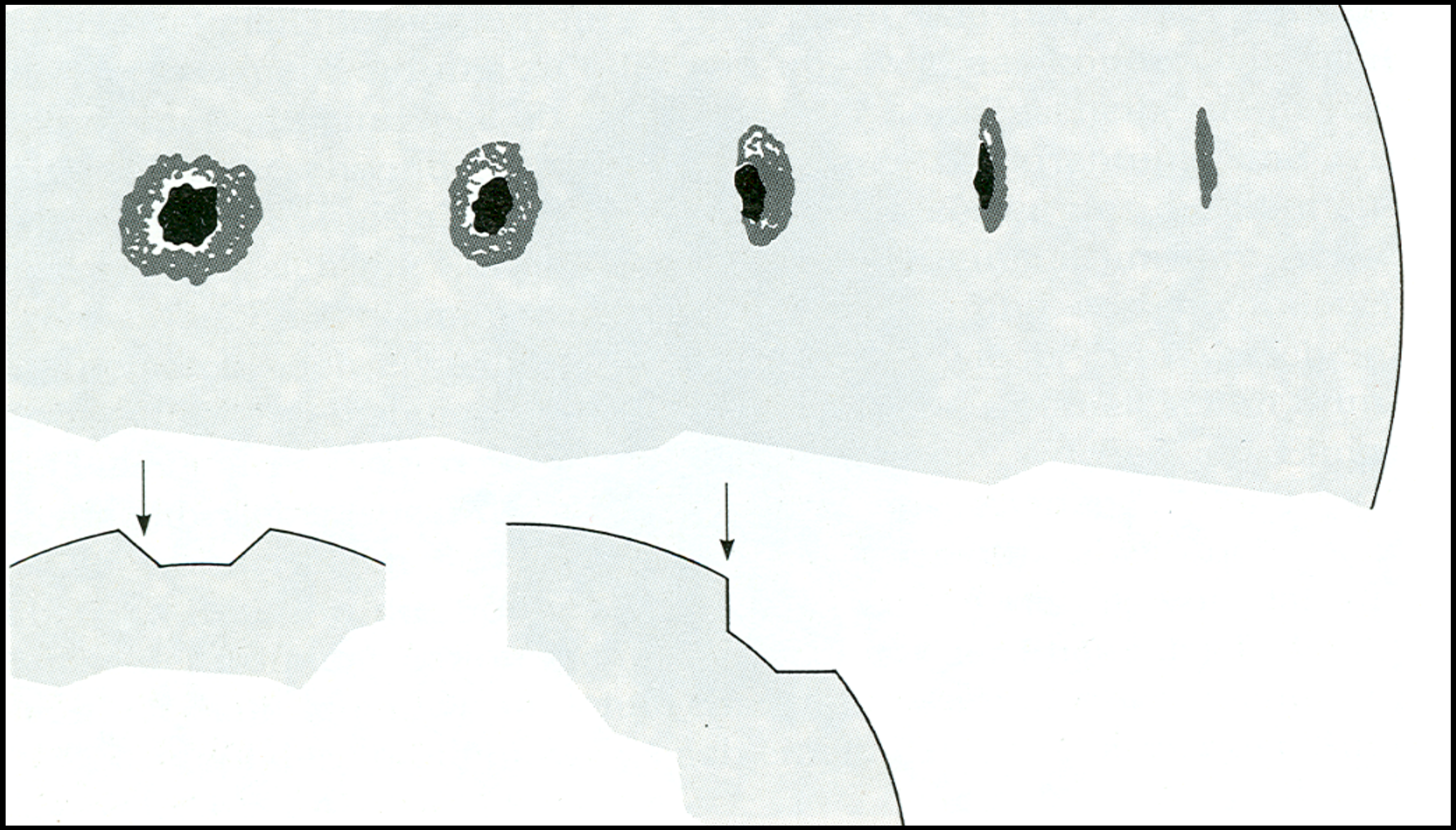


The Wilson effect

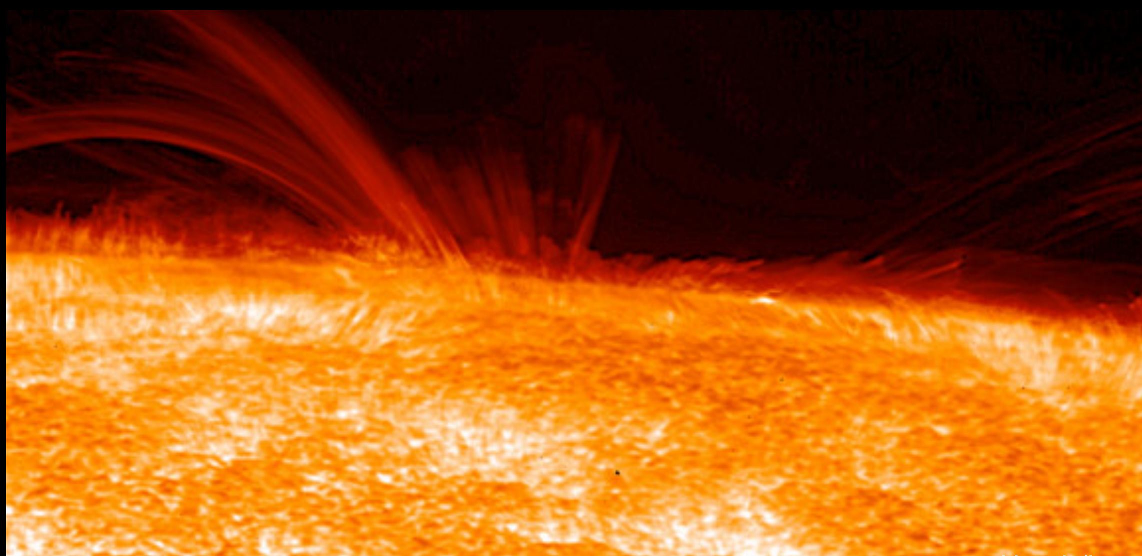
- Near the solar limb the umbra and centre-side penumbra disappear

➔ We see 400-800 km deeper into sunspots than in photosphere

- Correct interpretation by Wilson (18th century).



THE SUN´S ATMOSPHERE – THE CHROMOSPHERE

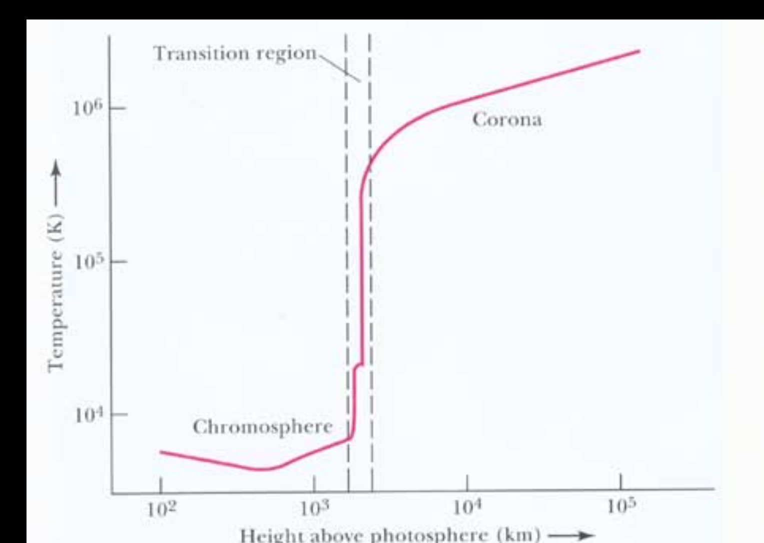


Hinode/Jaxa

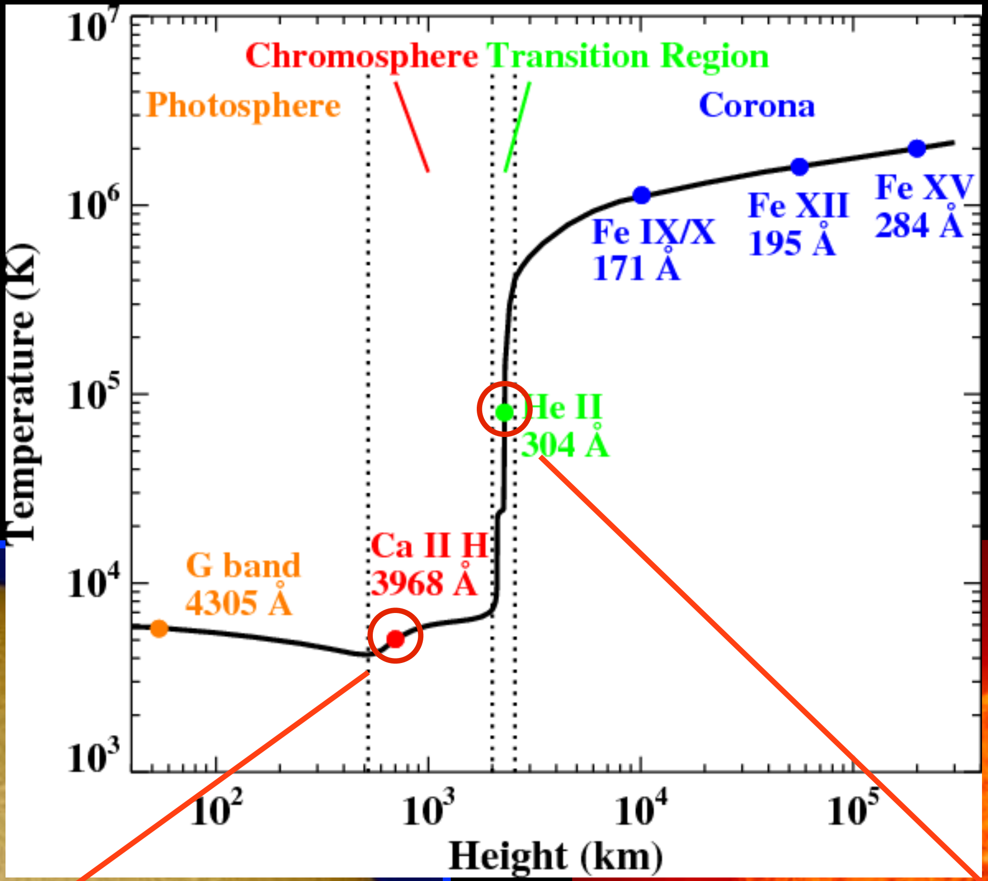
SOHO(NASA/ESA)

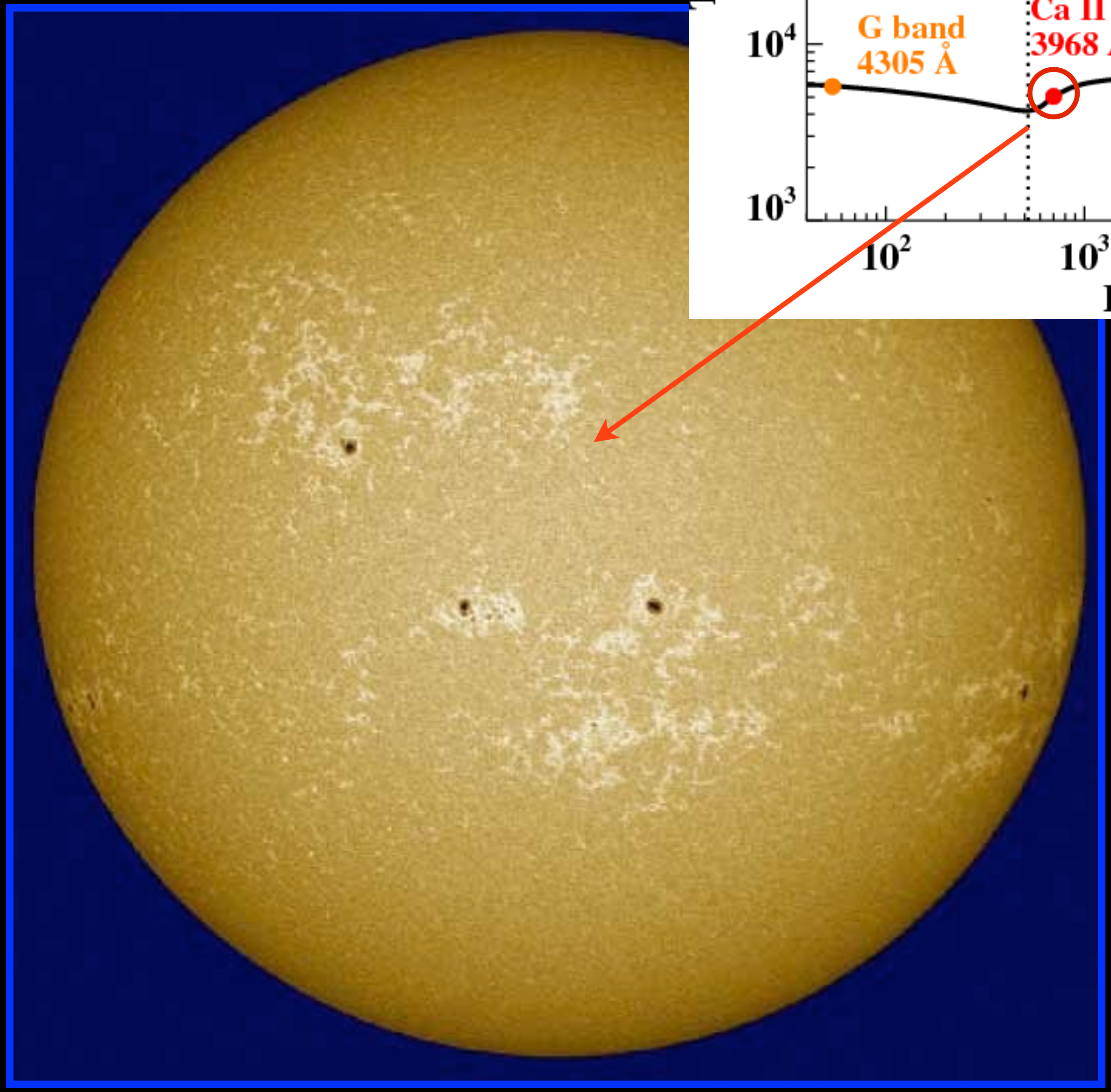
Above the photosphere we fond the lower solar atmosphere called the chromosphere. It is a pinkish layer of gas that can only bee seen during a total eclipse or by using special telescopes preferable in space. The chromosphere means “colour sphere”. It extends 3000 km out from the photosphere

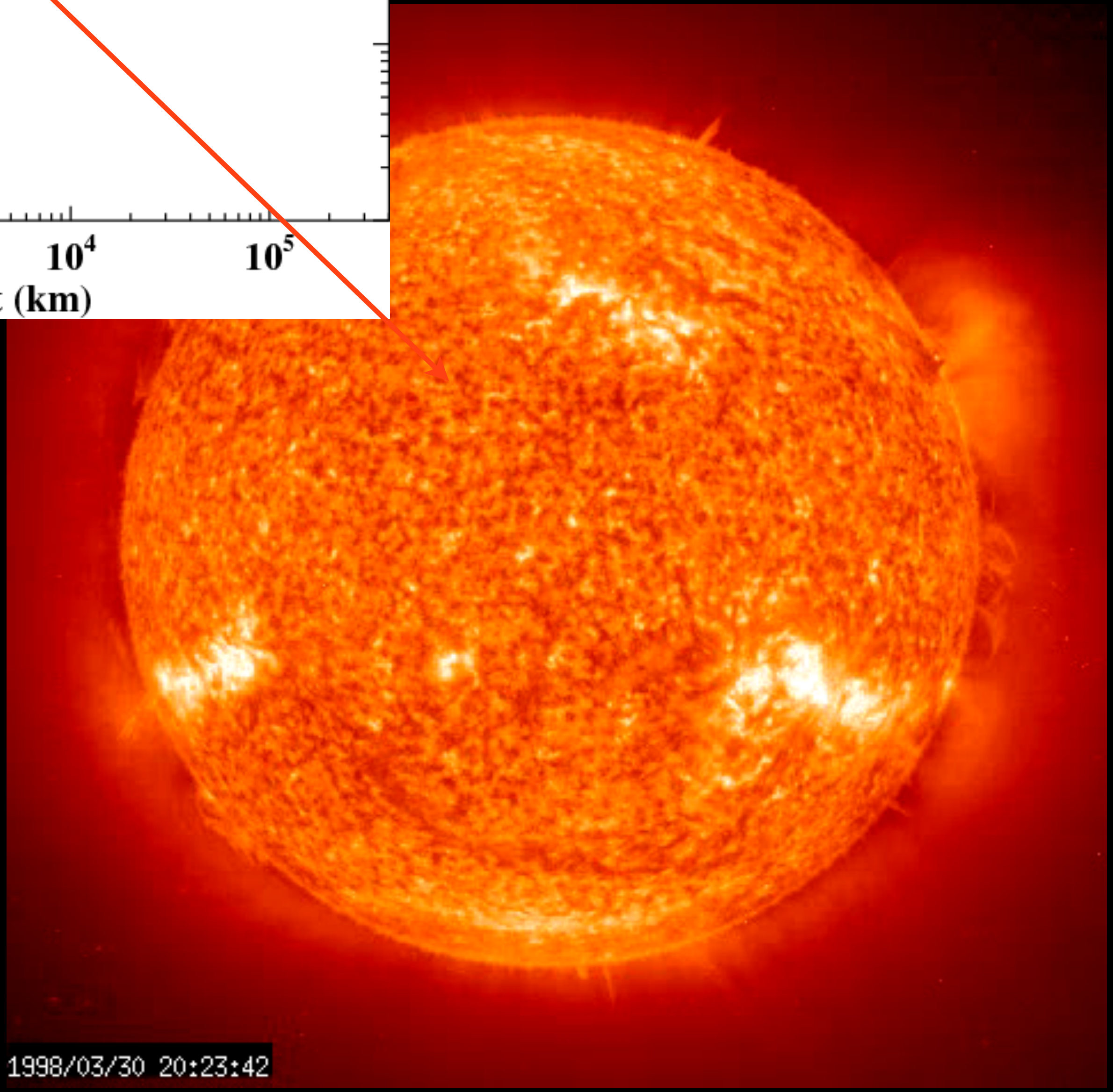
In the lowest part of the chromosphere the temperature continue to decrease down to about 4500 C. But then something strange happens – the temperature starts to increase again as we move further out. In the outer part of the chromosphere the temperature reaches 30,000 -70,000 degrees. This layer is mainly emitting ultraviolet radiation and thus, cannot be studied in detail from the ground.



Chromospheric structure





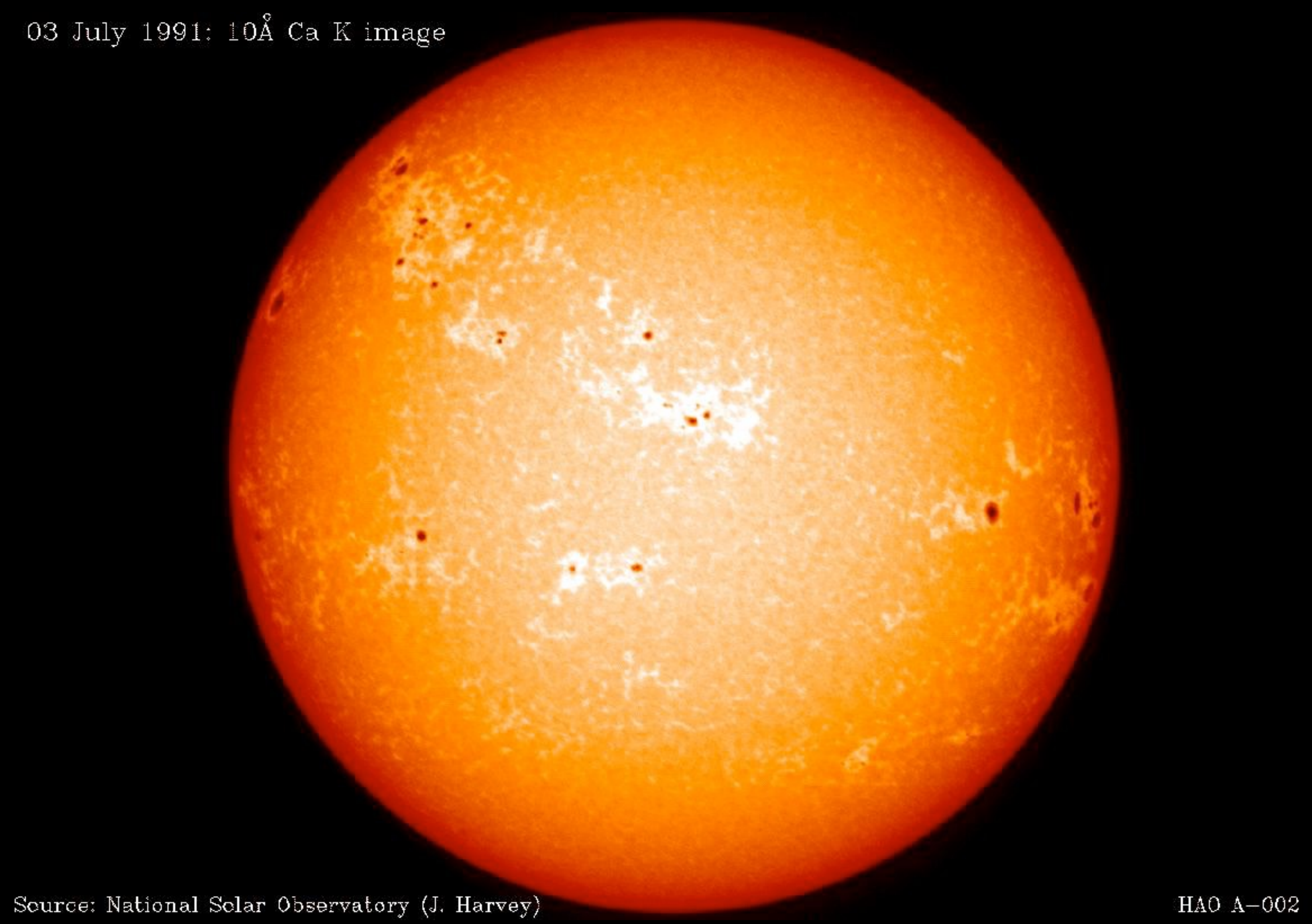


7000 K gas Ca II K

$5x10^4$ K gas (EIT He 304 Å)

Chromospheric structure II

- The chromosphere exhibits a very wide variety of structures. E.g.,
  - Sunspots and Plages
  - Network and internetwork (grains)
  - Spicules
  - Prominences and filaments
  - Flares and eruptions



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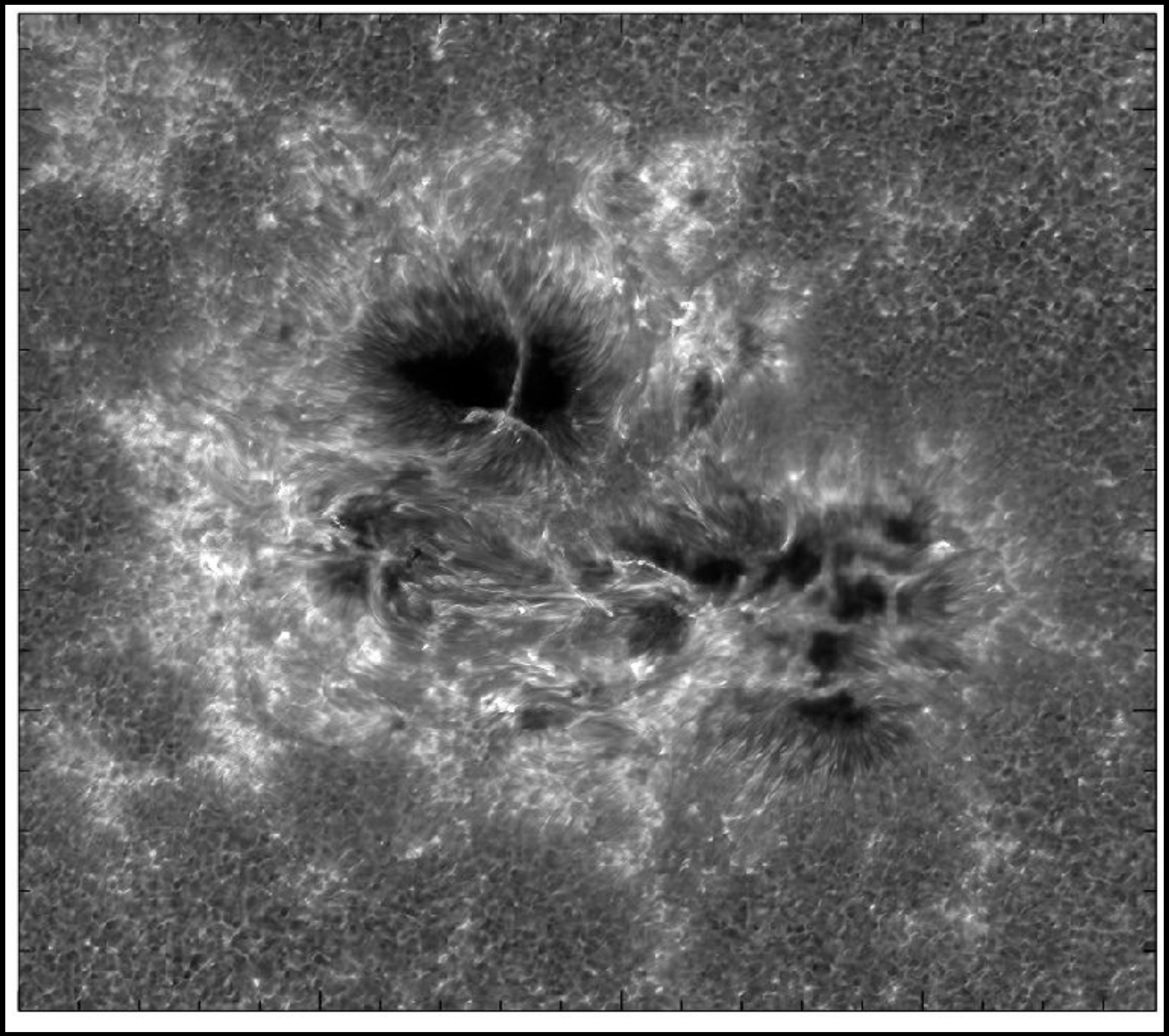

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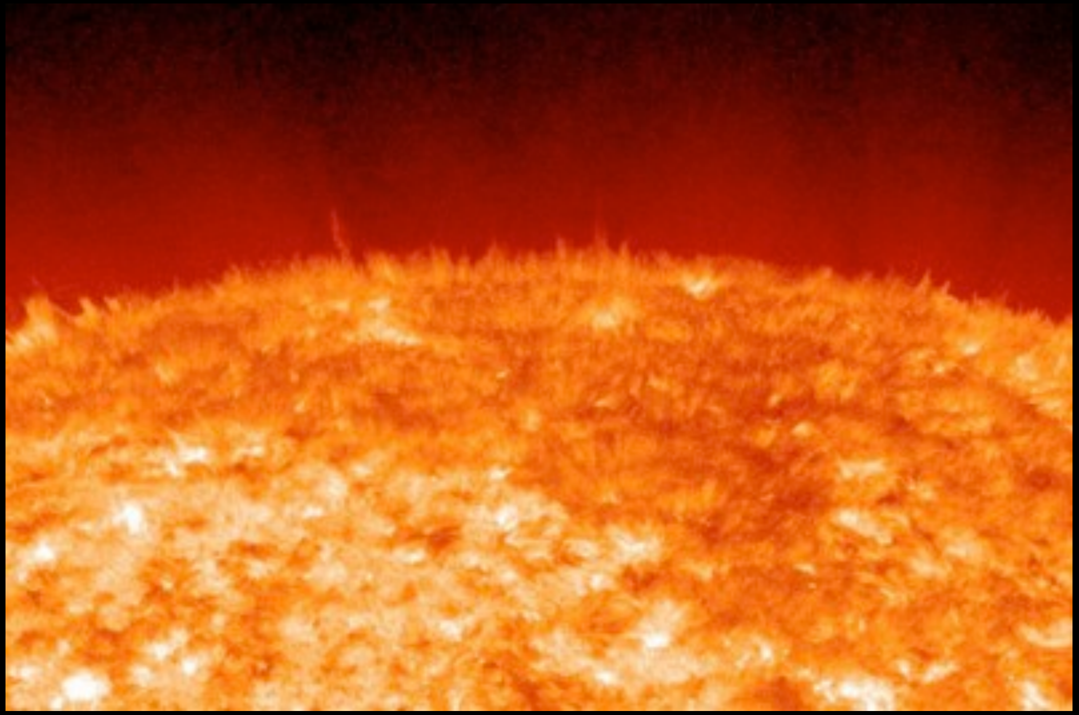

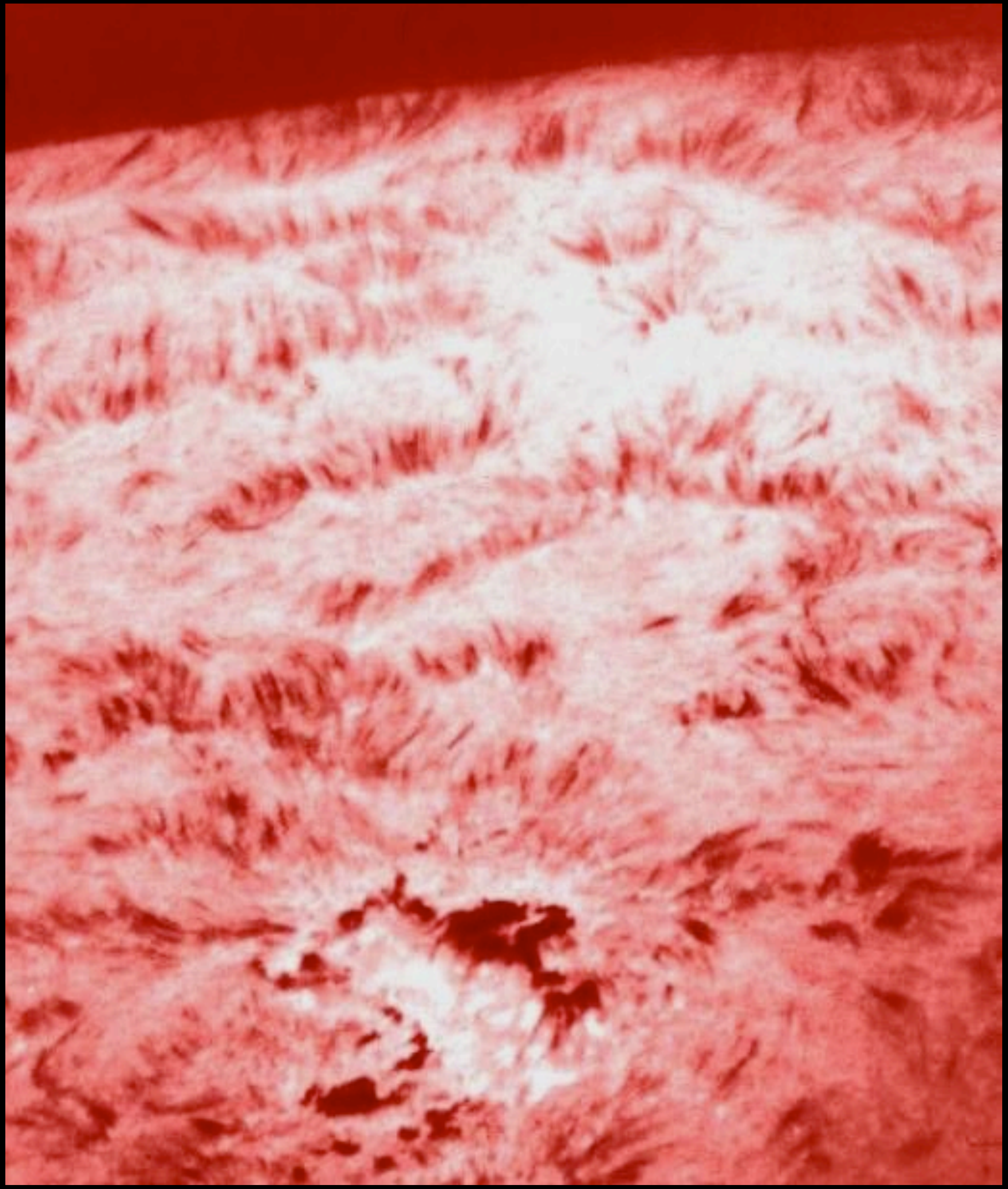

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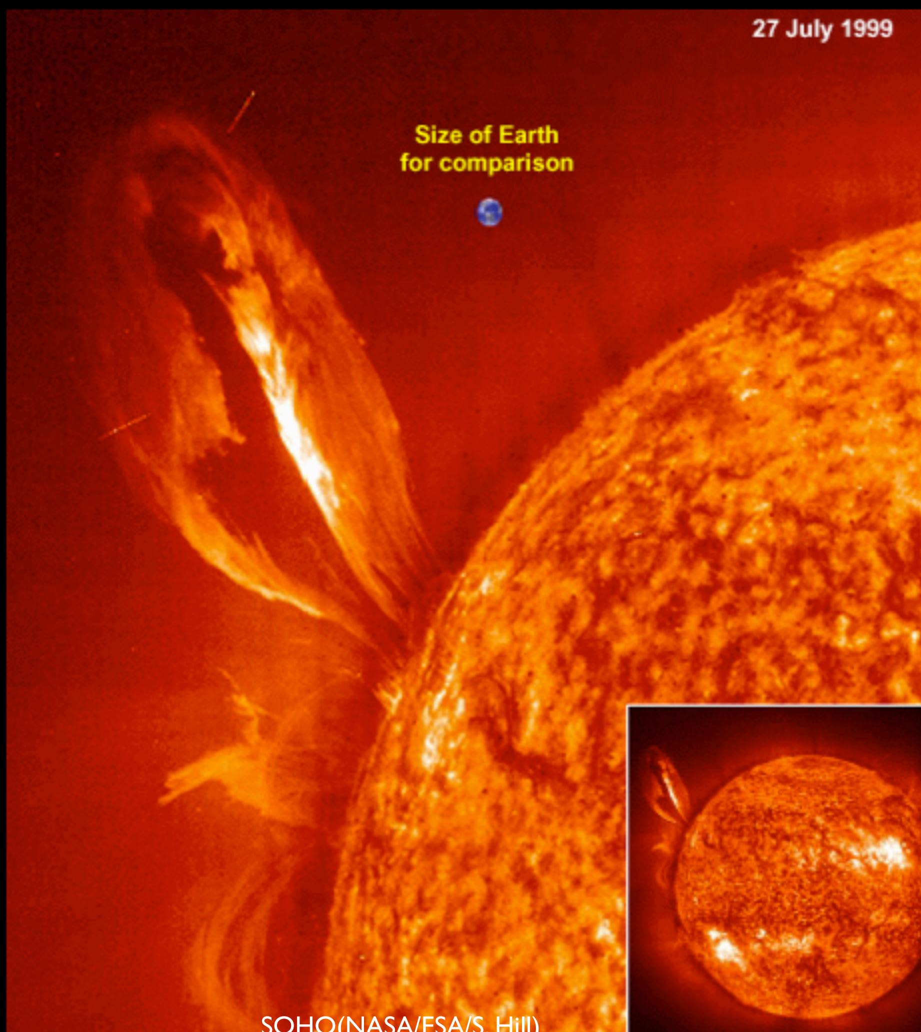
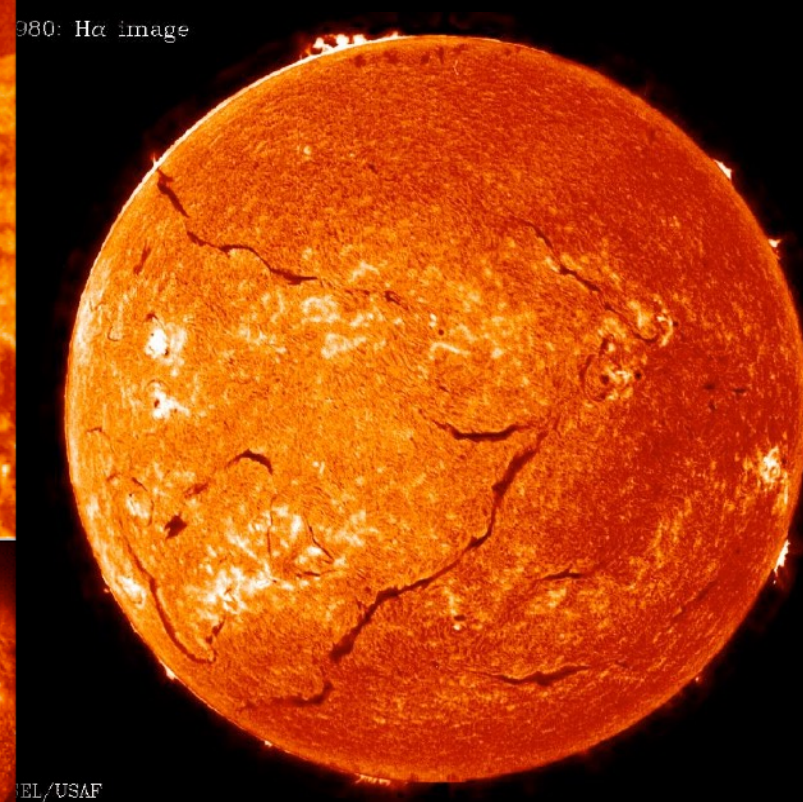
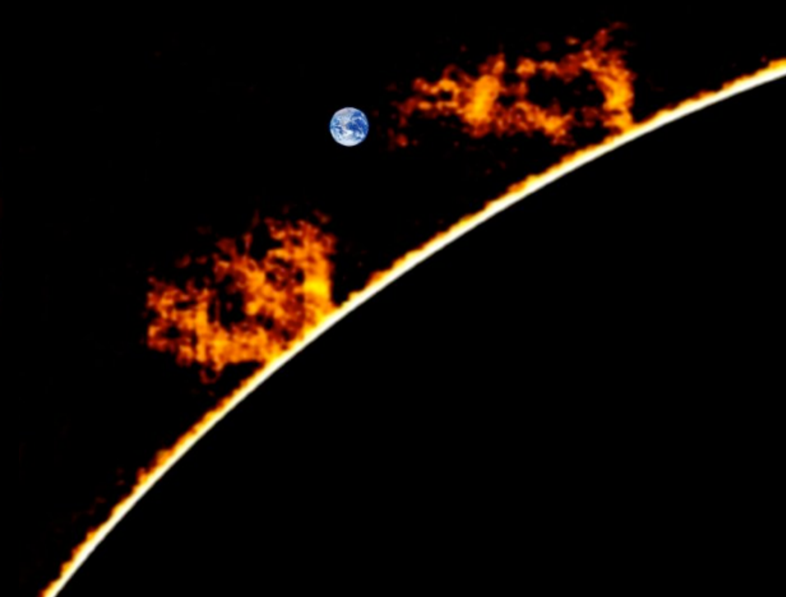
PROMINENCES /FILAMENTS



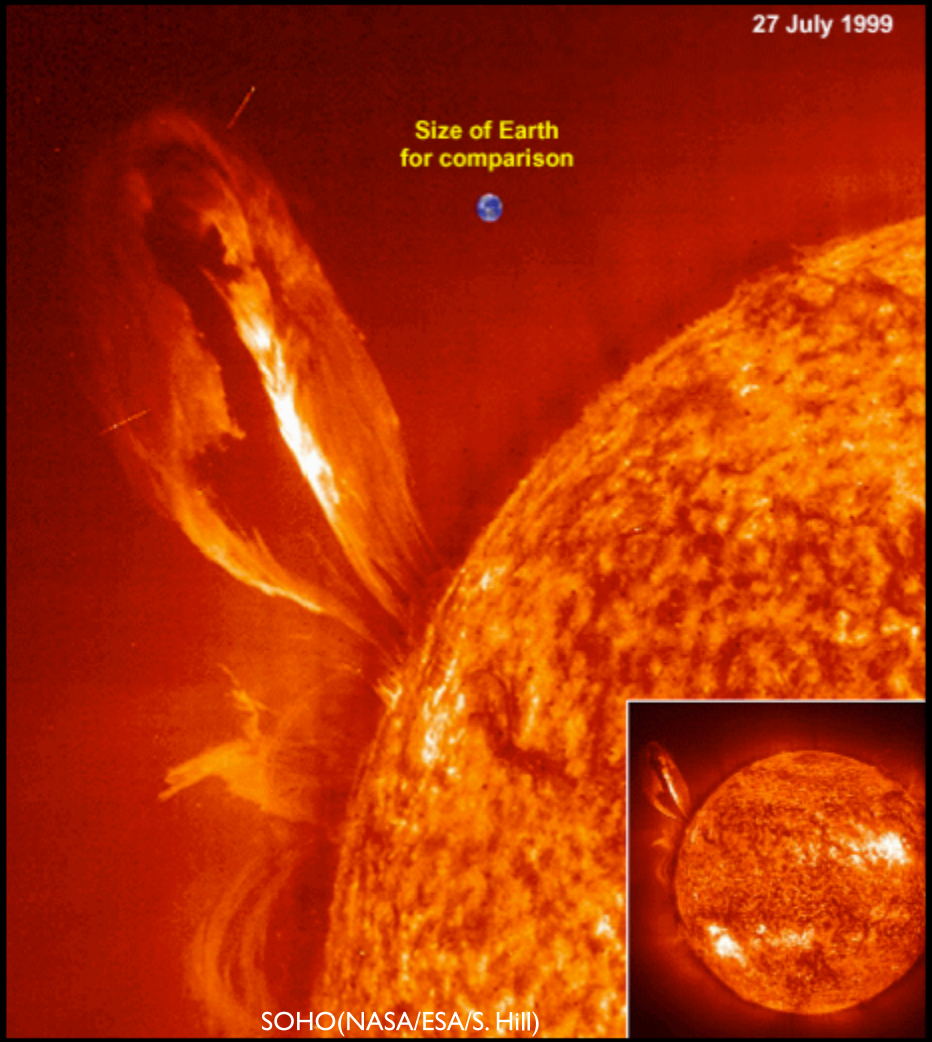
SOHO(NASA/ESA/S. Hill)


Big Bear Observatory


M. Zinkova

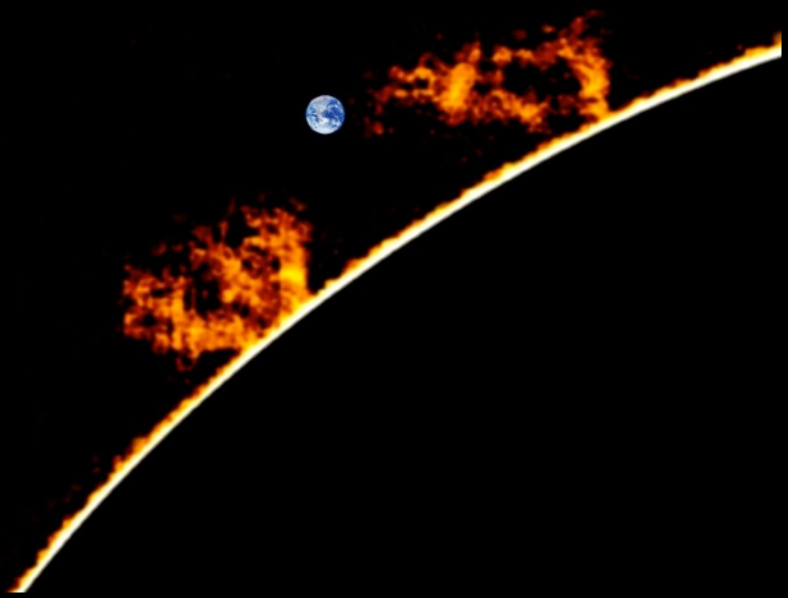
Prominences are chromospheric gas that is suspended up in the hot corona by strong magnetic fields. They can bee seen as bright structures above the solar limb. When these same structures are seen against the solar disk, they look dark since they absorb the bright light from the surface. They are then called filaments.

PROMINENCES /FILAMENTS



SOHO(NASA/ESA/S. Hill)

Big Bear Observatory



M. Zinkova

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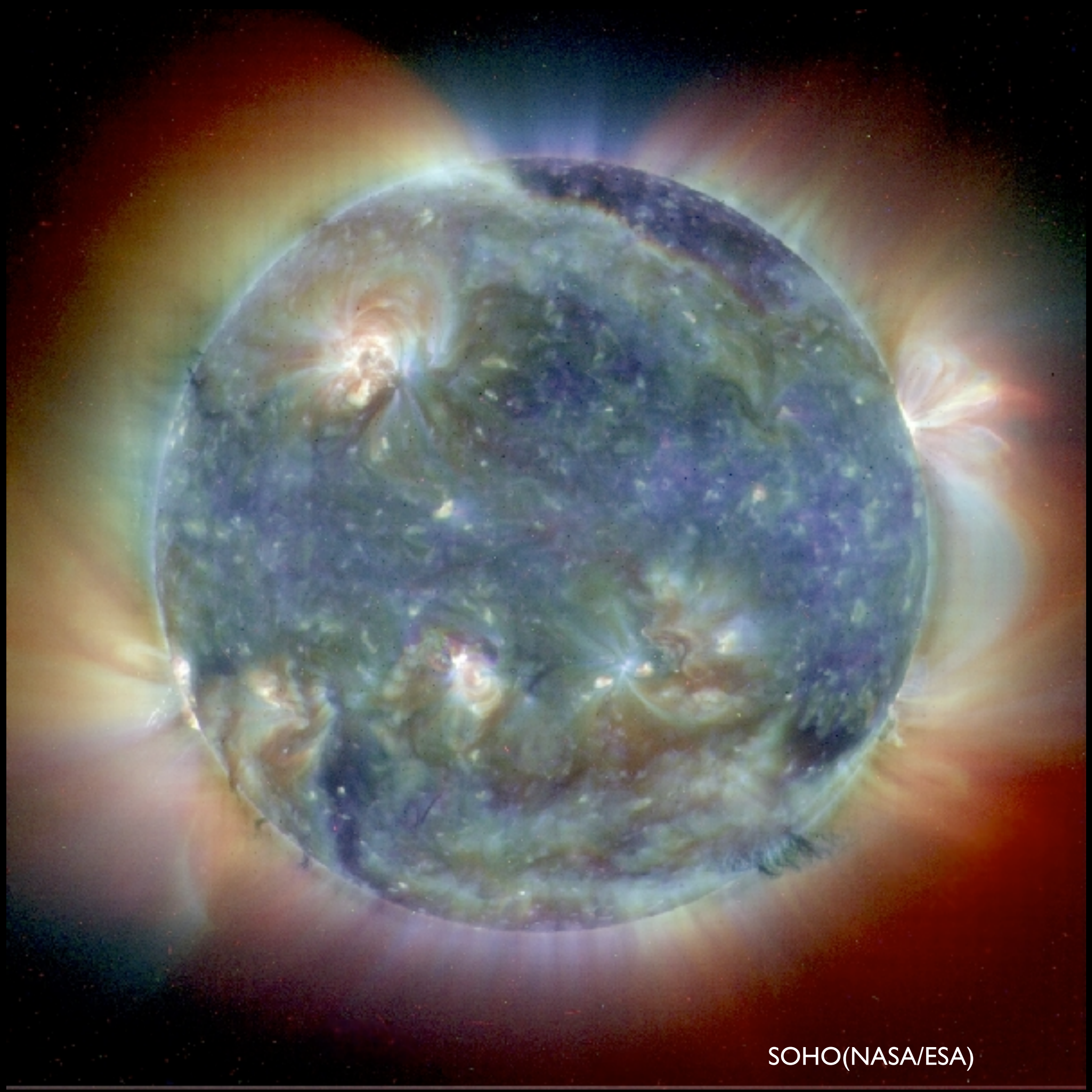
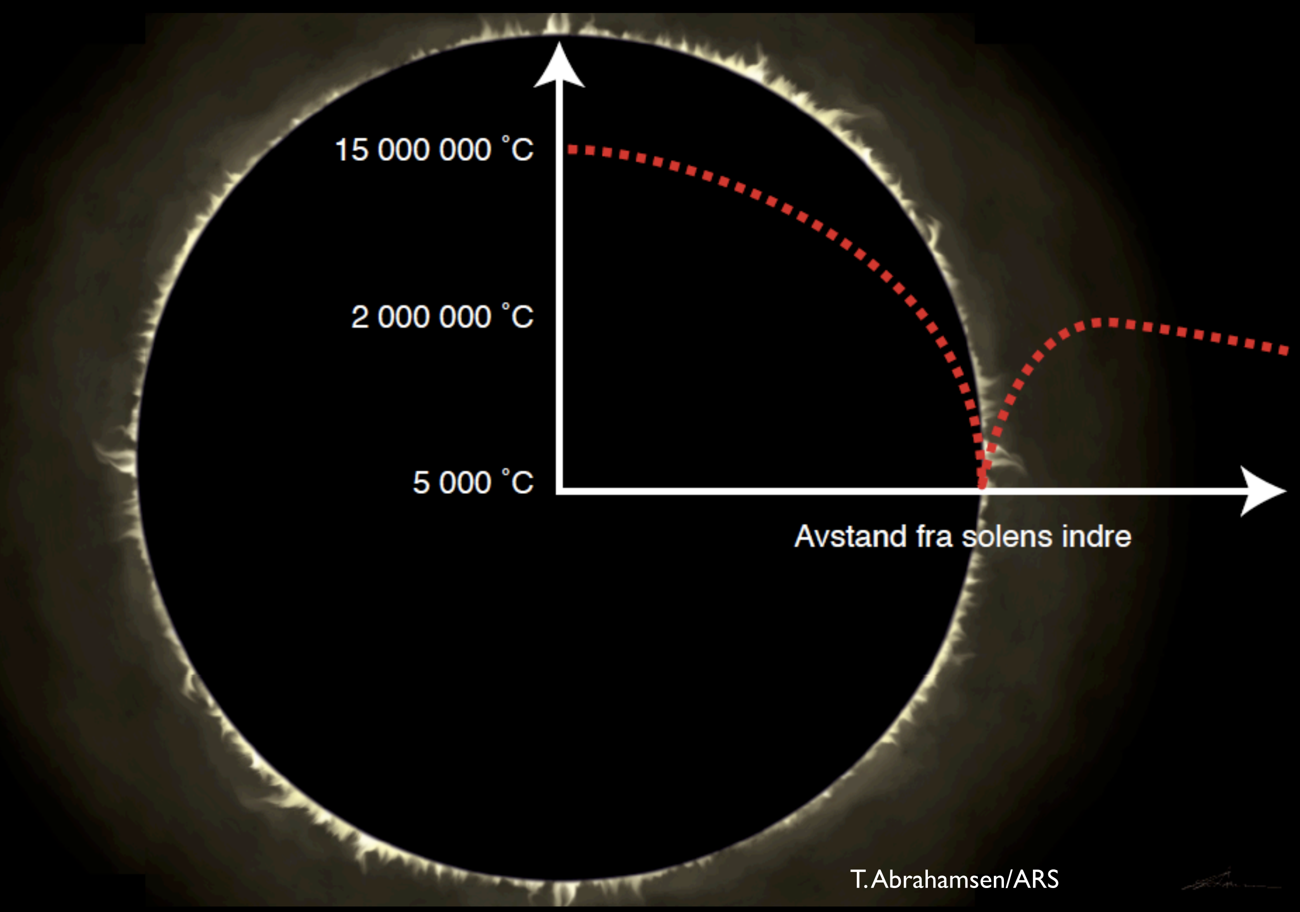
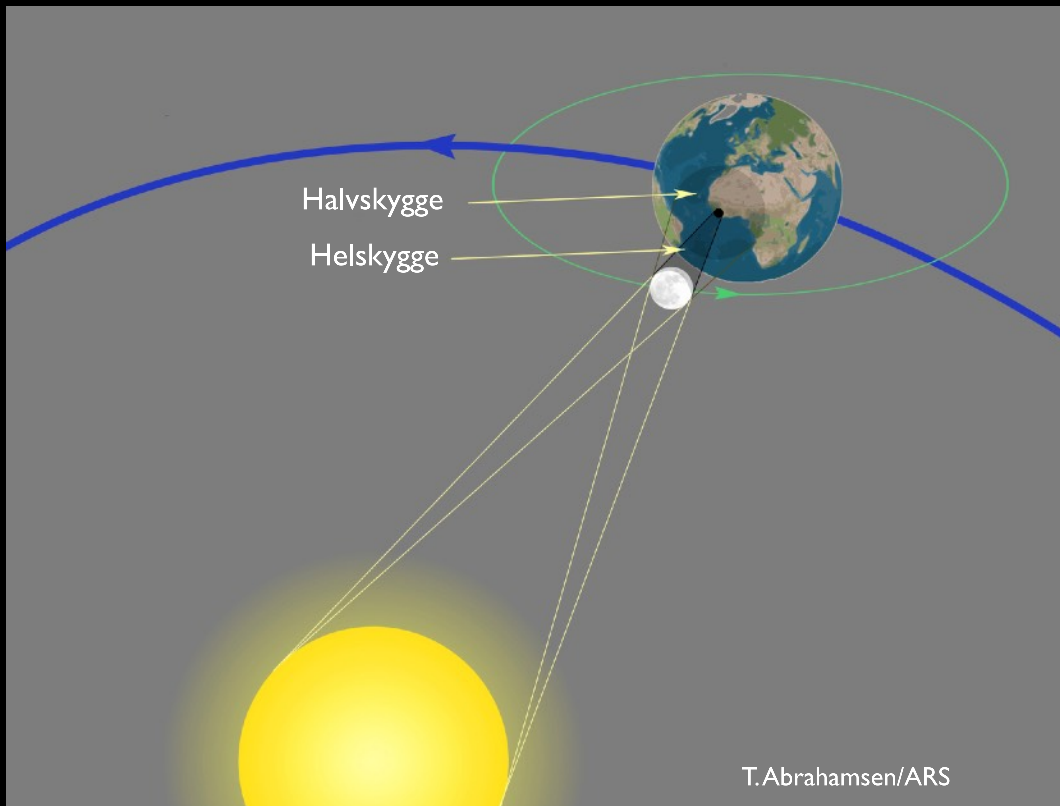
THE OUTER SOLAR ATMOSPHERE – THE CORONA





The corona is the outer part of the solar atmosphere and consists mostly of hydrogen gas. The temperature is between 1 and 2 million degrees. The density is very low, less than a millionth of the air density at Earth. The corona emits very little light so it is impossible to see it every day due to the strong light from the photosphere and the scattered light in the Earths atmosphere. Only during a total solar eclipse, when the Moon passes in front of the Sun and blocks the strong light from the photosphere, can we see the spectacular corona with the naked eye. With special telescopes that make artificial eclipses it is possible to study the corona.

SOLAR ECLIPSES



A. Danielsen

The Moon orbits the Earth, which in turn orbits the Sun. Thus, sometimes the Moon will be located between the Earth and the Sun and we will experience what we call a solar eclipse. By a coincidence he Sun and the Moon appear to have the same size in the sky as seen from the Earth. The shadow of the Moon can sometimes reach the surface of the Earth.

There are three different types of solar eclipses: total, partial and annular. During a total eclipse the size of the moon cover the entire Sun and one can see the chromosphere, prominences and the corona. The sky becomes dark and one can see the brightest stars and planets. The eclipse will appear total if you are located within the umbra shadow.

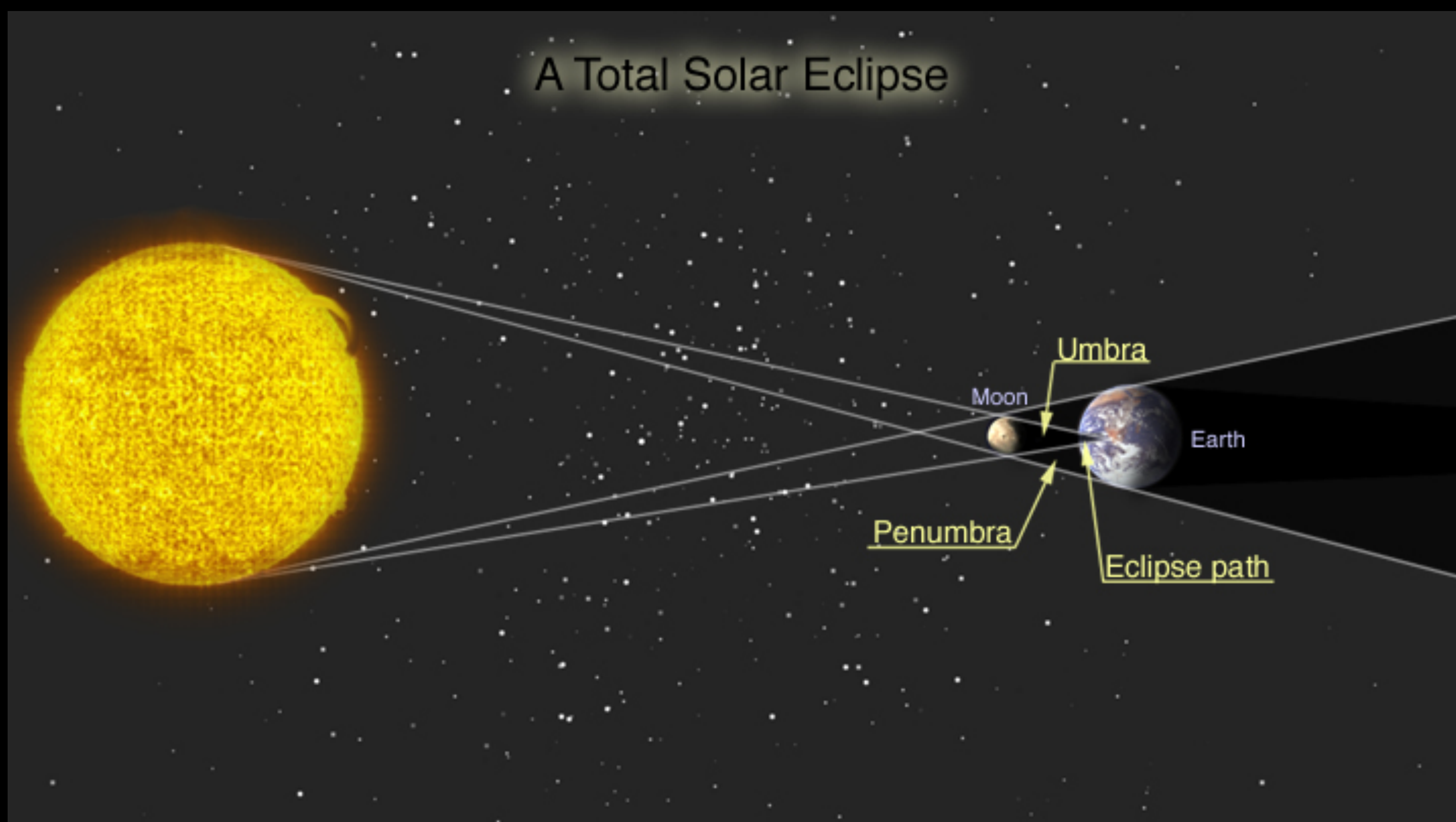
Annular eclipses occur when the Moon is a bit farter away so its apparent size is too small to cover the entire Sun. A thin ring of the solar surface will be visible around the Moon. Partial eclipses occur where only a part of the Sun is covered by the Moon.

SOLAR ECLIPSES

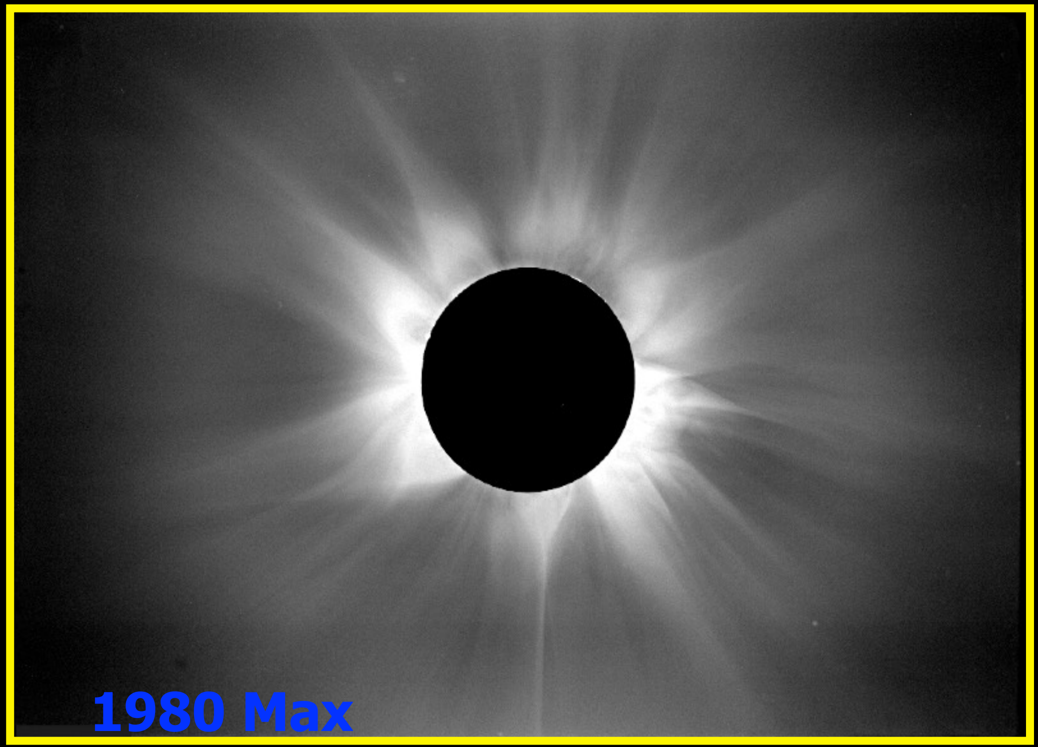
Partial Eclipse

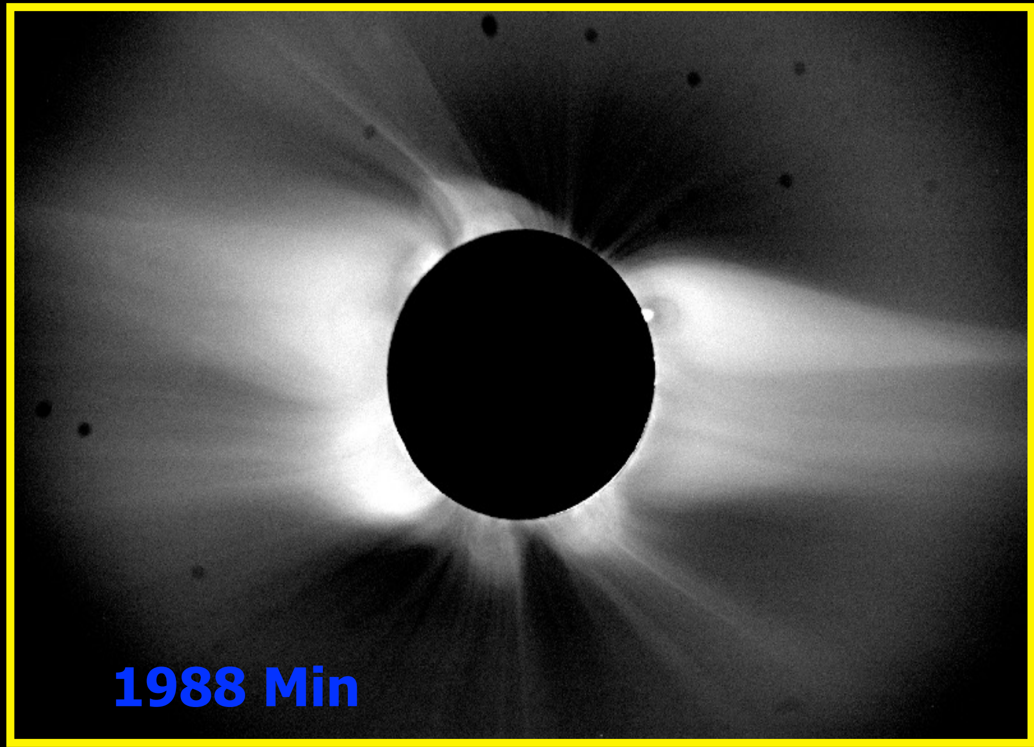
Total Eclipse

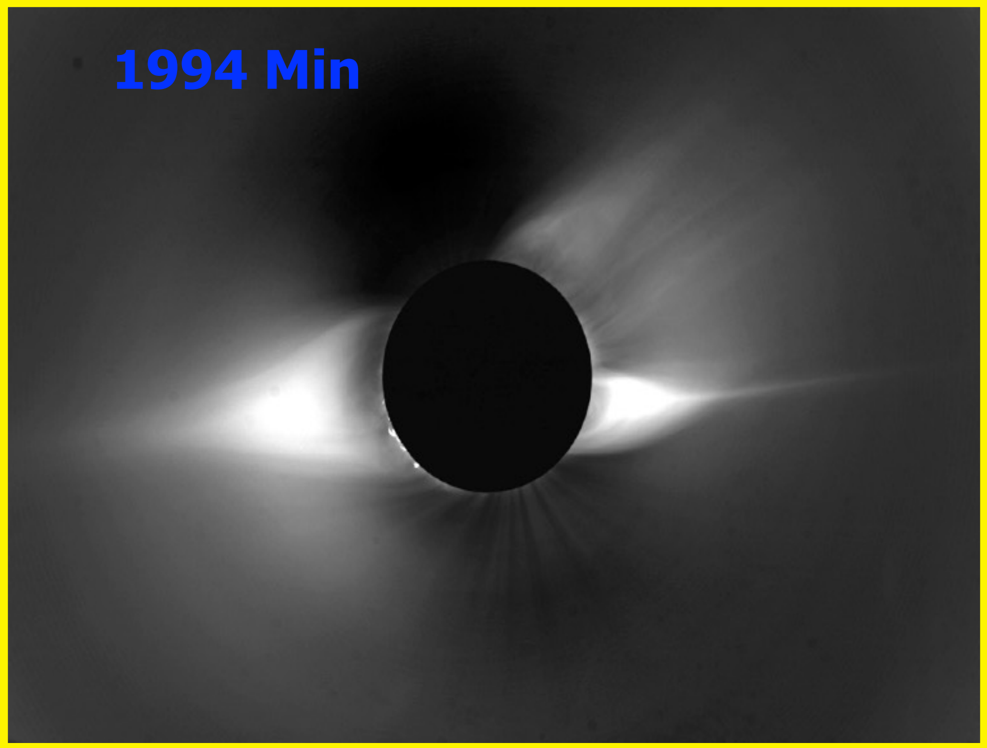
Annular Eclipse



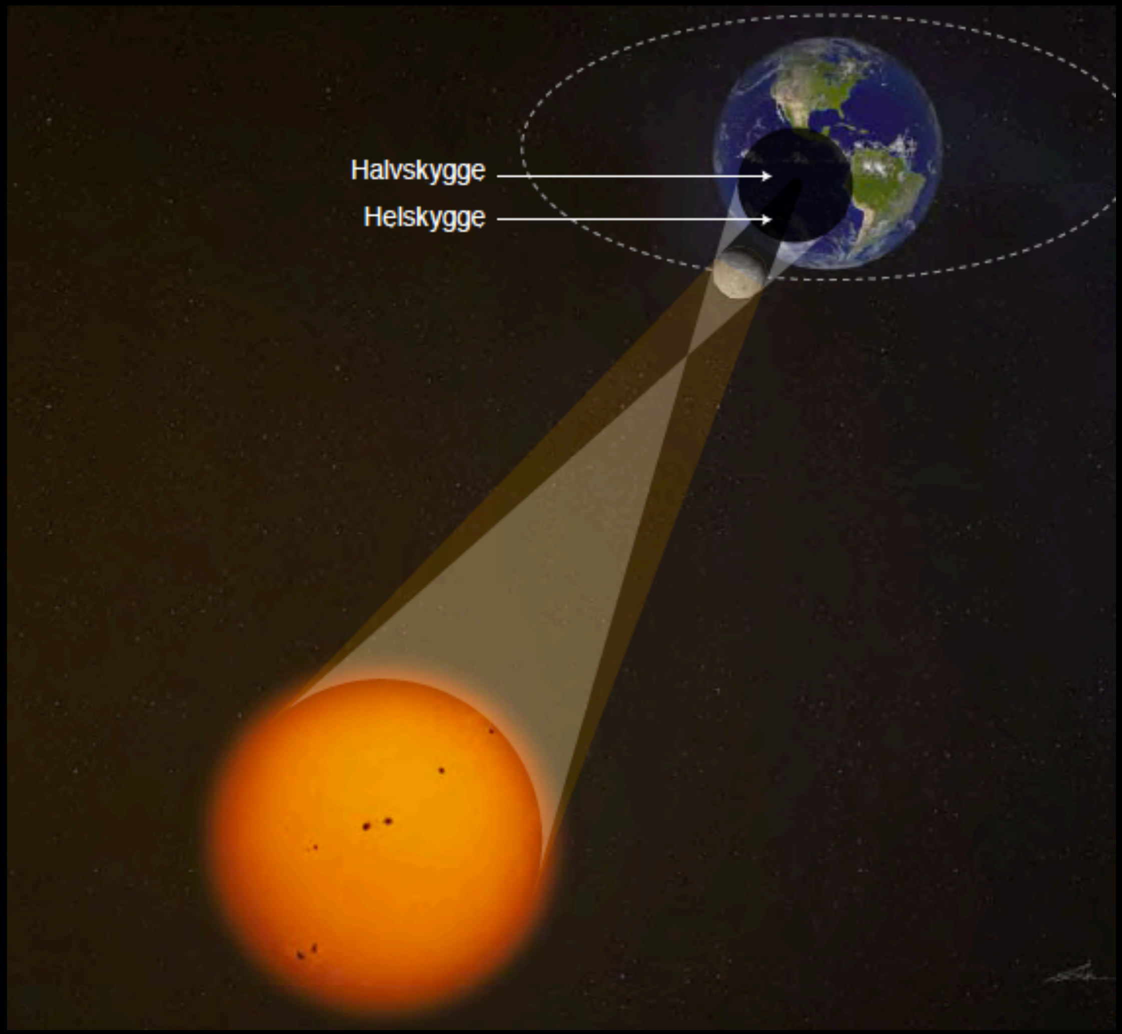
THE CORONA - DURING ECLIPSES

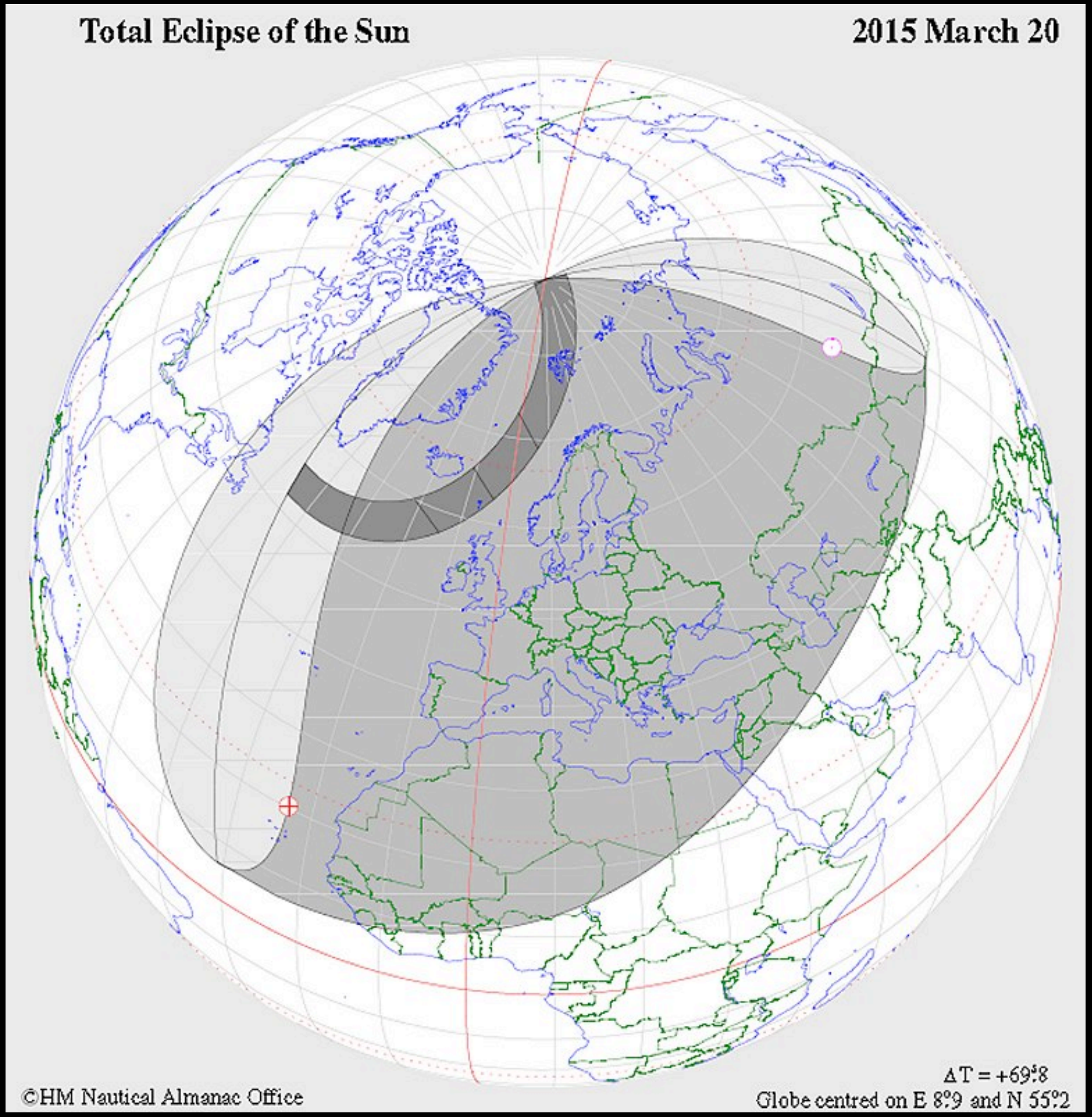






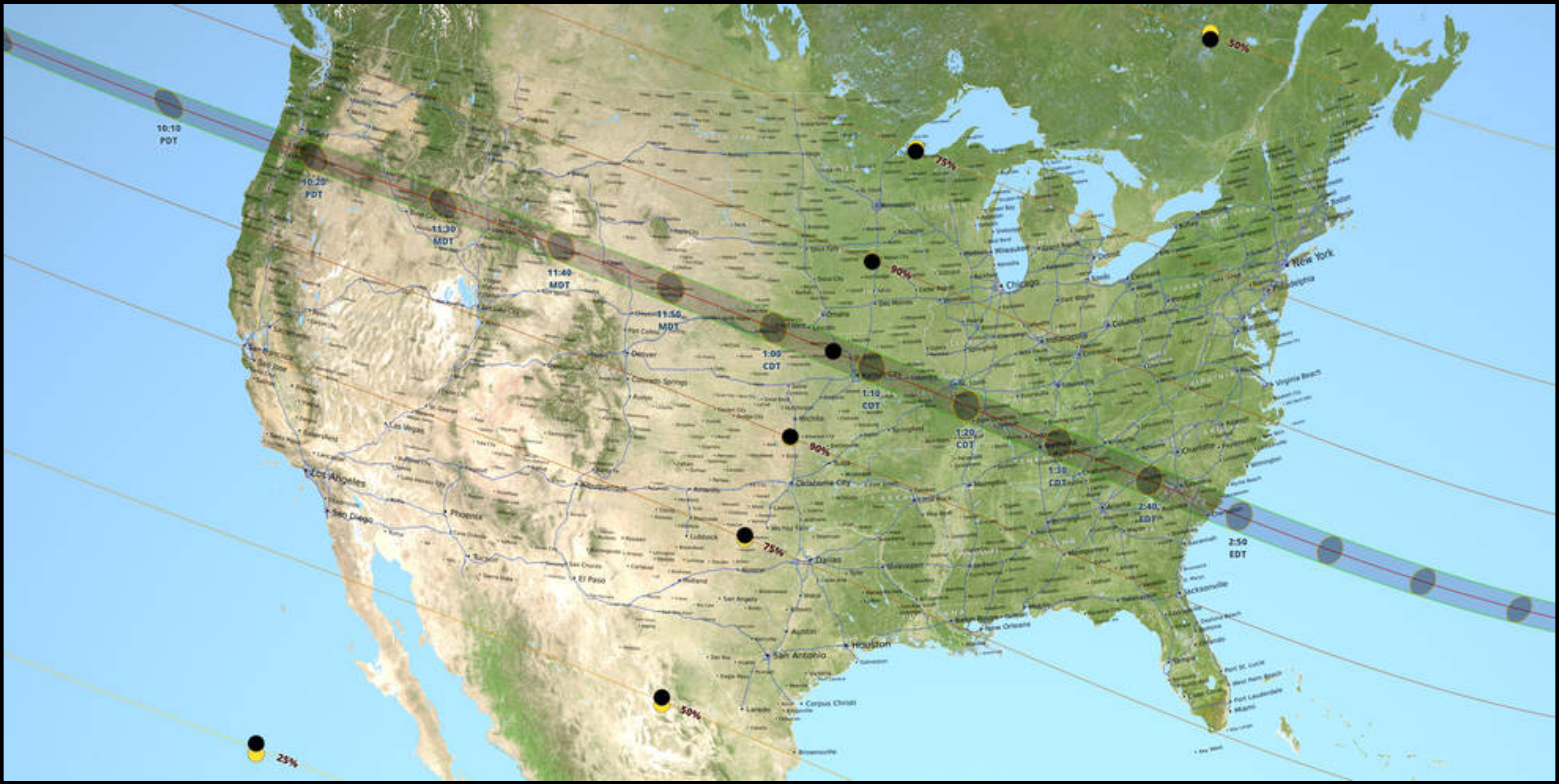
Total eclipse over Svalbard 2015



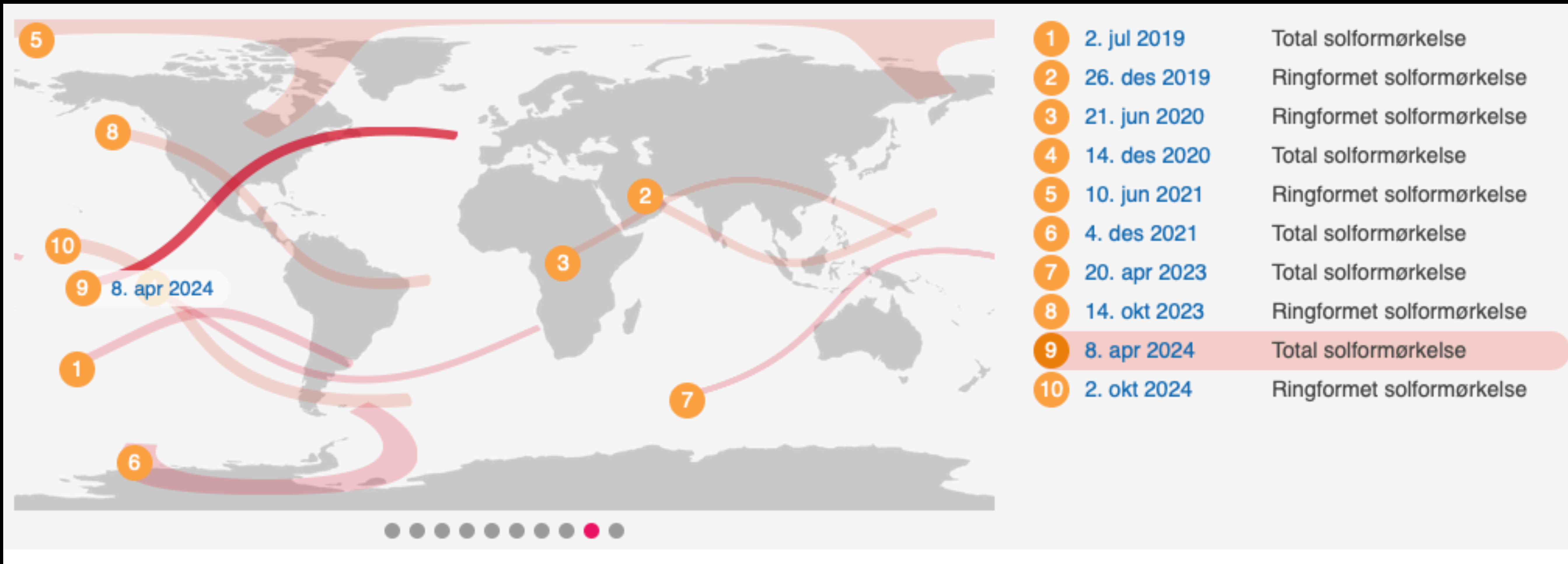


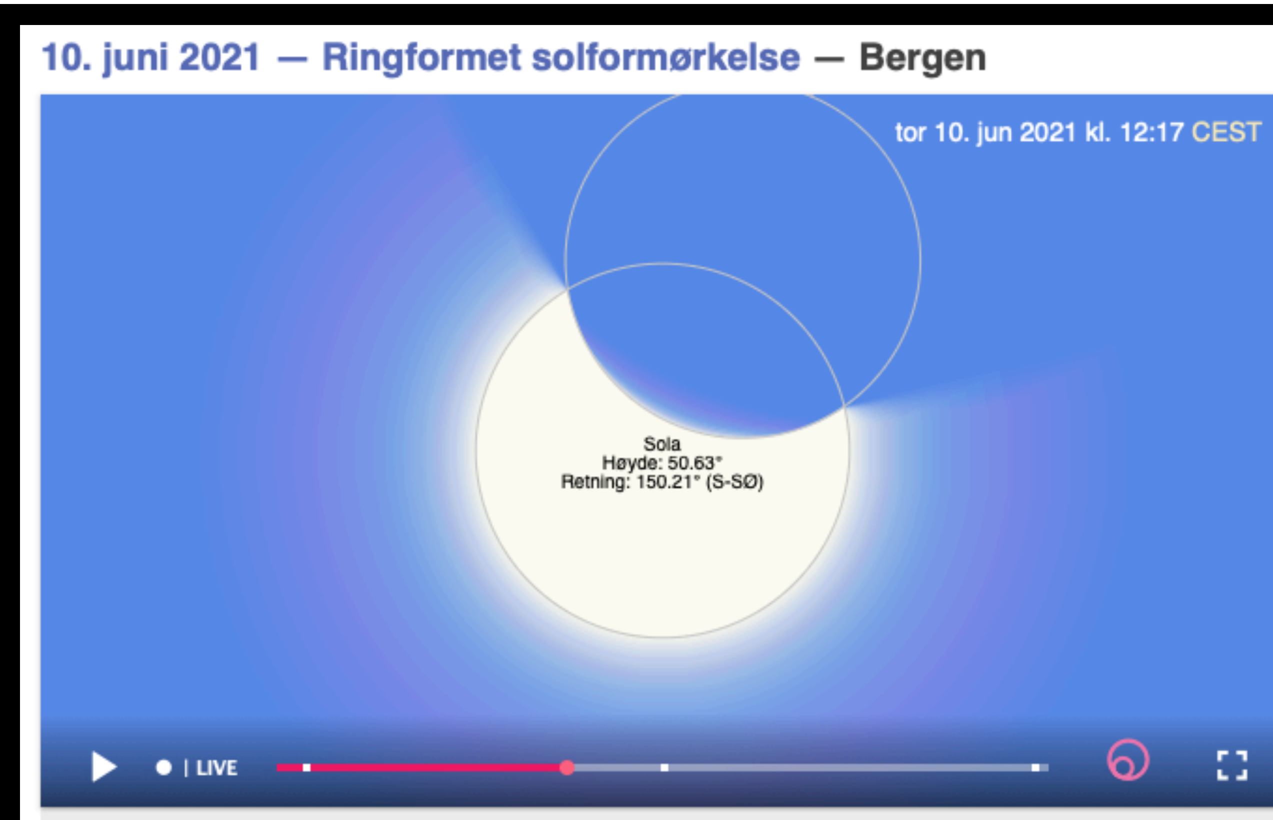
Total Eclipse over Svalbard 20 March 2015

Total Eclipse over USA 2017

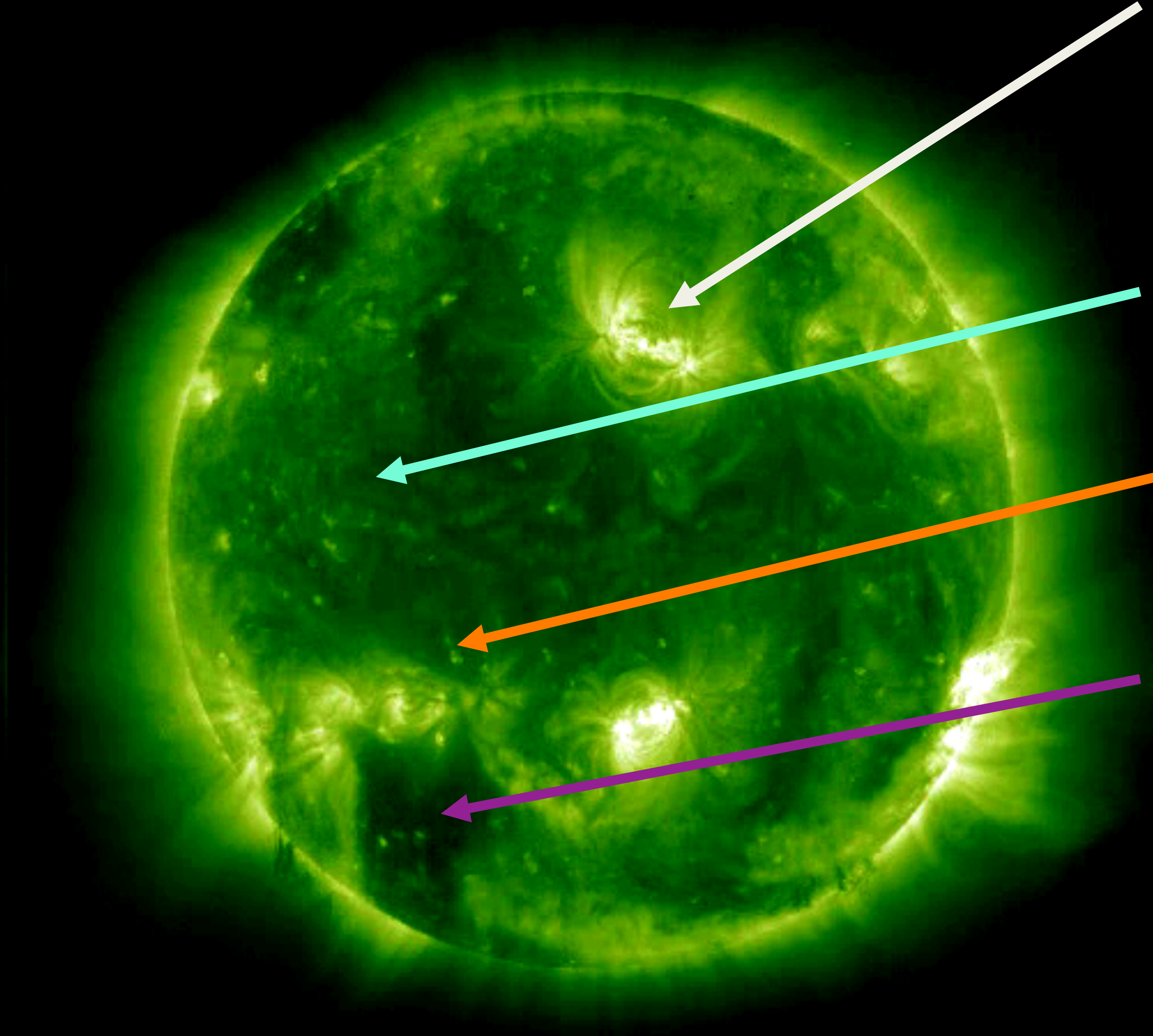


Future eclipses



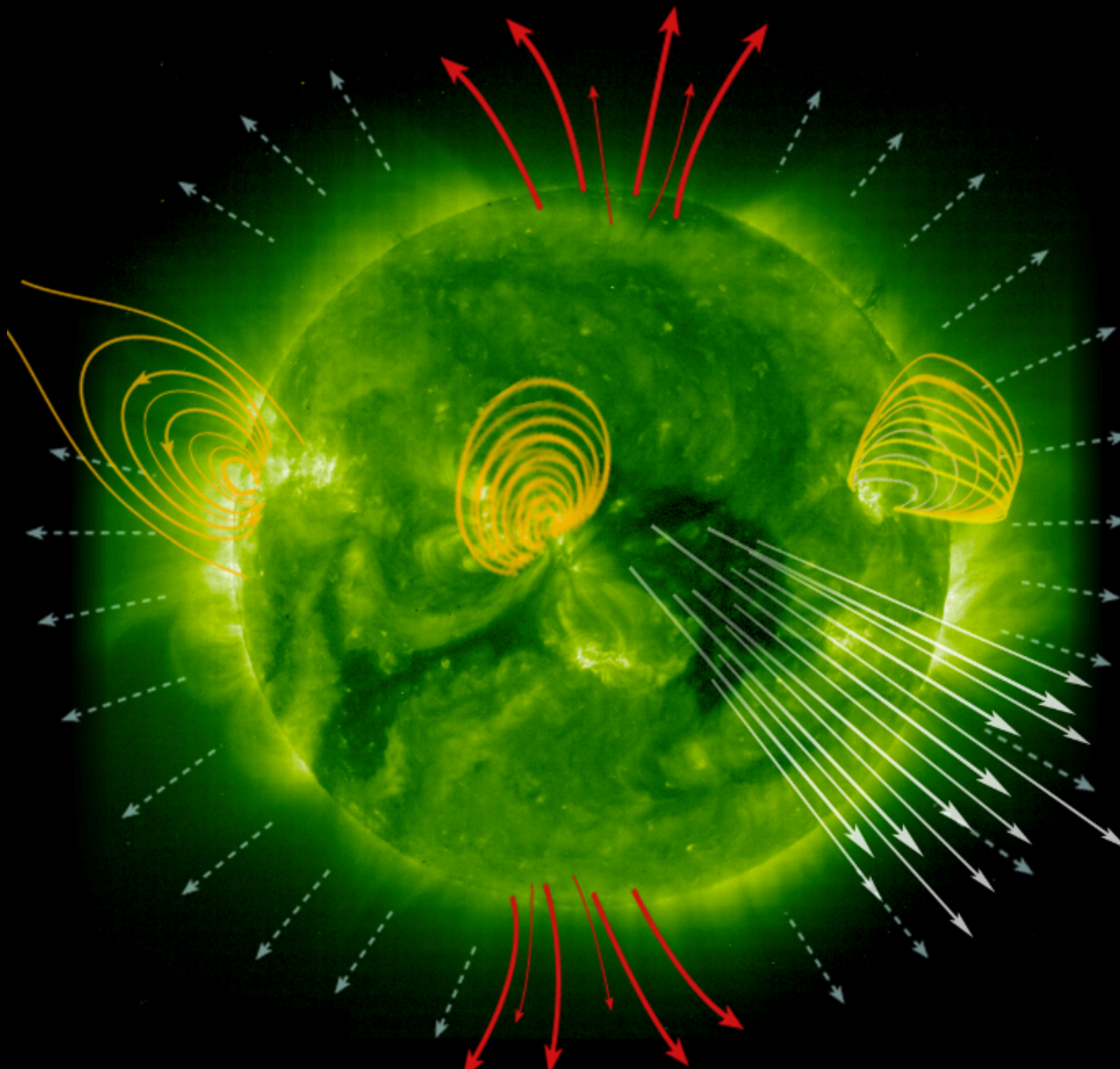


CORONAL FEATURES

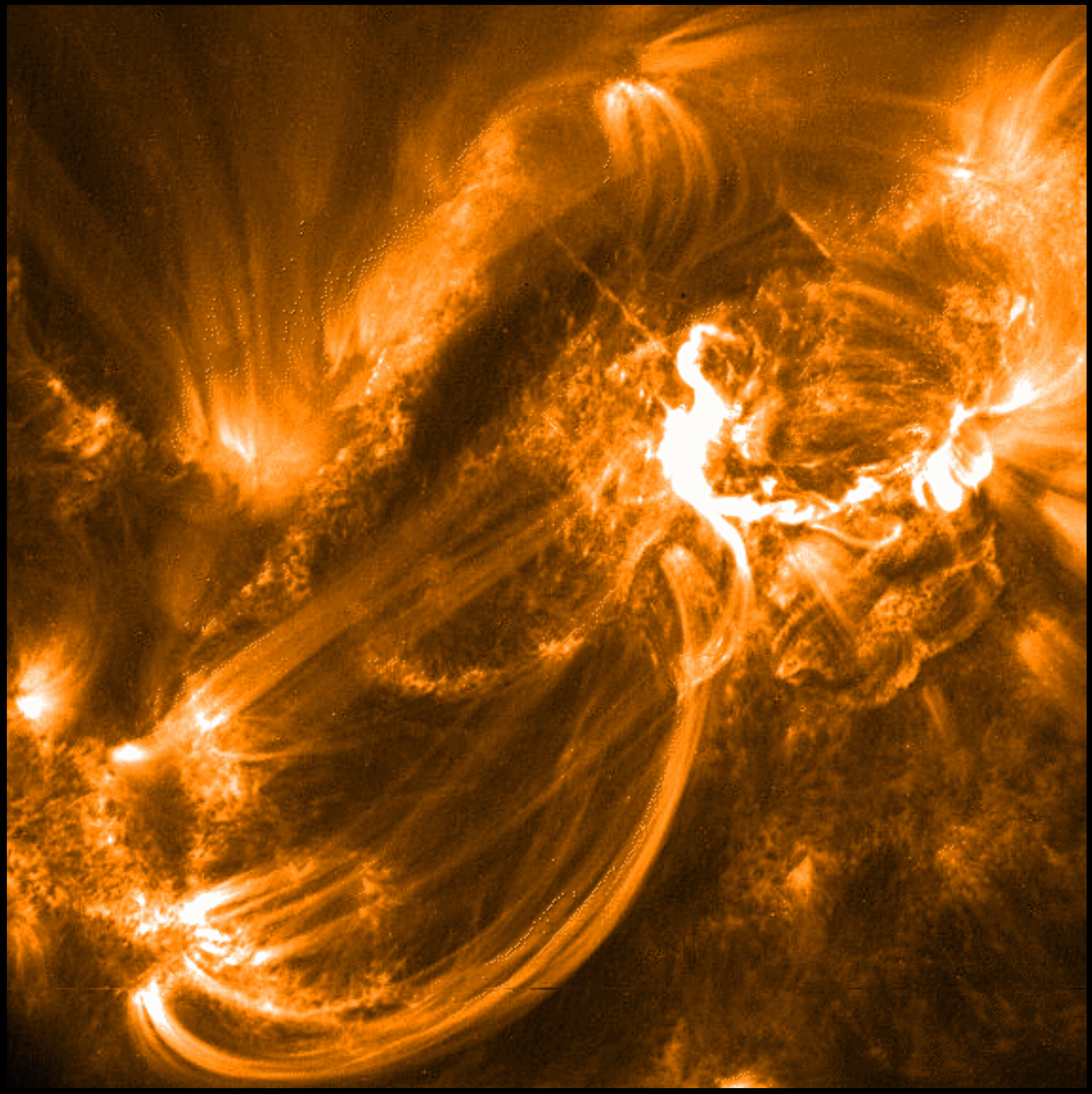


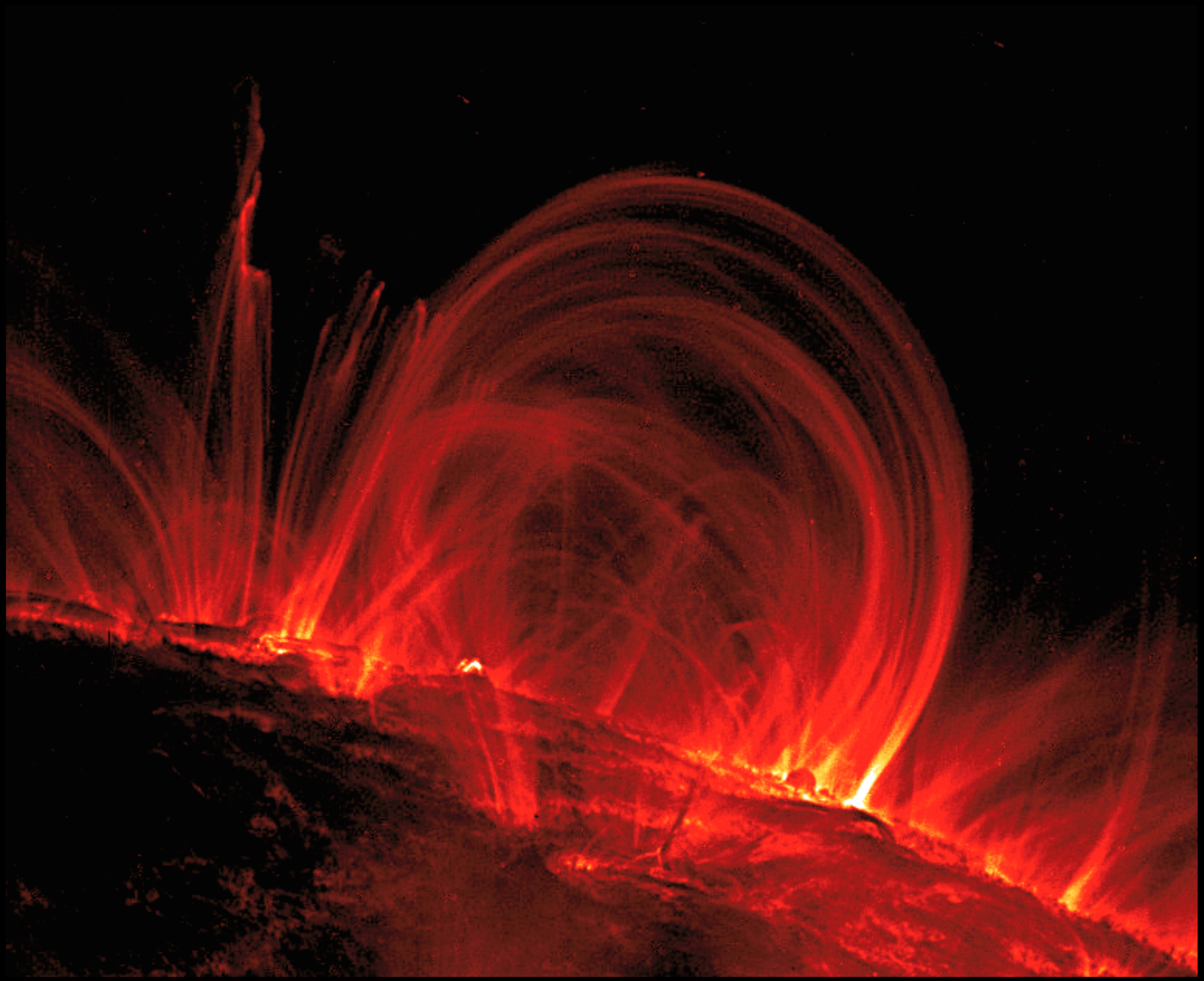
- Active regions (loops)
- Quiet Sun
- X-ray bright points
- Coronal holes

CORONAL FEATURES



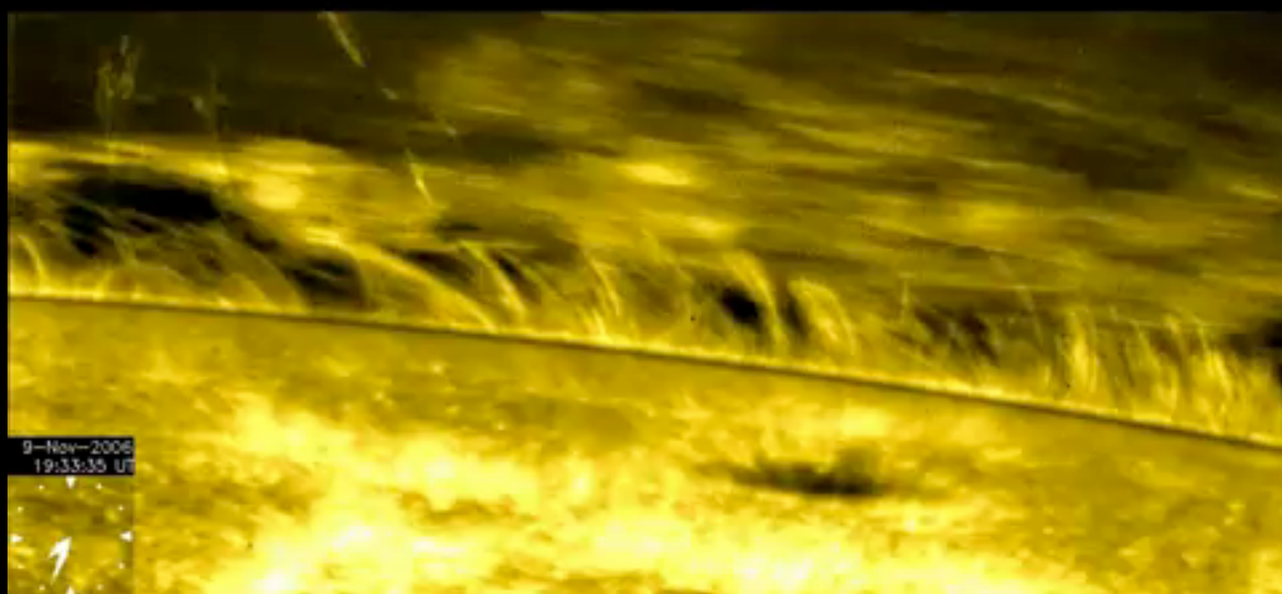
Coronal structure: active region loops



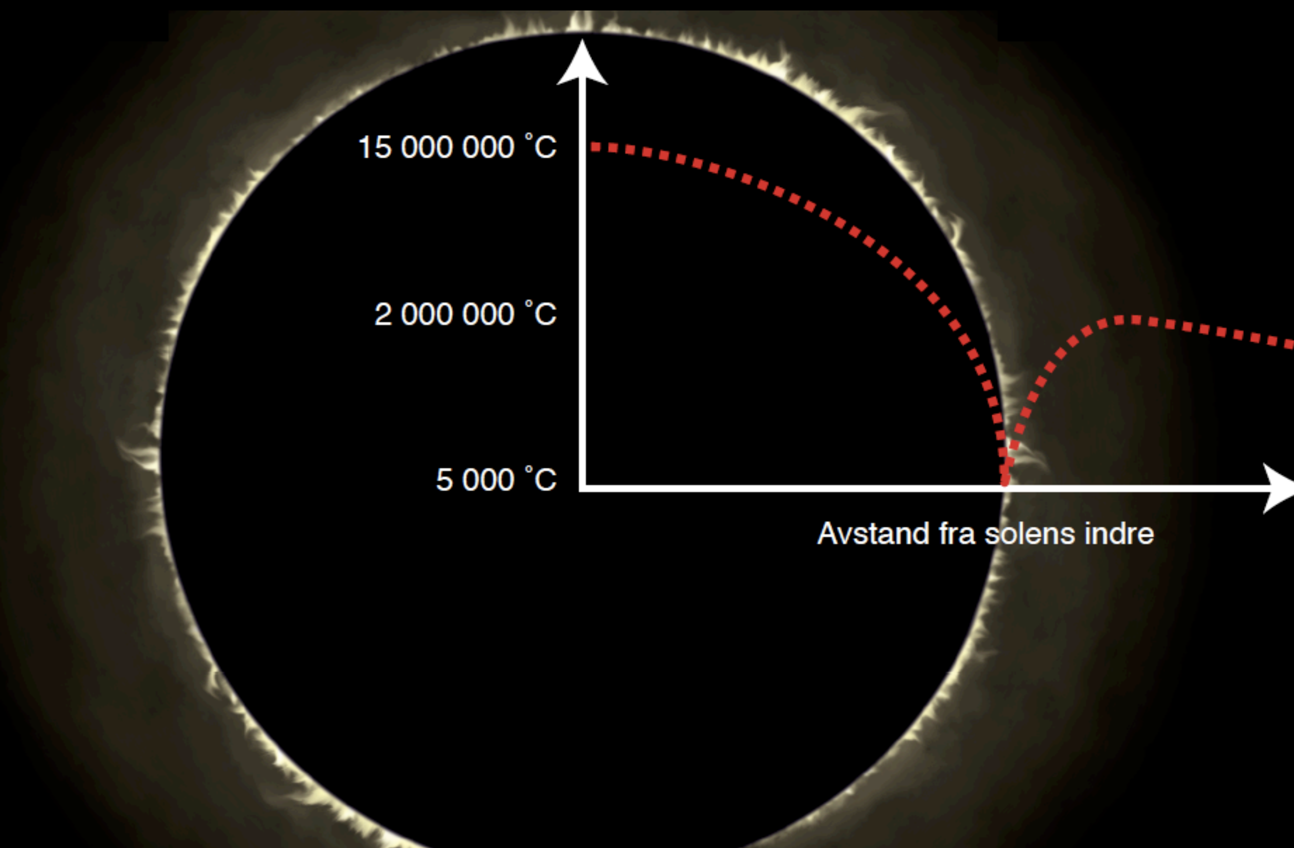


TRACE, 1999

WHY IS THE CORONA HOT?



SOT/Hinode

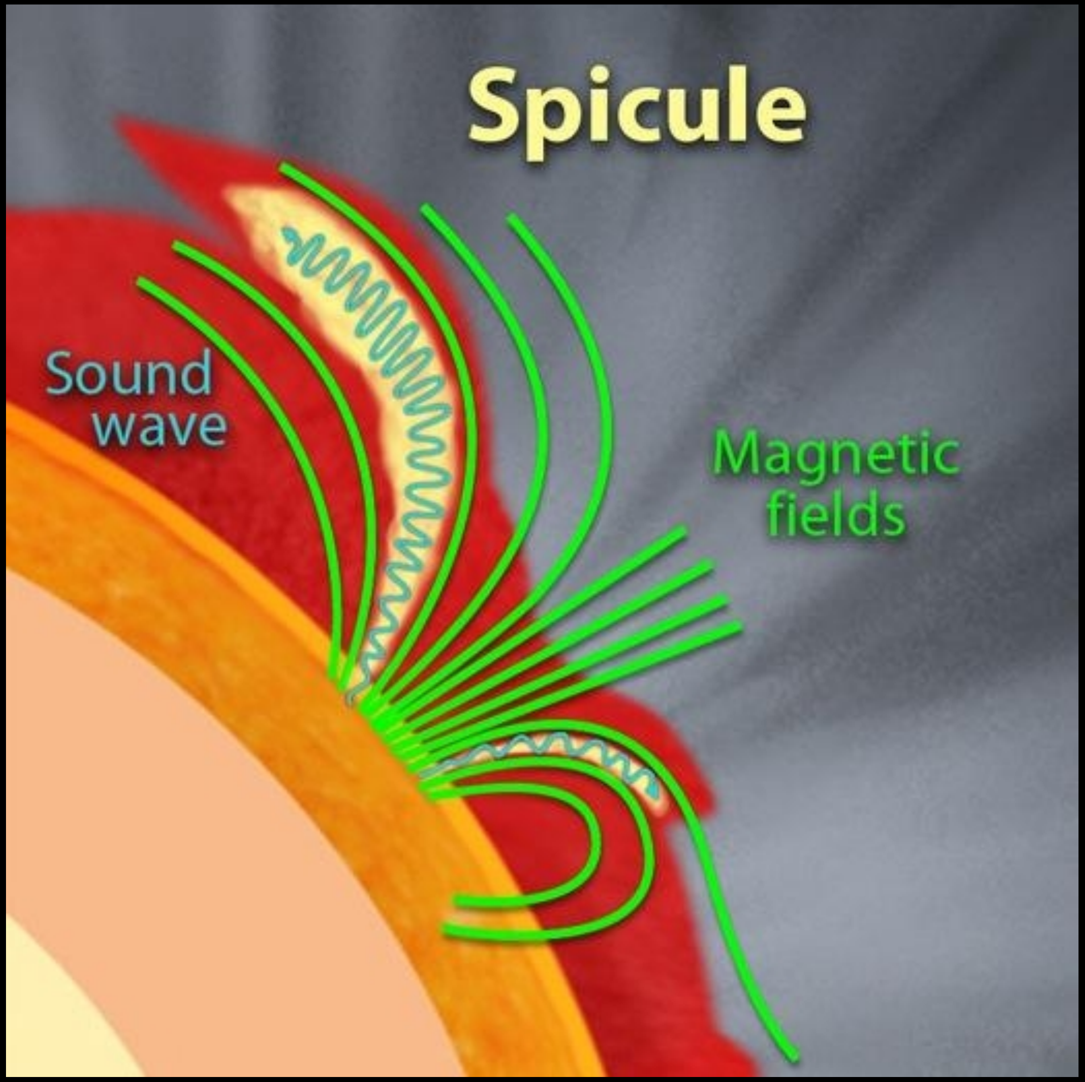


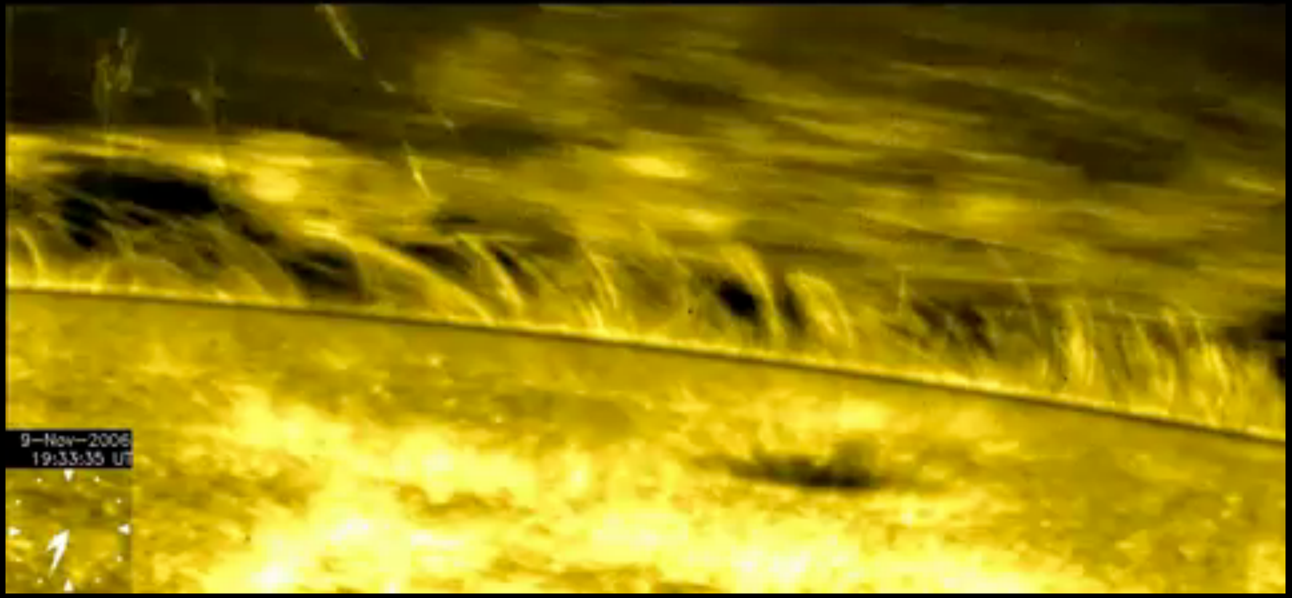
T.Abrahamsen/ARS

Most probably the heating is done via:

- Sound waves propagating up through the chromosphere
- Magnetic reconnections

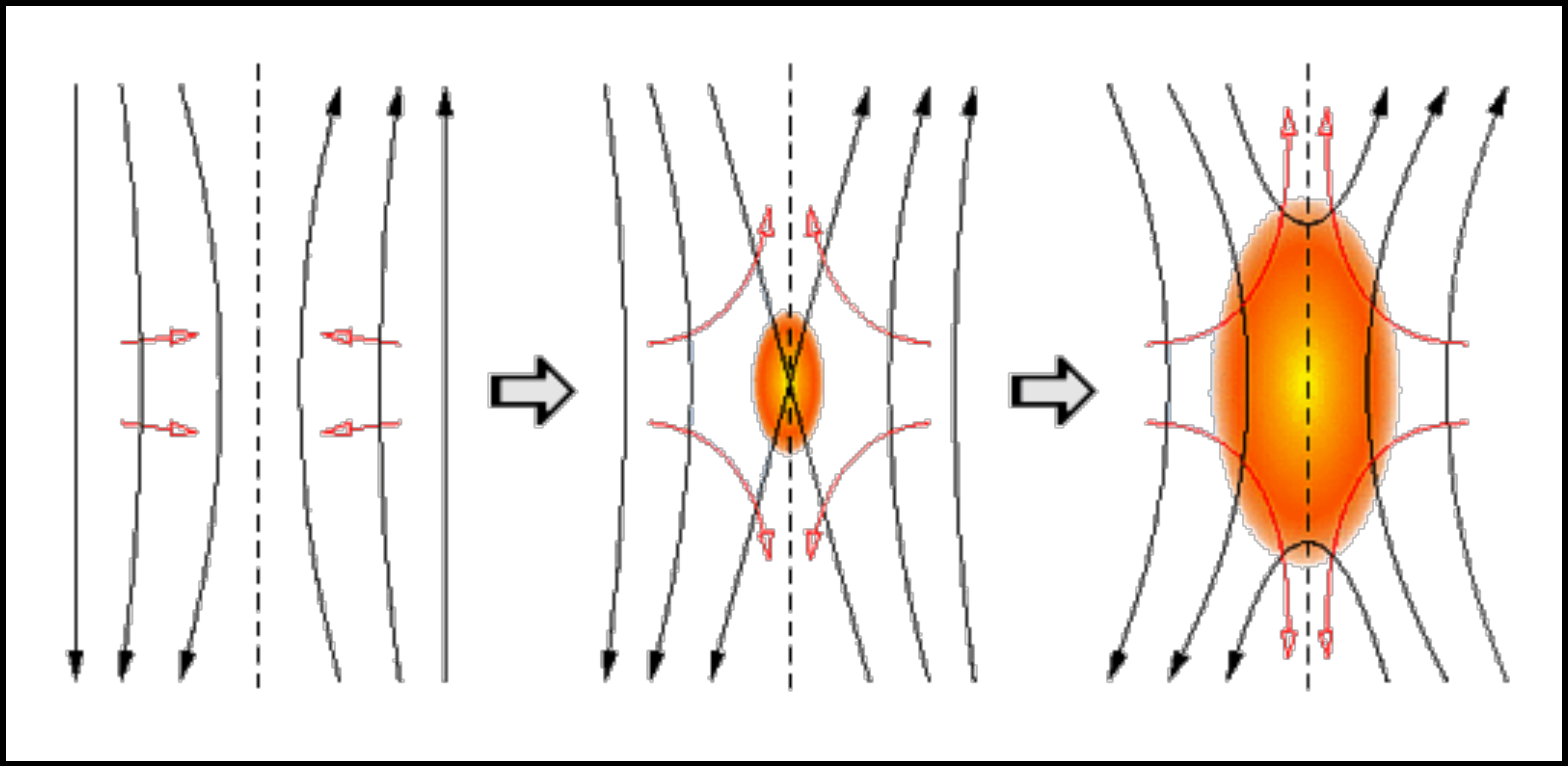
Sound waves





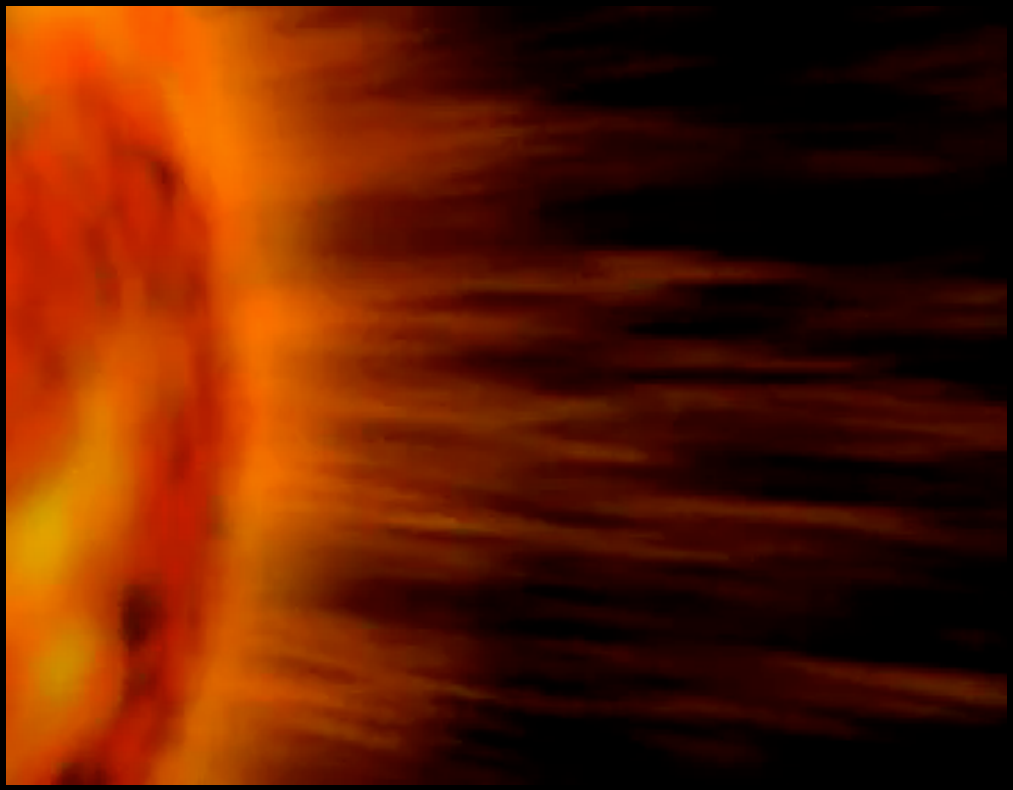
- Sound waves propagating up through the chromosphere

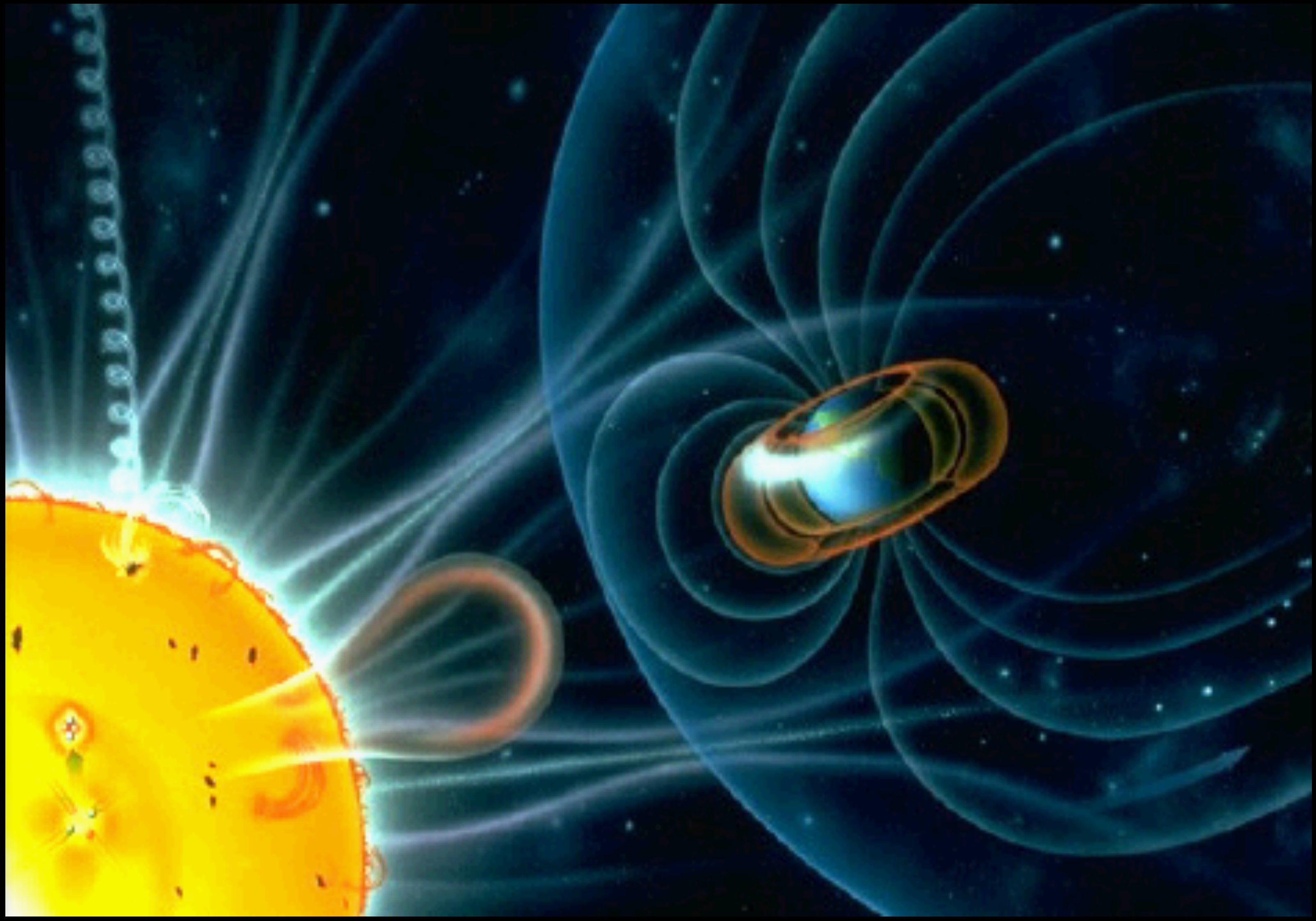
Magnetic reconnection



What is the Solar Wind?

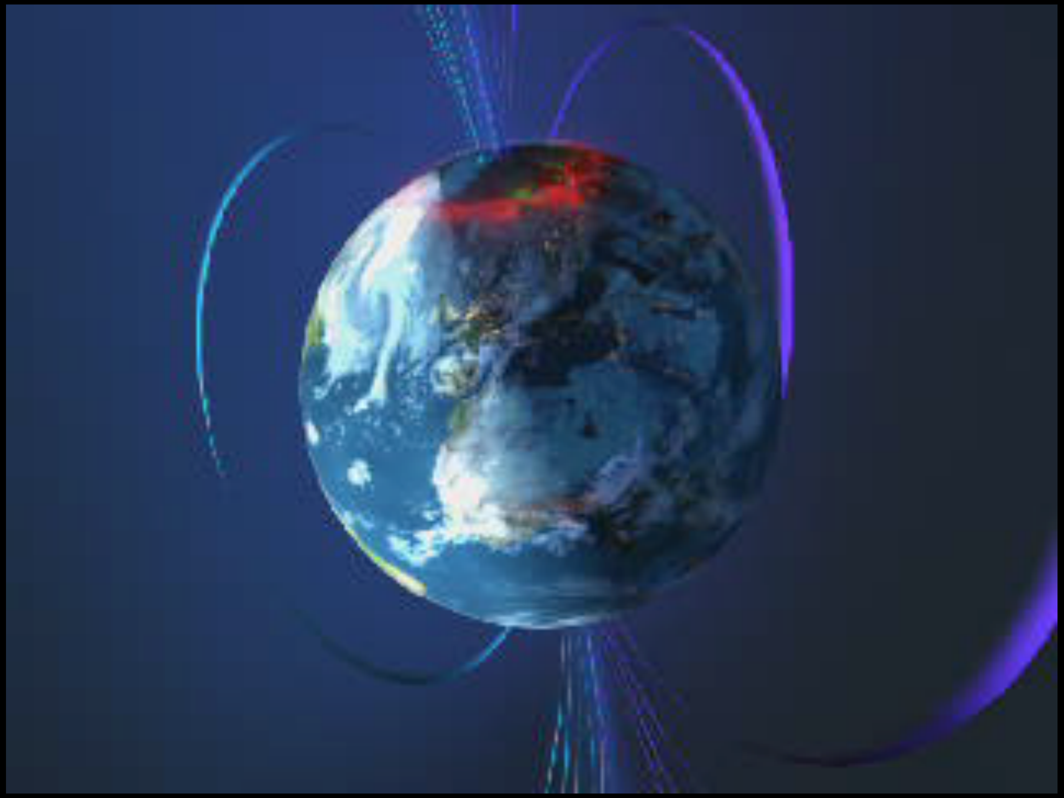
- A constant stream of particles flows from the Sun's corona, with a temperature of about a million degrees and with a velocity of about 1.5 million km/h. The solar wind reaches out beyond Pluto's orbit (about 5900 million kilometres). The drawing shows how it pushes on and shapes the Earth's magnetosphere.

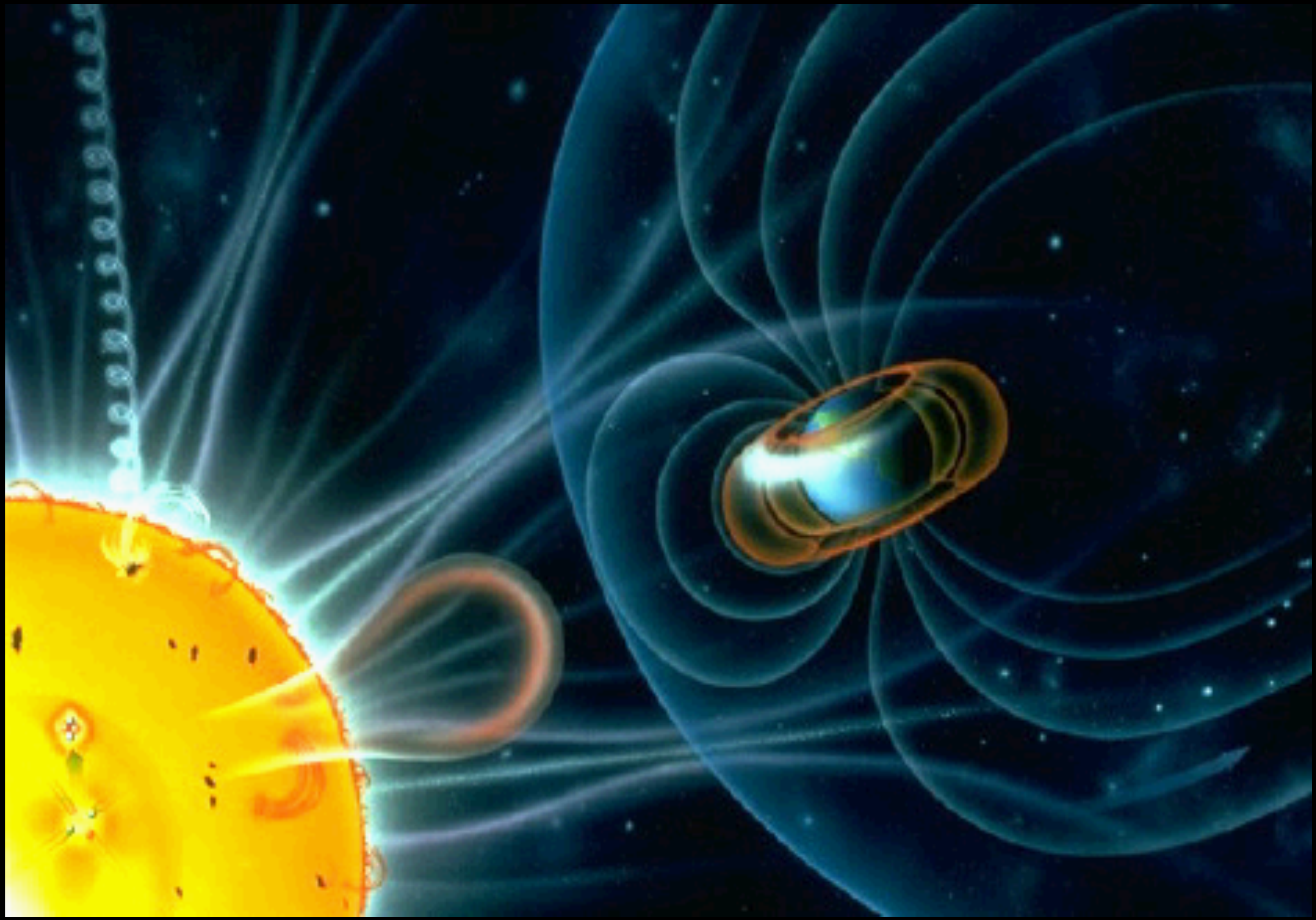




What is the Solar Wind?

- The solar wind is a stream of charged particles released from the upper atmosphere of the Sun, called the corona. This plasma consists of mostly **electrons, protons and alpha particles** with kinetic energy between 0.5 and 10 keV. Embedded within the solar-wind plasma is the interplanetary magnetic fiel



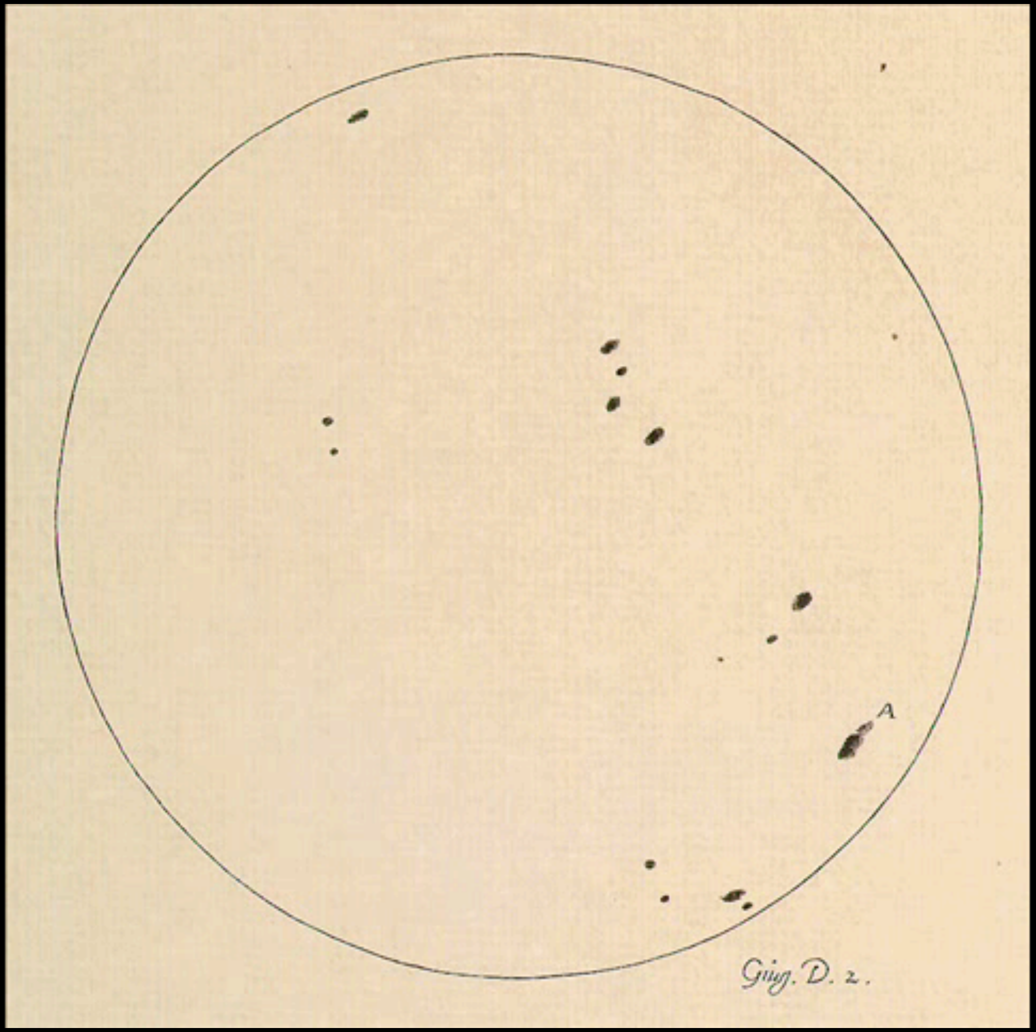


Discovery of solar rotation

- Galileo Galilei and Christoph Scheiner noticed already that sunspots move across the solar disk in accordance with the rotation of a round body

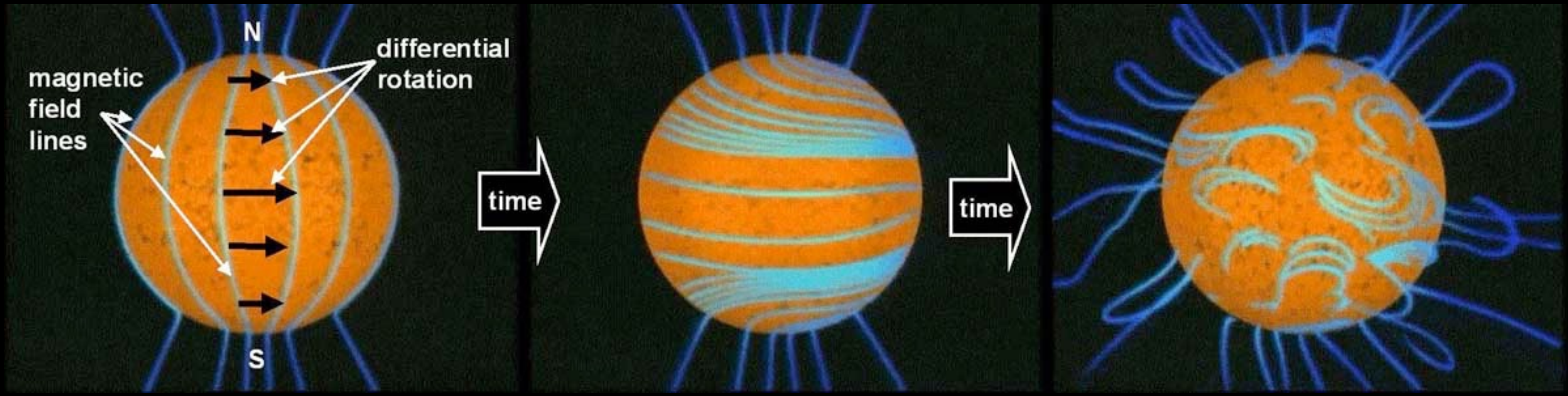
➔ Sun is a rotating sphere

- Movie based on Galileo Galilei's historical data



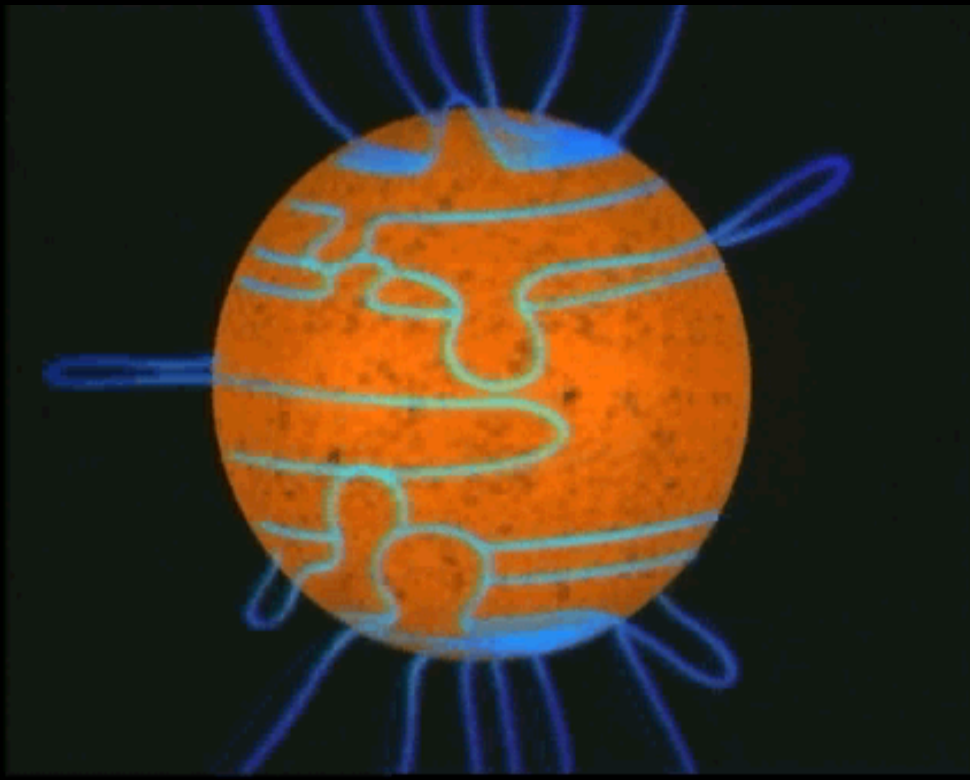
Solar rotation

- The Sun rotates differentially, both in latitude (equator faster than poles) and in depth (more complex).
  - Equatorial regions of the Sun make a complete rotation every 25 days while the poles may take 36 days.
- Standard value of solar rotation: Carrington rotation period: 27.2753 days (the time taken for the solar coordinate system to rotate once).

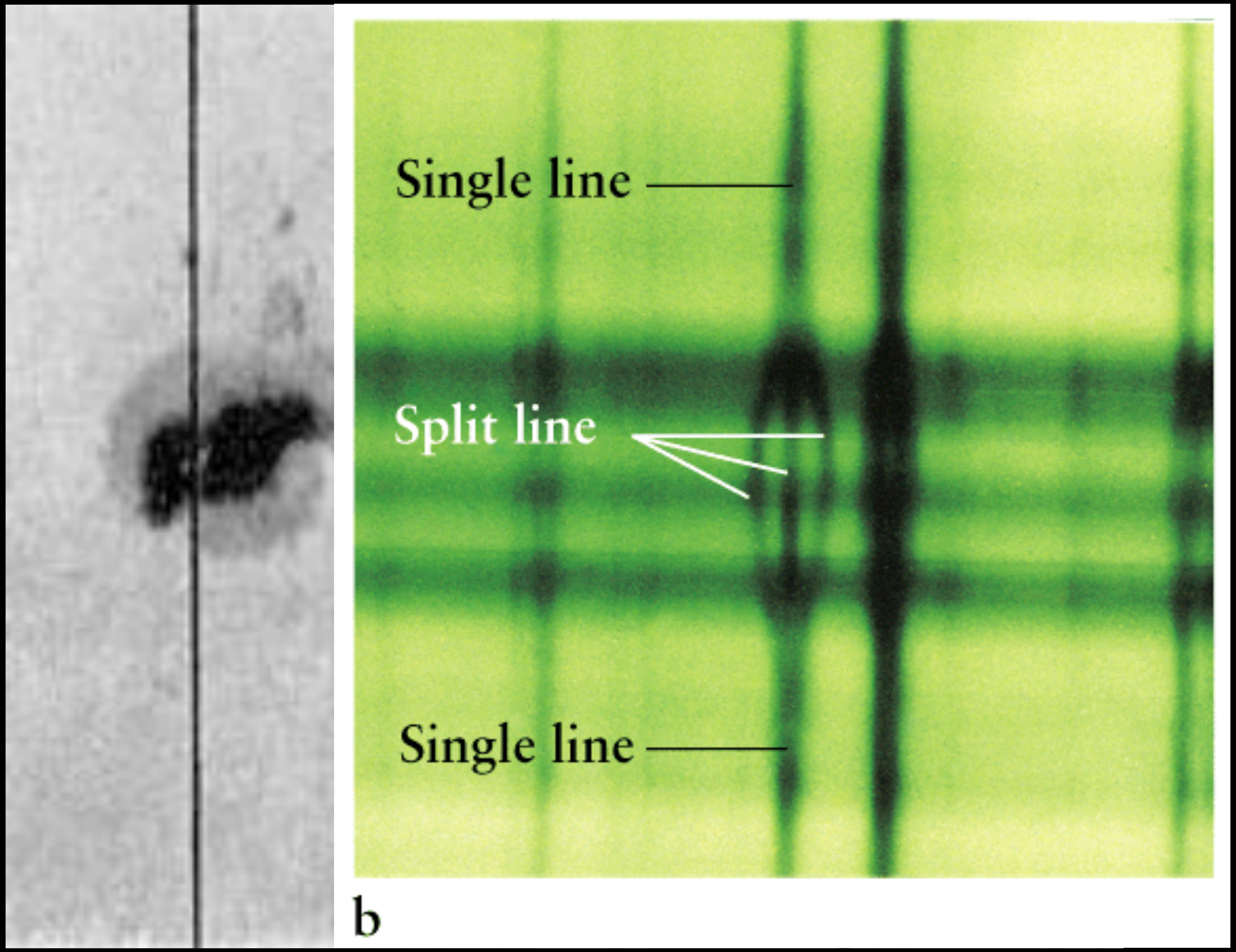


Differential Rotation - Magnetic Field

The differential rotaion of the Sun drags the magnetic field lines with it and winds them up

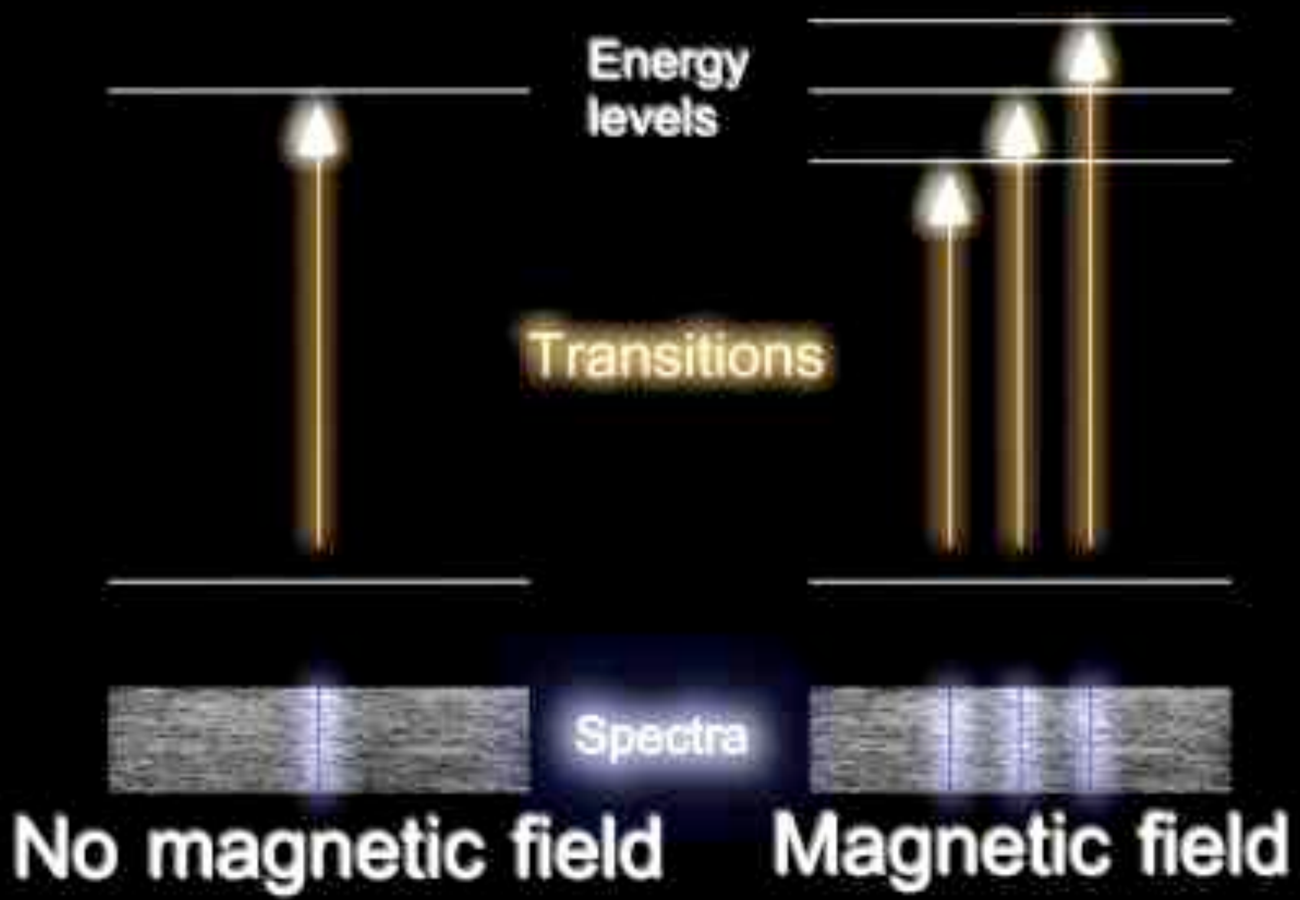


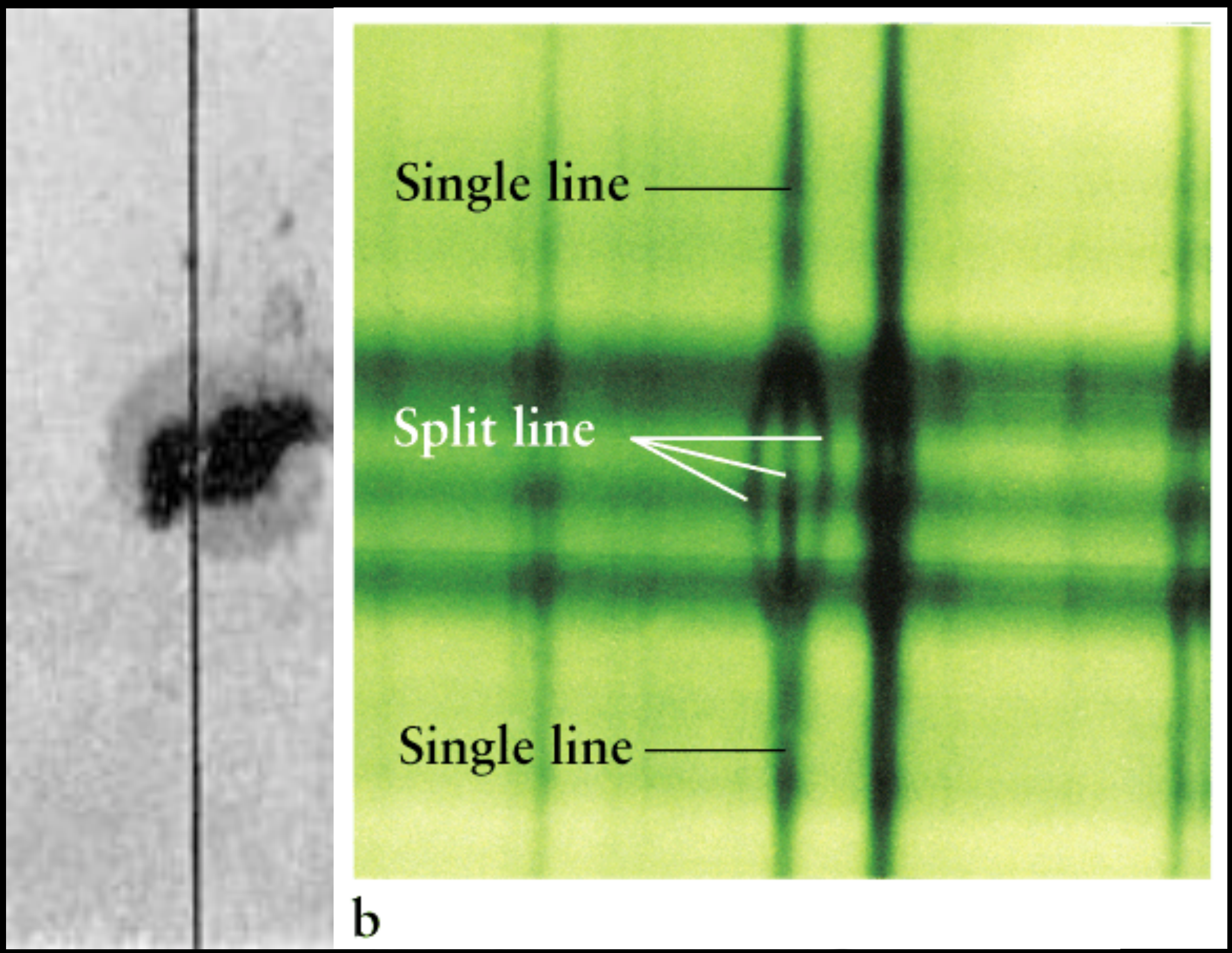
The Suns Magnetic Field - Zeeman-effect



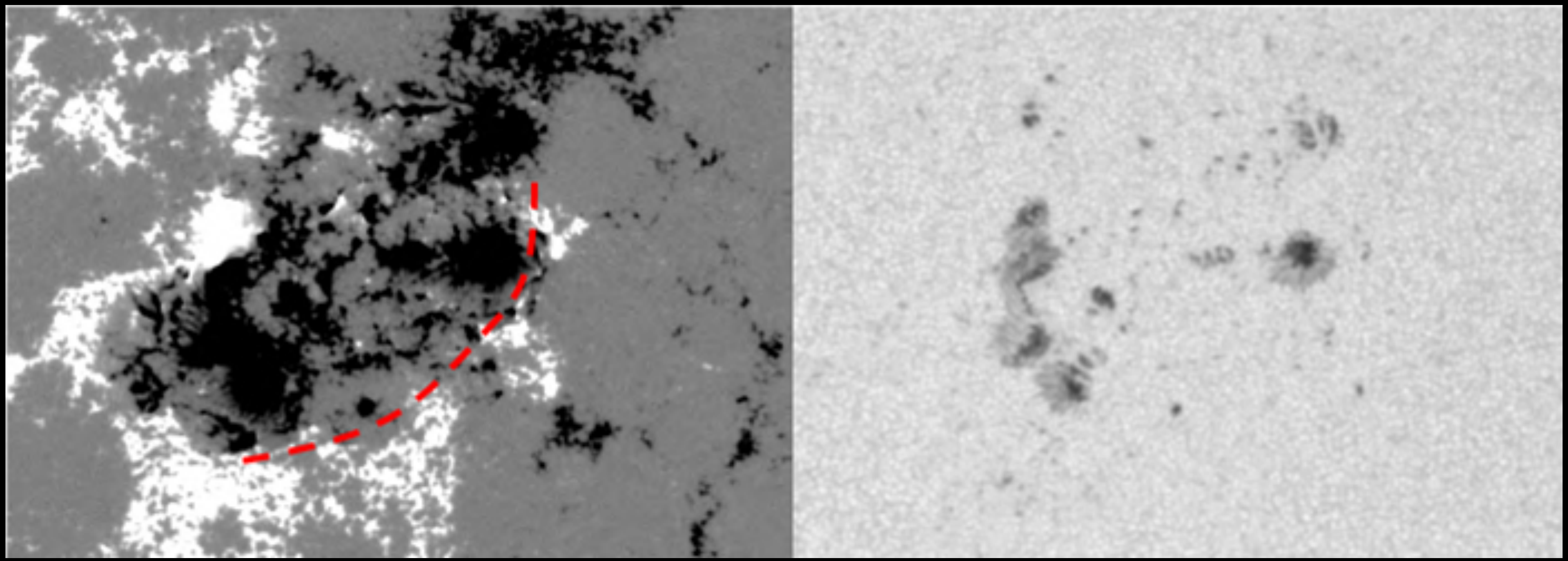
Zeeman effect,, in physics and astronomy, the splitting of a spectral line into two or more components of slightly different frequency when the light source is placed in a magnetic field. It was first observed in 1896 by the Dutch physicist Pieter Zeeman

The Suns Magnetic Field - Zeeman-effect



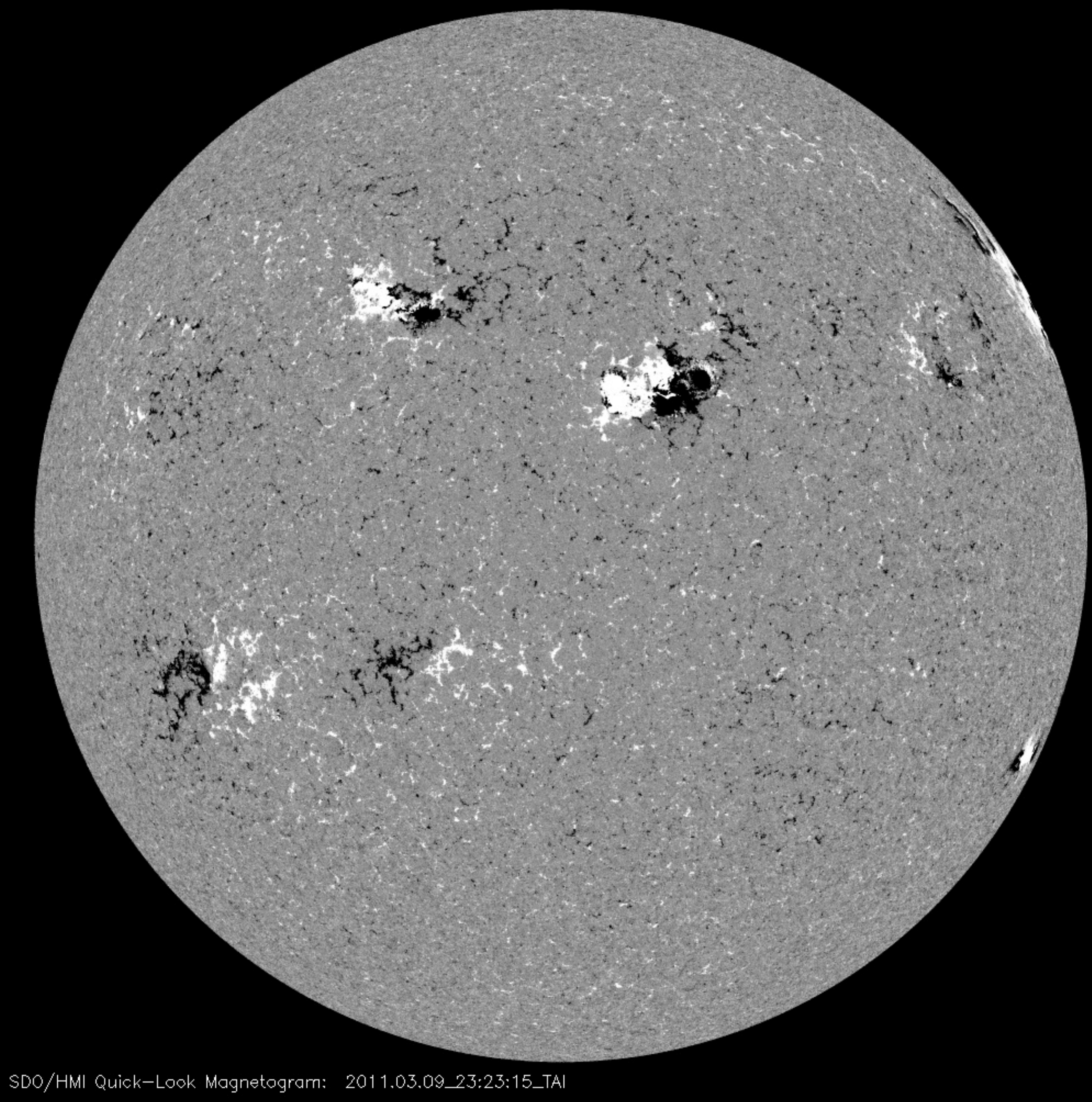


The Suns Magnetic Field - Zeeman-effect



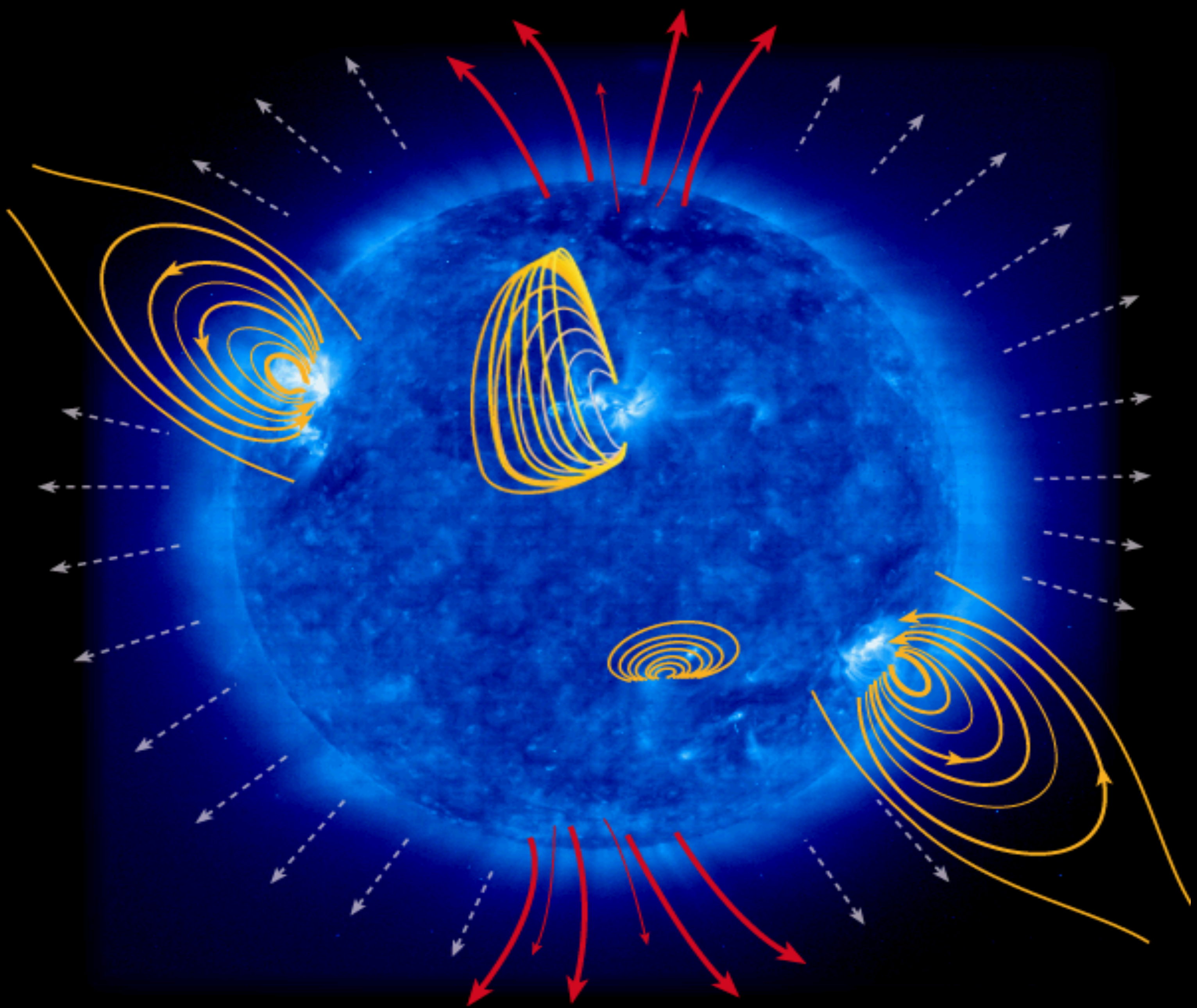
One can then derive maps of the solar surface where black shows areas where the magnetic field comes out of the Sun, and white shows where the magnetic field is directed into the Sun.

The Suns Magnetic Field - Zeeman-effect

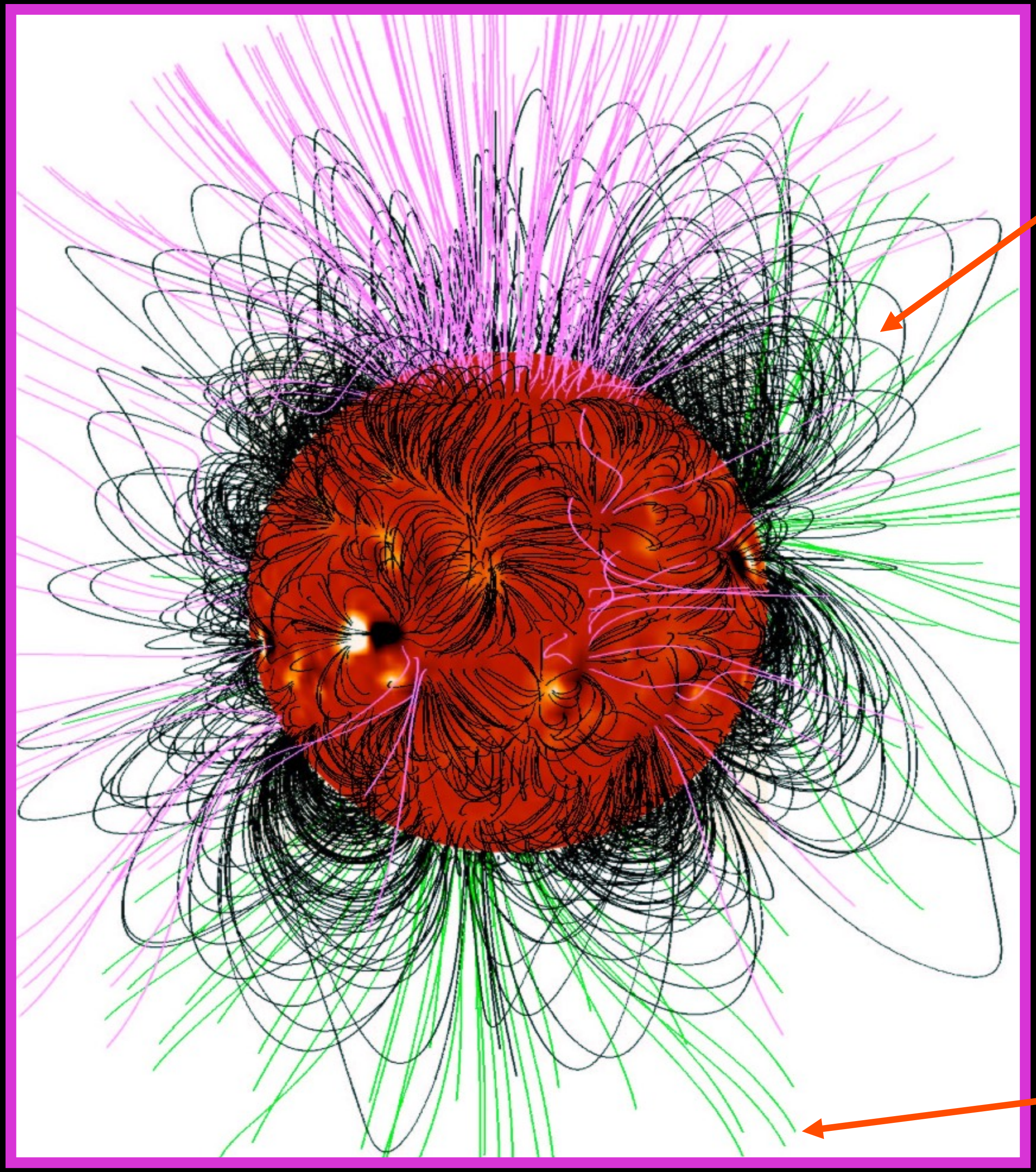


The Sun's Magnetic Field

- The Sun is strongly affected by magnetic forces.
- The red arrows show open magnetic field lines emerging from the poles.
- The gray arrows represent solar wind particles which carry field lines with it.
- The bright active regions have closed magnetic field lines (orange).



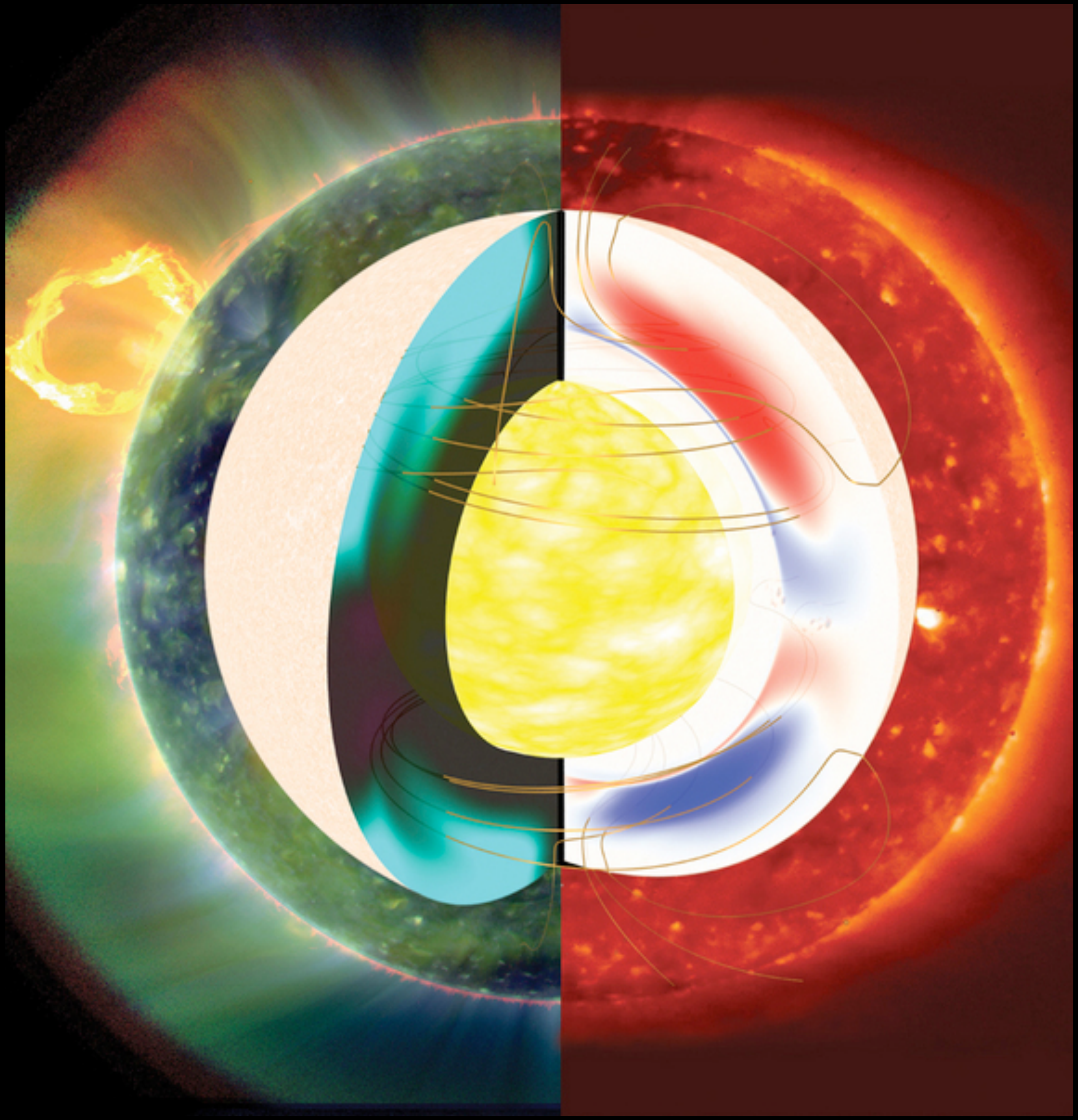
The Sun's Magnetic Field - real life



Closed flux: slow solar wind

Open flux: fast solar wind

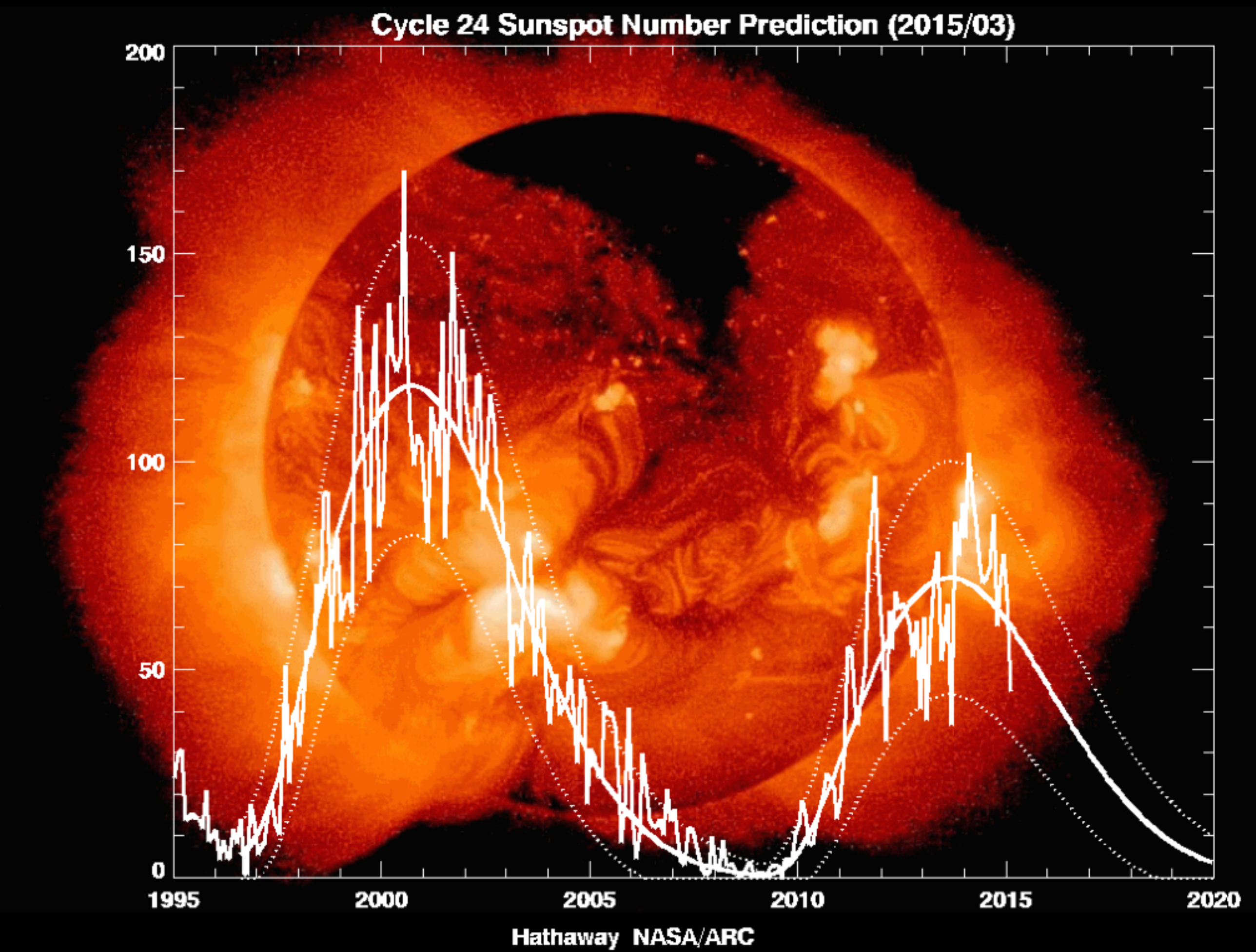
The Solar Dynamo



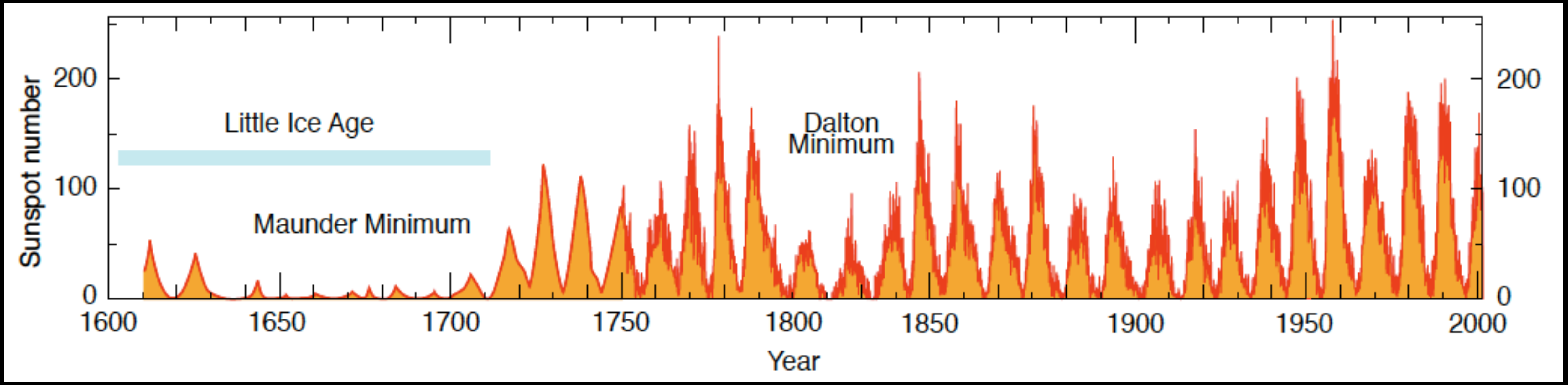
The solar dynamo is the physical process that generates the Sun's magnetic field.

The magnetic fields are generated close to the boundary between the radiation zone (yellow sphere) and the convection zone.

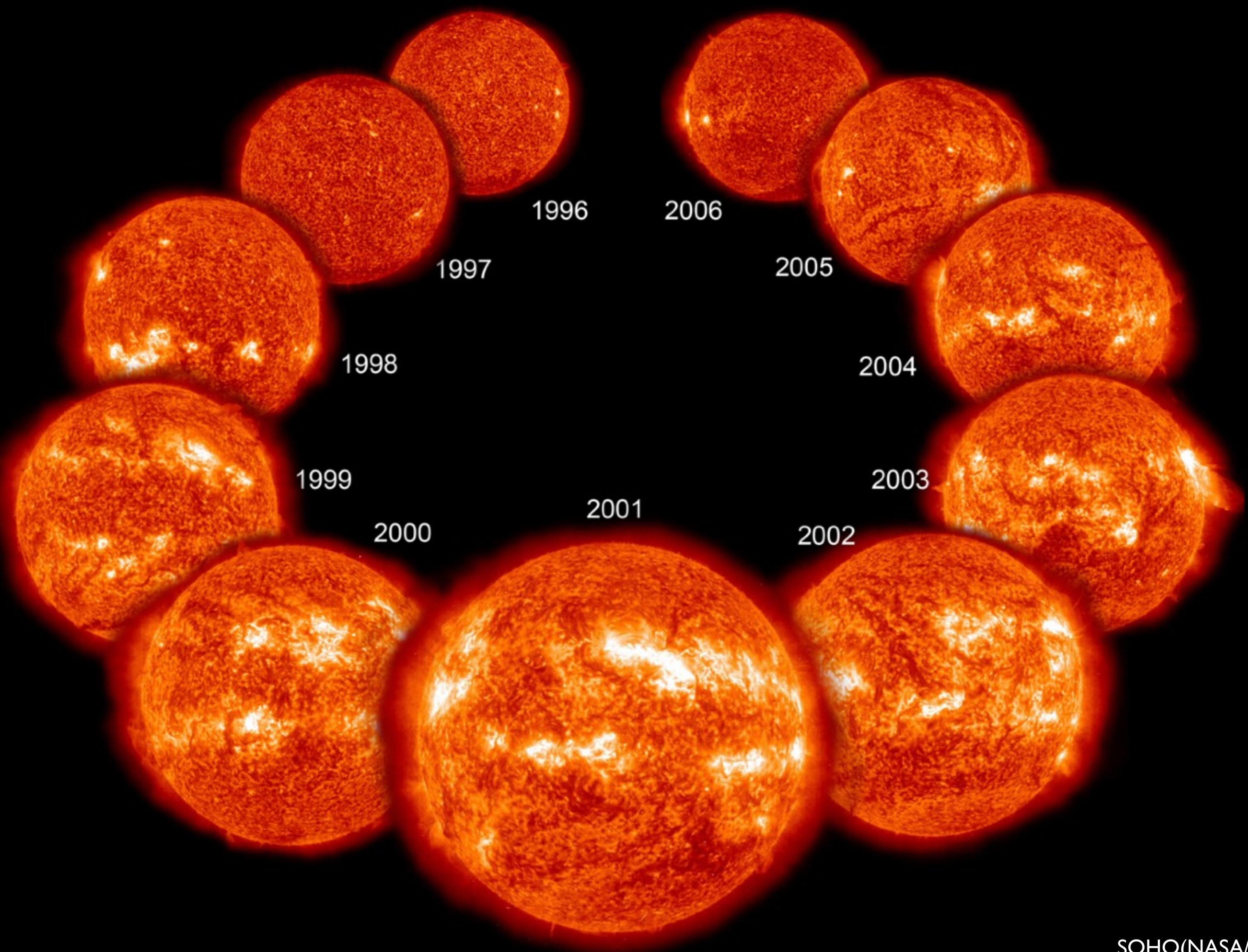
Solar Cycle - historical sunspot records



I 1610 pekte Galileo og Thomas Harriot teleskopet mot Solen for første gang. Galileo skadet synet p.g.a. disse observasjonene.



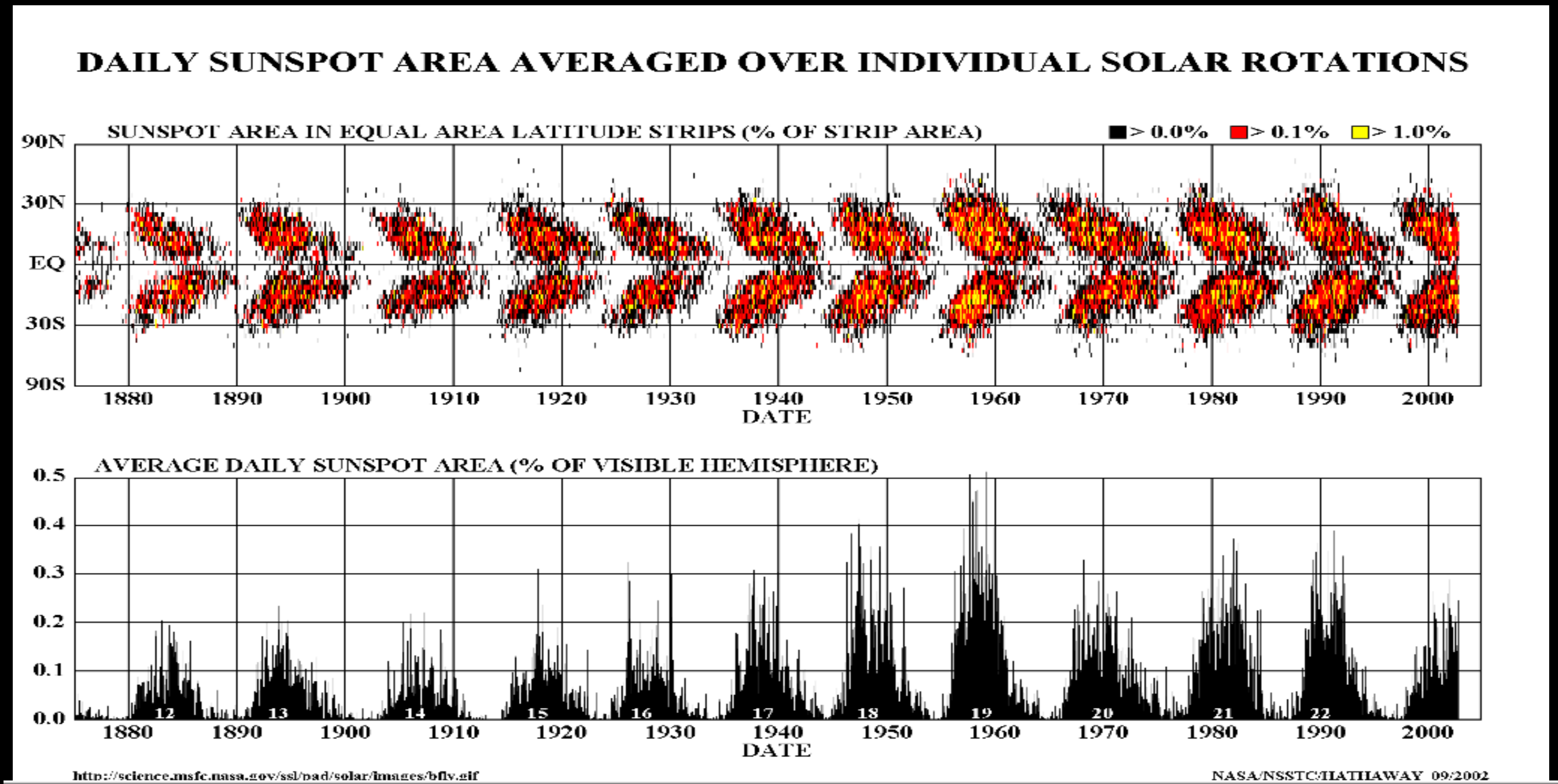
Solar cycles

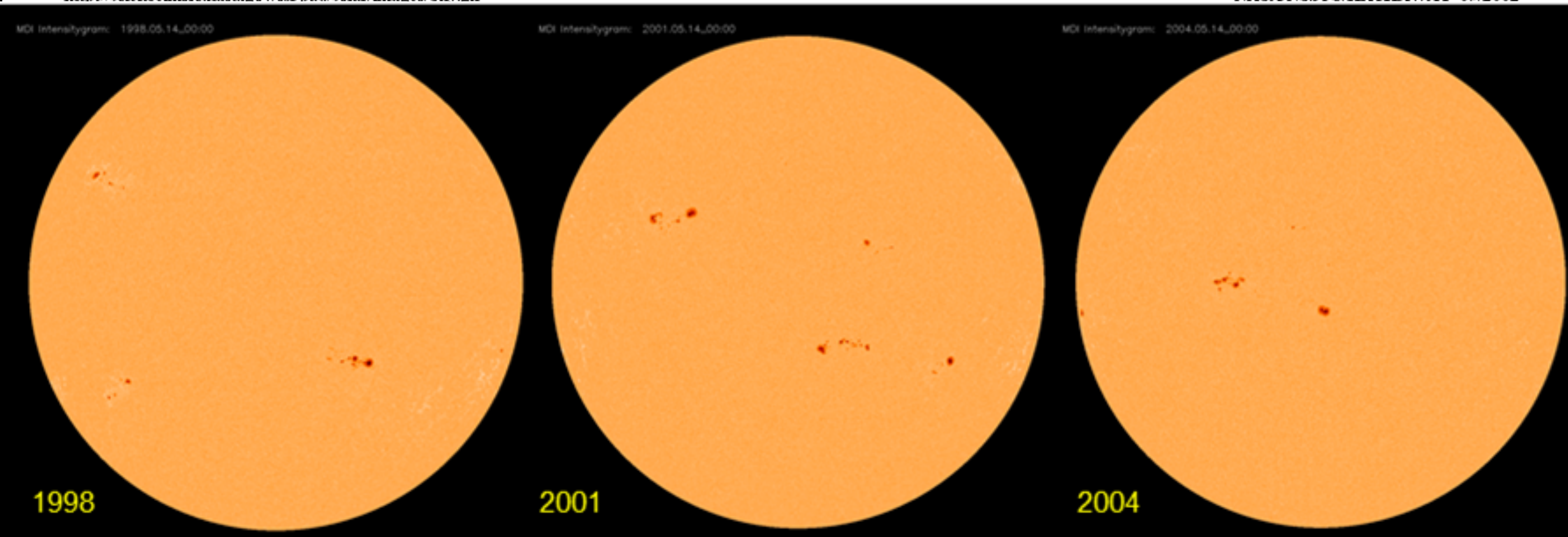


SOHO(NASA/ESA/S. Hill)

Seen from the Earth with the naked eye the Sun appears to be quite static and calm, yellow disk on the sky. However, the Sun is a very variable and stormy star and contributes with much more than just heat and light. It is the source of the fascinating auroras and it can affect our technology-based society. It also affects the climate since the amount of energy is varying. That is why it is so important to increase our knowledge about the Sun – our life supporting star.

Butterfly Diagram



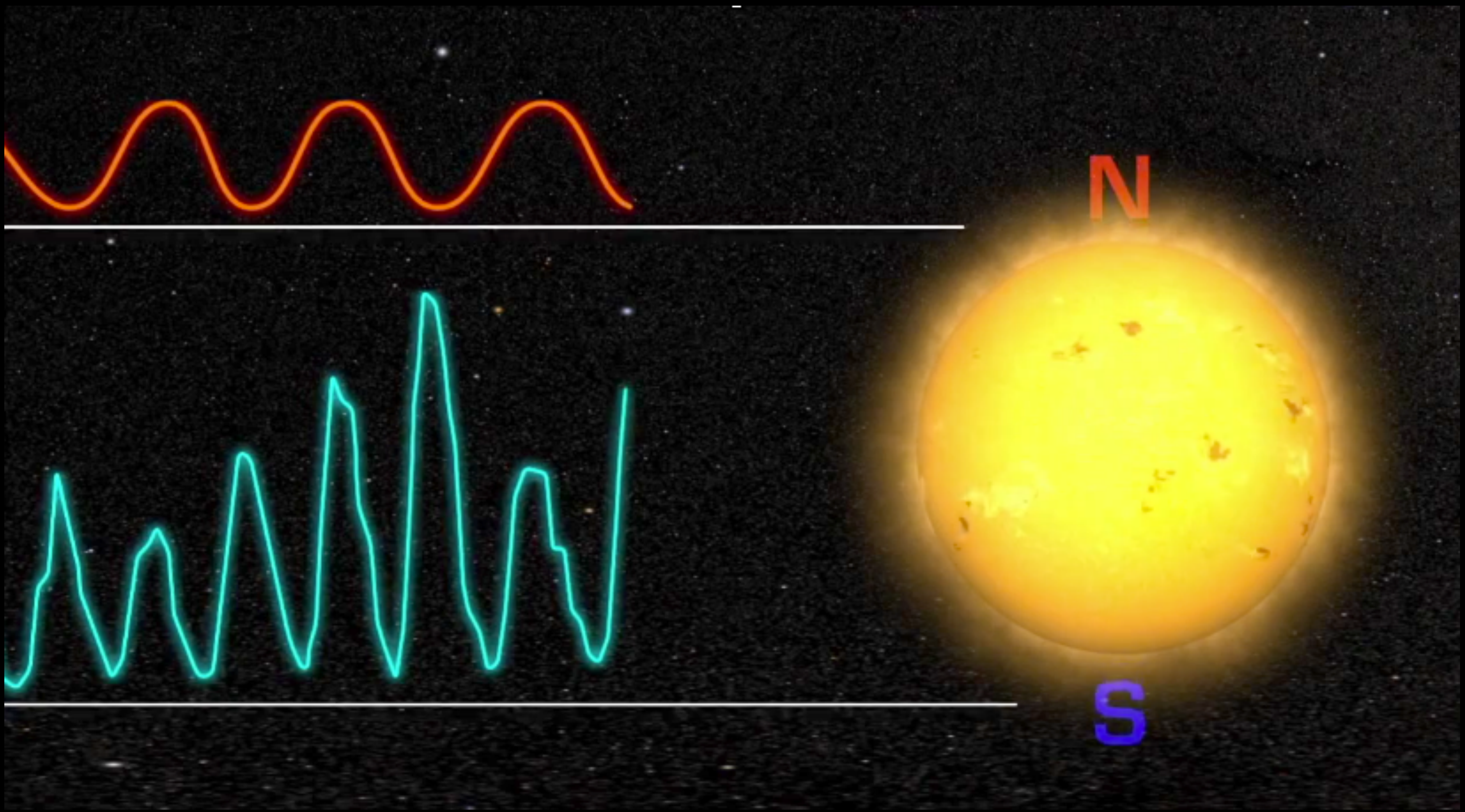


As each cycle begins, sunspots appear at mid-latitudes, and then move closer and closer to the equator until a solar minimum is reached. This pattern is best visualized in the form of the so-called **butterfly diagram**.

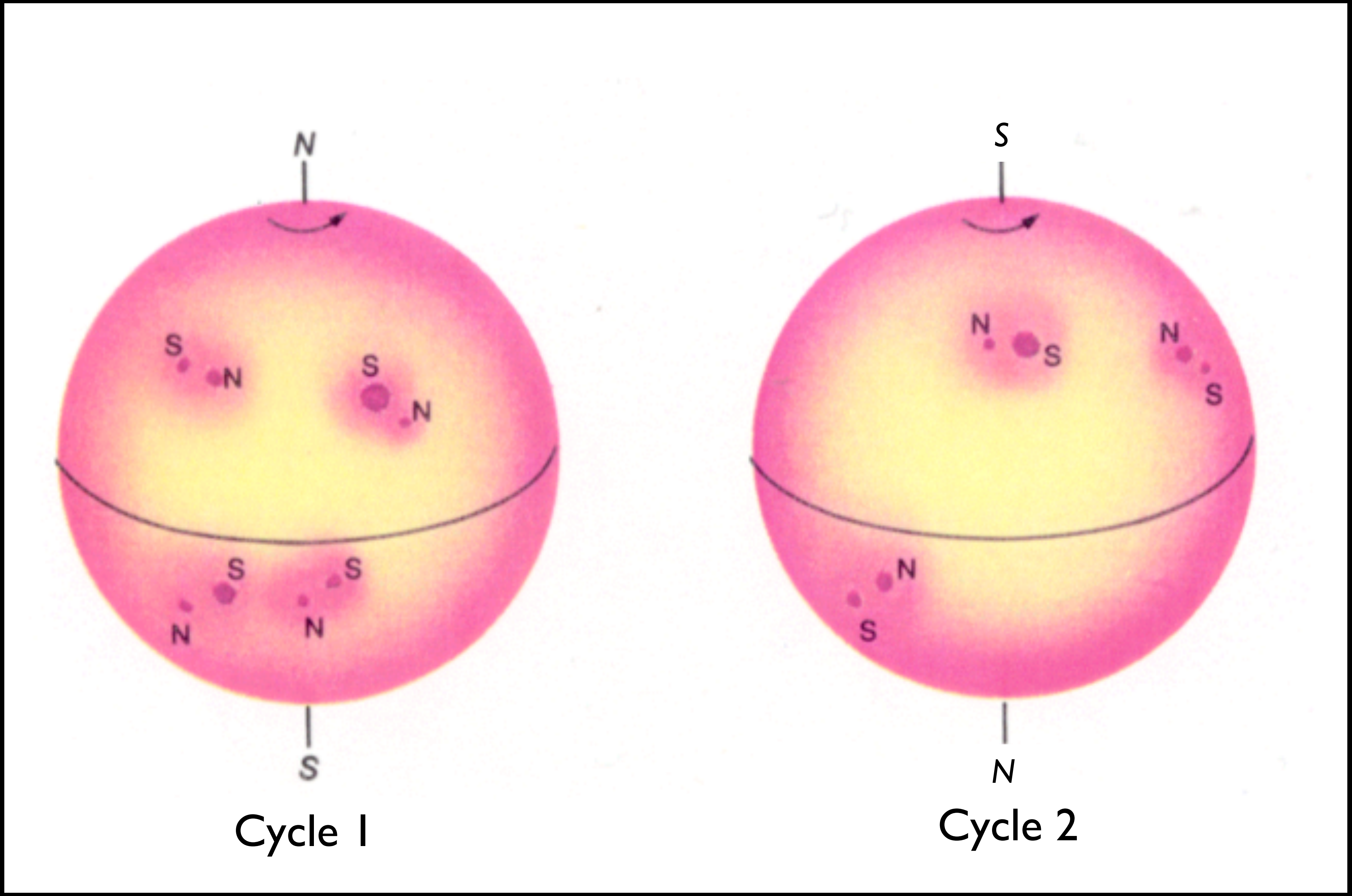
Magnetic Field Flip

The Solar magnetic field has a 22 year cycle, exactly twice that of the sunspot cycle, because the polarity of the field returns to its original value every two sunspot cycles (compared to the Earth where this happens 300-700 000 years).

NOTE: This flit happens during solar maximum



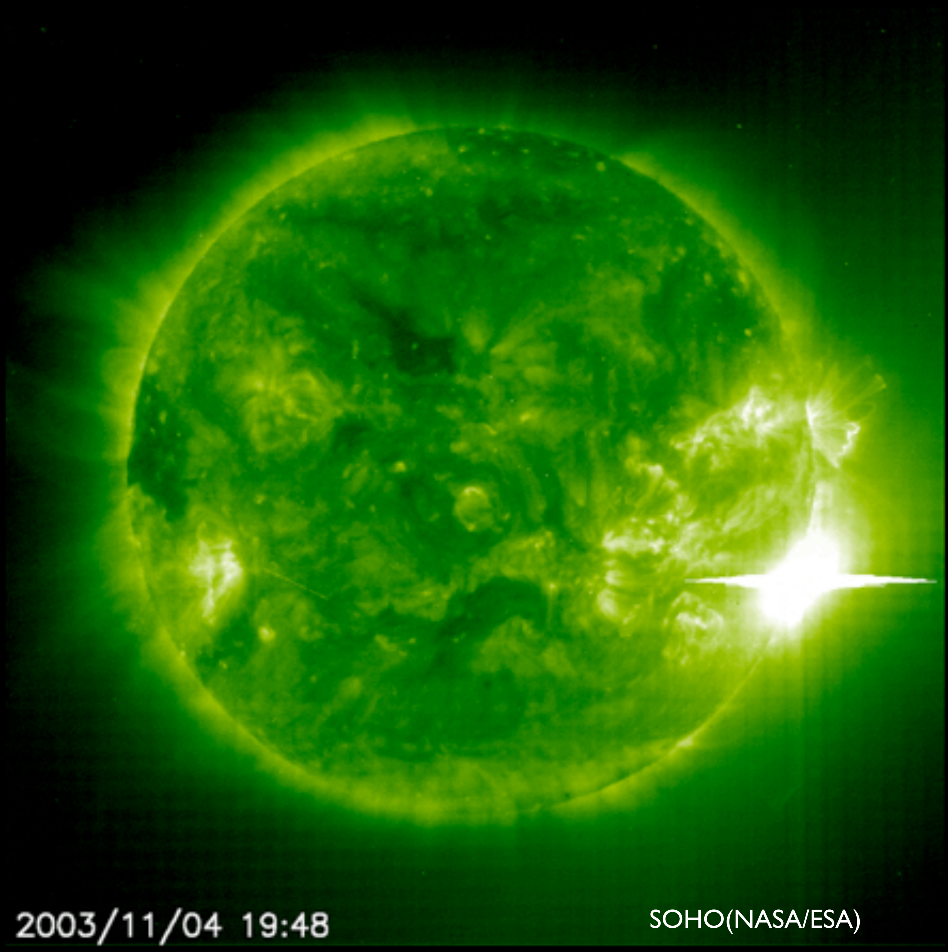
Sunspot polarity changes

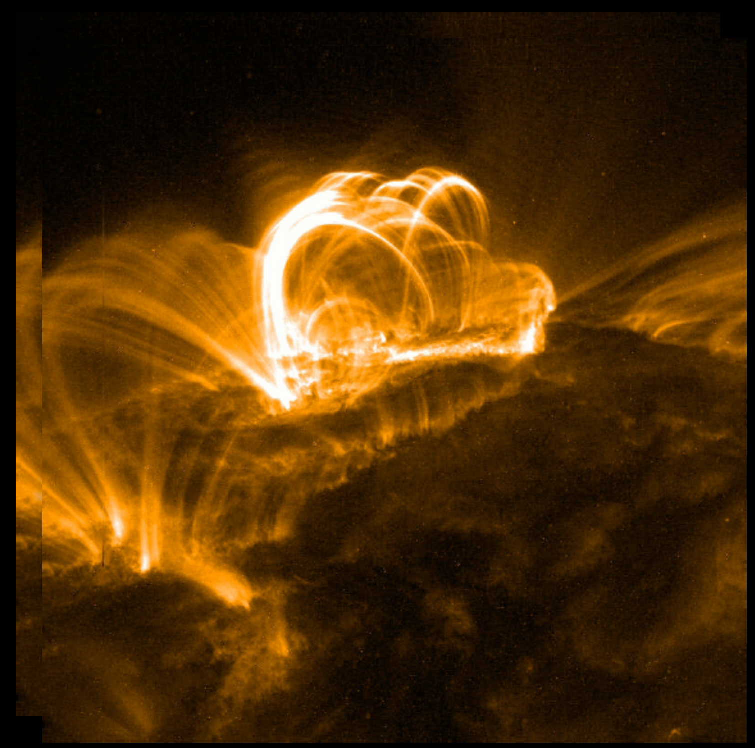


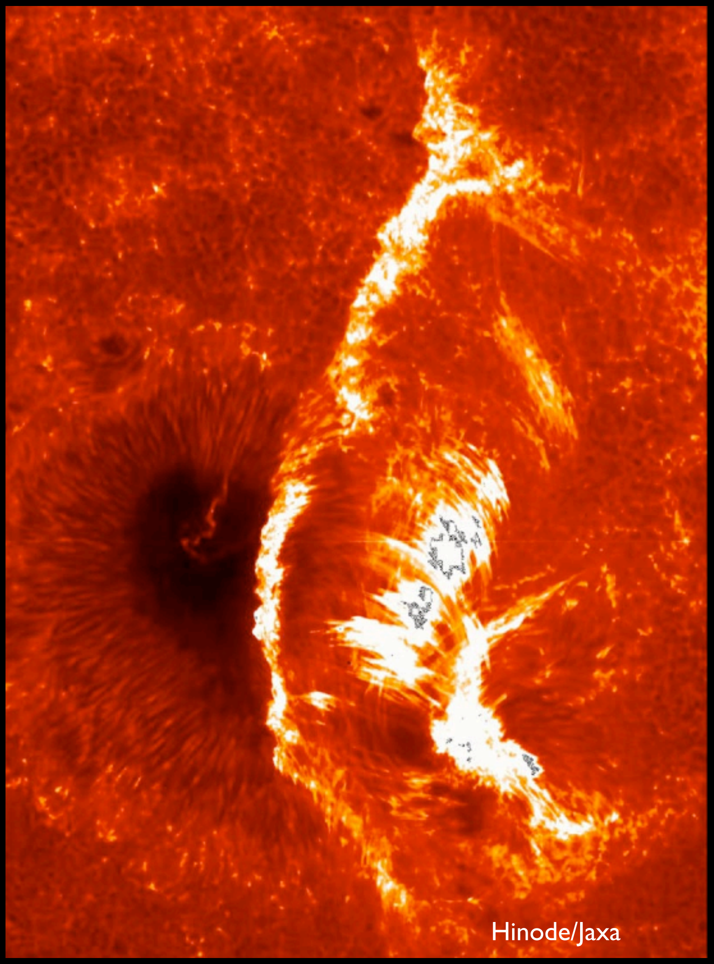
In the first cycle - leading spot on the northern hemisphere has N-directed magnetic field (outward)
- and trailing spot S
On the southern hemisphere it is the opposit

In the following cycle - this changes

EXPLOSIONS ON THE SUN



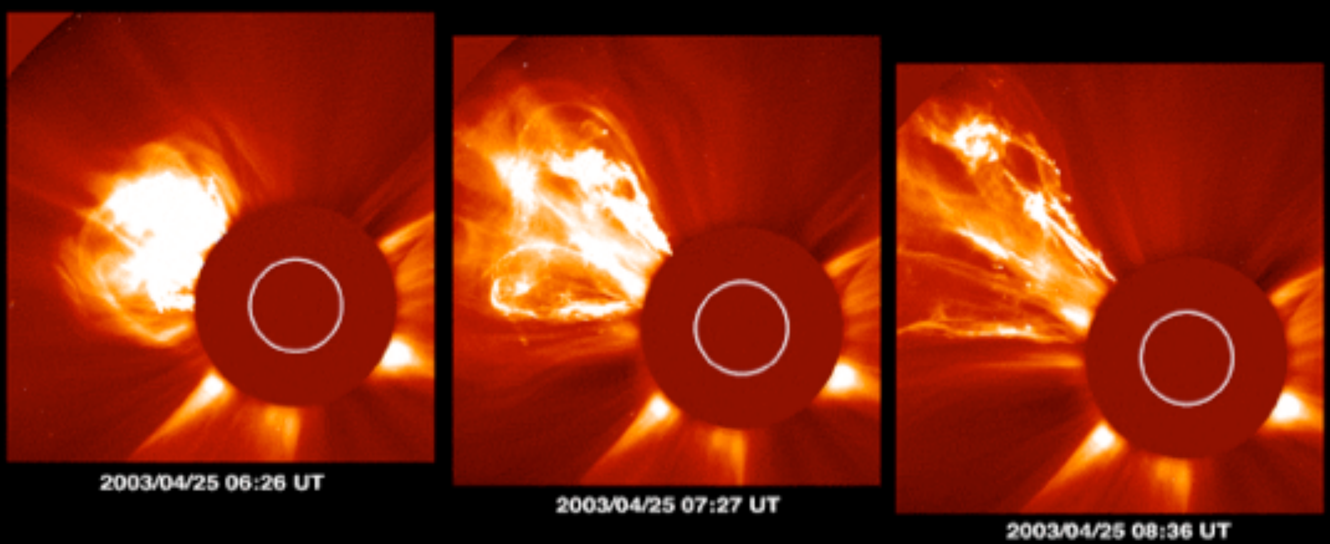




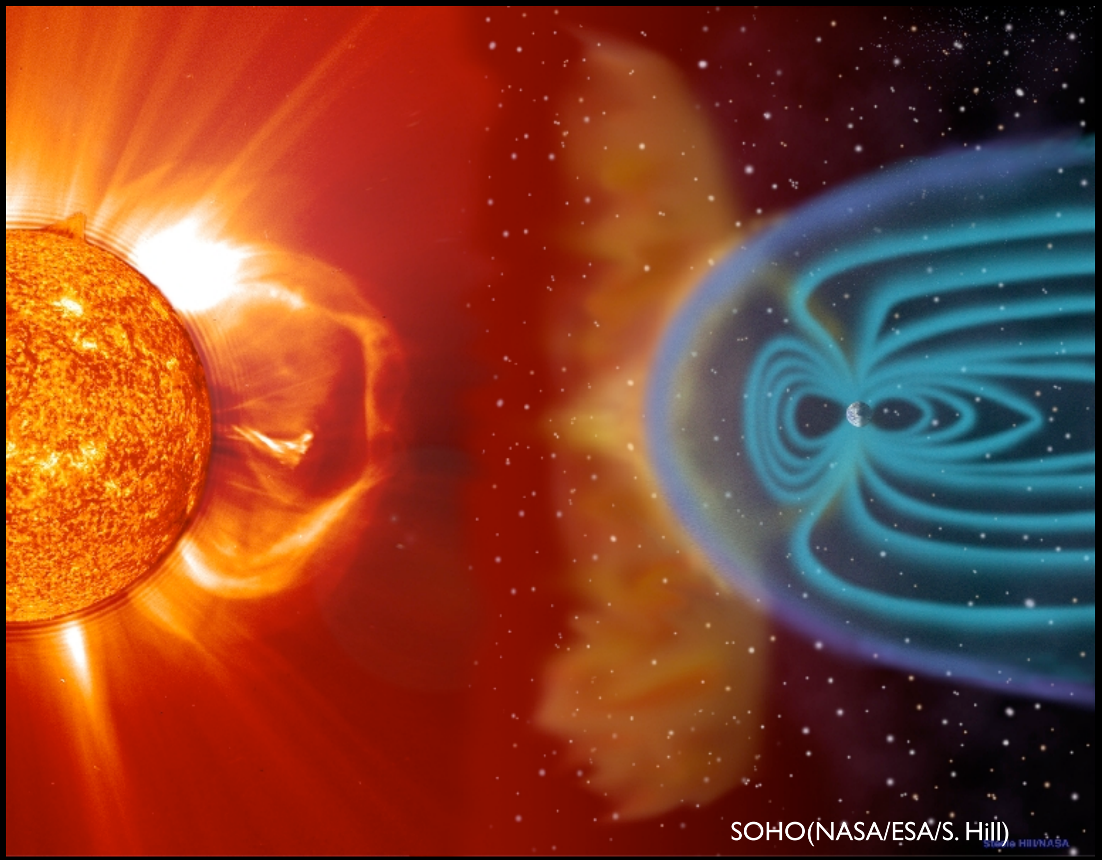
The magnetic field in large active regions on the Sun often gets unstable. This can result in violent explosions in the solar atmosphere – called "flares". A flare can release in seconds energy corresponding to several billion megatons of TNT. During such explosions the gas is heated to 20 million degrees.

This super heated gas will emit large amount of UV radiation and X-rays. The radiation travels with the speed of light and hits the Earths atmosphere 8 minutes 20 seconds later. Luckily, this hazardous radiation is blocked by gases in our protective atmosphere such as ozone. As will be described later such explosions can affect radio communication and satellite communication.

GAS ERUPTION ON THE SUN



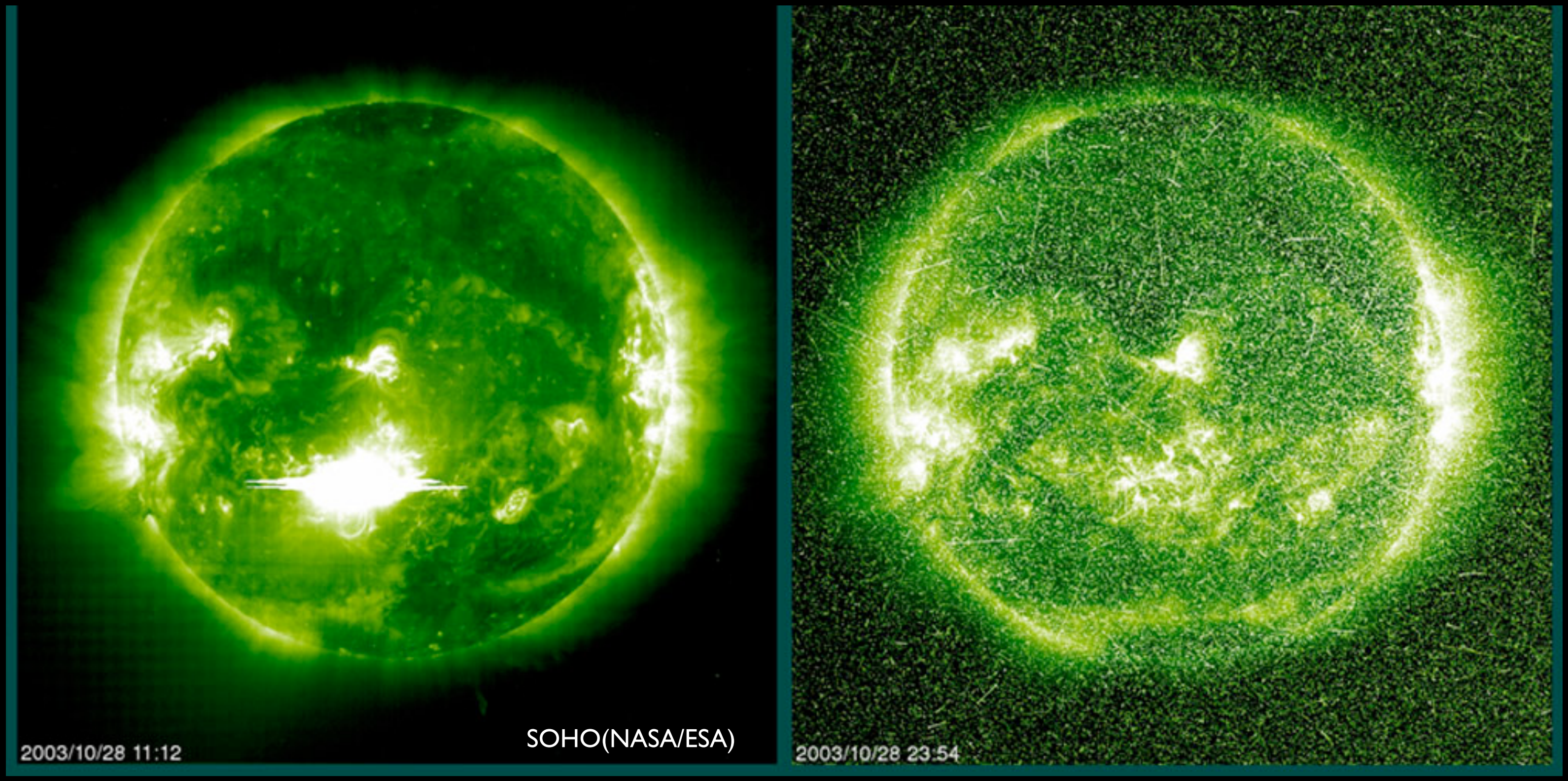
SOHO(NASA/ESA/S. Hill)

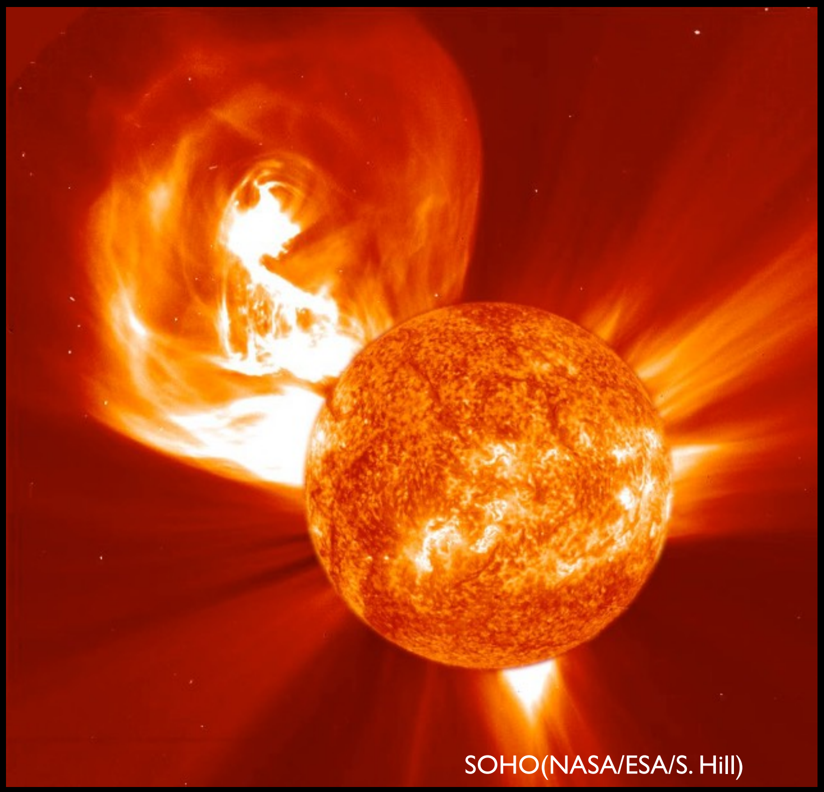


Sometimes large prominences can erupt and large amount of gas and magnetic fields are ejected out in space. The largest eruptions eject several billion tons of particles corresponding to 100,000 large battleships. Such eruptions are called Coronal Mass Ejections or CMEs for short. The bubble of gas will expand out in space and can reach velocities up to 8 million km/h. Still it would take almost 20 hours before it reach the Earth. Usually the solar wind spends three days on this journey.

If such an eruption is directed towards the Earth the particles will be deflected by our magnetosphere. The cloud of gas will push and shake the Earths magnetic field and generate a kind of "storm" which we call geomagnetic storms.

PARTICLE SHOWERS FROM THE SUN





A few times explosions or eruptions will accelerate large amount of particles that travel at almost the speed of light. Such showers of particles consist mostly of protons and it takes less then an hour to reach Earth.

The protons have such high speed and energy that they can penetrate satellites and space ships. Thus, they can damage vital electronic equipment. They can also destroy the quality of images and scientific data from those satellites that are surveying the Sun as shown in the picture above. The particles “blind” the digital cameras and we see a large amount of noise in the images.