From the formation of the Sun to a habitable planet

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Outline of today's presentation

- What do we need for a habitable planet?
- From Big Bang to formation of stars
    - How was the Sun formed?
- Formation of the solar system
- Key things about the Sun and Earth that enable a habitable planet.
    - What makes Earth different from our neighbouring planets?

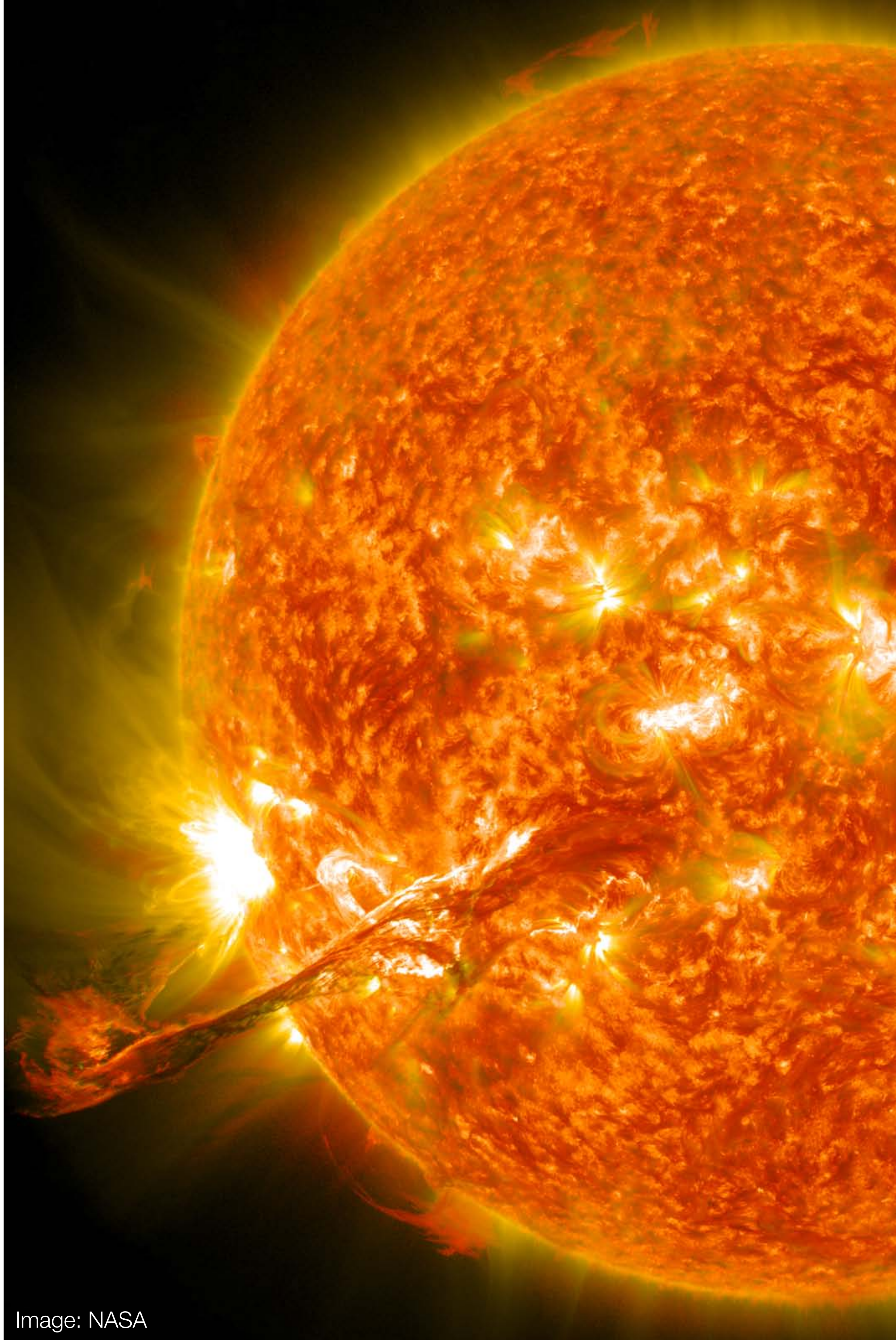


Image: NASA

Habitable planet

- General idea: requires the **planet to have such an orbit around a star that liquid water can exist on the surface**.
- These kinds of orbits are said to be in the **Goldilocks zone** from the fairytale *Goldilocks and the Three Bears*
  - “**Not too hot, not too cold, but just right**.”
- Later we will see that a few more things are needed too, but first we need the source of all the energy - a STAR!

Making a star

- Our star, the Sun, is the most dominant factor exerting an influence on our environment.
- Almost all of our energy comes from the Sun.
    - We receive it as solar radiation, but it arises originally from nuclear fusion in Sun's core.
- How is a star like the Sun formed? Where does all the energy come from?
- We need to go to the very beginning of the universe.

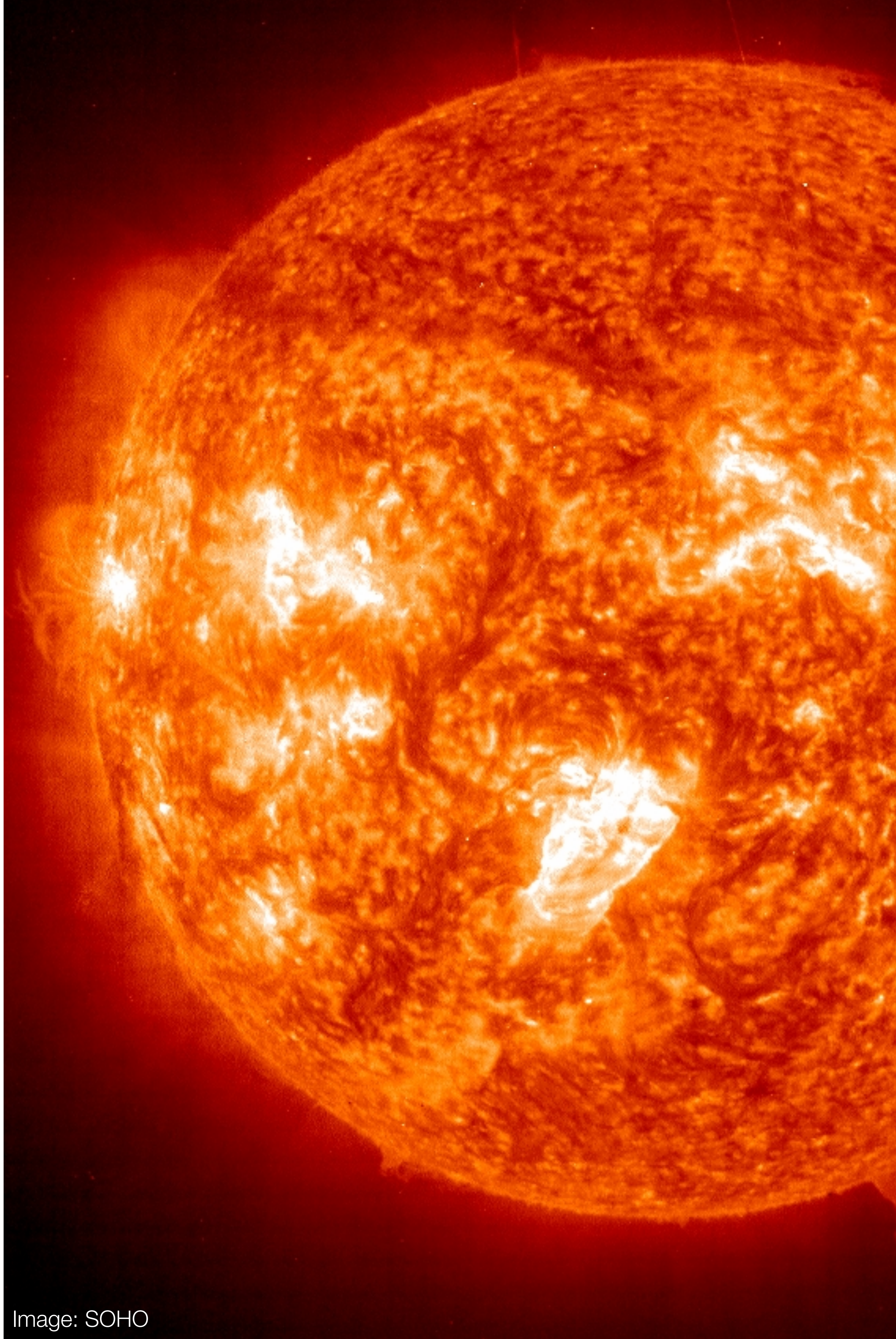


Image: SOHO

About 14 billion years ago a singularity started to rapidly expand.

We know this event as **the Big Bang**.

The Big Bang is the **beginning of our known universe**.

Origin of the Universe

- The Big Bang – about 14 billion years ago a singularity started to rapidly expand which issued the birth of the universe.
- In the early stages radiation energy condensed into matter expanding into nothingness.
- Light was not able to travel freely.
- When the universe was about 400,000 years old it had cooled down enough for atoms to start forming. This decoupled light and matter → Universe became "visible"!

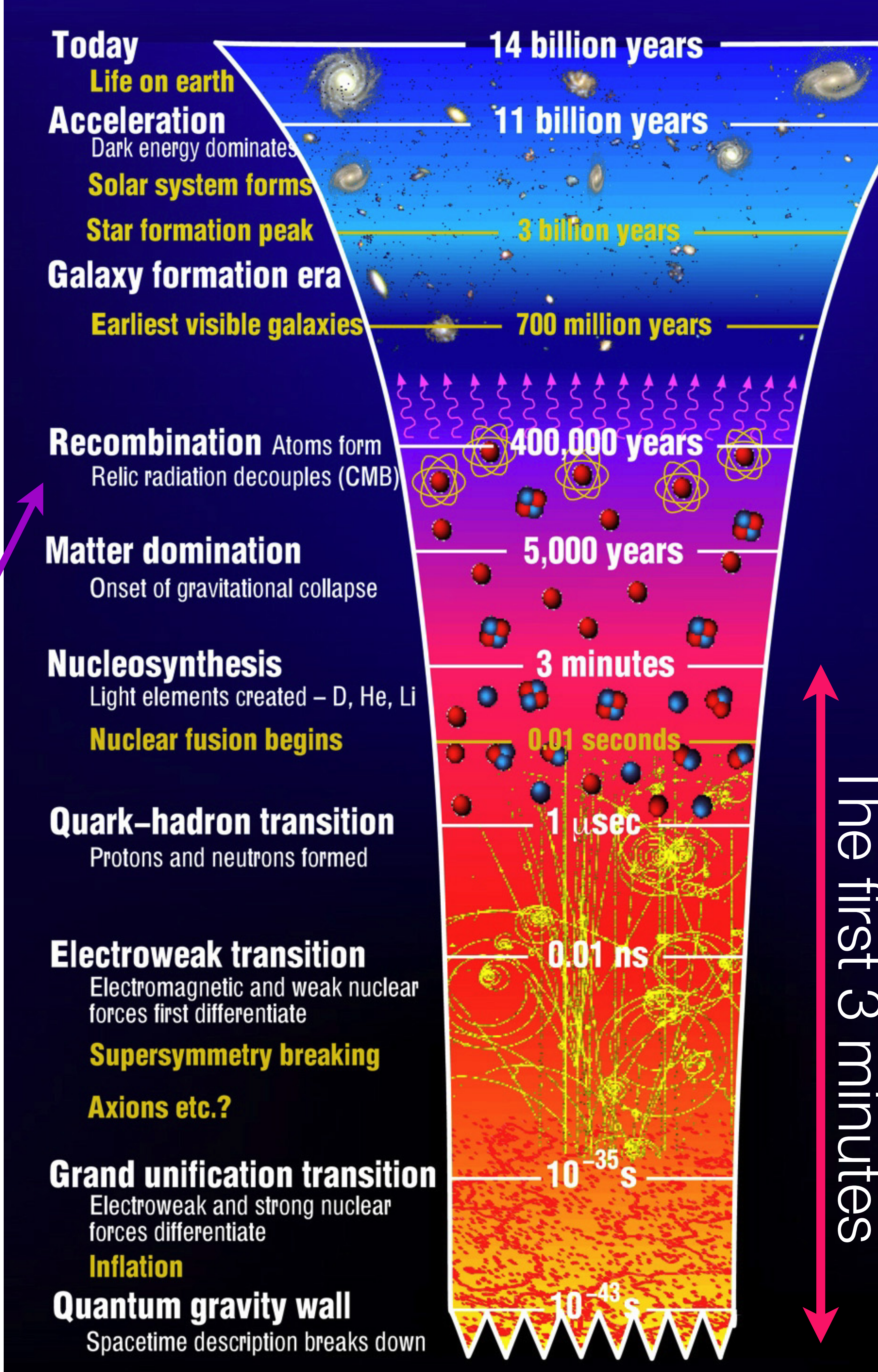


Image: The Stephen Hawking Centre for Theoretical Cosmology, University of Cambridge, 2018

Origin of the Universe

- The afterglow of the original explosion still exists as a 3°Kelvin (-270.15°C) background radiation which was first observed by Arno Penzias and Robert Wilson in 1964.
- This is known as the **Cosmic Microwave Background** radiation.
- Luckily the distribution of matter was not quite uniform, very small irregularities occurred. These acted as gravitational centers in which larger masses could accumulate.
- First galaxies and stars were created!

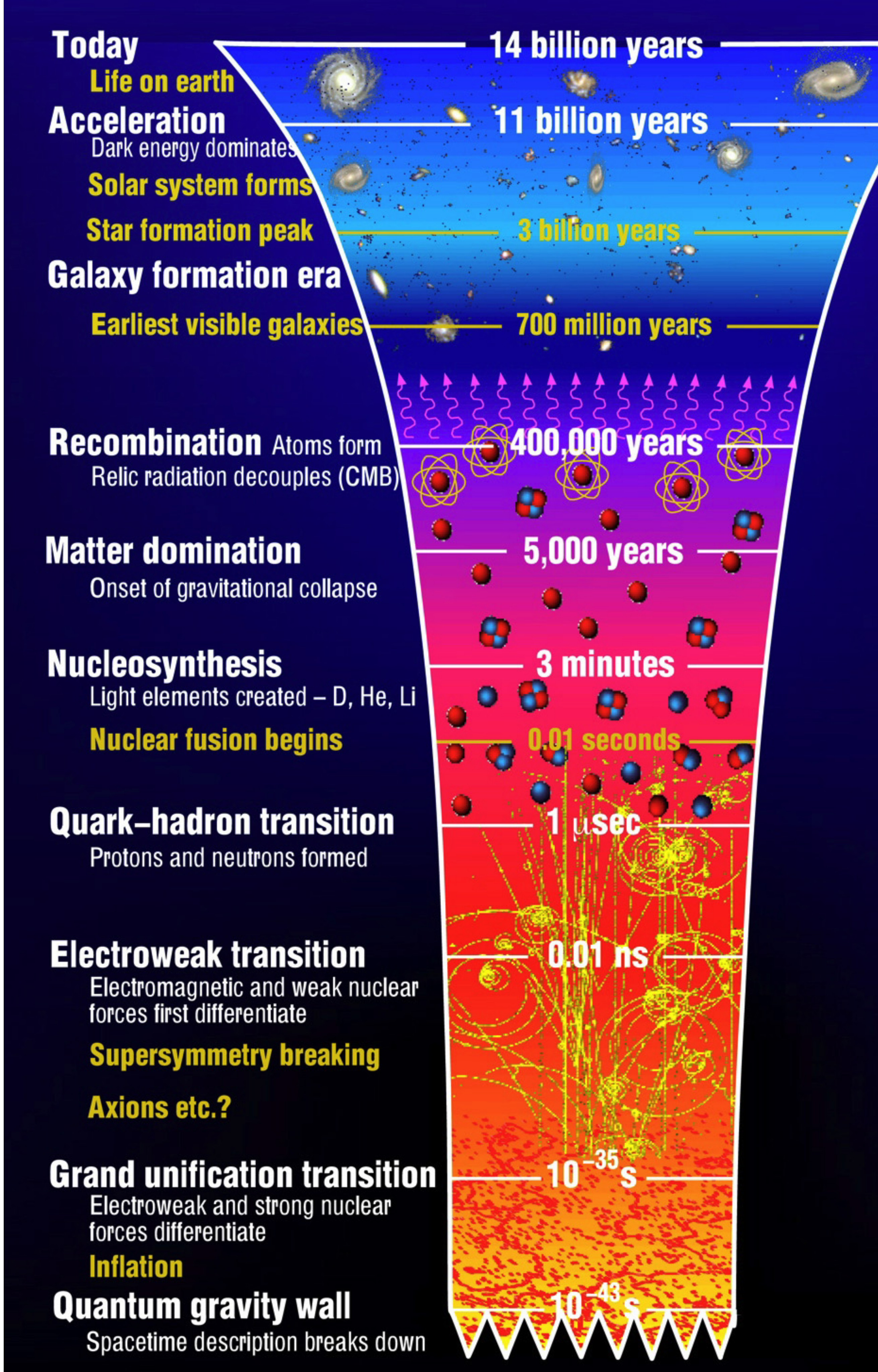


Image: The Stephen Hawking Centre for Theoretical Cosmology, University of Cambridge, 2018

Big Bang, Galaxies, Stars and solar system.

After the Big Bang more galaxies formed in clusters and superclusters in the gravitational centers.

Stars are born within galaxies, and solar systems can form around those stars.

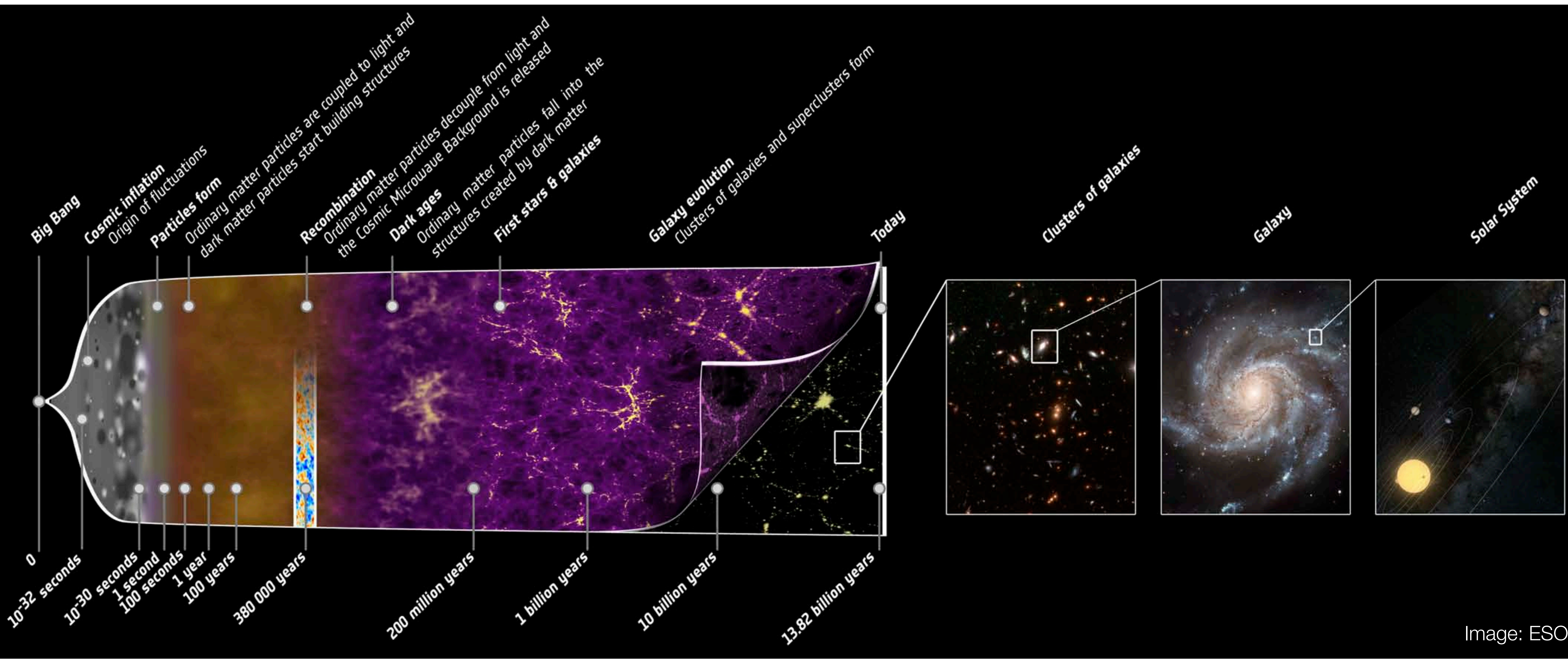


Image: ESO

Our home, the Milky Way galaxy.

Contains hundreds of billions of stars.

Sun is located in the Orion arm, 26,000 light years away from the galactic centre.

Light travels 300,000 km/s so this is ~250 million billion km.

Sun goes around the centre every 240 million years.

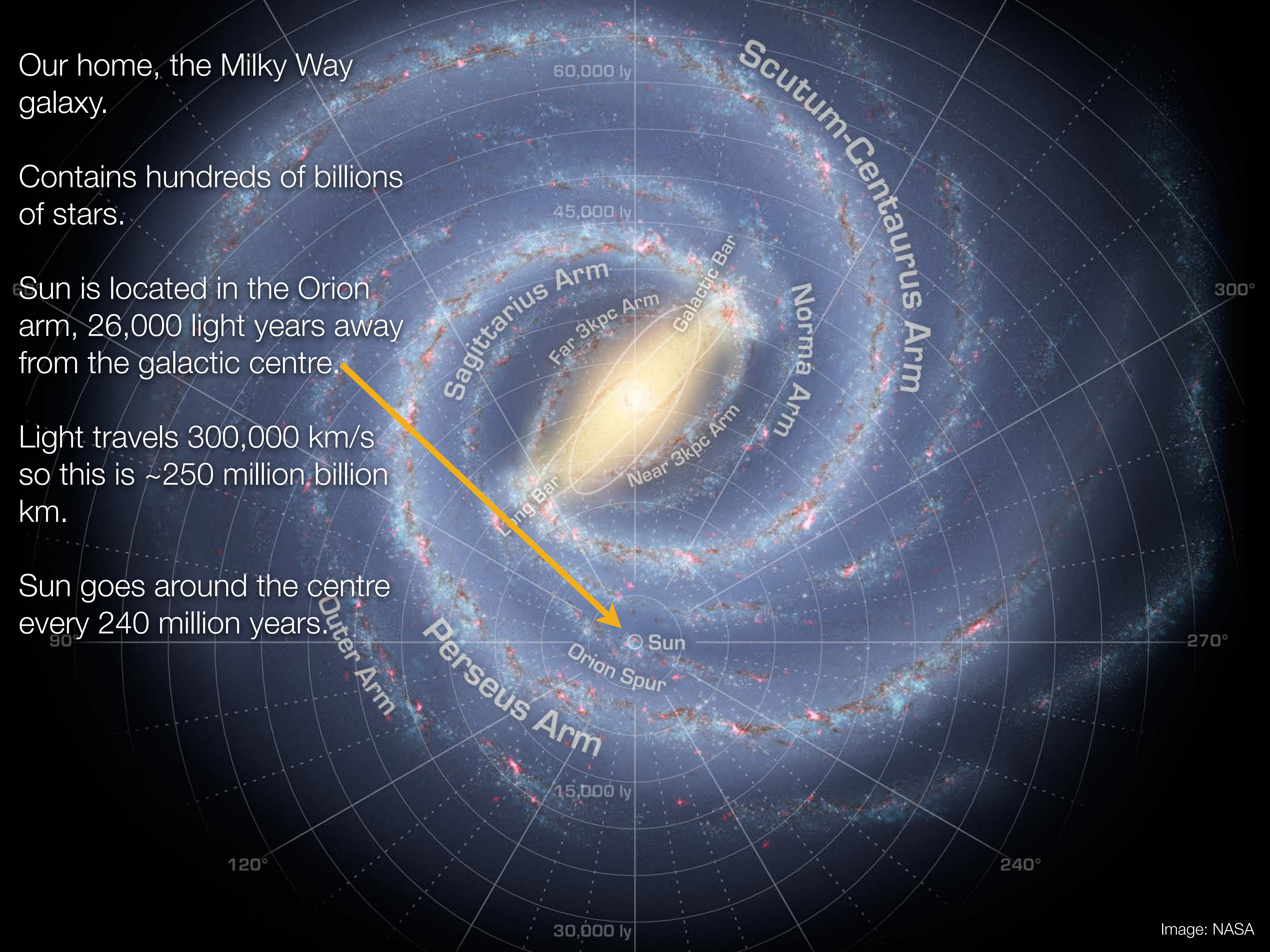


Image: NASA

The Milky Way seen from Earth.

Image: ESO/S. Brunier

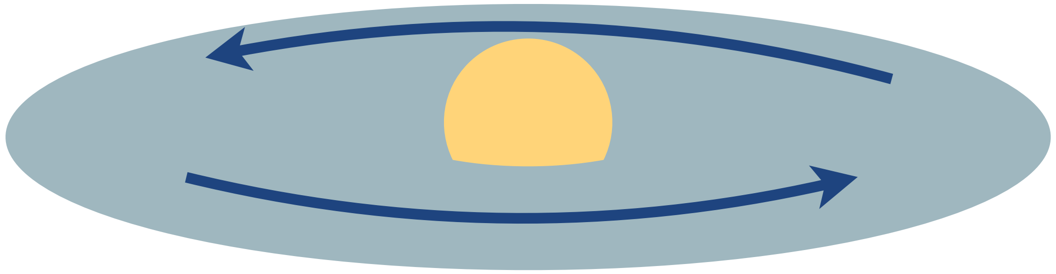
Formation of the Sun

Sun was formed about **4.6 billion years ago**.

Between stars, inside the galaxy, there are areas where gas is more dense.

The Sun was created in a **collapse of one of these interstellar gas clouds.**

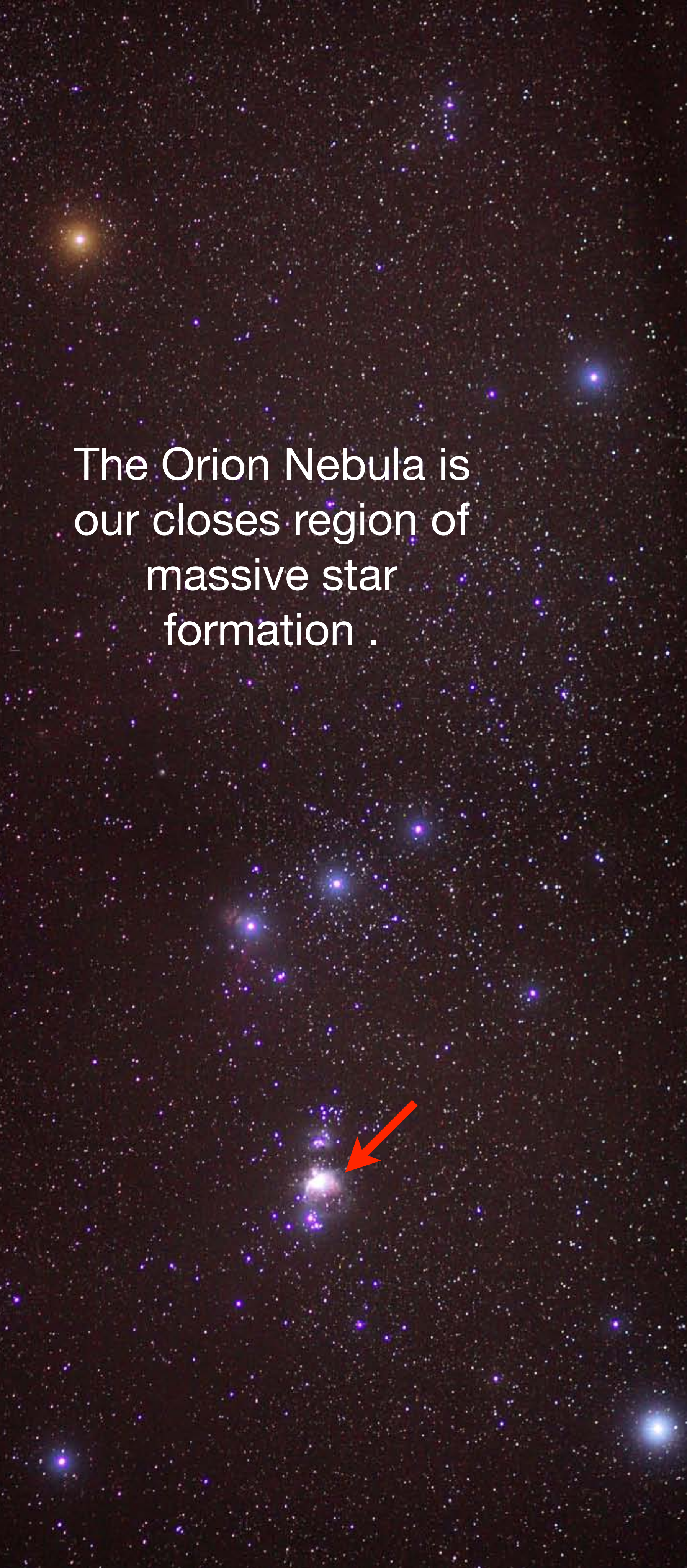
As the cloud collapses, it starts to swirl. Over millions of years, more hydrogen gas is pulled in the spinning cloud.



Collisions occurring between the hydrogen atoms **start to heat the gas in the cloud**. Once the temperature in the centre reaches 10 million K, **nuclear fusion begins in the core - a star is born**!

This process was probably triggered by interstellar gravitational perturbation, like a passing star or shockwave from a supernova.

Super computer simulation of collapse of 500 x solar mass cloud with a diameter of 2.6 light years.
The simulation covers 285,000 years. Brighter colours indicate higher density. **The white dots are new stars.**
Available from New Zealander Prof M. Bate https://www.astro.ex.ac.uk/people/mbate/
Stellar, brown dwarf, and multiple star properties from a radiation hydrodynamical simulation of star cluster formation
by Bate, M. R., 2012, MNRAS, 419, 3115-3146.


The Orion Nebula is
our closes region of
massive star
formation .


The simulation in the previous slide
aims to understand how stars are
created in a gas cloud the same size
as the Orion Nebula.
Image of the Orion Nebula from NASA's Spitzer
and Hubble Space Telescopes
Credit: NASA/JPL-Caltech/STScI

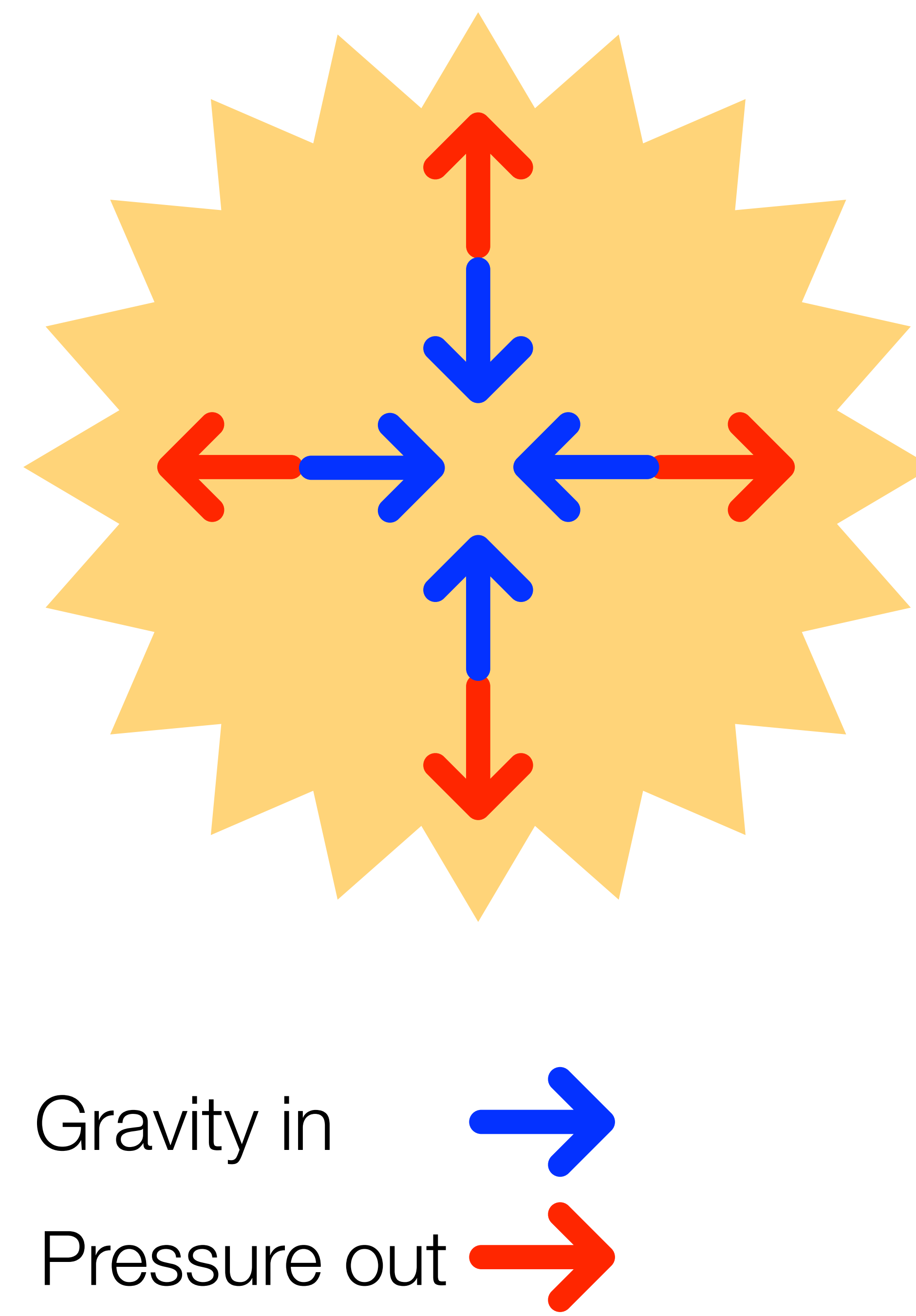
Evolution of stars

The rate of change and lifetime of stars depends on their initial mass.

Most stars spend the majority of their lives in a stable state on the **main sequence** where *pressure out* = *gravity in* at all locations. **This is where the Sun is located at present.**

When stars like Sun become unstable at the end of their lives they swell up and finally boil much of their material out in space.

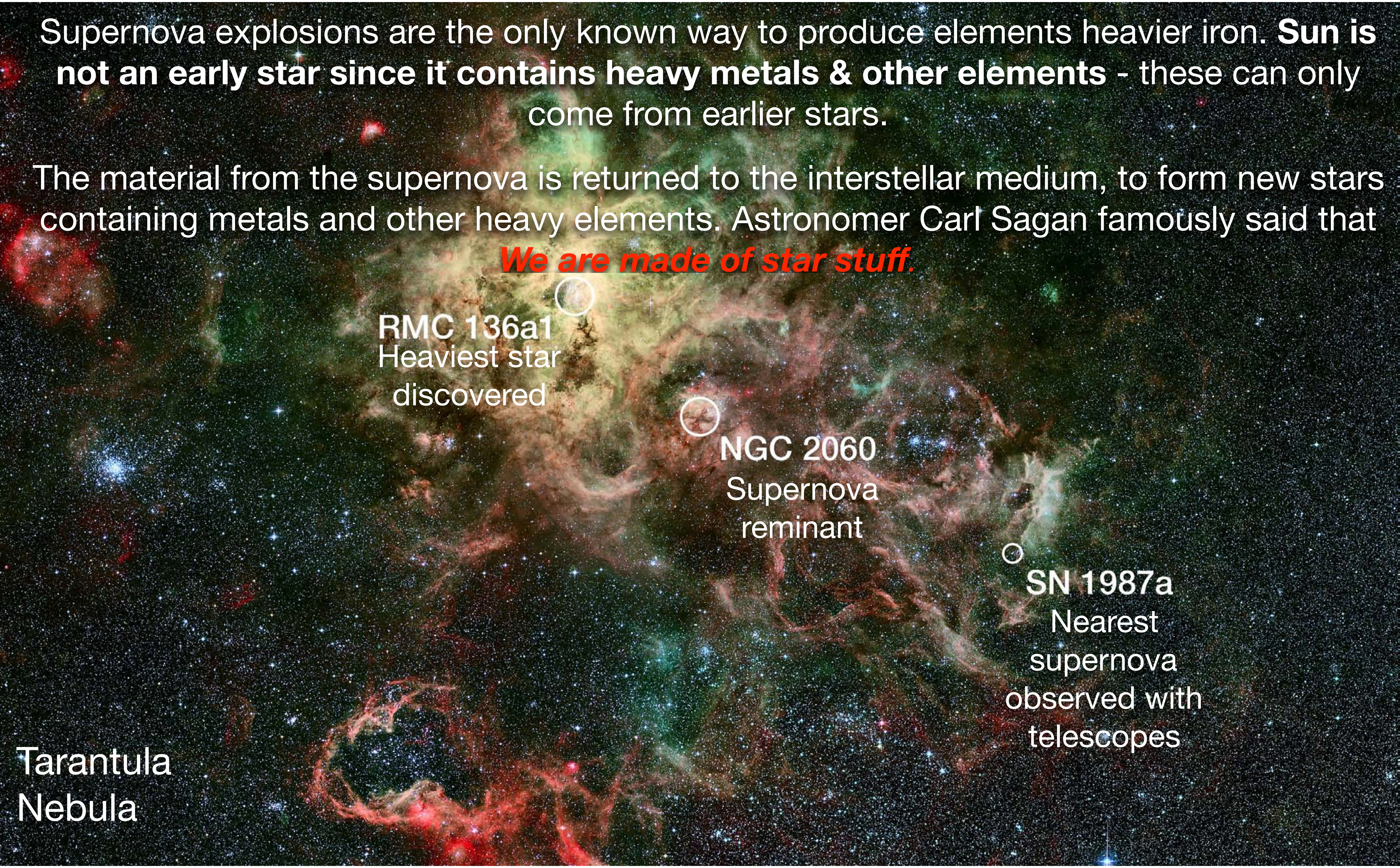
Really massive stars, with masses about $10 \times$ Solar mass undergo rapid internal changes leading to a **supernova explosion**.



Supernova 1987A (NS 1987A) in the Large Magellanic Cloud

Supernova explosions are the only known way to produce elements heavier iron. **Sun is not an early star since it contains heavy metals & other elements** - these can only come from earlier stars.

The material from the supernova is returned to the interstellar medium, to form new stars containing metals and other heavy elements. Astronomer Carl Sagan famously said that ***We are made of star stuff.***

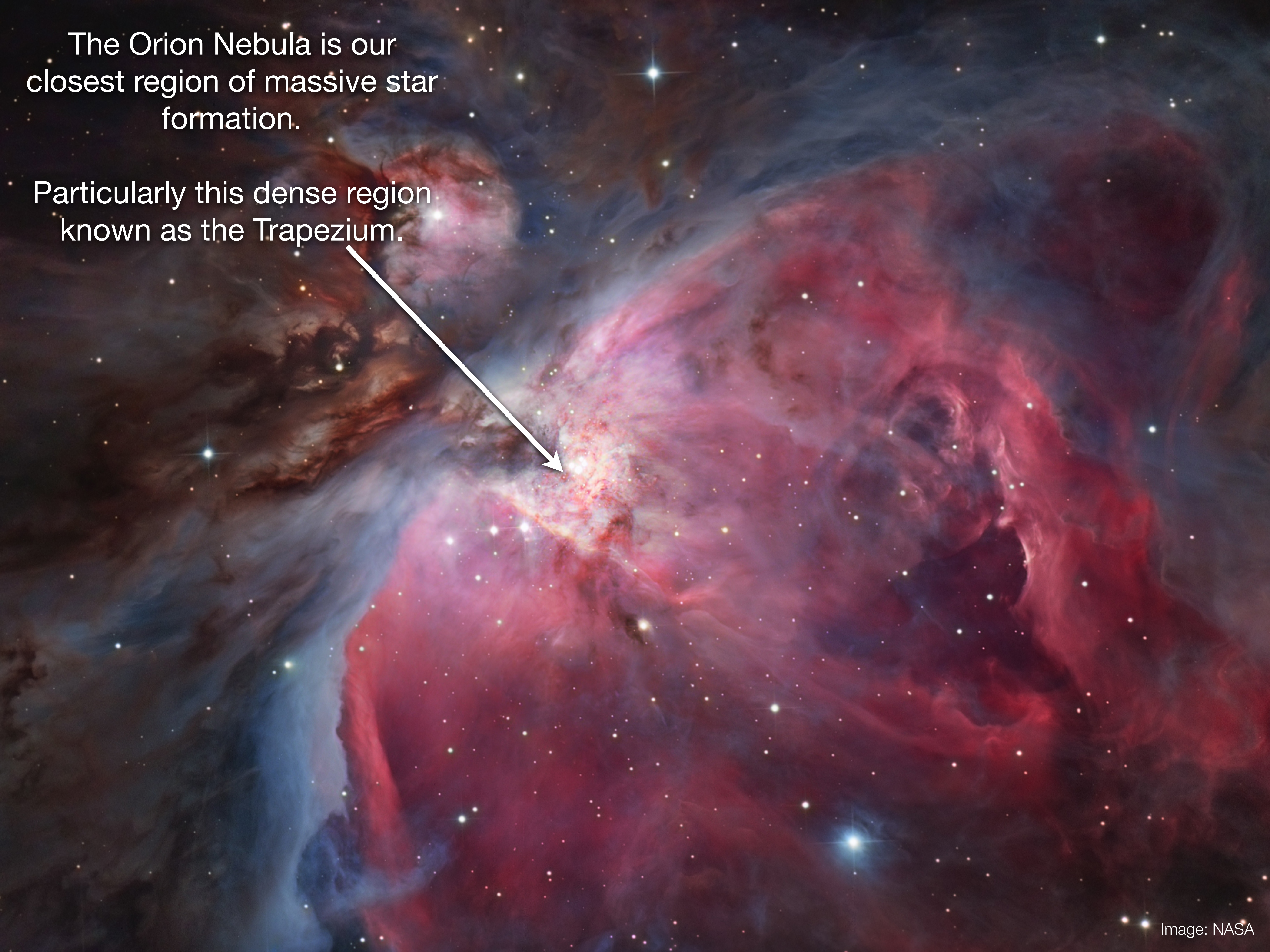


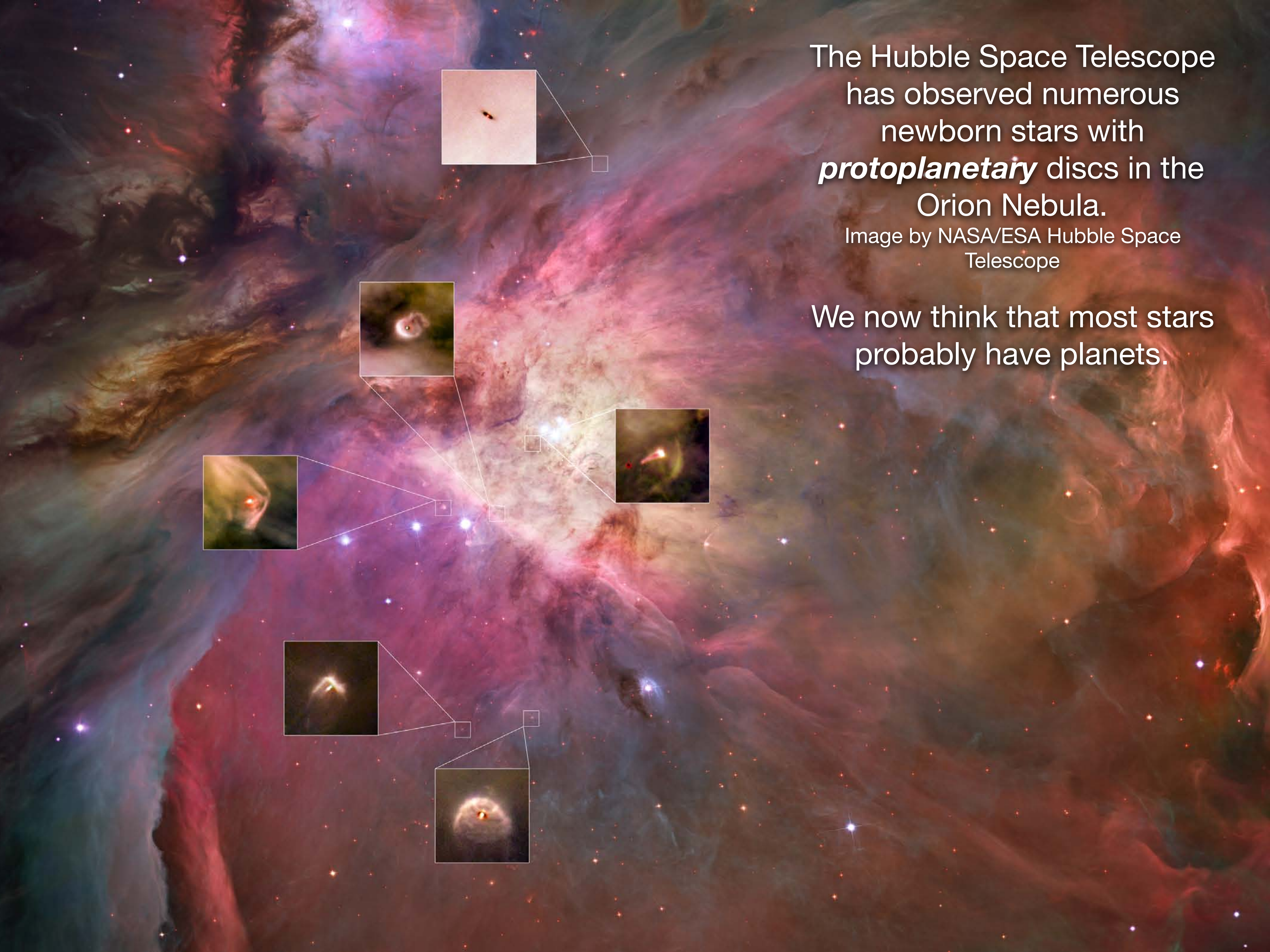
Credit: NASA, ESA, ESO (ground based image)

What about planets? Where do they come from?

What about planets? Where do they come from?

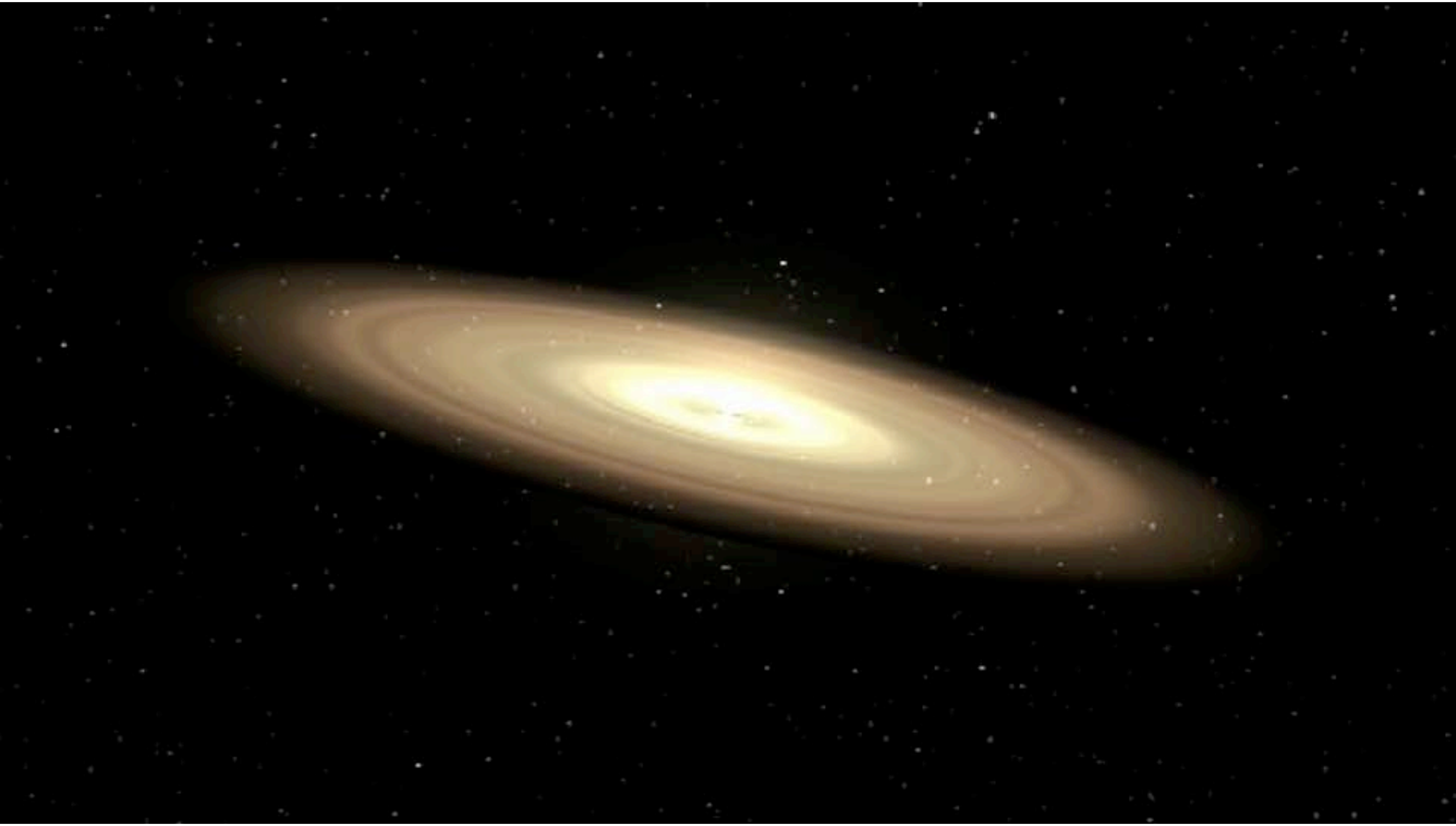
Let’s take another look at the interstellar gas clouds that make stars…


The Orion Nebula is our closest region of massive star formation.
Particularly this dense region known as the Trapezium.
Image: NASA



The Hubble Space Telescope has observed numerous newborn stars with ***protoplanetary*** discs in the Orion Nebula.
Image by NASA/ESA Hubble Space Telescope
We now think that most stars probably have planets.

Turning a dust disk into planets



Video courtesy of NASA/JPL-Caltech

So the Solar System developed around the same time as the Sun.

This doesn't mean it looked the same as it does now.

There may have been hundreds of planets that over time merged or were destroyed in collisions until we were left with the Solar System as it's known now.

Rocky planets known as **Terrestrial planets** were formed closer to the Sun, **Gas giants** were formed further out.

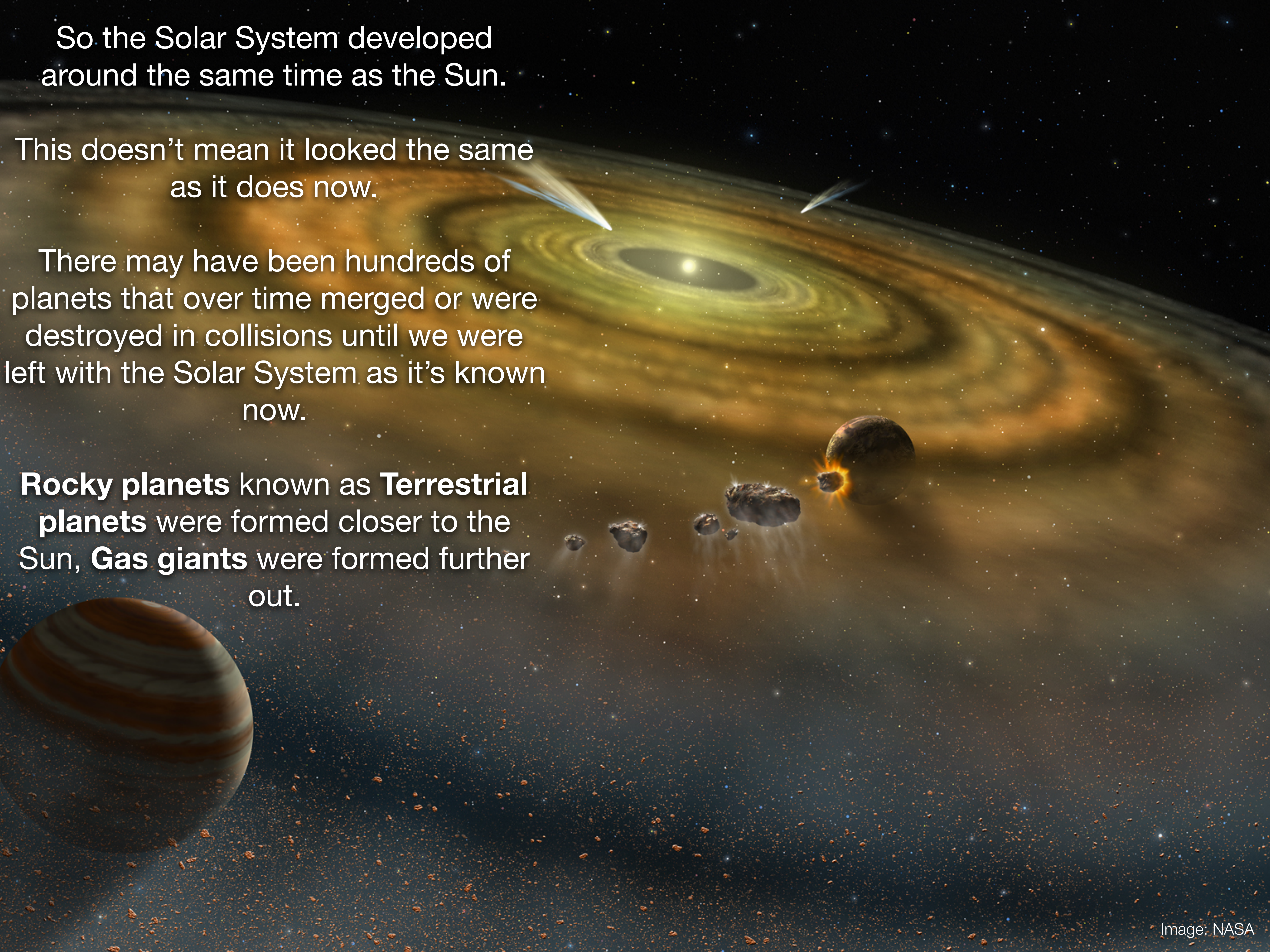
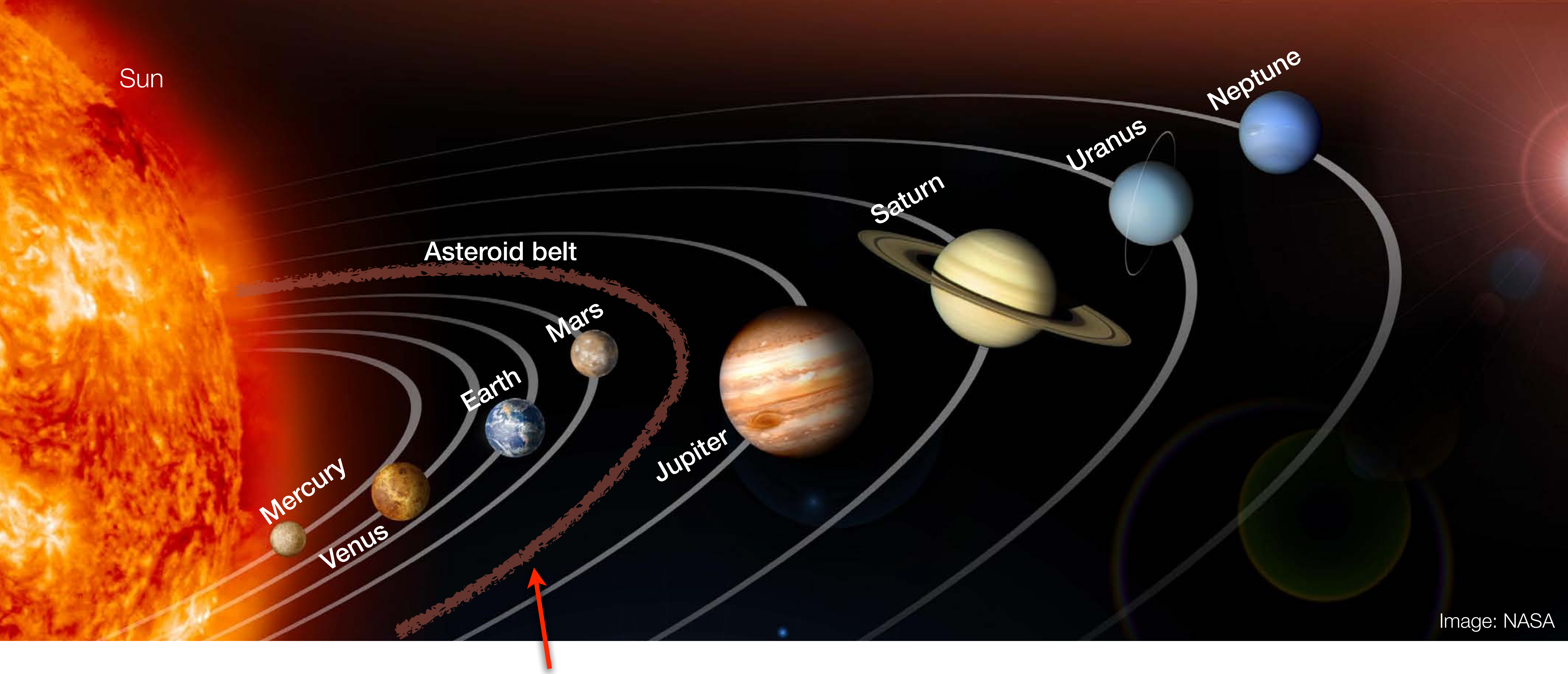


Image: NASA



Inner Rocky Terrestrial planets

- Mercury
- Venus
- **Earth**
- Mars

Asteroid belt in the gap between Mars and Jupiter: This region is too strongly influenced by Jupiter's gravity for planetary formation.

Outer Gas Giants

- Jupiter
- Saturn
- Uranus
- Neptune

Earth

Distance to Sun: about 150 million km

Orbital period: about 365 days (orbital speed 30 km/s)

Mean surface temperature: 15°C

Mean surface pressure: 1013 hPa

Atmosphere consists of:

- N_2 (78%)
- O_2 (21%)
- small amounts of Ar, CO_2, H_2O, O_3 etc

Earth

The blue marble, a water planet.

Origin of Earth’s water is still uncertain. Some probably originates from planetary formation, some may be from comets.

Liquid water is needed to sustain life!

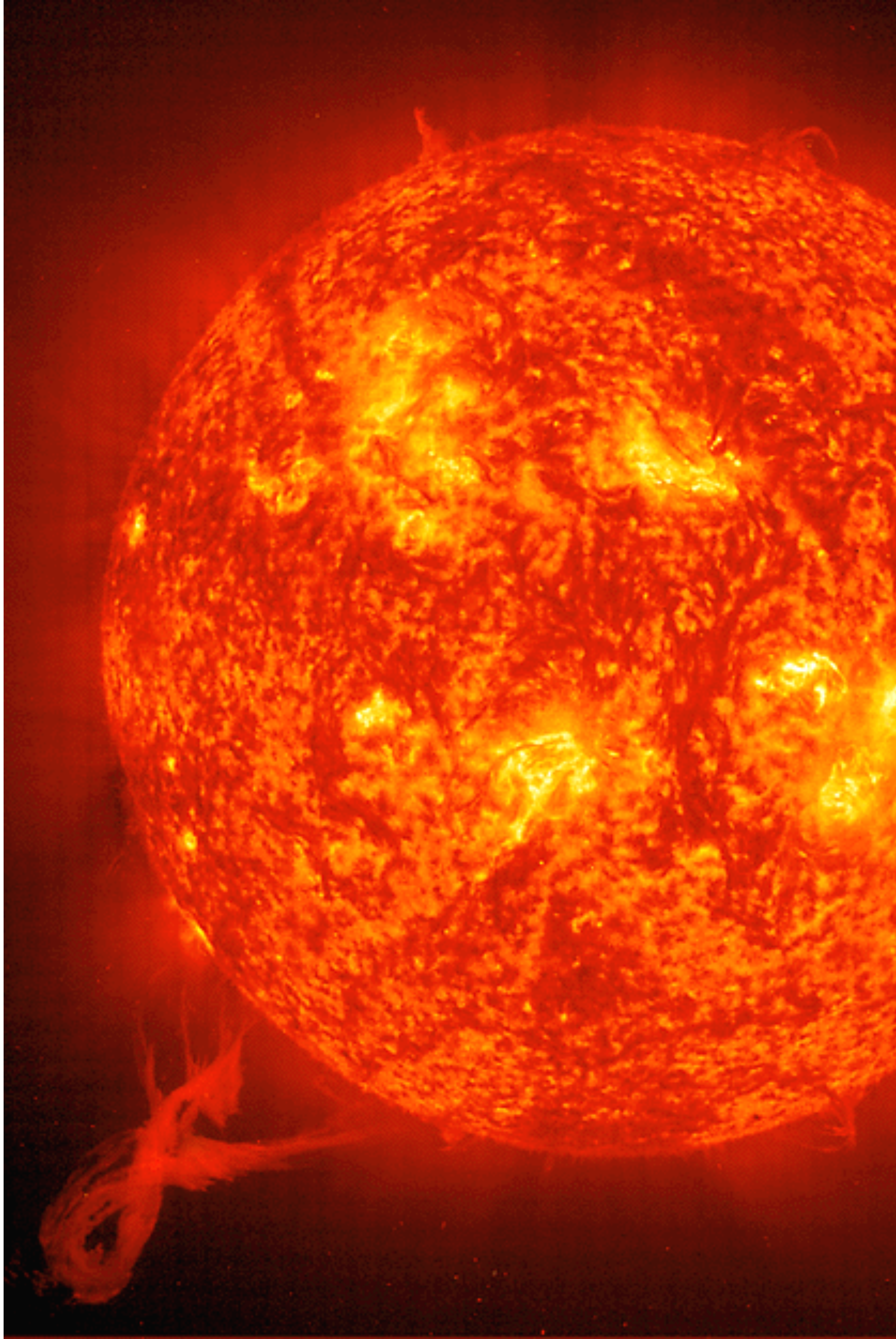
Besides presence of water at the surface and in the atmosphere Earth has **suitable temperature and atmospheric pressure** that allows the water to be liquid.

To have the right temperature we need **energy** - the Sun.

The Sun

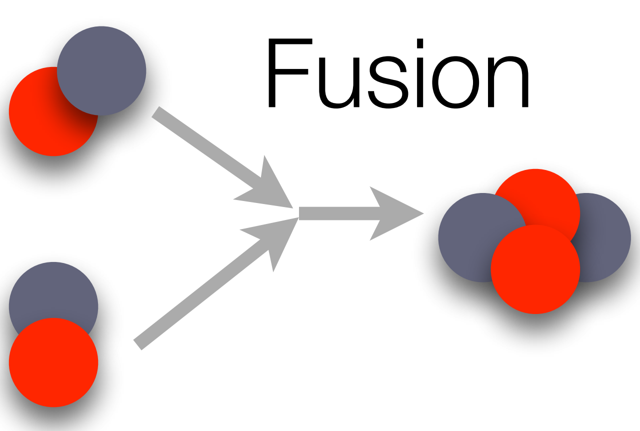
Let's look at the Sun in more detail.

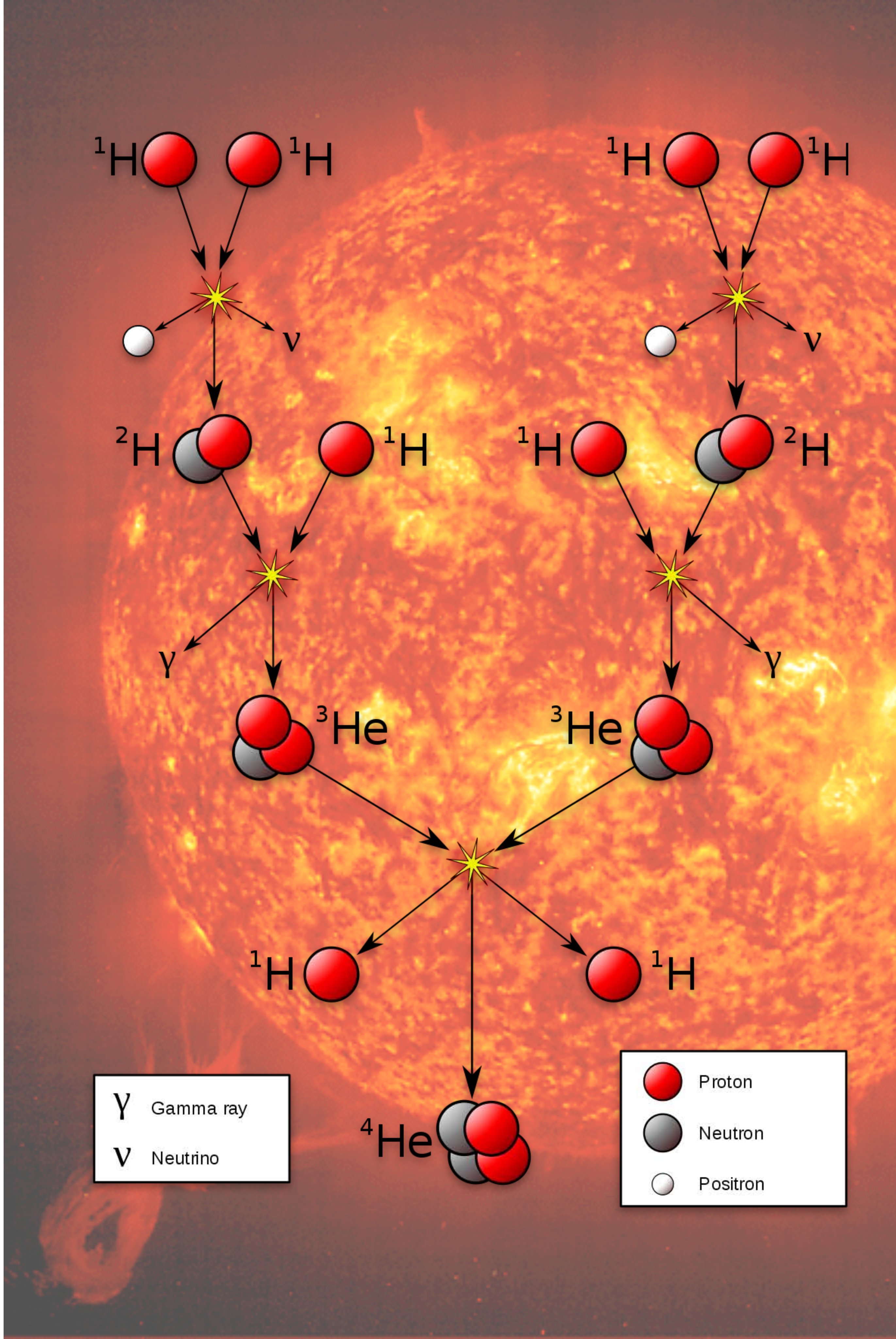
- Main components:
  - H (73%), He (25%), small fraction of heavier elements (O, C, etc.)
- Mass is about 300,000 x Earth
- The mean density is about same as water.
- Surface temperature is about 5800°C



Sun's energy source

- Very hot core, 15 million °C.
- At these temperatures the **hydrogen in the Sun can react, fusing with another Hydrogen atom to produce Helium.**
- In the process Sun's mass is slowly converted to energy according to Einstein's famous formula: $E = mc^2$
- Sun is getting lighter, at a rate of about 4 billion kg/s!

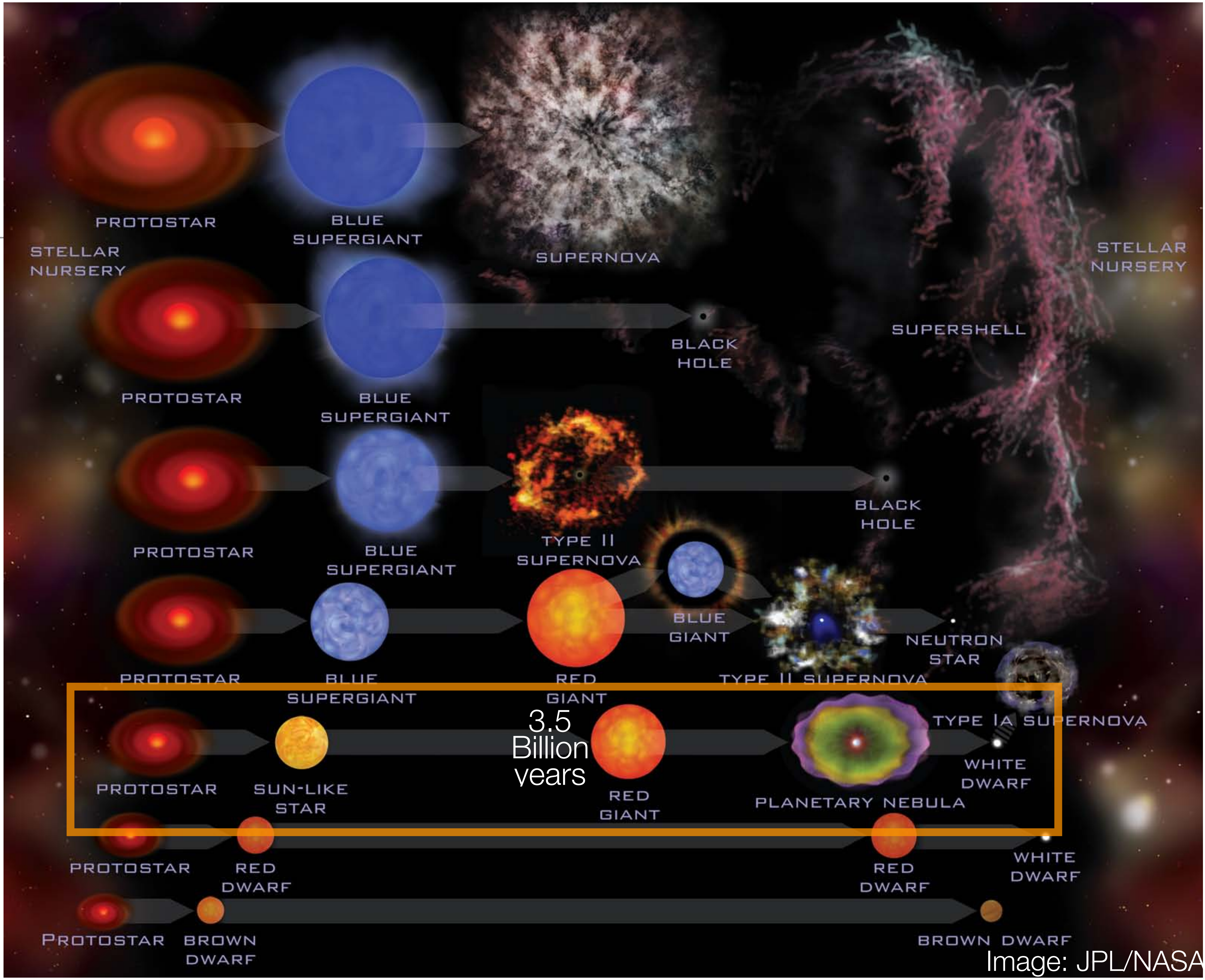




Fate of our Sun

Fusion inside the Sun is currently limited to the inner core.

In about **3.5 billion years** from now the fusion zone will move outwards making the Sun hotter.



Because the Sun will be hotter, pressure inside will increase and it will start to expand. It will turn into a **Red Giant**, then throw off a planetary nebula with a white dwarf at its core.

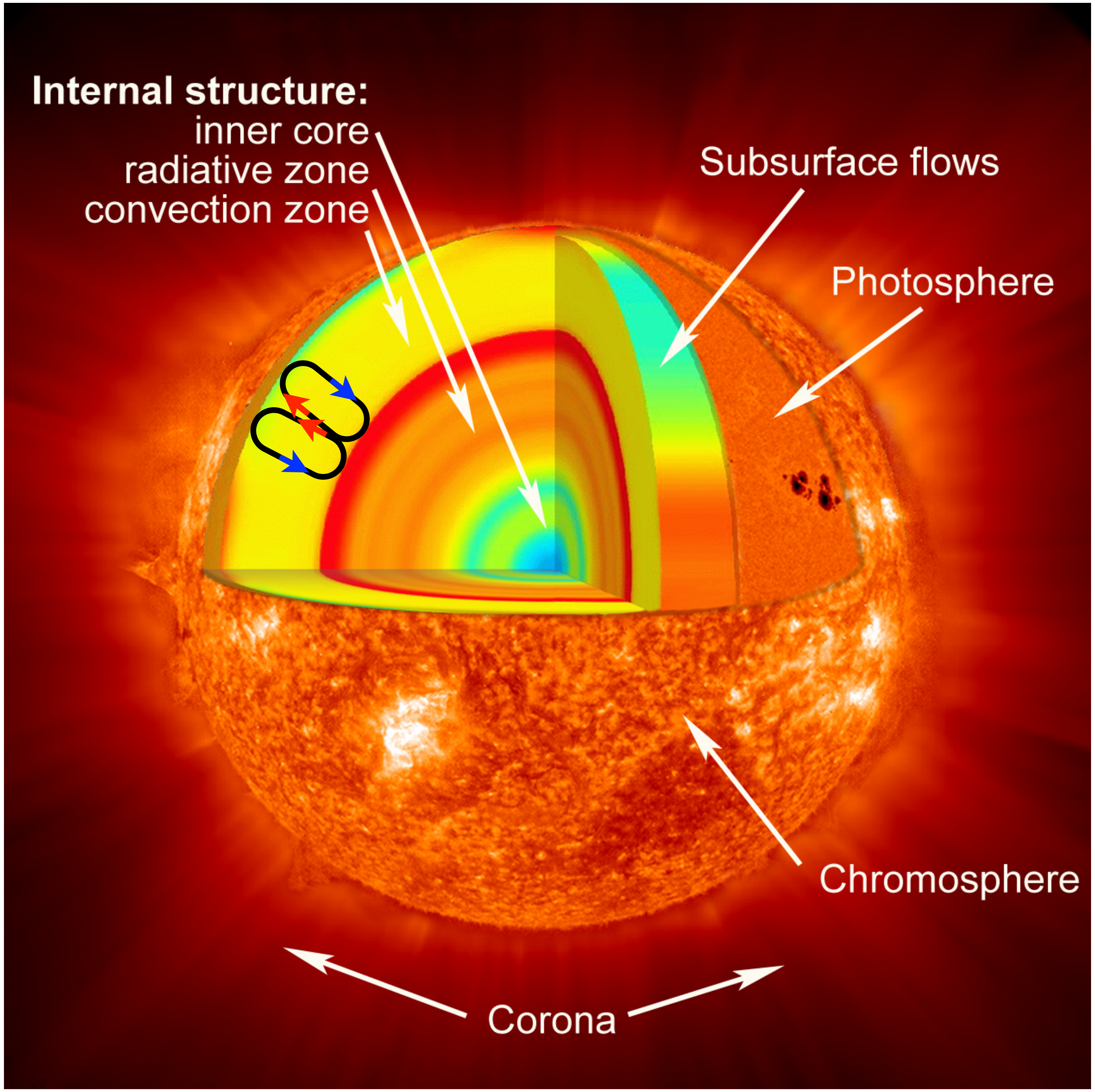
Structure of the Sun

Core is where the fusion reaction occurs. Contains 40% of the Sun's mass.

Density of core 160 tonnes/m^3

Radiation from the core works its way out and heats the **Radiative zone**. This zone has most of the remaining mass. Takes a million years for photons to cross this zone.

Convective zone is stirred like water boiling in a pot. Hot plasma moves up, cooled plasma moves down. Source of solar magnetic field.

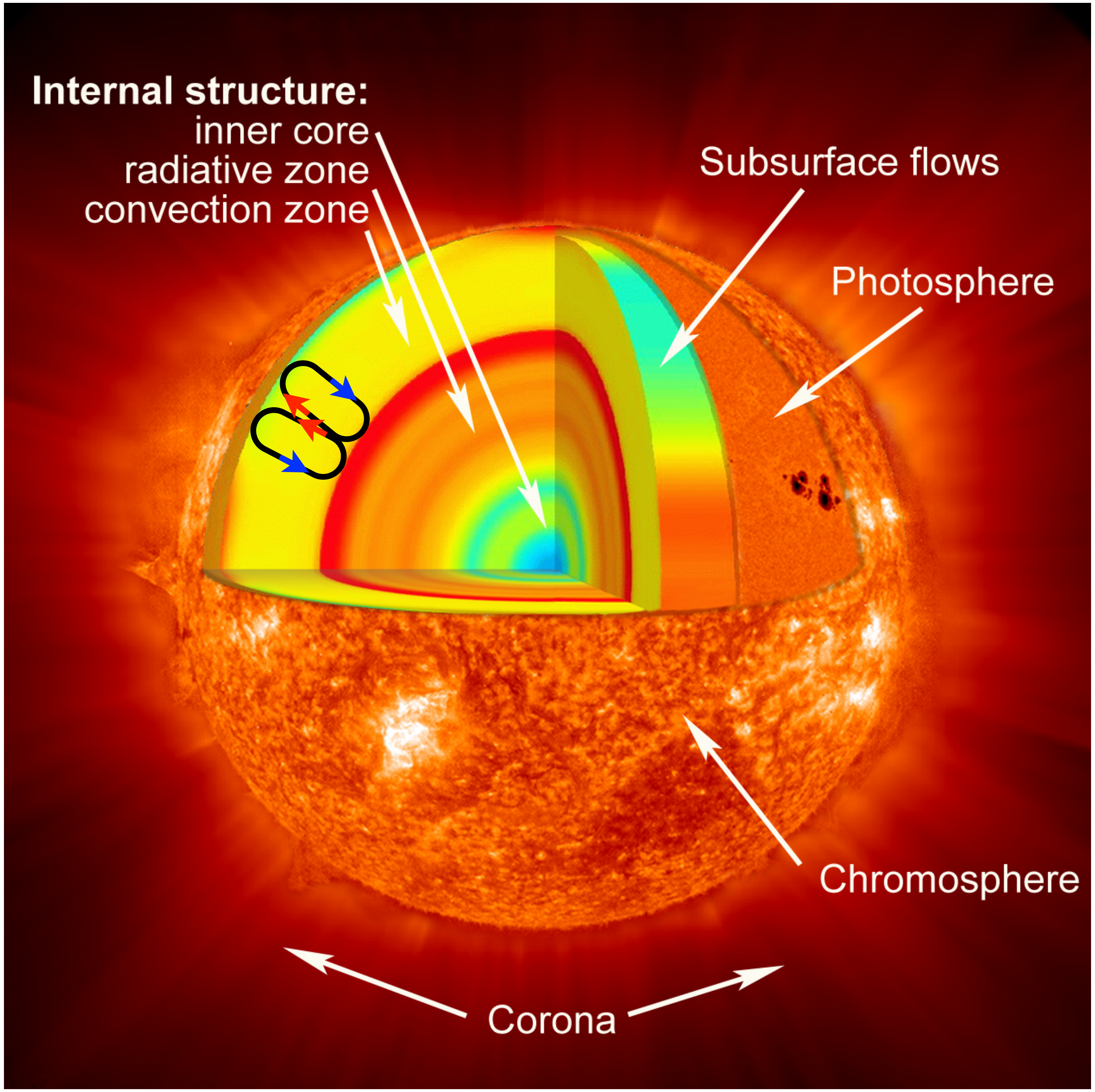


Structure of the Sun

Photosphere is the surface we see in visible light. Temperature: 5800°C

Chromosphere is the active layer (plasma in complex magnetic field) above the photosphere.

Corona is the Sun's atmosphere. It has very low density & very high temperatures (millions of K, we don't know what causes this). Extends millions of km out of the Sun turning into *Solar wind* (→ causes *Space Weather*).



Sun has two particular aspects that are important for life on Earth.

First one is **light** so let’s look at that. We will get to the second one a bit later.

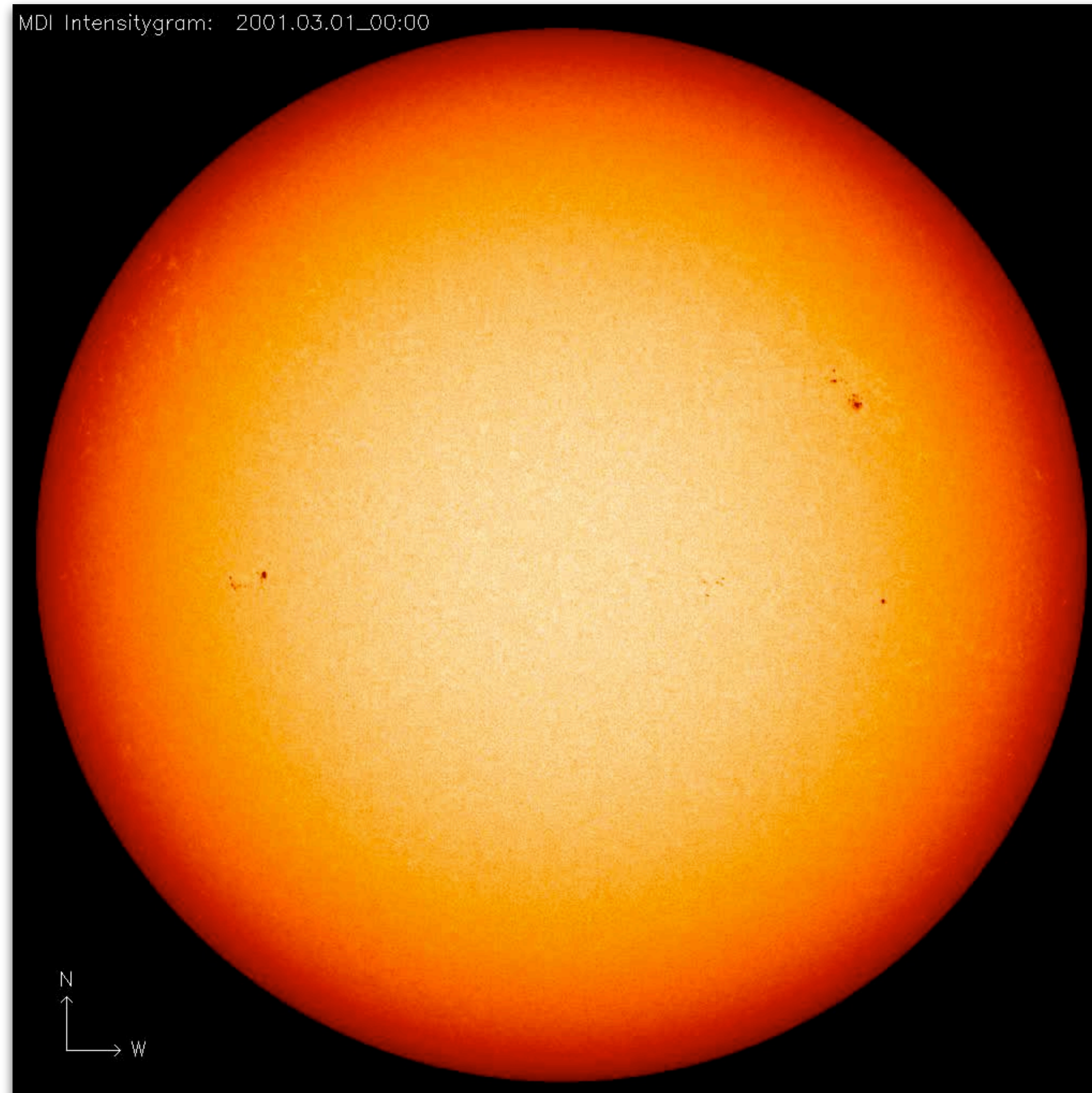
Solar radiation

The total power radiated by the Sun's surface is **3.86×10^{26} W**.

That is 0.386 octillion or **38.6 trillion trillion Watts.**

How long would the Earth's fossil fuel reserves last if they were burned to produce this much power?

…less than one second.



Solar energy heating the planet

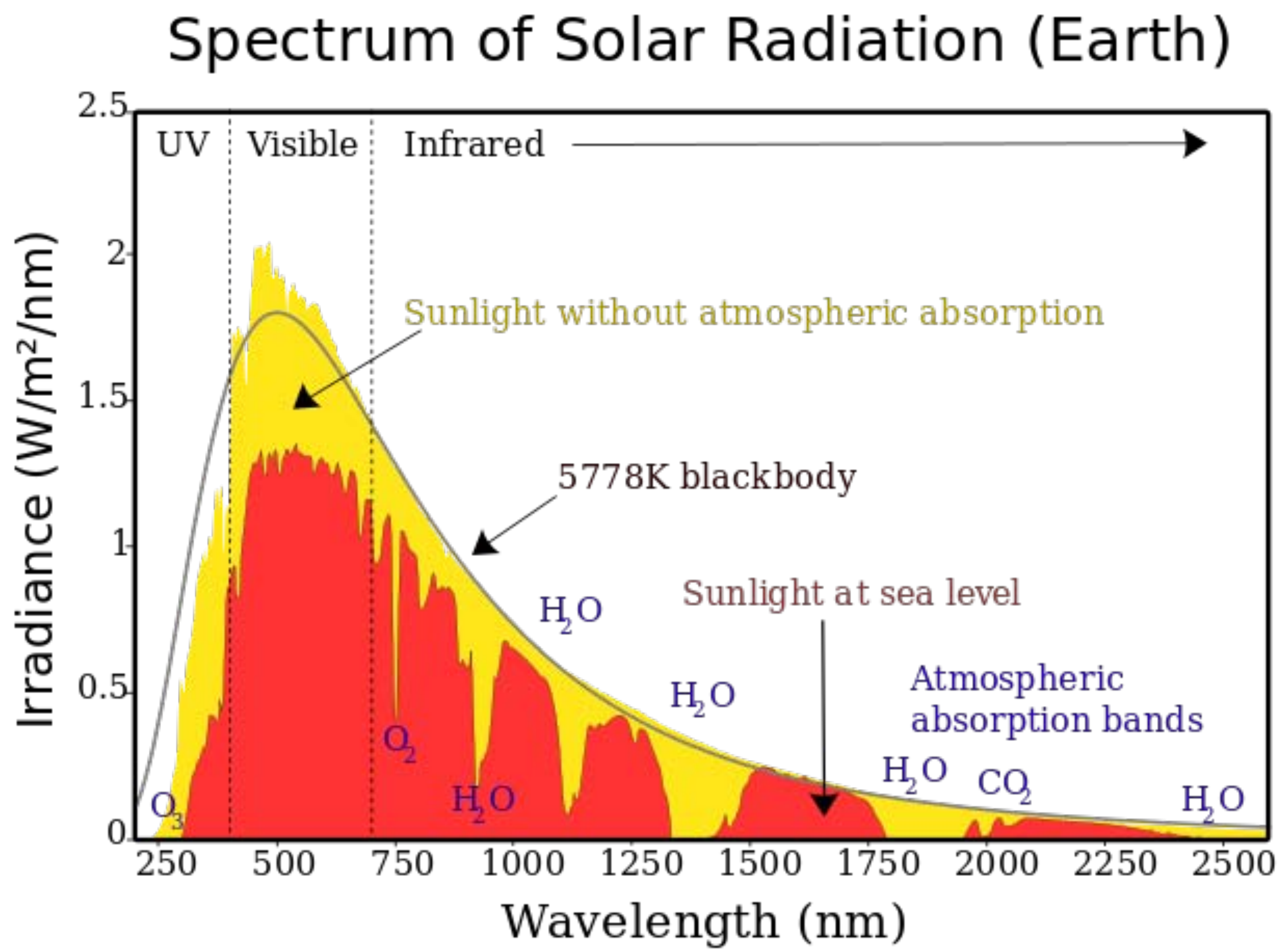
Of the power radiated by the Sun, Earth receives **1.736×10^{17} W.**

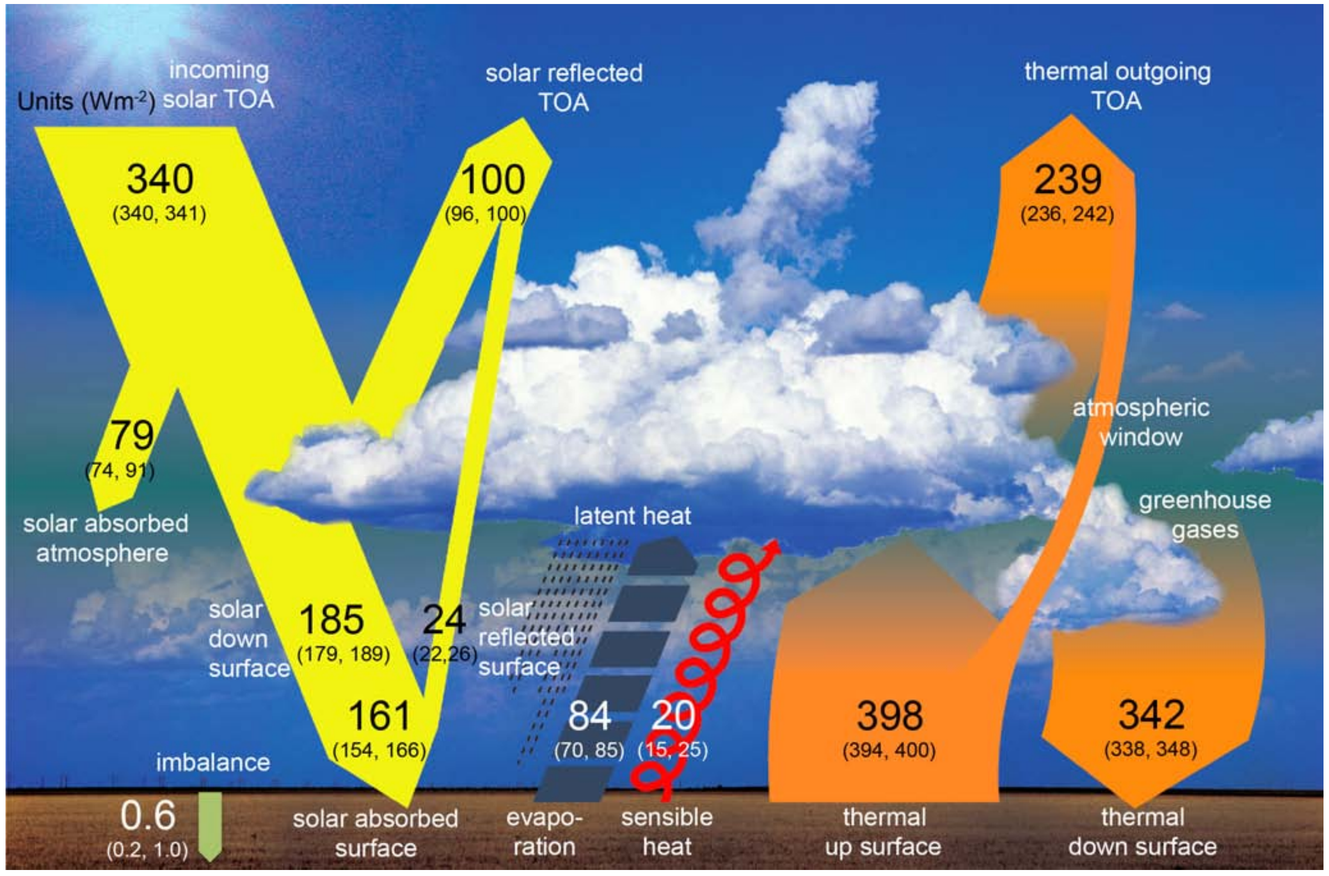
This powers our climate.

Most of solar radiation is at visible wavelengths.

Ozone in Earth's atmosphere absorbs the harmful solar ultraviolet (UV) radiation.

Without atmosphere Earth would be **cold**: $-18°C$. Atmosphere traps some of the incoming radiation and keeps temperatures warmer (= **Greenhouse effect**)!





Some greenhouse effect is good, too much isn't

- **Venus has a very dense atmosphere**, about 100 times more massive than the Earth's.
- Lots of CO_2 and other molecular gases.

Result: **run-away greenhouse effect**, surface of Venus is **>470°C** (hot enough to melt lead).

UV image of could covered Venus from NASA's Pioneer-Venus Orbiter in 1979

Surface of Venus. NASA Magellan mission 1990-1994.

Solar energy and the greenhouse effect

The **natural greenhouse effect** should be distinguished from the **enhanced greenhouse effect** which has anthropogenic ("originating from human activities") origins.

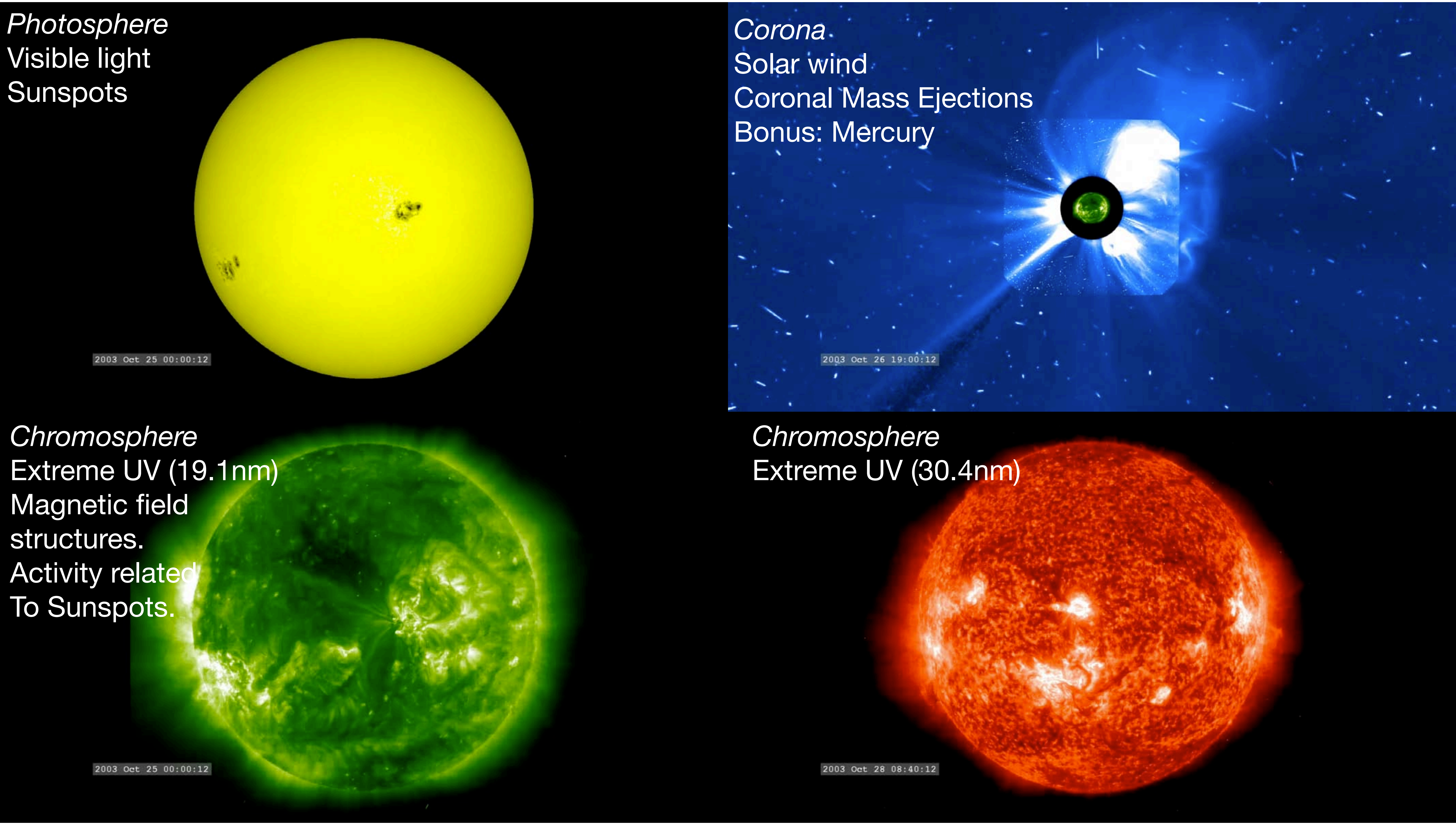
The enhanced greenhouse effect is an important issue, being at the focus of much of the present environmental debate. We don't want Earth to turn into Venus…

Sun has two particular aspects that are important for life on Earth.

First one was light.

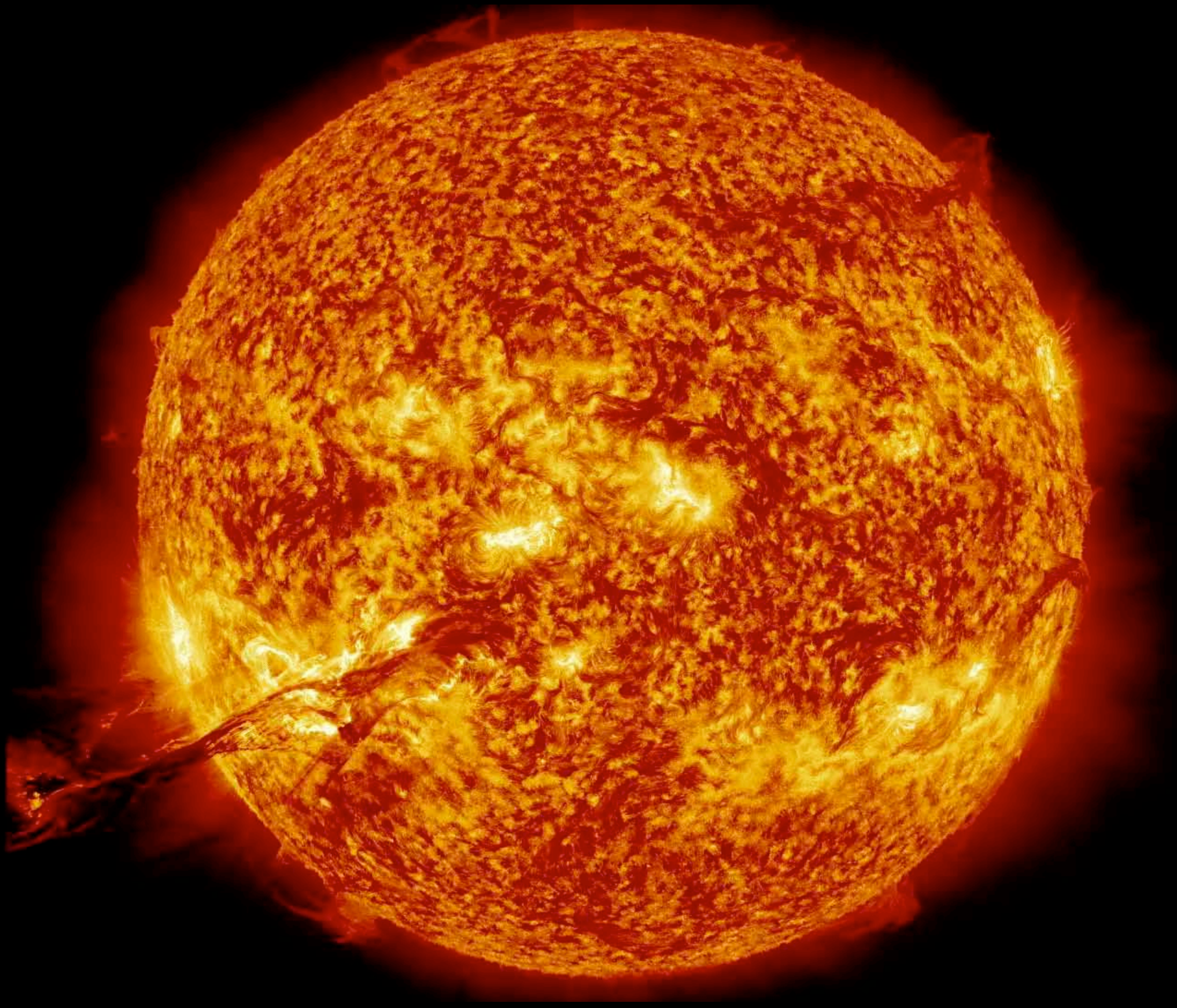
The second one is the ***solar wind***. Stuff being blown out of the Sun. Let’s look at that now.

Outer layers of the Sun in action

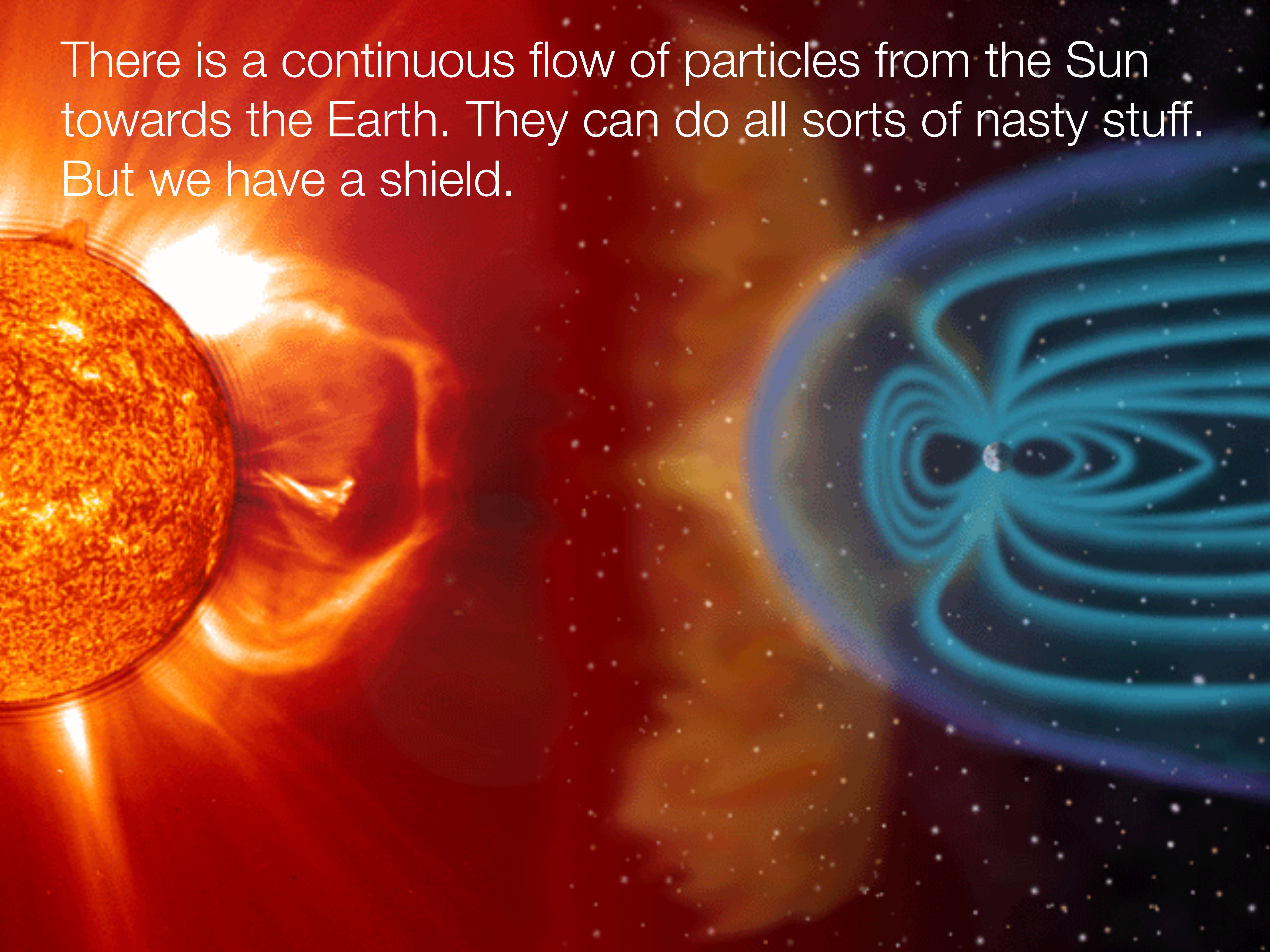


2 weeks of observations in Oct-Nov 2003 from the SOHO satellite. Source: NASA

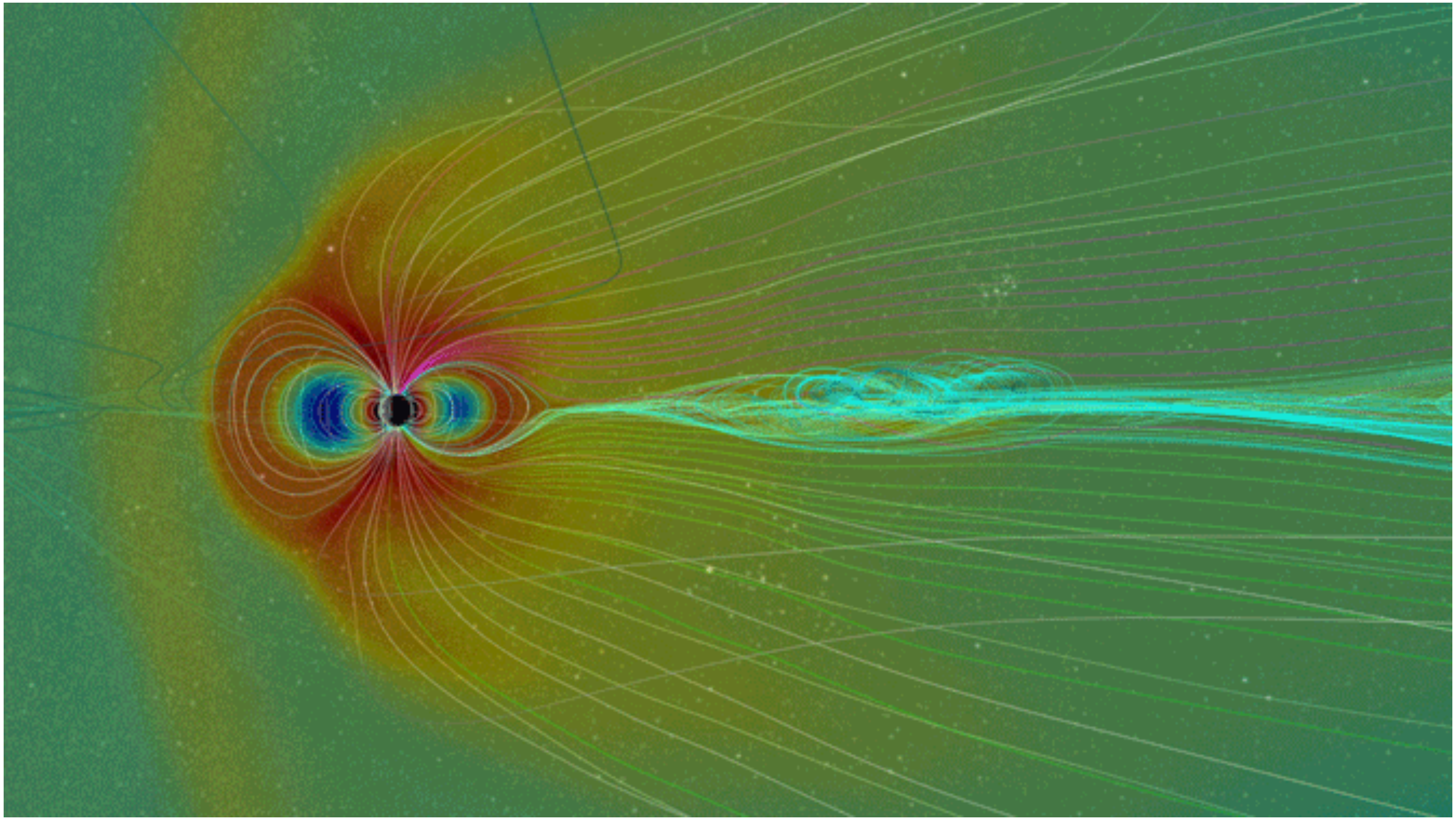
August 31st, 2012 CME as seen by NASA's Solar Dynamics Observatory (SDO), NASA's Solar Terrestrial Relations Observatory (STEREO), and the joint ESA/NASA Solar Heliospheric Observatory (SOHO) https://svs.gsfc.nasa.gov/11095



100 billion kg of matter being blown into space.


There is a continuous flow of particles from the Sun towards the Earth. They can do all sorts of nasty stuff. But we have a shield.

Magnetosphere - The extension of our magnetic field into space. Our shield agains solar wind.



Simulated response to the historical Carrington storm of 1859 (NASA/CCMC).

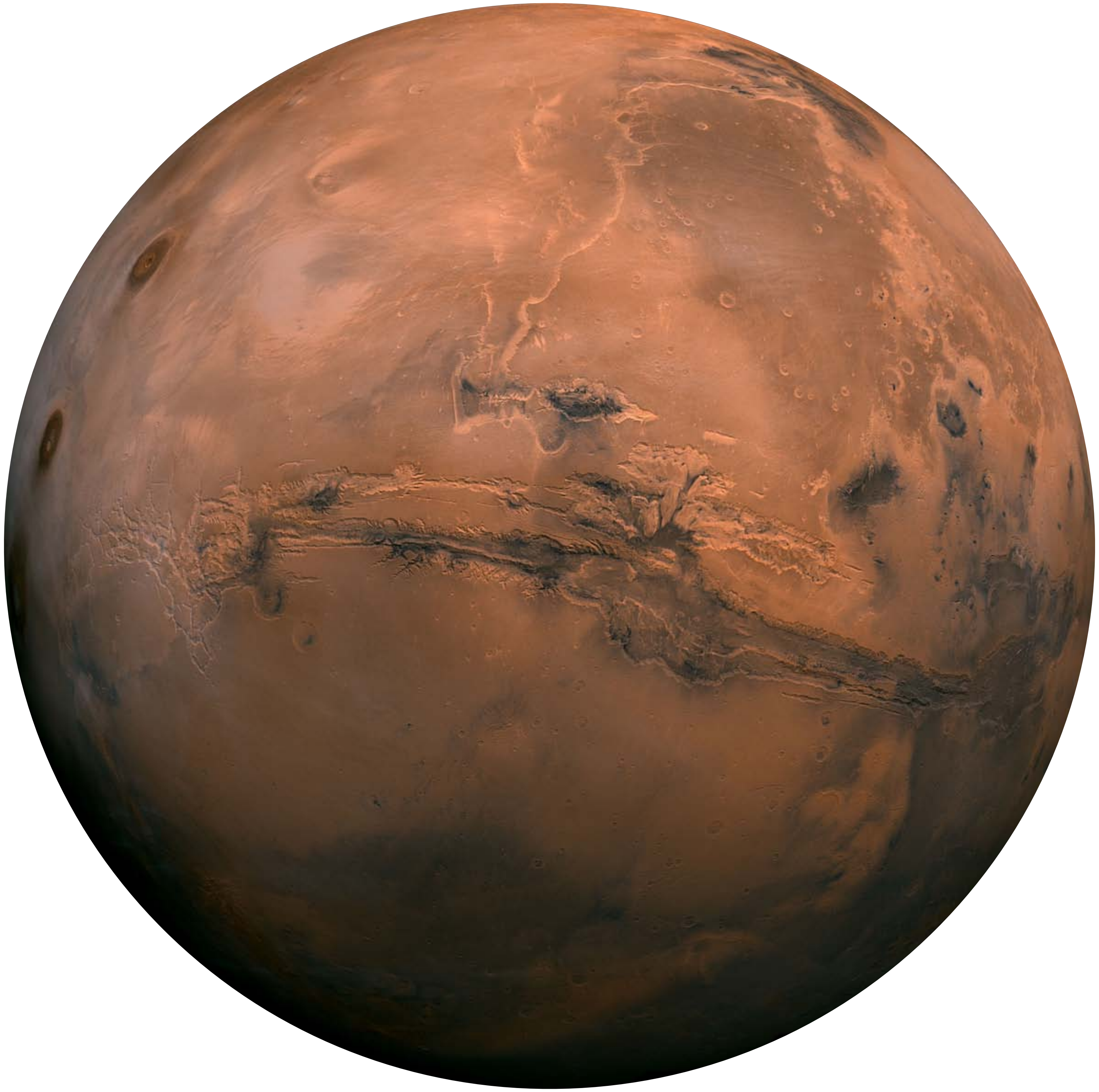
NASA's Scientific Visualization Studio, the Space Weather Research Center (SWRC), the Community-Coordinated Modeling Center (CCMC) and the Space Weather Modeling Framework (SWMF). https://svs.gsfc.nasa.gov/4189

This is what solar wind does to the atmosphere without a protective magnetosphere

Mars does not have a magnetosphere.

Solar wind blew its atmosphere away.

Average temperature around -55°C.



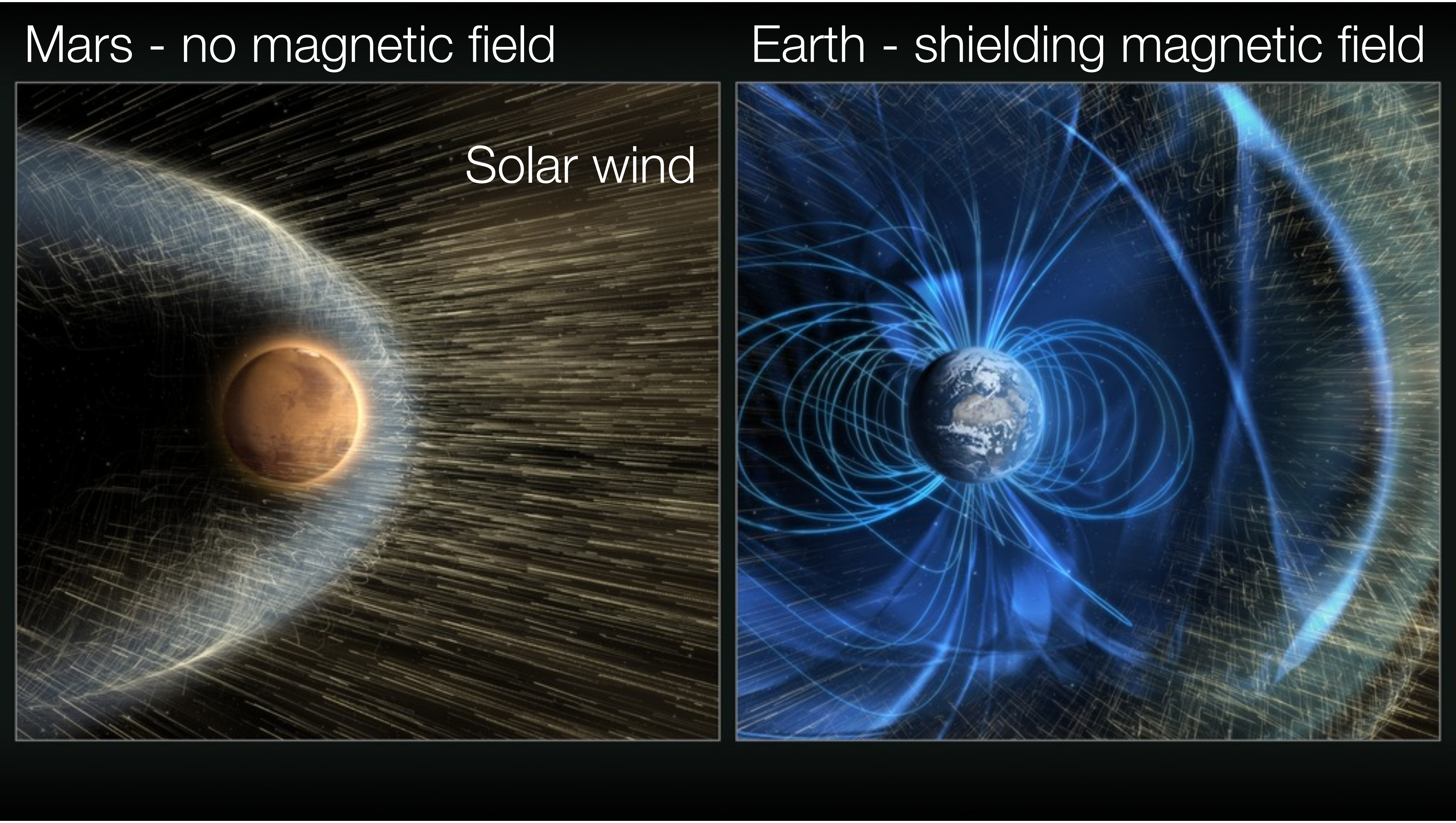


Image: NASA/GSFC

But… The faint young Sun paradox

Astronomers Carl Sagan and George Mullen pointed out in the 1970's that there is a contradiction in Earth's early history:

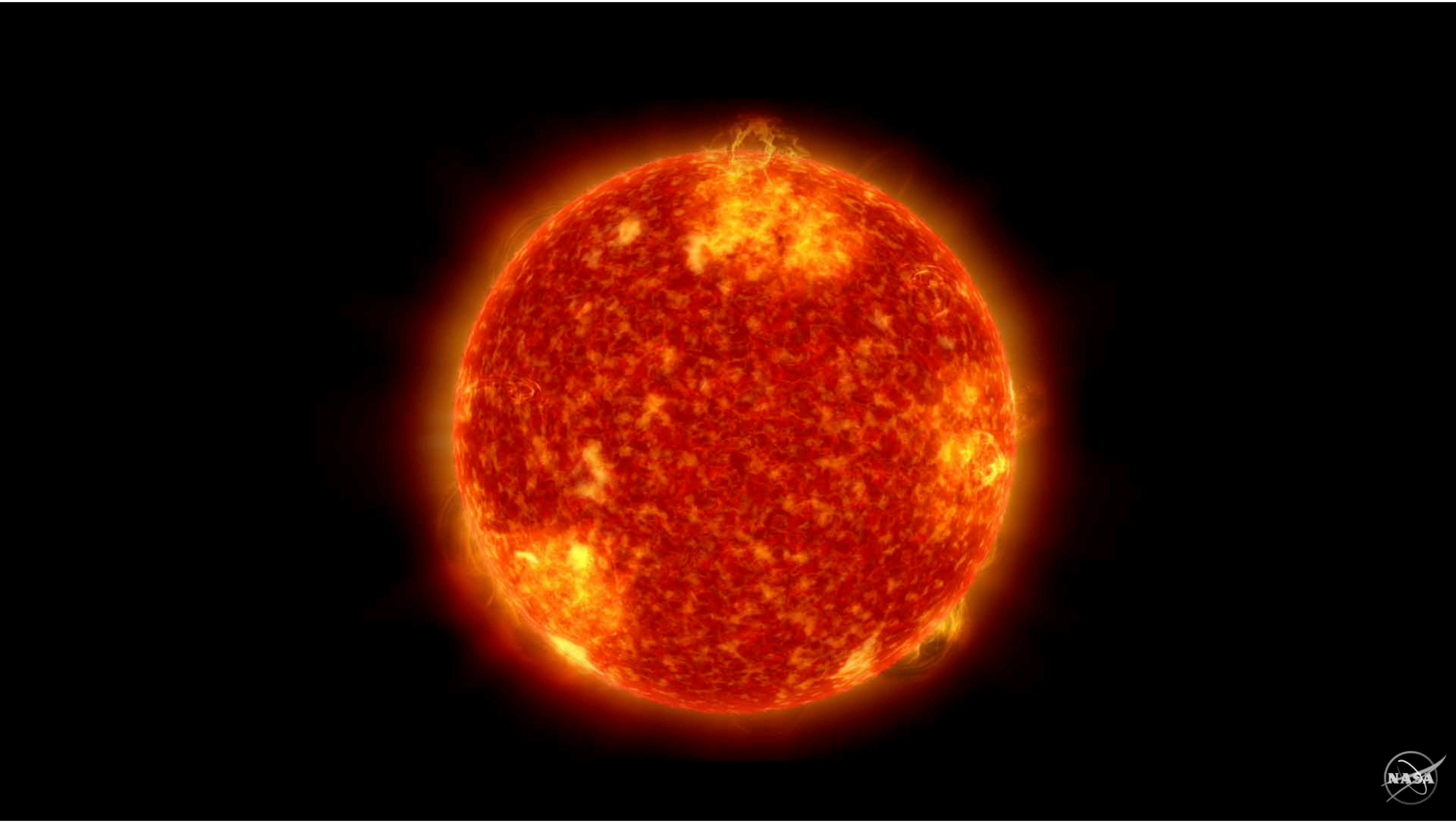
Geological records: ~4 billion years ago **Earth had liquid water**.

Astronomy (looking at Sun like stars): Sun wasn't as bright as it is now, we only received about 70% of the energy

- ➡ **Earth should have been an icy ball!**

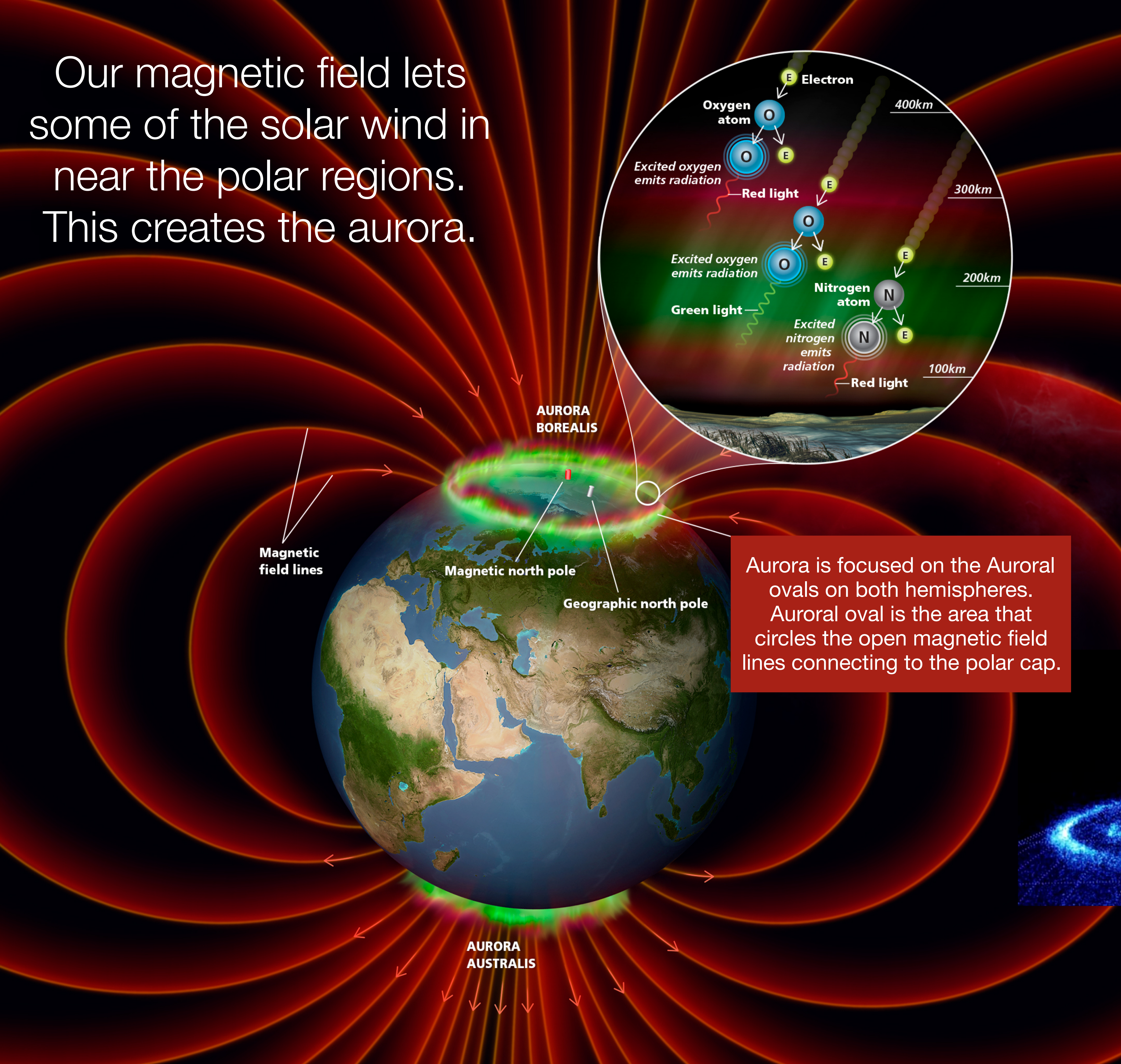
Saturn's moon Enceladus, a snowball in space by NASA's Cassini mission

Solar wind and big solar storms *may* have provided energy for life on Earth.



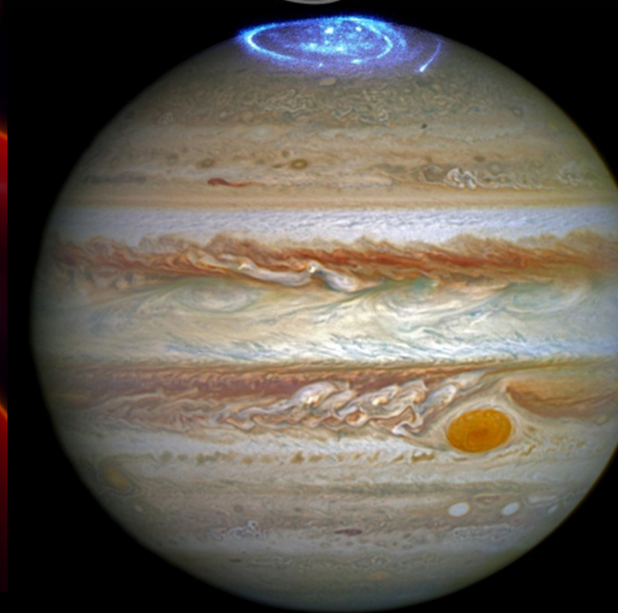
And solar wind does definitely does something nice too…

Our magnetic field lets some of the solar wind in near the polar regions. This creates the aurora.

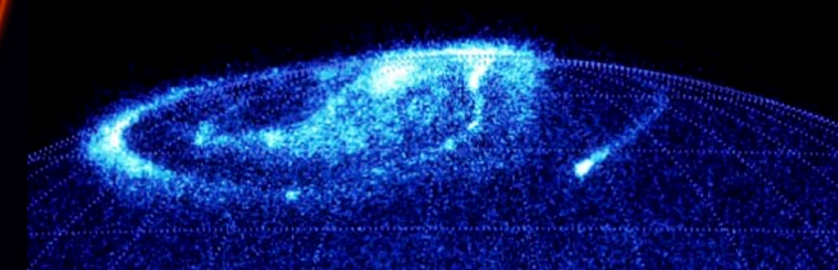


Aurora is focused on the Auroral ovals on both hemispheres. Auroral oval is the area that circles the open magnetic field lines connecting to the polar cap.

Image by Roen Kelly/Discover



Images of aurora in Saturn and Jupiter by NASA/ESA (Hubble, Juno)



Timelapse of aurora in Norway by Tor Even Mathisen
https://vimeo.com/16917950

Summary

For Earth to be habitable many things have worked in our favour.

- We get **energy from the Sun**.
- Earth has **water**.
- Earth has **atmosphere**.
- We are at the **right distance from the Sun** and have **some greenhouse** effect for surface temperature that allows the **water to be liquid**.
- Earth has a **magnetosphere** that protects us from solar wind.

Rare cloud-free true colour image of New Zealand. Taken byNASA's Terra satellite, on October 23, 2002.

Video: NASA/Goddard Space Flight Center Scientific Visualization Studio
http://svs.gsfc.nasa.gov/11525