Our Dynamic Sun

12 January 2017

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European Research Council
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Science & Technology Facilities Council

Our Dynamic Sun

A 21st Century View

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Our Dynamic Sun

Creating mathematical models to understand our local star

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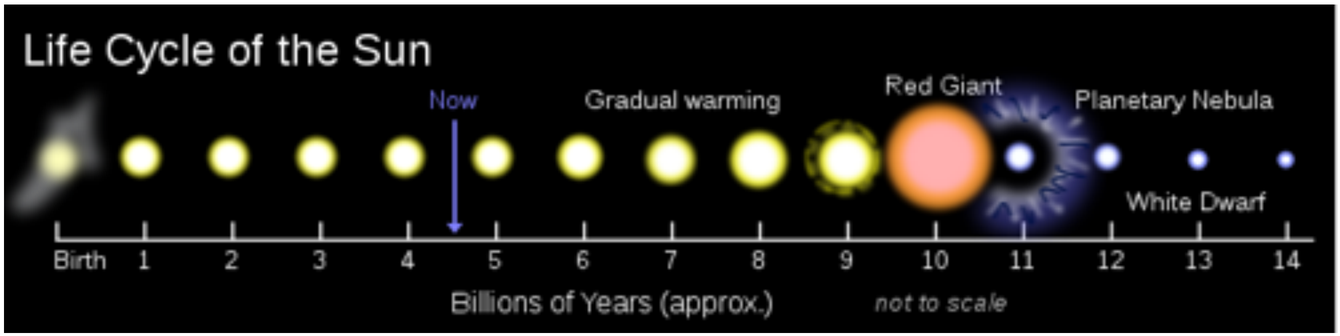
The Sun as a Star

- The Sun is an ordinary, middle-aged star (about 4.5 billion years)



- ~ 26,000 light years from the galactic centre
- Only ‘special’ because it is so close.
    - The Sun is the only star we can see in detail.

Solar Interior

Core
(T ~ 16 million °C)

↓

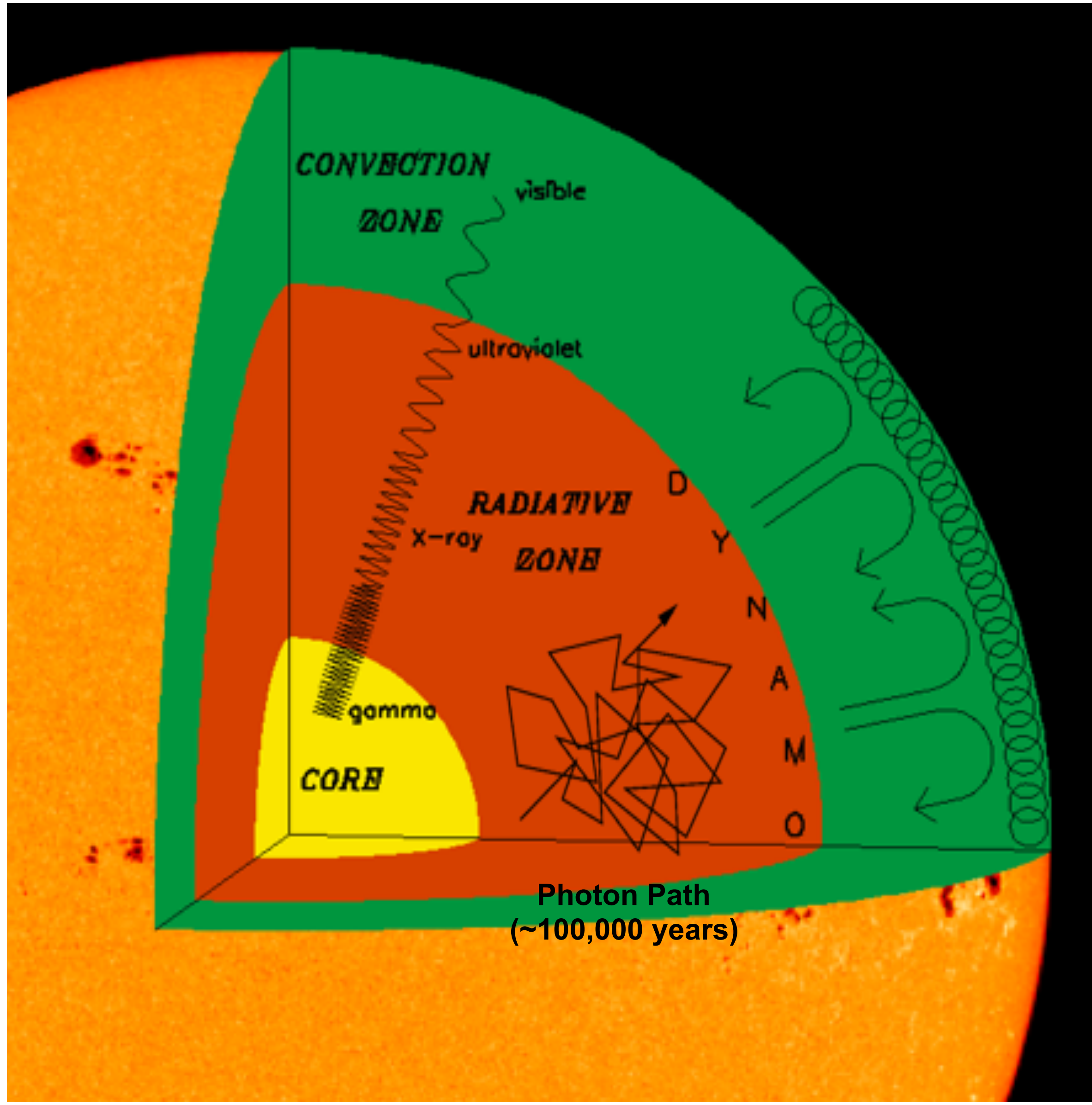
Radiative Zone
(T ~ 8 million °C)

↓

Convection Zone
(T ~ 2 million °C)

↓

Photosphere
(surface)
(T ~ 6,400 °C)



Solar Atmosphere

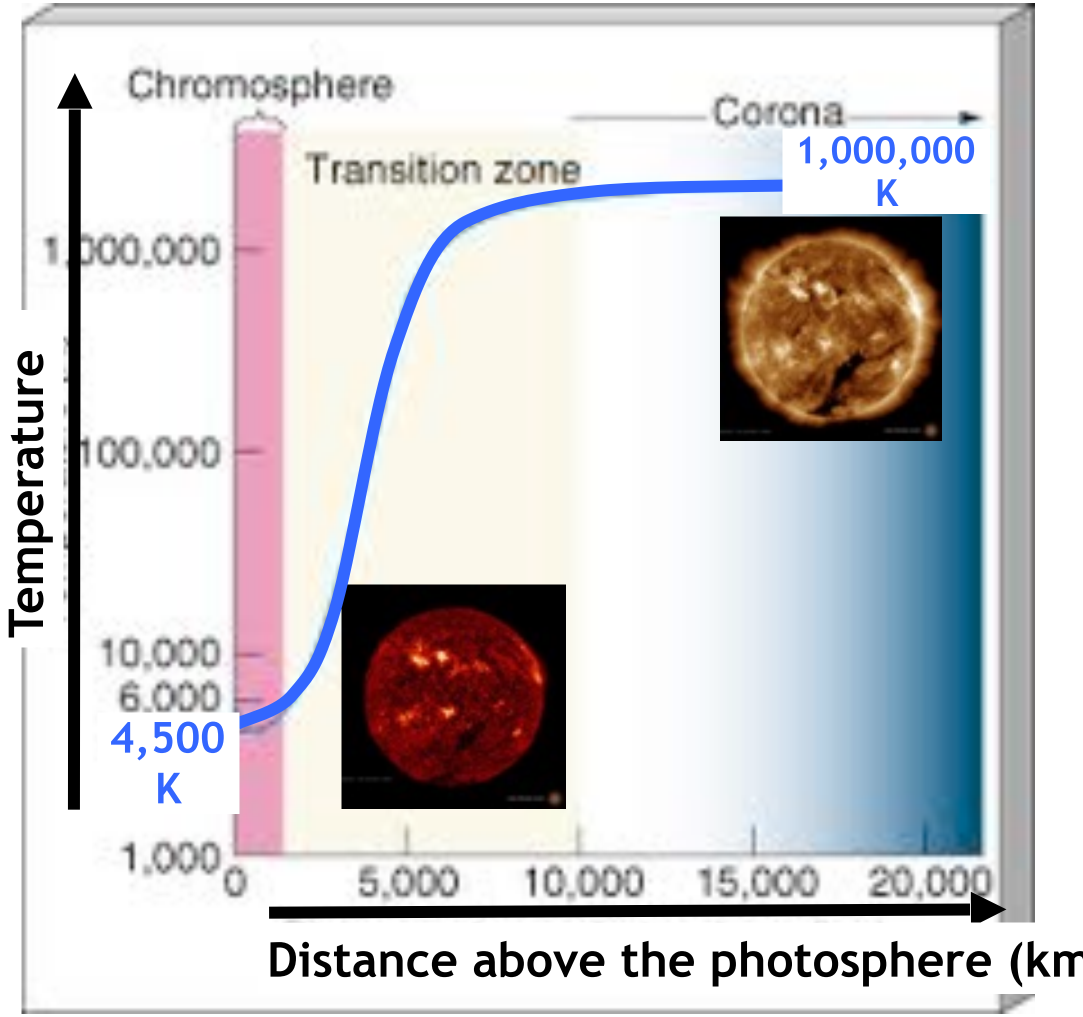
Photosphere
(T ~ 6,400 °C)

↓

Chromosphere
(T ~ 4,000 - 1 million °C)

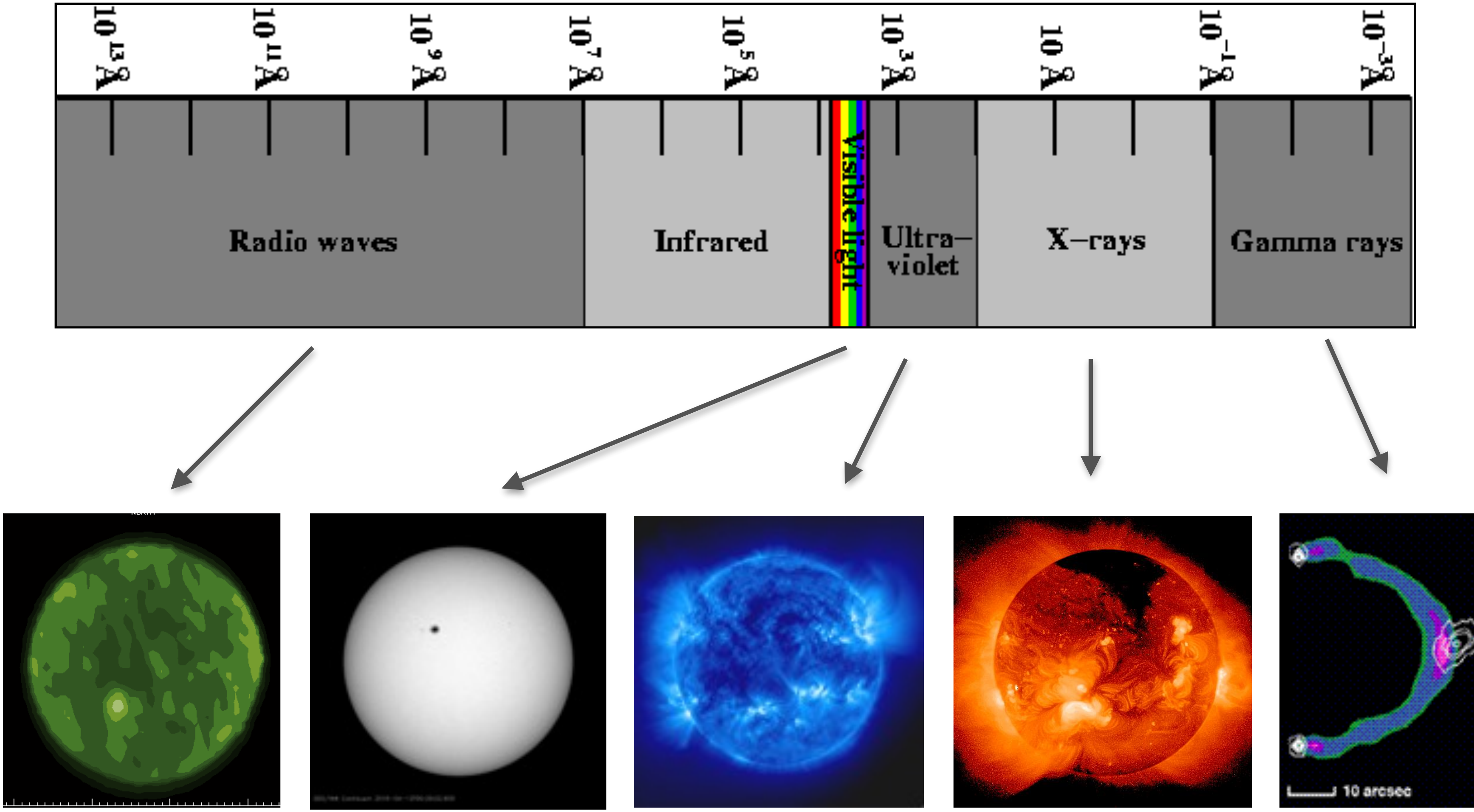
↓

Corona
(T > 1 million °C)



The "Coronal Heating Problem"

Observing The Sun’s Atmosphere



Solar Atmosphere

Photosphere
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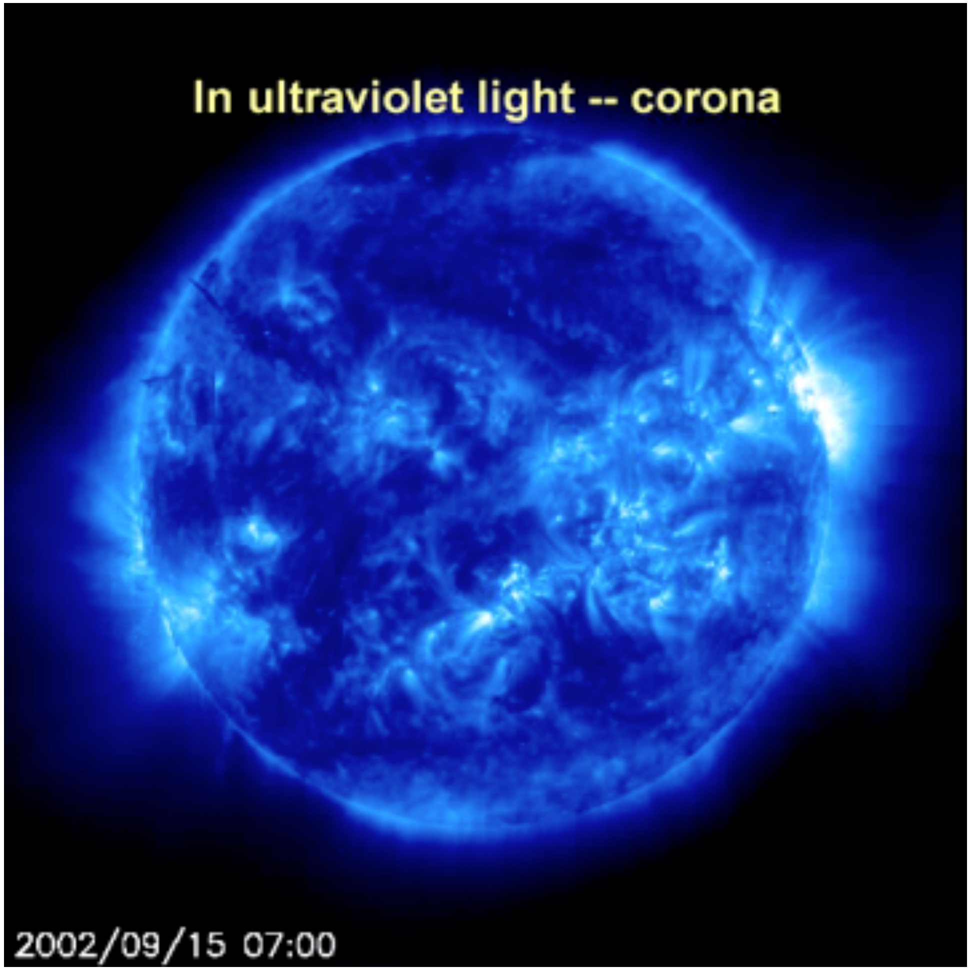
↓

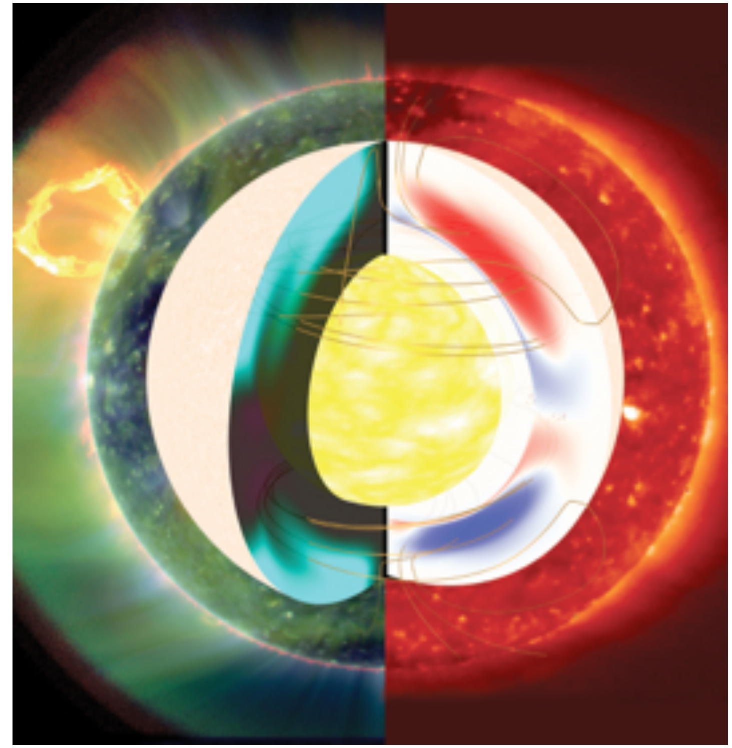
Corona
(T > 1 million °C)

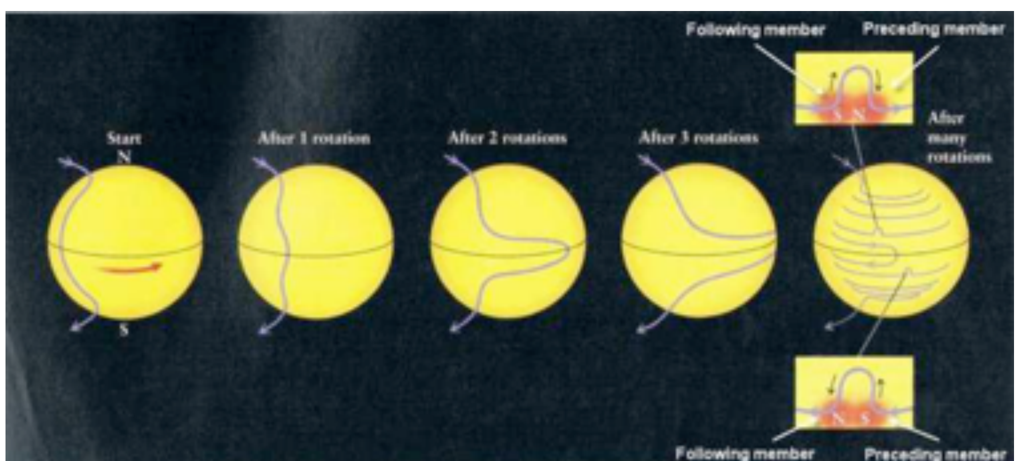


Regions with strong magnetic field = very bright emission

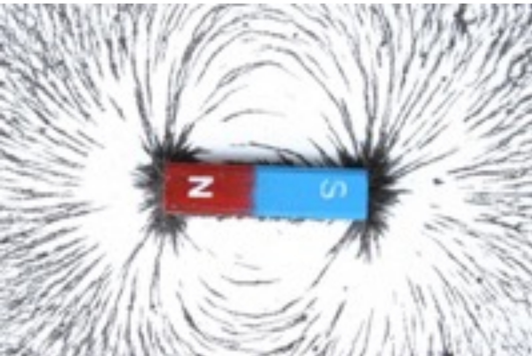
Solar Magnetic Field

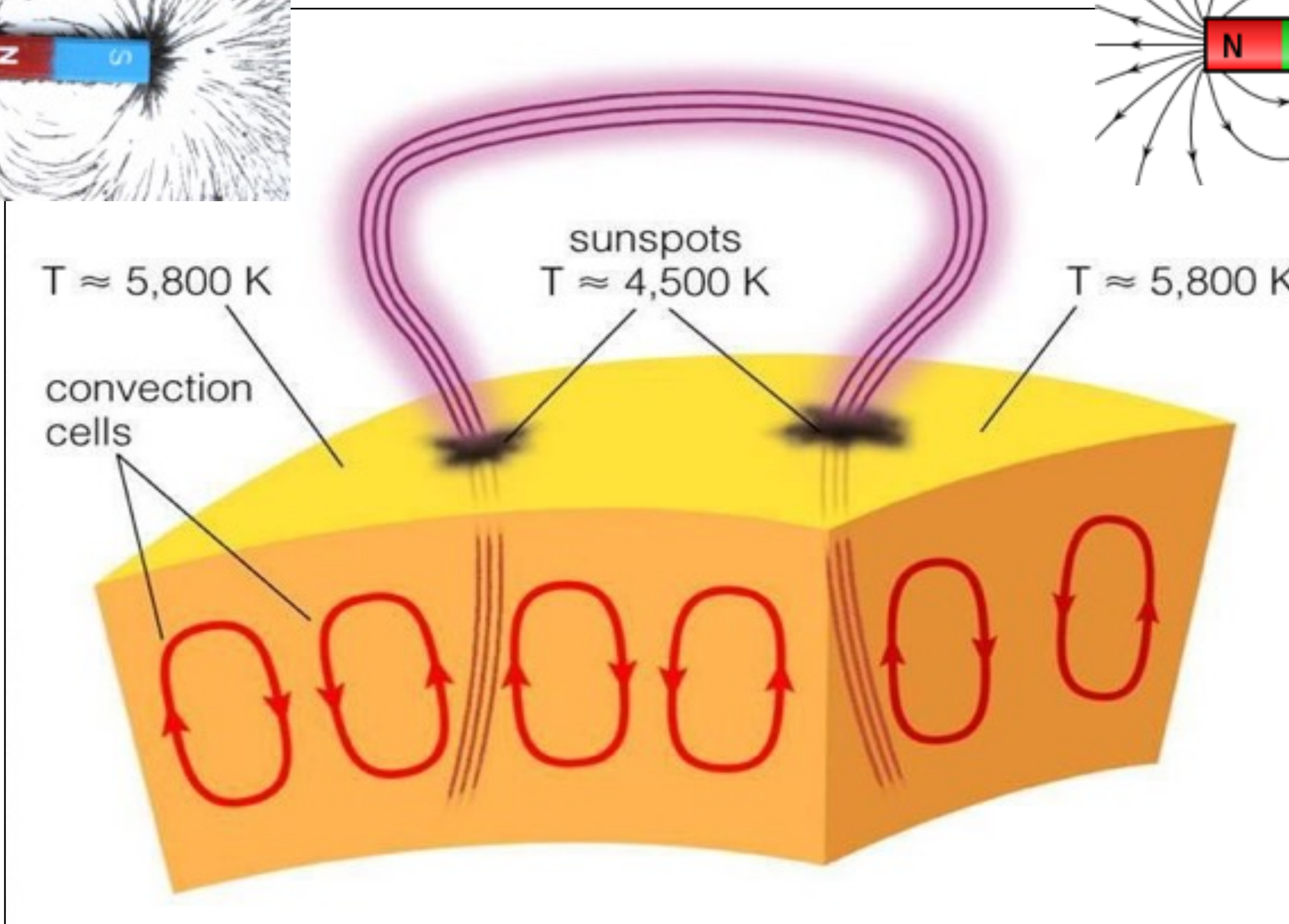
- Power source in the core
- “Differential” Rotation
- “Dynamo” in interior generates magnetic field
- Field rises and emerges through photosphere
  - ➢ sunspots etc

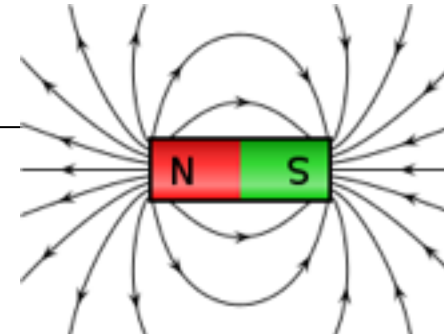




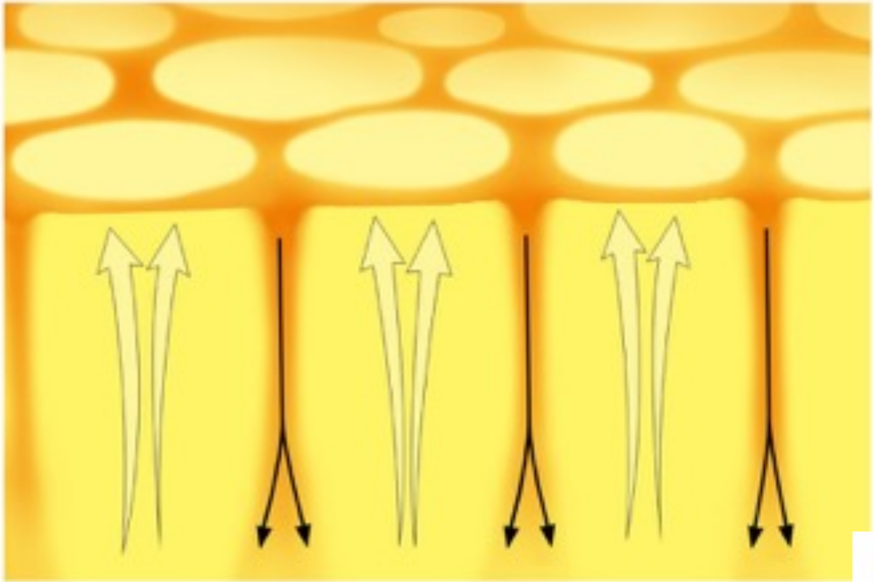
Magnetic Field





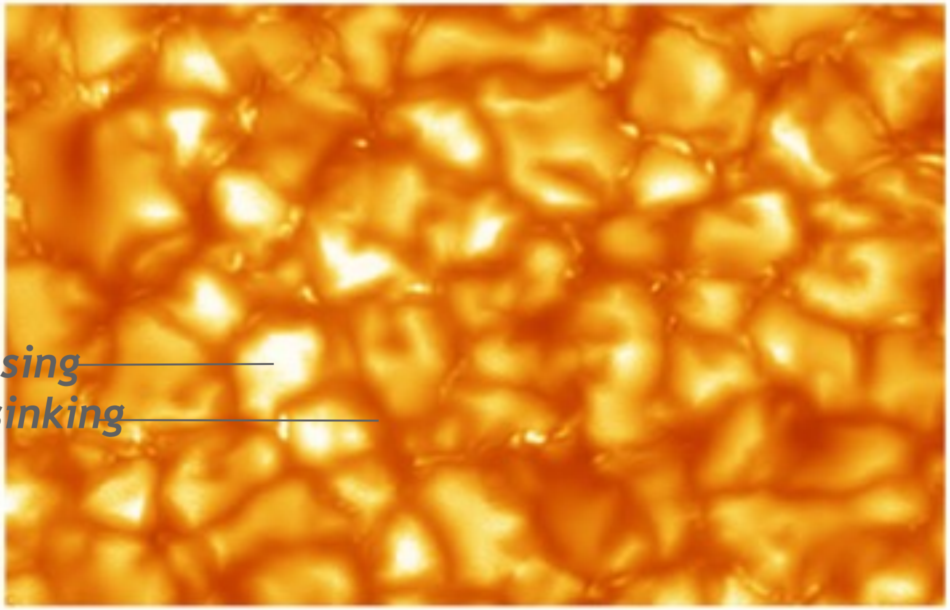


Granulation



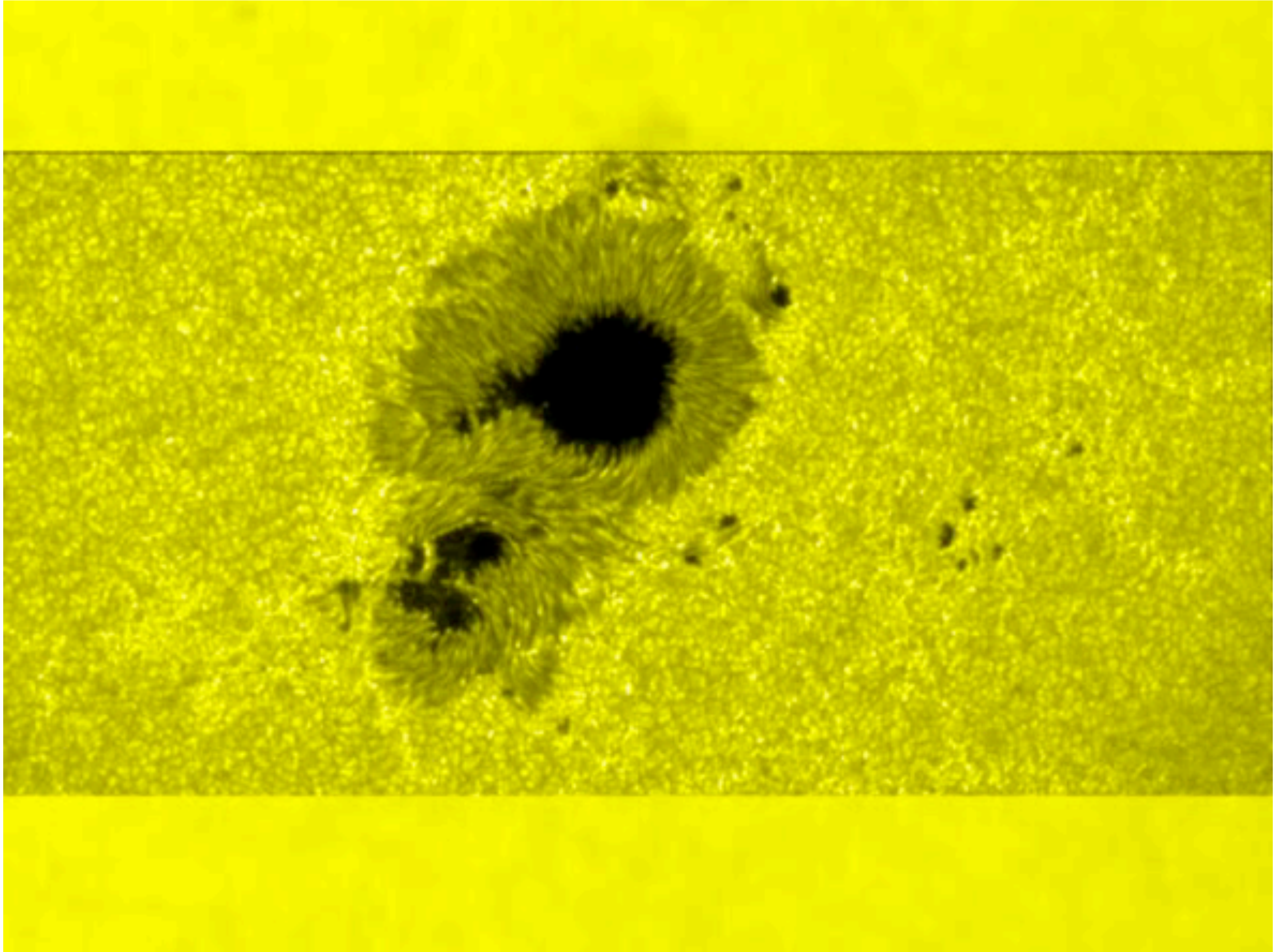
- Bright spots appear on Sun's surface where hot gas is rising.
- Then the gas cools and sinks.

  ➢ Convection

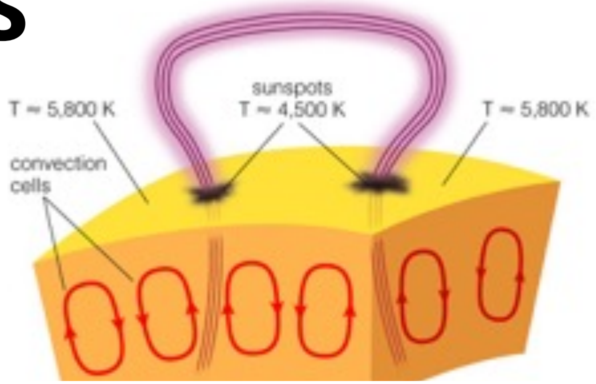


Picture of solar granulation

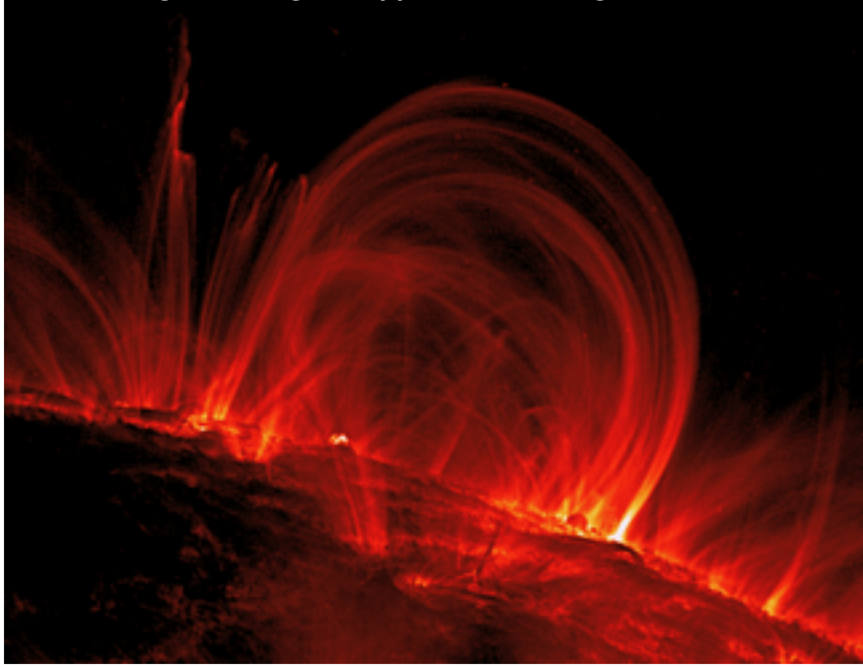
Granulation



Coronal Loops

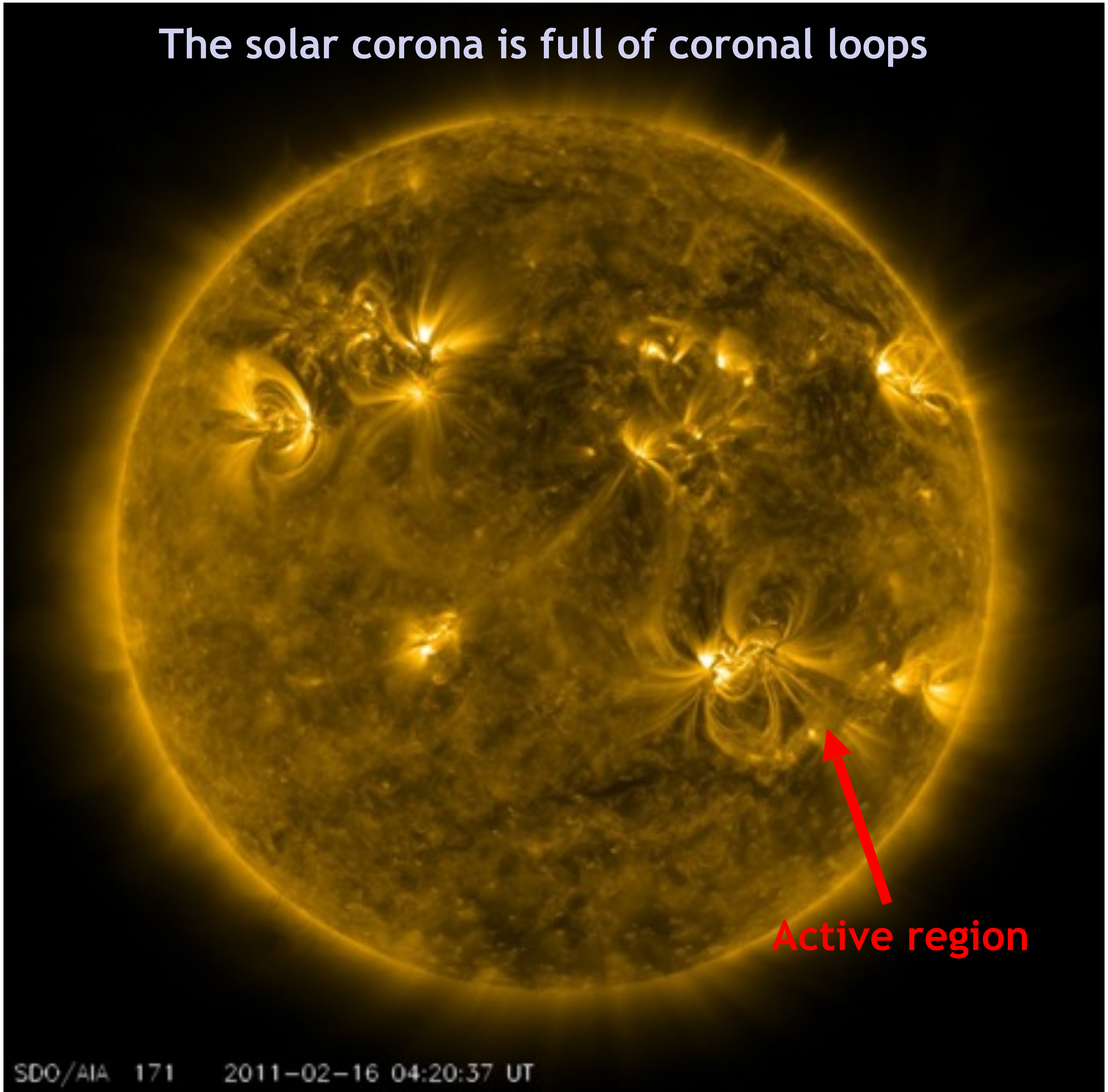


EUV image of hot gas trapped within magnetic field lines

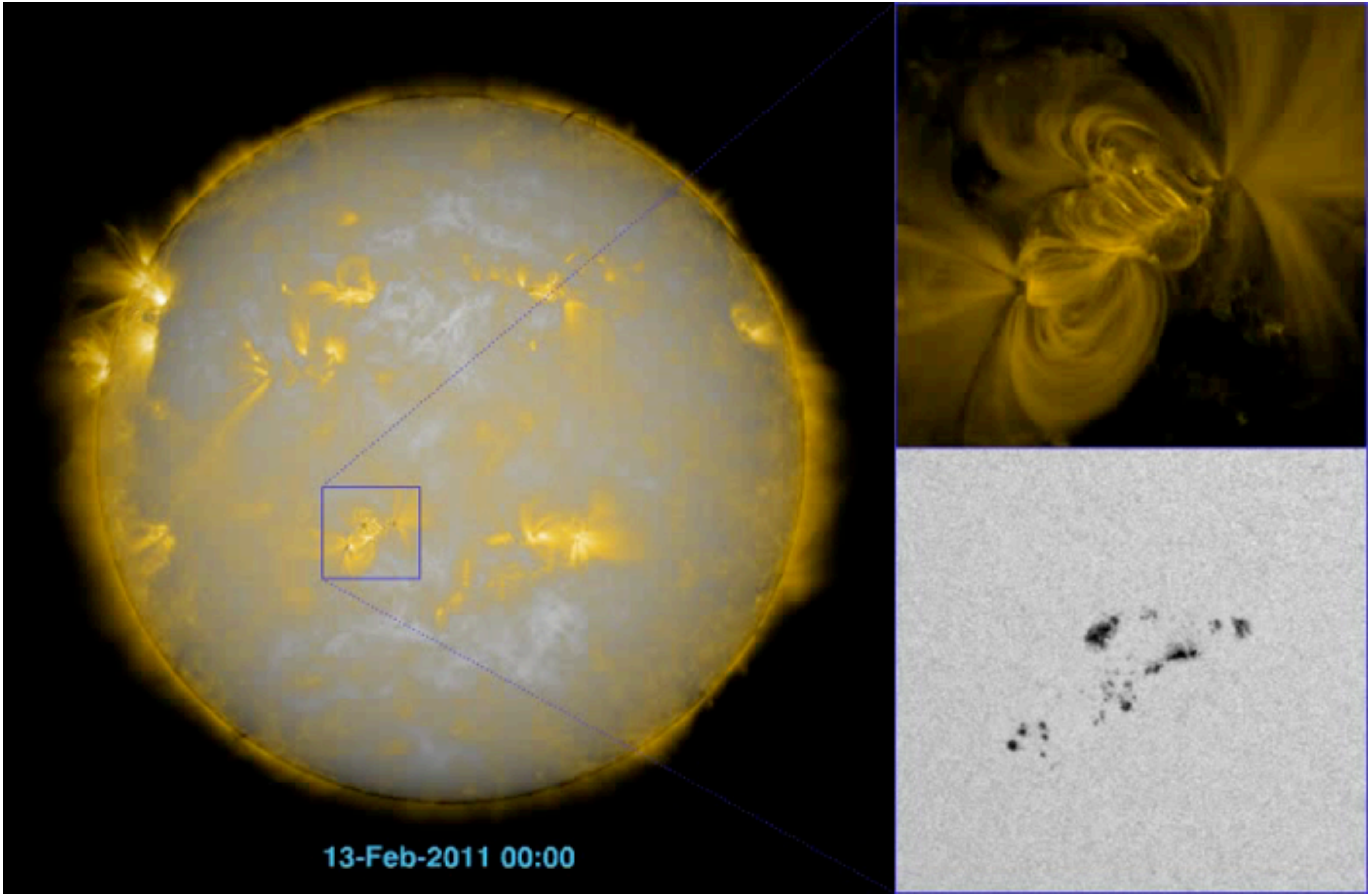


- Bright coronal loops outline magnetic field

The Solar Corona

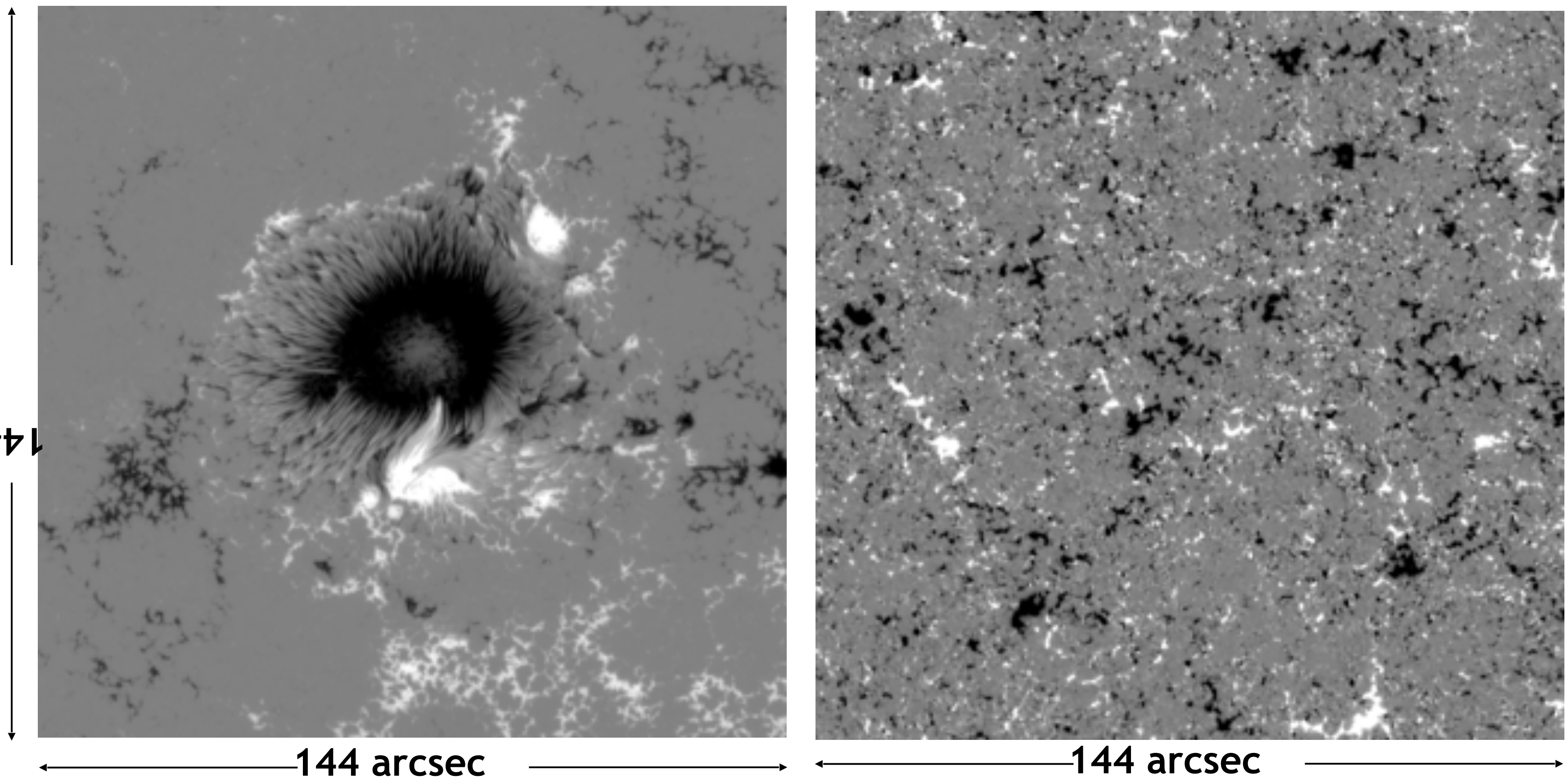


The Dynamic Solar Corona



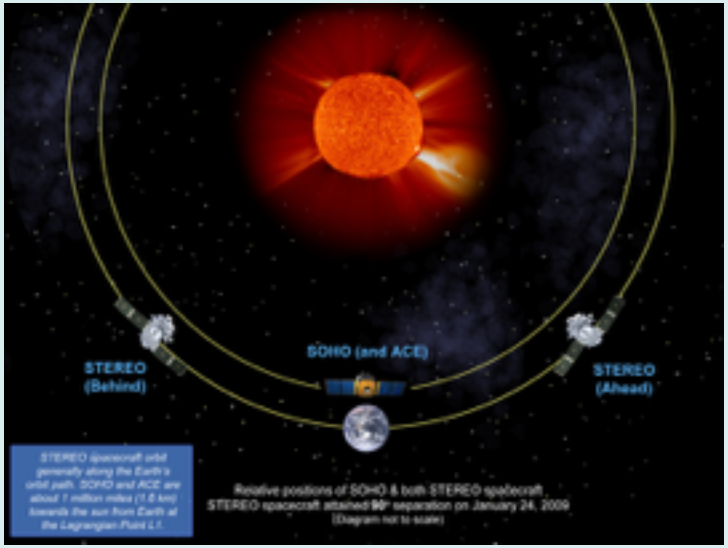
Magnetic Field on all scales

Hinode/SOT: Images taken in the blue wing of Fe I 6302 Å



- The Sun’s surface is threaded by magnetic fields on all scales.

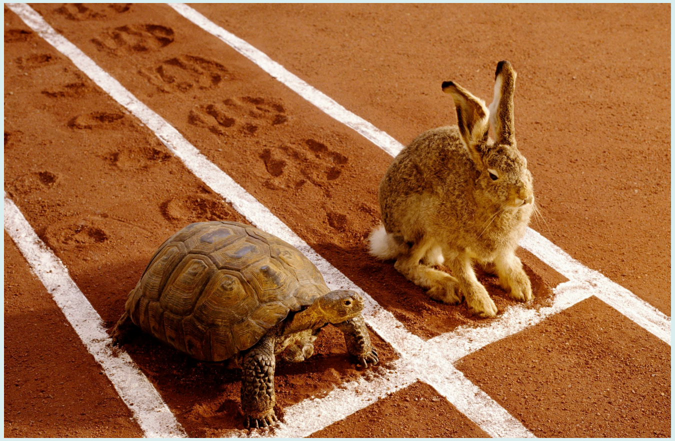
Where is the Maths?

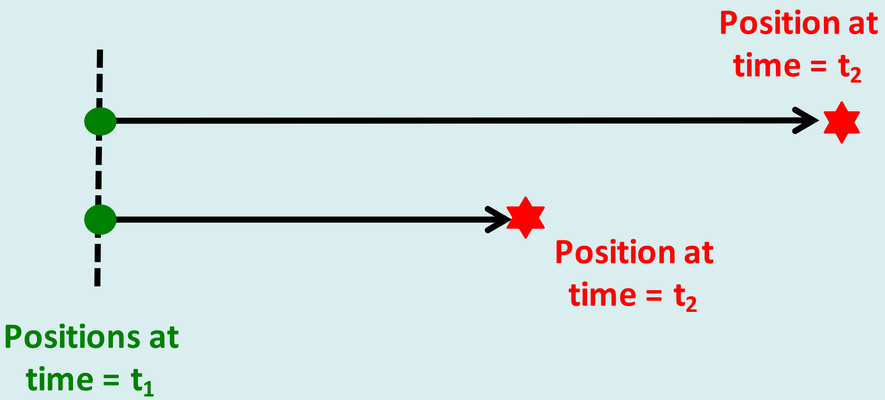


- So what do solar physicists (applied mathematicians!) do?
  - ➢ Create mathematical models to study the Sun’s physical processes.

- Why do we need models?
  - The Sun is not a controlled experiment so we need modelling.
  - Observations mostly tell us the outcome of the physical processes.
  - Try to explain the observations.
  - Try to predict some of the events (especially the ones that might affect the Earth).

Mathematical Interlude: Derivatives





$$\Rightarrow \text{velocity} = \frac{\text{distance}}{\text{time}} = \frac{\text{position}(t_2)\text{-position}(t_1)}{t_2 - t_1}$$

$$\Rightarrow \boxed{v = \frac{P_2 - P_1}{t_2 - t_1} = \frac{dP}{dt}}$$

- The time derivative tells us how ‘P’ (position) has changed in time.

MagnetoHydroDynamics (MHD)

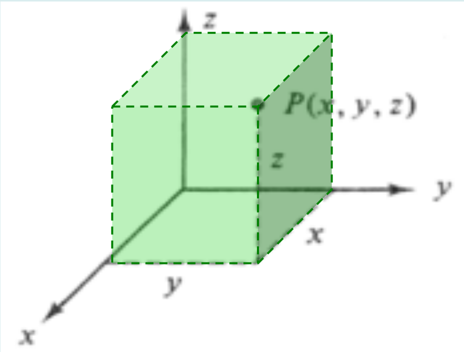
➢ The MHD equations are a combination of Maxwell's equations for magnetic fields and the fluid equations.

➢ The dependent variables:

- ρ - the mass density
- $v = (v_x, v_y, v_z)$ - the fluid velocity
- P - the gas pressure
- $j = (j_x, j_y, j_z)$ - the current density
- $B = (B_x, B_y, B_z)$ - the magnetic field
- T - the plasma temperature
- $E = (E_x, E_y, E_z)$ - the electric field

Maxwell Statue on George Street, Edinburgh

- All the variables depend on time (t) and space (x,y,z)



The MHD Equations

Time Derivative

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

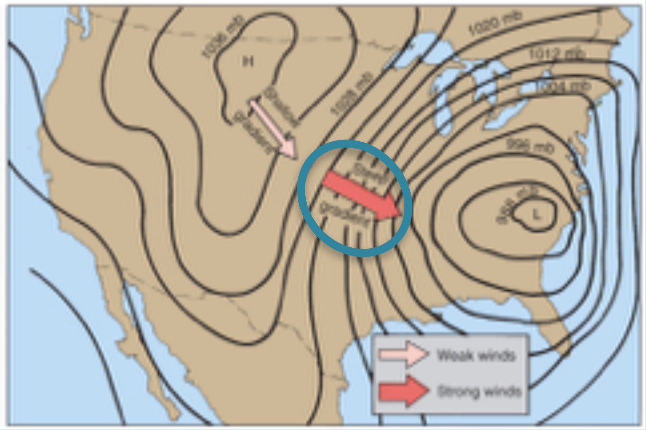
$$\rho \left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} \right) = \mathbf{j} \times \mathbf{B} - \nabla p + \mathbf{F}$$

Spatial Derivative → force
e.g. pressure chart

$$\frac{\partial p}{\partial t} + \mathbf{v} \cdot \nabla p + \gamma p \nabla \cdot \mathbf{v} = 0$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B})$$

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{j} \qquad \nabla \cdot \mathbf{B} = 0$$



The MHD Equations

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

$$\rho \left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} \right) = \mathbf{j} \times \mathbf{B} - \nabla p + \mathbf{F}$$

$$\frac{\partial p}{\partial t} + \mathbf{v} \cdot \nabla p + \gamma p \nabla \cdot \mathbf{v} = 0$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B})$$

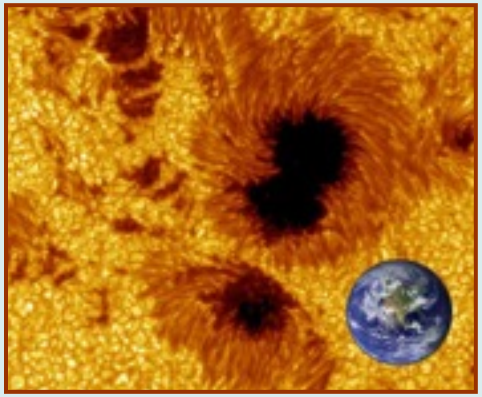
$$\nabla \times \mathbf{B} = \mu_0 \mathbf{j} \qquad \nabla \cdot \mathbf{B} = 0$$

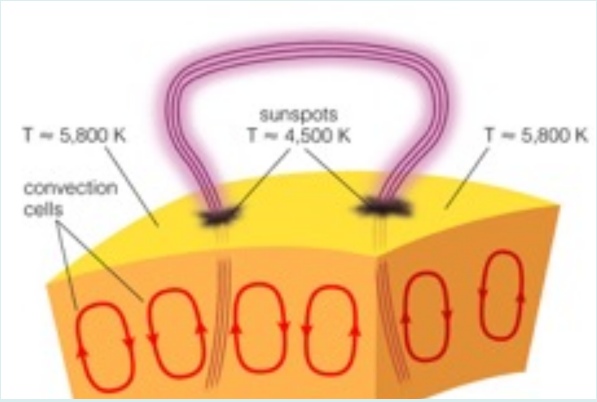
Coupled Equations!

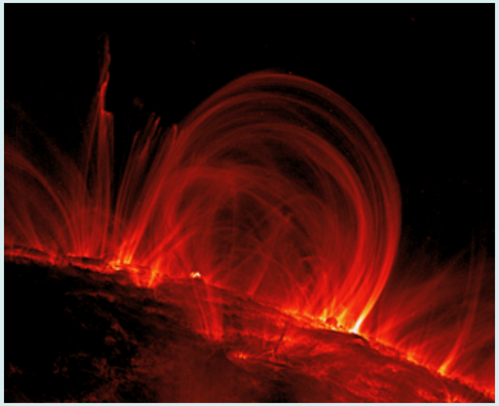
Magnetic Fields

- MHD is different from the usual fluid dynamics because the magnetic field introduces several new effects:

1. it exerts a force, which is perpendicular to the magnetic field B and which may either move the plasma or guide plasma motions
2. it provides support and stability (many solar phenomena are observed for days or even months);
3. it is elastic and so can support waves (coronal seismology);





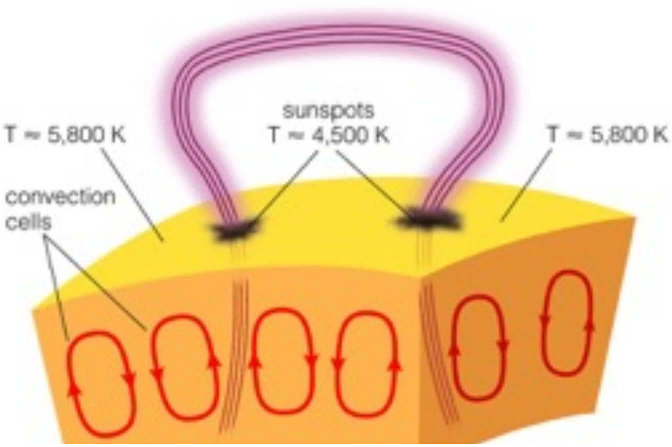


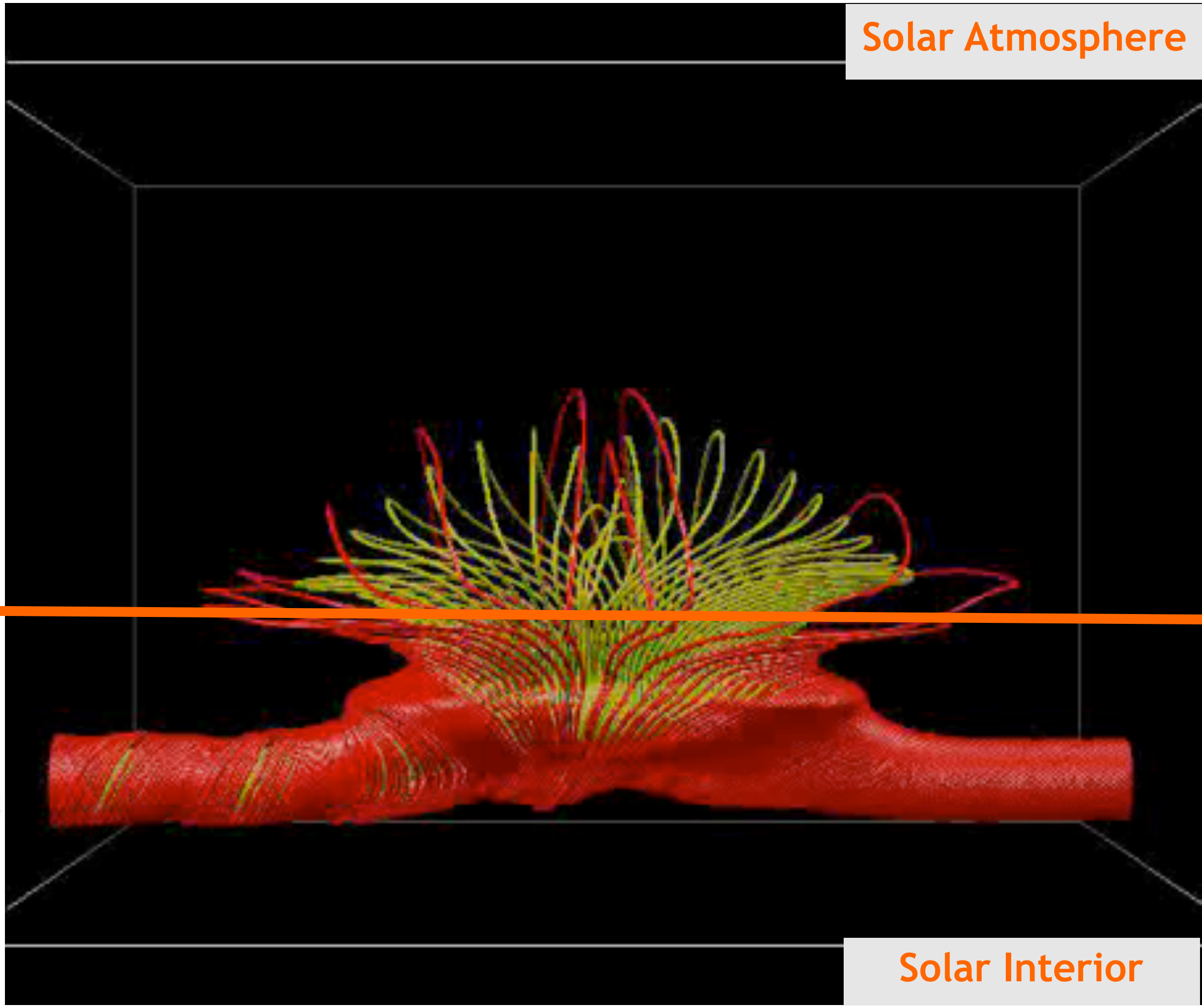
➢ The Solar Group in St Andrews focuses on the behaviour of the magnetic field in the Sun's atmosphere (coronal heating).

http://www-solar.mcs.st-and.ac.uk/

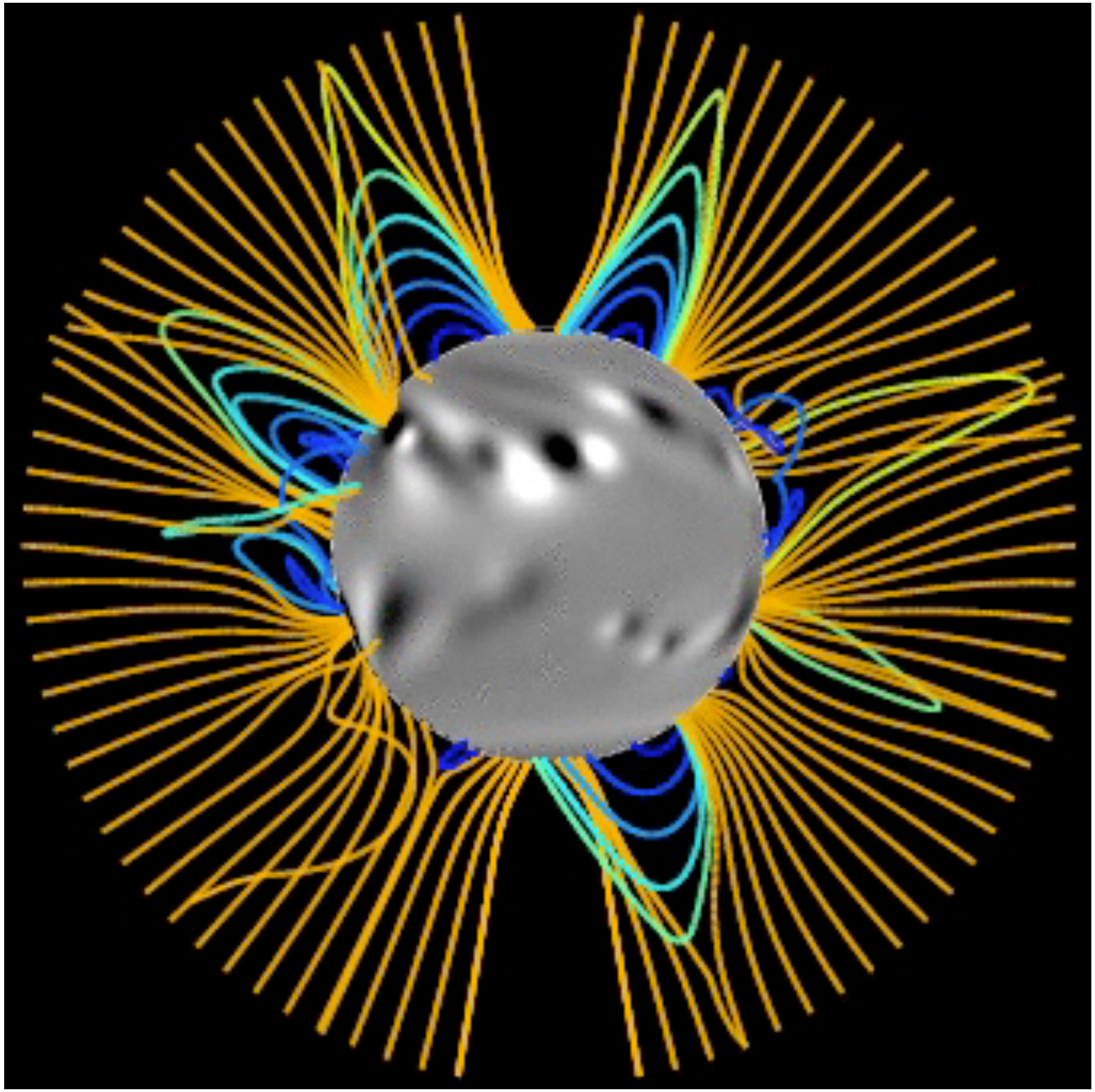
Emerging Coronal Loops

- 3D numerical model of emerging magnetic field forming
  - sunspot pair
  - coronal loops



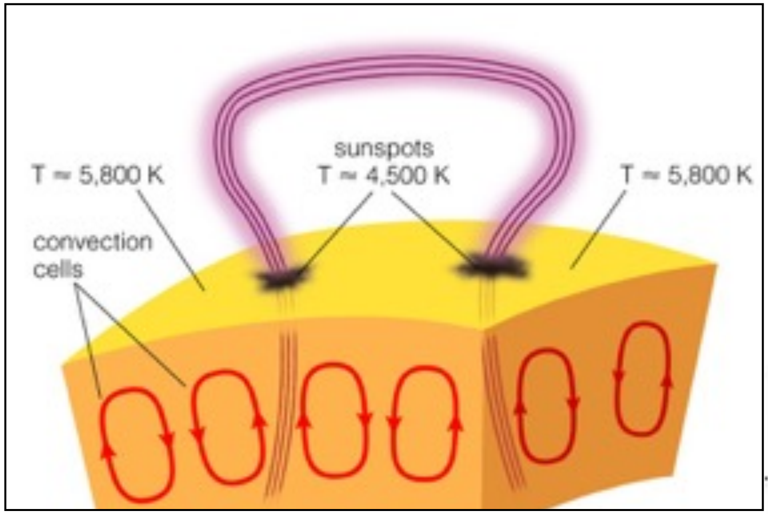


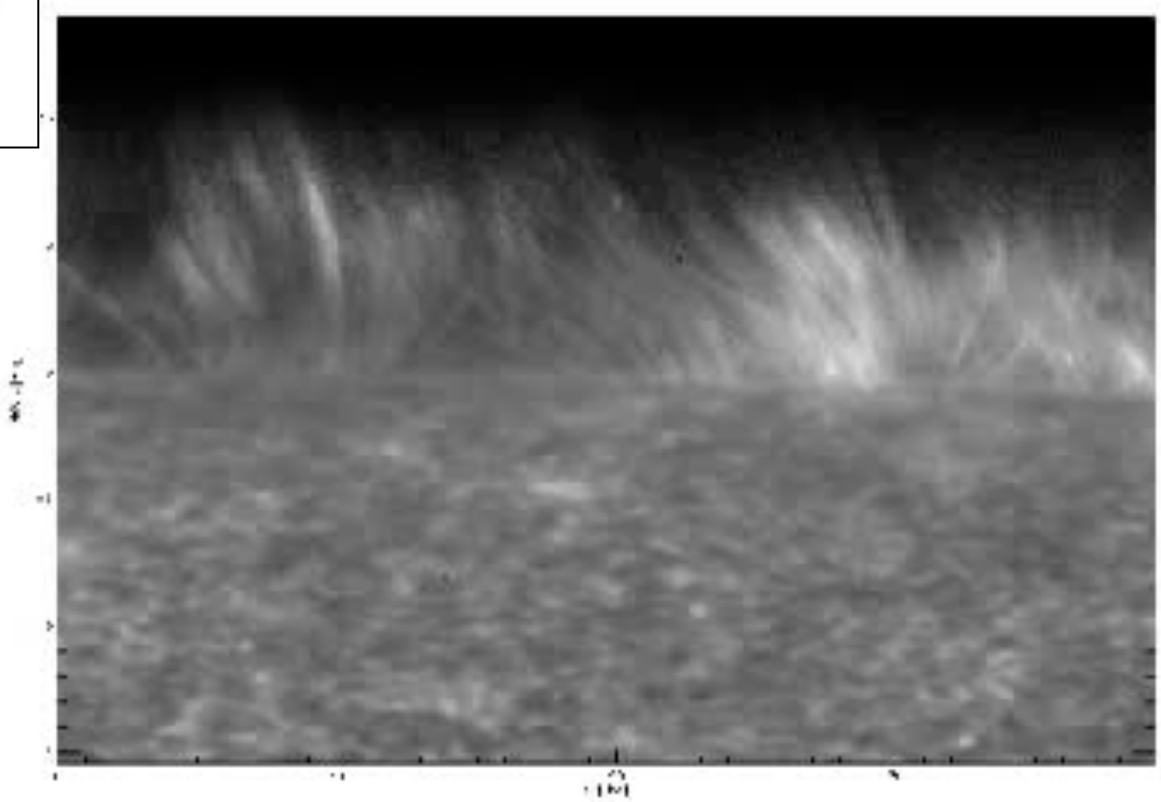
Modelling the large-scale magnetic field



3D numerical model of the long term, global evolution of the solar magnetic field.

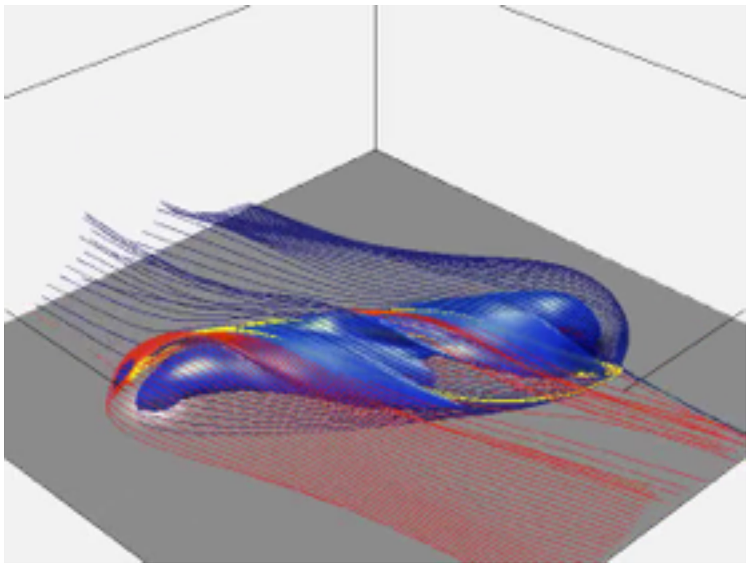
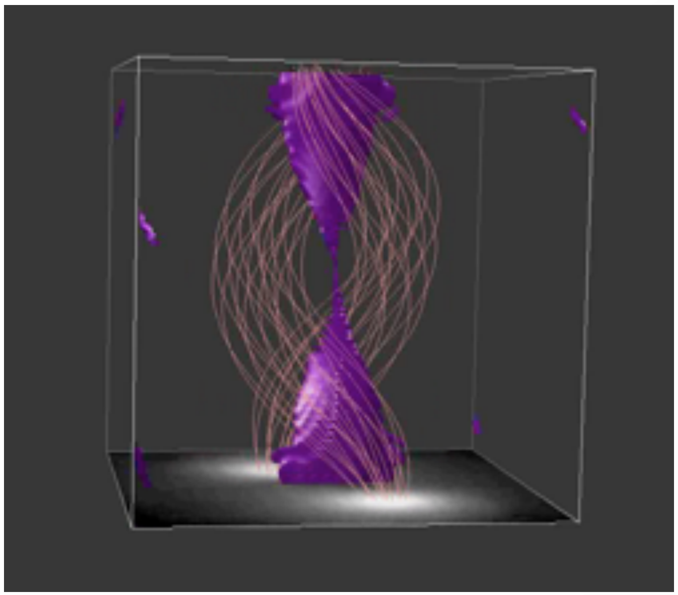
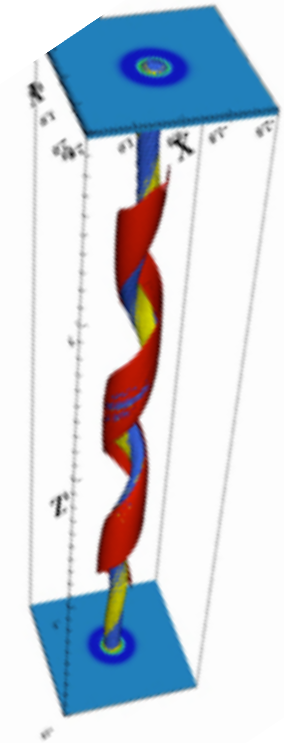
The Dynamic Solar Corona





- The Sun’s magnetic field is anchored in the interior
- The magnetic field is moved about by the convection
    - ➢ Coronal loops are continuously moving!

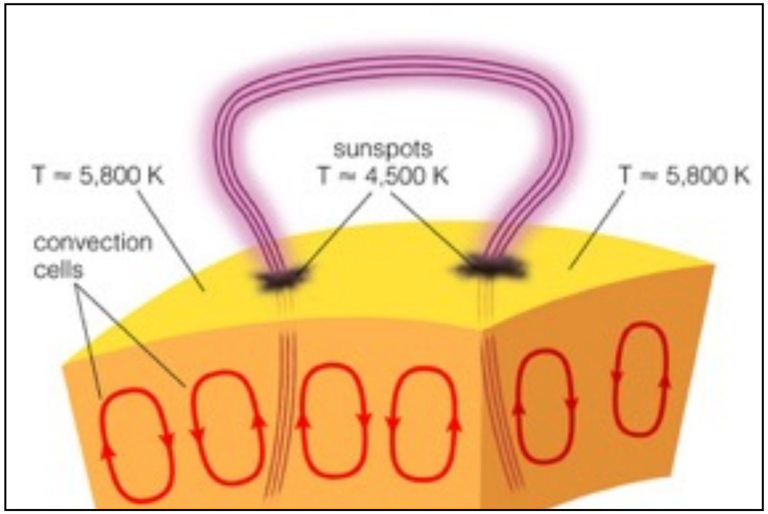
Modelling the small-scale magnetic field

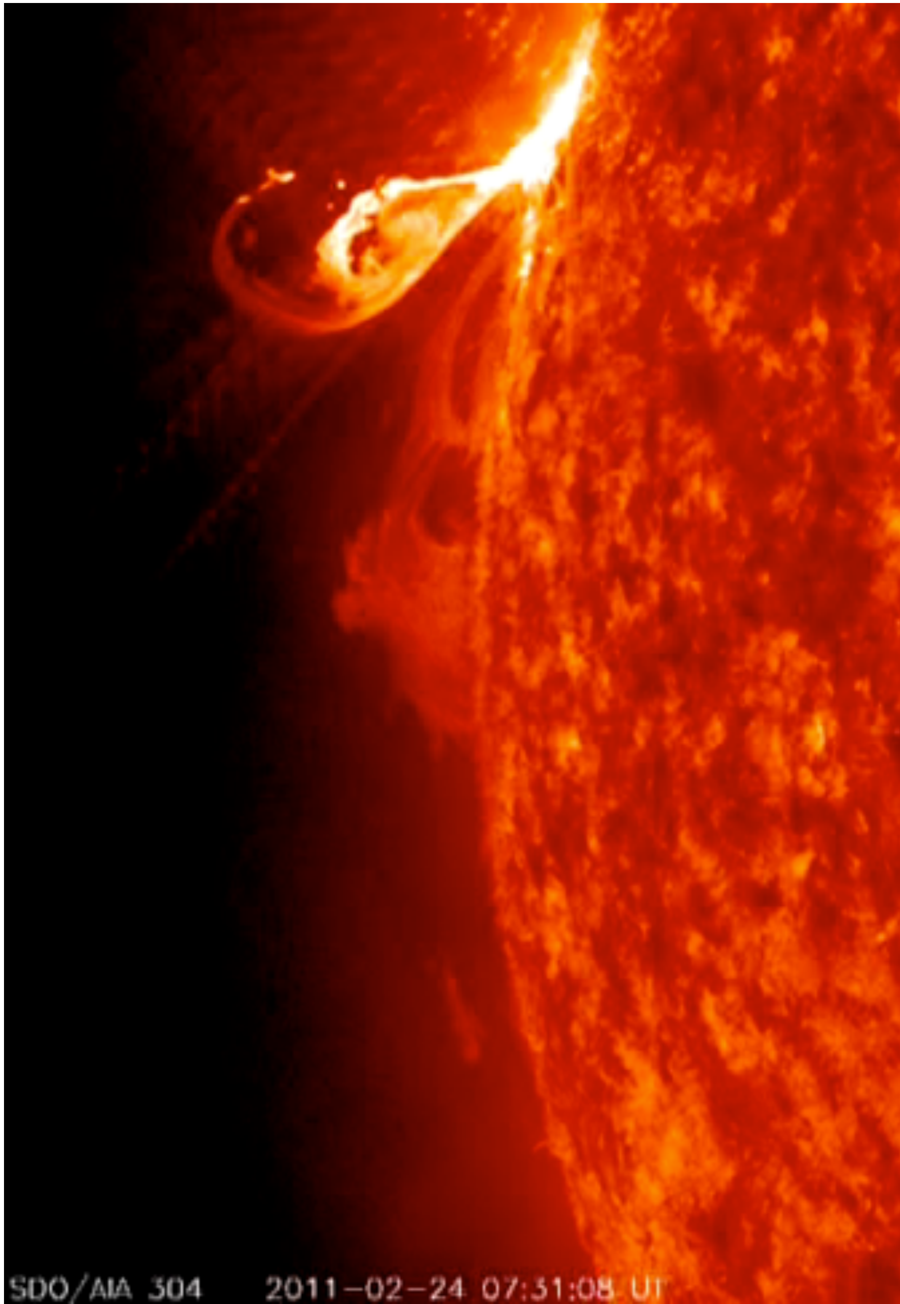




3D numerical model of the currents generated by moving magnetic fields

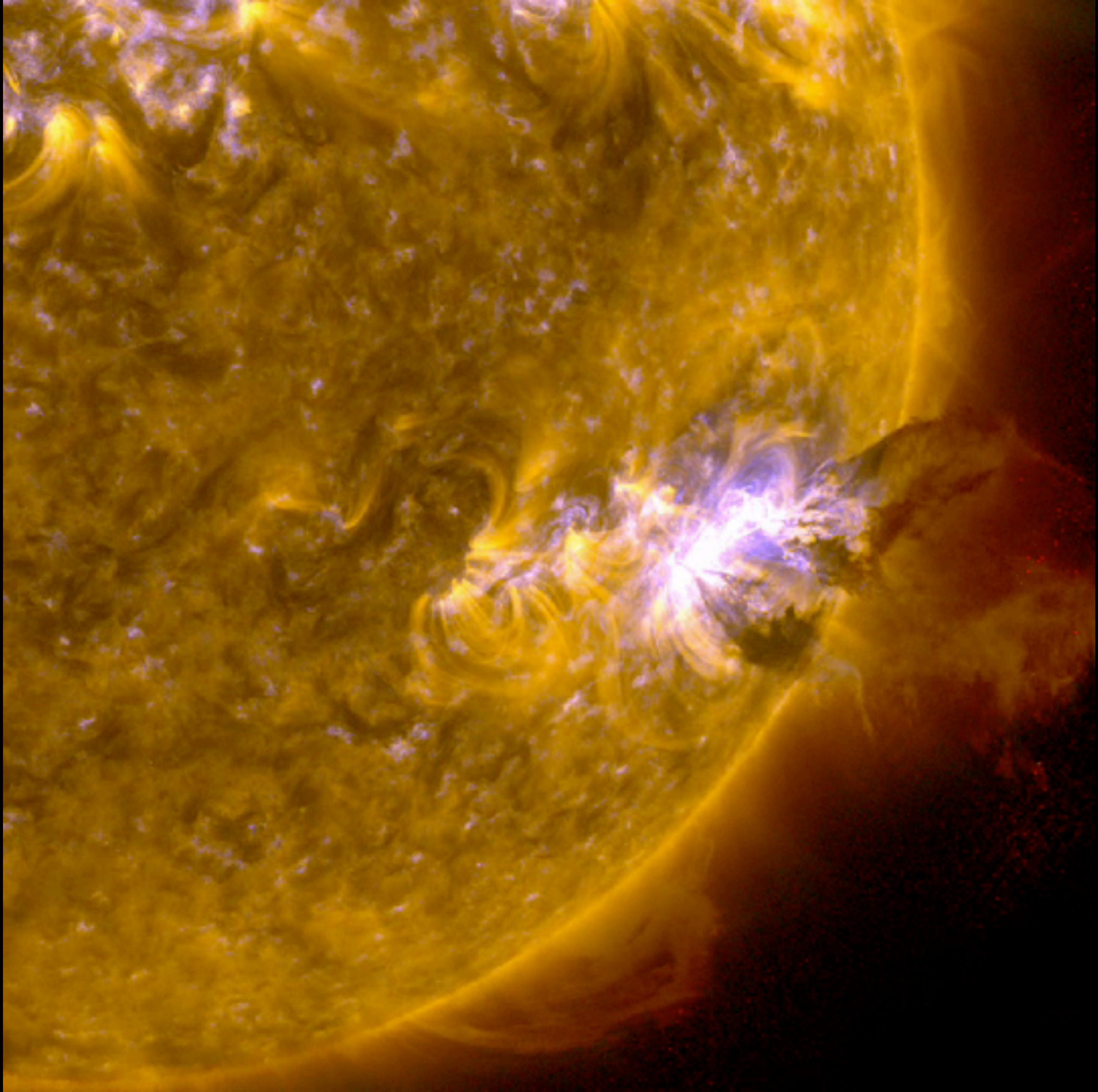
Currents = heating!

Eruptions

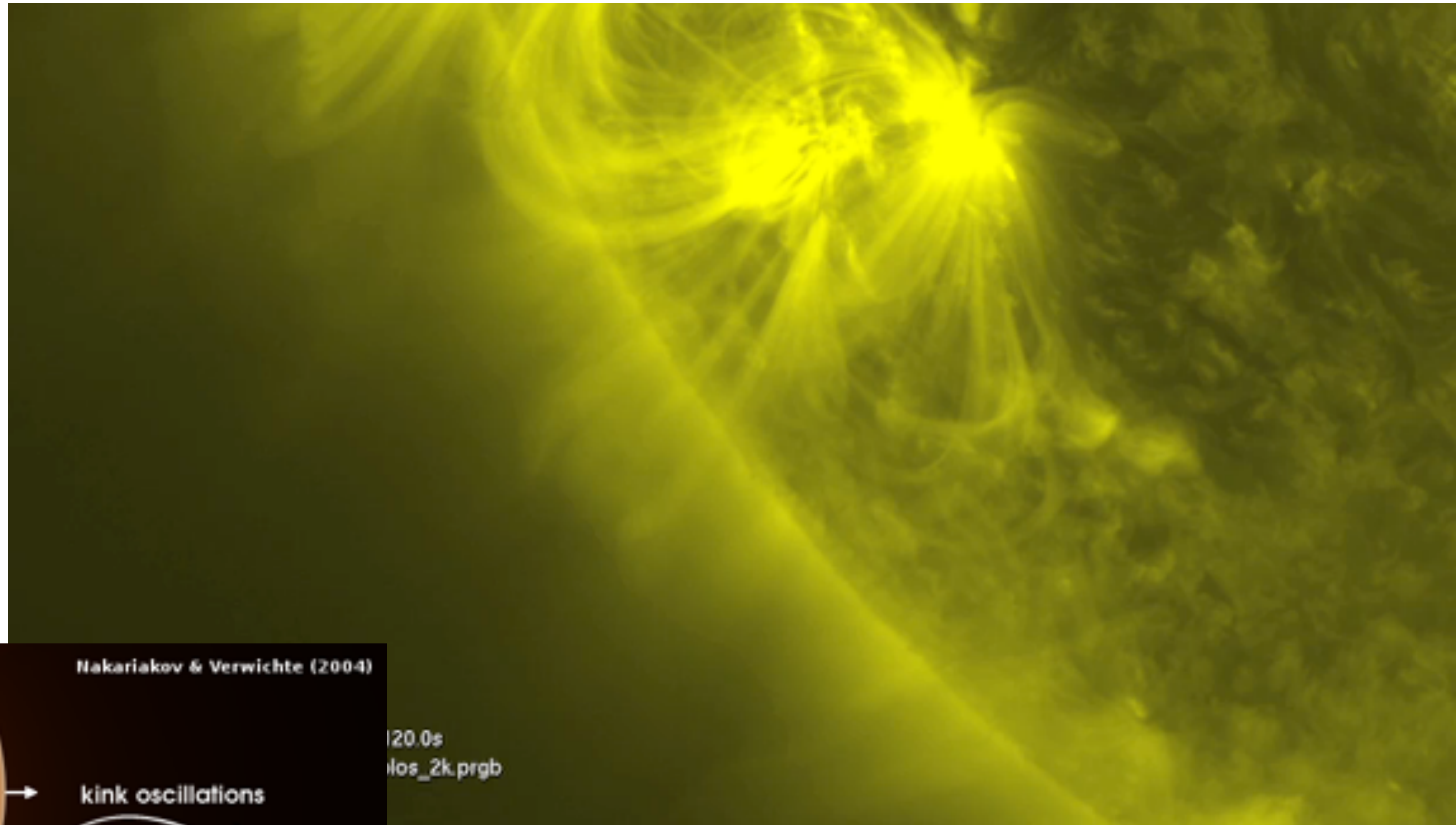


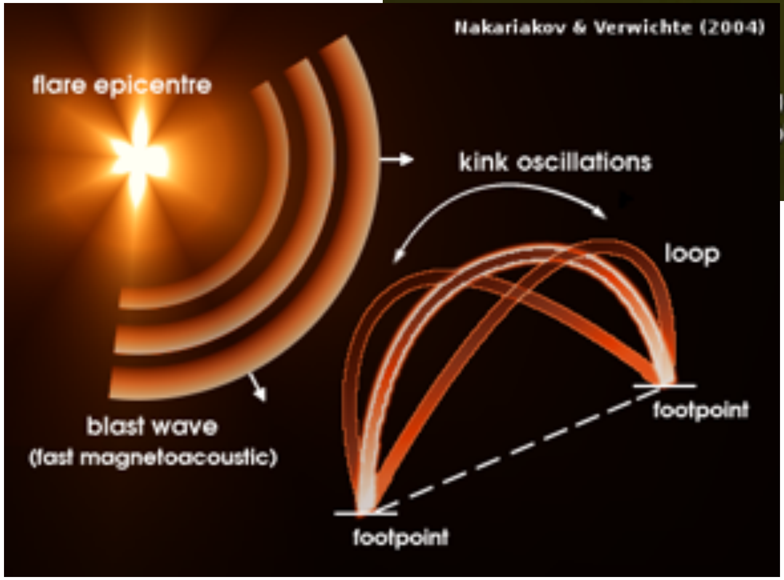


- The Sun's magnetic field becomes very twisted and tangled
- Explosions in the solar atmosphere are caused by the build up of magnetic energy
    - ➢ Solar Flares



Eruptions



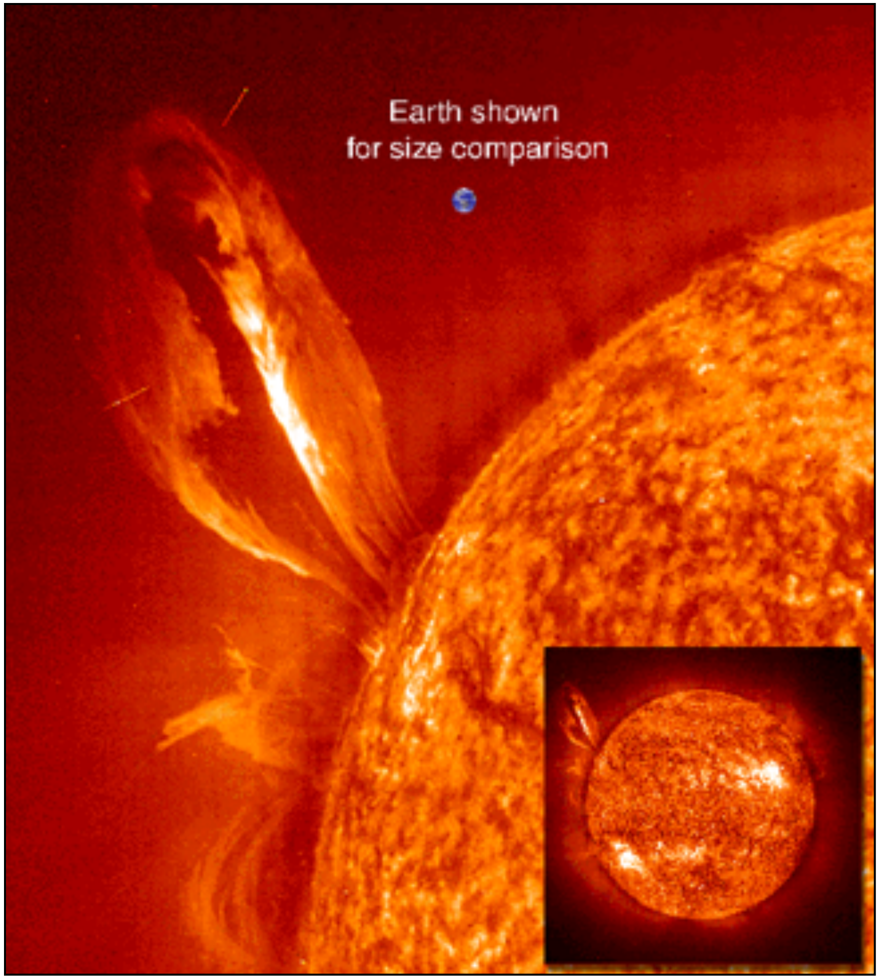


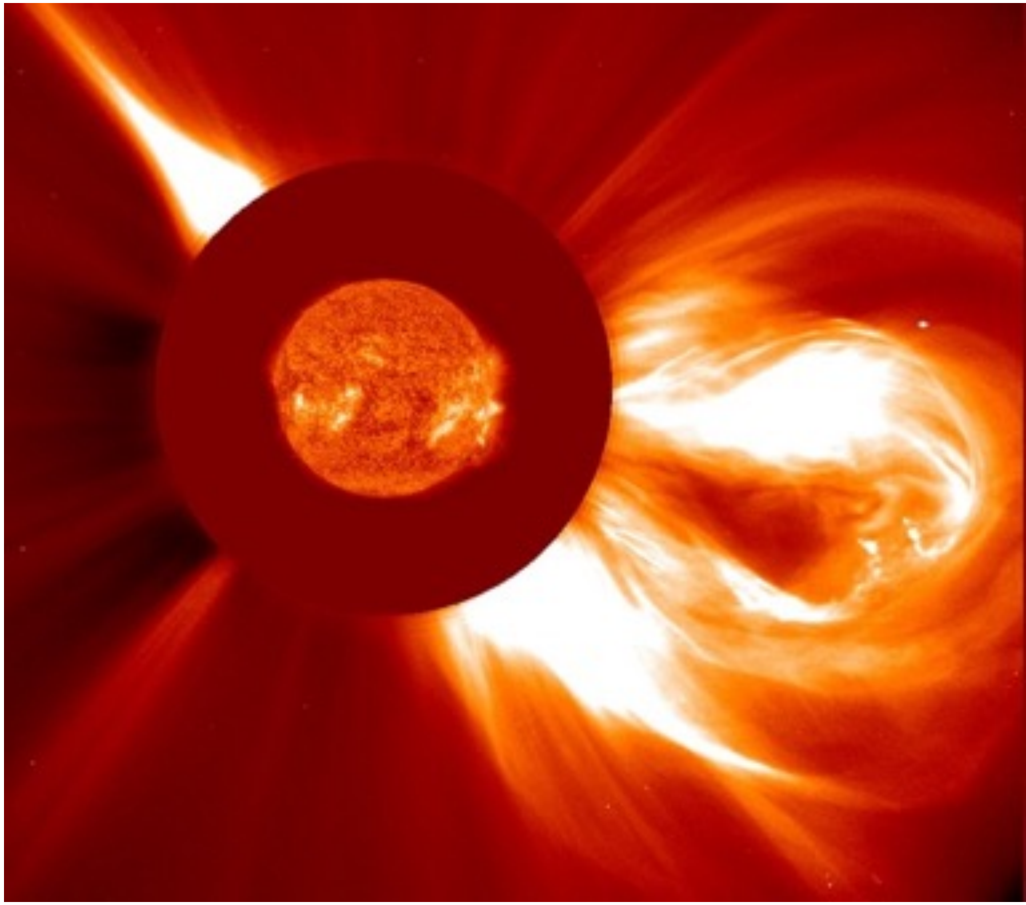
- After a flare, neighbouring loops are sometimes seen to oscillate.

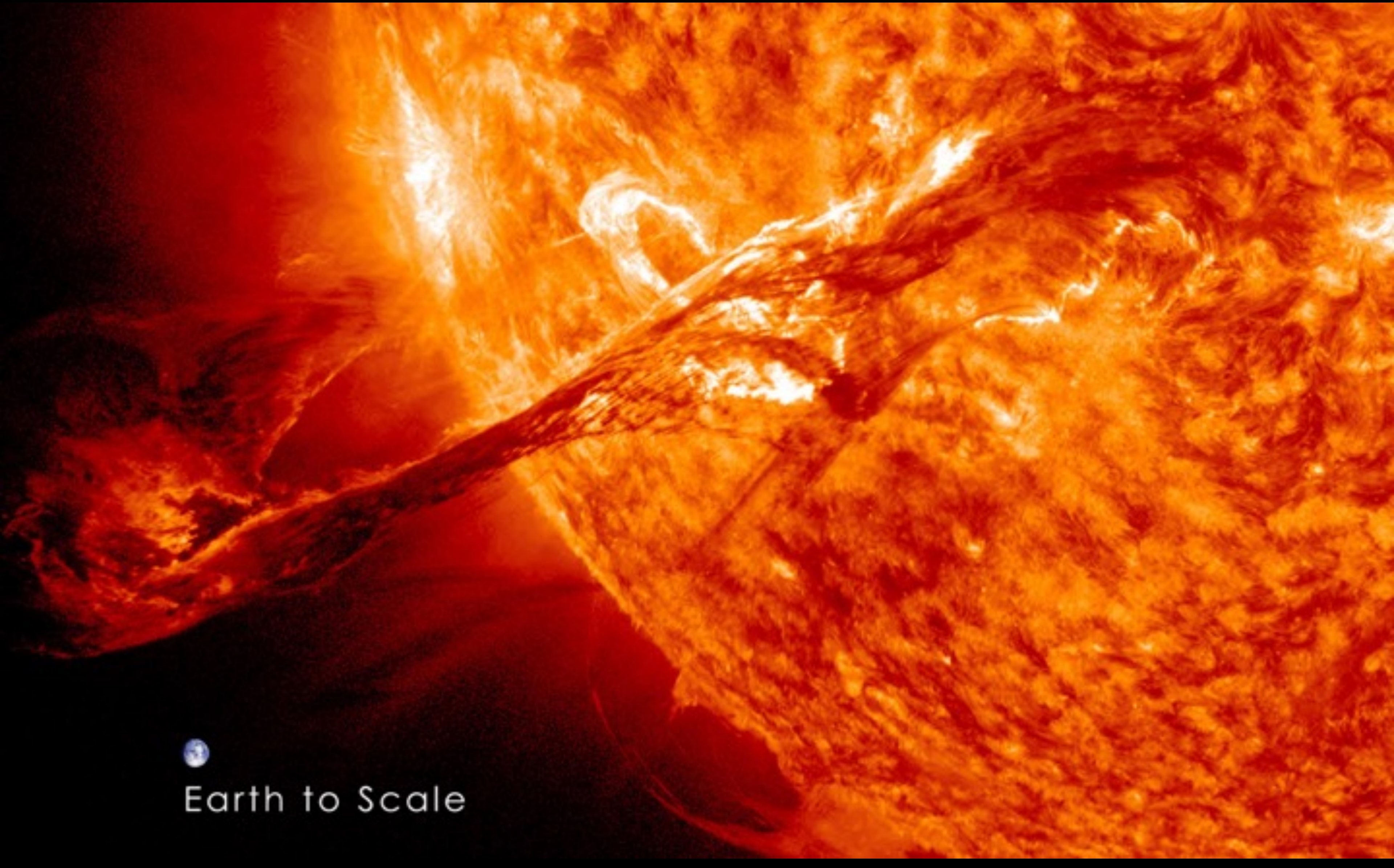
  ➢ Coronal seismology

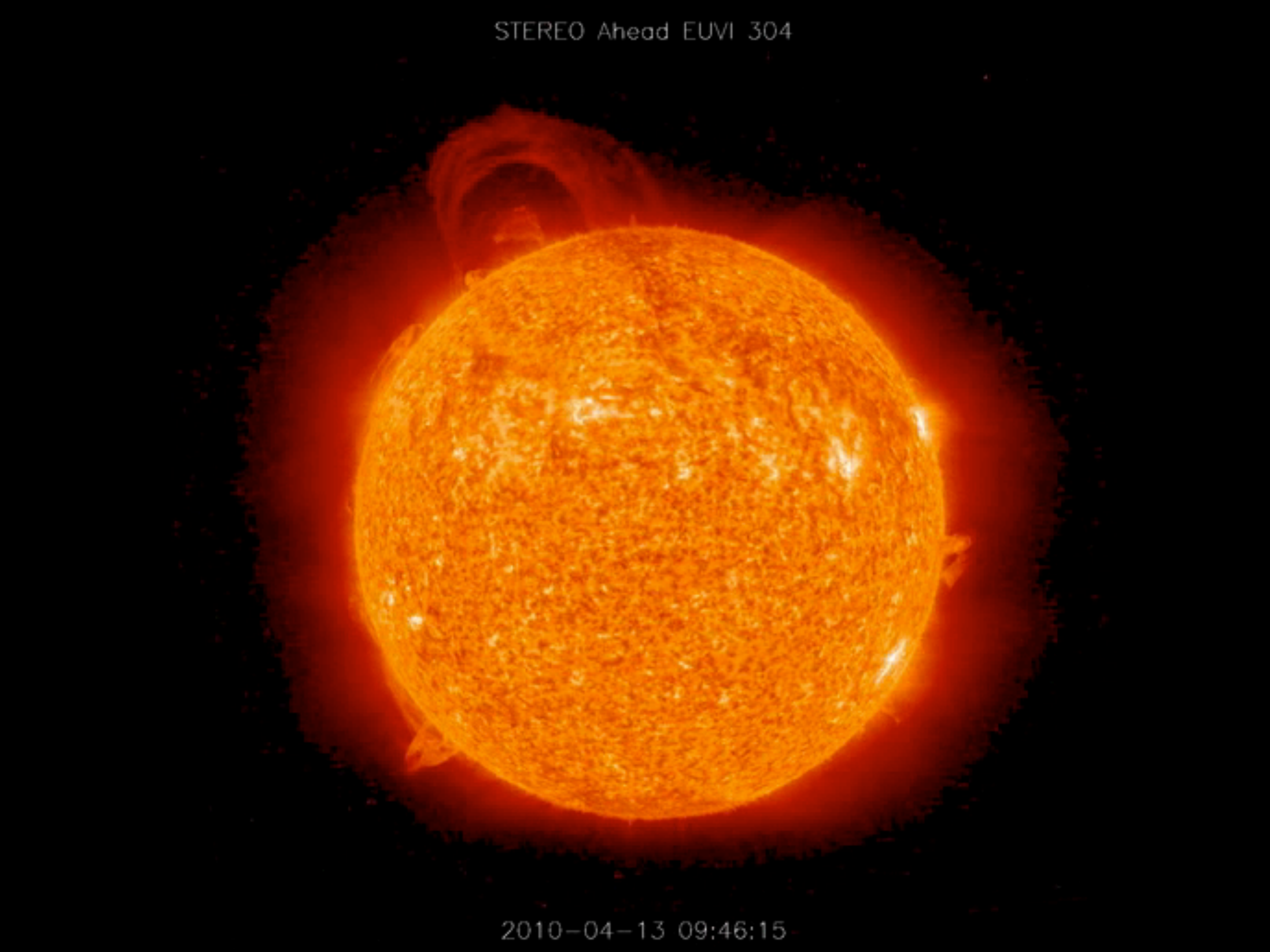
Start of a Coronal Mass Ejection

- Sometimes, large amounts of material are ejected from the Sun.
    - ➢ Coronal Mass Ejections (CME)






Earth to Scale


STEREO Ahead EUVI 304
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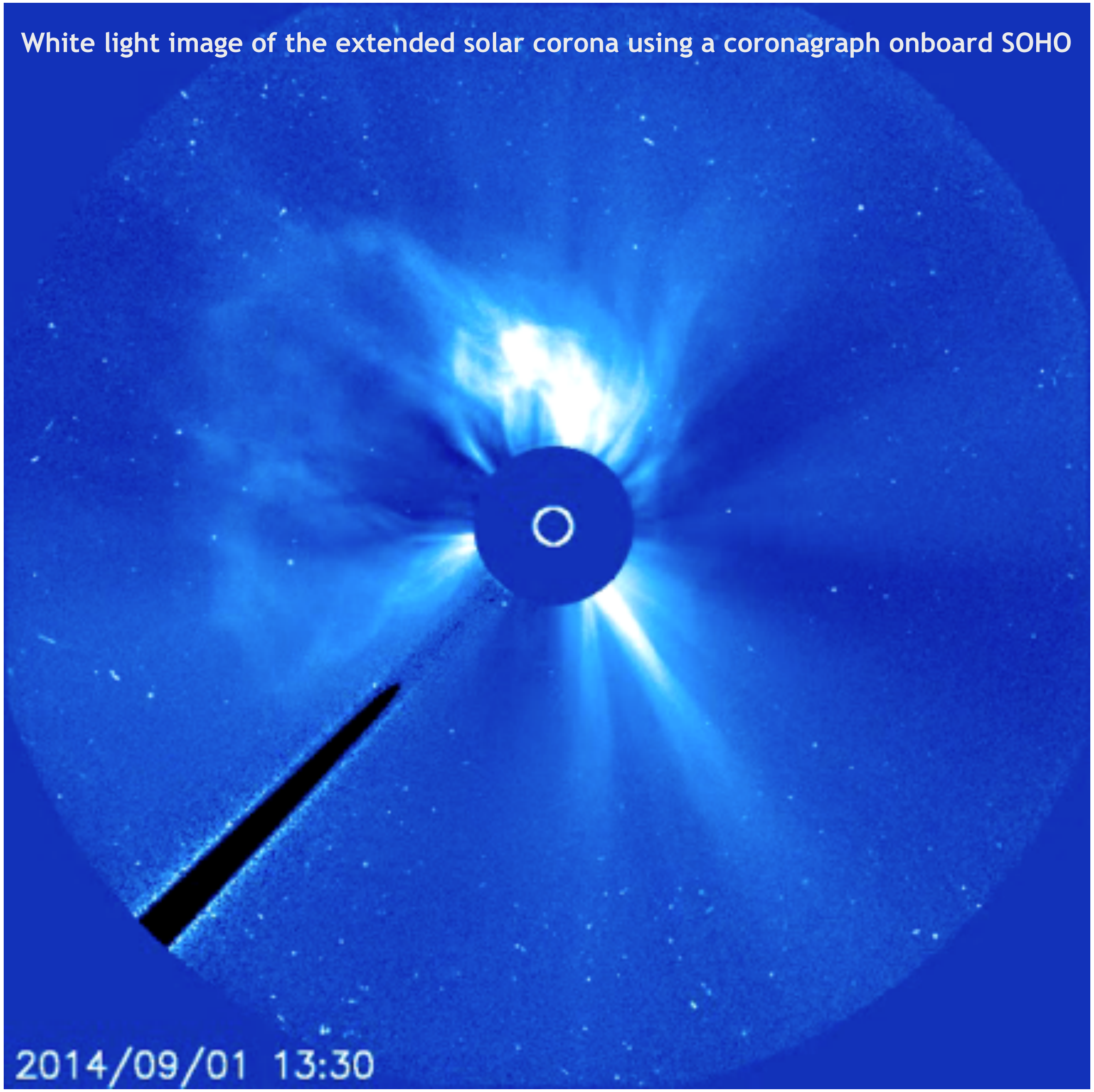
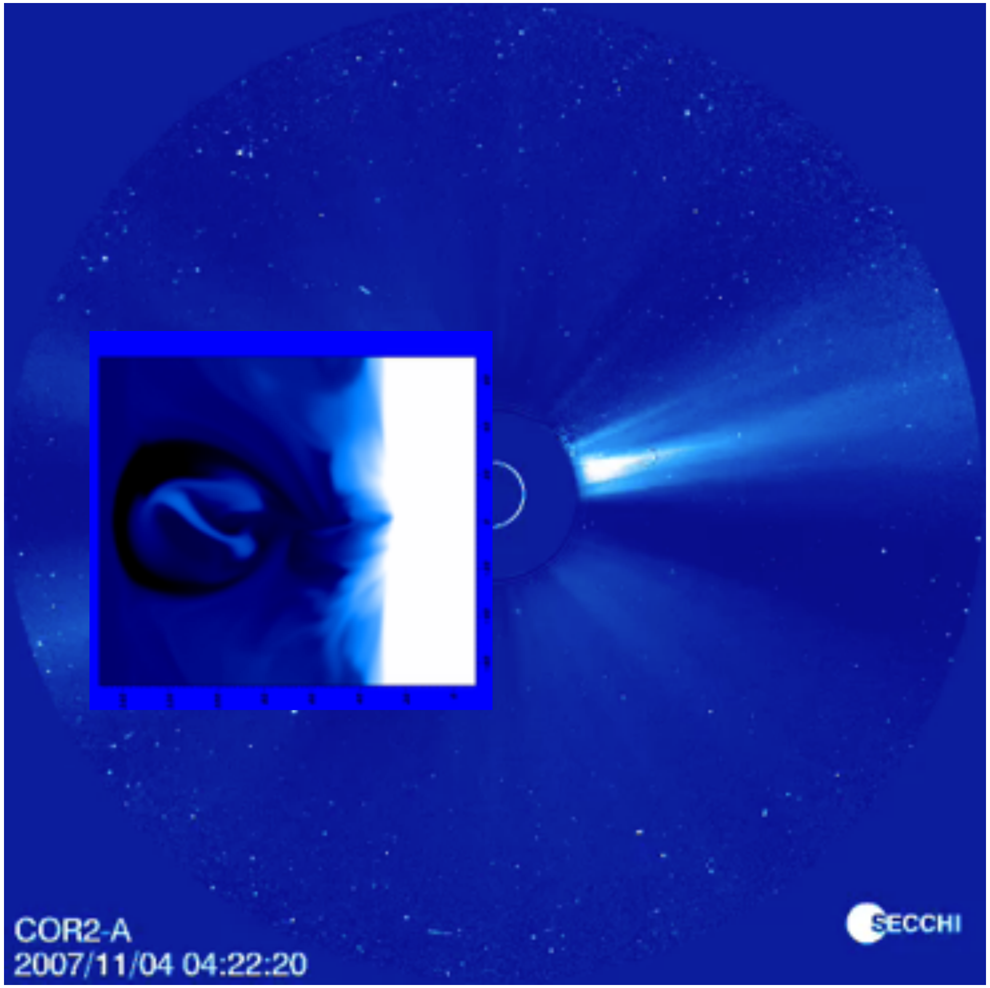
CME’s happen all the time



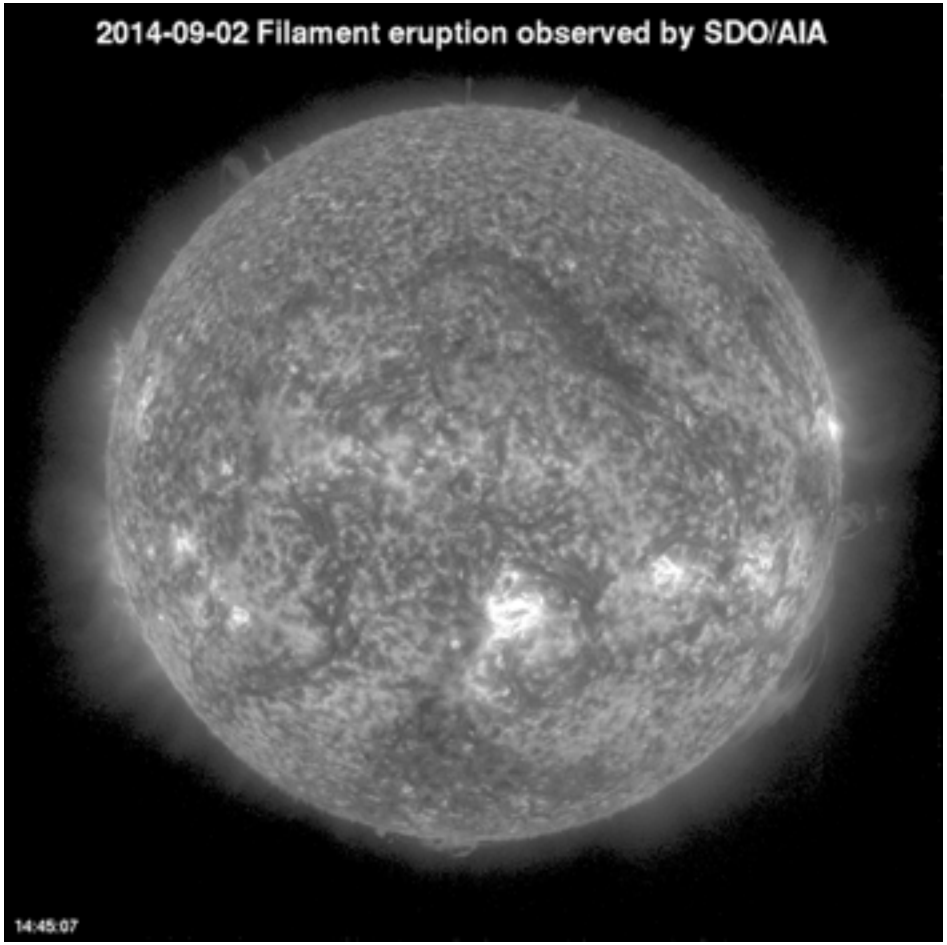
- During solar maximum, the Sun produces about 3 big mass ejections per day

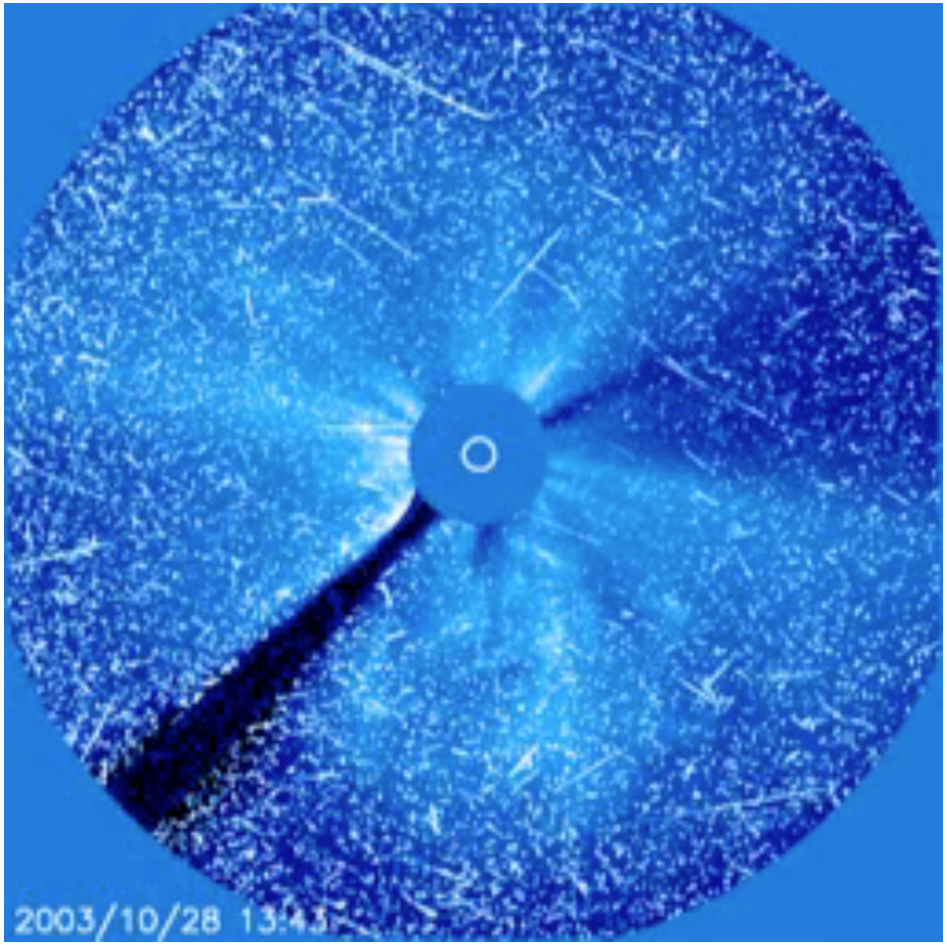
CME Modelling



2D Numerical model of the onset of a CME eruption

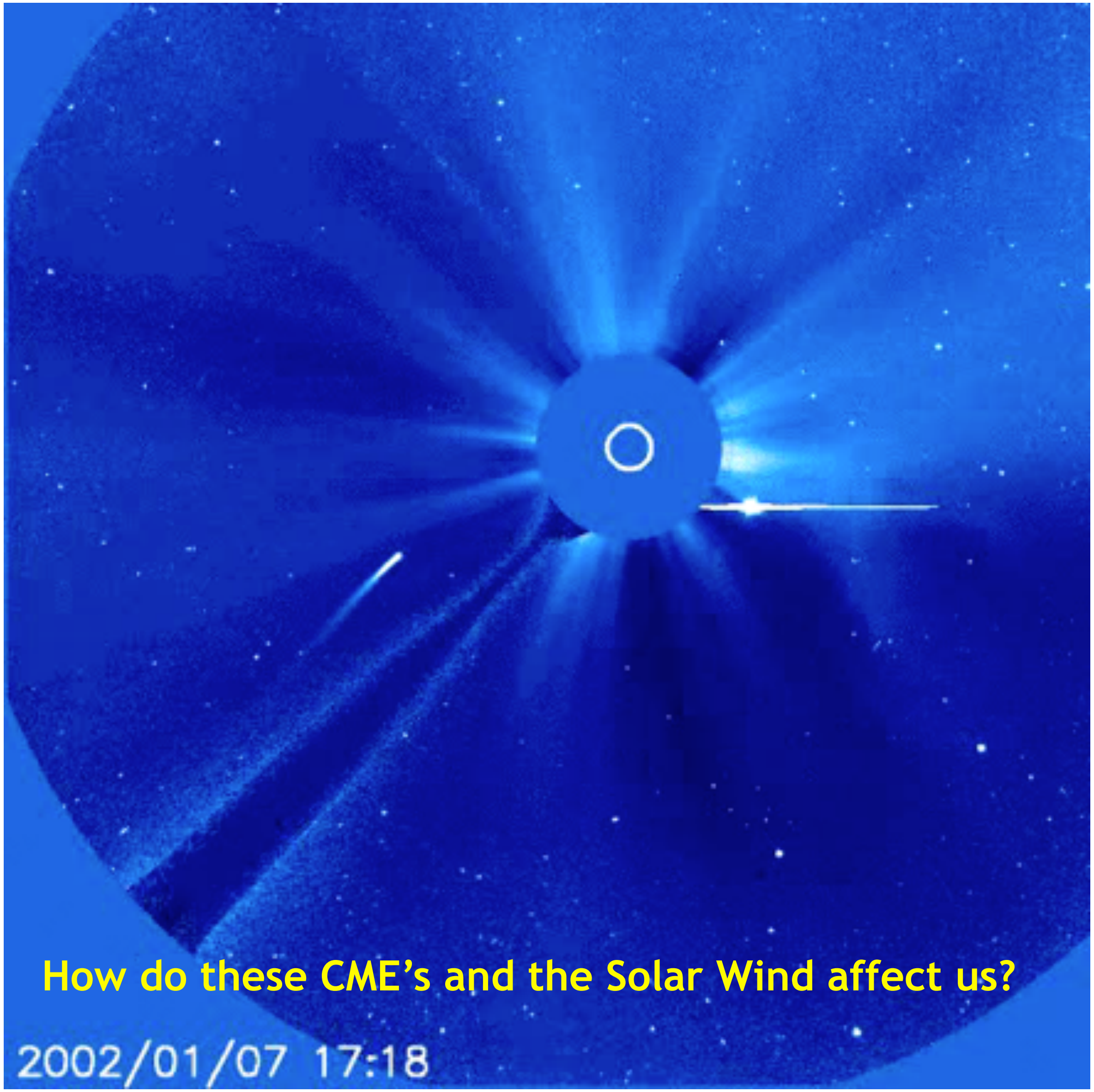
Earth-directed CME's





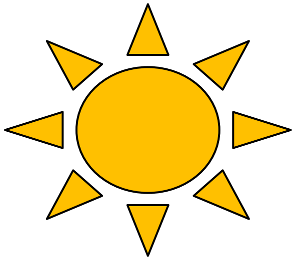
Solar Wind

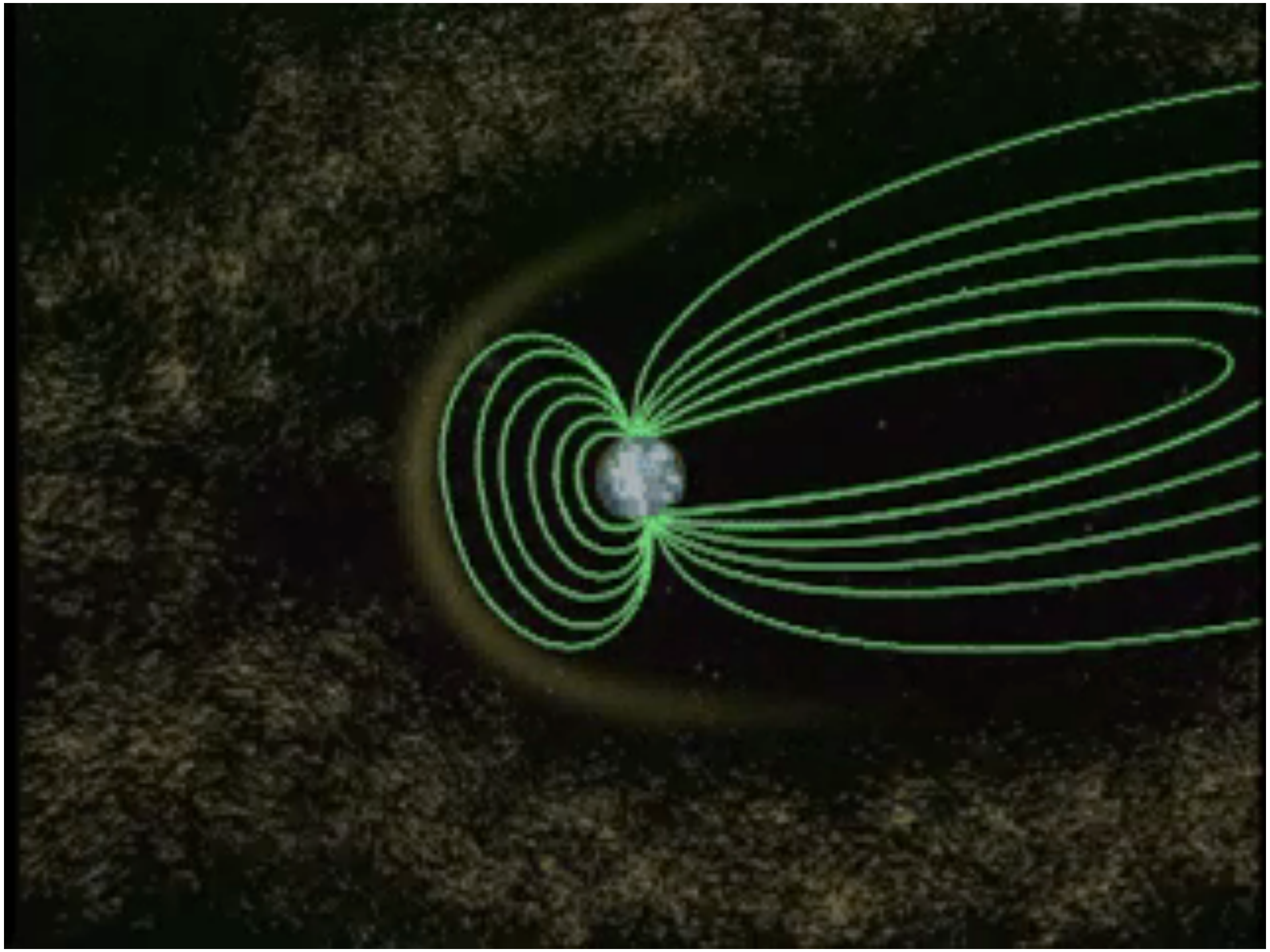
- Apart from impulsive CME's, matter streams out from the Sun continuously: The Solar Wind



Earth's Magnetic Field

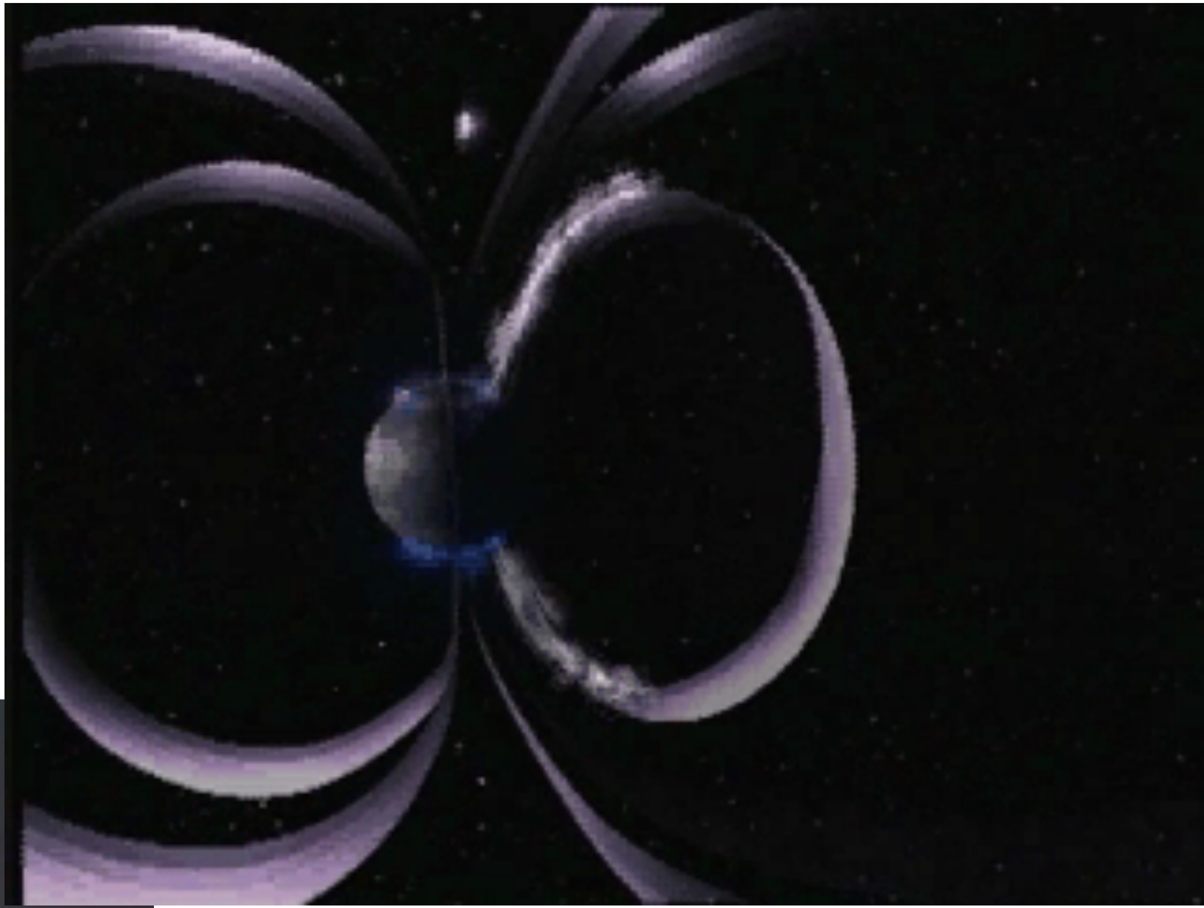
- The Solar corona doesn't just stop somewhere – we live inside the Sun's atmosphere.



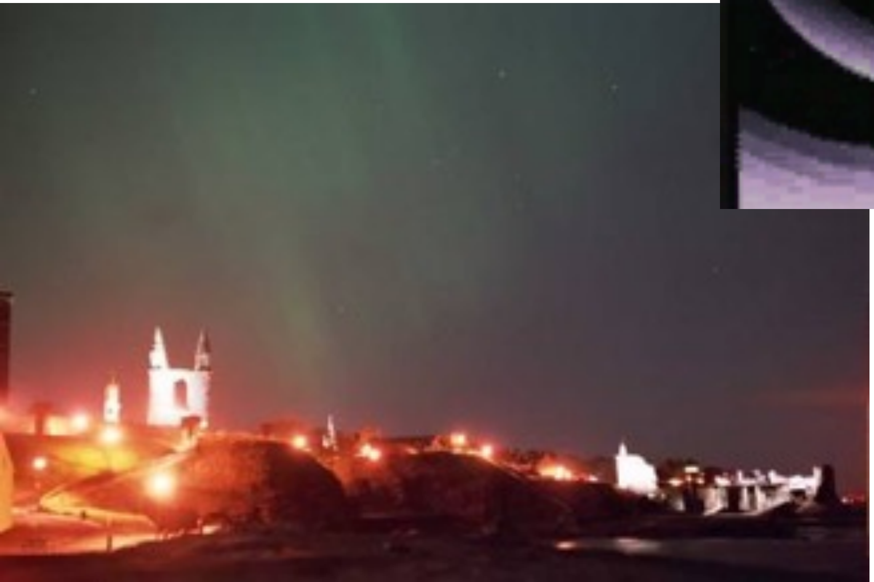


- The Earth's magnetic field provides a shield to protect us from most of the effects of the solar wind and solar storms…

Aurora



- …but it doesn't shield us from everything.



- Some energetic particles can enter the Earth's atmosphere near the poles
  - The Aurora (or Northern Lights)

How can solar storms affect us?

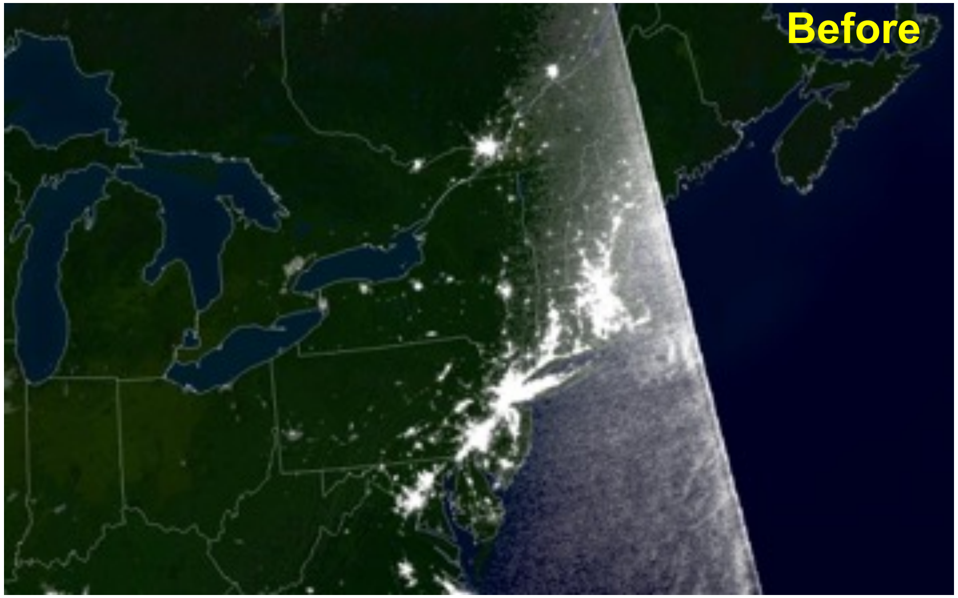
The Sun has a variety of effects on technology on Earth.

- **Communications:** radio signals, satellites (mobile phones, GPS)
- **Induce Electric Currents:** e.g in pipelines, train tracks, power lines (Blackouts, pipeline corrosion, sparks!)

March 1989 (Montreal, Quebec): 6 million people without electricity for 12 hours.

June 1989: gas pipeline explosion demolished part of the Trans-Siberian Railway, engulfing two passenger trains and killing 500 people.

(Solar Maximum 1990)



Space Travel

- Astronauts are outside Earth’s magnetic field
  - No longer shielded from solar wind and solar storms
  - Disorientation, nausea, vomiting, cancers, death.

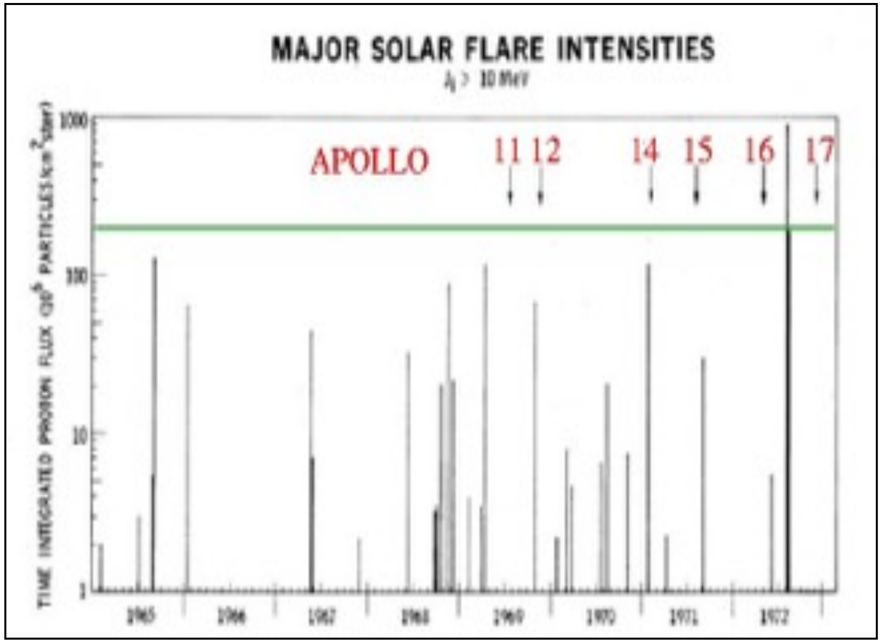
Chest X-ray	0.06 REM
Natural background radiation on Earth	0.35 REM per year
Maximum lifetime dosage of radiation	400 REM
Solar Flares	100 – 1000 REM

- International Space Station has special thick-walled room to retreat to during solar storms
- Crew get 30 times more radiation than whole year on Earth (10REM).
- During a solar storm in 1990, Mir cosmonauts received a full year's dosage in a few days.

Space Travel

Major problem:

- Moon (10 days) ➔ good odds.
- Mars (180 days) ➔ little chance of avoiding major solar event.
- Mars has no / very weak magnetosphere!

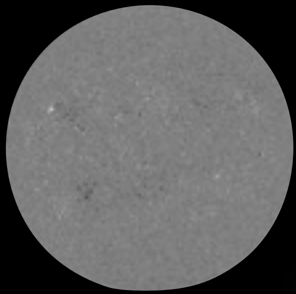


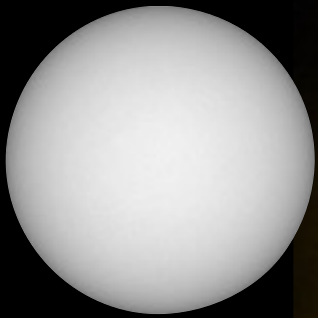
Forecasting ➔ days / a week.
Trips would take months /years!

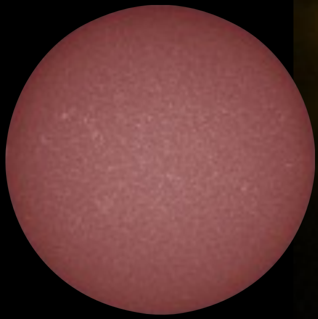
Thick-walls or lead shielding adds significant mass:
(1) more expensive
(2) more difficult to launch
(3) ship goes slower!

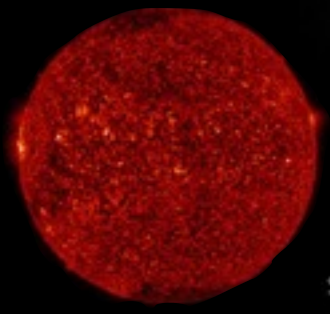
➢ So how could astronauts protect themselves?

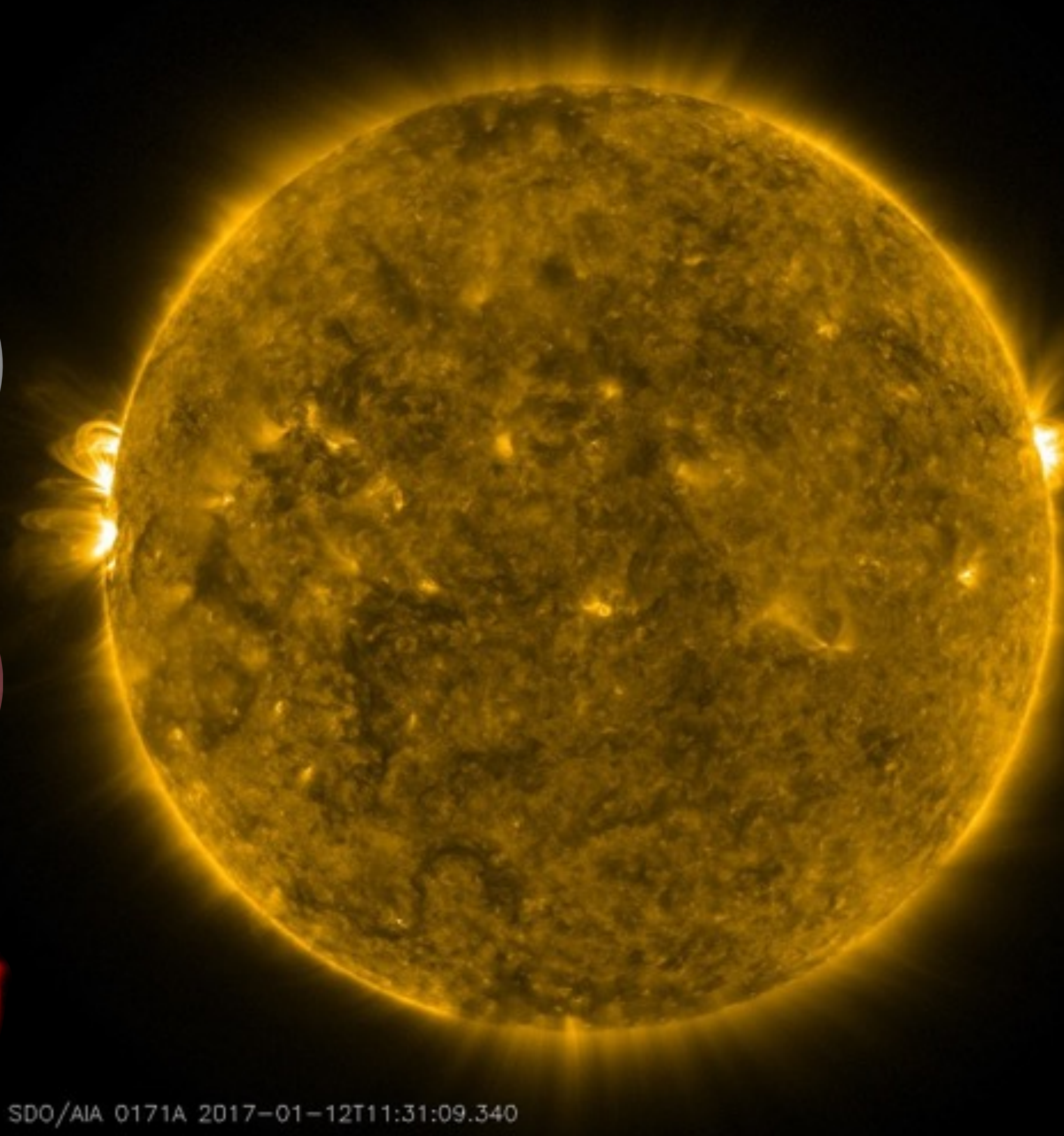
The Sun Today!

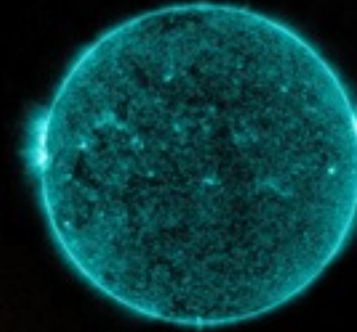


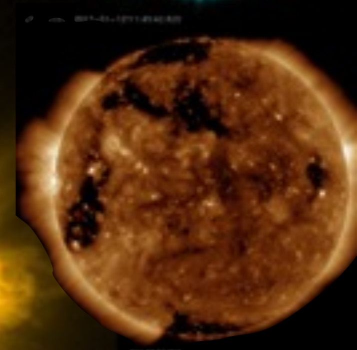


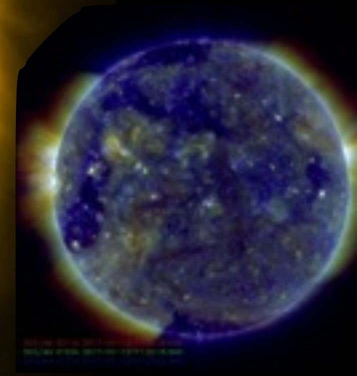


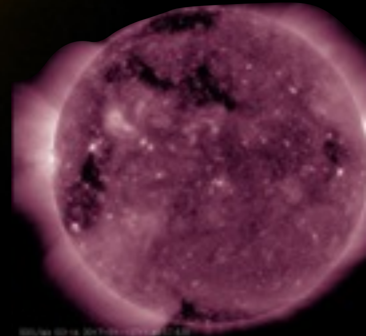












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