

La météorologie de l'espace : De la physique des couplages aux outils opérationnels



by Dr. Barbara Perri¹



1. AIM/Department of Astrophysics,
Observatoire Paris-Saclay, France

Space weather in the media

Everyone in France was made aware of space weather thanks to the beautiful **auroras of May 10 2024**



Space weather in the media

Everyone in France was made aware of space weather thanks to the beautiful **auroras of May 10 2024**



Mon séjour en montagne

Où et quand voir les aurores boréales en France : cette application vous alerte

Comment l'utiliser pour chasser les aurores boréales en France ? · Téléchargez l'application : · Configurez vos préférences : · Surveillez l'...

14 janv. 2025



Numerama

Verra-t-on des aurores boréales ce dimanche soir en France ?

Verra-t-on des aurores boréales ce dimanche soir en France ? ... Une chasse aux aurores boréales pourrait avoir lieu le soir du dimanche 1er juin...

Il y a 3 semaines



Centre national d'études spatiales (Cnes)

Aurores boréales en France : la face visible d'une activité solaire sous surveillance

Lorsque ces particules solaires atteignent notre planète, elles interagissent avec notre champ magnétique et forment des aurores boréales. Mais...

7 févr. 2025



www.cieletespace.fr

L'année 2025 débute sous les aurores boréales

Les deux premières nuits de l'année 2025 ont été marquées par des aurores boréales visibles en France. La météo n'a permis qu'aux...

2 janv. 2025



Generation Voyage

Des aurores boréales en France cet hiver ? Découvrez où voir cette féerie digne de la Scandinavie !

Des aurores boréales en France cet hiver ? Découvrez où voir cette féerie digne de la Scandinavie ! · Un balcon sur l'éphémère dans le Nord...

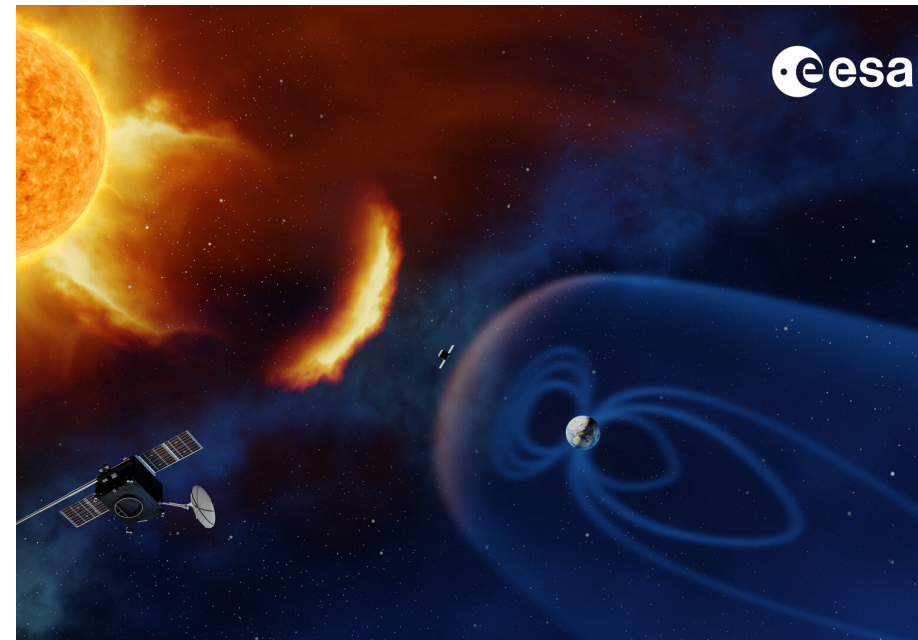
26 avr. 2025



Since then, it is everyone's guess when the next event will take place
But why is it **so difficult to predict?**

Definition of space weather

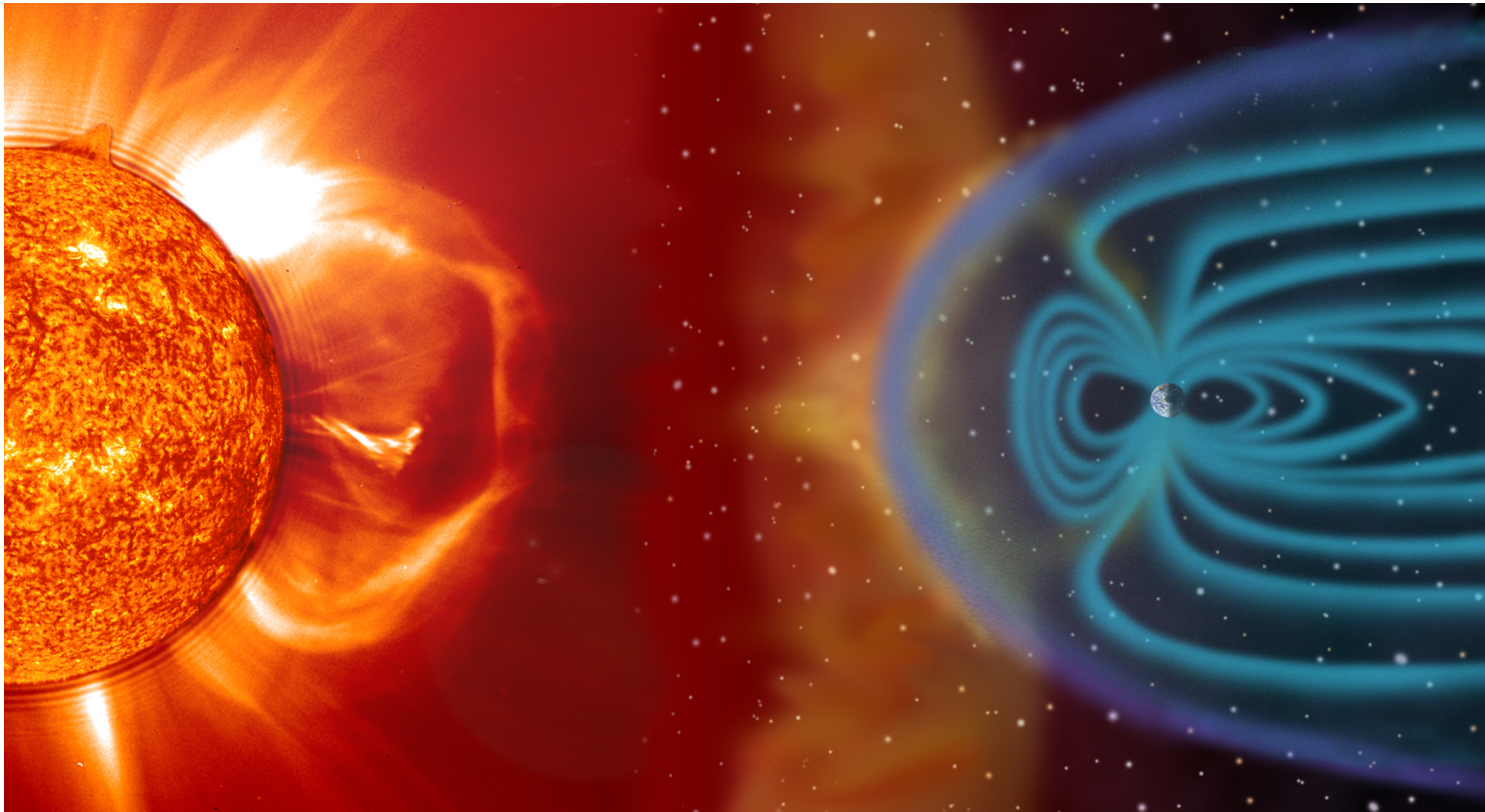
Space weather is often seen through the operational lense, with a specific focus on **technological impact and surveillance**



- Space weather is actually about **understanding** the Sun-Earth connection
- It is a rich discipline with **transdisciplanery approaches**

The various subsystems of space weather

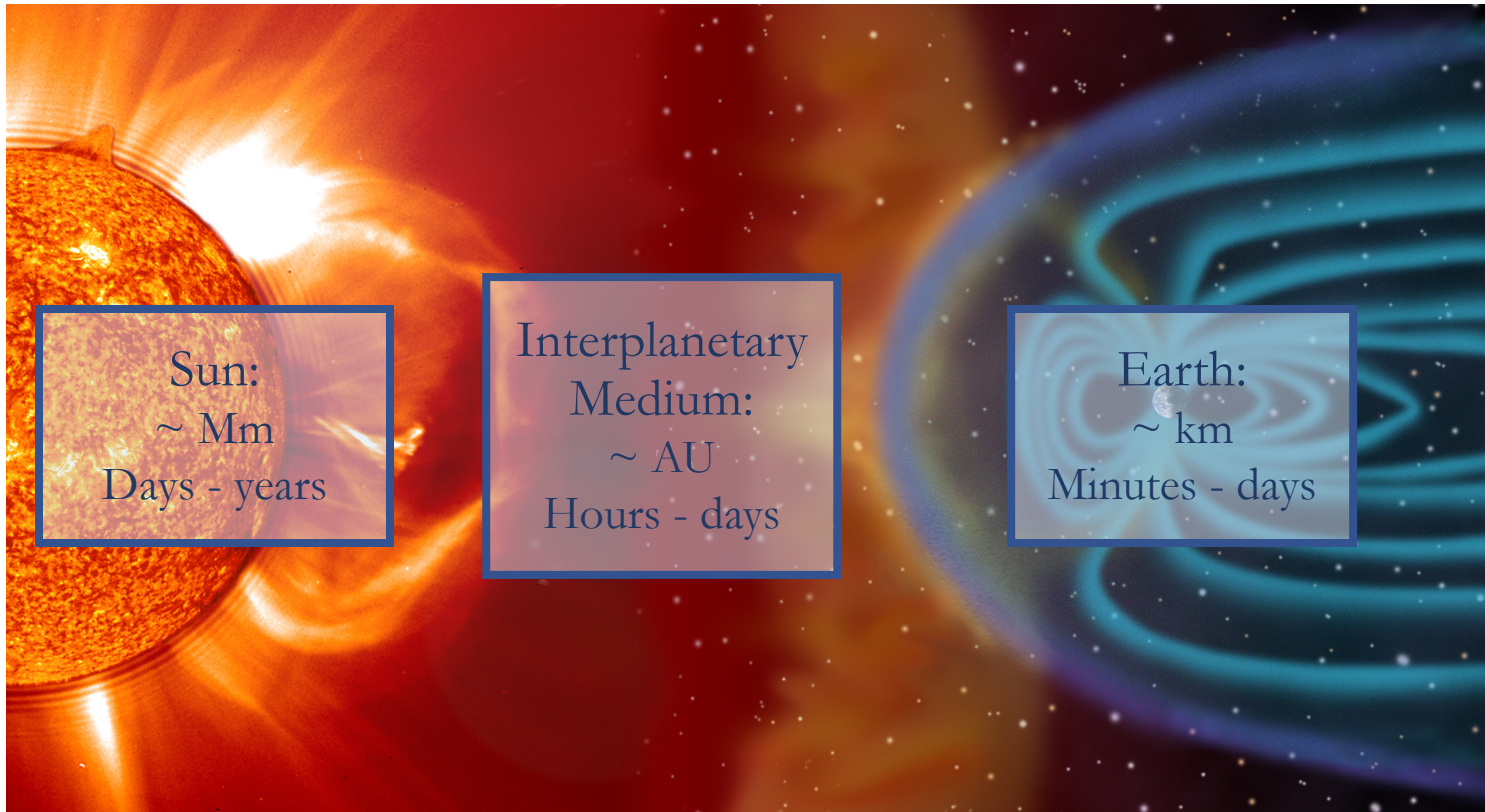
Space weather covers a wide variety of **scales** and **physical phenomena**



[NASA]

The various subsystems of space weather

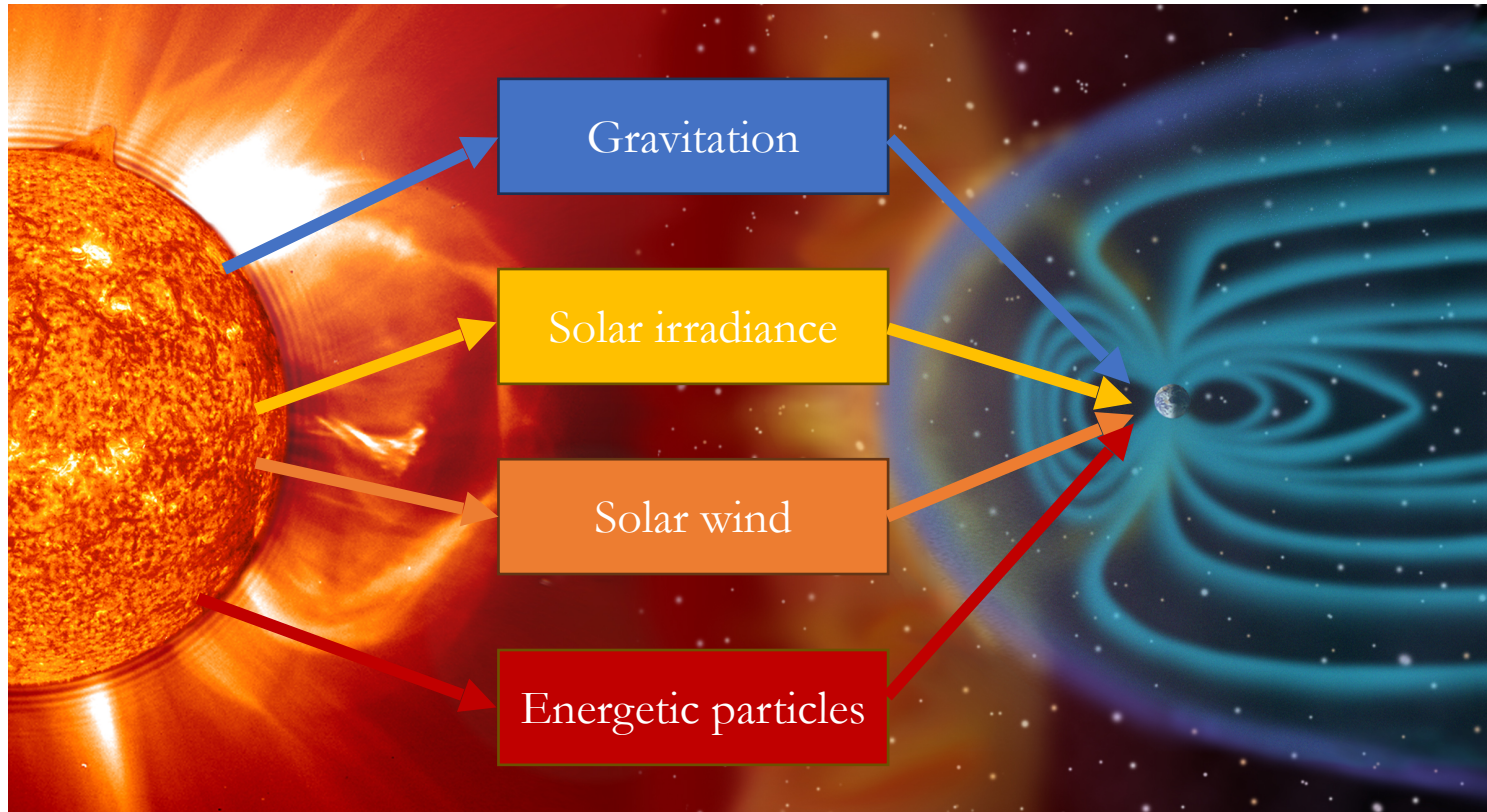
Space weather covers a wide variety of **scales** and **physical phenomena**



[NASA]

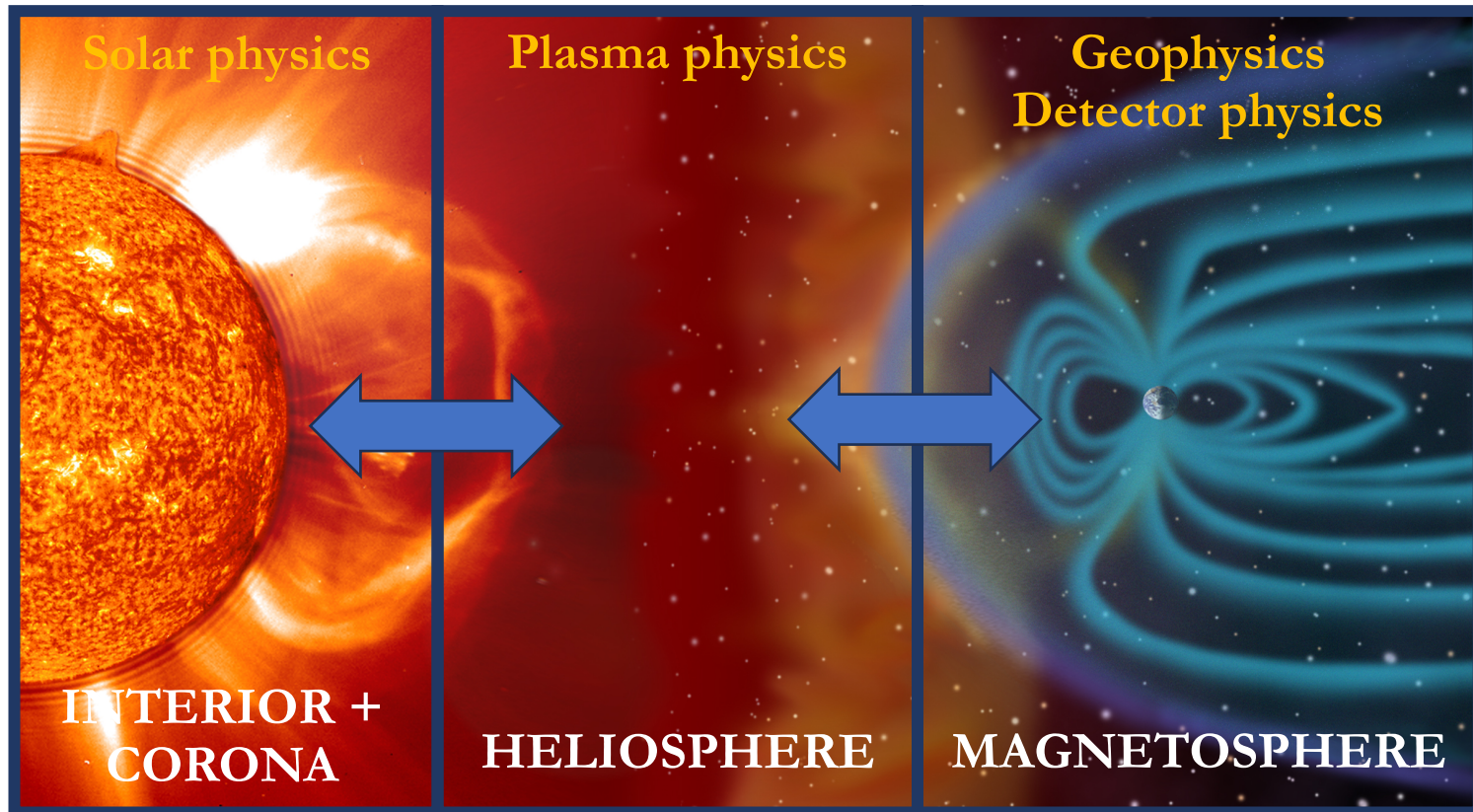
The various subsystems of space weather

Space weather covers a wide variety of **scales** and **physical phenomena**



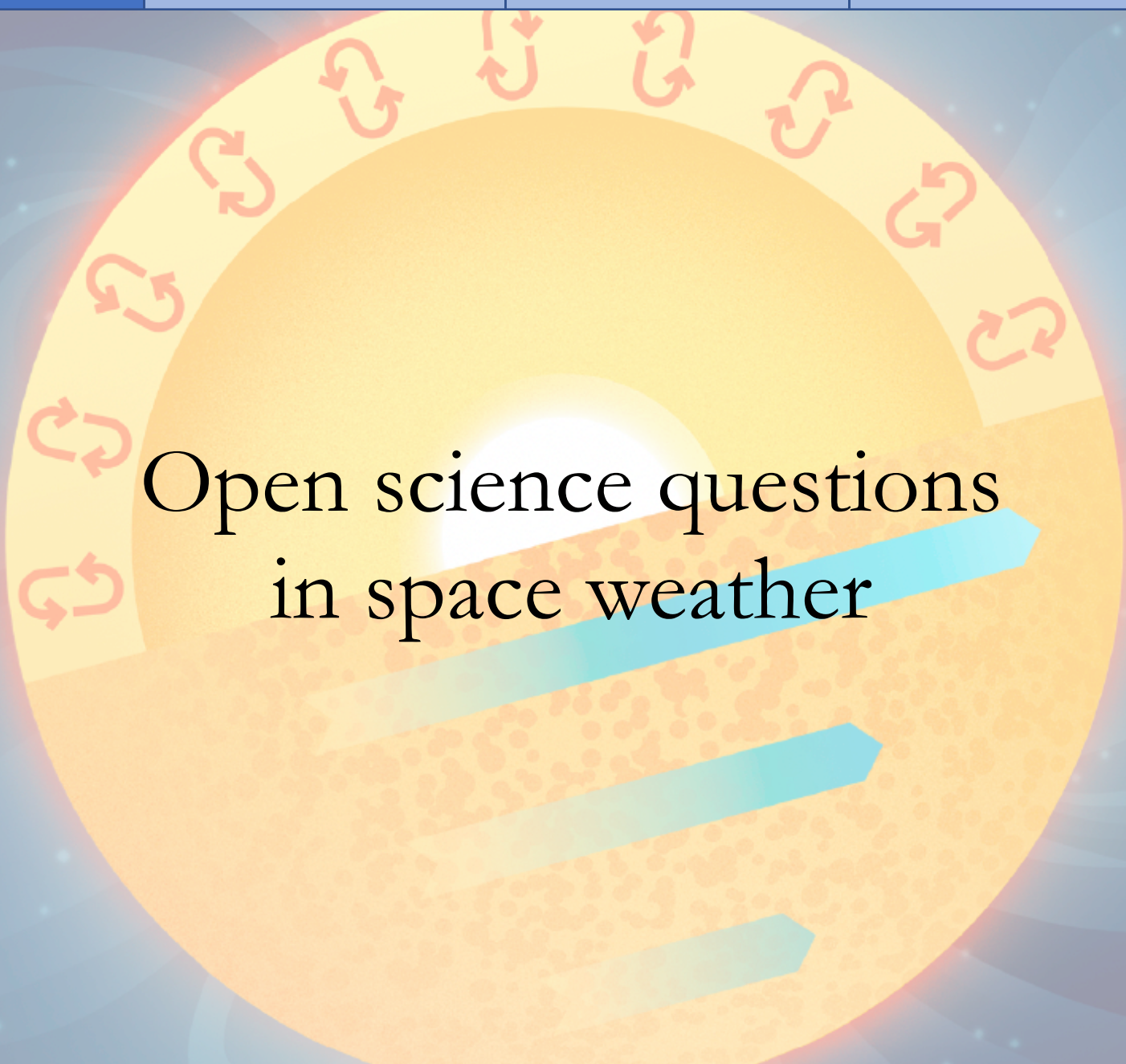
The various subsystems of space weather

Space weather covers a wide variety of **scales** and **physical phenomena**



One model to rule them
all? → **Impossible!**

Rather **chains of models** with the **best numerical
approach** + coupling at the **interfaces**

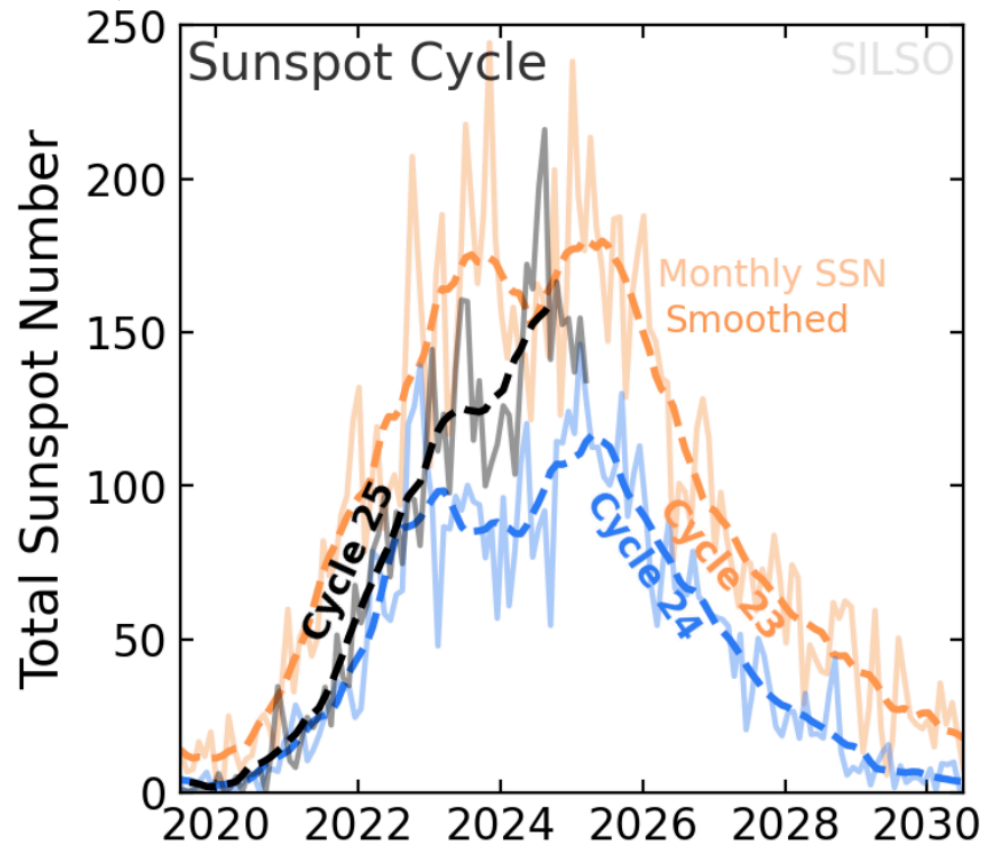


Open science questions in space weather

The solar interior

The solar activity is modulated in time by the **dynamo** cycle (internal **magnetic field**)

[A. Finley]

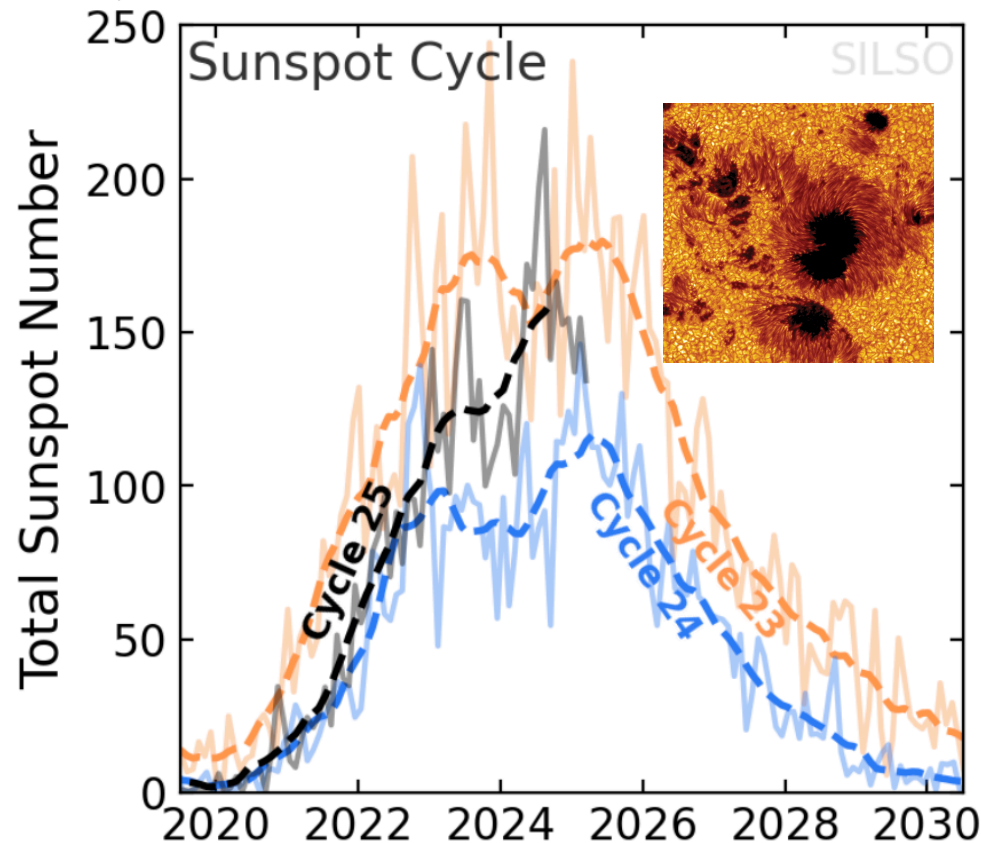


- Can we predict the **next cycle**?
- What are the conditions for **flux emergence**?

The solar interior

The solar activity is modulated in time by the **dynamo** cycle (internal **magnetic field**)

[A. Finley]

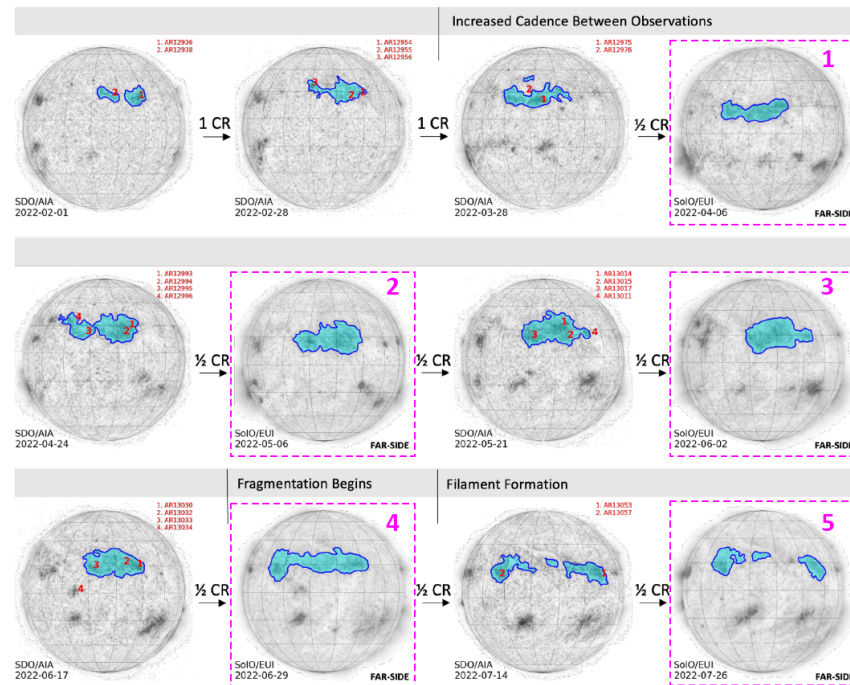
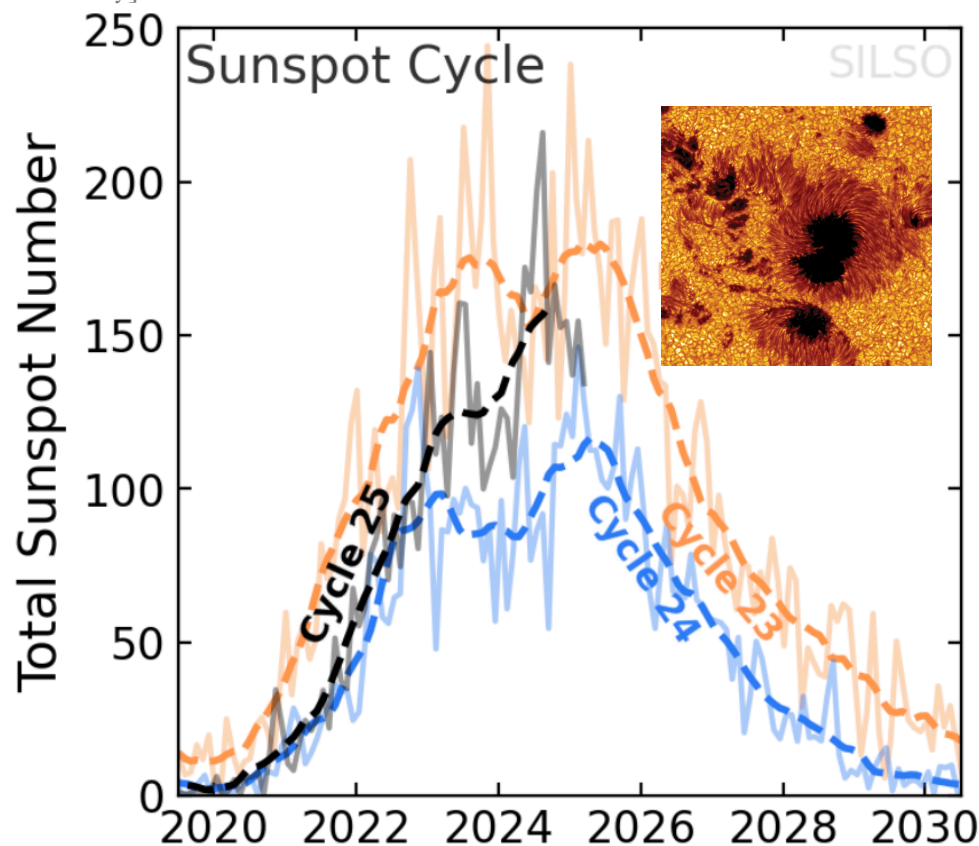


- Can we predict the **next cycle**?
- What are the conditions for **flux emergence**?

The solar interior

The solar activity is modulated in time by the **dynamo** cycle (internal **magnetic field**)

[A. Finley]



Finley et al. (2025)

adamjamesfinley.github.io

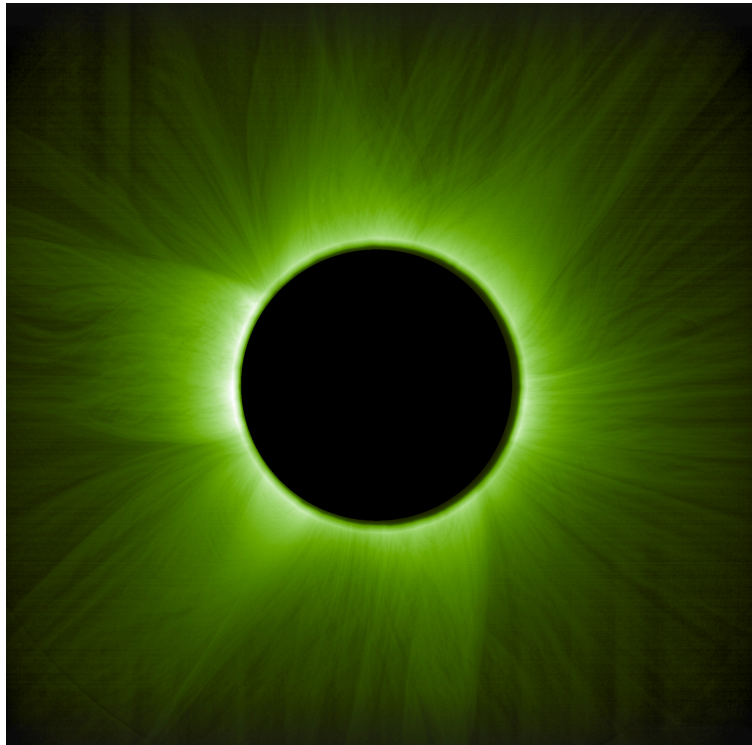
Example:

Study of an active region nest
with Solar Orbiter data



The solar atmosphere

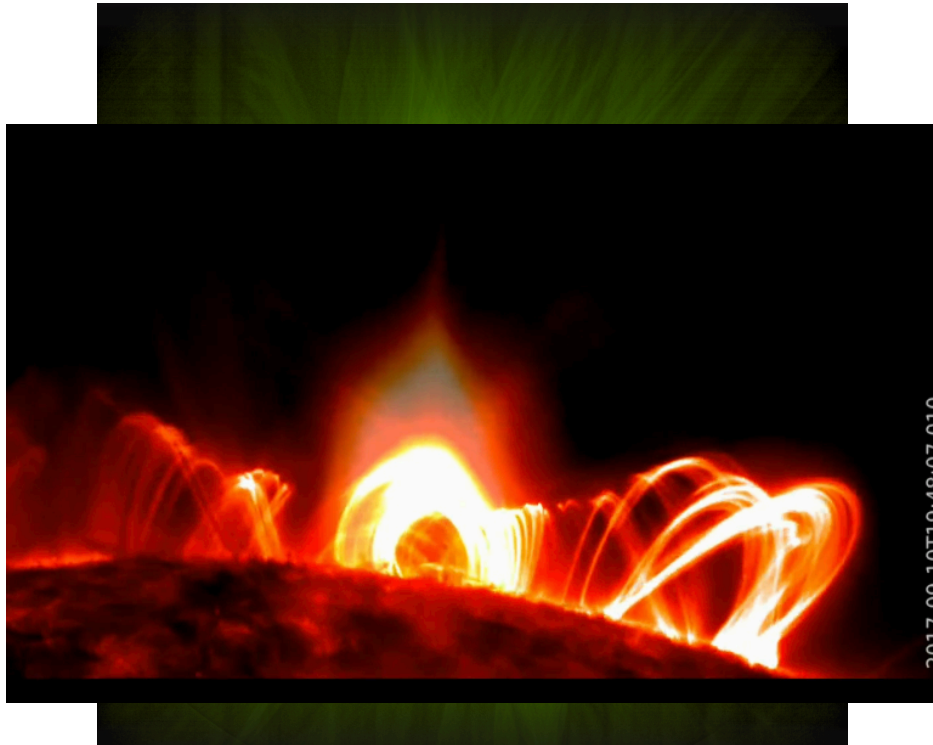
The solar atmosphere is the place of acceleration of the **solar wind**, as well as the place for liberation of magnetic energy through **flares**



- What are the **mechanisms** behind **solar wind**? (waves, reconnection...)
- Can we **predict** flaring activity and the related **acceleration of particles**?

The solar atmosphere

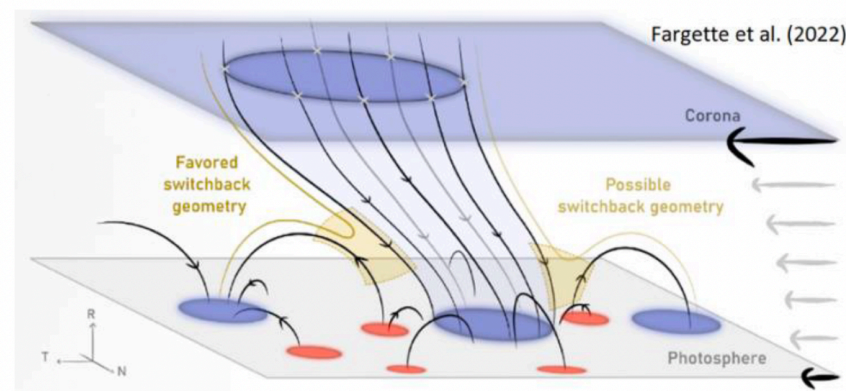
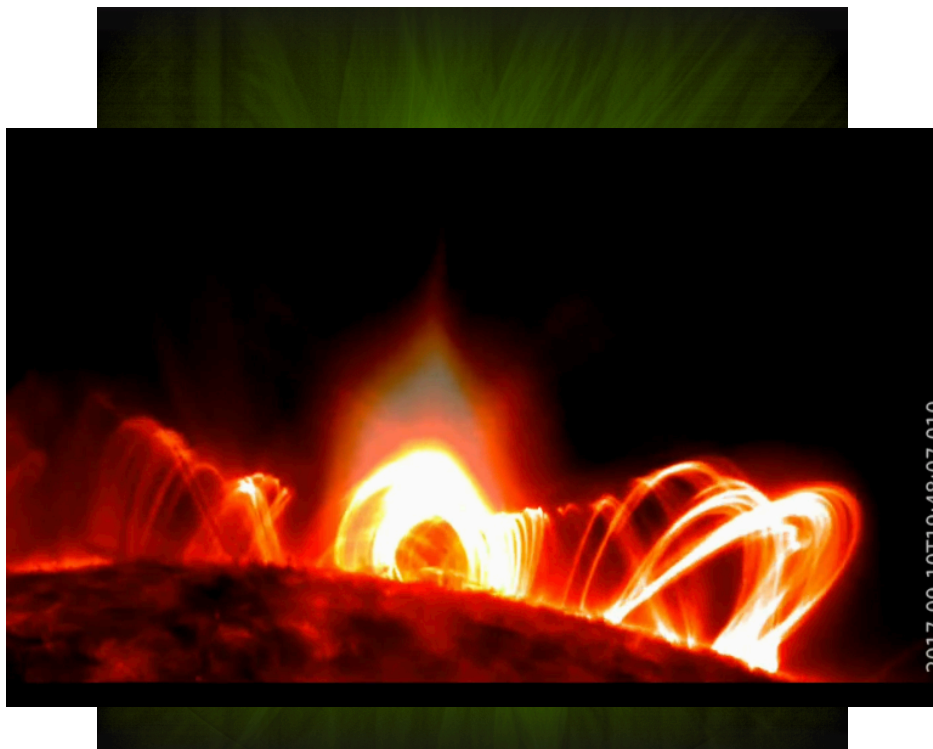
The solar atmosphere is the place of acceleration of the **solar wind**, as well as the place for liberation of magnetic energy through **flares**



- What are the **mechanisms** behind **solar wind**? (waves, reconnection...)
- Can we **predict** flaring activity and the related **acceleration of particles**?

The solar atmosphere

The solar atmosphere is the place of acceleration of the **solar wind**, as well as the place for liberation of magnetic energy through **flares**

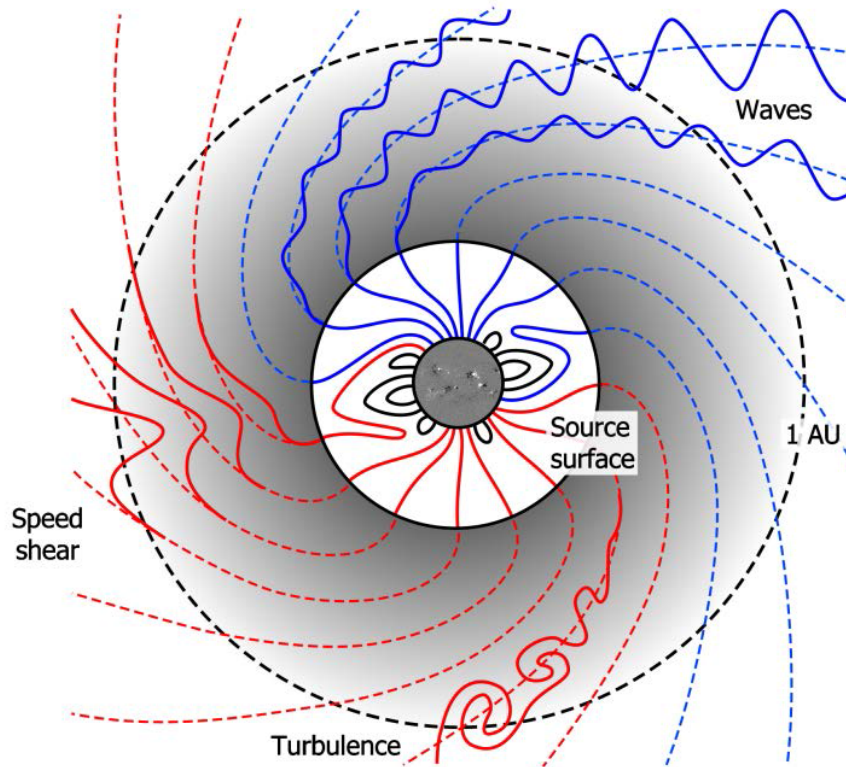


Example:

- Sources of PSP switchbacks and slow solar wind

The interplanetary medium

The solar wind flow and magnetic field will **structure** the interplanetary medium, which can affect the propagation of transients such as **CMEs**



[Owens & Forsyth 2013]

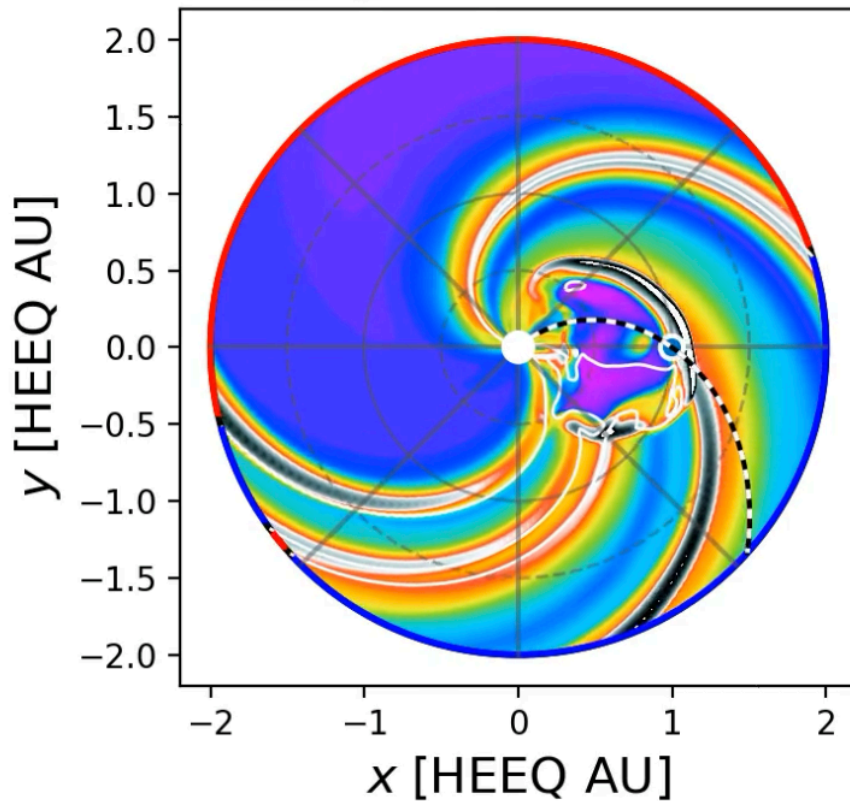
- Can we establish the **connectivity** between the Sun and the Earth?
- Can we predict the **trajectory and orientation** of CMEs?

The interplanetary medium

The solar wind flow and magnetic field will **structure** the interplanetary medium, which can affect the propagation of transients such as **CMEs**

[Perri+2024b]

2015-03-22 13:59



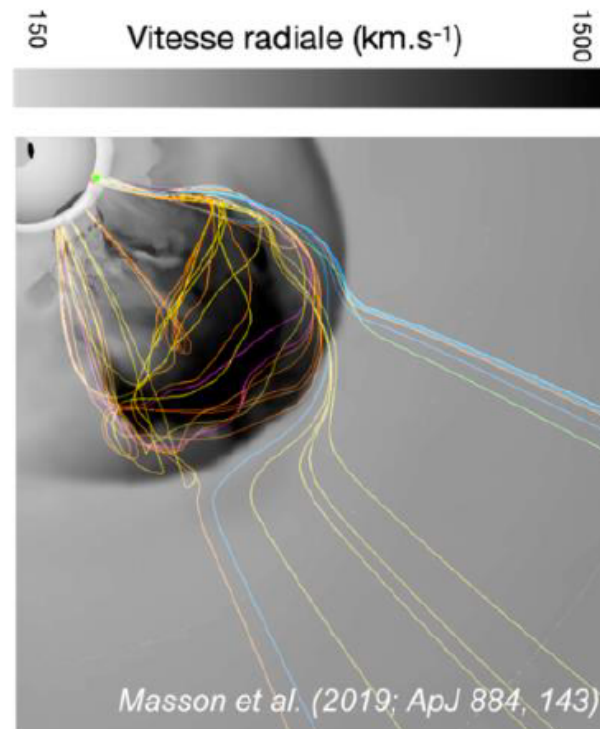
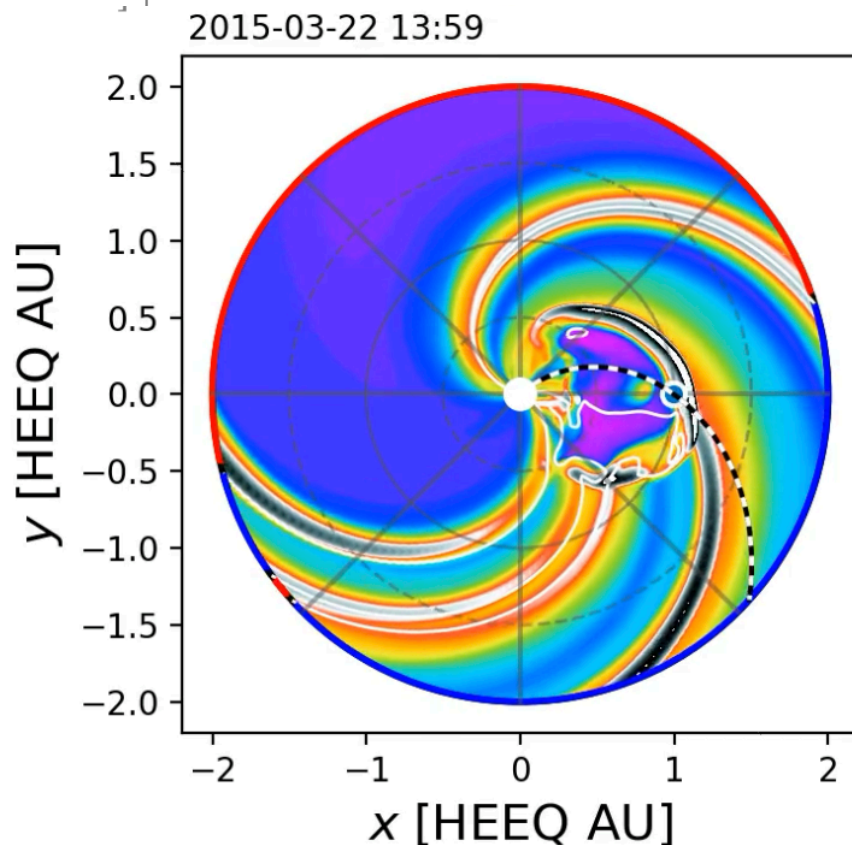
[Owens & Forsyth 2013]

- between the Sun and the Earth?
- Can we predict the **trajectory and orientation** of CMEs?

The interplanetary medium

The solar wind flow and magnetic field will **structure** the interplanetary medium, which can affect the propagation of transients such as **CMEs**

[Perri+2024b]



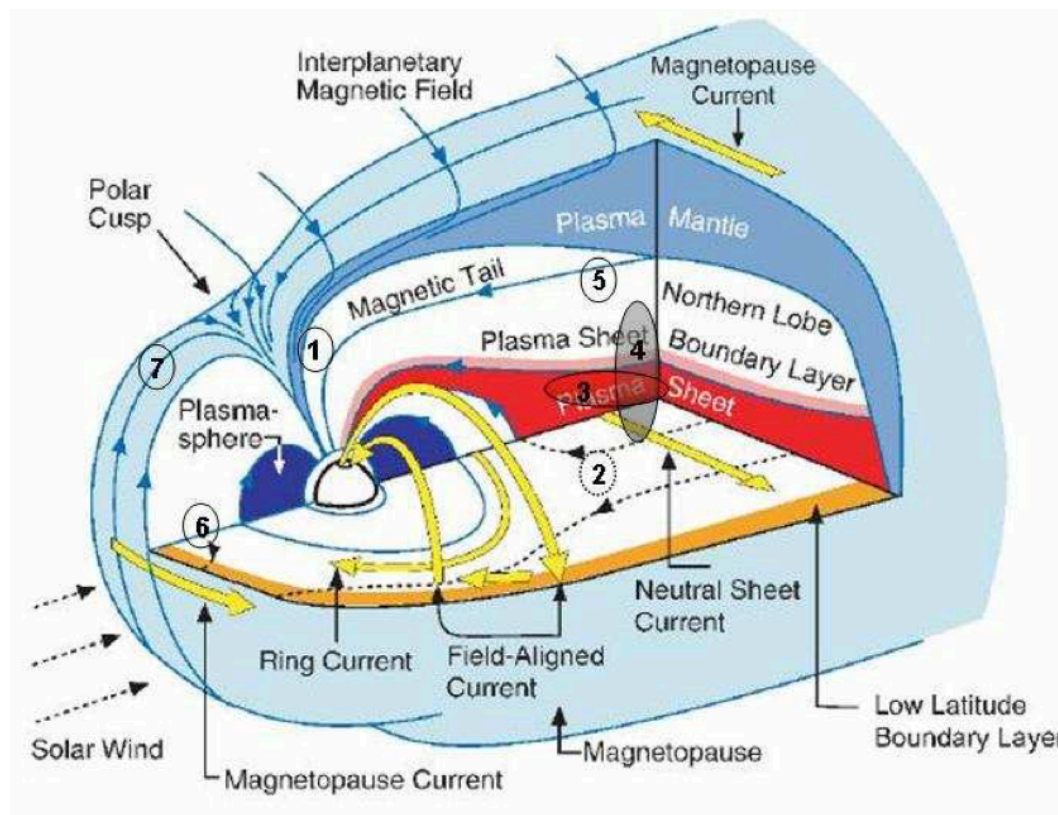
Example:

- Self-consistent simulations of the propagation of CME



The magnetosphere

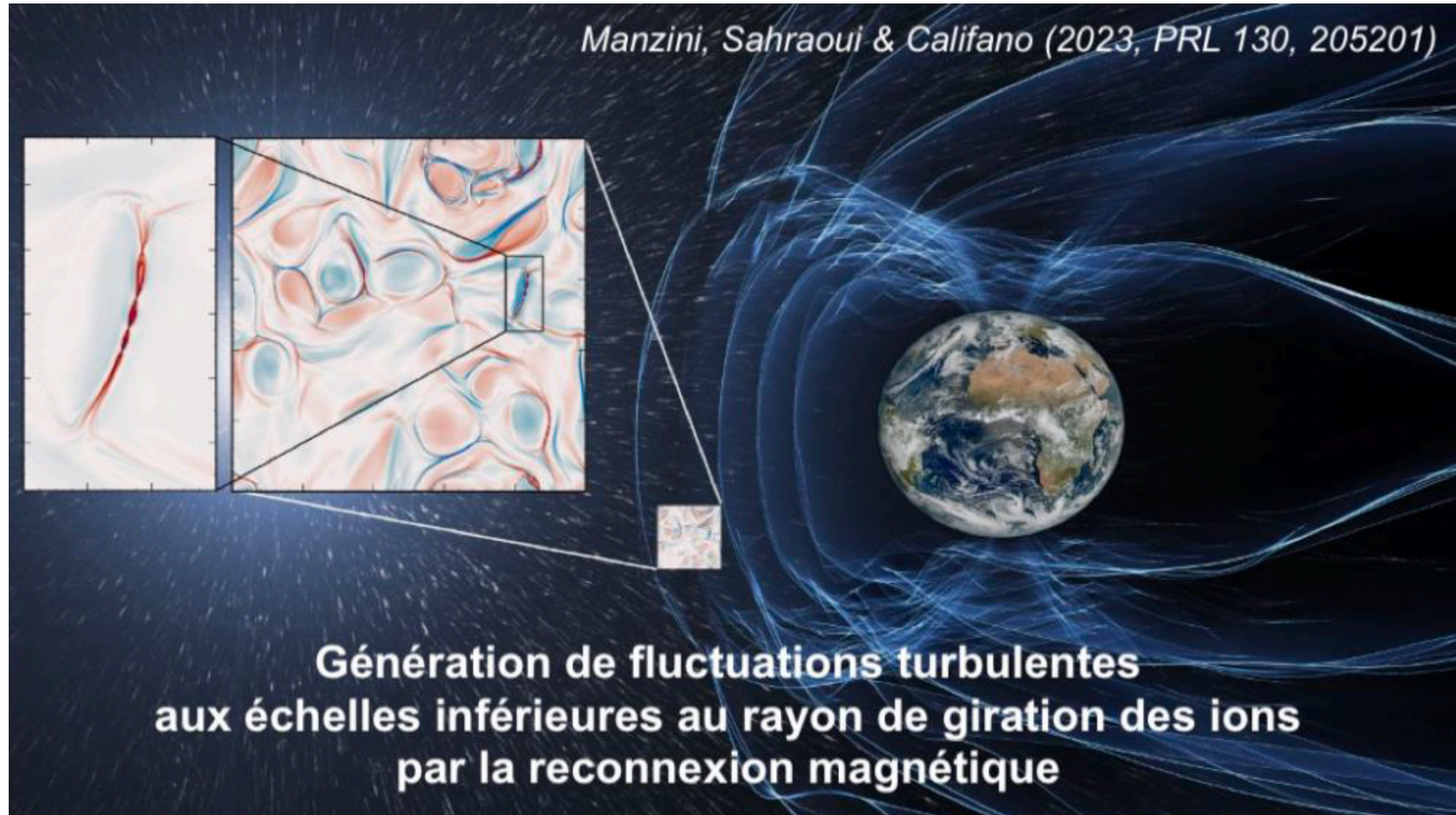
The magnetosphere is a complex **global** system dominated by **currents** and **reconnexion** processes



[R. Lopez]

- How does the magnetosphere **react** to **external** forces?
- How do the **various physical scales** connect?

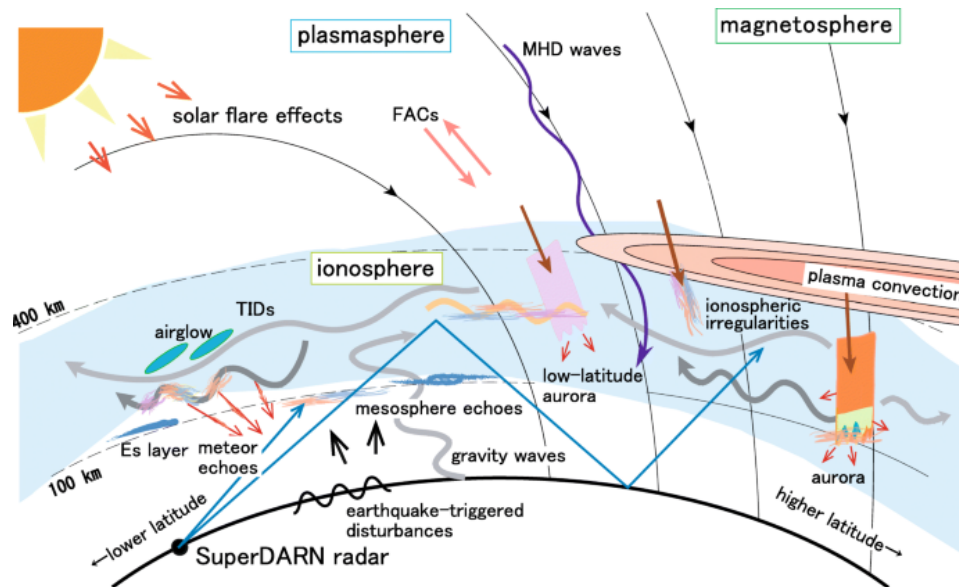
The magnetosphere



- How does the magnetosphere **react** to **external** forces?
- How do the **various physical scales** connect?
- Example:
Sub-ion scale turbulence driven by magnetic reconnexion

The Earth atmosphere

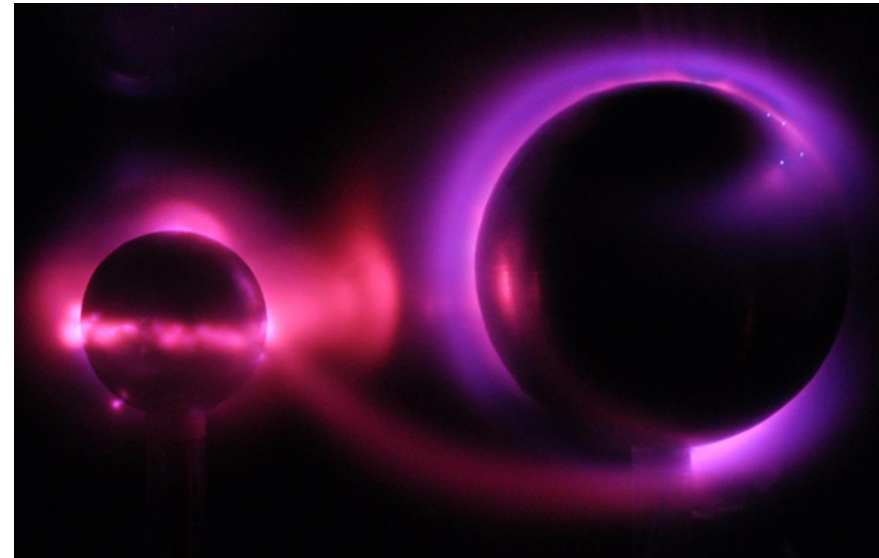
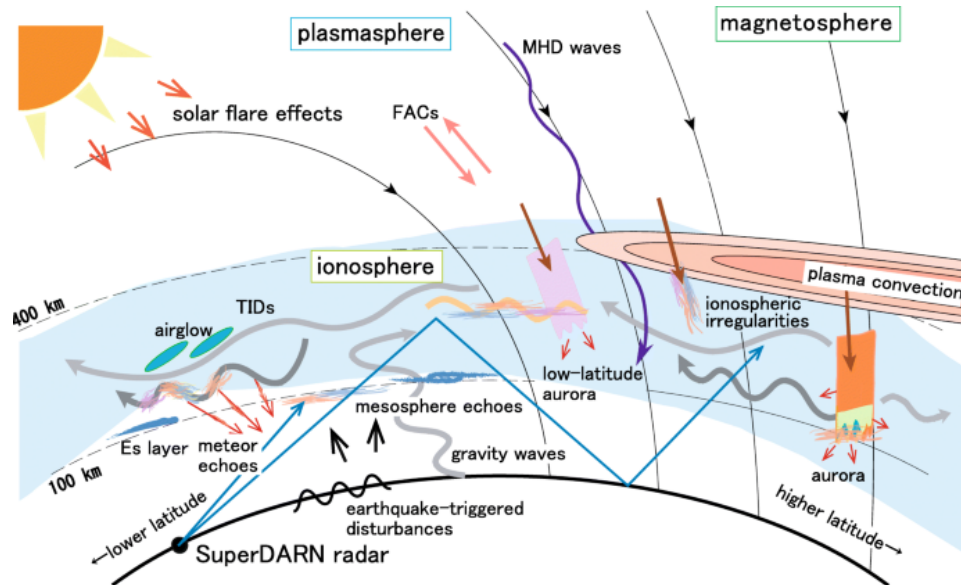
The **ionosphere** is the layer that reacts to electrical currents where we can see the **auroras**



- How are **geomagnetic storms** triggered?
- Can we predict the **perturbations** of the atmosphere?
- How can we measure the Earth magnetic field ?

The Earth atmosphere

The **ionosphere** is the layer that reacts to electrical currents where we can see the **auroras**



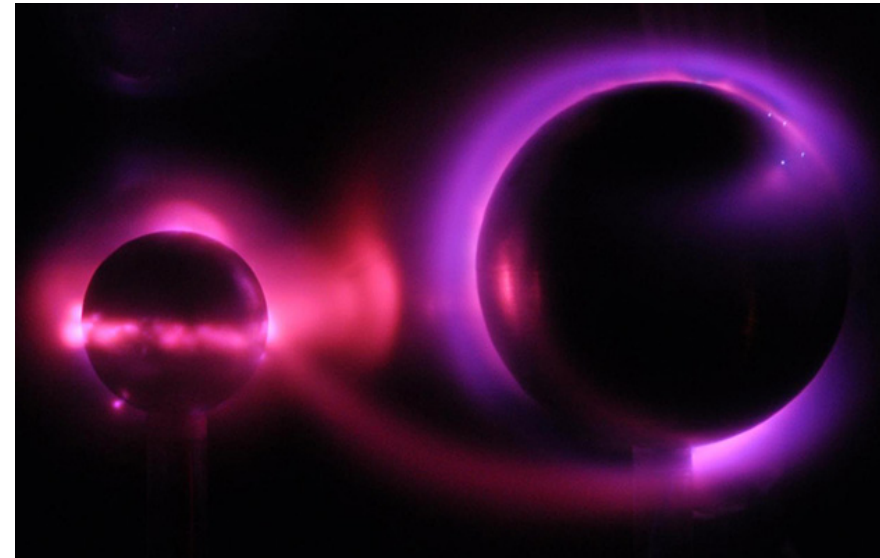
Example:

- Planeterrella and auroras on Jupiter and Mars



The Earth atmosphere

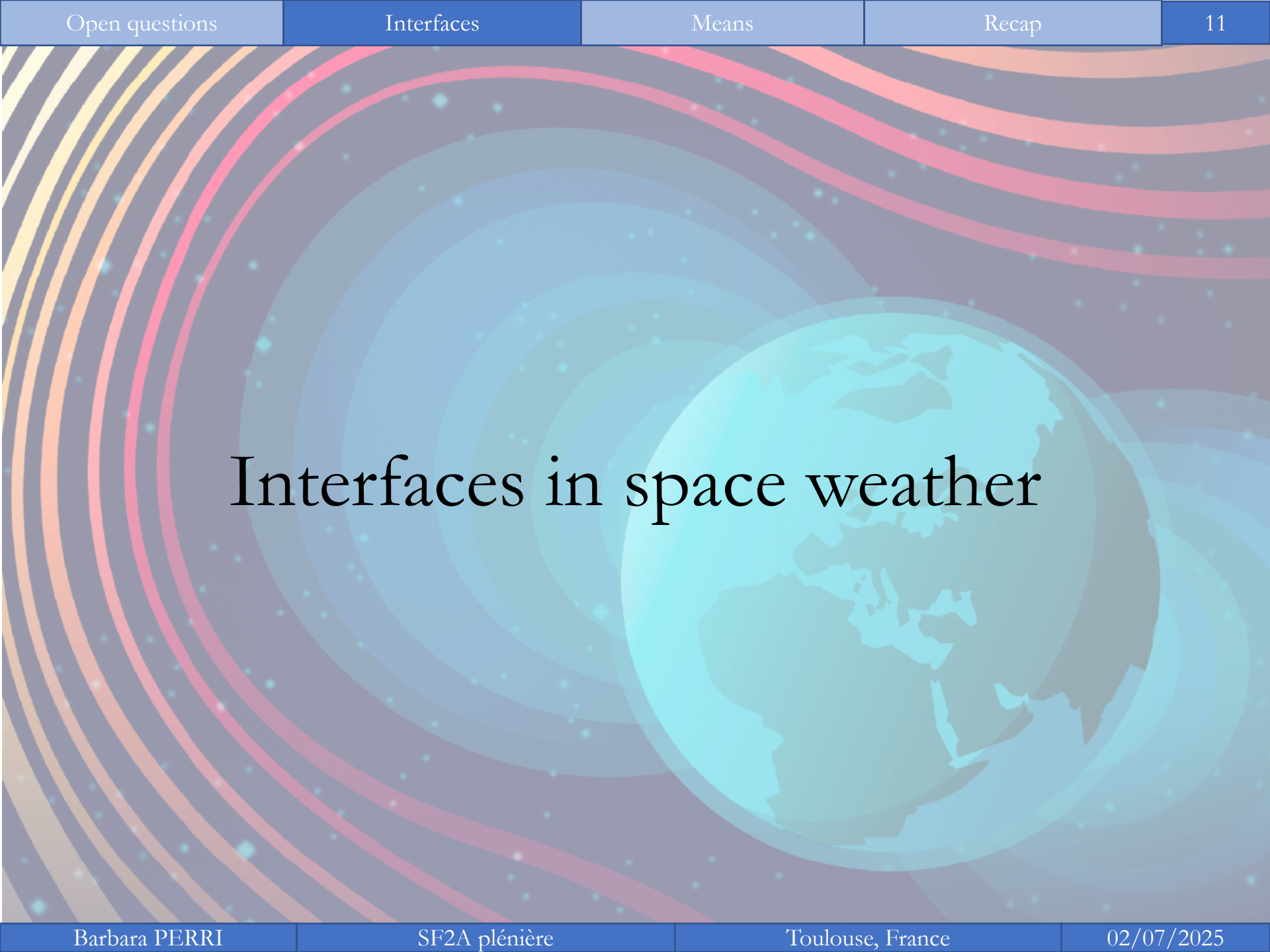
The **ionosphere** is the layer that reacts to electrical currents where we can see the **auroras**



Example:

- Planeterrella and auroras on Jupiter and Mars

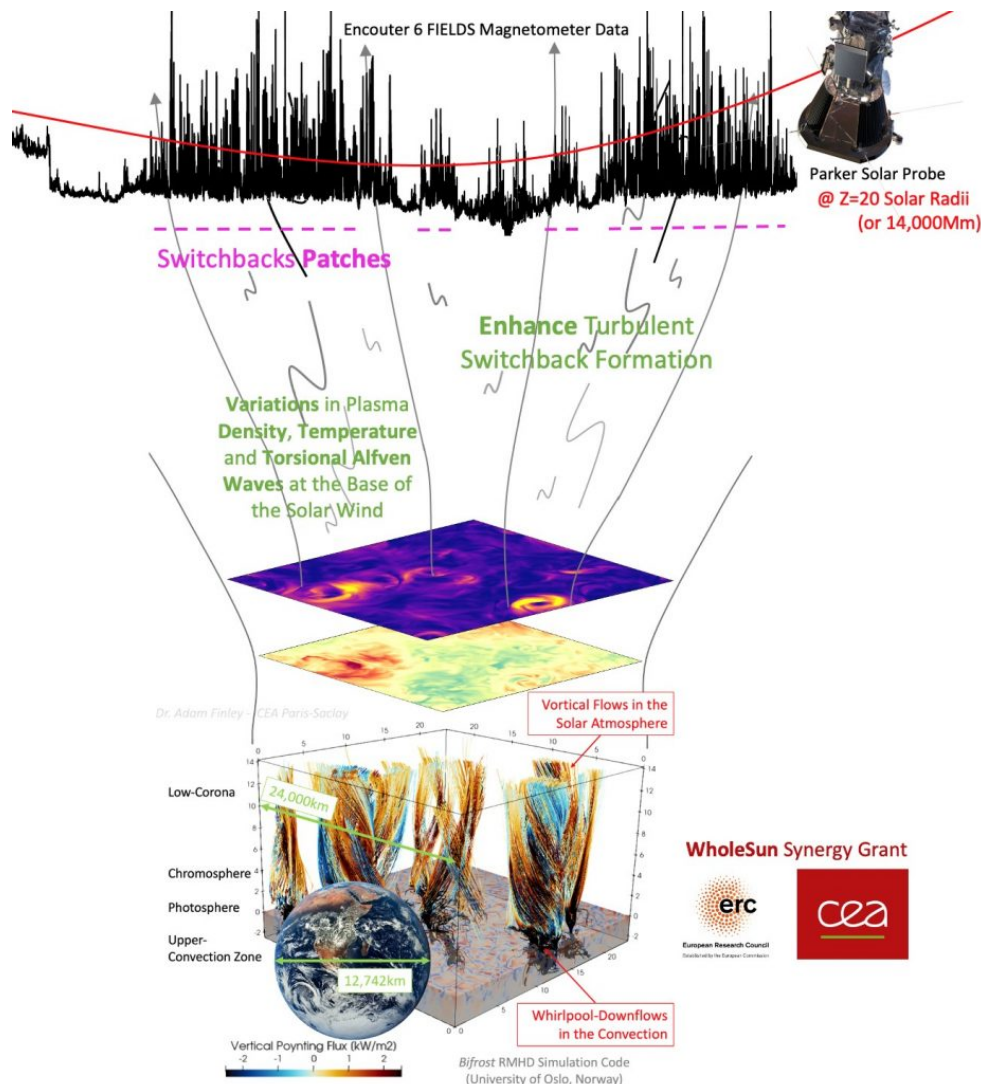


A stylized illustration of Earth centered on the Atlantic Ocean, showing the continents of North and South America. The Earth is surrounded by concentric, wavy lines in shades of blue, pink, and orange, representing magnetic field lines or space weather patterns. Small white dots are scattered throughout the background, suggesting stars or particles in space.

Interfaces in space weather

Small and large scales in the solar corona

[Finley+2022]

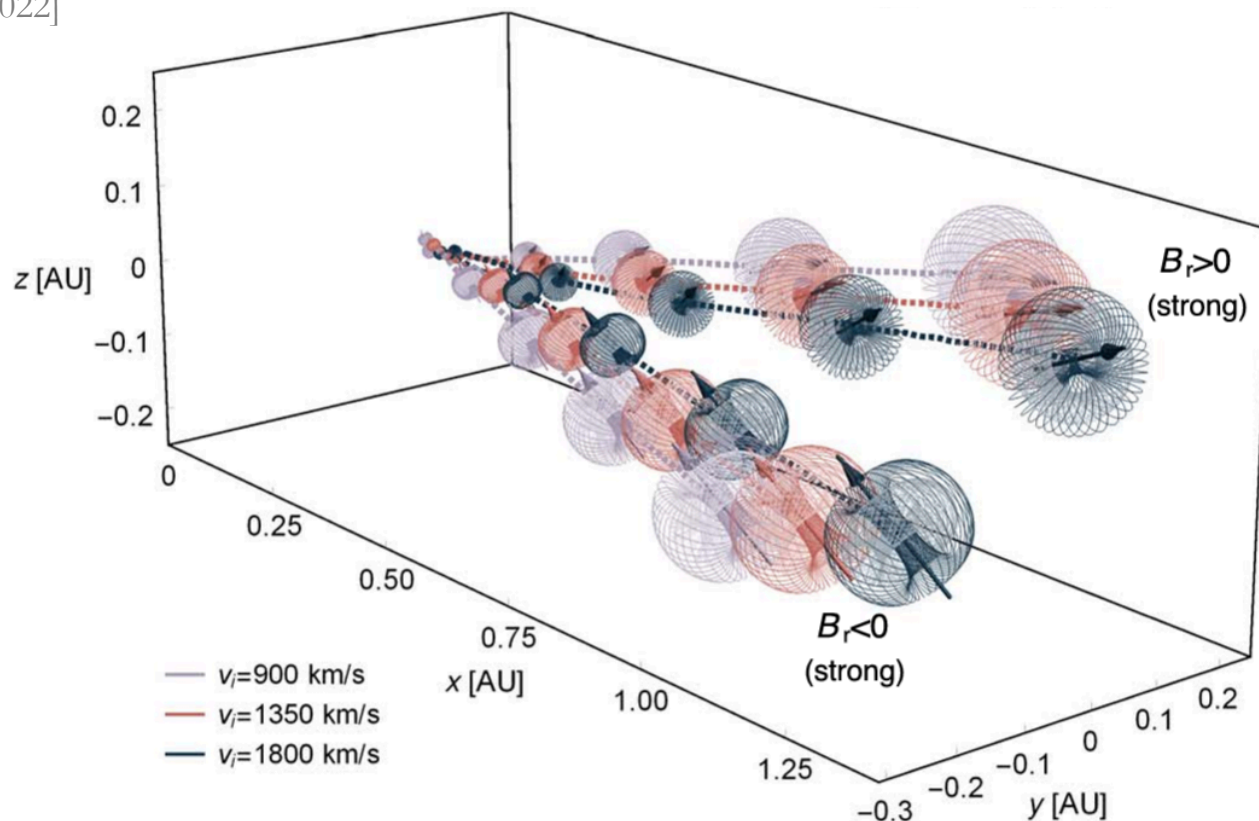


We still struggle to understand the **transfer of small-scale perturbations** in the lower atmosphere to **large-scale structures** in the corona (coronal heating, switchbacks, connectivity...)

→ Towards coupling between local and global numerical simulations

Interactions between solar wind and transients

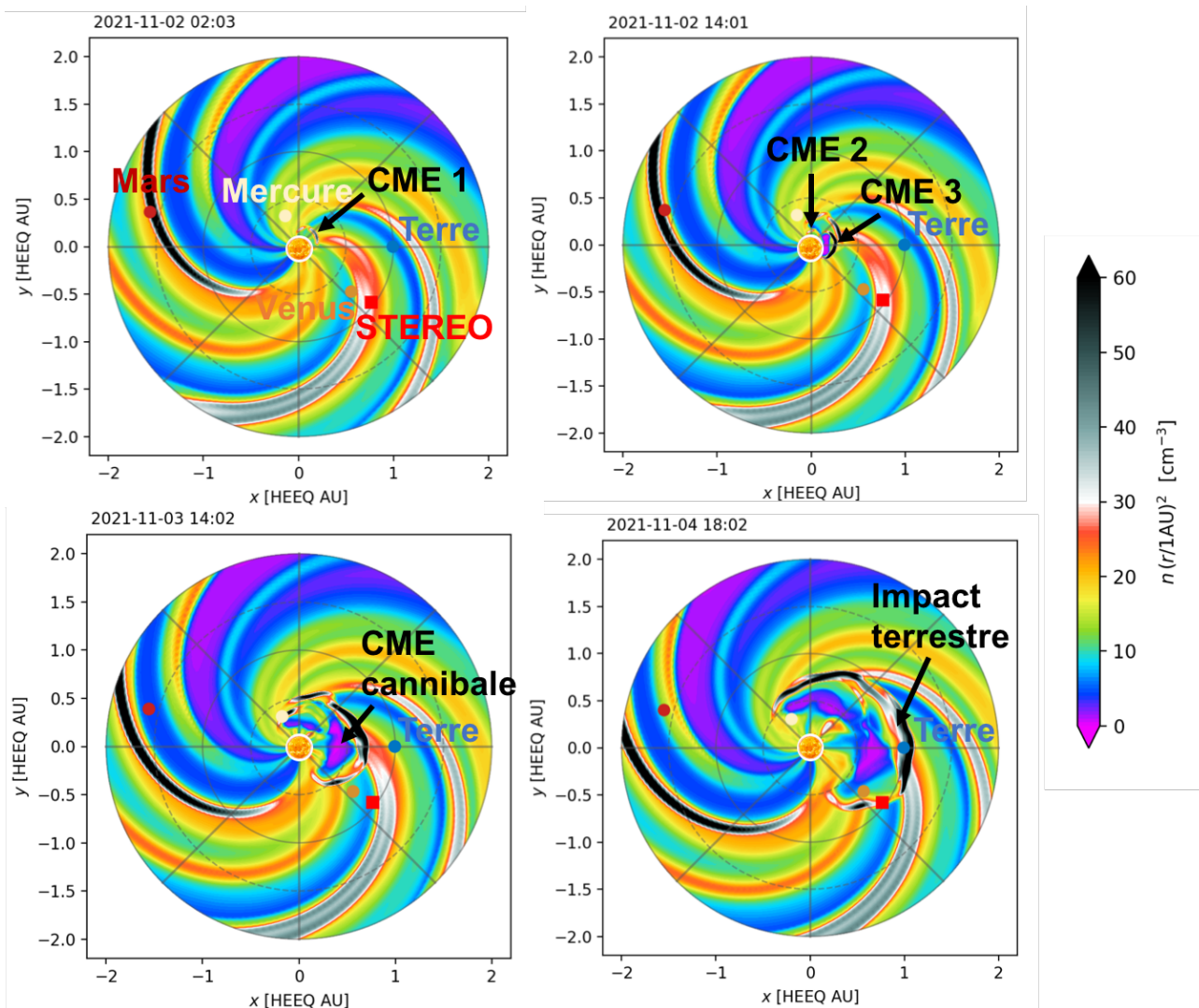
[Asvestari+2022]



Most of the **CME deformations** happen in the **close corona** (below 30 solar radii) due to the interaction with the solar wind and magnetic field
→ **Towards multi-factorial prevision of CME orientation**

Multi-events and their impact on Earth

[Brun & Perri, L'Astronomie 158]



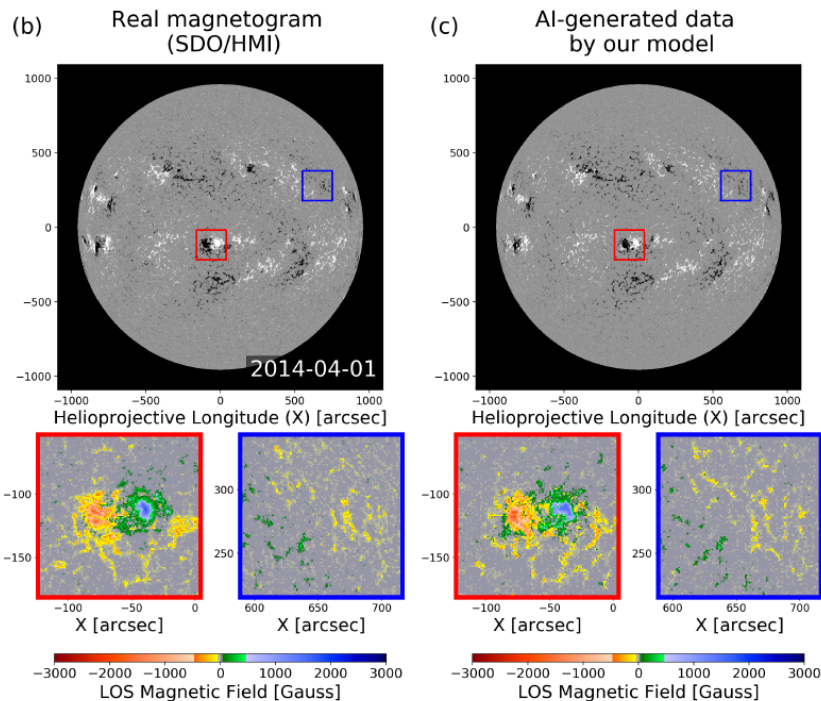
The most impactful events are **combined CMEs** that interact with each other (**canibal CMEs**)

→ Towards time-dependent wind-CME interactions

Space weather and modern computations

Artificial intelligence (AI) is also a powerful tool to **classify and automatize** the increasing amount of data (cf. session S05 yesterday)

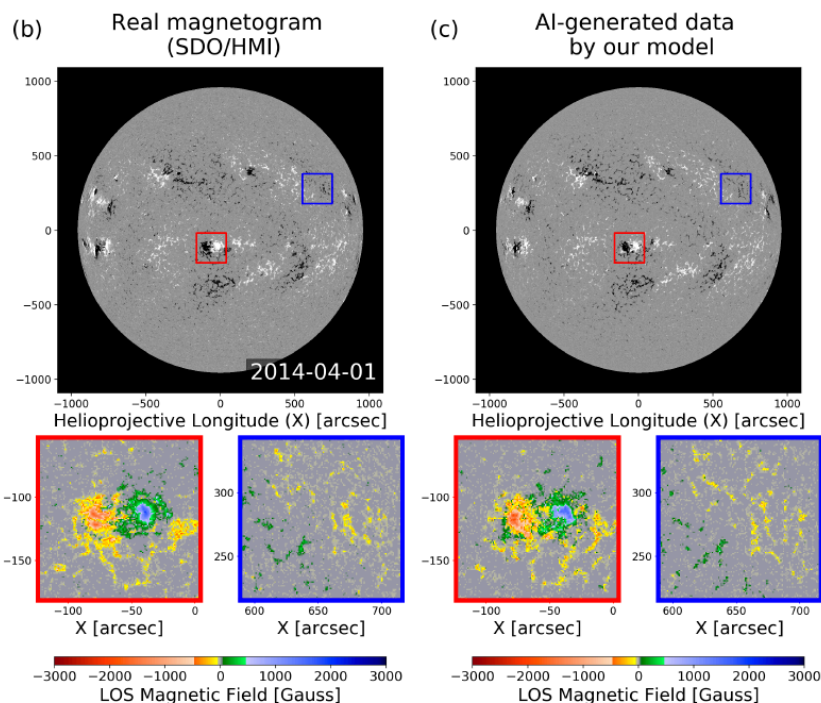
[Jeong+2020]



Space weather and modern computations

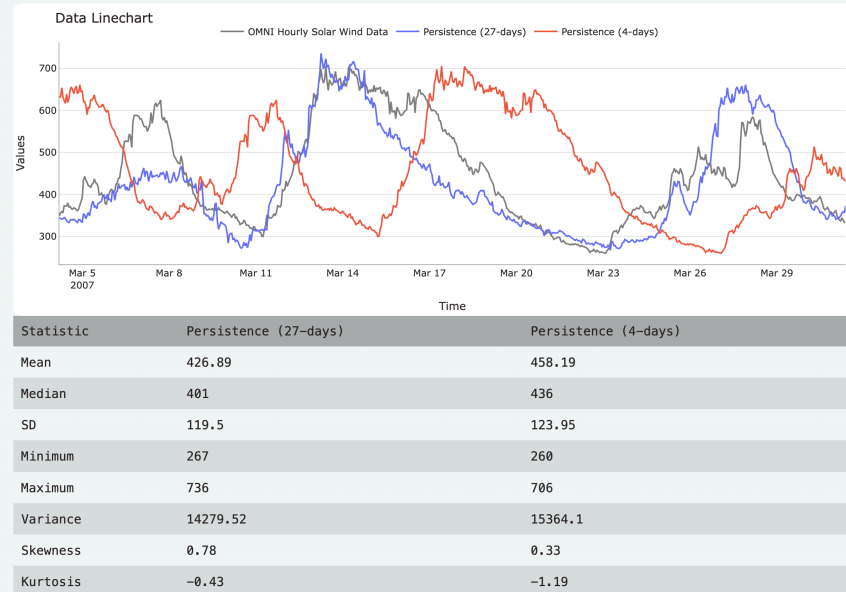
Artificial intelligence (AI) is also a powerful tool to **classify and automatize** the increasing amount of data (cf. session S05 yesterday)

[Jeong+2020]



[Reiss+2023]

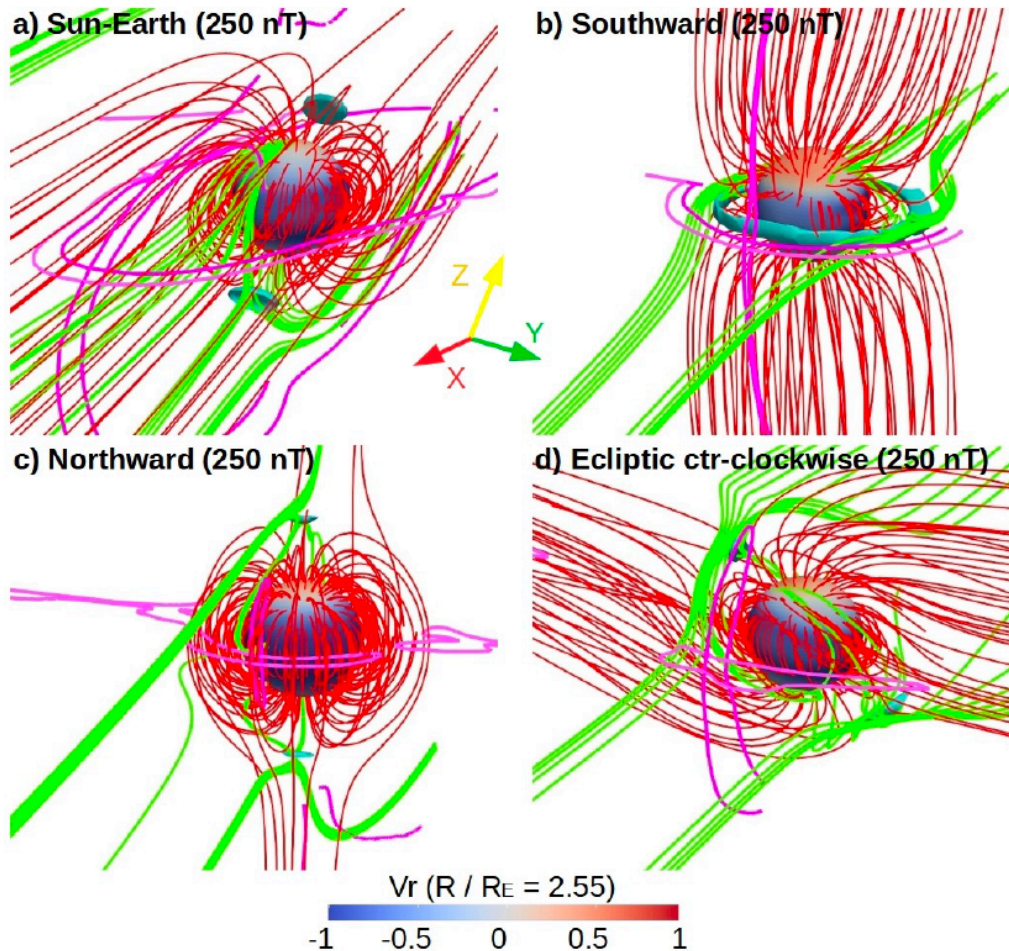
Multi-Model Comparison



→ We can learn from the weather community for the diversity of computing methods (HPC, GPU, hybrid) and the automatic validation and comparison metrics

Space weather and star-planet interactions

[Varela+2022, 2023]



The Sun-Earth chain is the most documented star-planet system we know

- From space weather to exo-space weather
- link with ATPS and PNP

An illustration depicting the effects of space weather. At the top, a satellite with solar panels is shown in space. Below it, a large, bright orange lightning bolt strikes the Earth's surface. In the foreground, a commercial airplane is flying in the lower atmosphere, also affected by the space weather. To the right, a radio tower is shown with several orange lightning bolts striking it. The background is a dark blue sky with stylized orange and yellow light rays and small white stars.

Means of French space weather

Ground observations

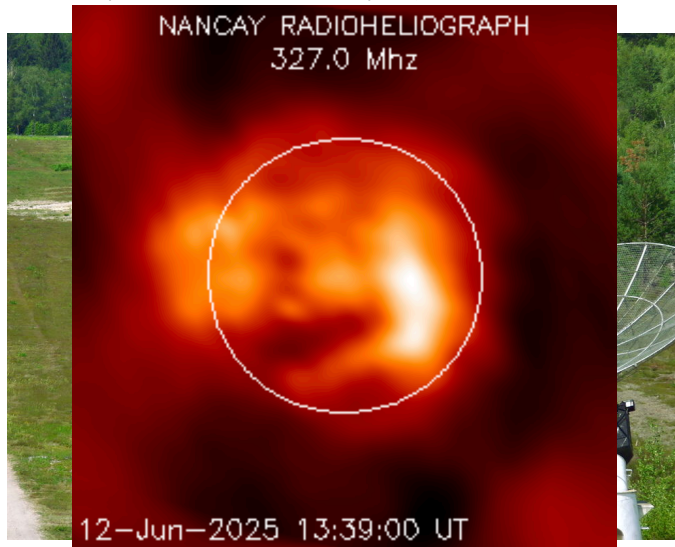
Ground observations

Nançay observatory (ORN) for radio



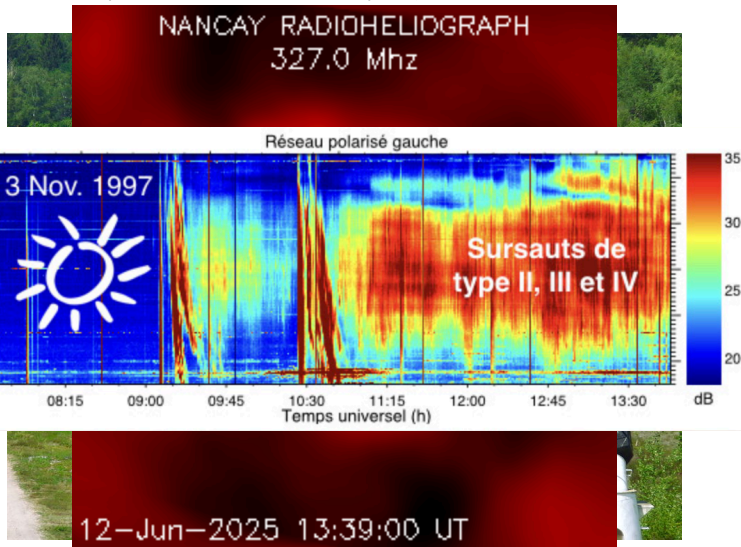
Ground observations

Nançay observatory (ORN) for radio



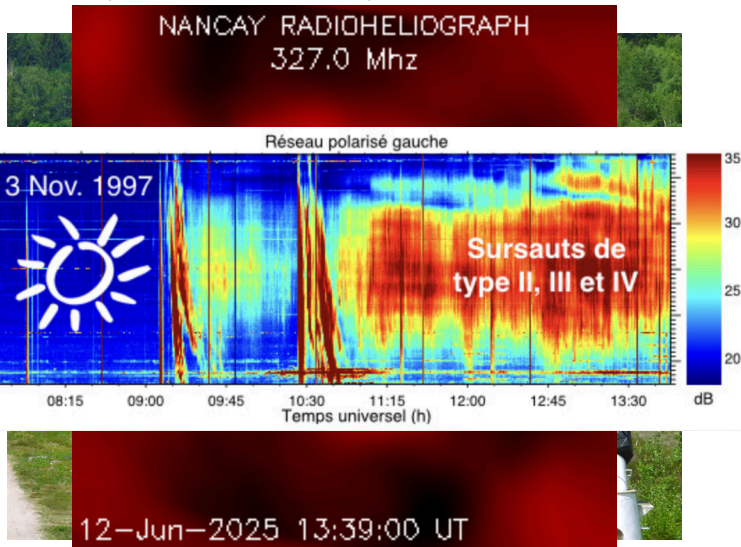
Ground observations

Nançay observatory (ORN) for radio



Ground observations

Nançay observatory (ORN) for radio

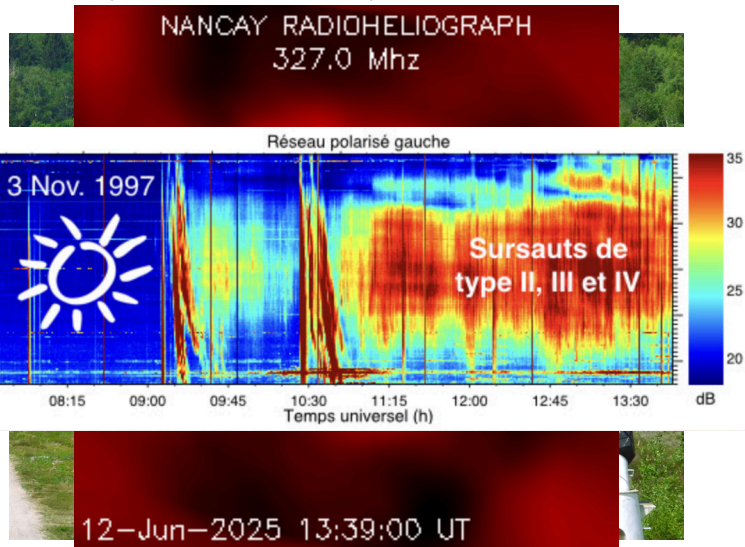


Halpha observatories
(Themis, CLIMSO, Meudon)

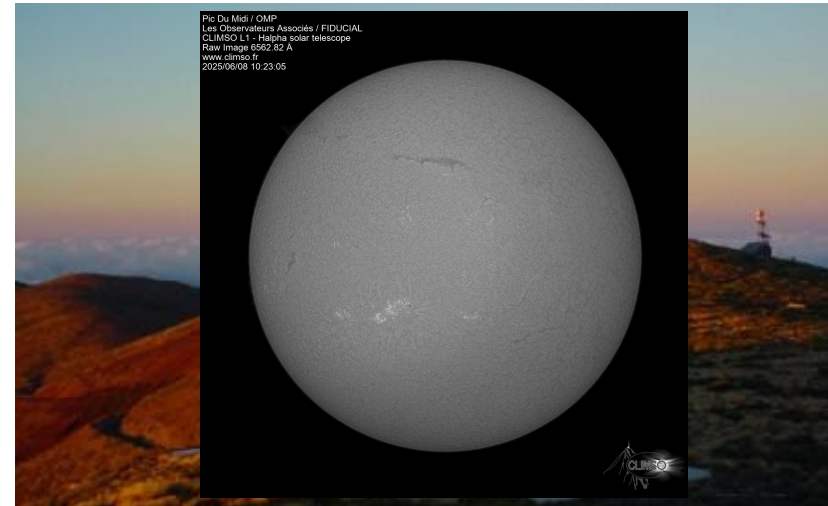


Ground observations

Nançay observatory (ORN) for radio

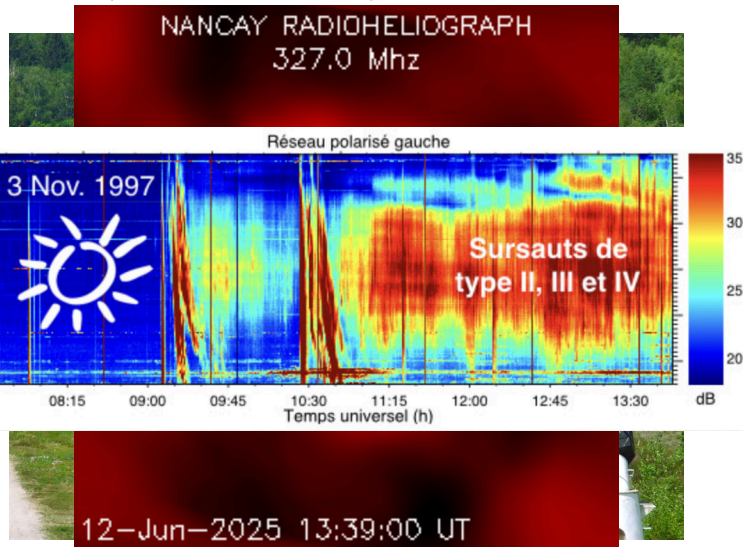


Halpfa observatories
(Themis, CLIMSO, Meudon)



Ground observations

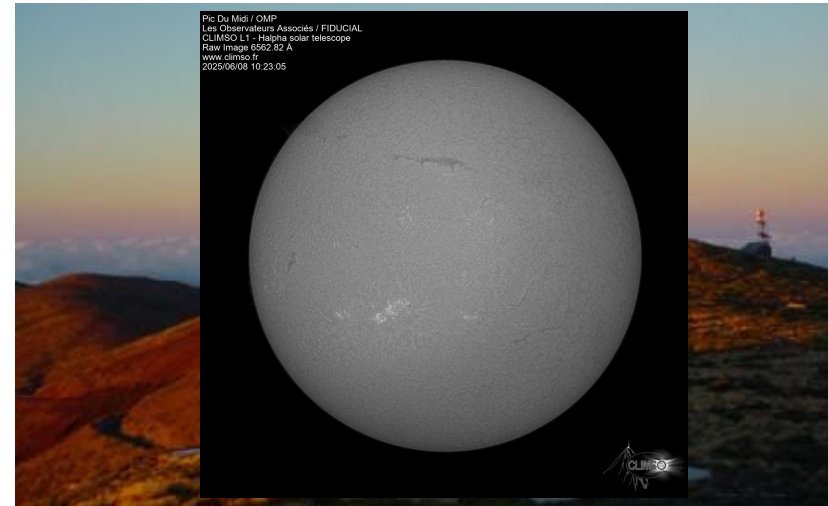
Nançay observatory (ORN) for radio



Ionosphere radars (SuperDARN)

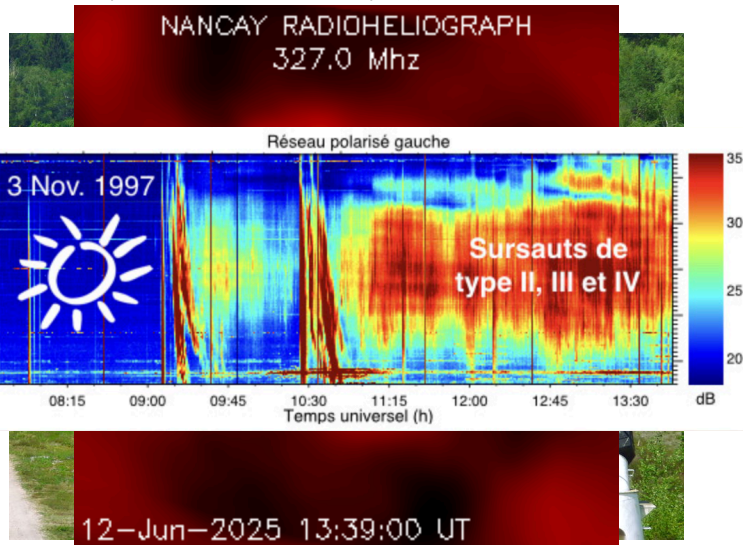


Halpa observatories
(Themis, CLIMSO, Meudon)

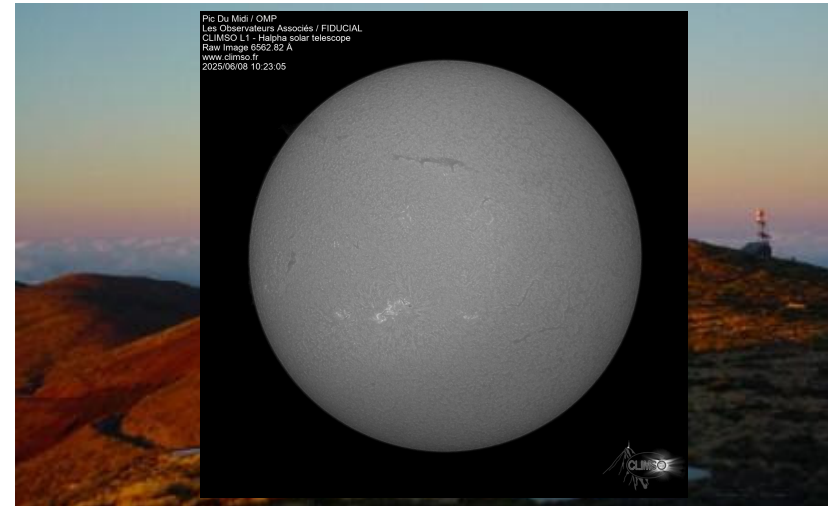


Ground observations

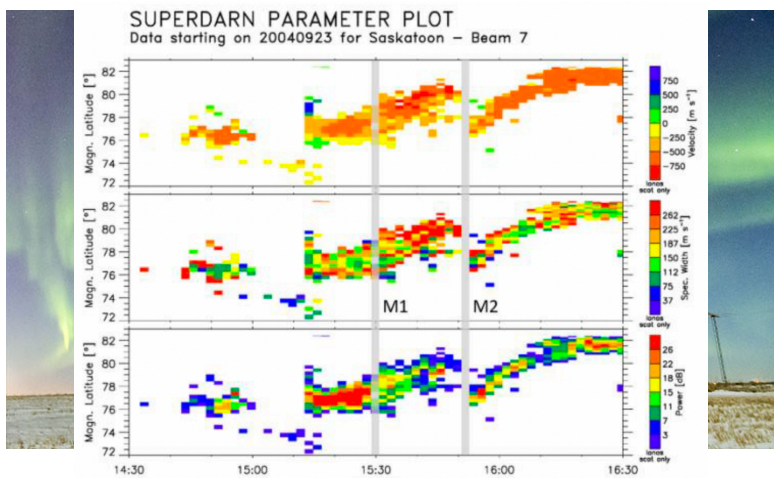
Nançay observatory (ORN) for radio



Halpfa observatories
(Themis, CLIMSO, Meudon)



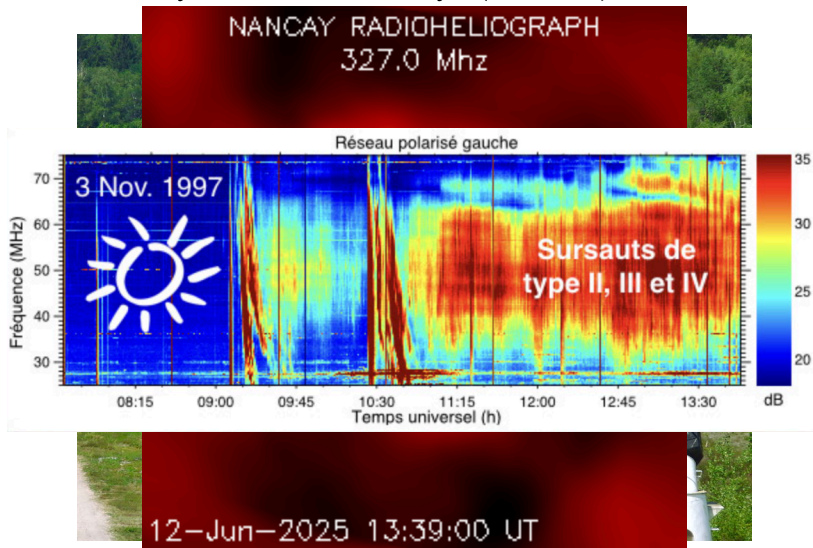
Ionosphere radars (SuperDARN)



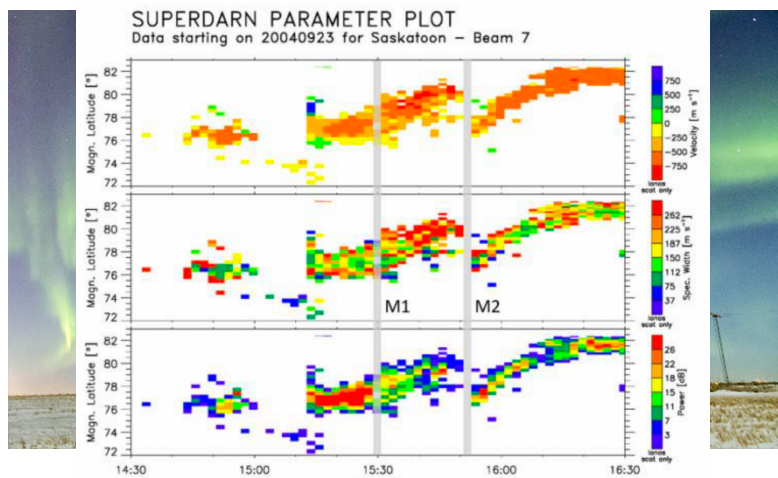
[Pitout+2020]

Ground observations

Nançay observatory (ORN) for radio

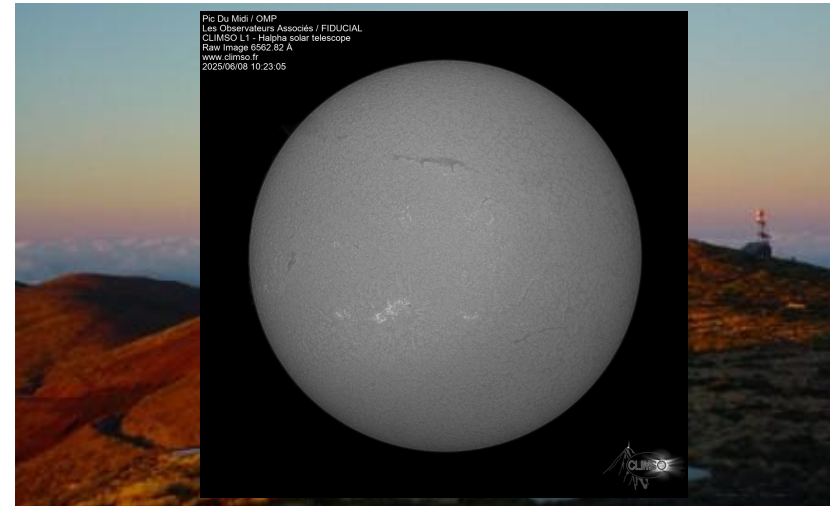


Ionosphere radars (SuperDARN)



[Pitout+2020]

Halpa observatories
(Themis, CLIMSO, Meudon)

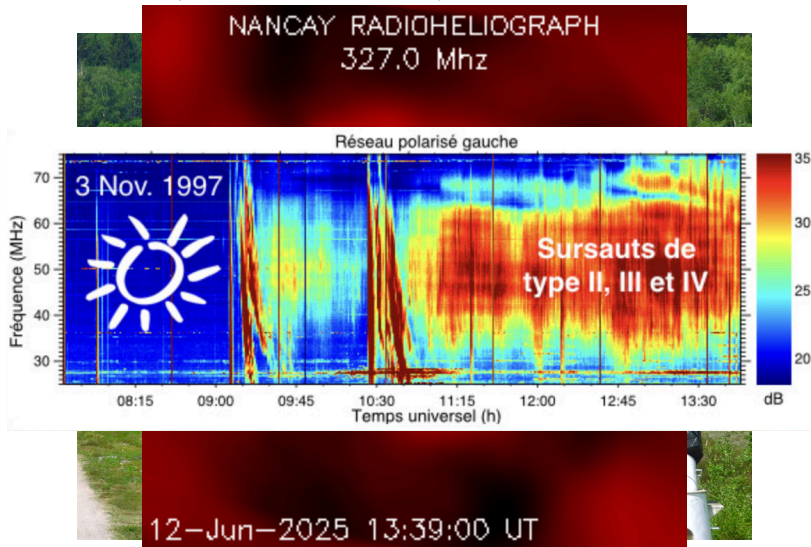


French databases

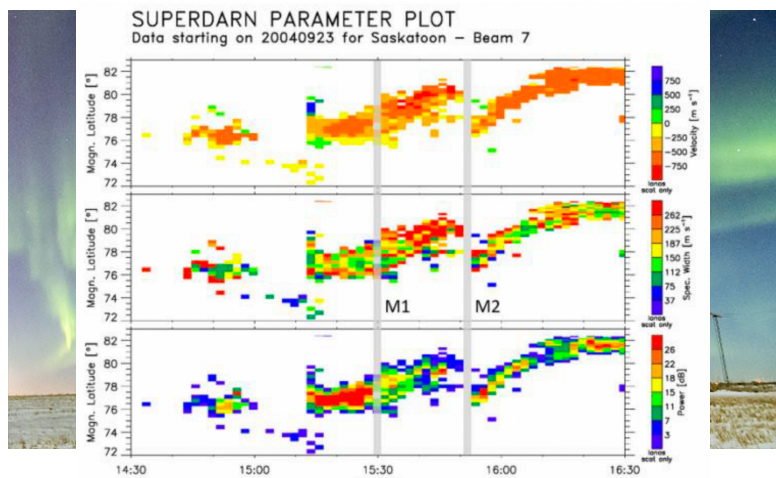


Ground observations

Nançay observatory (ORN) for radio



Ionosphere radars (SuperDARN)



[Pitout+2020]

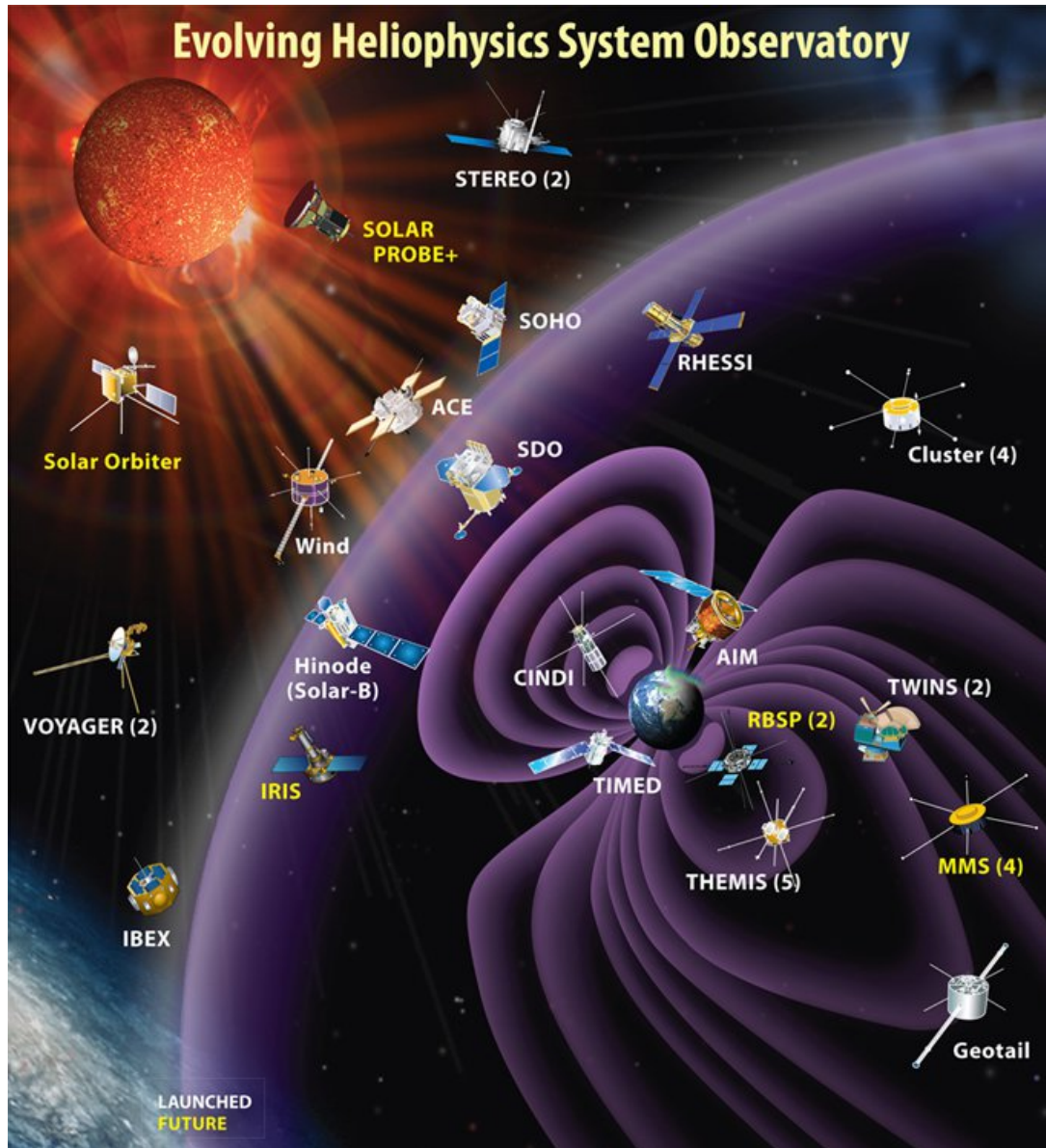
Halpa observatories
(Themis, CLIMSO, Meudon)



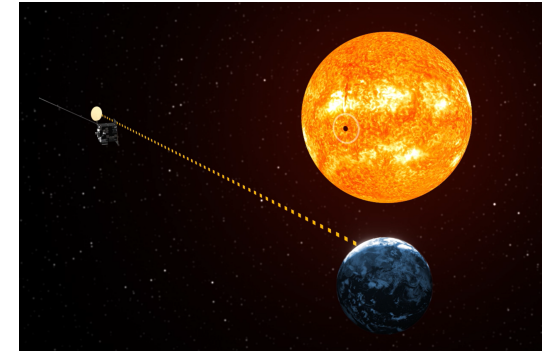
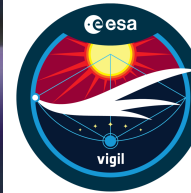
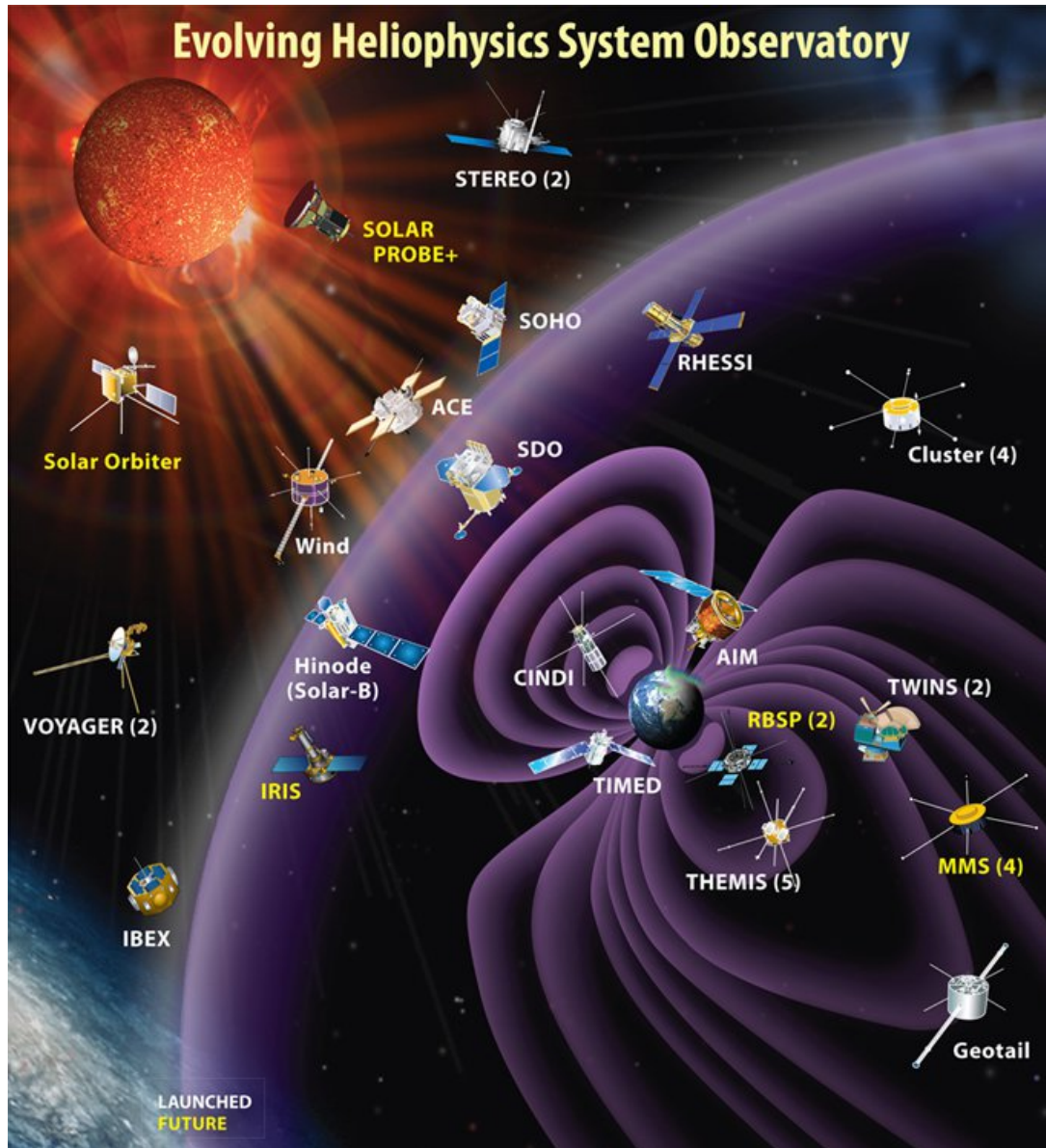
French databases



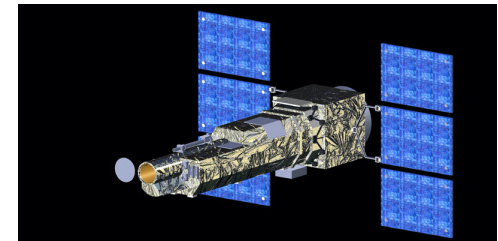
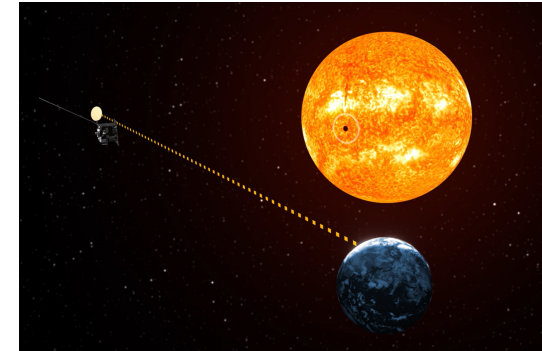
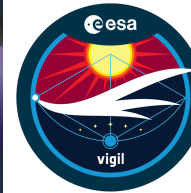
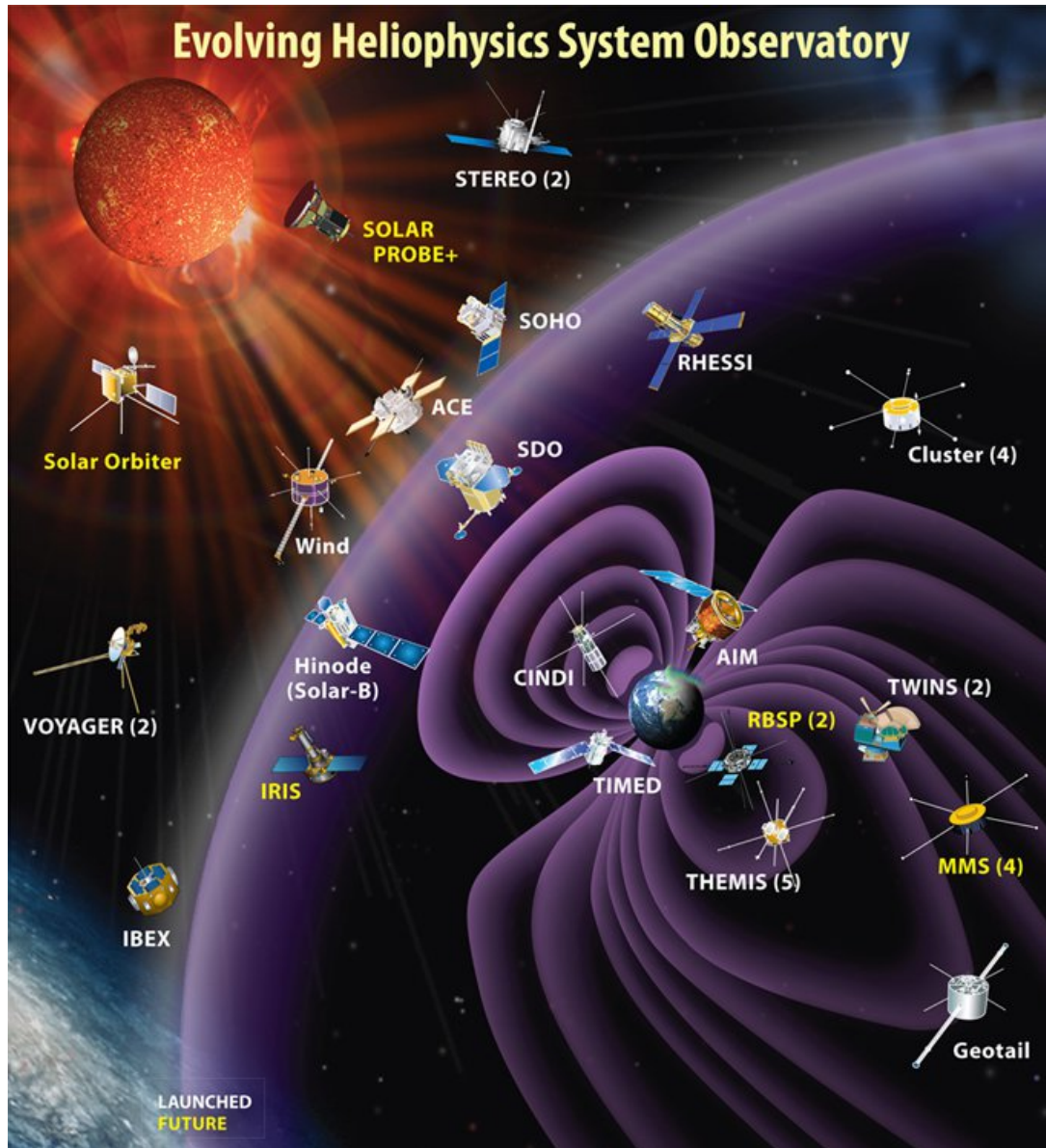
Space missions



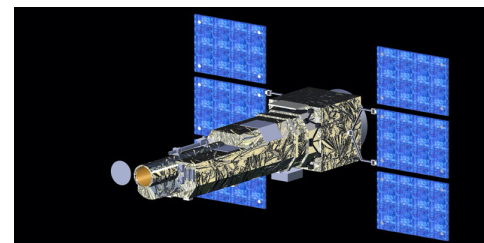
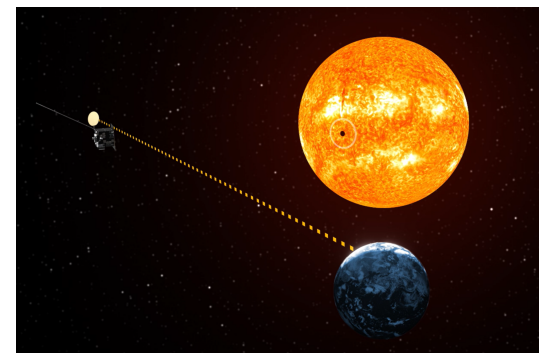
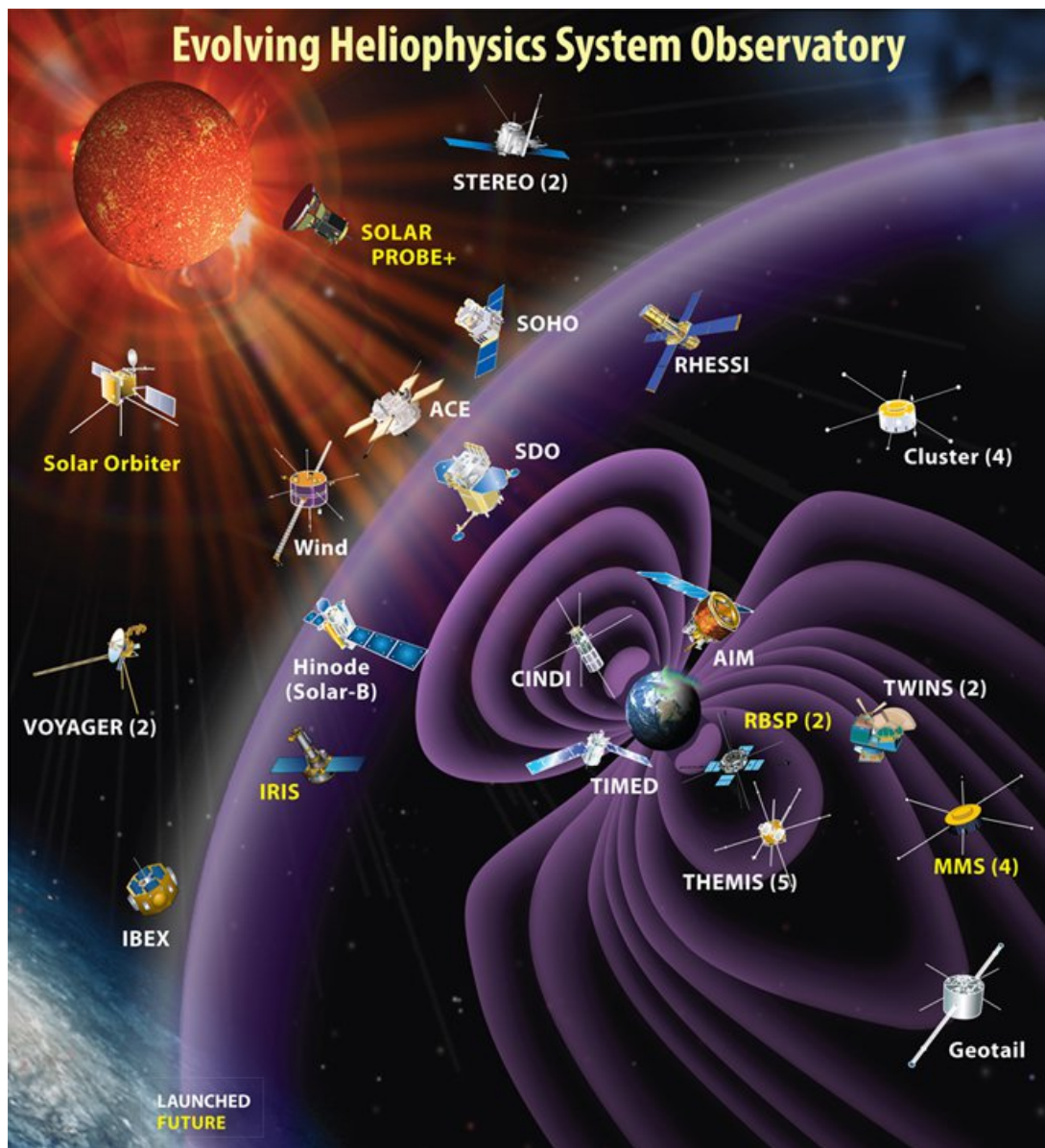
Space missions



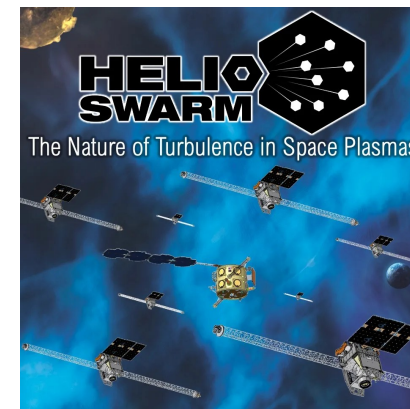
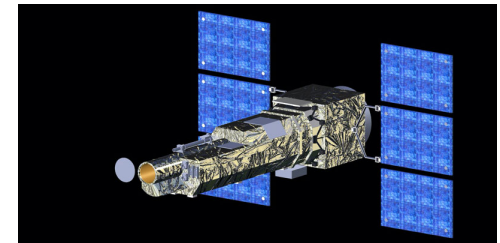
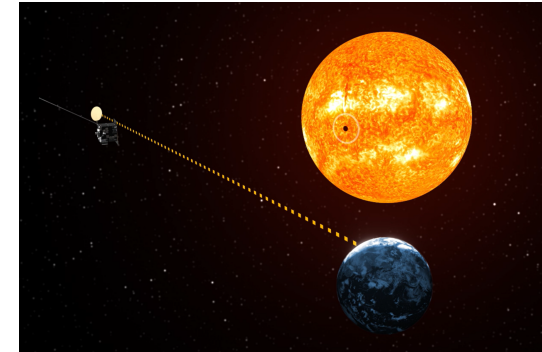
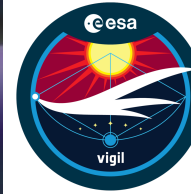
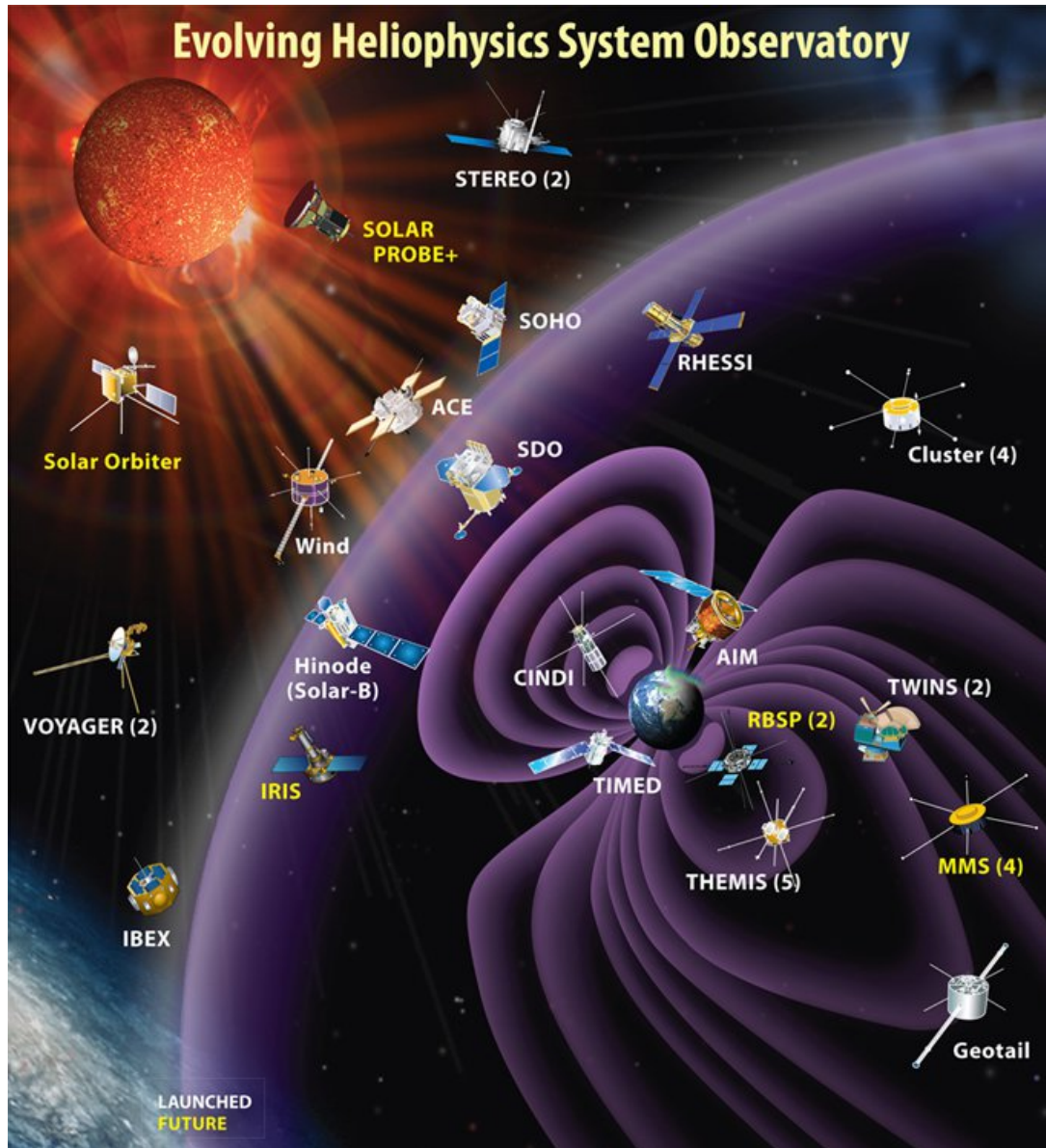
Space missions



Space missions



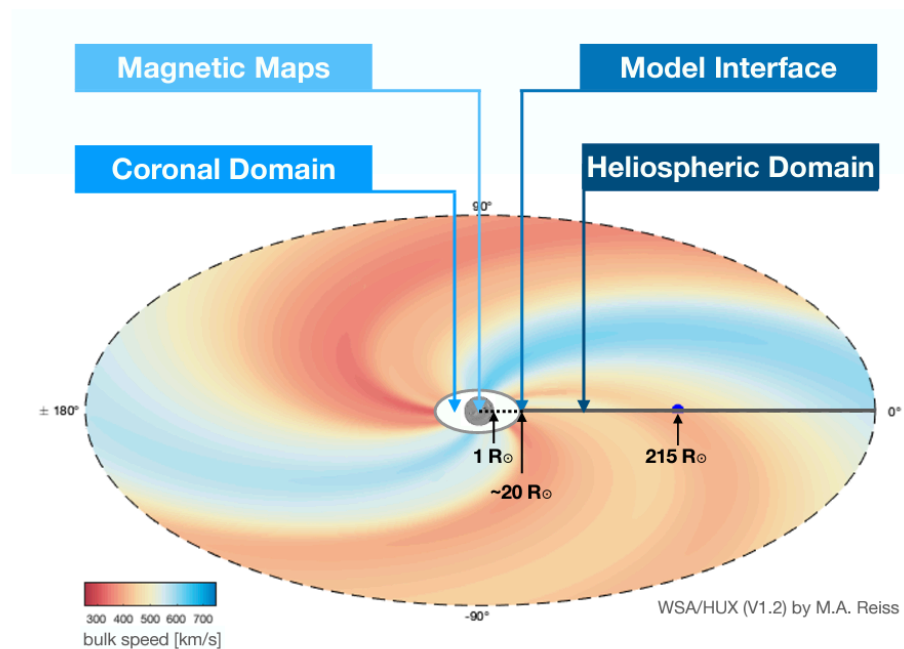
Space missions



Come at
session S08
(Thursday
afternoon)
to hear
more!

Forecasting centers

Virtual Space Weather Modelling Center (VSWMC): ESA forecasting center
(<https://swe.ssa.esa.int/kul-cmpa-federated>)



[Reiss+2023]

Coronal Domain:
MULTI-VP (IRAP)
Wind Predict (CEA)

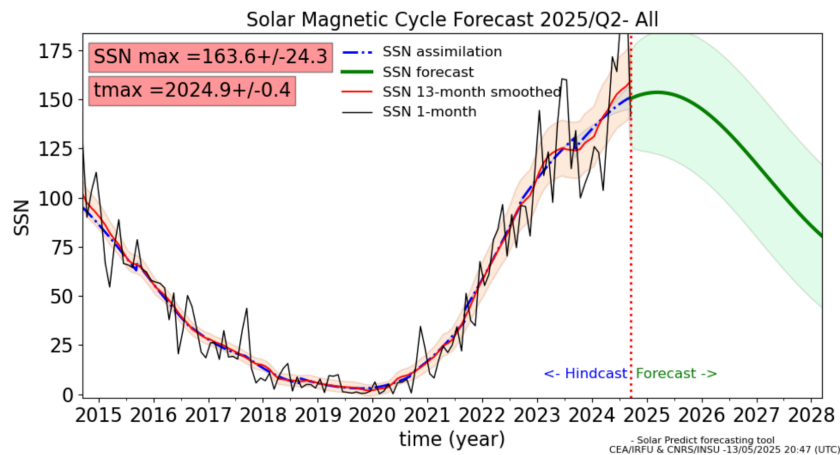
Model Interface:
Wind UV (CEA)

Heliospheric domain:
Heliocast (IRAP)

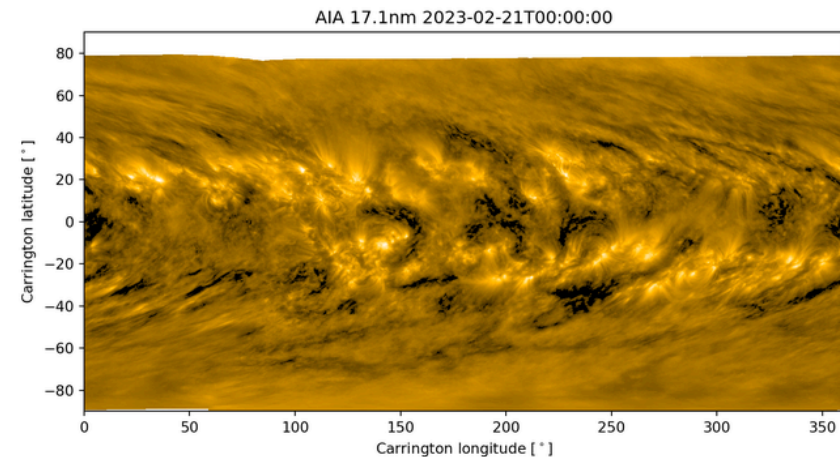
→ Example of forecasting chain: RB-FAN (ONERA) for radiation belts

Forecasting products

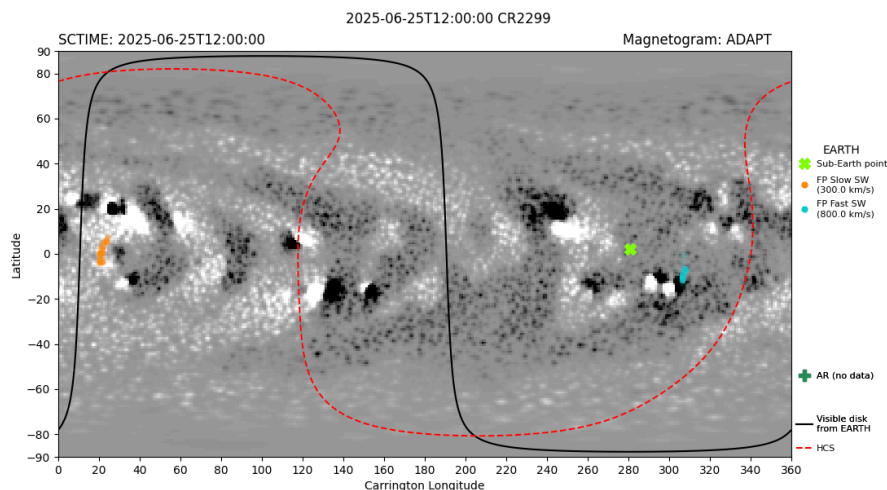
Visibility through ESA Space Safety Program (S2P) products (<https://swe.ssa.esa.int/>)



Solar Predict (CEA, Solar-ESC)

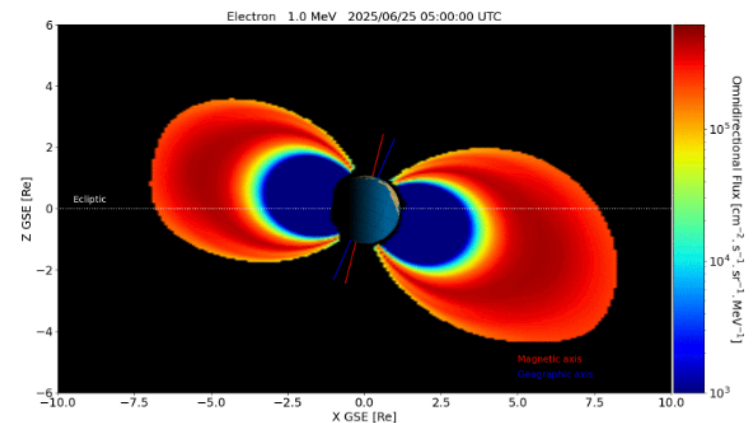


MEDOC products (IAS, Solar-ESC)



CDPP Tools (IRAP, Heliospheric-ESC)

Electron Radiation Belts animation from 2025/06/23 00:00:00 to 2025/06/28 23:00:00



RB-FAN (ONERA, Radiation-ESC)



Recap and useful links

Space weather in ATST in France



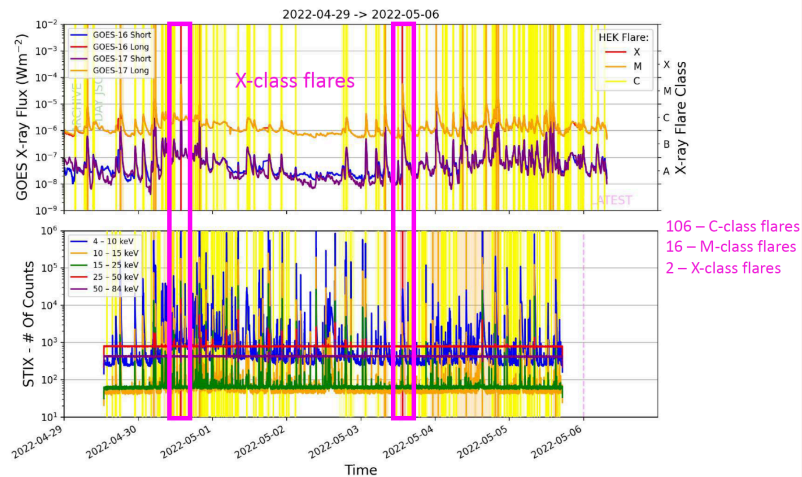
>16 ATST laboratories involved
in space weather projects

All methodologies: observations, data
analysis, modelling, theory, HPC, AI...

To go further

Perri, Finley

X-ray Data from GOES and STIX



Weekly bulletin produced by CEA to summarize solar activity

→ write an email to

barbara.perri@cea.fr to join the mailing list



Many ressources on the OFRAME website for public outreach (<http://www.meteo-espace.fr/oframe>)

Posters available at the following address:
<http://www.meteo-espace.fr/static/data/CEA-Posters-EN-RVB-A1-20231108.pdf>