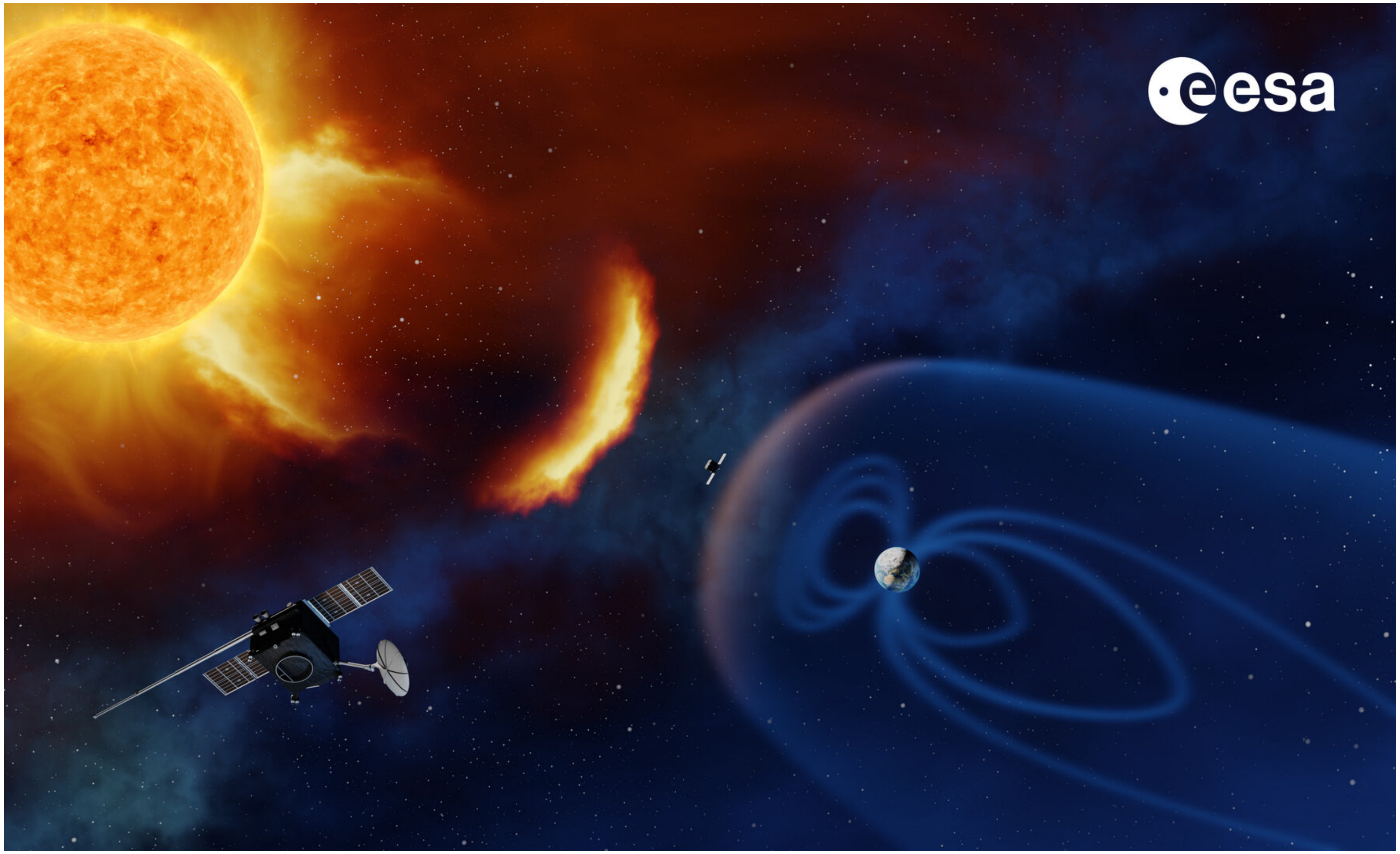
# Recent developments of the Wind-Predict model for space-weather applications

Barbara PERRI (AIM, France)

Collaborators:
Allan Sacha BRUN, Antoine STRUGAREK (AIM, France)
Victor RÉVILLE (IRAP, France)
Stefaan POEDTS, Evangelia SAMARA, Andrea LANI,
Andrey KOCHANOV (KU Leuven, Belgium)

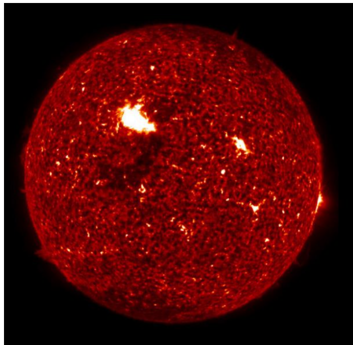
# Space weather



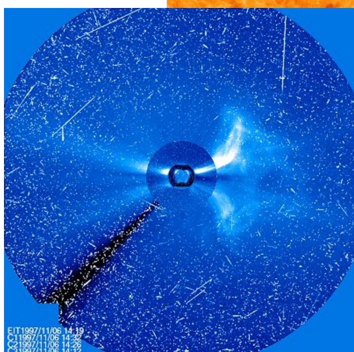
# Space weather

[GOES17]

flares

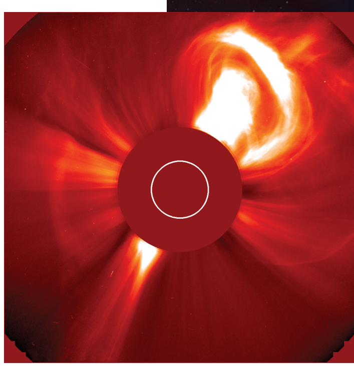


SEPs



[NASA]

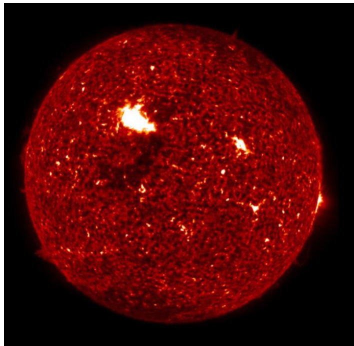
CMEs



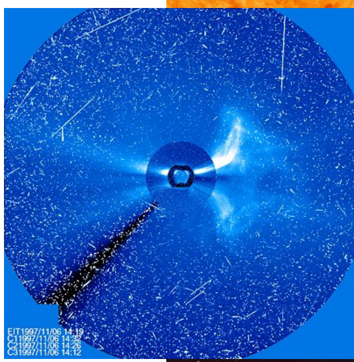
# Space weather

[GOES17]

flares

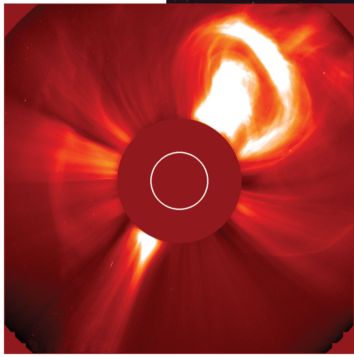


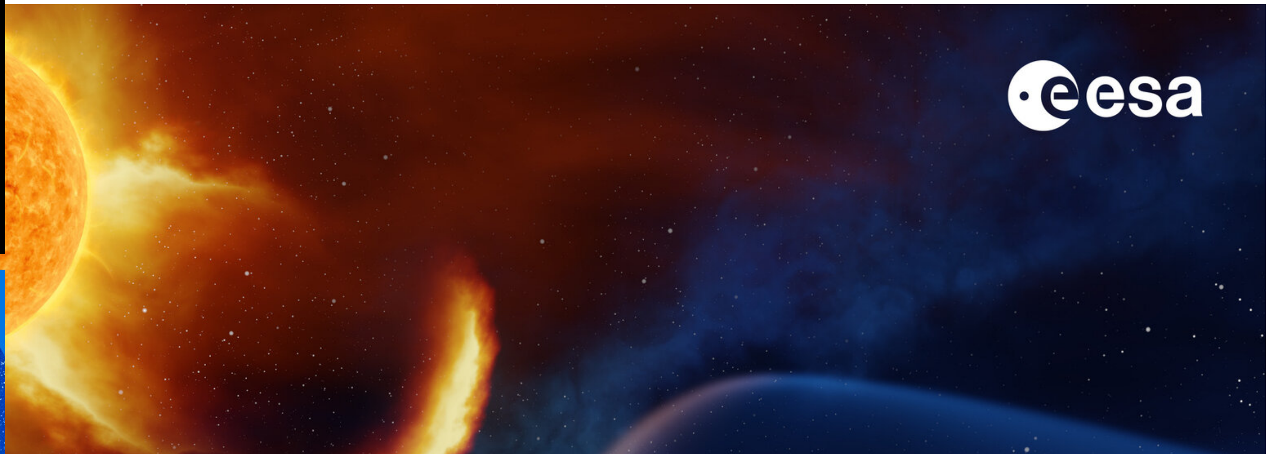
SEPs

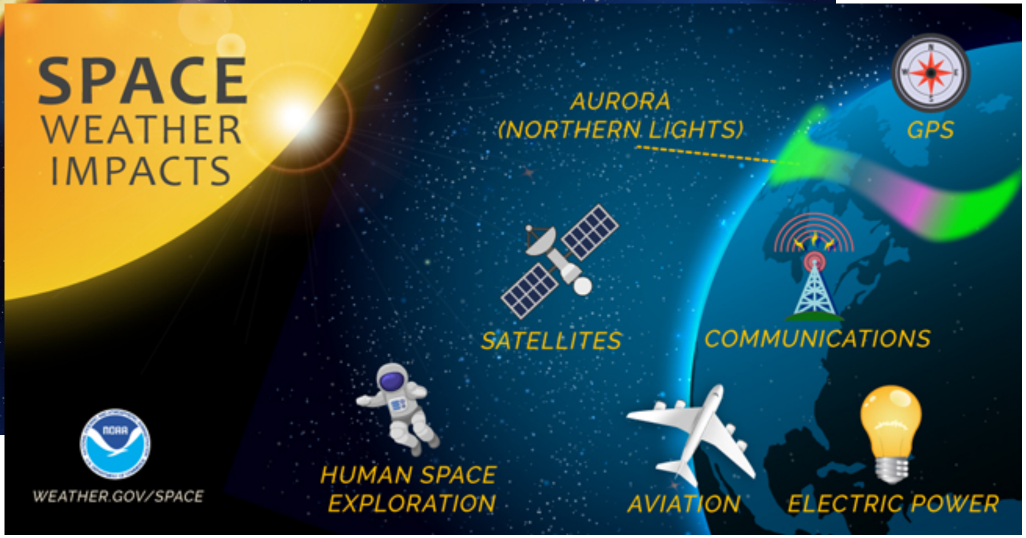


[NASA]

CMEs



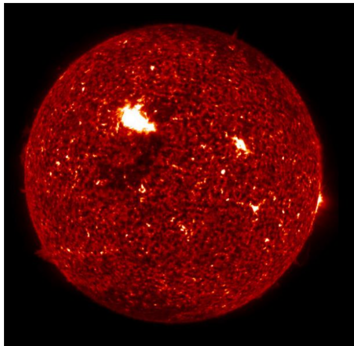


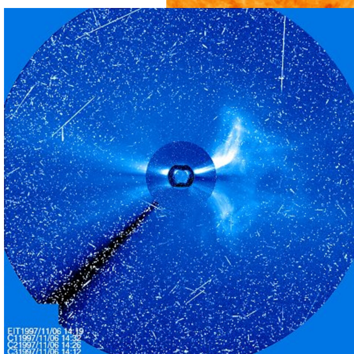
# Space weather

[GOES17]

flares

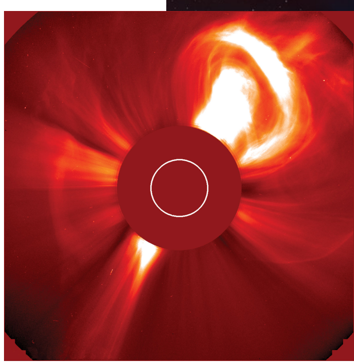


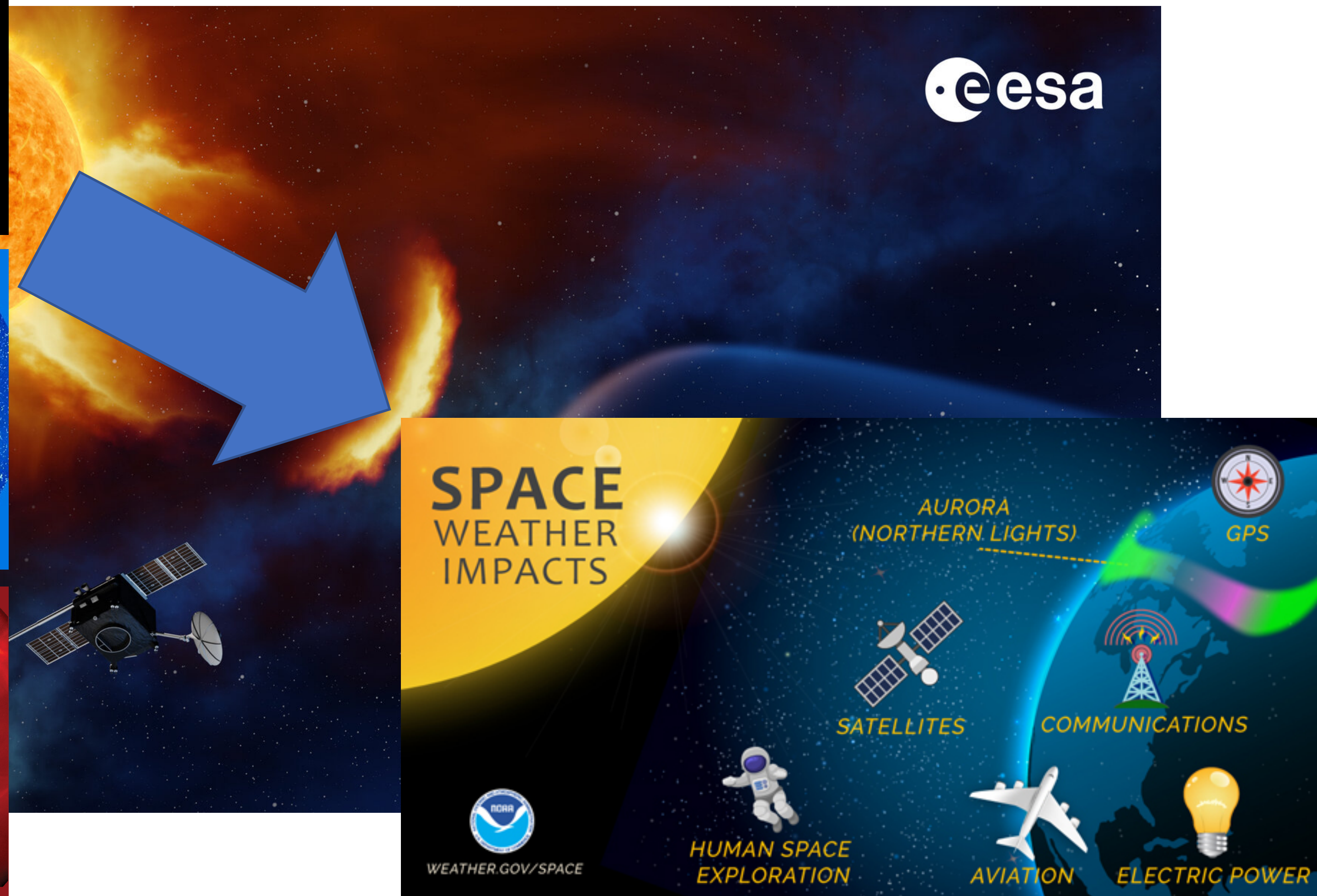
SEPs



[NASA]

CMEs



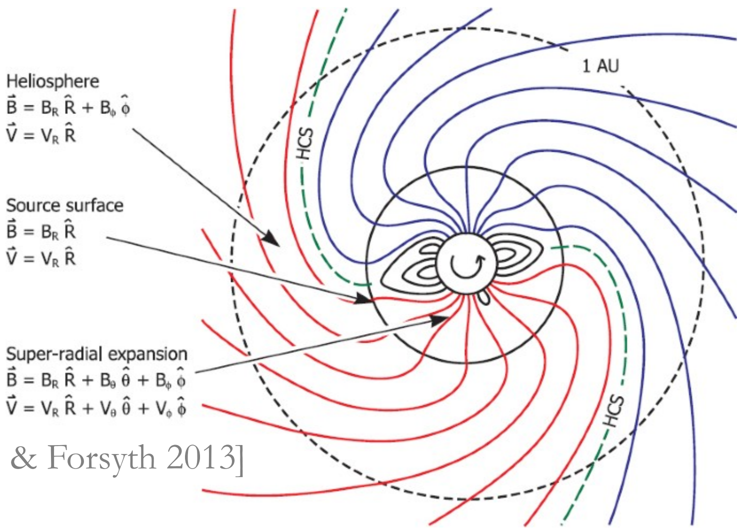



→ Space weather forecasting depends heavily on the modeling of the heliosphere

# Heliospheric structures

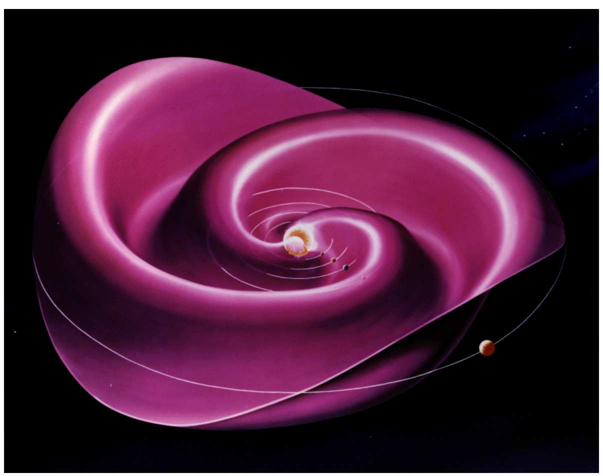
# Heliospheric structures

## Magnetic field




[Owens & Forsyth 2013]

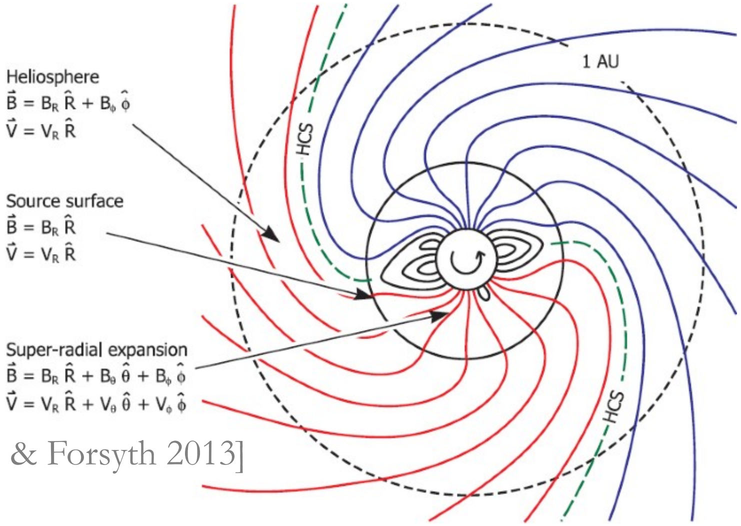
[NASA]



Large-scale structures:
Parker spiral + heliospheric current sheet (HCS)

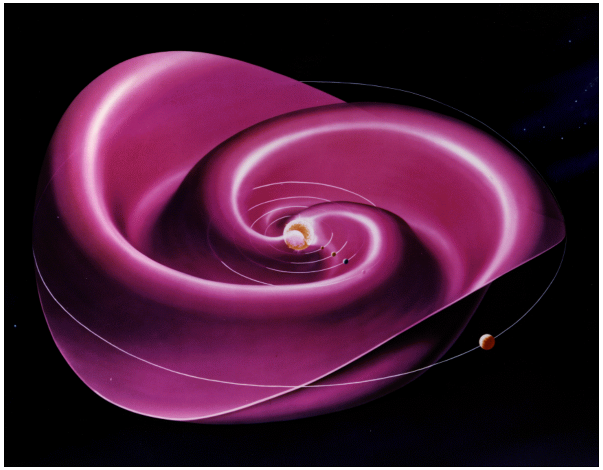
# Heliospheric structures

## Magnetic field




[Owens & Forsyth 2013]

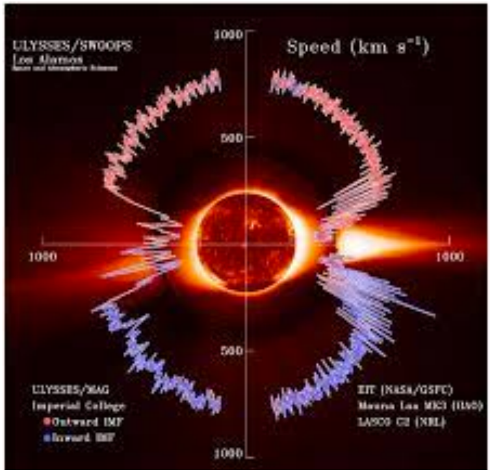
[NASA]



Large-scale structures:
Parker spiral + heliospheric current sheet (HCS)

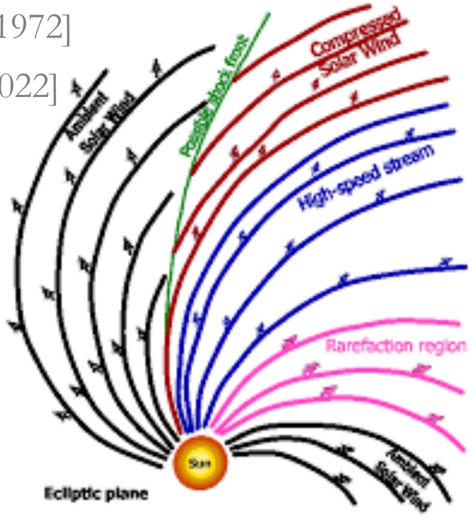
## Solar wind

[McComas+2003]




[Hundhausen 1972]

[Carnevale+2022]




High-Speed Streams (HSS) +
Co-rotating Interacting Regions (CIRs)

# VSWMC

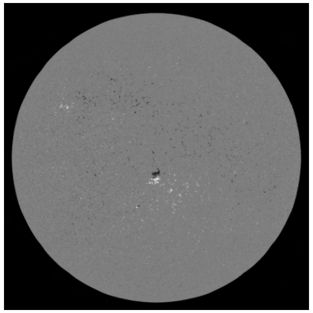
# VSWMC

Chain of data-driven heliospheric simulations from the solar surface to the Earth

# VSWMC

Chain of data-driven heliospheric simulations from the solar surface to the Earth

[SDO/HMI]

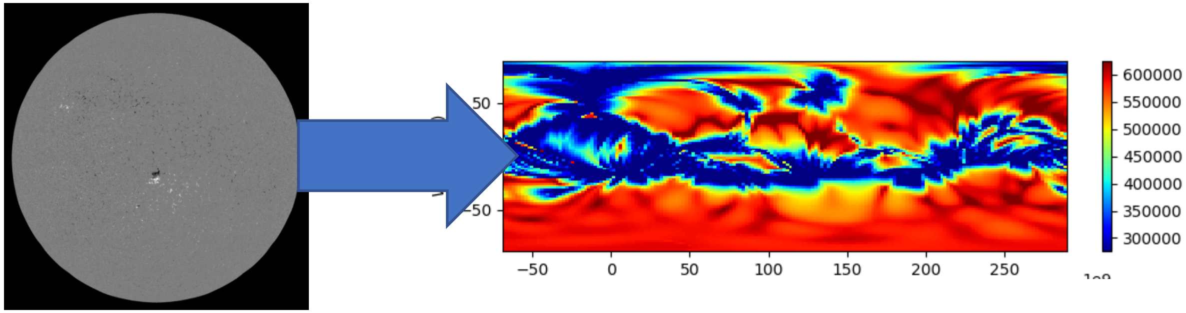


$1\ R_\odot$

# VSWMC

Chain of data-driven heliospheric simulations from the solar surface to the Earth

[SDO/HMI]



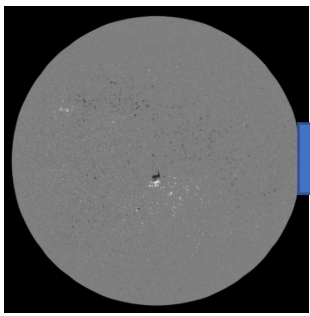

$1\ R_\odot$

$20\ R_\odot$

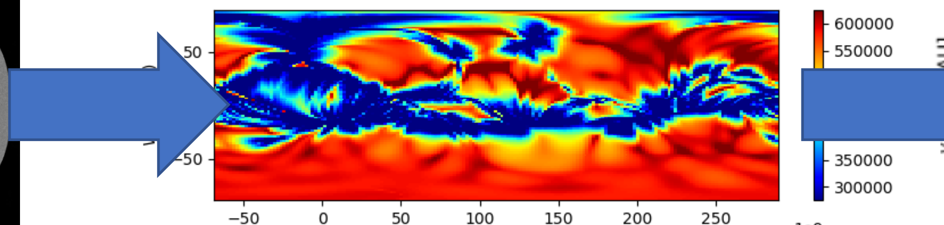
# VSWMC

Chain of data-driven heliospheric simulations from the solar surface to the Earth

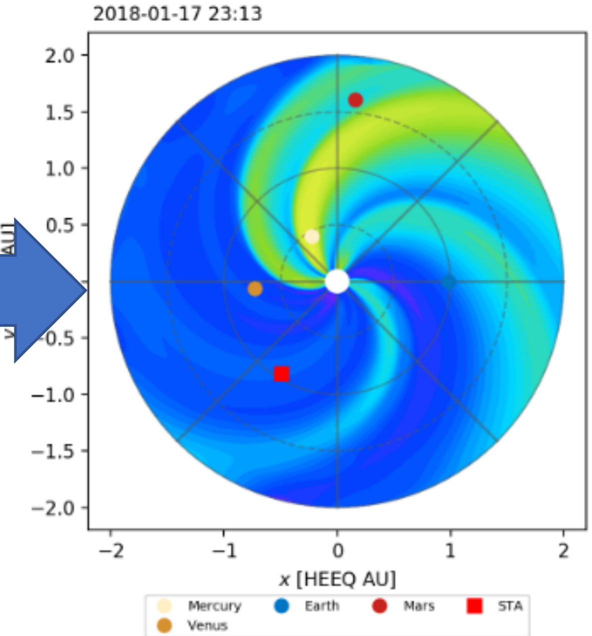
[SDO/HMI]



$1\ R_\odot$




$20\ R_\odot$

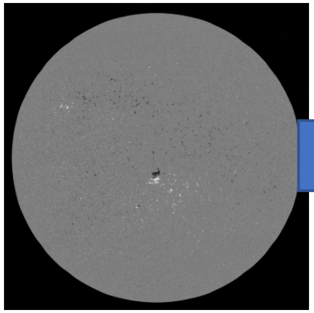



$20\ R_\odot - 2\ AU$

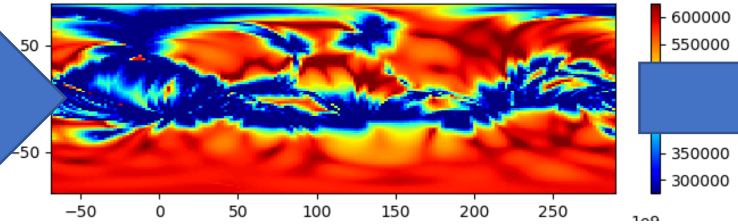
# VSWMC

Chain of data-driven heliospheric simulations from the solar surface to the Earth

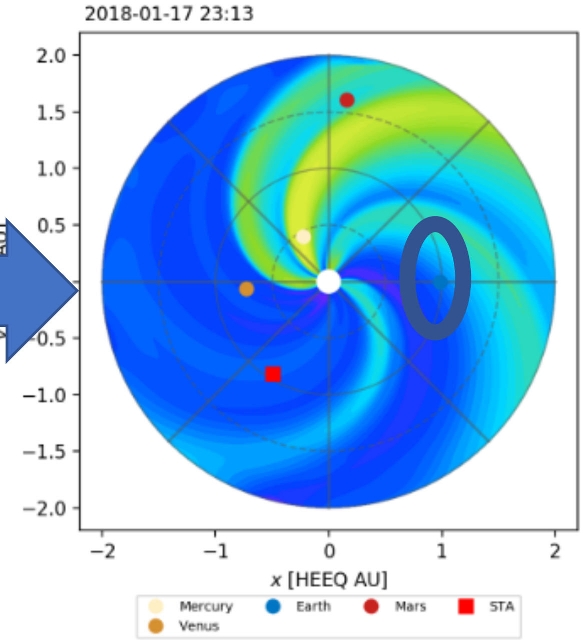
[SDO/HMI]



$1\ R_\odot$




$20\ R_\odot$

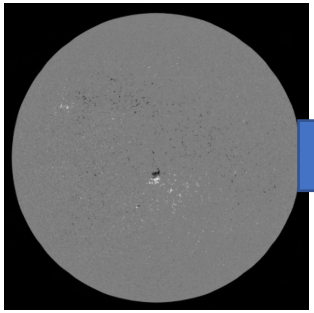



$20\ R_\odot - 2\ AU$

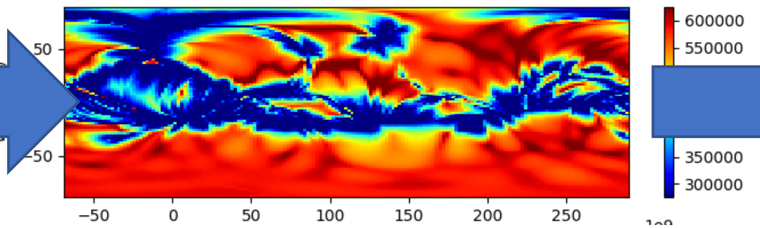
# VSWMC

Chain of data-driven heliospheric simulations from the solar surface to the Earth

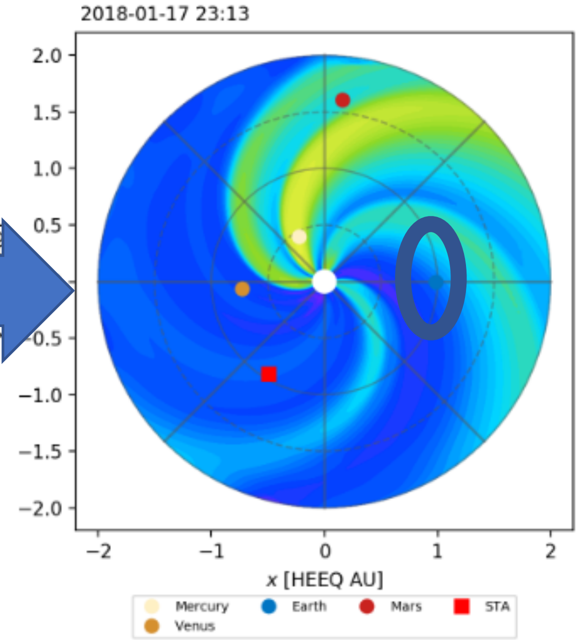
[SDO/HMI]



$1\ R_\odot$




$20\ R_\odot$




$20\ R_\odot - 2\ AU$

The extrapolations from 1 to 20 solar radii are semi-empirical
→ this is where most of the structures are created!
→ we want to replace it with a more physical code (MHD) BUT still fast!

# Wind-Predict model (I)

[Réville+2015a, Réville+2017, Perri+2018]

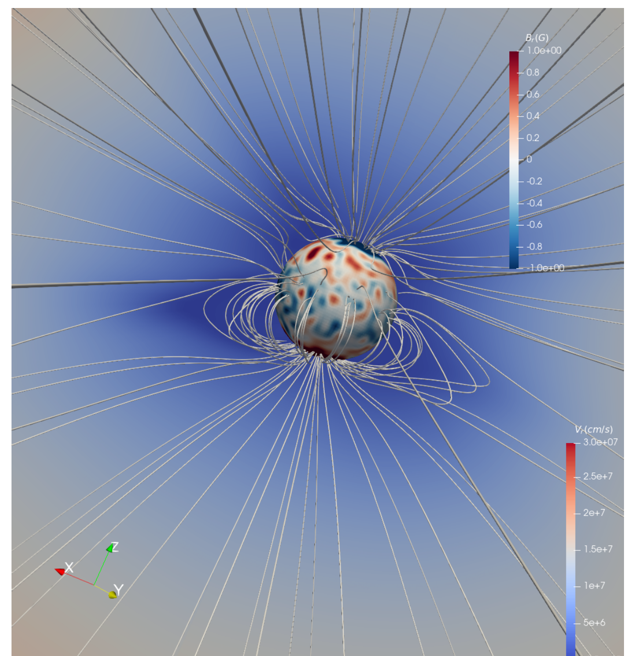
## Numerics :

- Based on the PLUTO code (Mignone+2007)
- Solves the set of ideal conservative MHD equations in spherical coordinates
- Finite-volume method with Riemann solver

## Physics :

- WP: Polytropic wind model with $\gamma = 1.05$
- Initialization with a Parker solution
- Relaxation to reach stationary state

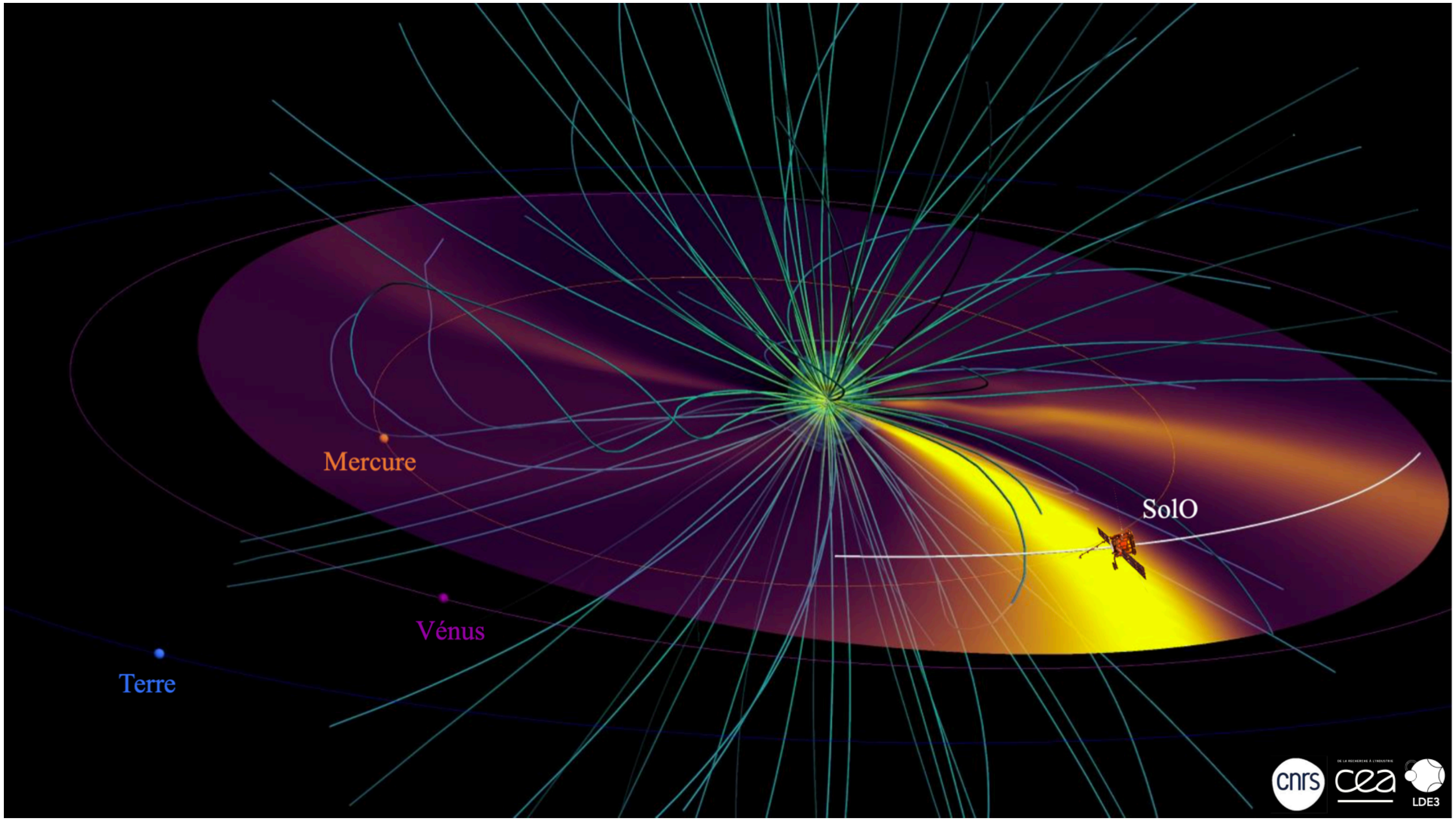
[Perri & Leitner+2022]



# Wind-Predict model (II)

Possibility to extend up to 1 AU to compute the state of the inner heliosphere for key dates

Example: first perihelion of Solar Orbiter (15/06/2020)




[https://tonione.github.io/windpredict.github.io/17062020.html]

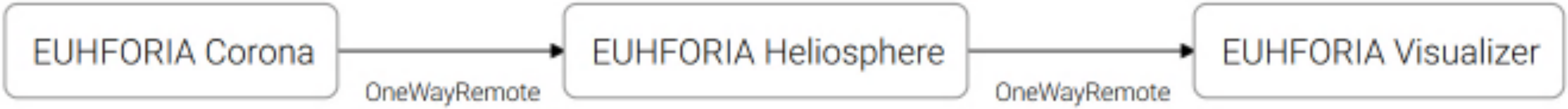
# Wind-Predict in the VSWMC

# Wind-Predict in the VSWMC

Coronal model successfully integrated in Phase 3

→ Provides magnetic field, wind speed, temperature and density at 21.5 Rs

→ Alternative to EUHFORIA corona (WSA empirical model) along with MULTI-VP



# Wind-Predict in the VSWMC

Coronal model successfully integrated in Phase 3

→ Provides magnetic field, wind speed, temperature and density at 21.5 Rs

→ Alternative to EUHFORIA corona (WSA empirical model) along with MULTI-VP

# Wind-Predict in the VSWMC

## Parametrize Wind-Predict

①–②

**Magnetogram Source**

Search Product Catalog

Upload Product

**Wind-Predict Computational Grid**

- ○ Low Resolution (64x32x64, RAM, very few time steps) - testing
- ○ Low Resolution (64x32x64, HPC, 1 node, few time steps) - testing
- ○ Low Resolution (64x32x64 - runs ~12 hours on 200 cores for quiet Sun)
- ◉ Medium Resolution (128x64x128 - runs ~25 hours on 400 cores for quiet Sun)
- ○ High Resolution (256x96x192 - runs ~50 hours on 900 cores for quiet Sun)

**Temperature (*10^6 K)**

1.5

Initial temperature of the corona at the bottom boundary condition. The wind speed increases with temperature: the hotter the corona, the faster the wind will be at 21.5 Rs.
Value range [1.0; 2.0]*10^6 K.

# Wind-Predict in the VSWMC

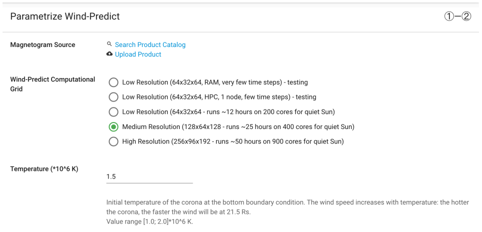
Coronal model successfully integrated in Phase 3

→ Provides magnetic field, wind speed, temperature and density at 21.5 Rs

→ Alternative to EUHFORIA corona (WSA empirical model) along with MULTI-VP


Typical inputs so far:

Types of outputs provided so far:


Parametrize Wind-Predict ①–②

Magnetogram Source
Search Product Catalog
Upload Product

Wind-Predict Computational Grid
- Low Resolution (64x32x64, RAM, very few time steps) - testing
- Low Resolution (64x32x64, HPC, 1 node, few time steps) - testing
- Low Resolution (64x32x64 - runs ~12 hours on 200 cores for quiet Sun)
- Medium Resolution (128x64x128 - runs ~25 hours on 400 cores for quiet Sun)
- High Resolution (256x96x192 - runs ~50 hours on 900 cores for quiet Sun)

Temperature (*10^6 K)
1.5

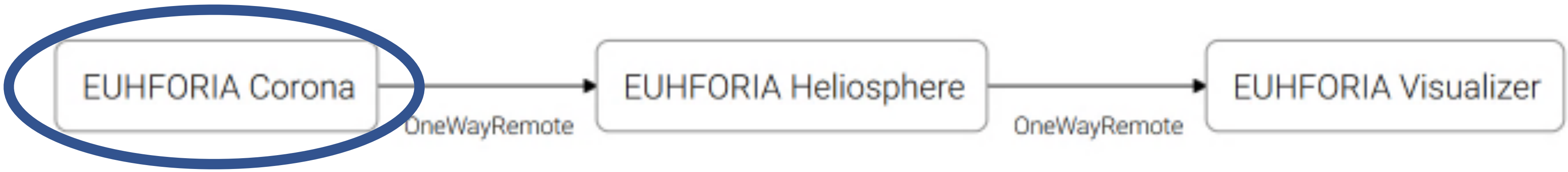
Initial temperature of the corona at the bottom boundary condition. The wind speed increases with temperature: the hotter the corona, the faster the wind will be at 21.5 Rs.
Value range [1.0; 2.0]*10^6 K.

# Wind-Predict in the VSWMC

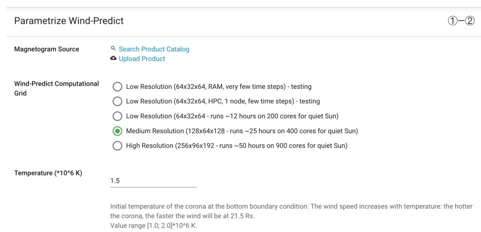
Coronal model successfully integrated in Phase 3

→ Provides magnetic field, wind speed, temperature and density at 21.5 Rs

→ Alternative to EUHFORIA corona (WSA empirical model) along with MULTI-VP




Typical inputs so far:


Parametrize Wind-Predict ①–②

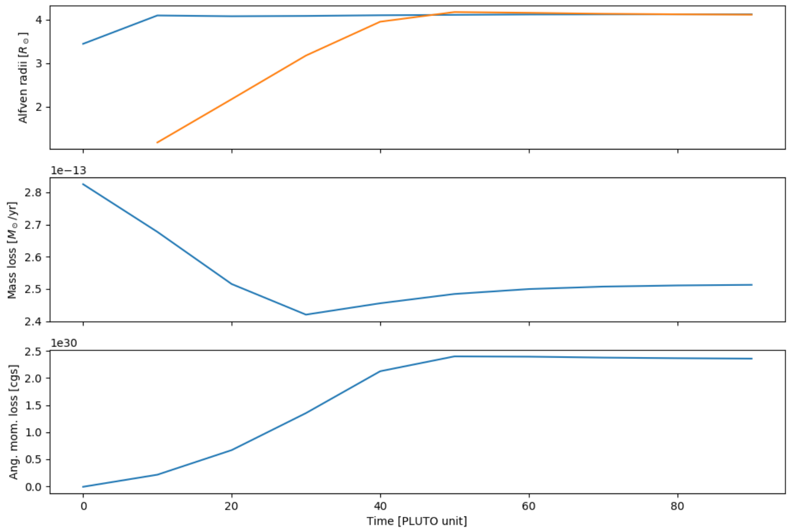
Magnetogram Source: Search Product Catalog / Upload Product

Wind-Predict Computational Grid:
- Low Resolution (64x32x64, RAM, very few time steps) - testing
- Low Resolution (64x32x64, HPC, 1 node, few time steps) - testing
- Low Resolution (64x32x64 - runs ~12 hours on 200 cores for quiet Sun)
- Medium Resolution (128x64x128 - runs ~25 hours on 400 cores for quiet Sun)
- High Resolution (256x96x192 - runs ~50 hours on 900 cores for quiet Sun)

Temperature (*10^6 K): 1.5

Initial temperature of the corona at the bottom boundary condition. The wind speed increases with temperature: the hotter the corona, the faster the wind will be at 21.5 Rs.
Value range [1.0; 2.0]*10^6 K.

Types of outputs provided so far:



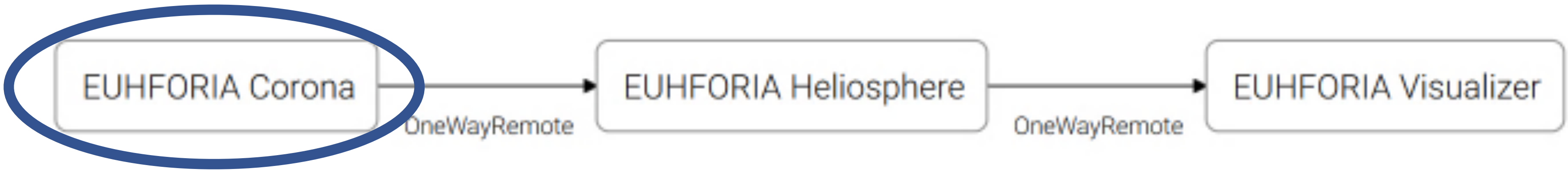

- 1D: to check quality of convergence

# Wind-Predict in the VSWMC

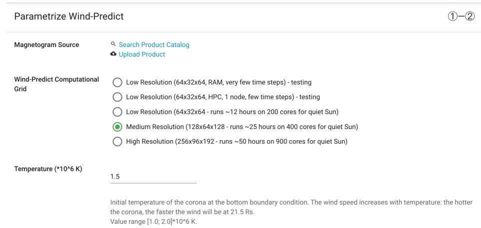
Coronal model successfully integrated in Phase 3

→ Provides magnetic field, wind speed, temperature and density at 21.5 Rs

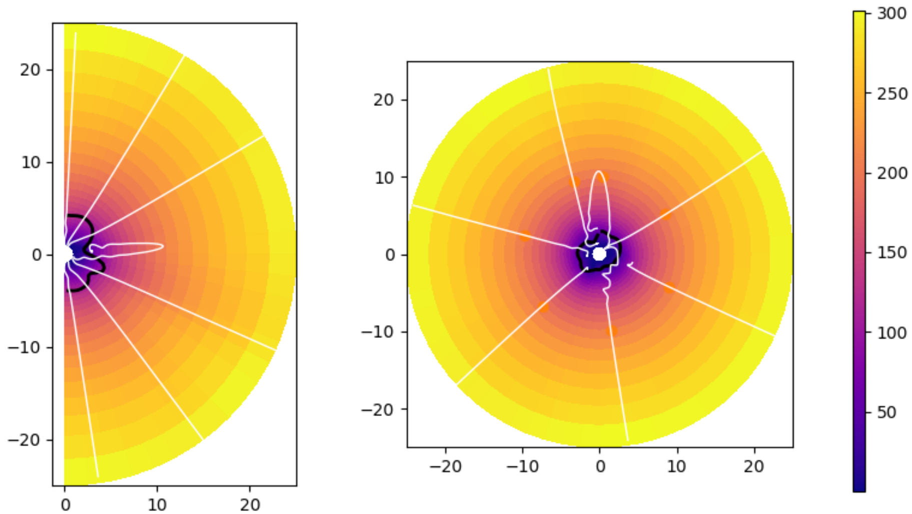
→ Alternative to EUHFORIA corona (WSA empirical model) along with MULTI-VP




Typical inputs so far:




Types of outputs provided so far:



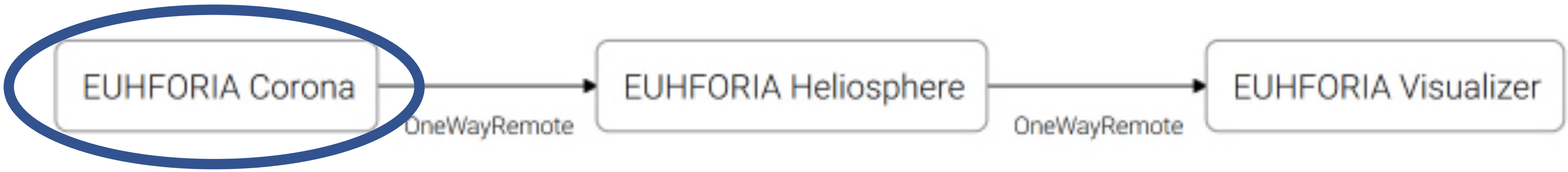

- 2D: to check the wind configuration

# Wind-Predict in the VSWMC

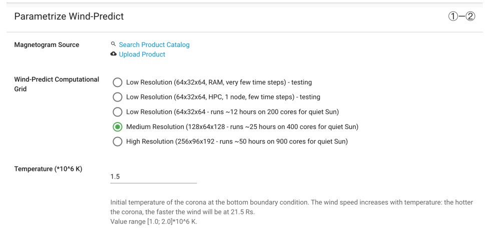
Coronal model successfully integrated in Phase 3

→ Provides magnetic field, wind speed, temperature and density at 21.5 Rs

→ Alternative to EUHFORIA corona (WSA empirical model) along with MULTI-VP




Typical inputs so far:



Parametrize Wind-Predict ①–②

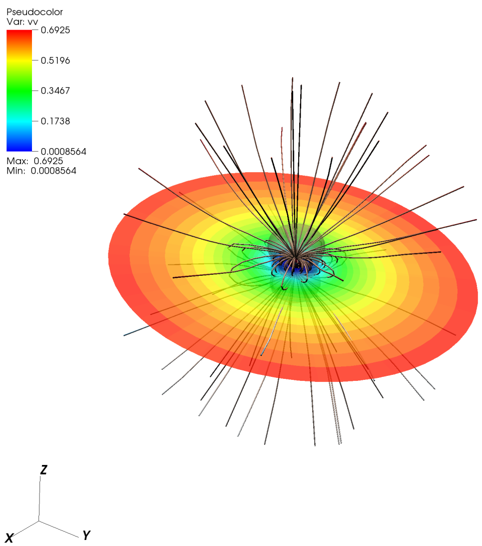
Magnetogram Source
Search Product Catalog
Upload Product

Wind-Predict Computational Grid
- Low Resolution (64x32x64, RAM, very few time steps) - testing
- Low Resolution (64x32x64, HPC, 1 node, few time steps) - testing
- Low Resolution (64x32x64 - runs ~12 hours on 200 cores for quiet Sun)
- Medium Resolution (128x64x128 - runs ~25 hours on 400 cores for quiet Sun)
- High Resolution (256x96x192 - runs ~50 hours on 900 cores for quiet Sun)

Temperature (*10^6 K)
1.5

Initial temperature of the corona at the bottom boundary condition. The wind speed increases with temperature: the hotter the corona, the faster the wind will be at 21.5 Rs.
Value range [1.0; 2.0]*10^6 K.

Types of outputs provided so far:



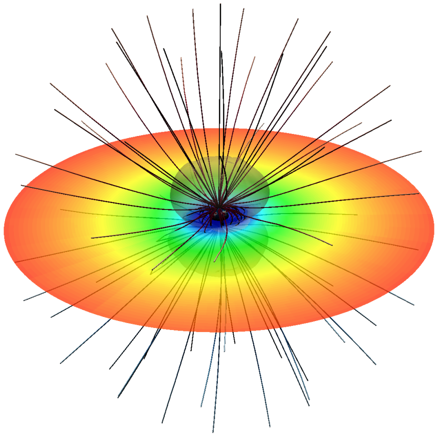

- 3D: to check the magnetic configuration

# Coupling with EUHFORIA

Successful integration of Wind-Predict into the VSWMC
as replacement of EUHFORIA corona

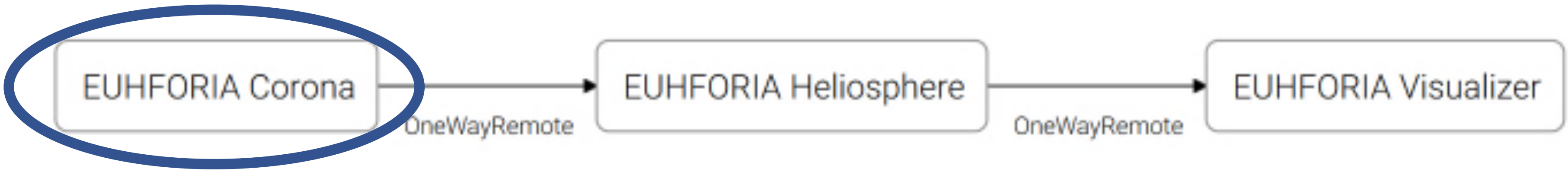
# Coupling with EUHFORIA

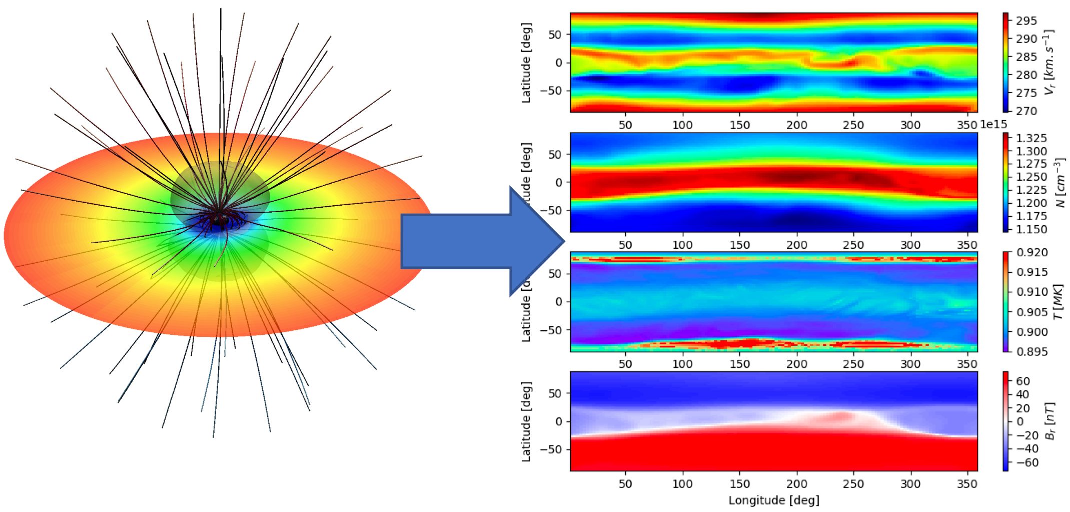
Successful integration of Wind-Predict into the VSWMC
as replacement of EUHFORIA corona

# Coupling with EUHFORIA

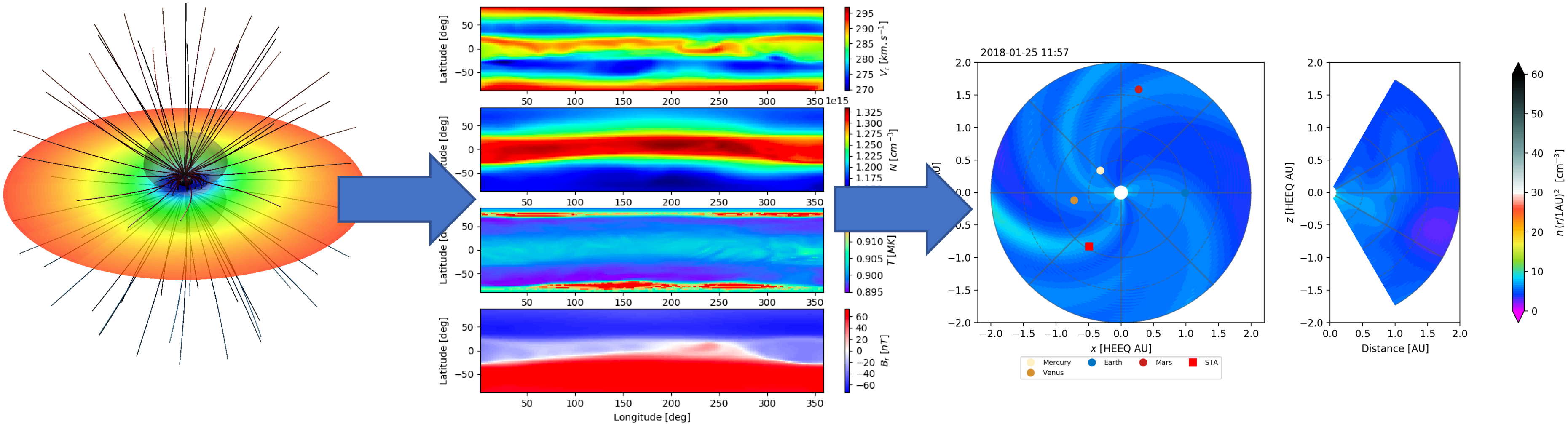
Successful integration of Wind-Predict into the VSWMC
as replacement of EUHFORIA corona



# Coupling with EUHFORIA

Successful integration of Wind-Predict into the VSWMC
as replacement of EUHFORIA corona

# Numerical scaling

# Numerical scaling

To be operational, tests of resolution:

[Perri 2019]

| Resolution | Minimum | Maximum |
|---|---|---|
| HighRes | 9.2 days | 23 days |
| NormalRes | 21 hours | 3 days |
| LowRes | 6 hours | 24 hours |
| CoarseRes | 1.4 hours | 3.5 hours |

→ Then interpolator to match the desired resolution

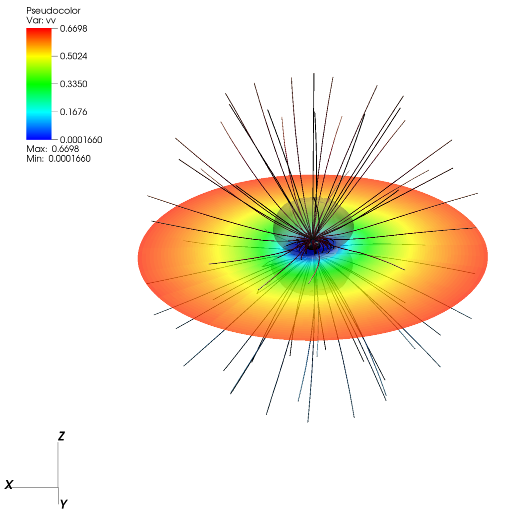
# Numerical scaling

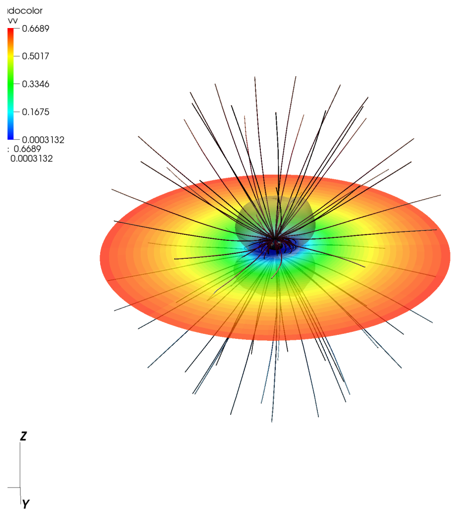
To be operational, tests of resolution:

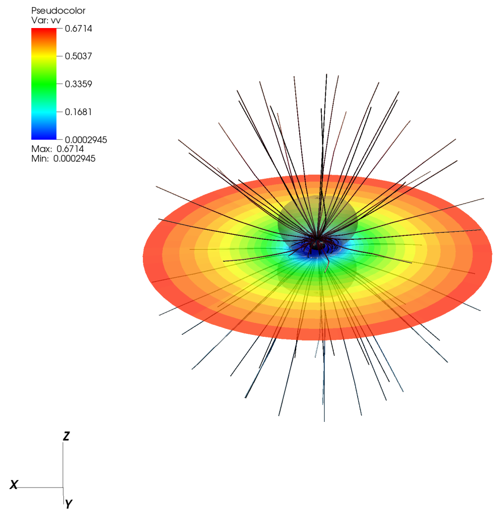
[Perri 2019]

| Resolution | Minimum | Maximum |
|---|---|---|
| HighRes | 9.2 days | 23 days |
| NormalRes | 21 hours | 3 days |
| LowRes | 6 hours | 24 hours |
| CoarseRes | 1.4 hours | 3.5 hours |

→ Then interpolator to match the desired resolution



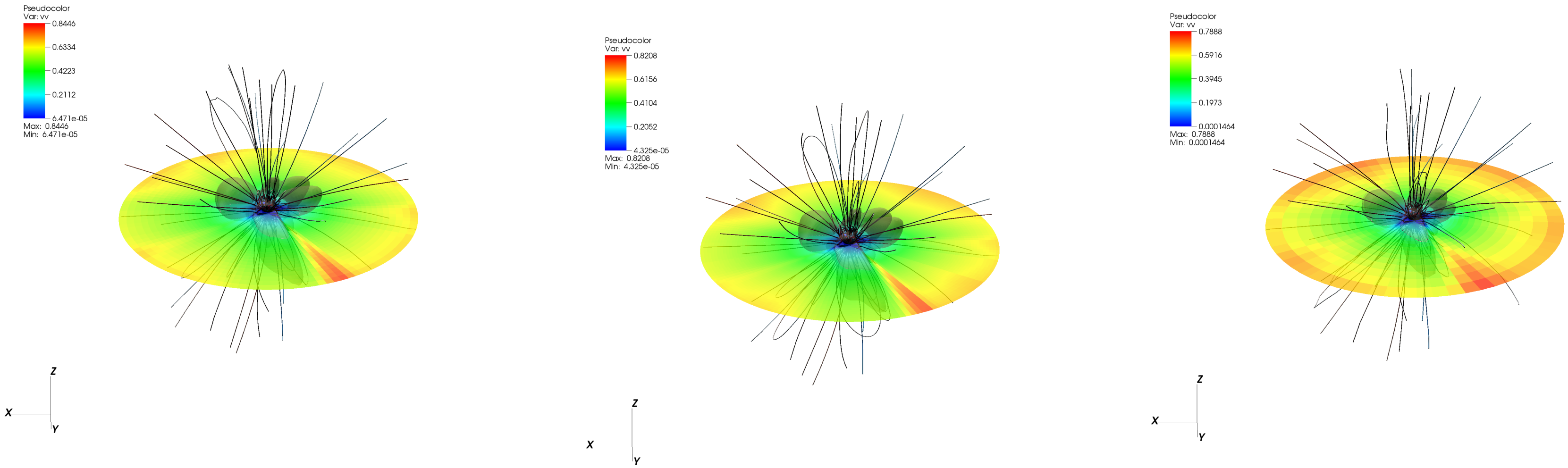
# Numerical scaling

To be operational, tests of resolution:

[Perri 2019]

| Resolution | Minimum | Maximum |
|---|---|---|
| HighRes | 9.2 days | 23 days |
| NormalRes | 21 hours | 3 days |
| LowRes | 6 hours | 24 hours |
| CoarseRes | 1.4 hours | 3.5 hours |

→ Then interpolator to match the desired resolution



# Robustness of the code

# Robustness of the code

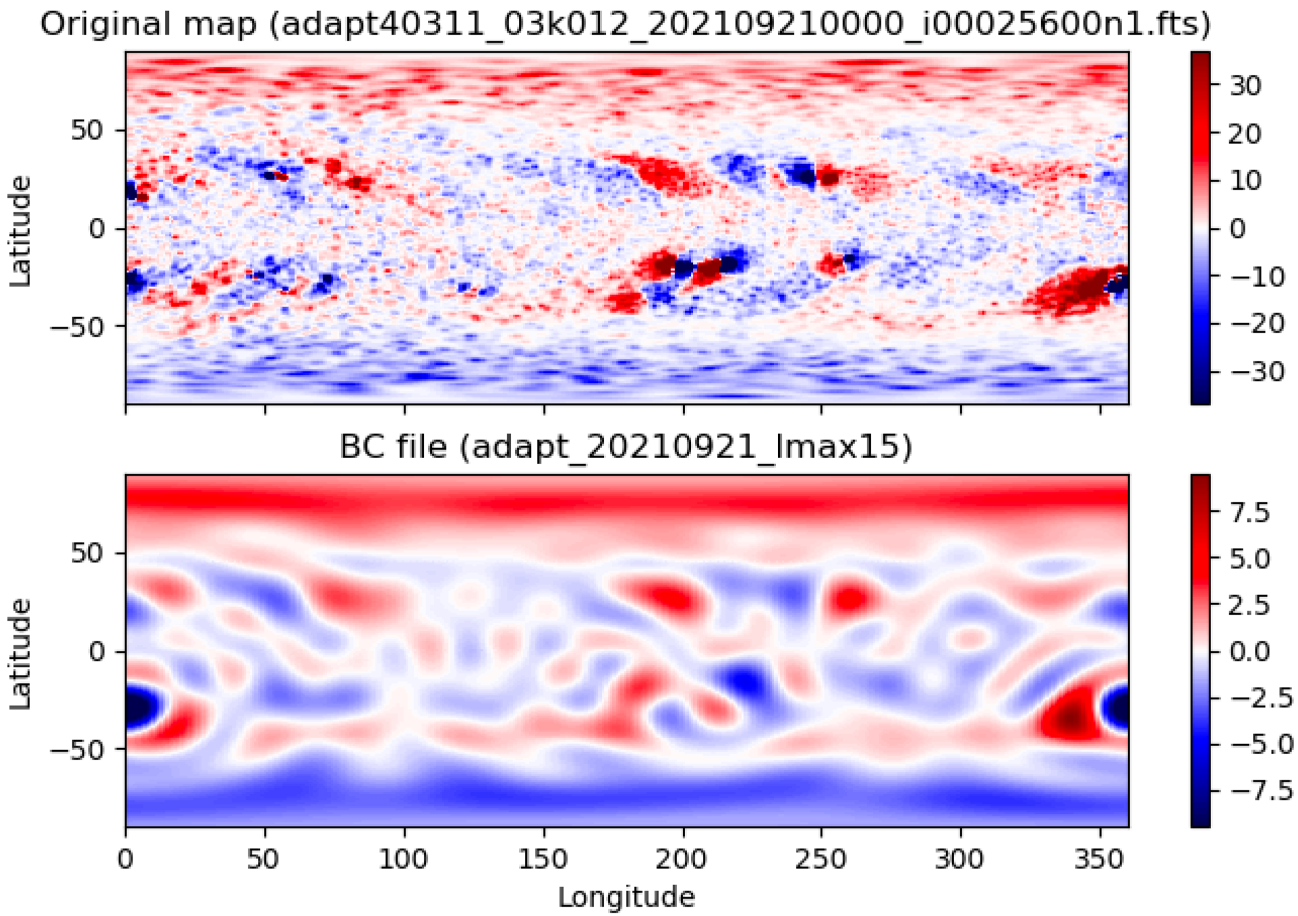
To be operational, need to make the code robust for all synoptic maps

→ Empirical criterion of $\frac{v_A}{v_{esc}} < 3$

# Robustness of the code

To be operational, need to make the code robust for all synoptic maps

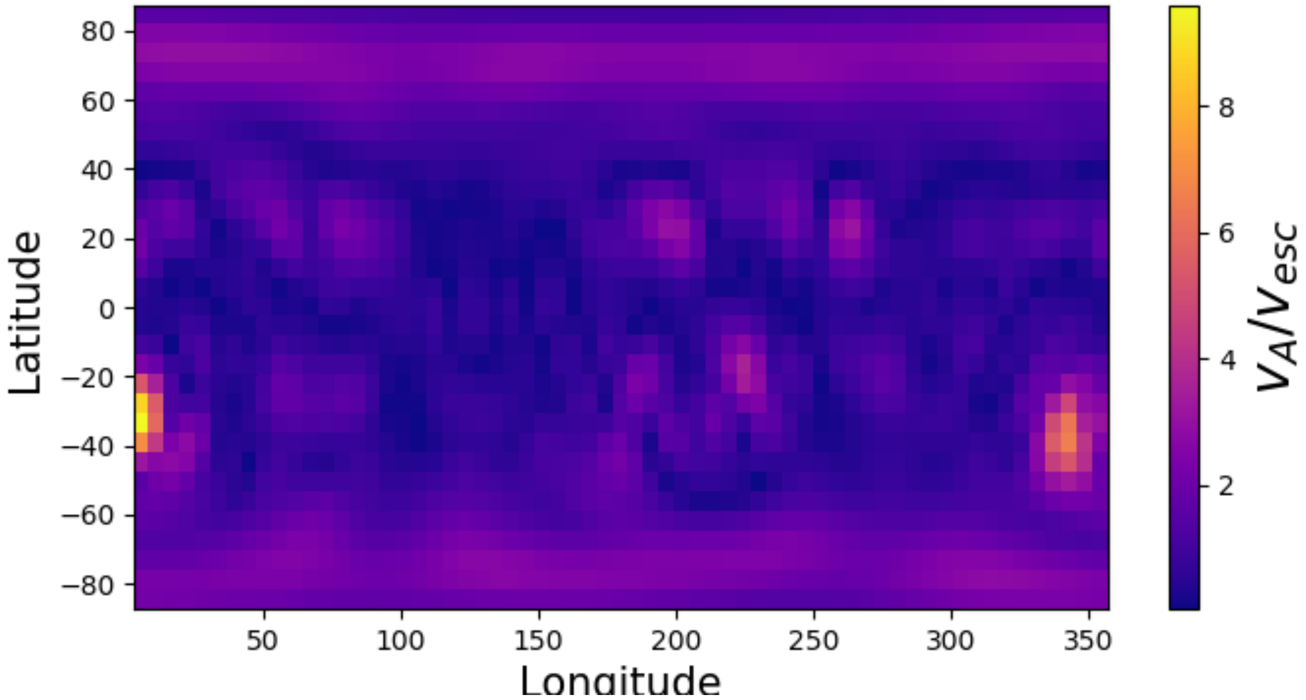
→ Empirical criterion of $\frac{v_A}{v_{esc}} < 3$



# Robustness of the code

To be operational, need to make the code robust for all synoptic maps

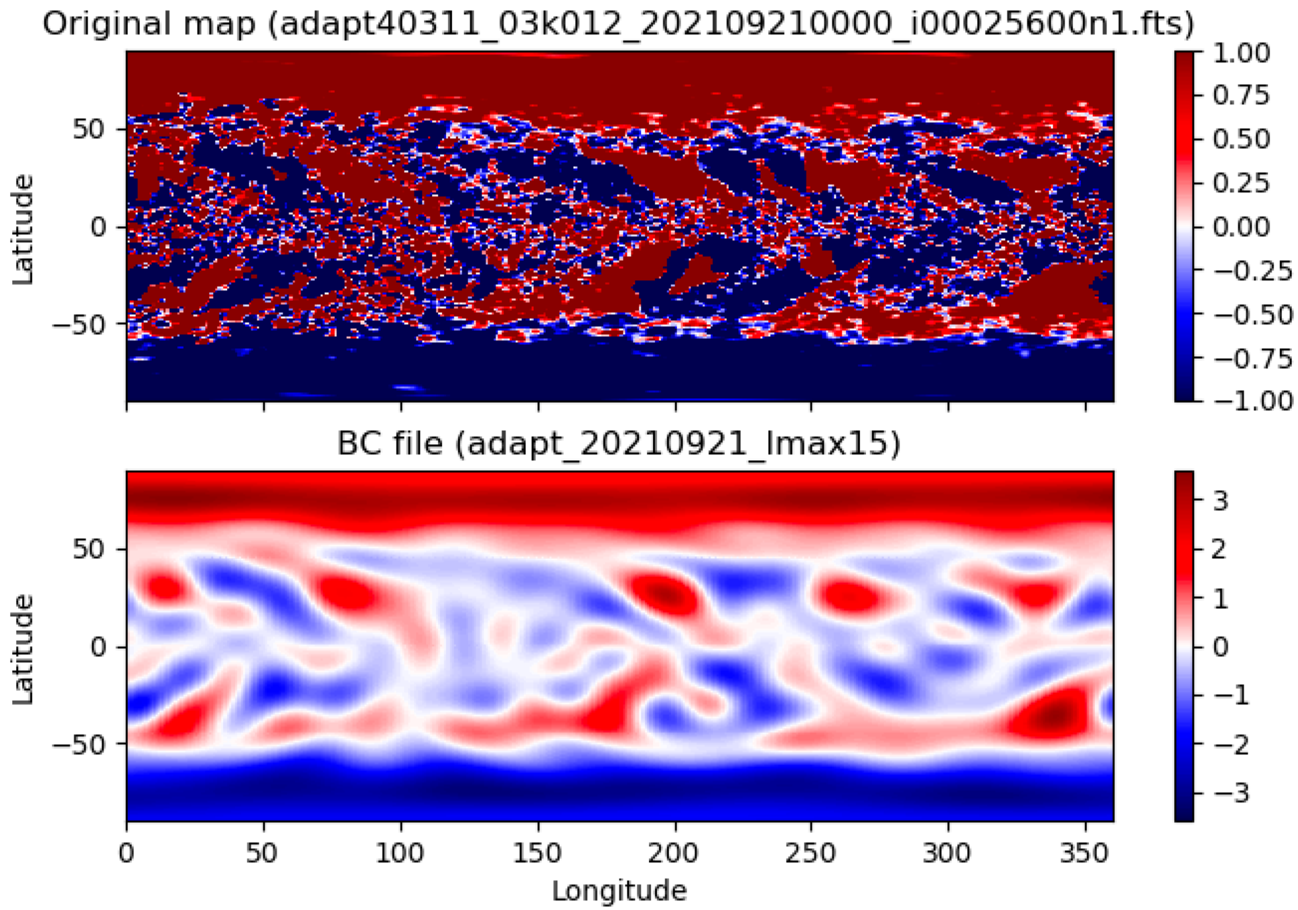
→ Empirical criterion of $\frac{v_A}{v_{esc}} < 3$



# Robustness of the code

To be operational, need to make the code robust for all synoptic maps

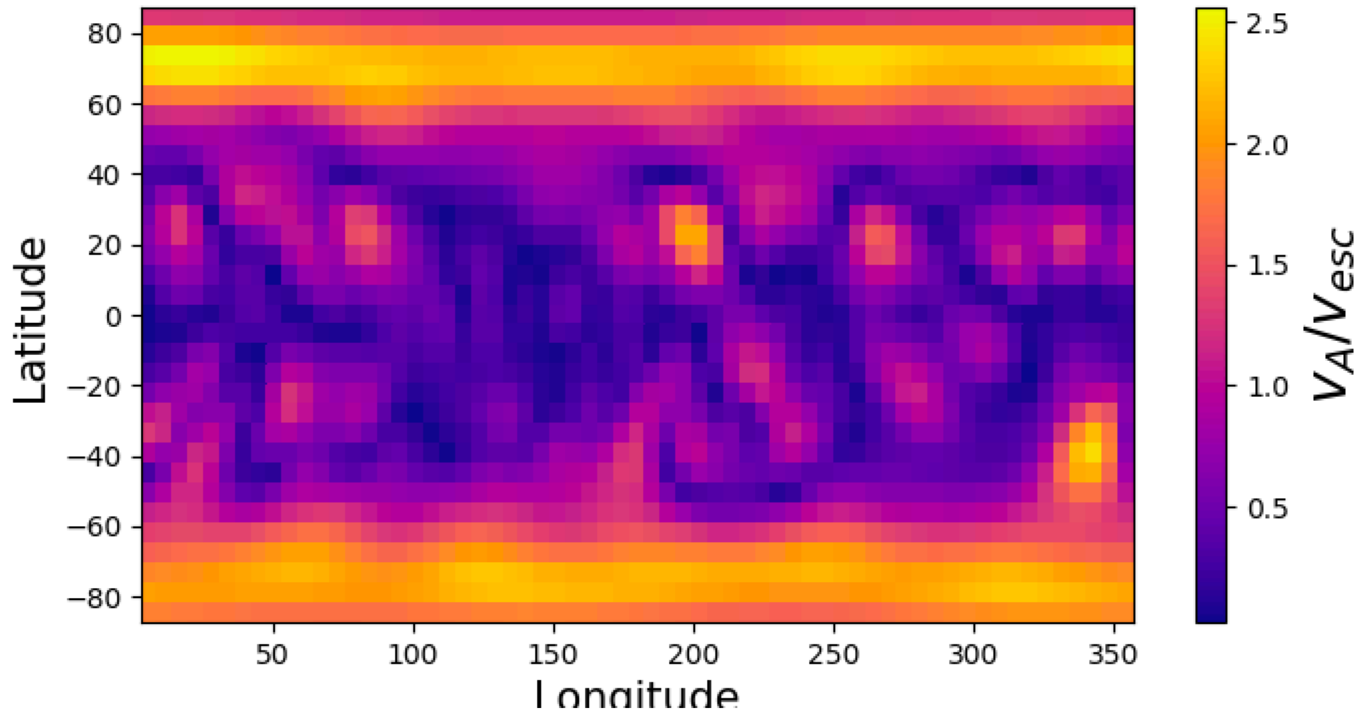
→ Empirical criterion of $\frac{v_A}{v_{esc}} < 3$



# Robustness of the code

To be operational, need to make the code robust for all synoptic maps

→ Empirical criterion of $\frac{v_A}{v_{esc}} < 3$



# Inclusion of source terms

The main limitation of the polytropic assumption
is that you do not get a bimodal wind

→ To get a realistic coronal heating, you need to add source terms:

Source term: [Réville+2020]

$$Q = Q_h + Q_w - Q_c - Q_r$$

Ad hoc heating term:

$$Q_h = F_h / H \left( \frac{R_\odot}{r} \right)^2 \exp\left( - \frac{r - R_\odot}{H} \right)$$

Turbulence term:

$$Q_w^\pm = \frac{\rho}{8} \frac{\left| z^\pm \right|^2}{\lambda} \left( R \left| z^\pm \right| + \left| z^\mp \right| \right),$$

$$R = 0.1, \lambda = \frac{\lambda_\odot}{\sqrt{B}}, \quad \delta v_\odot = \frac{z_\odot^\pm}{2}$$

Radiation term:

$$Q_r = n^2 \Lambda(T)$$

Thermal conduction:

$$Q_c = \nabla \cdot \left( \alpha q_s + (1 - \alpha) q_p \right),$$

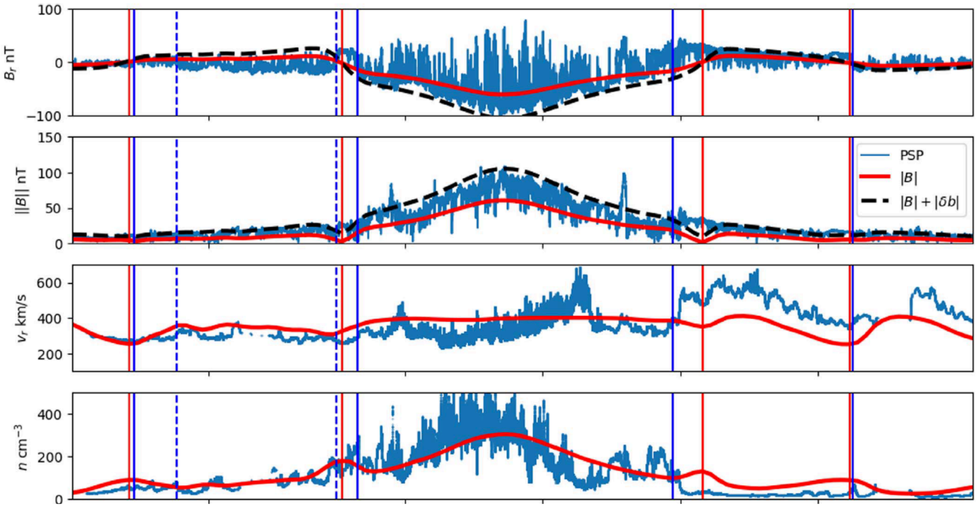
$$q_s = -\kappa_0 T^{\frac{5}{2}} \nabla T, \; q_p = \frac{3}{2} p_{th} v_e,$$

$$\alpha = \frac{1}{1 + \frac{(r - R_\odot)^4}{(r_{coll} - R_\odot)^4}}, r_{coll} = 5 R_\odot$$

# Wind-Predict-AW model

# Wind-Predict-AW model

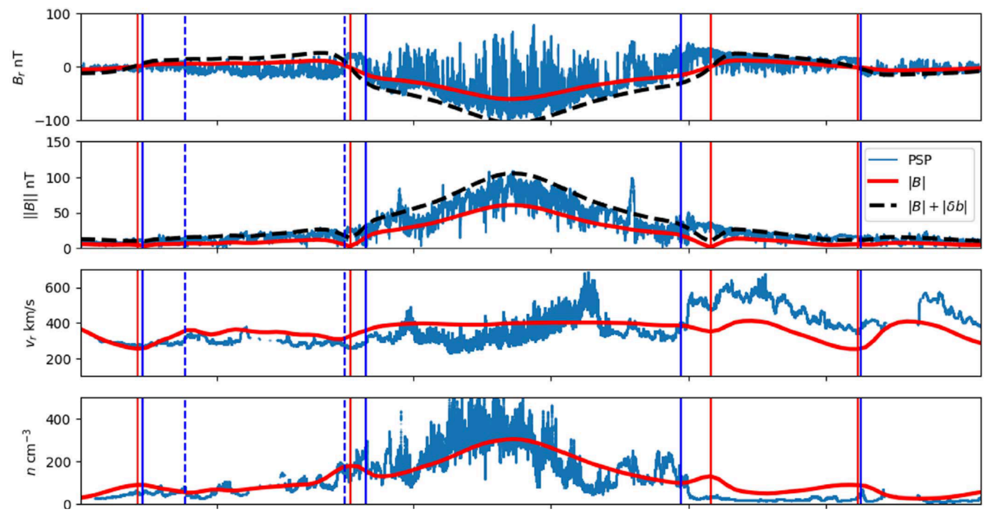
[Réville+2020]




Validated using in-situ data (PSP first perihelion on 06/11/18)

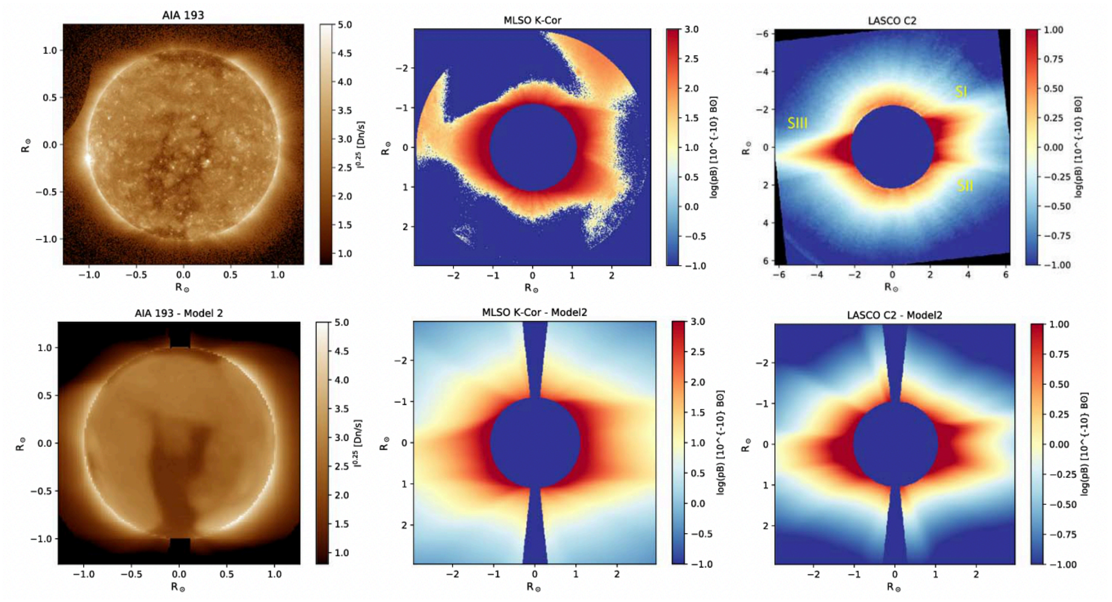
# Wind-Predict-AW model

[Réville+2020]




Validated using in-situ data (PSP first perihelion on 06/11/18)

[Parenti+2022]




Validated using remote-sensing data

→ EUV (SDO/AIA)
+ WL (LASCO/KCOR)

# ISWAT H1-01 validation

# ISWAT H1-01 validation

ISWAT = International Space Weather Action Team

H1-01 team dedicated to the validation of the ambient solar wind (CR2075-6-7)

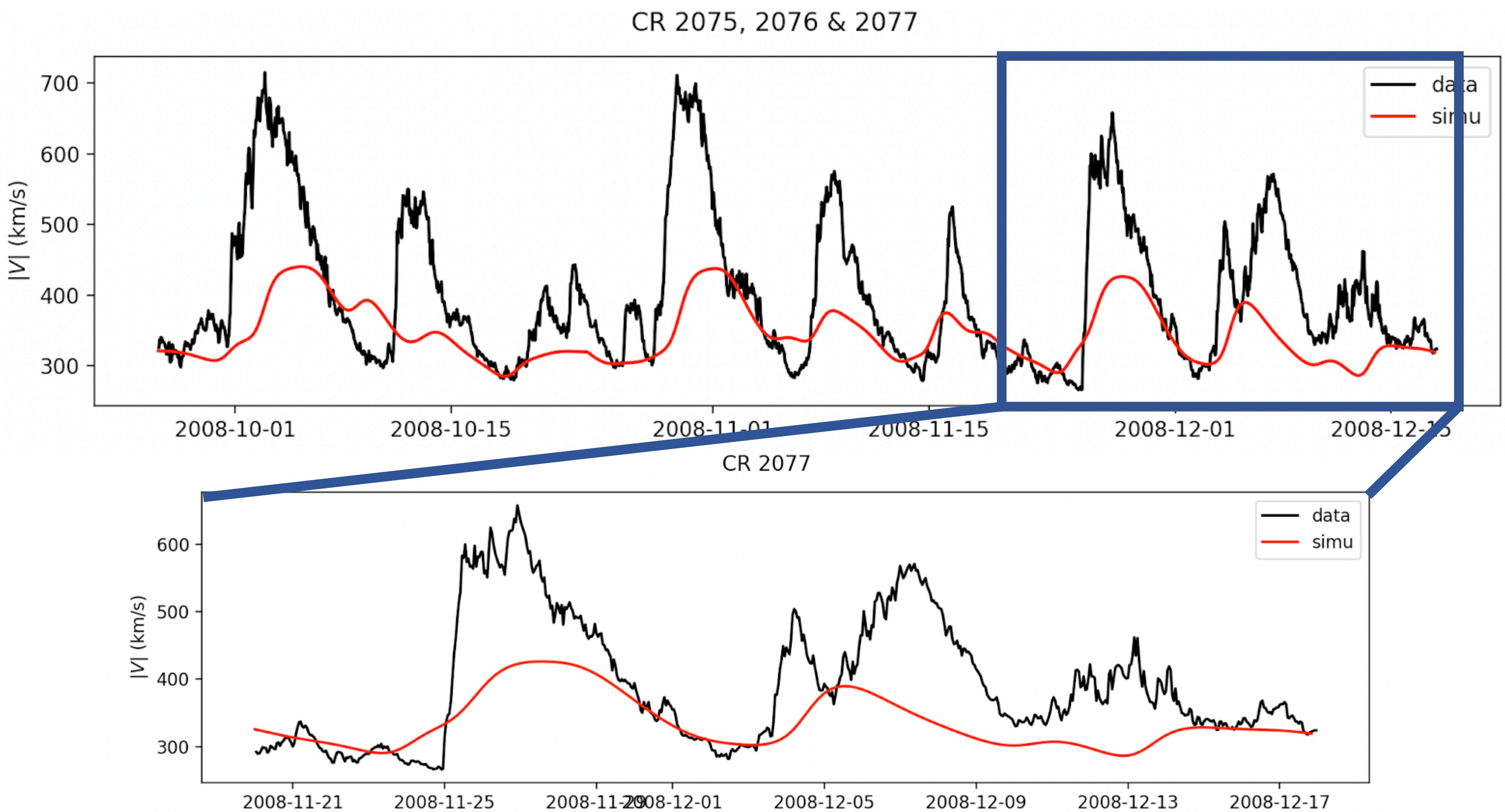
Initial validation : structures OK, but HSSs underestimated

# ISWAT H1-01 validation

ISWAT = International Space Weather Action Team

H1-01 team dedicated to the validation of the ambient solar wind (CR2075-6-7)

Initial validation : structures OK, but HSSs underestimated

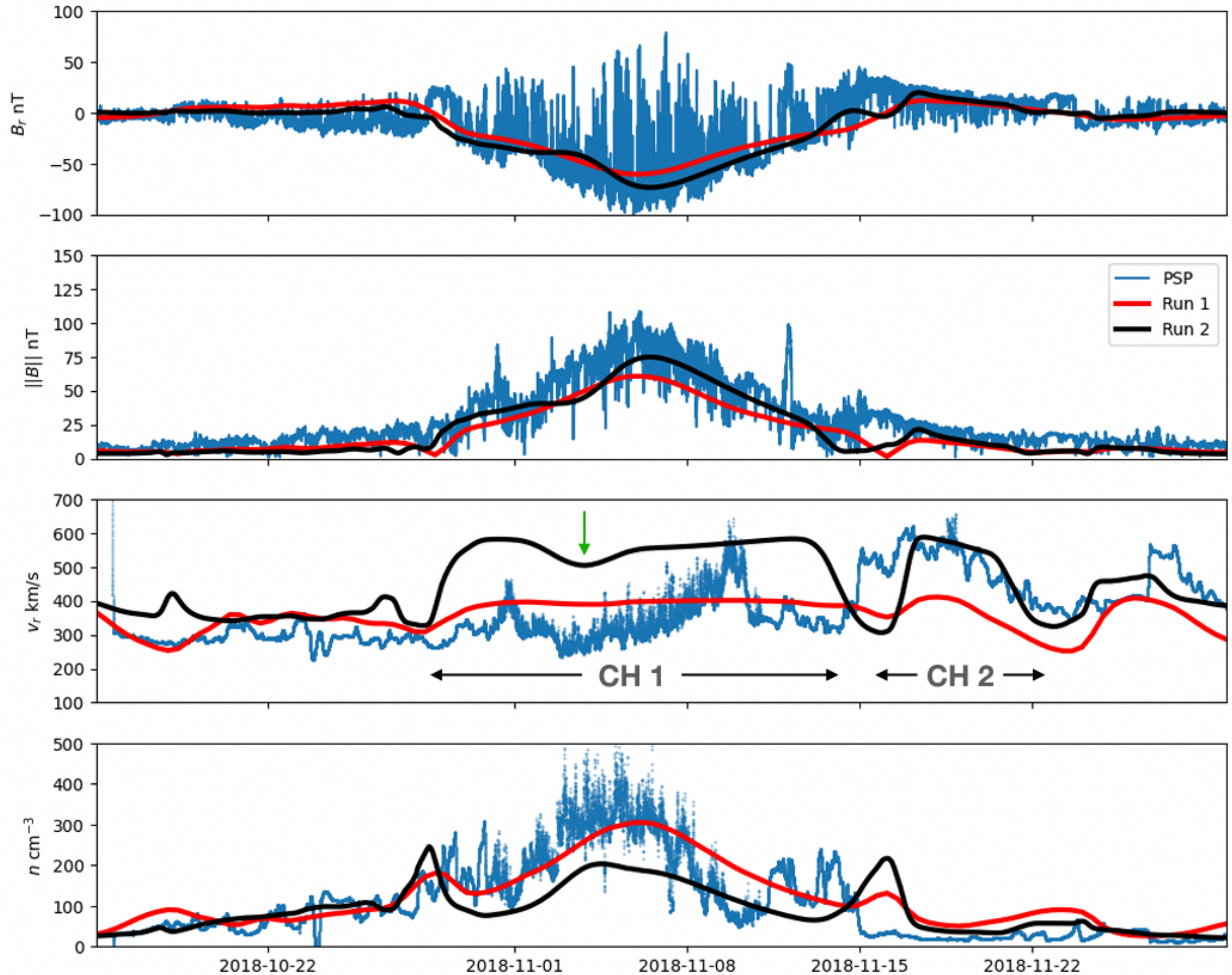


# Impact of the transition region

# Impact of the transition region

Addition of a transition region → coronal holes better captured in speed!

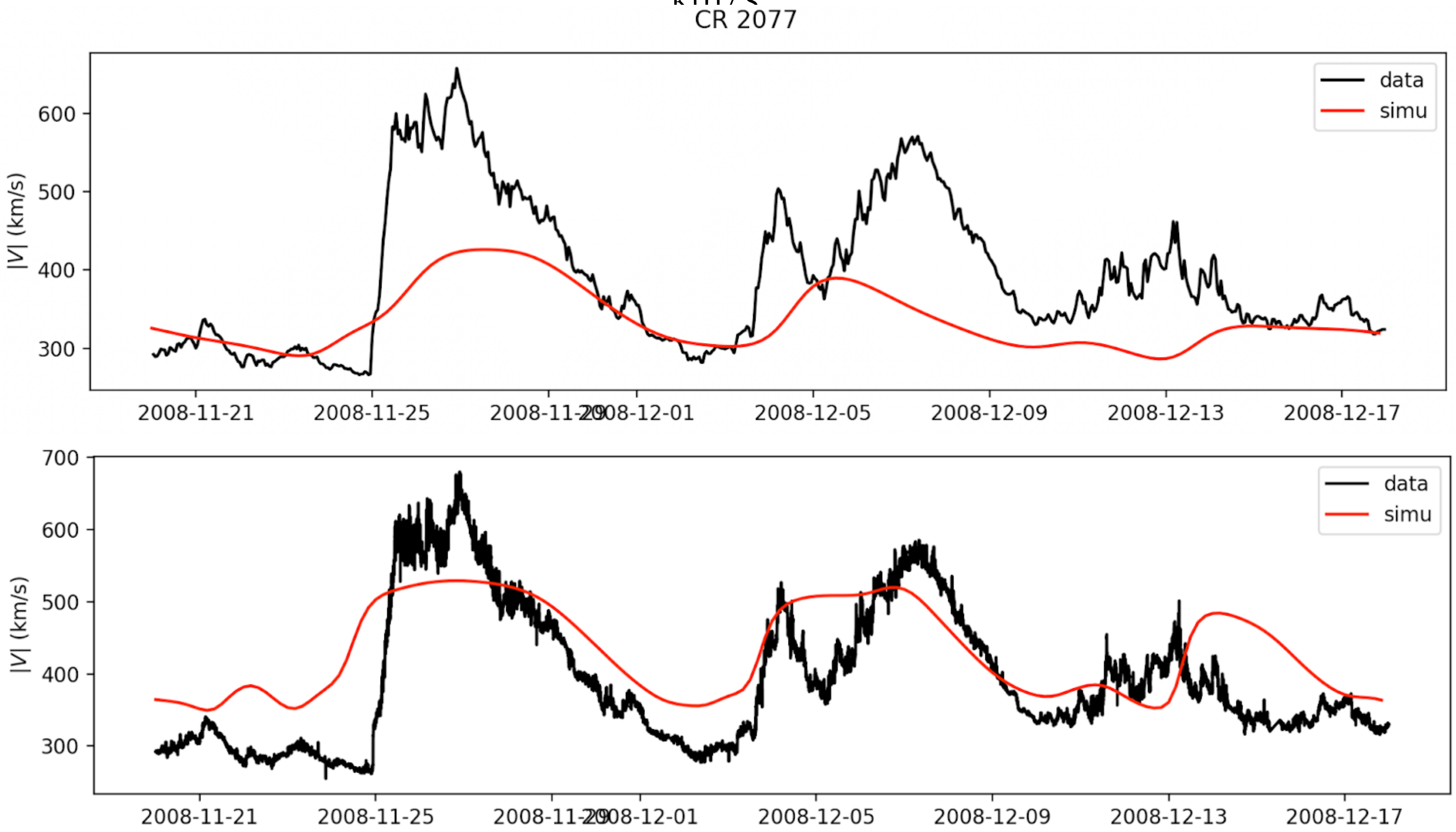
[Réville+2021]



# ISWAT validation (II)

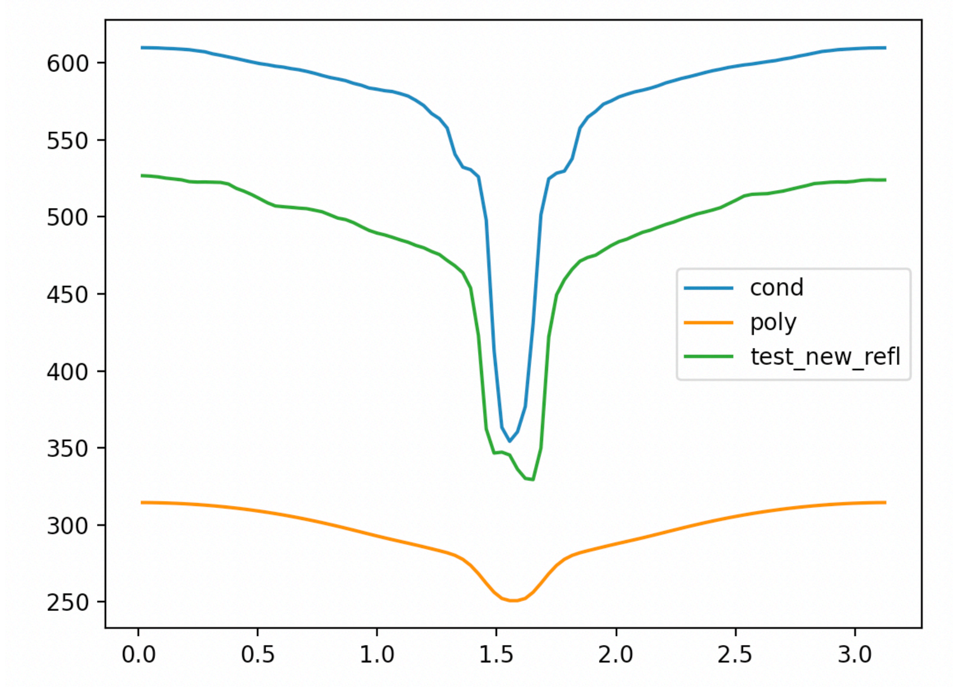
# ISWAT validation (II)

New validation → with the transition region, the error in the HSSs is reduced to 100 km/s



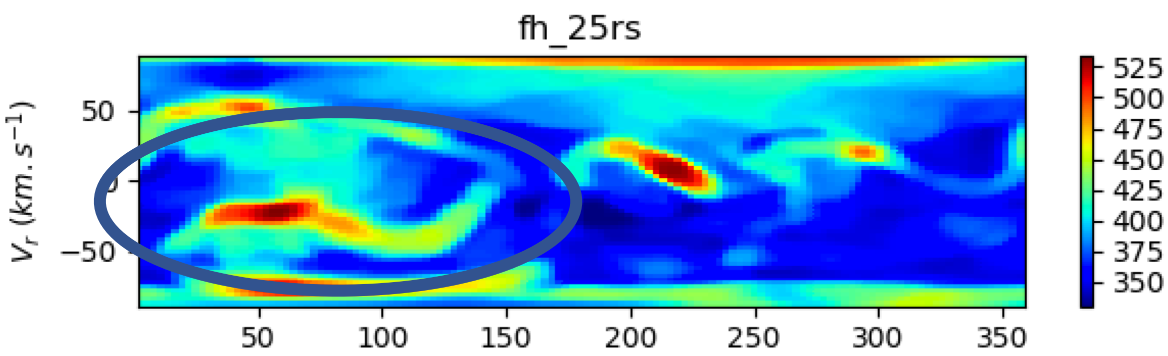
# Future developments

WP-AW-hyb:




Alfvén wave heating without thermal conduction and radiative losses

→ realistic heating + fast code!



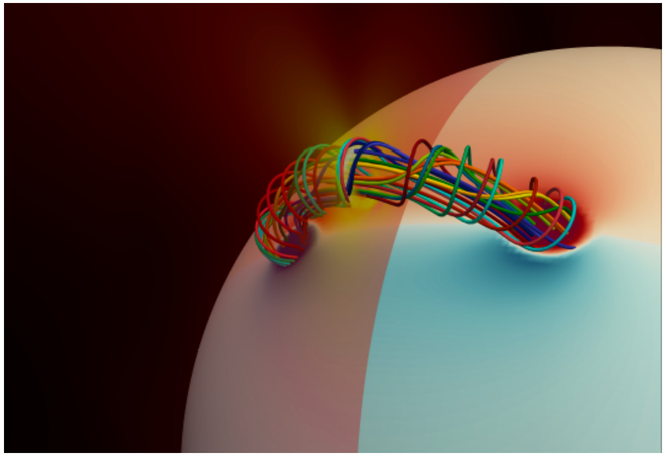

Can indeed recover CH acceleration

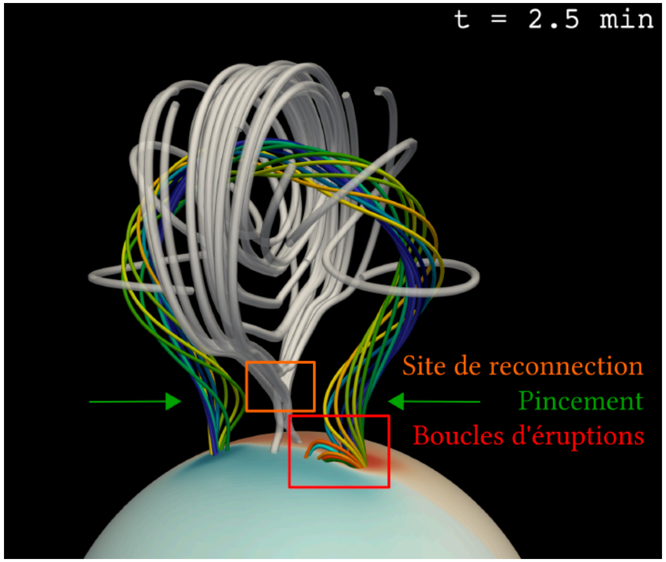
→ good sign for HSS

# Future developments

## CMEs

[Regnault+2023]






CME initialization with a Titov-Desmoulins flux-rope

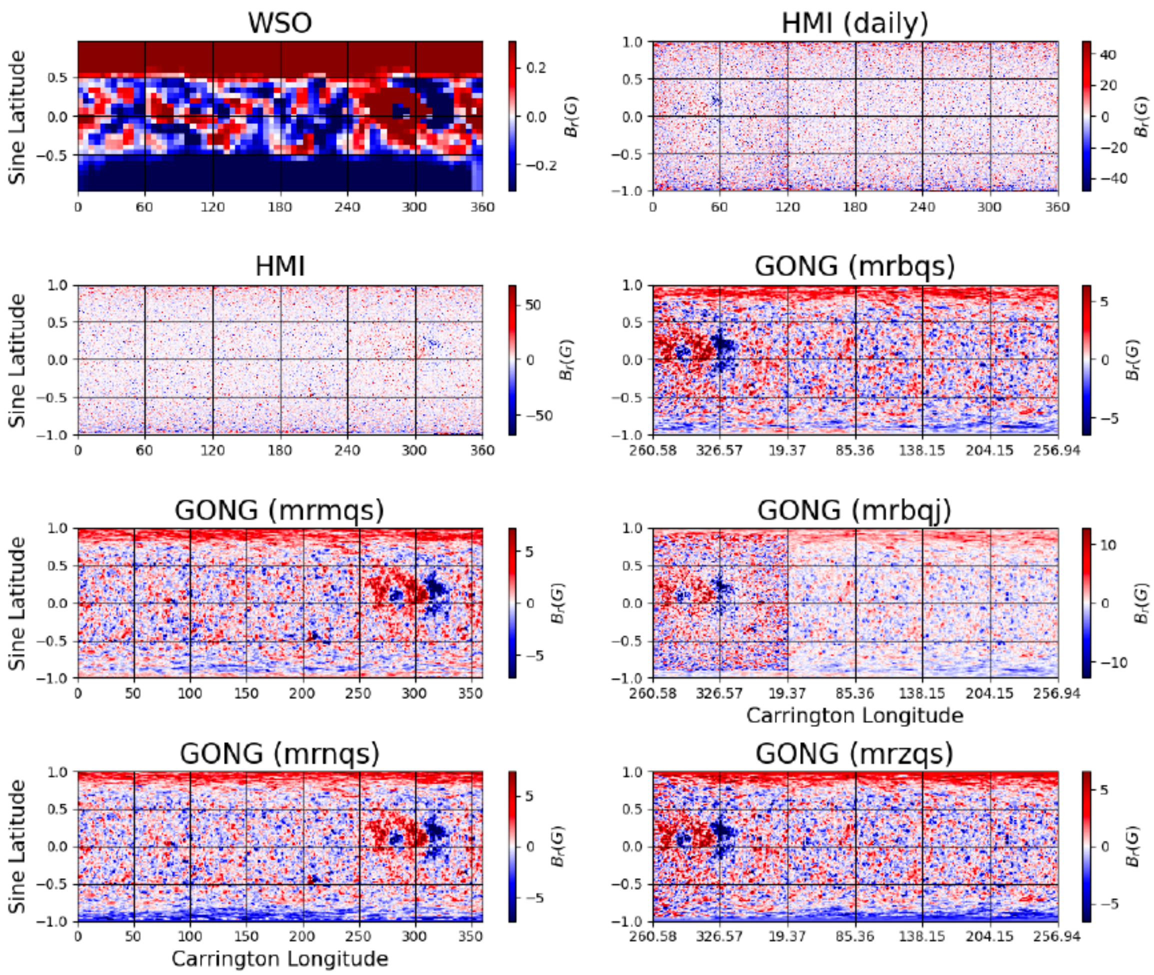
[Linan+2023] (to be submitted)

Propagation up until 1 AU

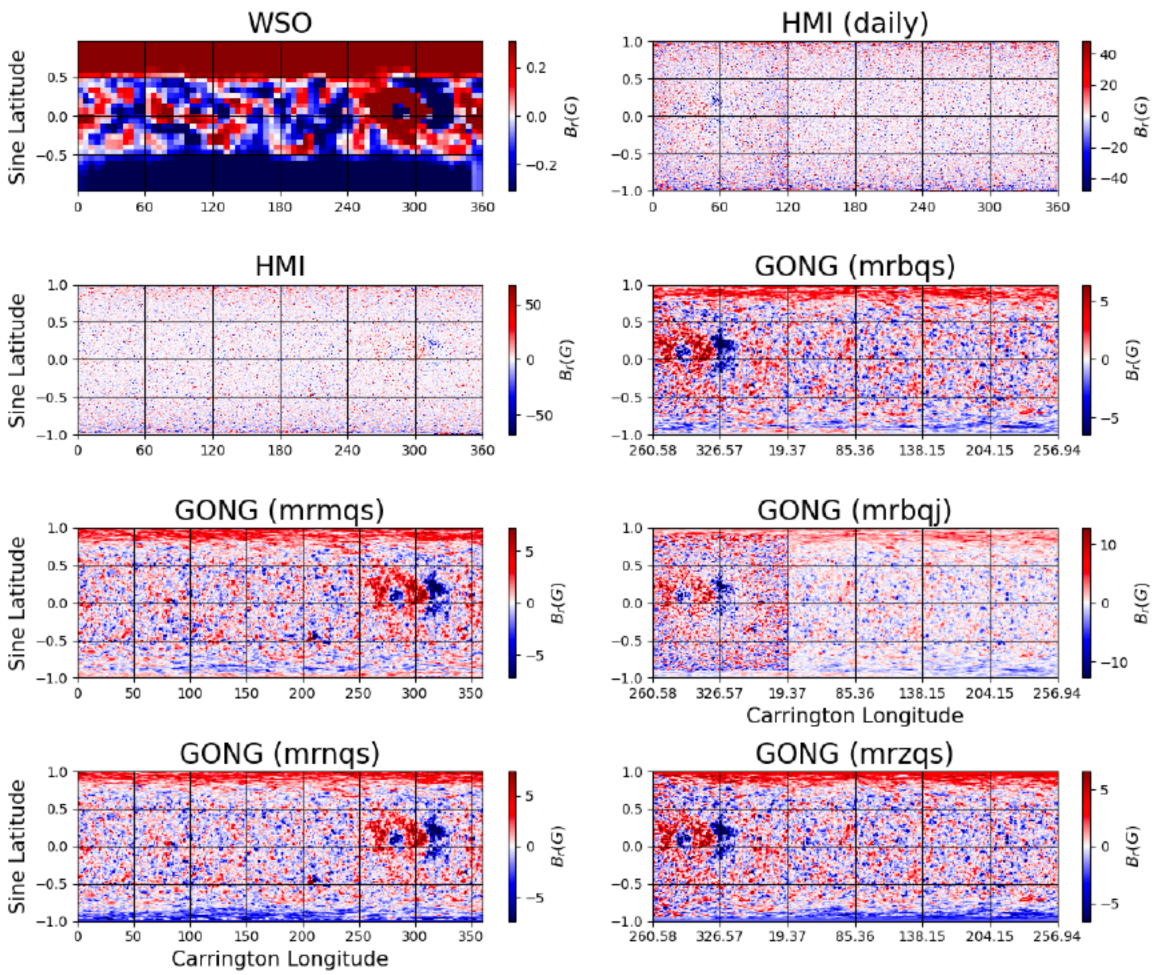
→ effects due to the corona (rotation)

→ how to couple with EUHFORIA?

# Open challenges: Input map



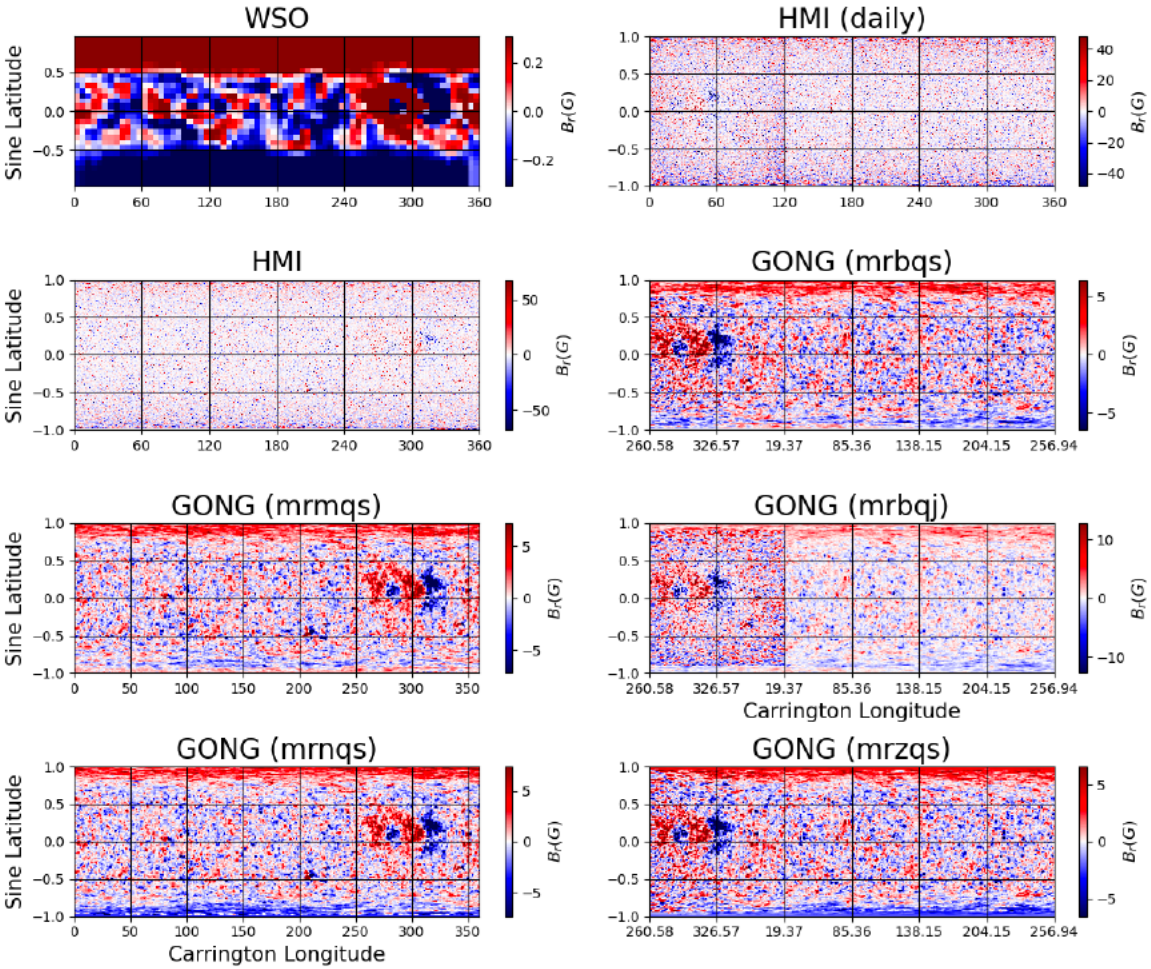
# Open challenges: Input map




- The choice of the initial map has a strong impact on the final coronal solution

→ need for standard input

# Open challenges: Input map




- The choice of the initial map has a strong impact on the final coronal solution
  → need for standard input

- The current maps lead to underestimating the magnetic flux at Earth → how to solve the open flux problem?

# Open challenges: Standard validation

# Open challenges: Standard validation

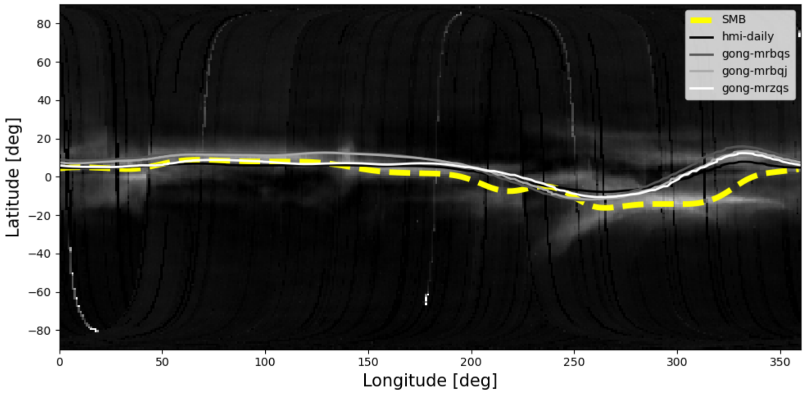
Still no stand-alone validation for coronal models in the VSWMC
→ We cannot evaluate properly why a forecast has failed!

→ Collaboration with KU Leuven and IAS to develop new validation frameworks
→ Following the recommendations from Wagner+2022 and Badman+2023

# Open challenges: Standard validation

Still no stand-alone validation for coronal models in the VSWMC
→ We cannot evaluate properly why a forecast has failed!

→ Collaboration with KU Leuven and IAS to develop new validation frameworks
→ Following the recommendations from Wagner+2022 and Badman+2023



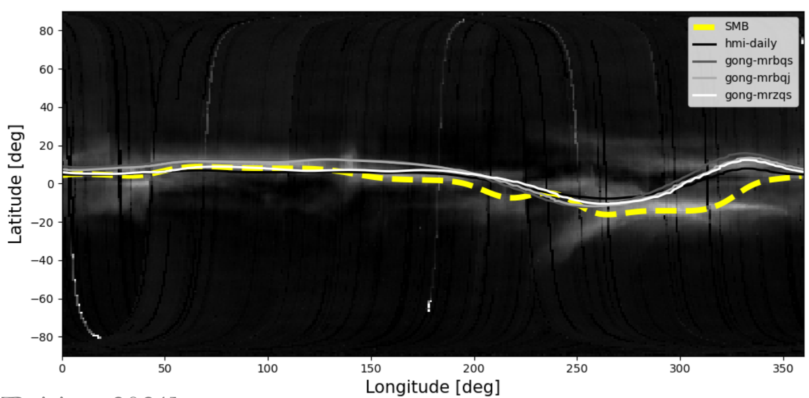

[Perri+2023]

WL maps of the streamer belt
→ proxy for the HCS

# Open challenges: Standard validation

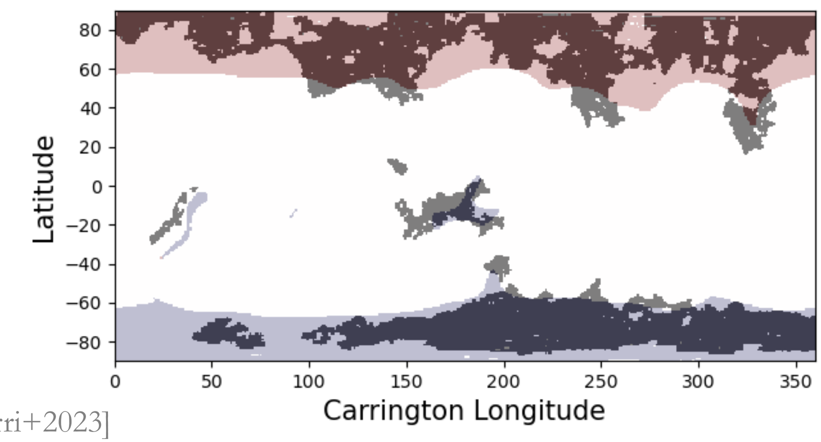
Still no stand-alone validation for coronal models in the VSWMC
→ We cannot evaluate properly why a forecast has failed!

→ Collaboration with KU Leuven and IAS to develop new validation frameworks
→ Following the recommendations from Wagner+2022 and Badman+2023




[Poirier+2021]

WL maps of the streamer belt
→ proxy for the HCS

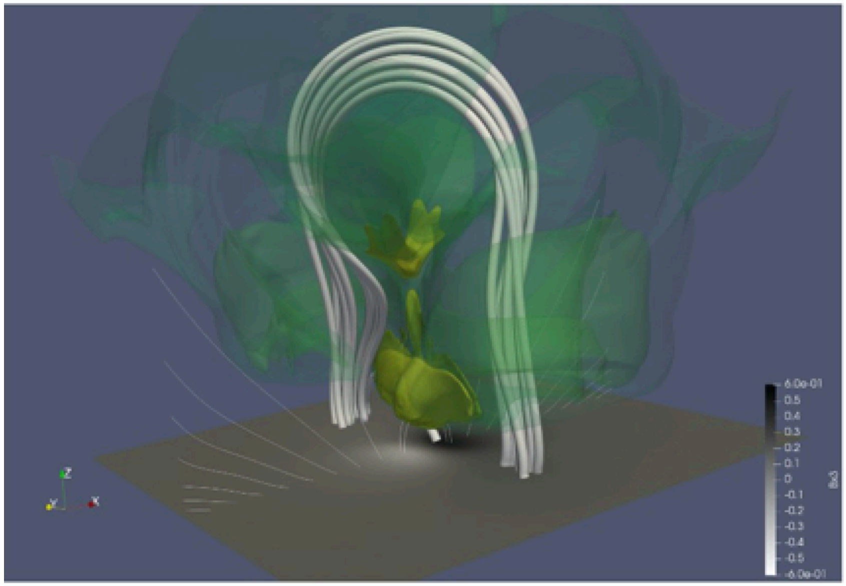



[Perri+2023]

Coronal hole maps with open/closed magnetic field lines

# Open challenges: Maximum of activity

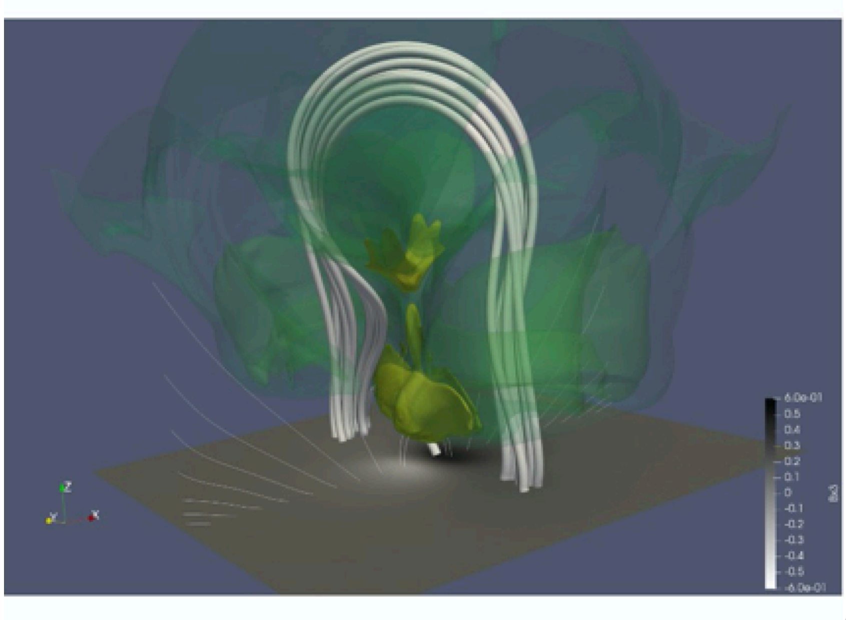
# Open challenges: Maximum of activity



Brun, Parenti, Pinto, Strugarek

- As the maximum of solar cycle 25 is approaching, need for models that can change quickly (time-dependent boundary condition, data assimilation...)

# Open challenges: Maximum of activity

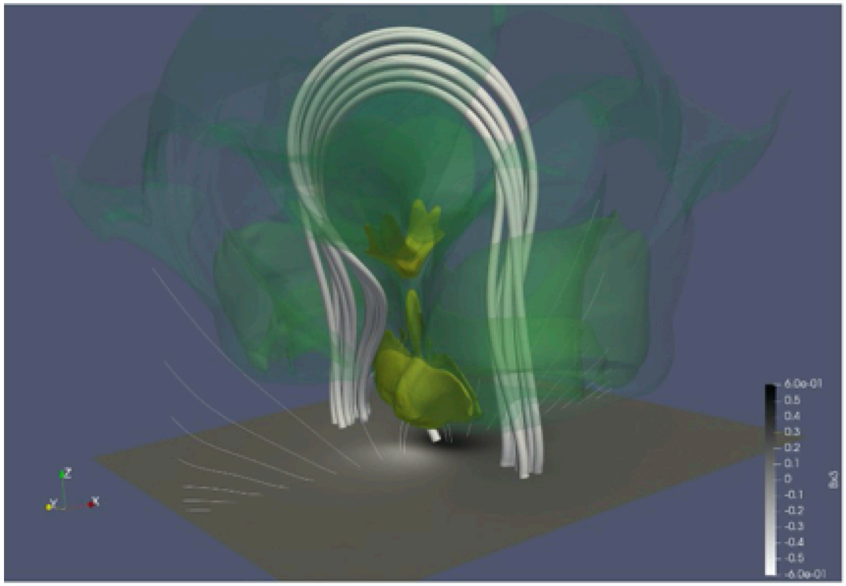


Brun, Parenti, Pinto, Strugarek

- As the maximum of solar cycle 25 is approaching, need for models that can change quickly (time-dependent boundary condition, data assimilation...)

- Active region are becoming more and more important → how to couple global coronal models with local eruption models?

# Open challenges: Maximum of activity



Brun, Parenti, Pinto, Strugarek

- As the maximum of solar cycle 25 is approaching, need for models that can change quickly (time-dependent boundary condition, data assimilation...)
- Active region are becoming more and more important → how to couple global coronal models with local eruption models?

Thank you for your attention!