MHD simulations of the heliosphere and solar wind

V. Réville,
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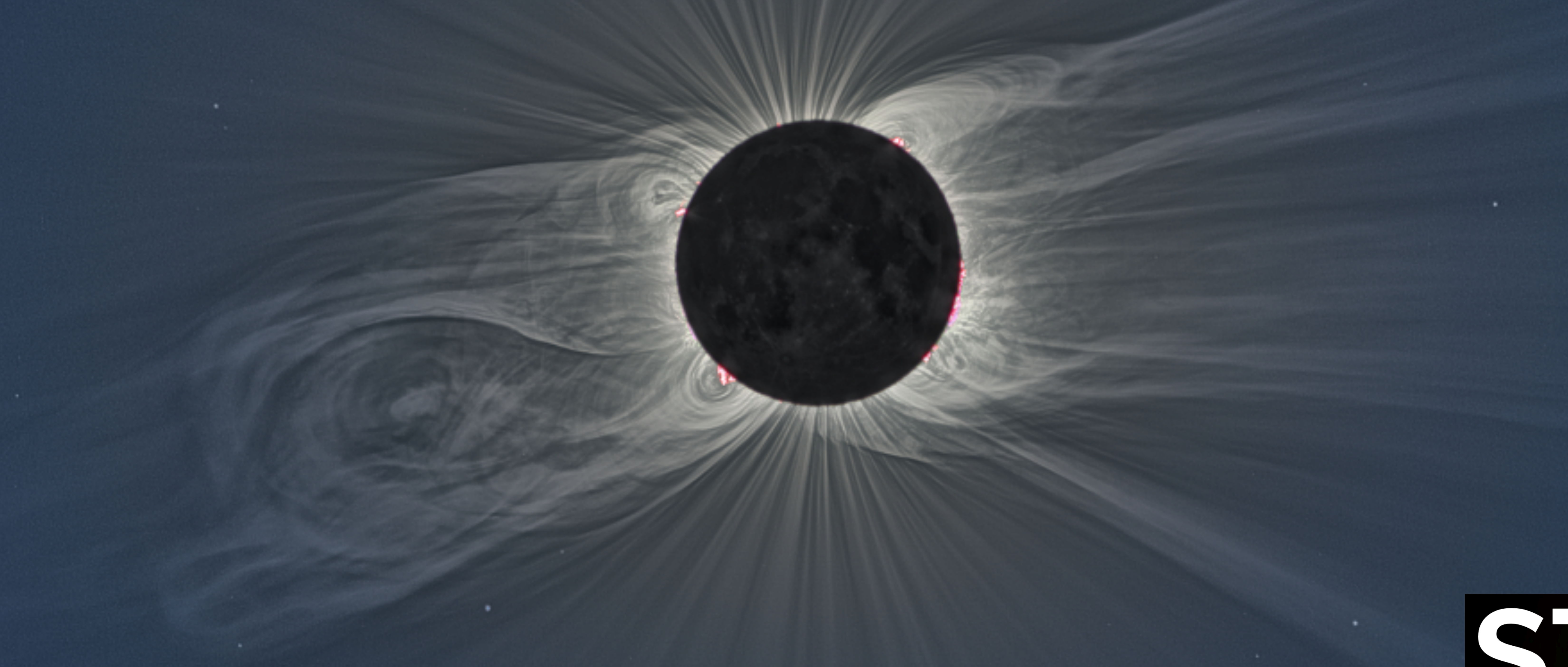

Atelier ASOV-ASN, 7 Octobre 2022

solar orbiter

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Solar Terrestrial ObseRvations and Modeling Service

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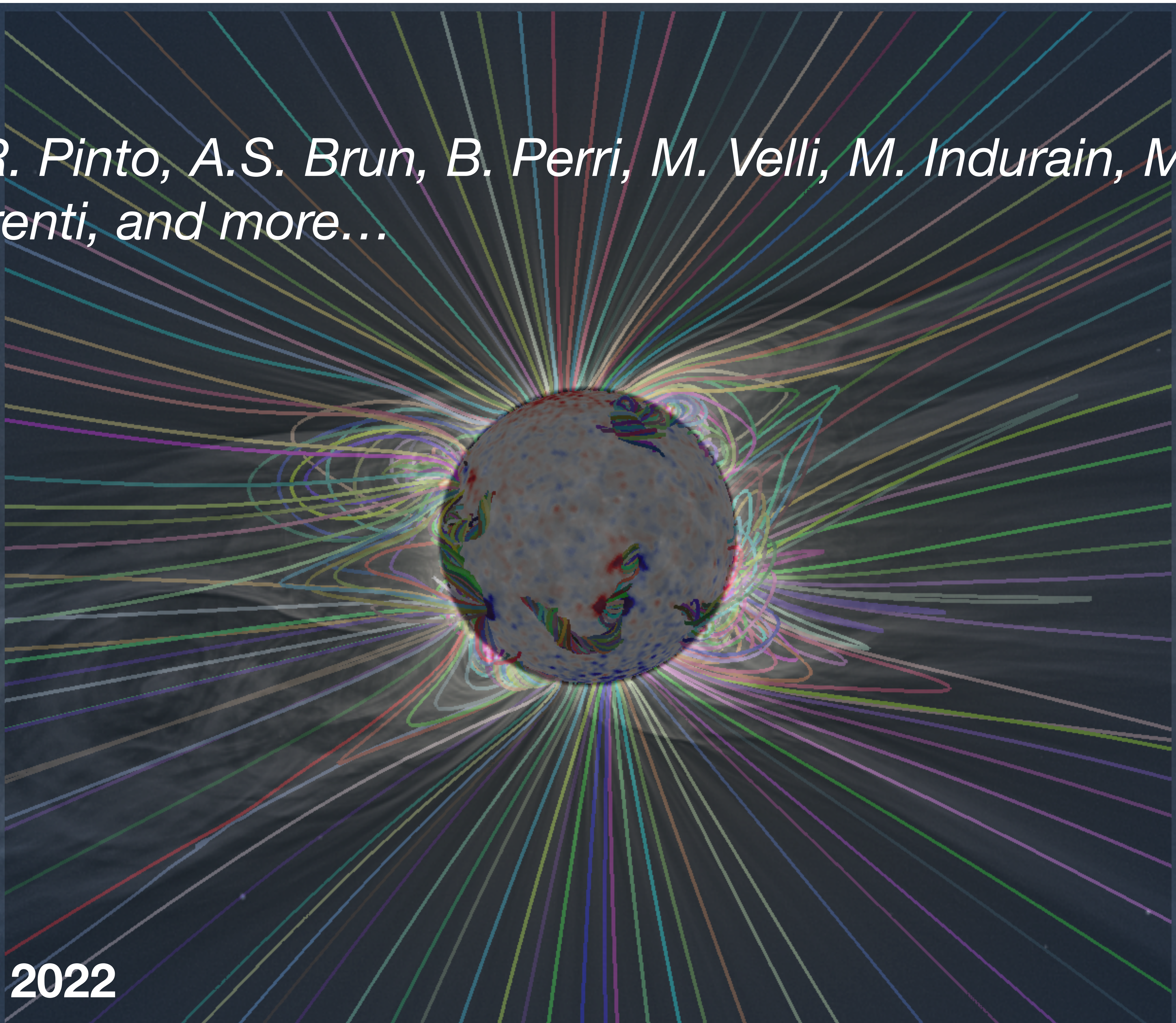

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Context

The heliosphere is a multi-scale system and modeling approach should vary as a function of the objective

- Low beta, complex fields, mostly current free (static)
- Fast / slow wind are accelerated

- Large scale structures
- Slow/Fast wind interactions
- Compressible

- Multi-scale
- Shocks / Kinetic effects

Global coronal & heliosphere models

Magnetostatic models

1) *Analytic simple static B*

2) *No self-consistent flows*

3) *Empirical wind*

[Altschuler & Newkirk 1967]
[Schatten 1967]

Polytropic models

1) *Simplified thermal conduction*

2) *Hot coronal boundary + B*

[Sakurai 1985 (analytical!!!)]
[Washimi & Shibata 1993]
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Alfvén wave driven models

1) *Spitzer (+ others) TC*
2) *Heating consistent with B*
3) *Fast wind due to wave pressure*

[Sokolov et al. 2013]
[van der Holst et al. 2014]
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Global coronal & heliosphere models

<u>*Magnetostatic models*</u> — <u>*Polytropic models*</u> — <u>*Alfvén wave driven models*</u>

Numerical cost →

Magnetostatic models

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Global CO_2 emissions:

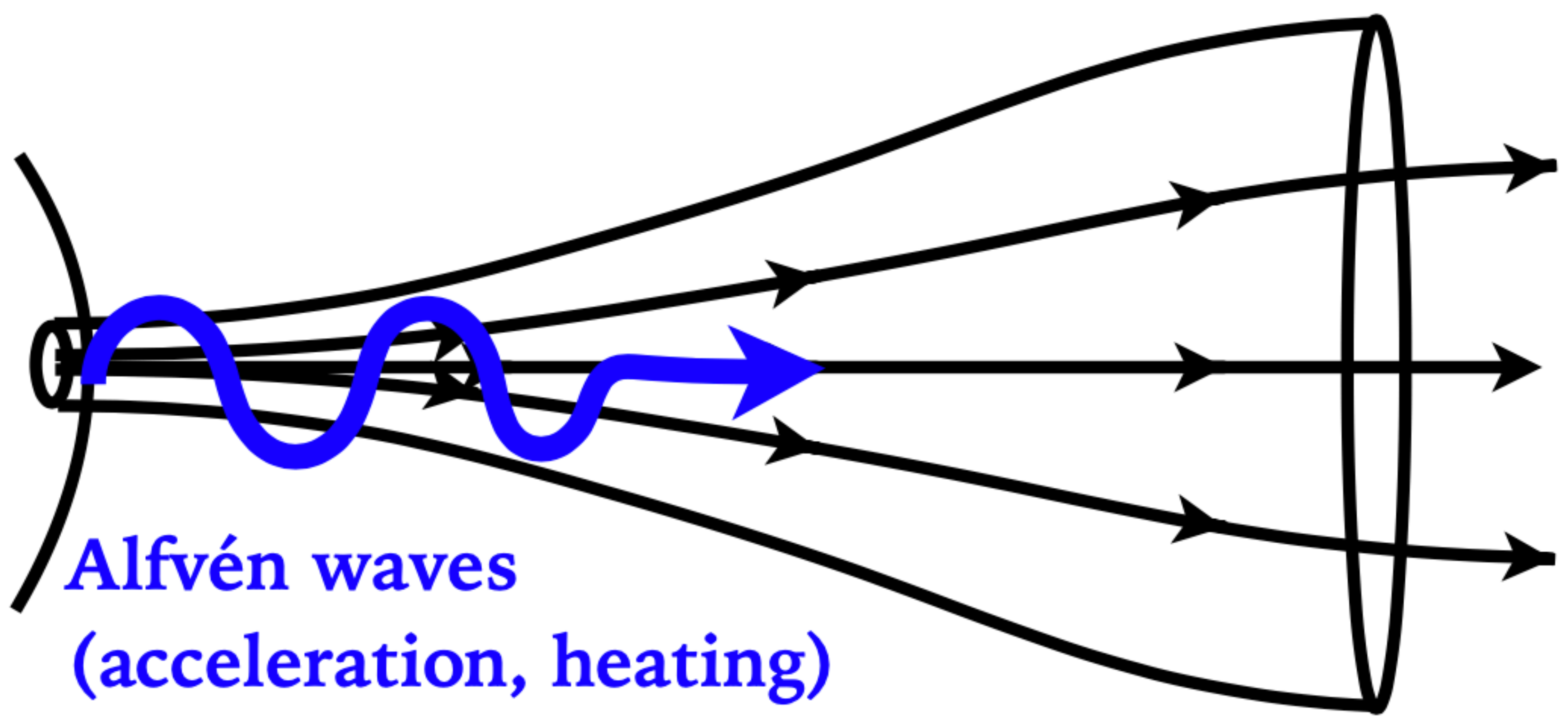
1 CPU-hour = 4g of CO_2
1 run = 100k CPU hours

1M CPU hours = 4T ~ 8 Paris - New York flights

Alfvén-wave driven models

WindPredict-AW

Numerics



$$\partial_t \rho + \nabla \cdot [\rho \mathbf{v}] = 0,$$

$$\partial_t(\rho \mathbf{v}) + \nabla \cdot [\rho \mathbf{v}\mathbf{v} - \mathbf{B}\mathbf{B} + \mathbf{I}(p + \mathcal{E}/2)] = -\rho \nabla \Phi,$$

$$\partial_t(E + \mathcal{E} + \rho\Phi) + \nabla \cdot \left[(E + p + \mathcal{E}/2 + \rho\Phi)\mathbf{v} - \mathbf{B}(\mathbf{v}\cdot\mathbf{B}) + \mathbf{v}_g^+ \mathcal{E}^+ + \mathbf{v}_g^- \mathcal{E}^-\right] = Q, \quad = Q_h - Q_c - Q_r$$

Volume heating (Q_h), Thermal conduction (Q_c), Radiative losses (Q_r)

$$\partial_t \mathbf{B} + \nabla \cdot [\mathbf{v}\mathbf{B} - \mathbf{B}\mathbf{v}] = \eta \nabla \times \mathbf{B},$$

$$\partial_t \mathcal{E}^\pm + \nabla \cdot \left[(\mathbf{v} \pm \mathbf{v_A})\mathcal{E}^\pm\right] = -\frac{\mathcal{E}^\pm}{2}\nabla \cdot \mathbf{v} - Q_w^\pm,$$

$$\mathcal{E}^\pm = \rho \frac{|z^\pm|^2}{4}$$

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

Reflection driven Kolmogorov turbulence

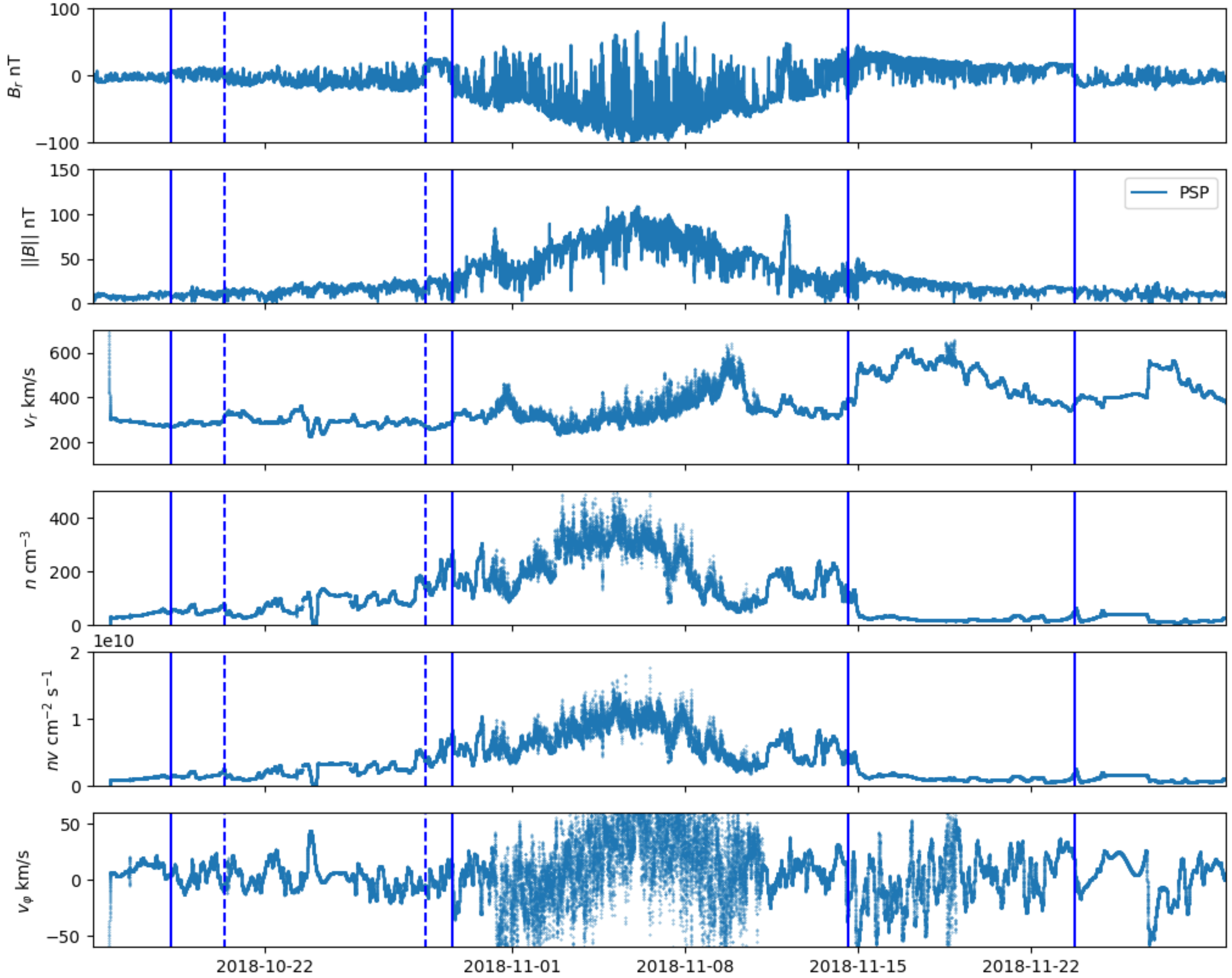
- Core = PLUTO code (open source) [Mignone et al. 2007,2012]
- Physics of Alfvén wave propagation and dissipation [Réville et al. 2020, ApJS]

Alfvén wave turbulence 3D MHD model

Comparisons with PSP E1 data

[Réville et al. 2020, ApJS]

- Particles (SWEAP) and magnetic field data (FIELDS)
- Single observational input : the magnetic field map (ADAPT) the day of perihelion.
- Average structures, change of polarity are very well reproduced.
- Fast evolving structure (switchbacks) are not meant to be reproduced.



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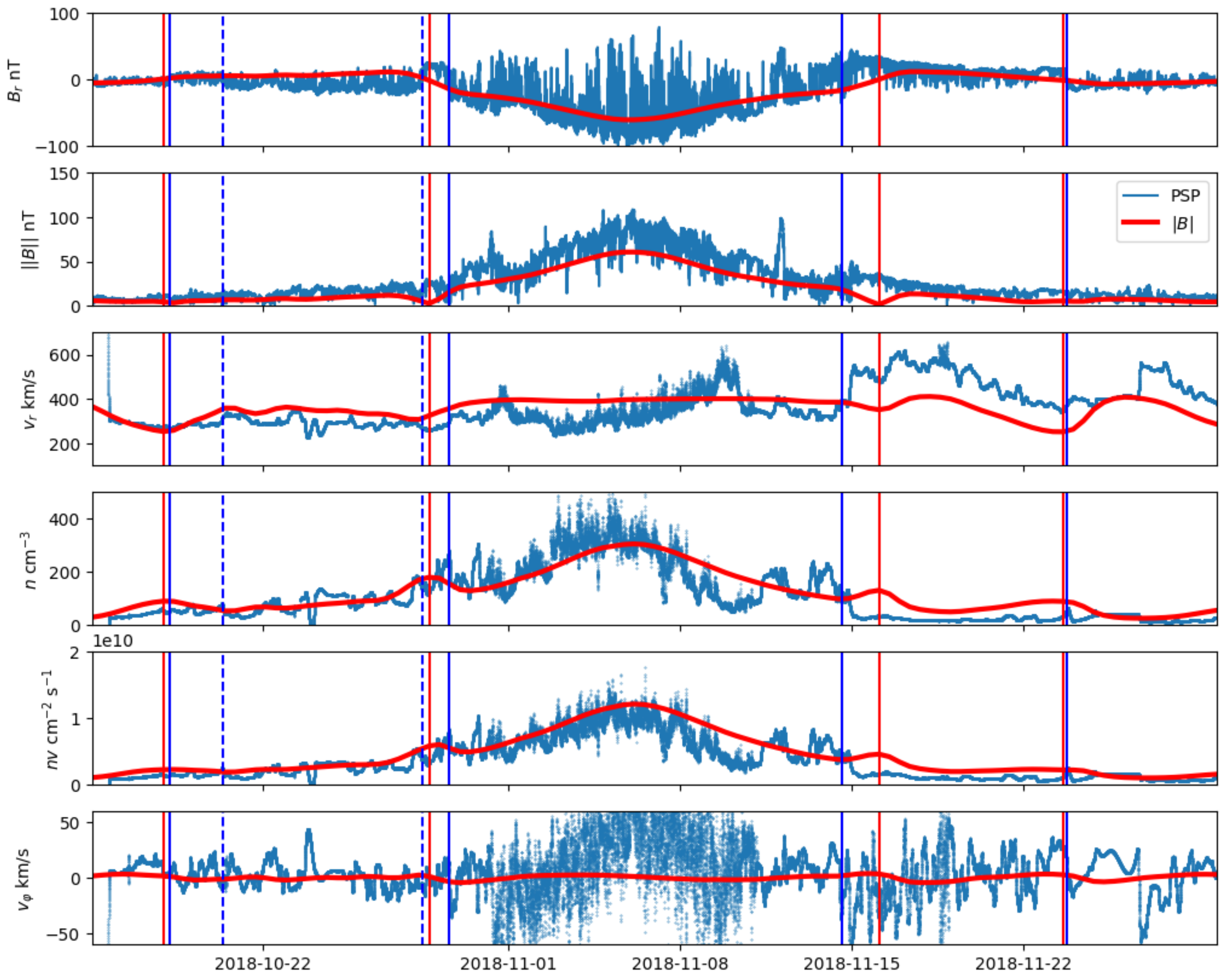


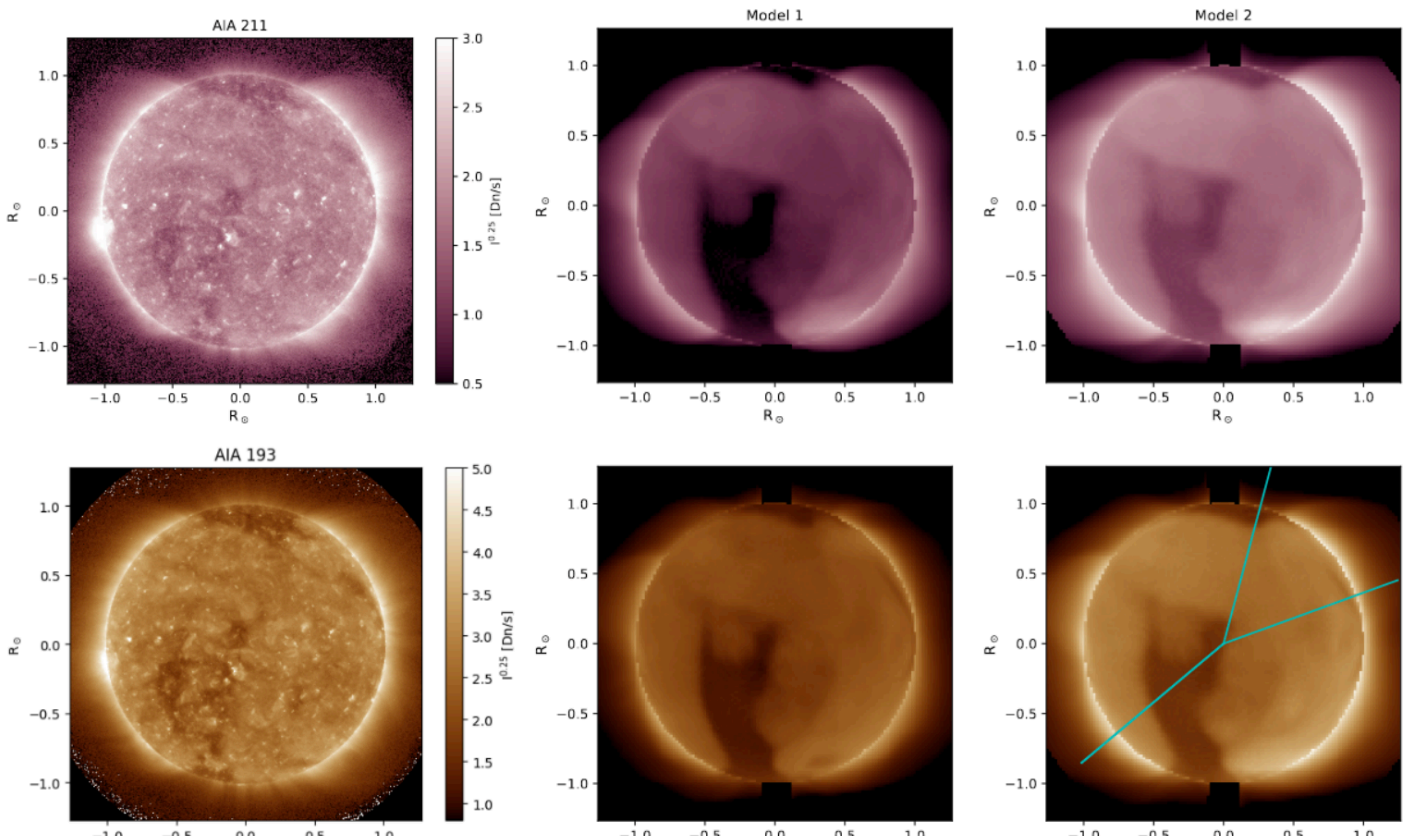
Comparison with remote sensing data

Finding the sources of the SW

[Parenti, Réville et al. 2022, ApJ]

- EUV instruments image the solar atmosphere using lines from strongly ionized ions (e.g. Fe)
- SDO/AIA probes temperatures ranging from 0.5 to 2-3 MK.
- We use the instrument response to compute the synthetic emissions from the model

$$I = \int_{LOS} n^2 \mathcal{R}(n,T) dl$$



STORMS

Solar Terrestrial ObseRvations and Modeling Service

Providing novel models and tools to the heliophysics community

ABOUT

CATALOGUES

SCIENCE TOOLS

FORECASTING TOOLS

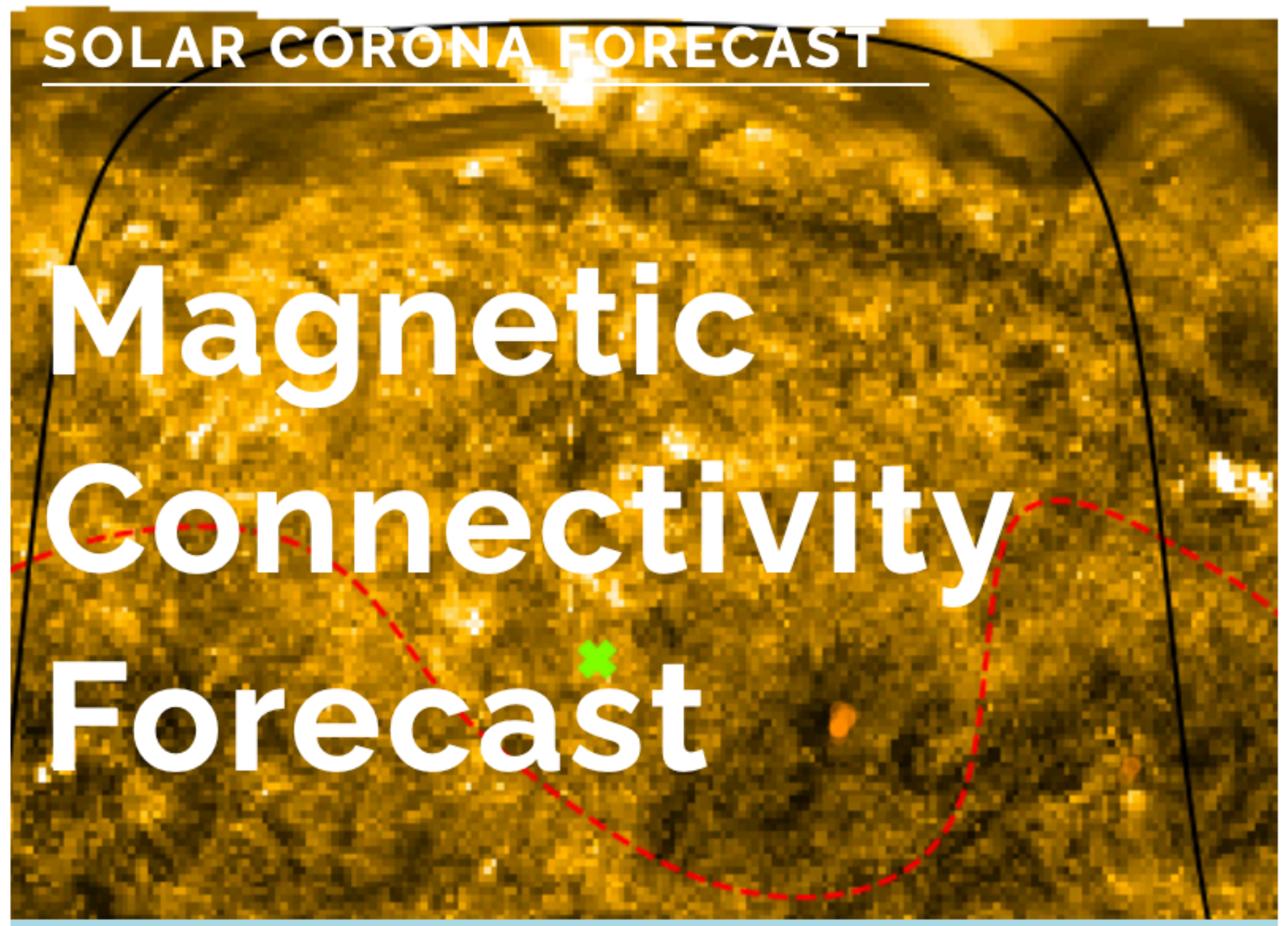
OPERATIONS

PROJECTS

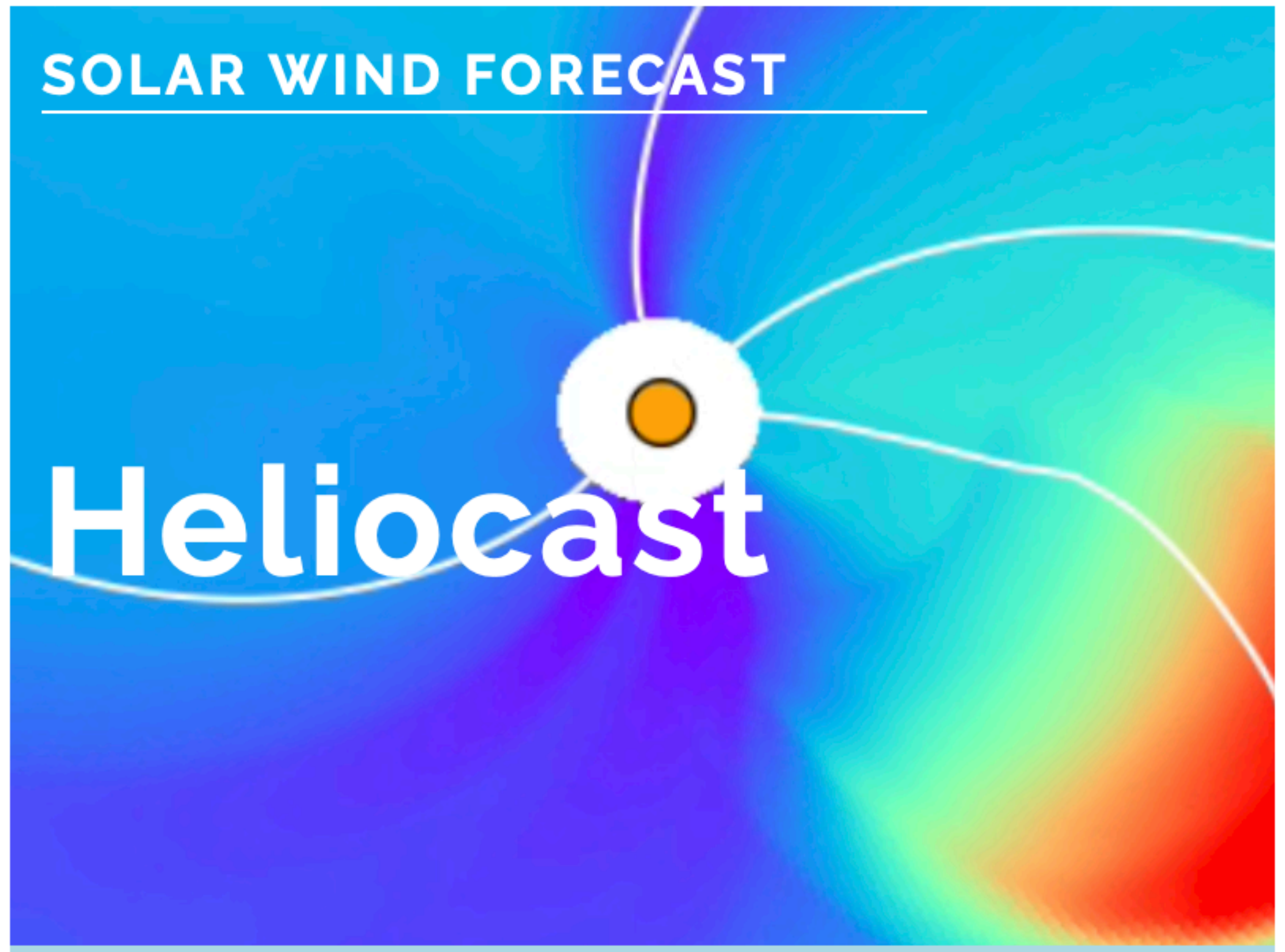
PUBLICATIONS & NEWS

FORECASTING TOOLS

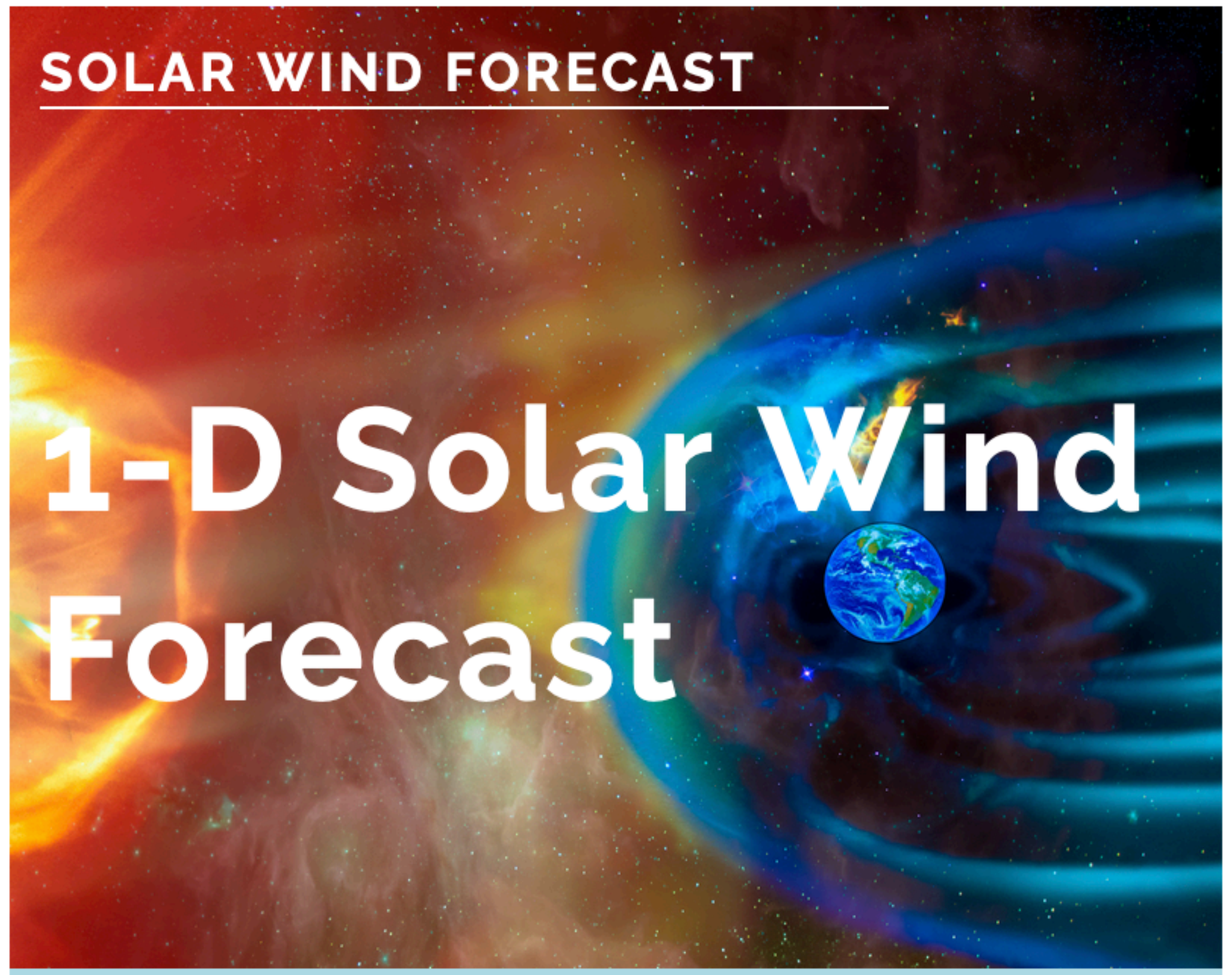
This page presents a number of tools that were developed to support research in space weather. They include tools to track the onset of CMEs and model their propagation, nowcasting and forecasting tools of the coronal magnetic field and the solar wind.



Find how an object is connected magnetically with the surface of the Sun. This connectivity is computed using different observations and models



Real time 3D MHD inner heliosphere model, based on multi-source coronal models. Nowcast and forecast of solar wind standard features are coming soon



Real-time forecasting tool of the state of the solar wind at Earth or at different spacecraft

Heliospheric polytropic models

Polytropic models

[Réville & Brun 2017, ApJ]

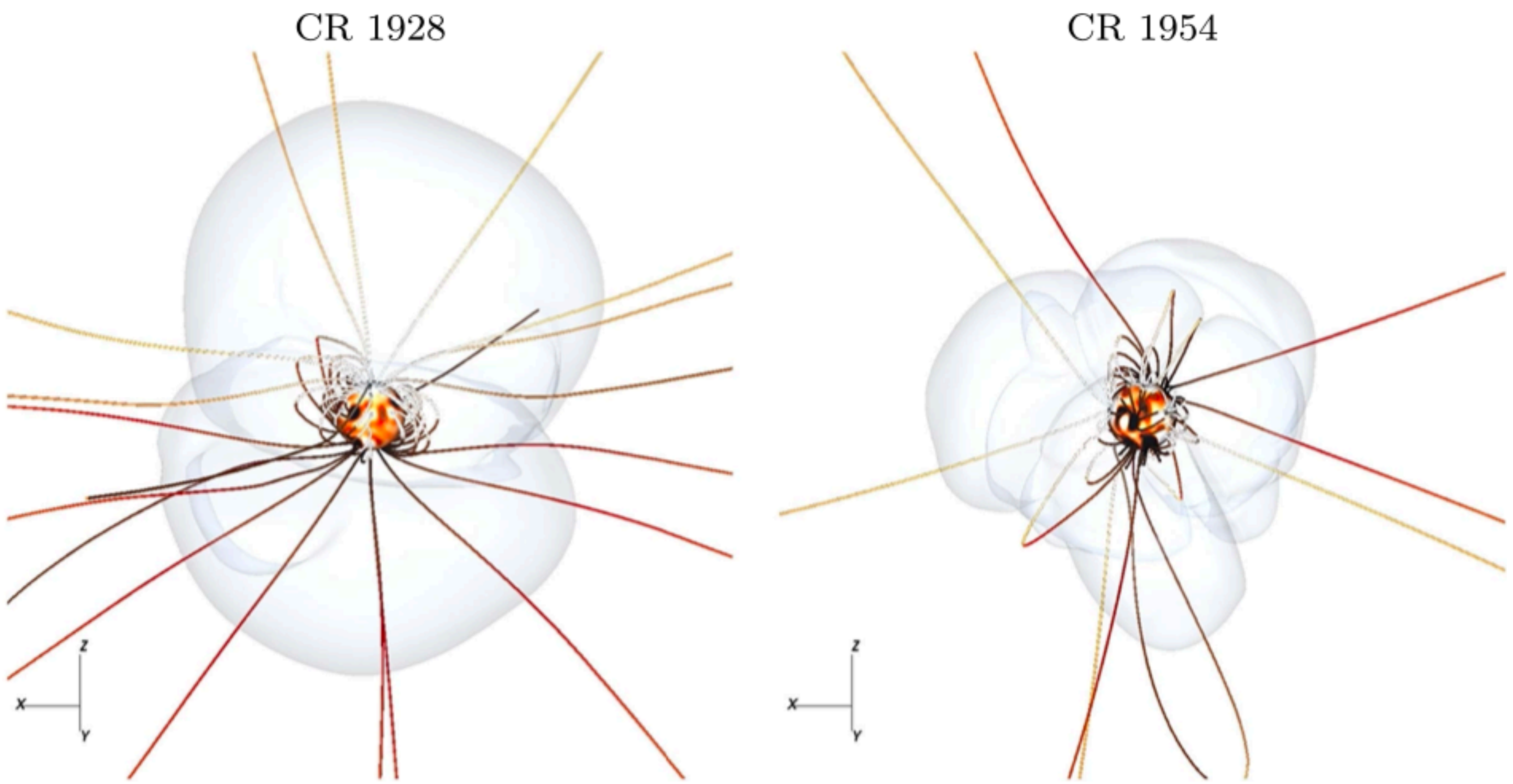
- Use an equation of state :

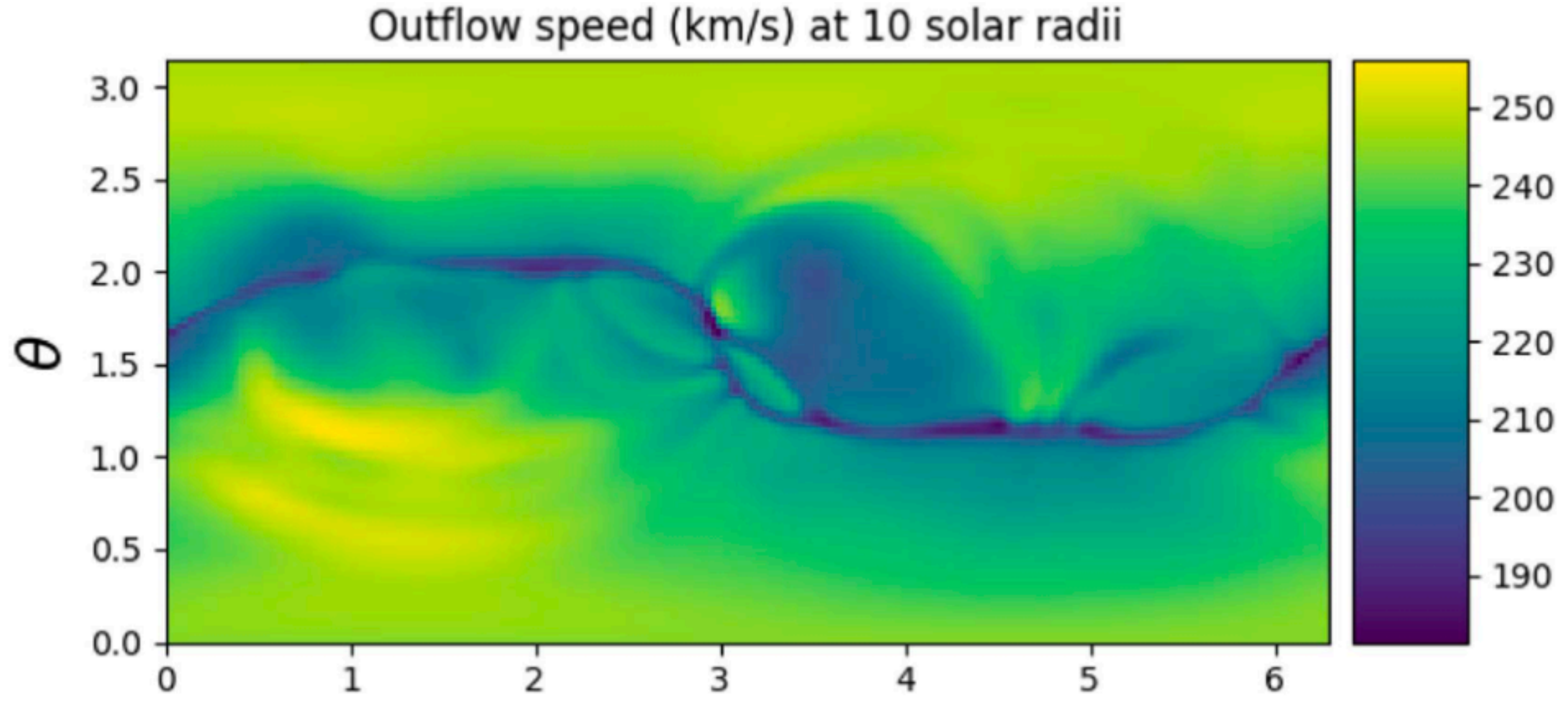
$$\rho e = \frac{p}{\gamma - 1} \qquad 1 < \gamma < 5/3$$

- Equivalent to a collisionless thermal conduction flux of the form :

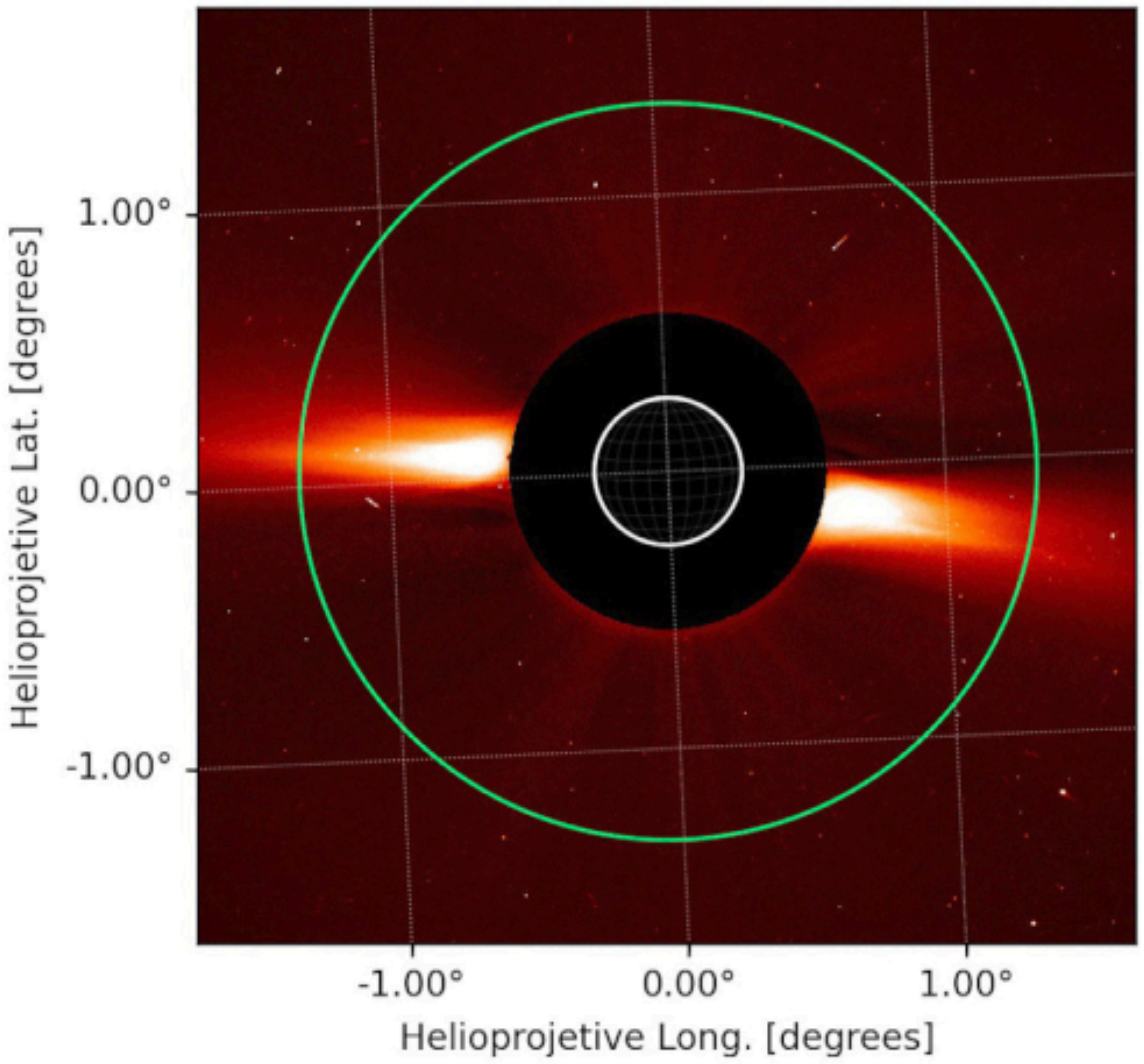
$$\vec{F}_c = \alpha p \vec{v}$$

- Very fast and efficient (hyperbolic) but :
- Monotonic temperature profile (≠ low corona)
- Cannot accelerate fast solar wind streams (≠ middle corona)





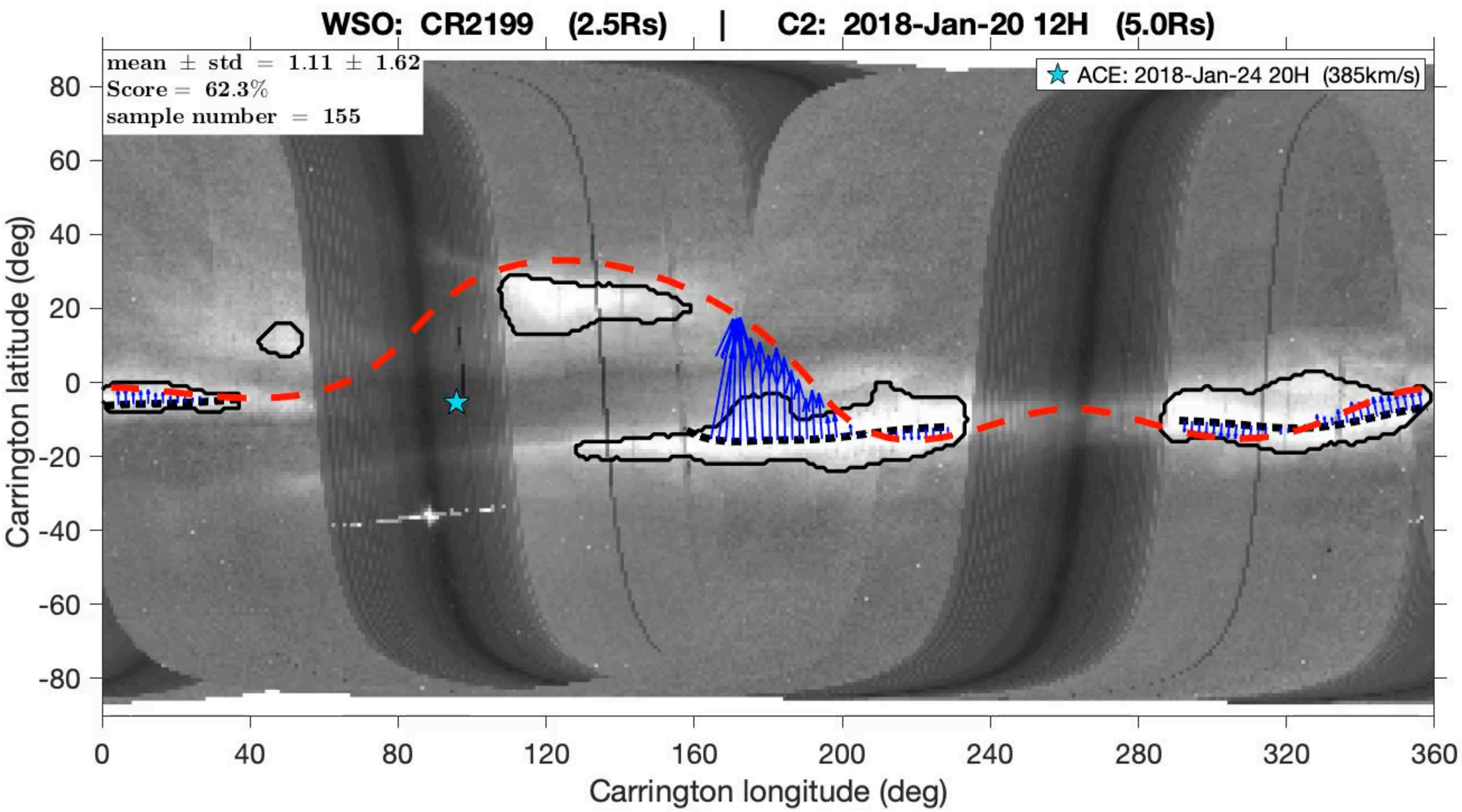
Solar maximum brightness



[Poirier et al. 2021, Frontiers ASpS]

- We use WL observations from SOHO/LASCO-C2
- Observations updated daily to recover the location of the heliospheric current (plasma) sheet.
- We take the maximum brightness as the most likely position of the HCS at 5Rs.
- Connectivity tool uses the algorithm to select best ADAPT magnetogram

Solar maximum brightness



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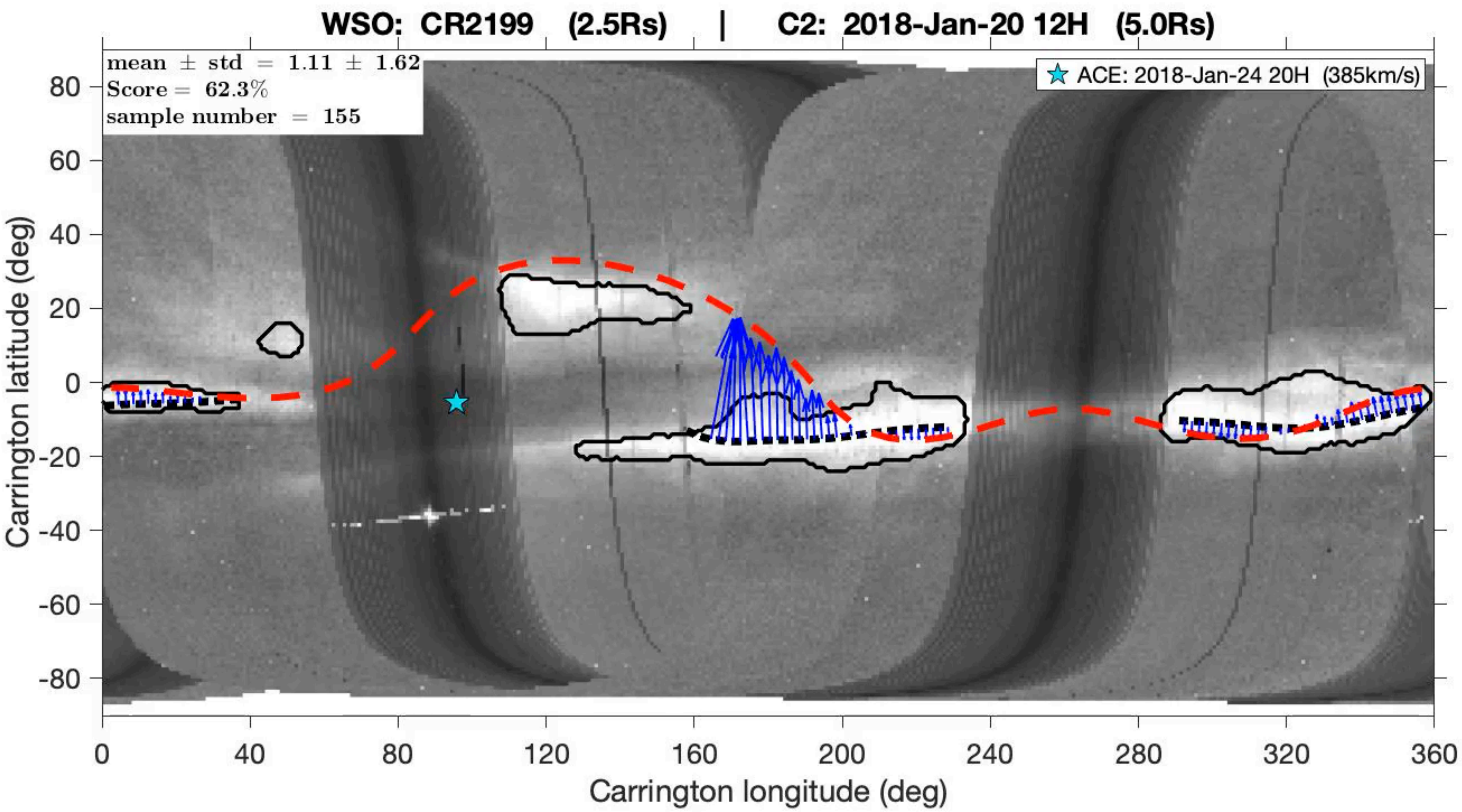

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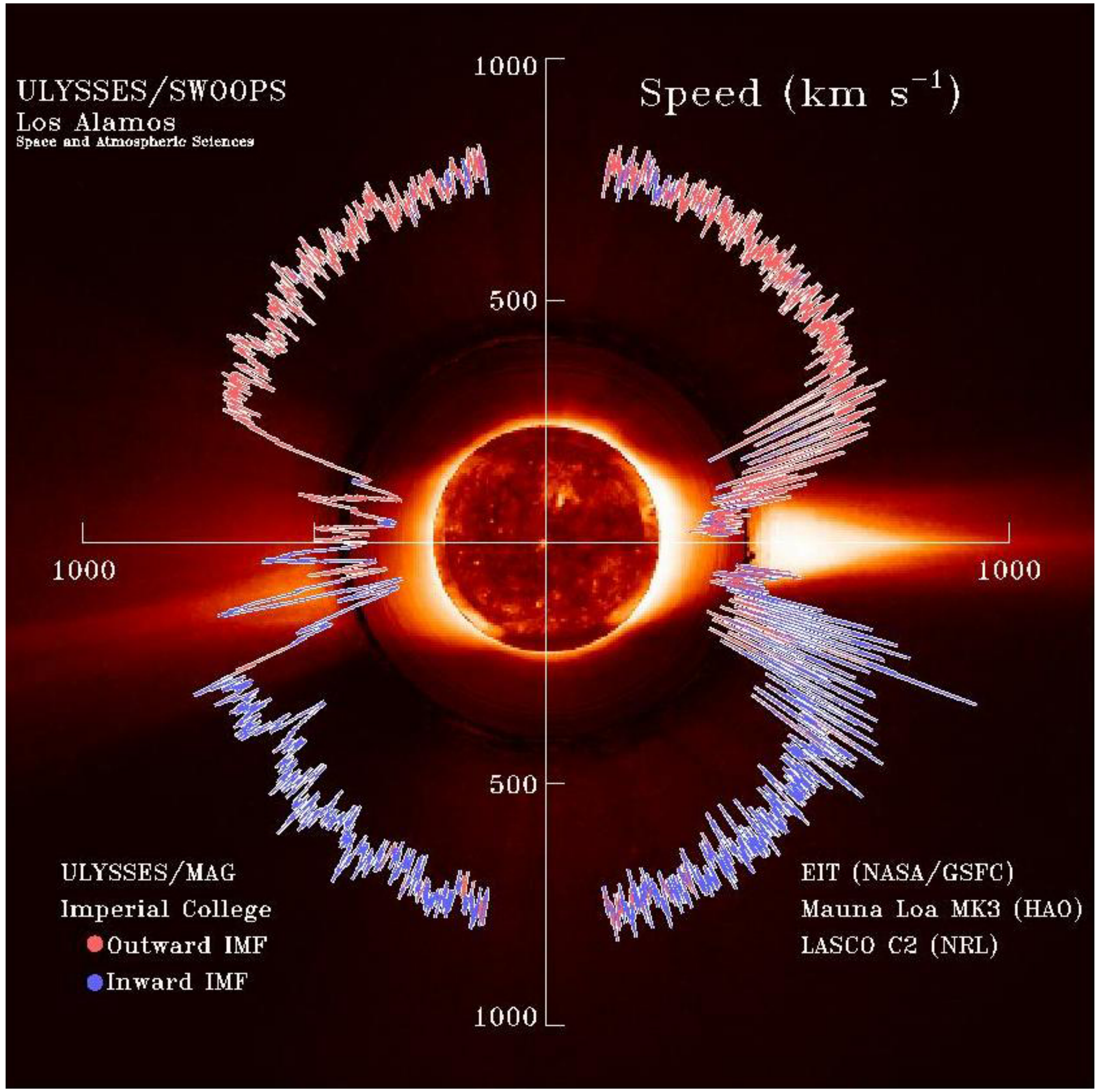
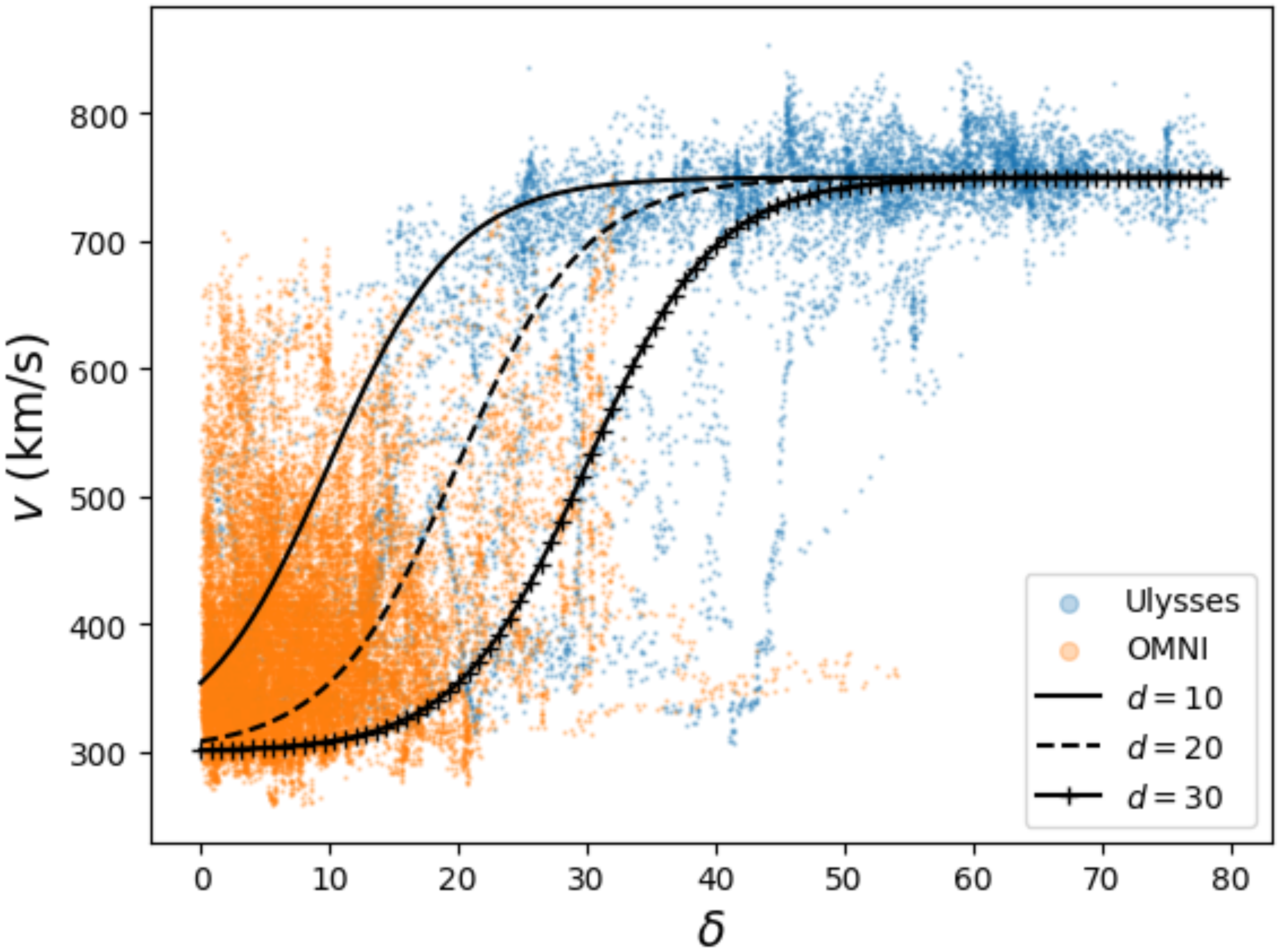
SMB and velocity



$$V(\delta) = 300 + \frac{350}{1 + e^{0.2(\delta - d)}} \text{ km/s}$$

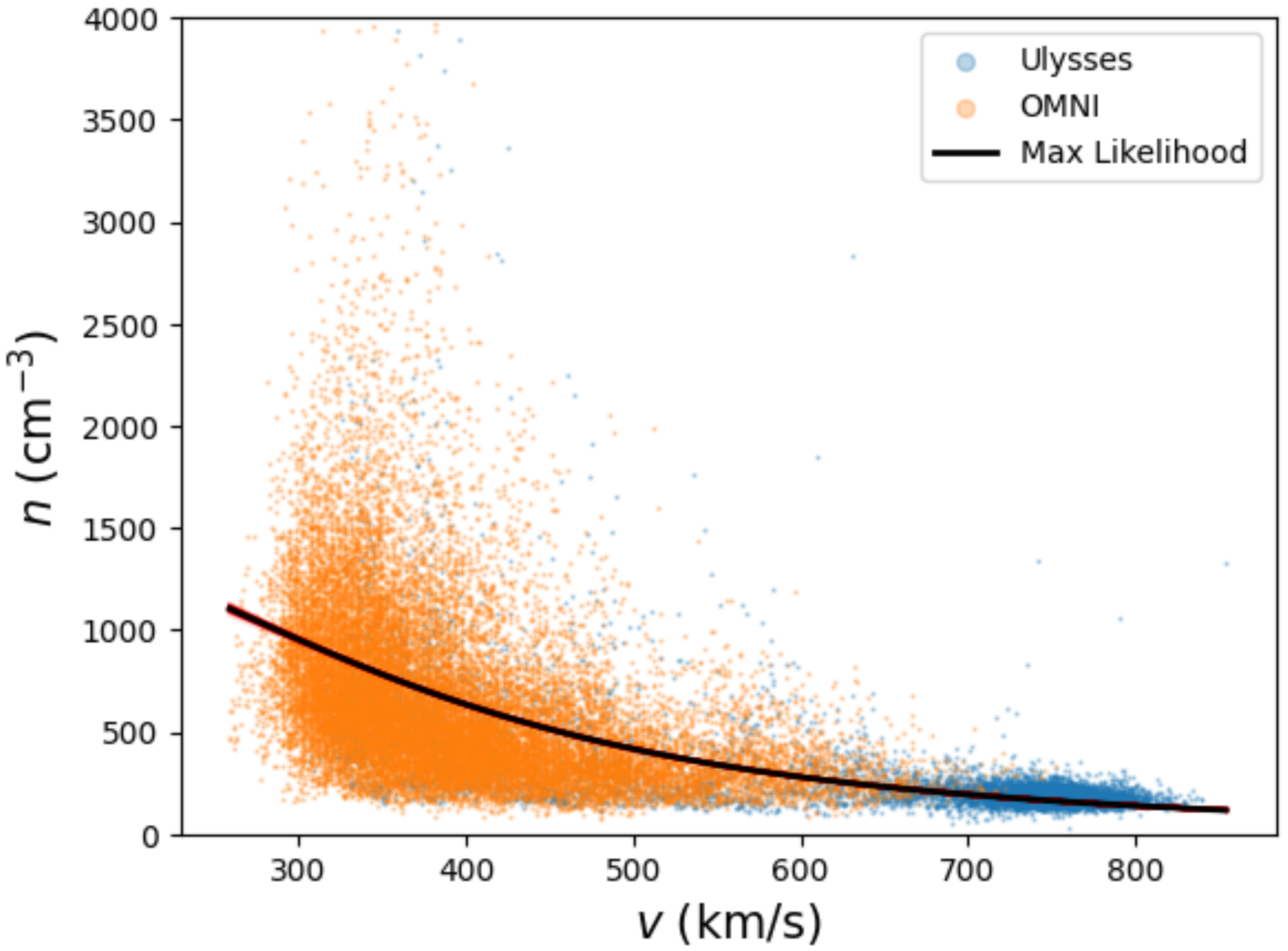


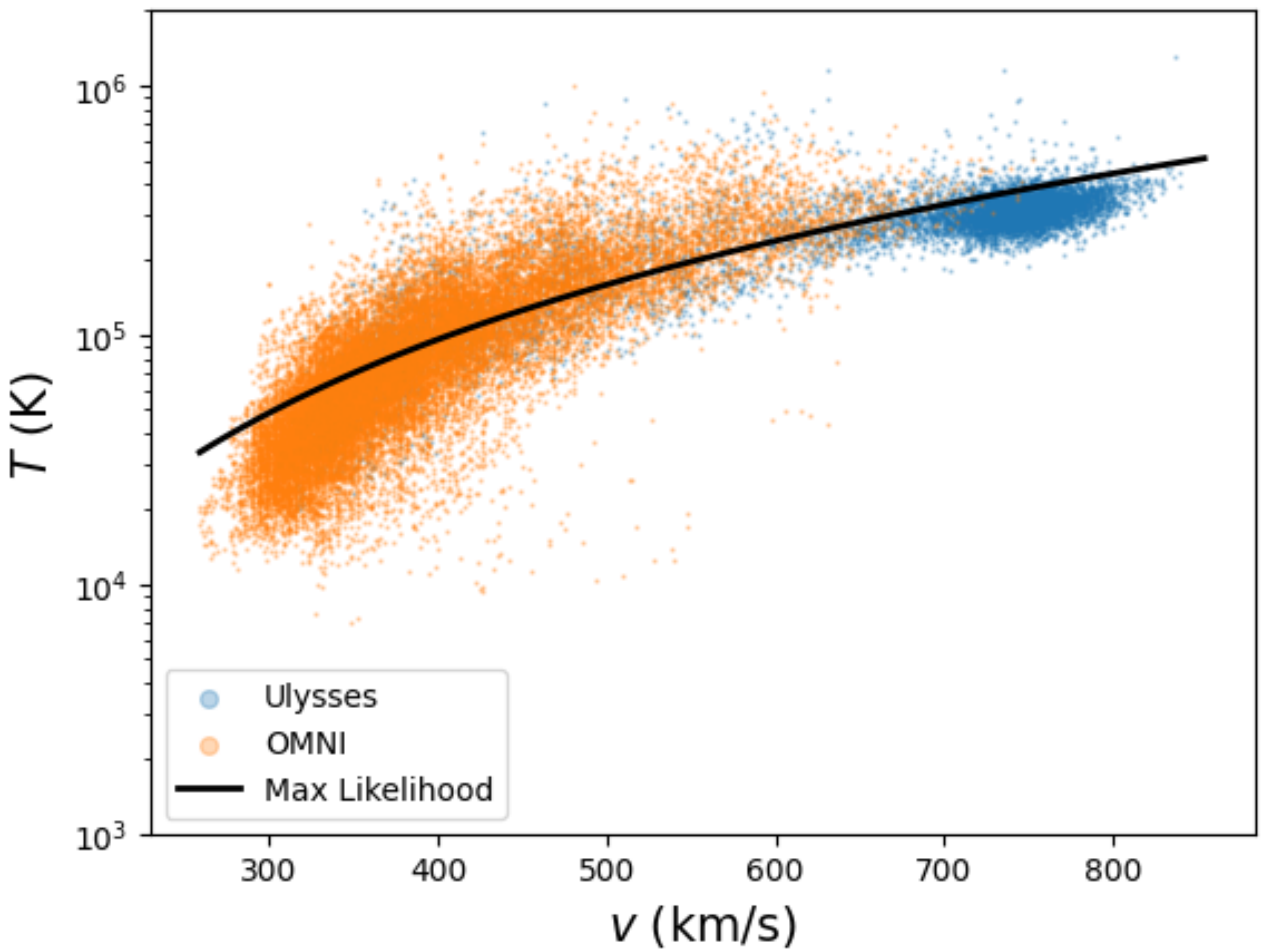
Density / Temperature

Relation with velocity at 0.1 AU

$$n(V(\delta)) = \frac{1582.6}{1 + (V(\delta)/347)^{2.8}}\ \mathrm{cm}^{-3}$$

$$T(V(\delta)) = (0.89 \times V(\delta) - 46)^2$$

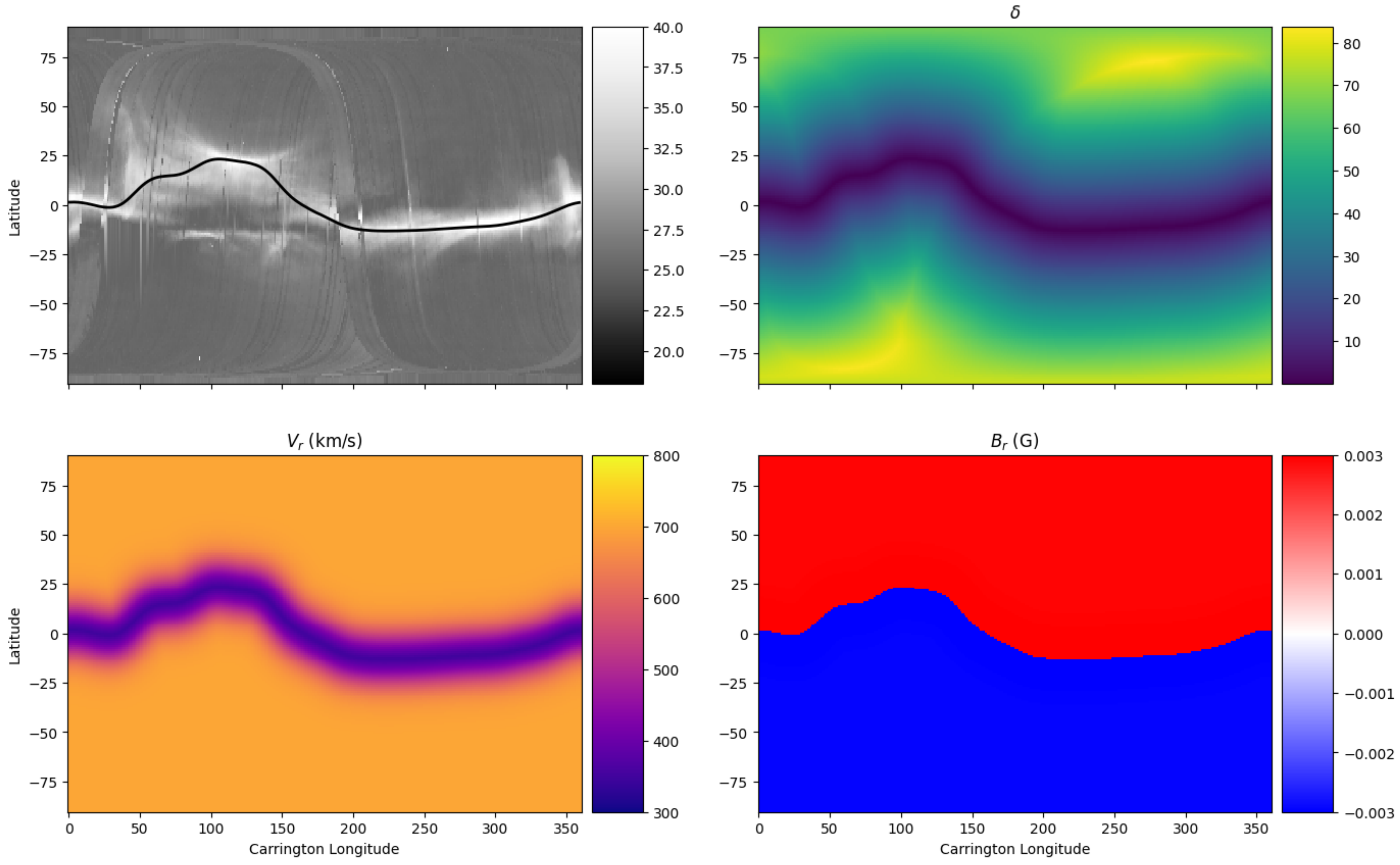




Empirical SW from SMB

Inner boundary conditions

- We identify the maximum of the solar maximum brightness with the Heliospheric Current Sheet
- Computes the angular distance delta with the SMB
- Converts delta in velocity, density and temperature
- B (3nT/AU^2) is distributed uniformly on the sphere at 0.1 AU

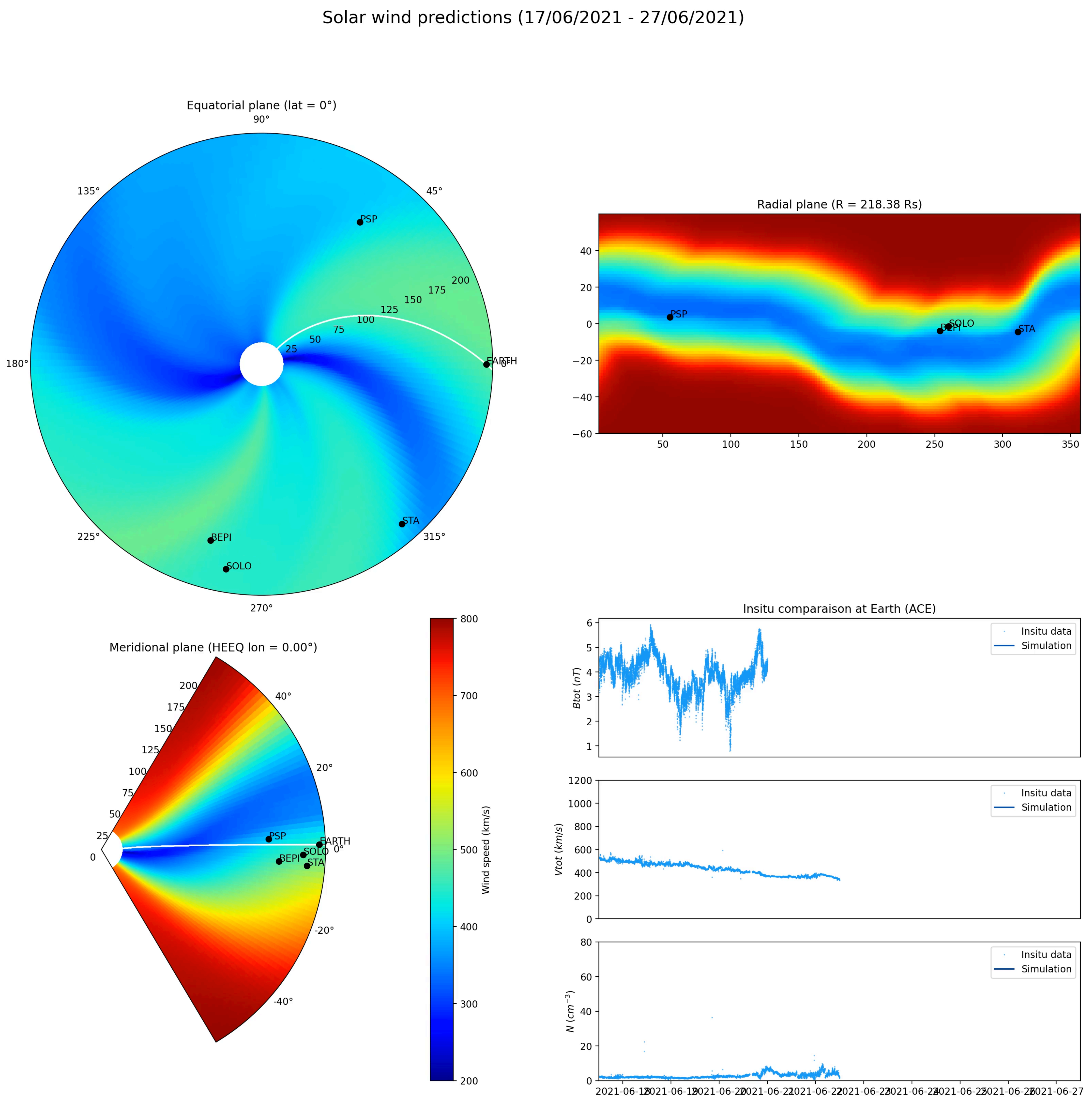


STORMS tool

HelioCast

http://heliocast.irap.omp.eu

- Based on the parallel MHD solver PLUTO [Mignone et al. 2007, ApJ]
- Godunov type Riemann solvers (HLL)
- Uses time evolving boundary conditions at 0.1 AU (super-Alfvénic regime)
- Polytropic solar wind with gamma=1.1
- Runs +7 days forecasts in a few hours (8 cores)



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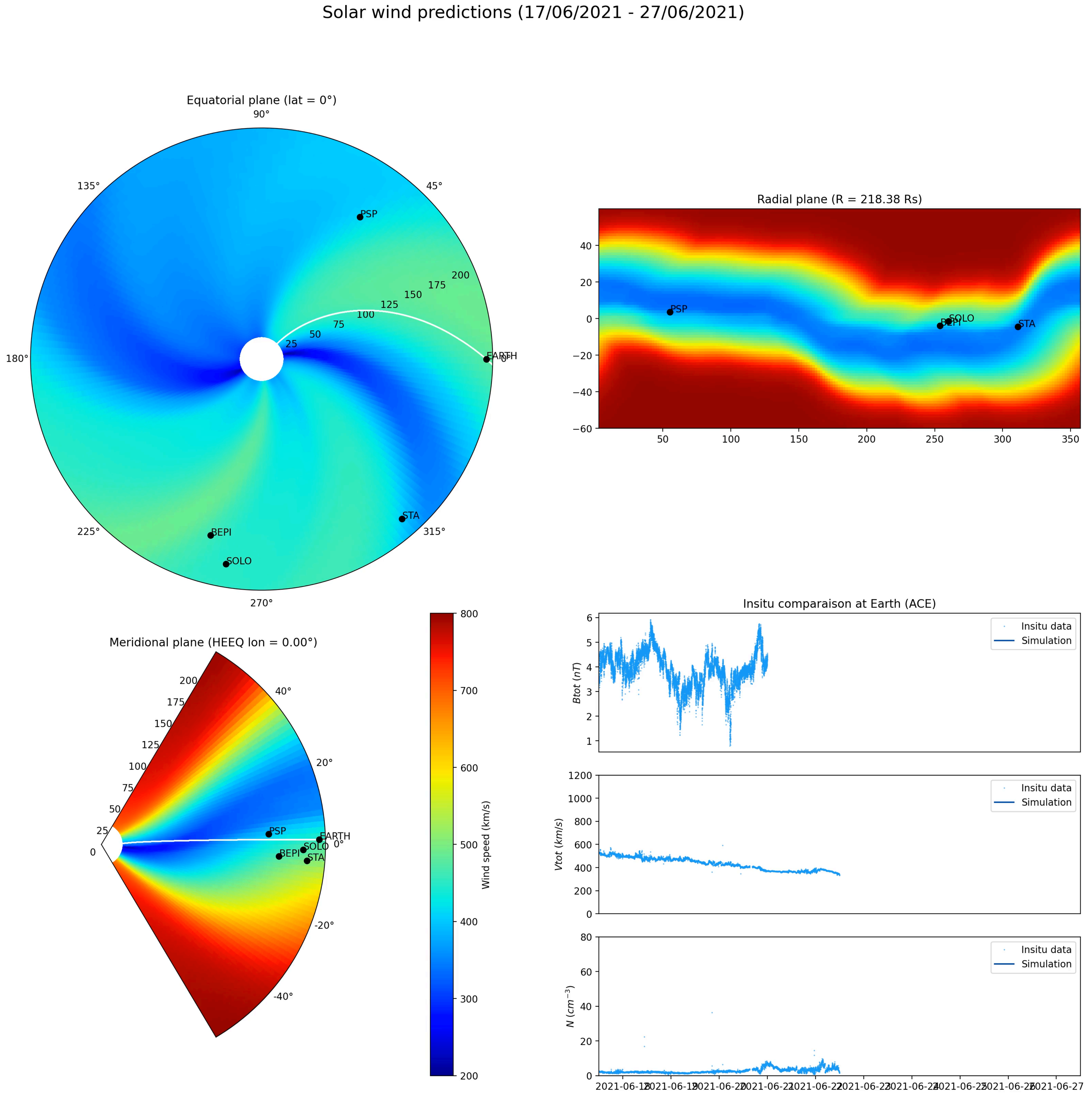
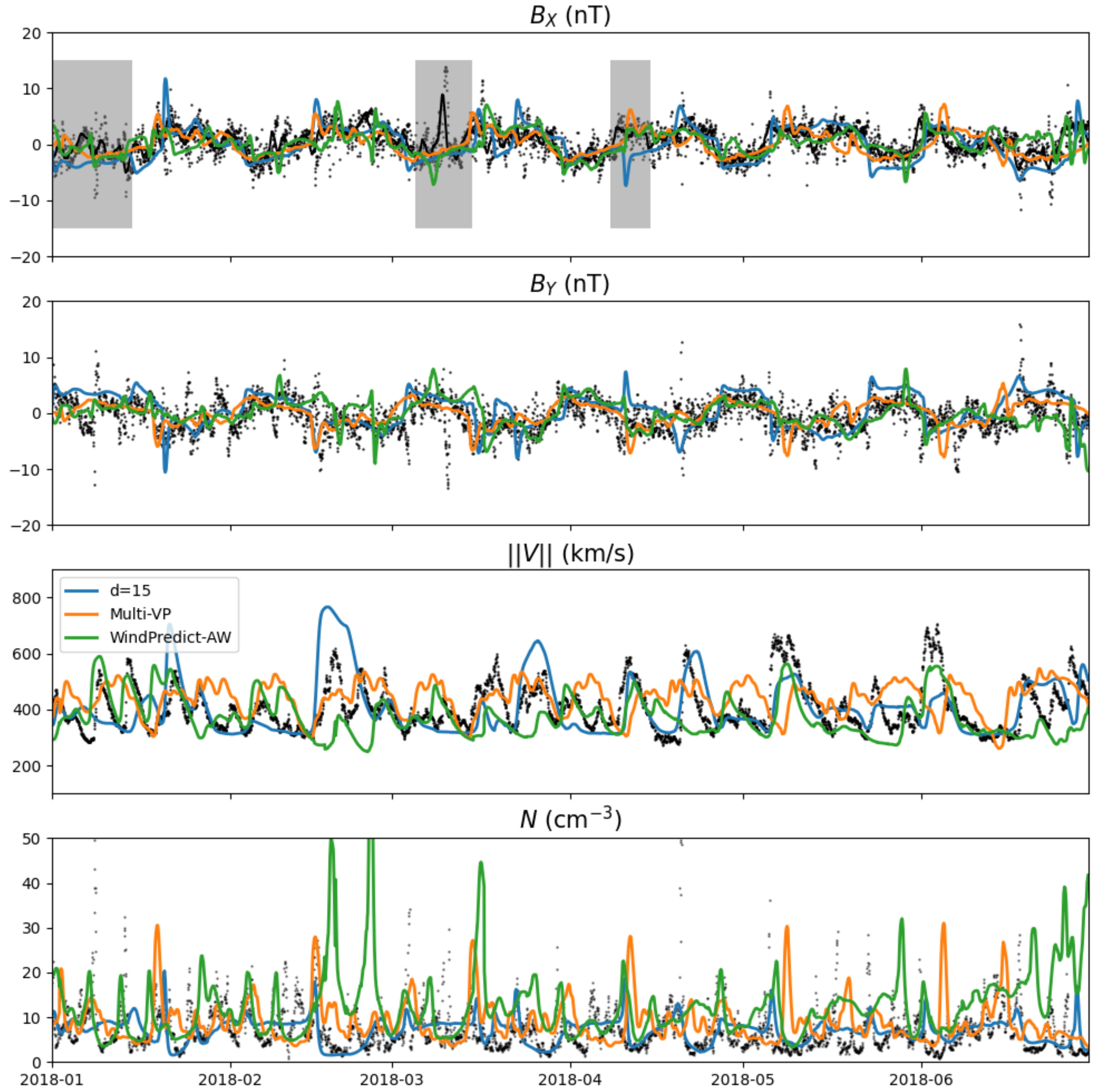


Comparison with other models

WindPredict-AW & Multi-VP: in situ

- 6 WP-AW run (one per CR)
- 6 Multi-VP run [Pinto & Rouillard 2017]
- HelioCast works as well or even better than full MHD models
- The WL technique has sometimes trouble catching the right polarity
- Leads for improvements are currently tested



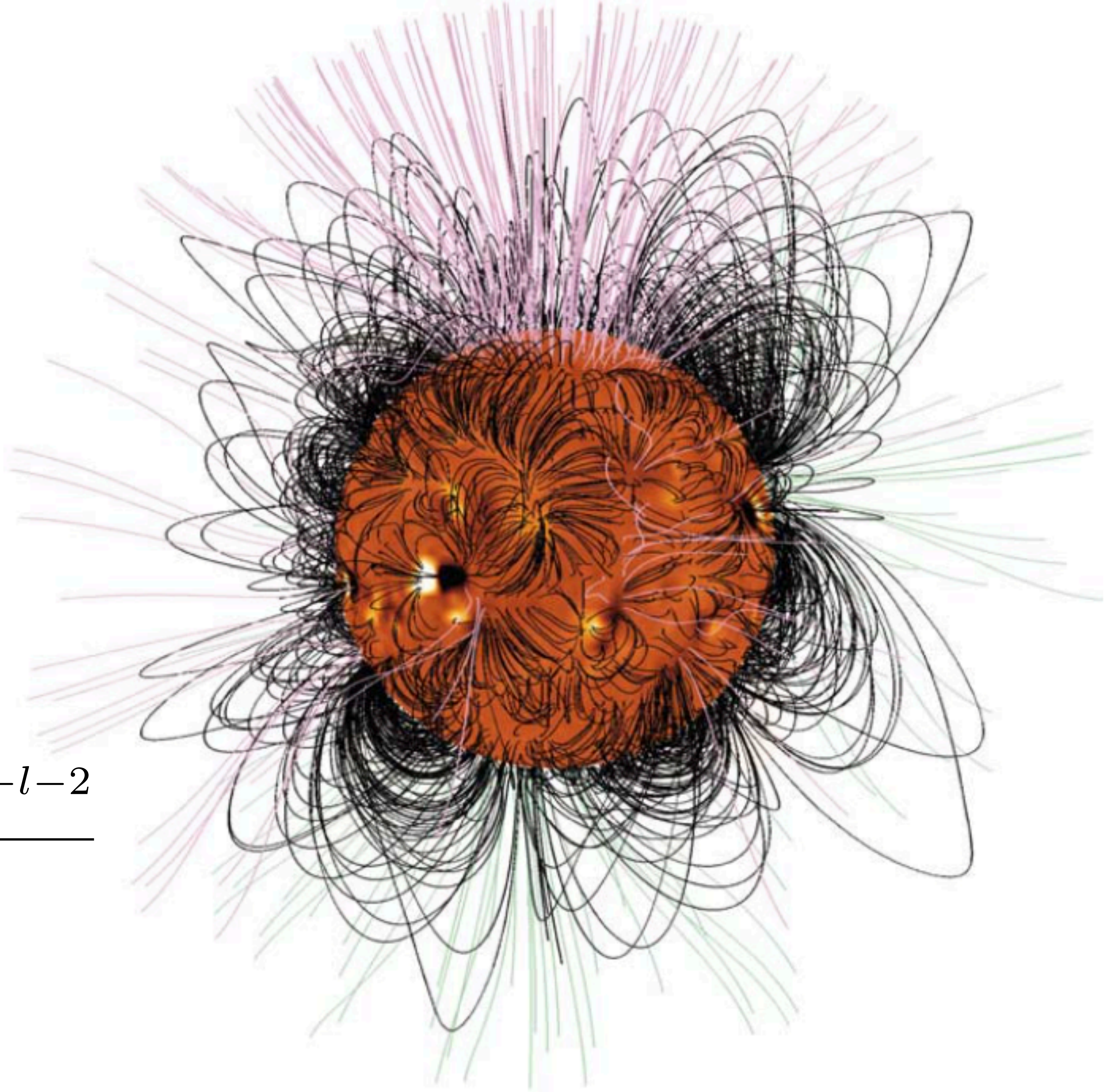
[Réville et al. 2022, submitted]

Magnetostatic / 1D MHD

Magnetostatic coronal models

Potential field source surface (PFSS) model

[Schrijver & De Rosa 2003]



The magnetic field is assumed to be current free:

$$\nabla \times \mathbf{B} = 0$$

[Schatten 1967, Altshculer & Newkirk 1967]

Decomposing the observed surface field on spherical harmonics and imposing radial field at the source surface:

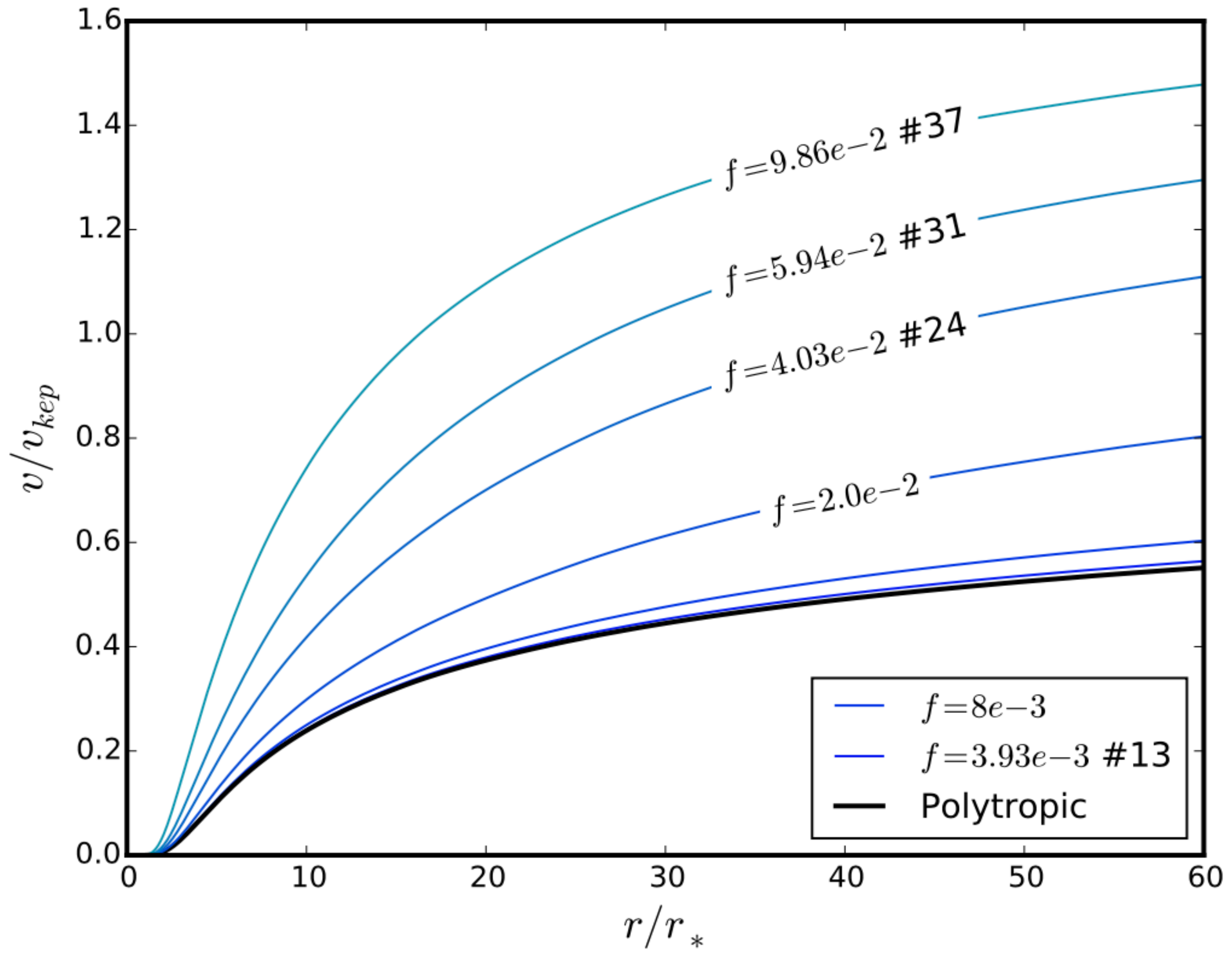
$$B_r = \sum_{lm} \alpha_{lm} Y_{lm} \frac{l(r_\odot/r_{ss})^{2l+1}(r/r_\odot)^{l-1} + (l+1)(r/r_\odot)^{-l-2}}{l(r_\odot/r_{ss})^{2l+1} + (l+1)}$$

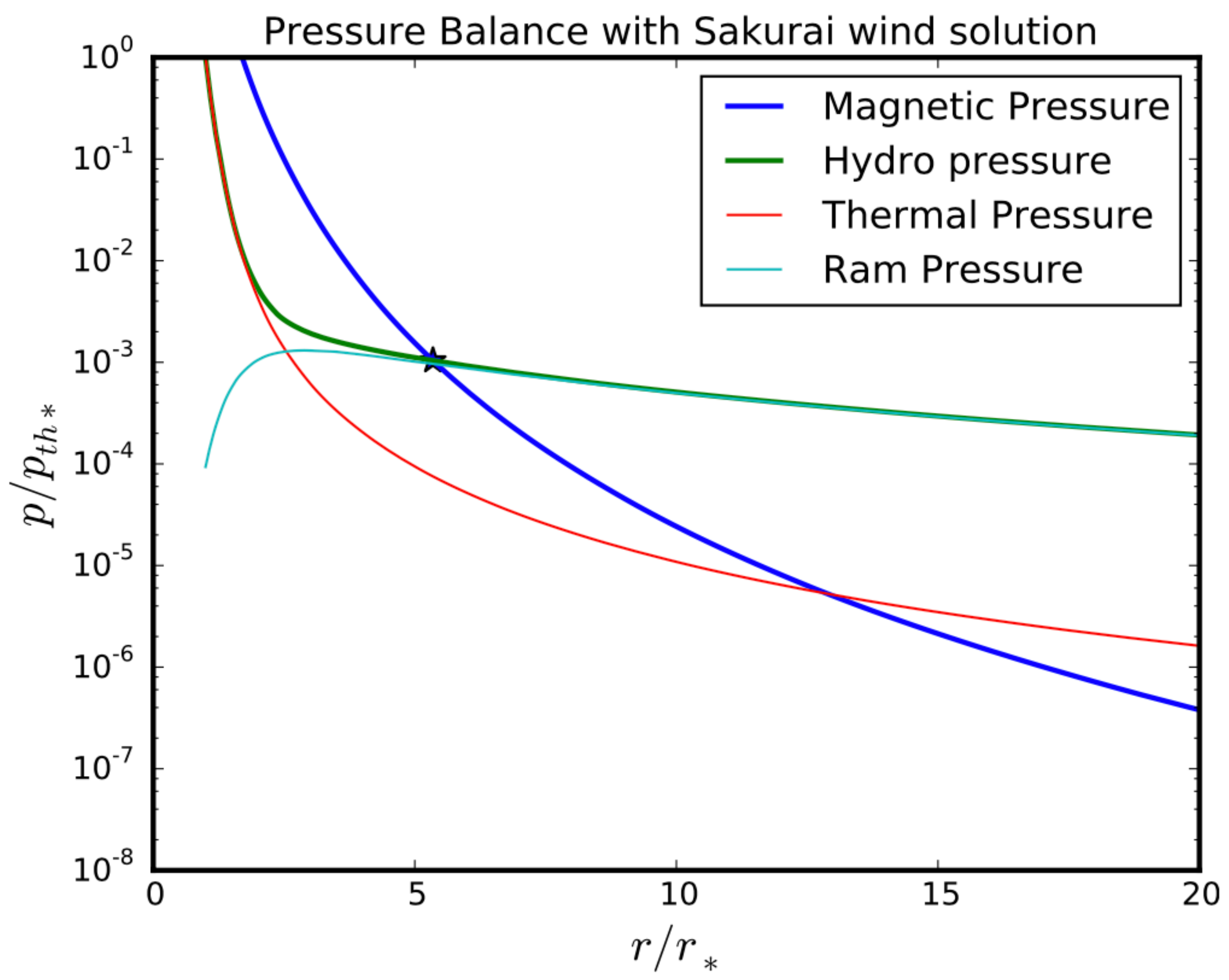
Key parameter : r_{ss}

starAML

An open source code for solar/stellar wind solutions

- Solves polytropic + magneto-centrifugal wind solutions
- Computes the location of the source surface with a pressure balance criteria
- Computes mass and angular momentum loss
- Open source python package





[Réville et al. 2015b]

https://github.com/vreville/starAML

STORMS tools

Magnetic Connectivity Tool

▼ CLOSE FORM

SPACECRAFT :

- ◉ EARTH
- ○ PARKER SOLAR PROBE
- ○ STEREO A
- ○ SOLAR ORBITER
- ○ BEPICOLOMBO
- ○ ALL

CORONAL MAGNETIC FIELD :

PFSS	MFM	PFSS/SCS
☐ WSO	☐ *DUMFRIC*	☐ *WSA*
☐ NSO		
☑ ADAPT		

INTERPLANETARY MAGNETIC FIELD :

BALLISTIC	MHD
◉ PARKER	○ *ENLIL*
	○ *HELIOCAST*

PROPAGATION MODE :

	SC ↓ SUN	SUN ↓ SC
SW LAG	○	○
EM LAG	◉	○

DATE

30 / 05 / 2022

TIME (UTC)

- ○ 00:00
- ○ 06:00
- ◉ 12:00
- ○ 18:00

Search

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CORONAL MAGNETIC FIELD :

PFSS	MFM	PFSS/SCS
☐ WSO	☐ *DUMFRIC*	☐ *WSA*
☐ NSO		
☑ ADAPT		

Future features

INTERPLANETARY MAGNETIC FIELD :

BALLISTIC	MHD
◉ PARKER	○ *ENLIL*
	○ *HELIOCAST*

PROPAGATION MODE :

	SC → SUN	SUN → SC
SW LAG	○	○
EM LAG	◉	○

DATE 30 / 05 / 2022

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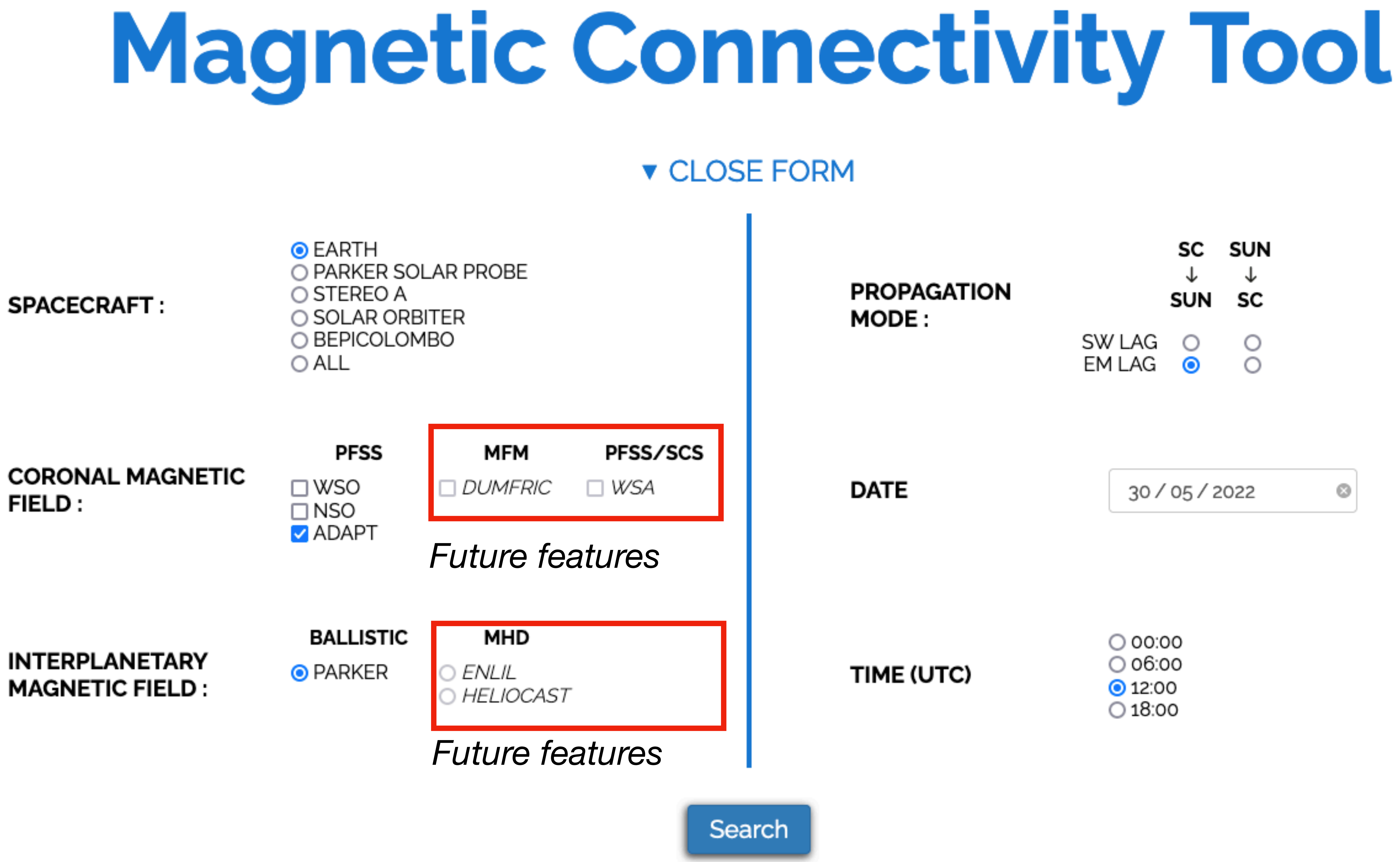
STORMS tools



STORMS tools

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PFSS	MFM	PFSS/SCS
☐ WSO	☐ *DUMFRIC*	☐ *WSA*
☐ NSO		
☑ ADAPT		

Future features

INTERPLANETARY MAGNETIC FIELD :

BALLISTIC	MHD
(●) PARKER	( ) *ENLIL*
	( ) *HELIOCAST*

Future features

PROPAGATION MODE :

	SC ↓ SUN	SUN ↓ SC
SW LAG	( )	( )
EM LAG	(●)	( )

Reference time
+ propagation time
SW ~few days
EM ~instantaneous

DATE

30 / 05 / 2022

TIME (UTC)

- ( ) 00:00
- ( ) 06:00
- (●) 12:00
- ( ) 18:00

Search

STORMS tools

Magnetic Connectivity Tool

▼ CLOSE FORM

SPACECRAFT :

- EARTH (selected)
- PARKER SOLAR PROBE
- STEREO A
- SOLAR ORBITER
- BEPICOLOMBO
- ALL

CORONAL MAGNETIC FIELD :

PFSS
- WSO
- NSO
- ADAPT (checked)

MFM
- *DUMFRIC*

PFSS/SCS
- *WSA*

Future features

INTERPLANETARY MAGNETIC FIELD :

BALLISTIC
- PARKER (selected)

MHD
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Future features

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SW LAG	○	○
EM LAG	◉	○

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SW ~few days
EM ~instantaneous

DATE

30 / 05 / 2022

TIME (UTC)

- 00:00
- 06:00
- 12:00 (selected)
- 18:00

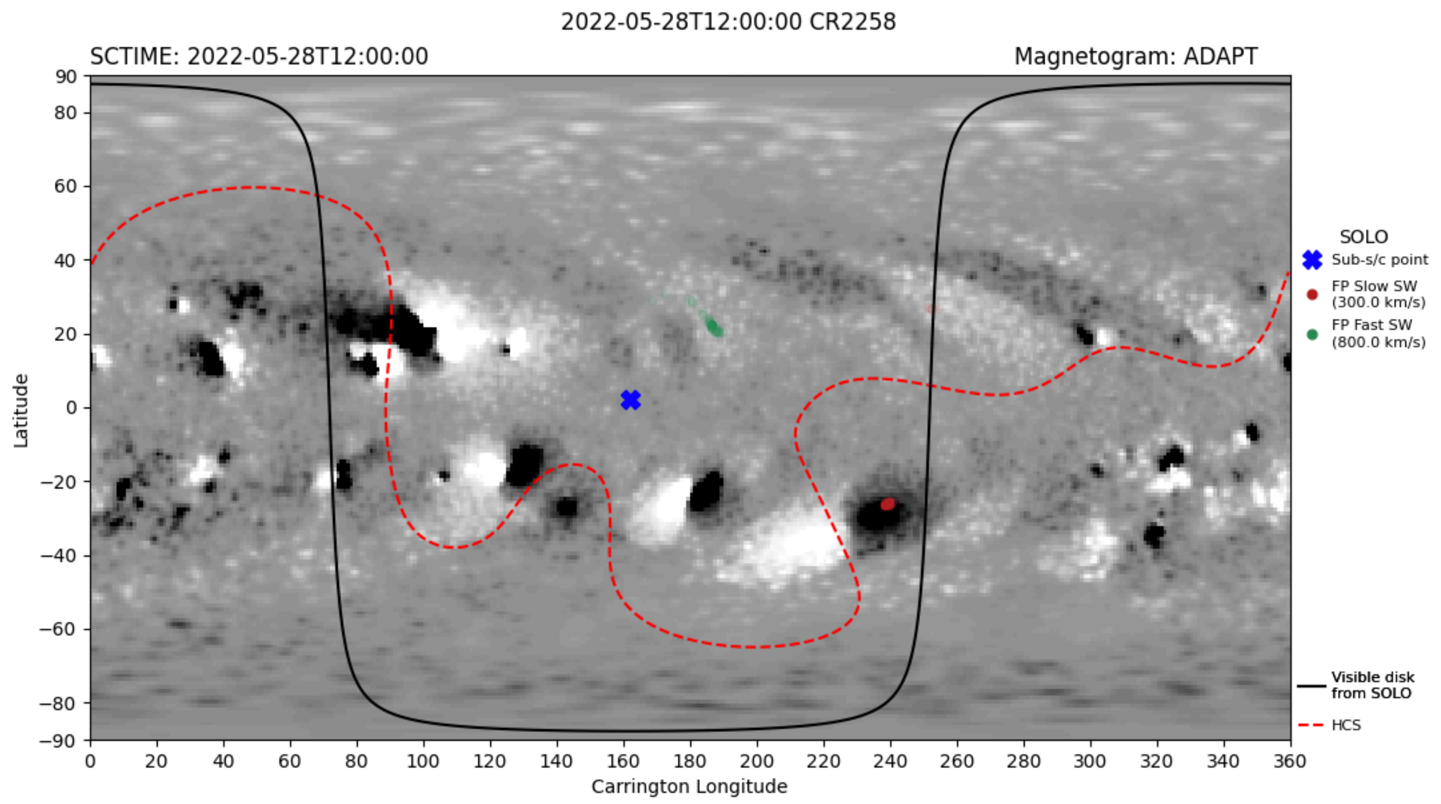
Computed every 6 hours

Search

Solar Orbiter Operations

Deciding the pointing in (almost) real time

adapt



Mode : SCIENCE

Coronal Model : PFSS (rss = 2.0 Rsun)

Magnetogram : ADAPT-11 (2022-05-28 12:00:00 UTC)

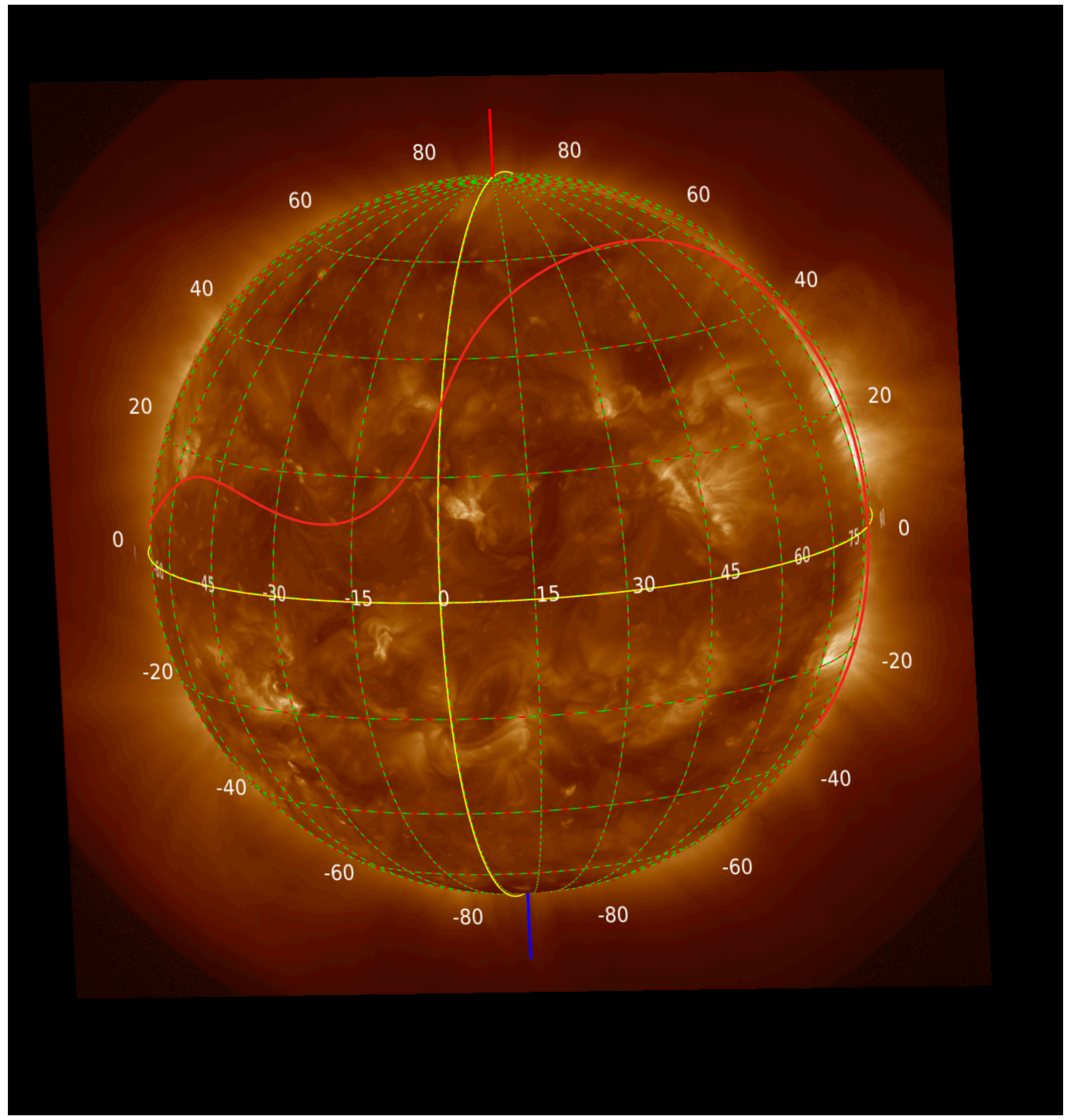
Reliability Test (WL) : 83.13%

▼ Download Data

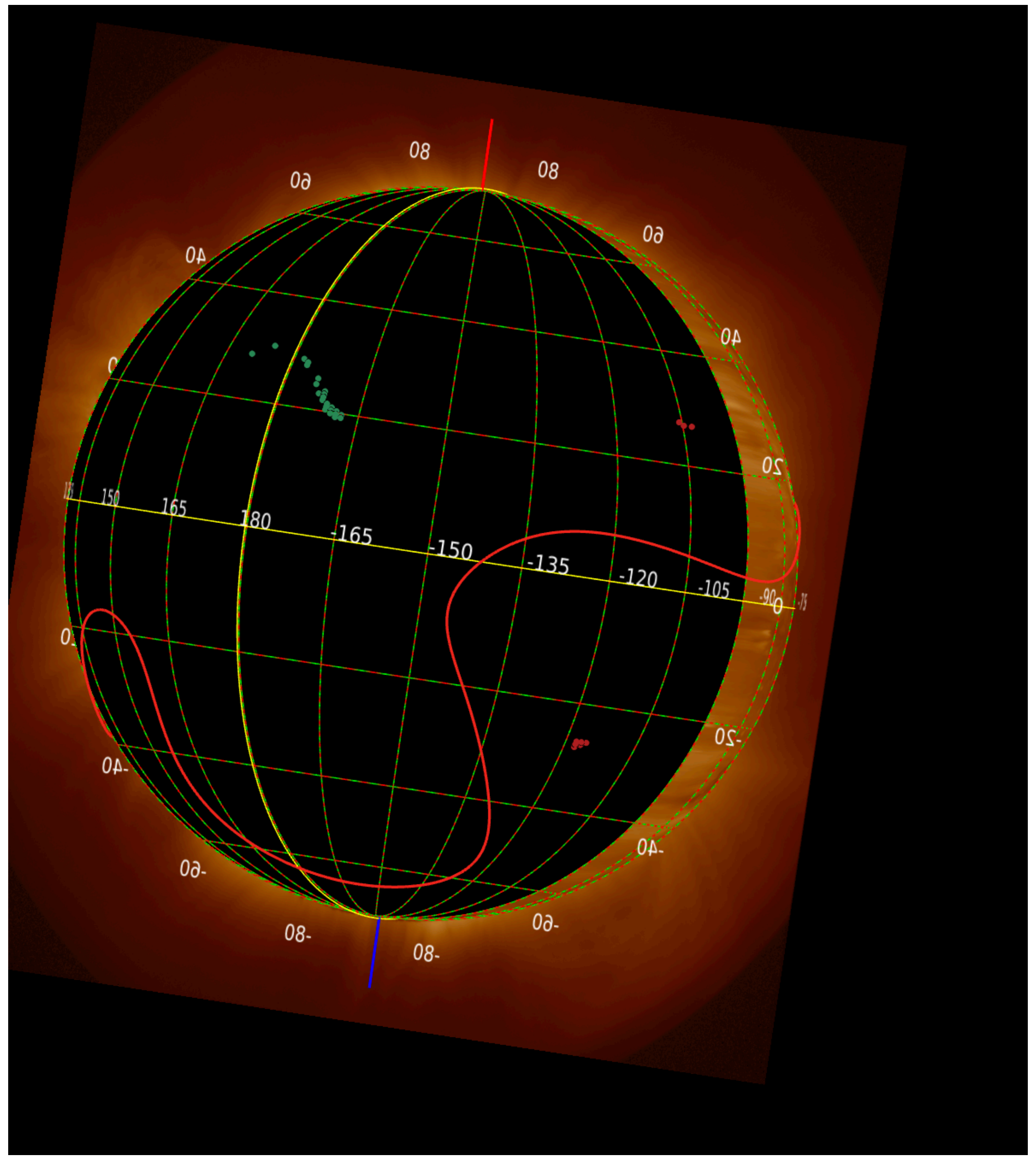
Download image

- Connectivity file ASCII JSON
- HCS file ASCII JSON
- Visible disk file ASCII JSON
- Flare file ASCII JSON
- X Flare file ASCII JSON
- CME file ASCII JSON
- FP file ASCII JSON
- Fieldline file ASCII JSON

JHelioviewer



May 5th AIA 193 image



Solar Orbiter connectivity points

Summary

Science

- Full MHD : no sharing so far. But a database of interesting periods has been considered
- Simple, semi-analytic model shared on GitHub but very few users…

Forecast and operation support

- Lots of reduced products shared through diverse formats
- A lot of users through dedicated interfaces (websites)
- Dedicated service funded by many projects (ERC, ANR, H2020)

astrophysique & planétologie

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Solar Terrestrial ObseRvations and Modeling Service

ESA | NASA

solar orbiter