Impact of magnetic photospheric observations on the modelling of coronal and heliospheric magnetic structures

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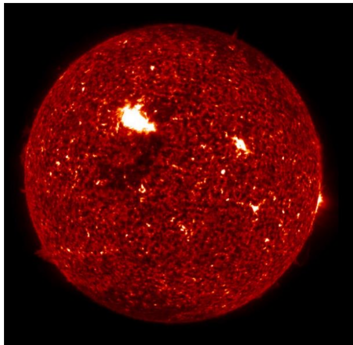
Horizon 2020

von KARMAN INSTITUTE FOR FLUID DYNAMICS

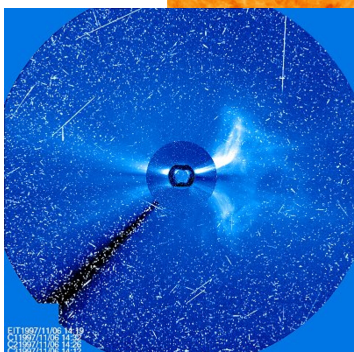
Space weather

[GOES17]

flares

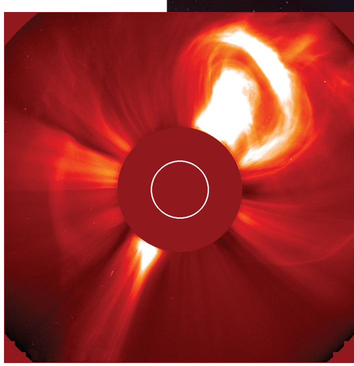


SEPs



[NASA]

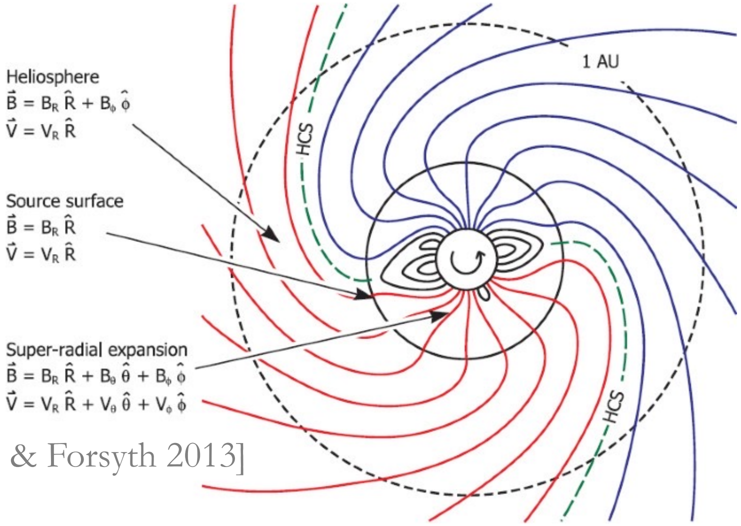
CMEs



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

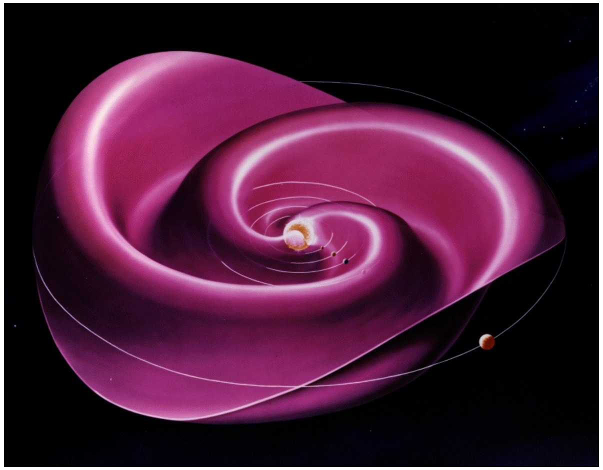
Heliospheric structures

Magnetic field



[Owens & Forsyth 2013]

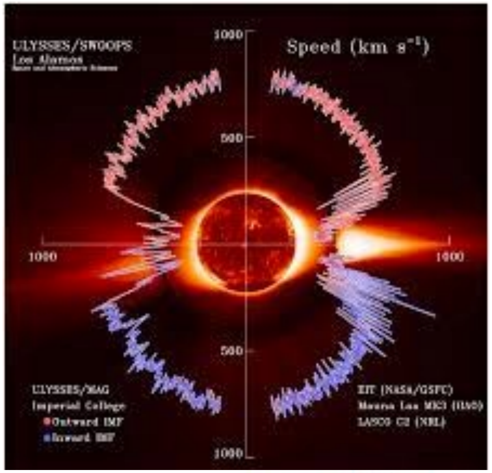
[NASA]



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

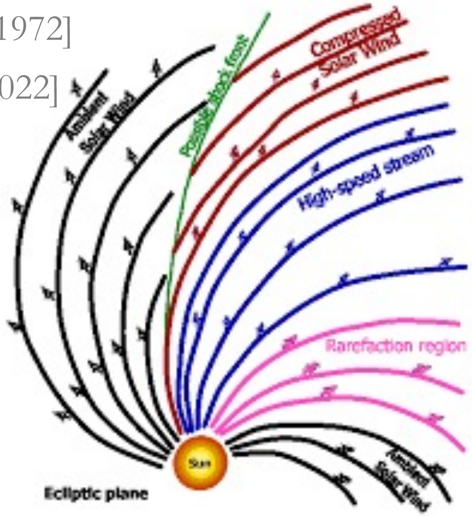
Solar wind

[McComas+2003]



[Hundhausen 1972]

[Carnevale+2022]

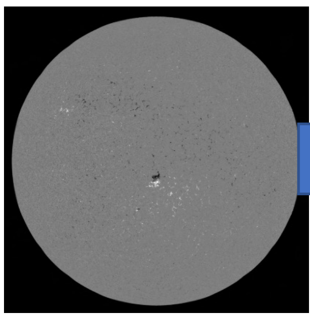


High-Speed Streams (HSS) +
Co-rotating Interacting Regions (CIRs)

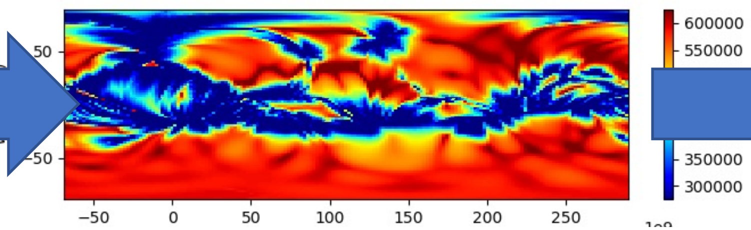
EUHFORIA 2.0

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

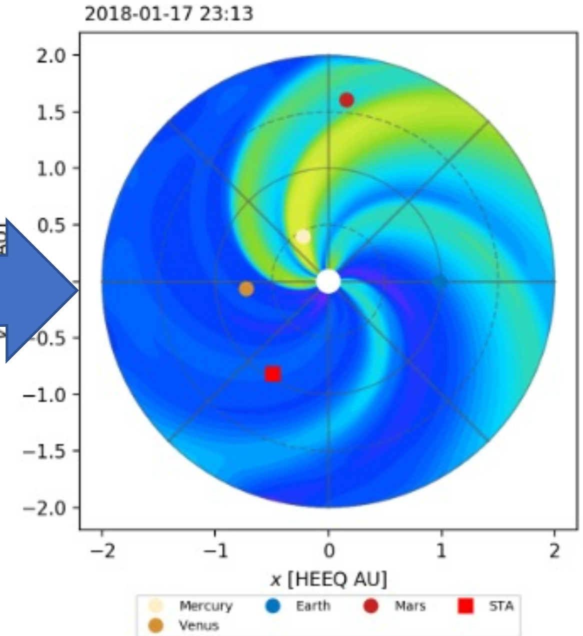
[SDO/HMI]



$1\ R_\odot$



$20\ R_\odot$



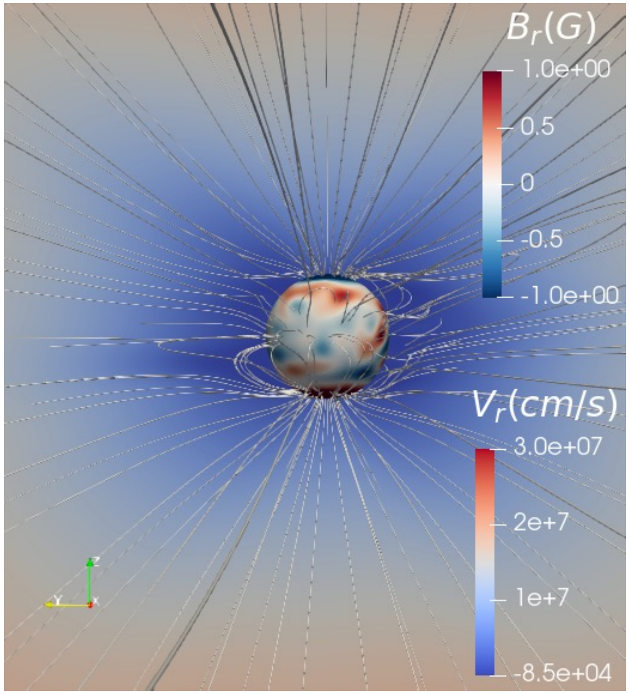
$20\ R_\odot - 2\ UA$

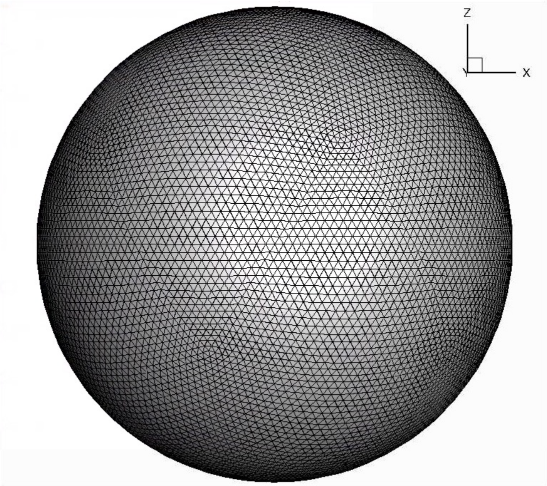
The extrapolations from 1 to 20 solar radii are semi-empirical

→ this is where most of the structures are created!

→ we want to replace it with a more physical code (MHD) BUT still fast!

[Perri+2022a] (under review)





[Brchnelova+2022]

COCONUT

COolfluid COronal uNstrUcTured

→ Based on the **COOLFluiD** framework

[Lani+2005/2006, Kimpe+2005, Maneva+2017]

Ideal MHD model for the solar wind in the corona (from 1 to 25 solar radii):

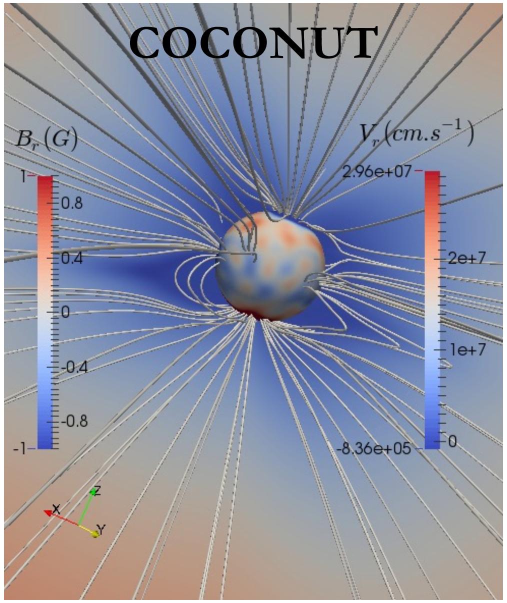
- Cartesian geometry
- Finite volume + Riemann solvers
- Polytropic heating

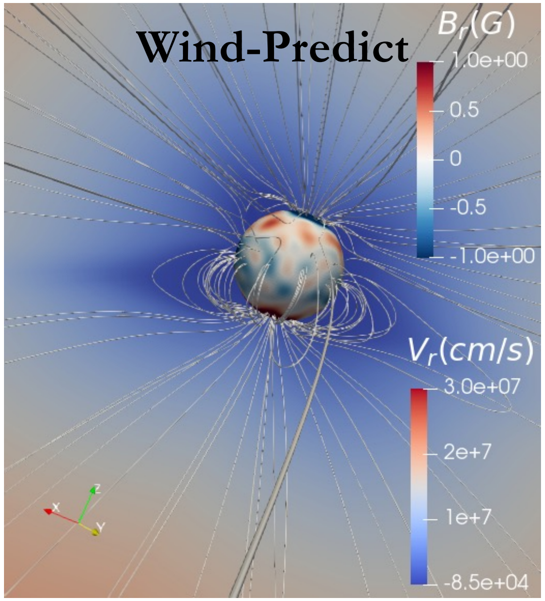
Advantages:

- **Unstructured** mesh → **no singularity** at the solar poles
- **Implicit** solving method → **fast** and accurate

[Perri+2022a] (under review)

Validation of the code





[Réville+2015a, Perri+2018]

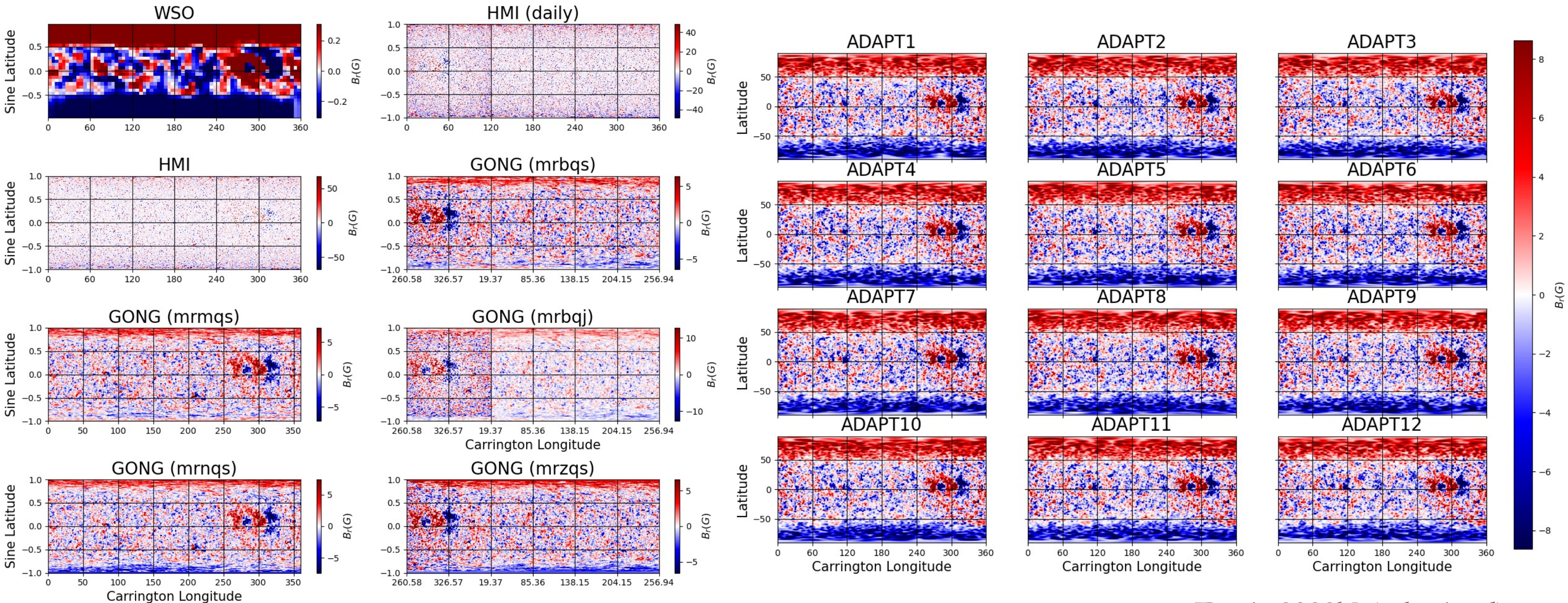
Benchmark with both **simulations** (Wind-Predict) and **observations** (WL + EUV)

Verification of the speed-up of the implicit solver → **operational running times**

Configuration	COCONUT running time
Dipole	5.9 min
Quadrupole	11.9 min
Magnetic map (l_{max} = 15)	87.5 min (1h28)
Magnetic map (l_{max} = 30)	86.8 min (1h27)

Impact of the input map

Diversity of magnetic maps available for each date (resolution, polar extrapolation...)
→ Test of all 20 maps available for a typical minimum of activity (2nd of July 2019)



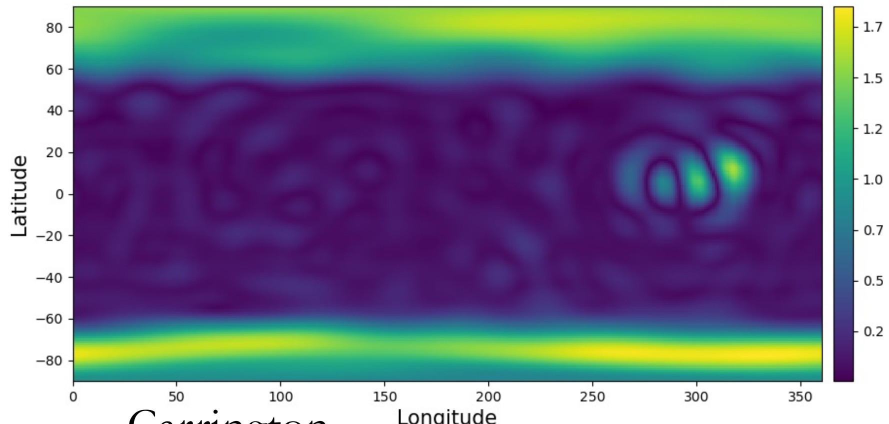
[Perri+2022b] (submitted)

Aims of the study:

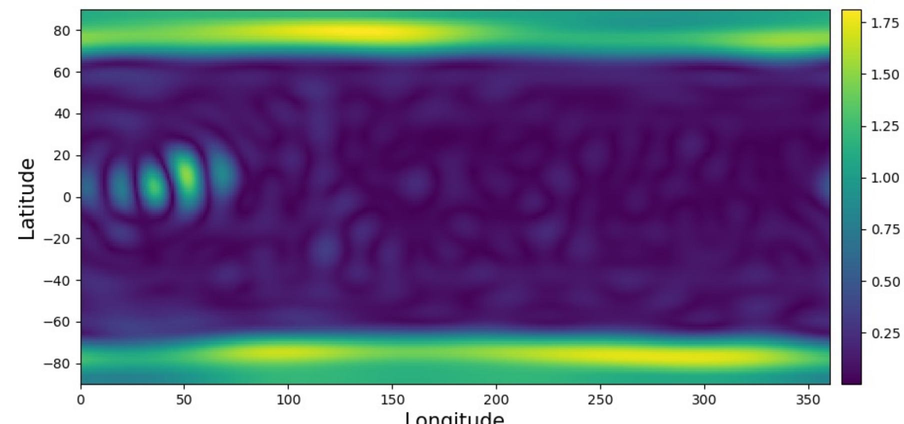
- Quantify which map works best at minimum of activity
- Evaluate the impact of the solar poles (space weather + Solar Orbiter)

Pre-processing of the maps

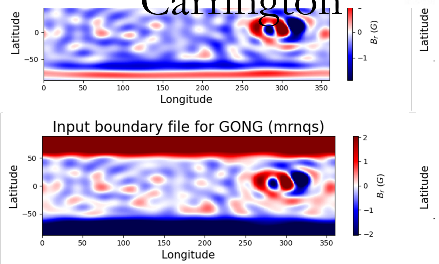
We apply a pre-processing by spherical harmonics cutting ($l_{max} = 15$)
→ Magnetic maps smoothened

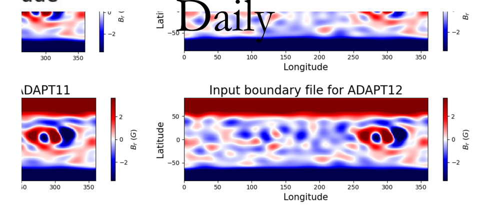


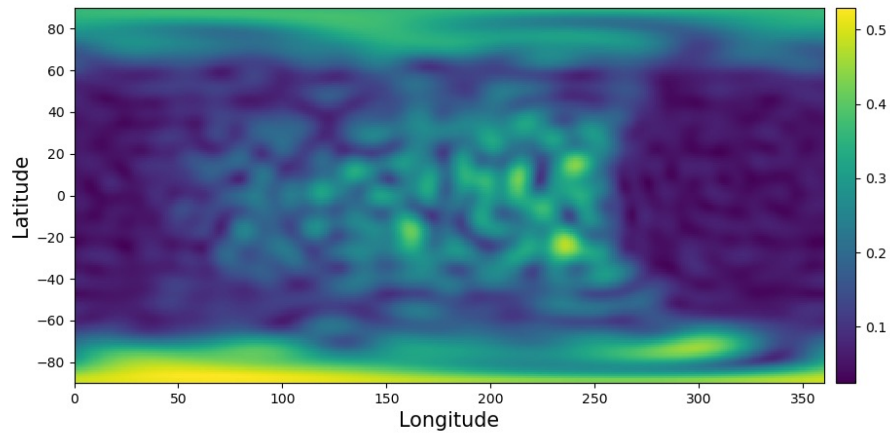
Carrington



Daily







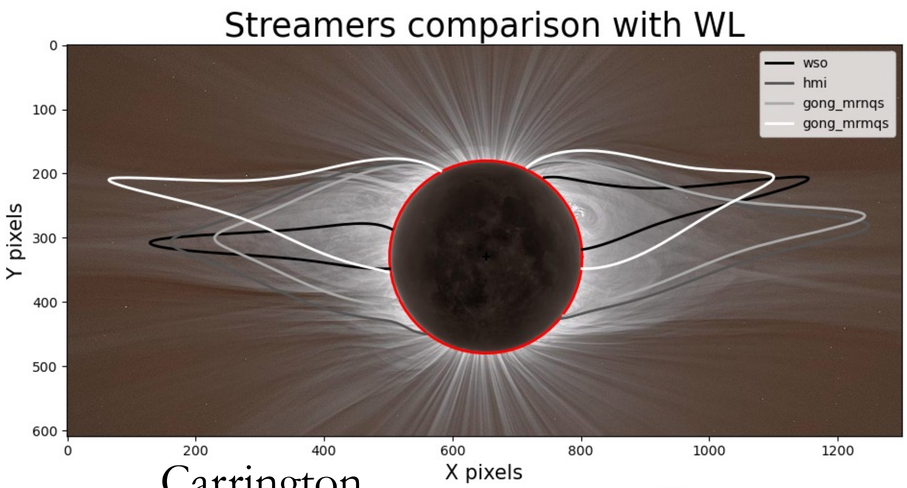
ADAPT

[Perri+2022b] (submitted)

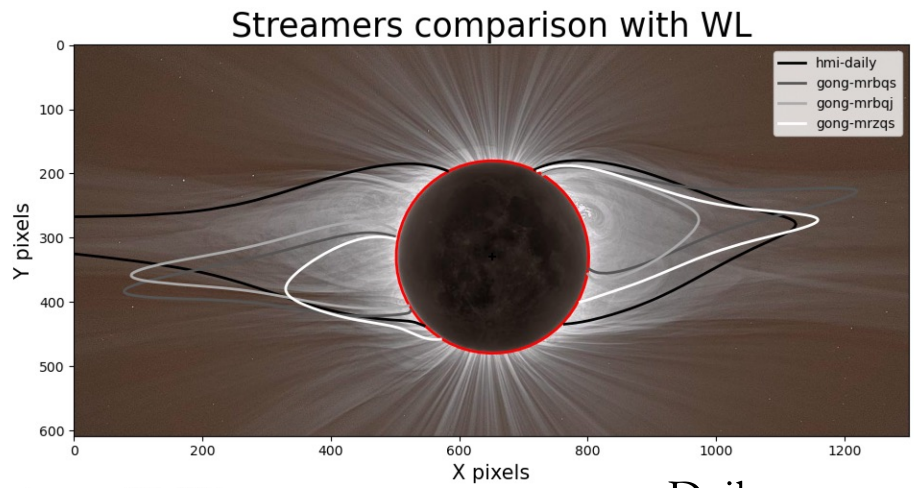
Standard deviation for 3 categories of maps (Carrington-frame, daily-frame, GONG-ADAPT frame)
→ The biggest source of difference between the maps are the poles

Comparison with observations: WL for streamers

We use white-light images of the corona to estimate the size and shapes of the magnetic streamers

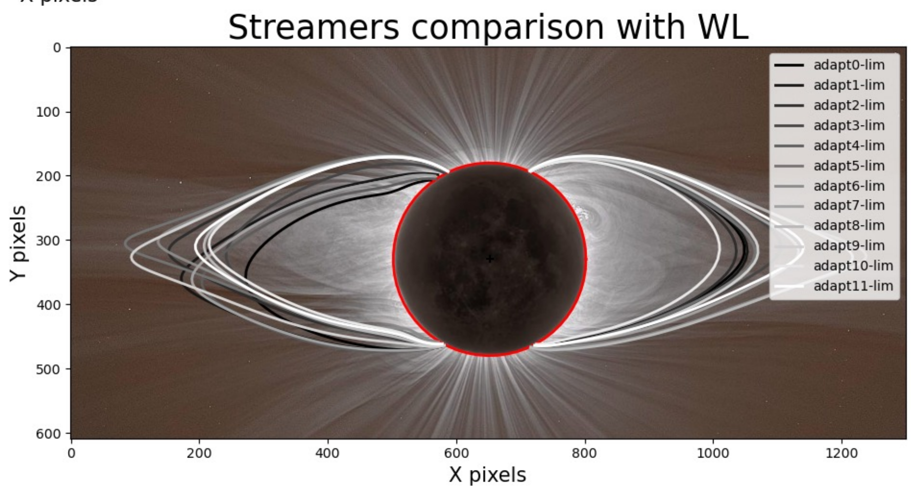


Carrington



Daily

[Perri+2022b] (submitted)



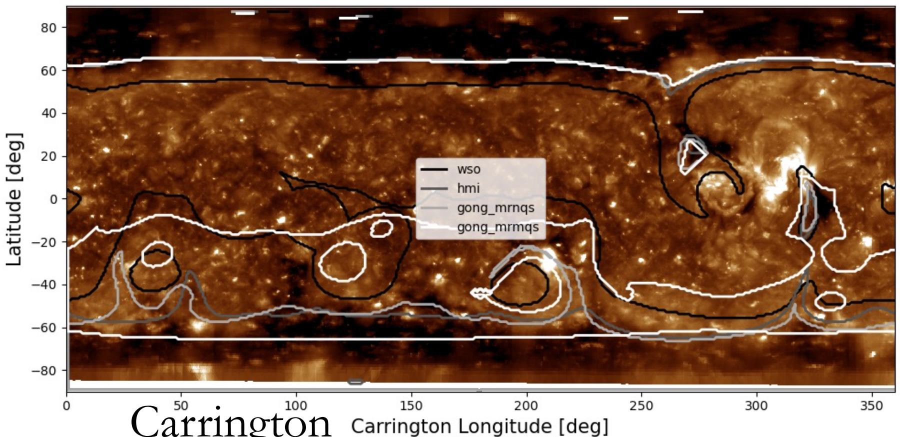
ADAPT

Already a lot of differences just for minimum of activity!

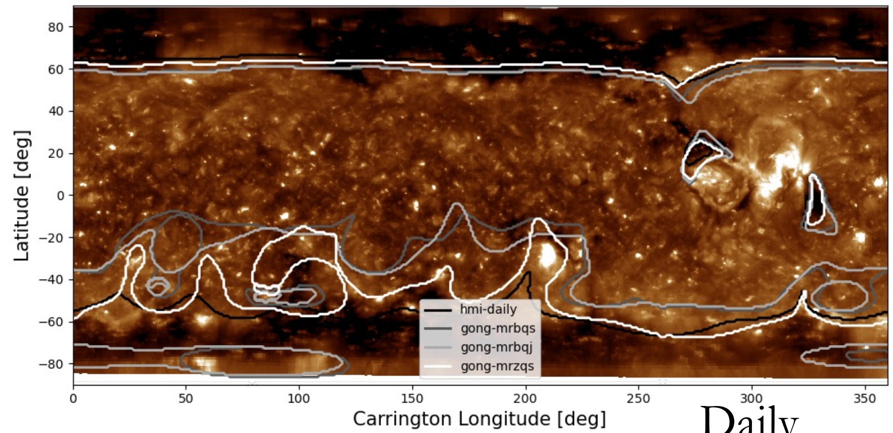
→ non-corrected WSO and GONG are off, the others perform well

Comparison with observations: EUV for coronal holes

We use EUV images of the corona to estimate the size and shapes of the coronal holes (CHs)

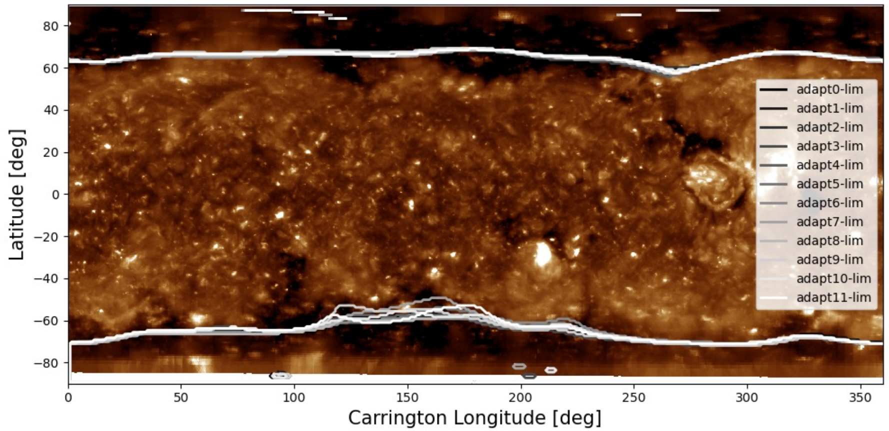


Carrington



Daily

[Perri+2022b] (submitted)



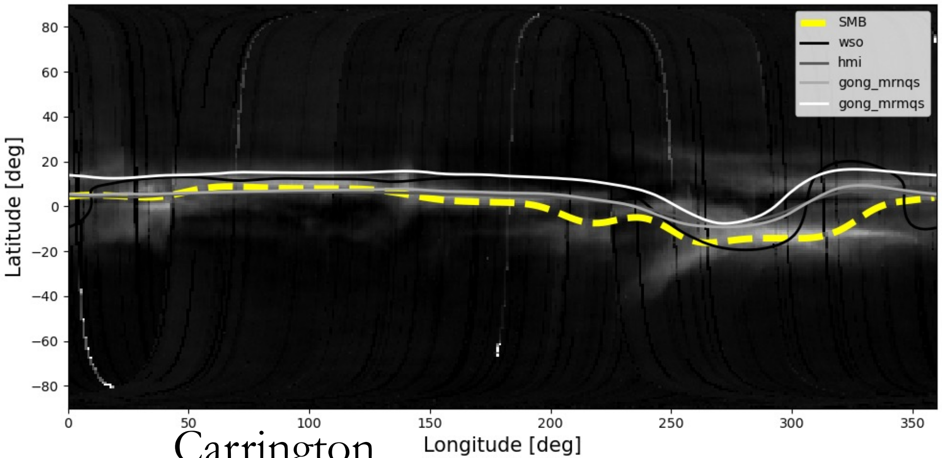
ADAPT

The northern coronal is well estimated, but a lot of differences for the southern and equatorial ones

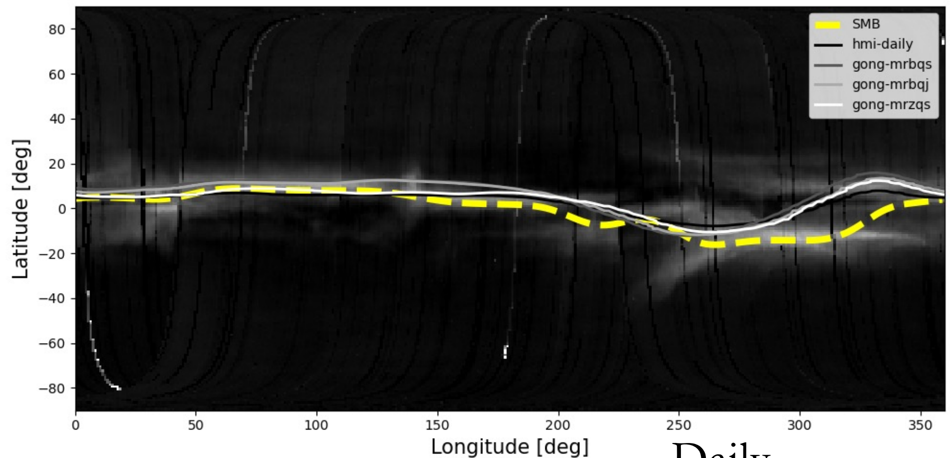
→ non-corrected WSO and GONG are off, and GONG-ADAPT misses the equatorial CHs

Comparison with observations: WL for HCS

We use white-light images of the corona to estimate the size and shape of the HCS



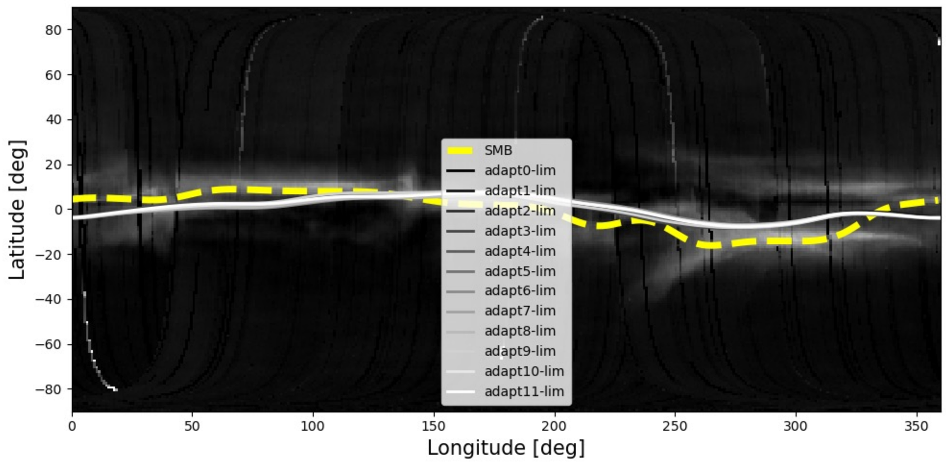
Carrington



Daily

[Perri+2022b] (submitted)

Crédits :
Nicolas POIRIER (IRAP)

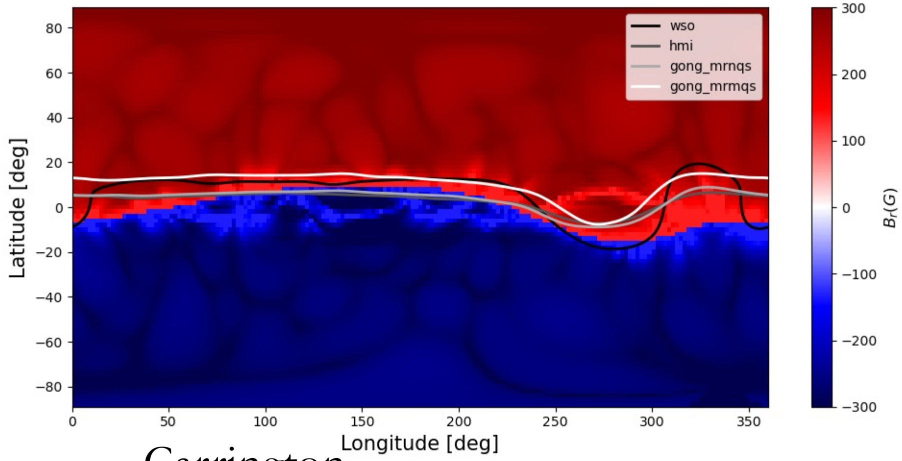


ADAPT

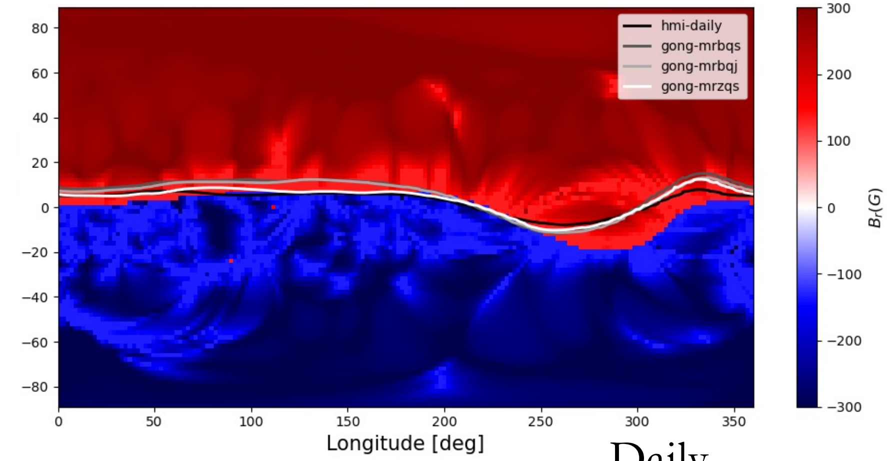
All maps perform well (but easy case at minimum of activity)

Impact for space weather forecasts

We compare the HCS found by our MHD model with the one found by PFSS+SCS

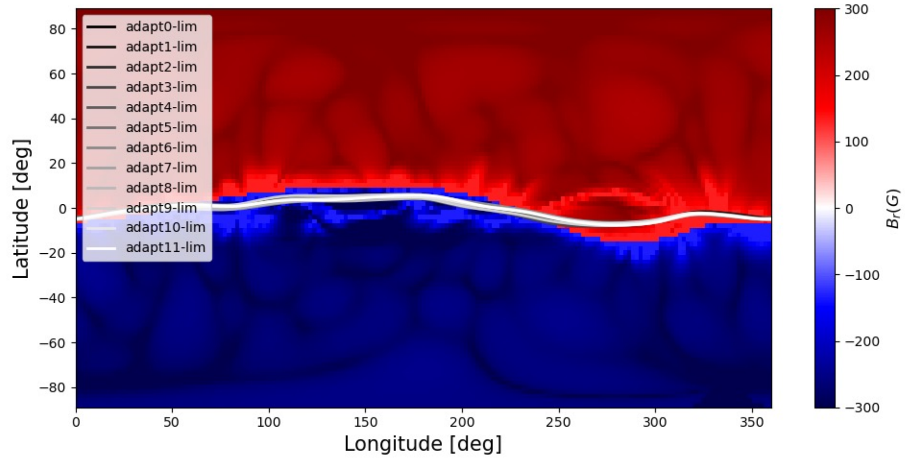


Carrington



Daily

[Perri+2022b] (submitted)



ADAPT

→ Even with the same input map,
we have a deviation of the HCS of several degrees at 20 solar radii!

Which map to choose?

[Perri+2022b] (submitted)

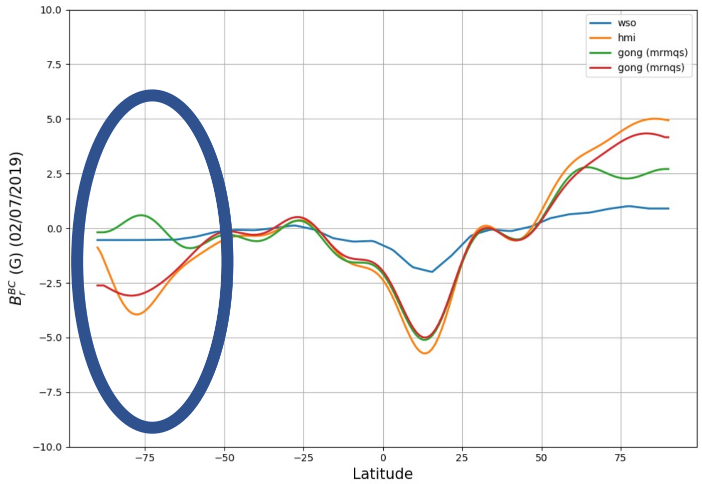
Map	Streamers ratio	Polar CH ratio	Eq. CH ratio	SB deviation
WSO	left: 28.0%, right: 24.0%	North: 72.8%, South: 33.7%	10.7%	$\delta_{max} = 30.8°$, $\delta_{mean} = 9.22°$
HMI	left: 84.2%, right: 74.7%	North: 86.1%, South: 40.6%	37.4%	$\delta_{max} = 17.5°$, $\delta_{mean} = 4.88°$
GONG (mrmqs)	left: 54.4%, right: 37.7%	North: 87.1%, South: 23.9%	8.8%	$\delta_{max} = 27.9°$, $\delta_{mean} = 11.9°$
GONG (mrnqs)	left: 74.9%, right: 65.6%	North: 86.2%, South: 42.0%	26.2%	$\delta_{max} = 19.1°$, $\delta_{mean} = 4.98°$
HMI (daily)	left: 66.2%, right: 70.1%	North: 86.3%, South: 40.1%	65.5 %	$\delta_{max} = 16.1°$, $\delta_{mean} = 4.30°$
GONG (mrbqs)	left: 39.1%, right: 41.6%	North: 80.3%, South: 33.9%	11.6%	$\delta_{max} = 23.9°$, $\delta_{mean} = 7.35°$
GONG (mrbqj)	left: 47.3%, right: 32.8%	North: 79.2%, South: 32.5%	11.4%	$\delta_{max} = 20.5°$, $\delta_{mean} = 6.43°$
GONG (mrzqs)	left: 29.1%, right: 53.6%	North: 85.2%, South: 39.2%	20.4%	$\delta_{max} = 19.7°$, $\delta_{mean} = 4.66°$
ADAPT (1)	left: 64.3%, right: 77.8%	North: 88.1%, South: 44.4%	0.0%	$\delta_{max} = 10.5°$, $\delta_{mean} = 5.36°$
ADAPT (2)	left: 61.7%, right: 77.1%	North: 87.9%, South: 44.1%	0.0%	$\delta_{max} = 9.99°$, $\delta_{mean} = 5.60°$
ADAPT (3)	left: 69.4%, right: 72.4%	North: 88.3%, South: 44.0%	0.0%	$\delta_{max} = 10.5°$, $\delta_{mean} = 5.57°$
ADAPT (4)	left: 77.0%, right: 85.5%	North: 87.9%, South: 43.9%	0.0%	$\delta_{max} = 9.69°$, $\delta_{mean} = 4.76°$
ADAPT (5)	left: 61.4%, right: 79.5%	North: 87.8%, South: 44.5%	0.0%	$\delta_{max} = 9.84°$, $\delta_{mean} = 5.09°$
ADAPT (6)	left: 66.3%, right: 78.1%	North: 87.5%, South: 44.1%	0.0%	$\delta_{max} = 10.0°$, $\delta_{mean} = 5.84°$
ADAPT (7)	left: 72.1%, right: 78.5%	North: 87.2%, South: 43.6%	0.0%	$\delta_{max} = 10.4°$, $\delta_{mean} = 6.20°$
ADAPT (8)	left: 61.9%, right: 87.9%	North: 87.4%, South: 45.3%	0.0%	$\delta_{max} = 9.63°$, $\delta_{mean} = 5.75°$
ADAPT (9)	left: 75.4%, right: 77.6%	North: 87.7%, South: 43.4%	0.0%	$\delta_{max} = 10.3°$, $\delta_{mean} = 5.91°$
ADAPT (10)	left: 61.3%, right: 80.5%	North: 88.0%, South: 44.9%	0.0%	$\delta_{max} = 9.39°$, $\delta_{mean} = 4.99°$
ADAPT (11)	left: 80.0%, right: 64.1%	North: 88.1%, South: 44.7%	0.0%	$\delta_{max} = 10.4°$, $\delta_{mean} = 5.73°$
ADAPT (12)	left: 76.1%, right: 85.8%	North: 87.9%, South: 44.5%	0.0%	$\delta_{max} = 10.0°$, $\delta_{mean} = 5.52°$

→ HMI and GONG-ADAPT perform the best

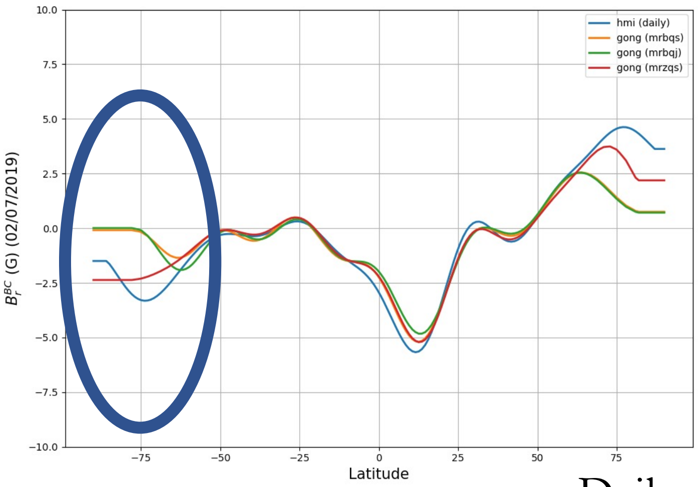
→ WSO and GONG should not be used without the proper corrections!

Influence of the solar poles

The biggest source of difference (and error) are the poles

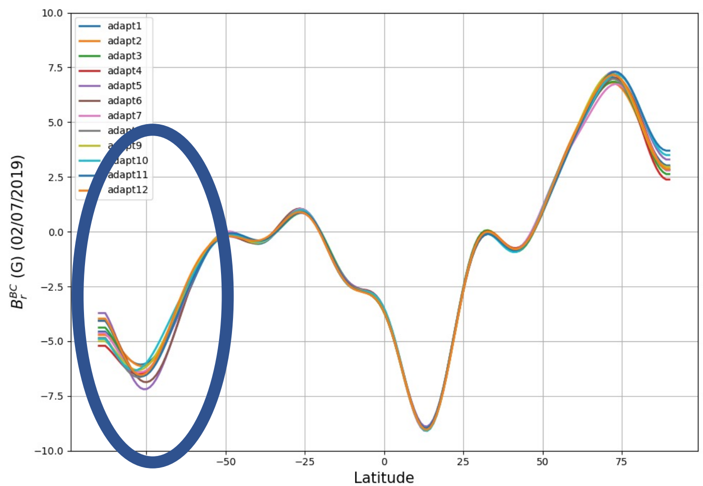


Carrington



Daily

[Perri+2022b] (submitted)



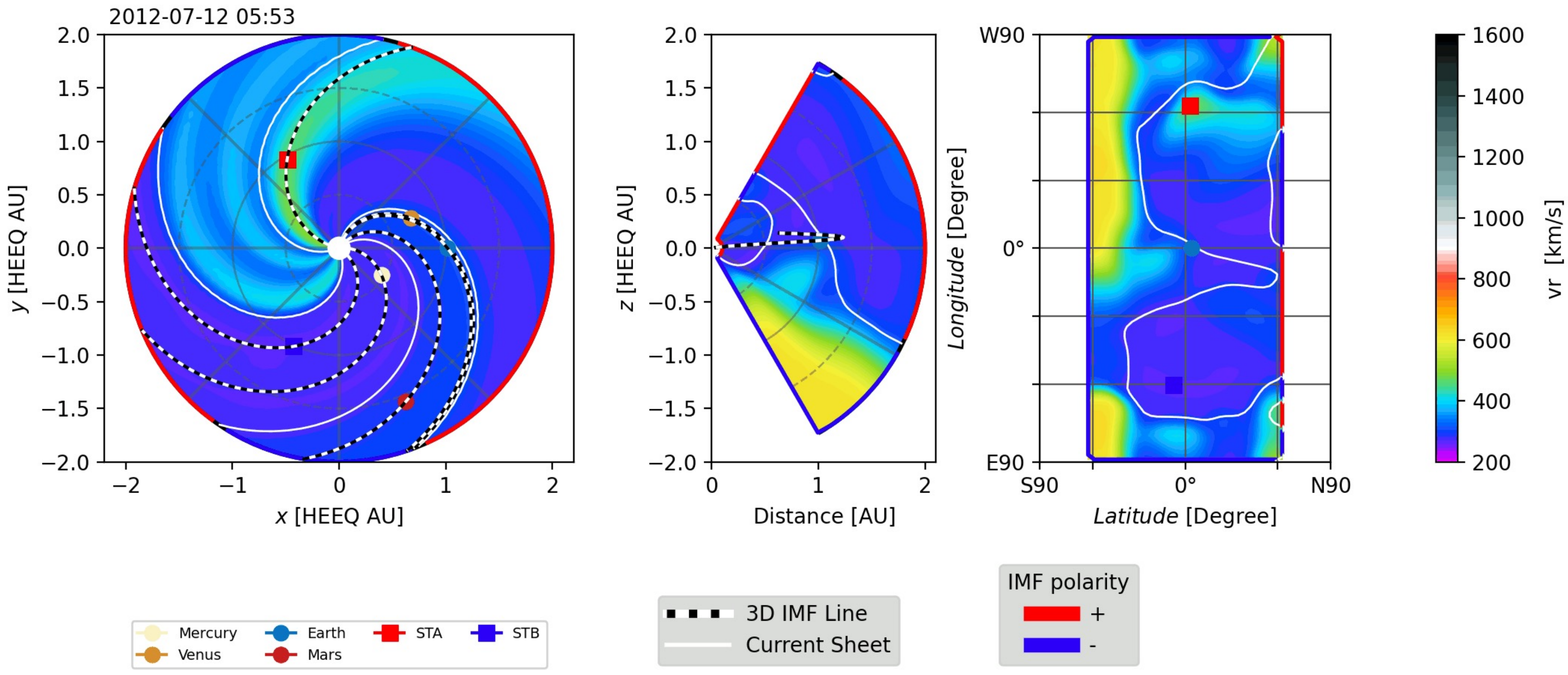
ADAPT

→ The solar poles have a crucial role for space weather forecast and should be kept in the corona

→ Solar Orbiter polar data are going to be extremely useful to harmonize the maps!

Next steps

- Improve COCONUT by improving the coronal heating
- Test the map results for other codes and other dates (maximum of activity)
- Test the results for space weather forecasts (WSA + CME)



Conclusion

Methods:

We have used our new coronal MHD model COCONUT to investigate the 20 magnetic maps available for the 2nd of July 2019

→ quantification of the results using WL (streamers) + EUV (CHs) + SMB (HCS)

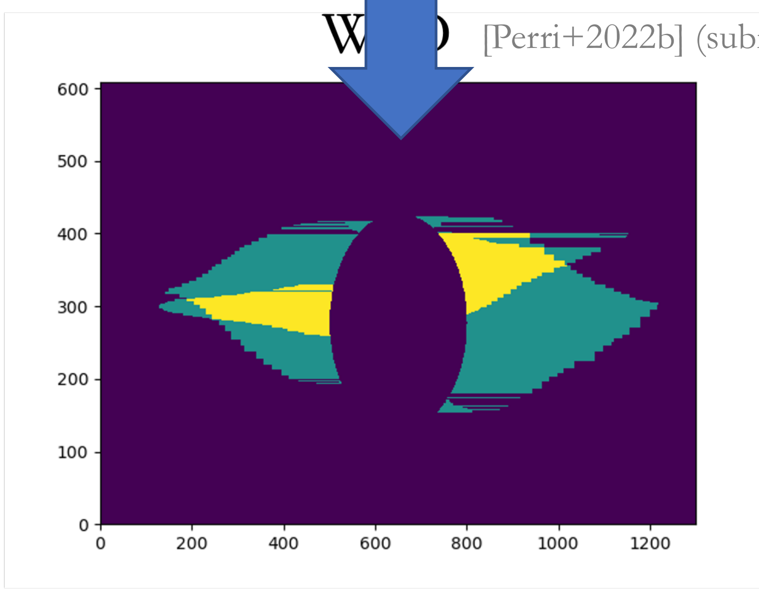
Take-home messages:

- Even at minimum of activity, different input magnetic maps are going to generate different configurations for the corona
- HMI and GONG-ADAPT are recommended
- WSO and GONG should always be used with the appropriate corrections
- The solar poles play an important role in space weather forecasting (HCS + CHs)

Thank you for your attention!

Acknowledgements:
European Union's Horizon 2020 No 870405
ESA project "Heliospheric modelling techniques" (AO10125-GT18-004EP)

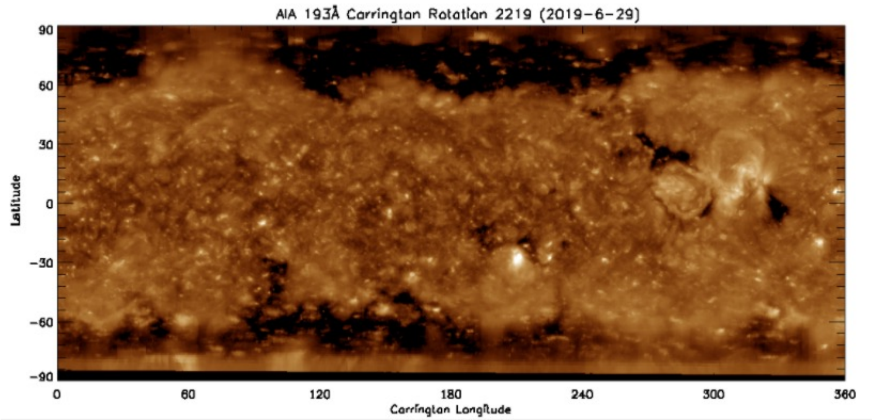
Appendix: Streamers coverage



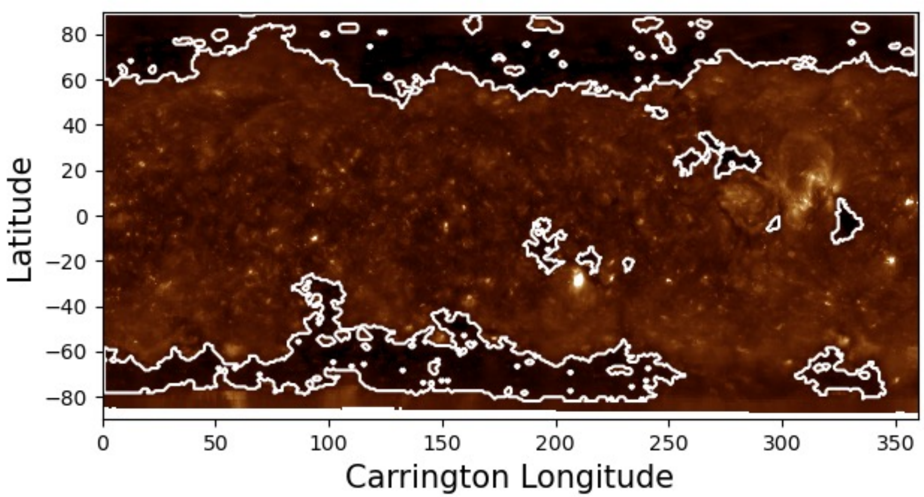
[Perri+2022b] (submitted)

1. We extract manually from the WL image the approximated shape of the streamers' edges
2. We extract automatically from our simulations the largest closed magnetic field lines for the streamers' edges
3. We adjust the two datasets to have the same reference length (solar radius)
4. We compute the coverage map (purple: pixel in no streamer; green: pixel in 1 streamer; yellow: pixel in 2 streamers)
5. We compute the coverage ratio (yellow pixels over the biggest streamer)

Appendix: Coronal holes extraction



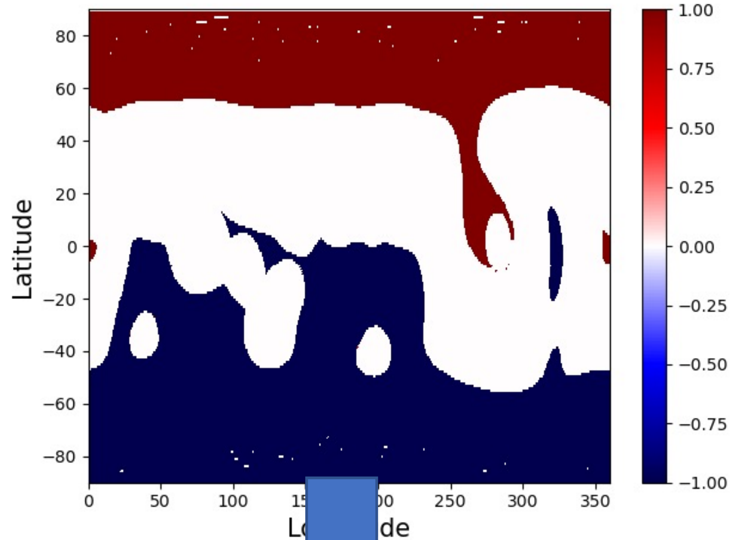
We download SDO/AIA EUV synoptic maps for one CR (195 channel)



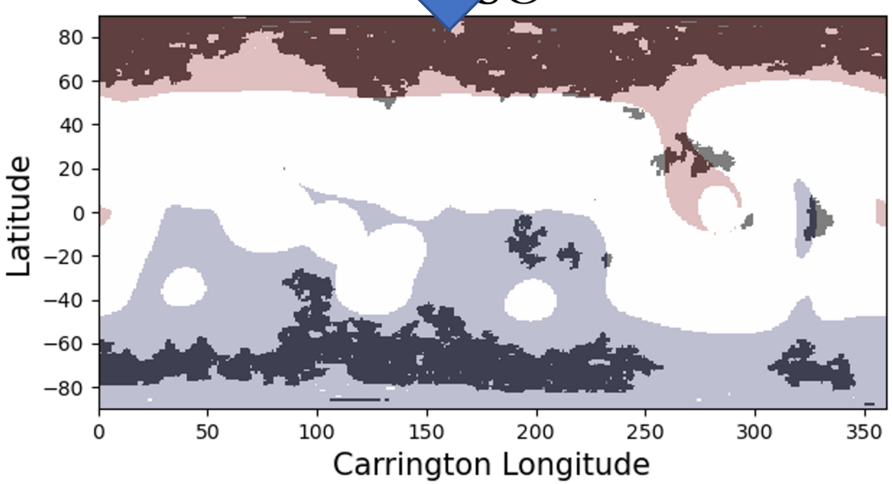
[Caplan+2016]

We extract automatically the coronal pixels by using the EZSEG algorithm (1st threshold: 20; 2nd threshold: 35; 3 neighbors)

Appendix: Coronal holes coverage



[Perri+2022b] (submitted)



1. We use magnetic seeds distributed over a 200x400 points sphere to compute field lines
2. We identify open field lines and mark their seeds with the corresponding polarity
3. We overimpose the coronal holes detected from data
4. We compute the coverage ratio (gray pixels over colored pixels)