Benchmarking and optimizing EUHFORIA2.0 coronal model for space weather

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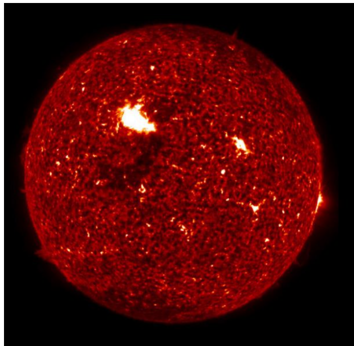
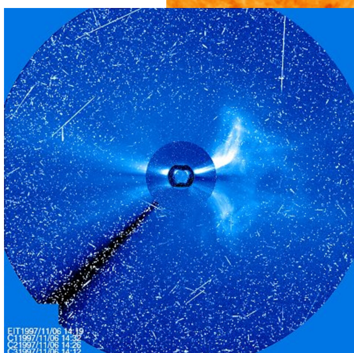
Space weather

[GOES17]

flares

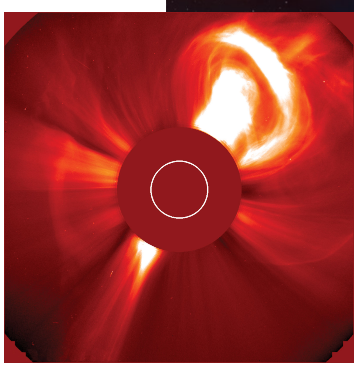


SEPs



[NASA]

CMEs



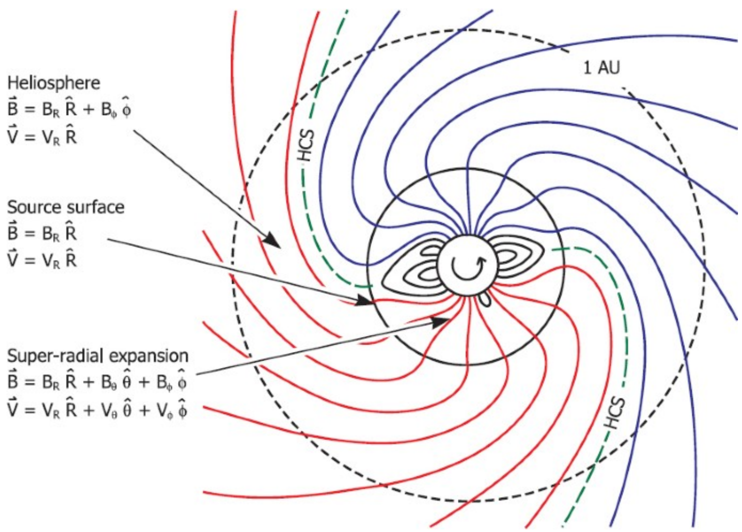
→ Space weather forecasting depends heavily on the modeling of the heliosphere

Heliosphere observations

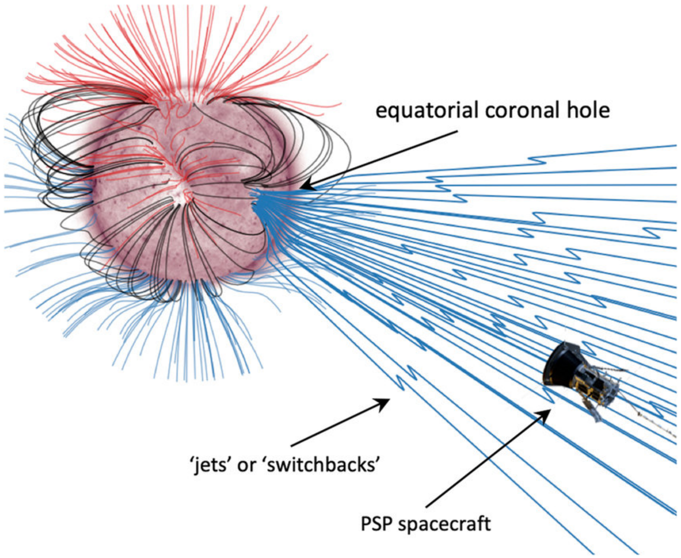
Magnetic field

Parker spiral at large scales, but also switchbacks at short scales

[Owens & Forsyth 2013]



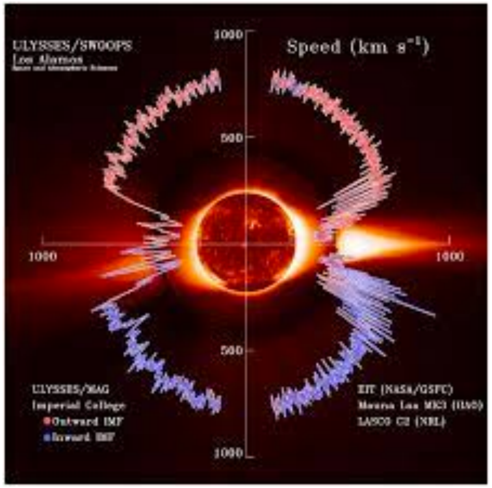
[Bale+2019]

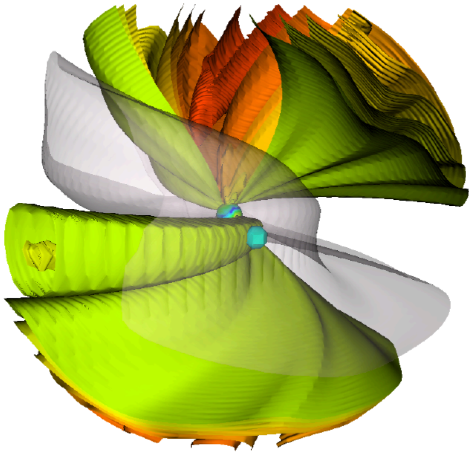


Solar wind

Bimodal distribution between fast and slow wind, but also localized structures such as CIRs or HSSs

[McComas+2003]





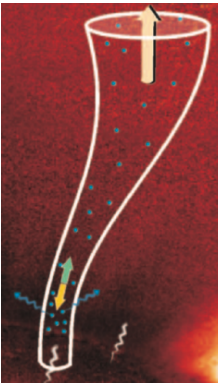
[Samara+2021]

→ Need to take into account the various structures at the different scales

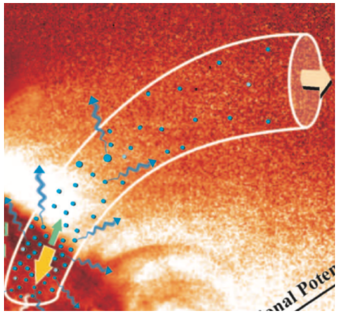
Solar wind modeling

Semi-empirical models (WSA + PFSS) (EUHFORIA until now)

fast wind

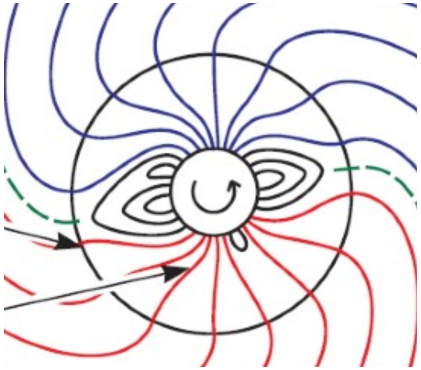


slow wind

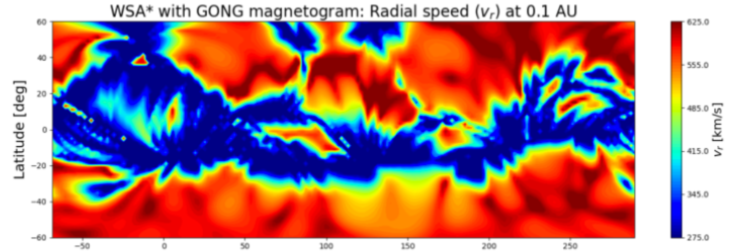


[Schwadron & McComas 2003]

[Owens & Forsyth 2013]

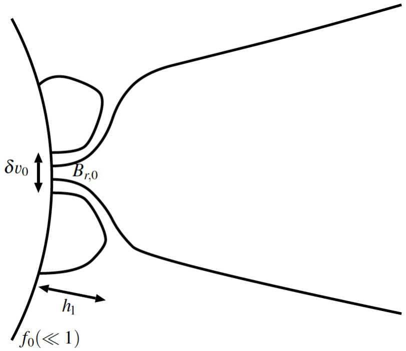


[Samara+2021]

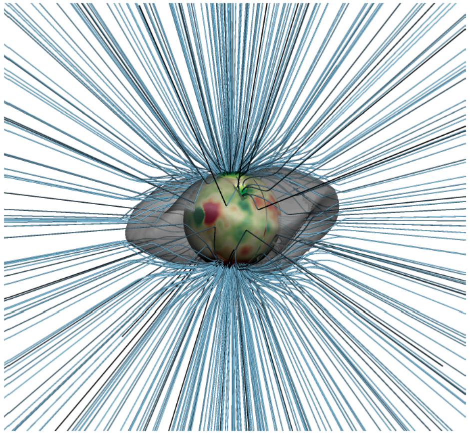


Data-driven MHD coronal models

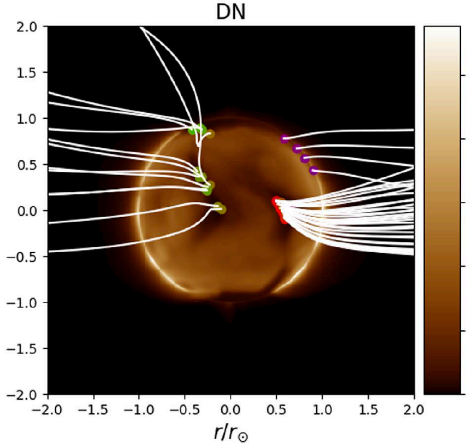
1D



[Suzuki+2013]

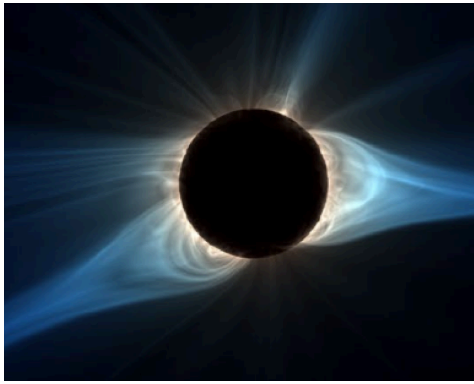


[Samara+2021]



[Réville+2020]

3D



[Mikic+2018]

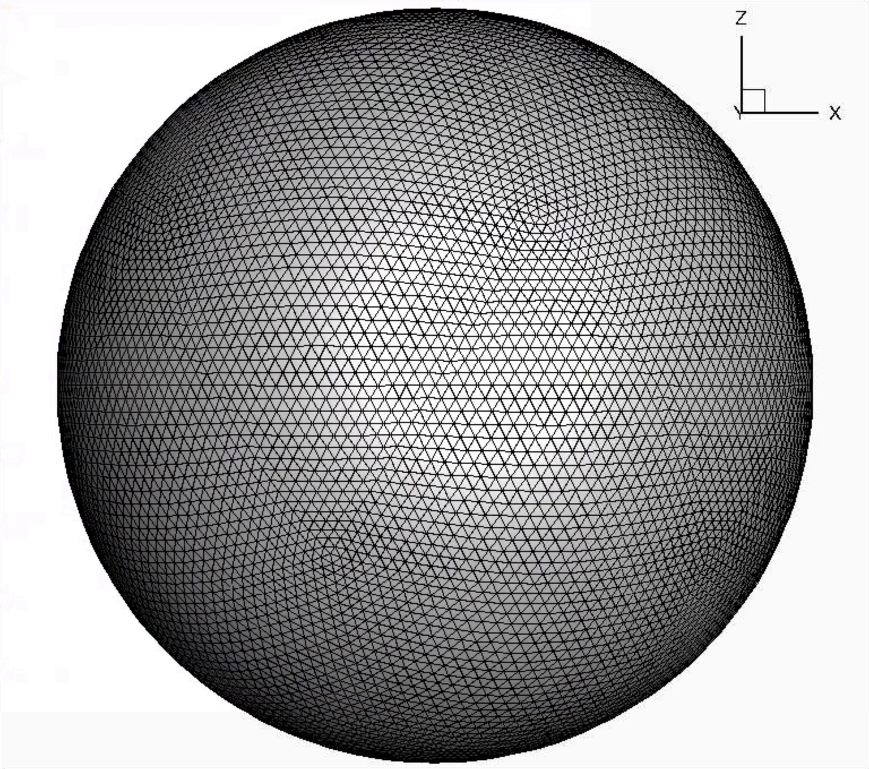
→ It is difficult to combine accuracy with speed

Description of the model

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

Use of the COOLFluiD framework for scientific HPC

→ Use of **implicit scheme for fast MHD solution**



Main features of the preliminary model:

- Ideal MHD
- Finite volume method
- Cartesian
- Inclusion of gravity
- Unstructured mesh (no polar singularity!)

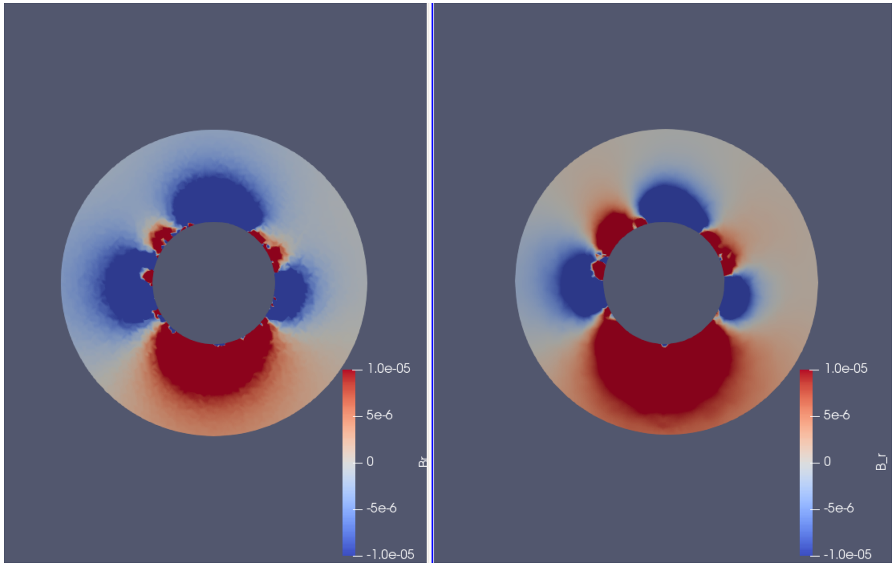
Approximations for the first most basic validation:

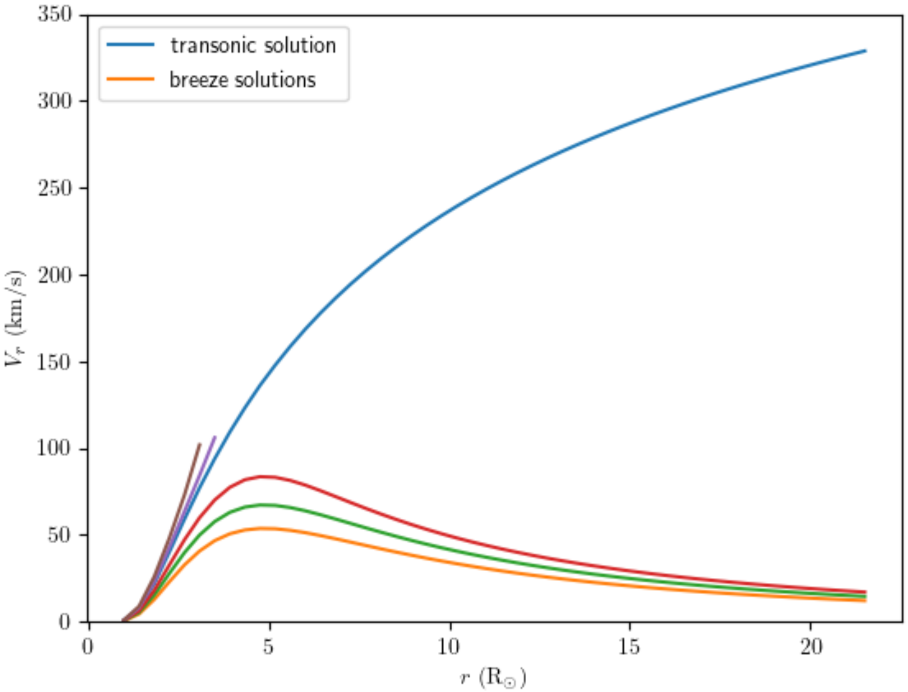
- The heating is polytropic
- We do not include rotation yet
- We use the HLL solver (HLLD in progress)

Description of the model

Initialization:

- Poisson solver for magnetic field
- Analytical polytropic wind solution





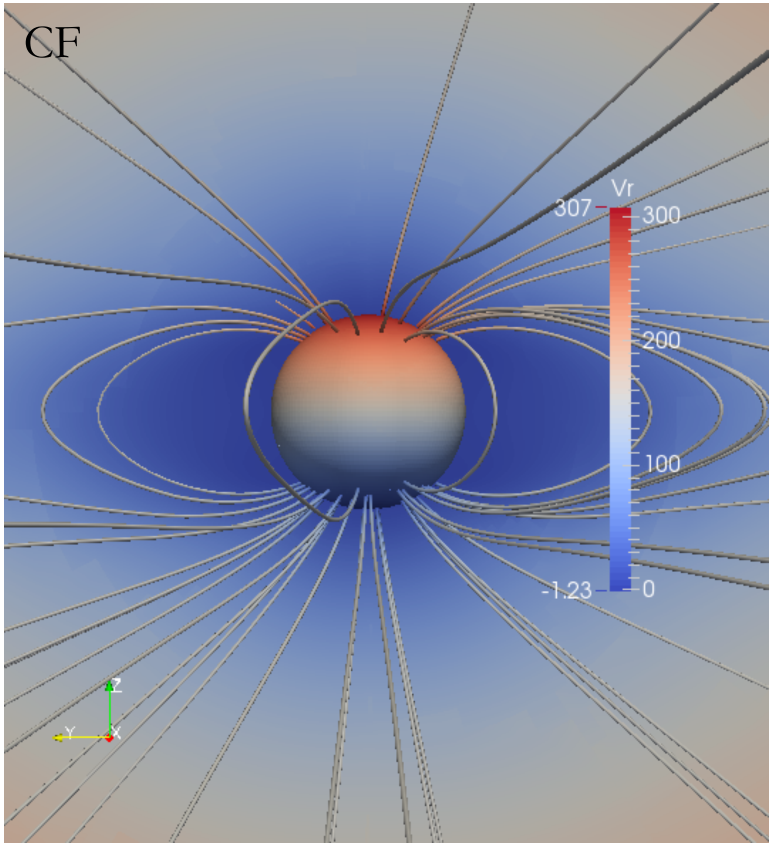
→ We will present here the benchmarking procedure we have used to validate the code

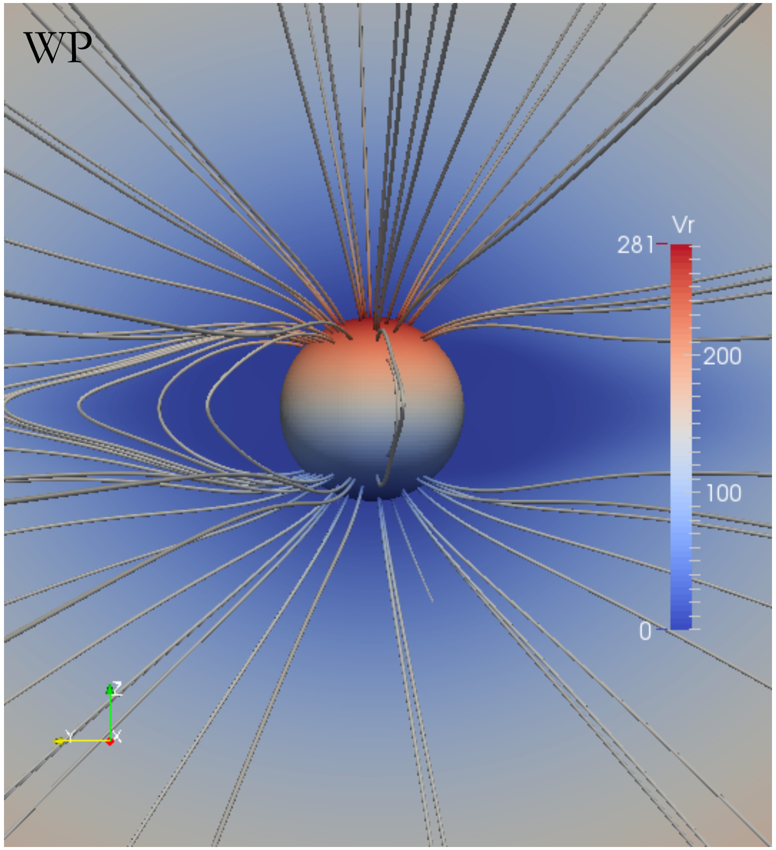
→ Comparison with the Wind-Predict code (same ICs and BCs) and observations

[Réville+2015a/2020, Perri+2018]

Limit case 1: Dipole

Dipole of 1G amplitude (at the poles) + 1.5 M K corona





→ Shape of the streamer and end velocity slightly different

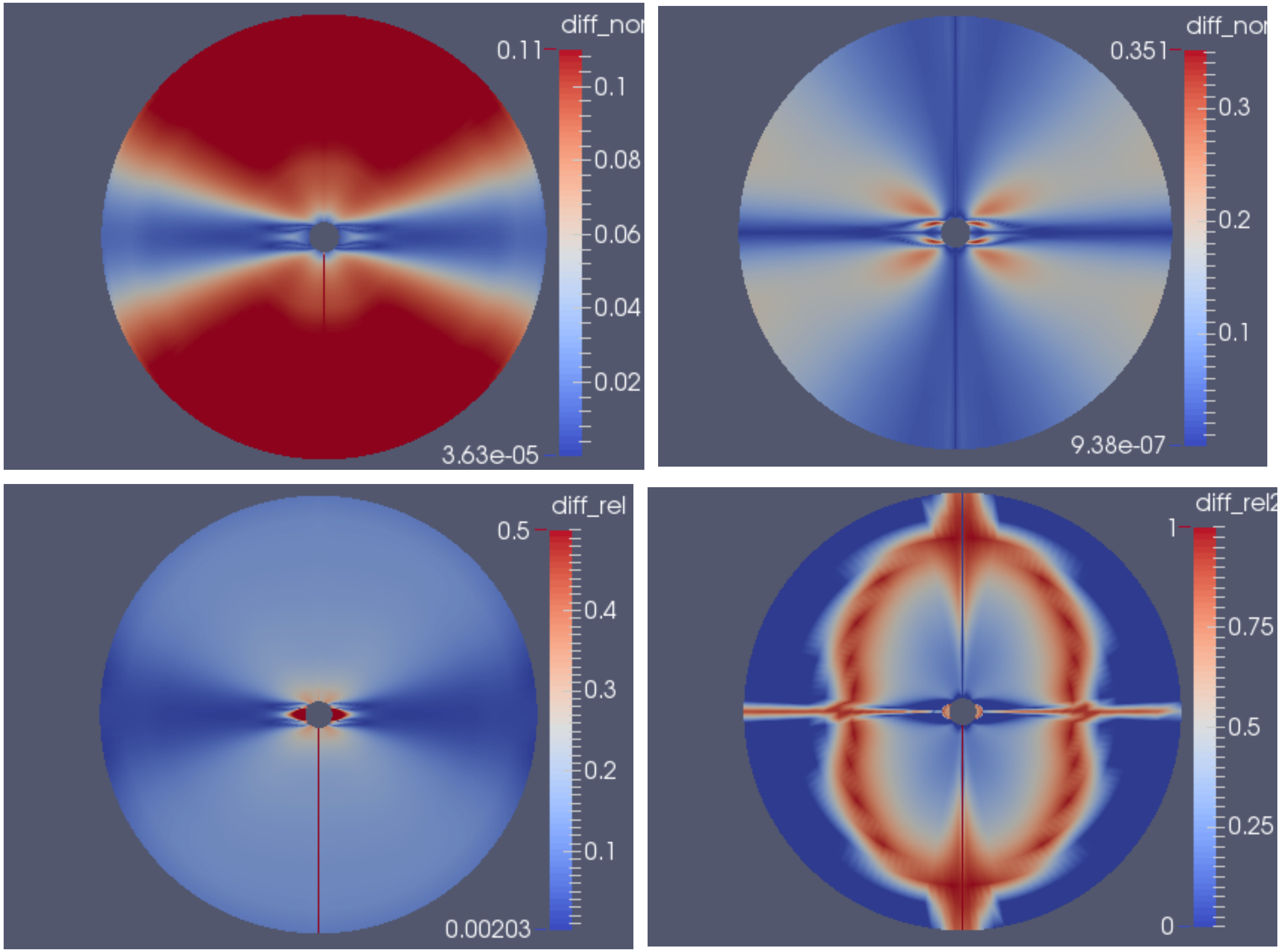
→ Effects of the numerical differences (probably effect of the limiter)

Limit case 1: Dipole

V_r V_θ

Normalized difference (CF-WP)/max

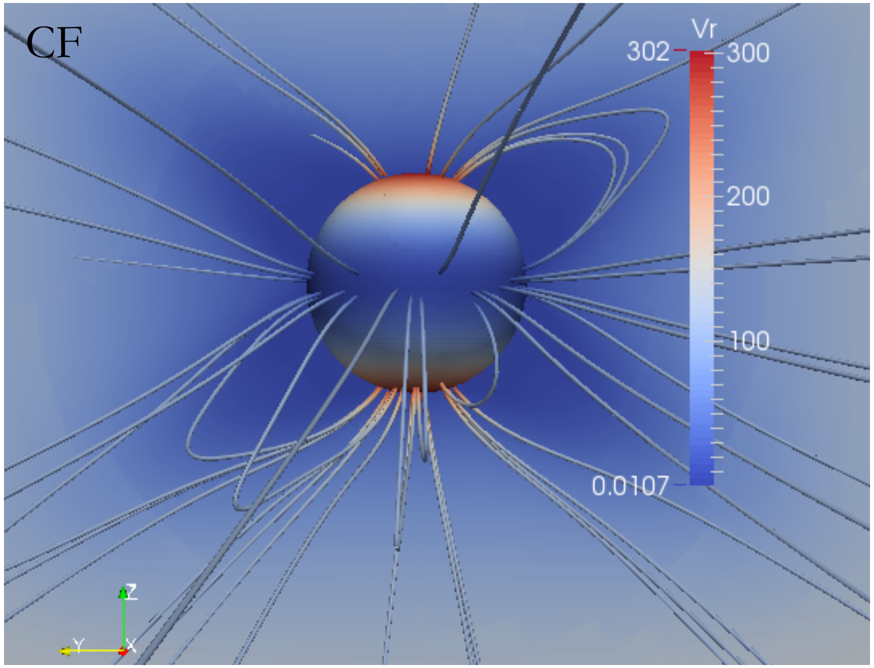
Relative difference (CF-WP)/CF

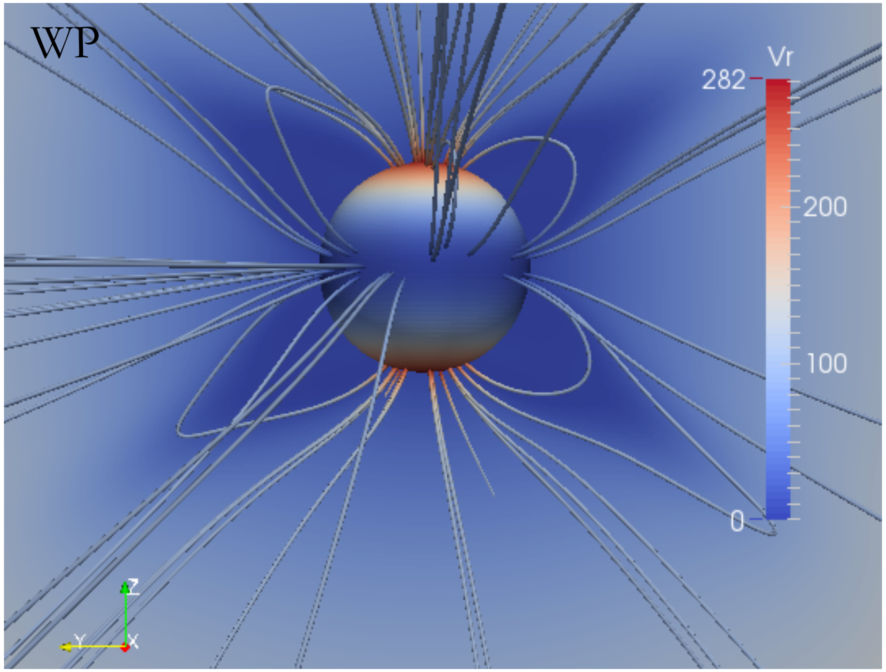


→ We see mainly the effect of the limiter and polar boundary condition

Limit case 2: Quadrupole

Quadrupole of 1G amplitude (at the poles) + 2 M K corona





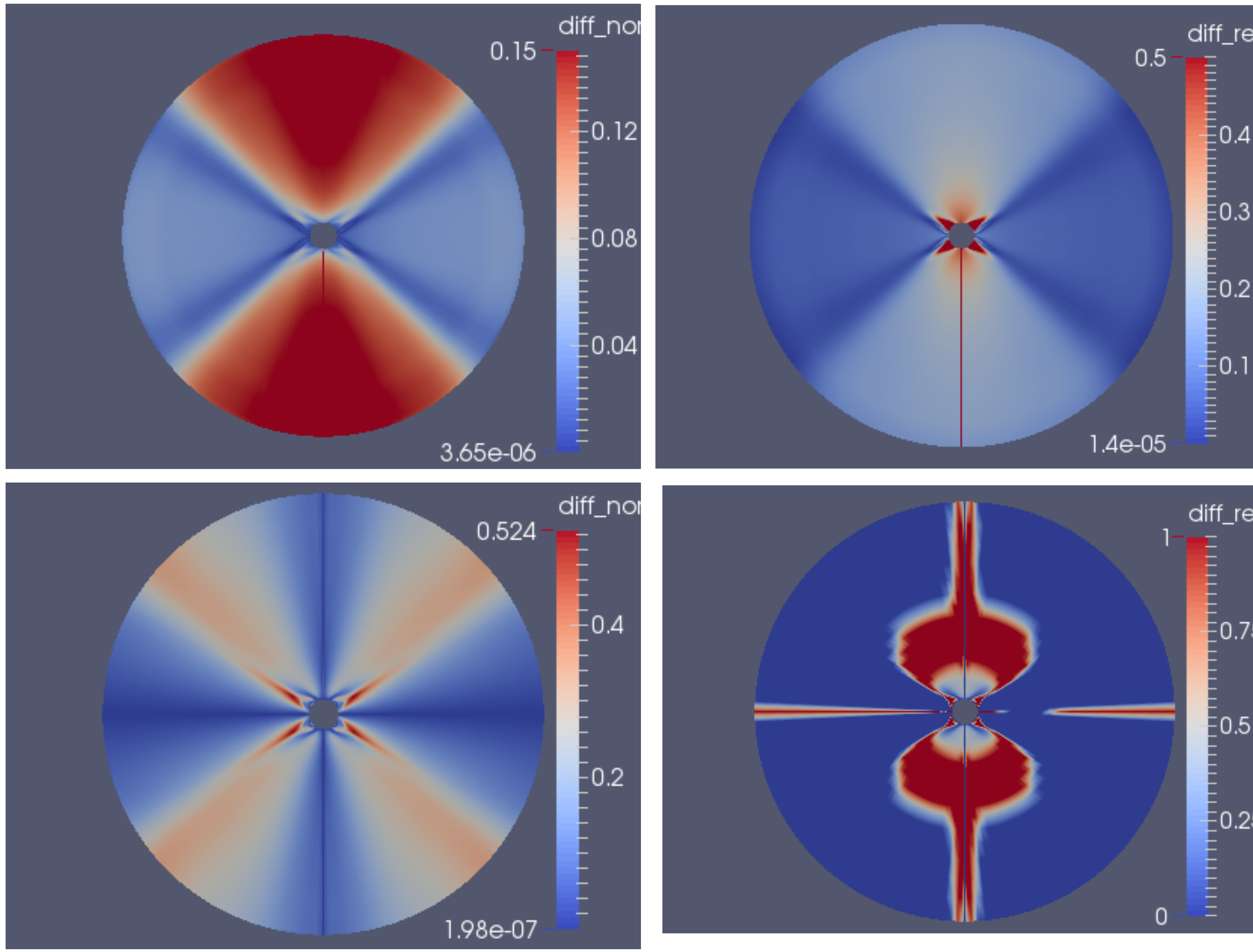
→ Very good qualitative agreement, the main difference being the sharpness of the streamers (due to the limiter)

Limit case 2: Quadrupole

V_r V_θ

Normalized difference

Relative difference



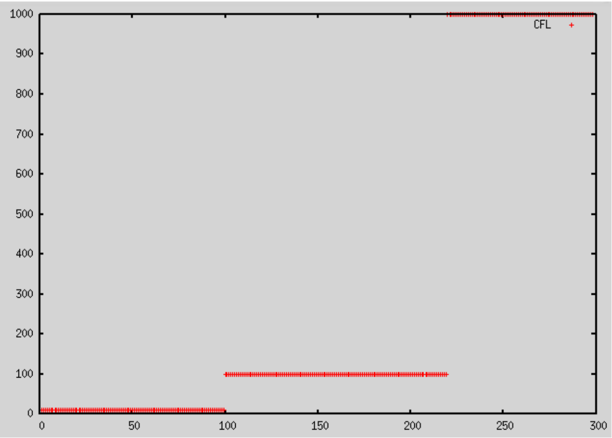
→ In normalized difference, the polar boundary condition has the most impact

→ In relative difference, the limiter has the most impact

Convergence of the limit cases

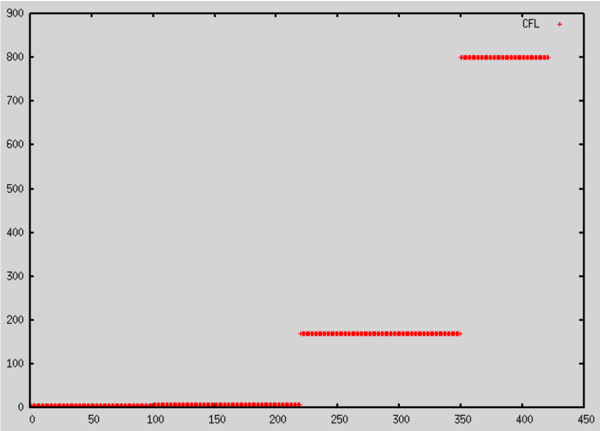
With the implicit scheme, we can optimize the CFL to reach convergence sooner
→ We compare the time needed to reach -3 residuals in velocity with WP

CFL dipole



Iterations

CFL Qua -drupole



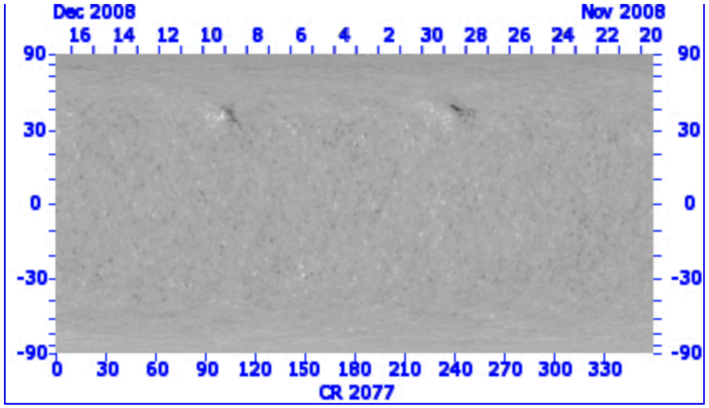
	COOLFluiD	Wind-Predict
Dipole (coarse mesh)	6.8 min	30 min
Quadrupole (coarse mesh)	9.8 min	30 min
Quadrupole (fine mesh)	58 min	3h30

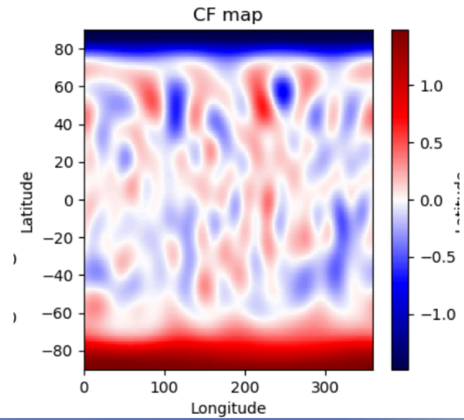
→ Even for simple cases, between 3 and 5 times faster than explicit MHD codes

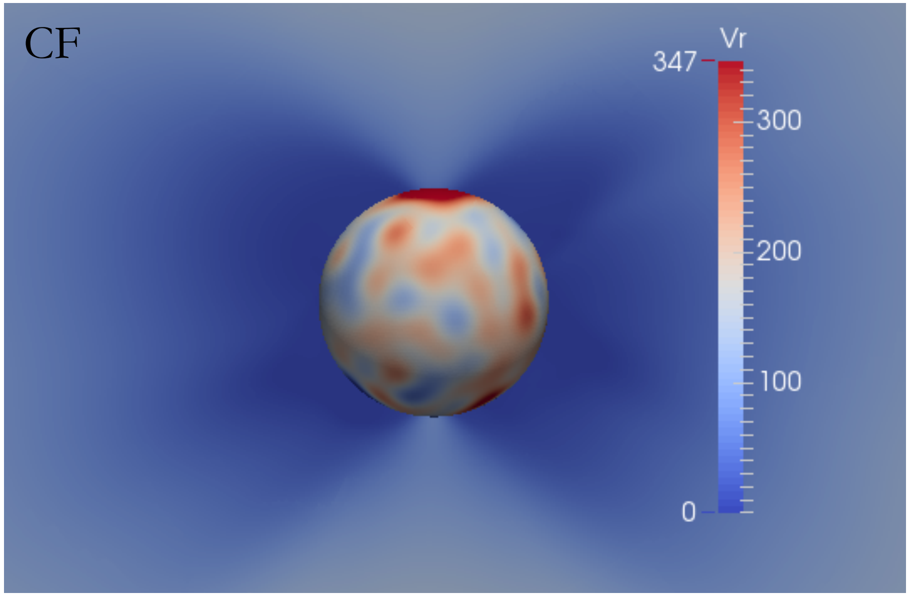
Benchmark on a synoptic map

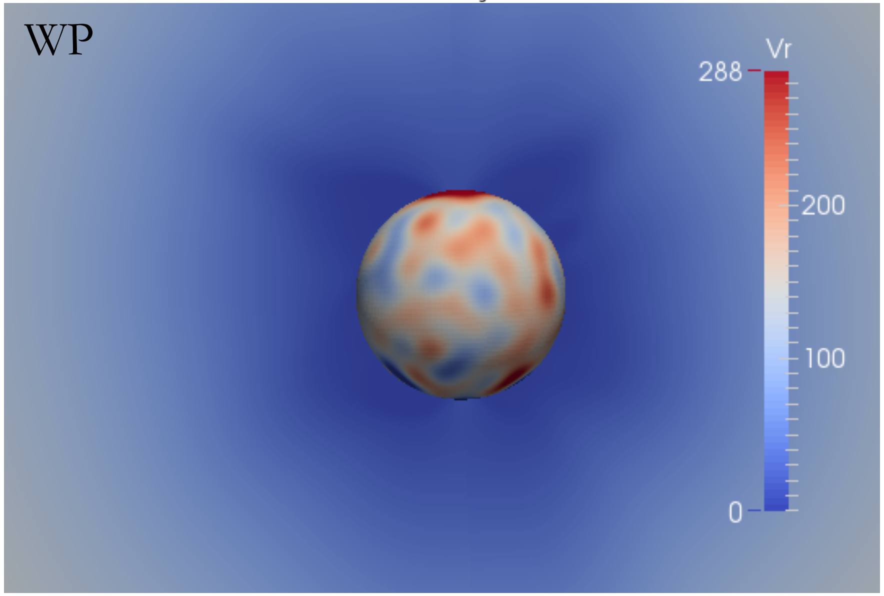
We used a GONG synoptic map corresponding to the CR2077

→ Minimum of activity but with some structures, so stable and suited for validation







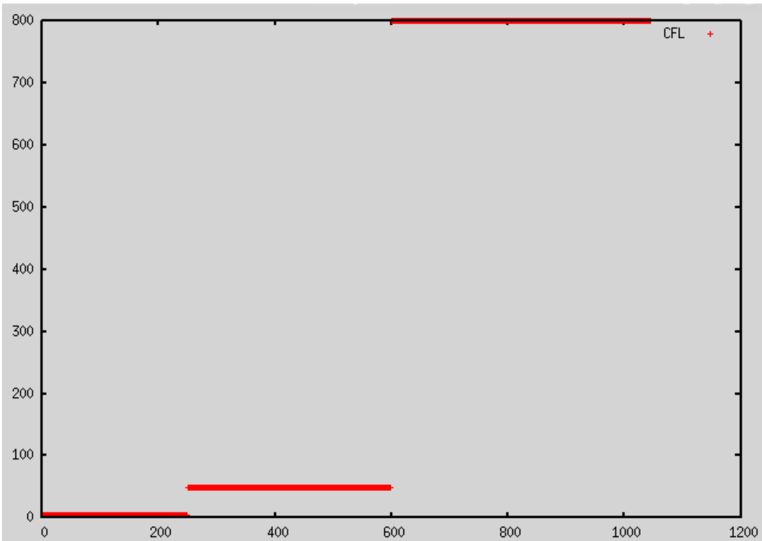


→ Good agreement, as expected we have effects of the polar BC and edges of streamers

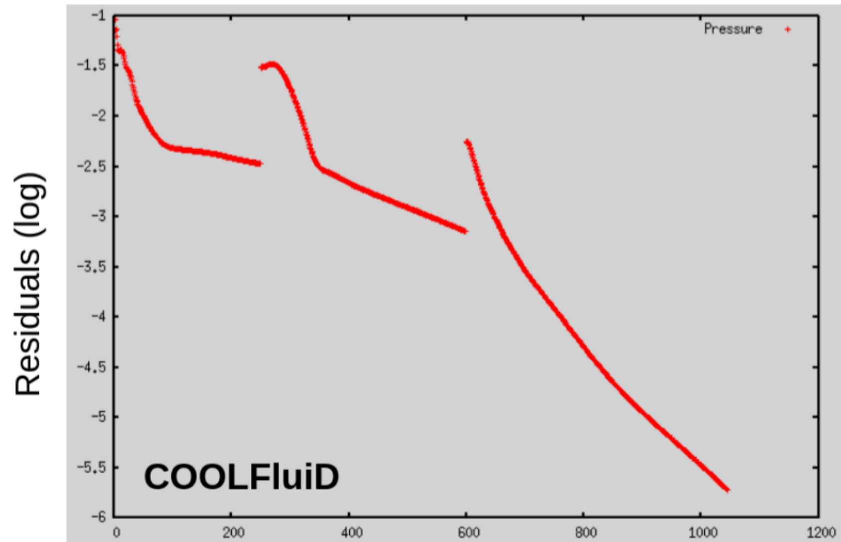
Convergence time

Same as for the limit cases, we optimize the CFL for the map case and compare with WP

CFL map



Iterations



Iterations

COOLFluiD	PLUTO
• 1.9M mesh	• 1.5M mesh
• 196 Processors	• 200 Processors
• HLL solver	• HLL solver
• Vr: -0.5 → 5sec	• Vr: -0.5
• Density: -2 → 0.7h	• Density: -2
• Br: -3 → 1.38h	• Br: -3
• Pressure: -5 → 1.97h	• Pressure: -5

36h

→ Depending on the criteria of convergence, between 18 and 26 times faster

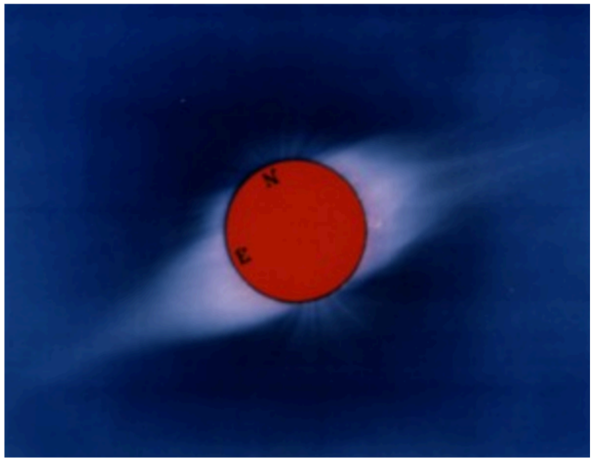
→ Very suited for space weather forecast (2h instead of >1 day)

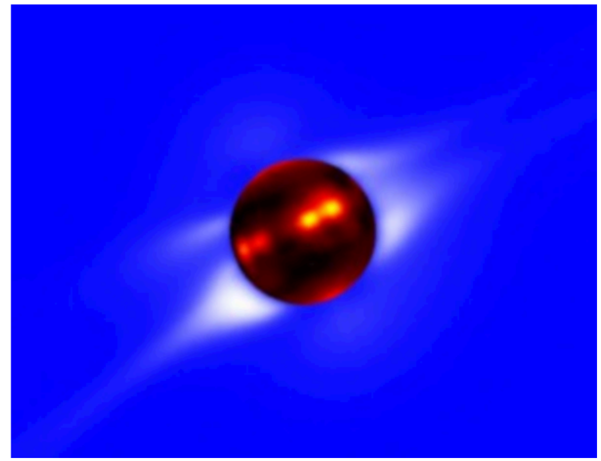
Observations at minimum of activity

For the minimum of activity, reproduction of the eclipse of the 24th October 1995

→ Use of the WSO map of CR1902, and comparison with the magnetic field

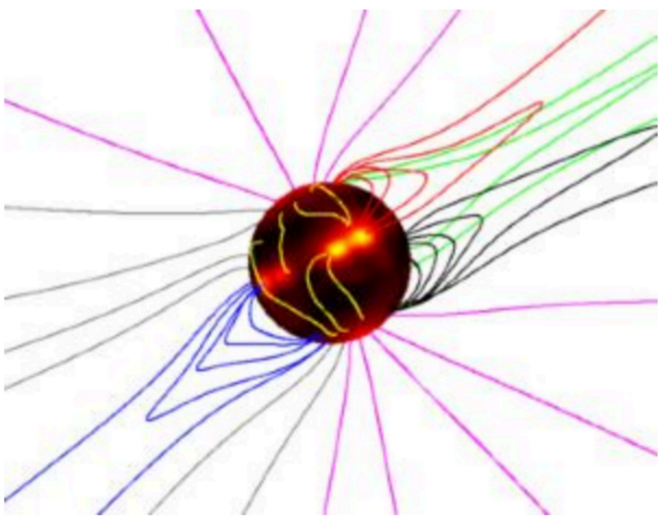
Eclipse picture

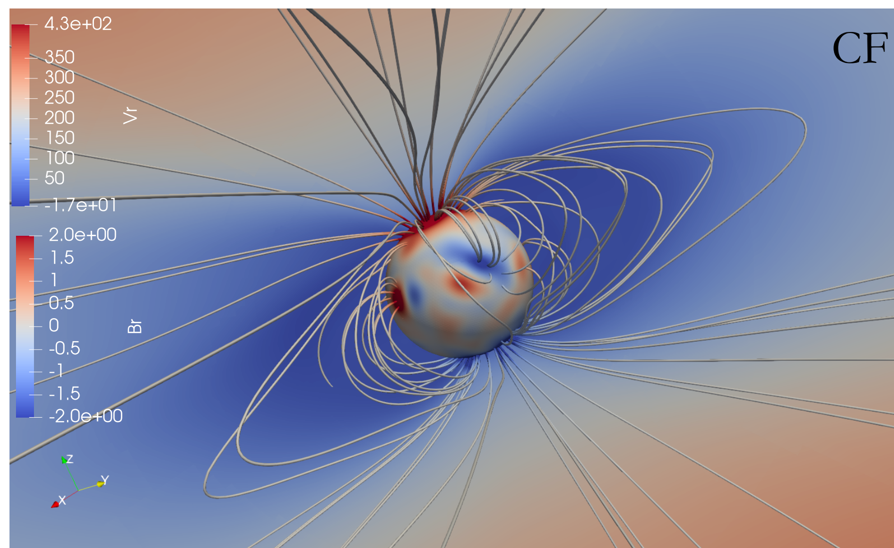




Example of white-light processing

[Mikic et al. (2008)]



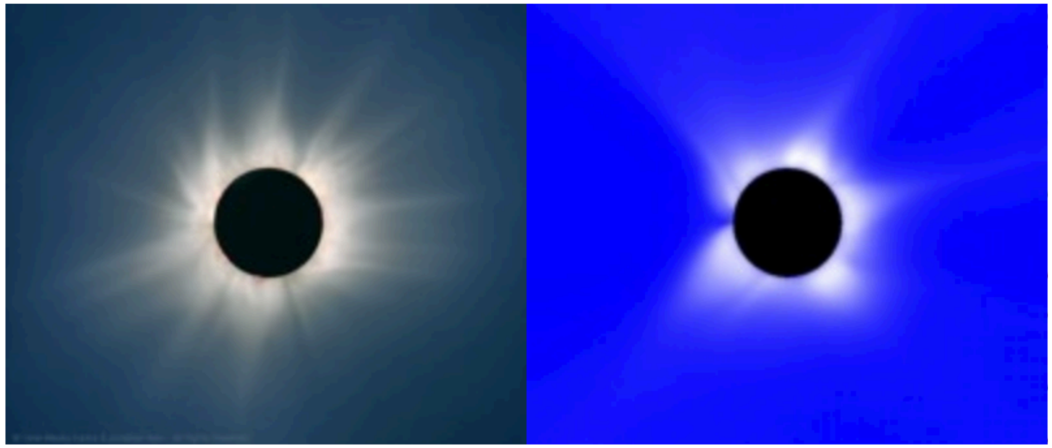


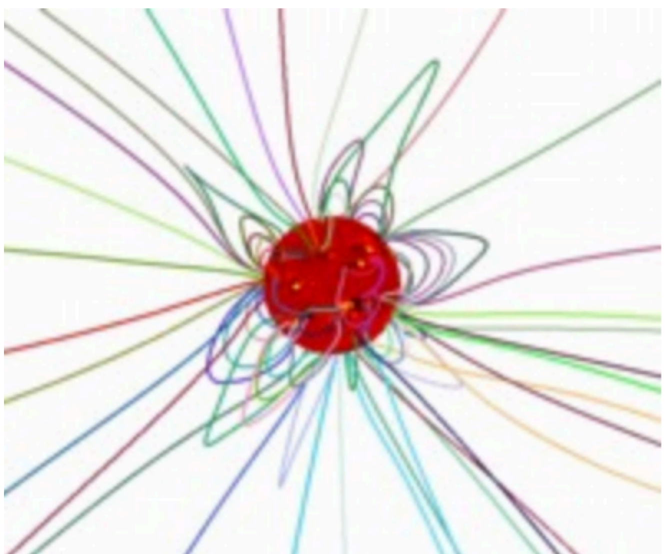
Observations at maximum of activity

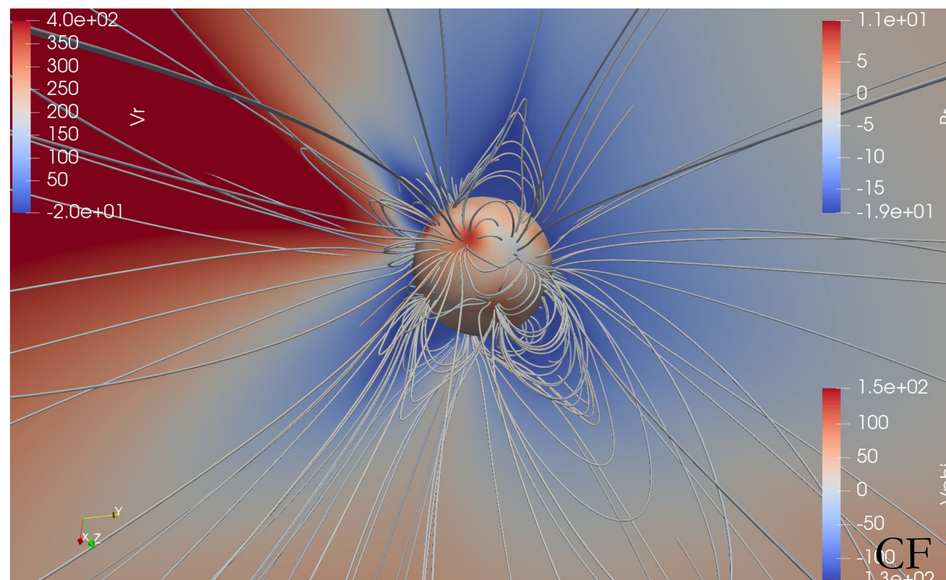
For the maximum of activity, reproduction of the eclipse of the 11th August 1999

→ Use of the WSO map of CR1954 (more difficult to compare with polytropic)

[Mikic et al. (2008)]







Conclusions and Perspectives

Conclusions:

- We have developed a **new coronal model** dedicated to **space weather forecasts**
- This model has been **validated on simple and realistic magnetic topologies** for a polytropic heating
- The **implicit scheme** allows us to be **faster than explicit MHD codes** at both minimum and maximum of activity
- The model **compares well with observations** at both minimum and maximum of activity

Perspectives:

- **Optimizing** the computing time → for **maximum of activity and different inputs**
- Inclusion of **rotation** → rotating frame
- Better **heating** → from polytropic to **heating terms**
- Better **accuracy** → use of **r-AMR** (r refined, mesh moving)
- Better description of the **small scales** → **multi-fluid** modeling

Thank you for your attention!

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European Union's Horizon 2020 No 870405
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