Physics-based models for forecasting

Space Weather

Stefaan Poedts

Emmanuel, Andrea, Peter, Marian, Shaaban, Andrey, Alexey, Camilla,

Christine, Dana, Nicolas, Immanuel, Skralan, *Evangelia*

CmPA, KU Leuven, Belgium

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Contents

- **Motivation / space weather**
  - *The need for integrated SWE modeling frameworks*
- **EUHFORIA:** *heliospheric wind + CMEs model*
  - *Rationale / aims*
  - *Some results*
- **Virtual Space Weather Modeling Centre**
  - *VSWMC ≠ CCMC, nor SWMF*
  - *Models, model couplings, and nodes included*
  - *Role of EUHFORIA*

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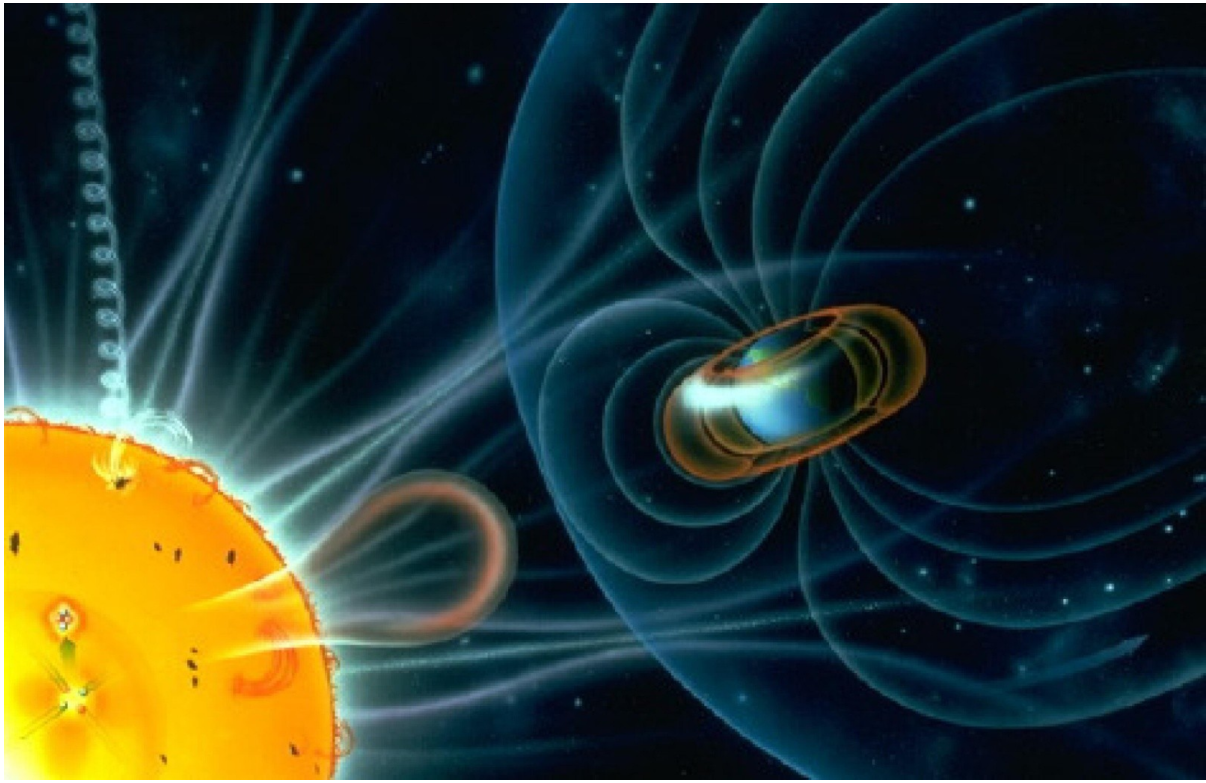
‘Space Weather’



cf. USA NSWP Strategic Plan:

“Space Weather refers to conditions on the sun and in the solar wind, magnetosphere, ionosphere, and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and can endanger human life or health.”

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Solar flares and CMEs

When a CME is ejected in the direction of the Earth, we see a so-called ‘halo CME’

(about 10% of all the CMEs, more than 1 per week during solar maximum)

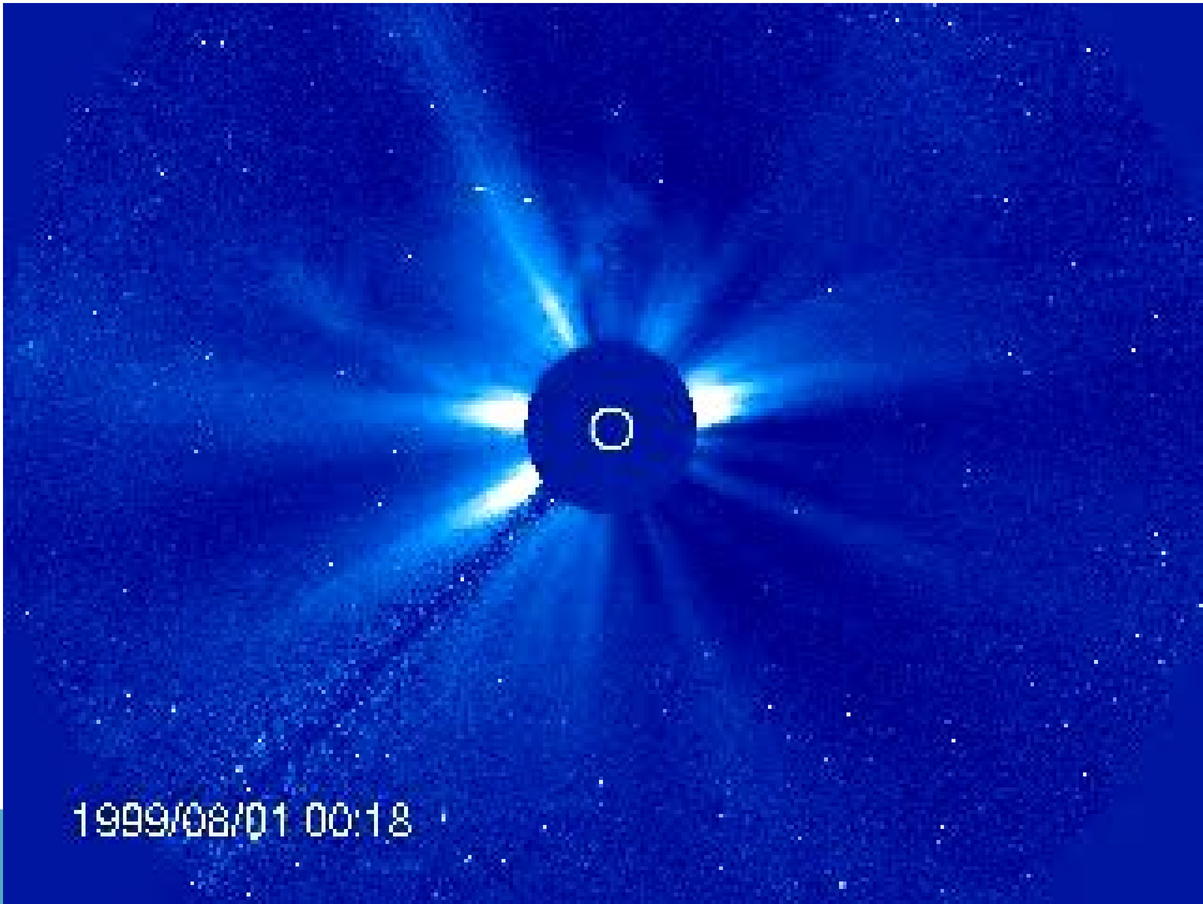
(halo) CMEs:

V_{cme} = 100 - 3000 km/s, typ. 450 km/s

Mass = 10^{13} - 1016 g

Energy = 1027 - 1033 erg

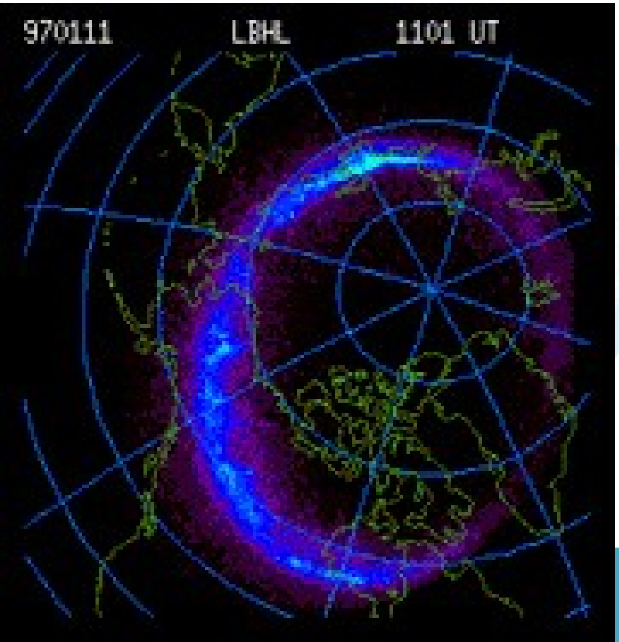
(1st: OSO7 (’71) see Bruecker et al. ’72)



SoHO-Lasco C3

Effects on Earth environment

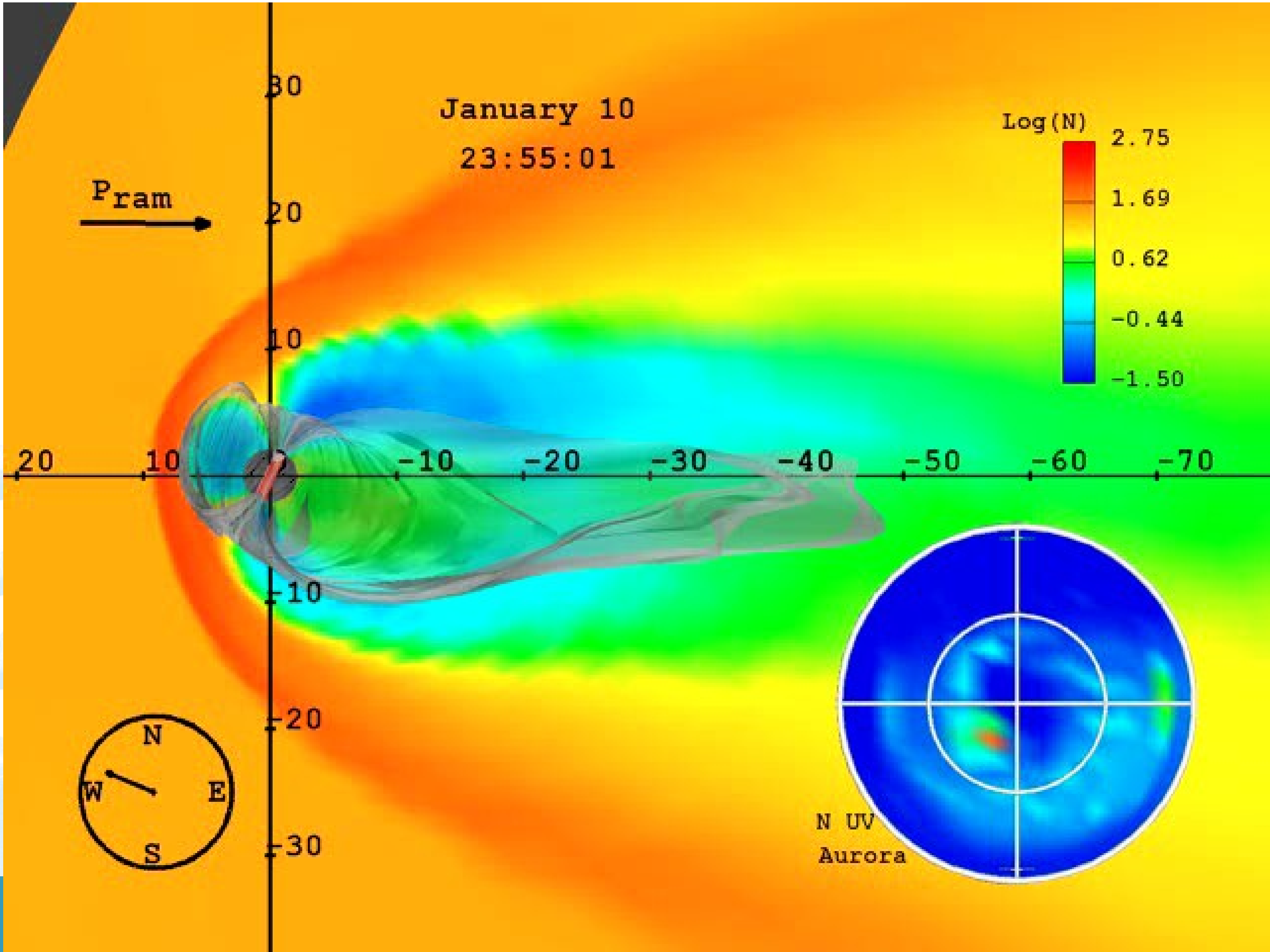
4500 spacecraft anomalies over last 25 years



Radiation (mSv):

- *astronaut during 1 EVA:* 50 mSv

Geomagnetic storms



Effects on Earth

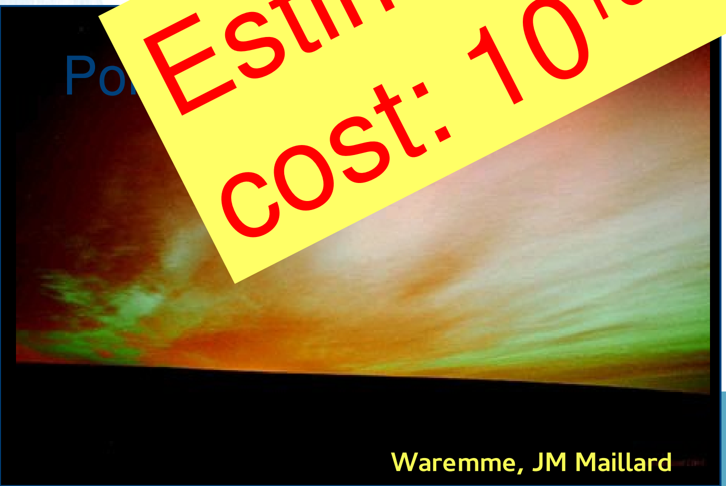
GEOM… ETIC STORMS:

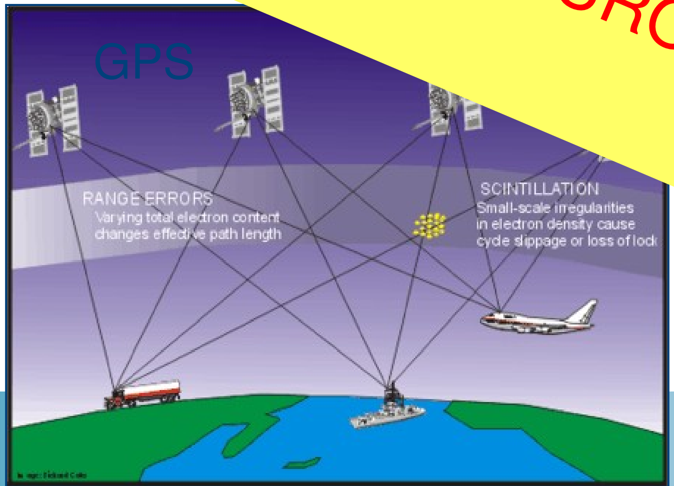
Most … ffects :

Economic cost of 1 ‘**extreme**’ event: up to 2.7 x 10^{12} EURO

[Eastwood et al. 2017]

Estimated … economic cost: 10^{10} EUR…





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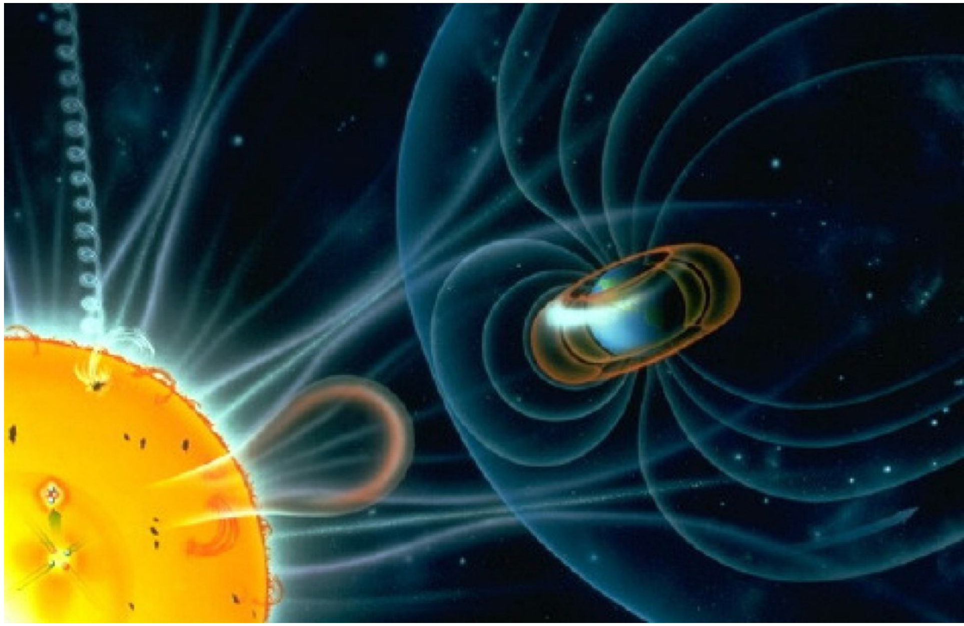
Need for reliable predictions

- Importance of **reliable predictions** of the space weather and its *effects on technological systems, human life and health*.
- Requires *a deeper insight in space weather physics*.
- Observations are much needed *but sometimes limited/difficult to interpret (projection effects, …) and* some things cannot be observed *(e.g. coronal magnetic field)*



- **Numerical simulation models** can provide (additional) information that cannot be observed directly (magnetic field topology, density structure, local velocity, etc.)

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EUHFORIA Rationale

Science:

- Quantify the deformation, deflection and erosion of flux ropes evolving in the inner heliosphere
- Characterize the magnetosheaths of CMEs
- Clarify the role of CME-CME interactions in enhanced SEP production

Applications:

- Space weather forecasts ("European ENLIL")
  - Time of arrival / *Geo-effectiveness*
- Support for space missions (e.g. SolO)

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Credit: Jens Pomoell

EUHFORIA

'European heliospheric forecasting information asset'

Taking coronal model as lower boundary condition

Solar wind at @ 0.1 AU

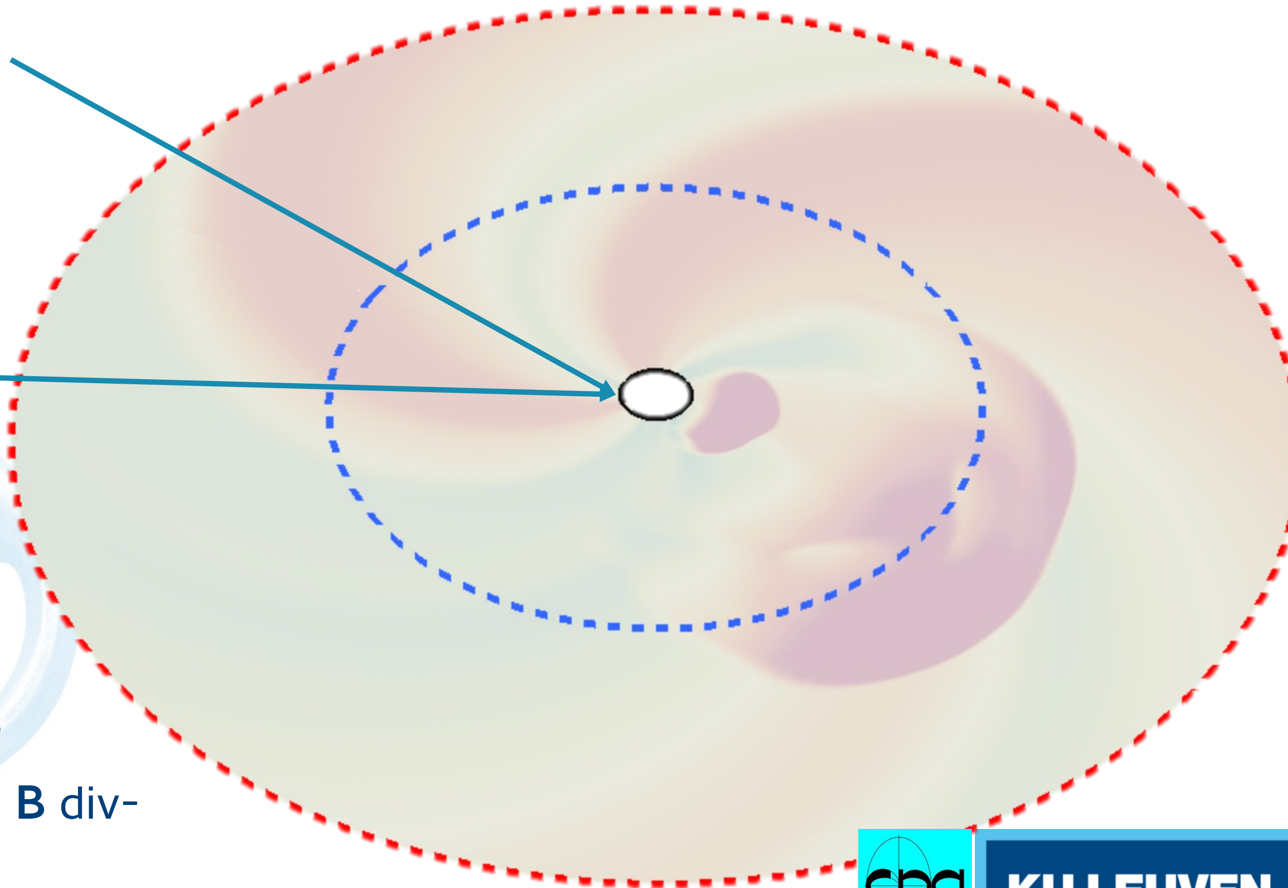
- Semi-empirical:
  - Gong or ADAPT
  - PFSS
  - WSA/DCHB+CSC

CMEs at @ 0.1 AU

- Cone model
- Spheromac + GL

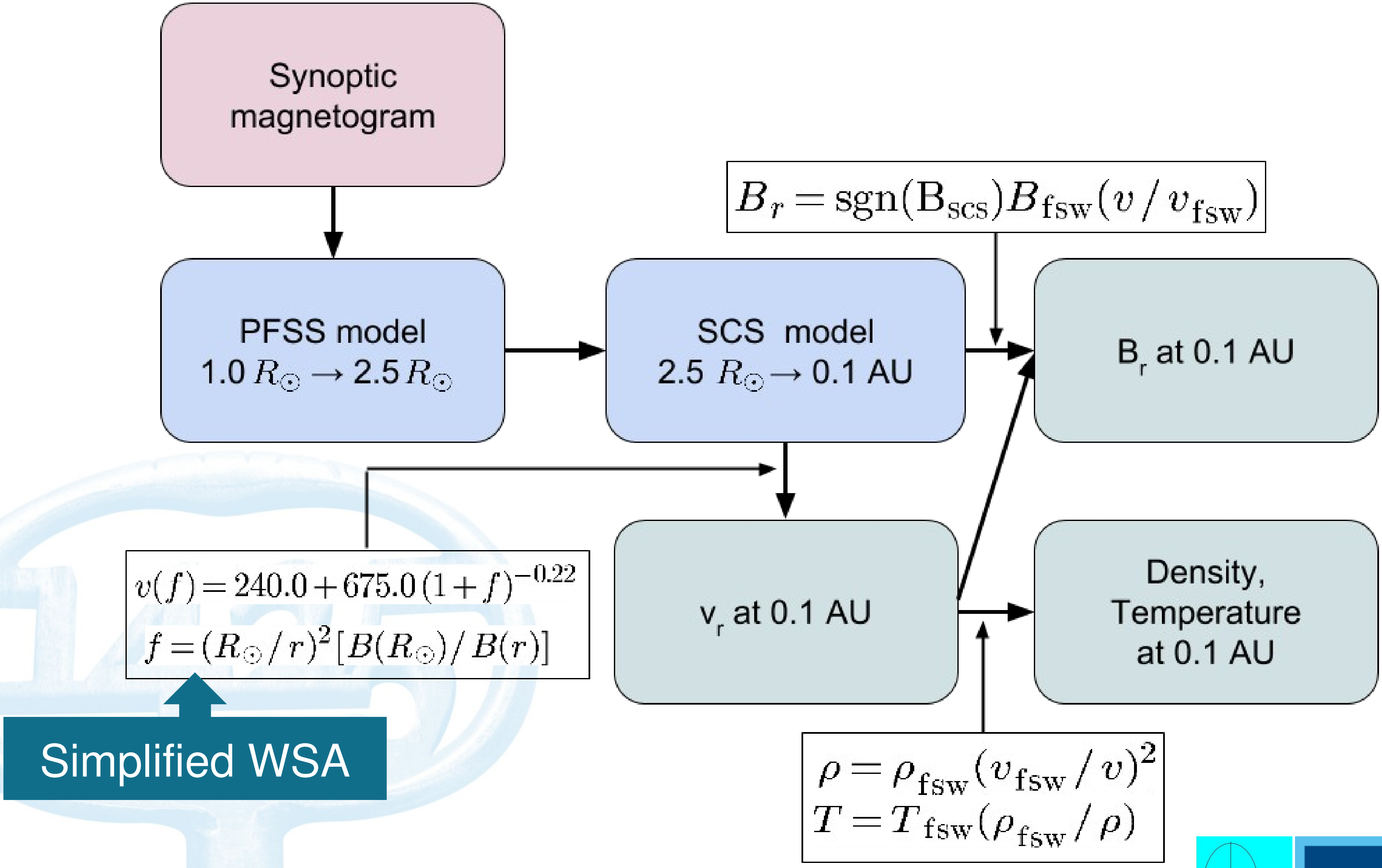
Inner Heliosphere

- 0.1 AU □ 2.1 AU
- Time-dependent 3D MHD (FVM with CT approach for advancing **B** div-free)



Credit: Jens Pomoell

Semi-empirical coronal model (v. 0.9)



Credit: Jens Pomoell

EUHFORIA 1.0 (8 June 2017)

Update on WSA empirical formula for *v* as a function of flux tube expansion factor *f* and the distance of the foot-point of the flux tube to the nearest coronal hole boundary *d* :

$$v(f,d) = v_0 + \frac{v_1}{(1+f)^{\alpha}}\left[1 - 0.8\exp\left(-(d/w)^{\beta}\right)\right]^3$$

which is the original WSA formula with parameters

- v_0 = 240 km/s, v1 = 675 km/s
- α = 0:22
- β = 1:25
- *w* = 0:02 rad (serves to normalize the dependence of the solar wind speed on the distance to the nearest coronal hole boundary)

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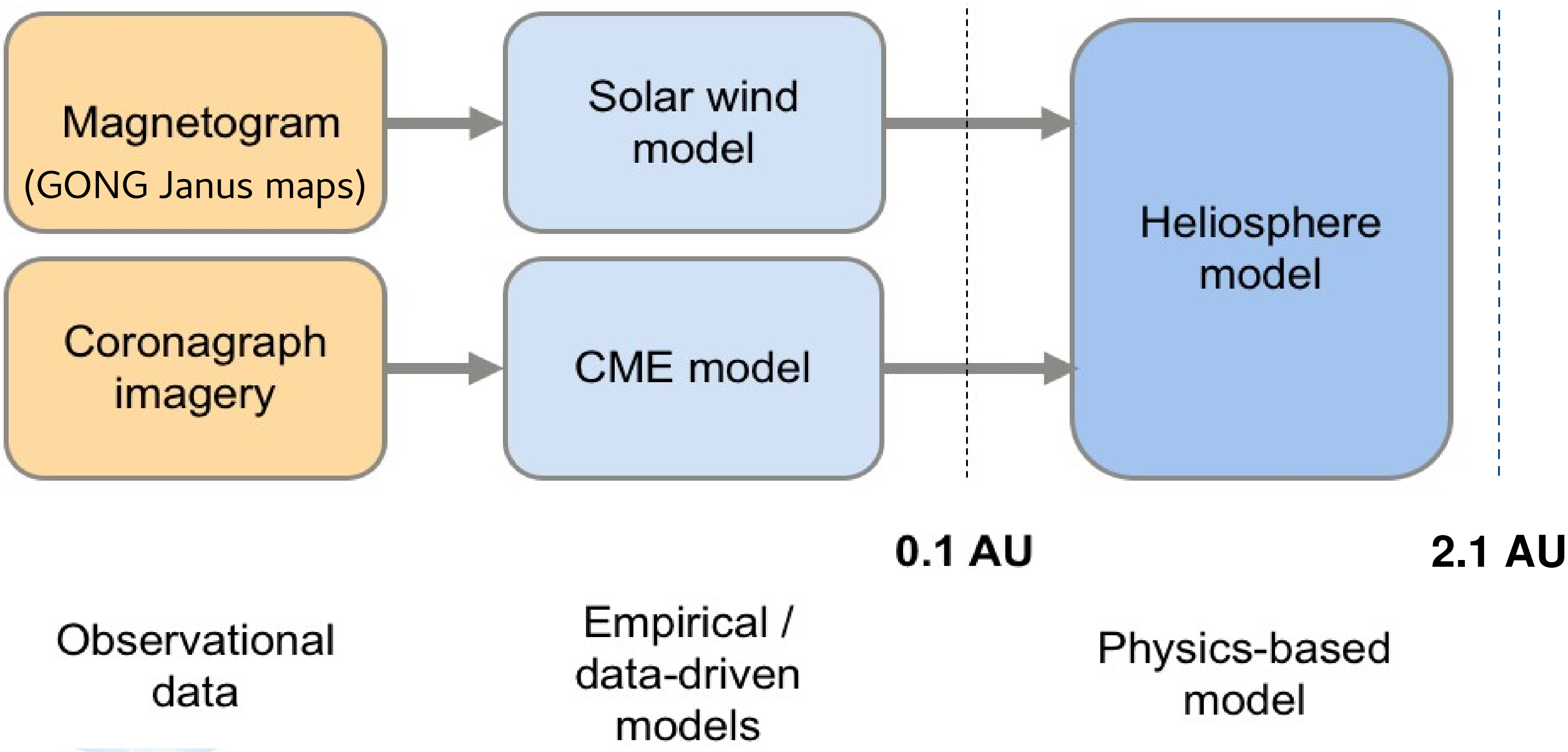
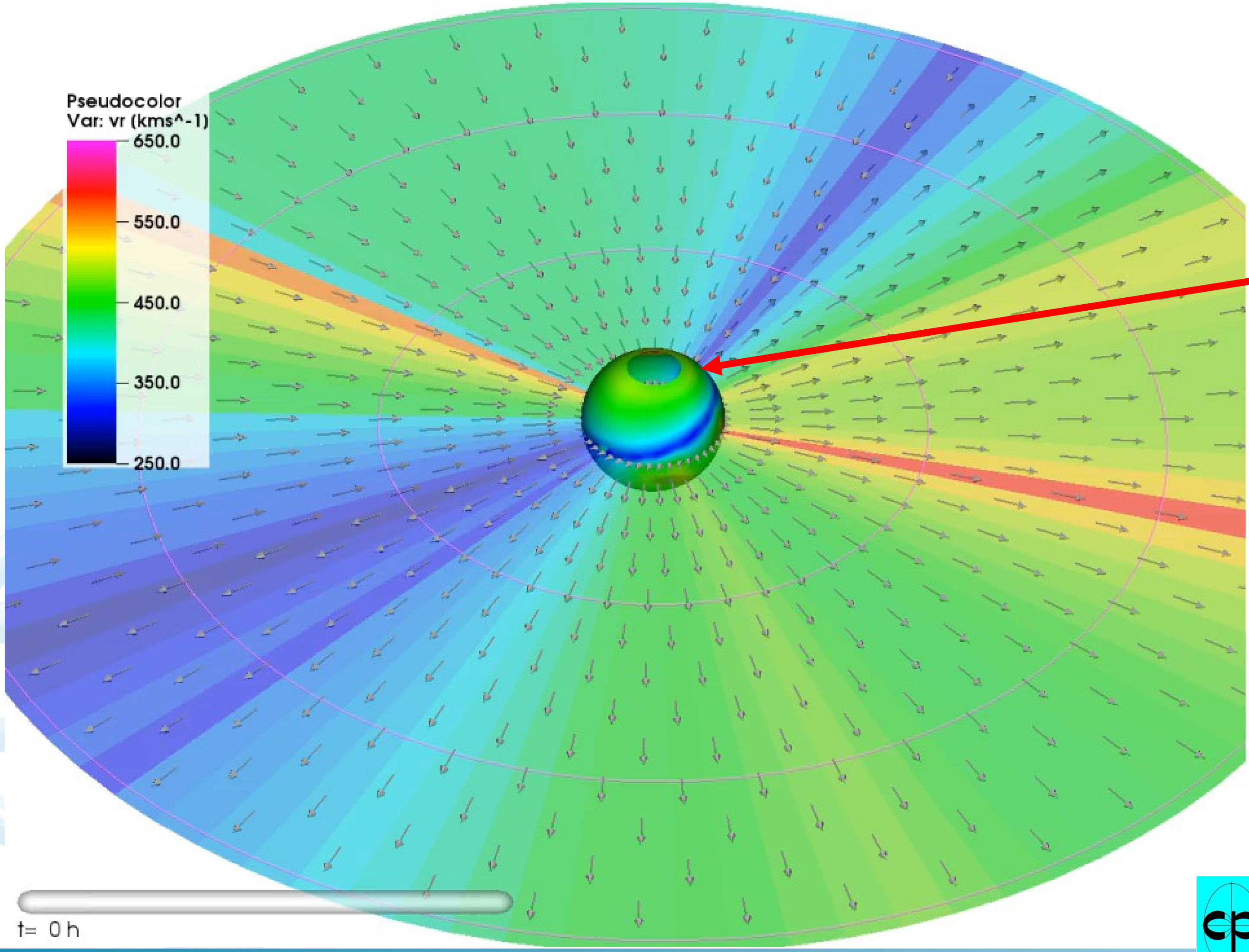
EUHFORIA model is data-driven

EUHFORIA v1.0:

3D heliospheric wind + CME evolution code



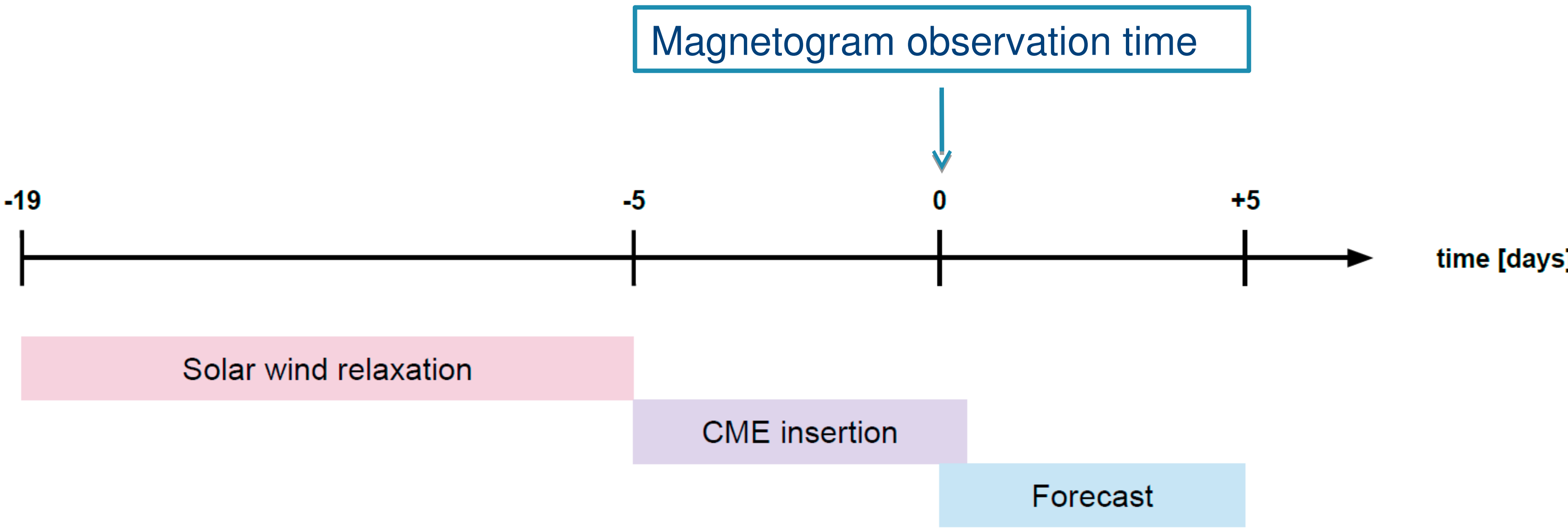
MHD wind relaxation in Euhforia



3D visualization of **MHD relaxation** in low resolution (same as ENLIL) 0.1 AU - 1 AU

Color = radial velocity (initially extended)
Arrows = magnetic field (initially radial)

Phases of a run



- 14 days relaxation is sufficient for slow wind (250 km/s) to reach 2 AU
- CMEs before the event to be forecasted significantly modify plasma in IP space. Typically, significant CMEs from 5 days prior to event are inserted.
- Starting time of forecast = observation time of magnetogram used to construct the coronal model.

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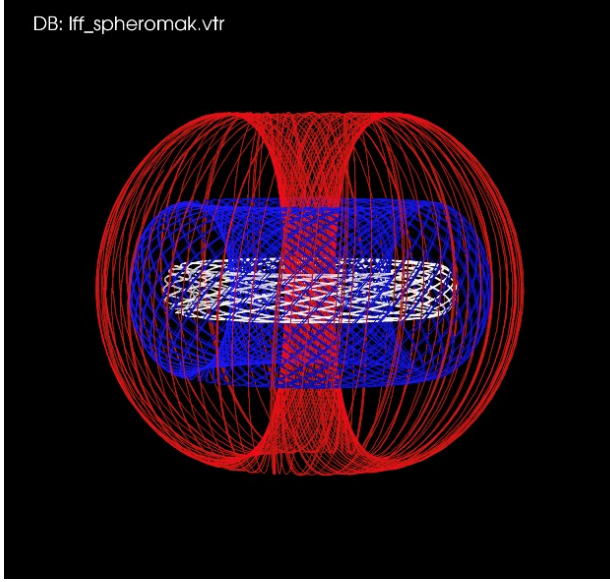
Credit: Jens Pomoell

CME input parameters



1. CME speed
2. CME insertion time
3. CME longitude
4. CME latitude
5. CME half width
6. CME density
7. CME temperature
8. FR tilt
9. FR helicity
10. FR toroidal **B** flux

Items 1–7: Cone CMEs / Flux-rope CMEs

Items 8–10: Flux-rope CMEs only

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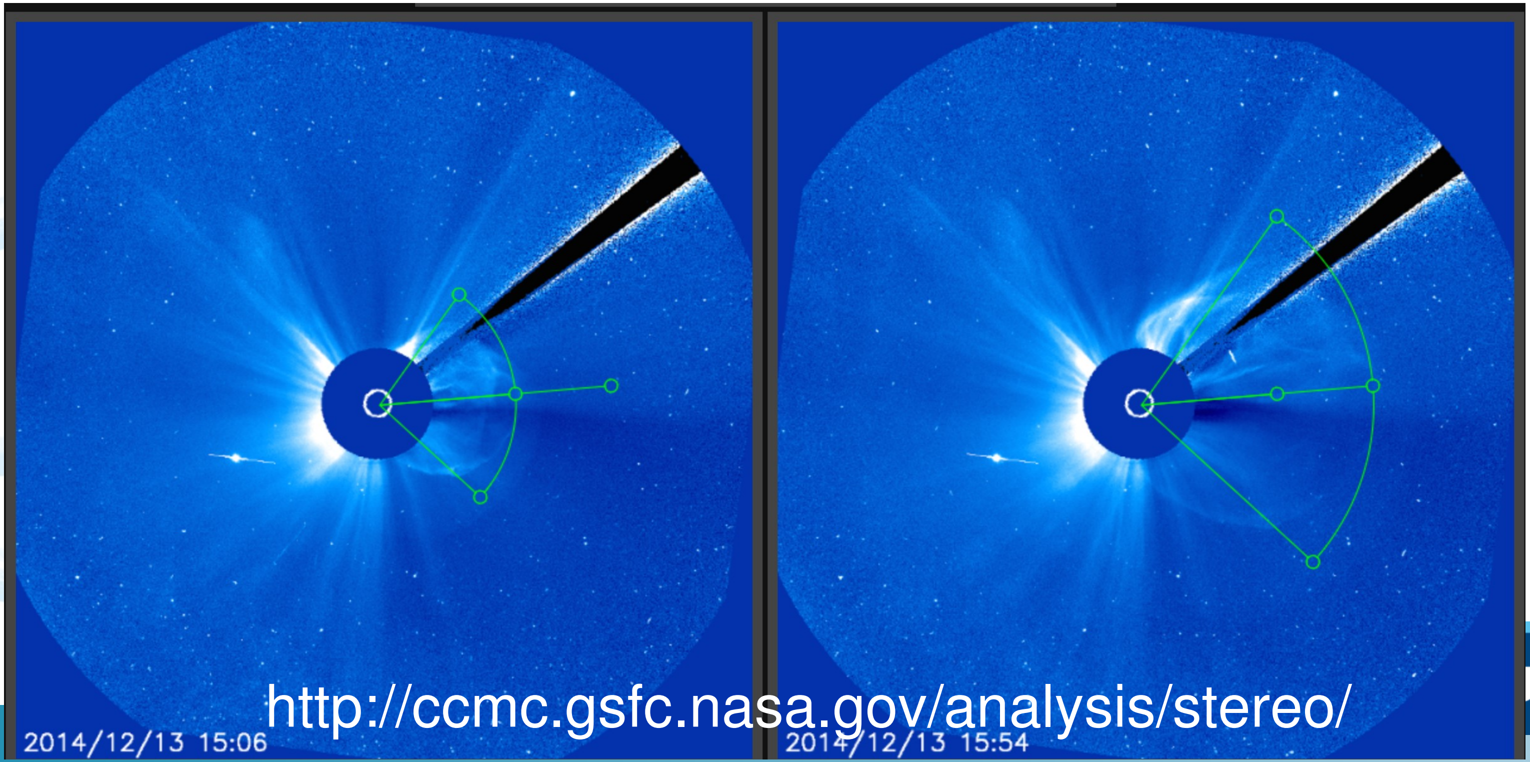
Credit: Camilla Scolini & Christine Verbeke

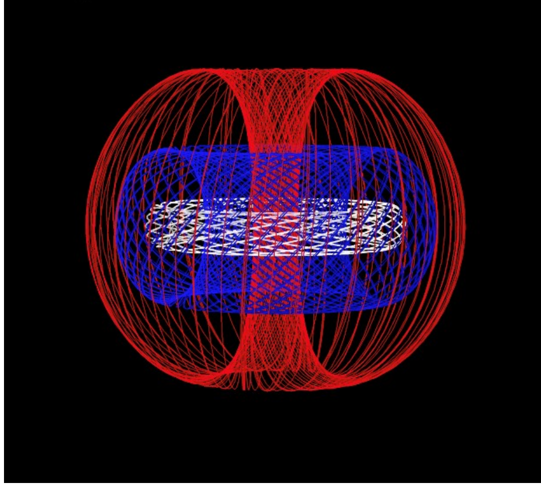
‘data-driven’ CME model parameters

- Parameters (speed, direction, width) obtained through fits to coronagraph data (e.g. via StereoCAT)
- Mass density and temperature need to be provided by forecaster



http://ccmc.gsfc.nasa.gov/analysis/stereo/

CME input parameters



- CME speed
- CME insertion time
- CME longitude
- CME latitude
- CME half width
- CME density (default value)
- CME temperature (default value)
- FR tilt
- FR helicity
- FR toroidal **B** flux

CME speed, insertion time, longitude, latitude, half width ← 3D reconstruction (GCS model)

FR tilt, FR helicity ← Magnetic+EUV observations of source region (Palmerio+2017)

FR toroidal **B** flux ← (Gopalswamy+2017) ← 3D reconstruction

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Consider June 18–27, 2015 events

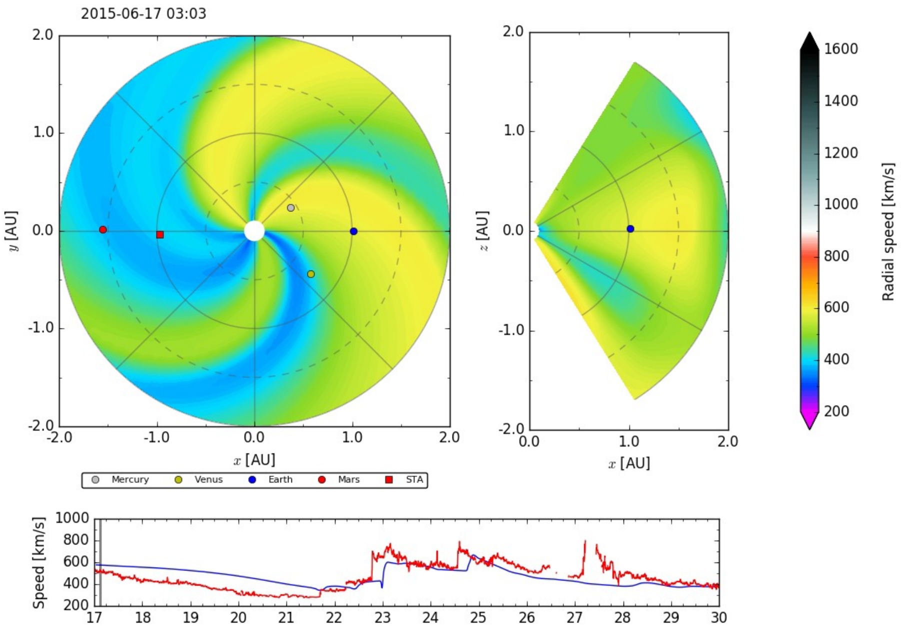
- 17 cone model entries in DONKI, 9 with little or no impact to Earth
- We selected the **5 events most apparently directed to Earth**:

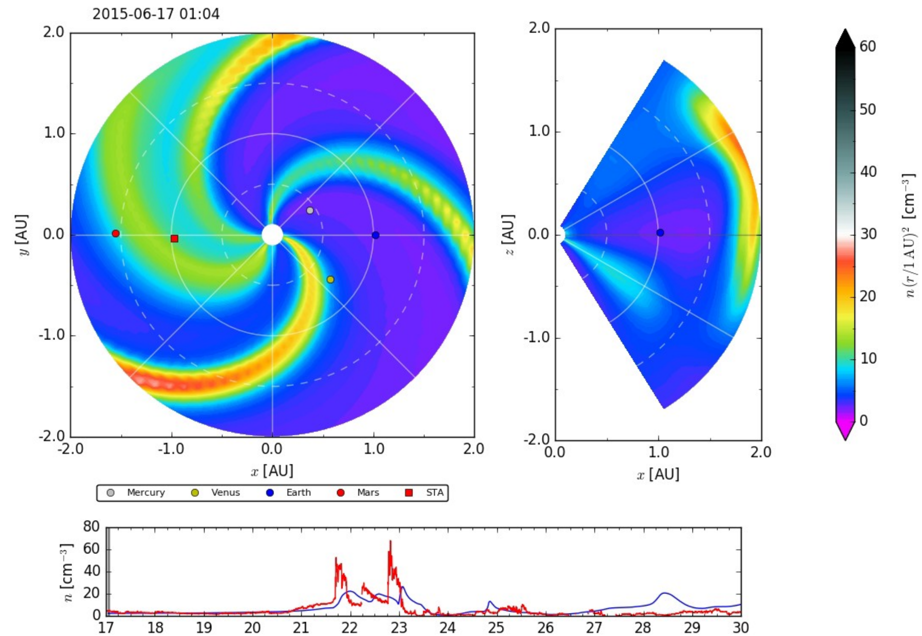
CME Number	Time at 0.1 AU	Lat (deg HEEQ)	Lon (deg HEEQ)	Half-width (deg)	Speed (km/s)
1	2015-06-18T20:00:00	11	-50	45	1000.0
2	2015-06-19T14:59:00	-33	9	54	603.0
3	2015-06-21T05:01:00	7	-8	47	1250.0
4	2015-06-22T21:10:00	14	3	45	1155.0
5	2015-06-25T10:51:00	23	46	41	1450.0

- Events 1, 4 and 5 are related to M-class flares from AR12371
- **No input for density and temperature**, hence assume
  - constant density: $\rho_{CME} = 10^{-18}$ kg m^{-3}
  - constant temperature: $T_{CME} = 0.8$ MK

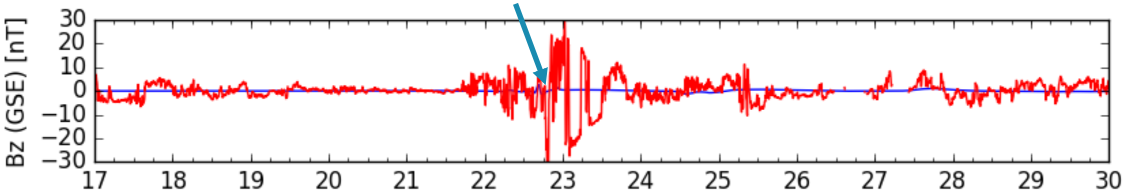
From: Pomoell & Poedts (SWSC, 2018)

Cone CME model run





Bad/wrong B_z from Cone CME



Cone model parameters (speed, direction, timing) from DONKI database

Credit: Jens Pomoell

CCSOM: EUHFORIA development project

Constraining CMEs and Shocks by Observations and Modelling throughout the inner heliosphere (CCSOM)

- PI: **J. Magdalenić**, co-PI: S. Poedts
- 4 years, started in March 2017
- Incl. ROB, KU Leuven, Univ. of Helsinki and Univ. of Graz

Objectives:

- to simulate the **propagation of flux rope CME-ICME structures** in realistic background solar wind conditions, with the resulting model exceeding the current state of the art,
- to compare the results of the obtained model with observations of a number of events of different types.

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Updated modeling chain (in progress)

Coronal model
R = 1 □ a few Rs

Non-linear force-free extrapolations

Time-dependent magnetofrictional model

CORMA

Intermediate model
R = a few Rs □ 0.1 AU

Cone + Flux rope CME models

Spheromak, FRi3D, GL, TDm

Heliosphere model
R > 0.1 AU

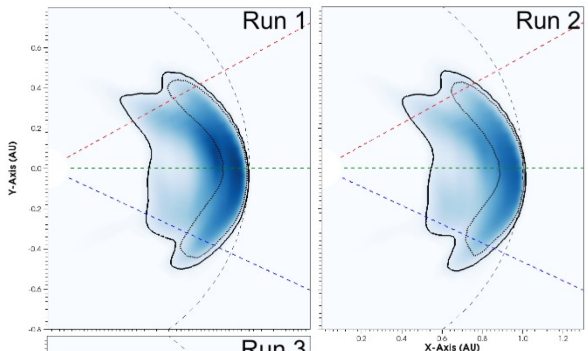
MHD evolution

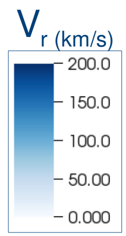
EUHFORIA

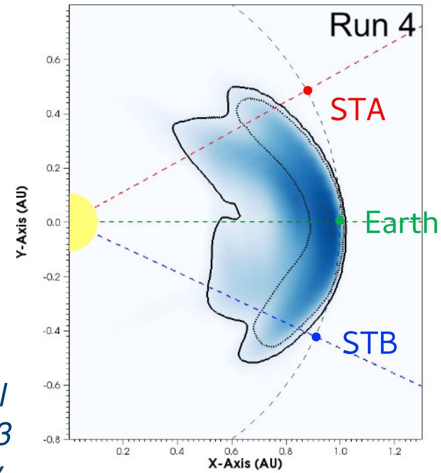
Parameter study: cone CME shapes in EUHFORIA

We have tested the effect of different spherical CME shapes in EUHFORIA comparing the results at different spacecraft locations at 1 AU and the impact on geo-effectiveness

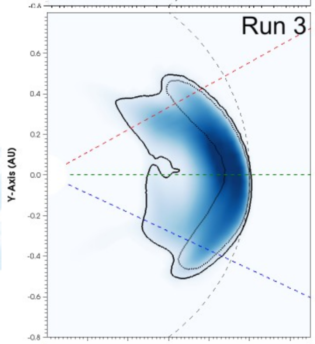
CME shape in the solar equatorial plane



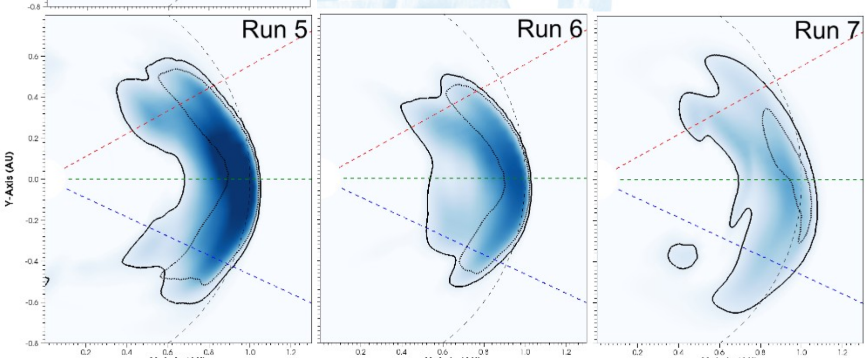




For more information about the effect of different CME shapes in EUHFORIA: ESWW14, C. Scolini et al.



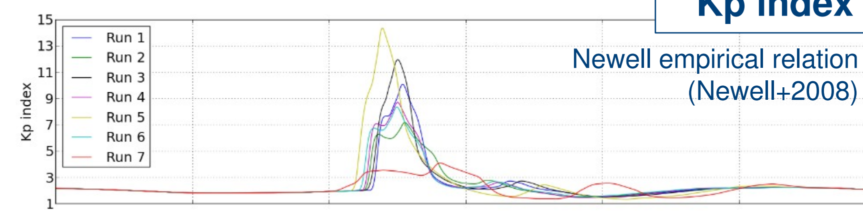
Background-subtracted radial speed on 2008-06-08 at 06:03 UT. The region influenced by the CME is delimited by the background-subtracted contour lines: $v_{r=20\ km/s}$ (continuous), nscaled=5 part/cc (dotted).



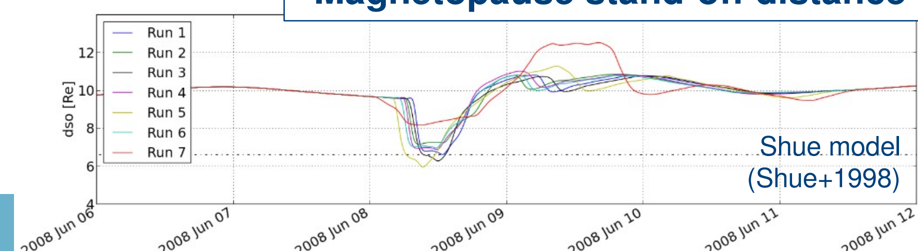
Geoeffectiveness predictions

Kp index

Newell empirical relation (Newell+2008)



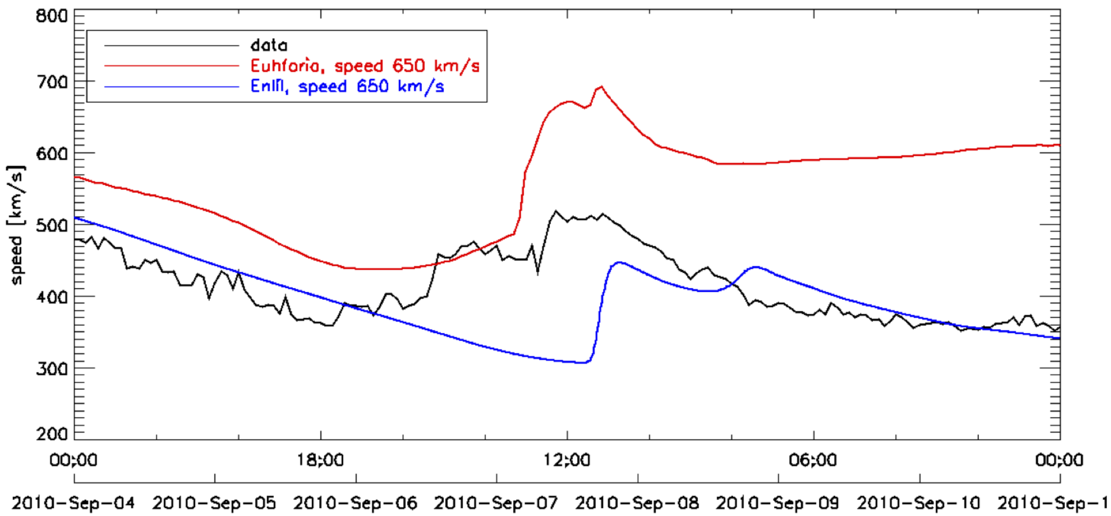
Magnetopause stand-off distance



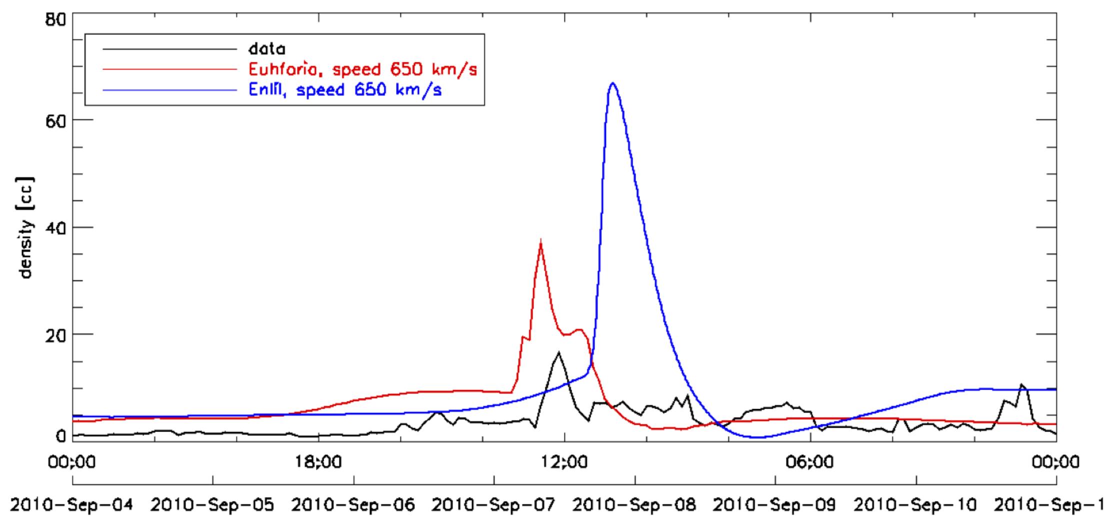
Shue model (Shue+1998)

Comparison EUHFORIA–ENLIL

CME on Sep 4, 2010 arriving to STEREO-A on Sep 7, 2010:



Conclusion:



EUHFORIA run anticipates the arrival of the CME at STEREO-A (up to 3h), while **ENLIL** delays it (up to 12h).

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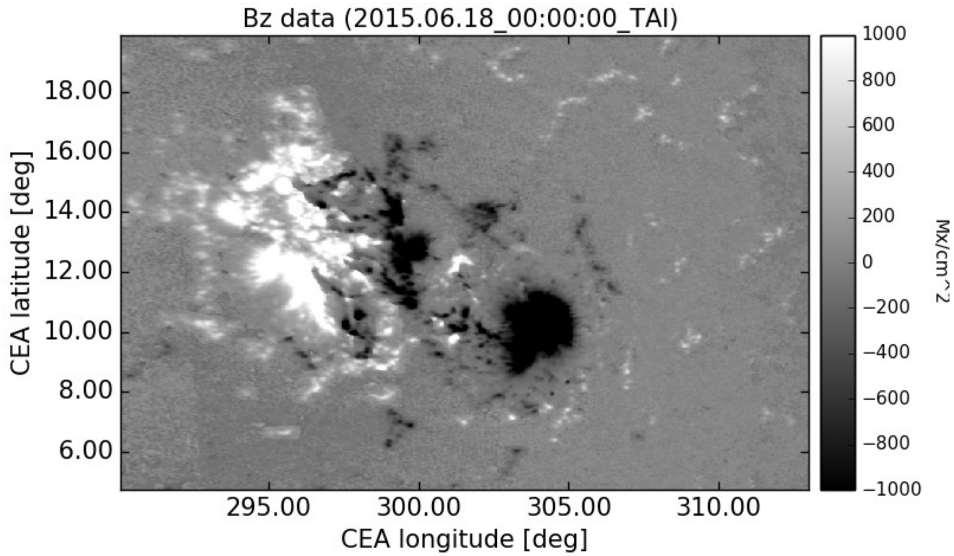
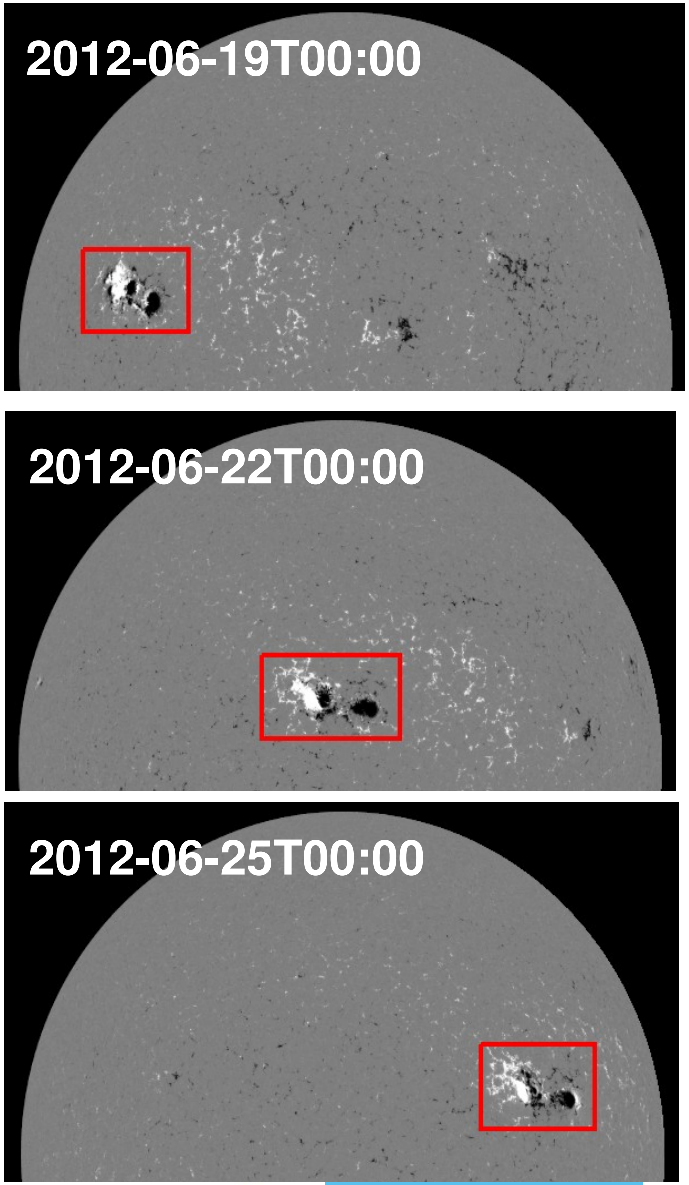
Scolini et al., to be submitted

AR evolution





- **NLFFF** extrapolations using time-series of HMI vector magnetograms 6 h cadence
- Optimization method:
  - 4th order finite difference
  - Separation of **B** into potential and non-potential part
  - Multigrid (coarse □ increasingly finer meshes)

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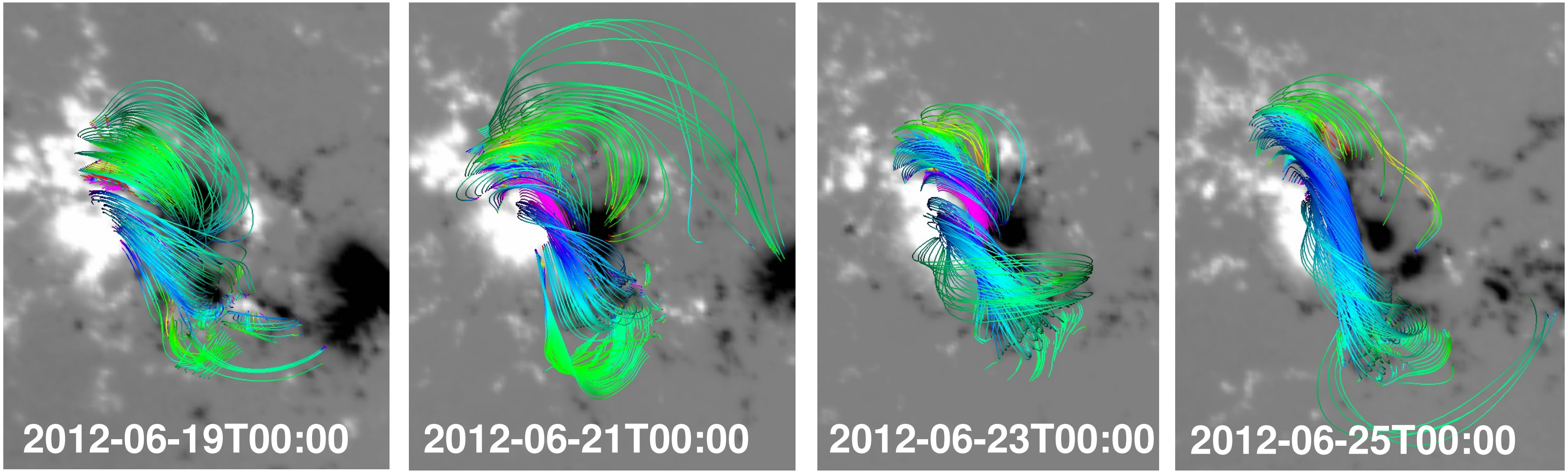
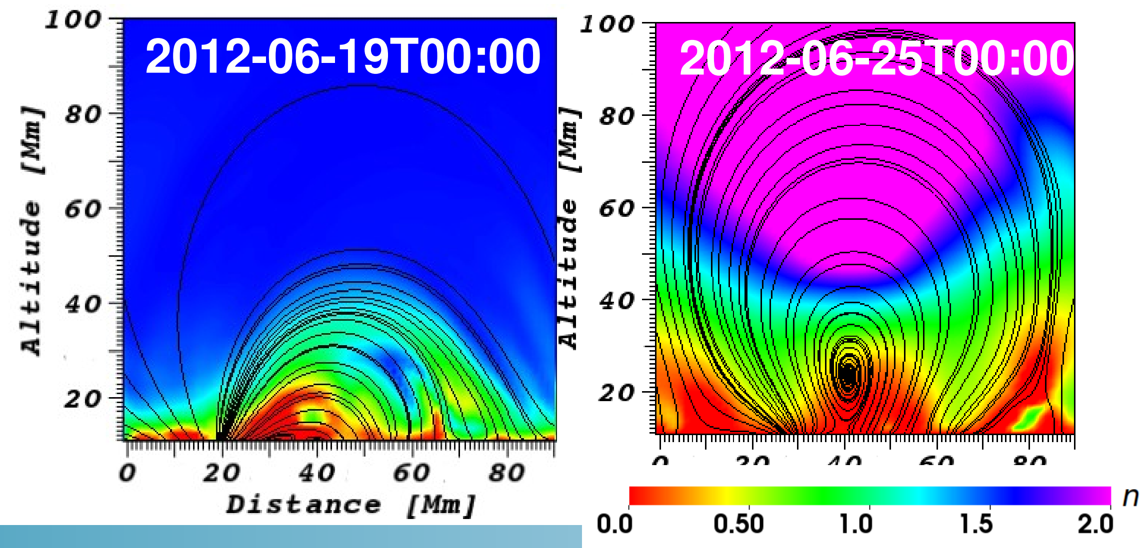
Credit: Jens Pomoell

NLFFF modeling



- Sequence of non-linear force-free field extrapolations (Optimization approach, Processed data from HMI full disk vector magnetograms)
- Initially, AR exhibits sheared arcade structure ▯ FR
- Evolves to a FR, possibly due to flux cancellation



Credit: Jens Pomoell

Connecting the corona and heliosphere

- MHD simulations currently too complex/labour-intensive for routine simulations
- Eruption realism not guaranteed
- Employ an intermediate FR model instead:
  - ✓ Fit kinematics to EUV & coronagraph observations
  - ✓ Use coronal model (NLFFF/magnetofriction) to estimate magnetic parameters (might need semi-empirical relations to be established)
  - ✓ Estimate of uncertainties (explore space of reasonable parameters) □ ensemble runs

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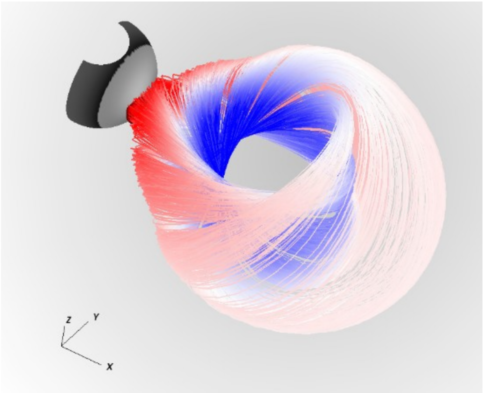
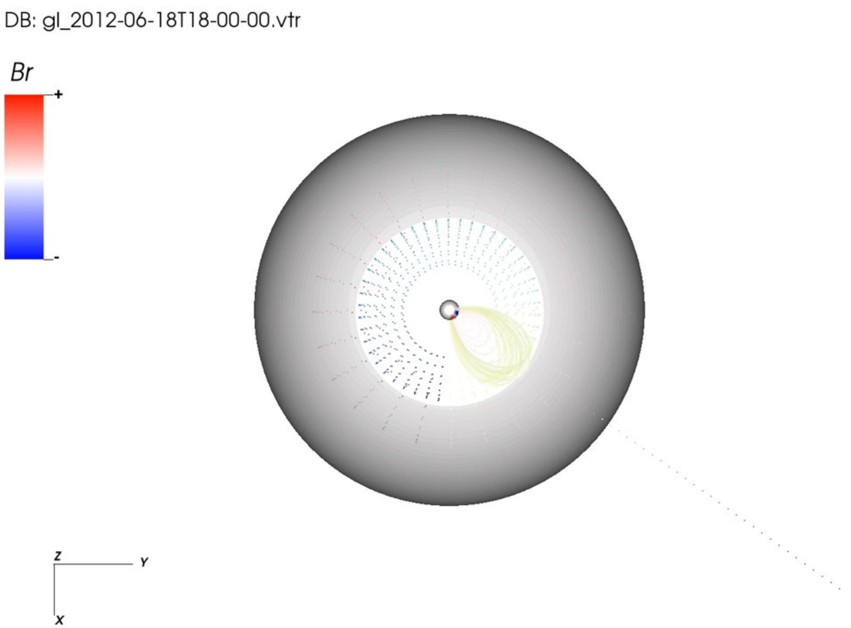
Connecting corona and IP space

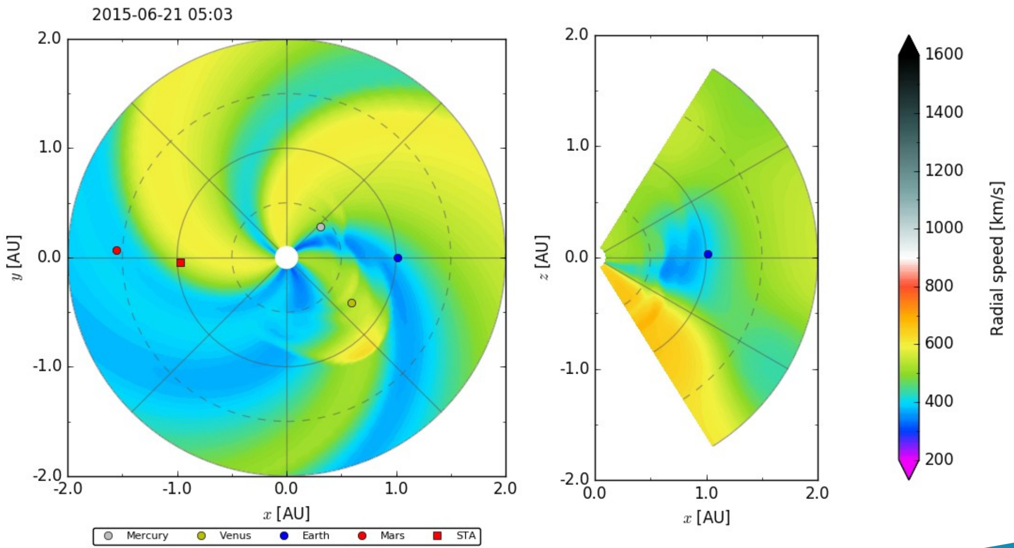
- Employ Gibson & Low 1999 CME model:
  - Analytic solution of the time-dependent 3D MHD equations of a FR expanding self-similarly
  - Stretched spheromak-like magnetic field structure
  - *Self-consistently includes low-density cavity, high-density core*
  - Has been used in a number of MHD studies
- Constrain parameters of the model:
  - Fit kinematics to EUV & coronagraph observations or use cone model estimate
  - Use coronal model to estimate magnetic parameters (chirality, flux)



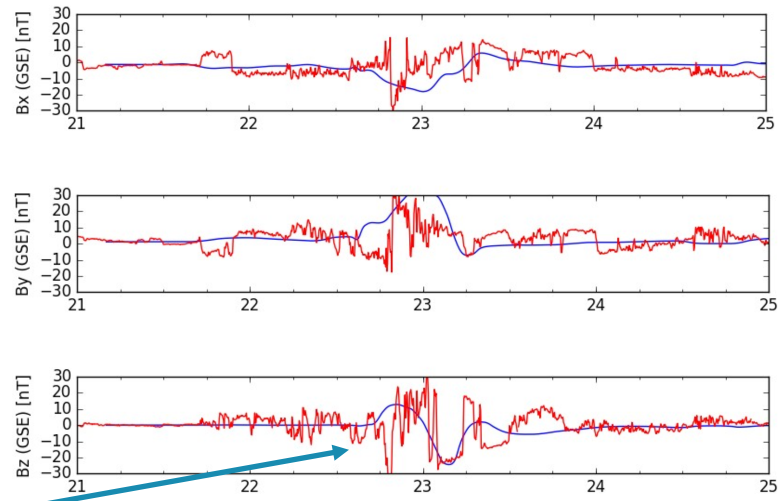


Credit: Jens Pomoell

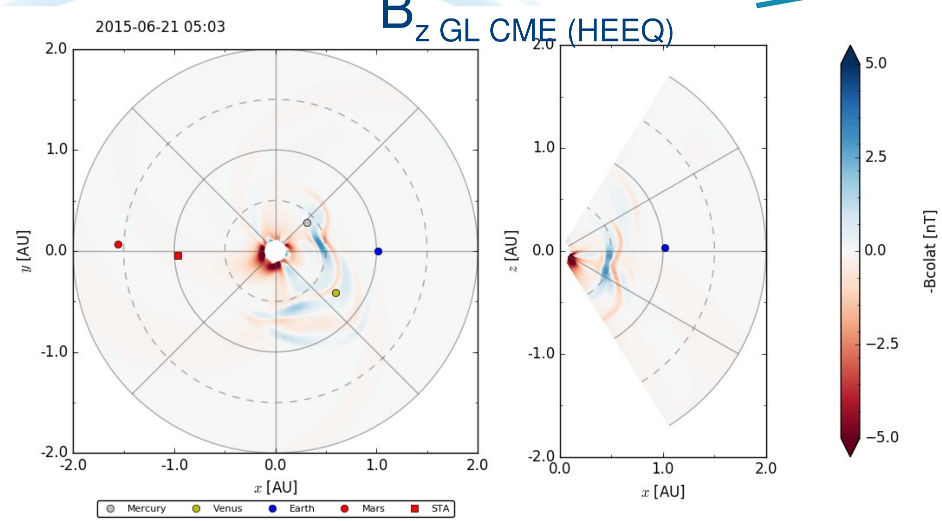
GL flux-rope CME model run



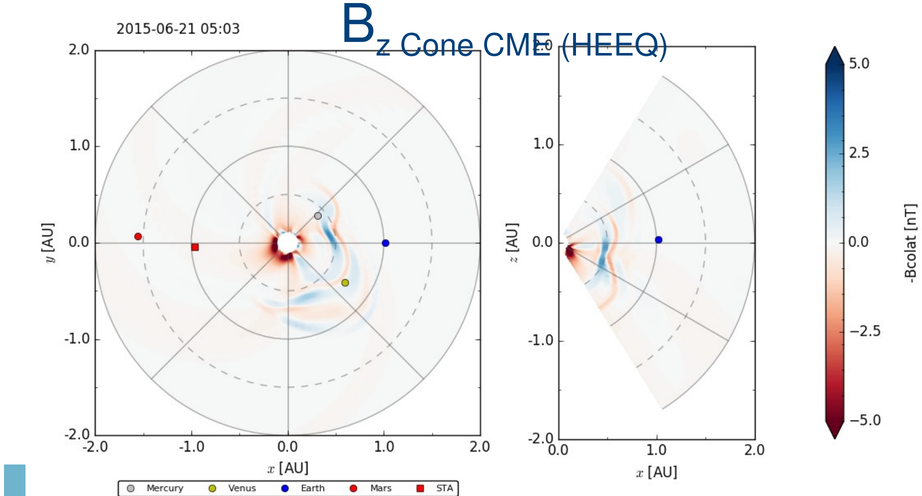
B-comp. fit with GL CME



B_z GL CME (HEEQ)

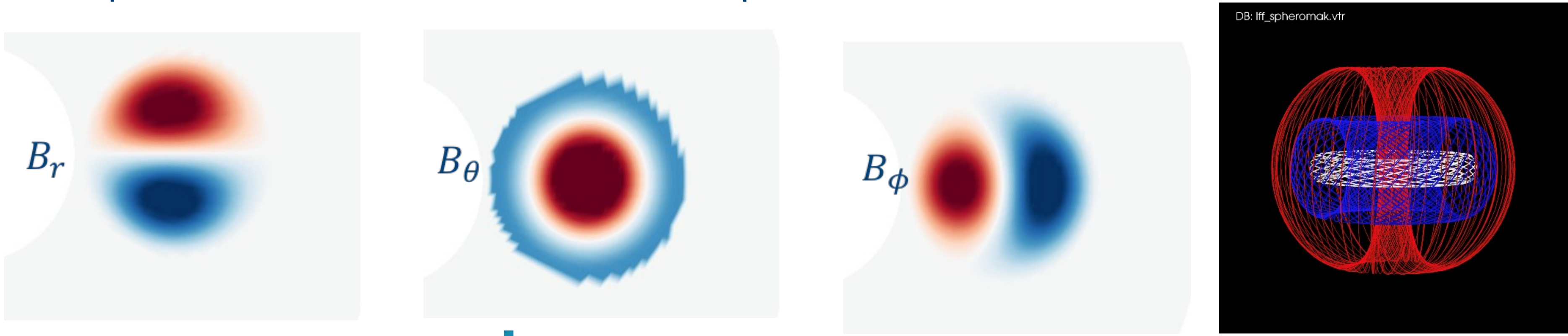


B_z Cone CME (HEEQ)



EUHFORIA: Spheromak CME

Flux rope modeled as Linear Force Free Spheromak



CME kinematics
Cone model

- Start time of CME
- Propagation velocity of CME
- Latitude of centre of CME source region
- Longitude of centre of CME source region
- Half-width of CME
- Density of CME
- Temperature of CME
- Title angle of the CME
- Helicity of the CME
- Total toroidal flux

Flux rope
parameters

+

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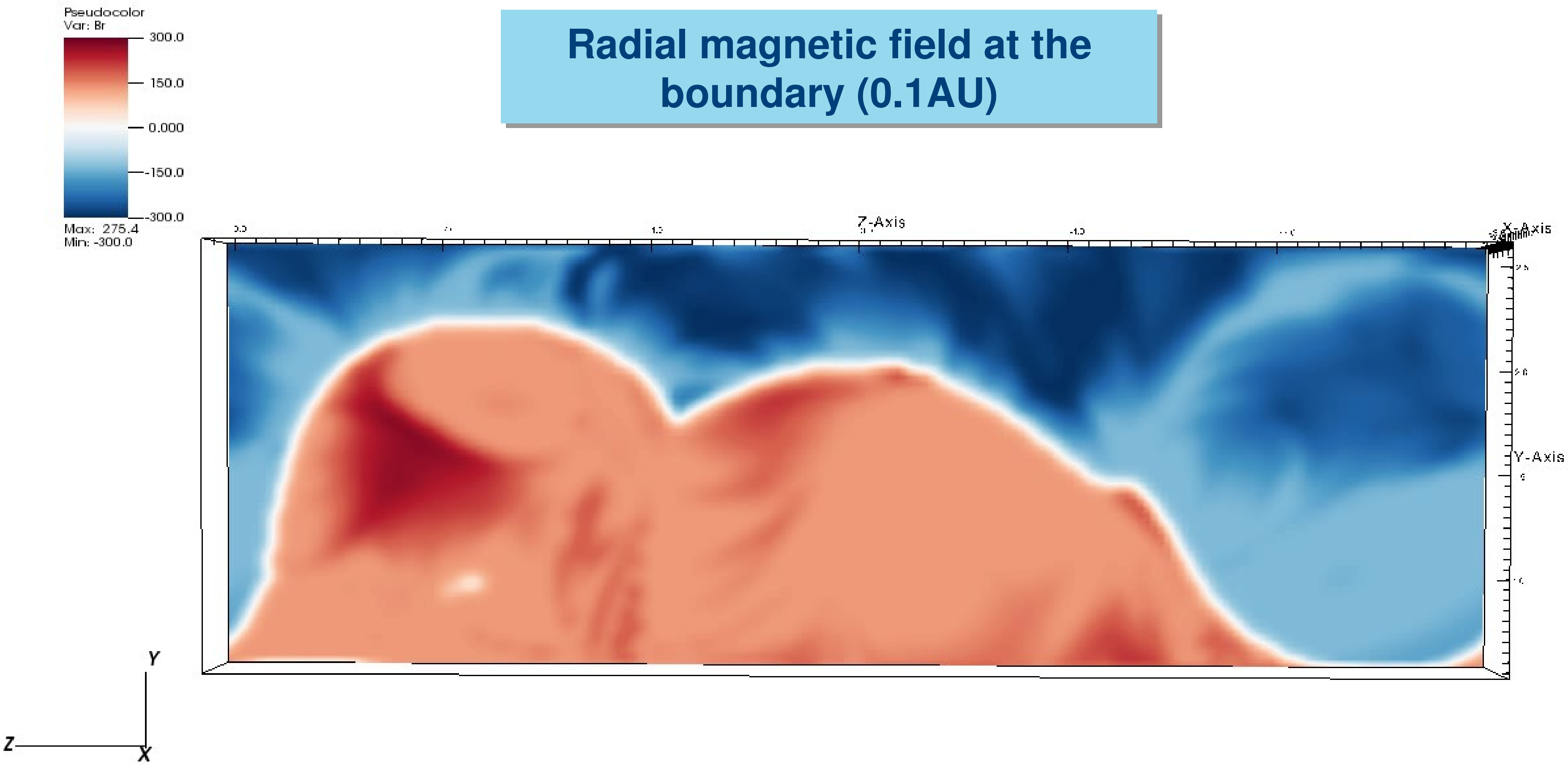
Spheromak example

Radial magnetic field at the boundary (0.1AU)

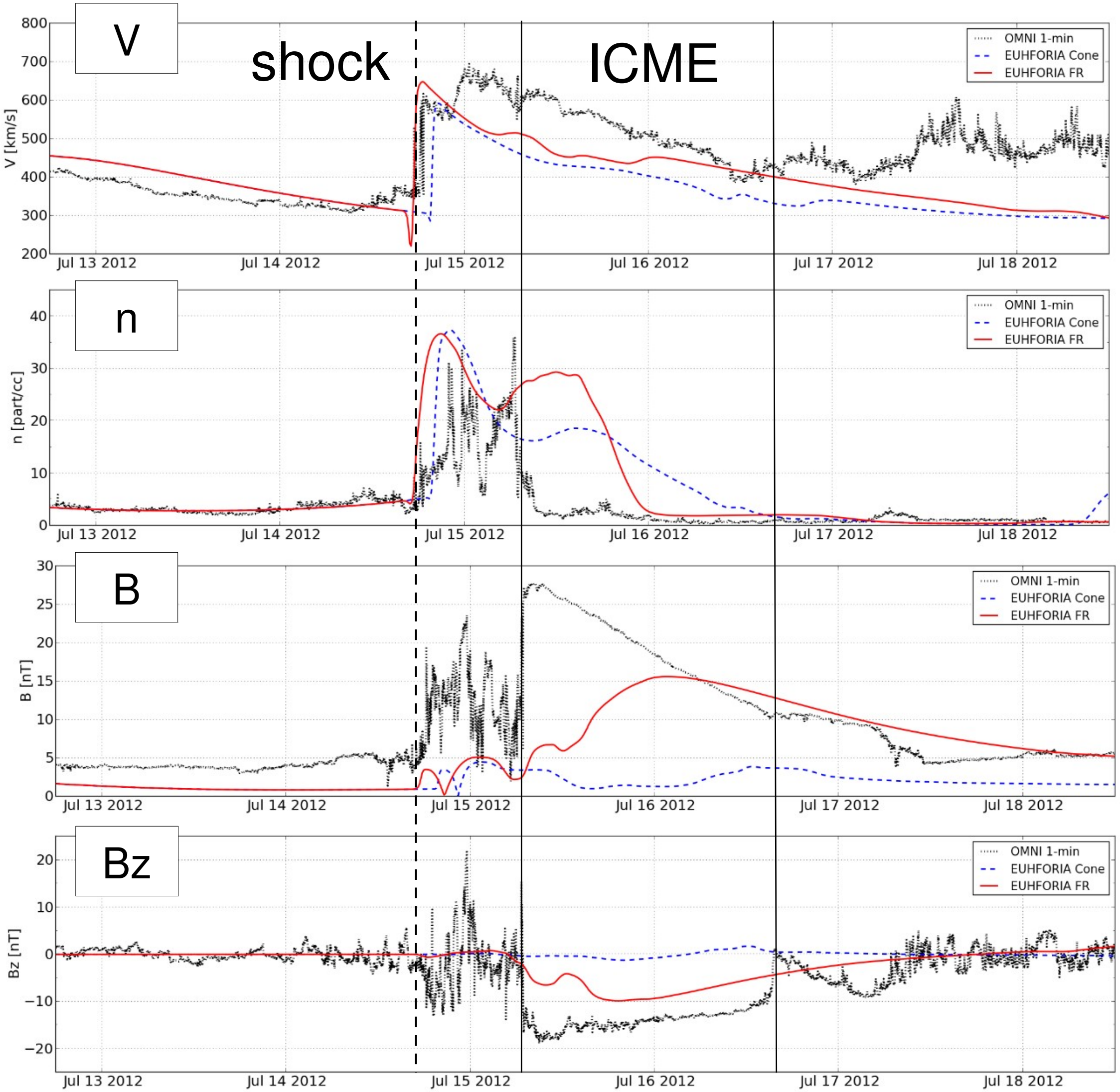


Cf. Verbeke et al., ESWW14

Spheromak vs cone model: predictions @ L1

July 12 2012 CME

ISEST WG4 Event 1



CME simulated using observation-based parameters

- **CME arrival time** and **peak density/speed** well reproduced by both models

? Magnetospheric compression

- **IMF rotations**: well reproduced with spheromak
- Min **Bz prediction** improved by **+40%** using spheromak compared to cone

? Dayside reconnection

& geomagnetic activity

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Credit: Camilla Scolini

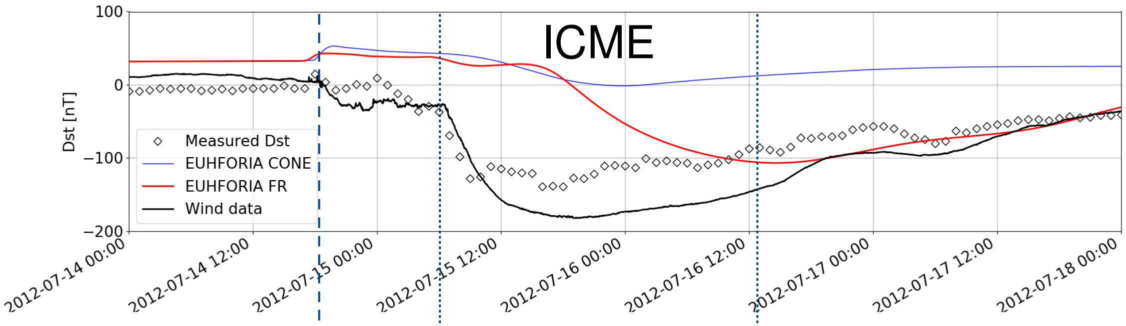
Spheromak vs cone model: geomagnetic activity predictions

July 12 2012 CME

ISEST WG4 Event 1

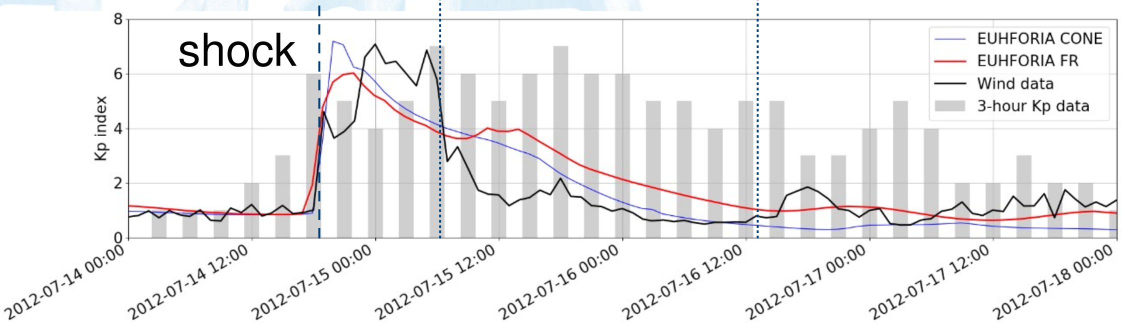
Dst: Empirical relation

(O'Brien & McPherron 2000)



Kp: Empirical relation

(Newell+2008)



EUHFORIA Dst prediction:

- Cone model misses completely the storm
- Spheromak improved the prediction of min Dst by **+80%**

? flux-rope CME model needed to predict Dst storms

EUHFORIA Kp prediction:

- Kp increase at shock time well predicted by both models
- High Kp tail missed by both

? Kp empirical relation mainly responsive to magnetospheric compression / shock parameters

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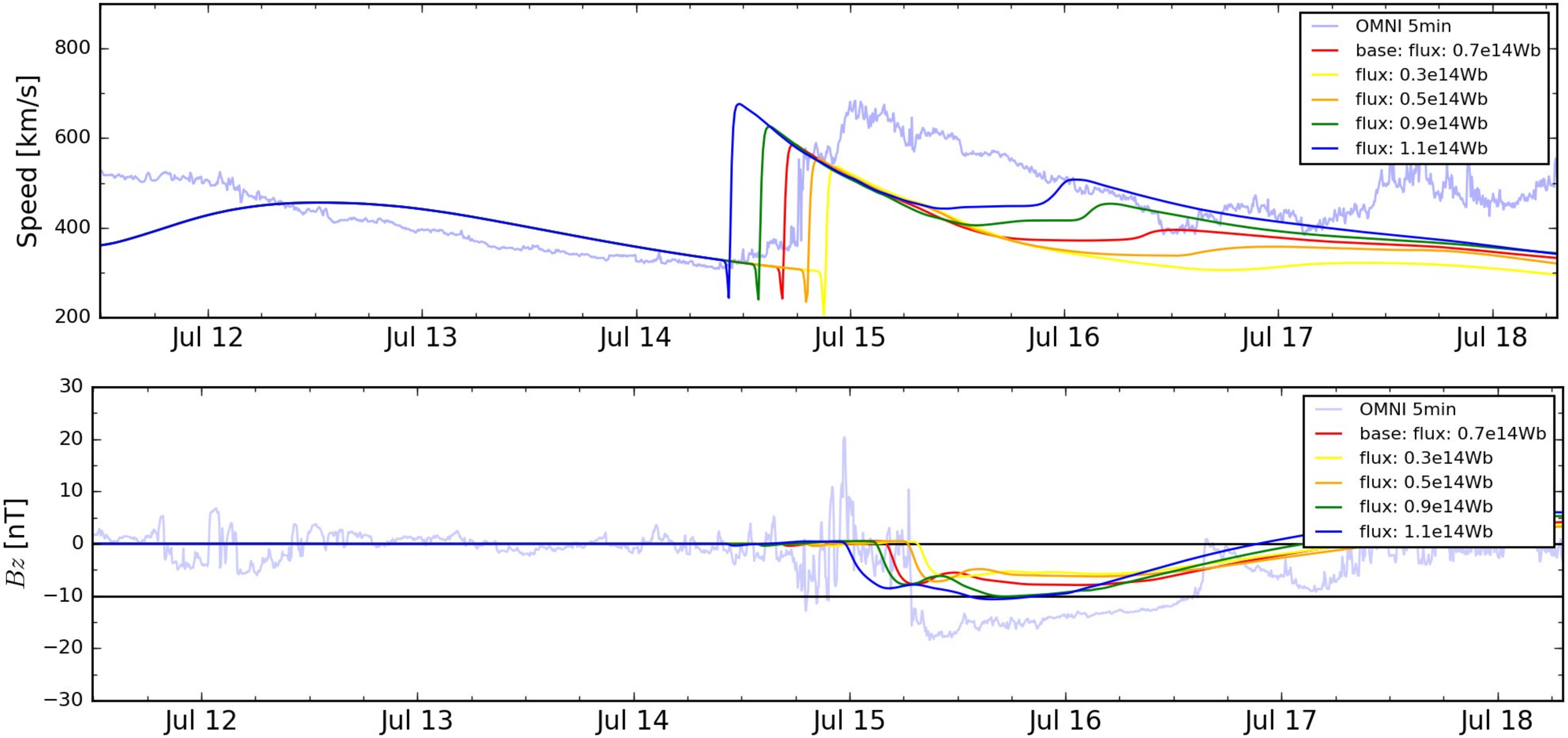
Credit: Camilla Scolini

Parameter study: toroidal flux



Flux affects arrival time and **B** strength, and also the deflection and expansion (as the total pressure is different)!

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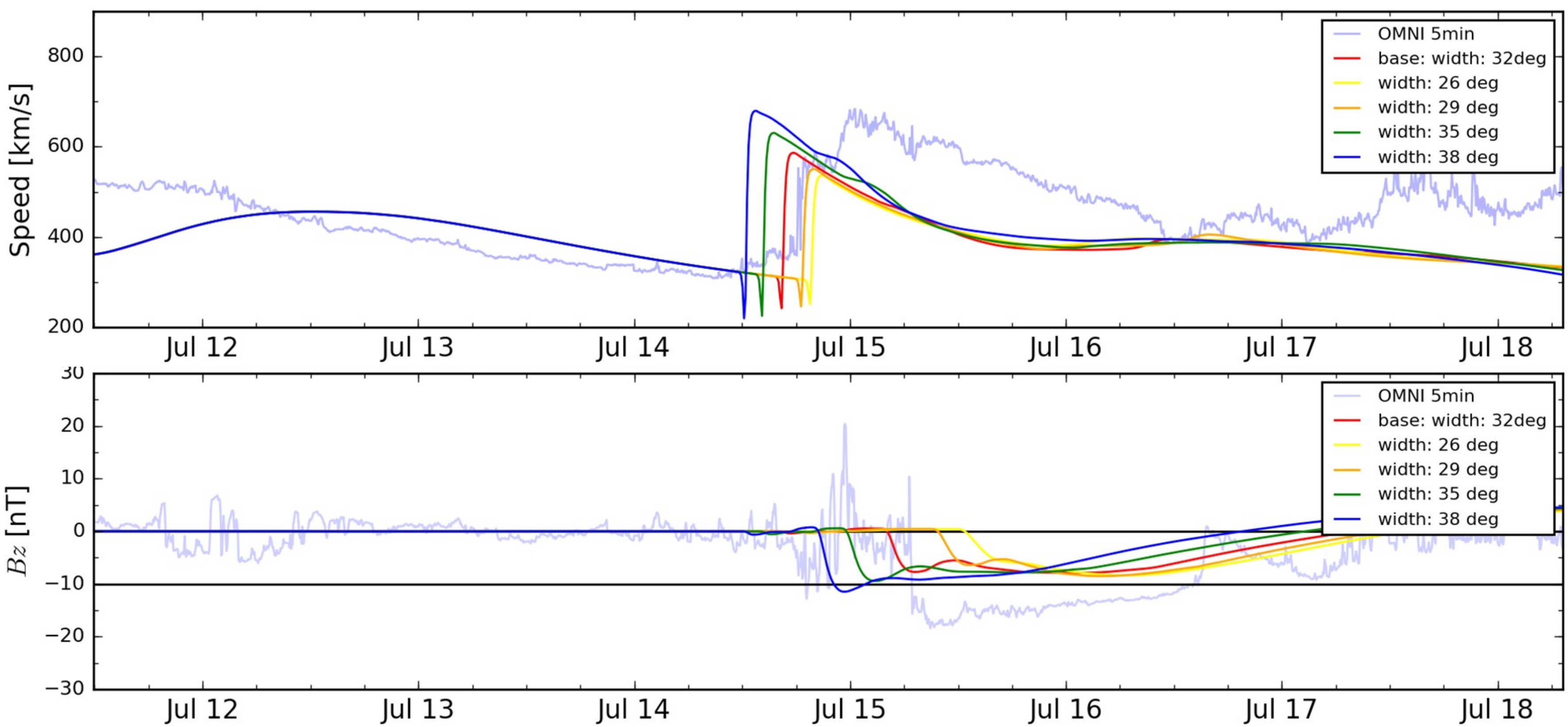
Credit: Christine Verbeke

Parameter study: Half-width *(different total mass)*



Less massive CME arrives later (lower initial momentum density), and they also have different deflection.

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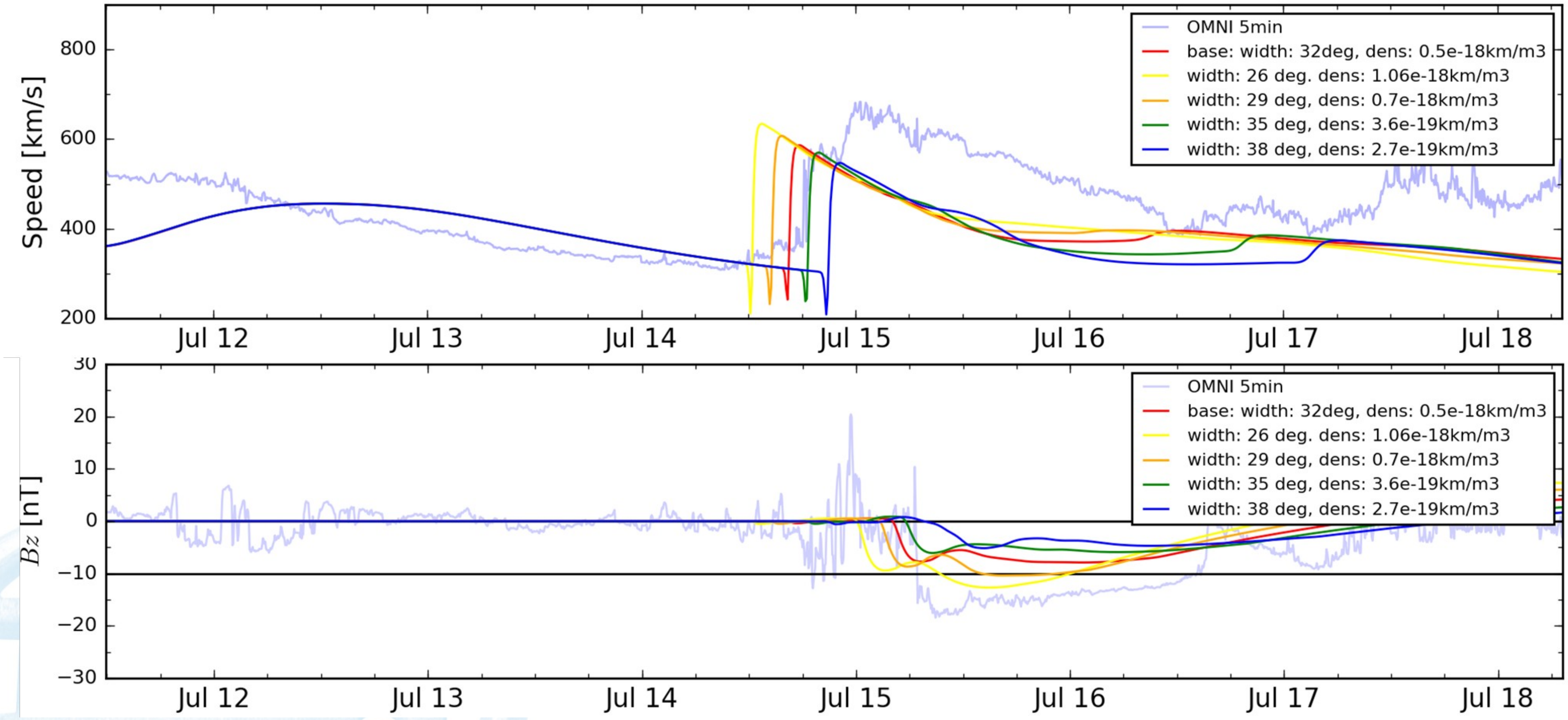
Parameter study: Half-width *(constant total mass)*



Higher density CMEs slow down less, have less deflection and different expansion ? a stronger $B_{z\text{-component}}$!

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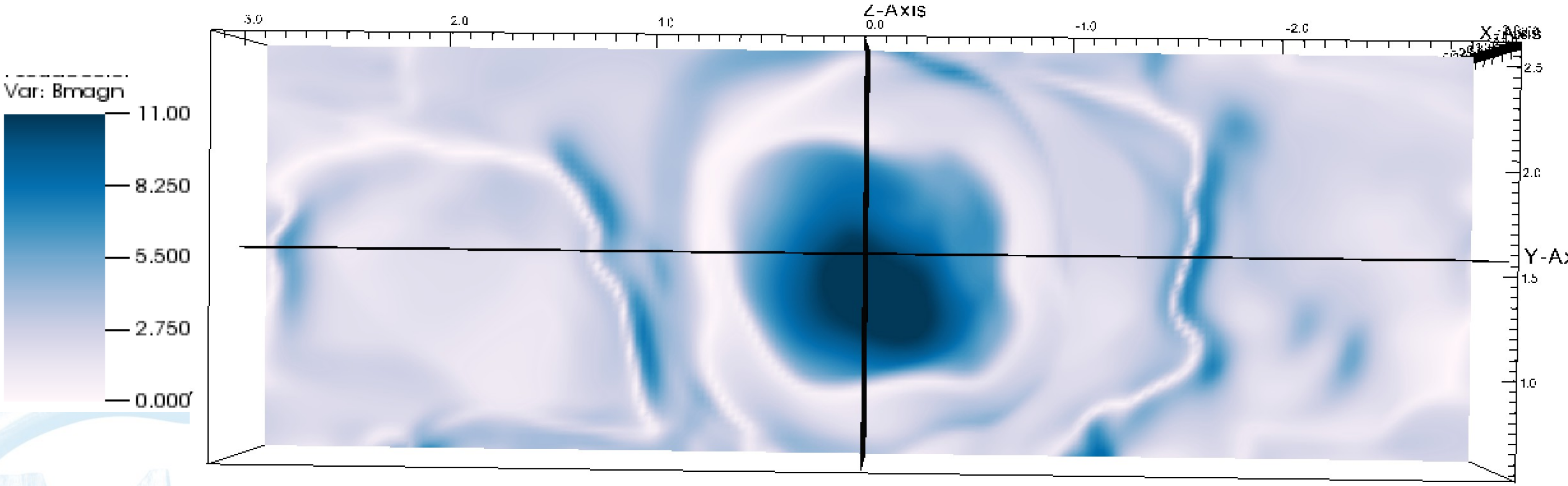
Credit: Christine Verbeke

Longitude: |B| at 1AU

PROBLEM: Centre of CME misses Earth (*deflection*):



- *Small changes* in input parameters can have large effect on **B**, **v** and *n* at 1AU, and ***thus the impact of the CME***
- Input parameters all have their errors

□ need *ensemble runs* for FR CME simulations!

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VSWMC: Motivation

NEED for integrated Space Weather model frameworks

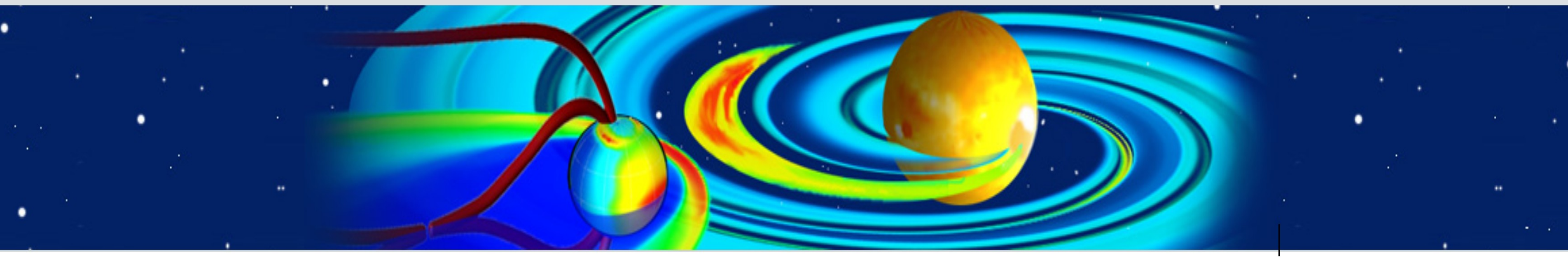
- **SW needs to be predicted** so that mitigation is possible
- **Physics based models are needed** as empirical semi-empirical models do not always work satisfactorily
- Simple **(G)UI needed for easy of use** of (complicated) simulation models
- **Standard environment** needed for
  - *Model (and data) repository*
  - *Optimal model simulations / verification / validation*
  - *Enable coupling(s) of (sub-)models*

Example1: CCMC (NASA)

Community Coordinated Modeling Center

Related Links | Frequently Asked Questions | Community Feedback | Downloads | Sitema

About | Models at CCMC | Request A Run | View Results | Instant Run | Metrics and Validation | Education | R2O Support | Mission Support | Community Support | Tools



Community Coordinated Modeling Center Mission Statement

The CCMC is a multi-agency partnership to enable, support and perform the research and development for next-generation space science and space weather models.

CCMC Services

- We provide, to the scientific community, access to modern space research models
- We test and evaluate models
- We support Space Weather forecasters
- We support space science education

cpa KU LEUVEN

British Antarctic Survey NATURAL ENVIRONMENT RESEARCH COUNCIL DH CONSULTANCY spaceapplications esa

Example 2: CSEM (UMICH)

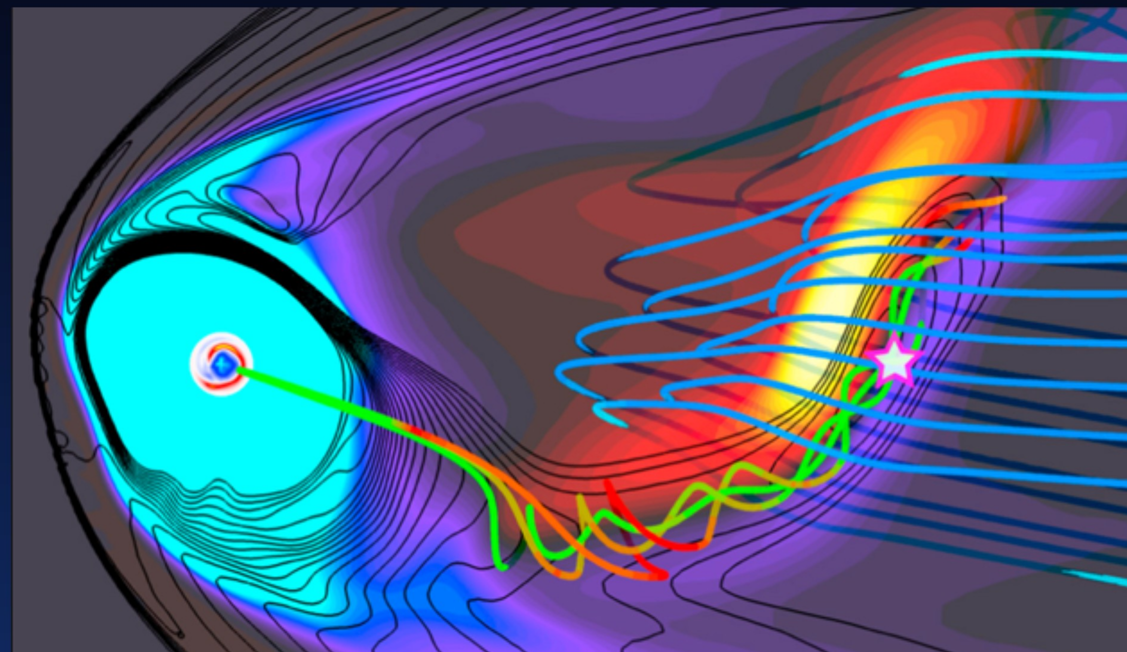
CSEM | Home | About | Models & Tools | Missions | Projects | People | Publications | Features | Internal | Contact

The Center for Space Environment Modeling (CSEM) at the University of Michigan develops high-performance, first-principles based computational models of the space environment and uses these models to predict "Space Weather", to understand space mission data and to further our understanding of the solar system.

Funding

CSEM is funded by grants from the following organizations:

- NASA SMD
- NSF GEO
- NSF CISE
- NSF MPS
- DoD AFOSR
- DoE NNSA



Understanding plasmoid formation in Saturn's tail

The SWMF is being used to study how plasma production and loss are balanced in Saturn's magnetosphere.

VSWMC-P2 objective and scope

- The **further development of the VSWMC** building on the Phase 1 prototype system and *focusing on the interaction with the SSA SWE system*.
- Efficient integration of **new models and new model couplings**, including a first demonstration of an *end-to-end simulation capability*.
- Further development and wider use of the **coupling toolkit** and **the front-end GUI** which will be designed to be accessible via the SWE Portal.
- Availability of more **accessible input and output data** on the system and development of **integrated visualization tool** modules.

Similarities with CCMC & CSEM…

Like CCMC & CSEM, the VSWMC is/will provide:

- *A **repository** for models (**and data**!)*
- *A facility that enables to **execute models and coupled model simulations***

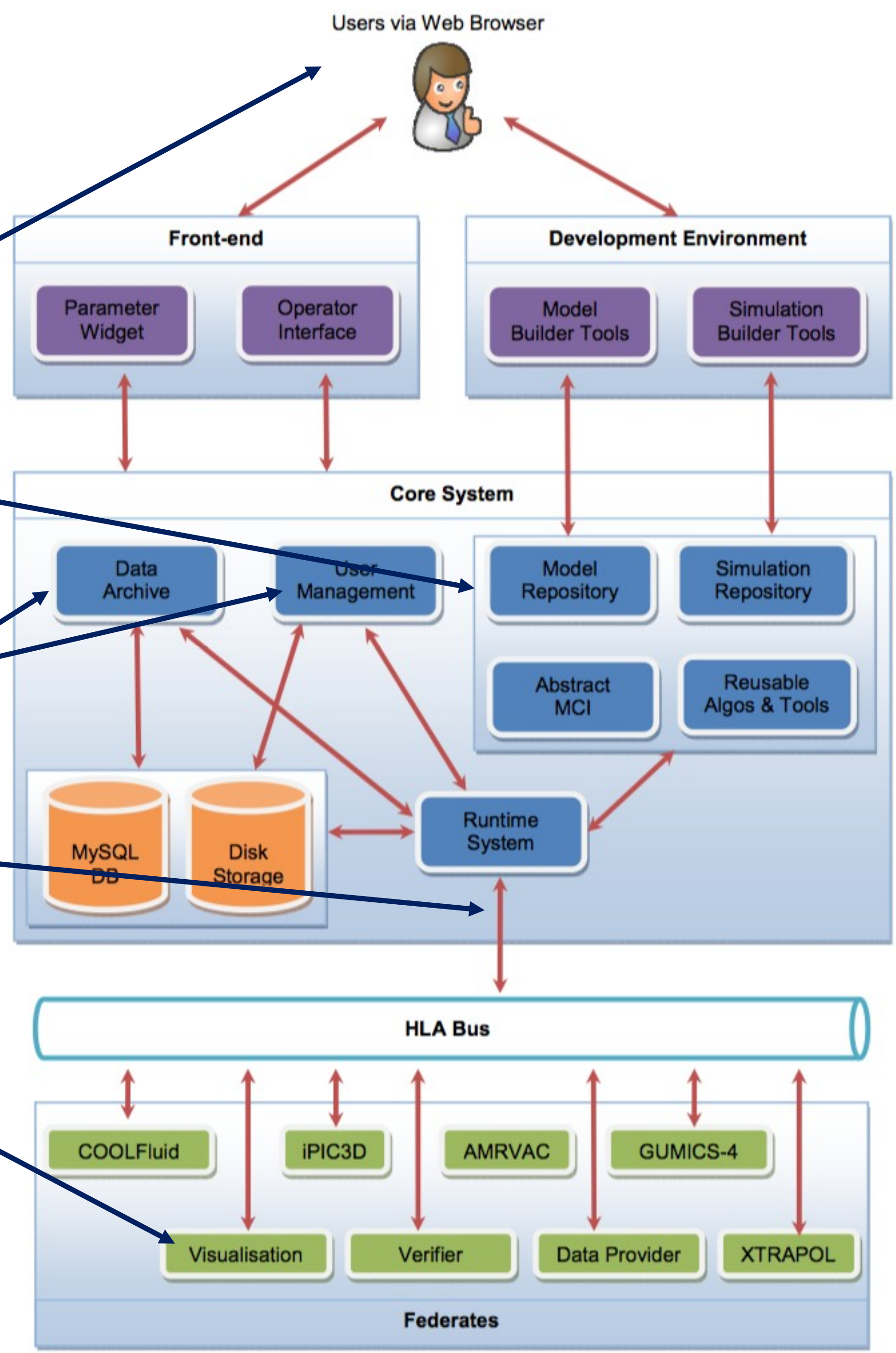
*However, **VSWMC ≠ CCMC, nor CSEM!***

… and differences!

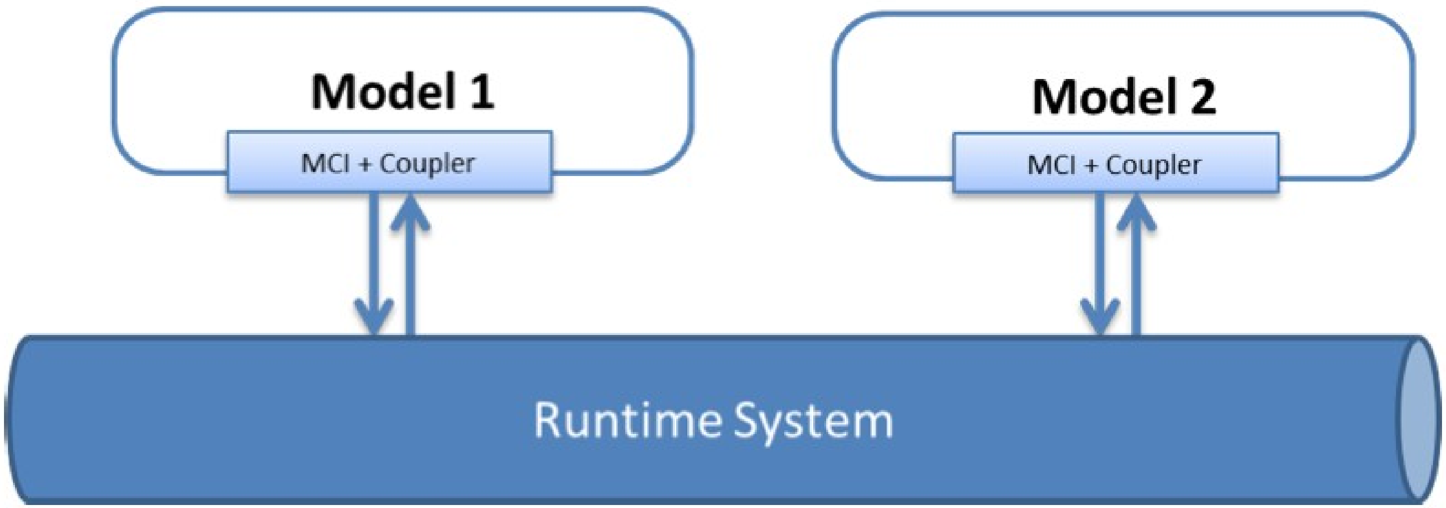
- **VSWMC is being developed**: only a limited version is available at the moment *(about 12 coupled models)*
- **Combination of local and distributed models**, so models can run remotely and are coupled over the internet
- **Visualization tools** are integrated as ‘models’ that can be coupled to any other integrated model
- **Interactive**: via a **‘developer tool’** the modelers will be able to install/adjust their own model and couple it to another model in the repository (at end of Part 2 project)

VSWMC-P2 overview

- Users interface via a web portal (in SSA SWE system)
- Developer environment with 4 service components
- Core system also contains data archive and user management component
- Only the runtime system interacts with HLA bus to coordinate simulations
- visualizations are implemented as 'federates'



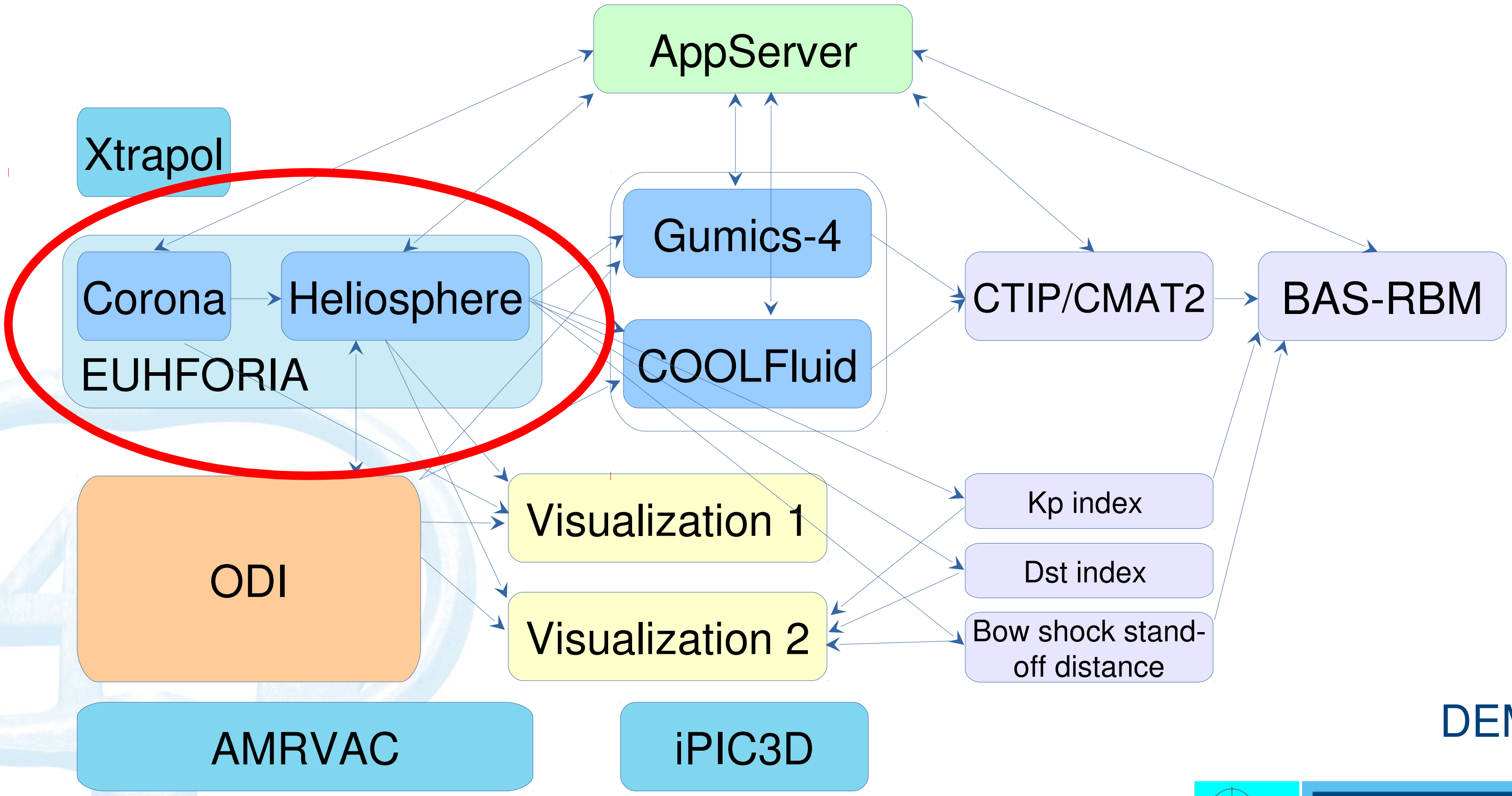
Run-time system (RTS)



- Prepares (coupled simulation) models for execution and manages data exchange between models
- Is capable of executing parameterized simulation (or federation) runs. As a simulation is interpreted, different models are retrieved from the Model Repository.

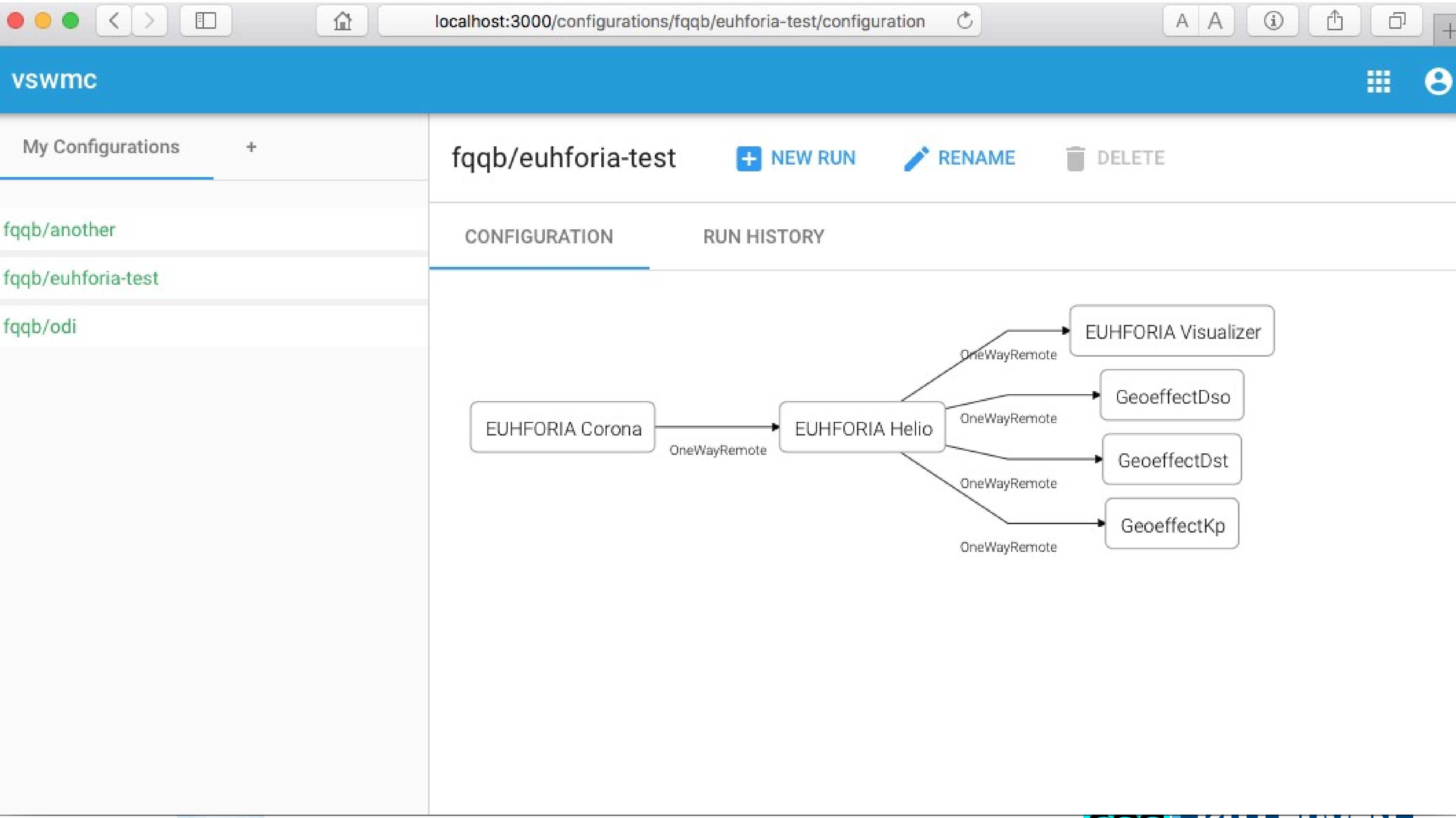
Virtual Space Weather Modeling Centre

Framework node communication

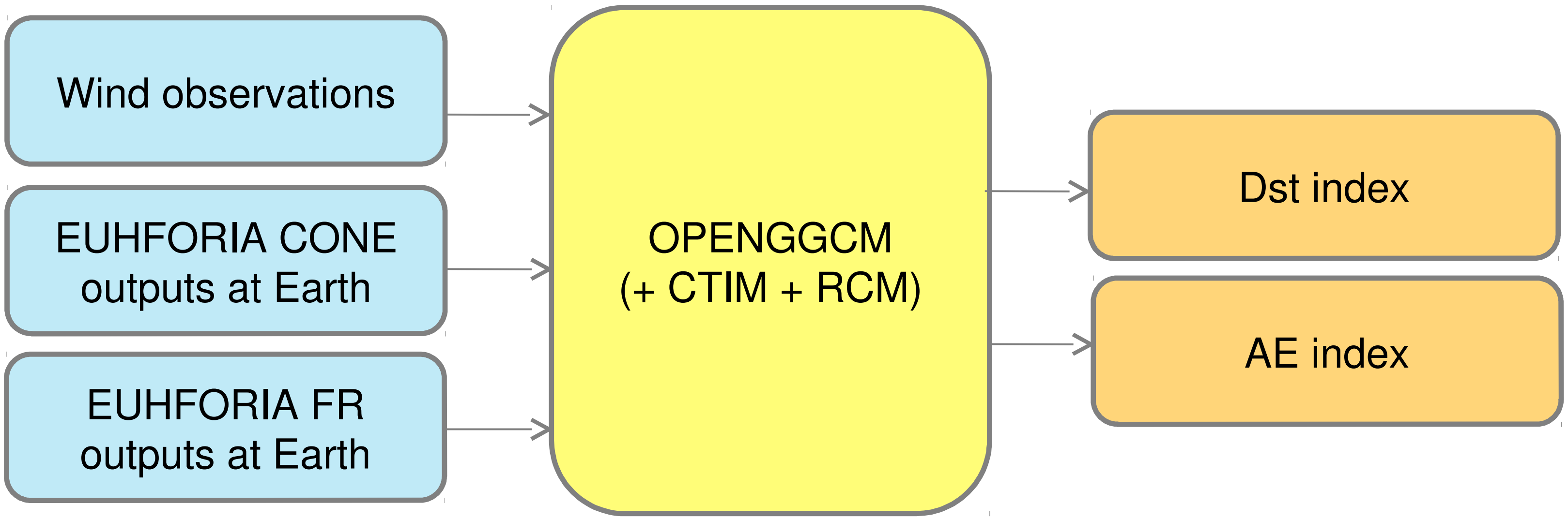


DEMO

Full screen view – new layout



Geoeffectiveness prediction



Input timeseries
L1

Magnetosphere
(+ ionosphere + ring current)

Geoeffectiveness

Geomagnetic storms (southward IMF):

- Dst index: sensitive to the ring current (equatorial)
- AE index: sensitive to auroral currents

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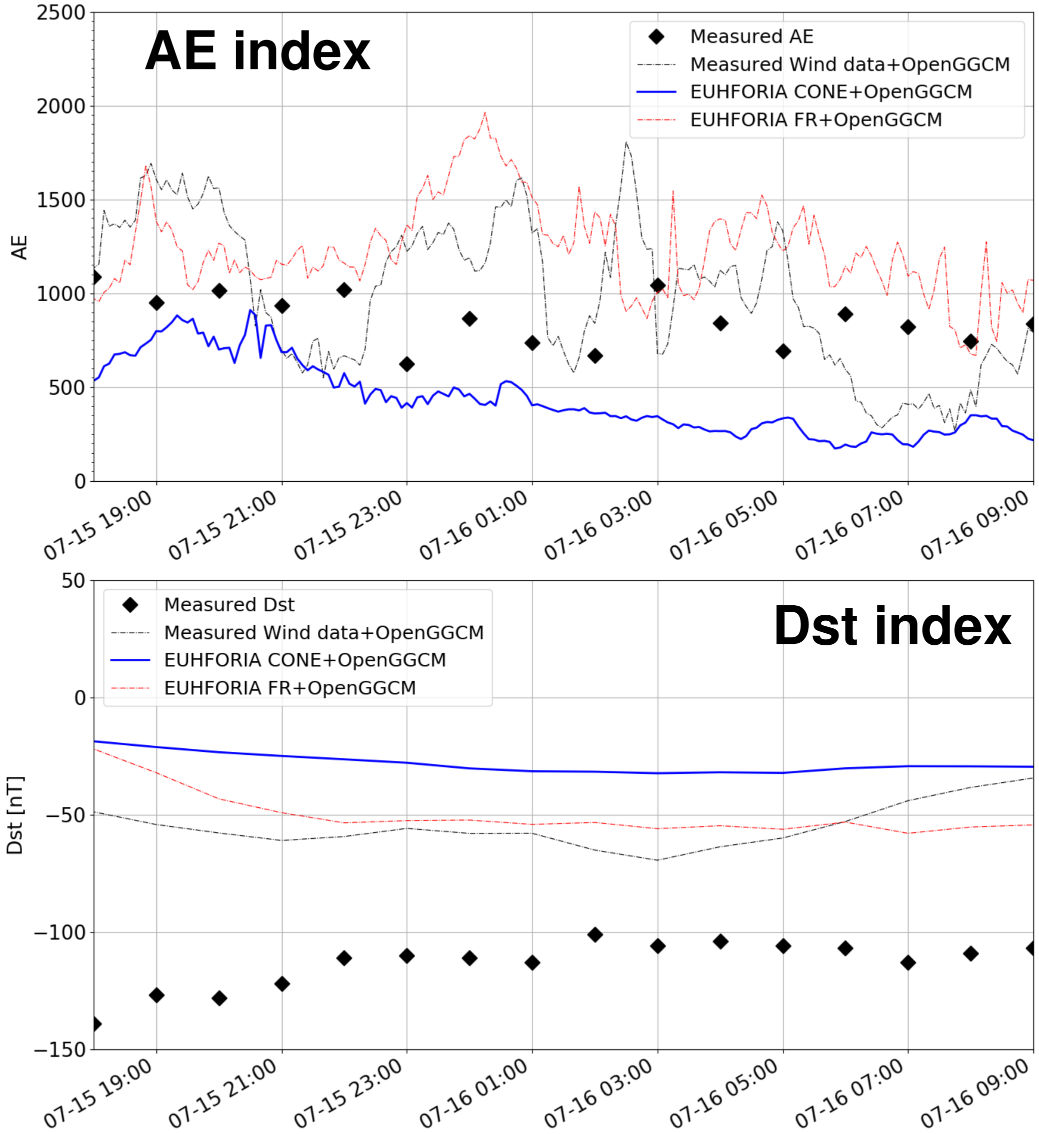
Geomagnetic activity from OpenGGCM



Cone CME model:

- AE is underpredicted
- Dst is overpredicted

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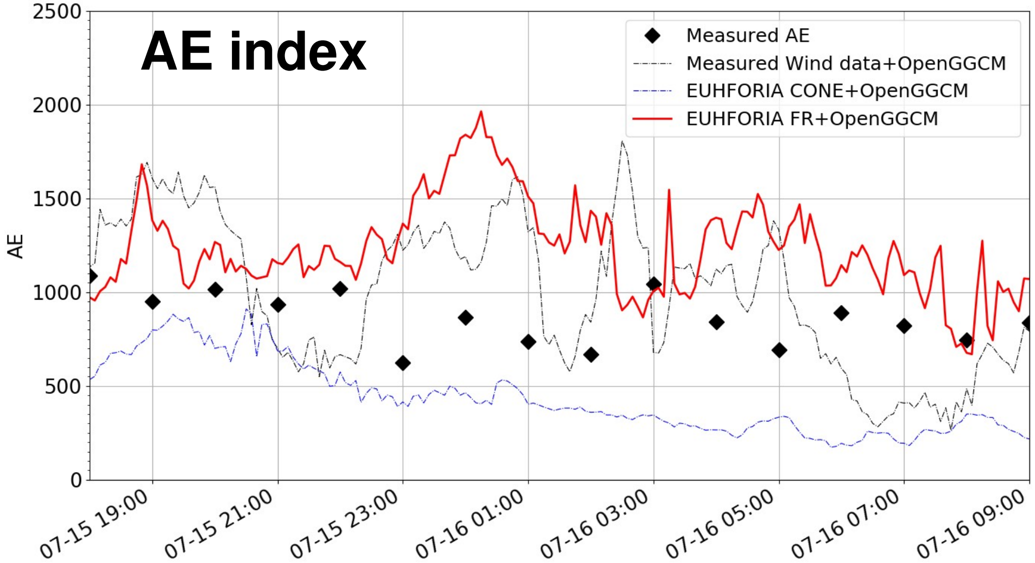
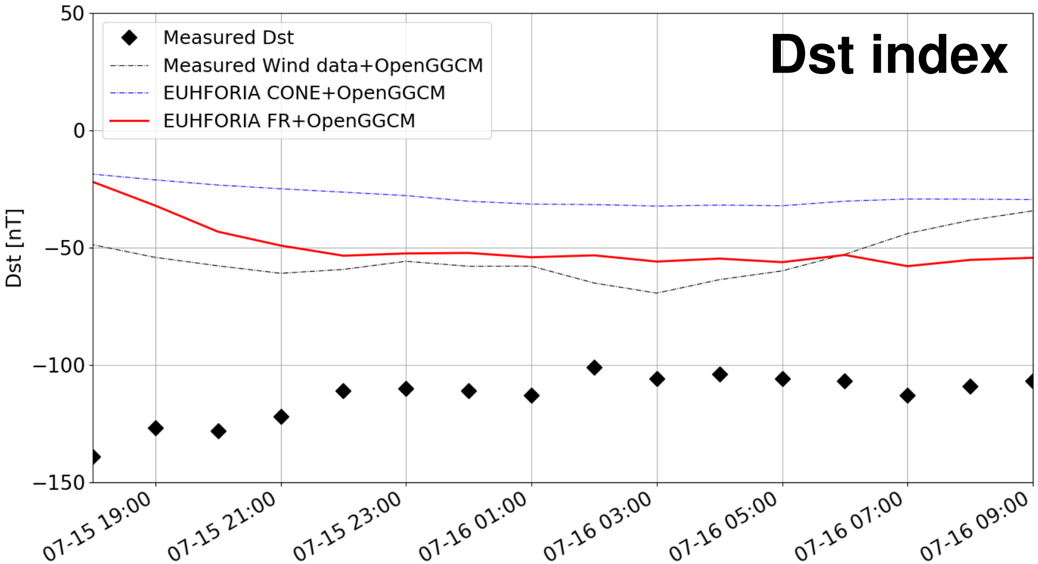
Credit: Camilla Scolini

Geomagnetic activity from OpenGGCM





Cone CME model:

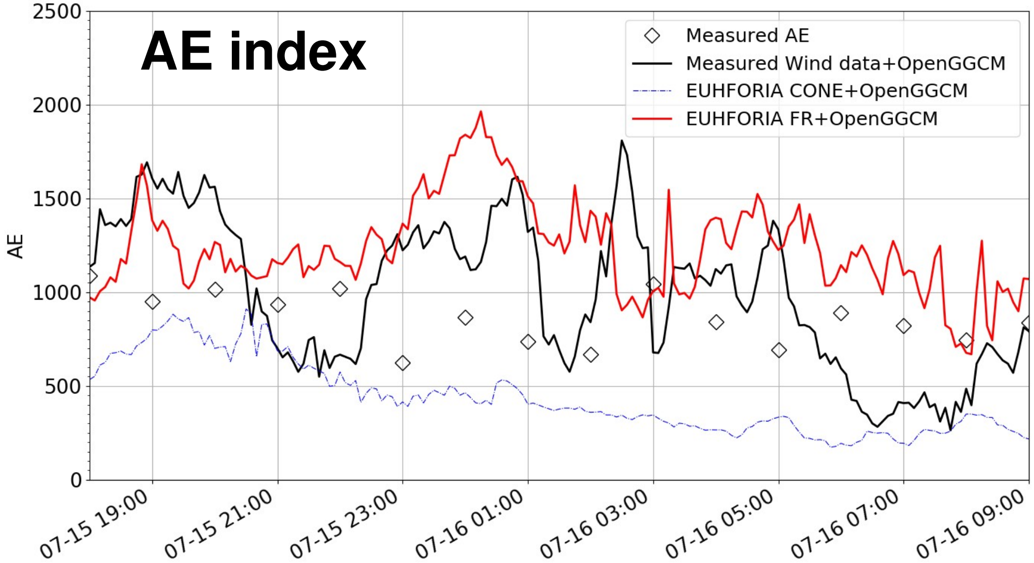
- AE is underpredicted
- Dst is overpredicted

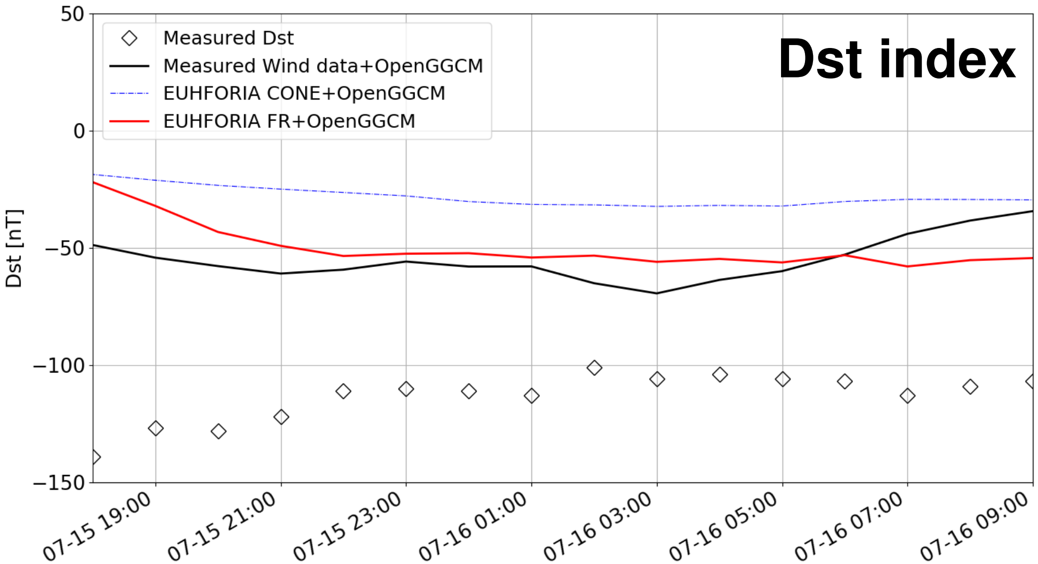
Flux-rope CME model:

- AE is overpredicted
- Dst is still overpredicted but signal is improved (stronger)

Credit: Camilla Scolini

Geomagnetic activity from OpenGGCM





Cone CME model:
- AE is underpredicted
- Dst is overpredicted

Flux-rope CME model:
- AE is overpredicted
- Dst is still overpredicted but signal is improved (stronger)

Reference model: Wind+OpenGGCM
- Good AE prediction
- Predicted Dst signal very weak

Good agreement between Wind+OpenGGCM and EUHFORIA FR+OpenGGCM timeseries

- Max AE: **+57%** improvement
- Min Dst: **+36%** improvement

using the flux-rope CME model compared to cone CME model

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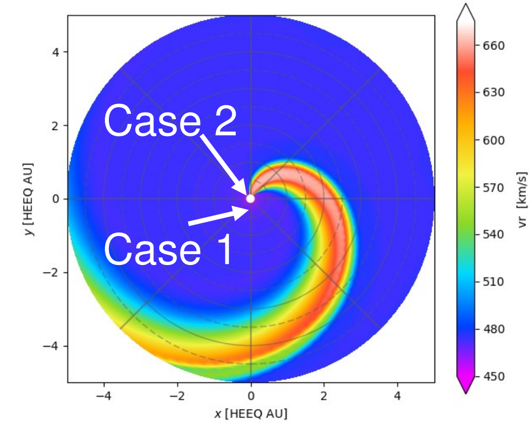
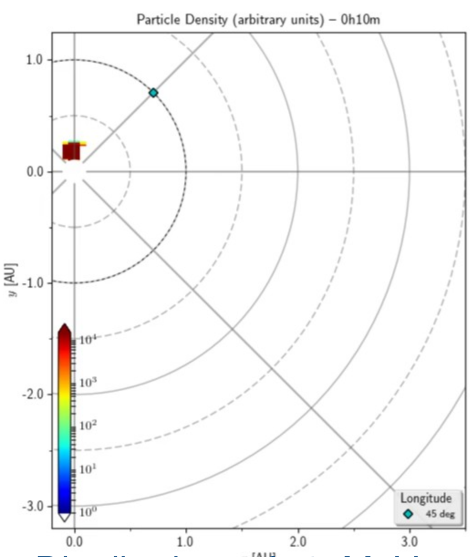
Credit: Camilla Scolini

Combining EUHFORIA with a Monte Carlo SEP transport model

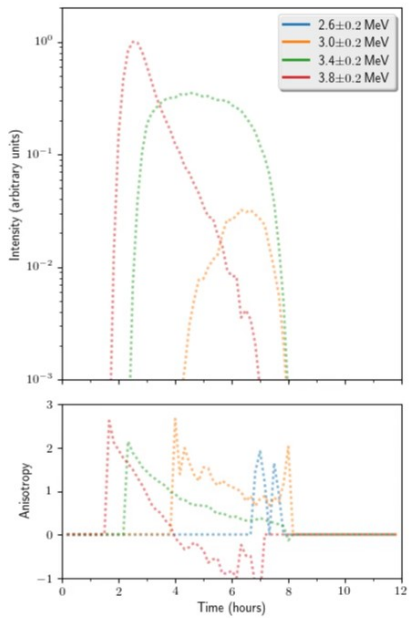
SW V_r and locations of injection zones



SEPs injected in the slow solar wind

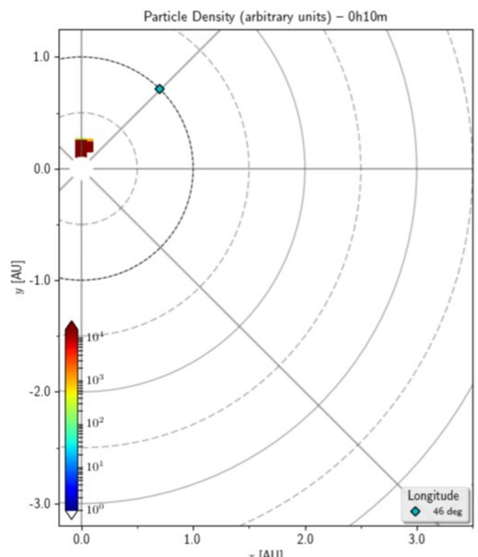


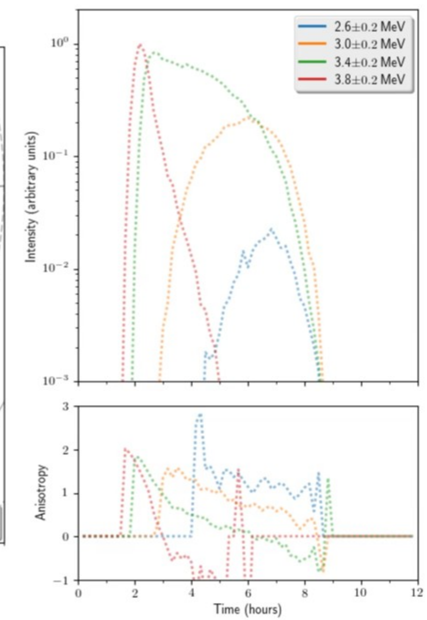
Distribution of 4 MeV protons after the impulsive injection in the slow SW at 0.1AU.



Observer near inner boundary injection zone.

SEPs Injected in the Fast solar wind Stream





Distribution of 4 MeV protons after injection in the CIR at 0.1AU.

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Cf. Wijsen et al., ESWW14

Summary and outlook

- ***EUHFORIA v. 1.0*** ready
  - ✓ Spheromak and GL flux rope incorporated, being tested
  - ✓ Ensemble modeling supported
  - ✓ Forecasting operations at SIDC/ROB being tested
  - ✓ Parameter studies for validation, accuracy tests ongoing
  - ✓ Integrated in the VSWMC and coupled to other models
- **Data-driven corona & FR model proceeding**:
  - ✓ Data-driven MFM simulations currently running
  - ✓ Other FR CMEs being tested: TD, FRI3D,...
  - ✓ Coupling NLFFF and magnetized CMEs, testing the estimation of magnetic parameters
- **Towards integrated SEP event modeling**:
  - ✓ EUHFORIA combined with a Monte Carlo SEP transport model
  - ✓ Plans to include Coronal Shock Acceleration (CSA) simulati ... Particle Acceleration in Coronal Shocks (SOLPACS) of Vain ...

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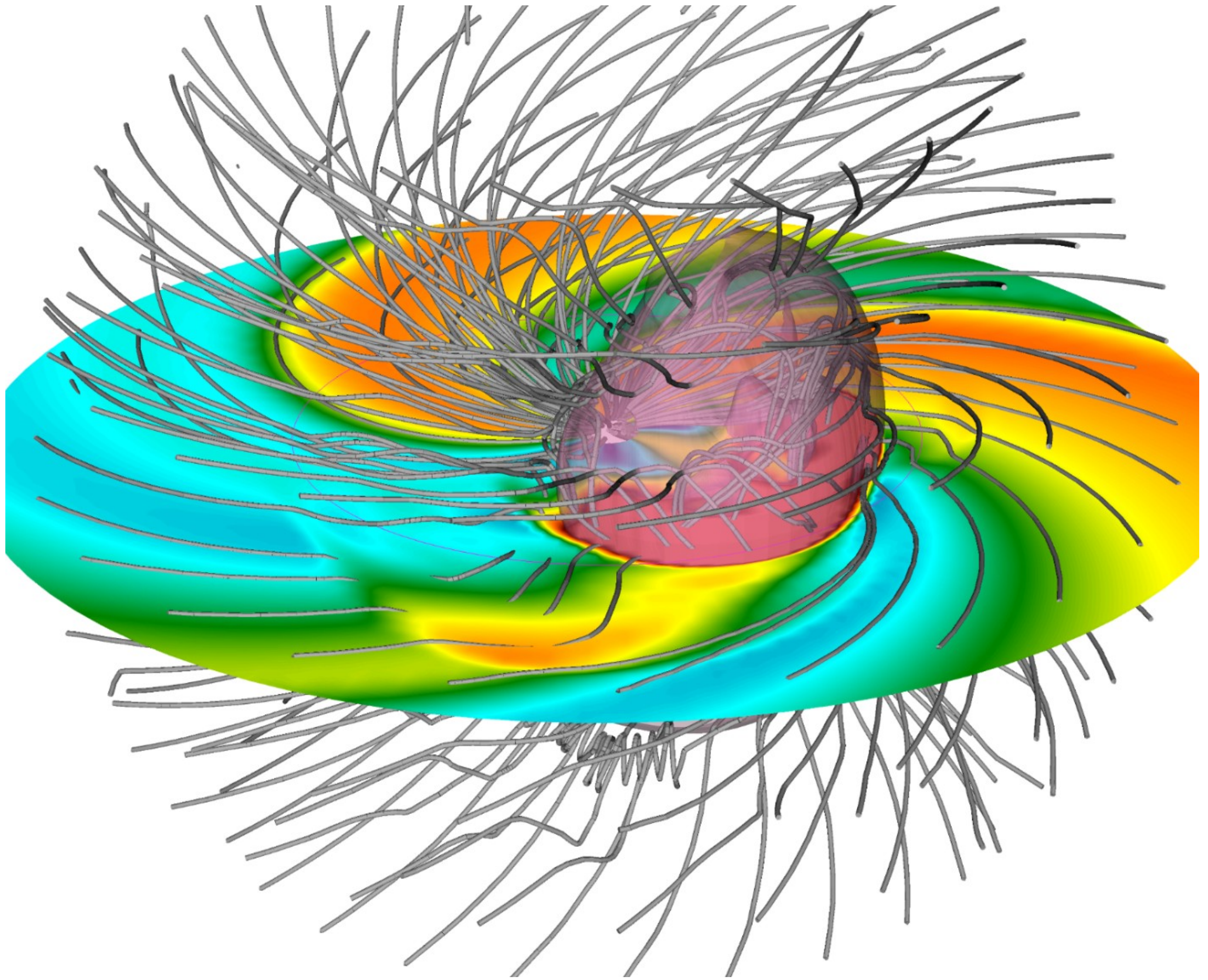

Thank you!

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- *Belspo*
- *FWO-Vlaanderen*
- *KU Leuven, Univ. of Helsinki, ROB, Univ. of Graz*