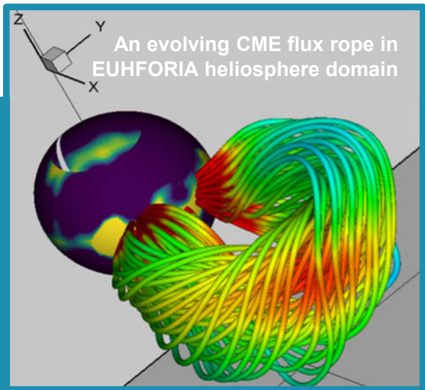

Improving space weather forecasting with flux rope CME models in EUHFORIA

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[1]Centre for mathematical Plasma Astrophysics, KU Leuven, Belgium,
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[3]Institute of Physics, University of Maria Curie-Skłodowska, Lublin, Poland

ISWI, Baku, 31 Oct - 4 Nov, 2022

Leuven

[Leuven municipality, 2022]

- A "stone's throw away" from Brussels
- Around 100k inhabitants (mostly university)
- Over 60k students

Leuven

TO AMSTERDAM
THE NETHERLANDS
110 MIN BY TRAIN

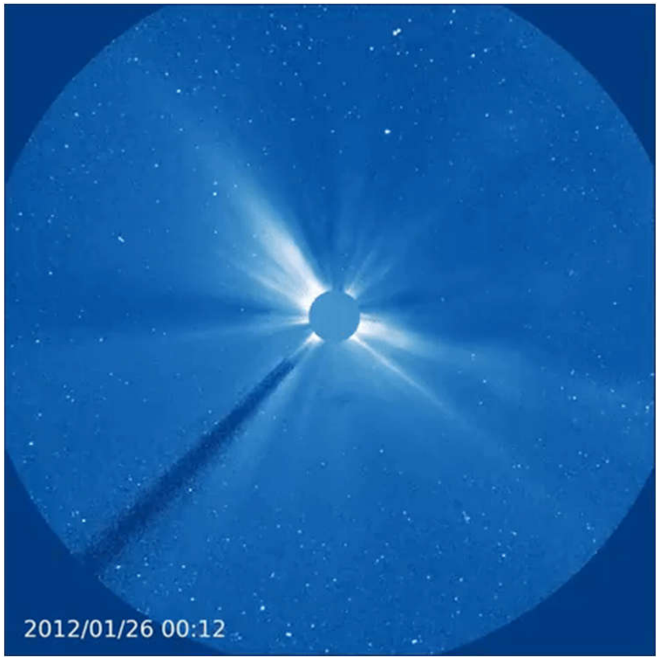
TO LONDON
UNITED KINGDOM
120 MIN BY TRAIN

TO PARIS
FRANCE
90 MIN BY TRAIN

TO COLOGNE
GERMANY
110 MIN BY TRAIN

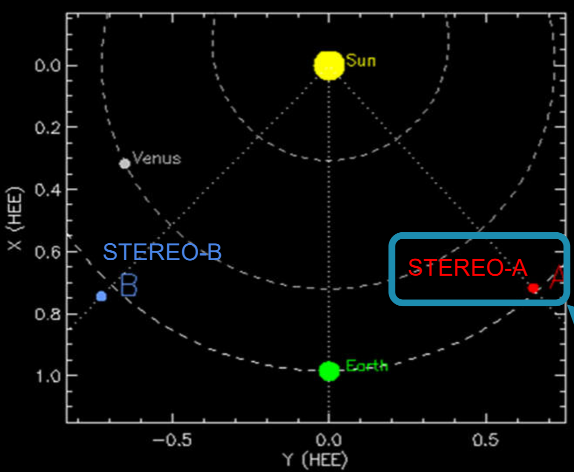
Context

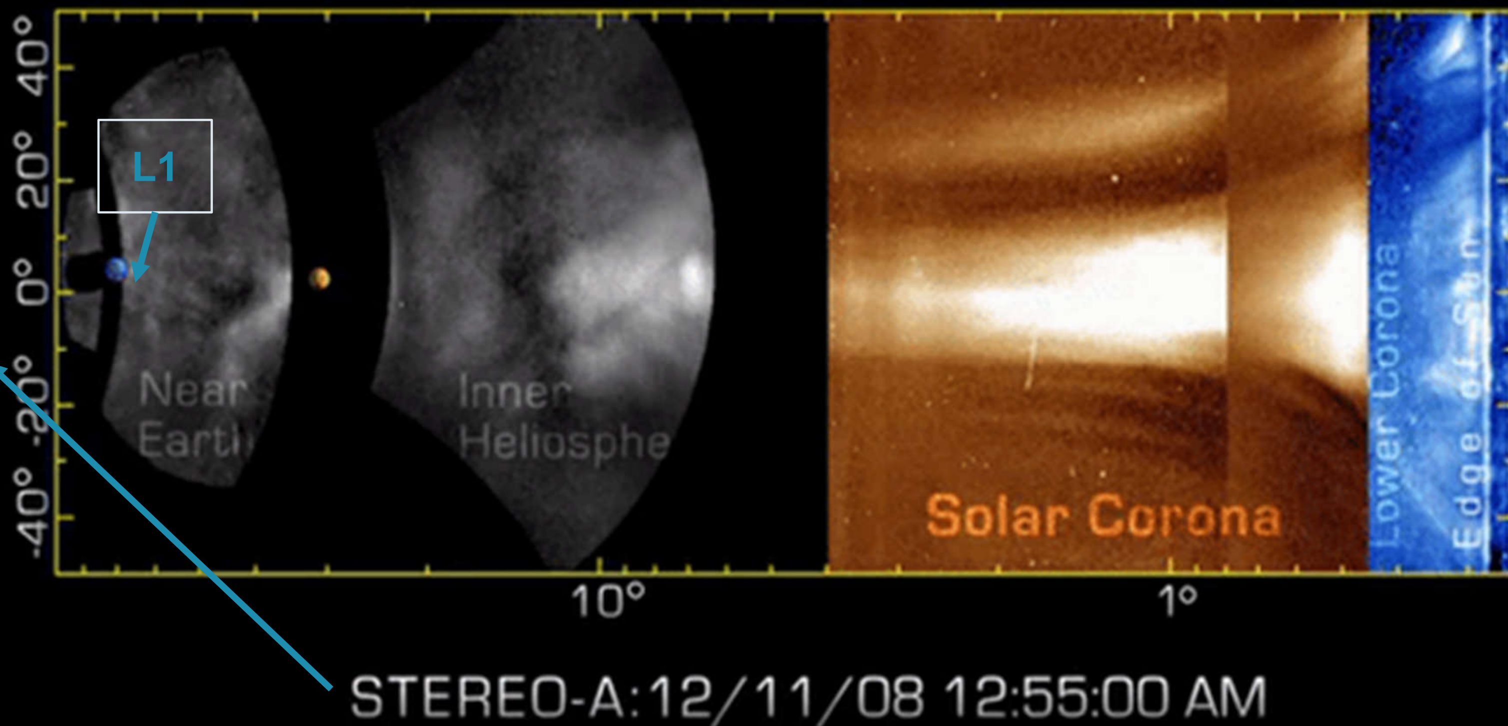
- **Coronal mass ejections (CME)** are major drivers of space weather storms.
- Speed of propagation→ ~250 - 3000 km/s
- Mass of magnetised plasma carried → ~10^{12} - 10^{14} kg
- Based on coronagraph images:
  - Limb CMEs
  - Halo CMEs



Courtesy: ESA (SOHO C2+C3 imagery)

Motivation





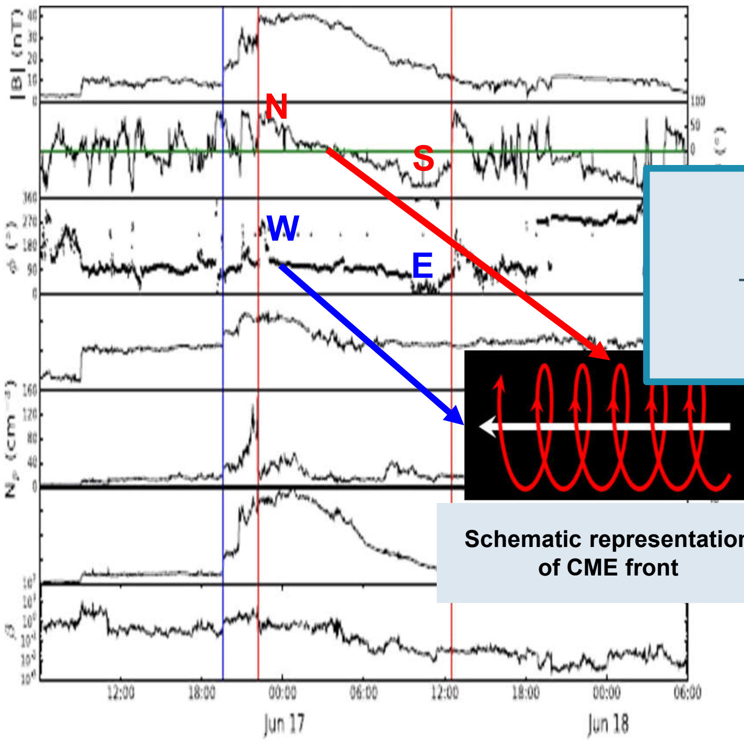
Credit: NASA/Goddard Space Flight Center/SwRI/STEREO

Modelling **CME arrival** based on CME initiation observations at the Sun (early warning time)

Understanding **CME internal magnetic field structure** (key to realistic modelling)

Operations-friendly CME models for early prediction of the **geoeffectiveness of CME impact**

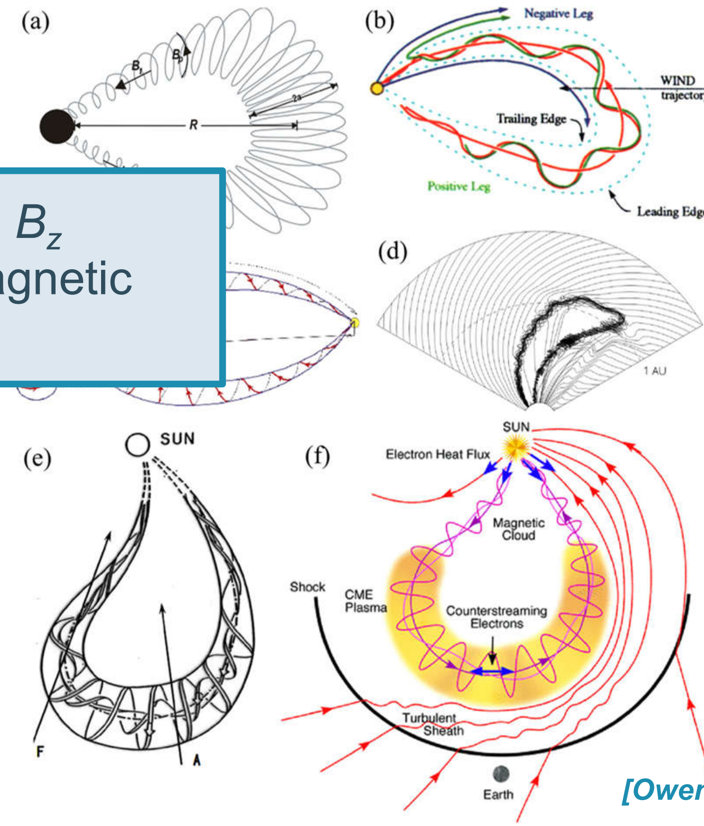
Interplanetary coronal mass ejection (ICME)



Schematic representation of CME front

Southward B_z
→High geomagnetic impact

[Palmerio et al, 2017]



[Owens et al, 2016]

Outline

1. Introduction to EUHFORIA
2. CME models in EUHFORIA
3. Observations based modelling of event 12 July 2012
4. Development of new flux rope CME model
5. Conclusions

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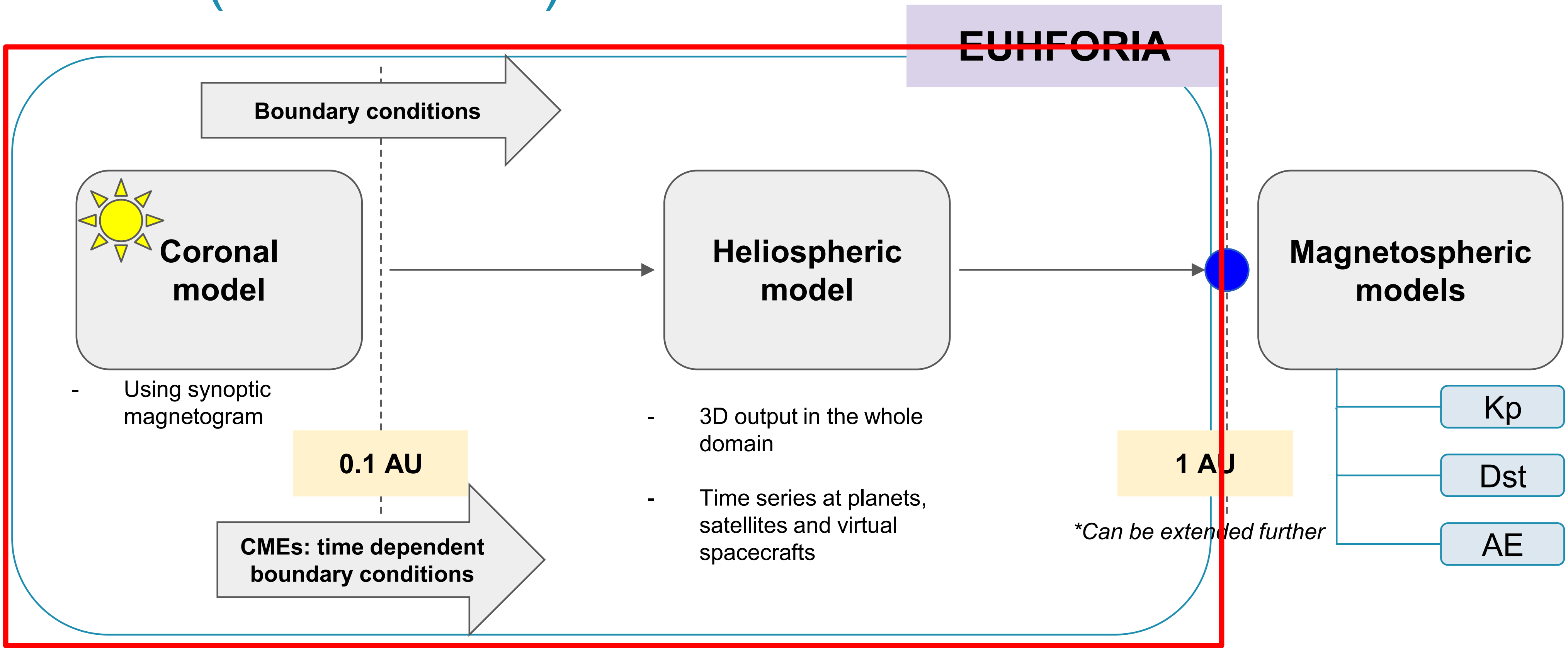
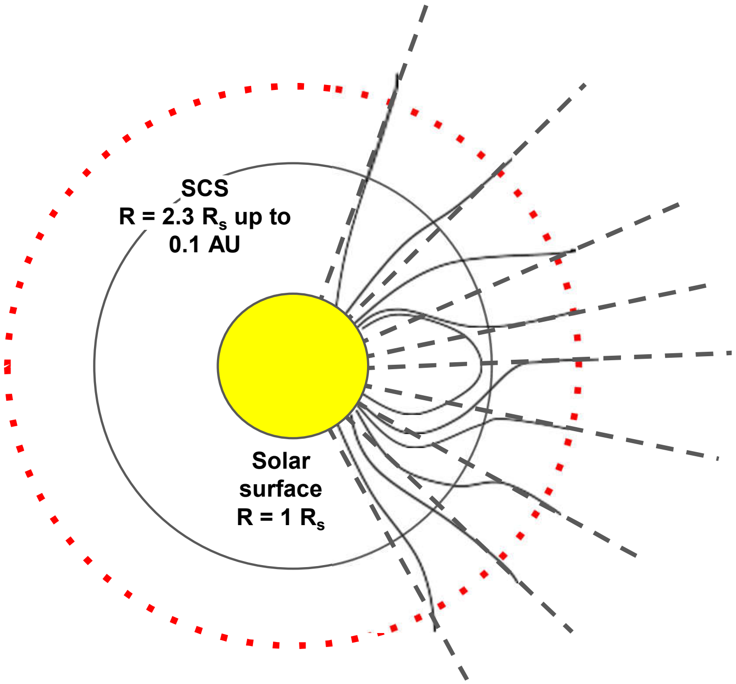
EUropean Heliospheric FORecasting Information Asset (EUHFORIA)



EUropean **H**eliospheric **FOR**ecasting **I**nformation **A**sset (**EUHFORIA**)

Pomoell & Poedts, 2018

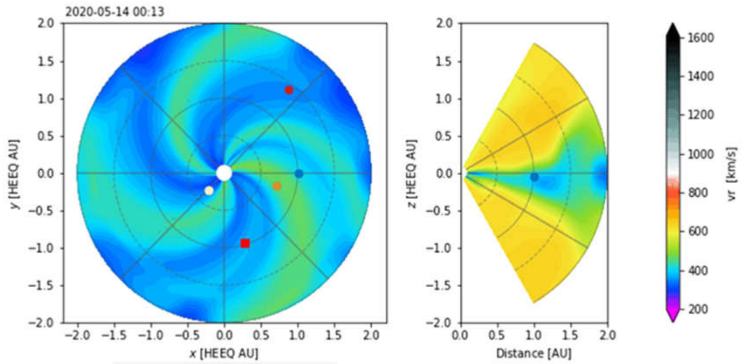
Corona:
Semi-Empirical WSA approach



0.1 AU

Heliosphere:
time dependent ideal MHD model

Evolves MHD parameters $\boldsymbol{v}, n, \boldsymbol{B}, T$
(0.1 - 2.0 AU)



Radial Speed v_r

Solar wind relaxation → CME insertion @0.1 AU → Forecasting

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CME models in EUHFORIA

Cone model
(unmagnetised)
Pomoell & Poedts, 2018

Operational in Virtual Space Weather Modelling Centre (**VSWMC**)

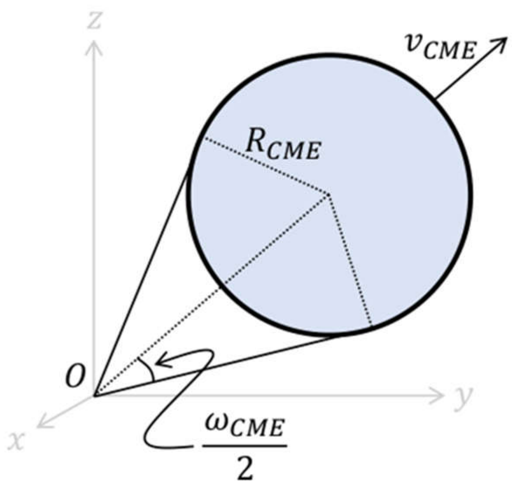
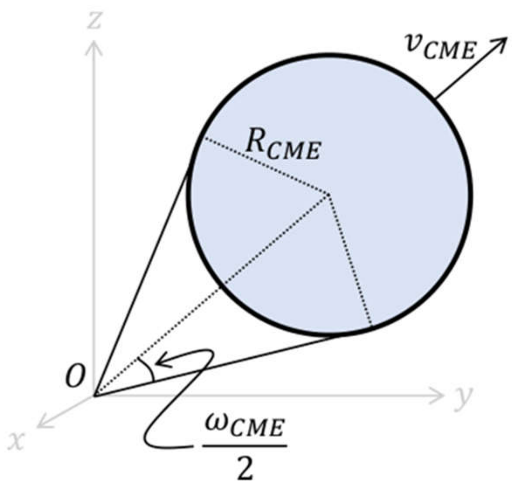


Image courtesy: Camilla Scolini

- Hydrodynamic spherical pulse
- No internal magnetic field
- Uniform speed, density and temperature

CME models in EUHFORIA

Cone model (unmagnetised) *Pomoell & Poedts, 2018*	Spheromak model (flux rope - spherical geometry) *Verbeke et al, 2019*



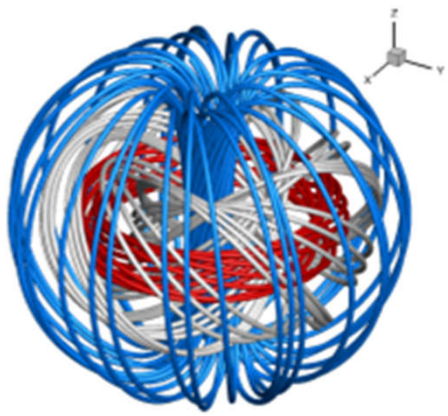


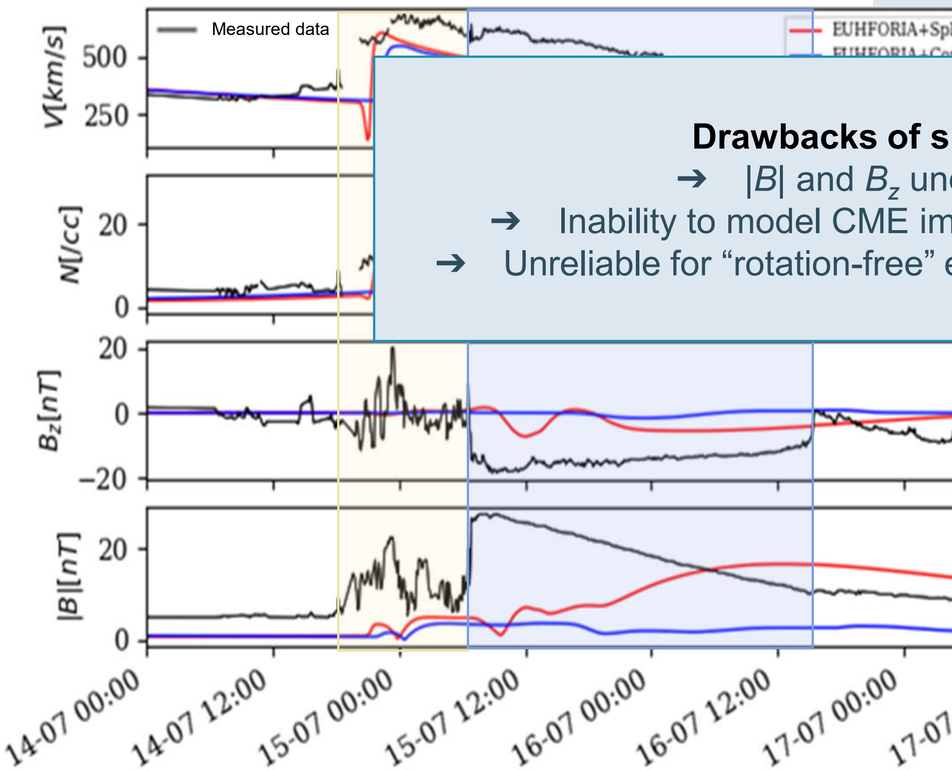
Image courtesy: Camilla Scolini

- Spherical plasma blob (CME legs not modelled)
- Uniform speed, density and temperature
- Linear force free magnetic field solution (Chandrasekhar & Kendall, 1957; Shiota and Kataoka, 2016)

Spheromak over Cone

- **Arrival time, speed** and **number density** peaks reproduced at Earth.
- IMF rotations in all magnetic field components of flux rope are captured.
- Spheromak model improves B and B_z up to 40% as compared to the cone CME.

Spheromak over Cone

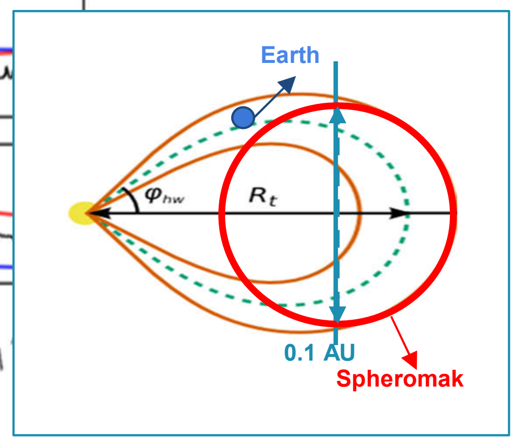


Drawbacks of spheromak model

➔ |*B*| and B_z underestimated at Earth

➔ Inability to model CME impact in a case of side encounters

➔ Unreliable for "rotation-free" expansion in the interplanetary space



- **Arrival time, speed** and **number density** peaks produced at Earth.

IF rotations in all agnetic field components of flux rope are captured.

Spheromak model improves B and B_z up to 40% as compared to the cone CME.

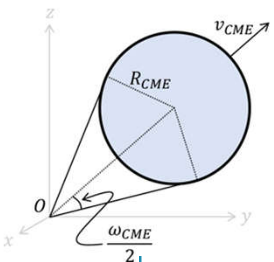
Centre for mathematical Plasma-Astrophysics
KU LEUVEN

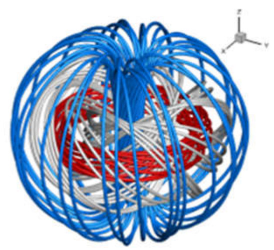
CME models in EUHFORIA

Cone-like model (unmagnetised)
Pomoell & Poedts, 2018

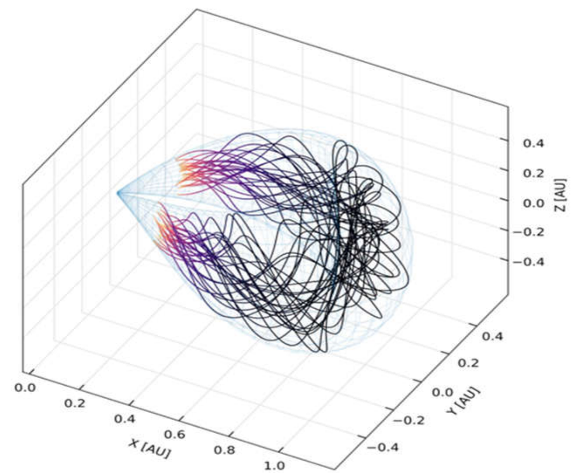
Spheromak CME
(flux rope - spherical geometry)
Verbeke et al, 2019

FRi3D model
(Flux Rope in 3D-extended geometry)
Isavnin et al, 2016





Spherical geometry



[Maharana et al, 2022]

- ➔ **F**lux **R**ope **i**n **3D (FRi3D)** is a fully analytic 3D CME model
  - ◆ Global CME geometry
  - ◆ 3D magnetic field configuration
  - ◆ Capable of modelling major CME deformations

Goals to achieve:

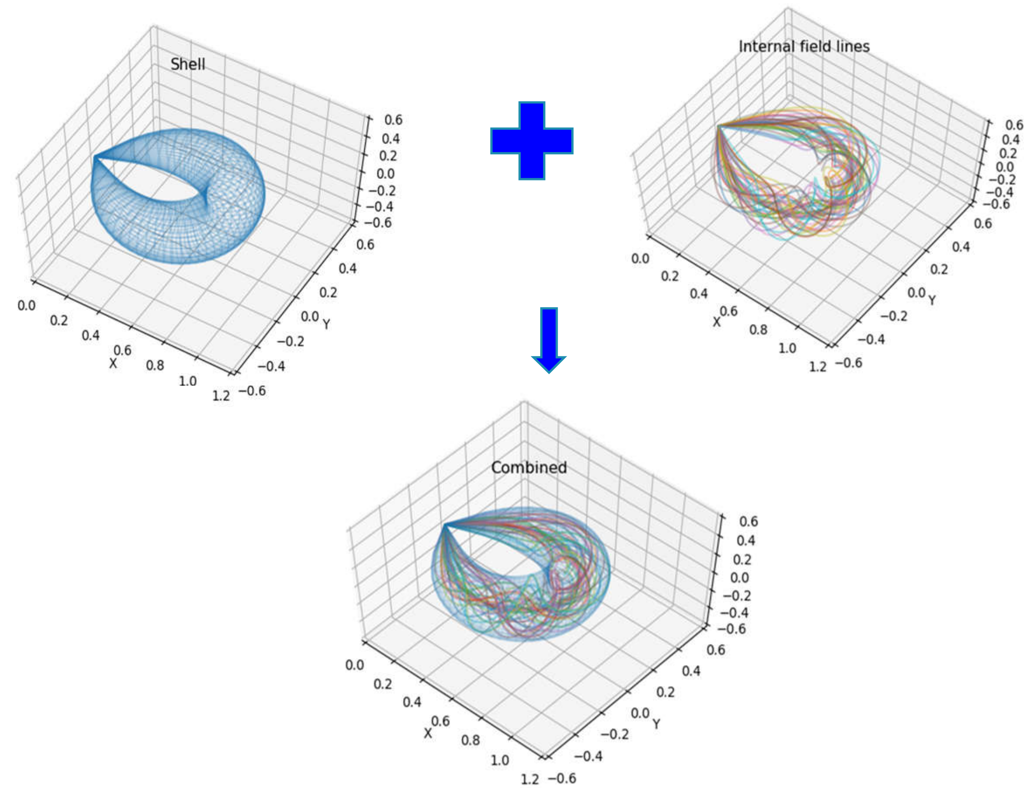
- ➔ Improving modelling of CME flank encounters at Earth
- ➔ Better prediction of magnetic field configuration

Modelling FRi3D flux rope

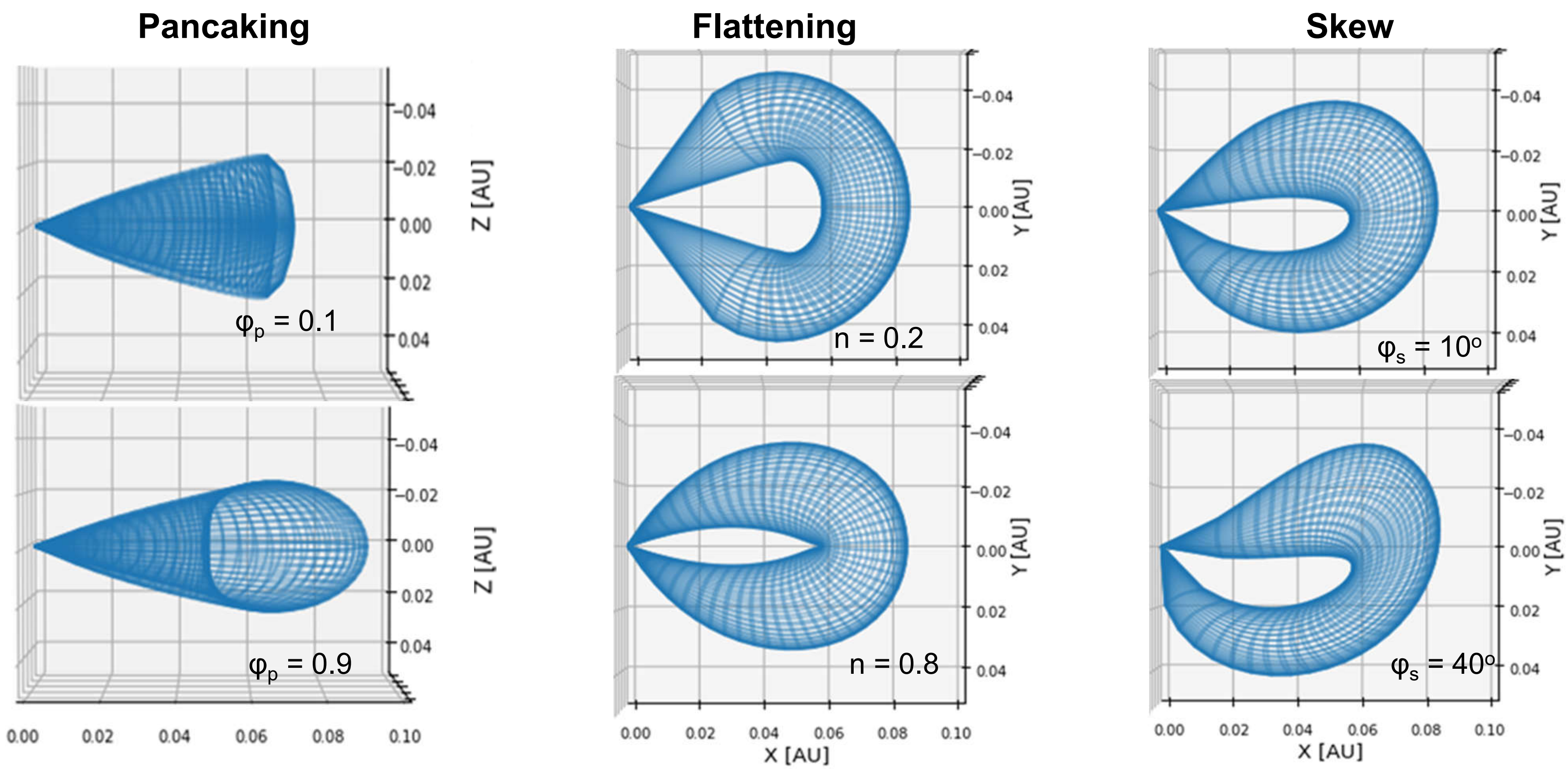
Flux rope geometry
- Half-width
- Half-height
- Toroidal height
- Poloidal height

Parameters to model CME deformations
- Pancaking
- Flattening
- Skew

Internal magnetic field
- Twist
- Magnetic flux
- Tilt



Modelling CME deformations with FRi3D



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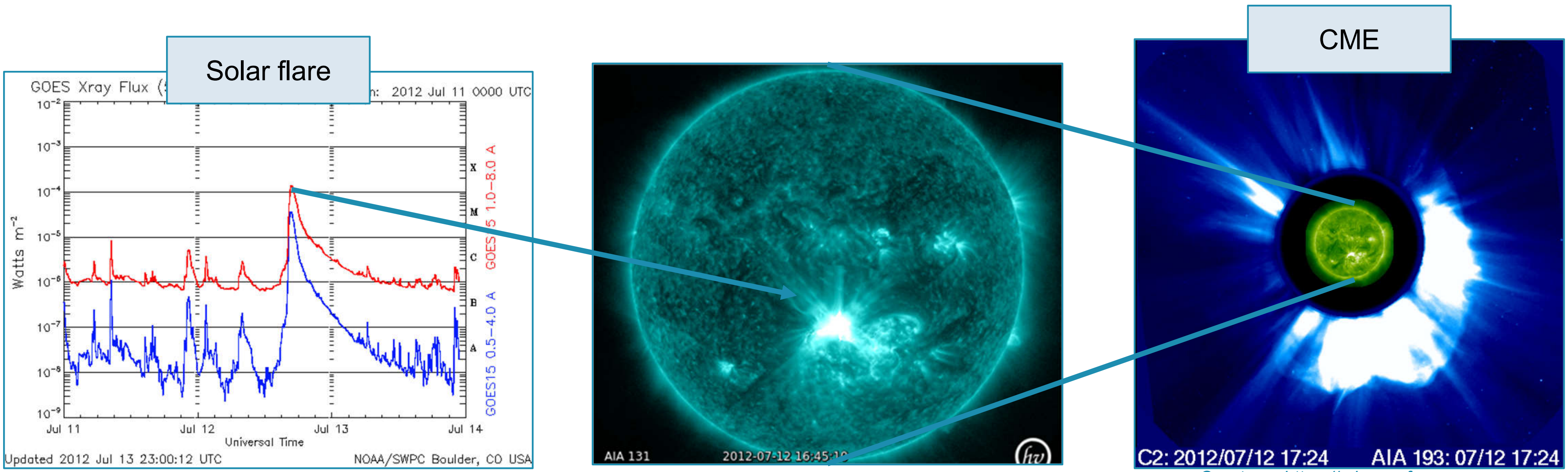
Test case event - 12 July 2012

Remote observations

- Fast Earth-directed halo CME
- Single CME event



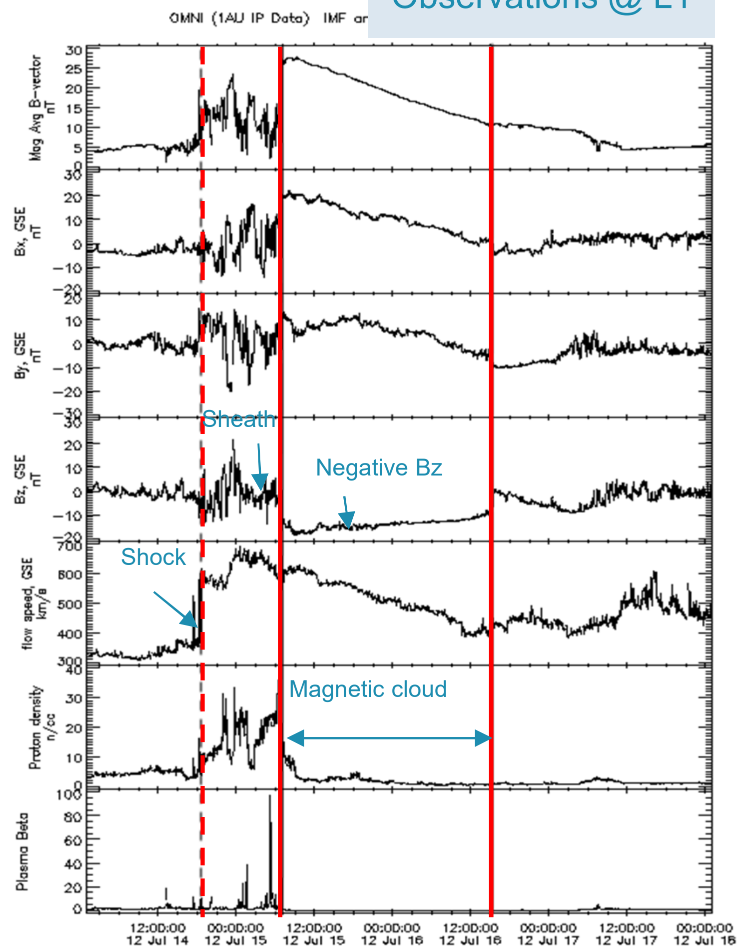
Courtesy: https://cdaw.gsfc.nasa.gov

Test case event - 12 July 2012

Remote observations
- Fast Earth-directed halo CME
- Single CME event

In-situ (@ L1)
- Clear CME/ICME association
- ICME: Shock+sheath+Magnetic cloud (flux-rope)

Observations @ L1



Test case event - 12 July 2012

Remote observations

- Fast Earth-directed halo CME
- Single CME event

In-situ (@ L1)

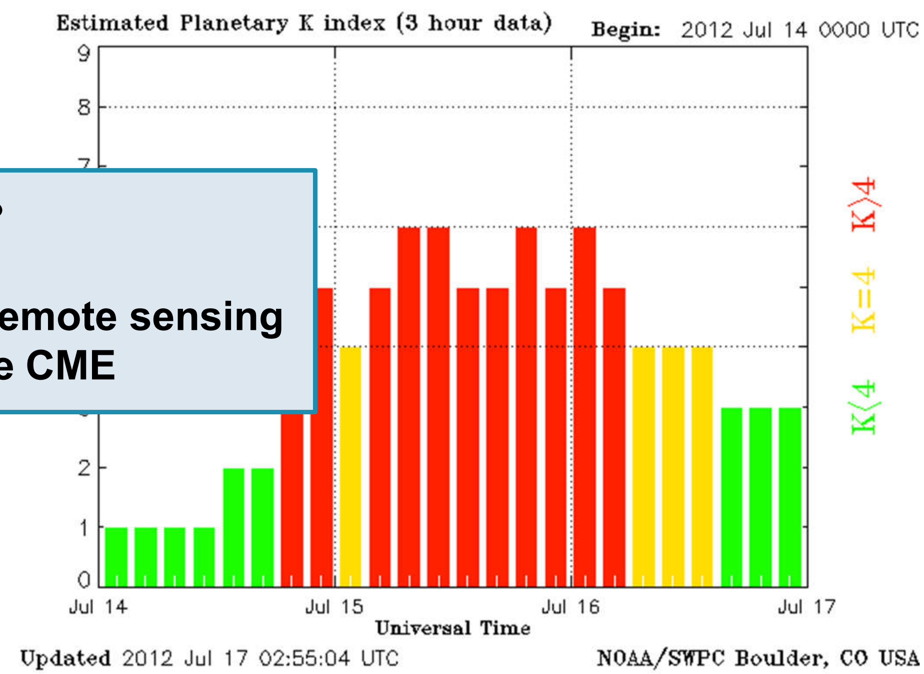
- Clear CME/ICME asso
- ICME: Shock+sheath+

What's next?

Constrain simulation with remote sensing observations of the CME

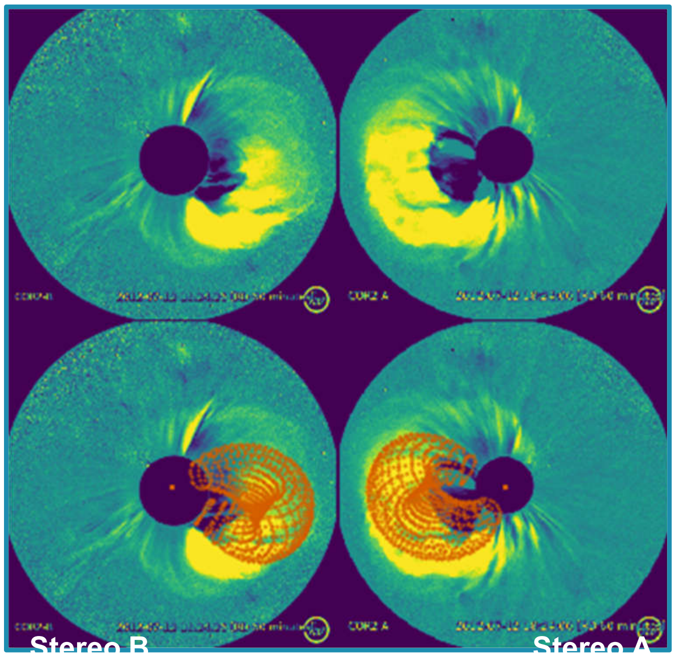
@ Earth

- Moderate geomagnetic storm (prolonged southward Bz)

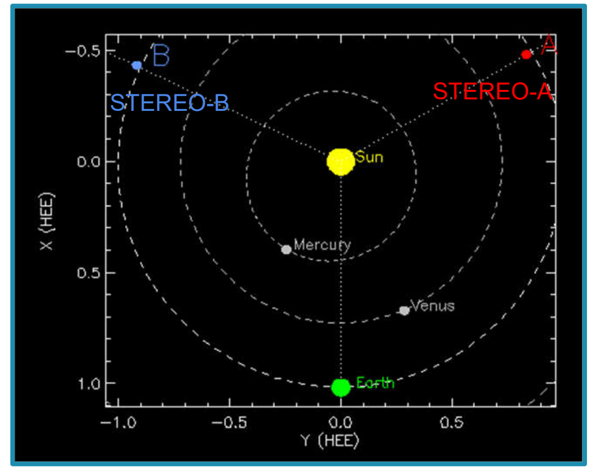


Test case event - 12 July 2012

Geometrical parameters



- Insertion time
- Latitude
- Longitude
- Half-width
- Half-height
- Toroidal height
- Poloidal height
- Pancaking
- Flattening
- Skew
- Speed



- CME parameters are constrained independently from remote observations.
- Geometrical parameters obtained using a **Graduated Cone Shell (GCS, *Thernisien et al, 2011*) type forward modelling** but with additional flexibilities for **FRi3D** using **multi-viewpoint observations**

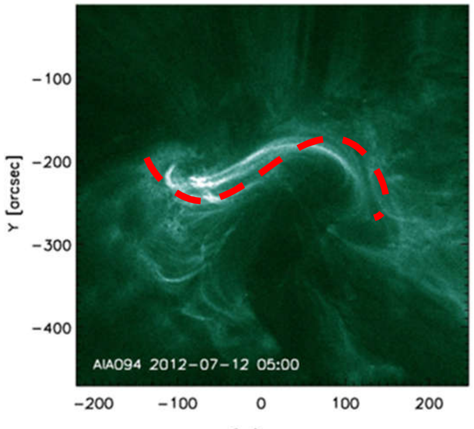
Test case event - 12 July 2012

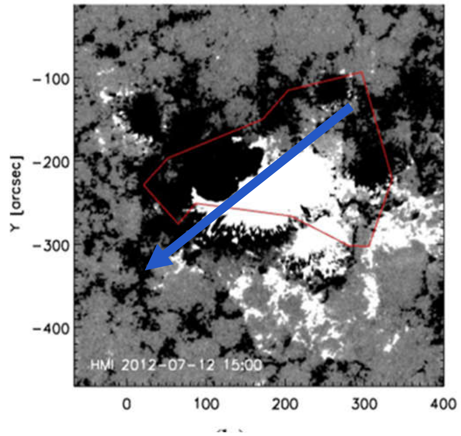
Magnetic field parameters

Polarity

Helicity

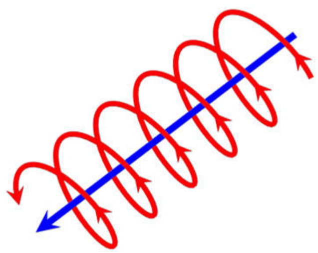
Tilt





EUV/X-ray sigmoid

- **Tilt/orientation:** 45°
- **Helicity:** +1 (right-handed)



Test case event - 12 July 2012

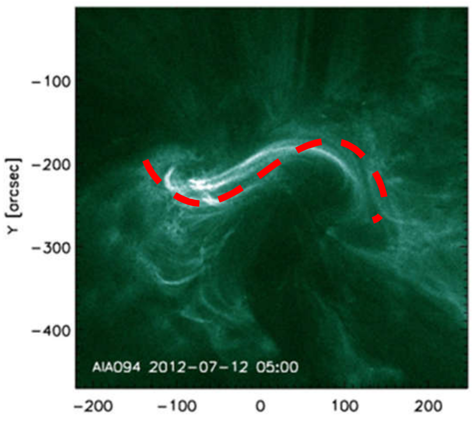
Magnetic field parameters

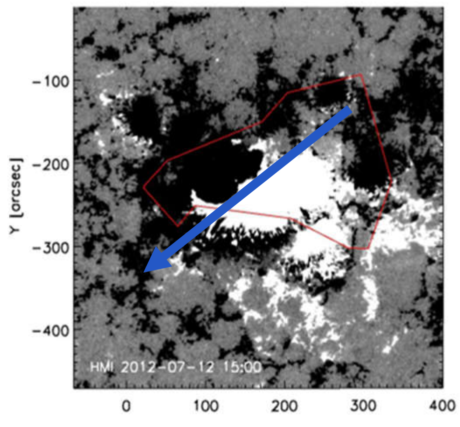
Polarity

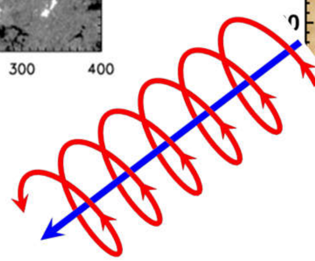
Helicity

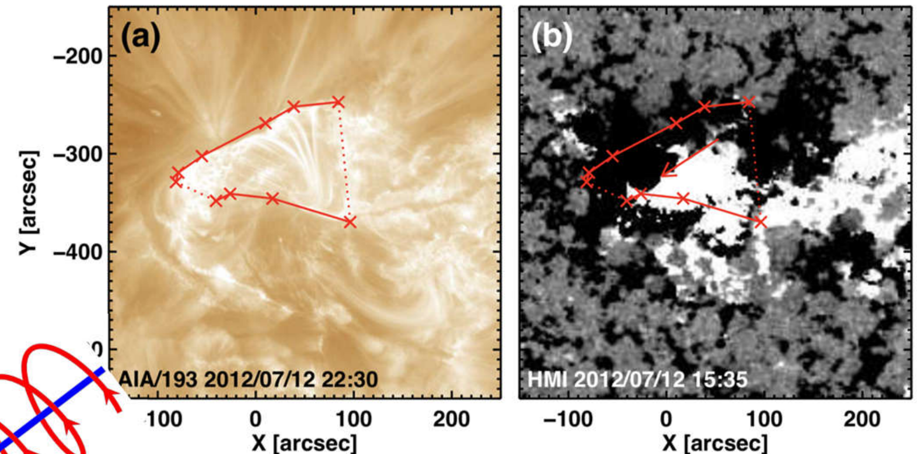
Tilt

Magnetic flux









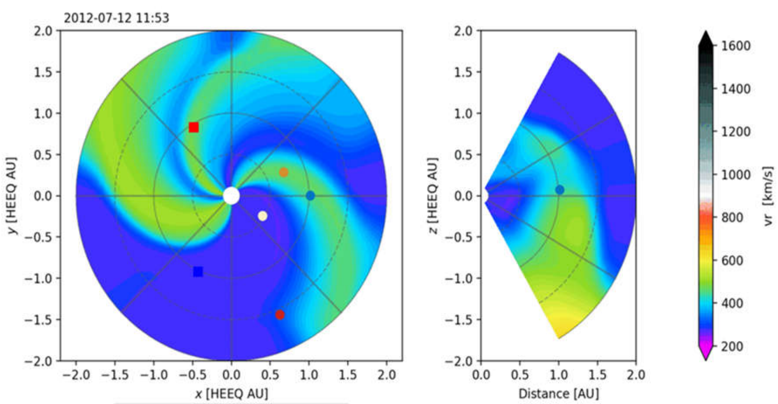
EUV/X-ray sigmoid

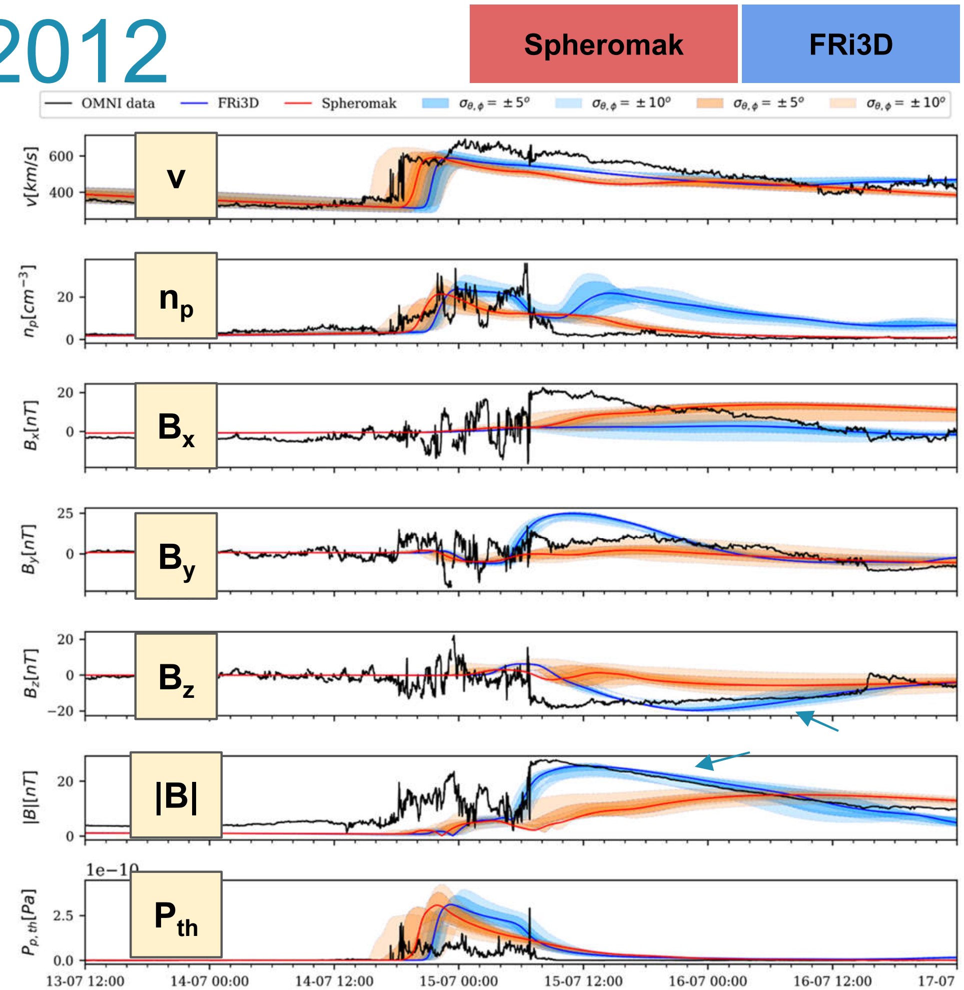
- **Tilt/orientation:** 45°
- **Helicity:** +1 (right-handed)

Reconnected (poloidal) flux using Post Eruptive Arcade (PEA) as proxy ***[Gopalswamy+2017]***

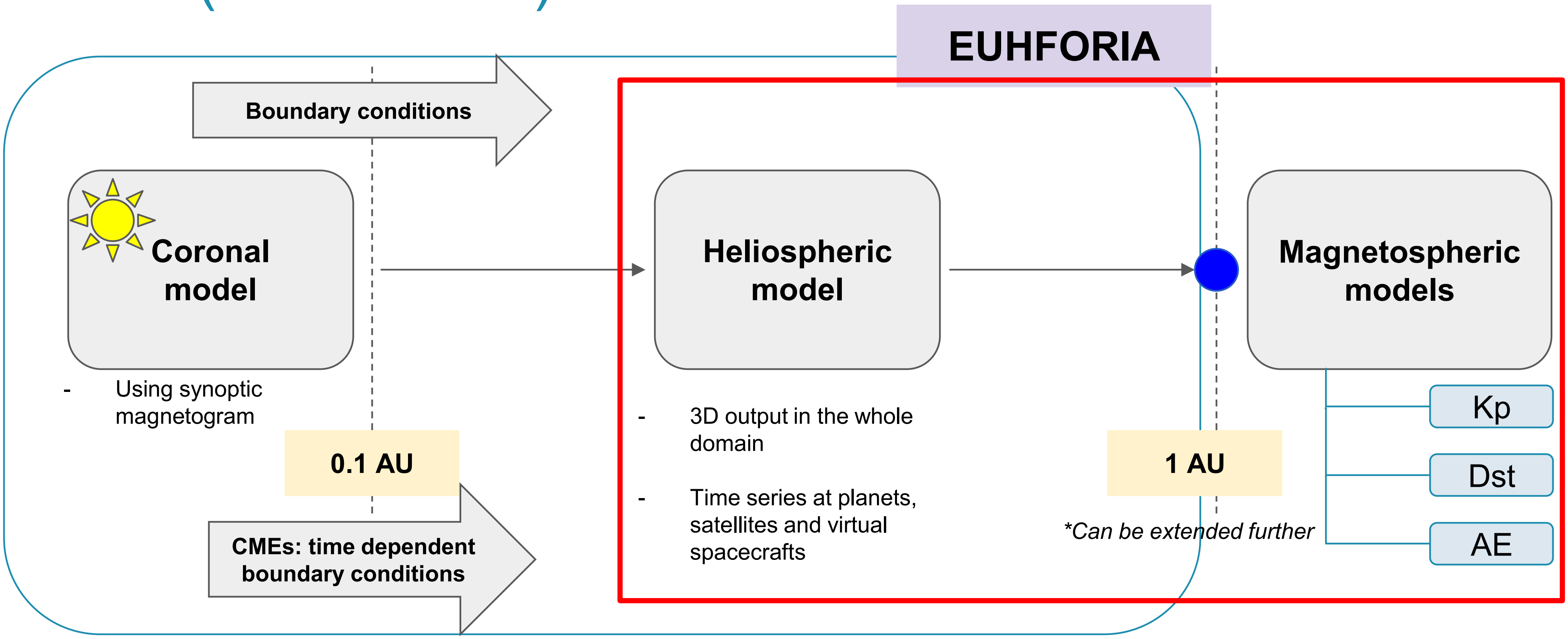
Test case event - 12 July 2012

- **FRi3D** arrival time is similar to Spheromak: ~3h delay in comparison to observed arrival.
- FRi3D enhances the predictions of |B| and B_z by around 37% and 76% as compared to spheromak.
- Prolonged magnetic field enhancement is reproduced by FRi3D.

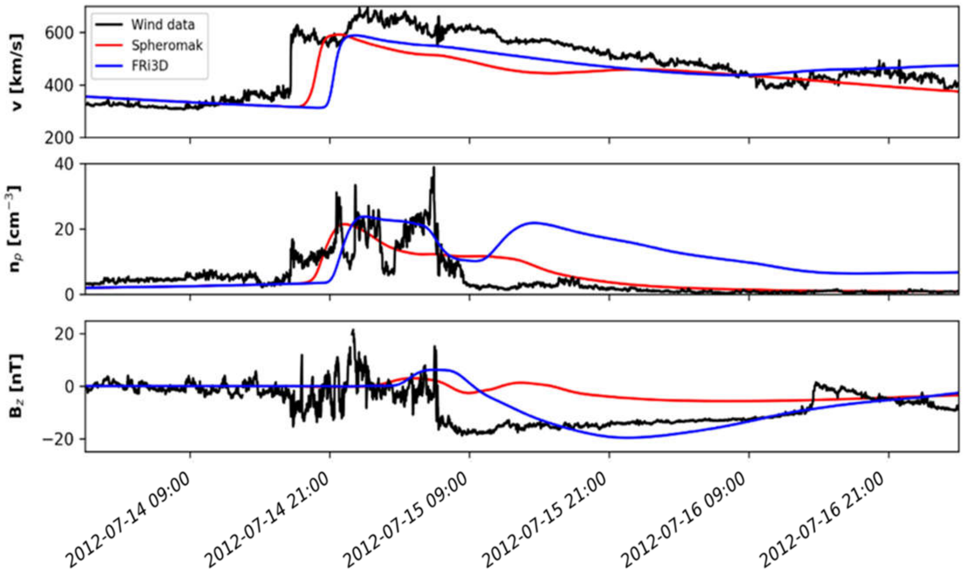




EUropean Heliospheric FORecasting Information Asset (EUHFORIA)



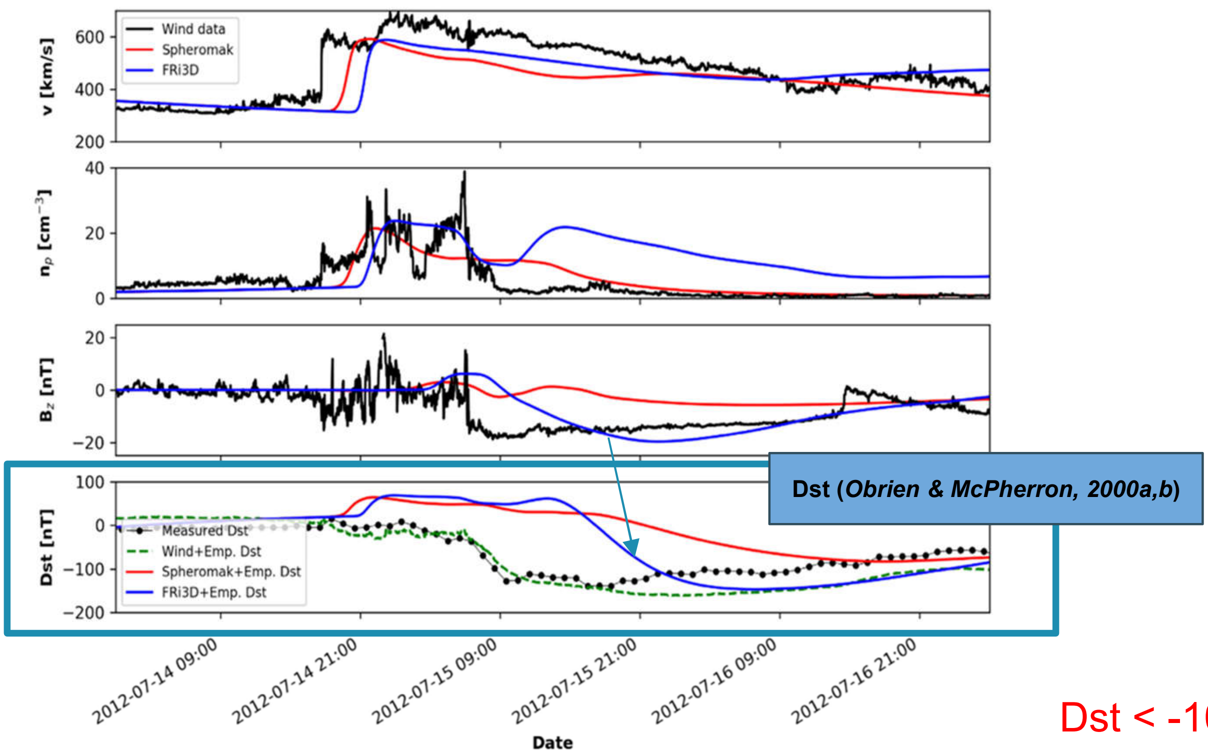
Geo-effectiveness predictions using EUHFORIA



Nowcasting vs forecasting

Nowcasting	forecasting
L1 observations ~1 hour in advance	EUHFORIA simulation ~1-2 days in advance

Geo-effectiveness predictions using EUHFORIA

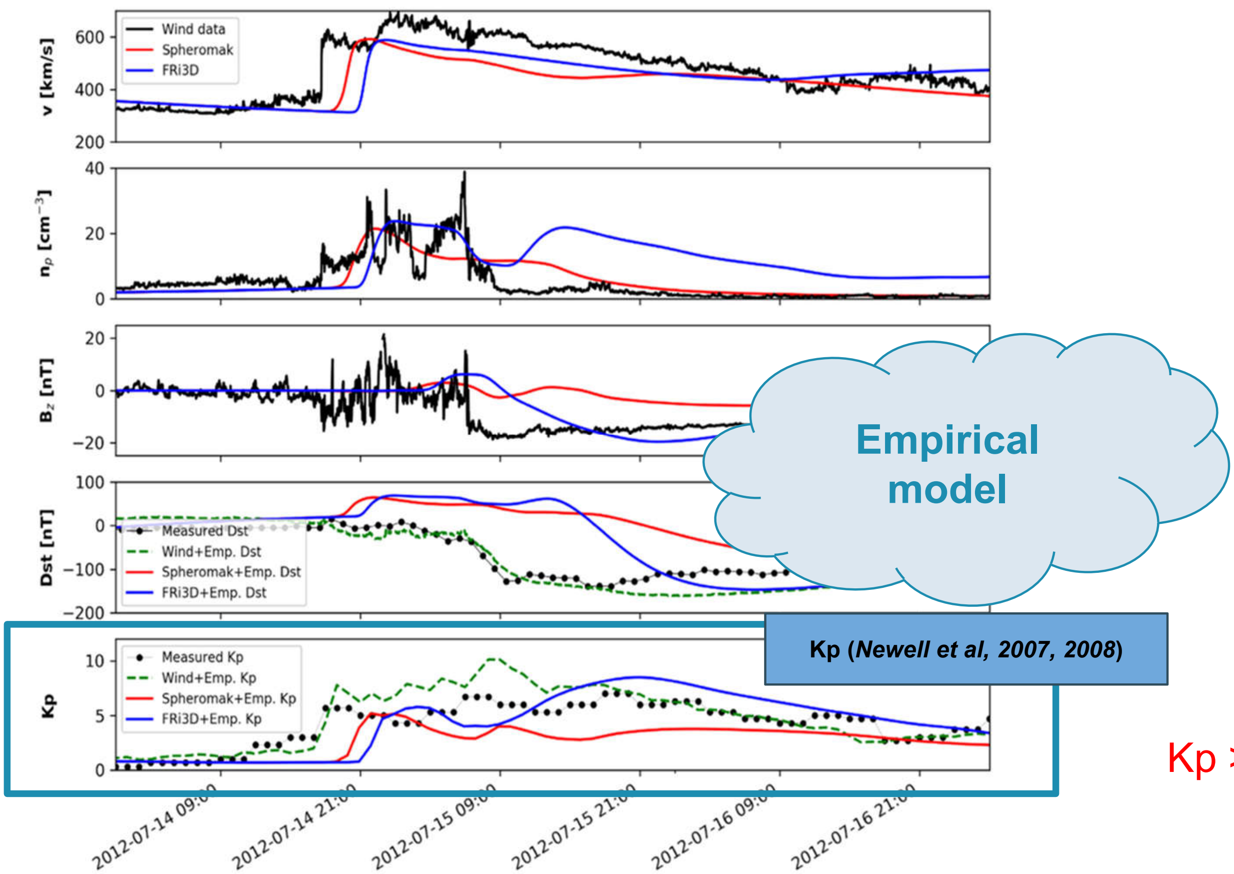


Nowcasting vs forecasting

- Using modelled solar wind plasma properties at Earth, empirical geomagnetic indices are computed.
- Solar wind - Dst coupling formula (***Obrien & McPheron, 2000a,b***)
- Improved minimum Bz modelled by FRi3D predicts the minimum Dst

Dst < -100 nT → Severe geomagnetic impact

Geo-effectiveness predictions using EUHFORIA

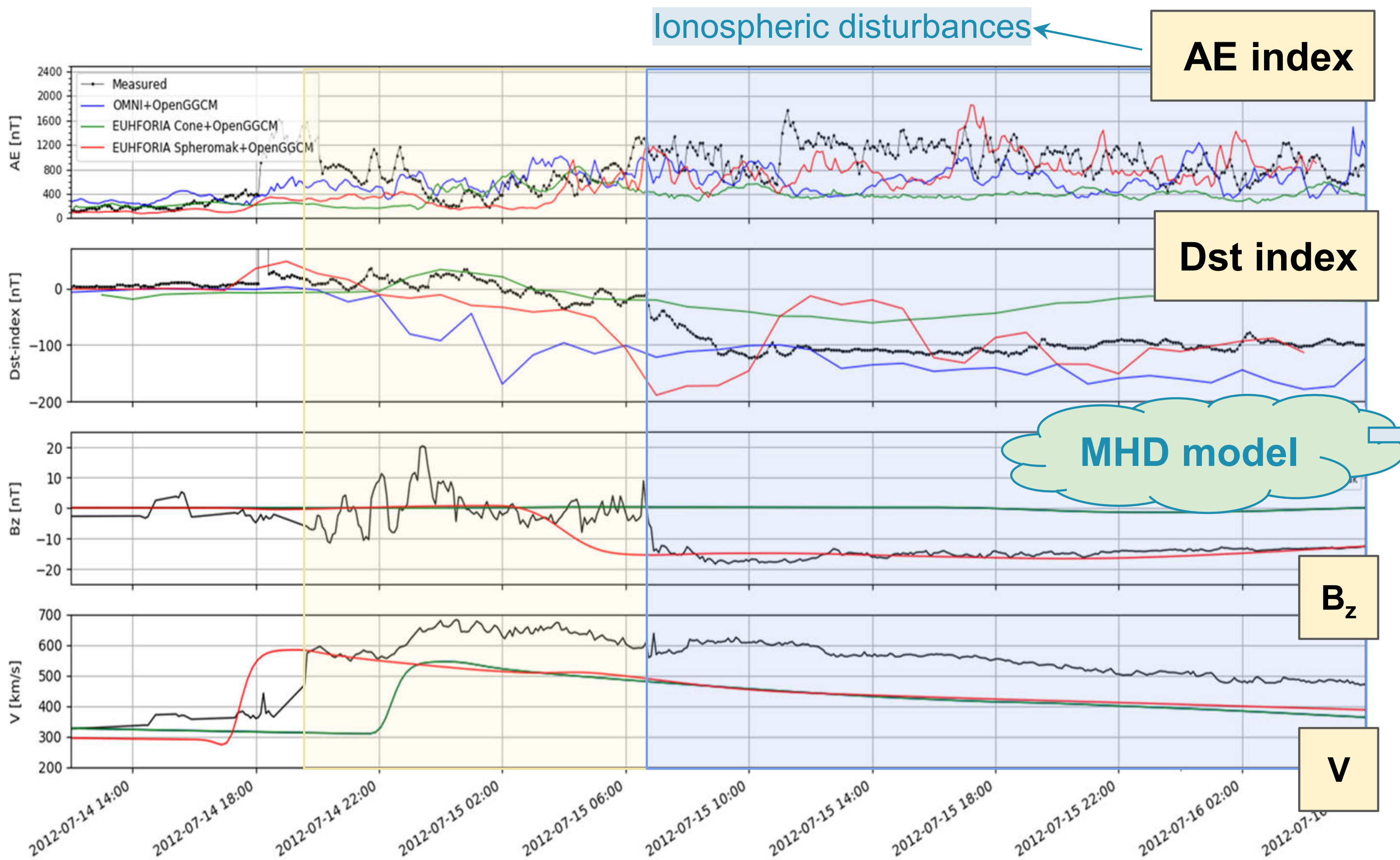


Nowcasting vs forecasting

- Using modelled solar wind plasma properties at Earth, empirical geomagnetic indices are computed.
- Solar wind - Kp coupling function (*Newell et al, 2007, 2008*)
- Kp index improved by 37% with FRi3D as compared to spheromak.

Kp > 5 → Severe geomagnetic impact

Coupling OpenGGCM to EUHFORIA



Simulated time series at L1

EUHFORIA

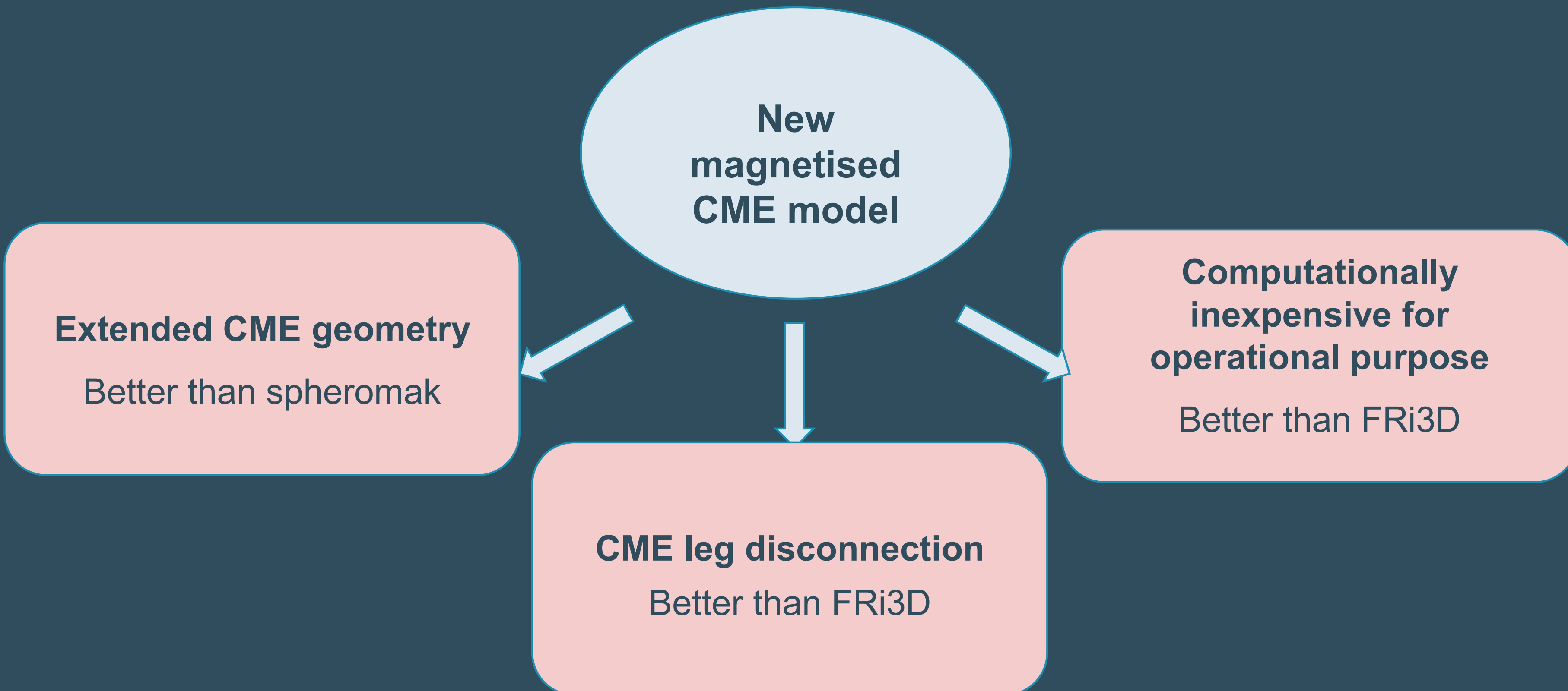
OpenGGCM

Magnetosphere + Ionosphere + Thermosphere

Geomagnetic indices

Dst & AE index

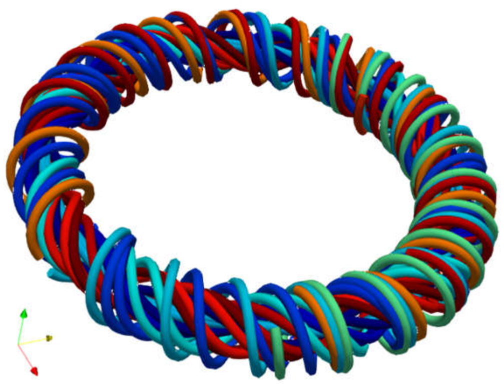
Outline


New magnetised CME model
Extended CME geometry
Better than spheromak
CME leg disconnection
Better than FRi3D
Computationally inexpensive for operational purpose
Better than FRi3D

Torus CME model: Under development

- ➢ In situ observations of CMEs suggest a toroidal geometry.
  [Marubashi 1997; Marubashi & Lepping, 2007; Kahler & Reames, 1991]

- ➢ Miller-Turner magnetic field topology
  - Toroidal geometry
  - Linear force-free ($\nabla \times B = \alpha B$)
  - Constant turn



Torus CME configuration

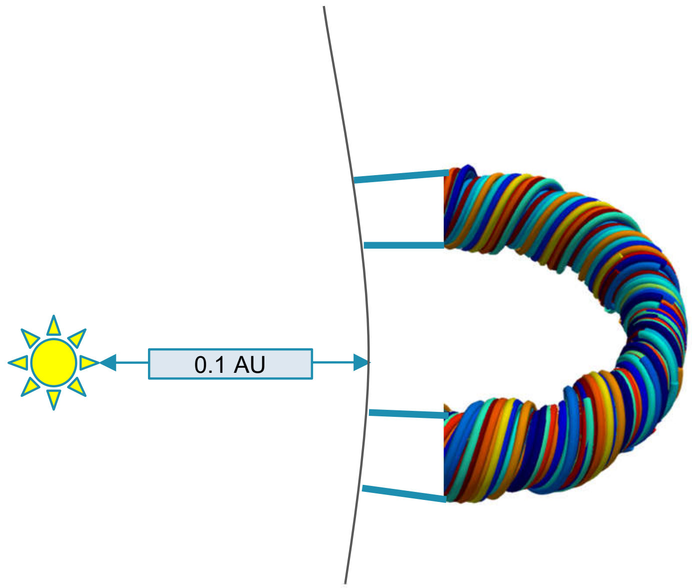
Implementation in ICARUS

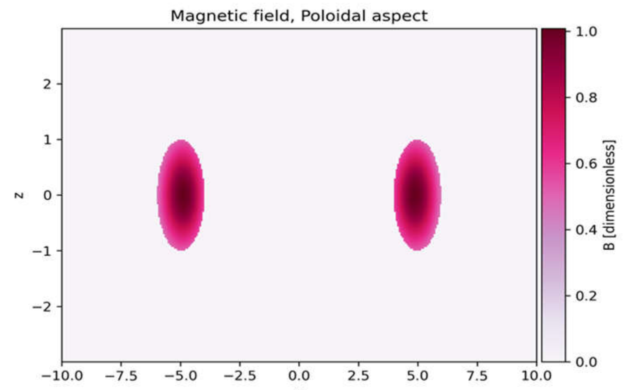
- ICARUS (*Verbeke et al, 2022*): Upgraded EUHFORIA with adaptive mesh refinement (AMR) and grid stretching criteria

- Torus is maintained at its half-crossing and CME injection is continued at the legs.

- *Advantage*: Simulations with Torus CME are as fast as the spheromak simulations.

- *Future work*:
  - Contraction of torus and pushing the whole structure through the boundary
  - Consistent CME disconnection from the Sun





Torus crossing through EUHFORIA boundary.

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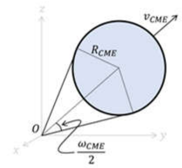
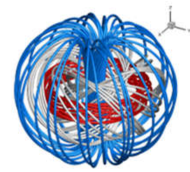
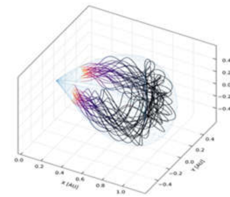
Conclusions



Cone


Spheromak


FRi3D


Torus

- ➢ Magnetized CME models in EUHFORIA improve the geo-effectiveness predictions.
  - FRi3D CME model, with a global CME geometry, is an upgrade over the spheromak model in EUHFORIA.
  - To overcome the computational resource demand by FRi3D, a simpler torus model with Miller-Turner magnetic field configuration is under development.
- ➢ Output of EUHFORIA can be coupled with magnetospheric-ionospheric models to predict geomagnetic indices.

Modular design of EUHFORIA enables coupling between CME, heliospheric and magnetospheric models

→Open to collaborations and suggestions for improvement

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Thank you

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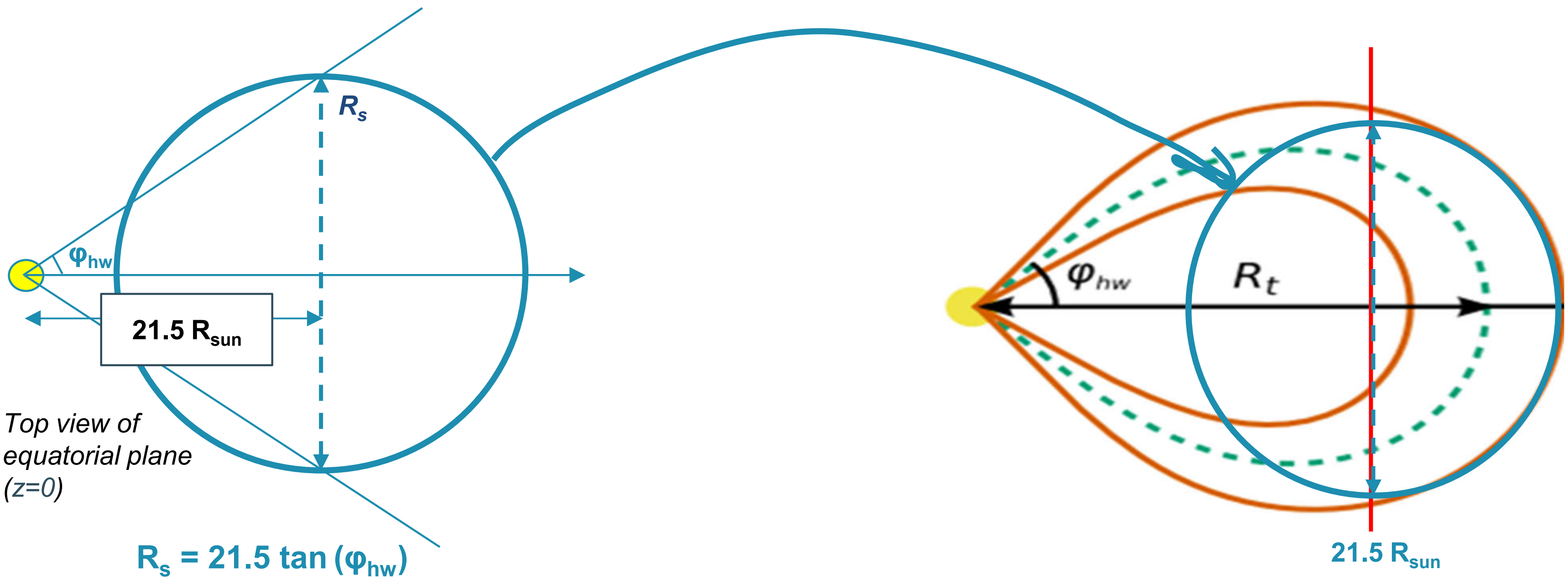
The circle shows spheromak CME cross-section as compared to FRi3D.

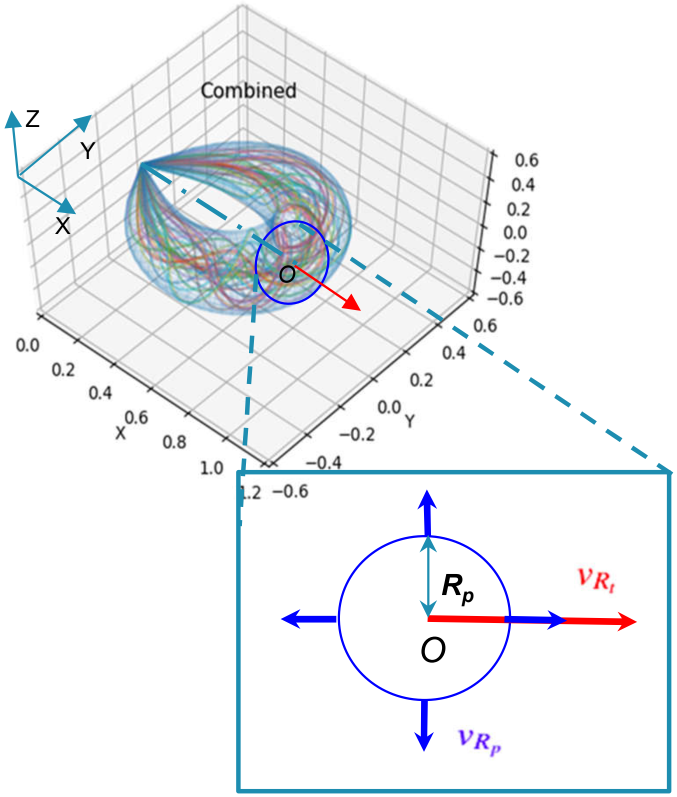
Geometry comparison



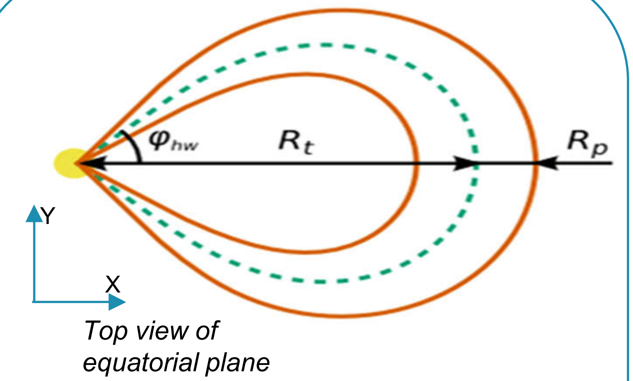
Radius when spheromak is halfway through the inner boundary

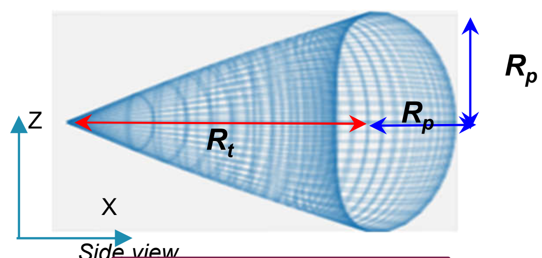
Spheromak CMEs are modelled with this geometry injected at EUHFORIA inner boundary provide the best agreement to predictions at Earth [*Scolini+2018*].

Optimising FRi3D speed



$$v_{3D} = \frac{d}{dt}(R_t + R_p) = v_{R_t} + v_{R_p}$$





$$R_p = R_t \tan(\varphi_{hh})$$

$$v_{R_t} = \frac{d}{dt}(R_t)$$

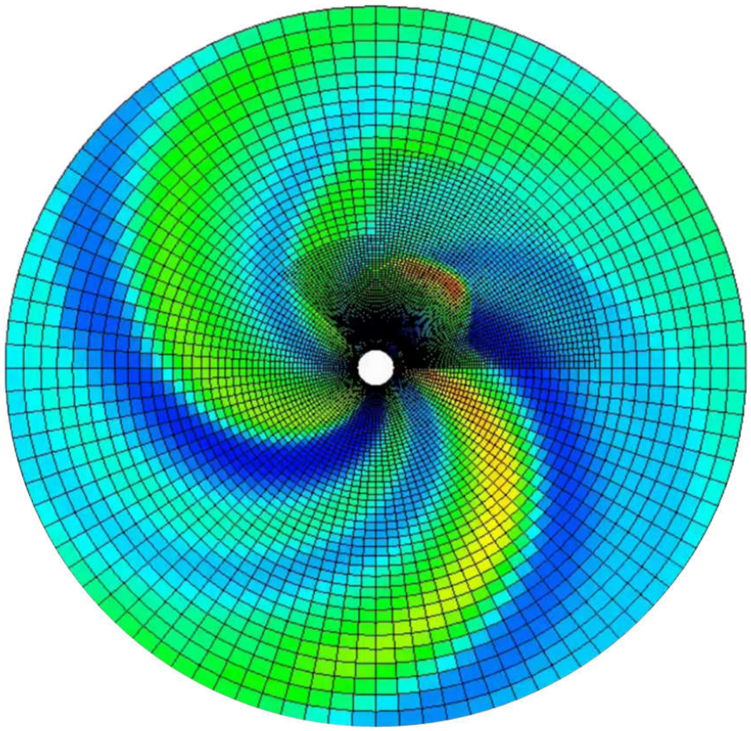
Rate of change of
toroidal radius (R_t)
⇒ Radial speed

$$v_{R_p} = \frac{d}{dt}(R_p)$$

Rate of change of
poloidal radius (R_p)
⇒ Expansion speed

Implementation in ICARUS

- ICARUS (*Verbeke et al, 2022*): Upgraded EUHFORIA with adaptive mesh refinement (AMR) and grid stretching criteria



Credits: Tinatin Baratashvili

Torus CME model: Under development

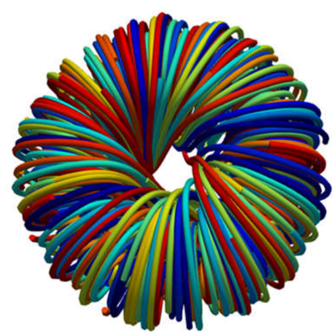
3

Geometrical parameters

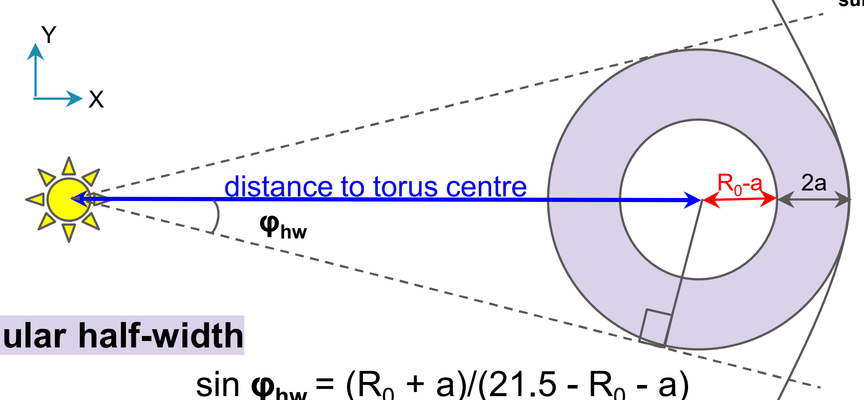
a: inner radius

R_0: outer radius

a=2, R_0=5



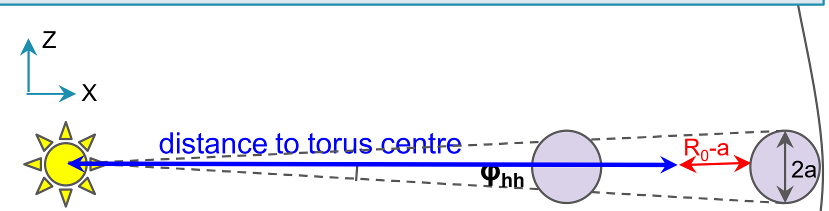
a=4, R_0=5



Angular half-width

$\sin \boldsymbol{\varphi}_{hw} = (R_0 + a)/(21.5 - R_0 - a)$

Connecting CME geometry to the torus parameters



Angular half-height

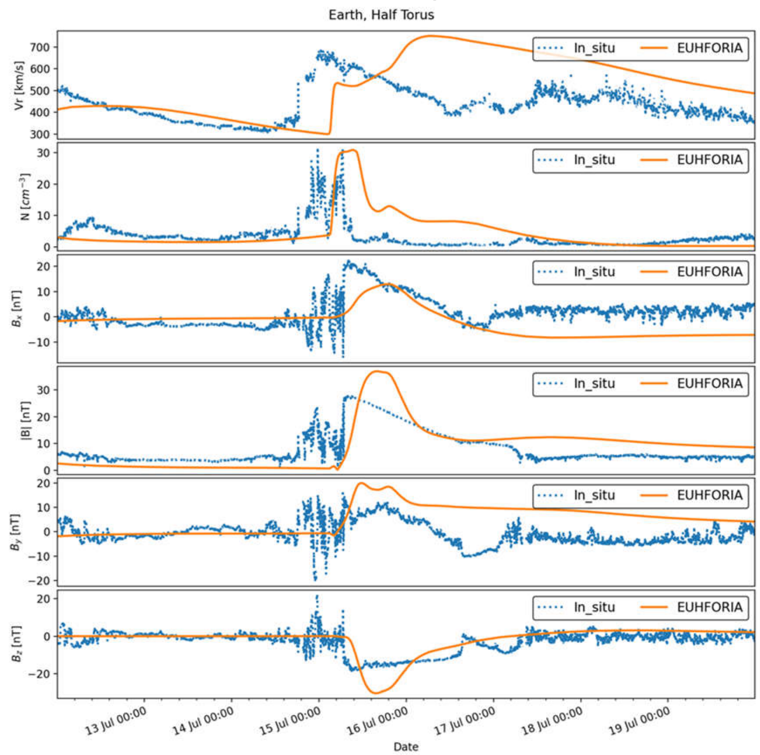
$\tan \boldsymbol{\varphi}_{hh} = a/(21.5 - a)$

r = 21.5 R_{sun}

Torus CME model: Preliminary results

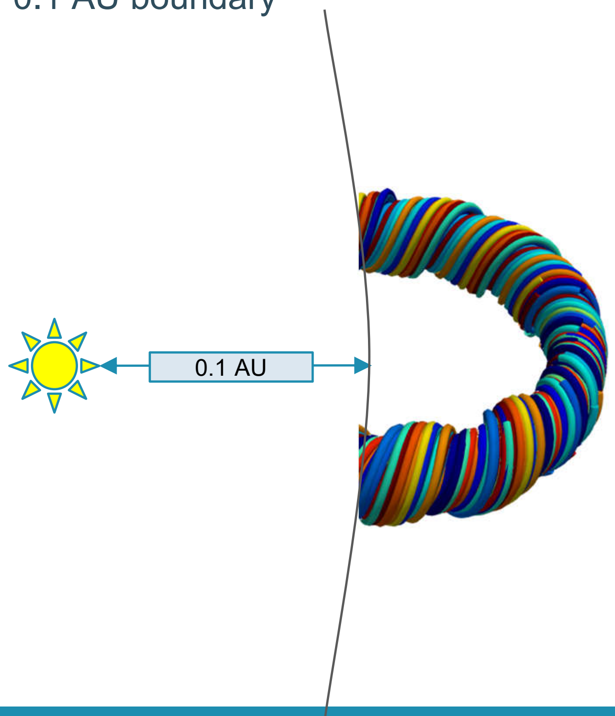
- ➢ Modelling of Event 12 July 2012 with Torus CME
- ➢ Speed is overestimated.
- ➢ Magnetic field strength can be reproduced up to correct order of magnitude.

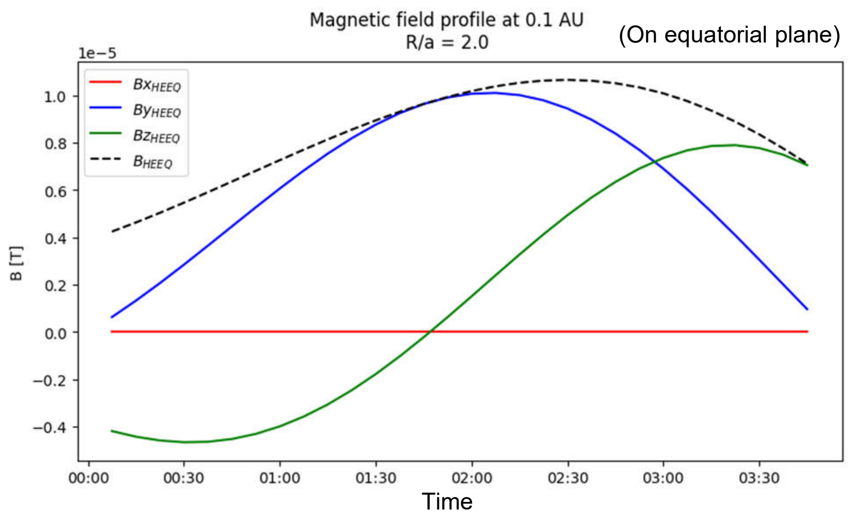
Event 12 July 2012



Torus CME model: Under development

Evolution of magnetic field profile as half-torus crosses the 0.1 AU boundary





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