Predicting southward magnetic fields in in CMEs for space weather modeling

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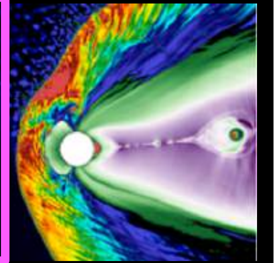

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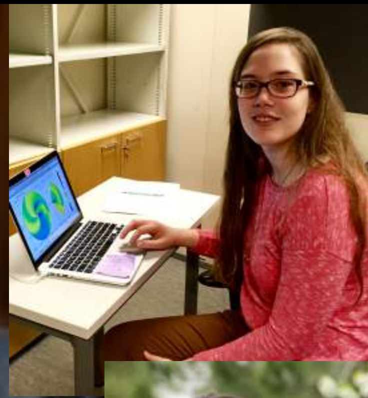
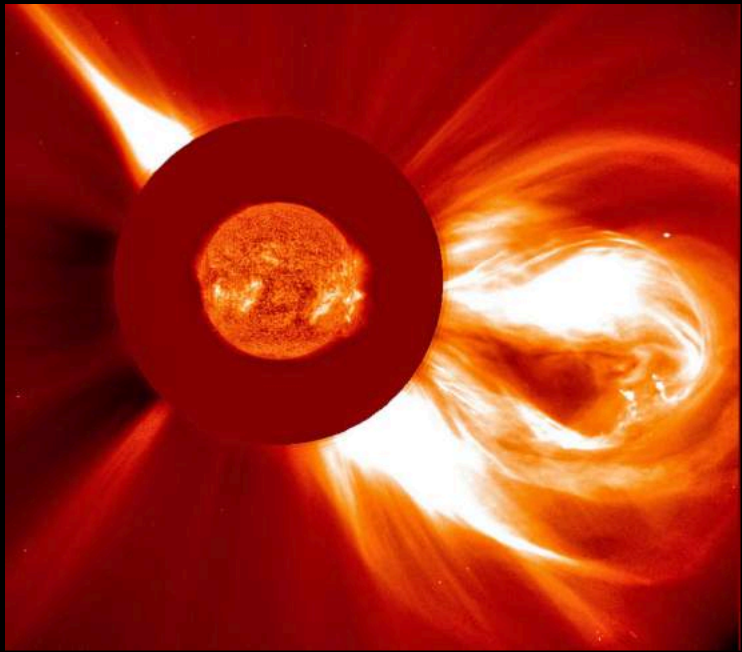
Emilia & Solar eruptions

Minna & Vlasiator

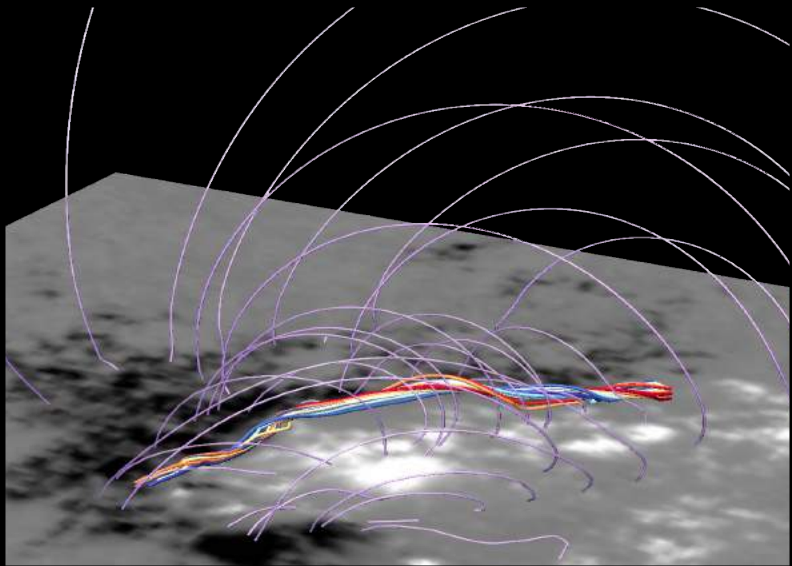

KU Leuven: Stefaan Poedts & team

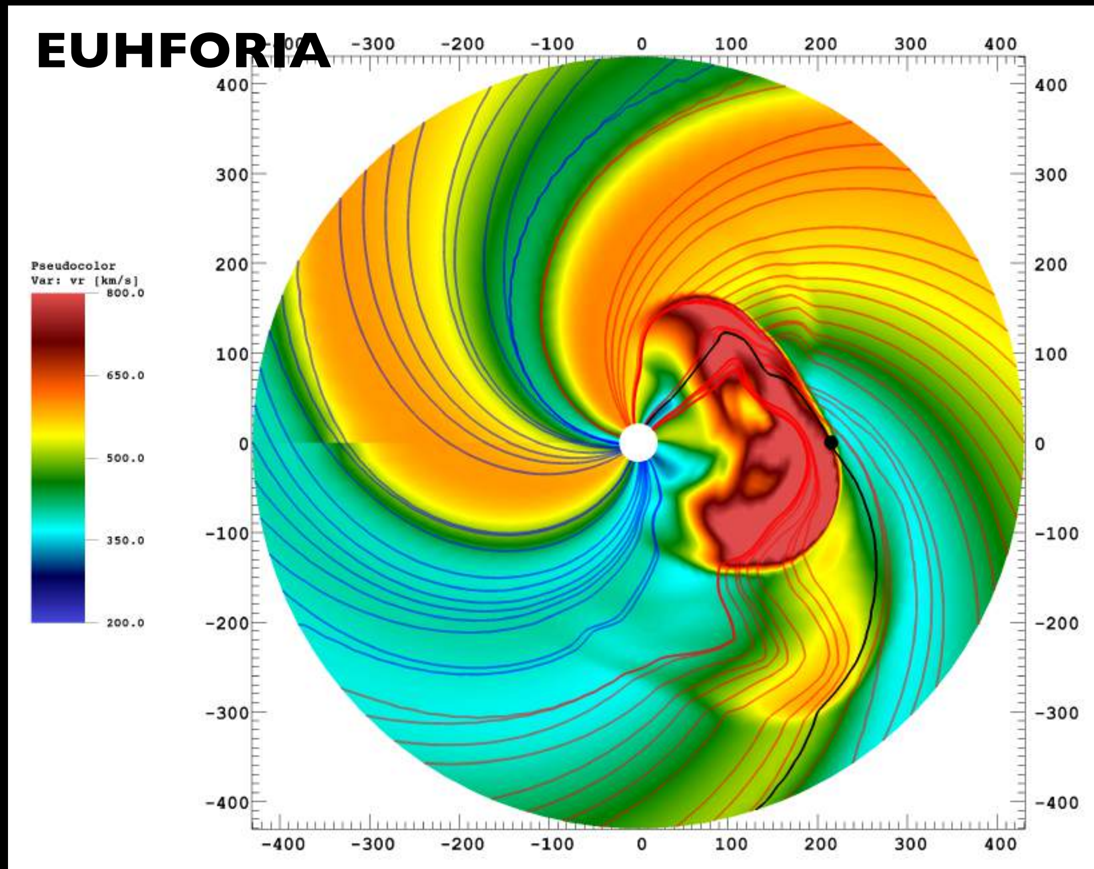



Royal Observatory of Belgium,
Jasmina Magdalenic & team



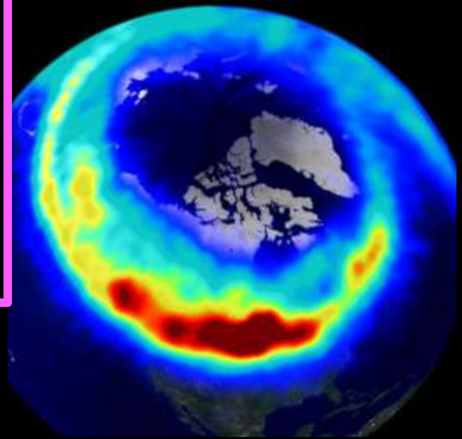

PHY

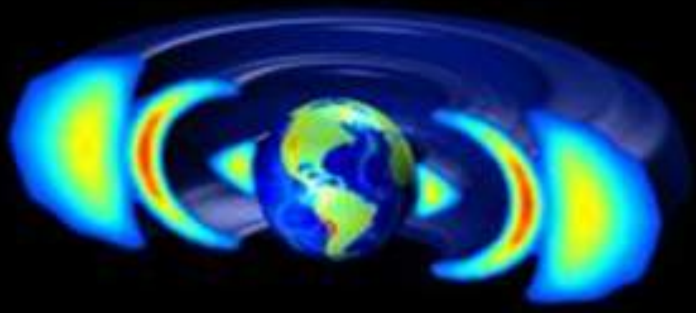


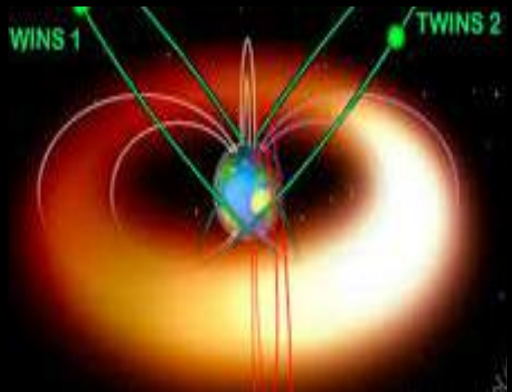

EUHFORIA
Pseudocolor
Var: vr [km/s]
800.0
650.0
500.0
350.0
200.0
-400 -300 -200 -100 0 100 200 300 400
400 300 200 100 0 -100 -200 -300 -400

Space weather

- auroral currents
- large-scale convection (ring current)
- Van Allen radiation belts
- atmospheric and ionospheric conditions







Controlling key parameters

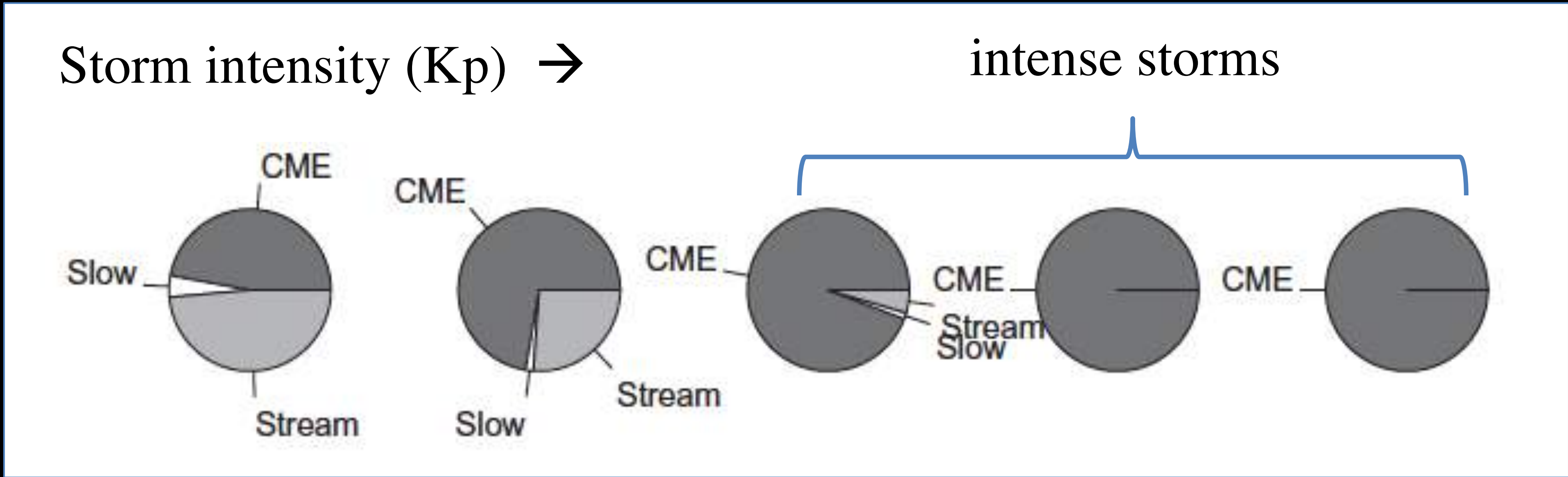
- Southward interplanetary magnetic field
- Solar wind speed
- Solar wind density
- Level of turbulence in solar wind
- Bow shock transition + magnetosheath (e.g, Alfvén Mach number)

dynamic pressure

dawn-dusk electric field

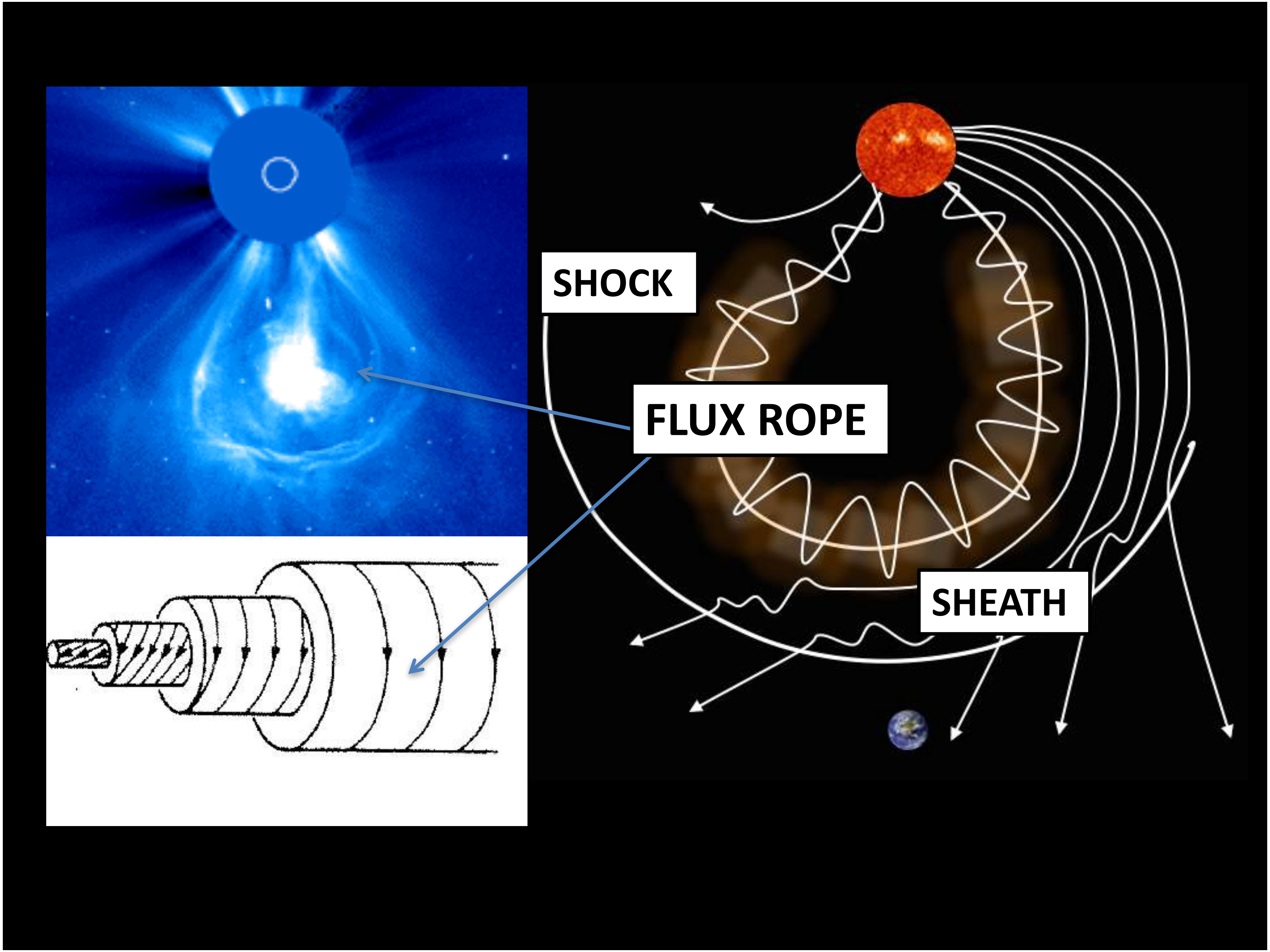
Kilpua et al., Geoeffective Properties of Solar Transients and Stream Interaction Regions, Space Sci. Rev., doi:10.1007/s11214-017-0411-3, 2017

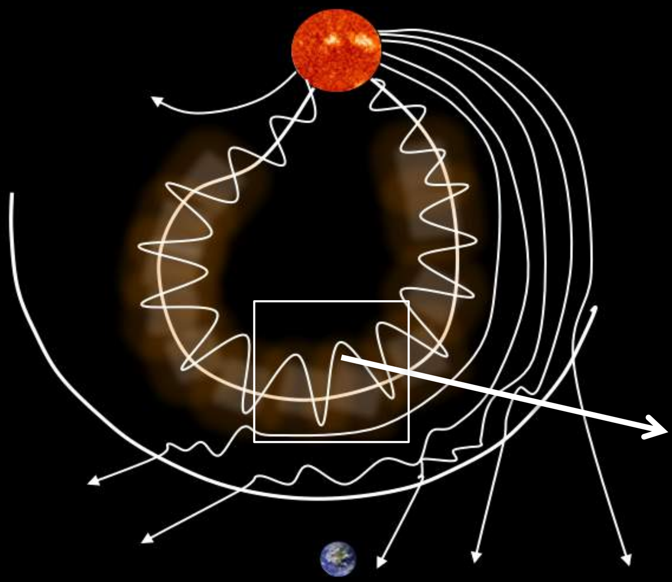
Small to Intense Storms during four Solar Cycles (1963 -2011)

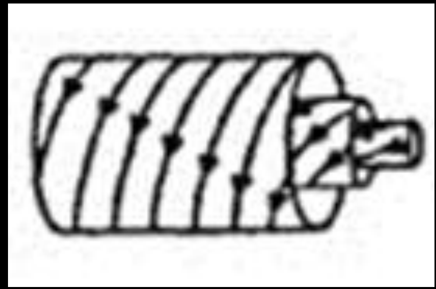


Richardson and Cane 2012,

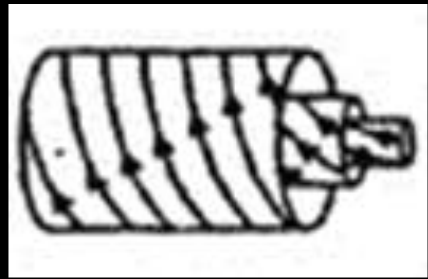
Coronal Mass Ejections (CMEs) drive nearly all intense geomagnetic storms


SHOCK
FLUX ROPE
SHEATH

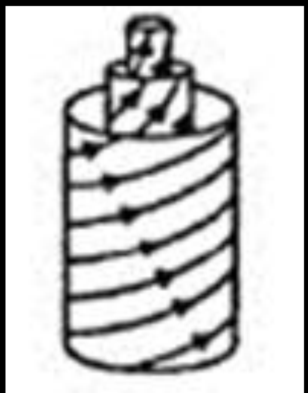




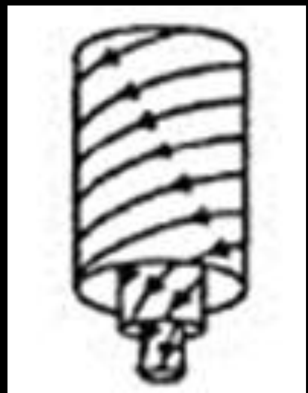
North → South (NS)



South → North (SN)



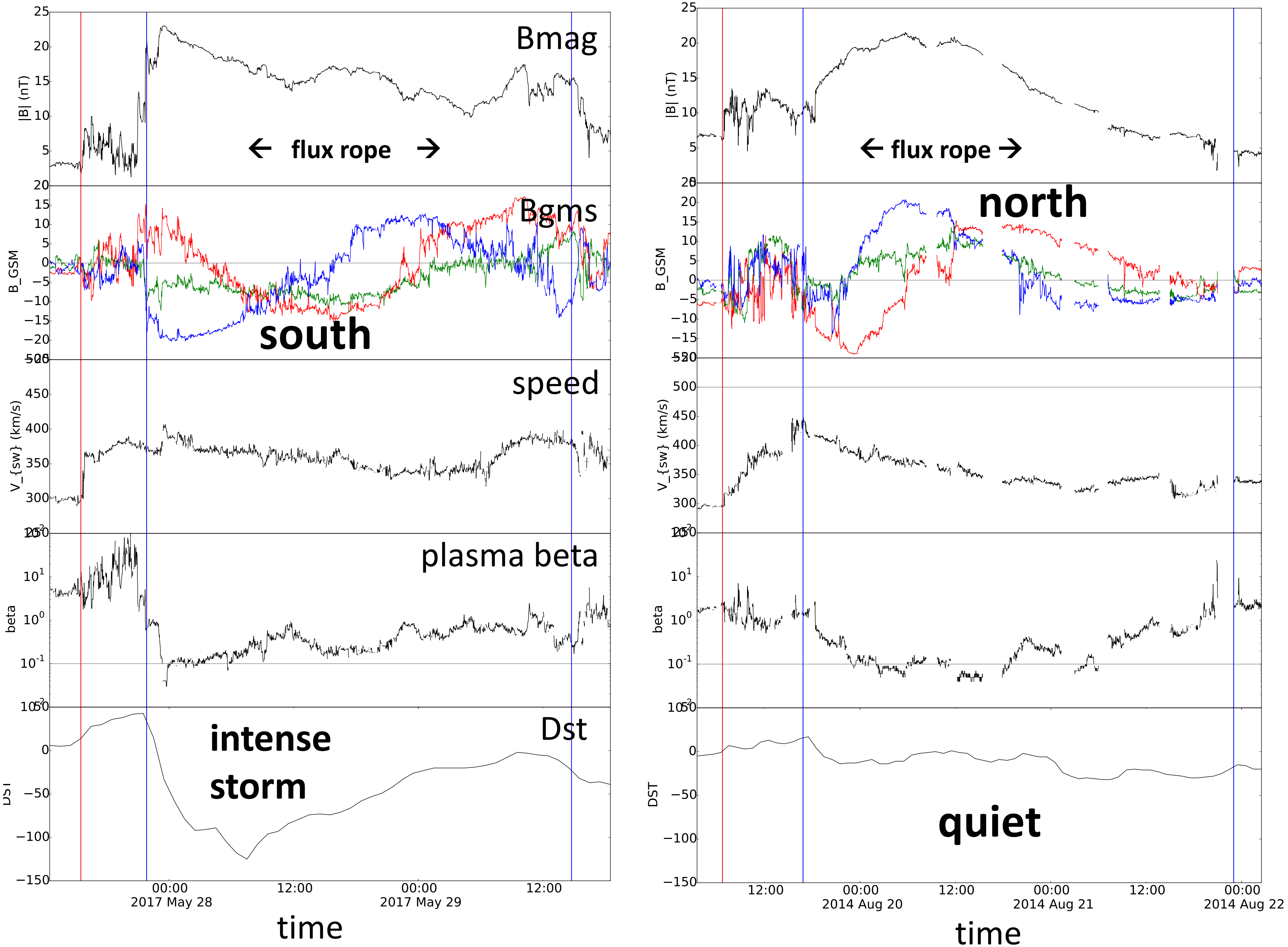
North (N)



South (S)

- Flux rope “type” (Bothmer and Schwenn, Ann. Geo., 1998; Mulligan and Russell, GRL, 1998) has a big impact on geomagnetic response Huttunen et al., Ann. Geo. 2005)

- Background solar wind modifies also response (e.g., Fenrich and Luhmann, GRL, 1998; Kilpua et al., Ann. Geo., 2012)



Bmag
|B| (nT)
flux rope
Bgms
B_GSM
south
speed
V_{sw} (km/s)
plasma beta
beta
Dst
DST
intense
storm
00:00
2017 May 28
12:00
00:00
2017 May 29
12:00
time
north
quiet
12:00
00:00
2014 Aug 20
12:00
00:00
2014 Aug 21
12:00
00:00
2014 Aug 22
time

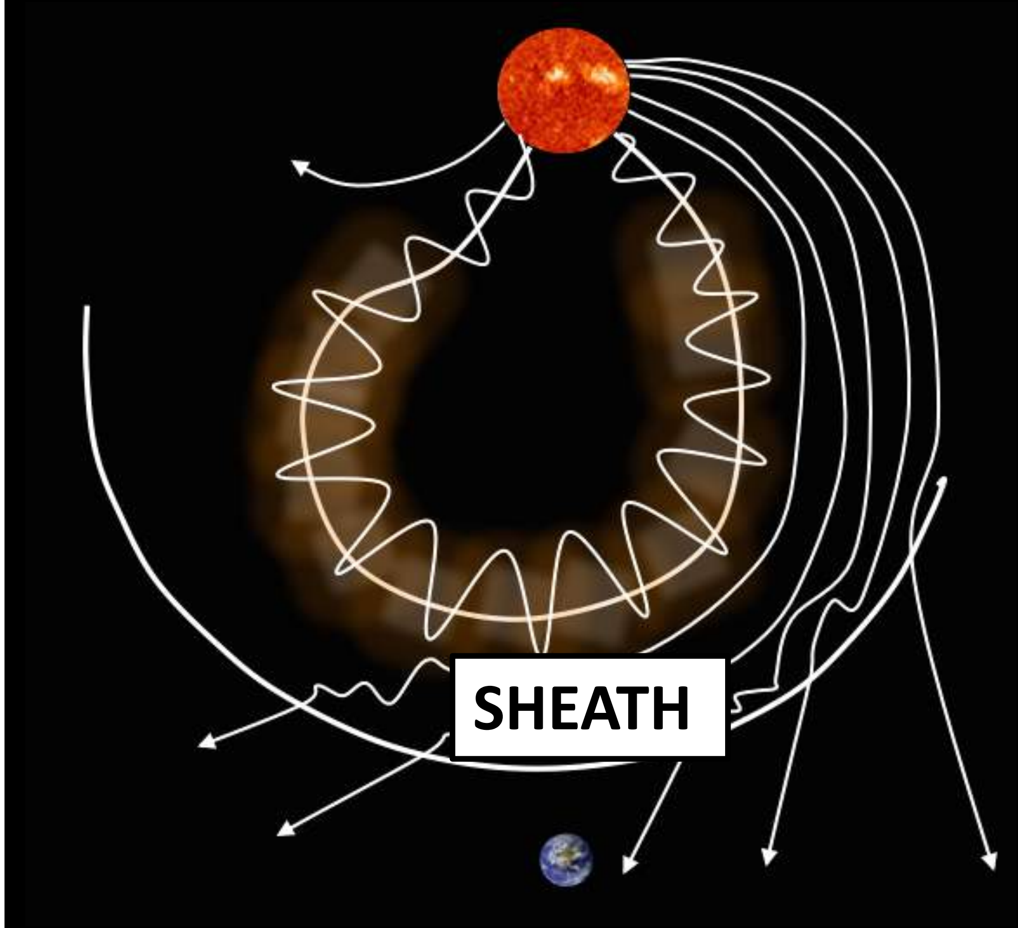
CME sheaths are also important

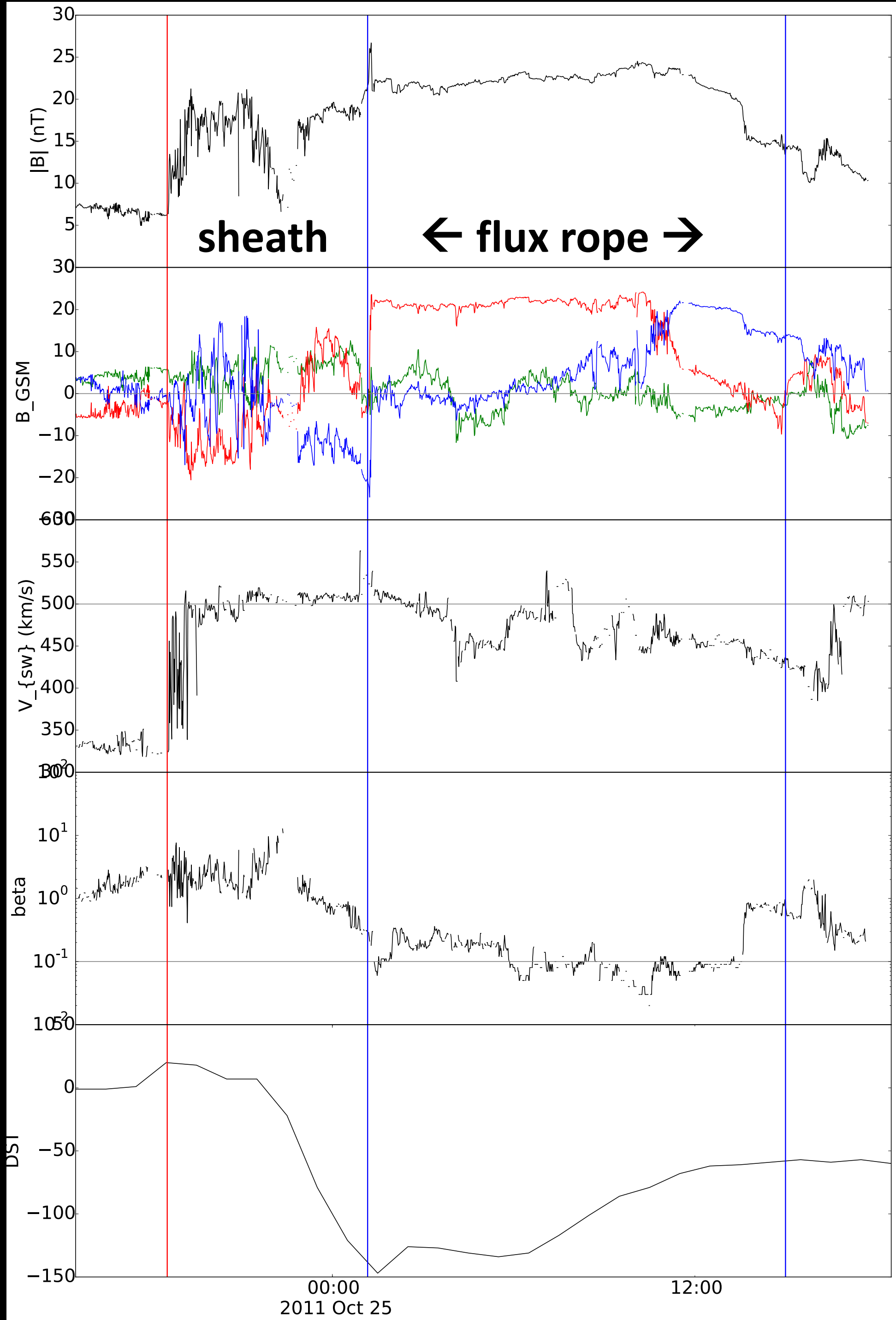
- Drive large geomagnetic storms
- In particular at high-latitudes
  (Huttunen et al, 2002; 2004)
- Intense GICs occur due to sheaths
  (Huttunen et al., SW, 2008)

- Deplete dramatically radiation belts (Kilpua et al., 2015)
- Conditions that enhance solar wind magnetosphere coupling, *i.e.*, turbulent, high Alfvén Mach number and dynamic pressure

Kilpua et al., Geoeffective Properties of Solar Transients and Stream Interaction Regions, Space Sci. Rev., 2017

Kilpua, Koskinen and Pulkkinen, Coronal mass ejections and sheath regions in interplanetary space, in press, Living Reviews in Solar Physics


SHEATH

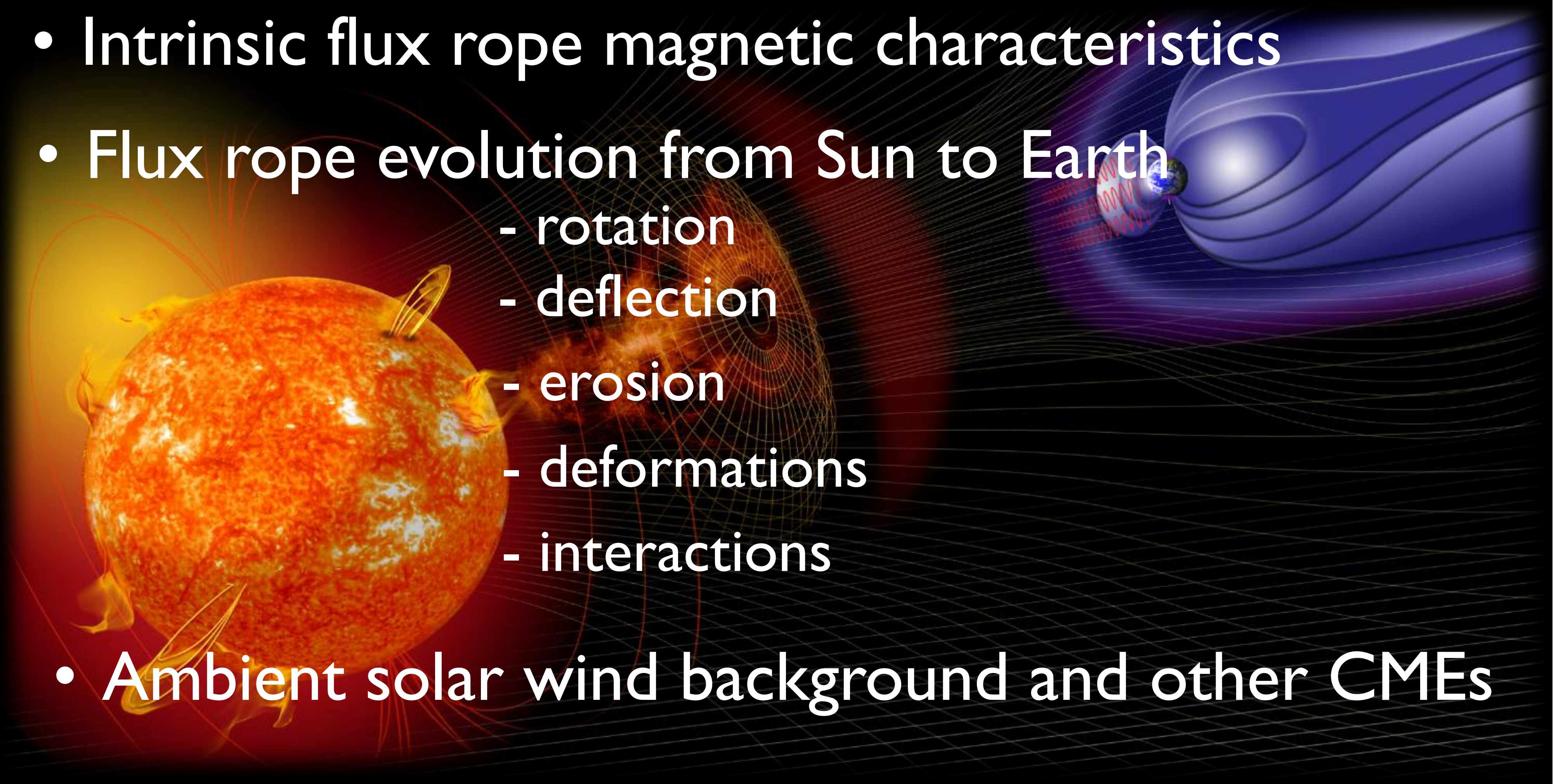

sheath
← flux rope →
|B| (nT)
B_GSM
V_{sw} (km/s)
beta
DST
00:00
2011 Oct 25
12:00

Magnetic field is the most crucial factor in determining the space weather response

BUT

It cannot be currently determined reliably

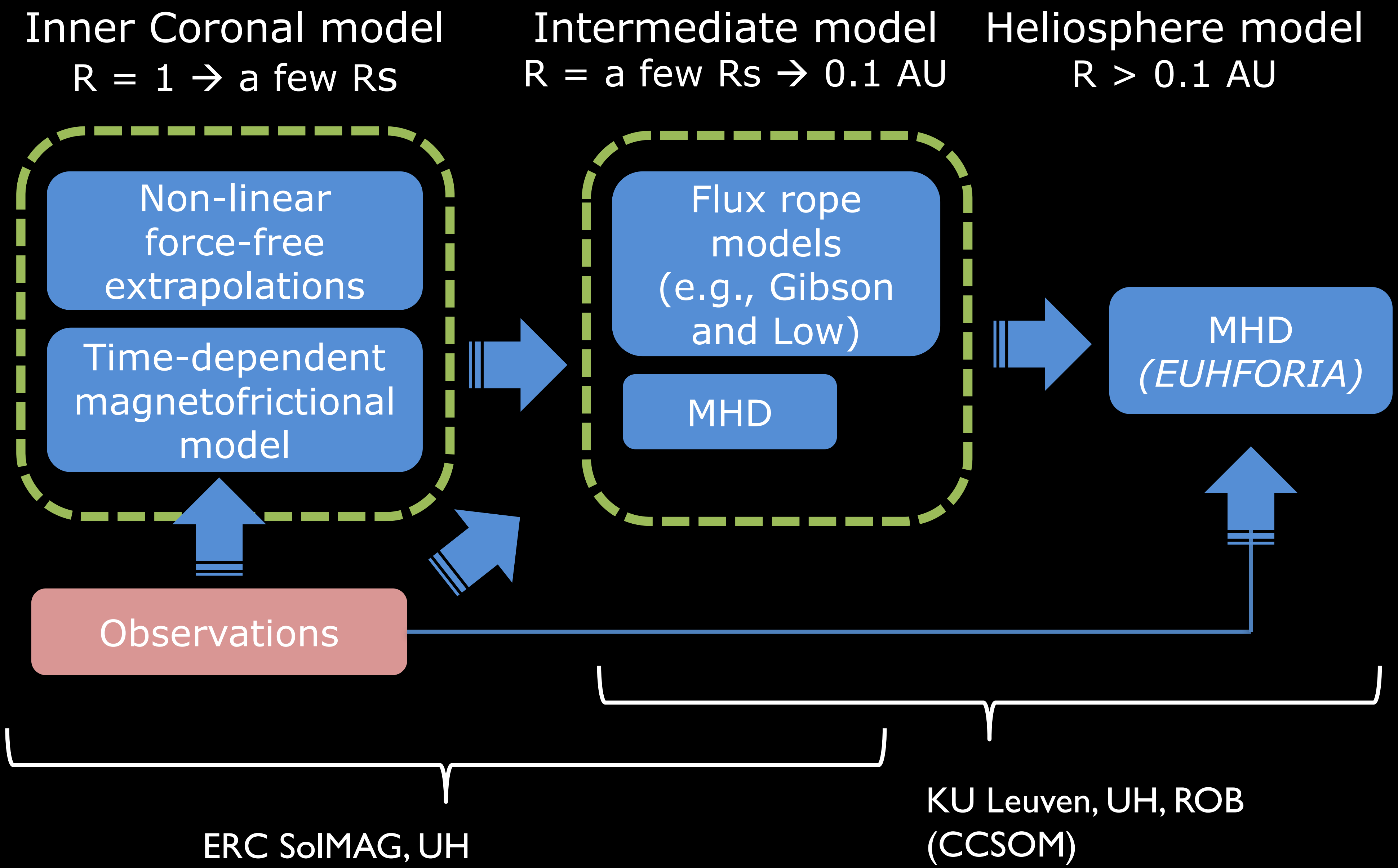
Key challenges



- Intrinsic flux rope magnetic characteristics
- Flux rope evolution from Sun to Earth
  - rotation
  - deflection
  - erosion
  - deformations
  - interactions
- Ambient solar wind background and other CMEs
- Turbulent sheath fields

Ultimate goal

Data-driven Space Weather Modelling chain



Determining intrinsic CME magnetic fields

1) Modelling approach: data-driven coronal simulations → CME (and sheath) fields self-consistently and time-dependently

2) Observational approach: synthesis of indirect proxies

Magnetofrictional Method

- Computationally efficient → strong space weather potential

$$\rho\frac{d\mathbf{v}}{dt} = -\nabla P + \mathbf{J}\times\mathbf{B} + \rho\mathbf{g} - k\mathbf{v}$$

frictional term to MHD momentum Eq.

→ $$\mathbf{v} = \frac{\mu_0}{\nu}\frac{\mathbf{J}\times\mathbf{B}}{B^2}$$

- magnetic field evolved using this velocity through induction equation (Yang et al., 1986)

- In *time-dependent* MFM photospheric boundary condition is evolved as well (force-free state not reached)

$$\mathbf{E} = -\frac{\partial\mathbf{A}}{\partial t}(\mathbf{r},t)\Big|_{r=R_\odot}$$

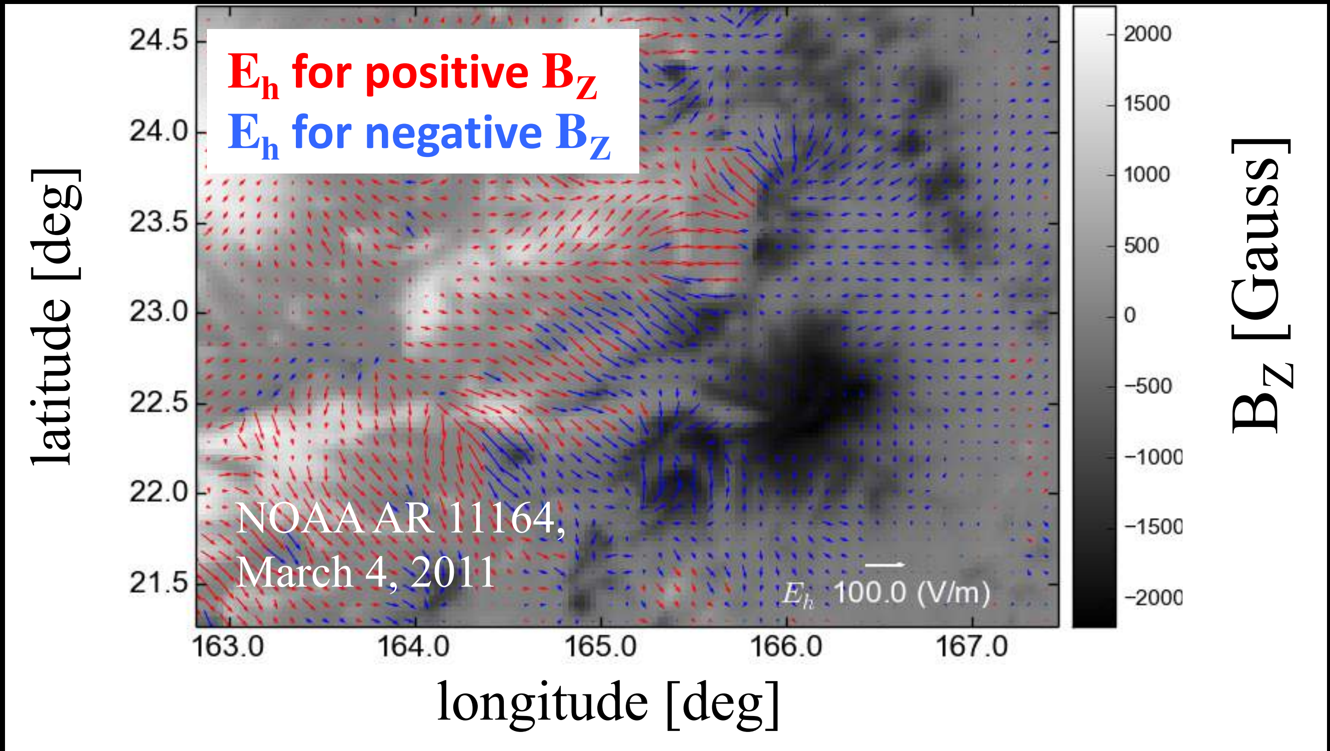
e.g., Cheung & DeRosa, 2012; Weinzierl et al., 2016

Photospheric boundary conditions

- Electric field is crucial input to MFM
- time-sequences of full-disk HMI vector magnetograms
- Poloidal-toroidal decomposition of $\boldsymbol{B}$ (e.g., Kazachenko et al. 2014)

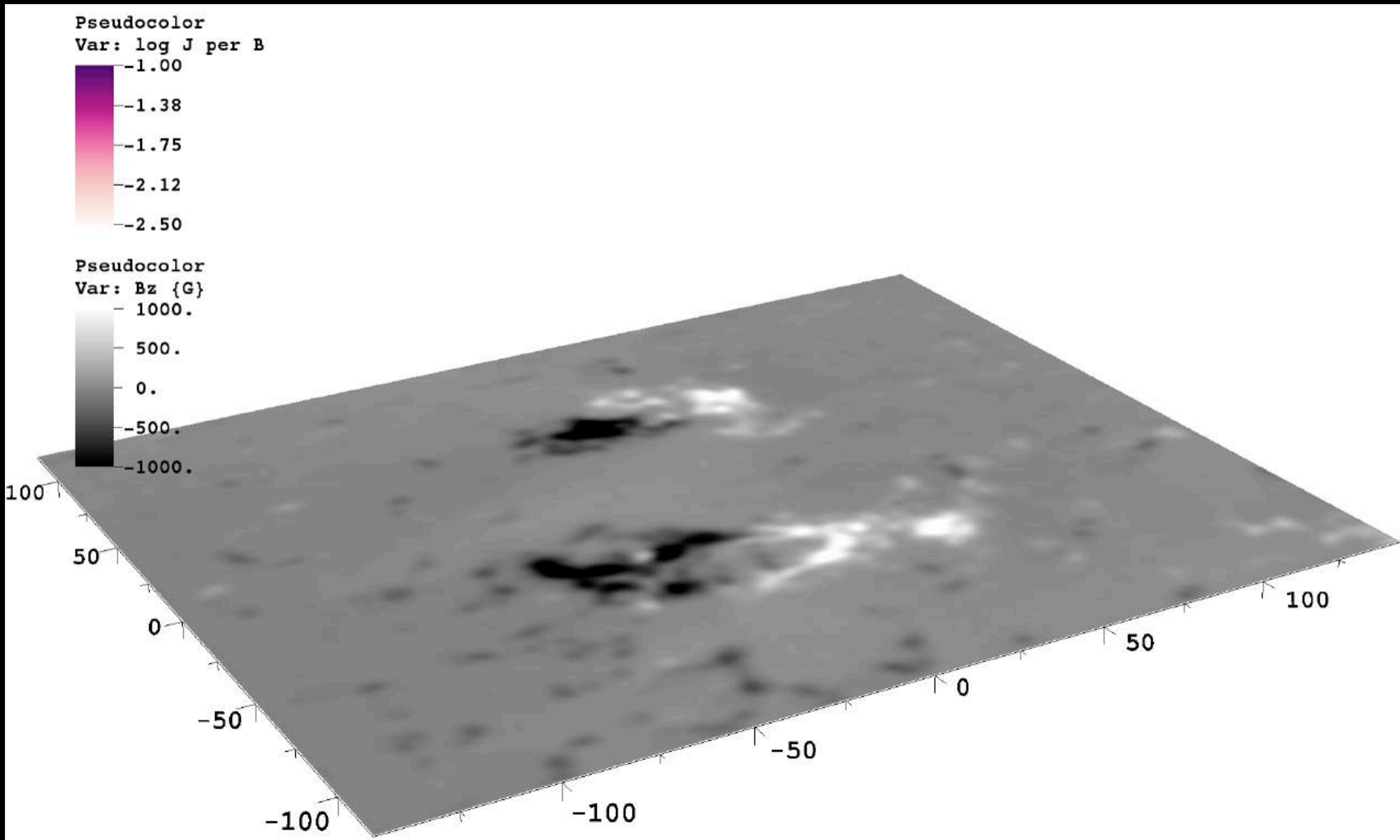
$$\boldsymbol{E} = \boldsymbol{E}_I - \nabla\psi, \qquad \nabla\times\boldsymbol{E}_I = -\frac{\partial \boldsymbol{B}}{\partial t} \; *$$

*Additional data/assumptions needed to obtain $\nabla\psi$



ELECTRICIT

Time-dependent MFM



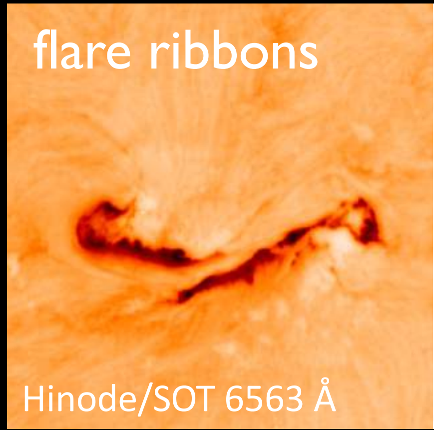
Determining intrinsic CME magnetic fields

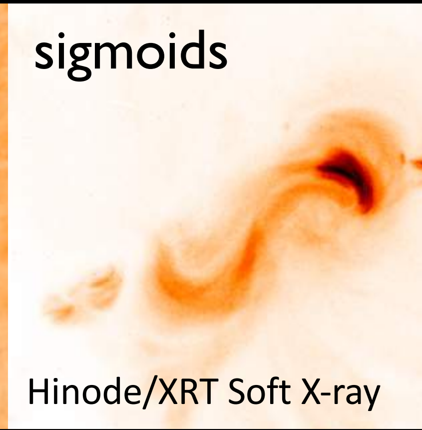
1) Modelling approach: data-driven coronal simulations → CME (and sheath) fields self-consistently and time-dependently

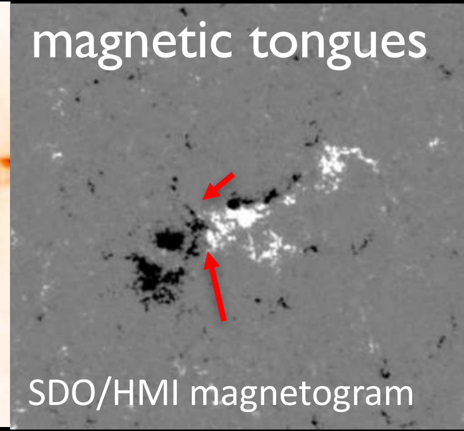
2) Observational approach: synthesis of indirect proxies

Observational determination

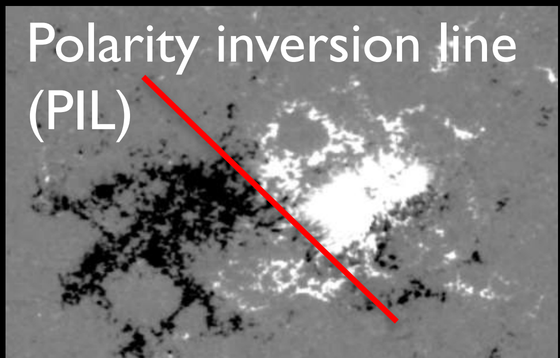
1) Helicity sign/chirality

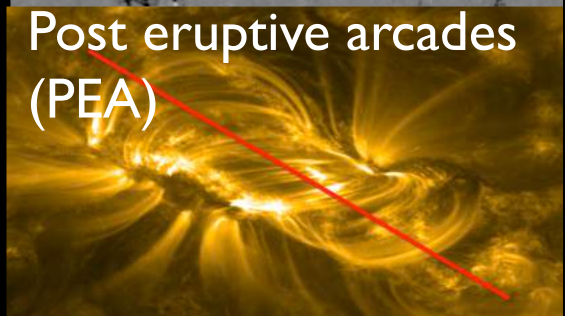




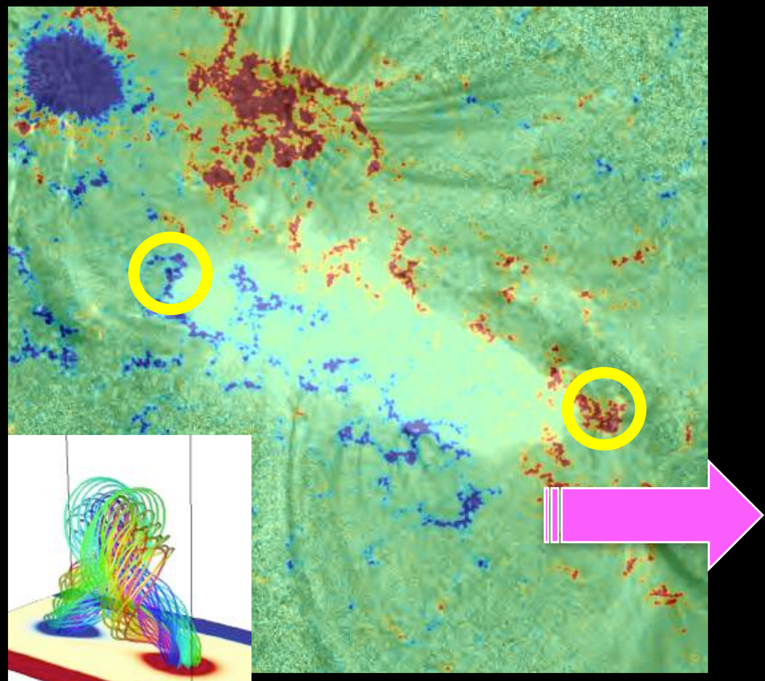


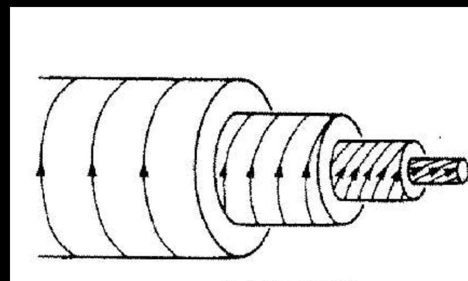
2) Axial tilt

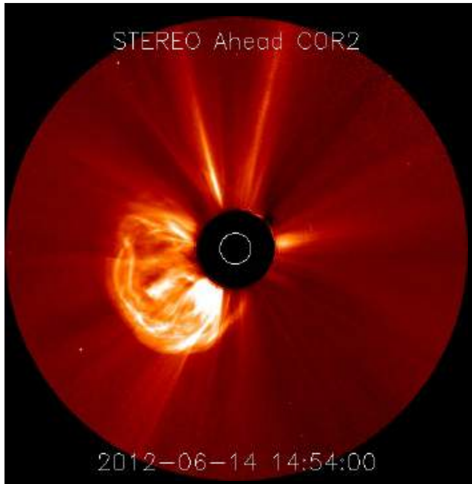




3) Axial field direction



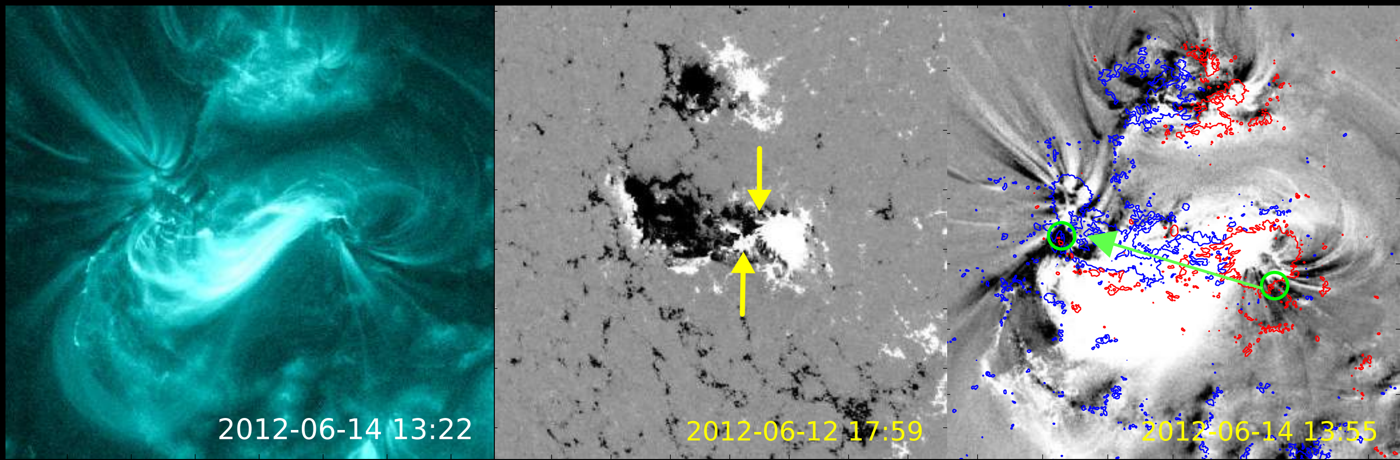




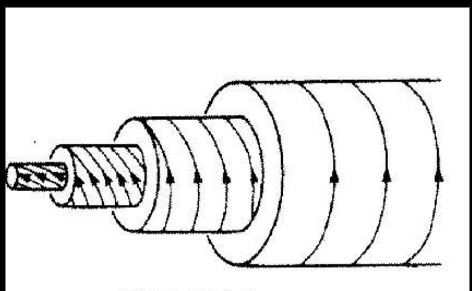
Example: Observations

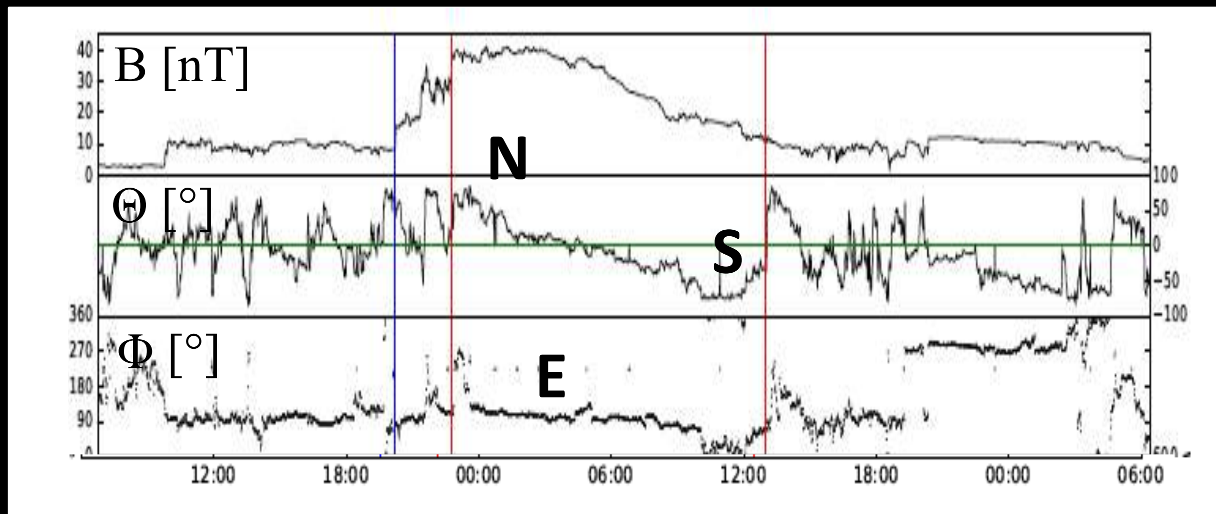
CME on June 14, 2012 (AR 11504)

Palmerio et al., Sol. Phys. 2017

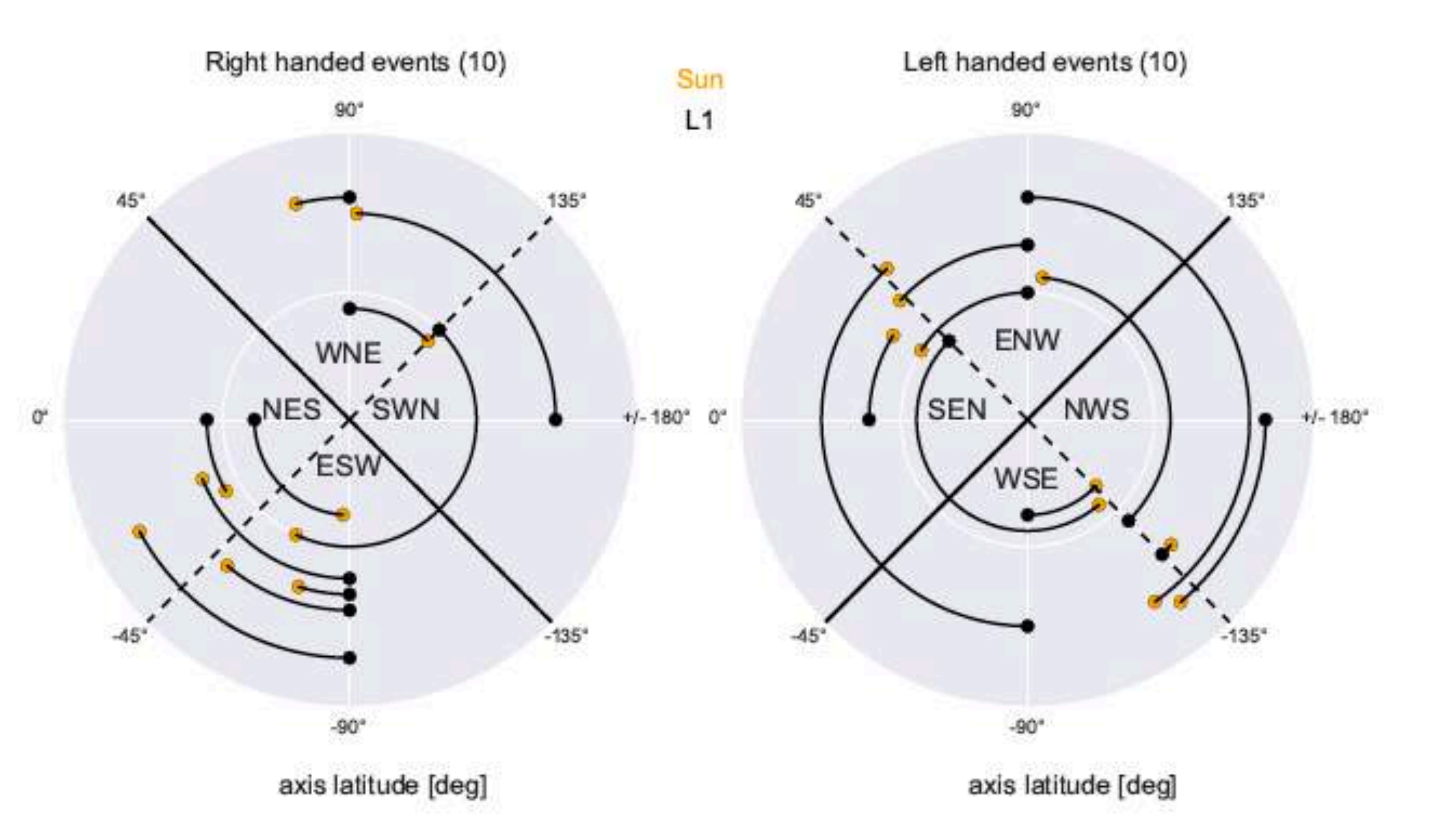


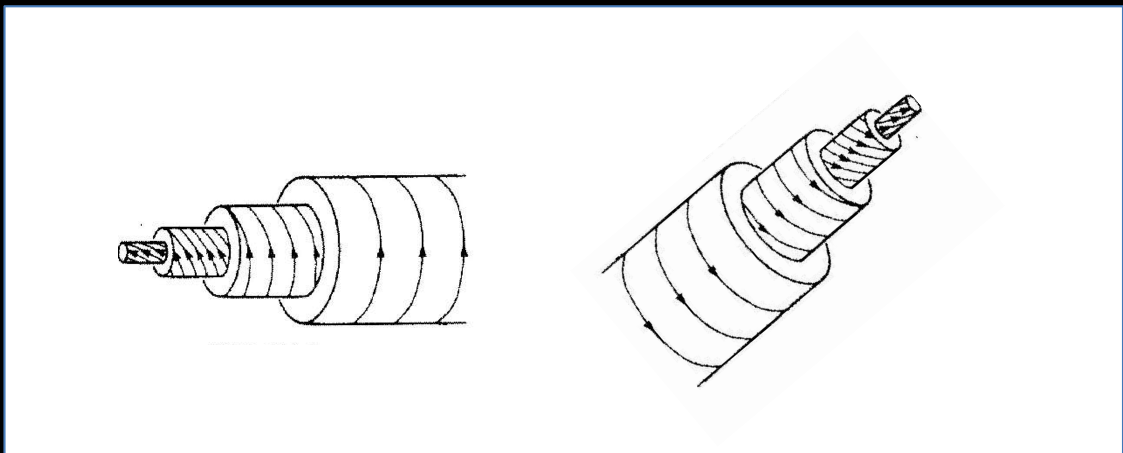
NES





Palmerio et al., submitted to Space Weather





EUHFORIA

EUropean Heliospheric FOrecasting Information Asset

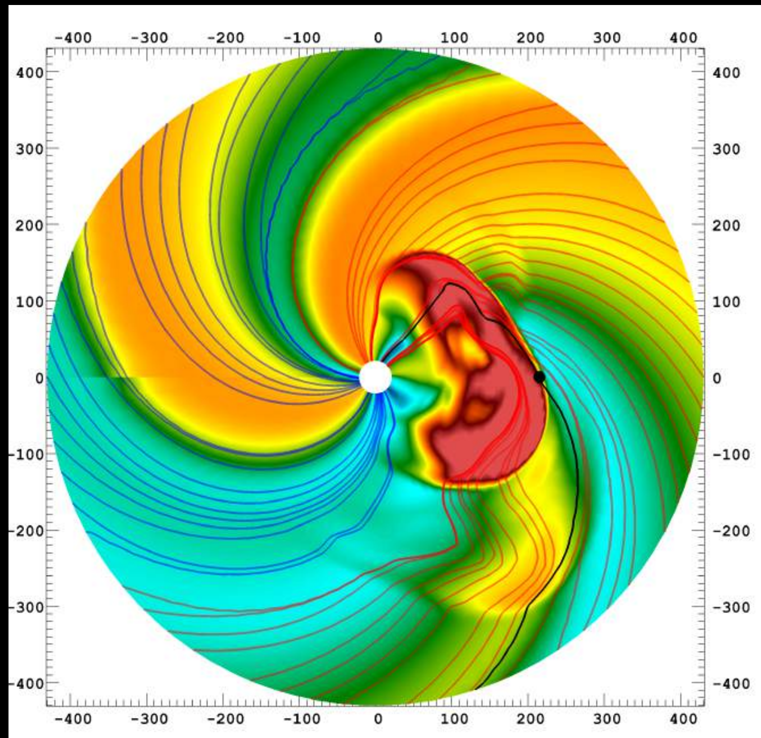
physical model of the inner heliosphere (from 0.1 AU up to ~2 AU)

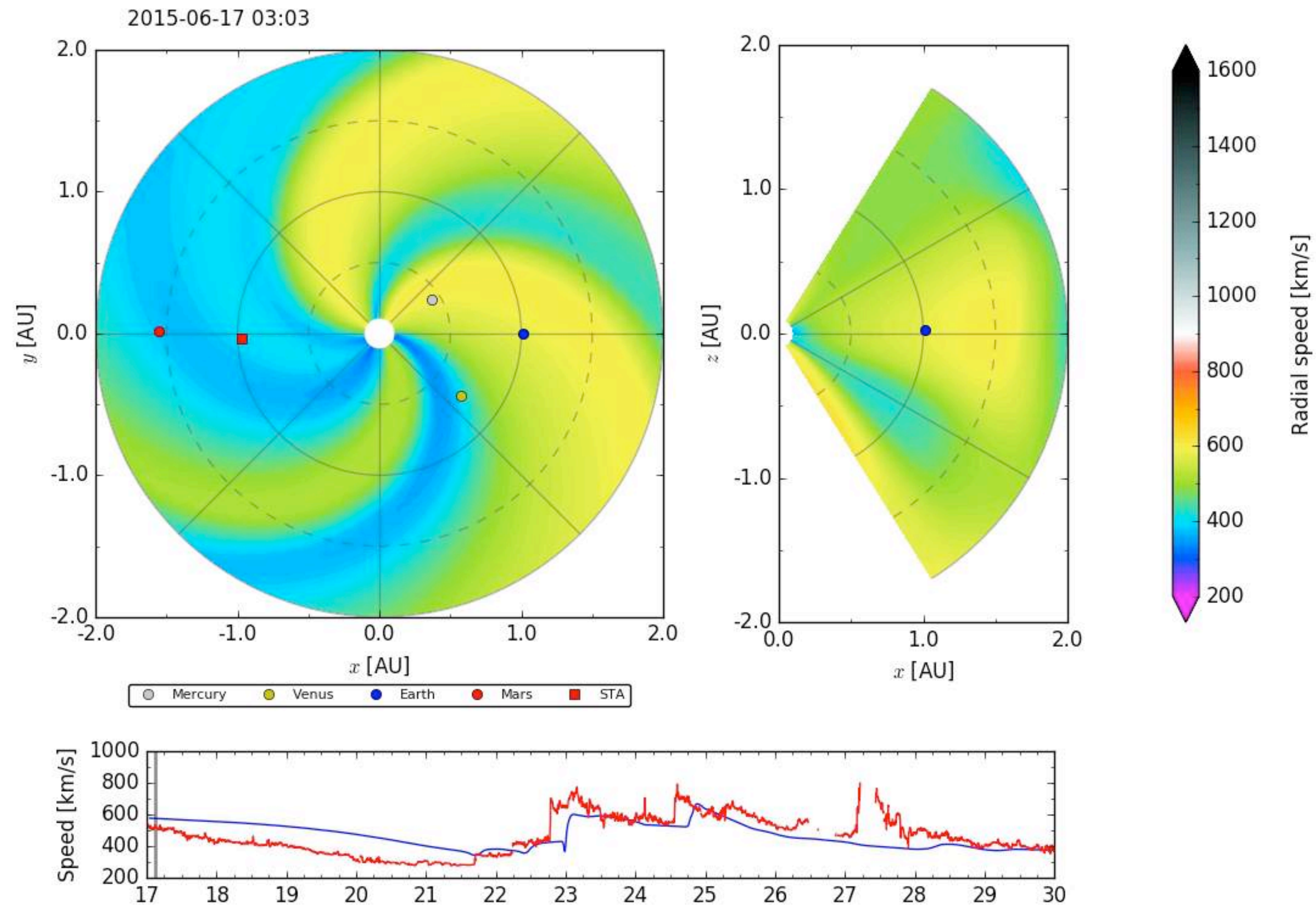
Key Science

- Quantify the deformation, deflection and erosion of flux ropes evolving in the inner heliosphere
- CME-CME interactions

Applications

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





2015-06-17 03:03
2.0
1.0
0.0
-1.0
-2.0
y [AU]
-2.0
-1.0
0.0
1.0
2.0
x [AU]
z [AU]
x [AU]
Mercury
Venus
Earth
Mars
STA
1600
1400
1200
1000
800
600
400
200
Radial speed [km/s]
Speed [km/s]
1000
800
600
400
200
17
18
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30

CCSOM

Constraining CMEs and Shocks by Observations and Modelling throughout the inner heliosphere

- Develops and tests EUHFORIA towards operational space weather forecasting tool
- Brains-be project: ROB (PI: Jasmina Magdalenic), KUL (co-PI: Stefaan Poedts), UH and Graz
- Simulates the propagation of flux rope CMEs in realistic background solar wind
- Compares the results of the obtained model with observations of a number of events of different types.

EUHFORIA models

Corona

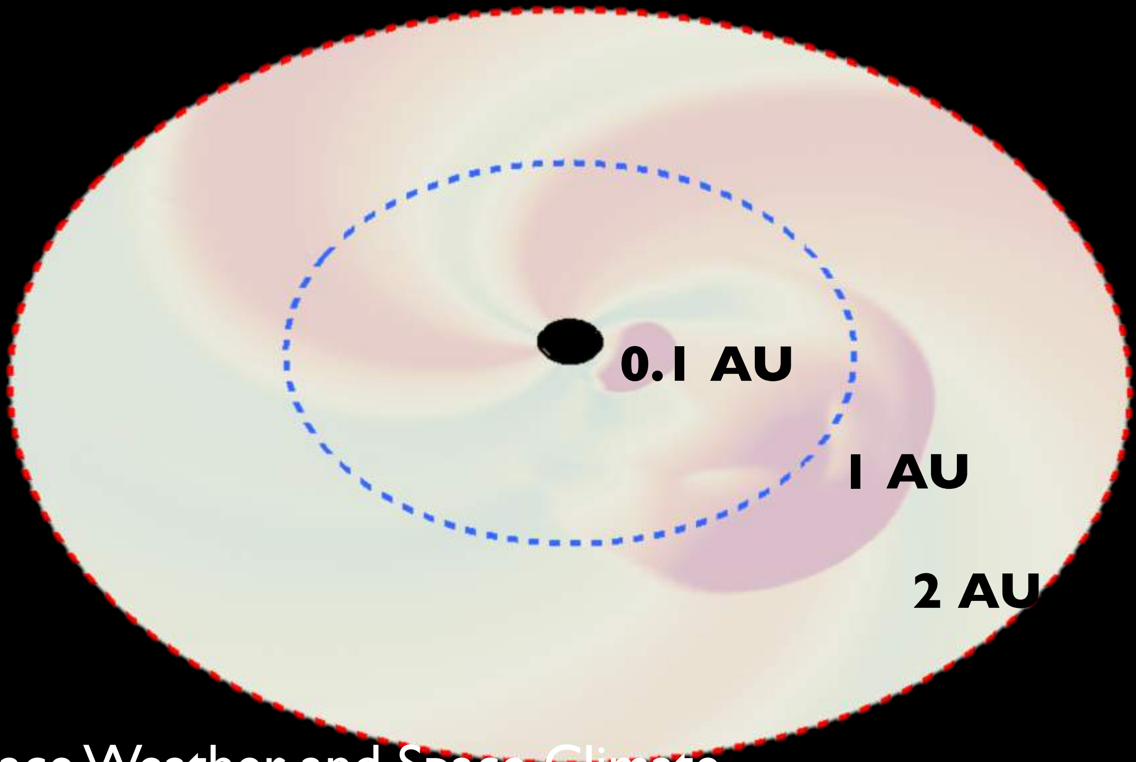
- 1 Rsun → 0.1 AU
- Semi-empirical (WSA)
- Provides solar wind boundary conditions for inner heliosphere

Inner Heliosphere

- 0.1 AU → 2 AU
- Solar wind
- Time-dependent MHD
- Evolves n, **B**, **v**, T in 3D + t

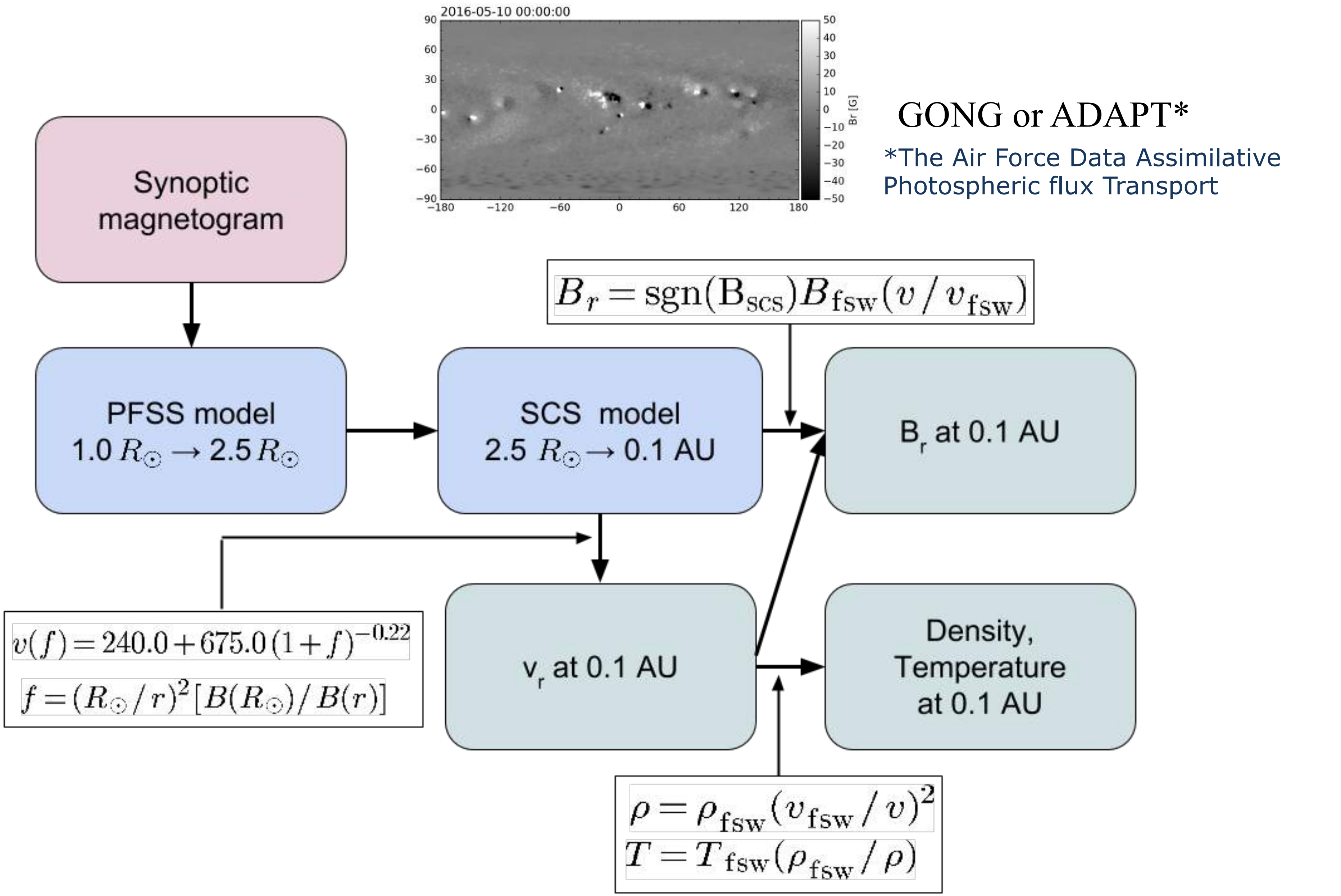
CME models

- Inserted as time-dependent boundary conditions at 0.1 AU
- Different models implemented and tested



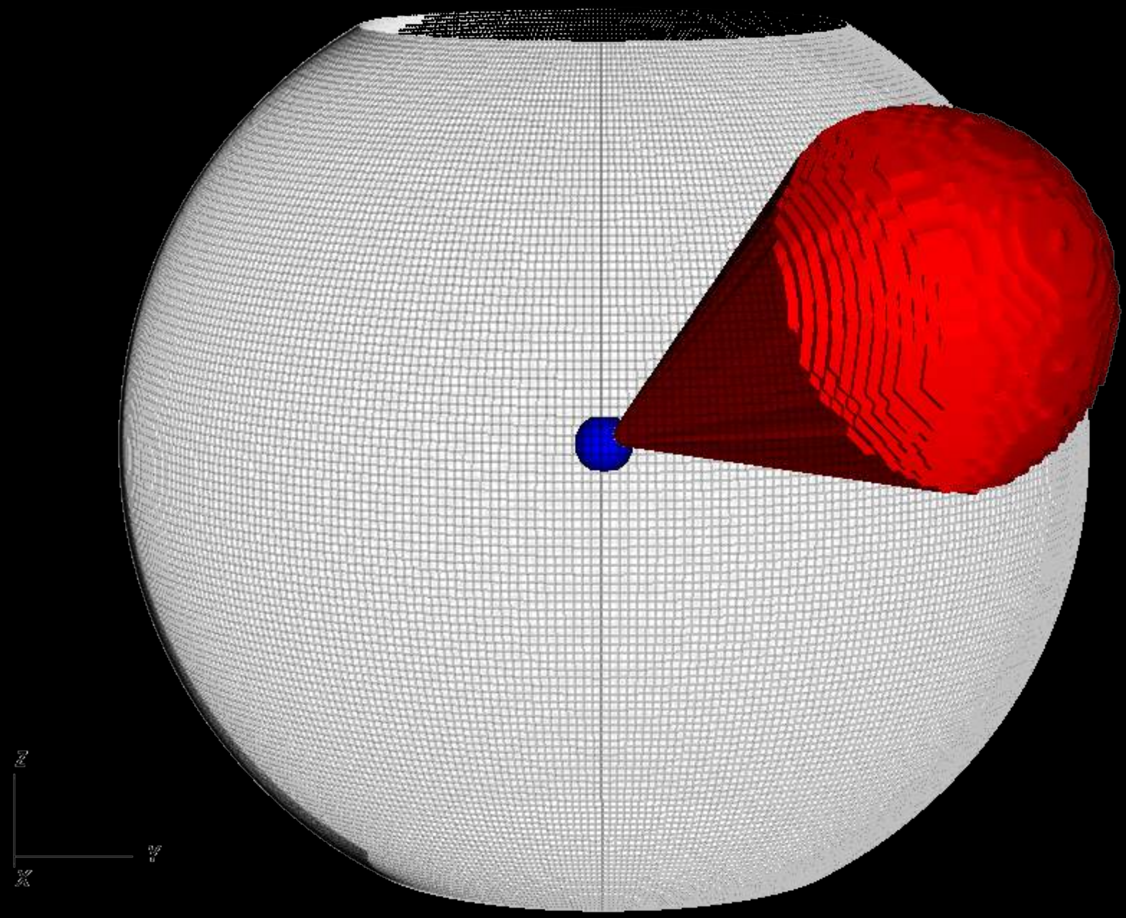
Pomoell and Poedts, in revision, J. Space Weather and Space Climate

Semi-empirical coronal model



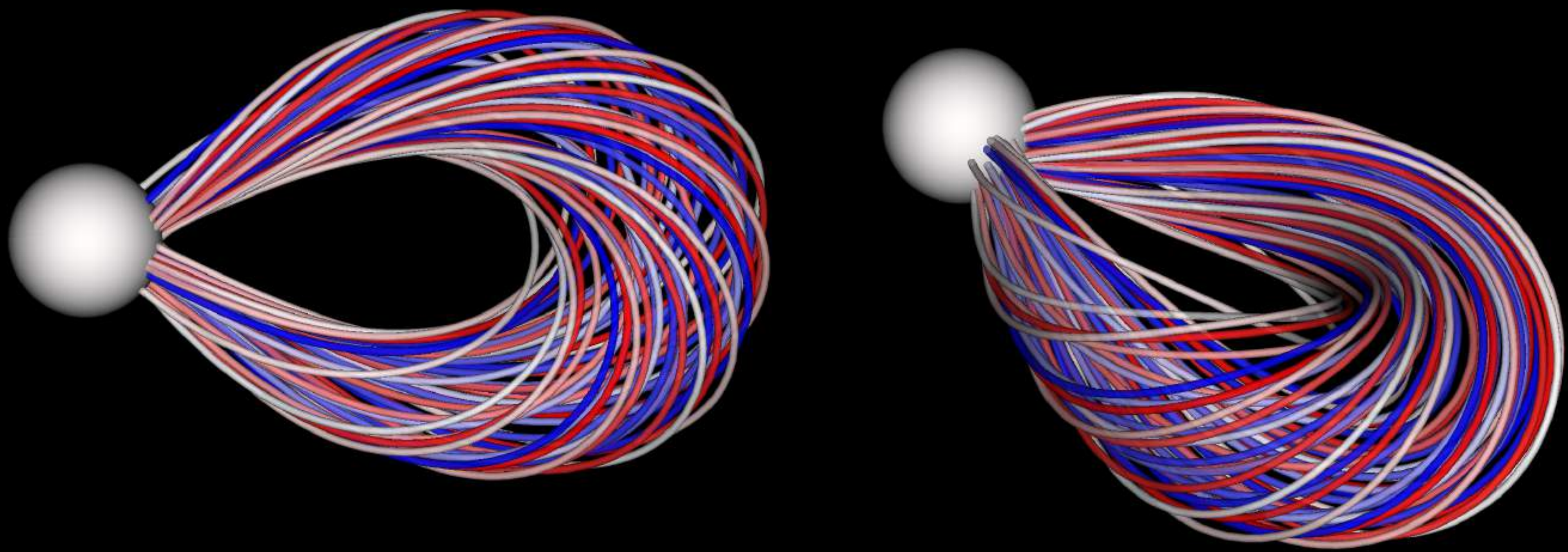
CME models

Hydrodynamic cone model (e.g., Xie et al., JGR, 2009)



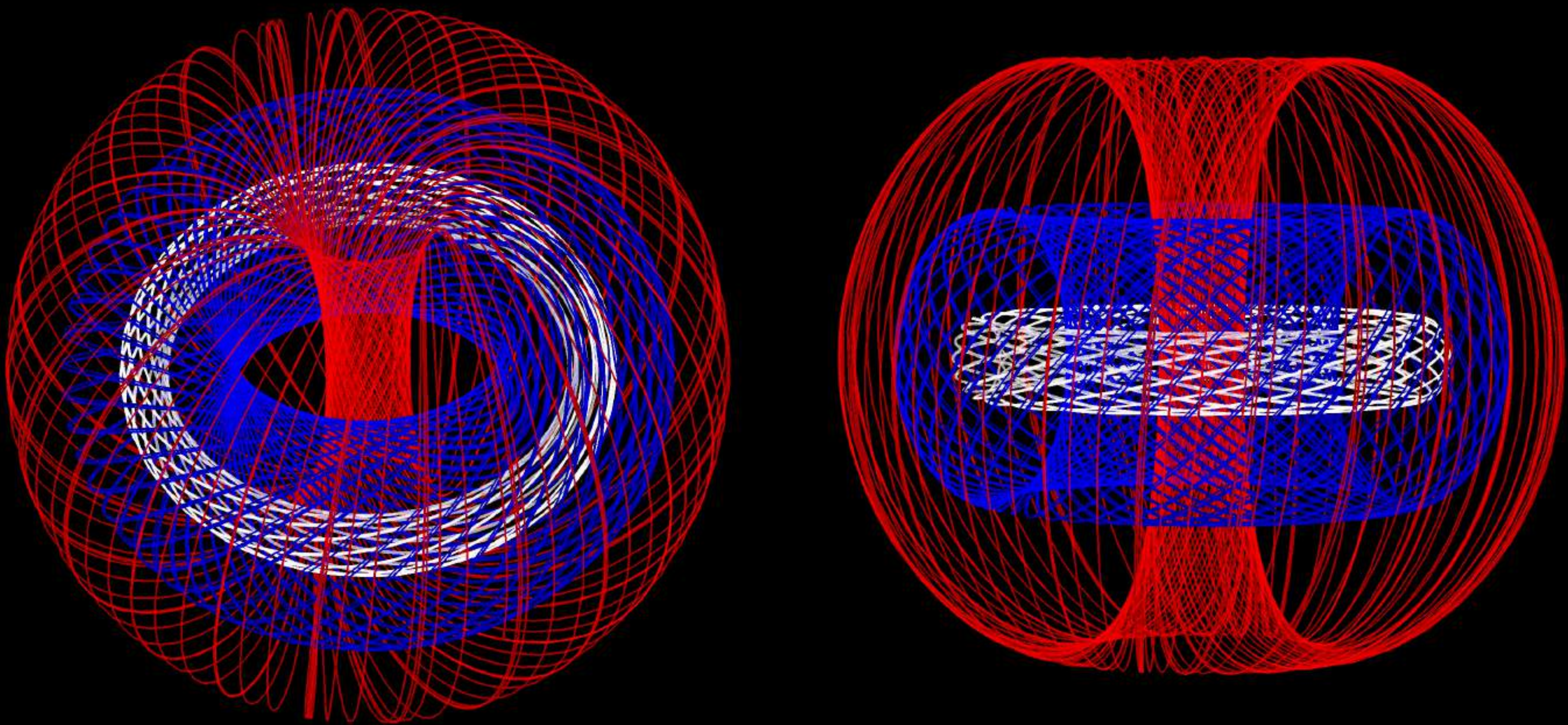
CME models

Gibson & Low flux rope (Gibson and Low, 1998)



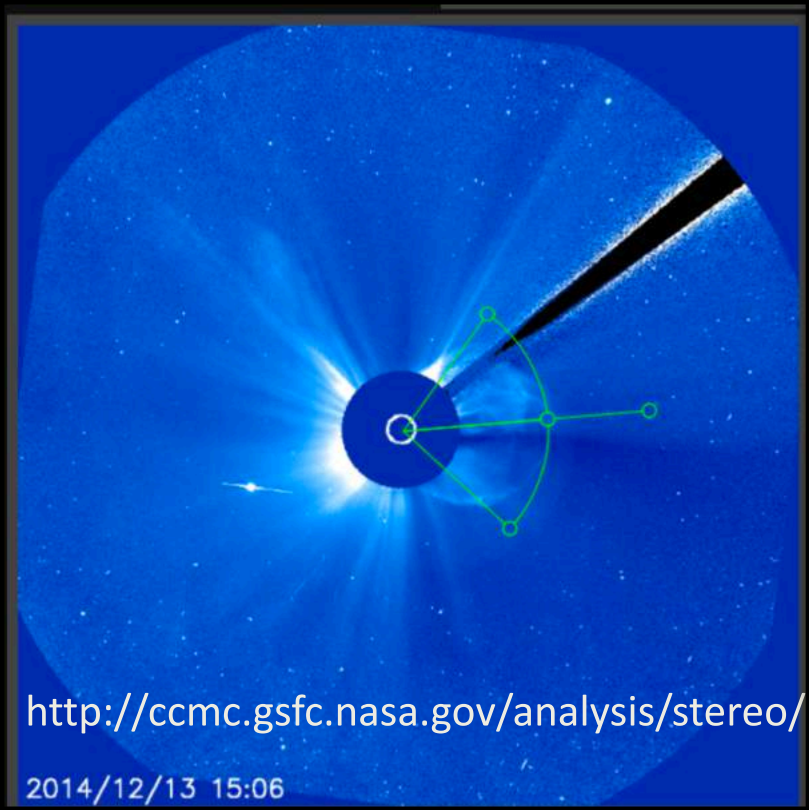
CME models

Spheromak (e.g., Lyutikov and Gourgouliatos, 2011)

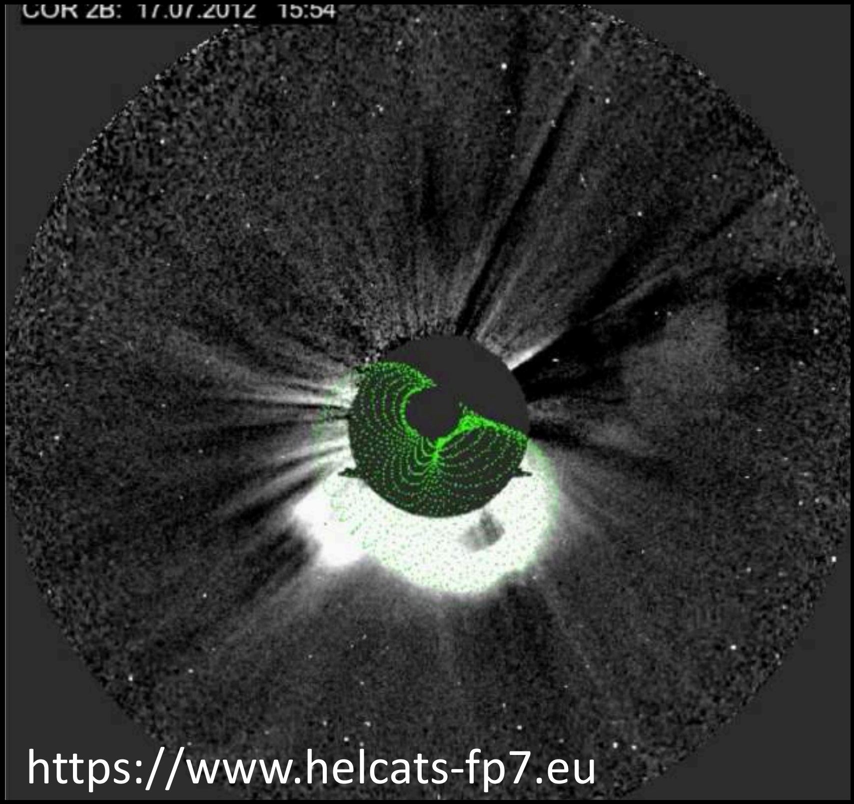


CME model input parameters

- Speed, direction, width, tilt (fits to coronagraph data, e.g., via StereoCAT or using forward modeling,e.g., HELCATS catalogs), magnetic flux and helicity (modelling or observations) mass density and temperature
- parameters needed depend on the CME model



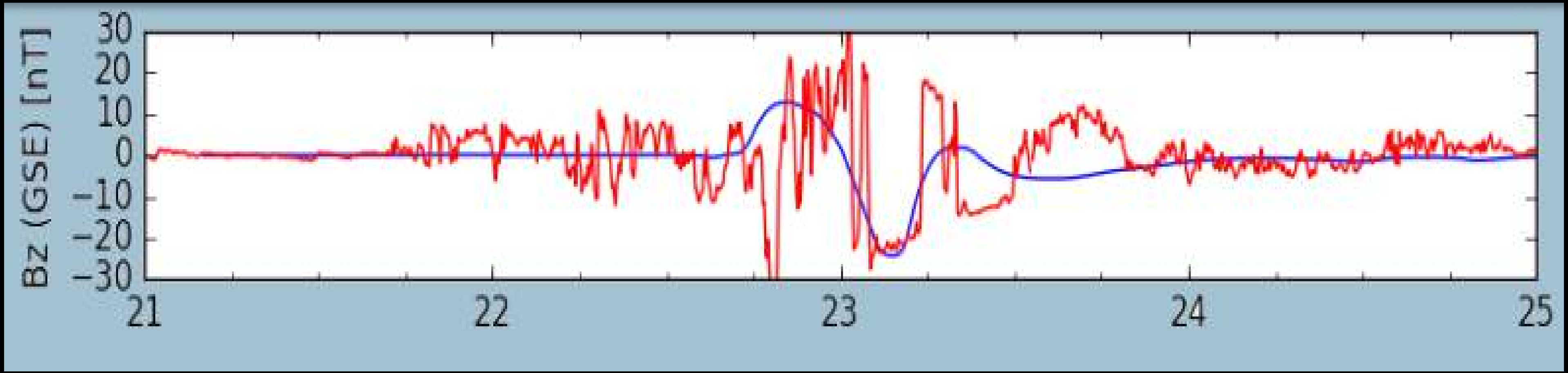
http://ccmc.gsfc.nasa.gov/analysis/stereo/

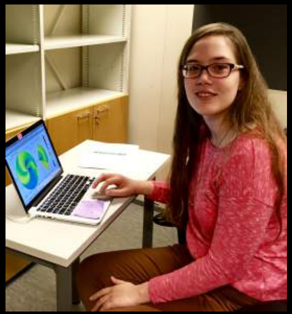


https://www.helcats-fp7.eu

Testing of EUHFORIA with FR models

GL FR model vs ACE





Eleanna Asvestari, UH

FR CME (PhD theses Christine and Camilla, KU Leuven)

Summary

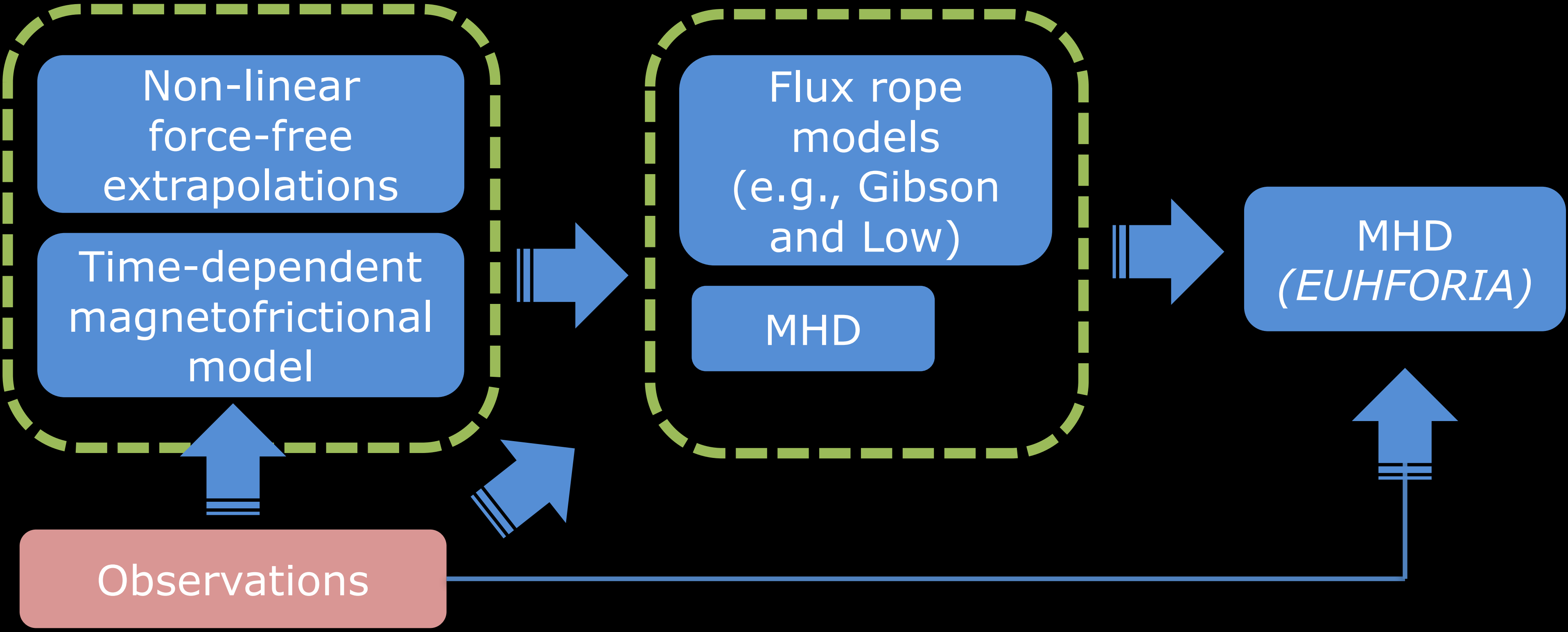
- Predicting CME magnetic structure well in advance is crucial for reliable space weather predictions
- CMEs have two distinct sub-structures: sheath and flux rope, both can drive intense geomagnetic storms
- Steps: Intrinsic flux rope type and background, evolution and propagation, solar wind – magnetosphere coupling
- Capturing the sheath effects is extremely challenging due to its turbulent nature

Summary

Inner Coronal model
R = 1 → a few Rs

Intermediate model
R = a few Rs → 0.1 AU

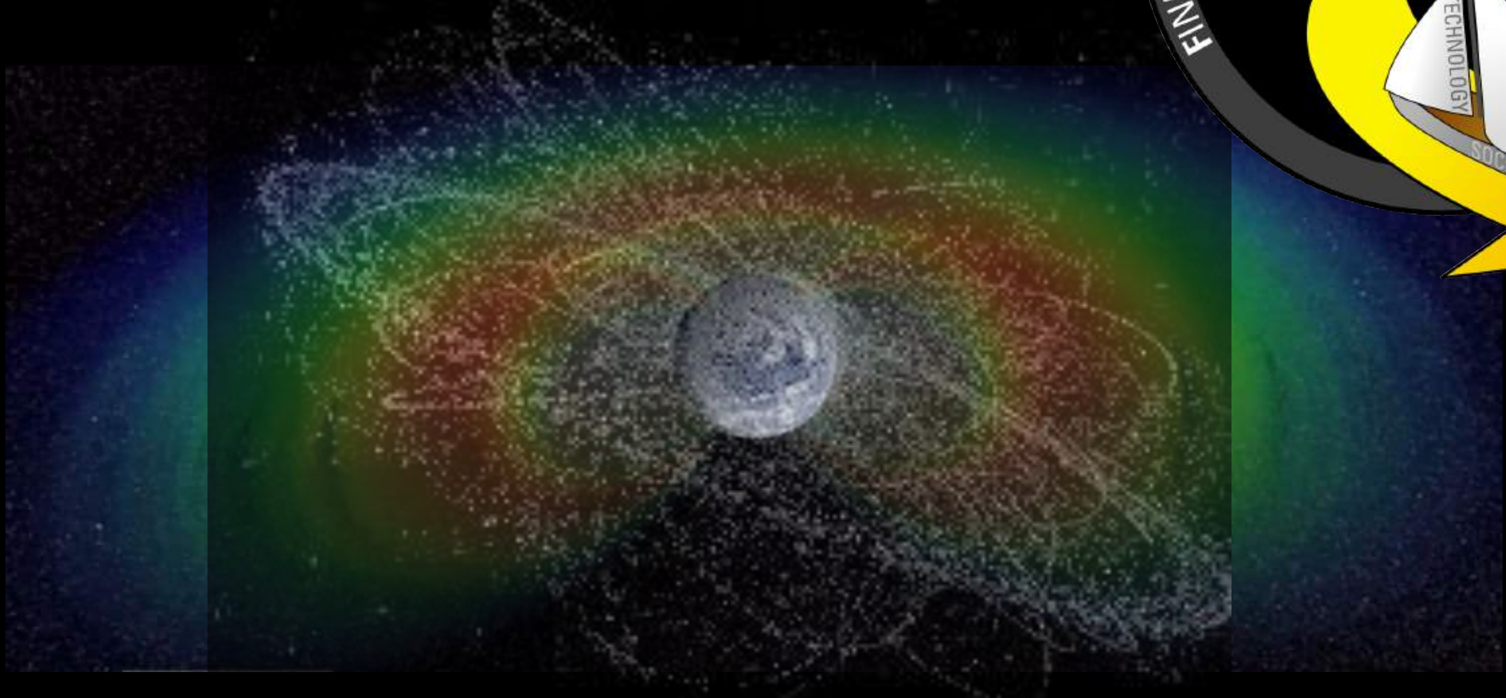
Heliosphere model
R > 0.1 AU



Intrinsic flux rope

← evolution →

Minna Palmroth (UH, PI): Modelling
Rami Vainio (UTU): Instruments
Pekka Janhunen (FMI): Propulsion
Emilia Kilpua (UH): Observations
Jaan Praks (Aalto): Platforms




THANK
YOU!

ELECTRICT

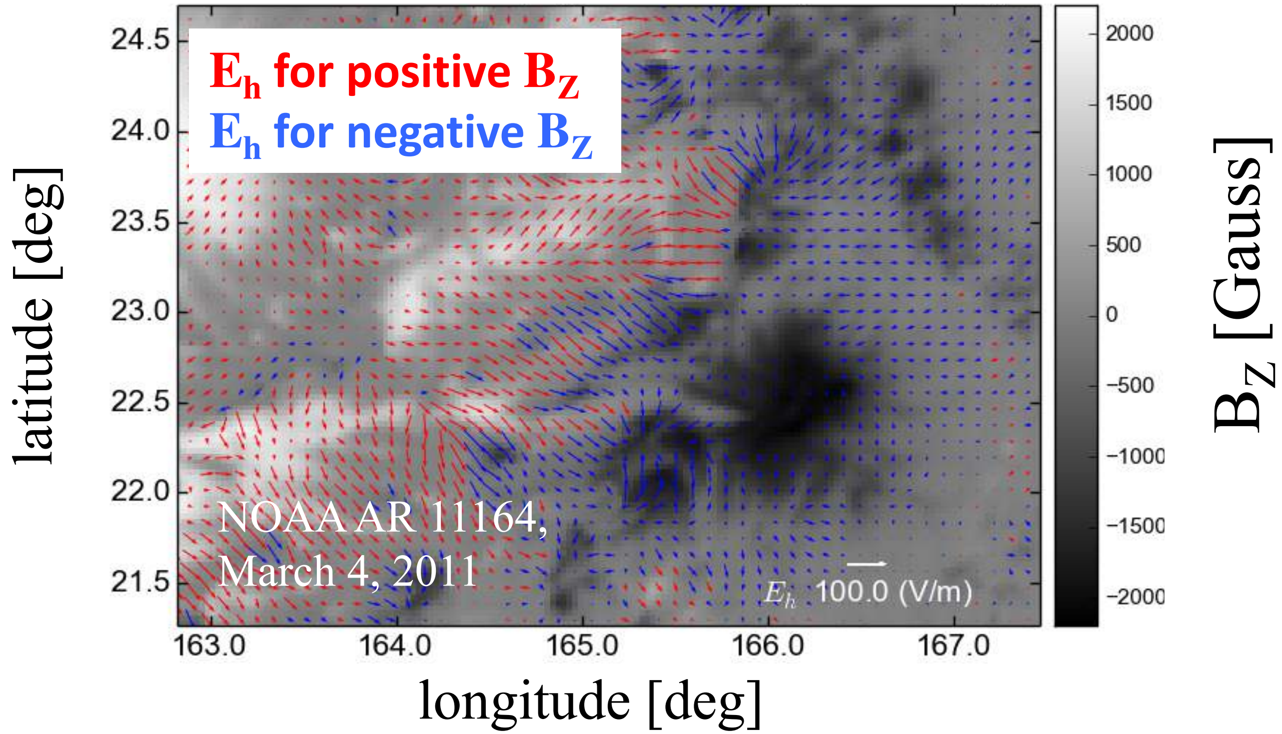
$$\mathbf{E} = \mathbf{E}_I - \nabla\psi$$

$$\nabla \times \mathbf{E}_I = -\frac{\partial \mathbf{B}}{\partial t}$$

non-inductive

1. $\nabla \cdot \mathbf{E} = 0$
2. $\nabla \cdot \mathbf{E} = \Omega B_z$
3. $\nabla \cdot \mathbf{E} = U j_z$

Horizontal electric field and vertical magnetic field



Snapshot for NOAA AR 11504

$$
\begin{aligned}
\mathbf{B}(\mathbf{r},t) &= \nabla \times \mathbf{A}(\mathbf{r},t) \\
\Rightarrow \mathbf{j}(\mathbf{r},t) &= \nabla \times \mathbf{B} \\
\Rightarrow \mathbf{V}(\mathbf{r},t) &= \frac{1}{\nu}\mathbf{j} \times \mathbf{B} \\
\Rightarrow \frac{\partial \mathbf{A}}{\partial t}(\mathbf{r},t) &= \mathbf{V} \times \mathbf{B} - \eta \mathbf{j} \\
\Rightarrow \mathbf{A}(\mathbf{r},t+\Delta t) &= \mathbf{A}(\mathbf{r},t) + \frac{\partial \mathbf{A}}{\partial t}(\mathbf{r},t)\Delta t
\end{aligned}
$$