Observation-based Sun-to-Earth simulations of geo-effective CMEs with EUHFORIA

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and

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Motivation & outline

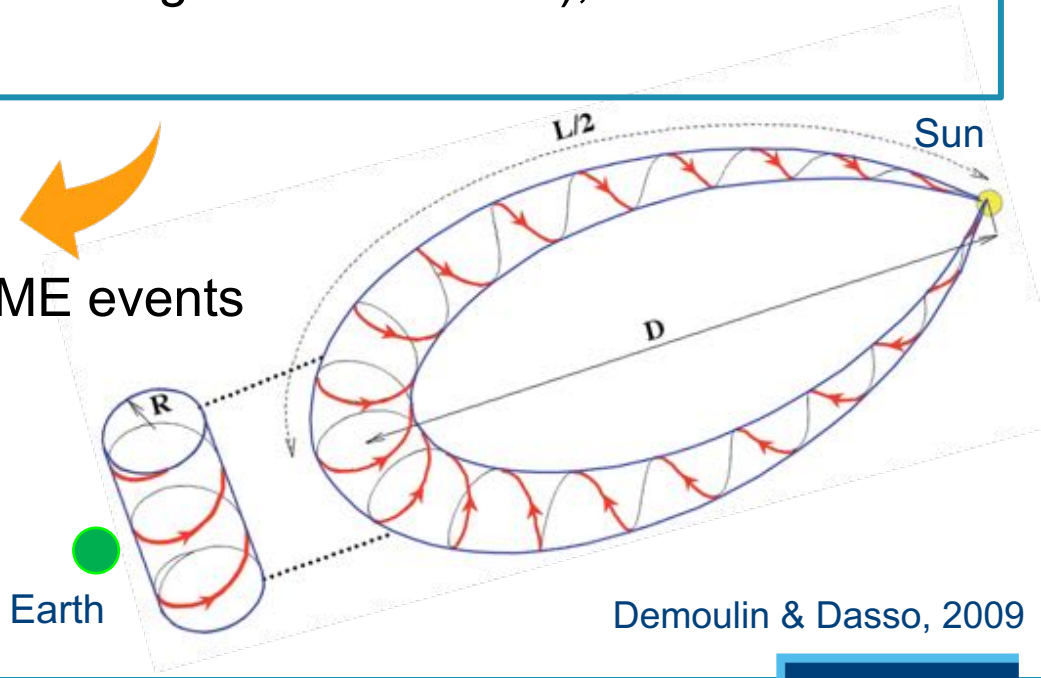
1) EUHFORIA: newly developed solar wind and CME propagation model designed for space weather purposes (Pomoell & Poedts 2018)

- **Flux-rope CME models** (spheromak and Gibson-Low) recently implemented (Verbeke et al 2018, in prep)

→ Goal of **this study:** assessing the predictive capability of the new flux-rope models at Earth (ICME and ICME geoeffectiveness), based on CME observations at the Sun

2) ISEST WG4 campaign events:
textbook (T) and problematic (P) CME events

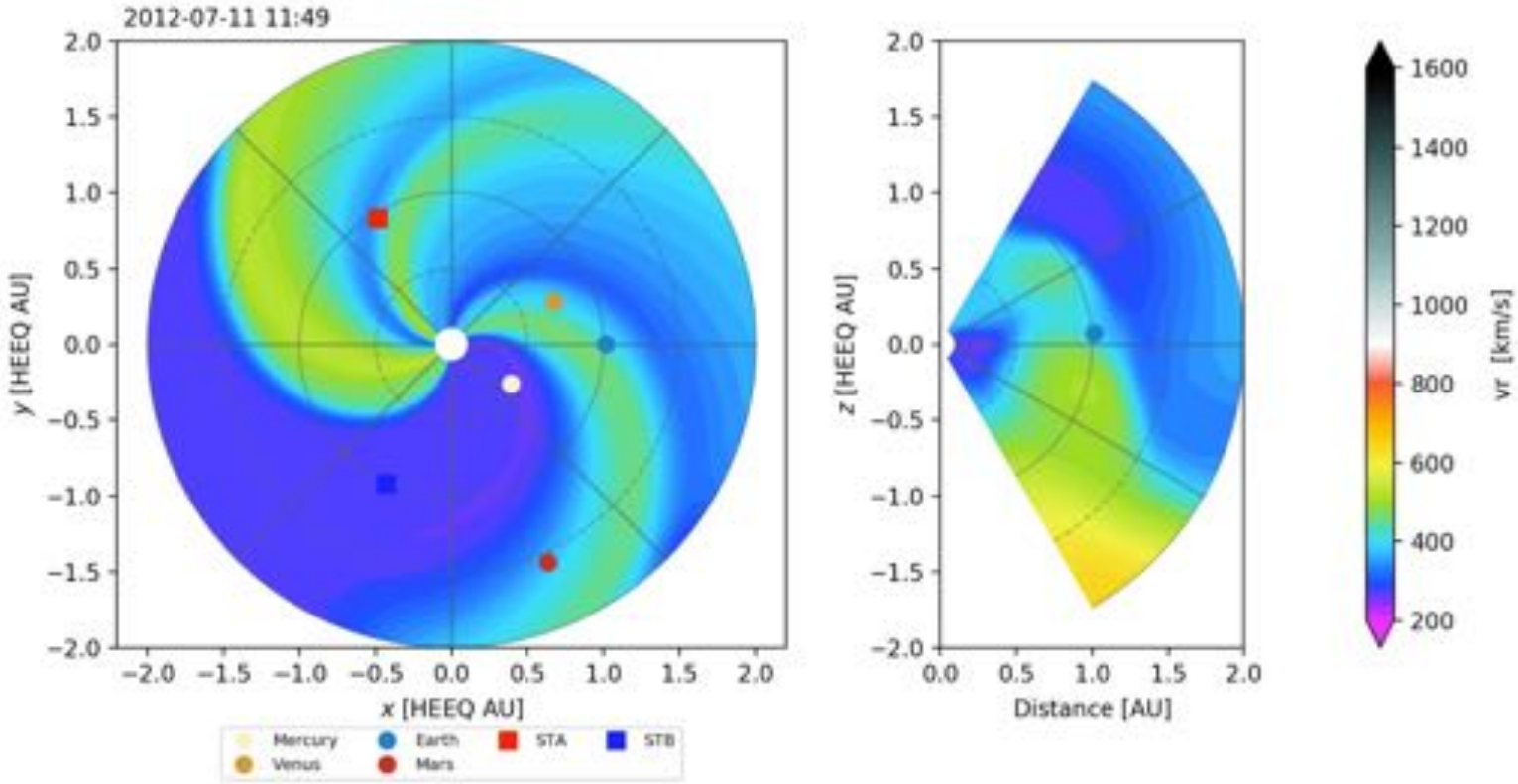
- July 12, 2012 (T)
- March 15, 2013 (T?)
- September 9-10, 2014 (P)



Demoulin & Dasso, 2009

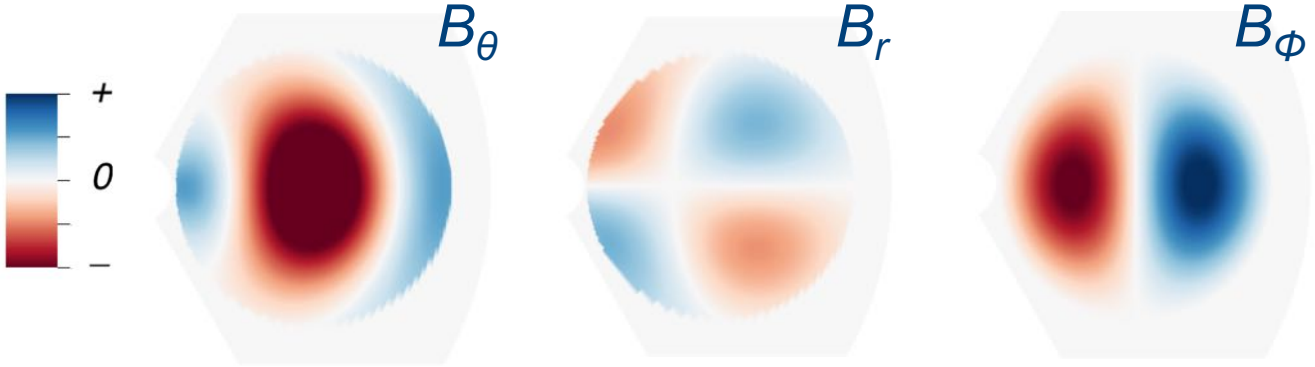
EUHFORIA

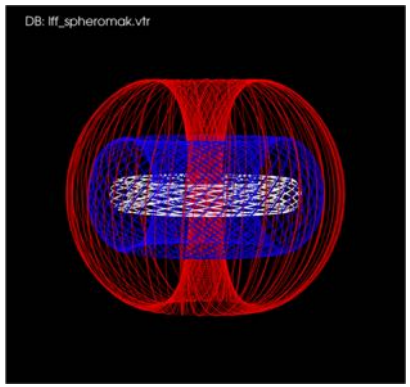
- 3D coronal and heliospheric model
  - Corona (up to 0.1 AU): magnetogram + semi-empirical WSA model
  - Heliosphere (0.1 AU to 2.0 AU): time-dependent 3D MHD model
  - CME models: cone CMEs or **flux-rope CMEs**



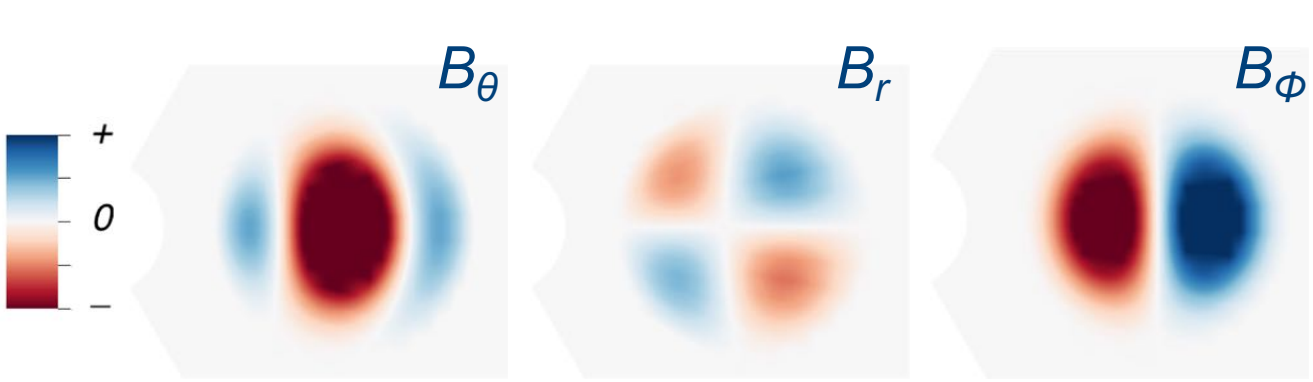
Flux rope CMEs in EUHFORIA

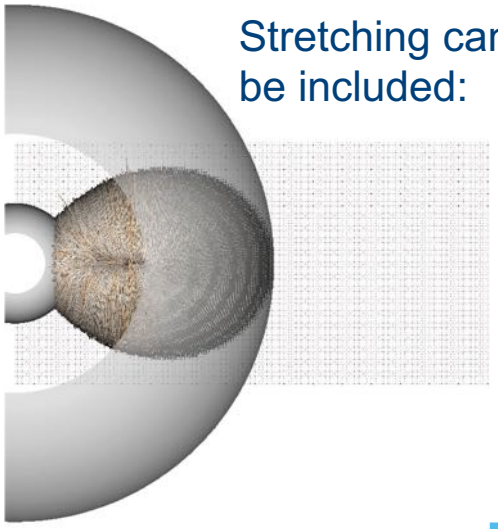
Linear Force Free Spheromak





Gibson & Low flux rope (under testing)





Stretching can be included:

CME parameters at 0.1 AU

Kinematic/geometric parameters

- CME speed
- CME insertion time
- CME longitude
- CME latitude
- CME half width
- CME density (default)
- CME temperature (default)

Cone CMEs &
Flux-rope CMEs

Magnetic parameters

- FR tilt
- FR helicity sign
- FR toroidal B flux

Flux-rope CMEs

CME parameters at 0.1 AU

Kinematic/geometric parameters

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3D reconstruction (GCS model, Thernisien+2009, 2011)

Magnetic parameters

- FR tilt
- FR helicity sign
- FR toroidal B flux / B strength

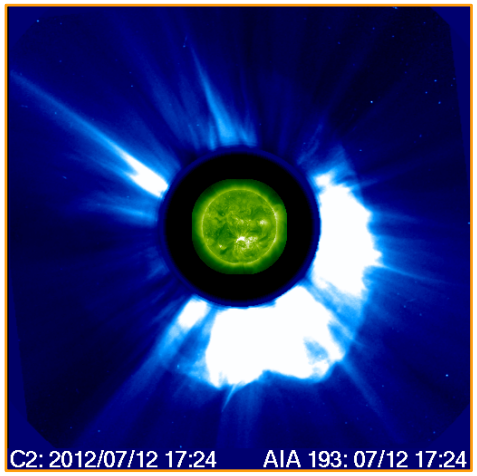
Magnetic+EUV observations of source region (Palmerio+2017)

FRED method (Gopalswamy+2017)

Event 1: 12 July 2012 CME

Remote observations

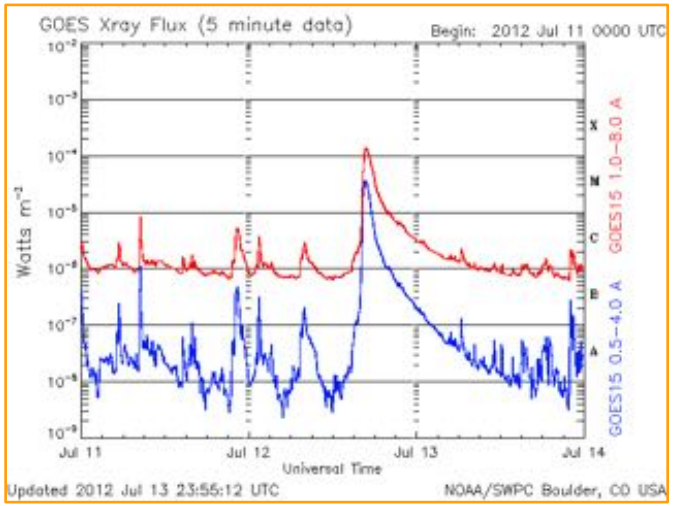
- Single CME event
- Fast Earth-directed halo CME
- Eruption from AR11520, X1.4 flare



https://cdaw.gsfc.nasa.gov

In-situ (@ L1)

- ICME: Shock+sheath+MC
- Prolonged southward Bz



Geomagnetic storm

- Intense geomagnetic storm
- WG4 event type: textbook (Webb & Nitta 2017)
  - Forecast success: underpredicted
- Dst: -127 nT | Kp: 6/7

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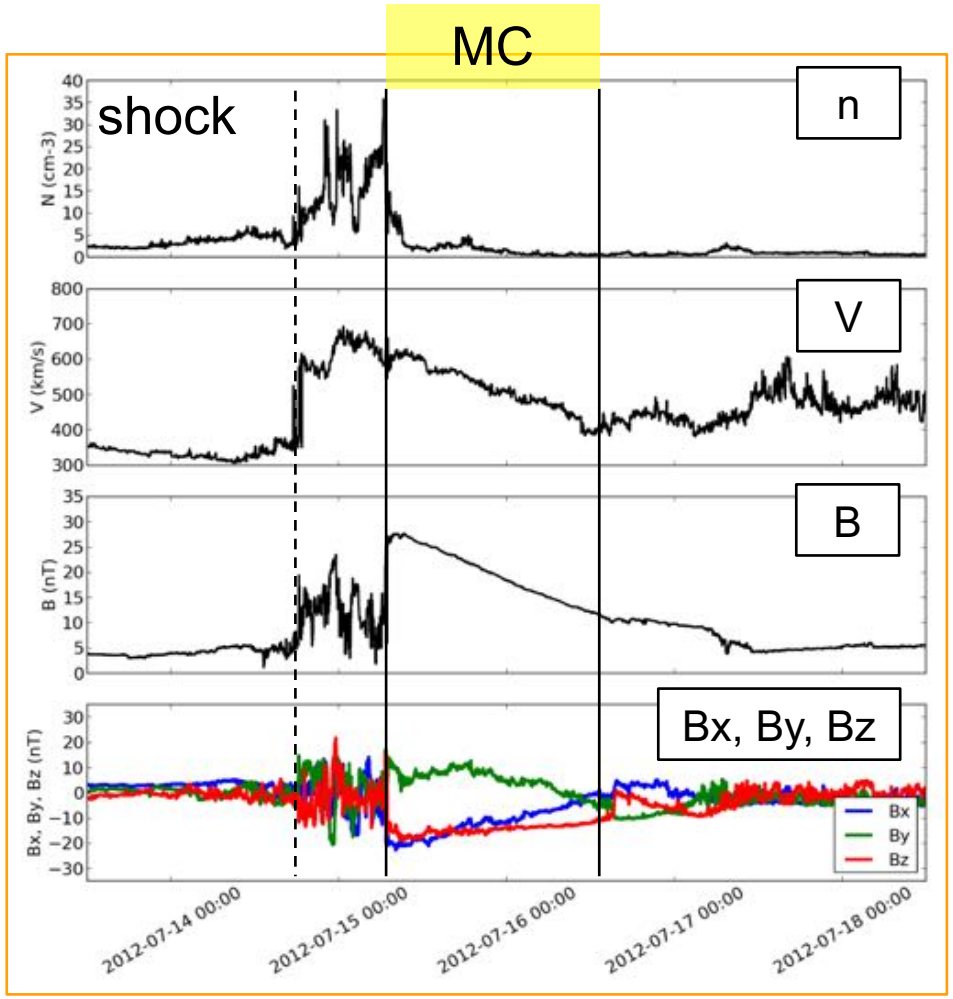

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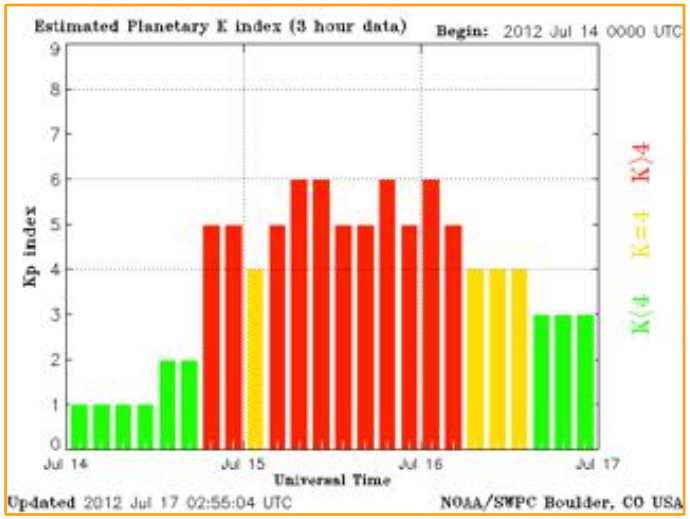

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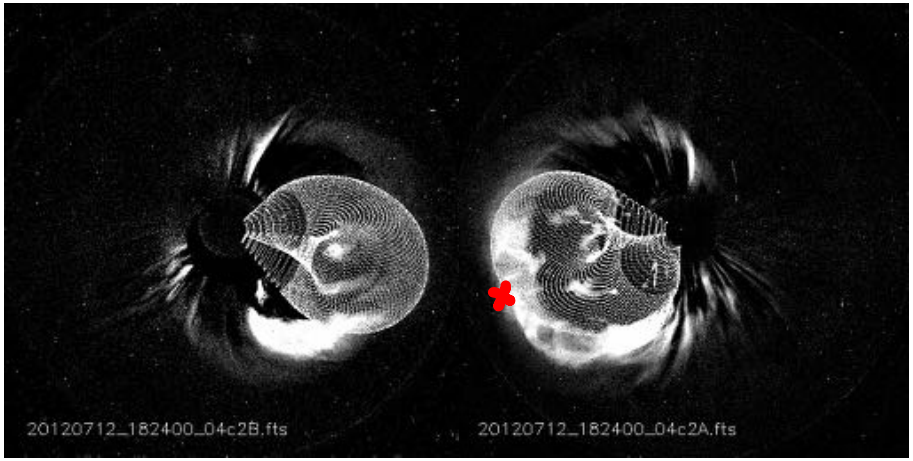

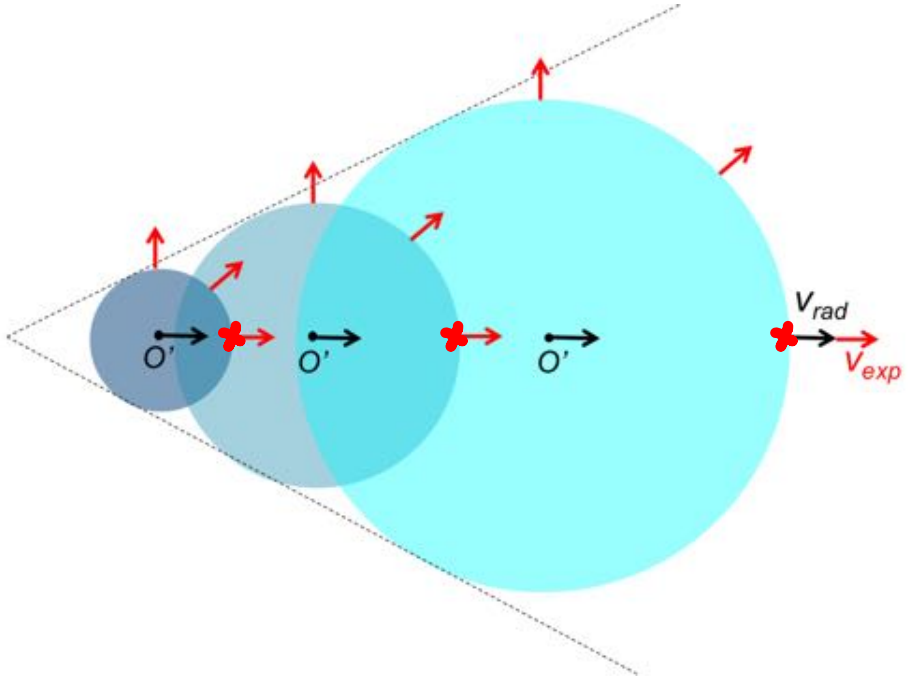

3D speed at the CME nose can be decomposed as: $V_{3D} = V_{exp} + V_{rad}$

- → Radial speed: displacement of CME center of mass
- → Expansion speed: variation of CME/FR radius

  Linked to magnetic pressure in the CME
- → **Different CME initialisation in cone / flux-rope models**

Textbook event; Webb & Nitta, 2017; Hu+2016; Gopalswamy+2017; Marubashi+2017 & many more

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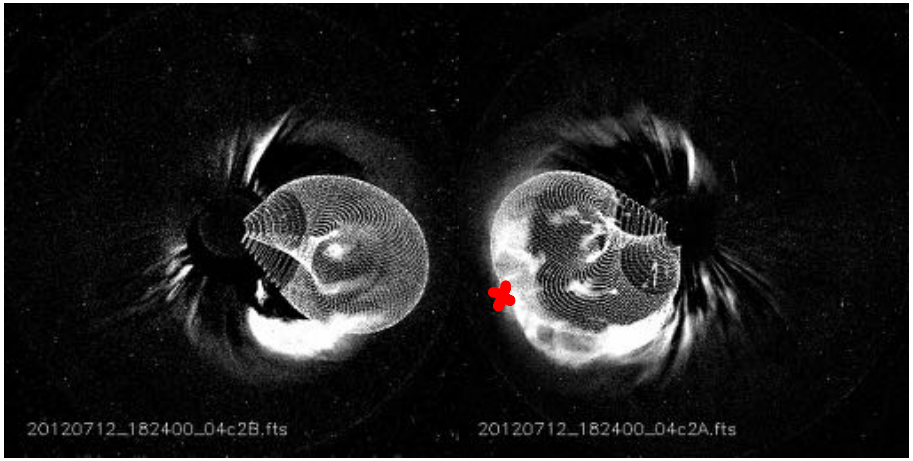
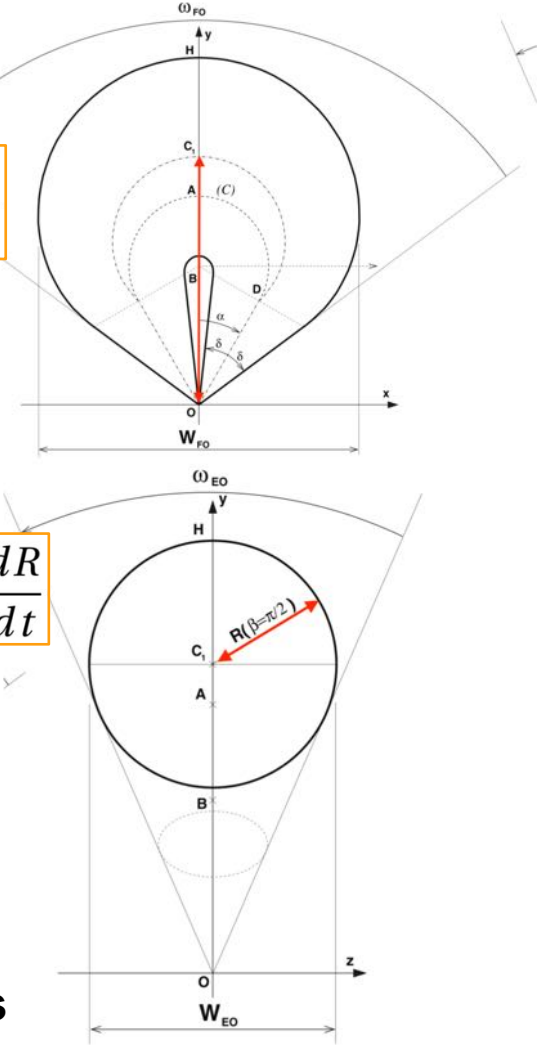


$$v_{rad} = \frac{dOC_1}{dt}$$

$$v_{exp} = \frac{dR}{dt}$$



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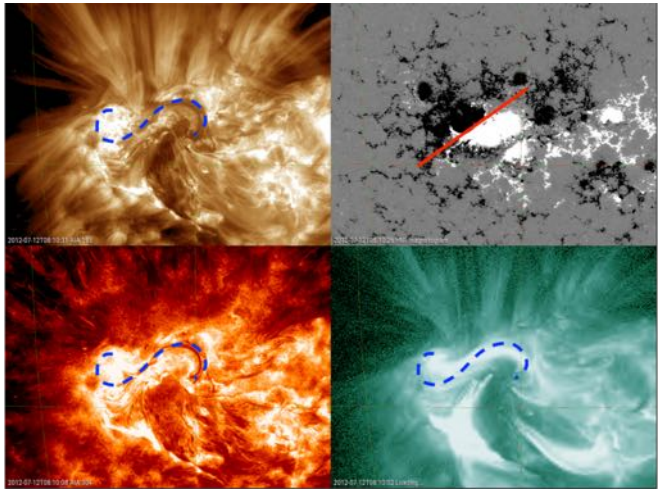
[Thernisien, 2011]

Magnetic parameters

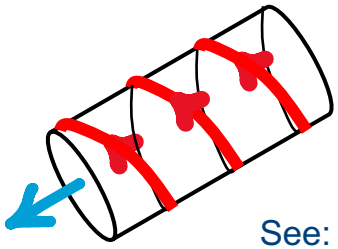
FR tilt and helicity sign

- EUV / X-ray sigmoid



→ Tilt/orientation: -135°

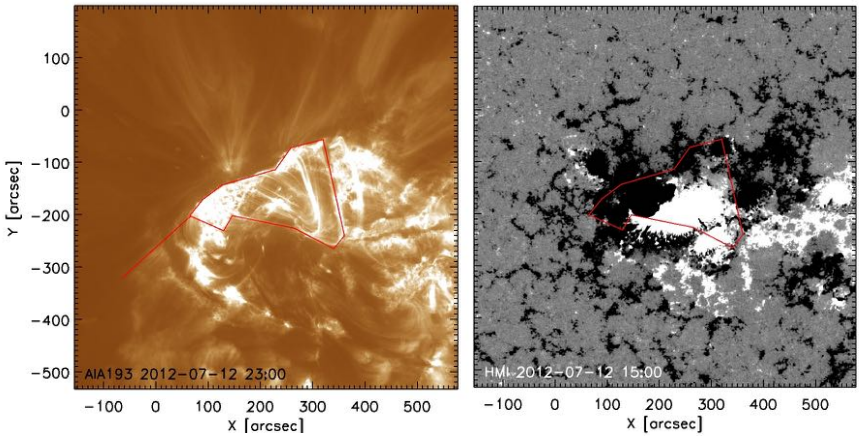
→ Helicity sign: +1 (right-handed)



See: Palmerio+2017, 2018

FR magnetic field strength (FRED method)

- Eruption near the solar disk center (small projection effects)
- Stable, long-lasting PEA

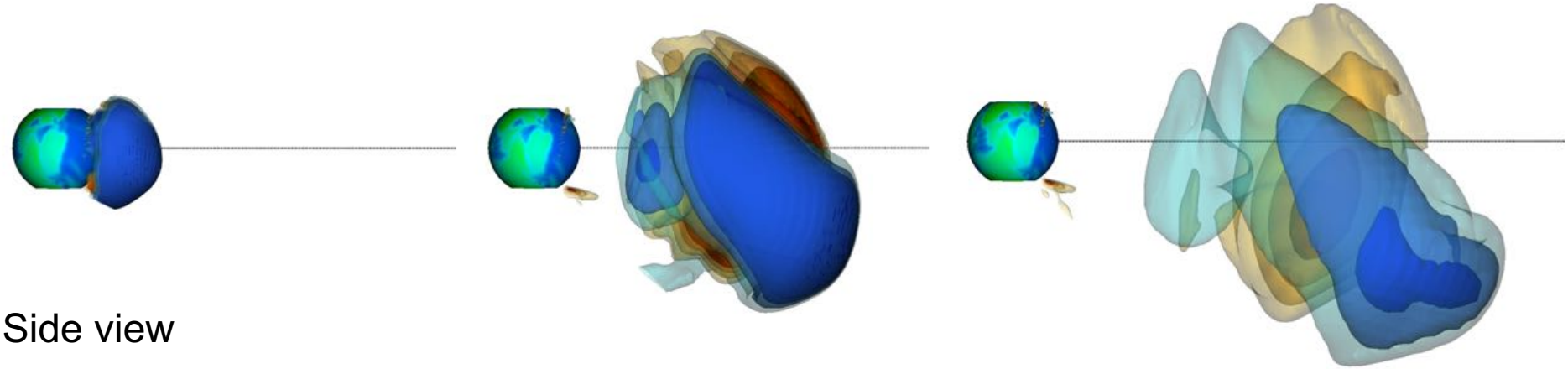


→ Toroidal B flux = 7 x10^{13} Wb @ 14.6 R_s (±45% uncertainty; Pal+2017)

See: Gopalswamy+2017

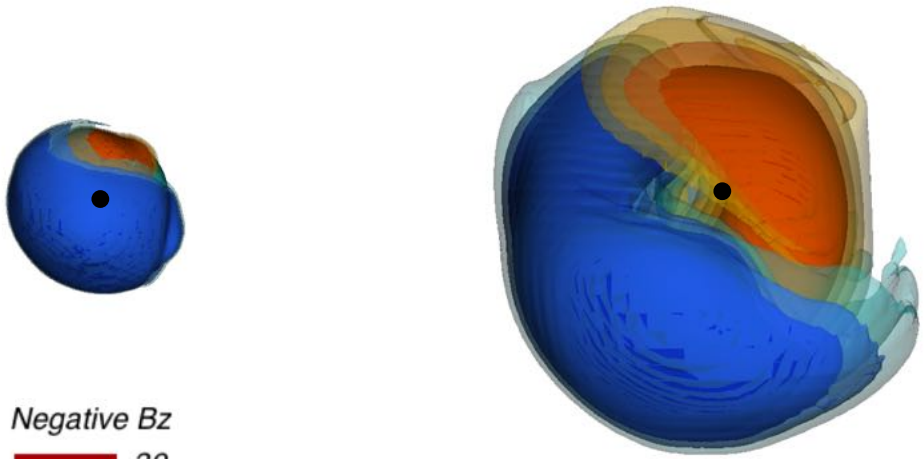
Flux-rope evolution

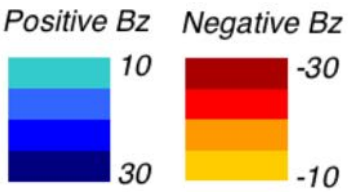
2012-07-13 00:53 2012-07-14 00:53 2012-07-14 18:53



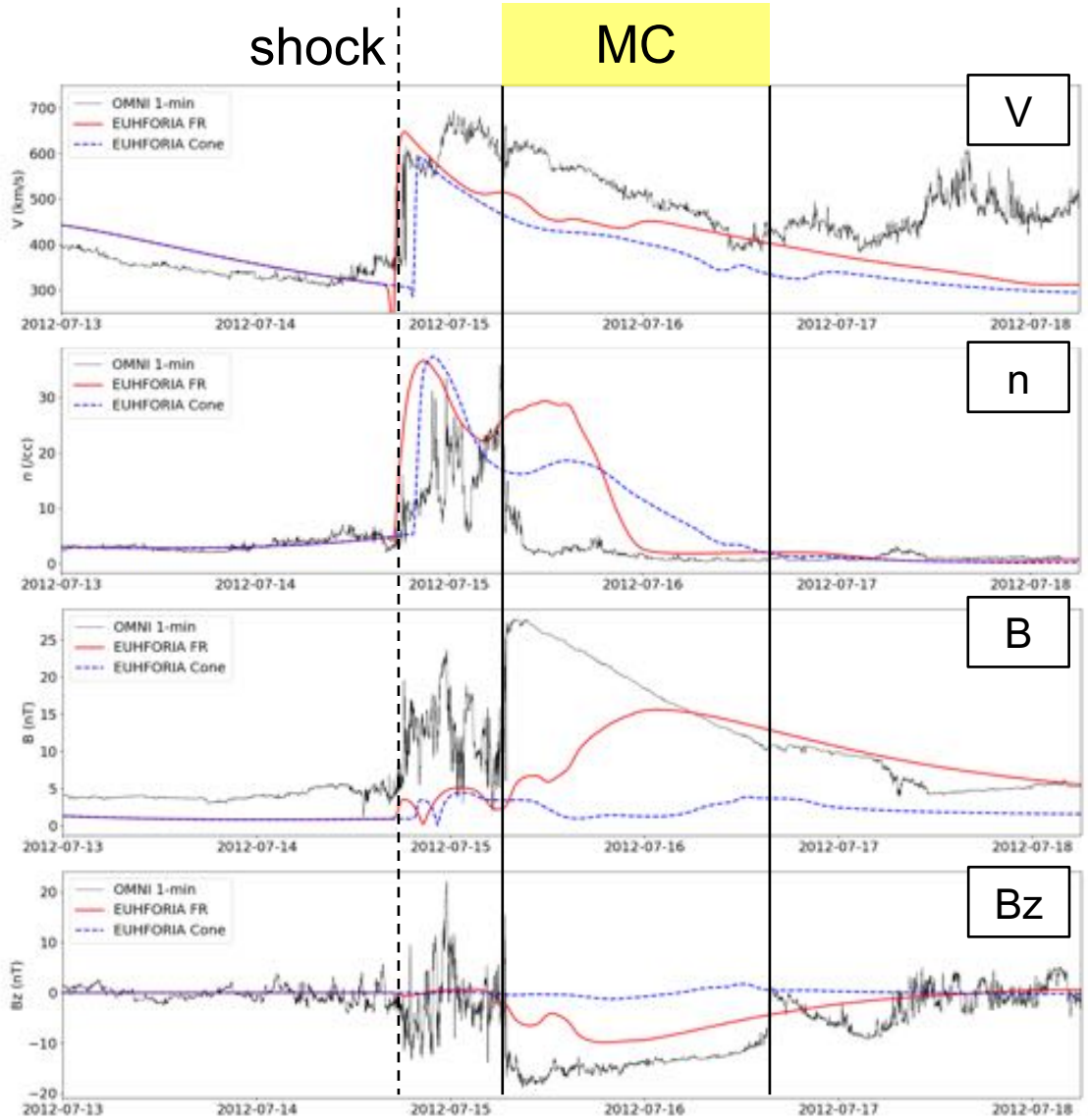
Side view

Front view





EUHFORIA predictions @ Earth (L1)



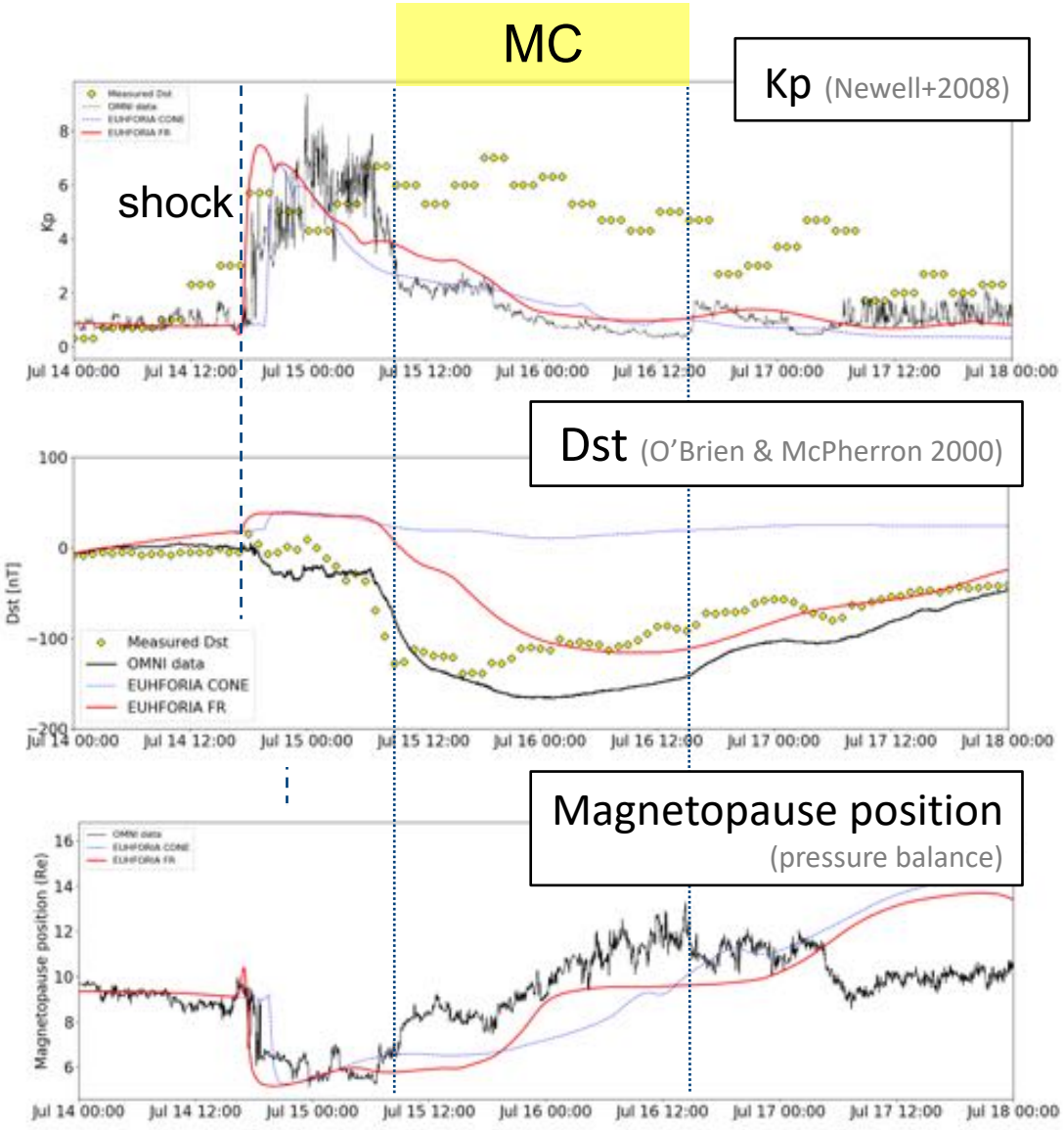
- **CME arrival time** and **peak density/speed** well reproduced by both models

→ Magnetospheric compression

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

→ Dayside reconnection & geomagnetic activity

Geoeffectiveness predictions



EUHFORIA Kp prediction:

- Max Kp well predicted by both models
- High Kp tail missed by both

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

EUHFORIA Dst prediction:

- Cone model misses the storm
- Flux-rope improves the prediction of min Dst by **+80pp**

→ flux-rope CME model needed to predict Dst storms

+ MP position similarly predicted by both models and using OMNI solar wind data

Event 3: 15 March 2013 CME

Remote observations

- Single CME event
- Fast Earth-directed halo CME

In-situ (@ L1)

- ICME: Shock+sheath+MC
- Bz rotation: S→N

Geomagnetic storm

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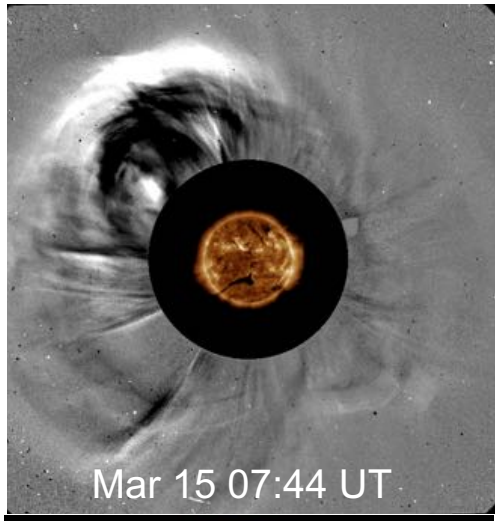
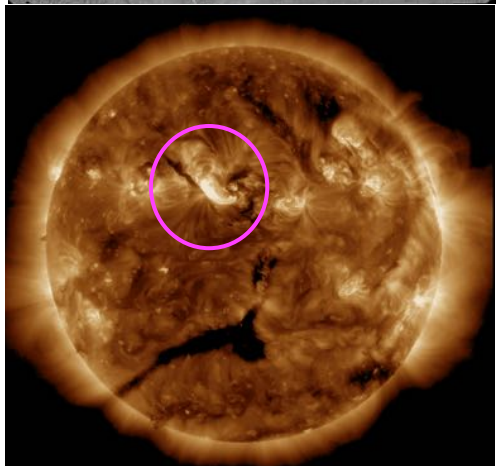
- WG4 event type: textbook (Webb & Nitta 2017)
  - Forecast success: -
- Dst: -132 nT | Kp: 6+





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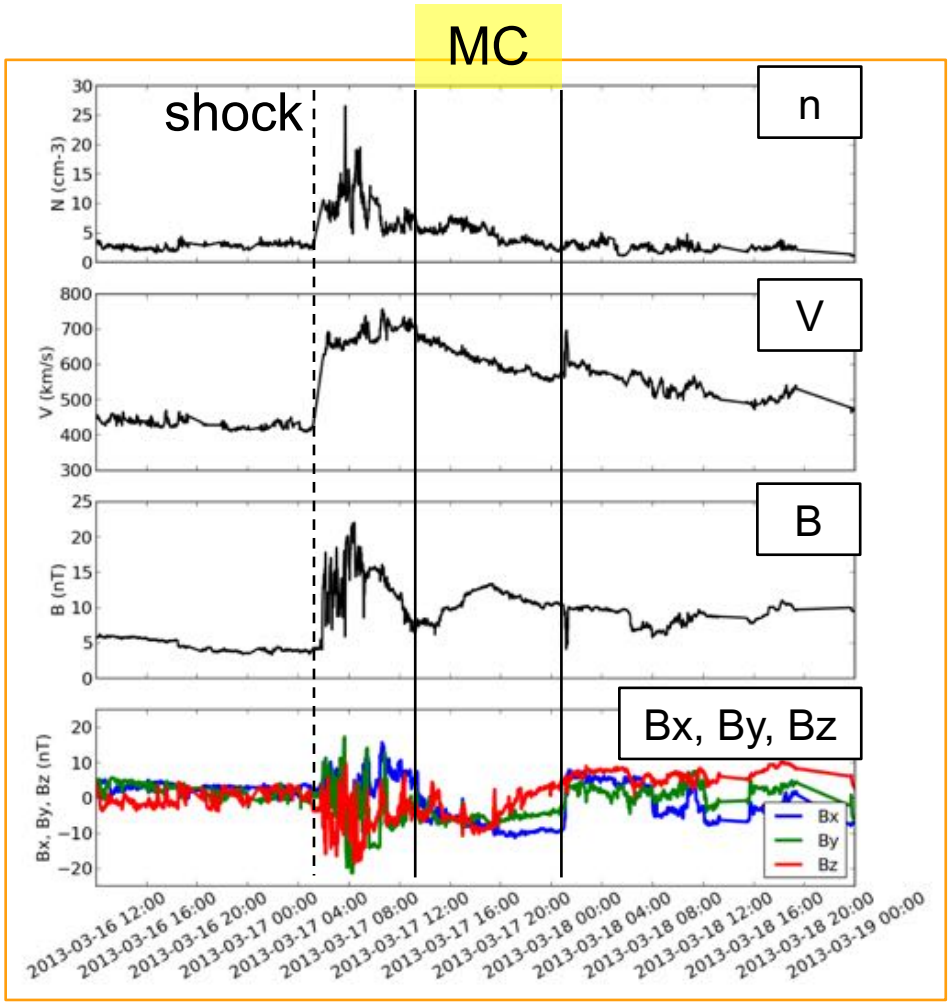

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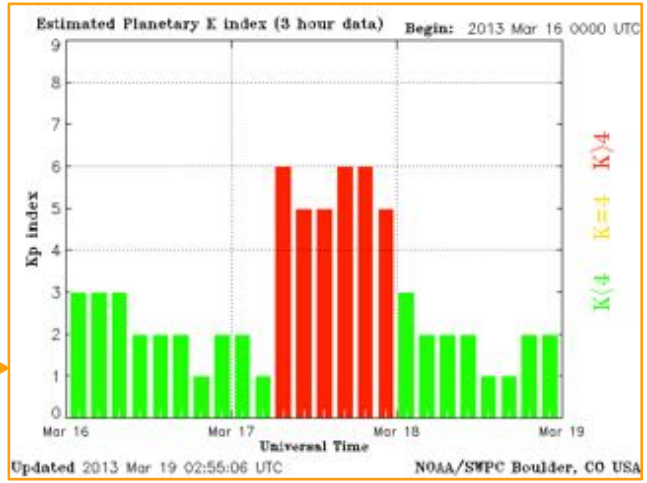

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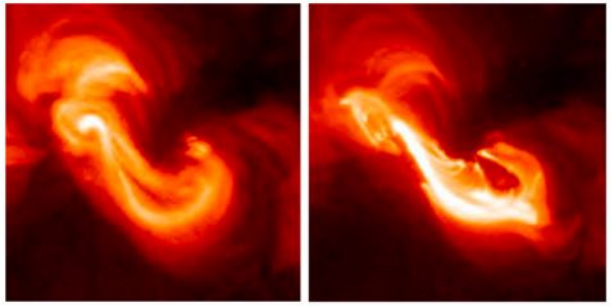
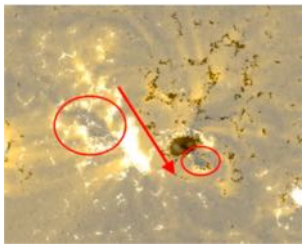
Evaluating helicity/chirality

Observations of the source region

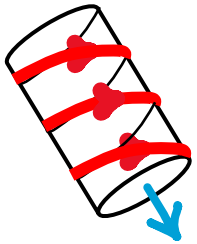
AR 11692: *Hinode/SXR images before and during the eruption*



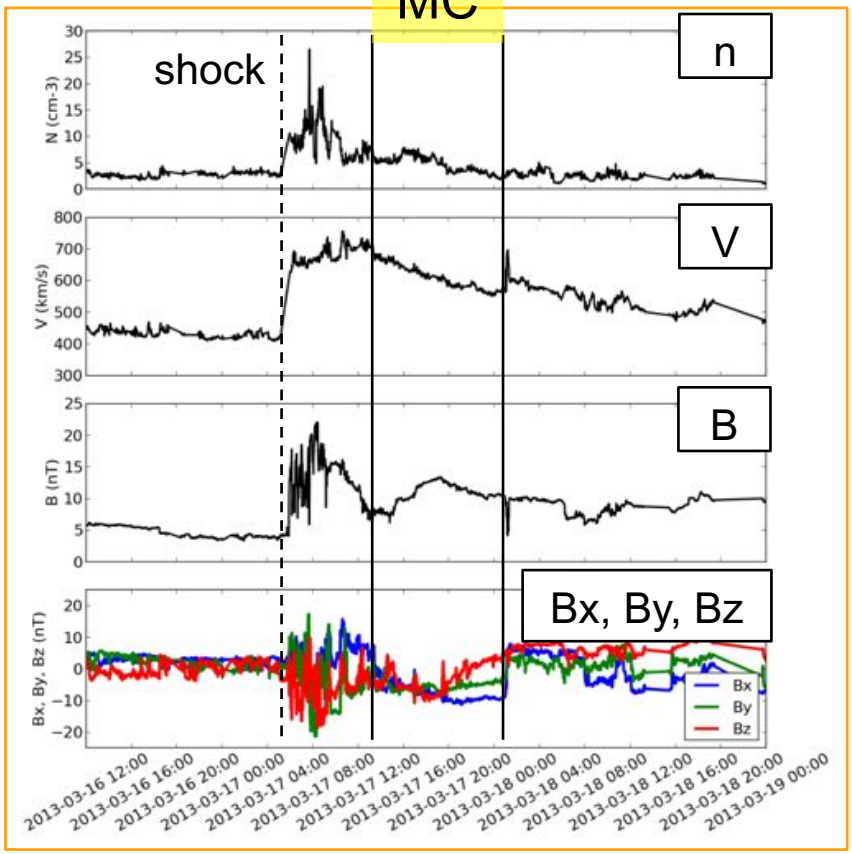


AR 11692:
HMI magnetogram with sigmoid footpoints

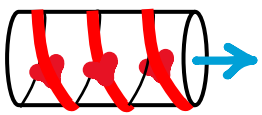
Observations of the source region AR11692 suggest a **left-handed** flux-rope (WSE type)



Magnetic cloud at L1

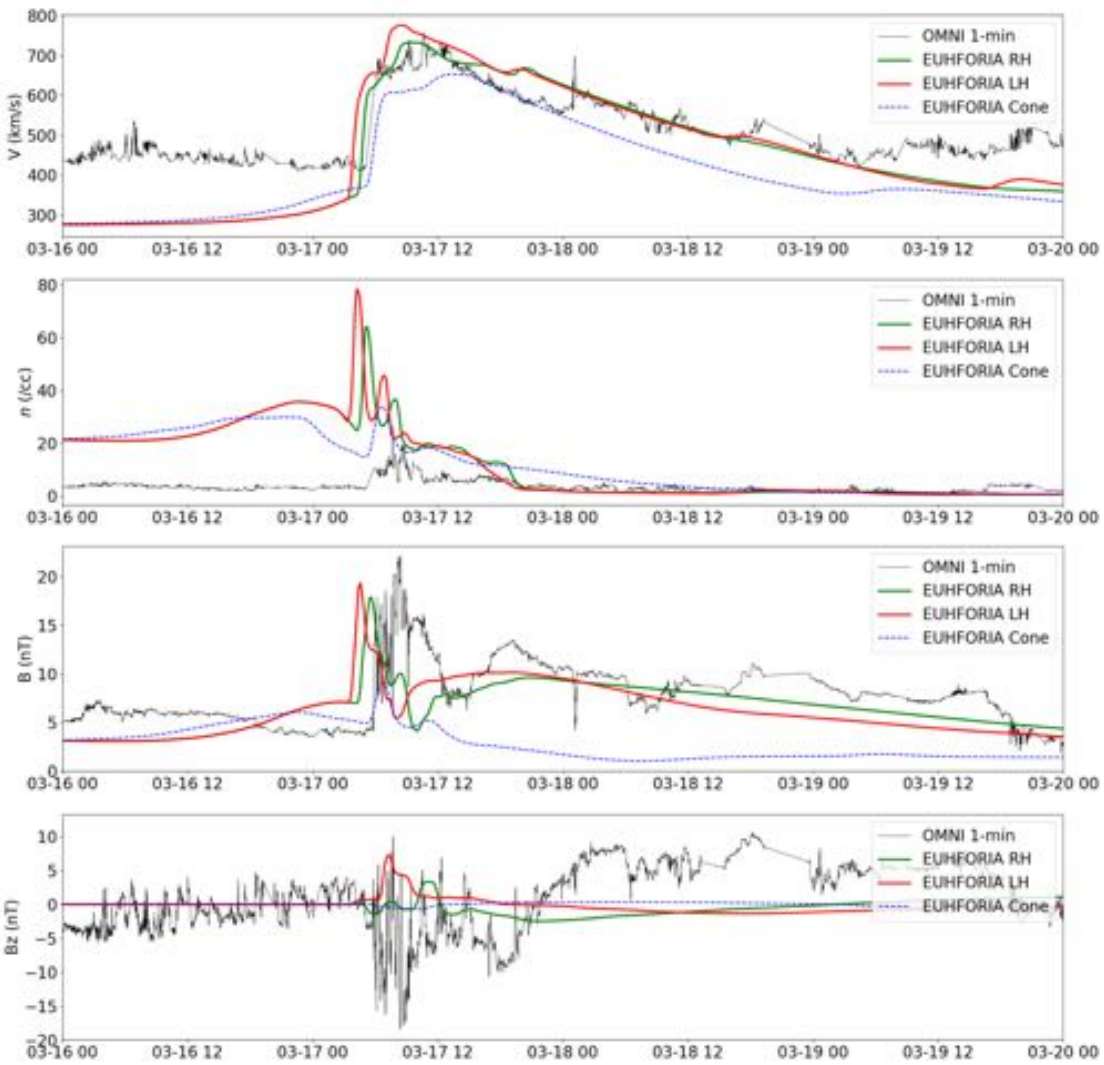


MC appears to be **right-handed** (flux rope type SWN)



See also: Pal+2017

EUHFORIA predictions @ Earth (L1)



1) Right-handed FR 

2) Left-handed FR 

- None of the two configurations matches the Bz observed in-situ (S→N)

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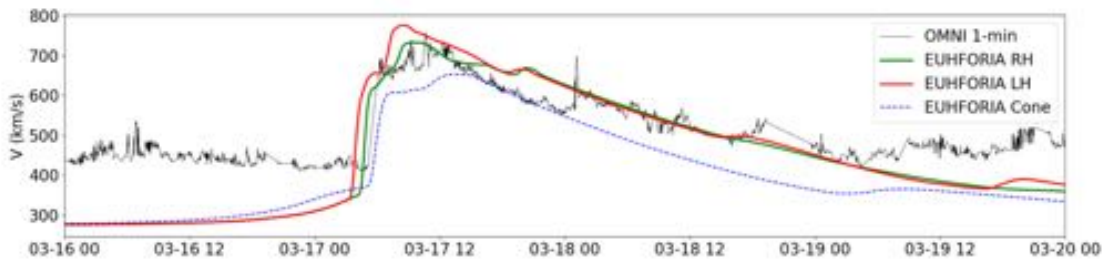

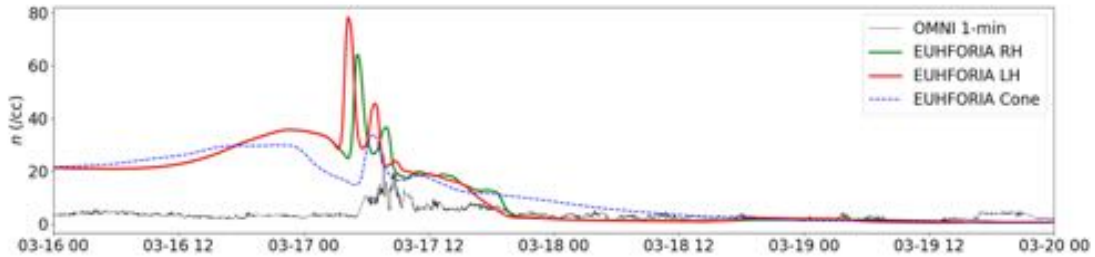

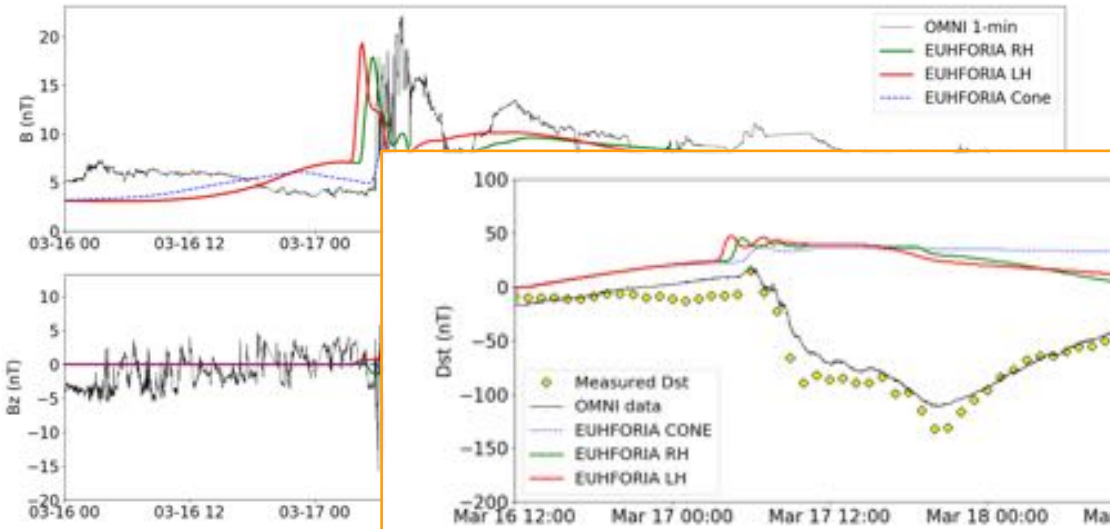

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2) Left-handed FR 

- None of the two configurations matches the Bz observed in-situ (S→N)
- No significant difference in Bz, reflecting on poor **Dst predictions**

EUHFORIA predictions near Earth

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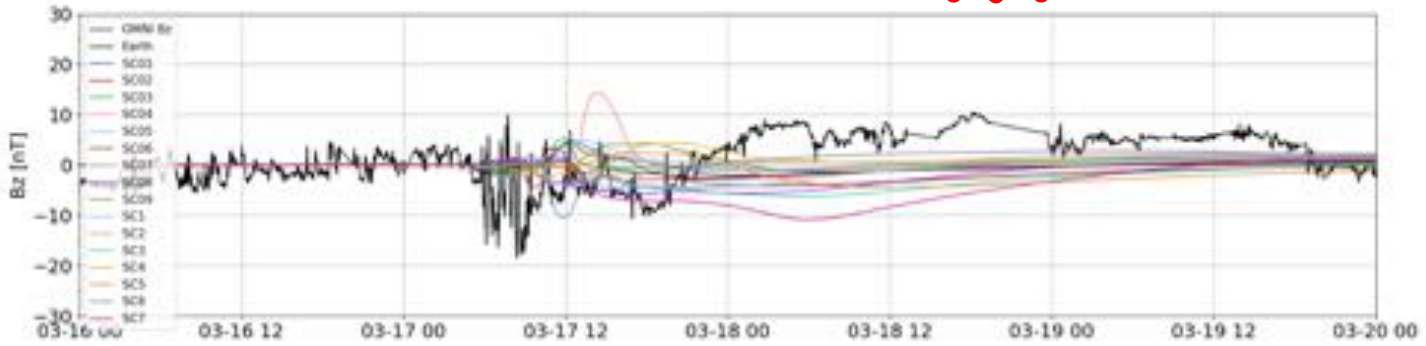

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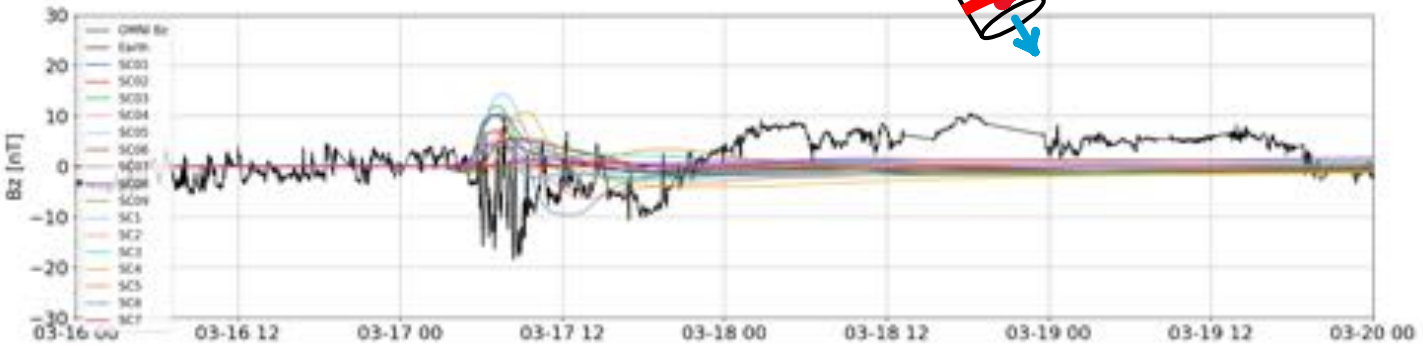


Results change significantly moving just a few degrees around Earth position

Event 11: 9-10 September 2014 CMEs

Remote observations

- Two CME from same AR (12158)
- CME1: partial halo, CME2: full halo

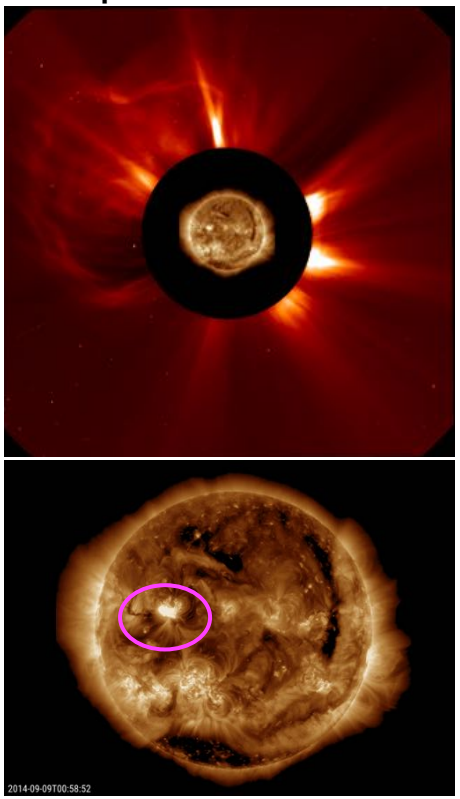
In-situ (@ L1)

- ICME1: Shock+sheath
- ICME2: Shock+sheath+MC
  - Negative Bz in the sheath, positive Bz in the MC

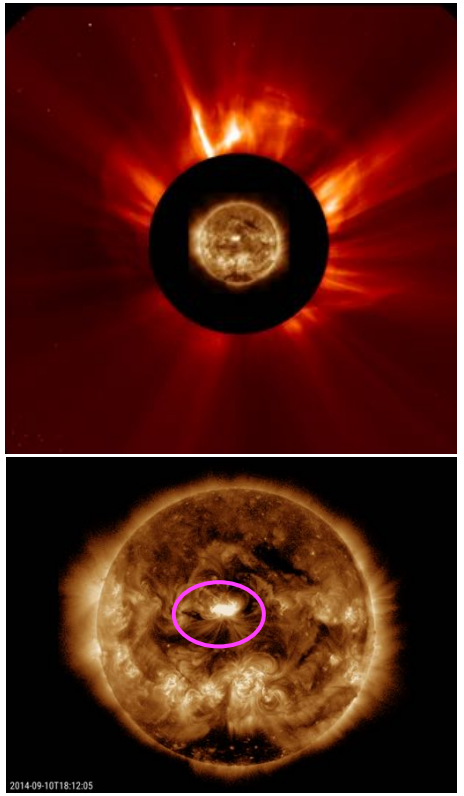
Geomagnetic storm

- Moderate geomagnetic storm
- WG4 event type: problematic
  - Forecast success: overpredicted
- Dst: -75 nT | Kp: 7 (sheath)

CME1:
Sep 09 00:58 UT



CME2:
Sep 10 18:12 UT



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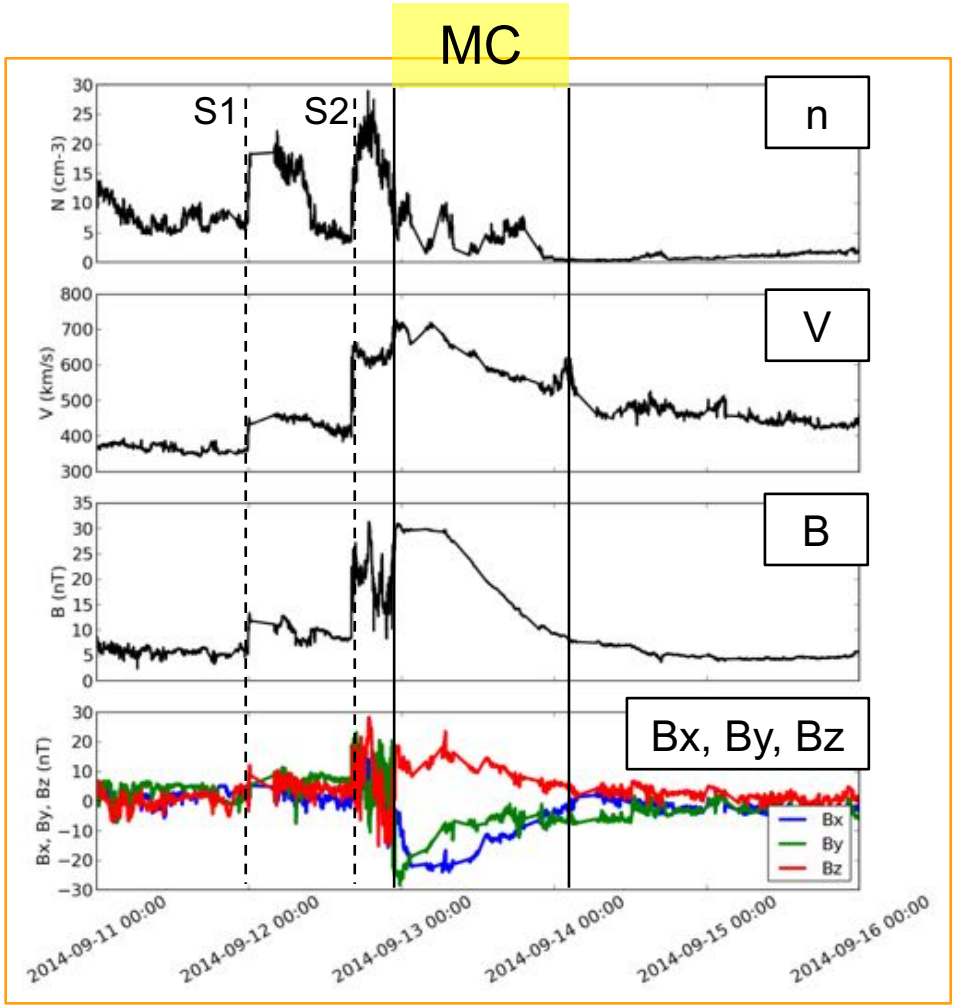

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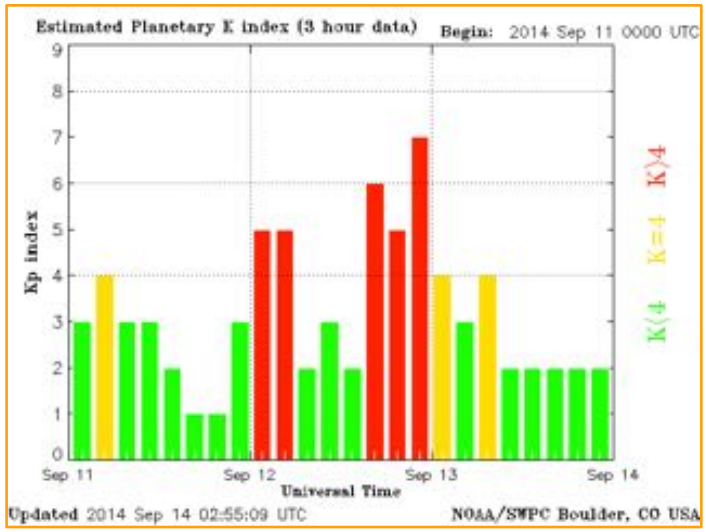
  - Negative Bz in the sheath, positive Bz in the MC

Geomagnetic storm

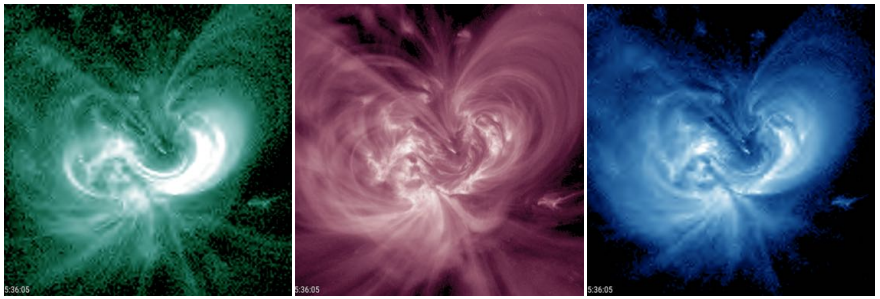


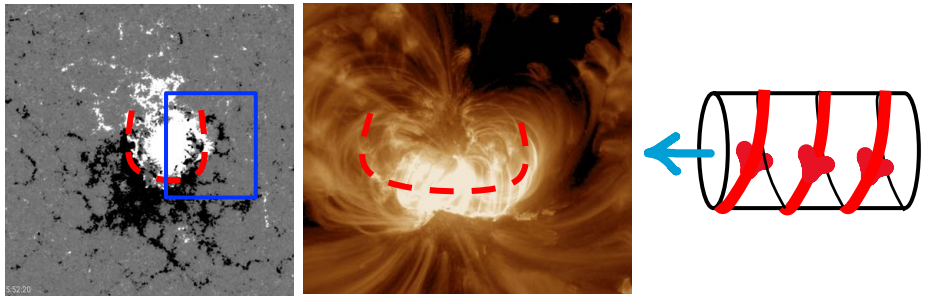
- Moderate geomagnetic storm
- WG4 event type: problematic (Webb & Nitta 2017)
  - Forecast success: overpredicted
- Dst: -75 nT | Kp: 7 (sheath)

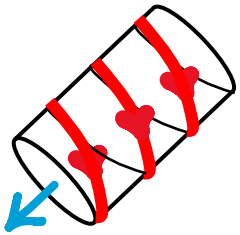
CME2: flux-rope orientation

Observations of the source region

AR 12158: *SDO/AIA and HMI images before and after the eruption of CME2*



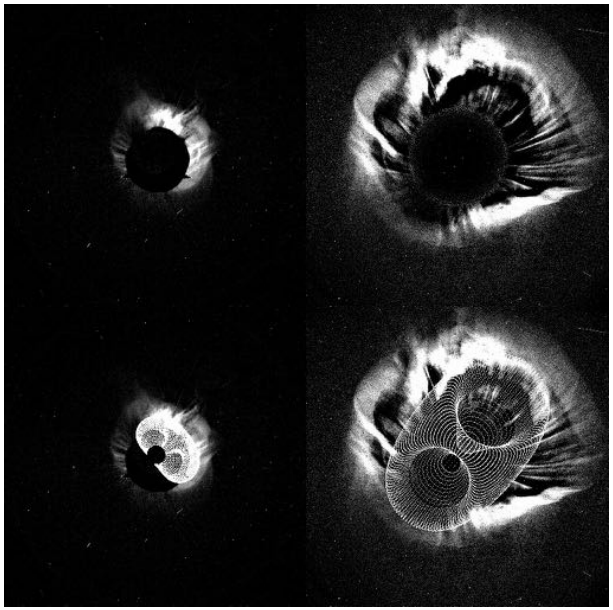




Source region observations suggest left-handed flux-rope

- PIL/PEA: **WSE/SEN type**

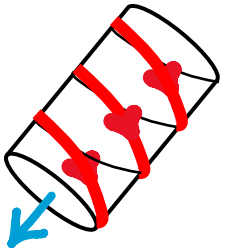
Coronagraphic images



COR2B *C2*

8 Rs → 22 Rs in the corona:

- GCS orientation **agrees with PIL orientation**

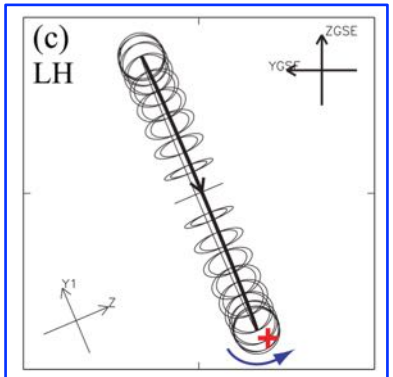


CME2: flux-rope orientation

In-situ ICME observations

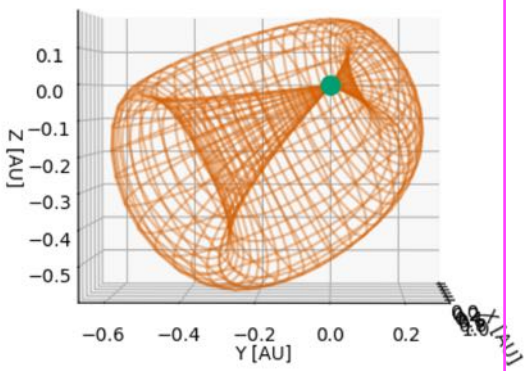
MC (associated with CME2):
flank encounter + positive Bz
→ not as geoeffective as predicted
→ geoeffectiveness from the sheath

Different methods reconstruct different in-situ **orientation** of the flux-rope

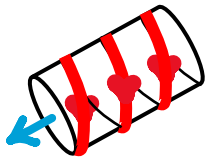


Cho+(2017)

Tilt 2

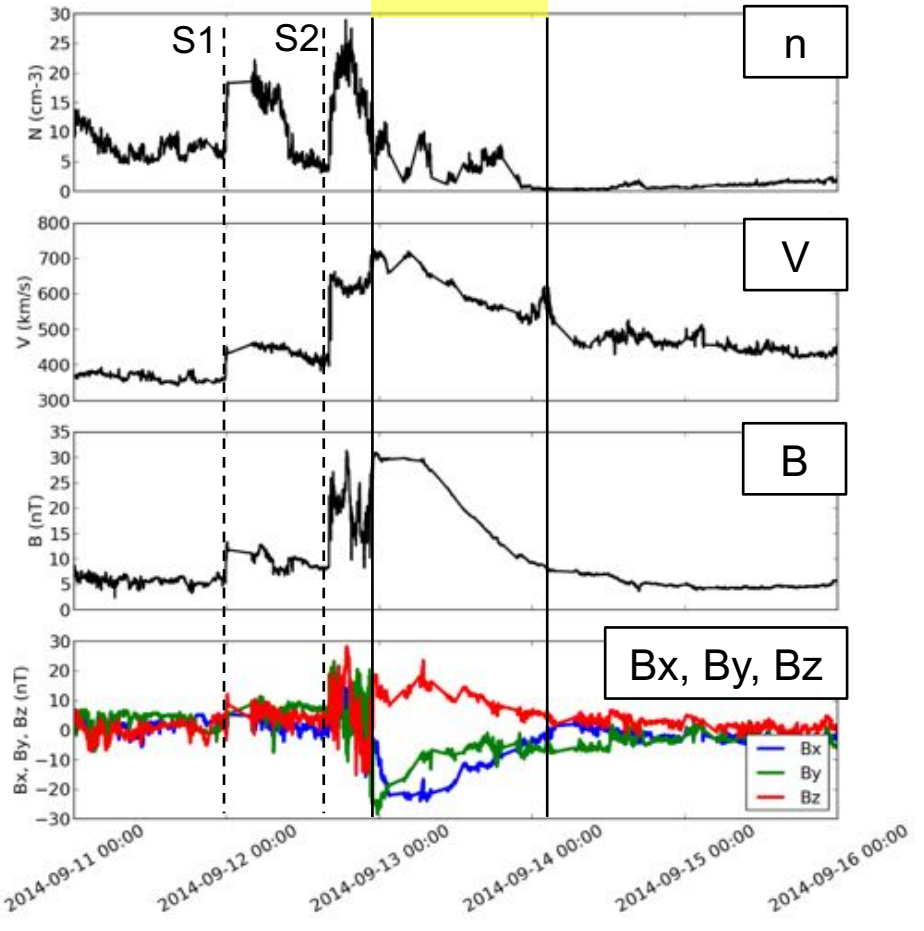


Courtesy of A. Isavnin

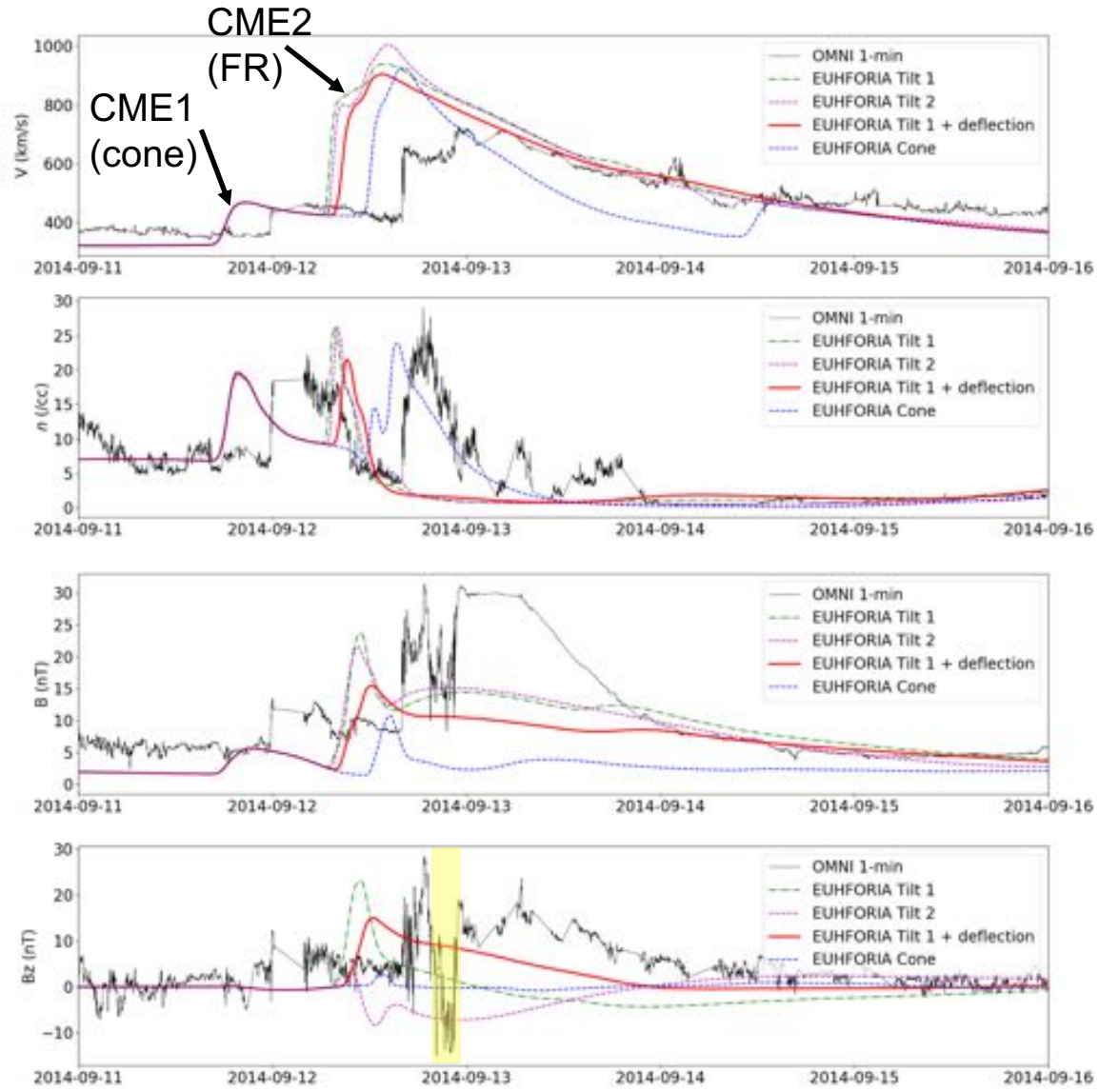


Tilt 1

MC



EUHFORIA predictions @ Earth (L1)



1) Tilt 1, lon=-2 deg

2) Tilt 2, lon=-2 deg

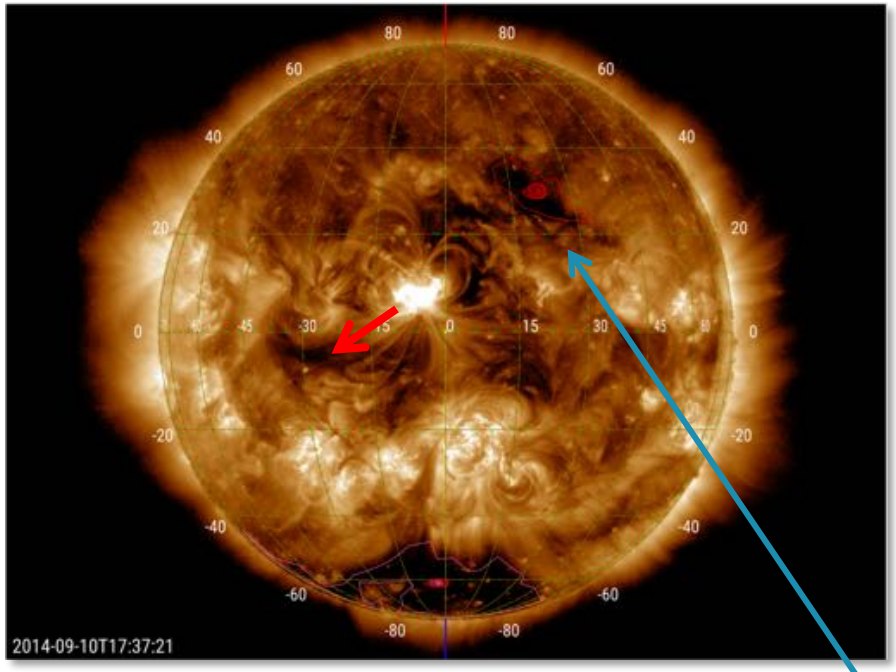
3) Tilt 1, lon=-20 deg (deflection)

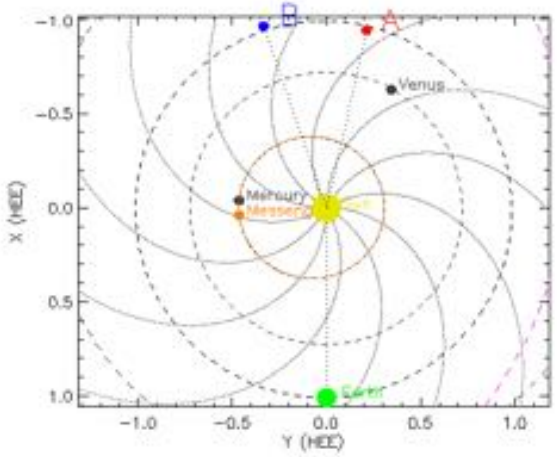
Tilt 1 matches coronal observations (PIL/PEA) but it does not predict Bz correctly (negative Bz)

Tilt 2 fits well the B signatures (positive Bz) but does not match coronal observations

Tilt 1 + deflection fits well all B components + matches coronal tilt

EUHFORIA predictions @ Earth (L1)





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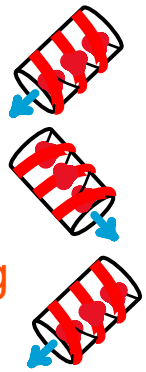
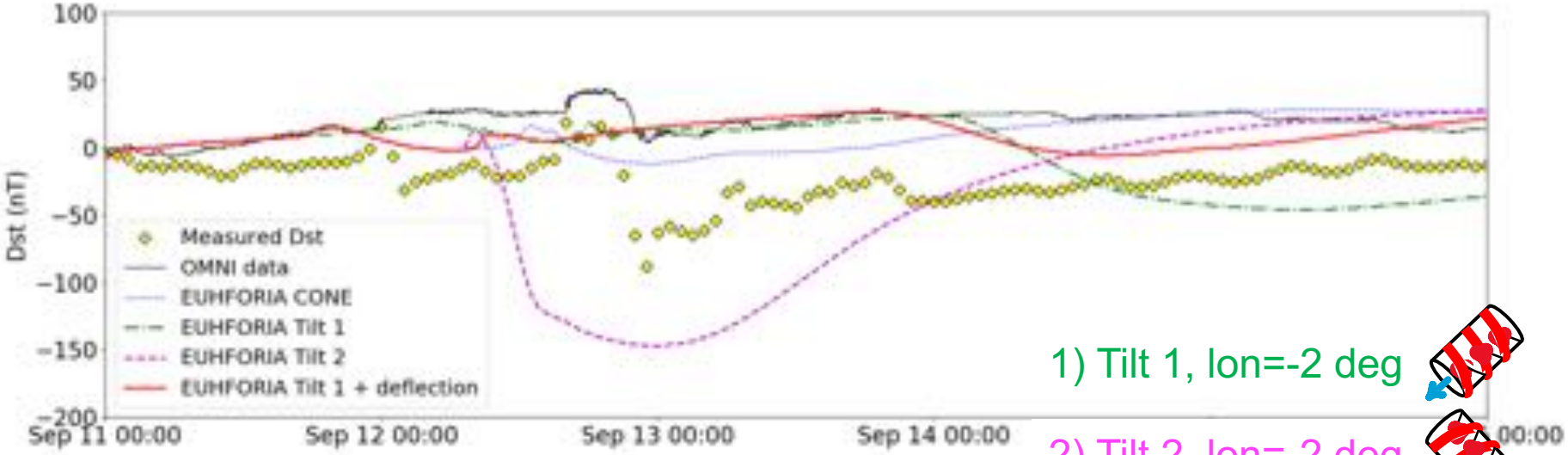


- Tilt 1 matches coronal observations (PIL/PEA) but it does not predict Bz correctly (negative Bz)
- Tilt 2 fits well the B signatures (positive Bz) but does not match coronal observations
- **Tilt 1 + deflection** fits well all B components + matches coronal tilt (cause: CH? Non-radial speed components? Unreliable GCS reconstruction?)

Geoeffectiveness predictions



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Dst prediction…

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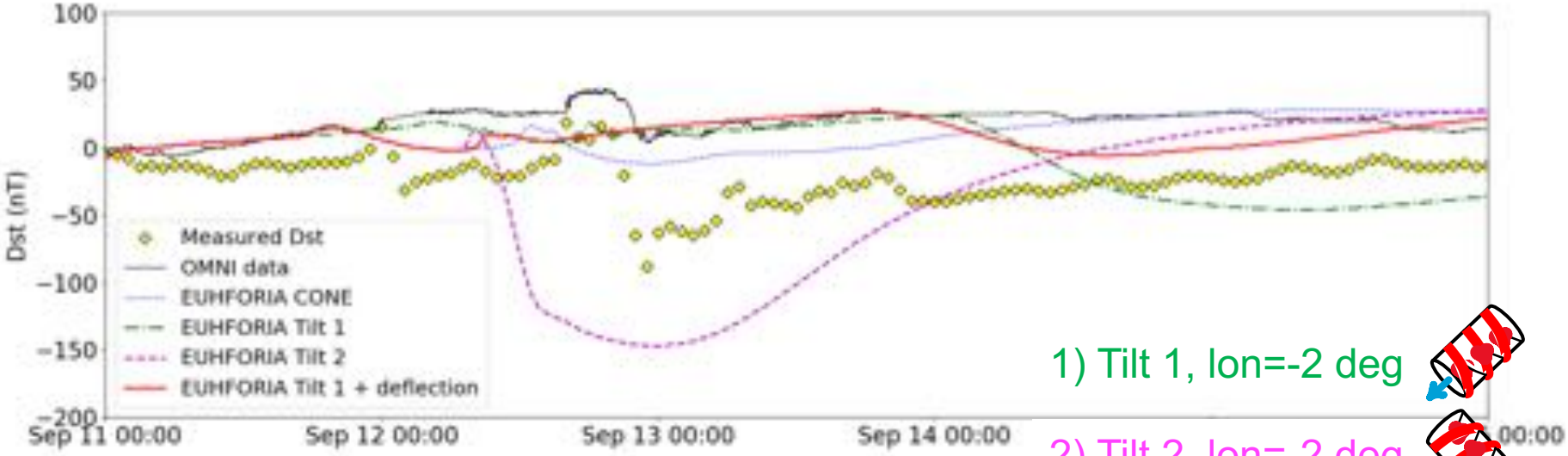
Geoeffectiveness predictions



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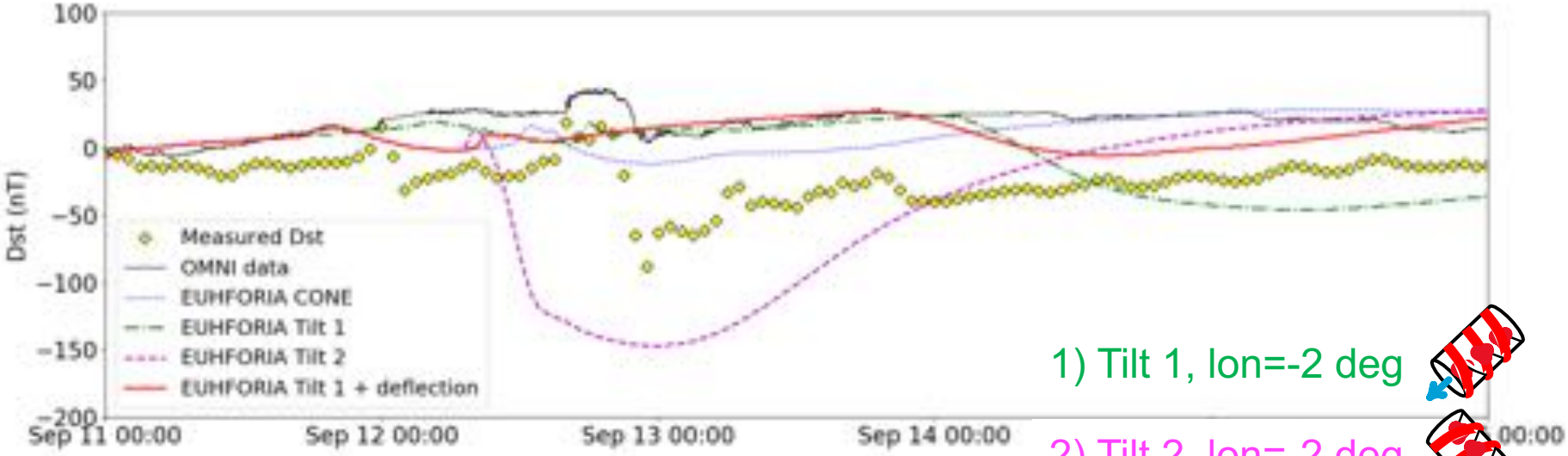
→ empirical relation does not react on sheath-associated negative Bz

→ flux-rope CME model does not even capture sheath-associated negative Bz

Geoeffectiveness predictions



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→ flux-rope CME model does not even capture sheath-associated negative Bz

CONCLUSIONS

First **observation-based** study of **magnetized CMEs** and their **impact on Earth** with EUHFORIA

Translating observations into a proper set of CME input parameters is non trivial

- Cone CMEs and flux-rope CMEs need to be initialized in different ways (separation between Vexp / Vrad needed)

How much do we improve using a flux-rope CME model?

- Up to +40pp(min Bz)/+80pp(min Dst) compared to cone model (2012-07-12)
- Modelling geoeffective sheaths beyond tested capabilities (2014-09-10)
- Flux-rope results vary significantly moving around Earth by just few degrees (2013-03-15)

Textbook events can be more complicated than expected (2013-03-15)

Uncertainty quantification needed to assess the quality of a prediction

- Uncertainty on observational parameters can be large (magnetic parameters)
- Parameter study to assess model sensitivity (work by C. Verbeke)