ICMEs, SEPs, CIRs, SIRs and their forecasting

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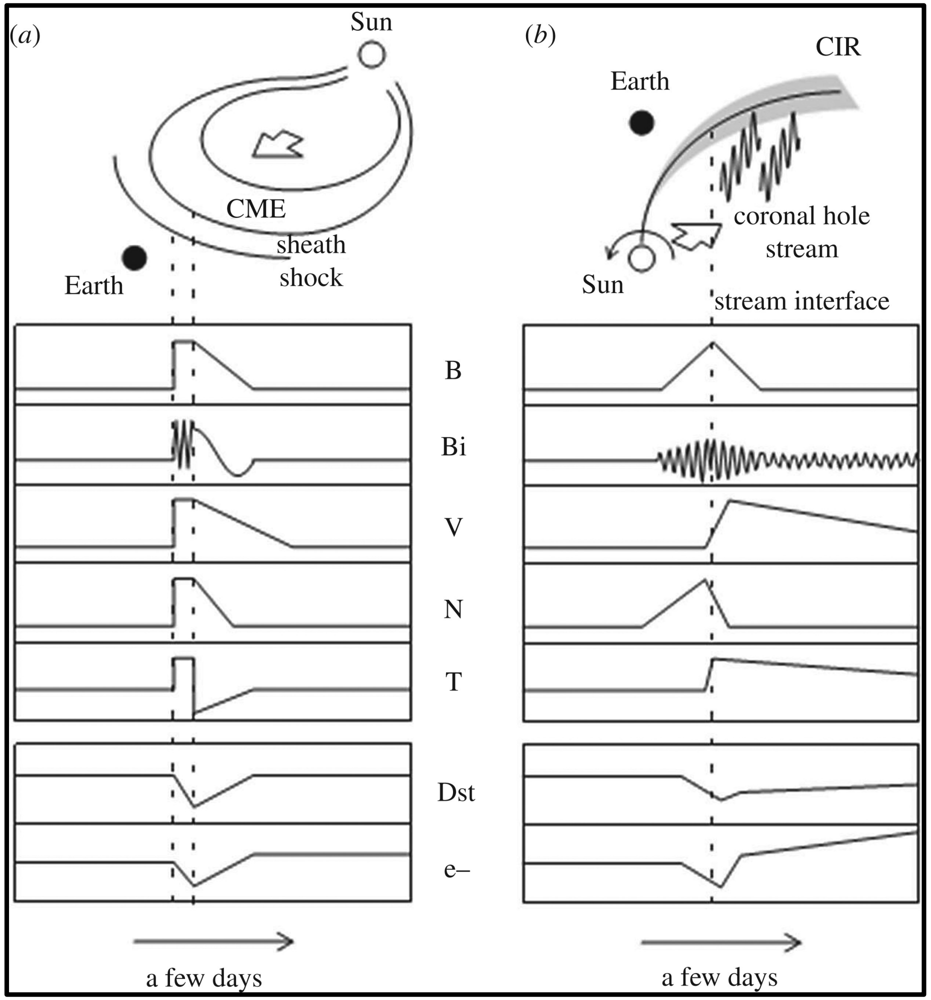
Here the focus will be on forecasting **direct interaction** of plasma and magnetic field in solar wind transients (**ICMEs** and **SIRs**) with the Earth's magnetosphere

For ICMEs and SIRs it takes usually between **1** to **5 days** to propagate from the Sun to the Earth's orbit

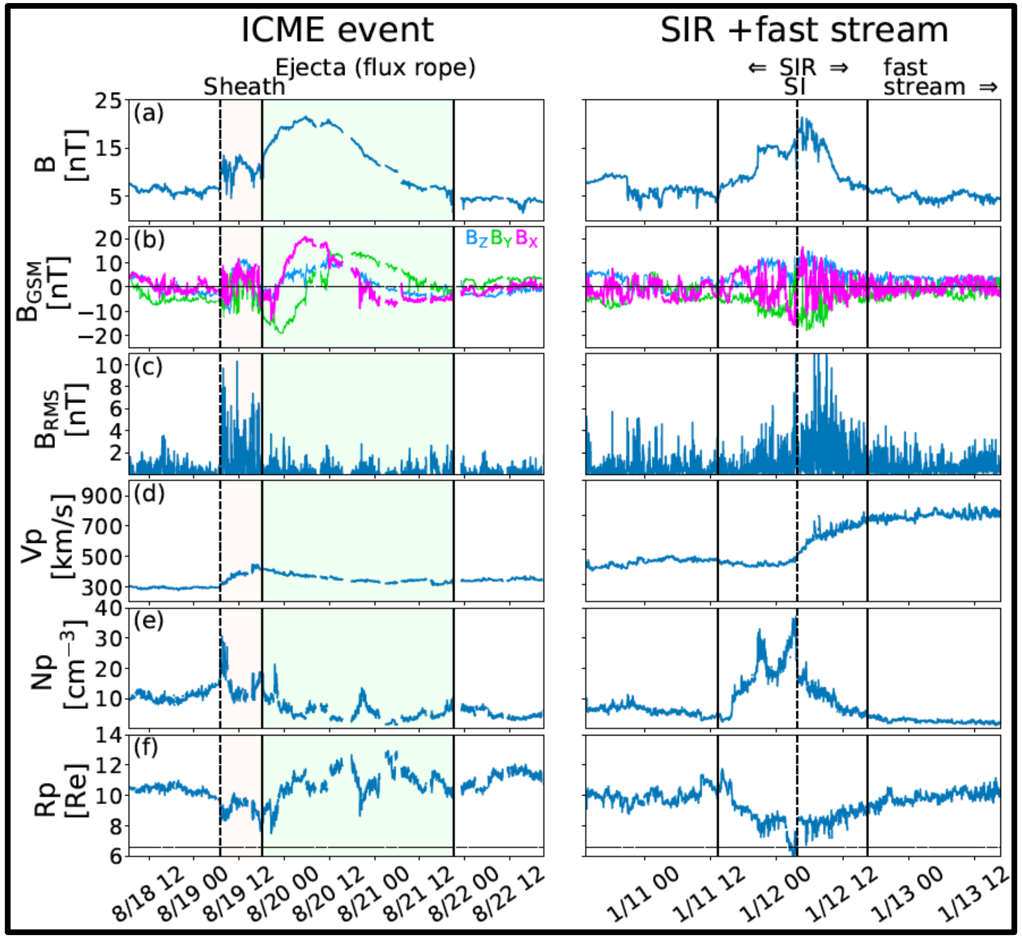
Now-casting: using the near-Earth data (30 min – 1 hours lead times)

Long-lead time forecasting: using remote-sensing data and modelling (at least half a day lead times)

ICMEs & SIRs: reminder from Day1



← Kataoka and Miyoshi, 2006



Kilpua et al., 2017

Forecasting the properties of ICMEs and SIRs differ

1. Forecasting **SIR** properties

(also important for forecasting CME propagation)

To forecast SIRs, one needs to model as realistically as possible the **solar wind** and its evolution

Slow – Fast Stream Interaction Regions (SIRs)

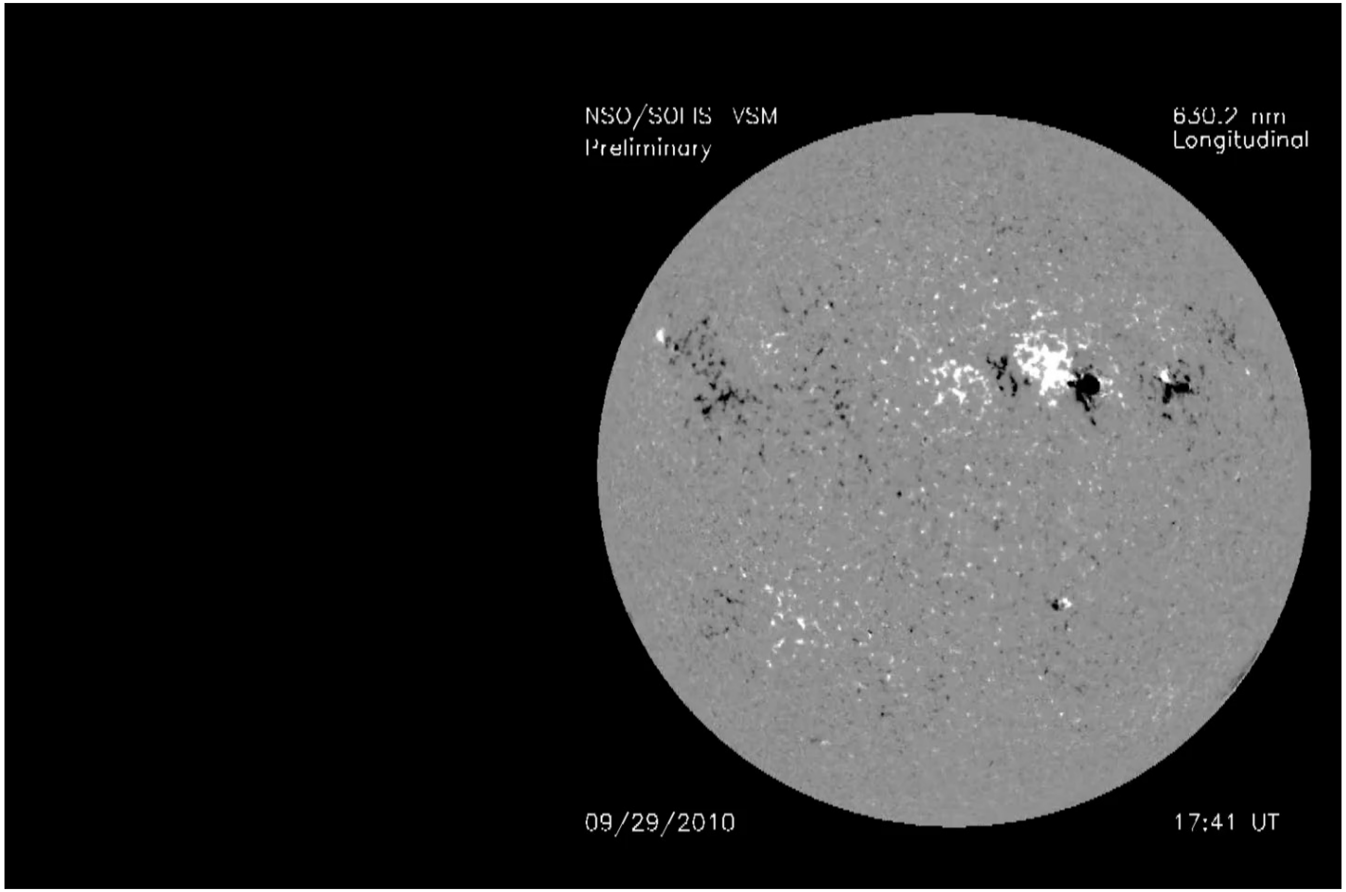
Solar magnetograms

Corona (< 21.5 Rs):

- **Magnetic field**: Potential Field Source Surface (PFSS) model, global magnetofrictional model
- **Plasma**: Wang-Sheeley-Arge model (flux tube expansion), MHD based models (e.g. 1D MULTI-VP, 3D Coconut), …

Heliosphere (> 21.5 Rs): Global magnetohyrdodynamics (MHD) models (EUHFORIA, ENLIL, SUSANOO etc) that evolve density, field, velocity and temperature in 3-dimensions

Synoptic maps



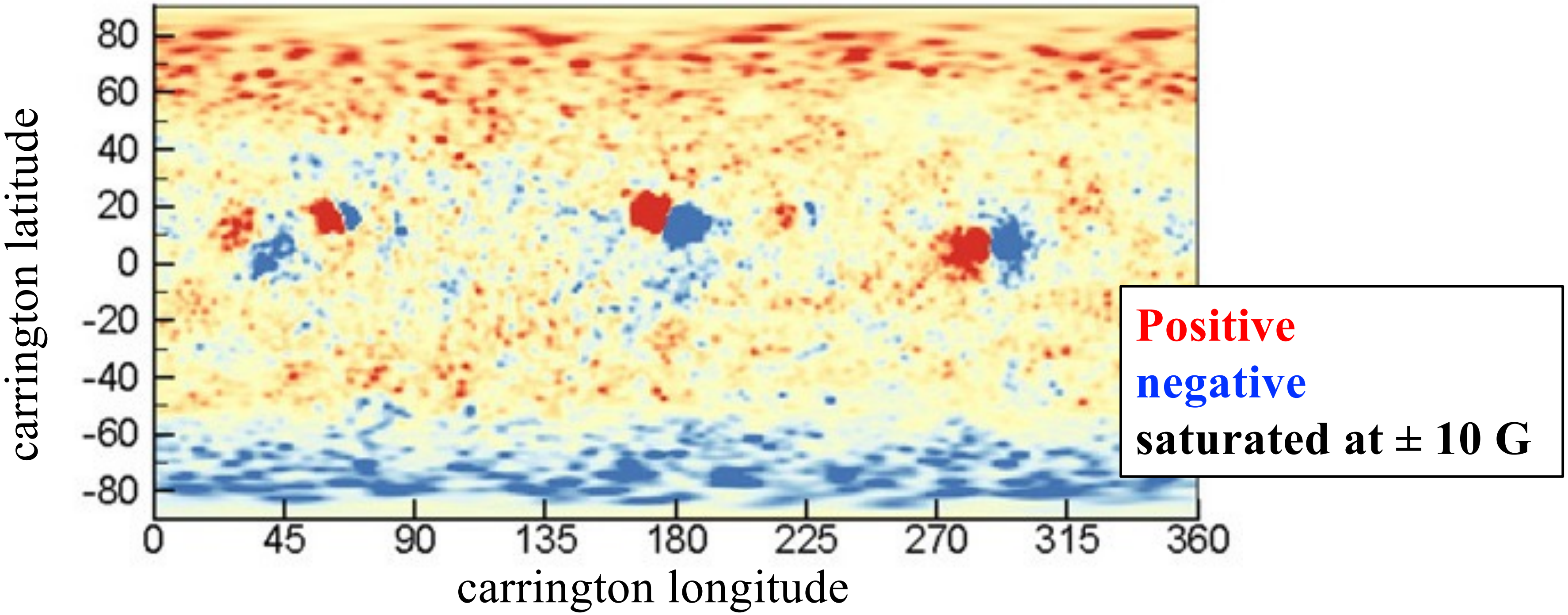
vertical axis: solar latitudes in respect to solar equator

horizonal axis: Carrington longitudes (360° at start of CR)

Carrington Rotation (CR): full rotation of the Sun, first started November 9, 1853 (now we are at **CR2284**).

Building the maps: constructed from daily maps assuming that Sun rotates as a rigid body and using certain weighting factors (https://nso.edu/data/nisp-data/synoptic-maps/)

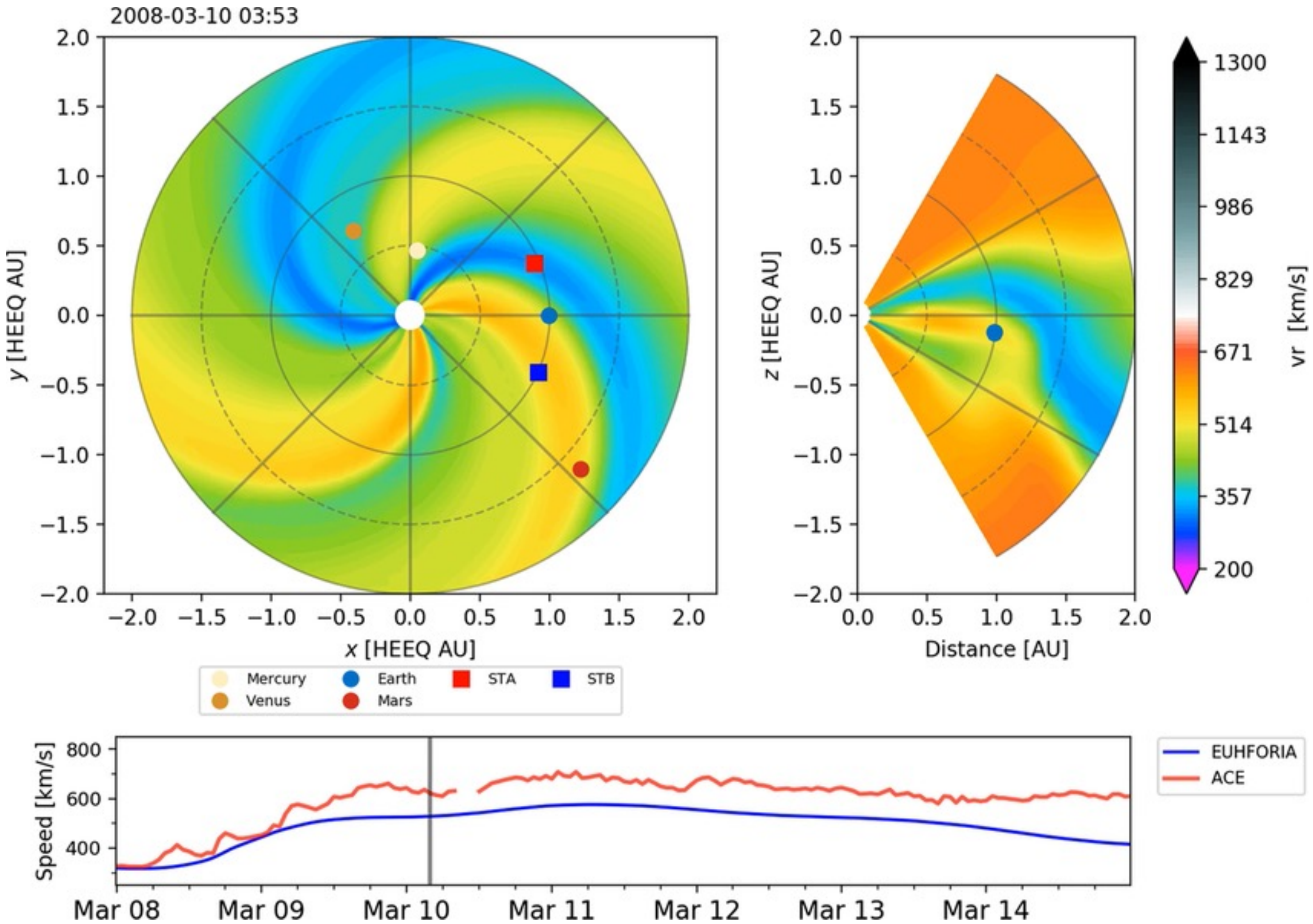
Synoptic maps



Synoptic maps represent the whole field over 27.7 days. E.g., from Wilcox Solar Observatory (WSO), Global Oscillation Network Group (GONG). ADAPT* maps are produced by applying a flux transport model and data assimilation techniques.

*Air Force Data Assimilative Photospheric Flux Transport

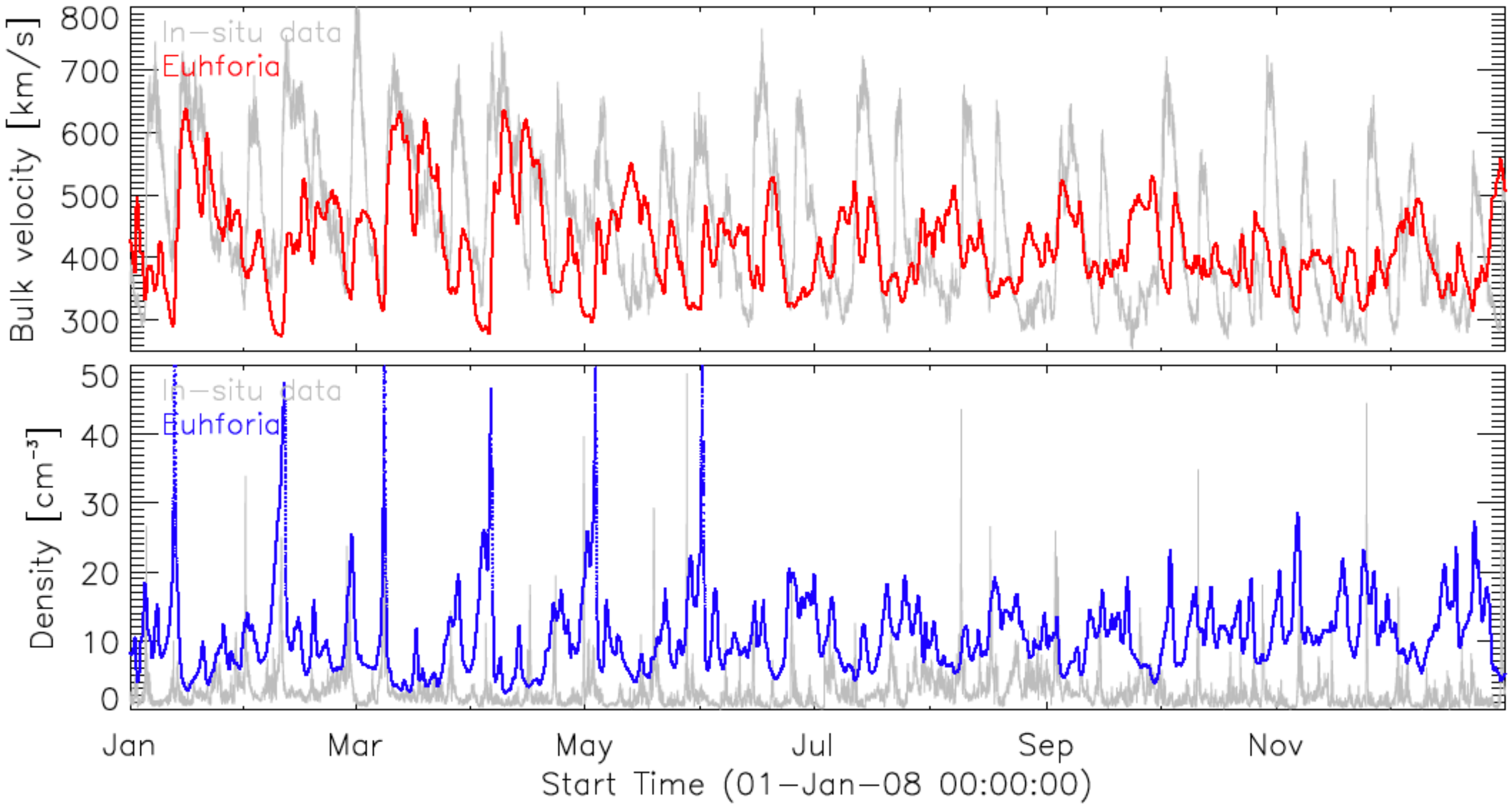
EUHFORIA space weather model



Hinterreiter al. 2019

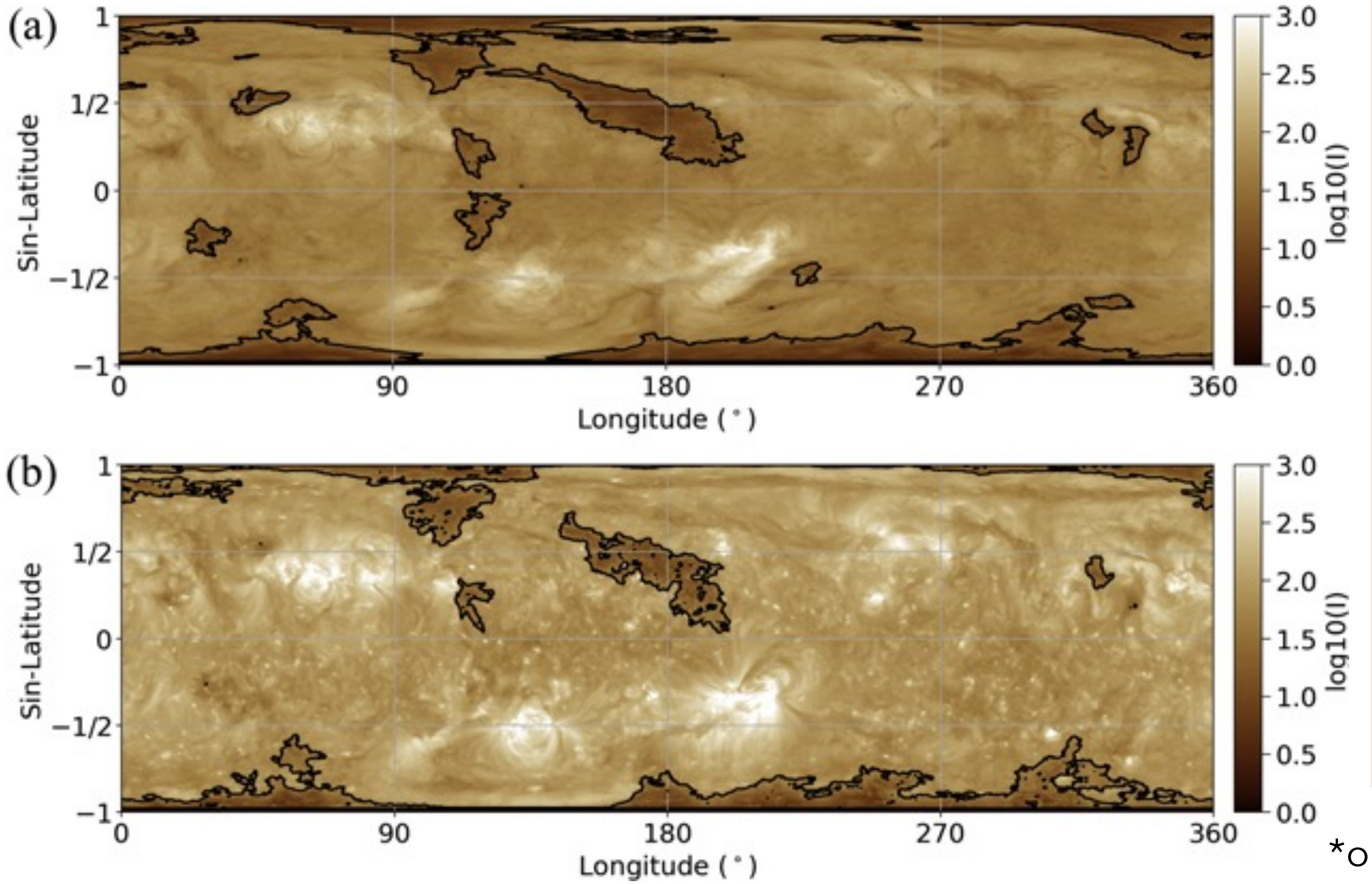
EUHFORIA: Pomoell & Poedts, 2018

EUHFORIA Example (with WSA)



Hinterreiter al. 2019

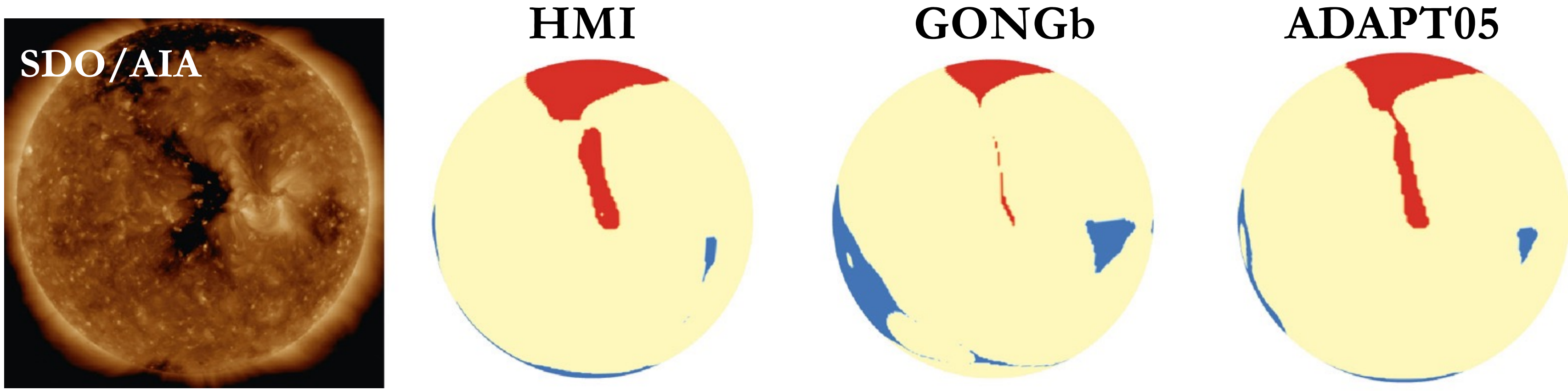
Synoptic maps/coronal holes



Different coronal hole detection methods (EUV data) can lead to different **coronal hole areas** and even to **different detections*** (Linker et al., 2021)

*open flux STD 26% with effect from magnetogram uncertainty ~46%

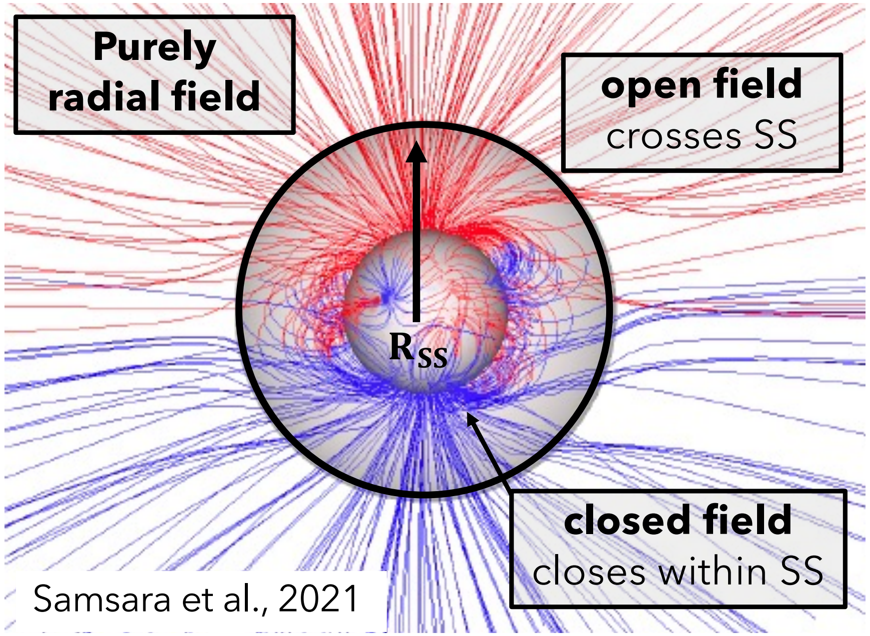
Synoptic maps/coronal holes

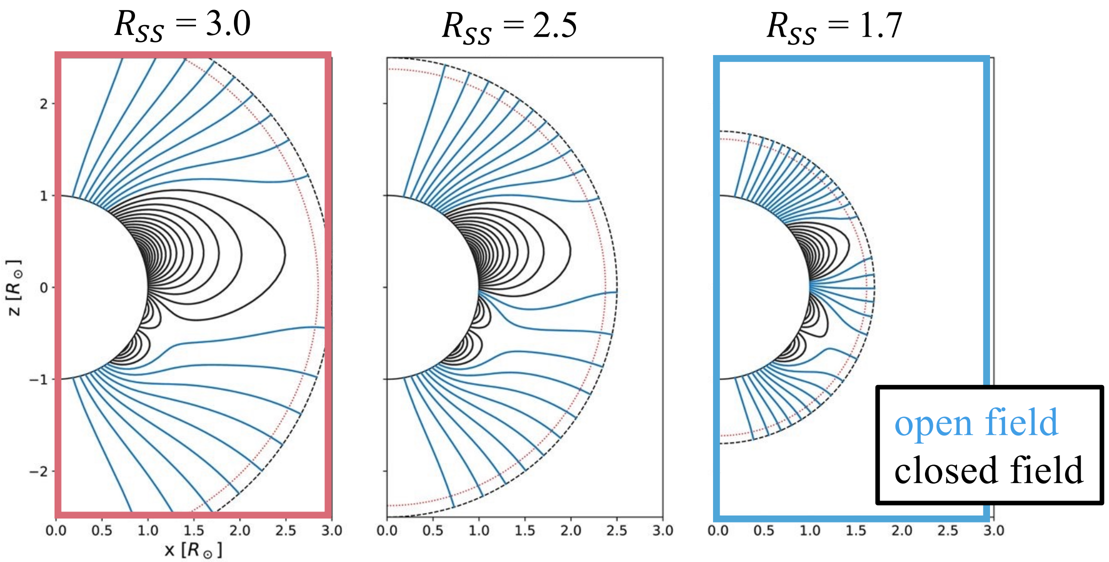


The used **magnetograms** have a significant effect to CH area (Li et al., 2021)

Solar Orbiter will soon provide more accurate measurements of the **polar magnetic fields** → better estimation of coronal holes.

Source Surface / Coronal Hole Area





One key parameter in PFSS is the **source surface height** (R_{SS}). SS is a spherical shell whose radius is R_{SS} (in reality, may vary in different areas).

SS **too high**: open flux under-estimated → coronal hole area **underestimated**

SS **too low**: open flux overestimated → coronal holes area **overestimated**

Asvestari et al., 2021

2. Forecasting **ICME** properties

1. **Intrinsic** flux rope (FR) properties
2. Heliospheric **evolution** and **distortions**, including **sheath formation**

Intrinsic FR Properties

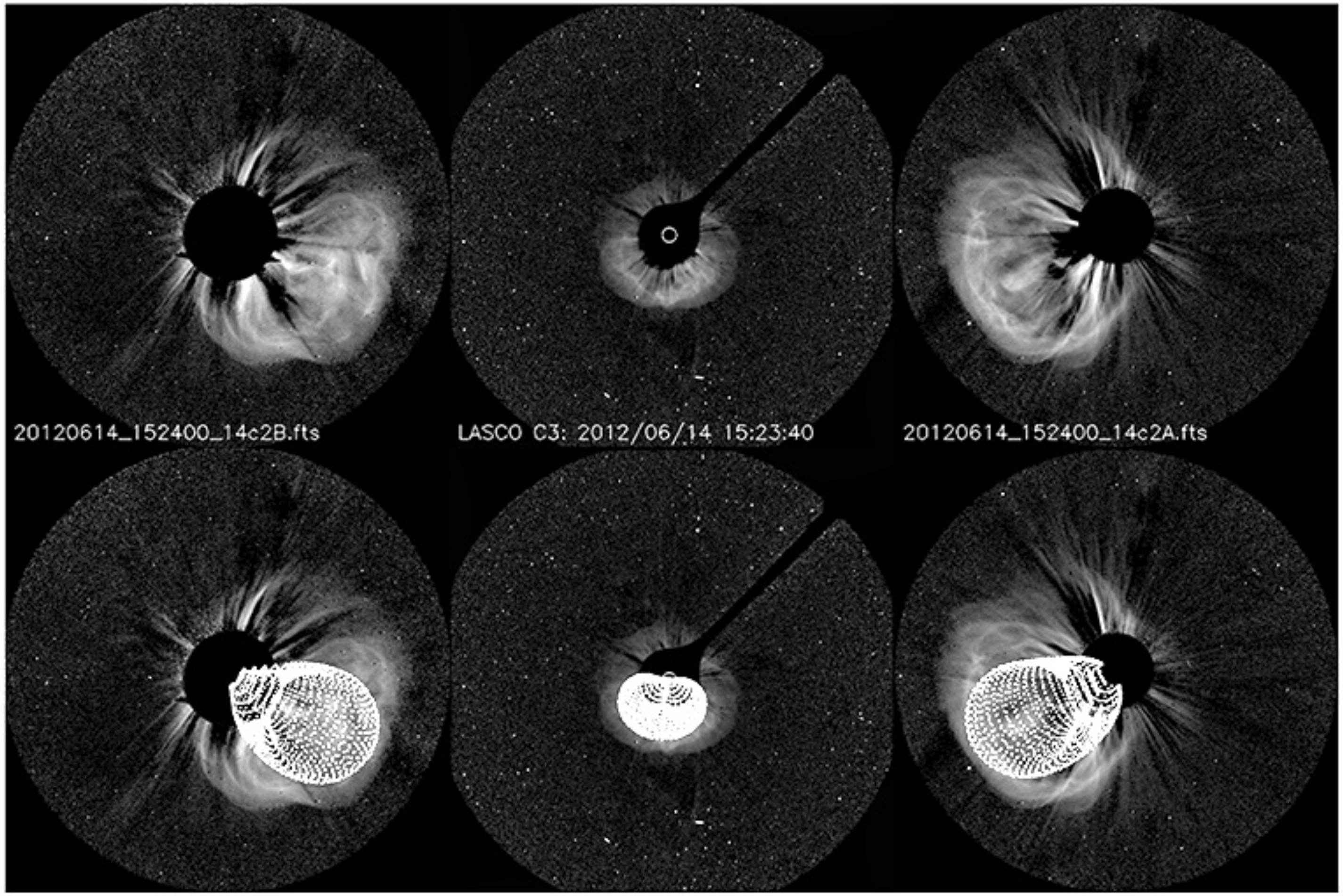
- Geometric (size, tilt)
- Kinematic (speed, acceleration)

- **Multipoint observations: 3D reconstructions,** e.g., Gradual Cylindrical Shell (Thernisien, Vourlidas & Howard 2009)
- **Single-point observations**: Line-off-sight obs. subject to projection effects, off-angle obs. give more realistic estimate

- Magnetic properties (helicity sign, axis orientation, axial field direction, magnetic flux)
  - Indirect proxies*
  - Data-driven modelling

*no direct remote-sensing obs. as the corona is very hot and tenuous → spectral lines broaden).

Geometric Fittings

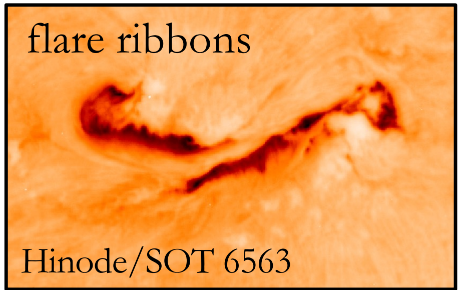


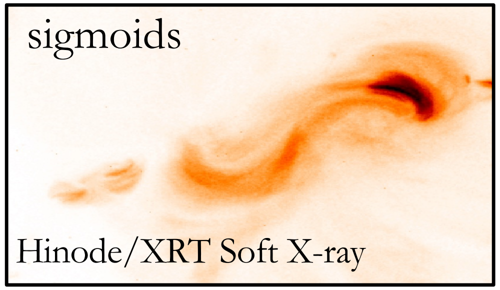
Kilpua et al., 2019

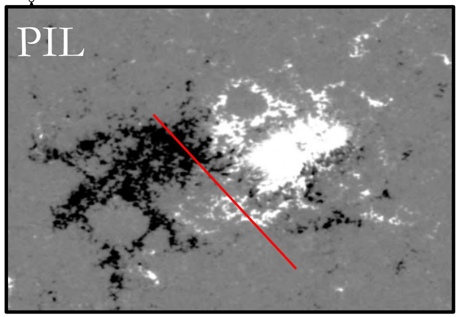
In-direct FR B-field proxies

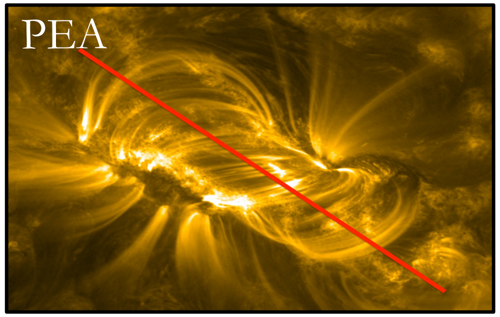
- **Helicity sign**: hemispheric rule 70% (north negative, south: positive), sigmoids, flare ribbons, filament details
- **Axial tilt**: polarity inversion line (PIL), post-eruption arcades (PEA)
- **Axial field direction**: EUV dimmings (footpoints) + magnetograms (field direction)
- **Magnetic flux**: pre-eruptive (flux cancellation upon formation) + added flux (flare ribbon/PEA analysis, core dimming)

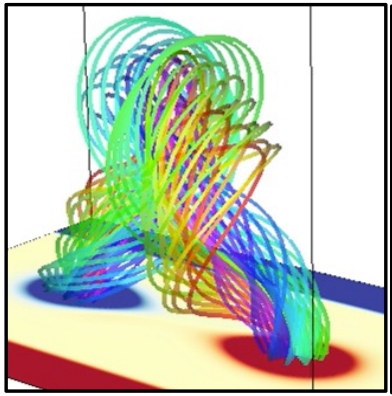
Palmerio et al., 2017; 2018, Sarkar et al., 2020

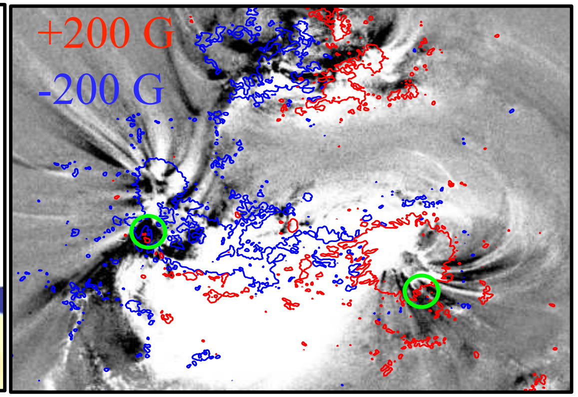






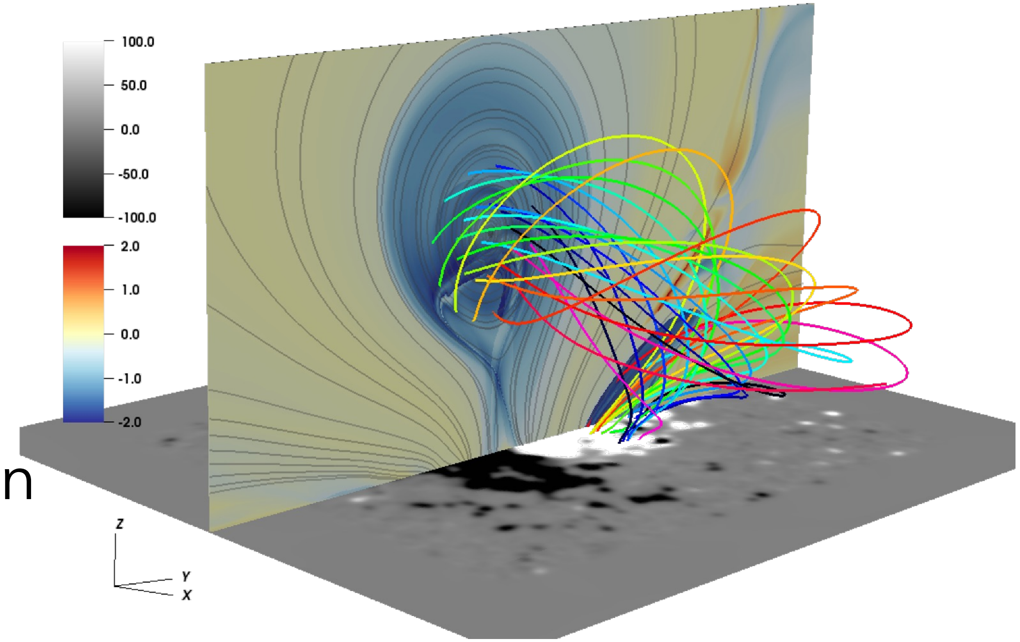






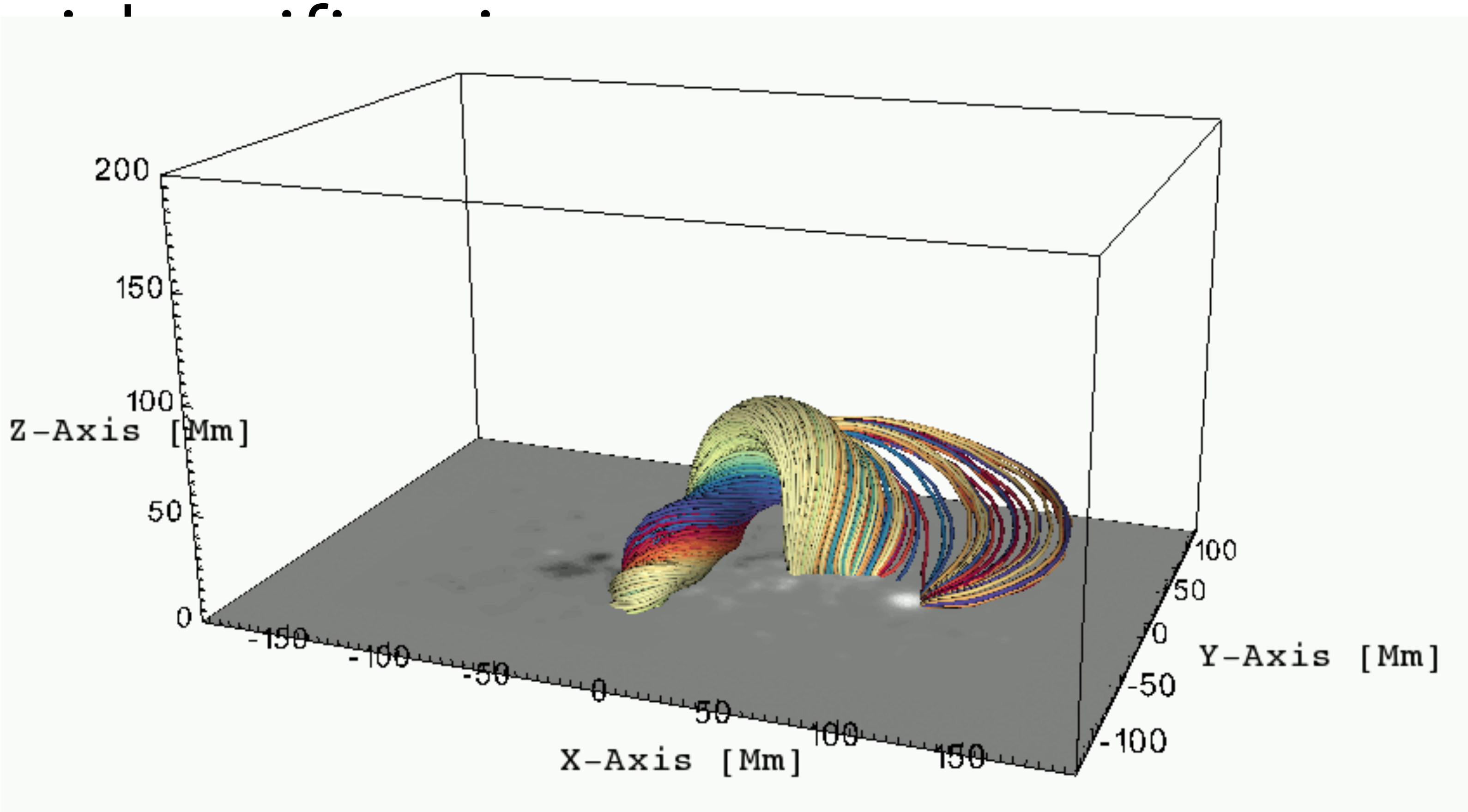
B-field from data-driven modelling

- **photospheric magnetograms** used as the **input** to **extrapolate** the field in the corona
- Nonlinear force-free field modelling **NLFFF** (static)
- **Magnetofrictional** modelling (can be done time-dependently and computer efficiently)
- **MHD** modelling (time-consuming, but includes plasma dynamics)



Realism versus computer efficiency and simplicity

Automated flux rope

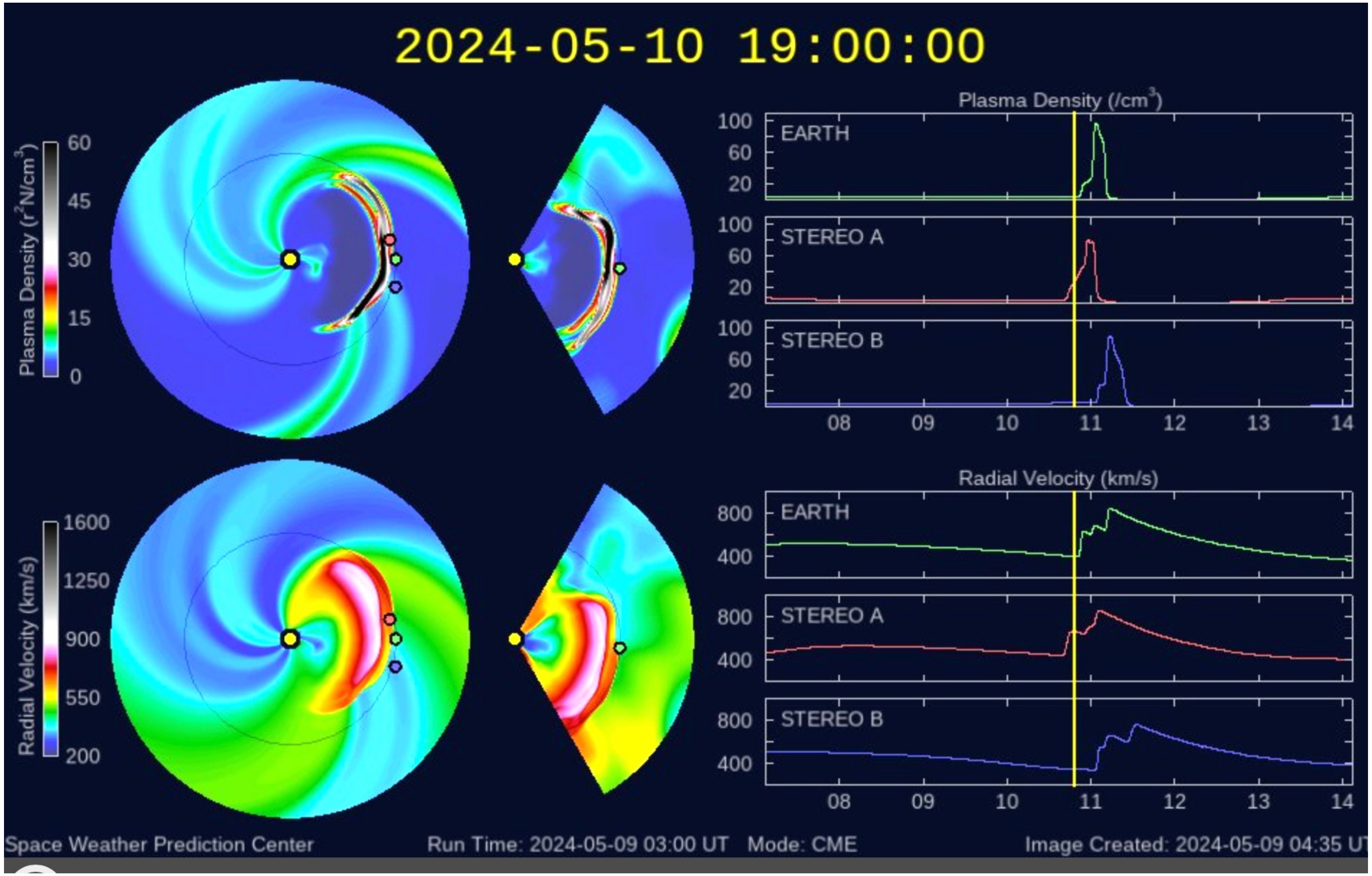


Wagner et al., 2022; 2023; 2024/SWATNet project

Modelling Evolution in the Heliosphere

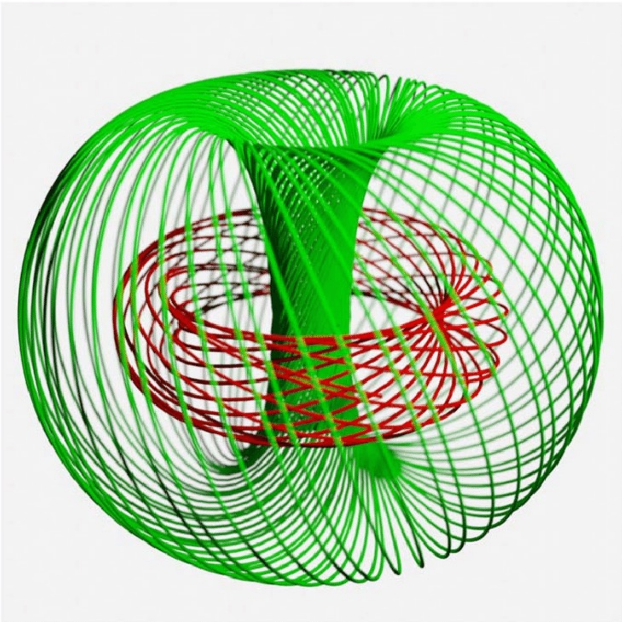
- Intrinsic FR properties can used to make the first estimate on geomagnetic response, constrain **CME models** in heliospheric simulations or in semi-empirical models
- **Cone CME model** does not have internal field, but gives information of CME's impact, speed, density and field magnitude
- Several **magnetized CME models** are implemented e.g., in EUHFORIA

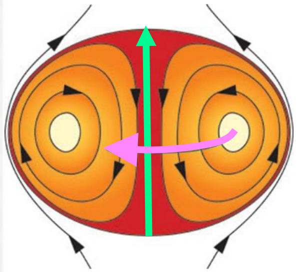
Cone model predictions

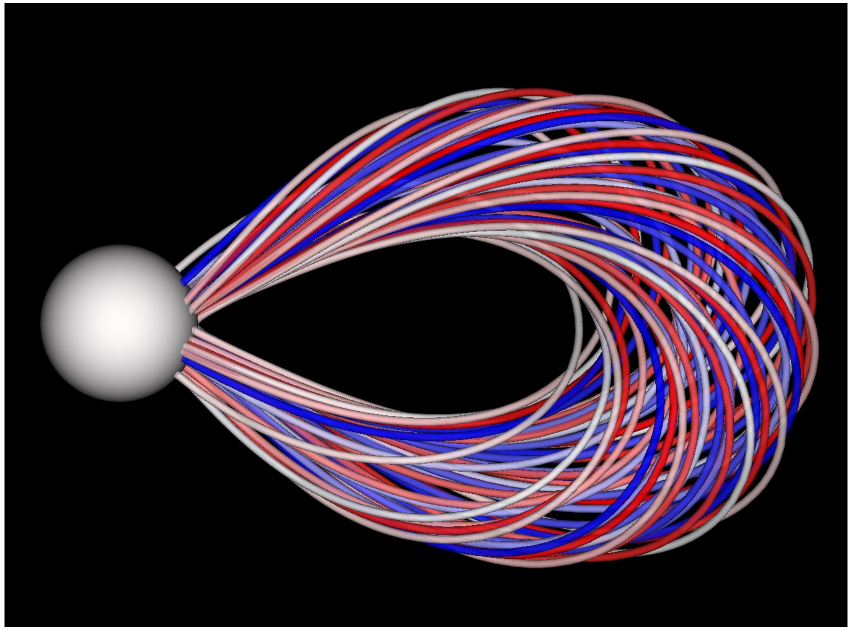


NOAA predictions

Magnetized CME models

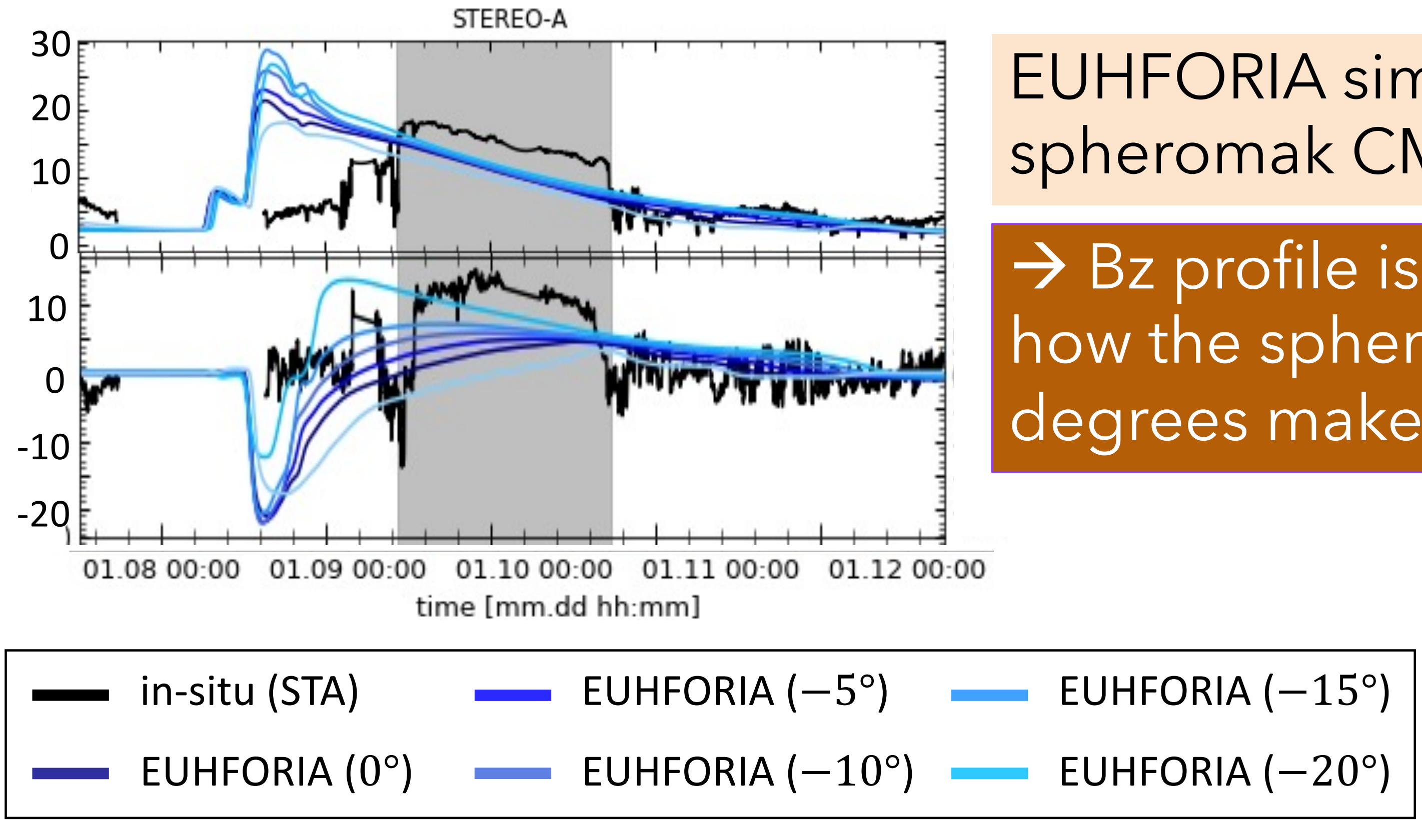






Courtesy: Jens Pomoell

EUHFORIA example (with magnetized CME)



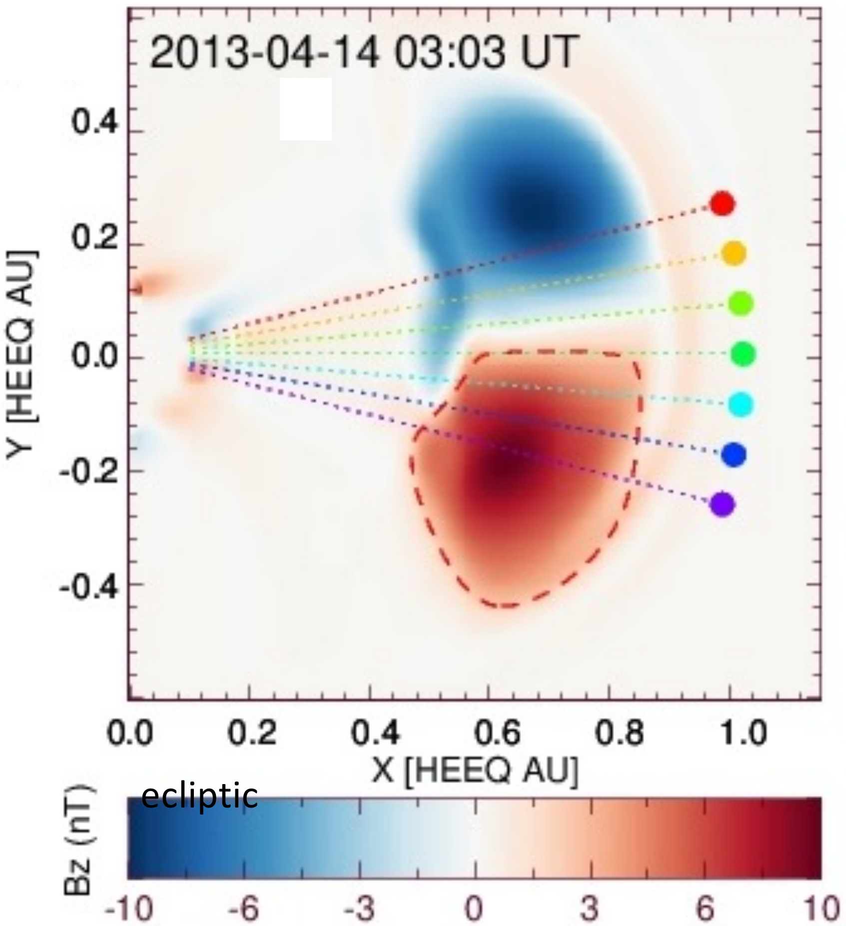
EUHFORIA simulation with a spheromak CME

→ Bz profile is **sensitive** to how the spheromak is cut (5 degrees makes a difference!)

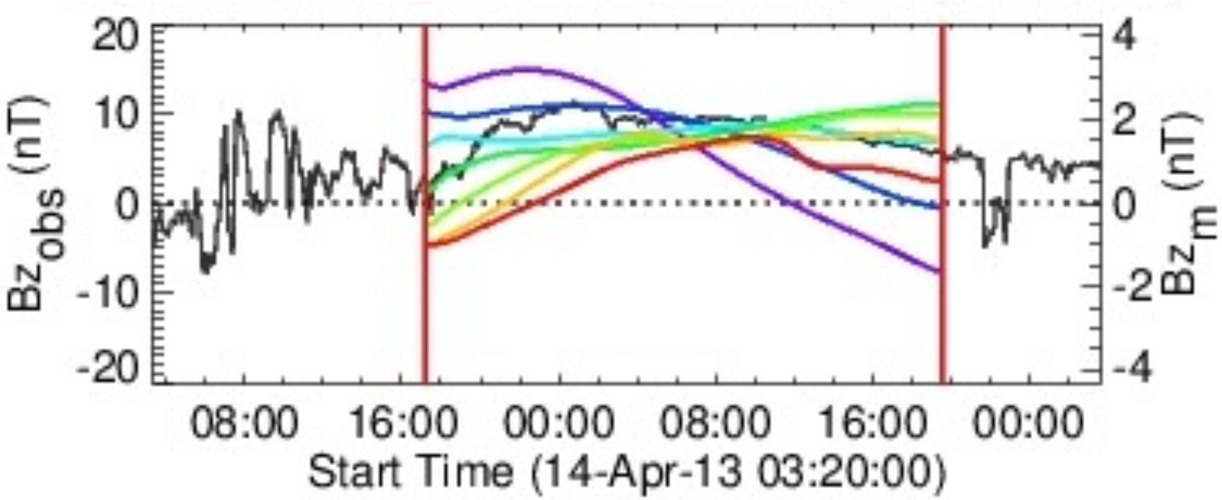
in-situ data compared with the virtual spacecraft at different longitude

Asvestari et al., A&A, 2021

Consequences to geoeffectivity

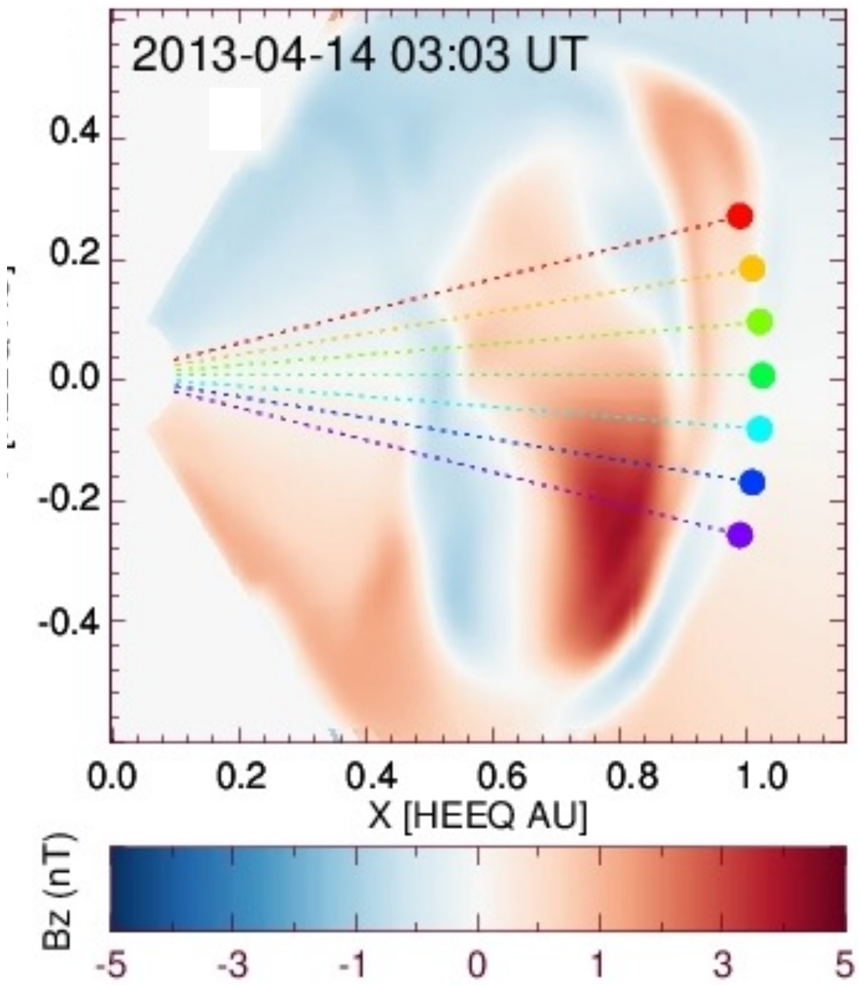


ecliptic

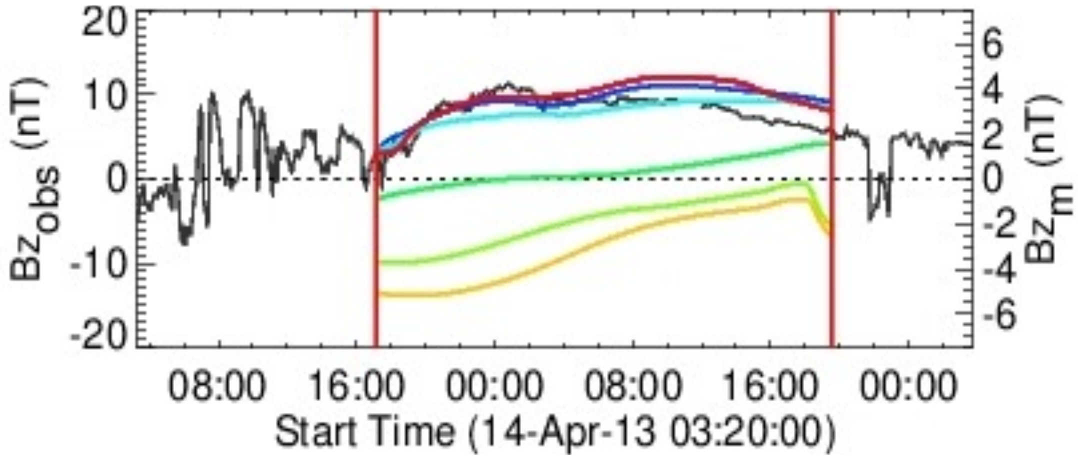


Sarkar et al., 2024

Consequences to geoeffectivity



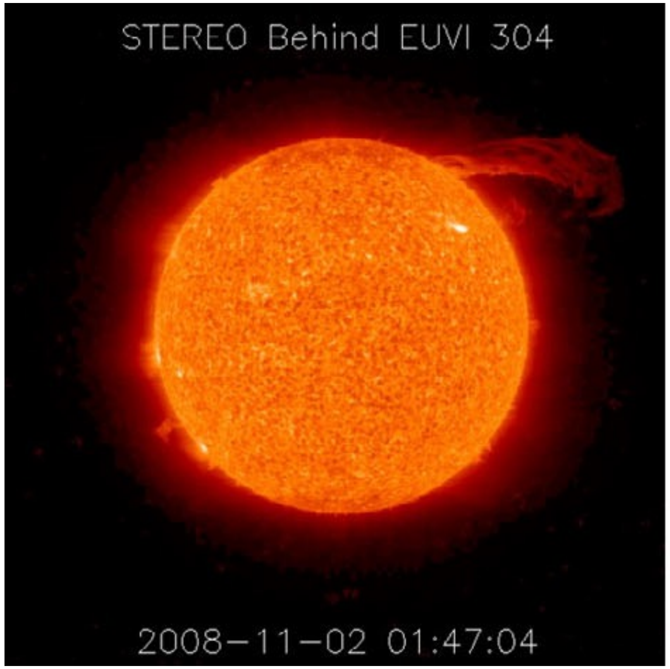
meridional

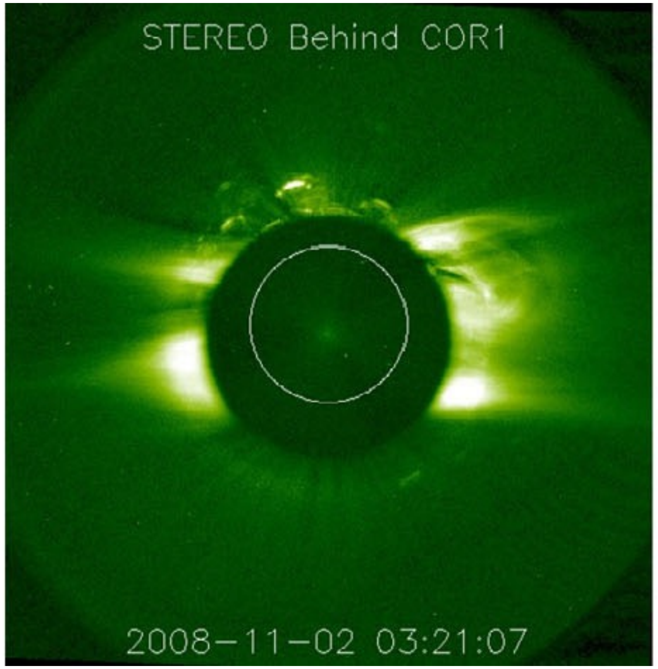


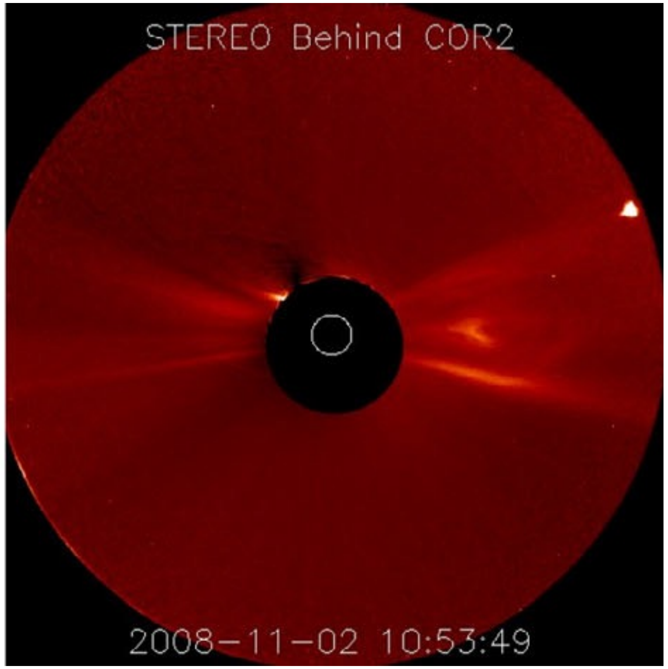
Sarkar et al., 2024

Challenges in forecasting FR properties

CME **deflection** in **longitude** and **latitude**



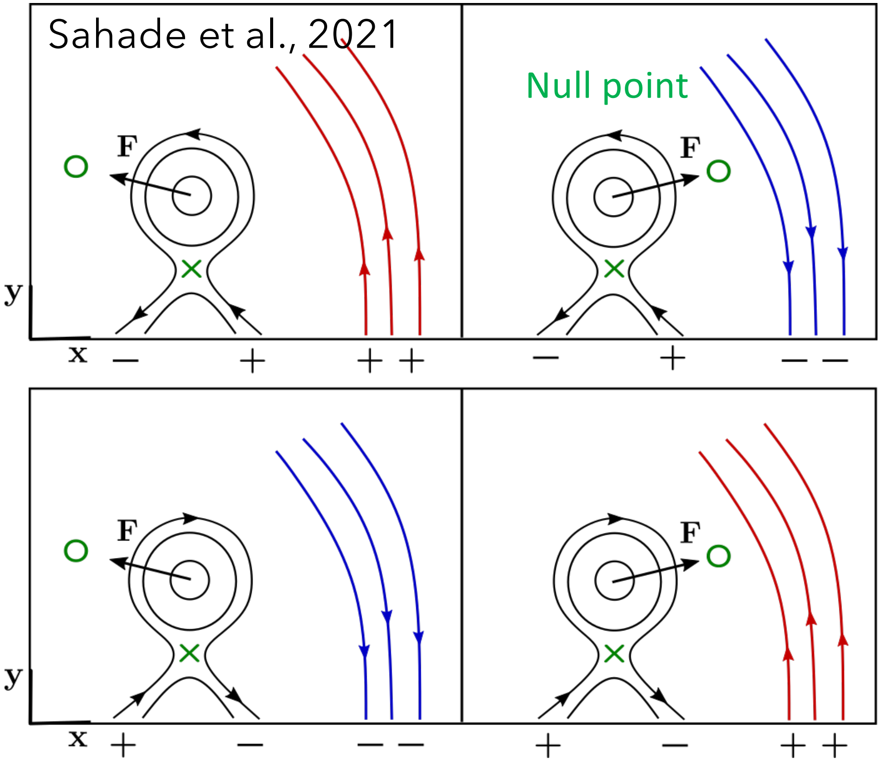




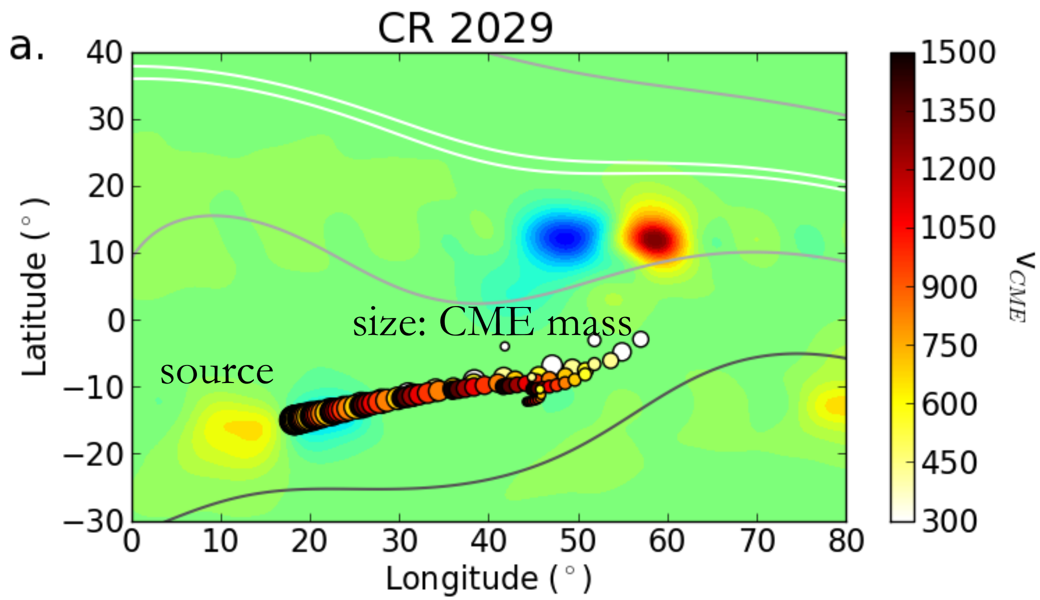
Kilpua et al., 2009

Challenges in forecasting FR properties

CME **deflection** in **longitude** and **latitude**



→ **Field direction** between **FR** and **ambient** dictate the direction

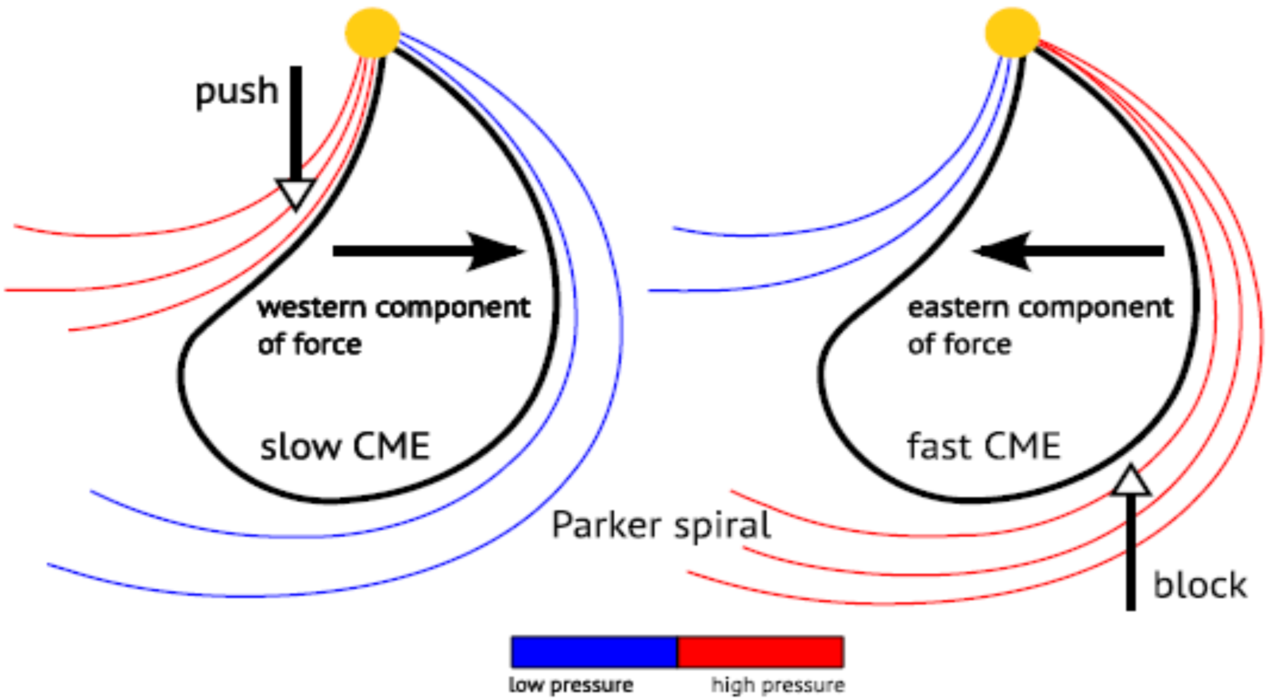


→ fast and massive CME deflect least

Kay et al., 2015

Challenges in forecasting FR properties

CME **deflection** in **longitude** and **latitude**

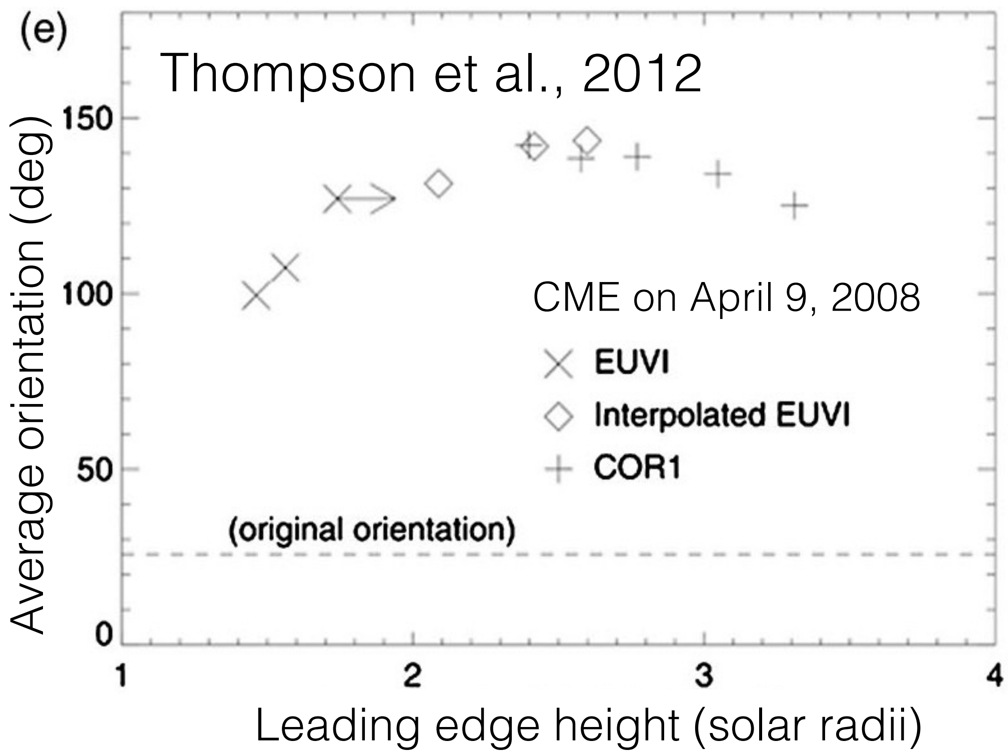


Wang et al., 2004

→ Slow CMEs deflect to the **west**, fast ones to the **east**

Challenges in forecasting FR properties

CME **rotation**



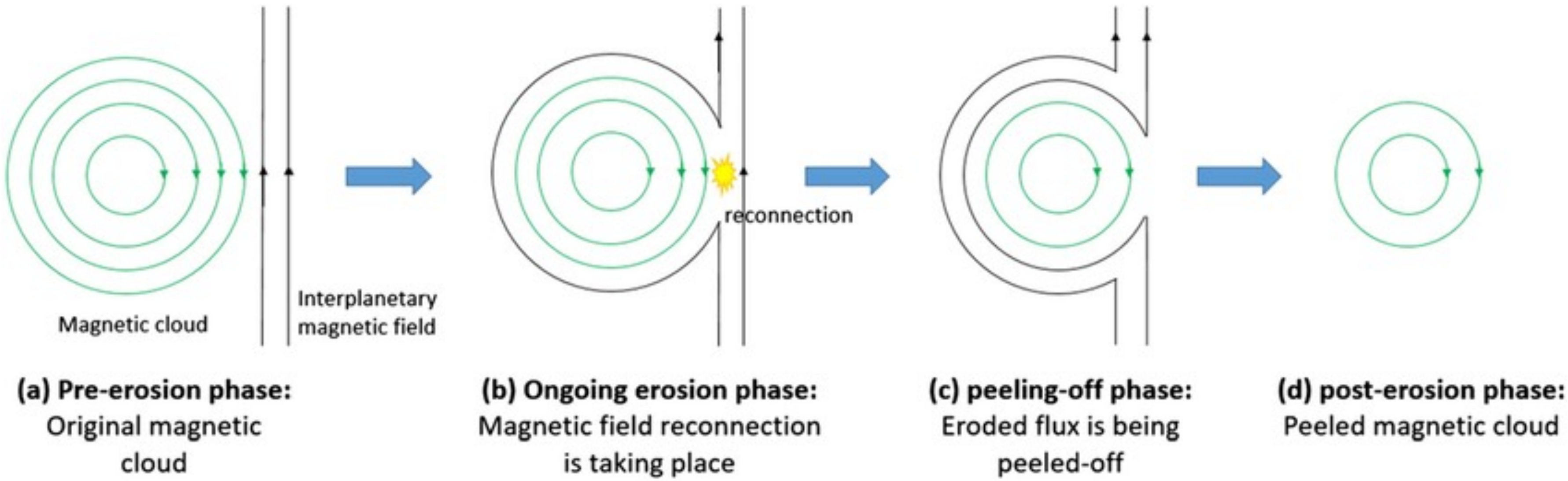
Some CMEs rotate very fast and over a large angle (> 90°), e.g. Vourlidas et al., 2011

Fast rotation occurs typically very low in the corona (where magnetic forces are strong)

The sense of the rotation depends on the **helicity sign** of the erupting **FR** (e.g. Zhou et al., 2022)

Challenges in forecasting FR properties

CME **erosion**

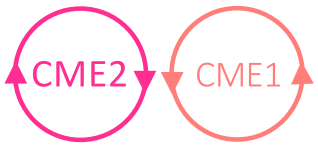


Stamkos et al., 2023

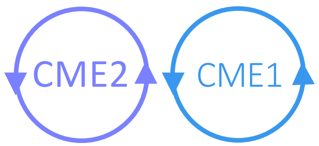
A significant amount of magnetic flux can erode during interplanetary propagation (up to ~50% by 1 au) (e.g. Ruffenach et al, 2015, Pal et al., 2021)

Challenges in forecasting FR properties

CME – CME **interactions**



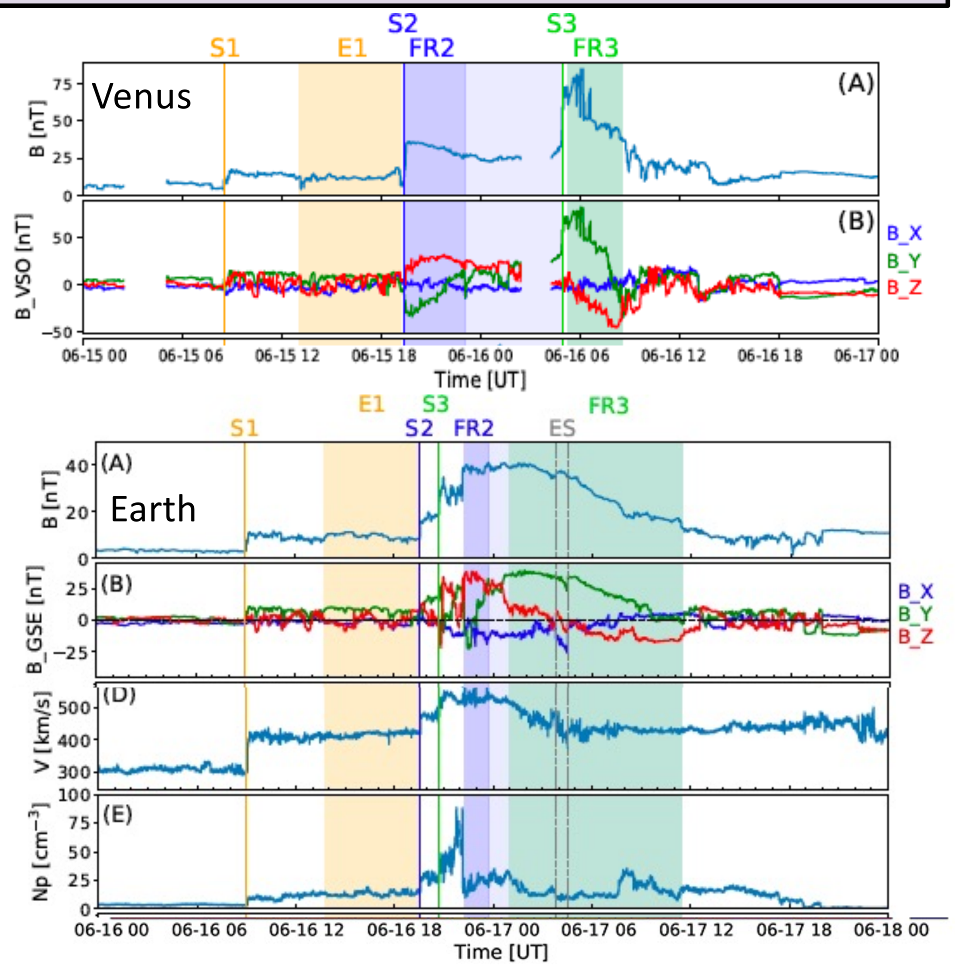
fields at the contact point in the **same direction** → compression → larger field



fields at the contact point in the **opposite direction** → reconnection → lower field (complex ejecta)

(e.g. Manchester et al., 2017; Lugaz et al., 2017; Kilpua et al., 2019)

Kilpua et al., 2019 →



Challenges in forecasting FR properties

CME – SIR/HSS **interactions**

- SIR/fast stream behind a CME **compresses** it

- Geomagnetic reponse depends strongly on the **FR type**
  - **NS**-type FR + SIR/HSS → **southward** fields compress → stronger storm
  - **SN**-type FR + SIR/HSS → **northward** fields compress → no effect

Finally CMEs and SIRs merge into large **compound structures**

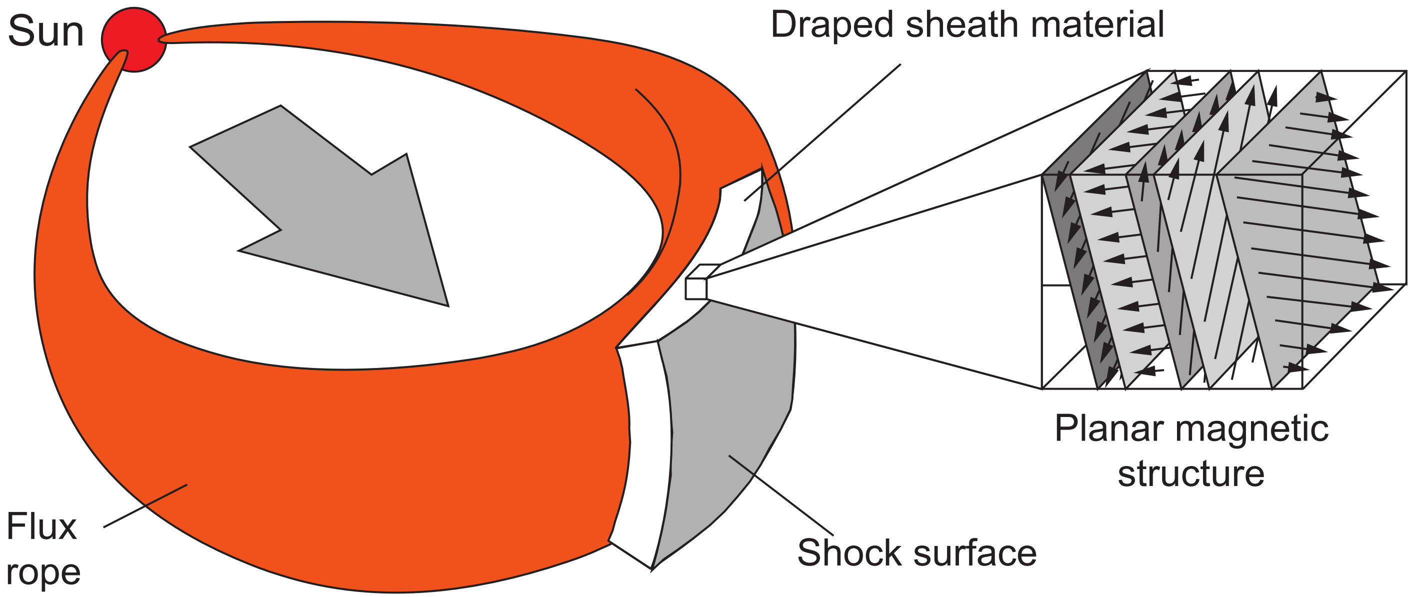
e.g. Fenrich and Luhmann, 1994; Kilpua et al., 2012

Challenges in forecasting FR properties

Preconditioning of the heliosphere

A CME /CMEs propagate(s) in the **low-density** wake of the previos CME(s)
→ **minimal drag**
→ minimal deceleration
→ higher speed and field maintained
→ "**perfect** (major) **storm**" (e.g., Liu et al., 2014)

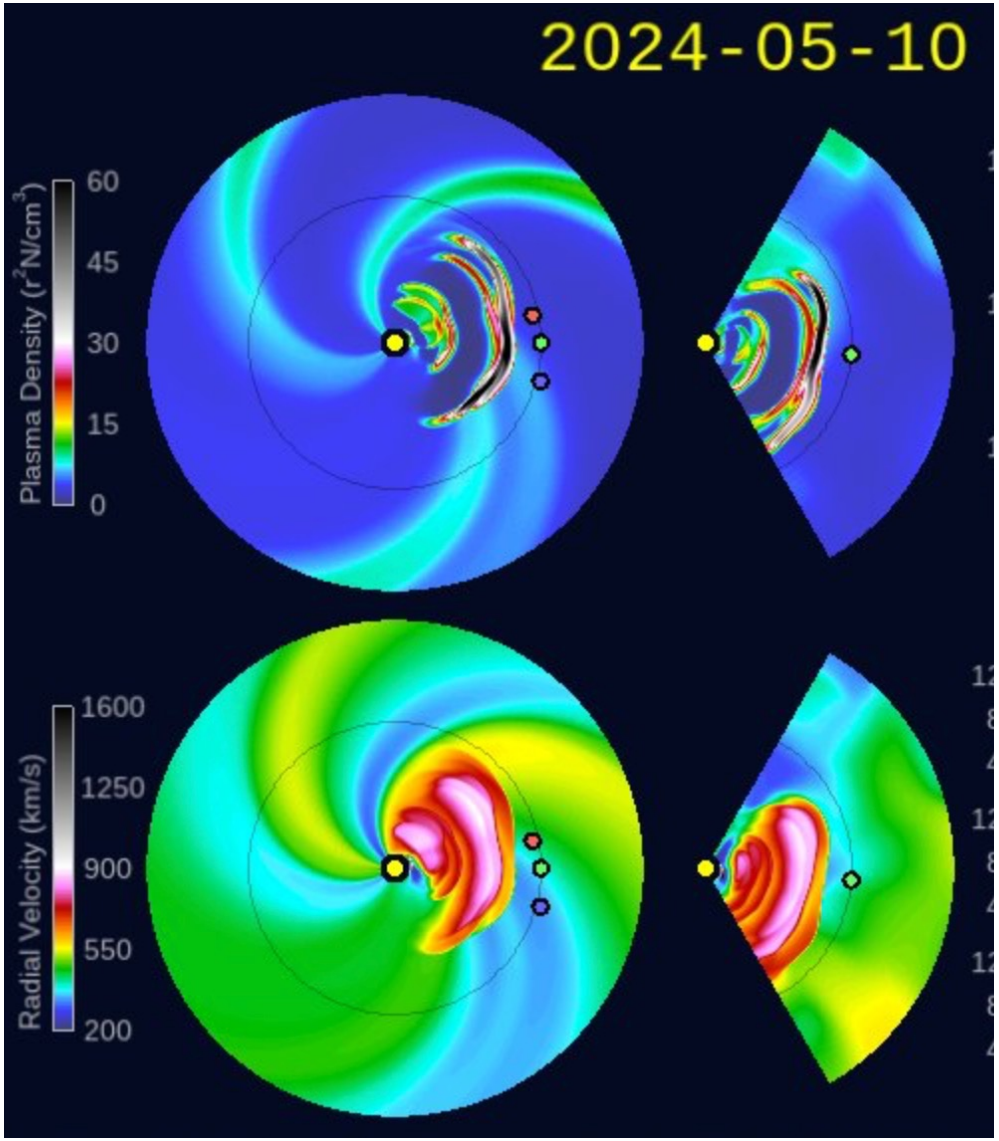
Forecasting sheath fields



Field variations tend to occur parallel to a single plane due to draping of the IMF and amplification and alignment of pre-existing discontinuities at the shock (e.g., Jones and Balogh, 2002; Kataoka et al., 2005). Planar parts are the most geoeffective (Palmerio et al., 2016)

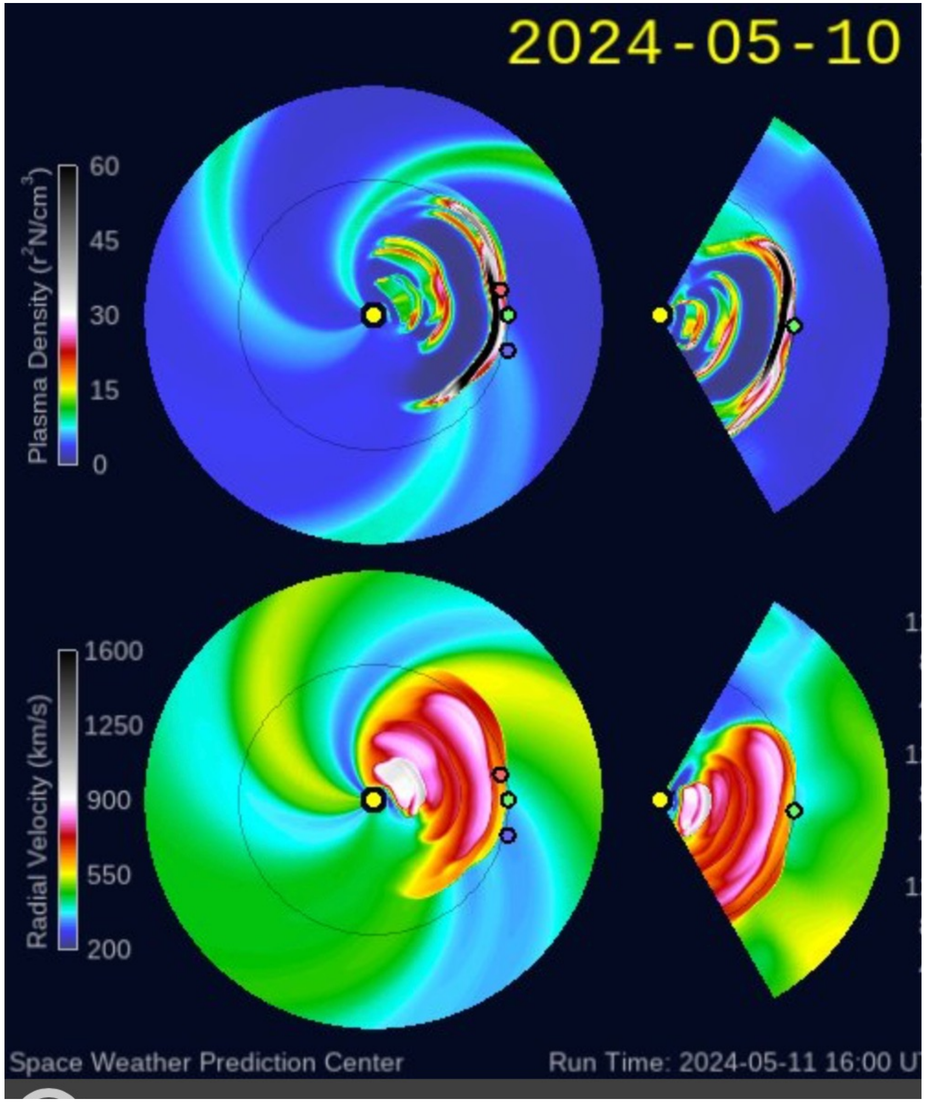
Challenge of predicting sheath fields

- Sheath properties depend strongly both on the background solar wind and driving characteristics
- Form gradually as CME propagates and expands from Sun to Earth
- Large variations from shock to the ejecta leading edge
- Small scale and kinetic properties / processes are important



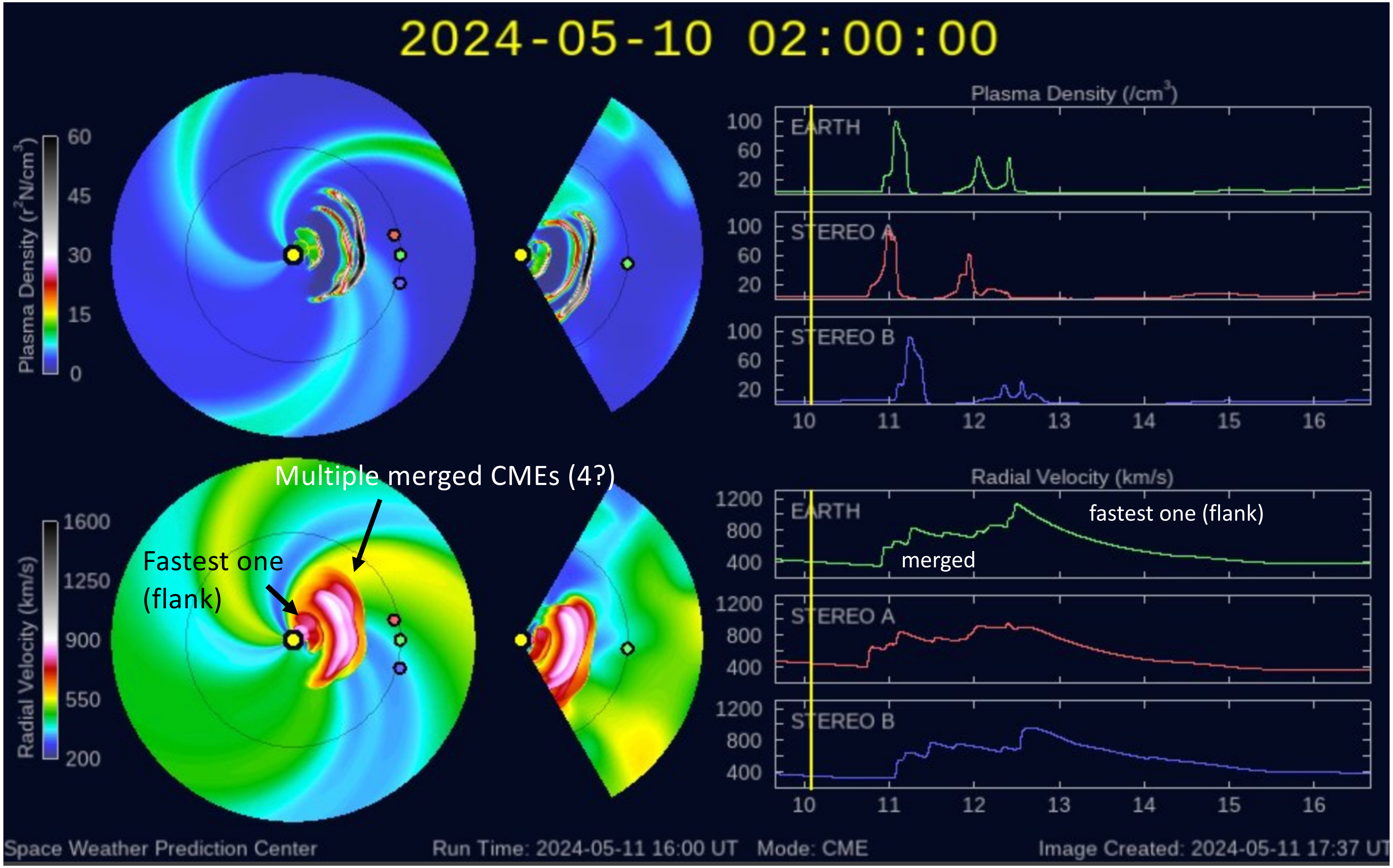
Four CMEs here coming towards the Earth! (two intersting pairs)

(fastest one still to be launched)

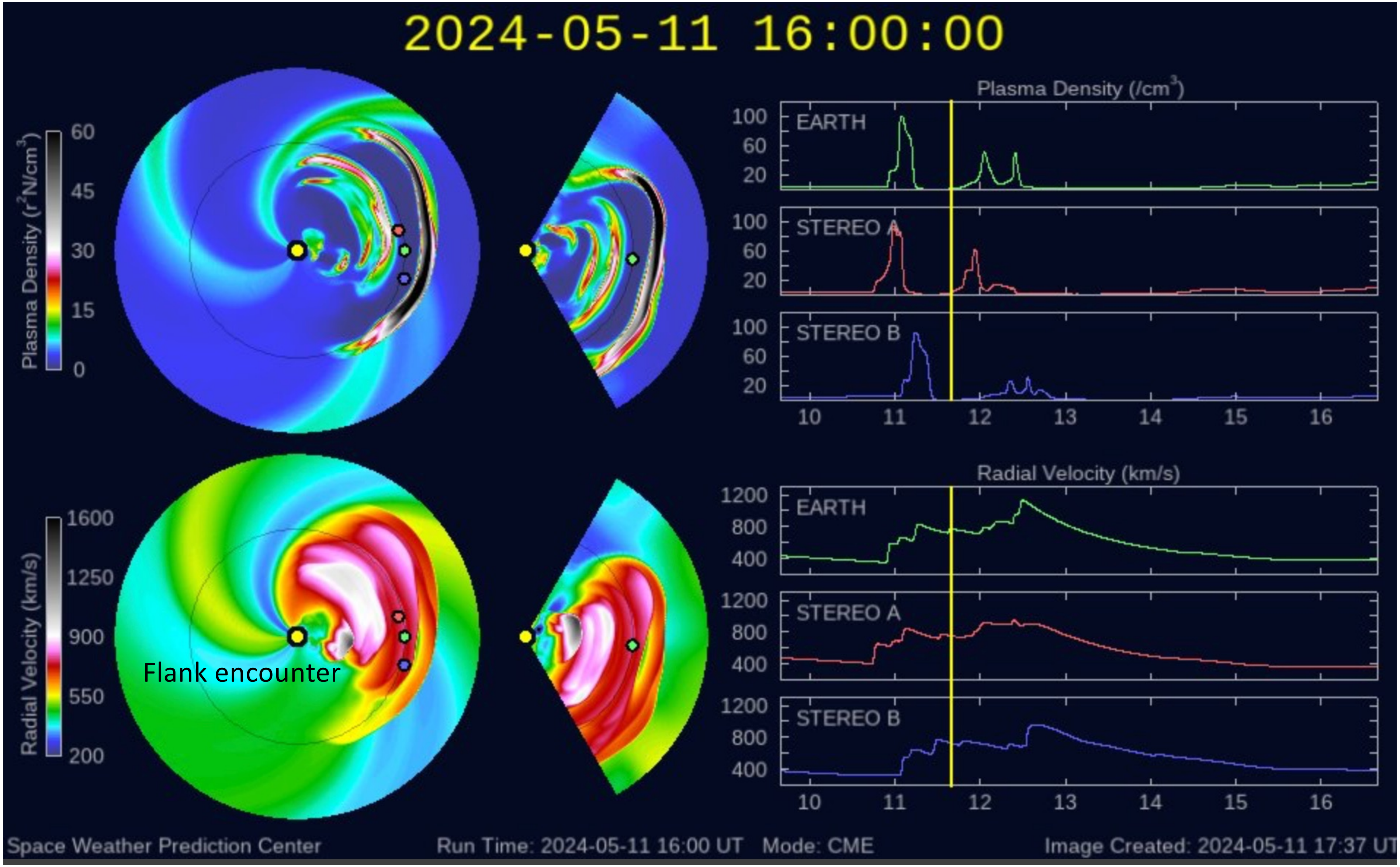


The first pair of merged CMEs hitting centrally the Earth

The fastest CMEs just launched and catching the other pair of merged CMEs



2024-05-10 02:00:00
Plasma Density (r²N/cm³)
60
45
30
15
0
Plasma Density (/cm³)
EARTH
STEREO A
STEREO B
100
60
20
10
11
12
13
14
15
16
Radial Velocity (km/s)
1600
1250
900
550
200
Multiple merged CMEs (4?)
Fastest one (flank)
Radial Velocity (km/s)
1200
800
400
fastest one (flank)
merged
Space Weather Prediction Center
Run Time: 2024-05-11 16:00 UT
Mode: CME
Image Created: 2024-05-11 17:37 UT



2024-05-11 16:00:00
Plasma Density (r²N/cm³)
60
45
30
15
0
Radial Velocity (km/s)
1600
1250
900
550
200
Flank encounter
Plasma Density (/cm³)
EARTH
STEREO A
STEREO B
100
60
20
Radial Velocity (km/s)
1200
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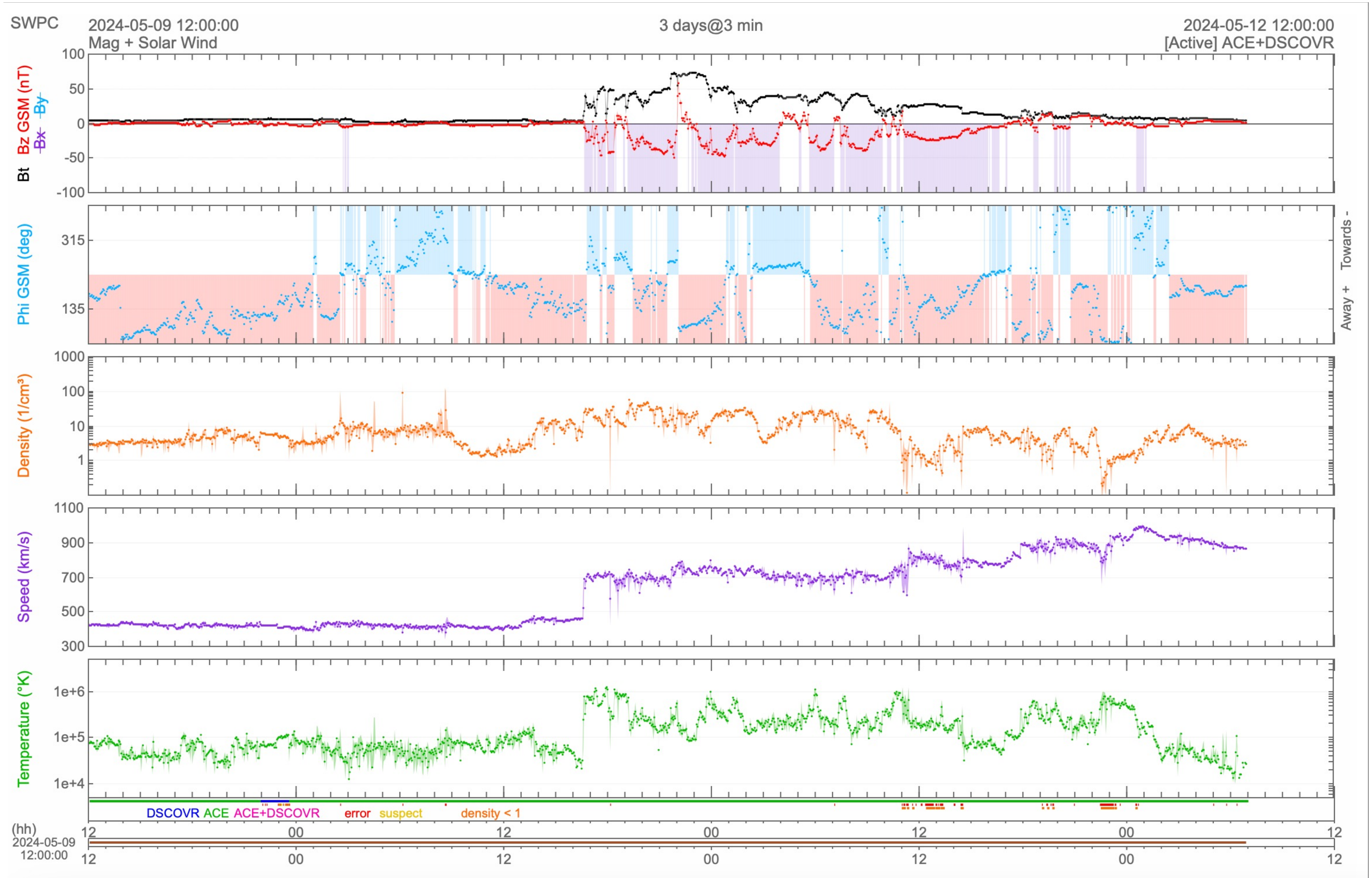
Space Weather Prediction Center
Run Time: 2024-05-11 16:00 UT
Mode: CME
Image Created: 2024-05-11 17:37 UT


SWPC
2024-05-09 12:00:00
Mag + Solar Wind
3 days@3 min
2024-05-12 12:00:00
[Active] ACE+DSCOVR
Bt
Bz GSM (nT)
Bx
By
Phi GSM (deg)
Towards -
Away +
Density (1/cm³)
Speed (km/s)
Temperature (°K)
DSCOVR ACE ACE+DSCOVR error suspect density < 1
(hh)
2024-05-09
12:00:00

Summary

- Forecasting of geoffects from SIRs and ICMEs is highly challenging
- Long-lead time forecasts require using remote-sensing solar observations and modelling (first-principle simulations, semi-empirical, …)
- A wide variety observations are needed (magnetograms, EUV, white-light, X-rays, …)
- Lack of direct magnetic field observations is a severe issue for reliable forecasts

Summary

- CME evolution and interactions complicate the predictions (intrinsic properties + modifications in interplanetary space)
- Turbulent sheath structure is also challenging to forecast