International Study of Earth-affecting Solar Transients (ISEST) 2018 Workshop

Working Group 3 (Simulation) Progress Report

Dusan Odstrcil and Fang Shen

with contribution from: Camilla Scolini, Christine Verbeke, Tibor Torok

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International Study of Earth-affecting Solar Transients (ISEST)

The main ISEST objective is to "*improve the scientific understanding of the origin and propagation of solar transients, and develop the prediction capacity of these transients' arrival and potential impact on the Earth*".

Working Groups (WG):

WG1 — Data

WG2 — Theory

WG3 — Simulation

WG4 — Campaign study

WG5 — Bs challenge

WG6 — SEPs

WG7 — Min/Max

WG3 Simulation — Scientific Objectives

Group leaders: *Fang Shen (Sigma Group)* and *Dusan Odstrcil (GMU/GSFC)*;
At-large leaders: *Noe Lugaz (UNH)* and *Chin-Chun Wu (NRL)*

(1) Provide global context for all CME events investigated by the ISEST team.

(2) Investigate processes of the CME initiation, heliospheric propagation, and CMEs interaction

(3) Develop tools to assist collaboration of numerical modelers, theoreticians, and observers

Numerical Models — ISEST & *Research Applications*

(1) ENLIL (Sumerian god of wind and storms) model: 1Rs-21.5Rs, WSA (Wang-Sheeley-Arge), transients: hydrodynamic ejecta (Cone or Rope geometry), heliosphere >21.5 Rs – 3D MHD model

(2) COIN-TVD (Corona-Interplanetary Total Variation Diminishing): 1Rs-beyond 1AU: 3D MHD model, transients: magnetized plasma blob model

(3) H3DMHD: 1RS-21.5RS, HAF (Hakamada-Akasofu-Fry) model > 21.5 RS, 3D MHD model

(4) SWMF (Space Weather Modeling Framework, BATSRUS): 1Rs-beyond 1AU: 3D MHD model, transient: transients: analytic magnetic flux rope

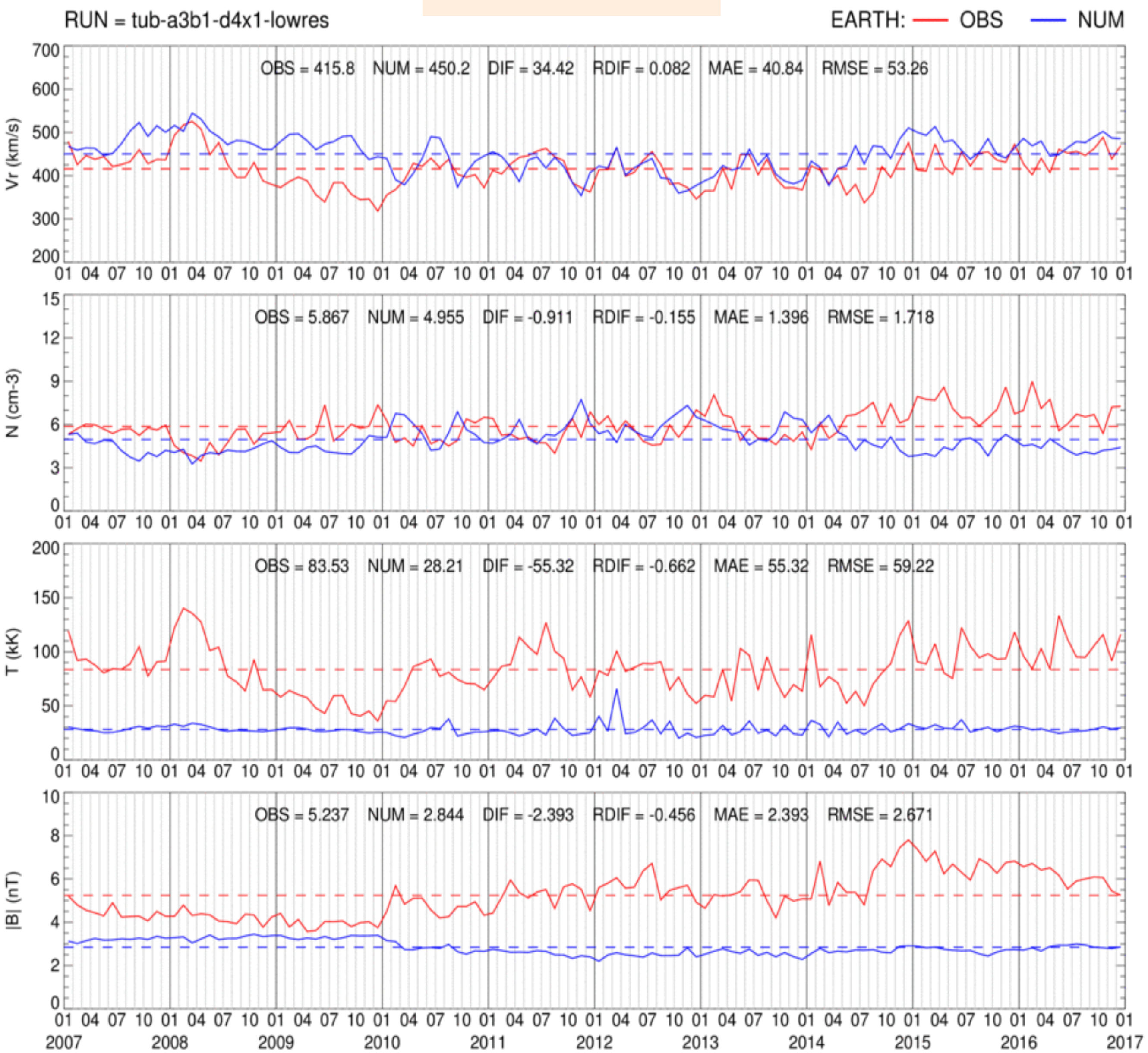
(5) EUHFORIA (European Heliospheric Forecasting Information Asset): 0.1-2 AU, 3D MHD model, transients: cone, flux-rope, spheromak

(6) MAS (Magnetohydrodynamic Algorithm outside a Sphere), coronal thermodynamics and heliospheric code and h, > 1Rs, transients: balanced Titov-Demoulin flux-rope)

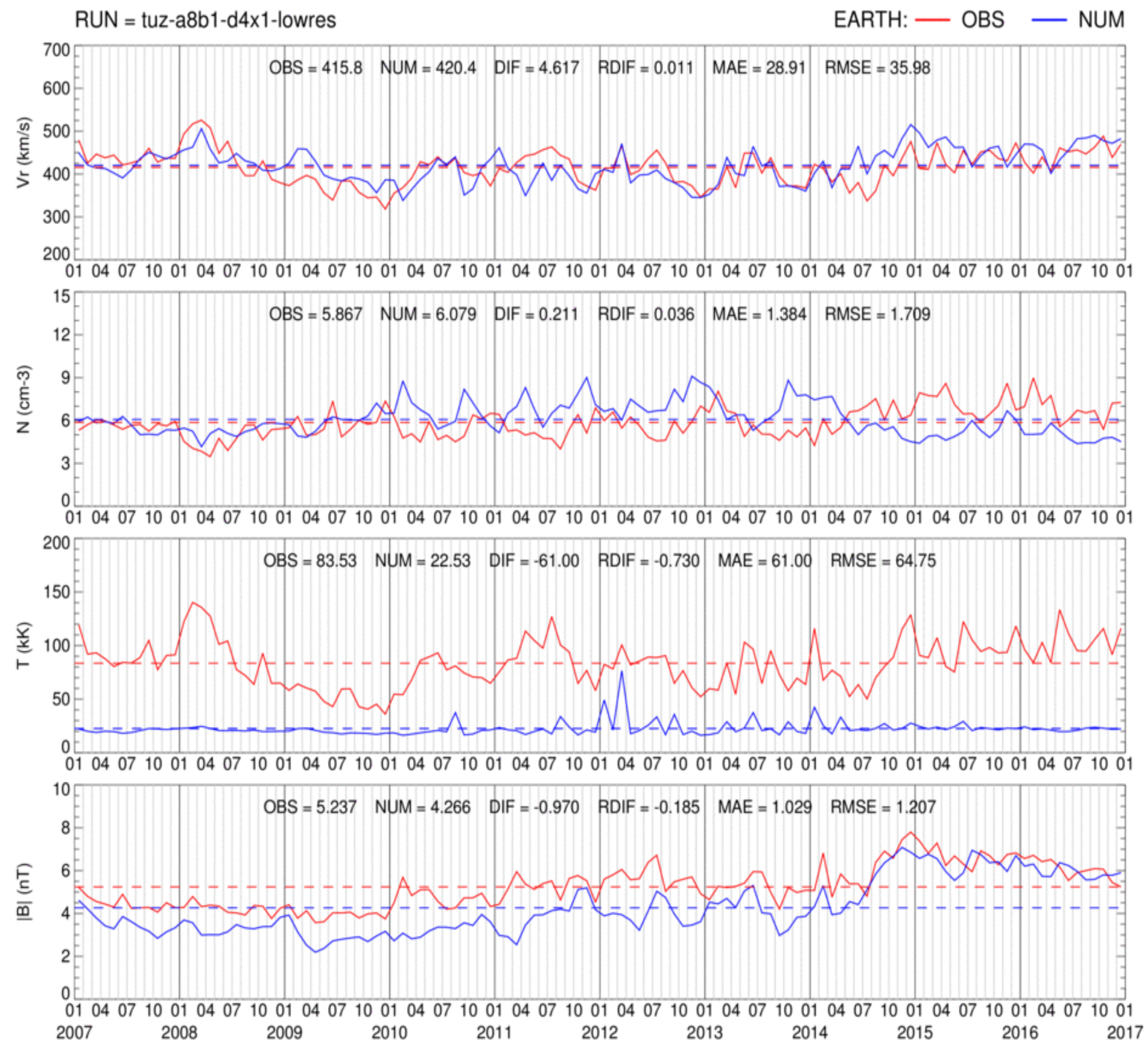
(7) *MS-FLUKSS (Multi-Scale FLUid-Kinetic Simulation Suite):*

ENLIL — Background Solar Wind — Calibration

old: “a3b1”



new: “a8b1”



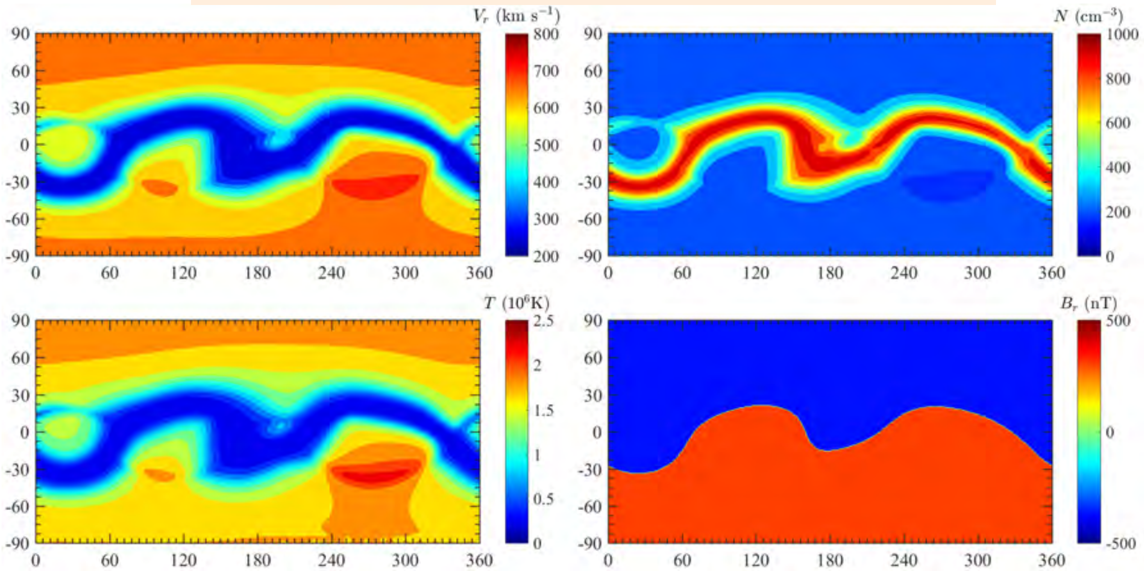
- Delivered: beginning of the solar cycle with limited calibration
- Motivation: ensure robustness & reasonable accuracy during the upcoming solar cycle maximum

- Revised calibration with 2007-2016 (WSA) and 2010-2016 (CME-“cone”) data & larger robustness experience
- Using “mrzqs” instead of “mrbqs” GONG data

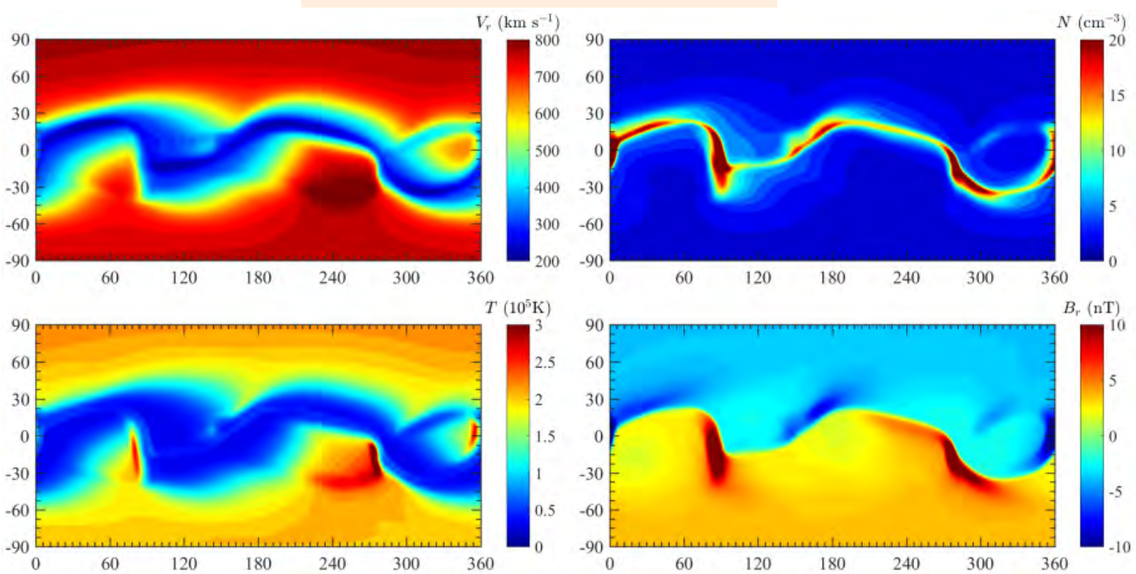
Simulation Results: CR2053 (from 2007-02-04 to 2007-03-04)

(*Fang et al., JSWSC 2018*)

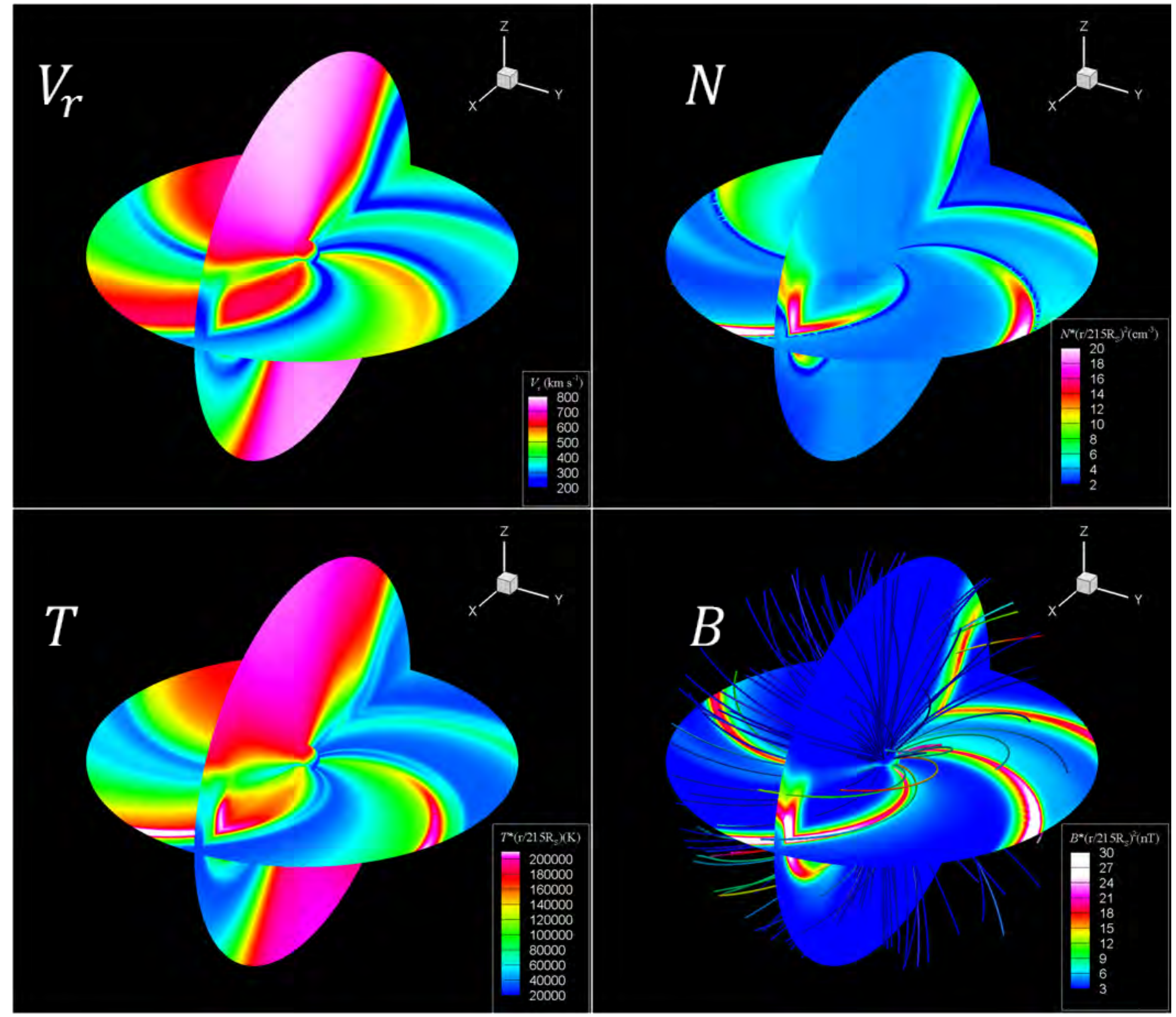
Distributions at the lower boundary



Distributions at 1AU



In the heliospheric equatorial and meridional plane

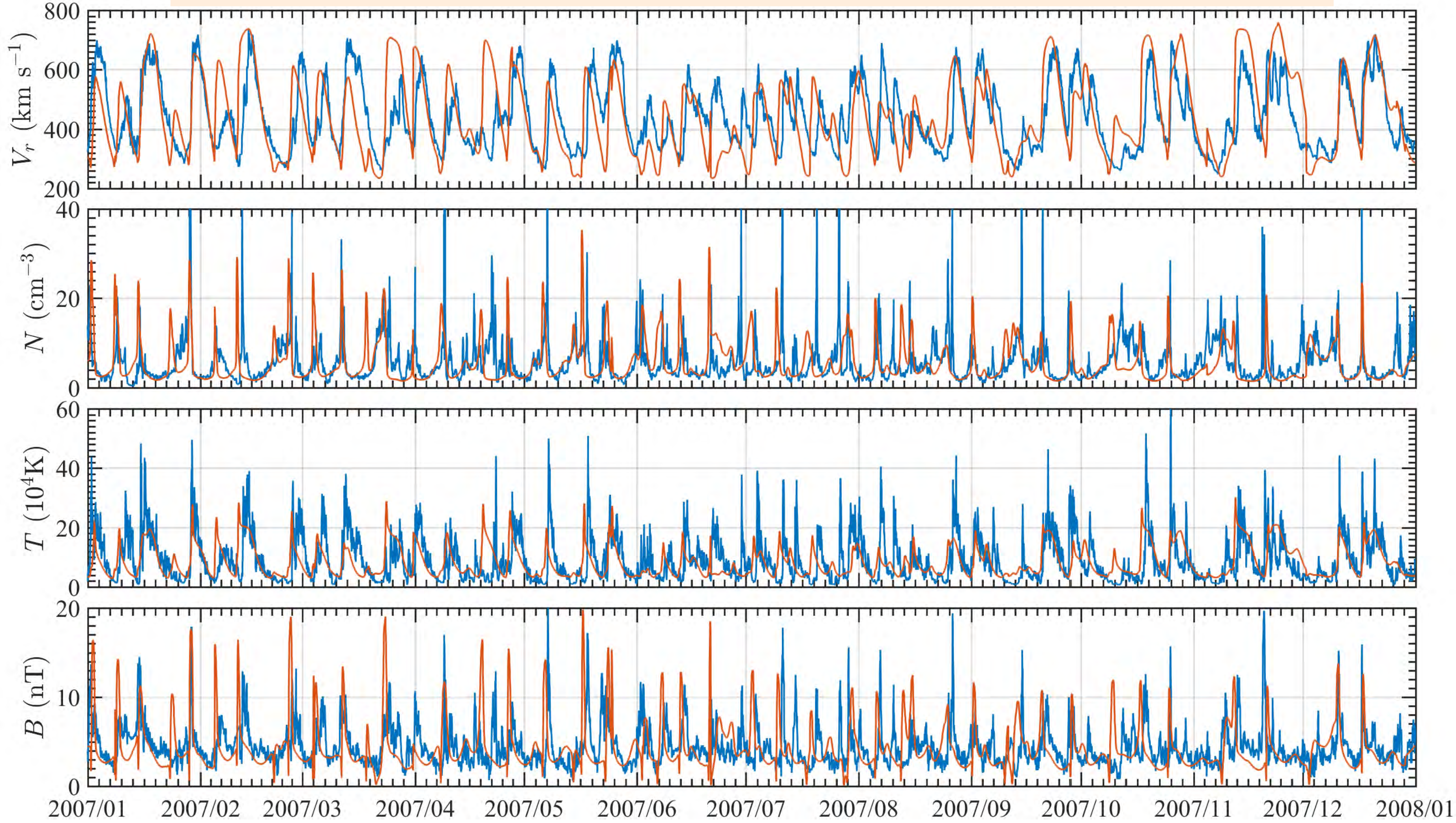


At 1 AU, there is a left shift of ~50^0 in longitude, which reflects the coronating effect. A few compression and rarefaction regions forms due to interactions of the fast and slow speed streams

High-density CIRs between fast and slow solar wind streams, can be clearly recognized. Near the north and south poles, high-speed wind dominates. However, there is a mix of slow and fast winds at all latitudes.

Simulation Results: CR2053 (from 2007-02-04 to 2007-03-04)
(*Fang et al., JSWSC 2018*)

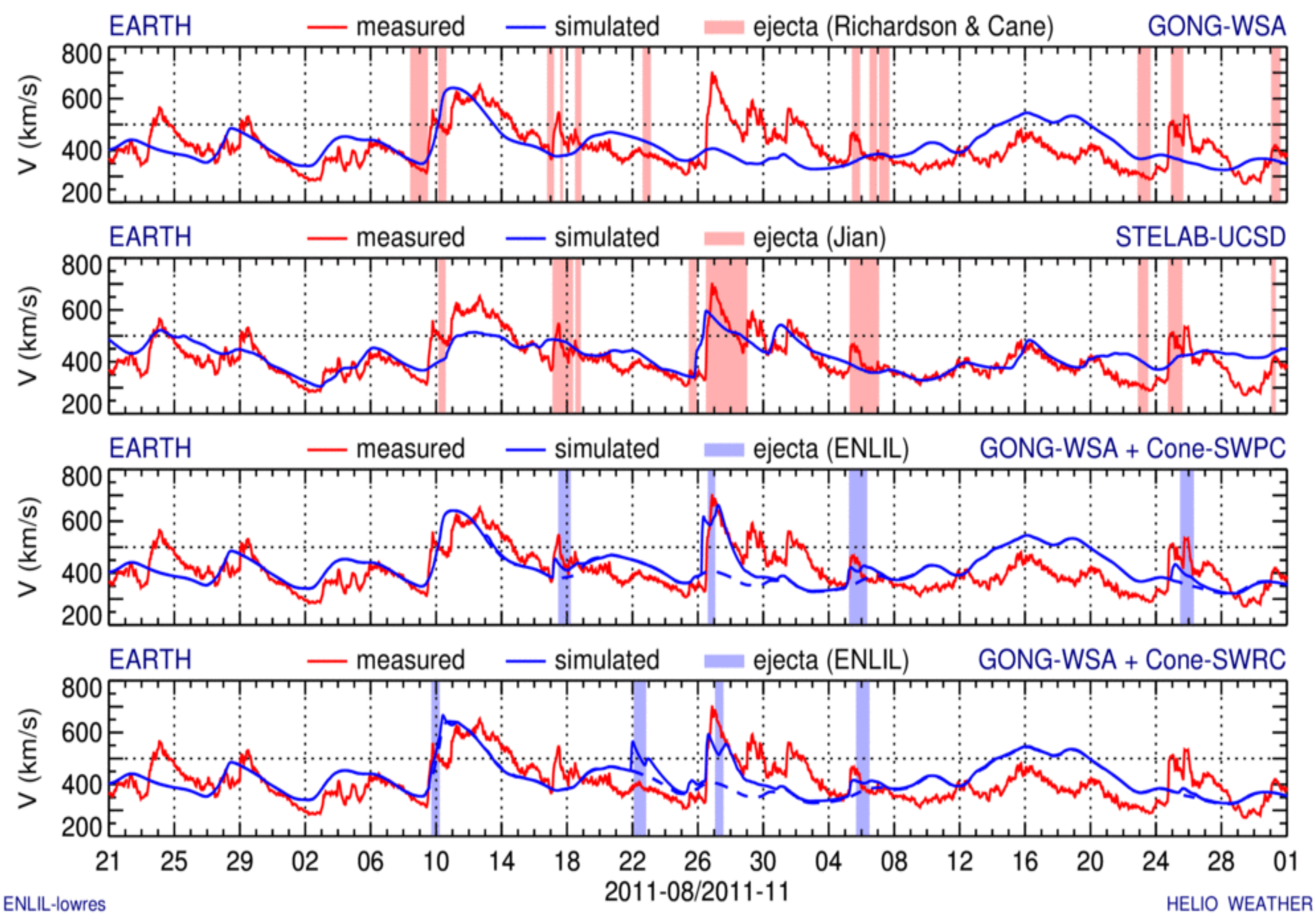
Modeled and observed profiles of solar wind parameters at 1AU



The ambient solar wind without transient events — an accurate speed boundary condition is very important for predicting the magnetic field strength.

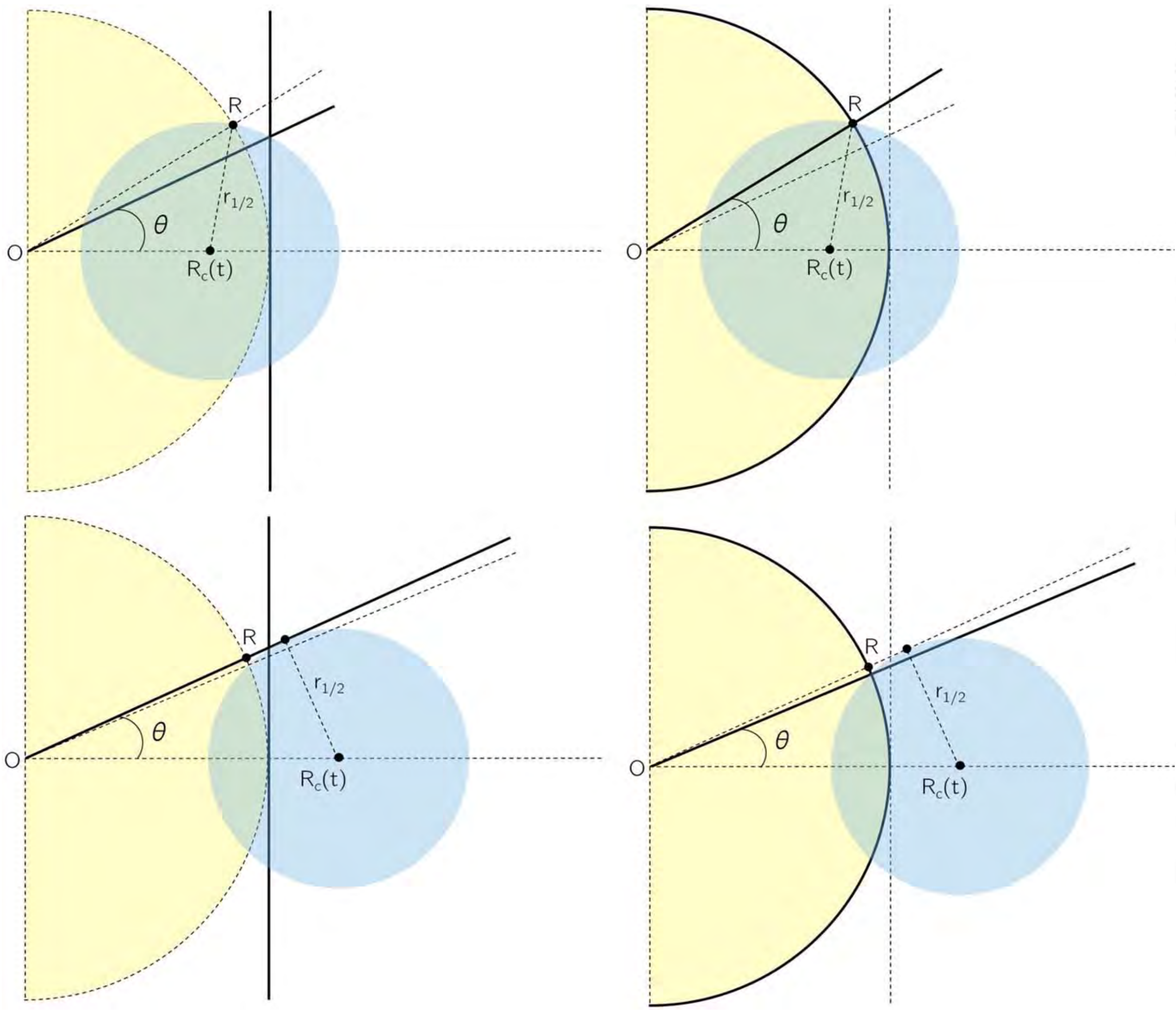
Space Weather at Venus During the Forthcoming BepiColombo Flybys
(*McKenna-Lawlor et al., PSS 2018*)

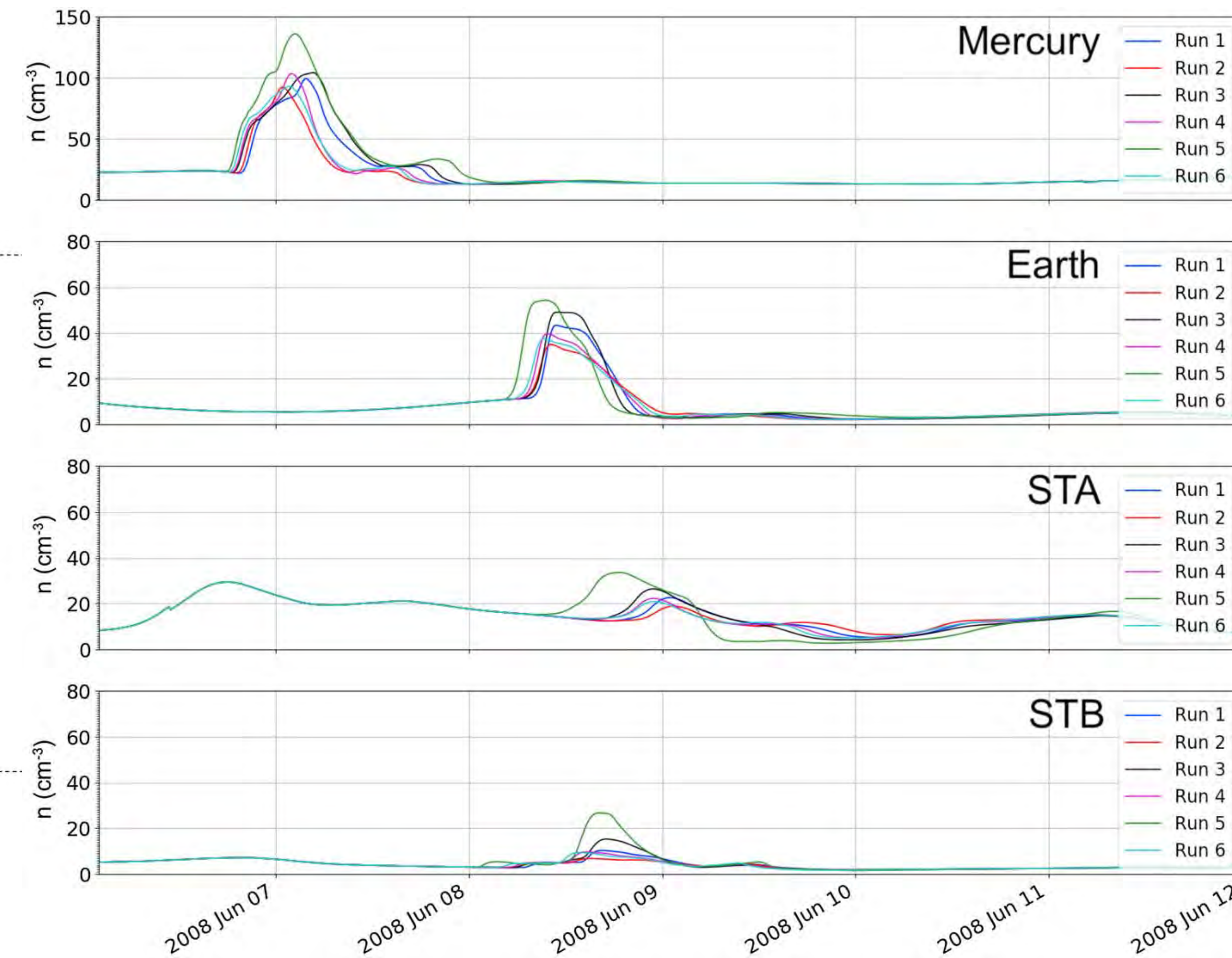
Driving the background solar wind by IPS data — alternative to magnetograms (WSA)



- No ICME on 2011-09-27 in Richardson & Cane caused by poor ACE data
- The 2011-09-24 CME arrives at Earth similarly on 09-27 for all cases

Effect of the Initial Shape of CMEs
(*Scolini et al., 2018*)





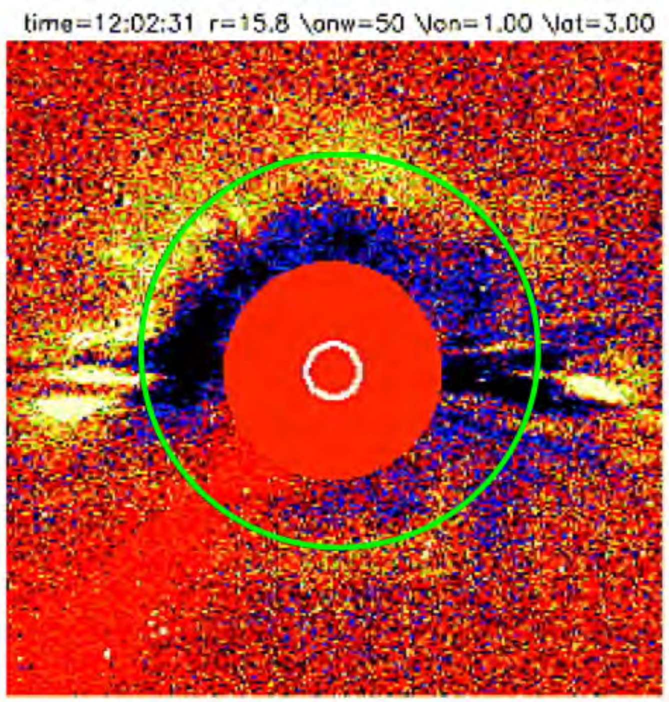
Opening angle at two different times: $0 < t < t1/2$ (top row) and $t1/2 < t < ttot$ (bottom row) in the case of a sphere crossing a planar boundary as defined by two different equations

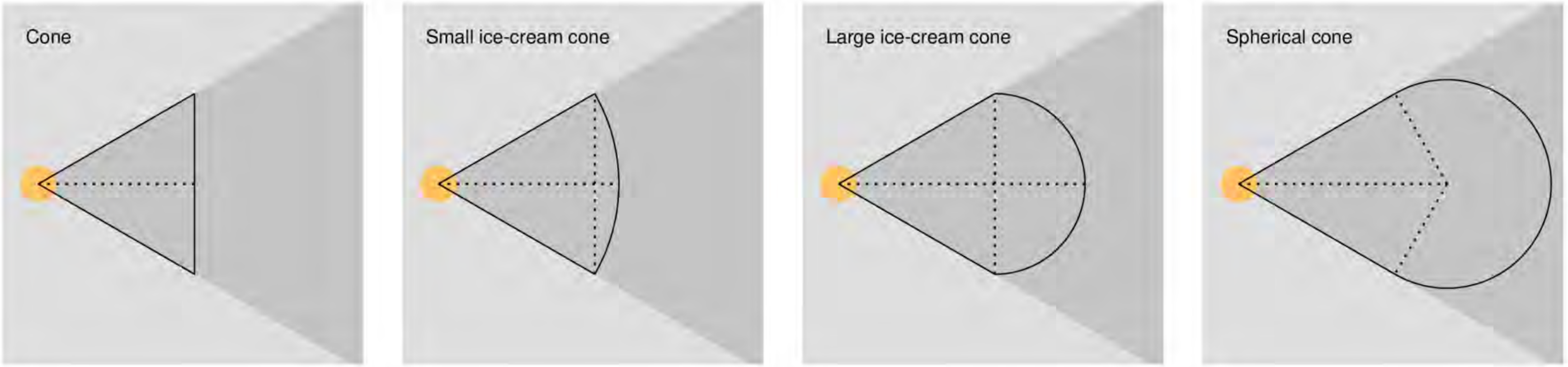
Number density at Mercury, Earth, STA, and STB, as function of time (saved with a 10-min cadence). The curves refer to the different configurations

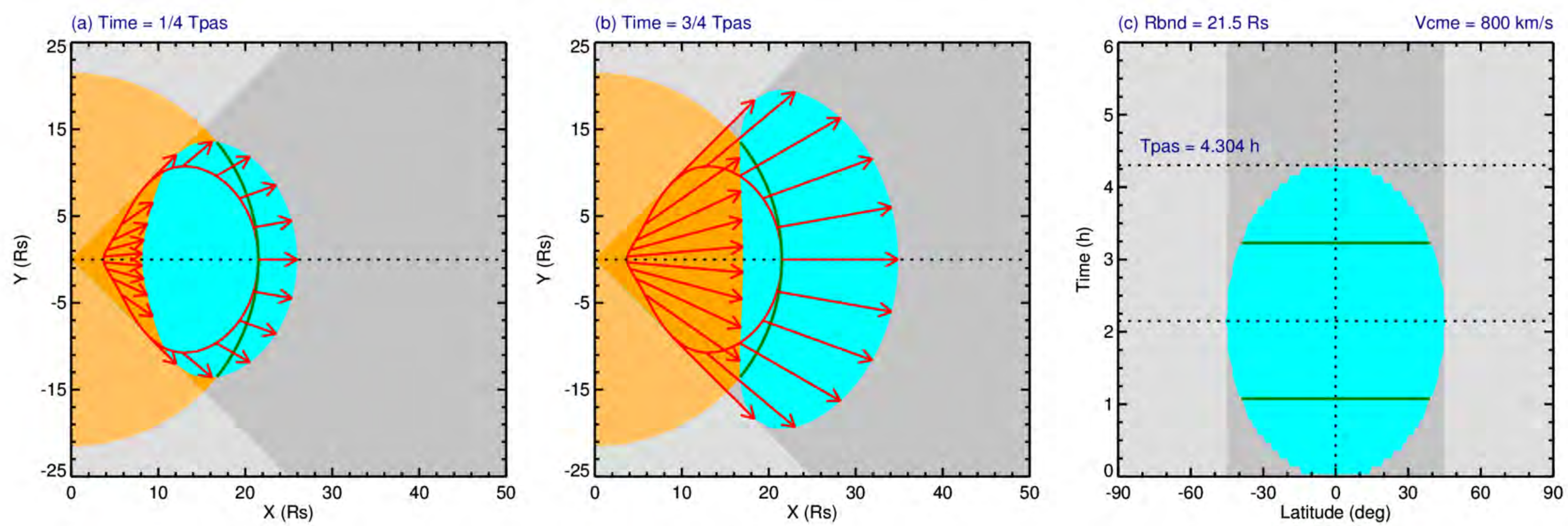
Launching Hydrodynamic Ejecta — Original Possibilities

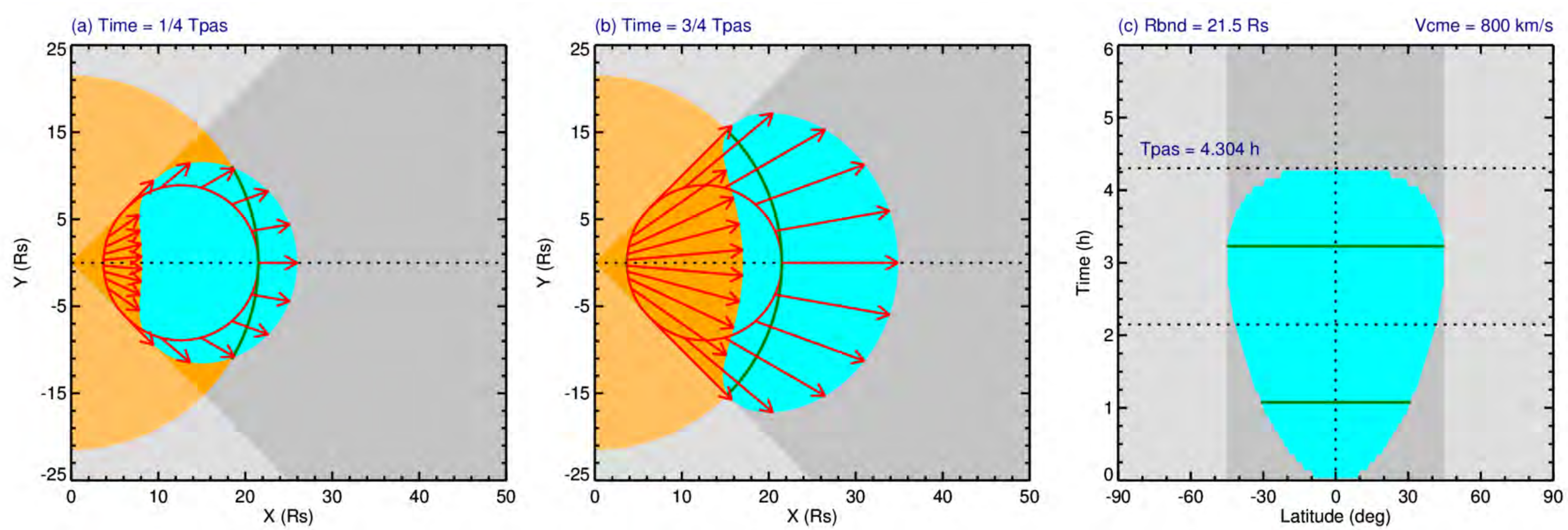
Single-perspective SOHO observations

Running Difference



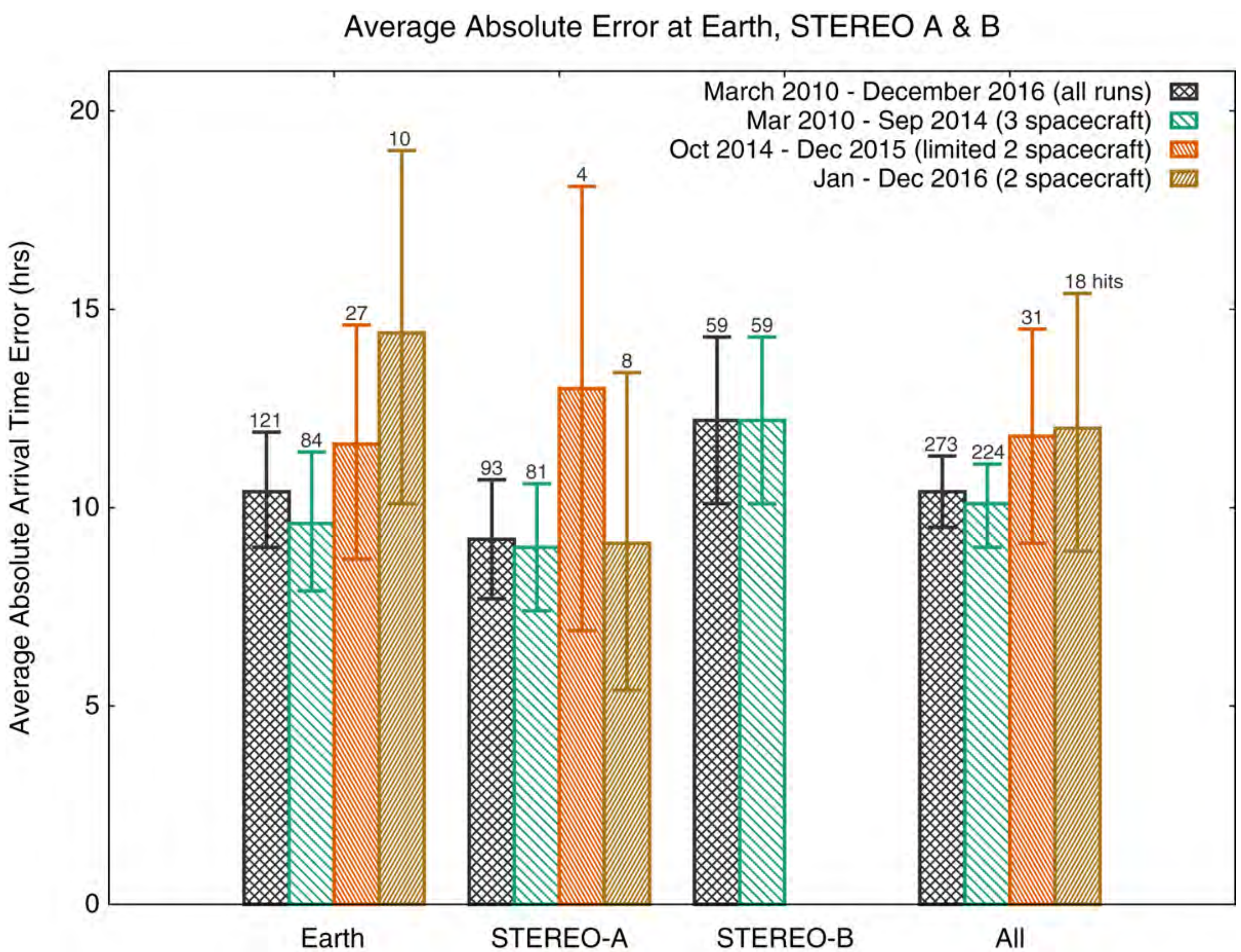


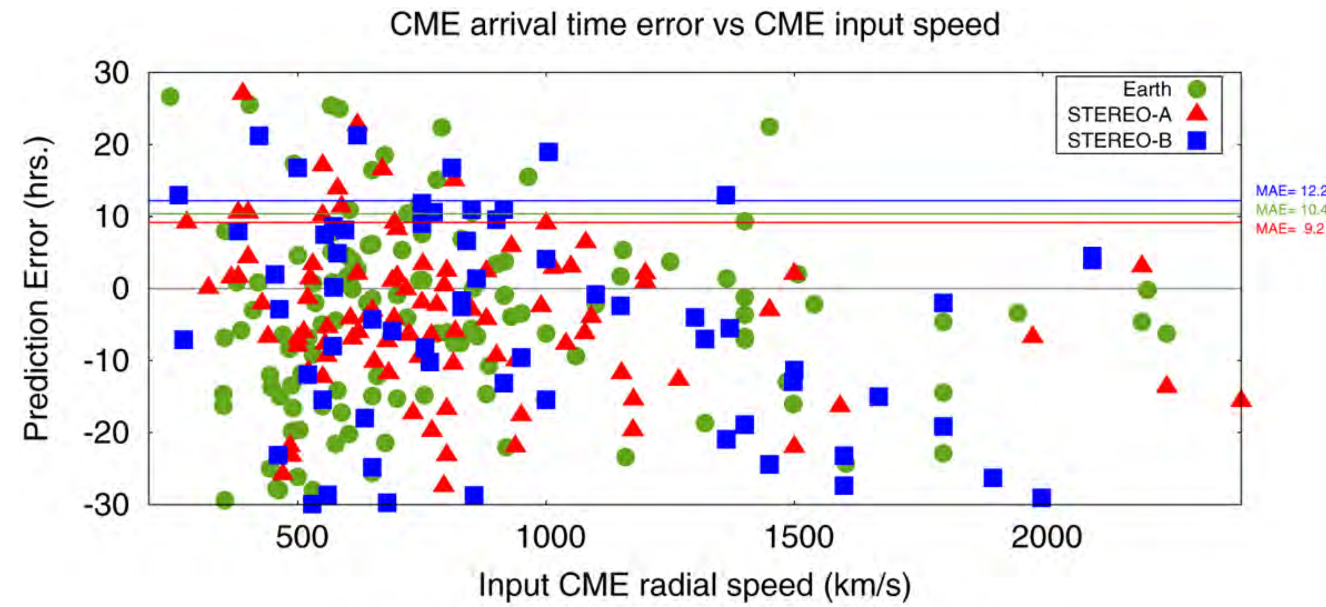


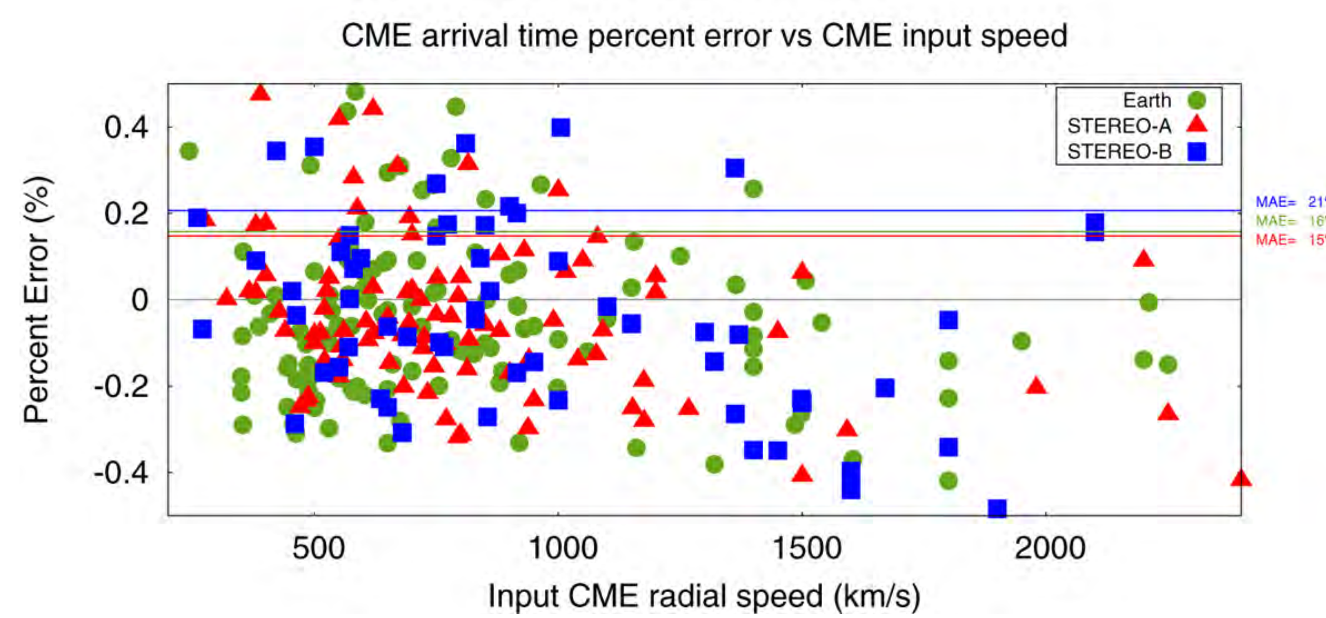


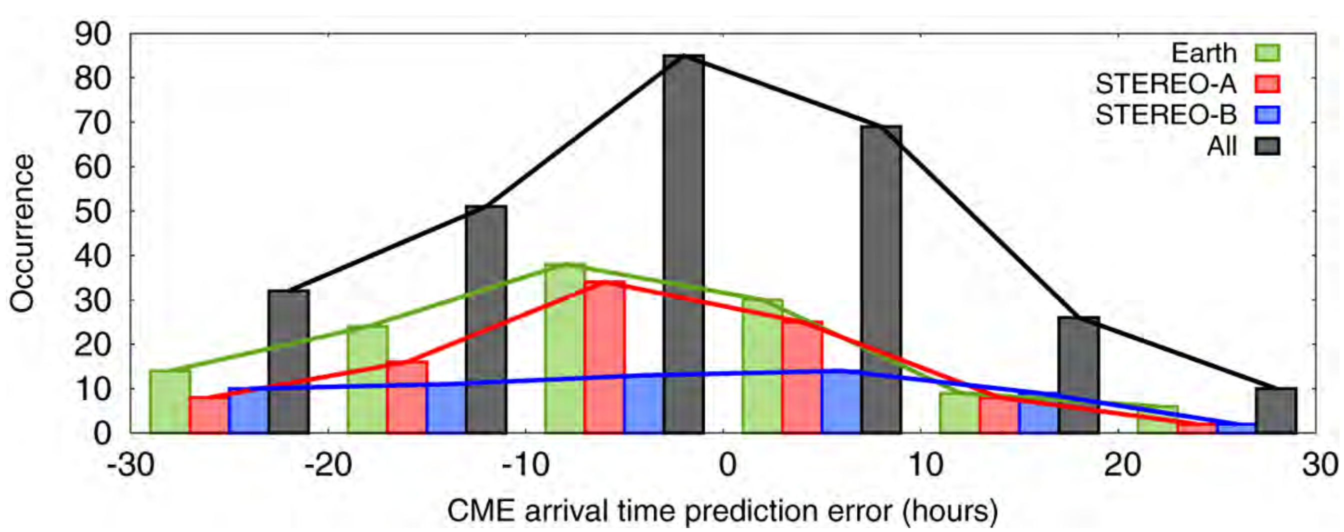
- Observed quantities: angular extent (“rmajor), directional latitude (“lat”) and longitude (“lon”), and speed (“vcld”)
- Model-free parameters: density (“dcld”), temperature (“tcld”), radial extent (“xcld”)

Verification of Real-time WSA-ENLIL+Cone Simulations of CME Arrival-time at the CCMC from 2010 to 2016 (*Wold et al., JSWSC 2018*)



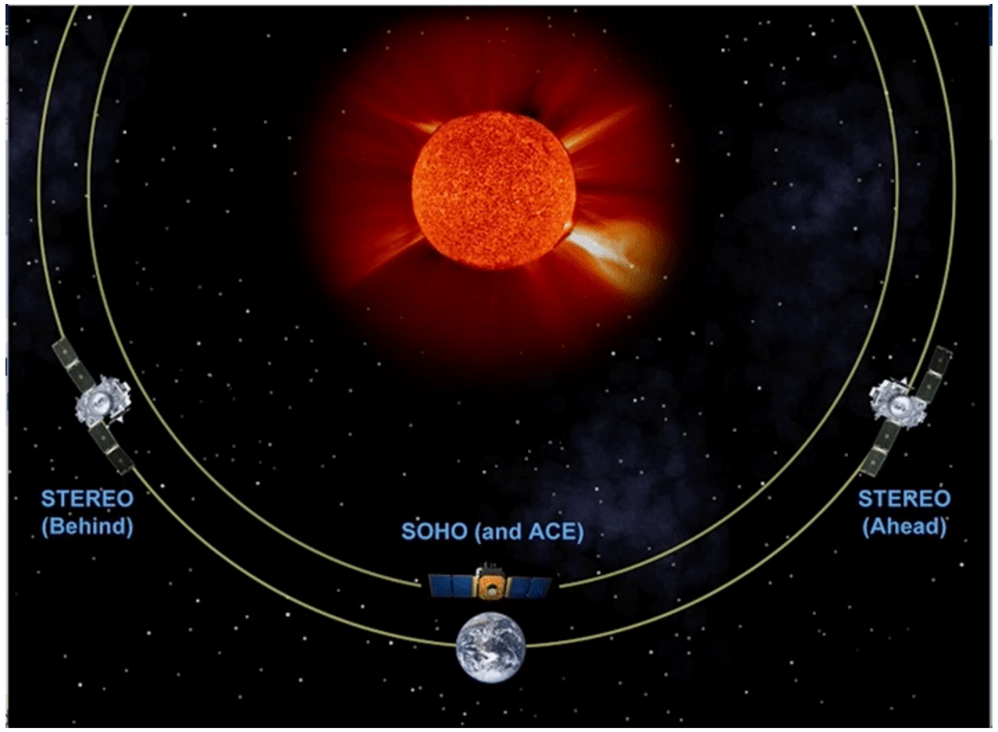






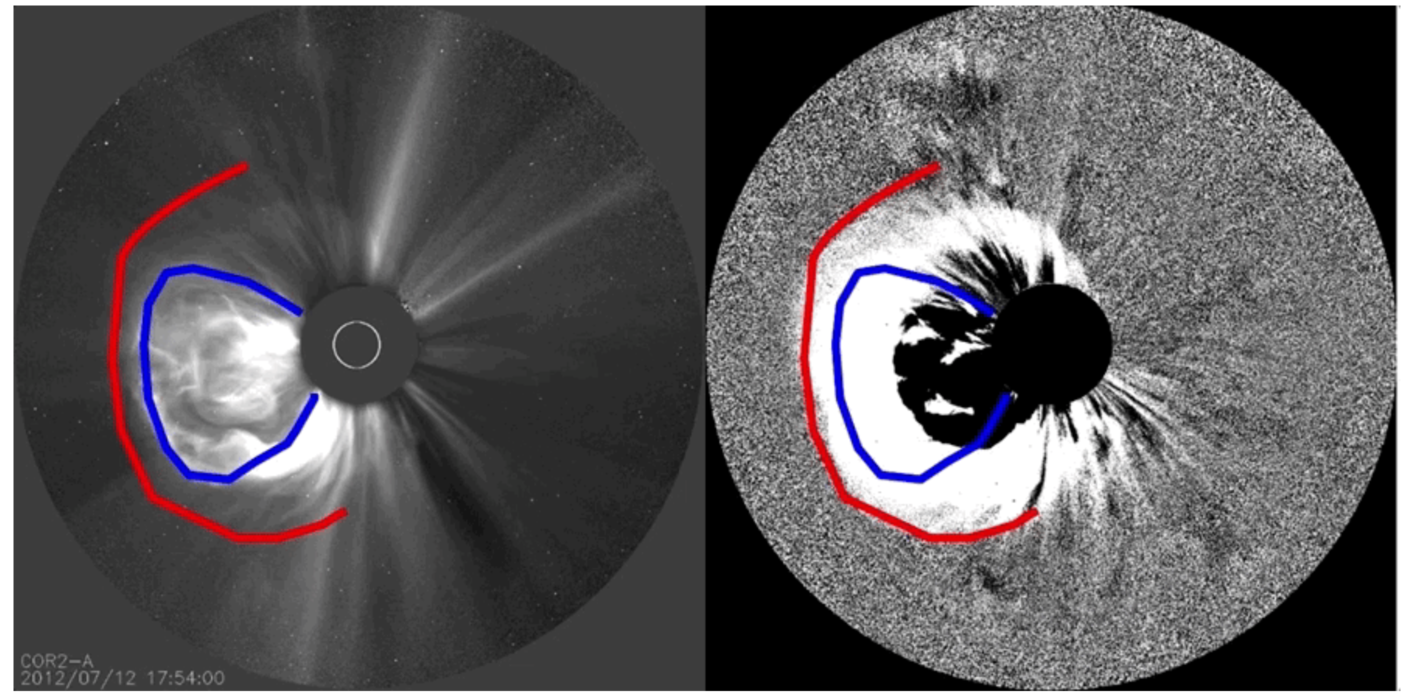
Launching Hydrodynamic Ejecta — New Possibilities

Multi-perspective STEREO observations

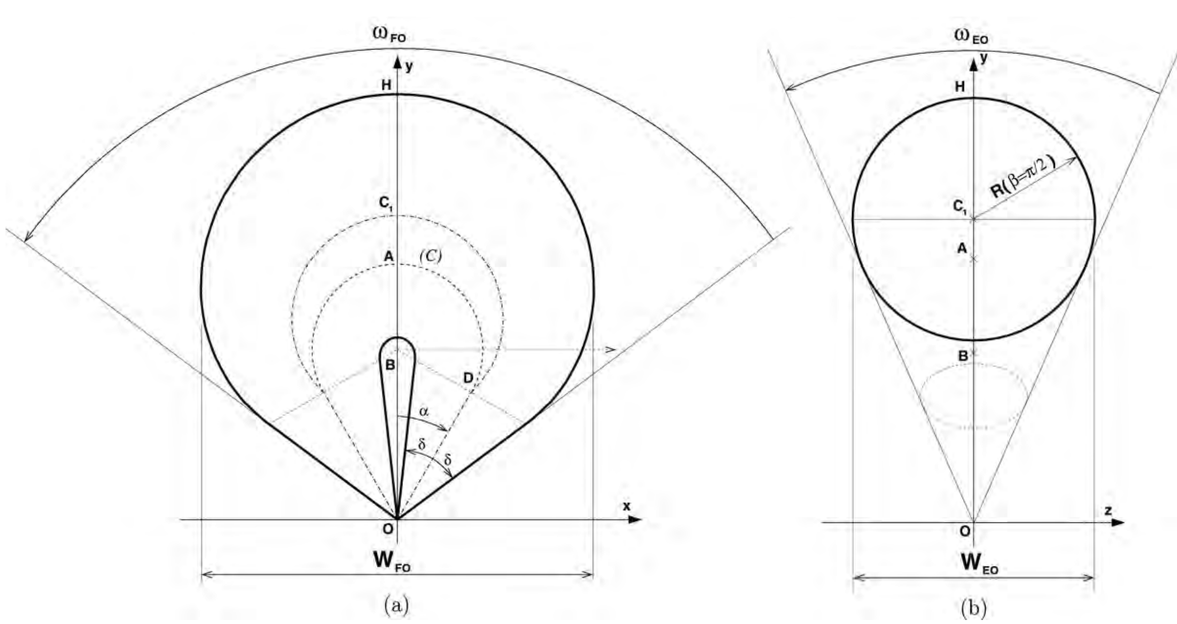


Ejecta/Driver vs Shock

Running Difference   Absolute Values

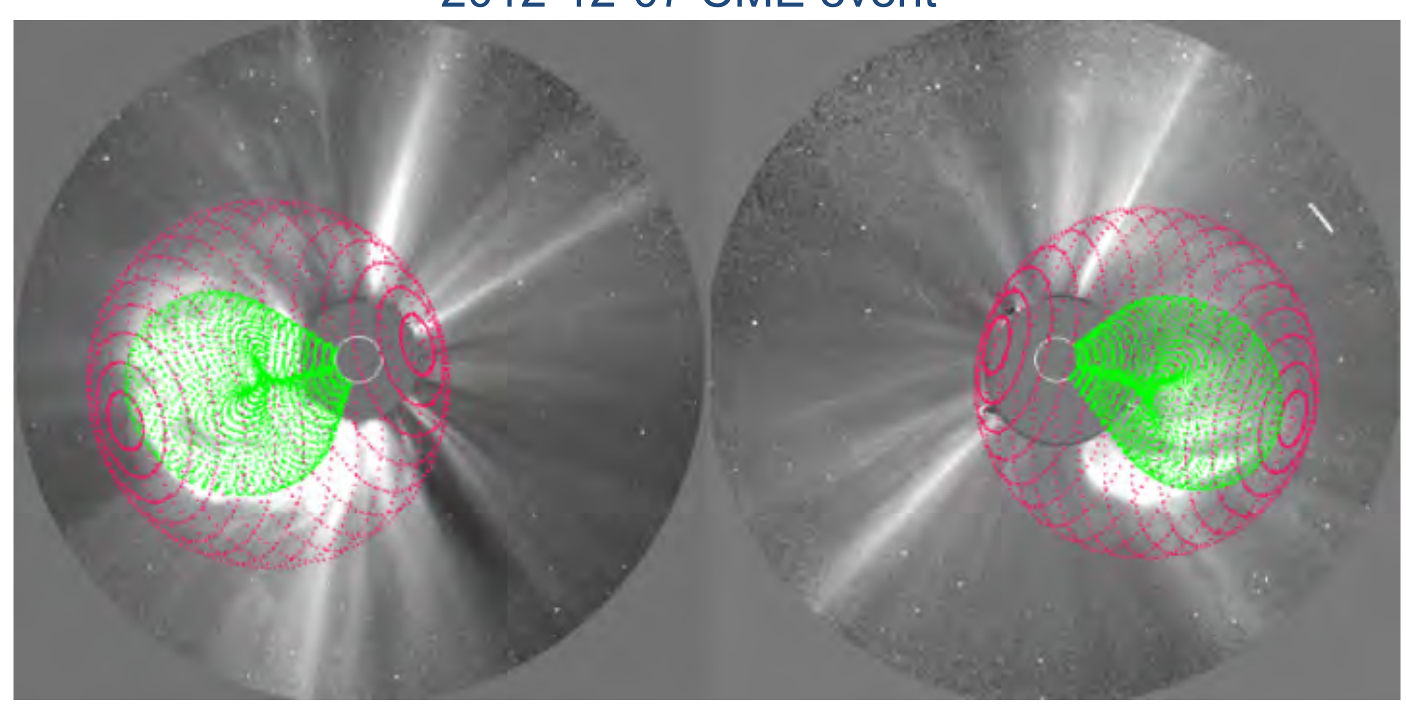


Graduated Cylindrical Shell (GCS) model

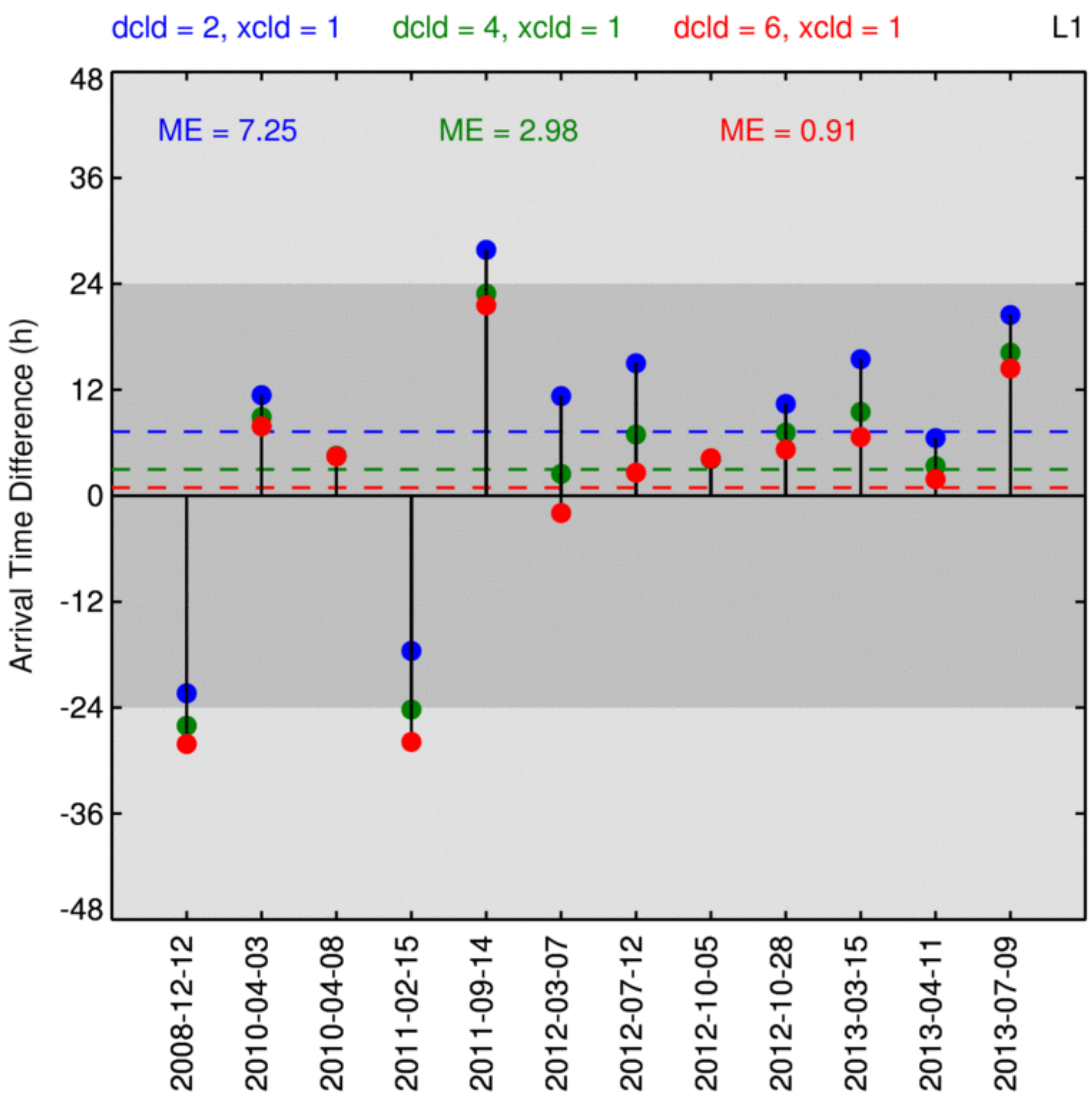


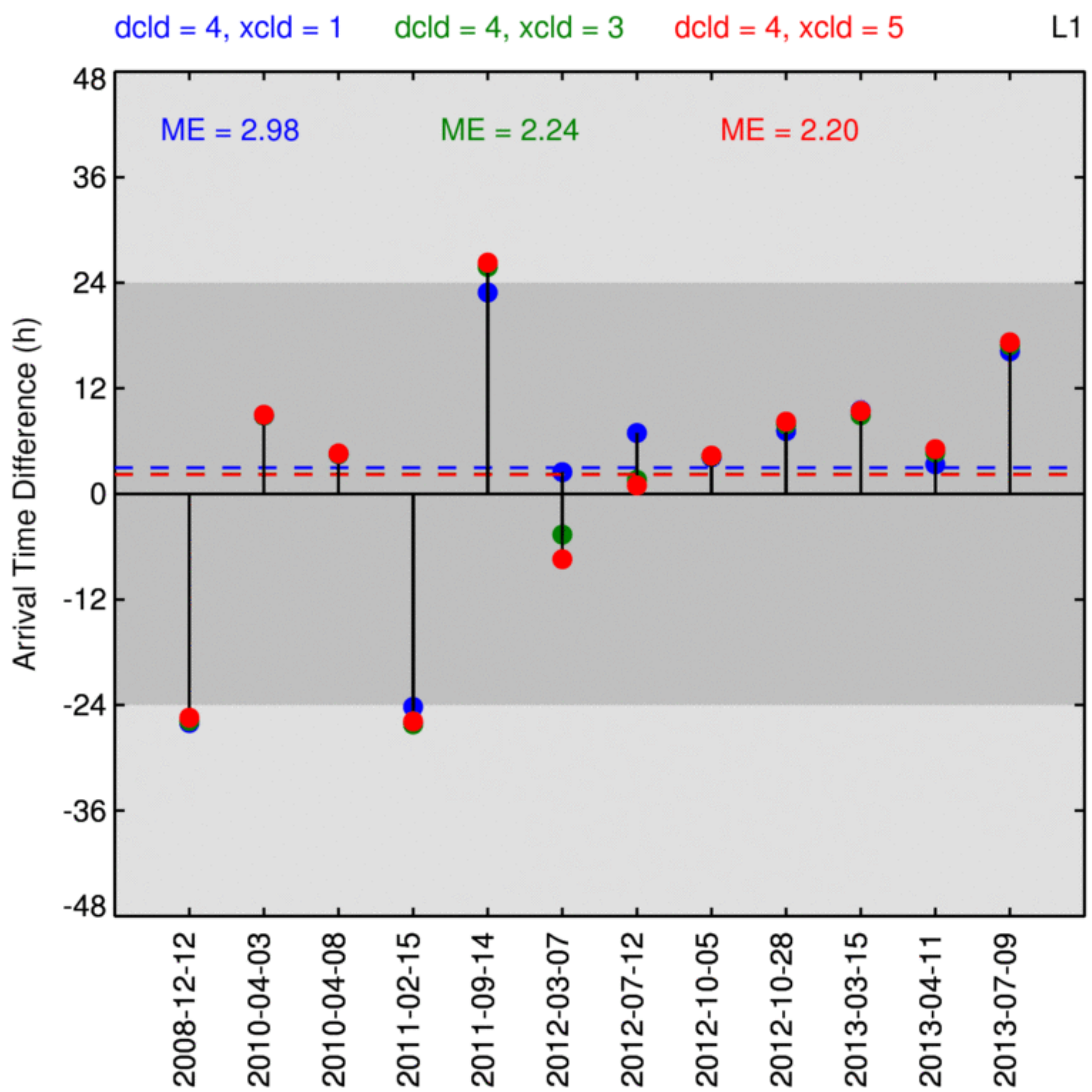
3D Shape and Direction

2012-12-07 CME event

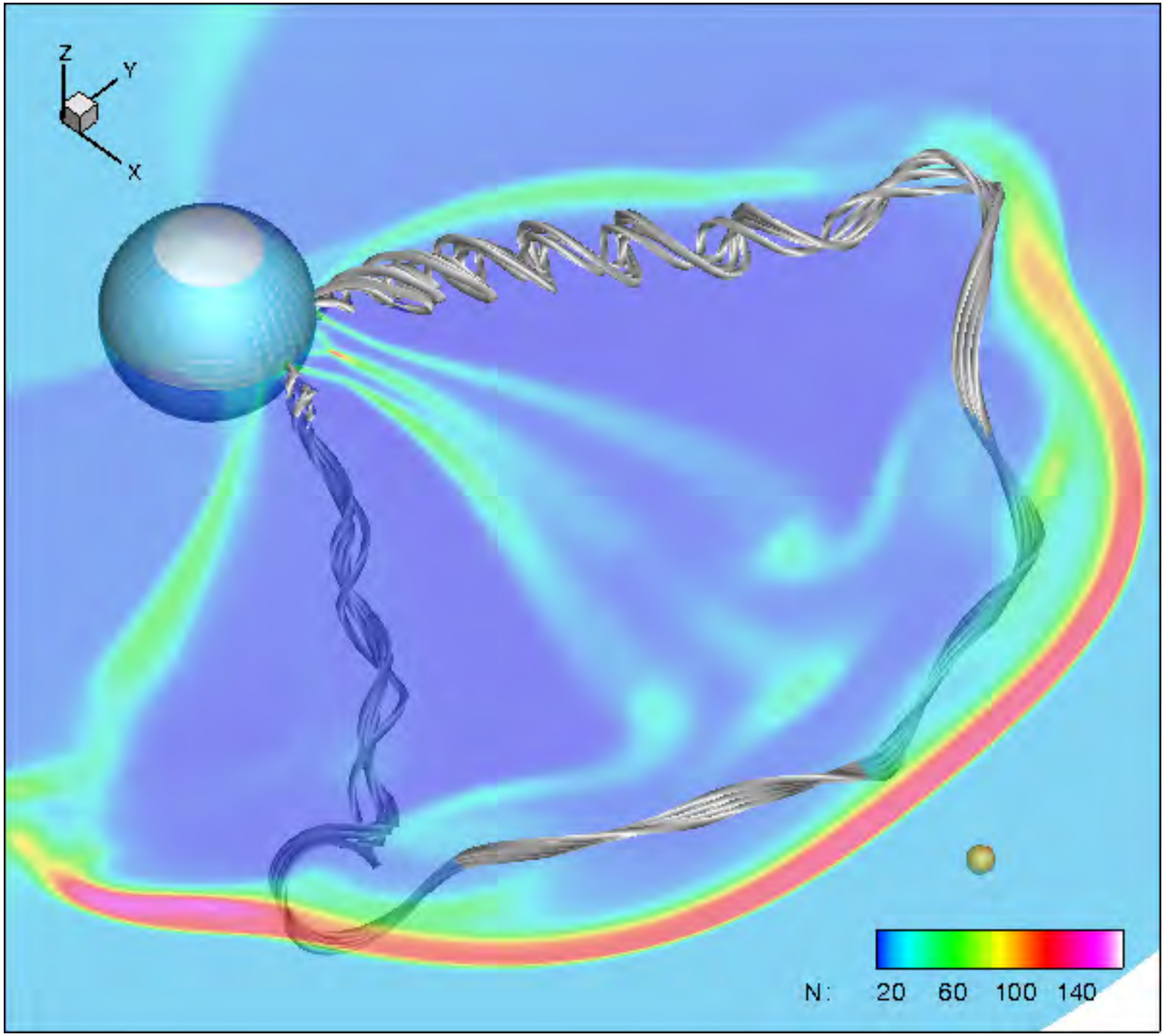


ICME Arrival Time — Effect of “dcld” and “xcld” for “dfast”





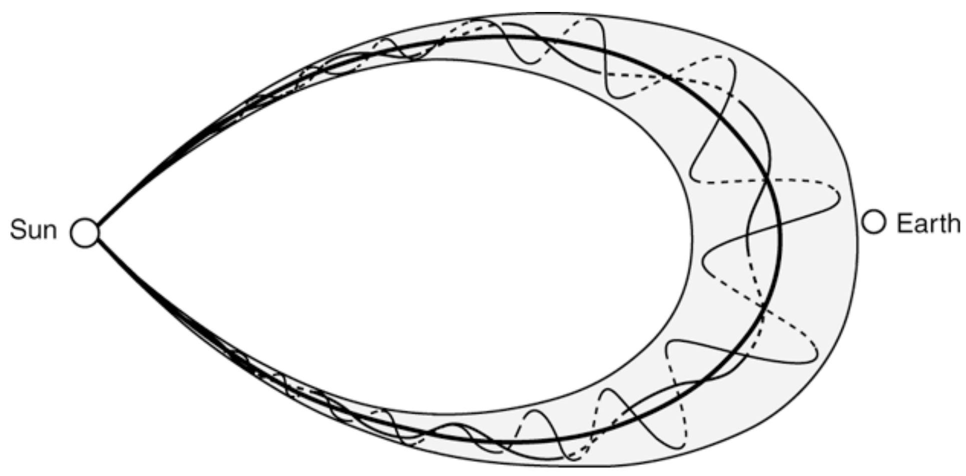
Launching a Magnetic Flux-Rope at Corona



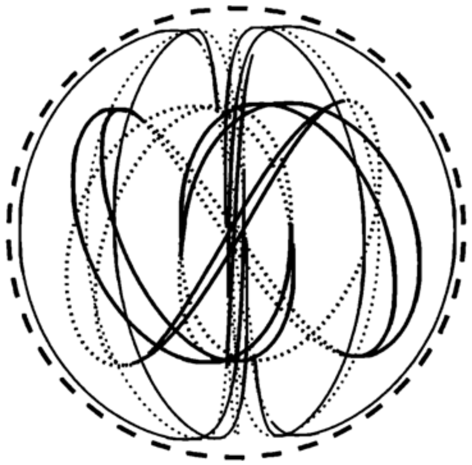
- The same 2^0 resolution as for cone model simulations – faster-than-real time
- Further development is needed

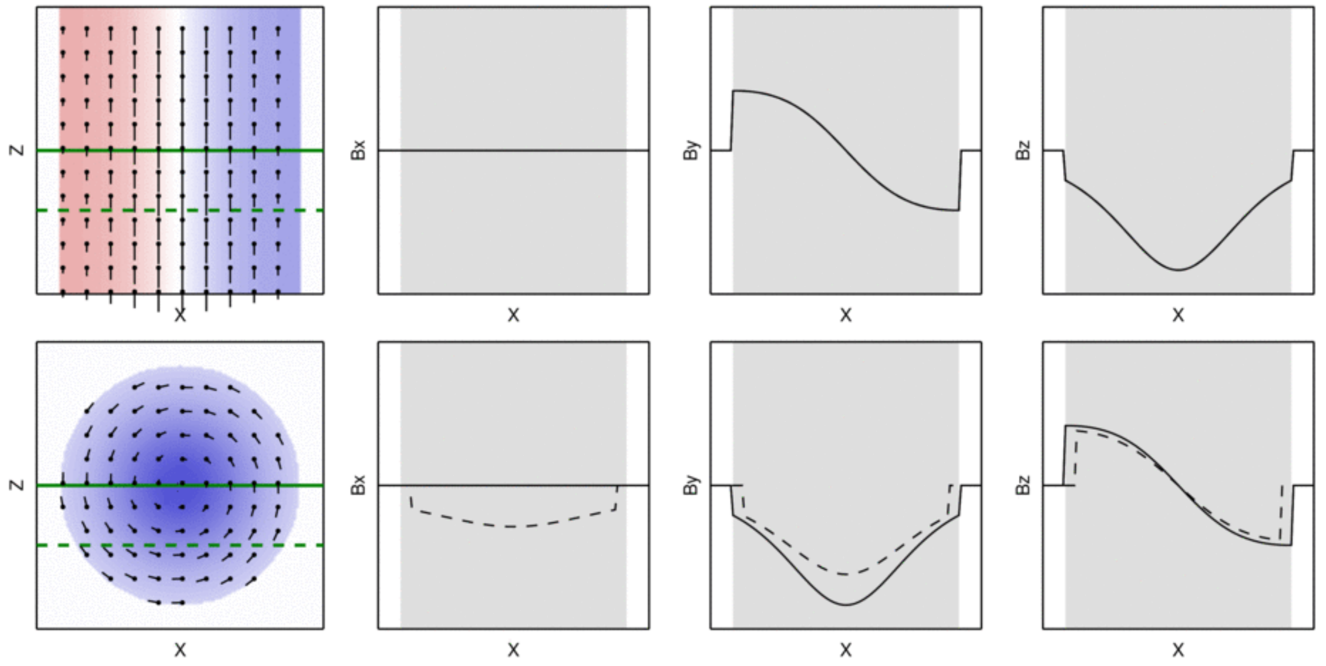
Launching Magnetic Structures

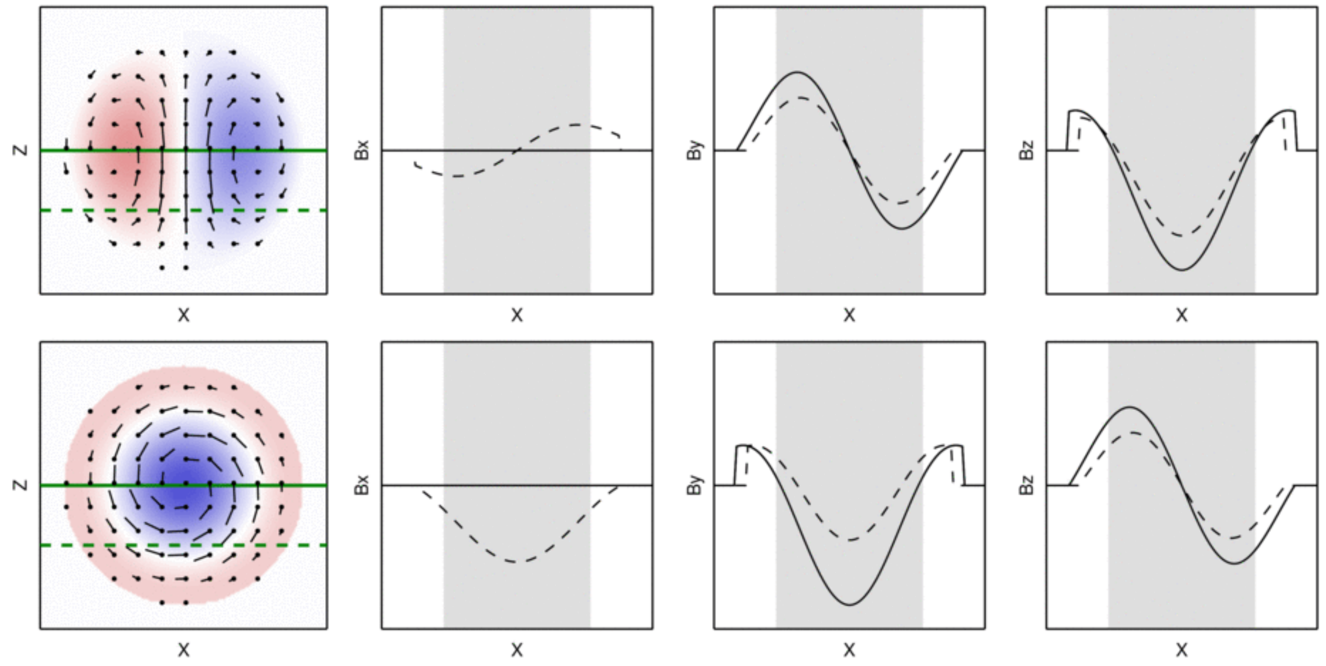
Flux Rope



Spheromak

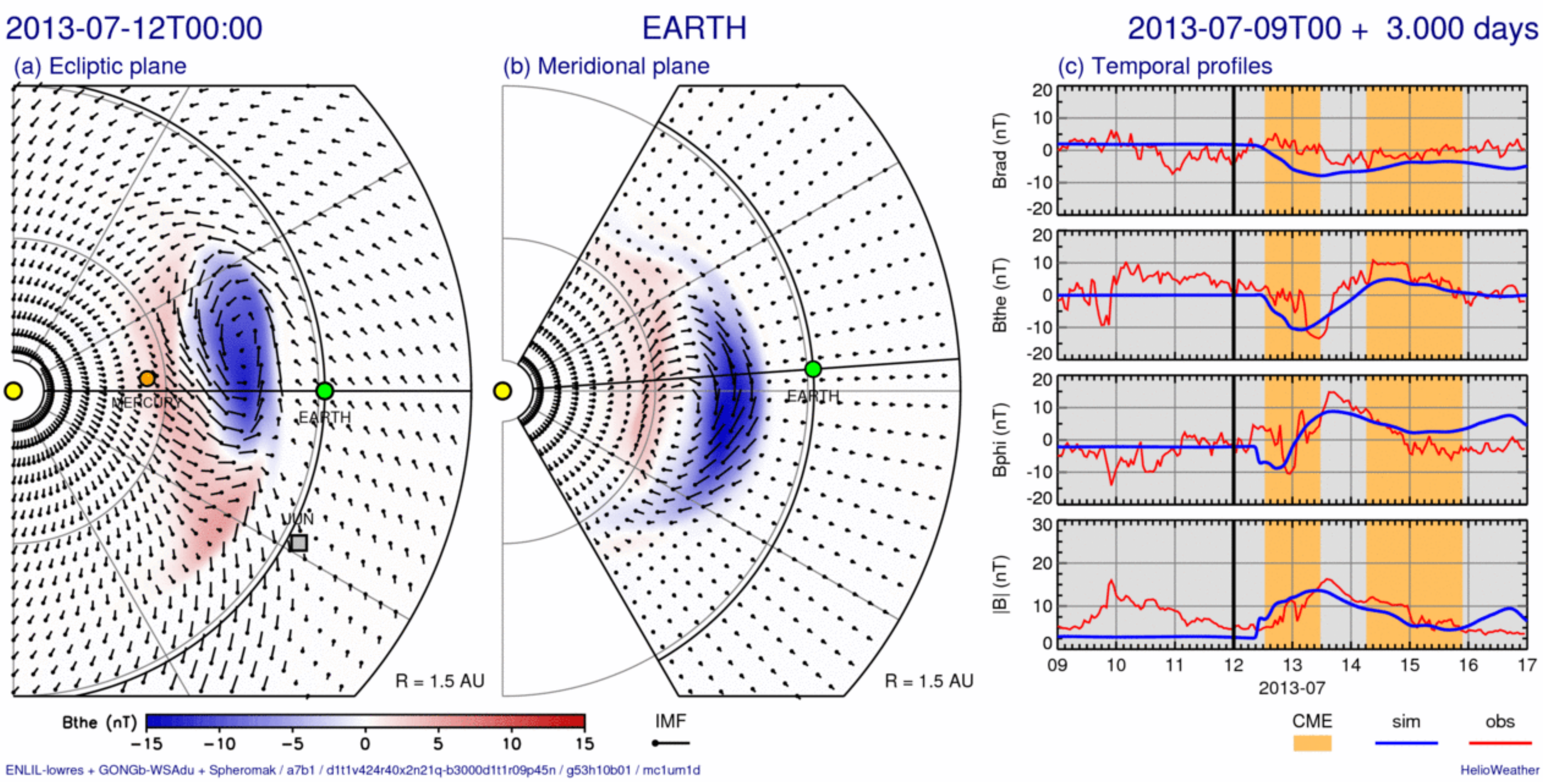




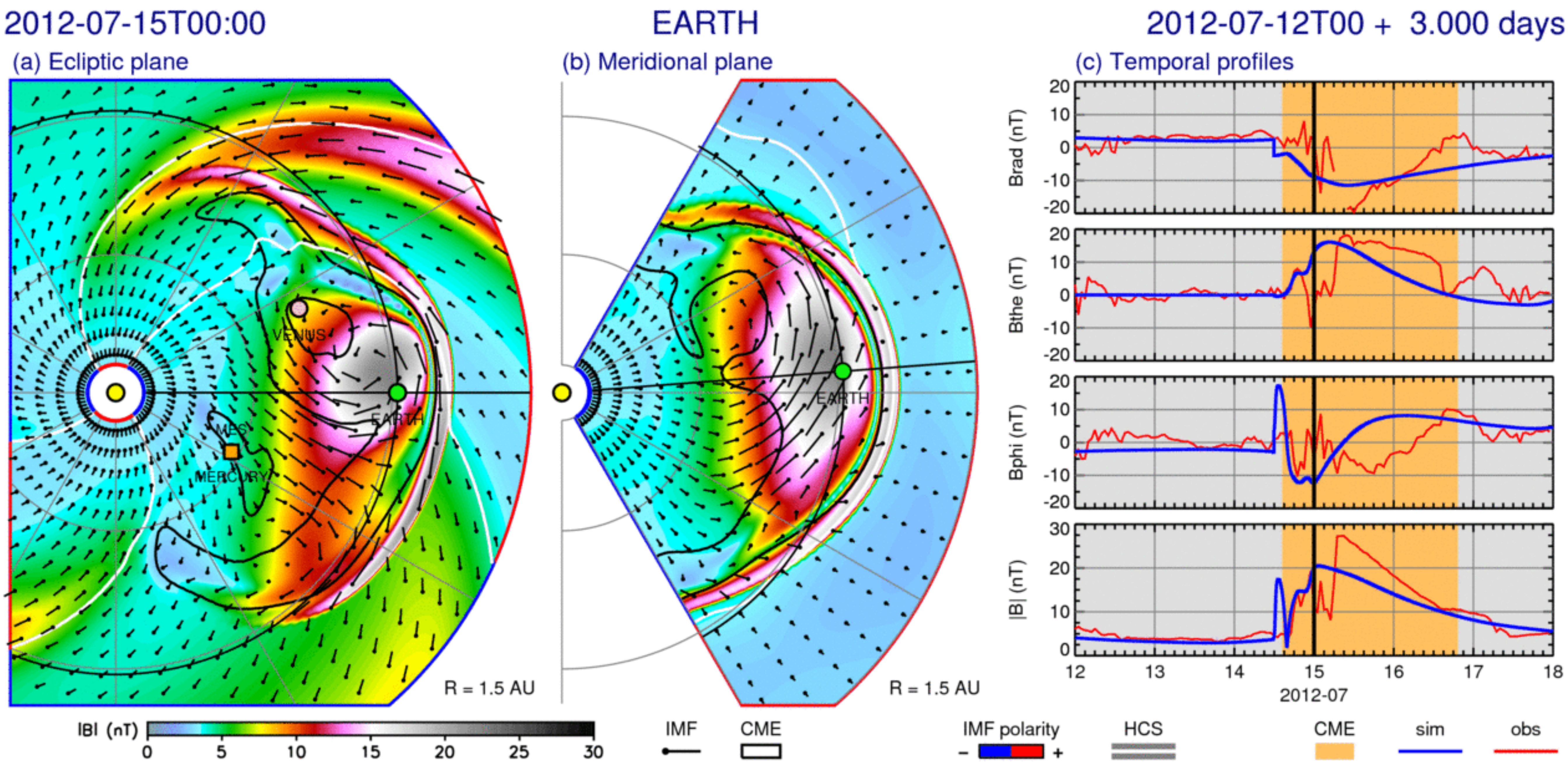


Numerical diffusion/erosion makes them even more similar (Savani)

CME Event 2013-07-12 — bthe2e4



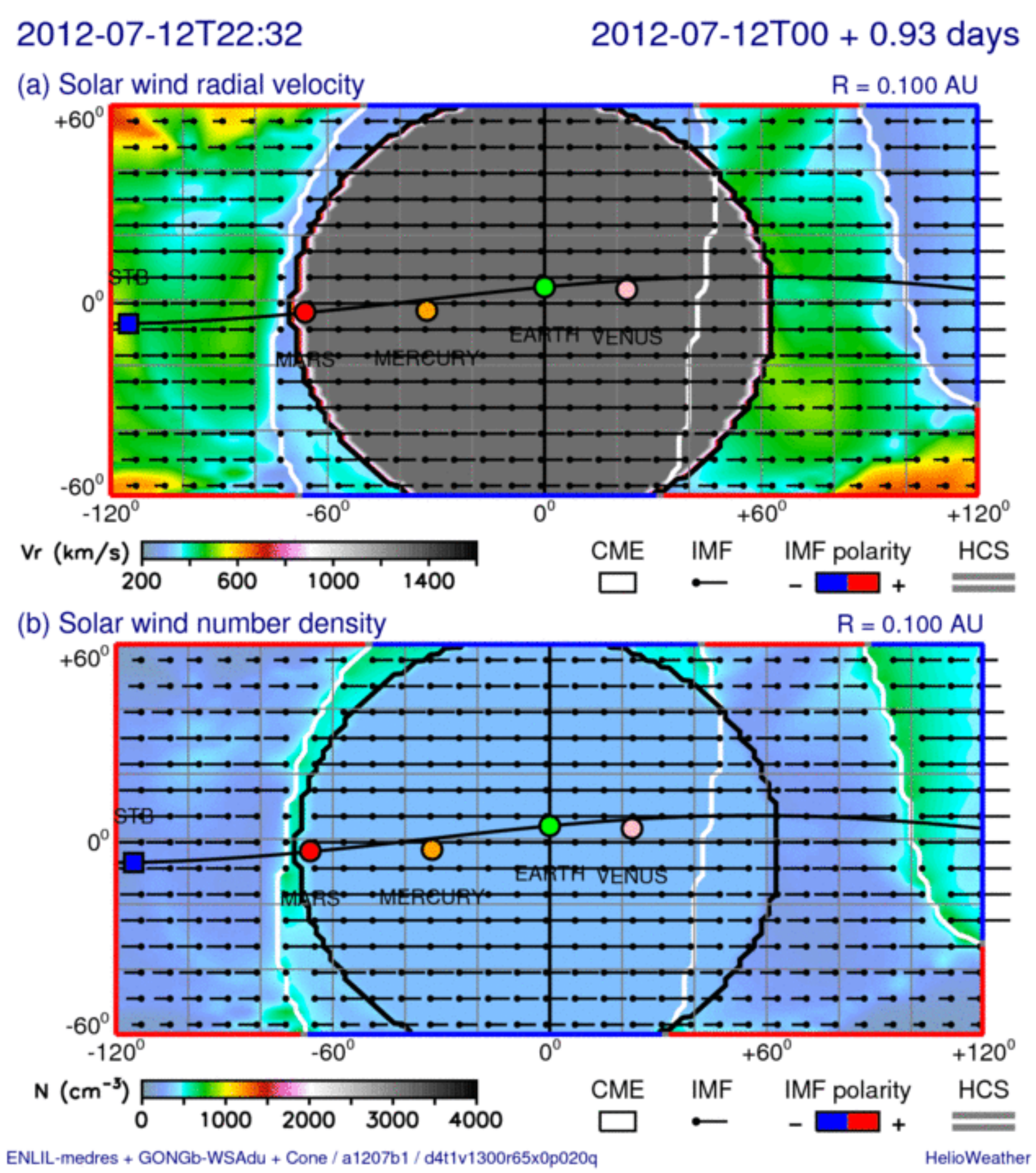
CME Event 2012-07-12 — btot2e4

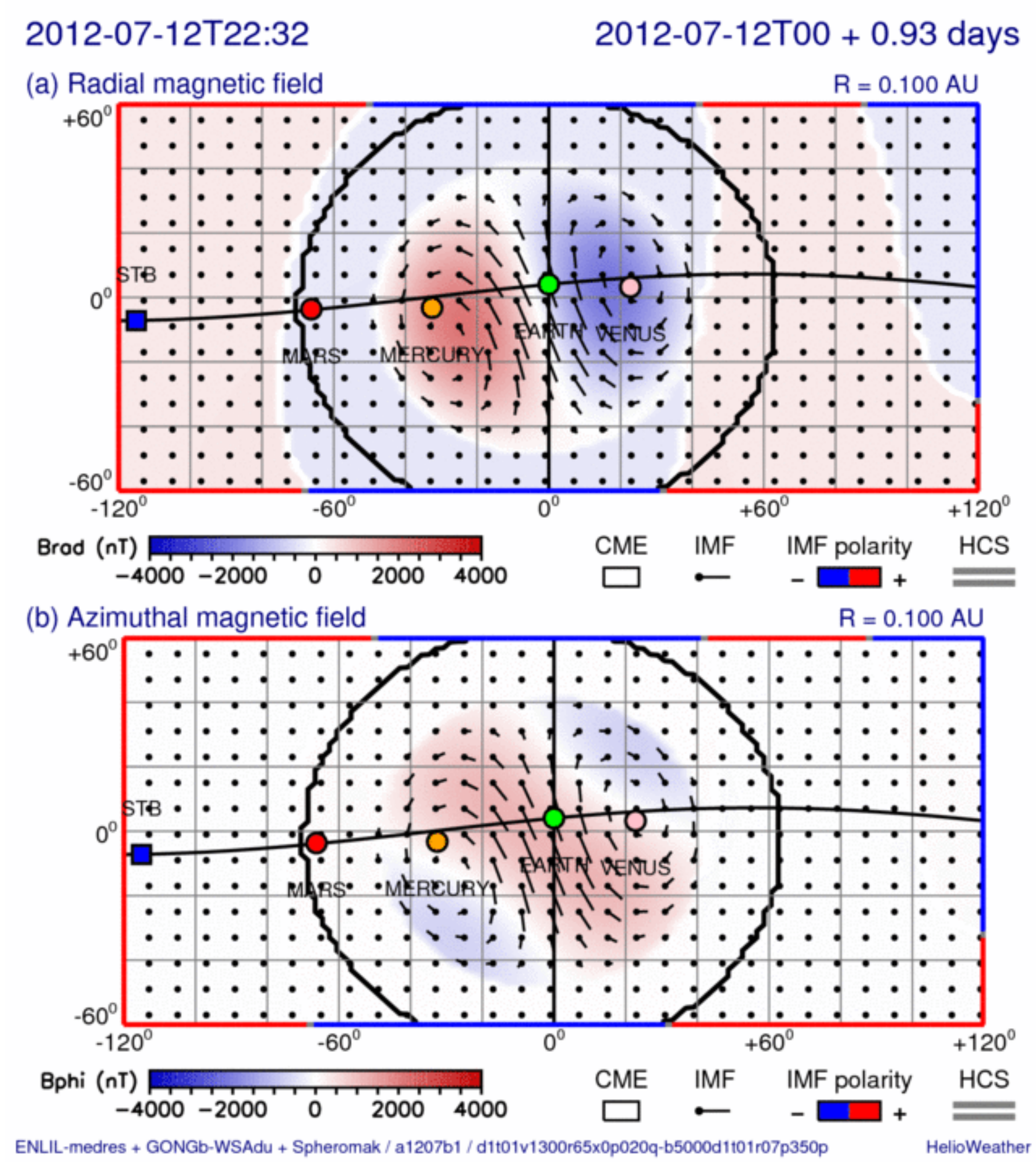


ENLIL-medres + GONGb-WSAdu + Spheromak / a1207b1 / d2t05v1000r65x0p020q-b5000d2t05r06p350p / g53h10b02 / mcp1um1cd

HelioWeather

Launching a Spheromak — Boundary Conditions — 2012-07-12





Pomoell & Poedts 2018

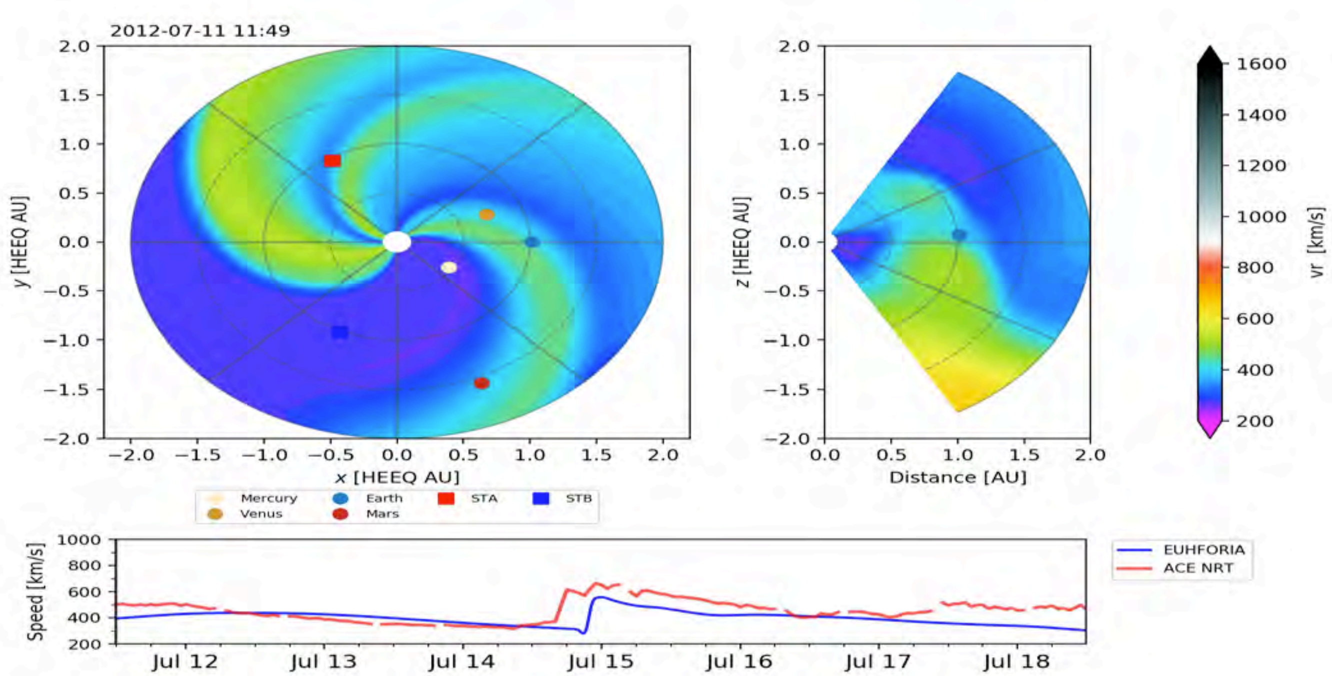
EUHFORIA: Introduction

Newly developed heliospheric 3D MHD model

Magnetogram: GONG → Solar wind model: Semi-empirical → Heliosphere model: Time-dependent 3D MHD

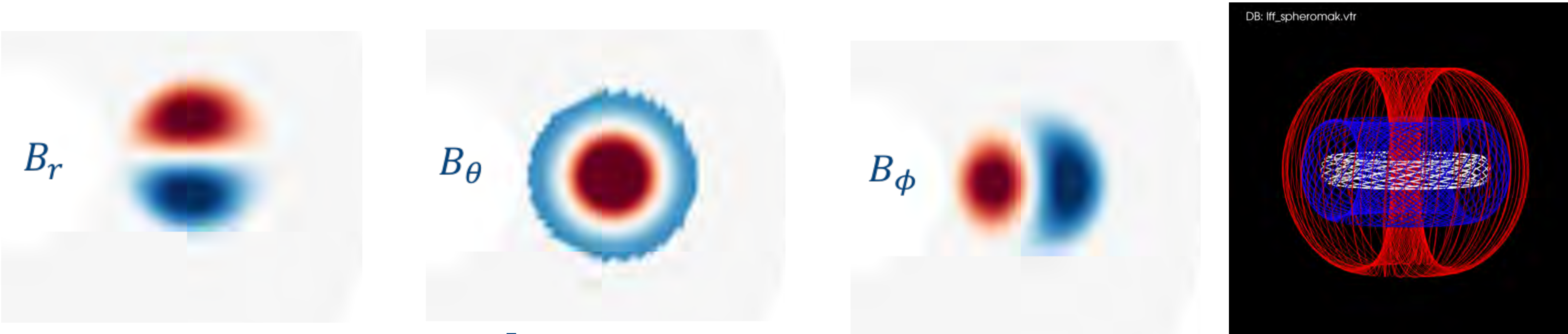
Coronagraph Imagery + others → CME model: - Cone model - Flux rope model → Heliosphere model: Time-dependent 3D MHD

Observational data | Empirical / data-driven models | **0.1 AU** | Physics-based model | **2 AU**



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

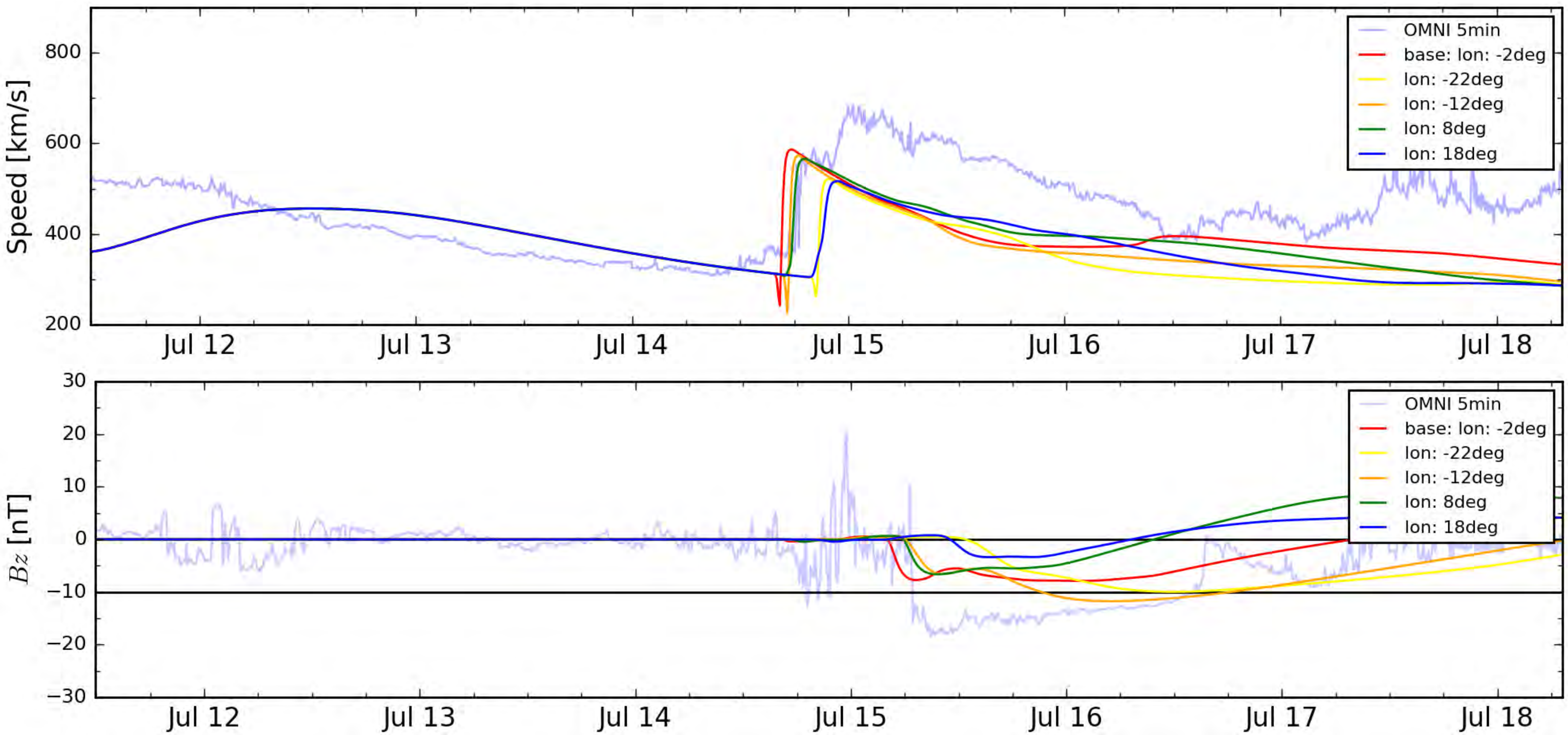
- Helicity of the CME
- Total toroidal flux

Flux rope parameters

EUHFORIA: Spheromak CME: parameter study

Multiple parameters studied - One example shown:

<u>Variation in longitude of centre of CME</u>



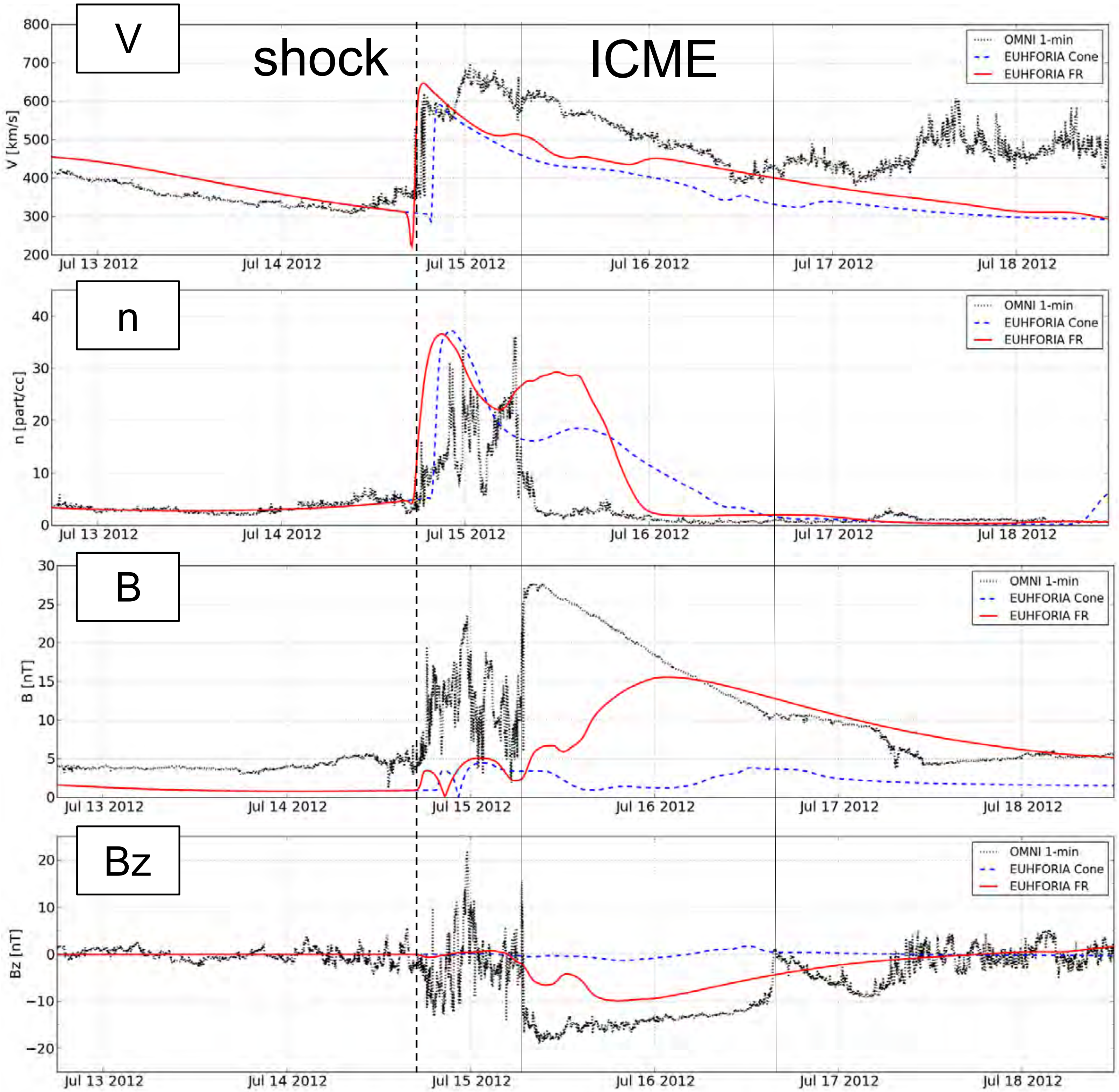
- Small changes in input parameters can have large influence on B, v and rho and thus the impact of the CME at Earth
- Input parameters all have their errors

→ We need ensemble runs for flux rope CME simulations

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

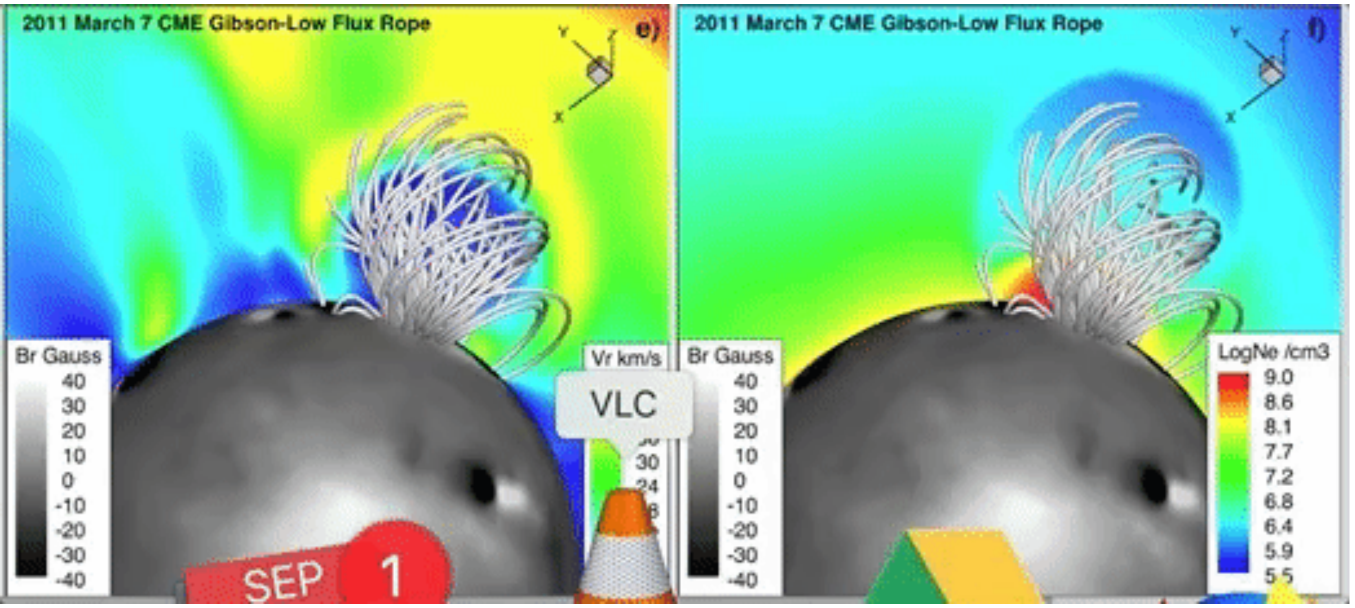
→ Magnetospheric compression

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

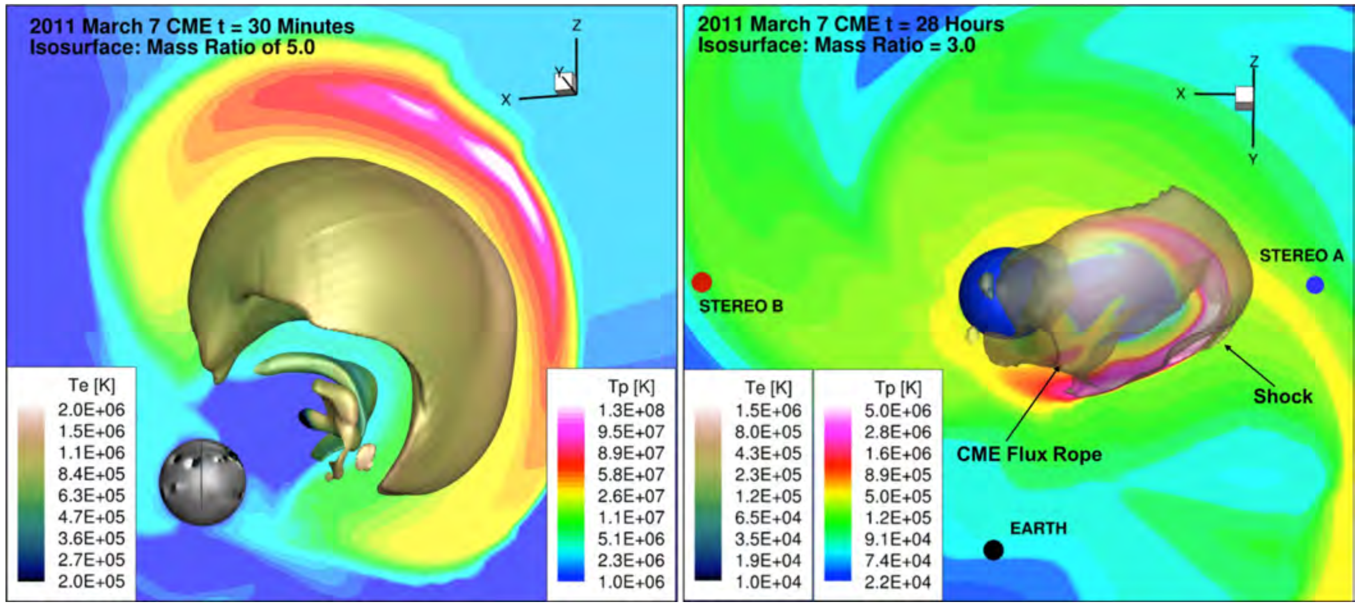
→ Dayside reconnection & geomagnetic activity

AWSoM+SWMF Codes: Chromosphere to 1 AU Simulation of the 2011-03-07 Event (*Jin et al., ApJ 2011*)

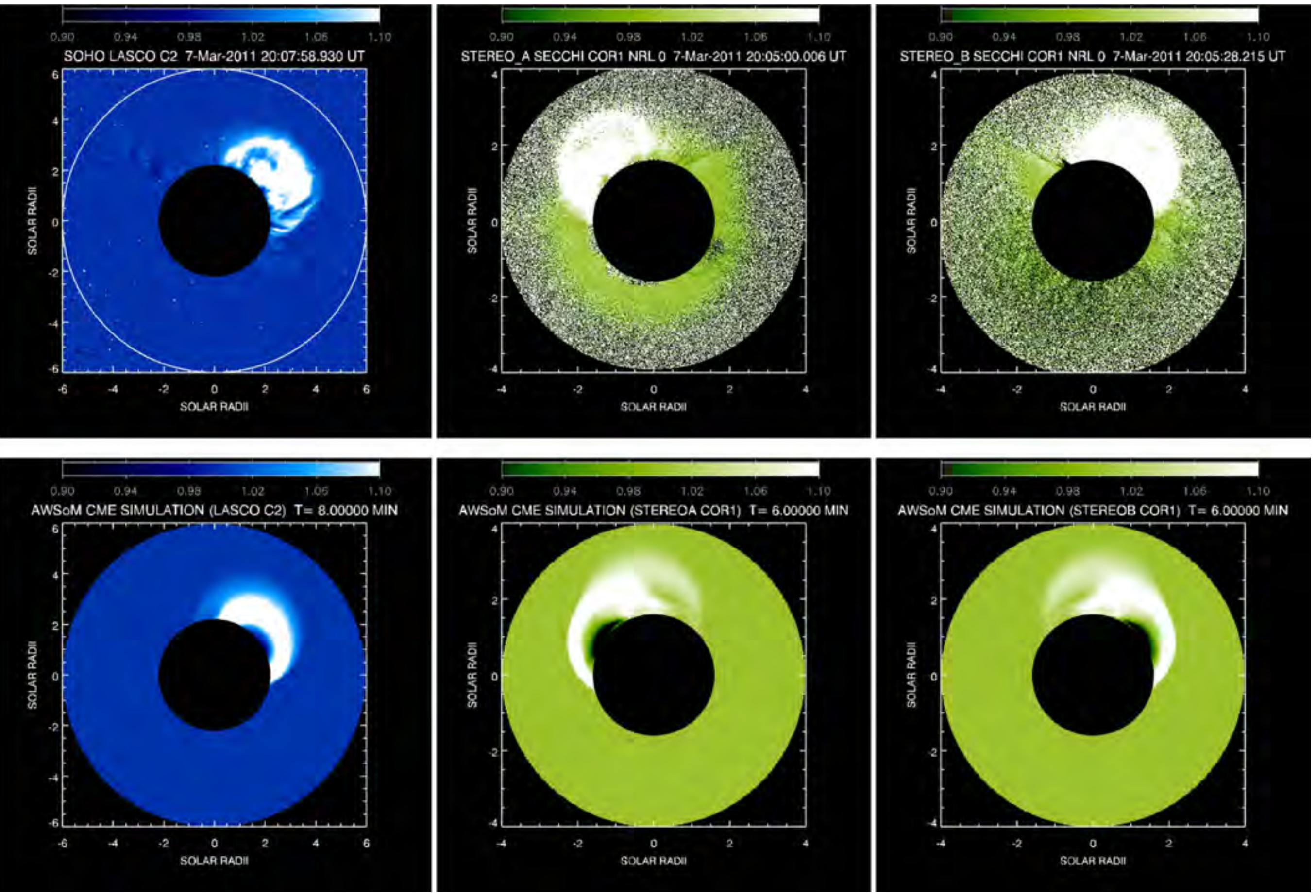
Inserting a magnetic flux-rope



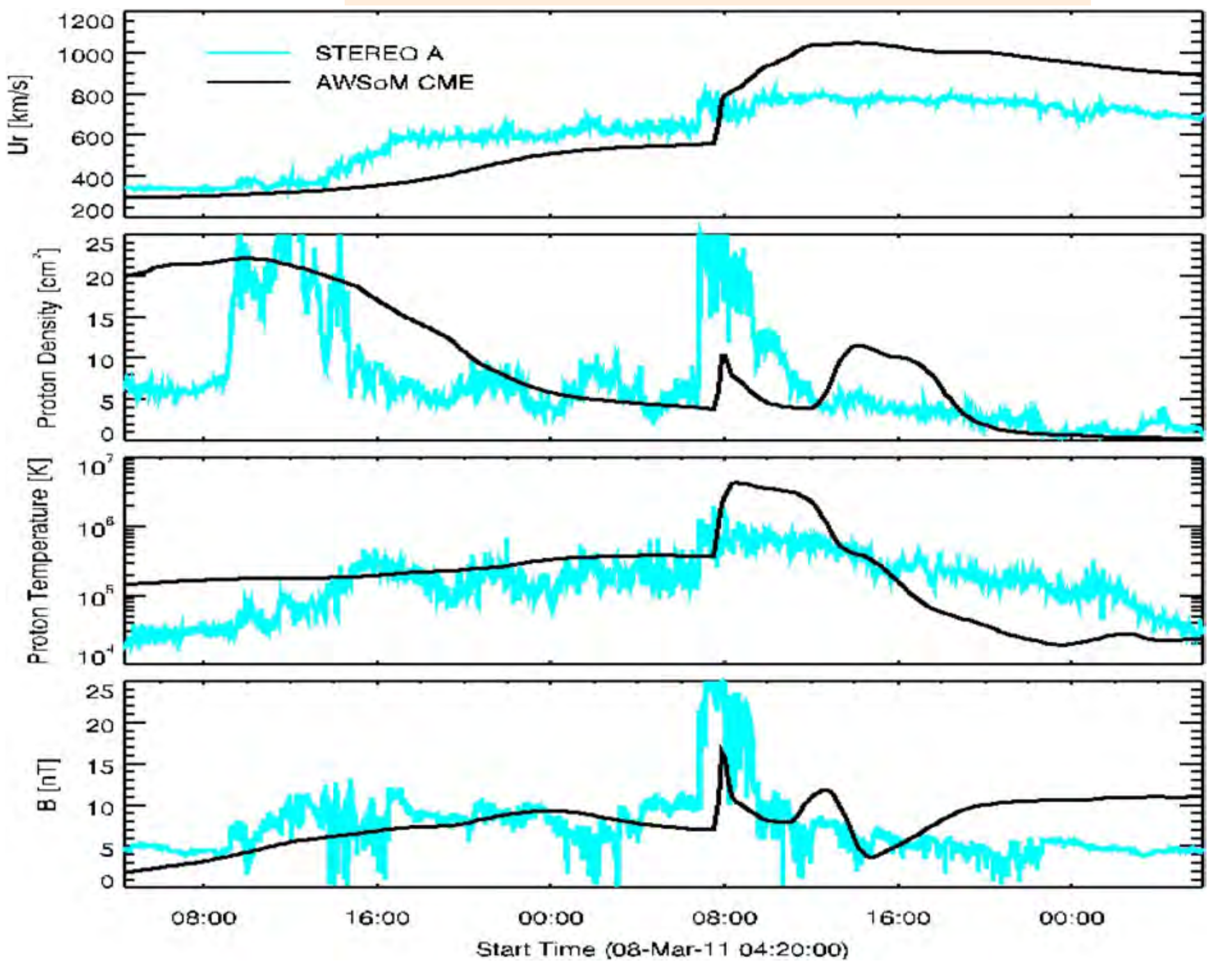
Propagation in the heliosphere



Observed and synthetic white-light images

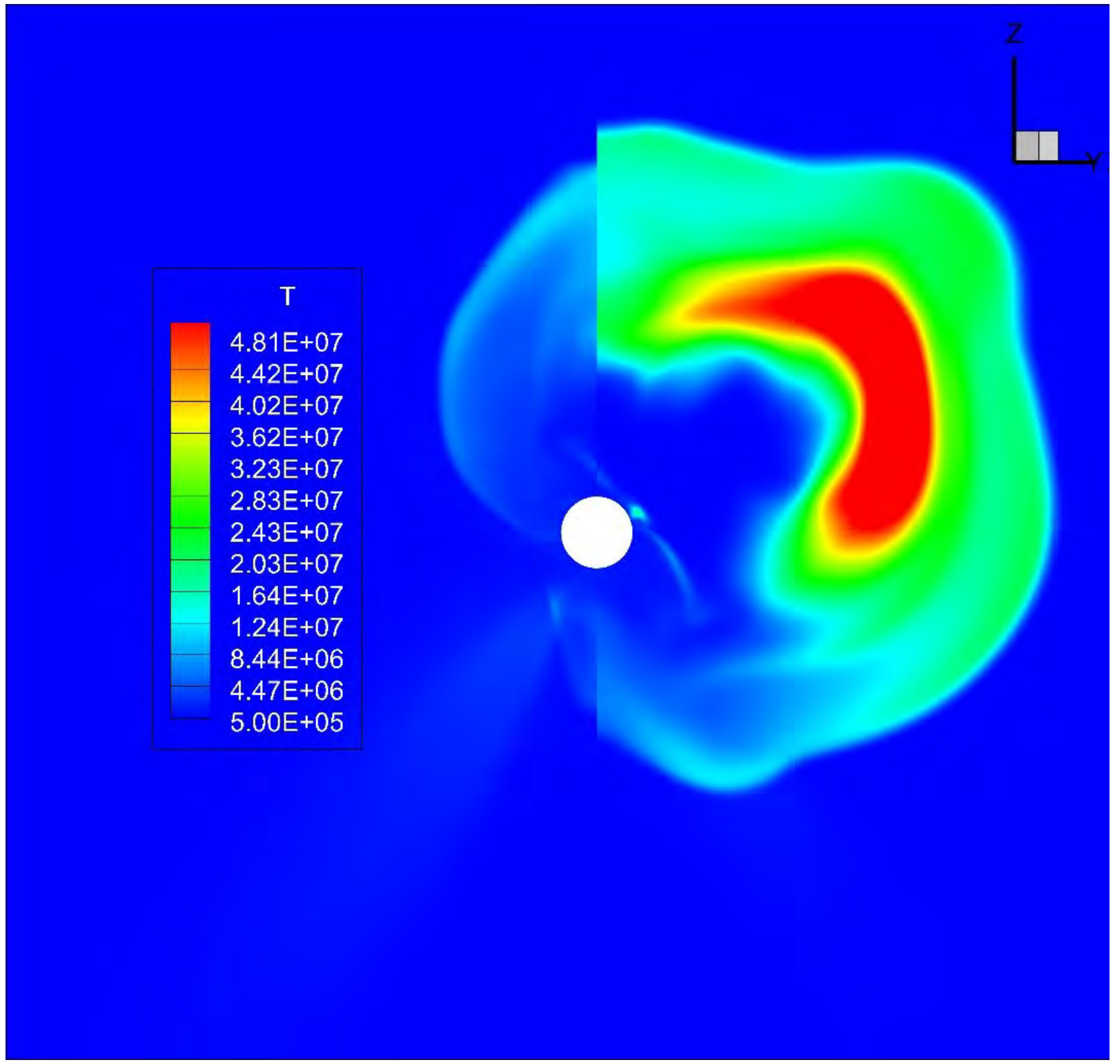


Temporal profiles at STEREO-A

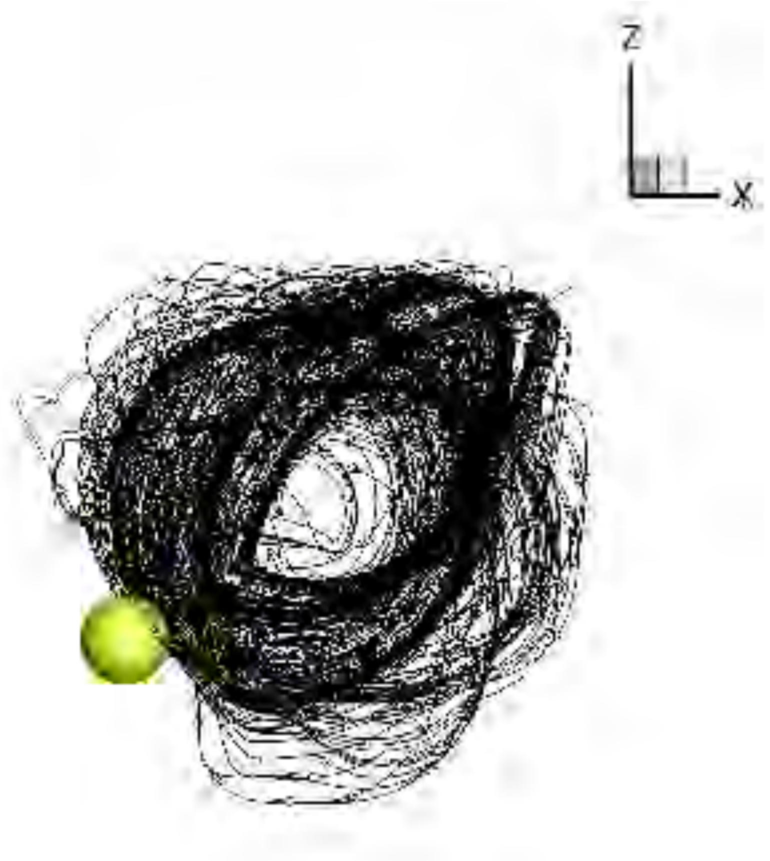


MS-FLUKSS Code: A Data-constrained Model for CMEs Using the Graduated Cylindrical Shell Method (*Singh et al., ApJ 2018*)

CME shown using temperature contours.



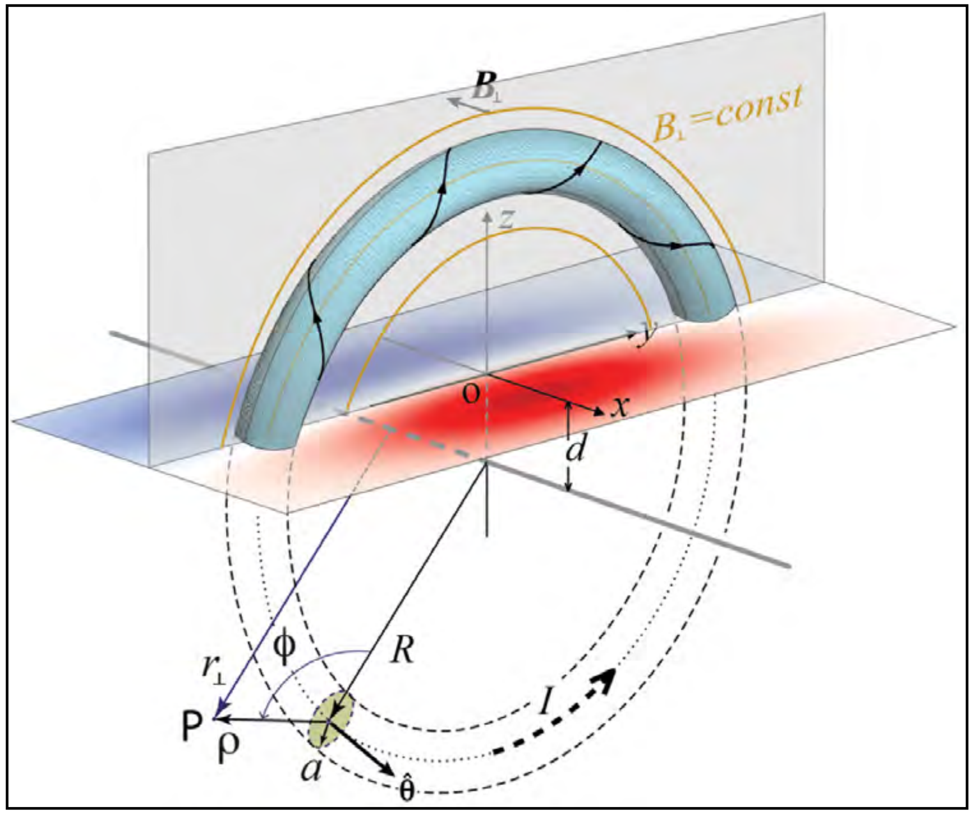
CME shown using magnetic field lines of flux rope.

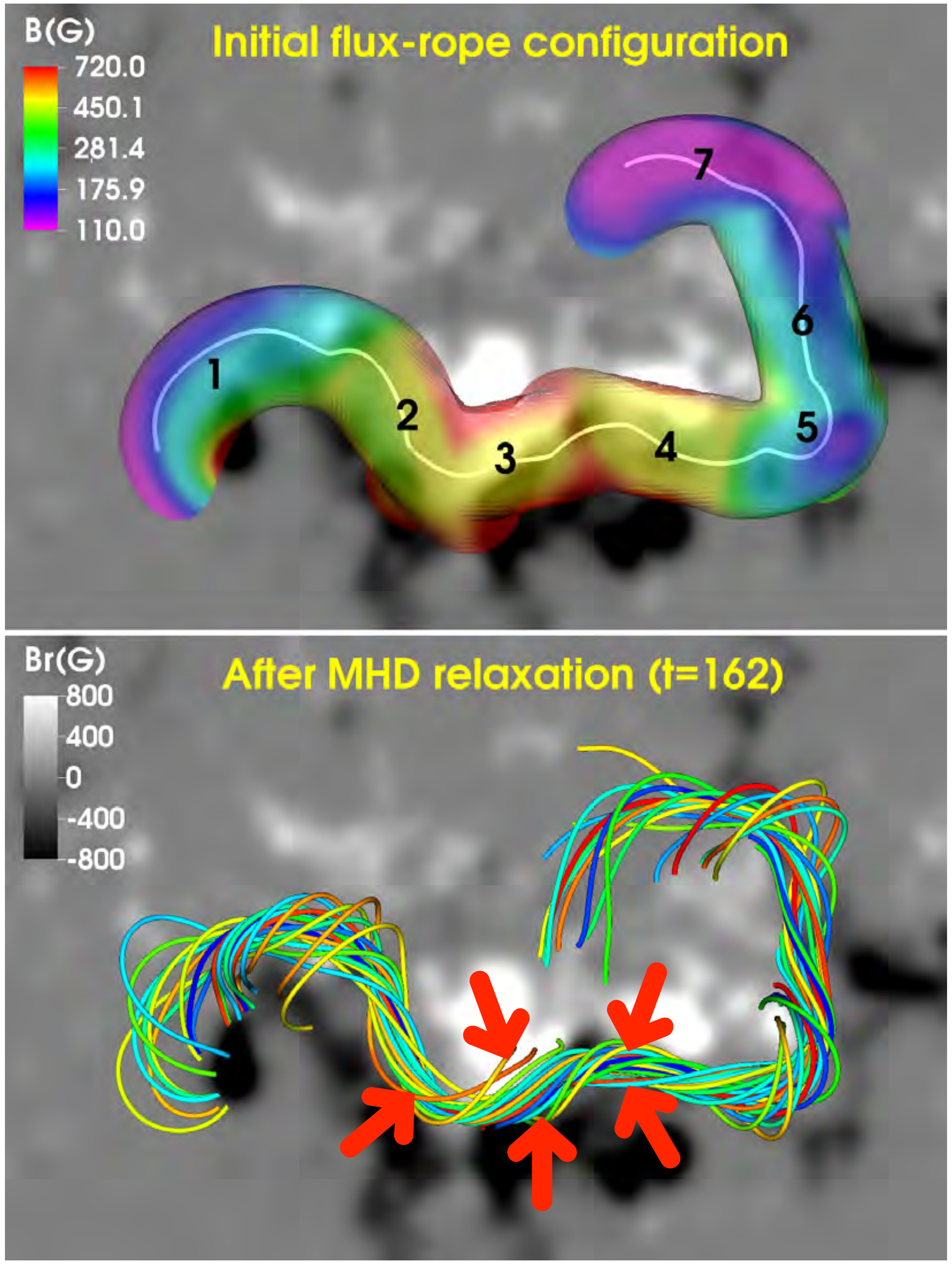


Sun-to-Earth MHD Simulation of the 14 July 2000 "Bastille Day" Eruption

Torok et al (2018)

Source-Region Energization & Eruption Initiation





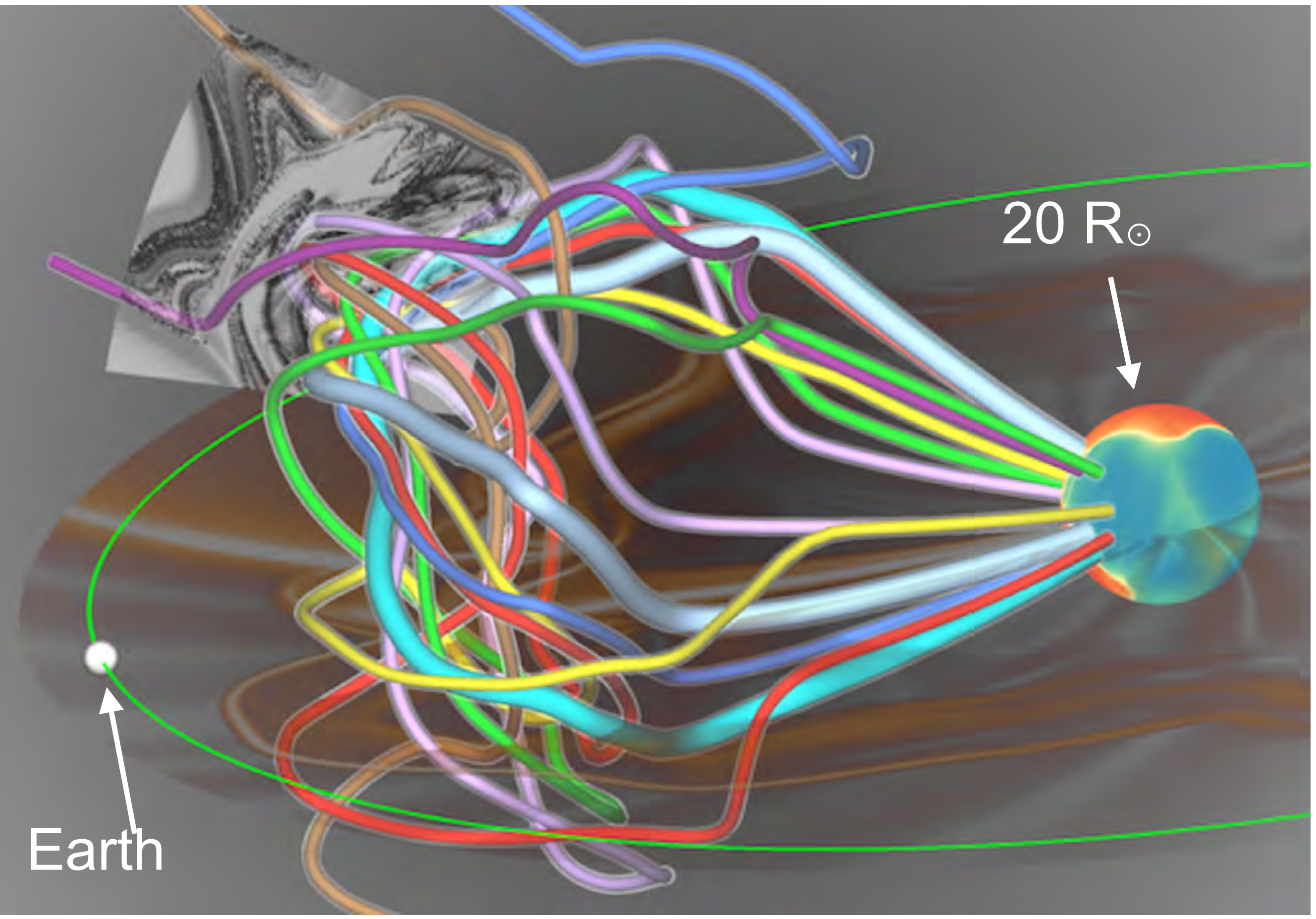
- Modified Titov-Démoulin (TDm) model: construct force-free flux ropes in an arbitrary (locally bipolar) ambient field.
- Use 7 overlapping TDm ropes to build elongated, curved stable flux rope inserted into background corona
- Converging flows to trigger eruption.

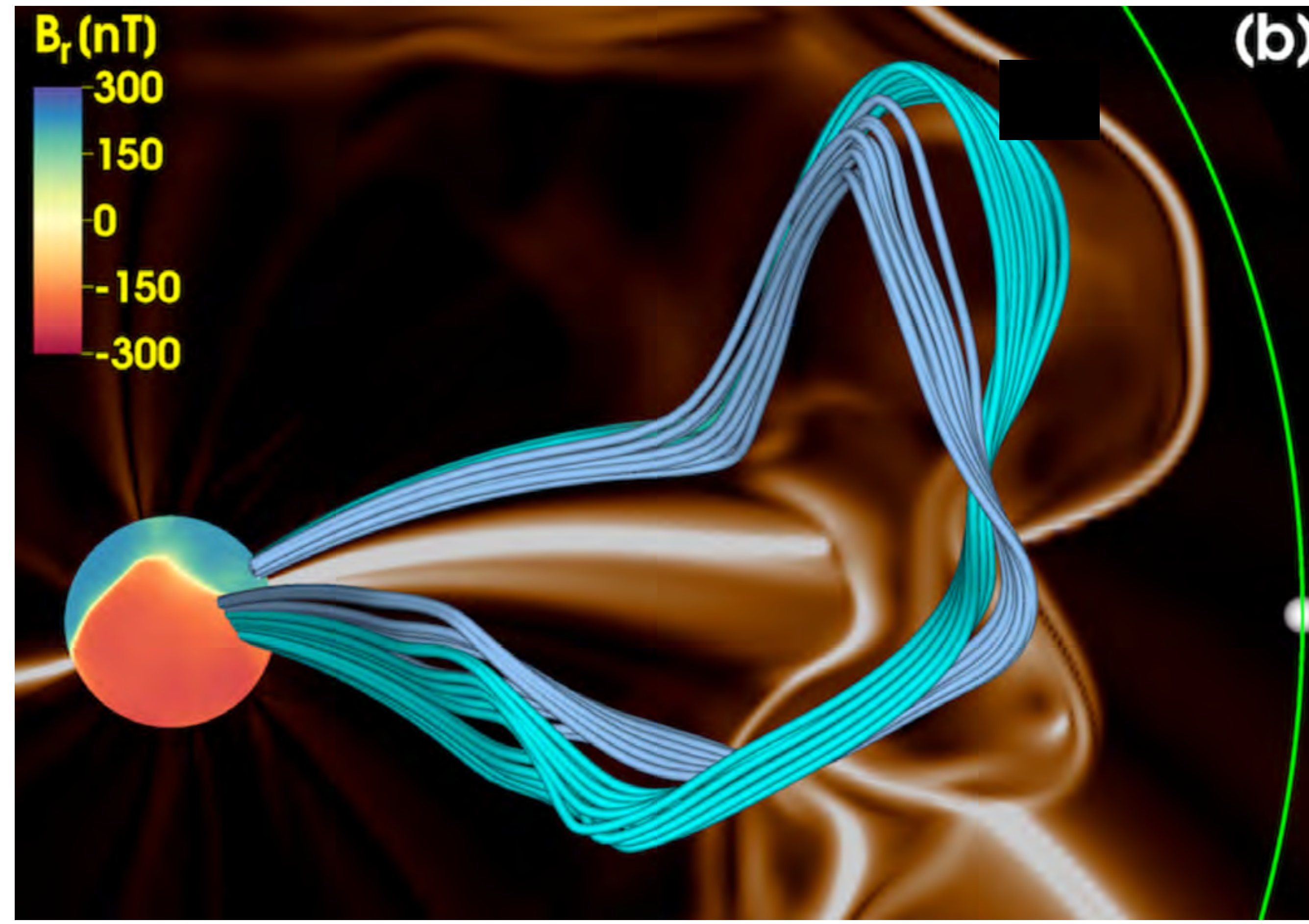
stable FR → self-consistent CME speed → simulation possible **prior** to erruption

Sun-to-Earth MHD Simulation of the 14 July 2000 “Bastille Day” Eruption

Torok et al (2018)

Heliospheric Simulation of the Bastille Day ICME (20-235 $R_\odot$)

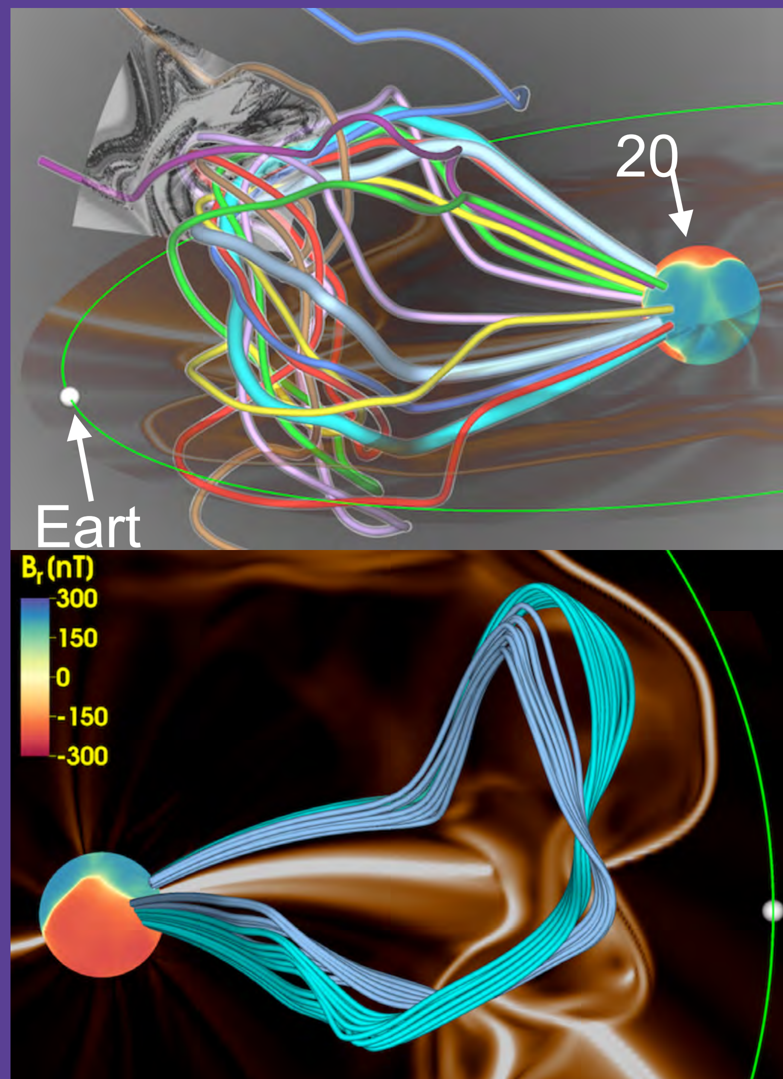


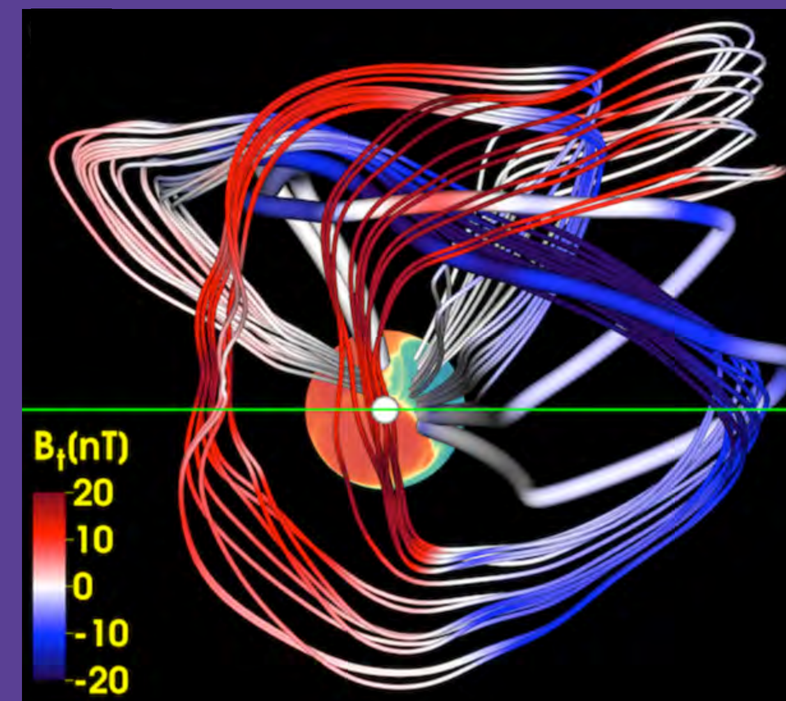


ICME propagation in equatorial plane

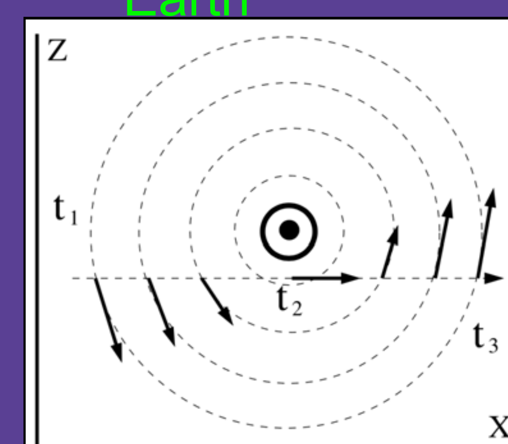
- Propagate CME to 1 AU: Coupling coronal to heliospheric MHD code
- No noticeable deflection by Parker IMF spiral
- ICME shape distorted by non-uniform solar wind
- Post-eruption jet due to the current sheet reconnection

ICME Magnetic Structure





view from Earth



Yurchyshyn *et al*. (2001)

- flux-rope core (MC) splits into two loops
- MC arrives about (15-20)° north of Ecliptic

Summary

- More numerical models has been developed and applied for heliospheric space weather
- Many interesting studies were realized to analyze specific events and to provide a global context
- Numerical models are continuously improving and their validation becomes more and more important
- Coordinated effort via the ISEST, CCMC/Scoreboard, etc., is becoming more and more beneficial