Near Real-Time Simulation of Heliospheric Space Weather

Dusan Odstrcil[1,2]

[1]*George Mason University,* [2]*NASA/GSFC*

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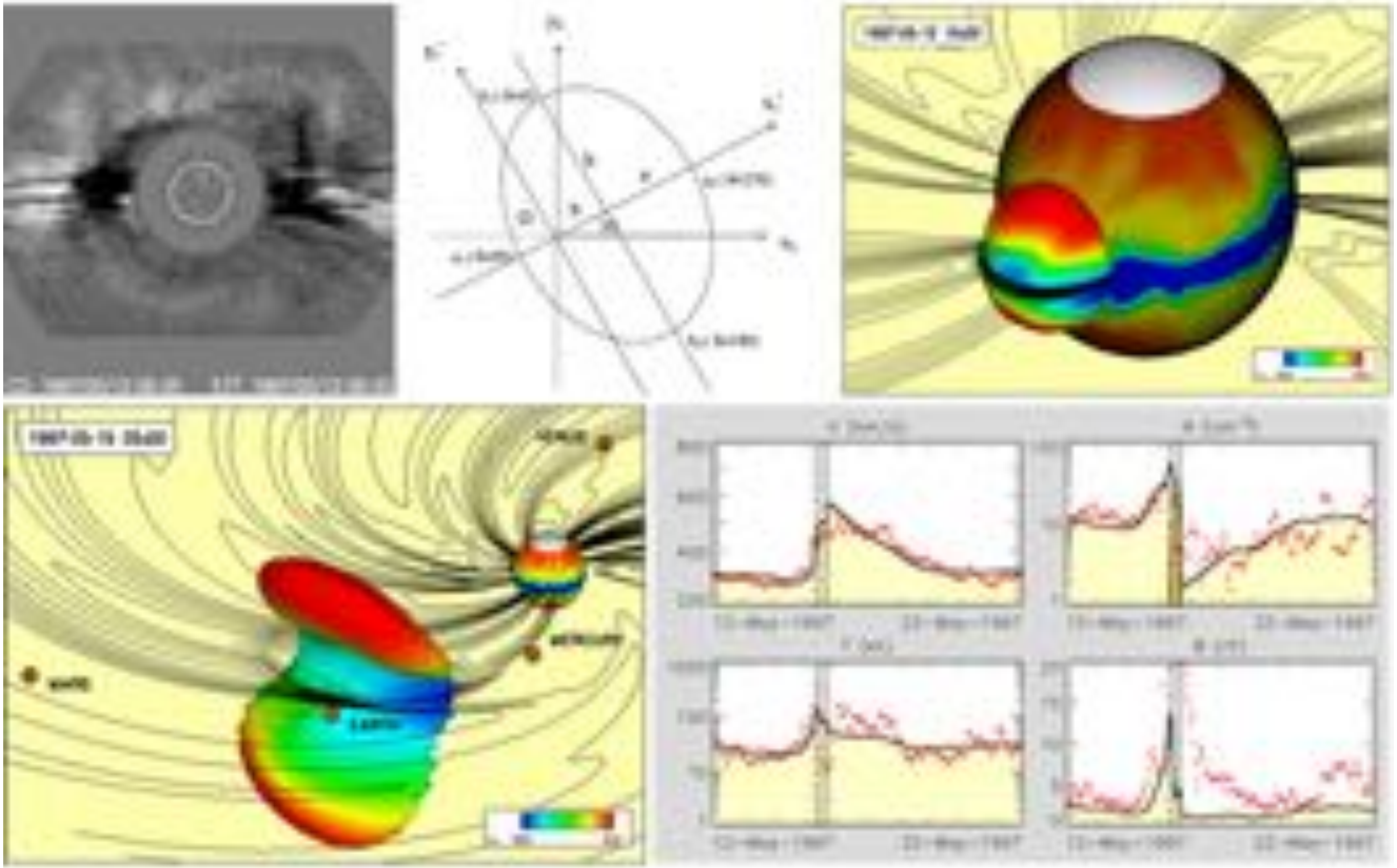
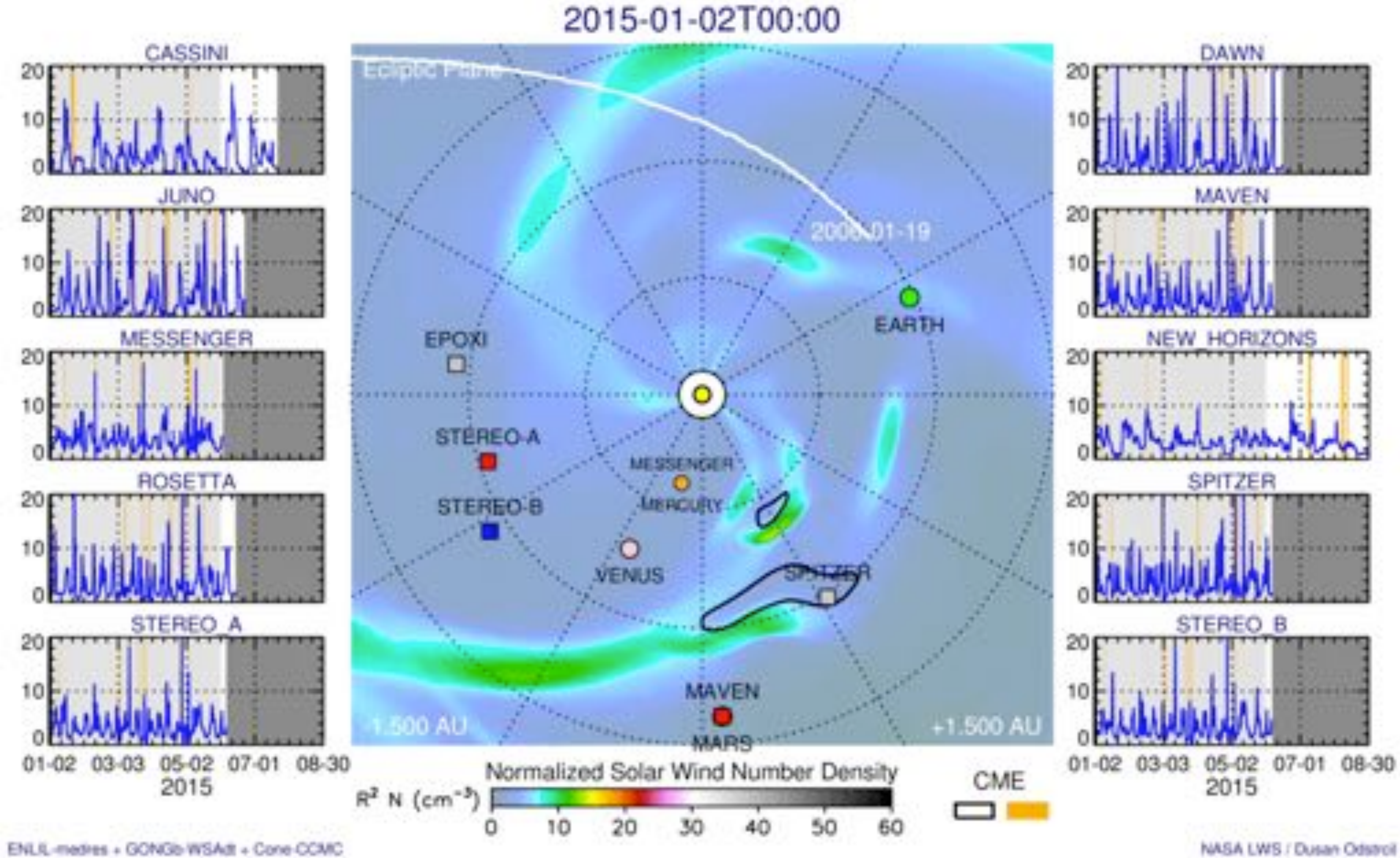
WSA-ENLIL-Cone — Operational Predictions of Heliospheric Disturbances



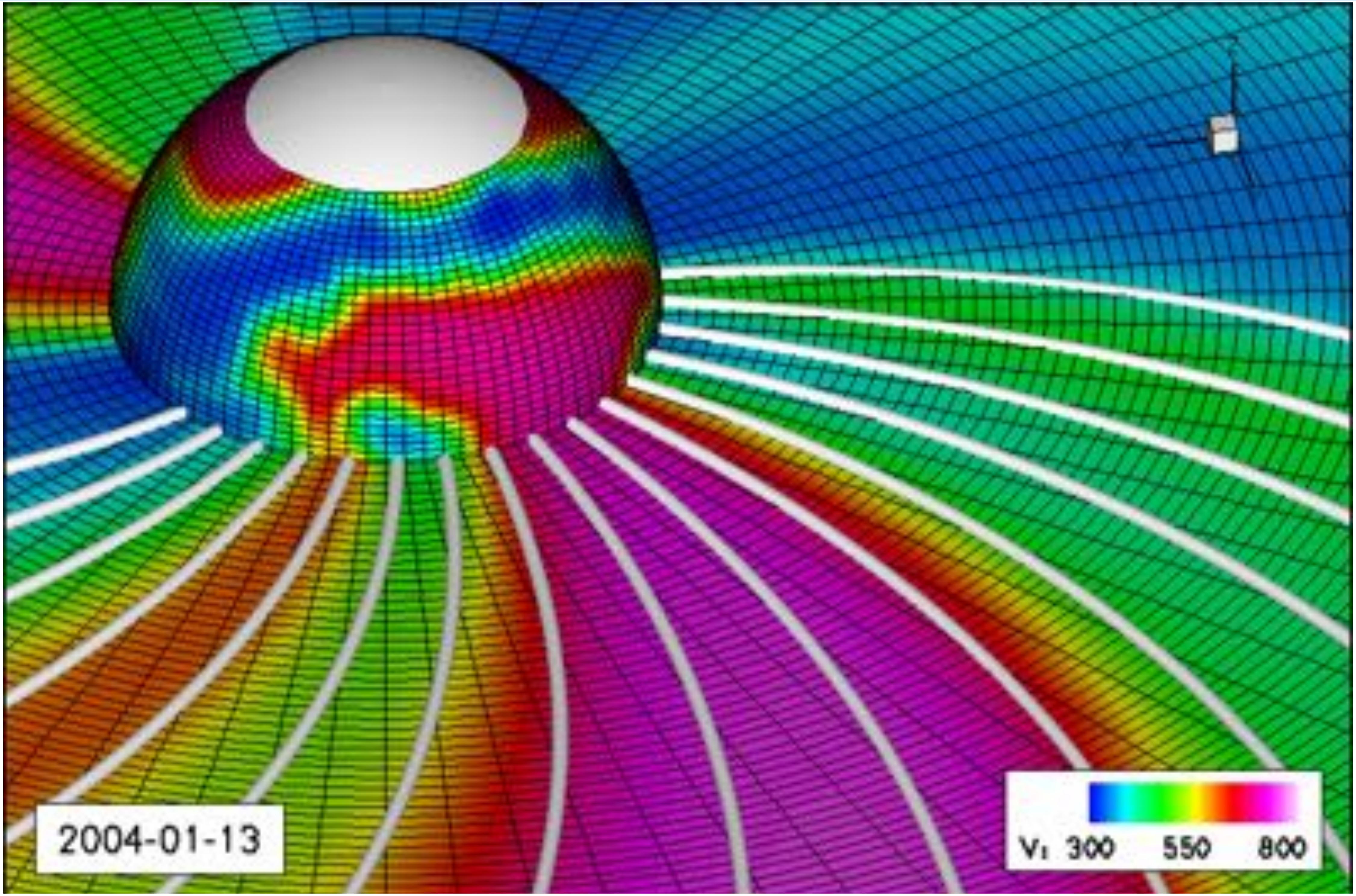
- Observationally driven, near-real time, “hybrid” modeling system for heliospheric space weather.
- Routine simulation of co-rotating streams and CMEs, event-by-event, much faster than real-time.
- Used at NASA/CCMC, NOAA/SWPC, UK Met Office, and Korean Space Weather Center.

WSA-ENLIL-Cone — Predictions at New Horizons / Pluto



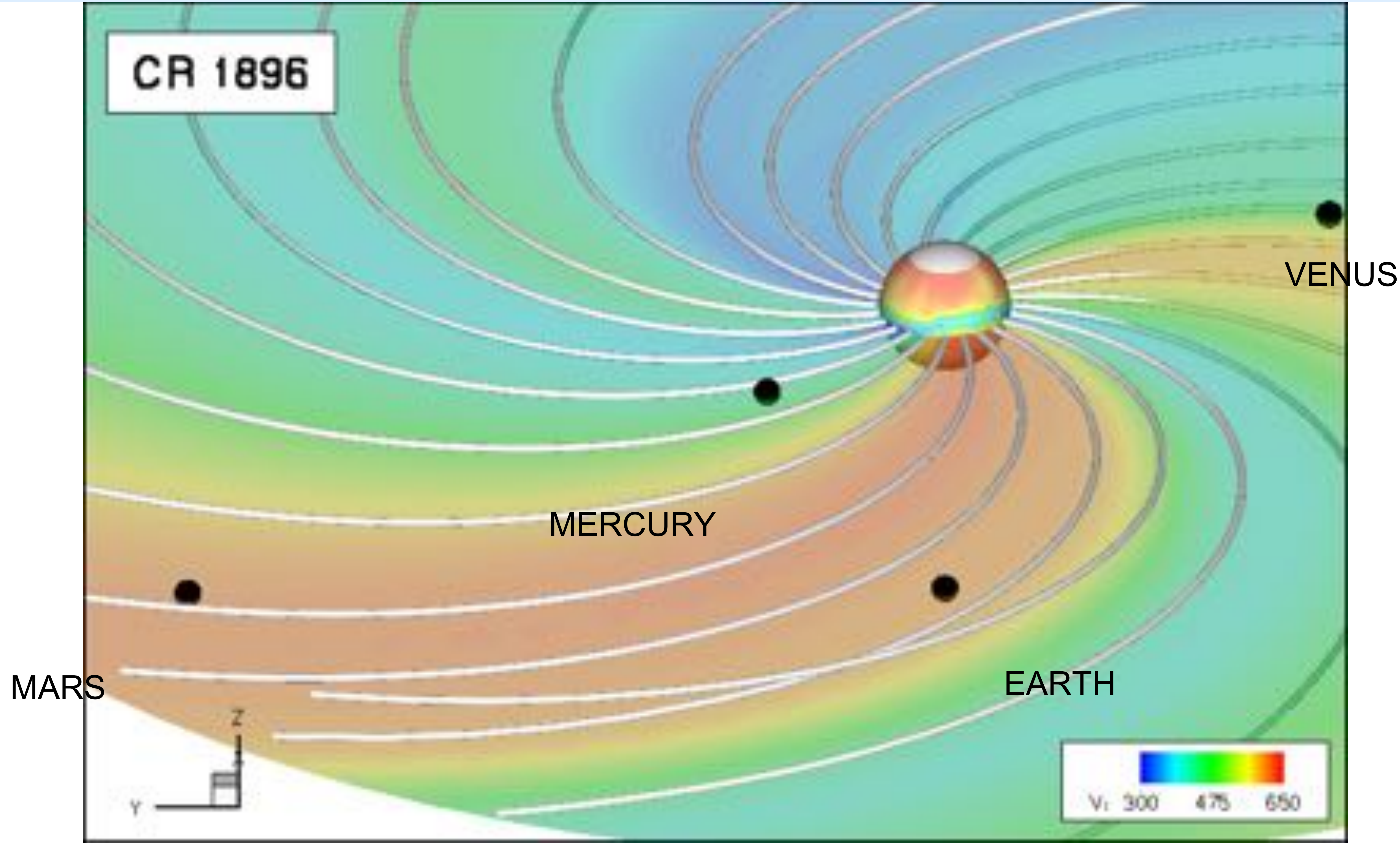
- All CMEs (>500 km/s) fitted by CCMC in past 8 months are used for 4-months prediction at NH.
- History (light-grey background) and prediction (white background) for heliospheric missions.
- Can be used for mission planning and operational support at NASA/CCMC.

Ambient Solar Wind at the Inner Boundary



- Numerical grids have angular spacing: 4^0 (low), 2^0 (medium), and 1^0 (high).
- This corresponds to the resolution of ~7.3, ~3.6 and ~1.8 hours of co-rotating structures.
- Full-rotation (daily-updated) maps have uniform (longitudinally-dependent) accuracy.

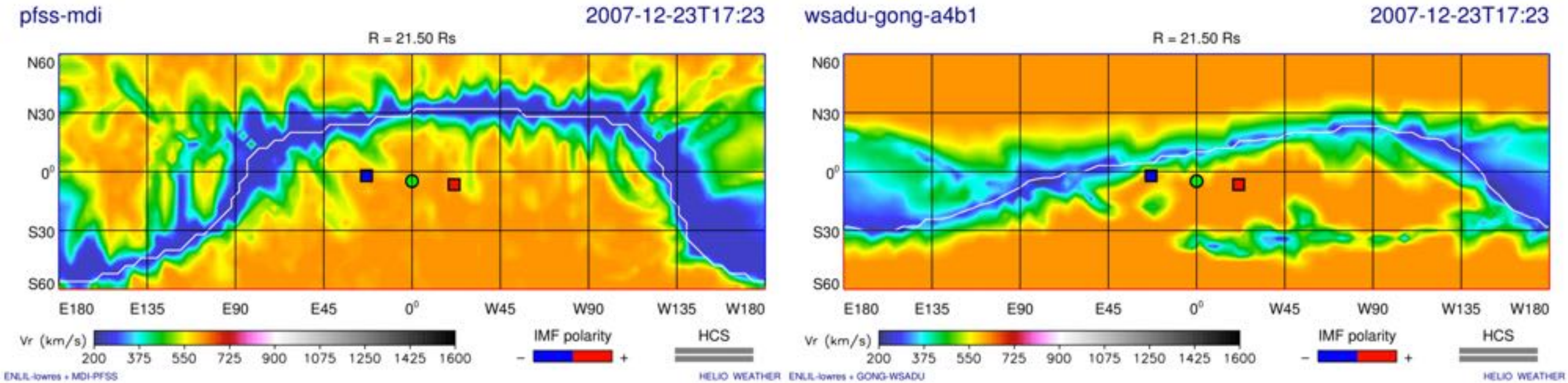
Ambient Solar Wind at the Equatorial Plane



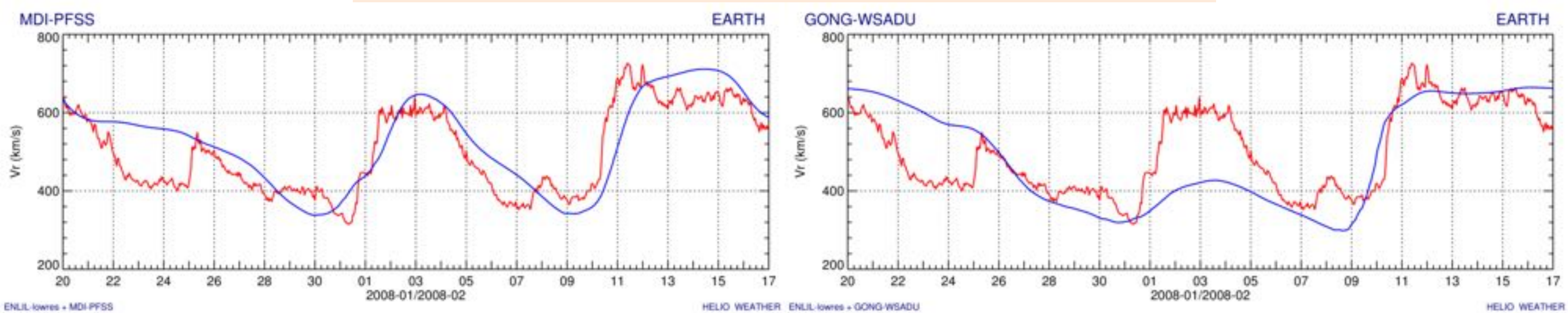
- Coronal magnetic field strongly depends on the photospheric observations near solar poles.
- These regions are poorly observed from Earth but they determine the current sheet topology.
- Near solar minima, the sheet structure is flat and thus a small latitudinal inaccuracy leads to large longitudinal errors in the stream arrival time.

Ambient Solar Wind — Using Different Maps

Boundary Conditions – Solar Wind Velocity at 0.1 AU



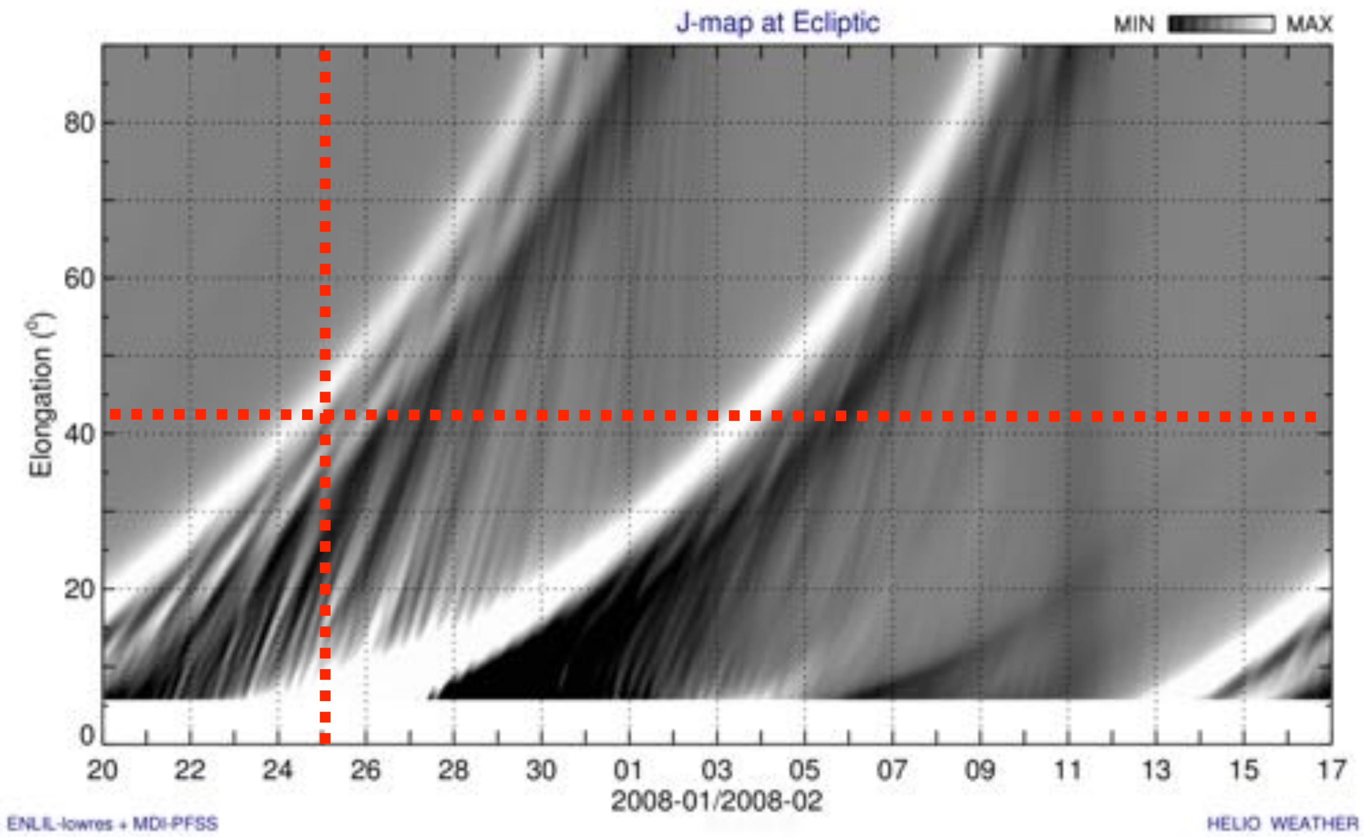
Predicted Solar Wind Velocity at Earth



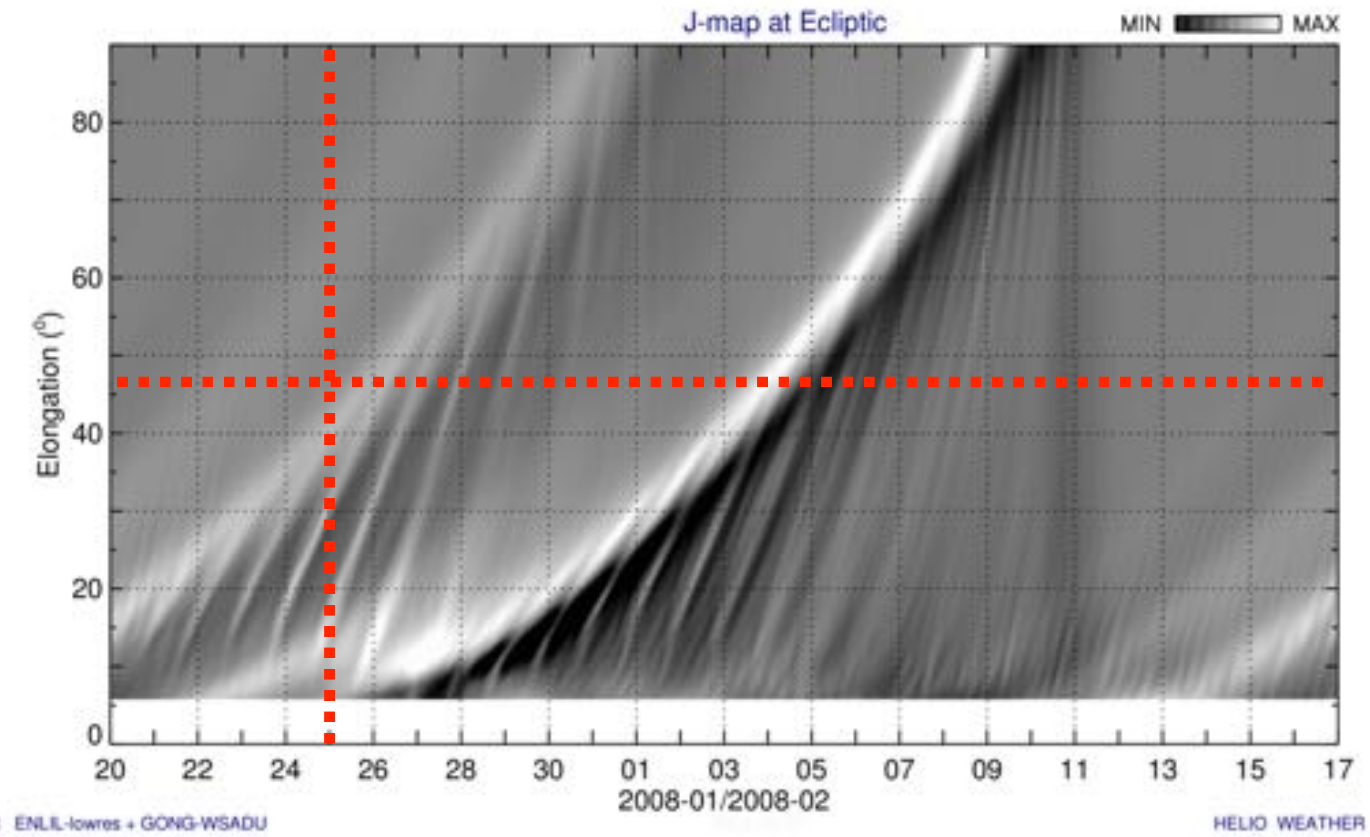
- Different remote observations of the photospheric magnetic field and/or different coronal models produce different synoptic maps of the solar velocity at 0.1 AU.
- These maps drive heliospheric simulations and it is unclear which prediction is more accurate until "it is too late" and values can be compared with in-situ measurements at Earth.

Comparison of Two Predictions — J-Maps

Run with MDI-PFSS



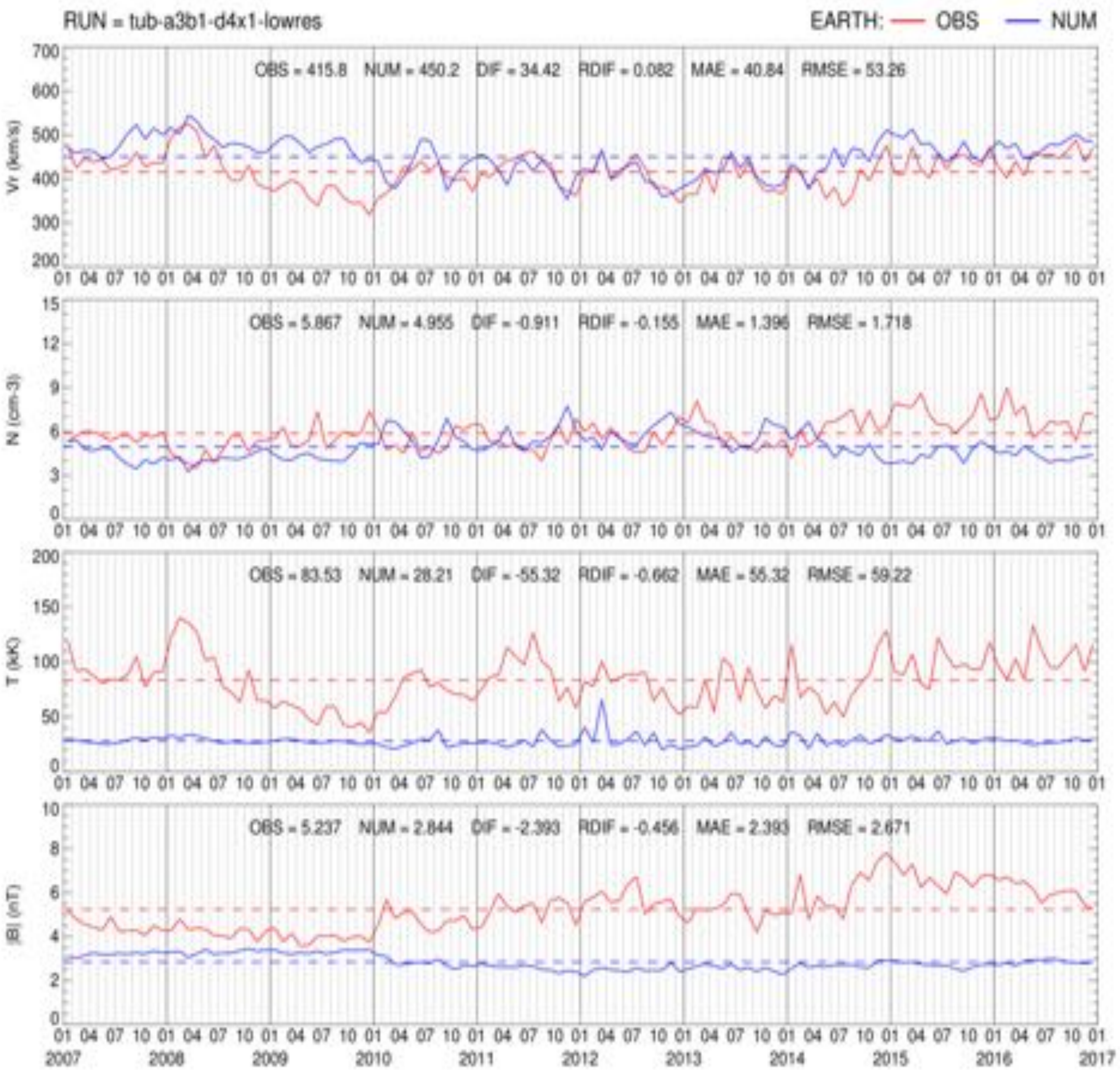
Run with GONG-WSADU



- Both runs show two bright structures – compressed density by solar wind stream interaction.
- Converging patterns of small-scale structures correspond to blobs that are overtaken by fast streams (this helps to differentiate between CMEs and streams).
- The difference in the brightness and slope can be clearly seen for the first streamer track while the second stream is about the same.
- This suggests that the MDI-PFSS run will cause stronger streamer with earlier arrival to Earth.
- Since the stream interaction regions can be seen well before their arrival to Earth, scientific (i.e., no need for beacon) data can be also used to suggest which prediction is more accurate.
- (There are very few clear “textbook” examples for possible “mid-course” correction use).

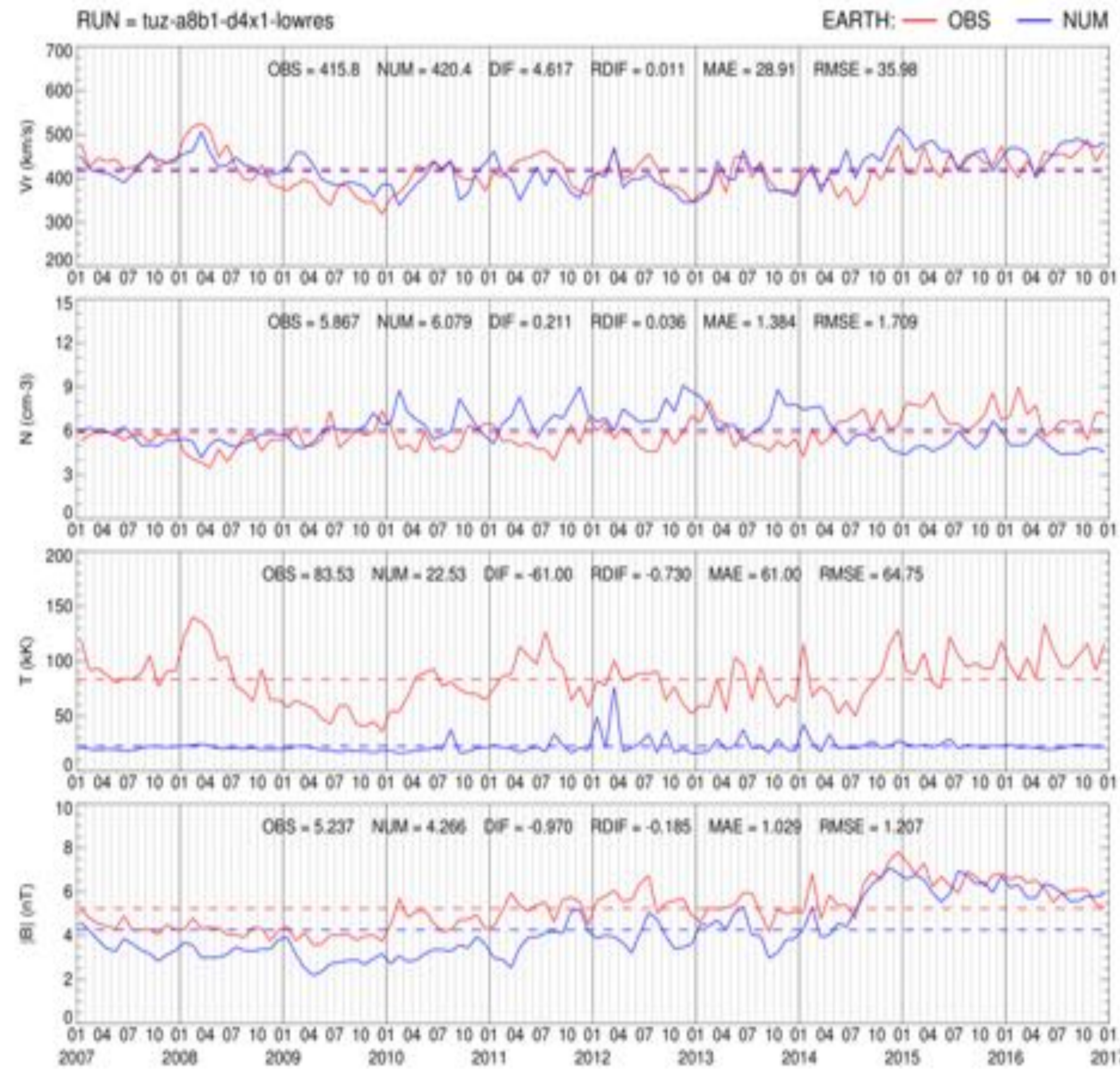
Model Free Parameters — Background Solar Wind — Calibration

Old: “a3b2



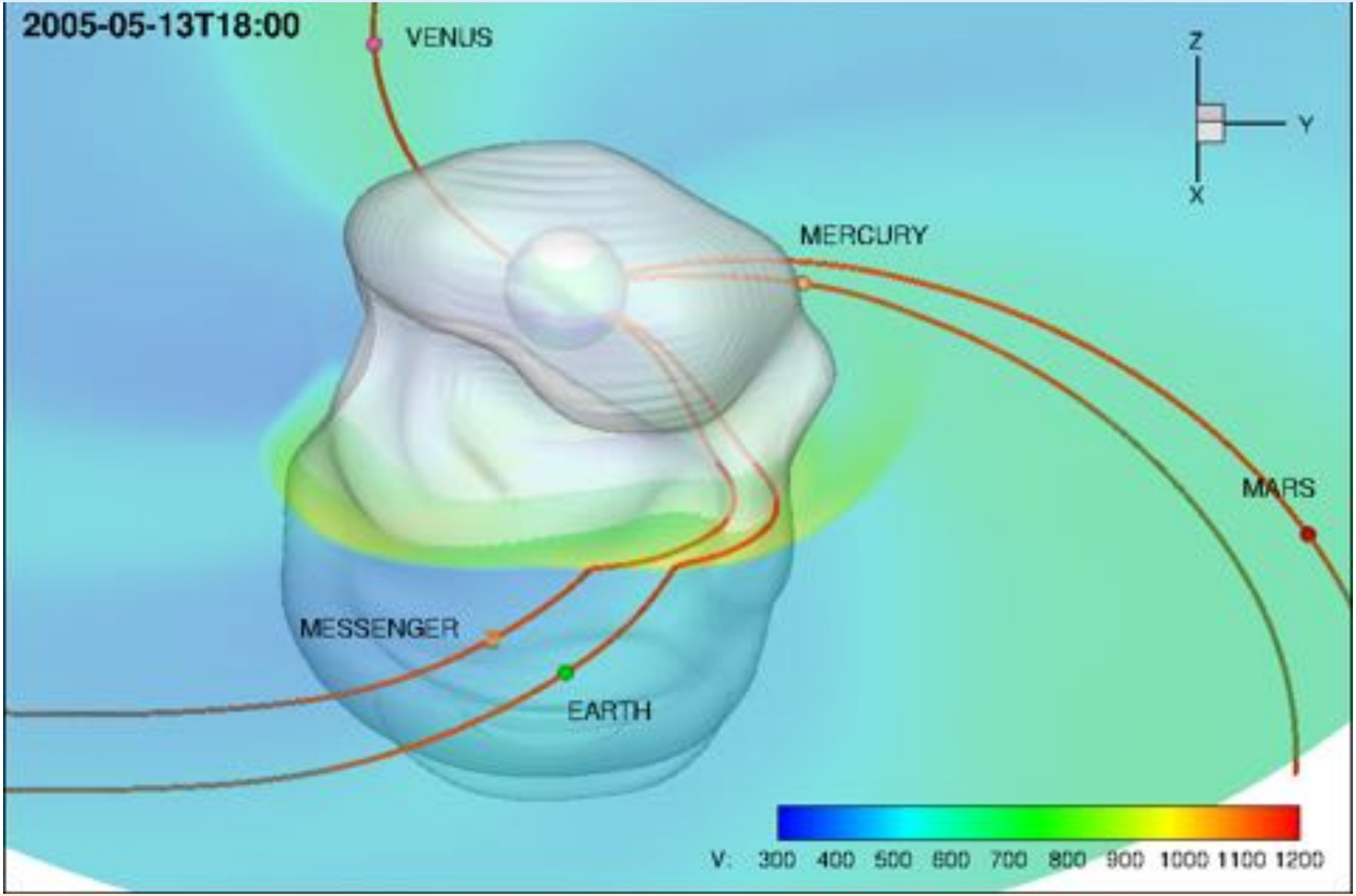
- Delivered: a beginning of the solar cycle with limited calibration.
- Motivation: ensure robustness & reasonable accuracy during the upcoming solar cycle maximum.

New: “a8b1



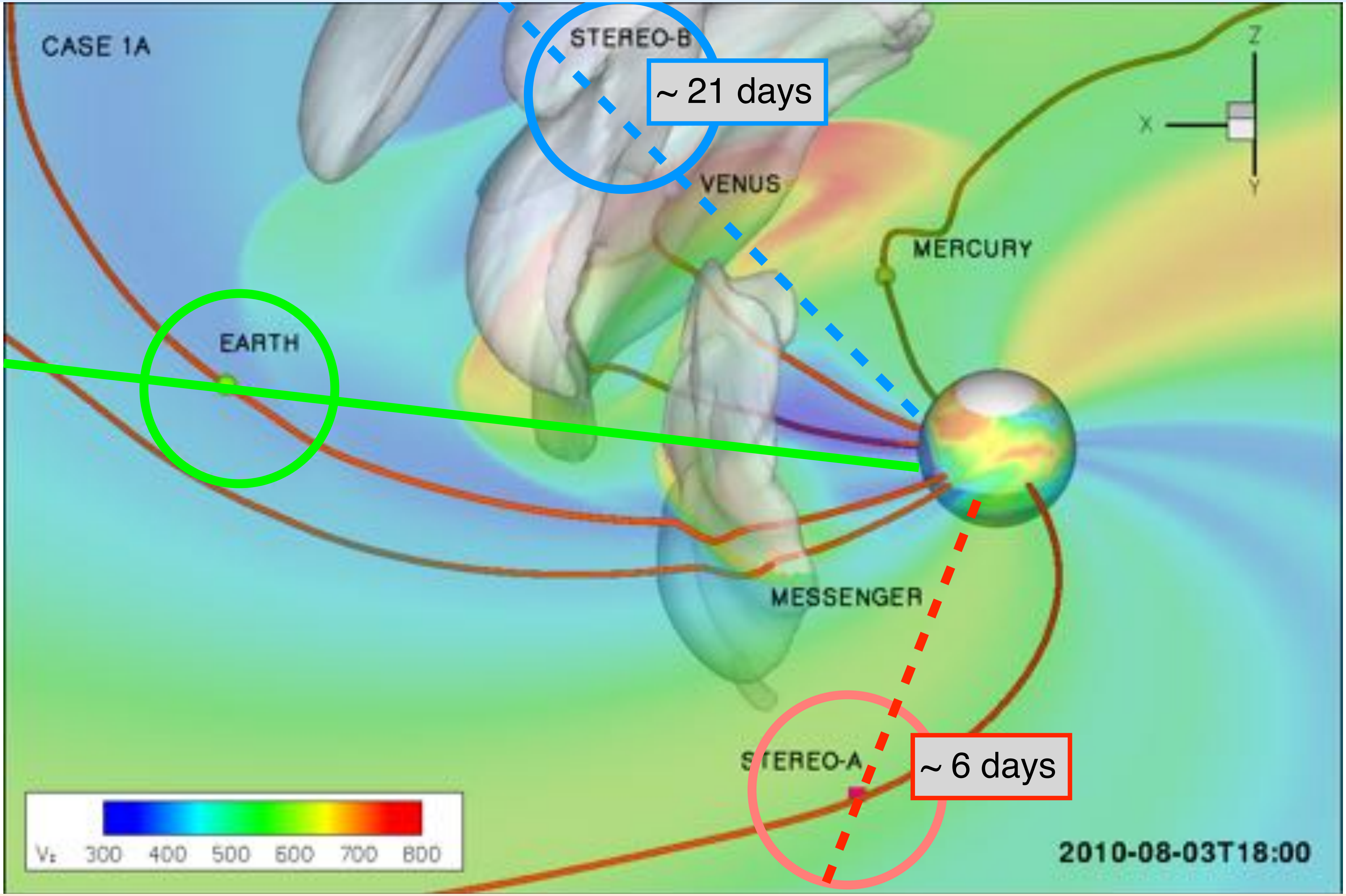
- Revised calibration with 2007-2016 (WSA) and 2010-2016 (CME-“cone”) data & larger robustness experience.
- Using “mrzqs” instead of “mrbqs” GONG data.

2005-05-13 CME — "Cone" Model Simulation



- CME axis close to the Sun-Earth direction — no Bz by shock compression and/or IMF draping.
- The model can predict the arrival of shock and/or ejecta, and IMF topology.
- Simulation is very fast — operational predictions, parametric studies, ensemble modeling.

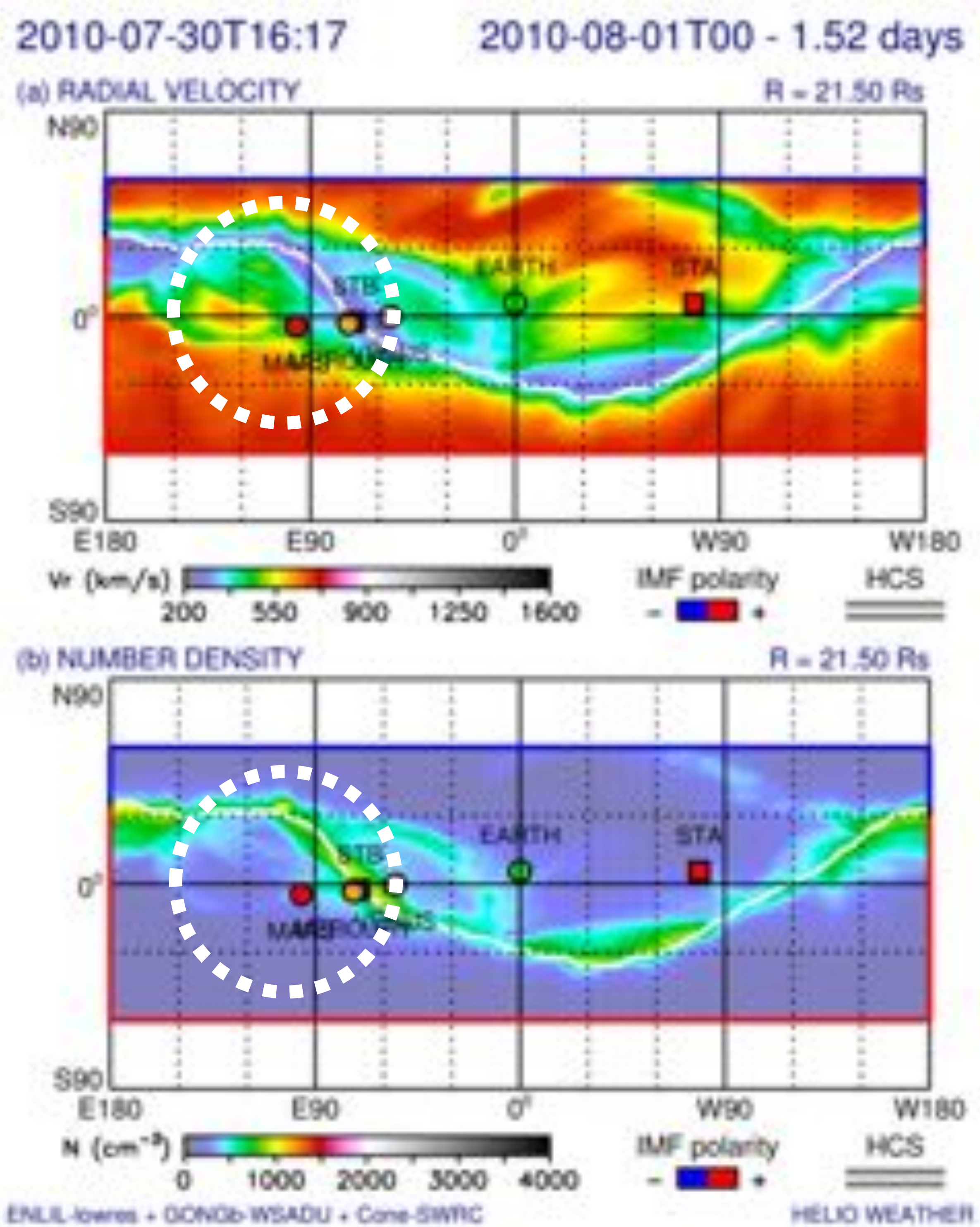
Simulation of Multi-CME Events



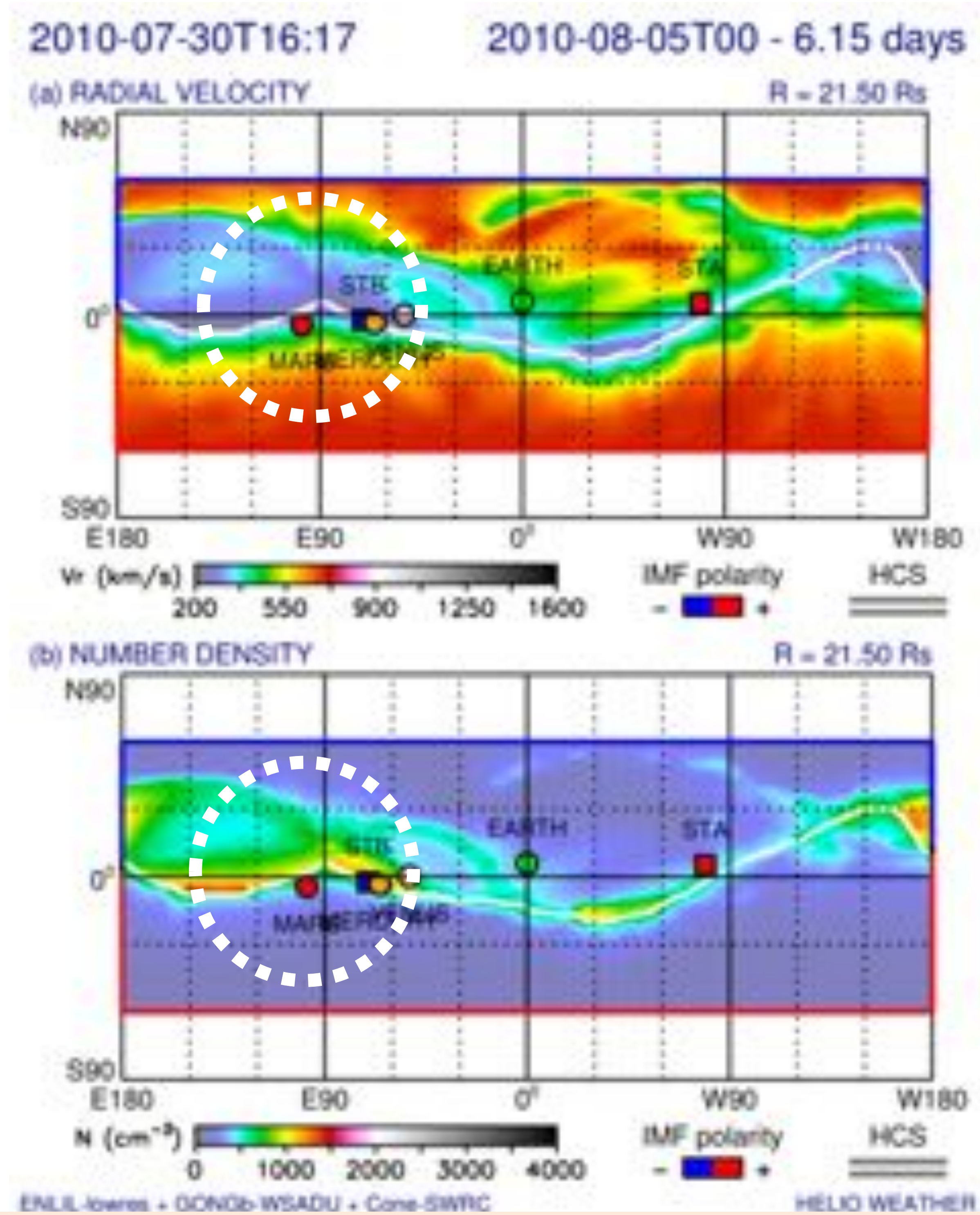
- Currently, the photospheric magnetic field is observed from the Earth-Sun direction only.
- Sun rotates counter-clockwise with the synodic rotation period of 27.2753 days.
- This means that the WSA maps are about 21 days old in the Sun-STB direction.

Boundary Conditions — Single WSA/GONG Map

WSA map of Aug 1 shifted to July 30 position



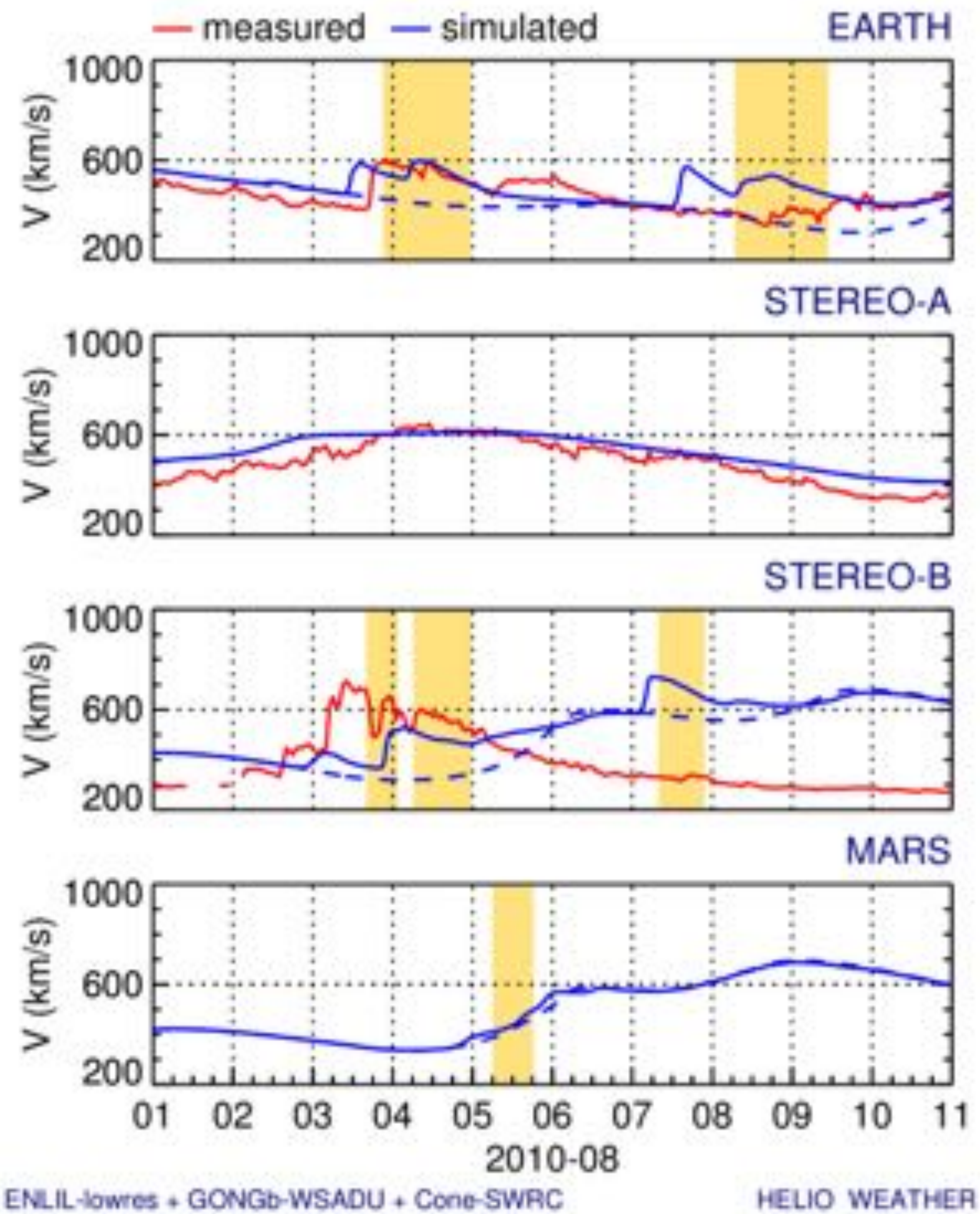
WSA map of Aug 5 shifted to July 30 position



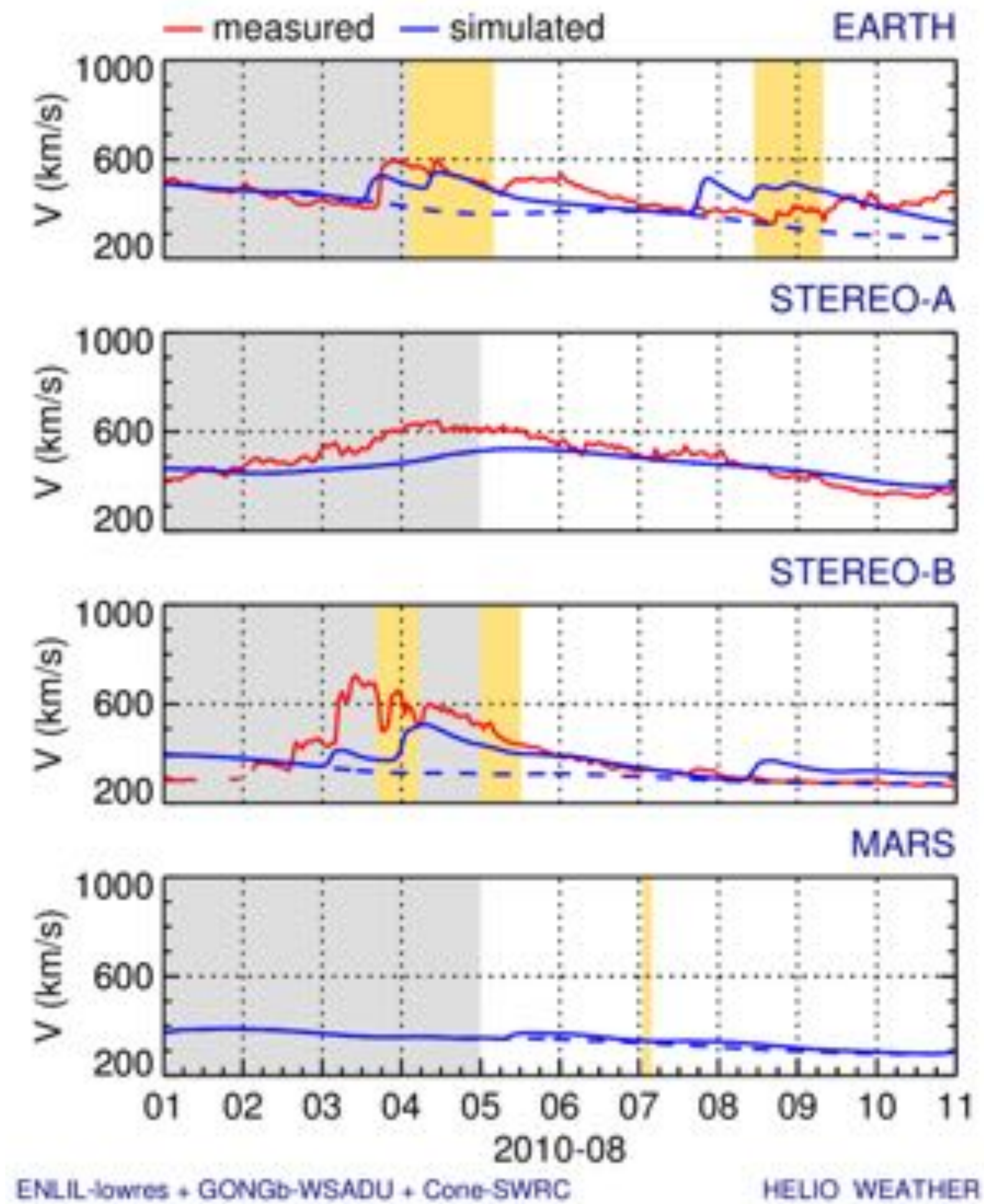
- Coronal magnetic field evolves slowly but it might change significantly after a large solar eruption.
- WSA-map structures are up to date in the Sun-Earth direction but not in the Sun-STB one.
- Namely, “old” map involves a fast stream that will reach STB at 1 AU.

Solar Wind Velocity at Various Locations

Using WSA Map of Aug 1



Using WSA Map of Aug 5

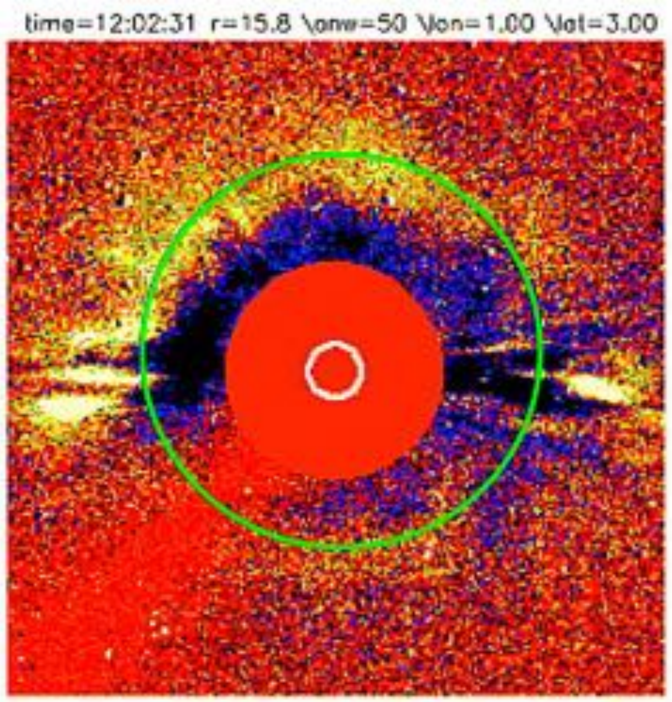


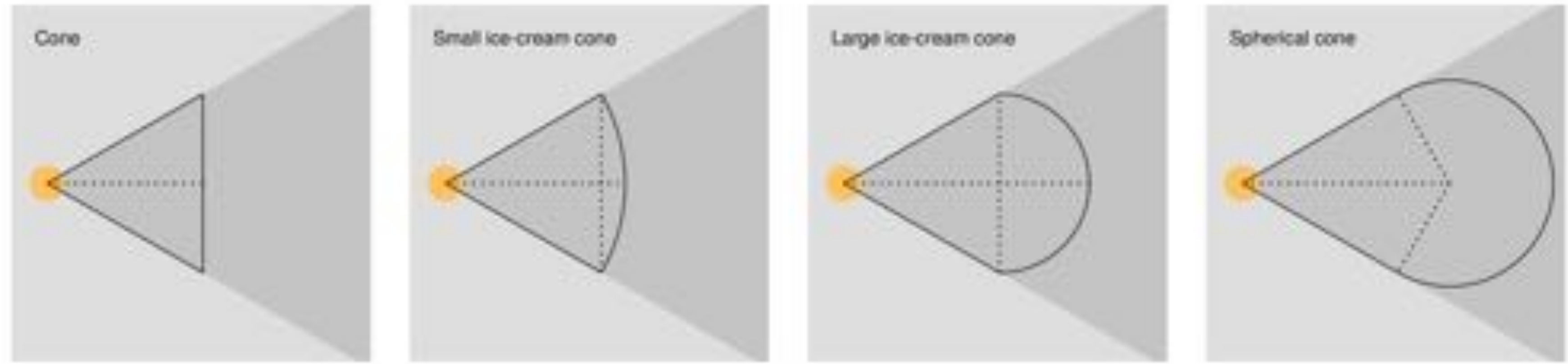
- Simulation with the “actual” map predict a false fast stream at STB.
- Prediction at STB significantly improves when using the “future” map.
- In operational predictions, such an improvement can be achieved with magnetograms at L5.

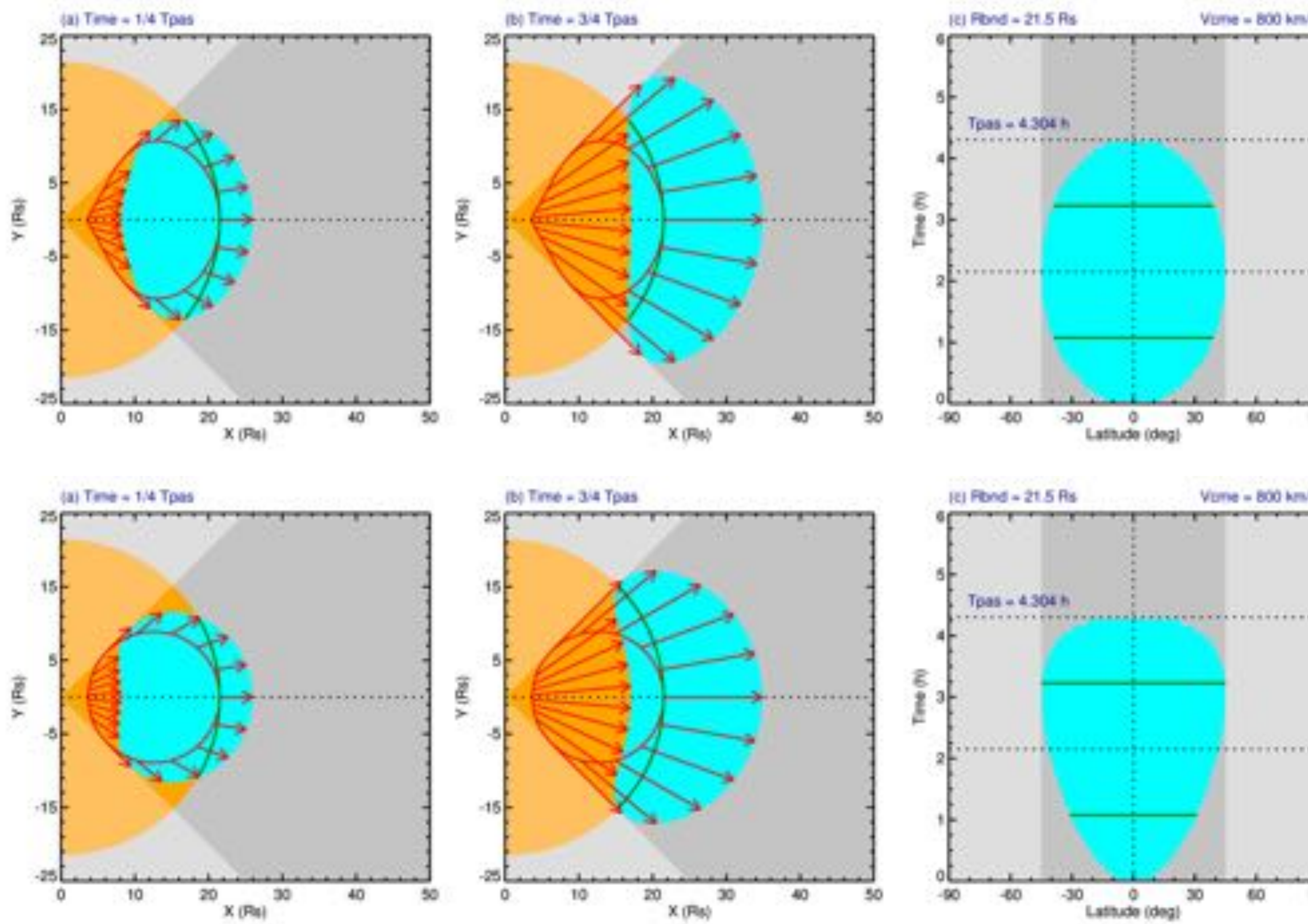
Launching Hydrodynamic Ejecta — Original Possibilities

Single-perspective SOHO observations

Running Difference

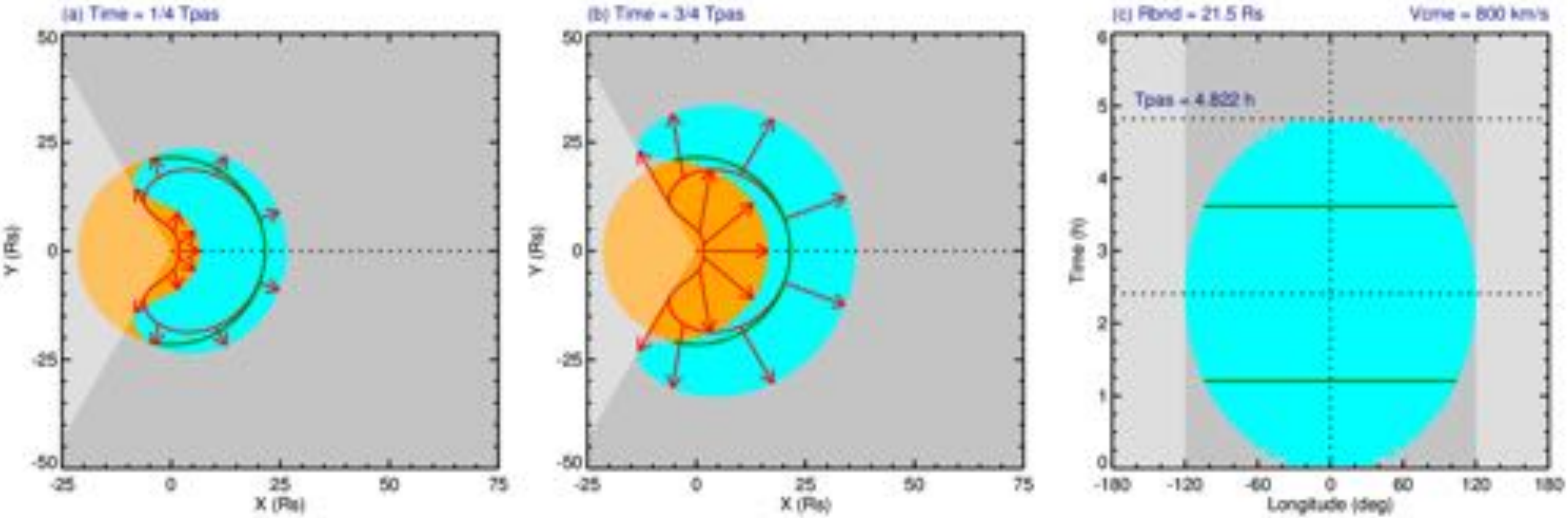


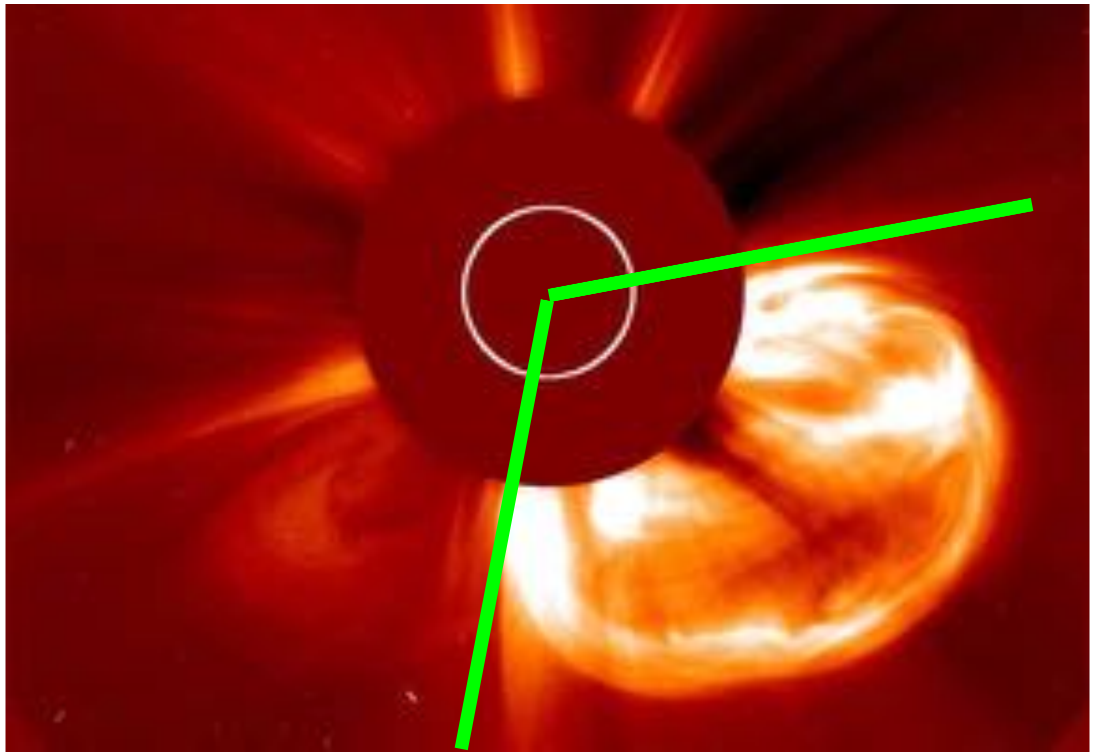




- Observed quantities: angular extent (“rmajor), directional latitude (“lat”) and longitude (“lon”), and speed (“vcld”).
- Model-free parameters: density (“dcld”), temperature (“tcld”), radial extenat (“xcld”).
- Two different realizations of the cone model.

Symmetric vs Asymmetric Sphere — 120 degs

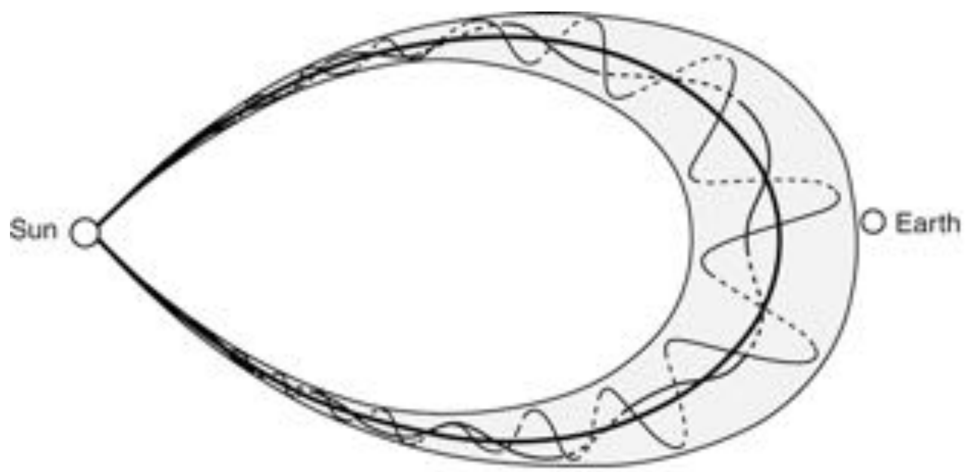


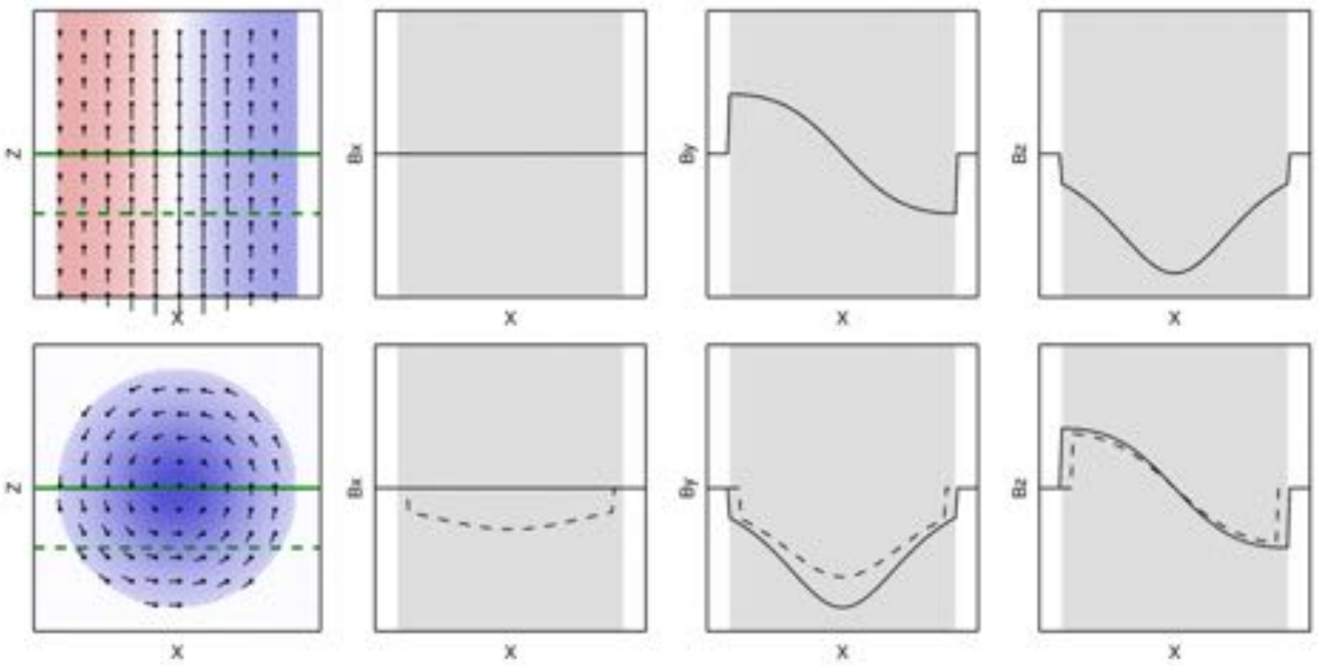


- “Asymmetric” (self-similar, spherical ice-cream) approach support is limited by the 90-deg half-width.
- “Symmetric” (lemniscal, large ice-cream) has no such restrictions.
- Operational WSA-ENLIL-Cone uses this approach for robustness.

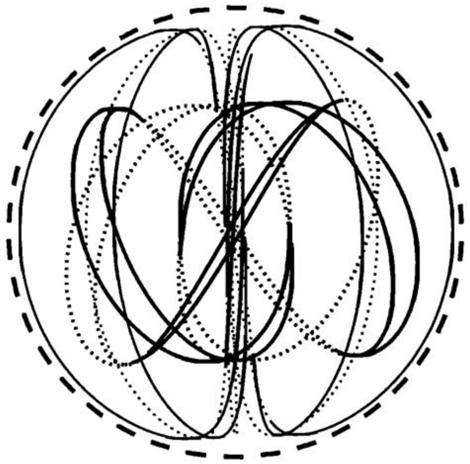
Launching Magnetic Structures

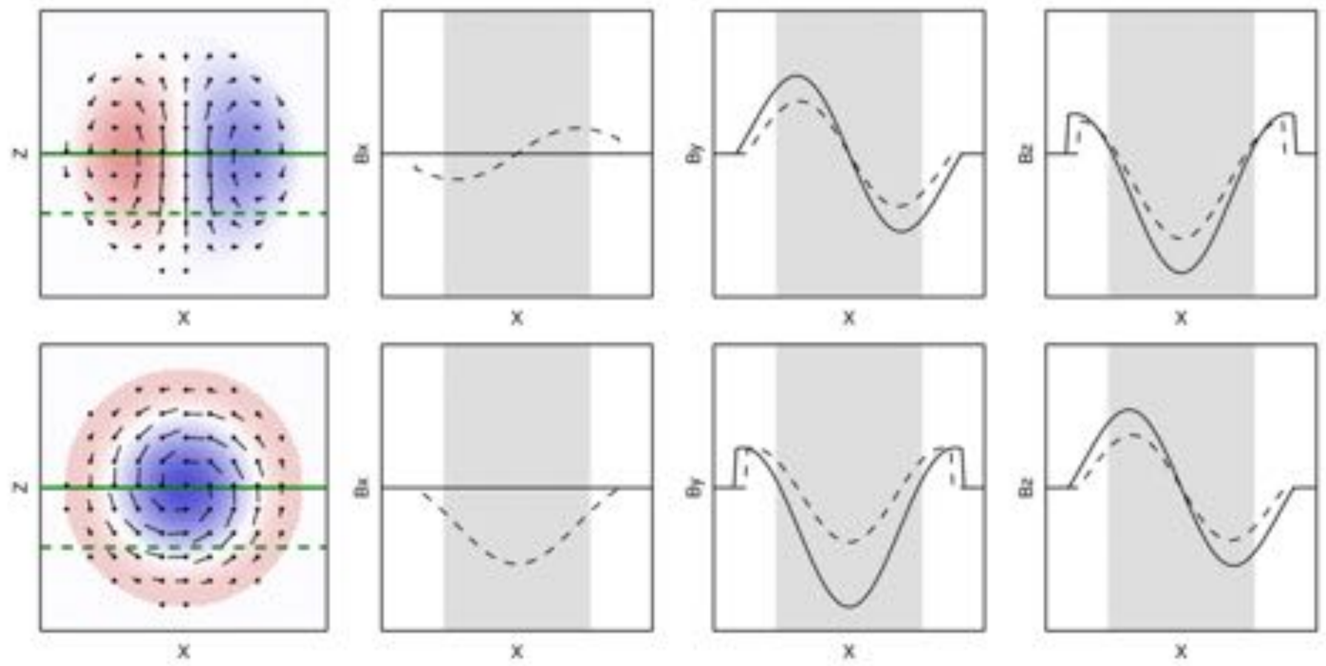
Flux Rope





Spheromak

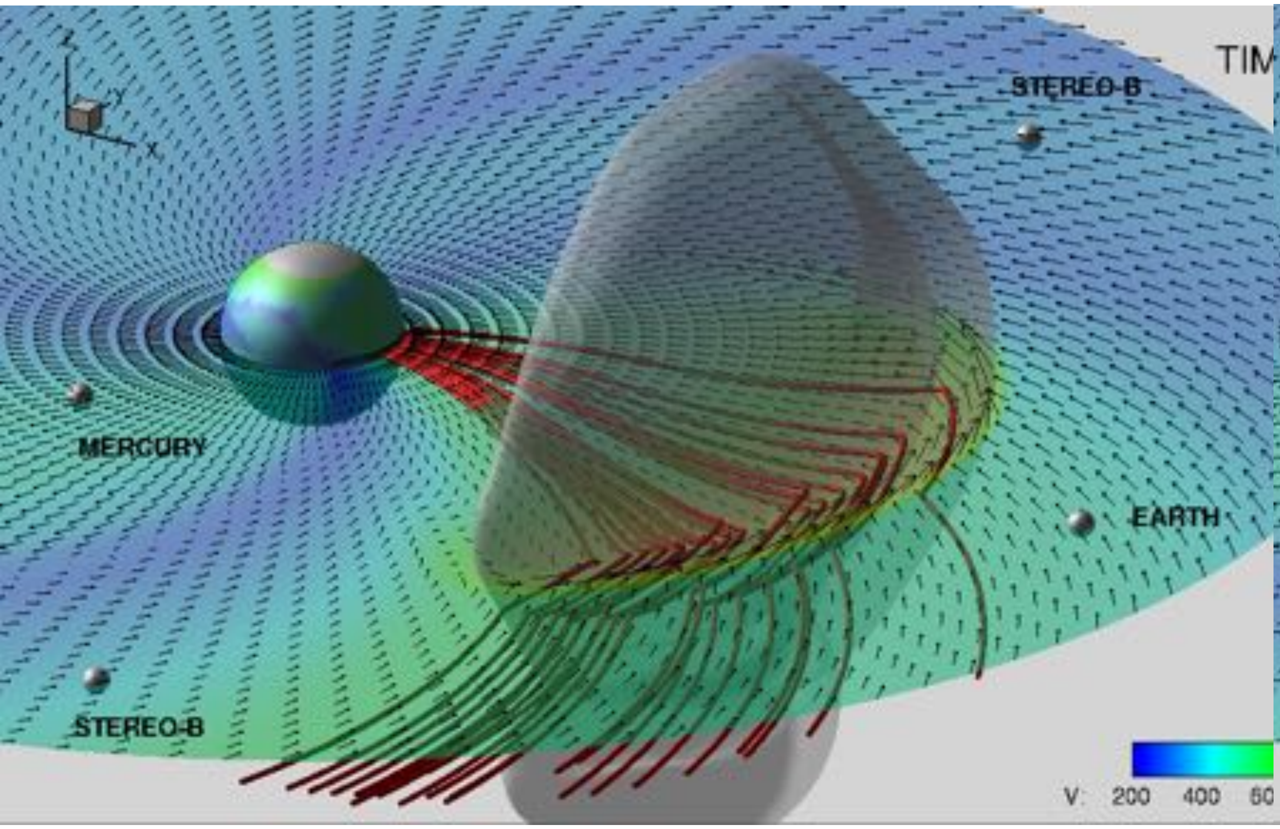




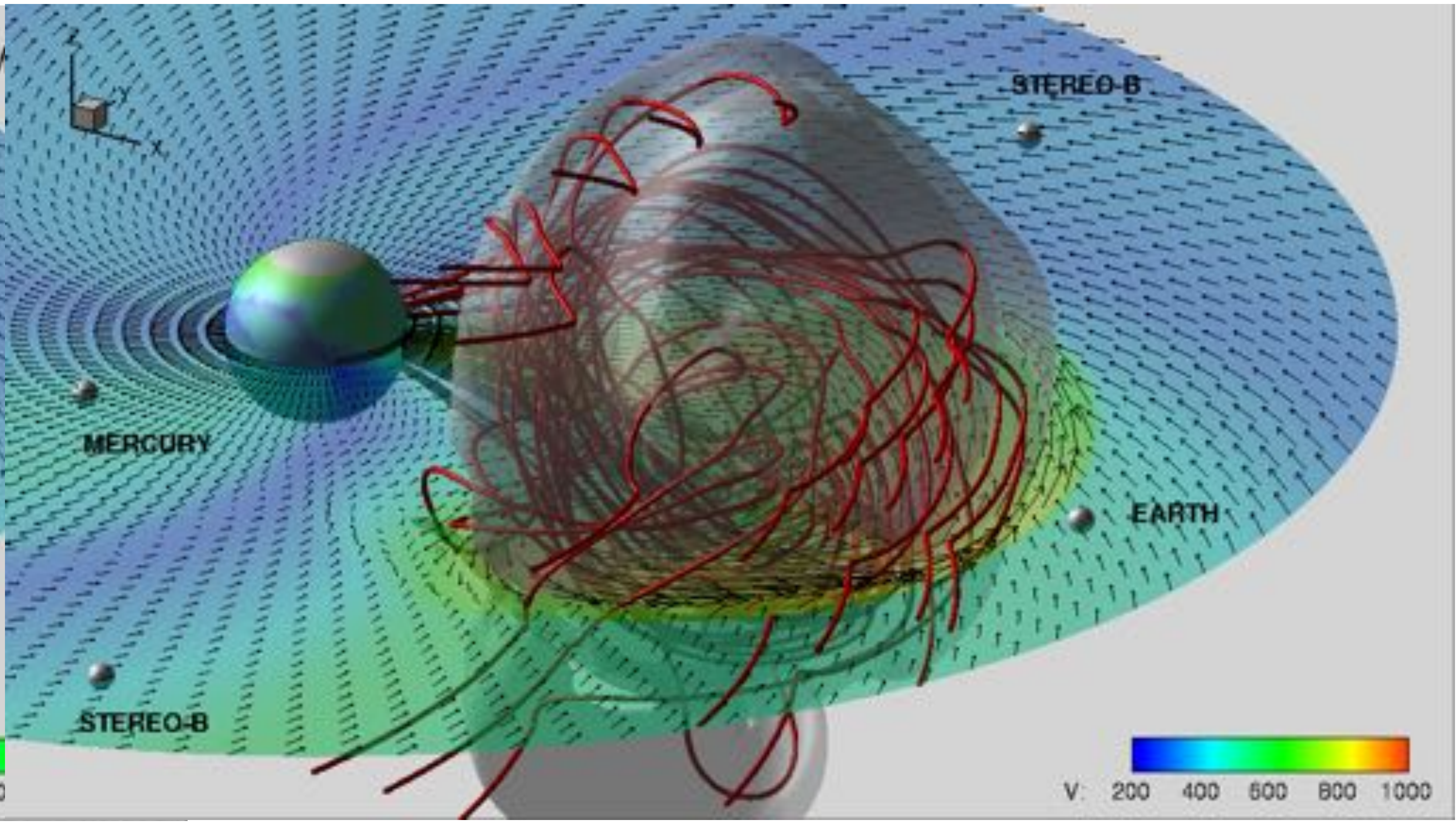
Numerical diffusion/erosion makes them even more similar (Savani)

Global View — "Cone" vs "Spheromak"

Cone



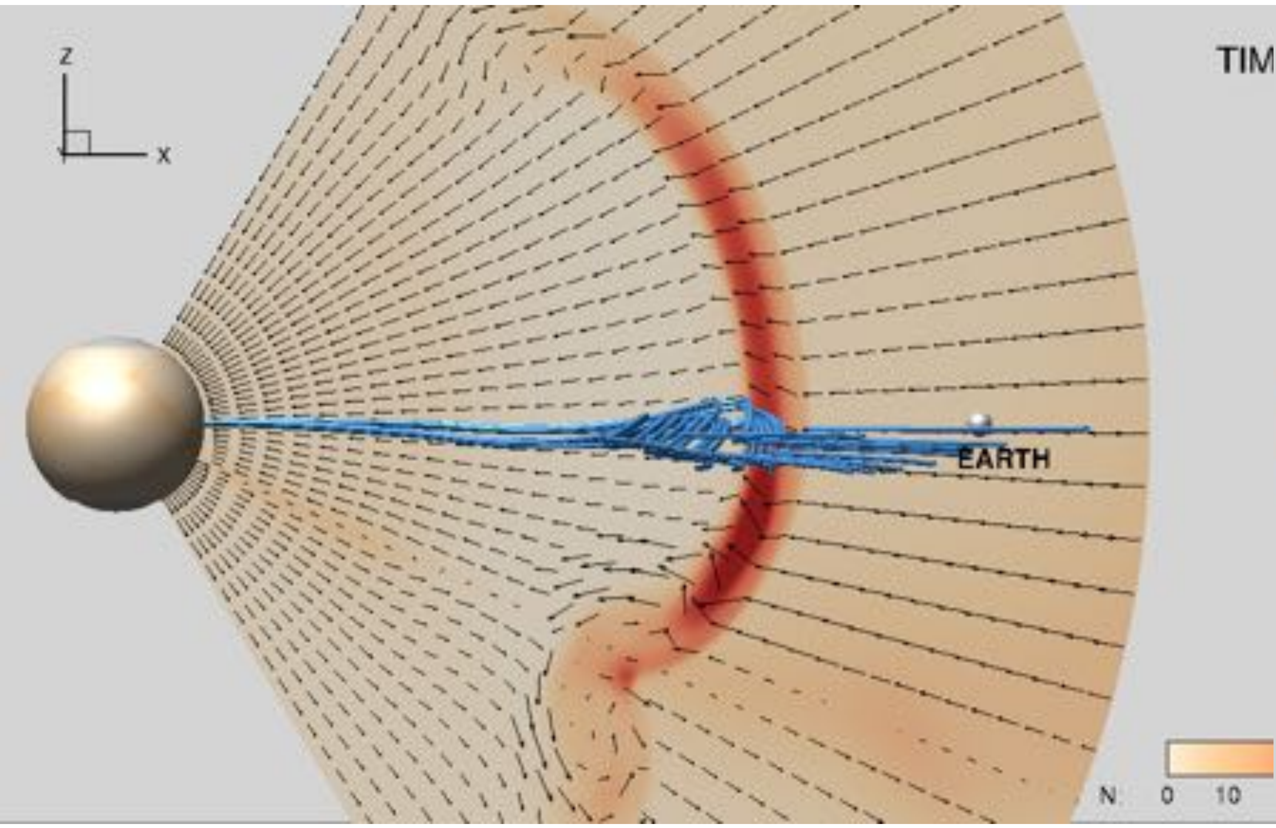
Spheromak



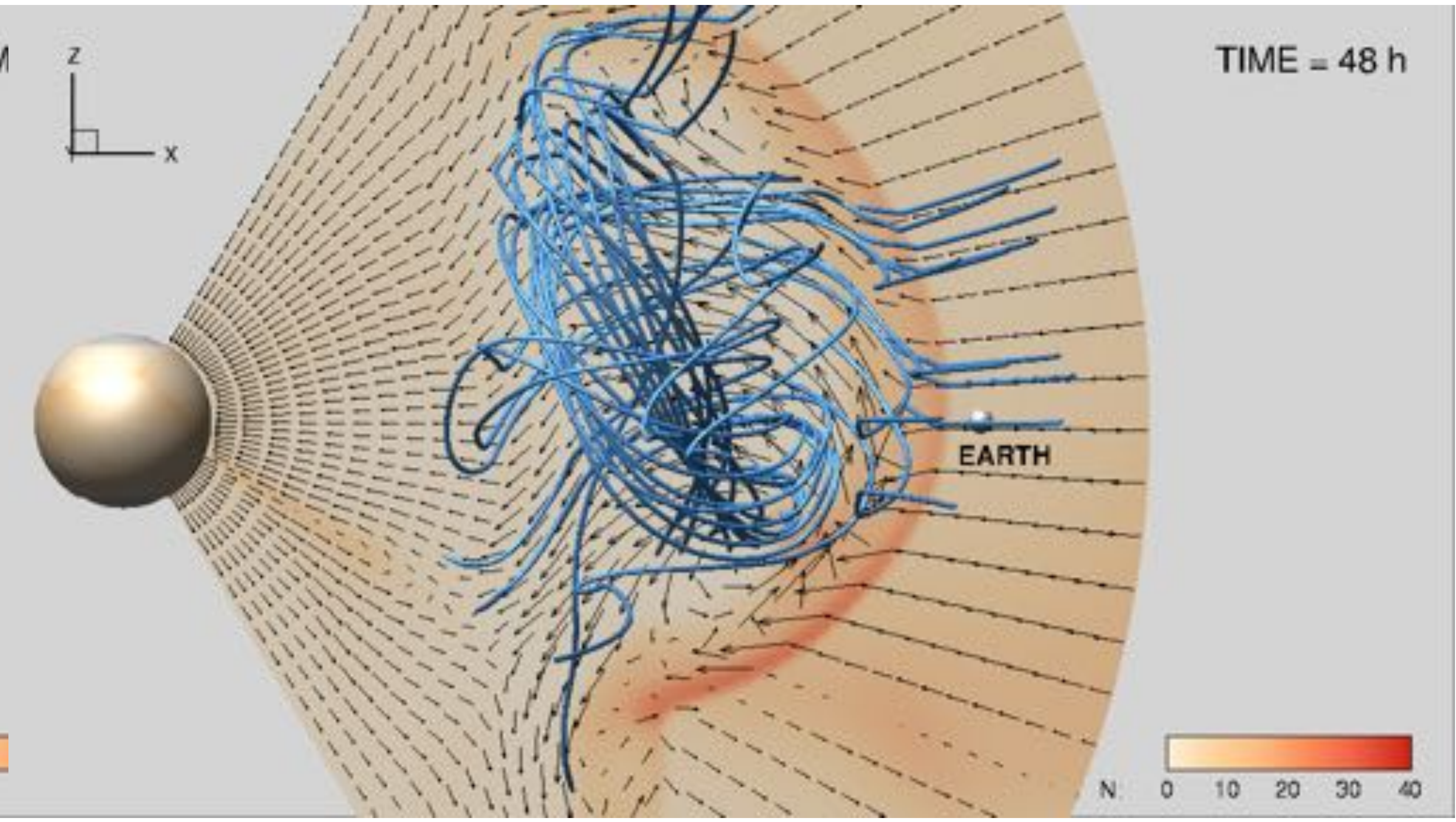
- IMF lines spiral in the heliosphere — there is a very small Bz component of the magnetic field.
- Shocks can compress the IMF and ejecta can drape the IMF — but without significant Bz enhancement.
- Embedded magnetic structures — can have strong Bz component.

Density Structure — “Cone” vs “Spheromak”

Cone



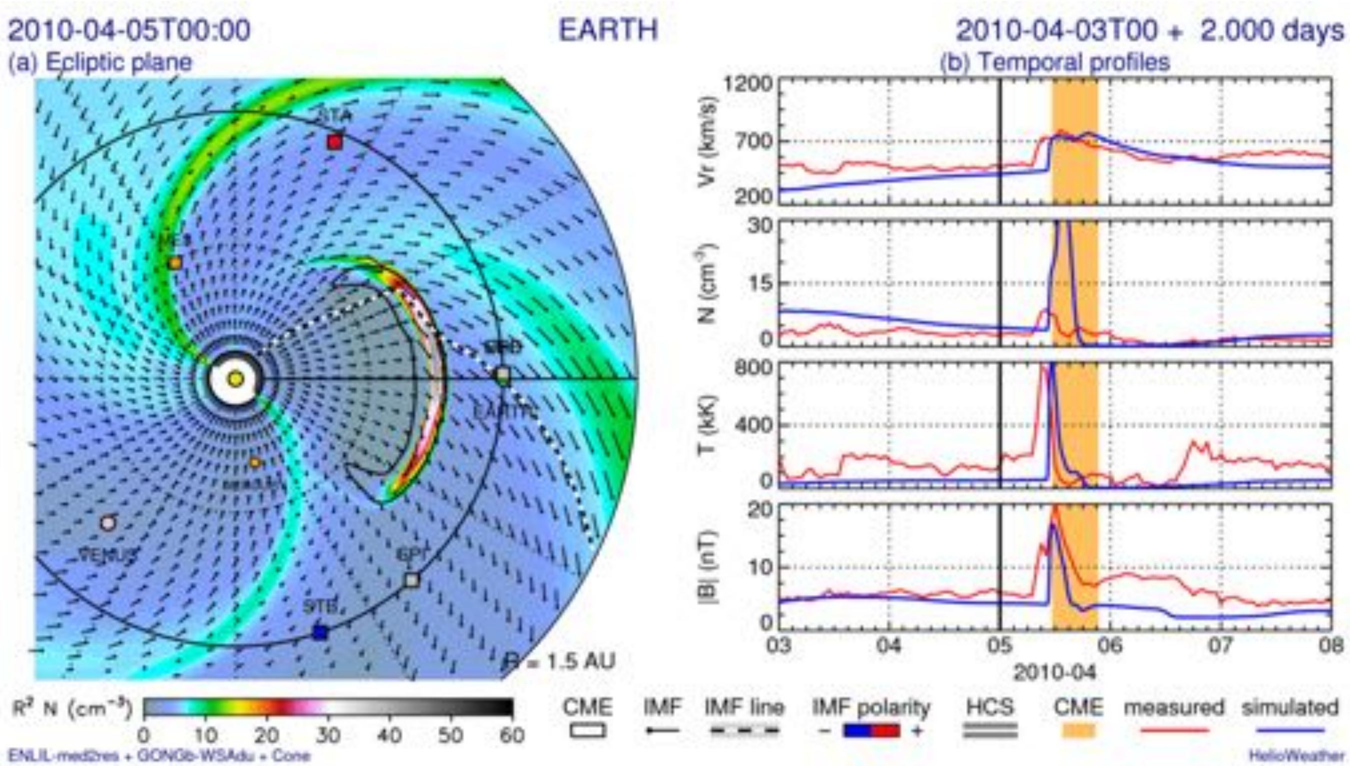
Spheromak



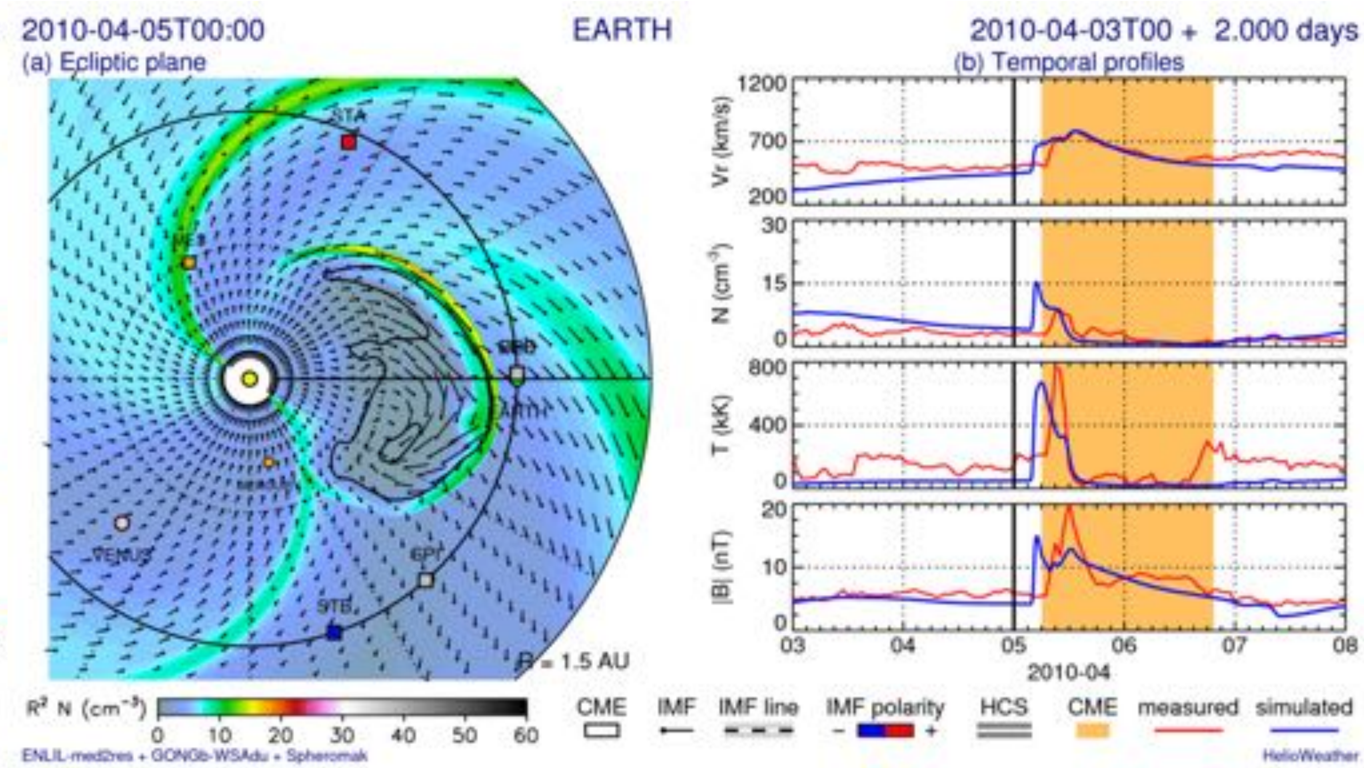
- “Cone” is launched with the initial density enhancement to crudely simulate CME expansion and initially overpressure hydrodynamic structures cannot resist to dynamic compression when interacting with background solar wind — large peaks and narrow extent of ejecta.
- Spheromaks can provide more realistic density structures no need for the initial density enhancement.

Cone vs Spheromak — Density Peak

Cone



Spheromak



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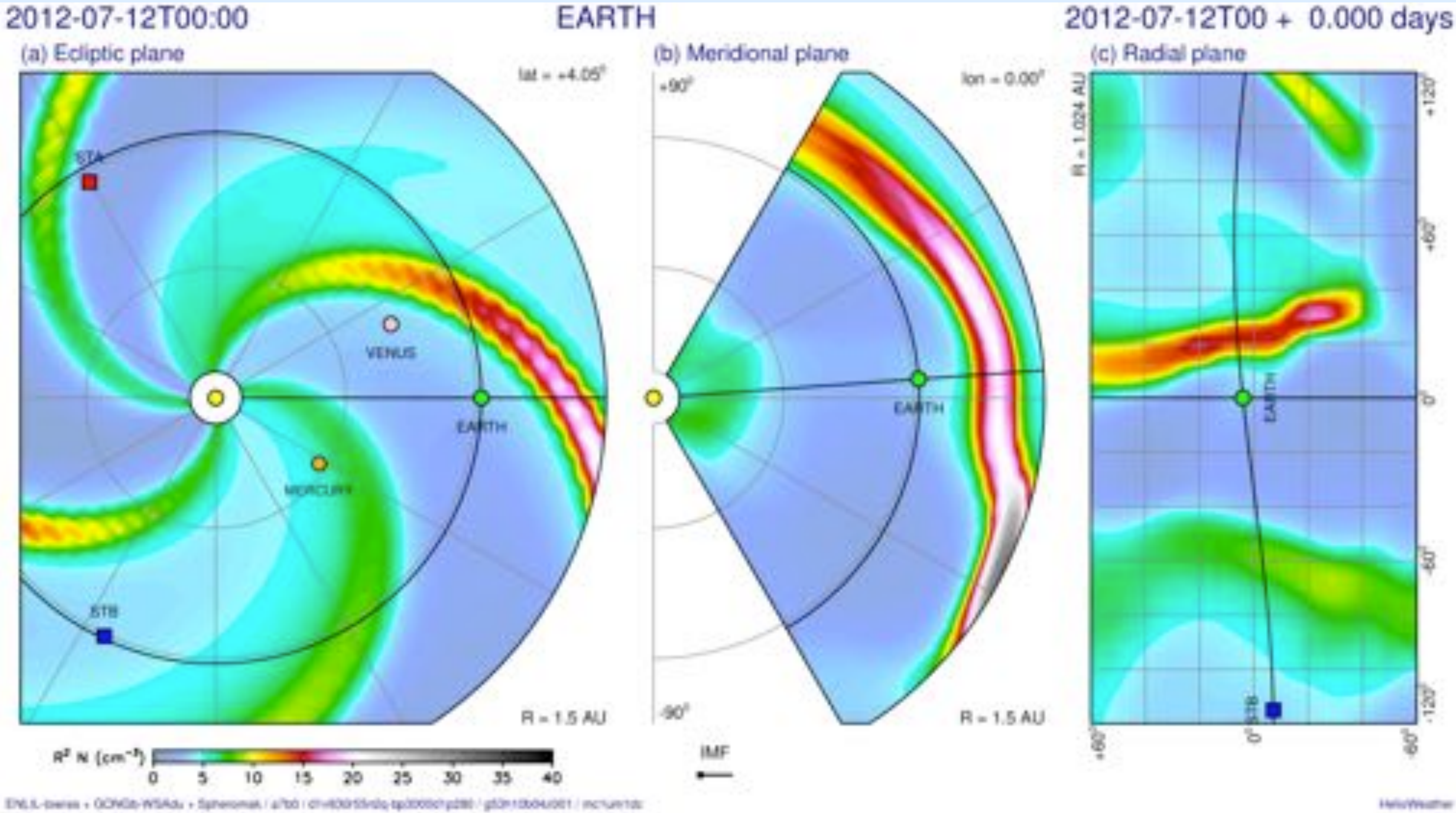
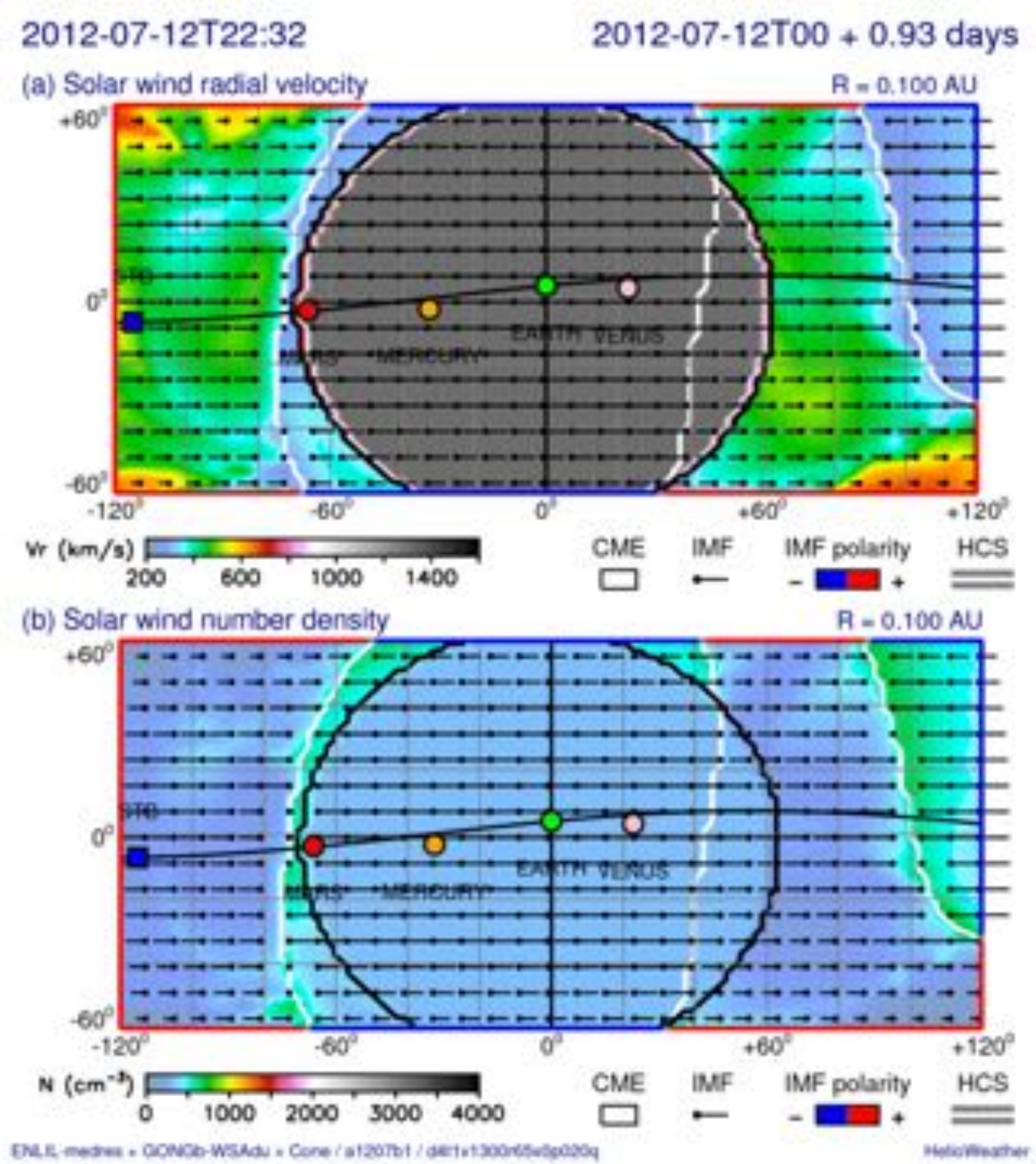
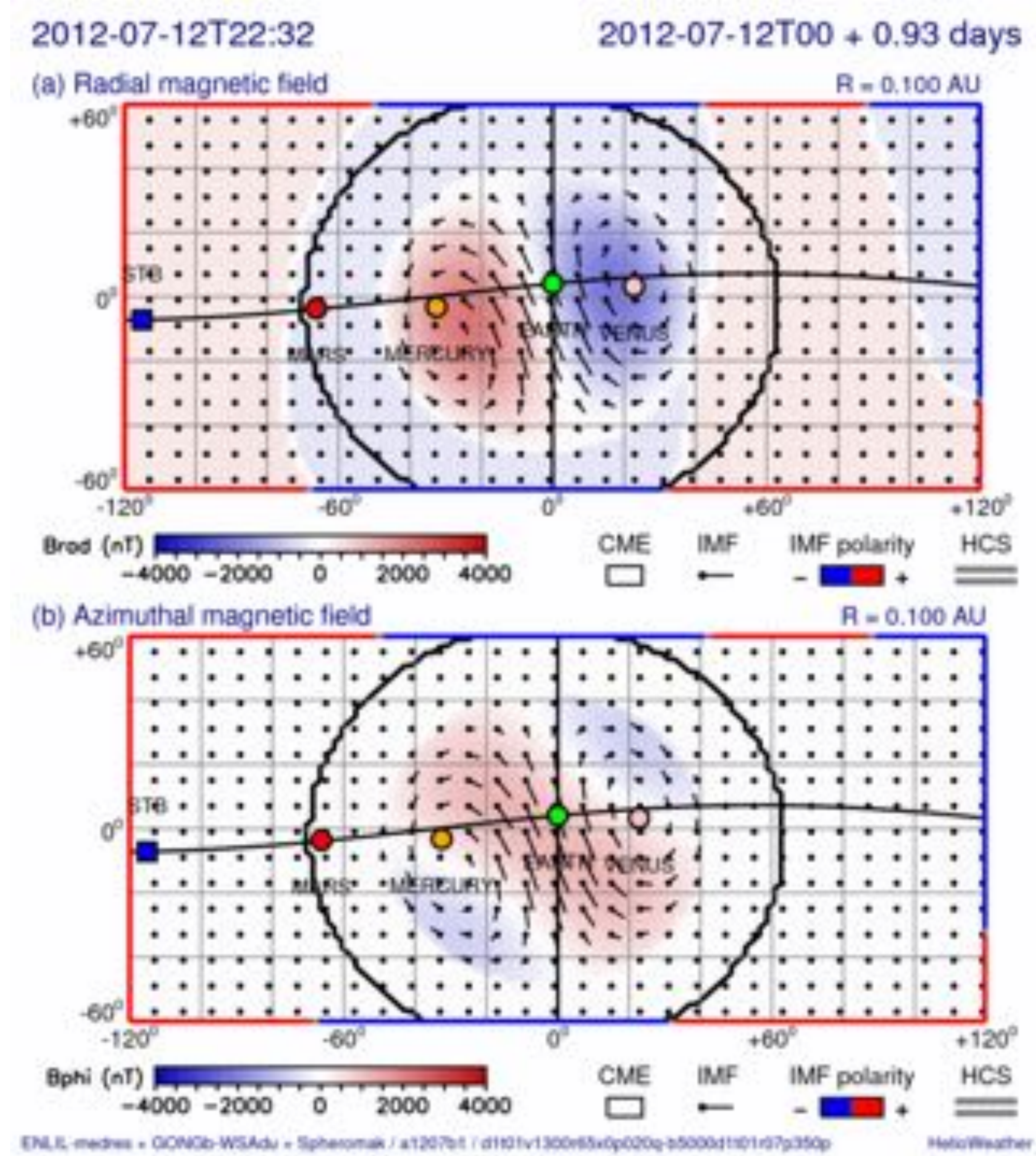
CME Event 2012-07-12 — bthe2e4



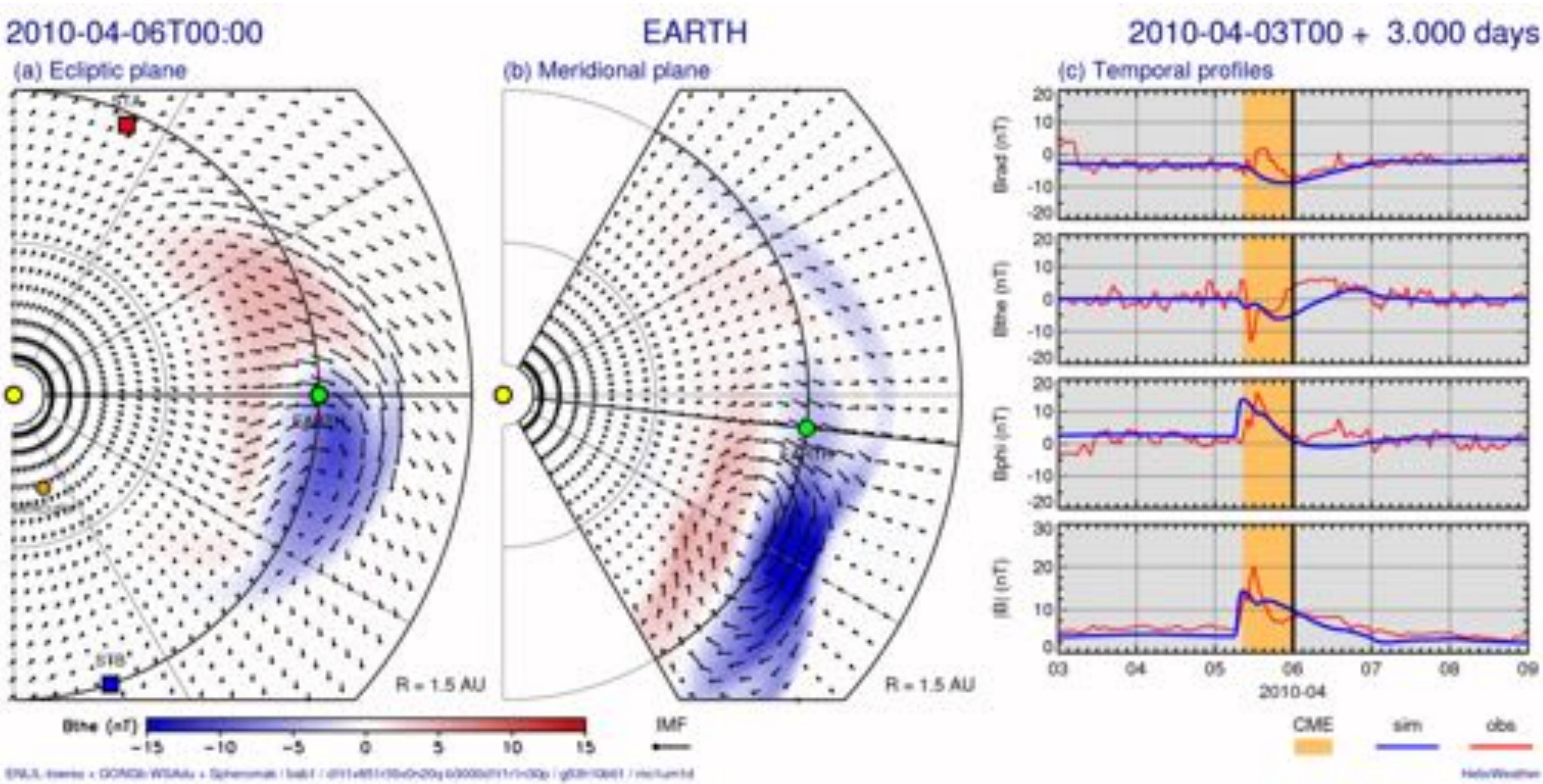
- A strong magnetic field in a spheromak causes its expansion and this leads to a low-density cavity.
- Such a cavity can be detected by heliospheric imagers before the ICME encounters Earth.
- This might be used for “mid-course” suggestions in ensemble modeling.

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

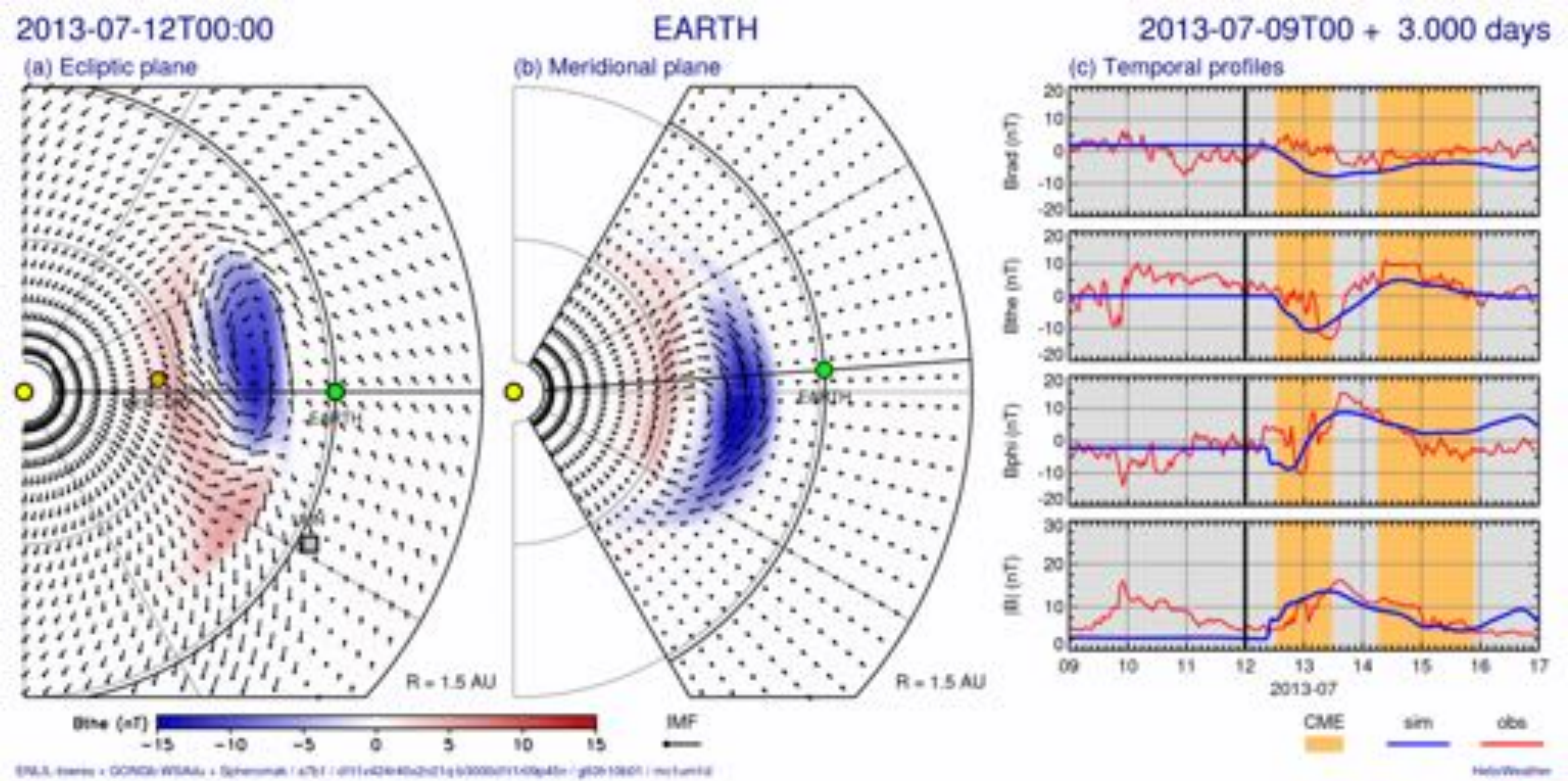




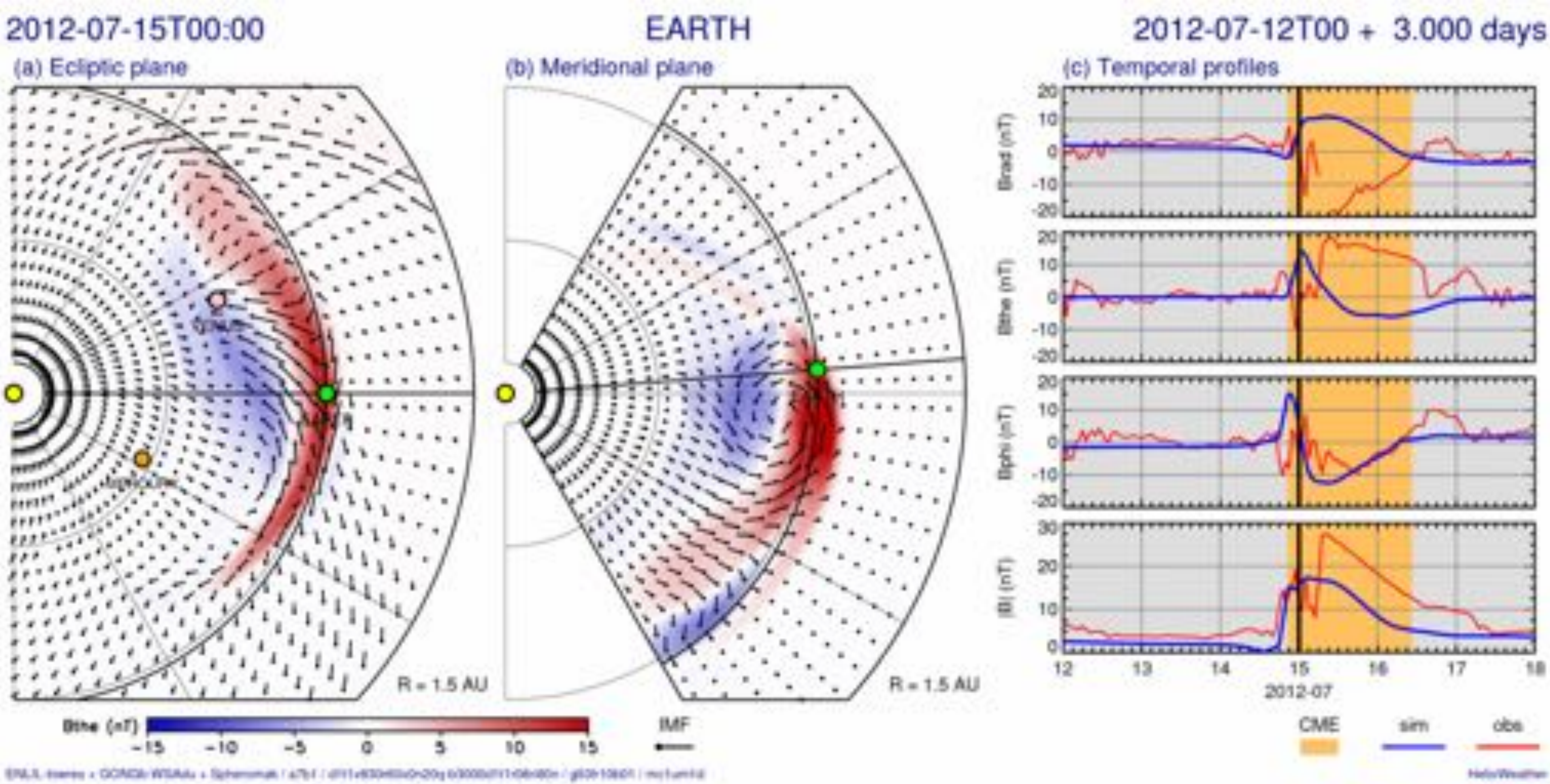
CME Event 2010-04-03 — bthe2e4



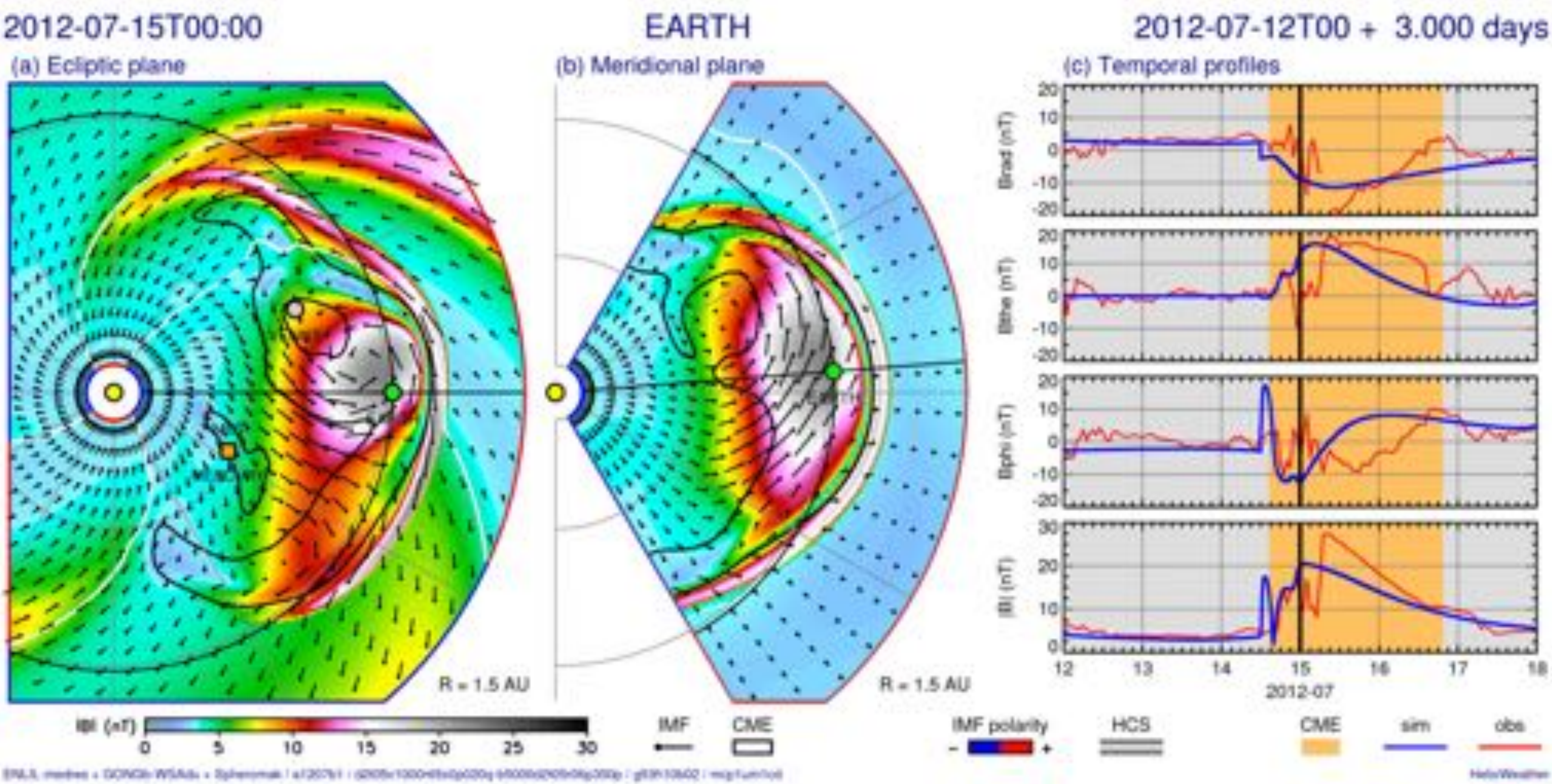
CME Event 2013-07-12 — bthe2e4



CME Event 2012-07-12 — bthe2e4

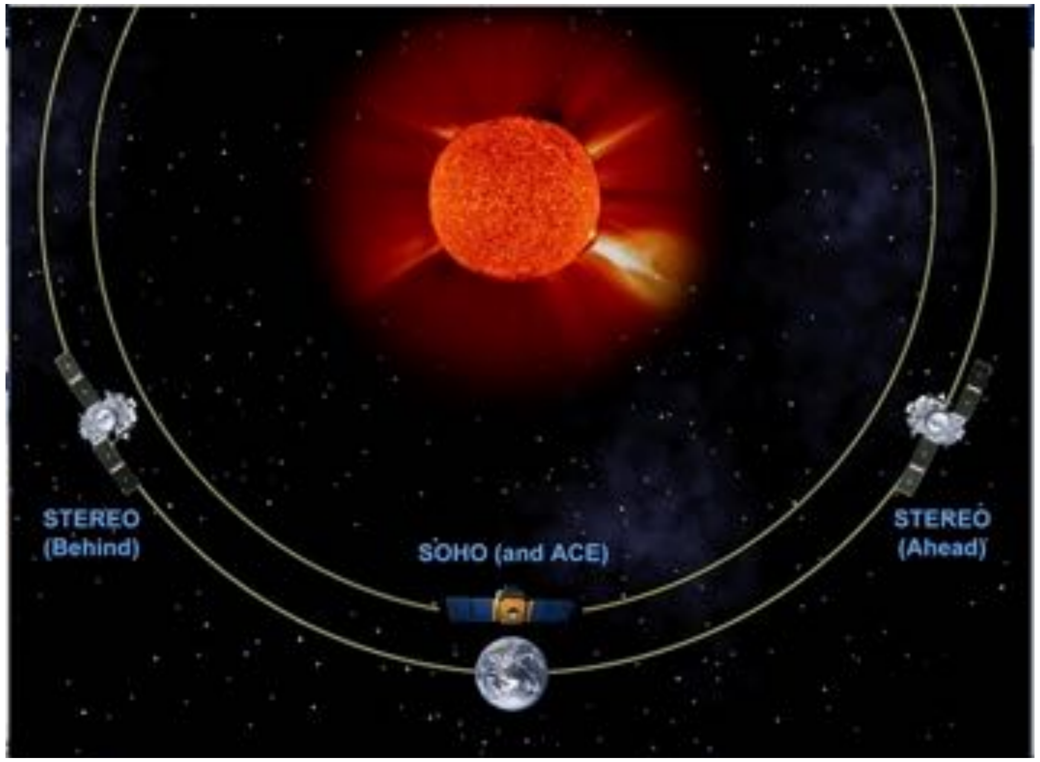


CME Event 2012-07-12 — btot2e4

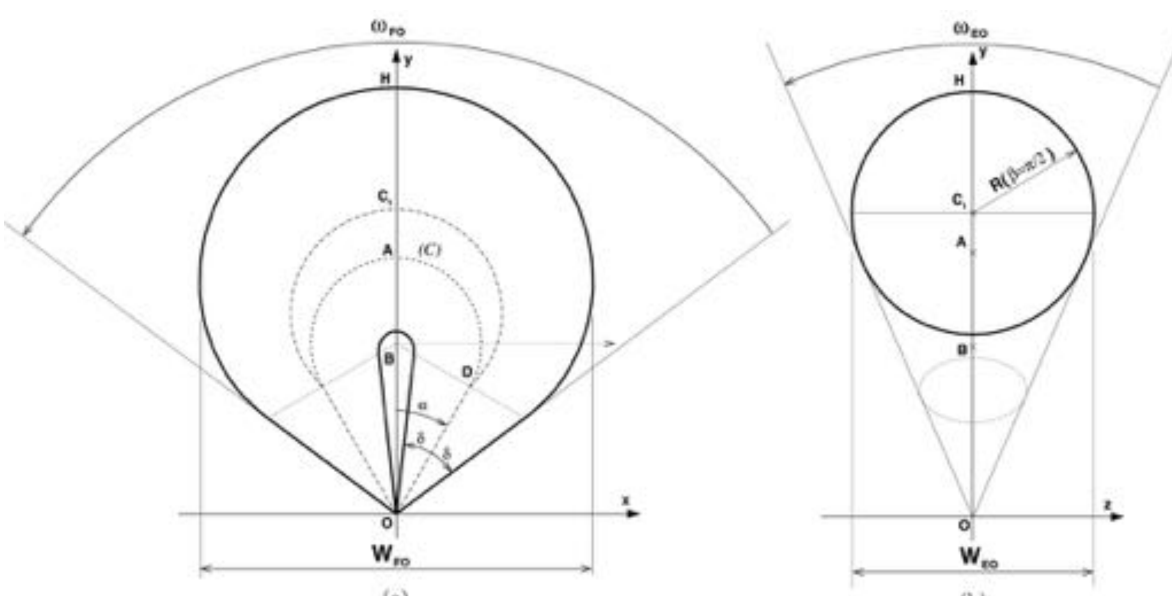


Launching Hydrodynamic Ejecta — New Possibilities

Multi-perspective STEREO observations



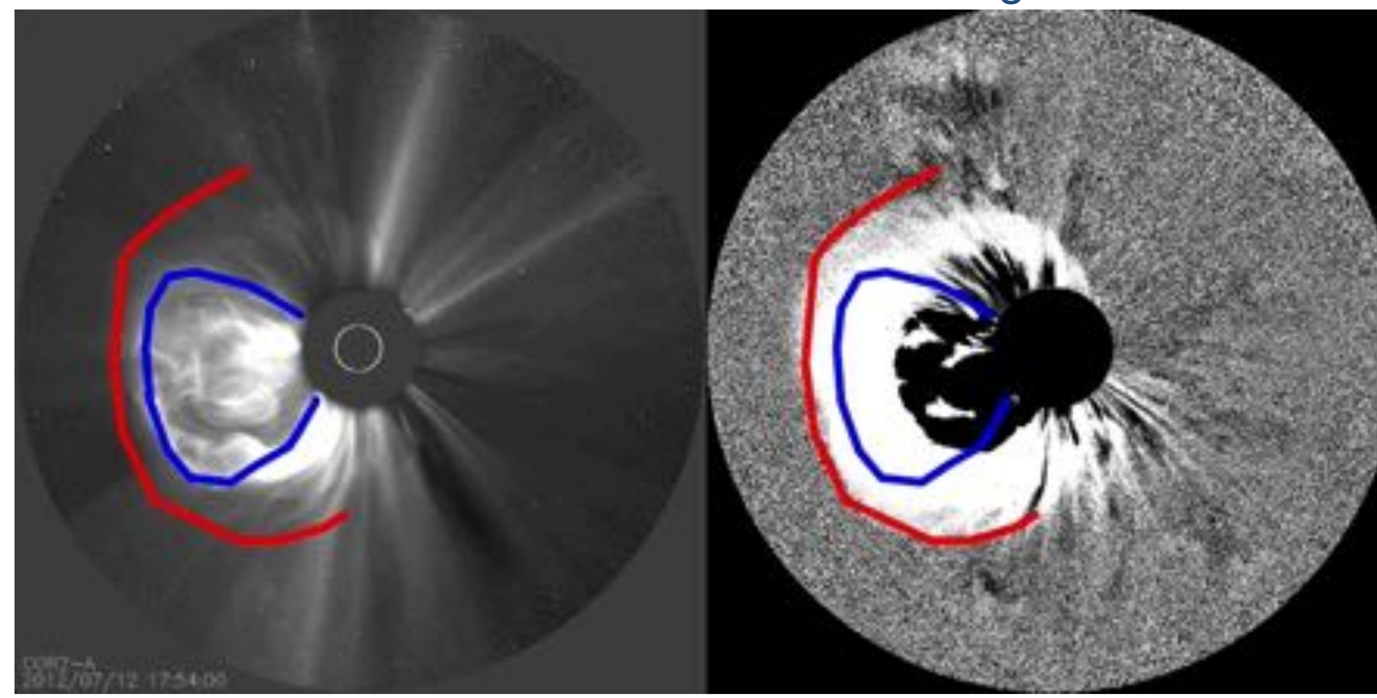
Graduated Cylindrical Shell (GCS) Model



Ejecta/Driver vs Shock

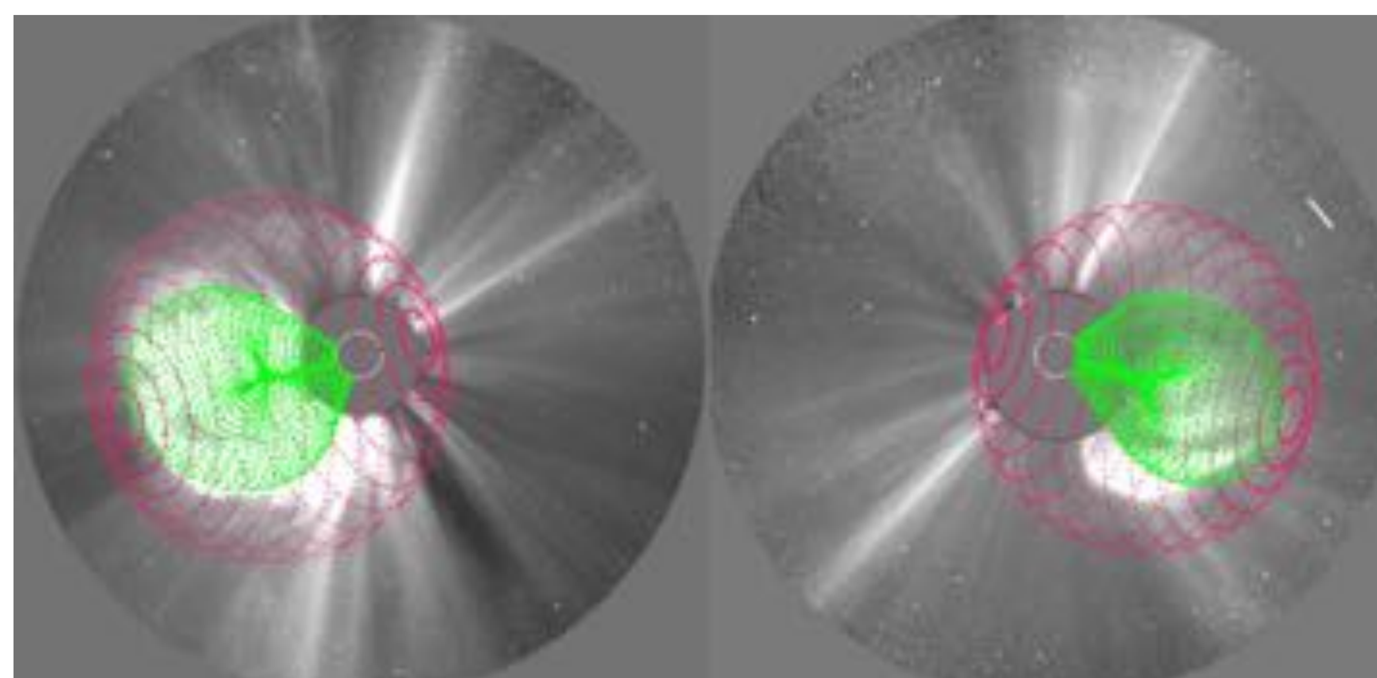
Base Difference

Running Difference



3D Shape and Direction

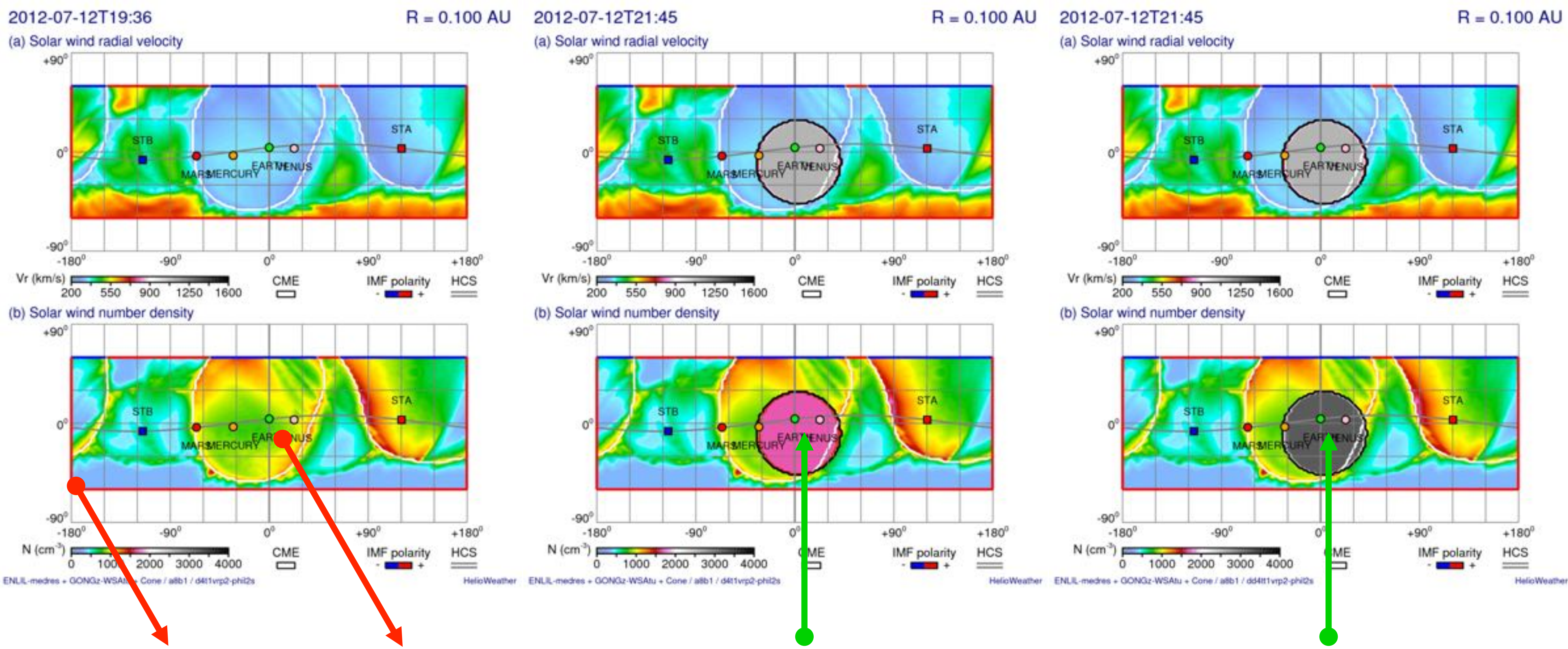
2012-12-07 CME event



Launching CMEs — Specification of the Ejecta Density

Ambient state just before the CME enters the boundary

Disturbed state when the CME passes through the boundary



Dfast = typical value   Damb = D(i0,j0)   D(i,j) = Dcld * Dfast   D(i,j) = Dcld * Damb

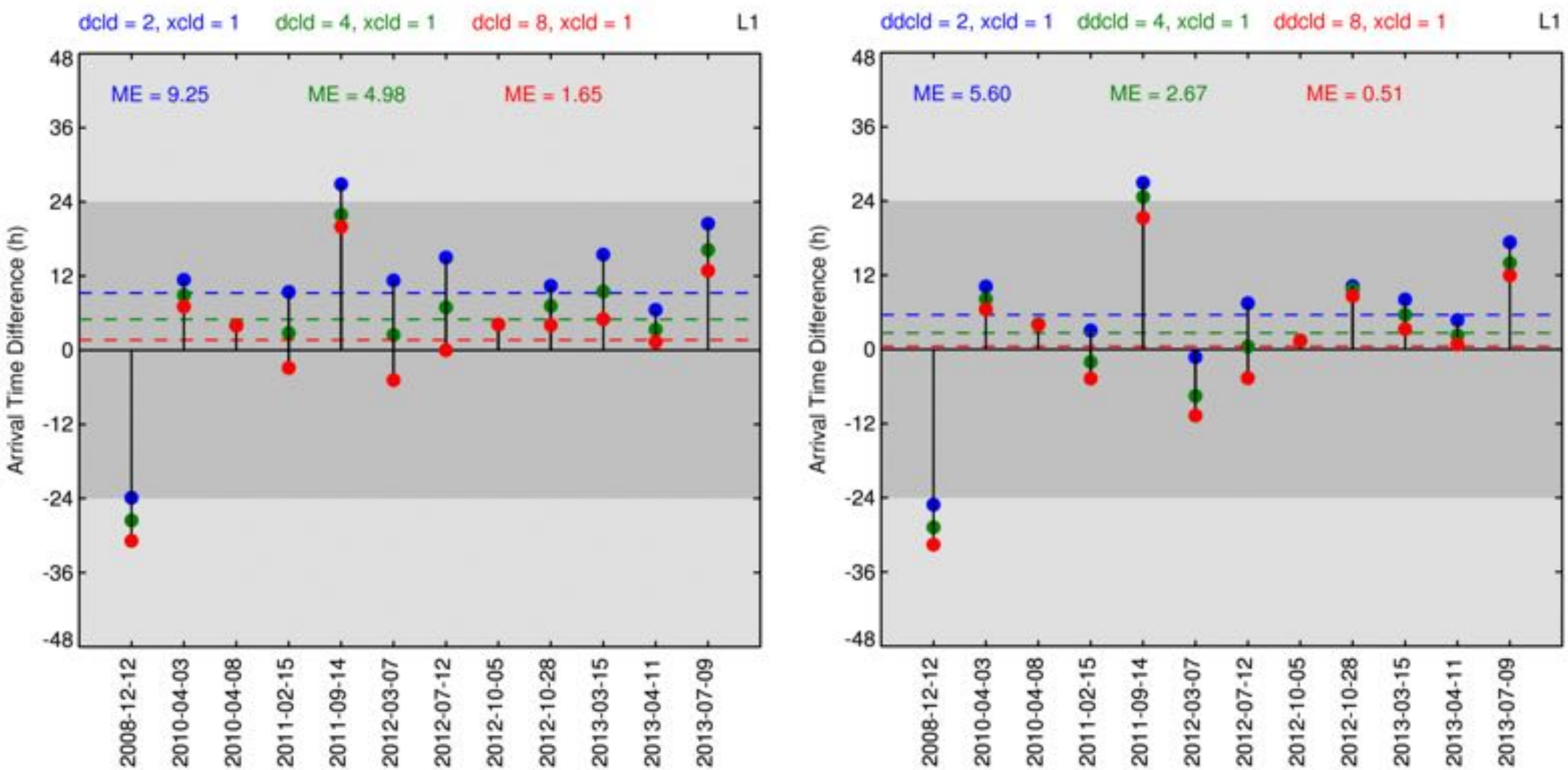
- CME speed can be derived from the remote observations but not the density and temperature.
- These quantities are the model-free parameters; their values can be derived by calibrating the arrival time.
- Cone model density was suggested to be 4x the typical fast stream values (300 cm^{-3}).
- Alternatively, the density can be derived as a factor of the actual background value at the CME center.

12 CME Events — Cone Parameters & Observed Arrival at L1

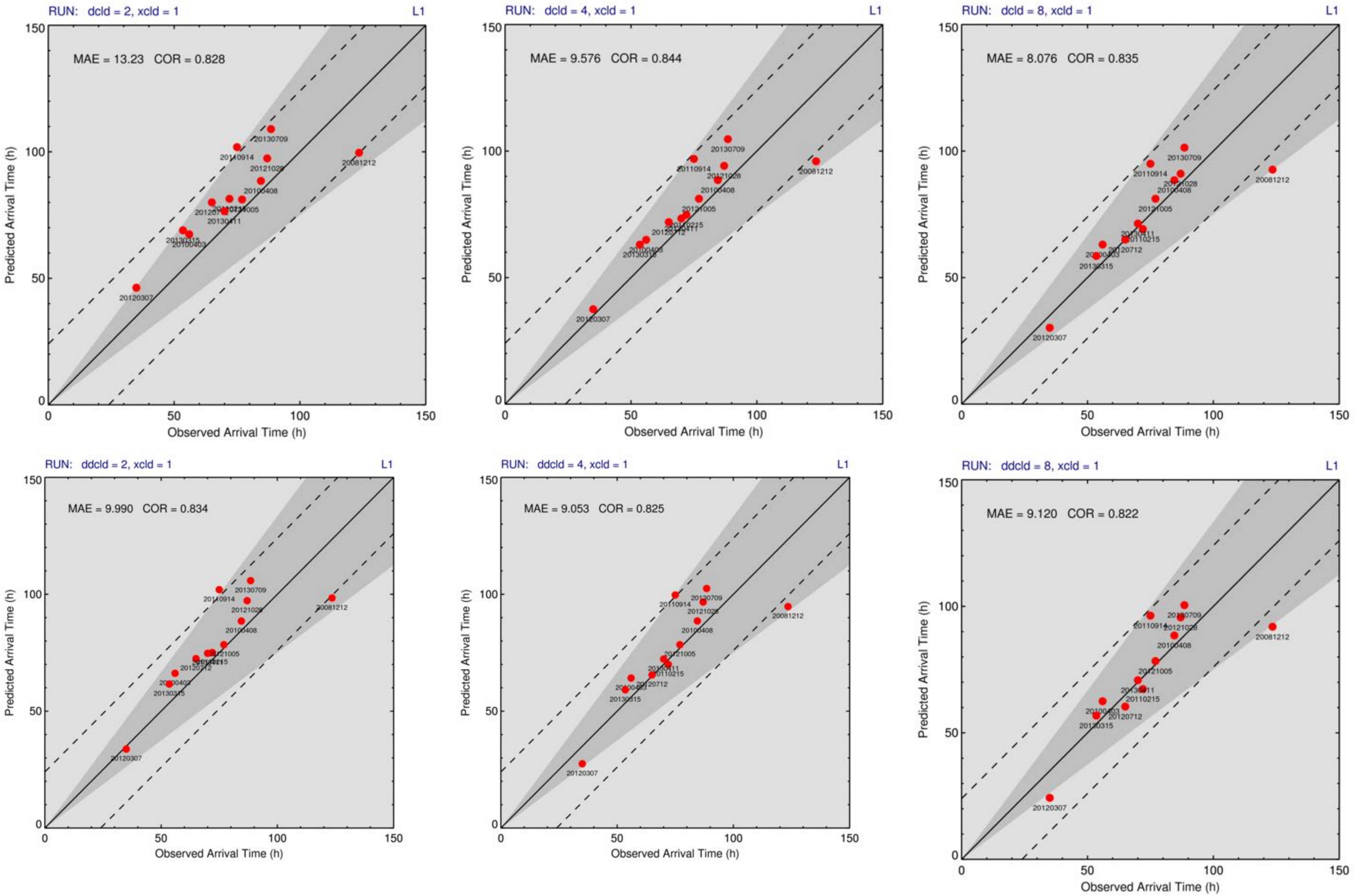
CME Leading Edge at 0.1 AU	Latitude (deg)	Longitude (deg)	Rmajor (deg	Speed (km/s)	ICME Leading Edge at L1
2008-12-12T15:50	12	10	39	500	2008-12-17T03:35
2010-04-03T13:59	-26	8	37	827	2010-04-05T07:55
2010-04-08T10:23	-6	2	38	488	2010-04-11T12:28
2011-02-15T06:15	-16	16	39	682	2011-02-18T00:43
2011-09-14T06:46	28	24	40	406	2011-09-17T03:04
2012-03-07T01:46	28	-22	40	2431	2012-03-08T11:00
2012-07-12T19:36	-9	1	37	1105	2012-07-14T17:59
2012-10-05T08:52	-16	11	39	621	2012-10-08T04:19
2012-10-28T00:24	12	16	41	393	2012-10-31T14:23
2013-03-15T09:52	-7	-23	39	873	2013-03-17T05:30
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

- CME geometric and kinematic parameters fitted by the GCS model.
- ICME arrival times from the HELCATS/LINKCAT, except the not listed 2012-03-07 and 2013-03-15 events that were taken from the ISEST Master CME List at GMU.

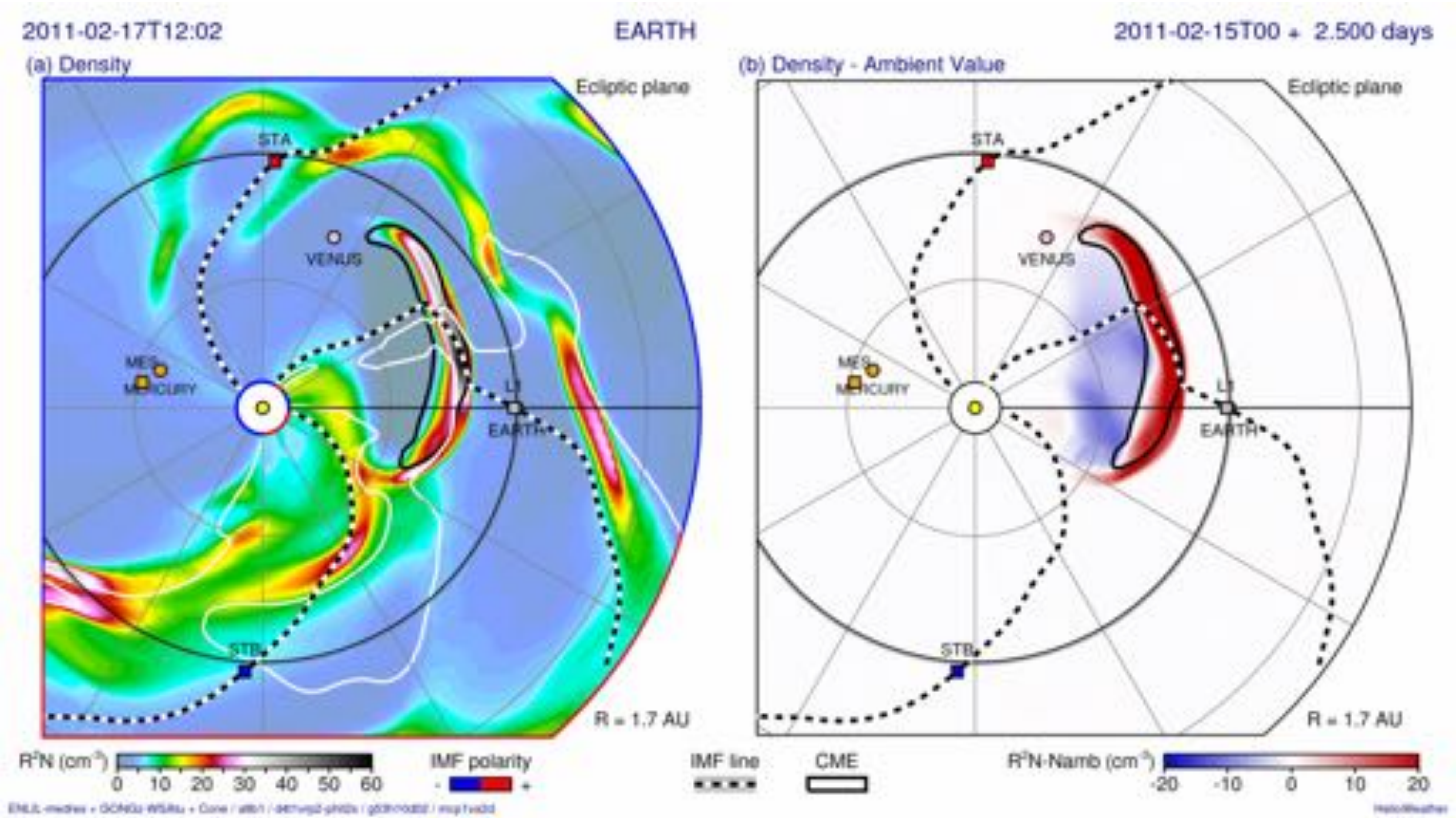
ICME Arrival Time — Effect of “dcld” for “dfast” (left) and “damb” (right)



ICME Arrival Time — Effect of “dcld” for “dfast” (top) & “damb” (bottom)

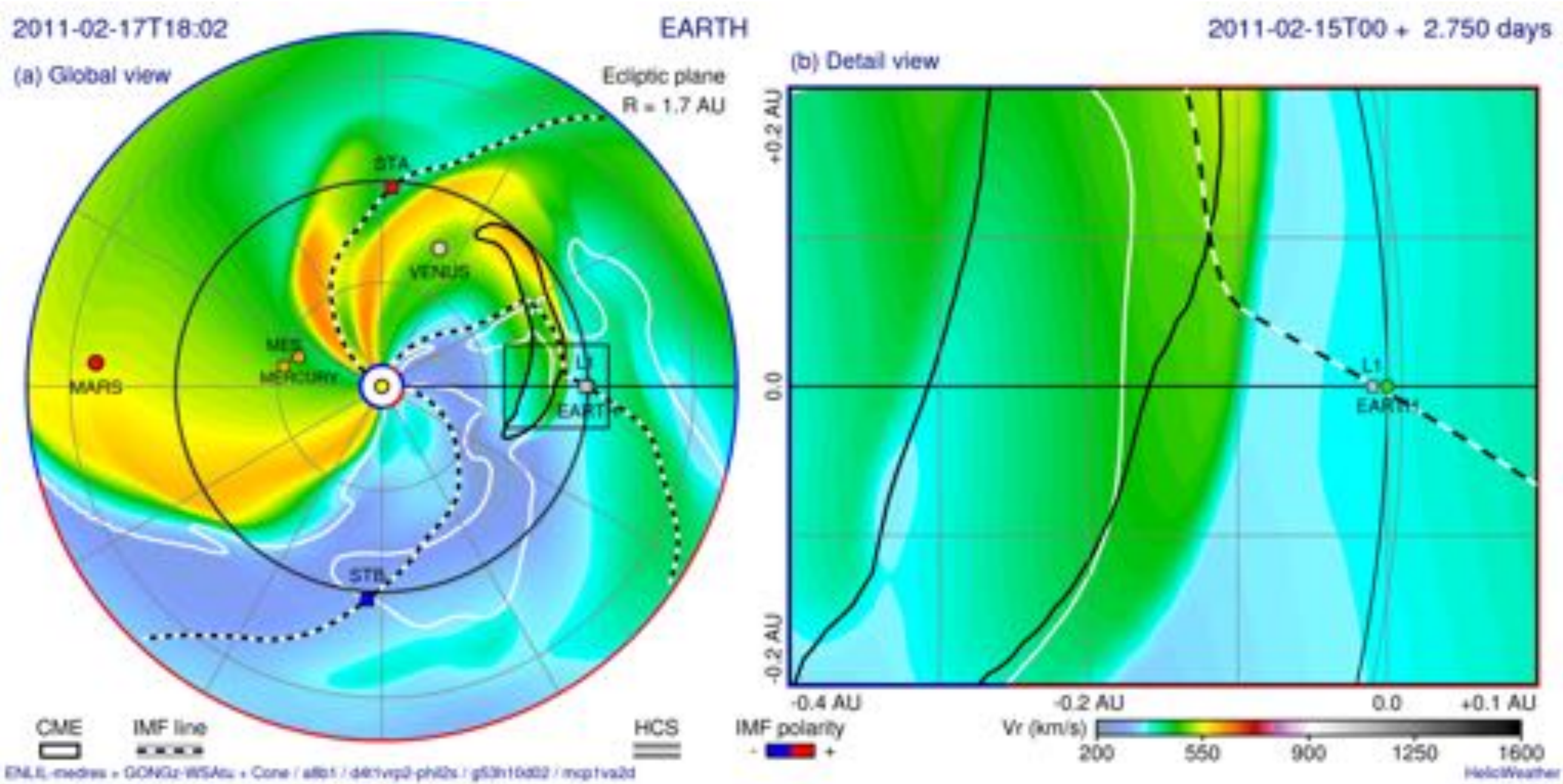


Detection of the ICME Leading Edge



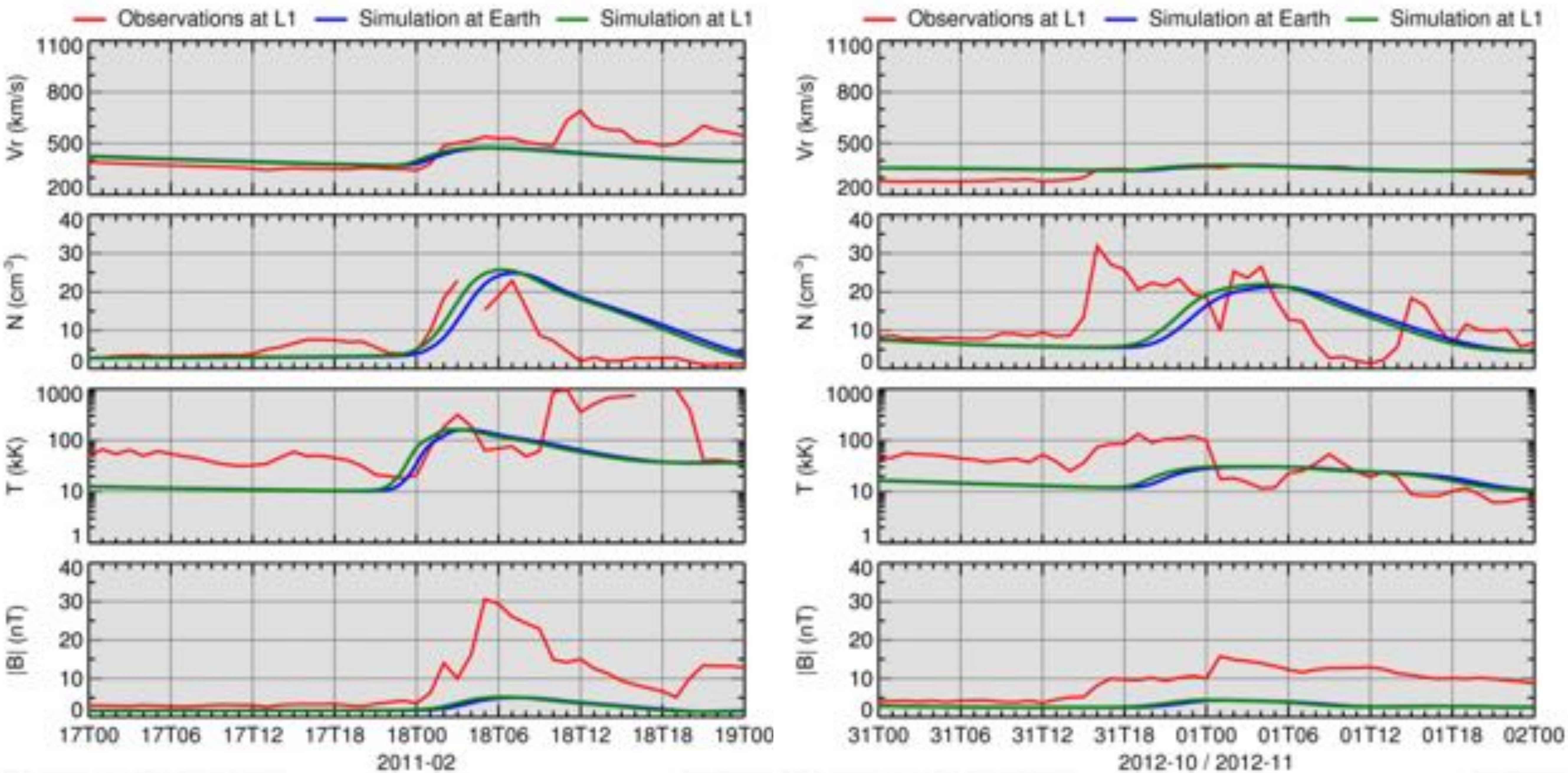
- Two scenarios, ambient-only & ambient+transient are computed simultaneously with the same time step.
- Difference between two solutions facilitates the identification of the leading edge position of the ICME as a function of time.
- Shock speed and ambient values enable to calculate all shock parameters.

ICME Arrival Time — Effect of the Observing Position



- Solar wind parameters are measured by ACE spacecraft at L1-point, ~150,000 km ahead of Earth.
- This separation corresponds to ~4 computational cells in the ENLIL medium-resolution grid.
- ICME arrival time may arrive by 0.5-1 hour earlier to L1 depending on the propagation speed.

ICME Arrival Time — Effect of the Observing Position



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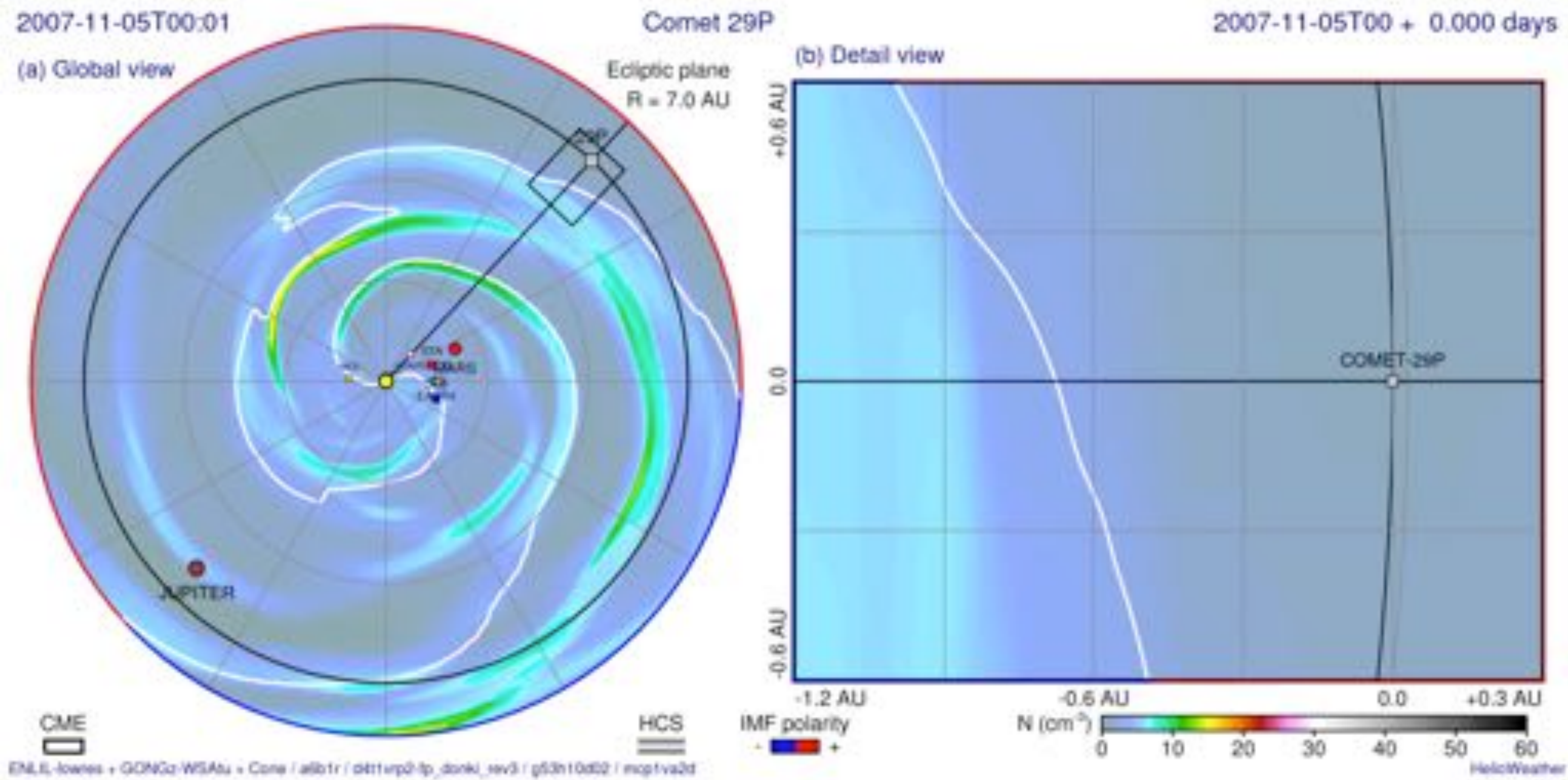
Predictions in the Mid-Heliosphere: Comet 29P/Schwassmann-Wachmann

HEE+180 Coordinate System



- Solar wind parcels reach the Earth, Jupiter, and Saturn in about 4-5, 20-25, 40-50 days, respectively.
- Therefore, when using the full-rotation WSA map, the previous CR map might be necessary to use.
- Note further, that distant objects sampling the solar wind moves by about 30^0/month in longitude.

Summary

- WSA-ENLIL-Cone “hybrid” modeling system:
  - routine, event-by-event, much faster than real time;
  - operational version used at NOAA/SWPC, NASA/CCMC, UK/MetOffice, Korea/KSWC;
  - research version is under continuous development.
- Cone model enables:
  - predictions of ICME arrival times (ejecta and/or shock);
  - SEP alerts and predictions;
  - synthetic white-light imaging (J-maps, mid-course correction).
- Launching of spheromaks is less realistic than the launching of flux ropes but it enables:
  - operational predictions in the inner- and mid-heliosphere;
  - utilization of existing tools.
- Improvements over hydrodynamic cone model:
  - more realistic radial extent = duration of the event at Earth, planets, and spacecraft;
  - more realistic density structure (peaks, cavity) = comparison with remote imaging;
  - estimate the strength and duration of the Bz effect at Earth = geospace events.
- Ongoing activities include calibration and ensemble modeling of the background solar wind with ADAPT, reducing the model-free parameters of the CME-like ejecta.