LFM-helio

Time-dependent modeling of the inner heliosphere

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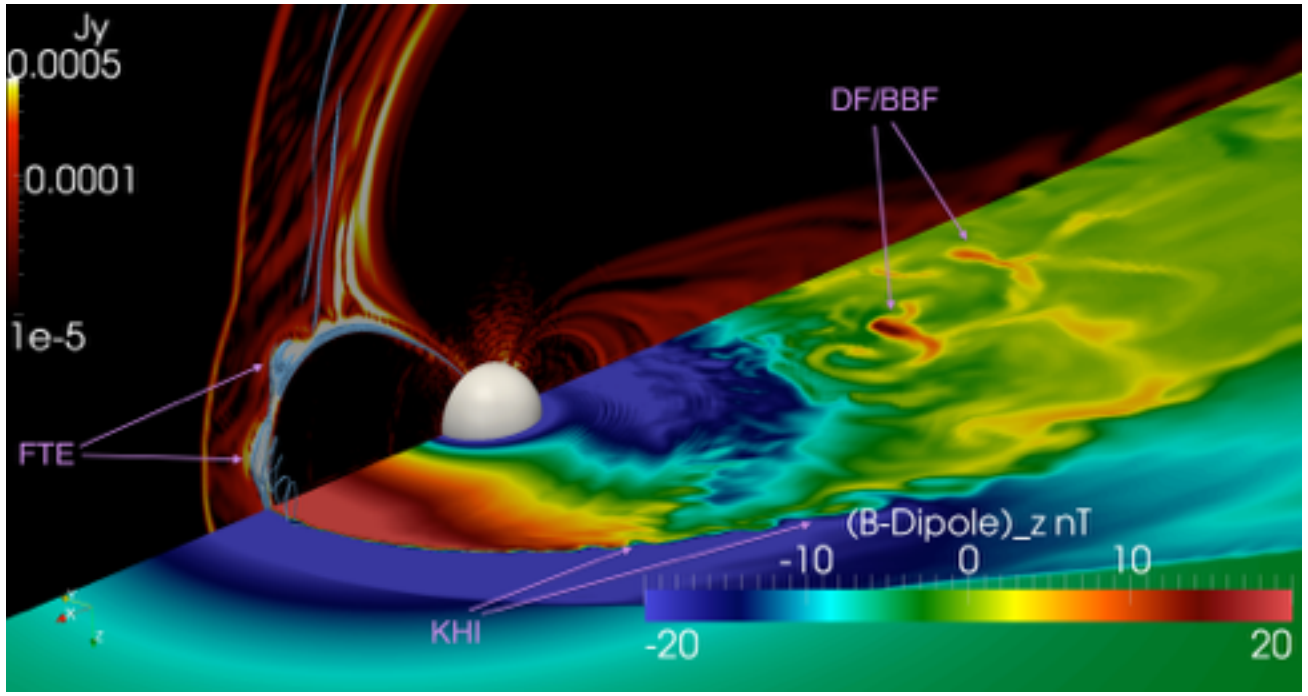
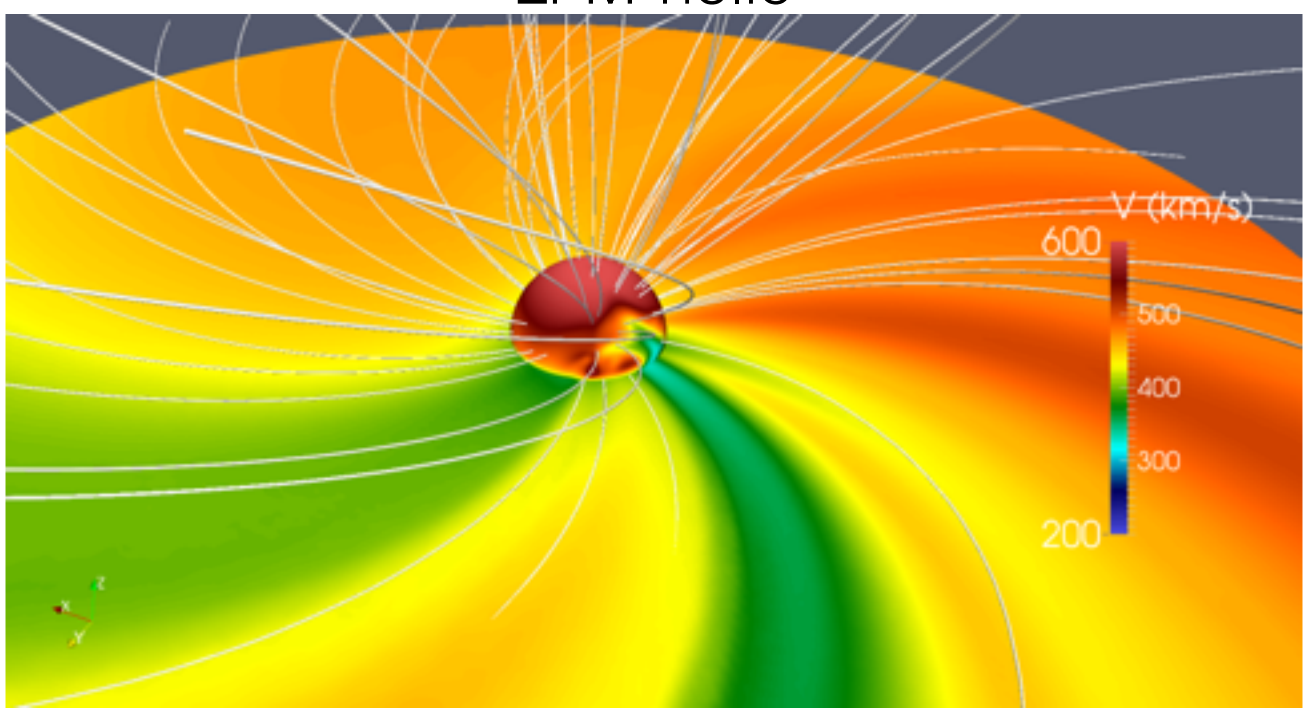
Outline

- LFM-helio introduction
- Recent work highlights: Time-dependent MHD modeling
    - Quiet heliosphere
    - Propagation of coronal mass ejections
- Conclusions
- Future directions and implications for CCMC

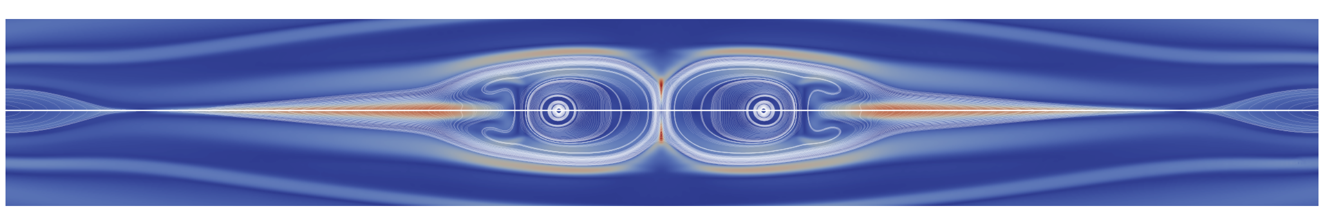
LFM-mag



LFM-helio



LFMBOX



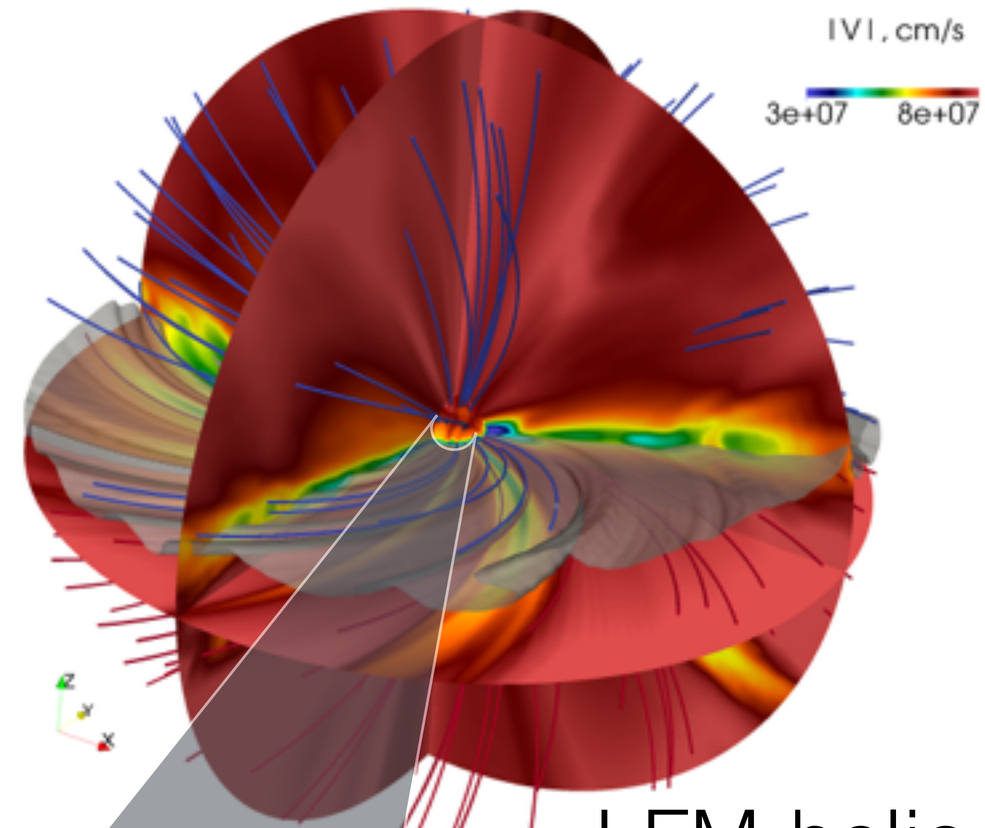
LFM-helio

- LFM — MHD code developed by J. Lyon, J. Fedder and C. Mobarry at NRL in the 80's
- Mainly applied to terrestrial magnetosphere; modified for inner heliosphere (Merkin et al., 2011, 2016a, 2016b; Pahud et al, 2012); regional plasma problems (Merkin et al., 2015)
- Very low-diffusion numerical scheme (8th order TVD)
- Adapted static mesh (Arbitrary hexahedral) and finite volume technique
- Generalized grid geometries and boundary conditions
- Magnetic field divergence-less to roundoff ($\nabla\cdot\mathbf{B}=0$)
- Fully parallelized
- Rotating/inertial frame calculations
- Full 3-D, poles included

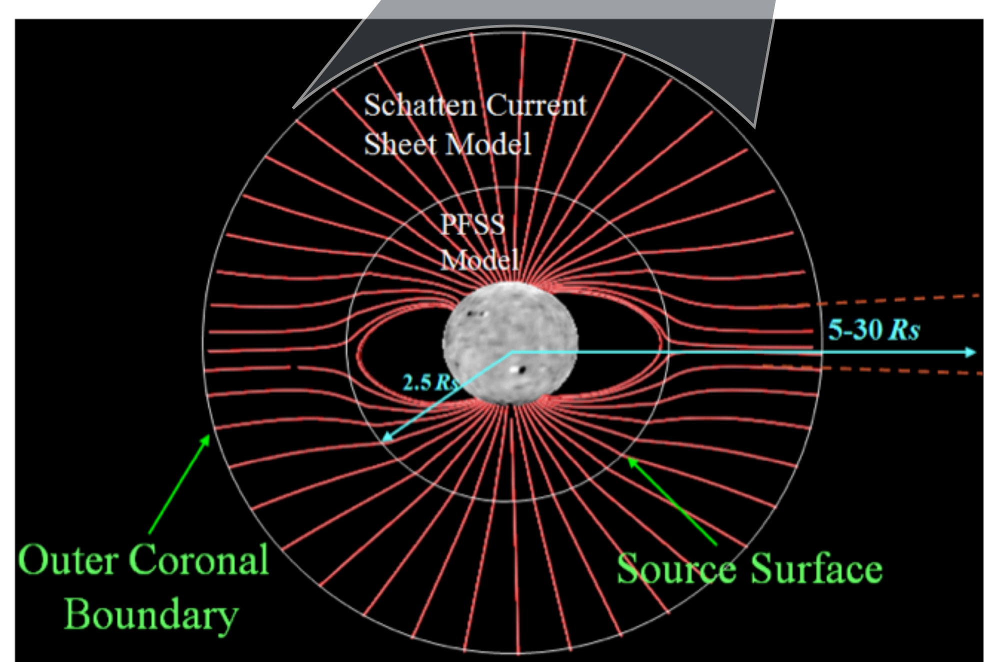
Two types of time-dependent modeling

- **Background solar wind**
  - Improve specification and prediction during quiet conditions
  - Improve background for CME propagation
  - Heliospheric consequences of transient changes on the sun, e.g., moving coronal hole boundaries
  - Complexity of heliospheric current sheet
  - Sources of slow wind

Merkin et al., JGR, [2016]

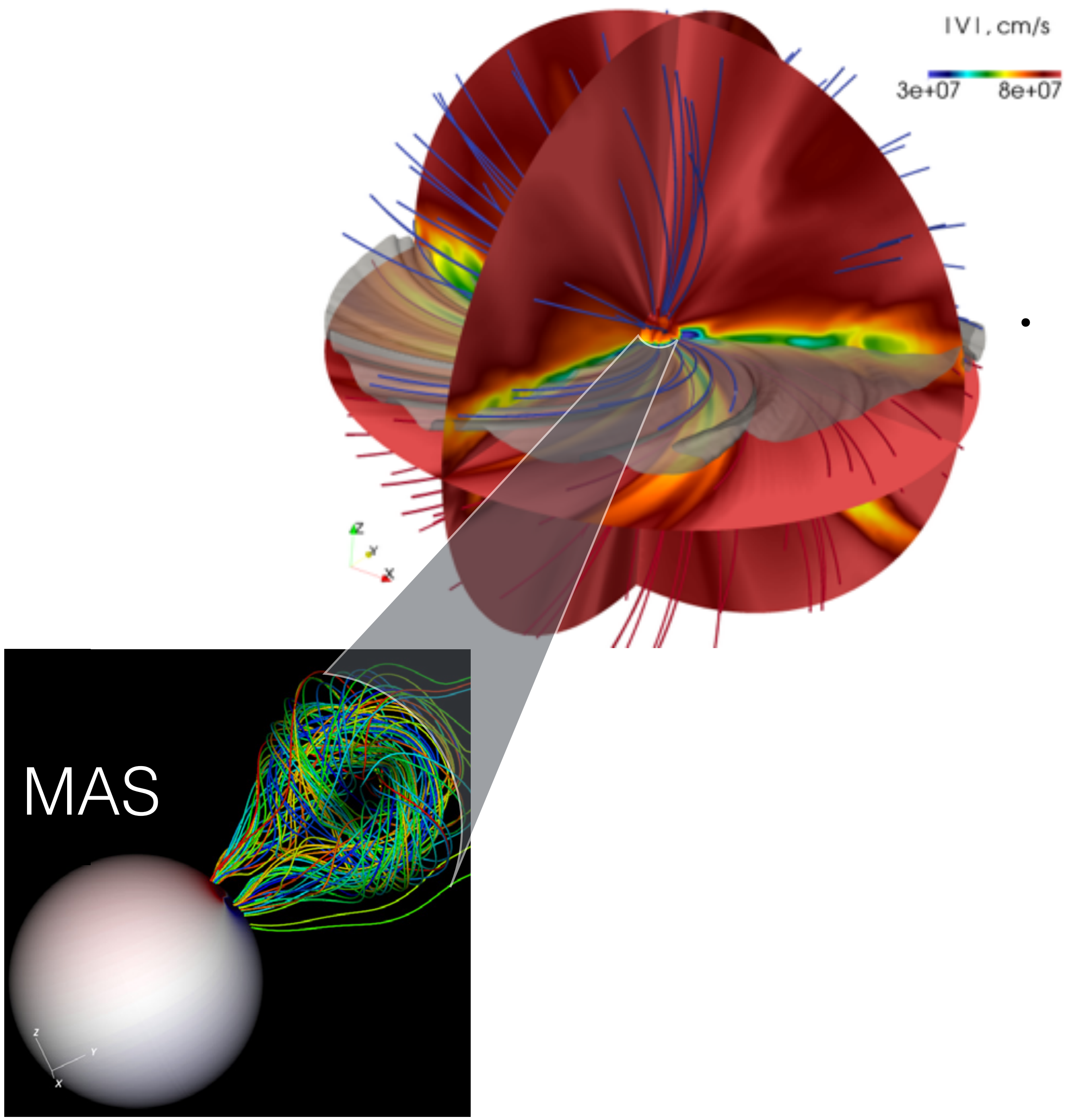


LFM-helio



ADAPT/ WSA

Two types of time-dependent modeling



Lionello et al., ApJ, 2013

- **CME propagation**
  - Space weather impacts
  - Basic plasma physics (instabilities, reconnection/ erosion)
  - Kinematics, distortion, rotation
  - Internal magnetic structure
  - Shocks, particle acceleration

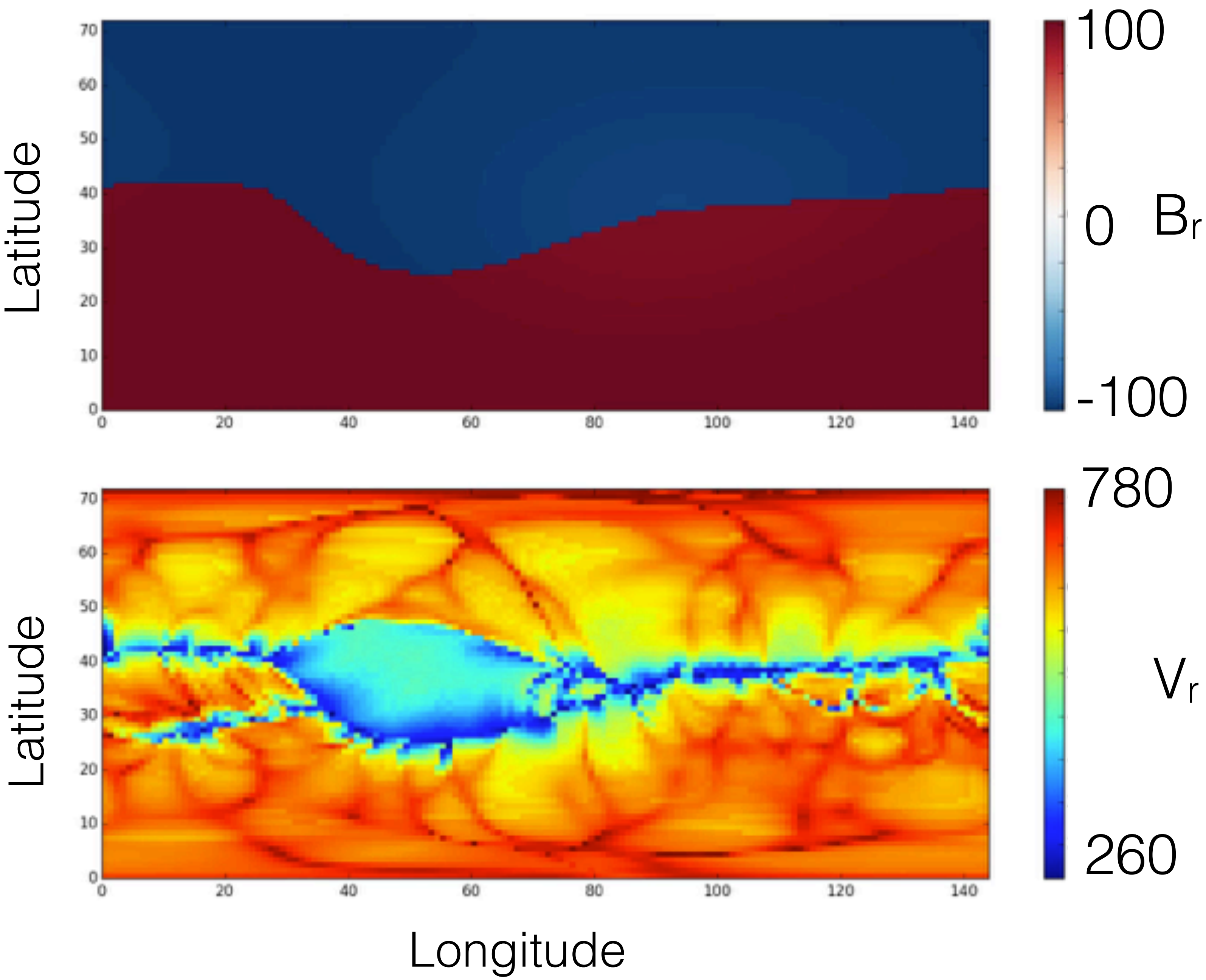
Merkin et al., ApJ, [2016]

Time-dependent quiet heliosphere

Coronal boundary

ADAPT/WSA — 1 d cadence

@ 0.1AU



- ADAPT: Air force data assimilative photospheric flux transport model
- Provides time-dependent inputs into MHD models of the solar wind
- Major problem: Radial magnetic field boundary condition should guarantee

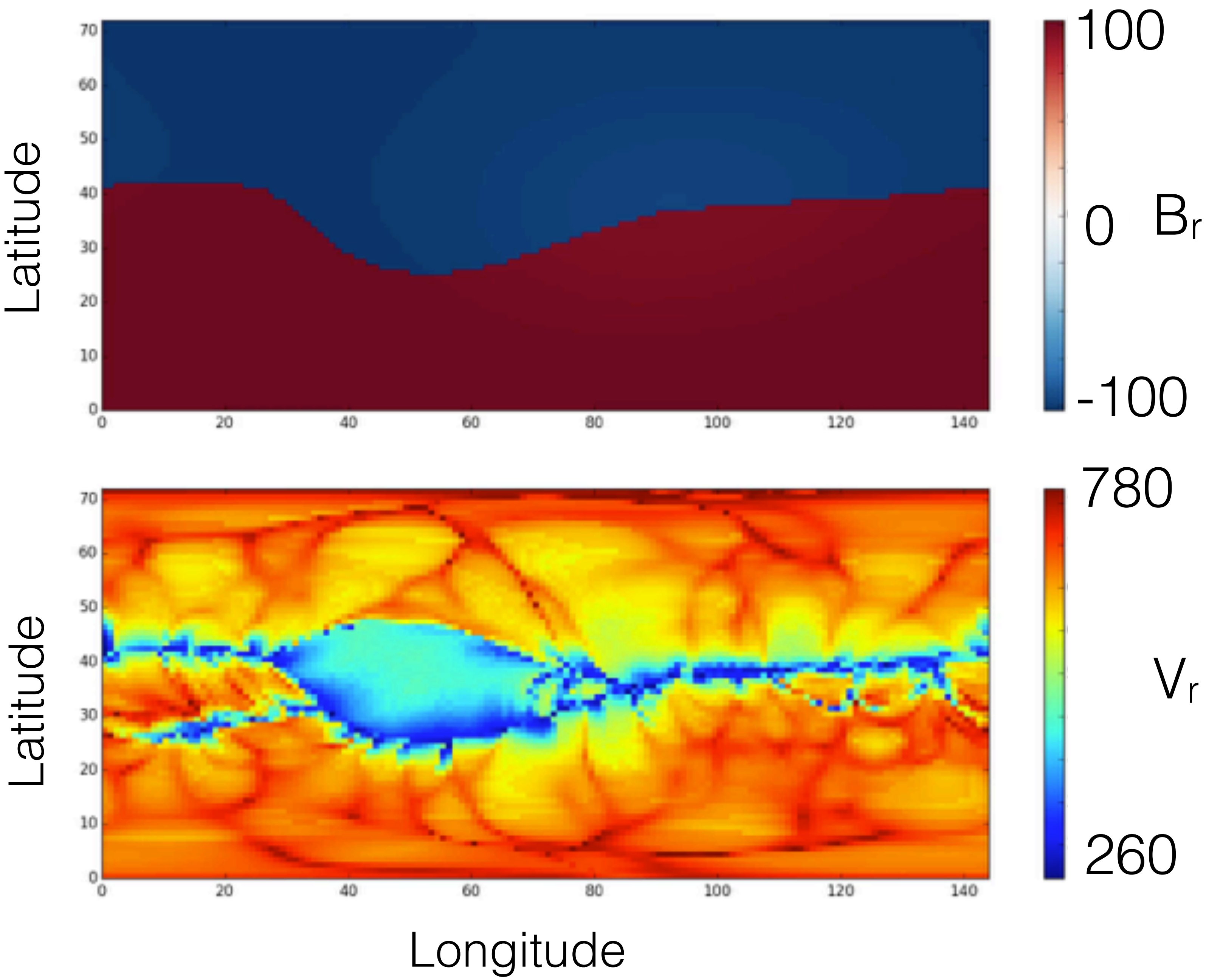
$$\nabla \cdot \mathbf{B} = 0$$

Merkin et al., JGR, [2016]

Radial magnetic field boundary condition

ADAPT/WSA — 1 d cadence

@ 0.1AU



Helmholtz Theorem on a sphere (e.g., Backus, 1989):

$$\mathbf{E}_\perp = \nabla_\perp \times \hat{\mathbf{r}}\Psi + \nabla_\perp \Phi$$

Assumption 1

$$\Delta_\perp \Psi = \frac{\partial B_r}{\partial t}$$

From ADAPT/WSA

$$E_\phi = B_r \delta V_\theta - \delta B_\theta V_r$$

$$E_\theta = \delta B_\phi V_r - B_r \delta V_\phi$$

Assumption 2

Merkin et al., JGR, [2016]

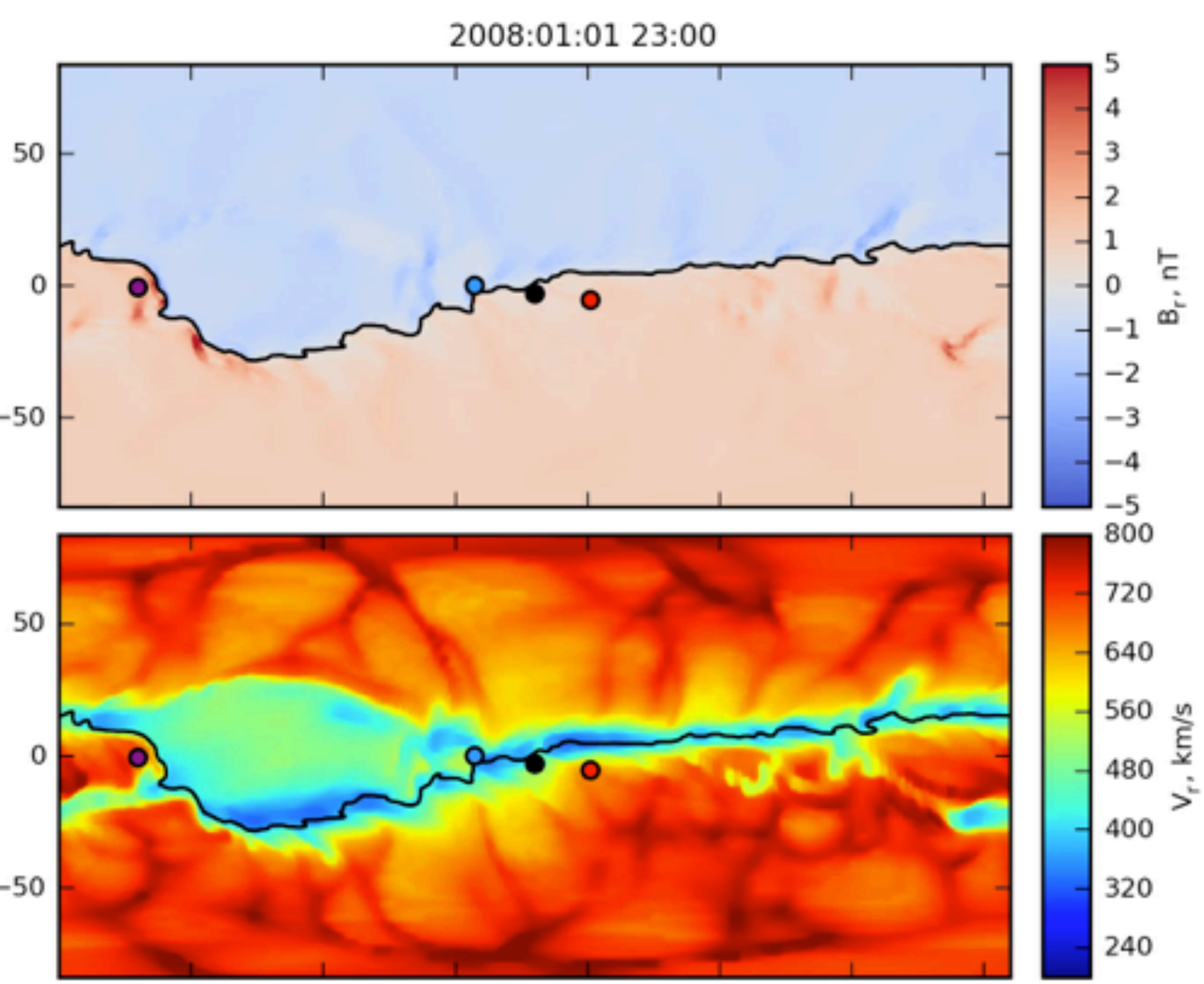
Time-dependent quiet heliosphere

- Jan-Feb 2008 - very quiet conditions
- Compare results with ACE, STEREO A/B, MESSENGER
- Calculations in rotating frame: SCs move eastward

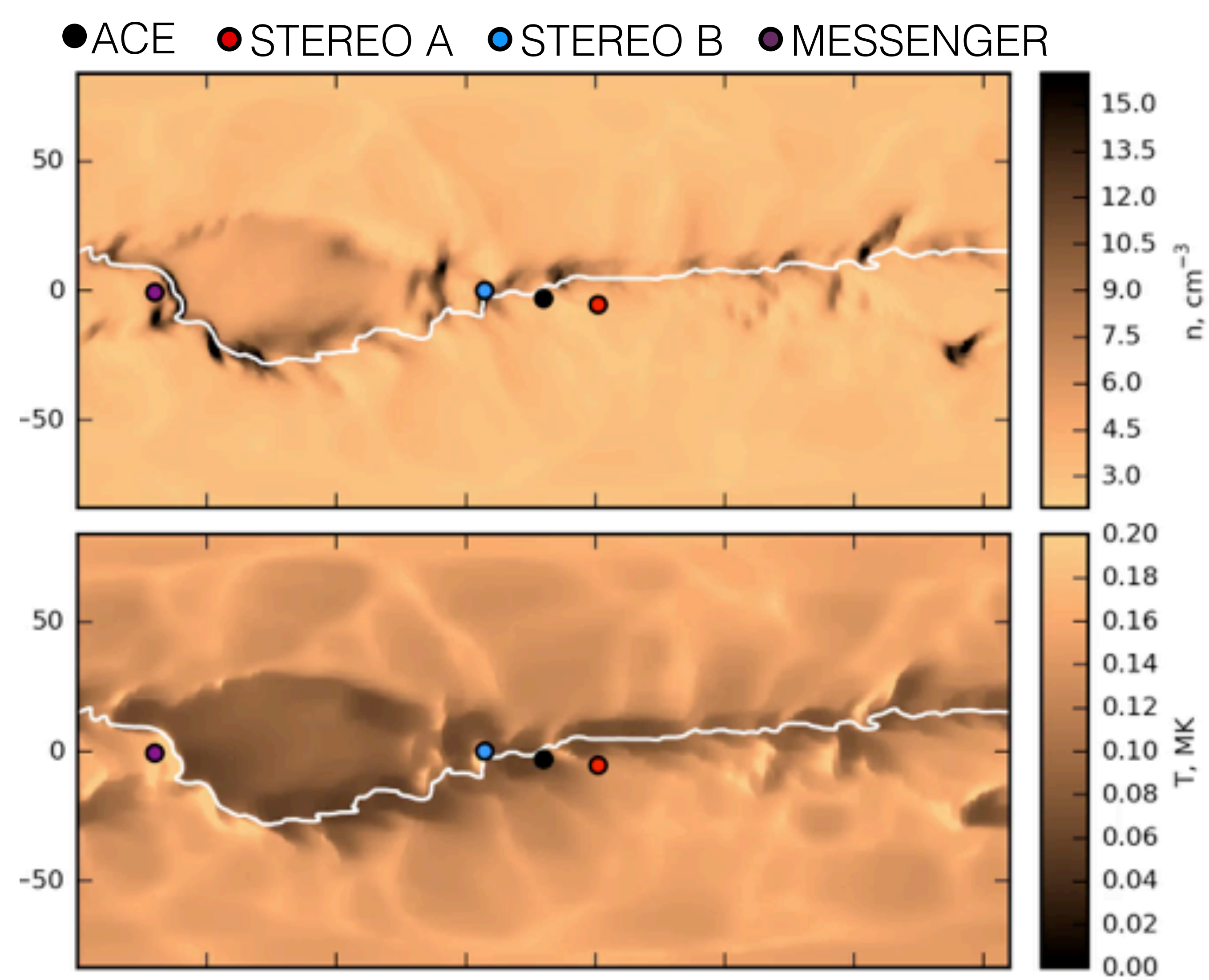
- HCS moves around
- Transient SW velocity streams
- Complex HCS crossings/transitions

28M cell simulation @ NCAR/Yellowstone

B_r and V_r @ 1 AU



n and T @ 1 AU



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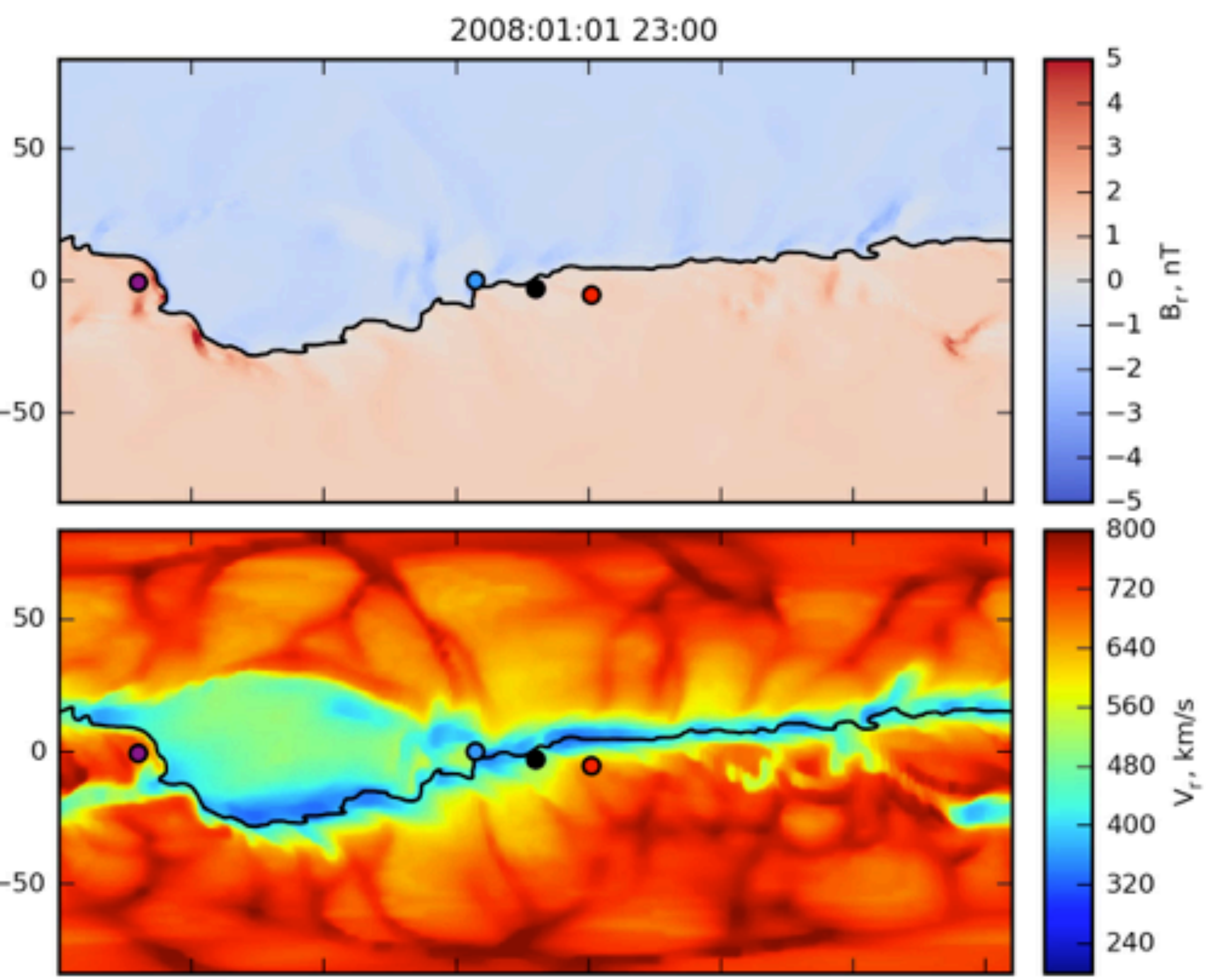
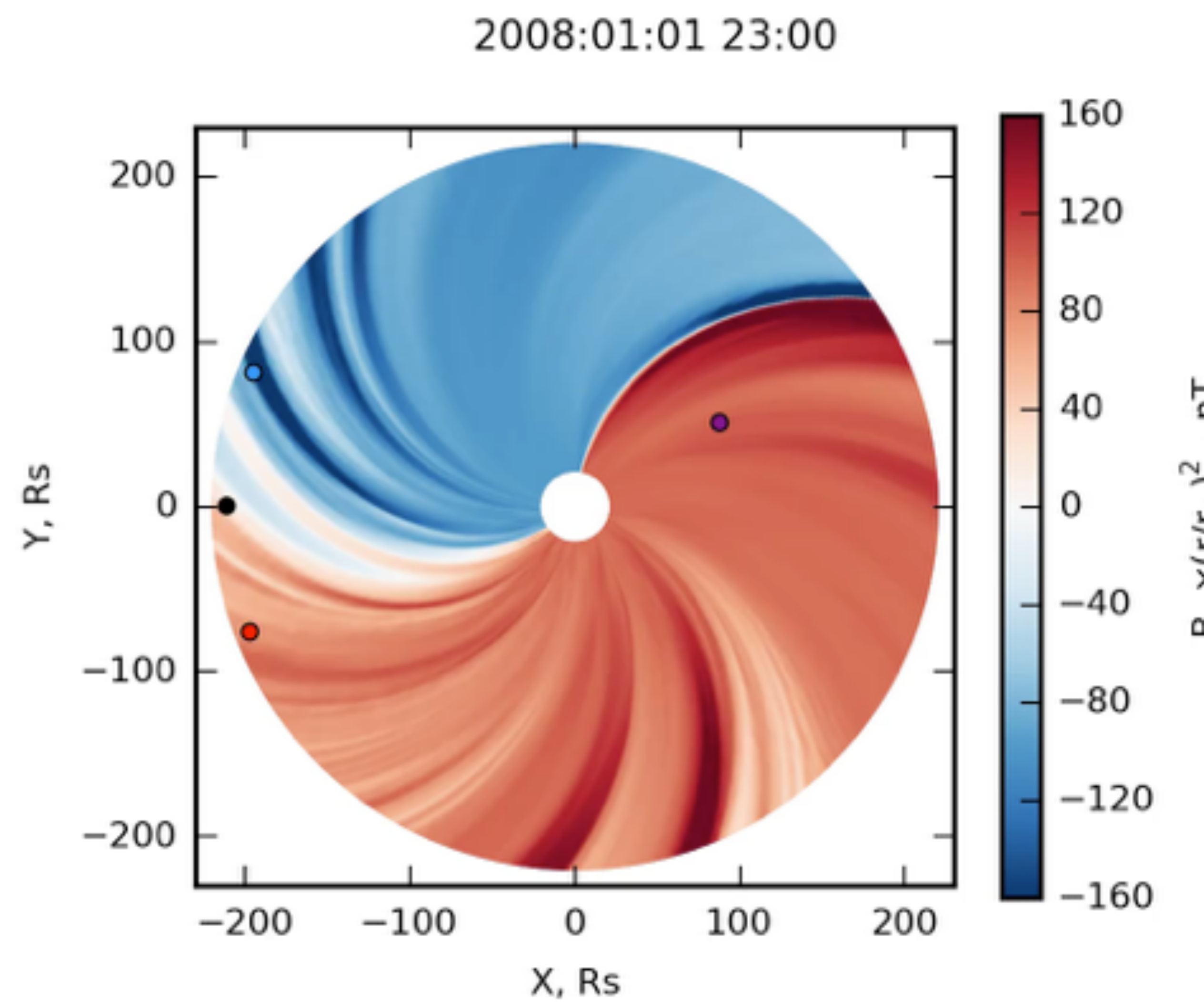
●ACE ●STEREO A ●STEREO B ●MESSENGER

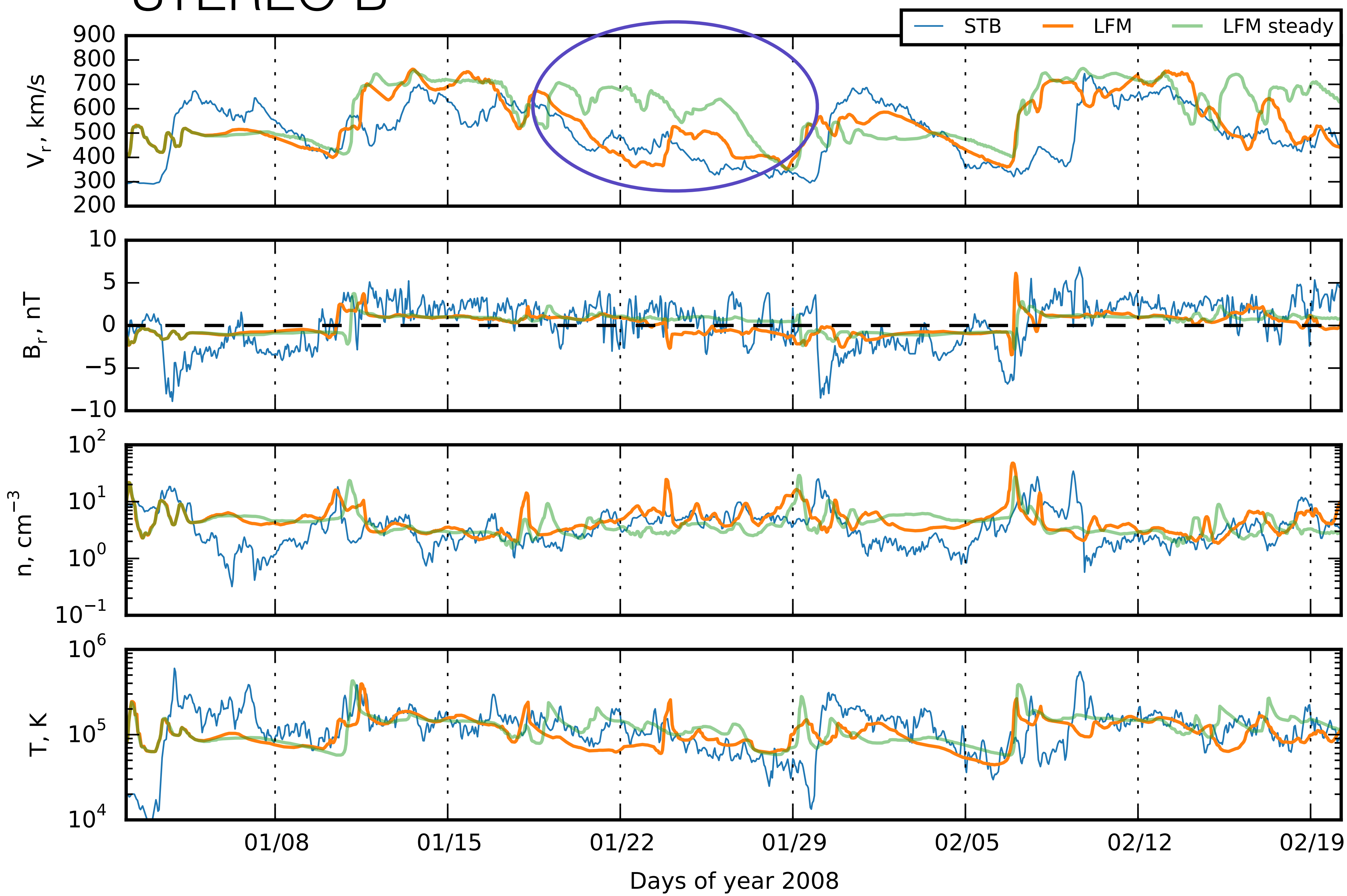
B_r and V_r @ 1 AU





Where time-dependence matters

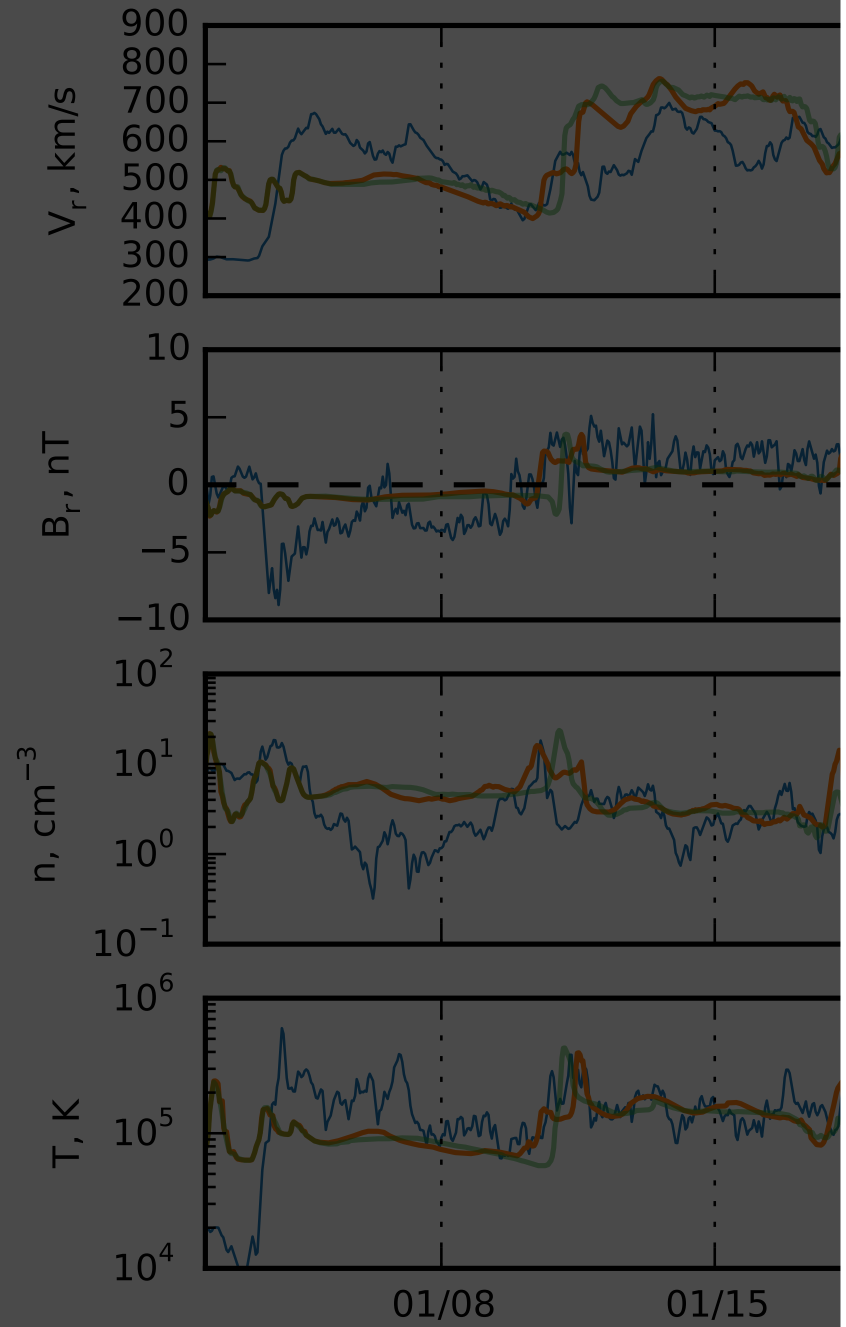
STEREO B

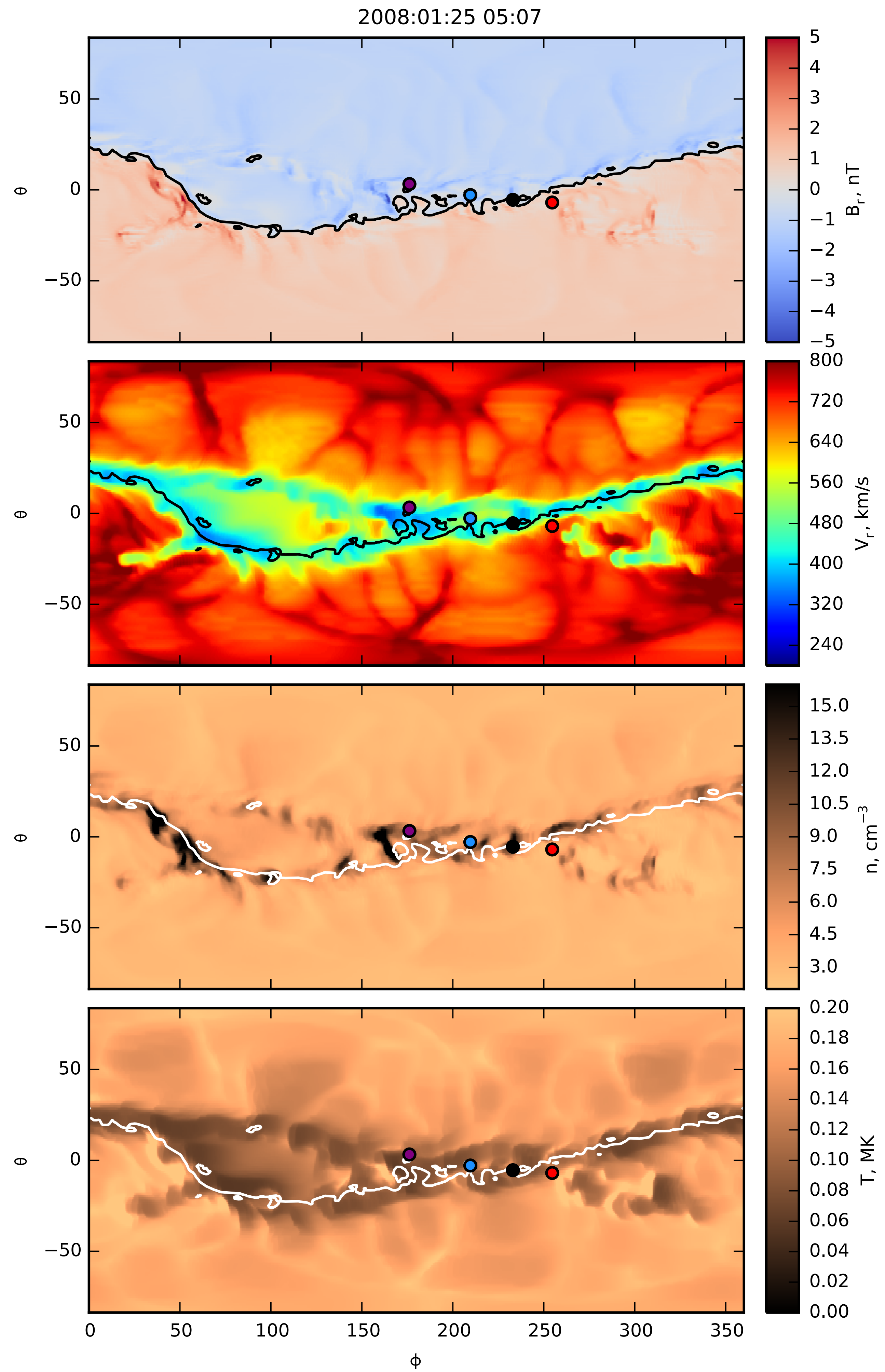


Merkin et al., JGR, [2016]

Time-depe... ...ere

STEREO B

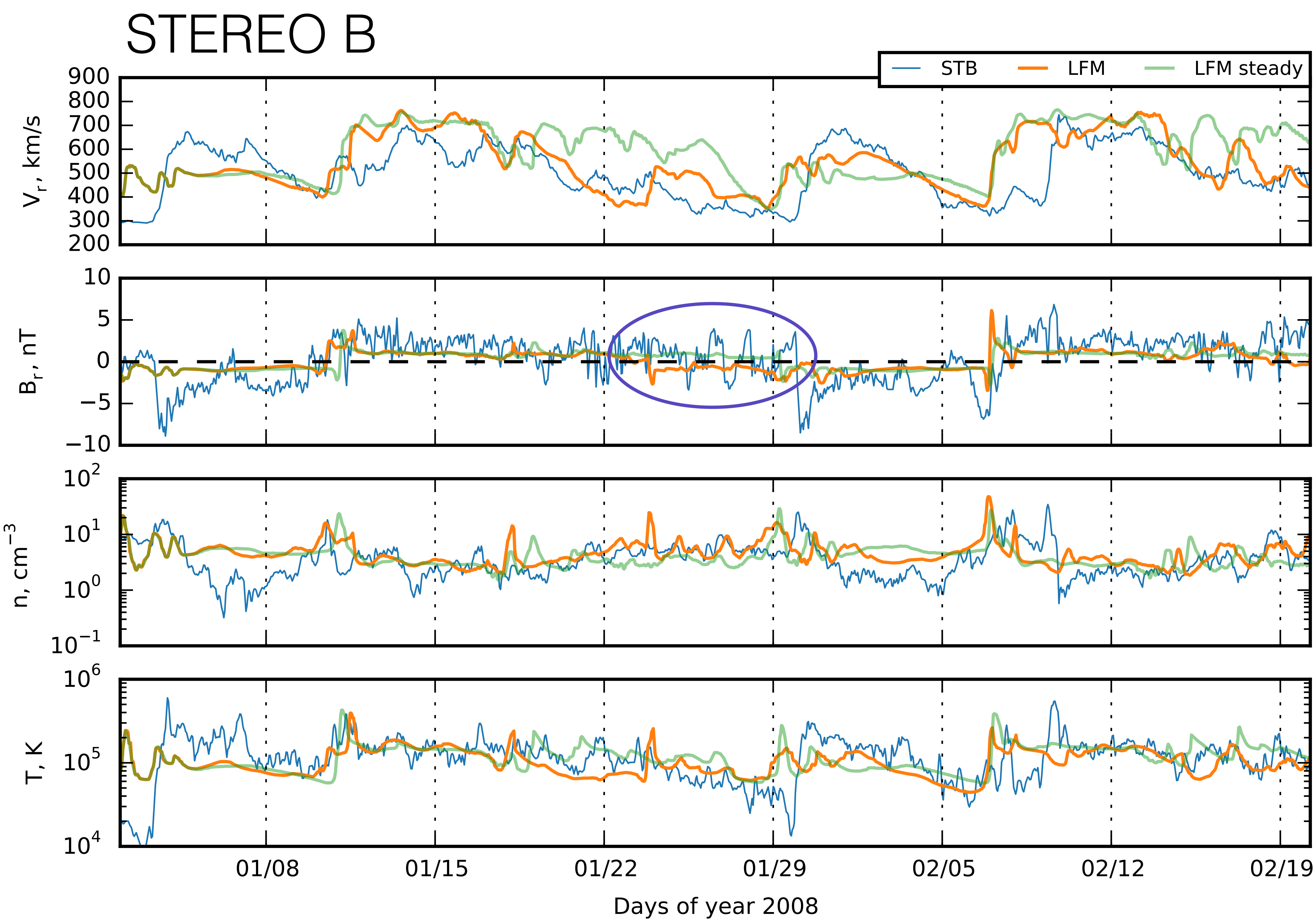




HCS and the equatorward boundary of the southern coronal hole moved southward over the course of January 2008

...et al., JGR, [2016]

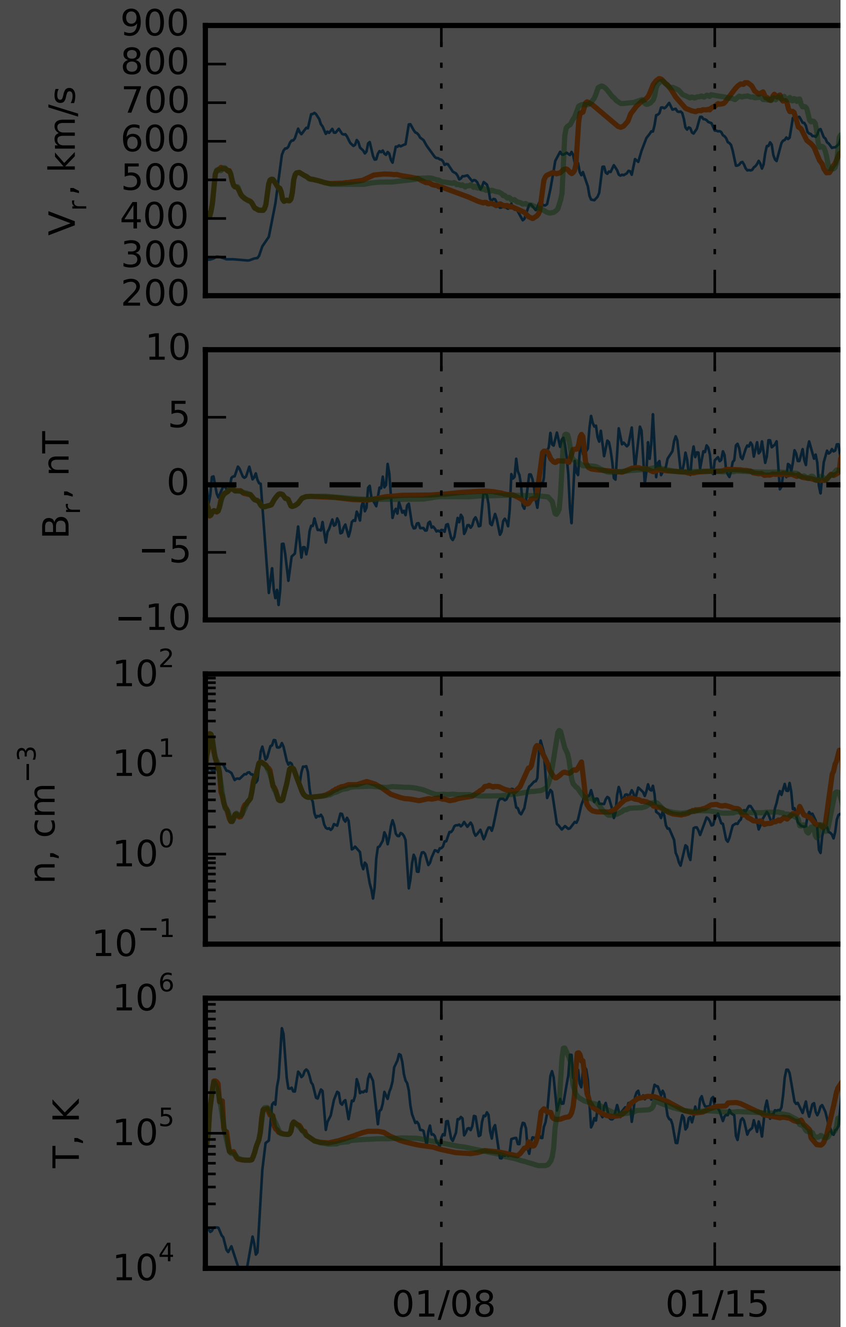
Spacecraft skimming HCS

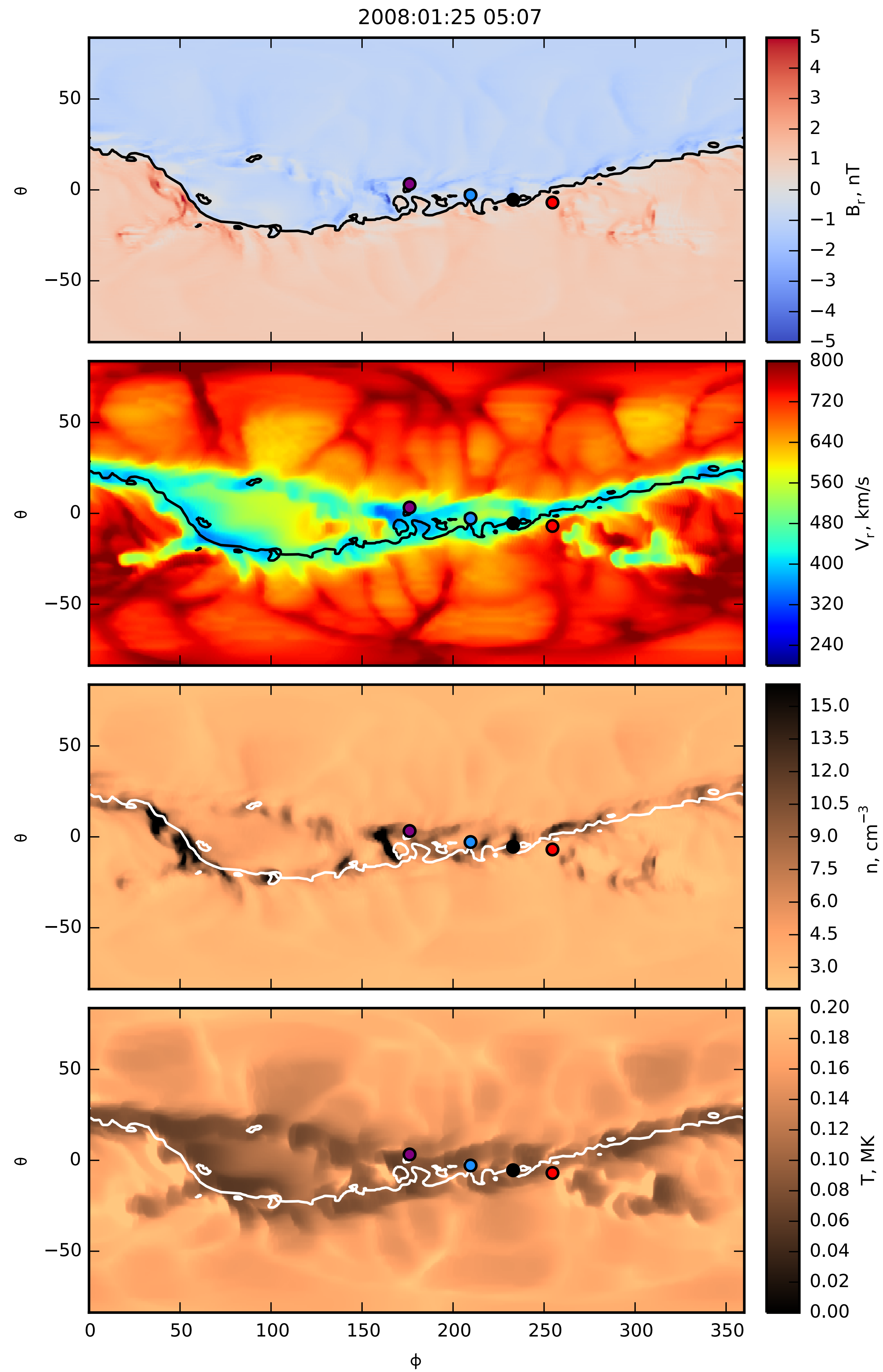


Merkin et al., JGR, [2016]

Time-depe… …ere

STEREO B



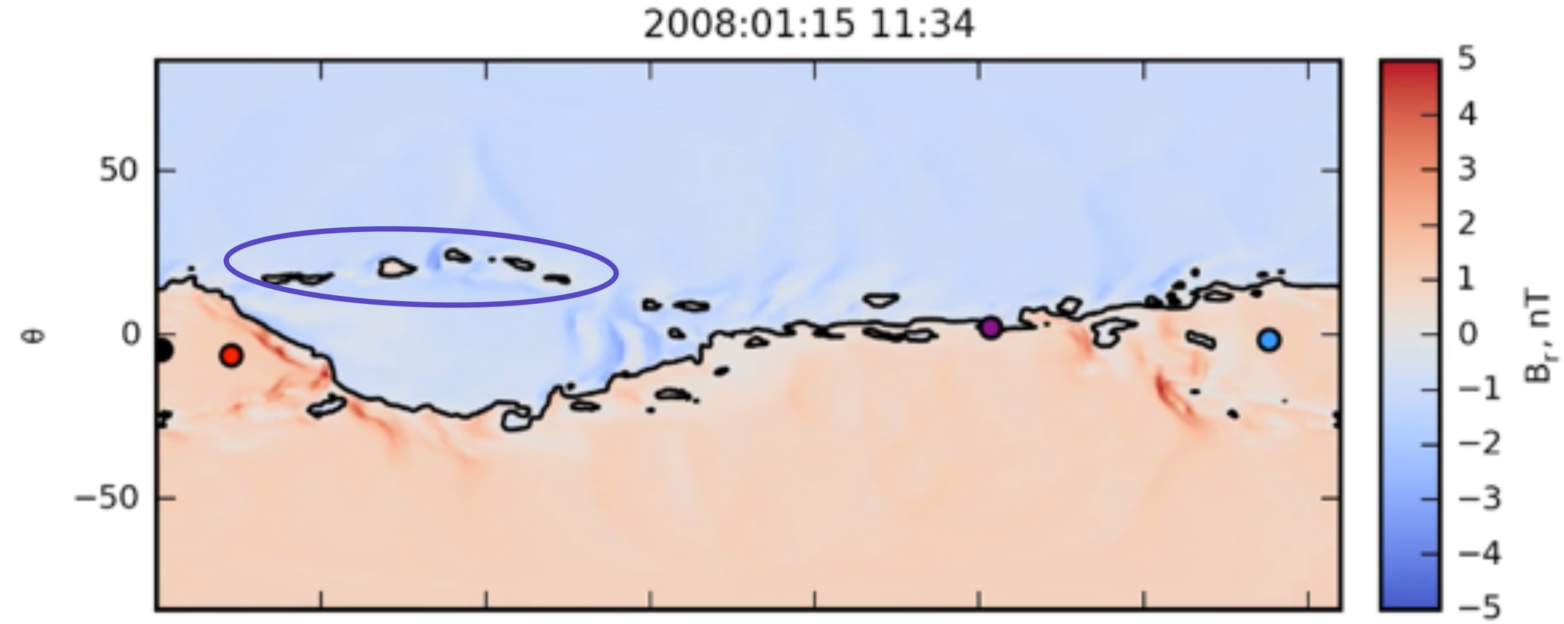


1 AU spacecraft skimming the HCS

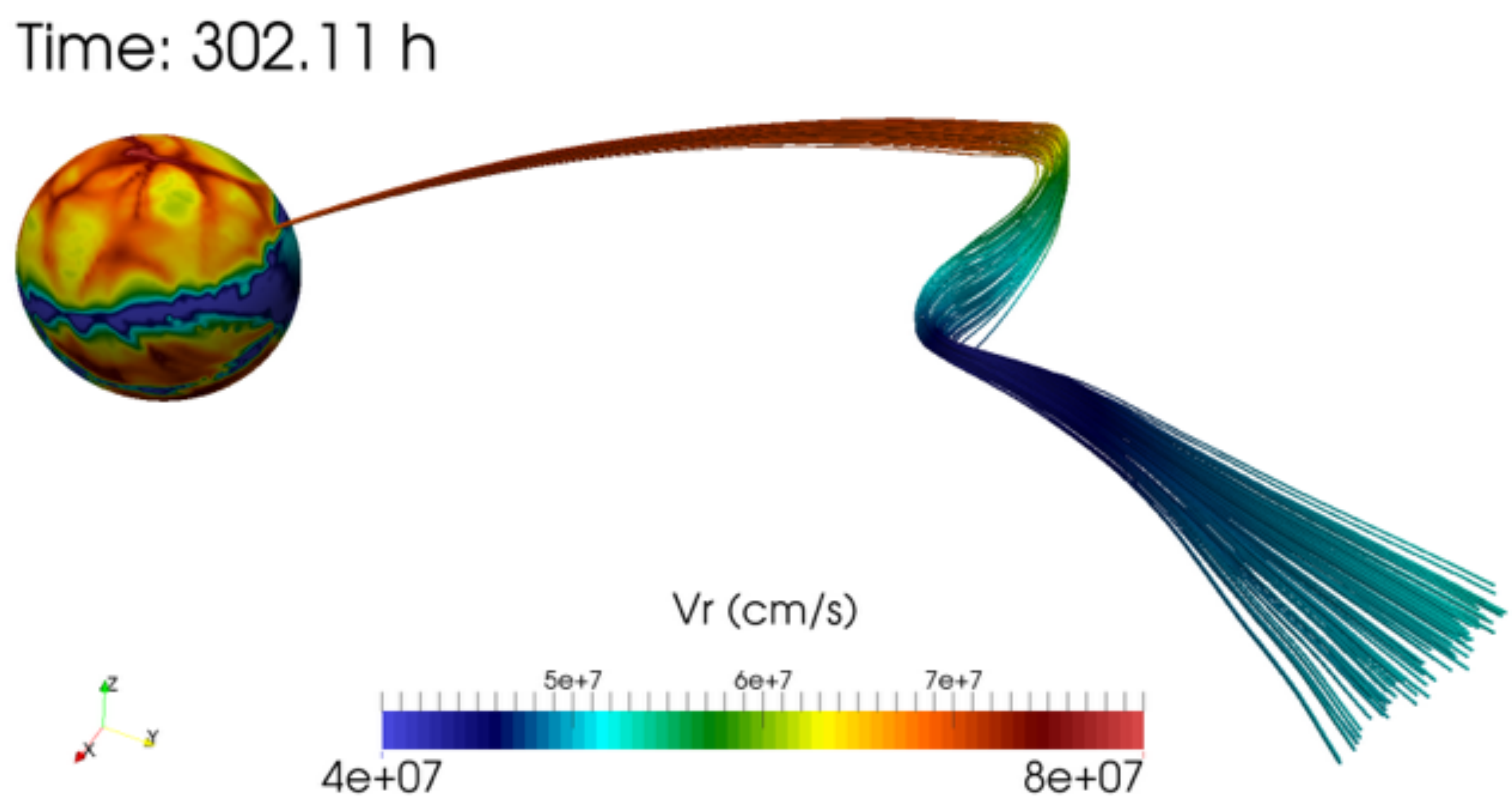
…et al., JGR, [2016]

Field reversals in pseudo-streamers

- Islands of opposite field polarity in pseudo streamer regions are due to inverted field lines
- Intrinsically, a time-dependent process
- These, in turn, are created by plasma parcels of varying speed that are fed into the same field line at the base of the simulation
- This is due to the field line footpoint being in the vicinity of high/slow speed flow boundary which moves with time
- This is in agreement with statistical observations by Owens et al. [2013]



Inner boundary and field lines colored by plasma speed

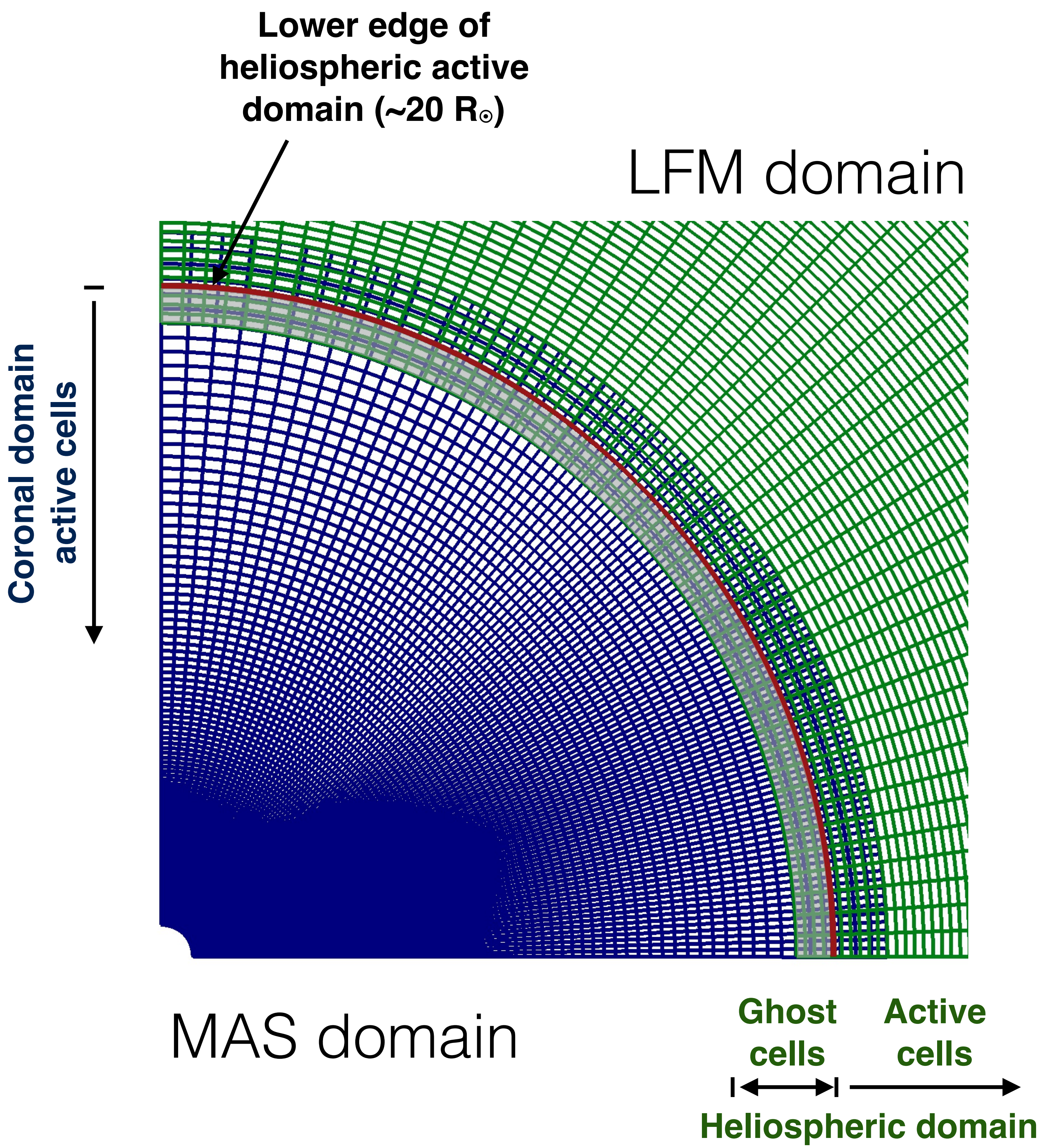


Merkin et al., JGR, [2016]

CME propagation

Strategy: Apply high-fidelity codes best suited to simulation of their corresponding domains

Coupling LFM-helio with MAS coronal MHD model

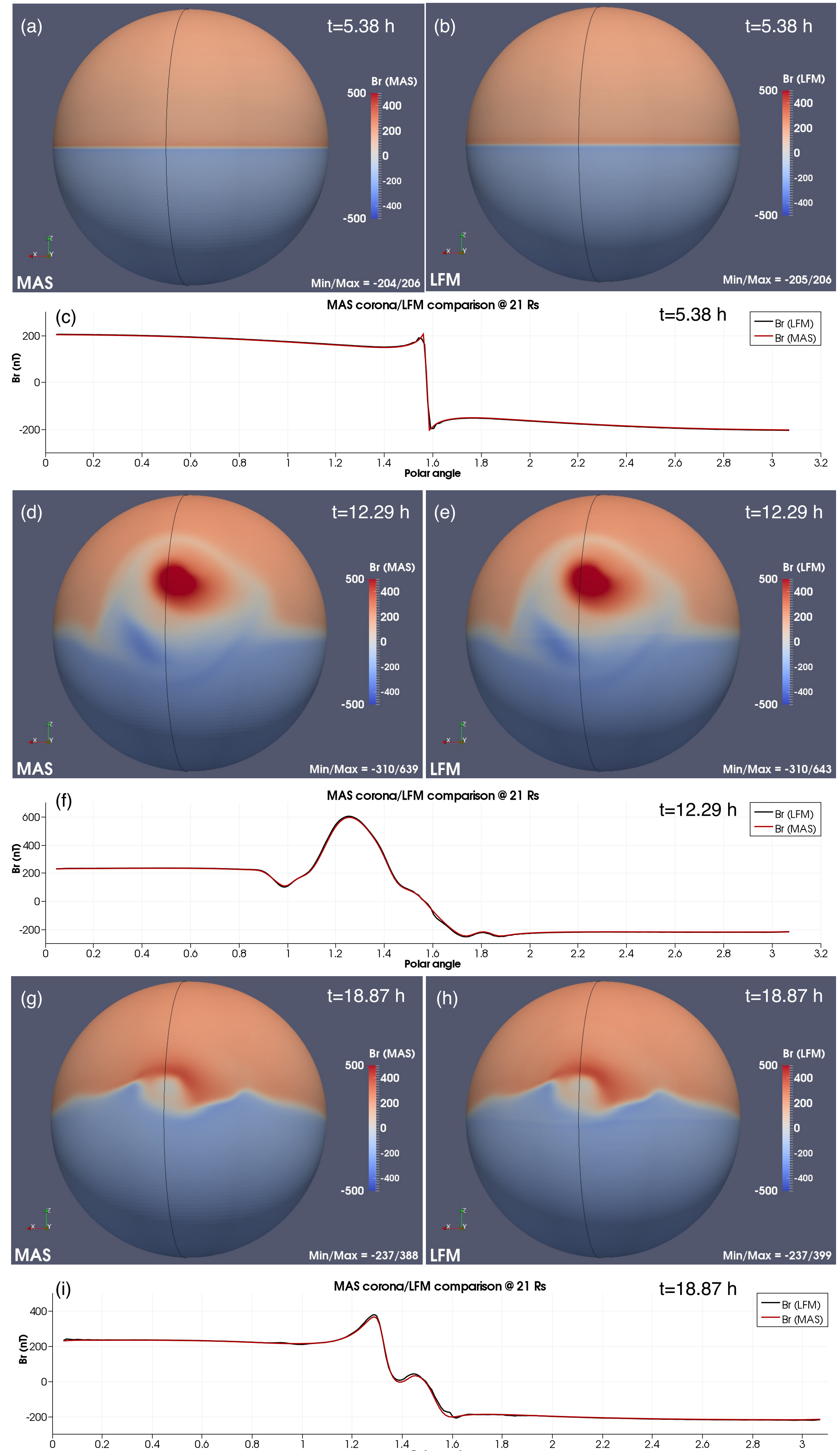


- LFM uses 8th order scheme — need ghost region 4 cells deep.
- LFM grid can be designed to overlap its inner boundary ghost region with the outer portion of the MAS coronal grid.
- Interpolation in the ghost region is necessary to keep the two grids arbitrary and independent.
- Variables are staggered differently between the two grids. Need to interpolate in radial and angular directions.

Merkin et al., ApJ, [2016]

Testing boundary interface

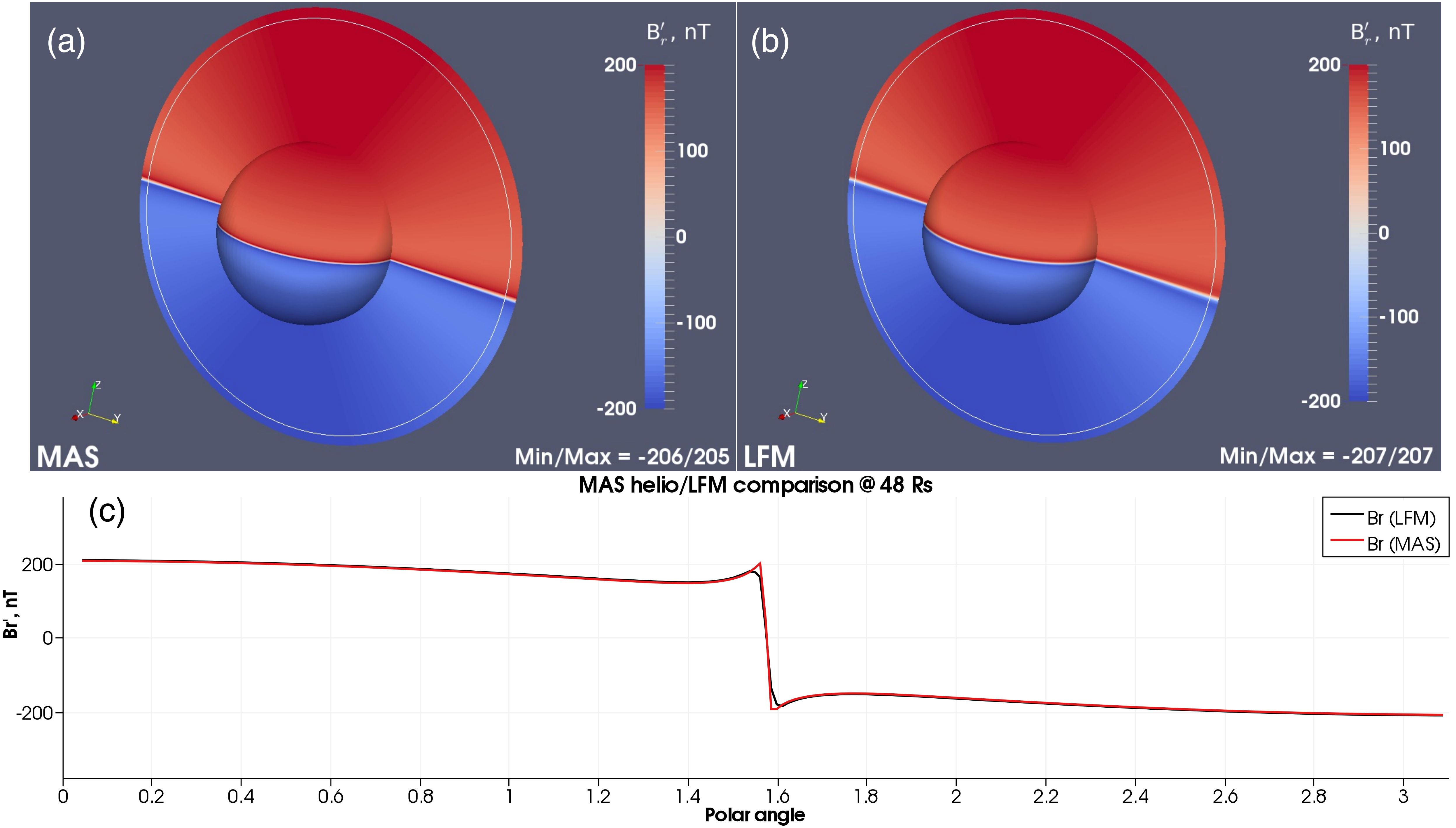
- Radial magnetic field, $B_r(t)$, at the boundary between MAS and LFM codes
- All variables, including B_r, propagate through the boundary seamlessly
- Boundary interface performs with very high accuracy



CME propagation

Azimuthally symmetric test (Lionello et al., 2013).

Matching initial states.



The background states match to within 1%.

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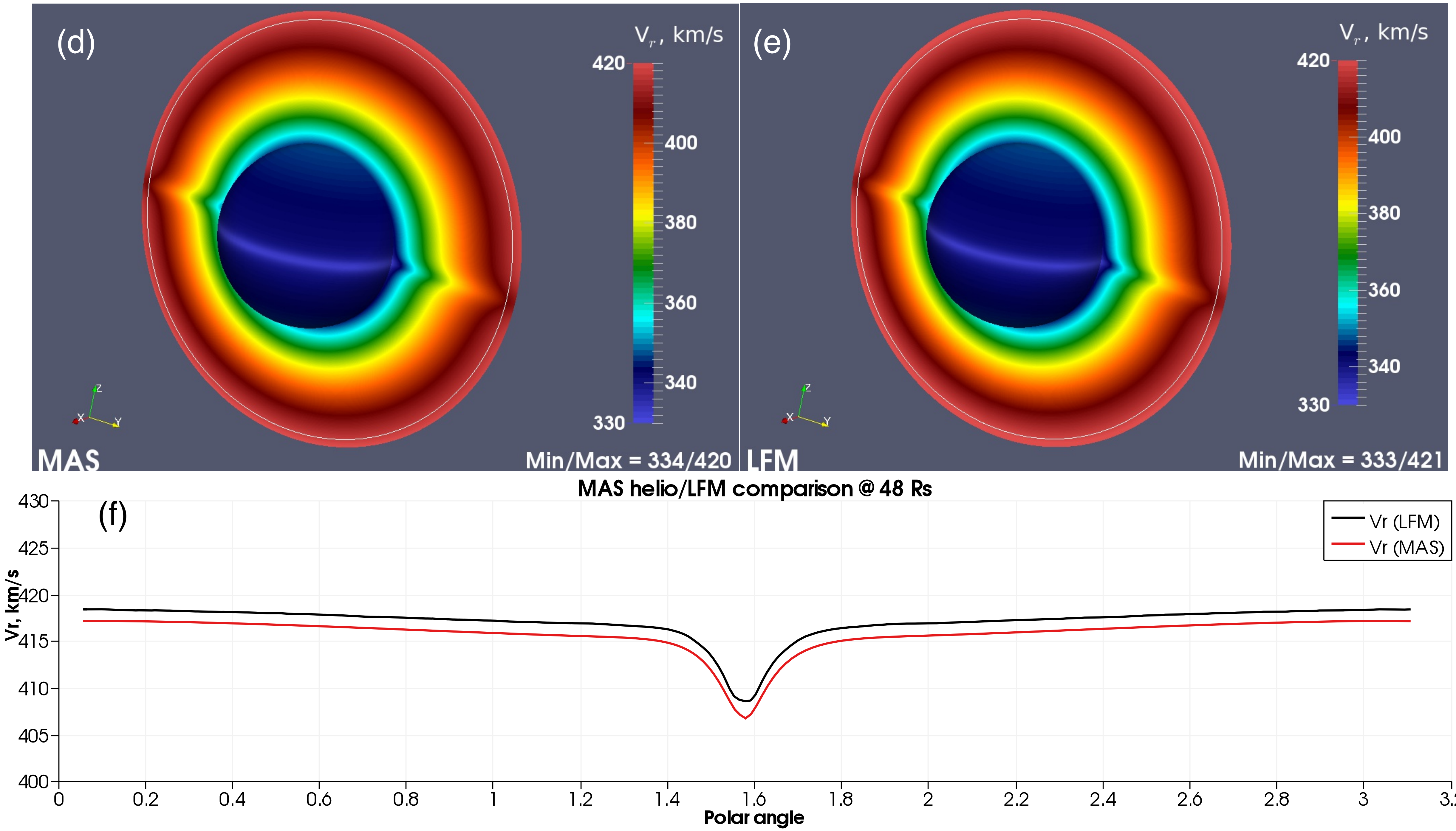

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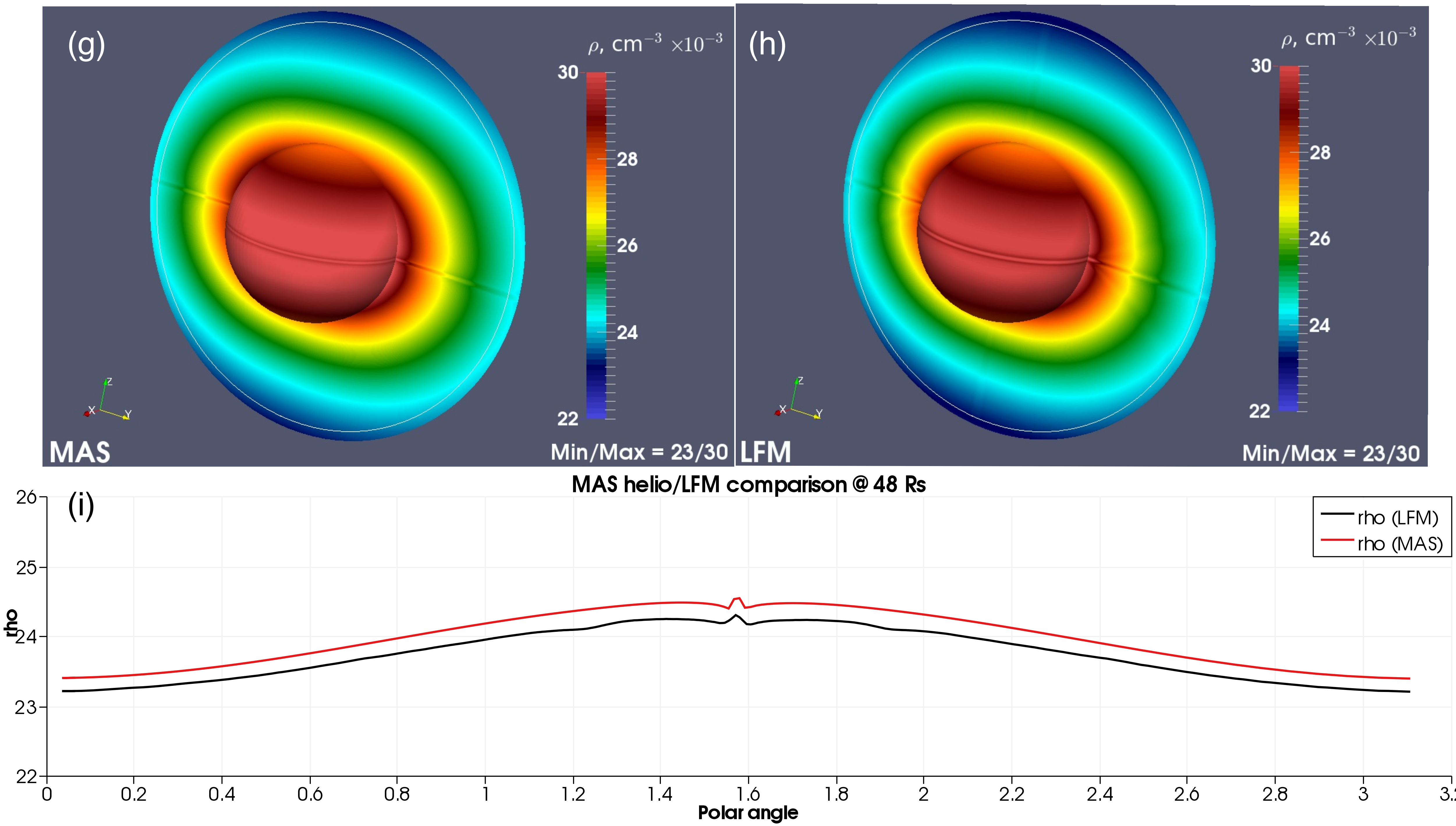

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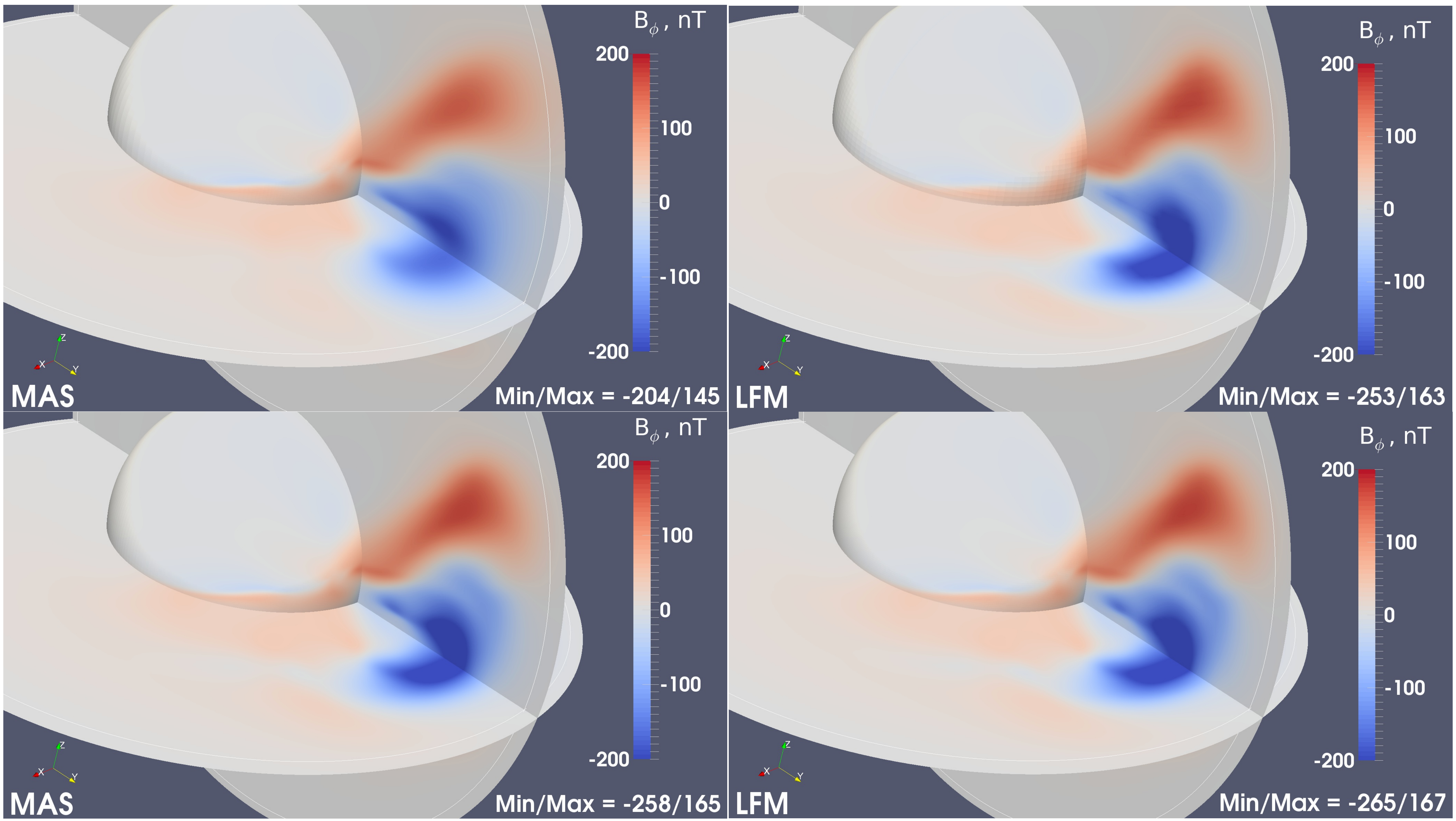
CME propagation

Azimuthally symmetric test. t=20 h. Polar magnetic field.

MAS LFM

Low resolution

High resolution



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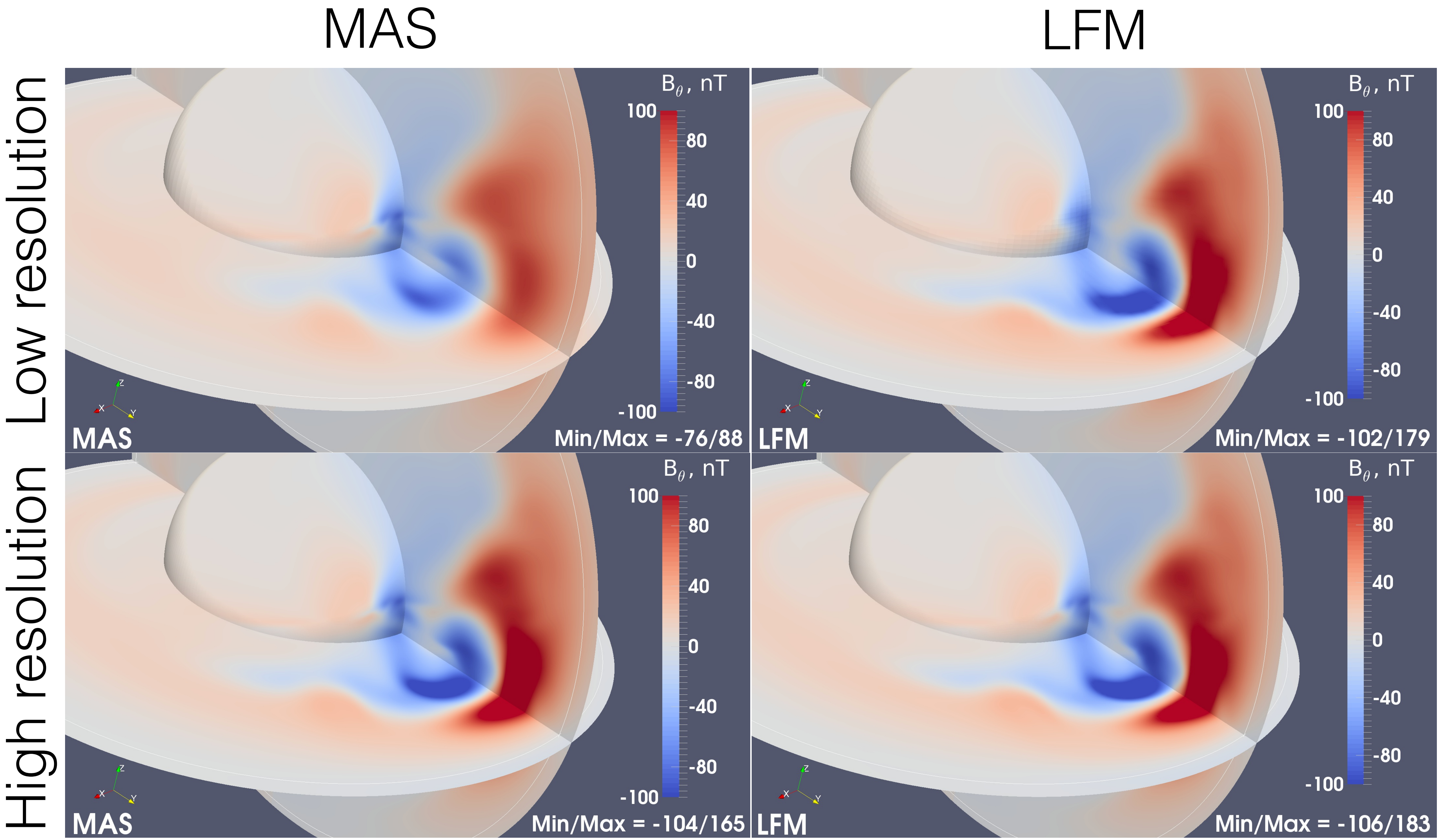
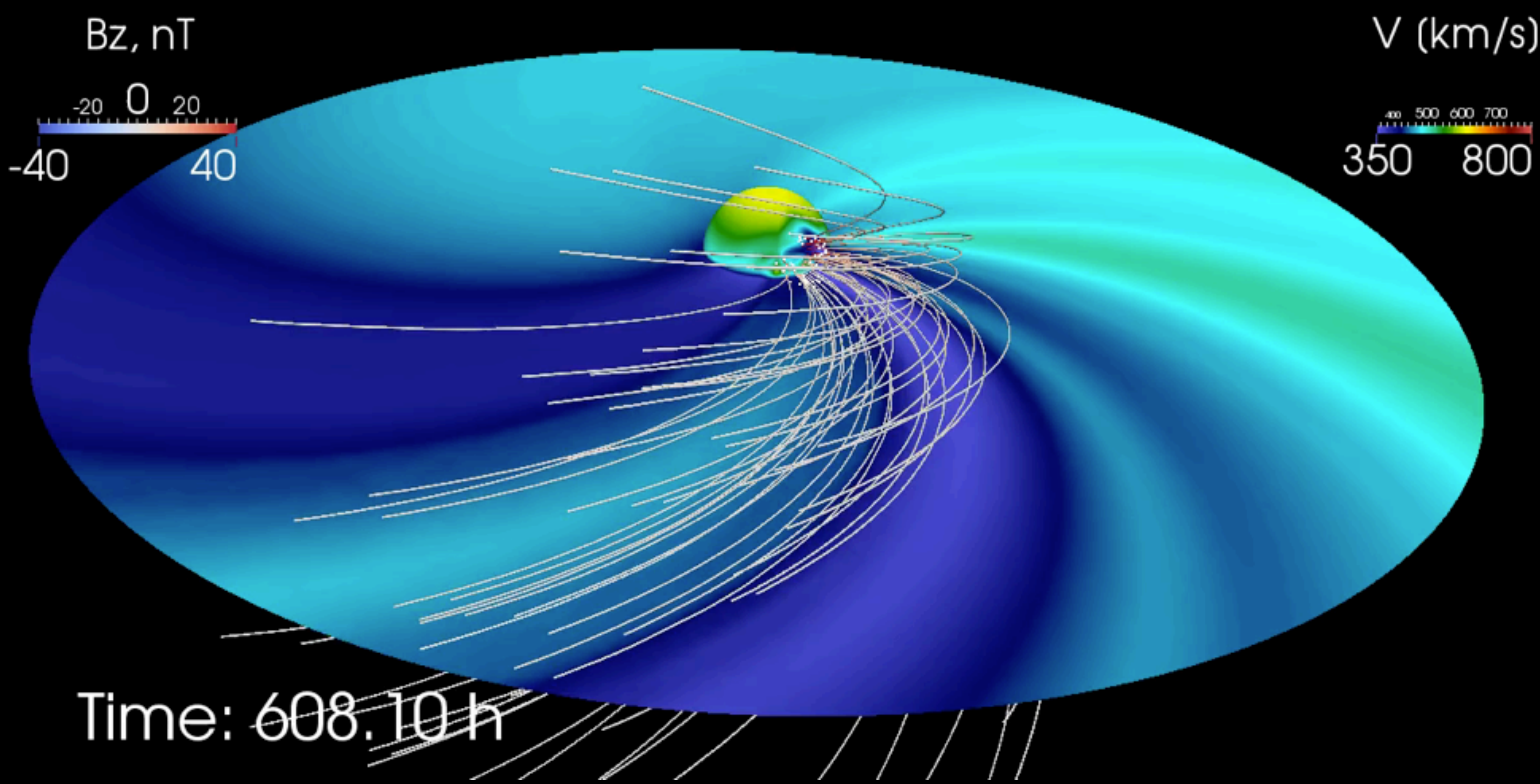


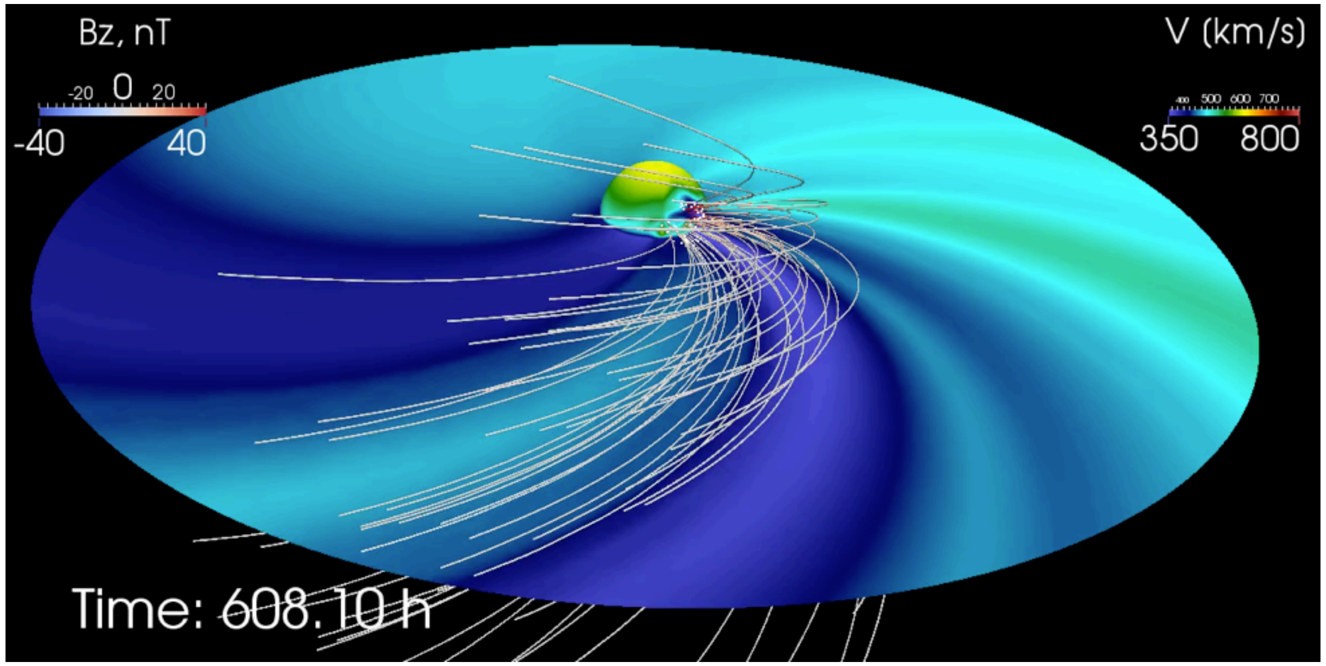
CME propagation

Realistic simulation. Rotation included. Asymmetric background.



Conclusions

- Performed time-dependent heliosphere simulations using two approaches
- Quiet time-dependent heliosphere was simulated using ADAPT/WSA to drive LFM-helio
- For CME propagation we coupled LFM-helio to MAS
- ADAPT/WSA-LFM-helio:
  - Time-dependent modeling allowed for more accurate prediction of high-speed streams at Earth and helped interpret complex HCS crossings at MESSENGER and 1 AU
  - Inverted field lines can be generated in pseudo streamer regions
  - HCS corrugation caused by SW velocity gradients



- MAS-LFM-helio:
  - Achieved virtually identical background states
  - With a propagating flux rope, the solutions diverge at larger heliospheric distances but increasing resolution leads to converging solutions
  - Performed realistic simulations with non-symmetric background and solar rotation
  - Ensemble modeling the way to go

Future

- Step-change in simulation resolution. MHD instabilities are likely currently suppressed due to coarseness of simulation grids. Removed by 2 orders of magnitude from ion scales.

- More realistic CME simulations.

- Include new physics: multi-fluid for ion species; two-temperature plasma; turbulent heating; pick-up ions.

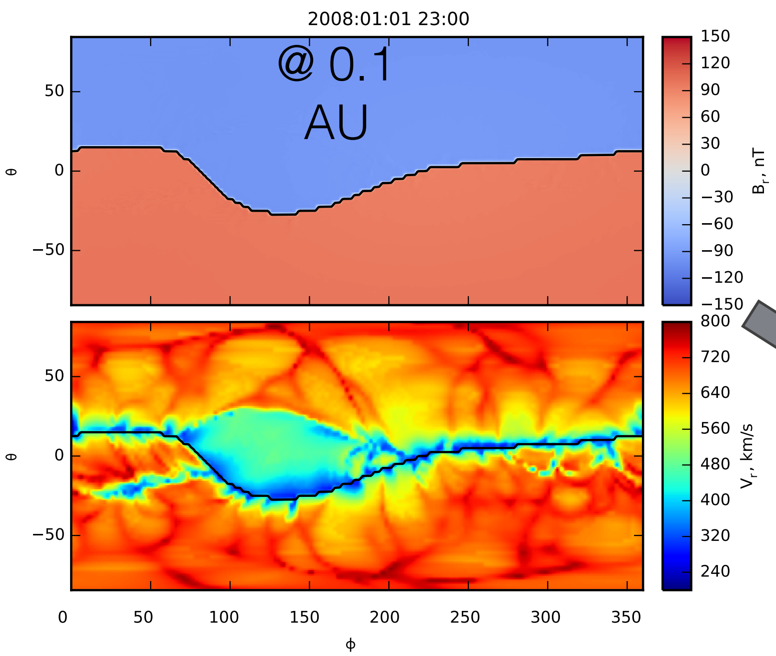
- Ensemble modeling the way to go

- Cleaning up the code base, boundary interfaces, user interface — ultimate goal — transition to CCMC — requires resources.

- Streamline common LFM code base between different applications — useful for developers, internal users, external users (CCMC), therefore, the community.

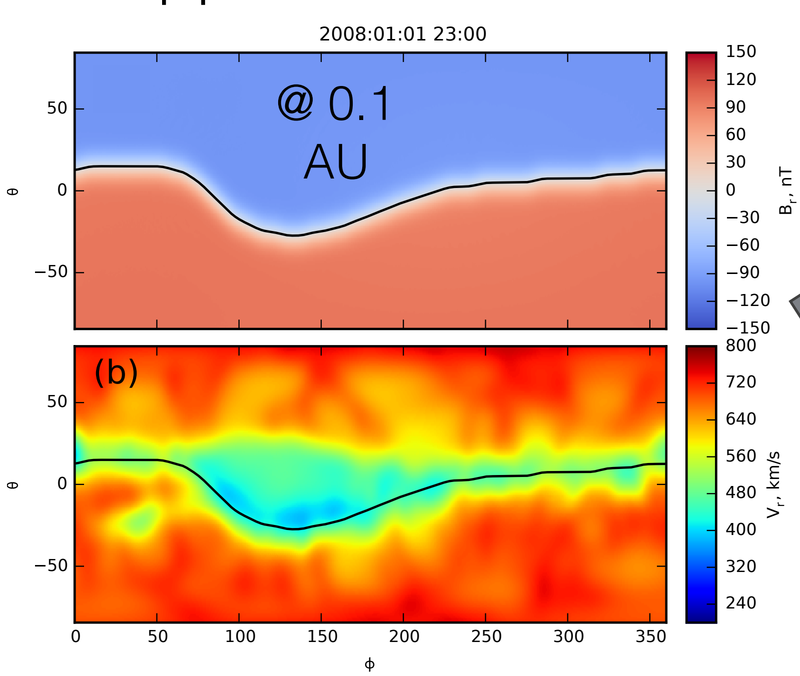
backup

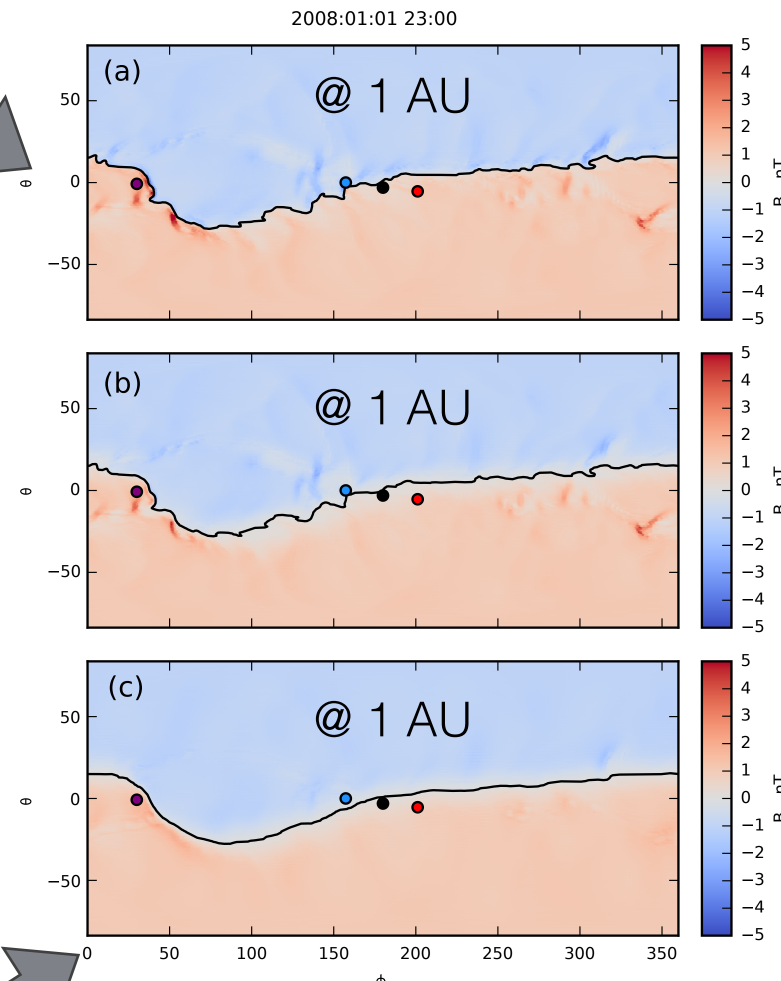
Heliospheric current sheet corrugation



8-point Gaussian smoothing

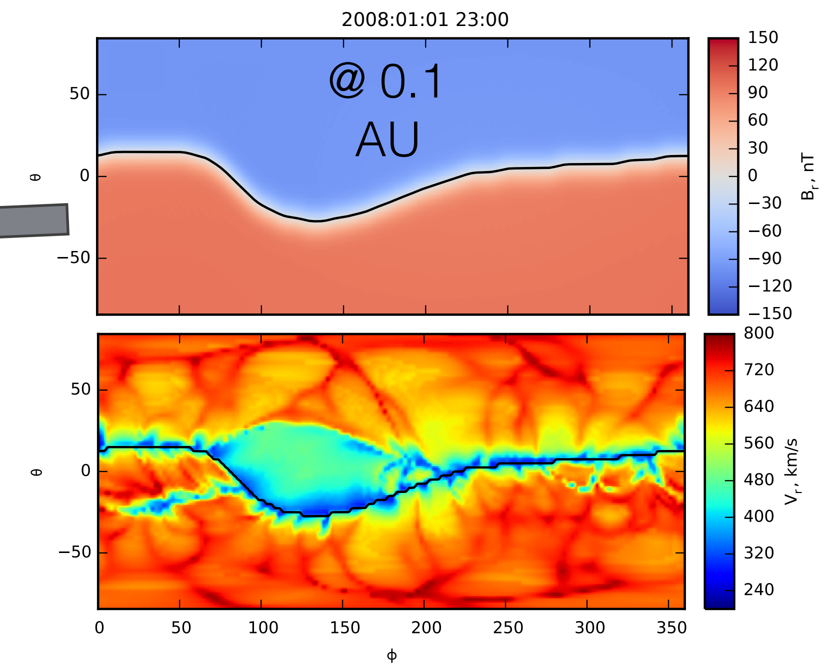
applied to B_r and V_r





8-point Gaussian smoothing

applied to B_r only



HCS corrugation at 1 AU is caused by solar wind velocity shears