JOHNS HOPKINS
APPLIED PHYSICS LABORATORY

Inner heliosphere modeling with LFM and Gamera

Space Plasma Theory and Modeling @ APL & collaborators

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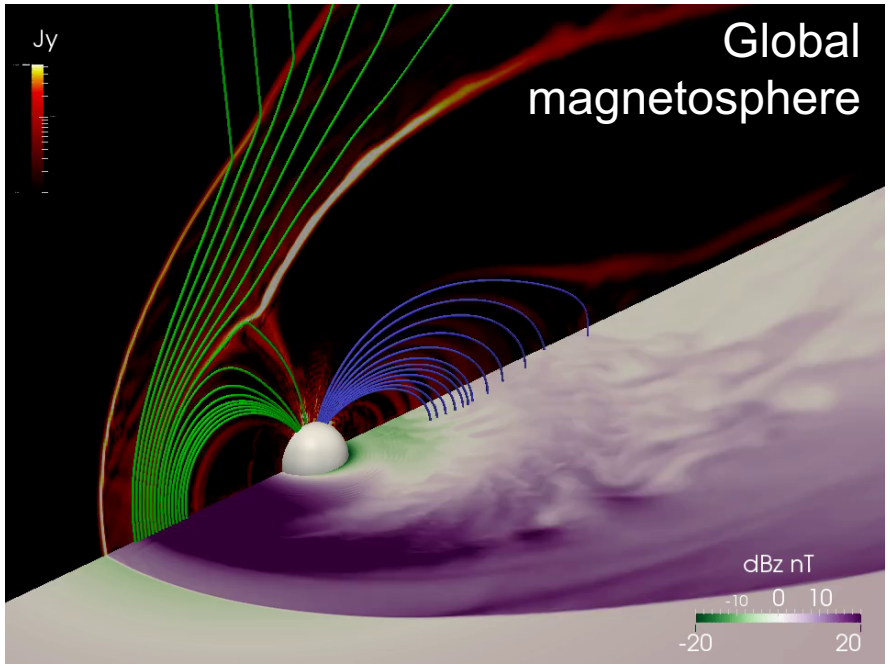
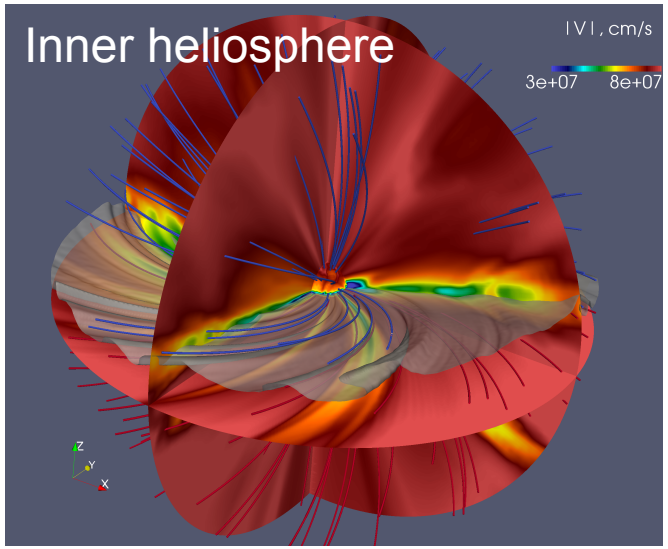
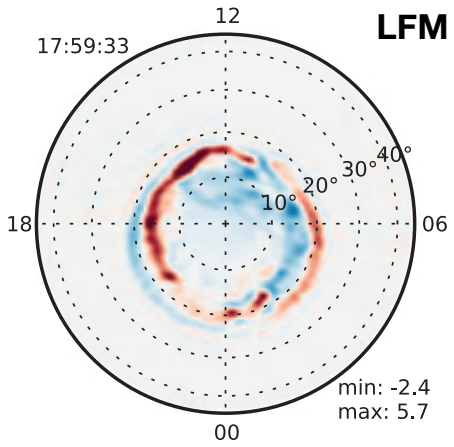
B. Zhang (HKU)
J. Lyon (Dartmouth)
M. Wiltberger (NCAR)

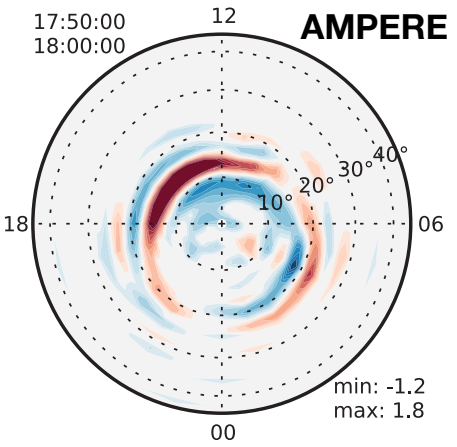
APL space weather simulation toolbox

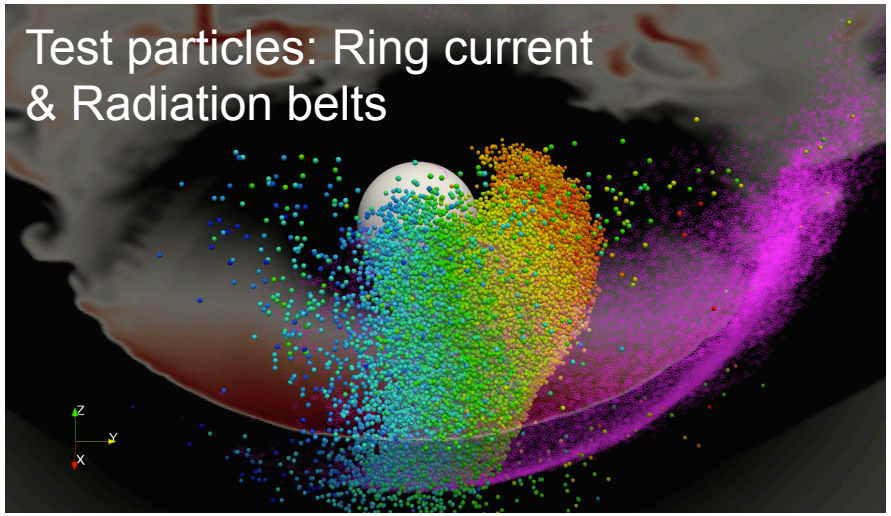


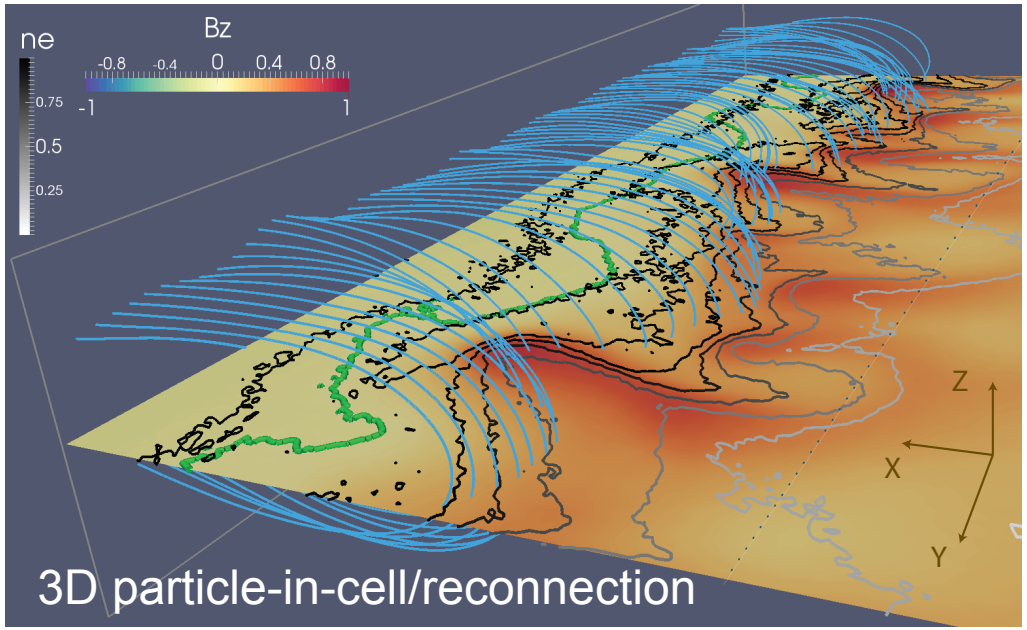


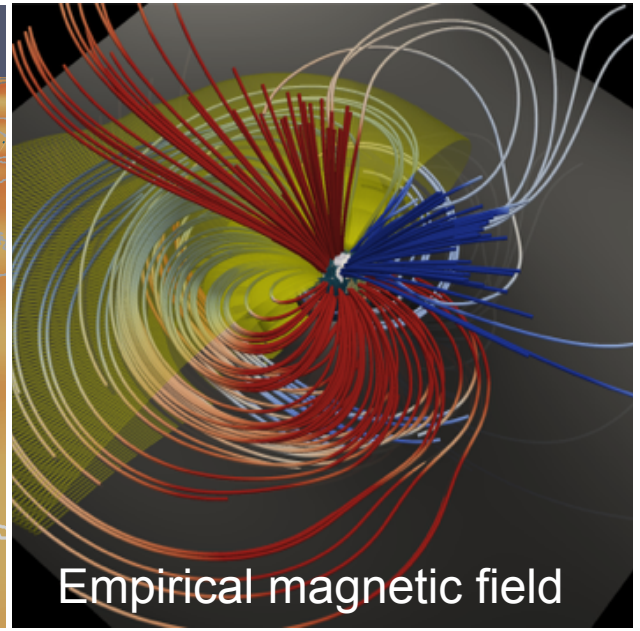
Magnetosphere-ionosphere coupling





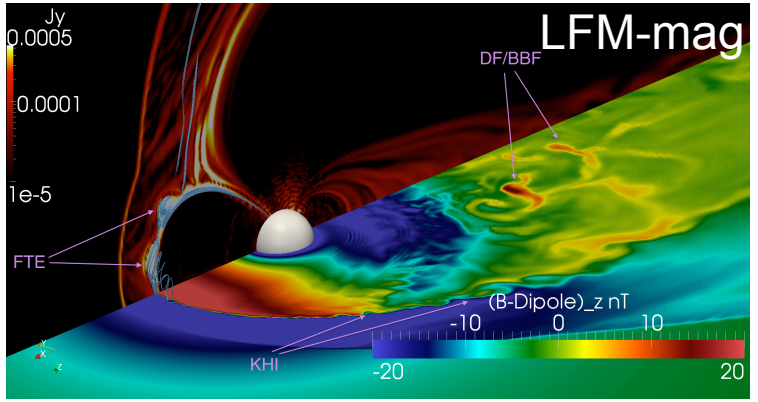


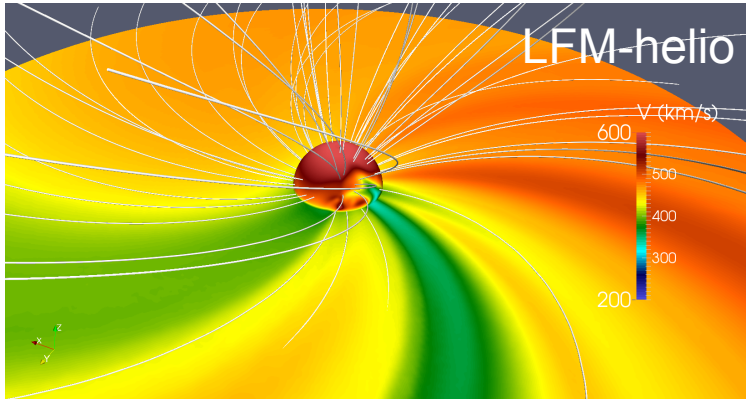


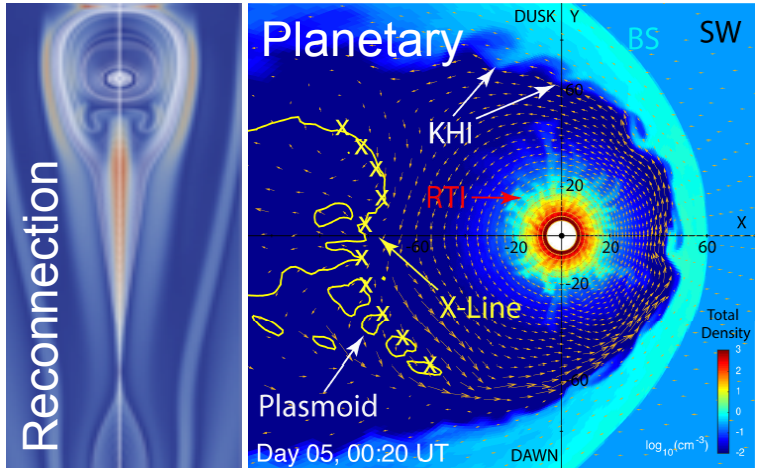


LFM-helio code

- 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,b); regional plasma problems (Merkin et al., 2015); planetary magnetospheres (Zhang et al., 2018)
- LFM numerics
  - Handles arbitrary, non-orthogonal (and singular!) grids
  - High-order spatial reconstruction
  - Can capture 3D dynamics with relatively few cells
  - Intrinsically div-free B updates (constrained transport)
- Rotating/inertial frame calculations
- Time-dependent coronal boundary conditions

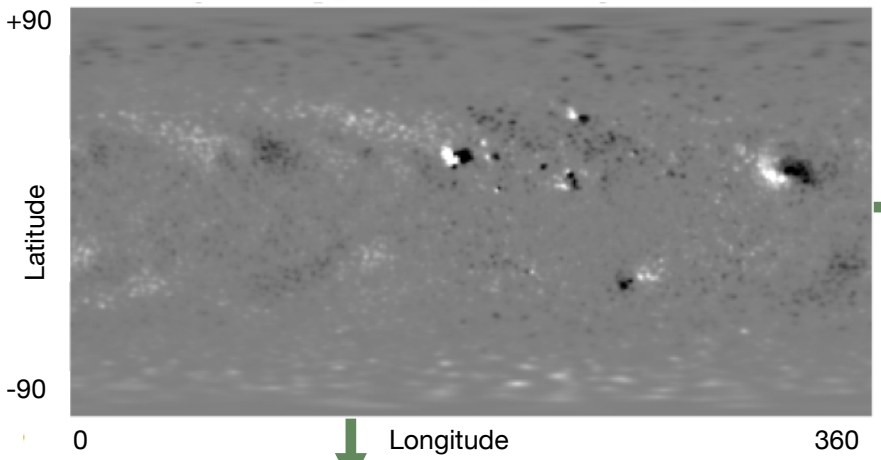




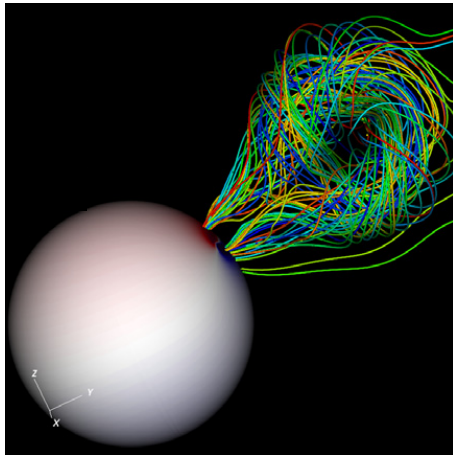


LFM-helio: Inner heliosphere modeling

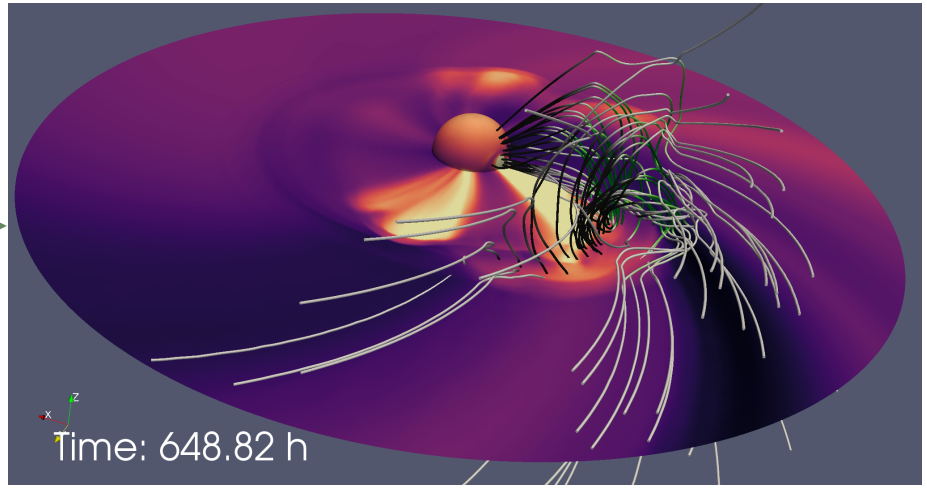
ADAPT photospheric maps



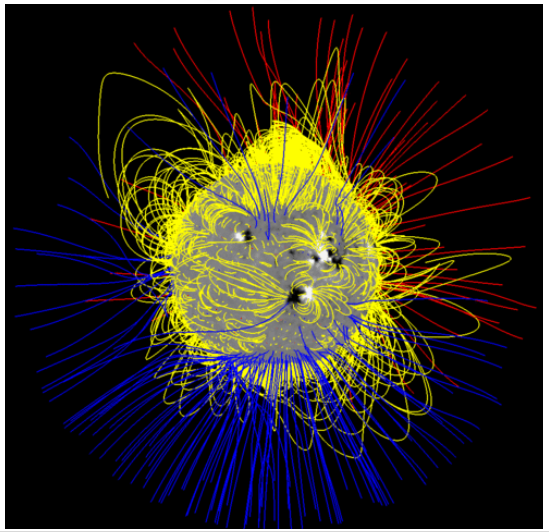
MAS corona



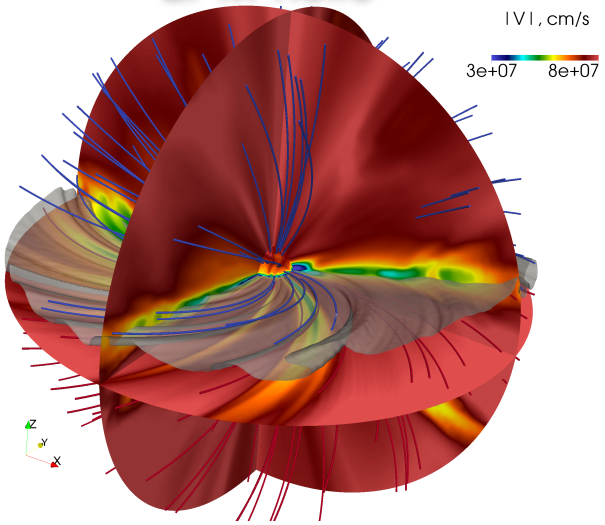
LFM-helio



WSA Corona



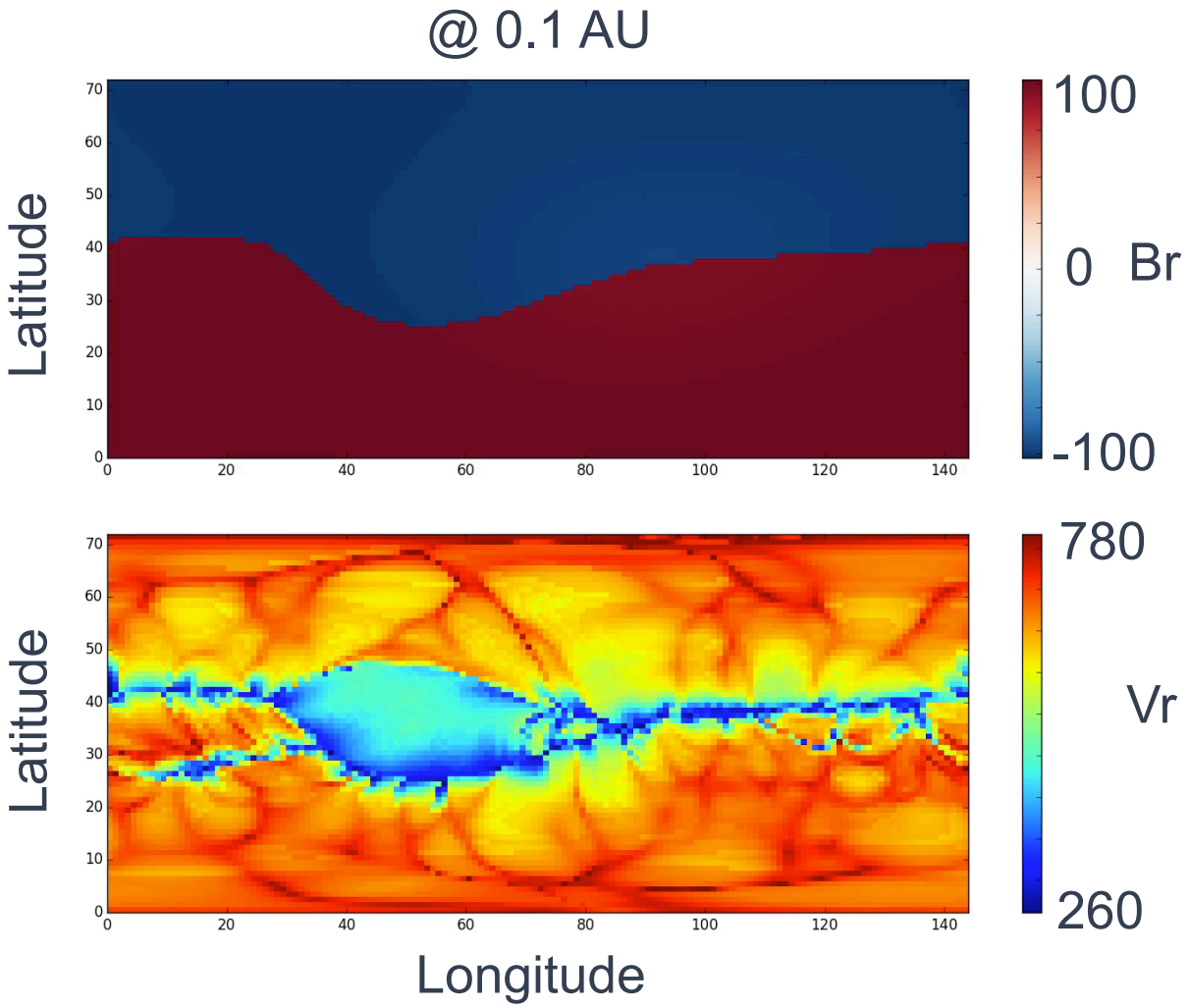
LFM-helio



- LFM serves as backbone for the inner heliosphere modeling pipeline
- Modeling is time-dependent
- ADAPT/WSA-driven for quiet heliosphere
- Coupled with MAS for CME propagation

Time-dependent quiet heliosphere

Driven by ADAPT/WSA



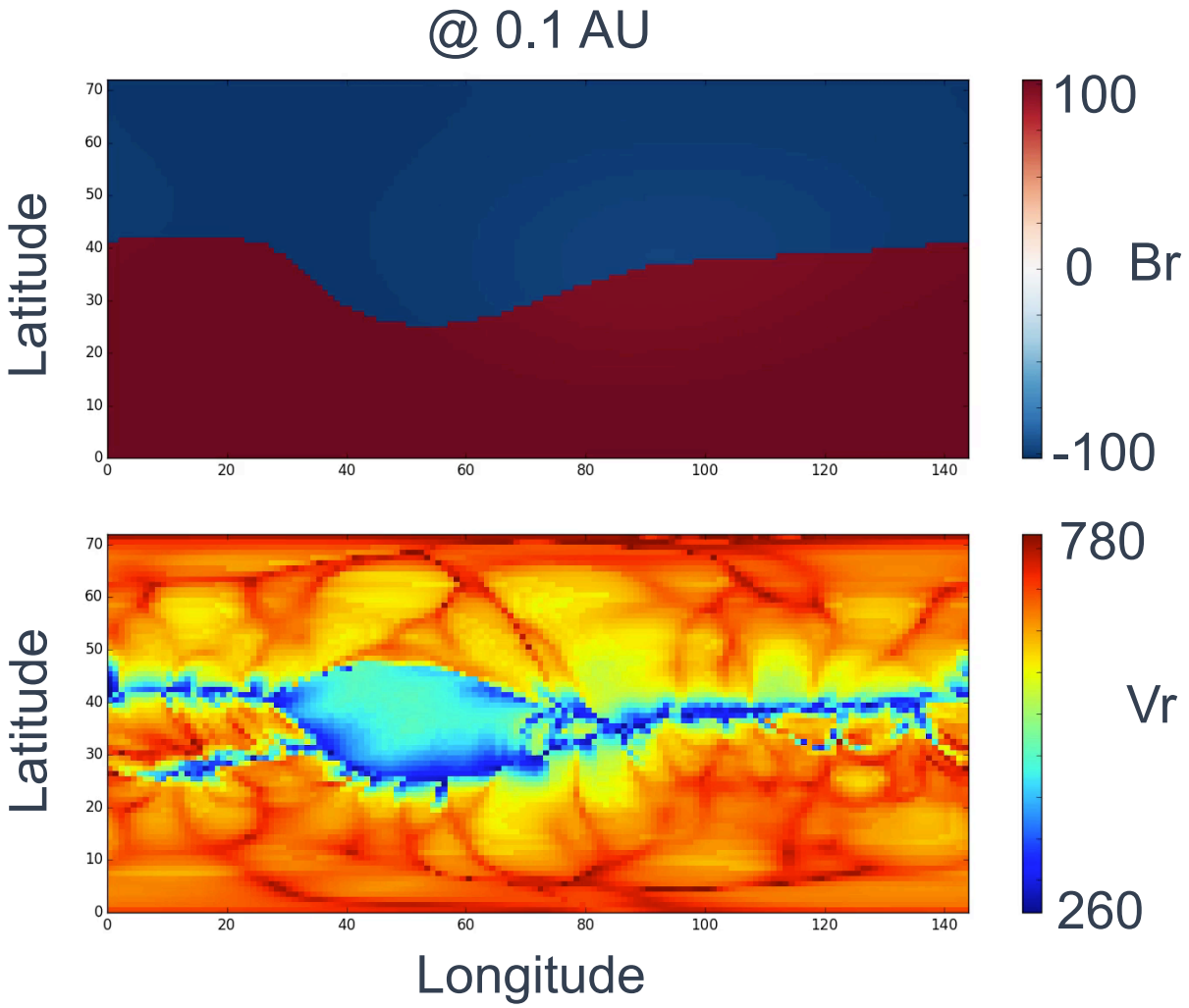
- ADAPT-driven WSA solutions
- 2-h to 1-d cadence
- Provide time-dependent inputs into MHD models of the solar wind
- Major problem: Radial magnetic field boundary condition should guarantee

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

Merkin et al., JGR, [2016]

Time-dependent quiet heliosphere

Driven by ADAPT/WSA



$$\mathbf{E}_\perp = \nabla_\perp \times \mathbf{r}\,\Psi$$

$$\Delta_\perp \Psi = \partial B_r / \partial t$$

From ADAPT/WSA

$$\mathbf{E}_\perp$$

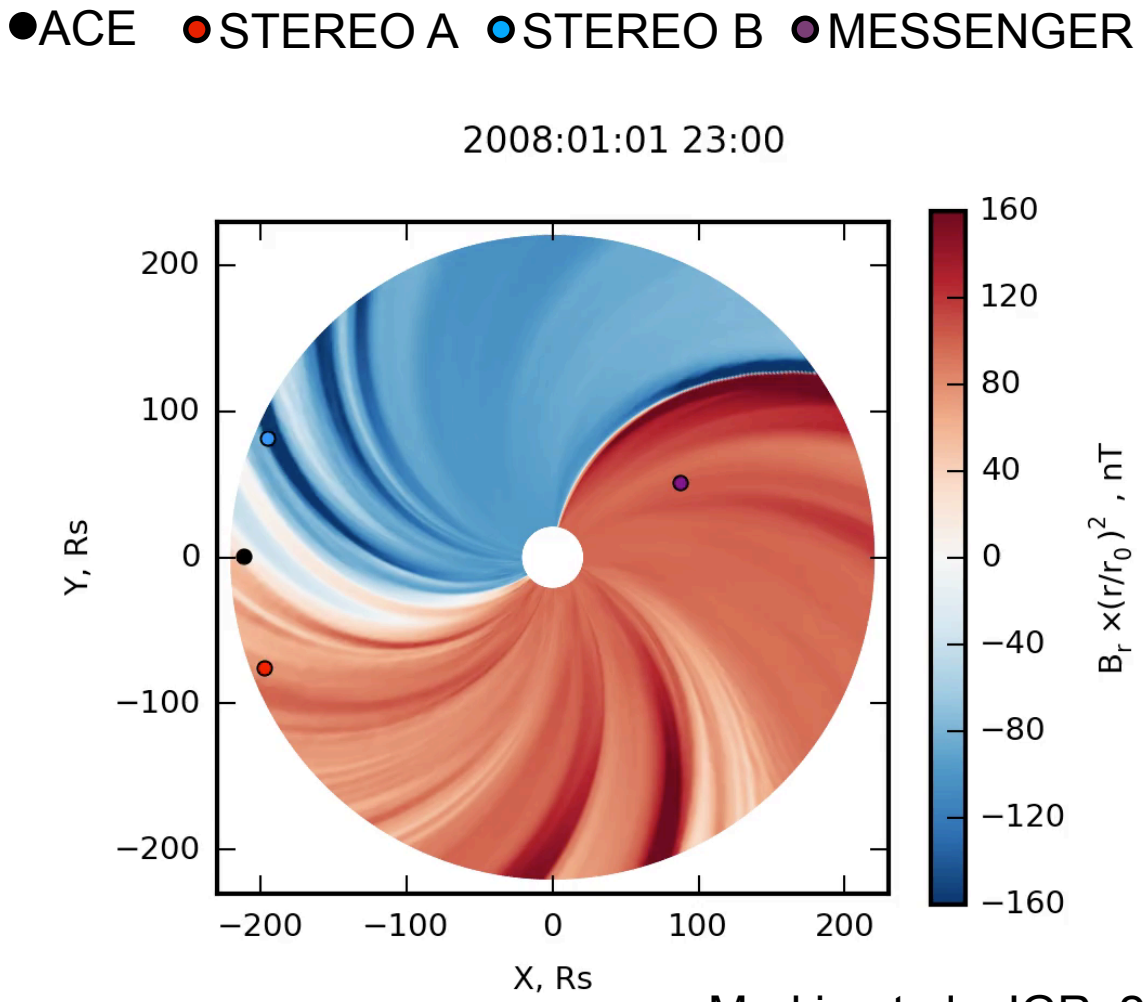
MHD boundary condition

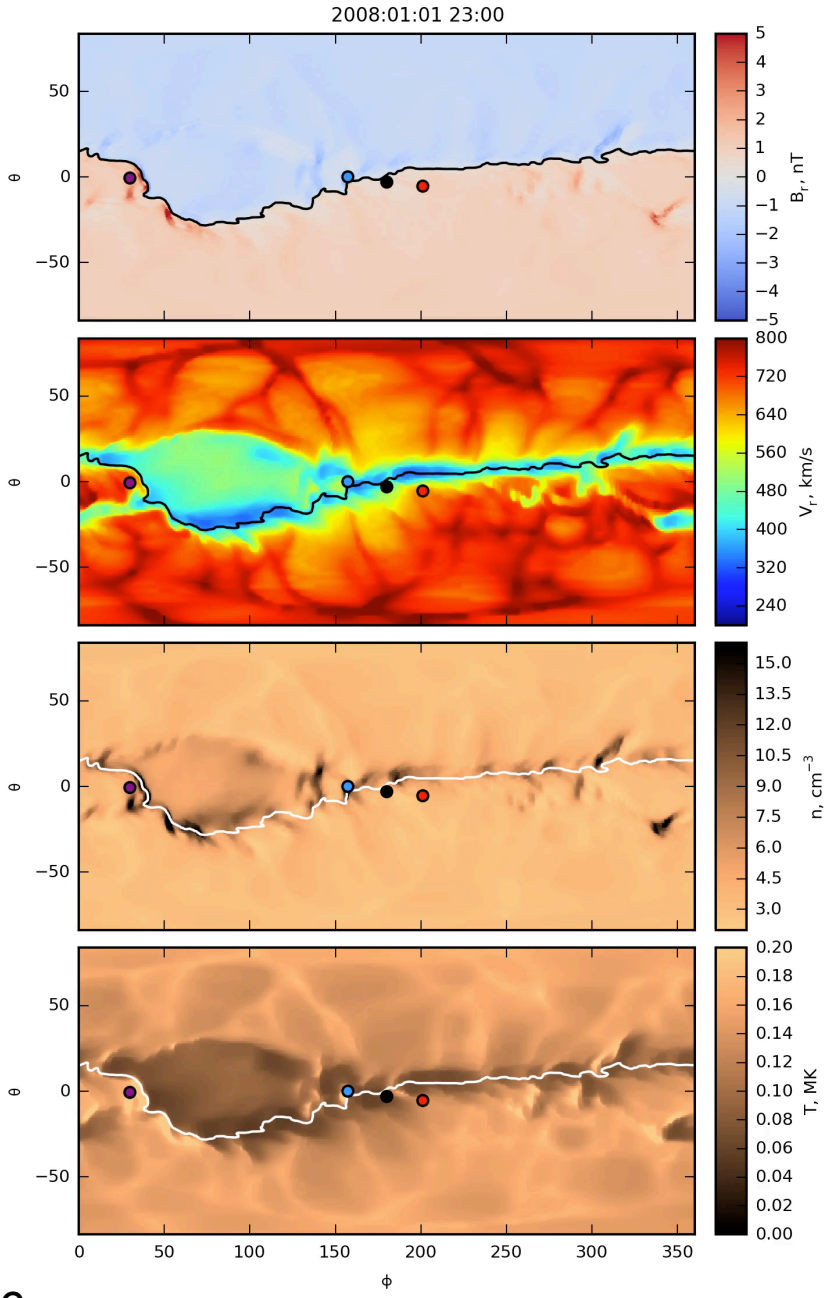
Merkin et al., JGR, [2016]
Linker et al., AIP, [2016]

Time-dependent quiet heliosphere

Driven by ADAPT/WSA

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

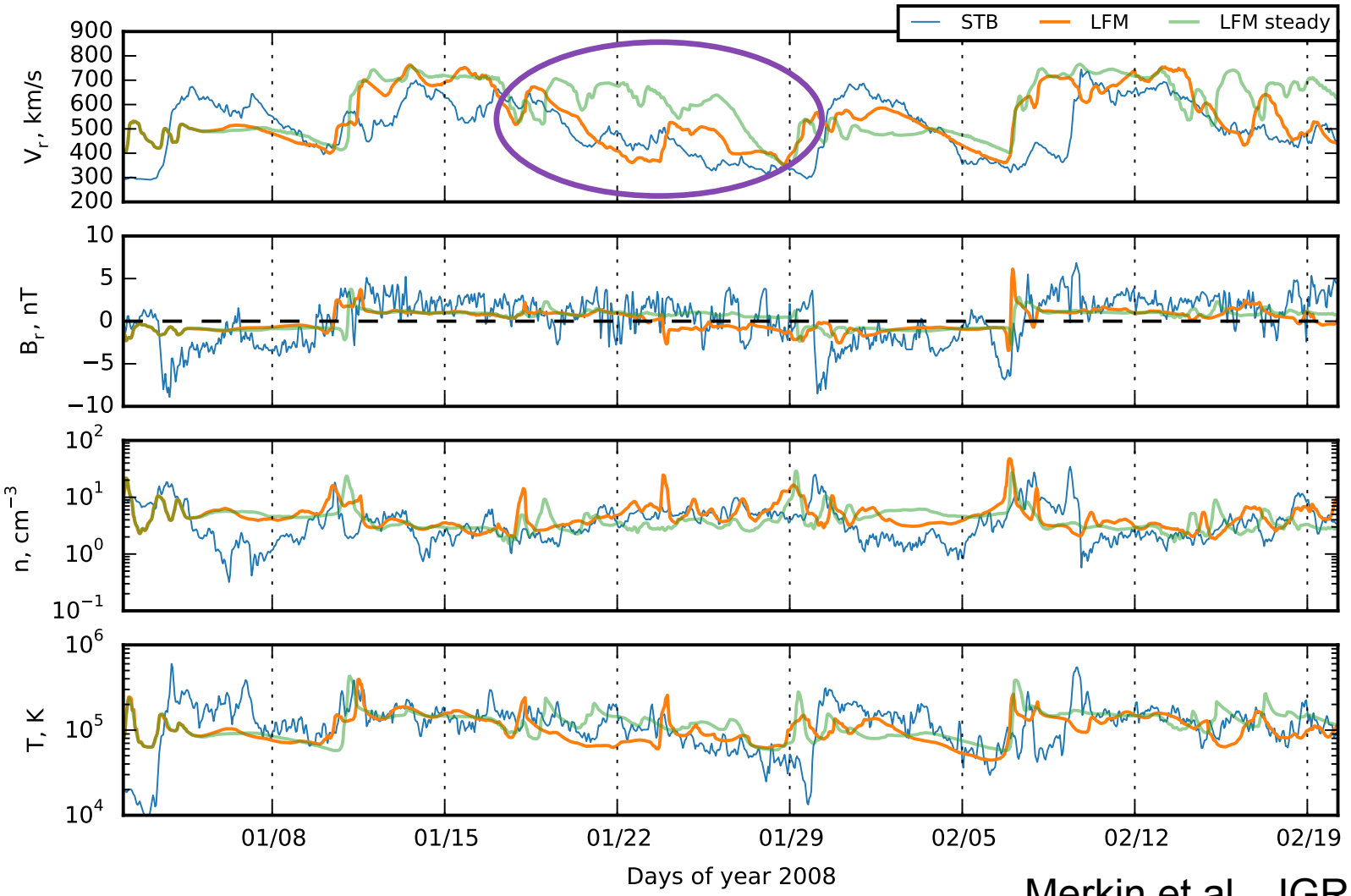


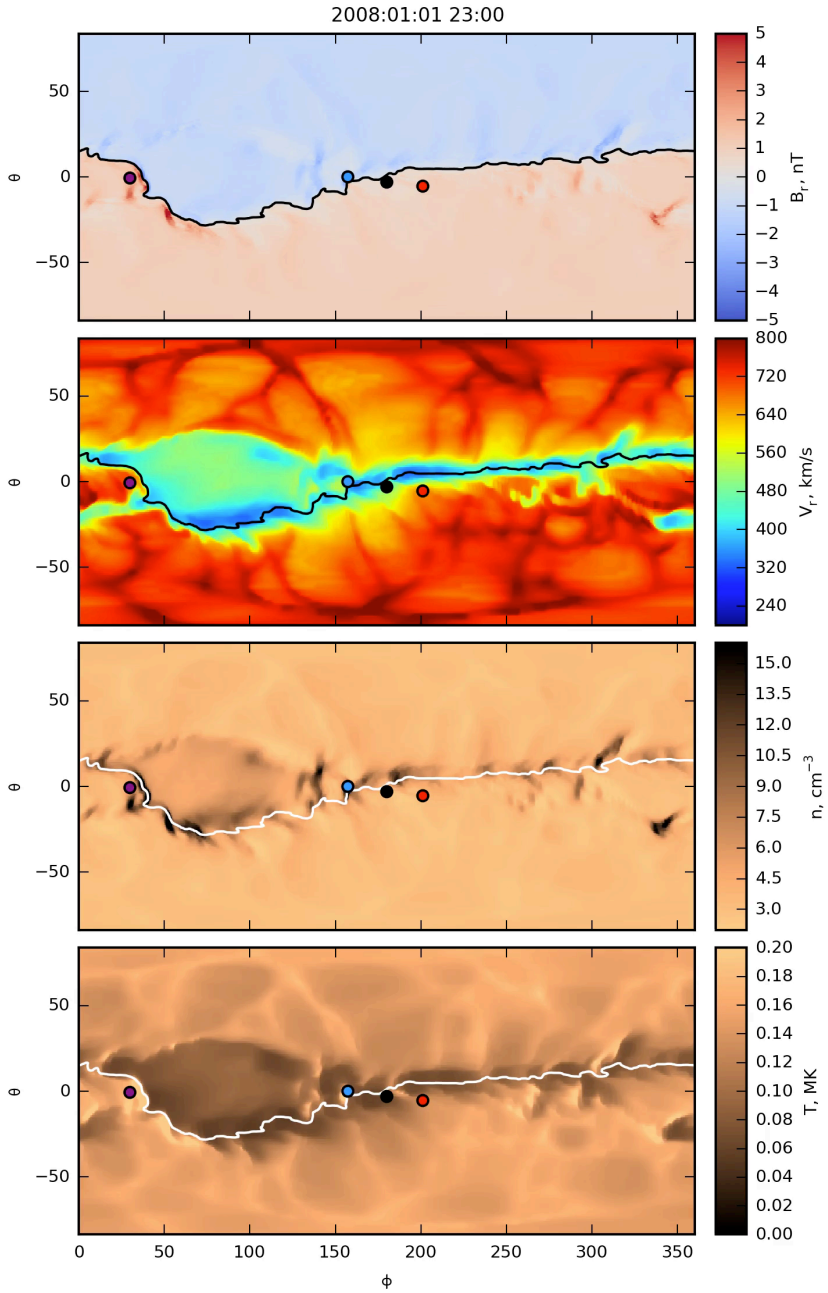


Merkin et al., JGR, 2016

Time-dependent quiet heliosphere

Driven by ADAPT/WSA

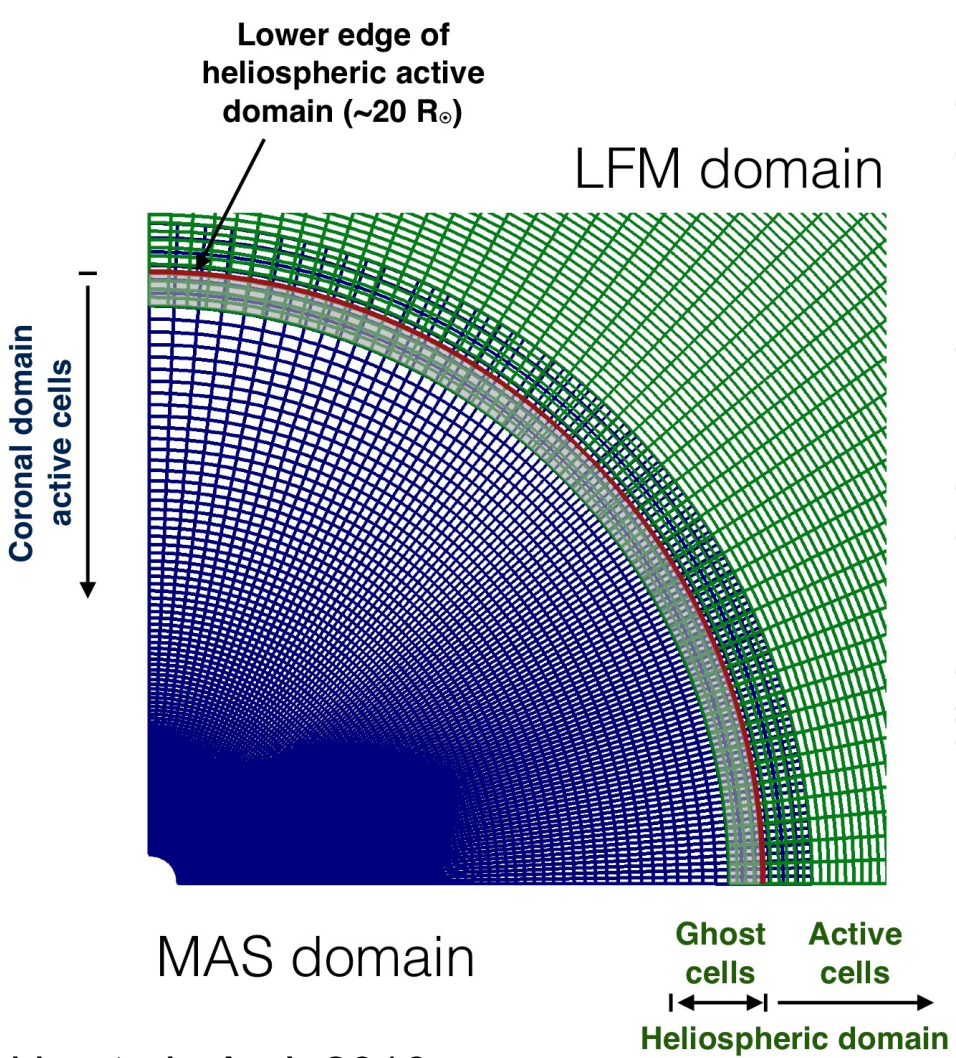


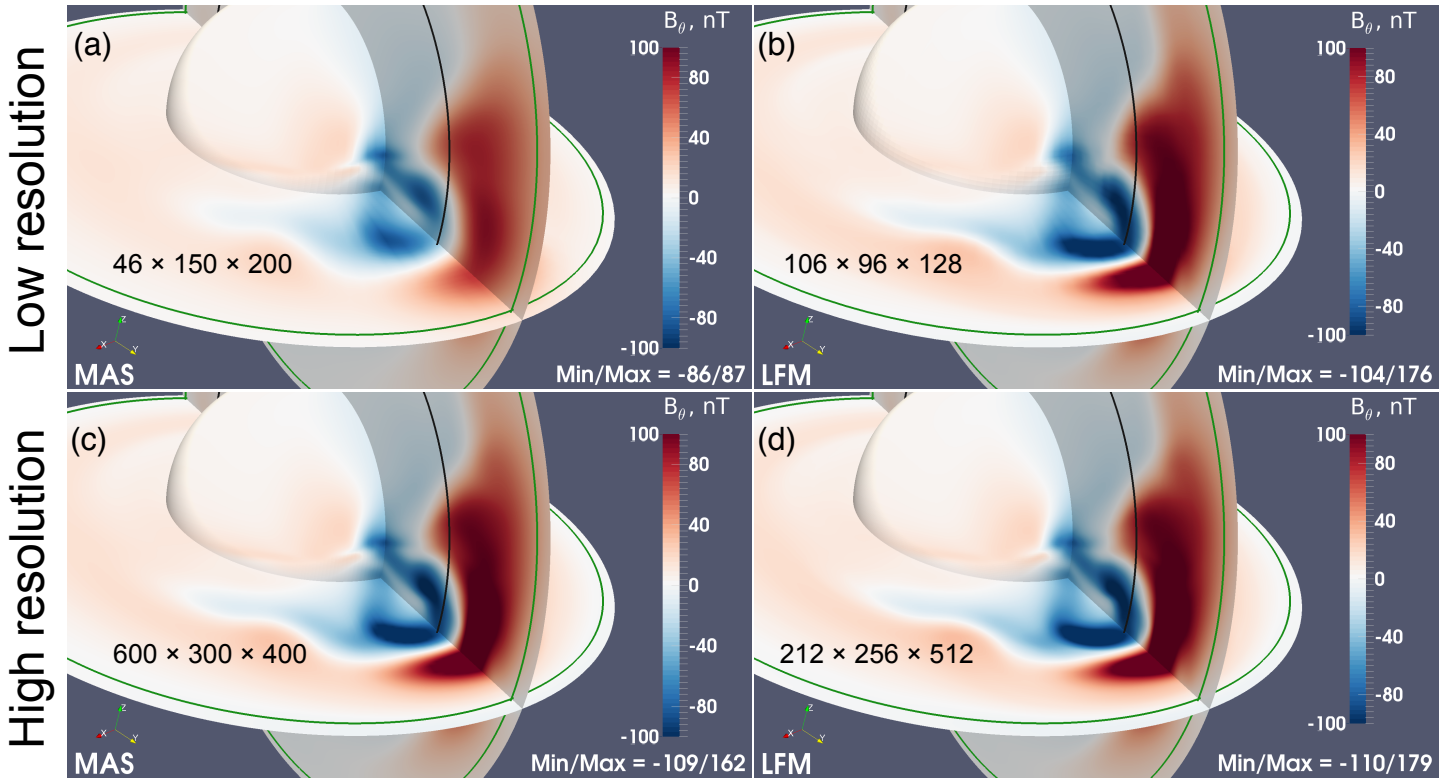


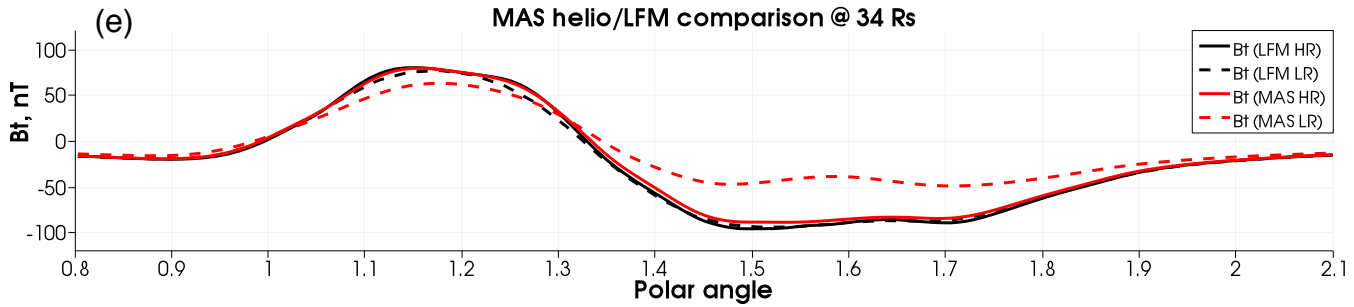
Merkin et al., JGR, 2016

Time-dependent heliosphere: Coronal mass ejections

MAS-driven CME propagation: First-principles from eruption to Earth



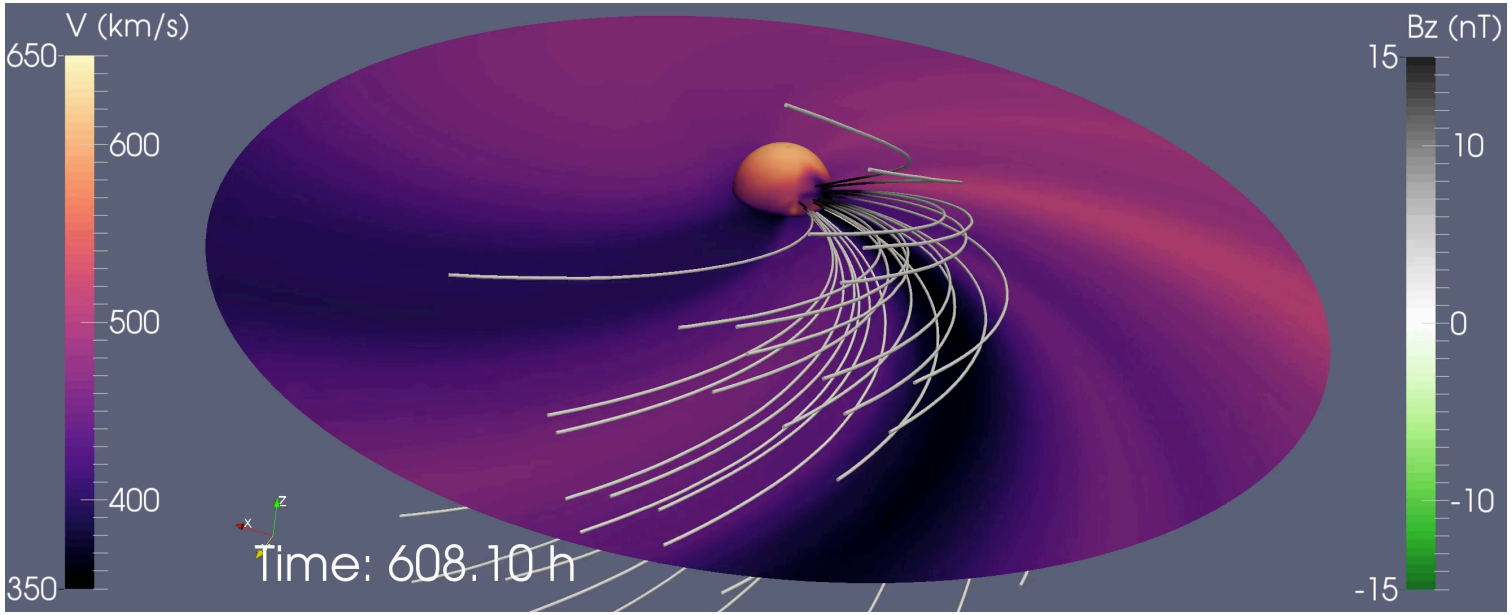




Merkin et al., ApJ, 2016

Time-dependent heliosphere: Coronal mass ejections

MAS-driven CME propagation: First-principles from eruption to Earth



LFM-helio driven by the MHD-around-a-sphere (MAS) code.
Work done in collaboration with Predictive Science Inc.

Merkin et al., ApJ, 2016

Going forward

- LFM underlying code was written a while ago (30-40 years)
- Optimized for architectures long gone
- The code is robust and performs well on existing architectures
- Speed and portability becoming an issue with time
- LFM numerics are quite unique
  - Handles arbitrary, non-orthogonal (and singular!) grids
  - High-order spatial reconstruction
  - Can capture 3D dynamics with relatively few cells
  - Intrinsically div-free B updates (constrained transport)
- Needs a serious upgrade for next generation supercomputers

What's next?

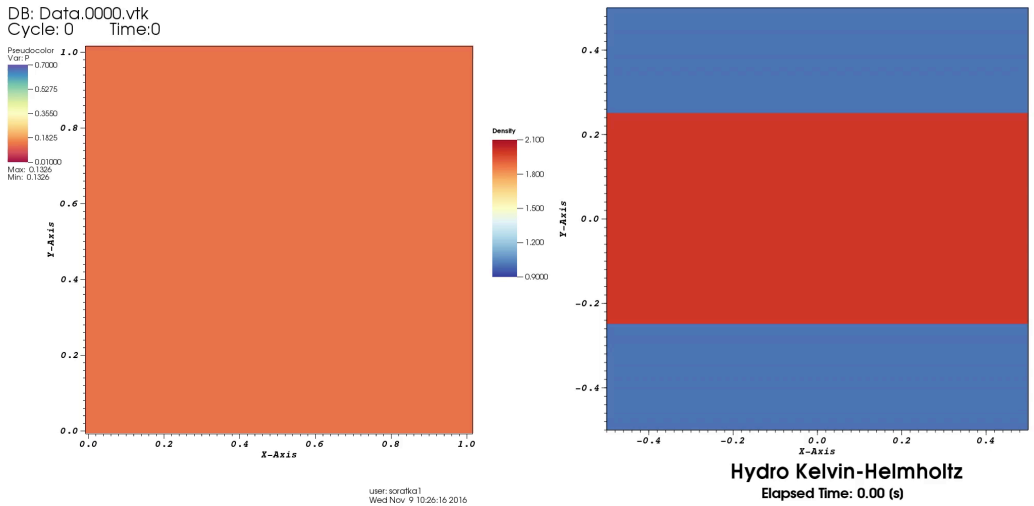
Gamera

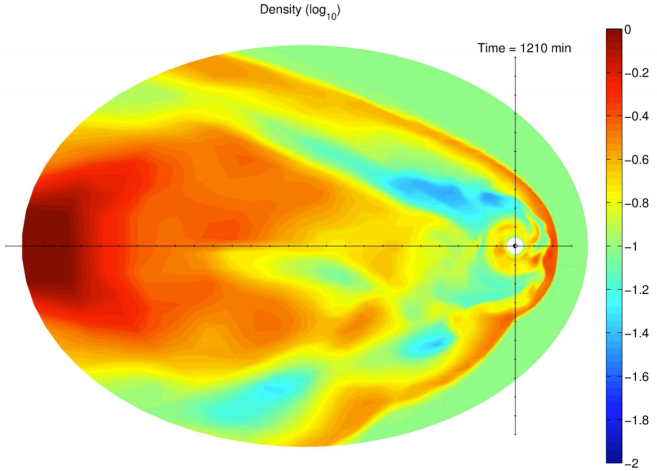
See Sorathia talk tomorrow

- Gamera is a reinvention of LFM
- Built to tackle modern challenges, but preserve the unique numerics of LFM
- Code written to expose multiple layers of heterogeneous parallelism
- Fortran 2003+, minimal external library dependence
- Portable, user-friendly, flexible
- Model coupling for inter-connected, multi-physics, multi-scale systems
- Standard tests to be published
- Website: civspace.jhuapl.edu/gamera

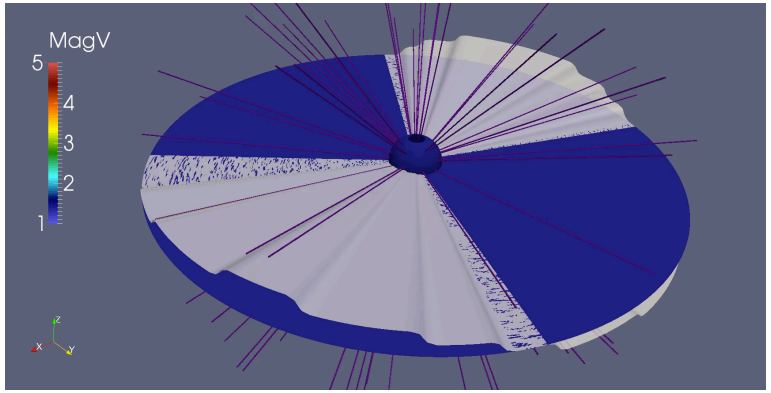
GAMERA

Grid Agnostic MHD for Extended Research Applications





Saturn magnetosphere



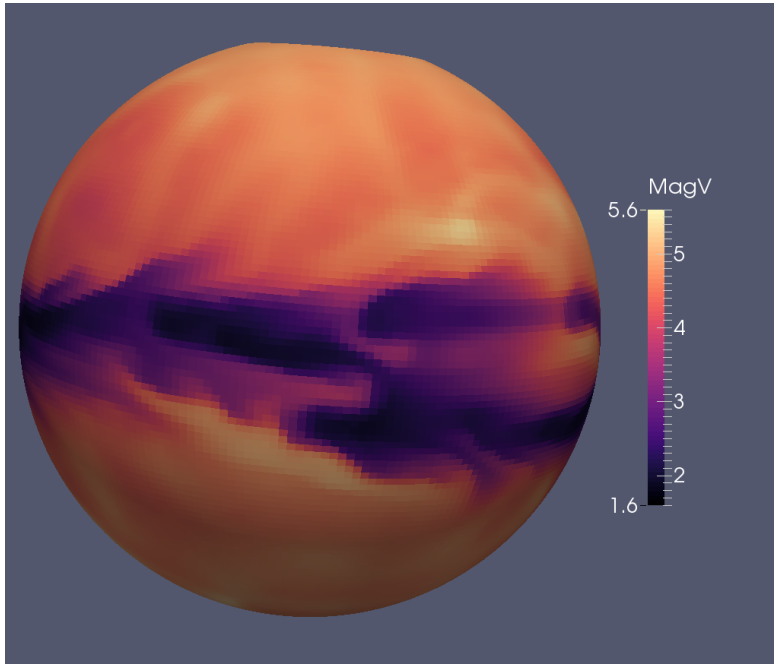
Inner heliosphere

Gamera

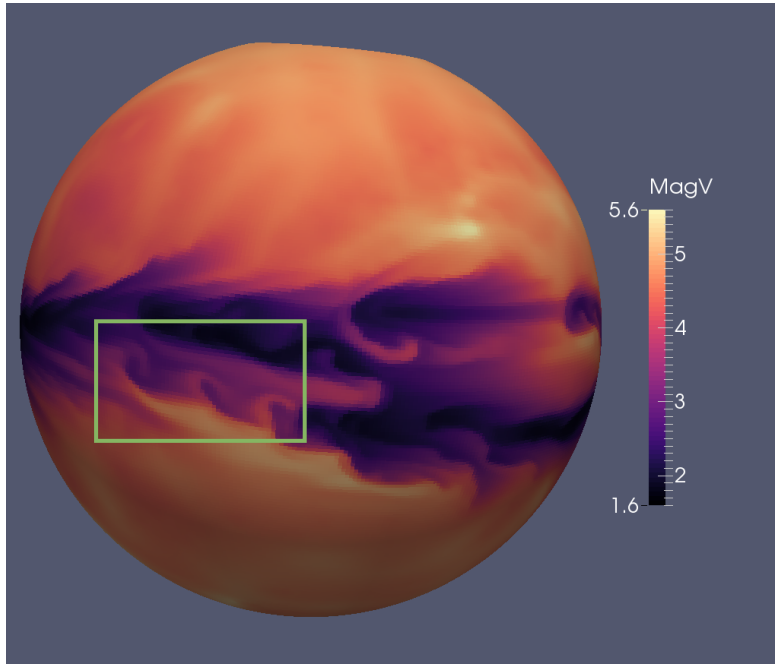
Heliosphere

Solar wind speed @ 1AU

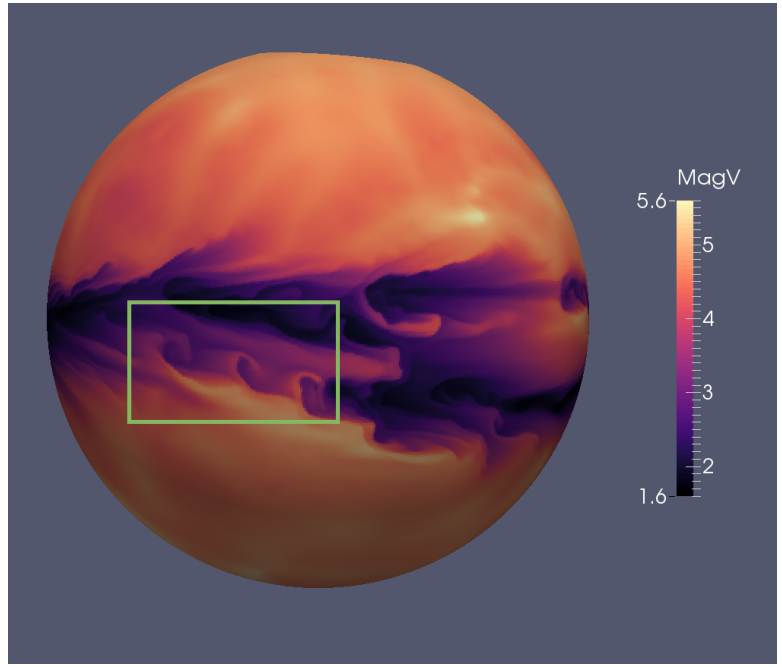
256x128x256



512x256x512



1024x512x1024



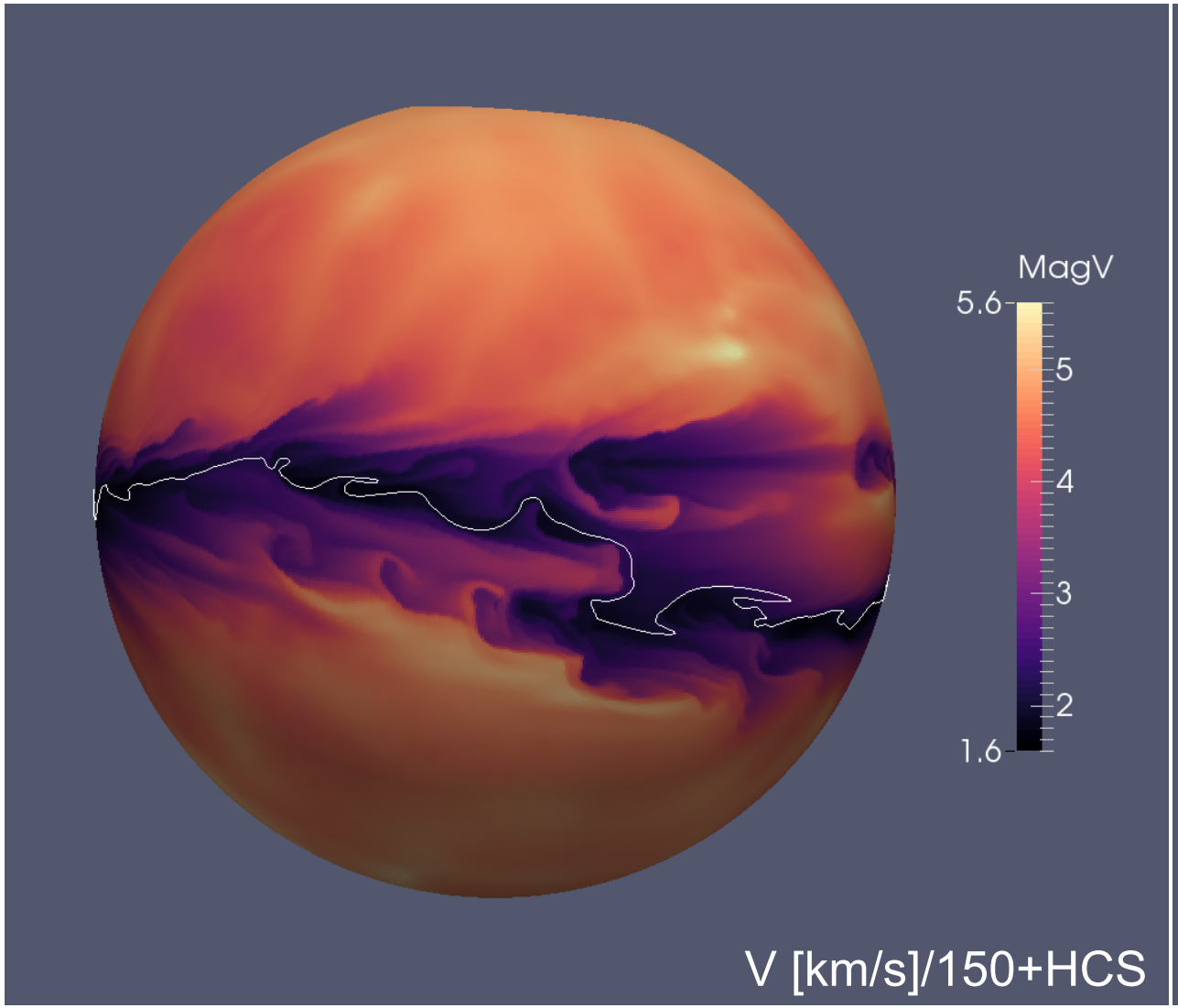
Linear scaling to 4600 CPUs

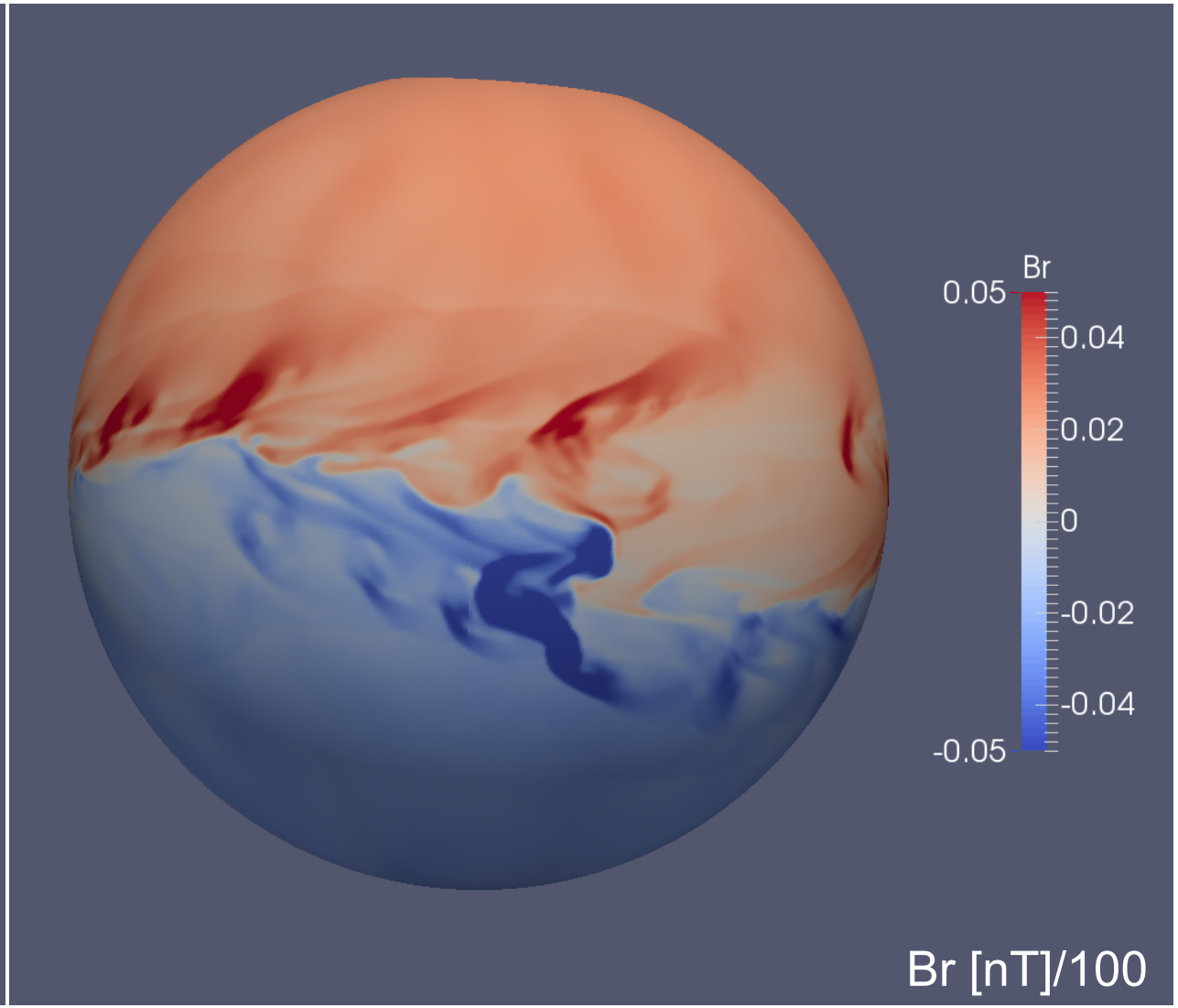
- Driven by WSA (or ADAPT-WSA)
- Allows heliosphere simulations with unprecedented resolution
- Working on Gibson-Low flux rope insertion

Gamera

Heliosphere

Simulation was run on 4608 CPUs for ~11h on Cheyenne
Half a billion cells (0.5×1024^3)

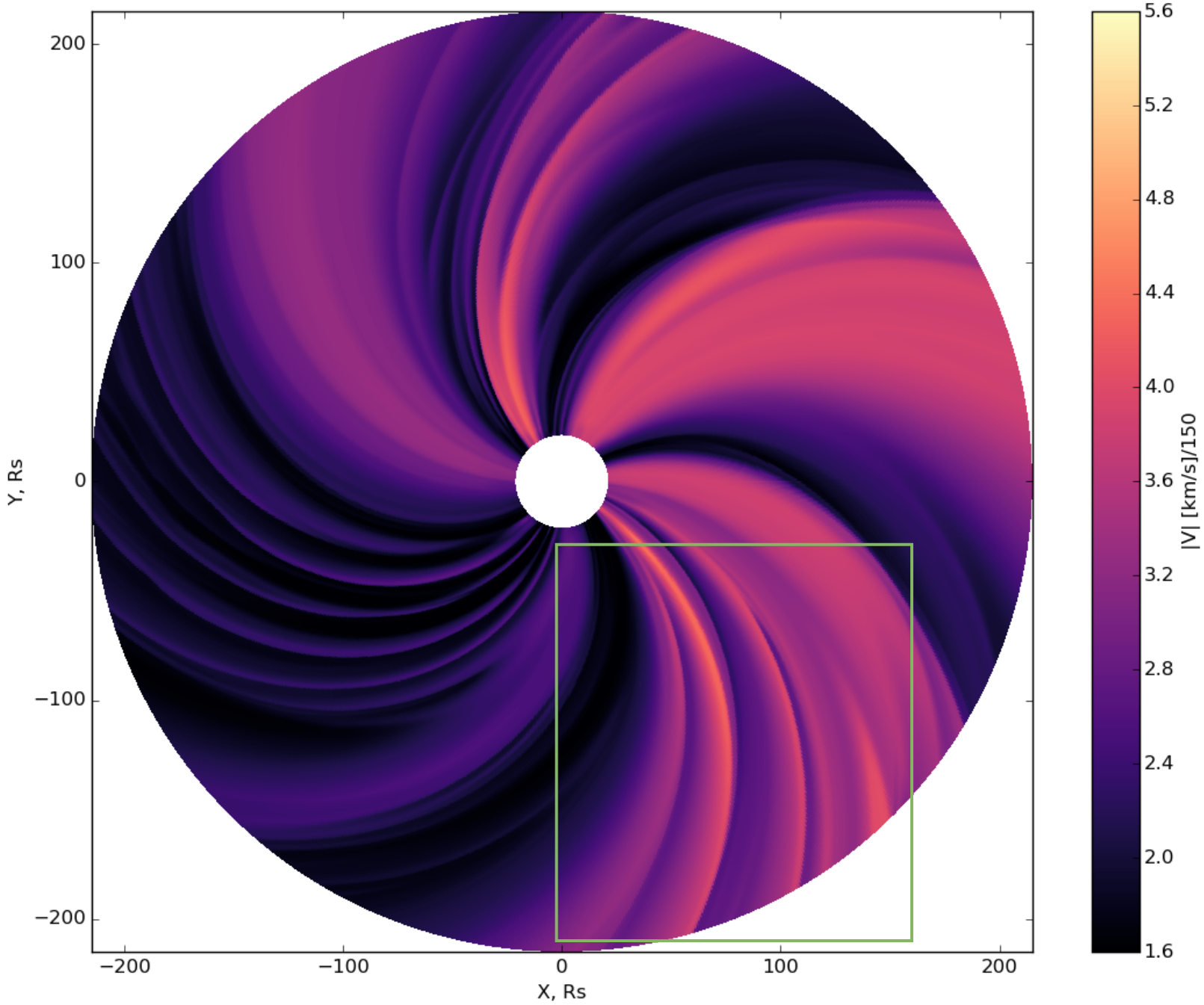




Gamera

Heliosphere

- Simulation was run on 4608 CPUs for ~11h on Cheyenne
- Half a billion cells (0.5×1024^3)
- Equatorial slice
- CIR substructure?
- There's likely more to even the steady state heliosphere than we're used to looking at
- Are we at the scale where we can resolve MHD instabilities in the solar wind?



Conclusions

- Diverse set of space weather simulation tools
- Primary applications:
  - Geospace
    - Magnetosphere-ionosphere-thermosphere coupling
    - Radiation belts
    - Ring current
  - Inner heliosphere
- Backbone is the global magnetosphere MHD code (LFM, and now Gamera)
- Developed time-dependent boundary conditions for LFM-helio, for coupling with ADAPT/WSA and MAS coronal codes
- Currently working on implementing the same in Gamera
- Including Gibson-Low flux ropes @ inner boundary (~0.1 AU)

- Developed next generation LFM (Gamera)
- Gamera preserves (and improves upon) all the high heritage LFM numerics
- Already running heliosphere simulations at unprecedented resolution
- Resolving “emergent” structure (CIR substructure?)
- Are we at the scale where we can resolve MHD instabilities in the solar wind?
- Website: civspace.jhuapl.edu/gamera
- Looking forward to working with CCMC on making it available

GAMERA

Grid Agnostic MHD for Extended Research Applications

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