SWMF New Developments

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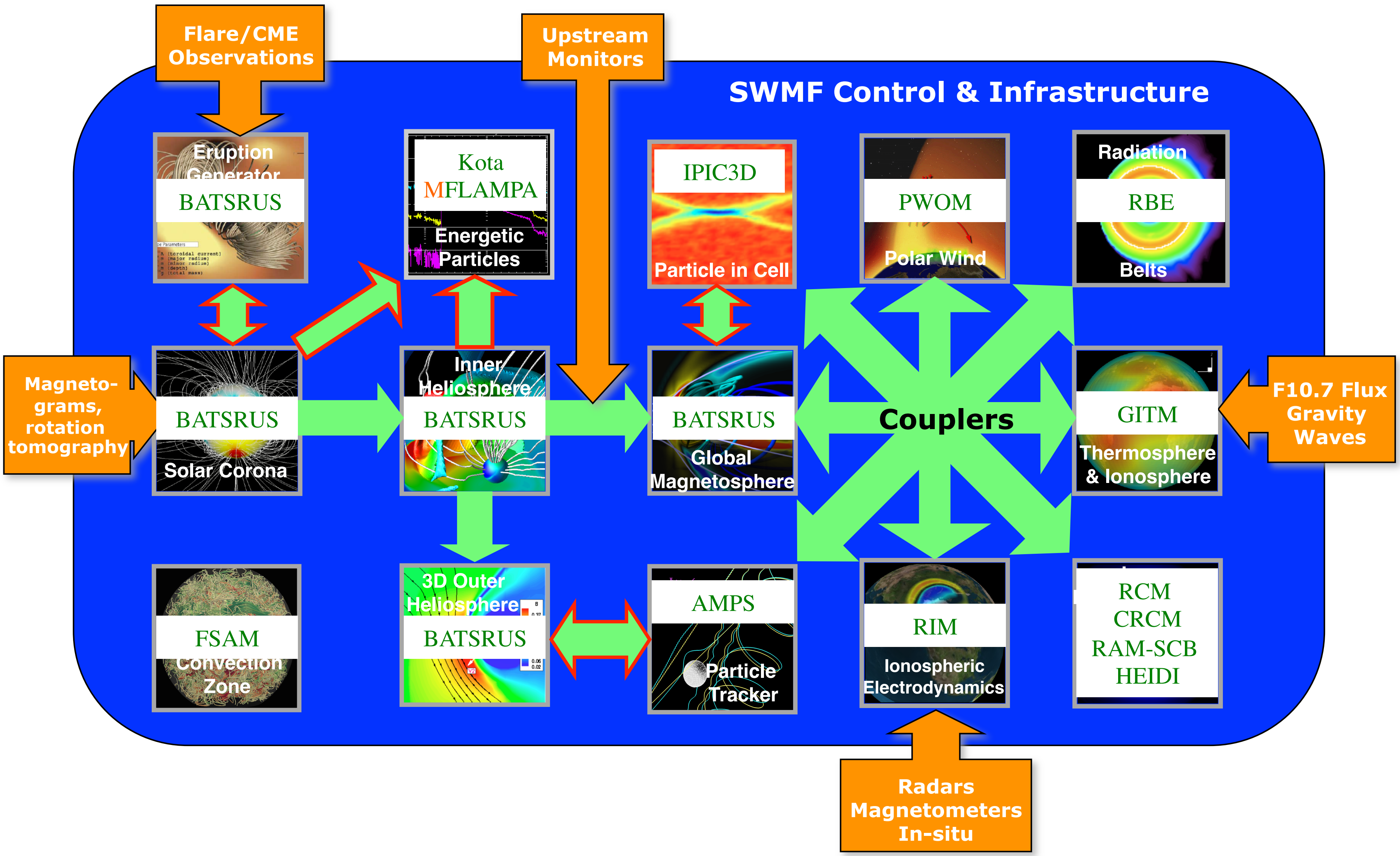
Space Weather Modeling Framework



SWMF is freely available at http://csem.engin.umich.edu and via CCMC

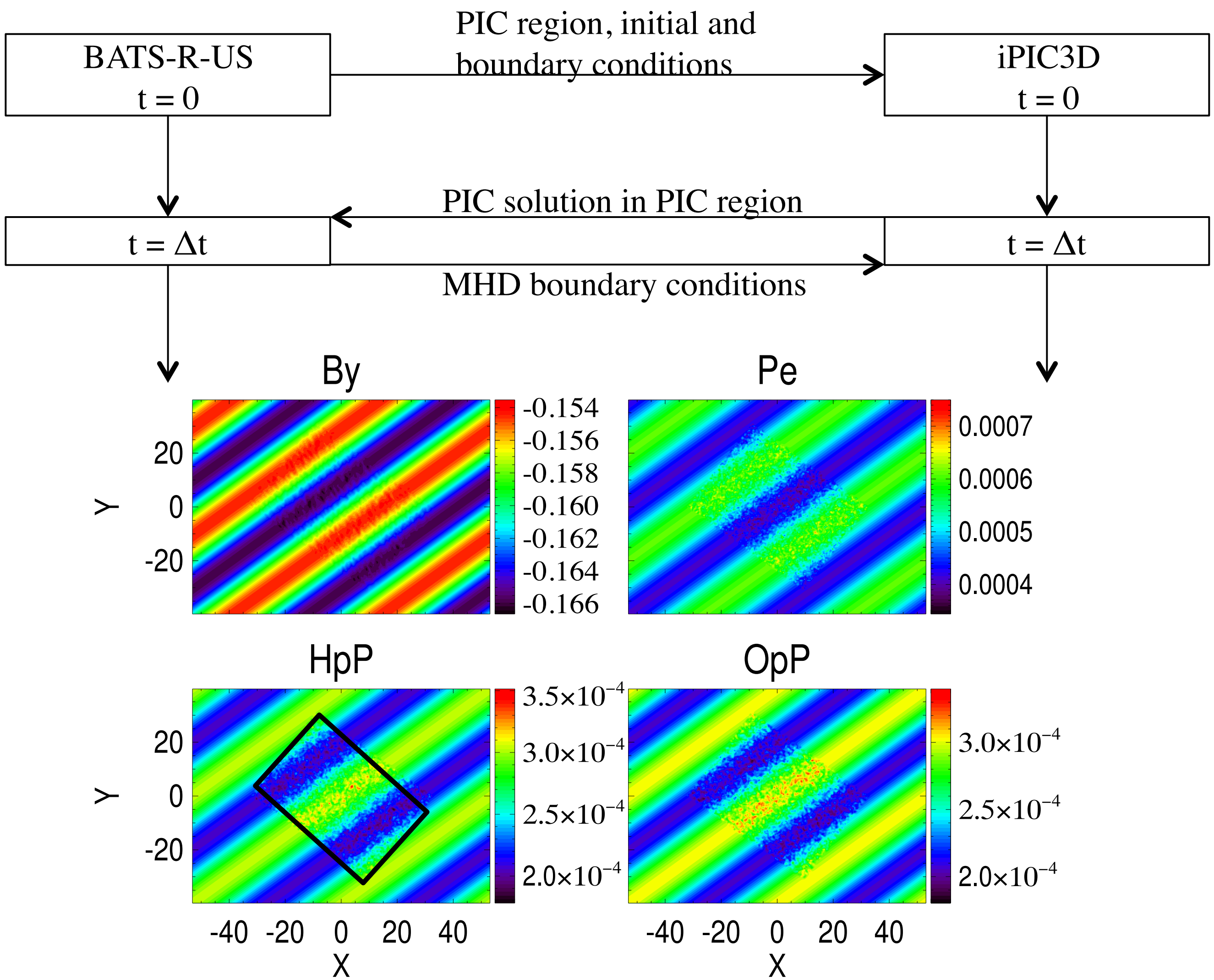
What's New?

- **Convection Zone/FSAM (to be coupled with EE and/or SC)**
  - Works in stand-alone mode inside the SWMF
- **Eruptive Event generator/BATS-R-US 2-way coupled to Solar Corona**
  - Spherical Wedge Active Region Model (SWARM)
- **Particle Tracker/AMPS 2-way coupled to Outer Heliosphere**
  - BATS-R-US solves for ions and magnetic field, AMPS solves for neutrals (kinetic)
- **Particle-in-Cell/iPIC3D 2-way coupled to Global Magnetosphere**
  - Switched to IPIC3D2 (KTH version): 3 times faster
  - Improved coupling efficiency: < 2% of execution time
  - Allow for different grids and different time steps, multiple PIC regions…
- **Inner Magnetosphere**
  - HEIDI coupled to Global Magnetosphere (R. Ilie)
  - RAM-SCB is included into SWMF distribution (V. Jordanova)
- **Solar energetic Particles: MFLAMPA coupled to SC, IH**
  - Multiple field lines (D. Borovikov, work-in-progress)

MHD-EPIC Algorithm

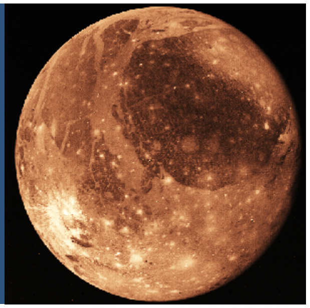
Daldorff et al. 2014 JCP

Combines the efficiency of the global (extended) MHD code with the physics capabilities of the local PIC code!

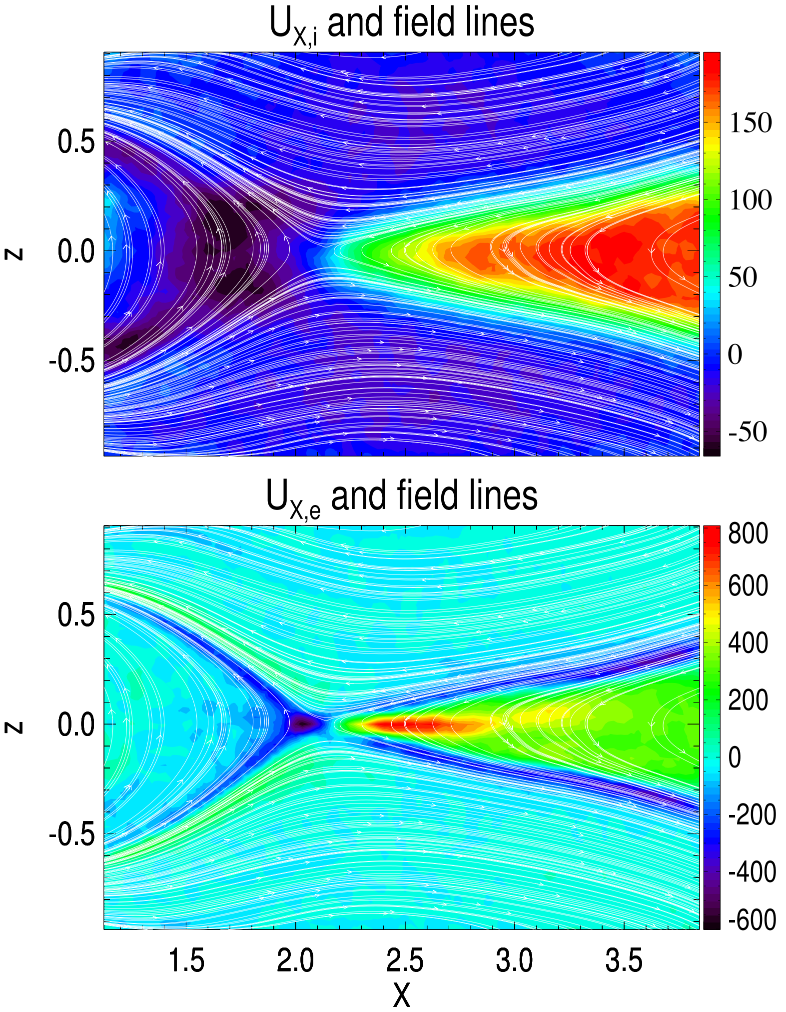


MHD-EPIC applied to Ganymede's Magnetosphere

Toth et al. 2016 JGR

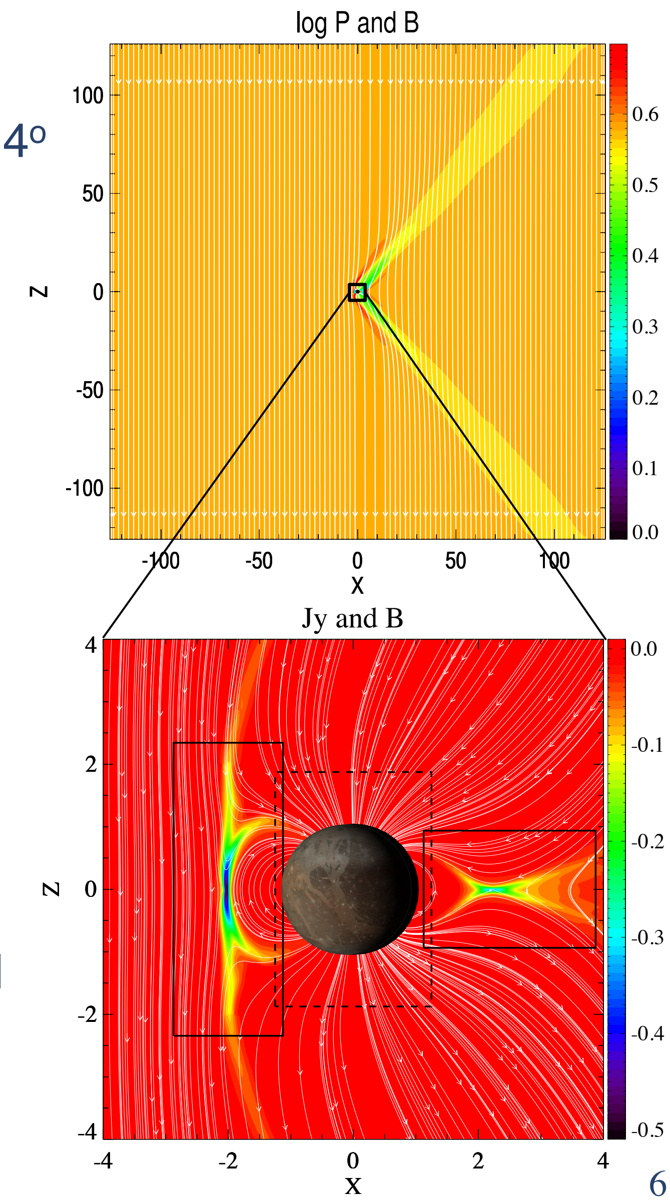


- **Ganymede is a nice initial application**
  - Short time scale: minutes
  - Small system size compared to ion inertial length: $d_i \sim 0.16\ R_g$
  - For $M_i/M_e = 100$ the electron skin depth is $d_e \sim 0.016\ R_g$
  - Figure shows the ion and electron jets in the tail PIC region with 0.03 R_g grid resolution: the electron jet is reasonably well captured, which indicates true kinetic reconnection in the simulation.
  - Galileo measurements for validation.



3D Ganymede simulation with Hall MHD-EPIC

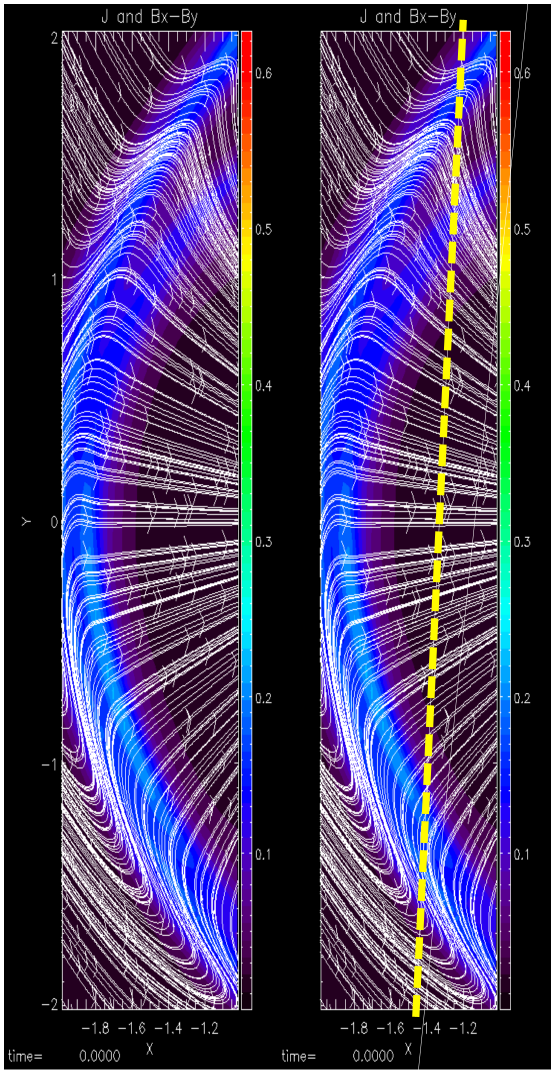
- Ganymede parameters:
  - R_g = 2634 km, dipole strength -719 nT, tilted by 4.4°
- Jupiter wind (sub-sonic and sub-Alfvenic)
  - n = 4/cc, M_i = 14
  - V_X = 140km/s, B = (0,-6,-77)nT, p = 3.8nPa
- Hall MHD domain: -128 R_g < x, y, z < 128 R_g
  - Fix values at inflow and outflow boundaries
  - Absorbing boundary condition at 1 R_g
  - Finest grid resolution 1/32 R_g ~ 0.2 d_i within -3 < x < 4, -3 < y < 3, -2 < z < 2
  - Coarsest grid cell size 4R_g , about 8.4M cells total
- 4 embedded PIC regions surrounding the moon
  - 1/32 R_g ~ 0.2 d_i resolution: 3.6M total
  - 216 macroparticles per species per cell: 1.5B total



Hall MHD, MHD-EPIC, Galileo

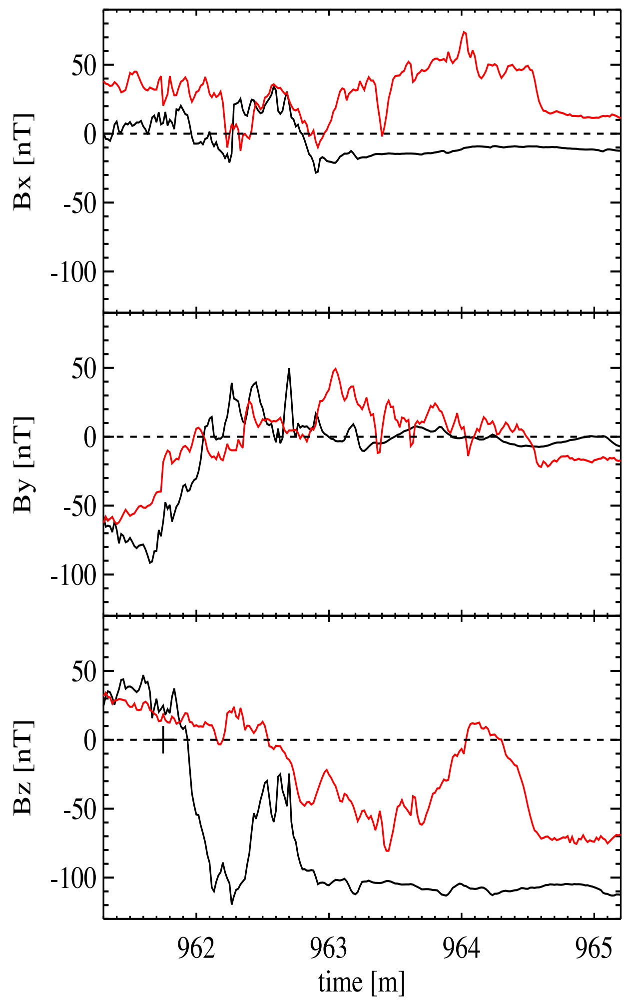
J and B_X-B_Y

Hall MHD **MHD-EPIC**

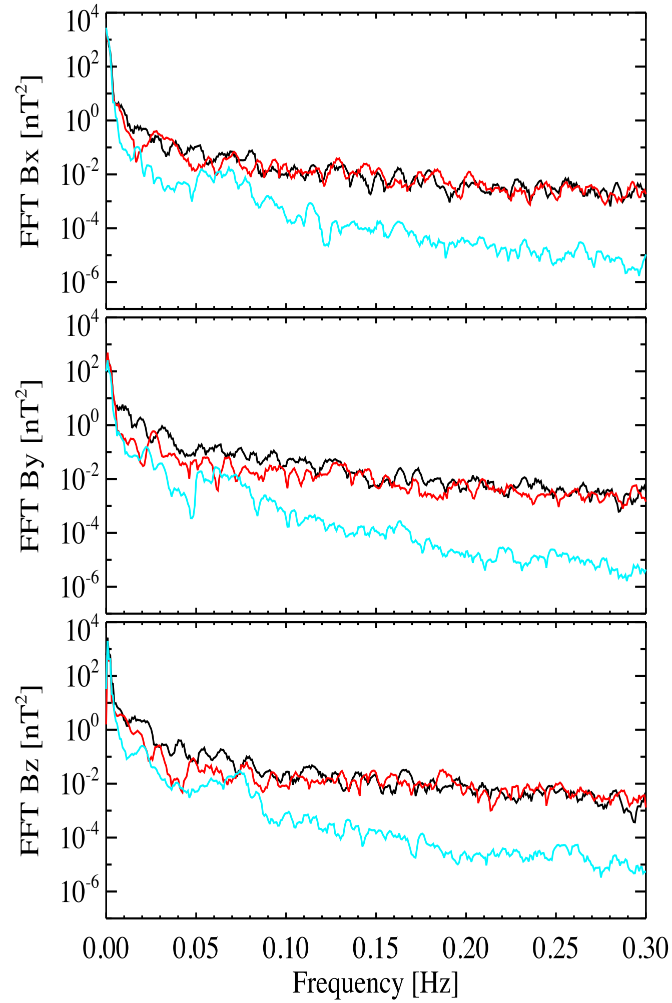


Z = 0.8 cut

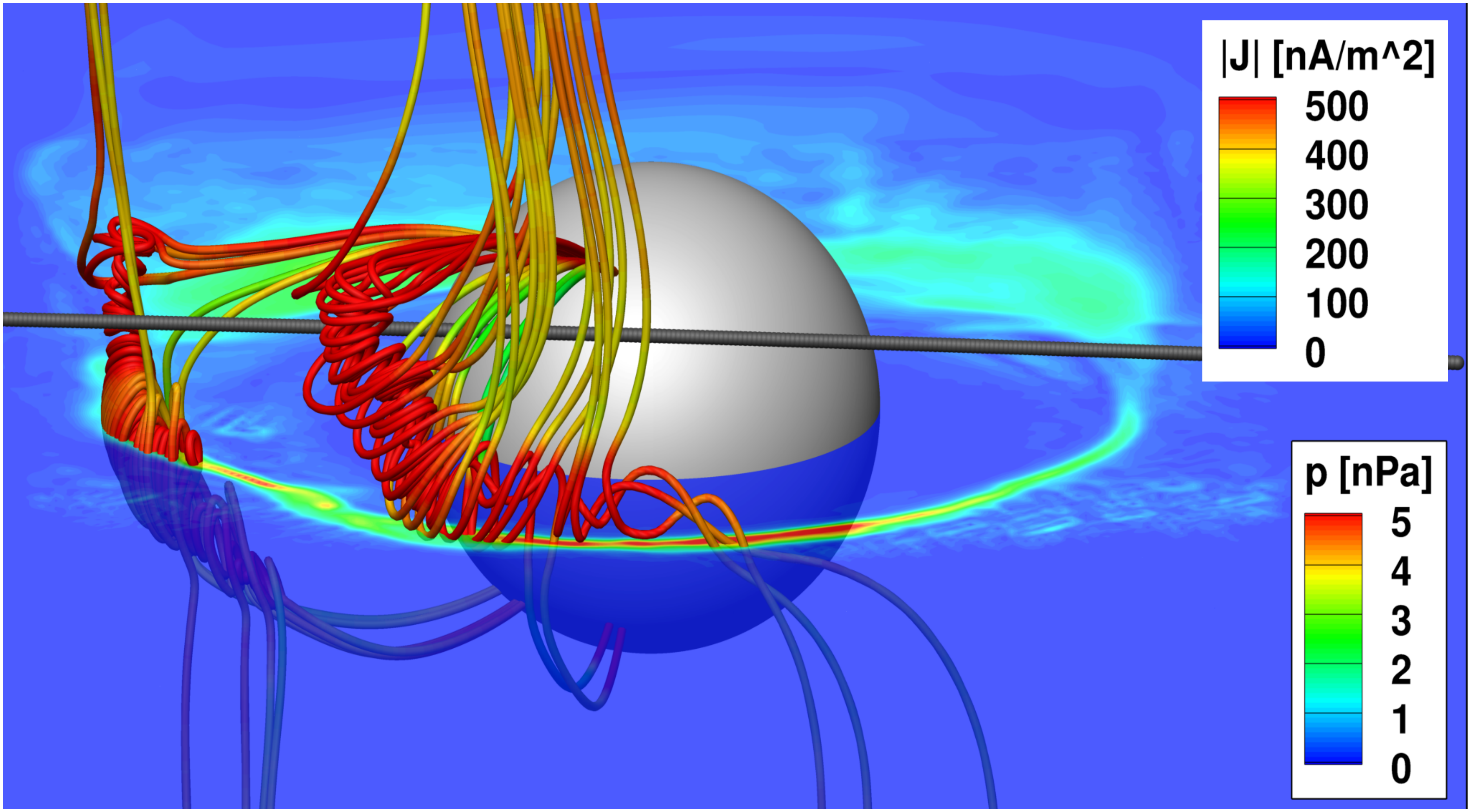
Signatures of Flux Transfer Event in MHD-EPIC and Galileo data



FFT transform of the B_Y component (ULF waves)



Is it really an FTE?

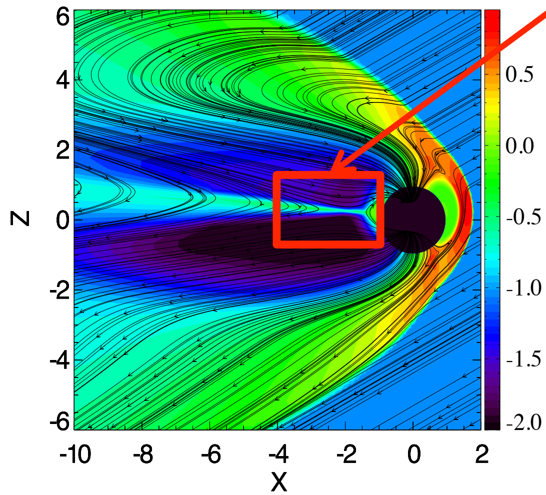


Yes!

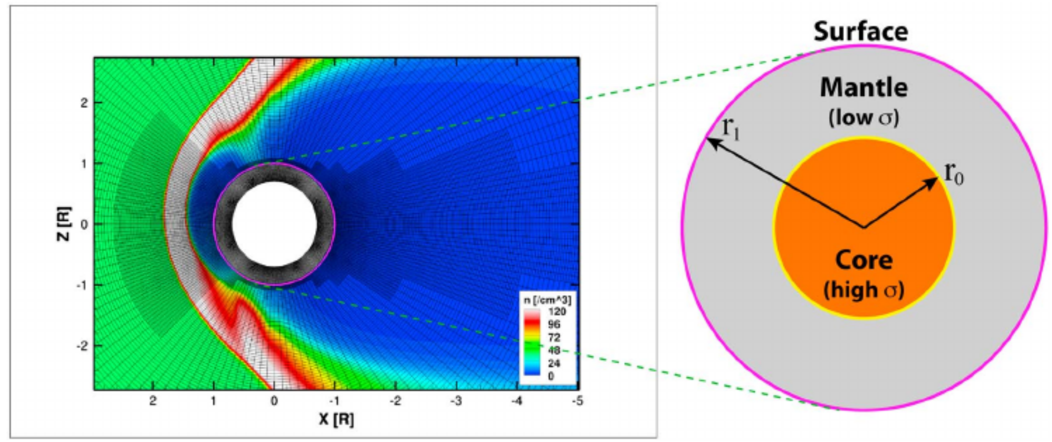
Mercury Simulation with MHD-EPIC

Y. Chen

log p and field lines



Stretched spherical grid and resistive body

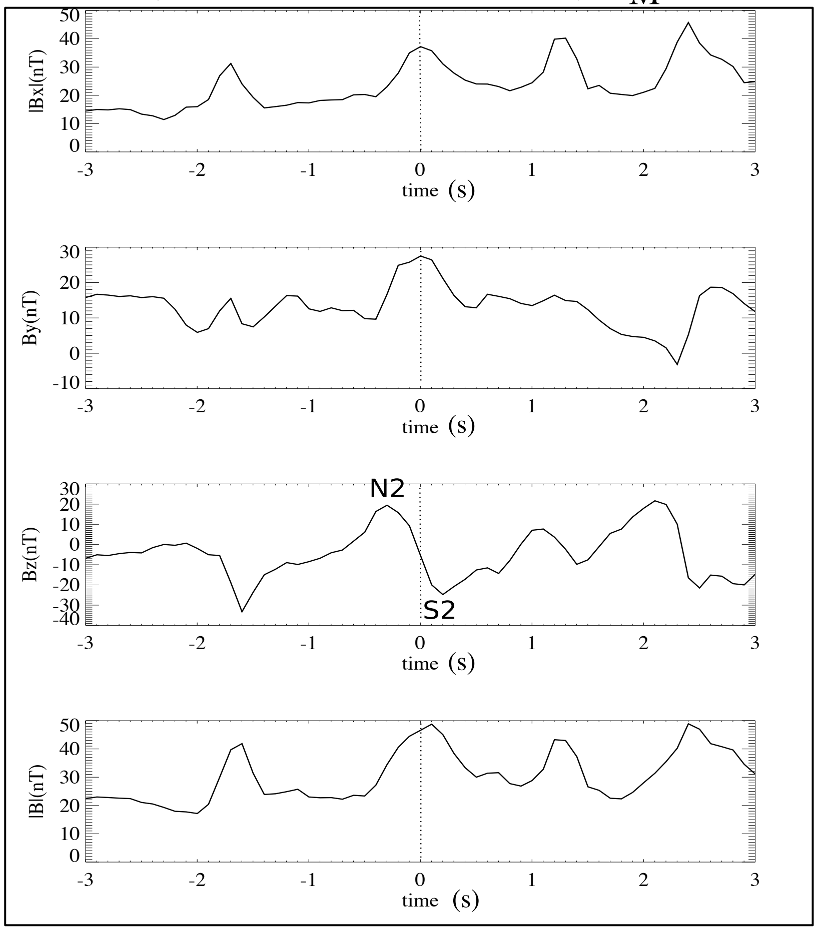


Hall MHD

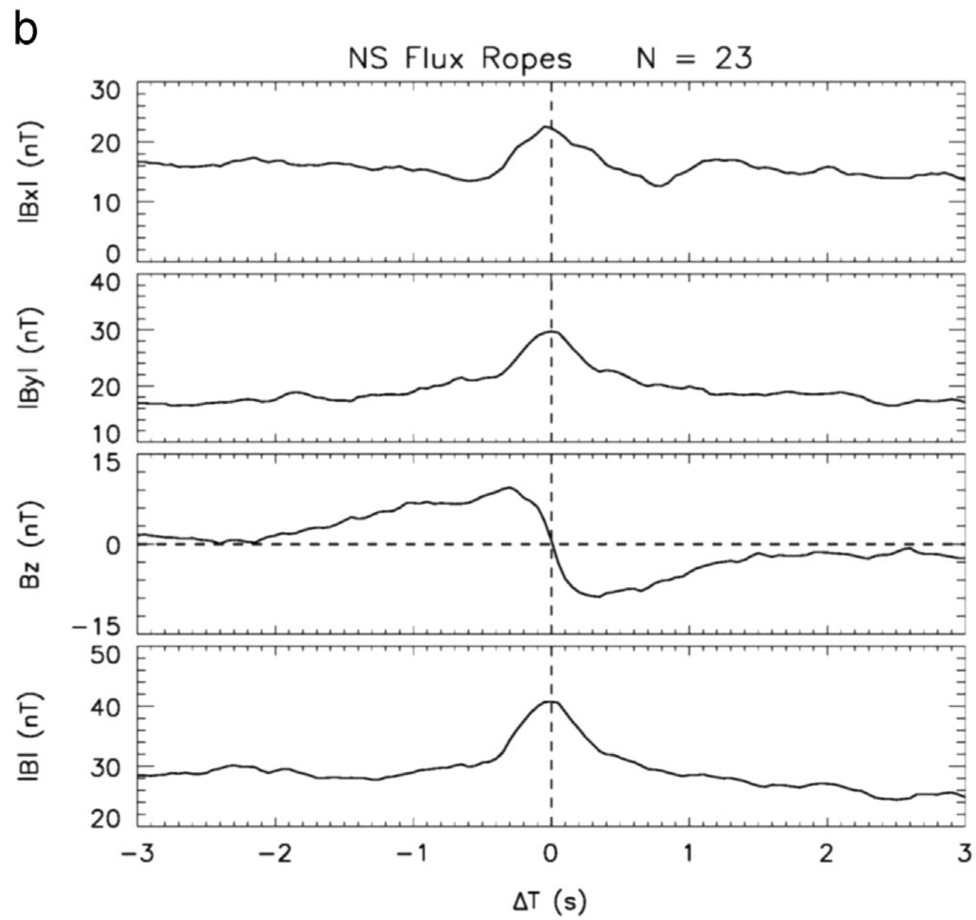
MHD-EPIC

Flux Rope Signatures

Simulated tailward plasmoid at (-2.11, -0.026, 0.273)R_M

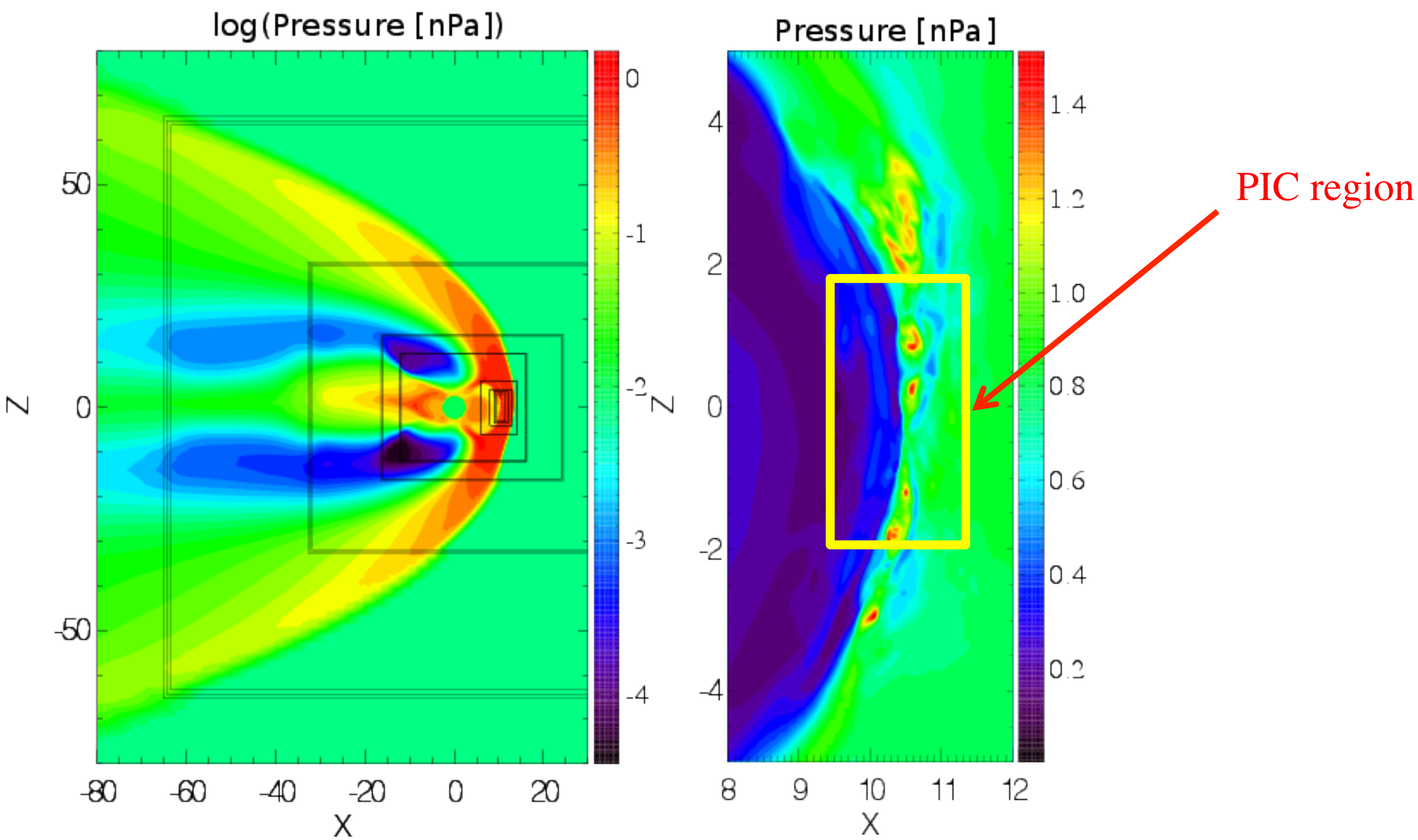


MESSENGER observation: average of 23 plasmoids (DiBraccio et. al., 2014)



First 3D Earth Simulations with MHD-EPIC

- Dayside reconnection covered with 2Re x 6Re x 4Re PIC region
- Ion mass 16amu ➔ inertial length ~1/25Re ➔ 1/60Re grid:
  - 31 million BATS-R-US grid cells
  - 10 million iPIC3D cells with 4.4 billion macro-particles
- 1 min simulation uses 5000 core hours: 71% iPIC3D, 27% BATS-R-US
- We are working on doing longer runs

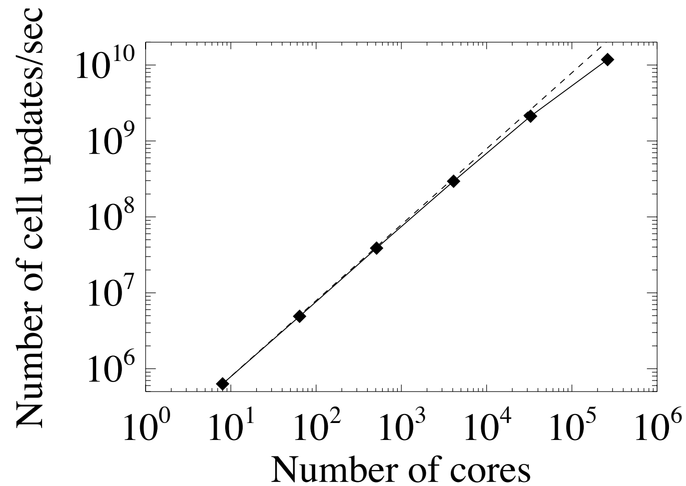


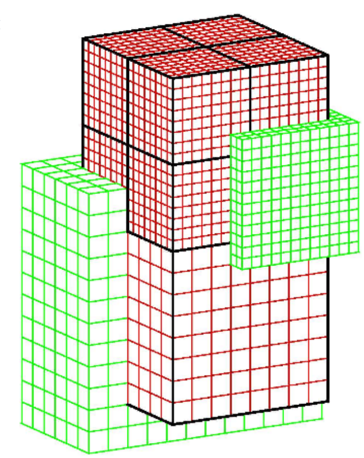
BATS-R-US

Block Adaptive Tree Solar-wind Roe Upwind Scheme

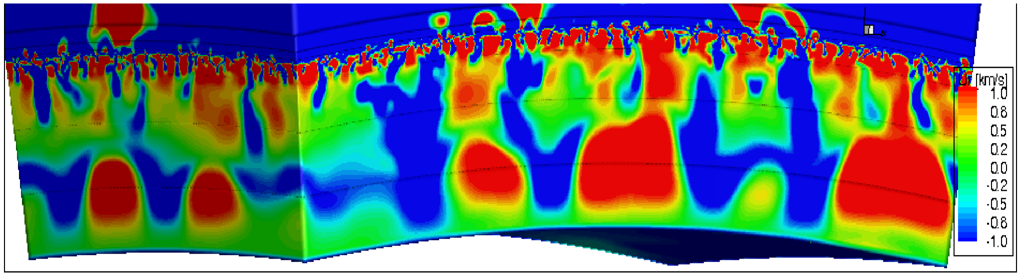
- **Physics**
  - Classical, semi-relativistic and Hall MHD
  - Multi-species, multi-fluid, anisotropic pressure
  - Radiation hydrodynamics multigroup diffusion
  - Multi-material, non-ideal equation of state
  - Heat conduction, viscosity, resistivity
  - Solar wind turbulence, Alfven wave heating
- **Numerics**
  - Parallel Block-Adaptive Tree Library (BATL)
  - Cartesian and generalized coordinates
  - Splitting the magnetic field into $B_0 + B_1$
  - Divergence B control: 8-wave, CT, projection, parabolic/hyperbolic
  - Numerical fluxes: Godunov, Rusanov, AW, HLLE, HLLD, Roe
  - Explicit, point-, semi-, part and fully implicit time stepping
  - Up to 4th order accurate in time and 5th order in space
- **Applications**
  - Heliosphere, sun, planets, moons, comets, HEDP experiments
- **150,000+ lines of Fortran 90+ code with MPI parallelization**

Parallel scaling from 8 to 262,144 cores on Cray Jaguar. 40,960 grid cells per core.

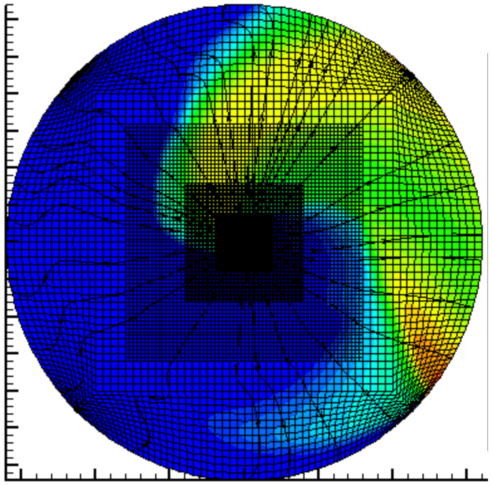


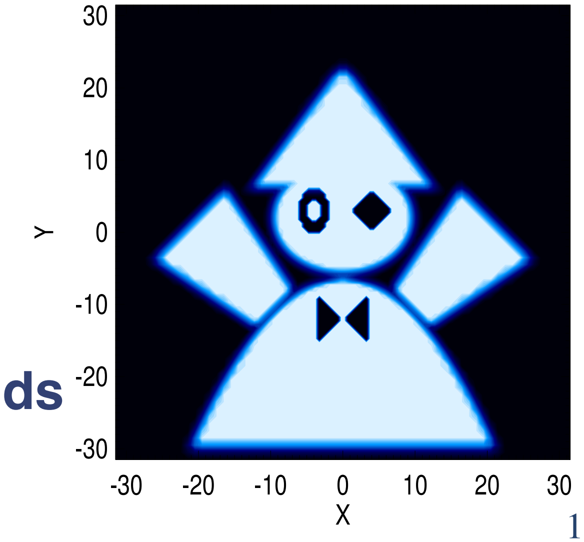


What's New?



- **Grid with limited generalized coordinates**
  - Used by SWARM, 2D outer heliosphere model…
- **Round cube grid**
  - Used in some comet CG simulations
- **Geometric control of schemes/features**
  - For AMR, semi-implicit Hall, high order scheme …
- **Load balancing for multiple schemes/features**
- **New plotting options**
  - Cuts in generalized coordinates
  - Spherical shell plot (SWPC request)
  - Magnetometer grid (SWPC request)
- **5th order scheme for AMR and non-Cartesian grids**

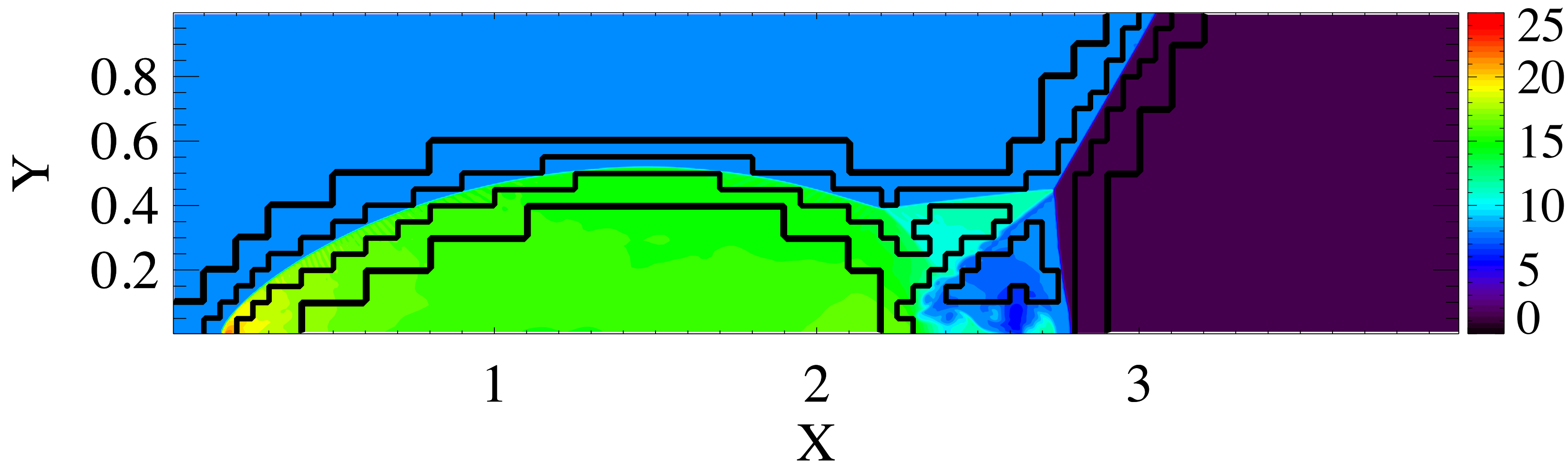




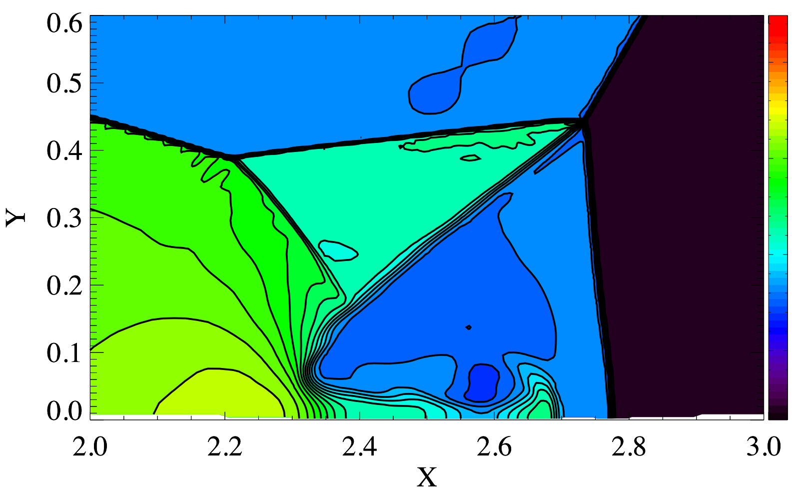
5^{th} order Finite Difference Scheme

Chen et al. JCP 2016

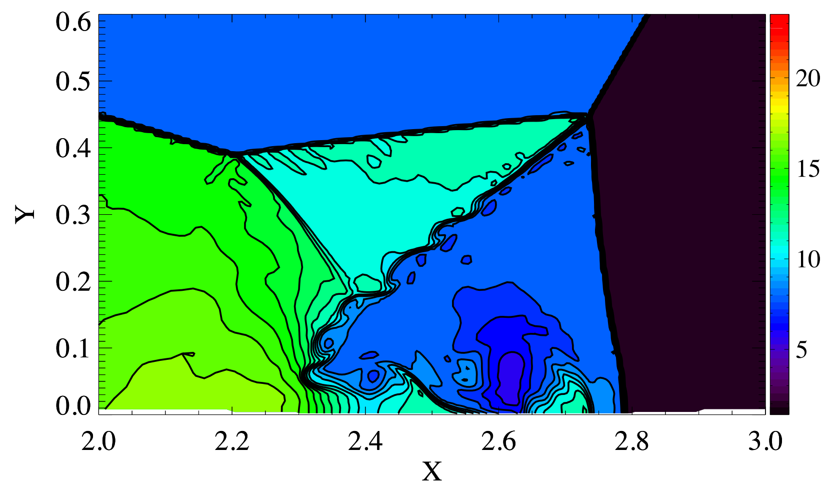
2-level refined, effective resolution 960 x 240, density



TVD



FD-MP5



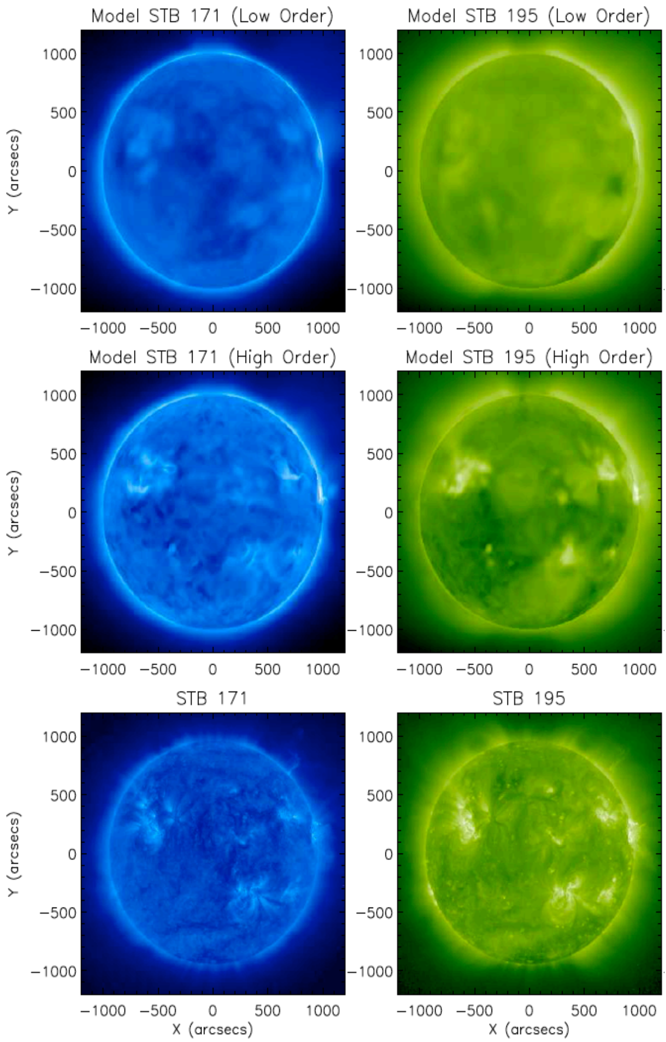
5th Order Scheme in Applications

Solar Corona Model (AWSoM) comparison with STEREO B

TVD

MP5

Obs.



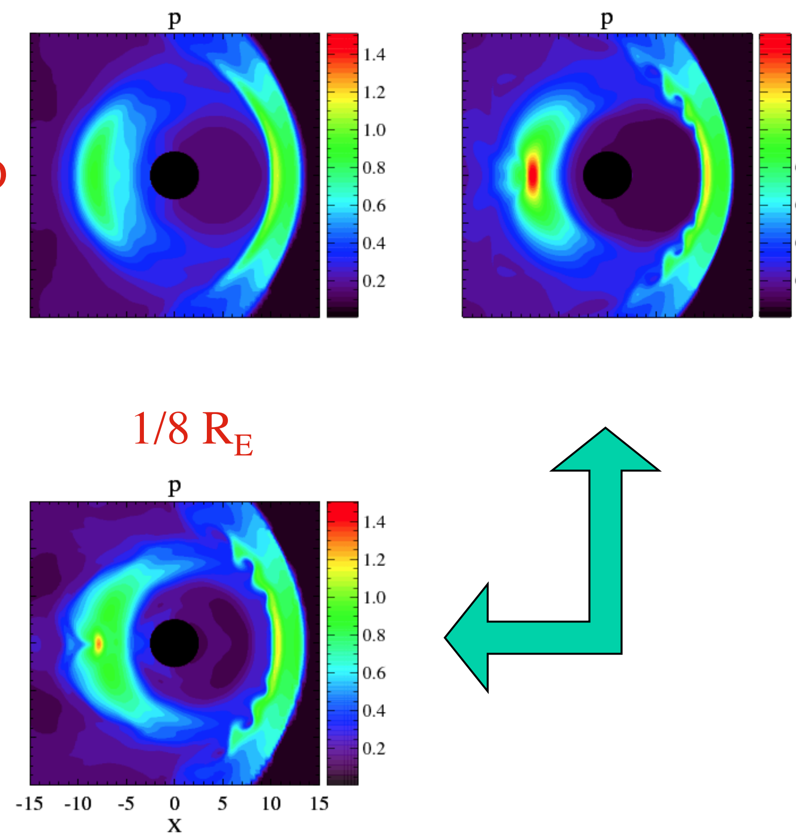
Magnetosphere Simulations

$1/8\ R_E$ $1/16\ R_E$

TVD

$1/8\ R_E$

MP5



Summary

- **SWMF is available for registered users and through CCMC**
- **AWSoM, AWSoM-R, EEGGL transitioned to CCMC**
- **SWMF Geospace has been transitioned to SWPC**
  - Currently running 30-day robustness test
- **Kinetic models**
  - Particle-in-Cell: MHD-EPIC developments and applications
  - Particle Tracker: AMPS developments
  - Solar energetic Particles: MFLAMPA development
- **Convection Zone Model (FSAM)**
- **Spherical Wedge Active Region Model (SWARM) coupled to SC**
- **Fifth order accurate scheme in BATSRUS**
- **Verification, validation and continuous automated testing**