Modeling: Global-Kinetic Coupling

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Outline

- **New SWMF Coupler in the SWMF**
- **New Particle Tracker Component**
  - Adaptive Mesh Particle Simulator model: AMPS
- **New Particle-in-Cell Component**
  - 3D Implicit Particle-In-Cell model: iPIC3D
- **MHD with Embedded PIC: MHD-EPIC**
- **Summary and Future Plans**

Particle Tracker

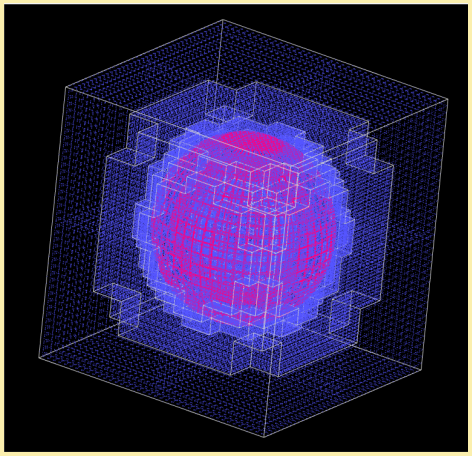
Task

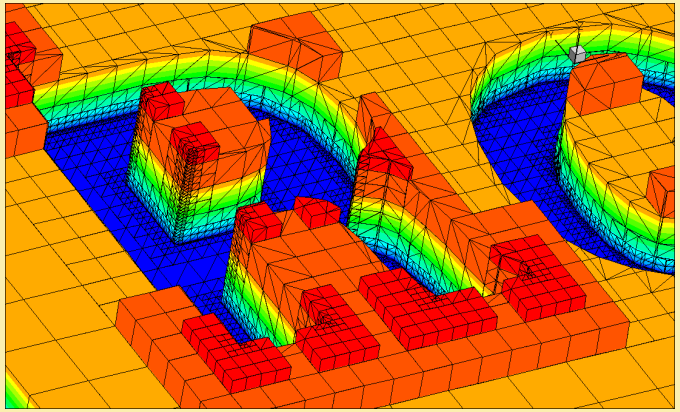
- Move particles in the MHD electric and magnetic field by solving

$$\frac{d\vec{r}}{dt} = \vec{v} \qquad \frac{d\vec{v}}{dt} = \frac{q}{m}(\vec{E} + \vec{v} \times \vec{B}) - \frac{GM\vec{r}}{r^3} - 2\vec{\Omega} \times \vec{v} - \vec{\Omega} \times \vec{\Omega} \times \vec{r}$$

Status

- Added new PT component to the Space Weather Modeling Framework
- Integrated Adaptive Mesh Particle Simulator (AMPS) into the SWMF
- Both AMPS and the MHD code BATS-R-US use distributed adaptive grids





- Coupled AMPS with BATS-R-US via a newly developed coupler

New Simple & Fast SWMF Coupler

Toth, Tenishev, Borovikov, Haiducek

- **Parallel coupling between non-trivial distributed grids**
- **Design Concept**
  - Send data from Source to Target at a set of points defined by Target
    - Assumption: models know how to interpolate data to an arbitrary location
- **Algorithm**
  - Check if there is a need for a new communication pattern. If yes then
    1. Target gets point positions, Coupler sends them to Source processors
    2. Source finds owners, Coupler sends back the owner processor info to Target
    3. Coupler sends point positions to the owner processors of Source
  - Source interpolates data, Coupler sends it back to Target for use
- **Coupling code is 1 line plus "get" and "put" routines in the models:**

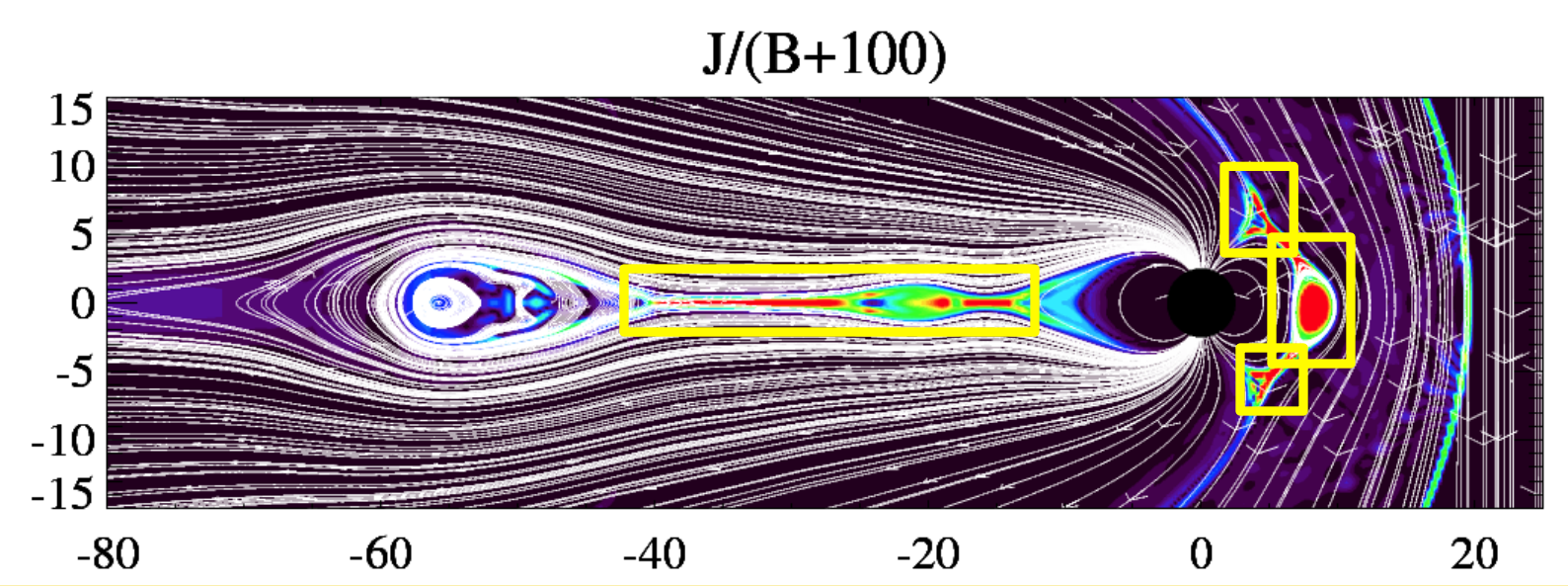
```
call couple_points(Coupler, GM_get_grid_info, GM_find_points, &
                   GM_get_for_pt, PT_get_grid_info, PT_put_from_gm)
```

Two-way MHD - PIC Coupling

- **Reconnection cannot be modeled well with fluid codes**
  - One may be able to reproduce the reconnection rate for a particular problem by tuning parameters, but the overall solution will not match
  - There is some promising work on anisotropic electron pressure models reproducing the basic reconnection features for simple geometries (Ohia et al. 2012, PRL)
- **Particle codes (Partile-In-Cell and Vlasov solvers) are expensive**
  - Explicit PIC codes need fine grid and time steps
  - Implicit PIC codes need an iterative solver
  - Vlasov codes solve the equations in 6+1D
  - Hybrid codes neglect some of the physics, and are still expensive
- **Additional observable quantities from the distribution function.**
- **The goal is to combine the efficiency of the global fluid code with the physics capabilities of the local PIC code!**

MHD with Embedded PIC regions: MHD-EPIC

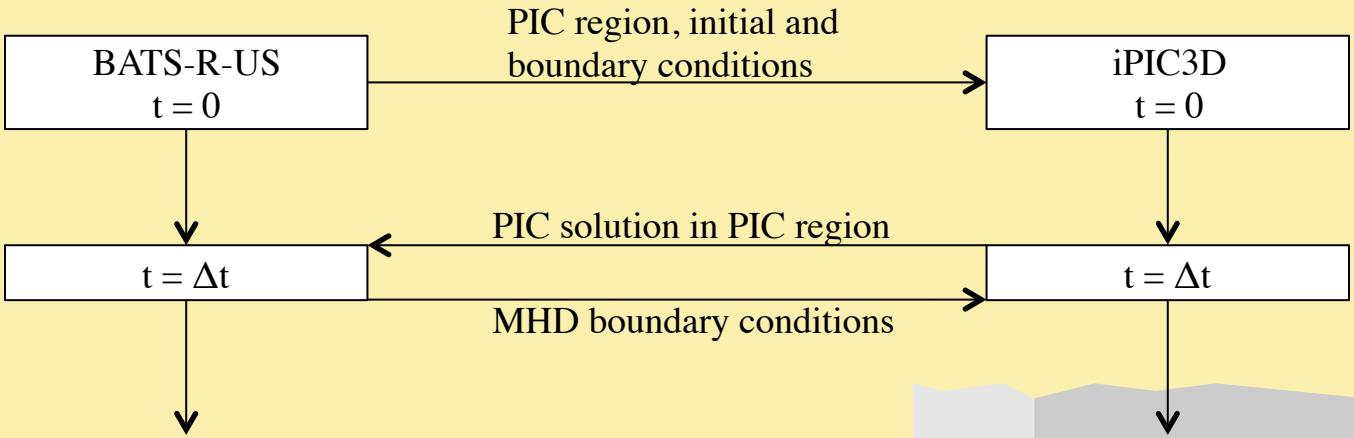
- **Algorithm Concept**
  - MHD code identifies potential sites of reconnection
  - PIC regions are created and initialized from the MHD solution
  - MHD code provides boundary conditions for the PIC regions
  - PIC solution overwrites the MHD solution inside the PIC regions
  - PIC regions are expanded/reduced as needed
  - PIC regions are removed when there is no more reconnection inside



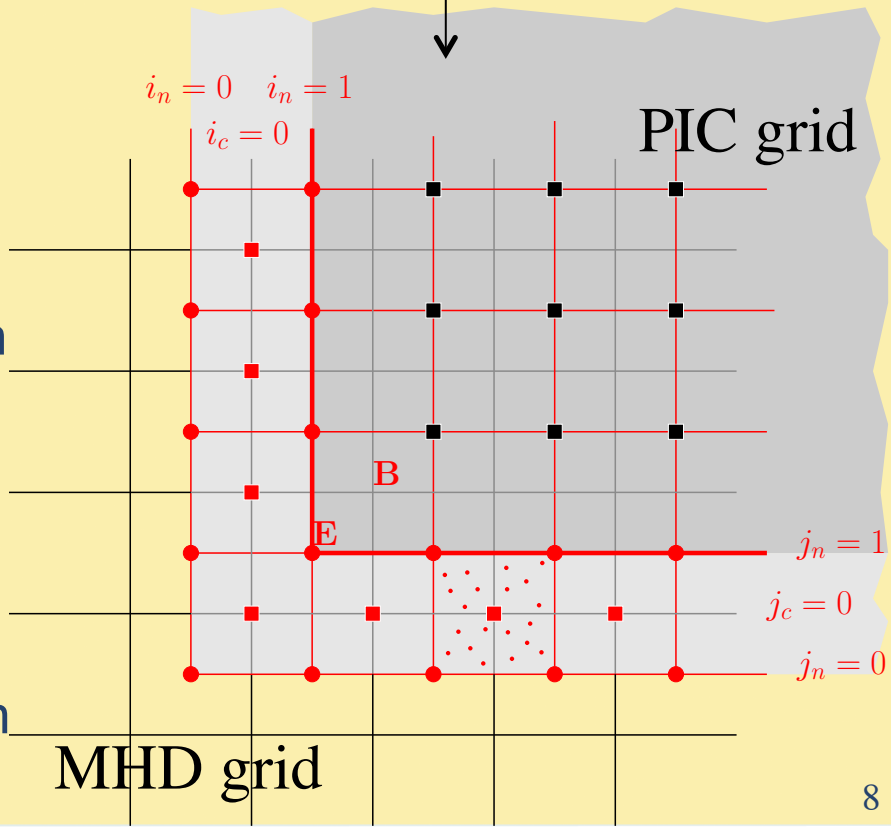
Codes and Current Status

- **BATS-R-US**
  - Massively parallel extended MHD (XMHD) code with adaptive mesh refinement using 1, 2 or 3D Cartesian or spherical grids
  - Ideal, resistive, semi-relativistic, Hall, anisotropic, multi-fluid MHD
- **iPIC3D**
  - Massively parallel Implicit Particle-in-Cell code on 3D uniform grid
- **Two-way Coupling**
  - Proof-of-concept coupling through flat files for 2D problems
- **Particle-in-Cell (PC) component was added to the SWMF**
  - iPIC3D is now fully integrated into the SWMF as a PC model.
  - Two-way 3D coupling via the new coupler is almost complete.
  - Single PIC region for now, preparing for multiple PIC regions

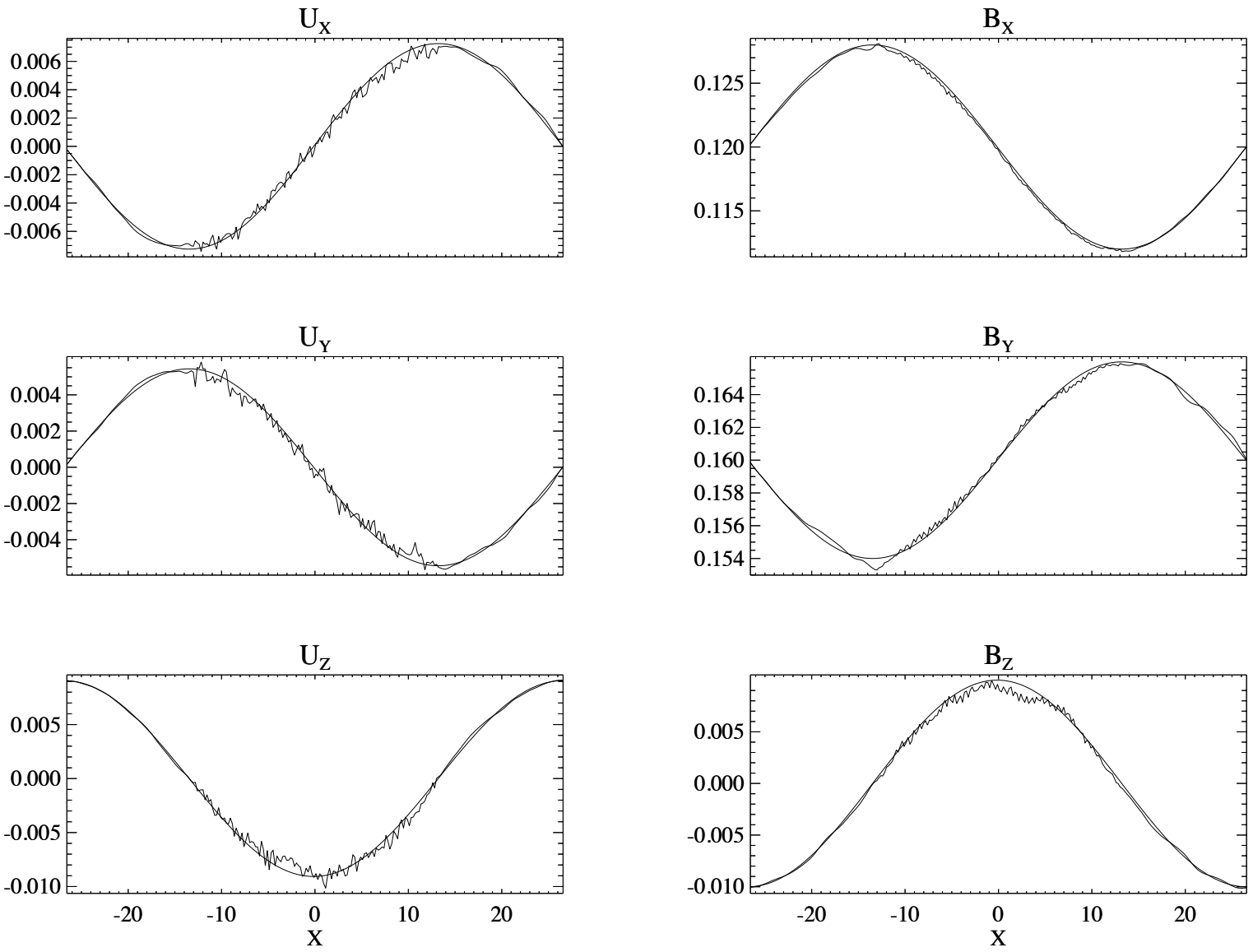
MHD-EPIC Algorithm
L. Daldorff et al. 2014 JCP



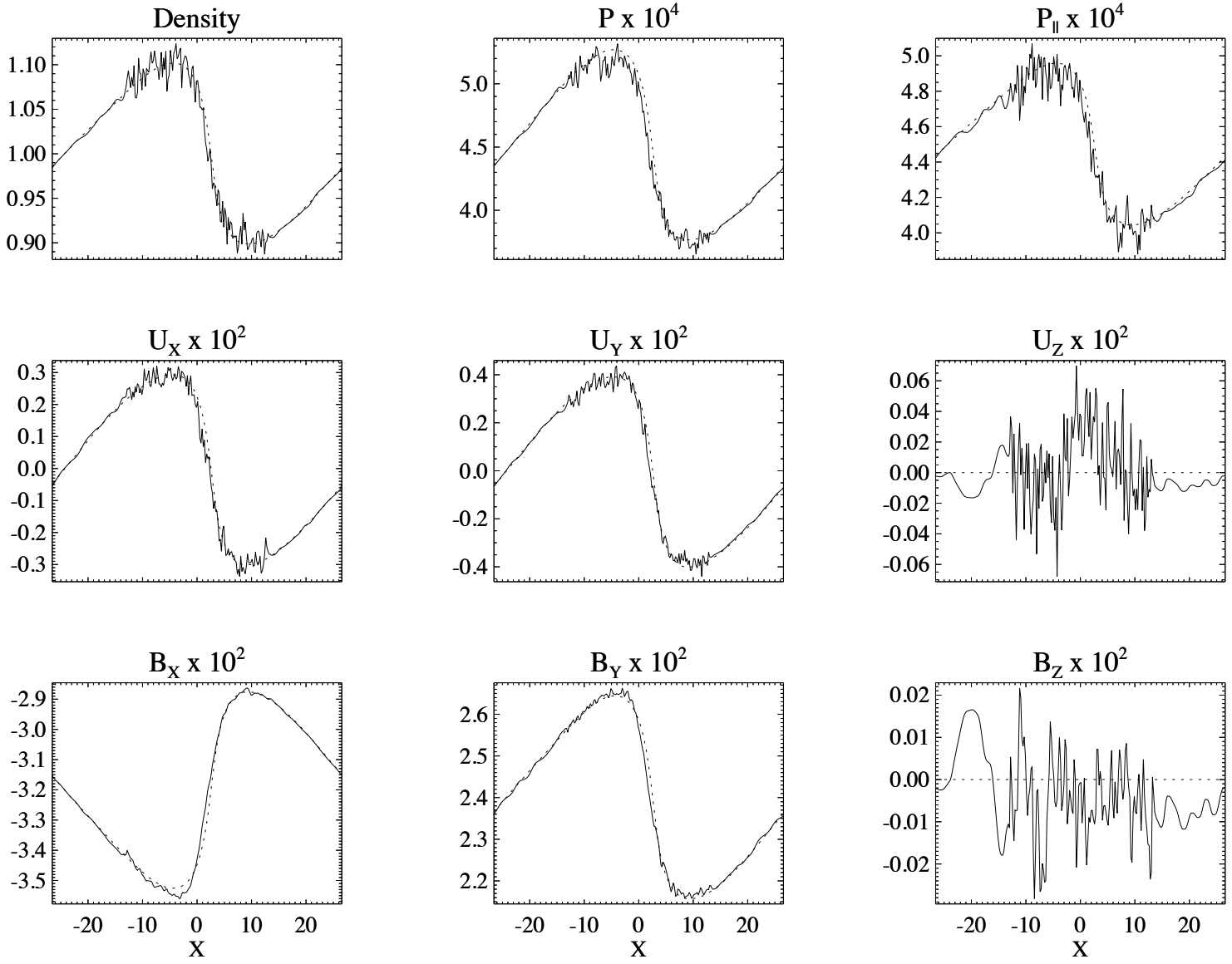
- **BATS-R-US to IPIC3D**
  - Send MHD variables and currents
  - iPIC3D uses **B**, calculates **E**, and creates particles with a (bi-)Maxwellian distribution in the ghost cells/nodes.
- **IPIC3D to BATS-R-US**
  - Send magnetic field and moments: **B**, ρ, ρv, P_{par}, P_{perp}, P_e
  - BATS-R-US overwrites PIC region with the PIC solution



Whistler Wave Test

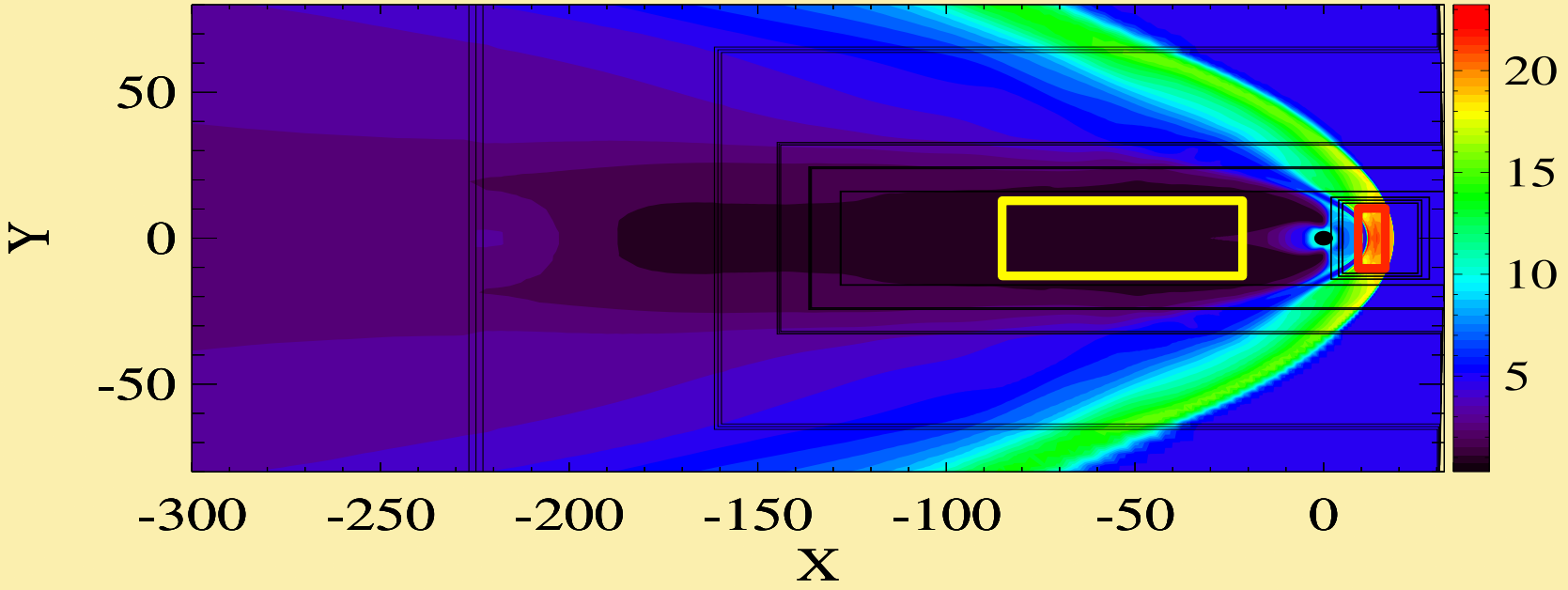


Fast Magnetosonic Wave Test

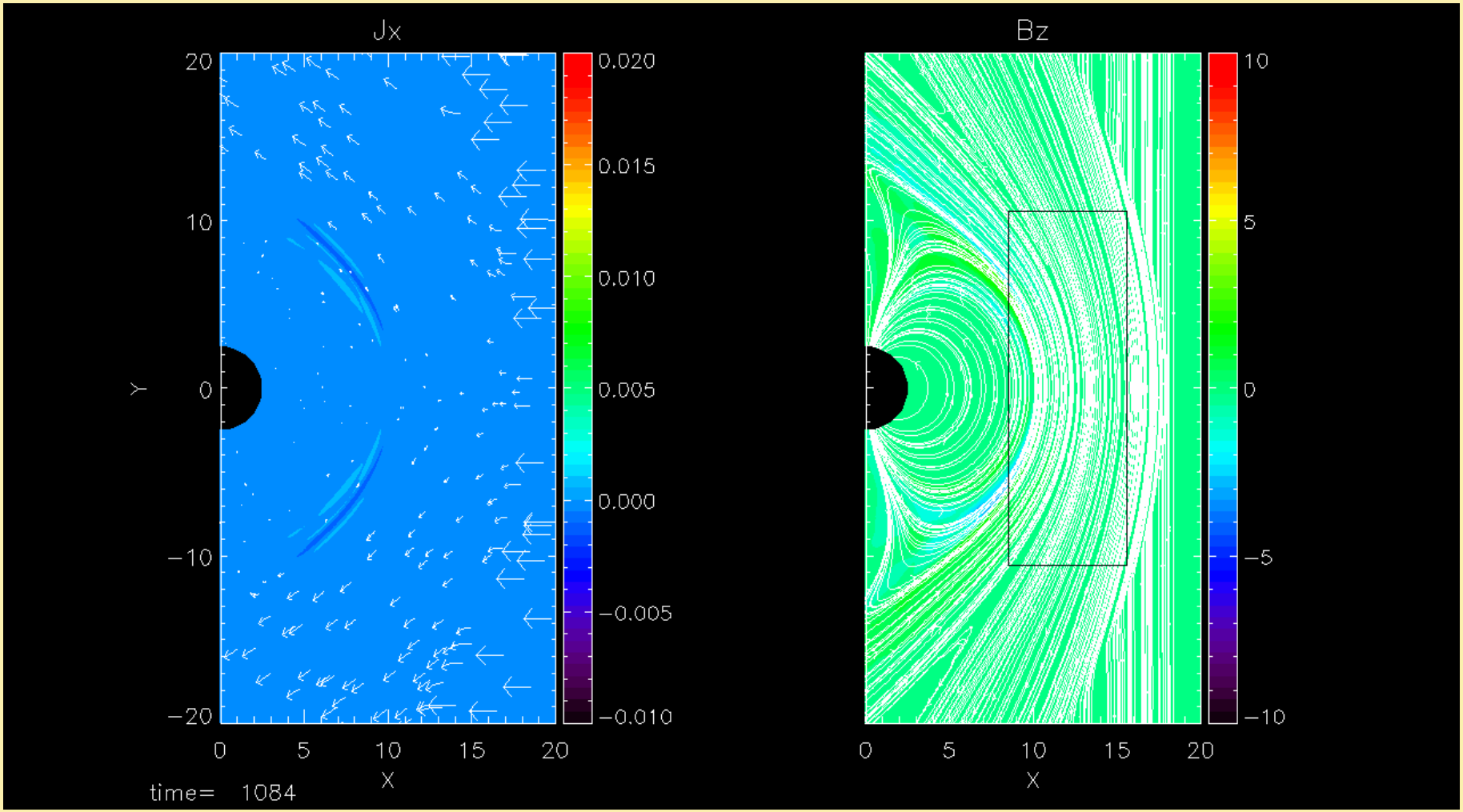


2D Magnetosphere with MHD-EPIC

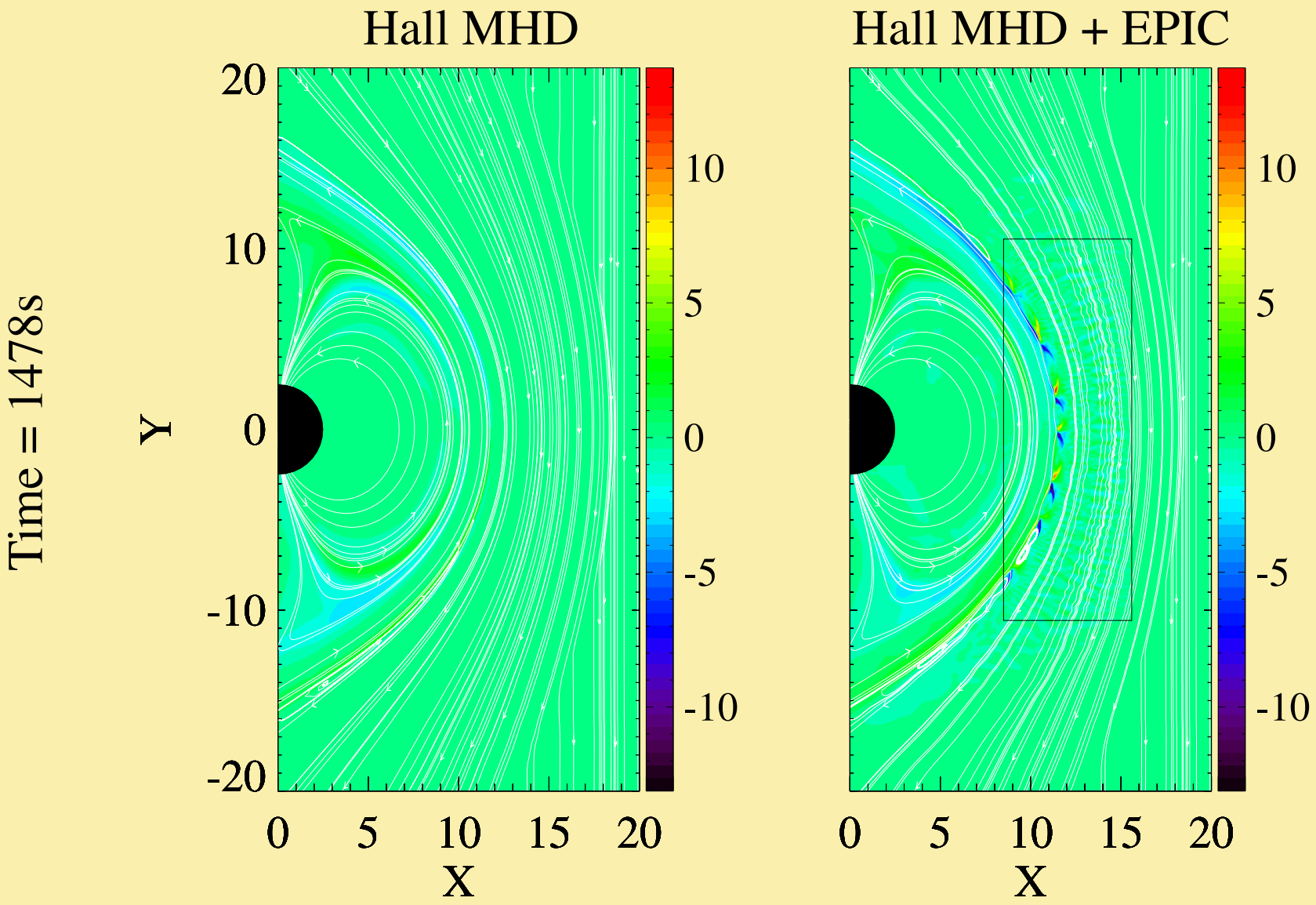
- Full domain x = [-480, 32] Re and y = [-128, 128] Re
- Solar wind: n = 5/cc, V_X = -400km/s, B_Y = -0.5nT and T = 10^5K
- Earth dipole strength is set to 3110 nT.
- Hall MHD with a Hall factor increased by factor of 10.
- PIC region resolution: ¼ Re at the tail and 1/32 Re on the dayside.
- PIC parameters: Pi/Pe = 5, Mi/Me = 25 and 1000 particles per species per cell.



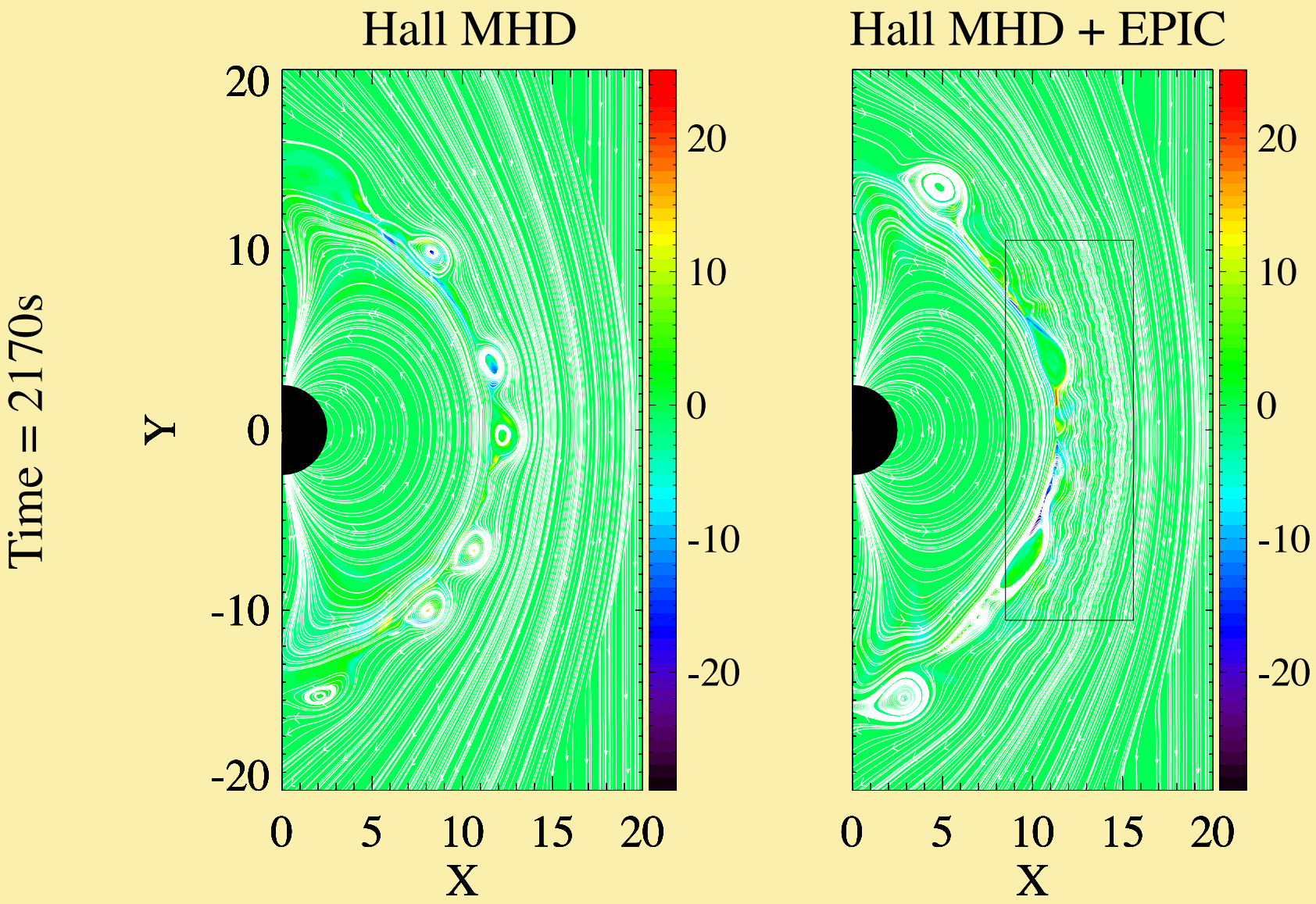
MHD-EPIC: Dayside Reconnection



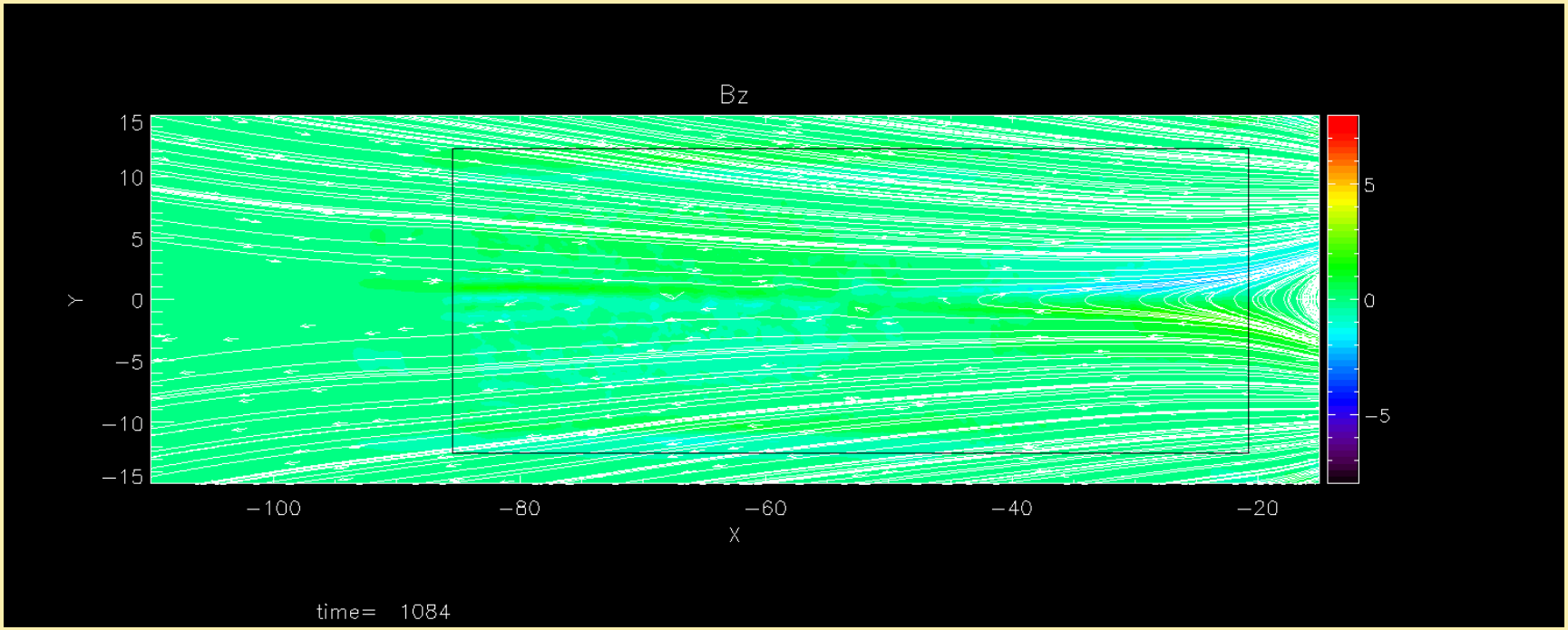
Dayside Reconnection



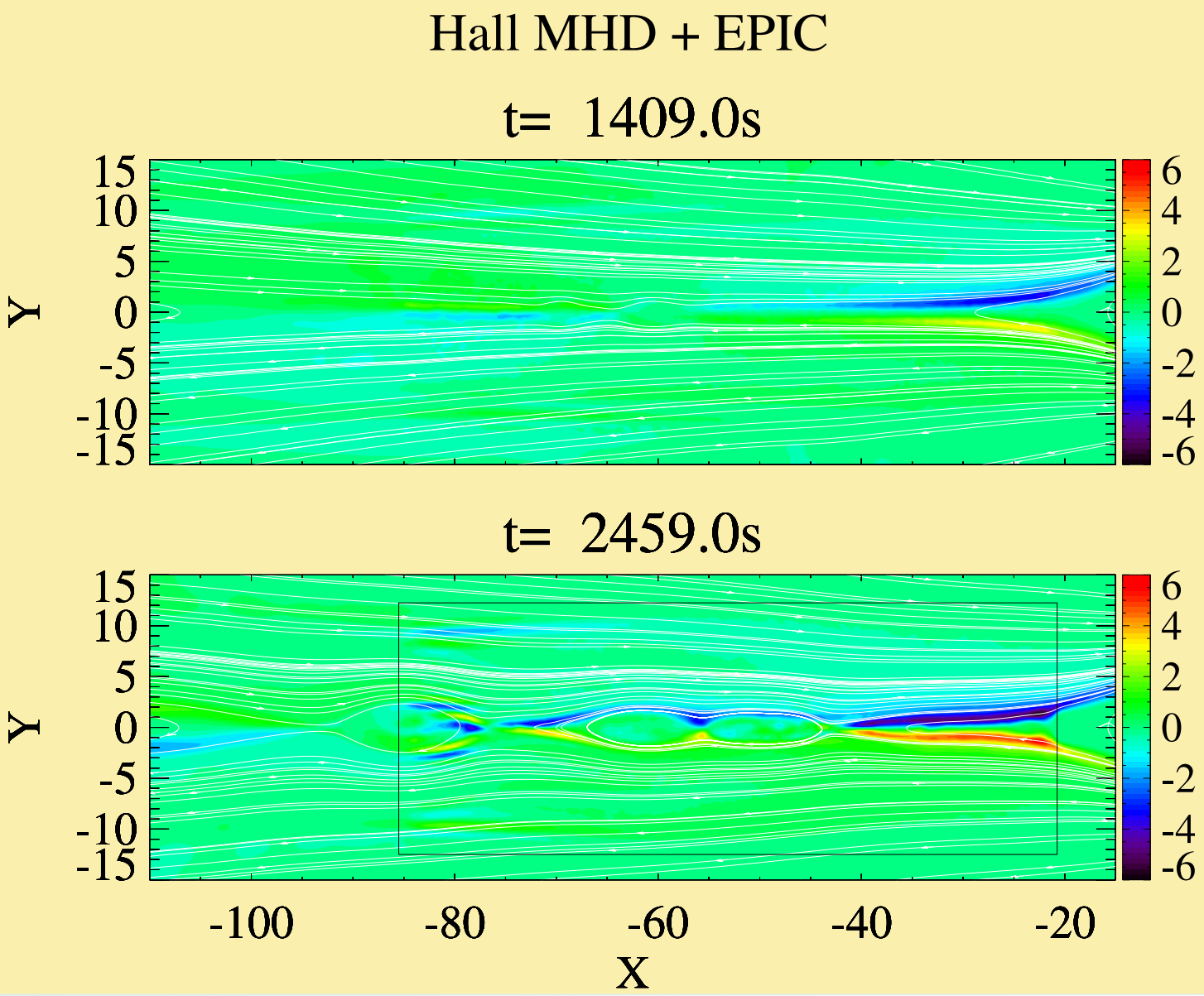
Dayside Reconnection



MHD-EPIC: Tail Reconnection



Tail Reconnection



Summary

- **Developed new simple and efficient parallel coupler in the SWMF.**
- **Added the Particle Tracker model AMPS to the SWMF**
  - Coupled with BATSRUS using the new coupler.
- **Two-way coupled BATSRUS and IPIC3D in 2D via flat files**
  - Verified the coupling for fast magnetosonic and whistler waves.
  - Successfully applied MHD-EPIC to 2D magnetospheric simulation.
  - Published algorithm: L. Daldorff et al. 2014 JCP
- **Added Particle-in-Cell model IPIC3D to the SWMF**
  - Runs inside the SWMF
  - Two-way coupling with BATS-R-US using the new coupler: almost done
- **Future work:**
  - Apply SWMF with AMPS to heliosphere / magnetosphere
  - Generalize MHD-EPIC to multiple / dynamic PIC regions...