SWMF Geospace

Gabor Toth

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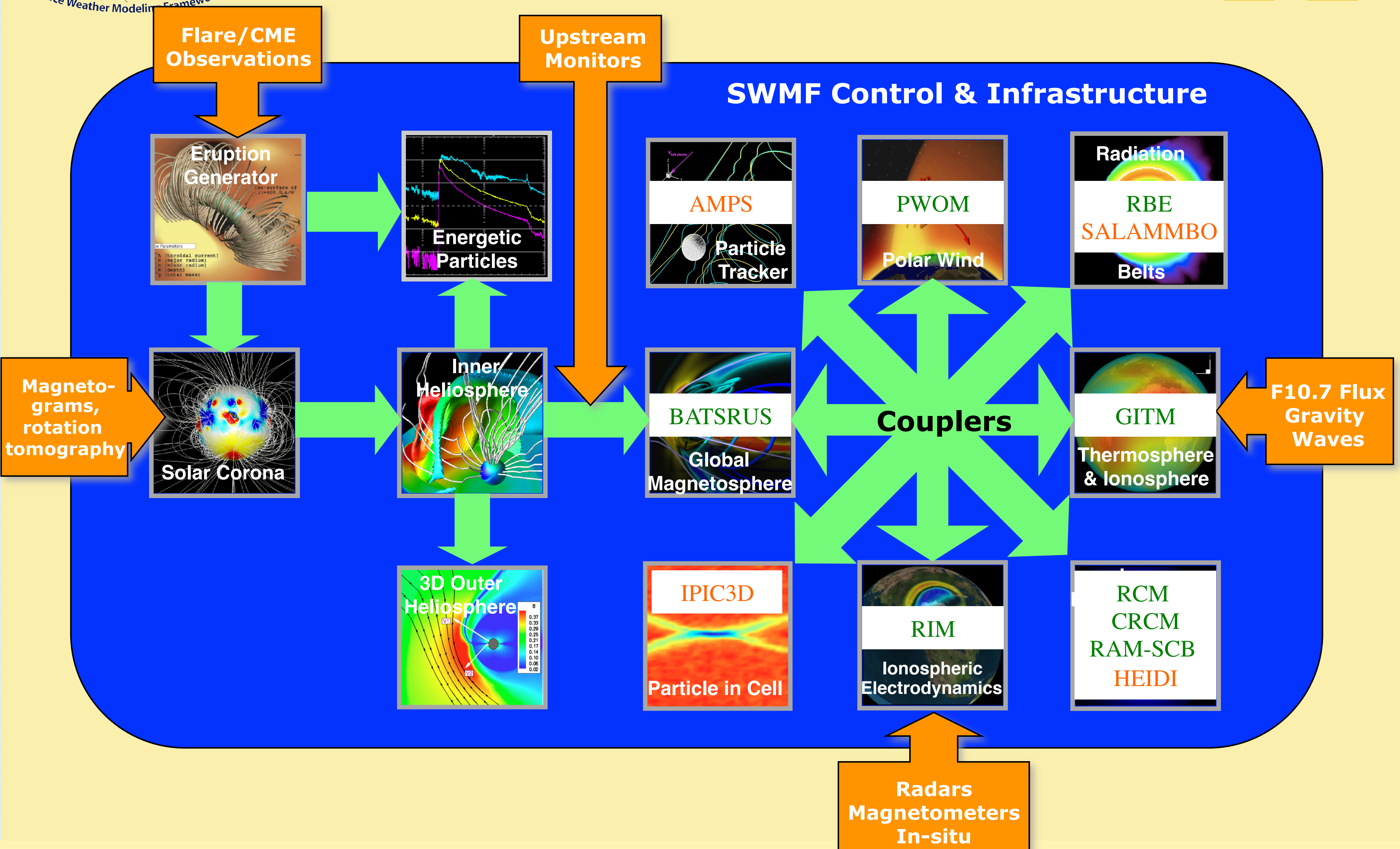
Outline

- **New Geospace Components in the SWMF**
  - Particle Tracker (PT): Adaptive Mesh Particle Simulator (AMPS)
    - Valeriy Tenishev
  - Particle-in-Cell (PC): Implicit Particle-In-Cell in 3D (IPIC3D)
    - Jerry Brackbill, Giovanni Lapenta, Stefano Markidis, Lars Daldorff
- **Transitioning the SWMF Geospace Model to SWPC**
- **Validation Studies**
  - Multi-fluid MHD, anisotropic MHD, CRCM coupling
- **New Physics and Numerics in BATSRUS**
- **Summary**

Geospace Components in the SWMF



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

New Simple & Fast SWMF Coupler

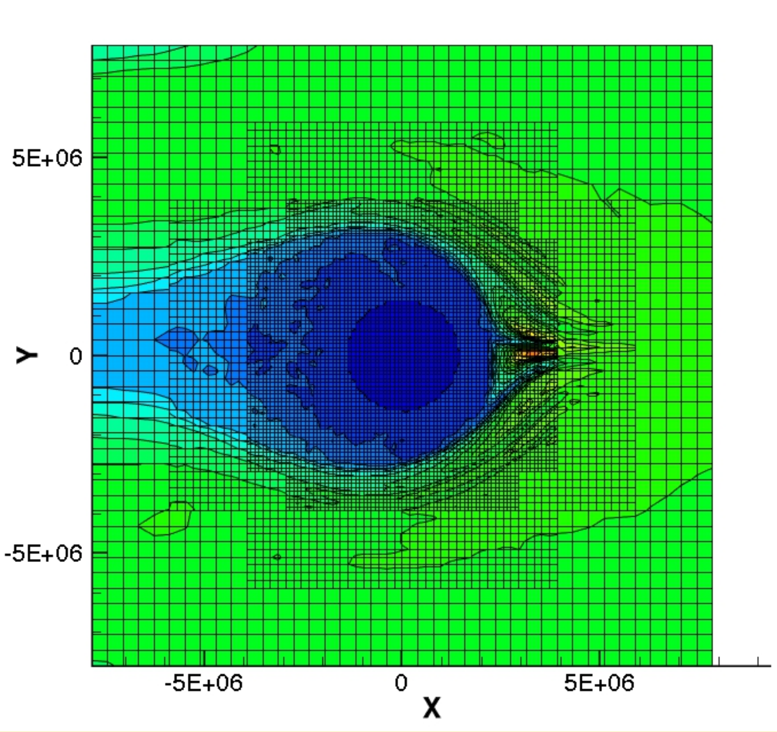
Toth, Tenishev, Borovikov, Haiducek

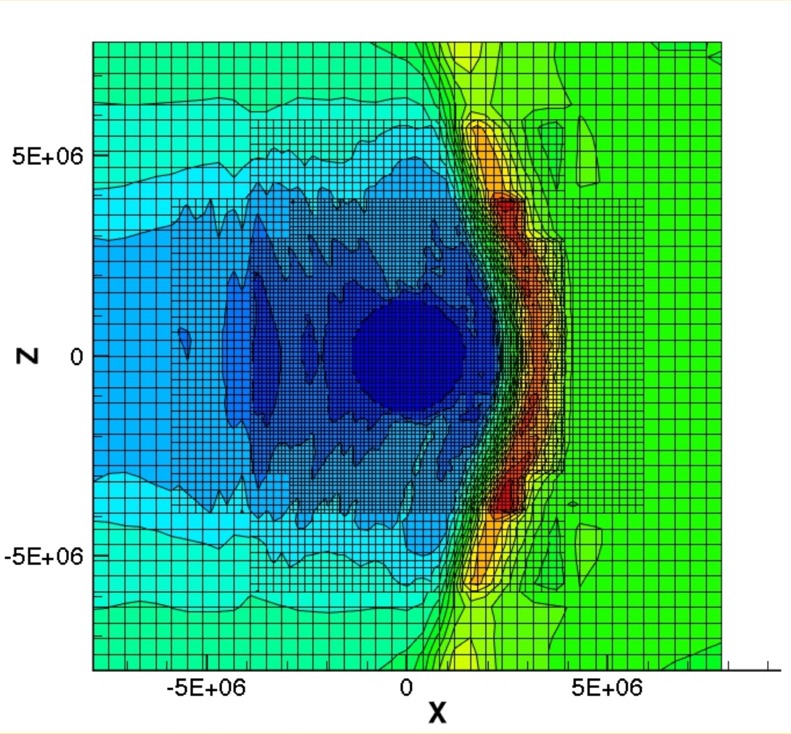
- **Parallel coupling between non-trivial distributed grids**
- **Design Concept**
  - Send data from Source to Target at a set of points defined by Target
    - Assumption: models know how to interpolate data to an arbitrary location
- **Algorithm**
  - Check if there is a need for a new communication 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)
```

GM/BATSRUS – PT/AMPS Coupling Test: thermal ions around Europa

- Magnetic field and plasma flow are sent from the MHD code BATSRUS to AMPS every 2 seconds of the model time using the new coupler
- The figure shows the number density of thermal Jovian ions obtained in the Monte-Carlo code AMPS

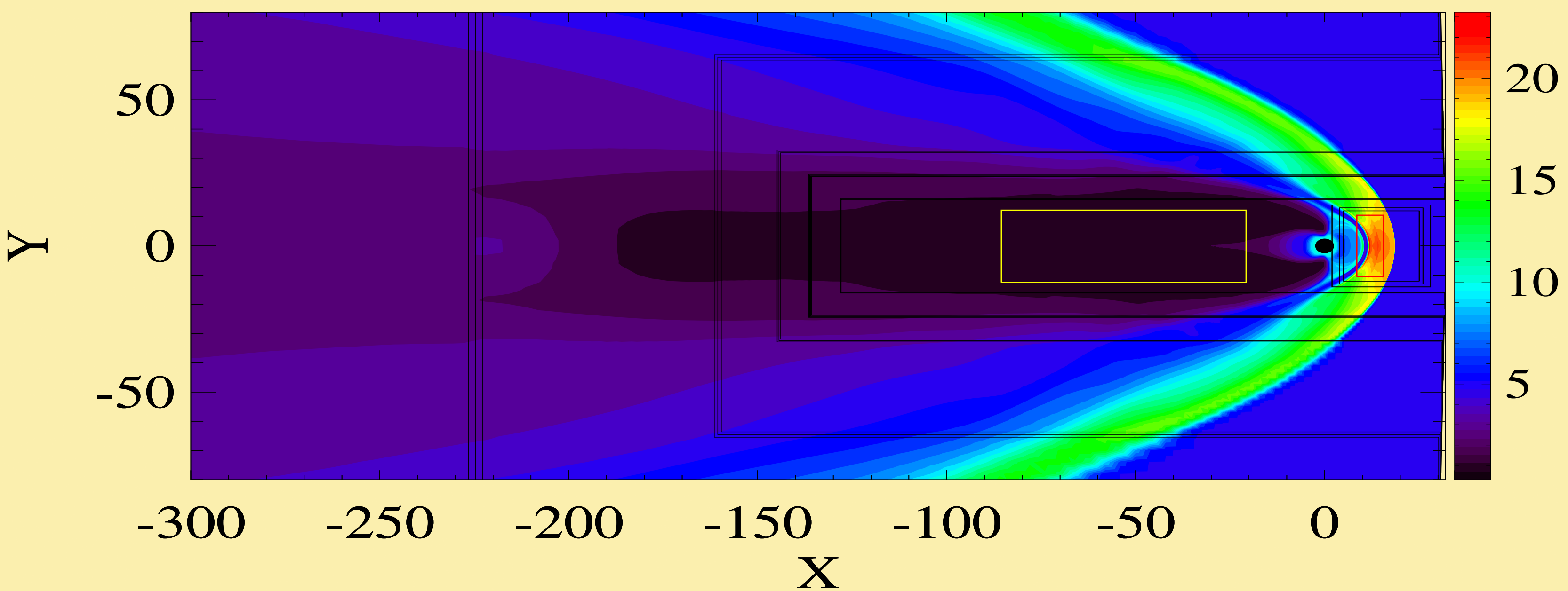




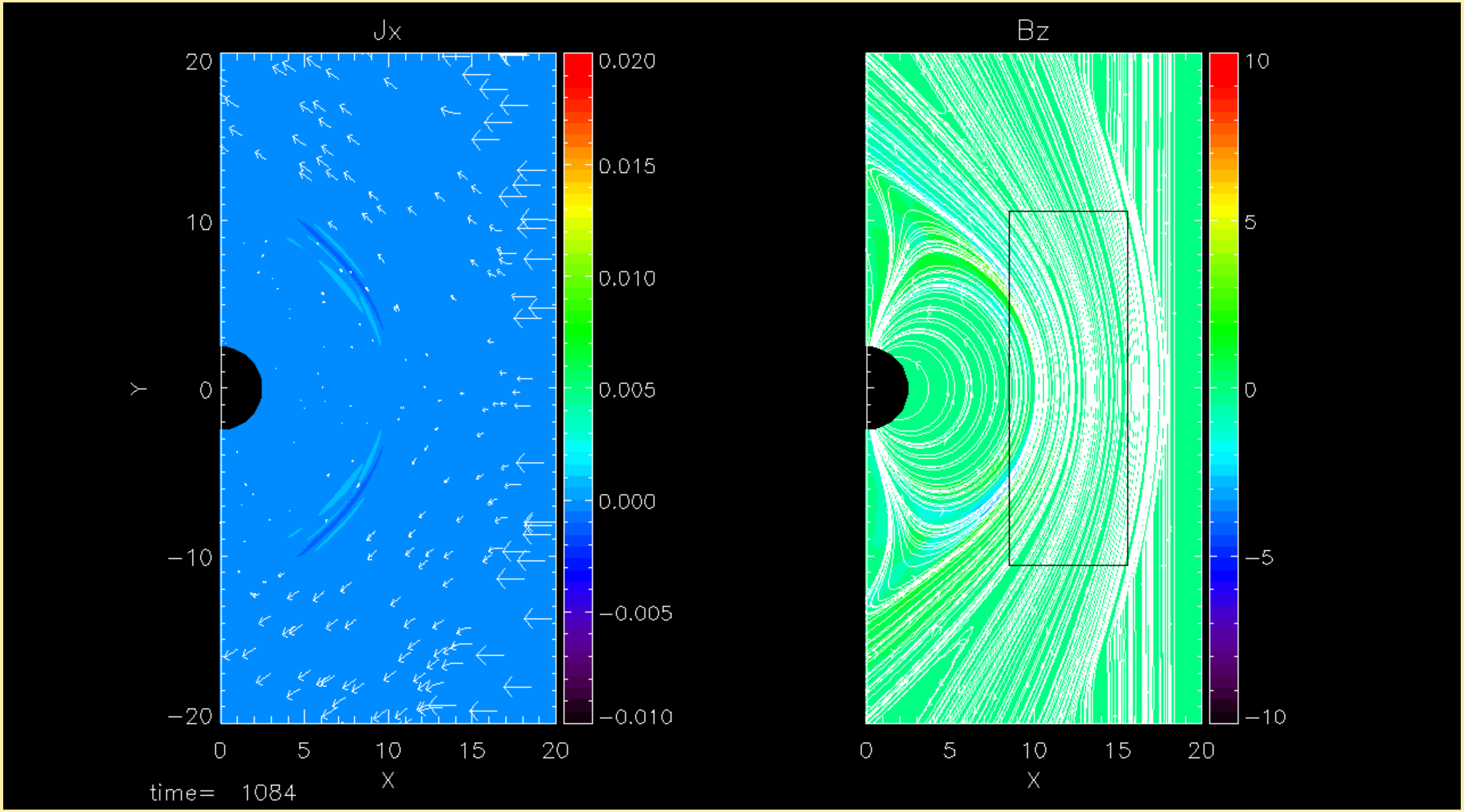
GM/BATSRUS and PC/IPIC3D Coupling

L. Daldorff et al. 2014 JCP

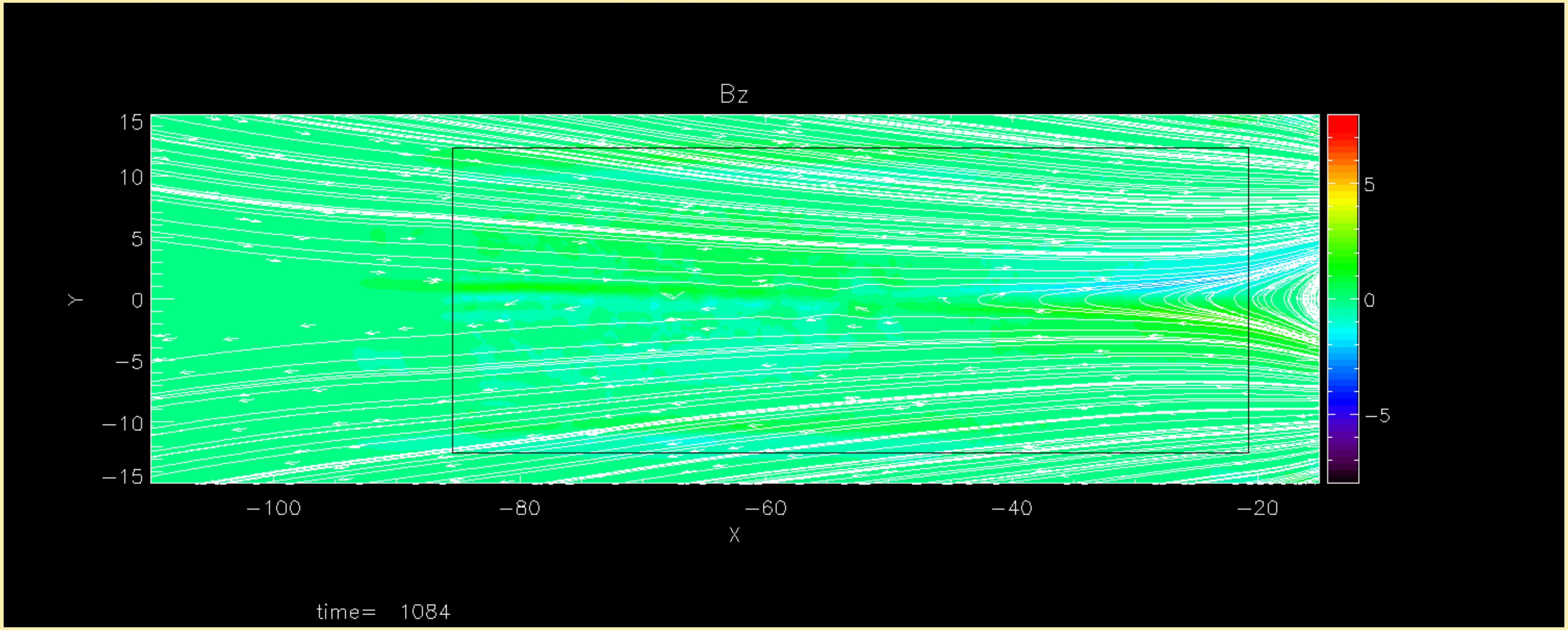
- **iPIC3D**
  - Massively parallel Implicit Particle-in-Cell code on 3D uniform grid
- **MHD-EPIC**
  - MHD with Embedded PIC regions combines the efficiency of the global MHD code with the physics capabilities of the local PIC code!
- **Test: 2D magnetosphere simulation**



MHD-EPIC: Dayside Reconnection



MHD-EPIC: Tail Reconnection



Transitioning Geospace SWMF to SWPC

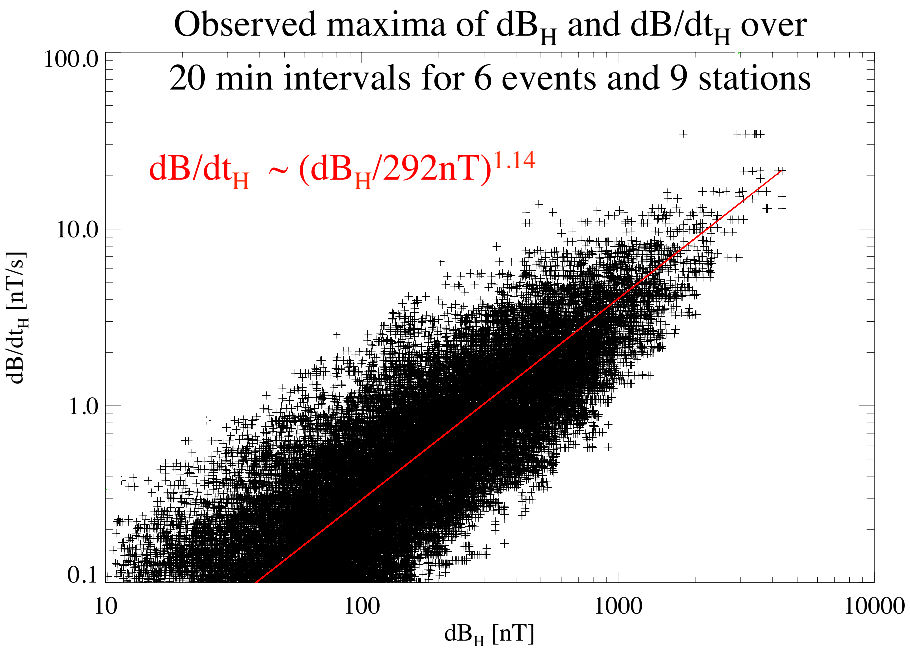
G. Millward, G. Toth, D. Welling

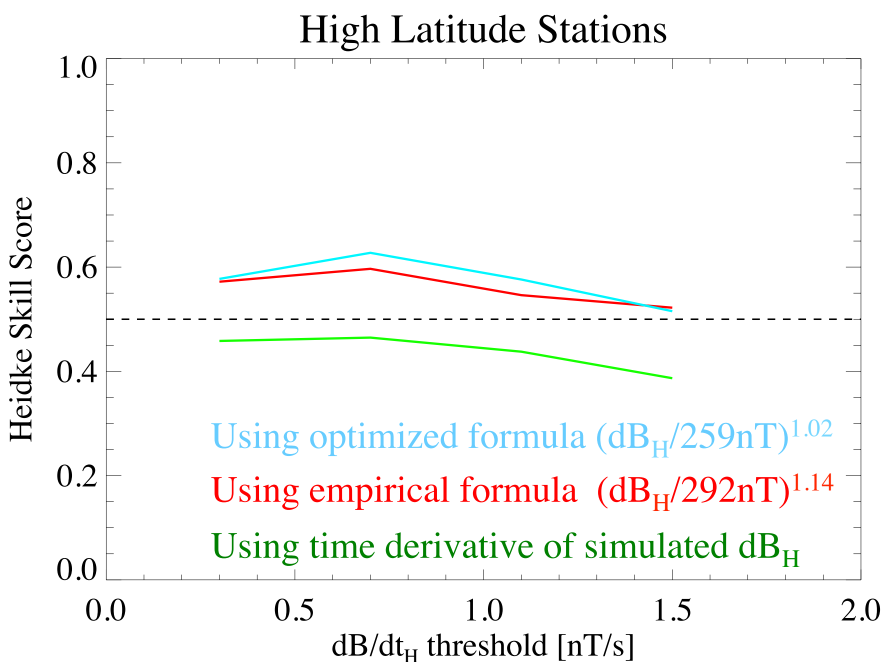
- **Based on the CCMC model evaluation SWPC selected the SWMF as the first-principles based Geospace model**
  - Models: GM/BATSRUS + IM/RCM + IE/RIM
  - Runs faster than real time on 64 cores
  - Driven by L1 solar wind observations (ACE): 1 hour to 20 min prediction
  - Can predict global indexes (Dst, Kp) and local perturbations (dB, dB/dt)
- **The transition to operations is underway**
  - The SWMF code has been installed at SWPC
  - The code compiles and runs correctly with SWPC compilers
  - The code speed has been verified on the SWPC machines
  - The real-time data-driven environment is under development
    - with experience and help from CCMC

Predicting dB/dt_H based on dB_H

G. Toth et al. JGR 2014

- **The local magnetic field perturbations are highly variable**
  - It is easier to predict dB crossing thresholds in 20m intervals than dB/dt
  - We found that observed dB and dB/dt are highly correlated: R = 0.85
- **We can predict dB/dt from simulated dB using a power law formula**
  - The skill scores can be improved especially for high latitude stations

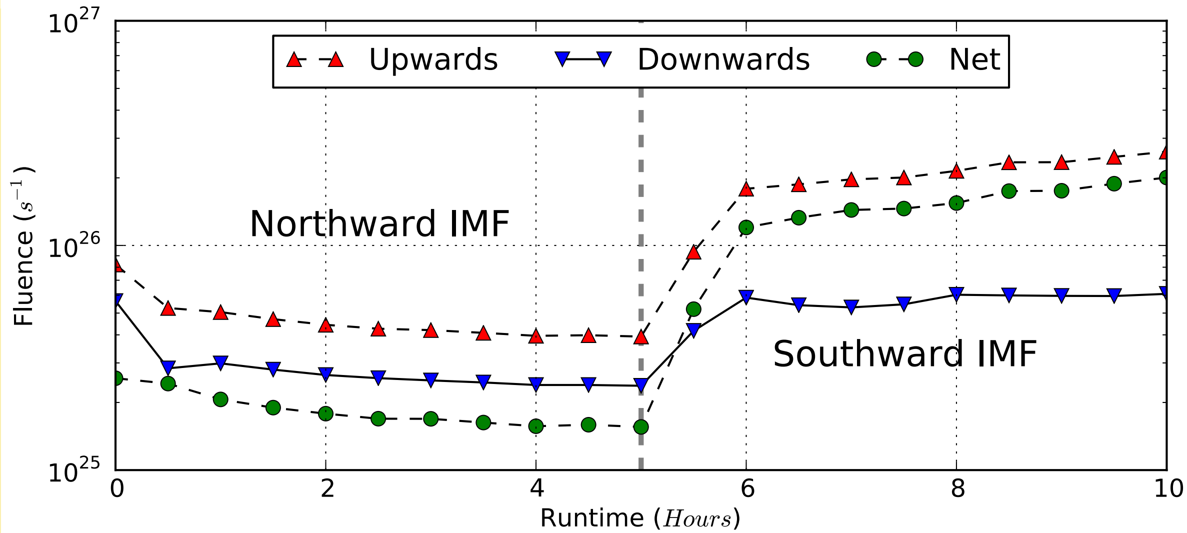




Validation: Ionospheric Outflow and Multifluid MHD

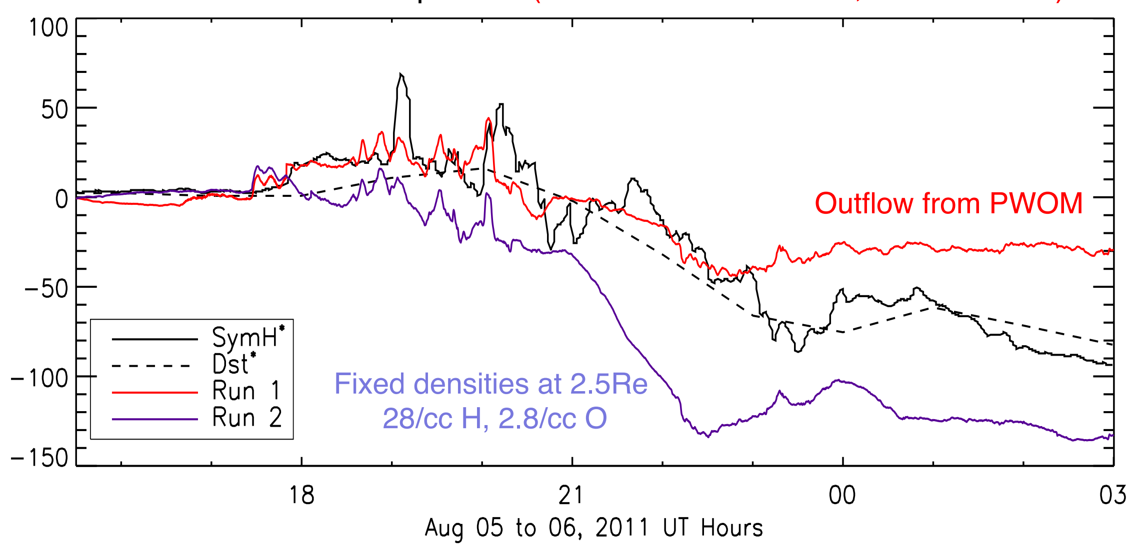
- **Ionospheric outflow**
  - Constant density BC
  - Empirical formula (Strangeway or CPCP)
  - First-principles based (PWOM)

Outflow from constant density BC (D. Welling and M. Liemohn 2014 JGR)



- **Multifluid MHD**
  - Separate momentum and energy equations for different ion species

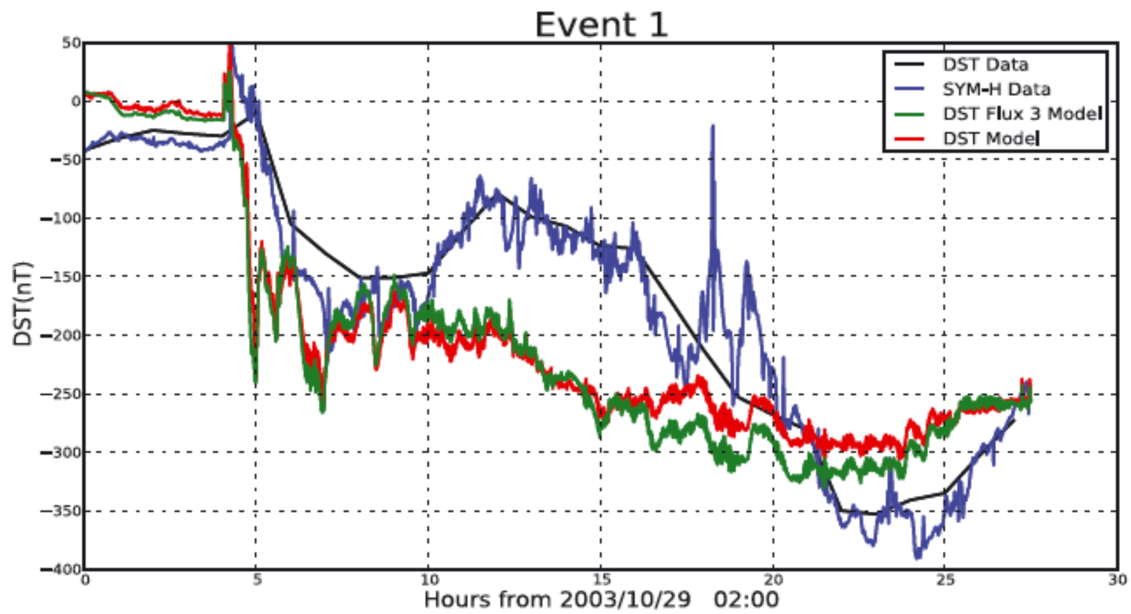
SYM-H / Dst comparison (R. Ilie et al. 2014 JGR, under review)

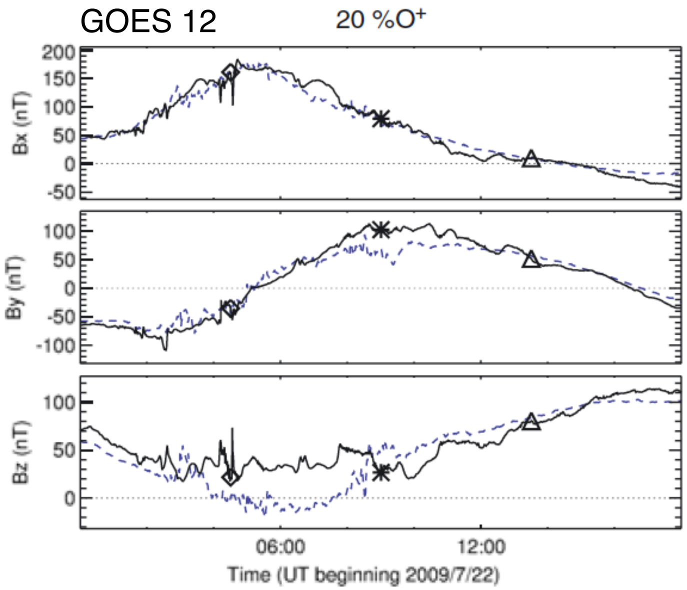


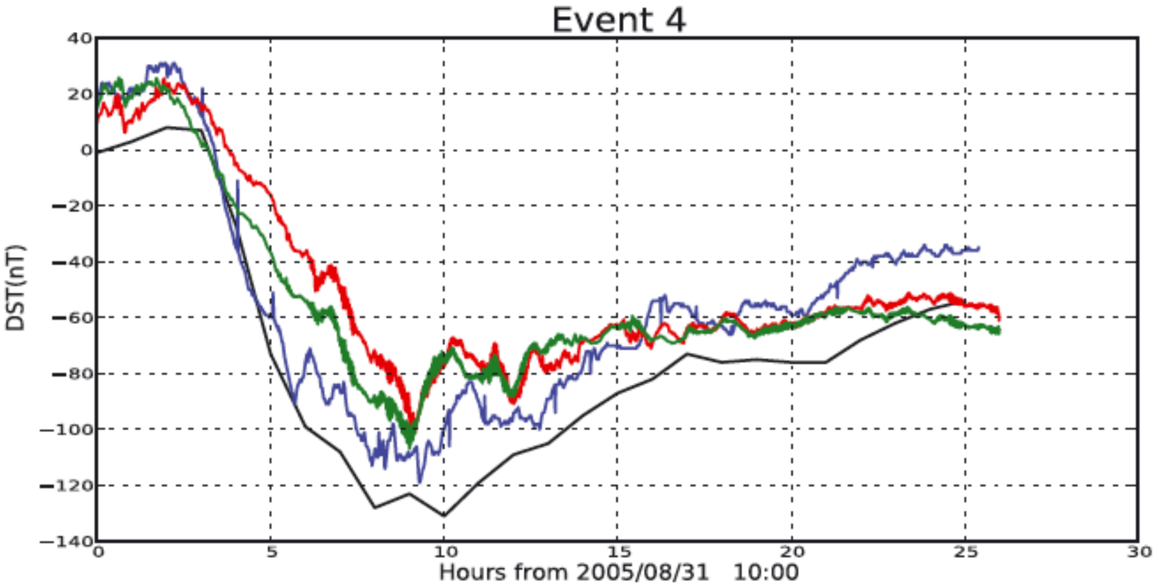
Validation: IM/CRCM in the SWMF

A. Glocer et al. 2013 JGR

- Two-way coupled CRCM
- BATSRUS: isotropic MHD
- Compared Dst / Sym-H with different model Dst definitions for 4 events
- Compared THEMIS energy spectra and GOES magnetic data assuming different O^+ ratios





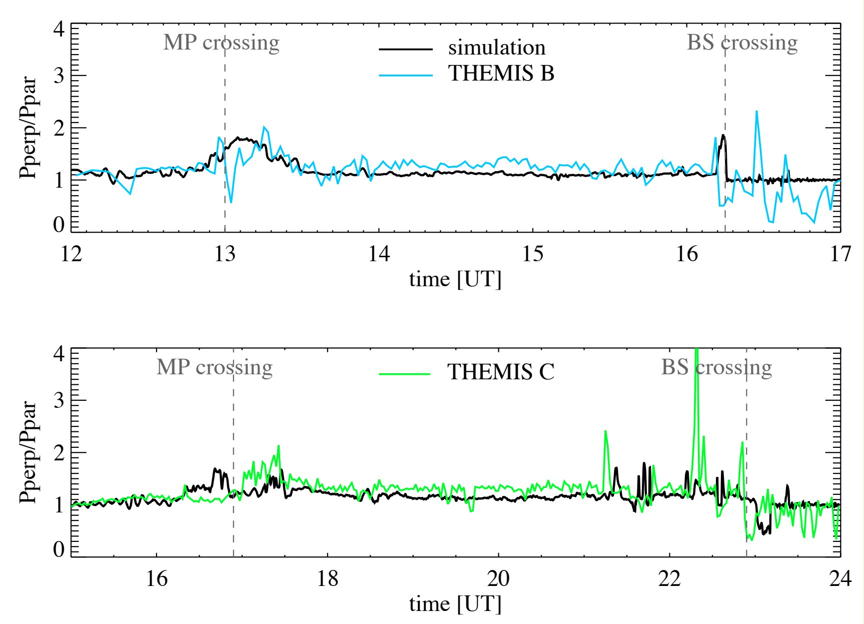


Validation for Anisotropic Pressure

X. Meng et al. 2012 JCP, JGR; 2013 JGR

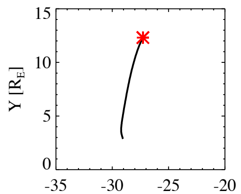
- **In collisionless plasma the pressure can become anisotropic**
  - Limited by firehose, mirror, and ion-cyclotron instabilities (including finite Larmor radius effects): relaxation terms in BATS-R-US
- **Quiet Time: GM/BATSRUS + IE/RIM**
  - Comparison: THEMIS on dayside

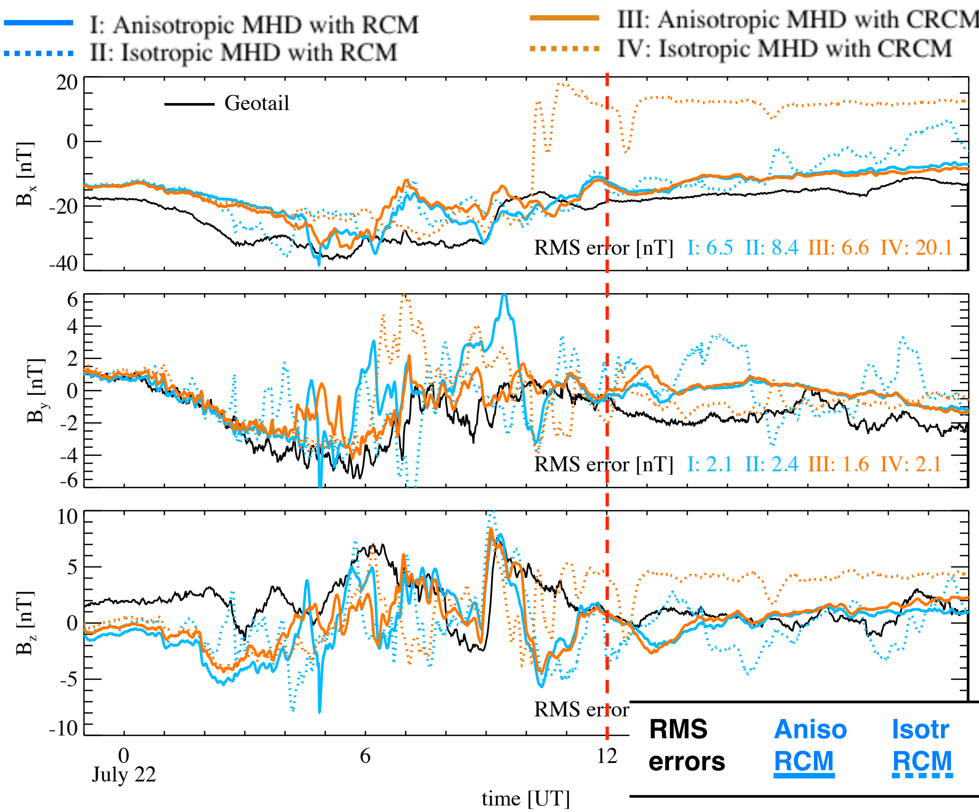
	THEMIS C	
	Isotropic MHD	Anisotropic MHD
n [/cc]	1.66	1.66
u_x [km/s]	80.21	74.22
u_y [km/s]	46.68	45.23
u_z [km/s]	42.52	42.30
b_x [nT]	3.95	3.93
b_y [nT]	6.85	6.70
b_z [nT]	10.13	10.32



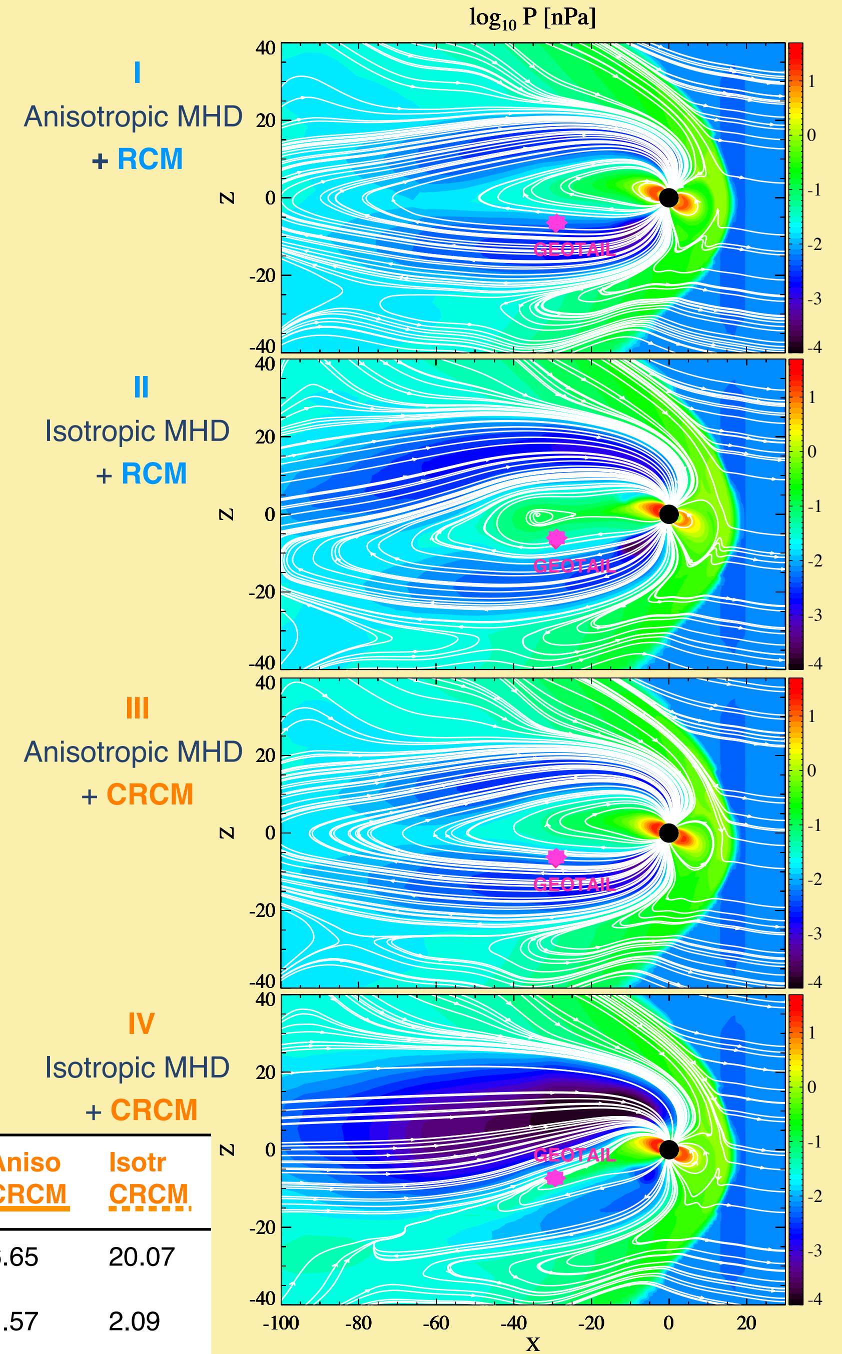
- **Storm Simulations**
  - GM/BATSRUS (isotropic or anisotropic MHD) + IE/RIM + IM/RCM (isotropic) or IM/CRCM (anisotropic)
  - Two Events. Comparison with Dst, GOES, THEMIS, Geotail.

Geotail comparison





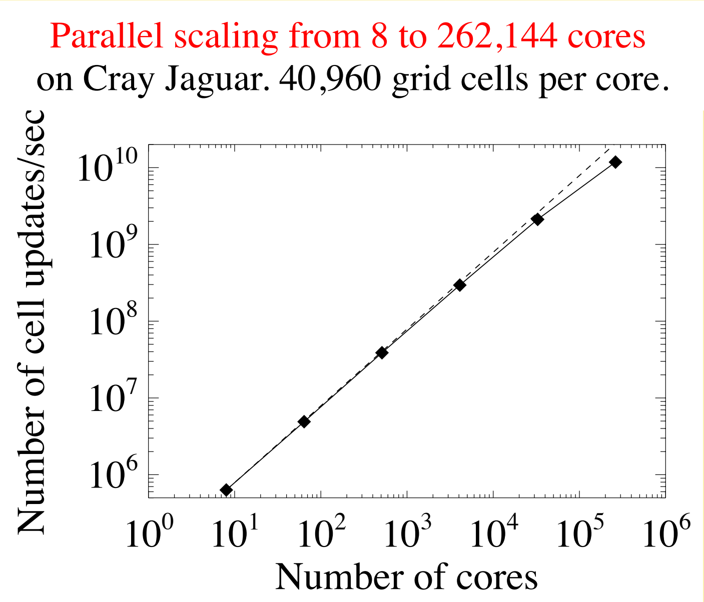
RMS errors	Aniso RCM	Isotr RCM	Aniso CRCM	Isotr CRCM
Bx [nT]	6.46	8.37	6.65	20.07
By [nT]	2.09	2.36	1.57	2.09
Bz [nT]	3.33	3.46	2.92	3.63



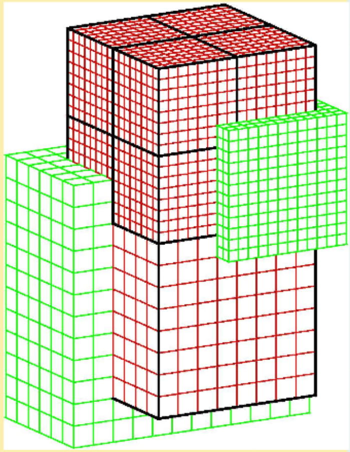
BATS-R-US

Block Adaptive Tree Solar-wind Roe Upwind Scheme

- **Physics**
  - Classical, semi-relativistic and Hall MHD
  - Multi-species, multi-fluid, anisotropic pressure
  - Resistivity, viscosity, heat-conduction
  - Radiation hydrodynamics multigroup diffusion
  - Multi-material, non-ideal equation of state
  - Solar wind turbulence, Alfven wave heating



- **Numerics**
  - Conservative finite-volume discretization
  - 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: Rusanov, AW, HLLE, HLLD, Roe
  - Explicit, point-implicit, semi-implicit, fully implicit time stepping
  - Up to 4^{th} order accurate in time and 5^{th} order in space
- **Applications**
  - Heliosphere, sun, planets, moons, comets, HEDP experiments
- **100,000+ lines of Fortran 90 code with MPI parallelization**



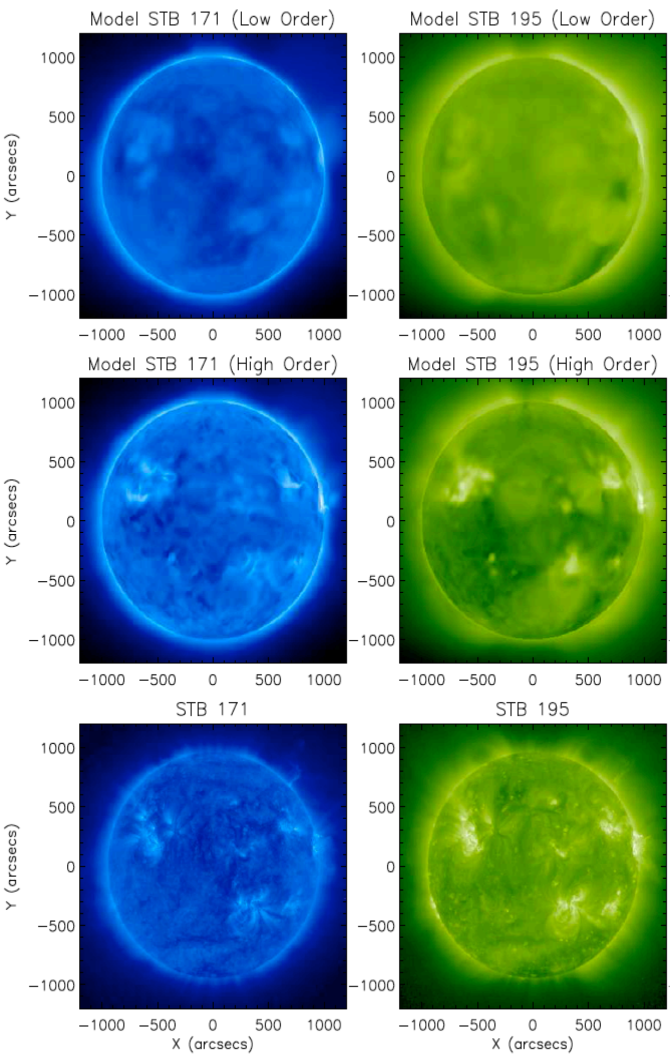
High Order Schemes

Solar Corona Model (AWSoM) comparison with STEREO B

TVD

MP5

Obs.

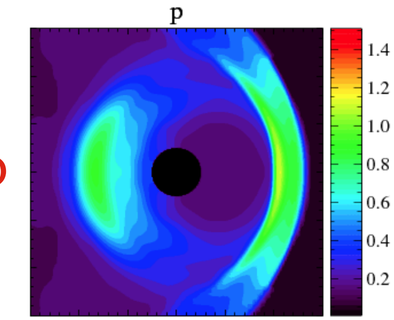


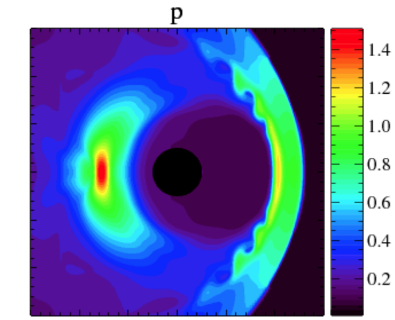
Magnetosphere Simulations

1/8 R_E

1/16 R_E

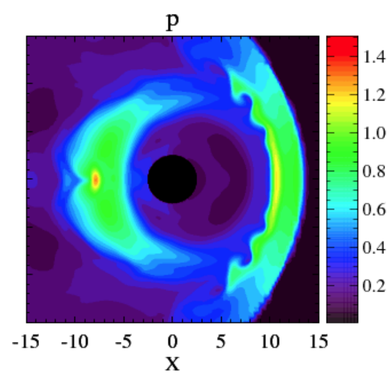
TVD





1/8 R_E

MP5



Summary

- **SWMF is available for registered users and through CCMC**
- **CCMC has been using BATSRUS-RCM-RIM-RBE for many years for runs-on-request as well as real-time now-casting. CRCM is available.**
  - Next: PWOM? Anisotropic MHD? Multifluid MHD?
- **SWMF Geospace (BATSRUS+RCM+RIM) is transitioned to SWPC**
- **New Particle Tracking and Particle-in-Cell Components**
  - kinetic models allow for more physics
  - MHD + Embedded PIC = MHD-EPIC
- **New semi-implicit and high order schemes in BATSRUS**
  - for more accurate and/or efficient simulations
- **Verification, validation and continuous automated testing**

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 = 25and 1000 particles per species per cell