SWMF at the CCMC and Plans for the Future

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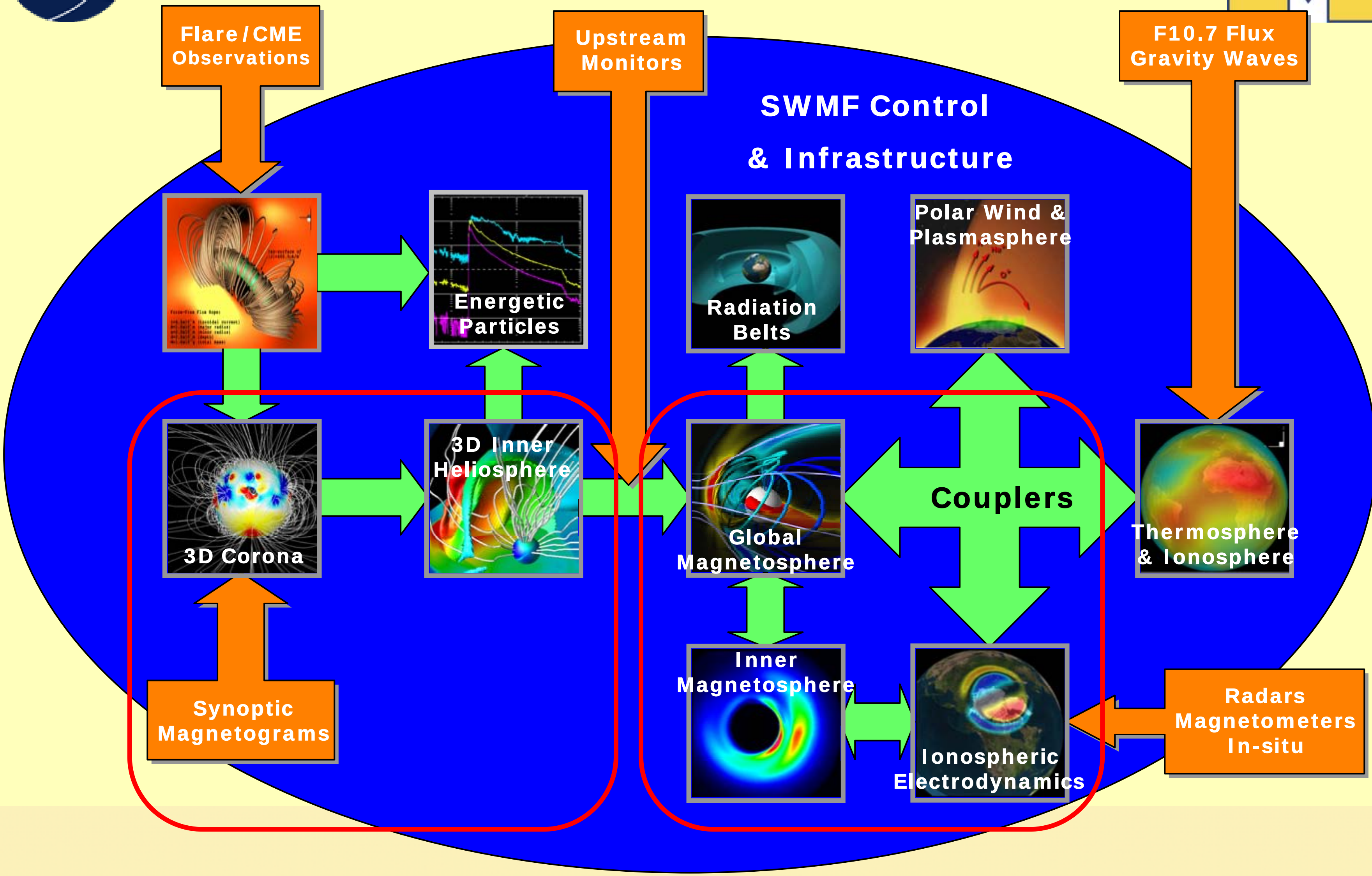
Outline

- **New SWMF features**
  - Polar Wind Outflow Model (PWOM)
  - Radiation Belt Models (RBE and SALAMMBO)
  - Plasmasphere Model (DGCPM)
  - Graphical User Interface
- **New BATS-R-US features**
  - Hall MHD
  - Multifluid MHD
  - Improved Roe solver and new HLLD solver
  - Non-gyrotropic resistivity model (by Masha)
- **Validation Efforts**
- **Future deliveries to CCMC**

Space Weather Modeling Framework



Available at the CCMC as runs-for-request

Physics Models in SWMF

	Physics Domain	ID	Model(s)	
1.	Solar Corona	SC	BATS-R-US	used by CCMC
2.	Inner Heliosphere	IH	BATS-R-US	
3.	Global Magnetosphere	GM	BATS-R-US	
4.	Inner Magnetosphere	IM	RCM	
5.	Ionosphere Electrodynamics	IE	RIM	
6.	Solar Energetic Particles	SP	Kóta & FLAMPA	at CCMC
7.	Eruptive Event Generator	EE	BATS-R-US	
8.	Upper Atmosphere	UA	GITM	
9.	Polar Wind	PW	PWOM	under development
10.	Plasmasphere	PS	DGCPM	
11.	Radiation Belt	RB	RBE & SALAMMBO	

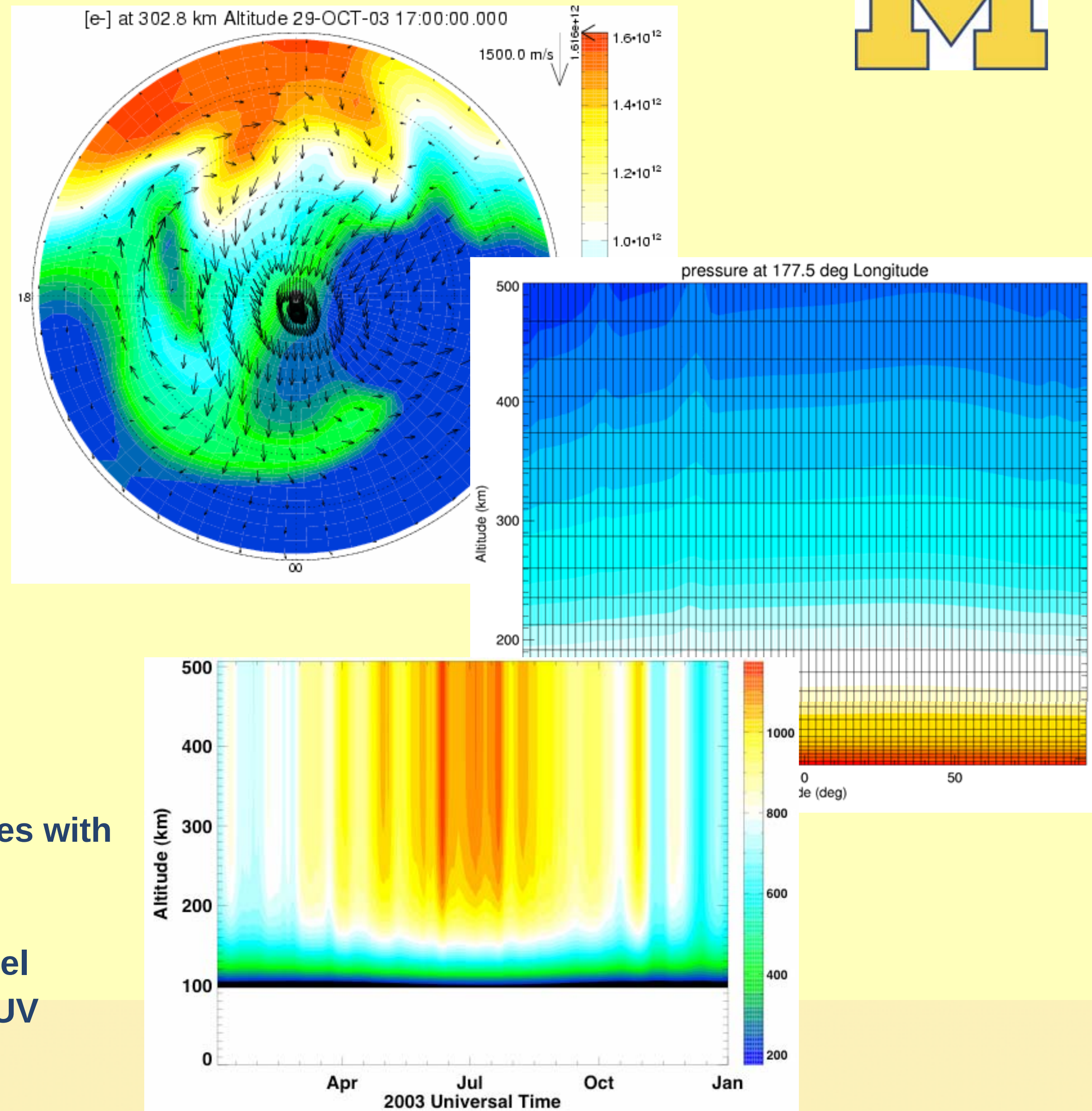
The Global Ionosphere-Thermosphere Model (GITM)

GITM solves for:

- **6 Neutral & 5 Ion Species**
- **Neutral winds**
- **Ion and Electron Velocities**
- **Neutral, Ion and Electron Temperatures**

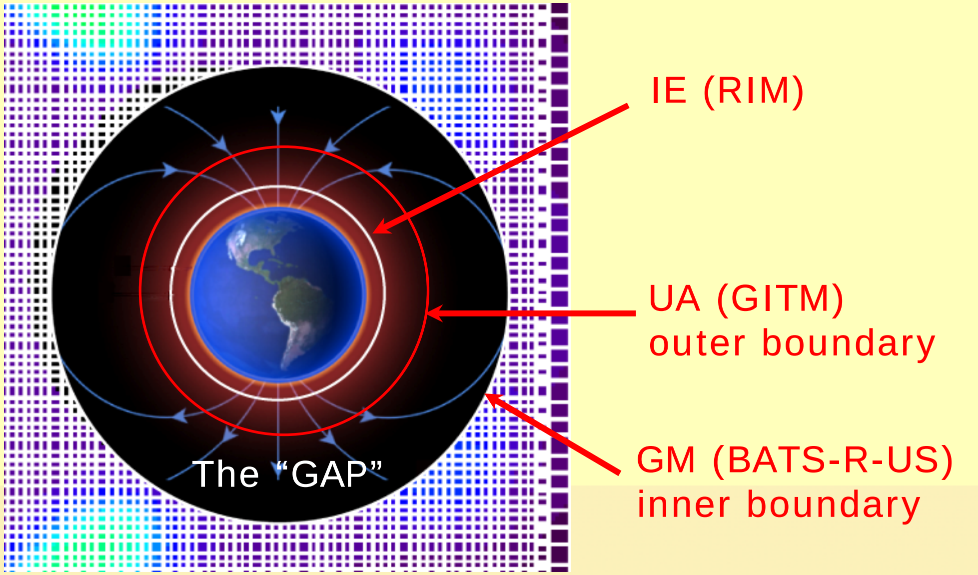
GITM Features:

- **Solves in Altitude coordinates**
- **Can have non-hydrostatic solution**
  - Coriolis force
  - Vertical Ion Drag
  - Non-constant Gravity
  - Massive heating in auroral zone
- **Runs in 1D and 3D**
- **Vertical winds for each major species with friction coefficients**
- **Non-steady state explicit chemistry**
- **Flexible grid resolution - fully parallel**
- **Variety of high-latitude and Solar EUV drivers**
- **Fly satellites through model**



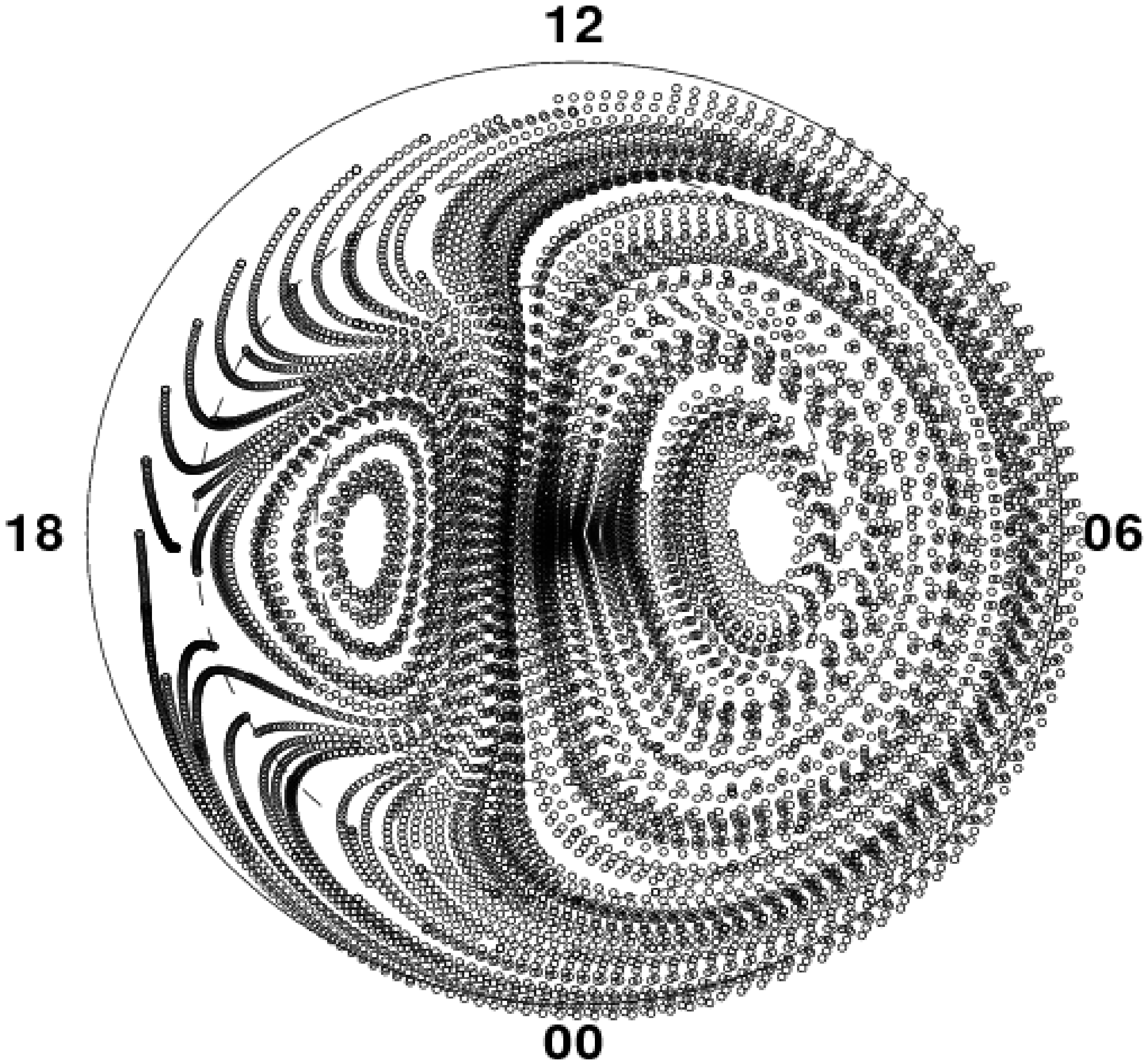
Polar Wind Outflow Model (PWOM) (Alex Glocer)

- **PWOM solves the time-dependent gyrotropic field-aligned transport equations for H^+, O^+, He^+ and e^- along multiple magnetic field lines.**
- **Ion-neutral friction, charge exchange drag, field-aligned currents, topside heating, ion and electron heat conduction, solar zenith angle effects, centrifugal force, chemical sources and losses are all included.**
- **PWOM is fully parallel**
- **Fully implicit time integration**
- **First order Godunov and second order Rusanov schemes**
- **PWOM provides outflow fluxes (density and velocity) for H^+ and O^+ to GM.**
- **PWOM obtains electric potential and field-aligned currents from IE.**



QuickTime™ and a
BMP decompressor
are needed to see this picture.

Overlaid Points Show Convection Pattern



Dynamic Global Core Plasma Model (Mike Liemohn)

- **DGCPM:**
  - Ober et al. [1997] dynamic plasmasphere model
  - Solves the continuity equation for total flux tube content
    - Ionospheric sources and sinks, dayside magnetopause loss
    - Carpenter and Anderson [1992] saturation levels
    - Fixed or variable ionospheric source
- **Already very fast (much faster than real time)**
- **Already capable of handling arbitrary B and E**
- **Already modular and can run as part of the SWMF**
- **To do: coupling**
  - It will affect density, but not pressure, in the MHD model
  - Distributing n_e along B-field lines is an open issue

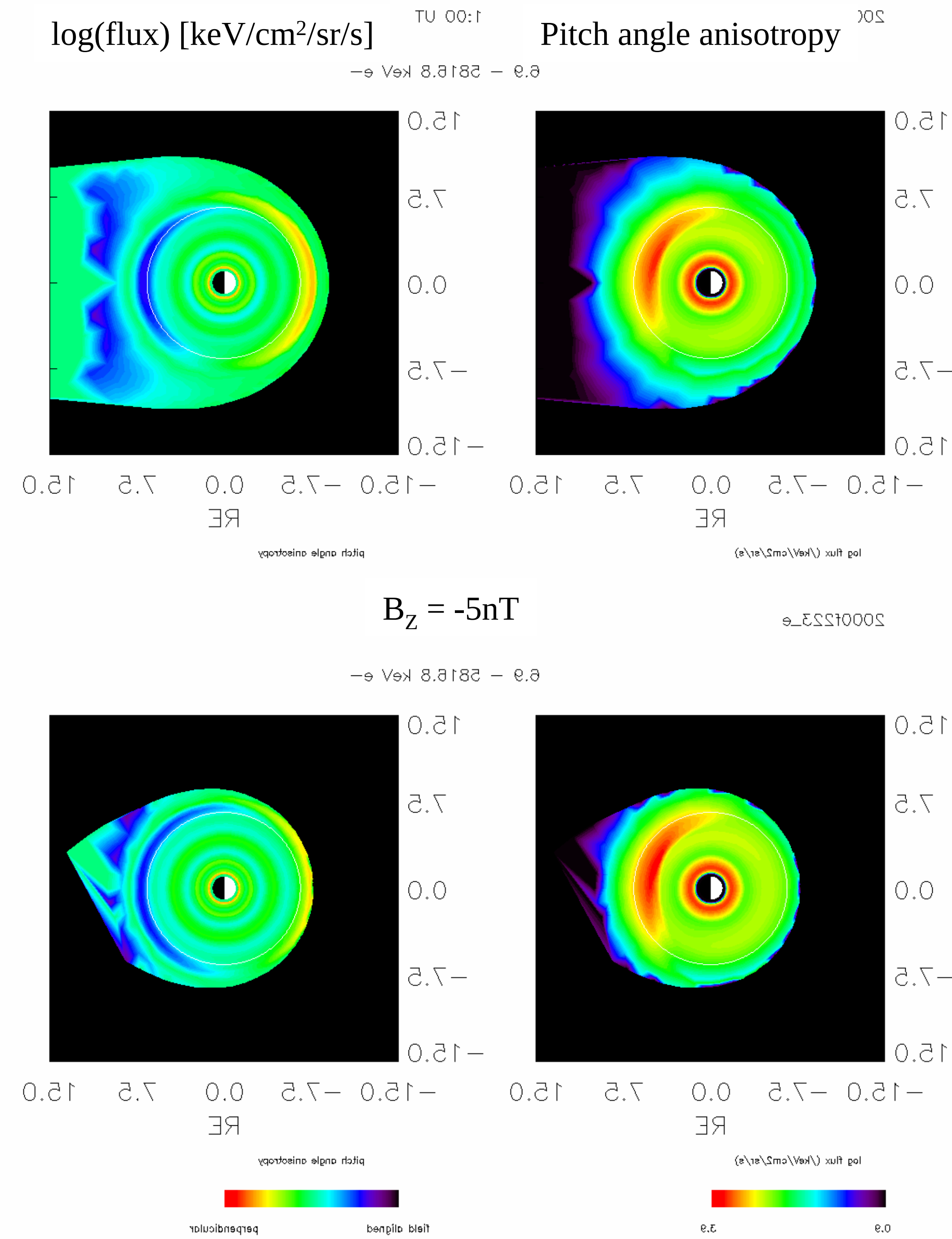
Radiation Belt Environment model (Mei-Ching Fok)

- **RBE:**
  - Solves the 2D drift equations for radiation belt e^- or H^+
  - Includes multiple energies (0.2 - 4 MeV) and pitch angles
- **Already very fast (faster than real time)**
- **Already capable of handling arbitrary B**
- **Runs stand-alone as well as part of the SWMF**
- **Coupling**
  - RBE obtains magnetic field strength and radial distance along closed field lines, and solar wind conditions from GM
  - To do: coupling with IE (currently uses Weimer’s model)

Standalone RBE (with Tsyganenko 2004)

vs.

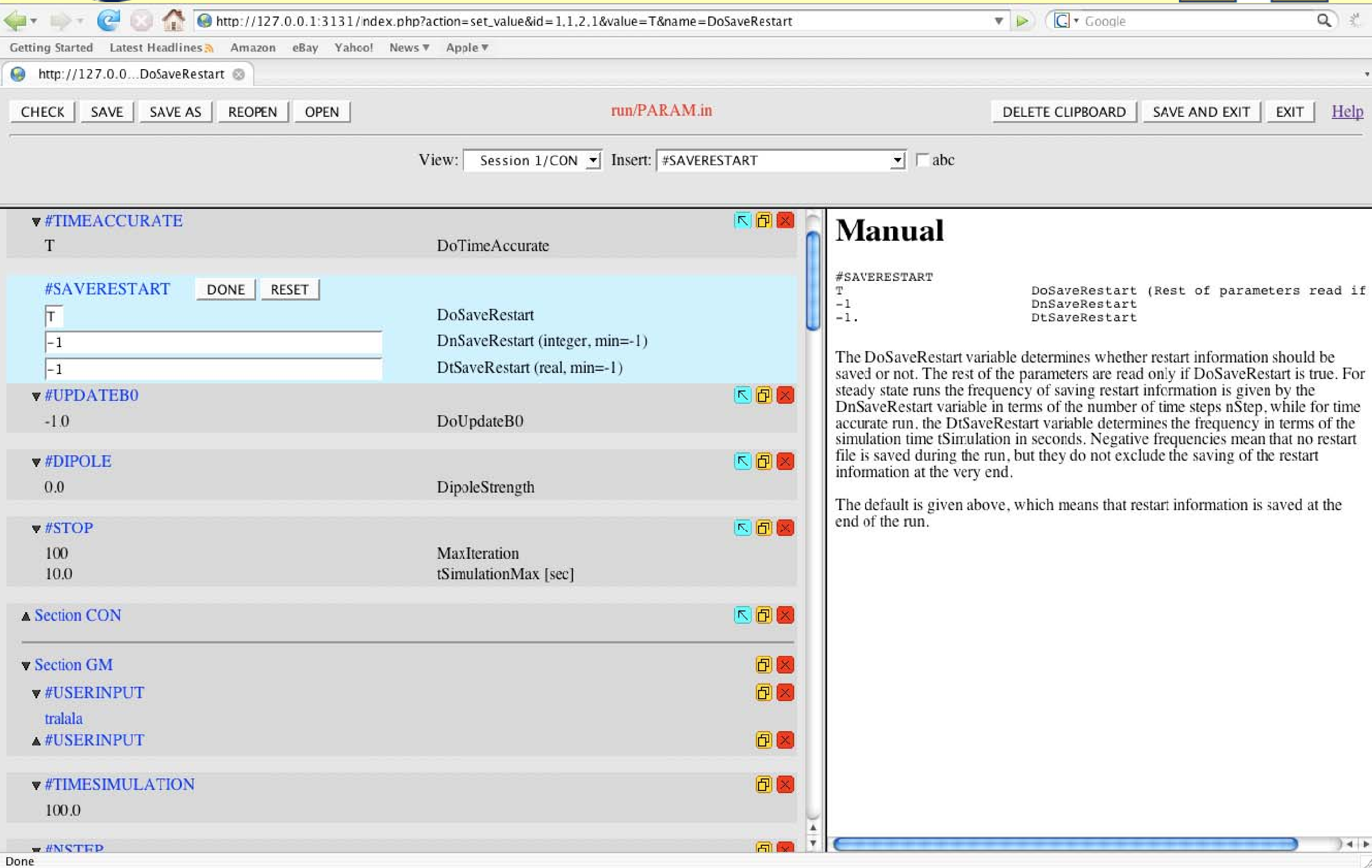
Coupled Model in SWMF



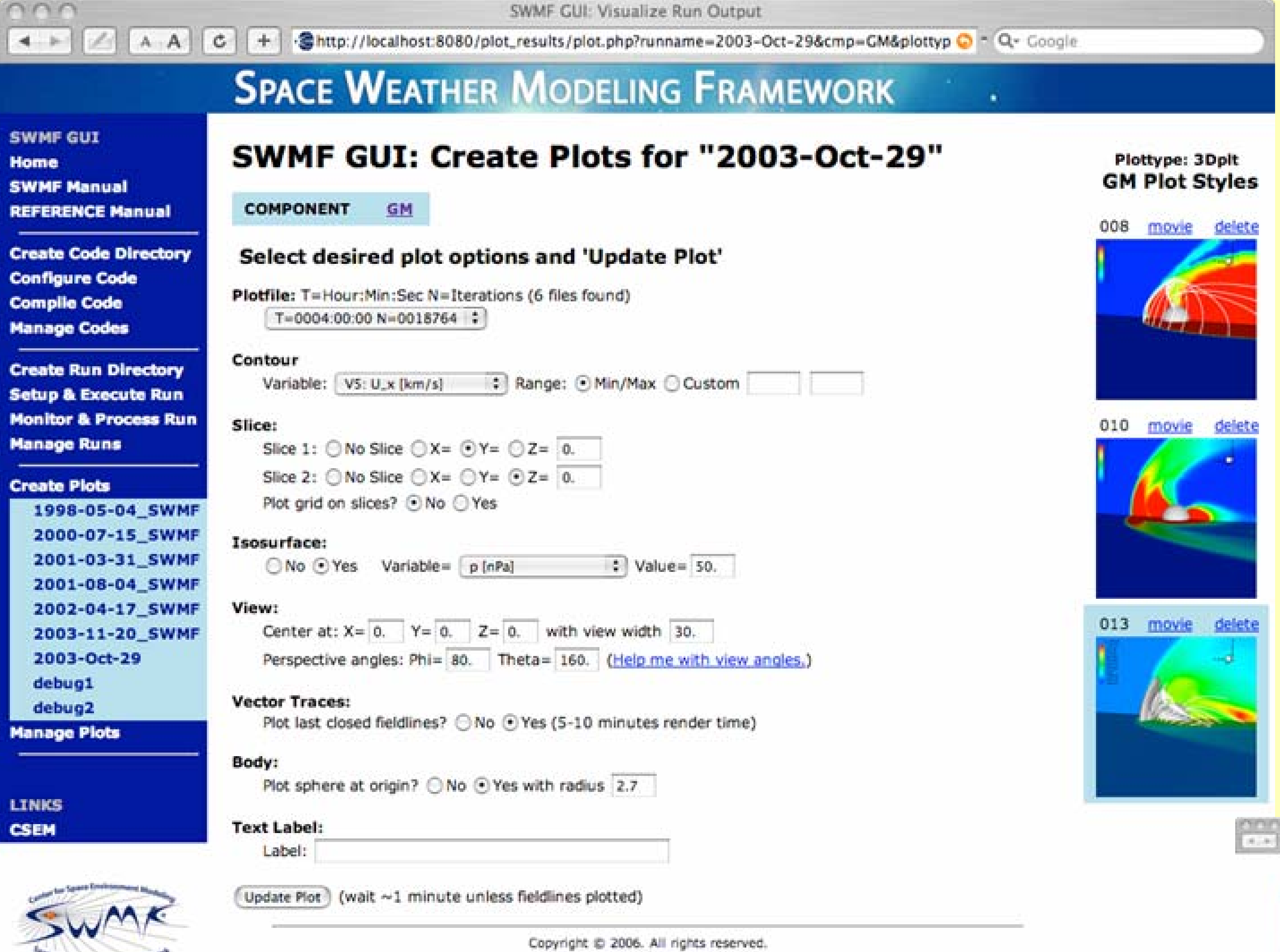
GUI: Code Control

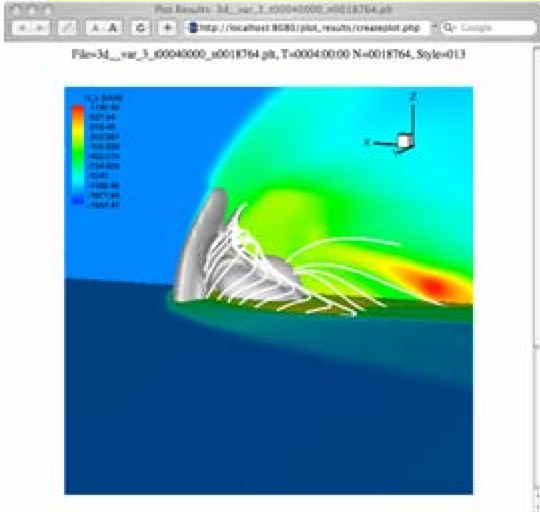
- Components of the framework can be easily selected for use.
- Some components have multiple versions or even alternative models.

Parameter Editor GUI



GUI: Visualization



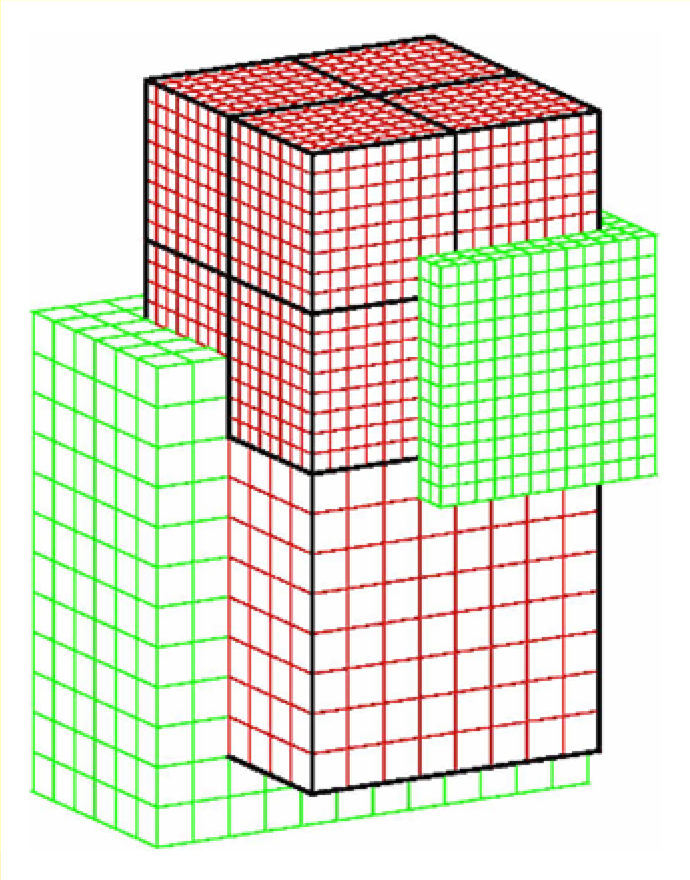


- Visualize run output using quality templates with many customizable options.
- Outputs postscript, png, animated gif, …

MHD Code: BATS-R-US

Block Adaptive Tree Solar-wind Roe Upwind Scheme

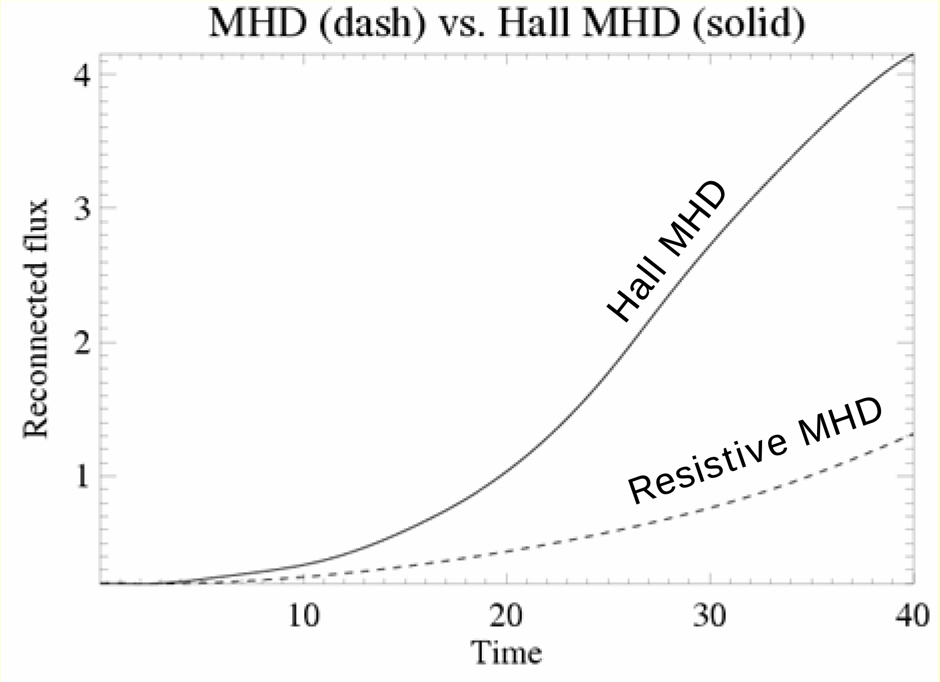
- **Conservative finite-volume discretization**
- **Shock-capturing TVD schemes**
  - Rusanov, HLL/AW, Roe, HLLD
- **Parallel block-adaptive grid**
- **Cartesian and generalized coordinates**
- **Explicit and implicit time stepping**
- **Classical, semi-relativistic and Hall MHD**
- **Multi-species and multi-fluid MHD**
- **Splitting the magnetic field into $B_0 + B_1$**
- **Various methods to control divergence B**



Hall MHD
(Gabor Toth & Yingjuan Ma)

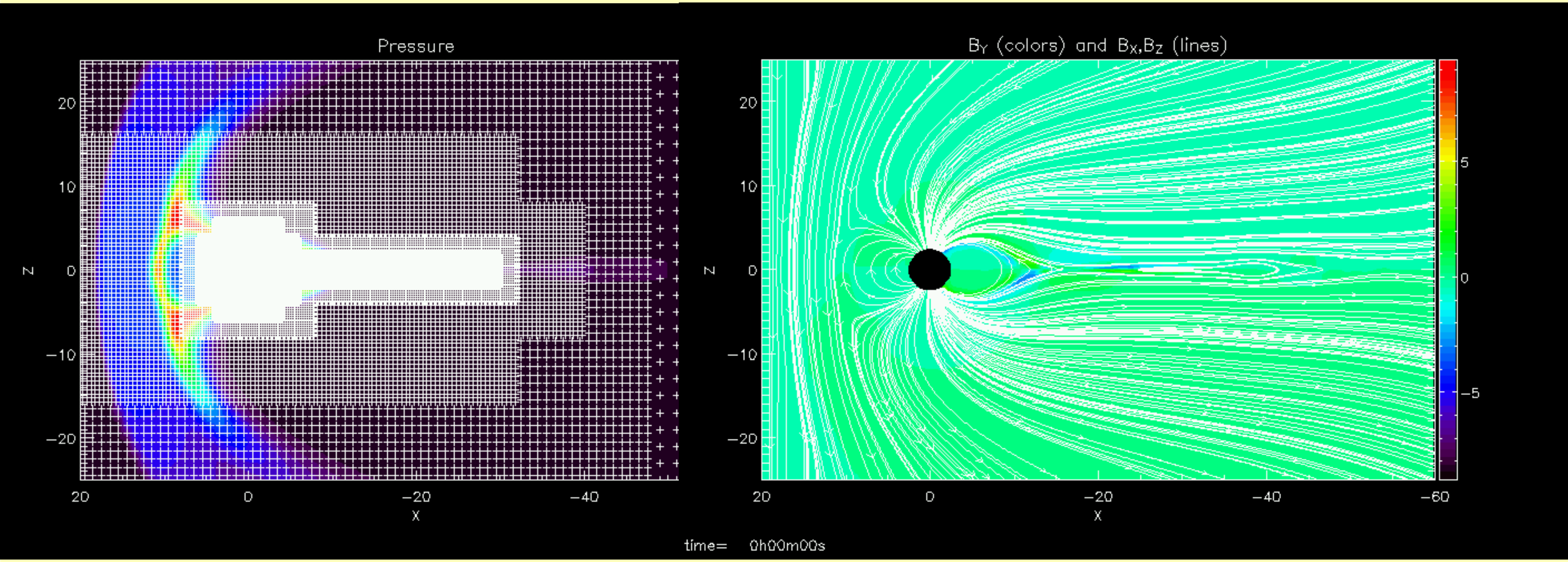
- **Hall physics can play a critical role in collisionless magnetic reconnection.**
- **The GEM challenge on reconnection physics concluded that Hall physics is the minimum physics needed to achieve fast reconnection (Birn et al., JGR, 106, 3715, 2001).**
- **Physically, the Hall term decouples the ion and electron motion on length scales comparable to the ion inertial length ($\delta = c/\omega_{pi} = V_A/\Omega_{ci}$). In essence, the electrons remain magnetized while the ions become unmagnetized.**
- **Consequences:**
  - **Whistler wave (very fast)**
  - **Introduces asymmetry**
  - **Ion kinetics can lead to fast reconnection**

$$\mathbf{E} = -(\mathbf{u} + \mathbf{u}_H) \times \mathbf{B} + \eta \mathbf{j} \qquad \mathbf{u}_H = -\frac{\mathbf{j}}{e n_e}$$



GEM Challenge simulation with BATS-R-US

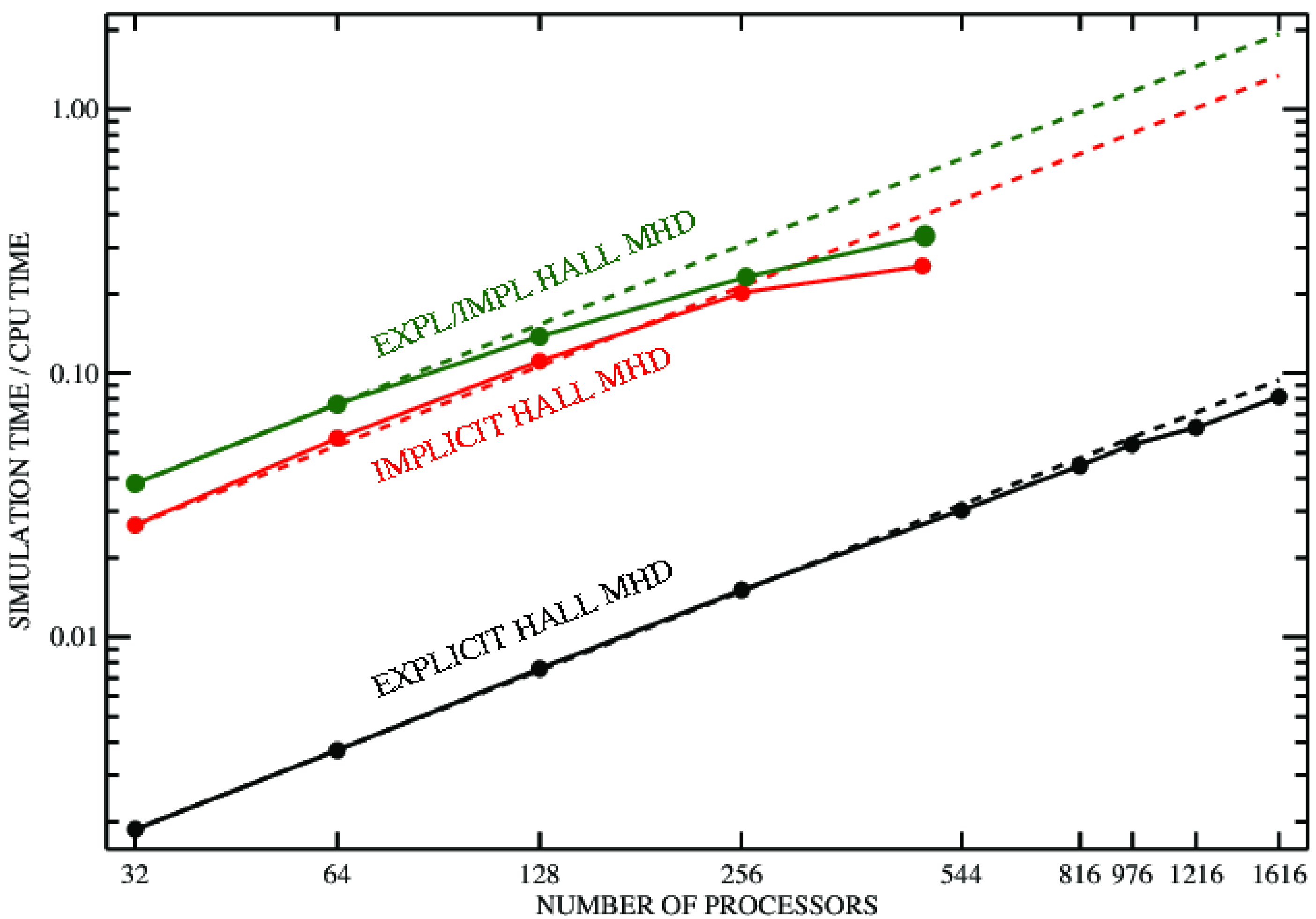
Hall MHD Magnetosphere Simulation



48,04 blocks with 8x8x8 cells (total 2.5 million cells) ranging from 8 to 1/16 R_E.

Solution shows blobs of plasma detaching in the tailward direction. Time scale is a few minutes.

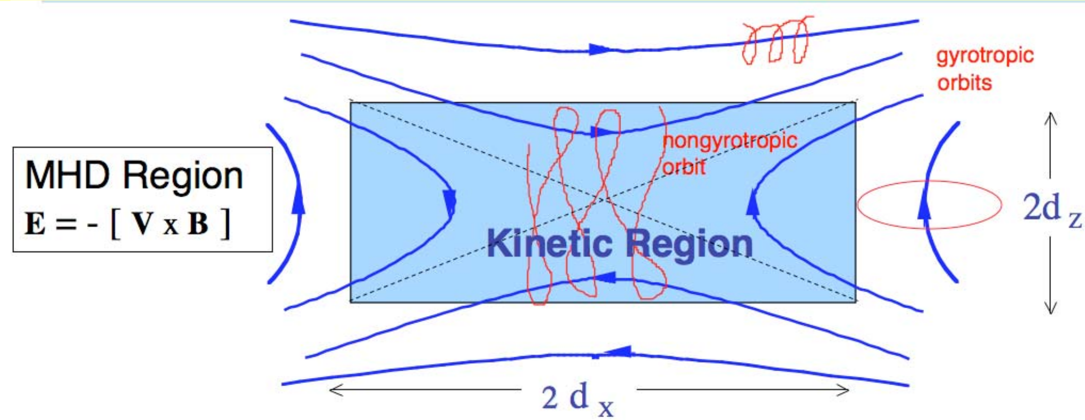
Parallel Scaling for Hall MHD

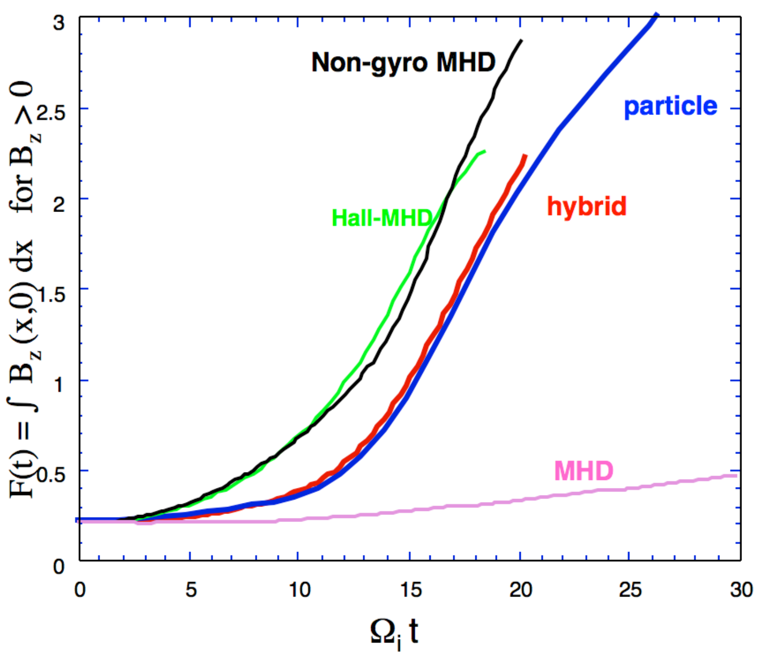


Grid: 4804 blocks with 8x8x8 cells (2.5 million cells) ranging from 8 to 1/16 R_E. Simulations done on an SGI Altix machine.

Non-Gyrotropic Reconnection Model (Masha Kuznetsova)

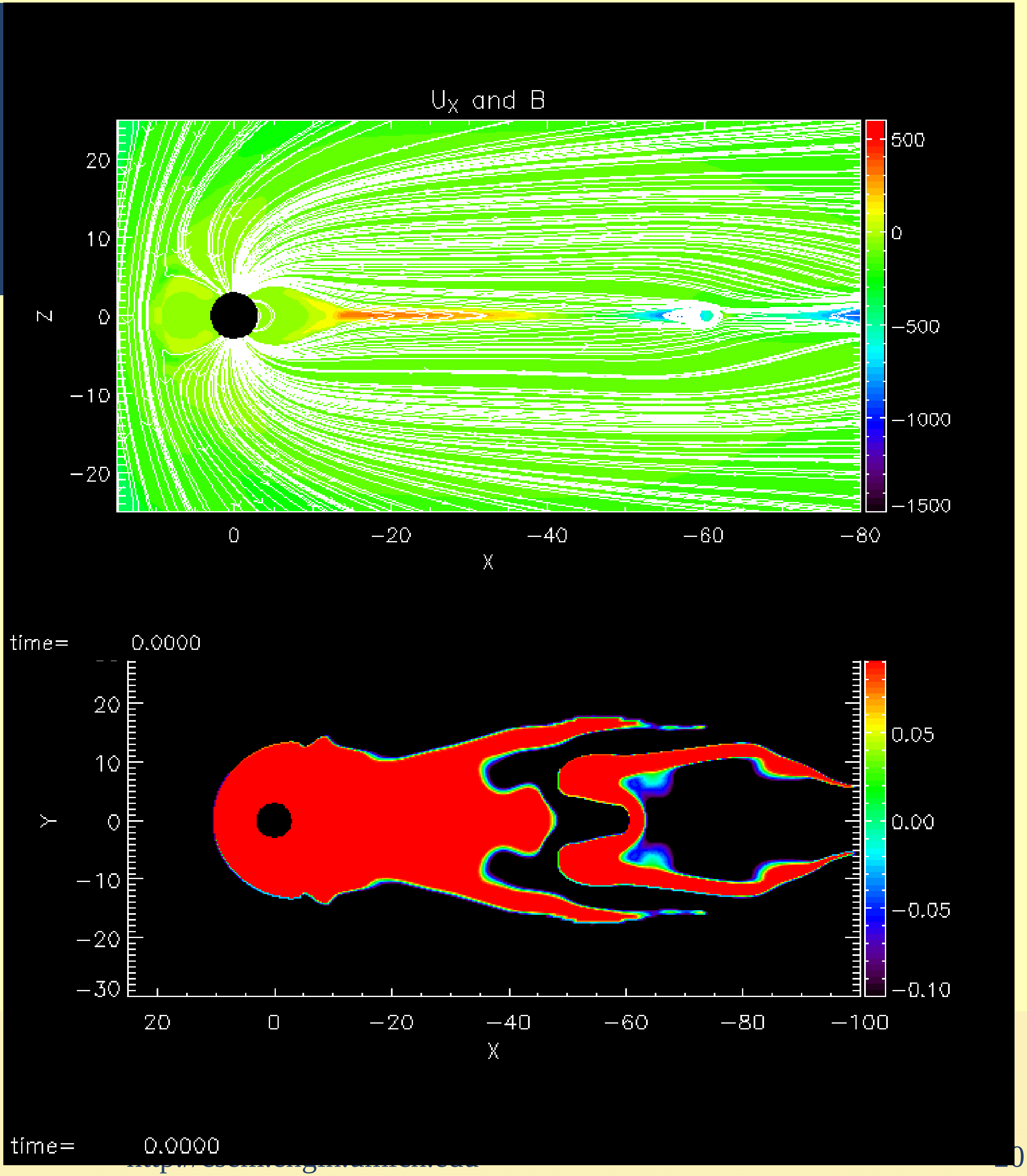
- **Idea:**
  - Use full particle and hybrid simulations to construct a phenomenological but quantitatively accurate reconnection model
- **Algorithm:**
  - Find reconnection sites
  - Fit an appropriately sized 'box' around it
  - Modify the electric field (and thus the induction equation) based on the model.
- **Advantage:**
  - Allows fast reconnection
  - Efficient and simple
- **Disadvantage:**
  - Finding reconnection site is not easy
  - Ad-hoc parameters need tuning
- **To do:**
  - **Find reconnection site and its orientation in general configurations**
  - **Validate/tune model against/for events**





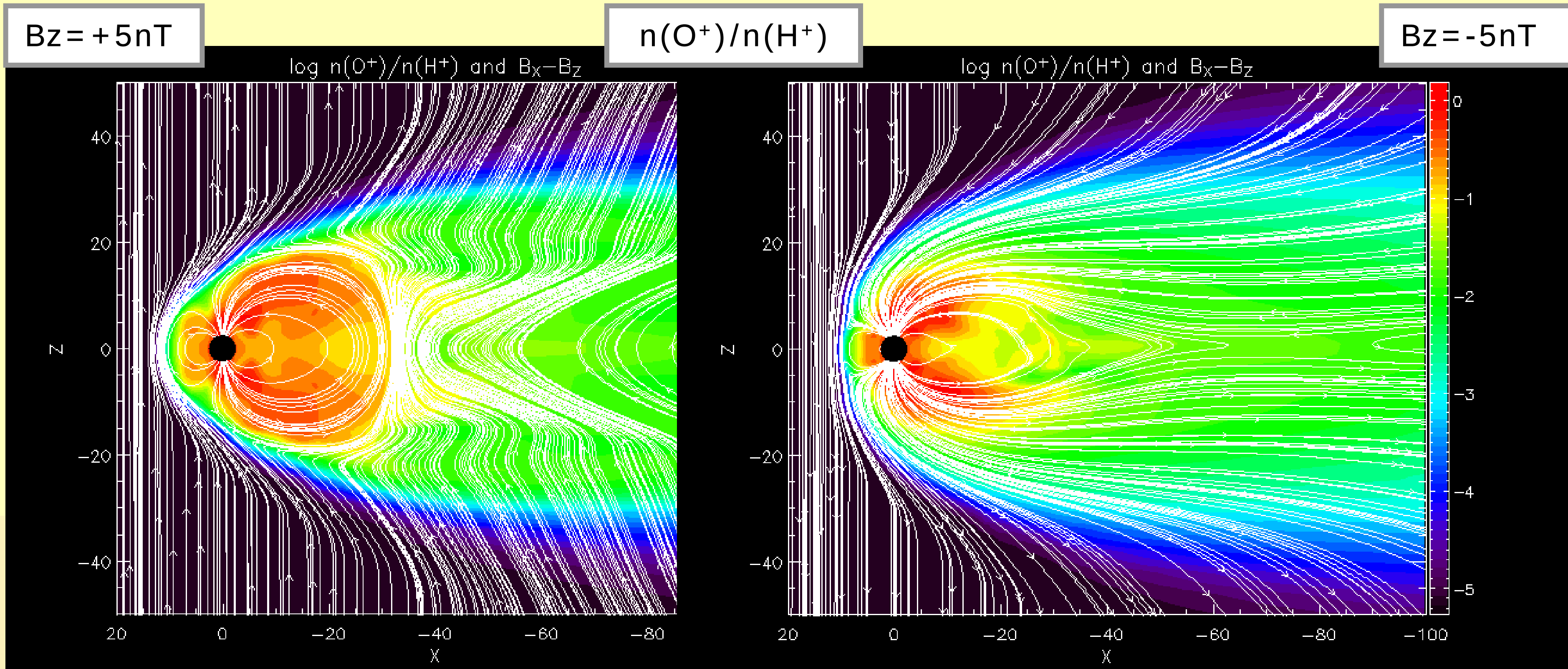
Non-Gyrotropic Reconnection Model simulation with the latest version of BATS-R-US

- **Solution shows large blobs of plasma detaching in the tailward direction (similar to Masha's earlier results).**
- **Time scale is more than an hour.**
- **Reconnection line is strongly curved in the Y=0 plane.**



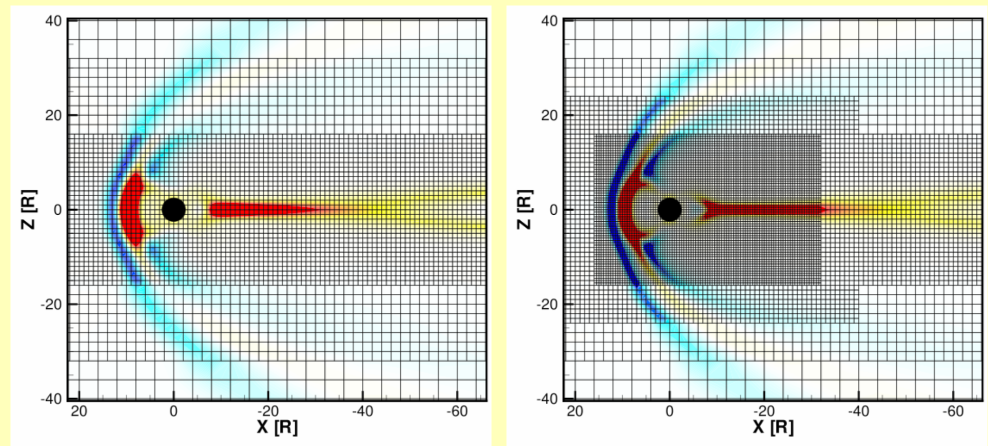
Multi-Fluid MHD
(Gabor Toth & Yingjuan Ma)

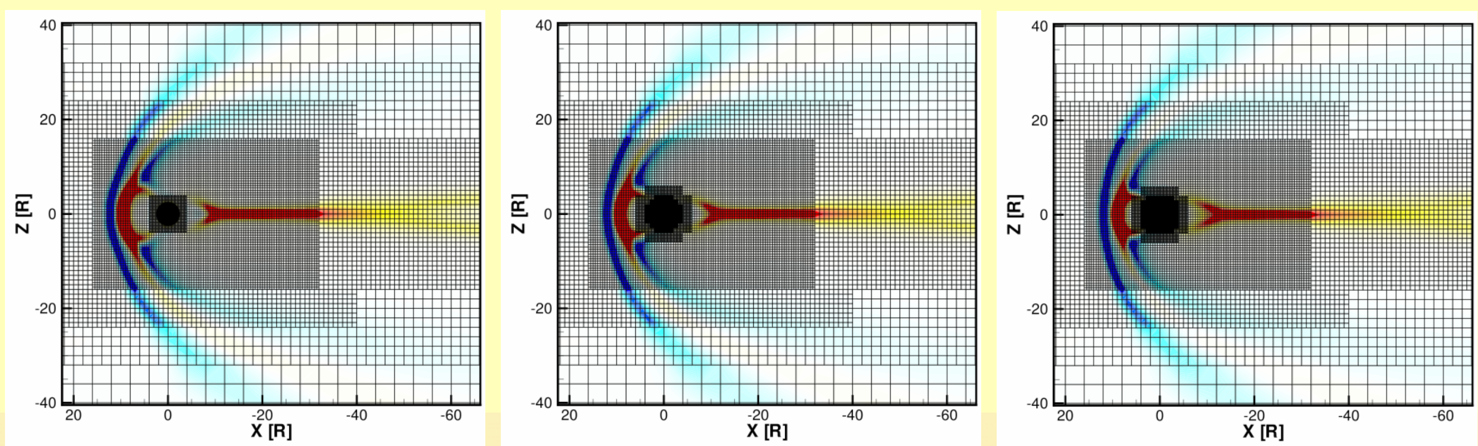
- **Multi-Fluid MHD has many potential applications**
  - ionospheric outflow, outer heliosphere interaction with inter stellar medium, etc.
- **We have implemented a general multi-fluid solver with arbitrary number of ion and neutral fluids.**
- **Each fluid has a separate density, velocity and temperature.**
- **The fluids are coupled by collisional friction/charge exchange and/or by the magnetic field.**
- **We are still working on improving the stability/efficiency of the scheme.**



Verification Study: Effect of Numerics on CPCP

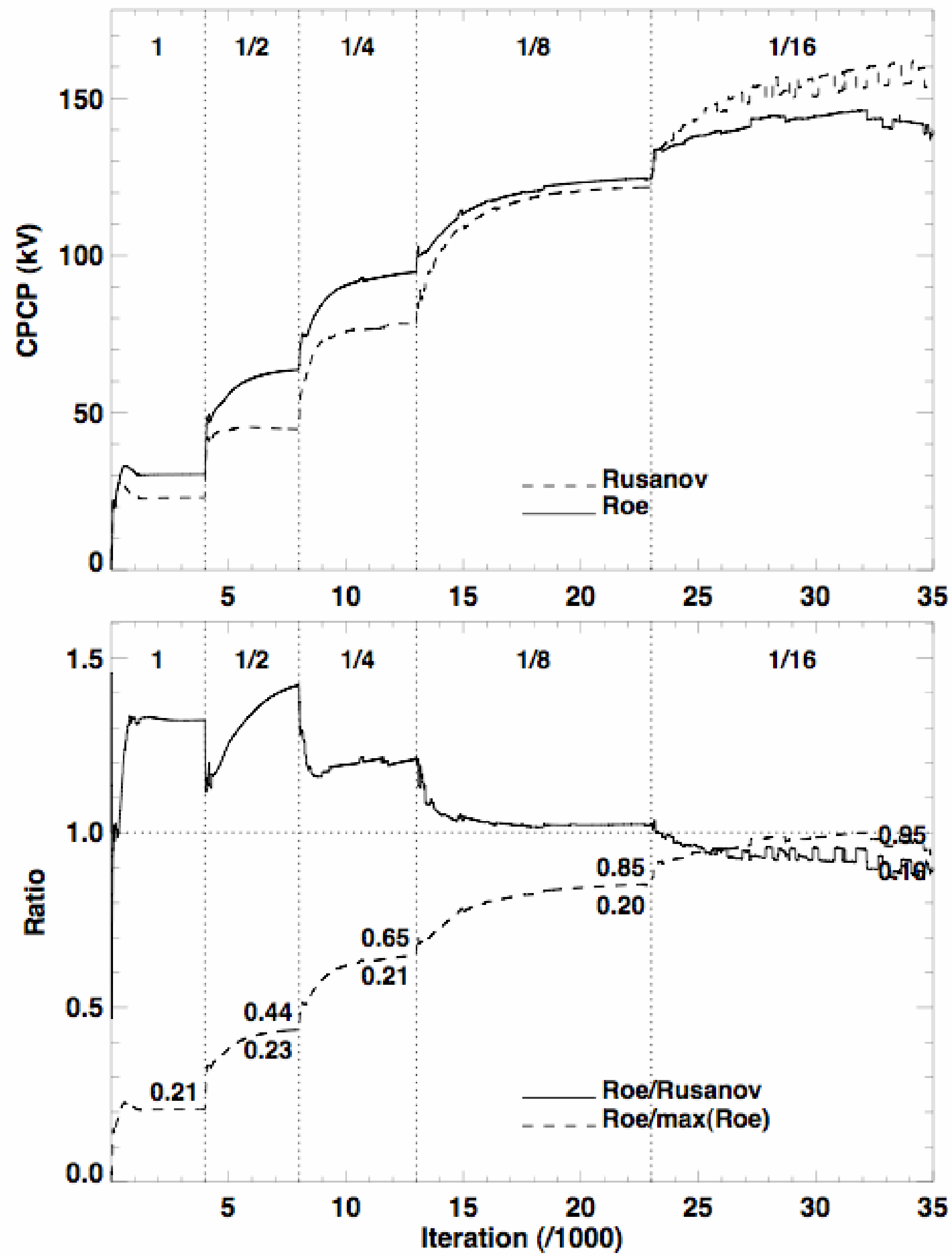
- Change resolution from 1.0 Re near body to 1/16 Re near body
- Run to steady state at each resolution
- Use various solvers/options to investigate numerical effects



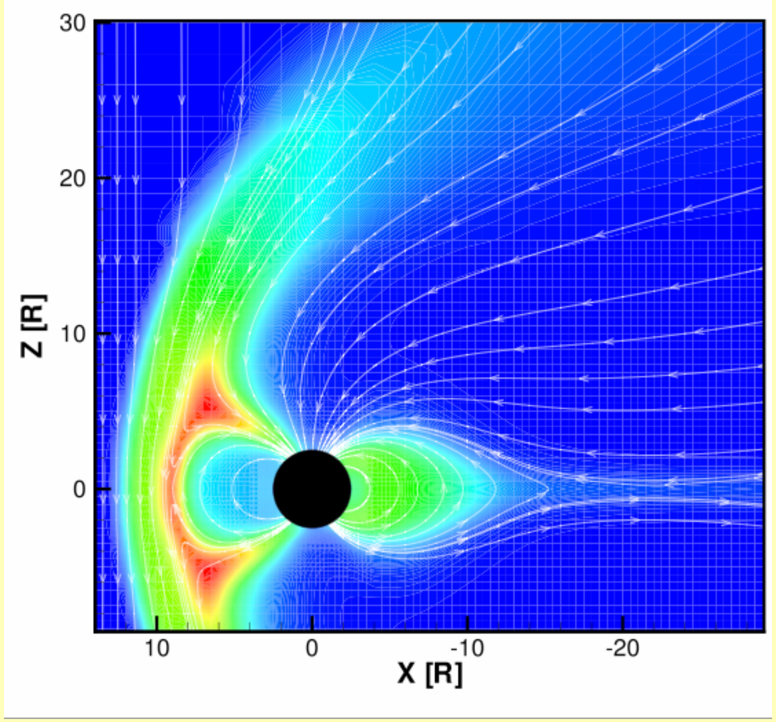


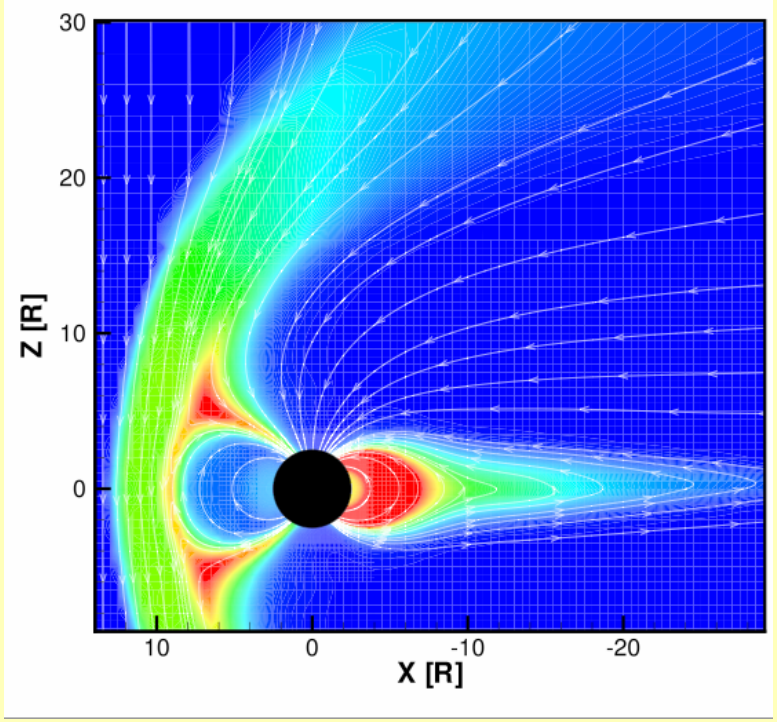
Grid Convergence and Rusanov vs Roe Scheme

- The CPCP starts to converge at the highest resolutions only
- Rusanov scheme is a very robust algorithm
- Roe solver has much less numerical diffusion
- Roe has larger CPCP than Rusanov on coarse grids (as expected), but smaller CPCP at high resolution. Why???



Pressure in the Y=0 Plane
Rusanov vs Roe

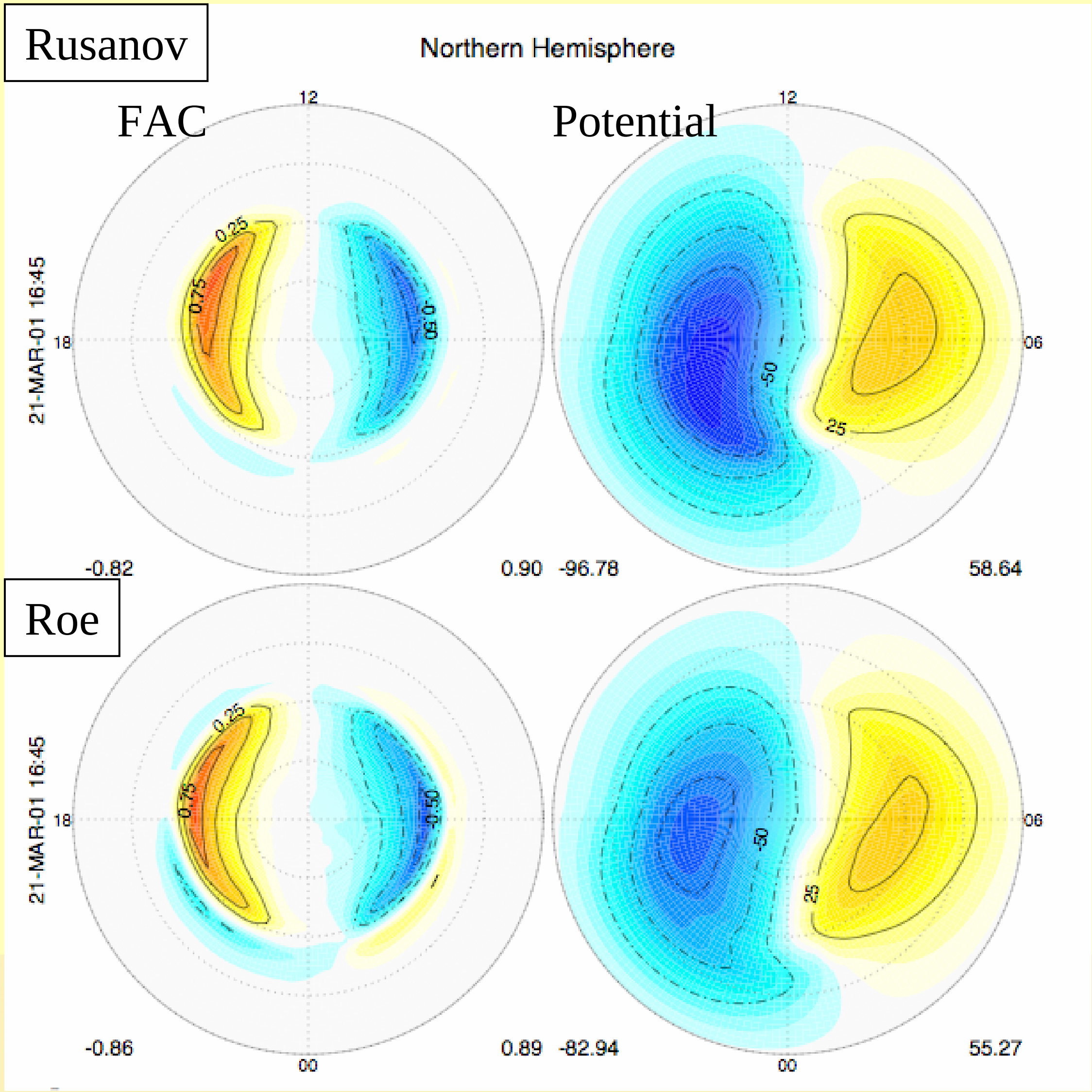




- **Pressure in the tail is MUCH larger for the Roe solver**
- **Field-lines are greatly stretched in tail**
- **Solution looks much better!**

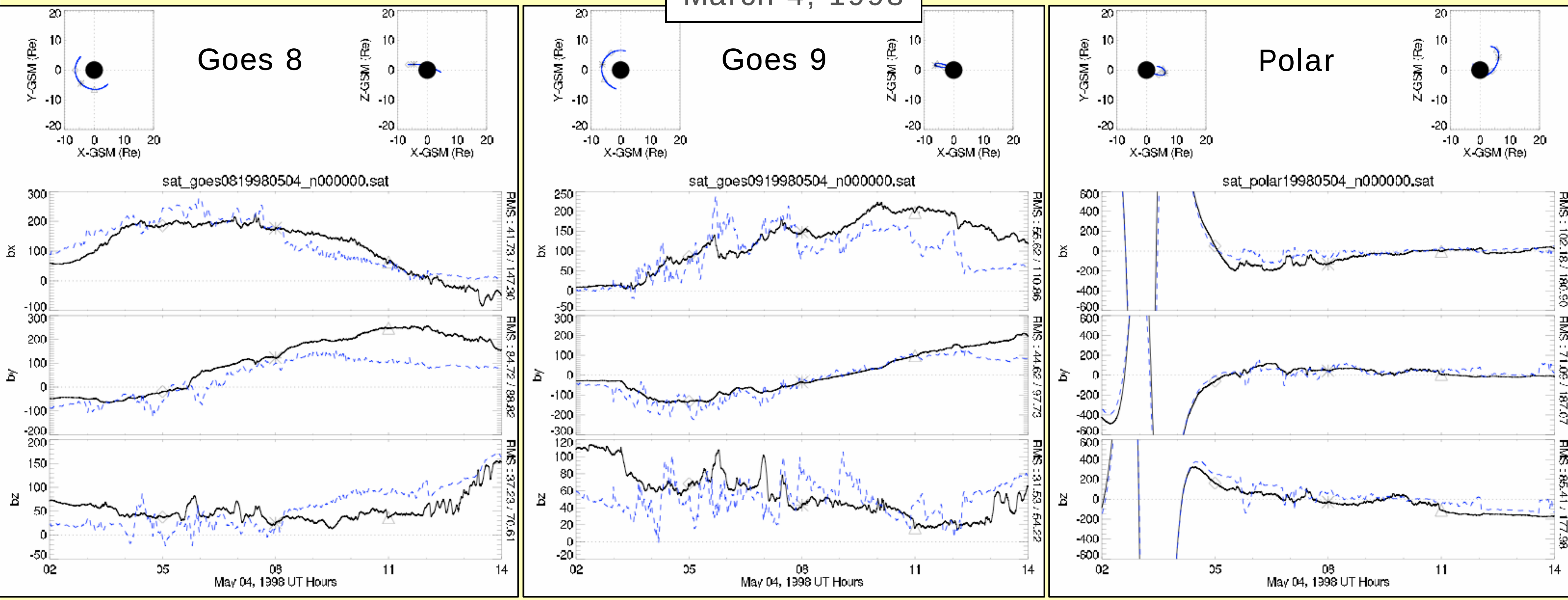
Ionosphere solution for Rusanov (top) vs Roe (bottom)

- Notice Region-2 currents on night-side in Roe simulation (bottom).
- Stronger region-2 currents allow Pedersen currents to close towards lower latitudes, thereby reducing the potential.
- This is why the Roe solver produces a lower potential.



Multi-Spacecraft / Multi-Storm Validation (Aaron Ridley)

March 4, 1998



- **Started to systematically and quantitatively validate the SWMF**
- **Track improvements in the code in a quantitative manner**
- **Run 10 time-periods ranging from quiet to superstorm**
- **Automatically downloads code and runs each event**
- **We validate against 150+ magnetometers, DMSP, CHAMP, GOES, Polar…**

Future Deliveries to CCMC

- CCMC already has a recent version of the SWMF.
- GITM could be added to the magnetosphere simulations.
- Improved Roe solver could be a new option in BATS-R-US.
- Hall and Multi-Fluid MHD could also be used after some validation and improvements.
- PWOM, RBE, SALAMMBO and DGCPM will be delivered once they are fully coupled and tested.
- SWMF GUI and Parameter Editor may be useful for CCMC.