Goddard SPACE FLIGHT CENTER

HSD

NASA

# Global Modeling of the Space Environment System

**Alex Glocer**

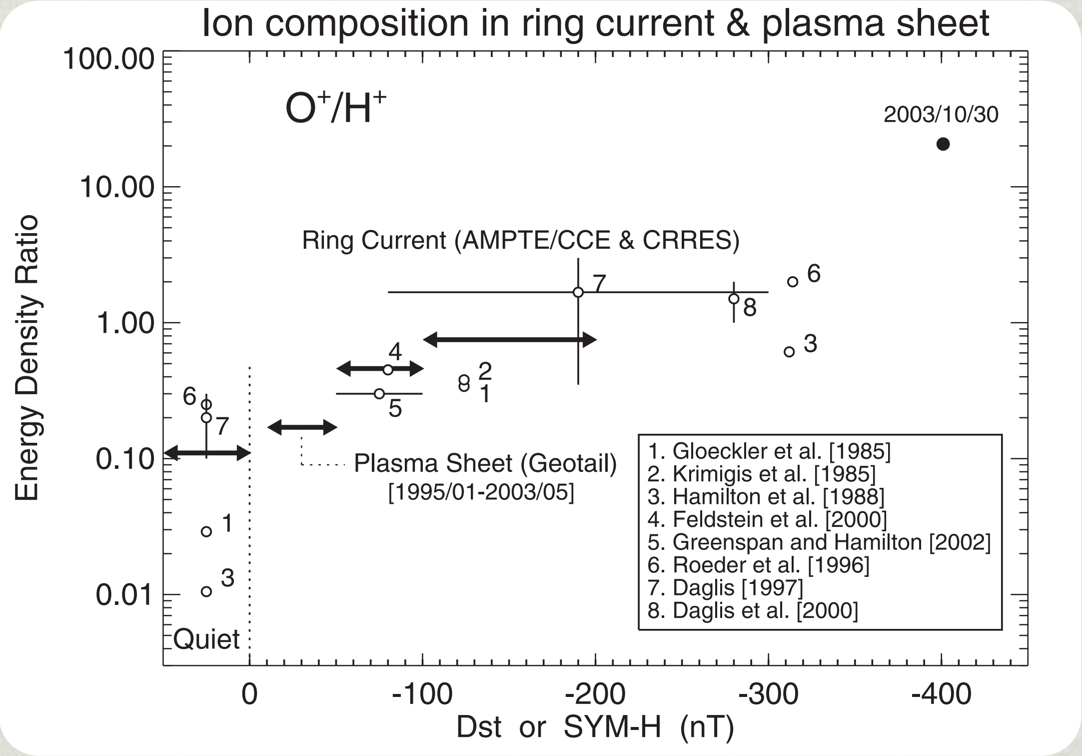
thanks to: J. Dorelli, L. Daldorff, G. Toth, D. Welling, G. Khazanov, C.Komar, L. Wang,

# Overview

- The space environment system is comprised of a myriad of constituents and regions with different:
  - Characteristic energies
  - Spatial and temporal scales
  - Physical processes
- Sometimes what is required is extending the equation set, and sometimes coupling tailored models is needed.
- Three topics covered:
  - Magnetosphere composition and ionospheric outflow
  - Inner magnetosphere coupling
  - Reconnection in global magnetosphere models
- I will cover these topics from a global modeling perspective.

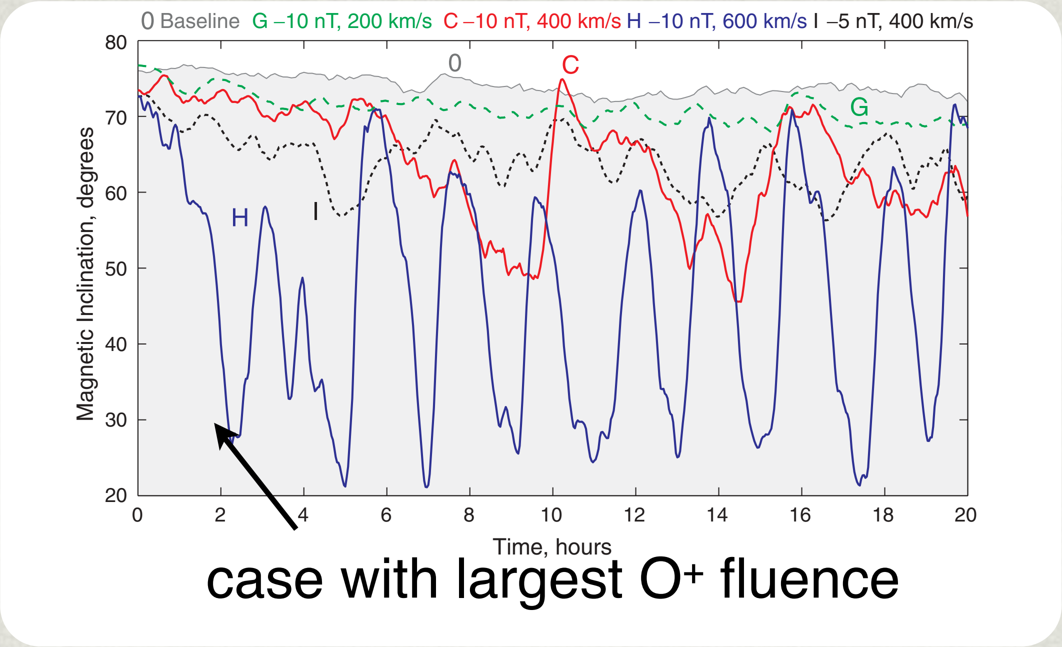
# O+ in the ring Current

Nose et al. [2005]



# O+ with Sawteeth

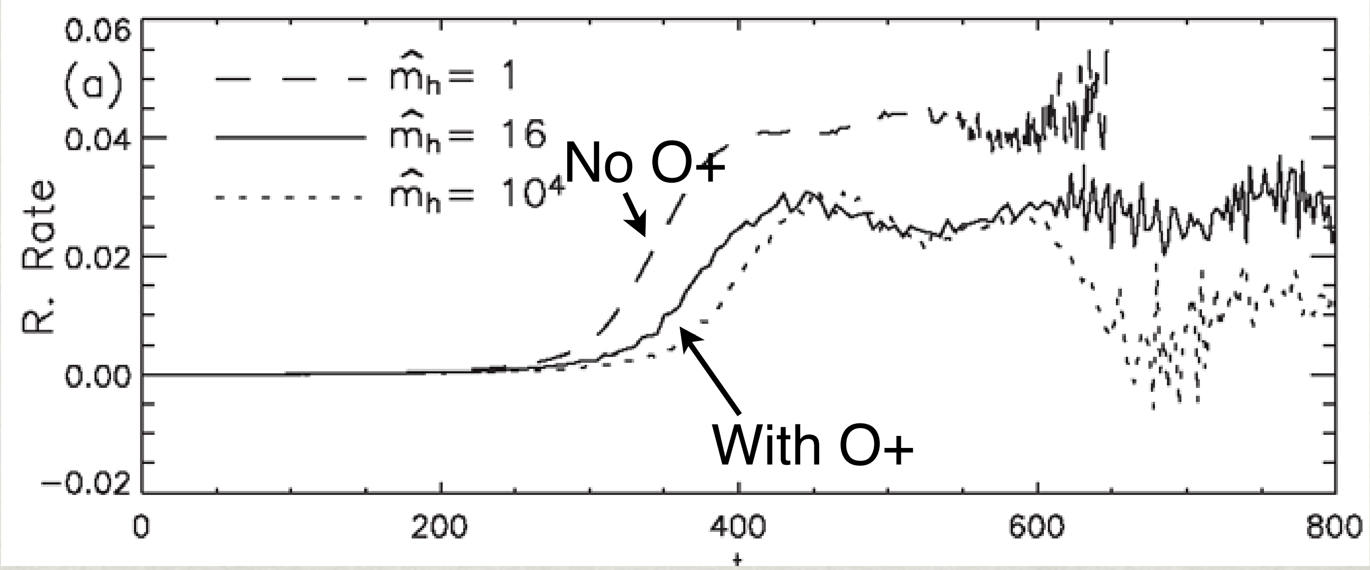
Brambles et al. [2010]



case with largest O+ fluence

# O+ and Reconnection

Shay et al. [2004]

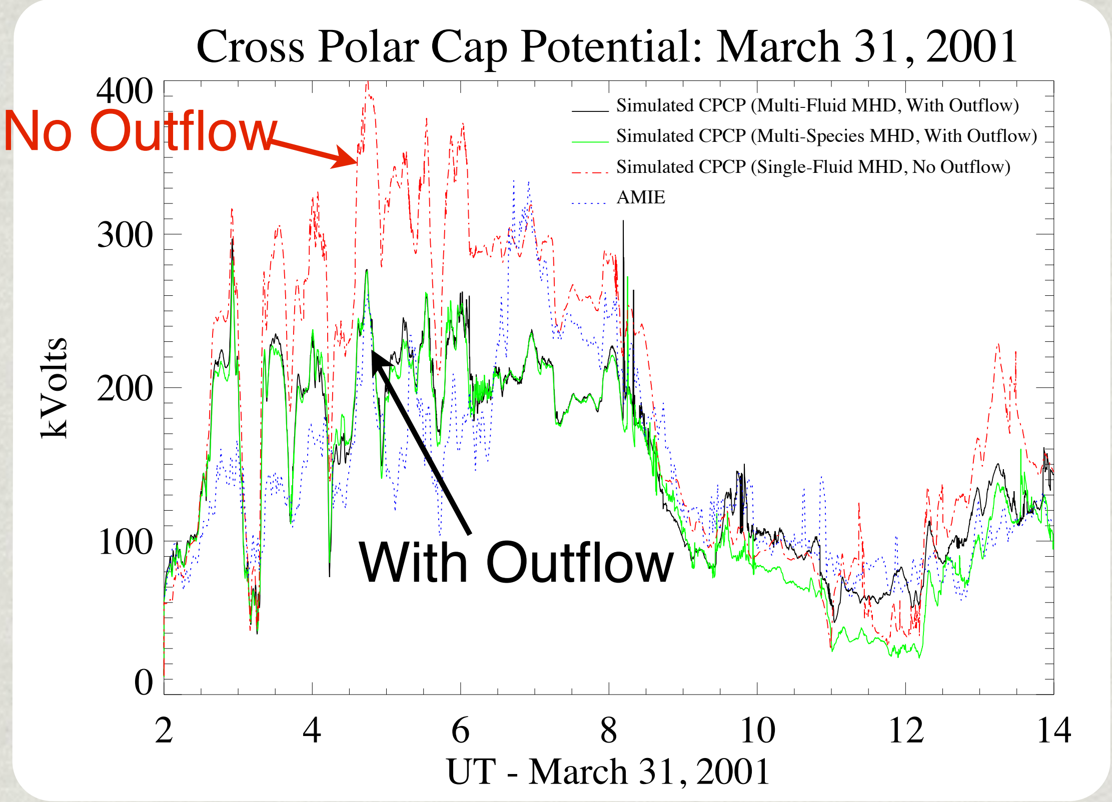


No O+

With O+

# O+ and CPCP

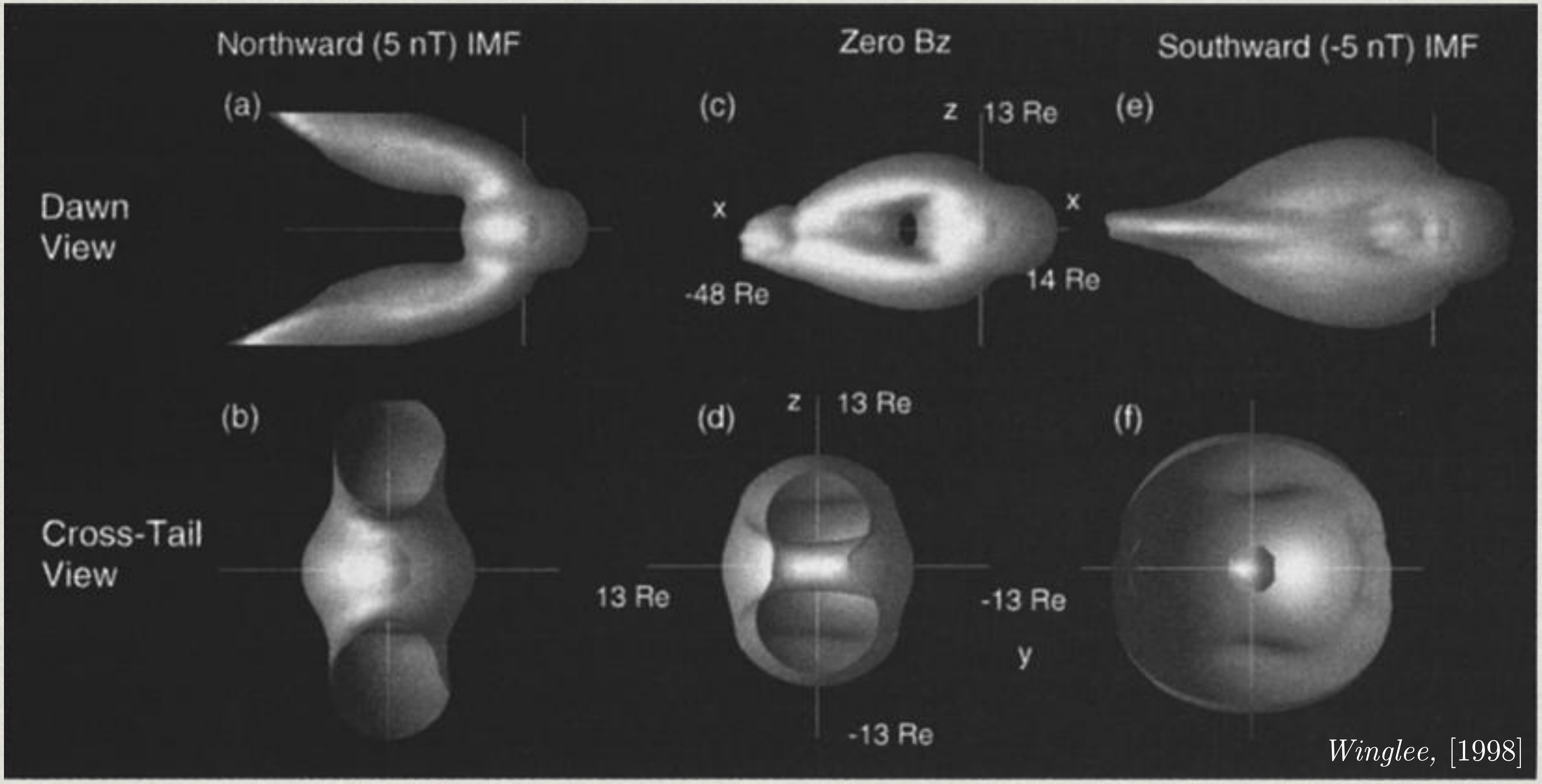
Glocer et al. [2009]



No Outflow

With Outflow

# First Multifluid MHD Modeling of the Magnetosphere

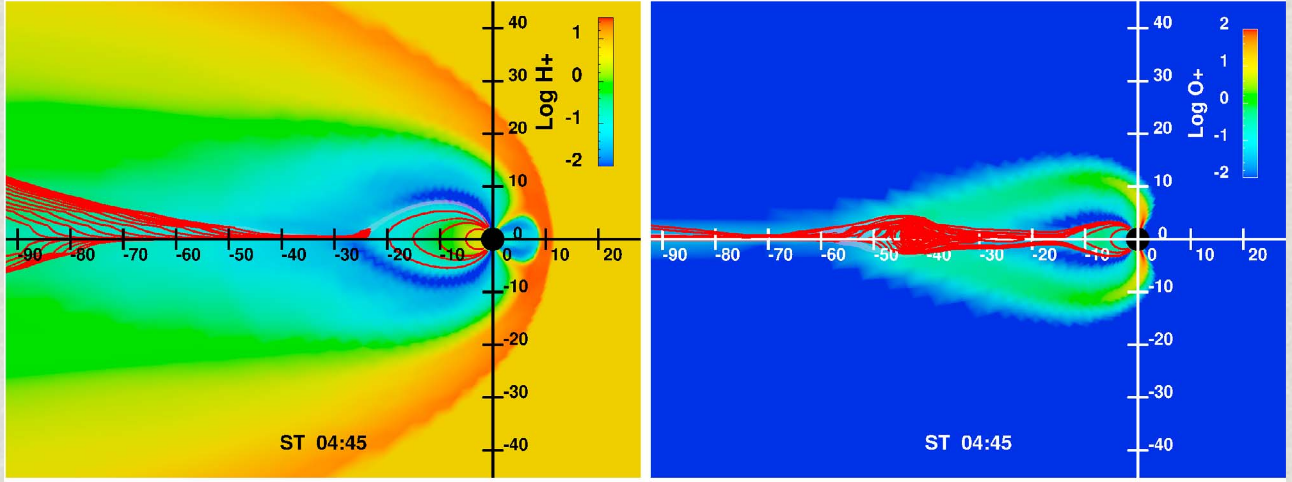


*Winglee*, [1998]

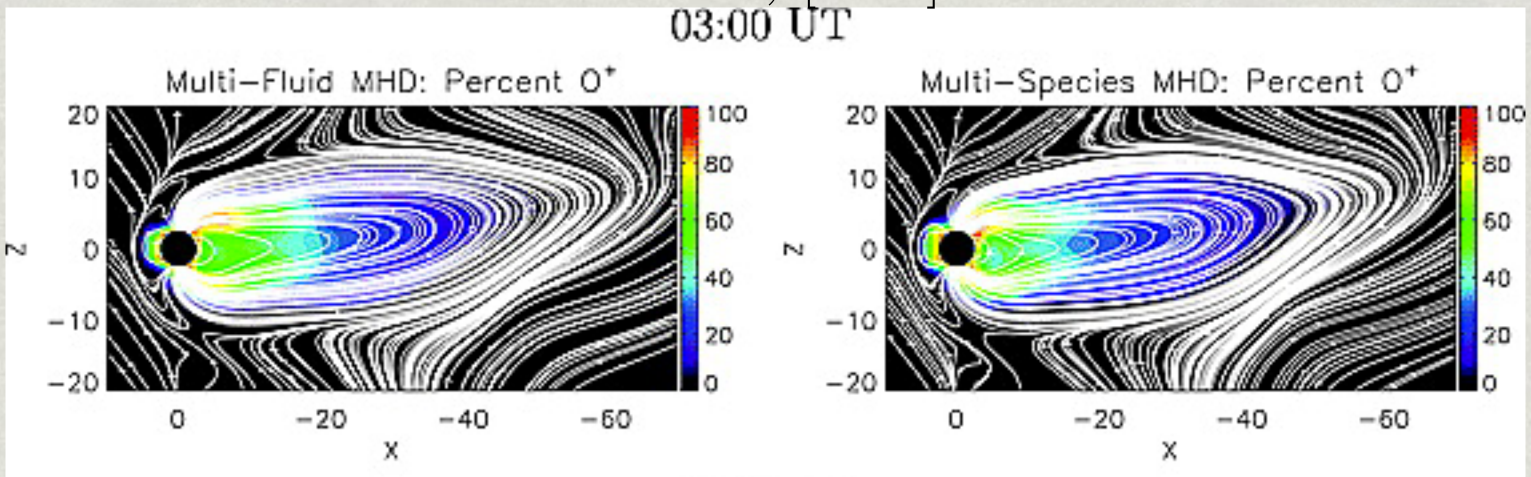
- Winglee [1998], first MFMHD simulations of the magnetosphere.
- Investigated geopause boundaries where the contributions to the magnetospheric density or pressure from the ionosphere equals that from the solar wind.

# 10 years later…

*Wiltberger et al,* [2010]

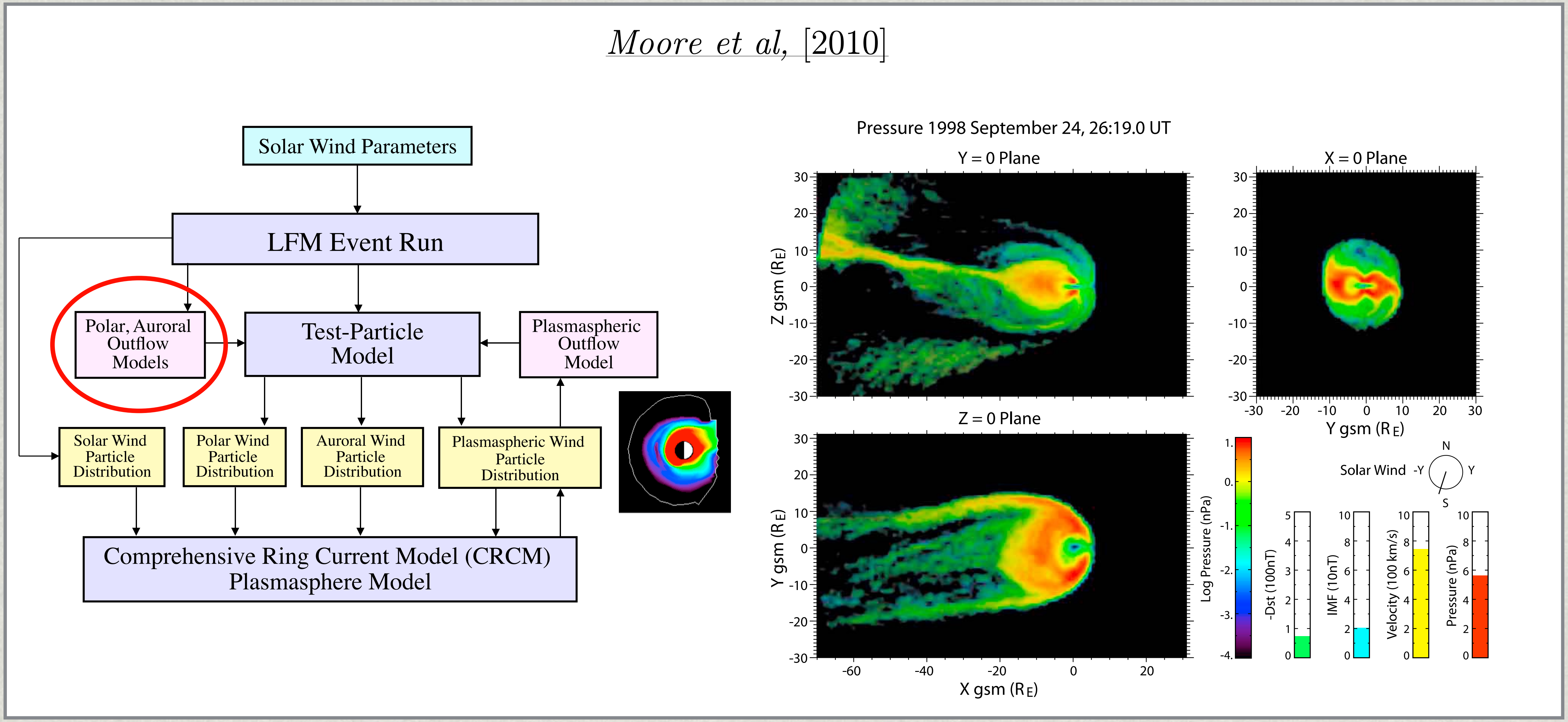


*Glocer et al,* [2009]



- Both LFM and BATS-R-US global magnetosphere models now have multi fluid capabilities
- Used to investigate consequences of ionospheric outflow.

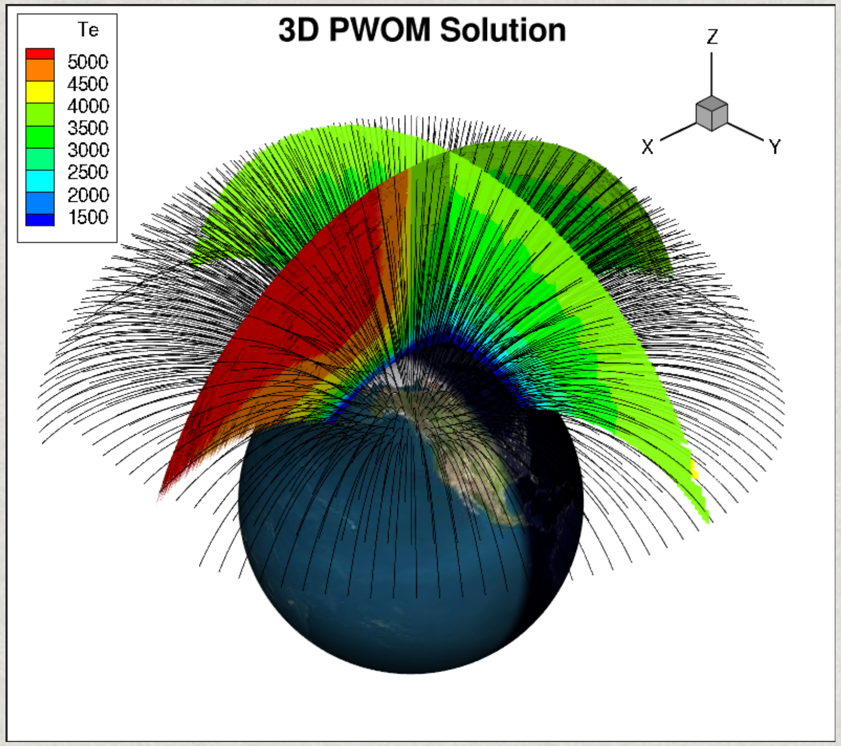
# Alternatives to Multifluid MHD

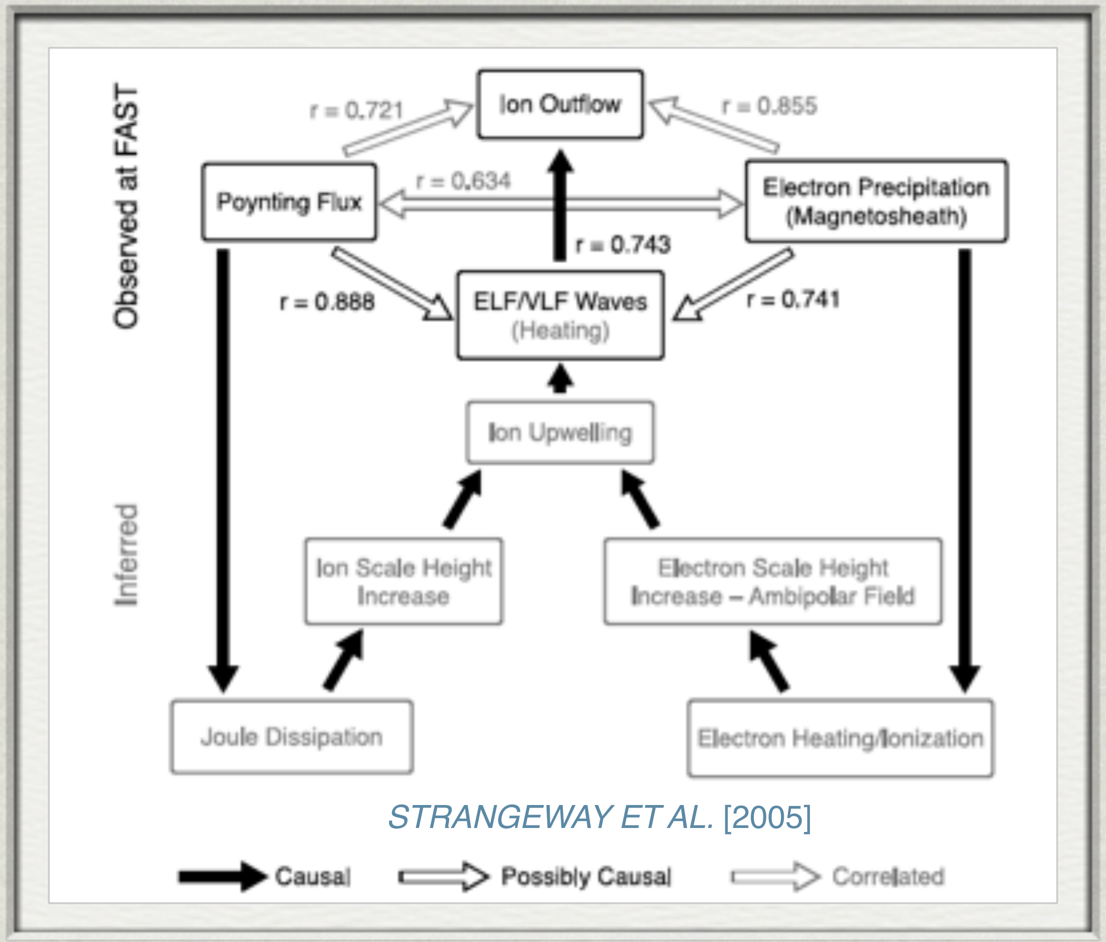


*Moore et al,* [2010]

- Using MHD simulation to provide the fields and using test particles to track outflow.
- Advantages: Test particles include non-fluid effects.
- Disadvantage: Fields do not evolve consistently with particle distributions.

# Representing the Ionospheric Source



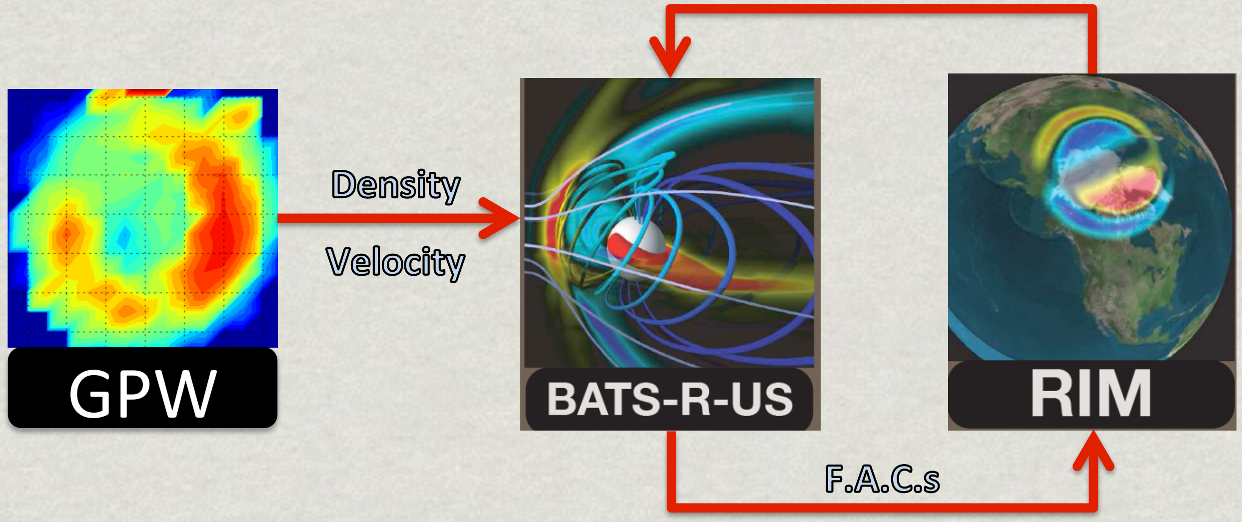


*STRANGEWAY ET AL.* [2005]

- There are pretty much three ways:
  1) Just specify an inner boundary density and let the pressure gradients and diffusion handle it. (Winglee et al. [2004], Welling et al. [2013]
  2) Use of an empirical model
     - Easy to implement and reasonable representation of source
     - Great for use a source for understanding consequences of outflow
     - No physics so not good for studying causes of outflow
  3) First principles modeling (Glocer et al [2009 & 2012])
     - Great for trying to understand physics of outflow
     - Computationally expensive lots of physics to account for

# More and More Outflow Models are being Merged

SWMF



GPW

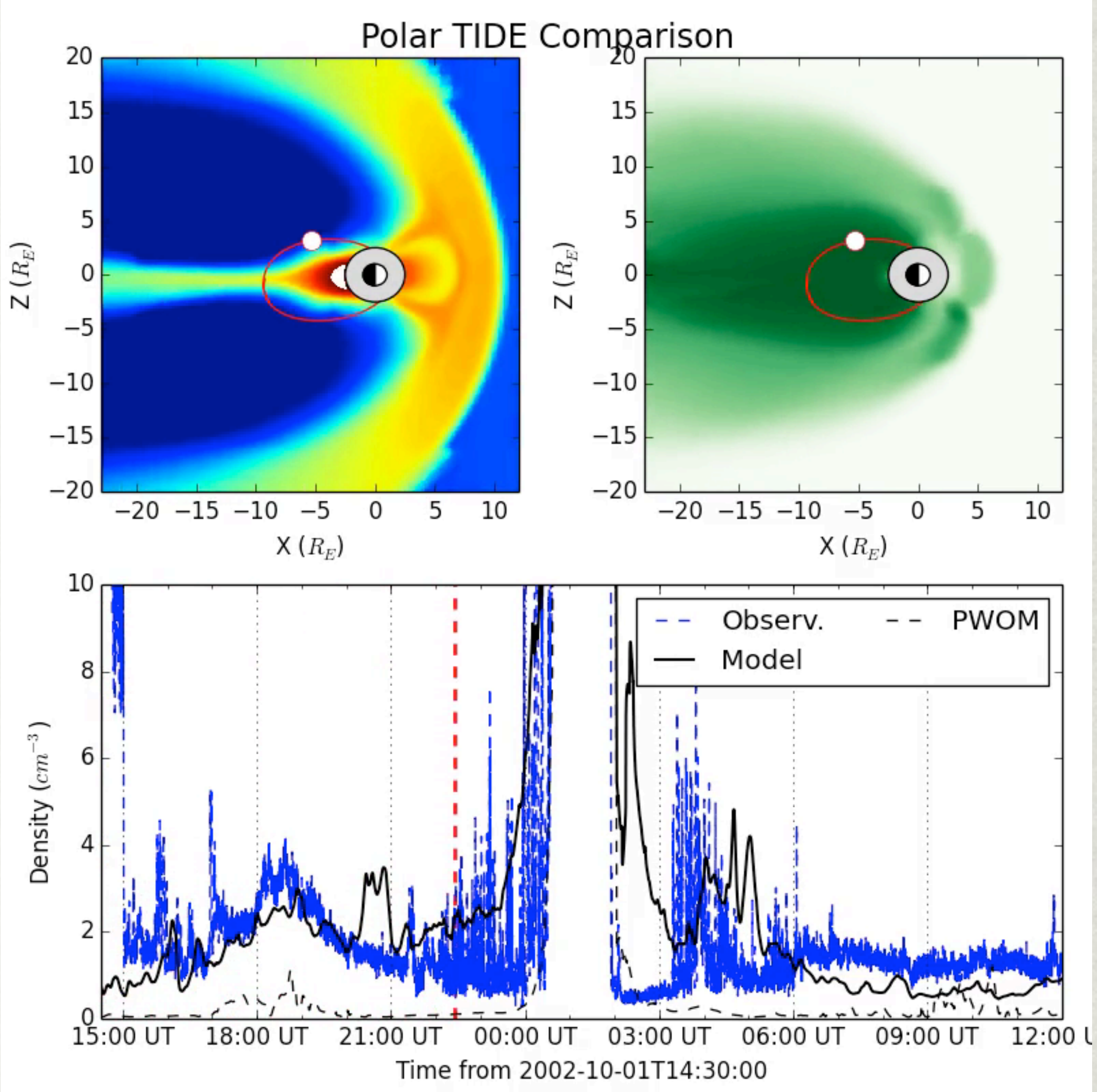
Density

Velocity

BATS-R-US

RIM

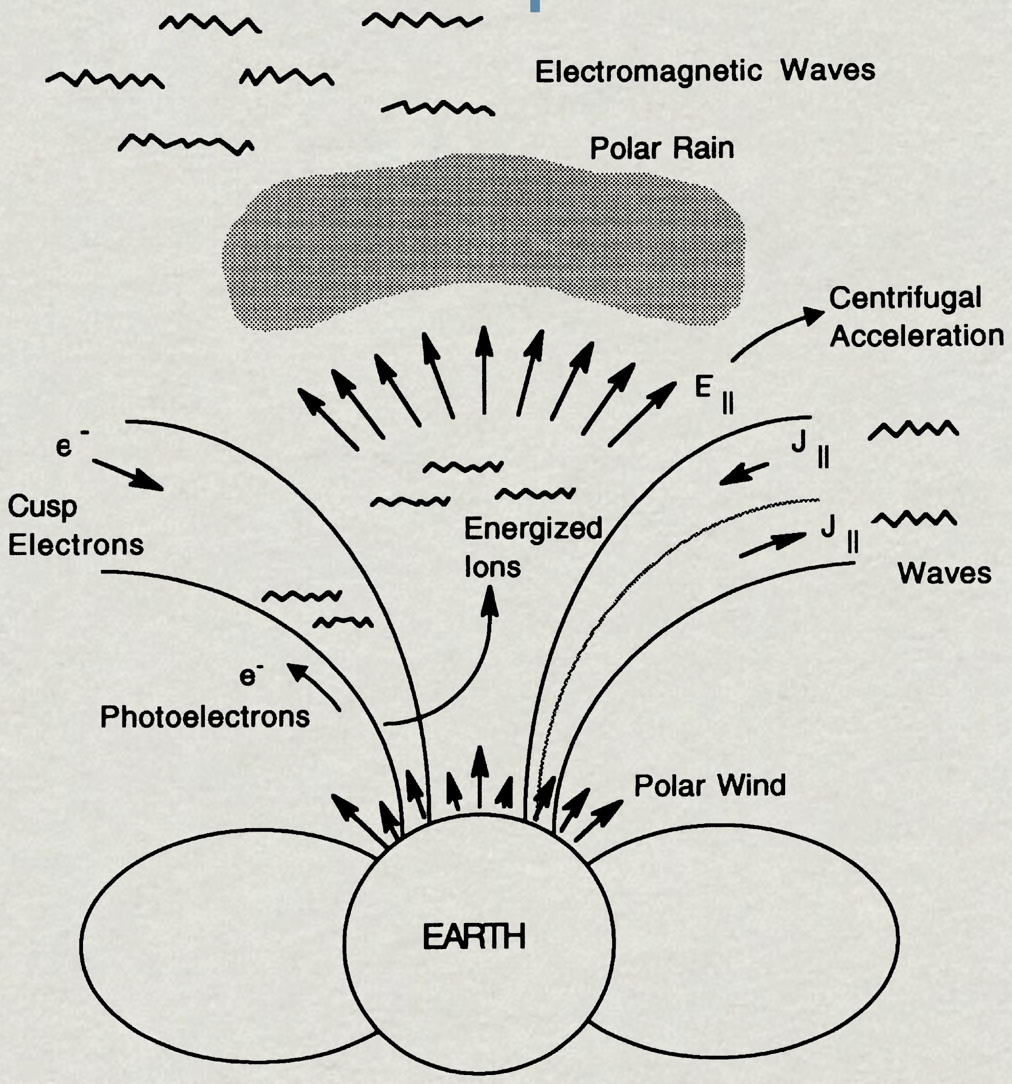
F.A.C.s



Polar TIDE Comparison

*Courtesy of D. Welling*

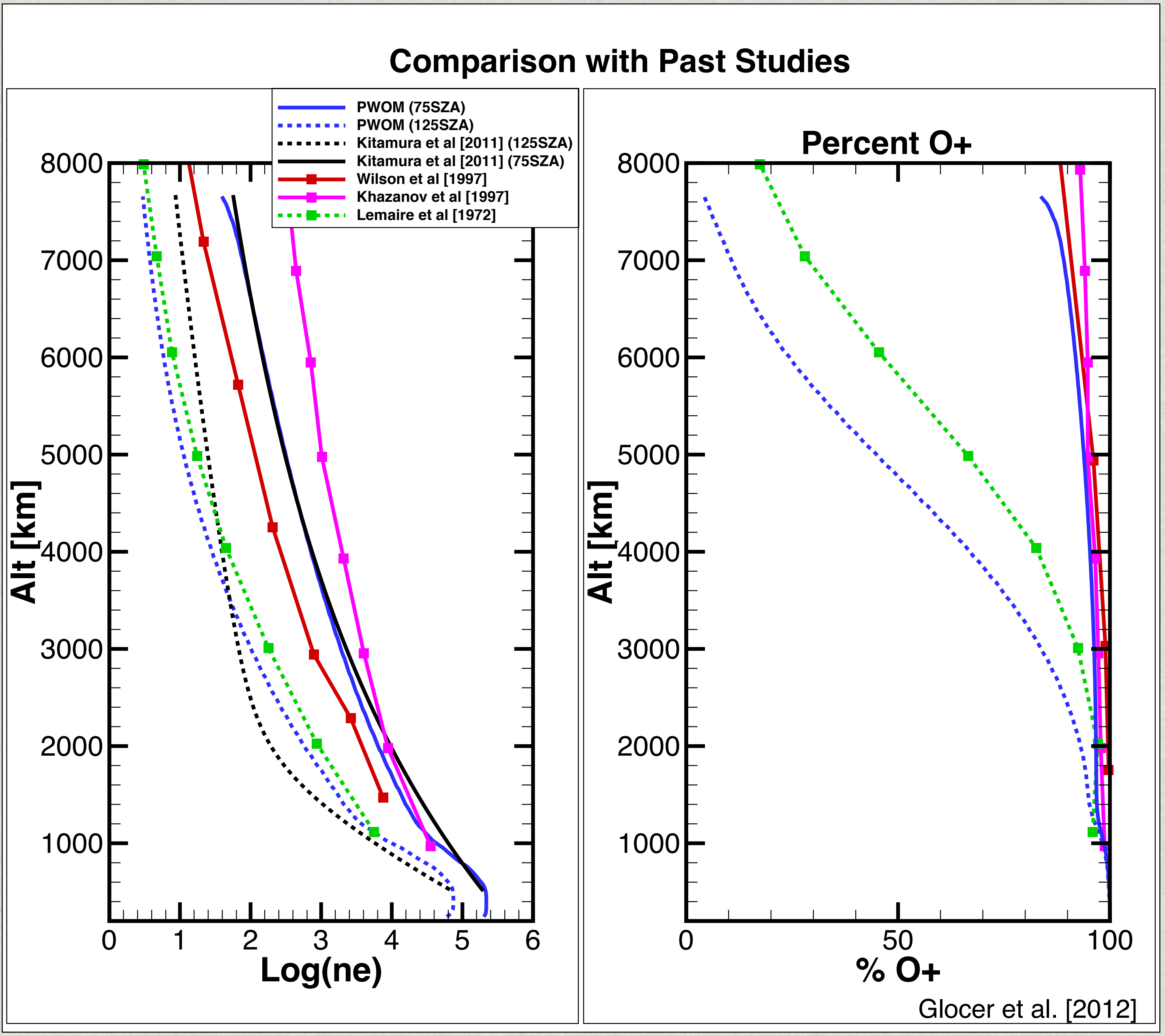
# Pathways of Ionospheric Outflow



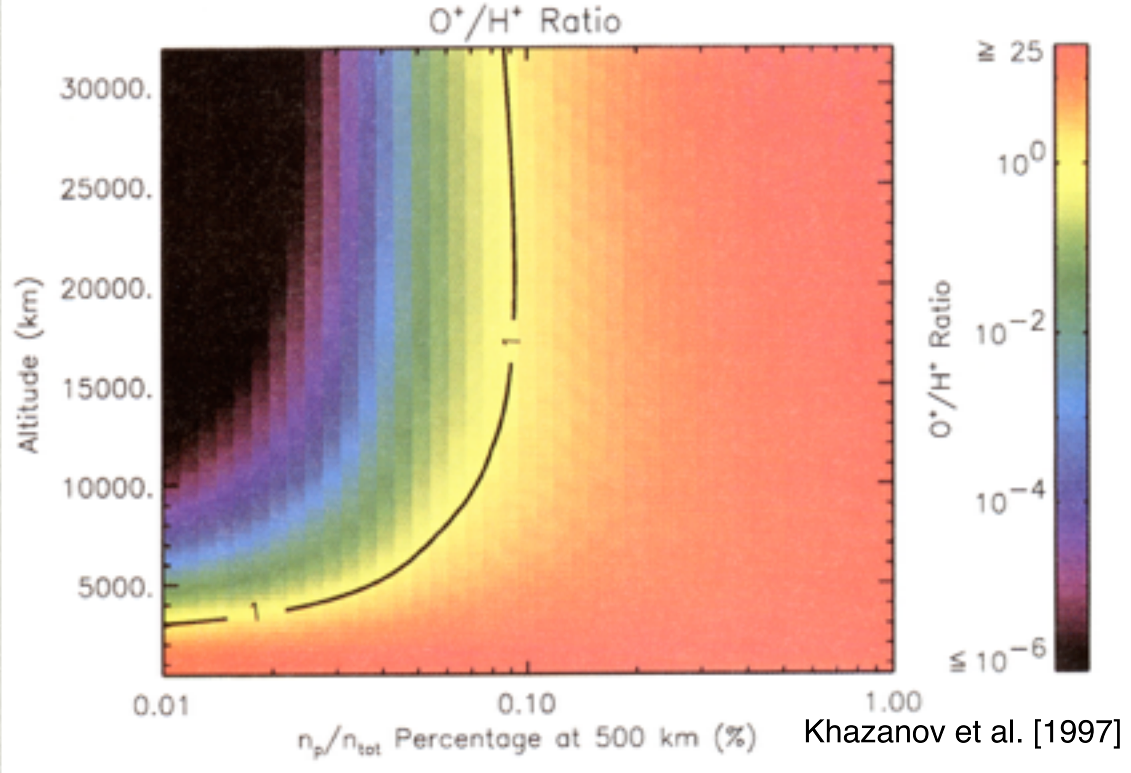
*Schunk and Sojka,* [1997]

- Superthermal Electrons (SEs) can reduce the potential barrier.
- Centrifugal force due to field line convection and curvature change.
- Transverse heating of ions at a result of WPI.
- Ponderomotive forces of Alfven waves.
- Other less discussed mechanisms include FACs driving $E_{\parallel}$ and low altitude frictional heating driving upwelling.

# Effect of SEs on Outflow



Glocer et al. [2012]



Khazanov et al. [1997]

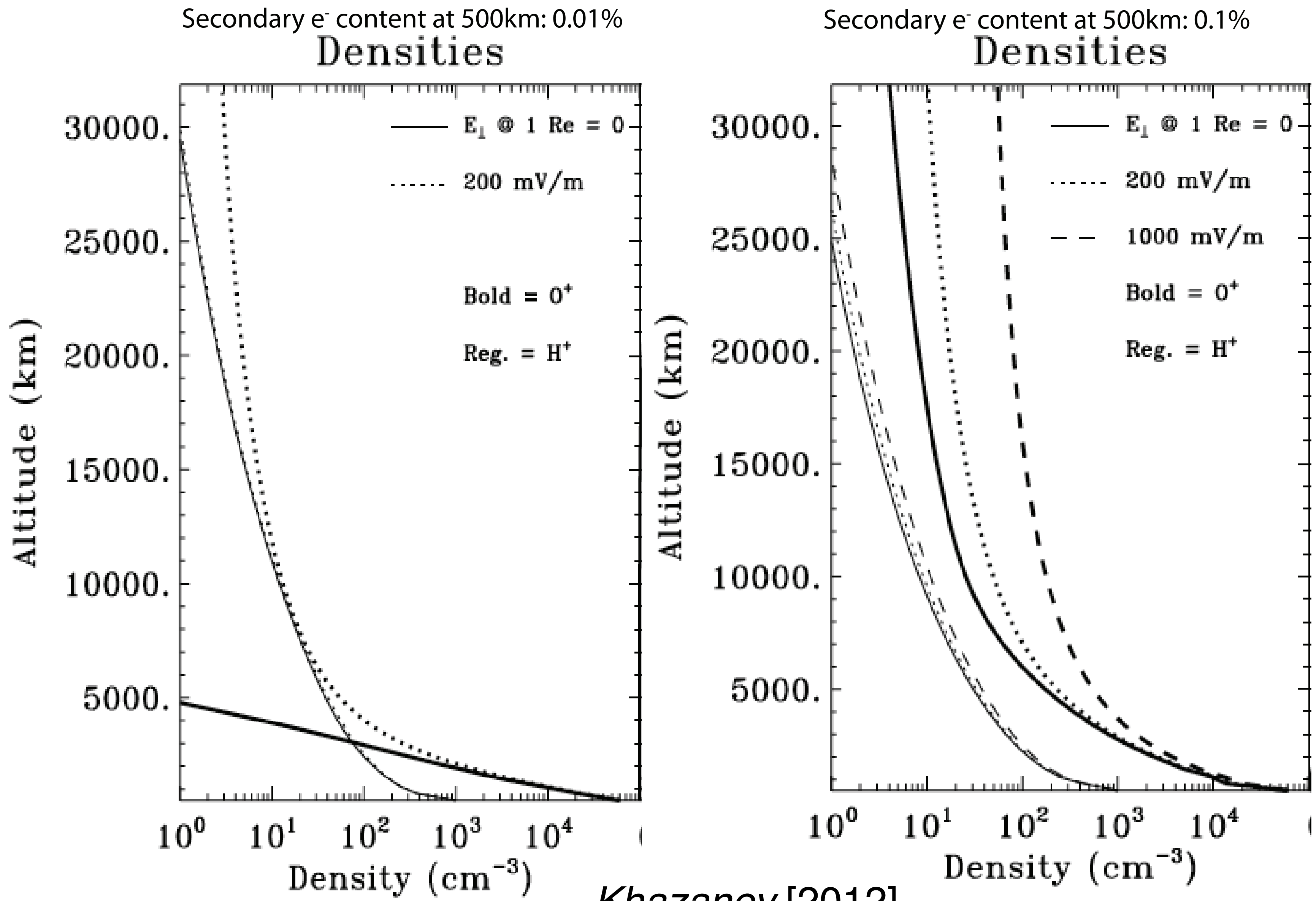
- Studies including photoelectrons are primarily $O^+$ to high altitude as photoelectron concentration increases.
- Secondary electrons act just as photoelectrons do.

# Effect of SEs on Outflow

- Studies including photoelectrons are primarily $O^+$ to high altitude as photoelectron concentration increases.
- Secondary electrons act just as photoelectrons do.

# Effect of SEs on Outflow

Comparison of the Effects of Secondary $e^-$ and Ponderomotive Forces



Secondary $e^-$ content at 500km: 0.01%

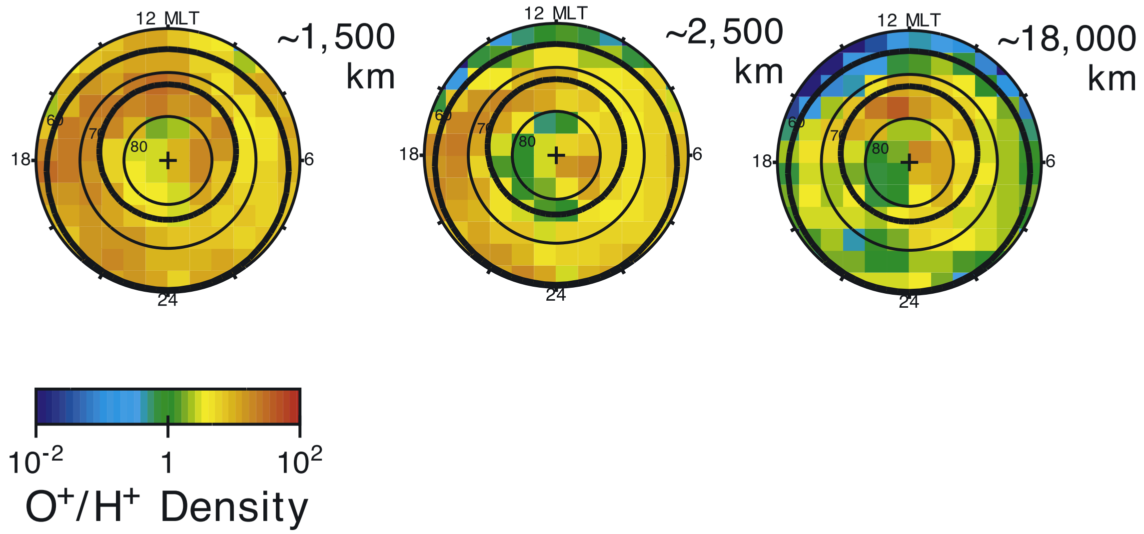
Secondary $e^-$ content at 500km: 0.1%

*Khazanov* [2012]

- Studies including photoelectrons are primarily $O^+$ to high altitude as photoelectron concentration increases.
- Secondary electrons act just as photoelectrons do.

# Wave-Particle Interactions in Outflow

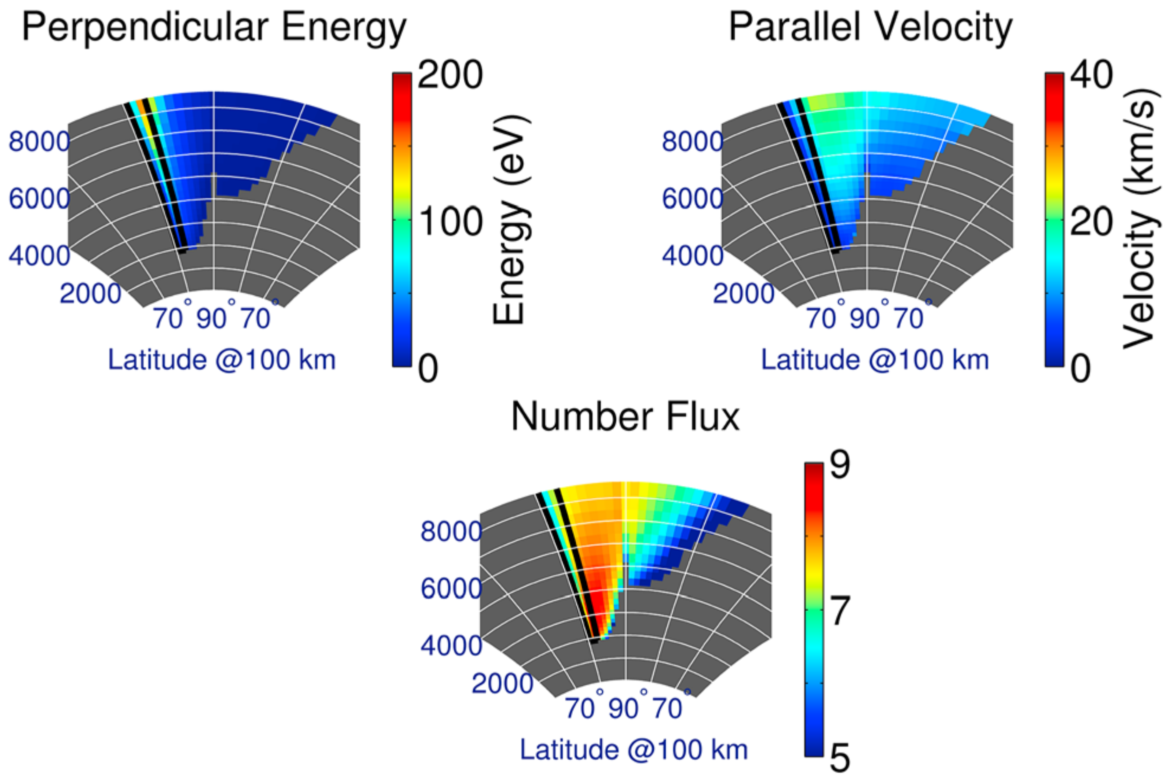
## GPW



- The solution along multiple flux tubes are followed to find the 3D solution.
- A hybrid solution with macroscopic PIC ions.
- The wave heating terms are empirical based on DE observations.

*Barakat and Schunk*, [2006]

## IPWM

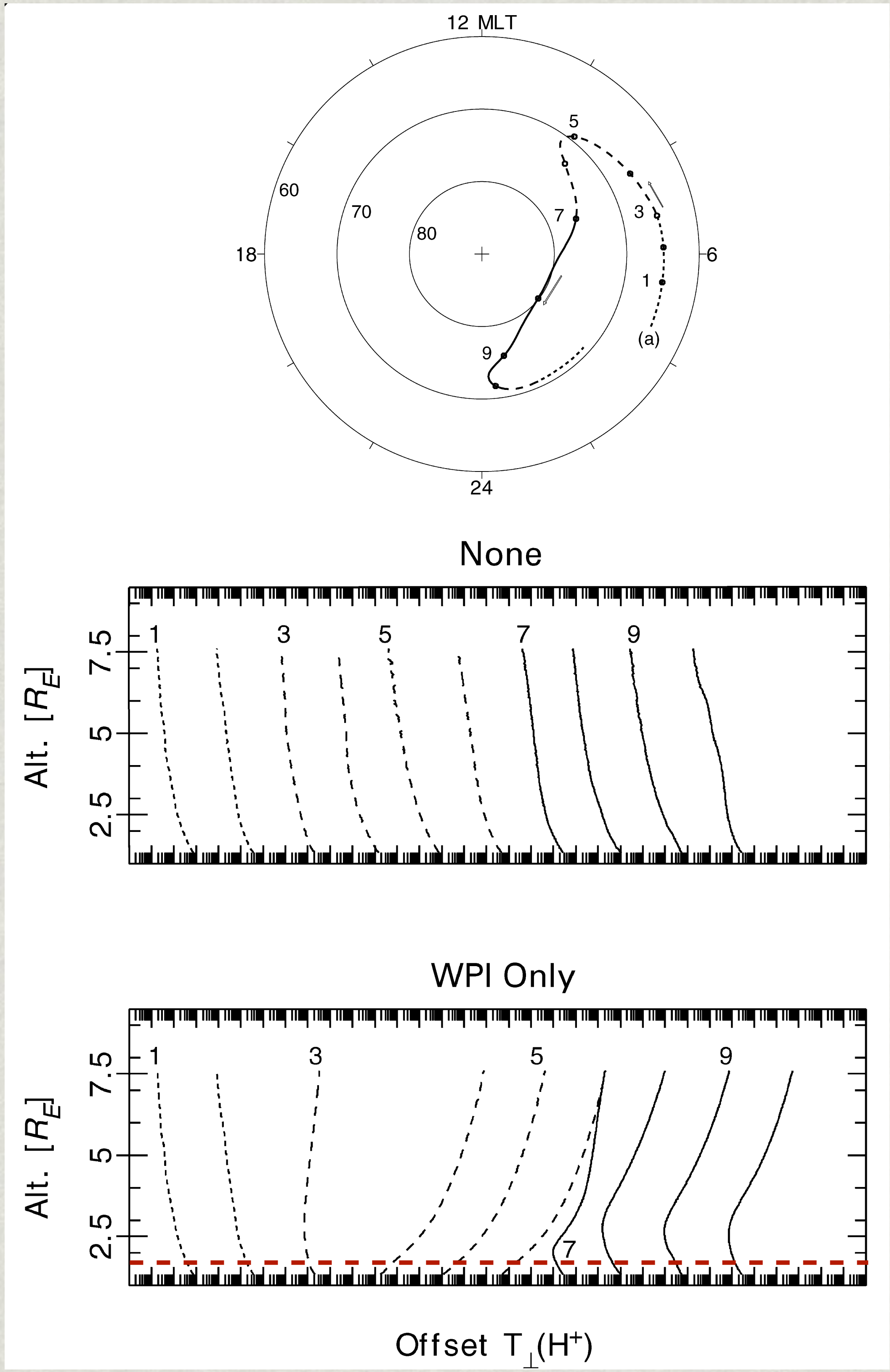


- Eight moment fluid solution for the outflow on Eulerian grid.
- A separate energized fluid is tracked to include wave heating.

*Varney et al*, [2015]

# The Missing role of Transverse Heating in Merging

- W-P interactions have a strong effect on $T_\perp$:
  - Starting at 1Re altitude in the cusp (5).
  - Starting at 2Re altitude in the polar cap (7).
  - In both cases the transverse heating increases with altitude.
- Heating of $T_\perp$ increases the mirror force which can result in strong field aligned flows.
- Typical MHD boundaries are at 1.5Re altitude misses a portion of the heating in the cusp.
- More importantly, MHD has an isotropic pressure which cannot account for transverse heating or the consequences.
- Current methods of merging rely entirely on the flux and completely neglect anisotropy.



*Barakat and Schunk* [2001]

# Extending MHD is Required

## Anisotropic MHD Equations

(*Meng et al.* [2012])

Mirror-like force, converts random perpendicular motion to organized parallel motion

$$\frac{\partial \rho}{\partial t} + (\mathbf{u} \cdot \nabla)\rho + \rho(\nabla \cdot \mathbf{u}) = 0$$

$$\rho \frac{\partial \mathbf{u}}{\partial t} + \rho(\mathbf{u} \cdot \nabla)\mathbf{u} + \nabla(p_\perp + p_e) + \boxed{\nabla \cdot [(p_\parallel - p_\perp)\mathbf{bb}]} + \frac{1}{\mu_0}\mathbf{B} \times (\nabla \times \mathbf{B}) = 0$$

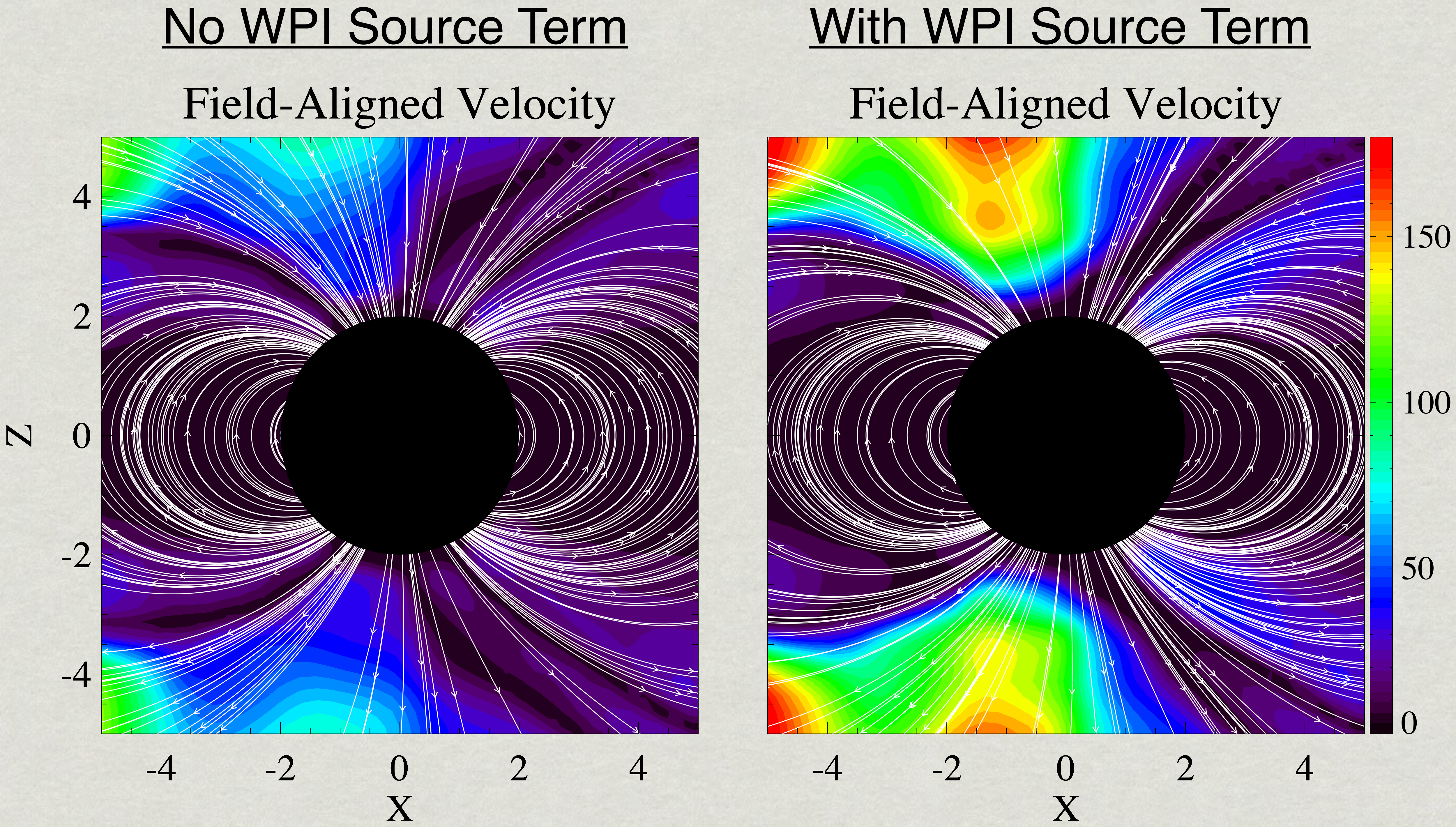
$$\frac{\partial \mathbf{B}}{\partial t} + \nabla \times [-(\mathbf{u} \times \mathbf{B})] = 0$$

$$\frac{\partial p_\parallel}{\partial t} + (\mathbf{u} \cdot \nabla)p_\parallel + p_\parallel(\nabla \cdot \mathbf{u}) + 2p_\parallel \mathbf{b} \cdot (\mathbf{b} \cdot \nabla)\mathbf{u} = 0$$

$$\frac{\partial p_\perp}{\partial t} + (\mathbf{u} \cdot \nabla)p_\perp + 2p_\perp(\nabla \cdot \mathbf{u}) - p_\perp \mathbf{b} \cdot (\mathbf{b} \cdot \nabla)\mathbf{u} = 0 + \langle \delta P_\perp / \delta t \rangle_{\text{waves}}$$

$$\frac{\partial p_e}{\partial t} + (\mathbf{u} \cdot \nabla)p_e + \frac{5}{3}p_e(\nabla \cdot \mathbf{u}) = 0$$

# Effect of WPI on Velocity



*Glocer,* [2015]

# Including The Ring Current

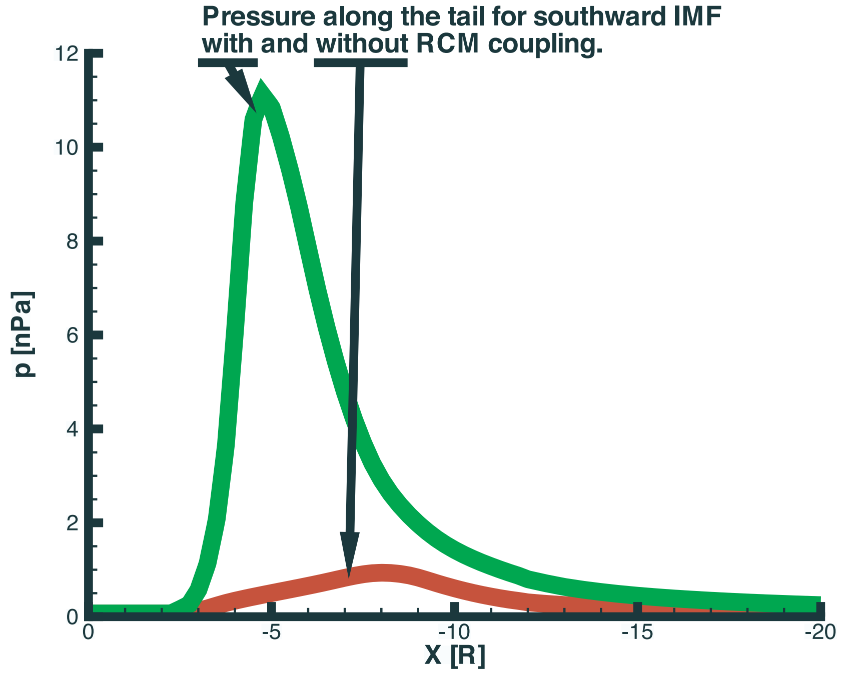
- Global MHD models do not include the drift physics required to capture the ring current.
- Putting the two approaches together yields advantages for each.
- For the global MHD model:
  - Improved representation of the inner magnetospheric pressure.
  - Better region 2 currents.
  - More accurate and consistent representation of the magnetic field.
- For the ring current model:
  - More accurate, consistent, representation of the magnetic and electric fields
  - Dynamic and MLT dependent boundary

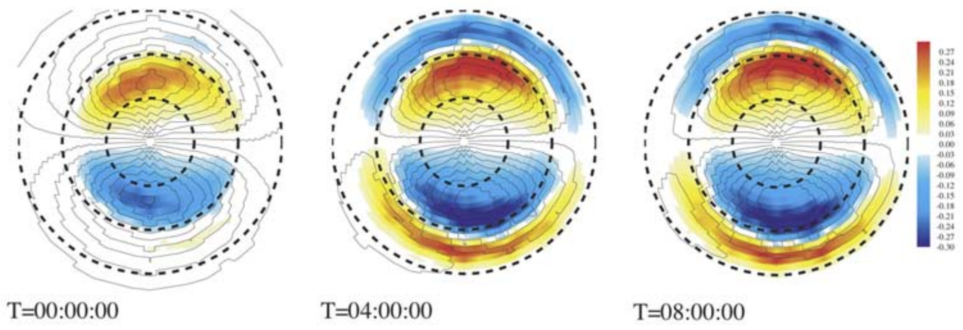
# Coupling RCM and BATS-R-US

$$\frac{\partial \eta_s}{\partial t} + \frac{\mathbf{B} \times \boldsymbol{\nabla}\left(\Phi + \Phi_c + \frac{\lambda_s}{q_s} V^{-2/3}\right)}{B^2} \cdot \nabla \eta_s = -L.$$

$$\lambda_s = W_s V^{2/3} \qquad \eta_s = n_s V$$

*Wolf,* [1983]

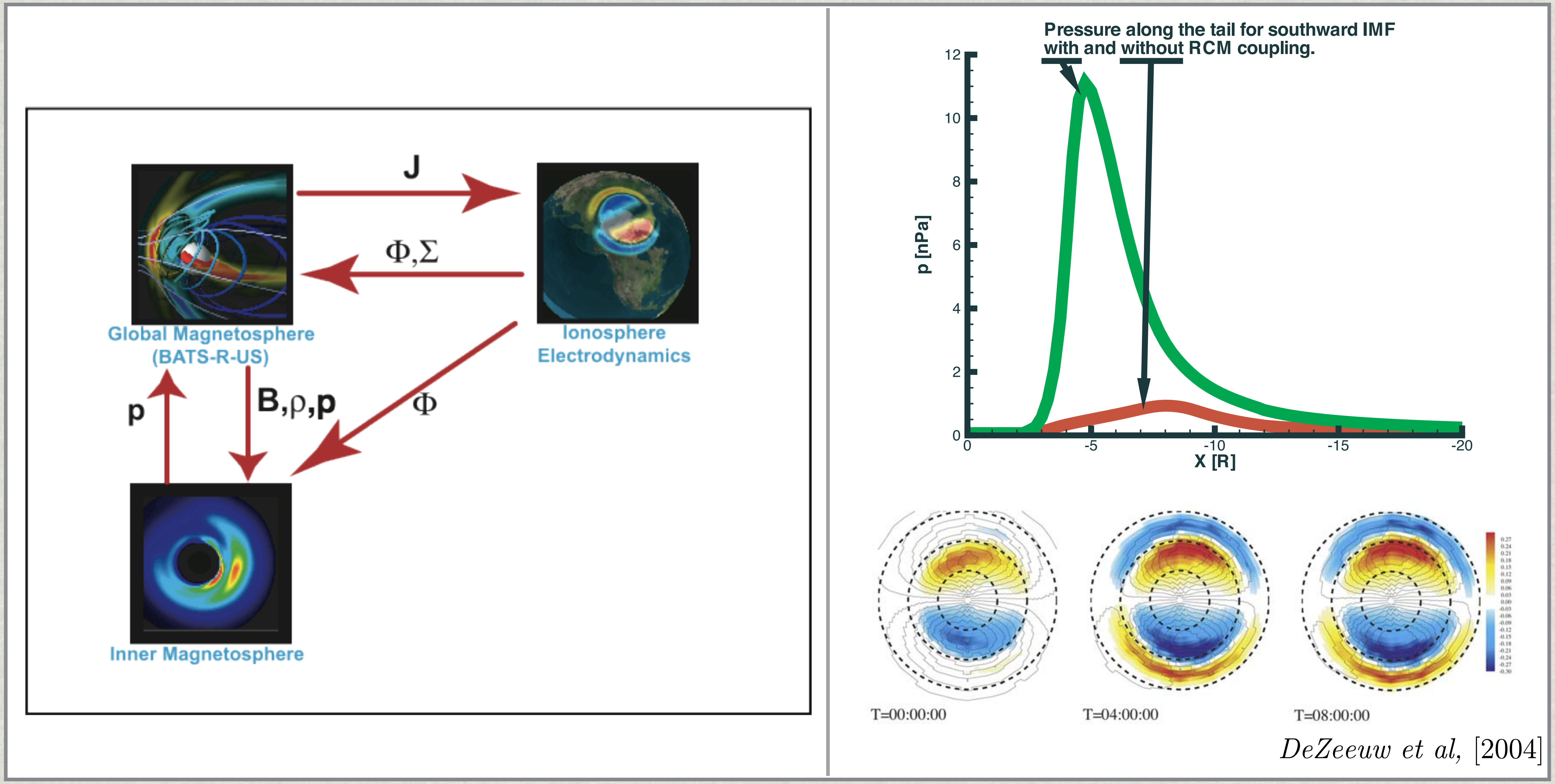




*DeZeeuw et al,* [2004]

- First coupling of ring current model to MHD
- Advantages: Ring current drift and pressure effects now represented in global magnetosphere model.
- Disadvantage: Only isotropic ring current distributions distributions.

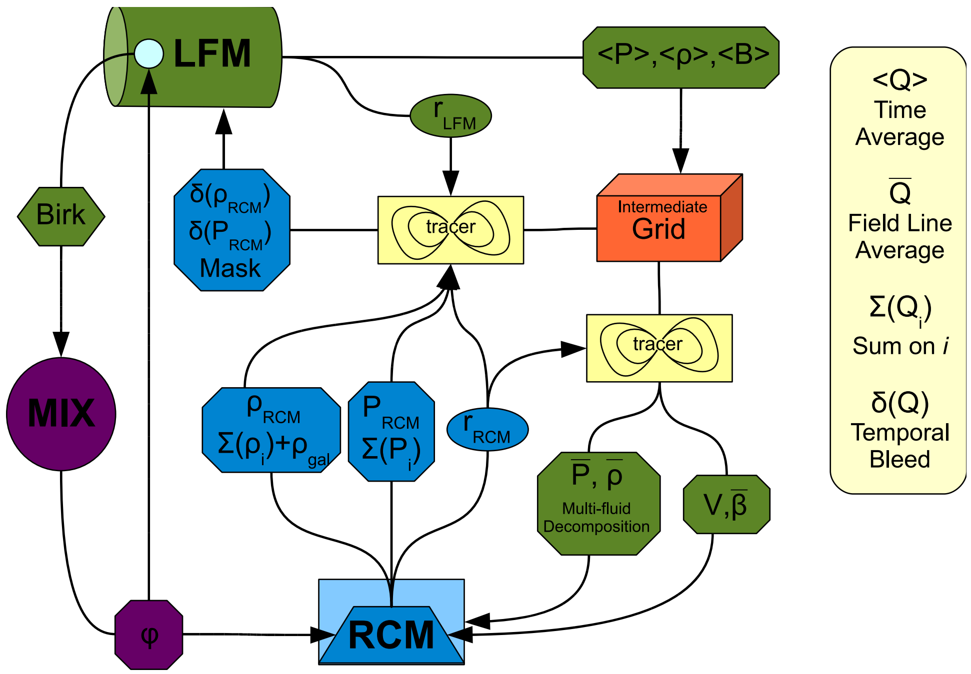
# Coupling RCM and BATS-R-US

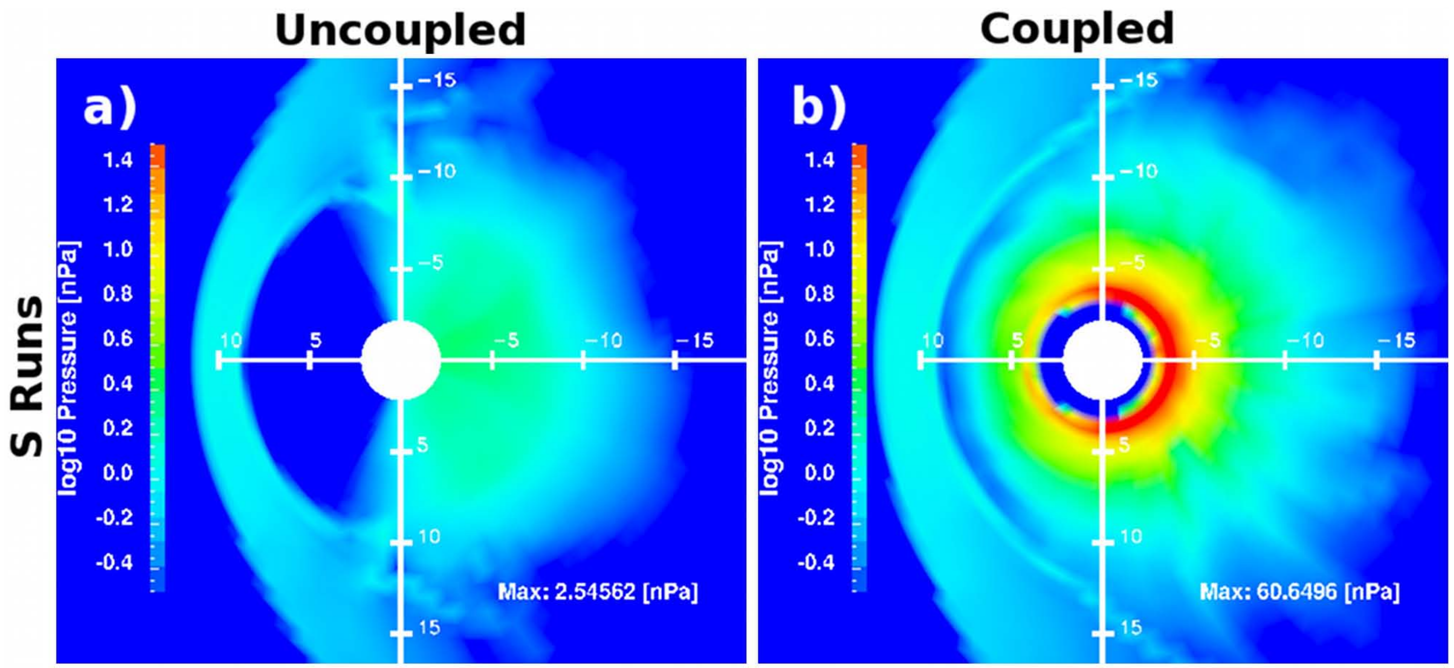


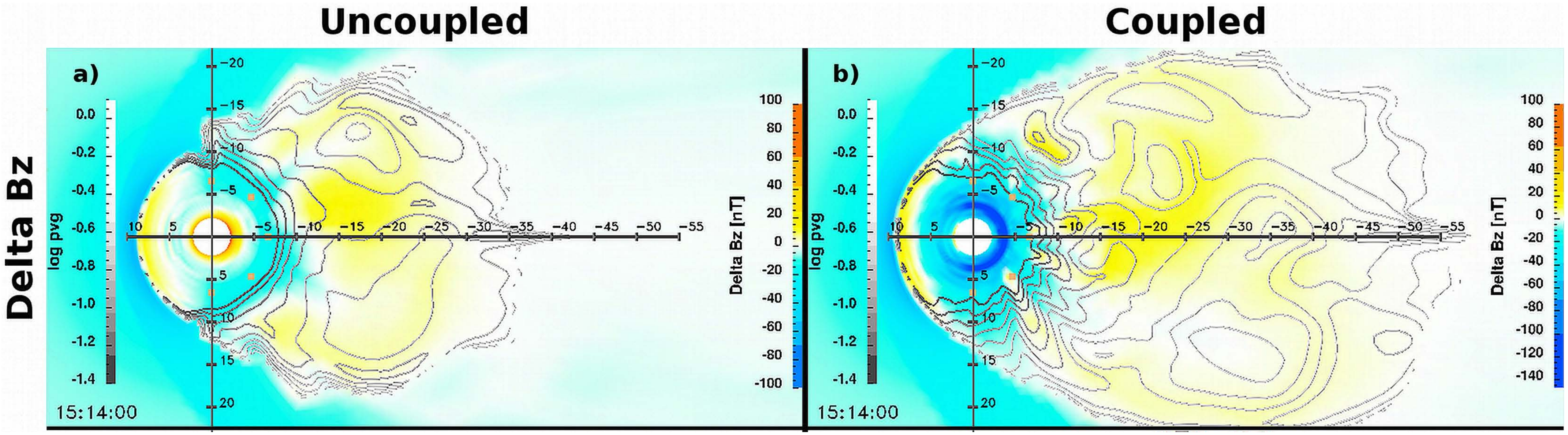
*DeZeeuw et al,* [2004]

- First coupling of ring current model to MHD
- Advantages: Ring current drift and pressure effects now represented in global magnetosphere model.
- Disadvantage: Only isotropic ring current distributions distributions.

# Coupling RCM and LFM-MIX

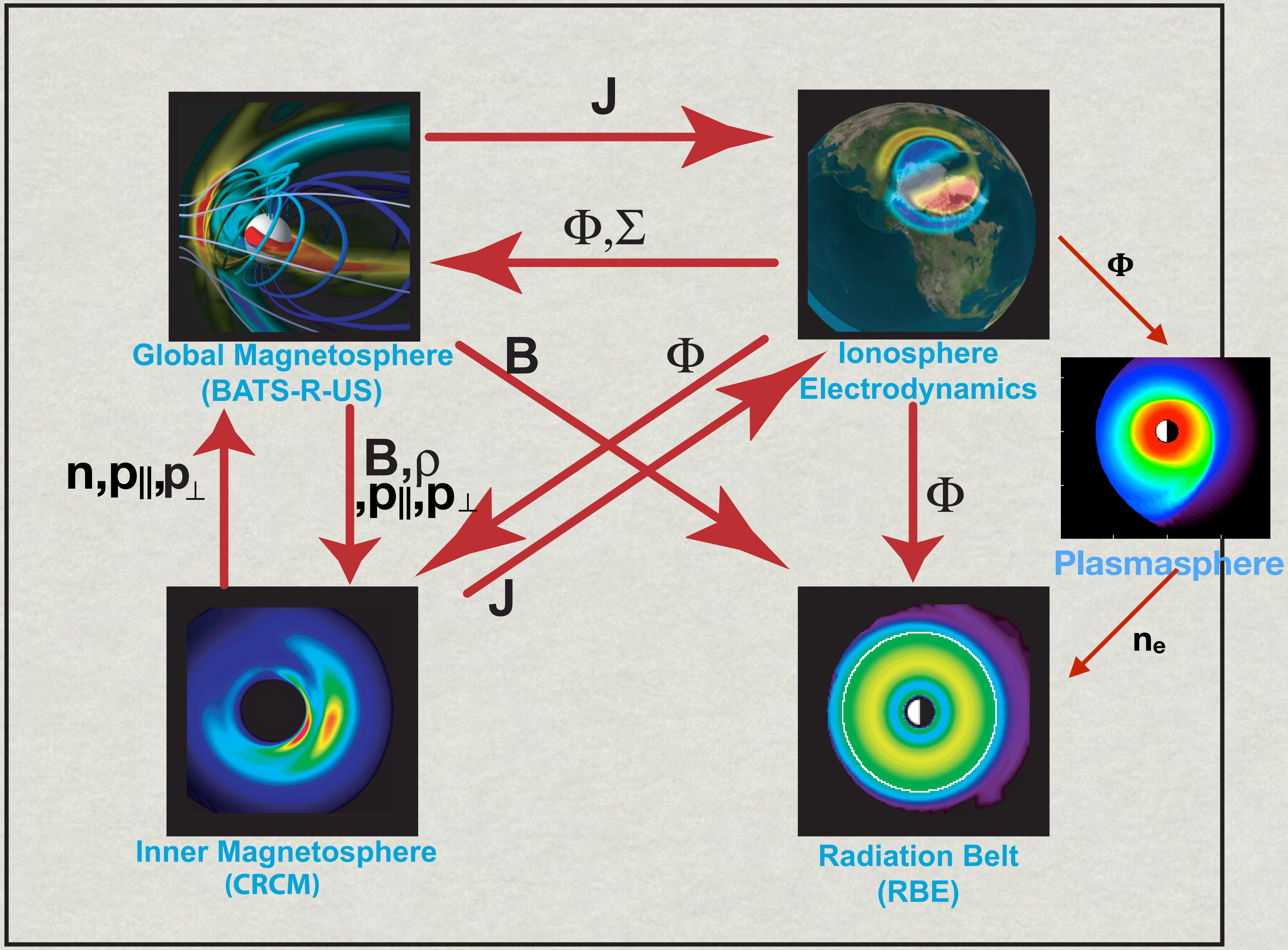






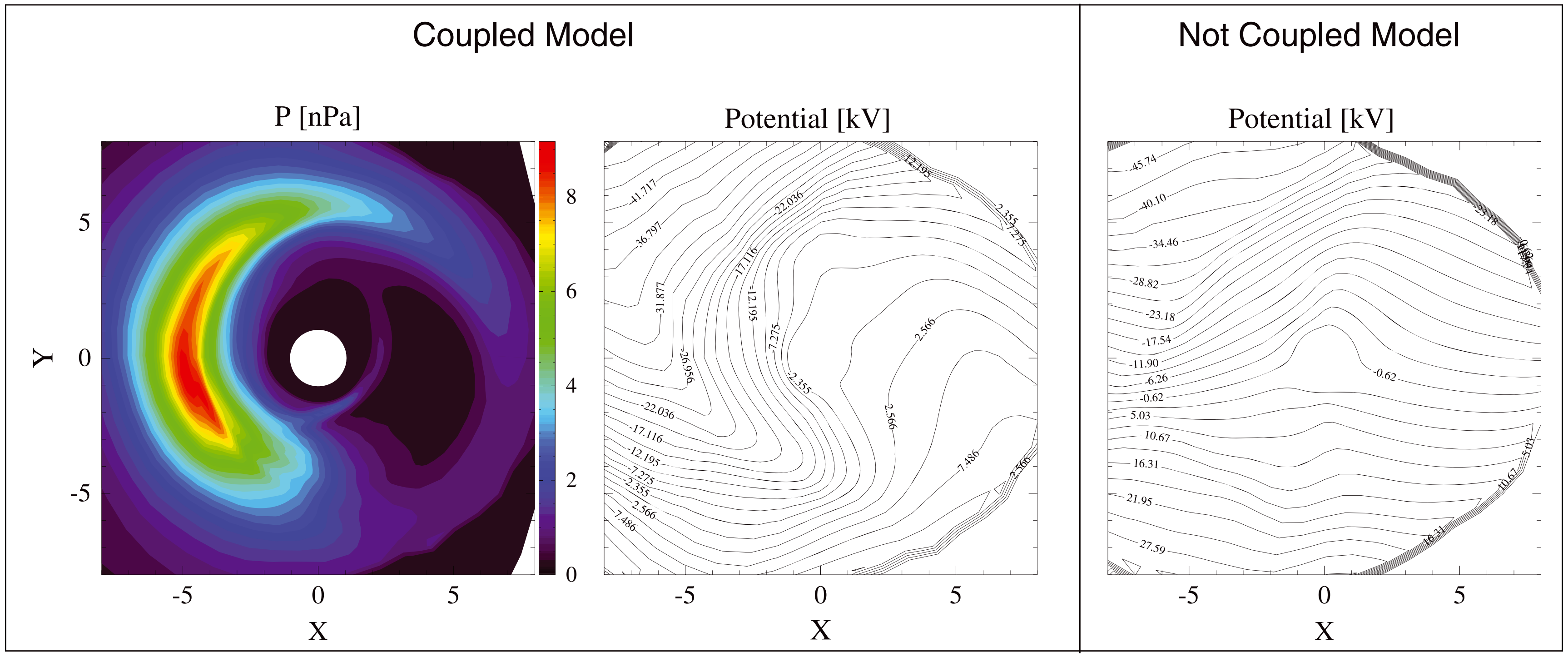
*Pembroke et al,* [2011]

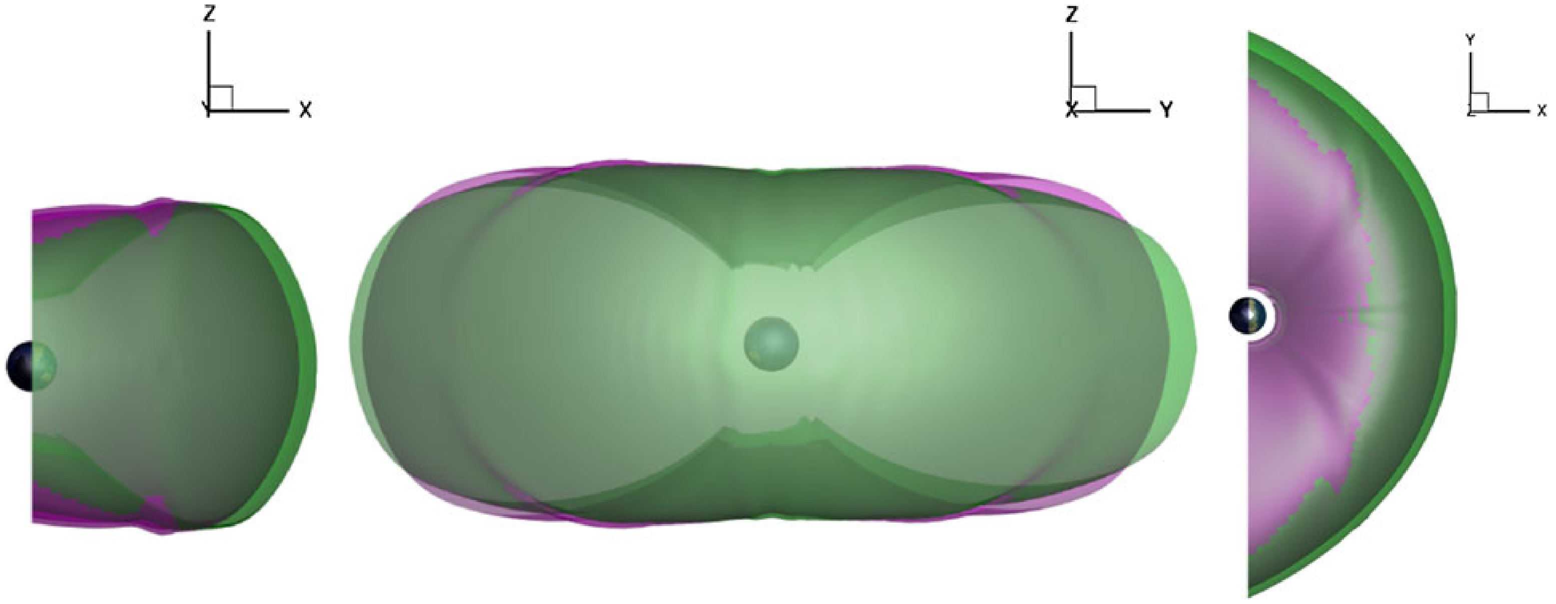
# Description of Existing Model Couplings



- Glocer, A., G. Toth, M. Fok, T. Gombosi, M. Liemohn (2009), Integration of the radiation belt environment model into the space weather modeling framework, Journal of Atmospheric and Solar-Terrestrial Physics, doi:10.1016/j.jastp.2009.01.003.
- Glocer, A., M. Fok, X. Meng, G. Toth, N. Buzulukova, S. Chen, and K. Lin (2013), CRCM + BATS-R-US two-way coupling, J. Geophys. Res. Space Physics, 118, 1635–1650, doi:10.1002/jgra.50221.
- Meng, X., G. Tóth, A. Glocer, M.-C. Fok, and T. I. Gombosi (2013), Pressure anisotropy in global magnetospheric simulations: Coupling with ring current models, J. Geophys. Res. Space Physics, 118, 5639–5658, doi:10.1002/jgra.50539.

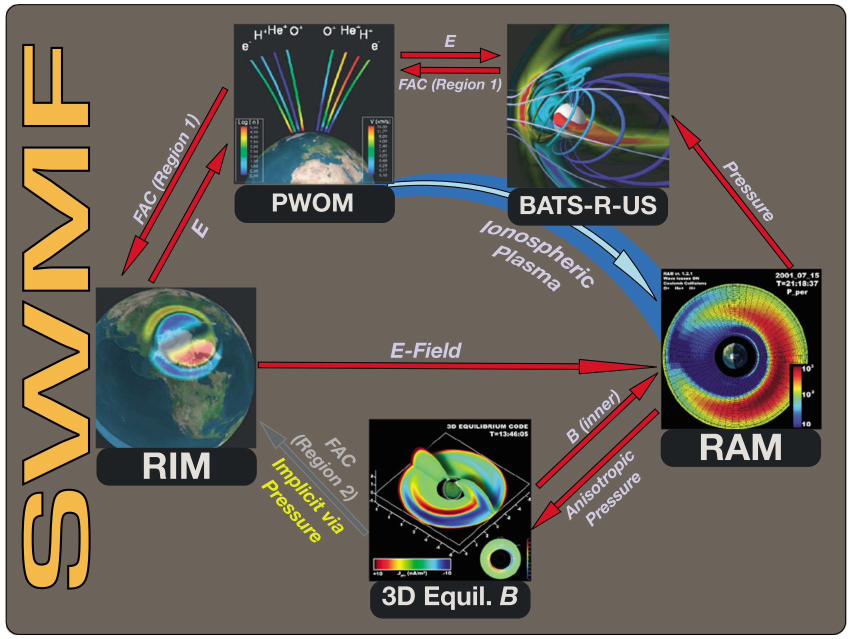
# Coupling RC models change E and B fields

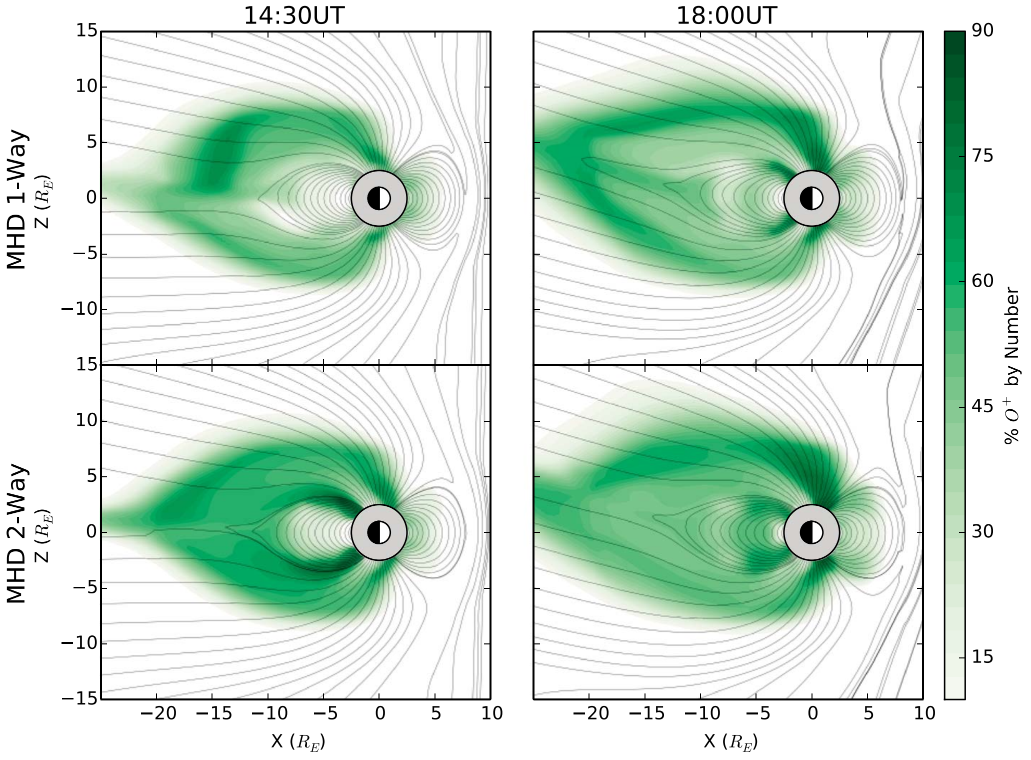


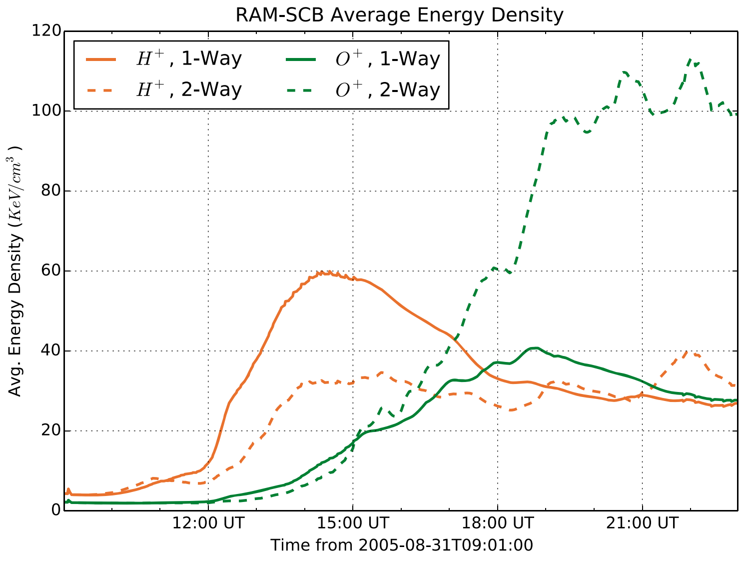


*Glocer et al,* [2013]

# Coupling RAM-SCB and BATS-R-US





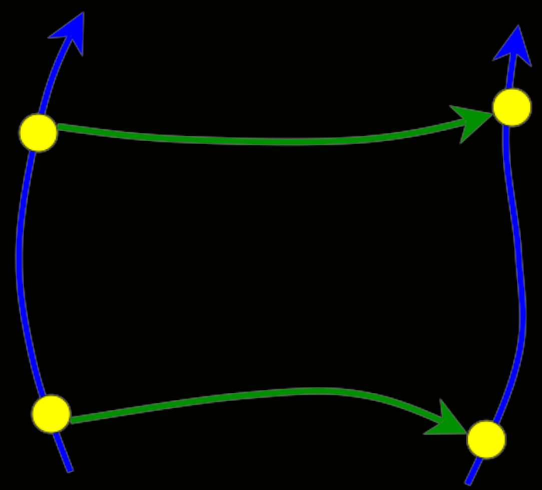


*Welling et al,* [2015]

- Welling et al., 2015 use the coupled RAM-SCB code to explore effect of including ring current feedback on the ionospheric source.
- Including ring current effects in the global model feedback to the outflow source and ultimately back to the ring current.

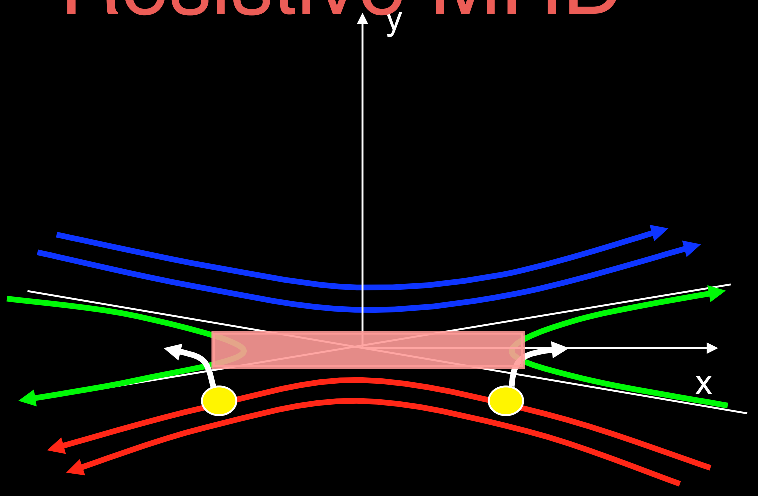
# Reconnection and Global Modeling

**Ideal MHD**



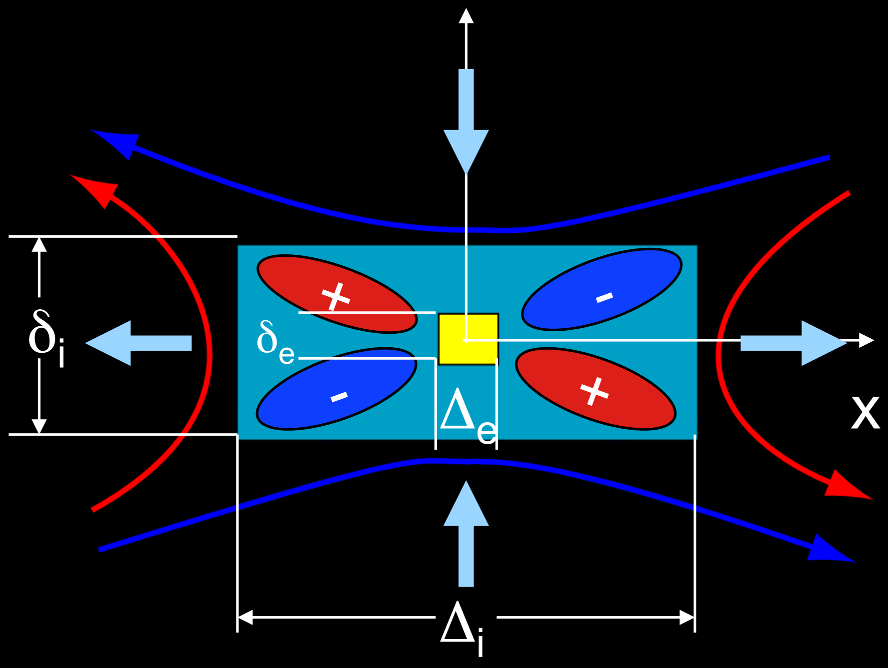
$$E = -\frac{1}{c} U \times B$$

**Resistive MHD**



$$+ \eta J$$

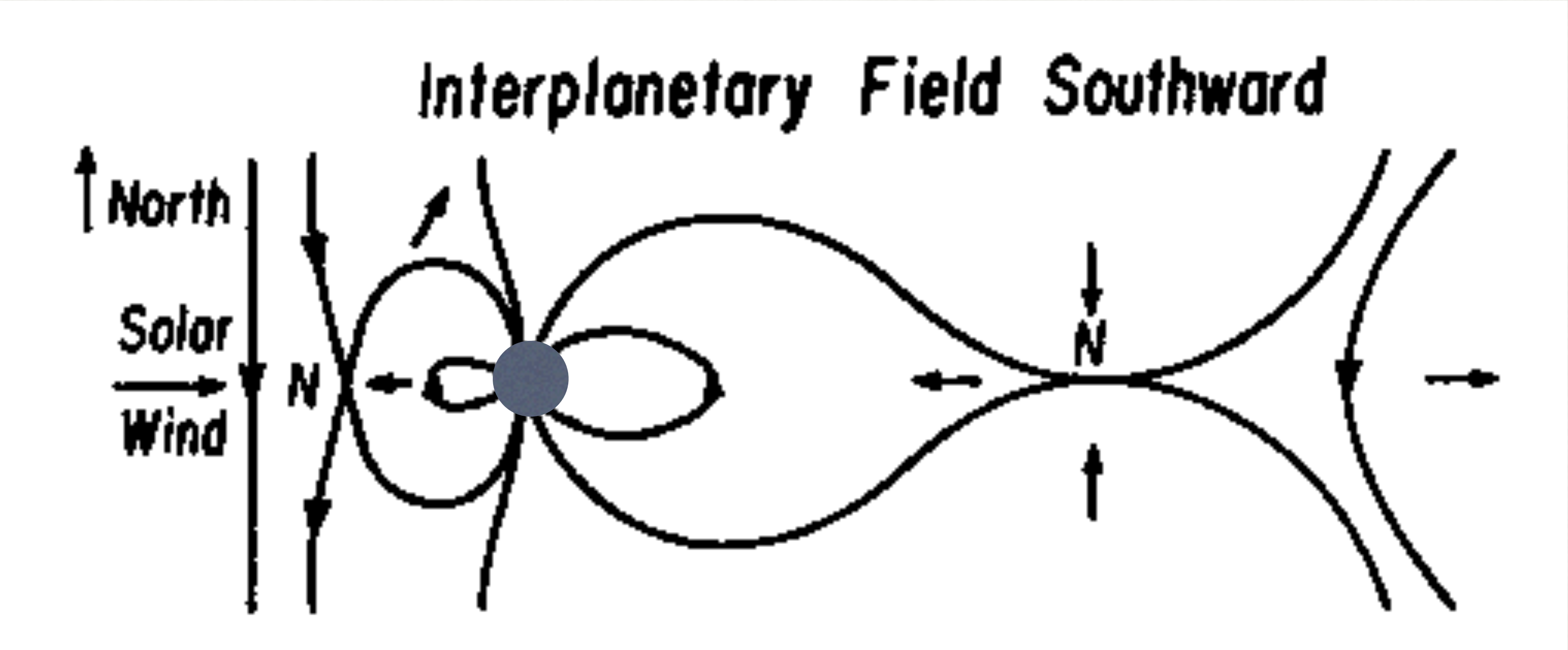
**Hall MHD**

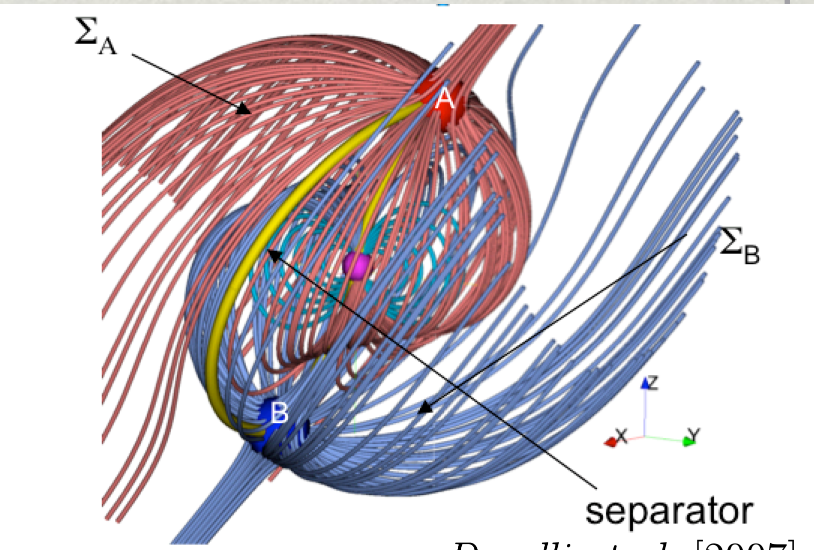


$$+ \frac{1}{nec} J \times B - \frac{1}{ne} \nabla \cdot P_e^{CM}$$

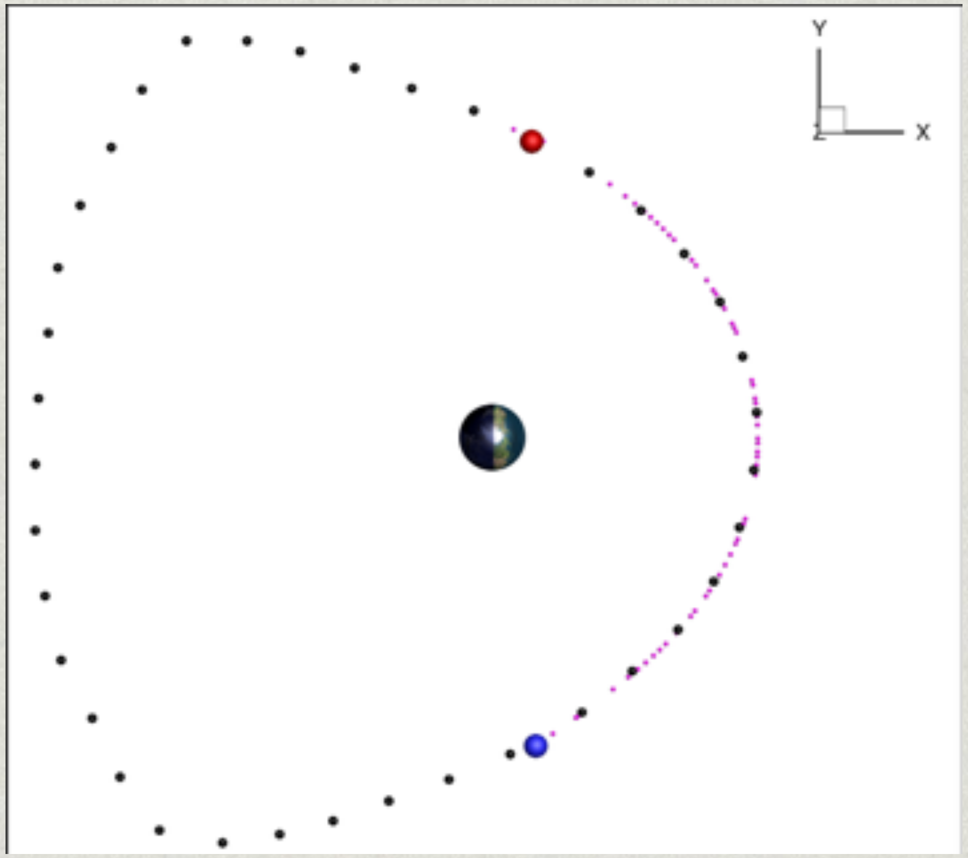
- Most global magnetosphere models are solving resistive MHD equations with either physical or numerical resistivity.
- We are starting to see more extensions to Hall MHD

# What is a Magnetic Separator?





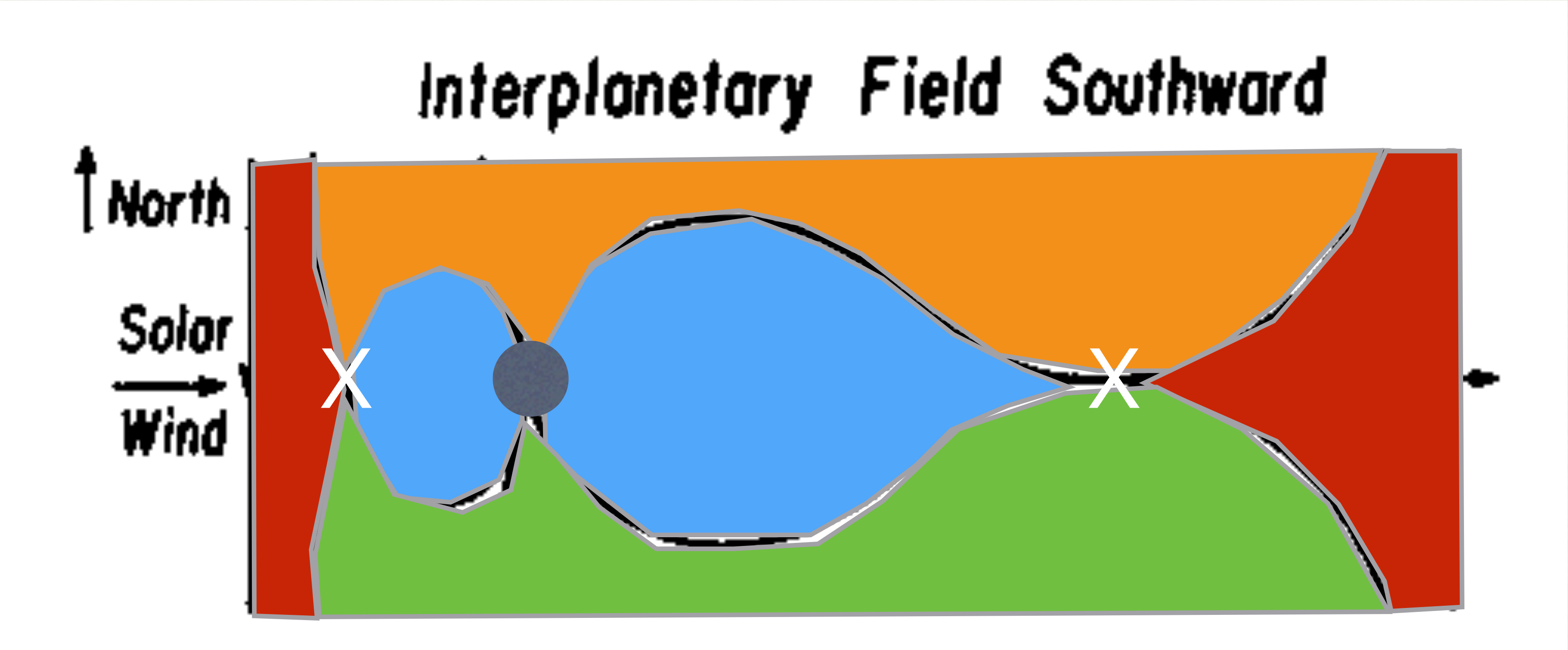
*Dorelli et al*, [2007]

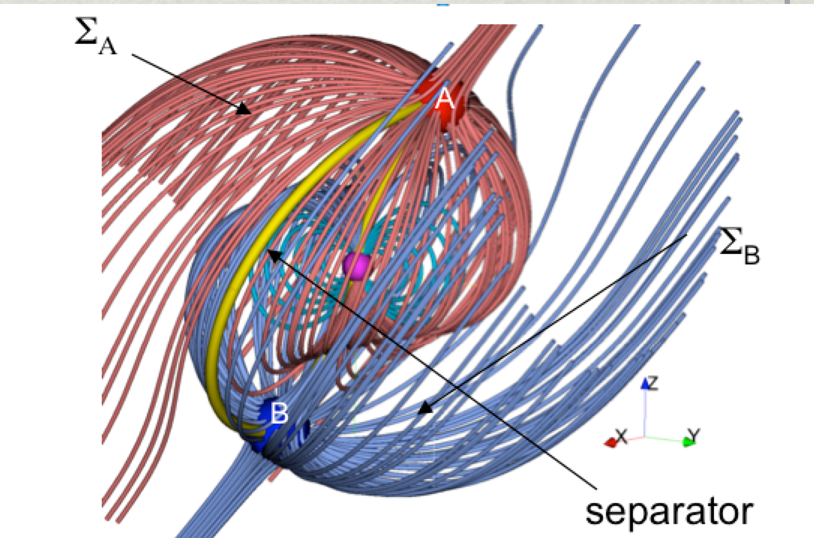


$$\frac{d\Phi_B}{dt} = \oint E_\parallel ds = \int_{DS} E_\parallel ds + \int_{NS} E_\parallel ds$$

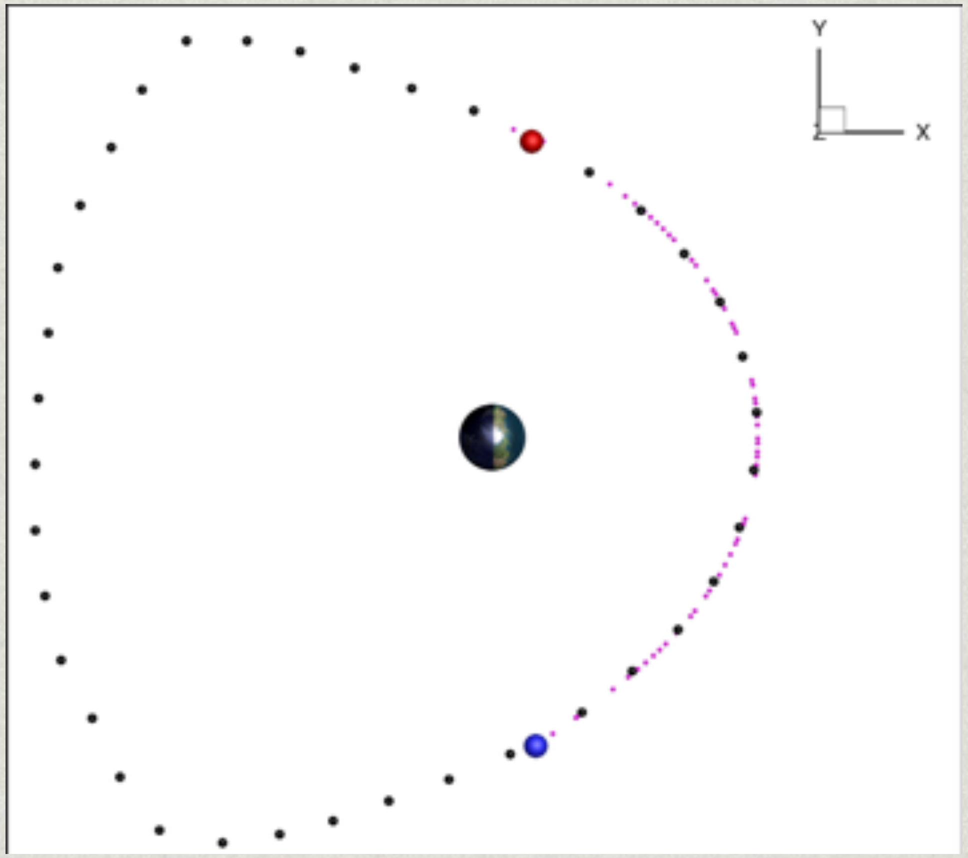
- For further reading about separators see:
  - Lau and Finn, [1990]
  - Sisco et al., [2001]
  - Dorelli et al., [2007]…

# What is a Magnetic Separator?





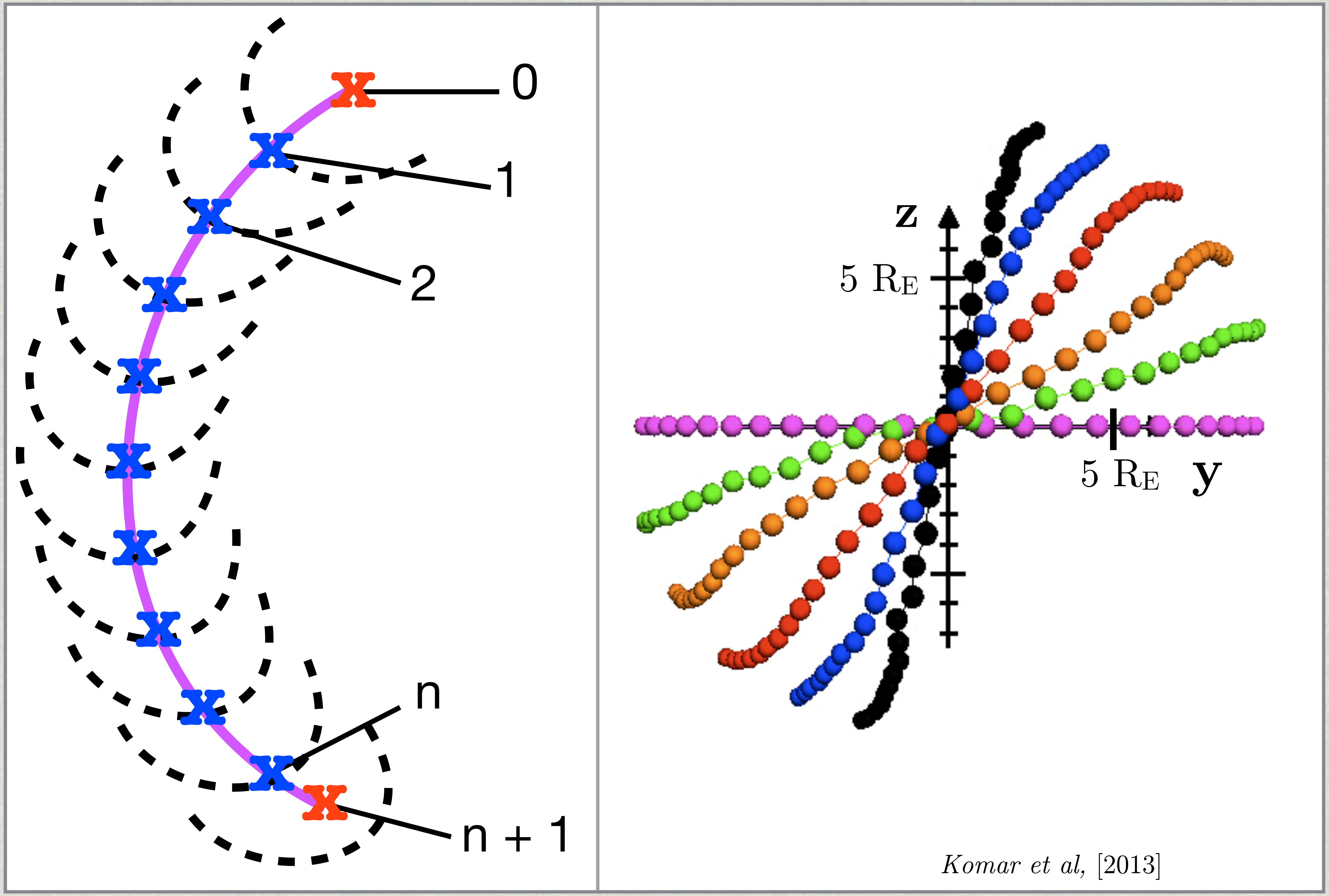
*Dorelli et al,* [2007]



$$\frac{d\Phi_B}{dt} = \oint E_{\parallel} ds = \int_{DS} E_{\parallel} ds + \int_{NS} E_{\parallel} ds$$

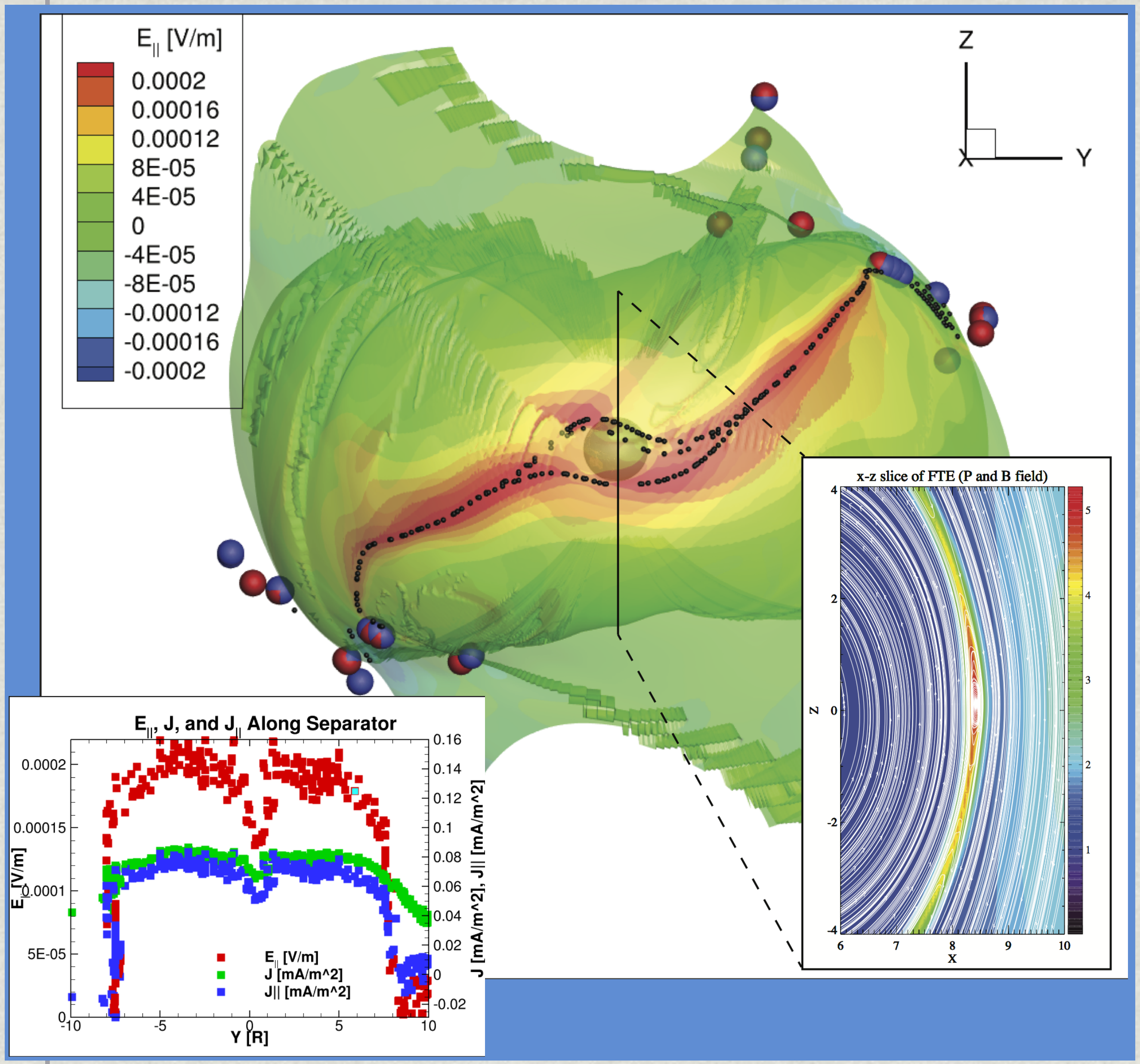
- For further reading about separators see:
    - Lau and Finn, [1990]
    - Sisco et al., [2001]
    - Dorelli et al., [2007]…

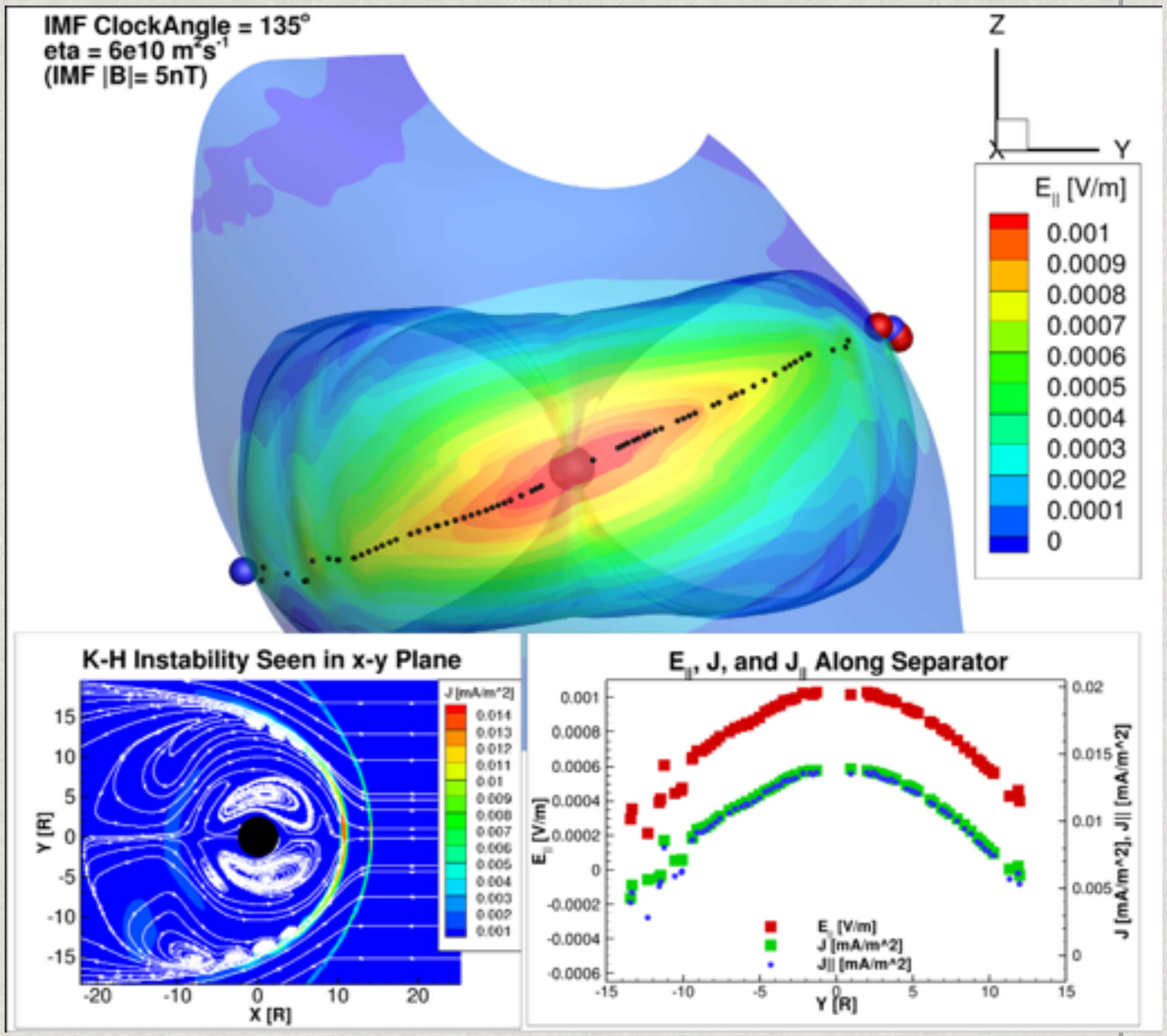
# Locating Separators



*Komar et al,* [2013]

# Separators for more complex cases





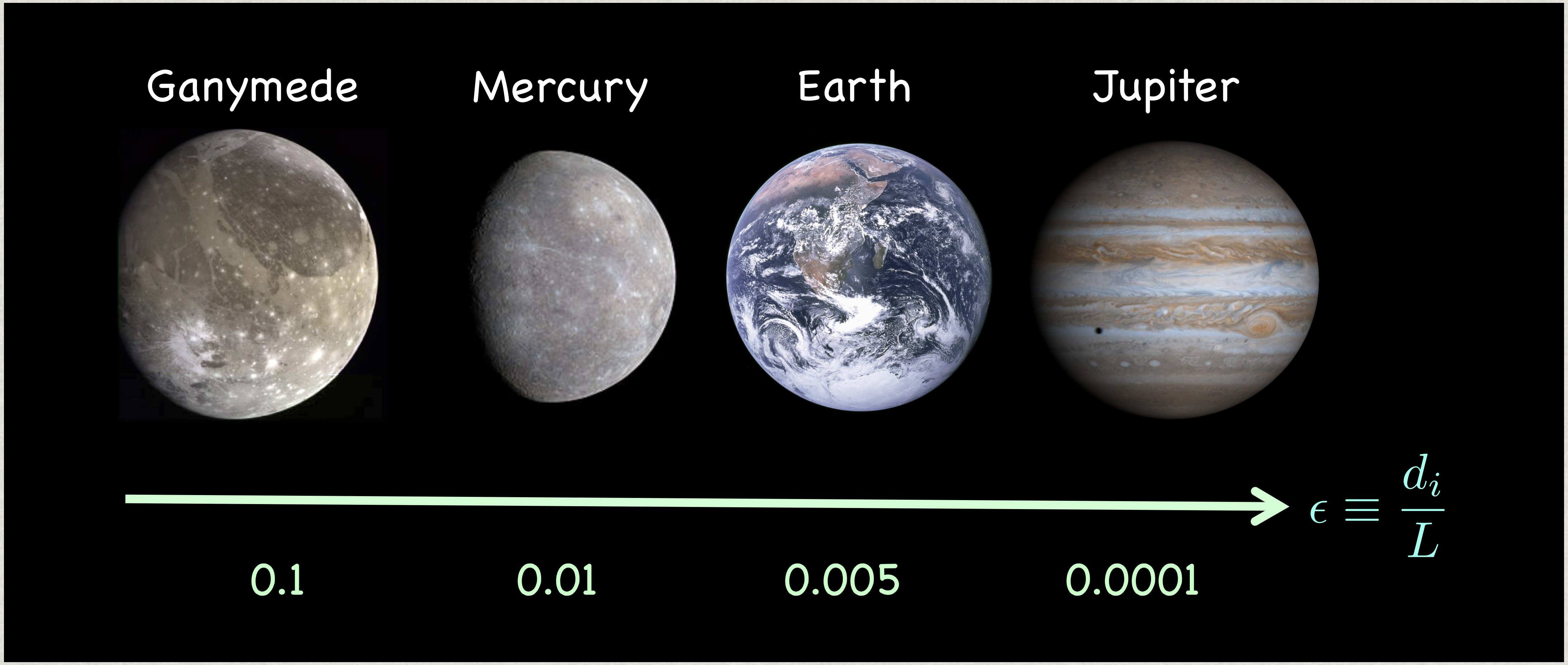
# Generalized Ohm’s Law

$$E = -\frac{1}{c} U \times B + \underbrace{\sum_{\alpha} \int dv\, q_{\alpha} n_{\alpha} v \left(\frac{\partial f_{\alpha}}{\partial t}\right)_{c}}_{\eta J} + \frac{1}{nec} J \times B - \frac{1}{ne} \nabla \cdot P_e^{CM} - \frac{m_e}{ne^2} \frac{\partial J}{\partial t} - \frac{m_e}{ne^2} \nabla \cdot (UJ + JU)$$

Ideal MHD term (Frozen Flux Theorem)
Hall term (Electron Frozen Flux Theorem) [ION INERTIAL SCALE]
Electron Pressure Anisotropy (thaws magnetic flux) [ION INERTIAL SCALE]
Electron Inertia (thaws magnetic flux) [ELECTRON INERTIAL SCALE]
Particle Scattering (thaws magnetic flux - e.g., resistivity)

- Assuming quasineutrality and neglecting terms ~me/mi gives the above expression for the electric field.
- Each color represents a different regime.
- The results on previous slide are for resistive MHD

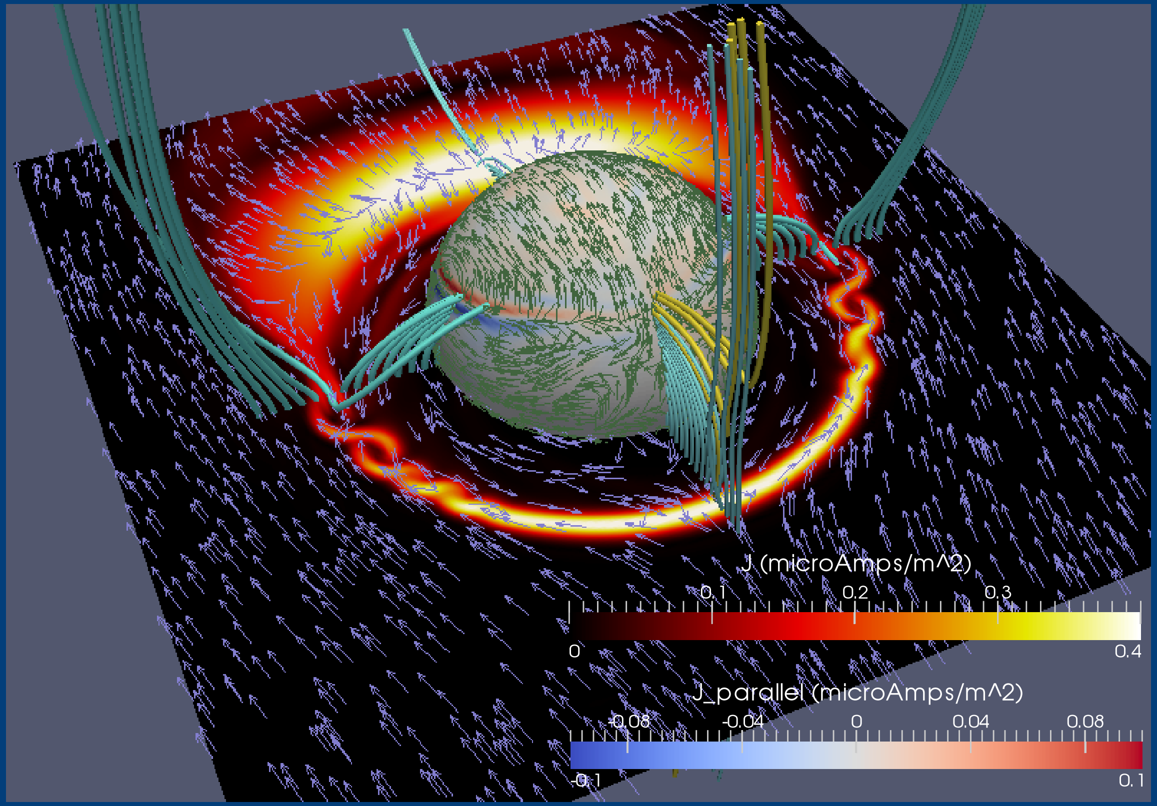
# Comparative Magnetospheres



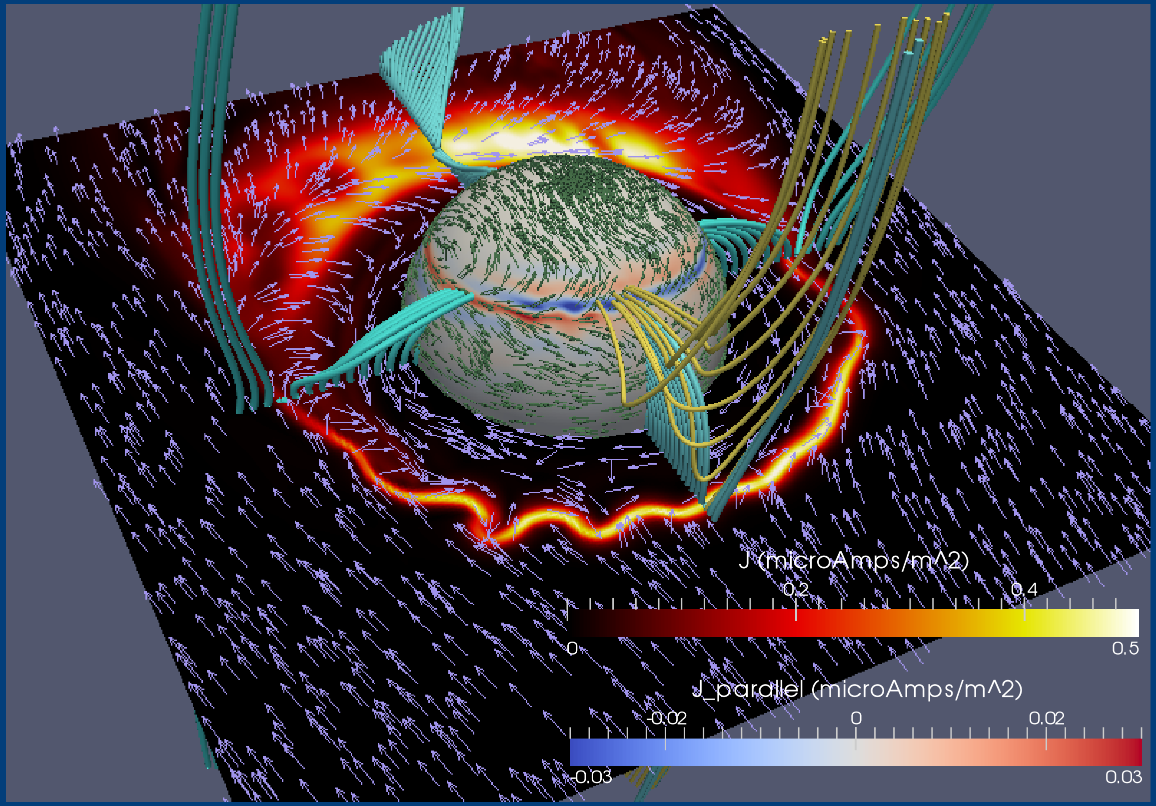
- To resolve ion scale effects you need to separate the ion scale from the diffusive scale.
- Relying on numerical resistivity would require 5-10 points per di
- Uniformly resolving the magnetopause at this level would require billions of cells.
- The situation improves when looking at planetary magnetospheres

# Implications of ion-scale physics

*(See Dorelli et al., 2015)*



**MHD**



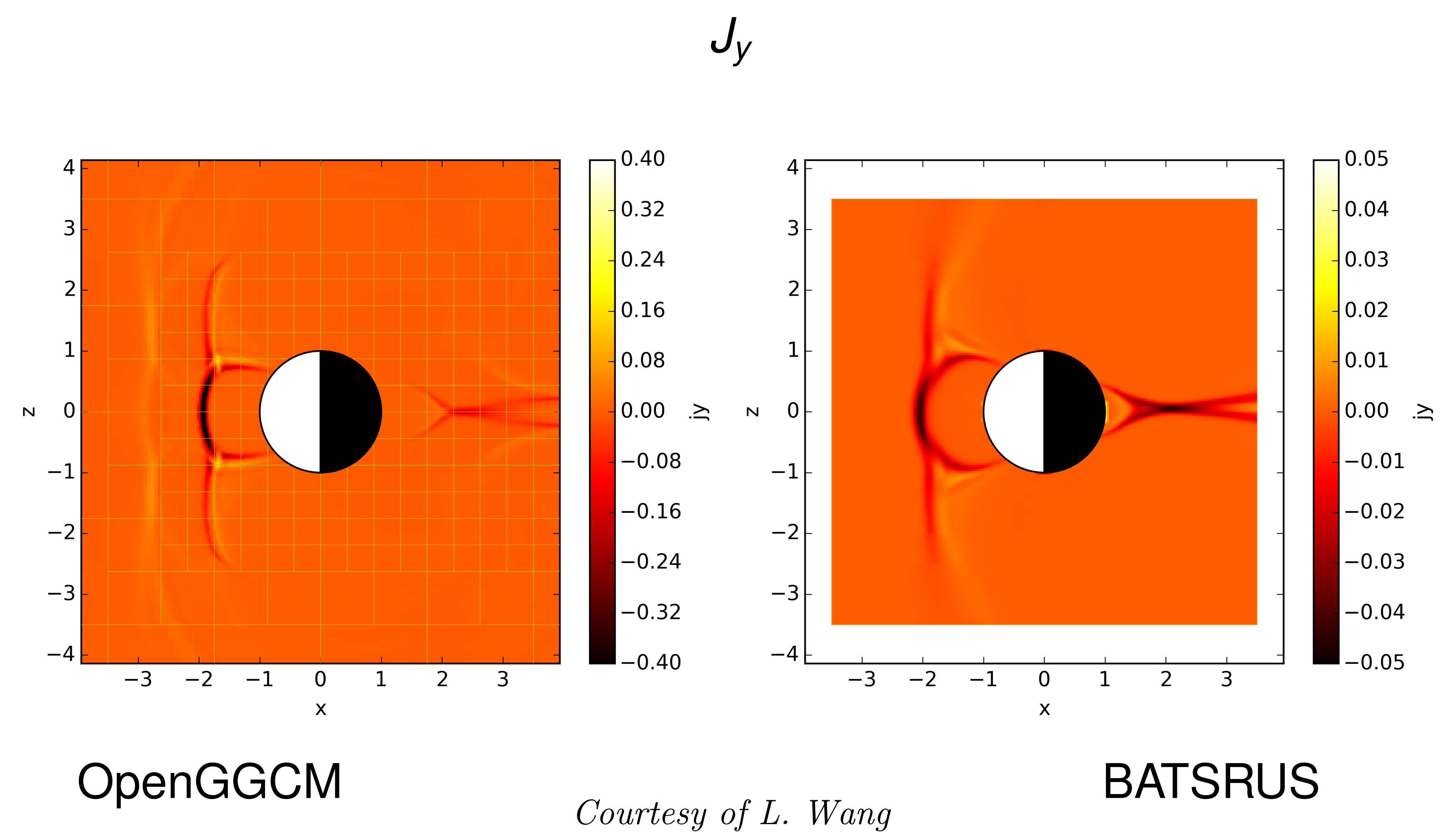
**Hall MHD**

- symmetric Dungey convection pattern
- typical region-1 field-aligned current pattern (supports Alfvén wing structure)
- symmetric pattern of Kelvin-Helmholtz waves

- strong asymmetries in convection pattern
- new reconnection-generated field-aligned current pattern (impact on Alfvén wing structure?)
- Asymmetric pattern of Kelvin-Helmholtz waves

*Courtesy of J. Dorelli*

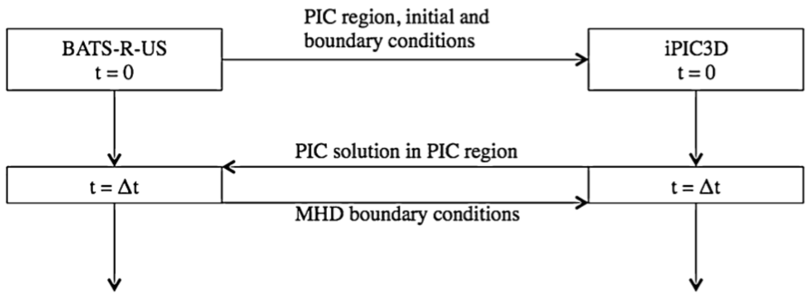
# Similar results for Ganymede for Different Models

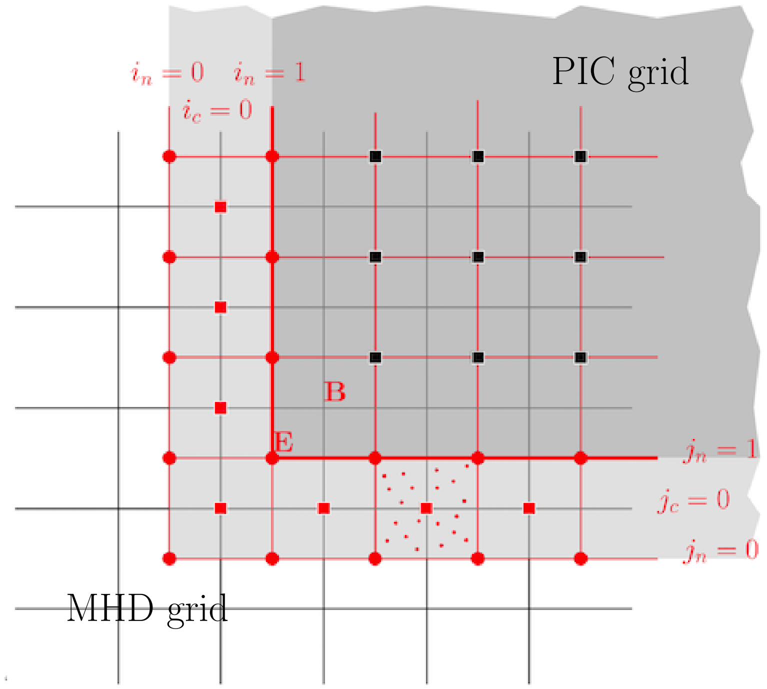


*Courtesy of L. Wang*

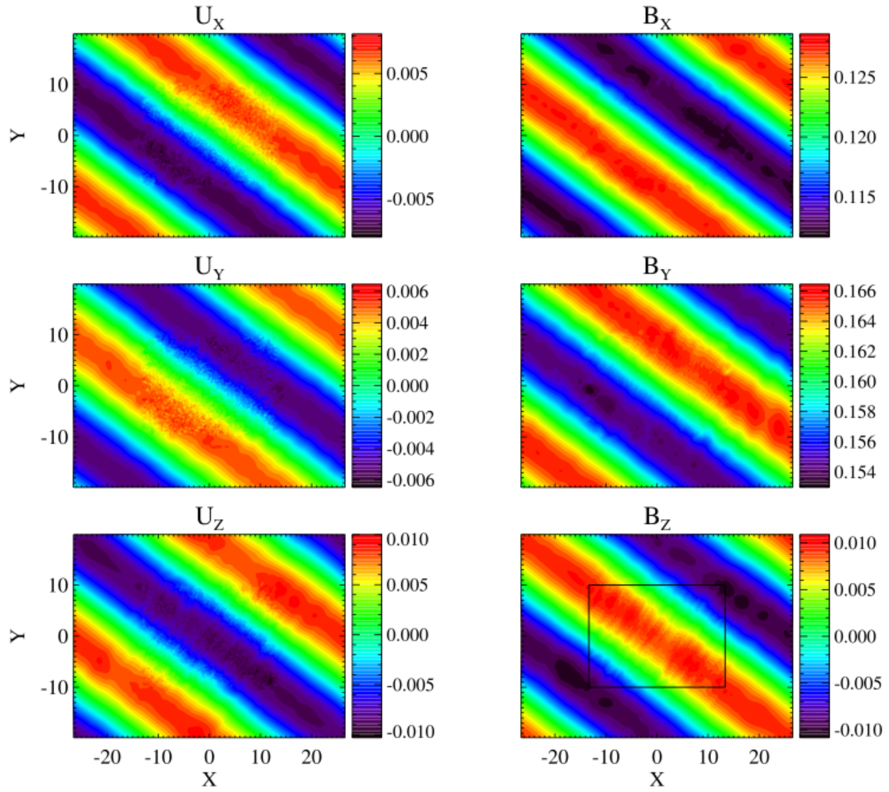
# Using EPIC-MHD

## Embedding Algorithm



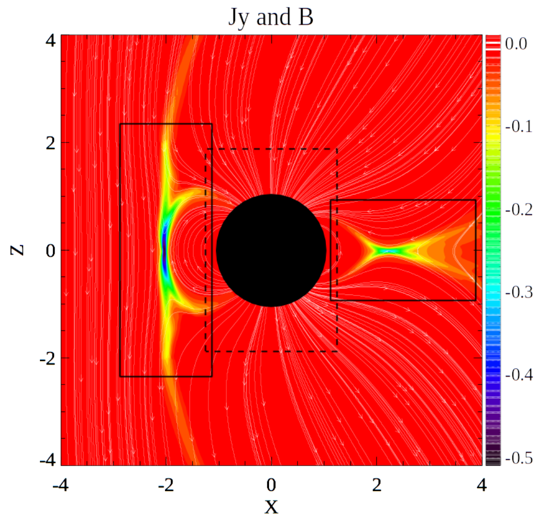


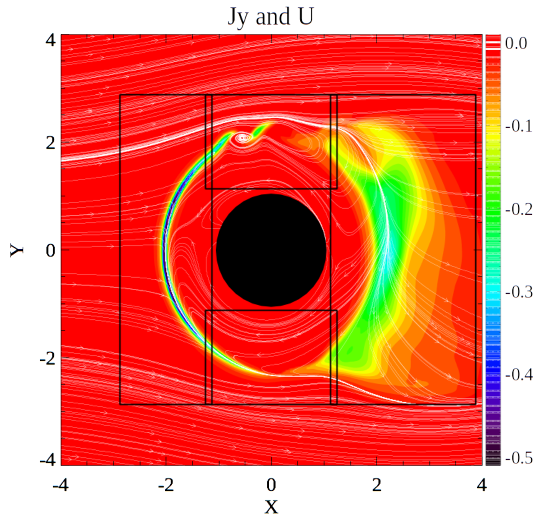
## Whistler Wave Test



*Courtesy of L. Daldorff*

## Ganymede

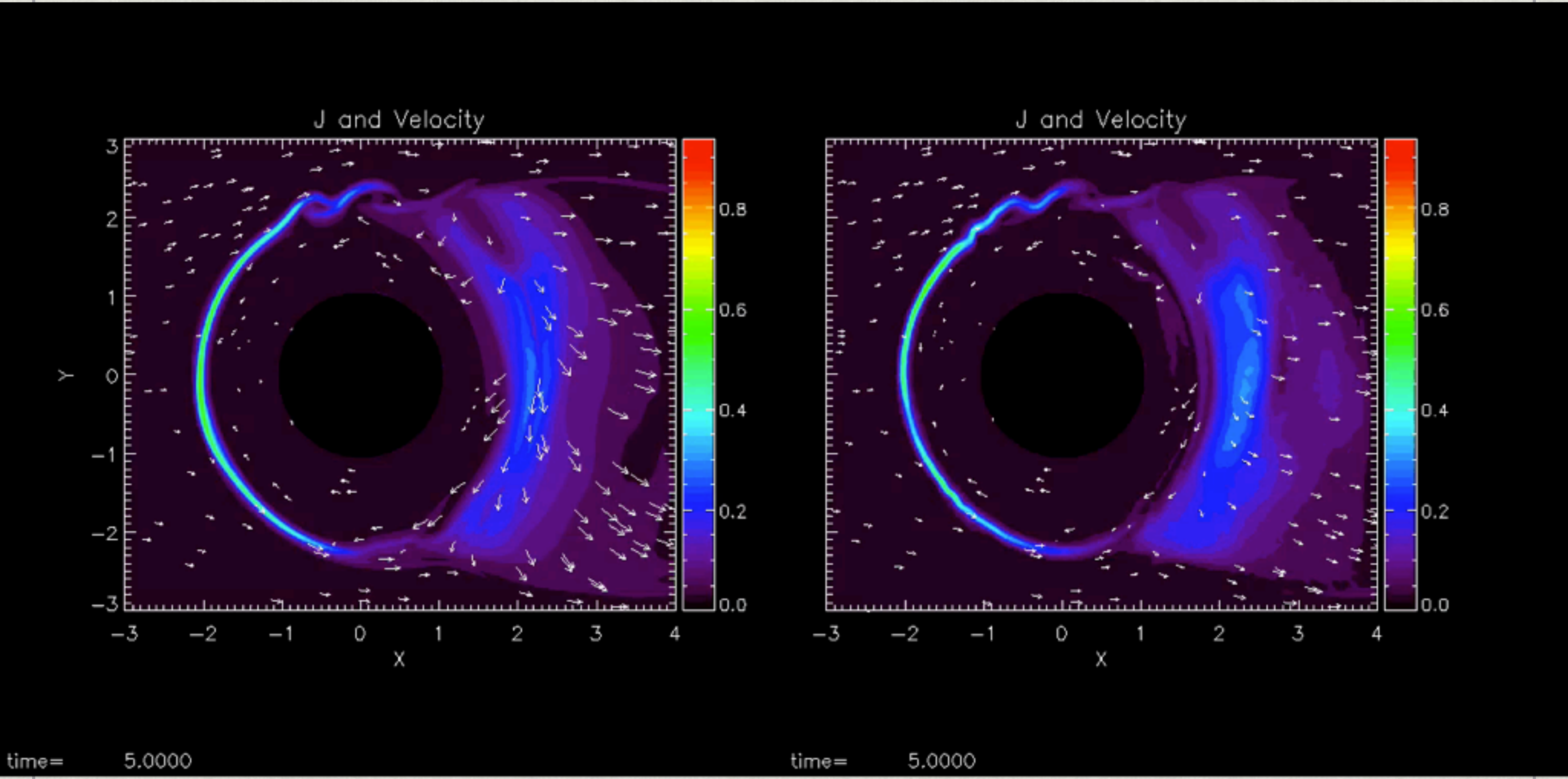




*Courtesy of G. Toth*

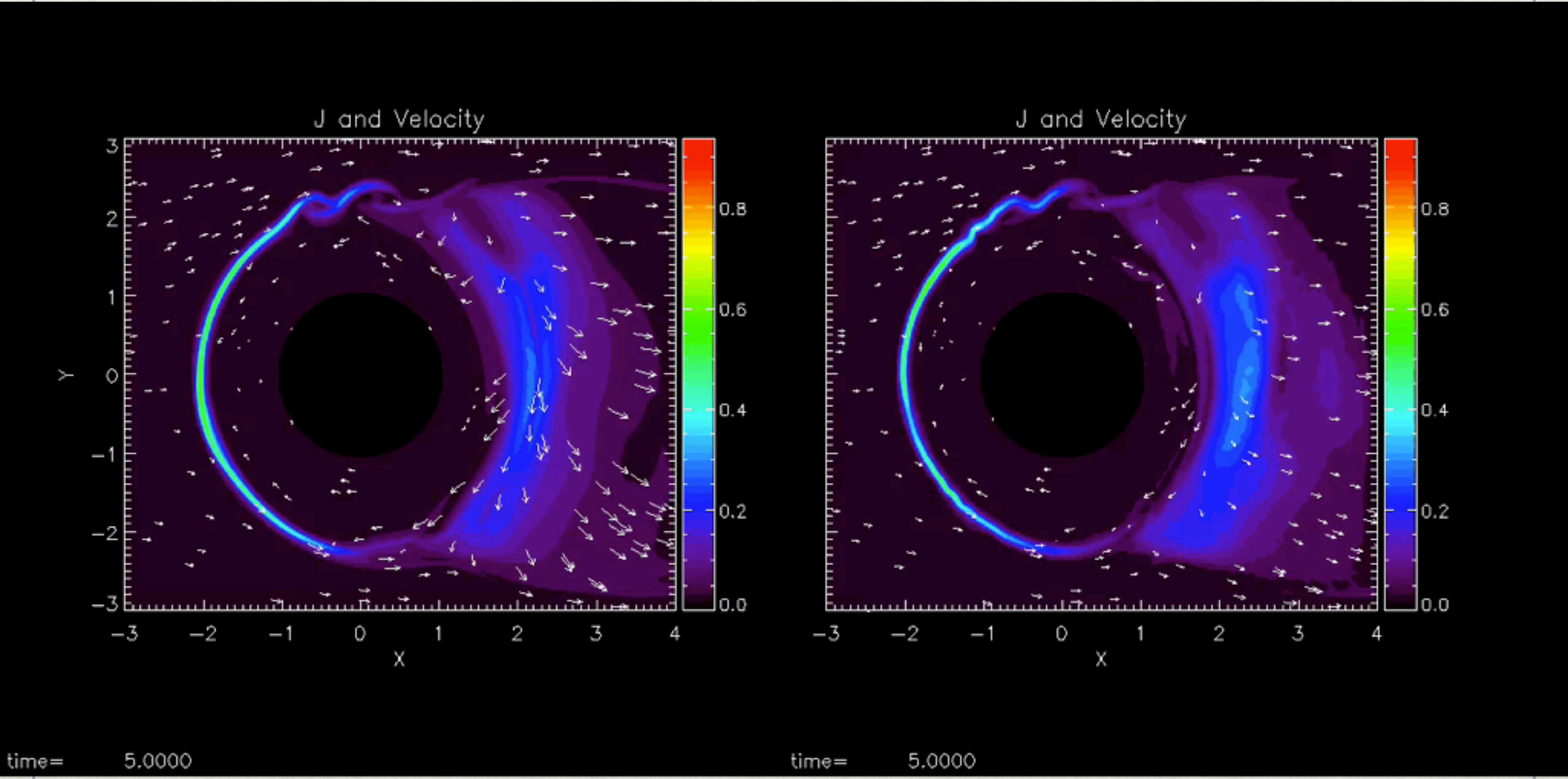
- IPIC3D model is now embedded in BATSRUS (see *Daldorff et al.*, 2014)
- Numerical tests show the embedding behaves as expected.
- Can use this to treat all the “interesting” regions of Ganymede and compare against the Hall solution.

# Comparing Hall MHD and EPIC-MHD



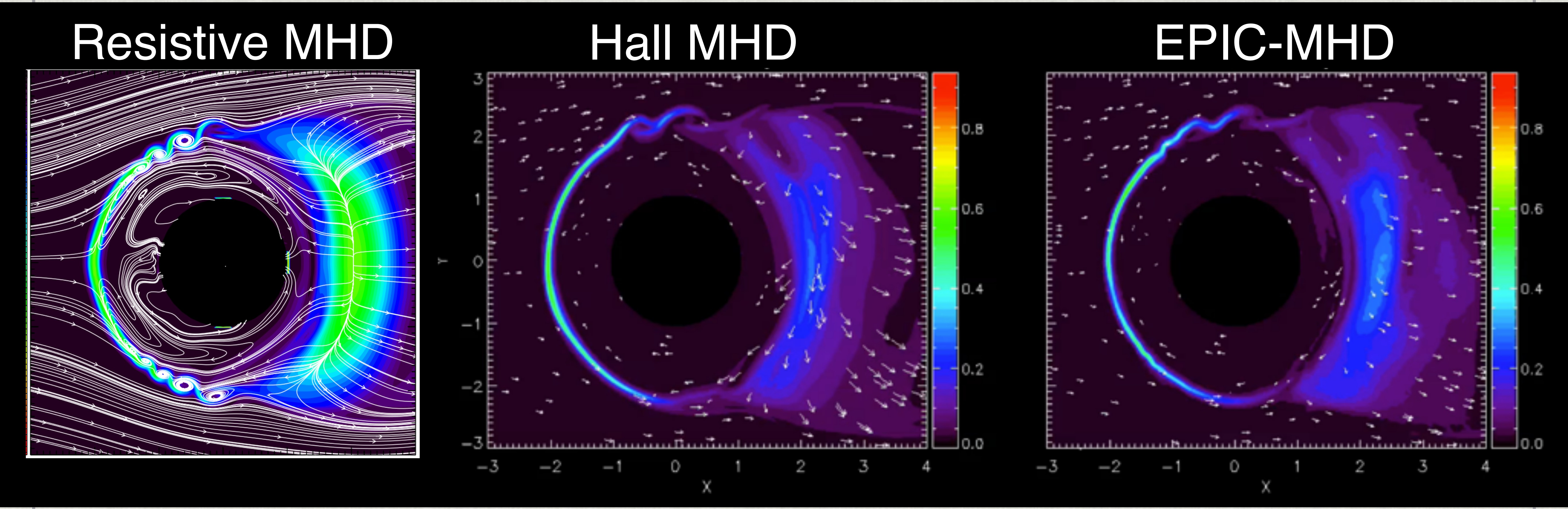
*Toth et al,* [2015]

# Comparing Hall MHD and EPIC-MHD



*Toth et al,* [2015]

# An Analogy to the GEM Challenge


Resistive MHD

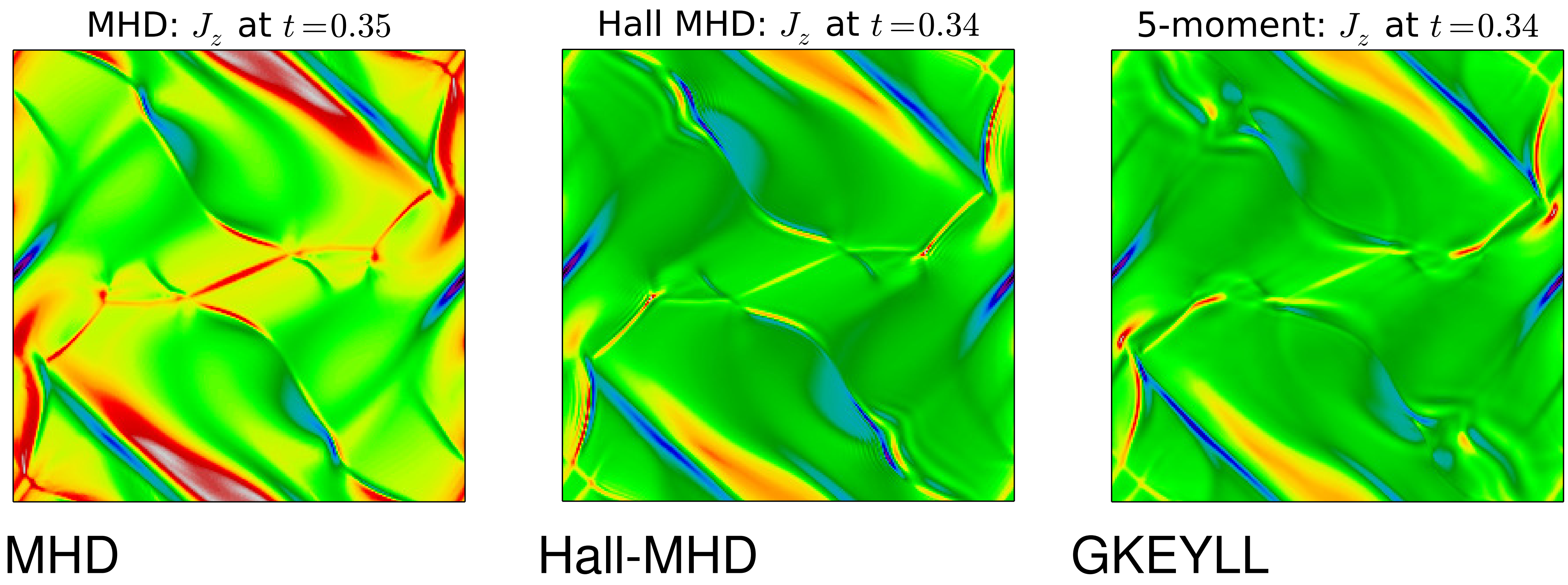
Hall MHD

EPIC-MHD

- In the GEM Reconnection Challenge many simulations were run with boundary conditions and initial conditions.
- All models with the Hall term gave fast reconnection.
- These results are like the GEM reconnection problem but with a real magnetosphere.
- Again, the Hall term seems to be the minimum extension of MHD that can capture the overall solution.

# Other Fluid Approaches to get Hall Physics

## Orszag-Tang Test



*Courtesy of L. Wang*

- Solving a multifluid set of equations (ion and electron fluids) is an alternative way to the generalized ohm's law approach for including Hall physics.
- Orszag-Tang test shows similar results between Hall-MHD and multi fluid, but not MHD.
- The GKEYLL code from PPPL is currently being included into the OpenGGCM magnetosphere code.

# Conclusions

- There is a very wide variety of modeling efforts on going in the community to capture the space environment system in all its complexity.
- While there are some similarity of approaches, differences exist between the models shown here.
- We have a long way to go to fully capture the multitude of scales and processes inherent in modeling the space environment system.

# Thank You