JOHNS HOPKINS
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Geospace Modeling with LFM and Gamera

Preparing for the Future, Remembering the Past

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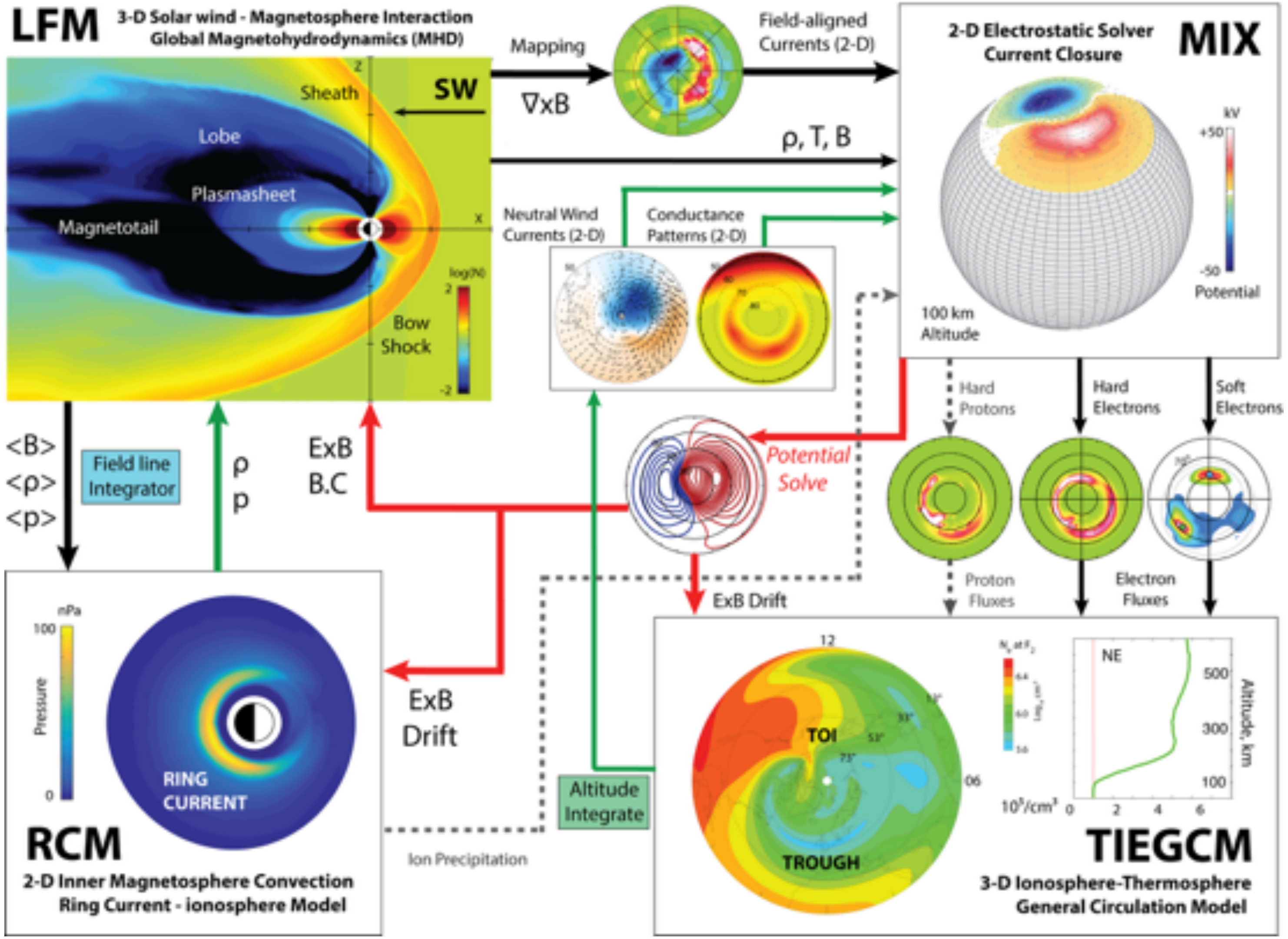
The CMIT Geospace Model

LFM-MIX-RCM-TIEGCM



CMIT Model

- Coupled Magnetosphere- Ionosphere-Thermosphere Model
- LFM+MIX+RCM+TIEGCM
- Includes global magnetosphere, ring current, precipitation, ionospheric electrodynamics, and ionosphere-thermosphere components
- Continuing collaboration (APL, NCAR, HKU, Dartmouth, Rice)
- Focus on global MHD (LFM) here

Talk Outline

- LFM Overview
- Recent research highlights
- Gamera: Reinventing LFM
- Next steps and future

LFM

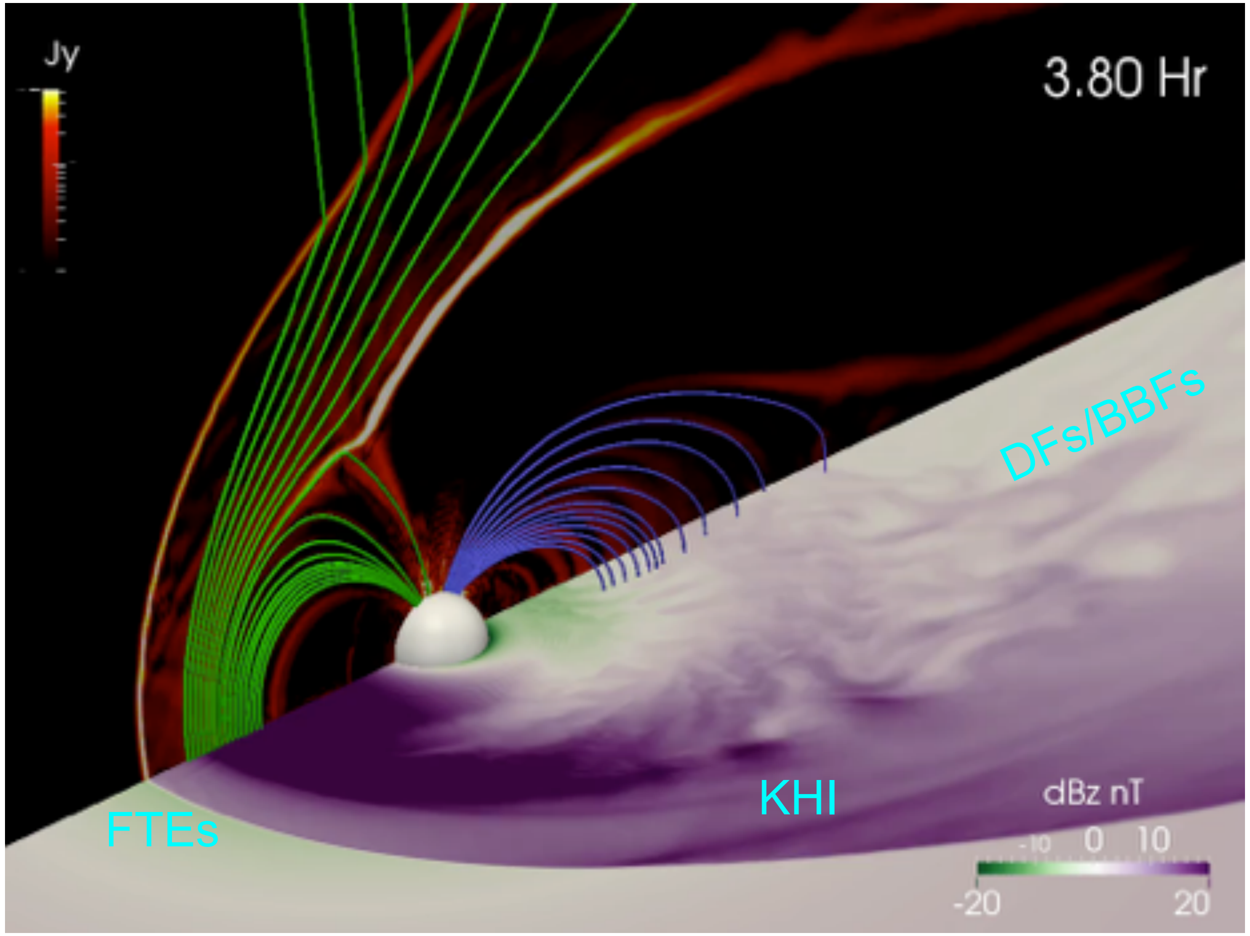
Overview and Timeline

- LFM — MHD code developed by J. Lyon, J. Fedder and C. Mobarry at NRL in the 80's
- MHD numerics by J. Lyon
- Heritage traced to pioneering work on Flux Corrected Transport (FCT) schemes in the same group (J. Boris, D. Book, S. Zalesak, K. Hain)
- One of the first FCT MHD codes in multiple dimensions
- Started with very high order fluid schemes (20th order, Lyon et al., PRL, 1981)
- Finite volume, arbitrary hexahedral mesh
- Constrained transport (Yee-mesh), Magnetic field divergence-less to round-off ($\nabla \cdot B=0$)

1980	MHD magnetosphere simulation (2-D)
1982	3-D magnetosphere
1985	Self-consistent ionosphere coupling
1992	CRRESS Barium release (Huba et al., JGR); Hall MHD
1995	Saturn, Neptune, Uranus simulations Higher resolution
1997	Acquired name (LFM)
1998	Venus simulation (Kallio et al., JGR)
1999	Outer heliosphere, neutrals, pickup ions (McNutt et al.)
2004	MPI parallelized Numerics paper written (Lyon et al., JASTP); done in 1987
2008-2010	Geospace coupling framework Operational at CCMC
2010	Multi-fluid extension
2011	Inner heliosphere, solar wind (Merkin et al., GRL)
2013	High-resolution magnetosphere KHI (Merkin et al., JGR)
2015	High-resolution magnetotail dipolarizations (Wiltberger et al., JGR)

Recent LFM/Geospace Highlights

- Magnetotail stability (Merkin++ 2015 & 2016)
- AMPERE data assimilation (Merkin++ 2016)
- Multifluid effects on dayside reconnection
  - Ionospheric outflow (Zhang++ 2016 & 2017)
  - Plasmasphere (Ouellette++ 2016)
- Multifluid coupling with first-principles polar wind model (Varney++ 2016ab)
- High-resolution magnetotail flows
  - BBFs, dipolarization fronts, injections
  - Wiltberger++ 2015, Ukhorskiy++ 2018, Sorathia++ 2018
- High-resolution boundary dynamics and particle losses (Sorathia++ 2017)
- Geomagnetic storm simulations
  - Macroscopic effects of microscopic ionospheric turbulence
    - Wiltberger++ 2017, Merkin++ 2017
  - MHD+TP outer belt modeling (Li++ & Hudson++ 2017, Sorathia++ 2018)



High quality MHD numerics are key to realistic description of the magnetosphere during both quiet and disturbed conditions (e.g., dipolarization fronts, injections, KHI, FTEs)

Fully Coupled LFM-MIX-RCM-TIEGCM (2013 St. Patrick's Day Storm)

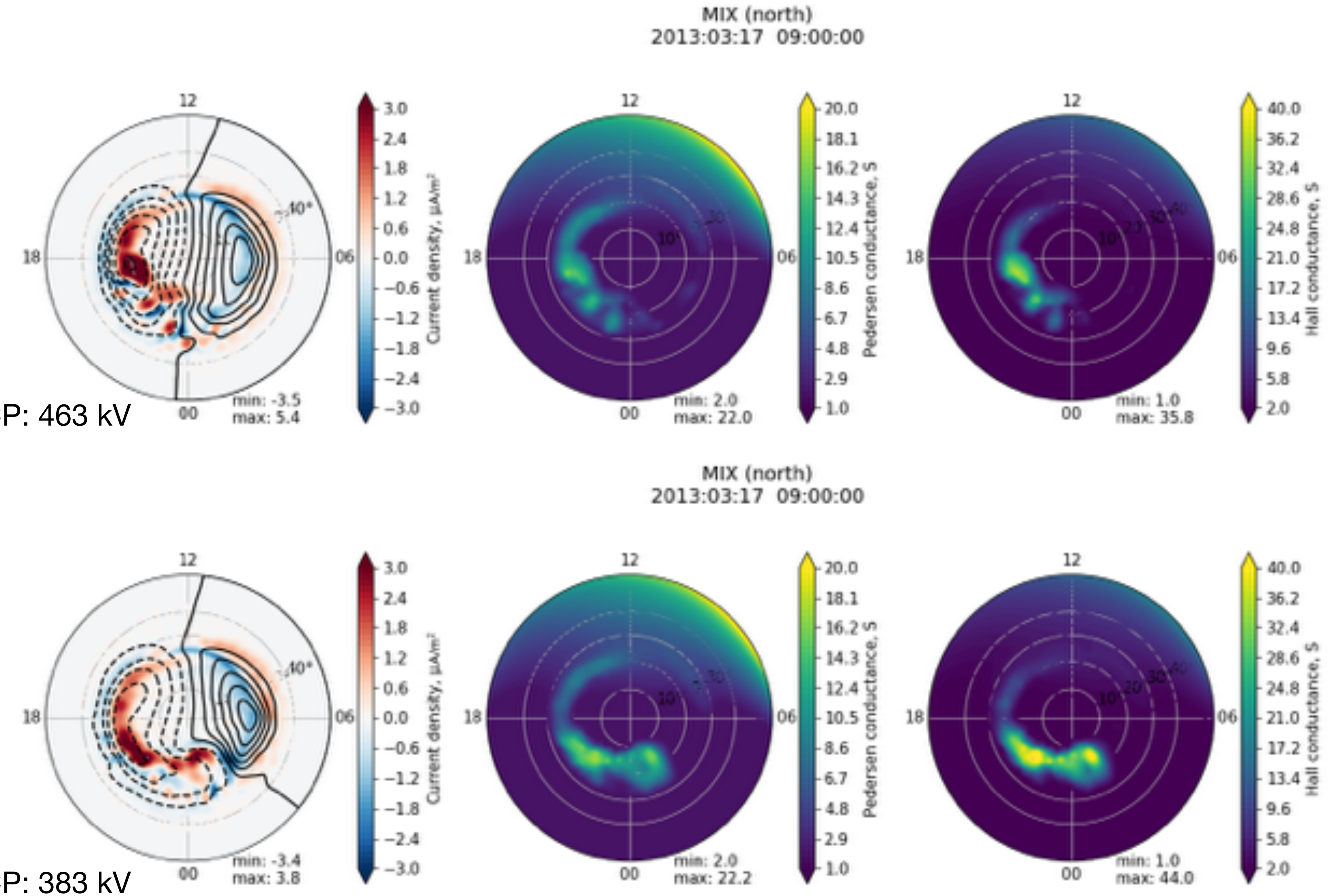
Electrojet turbulent (ET) heating included directly in TIEGCM

W/O ET

CPCP: 463 kV

W/ ET

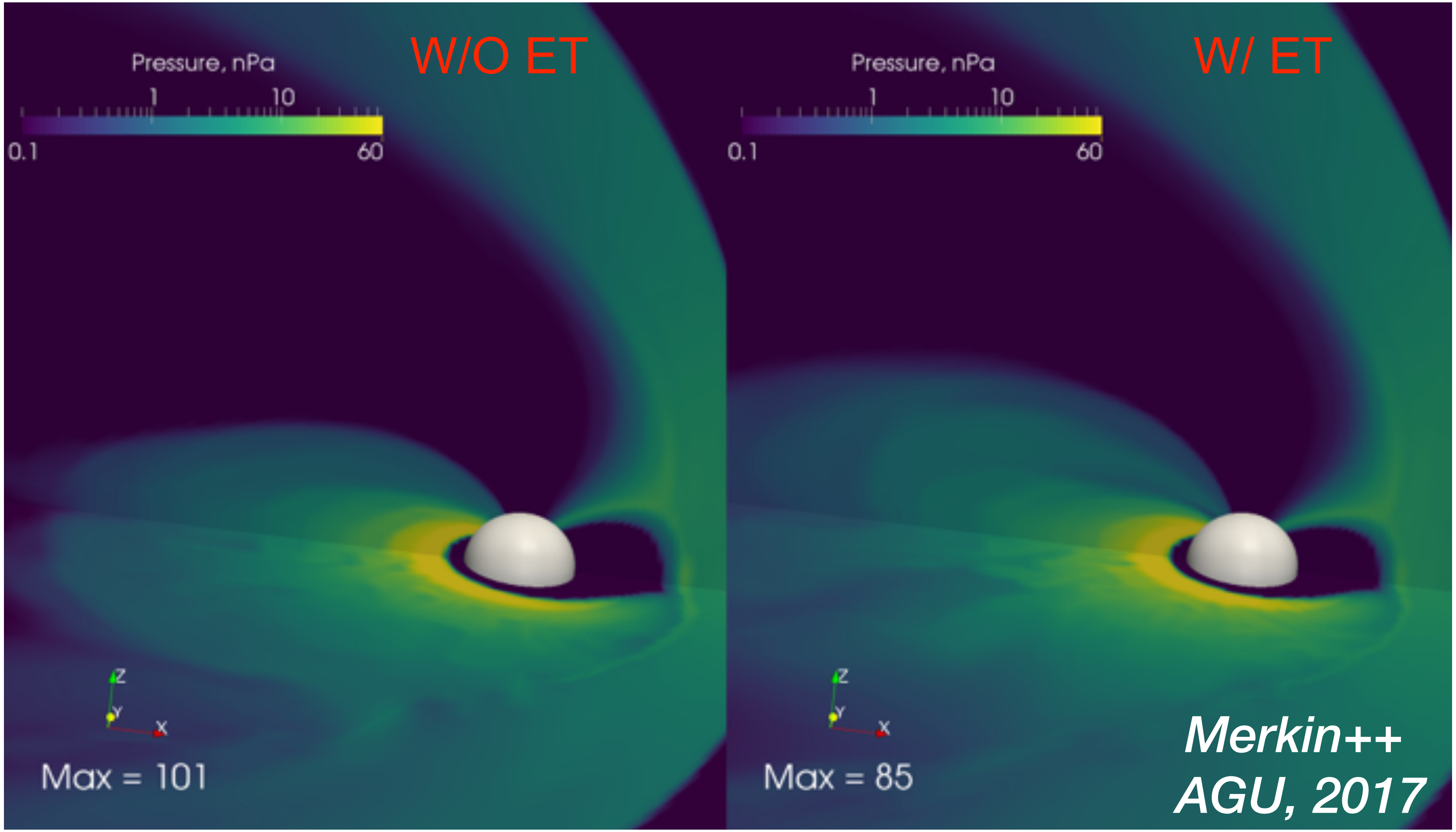
CPCP: 383 kV



- All major geospace components coupled
- Microscopic E-layer electrojet turbulence (ET) modifies ionospheric conductivity
- ET heating terms included directly in TIEGCM

Merkin++ AGU, 2017

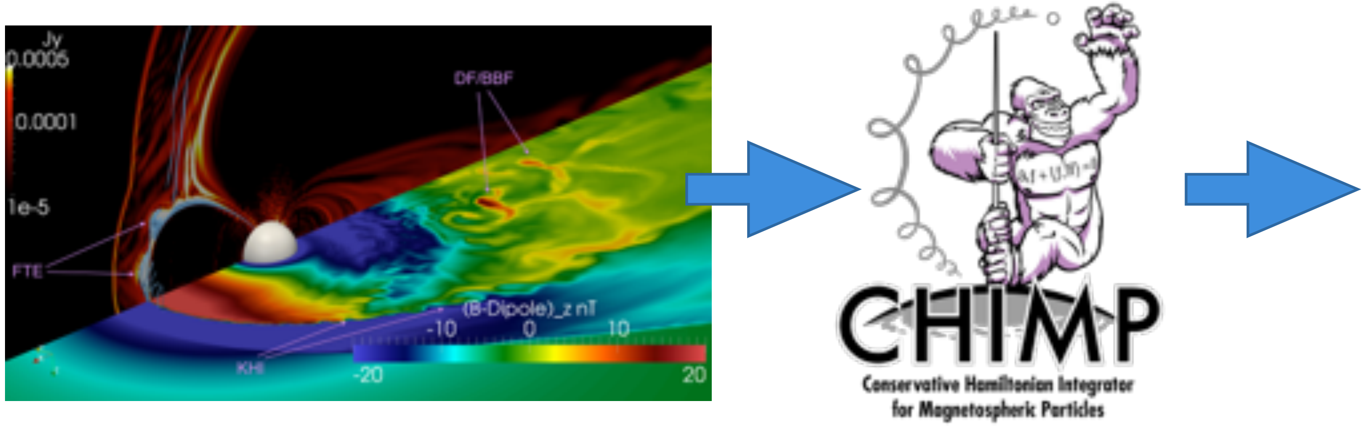
The Large Effect of Small Scales



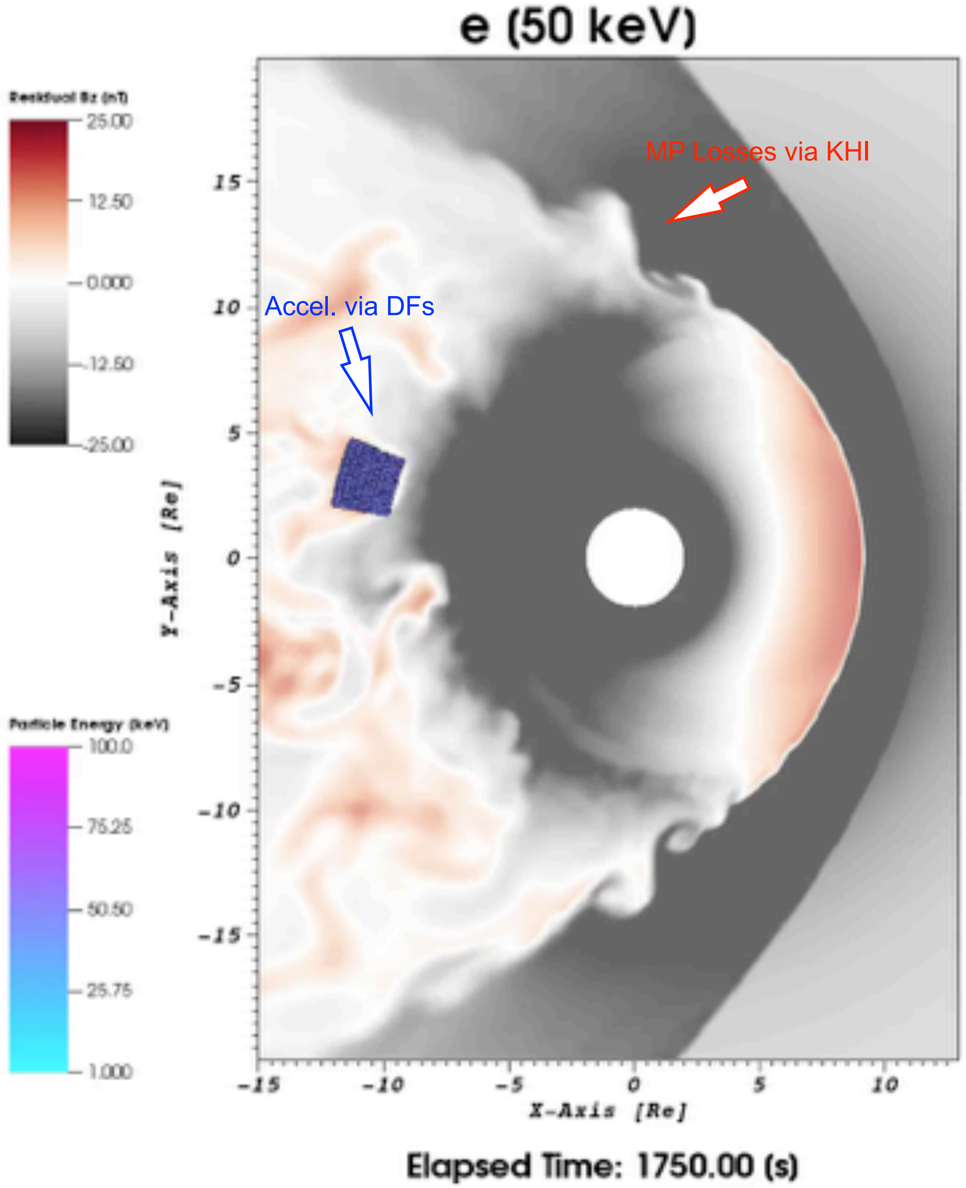
- Microscopic physics @ 100km has major macroscopic effects on magnetospheric plasmas at 60,000 km

Mesoscale Fluid-Particle Processes

CHIMP + LFM: Particle Tracing in high-resolution MHD



- How do energetic particles interact w/ mesoscale MHD flow structures?
- CHIMP
  - Evolve test particles (TPs) in 3D MHD-generated EM fields
  - Post-proc step, interpolate from high-cadence saved MHD data
  - FO/GC switching based on local field
- Production & reduction of energetic particles
  - Transport & acceleration via magnetic gradient trapping in DFs
  - Magnetopause losses via KHI vortices



Example: Electron TP's initialized on MHD dipolarization front, Z=0 plane.

CHIMP RB Model

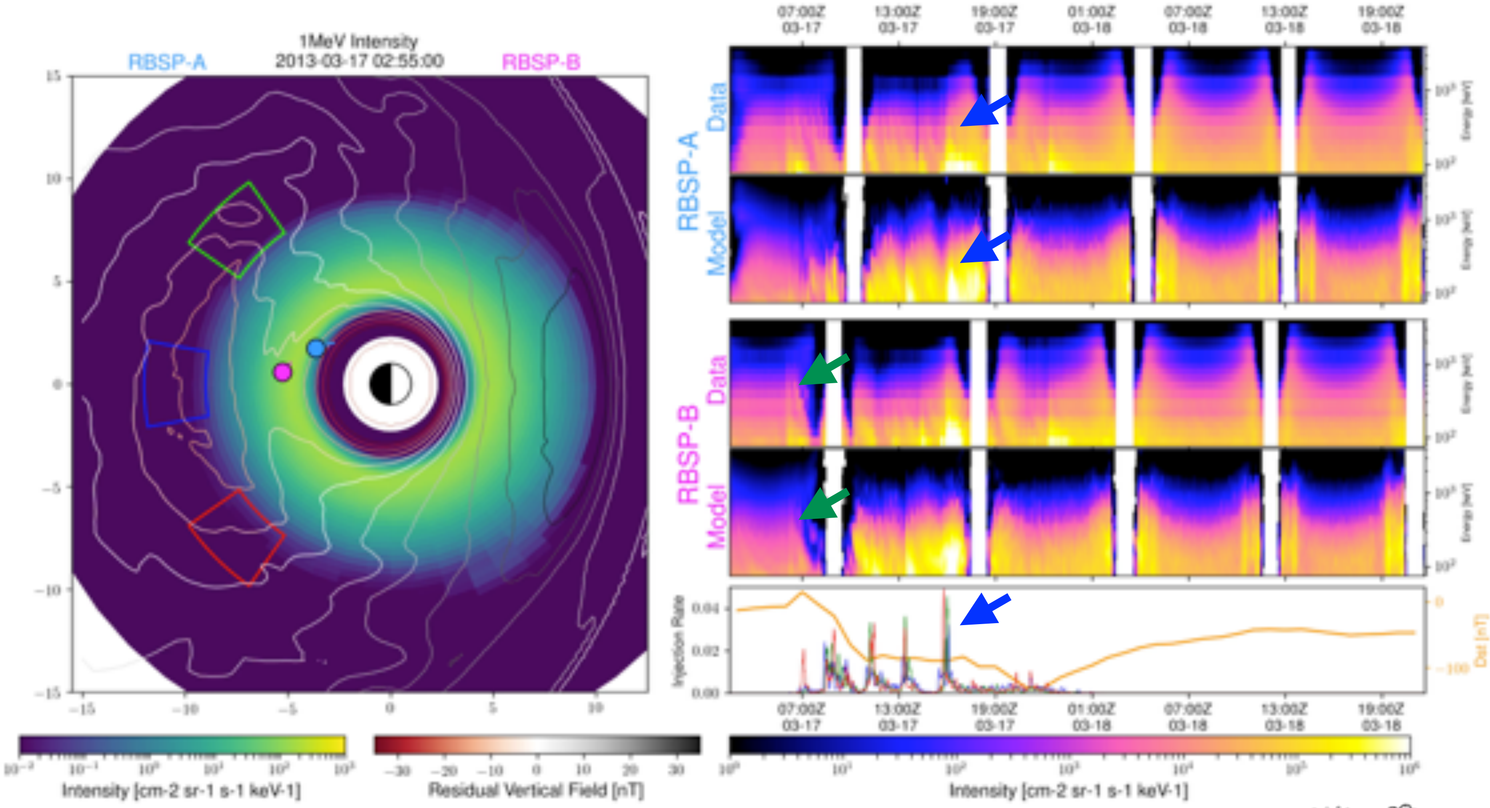
Modeling the Outer Radiation Belt w/ MHD+TP

Framework

- Input: Solar wind/F10.7
- Global 3D MHD+RC
- Use MHD flow data (n,T,V) to seed TPs
    - i.e., aim TP's at injection fronts
- Convert TPs to electron PSD

Application to March 2013 Storm

- Comparison w/ in situ RBSP measurements
- Reproduce global evolution
    - Cycle of depletion, recovery, enhancement
    - Ratio of pre- and post-storm intensities
- Reproduce localized (space+time) features
    - Compression/drift-echo signature of CME shock
    - Nightside injection signatures



2013 St. Patrick's Day Storm
Model vs. RBSP comparison

CHIMP
Conservative Hamiltonian Integrator for Magnetospheric Particles

How do we move forward?

LFM has come a long way in 40 years, but age takes its toll

Between a rock and hard place

- Modern supercomputing landscape is unforgiving
- LFM is robust and works well on existing architectures, but its age makes it hard to adapt to next-gen SCs (e.g. CORAL & TRINITY)

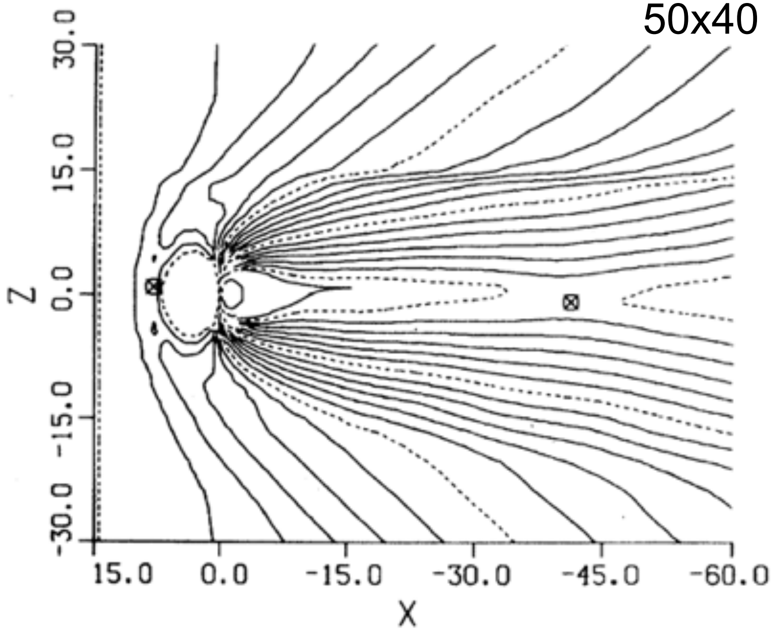
Easy to get left behind on march to exascale

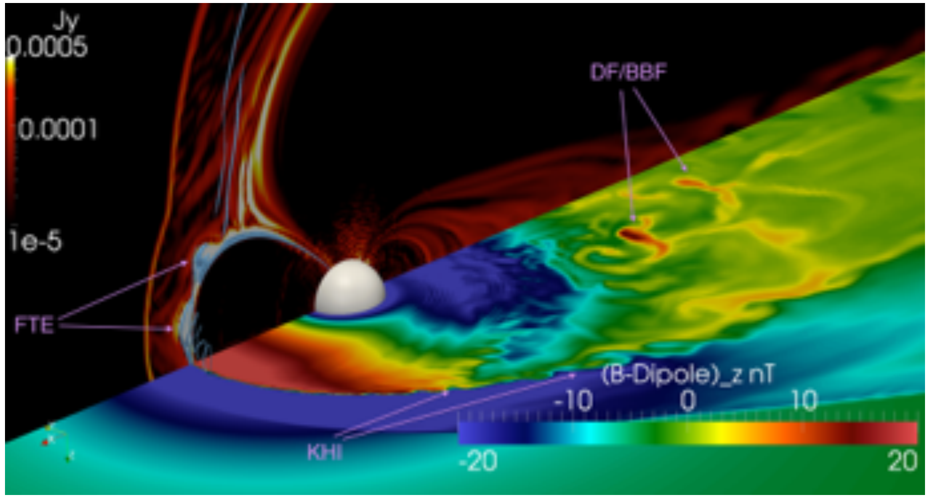
- Economies of scale (e.g. GPUs) => great flops/$
- Hard to map to better science/human-time, juggle low-level & high-level
- Low-level
    - Code has to be written to expose multiple layers of heterogeneous parallelism
    - Comm & branching avoidance, MAP, vectorization
- High-level
    - Model coupling for inter-connected, multi-physics, multi-scale systems
    - Newly resolved spatiotemporal scales can require new self-consistent physical models and algorithms

Need to move beyond LFM

- LFM core was written ~40 years ago and optimized for architectures long retired
- LFM built to rely on libraries (P++, Intercom) and programming (F77) that are now deprecated
- Serious changes needed for a sustainable future, reinvent LFM as **Gamera**

Lyon++ 1981
50x40



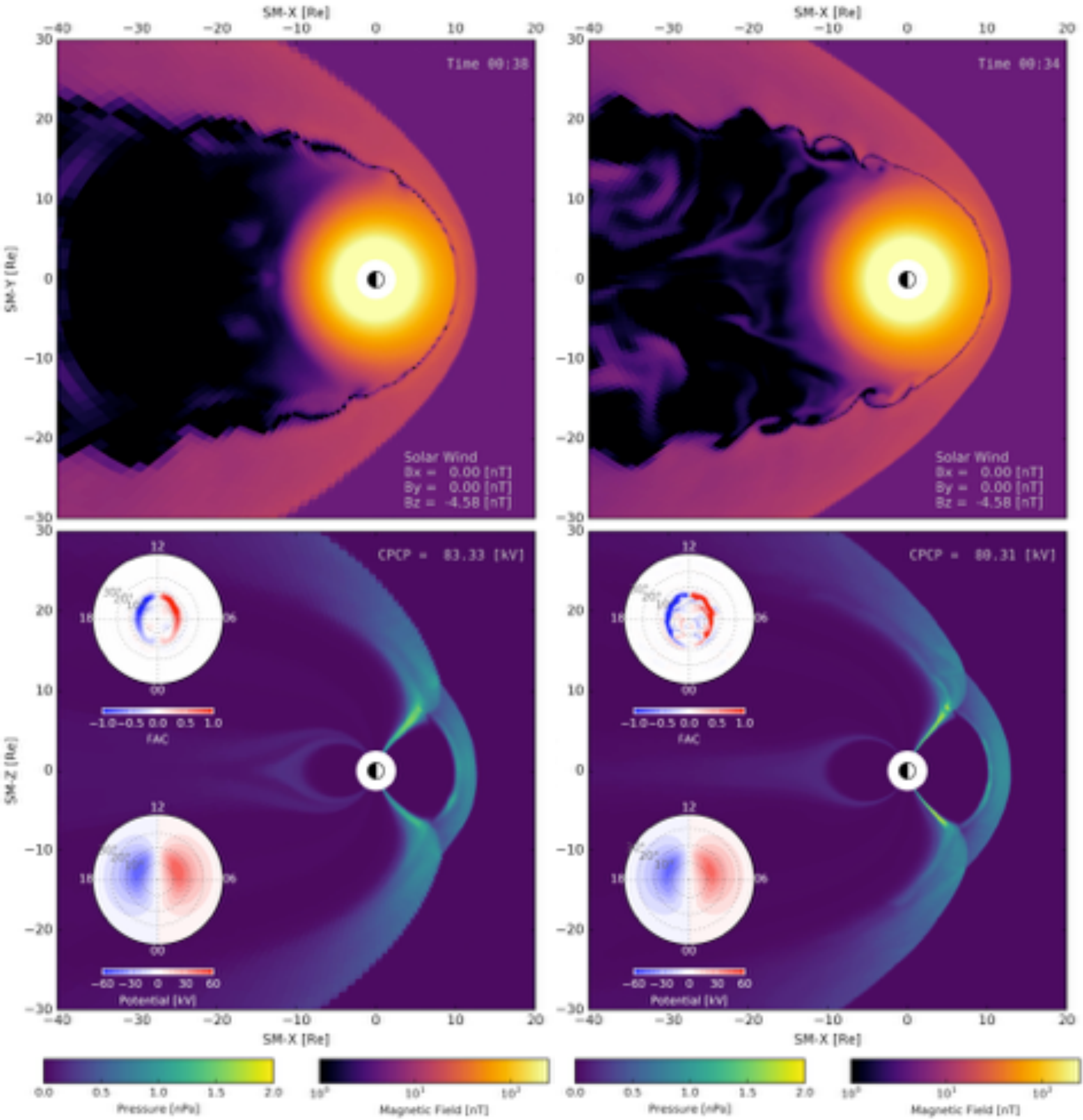


Wiltberger++ 2016
212x196x256

From LFM To Gamera

Prepare for the future, remember the past

- Why keep decades-old numerics?
- LFM is fairly unique
  - Handles arbitrary, non-orthogonal (and singular!) grids
  - High-order spatial reconstruction, intrinsically div-free B updates
- Resolution is more than number of cells
  - LFM has added algorithmic complexity, but can do a lot w/ a little
  - Can capture 3D dynamics with relatively few cells
- Example: Coupled magnetosphere-ionosphere w/ Gamera
  - Gamera QUAD
  - 96x96x128, comparable to LFM quad (left)
  - 2-3x slower than real-time on single Cheyenne node
  - BBFs, KHI, FTEs



Gamera QUAD

Gamera OCT

Meet Gamera

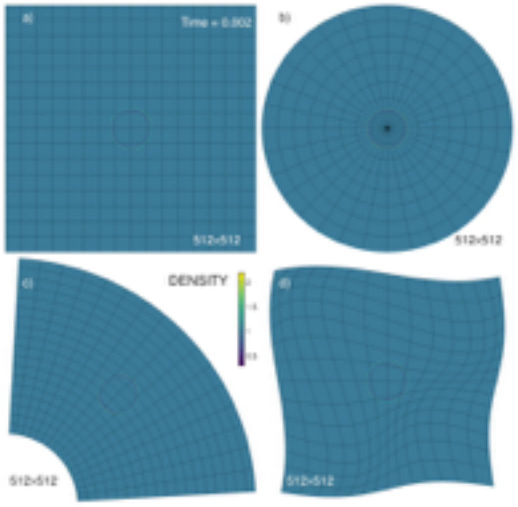
LFM Reinvented

Computational Advances

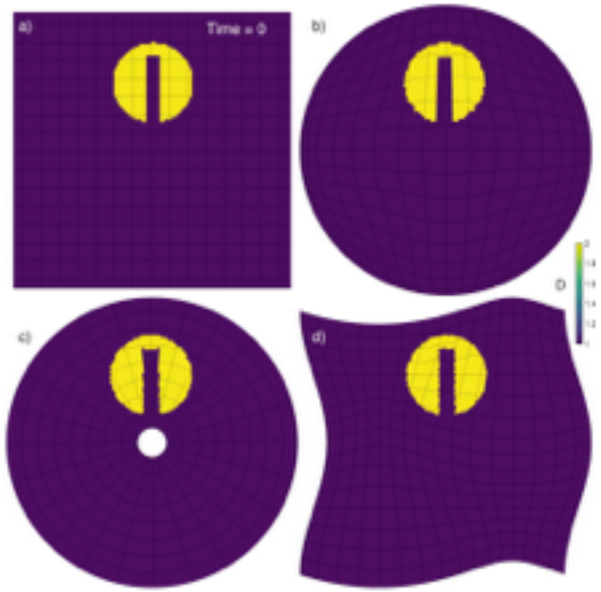
- Rebuilt from scratch (Fortran 2003+)
- Minimal external library dependence (HDF5)
- HPC friendly
  - Exposes multiple layers of heterogeneous //-ism
  - SIMD/OpenMP/MPI
  - MAP: Contiguous 4D arrays, stride-1 comp. loops
- Rebuilt & streamlined coupling interface
  - Concurrent component execution

Algorithmic Advances

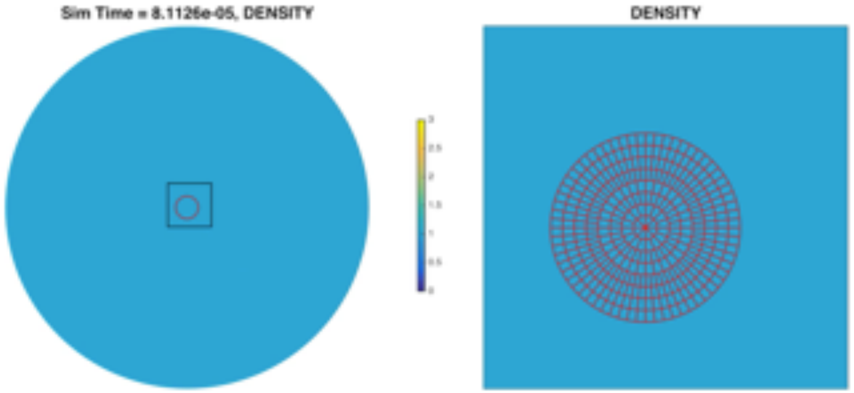
- Improved treatment of coordinate singularity
  - JCP submitted (Zhang++ 2018)
  - New ring-avg implemented in TIE-GCM to enable highest res. runs to date
- Optional 7th order unwinding + non-clipping limiter
- Higher-order metric calculations (12th order Gaussian quadrature)
- Tested against full suite of MHD test problems
  - Method paper + tests in prep for JCP



MHD Blast Wave



Slotted Cylinder Advection



Blast wave through singularity

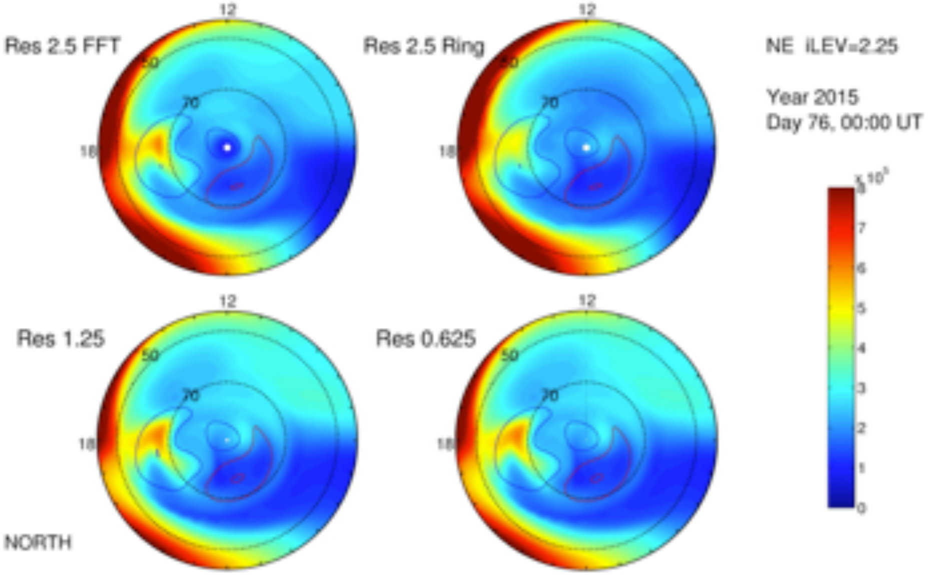
Videos courtesy of B. Zhang

Gamera

Beyond Ideal MHD

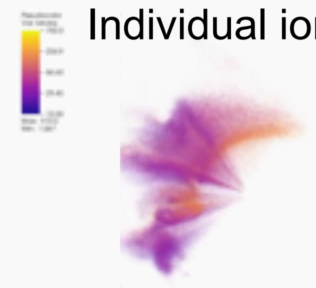
Magnetospheres are more than ideal MHD

- Ionospheric electrodynamics: Rewritten ion. solver (MIX->ReMIX)
- Fluid extensions: Carrying over multi-fluid & Hall MHD from LFM
- Model coupling
  - Flexible coupling framework, other models easily incorporated
  - Rebuilding coupling mechanisms to RCM & TIEGCM
  - Working towards OCT + 0.625 deg. TIEGCM w/ Gamera ring-avg
- RC coupling
  - Streamlined via FL tracing on native, curvilinear grid
  - RC model agnostic, including empirical pressure ingestion
  - Working towards in situ TP-based RC model
    - Ion TPs + MHD (n,T) => RC PSD

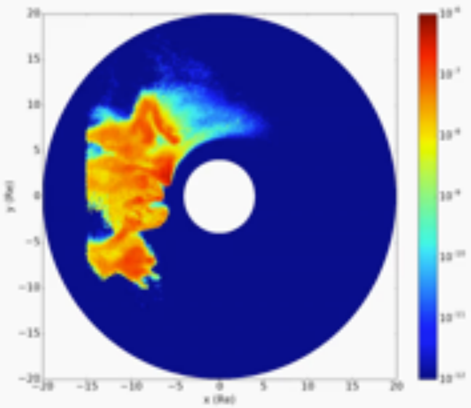


High-res TIEGCM using Gamera ring-avg
Courtesy Tong Dang

Individual ion TPs

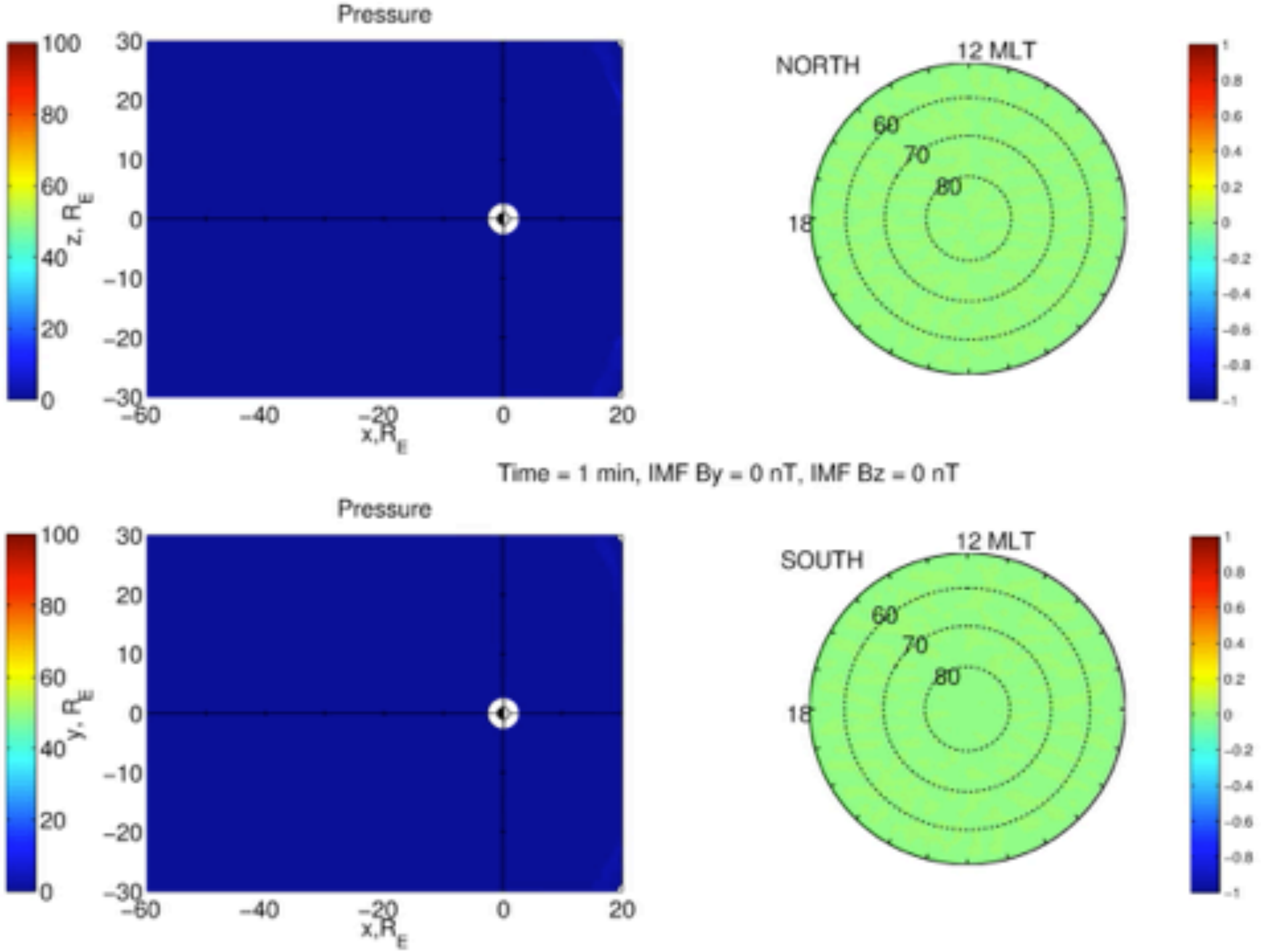


Synthesized ion PSD



Summary

- CMIT backbone is the global magnetosphere MHD code (LFM)
- LFM has been in production >30 yrs
- High-quality numerics, but needs upgrades for a sustainable future
- Developed Gamera, a general-application, flexible, portable and efficient MHD code
- Gamera preserves (and improves upon) the high-heritage LFM numerics
- Modern Fortran, minimal external lib. dependence
- Building a robust and flexible-coupling framework for Gamera (incl. model-agnostic RC coupling)
- Ready for RCM & TIEGCM (high-res) coupling
- Magnetosphere applications operational and used for science-quality production runs
- New TP code (CHIMP) is tightly integrated w/ Gamera
- CHIMP + Gamera: Mesoscale injections and dipolarizations enable realistic RC/RB modeling
- New tools (CHIMP/Gamera) much easier to transition to CCMC and we're looking forward to working towards this goal
- Learn more @ civspace.jhuapl.edu/gamera



Coupled Gamera+ReMIX / By IMF

GAMERA
Grid Agnostic MHD for Extended Research Applications

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