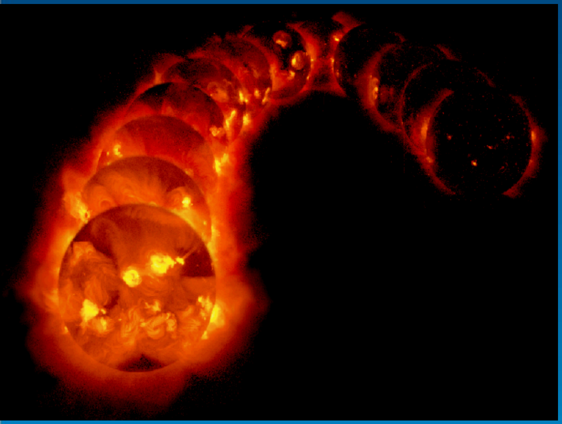
Surface Charging Environment Modeling With the SHIELDS Framework

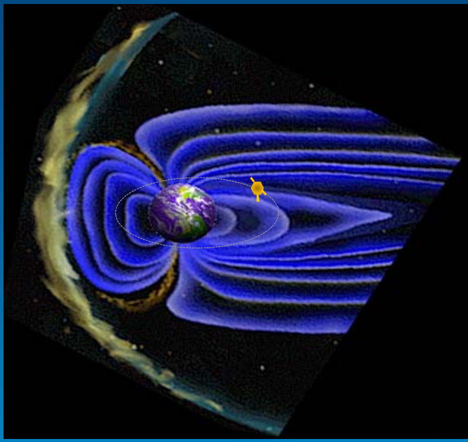
Vania Jordanova & the SHIELDS Team
Los Alamos National Laboratory



Project Goals & Scientific Impact:

- **Develop a new space weather capability to understand, model, and predict:**

  Space Hazards Induced near Earth by Large, Dynamic Storms (SHIELDS)

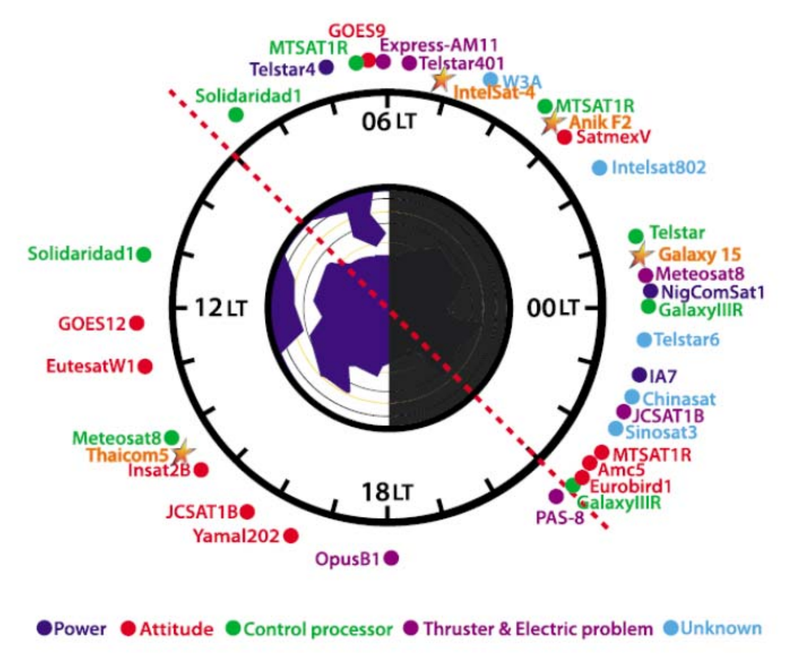


Active Experiments in Space Workshop
Santa Fe, NM, 11-15 September 2017

Satellite Anomaly Database

- GEO satellite anomalies occur mainly on the nightside, where the hot ~10's keV electron fluxes maximize

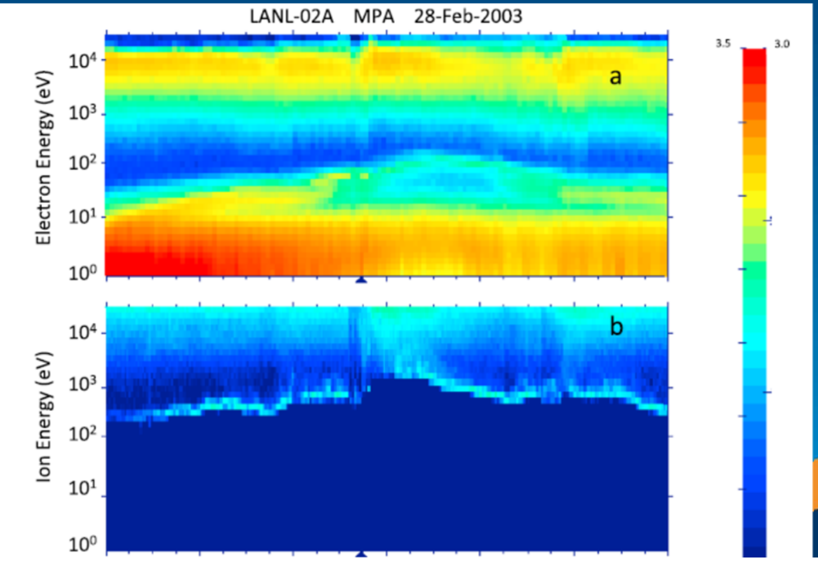
[Choi et al., 2011]



- LANL MPA data reveals the electron energy range (~5–10 keV) are most closely associated with satellite surface charging

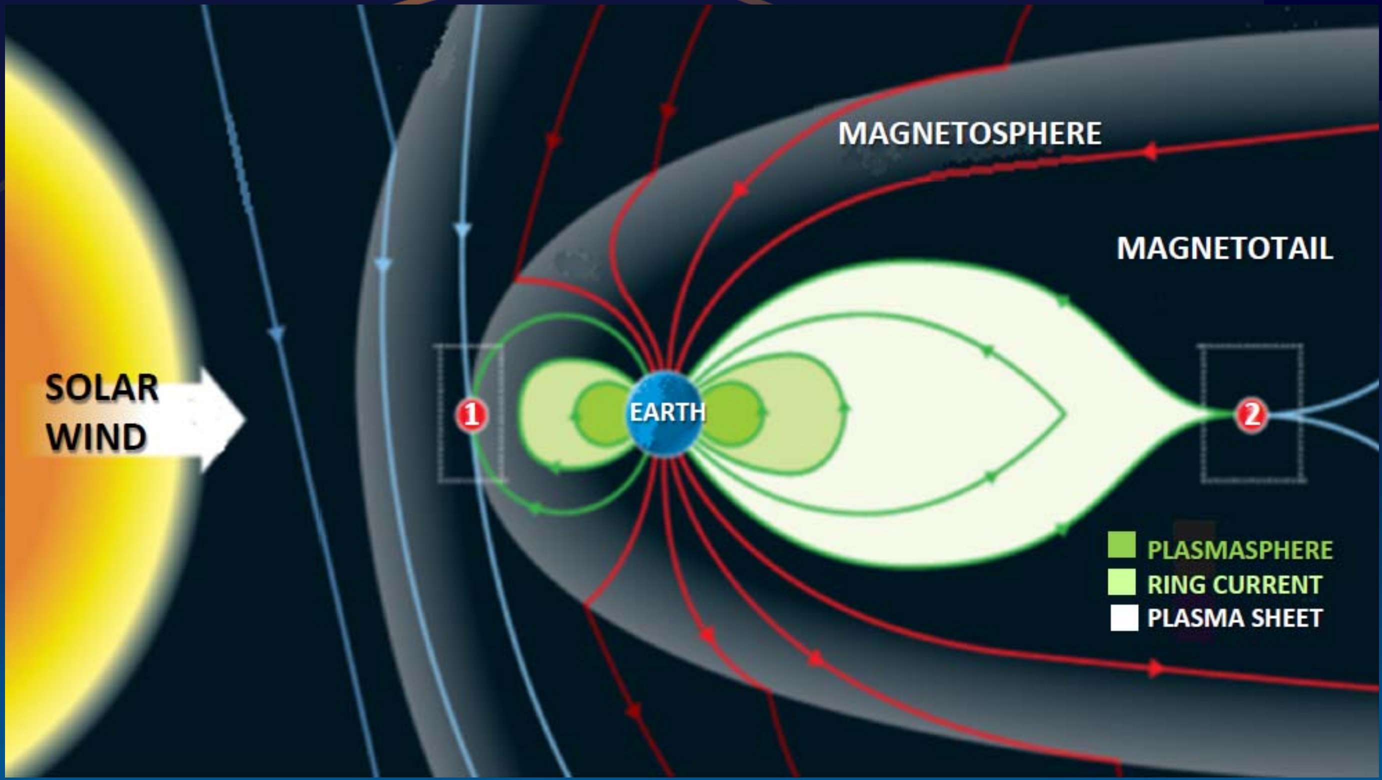
- Enhanced surface charging probability exists (a) during higher values of Kp, (b) in the local time range from premidnight through dawn, (c) during equinox seasons, and (d) during the declining phase of the solar cycle

[Thomsen et al., 2013]



The accurate global specification of the surface charging environment (SCE) fluxes of hot (~10's keV) electrons is the gap that SHIELDS fills!

SHIELDS Science Goals & Outcomes



Outstanding science questions related to storm/substorm dynamics we investigate:

- **What determines where and when hot plasma is injected into the inner magnetosphere?**
- **How are the injected particles transported, and how does the magnetosphere respond?**
- **What waves do the injected particles excite and how do these waves feed back on the acceleration and loss of the particles?**

Observations are inadequate to address these questions globally; modeling is the only way!

Computer, Computational, and Statistical Sciences Division CCS

SHIELDS Team

Theoretical Division

U. Michigan

Funded by the U. S. Department of Energy through the Los Alamos National Laboratory (LANL) Laboratory Directed Research and Development (LDRD) program, the SHIELDS framework is being developed by world-class experts in the fields of space sciences and computational plasma physics:

- V. Jordanova (PI), M. Henderson, C. Jeffery, S. Morley, D. A. Panaitescu, J. Woodroffe, C. Meierbachtol, T. Brito, M. Engel, ISR, LANL
- G. L. Delzanno (Co-PI), J. D. Moulton, H. Godinez, D. Svyatsky, T, LANL
- E. Lawrence, L. Vernon, CCS, LANL
- G. Tóth (Co-PI), D. Welling, Y. Chen, J. Haiducek, University of Michigan

Collaborators:

- M. Thomsen (PSI) and J. Birn, J. Borovsky and M. Denton, SSI
- J. Albert and S. Young, AFRL, Albuquerque, NM
- R. Horne, BAS, Cambridge, UK
- C. Lemon, The Aerospace Corporation, CA
- S. Markidis, I. B. Peng, KTH Stockholm, Sweden
- Y. Yu, Beihang University, Beijing, China

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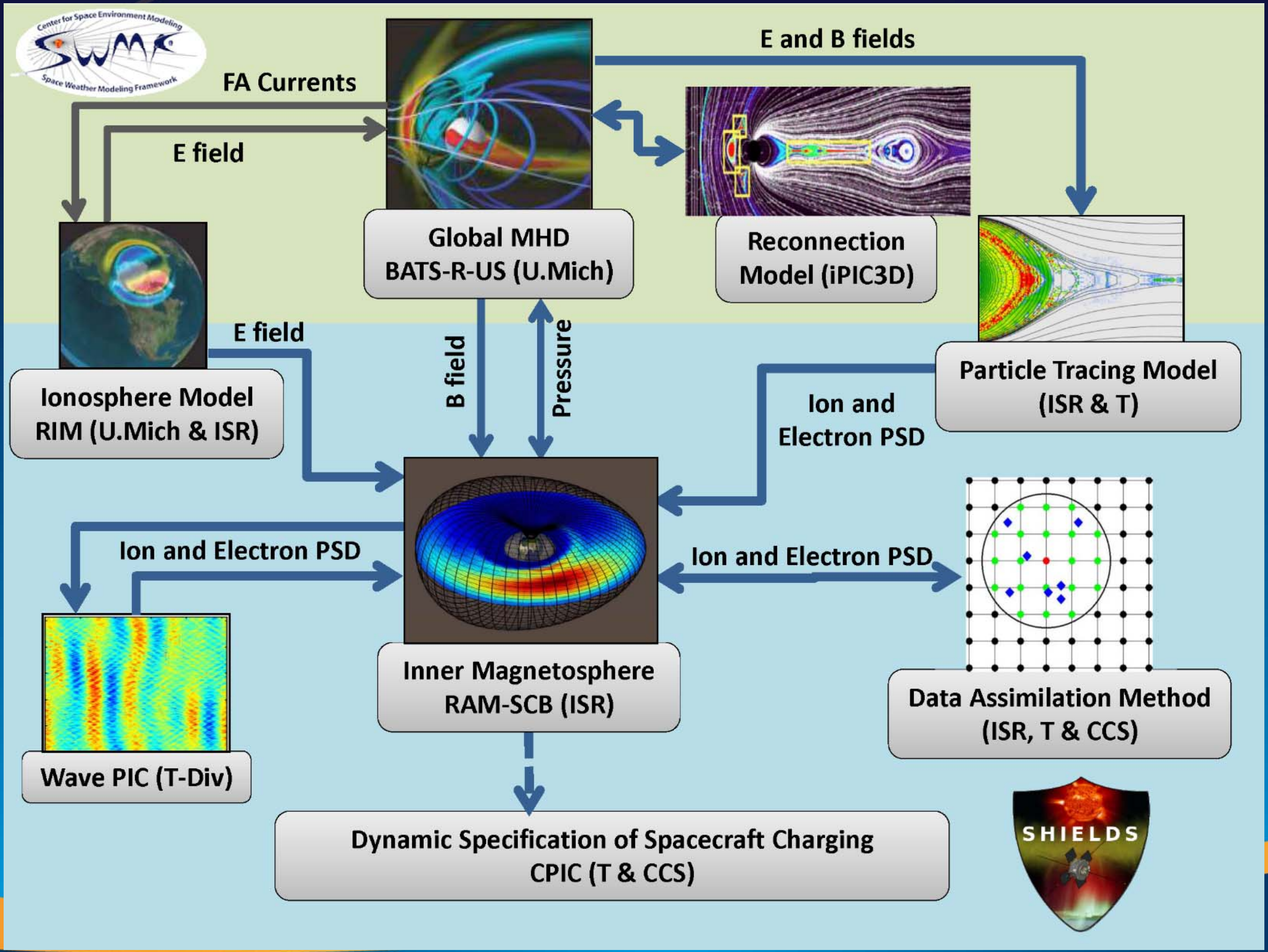
LDRD Innovation for our nation

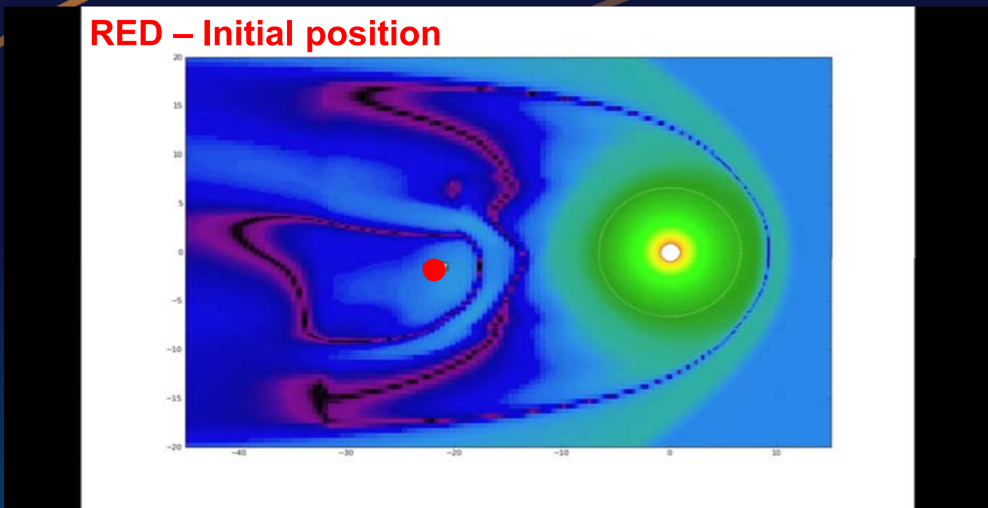
The SHIELDS Framework

Bridging macro- and micro-scale models, combined with data assimilation tools:
- **Capture rapid particle injection and acceleration during storms/substorms**
- **Include plasma wave generation and their feedback on the particles**



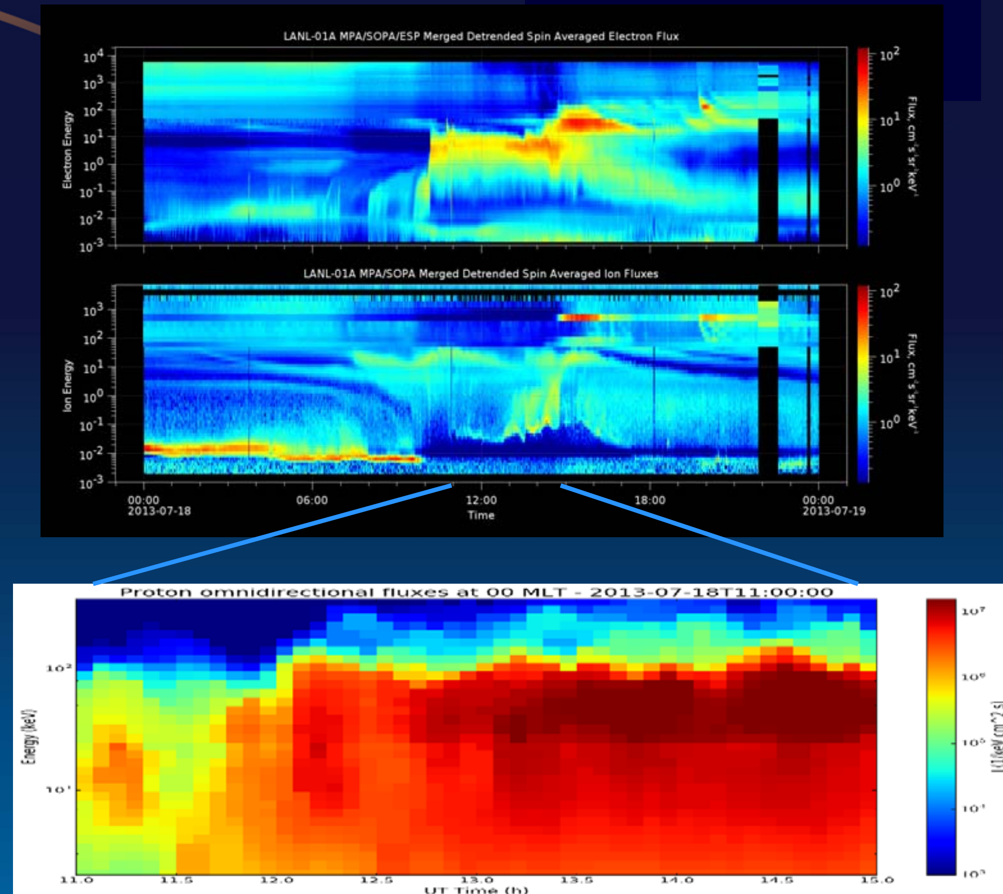
POC: Vania Jordanova, vania@lanl.gov

Strom/Substorm Dynamics



RED – Initial position

WHITE – Current position



- ➢ The Particle Tracing Model (PTM) was coupled with BATS-R-US
- ➢ Challenges that have been met:
  - interpolation across different levels of spatial resolution in BATS-R-US
  - Initial attempts using only MHD fields were not successful; coupling of inner magnetosphere via RAM-SCB is crucial for realistic results

- LANL spectrograms showing “perturbation-fluxes” (spectra are flattened to highlight energy dispersion features)
- Dispersionless electron injection at ~10UT; more complex ion injection activity between 13-15 UT
- The PTM qualitatively captures injection dynamics (note different scales)

POC: Mike Henderson, mghenderson@lanl.gov

3D MHD-EPIC Simulation of Earth's Dayside Reconnection

Physical parameters

- Ion inertial length scaling factor f =16
- Typical solar wind conditions:
  ρ= 5 amu/cm^3, U_X = -400km/s, B = [0,0,-5] nT

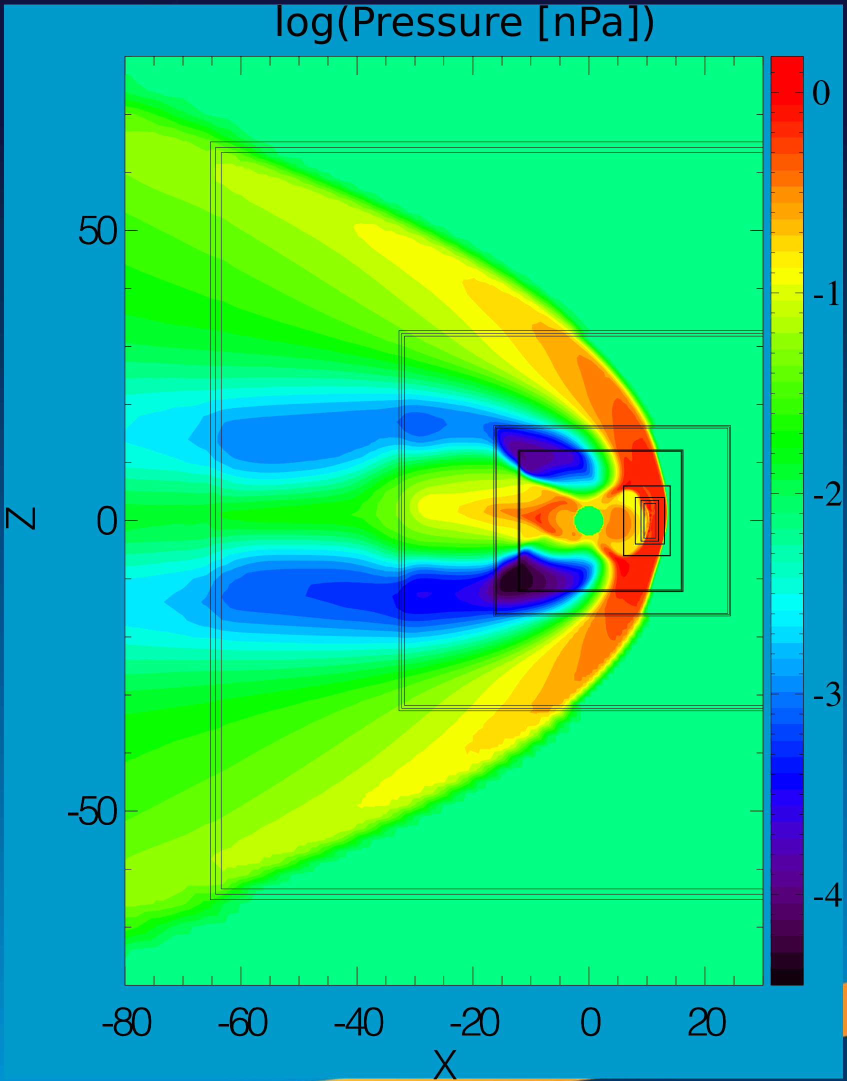
Hall MHD

- MHD domain: -224 < x < 32, -128 < y, z < 128Re
- At the magnetopause Δx=1/32Re (~200km)
- Hall MHD uses ~20% CPU time

PIC

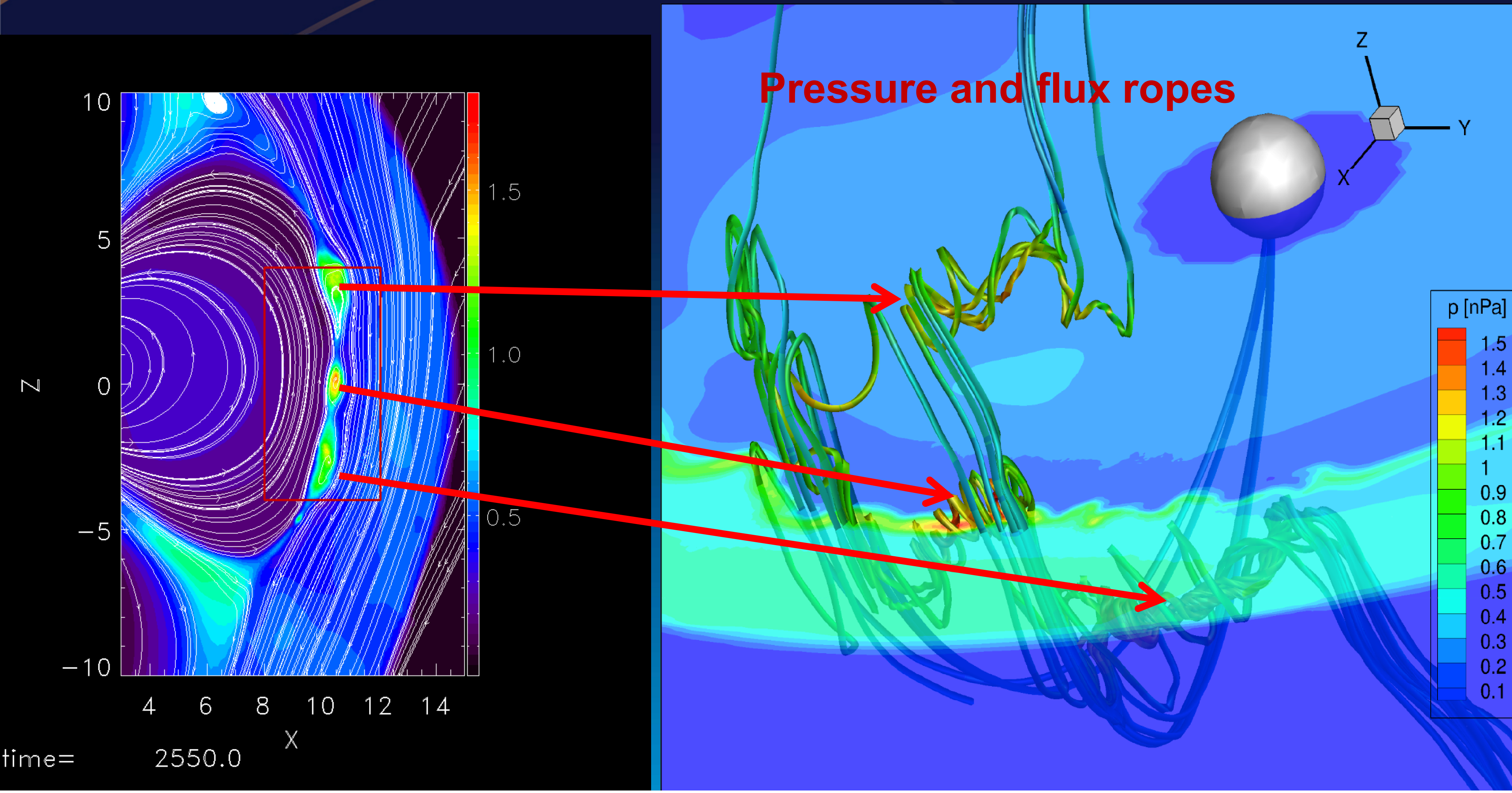
- PIC domain: 8 < x < 12, -6 < y < 6, -4 < z < 4Re
- Δx = 1/30Re: 5 cells per d_i (for f = 16)
- 216 particles per cell per species: 4.3B total
- Consuming ~80% simulation time

~2000 core hours modeling 1min



POC: Gabor Toth, gtoth@umich.edu

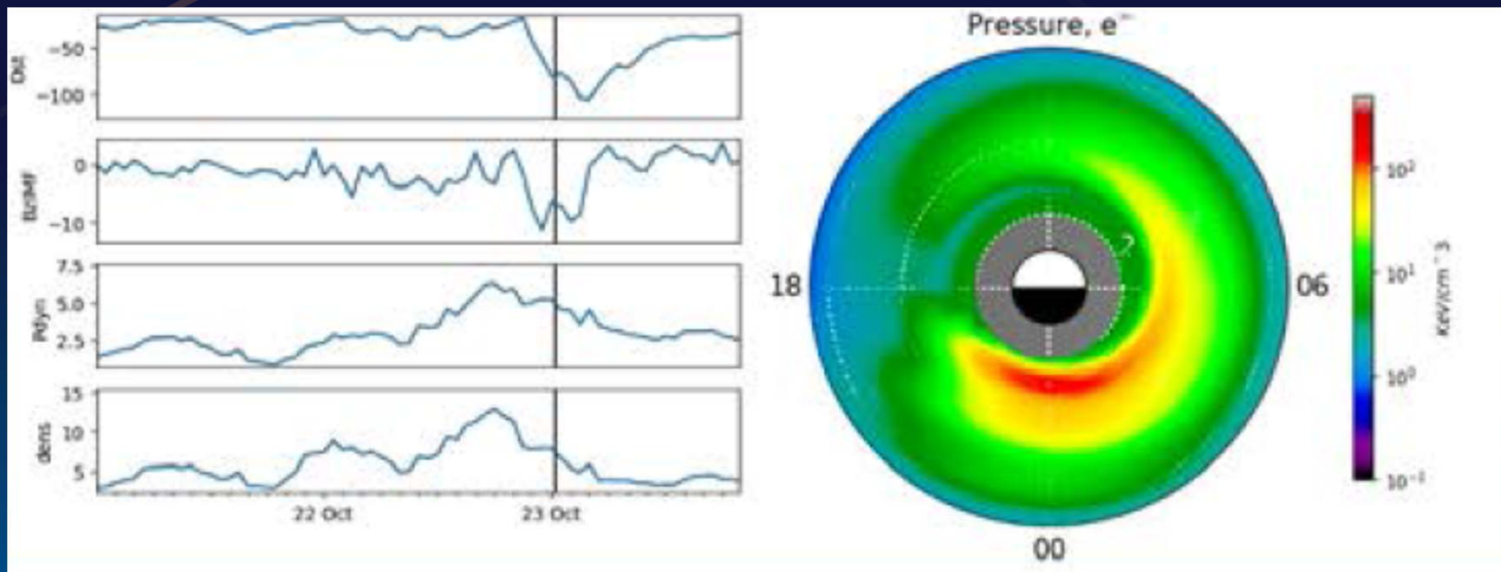
3D Structure of Flux Ropes at Earth Magnetopause



- Magnetic reconnection happens inside the PIC region & generates flux transfer events (FTEs)
- Shows that MHD-EPIC is the most efficient approach to kinetic modeling in a global system

RAM-SCB

Ring current - Atmosphere interactions Model with Self-Consistent magnetic (B) field



» Ring current-atmosphere interactions model (RAM) [Jordanova et al., 1994, 2006; 2012]

- Kinetic equation for H^+, O^+, and He^+ ions and electrons
- Including all major loss processes
- Convection and corotation E field
- Updated to general B field

» 3D equilibrium code [Cheng, 1995; Zaharia et al., 2004; 2010]

- Force-balanced equation

$$\mathbf{J} \times \mathbf{B} - \nabla \cdot \mathbf{P} = 0$$

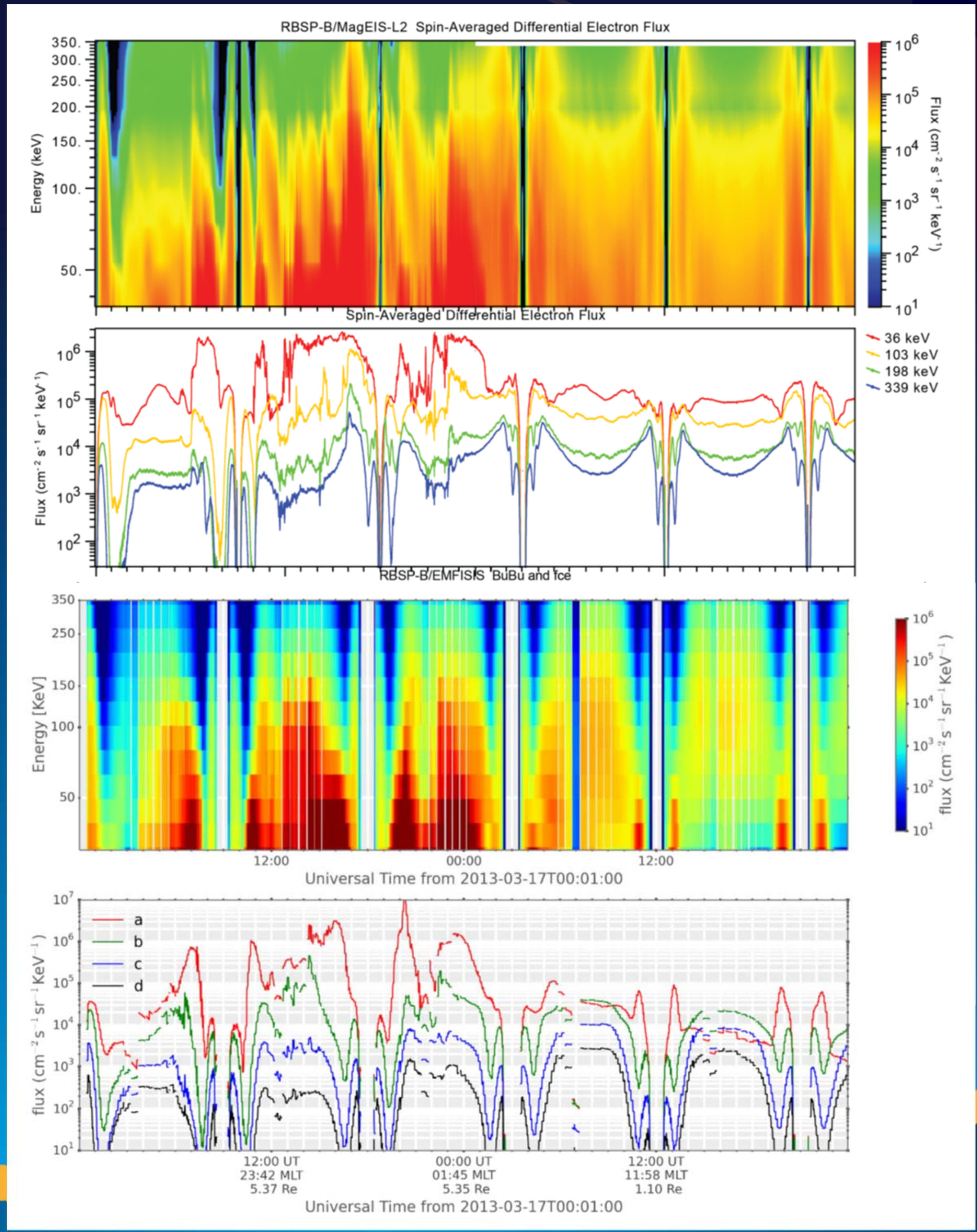
- Euler potentials (flux coordinates)

Open source & available at: https://github.com/lanl/ram-scb

Spacecraft Charging Challenge: 17-18 March 2013

During the geomagnetic storm of 17-18 March 2013, the Van Allen Probes were along an elliptical orbit on the night-side with apogee at MLT~1 and L~6:

- **Significant 30-350 keV electron flux enhancement is observed with MagEIS near Dst min**
- **Intense chorus wave activity measured with EMFISIS throughout the storm**
- **Could we reproduce these variations of the spacecraft charging environment?**



RBSP Observations

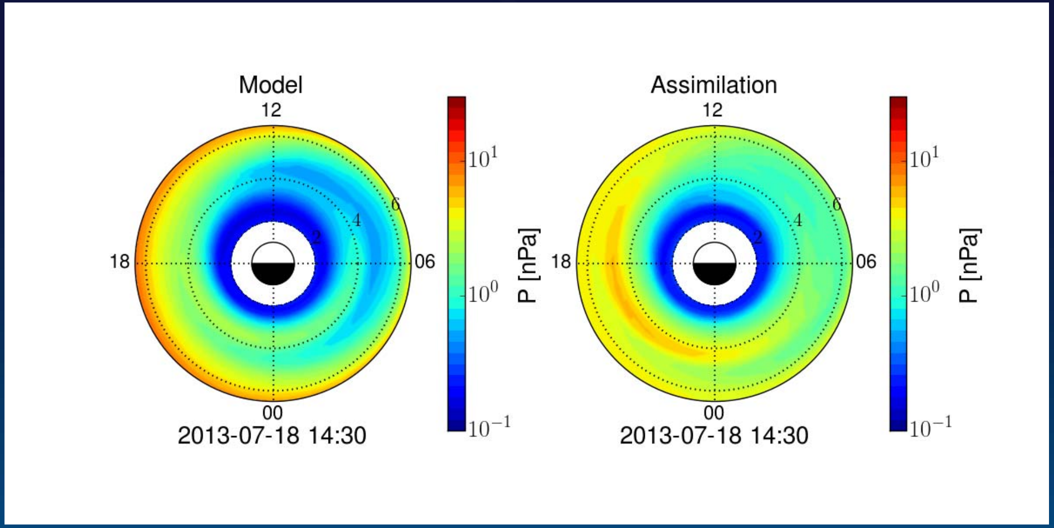
Initial SHIELDS Simulations (No WPA)

National Nuclear Security Administration

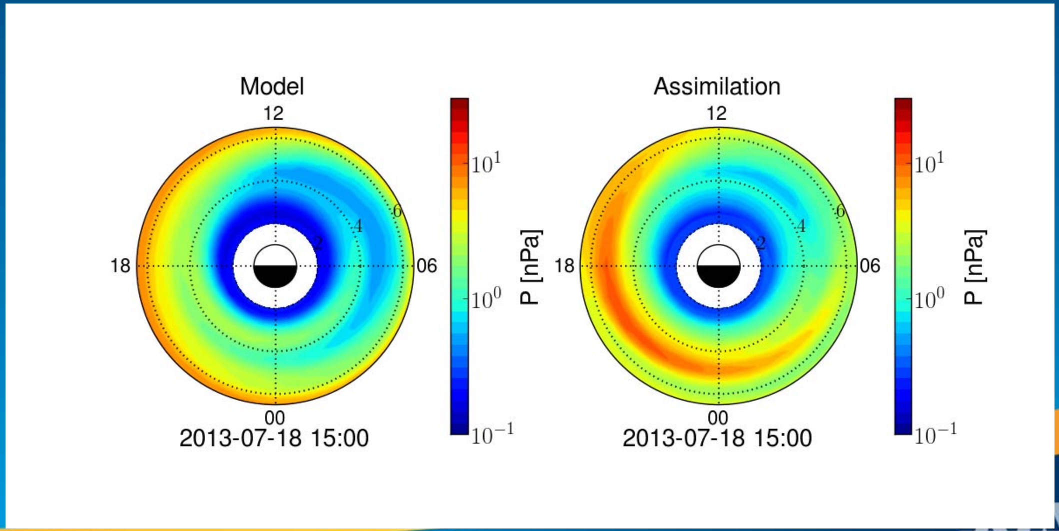
Data Assimilation

- Data assimilation fuse observations and model
- Assimilate VA Probe-B data into RAM-SCB, validate with VA Probe-A
- Use Singular Valued Decomposition (SVD) to define a new (better) basis for the state variables
- Significant enhancement is obtained compared to previous conventional method (LETKF)

Traditional LETKF method



New SVD based method

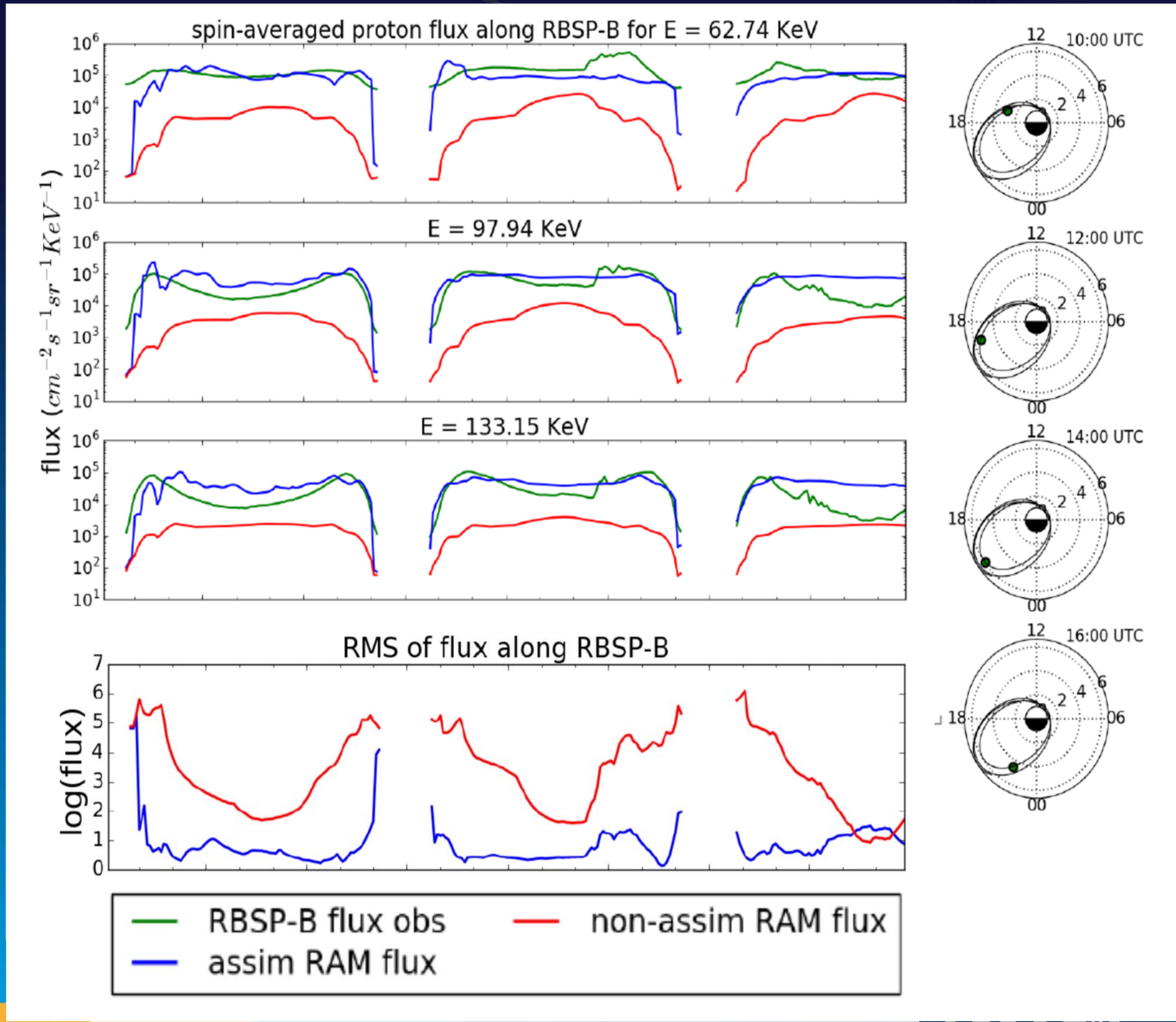


POC: Humberto Godinez, hgodinez@lanl.gov

Data Assimilation in RAM-SCB

- Assimilate VA Probe-A data into RAM-SCB, validate with VA Probe-B
- Results showed an order of magnitude improvement and significant error reduction

⇒ First data assimilation for RAM-SCB completed, paper by Godinez et al. [2016] published in the *Geophys. Res. Letters*



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A Self-consistent Treatment of Wave-Particle Interactions

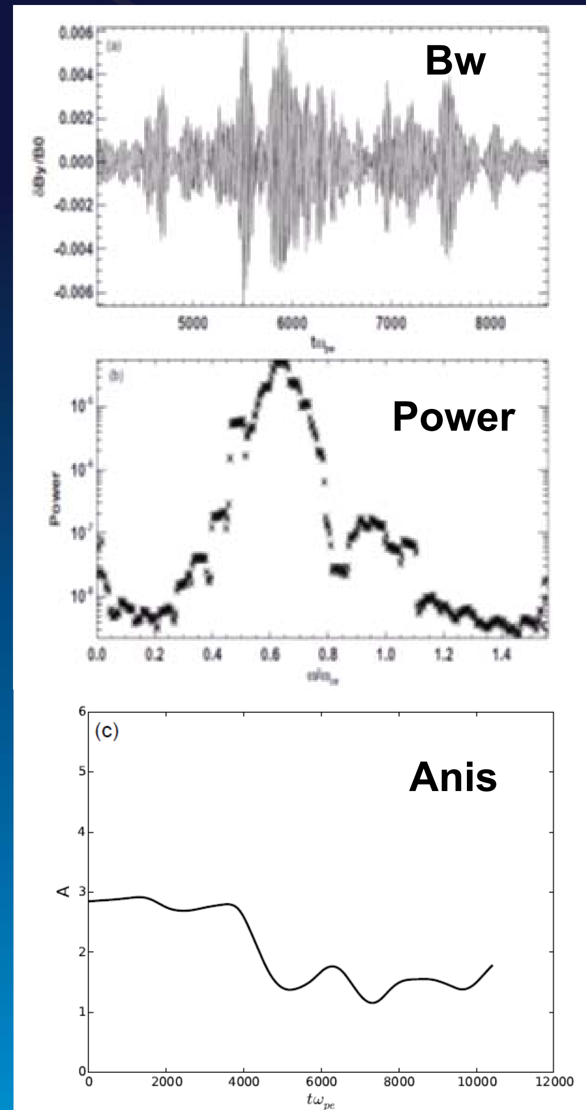
Coupling of iPIC3D with RAM-SCB:

- Load unstable RAM-SCB particle distribution in iPIC3D
- Obtain self-consistent instability, wave growth and saturation
- Evaluate feedback on particle dynamics

⇒ Whistler waves were excited and grew exponentially, propagating mainly along the background magnetic field

⇒ The high anisotropy distinctly dropped when the waves were fully developed

First results published in a Special Issue of JASTP [*Yu et al.*, 2017]



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Curvilinear Particle-In-Cell (CPIC)

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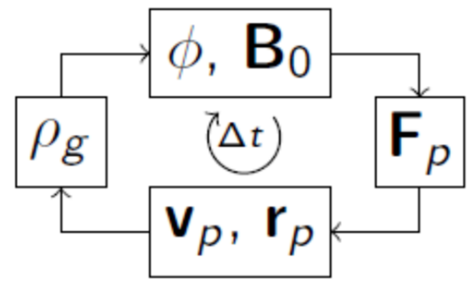
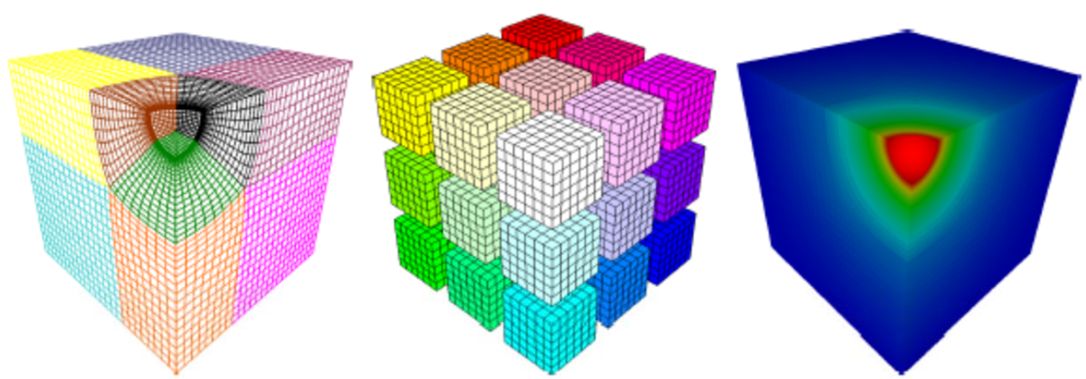
- Plasma simulation using macroparticles in self-consistent fields
- Solves the **Vlasov-Poisson equations** using the **PIC method** ...

$$\frac{\partial f_\alpha}{\partial t} + \mathbf{v} \cdot \nabla_{\mathbf{x}} f_\alpha + \frac{q_\alpha \left(-\nabla \phi + \mathbf{v} \times \mathbf{B}_0 \right)}{m_\alpha} \cdot \nabla_{\mathbf{v}} f_\alpha = 0$$

$$-\epsilon_0 \nabla^2 \phi = \rho = \sum_\alpha q_\alpha \int_{\mathbf{v}} f_\alpha d^3 \mathbf{v}$$



... on a **logically mapped curvilinear mesh** using **fast methods**



(a) Curvilinear (b) Logical (c) Solution

- Structured logical mesh
  (Faster solver, mover)
- Multigrid Solver
  (Near-optimal scaling)
- Hybrid particle mover:
  (No tracking, >5x faster)

- **Main Features**: Accurate, Scalable, Flexible

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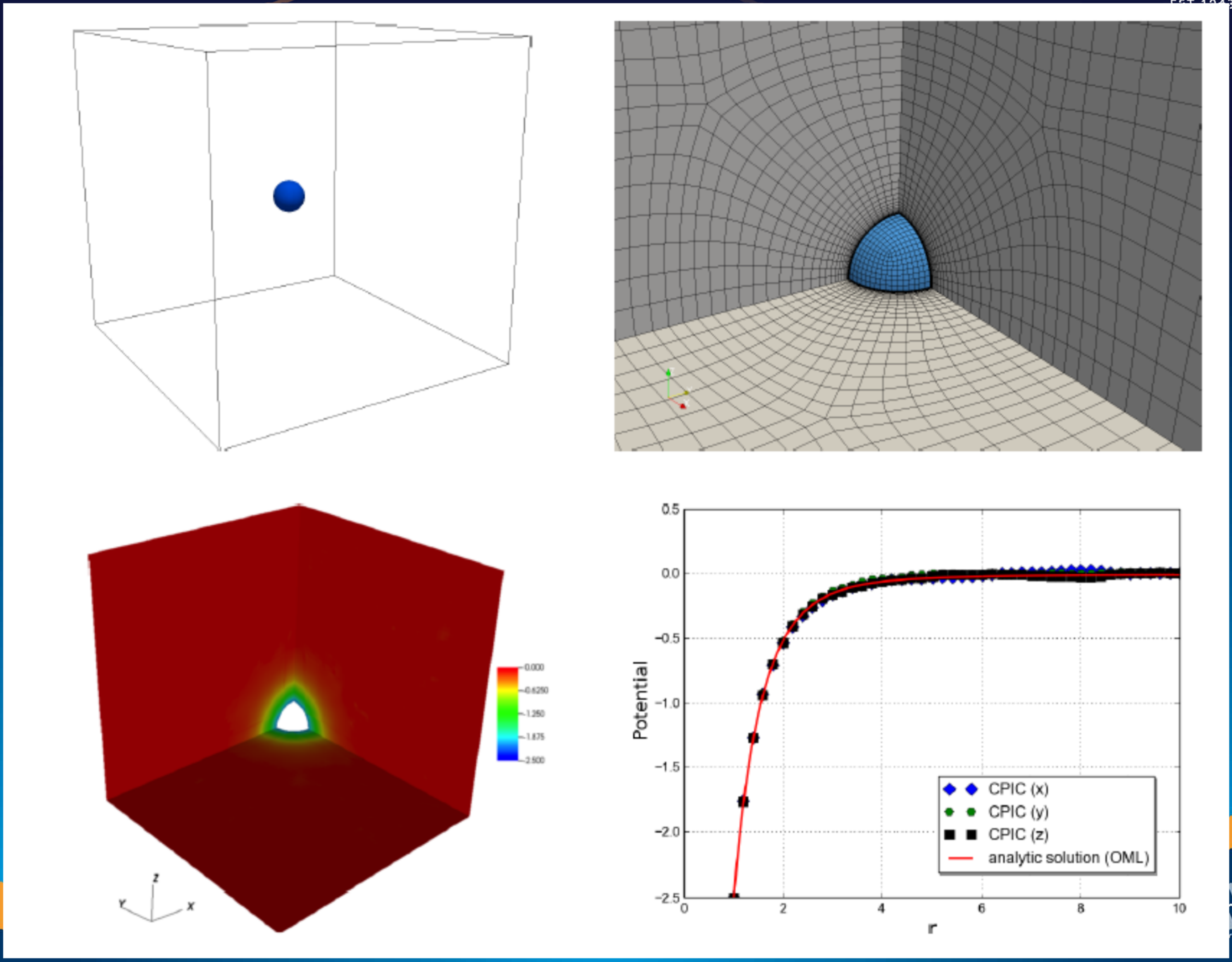
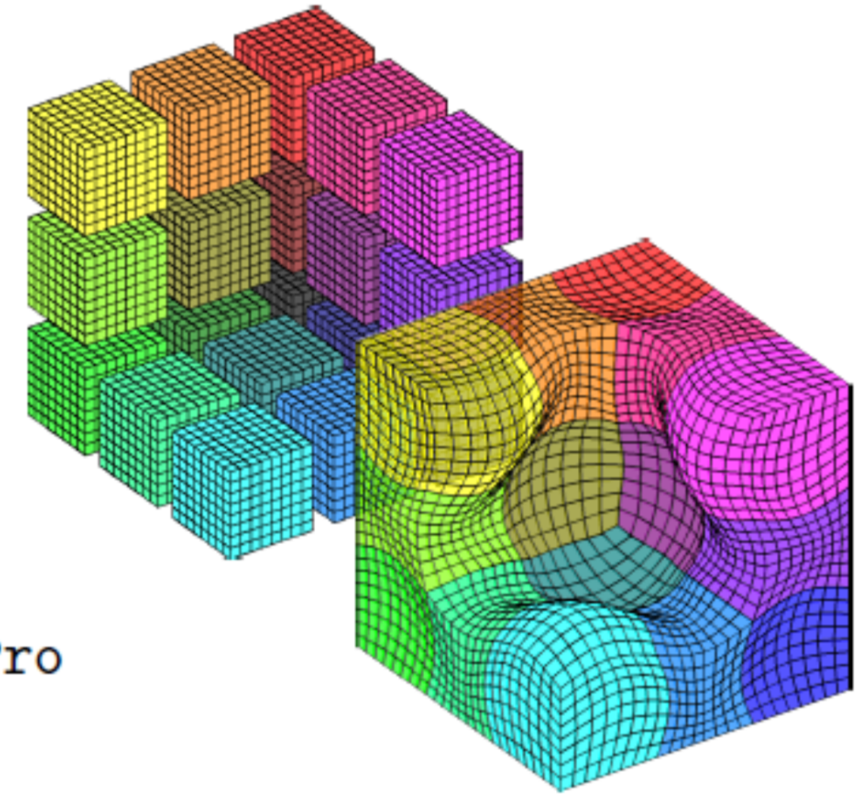
POC: Gian Luca Delzanno, delzanno@lanl.gov

CPIC Verification: Sphere Charging



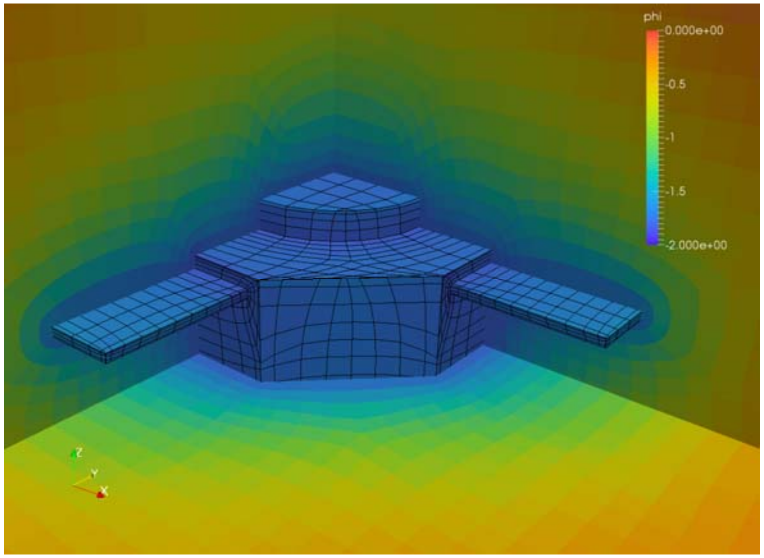
Multi-block CPIC:



- **Multi-block CPIC successfully developed and tested for charging on a sphere in a plasma**
- **Initial simulations with Van Allen Probes geometry performed**
  - **Accurate**, **detailed** models of S/C
  - Params from `SWMF`; mesh from `GridPro`
  - Highly parallelized, typical runs yield charging equilibrium in few hours

Future work:

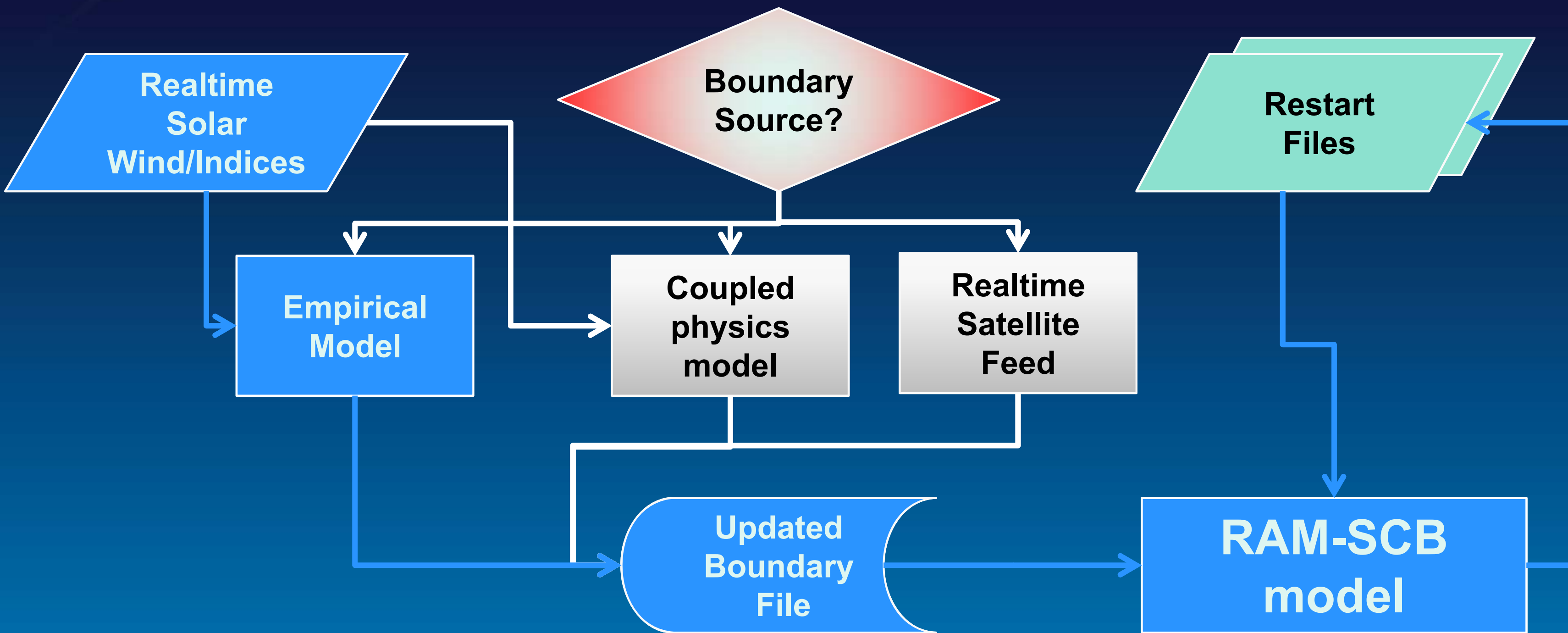
- Add emission: (therm, sec, photo)-emission
- Allow dielectrics
- Differential charging
- Mesh more s/c geometries
- Direct comparison with s/c data



(e) Potential

Near Real-Time SHIELDS-RC Operation

Data and Software Block Diagram



- Development of a Real-Time SHIELDS capability, a simplified RAM-SCB model driven by solar wind conditions
- Given appropriate upstream solar wind measurements, the model provides a forecast of the SCE with a ~1 hour lead time

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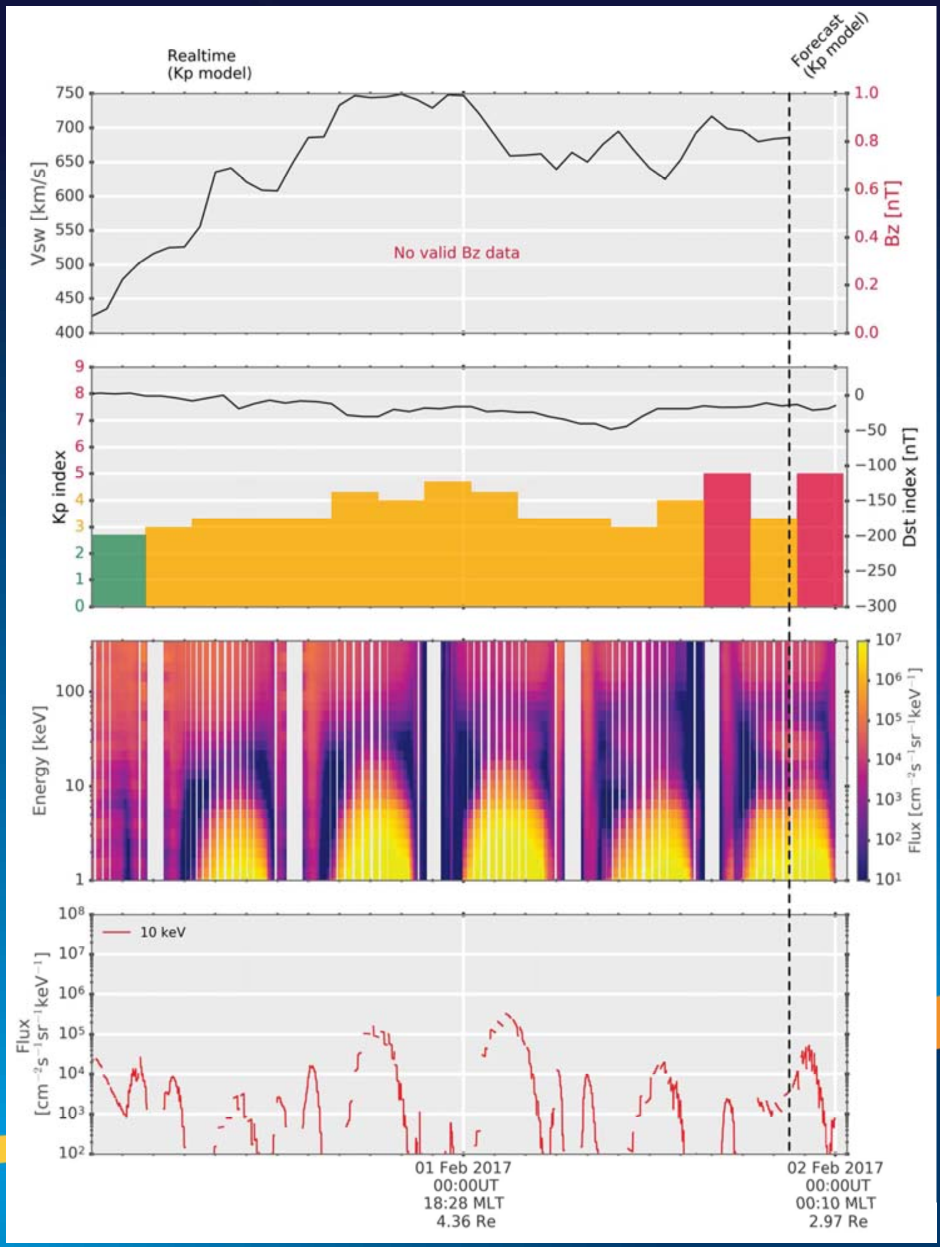
Near Real-Time SHIELDS-RC Operation

Sample Model Output

The operational SHIELDS-RC provides output along specific satellite trajectory in the inner magnetosphere, example shown for the Van Allen Probes:

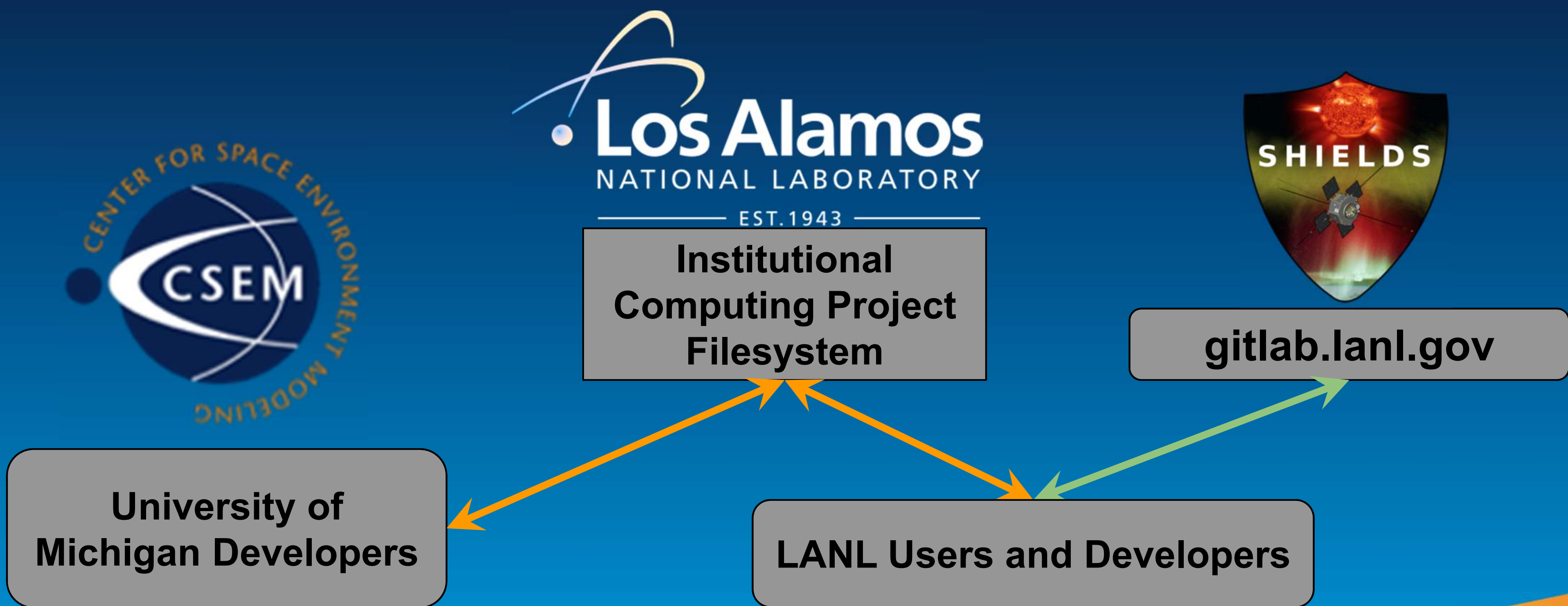
- Drivers (Vsw, Bz) and Kp & Dst indices as a function of time
- Electron energy spectra from ~1 to 350 keV
- Electron flux at 10 keV as an indication of SCE hazard



SHIELDS Collaborative Software Development

Migrate Codes / Developers to Distributed Version control System (DVS)

- Transitioned CVS, Mercurial, etc. into a Git repository
- Work with IC-Project Filesystem & github.com/lanl/



POC: Louis Vernon, vernon@lanl.gov

Intelligence and Space Research ISR

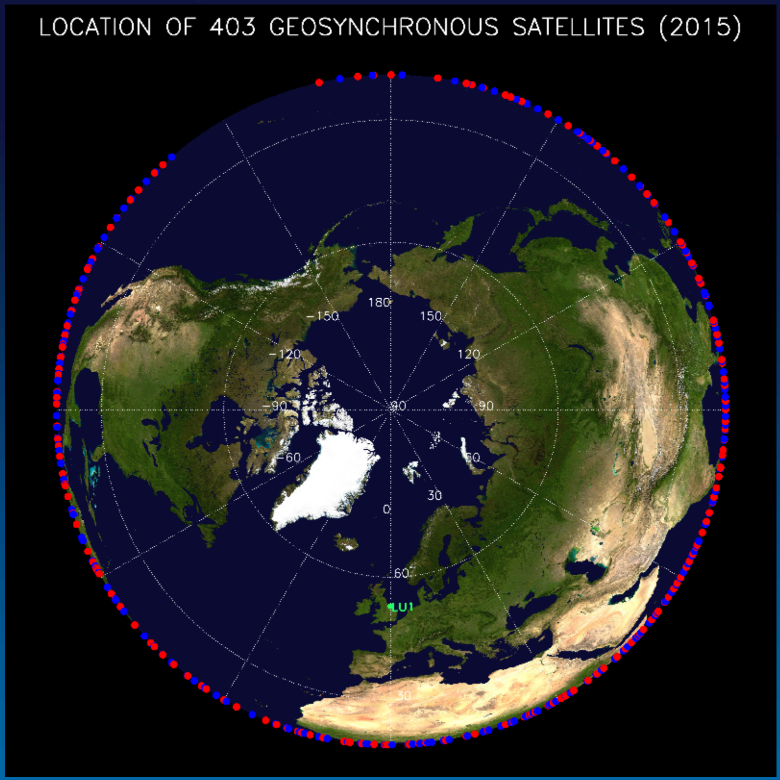
Computer, Computational, and Statistical Sciences Division CCS

SHIELDS Impact

Theoretical Division

U. Michigan

- ➢ **Space weather research is rapidly gaining public recognition since economically important decisions could be made as the accuracy of space weather forecasts improves**
- ➢ **A unique space weather model will position LANL as a world leader in Space Situational Awareness and forensic analysis of space system failures**
- ➢ **In collaboration with NSF/GEM Workshop and CCMC organize a surface charging challenge to assess the accuracy of spacecraft charging predictions**
- ➢ **Building strategic partnerships with other agencies (DOD, NOAA, NASA, NSF, FAA), institutions (Aerospace, universities), and commercial customers (satellite operators, etc.)**



Approximate location of over 400 military, scientific, and communications spacecraft orbiting at GEO - projected to the Earth's equator [Denton et al. *Space Weather*, 2016].

➢ **Website with lists of presentations and publications: http://www.lanl.gov/projects/shields/**

NNSA National Nuclear Security Administration