JOHNS HOPKINS
APPLIED PHYSICS LABORATORY

Global Radiation Belt Modeling

Combined MHD, Ring Current and Test-Particle Simulations

Kareem Sorathia

CHIMP
Conservative Hamiltonian Integrator for Magnetospheric Particles

$\partial_t f + \{f, H\} = 0$

Collaborators:
S. Ukhorskiy
V. Merkin
M. Wiltberger
J. Lyon
S. Claudepierre
J. Fennell

Motivation/Overview

- Goal: Develop a global, physics-based radiation belt model driven by solar wind conditions

- Framework
  - Solar Wind => 3D MHD/RC (LFM-RCM) => Test-Particle (TP) => electron PSD
- Components
  - MHD: ULF perturbations/boundary dynamics (KHI) => losses and transport, mesoscale electrodynamics => injections
  - Ring Current: Realistic storm-time inner magnetosphere
  - Particle dynamics: Lorentz/Guiding center (GC) trajectories (non-diffusive/non-adiabatic transport)
- Test Case
  - RB evolution during March 2013 storm, comparison w/ RBSP data

Simulation Pipeline

Global magnetosphere (LFM-RCM-MIX)

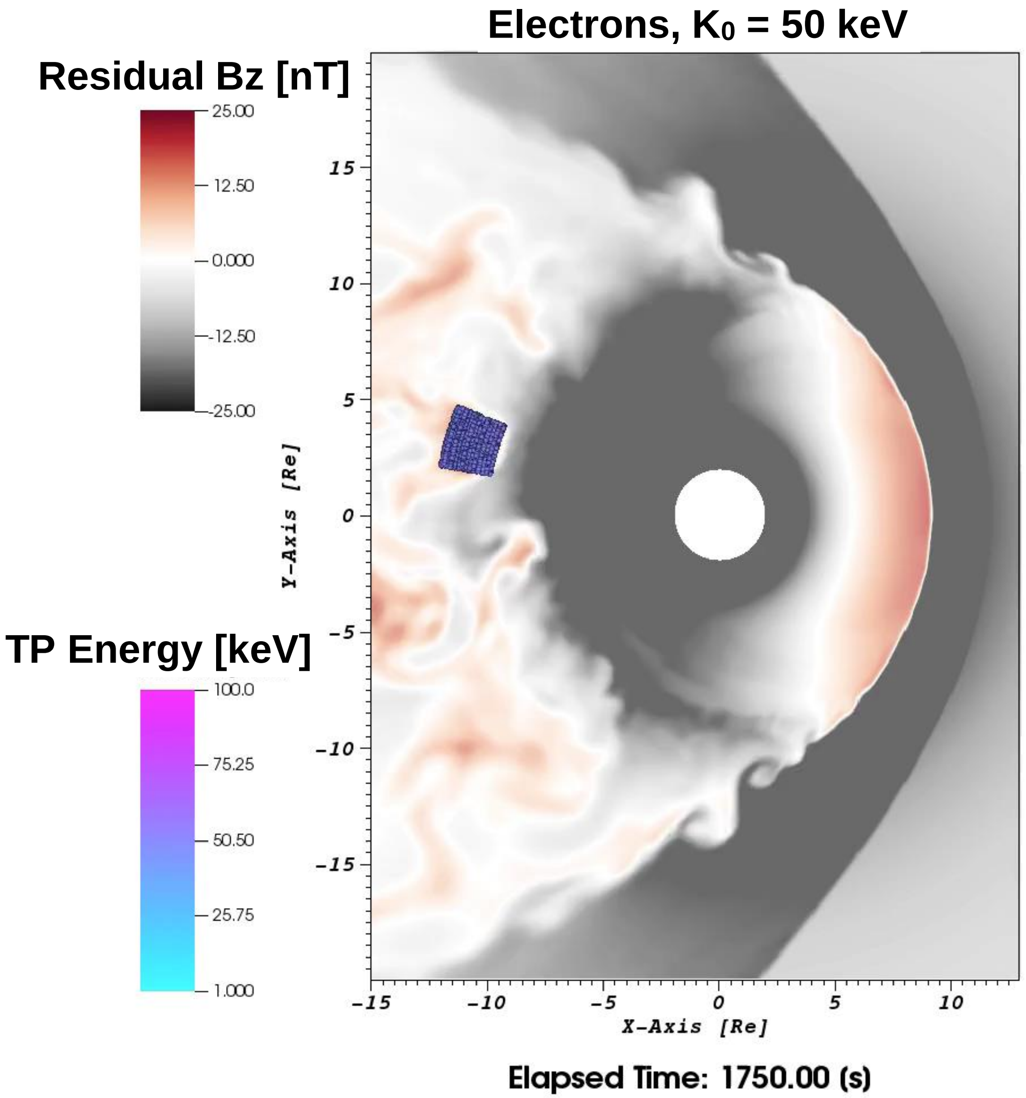
- Domain (XYZ) ~ [-300,30]x[±100]x[±100] R_E
- Driving BCs: Solar wind (@ X=30 R_E), F10.7 (ion. conductivity)
- Save flow/EM field data @ high cadence
- Interpolate to smaller Cartesian domain, approx. $30R_E^3$

TP Initialization/Evolution

- Initial & Injected population (e.g. Li++ 2015)
- Use MHD flow data (n,T,V) to seed TPs
  - **i.e., aim TP's at injections**
- Use MHD EM fields to integrate particle trajectories
  - Dynamic switching between full orbit/GC formulations based on local field lengthscale

PSD Evolution

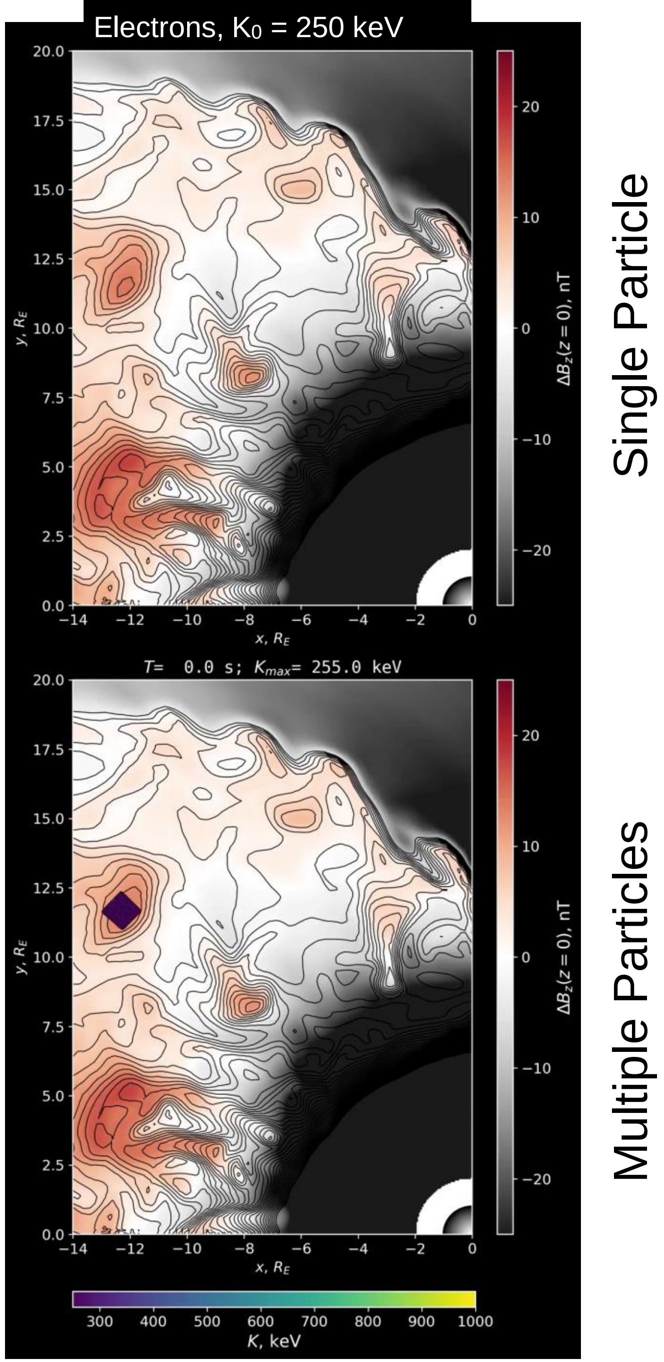
- Electron PSD on discretized 4D $\mathbf{\Gamma} = (L,\varphi,K,\alpha_{eq})$
- **Assign each TP weight (w_i) using PSD IC (f_0)**
  - Correlation between TP and RP (# RP $\cong f_0\, d\mathbf{\Gamma}$)
  - $d\mathbf{\Gamma} = V_\Phi(L,\varphi,\alpha_{eq})\, d\mathbf{\Gamma}_p(K,\alpha_{eq})$
    - $V_\Phi(L,\varphi,\alpha_{eq})$ is accessible flux tube volume
- Use particle trajectories to calculate evolved $f(\mathbf{X},t)$



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

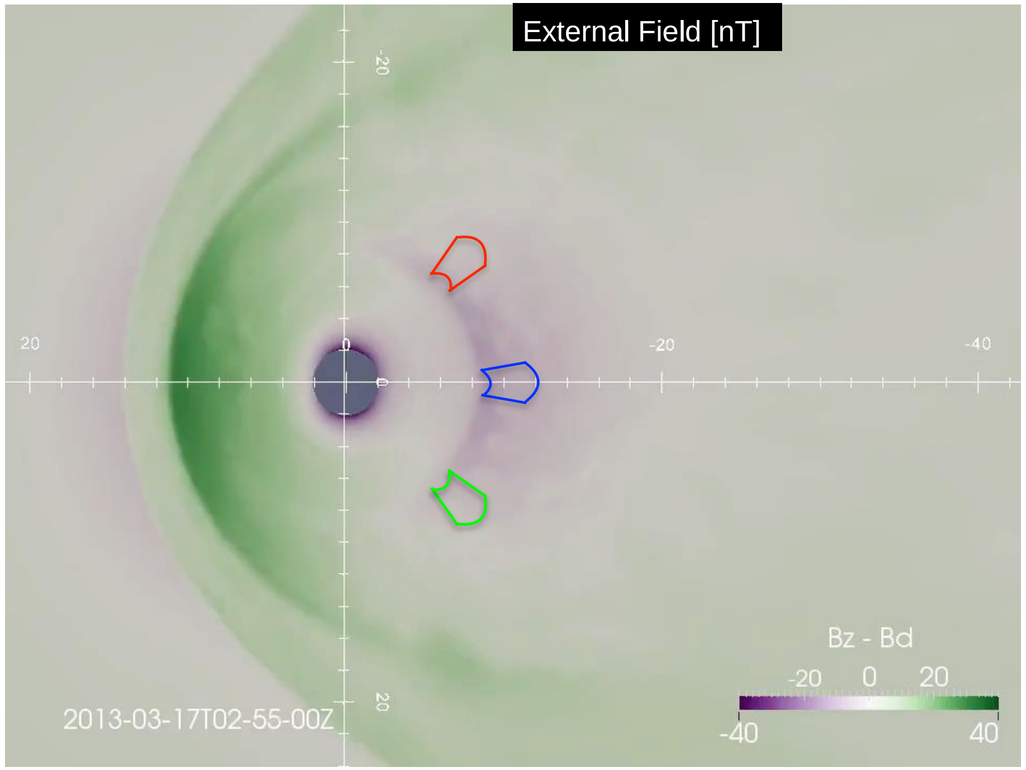
Importance of Mesoscale Structures

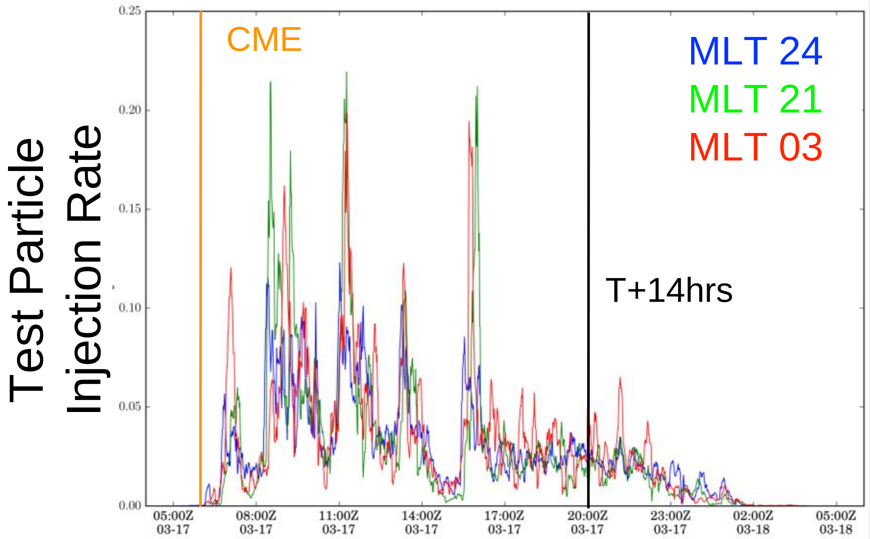
- Localized flow channels can play an important role in radial transport via trapping
- Initialize particles on flow channel from MHD sim
  - Contours show total field strength
  - Width ~ $1R_E$, V ~ O(100) km/s, $E_\varphi \lesssim 10$ mV/m
  - Transport, ΔL ~ 10
  - Energization from K_0 = 250keV => K~1MeV
- Magnetic gradient of dipolarization front confines azimuthal drift
  - c.f. smooth convection surge, particle motion drift orbit dominated
  - Potential interactions with multiple flow channels
  - Mechanism to energize/transport O(100) keV electrons into core RB population



17 March 2013 Storm
Test Particle Test Drive

- MHD Simulation
  - LFM/MIX/RCM
  - Wiltberger++ 2017
  - Save 3D data @1m cadence
- Test Particle Simulation
  - Duration: **48hrs, 37M TPs**
  - Initial & Injected populations (e.g. Li++ 2015)
  - Initial population (1M)
    - L=[3,8], K=[50,3000] keV
    - f_0 matches pre-storm RBSP data
  - Injected population (12M x 3)
    - 3 injection regions (**MLT: 03,21,24**)
    - **L=[9,12]**, ~1hr MLT
    - Use n,T,V in each region to seed/weight TP's
    - **Injection rate ~ Earthward flux K>10keV particles**
    - f_0 = Isotropic $\boldsymbol{\kappa}$-distribution ($\boldsymbol{\kappa}$ = 3.5, $T_e = 0.25\ T_{ion}$)

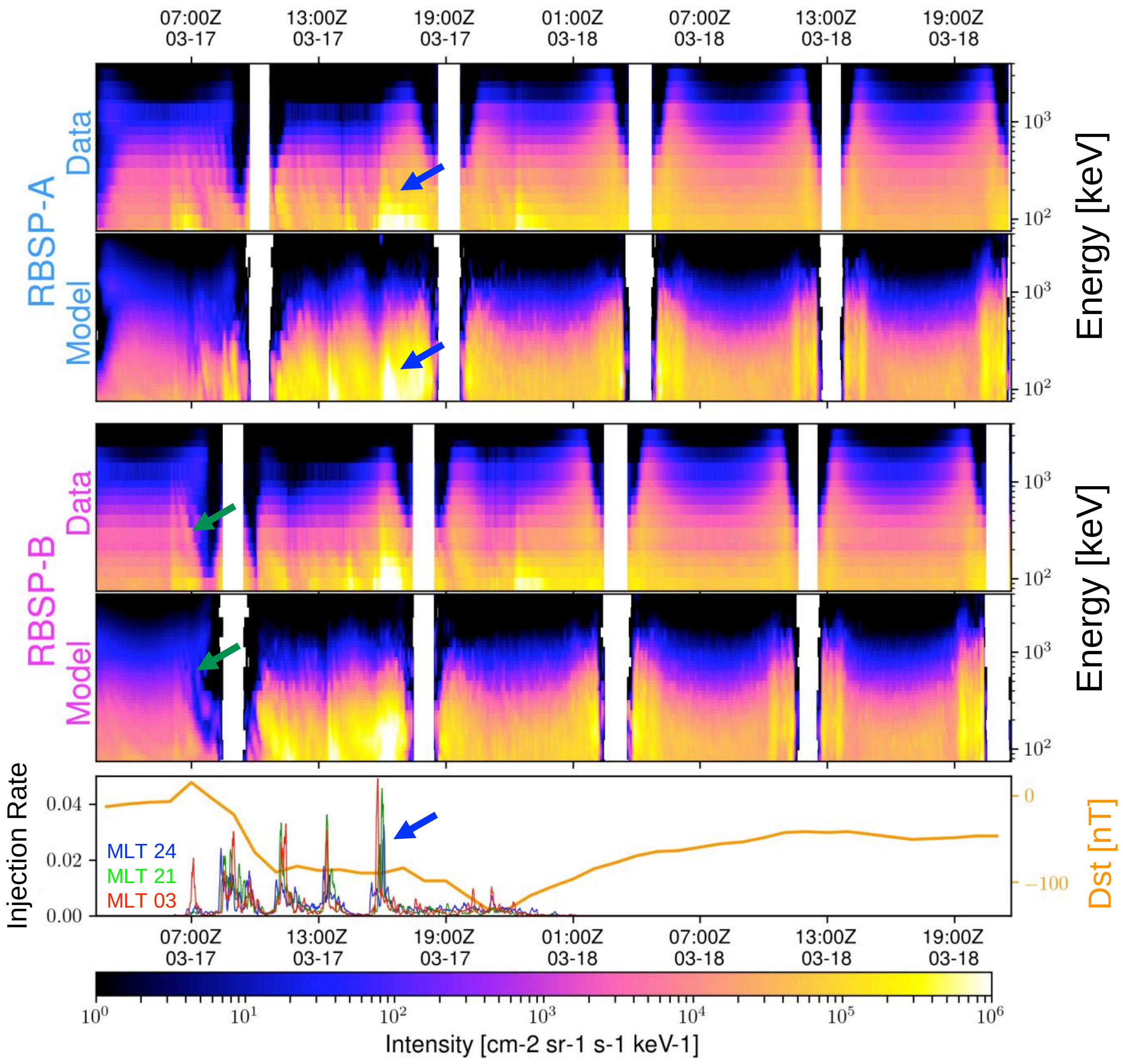




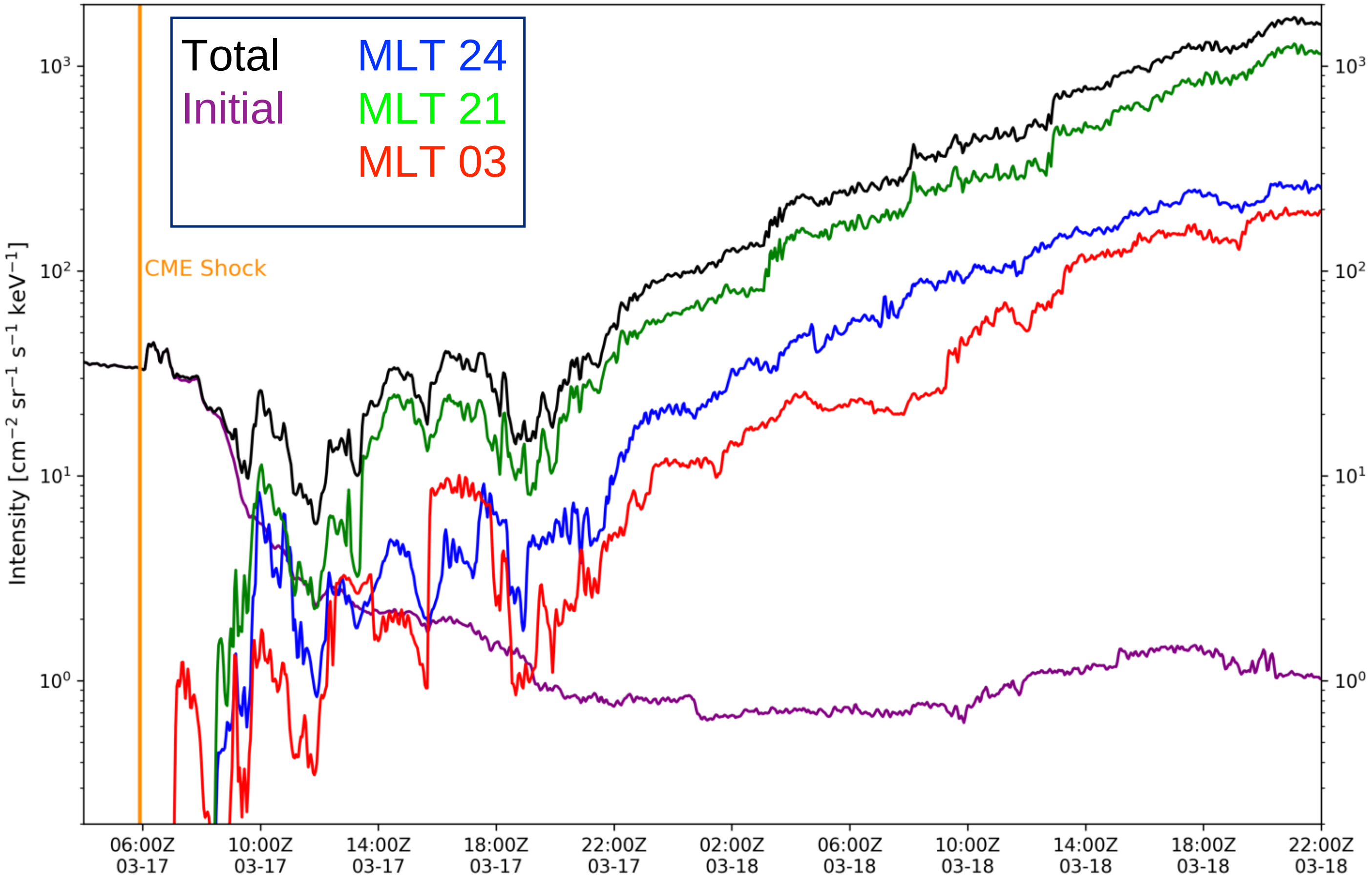
Comparing w/ Observation

- Evaluate model intensity along matching trajectory to RBSP-A/B MagEIS
  - Attenuate model intensity to account for RBSP distance from eq. plane
  - Approximate portion of flux tube sampled by RBSP
  - Comparing over 42 hours
- Good overall qualitative agreement, replicate several matching features
  - Depletion, recovery & enhancement
  - Compression/Drift-echoes in 1st orbit
  - Nightside injections during 2nd orbit

Model Intensity v. RBSP



Out With the Old, In With the New



Intensity Contribution per Population
K = 1 MeV, L<6

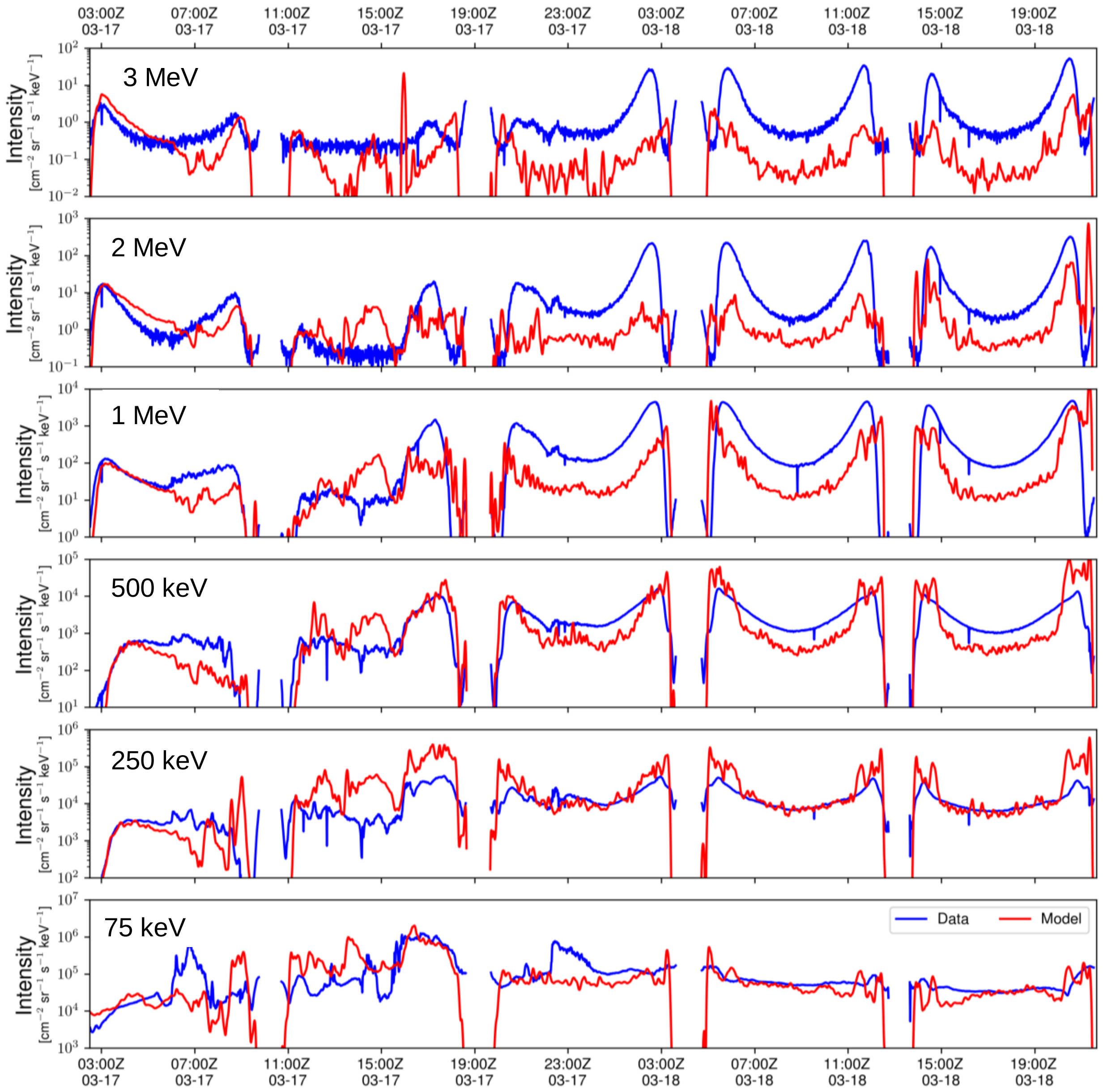
- Split contributions from initial/injected populations
  - Average intensity @ K=1 MeV, L<6
  - 30x enhancement from pre- to post-storm
- Initial population
  - Rapid depletion post-compression
  - **Predominantly lost to MP**
  - Overtaken by injected population by T+4
  - **Negligible contribution to post-storm intensity**
- Injected
  - Bursty intensity increases between T+4 and T+12
- Duskward bias
  - 1:1.5:5 (MLT: 0300,2400,2100)
  - Little MLT bias in injected particle flux
  - Attribute MLT bias in final intensity contribution to selective radial transport
  - Duskward injected particles have more opportunities for interactions with flow channels

Existing RB is largely wiped out and rebuilt via discrete, duskward-biased injections

Quantitative Comparisons w/ RBSP

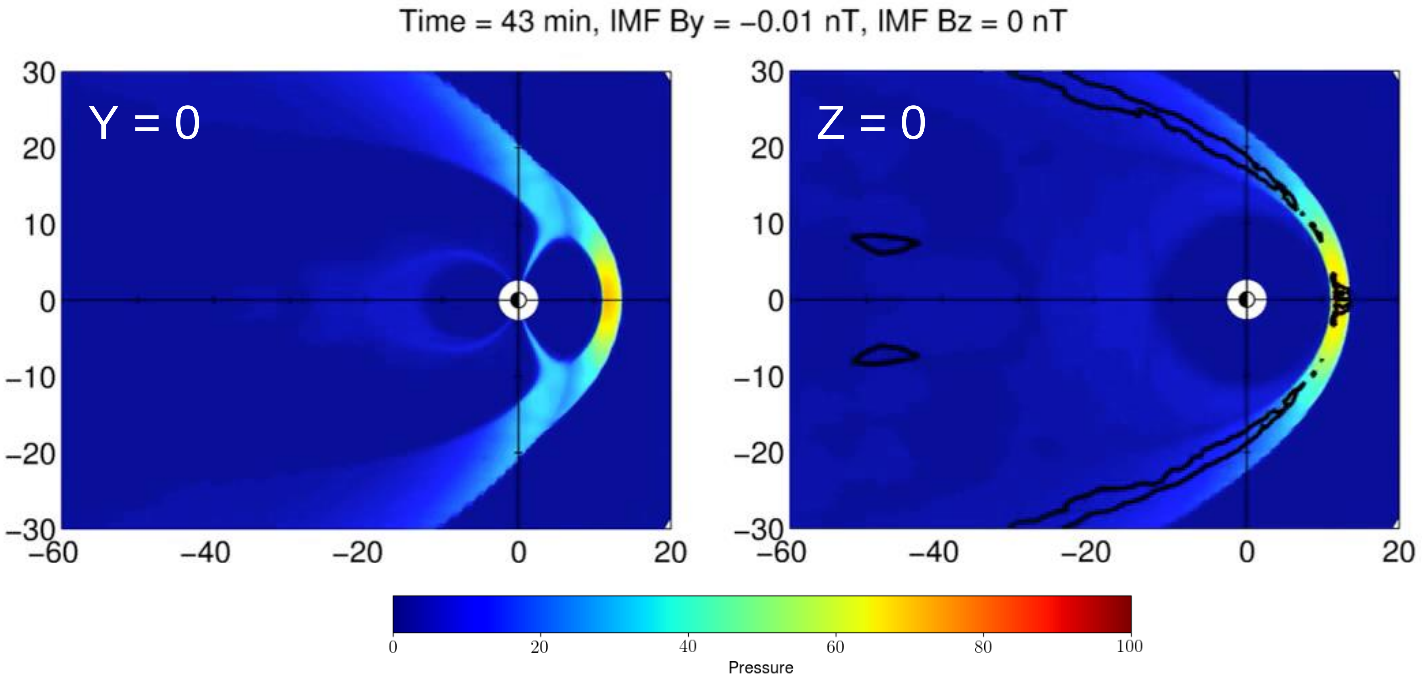
- Logarithmic colormaps are very forgiving
- Compare @ selected K's
  - 75k-3M (40x range)
  - 4 decades in intensity each
- Decent quantitative agreement <= 1 MeV
- K = 1MeV
  - Match ~50X enhancement from pre- to post-storm
- K = 250 - 500 keV
  - Early over-injection
  - Over-predict final peaks
- K > 1MeV
  - Slower recovery
  - Less enhancement
  - Lack of local wave/particle interactions

RBSP-A Intensity (Model/Data)



Summary and Future

Gamera global magnetosphere w/ coupled ionospheric solver
Equivalent to LFM quad resolution
2x slower than real-time on single HPC node



Combined-simulation radiation belt model

- MHD+RC => TP => PSD
- Minimal data driving, only upstream BC (solar wind)
- Novel use of global MHD data
  - Location/time of TP injection, particle weighting for PSD evolution

Application to March 2013 storm

- Comparison w/ RBSP MagEIS, K=75k-3M
  - Inject @ L>9, compare w/ RBSP at L<6
  - Match qualitative evolution of RB during storm (depletion, recovery, enhancement)
  - Replicate specific features (compression, drift-echoes, channels)
  - Quantitative agreement, K <= 1MeV
- RB Evolution
  - Pre-existing population largely wiped out, lost primarily through MP
  - RB replenished/enhanced via discrete, bursty injections
  - Trapping a potentially important source of core RB population

Future

- Rebuilt, modernized global MHD
  - LFM => Gamera
  - Algorithmic and computational advances
- Closer integration between MHD/TP
  - In situ TP tracing/EM field interpolation on MHD grid
  - Higher order EM field interpolation
- Building towards near-real time space weather model

GAMERA
Grid Agnostic MHD for Extended Research Applications

Mapping TP Statistics to Electron PSD

- Work in discretized 4D phase space corresponding to Z=0 hyperplane
  - **X** = (L,φ,K,α_{eq})
  - PS volume element, d**Γ** = d^3**x** d^3**p**
    - d**Γ**(L,φ,K,α_{eq}) = V_Φ(L,φ,α_{eq}) d$\boldsymbol{\Gamma}_p$(K,α_{eq})
    - Spatial component of volume element based on accessible flux-tube volume
- PSD Calculation
  - Use PSD IC (f_0) to calculate particle weights, use particle trajectories to calculate evolved f(**X**,t)
  - Particle weighting, f_0 => w_i
    - Assign each TP weight (w_i), correlation between TP and RP
    - Weight TP's in cell **X** to match given PSD IC. Σw_i ≅ # RP ≅ f_0 d**Γ**
  - Evolved PSD, w_i => f(**X**,t)
    - PSD at later times calculated via total weight (# RP's) in each cell at given time
    - f(**X**,t) = (Σw_i)/d**Γ**
- Initial population: f_0 matched to pre-storm RBSP data
- Injected population
  - f_0 = Isotropic ***κ***-distribution w/ mass/temperature taken from time dep. MHD flow
    - ✦ ***κ*** = 3.5, T_e = 0.25 T_{ion}
  - Weight normalized to incorporate injection over time
    - Velocity, area, Δt => # RP injected in each region over (t,t+ Δt)

PS Volume

$$V_\Phi = \Phi \int_{\lambda_M}^{\lambda'_M} \frac{ds}{B}$$

$$\Phi = B(L,\phi,z=0)L\Delta L\Delta\phi$$

$$d\Gamma = 2\pi m^2 c\gamma\sqrt{\gamma^2-1}\,\sin(\alpha_{eq})V_\Phi\Delta\alpha_{eq}\Delta K$$

Initial Population

$$f_0 = \sin^a(\alpha_{eq})F(L,K)$$

$$F_K(L) = \ell_K^2\exp(1-\ell_K^2)$$

$$\ell_K(L) = \frac{L-L_0}{L-L_m}$$

Injected Population

$$f_0 = n\left(\frac{m}{2\pi\kappa K_0}\right)^{3/2}\frac{\Gamma(\kappa+1)}{\Gamma(\kappa-1/2)}\left(1+\frac{K}{\kappa K_0}\right)^{-(\kappa+1)}$$

$$K_0 = k_B T_e(1-3/2\kappa)$$