Radial Transport Due to ULF Field Line Resonances and Cavity Modes in the Inner Magnetosphere

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- Inhomogeneities in the magnetosphere lead to the formation of cavity modes and field line resonances
- The density enhancement in the plasmasphere can form discrete cavity mode resonances.
- Inhomogeneous density along field lines leads to field line resonances, with frequency varying with L-shell
- These discrete modes call into question the quasi-linear diffusion model of radial transport.
- How do wave-particle interactions work with such modes?

Outline

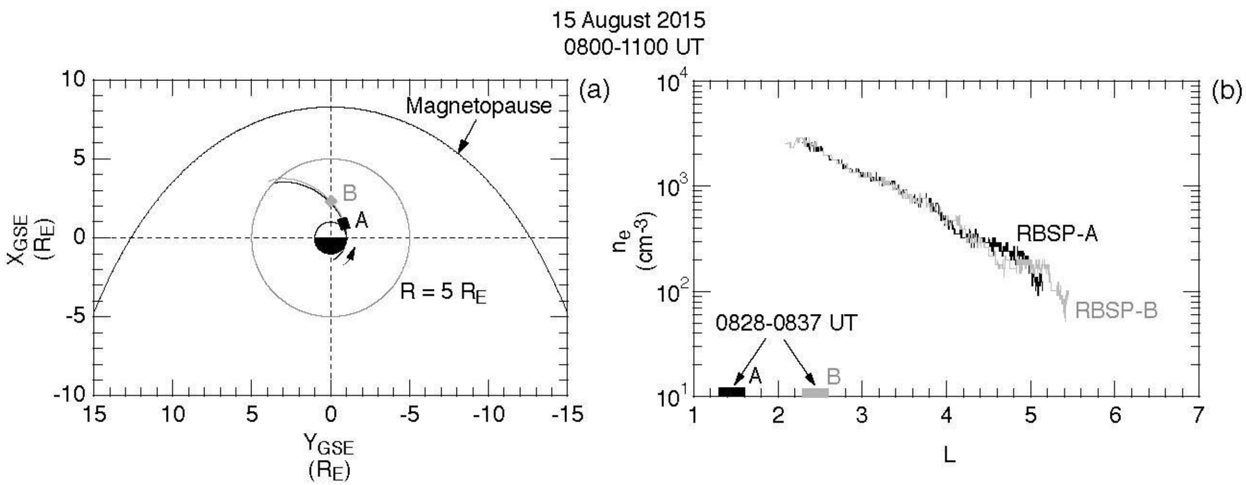
- Excitation of cavity modes and FLRs by shock impact: 2015/8/15 event
  - Evolution of fields
  - Spectral structure of waves
  - Ground signatures
- A new test particle model for radial transport in ULF waves
  - Effects of cavity modes on energization and transport

Cavity Modes and Field Line Resonances

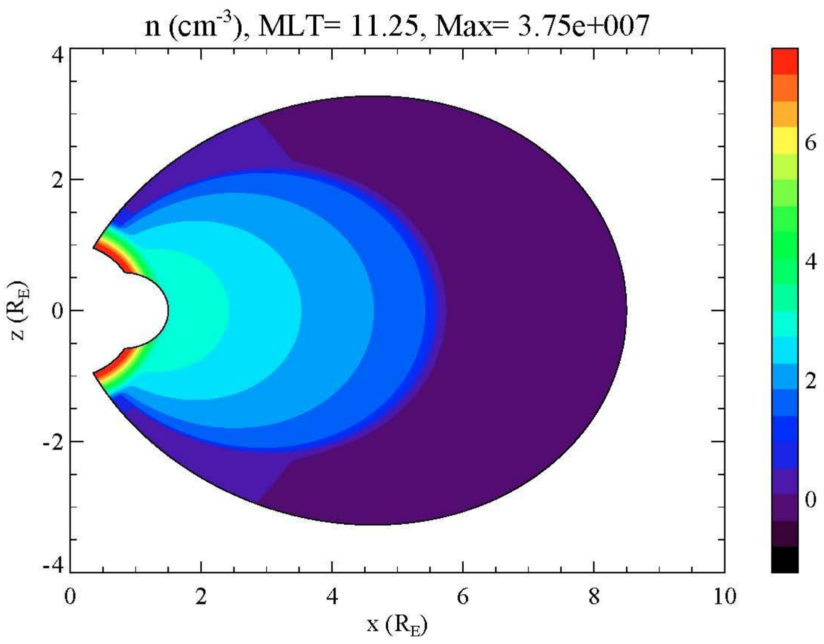
- We use dipole coordinate system:
  - ν (=1/L, outward or poleward)
  - φ (azimuthal, usually measured in Magnetic Local Time, MLT)
  - μ (field-aligned)
- At low azimuthal mode number m ($e^{im\varphi}$ dependence):
  - Poloidal mode (E_φ, B_ν, B_μ) is compressional (fast mode), propagates isotropically
  - Toroidal mode (E_ν, B_φ) is guided along field (shear Alfvén mode)
- So poloidal components can form cavity modes, toroidal components give field line resonance

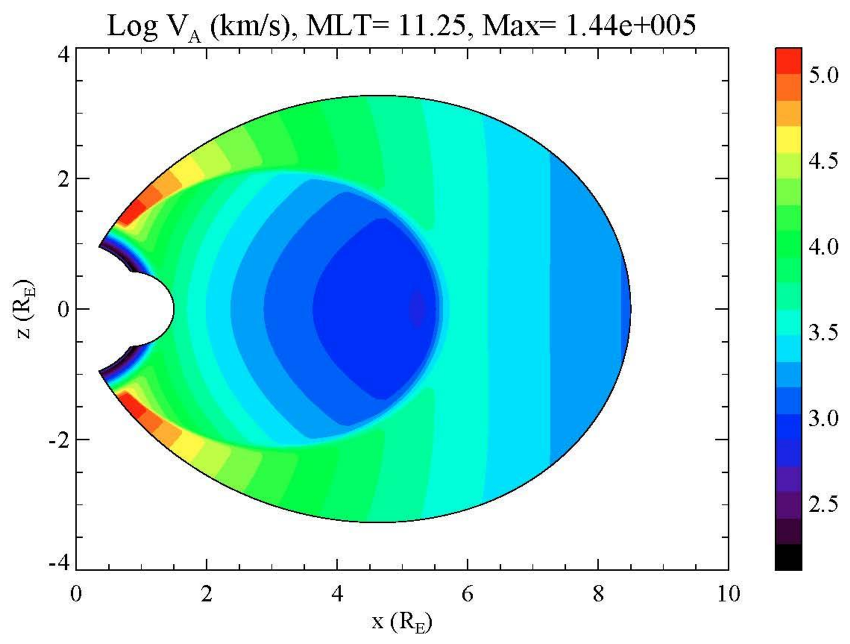
Shock Event: August 15, 2015
(Takahashi et al., JGR, 2018)

- Van Allen Probes in the plasmasphere during impact of interplanetary shock
- Magnetopause compressed to 8.5 R_E, plasmasphere extends to 5.5 R_E (Electron density below from plasma waves)
- Van Allen Probe-A outside simulation volume, so we'll concentrate on B.



Density and Alfvén speed profiles





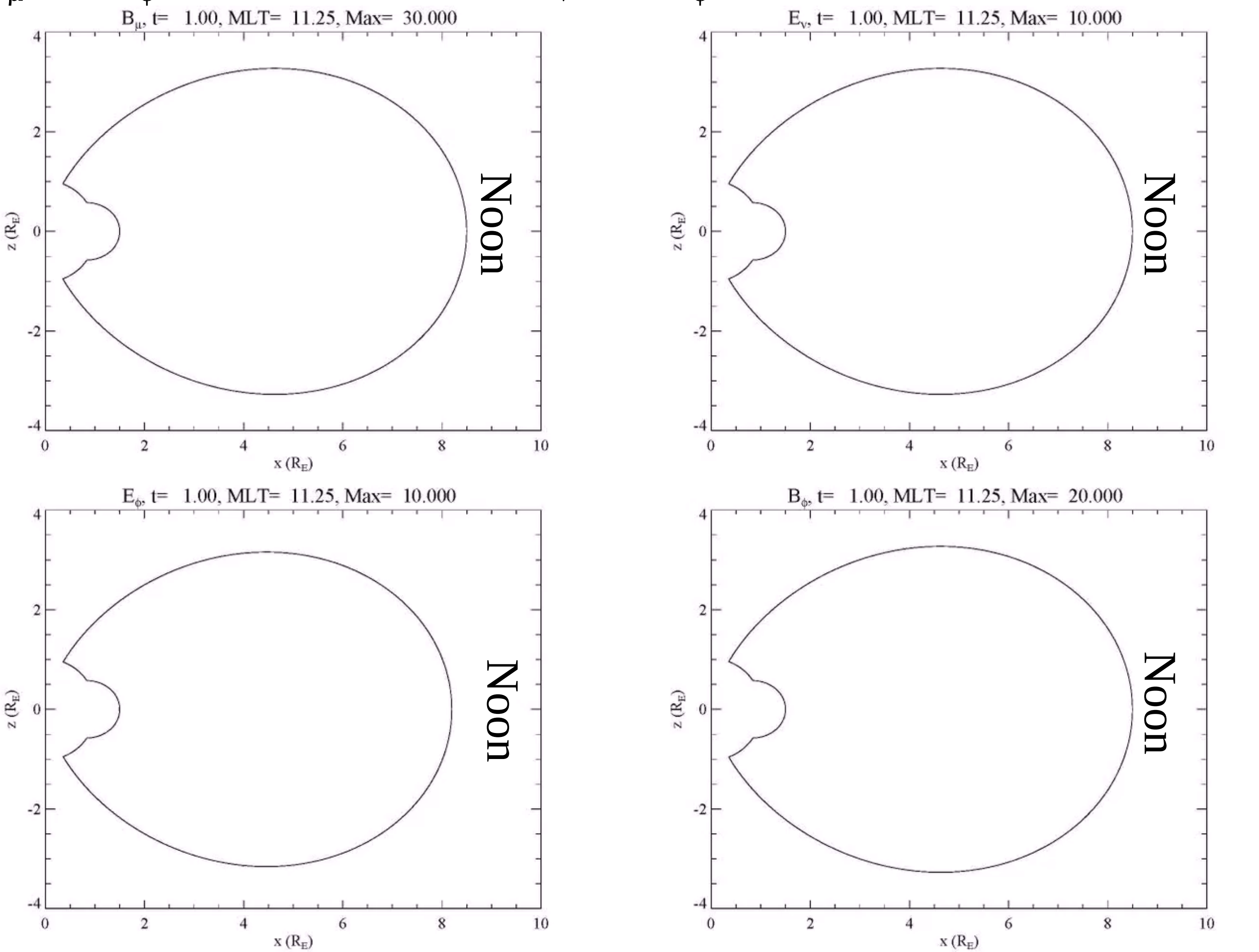
- 3-d ULF wave model in dipole filed with density based on ionospheric model as in Kelley (1989), plasmasphere model of Chappell (1972), 1/*r* density dependence along high-latitude field lines.
- Plasmapause density based on RBSP measurement, reduced to account for compression of magnetic field above dipole values.
- Magnetopause at 8.5 R_E to be consistent with data.

Excitation of waves by shock

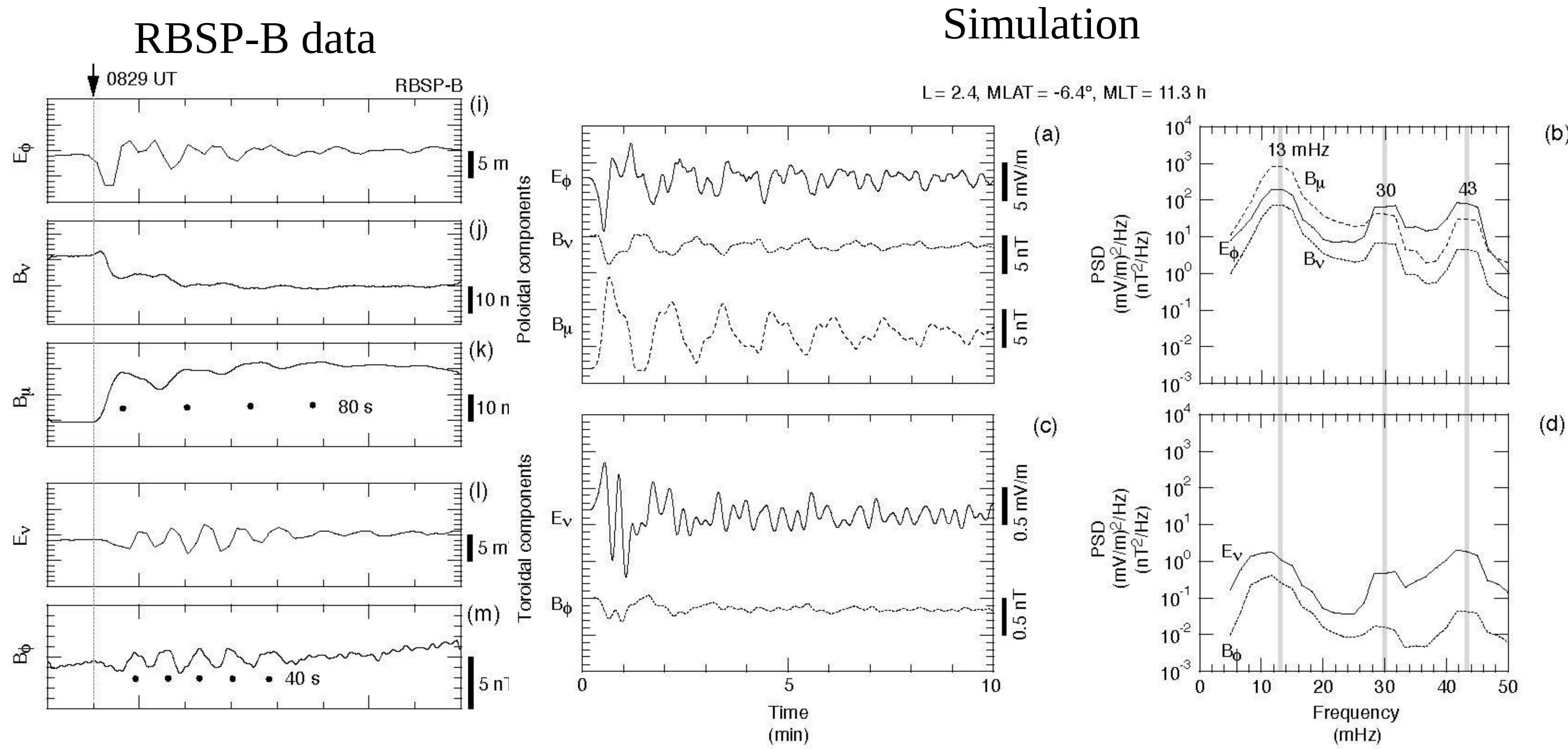
- Evolution of simulation driven by compression at noon magnetopause
- B_μ and E_φ show cavity mode; E_ν and B_φ show field line resonances

B_μ **E_ν**

E_φ **B_φ**

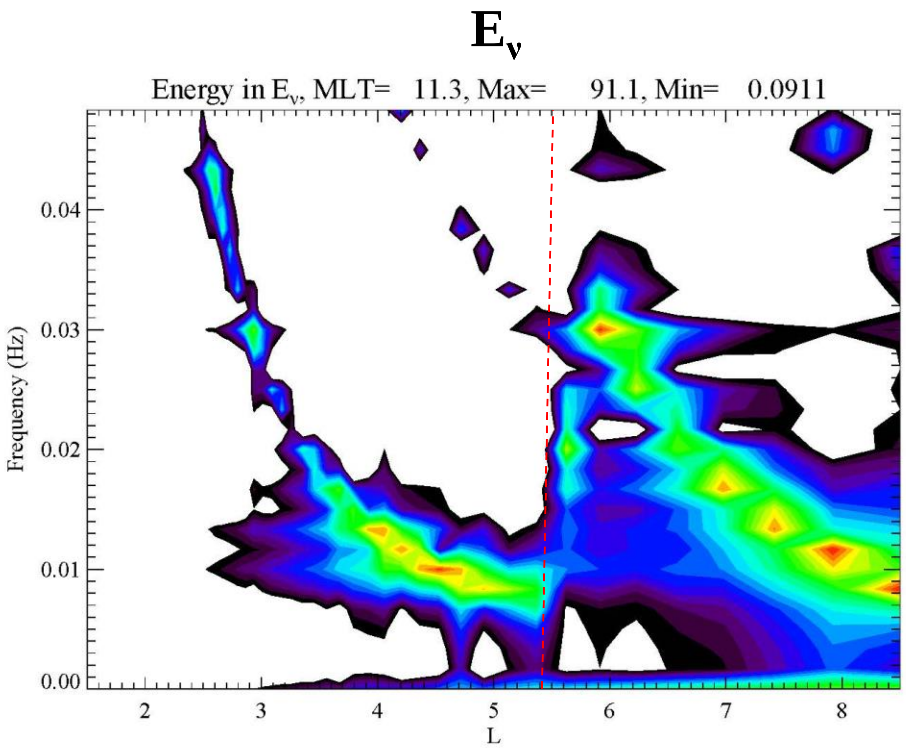


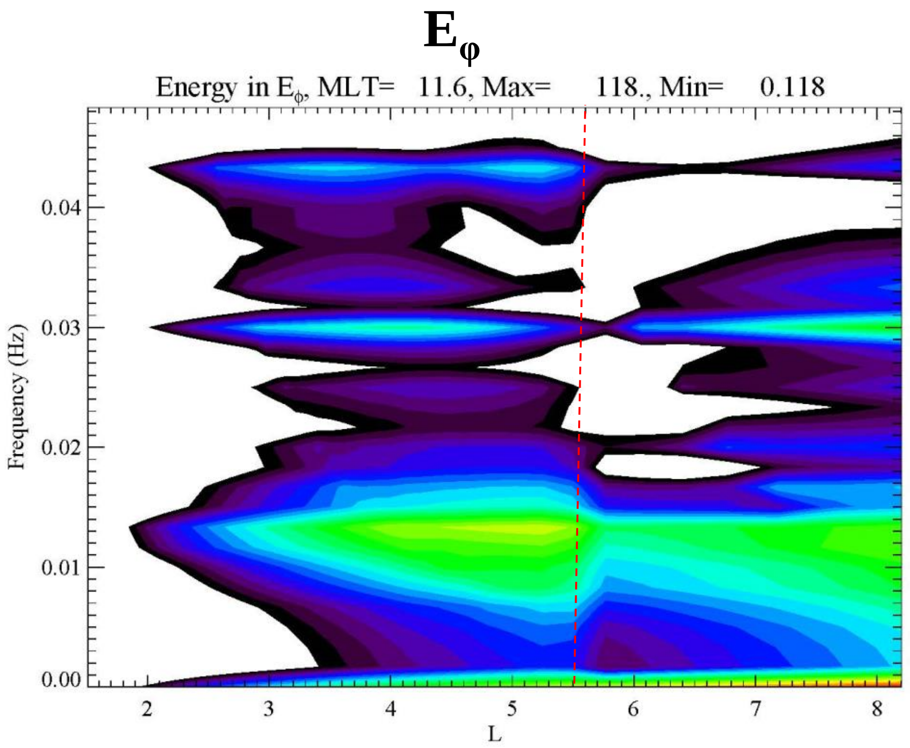
Comparison with Observation



- Compression somewhat smaller than in data, but same basic trend: enhancement of B_μ (solid line), decrease of B_ν, 13 mHz oscillation
- Toroidal components very weak, but show 40-s oscillation as in data.

Energy Density





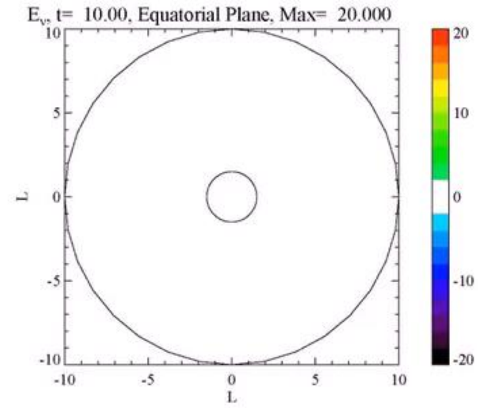
- Electric Field spectral energy density integrated along field line
- Left: E_ν (toroidal mode) shows L-shell dependent field line resonances: note decrease in frequency at plasmapause (red dashed line at L=5.5)
- Right: E_φ (poloidal mode) shows cavity mode at ~12 mHz and harmonics: largely but not totally confined in plasmasphere

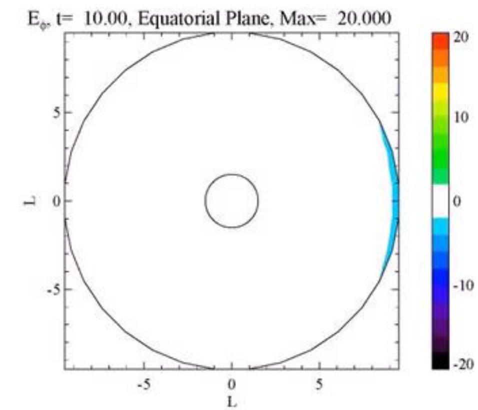
Test Particle Runs in ULF wave code

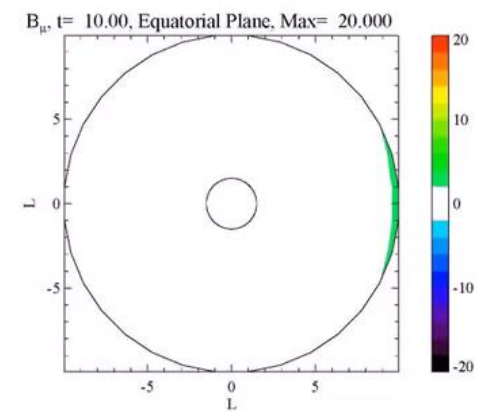
- We have used the fields from the ULF wave code to drive a test particle model
- First results: we will consider equatorial mirroring particles
  - So only drift resonance, no bounce resonance
- We perform runs with a 10 mHz wave injected from the tail
  - Day-night gradient in conductivity
  - Plasmapause at 4 R_E: 10 mHz is resonant frequency of plasmasphere cavity mode
  - Gaussian profile in local time and latitude (so not a single *m* value)
- Goal is to understand dynamics of wave particle interaction in coupled poloidal-toroidal modes

Wave fields in equatorial plane

- Simulation is fully 3-d
- Equatorial fields shown:
- Top Panel: E_ν (toroidal)
- Middle Panel: E_φ (poloidal)
- Bottom Panel: B_μ (compressional)
- Top panel shows toroidal field line resonances
- Bottom 2 panels show poloidal fields
- Plasmaspheric cavity mode most distinct in magnetic field
- Localized wave structure: no clearly defined *m* value

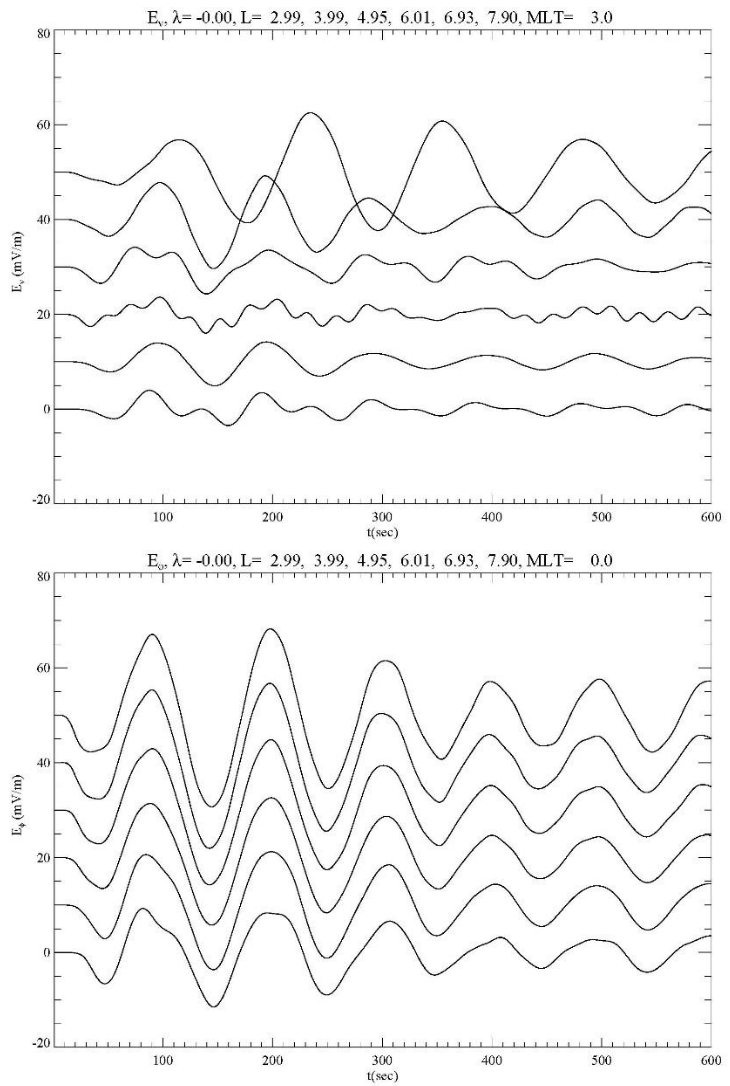






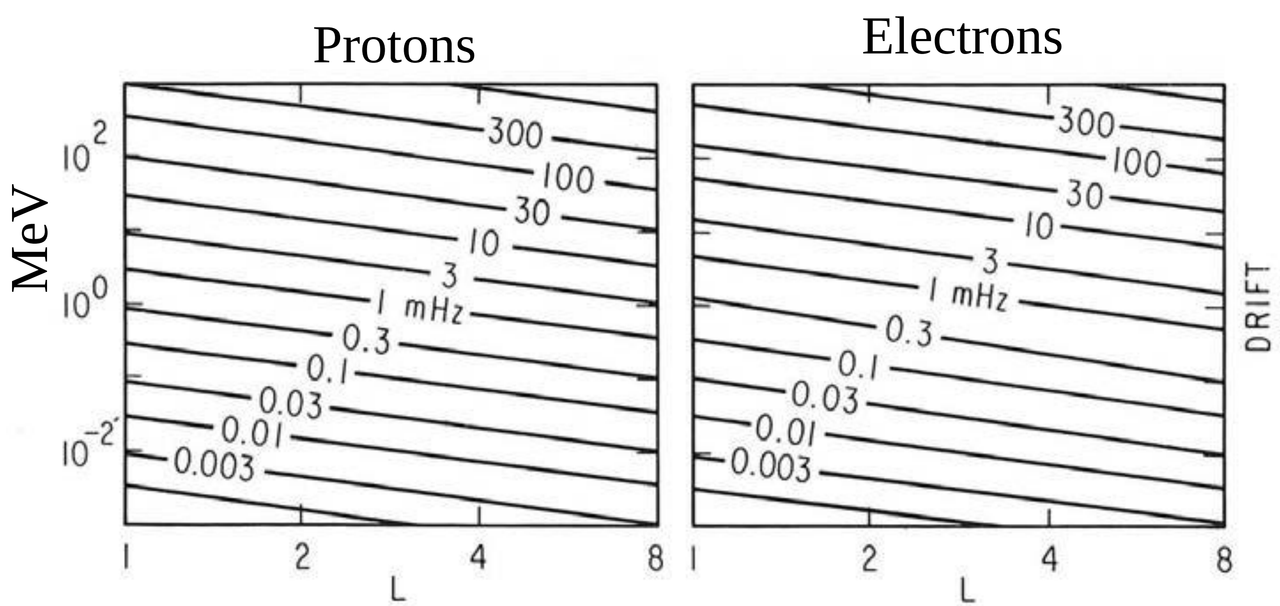
Time history of equatorial fields

- Top panel: E_ν, toroidal mode, showing field line resonances
  - Frequency dependence on field line
- Bottom panel: E_φ, poloidal mode
  - Coherent frequencies on all field lines



Test particle runs

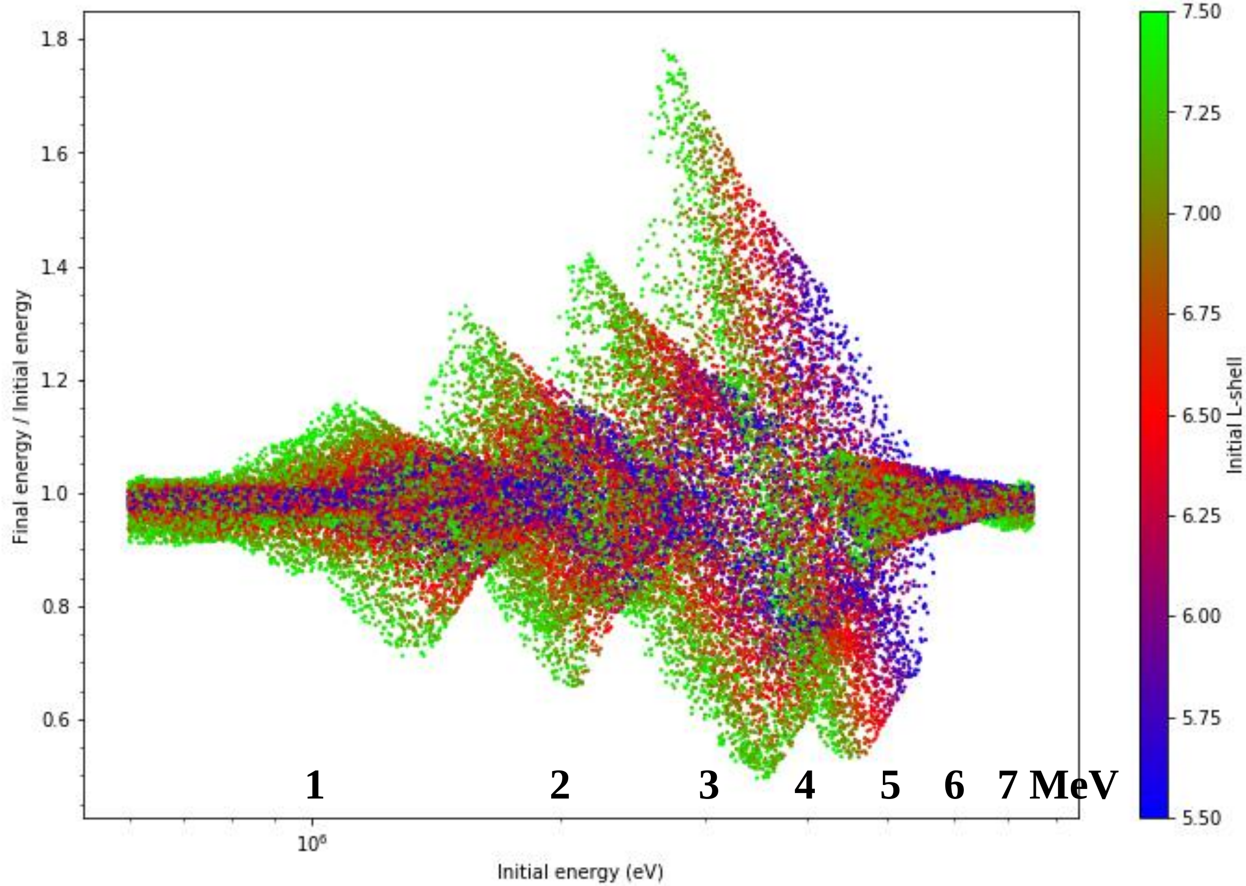
- Each run follows 50,000 particles (protons in plot below)
- Original positions distributed evenly in MLT and in L-shell from 5.5 to 7.5.
- Energy evenly distributed in log E, from 0.6 to 7.6 MeV
- Color bar gives initial L-shell
- Note: 10 mHz wave resonates with protons in L=4-8 range at 3-10 MeV
  - Electron resonant energies twice as high at relativistic energies
- For protons in dipole field: $\nu(\text{mHz}) = 0.377\, W(\text{MeV})\, L$



(Schulz and Lanzerotti, 1974)

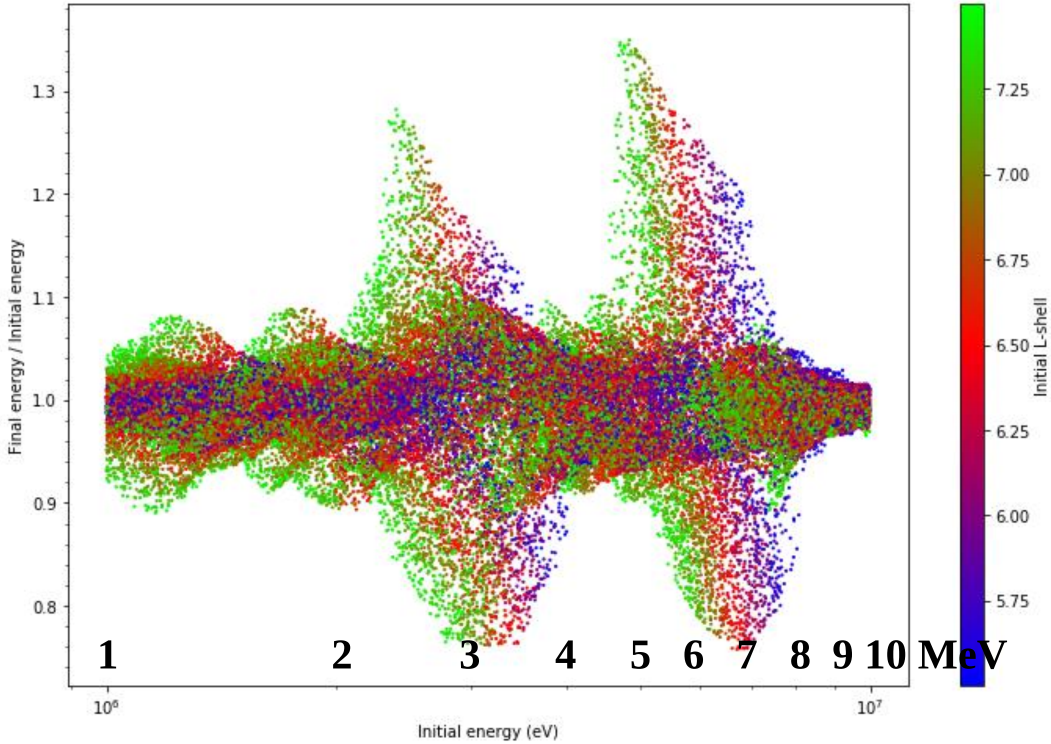
Test particle runs: Cavity mode

- Proton of 4 MeV has fundamental drift resonance of 10 mHz at L = 6.5
- Protons just below this energy gain most energy, just above lose energy
- Peak at 2nd harmonic (2 MeV) and 3rd (1.3 MeV) seen
- What about 3 MeV peak? 3:2 resonance?



Test particles: Off cavity mode resonance

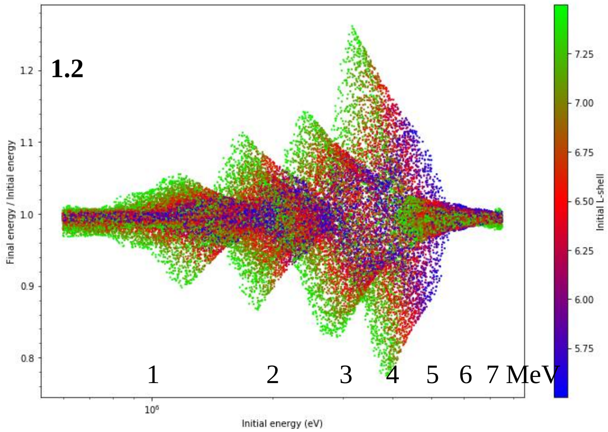
- To check on effect of cavity modes, a run driven at 15 mHz was done (non-cavity mode) with same driving amplitude
- Resonance at fundamental (6 MeV) and harmonic (3 MeV) seen, but other peaks weak or absent.
- Peak energization weaker in this case (E_f/E_i = 1.3, vs. 1.8 in 10 mHz case)



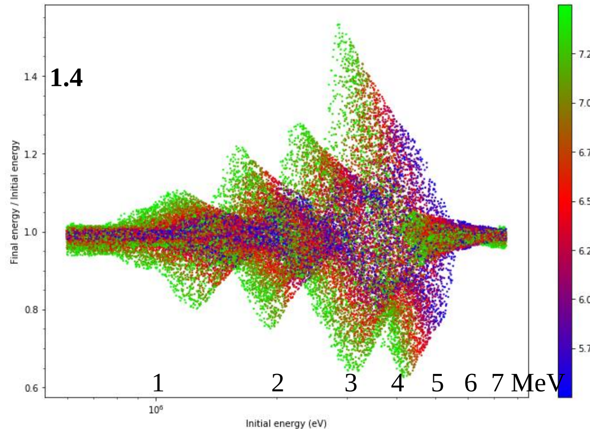
Ampitude dependence

- How does energization scale with wave amplitude?
- Wave fields scaled by 15%, 30% and 45% (Peak E_φ ~ 3,6,9 mV/m)
- Max $\Delta E/E_i$ ~ 25%, 50%, 75%: roughly linear scaling with wave amplitude
- Implies non-diffusive energization, energy gain stronger than increase in wave power.

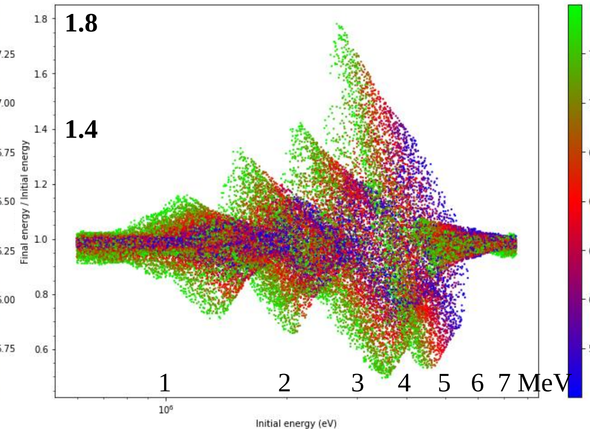
15%



30%

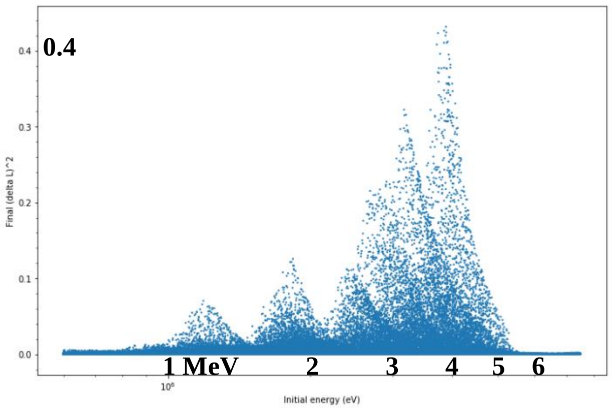


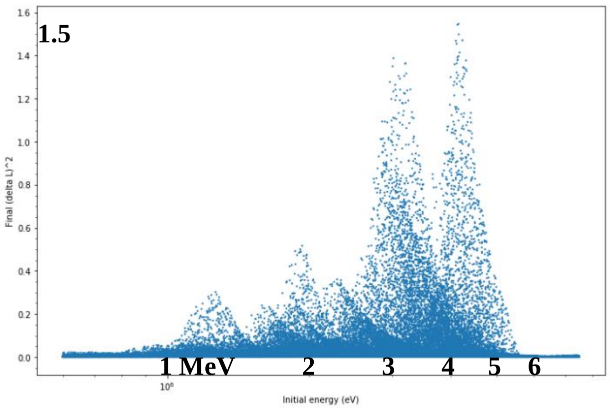
45%

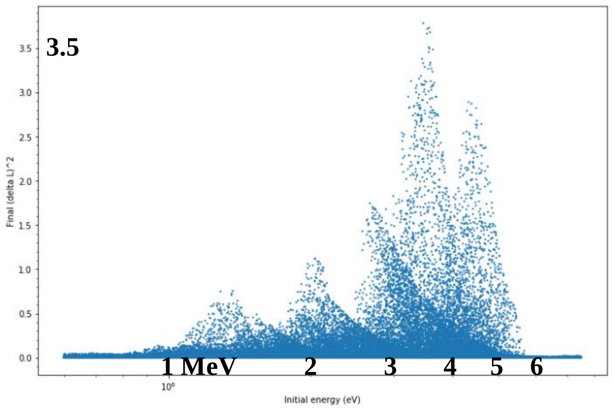


Radial Transport

- Is radial transport diffusive?
- Plot $(\Delta L)^2$ as function of initial energy for 15%, 30% and 45% runs
- Final values consistent with scaling with energy density

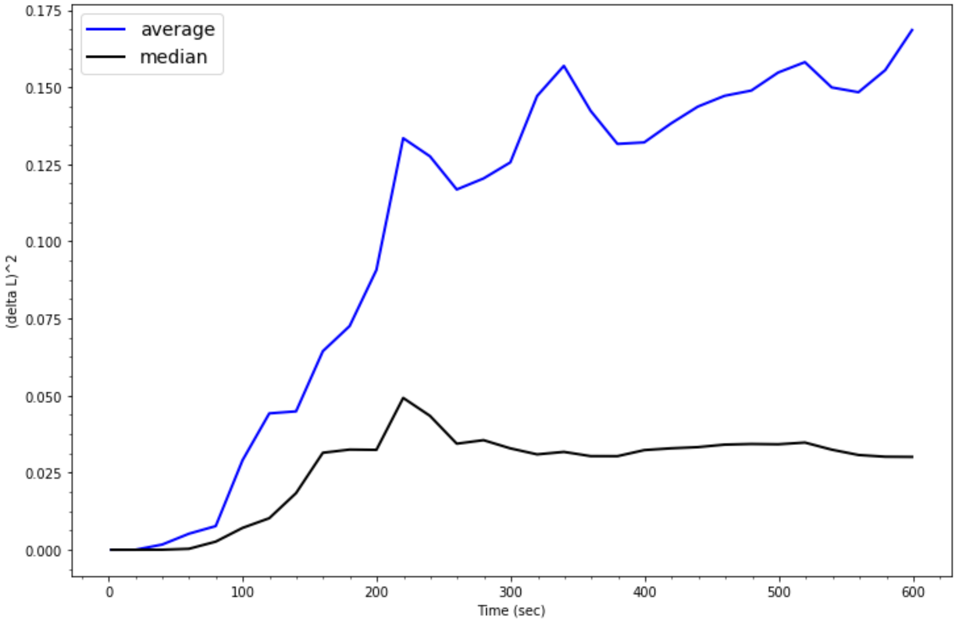






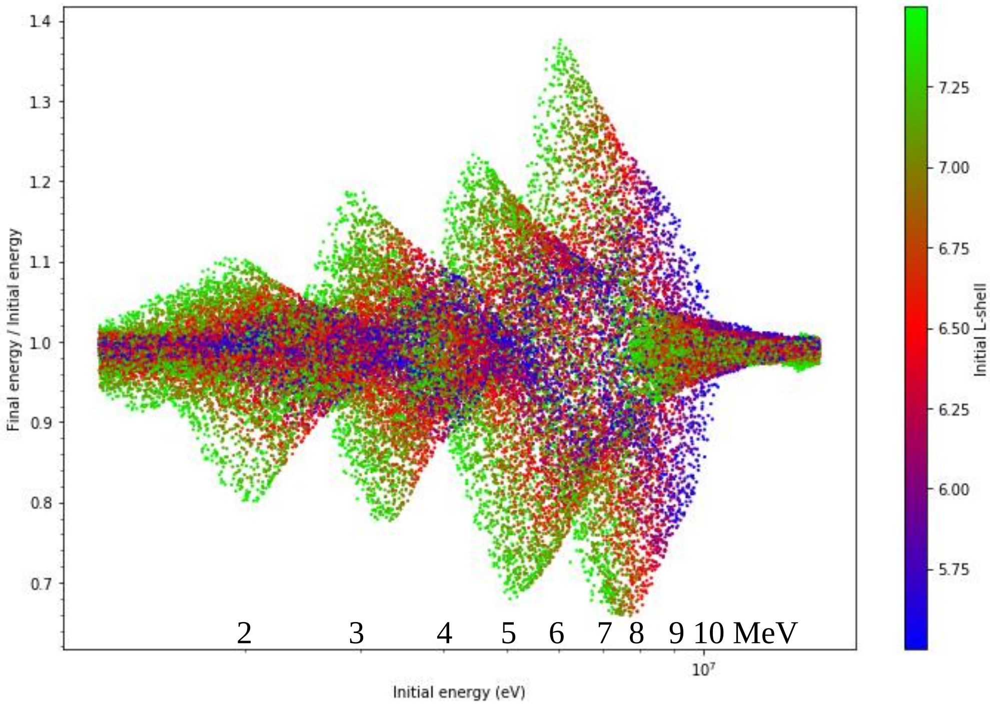
Time dependence Radial Transport

- Is radial diffusion diffusive?
- Plot mean and median of $(\Delta L)^2$ as function of time for resonant protons
- More quadratic in early phase, then saturates.
- Suggests diffusive behavior as a result of series of impulses



Electrons

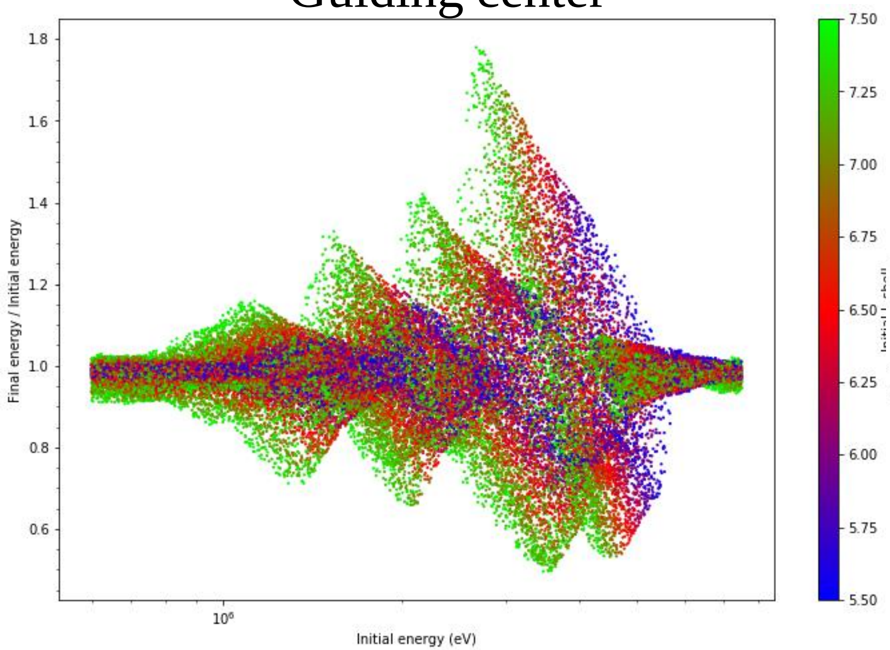
- Electrons have similar behavior, but grad-B drift is half as big (for same energy) for relativistic particles, so resonant energies are twice at same frequency
- Energization (ΔE) similar to protons, but $\Delta E/E_i$ smaller since initial energy larger



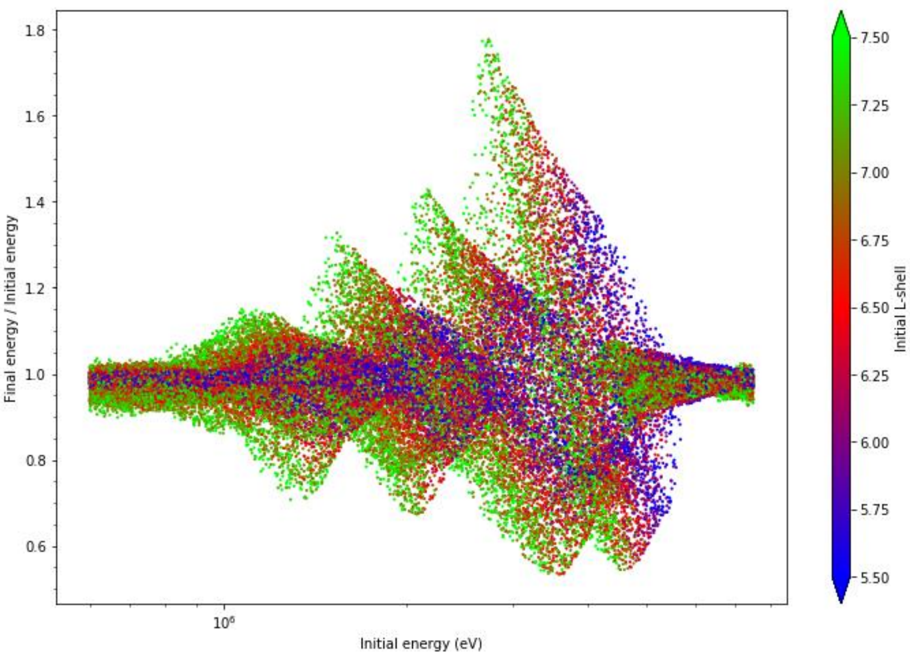
Guiding Center vs. full Lorentz force

- Runs shown use guiding center approximation to push particles (MeV proton at L=7, gyroradius is 0.25 R_E)
- Is this sufficient; what about full Lorentz solver?
- Results very similar, guiding center approx. ok
  - Caveat: Initial L-shell is particle position for Lorentz, gc position in guiding center run

Guiding center



Lorentz



Conclusions

- Wave modeling can give global context for magnetospheric measurements
- Shock event: compression of dayside magnetopause can excite both compressional and shear mode waves in magnetosphere, forming cavity modes and field line resonances.
- First results from test particle run show drift resonance energization and radial transport
- Runs at cavity mode resonance produce stronger energization, more harmonic structure
- Future work:
  - Range of frequencies: “Green’s function” for energization
  - Add bounce motion: resonance for lower energy particles
  - Add parallel electric fields: Kinetic Alfvén waves