The Radiation Belt Revolution

Geoffrey Reeves

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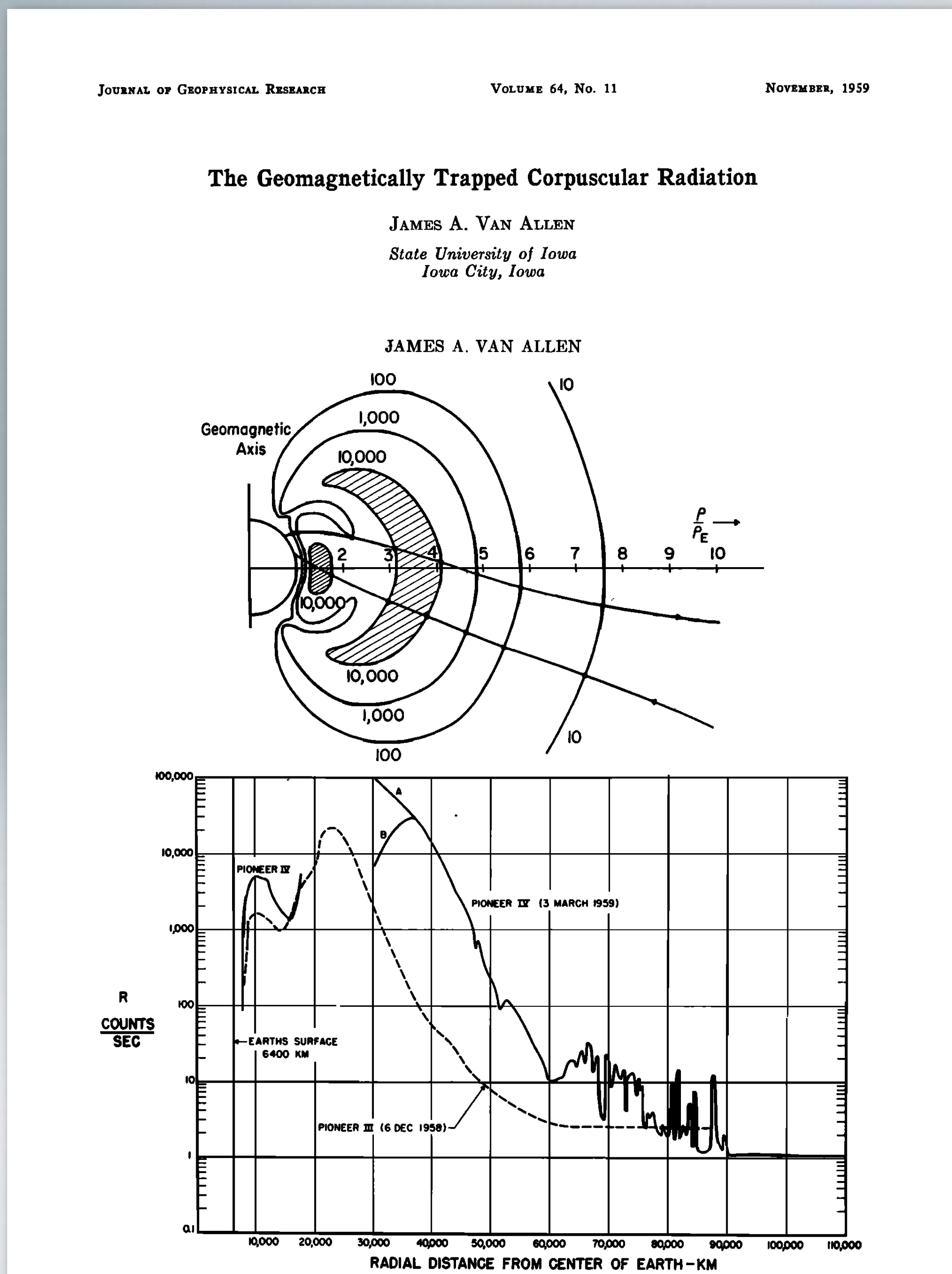
LA-UR-19-23102'

'First Discovery of the Space Age'



Journal of Geophysical Research   Volume 64, No. 11   November, 1959

The Geomagnetically Trapped Corpuscular Radiation

James A. Van Allen
State University of Iowa
Iowa City, Iowa

- Electrons & Ions trapped in Earth's magnetic field
- Energies that penetrate shielding
  - MeV Electrons (i.e. relativistic)
  - 100s MeV Protons
- Early observations did not resolve energy or species

The Radiation Belts are important as a ‘local laboratory’ for acceleration physics and as a source of satellite ‘Anomalies’

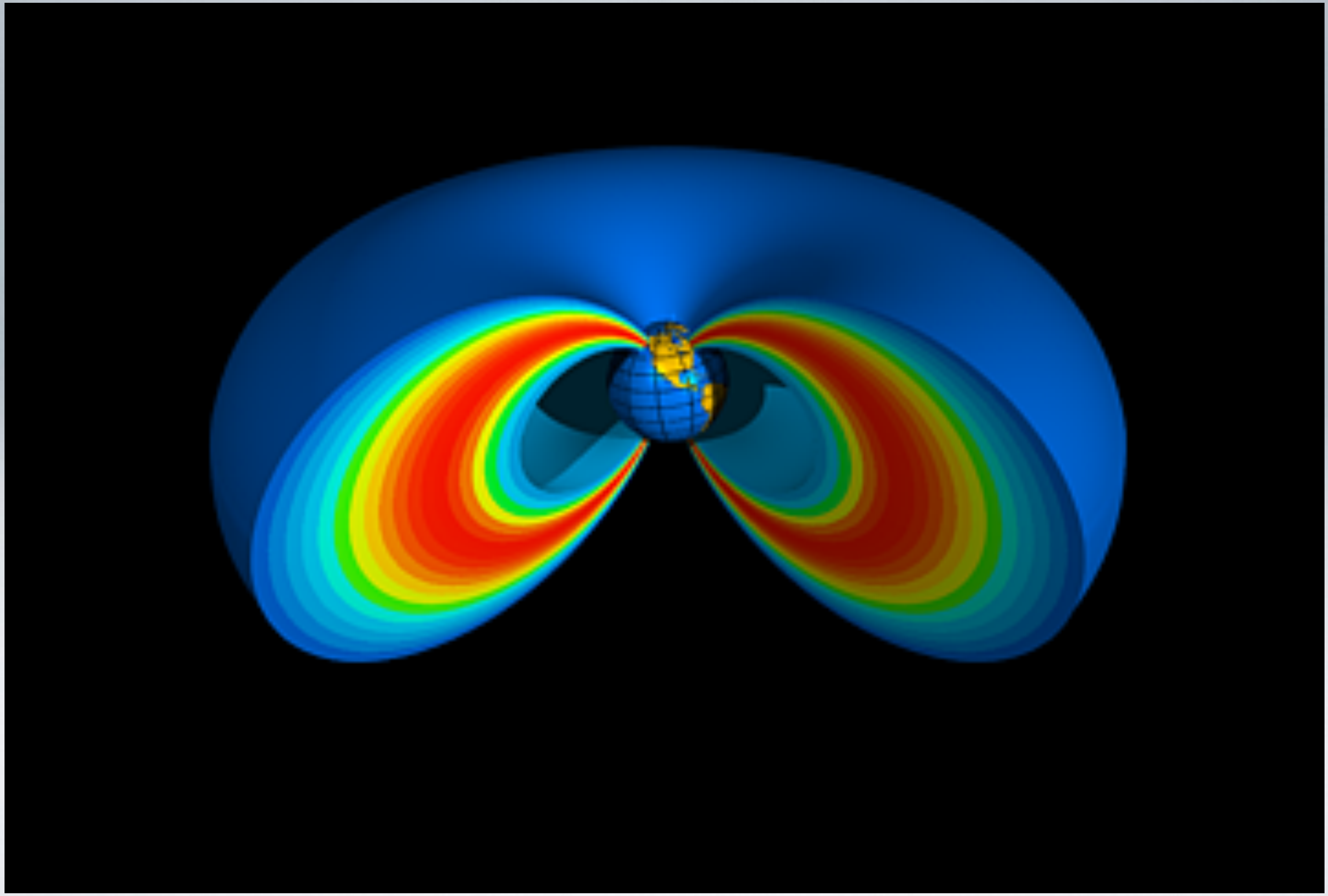
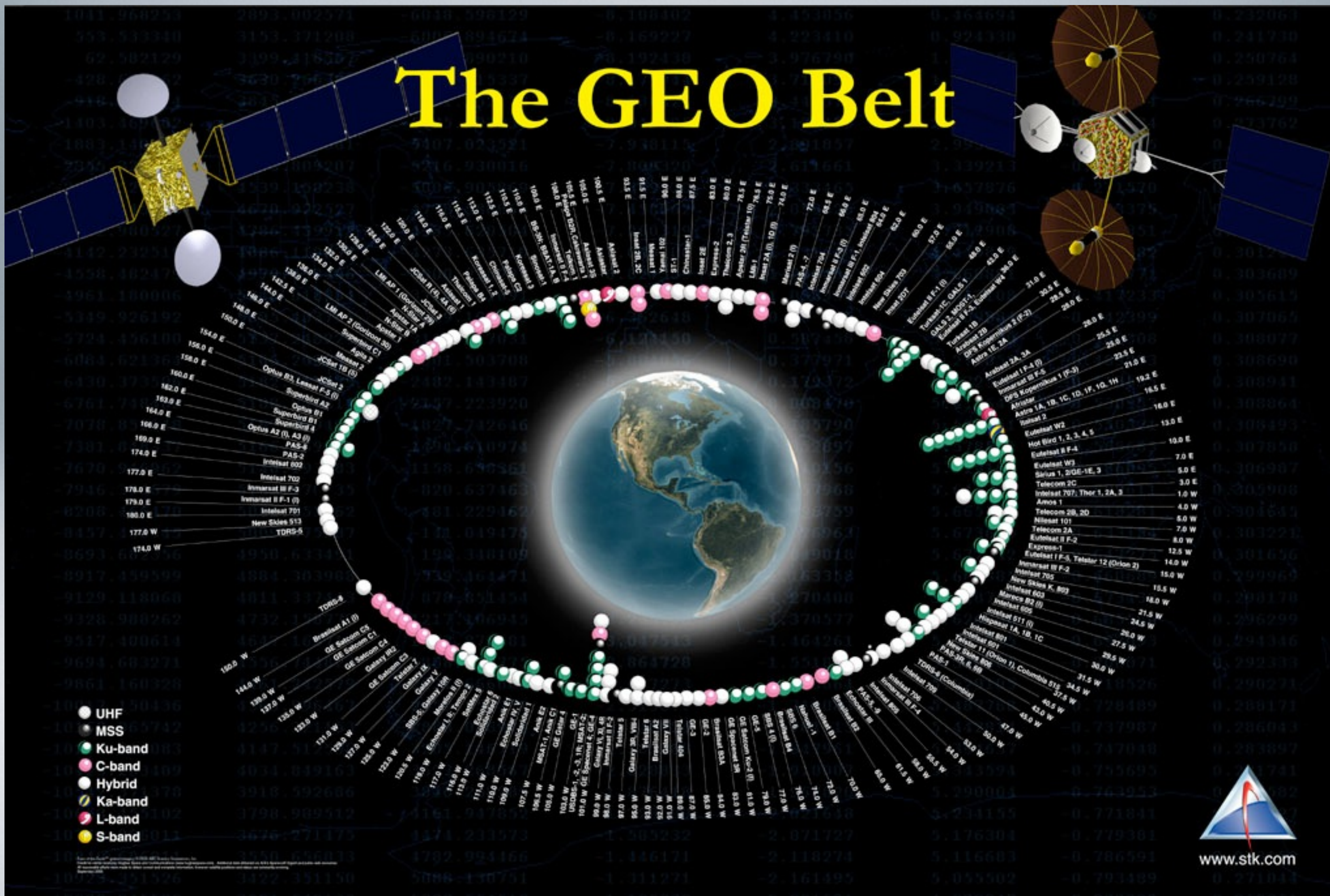
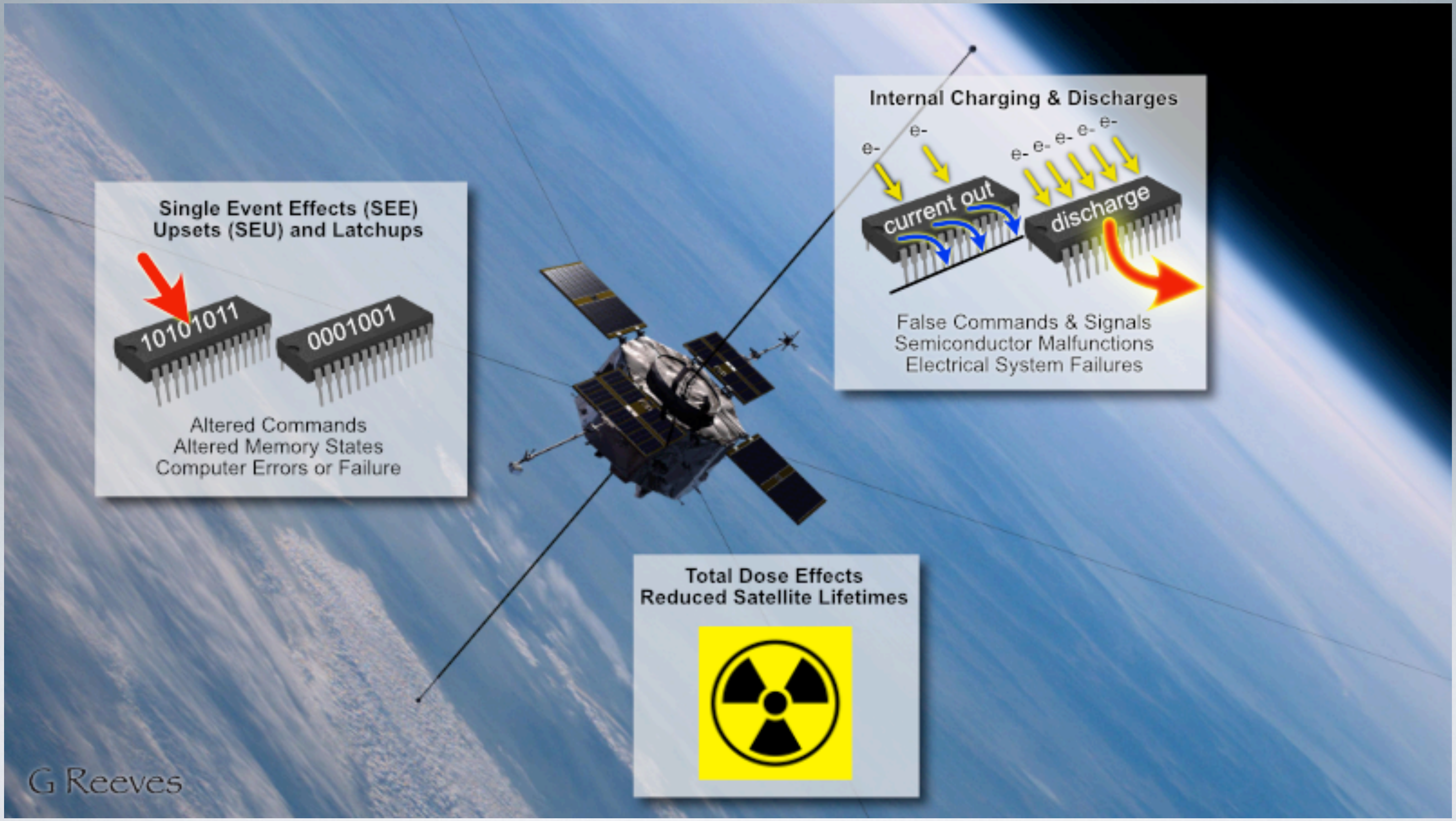


image: Henderson & Reeves, LANL

We depend on satellites for all sorts of day-to-day activities

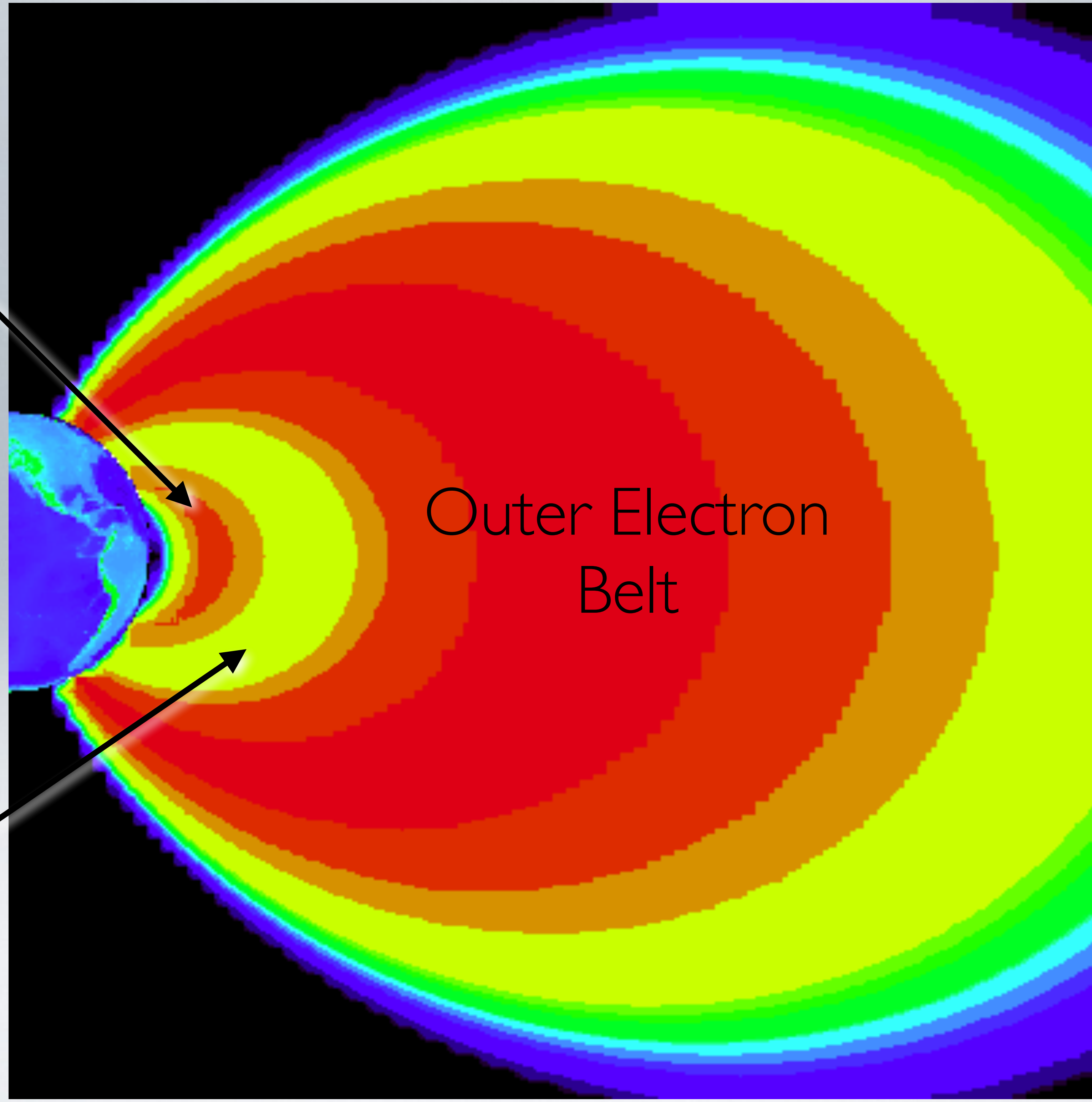


Internal Charging & Discharges are the #1cause of premature satellite failure



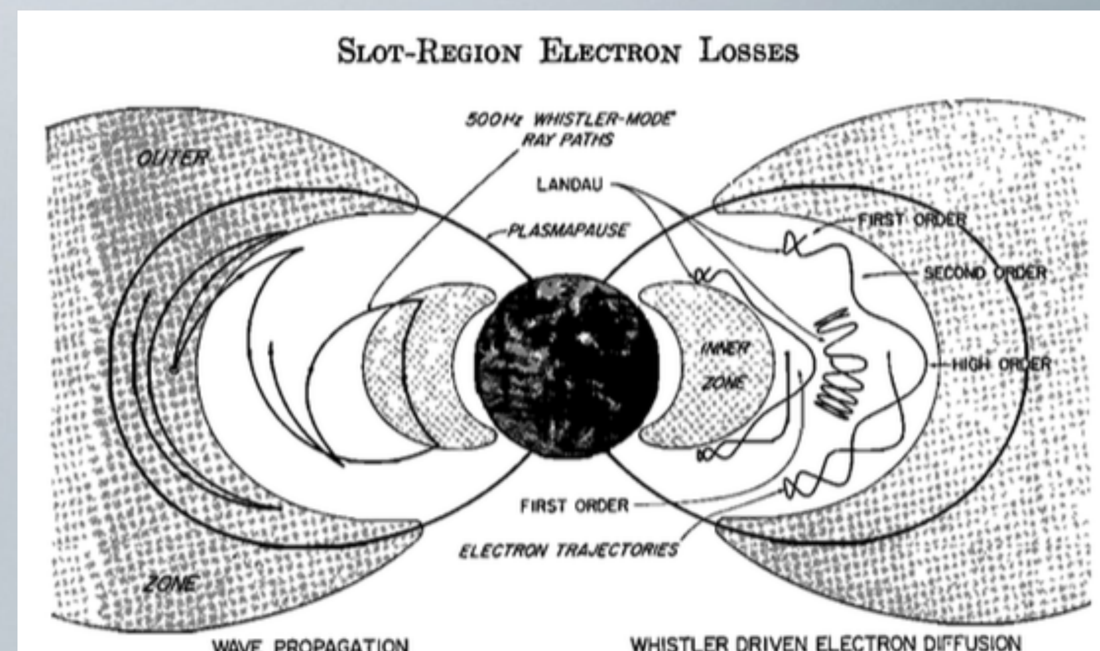
Radiation Belt Structure & Dynamics

The Standard Electron Radiation Belt Model



The Near-Equilibrium Model

- Radial diffusion transports electrons Earthward
- In the process they gain energy through betatron & Fermi acceleration
- Radial diffusion slows down dramatically closer to the Earth
- Plasmaspheric 'Hiss' pitch angle scatters electrons into the atmospheric loss cone
- When losses are faster than diffusion a 'slot' forms
- The few electrons that get far enough in form an 'inner belt' where lifetimes get long again



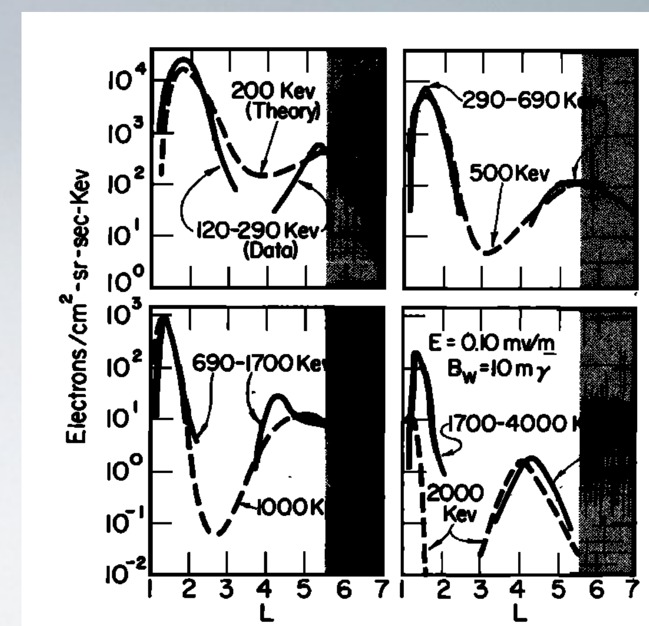


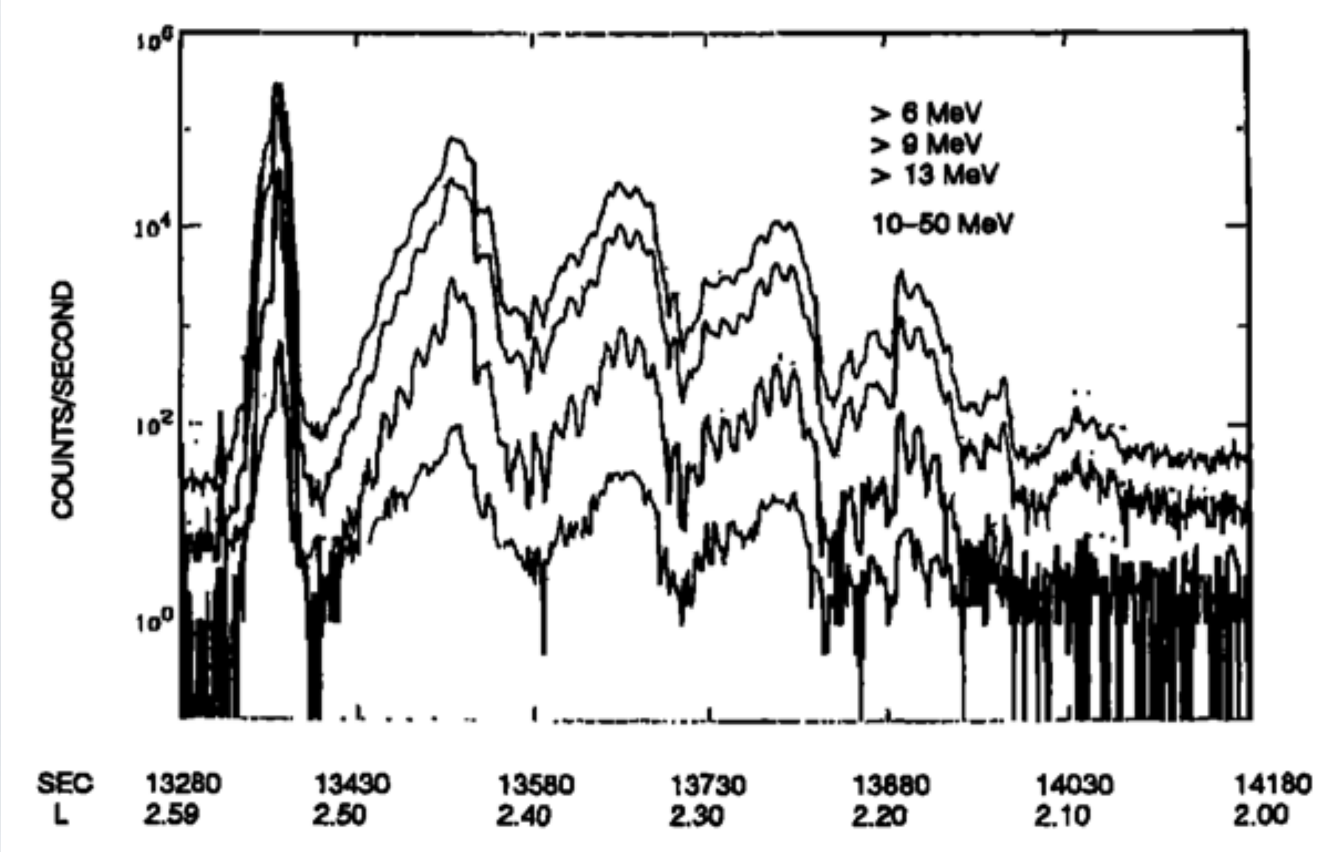
Fig. 3. Theoretical flux profiles for $E = 0.10$ mv/m and $B_W = 10$ mγ are compared with quiet time solar minimum observations [*Pfitzer et al.*, 1966].

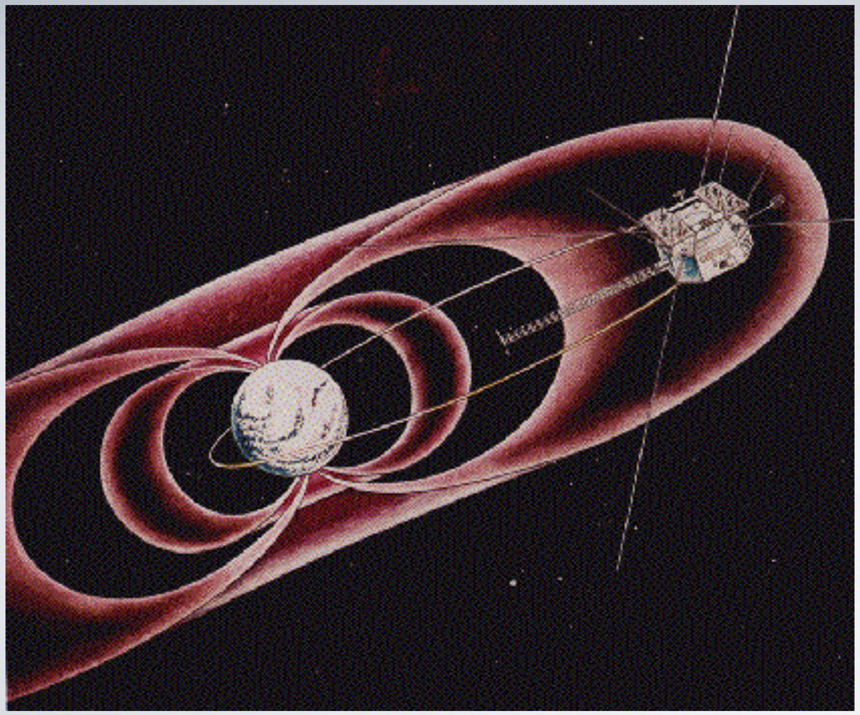
Lyons, JGR, 1972 & Lyons & Thorne, JGR, 1973

We thought that…

The radiation belts change slowly over time so the equilibrium model should be approximately correct

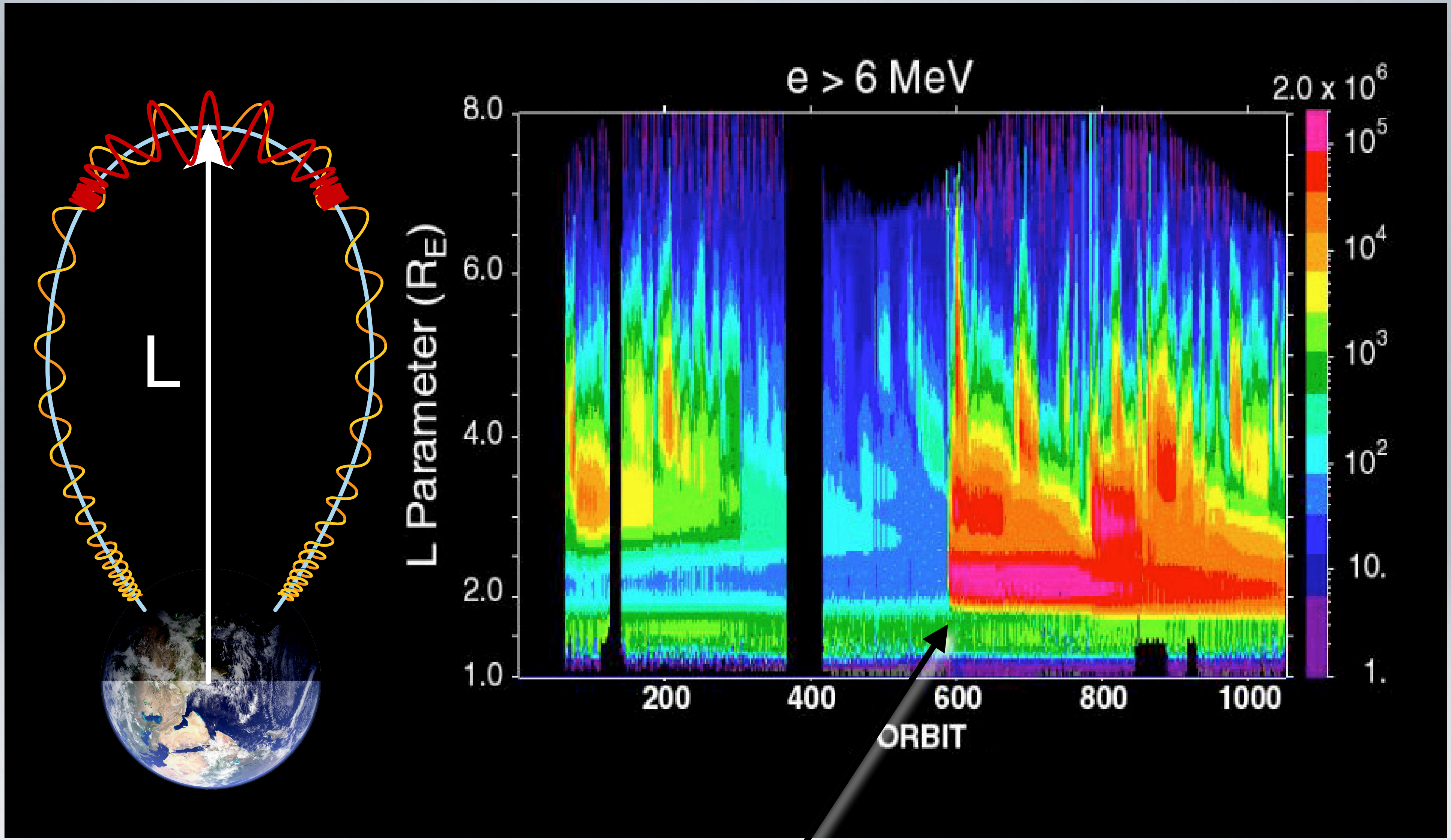
The Revolution Begins…





- CRRES: a GTO satellite 1990-1991
- The time scale for this plot is 15 min!
- ≈1 min injection of >24 MeV electrons at <1.5 Re altitude

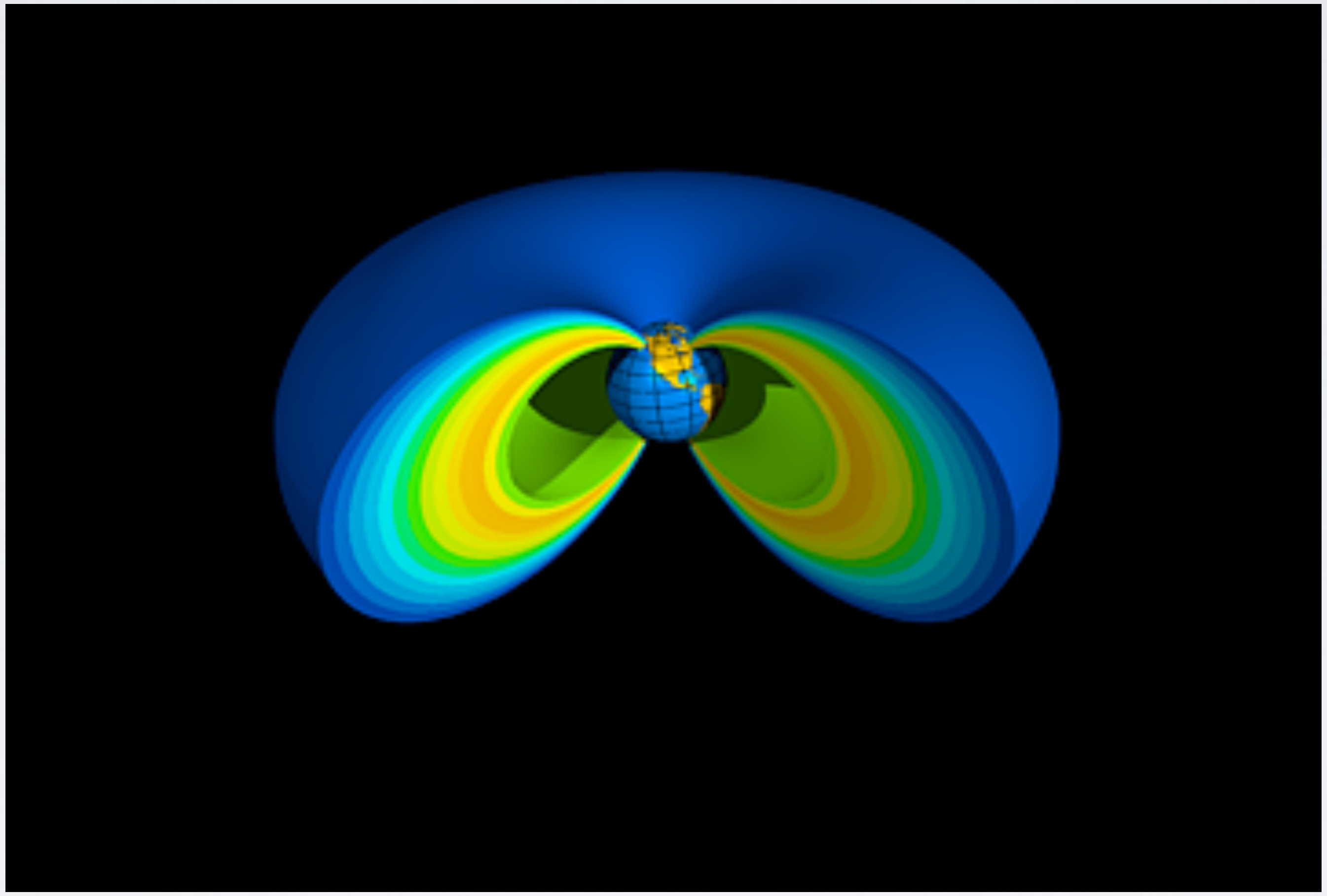
L-shell & the Dynamic Belts



March 1991 Event

The "New" Dynamic Belts

The Radiation Belts vary on time scales from minutes to years



Data Visualization from NASA's Polar Satellite
1 frame = 18 hours

image: Henderson & Reeves, LANL

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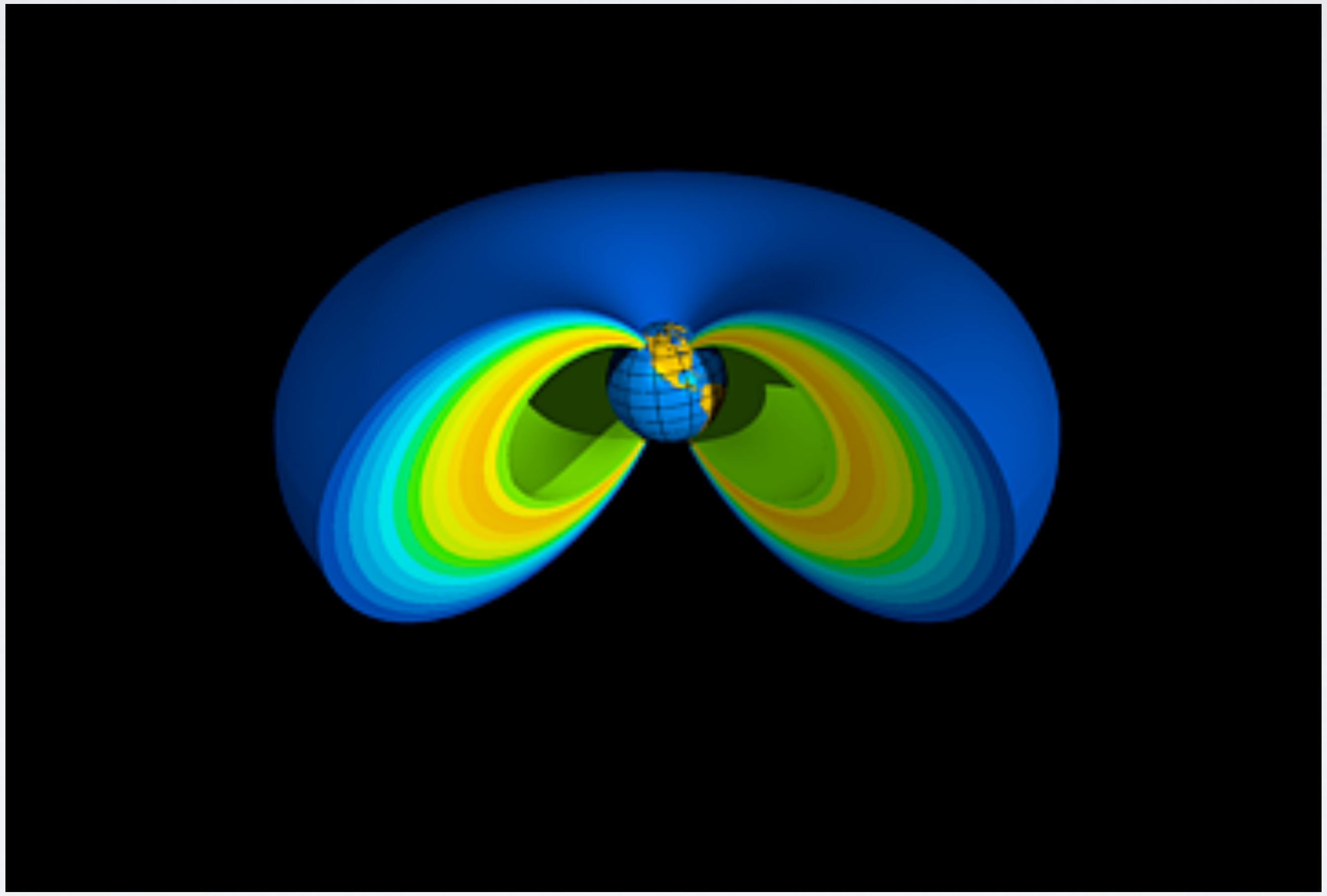


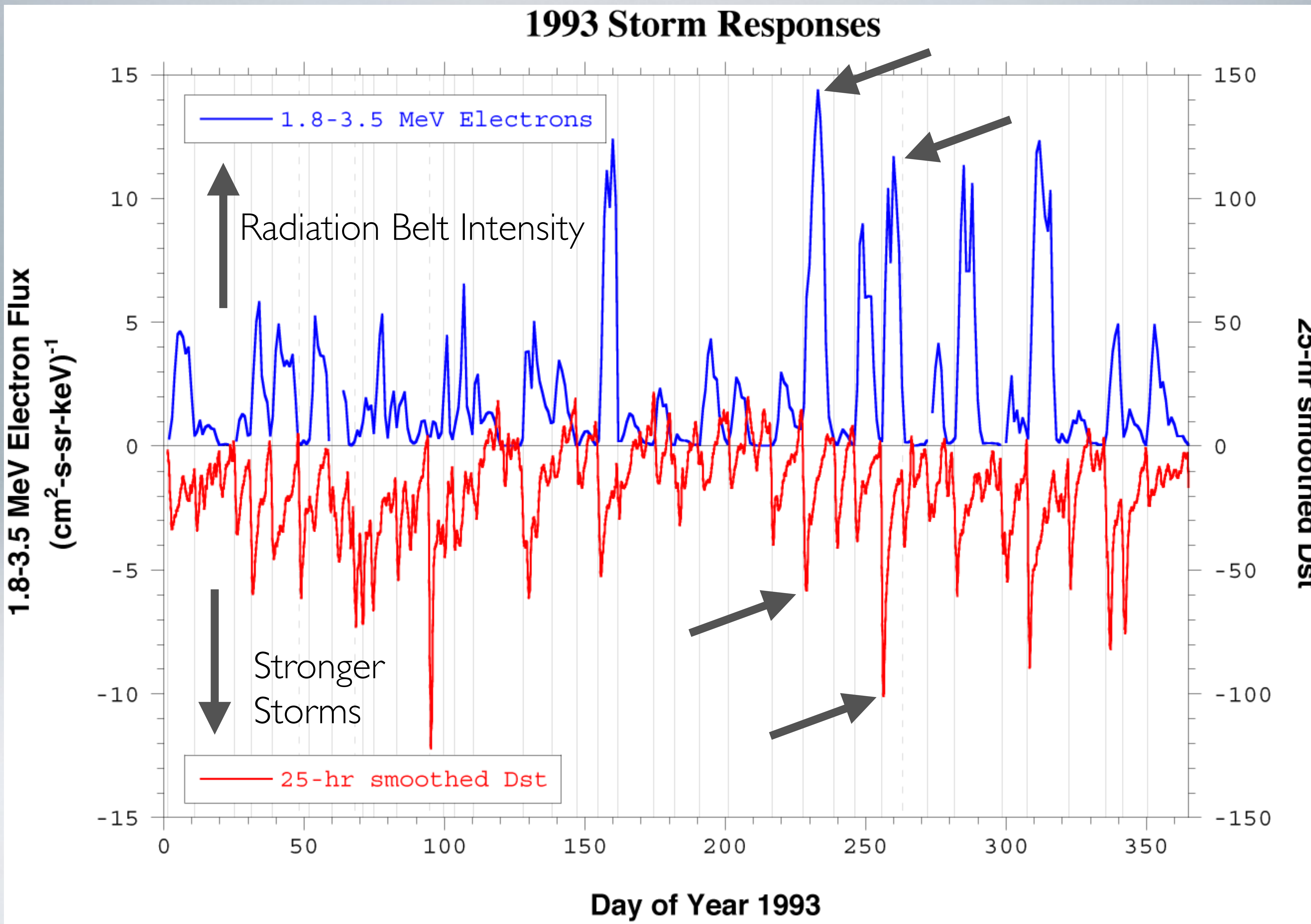
Data Visualization from NASA's Polar Satellite
1 frame = 18 hours

image: Henderson & Reeves, LANL

We thought that…

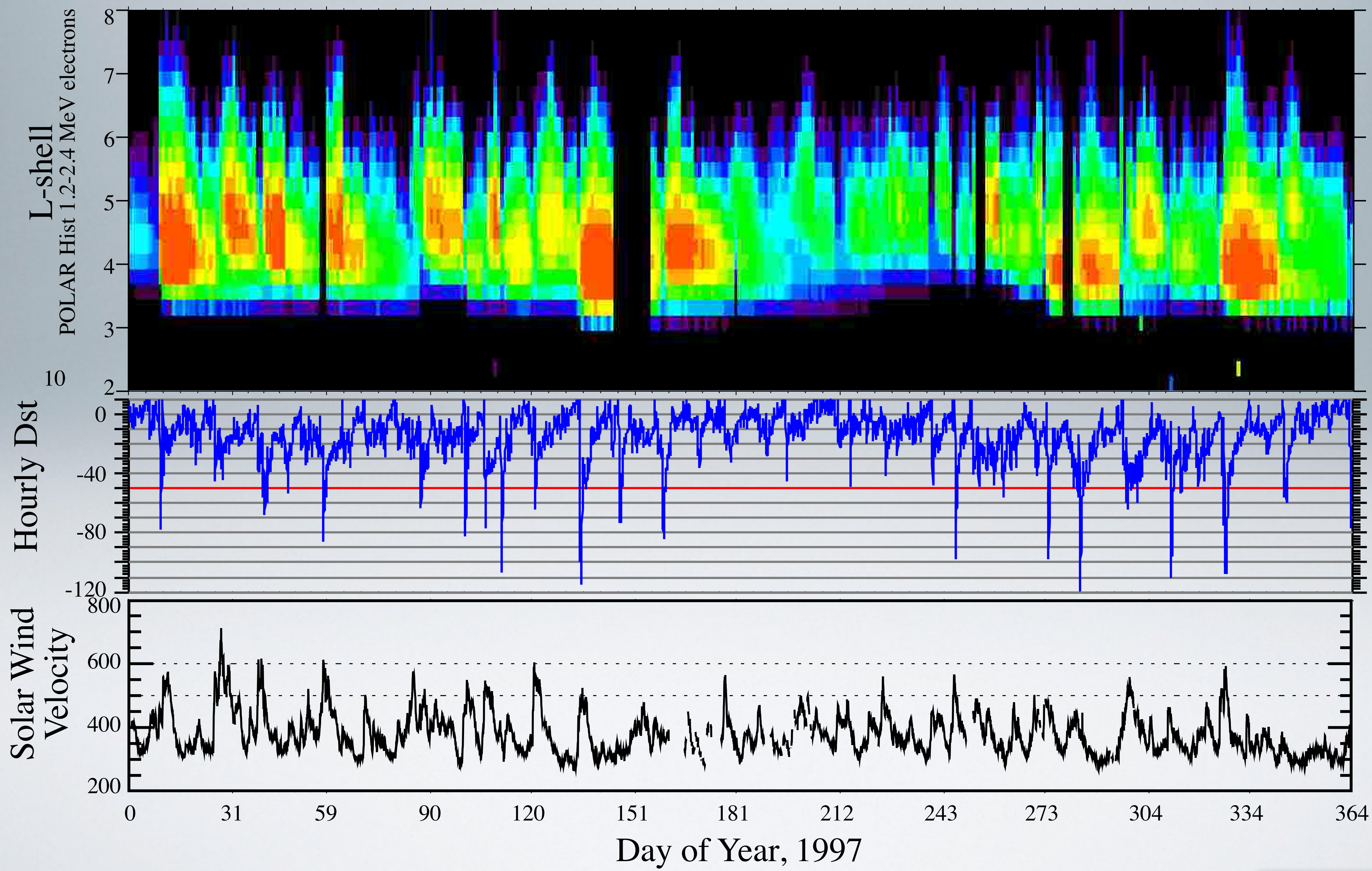
Stronger geomagnetic storms will produce stronger radiation belt response

Storms and Electron Flux



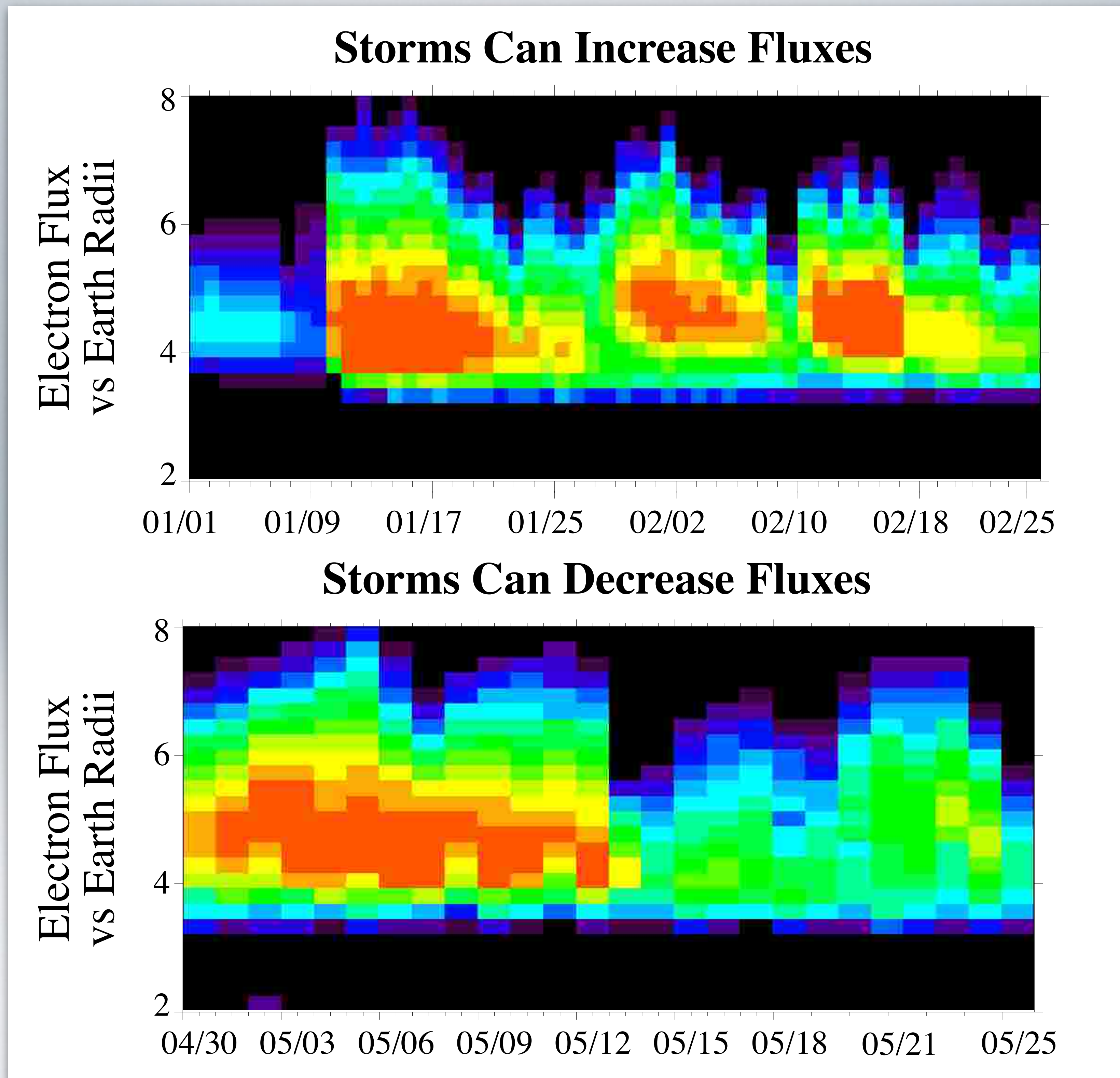
Reeves, Geophys. Res. Lett, 1998

Quantifying the Radiation Belt Response to Storms



Reeves et al., GRL, 2003

The Unexpected Result Was…



Reeves et al., Geophys. Res. Lett, 2003

These and other studies showed that we really didn't understand the physics of the radiation belts after all

The Van Allen Probes

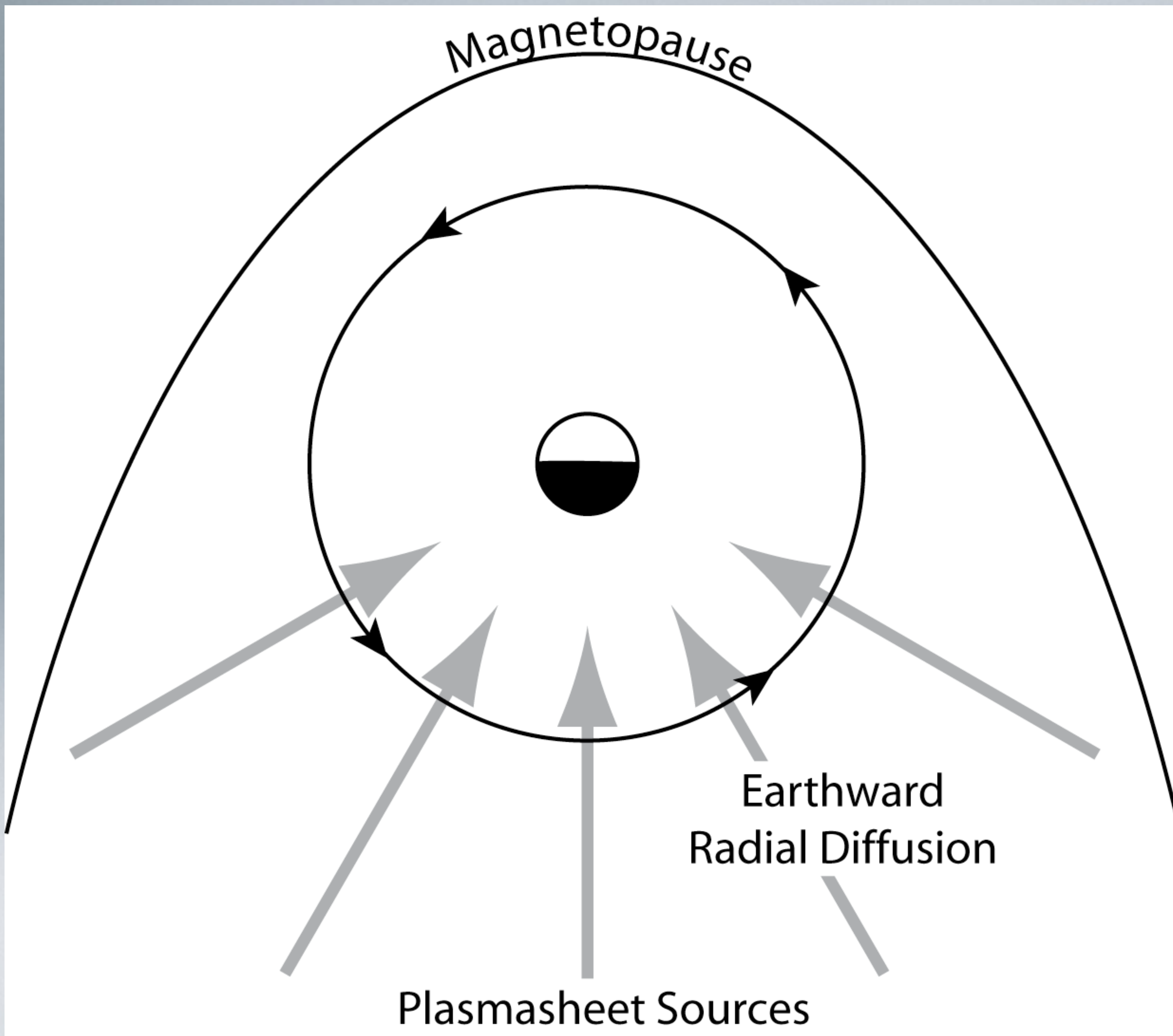
Exploring the Extremes of Space Weather

Van Allen Probes

The Van Allen Probes Primary Science Objectives

- **Relativistic Electron Acceleration**
- Relativistic Electron Losses
- Wave Particle Interactions
- Coupling of the Ring Current - Magnetic Field - Radiation Belts
- (The Role of the Plasmasphere)

Classic Theory: Radial Diffusion



Earthward Radial Diffusion produces betatron & Fermi acceleration as electrons move to regions of higher B

$$\frac{\partial f}{\partial t} = L^2 \frac{\partial}{\partial L} \left(\frac{D_{\mathrm{LL}}}{L^2} \frac{\partial f}{\partial L} \right)$$

Perpendicular energy gain enhances the flux of 90° pitch angles.
Magnetic moment, μ, is conserved

There are models that show how this works

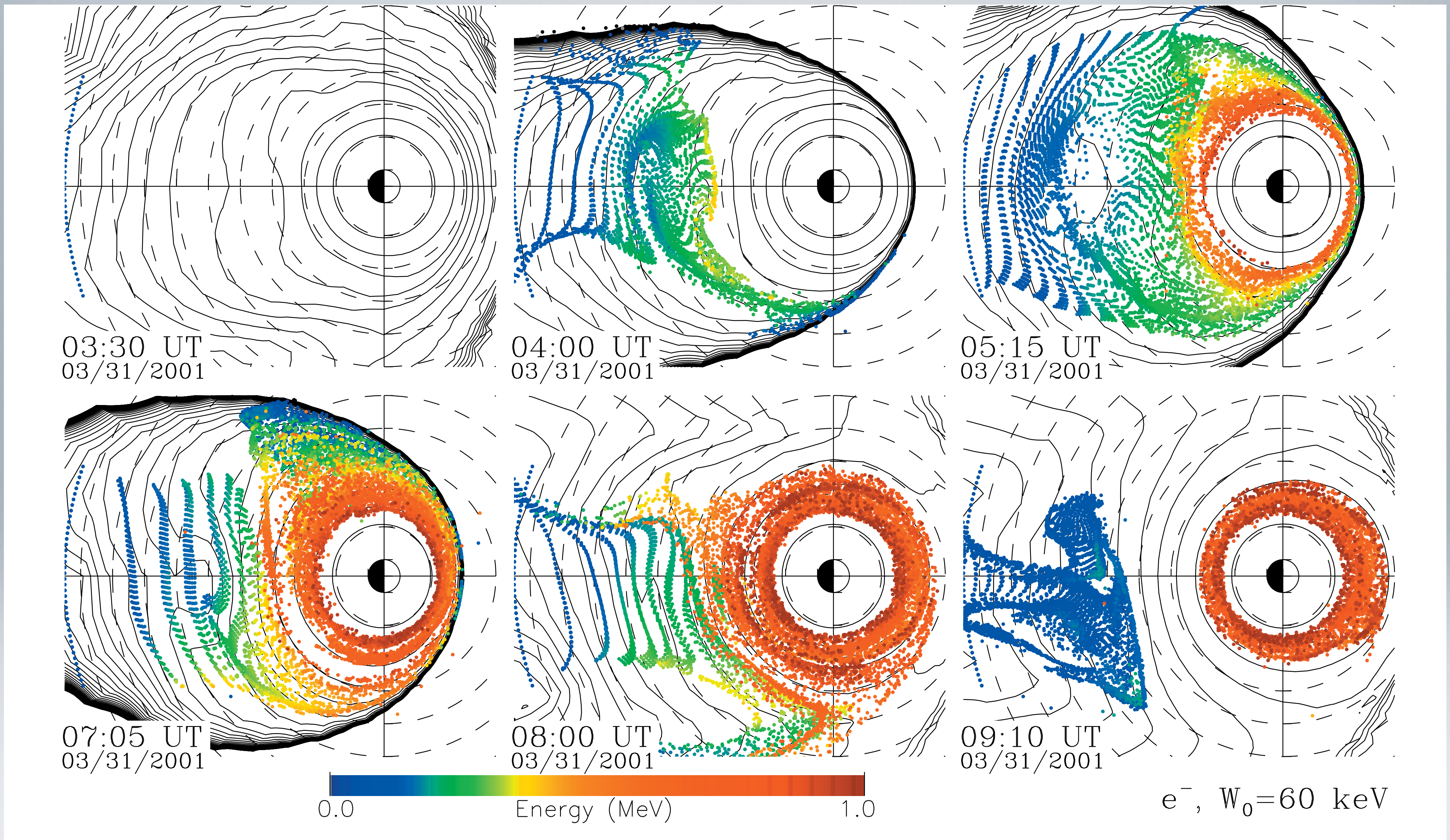
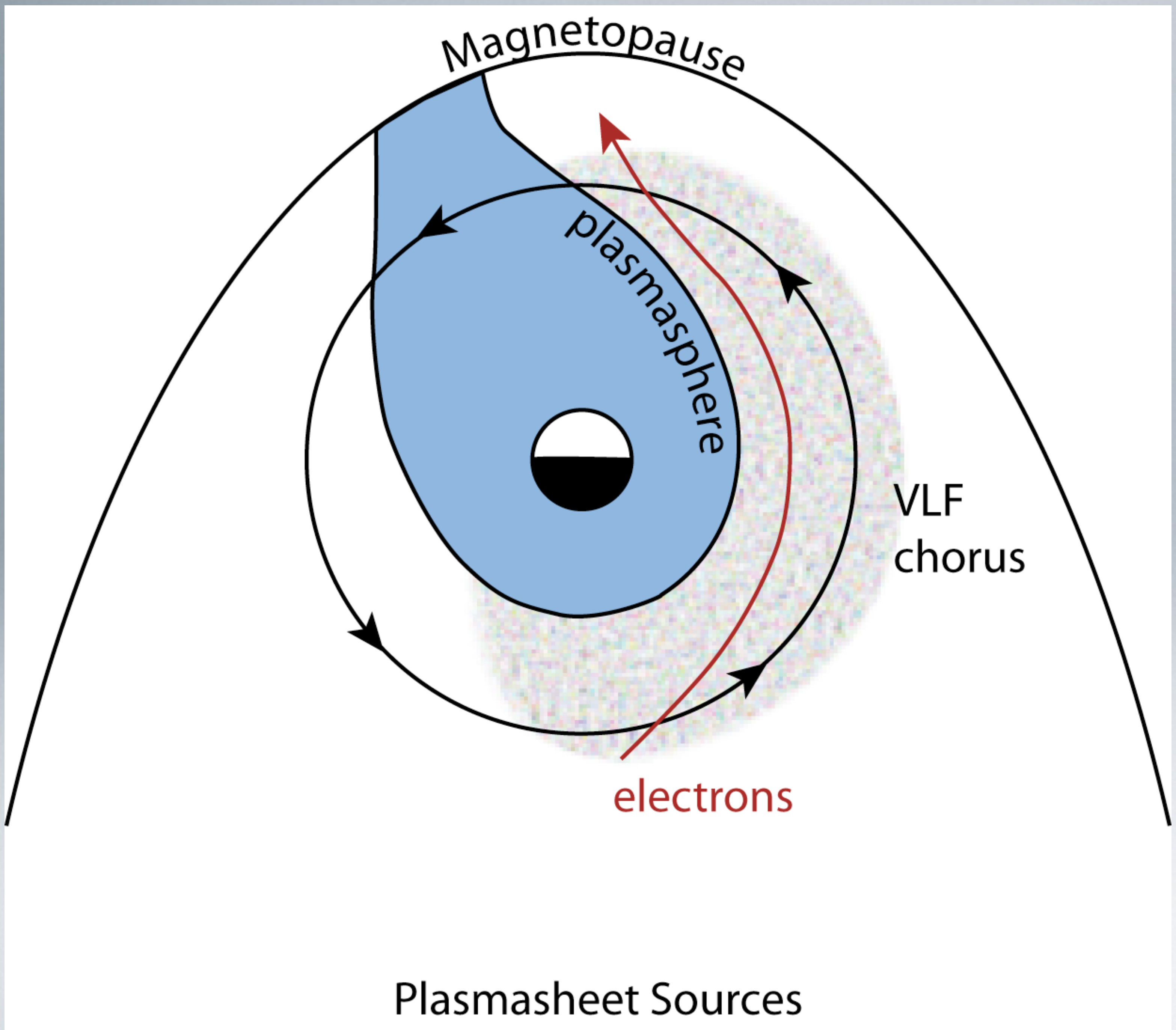


Plate 2. keV electrons in the plasmasheet may be convectively injected into the inner magnetosphere, gaining energy through conservation of the first invariant in the process [*Elkington et al.*, 2004]. The plasmasheet population acts as a boundary condition on the trapped particles undergoing diffusion in the inner magnetosphere.

Elkington et al., JGR, 2003, 2004
Degeling et al., Adv. Space Res., 2006

New Theory: Wave-Particle Interactions



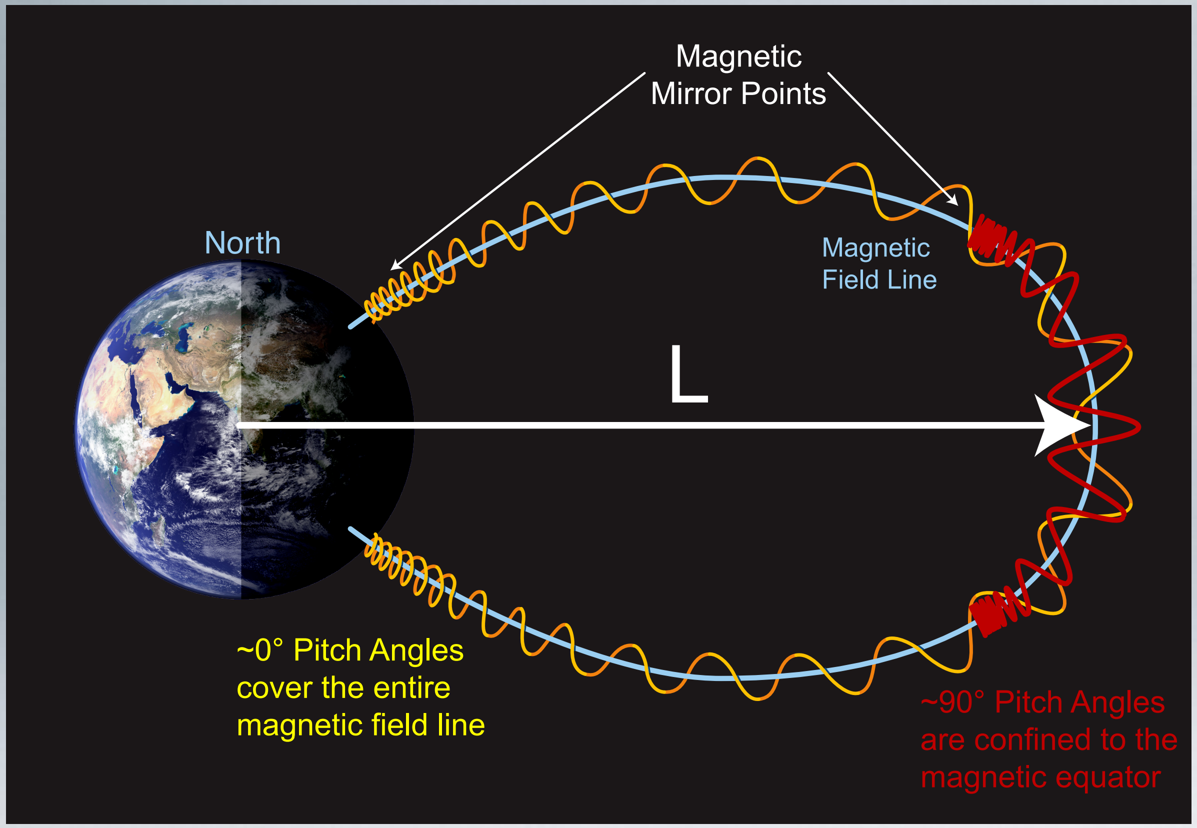
VLF Chorus is produced by injected hot electrons.

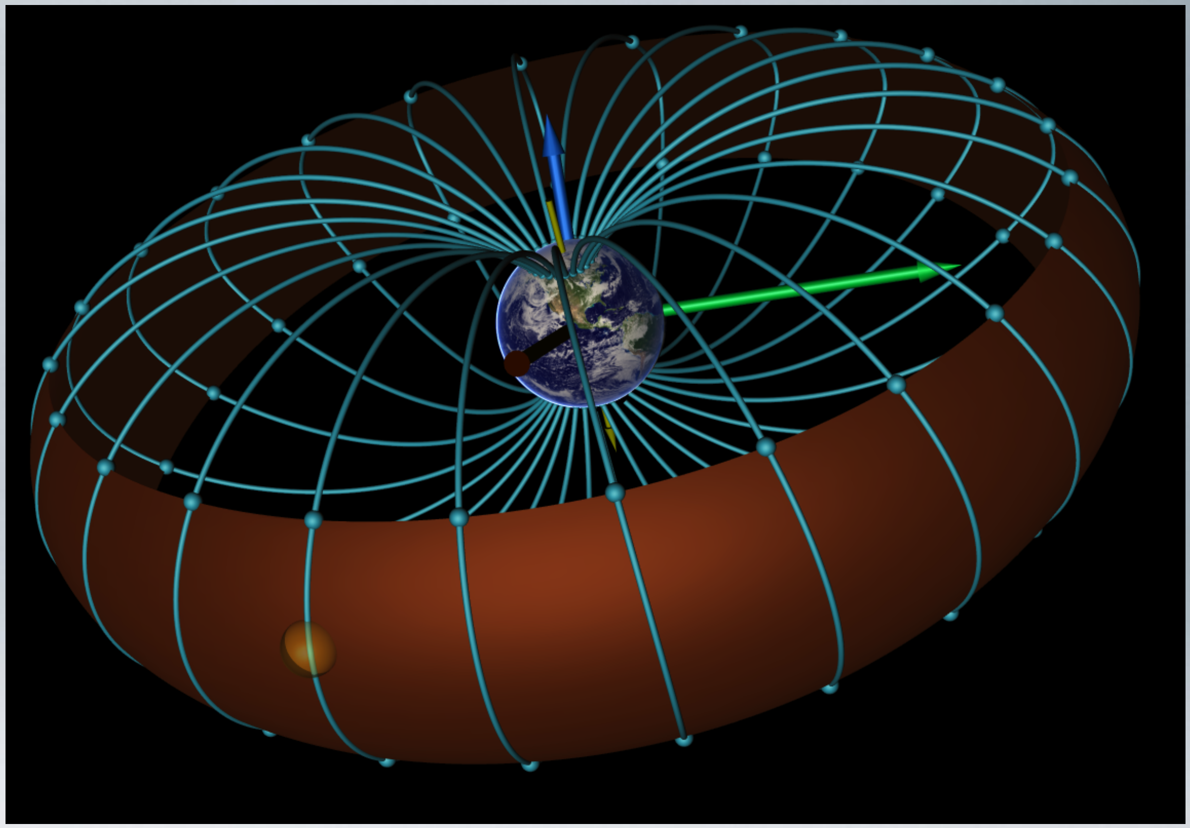
Doppler-shifted cyclotron resonance can produce both pitch angle diffusion (losses) and energy diffusion (acceleration).

We know that radial diffusion is important but determining whether wave-particle interactions are also important was a major challenge

Reeves, Space Weather, 2009 (after Summers et al., JGR, 1998)

Electron motion in the Earth's magnetic field

A


B


Electrons "gyrate" around the magnetic field
They "bounce" along the field line between magnetic mirror points
They "drift" around the Earth on a drift shell

A critical consideration is that the magnetic field is constantly changing

Flux & Phase Space Density

Flux is the number of particles passing through a given area in a given time.

particles/cm^2/s or particles/cm^2/s/sr or particles/cm^2/s/sr/keV

Flux is not a conserved quantity

Phase space density (PSD) is conserved as a particle moves provided the motion is adiabatic (reversible)

PSD (f) equals flux (j) divided by the momentum squared

$$\boxed{f = \frac{j}{p^2}}$$

Magnetic Adiabatic Invariants

Each periodic motion of an electron in the geomagnetic field has an adiabatic invariant. If all three invariants are conserved then PSD is conserved

$$\mu = \frac{p_\perp^2}{2m_0 B}$$

- The first invariant is defined by gyration

$$J = \oint p_{||} ds$$

- The second invariant, J (or K) is defined by bounce

$$\Phi = \oint A_\phi \, dl$$

$$L^* = \frac{2\pi k_o}{\Phi R_E}$$

- The third invariant, Phi (or L*) is defined by drift

To first order, non-conservation of the invariants can be described by Fokker-Planck Diffusion

$$\boxed{f = \frac{j}{p^2}}$$

$$\frac{\partial f}{\partial t} = L^2 \frac{\partial}{\partial L}\left(D_{LL} L^{-2} \frac{\partial f}{\partial L} \right) + \frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2 \left\langle D_{pp}(y,p) \right\rangle \frac{\partial f}{\partial p} \right) + \frac{1}{T(y)y}\frac{\partial}{\partial y}\left(T(y)y \left\langle D_{yy}(y,p) \right\rangle \frac{\partial f}{\partial y} \right) - \frac{f}{\tau}$$

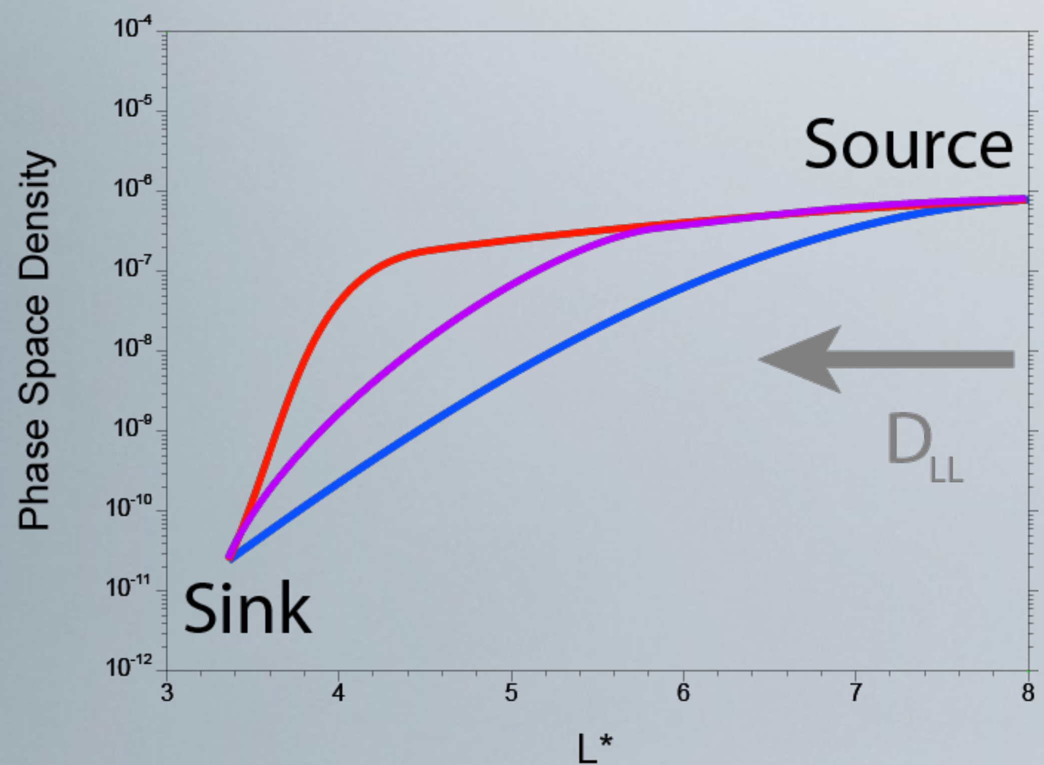
Radial (L)

Momentum
or Energy

Pitch Angle
y = sin(α)

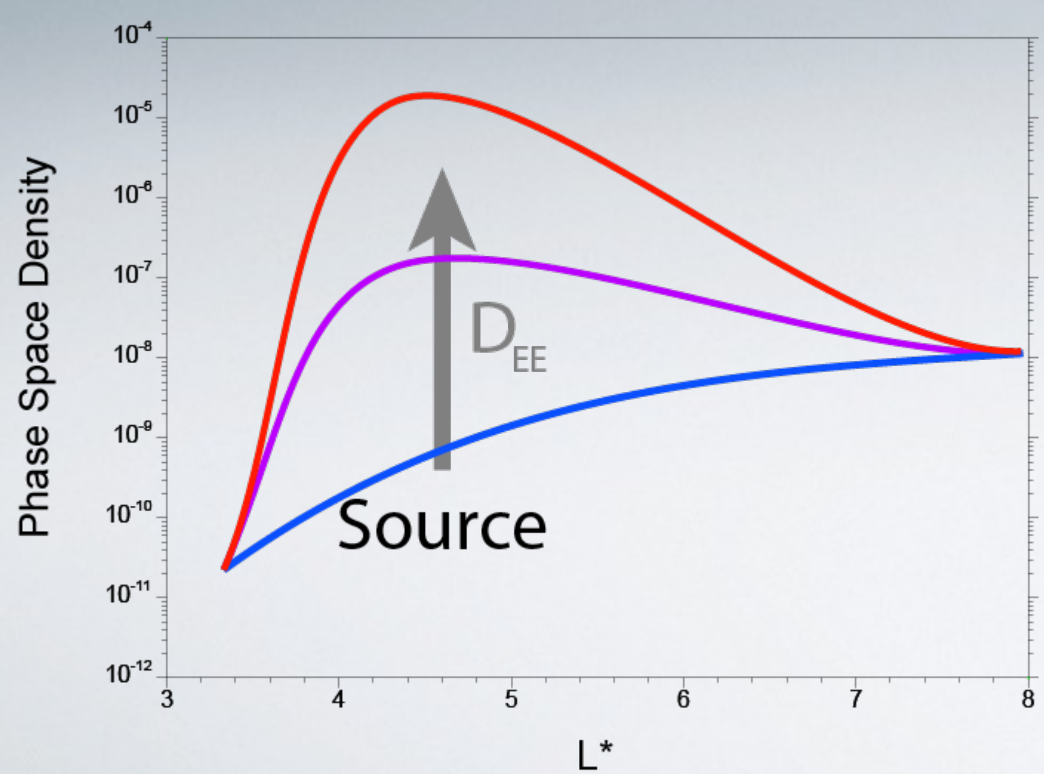
these two are linked

Competing Acceleration Theories



Radial / Diffusive Acceleration

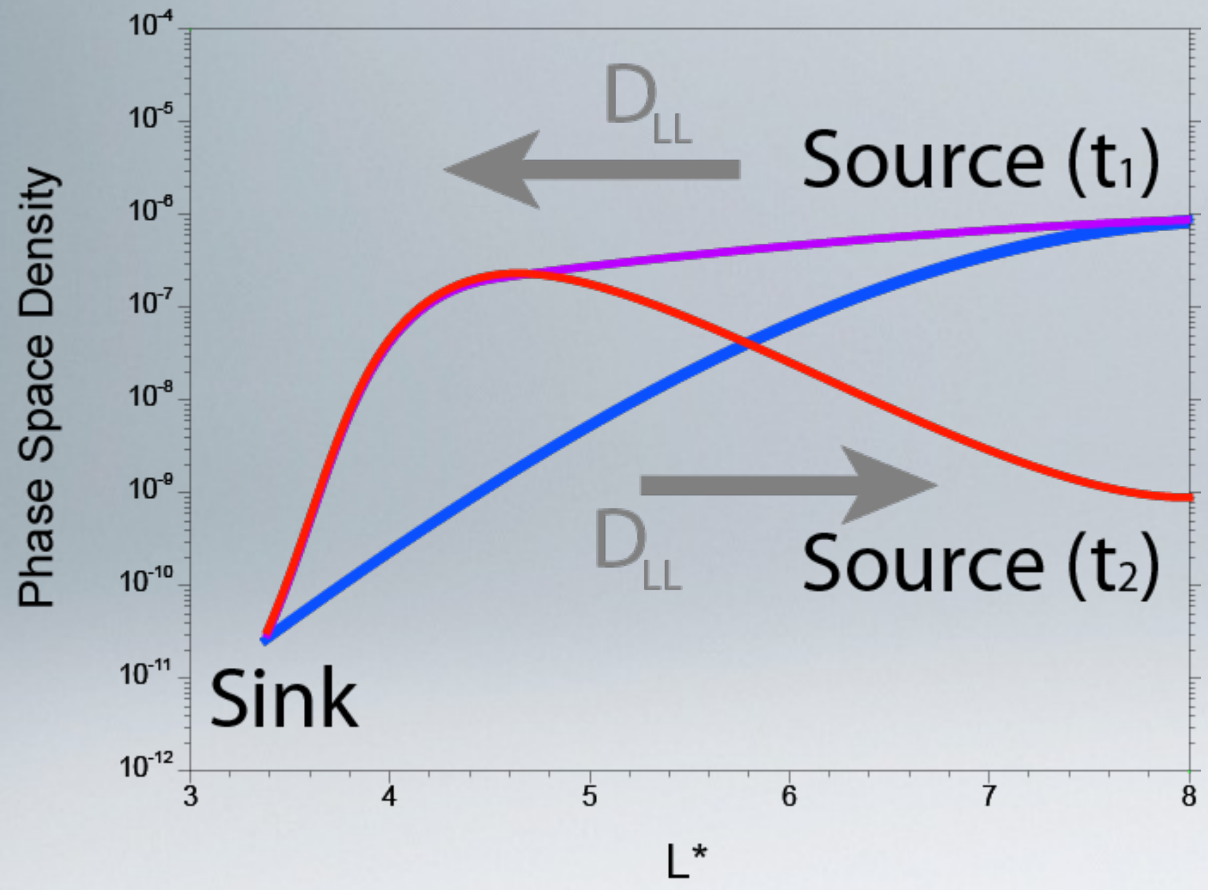
- The source of electrons is the magnetotail at high L-shells
- Electrons are betatron accelerated to relativistic energies
- Transport is the essential feature



Local Wave-Particle Interactions

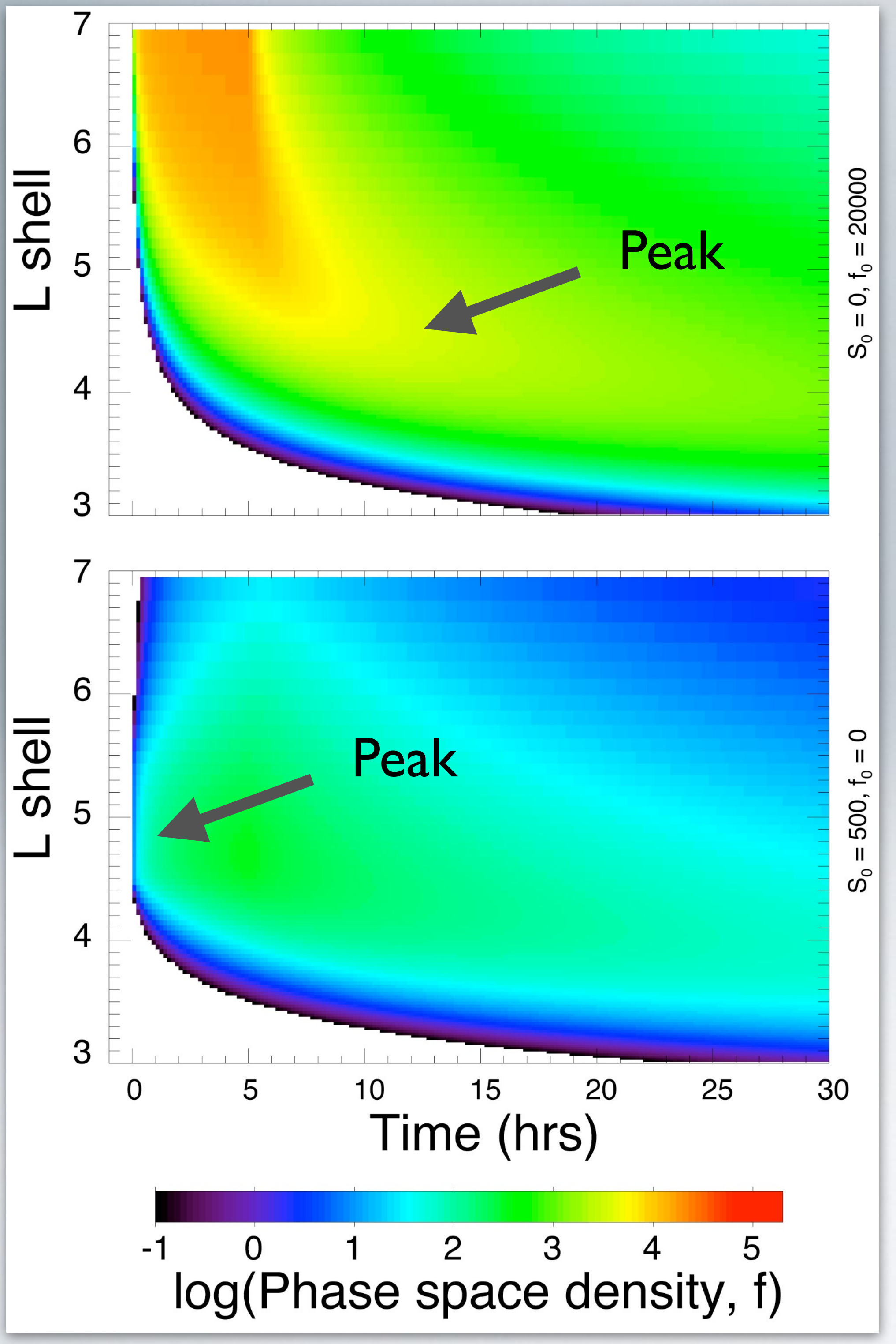
- Wave-particle resonances accelerate electrons to relativistic energies
- Characteristic signatures are growing radial peaks in phase space density
- Changes happen locally without significant radial transport

Temporal Variations complicate



- Radial diffusion smooths out gradients
- It can go both directions
- If the source of particles is time-varying then radial peaks in PSD can form from radial diffusion only

There are models that show how both work



Selesnick et al., JGR, 1998

Radial / Diffusive Acceleration

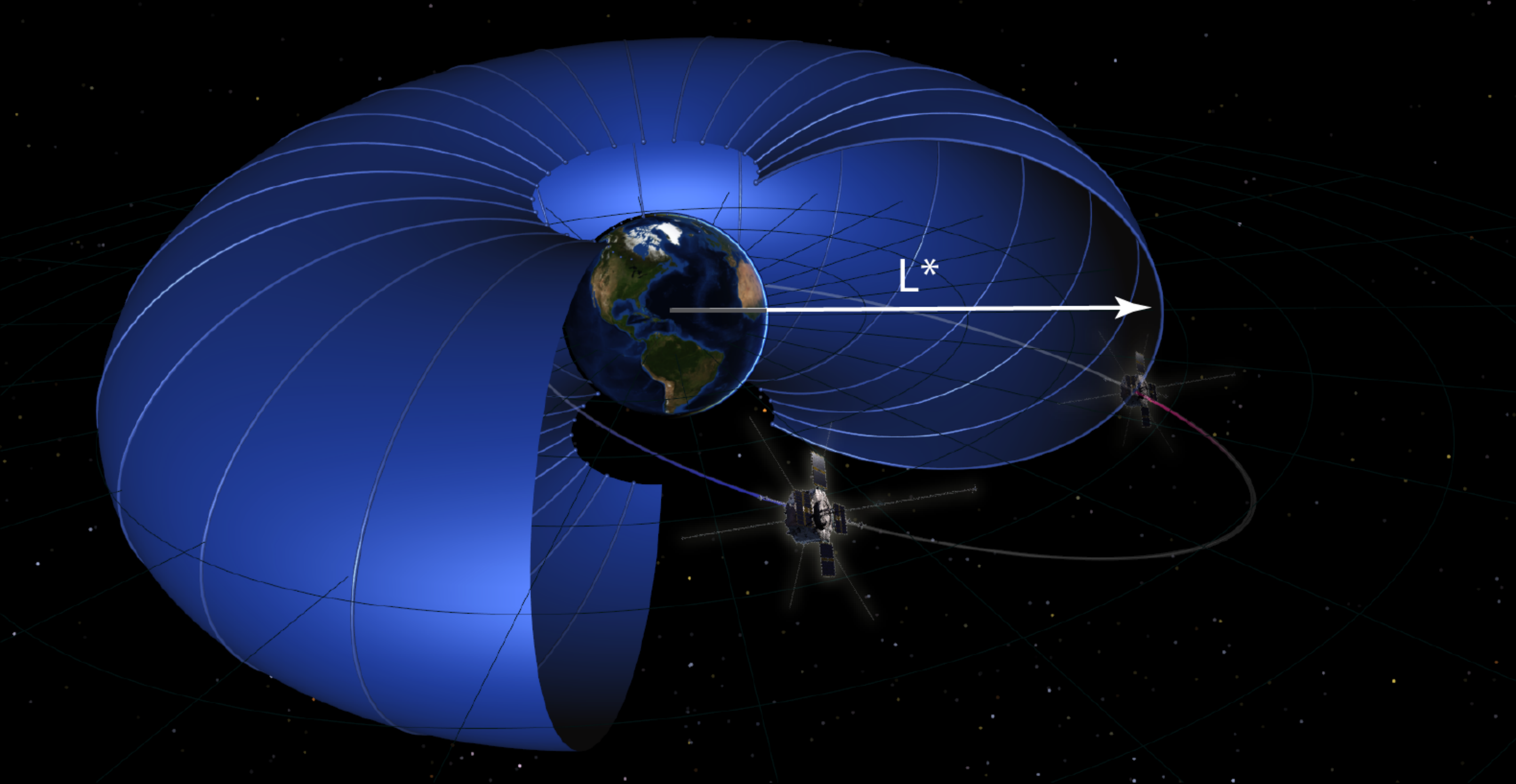
- A source at high L diffuses inward
- If that source shuts off the "hole" also diffuses inward
- Radial gradients change in time

Local Wave-Particle Interactions

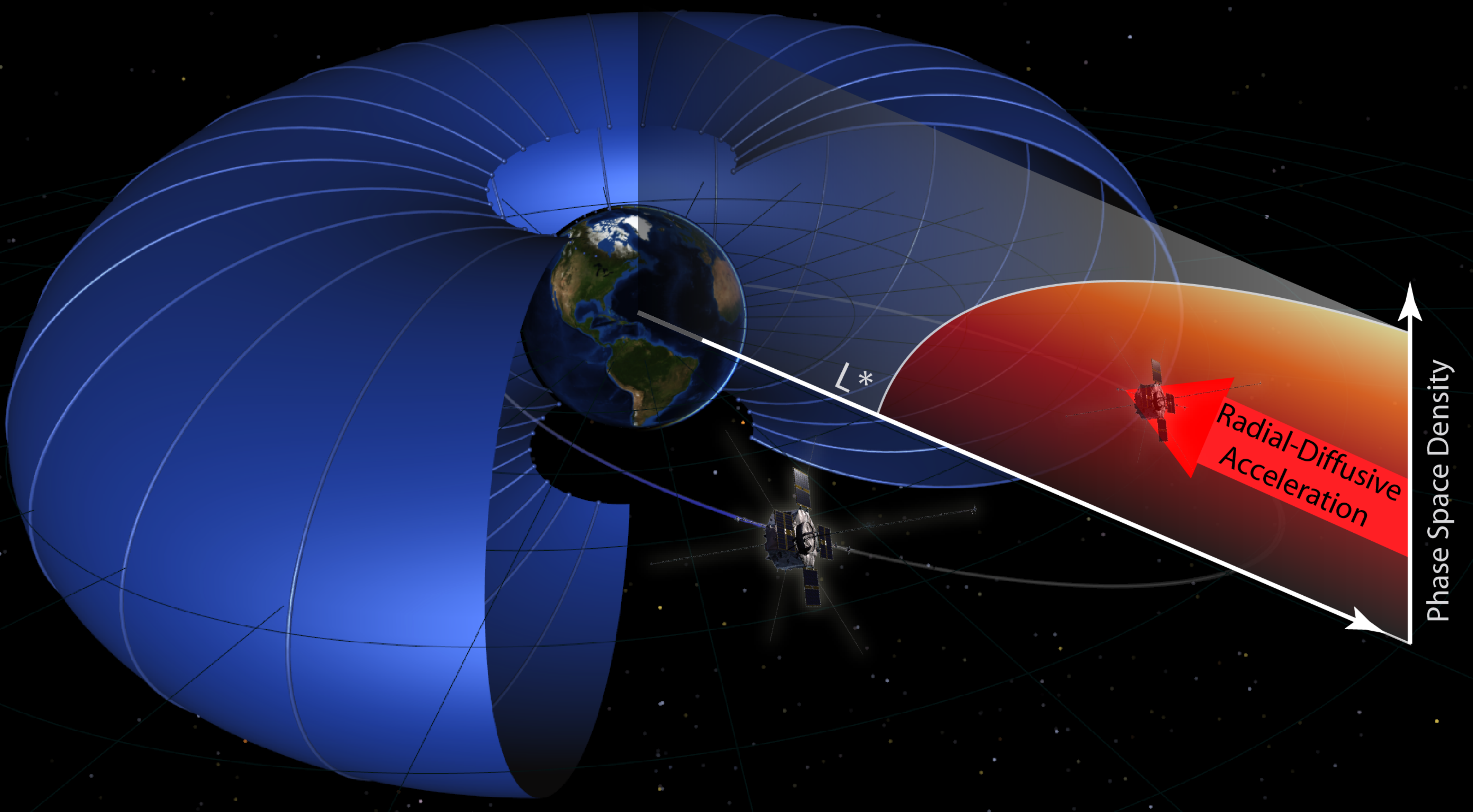
- Electrons are accelerated locally while waves are present
- Even the initial distribution has a radial peak
- Radial diffusion is both outward and inward

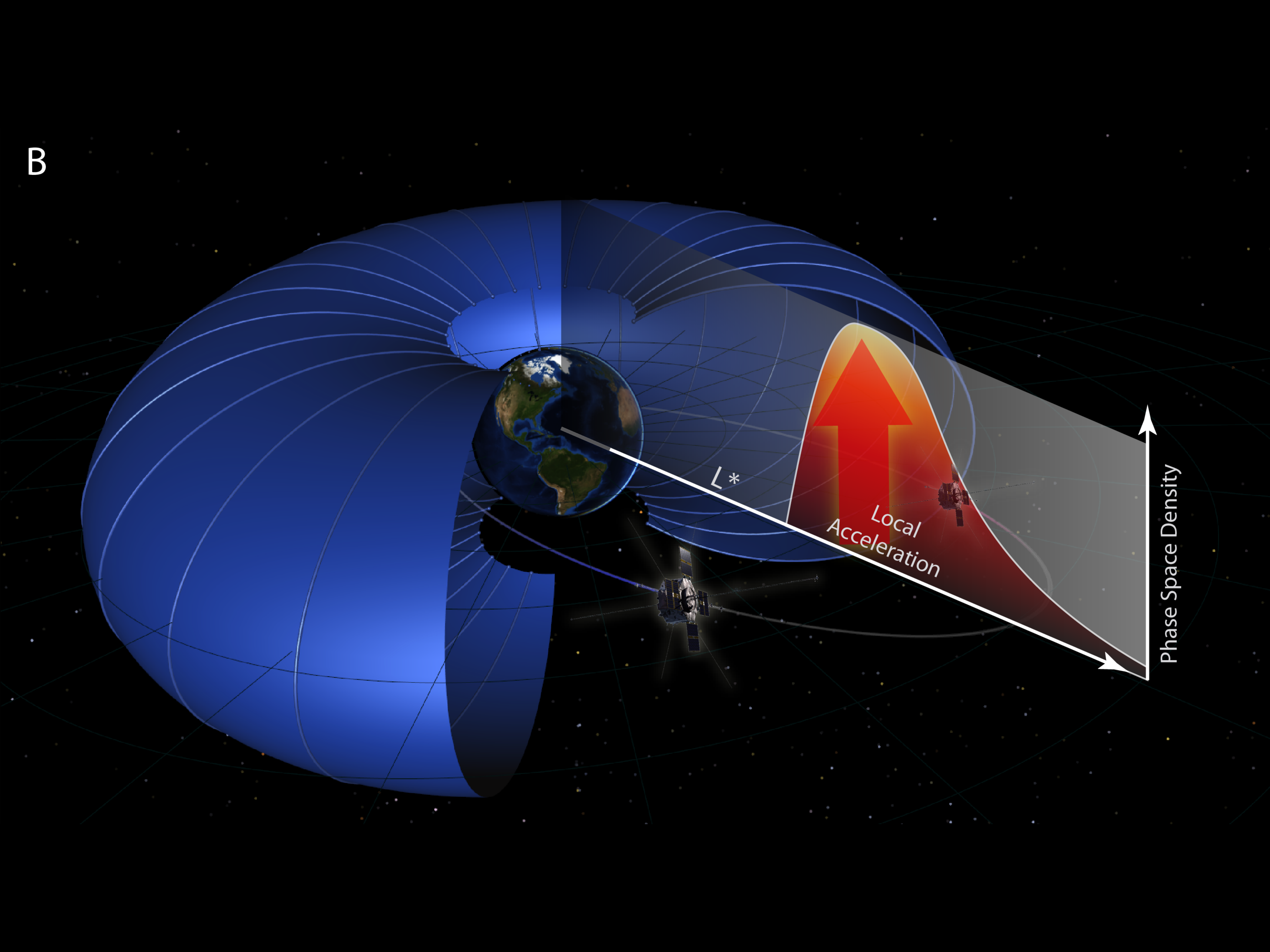
Missions like CRRES or POLAR could not resolve these time scales

Dual-Satellite, GTO, 9 hr orbit

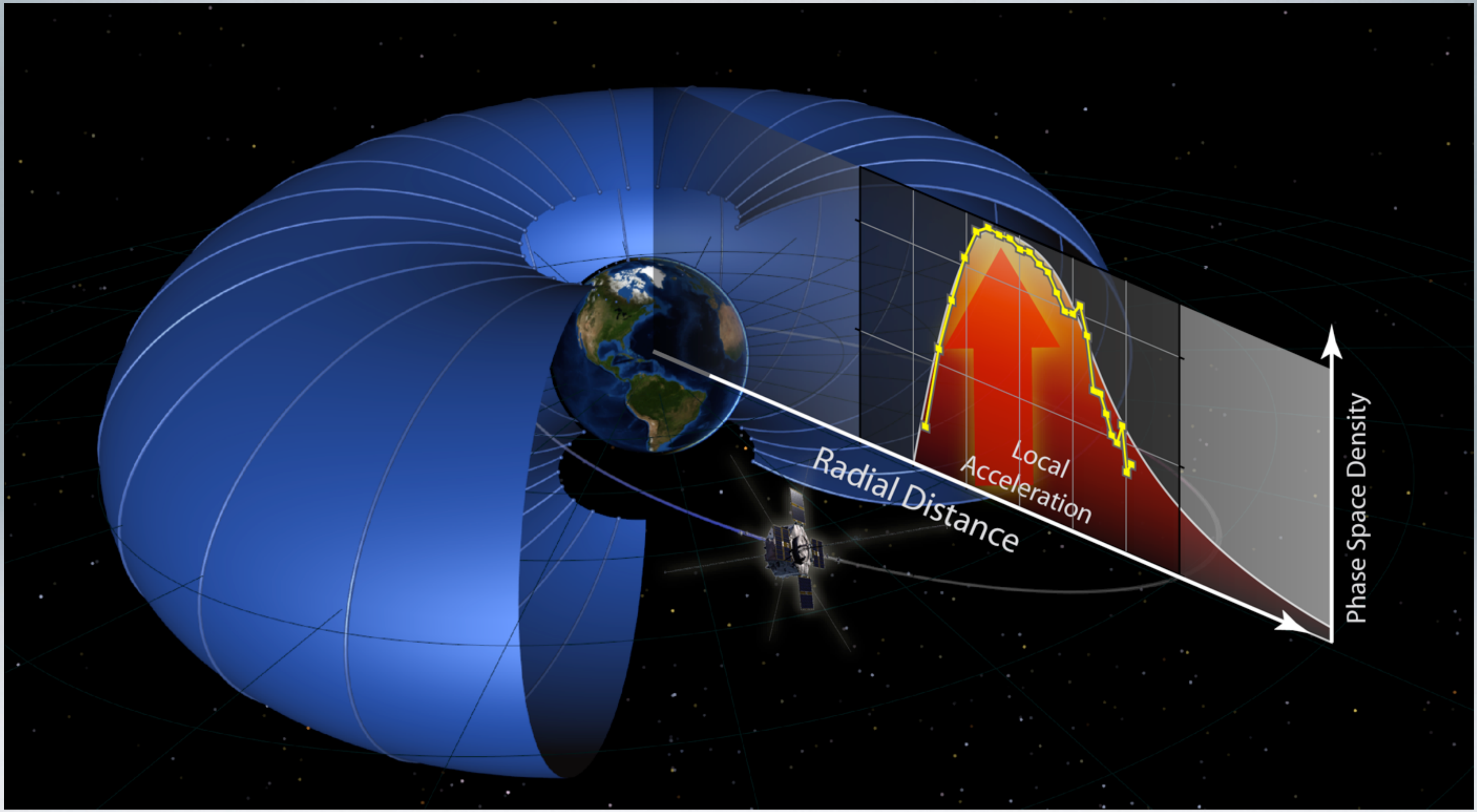


A



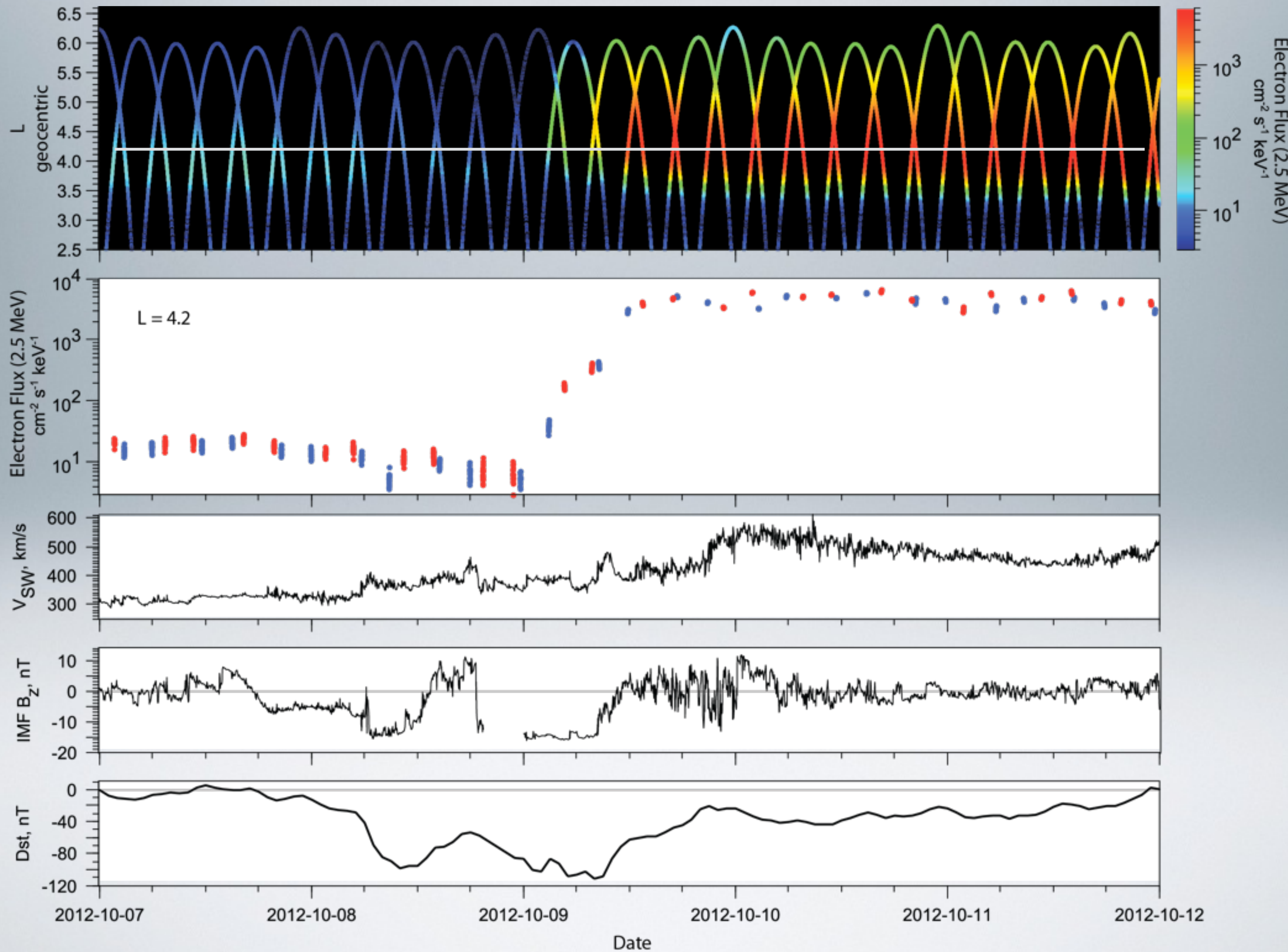

B
L*
Local
Acceleration
Phase Space Density

Schematic & Observed PSD

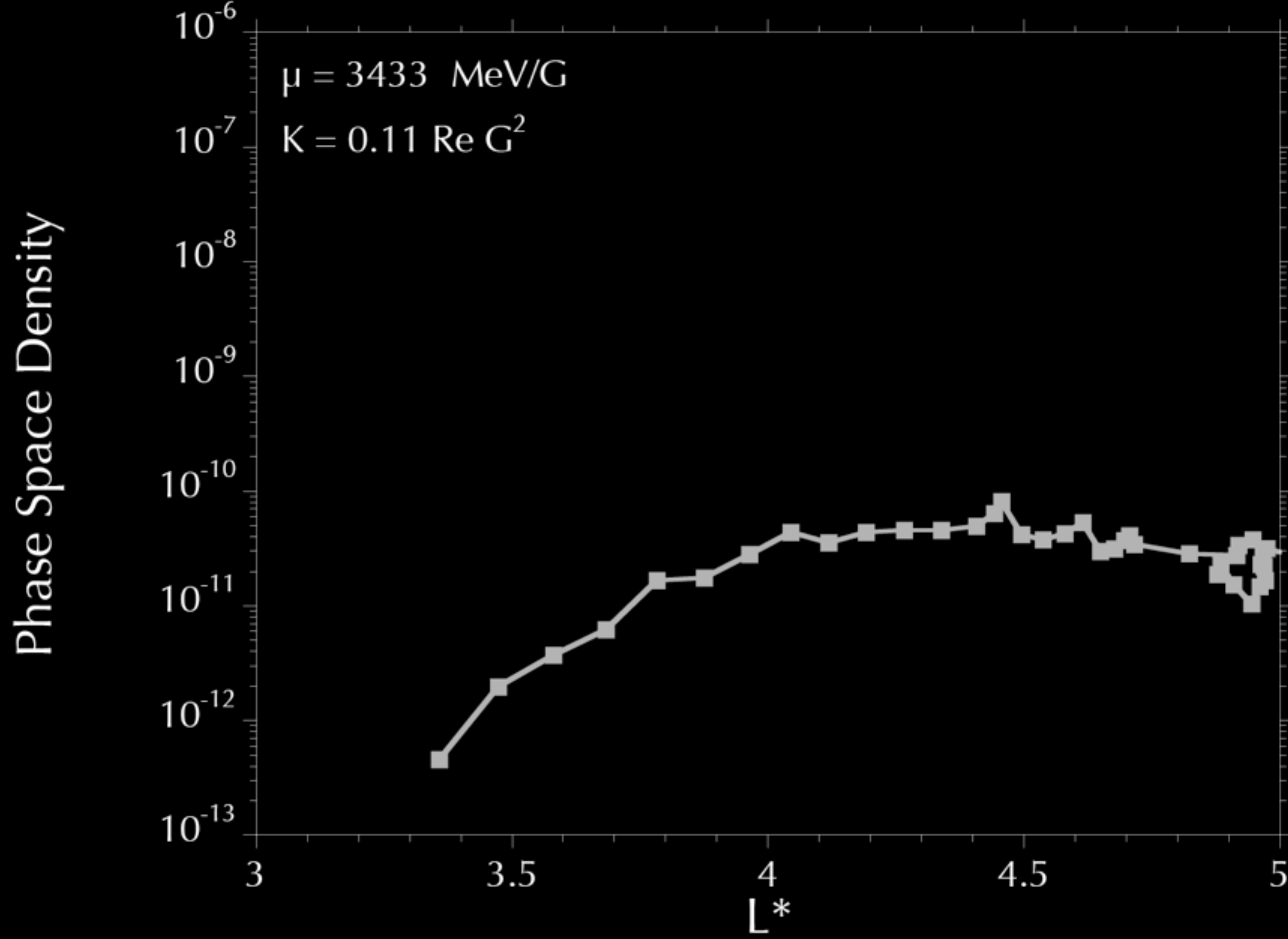


Reeves et al., Science, 2013

October 2012 - MagEIS Electron Flux and Solar Wind



Oct 8
18:22



TS04 Model

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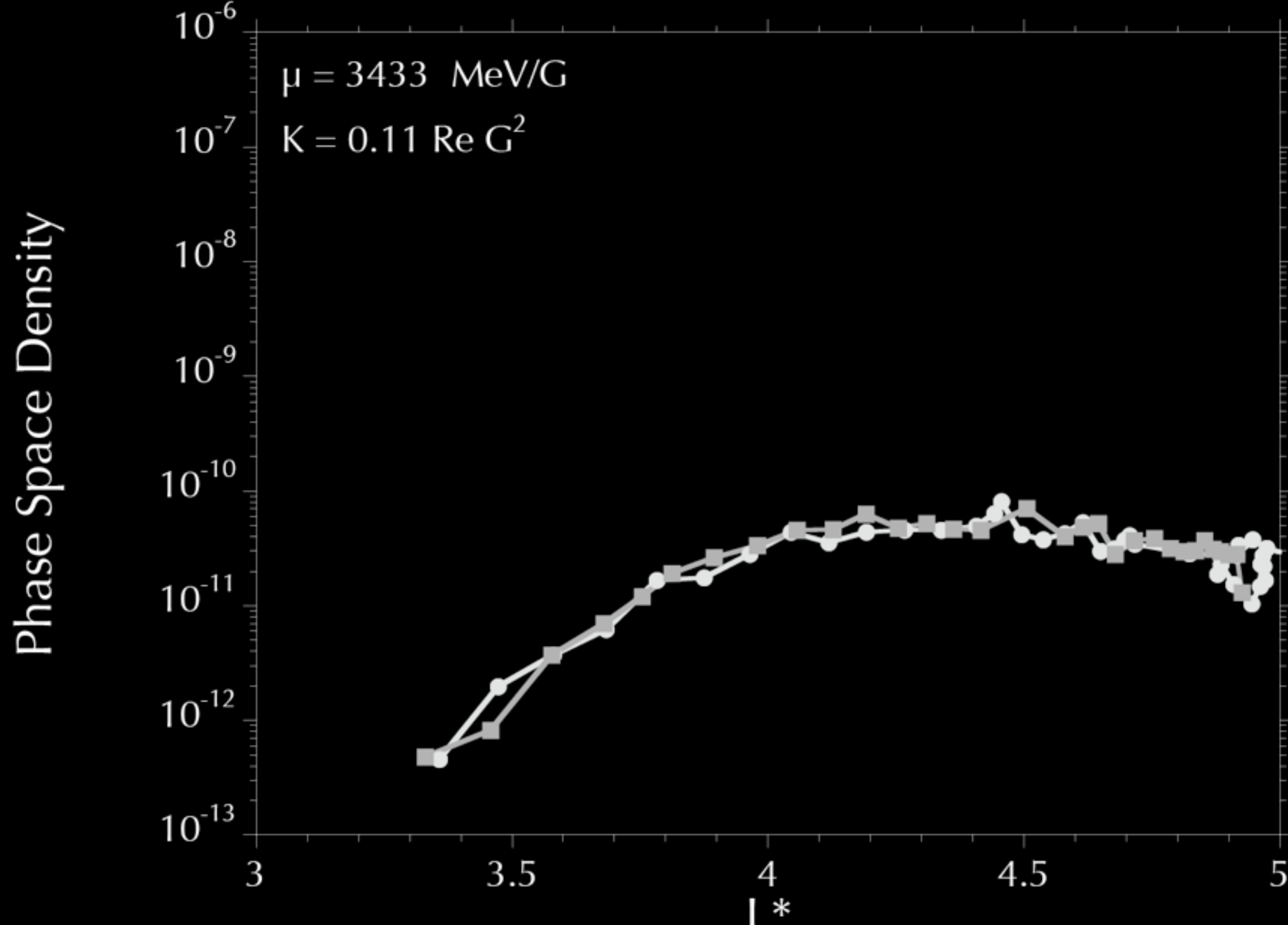

TS04 Model

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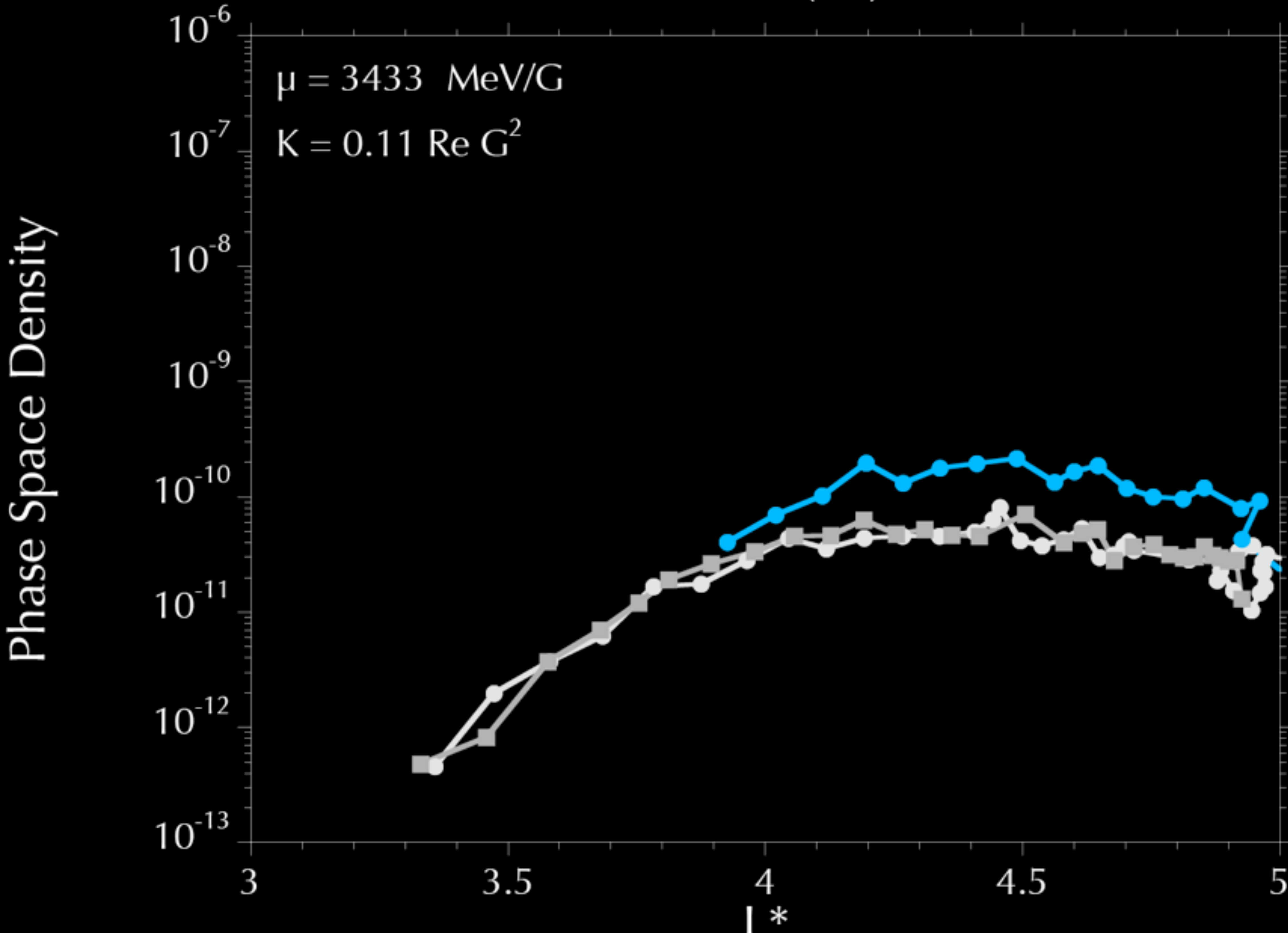

TS04 Model

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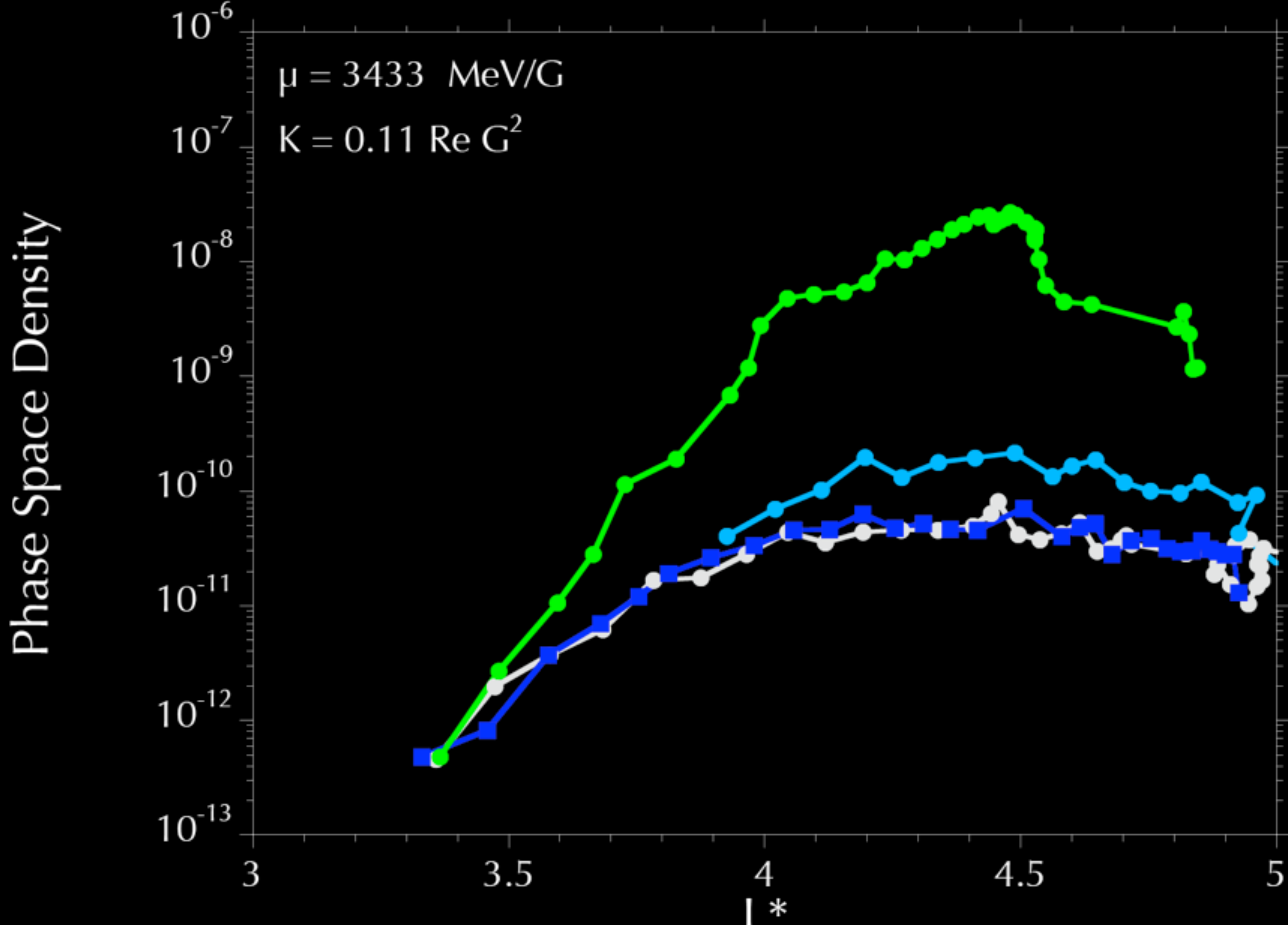
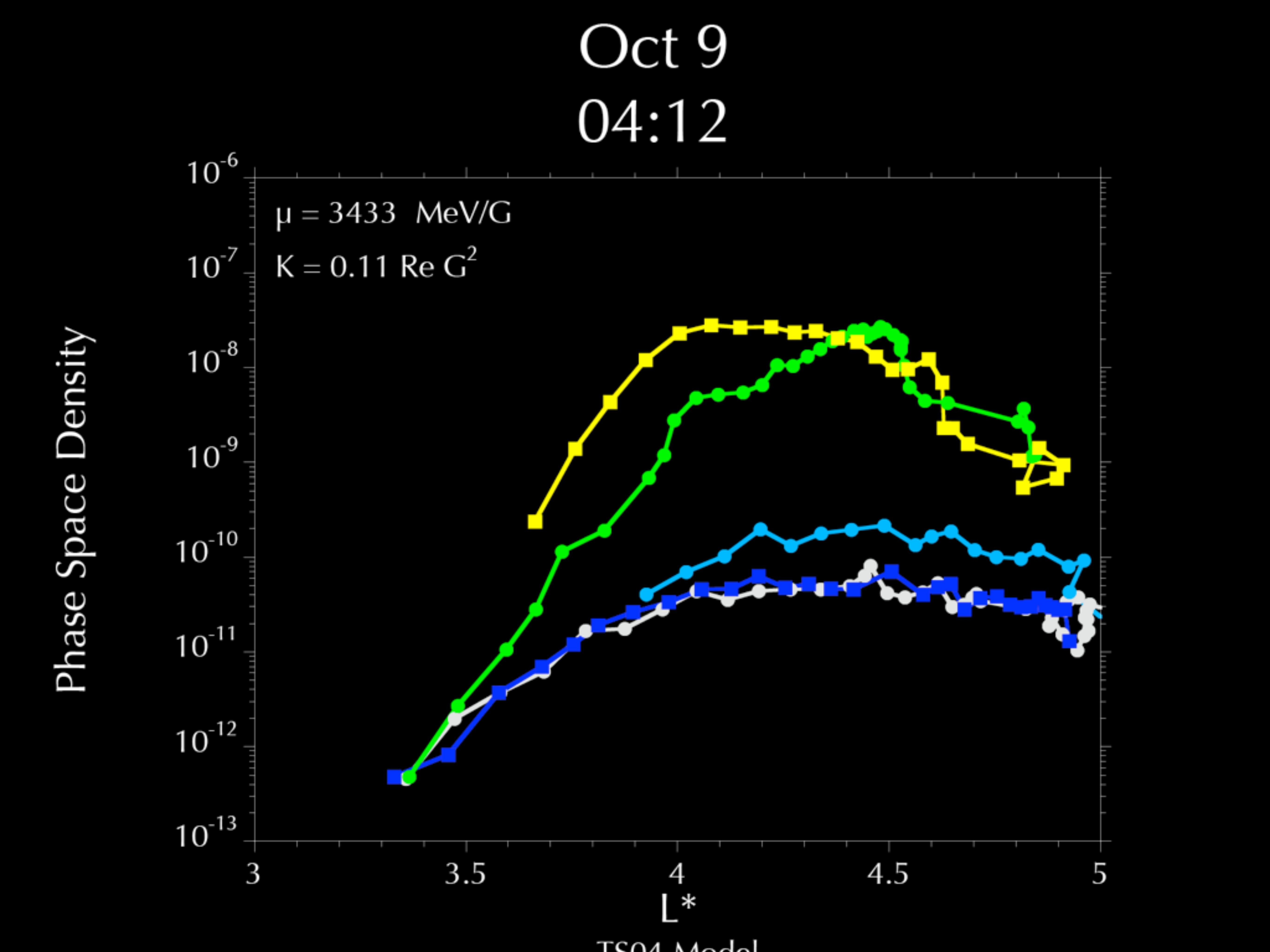
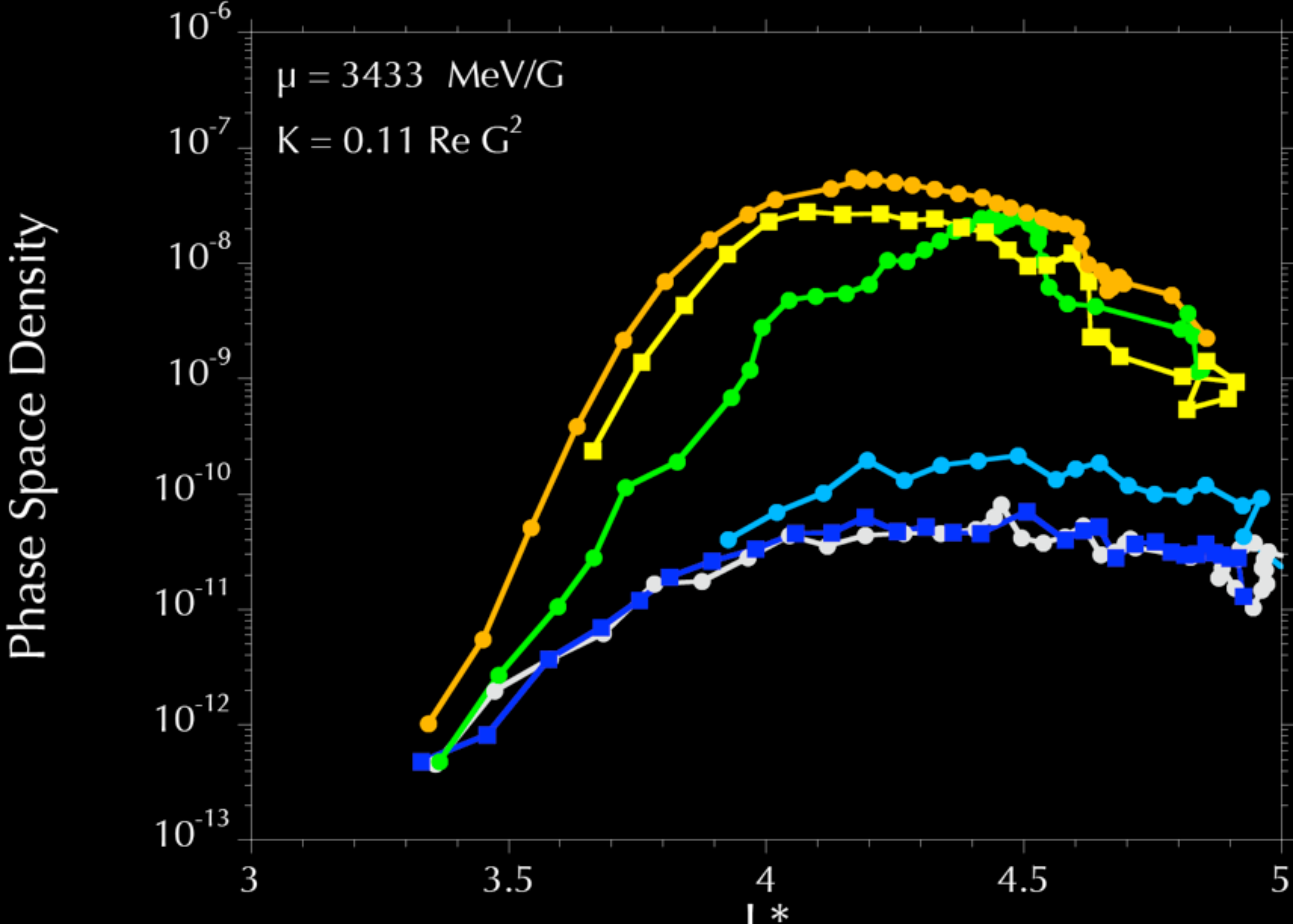


TS04 Model



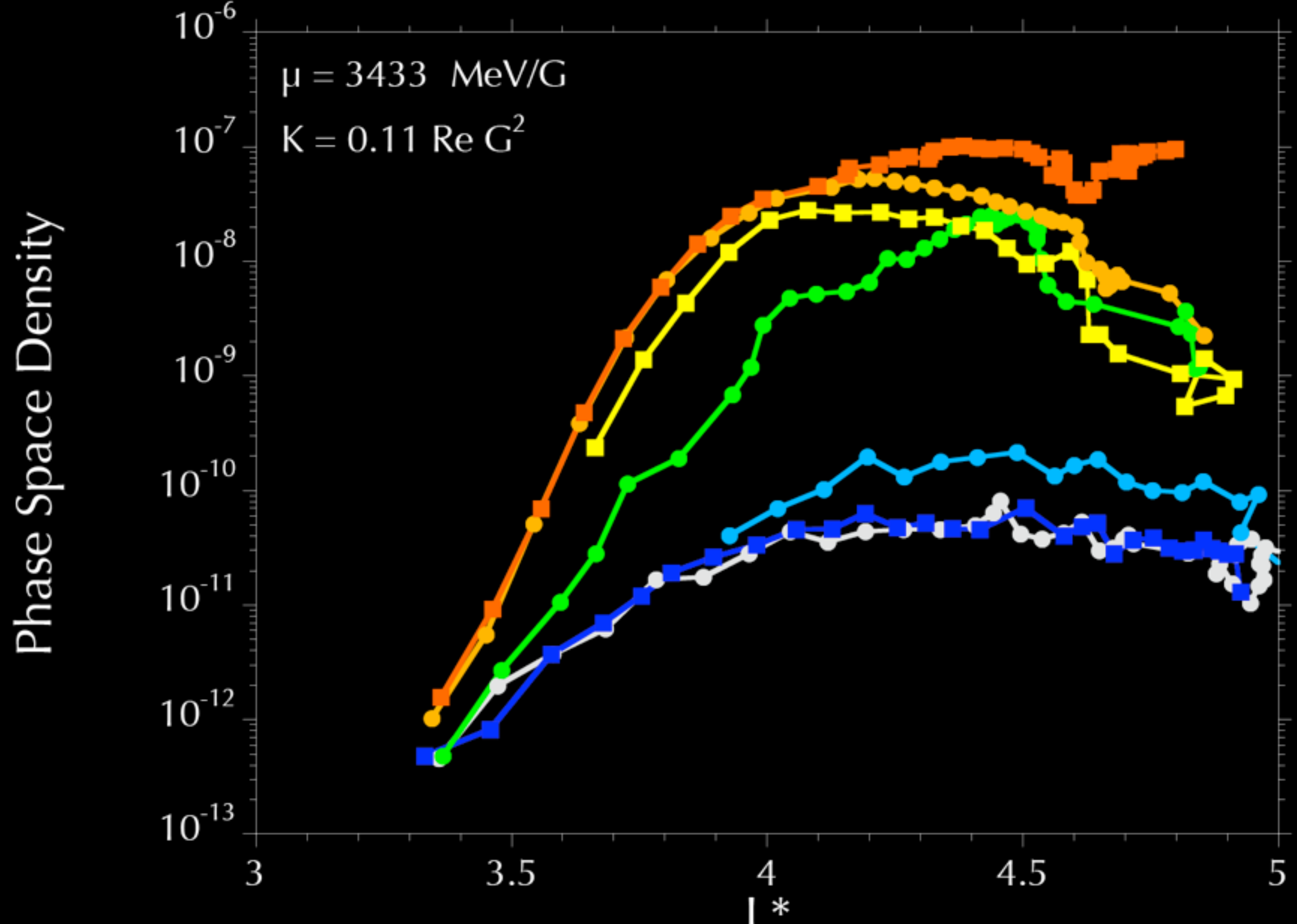
Oct 9
04:12
μ = 3433 MeV/G
K = 0.11 Re G²
Phase Space Density
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
10⁻¹¹
10⁻¹²
10⁻¹³
3
3.5
4
4.5
5
L*
TS04 Model

Oct 9
07:57



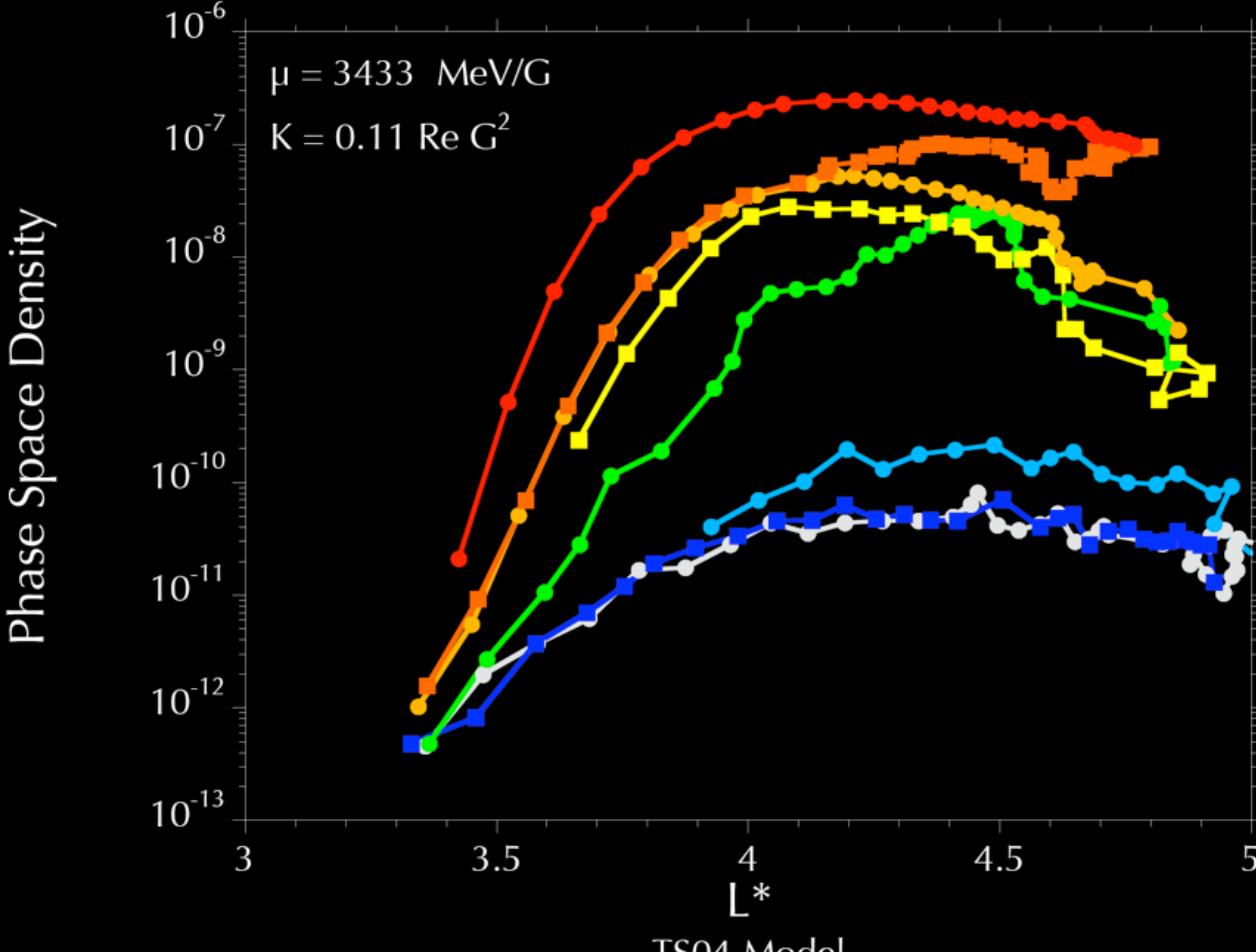
TS04 Model

Oct 9
08:22



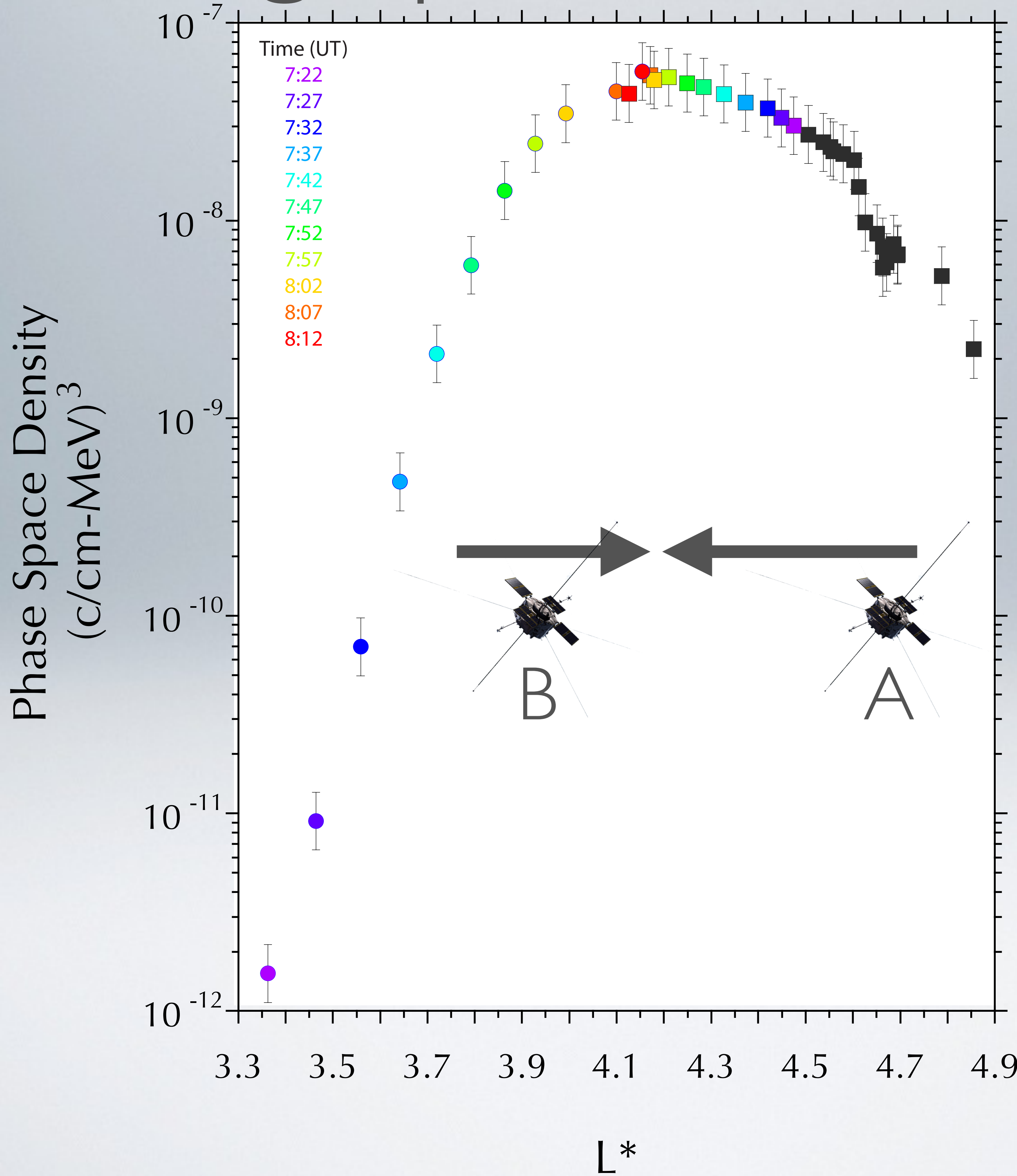
TS04 Model

Oct 9
13:02



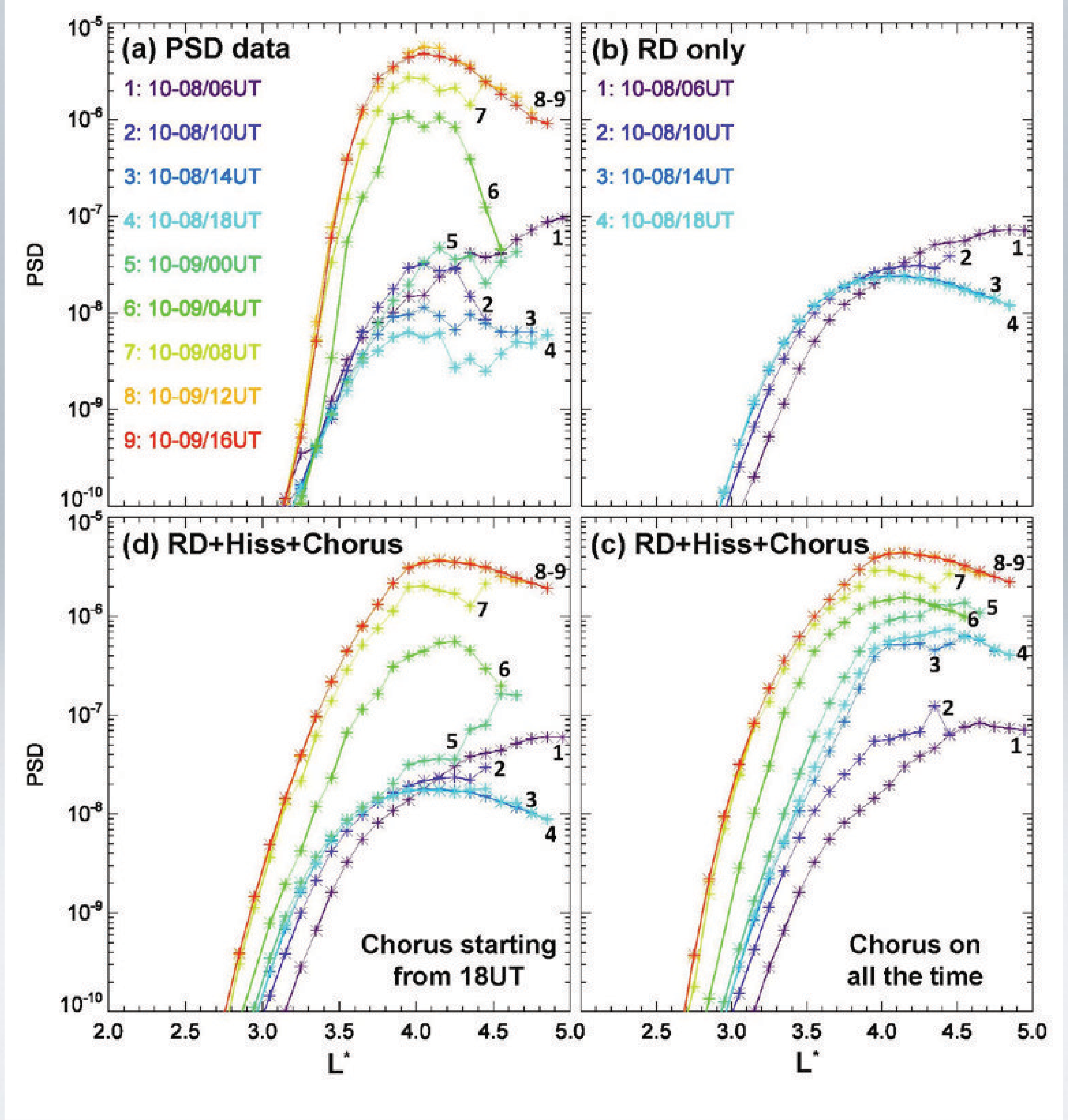
μ = 3433 MeV/G
K = 0.11 Re G^2
Phase Space Density
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
3
3.5
4
4.5
5
L*
TS04 Model

Resolving Space-Time Ambiguity



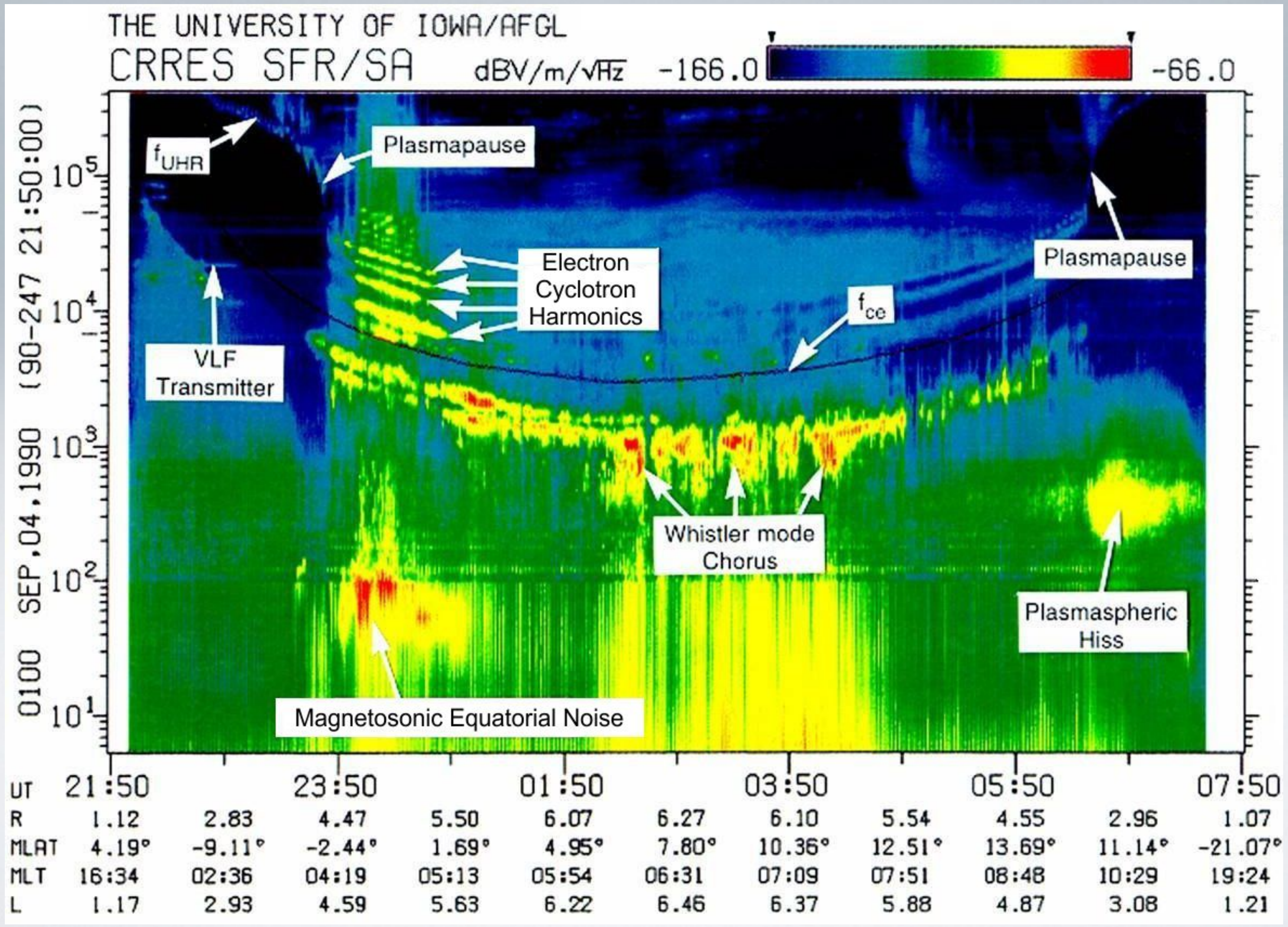
Reeves et al., Science, 2013

Simulations Confirm Physics

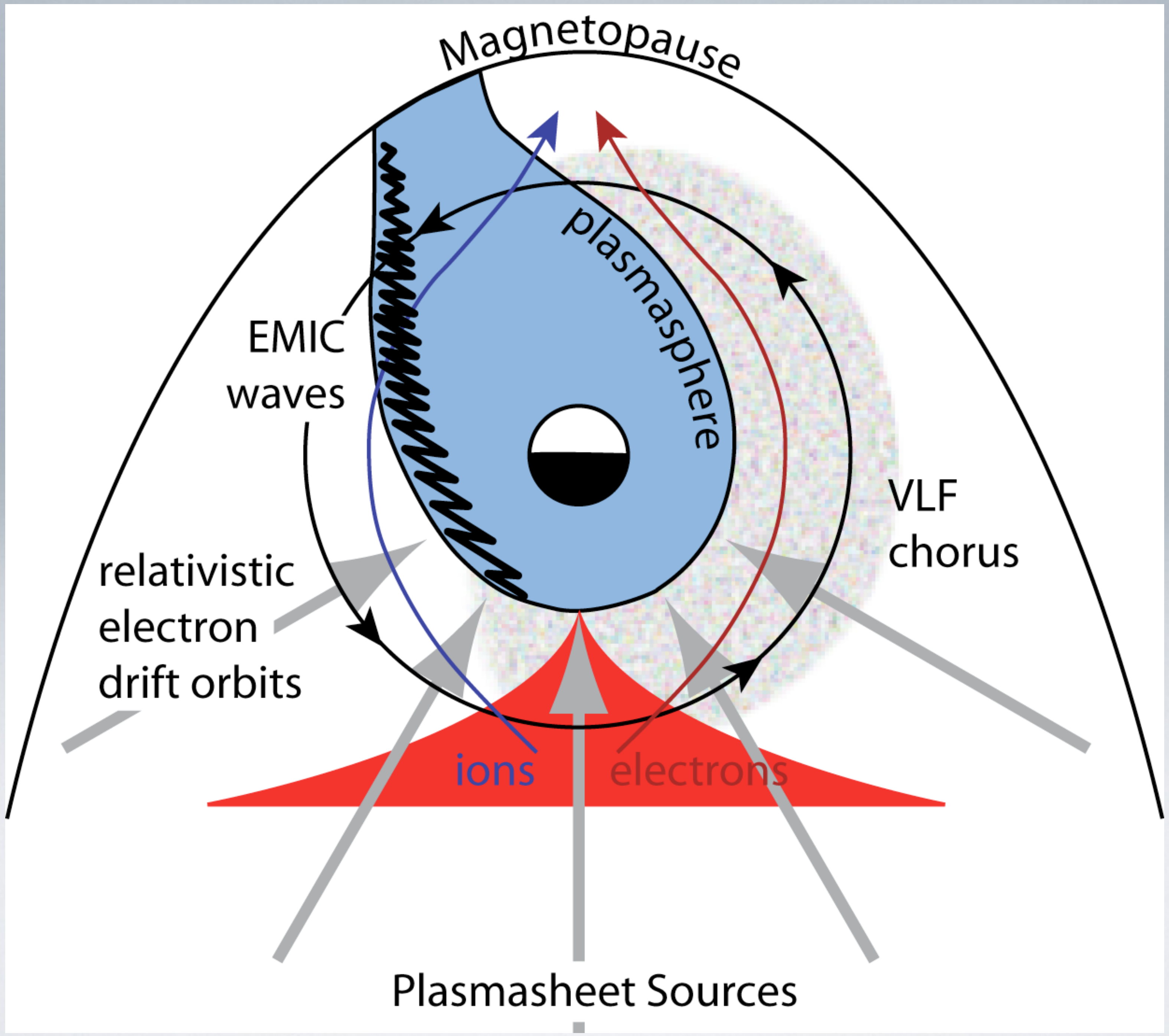


Weichao Tu et al., GRL, 2014

A Fundamental Change in our Understanding of Radiation Belt Physics is the Key Role of Waves

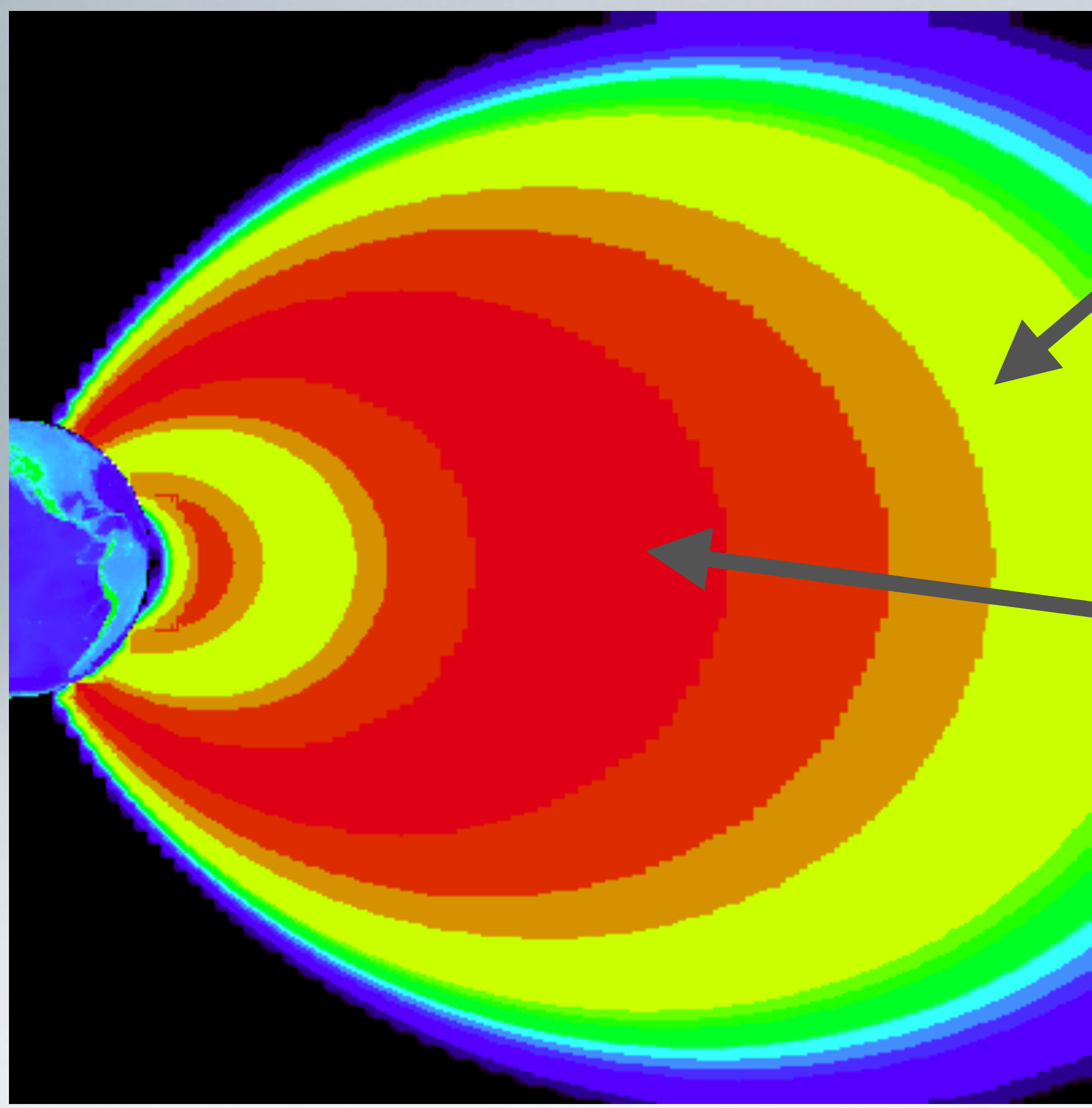


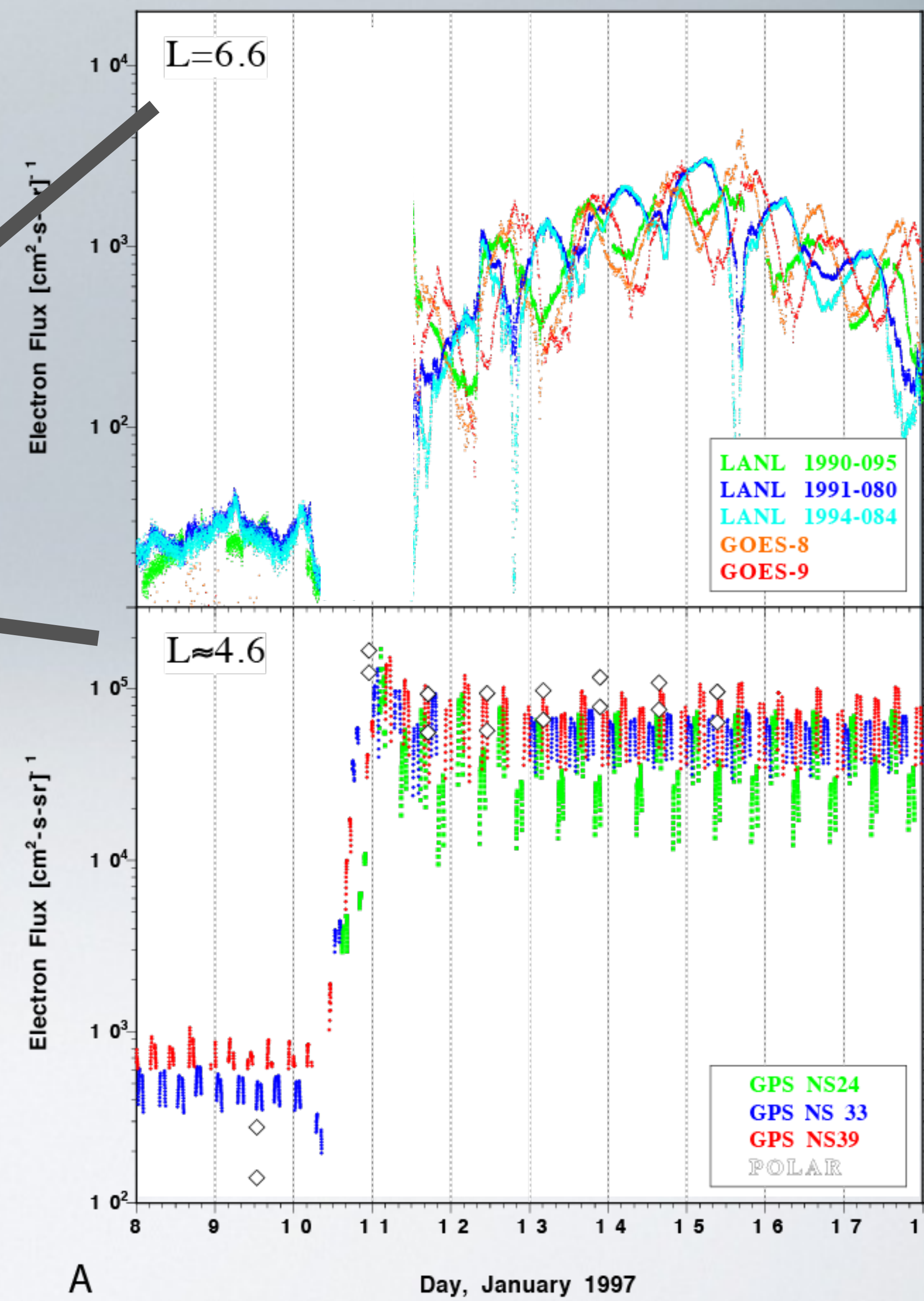
However No One Process Ever Acts in Isolation



Reeves, Space Weather, 2009 (after Summers et al., JGR, 1998)

Rapid internal acceleration events also didn't fit the classic picture

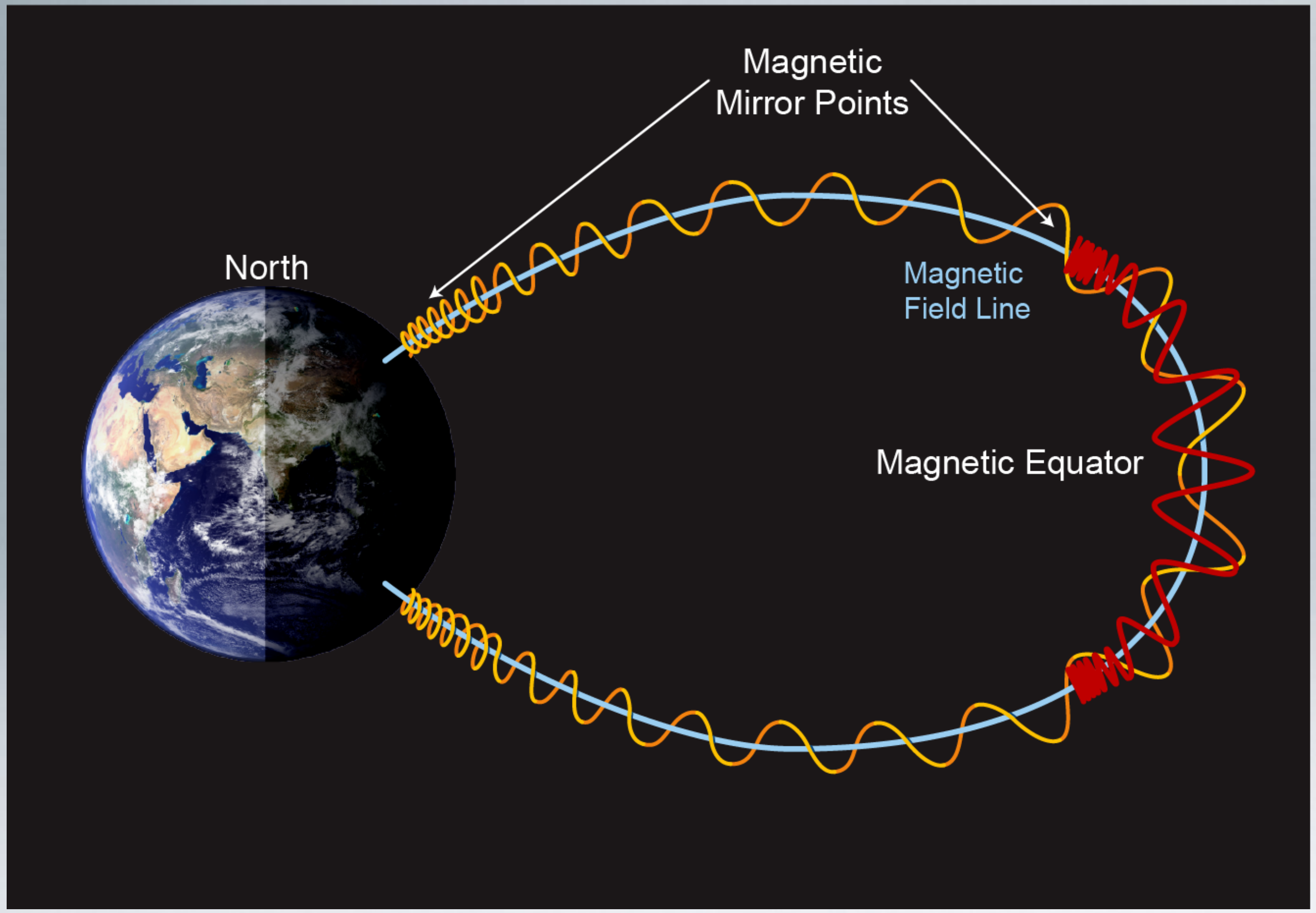


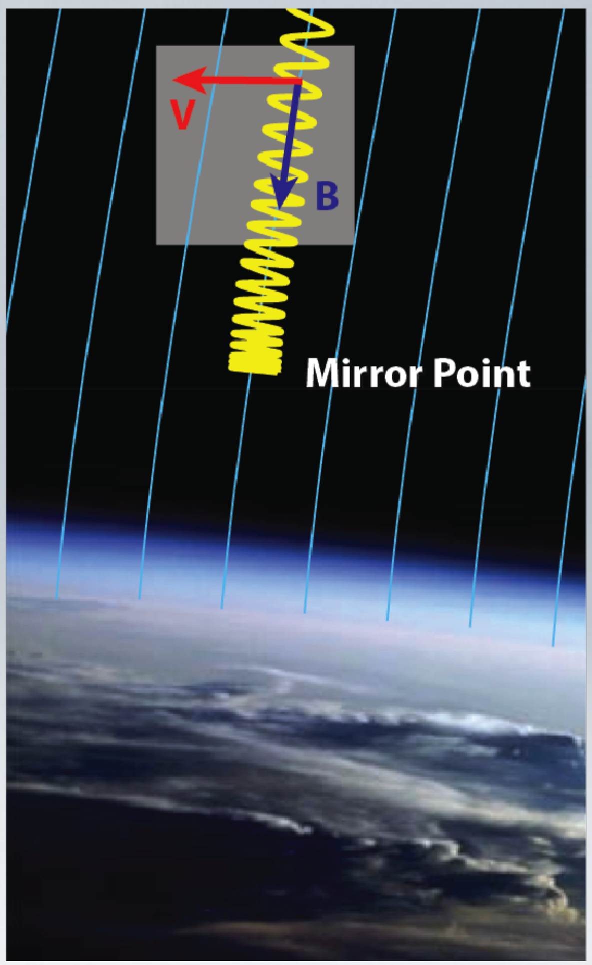


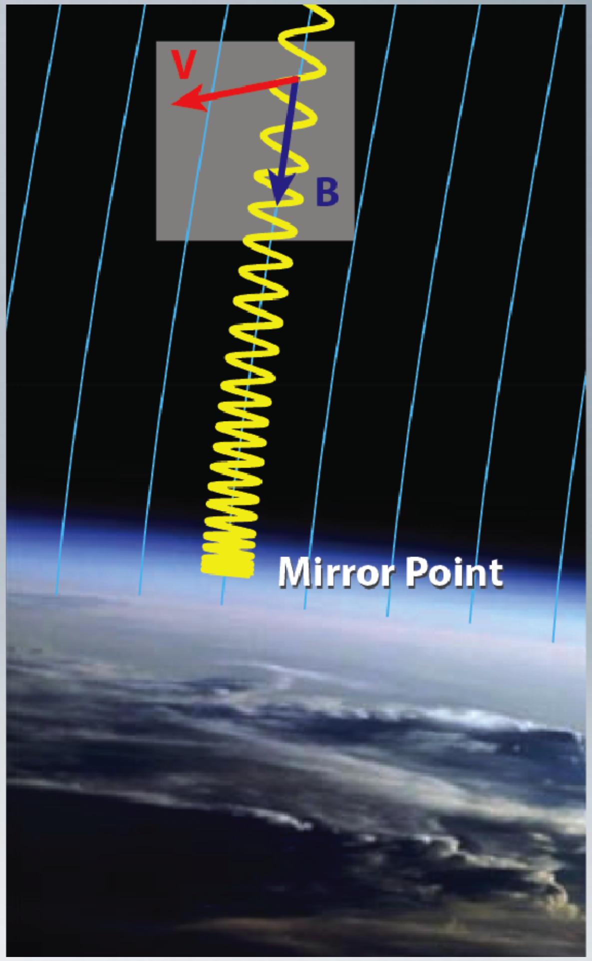
January 1997 Event

Reeves et al., JGR, 1998

Pitch Angle Scattering and electron 'precipitation'

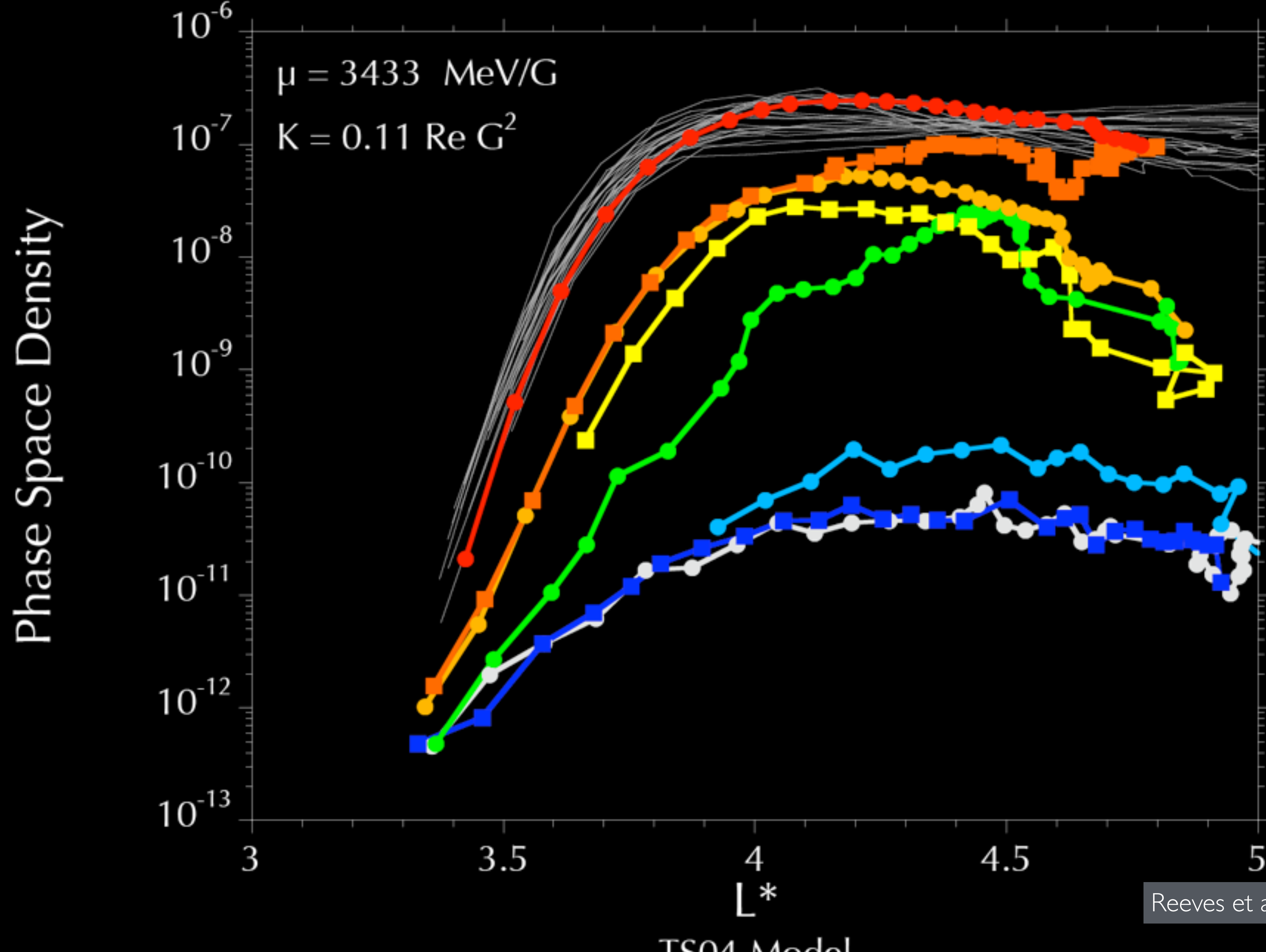




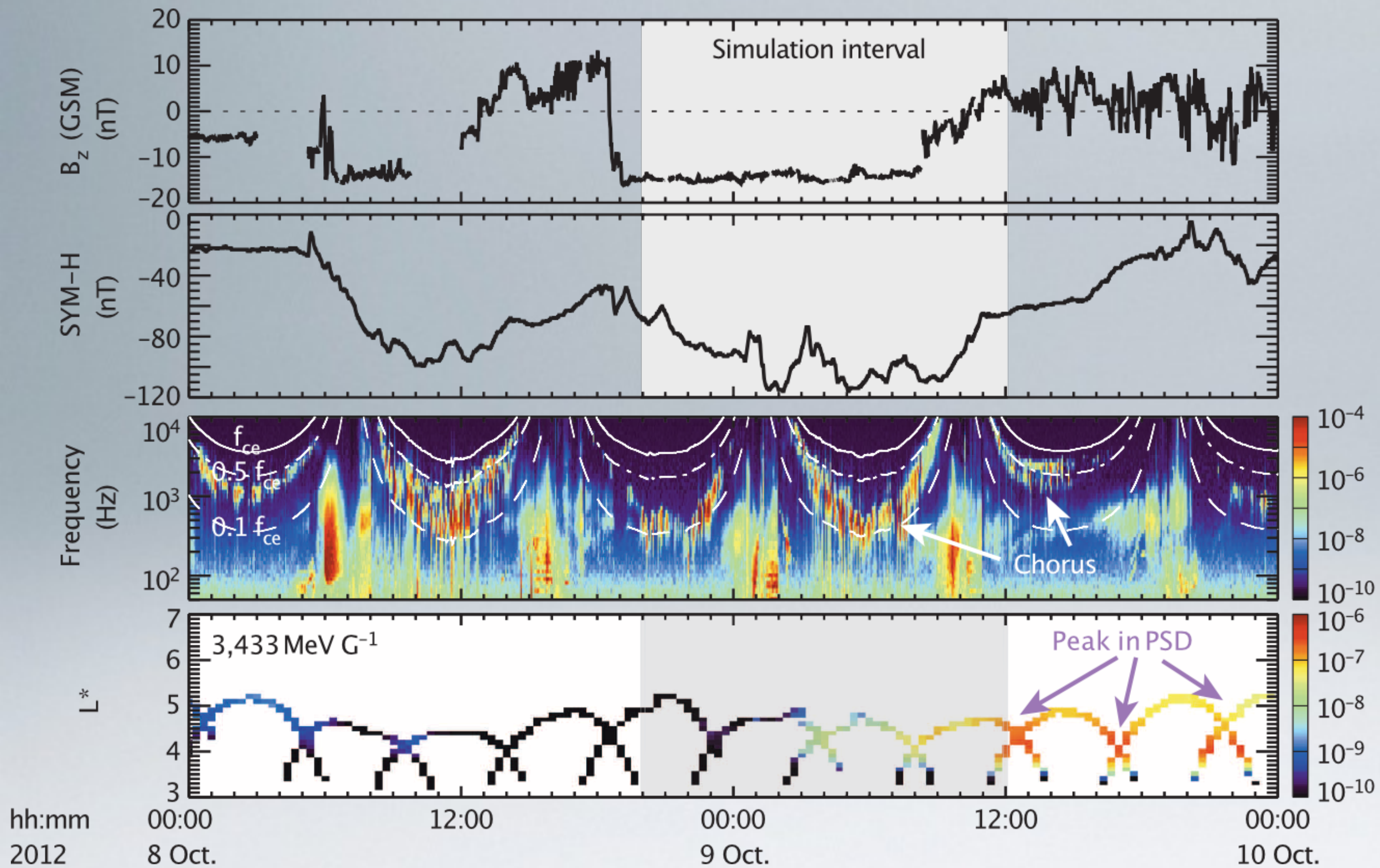


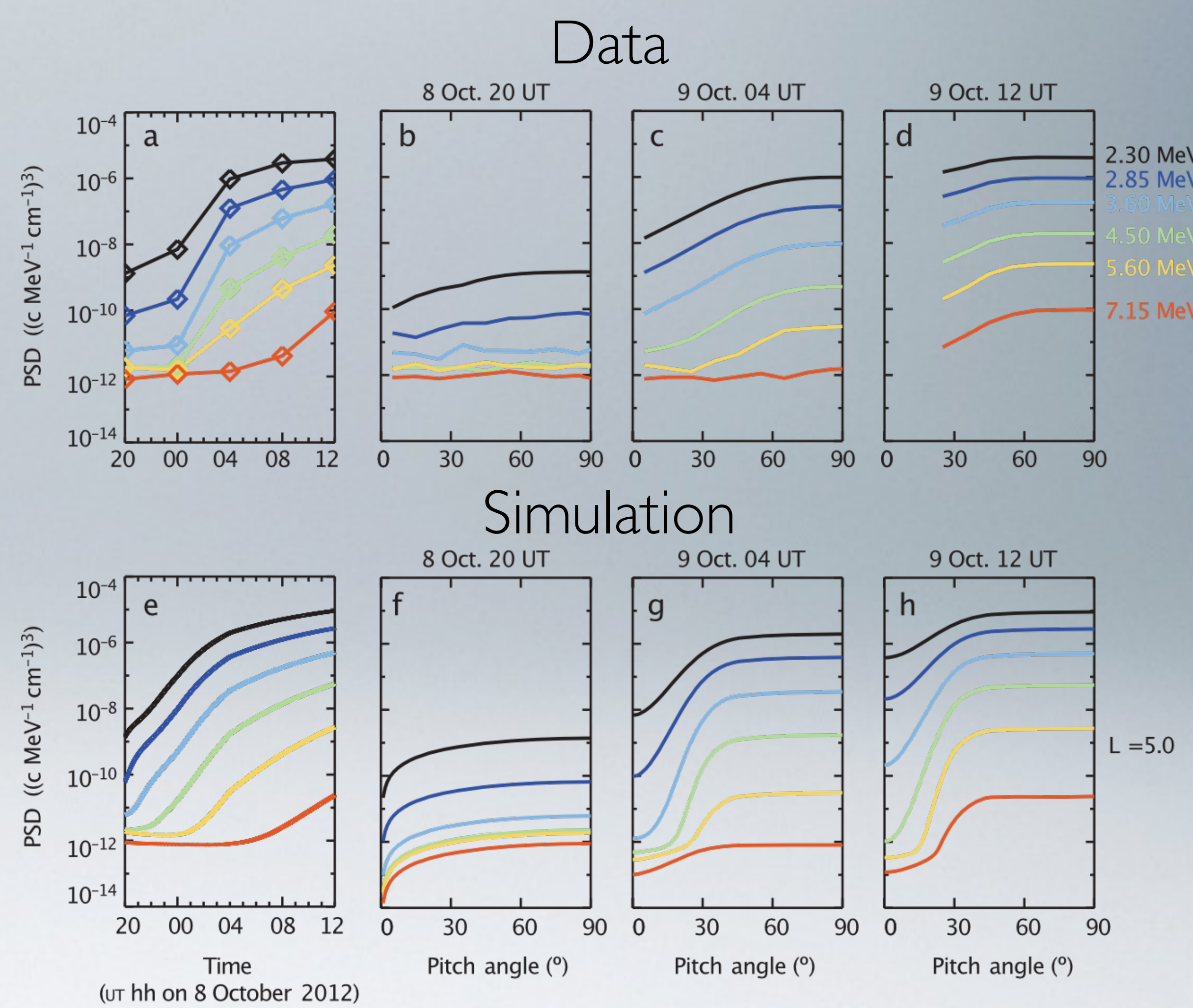
- Pitch Angle, α, is defined as the angle between **V** and **B**
- Equatorial pitch angle is that value at the magnetic equator

Oct 9-12
Post Acceleration Phase



Reeves et al., Science, 2013





Thorne et al., Nature, 2013