Professor Allison N. Jaynes
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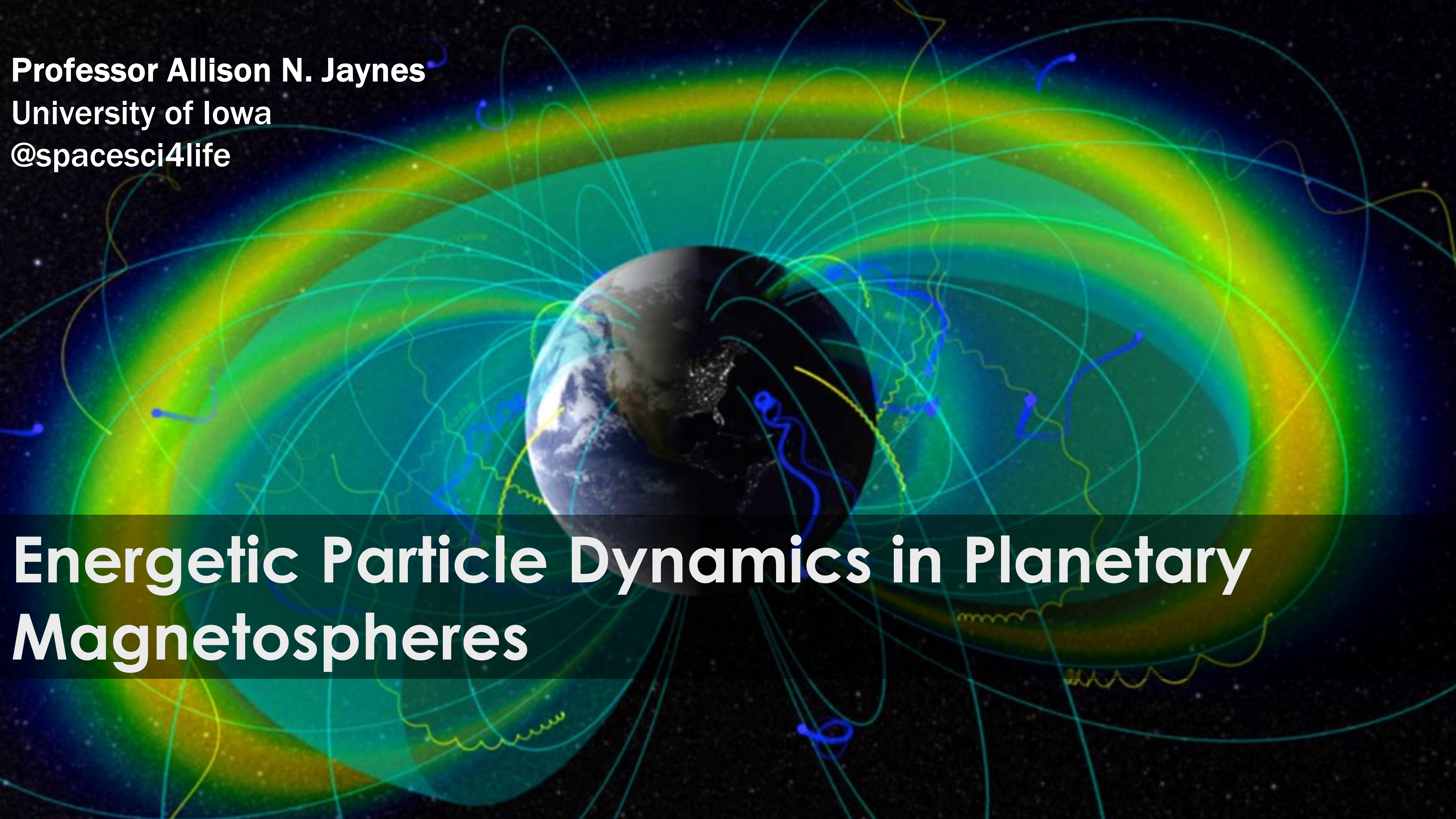


Energetic Particle Dynamics in Planetary Magnetospheres

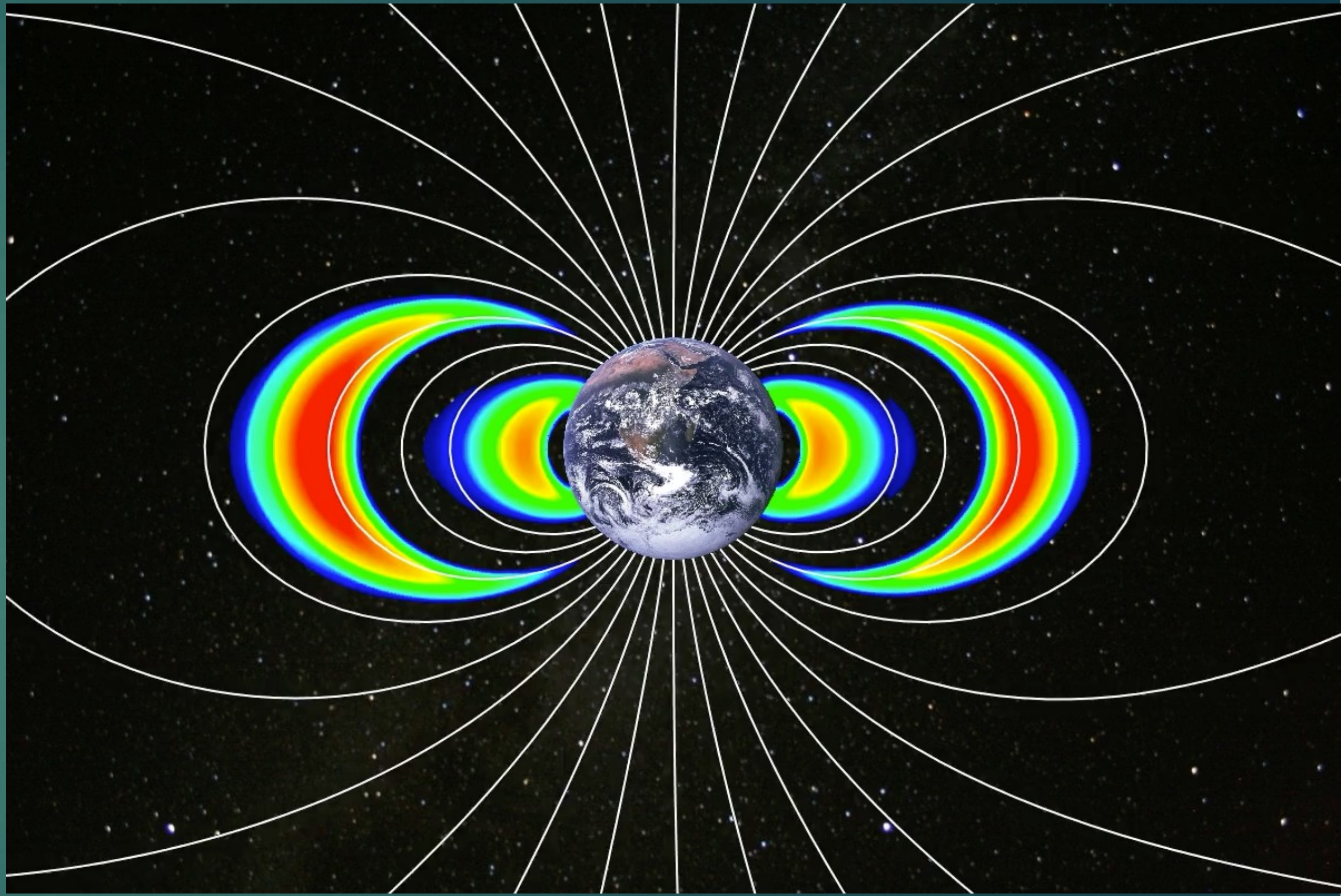
The fundamental questions

- Where do the highest energy (ultrarelativistic) particles come from?

- How are they transported through the inner magnetosphere?

- What happens to them?

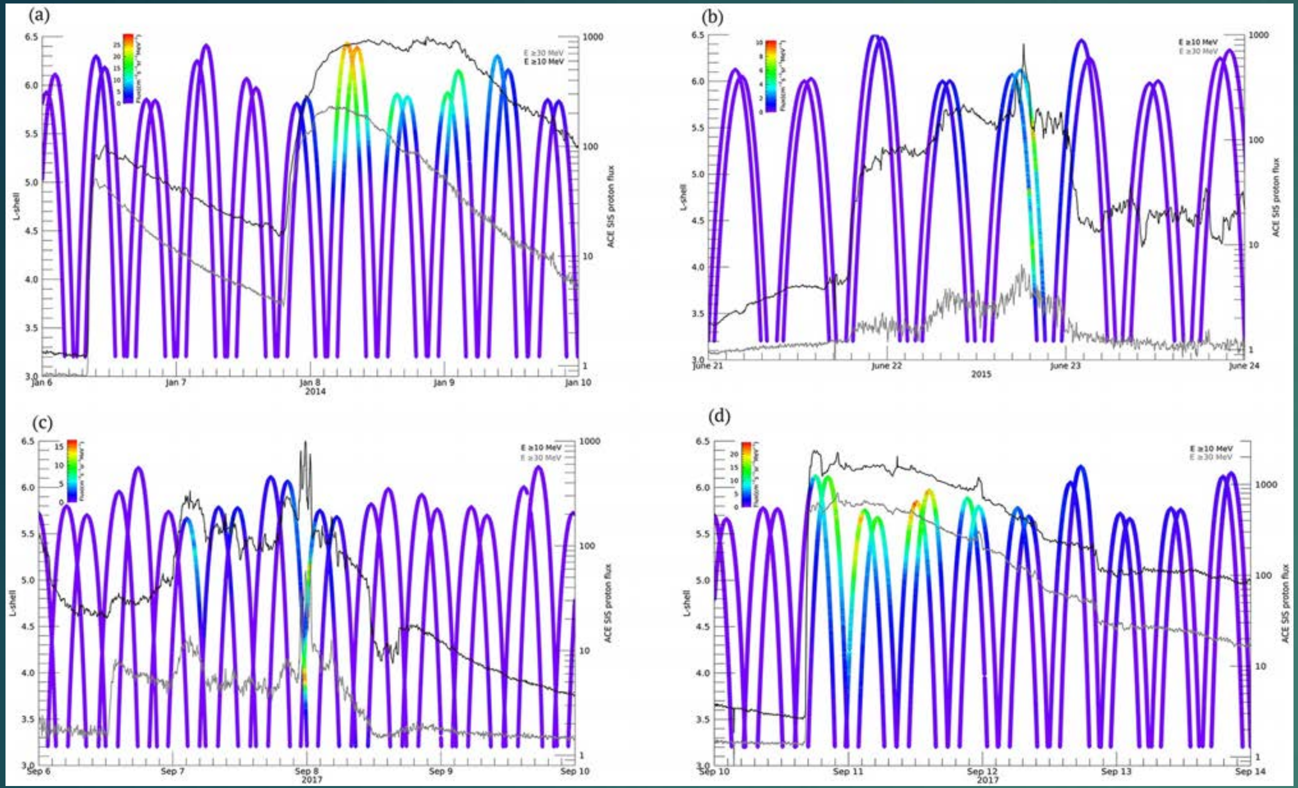
Where can energetic particles be created outside of planetary magnetospheres?



- Evolution of the 'long-lived storage ring' or three-belt structure first reported on in Baker+ 2013

(Movie courtesy of Dan Baker)

Solar Energetic Particles

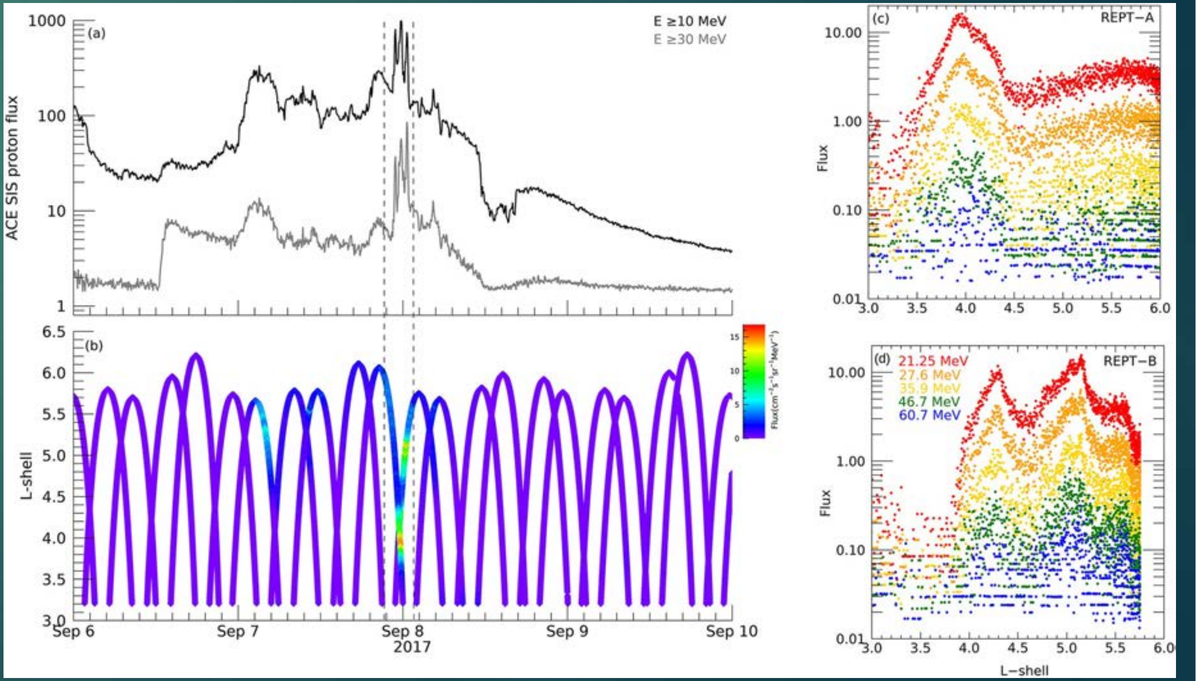


Filwett+ 2020

- SEP events are primarily made up of highly energetic protons accelerated either at a flare site or within a CME
- Not many good observations of SEP events during RBSP lifetime
- Filwett+ 2020 studied several events:
  - Remarkable correlation with solar proton observations out at L1
  - Cutoffs don't align with theory

We don't yet understand the access of SEPs to the inner magnetosphere!

SEPs can get trapped close to Earth and end up concentrated in the inner radiation belt

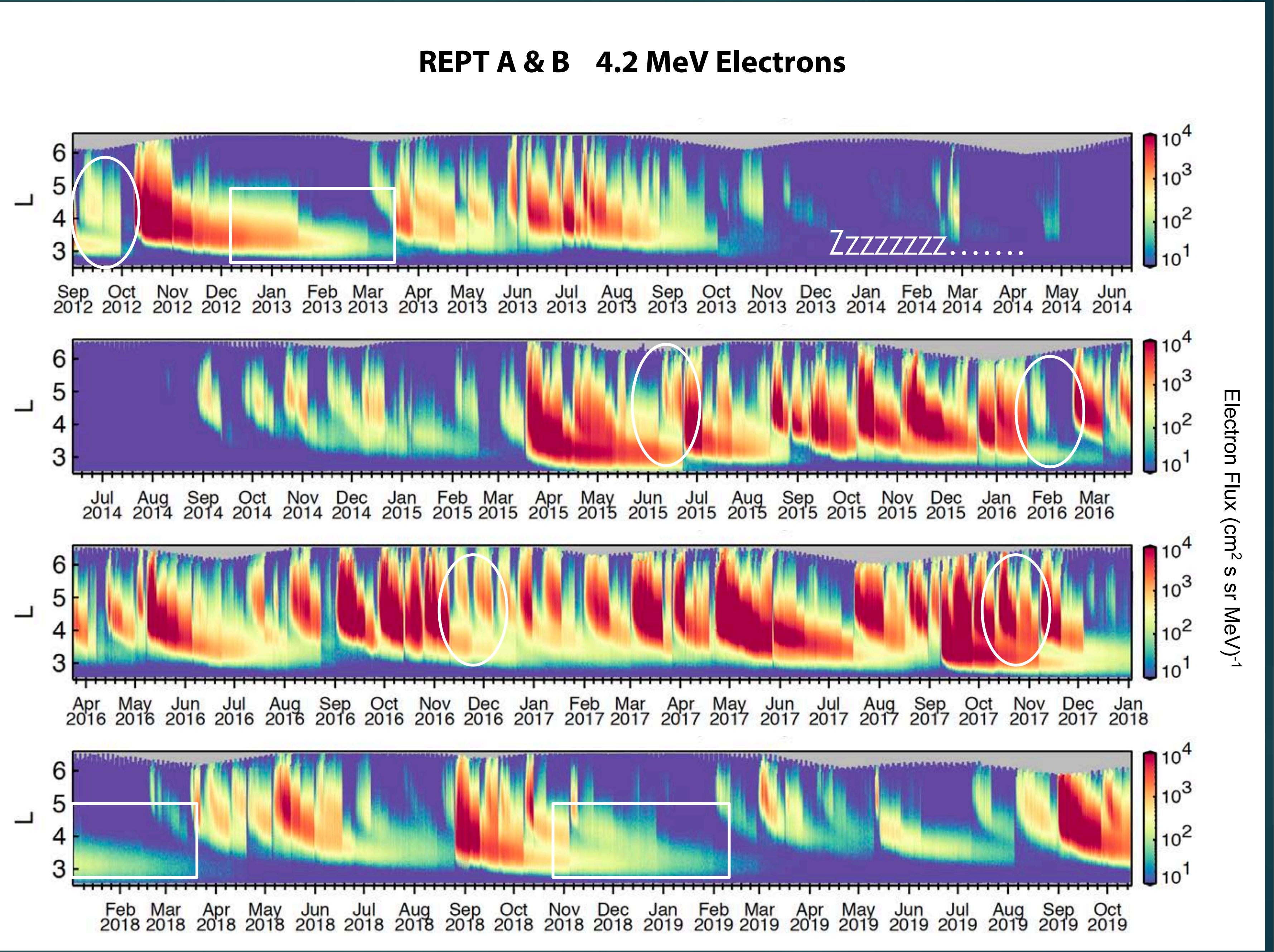


Filwett+ 2020

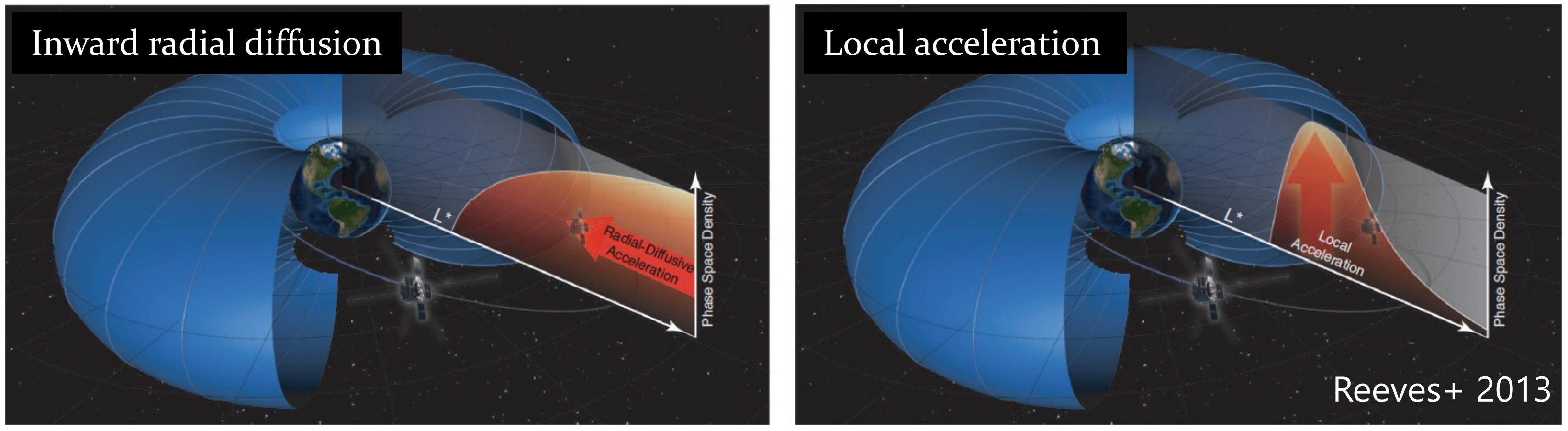
Electron radiation belts at Earth

Seven years of data show amazing variability of high-energy electrons

- Extremely quiet through 2013-2014
- Remnant belts appear regularly (double outer belt), Baker+ 2013
- Quiet periods of slow decay make great tests of diffusion rates
- HSS activity picked up in declining phase (2015 - now), with noticeable repeat enhancements from coronal holes

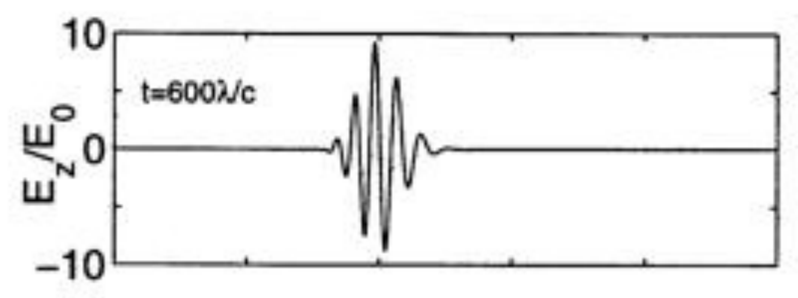


What is the dominant mechanism behind acceleration to ultrarelativistic energies?



Reeves+ 2013

Wave-particle interactions!



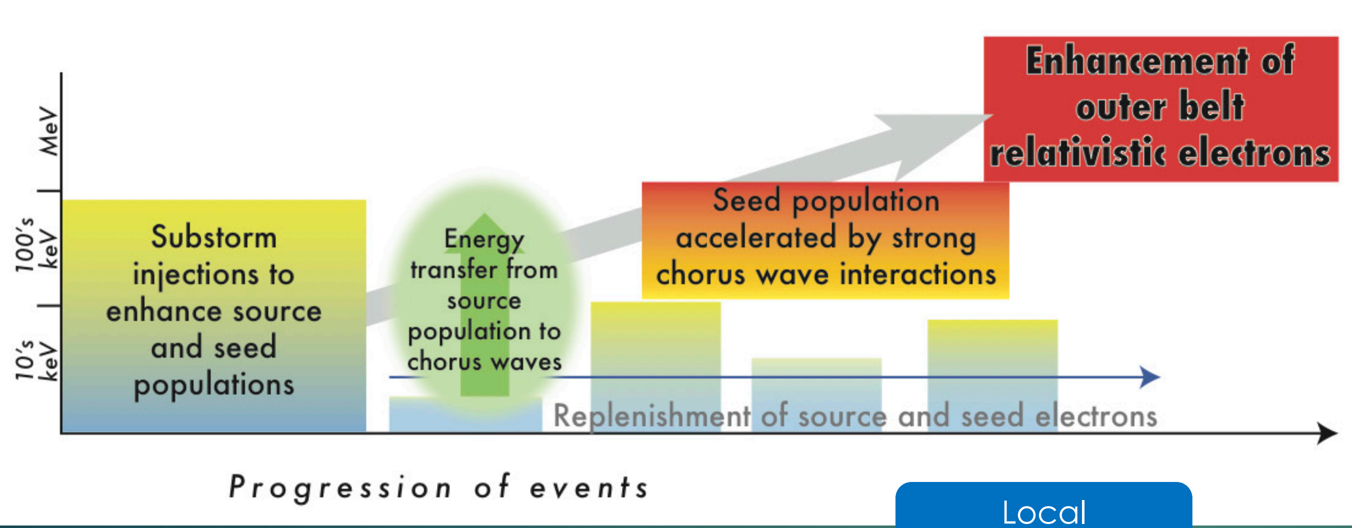
Shvets and Tushentsov (2005)

Inward radial diffusion:
- Driven by ULF waves
- Stochastic changes in L-shell, result in changes in energy
- Source is from outward location to more inner location

Local acceleration
- Driven by VLF (chorus) waves
- Stochastic changes in energy
- Source is in place (e.g. “local”)

New question: When and under what conditions is one mechanism or the other the dominant factor?

Different events show evidence of each mechanism



Jaynes+ 2015

Local acceleration

In September, 2014 a storm period failed to produce high-energy electrons in the radiation belts

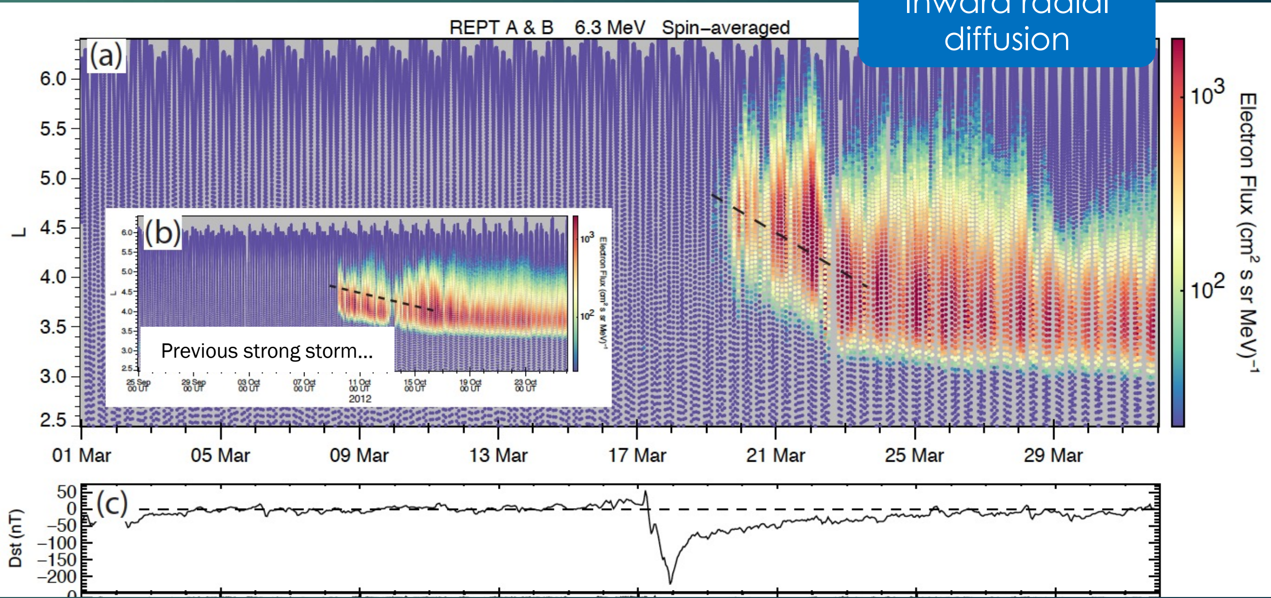
- No low-energy particles to drive VLF waves
- Local acceleration could not take place

In March, 2015 a storm period produced ultrarelativistic electrons during recovery period

- VLF waves were absent
- Acceleration was due to strong inward radial diffusion

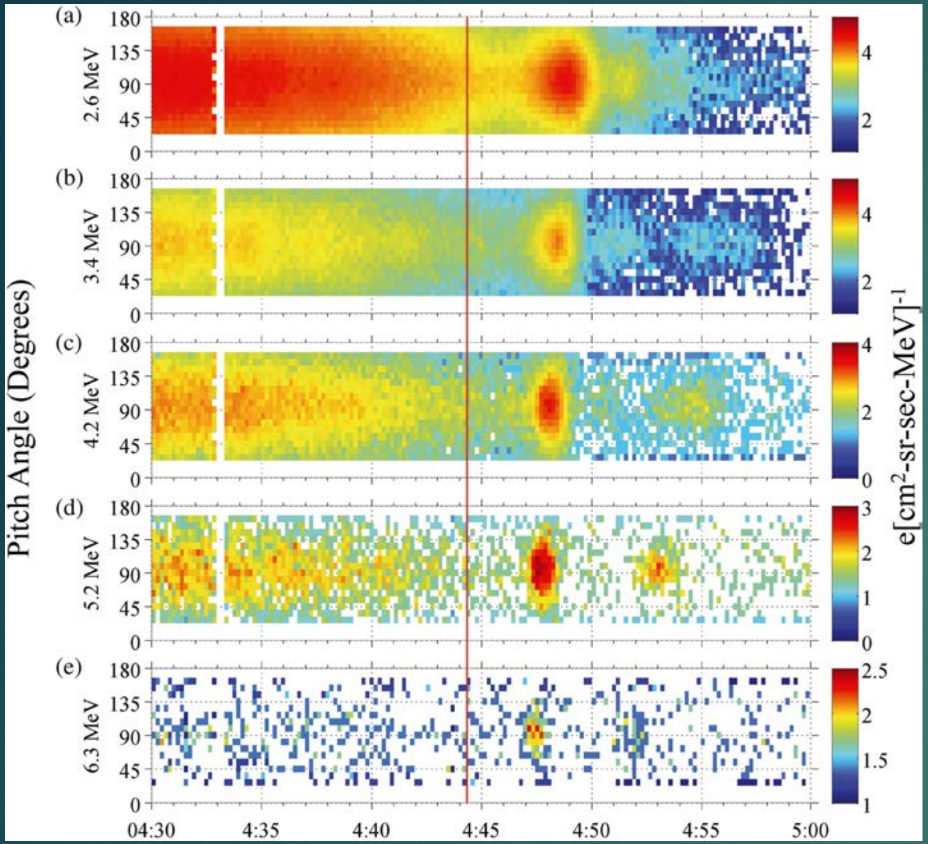
The emerging picture is one where BOTH mechanisms operate, often at the same time, potentially acting on different energies.

Jaynes+ 2018



Inward radial diffusion

Shock-induced acceleration

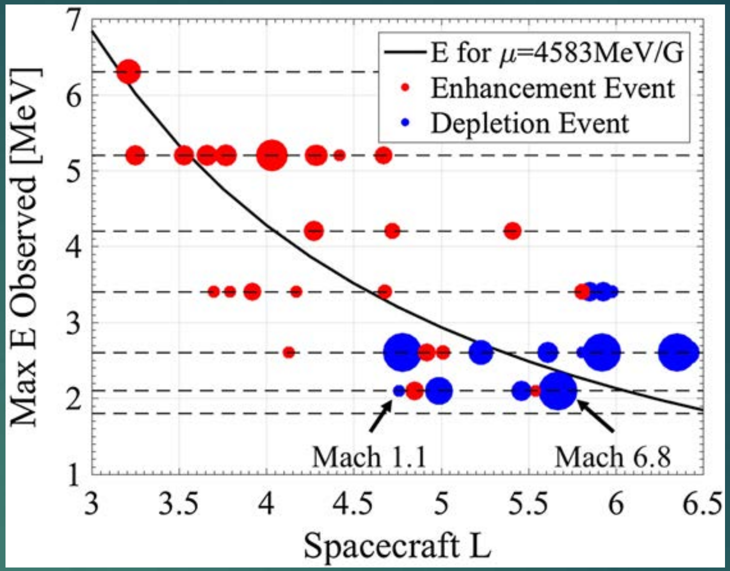


Kanekal+ 2016

March 17, 2015 storm

- Prompt appearance of ultrarelativistic electrons within two minutes of IP shock impact
- In this case, up to 6.3 MeV

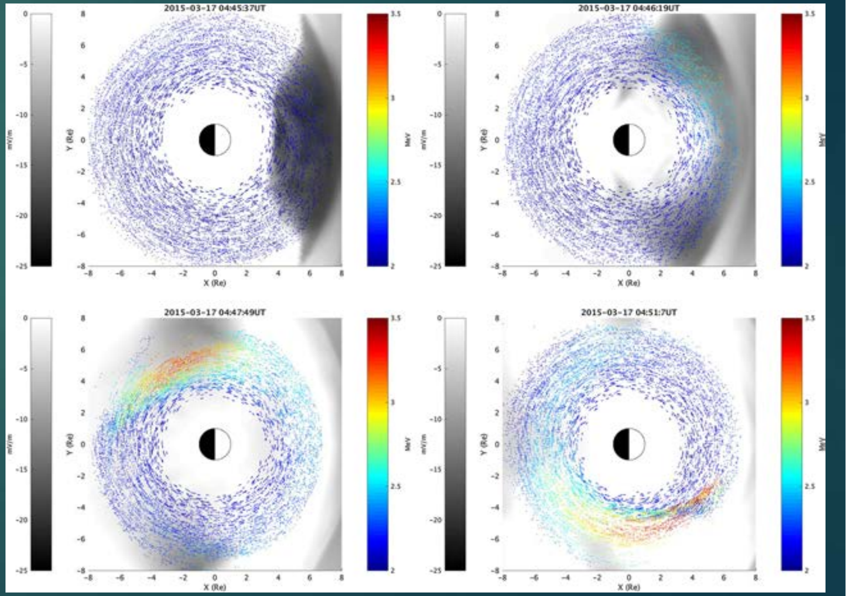
(Cf. Foster+ 2015)



Schiller+ 2016

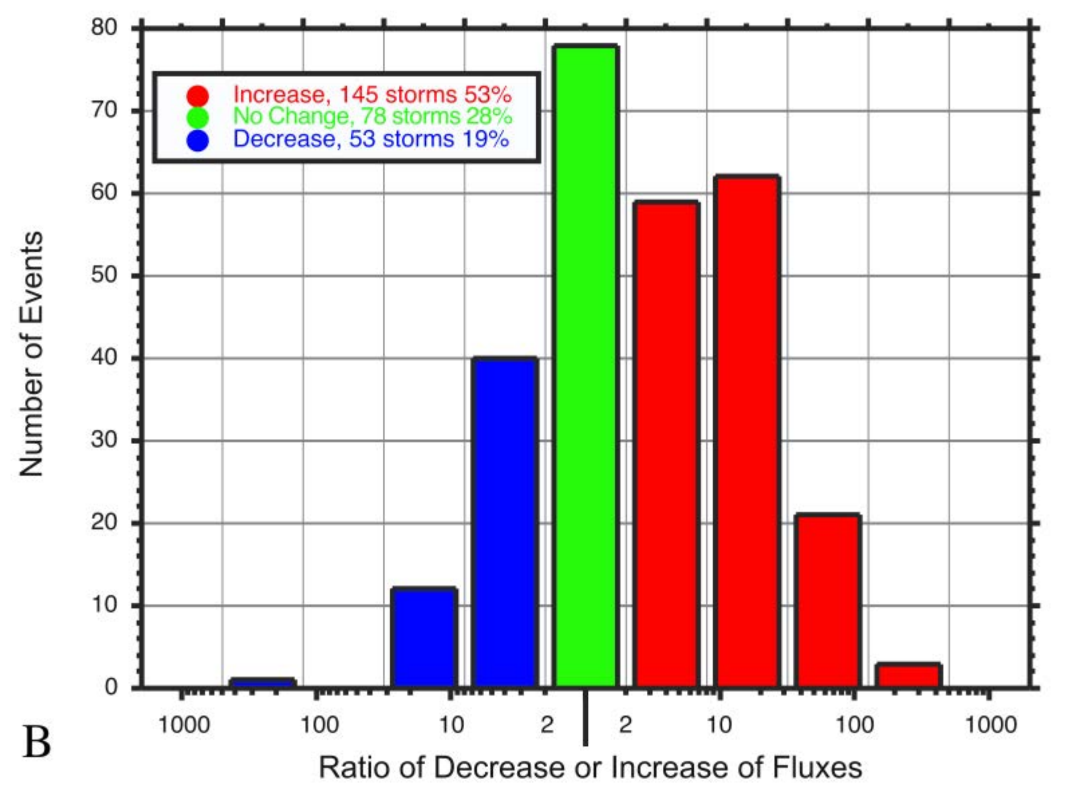
- 25% of IP shock impacts produce shock-induced enhancements
- 14% produce sudden depletions (at higher L)

- The March 2015 case was reproduced with MHD test particle simulations using a strong azimuthal electric field to produce prompt injection



Hudson+ 2017

How are geomagnetic storms related to radiation belt changes?



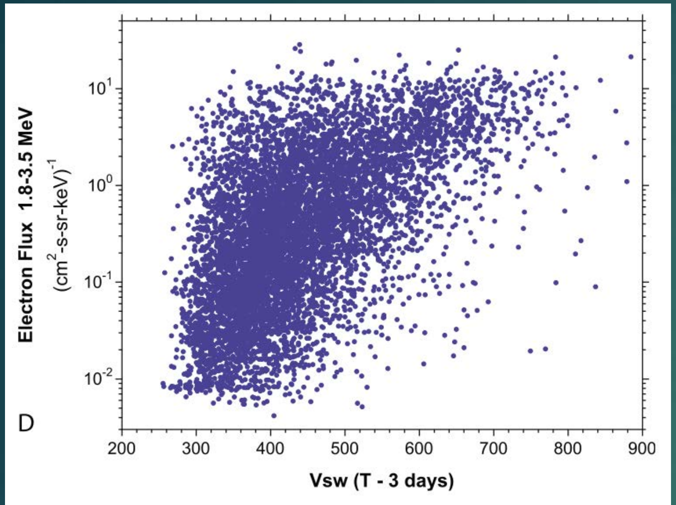
Reeves+ 2003

Response of 1-3 MeV electrons in outer radiation belt over 11 years (276 storms!)

What does this plot tell you?

- A given storm can increase or decrease relativistic flux
- Almost no correlation between pre- and post-storm fluxes
- No relation to Dst, slight relation to solar wind speed
- "If you've seen one storm, you've seen one storm"

Substorms (not storms) are critical



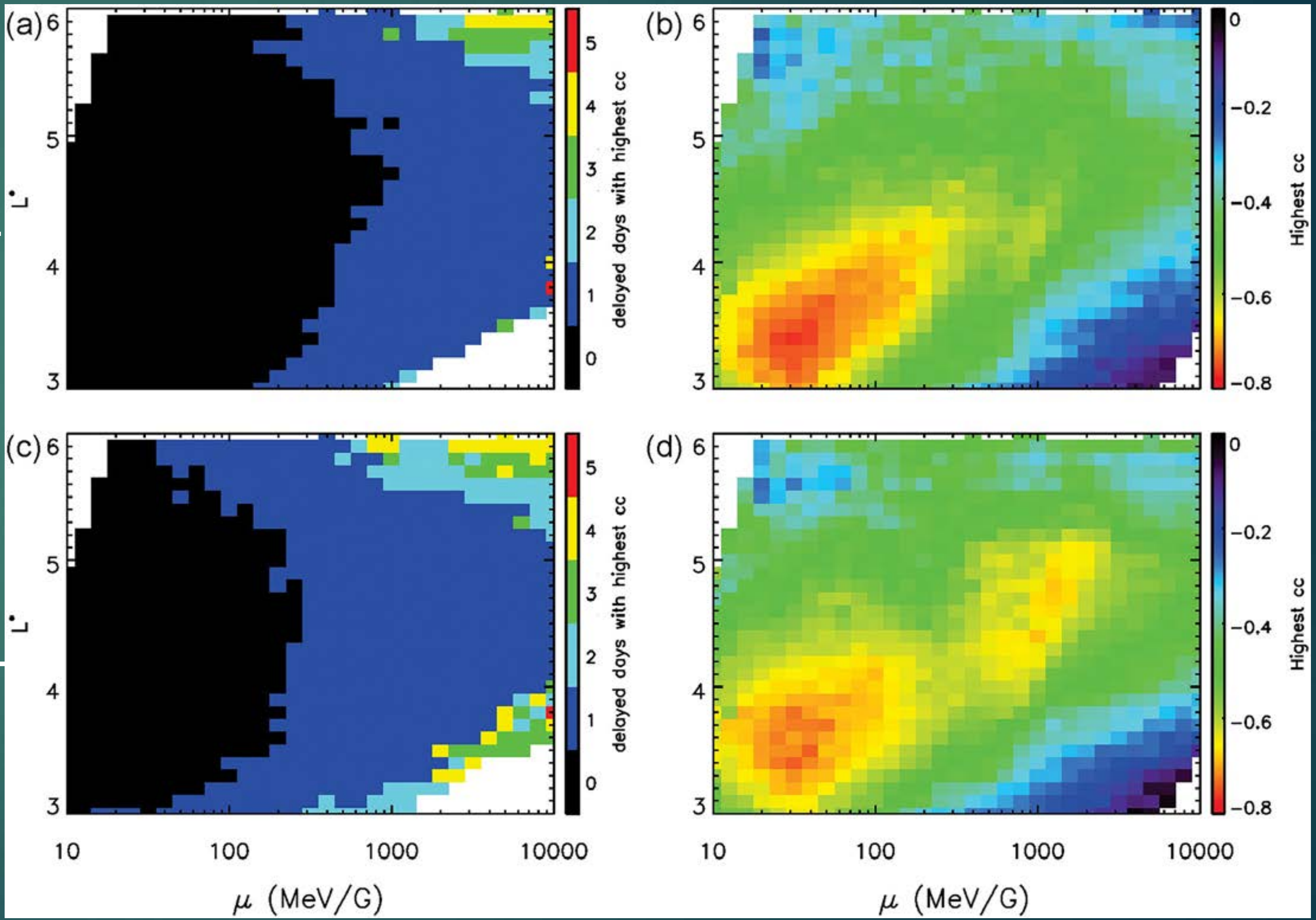
Reeves+ 2017

Corresponding time lag

Highest correlation coefficient

SYM-

AL



Zhao+ 2017

- For high energies (Mu), substorm index has higher correlation than storm index (Zhao+ 2017)
- Substorms can contribute to increased power in both VLF waves (local acceleration) and ULF waves (inward radial diffusion)

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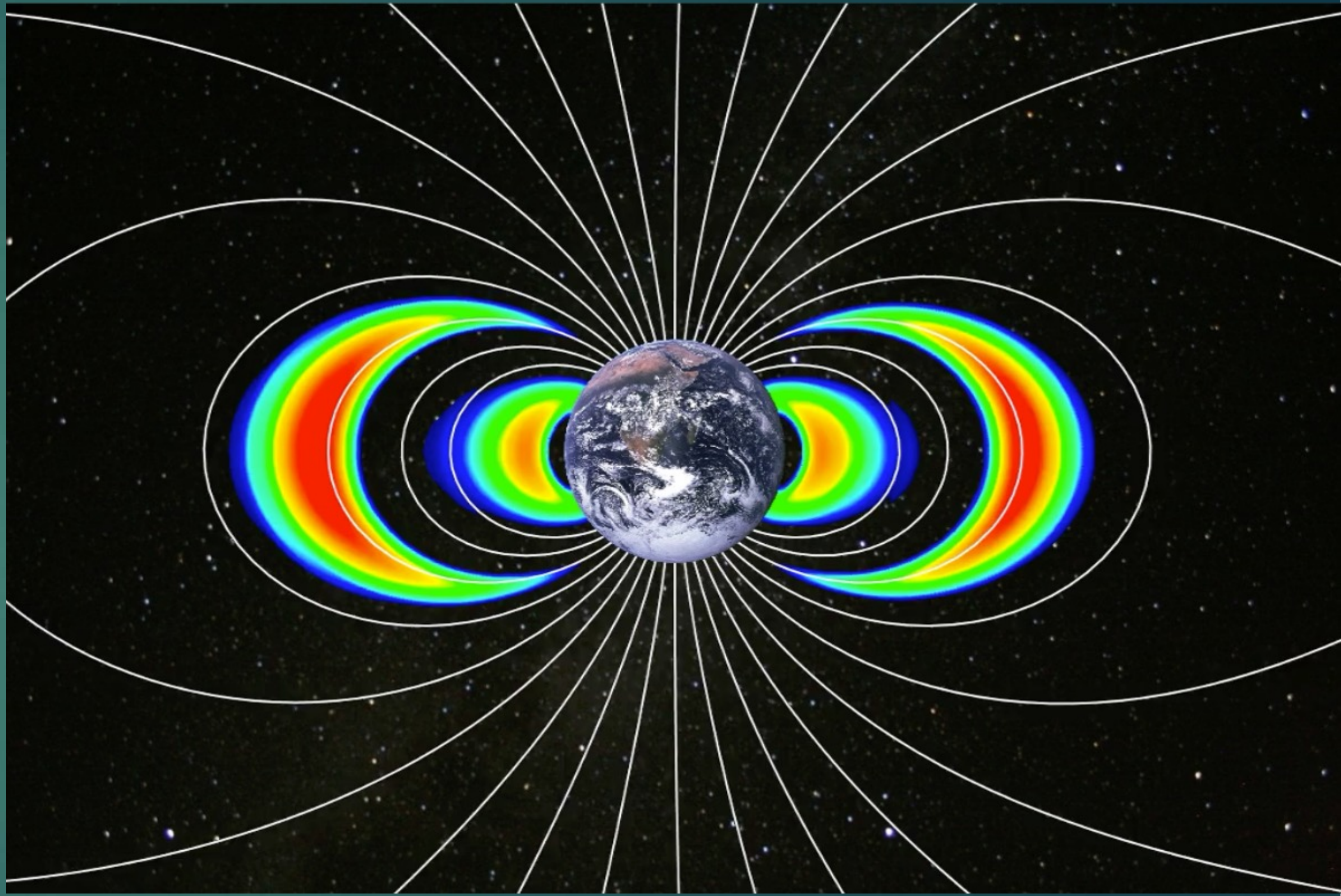
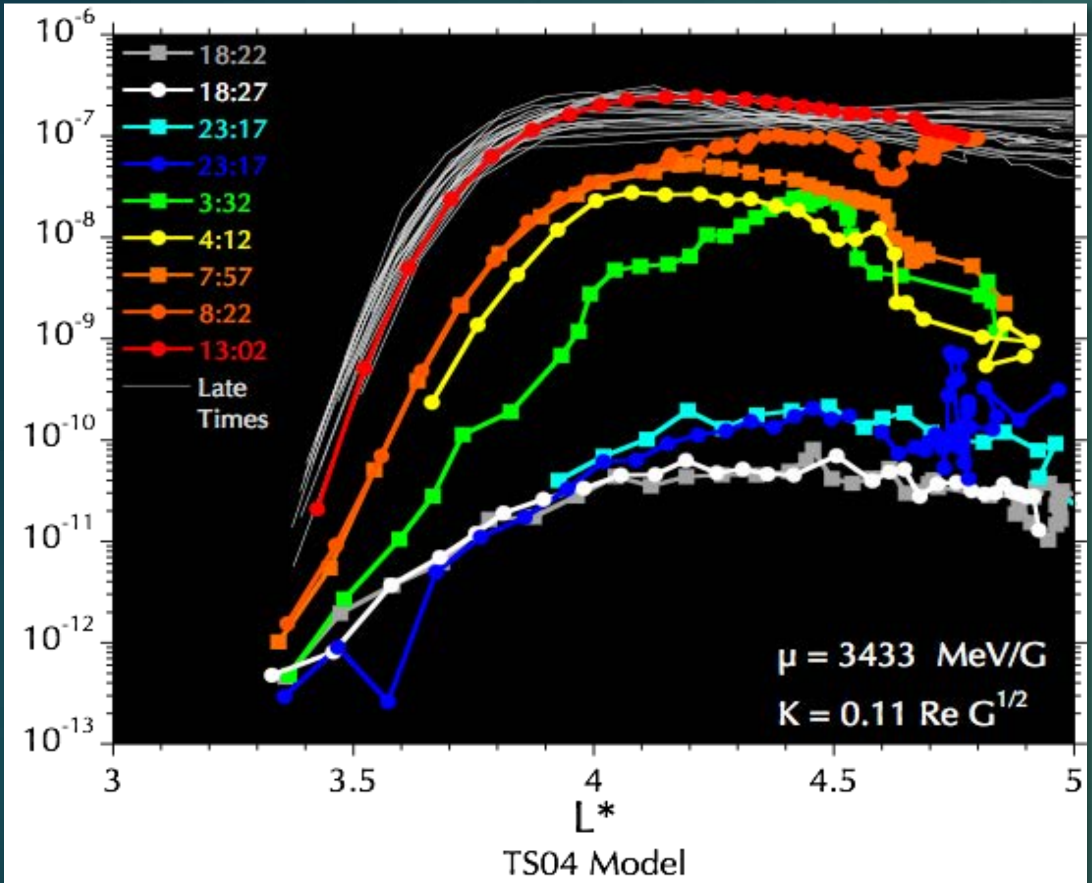


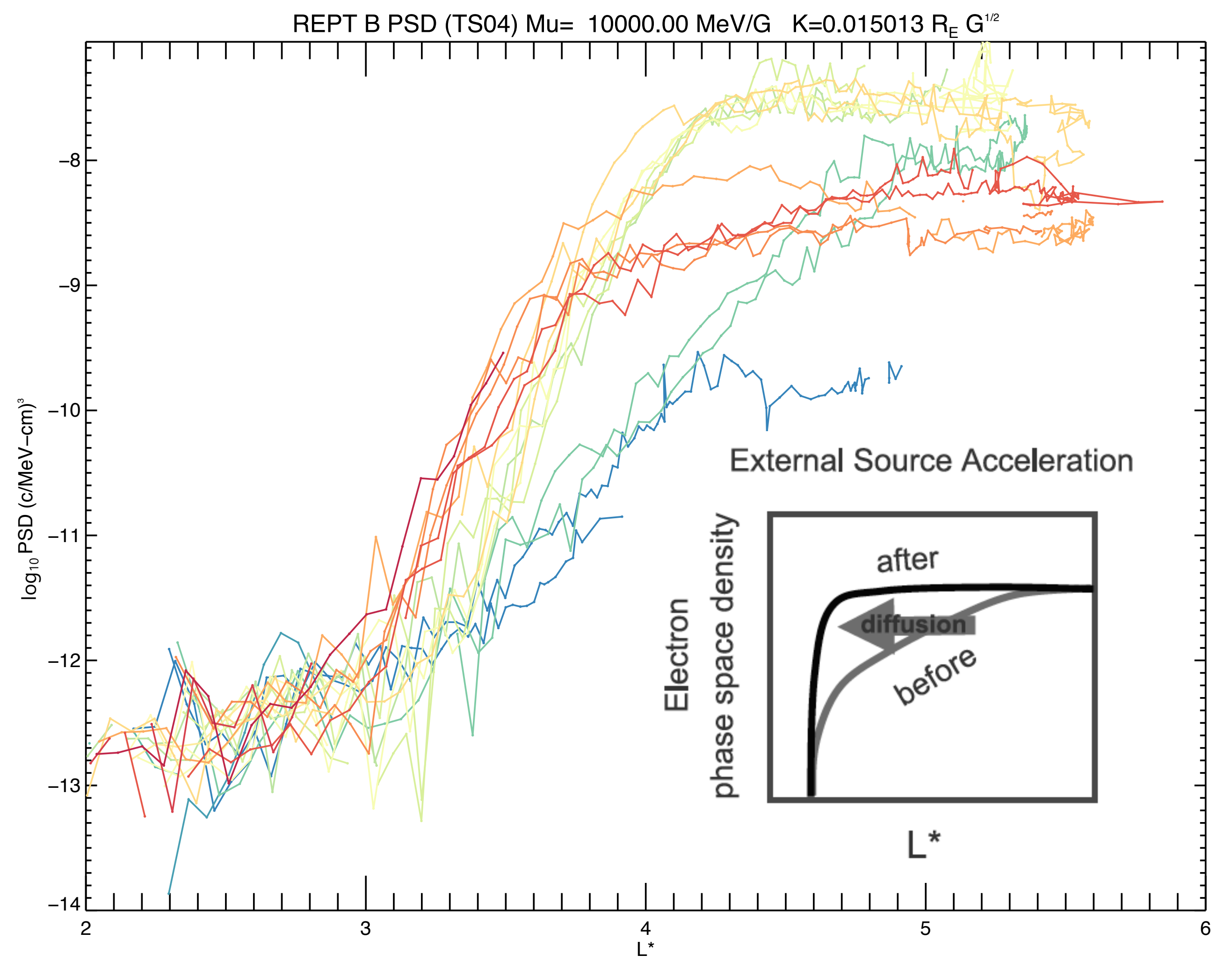
- Evolution of the 'long-lived storage ring' or three-belt structure first reported on in Baker+ 2013

(Movie courtesy of Dan Baker)

Inward and outward radial diffusion



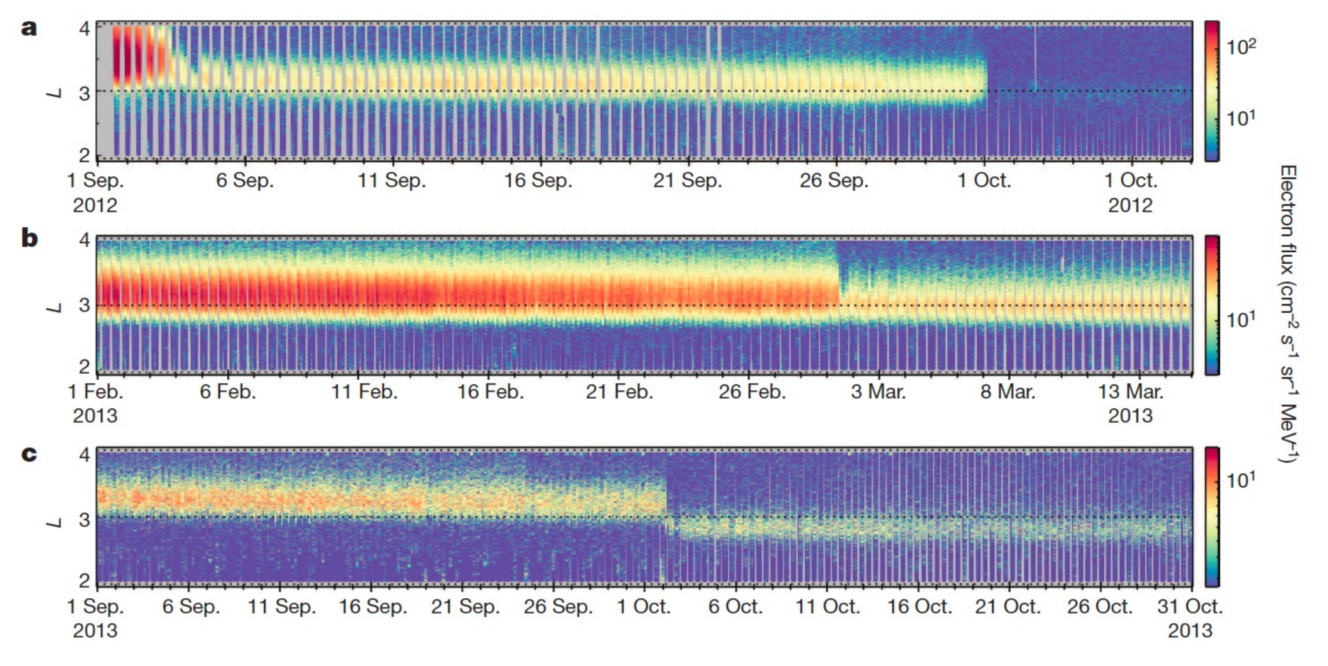
Reeves+ 2013



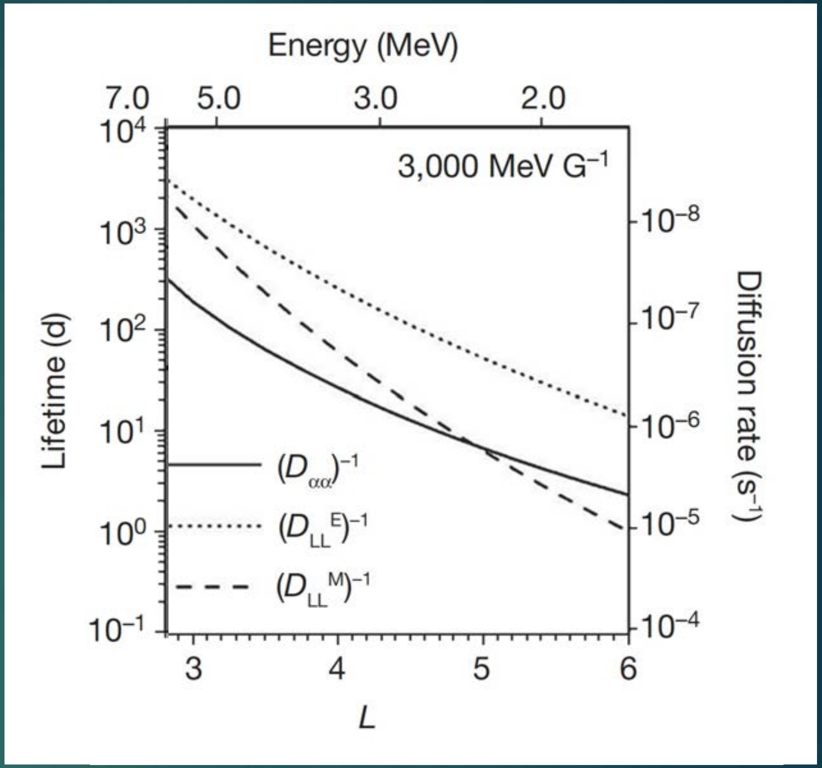
Jaynes+ 2018

- Outward: intersect the magnetopause → open field lines
- Inward: ?

The "Impenetrable Barrier"

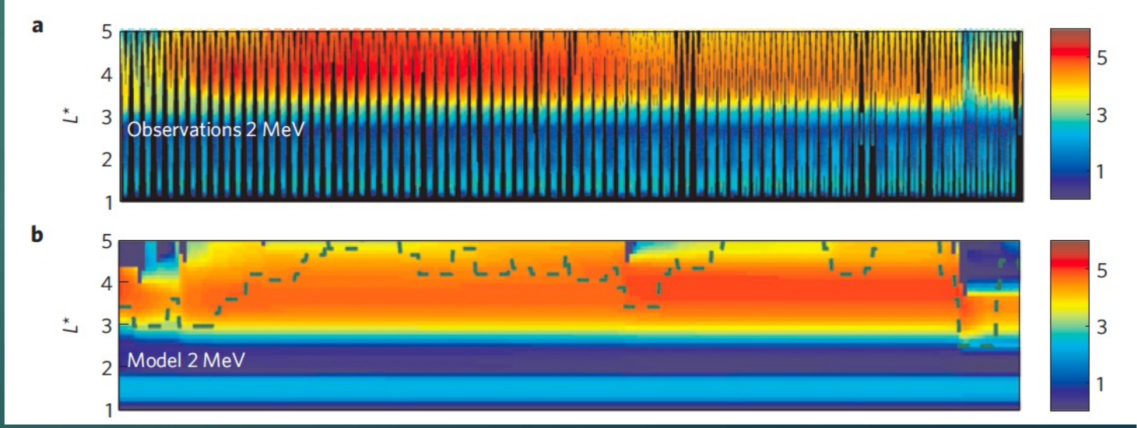


Baker+ 2014



Baker+ 2014

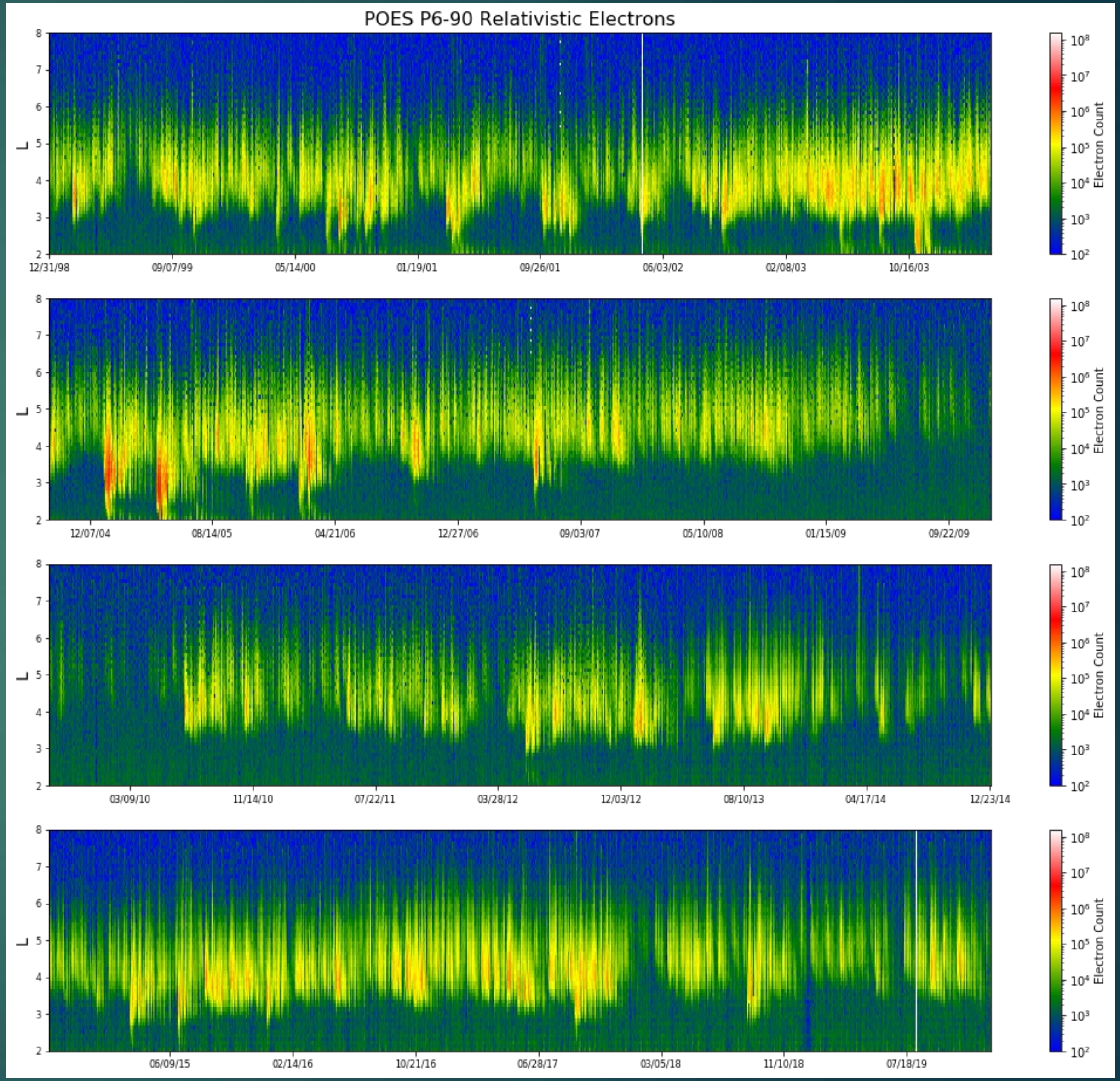
- There exists an effective barrier to ultrarelativistic electrons almost all the time at L~2.8 (Cf. Li+ 2015)
- Strong solar driving can breach this barrier
- Originally, the only cause was thought to be a balance of inward radial diffusion and pitch angle diffusion driven by hiss waves, both with very high lifetimes



Shprits+ 2013

Long-term observations of the barrier

- Long-term continuous POES observations allow us to see the times when the barrier has been breached (for >1 MeV electrons)
- What solar wind conditions are necessary for this to occur?
- This is not a very common feature – happening only a couple dozen times over the past 20 years



Joseph+ 2021

The fundamental questions

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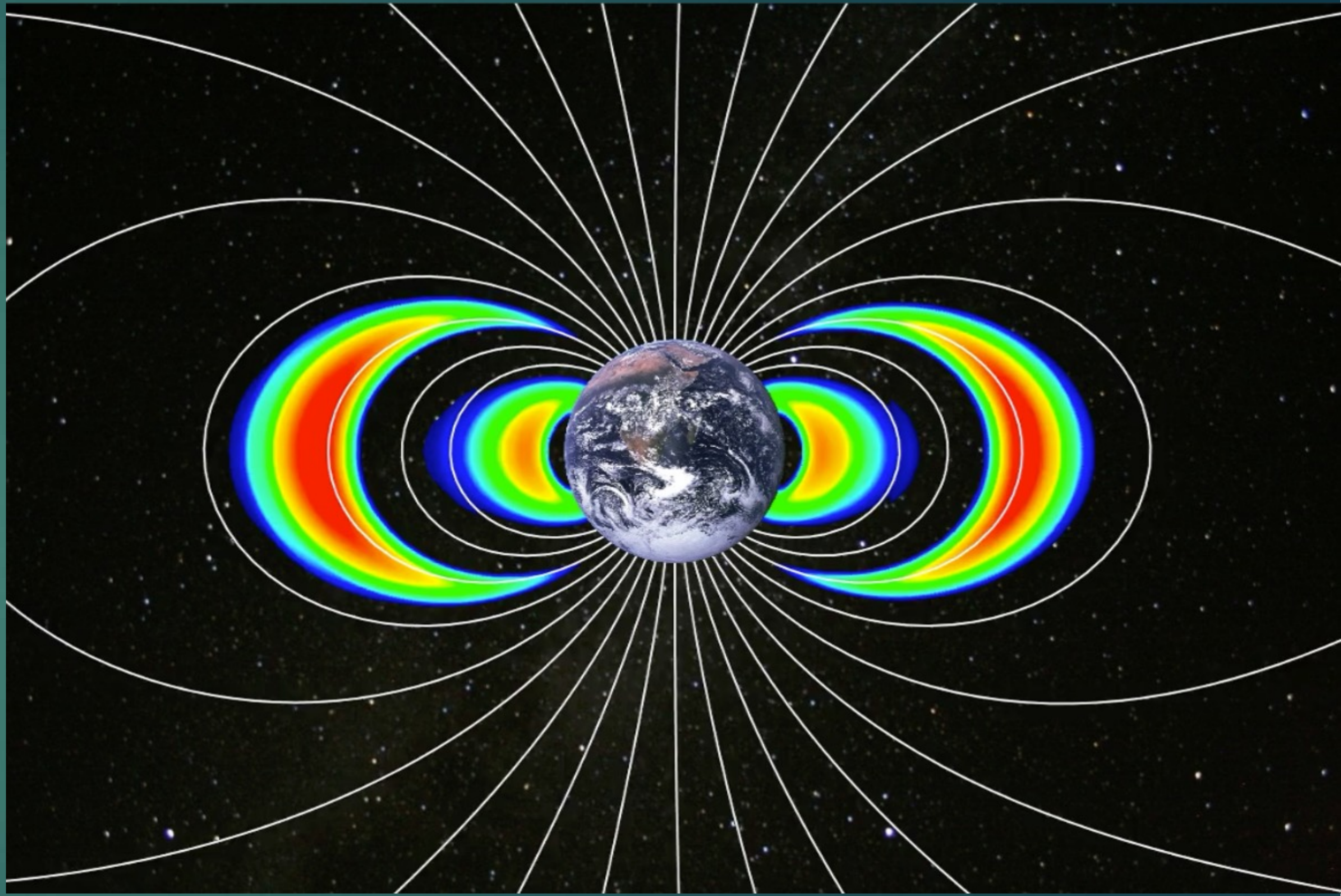


- Evolution of the 'long-lived storage ring' or three-belt structure first reported on in Baker+ 2013

(Movie courtesy of Dan Baker)

Loss mechanisms

Loss to the atmosphere

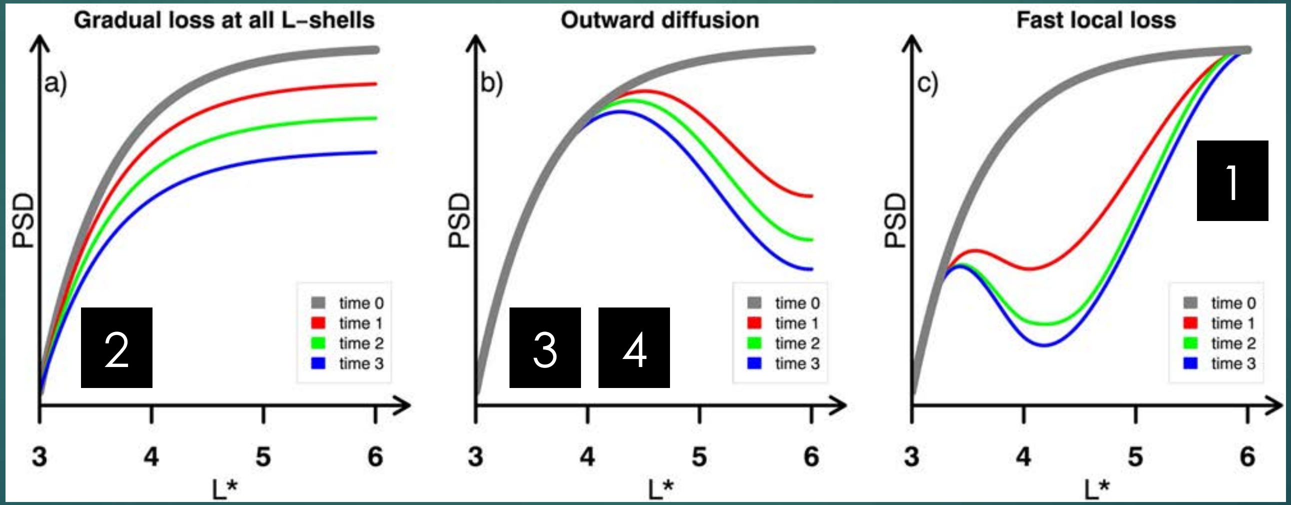
1 Pitch angle scattering by EMIC waves

2 Pitch angle scattering by VLF hiss waves

Loss to the magnetopause

3 Outward radial diffusion

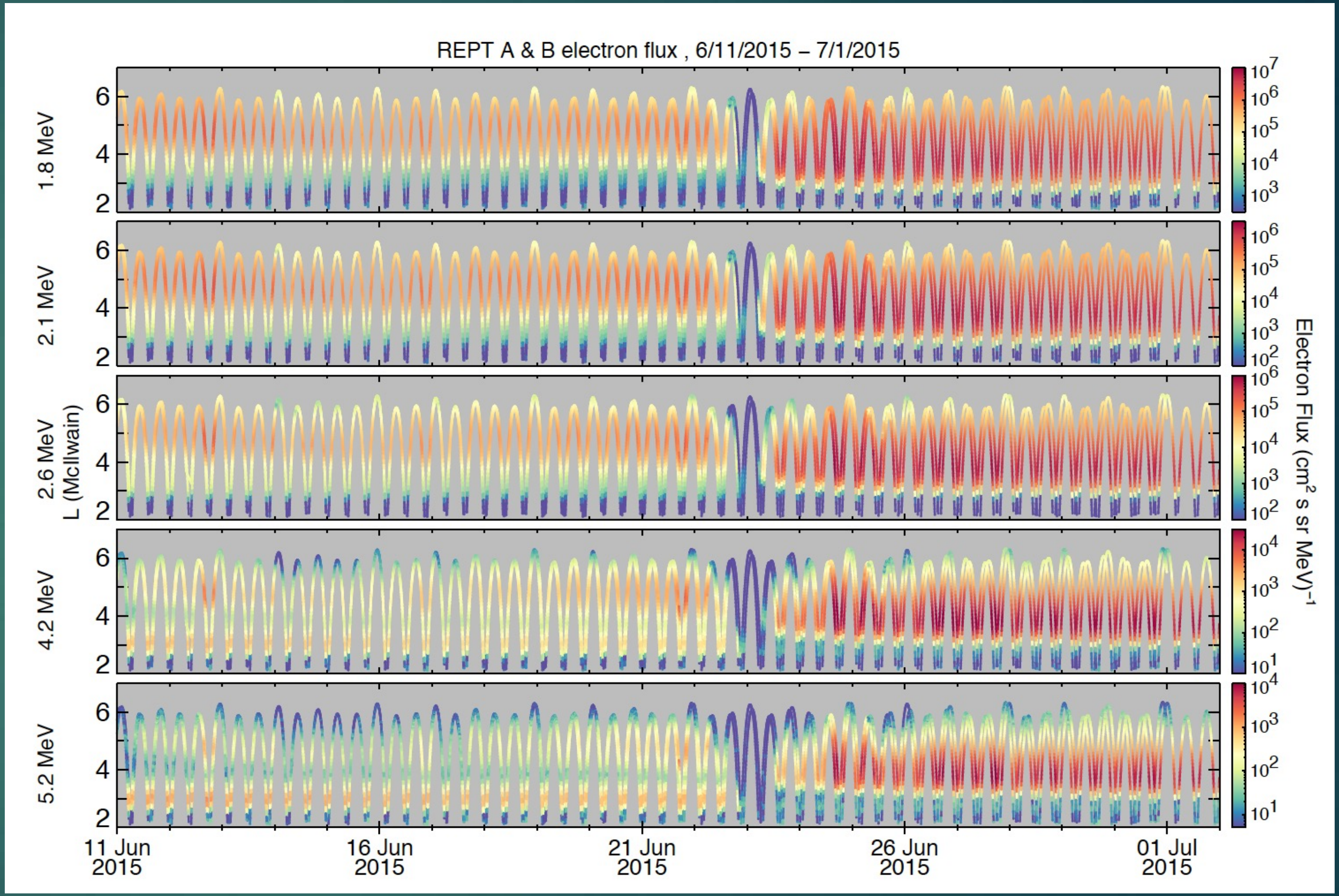
4 Sudden magnetosphere compression



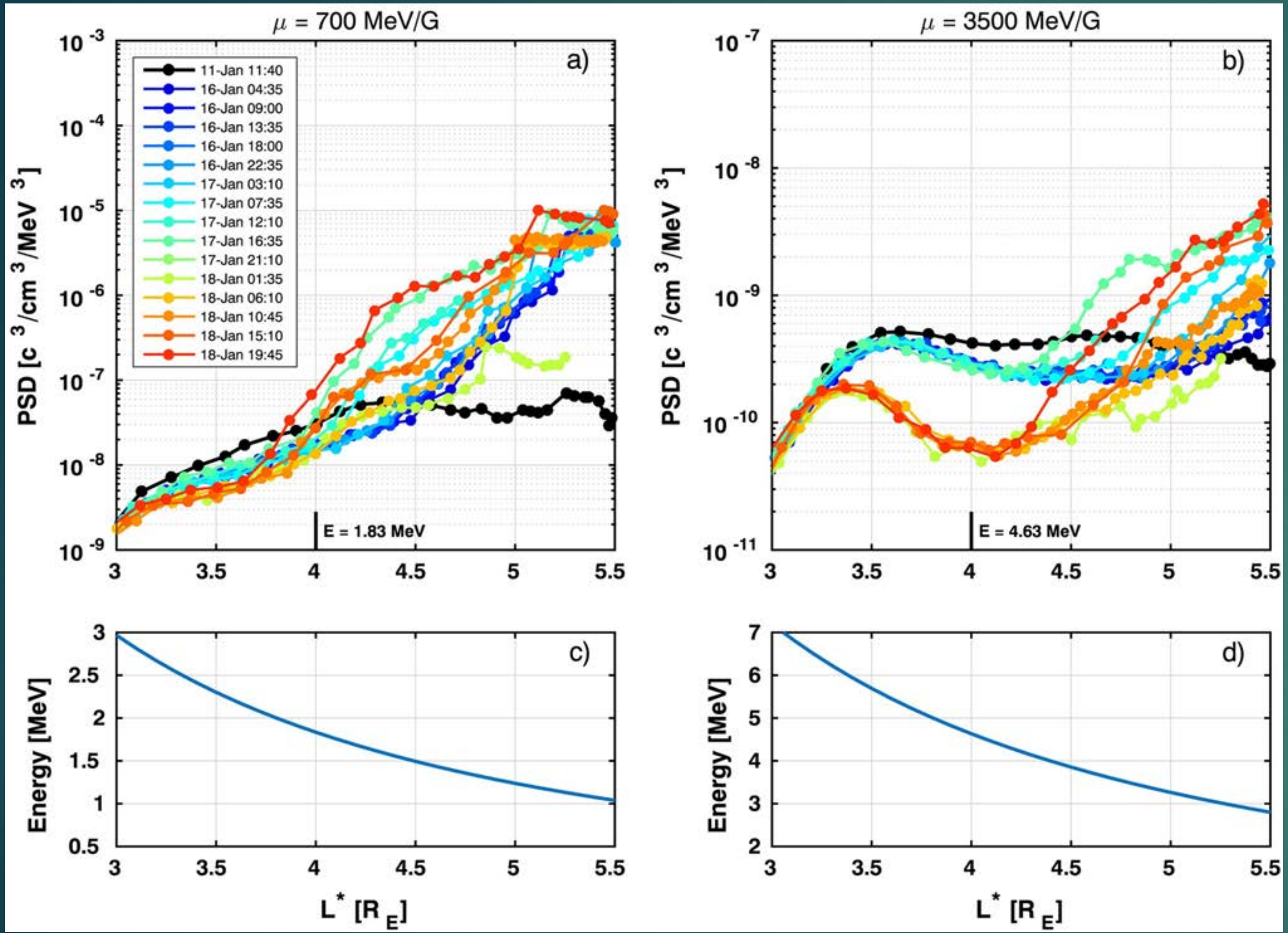
Shprits+ 2017

The mystery

- Sudden losses across wide range of Lshells and energies (”dropout events”)
- Magnetopause is often compressed, but we either have outward diffusion rates wrong or there is something else at play



EMIC wave loss

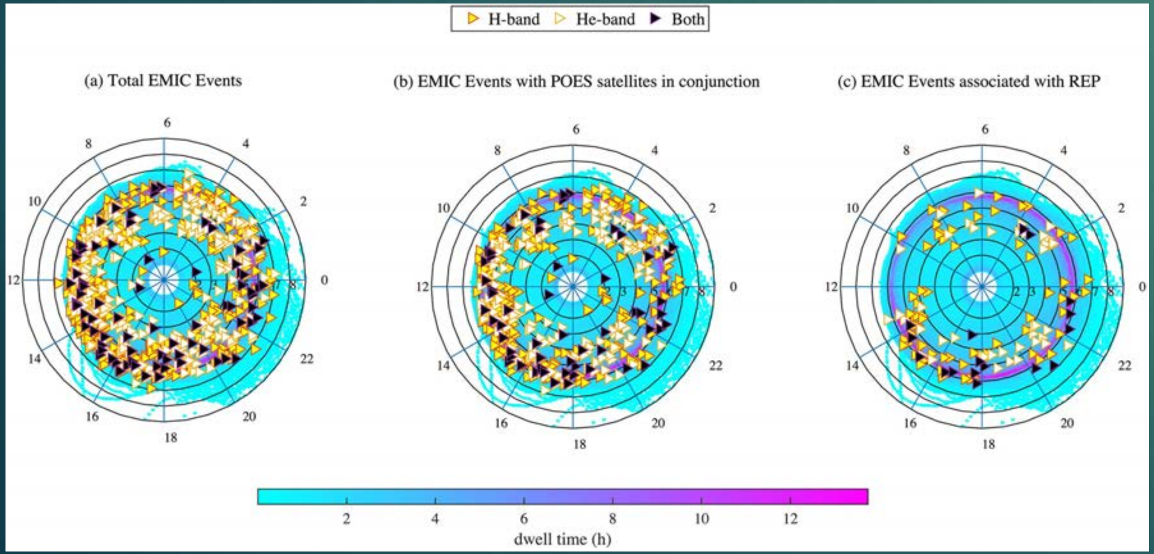


Shprits+ 2017

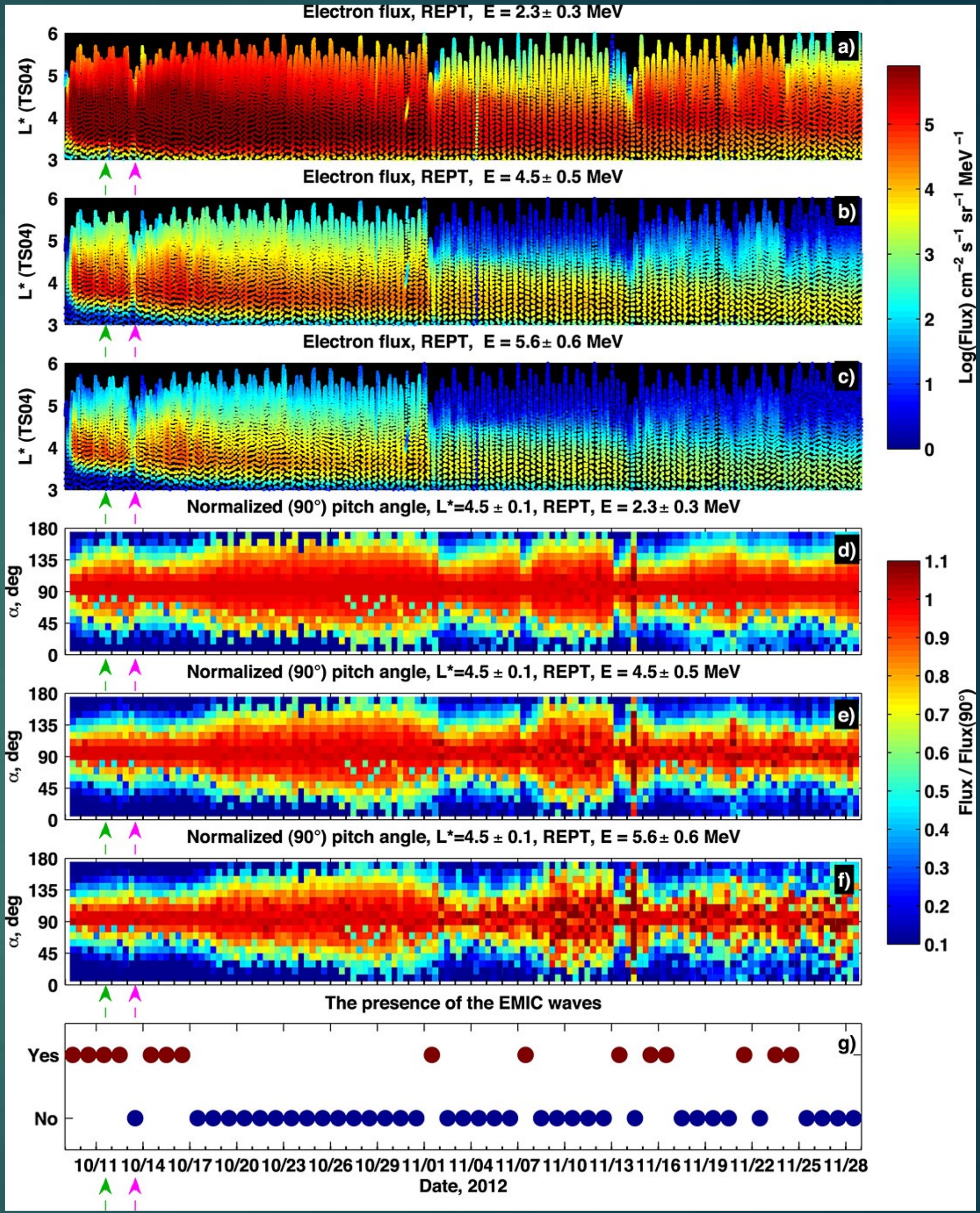
- EMIC waves: do they significantly affect >MeV electrons?
- Evidence shows ‘bite-outs’ of PSD profile – can only be explained by fast loss due to EMIC waves
- How common is this?

EMIC wave loss

- EMIC waves certainly cause losses at low pitch angles (Usanova+ 2014)
- But comparing Relativistic Electron Precipitation (REP) with EMIC waves shows only a weak relationship
- Open question: can EMIC losses account for a substantial part of total radiation belt loss?

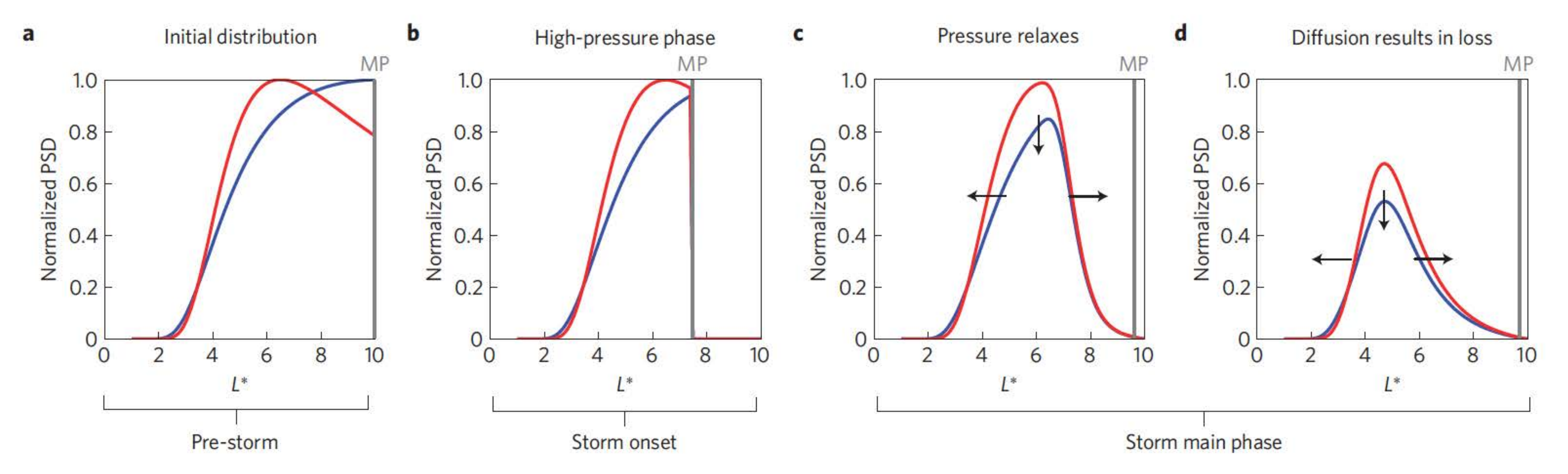


Qin+ 2016



Usanova+ 2014

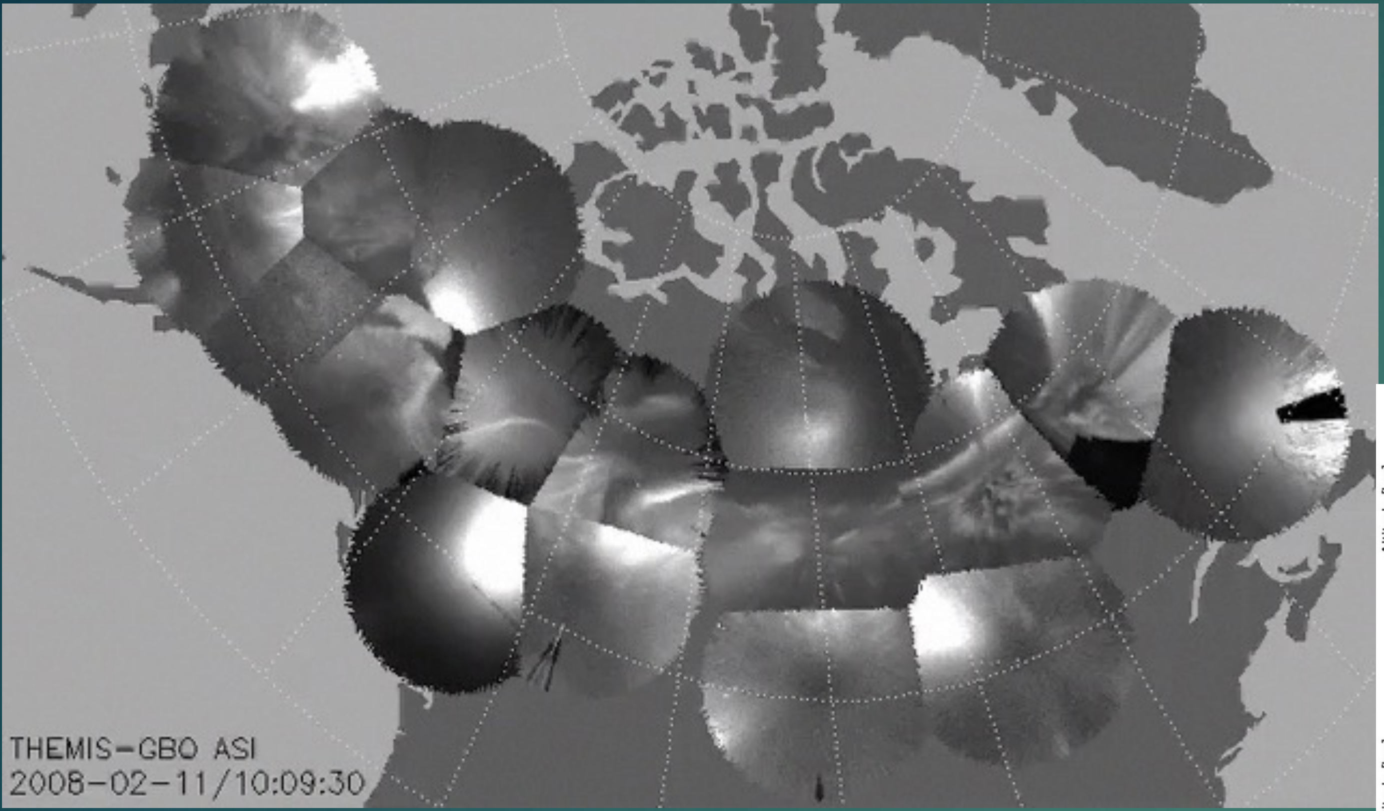
MP compression + outward radial diffusion



Turner+ 2012

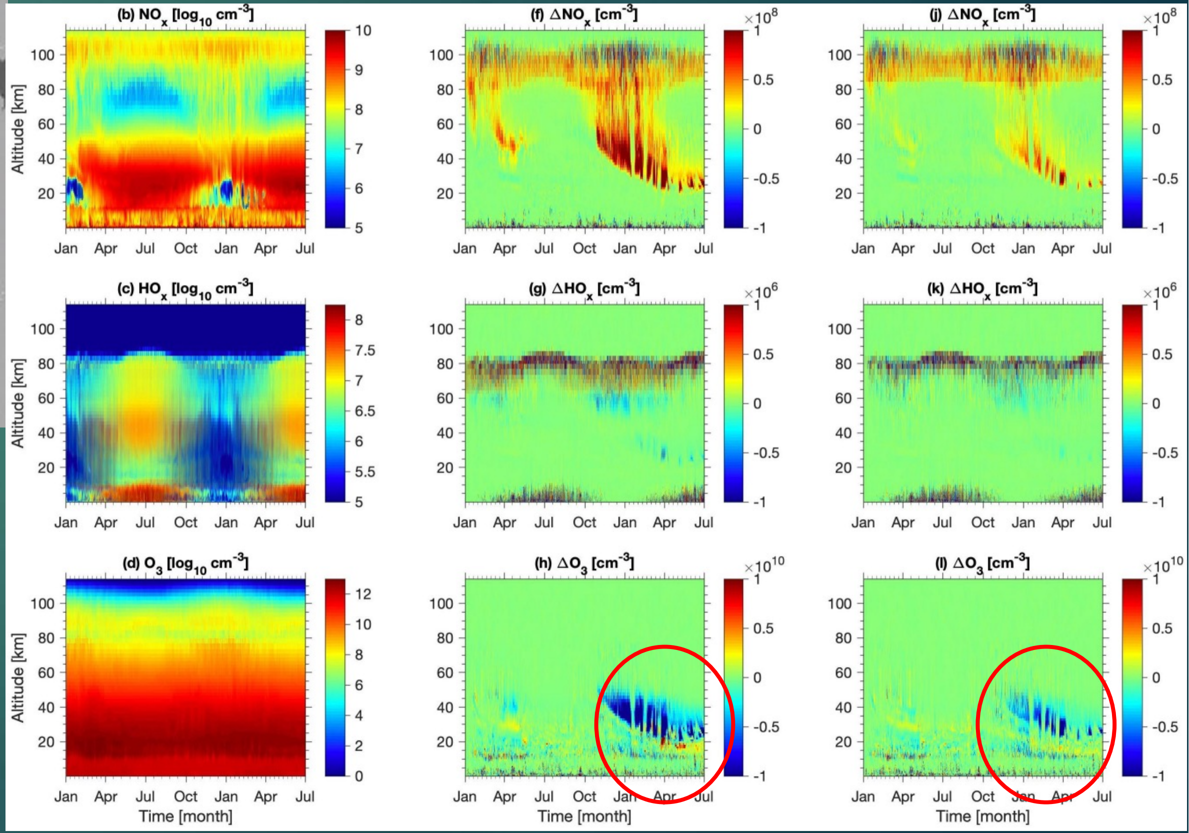
- This describes some events very well but those that effectively empty the radiation belts are more tricky
- <u>Ring current expansion</u> is likely very involved
- Just MP ~~shadowing~~ incursion + outward diffusion does not explain emptying of radiation belts down to low L-shells (diffusion rates are not quick enough)

Energetic precipitation associated with aurora



Jones+ 2013

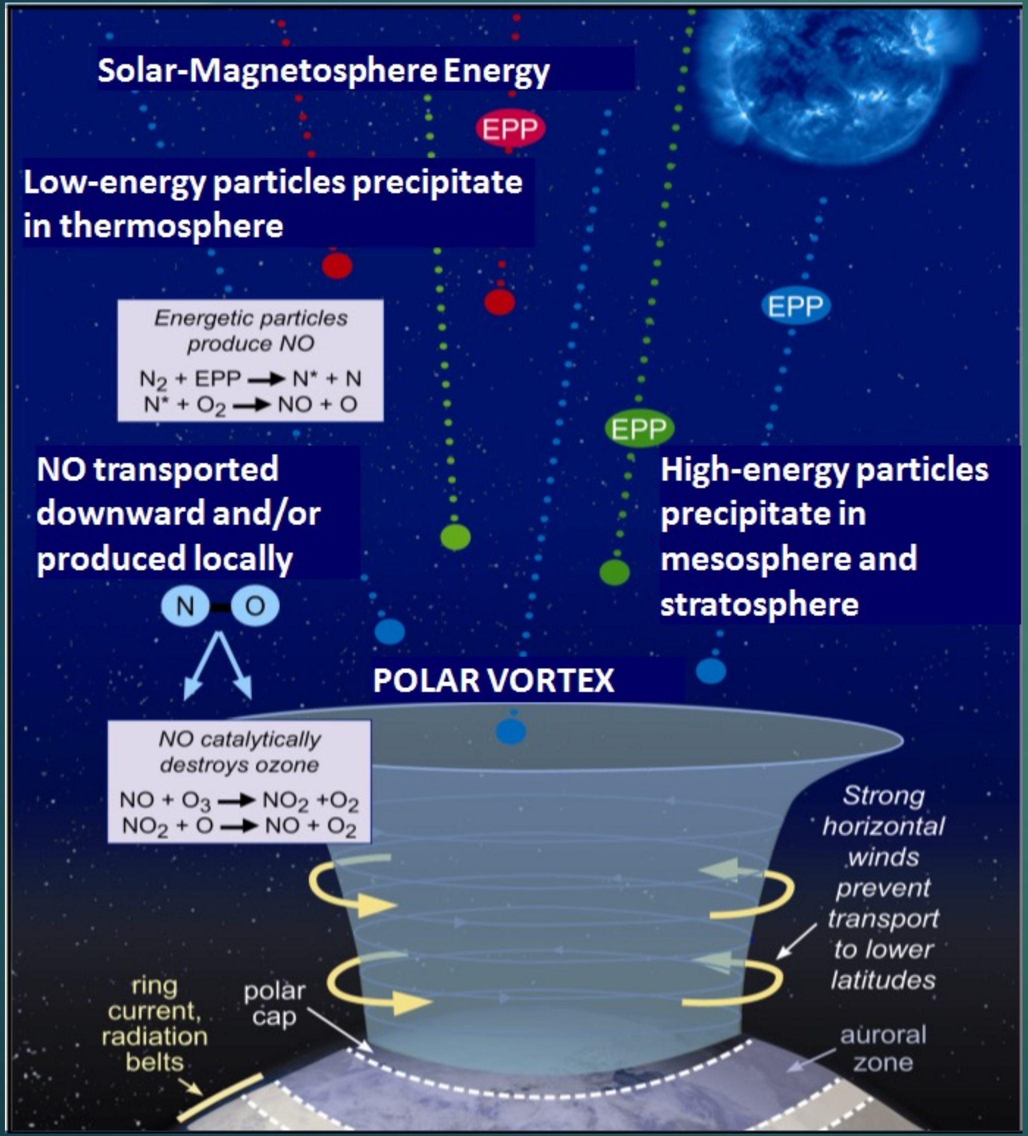
Pulsating aurora driven NOx can be circulated down to lower altitudes and drive long-term ozone loss

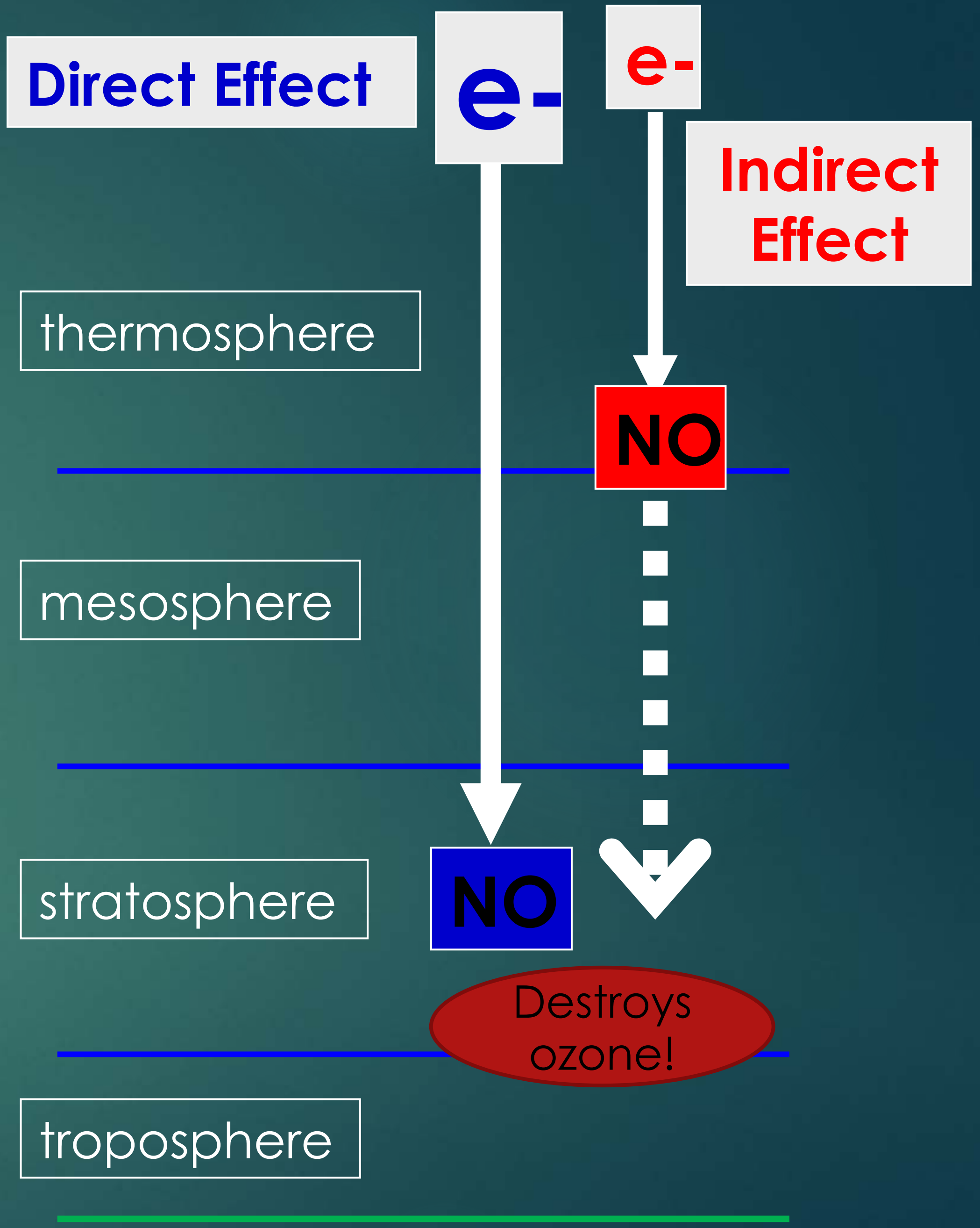


Verronen+ 20

Pulsating aurora contains a high energy tail up to >100 keV and likely constitutes a significant amount of the total energy dumped from the magnetosphere to our

Energetic particle precipitation impacts long-term weather & climate





Calculating Quantities

Solid state detector instruments

How do we get from count rate to particle flux?

Geometry factor

Energy spectrum

$$R = \Omega \int_0^\infty J_0 E^{-\gamma} \eta(E) dE$$

Count rate

Flux

Efficiency

The tricky part is getting the efficiency for your instrument!

We use what is called bow-tie analysis, with examples from the REPT instrument on Van Allen Probes

Bow-tie Method #1: Van Allen/Baker method

$$R = \Omega \int_0^{\infty} J_0 E^{-\gamma} \eta(E) dE = \Omega <\eta> \int_{E_1}^{E_2} J_0 E^{-\gamma} dE$$

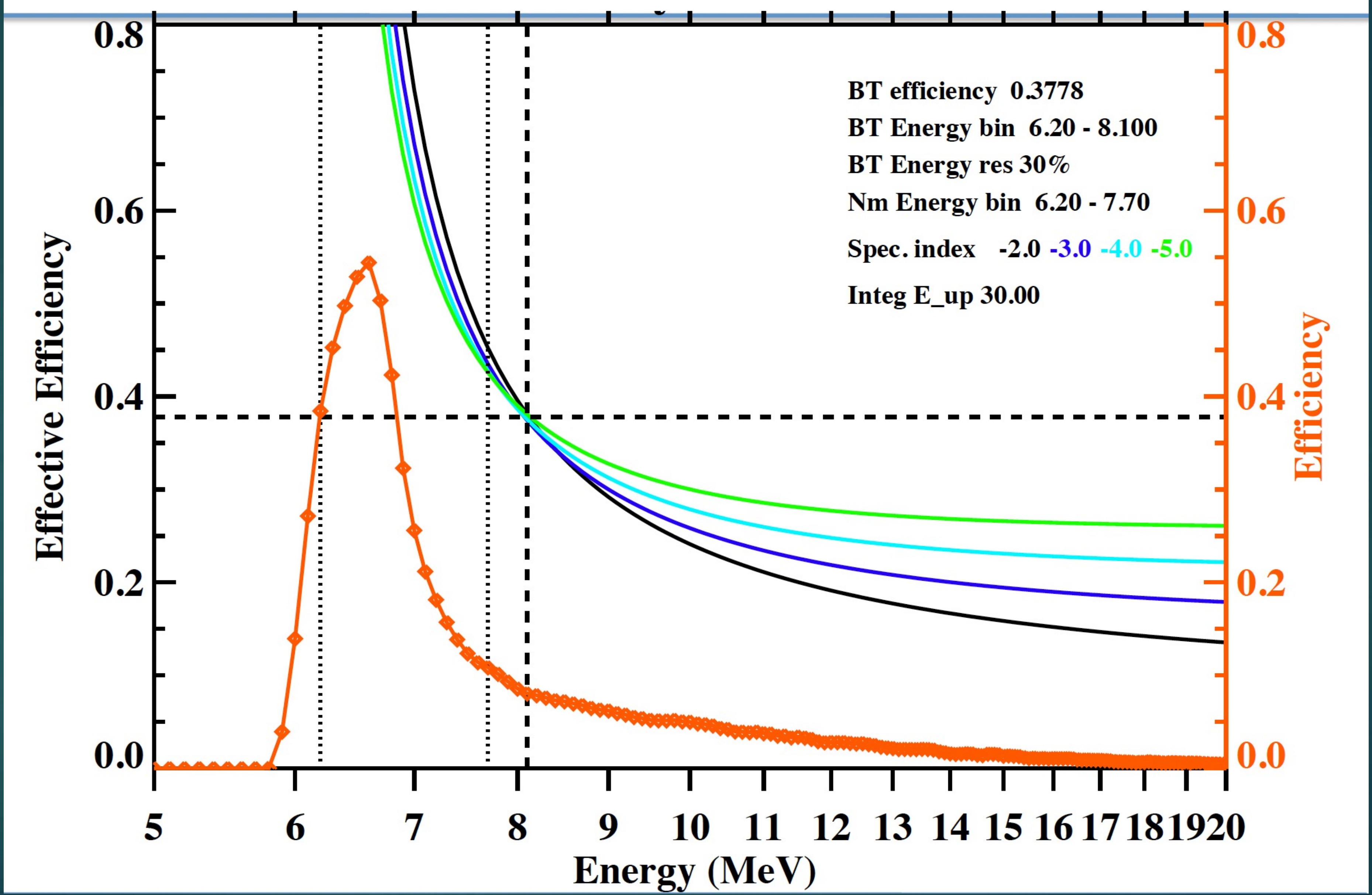
Where R is the count rate (number of particles/sec) observed and η(E) is the detection efficiency as a function of energy of the incident electron and Ω = 0.2 cm²-sr , the REPT geometry factor

$$<\eta> = \frac{\int_0^{\infty} E^{-\gamma} \eta(E) dE}{\int_{E_1}^{E_2} E^{-\gamma} dE}$$

Keeping E1 fixed to the nominal value and integrating up to different values of E2, we obtain a curve for <η> vs. E2 for each $J(E) = J_0 E^{-\gamma}$

The point where curves for a set of γ values intersect then gives E2 (x-axis) and <η> on (y-axis)

Example: e- 6.2-7.7 MeV



Bow-tie Method #2: Selesnick/Blake method

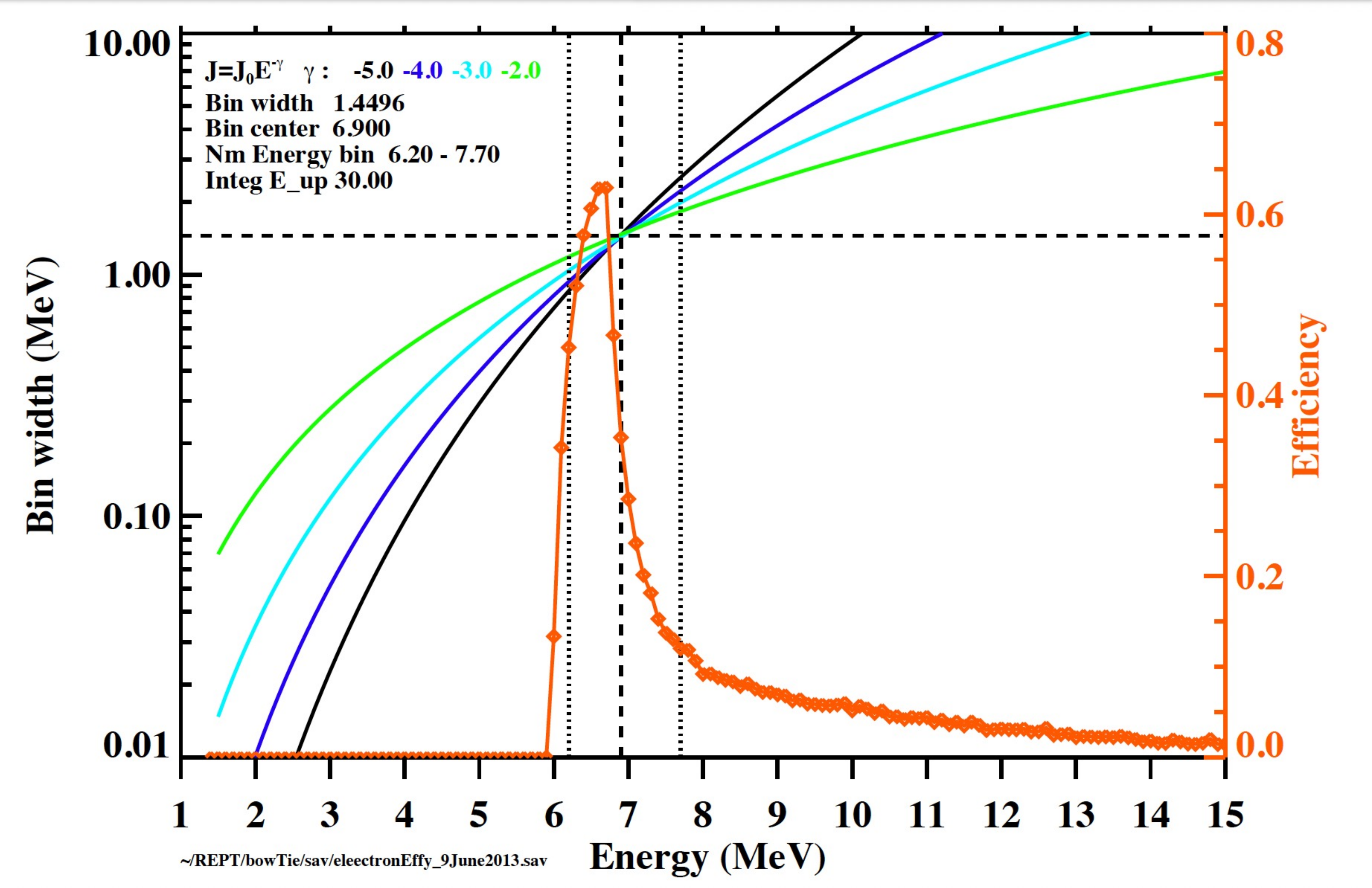
$$R = \Omega \int \eta(E) J_0 E^{-\gamma} dE = \Omega \delta E J_0 \bar{E}^{-\gamma}$$

$$\delta E = \bar{E}^{\gamma} \int \eta(E) J_0 E^{-\gamma} dE$$

Plotting right hand side of second equation vs. E for various values of γ, we obtain a curve for δE vs. E for each $J(E)= J_0E^{-\gamma}$

The point where curves for a set of γ values intersect then gives E (x-axis) and δE on (y-axis)

Example: e- 6.2-7.7 MeV



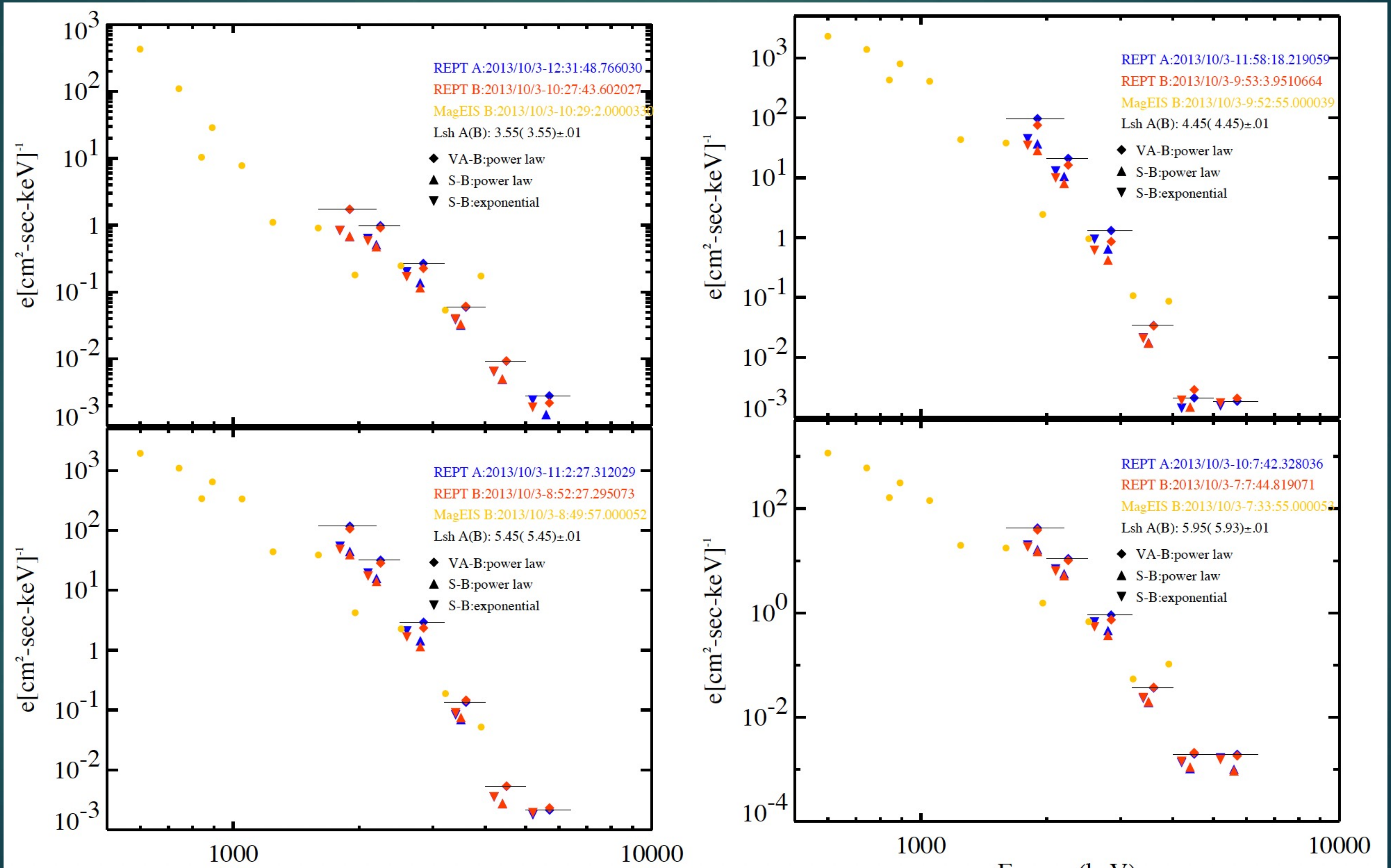
$J = J_0 E^{-\gamma}$ $\gamma = -2, -3, -4, -5$ $J = J_0 \exp(-E/E_0)$ $E_0 = 0.2, 0.4, 0.6, 0.8, 1.0$

Method 1 (power law)			Method 2 (power law)		Method 2 (exponential)	
Nominal channel	Effective efficiency<η>	Bow tie bin (MeV)	Bow tie Energy <E> (MeV)	Bin width δE (MeV)	Bow tie Energy <E> (MeV	Bin width δE (MeV)
1.6-2.4	0.070	1.6-2.2	1.9	0.11	1.8	0.09
2.0-2.5	0.162	2.0-2.5	2.2	0.16	2.1	0.13
2.5-3.2	0.364	2.5-3.2	2.8	0.51	2.6	0.35
3.2-4.0	0.322	3.2-4.0	3.5	0.49	3.4	0.41
4.0-5.0	0.574	4.0-5.0	4.4	1.10	4.2	0.85
5.0-6.2	0.450	5.0-6.4	5.6	1.24	5.2	0.75
6.2-7.7	0.380	6.2-8.1	6.9	1.45	6.3	0.70
7.7-9.7	0.265	7.7-9.9	8.5	1.16	7.7	0.52
9.7-12.1	0.132	9.7-13.6	11.2	0.97	9.9	0.30
12.1-15.1	0.079	12.1-18.6	14.1	0.93	12.3	0.17

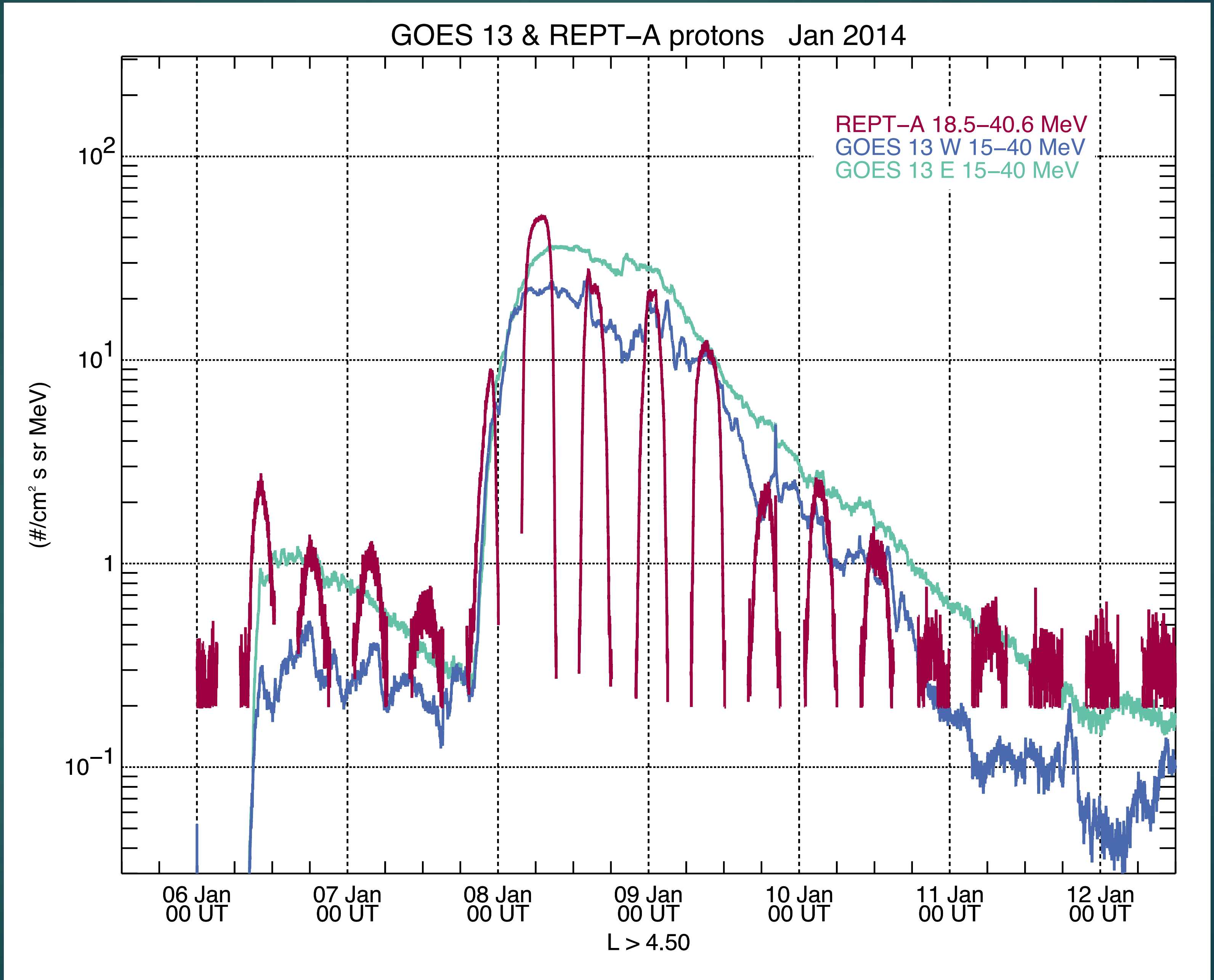
How can we check the fluxes we calculate to be sure they are correct?

Cross-calibrate with another instrument

REPT & MagEIS – both on board Van Allen Probes



Cross-calibrate with another spacecraft



Additional Slides

Plasma waves in the magnetosphere

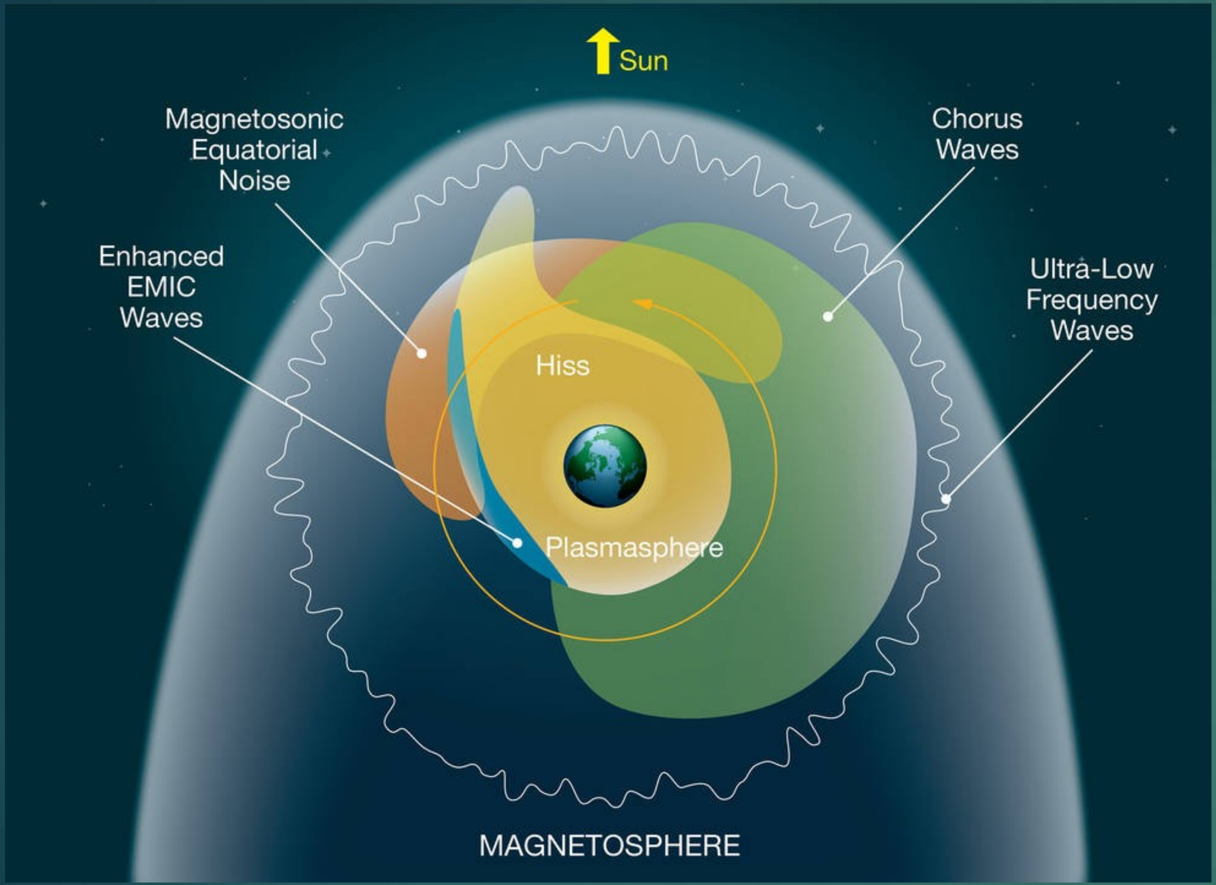
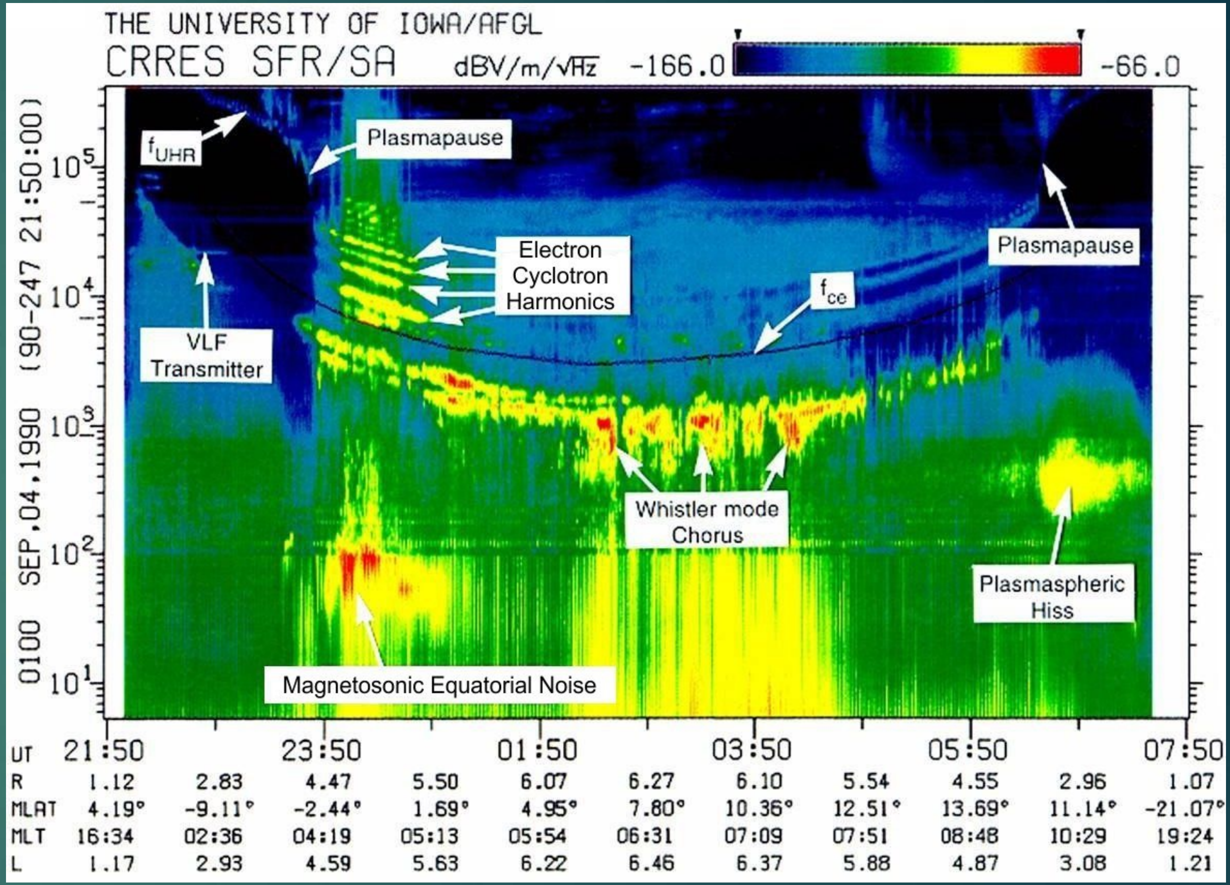
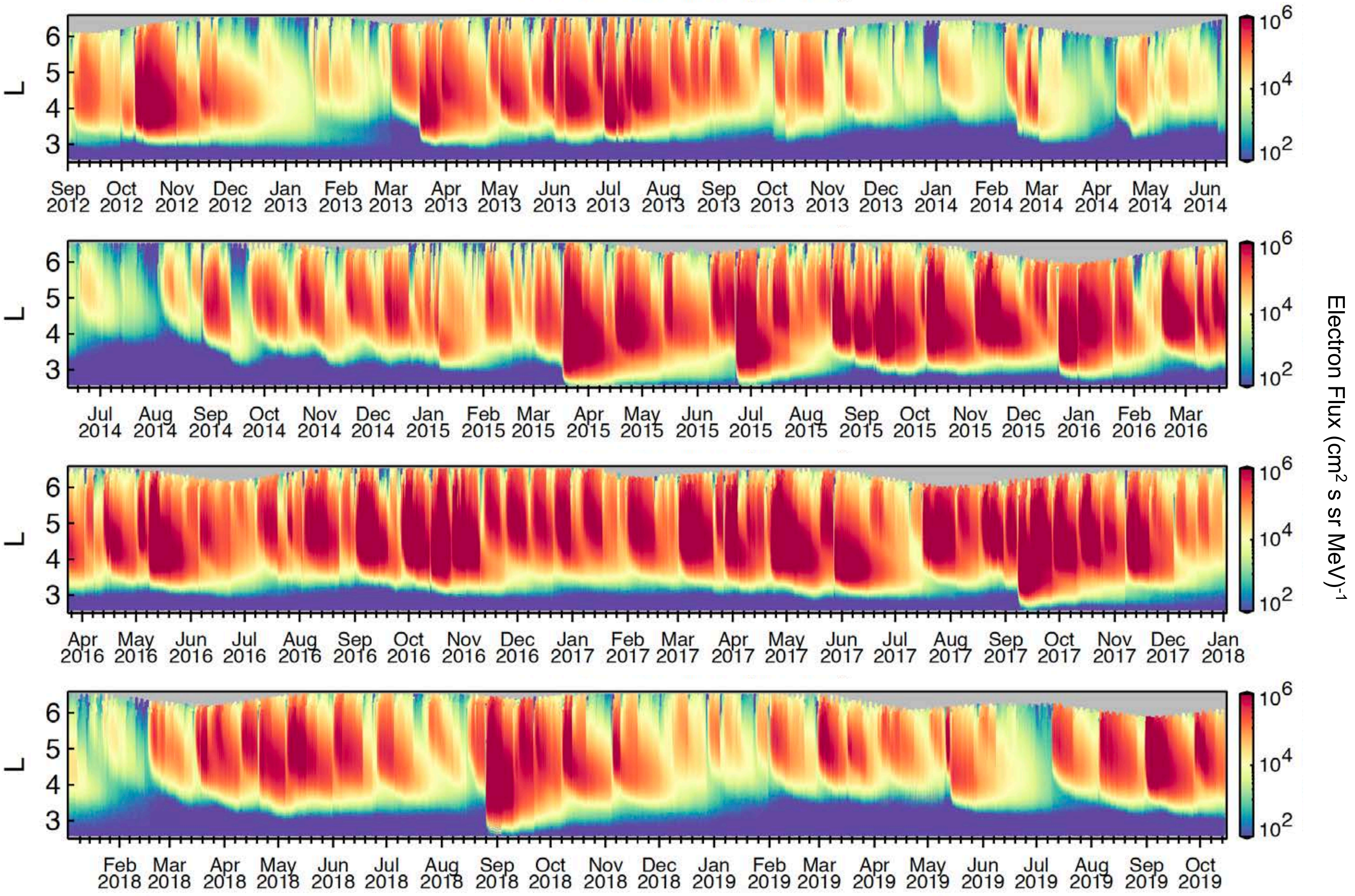


Figure from NASA GSFC, adapted from Thorne et al. 2005

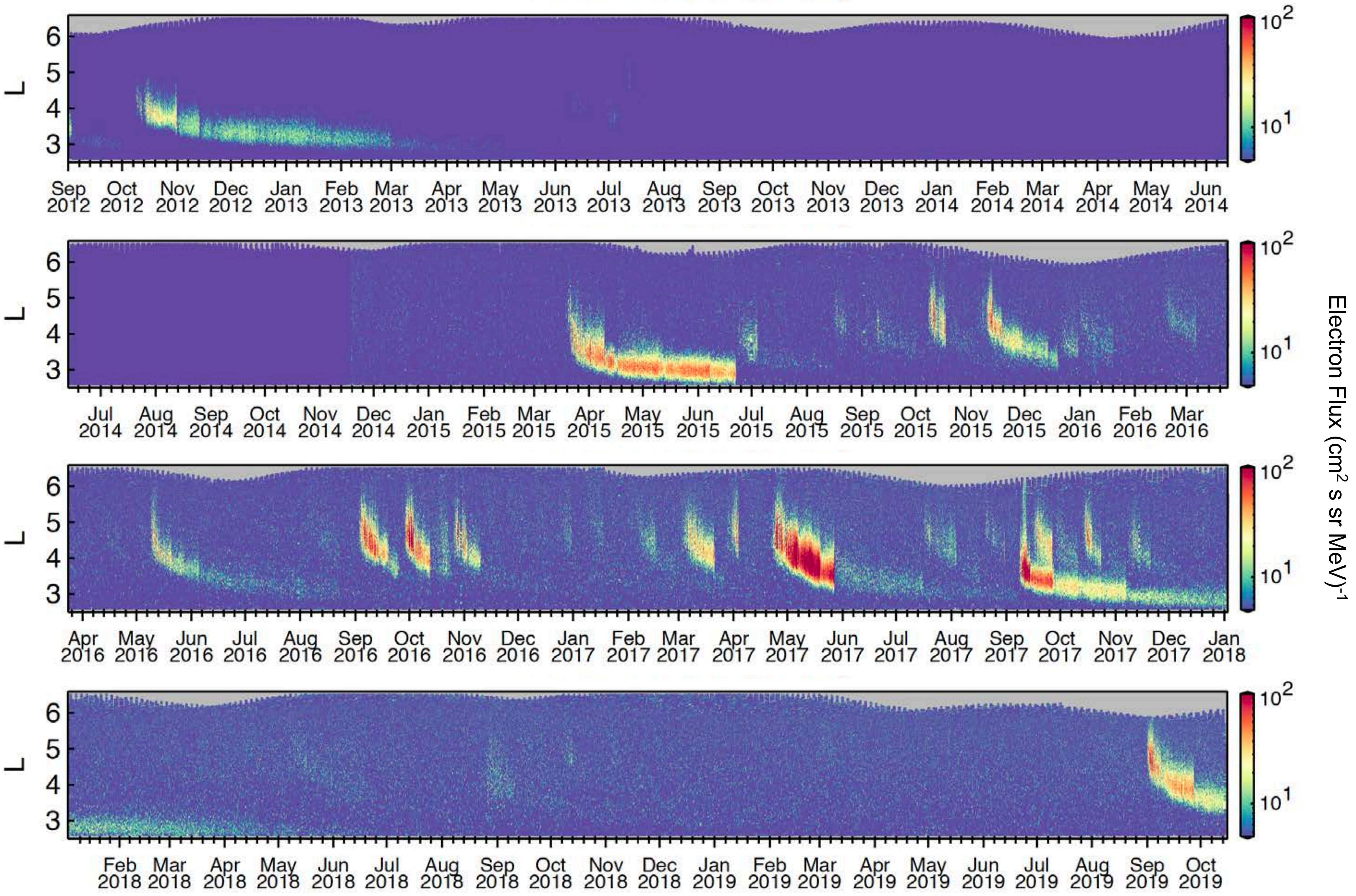


Tsurutani and Smith, 1974

REPT A & B   1.8 MeV Electrons



REPT A & B 7.7 MeV Electrons



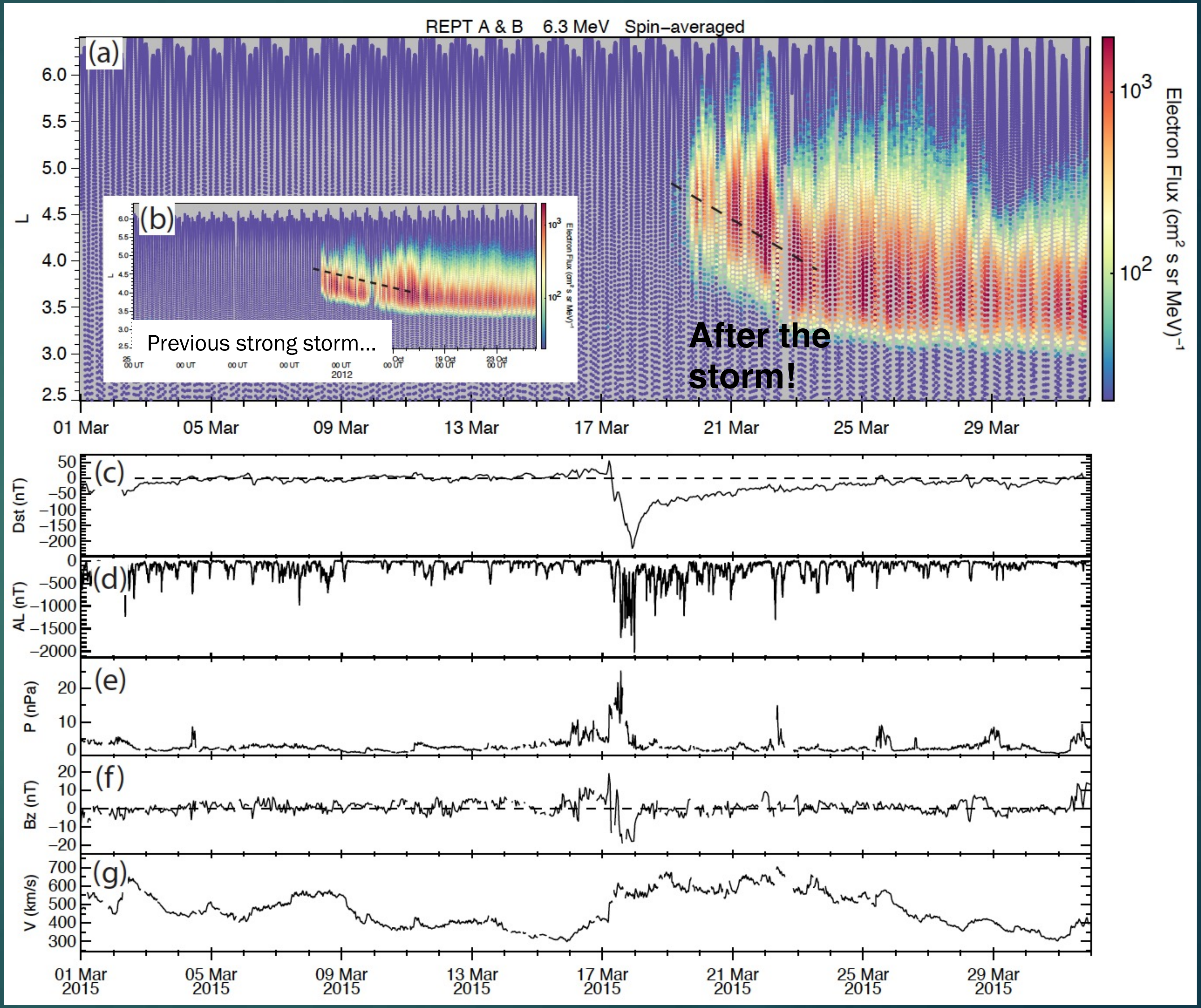
17 March 2015 storm event: fast diffusion of ultra-relativistic electrons

Inward radial diffusion that results in multi-MeV electrons at L~4 is apparent in both flux and PSD data

Almost no chorus waves by the time ultra-relativistic energies start to appear in the outer belt

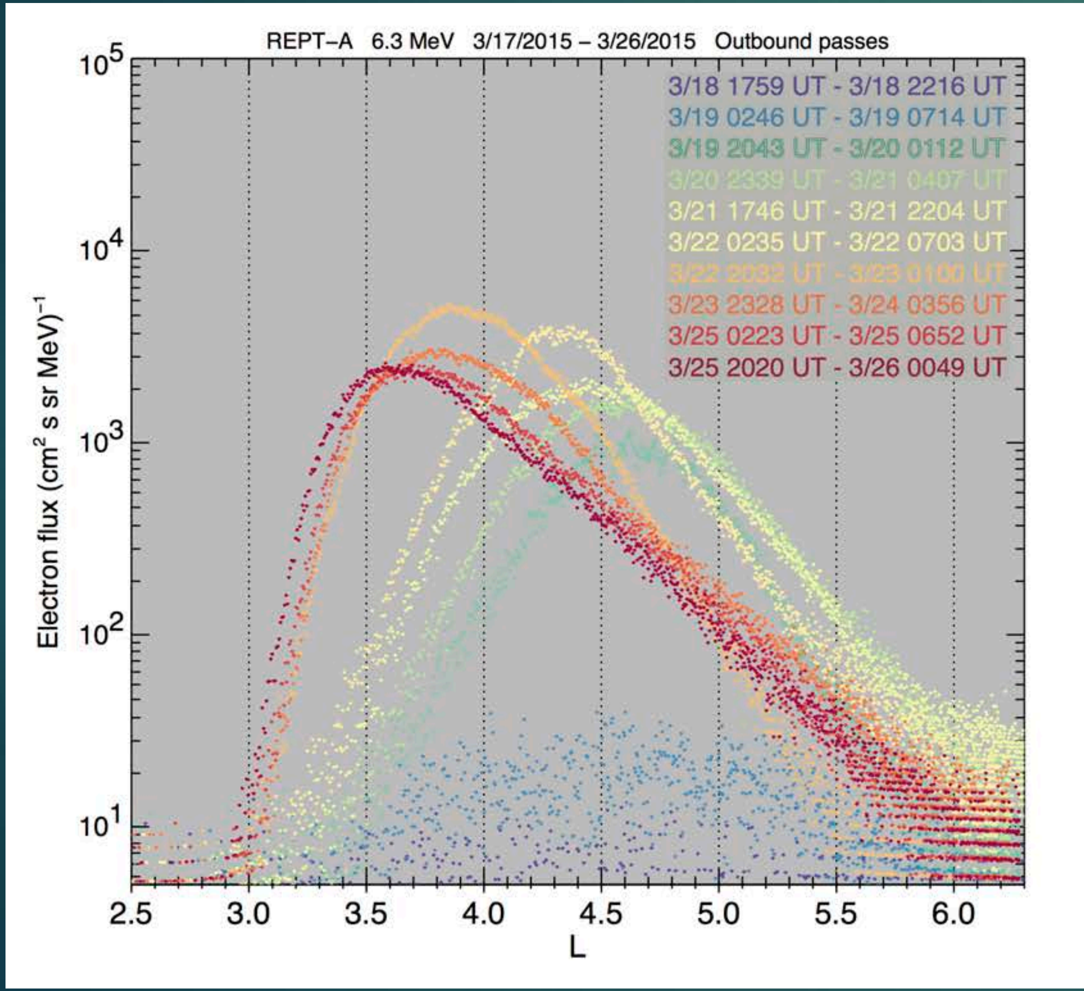
Acceleration occurs <u>after</u> the storm, well into the recovery phase

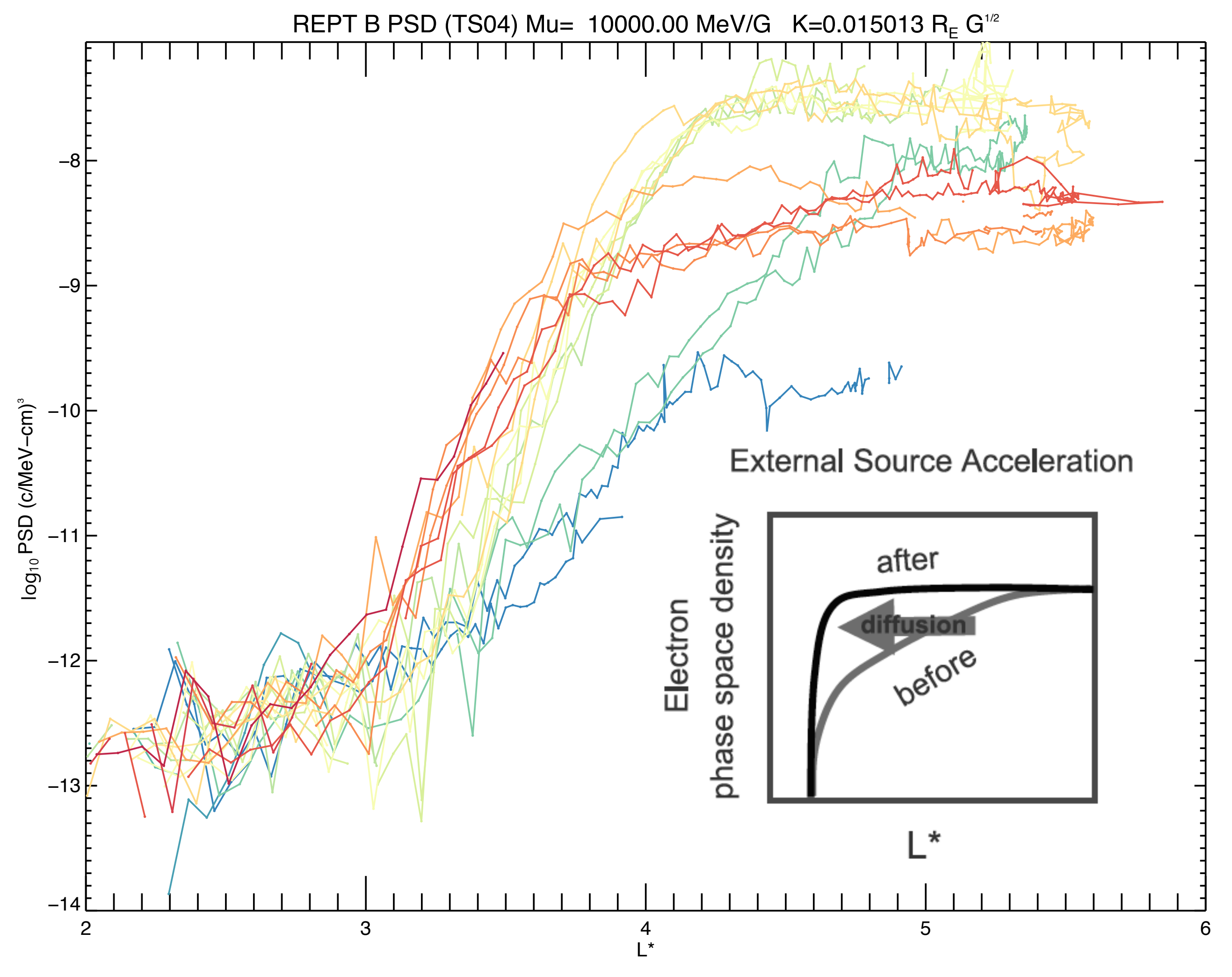
Jaynes+ 2018, *GRL*



Fast radial diffusion

- Flux peak rises and shifts to lower L, phase space density increases by 2 orders of magnitude
- Acceleration from external source is clear in PSD data (right panel)

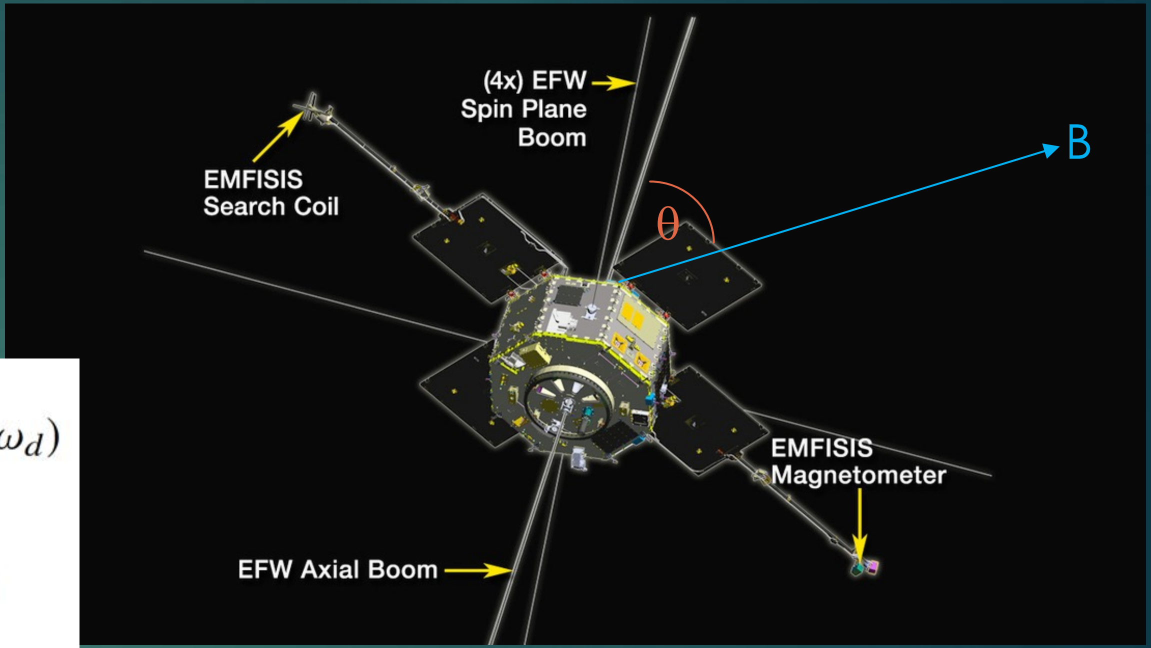




Jaynes+ 2018, *GRL*

ULF wave power

- EFW axial E field derived from E•B=0
  - If B is greater than ~6º from spacecraft spin axis
- Components of E and B used to obtain $B_{||}$ and E_ϕ
- Method detailed in Ali+ 2016

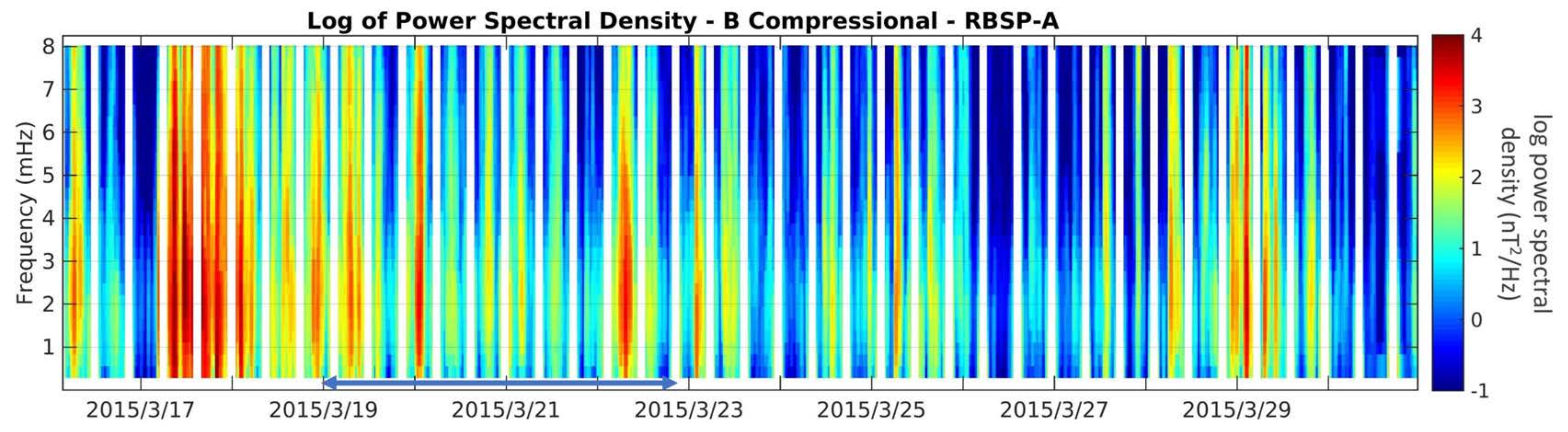


- Diffusion coefficients from Fei+ 2006 formulation

$$D^B_{LL} = \frac{M^2}{8q^2\gamma^2B_E^2R_E^4} L^4 \sum_m m^2 P^B_m(m\omega_d)$$

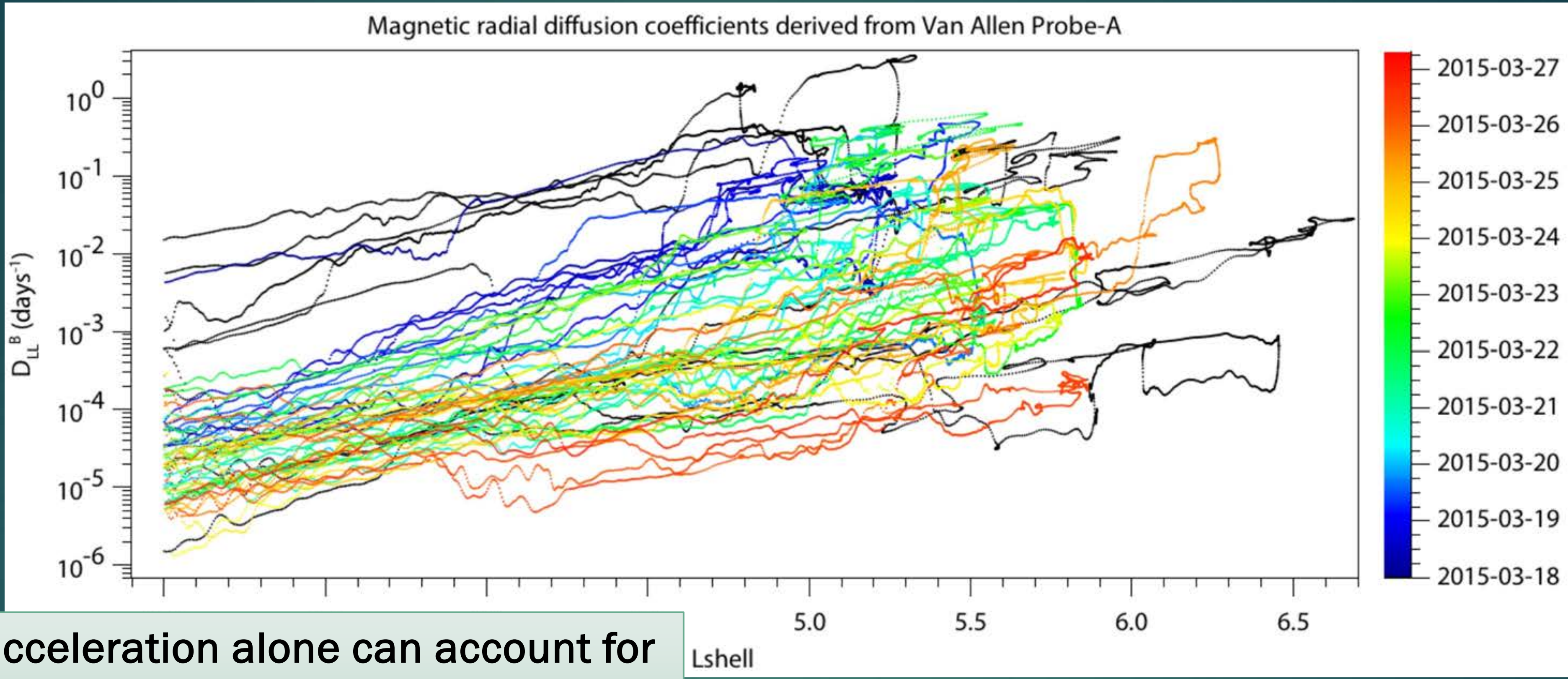
$$D^E_{LL} = \frac{1}{8B_E^2R_E^2} L^6 \sum_m P^E_m(m\omega_d)$$

March 17, 2015 storm ULF wave power



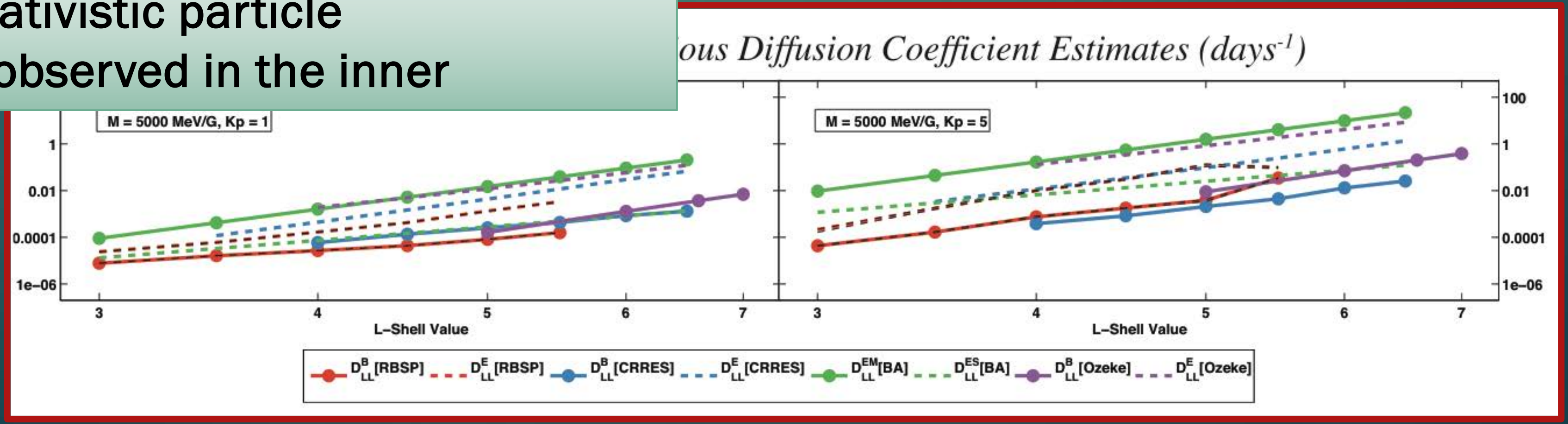
Jaynes+ 2018, *GRL*

Radial diffusion rates are event-specific (and magnitudes change throughout)



Jaynes+ 2018, GRL

ULF-driven acceleration alone can account for intense ultra-relativistic particle enhancements observed in the inner magnetosphere



Ali+ 2016

Back to VLF chorus waves…

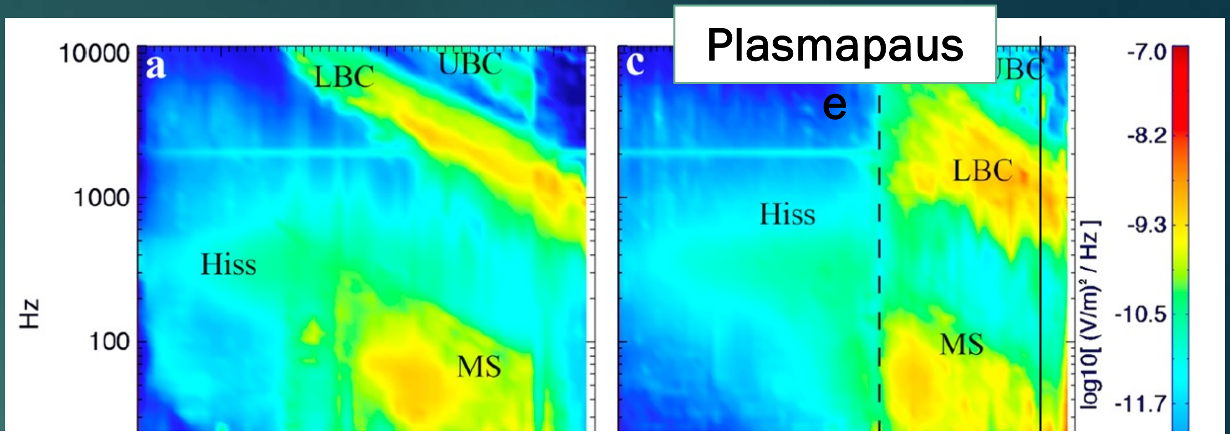
Tasked an REU undergraduate summer student with sorting through and aggregating all wave power over 3+ years of the Van Allen Probes mission

Mean electric and magnetic field spectra covering 3 years for the dawn MLT sector

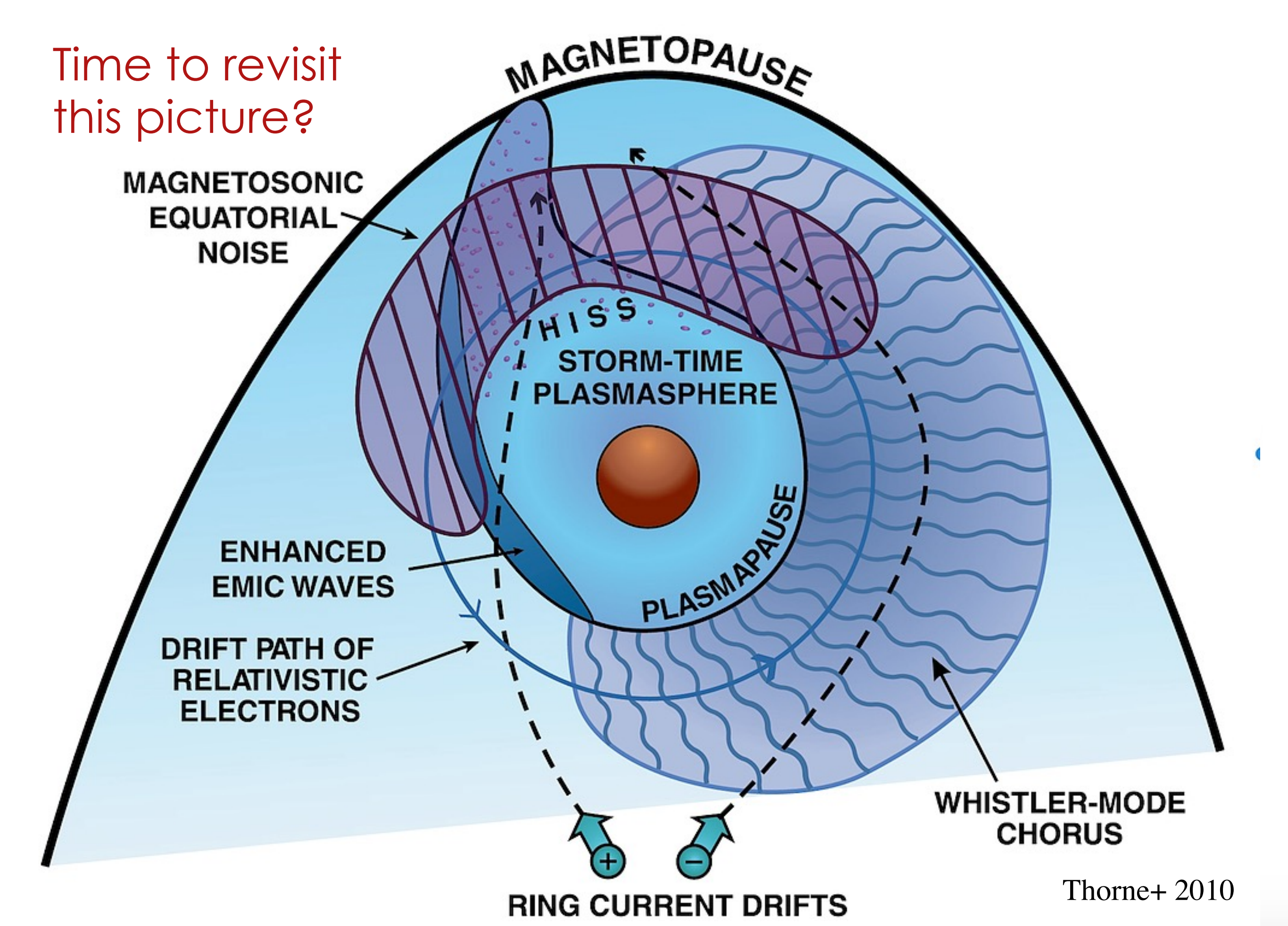
Waves are <u>highly organized</u> with respect to the plasmapause! (right panels)

VLF chorus exhibits a ~1 L-shell stand-off distance outside the plasmasphere boundary

Malaspina+ 2016



Time to revisit this picture?



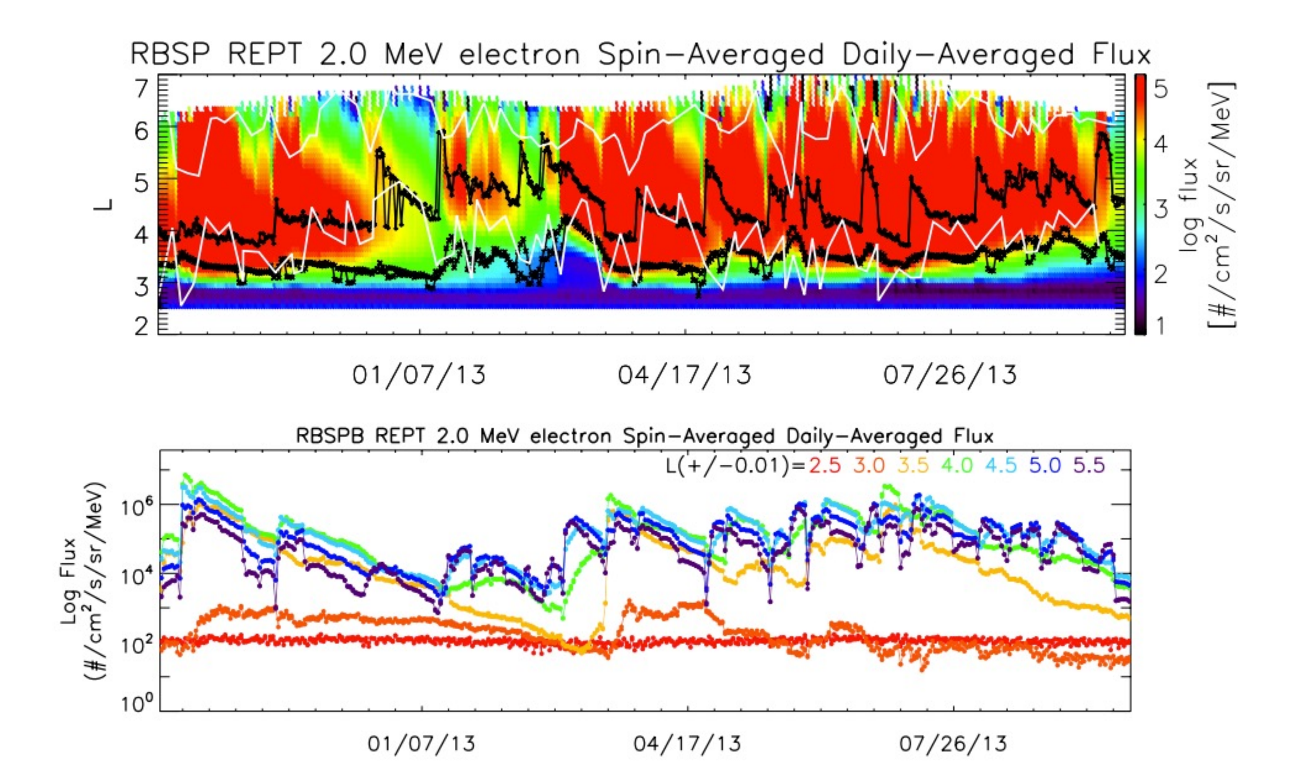
Thorne+ 2010

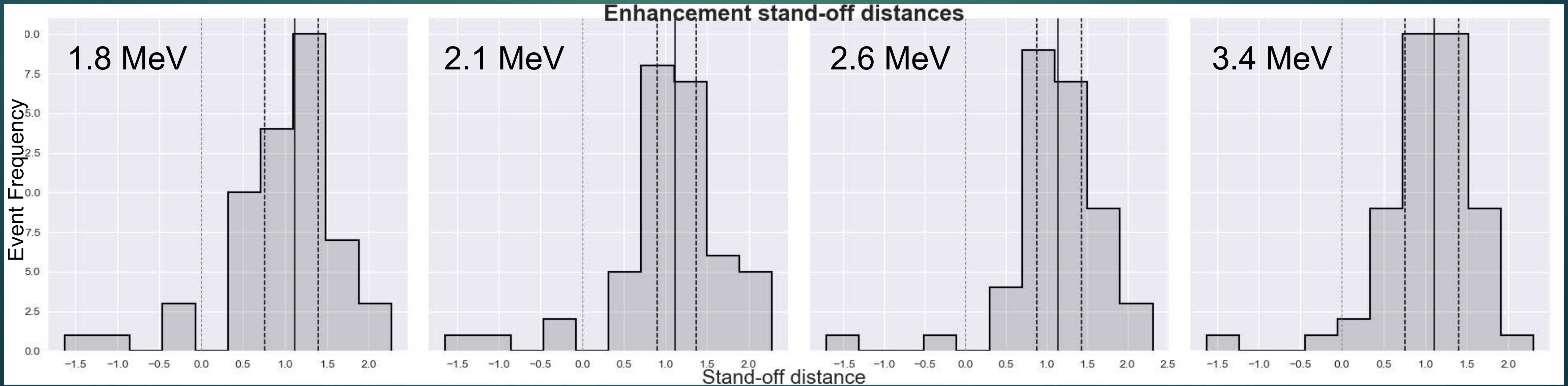
Connection to ultra-relativistic enhancements

Next year, a different REU undergraduate summer student found the locations of peak flux following enhancement events – and their distance from the local plasmapause

Spatial distribution of relativistic electron enhancements is very similar to VLF chorus wave distribution: stand-off of ~1 L-shell from the plasmapause

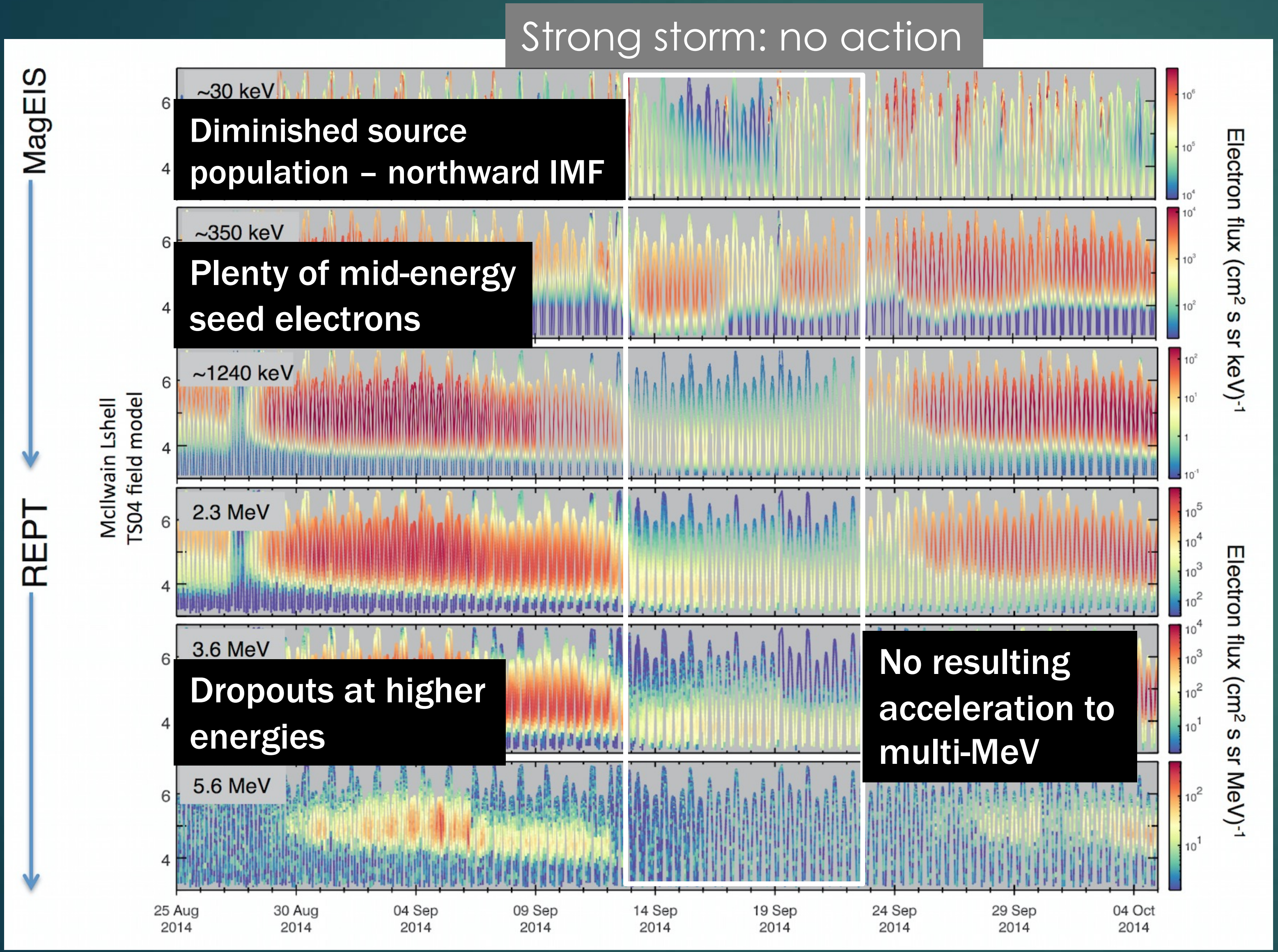
Hints that local acceleration by VLF chorus may *usually* be the dominant mechanism





Bruff+ *in prep*

The case for local acceleration

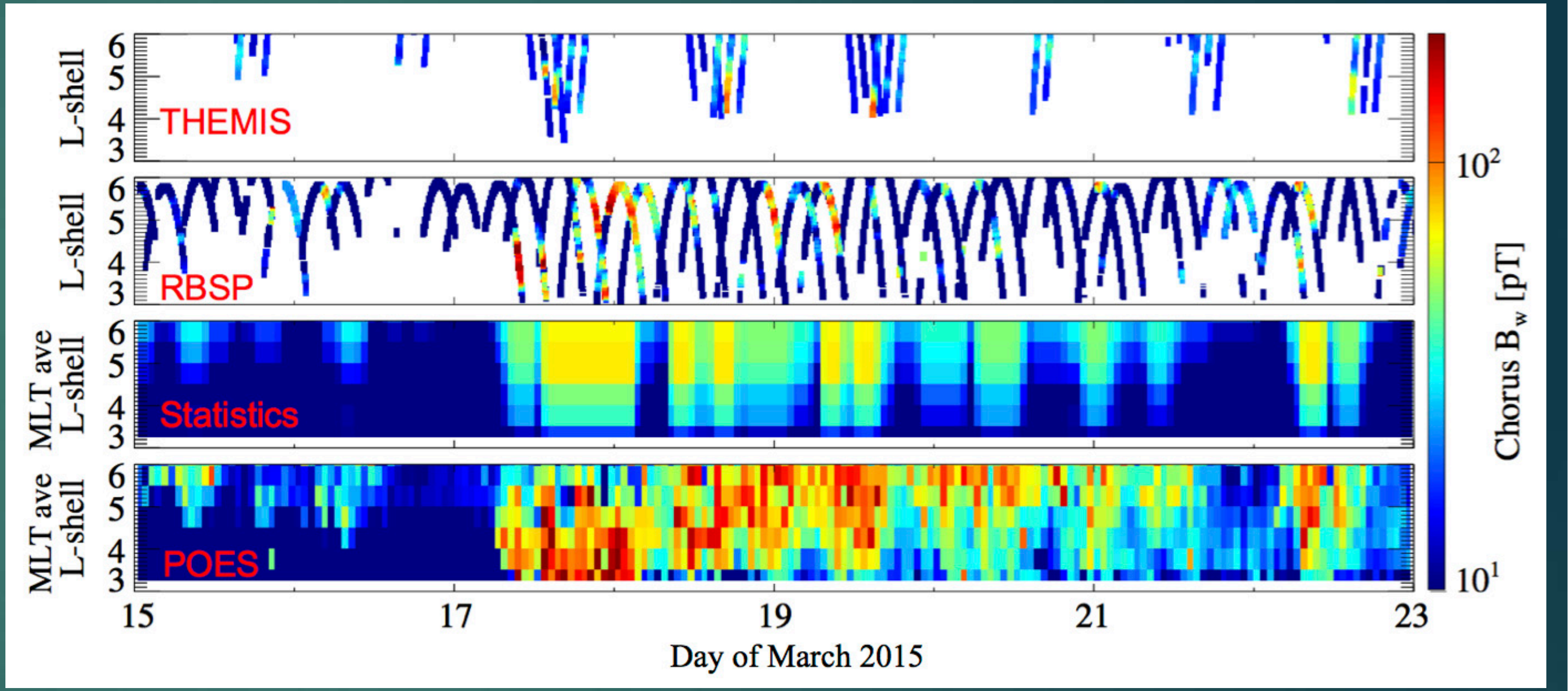


September 2014 storm event (Dst = -100 nT) with no enhancement of relativistic electron populations

Jaynes+ 2015

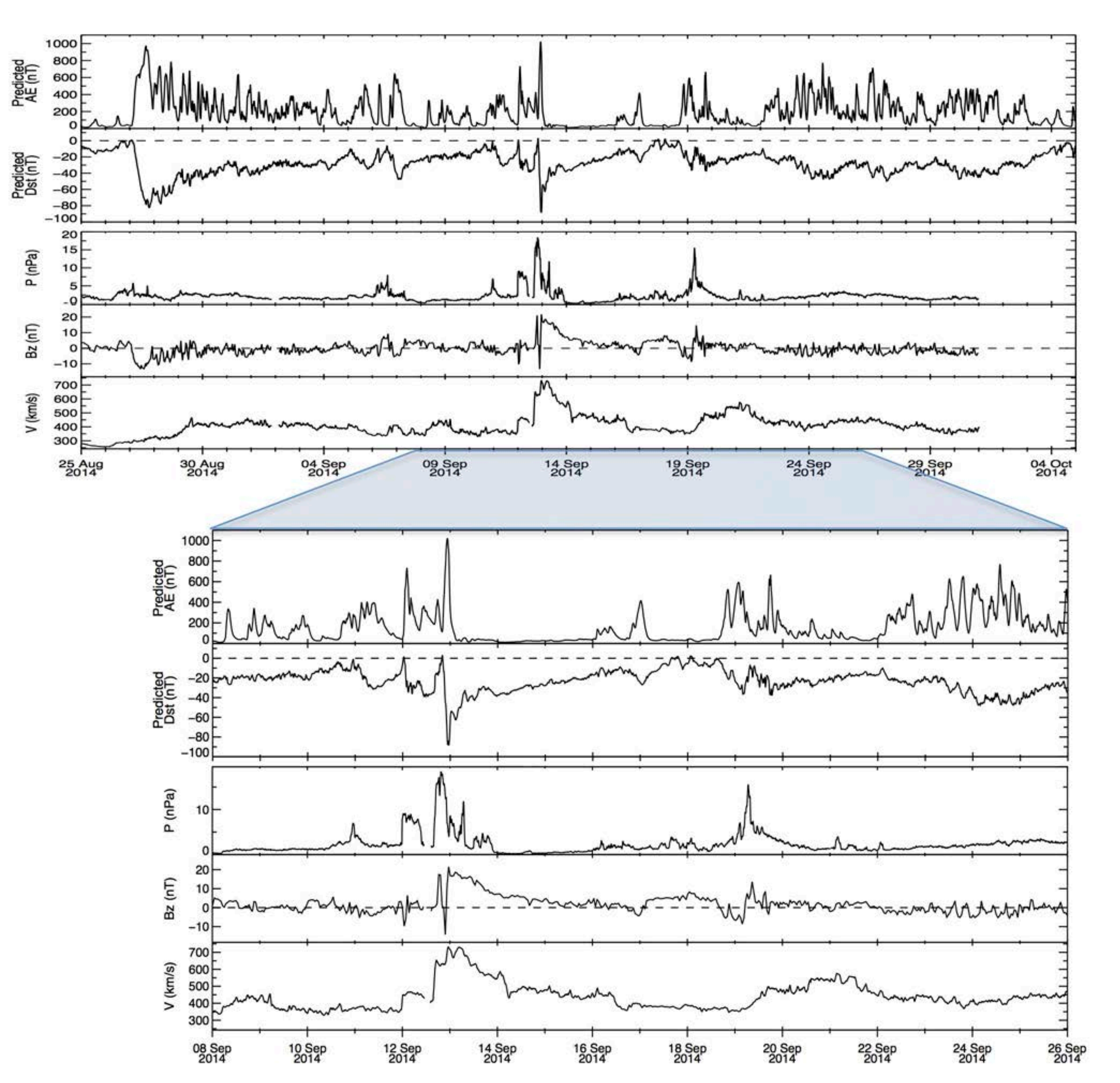
Response to storm

- Acceleration of lower relativistic energies (~800 keV) started within <1day
- Higher energies showed up later and later, with the 7.7 MeV electrons appearing on March 20 (3 days after storm commencement)
- Lower energies are accelerated in the heart of the outer belt; higher energies are driven inward from higher L-shells
- Chorus waves have subsided by the time ultra-relativistic energies appear in the outer belt

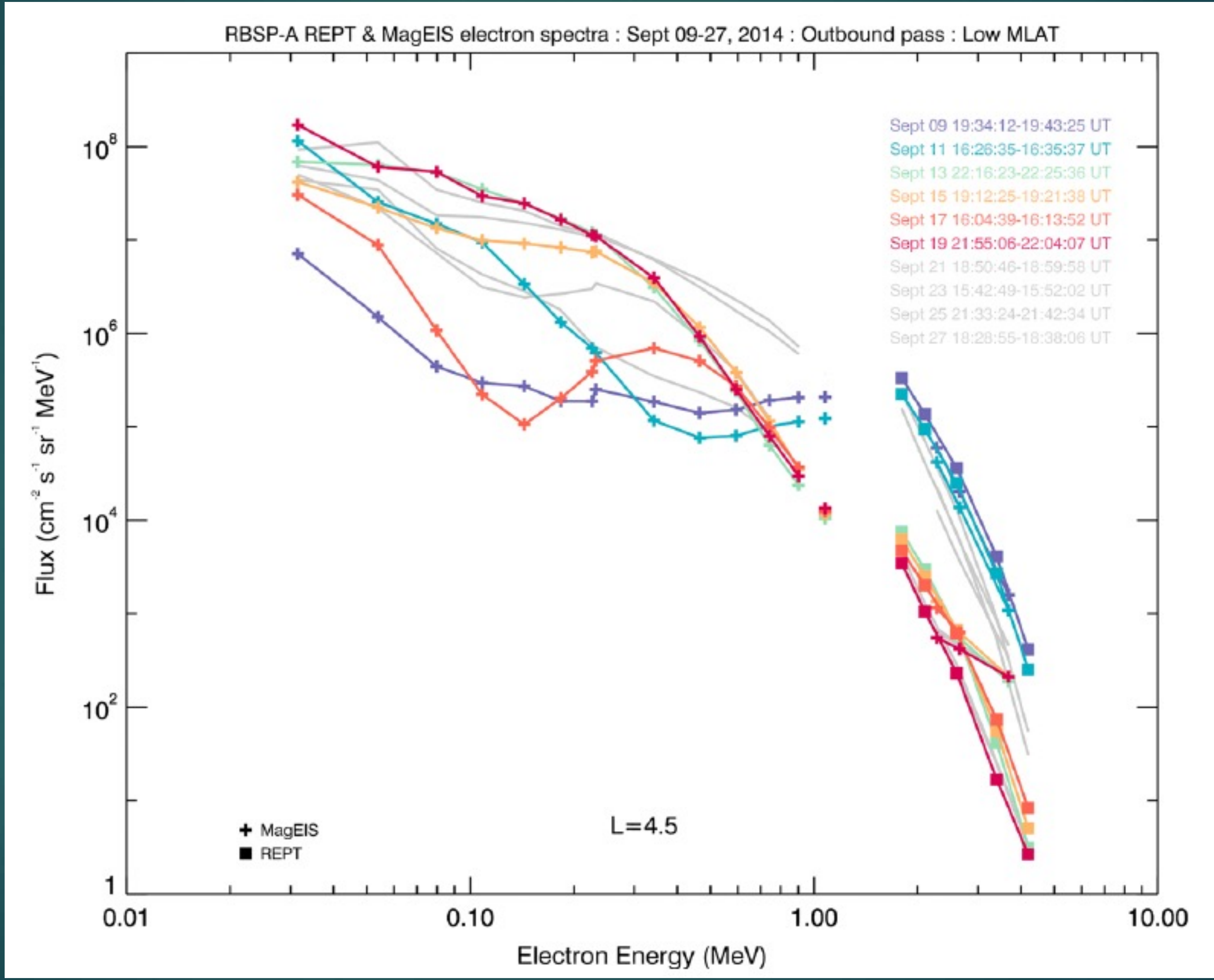


Solar wind driving

September 2014 storm event with little/no enhancement of relativistic electron populations



"Pivoting" electron spectrum



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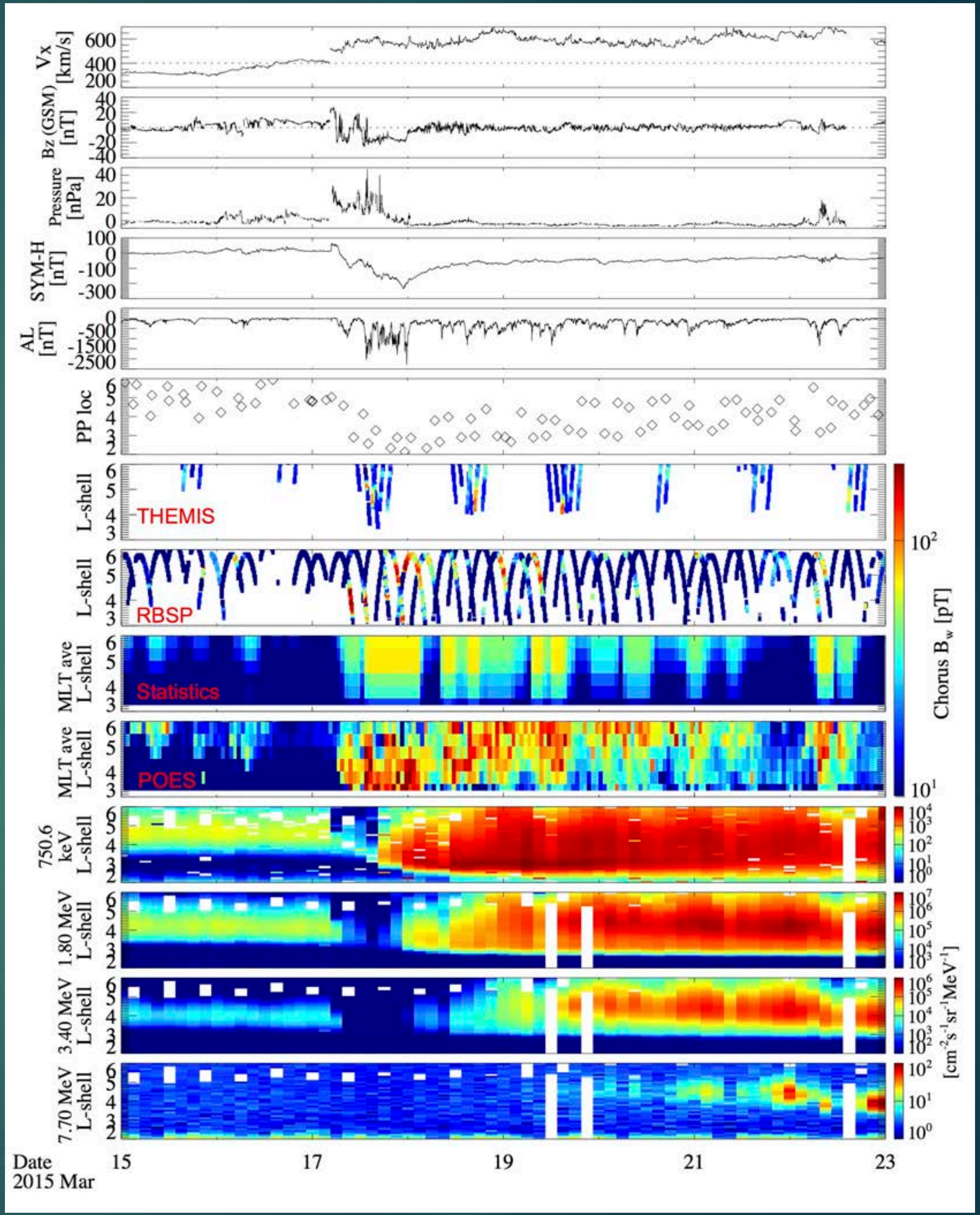
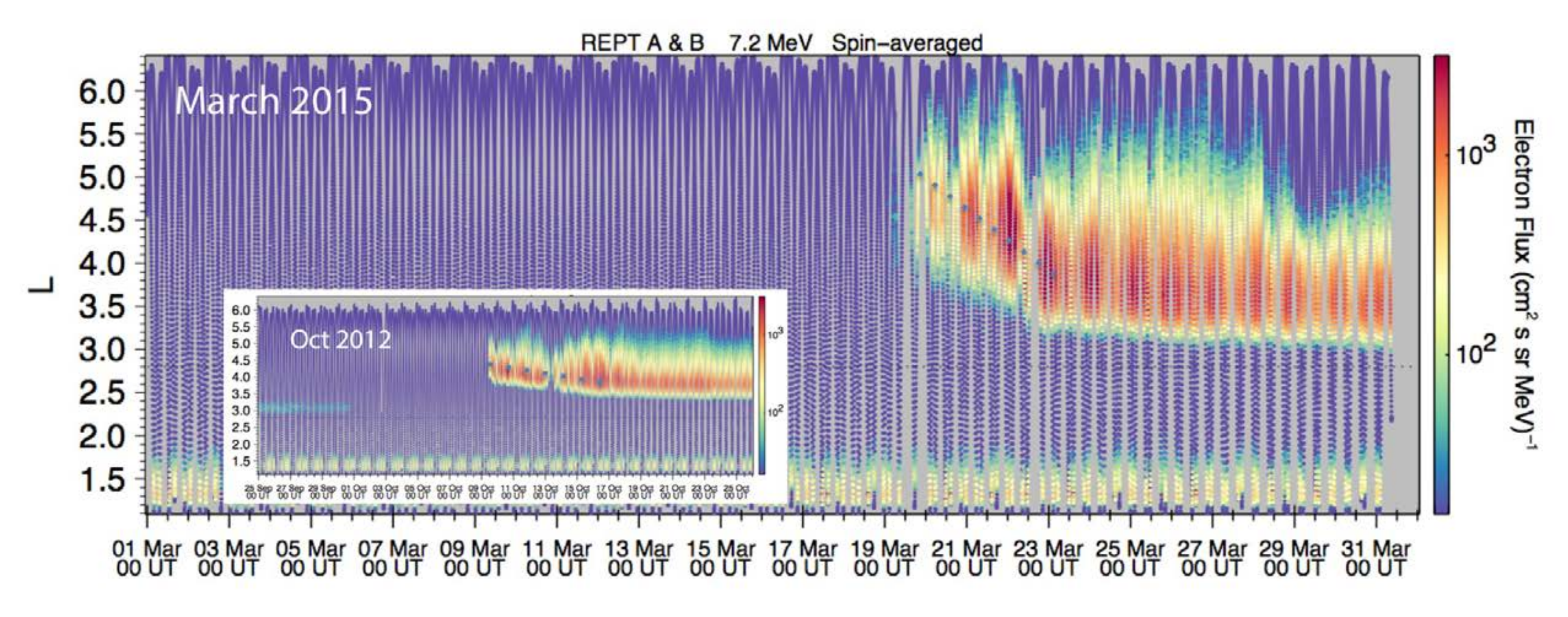


Figure courtesy of Wen Li

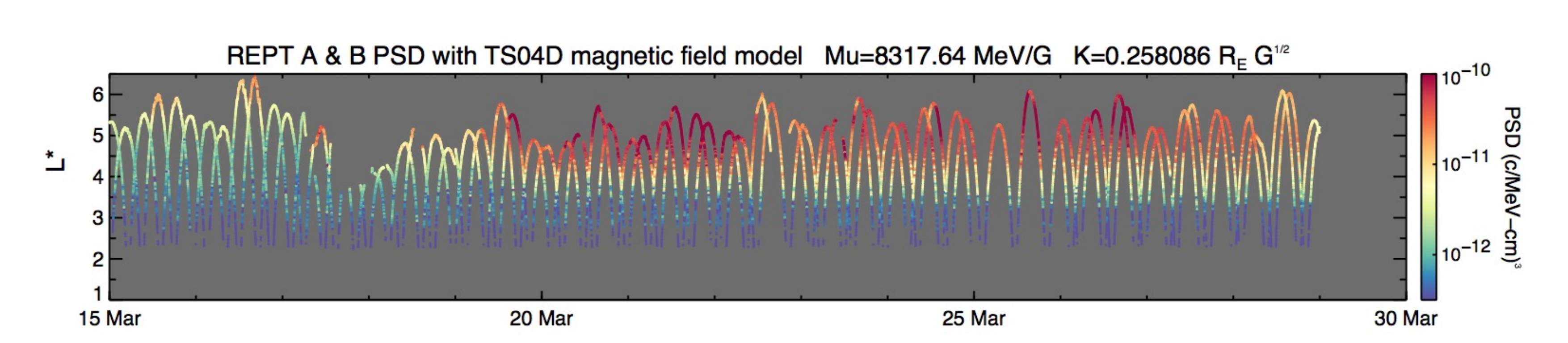
Fast radial diffusion

Energy flux



Jaynes+ 2018, to be submitted

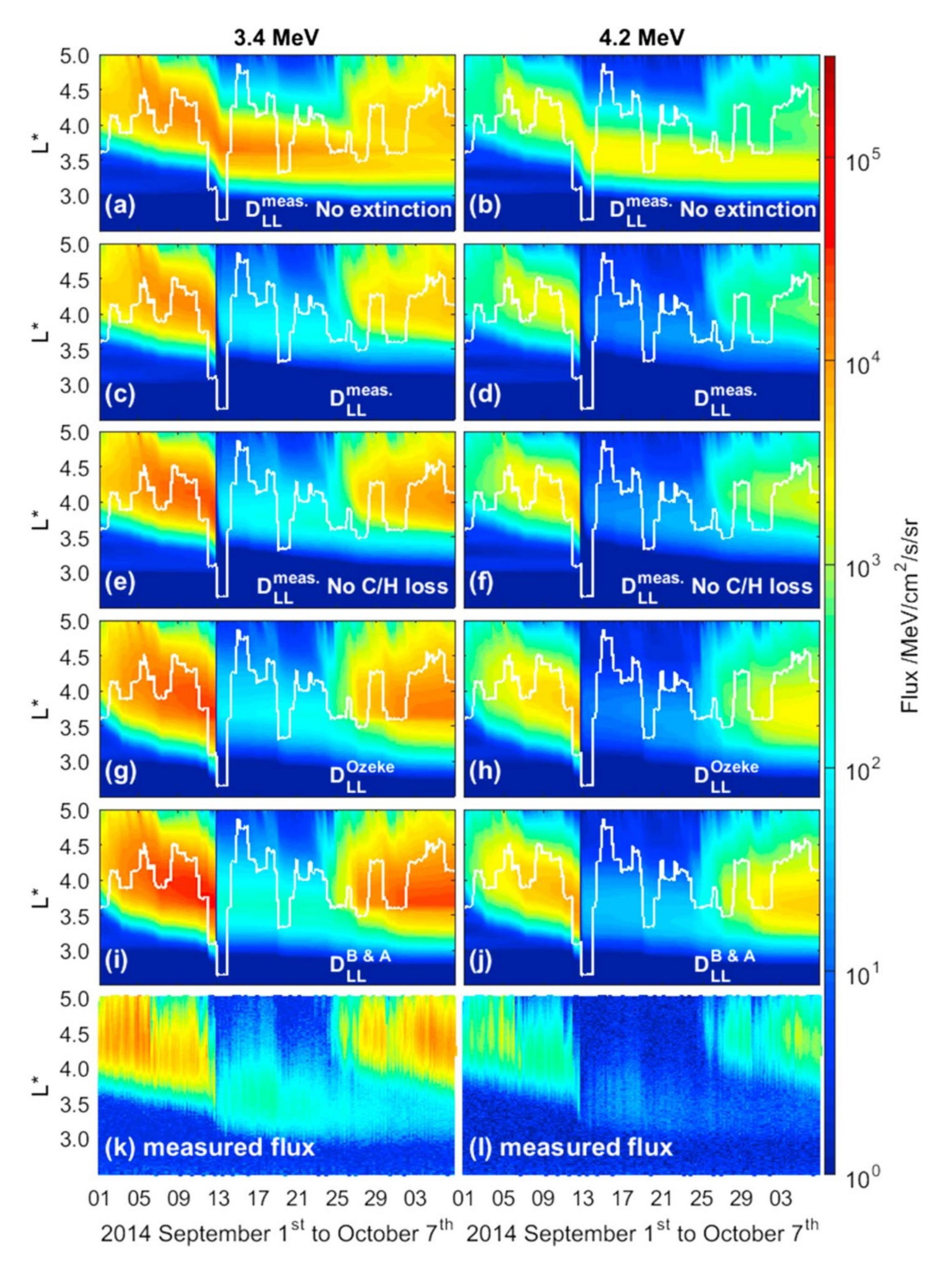
Phase space density



Inward radial diffusion that results in multi-MeV electrons at L~4 is apparent in both flux and PSD data.

Modeling the September 2014 event

- ULF wave-driven radial diffusion may be sufficient to simulate extended dropout of September 2014 and subsequent enhancement
- No local acceleration or ongoing hiss/chorus loss was included in this work
- The initial dropout still unexplained
- ULF wave contribution should clearly be considered during dynamic events– need to disentangle the role of VLF vs. ULF



Ozeke et al., 2017, *GRL*