JOHNS HOPKINS
APPLIED PHYSICS LABORATORY

Radiation Belts

Some of Nature's own particle accelerators

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The Johns Hopkins University
Applied Physics Laboratory
14 September 2020

Outline

- History and background
- Earth's Radiation Belts
  - Inner Radiation Belts: Protons
  - Inner Radiation Belts: Electrons
  - Outer Radiation Belt(s)
- Radiation Belts throughout the Solar System
- Radiation Belts throughout the Cosmos
- Summary and Conclusion: Where to next?

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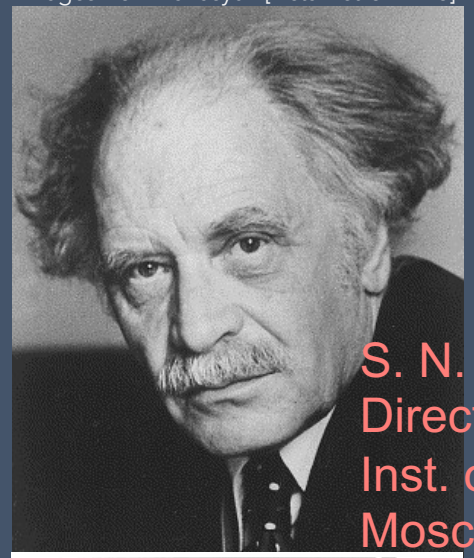
Discovery of Earth's Radiation Belts

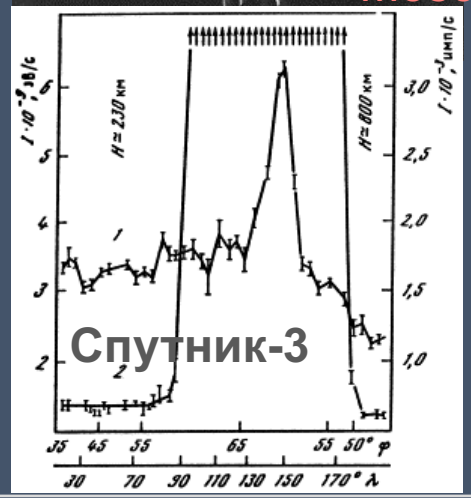
- van Allen and Frank [Nature 1959]
- Vernov and Chudakov [SPU 1960]

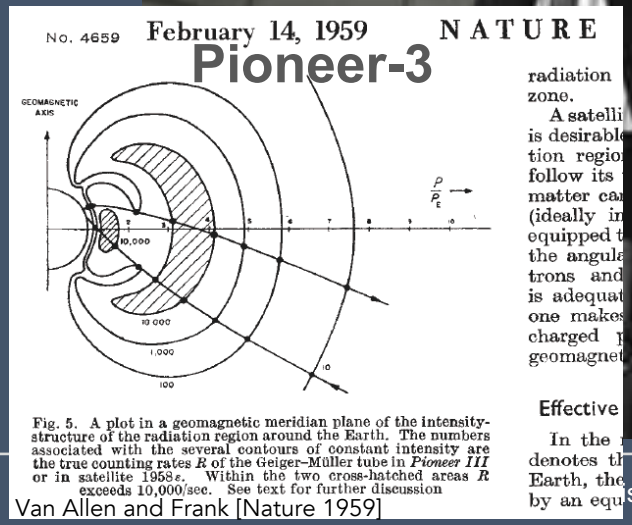
Soviet scientists observed first (Sputnik-2: 7 Nov 1957)…
American scientists reported first (NAS/APS: 1 May 1958)

Images from Panasyuk [Acta Astro. 1998]



S. N. Vernov
Director
Inst. of Nuc. Phys.
Moscow State Univ.





Van Allen and Frank [Nature 1959]

Explorer-1
Launched 31 Jan 1958

J. Pickering
Director
JPL

J. A. van Allen
Professor
Univ. of Iowa

W. von Braun
Technical Director
Army Ballistic Missile Agency
(also former Nazi and SS Officer)

Jupiter-C
(mod. Redstone)
launch vehicle (model)

Images from Wikimedia Commons]

Earth's Electron Radiation Belts

Dealing out scientific mysteries since 1958

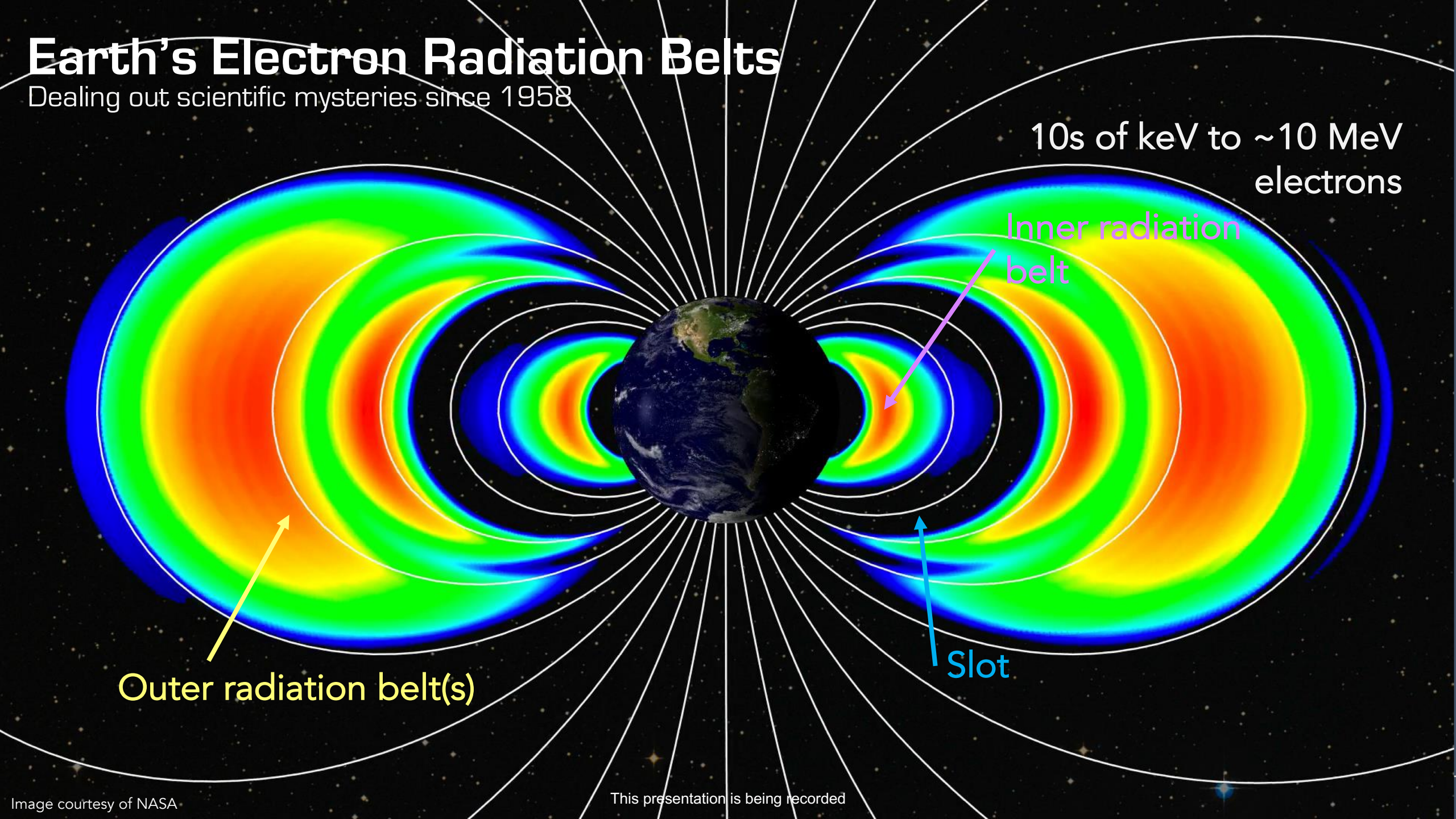


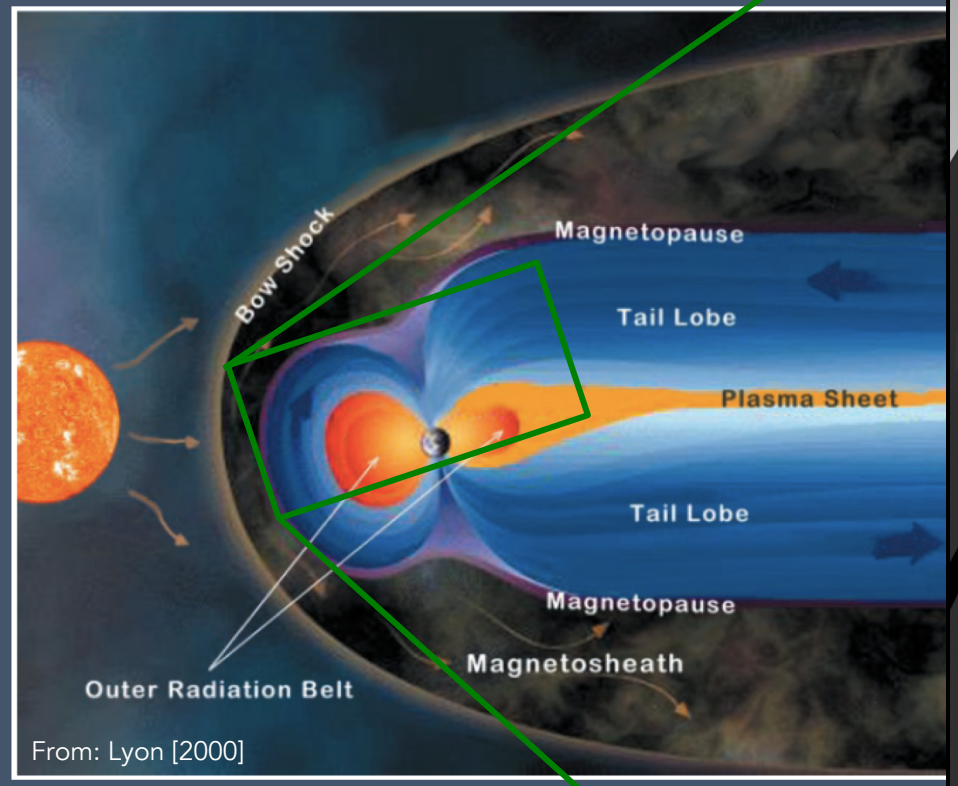
Image courtesy of NASA

This presentation is being recorded

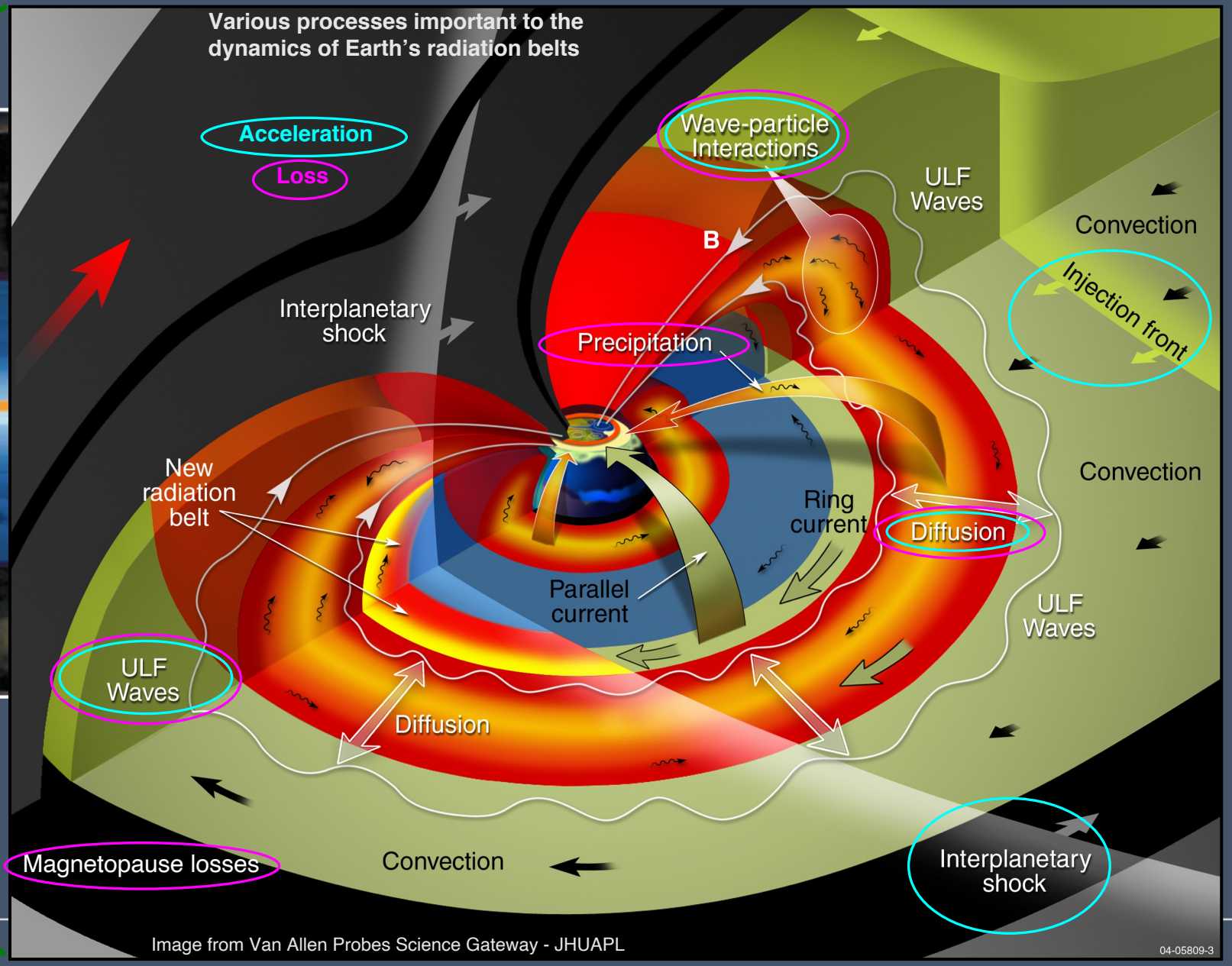
Earth's Electron Radiation Belts

Current Understanding:

Important Processes

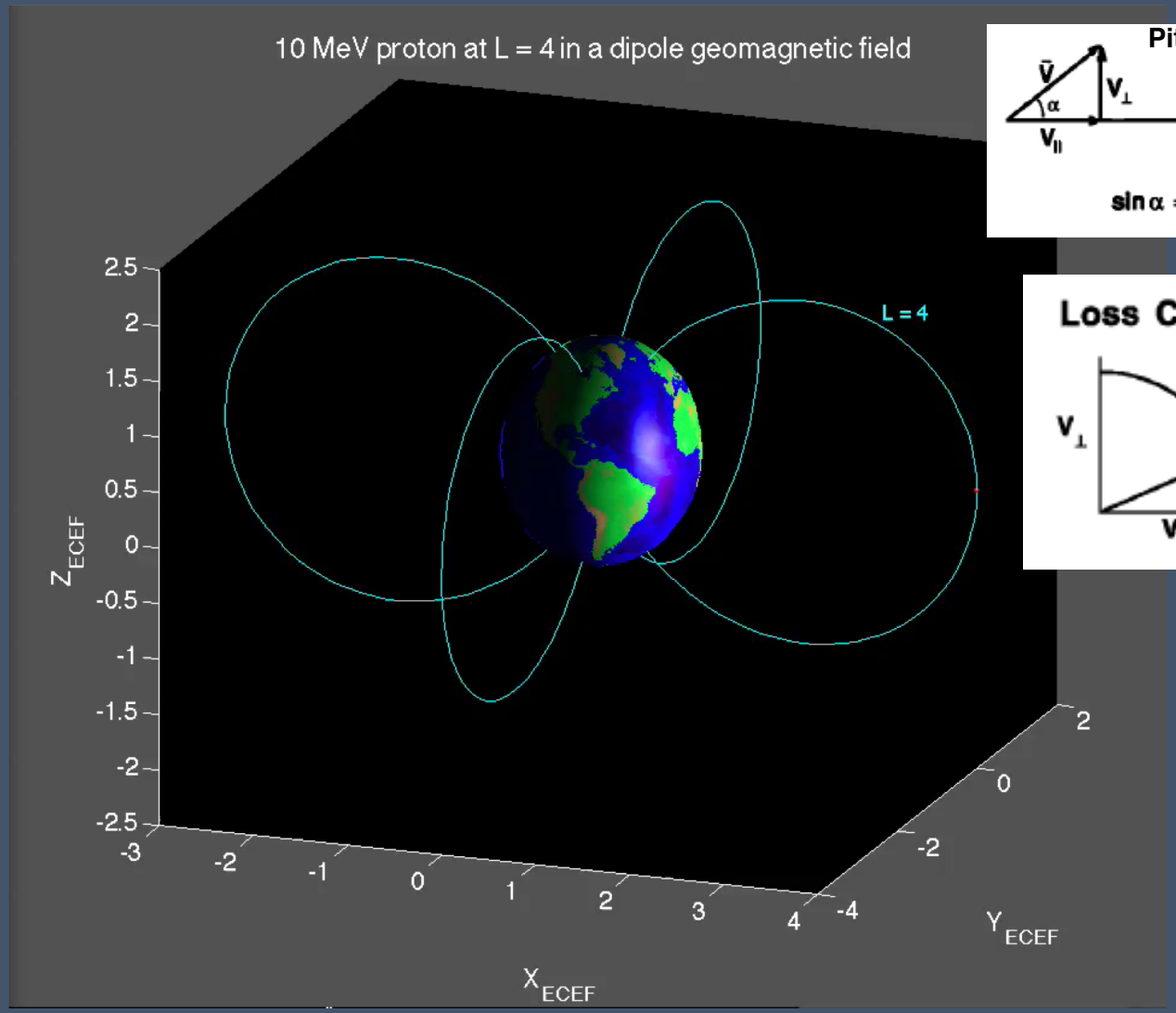


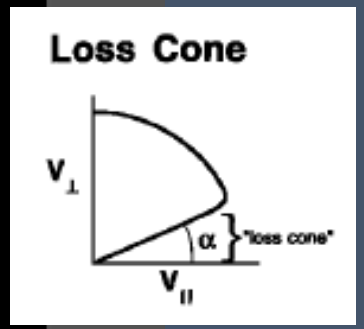
From: Lyon [2000]



Earth's Radiation Belts

Concepts and Understanding: Adiabatic Invariants





- Energetic particles (E_{elec} > ~200 keV):
  - *Motion is dominated by the **VxB** term of the Lorentz force (E-fields relatively insignificant in inner magnetosphere)*
  - *True test particles: there are too few of them to significantly contribute to the self-consistency of the global E- and B-fields*
- 3 characteristic periodic motions (ex. time scales for 1 MeV elec. near GEO):
  - *Gyro: ~ 10^{-3} sec (kHz)*
  - *Bounce: ~ 10^{0} sec (Hz)*
  - *Grad./Curv. Drift: ~ 10^{3} sec (mHz)*
- Adiabatic invariants (constants of motion in ideal B-field):

$$\mu = p_{\perp}^2 / 2m_0 B \,(1\text{st})$$

$$J = \oint p_{\parallel} ds \,(2\text{nd}) \Rightarrow K = J / 2\sqrt{2m_0 \mu}$$

$$\Phi = \oint \vec{B} d\vec{A} \,(3\text{rd}) \Rightarrow L^* = 2\pi M / (\Phi R_E)$$

Any significant changes in the fields (e.g., waves) at time scales faster than the periodic motions will violates the corresponding invariant

Cosmic Ray Albedo Neutron Decay

A dominant source for Earth's inner radiation belt

Graphic in Mazur+ [SSR 2013]

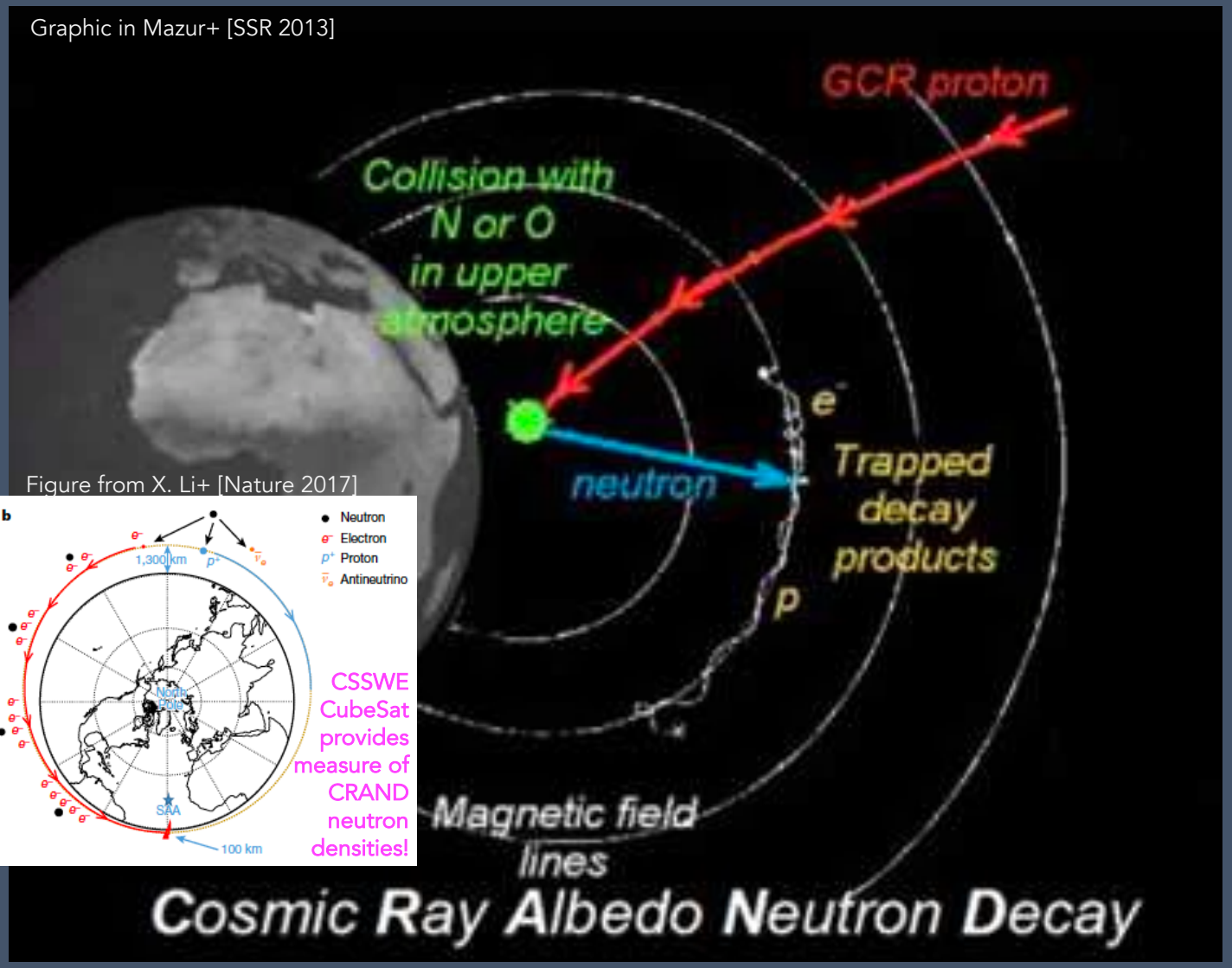


Figure from X. Li+ [Nature 2017]

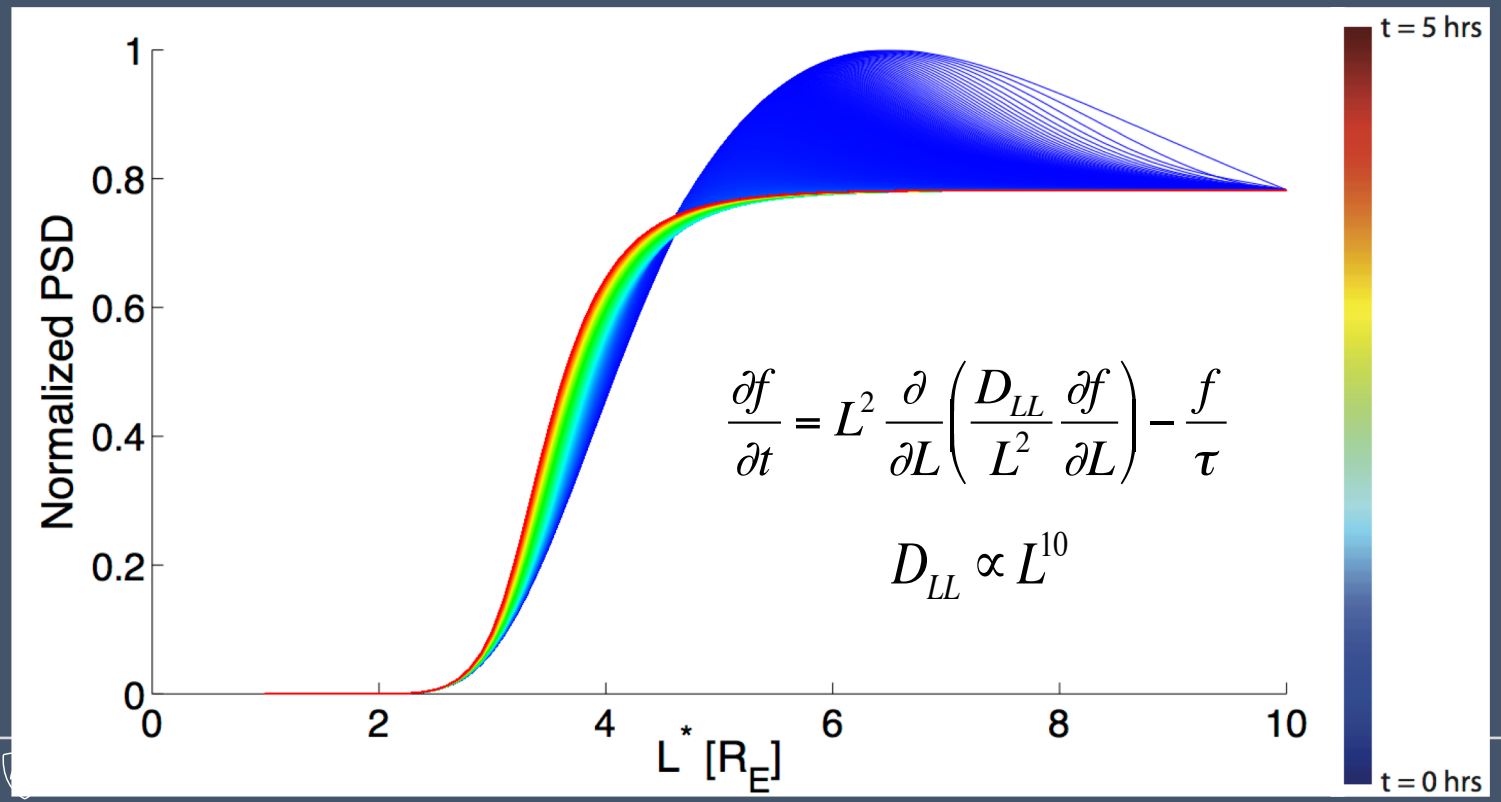
CSSWE CubeSat provides measure of CRAND neutron densities!

- Cosmic rays continuously rain down upon Earth's atmosphere; these are ≥10s MeV ions
- When CRs collide with atmospheric neutrals: they can knock free neutrons from atomic nuclei; about 10% of those leave the atmosphere as "albedo" neutrons; those neutrons can carry a significant amount of the initial CR kinetic energy
- Those free neutrons are unstable and decay into a proton, an electron, and an electron-type antineutrino
  - *Decay half-life: ~10 mins: w/ energy, dictates distance neutron travels away from atmosphere prior to decay*
  - *Proton carries most of the neutron's kinetic energy after the decay*
  - *Energetic protons can then become trapped in Earth's field*
- *Result at Earth: Regular, long-term stable [some solar cycle variation on CR intensity at Earth] production of ≥10s of MeV protons and >2 MeV electrons in Earth's inner zone [L ≤ ~1.5]*
- *Many references, incl: Selesnick+ [JGR 2015]; Selesnick and Albert [JGR 2019]; X. Li [Nature 2017]*

Earth's Radiation Belts

Concepts and Understanding: Diffusive Transport

- A modified Fokker-Planck eq. models evolution of the particle distribution function, *f* [Schulz and Lanzerotti, 1974]
- When small disturbances are present, particles get random kicks; if kicks are Gaussian in distribution, they should average to zero (i.e., D_{JiJj} very small)… here, only the gradients in phase space will play a key role (i.e., if df/dJ very large and D_{JiJj} finite)



For energetic particles (adiabatic motion):

$$\frac{\partial f}{\partial t} = \sum_{i,j=1}^{3} \frac{\partial}{\partial J_i} D_{J_i J_j} \frac{\partial f}{\partial J_j}$$

- However, if the kicks are from waves at particular frequencies, then resonance can occur with some particles…
- When resonance occurs, D_{JiJj} can be very significant, and enhanced diffusion can occur

$$\omega - \mathbf{k} \cdot \mathbf{V} = n\Omega$$

- There are several key assumptions for quasi-linear diffusion theory: waves are low amplitude and incoherent (unstructured spectra); more assumptions go into deriving diffusion coefficients…

Nature is (of course) more complicated than this…

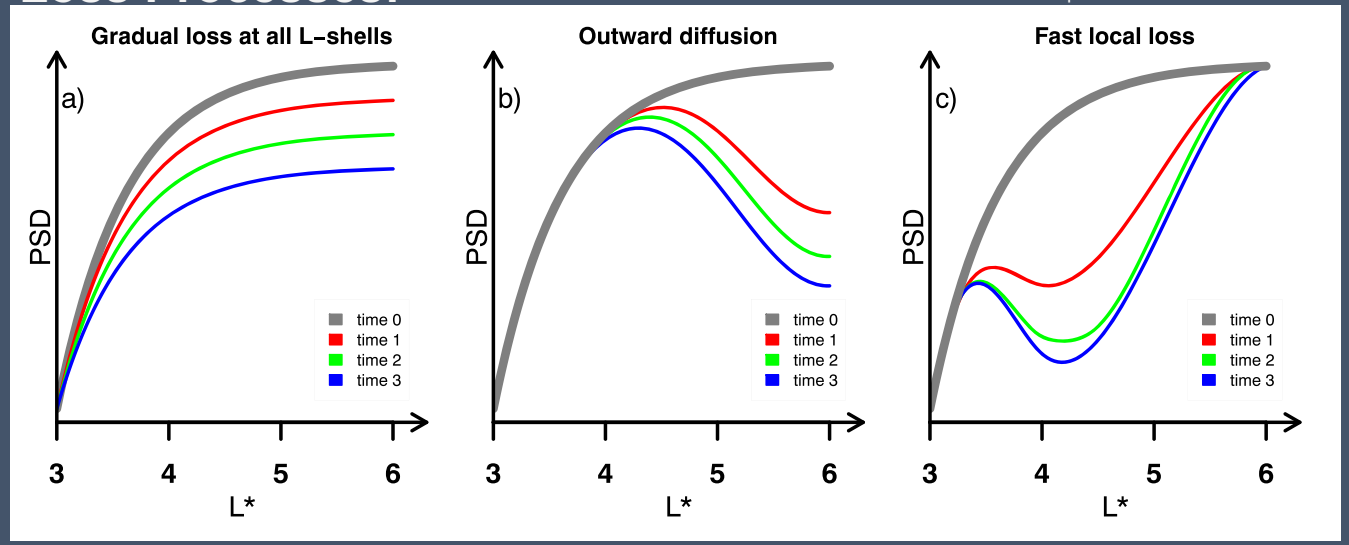
Earth's Radiation Belts

Concepts and Understanding: Phase Space Density

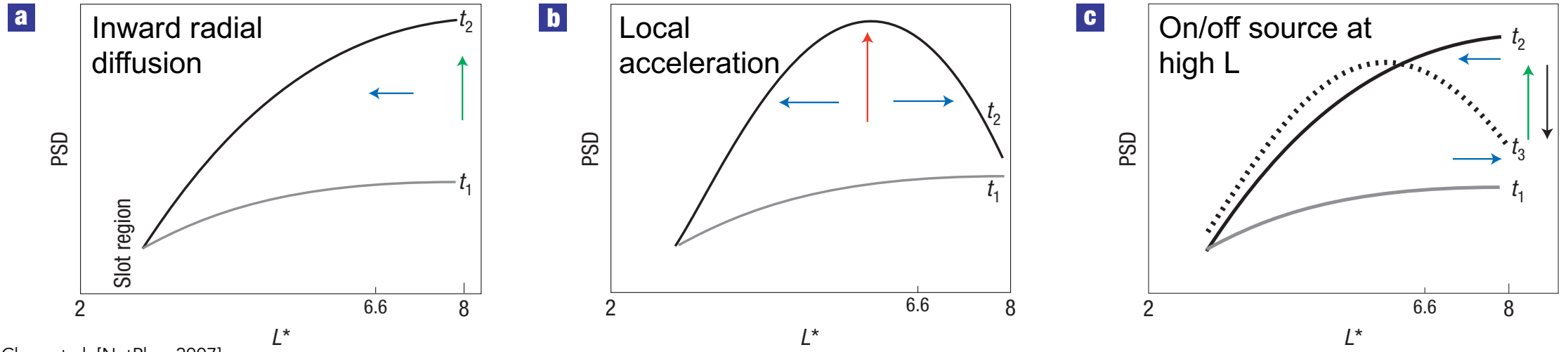
The temporal evolution of phase space density distributions for fixed adiabatic invariants are crucial for determining dominant source and loss processes in Earth's electron radiation belts

Loss Processes:

Shprits et al. [JGR 2017]



Source Processes:



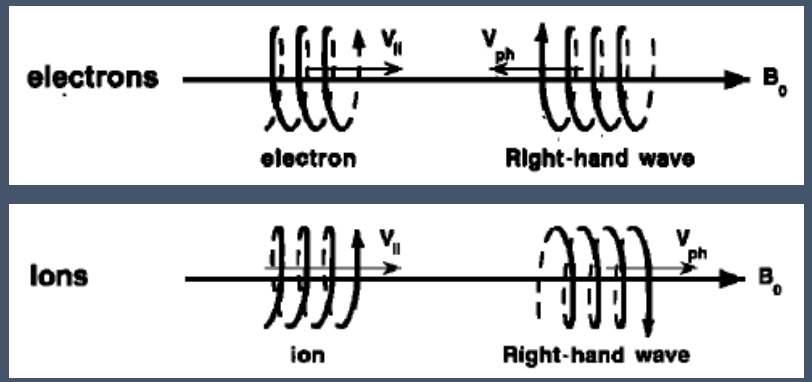
Chen et al. [NatPhys 2007]

Earth's Radiation Belts

Concepts and Understanding: Wave-Particle Interactions

- Electromagnetic ion cyclotron (EMIC) and whistler-mode waves are generated naturally in anisotropic plasmas
- Wave-particle interactions and the resonance condition
- Good overview papers: *Tsurutani and Lakhina [Rev. Geophys., 1997]; Thorne et al. [GRL, 2010]*
- Effects of WPI have now been directly observed: *Fennell et al. [GRL, 2014]*
- WPI are considered highly important to both acceleration and loss of outer belt electrons via quasilinear diffusion and nonlinear interactions:
  - Acceleration:
    - Inward radial diffusion from and/or drift resonance with ULF waves: e.g., *Elkington et al. [GRL, 1999*]; *Claudepierre et al. [GRL, 2013]*
    - Gyro resonance with whistler-mode chorus: e.g., *Thorne et al. [Nature, 2013]*
    - Landau resonance with magnetosonic waves: e.g., *Horne et al. [GRL, 2007]*
  - Loss:
    - Slow, energy- and α-dependent scattering with hiss waves: e.g., *Thorne et al. [GRL, 2013]*
    - Rapid, energy- and α-dependent scattering with EMIC waves: e.g., *Usanova et al. [GRL, 2014]*
    - Outward radial diffusion from ULF waves: e.g., *Shprits et al. [JGR, 2006]*

$$\omega - \mathbf{k} \cdot \mathbf{V} = n\Omega$$



Sketches of normal (top) and anomalous (bottom) gyro-resonant wave-particle interactions from *Tsurutani and Lakhina [Rev. Geophys., 1997]*

Note: Interactions are more complex for non-circular wave polarizations and oblique wave-normal angles (i.e., reality)

Quasi-Linear Transport and Loss

Explaining the 2-zone structure and intensity limits of Earth's electron radiation belts

- How we explained the two zone structure of Earth's electron radiation belts for decades: Equilibrium between inward radial diffusion from some source population beyond GEO and atmospheric scattering losses from interactions with whistler-mode turbulence in the plasmasphere (i.e., plasmaspheric hiss waves)
- Also critical: Kennel and Petschek [JGR 1966]: Self-limiting intensities via wave-particle interactions

VOL. 78, NO. 13 JOURNAL OF GEOPHYSICAL RESEARCH MAY 1, 1973

Equilibrium Structure of Radiation Belt Electrons

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RICHARD MANSERGH THORNE[1]

Department of Meteorology, University of California Los Angeles, California 90024

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

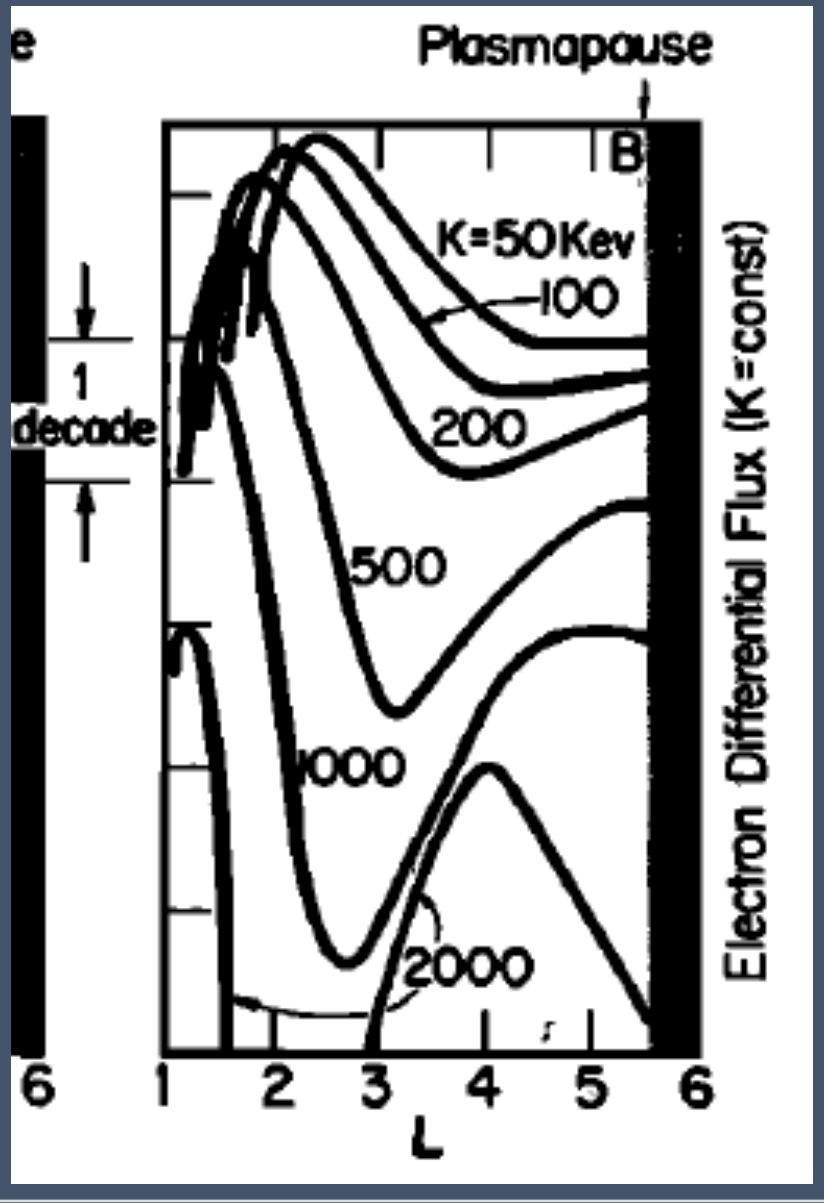
Journal of
GEOPHYSICAL RESEARCH

VOL. 71 JANUARY 1, 1966 No. 1

Limit on Stably Trapped Particle Fluxes

C. F. KENNEL AND H. E. PETSCHEK

Avco-Everett Research Laboratory, Everett, Massachusetts



Enter: CRRES and SAMPEX

Harbingers of a shift in paradigm

- With new, comprehensive observations came some big surprises… e.g., shock injections
- Sudden enhancements too fast for inward radial diffusion; concept of rapid, local acceleration proposed: Temerin+ [EOS 1994], Horne and Thorne [GRL 1998], Summers+ [JGR 1998]
- Extreme variability (next slide)

Figure from Blake et al. [GRL 1992]

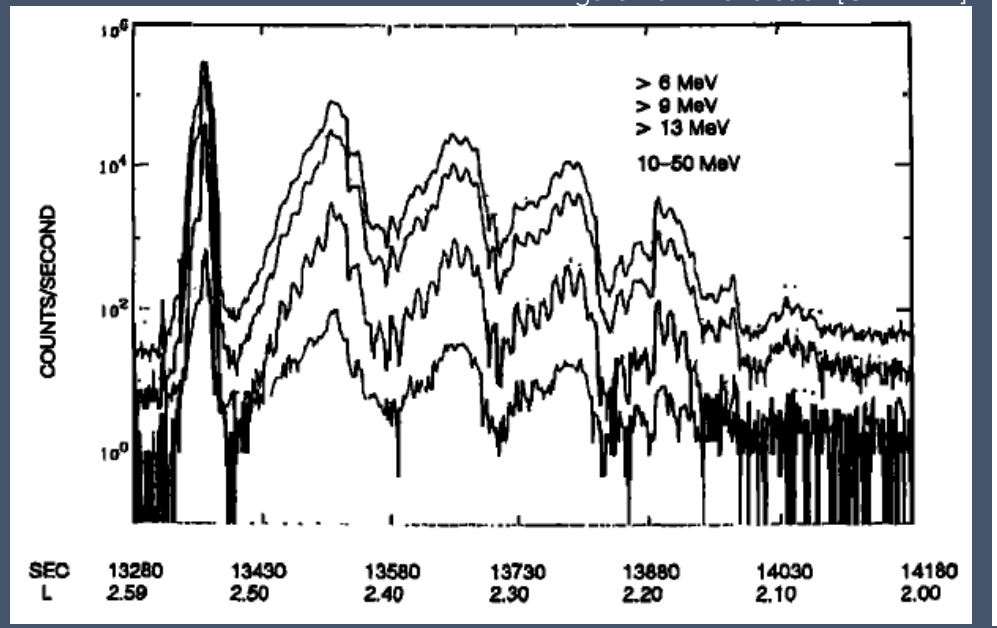
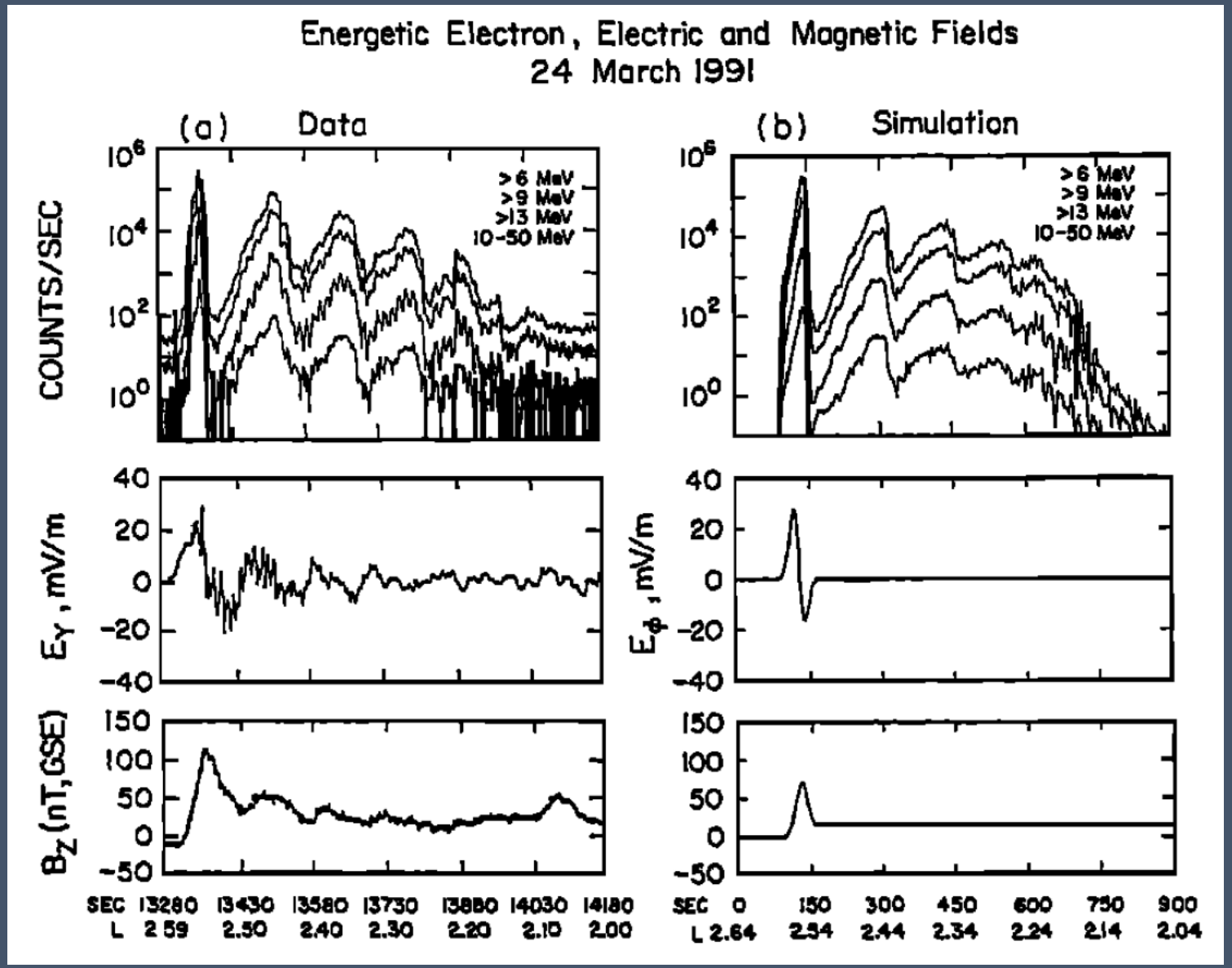


Figure from X. Li et al. [GRL 1993]



Enter: CRRES and SAMPEX

Extreme variability over a broad range of time scales

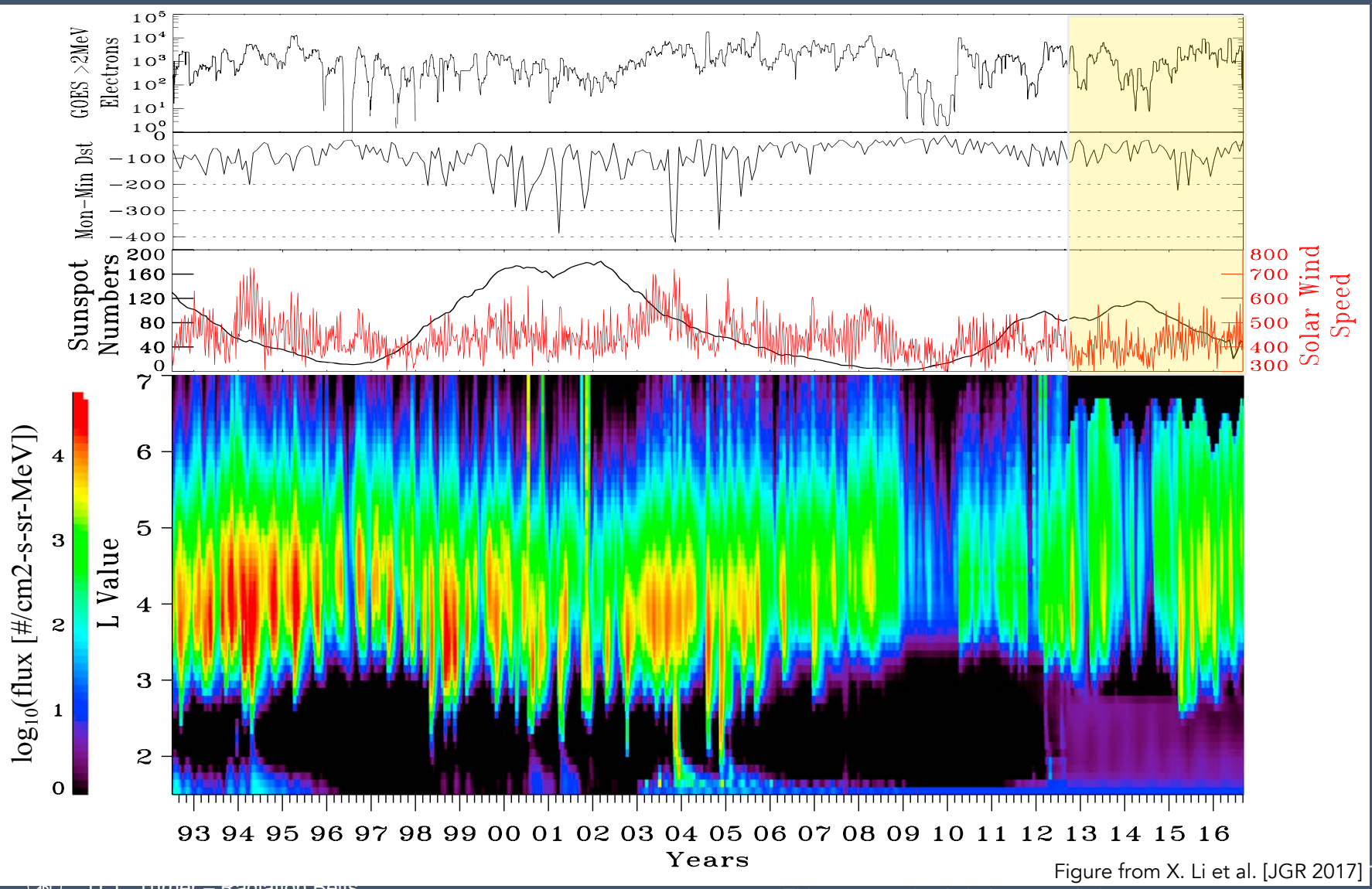


Figure from X. Li et al. [JGR 2017]

- Theory and modeling are still challenged to accurately predict such drastic changes over such a wide range of timescales: Energy- and pitch angle – dependent, orders of magnitude variations over just seconds to many years

Some human perspective:

What if your bank account changed from $100,000 to $1 unexpectedly in just a few hours?

NASA's Van Allen Probes

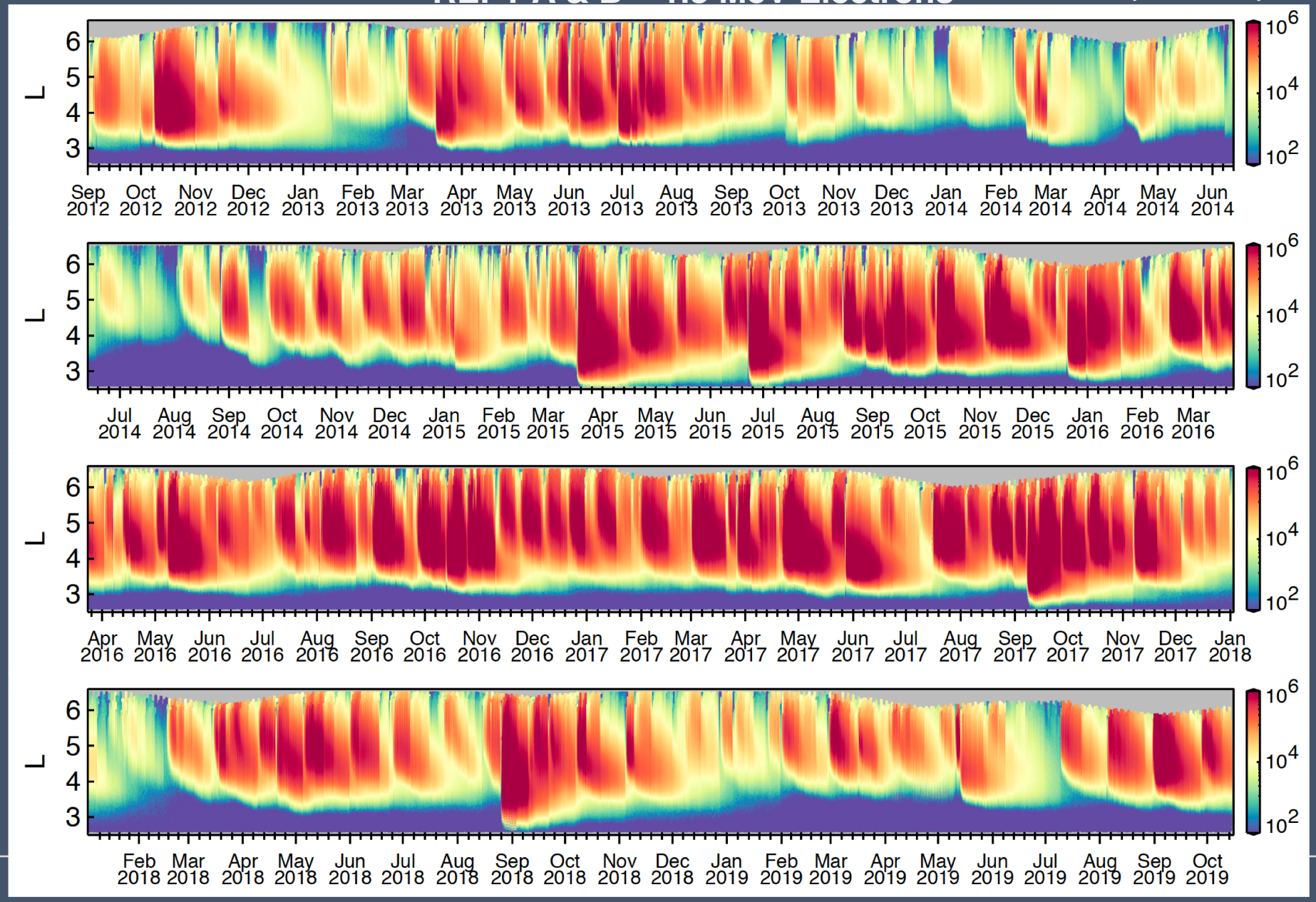
- Launched August 2012
- 2 identical s/c in GTO-like orbits at various separations

Image courtesy of Van Allen Probes Science Gateway – JHU APL

Earth's Electron Radiation Belts

Extreme Variability

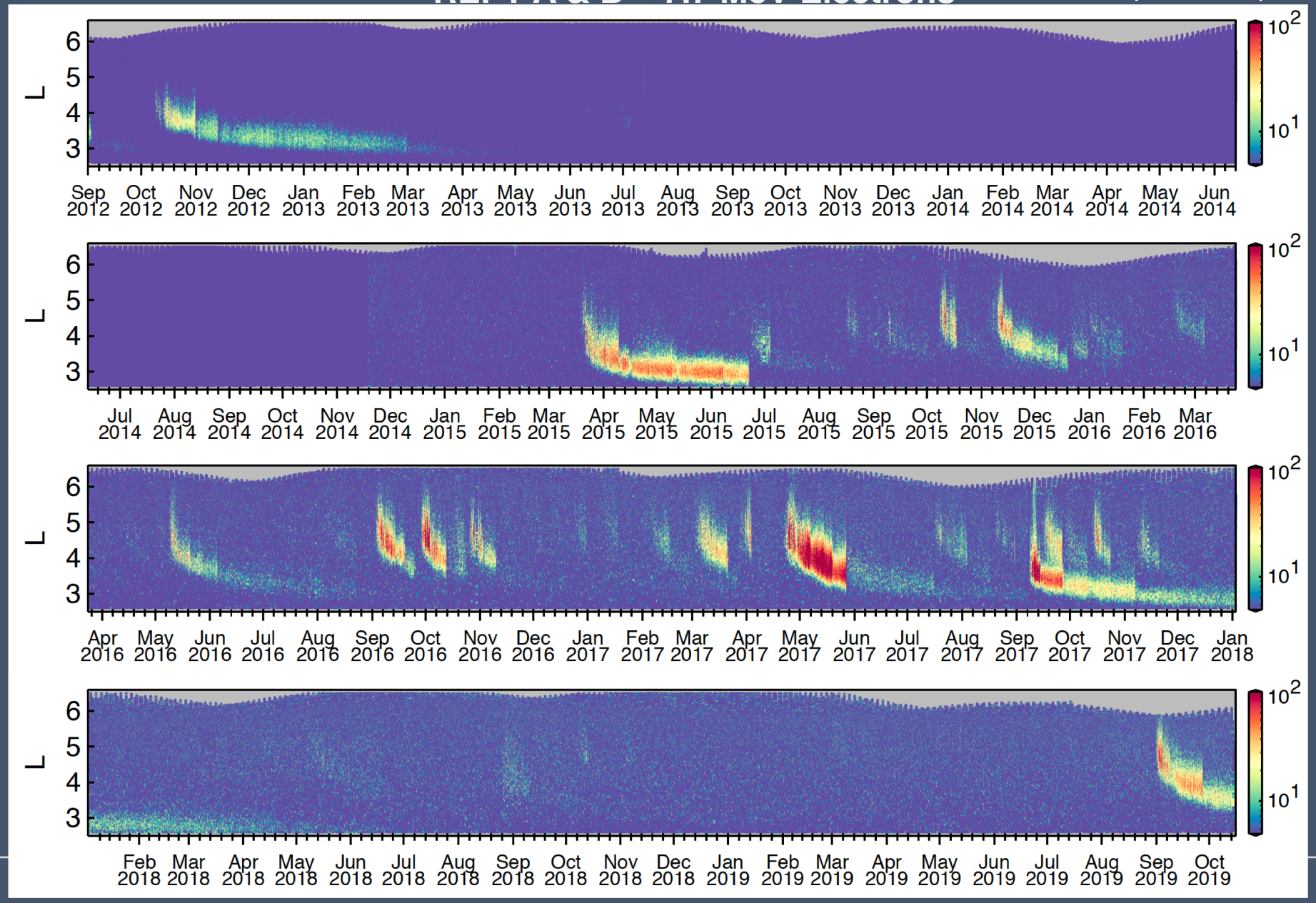
Core radiation belt electrons…



Earth's Electron Radiation Belts

Extreme Variability

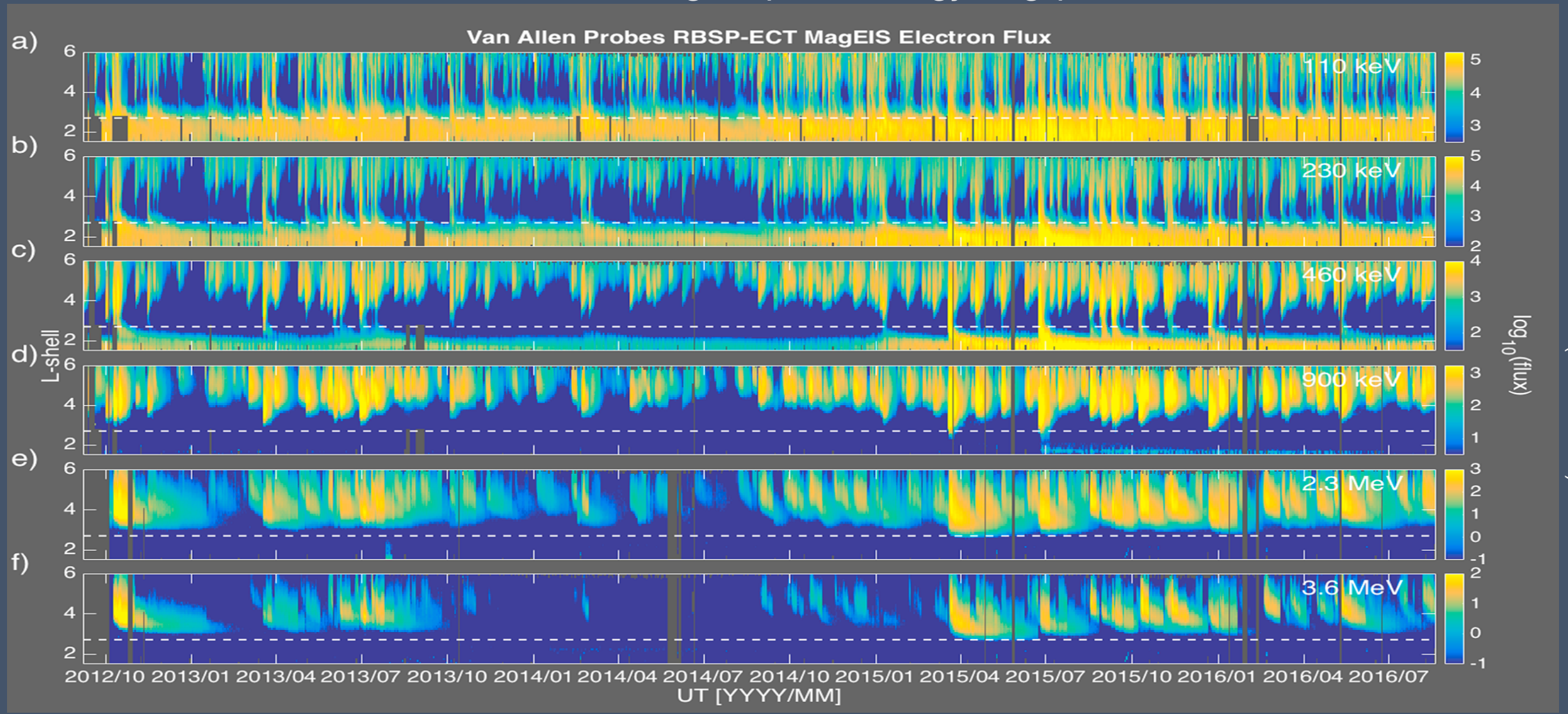
Higher energies…



Earth's Electron Radiation Belts

Extreme Variability

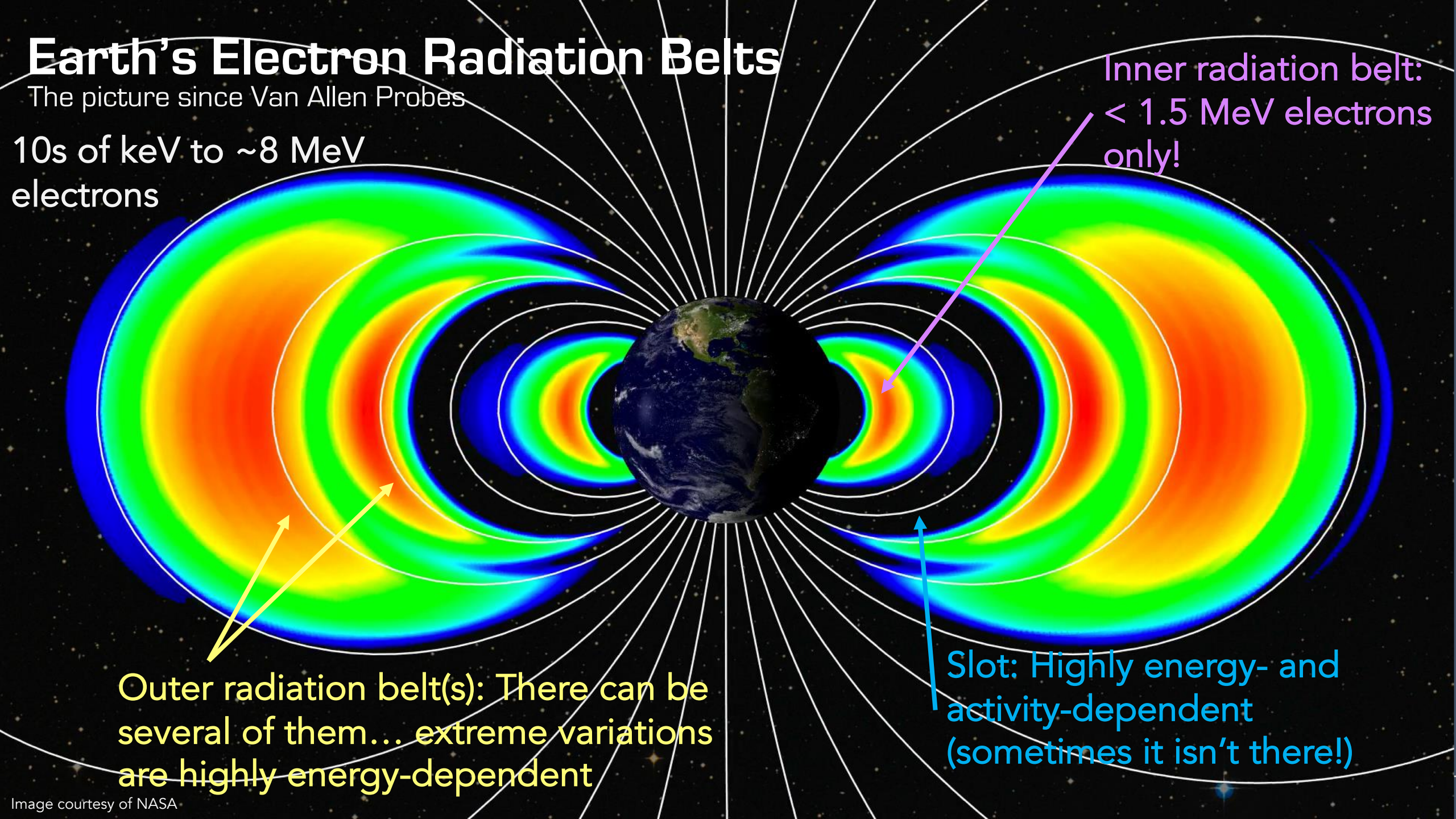
REPT A & B: MagEIS (broad energy range)



Earth's Electron Radiation Belts

The picture since Van Allen Probes

10s of keV to ~8 MeV electrons



Inner radiation belt: < 1.5 MeV electrons only!

Outer radiation belt(s): There can be several of them… extreme variations are highly energy-dependent

Slot: Highly energy- and activity-dependent (sometimes it isn't there!)

Image courtesy of NASA

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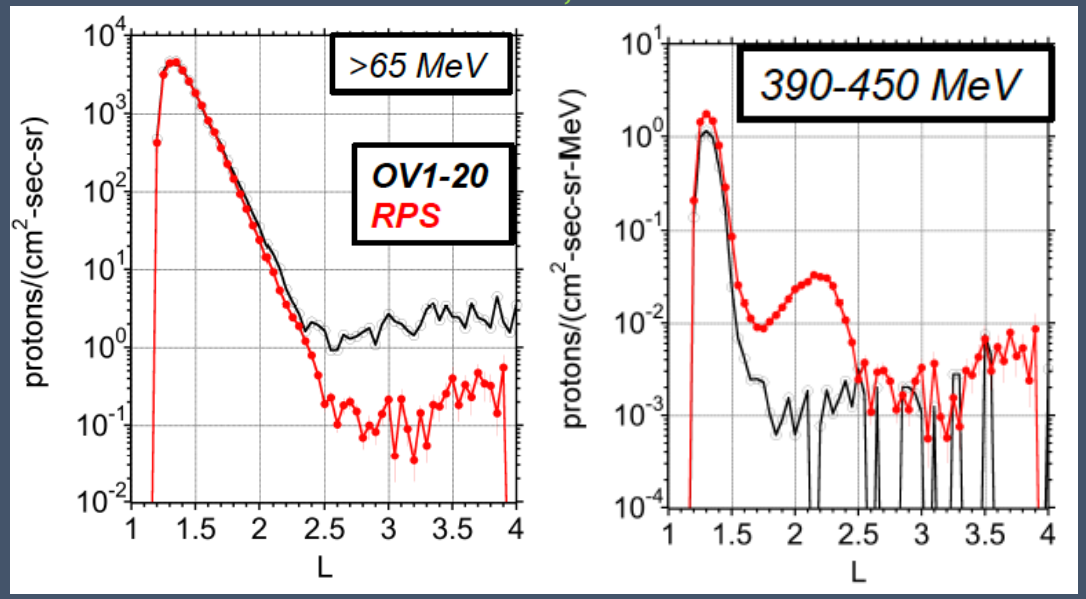
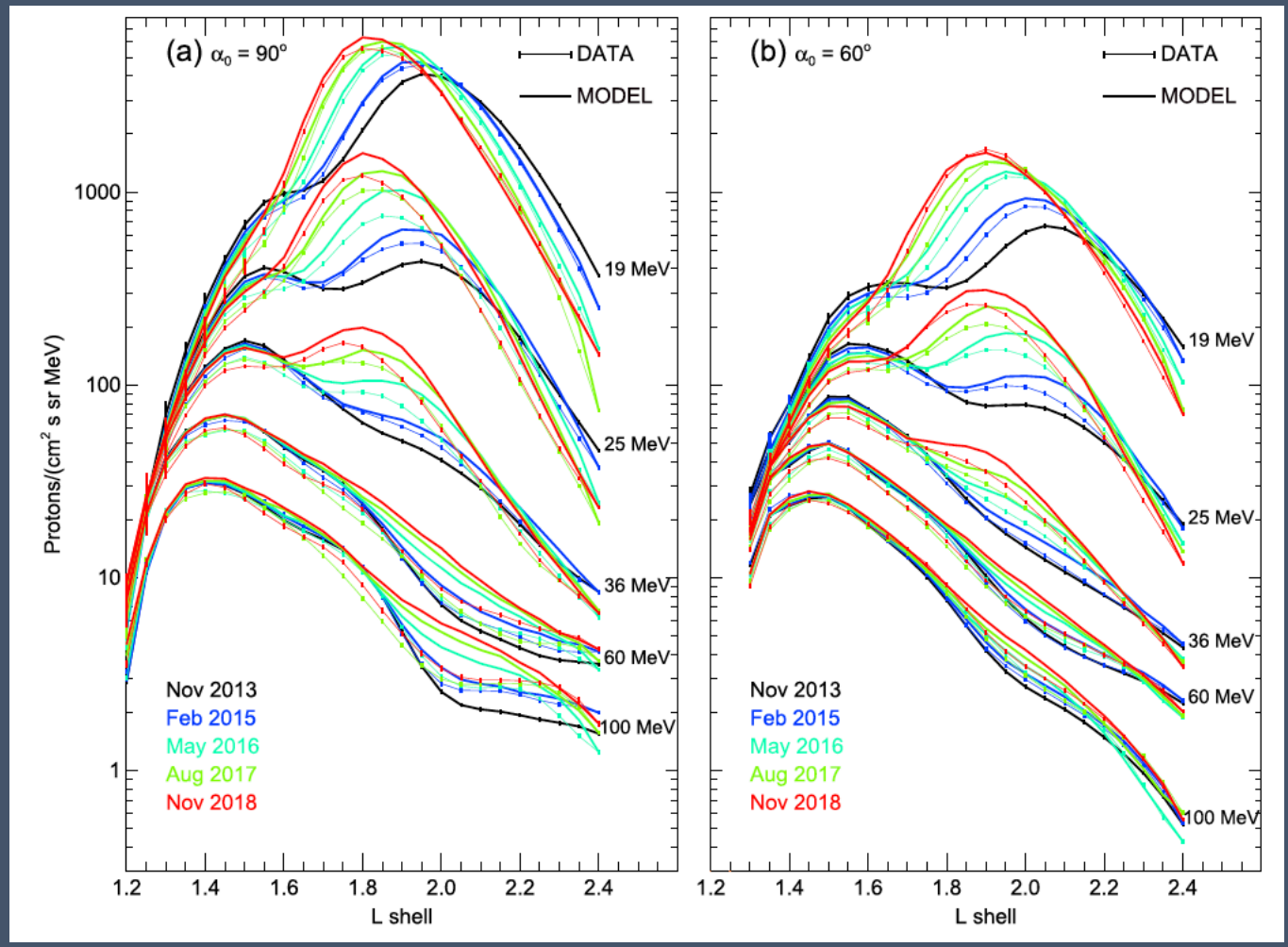
Earth's Inner Radiation Belt: Protons

- Inner belt protons are quite stable [e.g., Mazur et al. AGU FM 2014]

OV1-20: data from 1971; RPS data from 2013



- However, at L > 1.5, there is a shoulder/peak that is temporally variable, affected by SEPs (injection source) and subsequent inward radial diffusion [Selesnick and Albert, JGR 2019]



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Electrons in the Inner Radiation Belt

An unexpected discovery from Van Allen Probes

- Fennell+ [GRL 2015], X. Li+ [JGR 2015], and Claudepierre+ [JGR 2015]: There have been no observable levels of electrons with E > 1.5 MeV in the inner zone during the Van Allen Probes era…

Figure from Fennell+ [GRL, 2015]

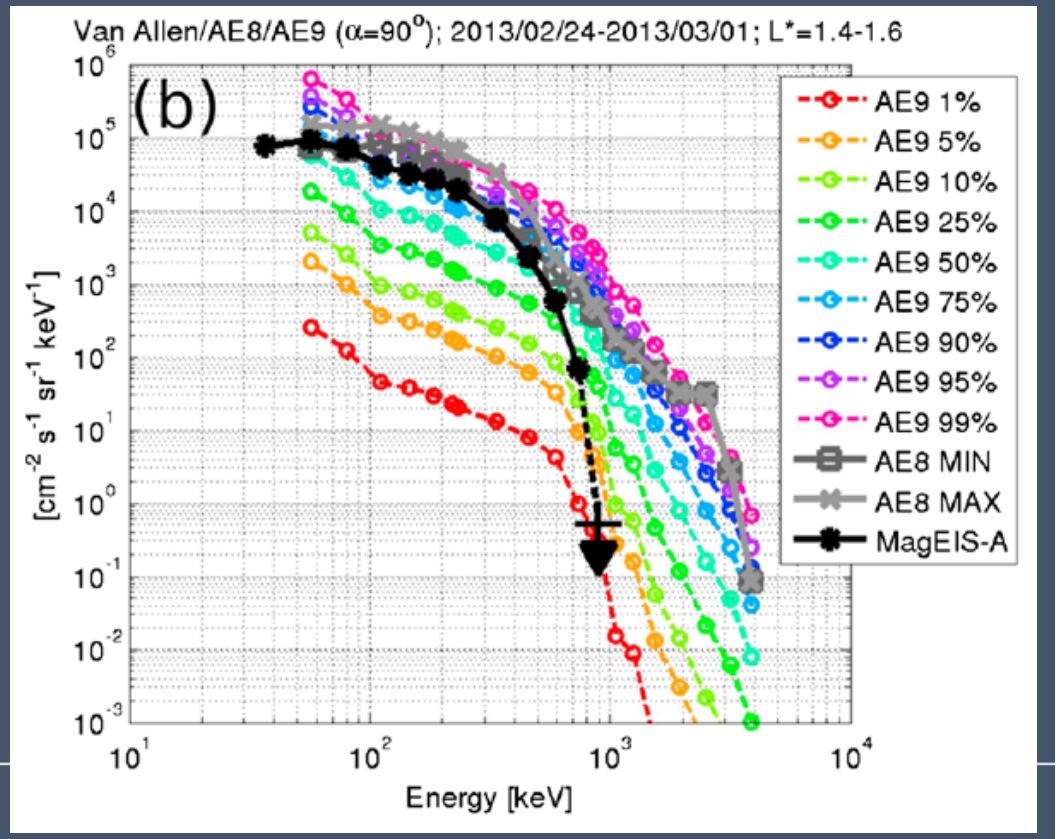
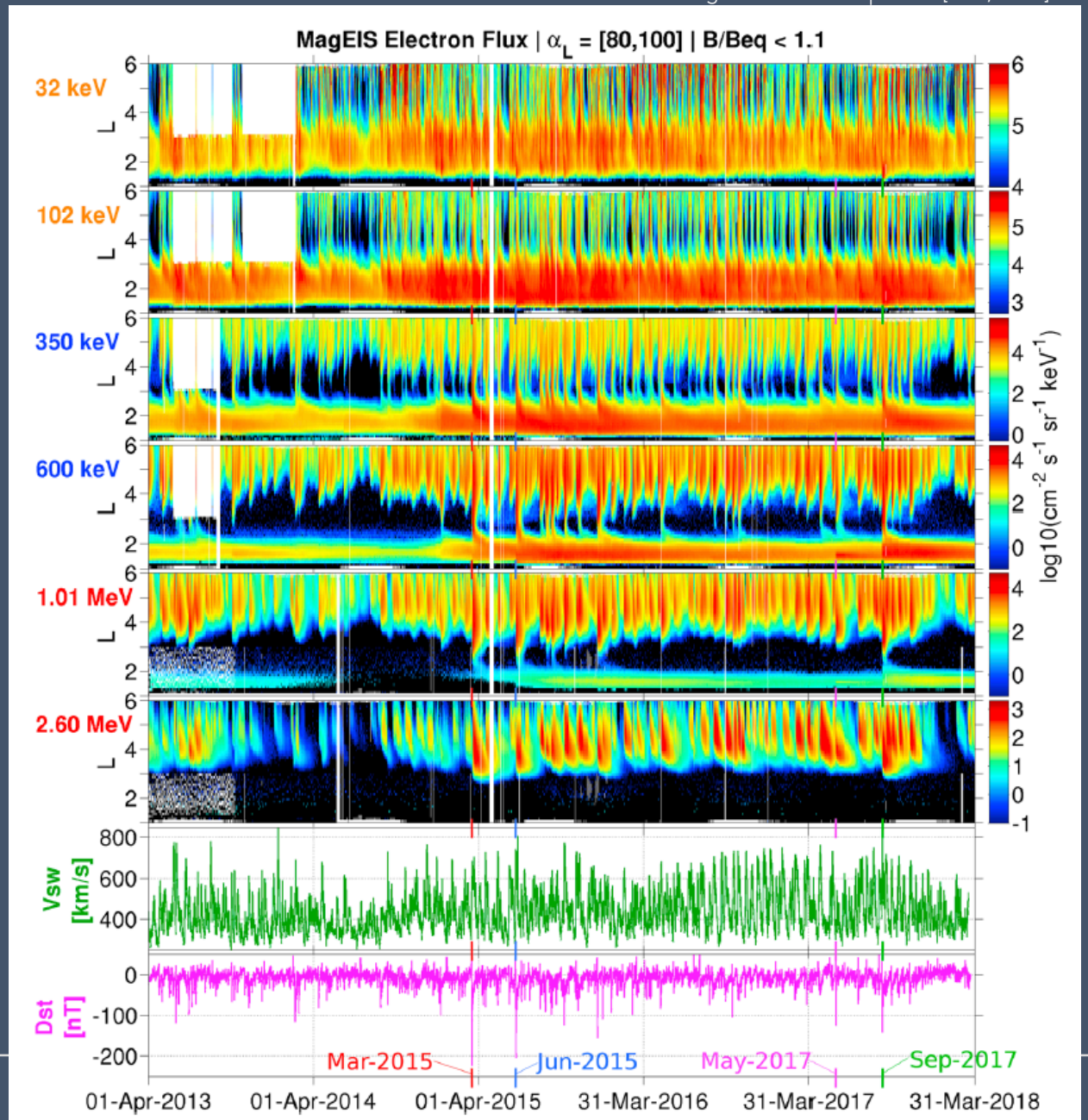


Figure from Claudepierre+ [JGR, 2019]

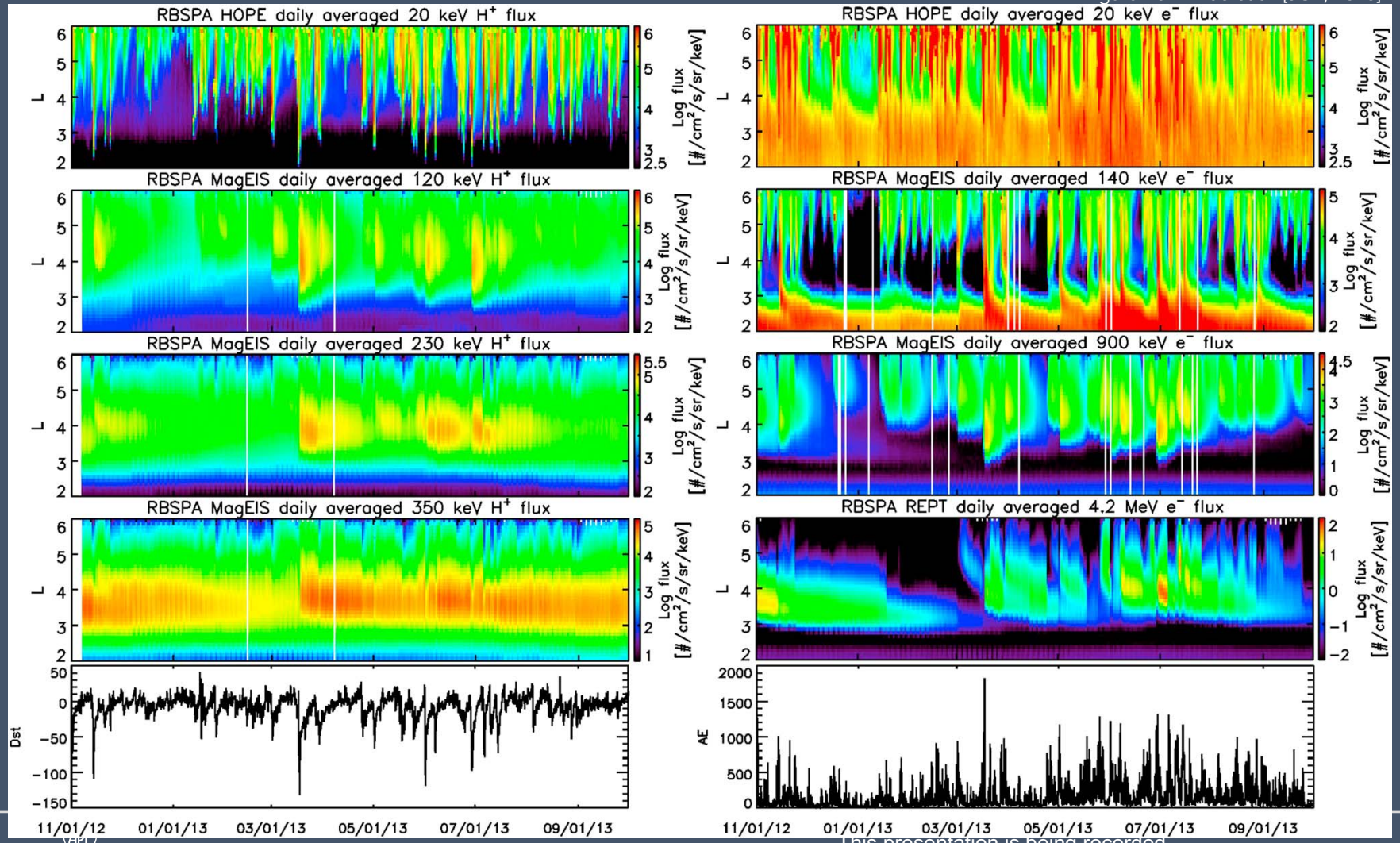


Electrons in the Inner Radiation Belt

Sudden particle enhancements at low L-shells (SPELLS)

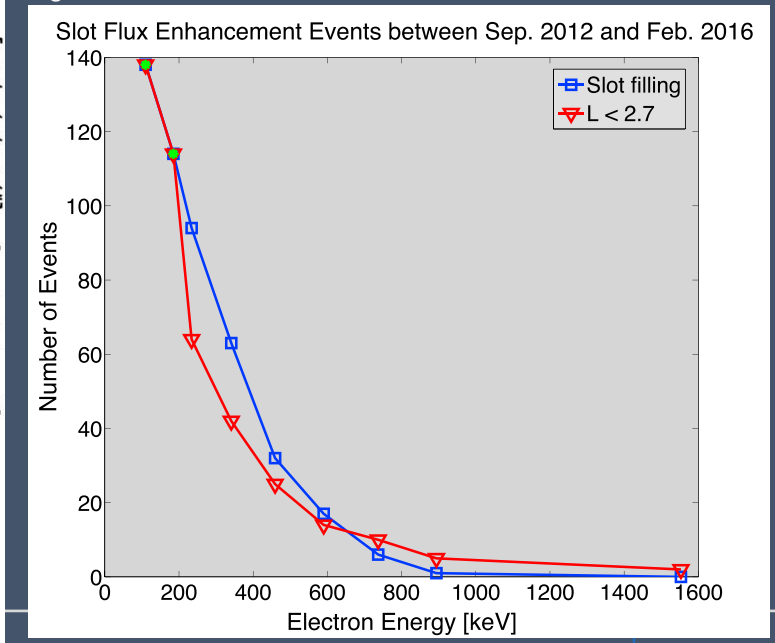
Protons **Electrons**

Figure from Zhao et al. [JGR, 2016]



SPELLS are common but only for electrons and they occur within the plasmasphere: they are not simply a result of enhanced global convection

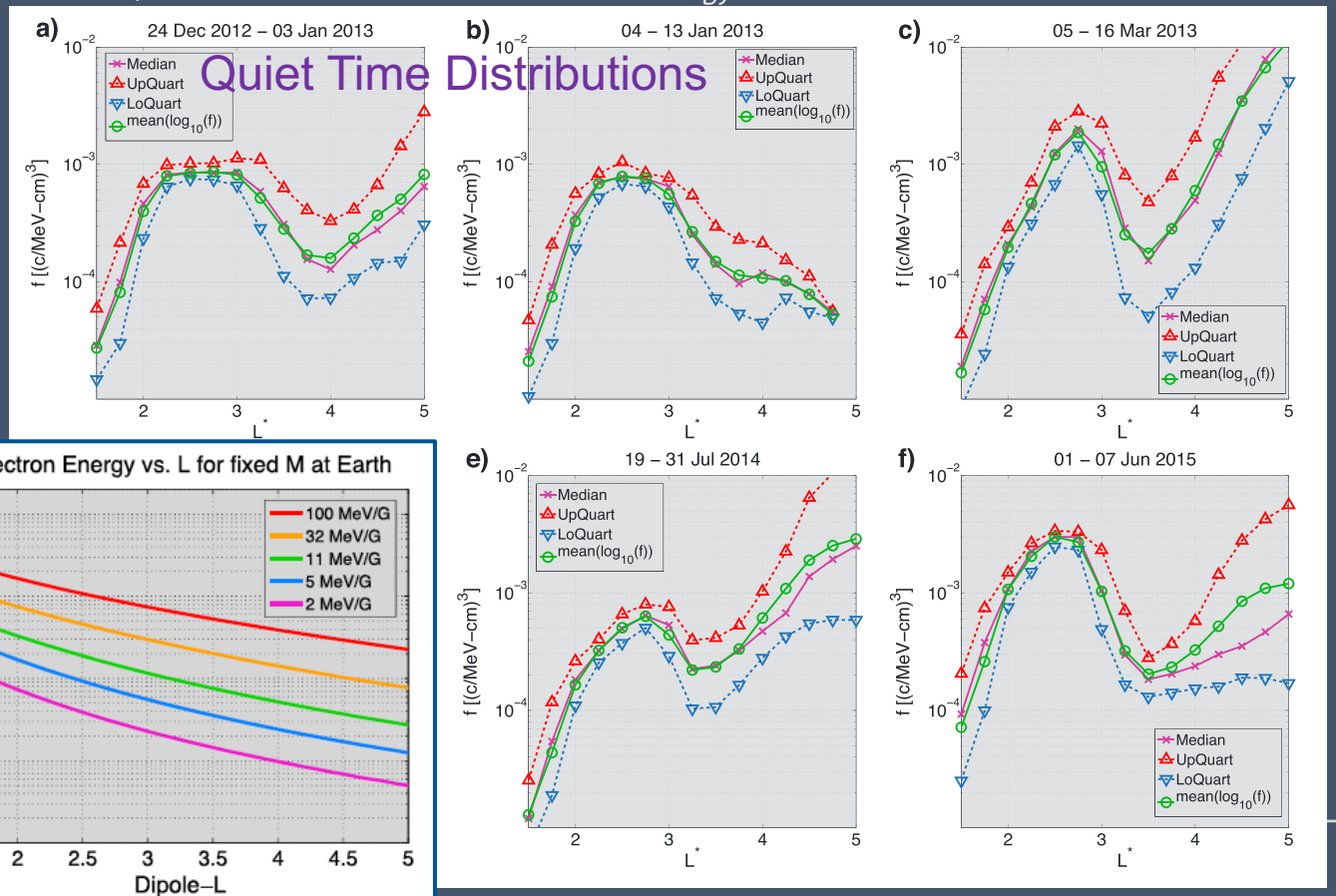
Figure from Turner et al. [JGR, 2017]



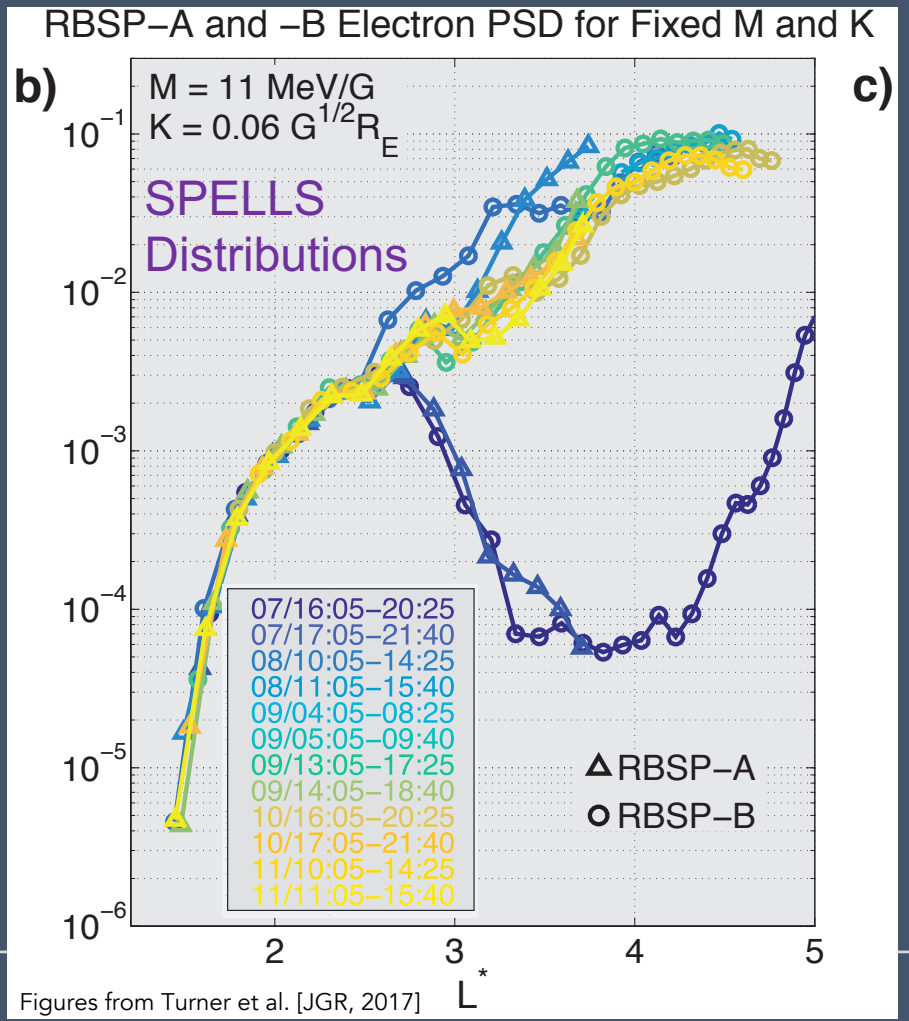
Electrons in the Inner Radiation Belt

SPELLS and the source of inner belt electrons

- Turner et al. [JGR 2017]: **These low-L injections are the dominant source of 10s to 100s of keV electrons in the inner belt**
  - *The PSD distributions of electrons in the inner belt are typically peaked during quiet times*
  - *Inward radial diffusion only effective over timescales of days, but SPELLS occur in < 2 hrs!*
  - *SPELLS represent an "on/off" source from higher L, resulting in the formation of the peaked distributions [e.g., Chen et al. NatPhys 2007]*
  - *Consistent with Selesnick et al. [JGR 2015]: CRAND only sufficient for >2 MeV electrons in inner zone; some other source needed for lower energy intensities*



- SPELLS are not the innermost extent of classic substorm injections, but…
- SPELLS injection events are localized in MLT
- See Turner et al. [GRL 2015] and Zhao et al. [JGR 2017] for details



Figures from Turner et al. [JGR, 2017]

Electrons in the Inner Radiation Belt

SPELLS and the source of inner belt electrons

SPELLS likely result from enhanced and potentially localized convection E-fields during active times (e.g., SAPS): Simulations reproduce MLT-localized injections on comparable timescales

Figure from Lejosne et al. [GRL, 2018]

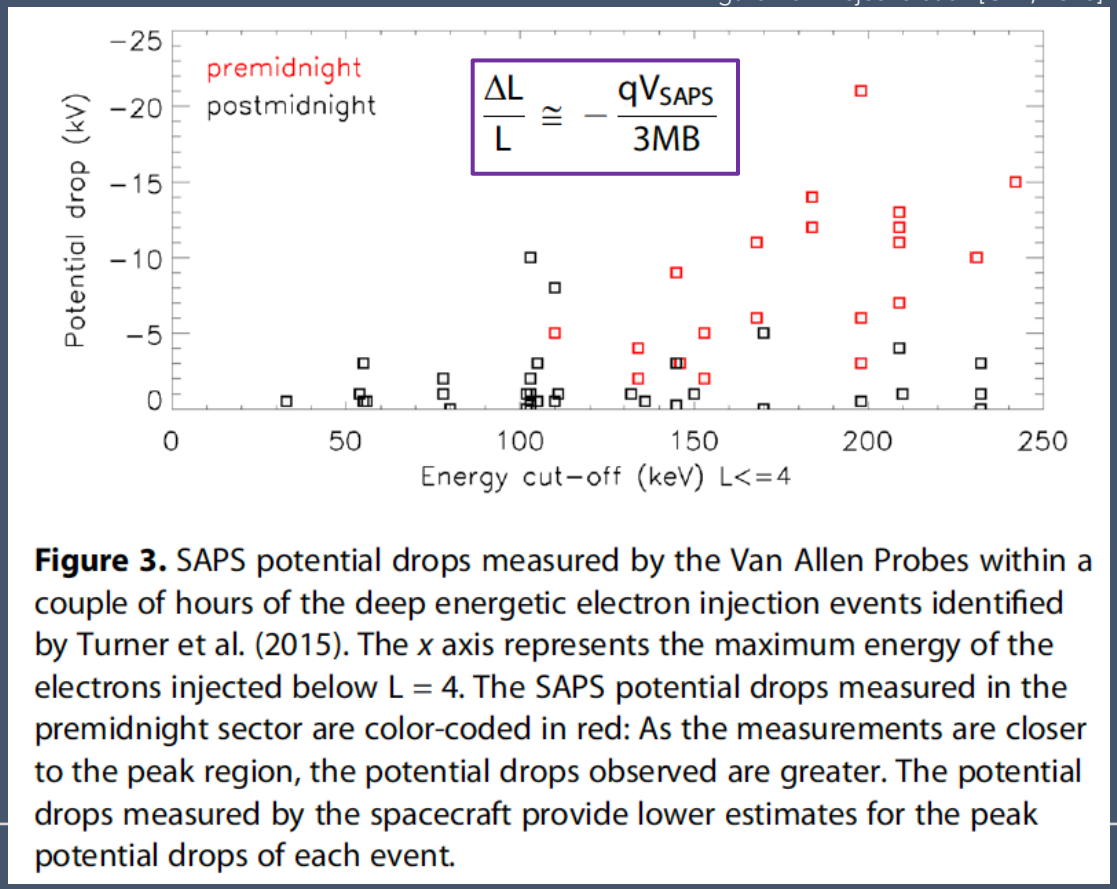
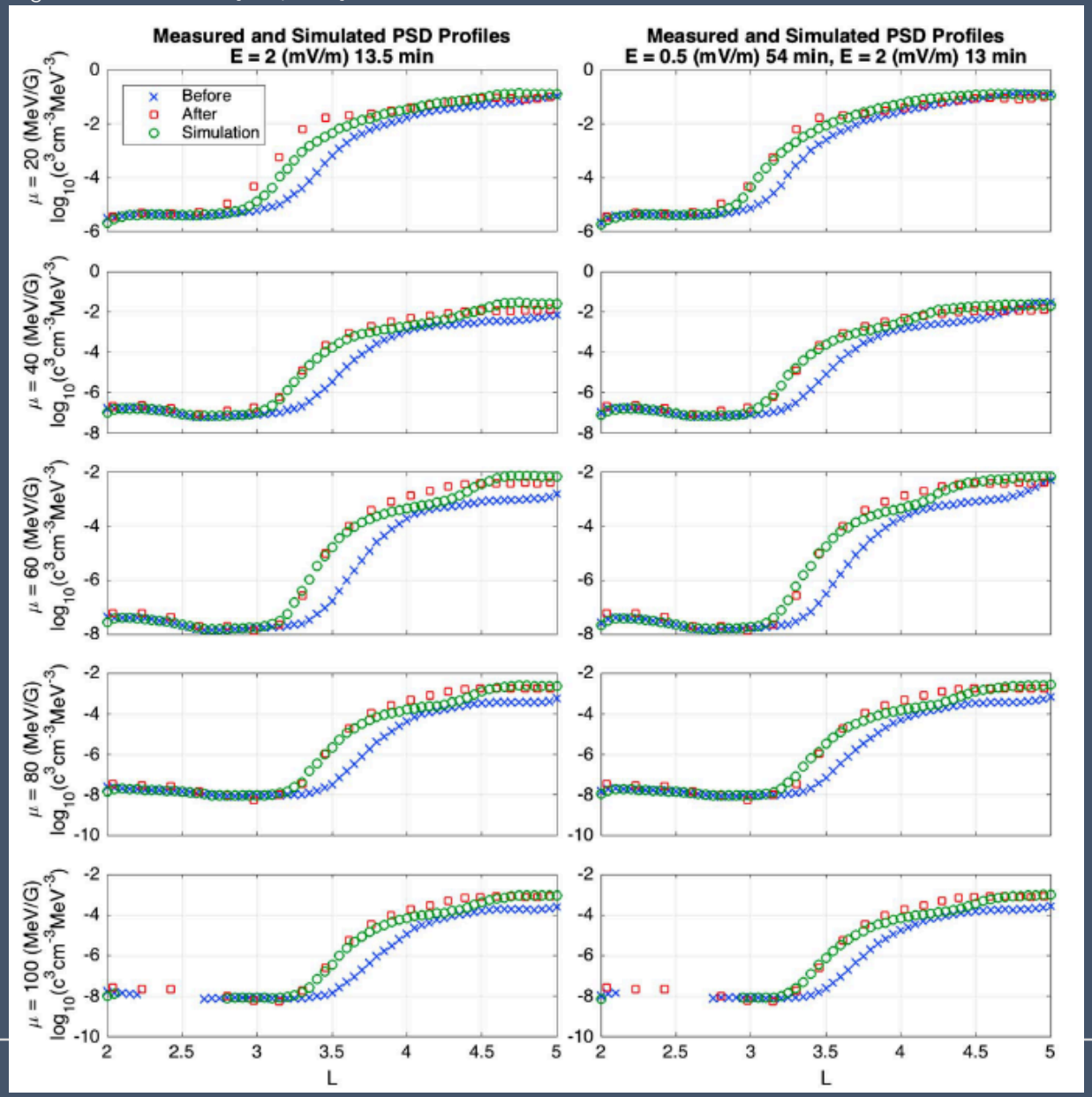


Figure 3. SAPS potential drops measured by the Van Allen Probes within a couple of hours of the deep energetic electron injection events identified by Turner et al. (2015). The *x* axis represents the maximum energy of the electrons injected below L = 4. The SAPS potential drops measured in the premidnight sector are color-coded in red: As the measurements are closer to the peak region, the potential drops observed are greater. The potential drops measured by the spacecraft provide lower estimates for the peak potential drops of each event.

Figure from Califf et al. [JGR, 2017]



Electrons in the Inner Radiation Belt

SPELLS and the source of inner belt electrons

Reformation of the slot after SPELLS event is energy and L-shell dependent, fully consistent with scattering by plasmaspheric hiss

Figures from Reeves et al. [JGR, 2016]

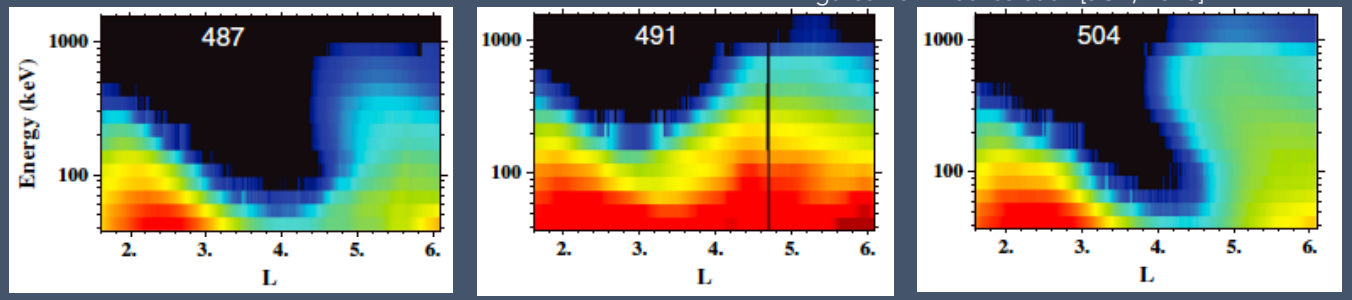


Figure from Ripoll et al. [GRL, 2016]

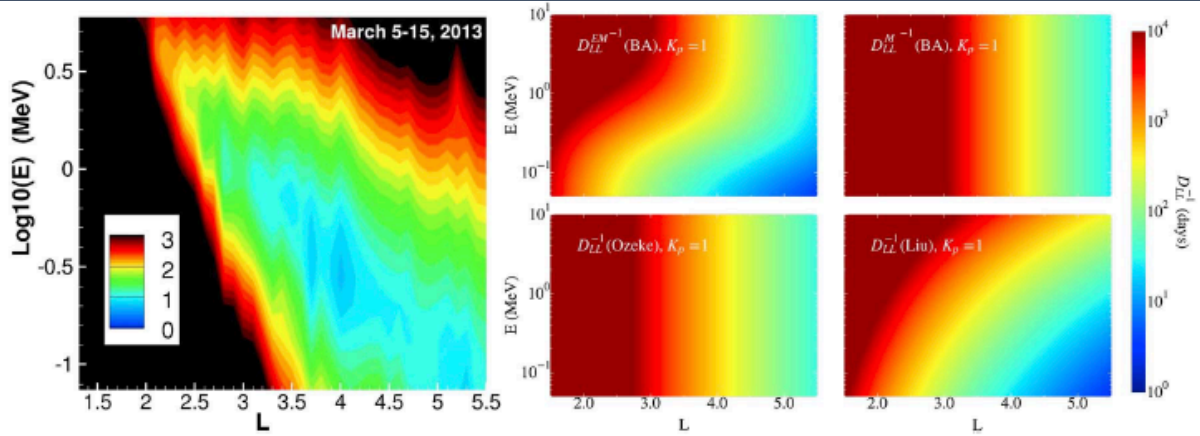
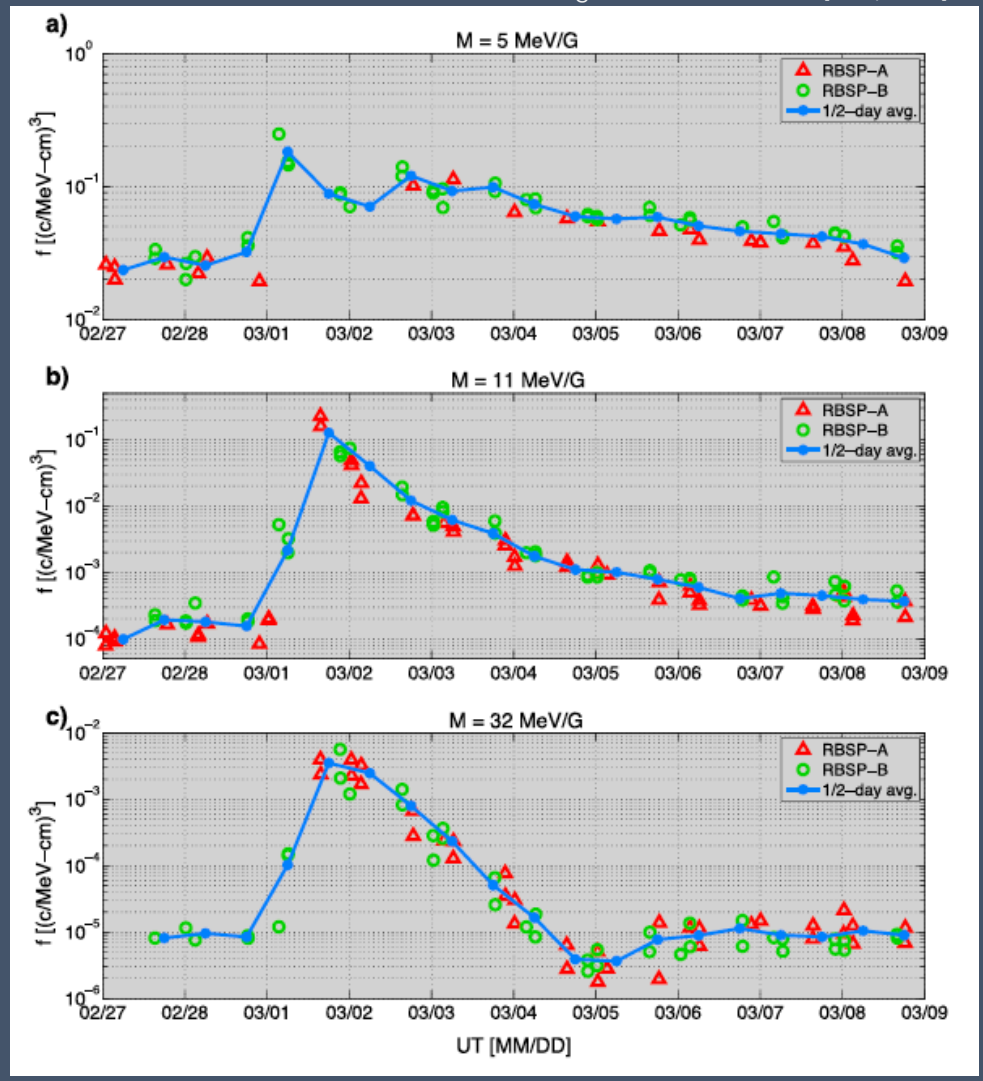


Figure 2. (left) Average electron lifetime ($\log_{10}$) as a function of L shell and energy for 5–15 March 2013. Lifetimes are calculated based on the observed, time-resolved hiss wave, dipolar *B* field, and plasma characteristics. Values of 1000 days and above are indistinctly plotted in black. On the right, the inverse of the radial diffusion coefficient (in days) for the four models used in sections 5 and 6: *Brautigam and Albert* [2000], both magnetic and electric components (right, top left) and magnetic component only (right, top right), both magnetic and electric components of *Ozeke et al.* [2014] (right, bottom left), and the electric component of *Liu et al.* [2016] (right, bottom right).

Figure from Turner et al. [JGR, 2017]



Outline

- History and background
- *Earth's Radiation Belts*
  - Inner Radiation Belts: Protons
  - Inner Radiation Belts: Electrons
  - *Outer Radiation Belt(s)*
- Radiation Belts throughout the Solar System
- Radiation Belts throughout the Cosmos
- Summary and Conclusion: Where to next?

Earth's Outer Radiation Belt Electrons

Sources

Electron Outer Belt Sources: Local Acceleration

Growing peaks in electron phase space density

Growing peaks in electron phase space density for fixed adiabatic invariants are a telltale sign of local acceleration occurring

From those peaks, inward radial diffusion can result in further enhancements of more energetic, several-MeV electrons at lower L-shells (L* < 4) [Zhao+, JGR 2018]

Figure from Reeves et al. [Science 2013]

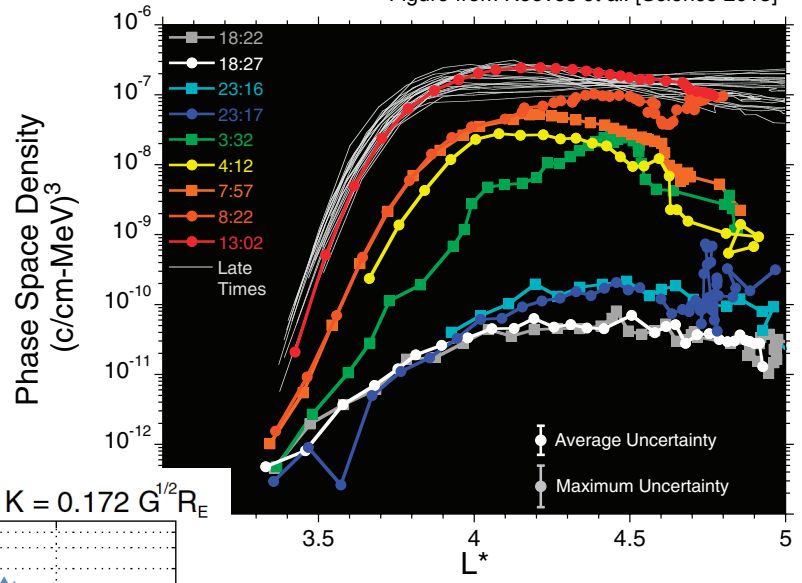
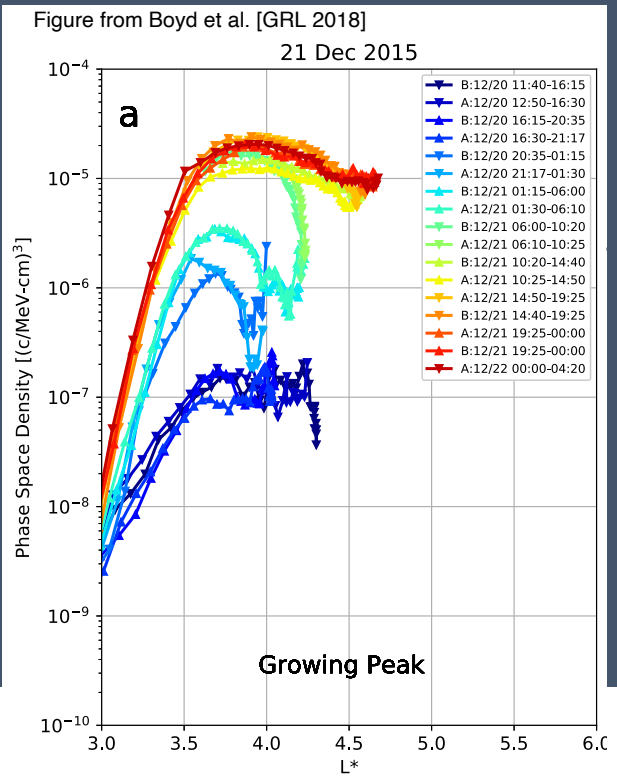


Figure from Boyd et al. [GRL 2018]



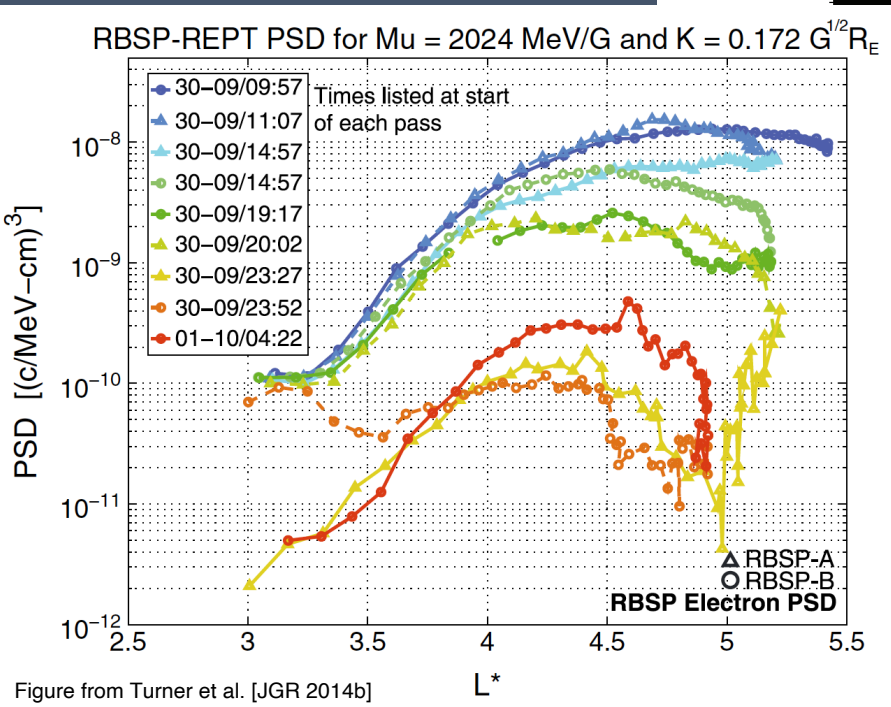
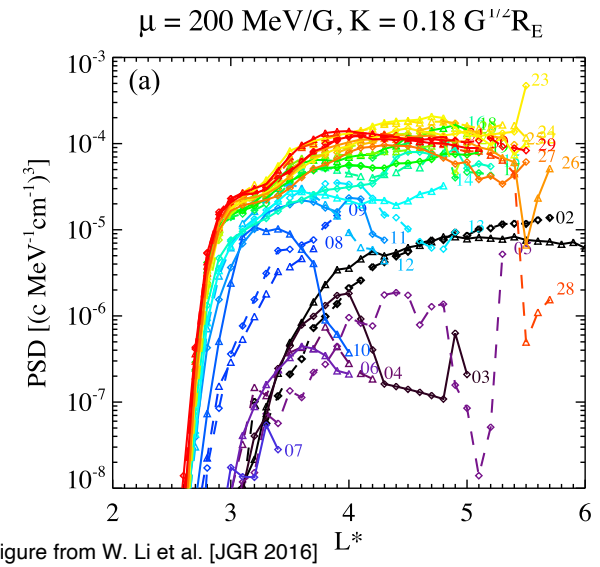


Figure from Turner et al. [JGR 2014b]



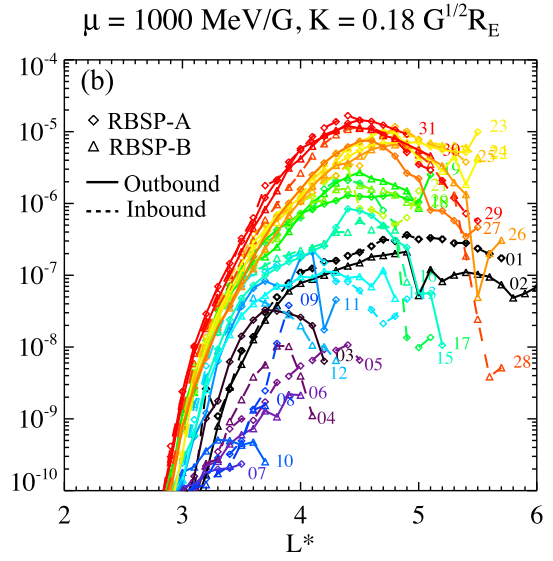


Figure from W. Li et al. [JGR 2016]

2015-03-17/01:20:00 (01)
2015-03-17/02:15:00 (02)
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2015-03-17/19:15:00 (09)
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2015-03-18/05:20:00 (14)
2015-03-18/08:45:00 (15)
2015-03-18/09:50:00 (16)
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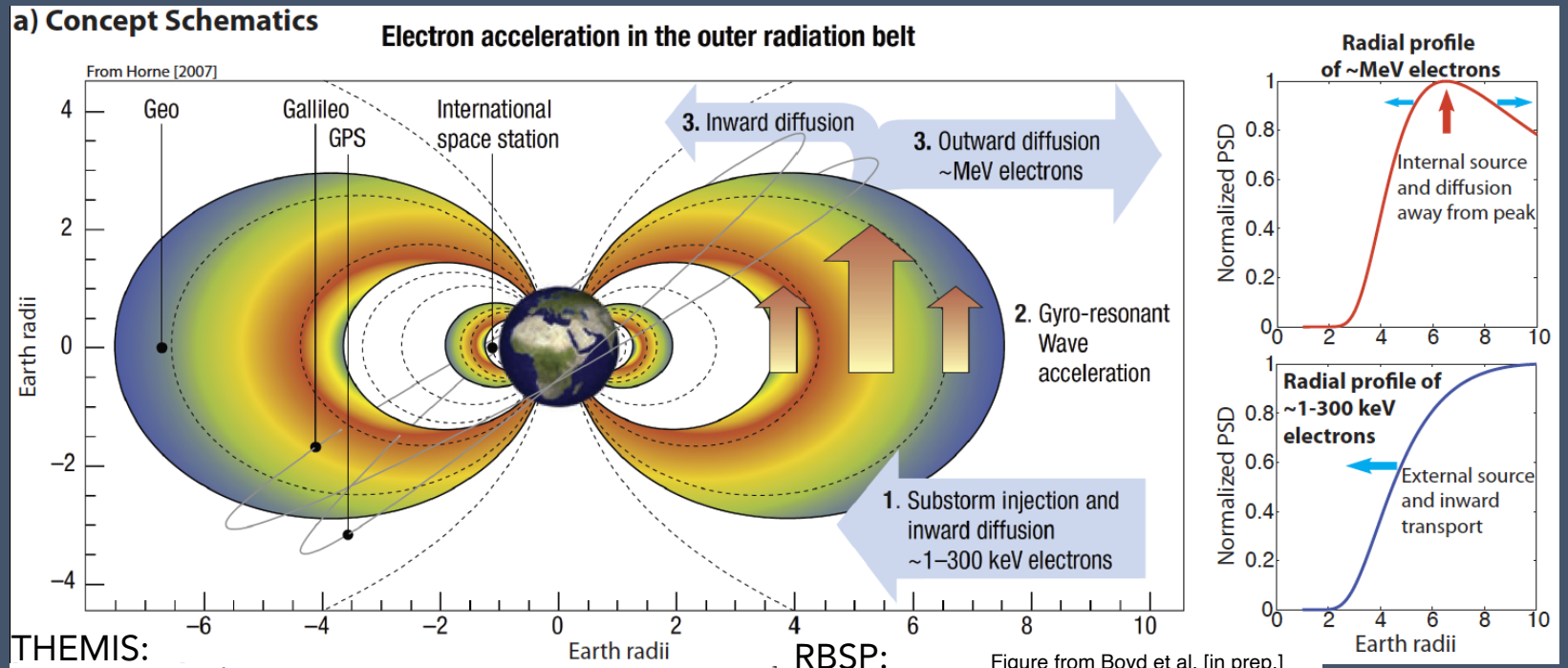
2015-03-19/07:10:00 (25)
2015-03-19/08:25:00 (26)
2015-03-19/11:40:00 (27)
2015-03-19/12:55:00 (28)
2015-03-19/16:10:00 (29)
2015-03-19/17:25:00 (30)
2015-03-19/20:40:00 (31)

Acceleration and the importance of substorm activity

Sources are energy dependent

Figure from Turner and Angelopoulos [2016]



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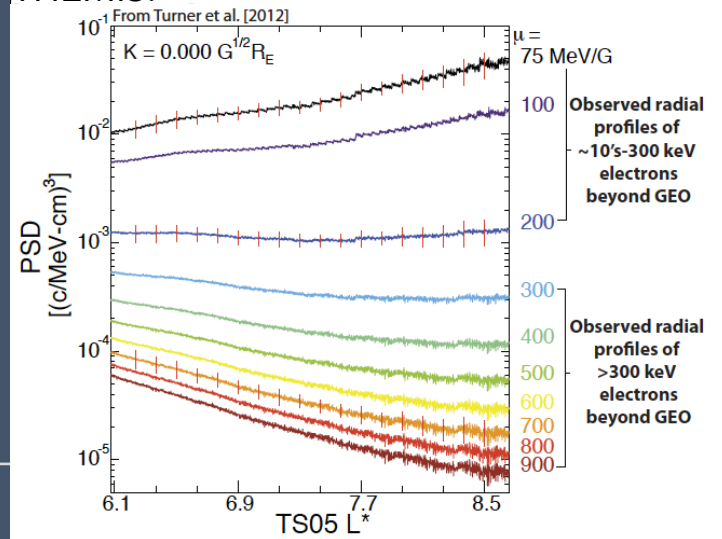
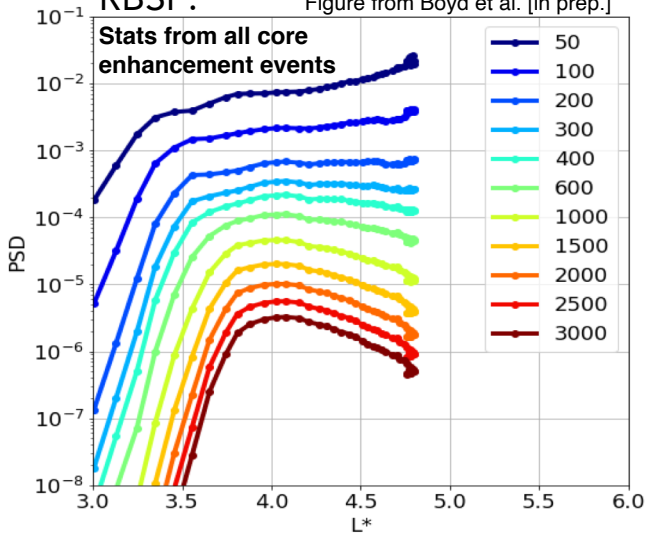


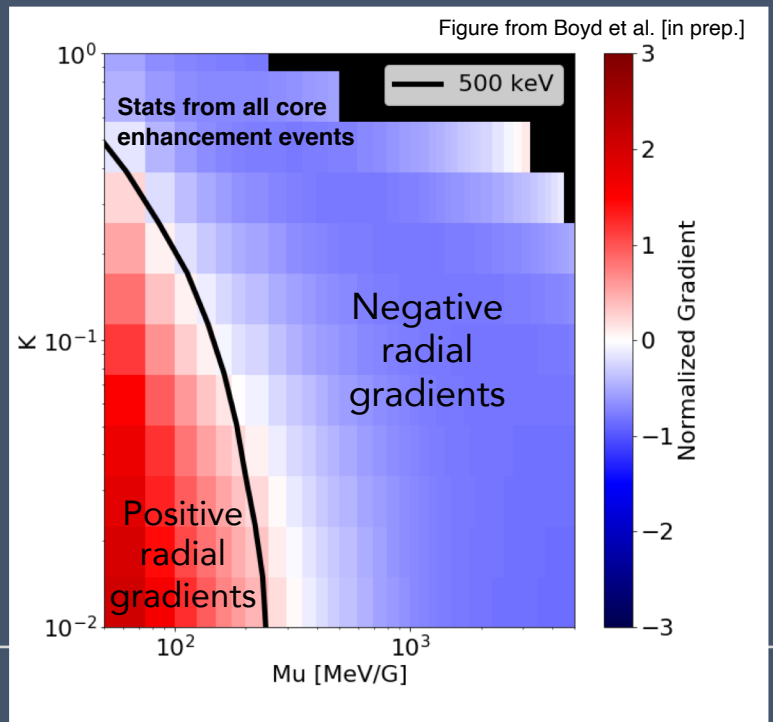
RBSP:

Figure from Boyd et al. [in prep.]



- 10s – 100s keV source is plasma sheet; >500 keV source is local acceleration from interactions with chorus waves [e.g., Reeves et al., Science 2013]
- Particle injections are critical to outer belt dynamics! They introduce:
  - The source of chorus waves (10s keV) and
  - The seed population for local acceleration (100s keV)
- Transition at ~200 MeV/G between monotonic and peaked profiles
- Corresponds to ~500 keV at low K, the critical energy where electrons can be accelerated by VLF Chorus faster than they are scattered [Horne et al. 2005]

Figure from Boyd et al. [in prep.]



Acceleration and Substorm Activity

Broader community consensus

- Meredith et al. [JGR 2002; JGR 2003]: stressed the importance of substorms for enhancements of the relativistic electrons in Earth's outer radiation belt
- Miyoshi et al. [GRL 2013]: High speed stream storms with Bz-south cause chorus and seed populations from injections → outer belt enhancements
- Schiller et al. [GRL 2014] and Su et al. [GRL 2014]: Substorm activity important for non-storm enhancements of the outer belt electrons
- Gkioulidou et al. [JGR 2014]: Ion injections contribute significantly to the storm-time ring current and pressure in the inner magnetosphere
- Hajra et al. [PSS 2015]: Prolonged substorm activity → outer belt enhancements
- Ingraham et al. [JGR 2001] and Dai et al. [GRL 2015]: MeV electron injections in strong events
- Jaynes et al. [JGR 2015]: Key ingredients for MeV electron acceleration are chorus waves and seed electrons from substorm injections!

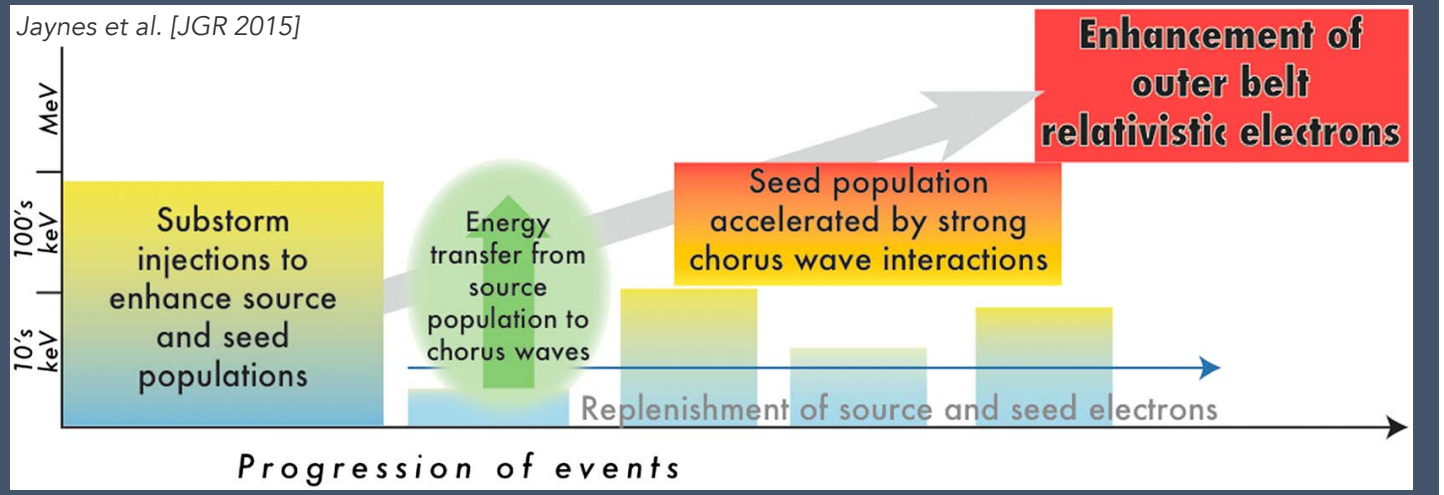
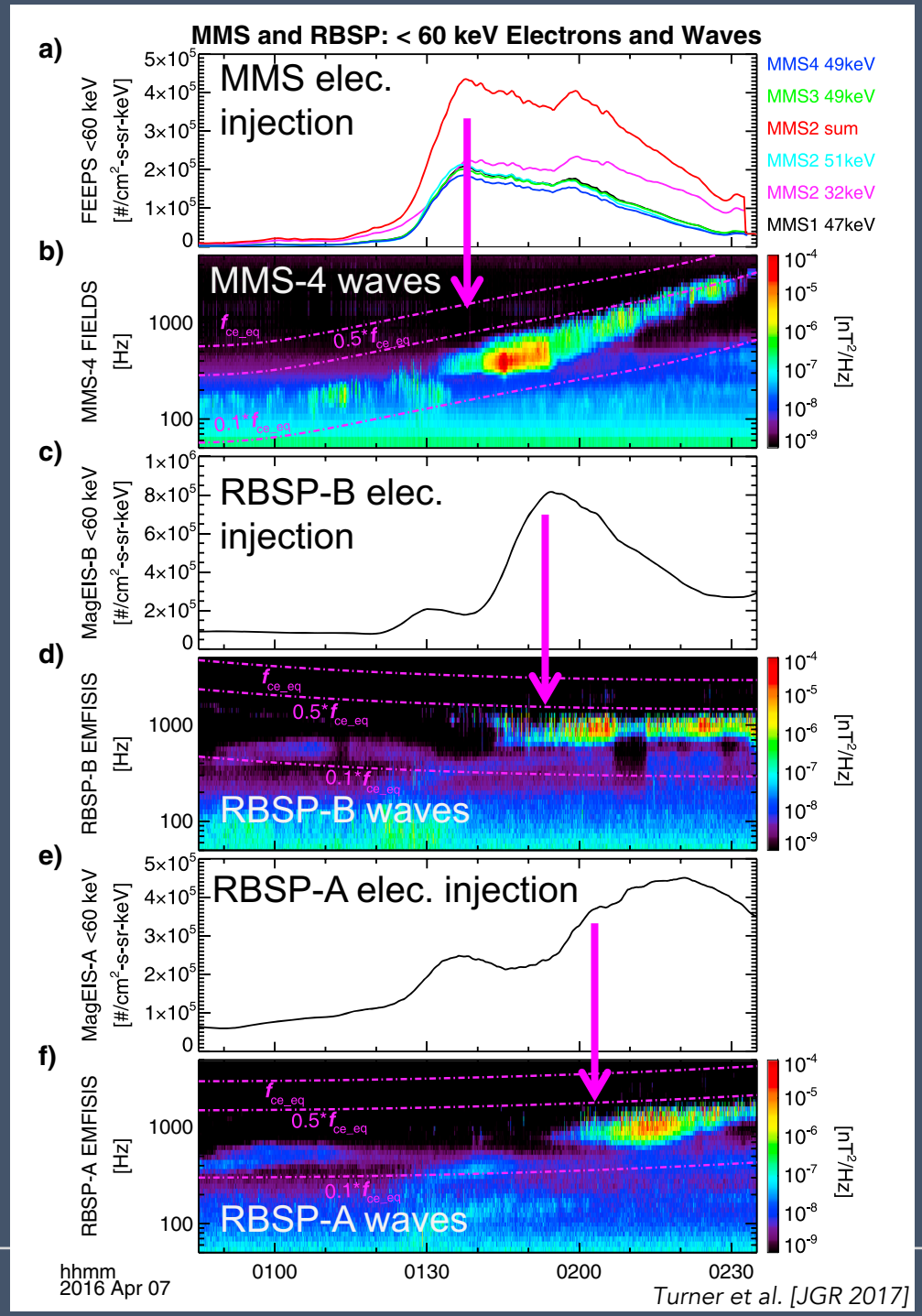


Figure 1. Schematic of the ideal setup and sequence for strong enhancement of outer belt electrons >1 MeV.



Electron Injections as Sources

Outstanding questions and ongoing challenges

- Open questions on complexity of injections: Gabrielse+ [JGR 2014; JGR 2019]; Turner+ [JGR 2017]; Sorathia+ [JGR 2018]; (many others)
- MeV injections [e.g., Dai+, GRL 2015]: They are very infrequent, but they can occur… why are they so infrequent?
- Sufficient sources in the plasma sheet (?) and dominant acceleration processes for electrons and ions there

Figure from Turner+ [in prep.]

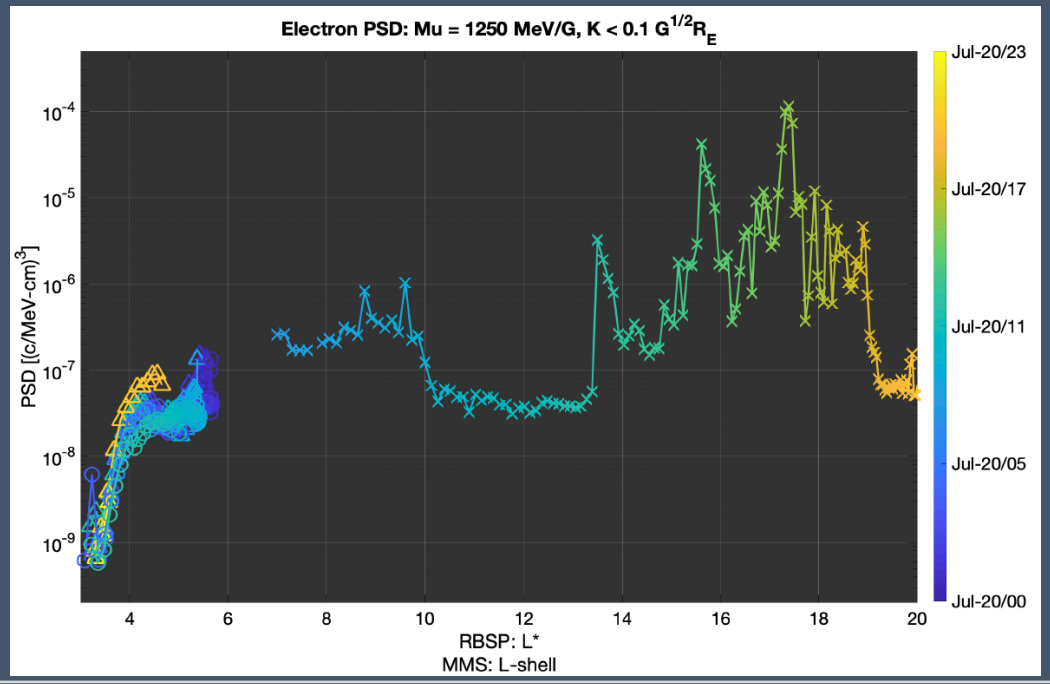
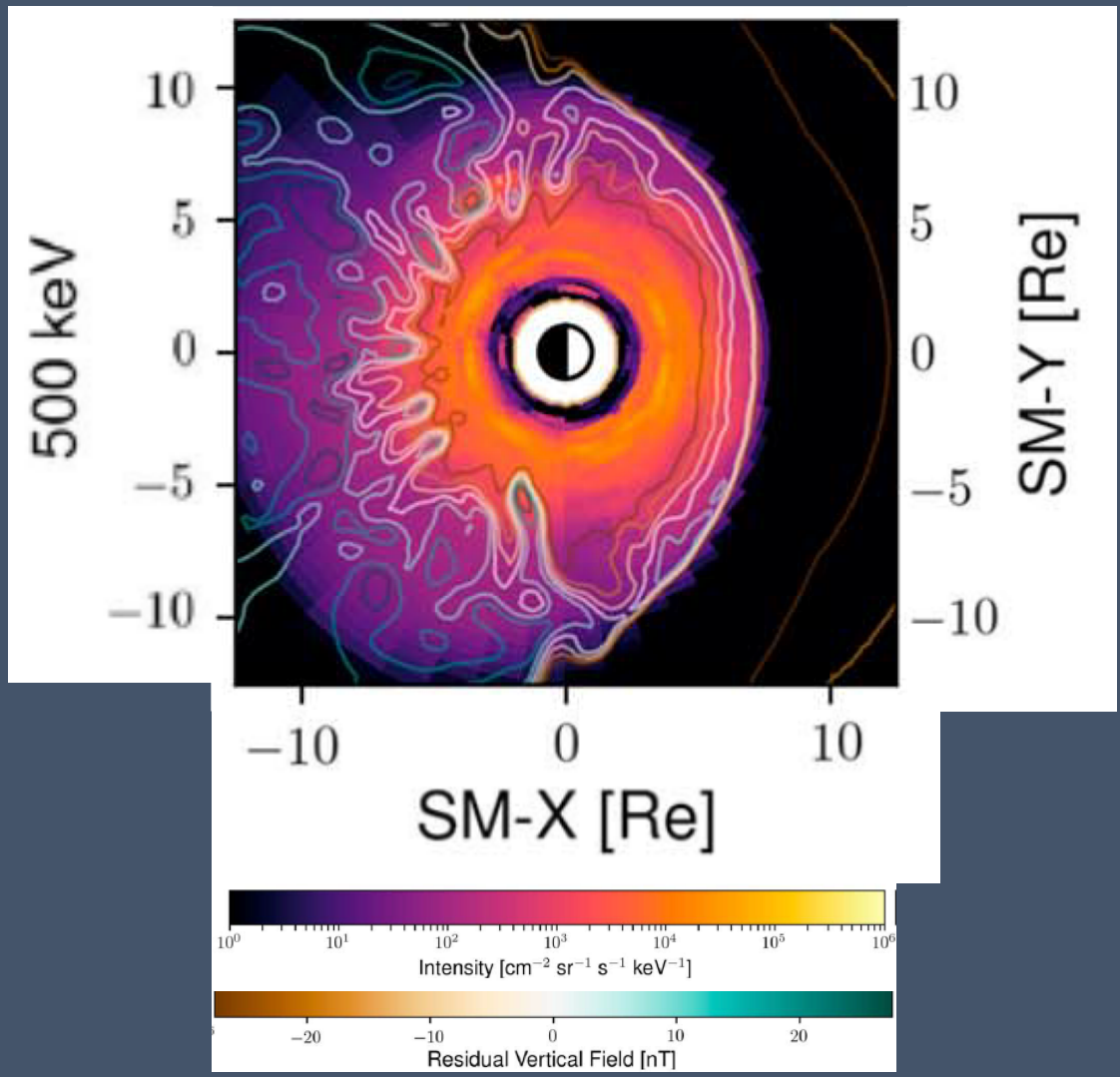


Figure from Sorathia+ [JGR 2018]



Earth's Outer Radiation Belt Electrons

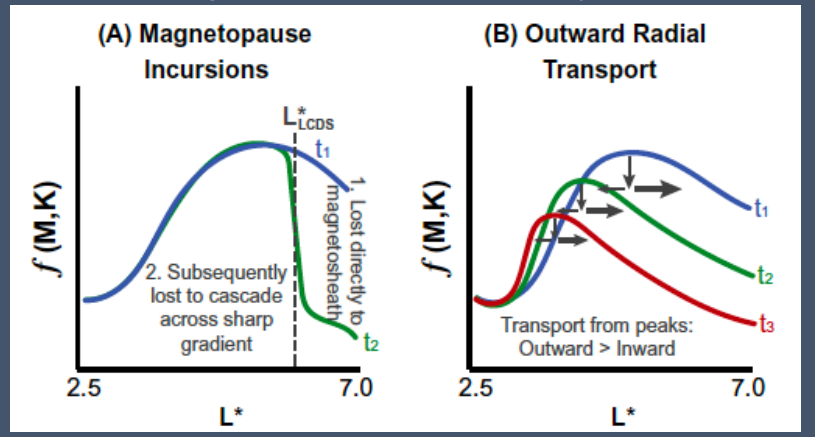
Losses

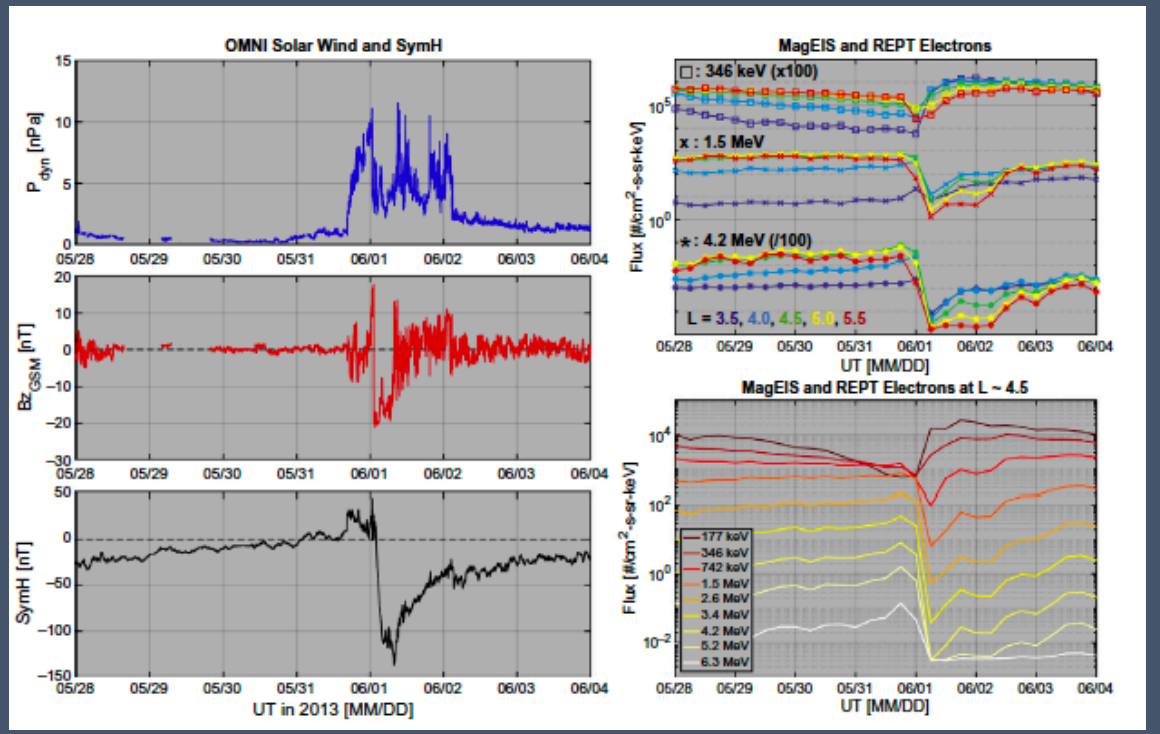
Outer Belt Electron Dropout Events

Combined effects of loss processes

- **Dropouts are the sudden (hrs), drastic (OoM) decrease in flux in the outer belt over a wide range of energies and L-shells**
- See reviews: Turner et al. [2012]; Turner and Ukhorskiy [2020]
- At higher L (L* > ~4), the majority of dropout event losses are dominated by combined effects of loss through the magnetopause and rapid outward radial transport
- Other loss processes needed to explain losses at L* < ~4
- Simulations and modeling:
  - *Shprits et al. [JGR, 2006]*
  - *Ukhorskiy et al. [JGR, 2006]*
  - *Nishimura et al. [JGR, 2006]*
  - *Kim et al. [JGR, 2008]*
  - *Kim et al. [JGR, 2010]*
  - *Ukhorskiy et al. [JGR, 2015]*
  - *Mann et al. [Nat. Phys., 2016]*
  - *Sorathia et al. [JGR 2018]*
- Observations:
  - *Loto'aniu et al. [JGR, 2010]*
  - *Matsumura et al. [JGR, 2011]*
  - *Shprits et al. [JGR, 2012]*
  - *Turner et al. [Nat. Phys., 2012]*
  - *Hwang et al [JGR, 2013]*
  - *Turner et al. [JGR, 2013]*
  - *Turner et al. [JGR, 2014a]*
  - *Xiang et al. [JGR, 2017]*
  - *Xiang et al. [GRL, 2018]*

Figures from Turner and Ukhorskiy [Elsevier, 2020]



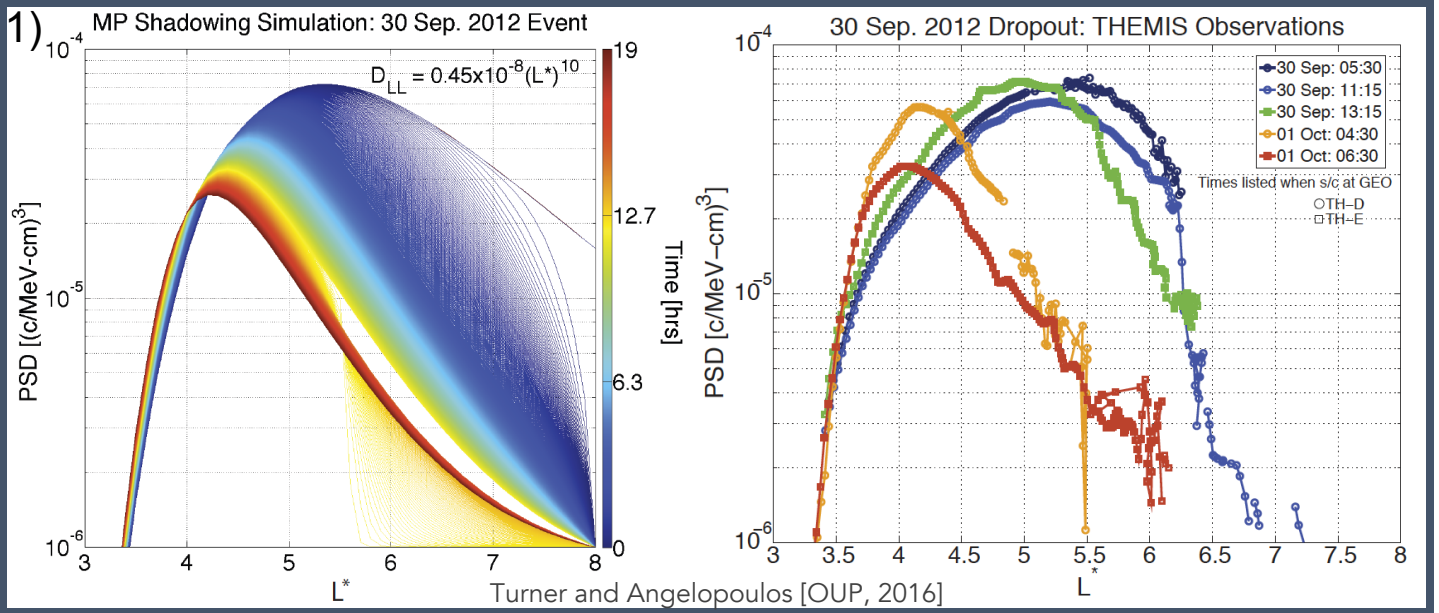


Both EMIC waves and MP loss/outward transport important for MeV electron losses in dropouts w/ sig. L-dependence

Dropouts and Remnant Belts

Combined effects of loss and acceleration

1)



Turner and Angelopoulos [OUP, 2016]

2)

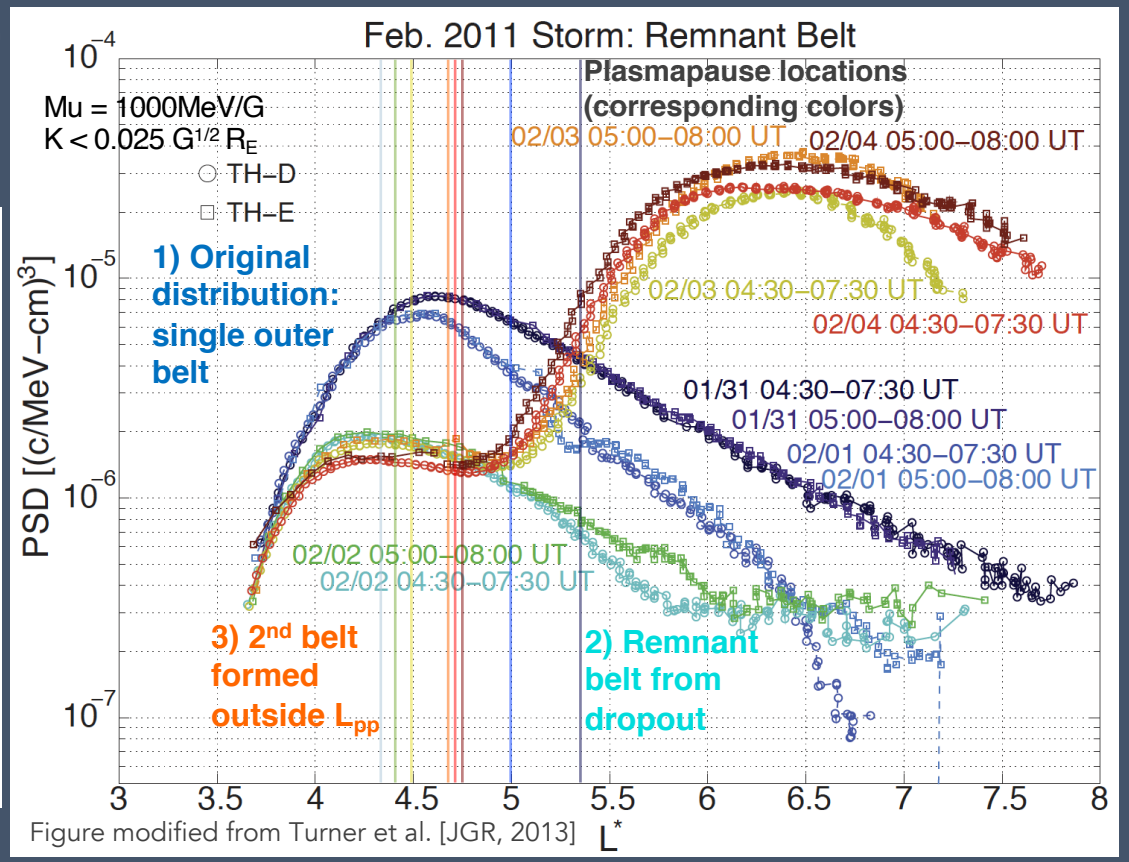


Figure modified from Turner et al. [JGR, 2013]

- See Turner et al. [JGR 2013] for definition and description
- Also, the "storage ring" event of Baker et al. [Science 2013] and Shprits et al. [Nat. Phys. 2013] vs. Mann et al. [Nat. Phys. 2016]; Plus Thorne et al. [GRL 2013] for importance of E-dependent WPI with plasmaspheric hiss
- So far, >30 such events during the Van Allen Probes era: see Pinto et al. [GRL 2018]

Double outer belts are just the remnant belt from a dropout plus new belt at higher L from acceleration; they are common

3)

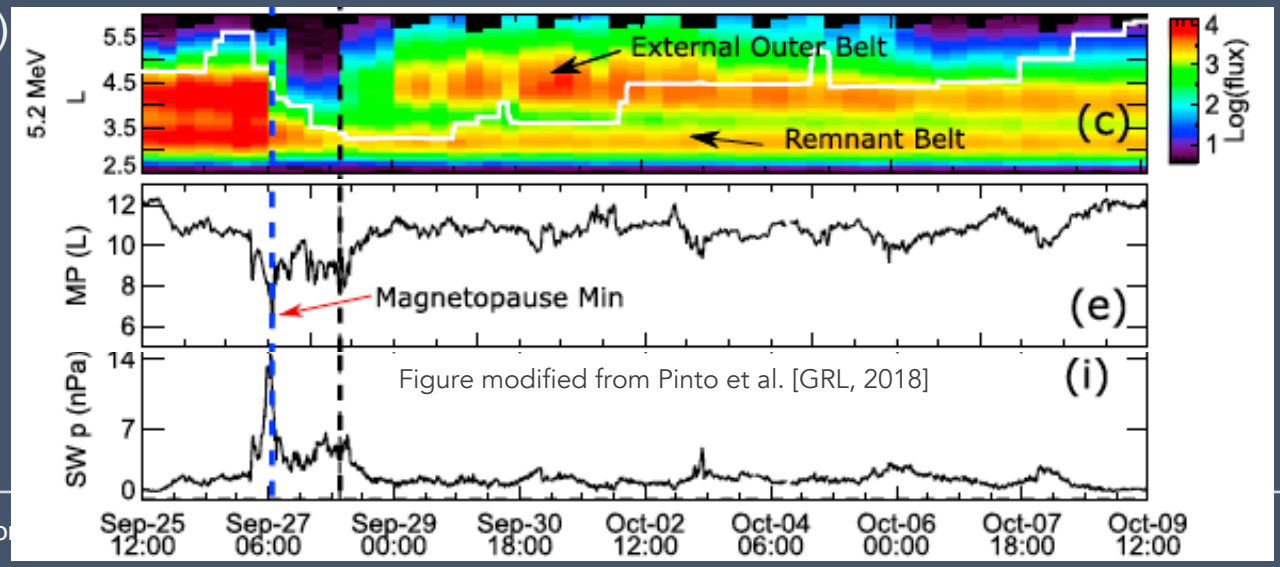
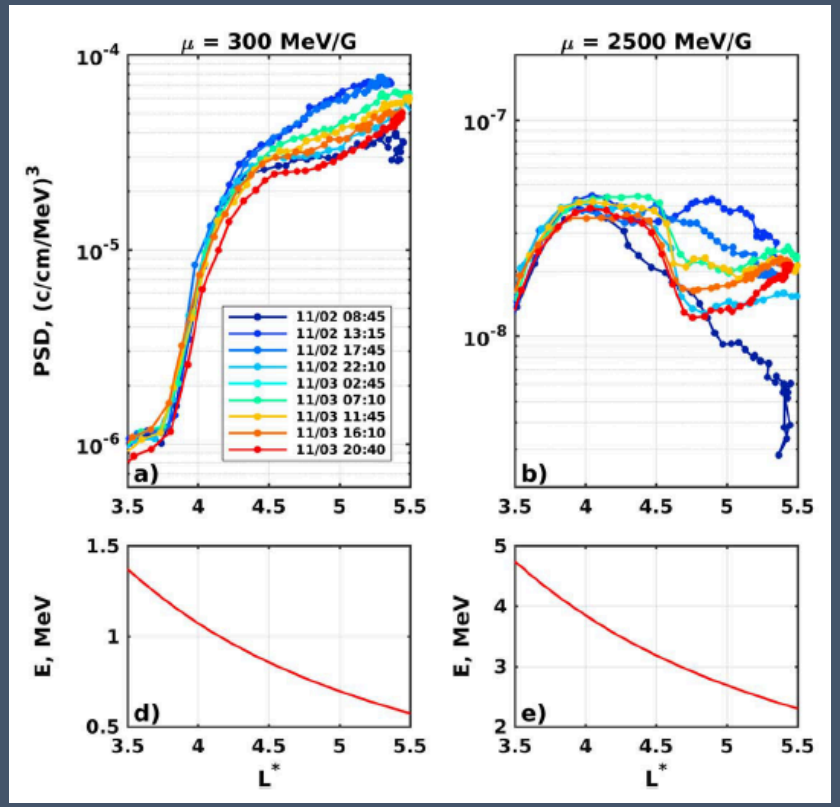


Figure modified from Pinto et al. [GRL, 2018]

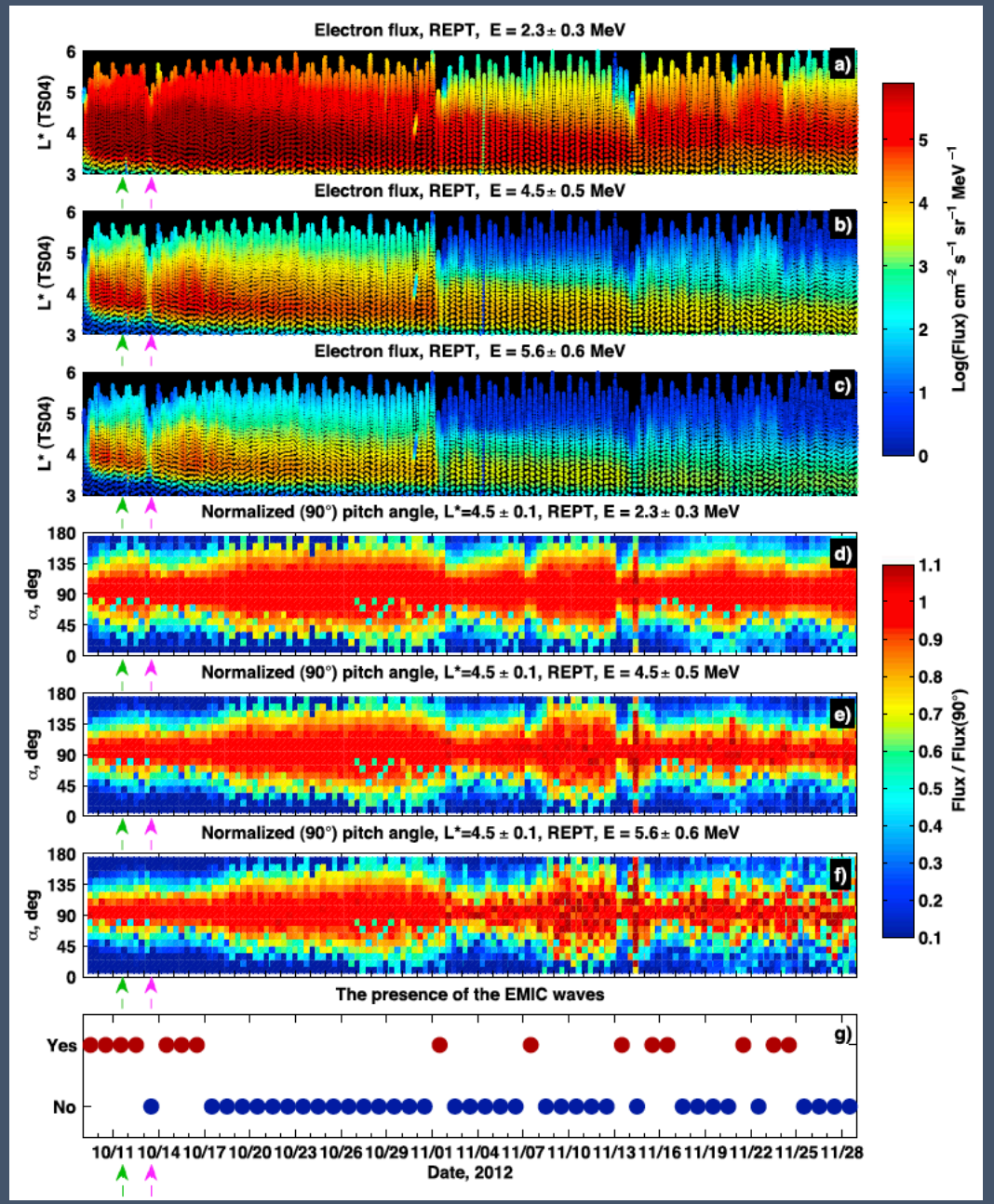
Scattering by EMIC Waves

- EMIC losses represent a major loss process for outer belt electrons, particularly during active times [e.g., Ukhorskiy+ GRL 2010; Blum+ 2015; Capannolo+ JGR 2019;] and may play a contributing role during dropouts, especially at low L (L* < 4.5) [Xiang+ GRL 2018]
- Interaction with EMIC waves (anomalous resonance) is highly energy and pitch angle dependent: strongest losses for several MeV electrons that mirror at higher latitudes [e.g., Usanova+, GRL 2014]
- EMIC scattering evidence directly seen in electron PSD data as deepening, localized troughs over time [e.g., Aseev+, JGR 2017]
- EMIC waves also related to injections and substorm activity [e.g., Meredith+, JGR 2014]

Aseev+ [JGR 2017]



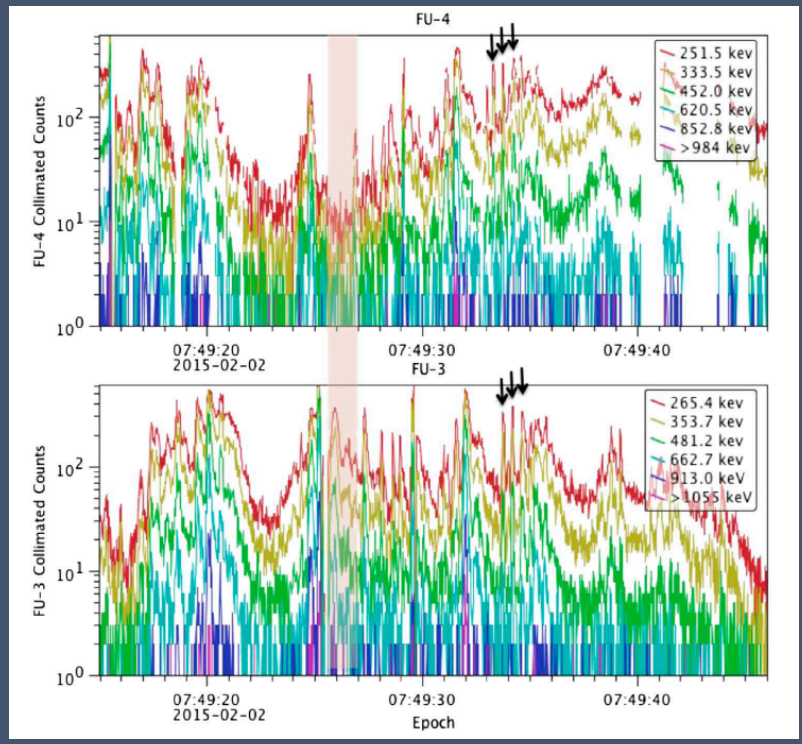
Usanova+ [GRL 2014]



Microburst Precipitation

- Microbursts are ~100 ms enhancements in electron intensity in the atmospheric loss cones; first observed by SAMPEX: Lorentzen+ [JGR 2001]; O'Brien+ [GRL 2004]
- Size scales: Blake and O'Brien [JGR 2016]; Crew+ [JGR 2016]; Anderson+ [JGR 2017]; Breneman+ [GRL 2017]
  - Individual microbursts: 30 km and >120 km from AC6 and FIREBIRD-II
  - Microburst active region can span most of the morning and early afternoon LT sector [Anderson+]
- First observations from RBSP (non LEO) [Shumko+ GRL 2018] reveals nonlinear nature
- New insights from AeroCube-6: **Curtains** [Blake and O'Brien, JGR 2016; Shumko et al., under review] vs. **Flashes** [Shumko et al., JGR 2020]
  - **Curtains**: spatial precipitation structures in the DLC; <35 km wide (in Lat) at LEO
  - **Flashes**: temporal precipitation burst in the BLC (*only!?!*); ~40 – 105 km in scale at LEO
- Cause is apparently nonlinear scattering by chorus waves, possibly biproduct of acceleration [e.g., Bortnik+., GRL 2008; Tao+, GRL 2012; Breneman+, GRL 2017]

Crew et al. [JGR 2016]

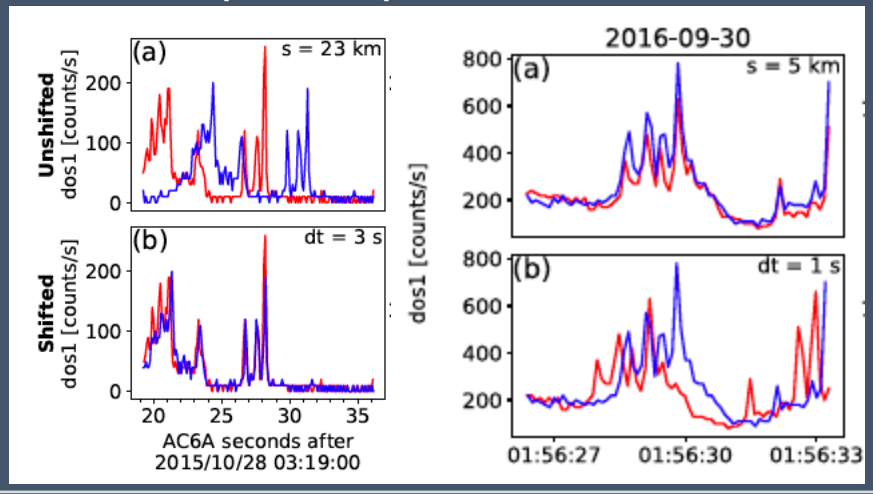


Curtains

Shumko+ [under review]

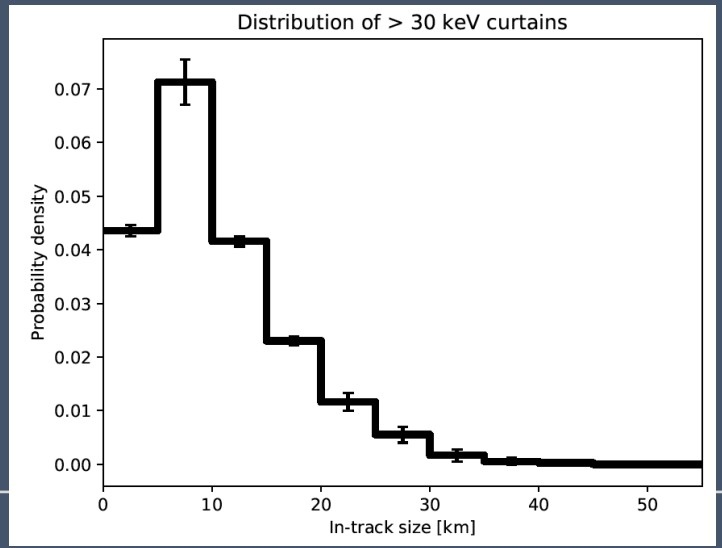
Flashes

Shumko+ [JGR 2020]



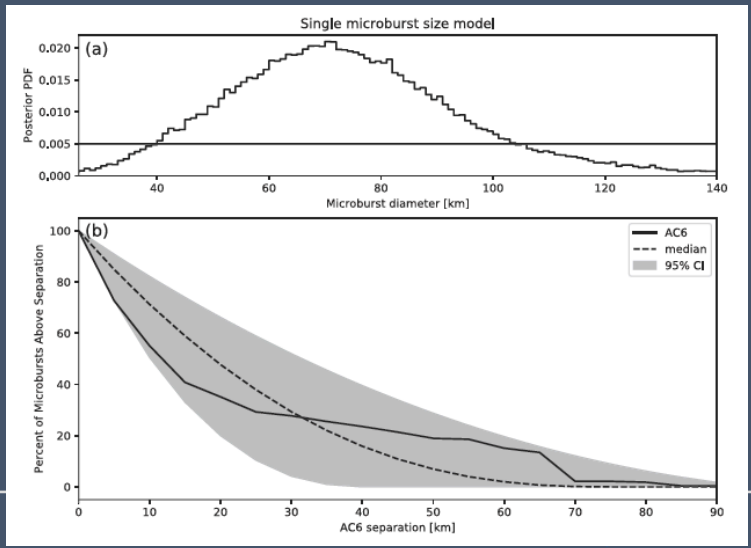
Curtains

Shumko+ [under review]



Flashes

Shumko+ [JGR 2020]



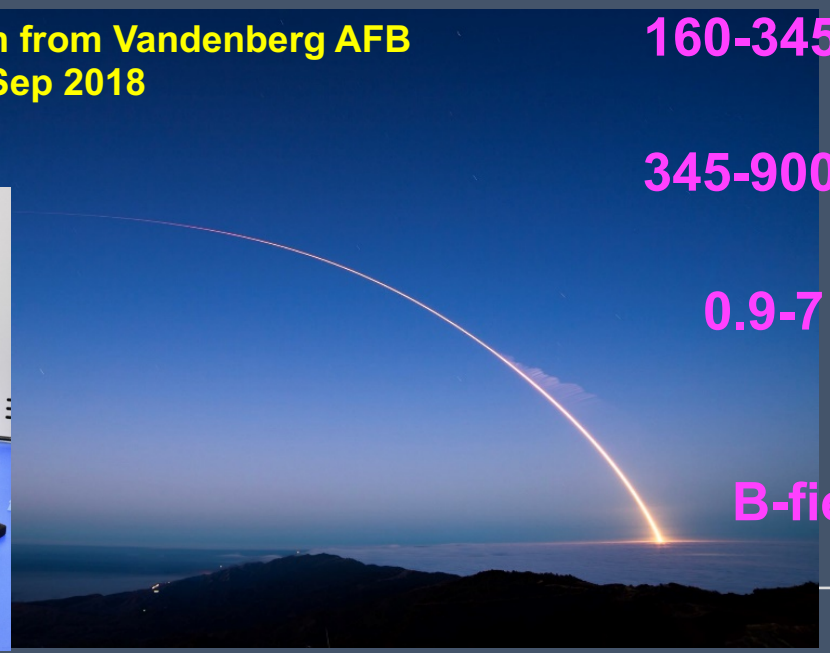
New Insights on Precipitation and Atmospheric Backscattering

Electron Losses and Fields Investigation (ELFIN)

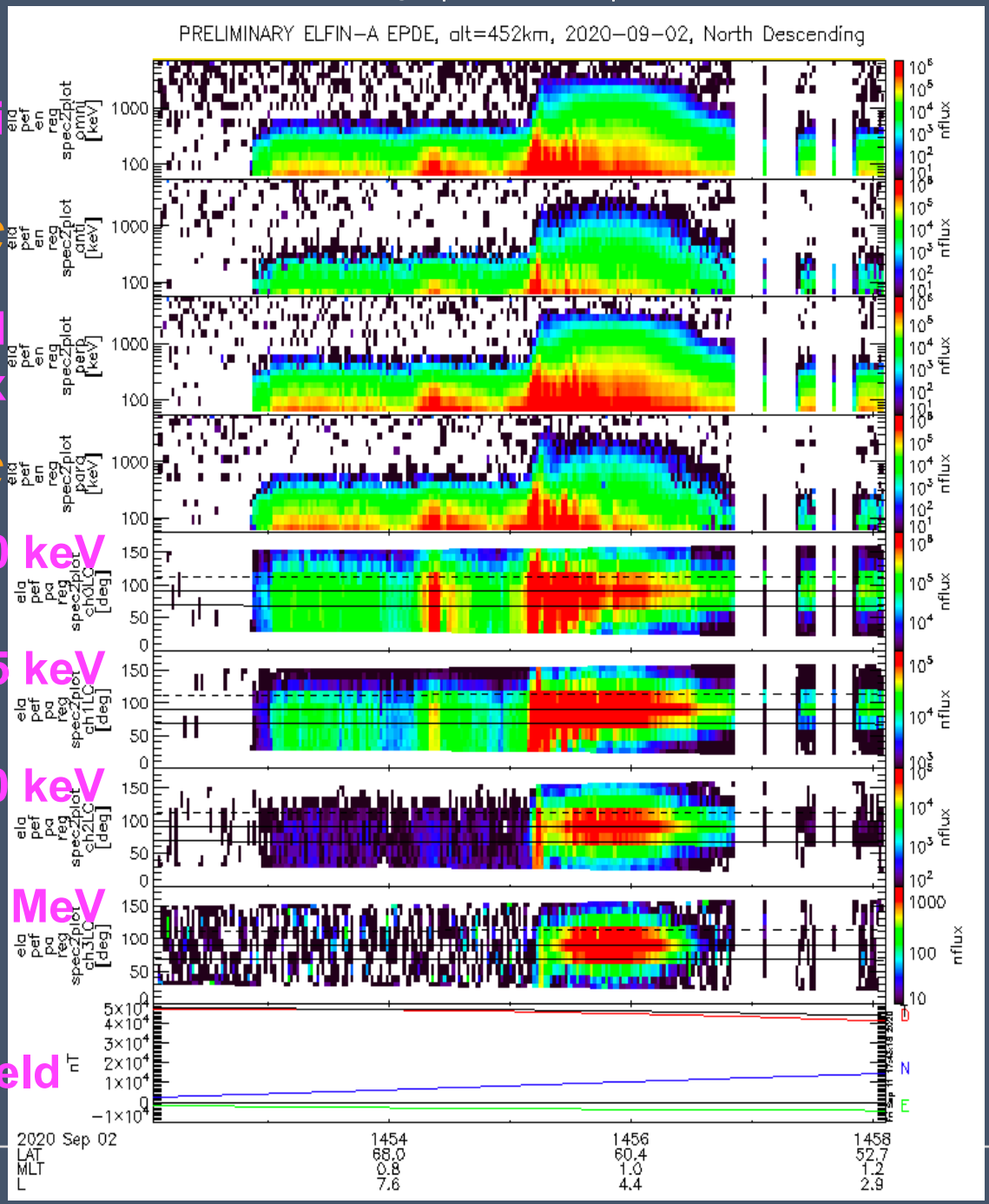
- First pitch angle distributions within the atmospheric loss cones
- ELFIN consists of twin 3U spinning CubeSats
- Built primarily by undergraduates (!!!) at UCLA
- Primary Payload Instruments
  - Energetic Particle Detectors (EPD): Differential flux of electrons with PADs
  - Boom-mounted Fluxgate Magnetometer (FGM)

Launch from Vandenberg AFB on 15 Sep 2018

UCLA's ELFIN



See Angelopoulos+ [SSR in press]



Earth's Outer Radiation Belt Electrons

Storm-time Responses

Storm-time Responses

- O'Brien+ [JGR 2001]: Inconclusive evidence for either local acceleration or inward radial diffusion as acceleration mechanism based on waves, proxies, and GEO fluxes; both ULF and VLF waves are very active during storm main and recovery phases
- Reeves+ [GRL 2003]: Post-storm outer radiation belt is a result of a "delicate balance" between source and loss processes

Figures from Reeves+ [GRL 2003]

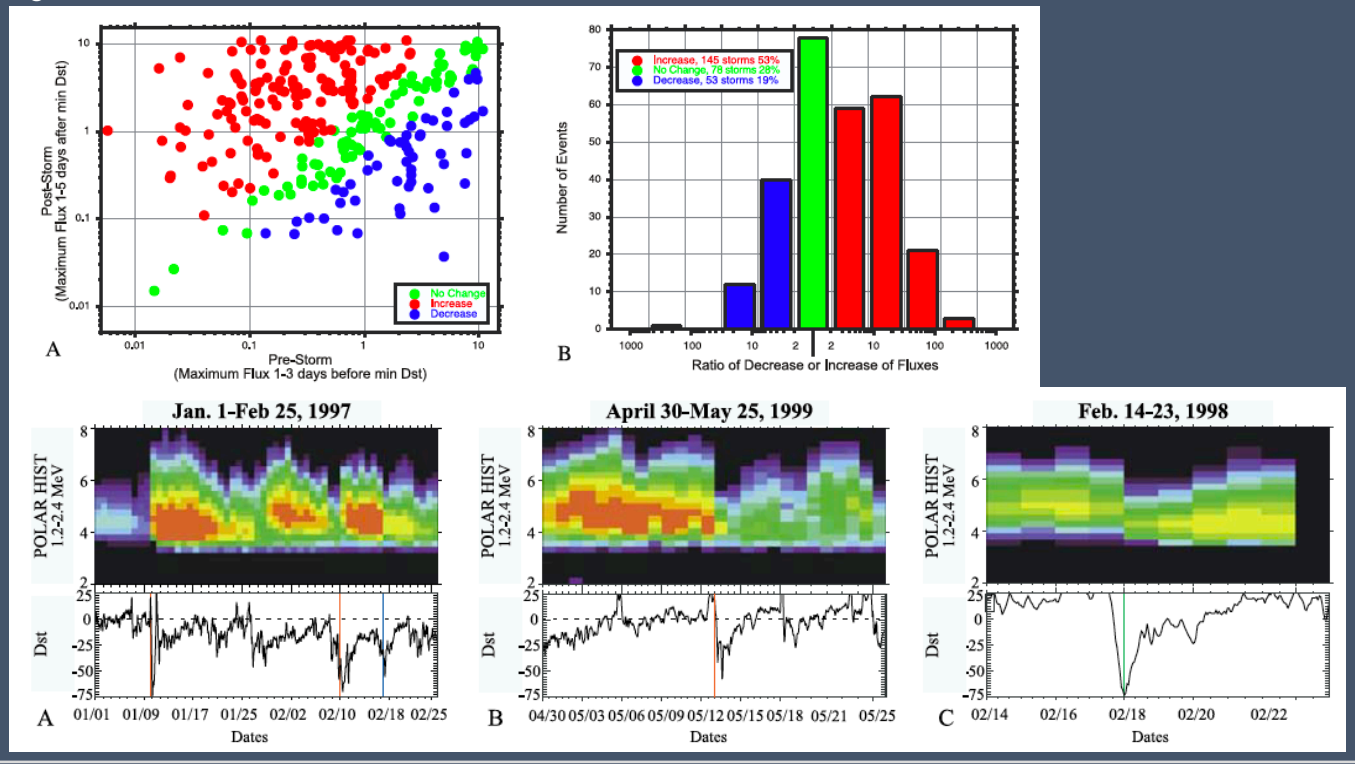
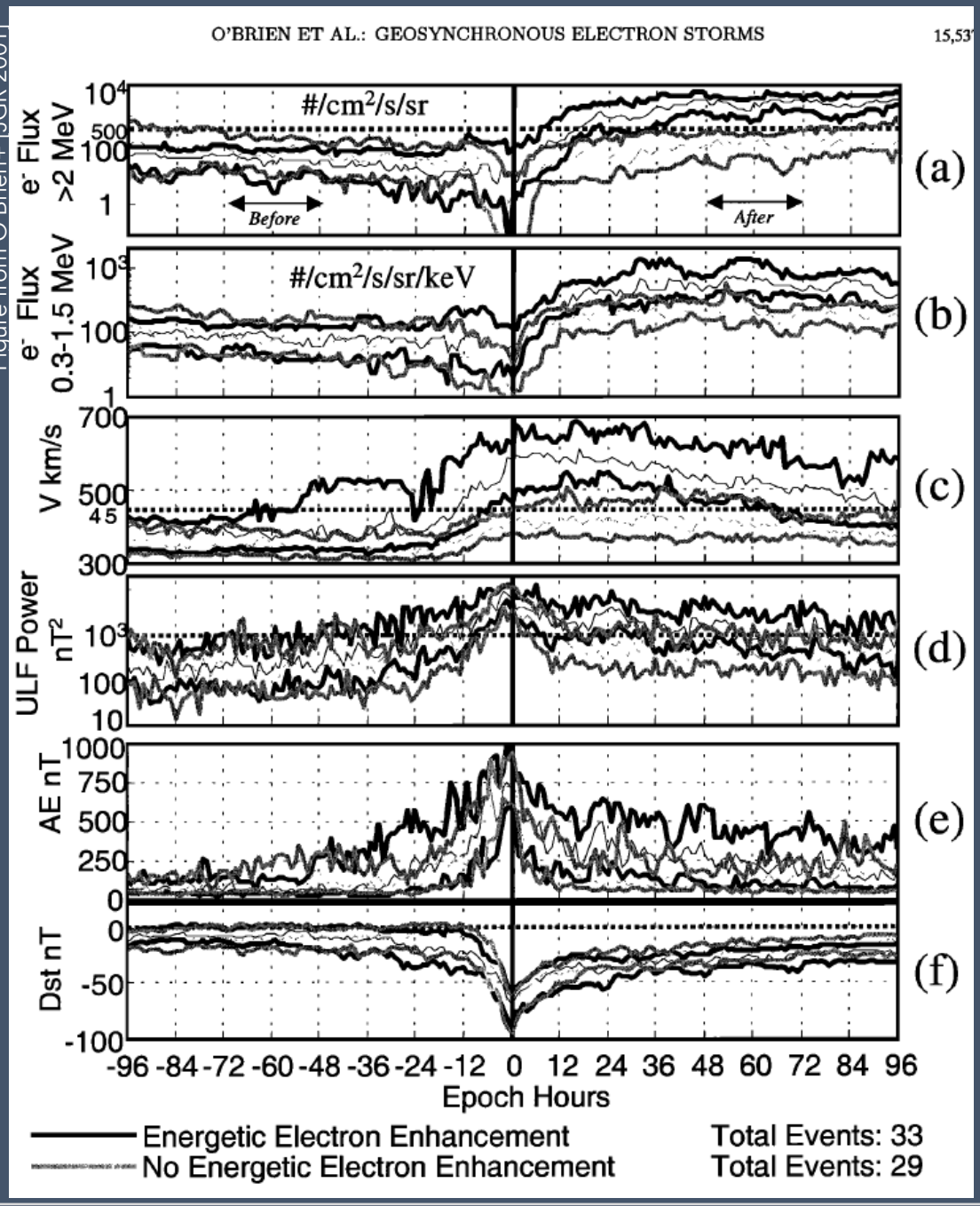


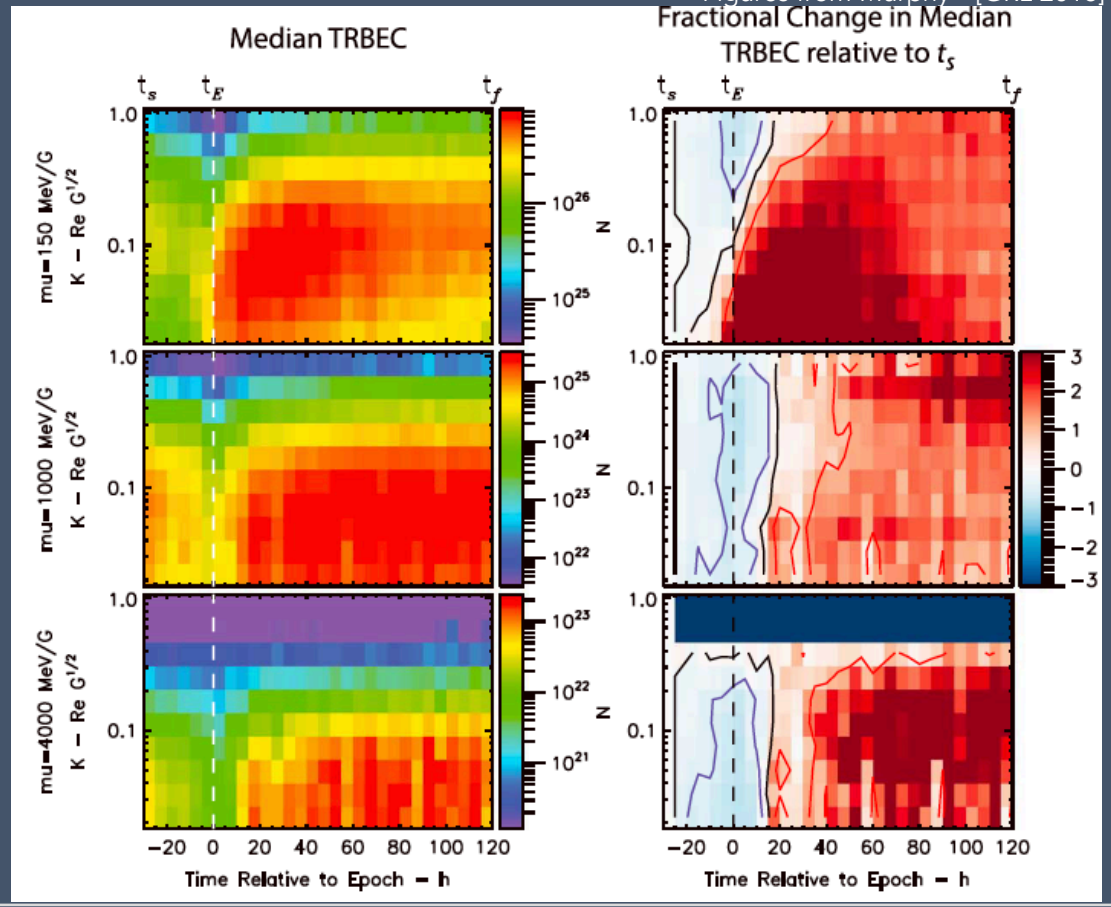
Figure from O'Brien+ [JGR 2001]

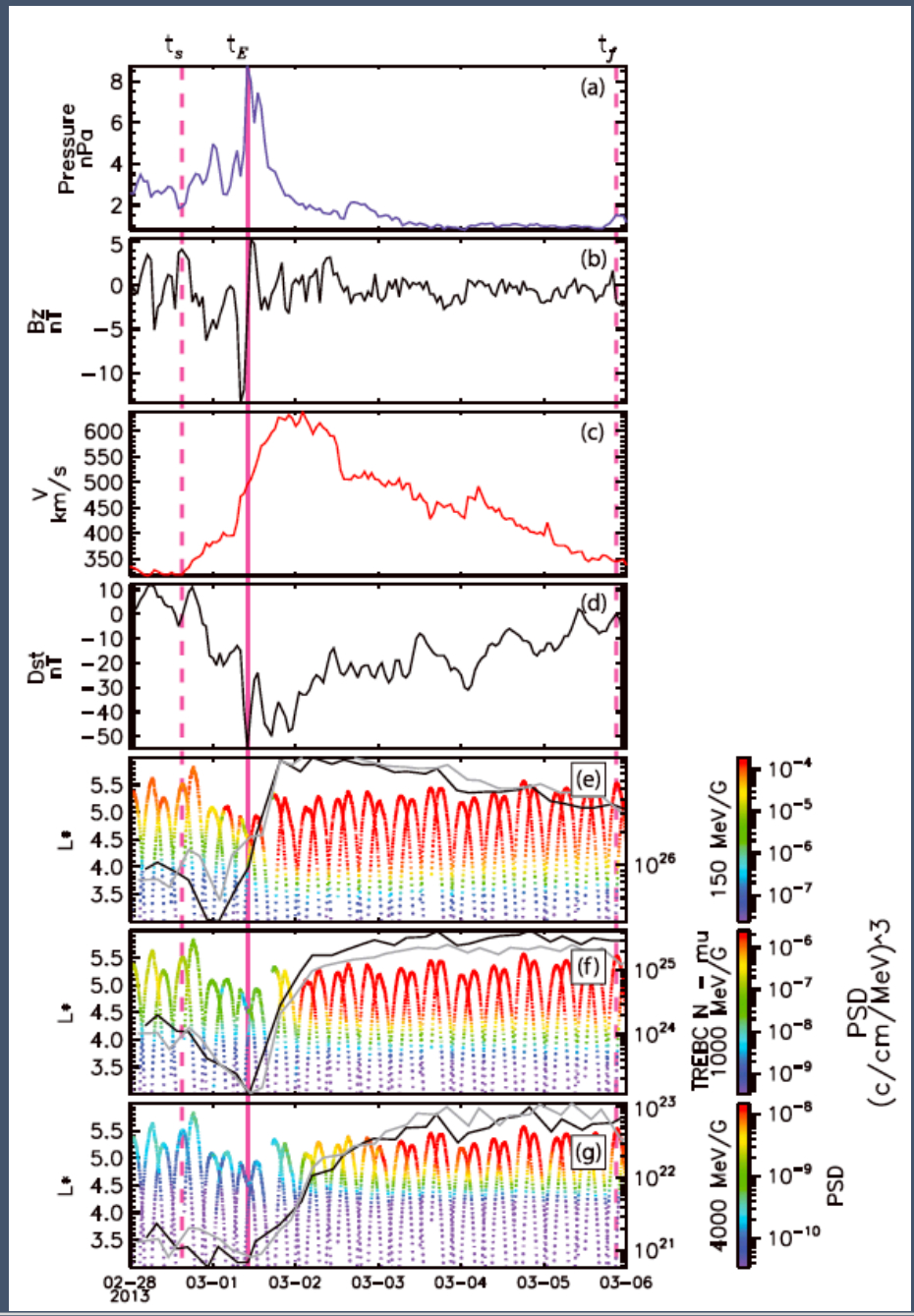


Storm-time Responses

- Storm-time response stats from Murphy et al.: Peak PSD shows distinct pattern of behavior during storms, but it is Mu-dependent
- For relativistic electrons:
  - Initial phase characterized by true loss, nearly eradicating (>90% loss) the pre-existing belt
  - Second phase of rapid acceleration which may or may not enhance above pre-storm levels
- For seed electrons: little to no loss, just enhancements during storm main phase
- Turner+ [GRL 2015]: 100 – 600 keV electrons are enhanced around L ~4 in nearly 90% of all storms

Figures from Murphy+ [GRL 2018]





Storm-time Responses

- Storm-time response stats:
  - Bingham et al. [JGR 2018], 60 storms: Chorus activity and growing peaks in PSD for enhancement events
  - Turner et al. [JGR 2019], 110 storms: SPELLS, dropouts, enhancements and storm drivers
  - Many, many other references on this (see refs in papers)

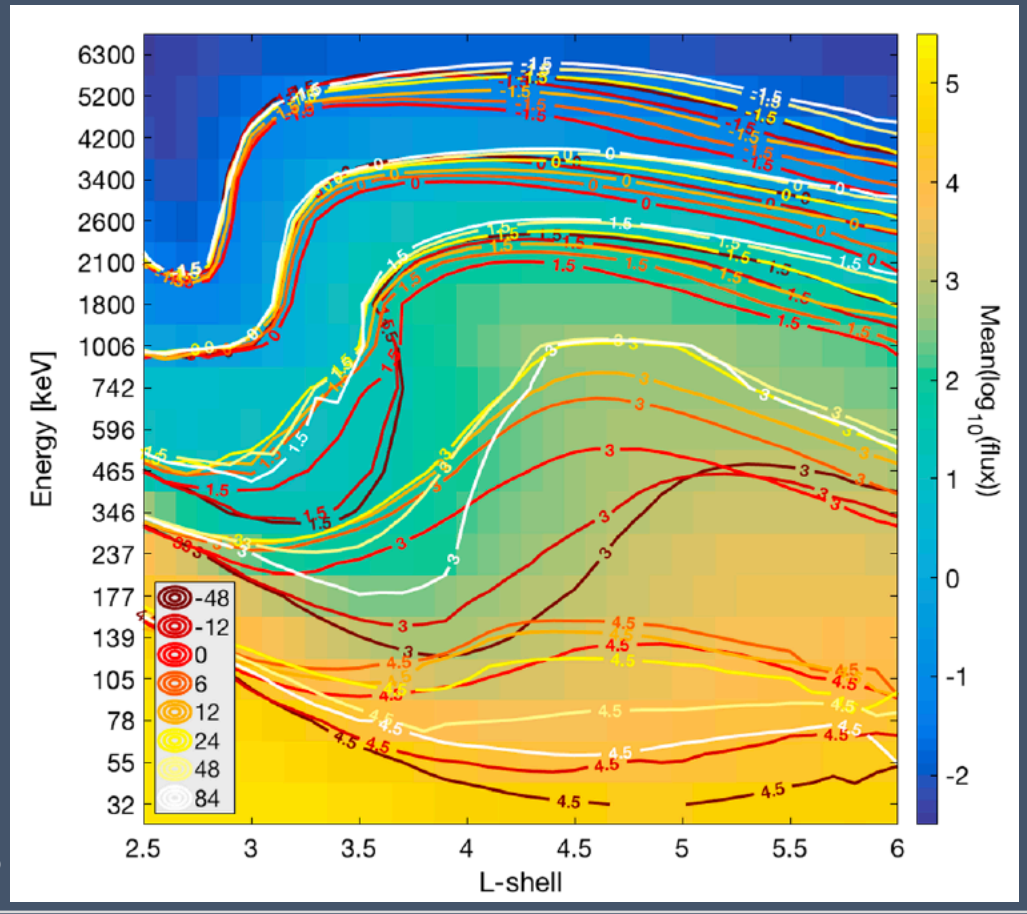
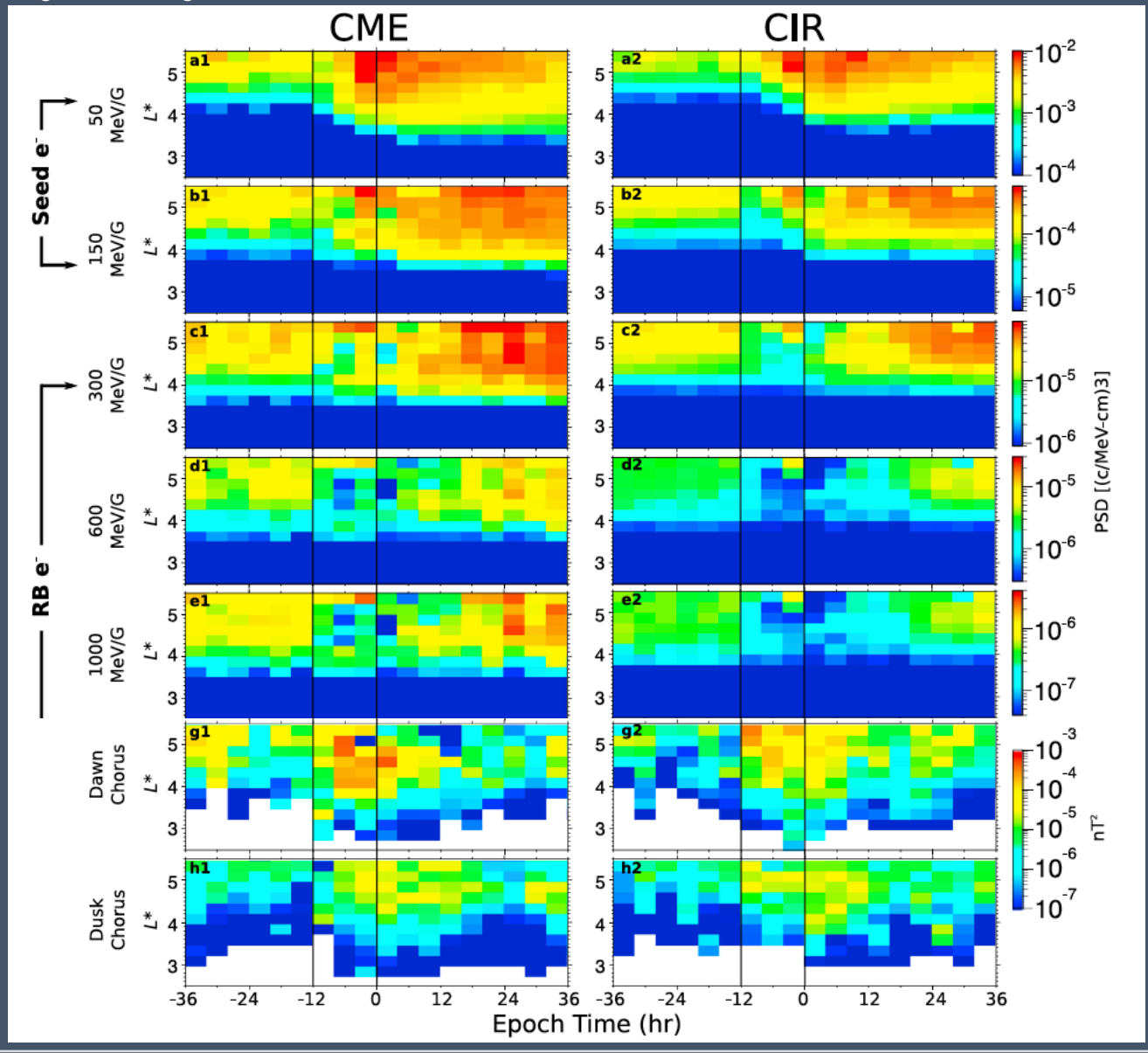


Figure from Turner+ [JGR 2019]

Figure from Bingham+ [JGR 2018]



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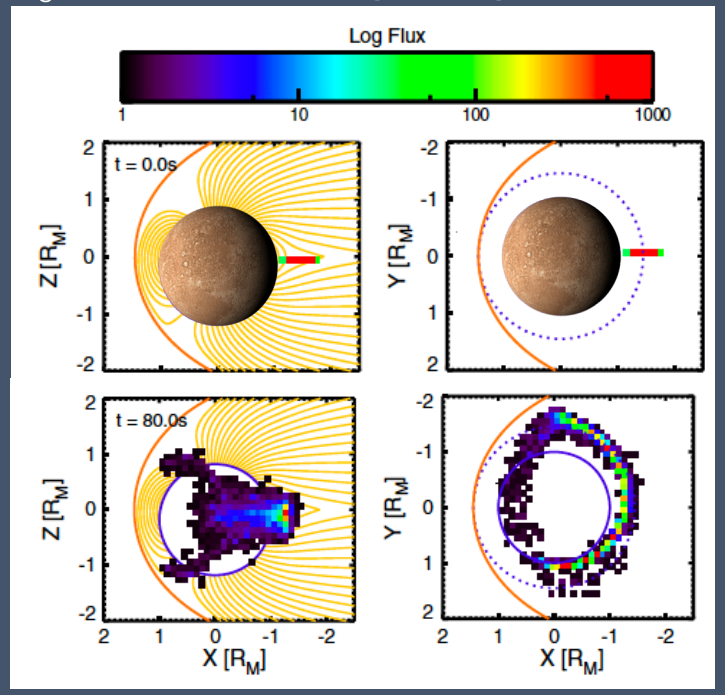
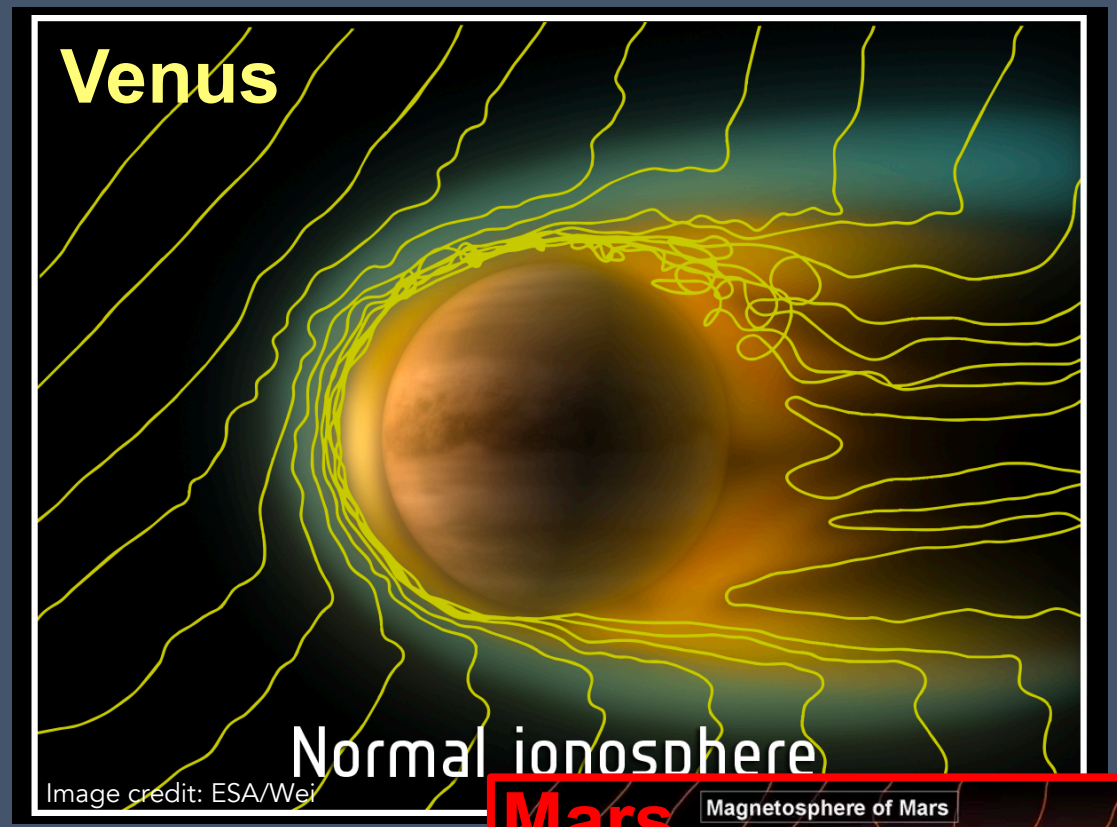
Radiation Belts throughout the Solar System

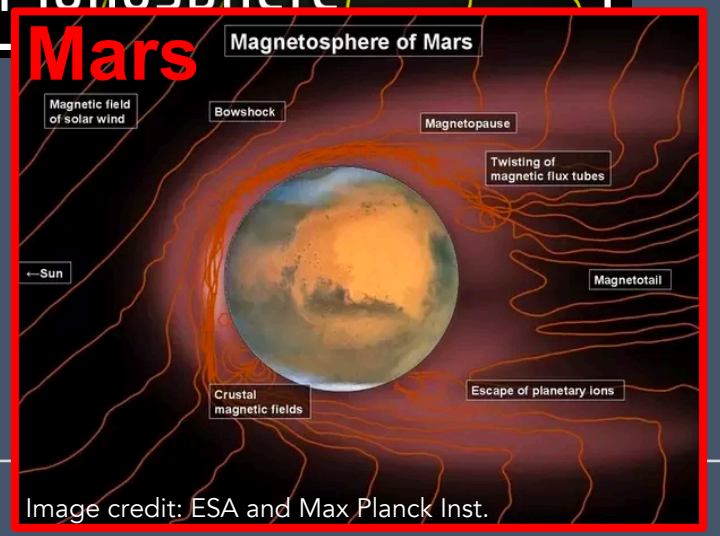
None at Mercury, Venus, Mars, Ceres, Pluto-Charon(?): insufficiently magnetized planetary bodies

Mercury

Figure modified from Walsh+ [JGR 2013]







Ceres

Image credit: NASA

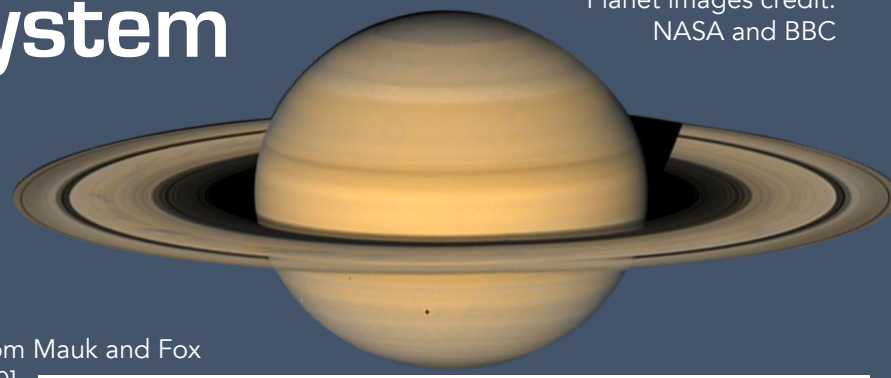
Pluto

Charon

Images credit: NASA

Radiation Belts throughout the Solar System

Planet images credit: NASA and BBC



- Saturn and the Ice Giants
  - Unknown questions: Uranus and Neptune are unique worlds; we need orbital missions to each of the Ice Giants with *dedicated energetic particle instrumentation!*
  - We know essentially nothing about time-variability at these systems
  - *Ice Giants also offer strong relevance to exoplanetary systems*

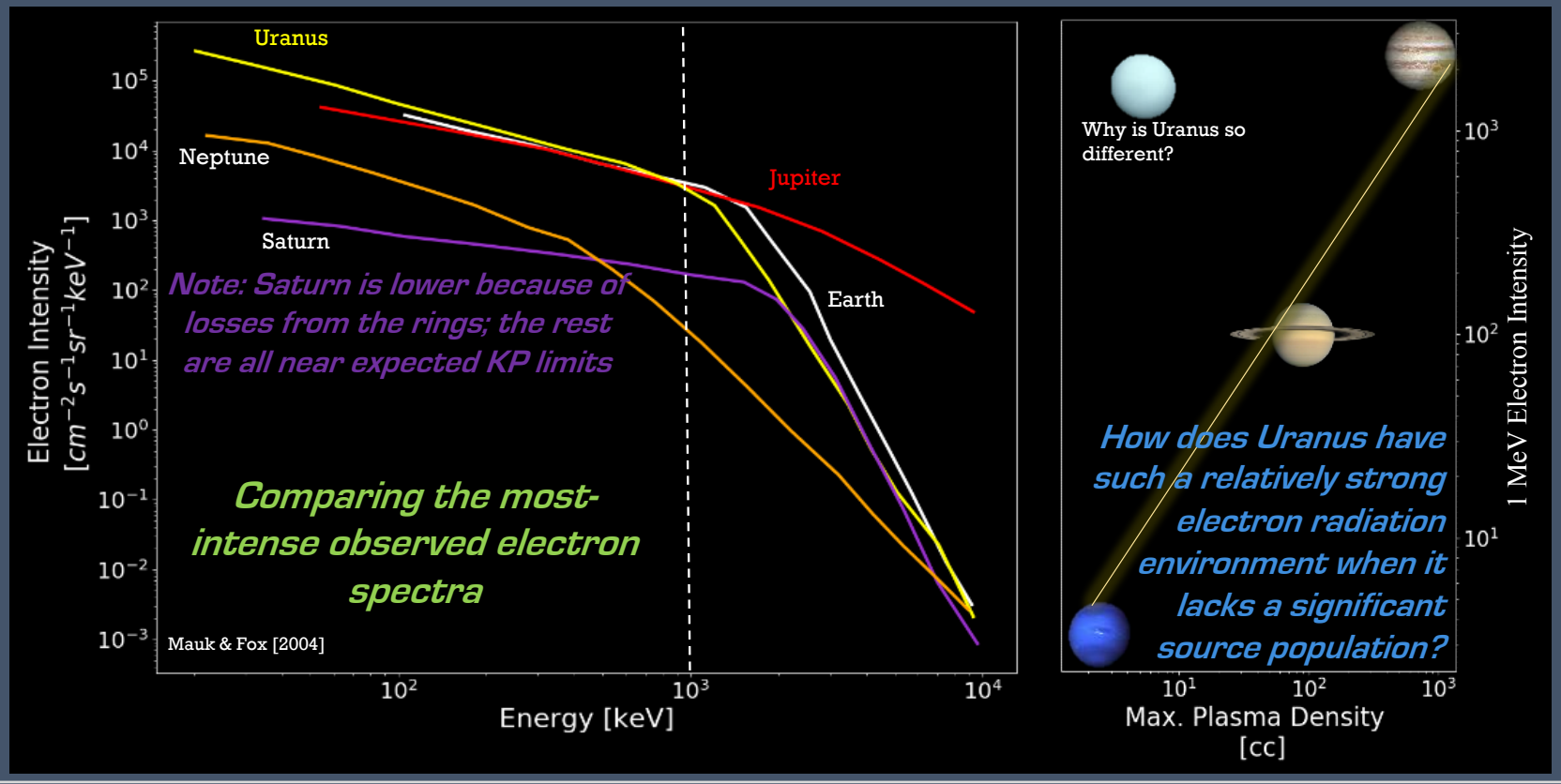
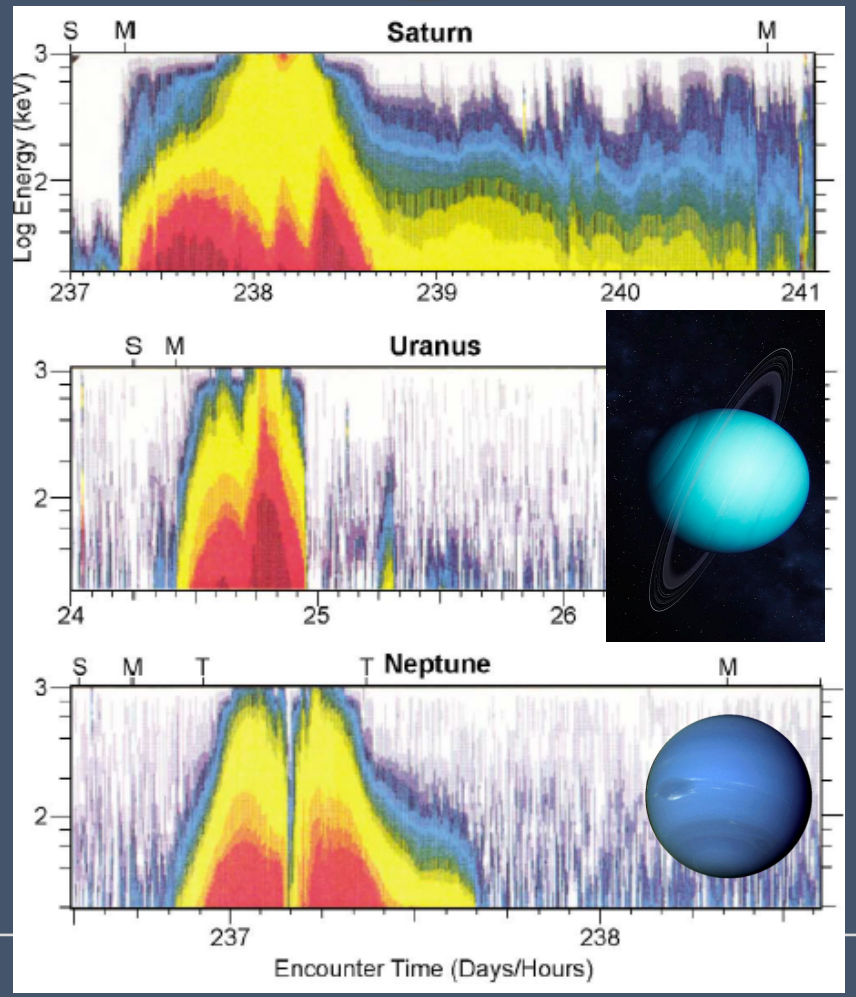


Figure from Mauk and Fox [JGR 2010]

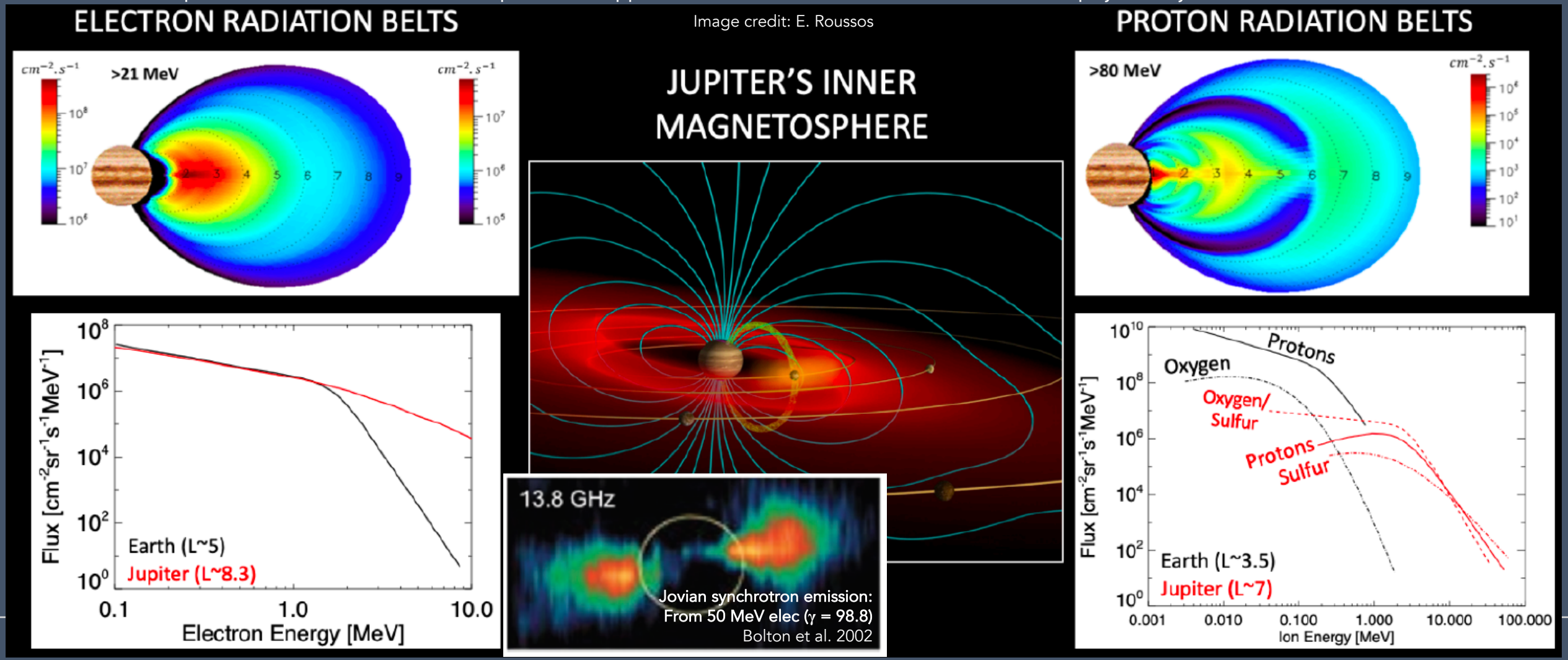


This presentation is being recorded

Radiation Belts throughout the Solar System

- Jupiter: a true juggernaut
  - By several metrics: ***the Jovian magnetosphere is the Solar System's most efficient particle accelerator***
  - Synchrotron emission: >50 MeV electrons (!!!); Mauk et al. [GRL 2018]: >1 MeV electrons streaming upward from the auroral zone (!!!)
  - Jupiter's radiation belts offer unique in situ opportunities to understand more exotic astrophysical systems

Image credit: E. Roussos



Outline

- History and background
- Earth's Radiation Belts
  - Inner Radiation Belts: Protons
  - Inner Radiation Belts: Electrons
  - Outer Radiation Belt(s)
- Radiation Belts throughout the Solar System
- ***Radiation Belts throughout the Cosmos***
- Summary and Conclusion: Where to next?

Radiation Belts throughout the Cosmos

- Open questions for more exotic systems with dipole-like, rapidly rotating magnetospheres:
  - Dwarf stars
  - Pulsars
  - Black holes and accretion disks
- What we learn throughout the Solar System will inform us about more universal processes

Figure from Mauk+[GeoMono 2012]

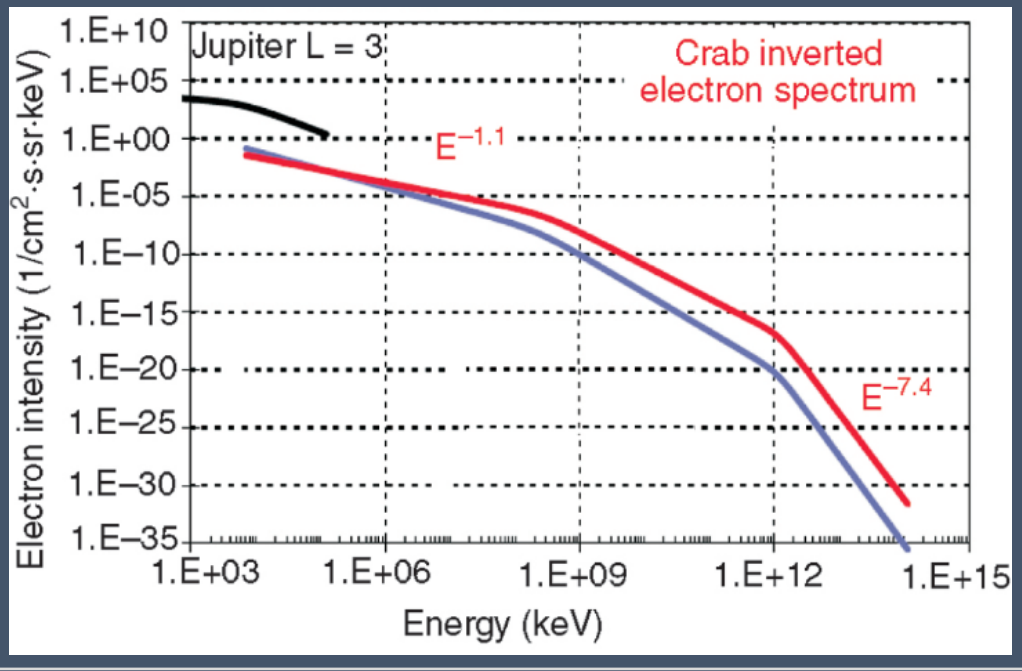
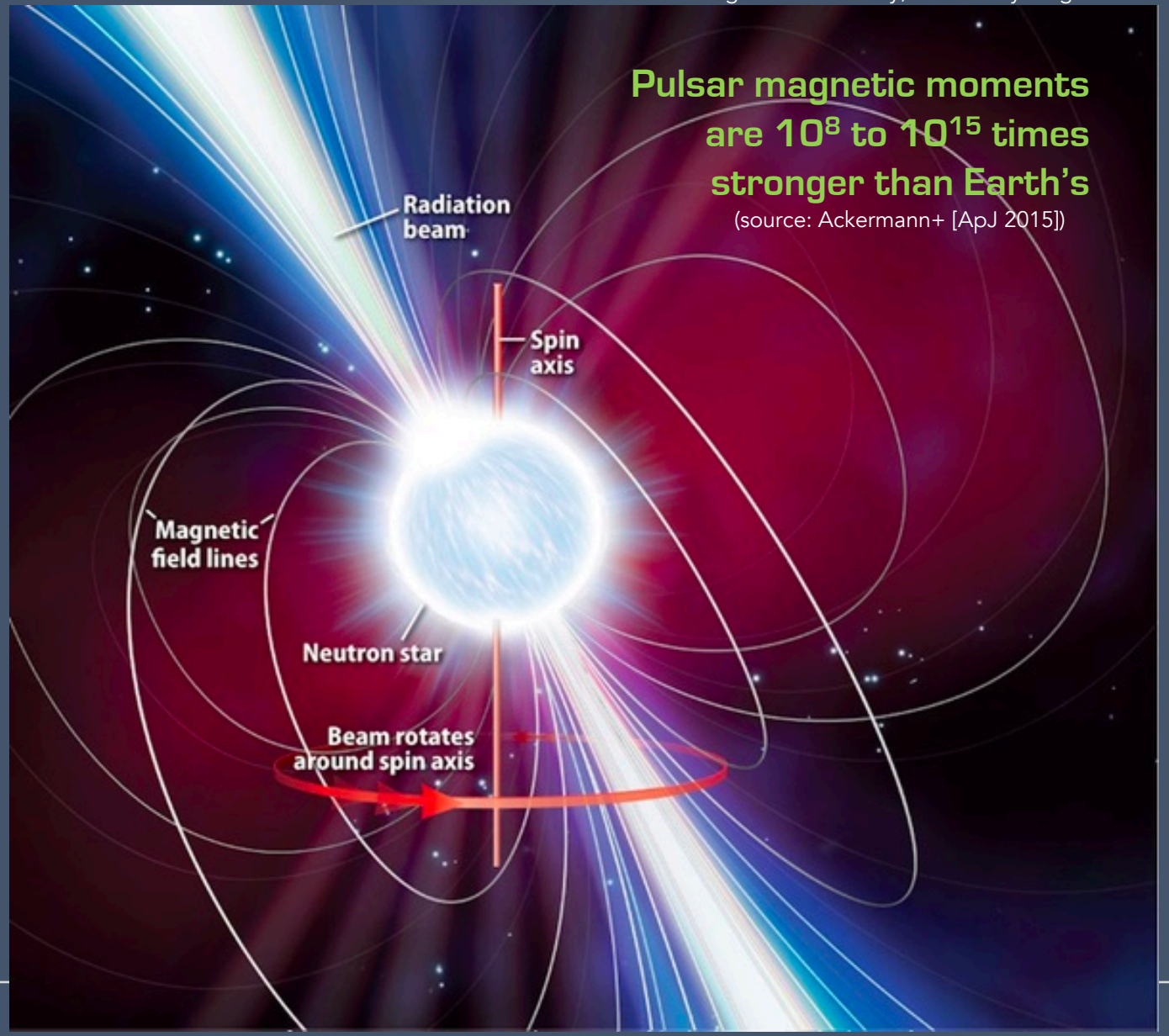


Image credit: R. Kelly, Astronomy Magazine



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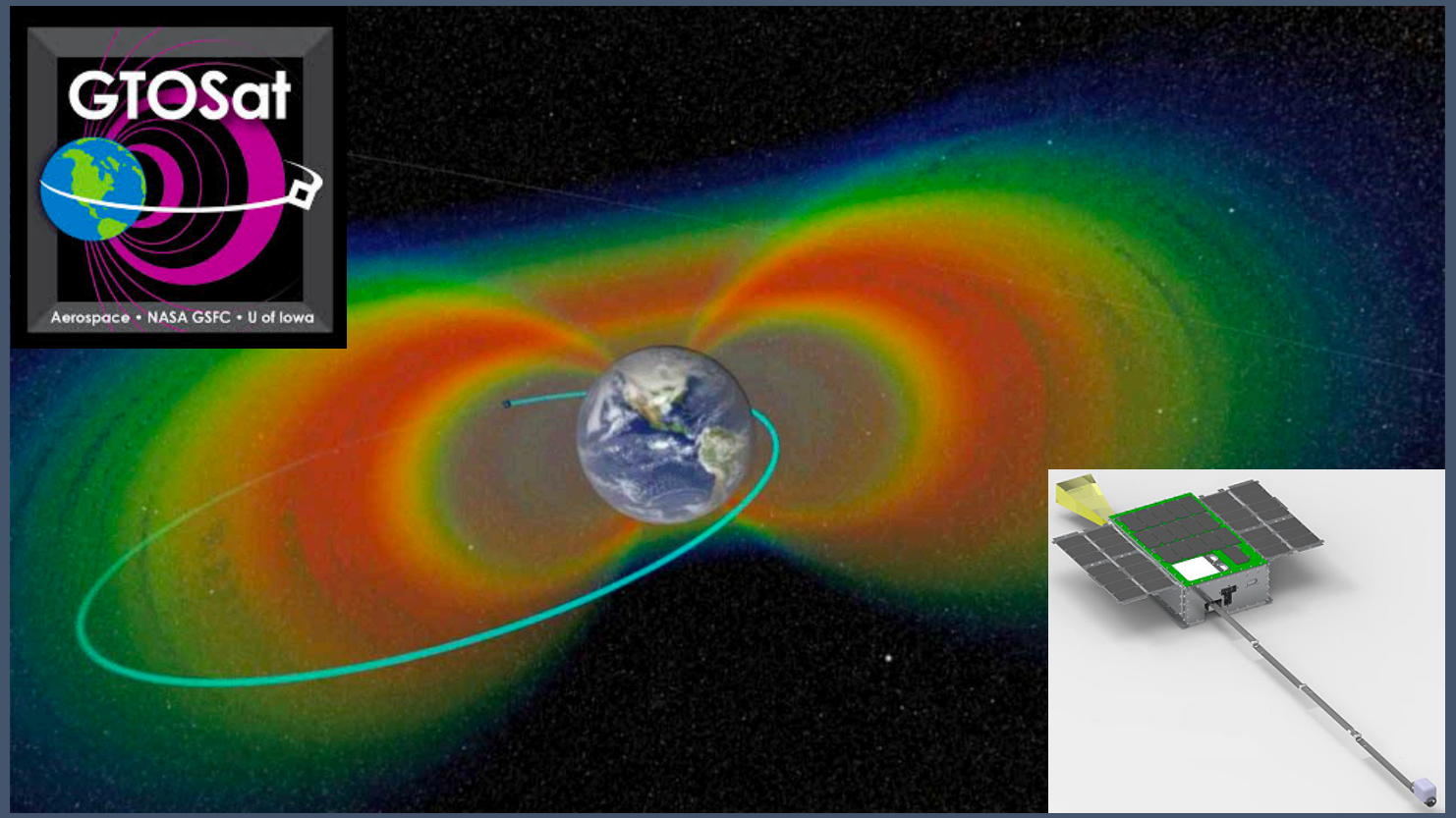
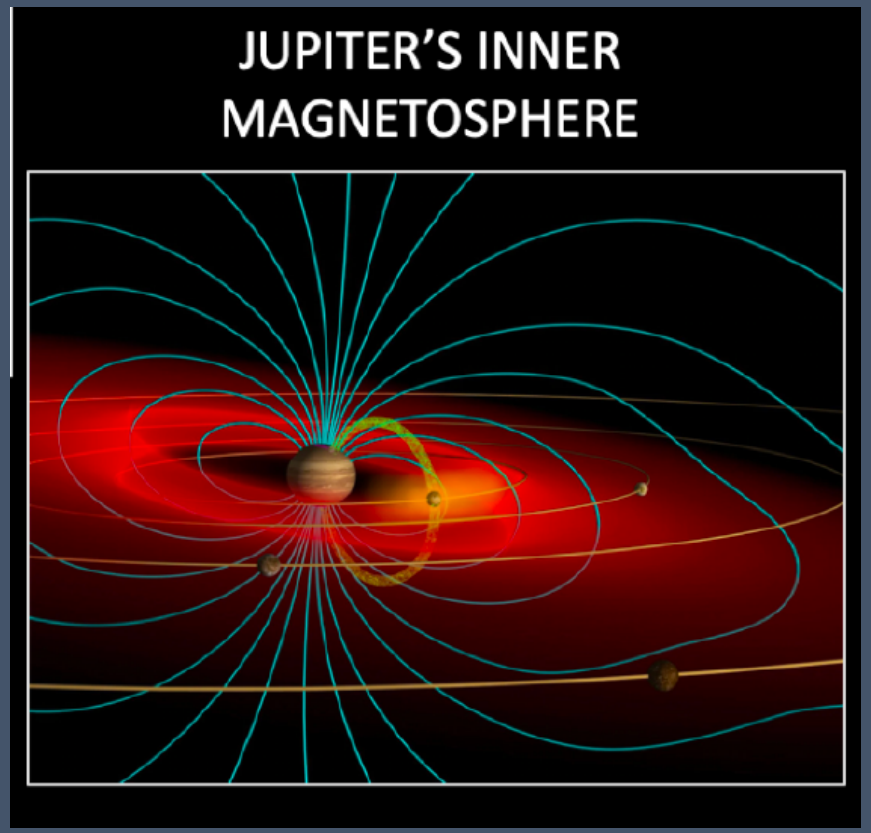
Summary and Conclusion: Where to next?

- There is still plenty to learn at Earth after Van Allen Probes:
  - JAXA's Arase (ERG), USAF's DSX, NASA's GTOSat… and hopefully future dedicated, multipoint SpWx observatories traversing the belts
  - Needed: More multipoint observations of electron precipitation and impacts on Earth's atmosphere (e.g., FIREBIRD-II, AeroCube-6 and -10, ELFIN)



- We should also be pushing for dedicated instrumentation (and missions!!!) to the Solar System's other radiation belt systems to learn more about both the unique and universal processes in each system



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