Cross-Scale Processes in Radiation Belt Dynamics

Ioannis (Yannis) Daglis

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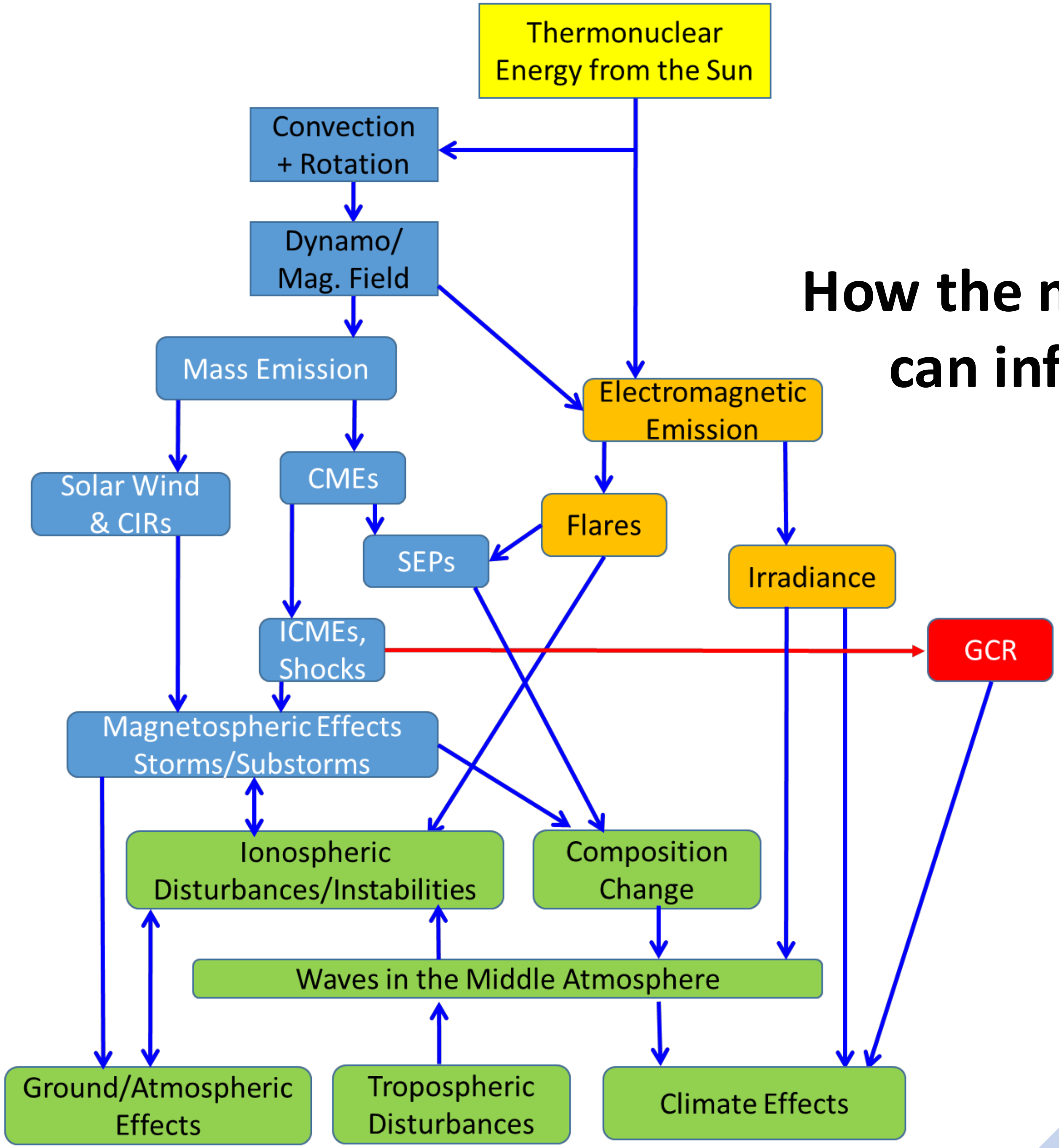
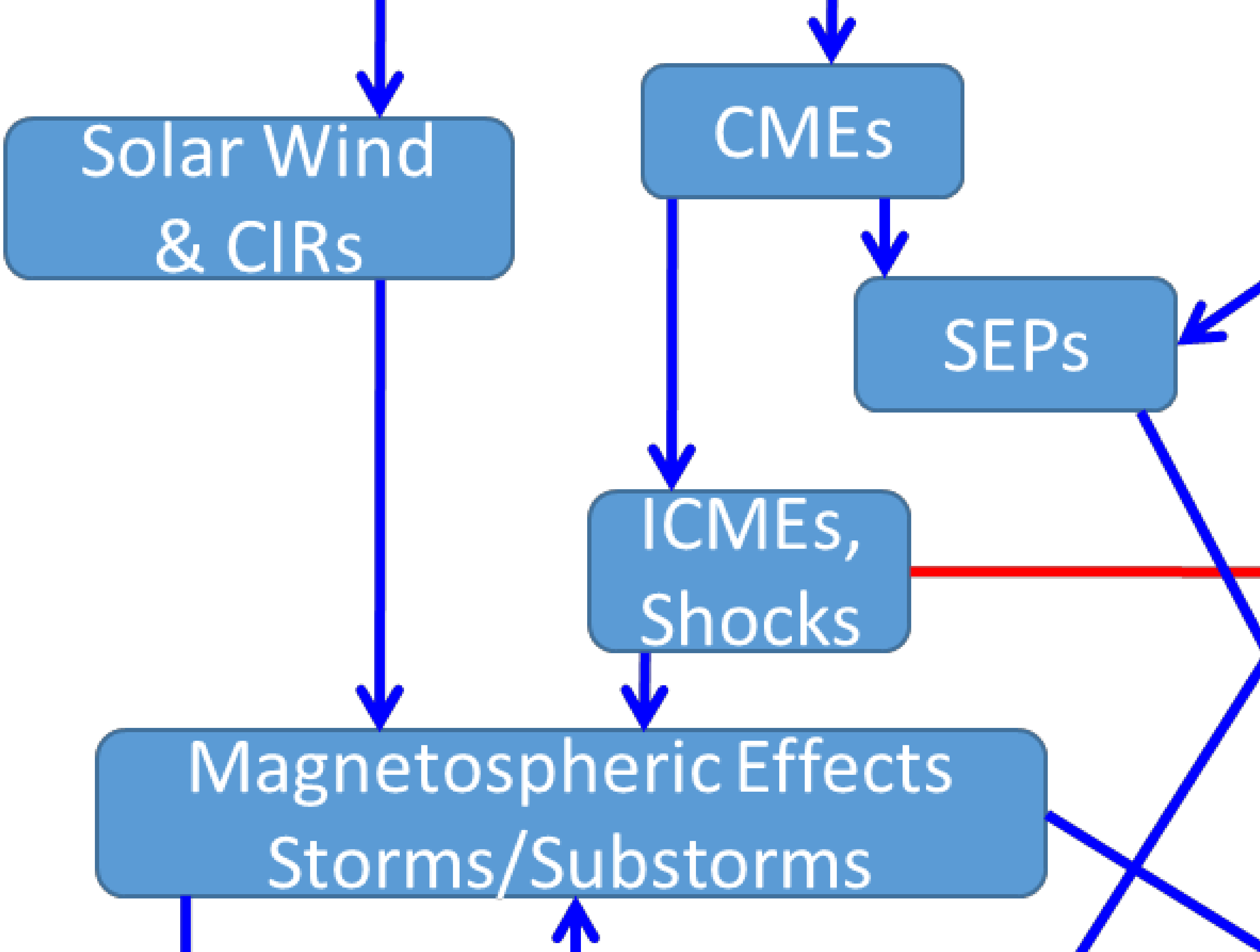
How the magnetic variability of a star can influence a magnetized planet





Solar Wind
& CIRs
CMEs
SEPs
ICMEs,
Shocks
Magnetospheric Effects
Storms/Substorms

Probably the earliest account of observations of ***cross-scale processes***

[425]

V.

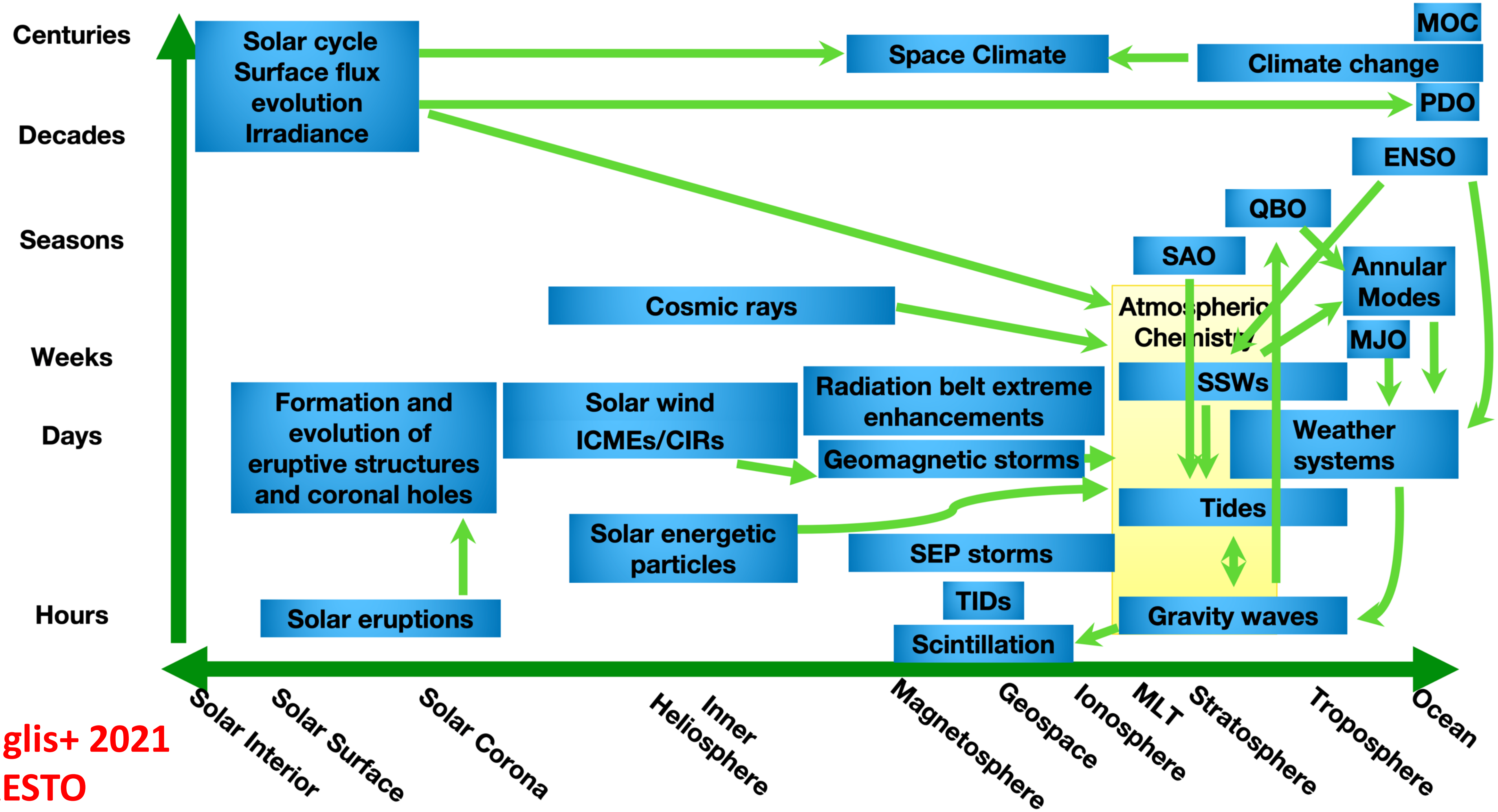
Die vollſtändigſte aller bisherigen Beobachtungen über den Einfluſs des Nordlichts auf die Magnetnadel;

angeſtellt von Herrn ALEXANDER VON HUMBOLDT zu Berlin am 20ſten Dec. 1806.

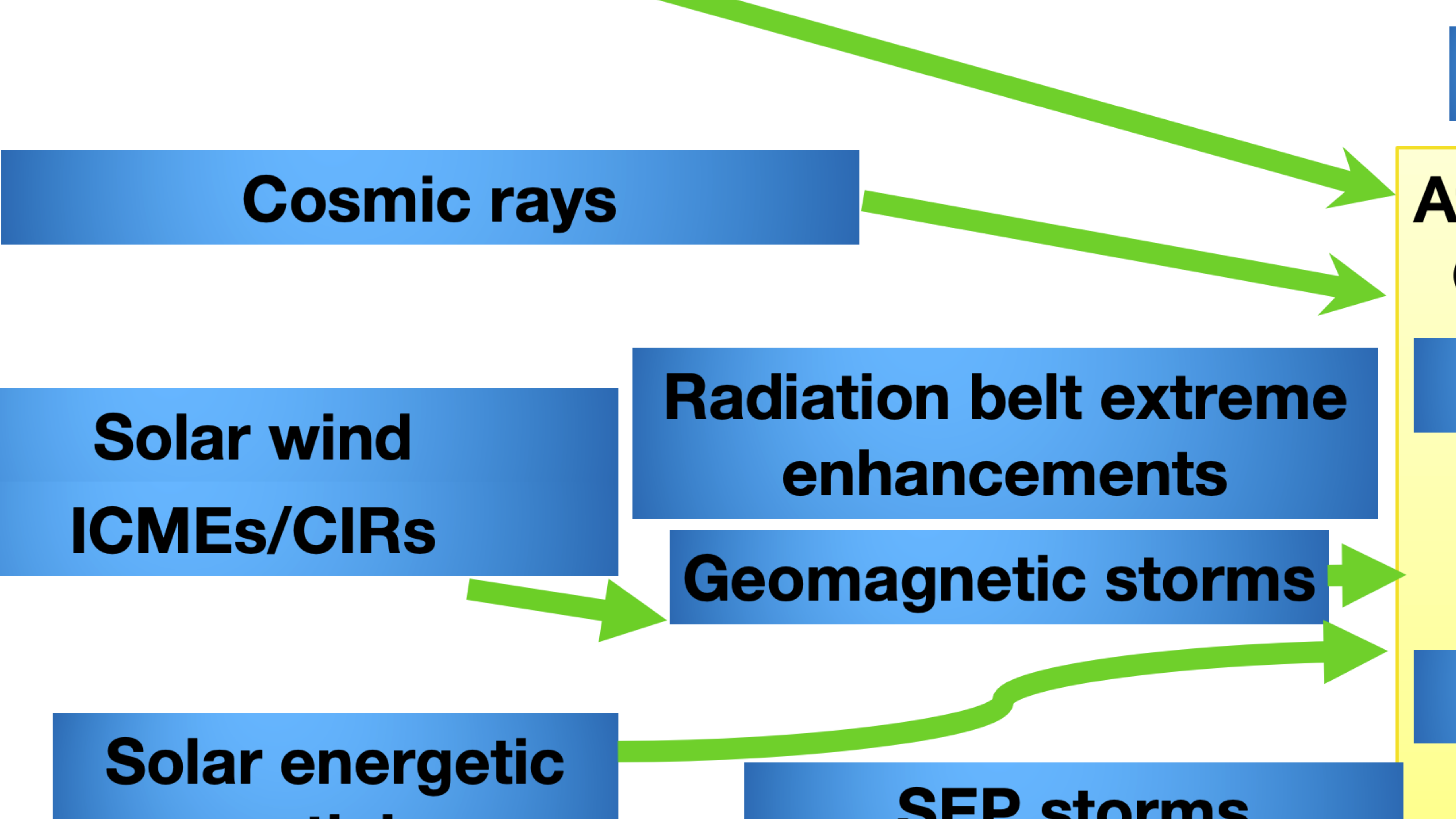
Annalen der Physik, 1808, Alexander von Humboldt

(The most comprehensive, so far, observations of the influence of the aurora on the magnetic needle)

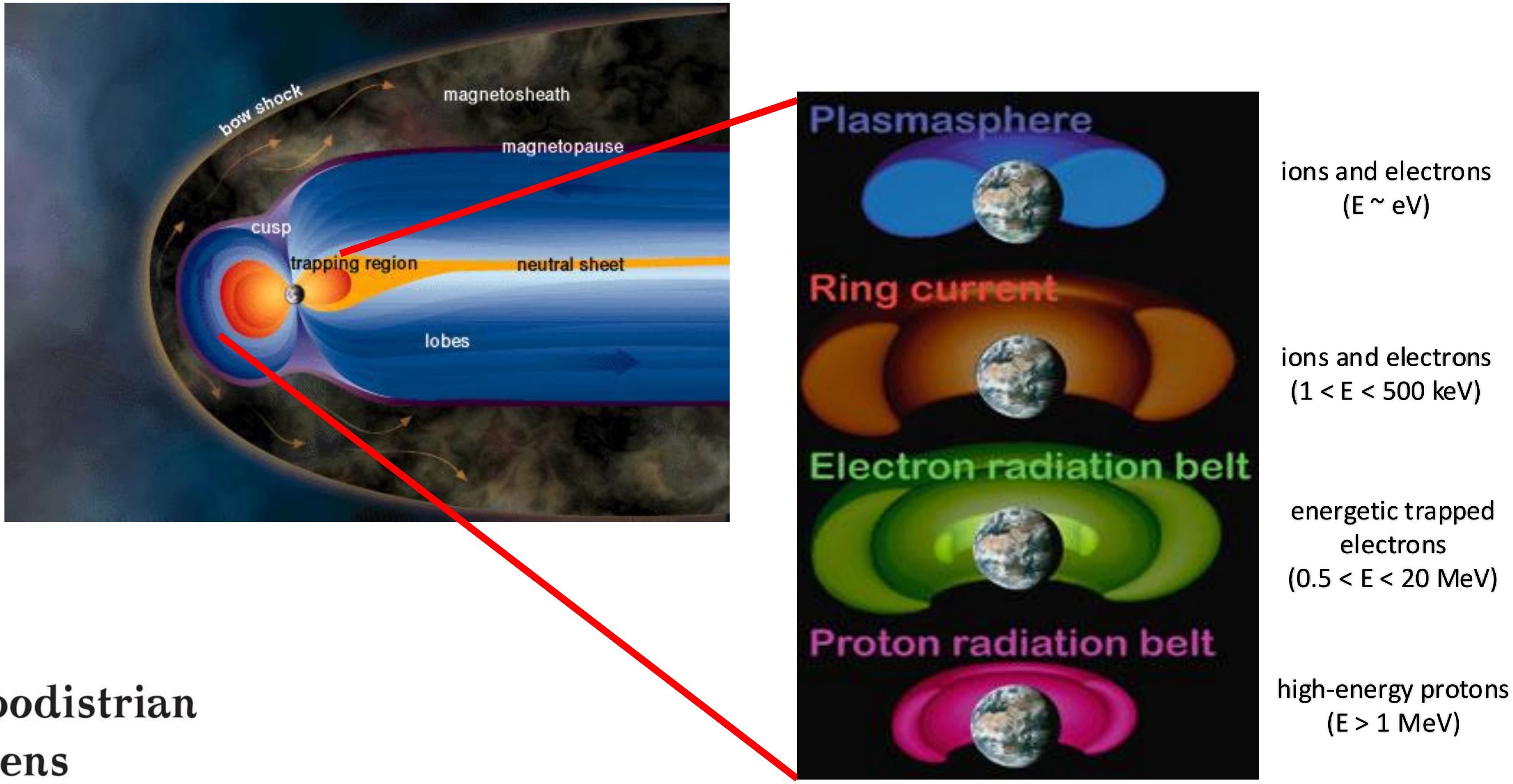
An integrated view of solar-terrestrial prediction
Solar-Terrestrial phenomena in various spatial & temporal scales



Daglis+ 2021
PRESTO


Cosmic rays
Solar wind
ICMEs/CIRs
Radiation belt extreme enhancements
Geomagnetic storms
Solar energetic

Geospace: Highly dynamic and complex **system of systems**, comprising an internally generated magnetic field and several distinct charged particle populations, which can form current systems and thus alter the magnetic configuration, which in turn influences particles. Moreover, particle anisotropies drive waves, which in turn influence particles.



From Ebihara and Miyoshi, 2011

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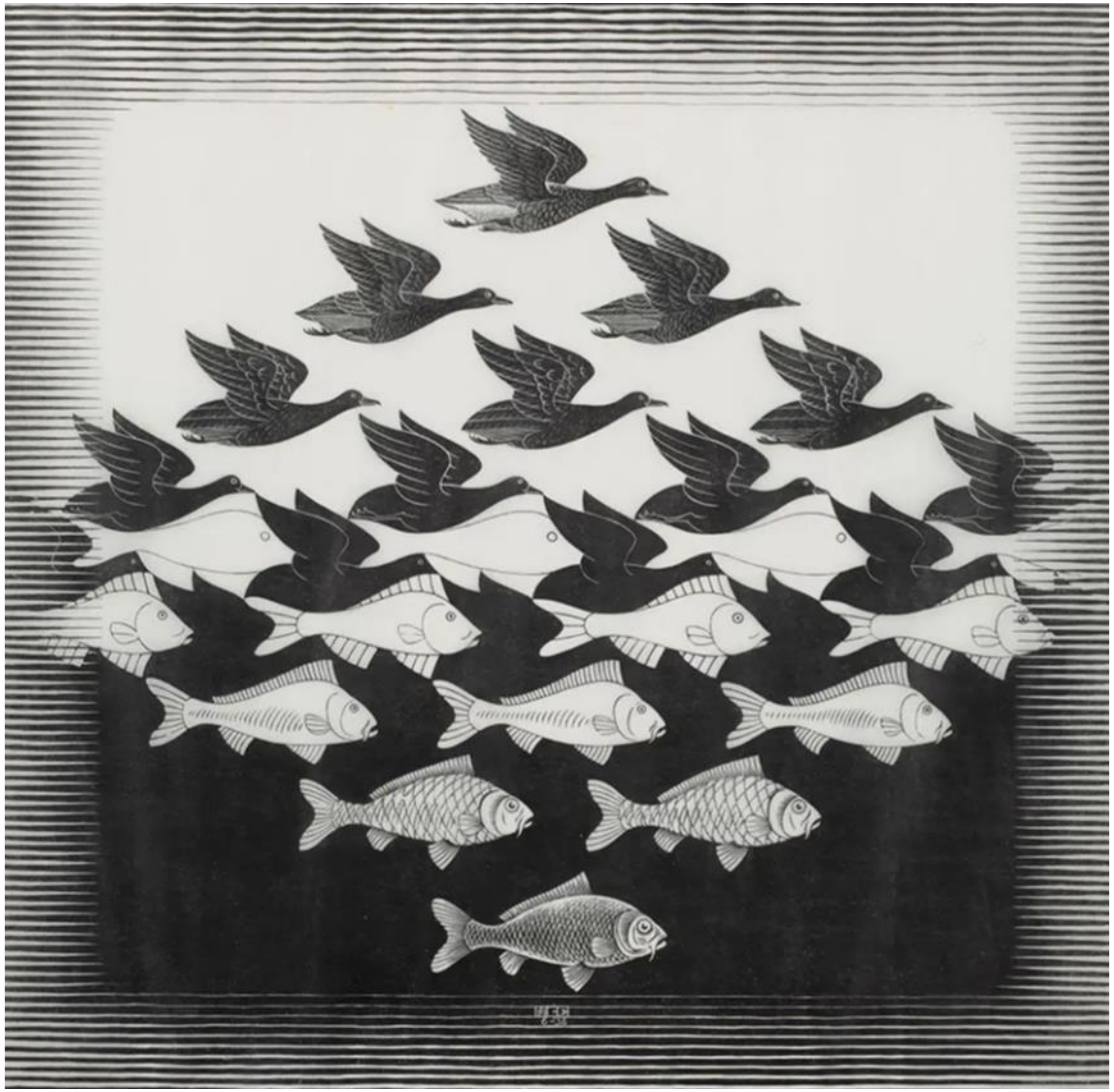
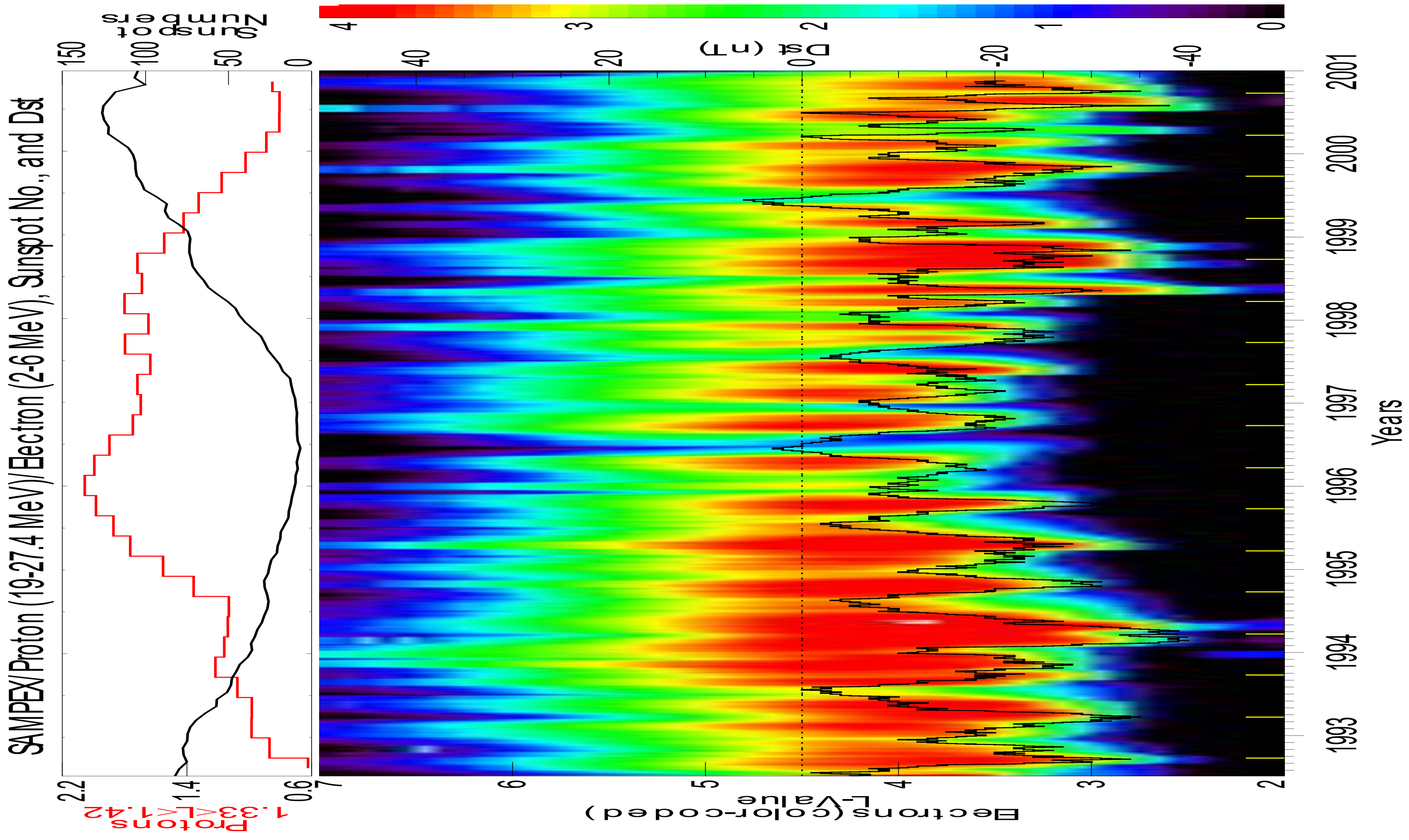
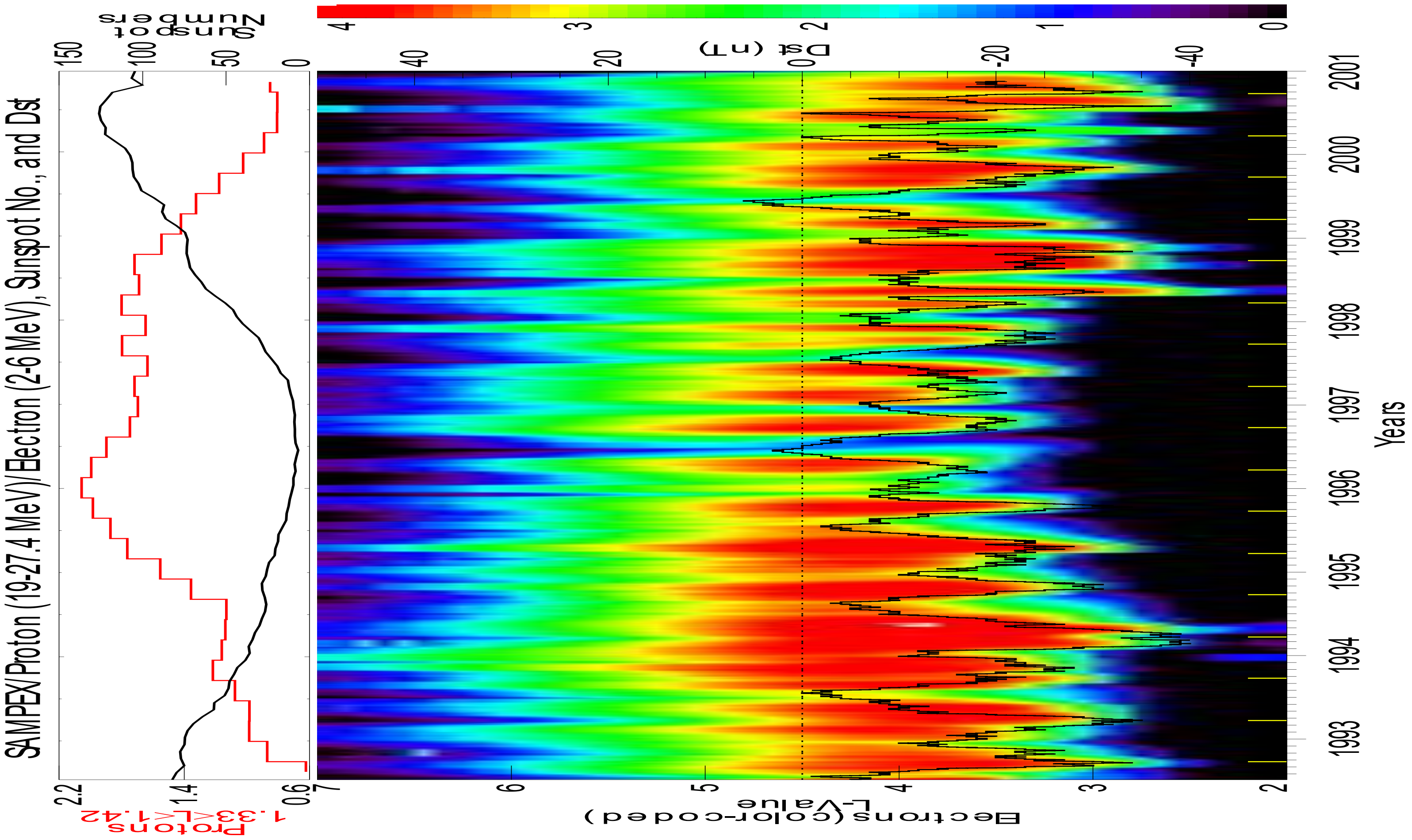


Outer Van Allen belt multi-scale variability



- Solar cycle: years
- Seasonal: Months
- Solar rotation: 13-27 days
- Storm recovery: days
- Storm main phase: hours
- SSC: minutes
- Wave-particle interactions: (sub)seconds

Outer Van Allen belt multi-scale variability



- Solar cycle: **years**
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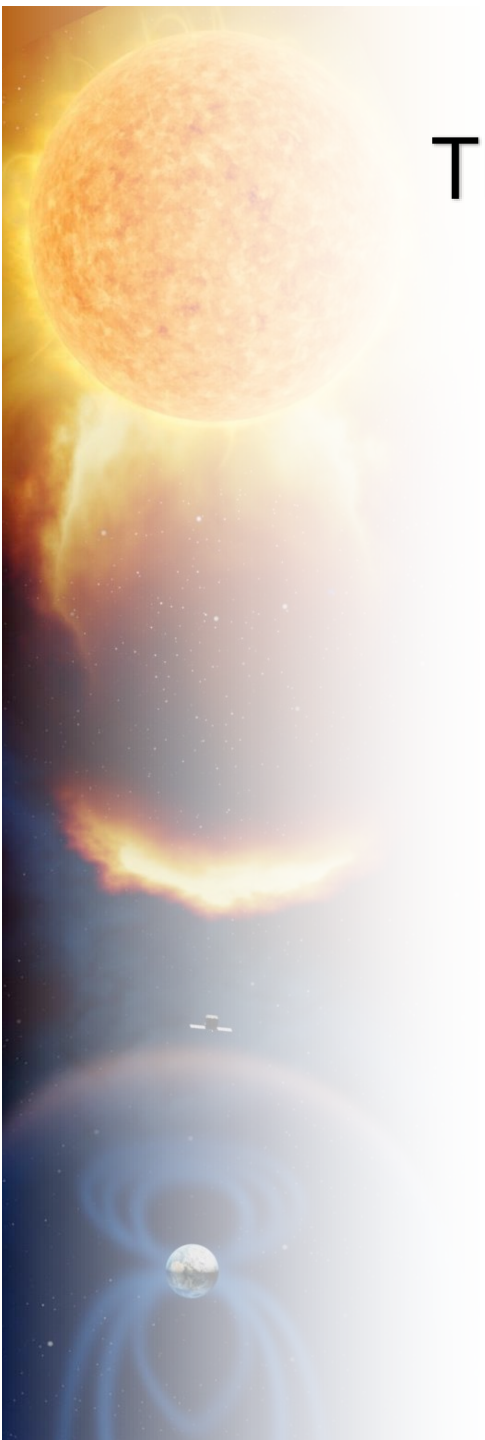


The basic facts of the outer Van Allen belt variability

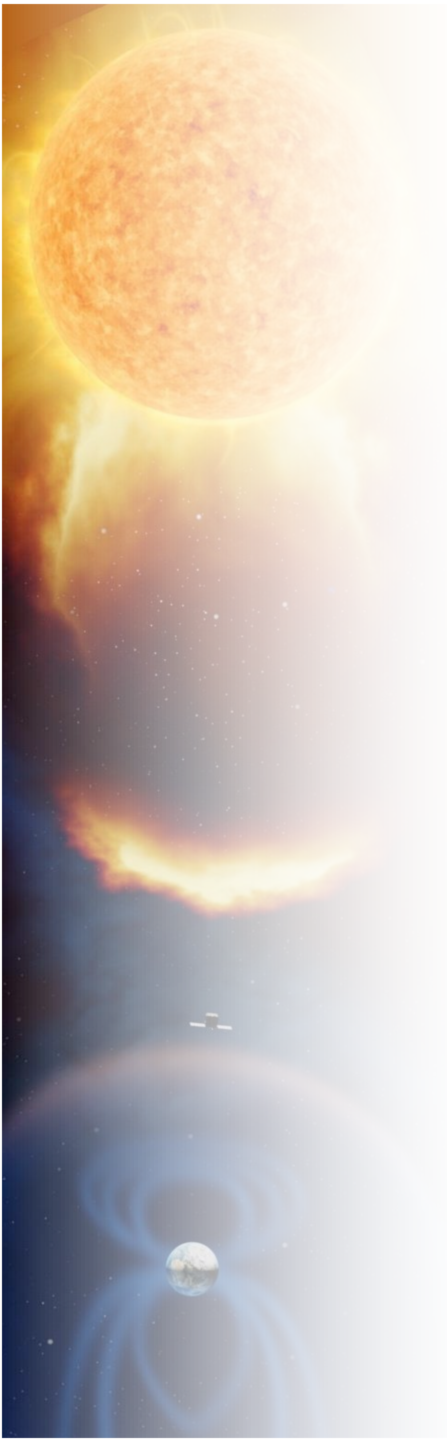
1. The Sun

Occasional Coronal Mass Ejections

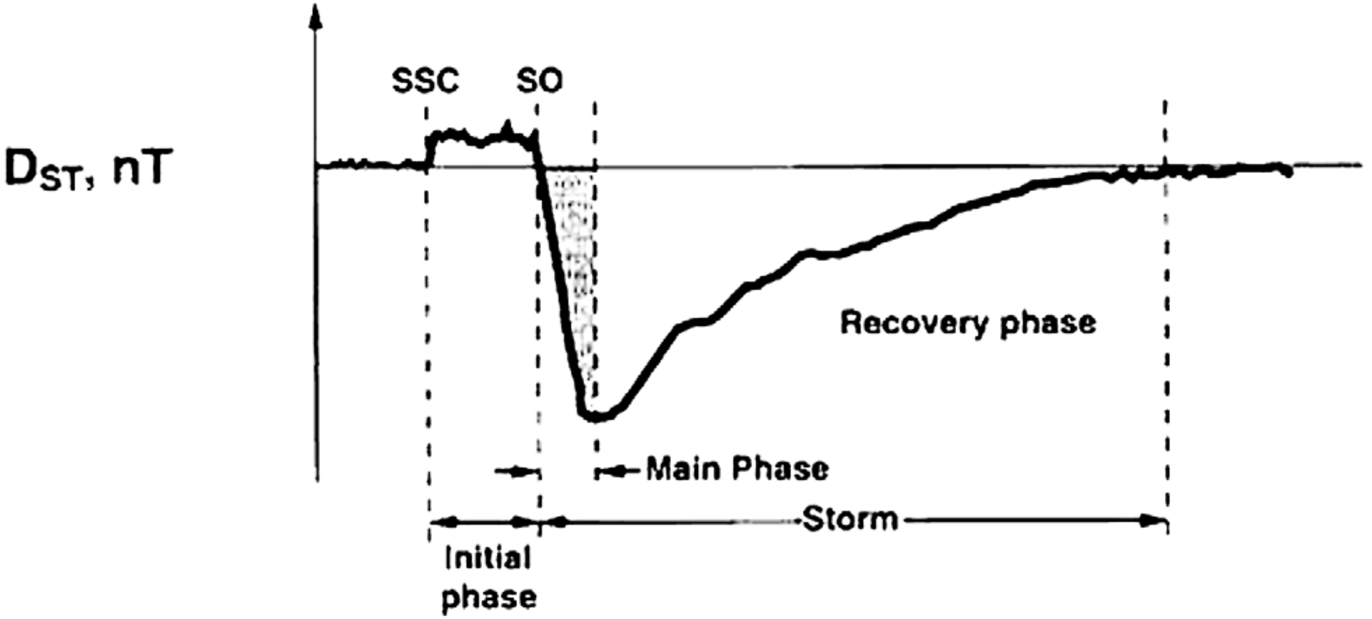
Occasional High-Speed Streams

CIRs: Corrotaning Interaction Regions,
i.e., recurrent High-Speed Streams

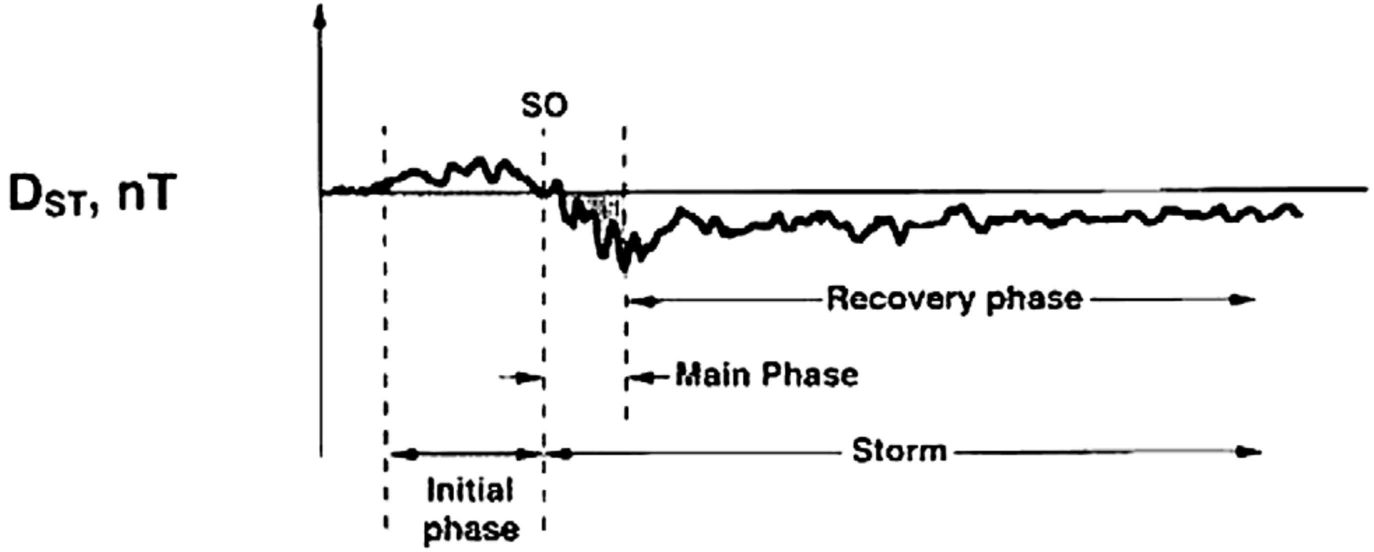
All are geoeffective – in different ways

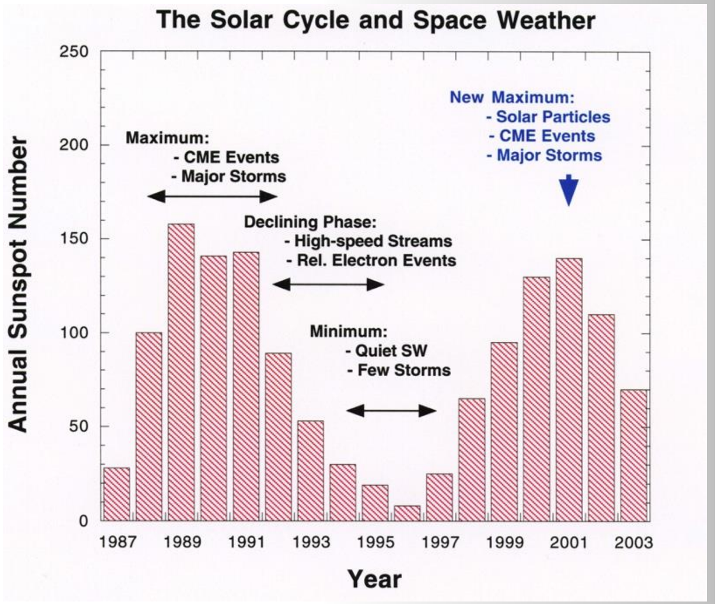


Solar Maximum (ICME) Storm

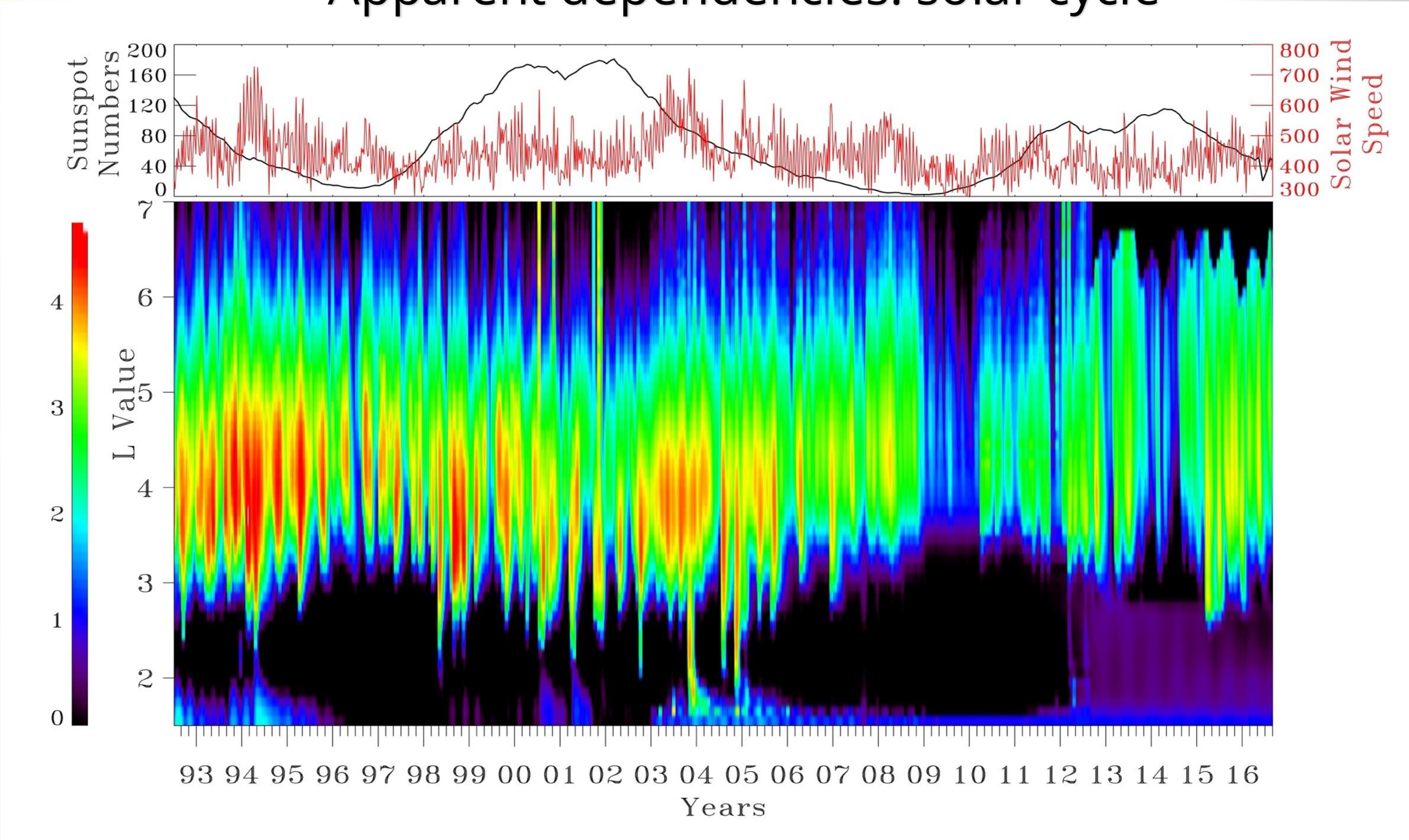


Solar Minimum (CIR) Storm





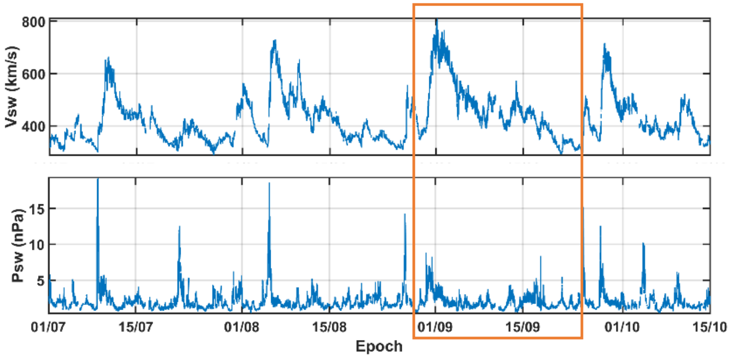
Basic facts of the outer belt variability
Apparent dependencies: solar cycle



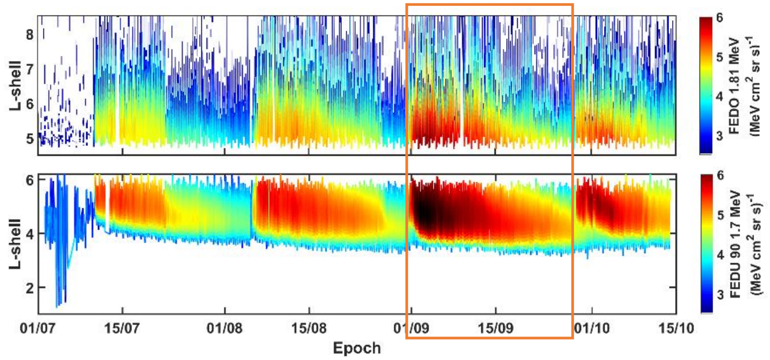
Effect of consecutive HSS

Sequence: During the second half of 2019 (July-October).
Interesting pulse: The third one, arriving in September 2019.
Reason: It resulted in intense wave activity and substantial and long-lived energisation of radiation belt electrons, especially for relativistic and ultra-relativistic energies.

e.g.: The arrival of the Sept. HSS pulse caused…



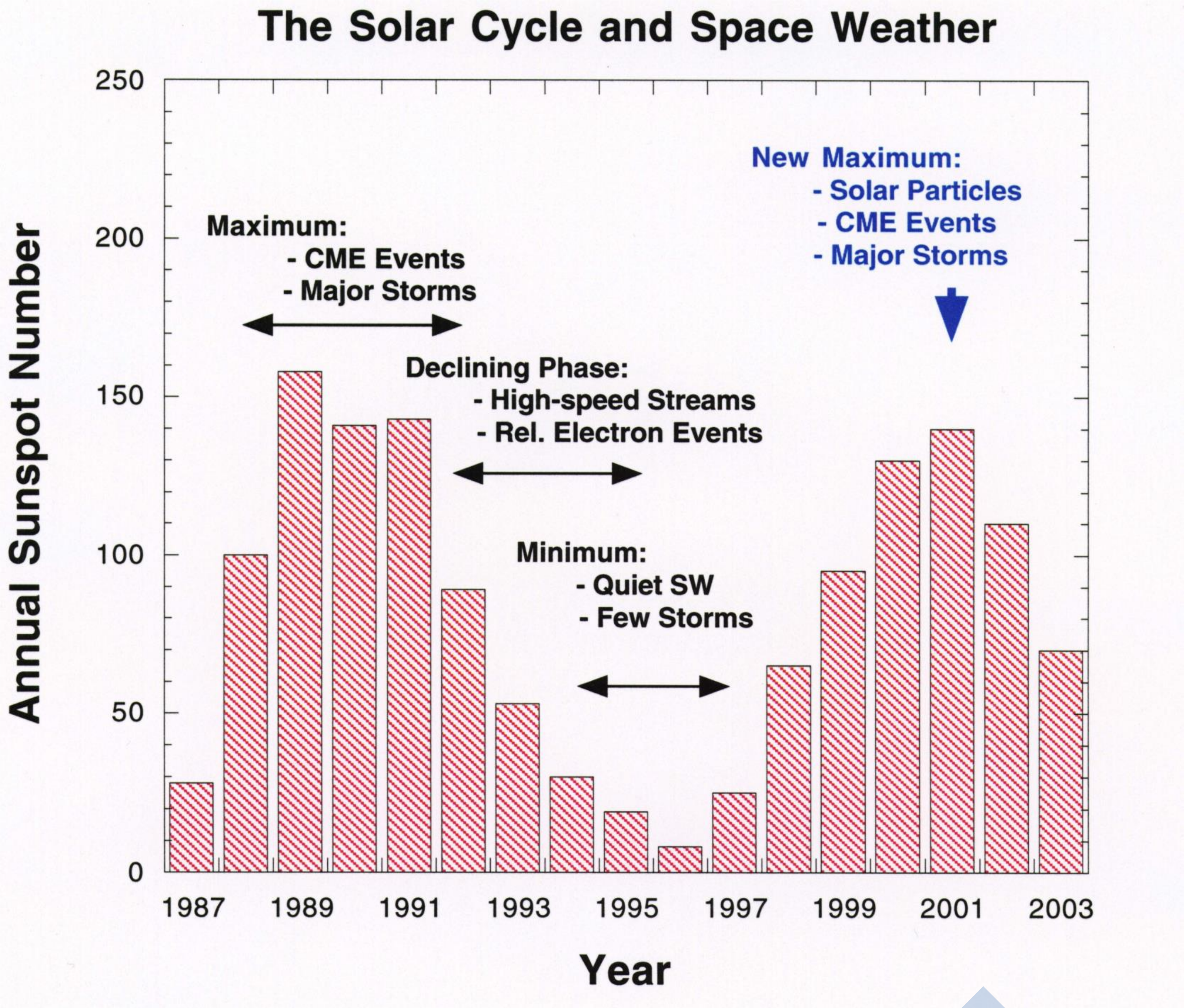
… pronounced electron flux enhancements



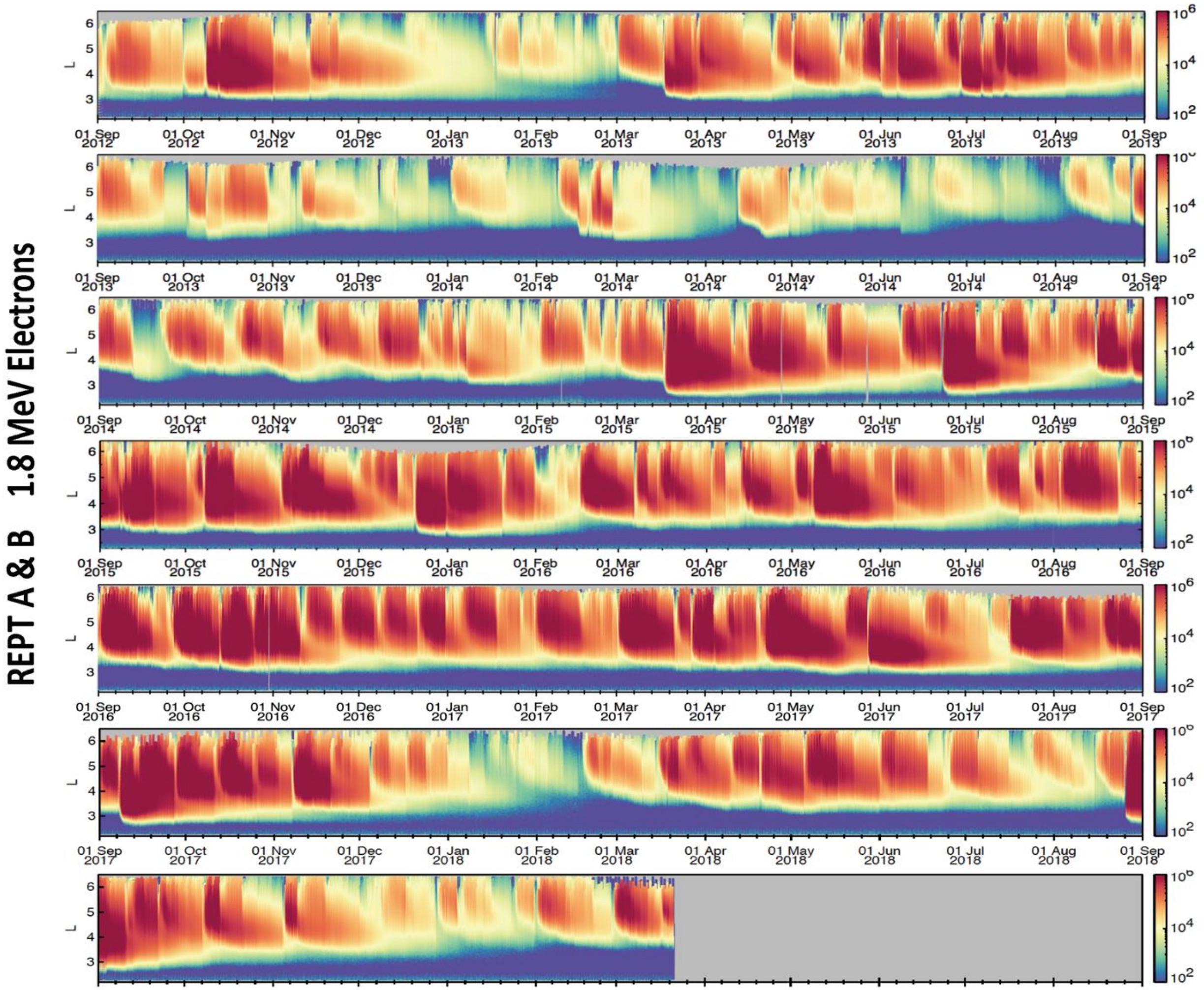
To study this event, we use the following data:

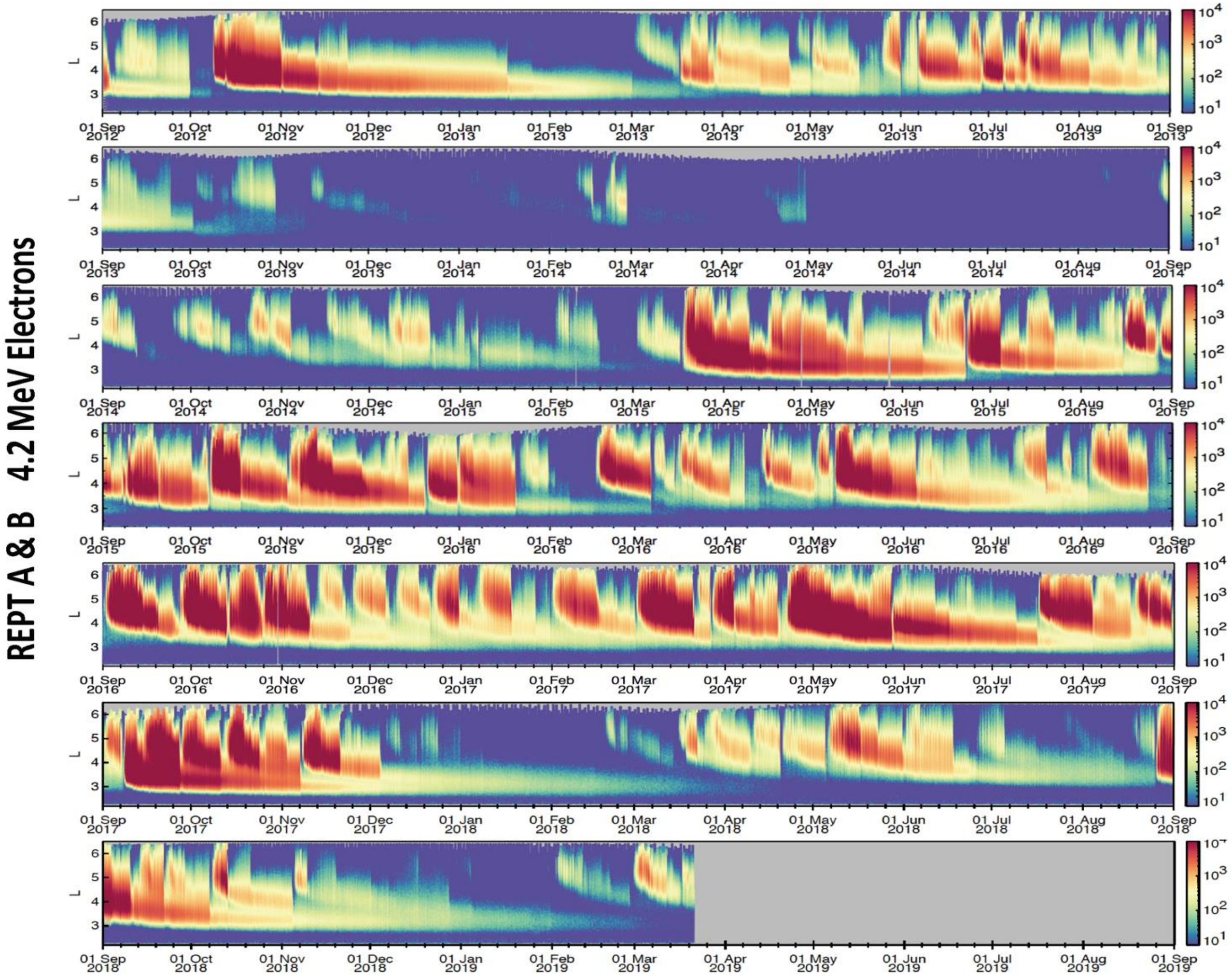
Solar Wind parameters Geomagnetic & Magnetospheric parameters	**NASA OMNIWEB** and **SUPERMAG** databases
ULF & VLF wave parameters	**THEMIS** and **POES** & **MetOp** satellites
Electron flux	**Galileo 207 & 215**, and **RBSP-A** satellites
Electron Phase Space Density (PSD)	**RBSP-A** and **ERG/Arase** satellites

Introduction
Event & Data selection
Solar Wind parameters
Geomagnetic & Magnetospheric parameters
ULF & VLF wave parameters
Electron flux
Seed e (< 0.5 MeV)
Relativistic e (1-2 MeV)
Ultra-relativistic e (> 4 MeV)
Electron Phase Space Density (PSD)
Conclusions
References

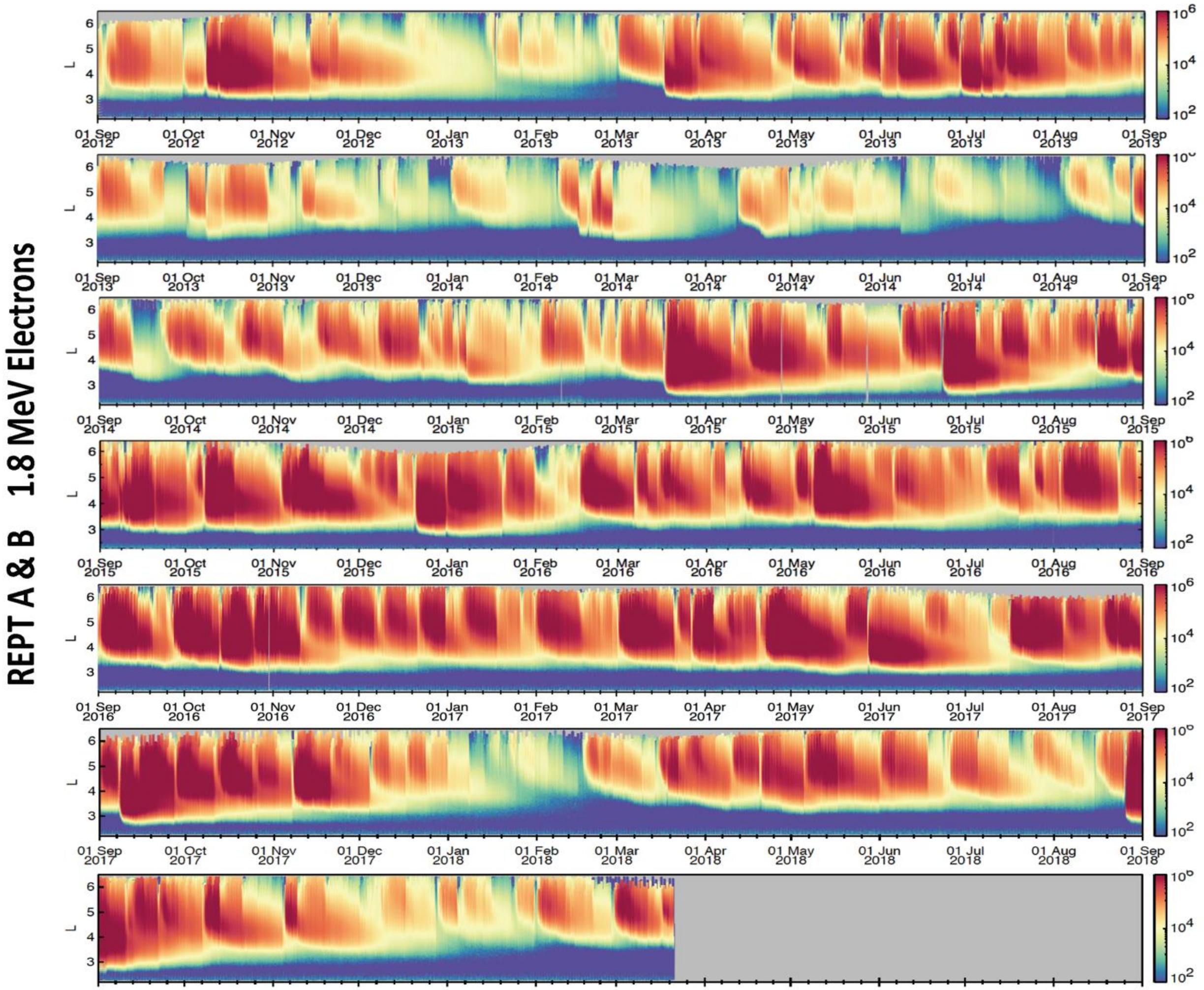

The Solar Cycle and Space Weather
Annual Sunspot Number
250
200
150
100
50
0
Maximum:
- CME Events
- Major Storms
Declining Phase:
- High-speed Streams
- Rel. Electron Events
Minimum:
- Quiet SW
- Few Storms
New Maximum:
- Solar Particles
- CME Events
- Major Storms
1987
1989
1991
1993
1995
1997
1999
2001
2003
Year

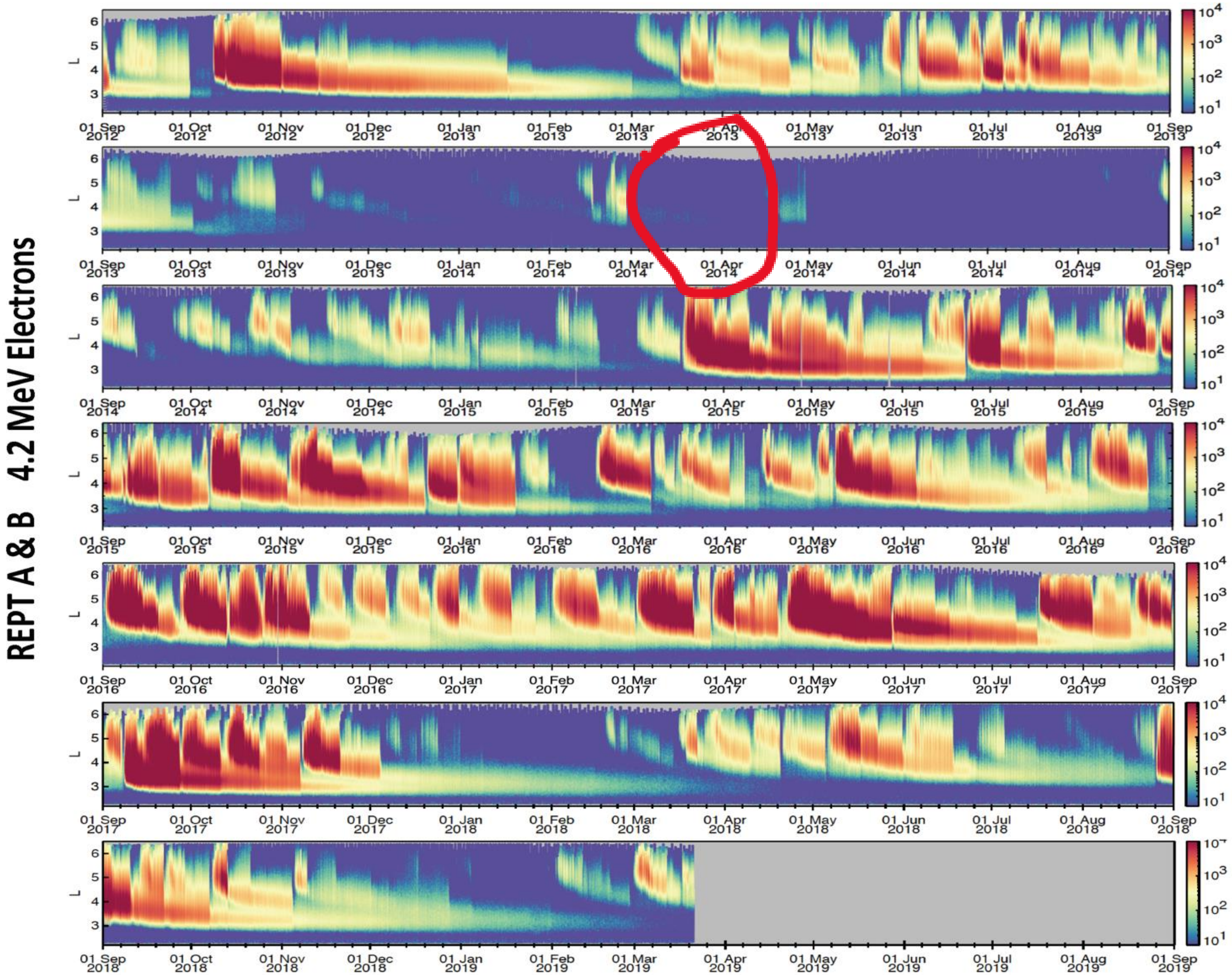
BUT …



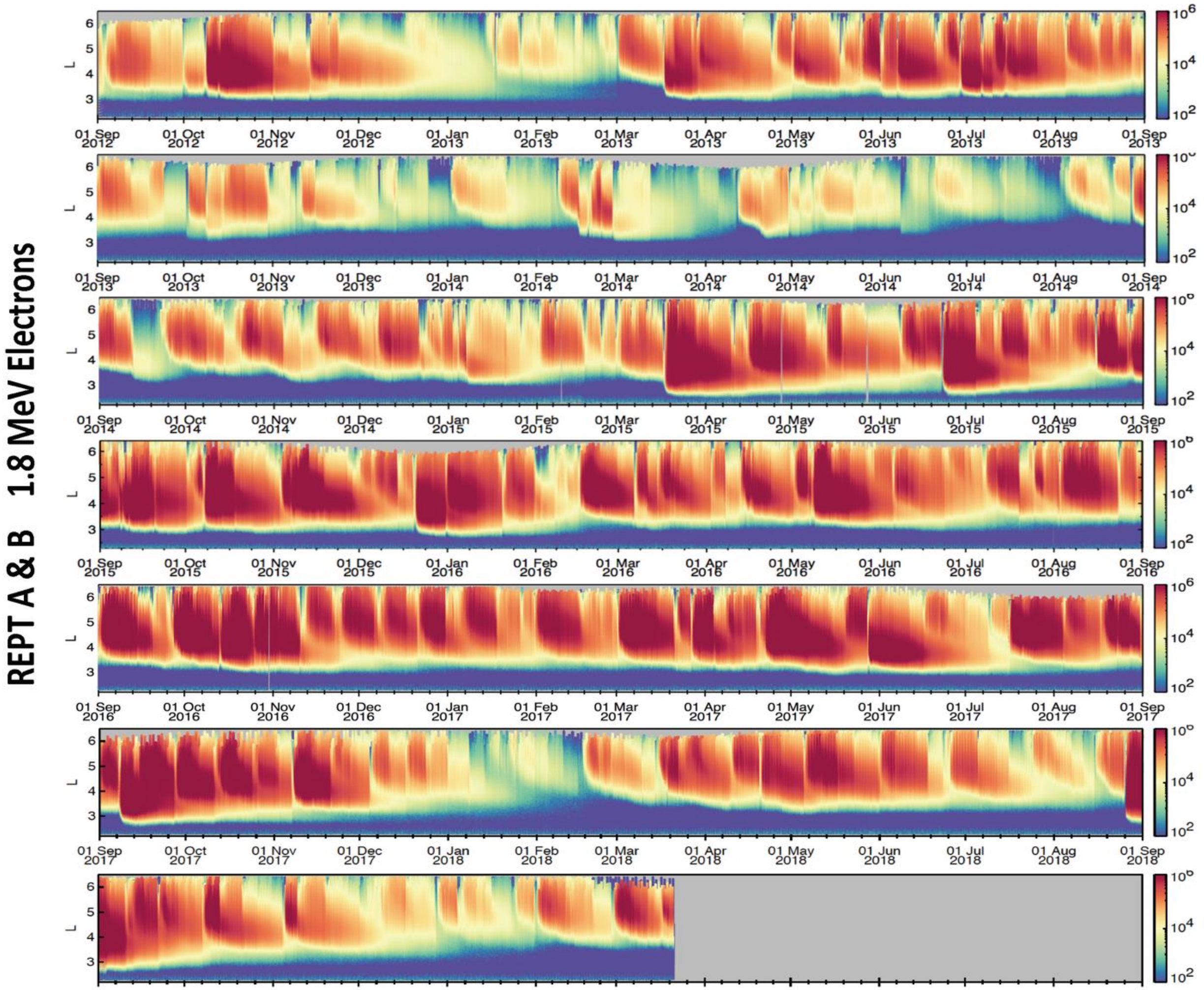


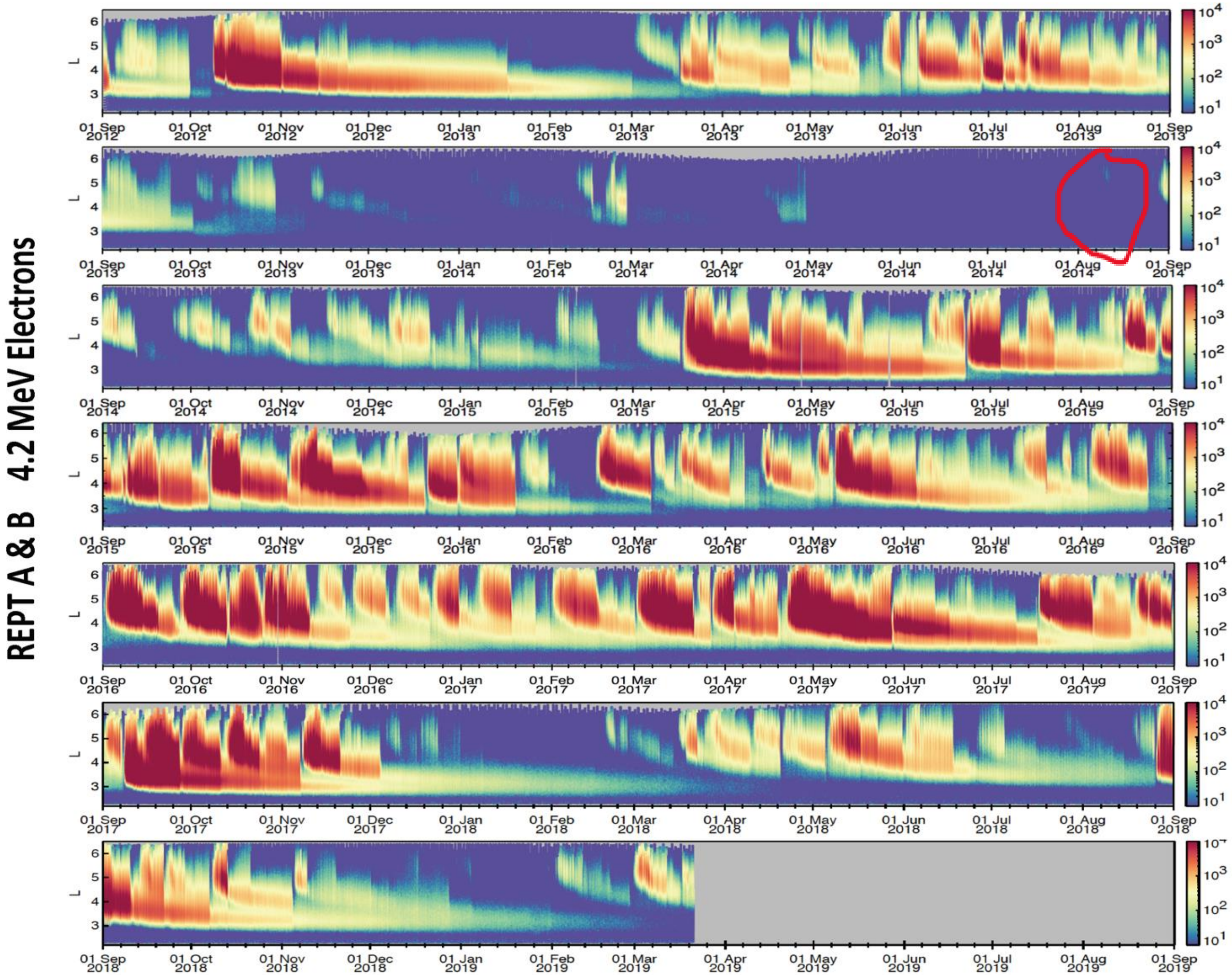
March 2014 – 4 MeV electrons



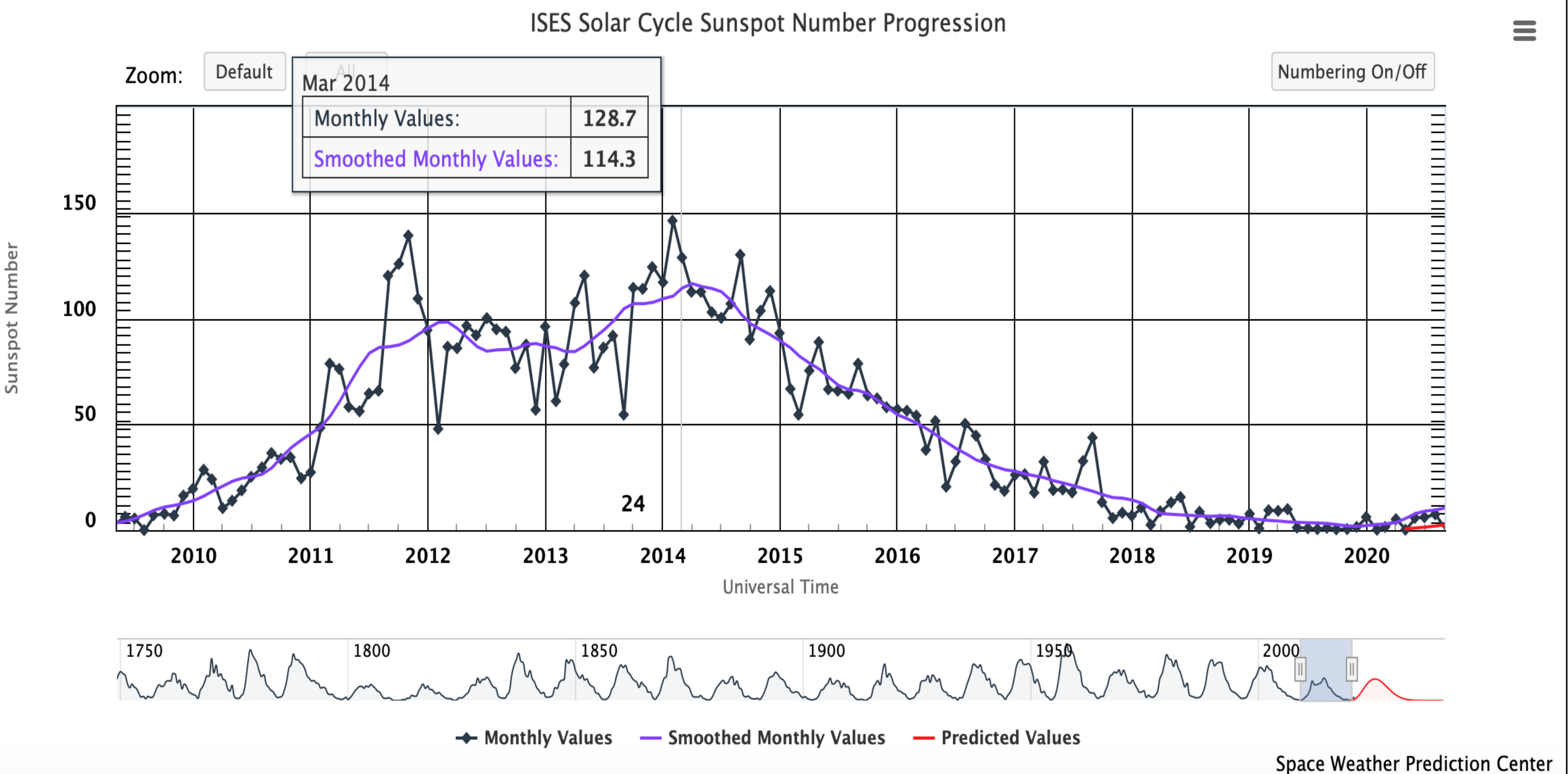


and August 2014

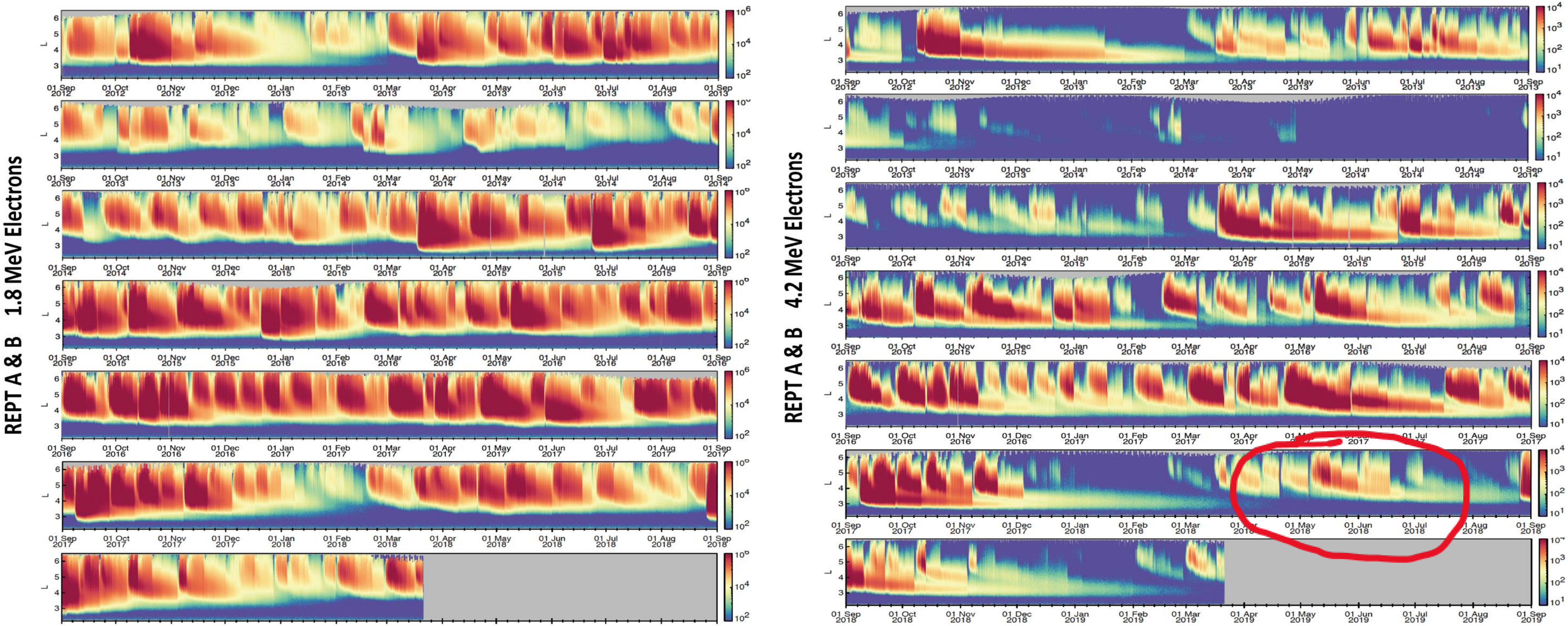




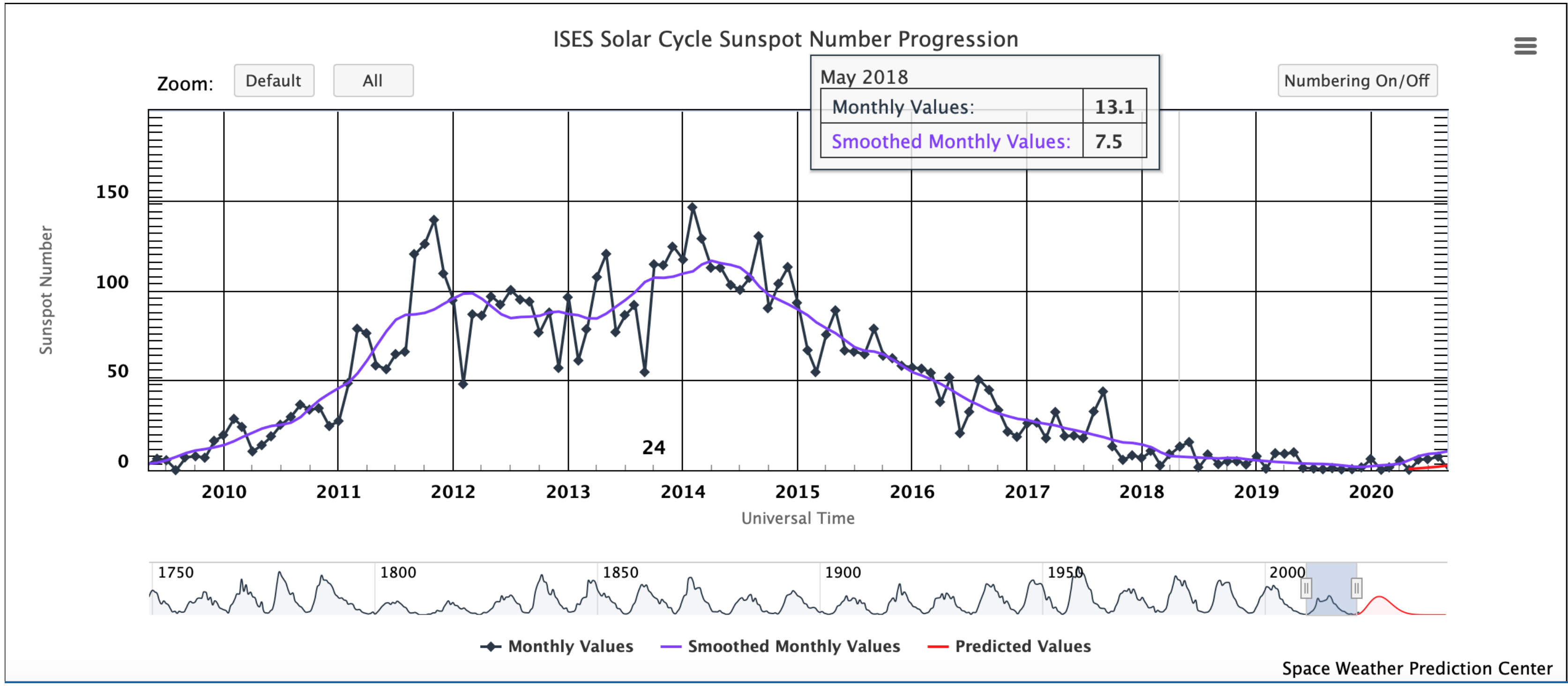
Lack of enhancements at solar maximum and early declining phase



May 2018



Clear enhancement at solar minimum



The basic facts of the outer Van Allen belt variability

2. The Belt itself

The usual peaceful electrons
in the solar wind / Earth's atmosphere: 1-10 eV
Occasional killer electrons in the outer belt: up to 10+ MeV

One million times more energetic
An unavoidable hazard leading to significant potential risks
No single acceleration process can do that

Hazards and risks

Risk = Hazard x Vulnerability

Hazards and risks

Risk = Hazard x Vulnerability x Exposure

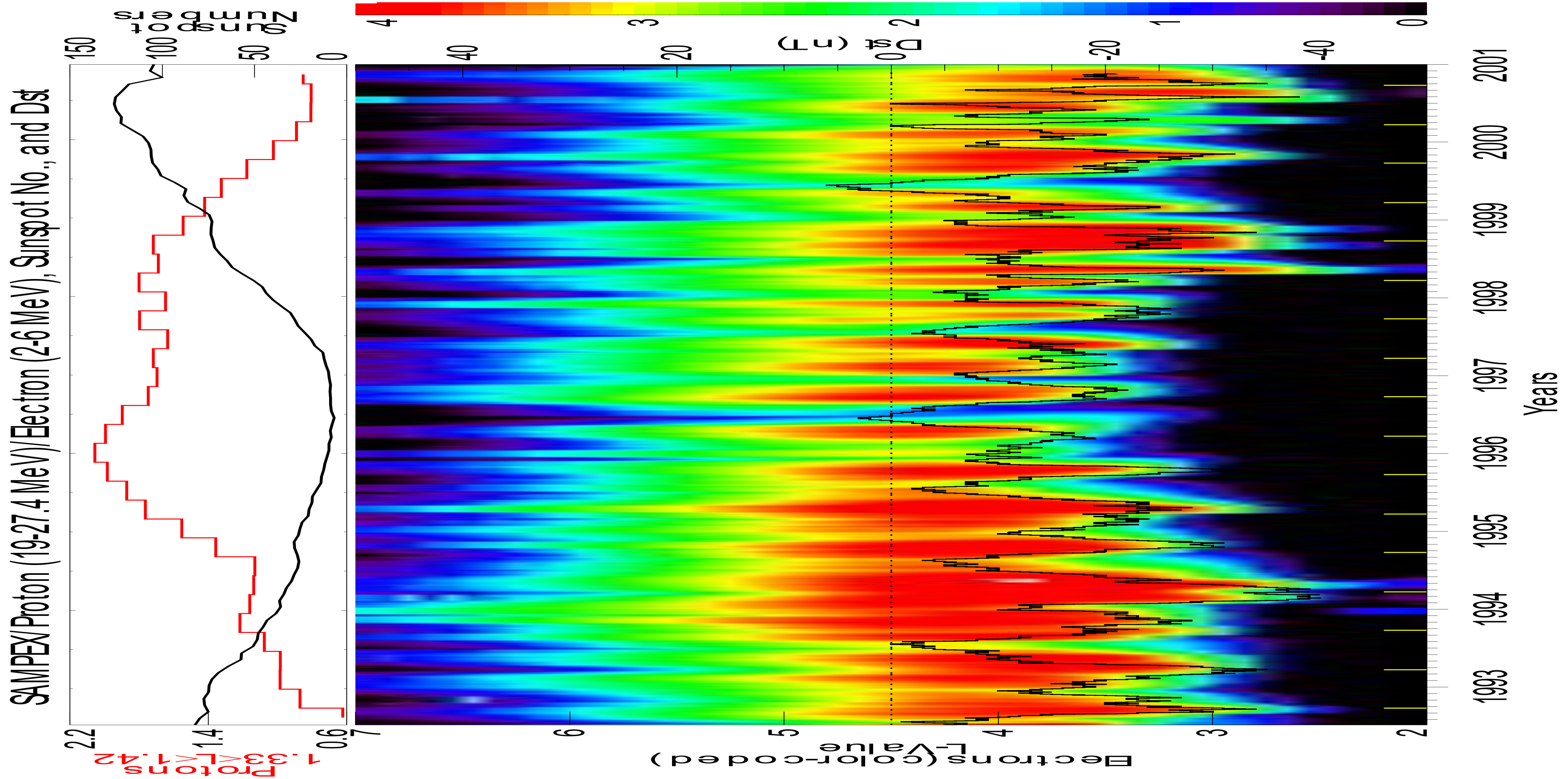
Hazards and risks

Risk = Hazard x Vulnerability x Exposure

Minimize risk through:

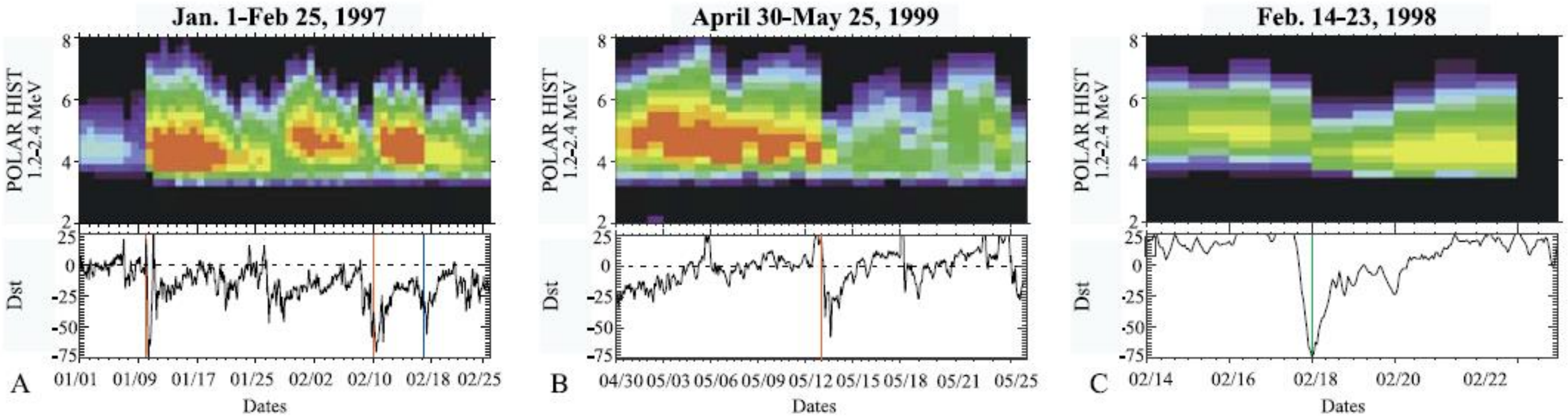
- Reduction of exposure (e.g., GTO orbit)
- Reduction of vulnerability (conditionally feasible)
- Timely and accurate forecast of hazard, enabling protective measures

Basic facts of the outer belt variability
Apparent dependencies: magnetic storms



However:
Variability of the Outer Belt during Magnetic Storms

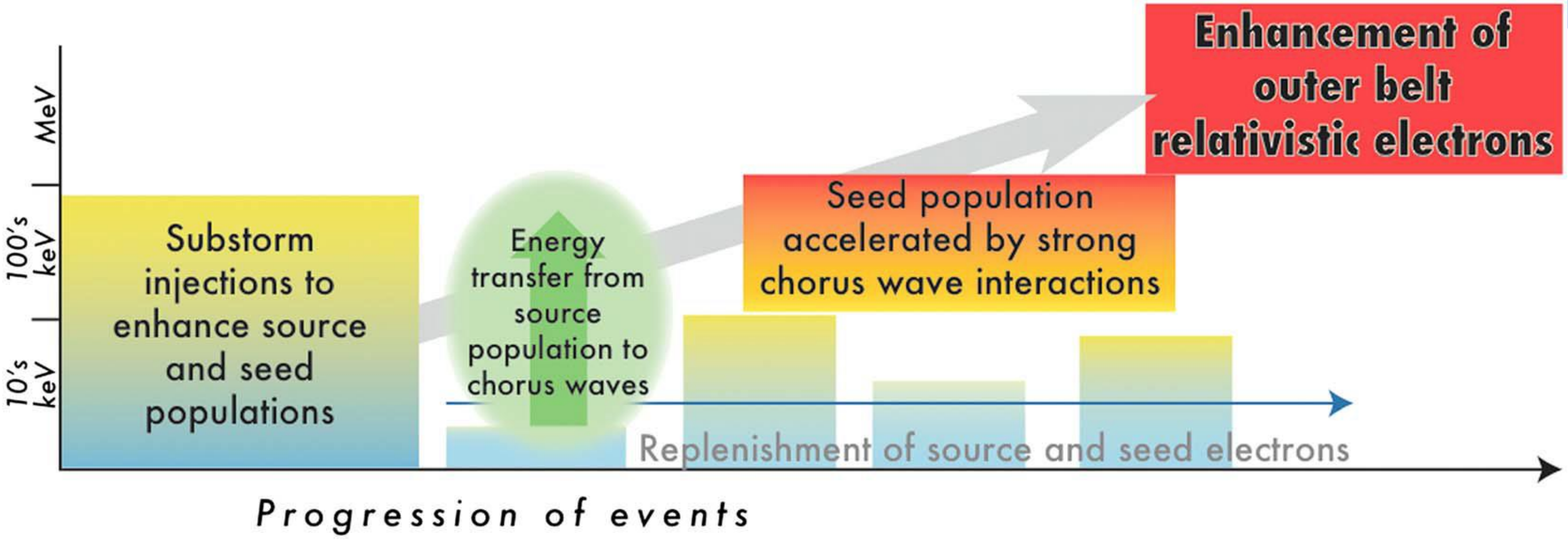
53 %　　19 %　　28 %



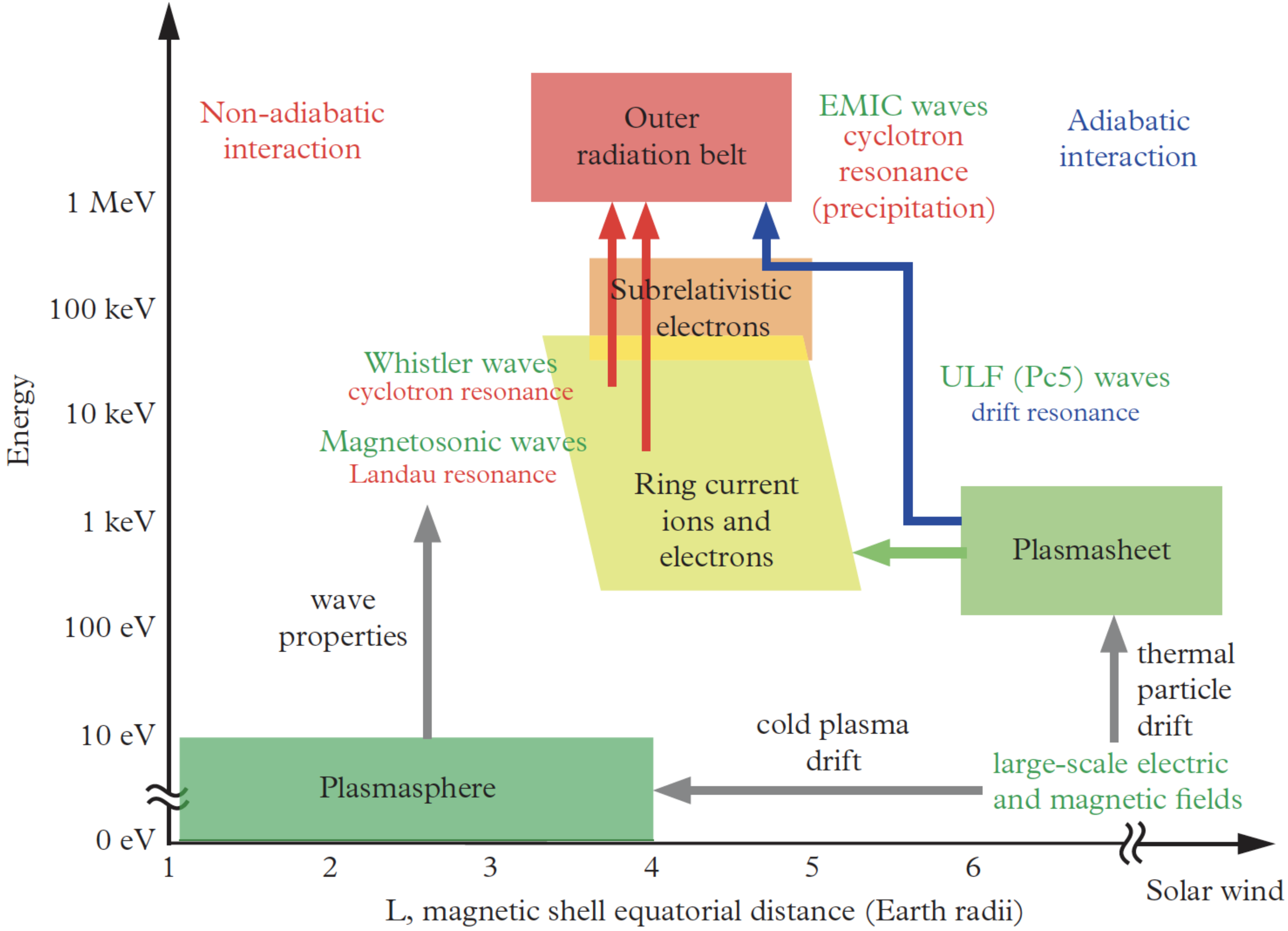
Reeves et al. 2003

<u>**Similar studies:**</u>

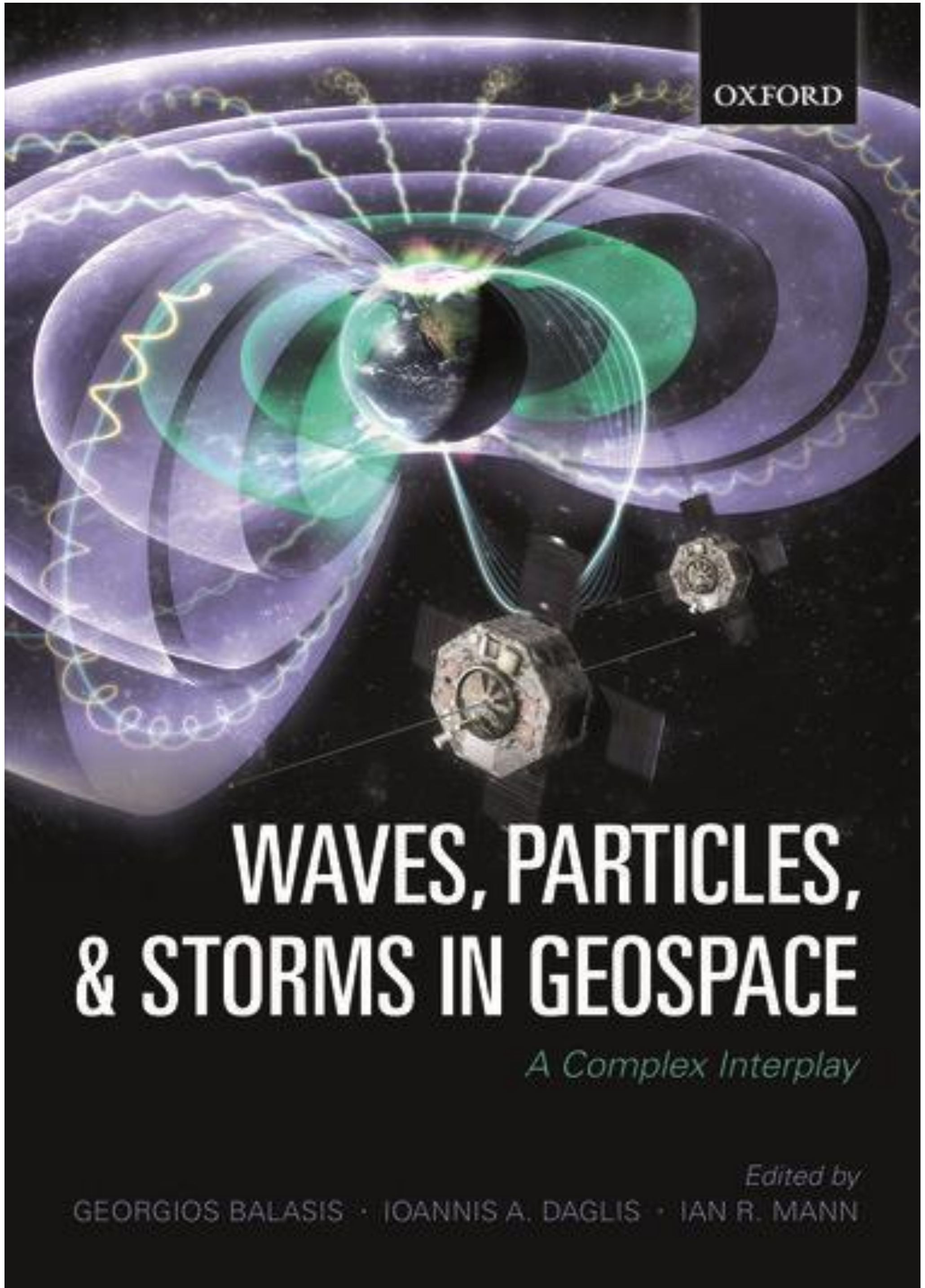
- Turner et al., 2013
- Zhao & Li, 2013
- Turner, O'Brien, et al., 2015
- Moya et al., 2017


MeV
100's keV
10's keV
Substorm injections to enhance source and seed populations
Energy transfer from source population to chorus waves
Seed population accelerated by strong chorus wave interactions
Enhancement of outer belt relativistic electrons
Replenishment of source and seed electrons
Progression of events

Jaynes+, 2015



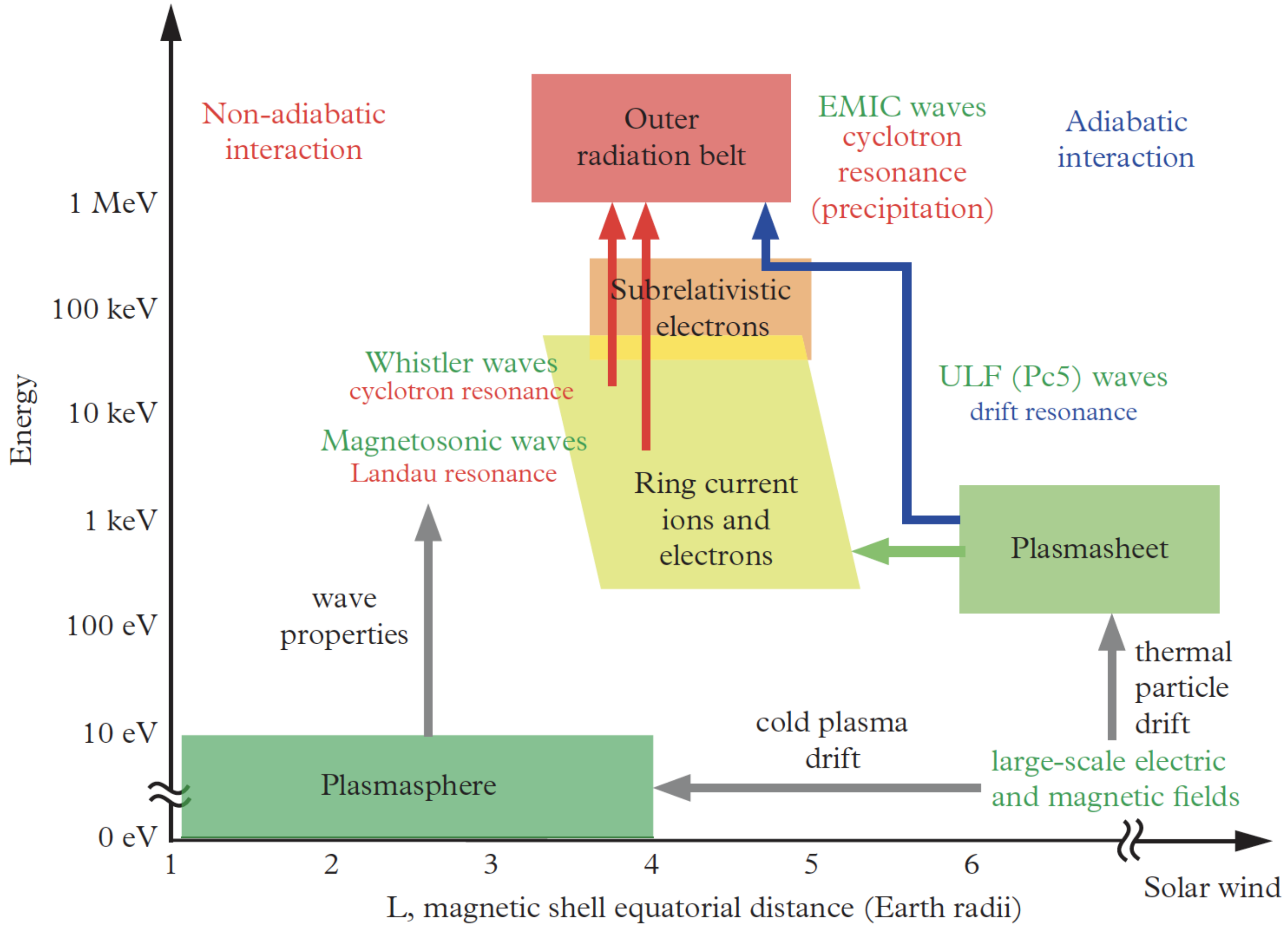
Takahashi & Miyoshi, 2016



Shameless advertising

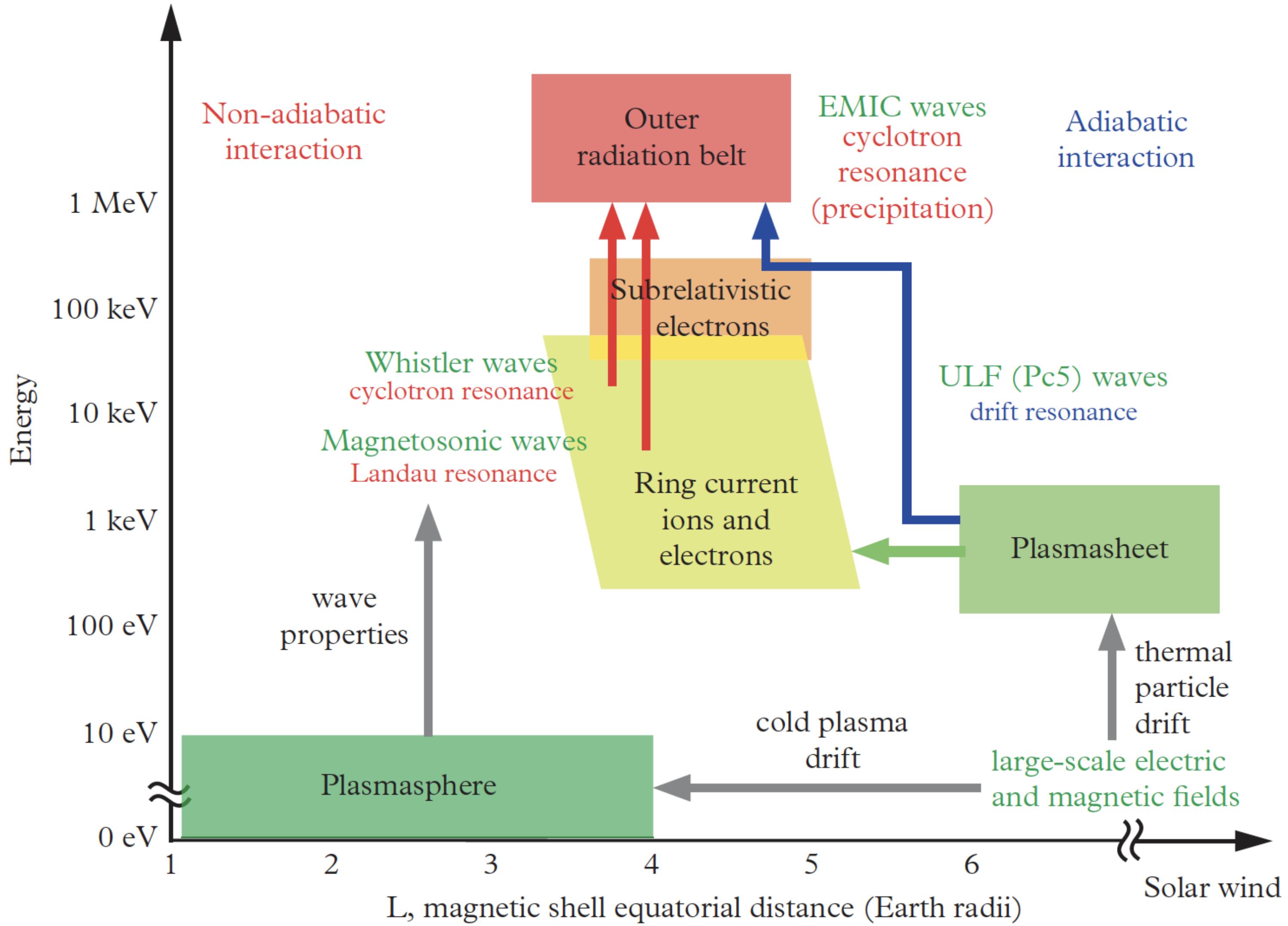
Oxford University Press, 2016

What is the problem with this logic diagram?



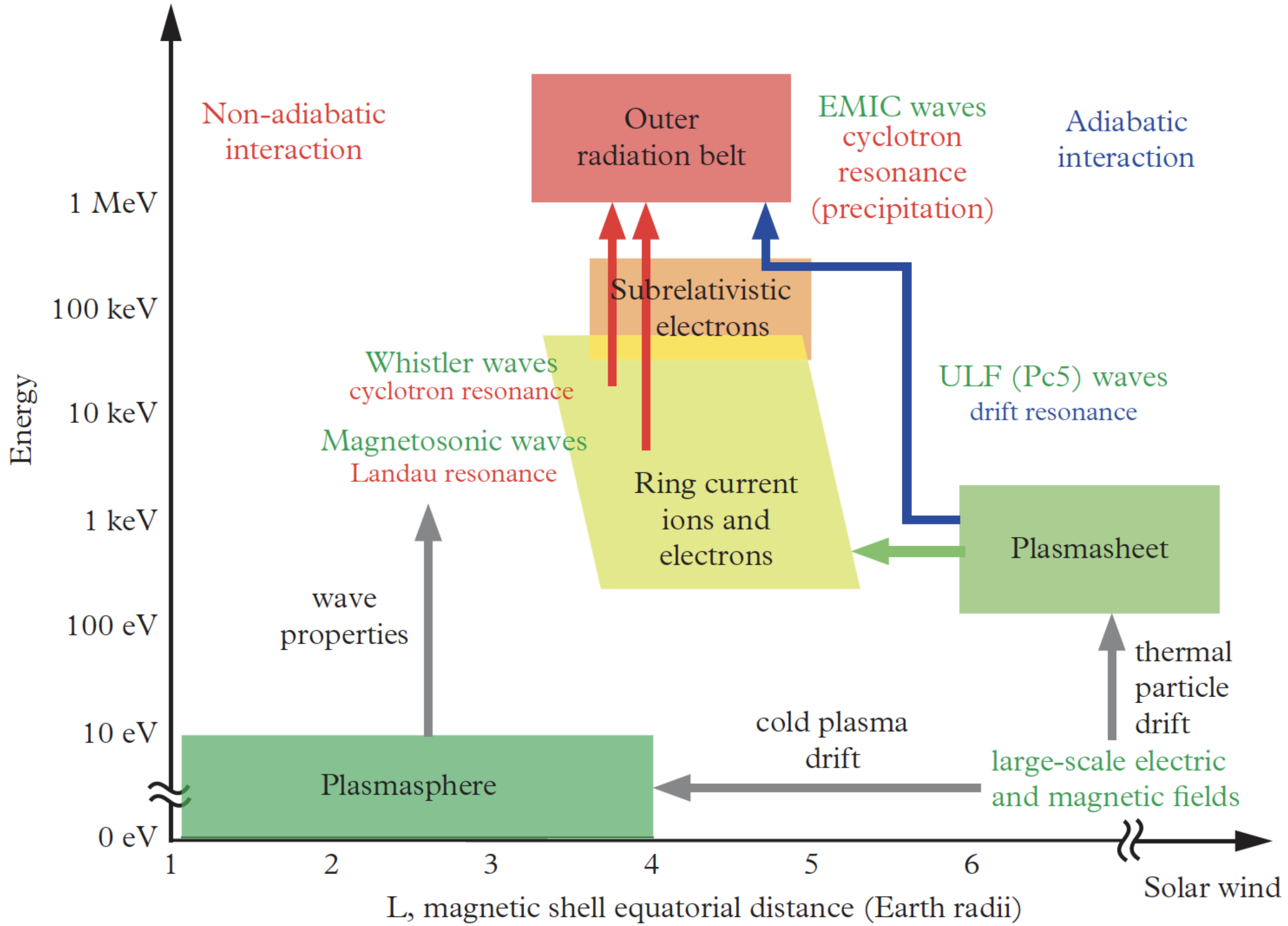
Takahashi & Miyoshi, 2016

Is something missing ?



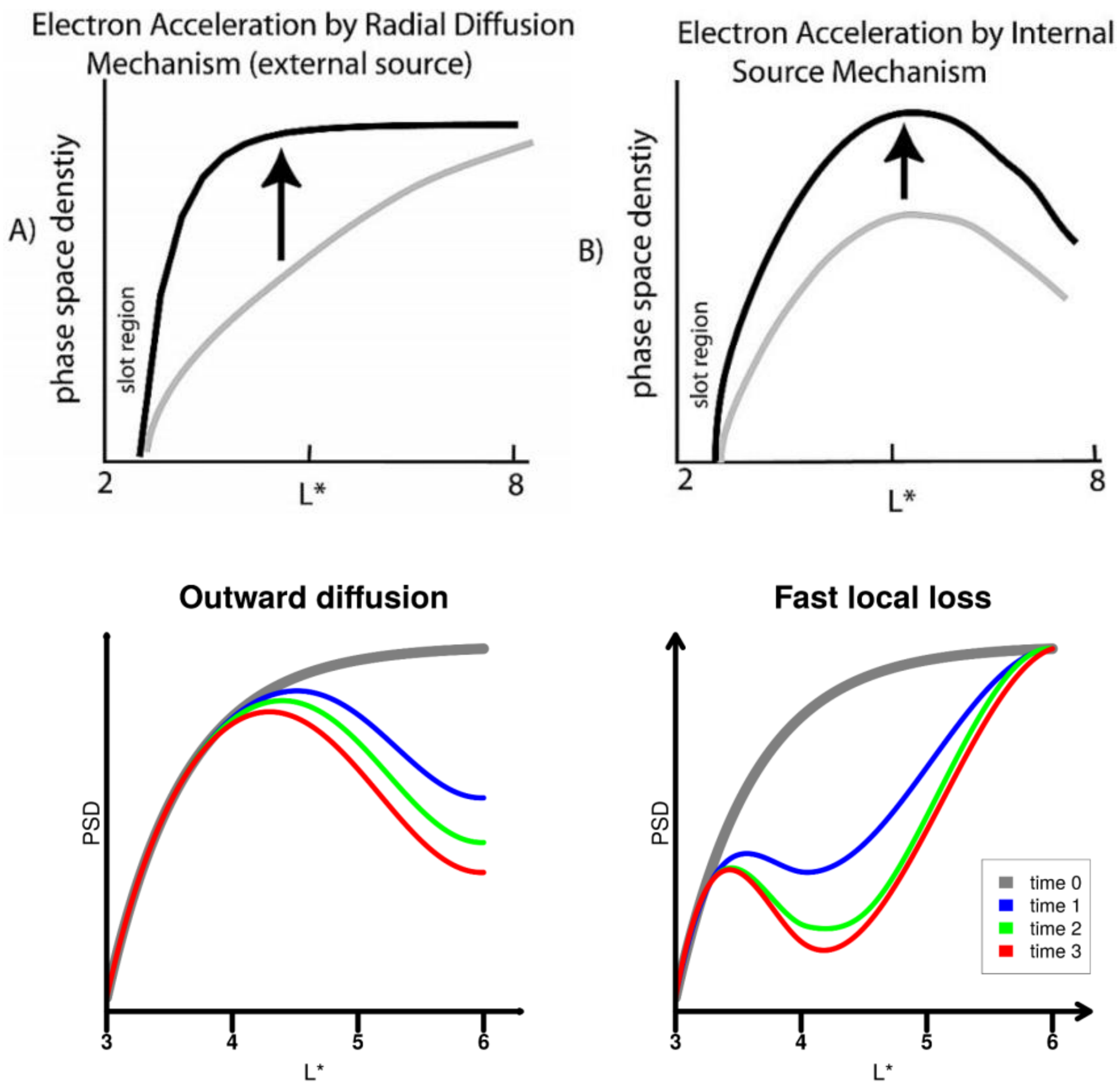
Takahashi & Miyoshi, 2016

Yes. Losses are missing.



Takahashi & Miyoshi, 2016

Variability of the Outer Belt - The basic mechanisms



Acceleration Mechanisms

1. Inward **radial diffusion** driven by Pc4-5 waves
2. Local heating by **gyro-resonance** with whistler chorus waves

Loss Mechanisms

1. Outer boundary losses (magnetopause shadowing)
2. Atmospheric losses (whistler chorus mode, plasmaspheric hiss and EMIC waves)

The eventual evolution of relativistic electron flux
in the outer Van Allen belt,
i.e. the net **loss** or net **enhancement**,
is the result of a **delicate balance** of
acceleration, transport, and loss mechanisms

Complex interplay of various physical processes, operating **across different spatial and temporal scales:**

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Microscale processes:

Spatial scale: meters to a few kilometers

Time scale: milliseconds to seconds

Complex interplay of various physical processes, operating **across different spatial and temporal scales:**

Microscale processes:

Spatial scale: meters to a few kilometers

Time scale: milliseconds to seconds

Mesoscale processes:

Spatial scale: tens to hundreds of kilometers

Time scale: seconds to minutes

Complex interplay of various physical processes, operating **across different spatial and temporal scales:**

Microscale processes:

Spatial scale: meters to a few kilometers

Time scale: milliseconds to seconds

Mesoscale processes:

Spatial scale: tens to hundreds of kilometers

Time scale: seconds to minutes

Macroscale processes:

Spatial scale: thousands to tens of thousands of kilometers

Time scale: minutes to hours or longer

- Global-scale (macroscale) processes:

Magnetopause shadowing losses

Magnetospheric convection, leading to magnetic storms

- Mesoscale processes:

10-30 keV electron substorm injections (10-30 minute duration) modifying chorus wave amplitudes

- Microscale processes:

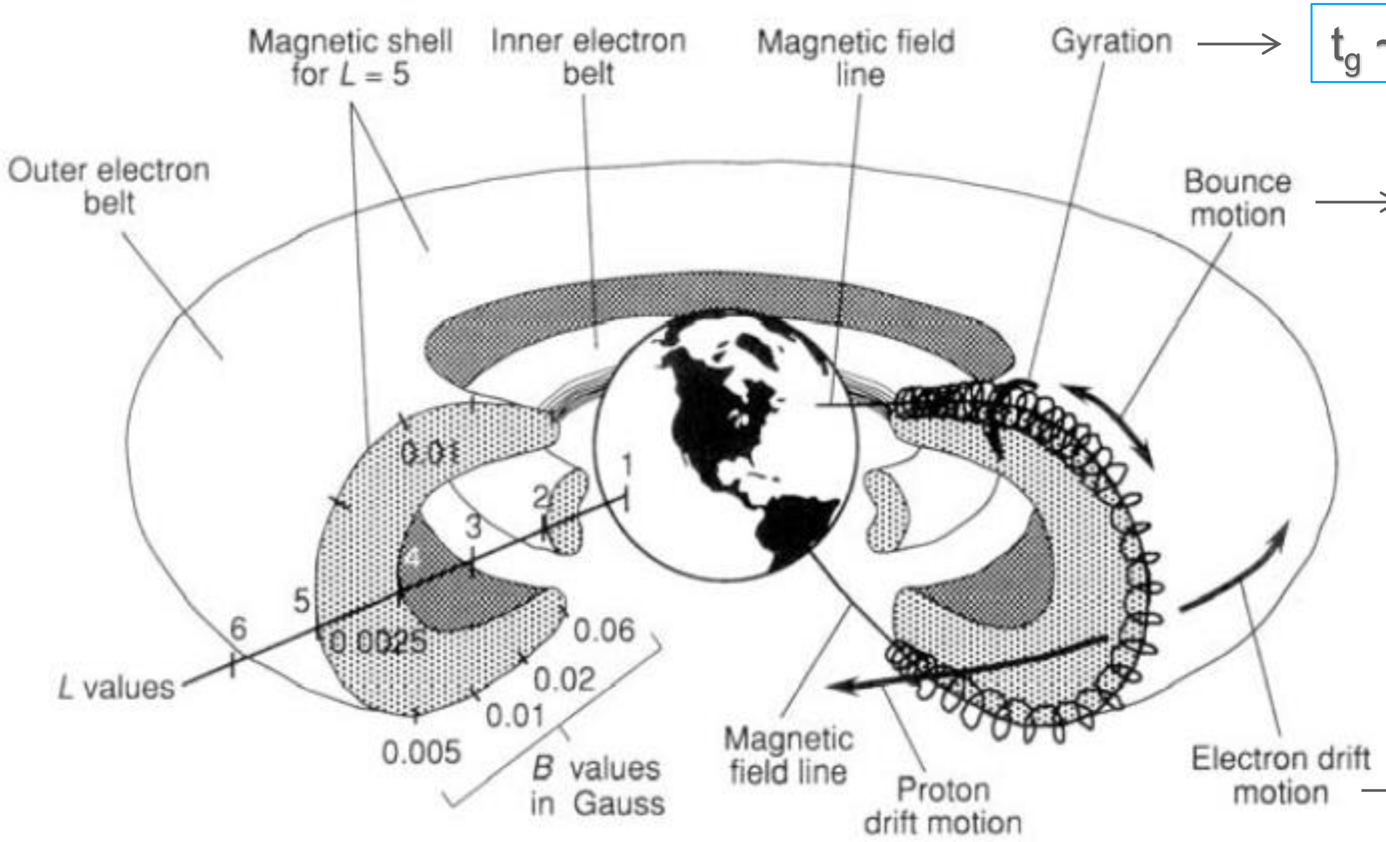
electron interactions with chorus waves on sub-second time scales

Motion of electrons and adiabatic invariants

$$\mu = \frac{P^2 sin^2\alpha}{2m_0B}$$

$$J = (8m_0\mu)^{1/2}\int_{a_m}^{b_m} B_m - B(s)ds$$

$$\Phi = \oint u_{drift} r d\varphi$$

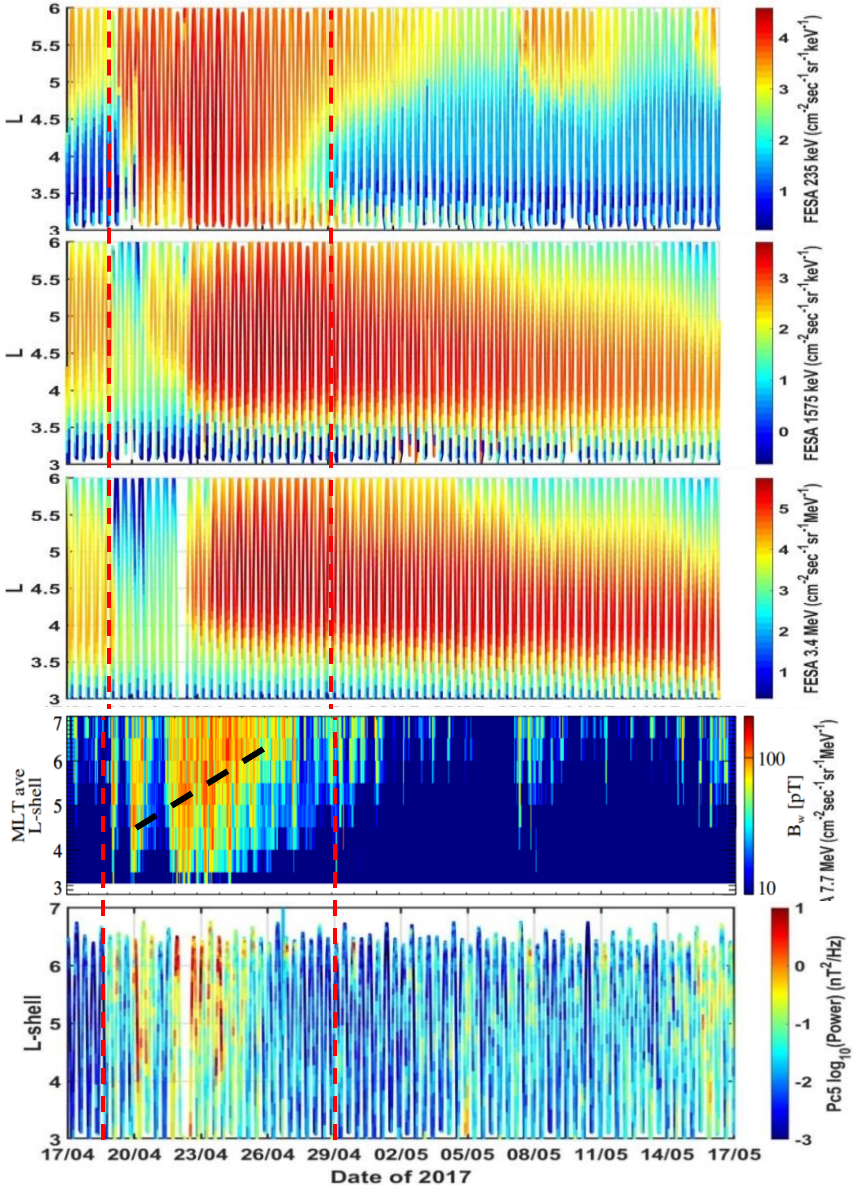


$t_g \sim 10^{-3}$ sec

$t_b \sim 1$ sec

$t_d \sim 10^{3}$ sec

Contribution of (ULF) Pc5 and (VLF) chorus waves to electron acceleration during a weak storm

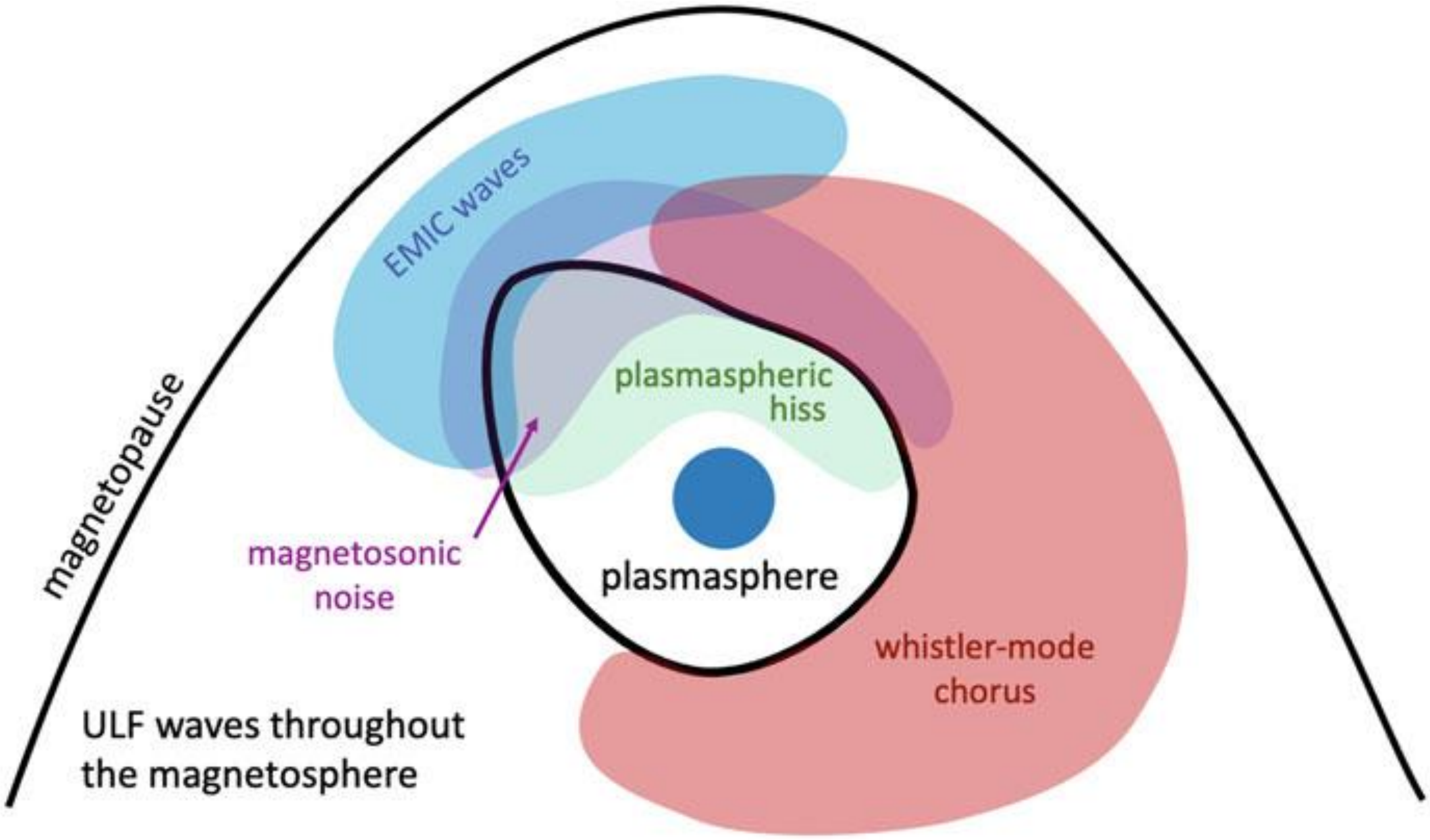


More than 1 order of magnitude enhancement of chorus amplitude

More than 2 orders of magnitude enhancement of Pc5 power

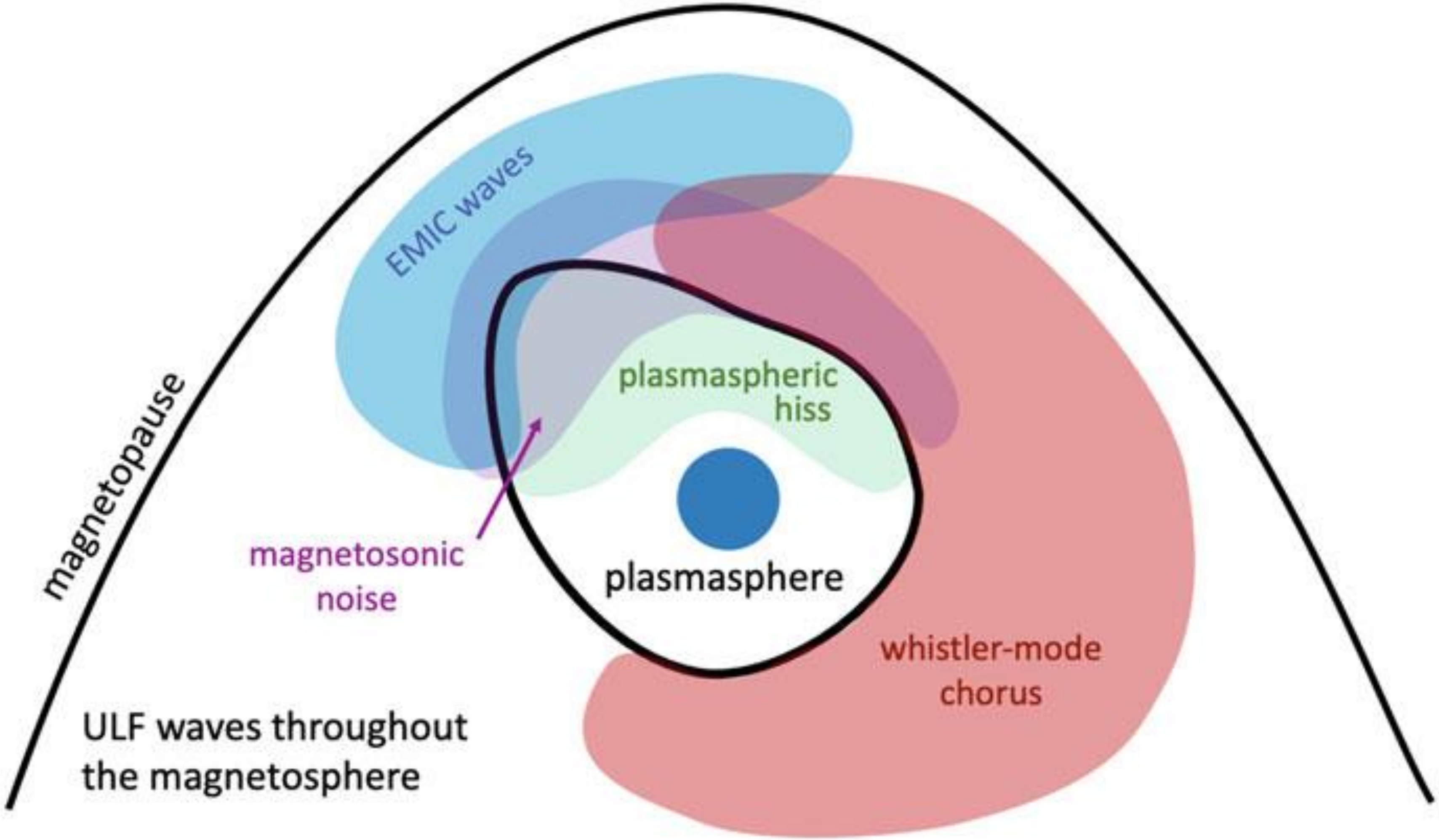
Katsavrias+, JGR2019

Outer Belt Dynamics – The Waves



Koskinen+, 2021

Outer Belt Dynamics – The Waves



Koskinen+, 2021

ULF: mHz / spatial scales of the order of Earth radius
Chorus: kHz / spatial scales of the order of 0.5-10 km (~n_p, v_{ph})

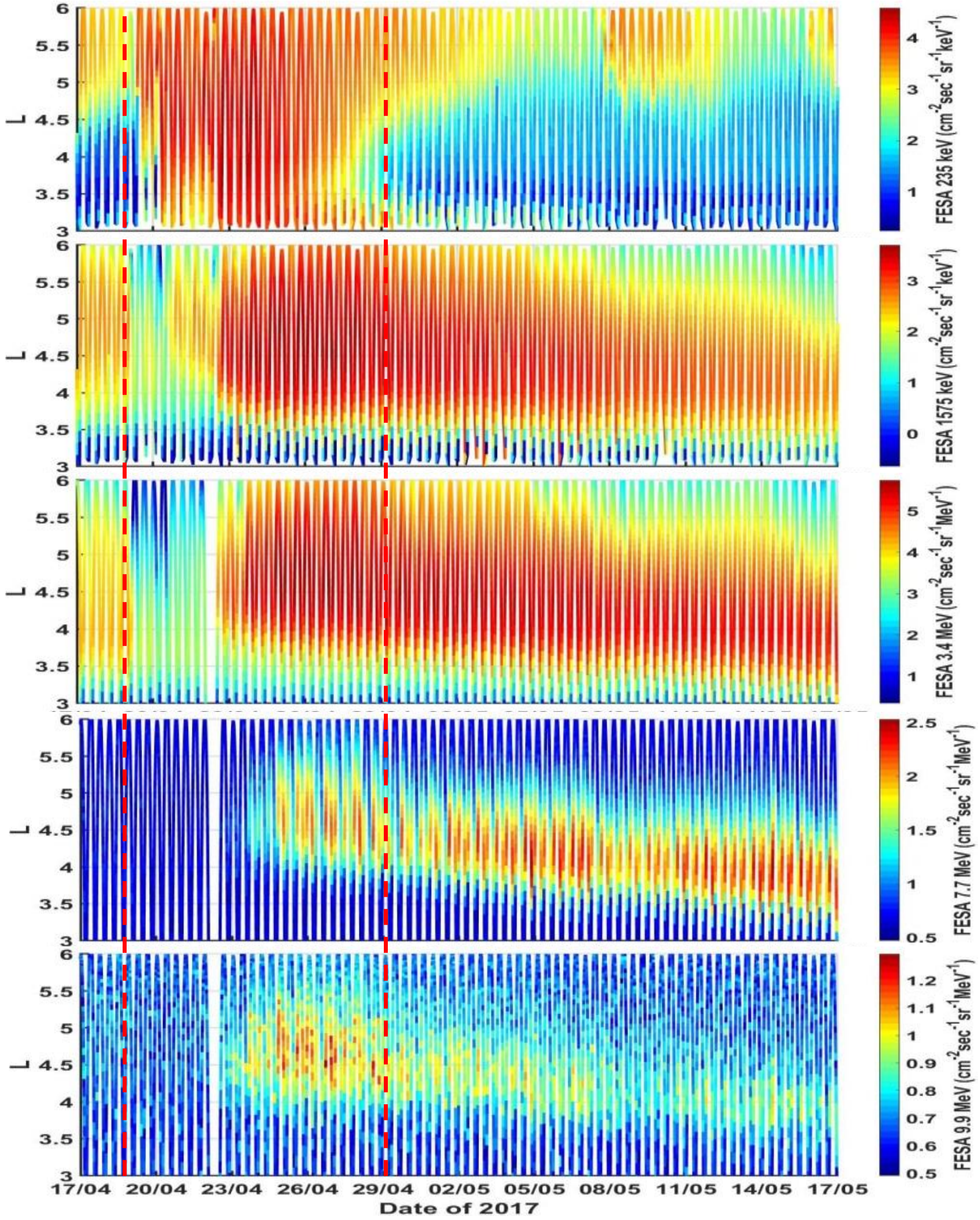
Practical Consequences

- ULF waves: **Fluxgate magnetometers (space and ground)** measure the 3-D magnetic field from DC up to a few tens of Hz
- VLF waves: **Search-coil magnetometers (space and ground)** measure only time-varying magnetic fields, typically from ~0.1–1 Hz up to several kHz.
- In addition, VLF chorus and hiss waves require measuring the wave electric field. **Double-probe electric field instruments (wire antennas or fixed booms)** are used, typically covering DC up to tens or hundreds of kHz

Thank you for your attention

Additional material

Contribution of Pc5 and chorus waves to electron acceleration during a weak storm



More than three orders of magnitude enhancement of 3.4 MeV electron flux

Acceleration of electrons up to 9.9 MeV.

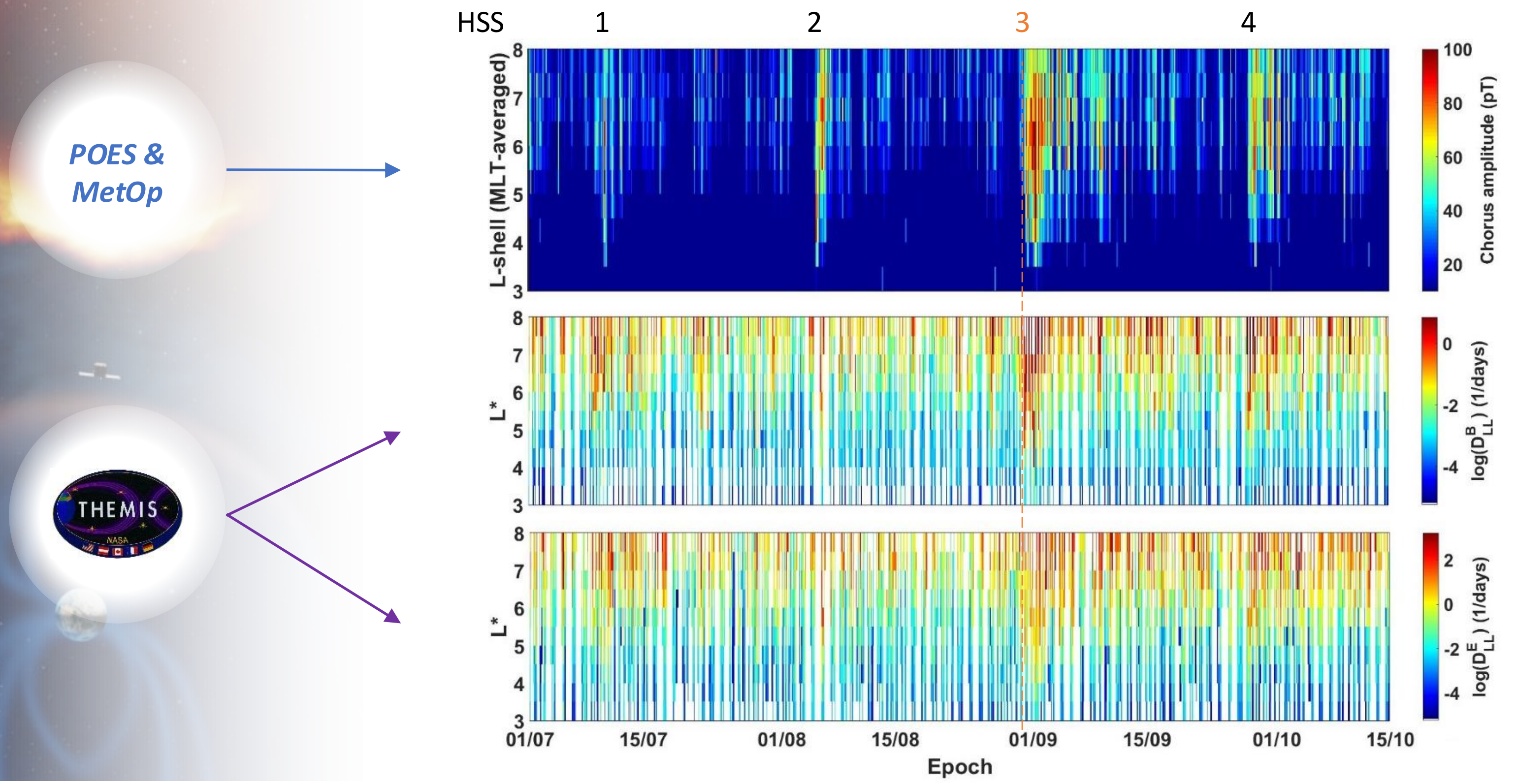
Effect comparable to the St. Patrick's 2015 storm "...the strongest storm seen over the past decade..."

Katsavrias+, JGR2019

ULF & VLF wave parameters

The third HSS pulse exhibited:

- The **greatest, deepest and more prolonged chorus wave excitation**, reaching L < 4 R_E for several days.
- The **most prominent, persistent and inward D_{LL}^{B} and D_{LL}^{E} increase**, indicating **enhanced radial diffusion** of electrons **(Ultra Low Frequency waves)**



Chorus wave amplitude is inferred by precipitating electron fluxes measured by POES and MetOp satellites, following the technique of Li et al. (2013).

The use of L instead of L* for the chorus waves is done with caution. The broad binning that we use (dL=0.5 and dT=1h), as well as the qualitative nature of this study, leads as to believe that this will not significantly affect the nature of our results.

D_{LL} are radial diffusion coefficients corresponding to μ=1000 MeV/G electrons, calculated using data from THEMIS satellites. More information in EGU21-10563 (Katsavrias) and EGU21-13466 (Daglis).

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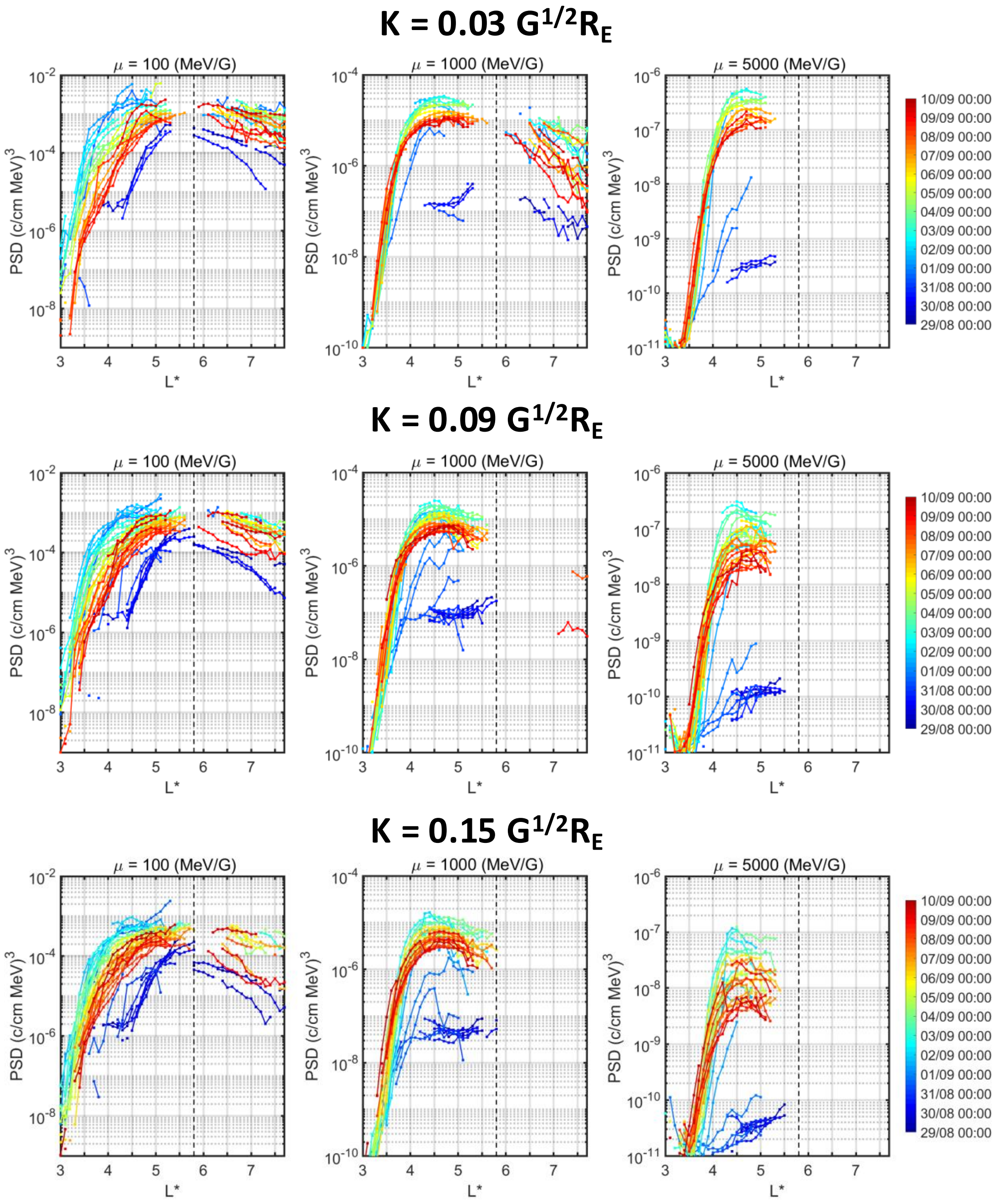
Geomagnetic & Magnetospheric parameters
ULF & VLF wave parameters
Electron flux
Seed e (< 0.5 MeV)
Relativistic e (1-2 MeV)
Ultra-relativistic e (> 4 MeV)
Electron Phase Space Density (PSD)
Conclusions
References



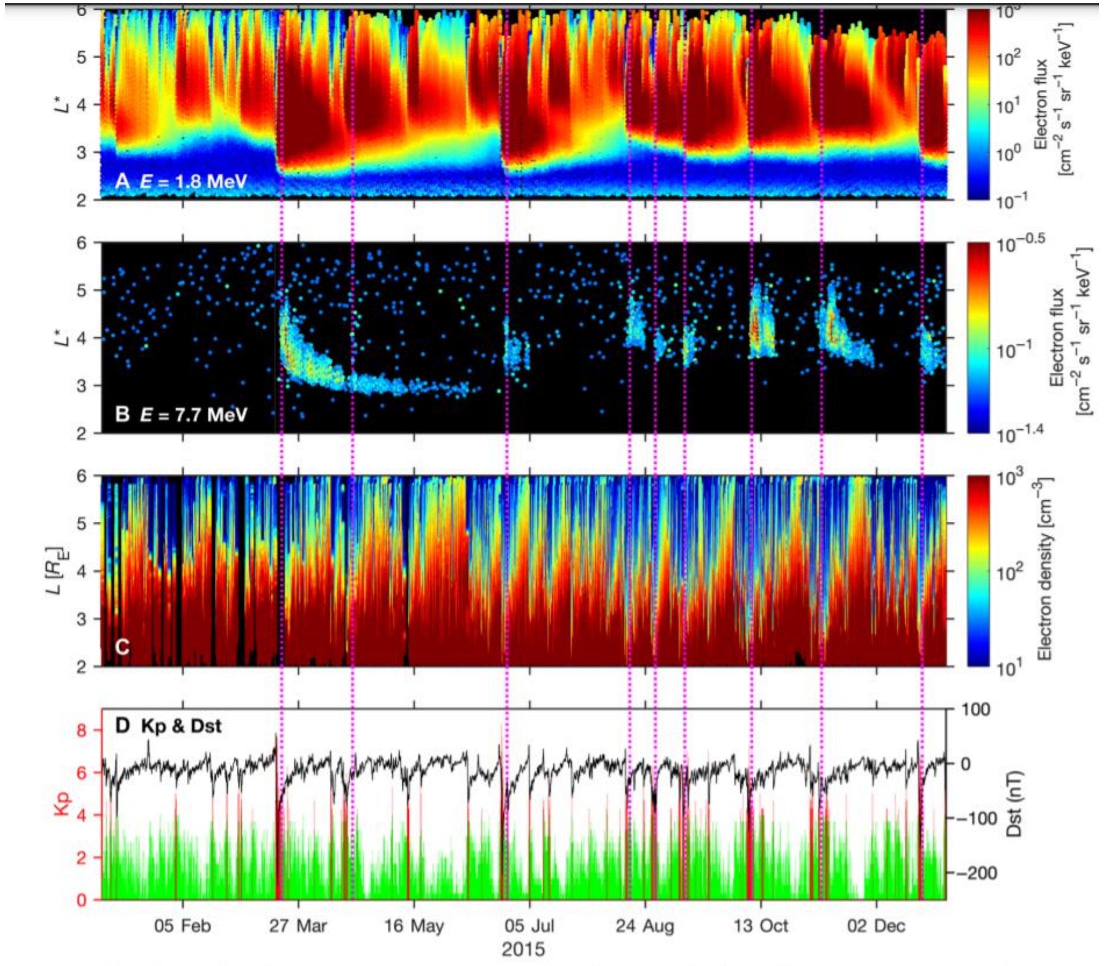
PSD radial profiles for three K values
during the 29/8 – 10/9, 2019 time period.
The dashed vertical lines separate RBSPA-ERG
measurements (inside the outer belt)
from THEMIS measurements (outside GEO).

The relative contribution of local heating
and radial diffusion depends on the K value.
With increasing K, the peaks in PSD become much
more prominent. This feature is even more pronounced
with increasing mu value (e.g. 5000 MeV/G).

The relative contribution of Pc5 and chorus waves in electron acceleration

From Allison et al. SciAdv2021

During periods when the plasma density is significantly depleted below average levels, chorus waves, if present, are capable of producing local enhancements of >7 MeV electrons.



3-step Acceleration ????

Is there a level of predictability in radiation belt dynamics?

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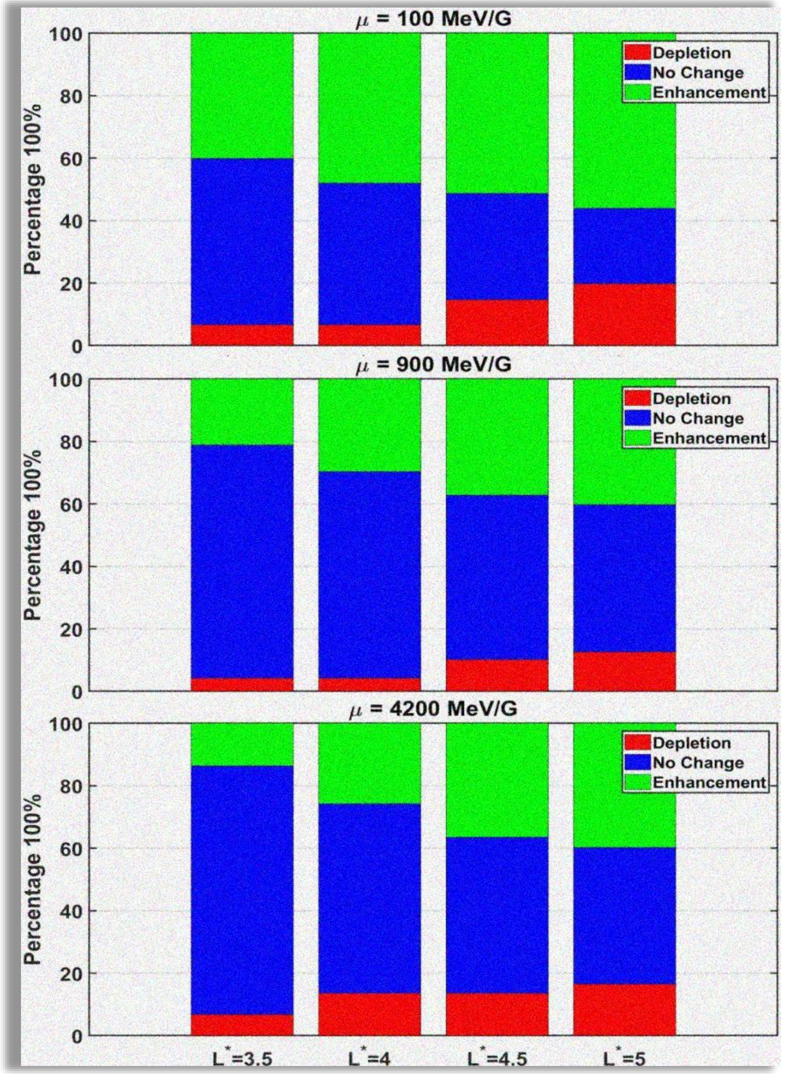
71 events during the RBSP era (9/2012 – 4/2018) spanning the maximum/declining phase of Solar cycle 24.

Enhancements	$PSD_{Post}/PSD_{Pre} \geq 6$
Depletions	$PSD_{Post}/PSD_{Pre} \leq 1/4$
No Change	$1/4 < PSD_{Post}/PSD_{Pre} < 6$

- <u>Enhancements occurrence increase with increasing L* and decreasing energy.</u>
- <u>Loss occurrence increace with increasing L* but there is no pattern with energy.</u>



From Katsavrias et al. JGR2019

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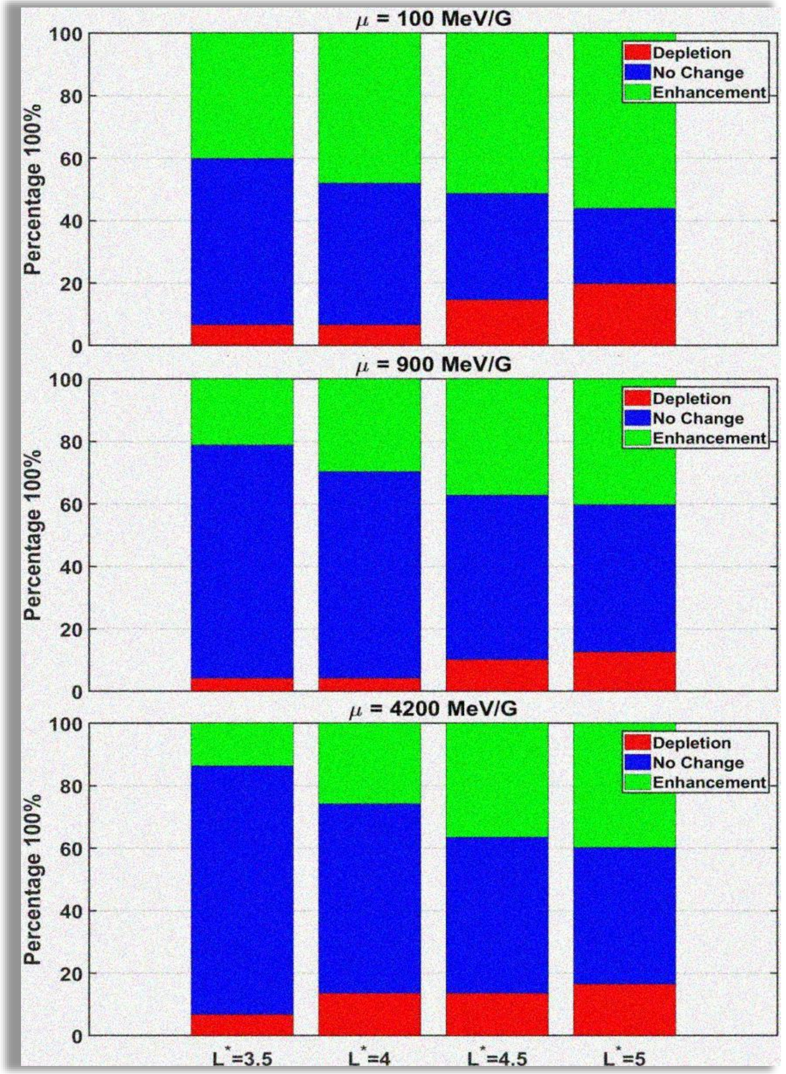
Depletions	$PSD_{Post}/PSD_{Pre} \leq 1/4$
No Change	$1/4 < PSD_{Post}/PSD_{Pre} < 6$

- <u>20 Events</u> with enhancement of the relativistic (μ = 900 MeV/G) electron population at L*≥4.5
- <u>8 Events</u> with depletion of the relativistic (μ = 900 MeV/G) electron population at L*≥4.5



From Katsavrias et al. JGR2019

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Summary

- <u>The relative contribution of acceleration mechanisms</u>

1. ULF-waves have a dual role
   I. Dominant loss mechanism for near-equatorial mirroring relativistic electrons
   II. Acceleration mechanism for ultra-relativistic electrons

2. Three-step (or four-step) acceleration scenario:
   I. Intense substorms + chorus activity → enhancement of seed electrons
   II. Local heating (via chorus waves) → enhancement of relativistic electrons
   III. Inward diffusion (via Pc5 waves) → enhancement of ultra-relativistic electrons
   IV. Energy diffusion enhancement (due to decrease in electron density) → Further acceleration via gyro-resonant interactions

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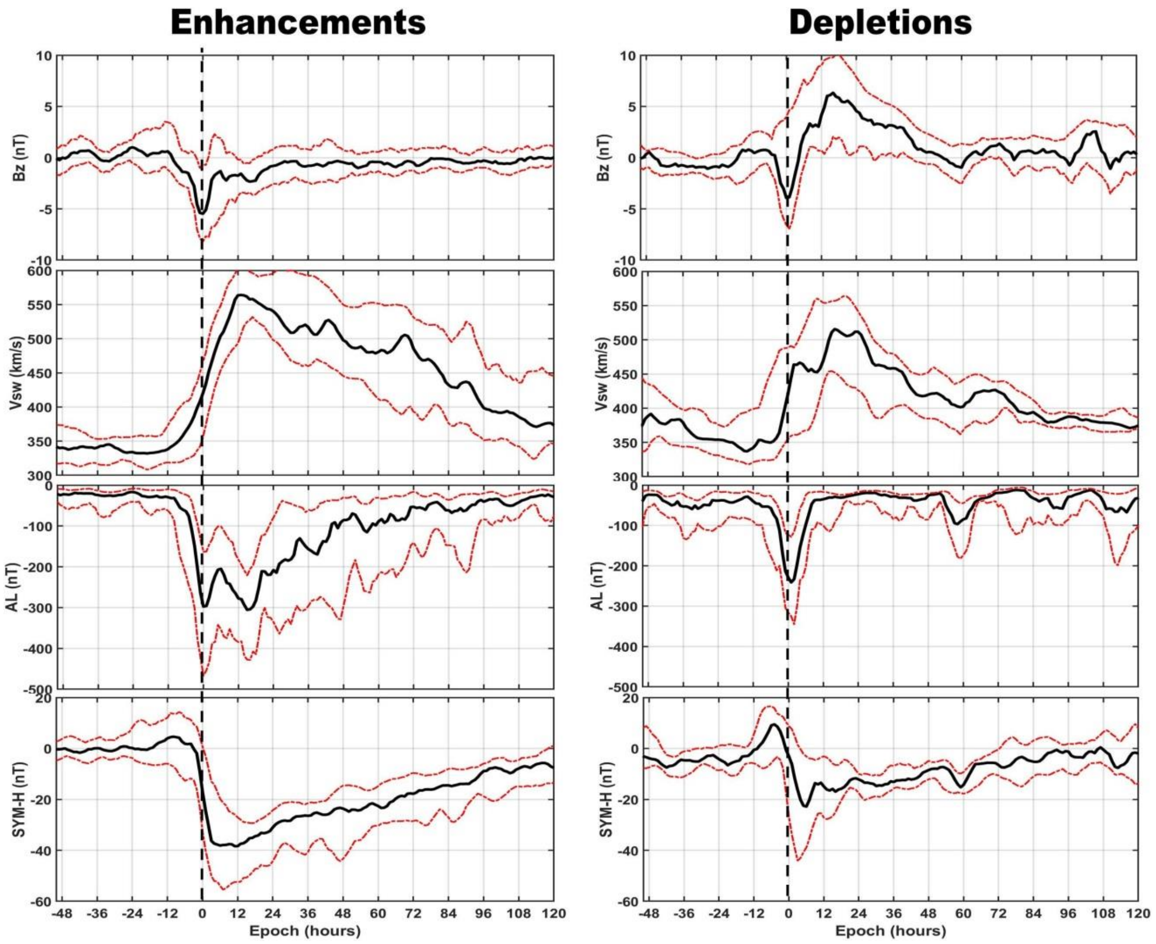
Is there a level of predictability in radiation belt dynamics?



- **continuously negative values of Bz** up to 1.5 day
- **higher and long-lasting values of solar wind speed**
- **More intense and prolonged substorm activity** as reflected in the AL index

From Katsavrias et al. JGR2019

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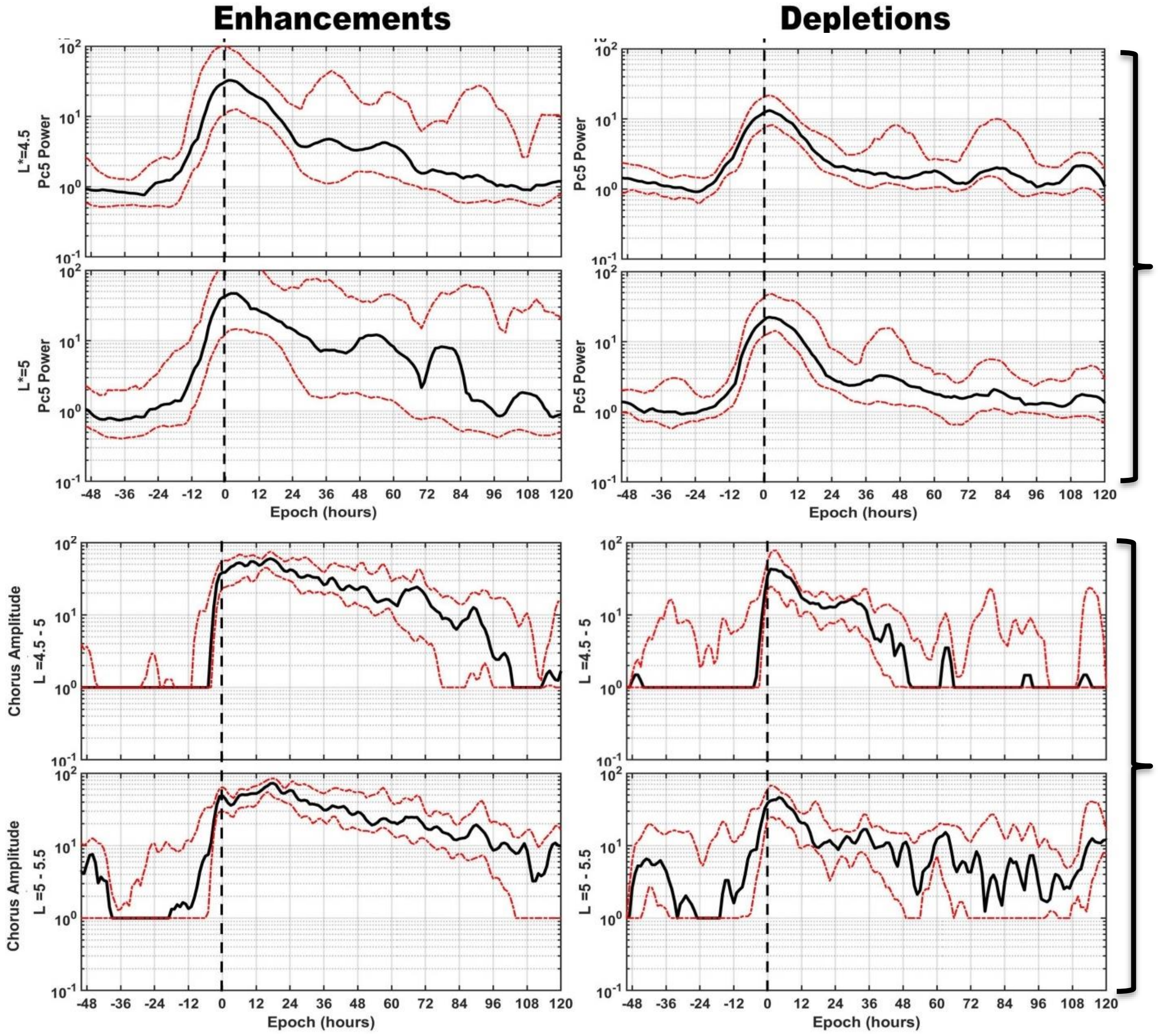
Is there a level of predictability in radiation belt dynamics?

From Katsavrias et al. JGR2019



- longer-lived Pc5 wave activity, especially at L*>4
- more pronounced and long-lived chorus wave activity, over a broad L-shell region

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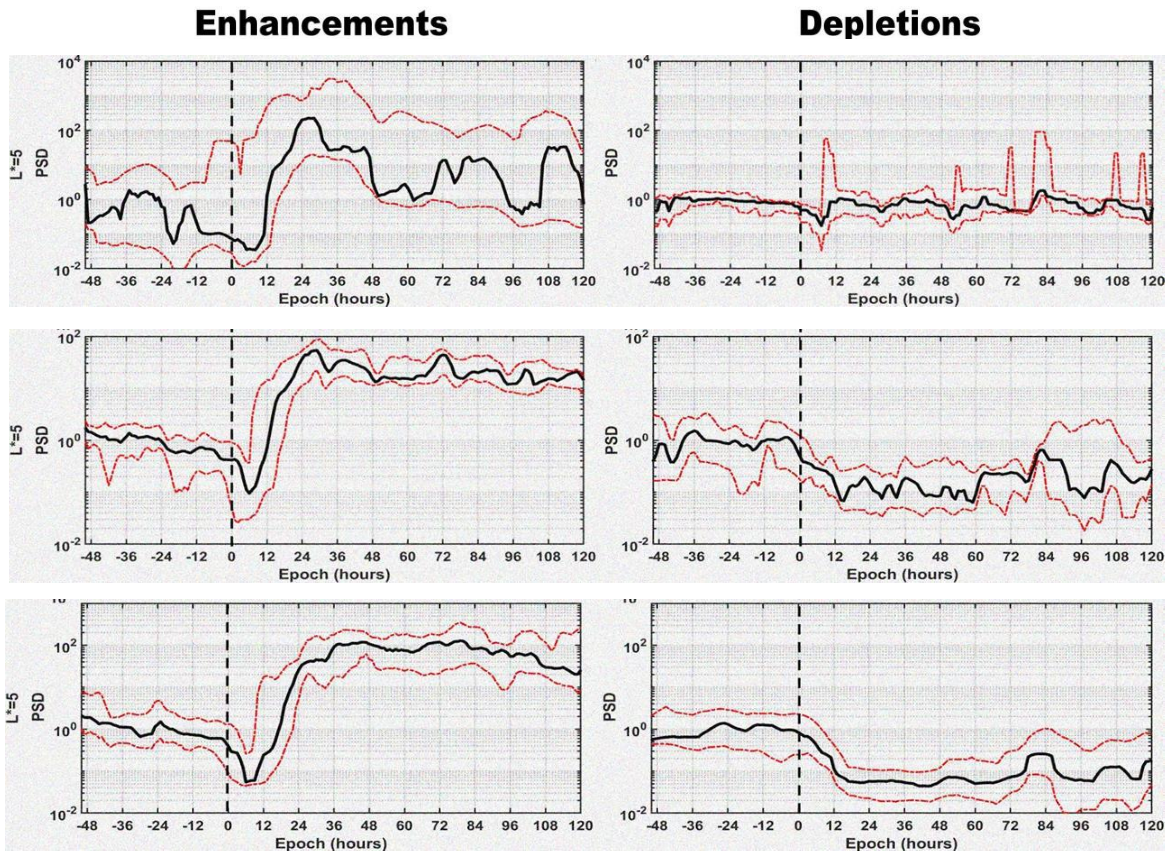
Is there a level of predictability in radiation belt dynamics?

From Katsavrias et al. JGR2019



- **Significant abundance of seed electrons during enhancement events.**

- <u>**Phase 1 (t_0 – t_0+12 hours):**</u>

Relativistic PSD dropout which coincides with the minimum Lmp_min and max Pc5 power.

- <u>**Phase 2 (t_0 +12 – t_0+120 hours):**</u>

Enhancement events: relativistic electrons quickly replenished as the **pronounced and long-lived chorus** accelerate the enhanced seed population.

Depletion events: at the absence of significant seed population, **relativistic electrons remain depleted.**

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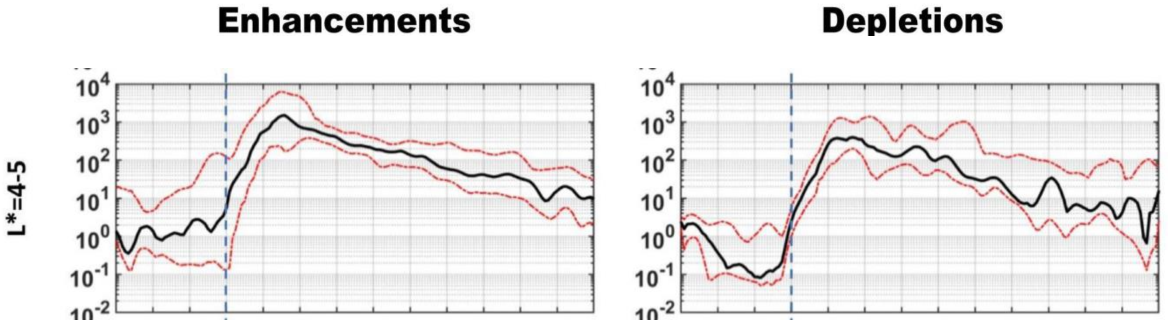
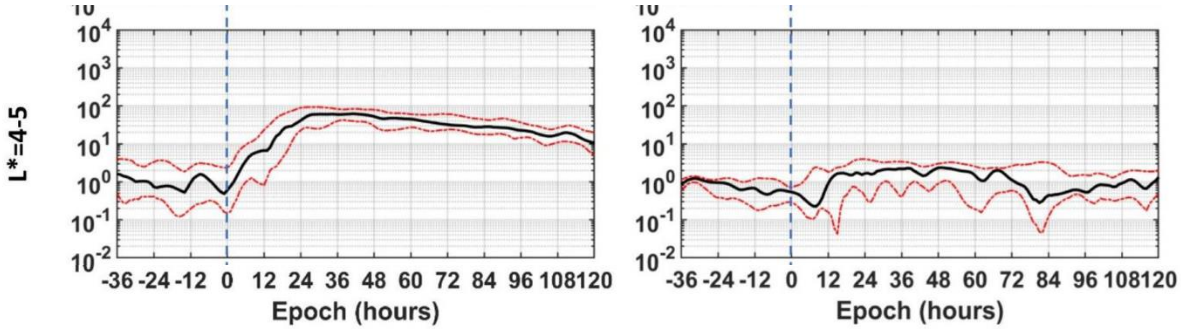
Is there a level of predictability in radiation belt dynamics?

From Nasi et al. JASTP2020



- ➢ **μ=10 MeV/G**

Source electrons appearing pronounced and more prolonged during enhancement events. No enhancement is seen at lower μ values defining a cut-off energy of E = 10 keV.



- ➢ **μ=100 MeV/G**

The appearance of Seed electrons does not depend on the appearance of source electrons alone, but additional mechanisms are important.

They either get directly injected from the plasma sheet as an effect of substorm activity, or they are comprised by diffused electrons previously located at larger L*, source electrons or other.

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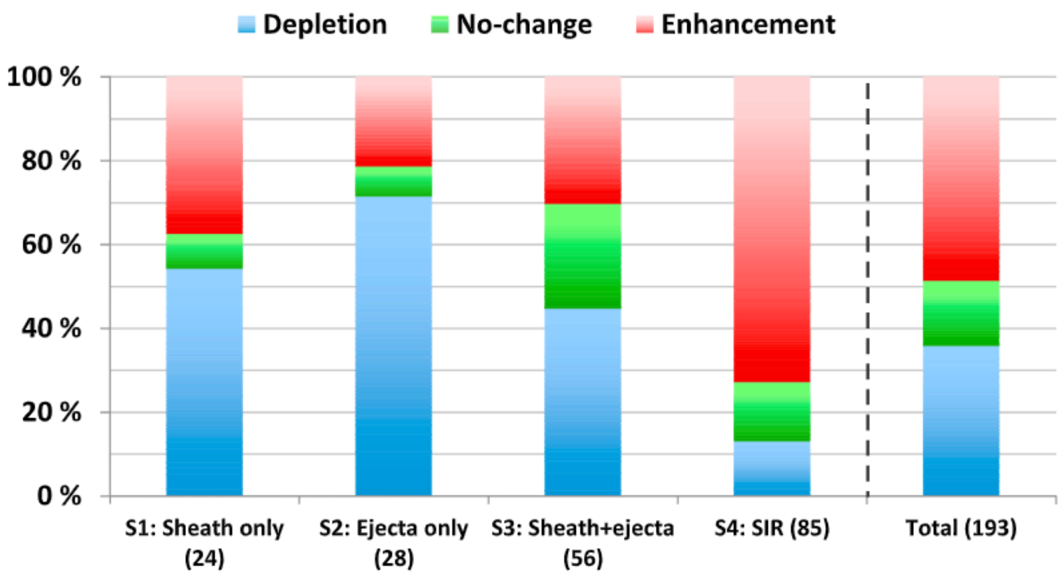
What is the response due to various IP drivers (e.g. ICMEs or SIRs)?

From Kilpua et al. GRL2015



- Depletions during stream interface regions, CME ejecta, and sheath regions, predominantly due to effective magnetopause shadowing.
- Increases occur primarily during fast streams due to prolonged electron injection.

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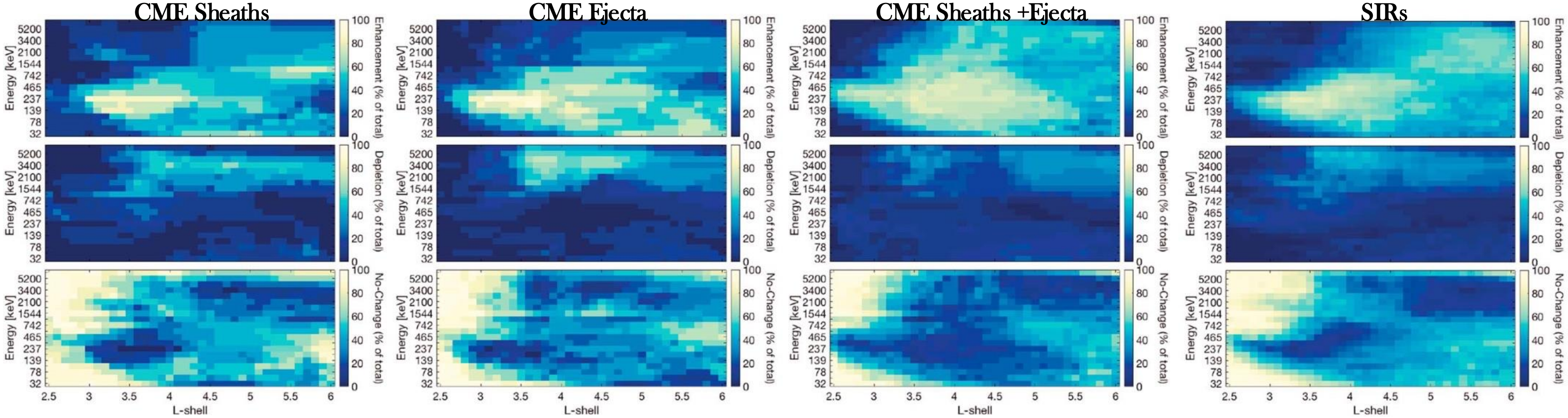
What is the response due to various IP drivers (e.g. ICMEs or SIRs)?

From Turner et al. GRL2019

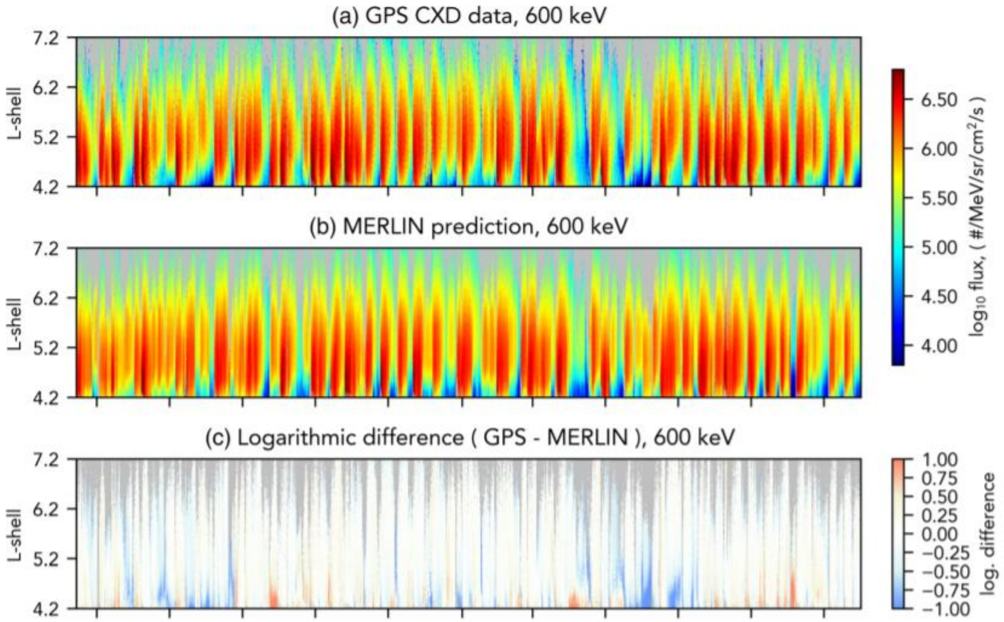


- Full CME storms are especially effective at causing enhancements of multi-MeV electrons at lower L-shells (L < 5)
- SIR-driven storms are especially effective at causing enhancements of multi-MeV electrons at higher L-shells (L > 4.5).

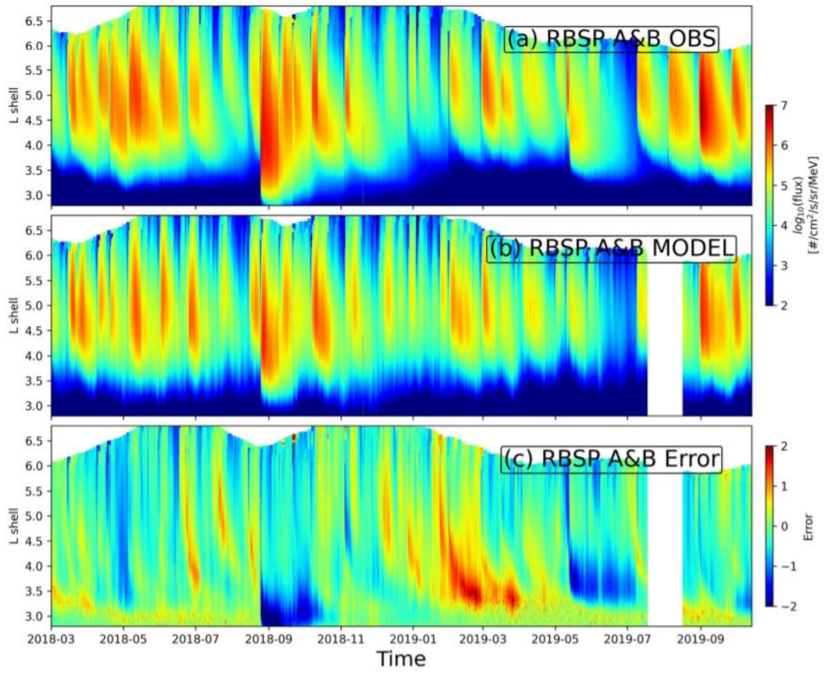
The importance of ML methods in the prediction of RB dynamics

Direct solar wind and geomagnetic inputs reduce the uncertainties introduced by the combination of various physics-based models.

MERLIN *[Smirnov et al. 2020]*
100 < E < 600 keV in MEO orbit



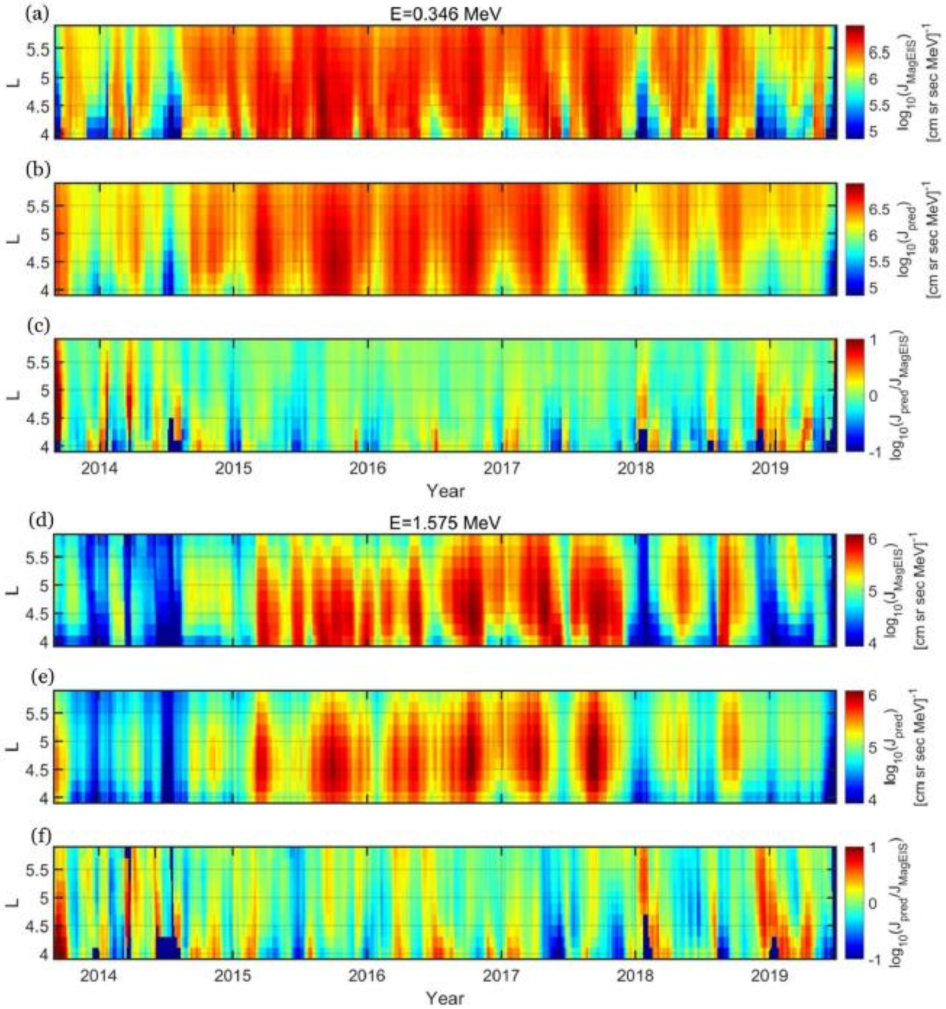
ORIENT-R *[Chu et al. 2021]*
E > 1.8 MeV in GTO orbit



The importance of ML methods in the prediction of RB dynamics

SENTINEL *[Katsavrias et al. 2021]*

- Solar/solar wind inputs only
- L is used as an input (2.5<L<5.9)
- Spectral coherence (0.033 – 4.062 MeV)
- The output provides distribution of fluxes.
- Generalization outside the spatial and temporal training scheme



Contribution of ML methods to physics-based models

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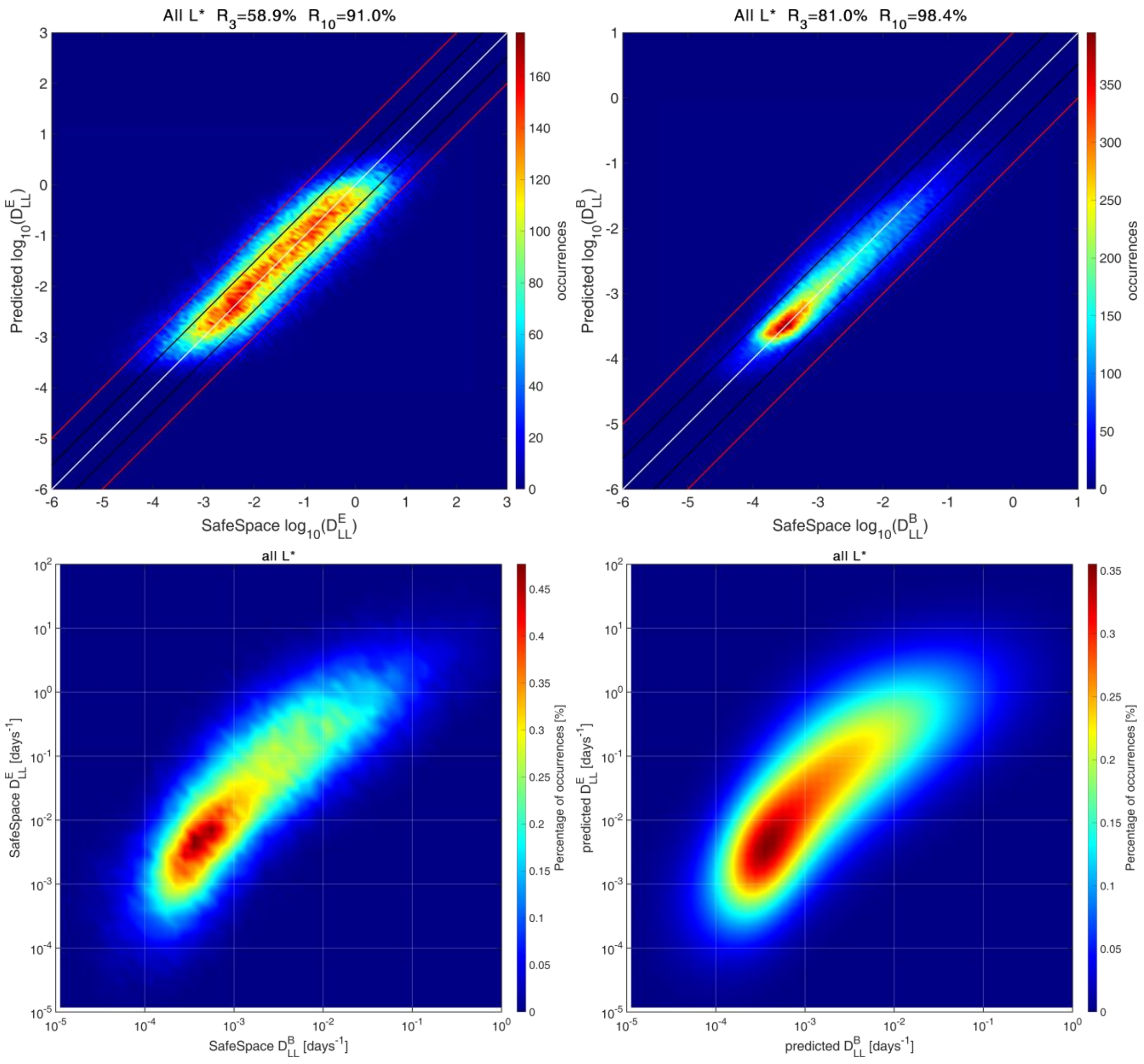
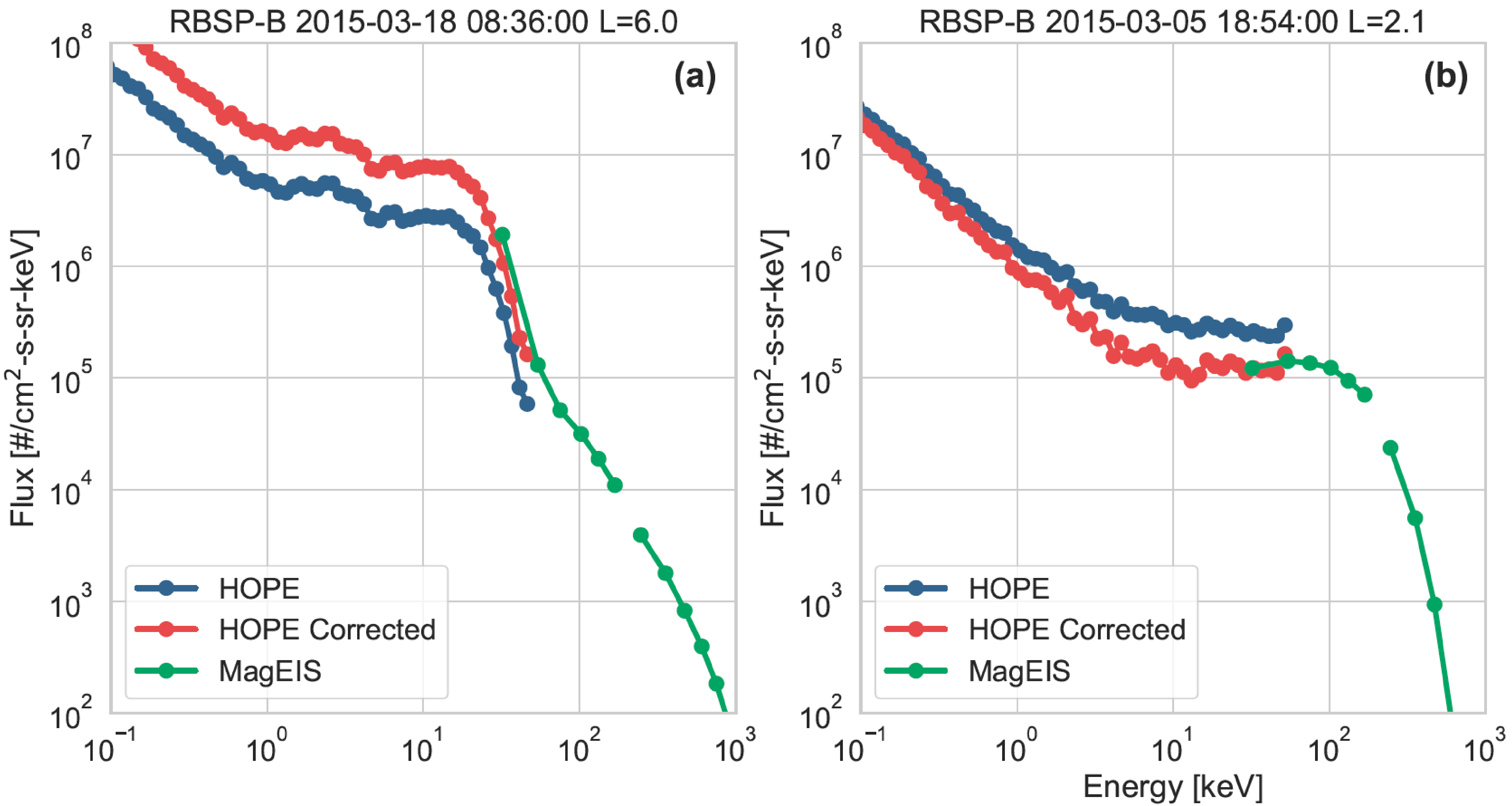
- Prediction of radial diffusion coefficients with significantly increased accuracy compared to semi-empirical models.
- Solar wind inputs only.
- The output provides distribution of D_{LL} using bayesian NN.
- Generalization outside the spatial and temporal training scheme.
- The output preserves the coherency and interdependence between the two components.

RADIAL *[in preparation for the SafeSpace project pipeline]*




RBSP-B 2015-03-18 08:36:00 L=6.0
RBSP-B 2015-03-05 18:54:00 L=2.1
(a)
(b)
Flux [#/cm^2-s-sr-keV]
Energy [keV]
HOPE
HOPE Corrected
MagEIS
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^{-1}
10^0
10^1

PHILOSOPHICAL TRANSACTIONS A

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Review

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http://dx.doi.org/10.1098/rsta.2018.0097

Accepted: 19 March 2019

One contribution of 9 to a theme issue 'Solar eruptions and their space weather impact'.

Subject Areas:
astrophysics, solar system, space exploration

Keywords:
radiation belts, trapped particles, plasma waves, wave–particle interactions, coronal mass ejections, stream interaction regions

From solar sneezing to killer electrons: outer radiation belt response to solar eruptions

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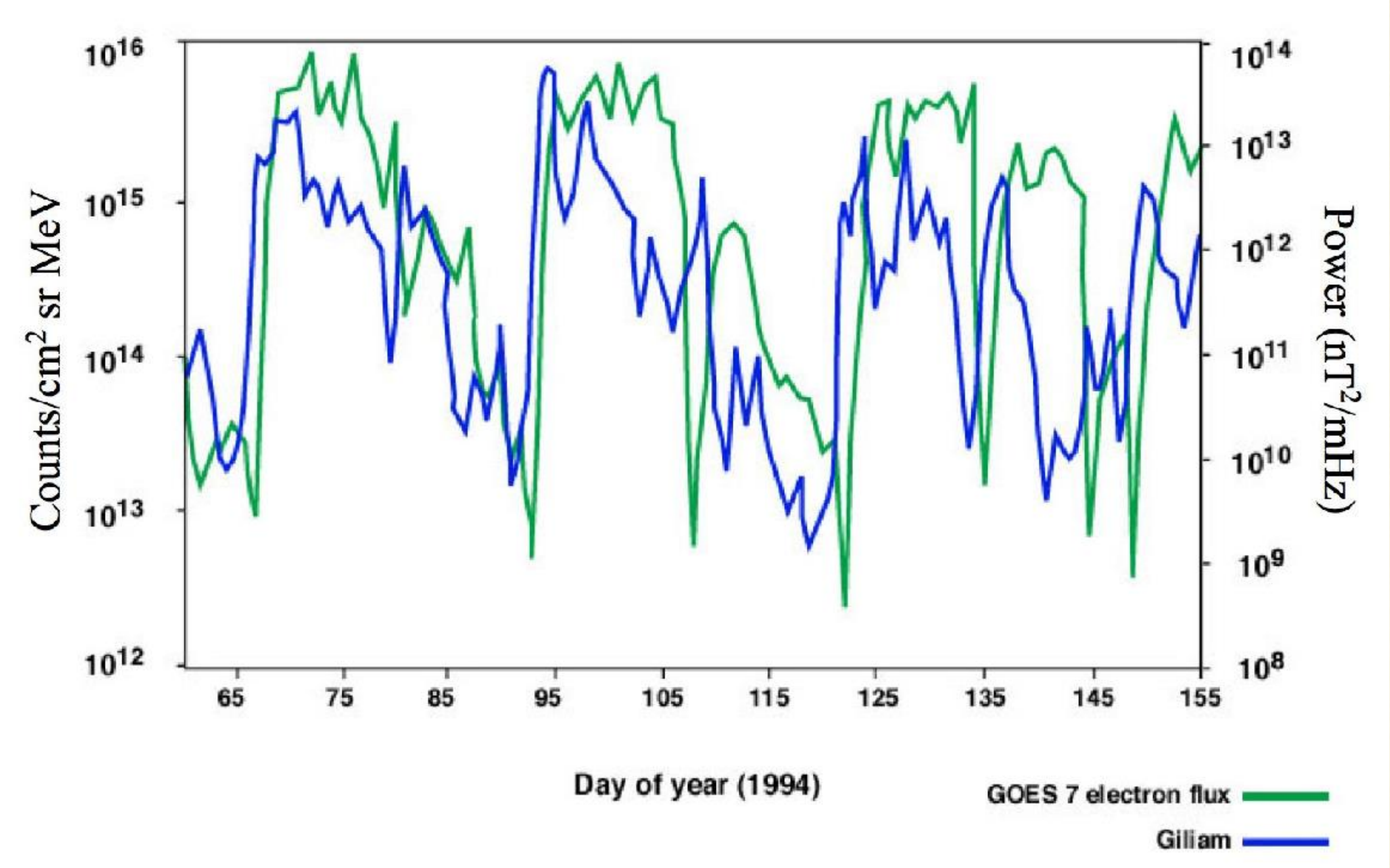
[3]Institute for Astronomy, Astrophysics, Space Applications and Remote Sensing, National Observatory of Athens, 15236 Penteli, Greece
[4]Mullard Space Science Laboratory, Department of Space and Climate Physics, University College London, Dorking RH5 6NT, UK

IAD, 0000-0002-0764-3442

Electrons in the outer Van Allen (radiation) belt occasionally reach relativistic energies, turning them into a potential hazard for spacecraft operating in geospace. Such electrons have secured the reputation of satellite killers and play a prominent role in space weather. The flux of these electrons can vary over time scales of years (related to the solar cycle) to minutes (related to sudden storm commencements). Electric fields and plasma waves are the main factors regulating the electron transport, acceleration and

Pc5 waves – RB connection



Rostoker et al., 1995

Increases in the Pc5 wave power
observed by ground magnetometers match
increases of the relativistic electron flux observed by GOES-7

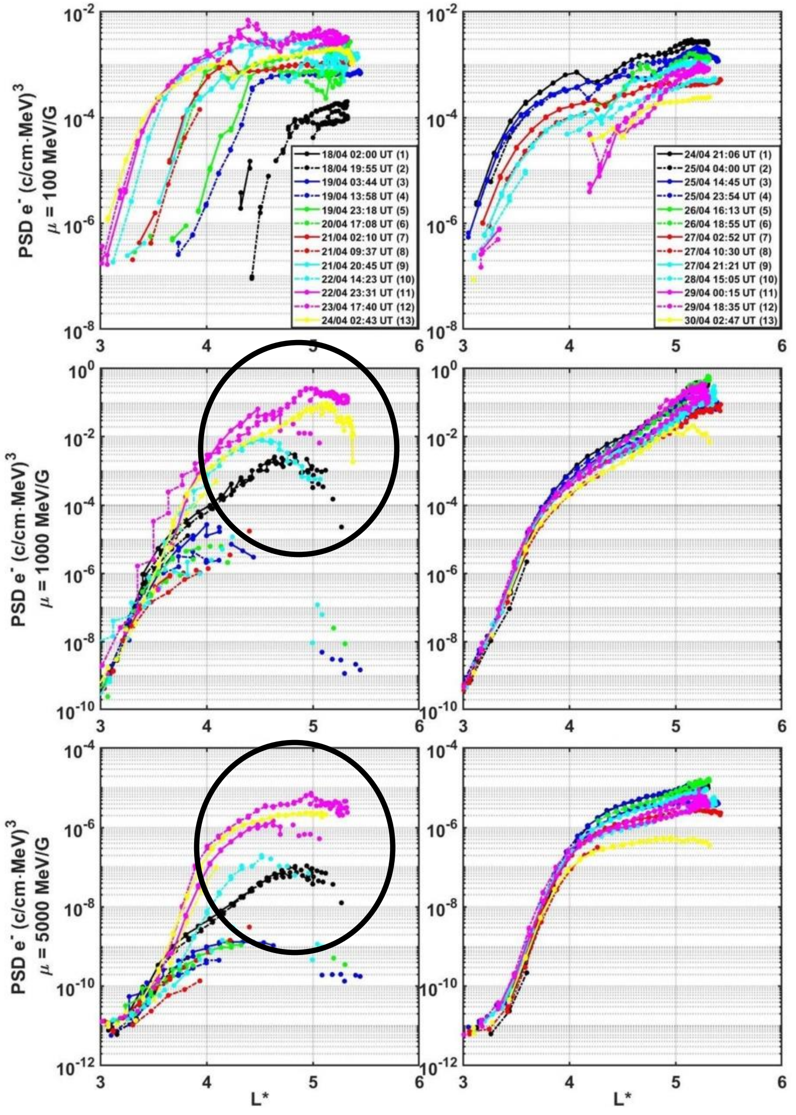
Variability of the Outer Belt - The Key Issues

1. What is the relative contribution of different mechanisms to the acceleration of electrons to relativistic energies (and to their loss)?

2. What is the outer belt response to various IP drivers (ICMEs / SIRs)

3. Is there a level of predictability in radiation belt dynamics?

The relative contribution of Pc5 and chorus waves to electron acceleration during a weak storm

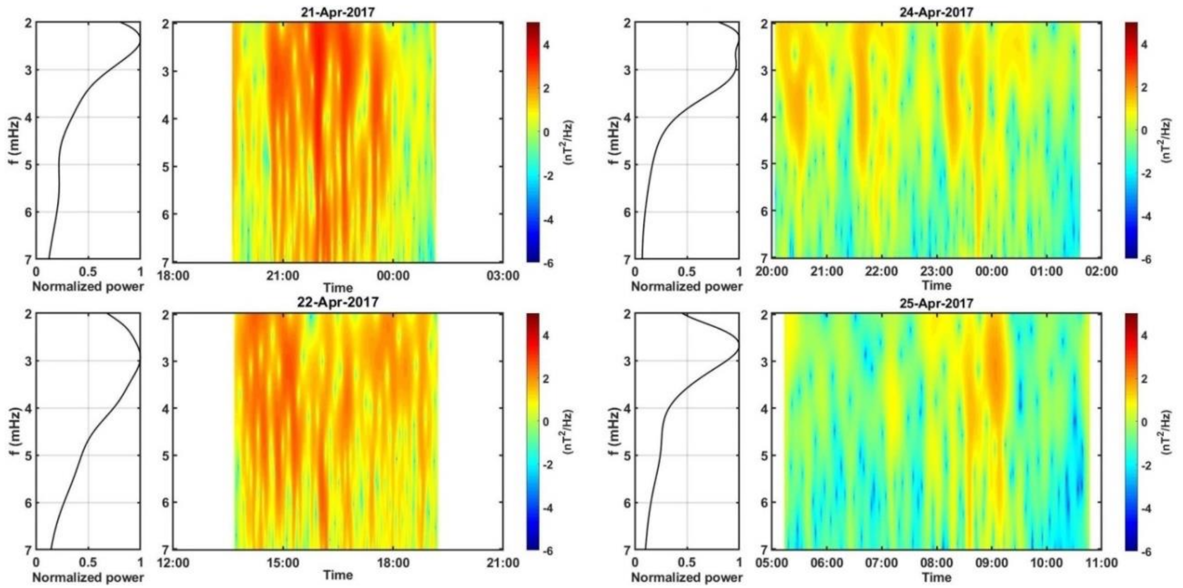


Rising peaks (local heating)

Positive/flat gradients (inward diffusion)

Katsavrias+, JGR2019

The relative contribution of Pc5 and chorus waves in electron acceleration



ω_d of near–equatorially mirroring electrons with μ =1000 MeV/G

$2.3 < \omega_d < 3$ mHz

Power spectral density and global wavelet spectrum of Pc5 waves (Katsavrias+, JGR2019)

Two plus one step acceleration?

2 - step acceleration scenario:

I. Intense substorms $\rightarrow$ enhancement of source and seed electrons, source electrons lead to chorus
II. Local heating (via chorus waves) $\rightarrow$ enhancement of relativistic electrons

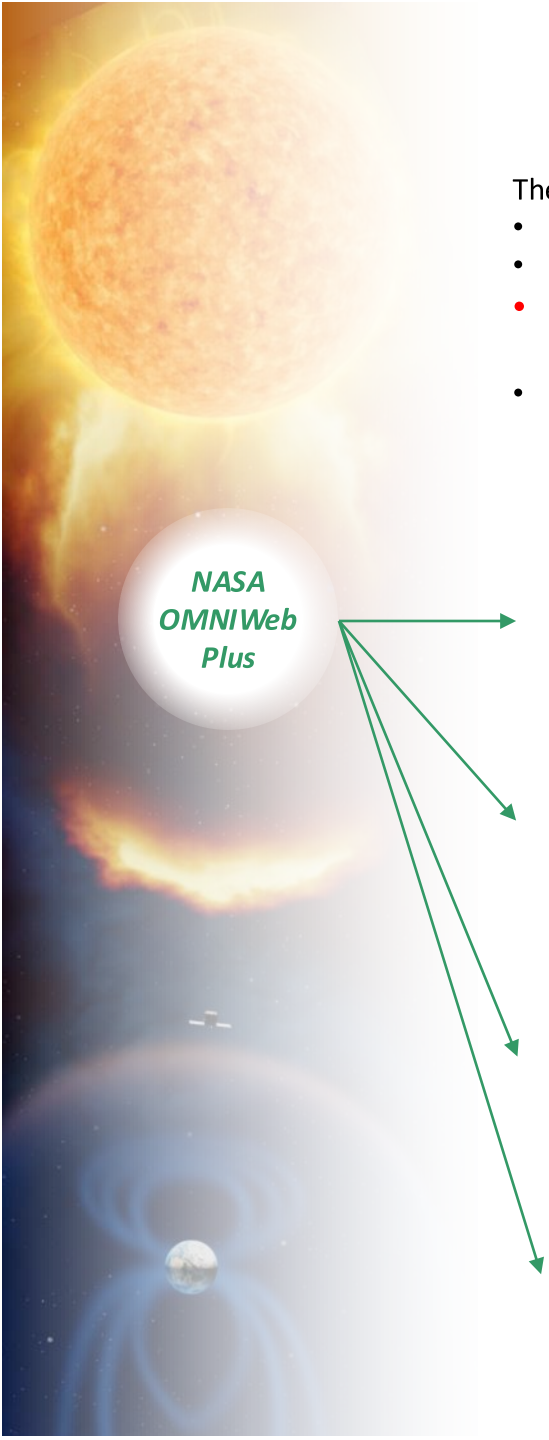
3 - step acceleration scenario:

I. Intense substorms → enhancement of source and seed electrons, source electrons lead to chorus
II. Local heating (via chorus waves) → enhancement of relativistic electrons
III. Inward diffusion (via Pc5 waves) → enhancement of ultra-relativistic electrons

4 - step acceleration scenario:

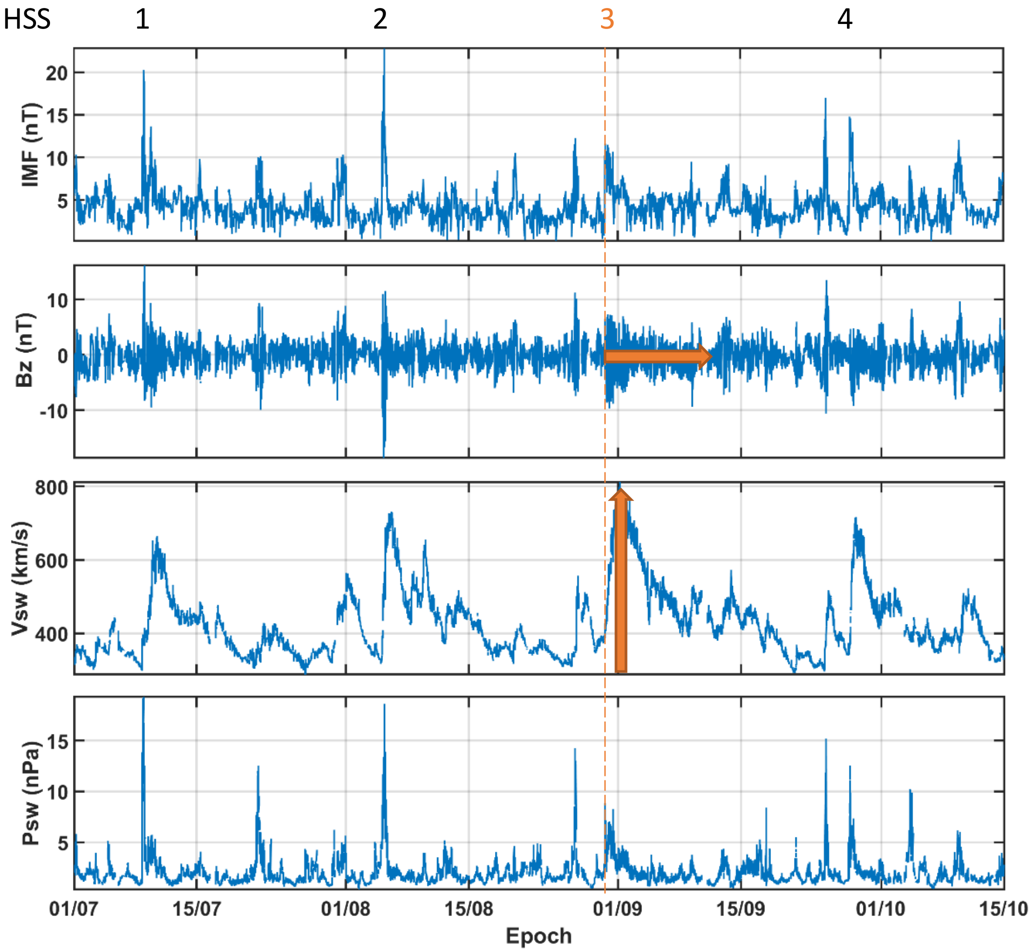
I. Intense substorms → enhancement of source and seed electrons, source electrons lead to chorus
II. Local heating (via chorus waves) → enhancement of relativistic electrons
III. Inward diffusion (via Pc5 waves) → enhancement of ultra-relativistic electrons
IV. Energy diffusion enhancement (due to decrease in electron density) → Further acceleration via gyro-resonant interactions

Solar Wind Parameters



The third HSS pulse exhibited:

- Lower IMF maximum values, but prolonged enhancement.
- Small but **quite prolonged negative Bz values** (southward IMF)
- The **greatest Vsw maximum value, reaching 800 km/s**, and longer-lasting high-Vsw values, reaching over 600 km/s for nearly four days.
- Lower Psw maximum value, but longer-lasting enhancement.



IMF, Bz, Vsw, Psw acquired from NASA OMNIWEB database.

Introduction
Event & Data selection
Solar Wind parameters
Geomagnetic & Magnetospheric parameters
ULF & VLF wave parameters
Electron flux
Seed e (< 0.5 MeV)
Relativistic e (1-2 MeV)
Ultra-relativistic e (> 4 MeV)
Electron Phase Space Density (PSD)
Conclusions
References

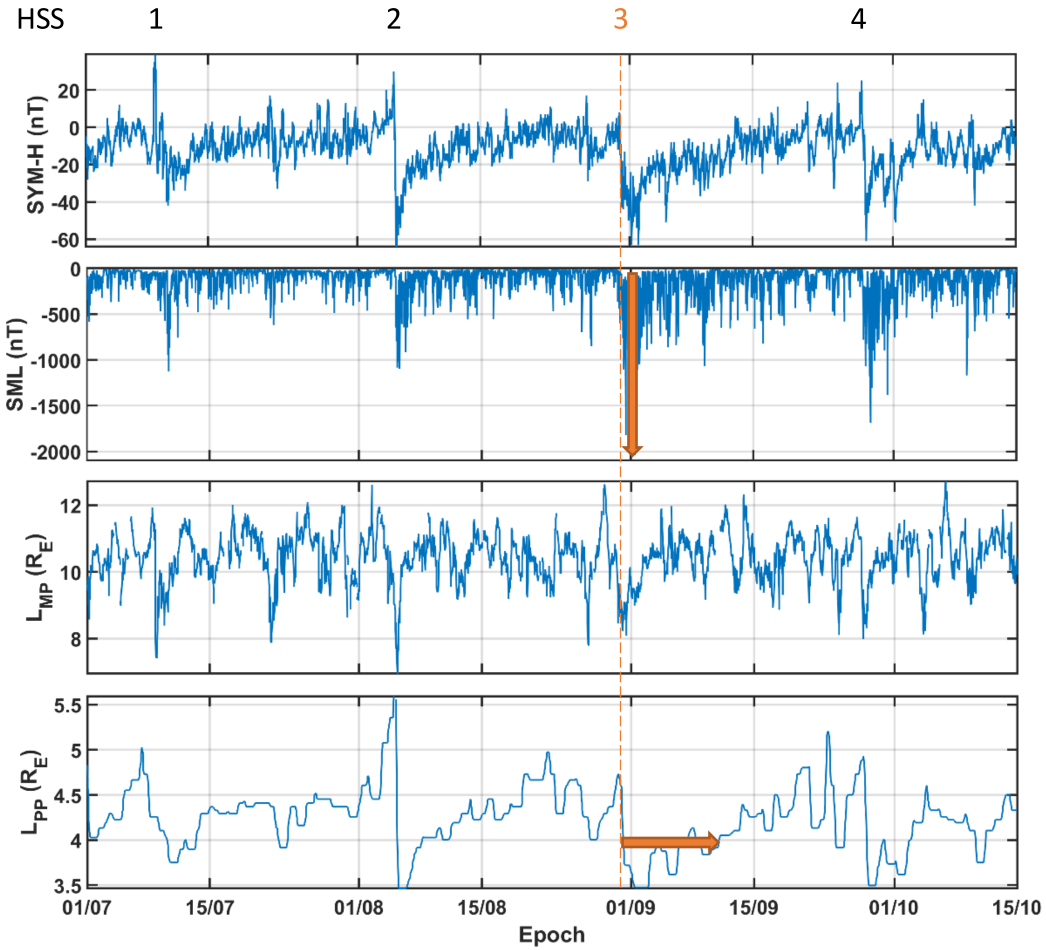
Magnetospheric parameters

The third HSS pulse exhibited:

- Comparable SYM-H values and duration, indicating relatively moderate geomagnetic storm activity.
- **Extremely low values of SML index, reaching -2000 nT**, indicating **intense and prolonged substorm activity**.
- Comparable but more prolonged dayside magnetopause compression.
- **Significantly prolonged plasmapause compression**, reaching L < 4 R_E for nearly 10 days.

NASA OMNIWeb Plus

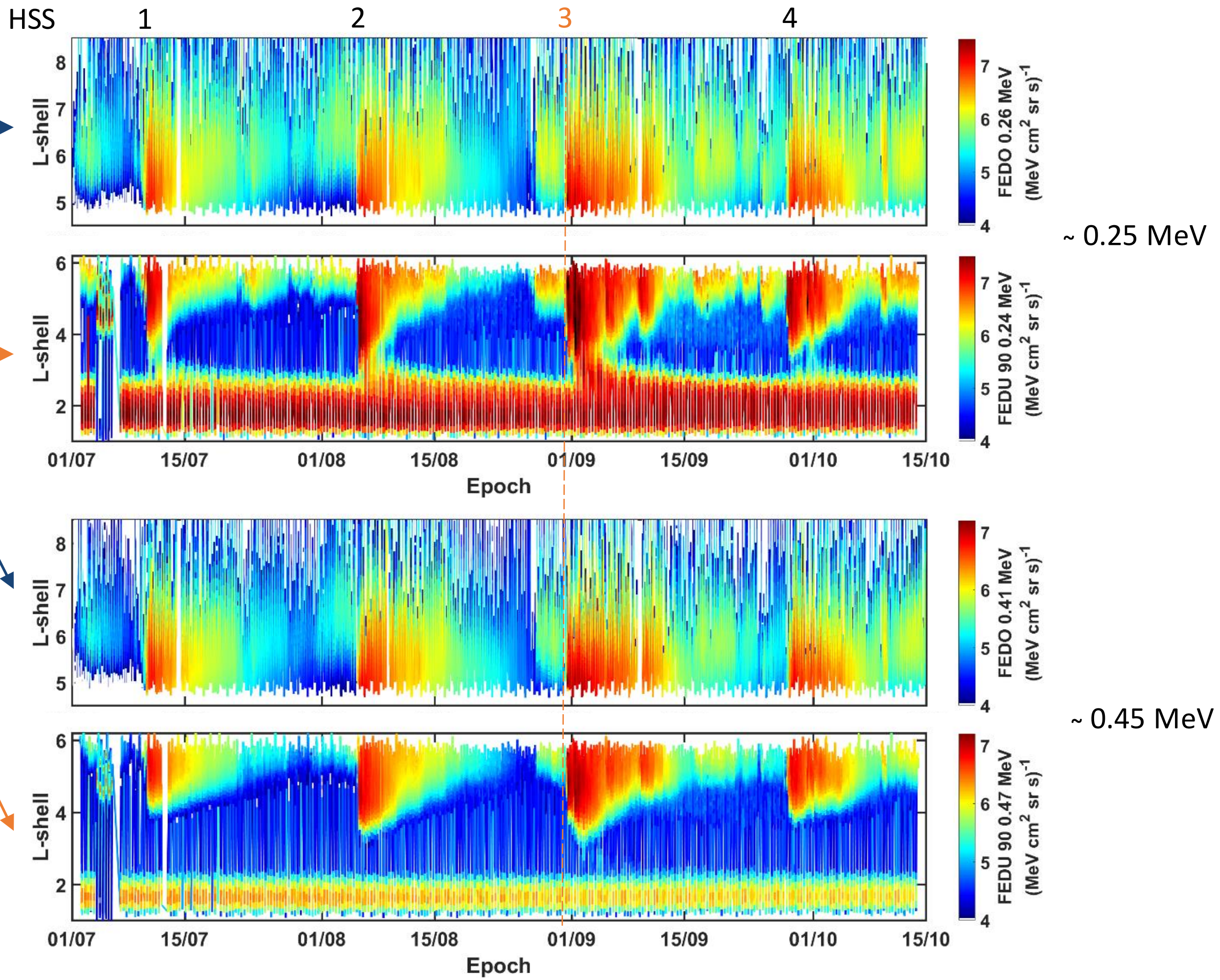
SuperMAG



SYM-H acquired from NASA OMNIWEB database.
SML acquired from SUPERMAG (similar to AL).
L_{MP} is MLT-averaged dayside magnetopause location, following Shue et al. (1998) model.
L_{PP} is MLT-averaged plasmapause location, following O'Brien & Moldwin (2003) model.

Flux intensity of seed electrons (< 0.5 MeV)

All four HSS pulses were followed by seed electron enhancements.
After the third HSS pulse we observe
more intense and persistent enhancement of seed electrons.
We notice that lower energy electrons appear earlier and have more intense enhancements.



FEDO are omni-directional Galileo fluxes from SEM unit. L-shell provided by Galileo ephemeris, corresponding to quiet-time conditions.

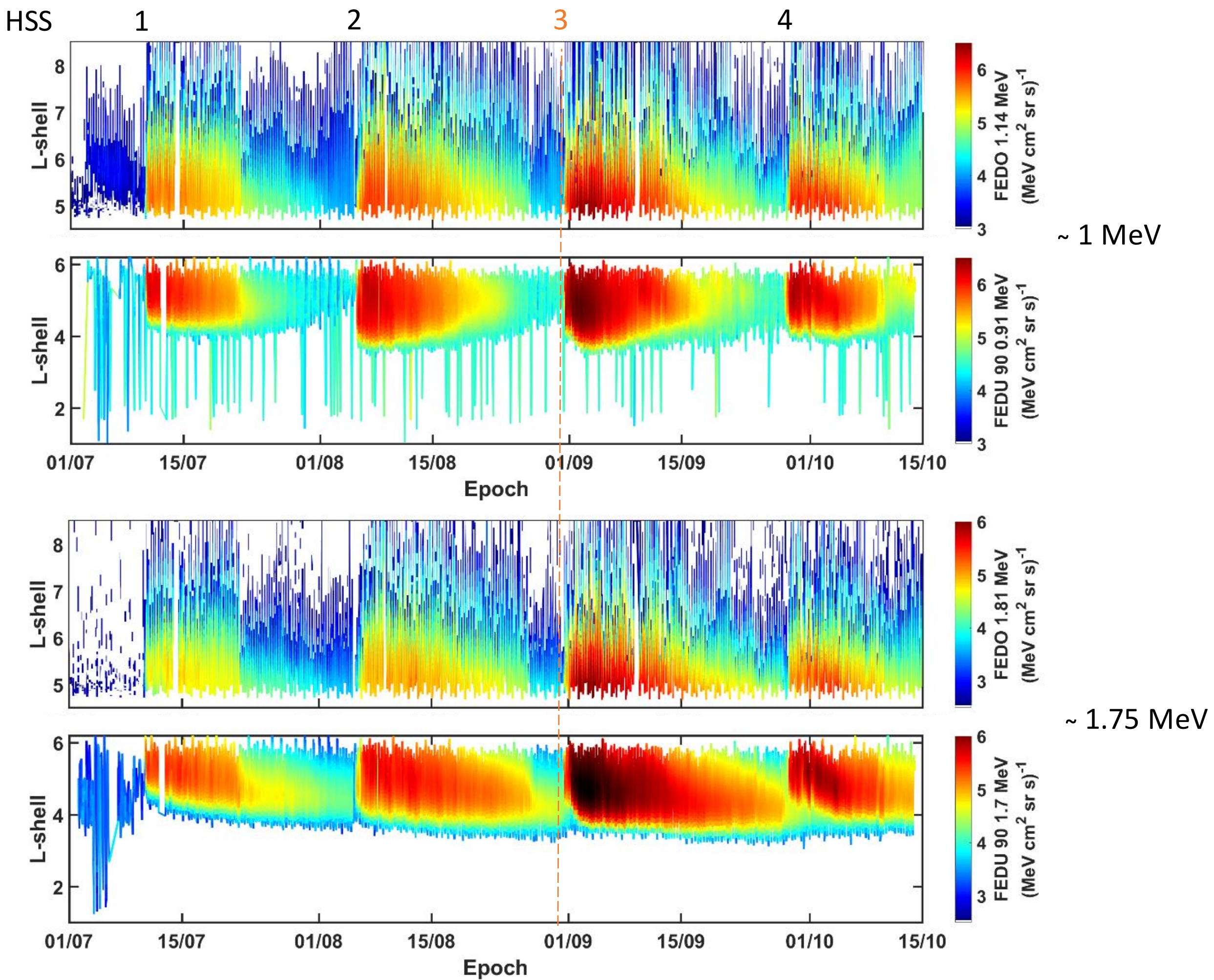
FEDU 90 are RBSP-A L3 fluxes from MagEIS unit, plotted here only for 90º pitch angle. L-shell calculated via TS04 model.

Flux intensity of relativistic electrons (1-2 MeV)

All four HSS pulses exhibited relativistic electron enhancements.
The third HSS pulse exhibited:

- More intense enhancement of relativistic electrons, which was also more long-lasting.
- An extreme enhancement of relativistic electrons of > 1 MeV, lasting until the arrival of the next HSS.

We notice that relativistic electrons appear more inward with increasing energy.



FEDO are omni-directional Galileo fluxes from SEM unit. L-shell provided by Galileo ephemeris, corresponding to quiet-time conditions.

FEDU 90 are RBSP-A L3 fluxes from MagEIS unit, plotted here only for 90° pitch angle. L-shell calculated via TS04 model.

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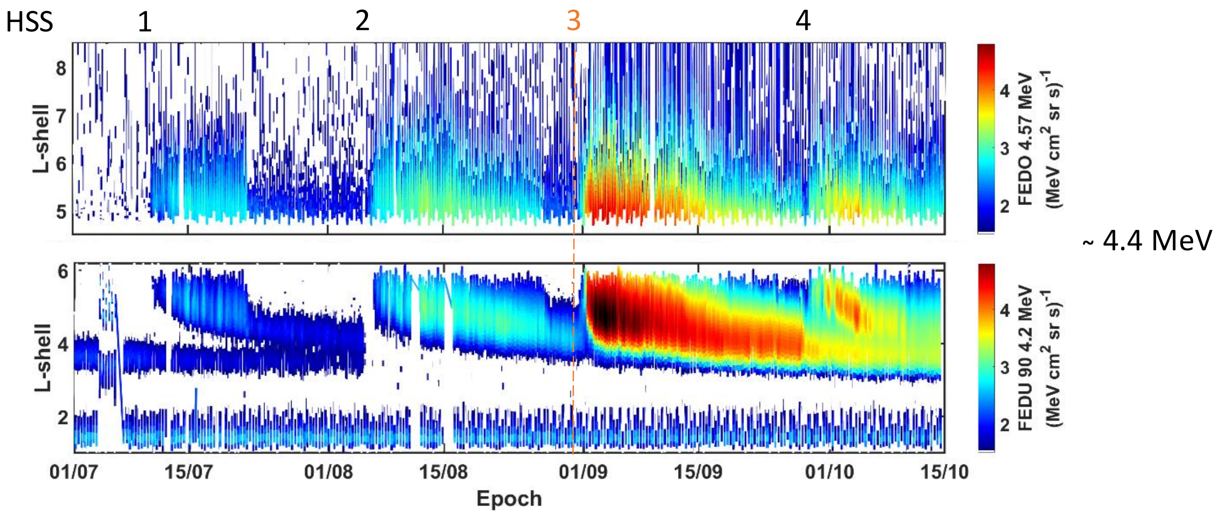
Ultra-relativistic e (> 4 MeV)
Electron Phase Space Density (PSD)
Conclusions
References

Flux intensity of ultra-relativistic electrons (> 4 MeV)

All four HSS pulses exhibited subtle relativistic electron enhancements.
The third HSS pulse exhibited:

- The most intense enhancement of ultra-relativistic electrons, which also lasted until the next HSS arrival.

This is the most prominent difference of the September HSS electron behaviour compared to the rest of this studied event.



FEDO are omni-directional Galileo fluxes from SEM unit. L-shell provided by Galileo ephemeris, corresponding to quiet-time conditions.

FEDU 90 are RBSP-A L3 fluxes from REPT unit, plotted here only for 90º pitch angle. L-shell calculated via TS04 model.