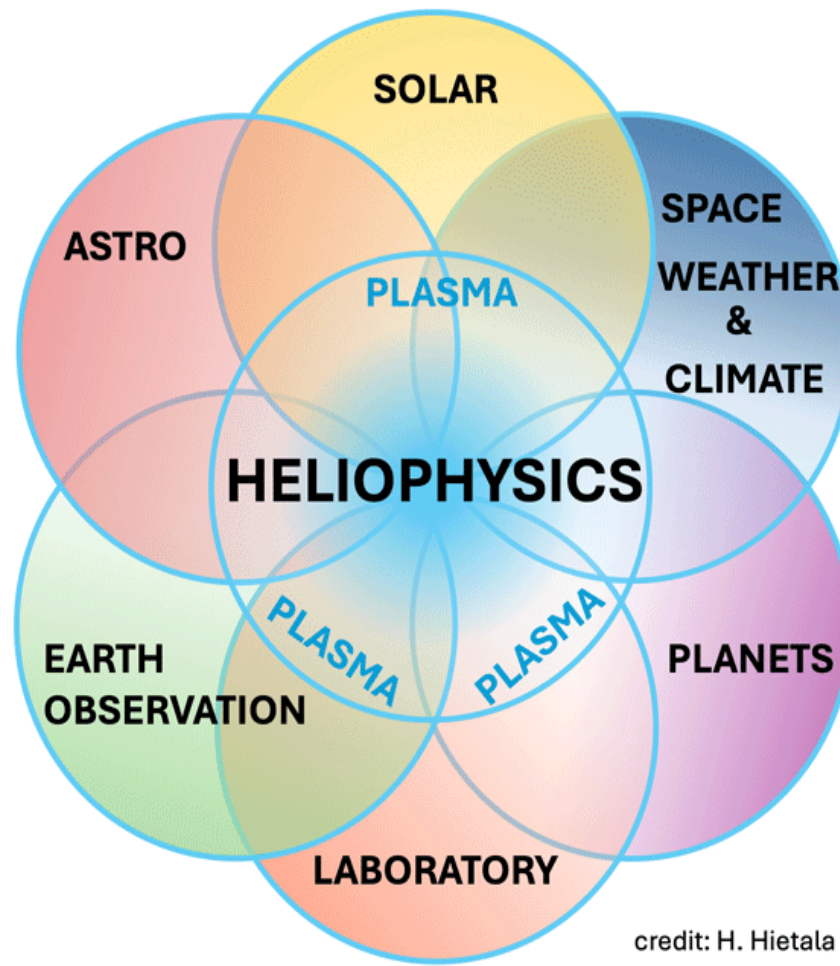


Επιτάχυνση φορτισμένων σωματιδίων στο γεωδιάστημα
ως αποτέλεσμα της γεωηλιακής σύζευξης
και επιπτώσεις σε διαστημικά συστήματα

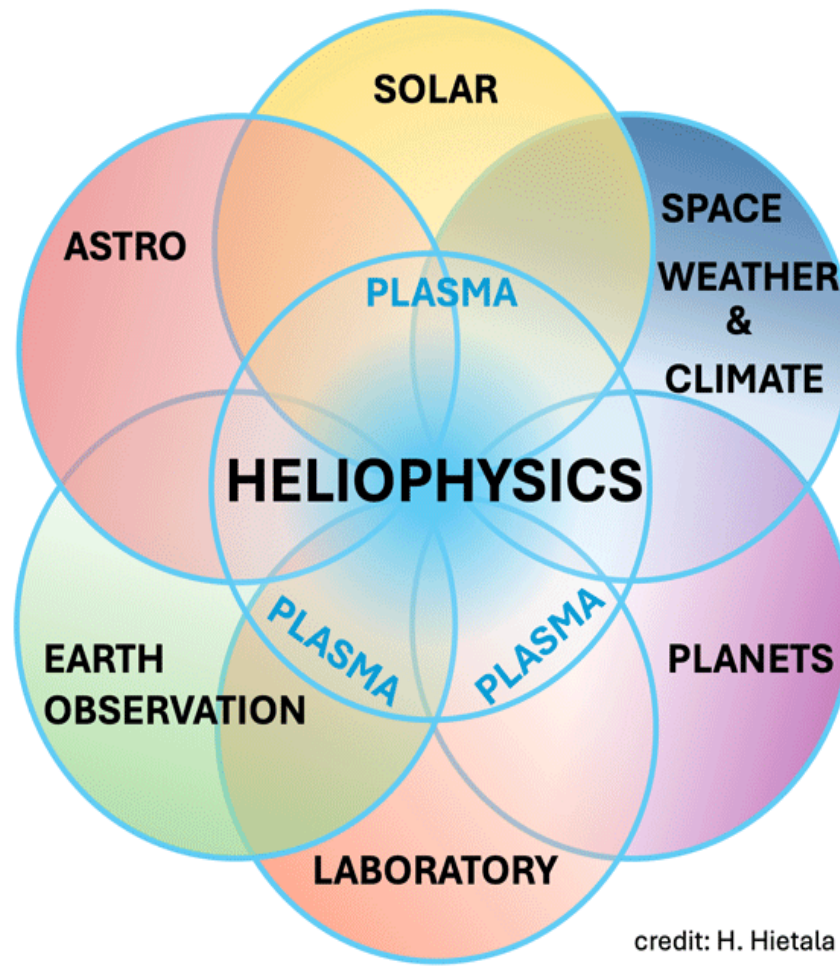
Γιάννης Δαγκλής

Department of Physics, National & Kapodistrian University of Athens





credit: H. Hietala



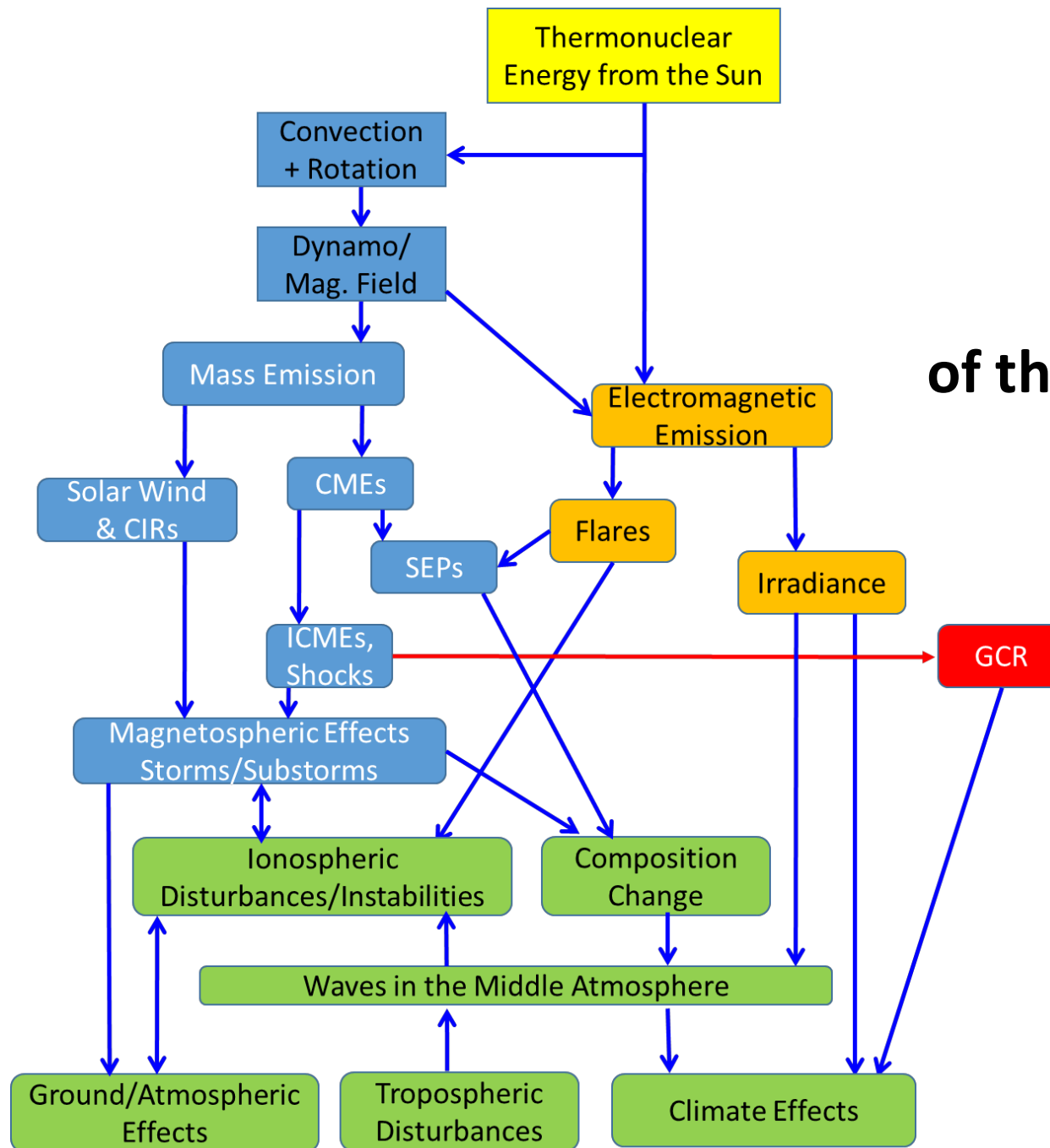
credit: H. Hietala

... because in the beginning was the plasma

Hannes Alfven

Nobel Prize in Physics 1970

and starlight is created by plasma

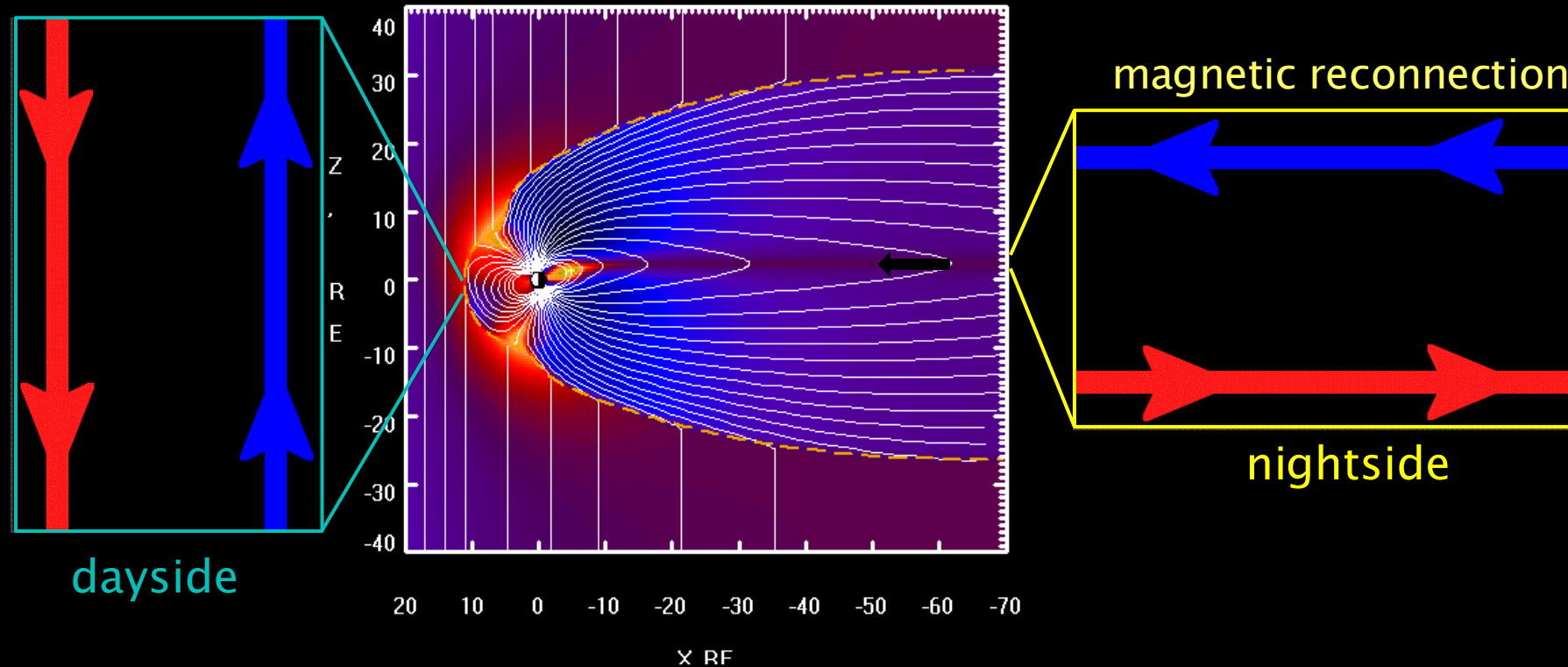


**The many different paths
of the influence of a variable star
on a magnetized planet**

The Earth's space environment is buffeted by the dynamic solar wind,
which drives space weather

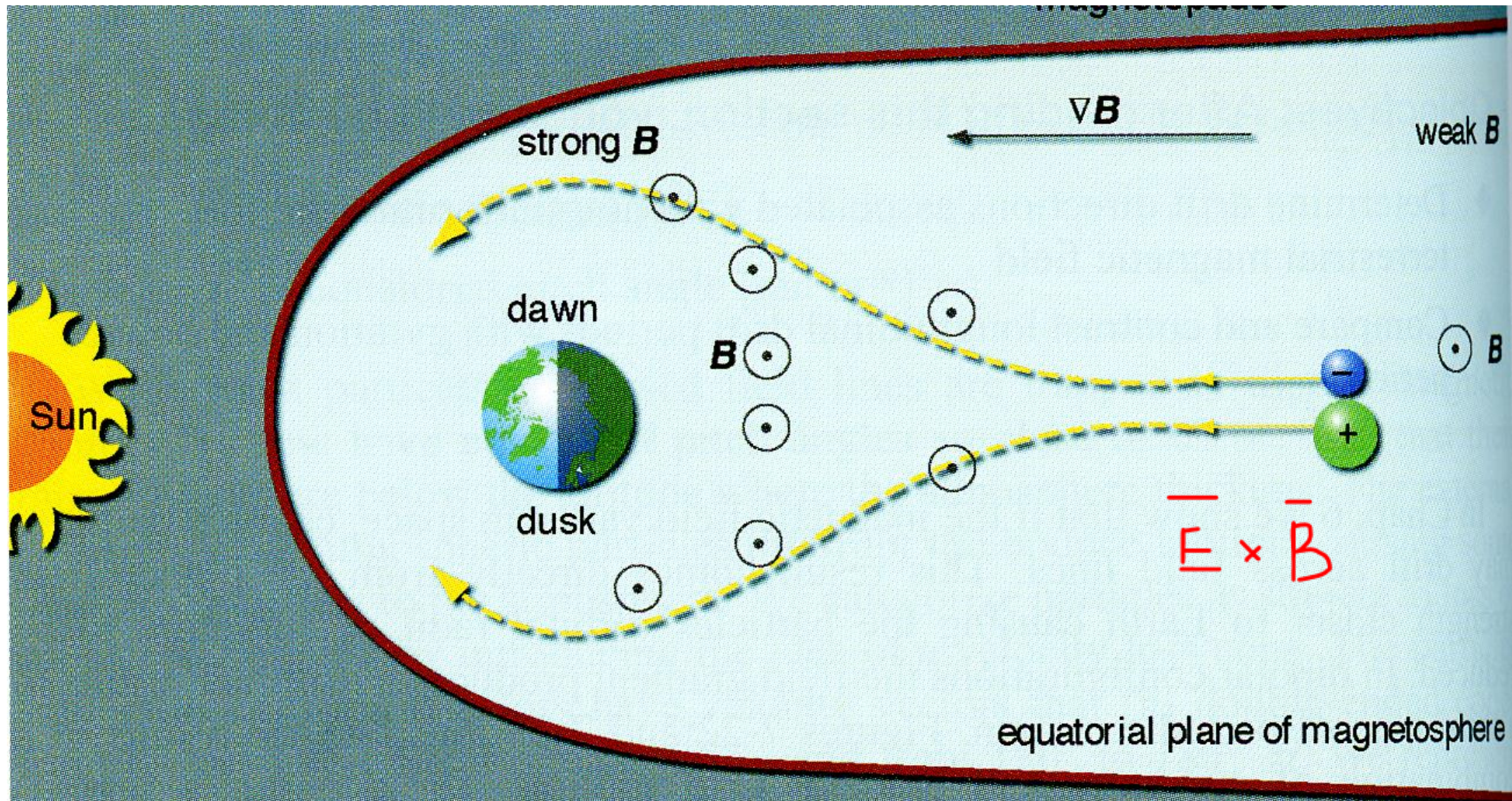


Main mechanism of penetration of solar wind energy

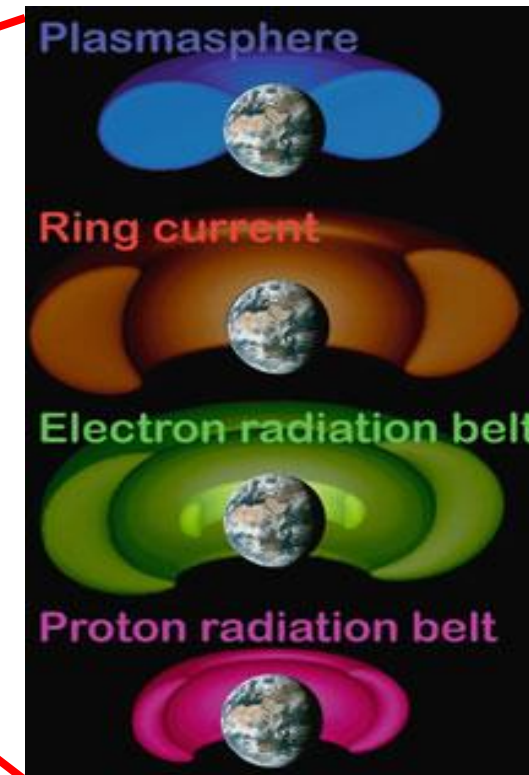
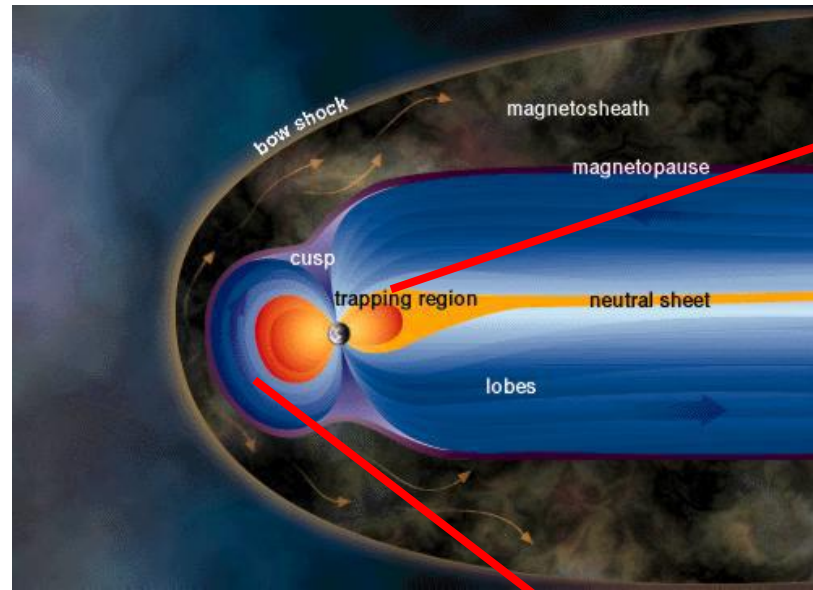


- About 10% of solar wind energy ($\sim 1 \text{ PJ/hr}$) enters the magnetosphere due to **magnetic reconnection**, stripping away flux tubes at dayside.
- Nightside reconnection then jets plasma toward Earth
- $1 \text{ PJ} = 10^{15} \text{ J} = 280 \text{ GWh}$ – approx. 2 days of electrical energy consumption in Greece

Charged particles transport into inner magnetosphere



Geospace: Highly dynamic and “rich”, complex **system of systems**, comprising an internally generated magnetic field and several distinct charged particle populations (with energies spanning **9 orders of magnitude**), which can form current systems and thus alter the magnetic configuration (**ring current** => **magnetic storms**), which in turn influences particles. Moreover, particle distribution anisotropies drive plasma waves, which in turn influence particles.



ions and electrons
($E \sim \text{eV}$)

ions and electrons
($1 < E < 500 \text{ keV}$)

energetic trapped
electrons
($0.5 < E < 20 \text{ MeV}$)

high-energy protons
($1 < E < 200 \text{ MeV}$)



HELLENIC REPUBLIC

National and Kapodistrian
University of Athens

— EST. 1837 —

From Ebihara and Miyoshi, 2011

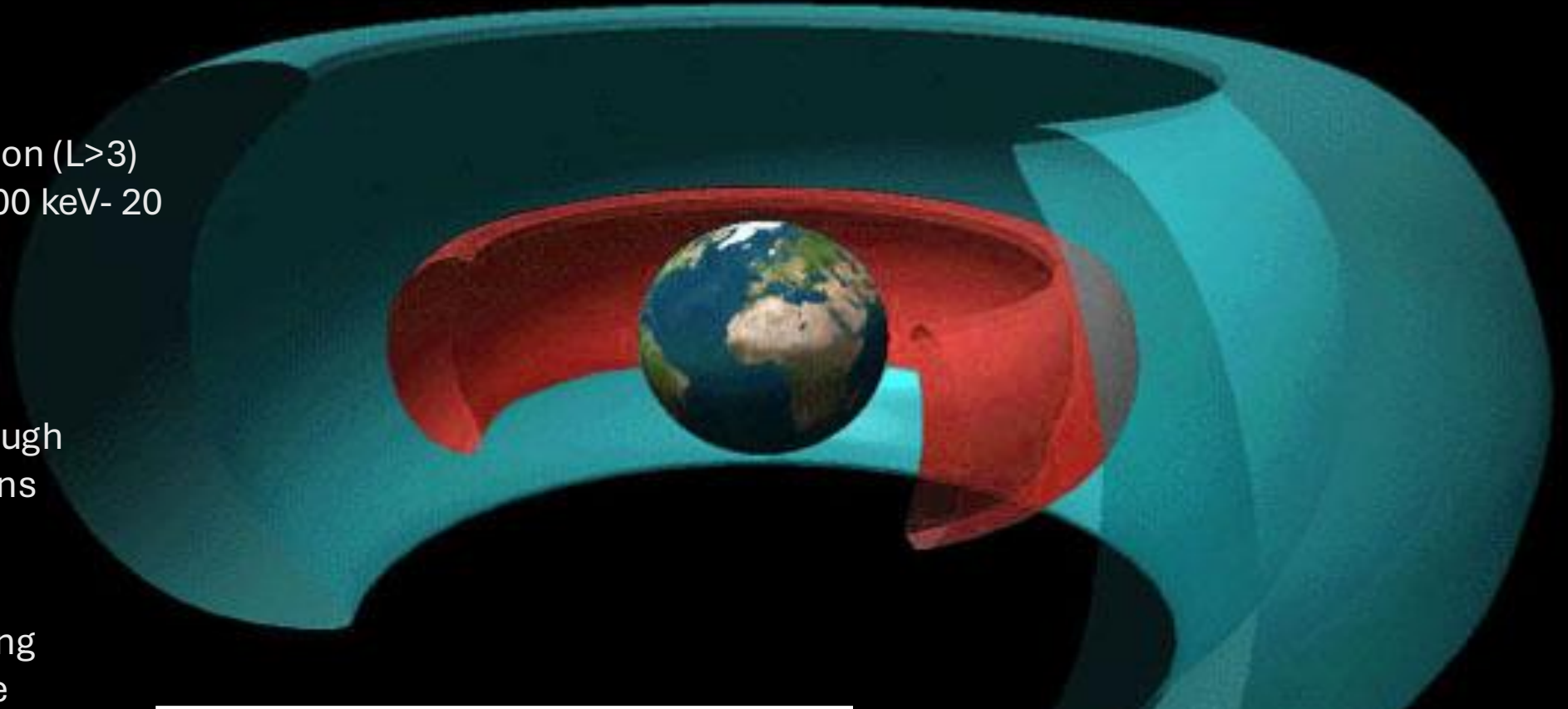
Van Allen (radiation) belts

Inner belt: stable population ($\sim 1.2 < L < 2$)
High-energy protons- CRAND/SEPs
(100 keV- 200 MeV)
Energetic electrons

Outer belt: dynamic population ($L > 3$)
Relativistic electrons (500 keV- 20 MeV)

Acceleration mechanisms:
Radial diffusion
In-situ acceleration through
wave-particle interactions

Loss mechanisms:
Magnetopause shadowing
Precipitation through the
bounce loss cone (wave-
particle interactions - pitch
angle scattering)



Relatively stable **inner belt**
mostly high-energy protons
Sources: CRAND protons
SEP events

Dynamic **outer belt**
mostly relativistic electrons
Sources: Magnetotail electrons

Ring current

Dynamic population of
energetic ions and electrons
(1-500 keV)

Drives geospace magnetic storms

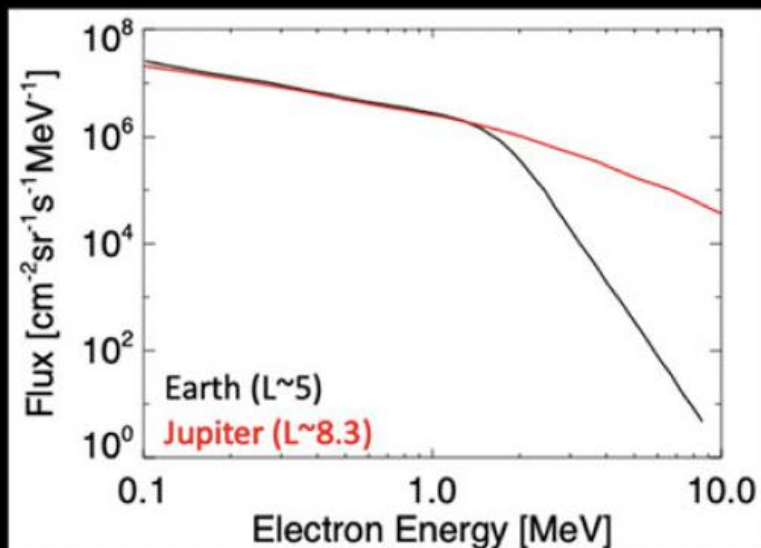
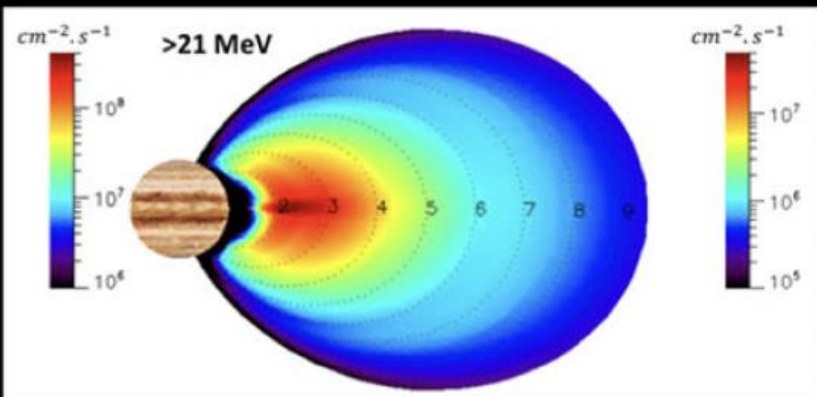


Ring current

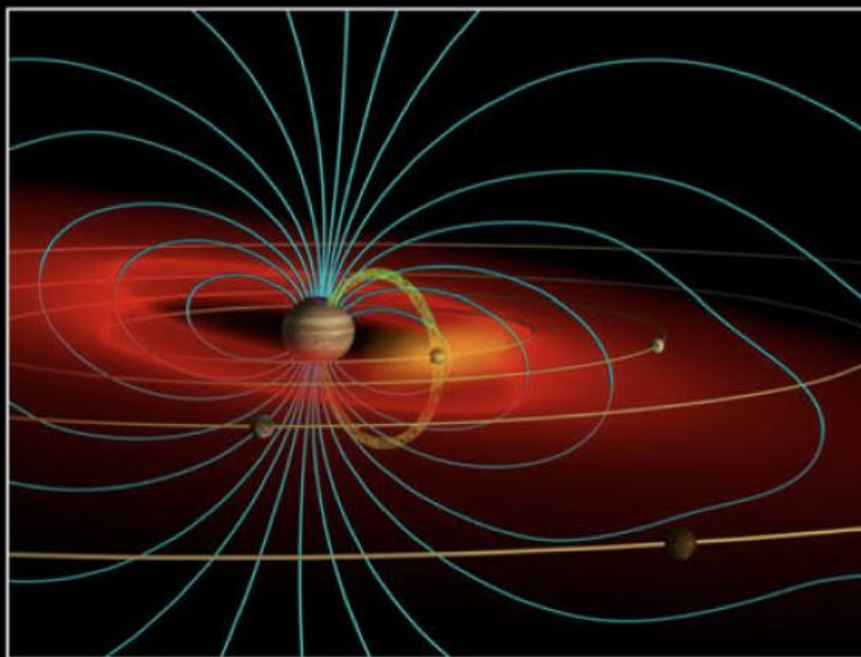
co-located with outer Van Allen belt

Sources: Solar wind, Earth's ionosphere

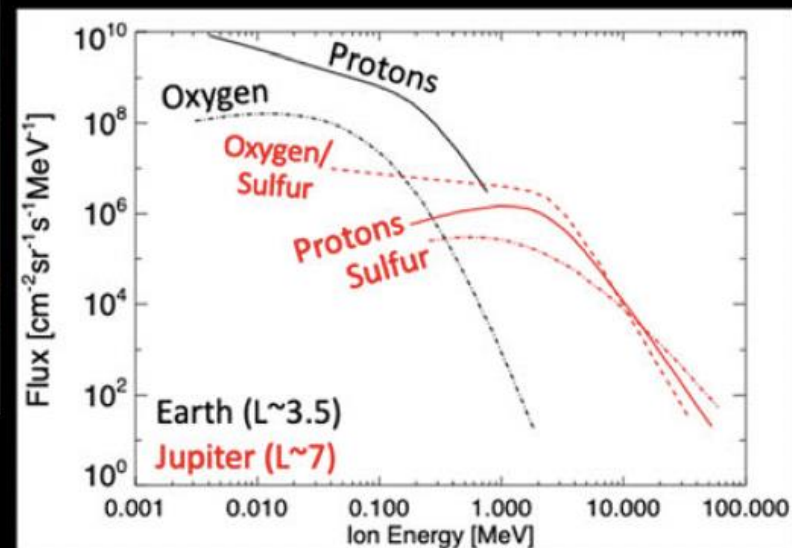
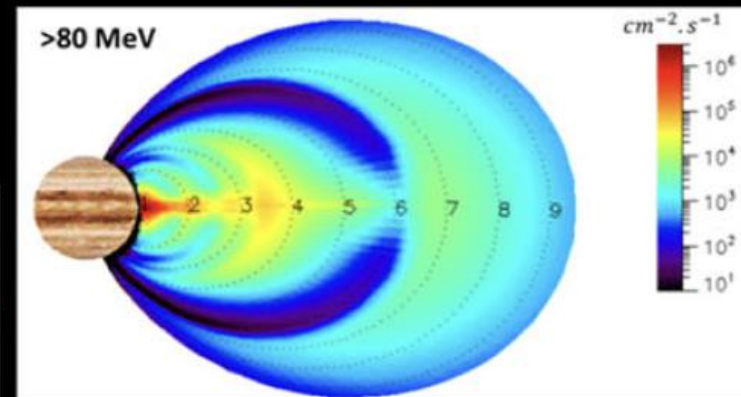
ELECTRON RADIATION BELTS



JUPITER'S INNER MAGNETOSPHERE



PROTON RADIATION BELTS

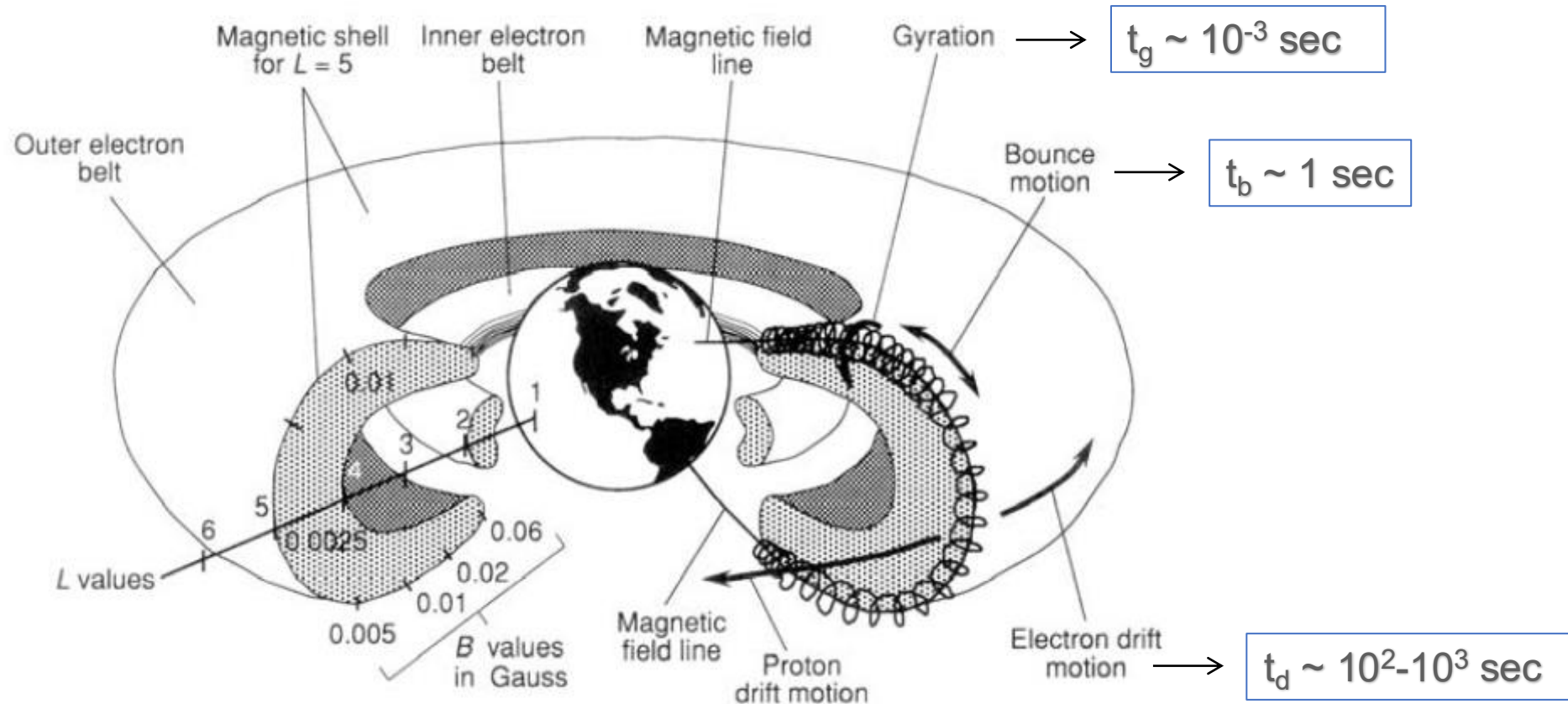


Motion of outer belt electrons and adiabatic invariants (action integrals)

$$\mu = \frac{P^2 \sin^2 \alpha}{2m_0 B}$$

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

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



The evolution of relativistic electron flux in the outer Van Allen belt,
i.e., the net **loss** or net **enhancement**,
is the result of a complex delicate balance
of **cross-scale processes** involving
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 (e^- gyroradius)

Time scale: milliseconds to seconds

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Time scale: seconds to minutes

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Time scale: milliseconds to seconds

Mesoscale processes:

Spatial scale: tens to hundreds of kilometers (ion gyroradius)

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

- Global-scale (macroscale) processes:

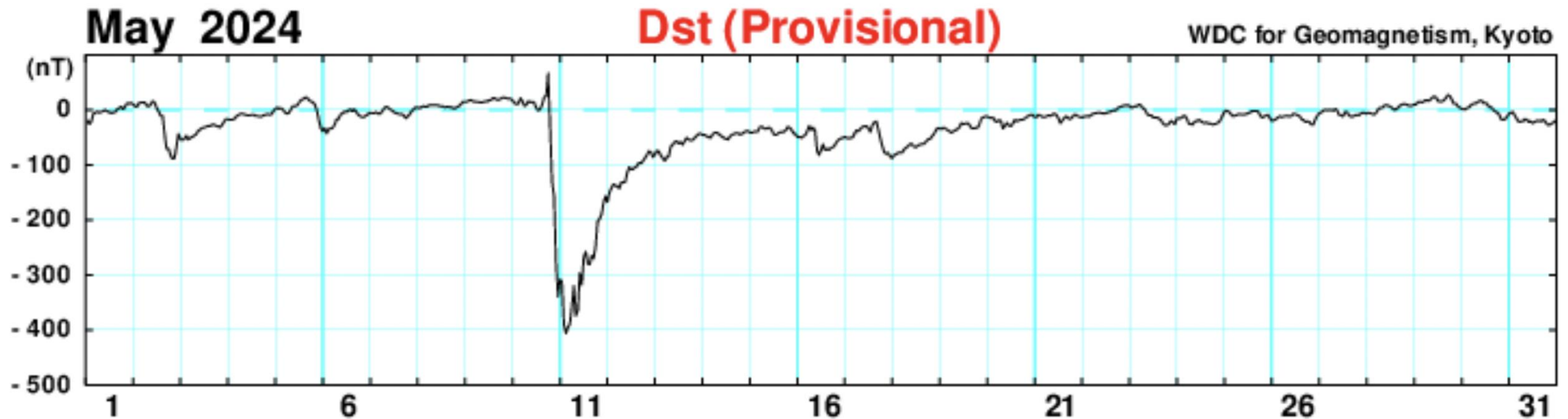
Magnetopause shadowing losses

Magnetospheric convection, leading to **magnetic storms**

- Global-scale (macroscale) processes:

Magnetopause shadowing losses

Magnetospheric convection, leading to **magnetic storms**



- Global-scale (macroscale) processes:

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Magnetospheric convection, leading to magnetic storms

- Mesoscale processes:

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

- Global-scale (macroscale) processes:

Magnetopause shadowing losses

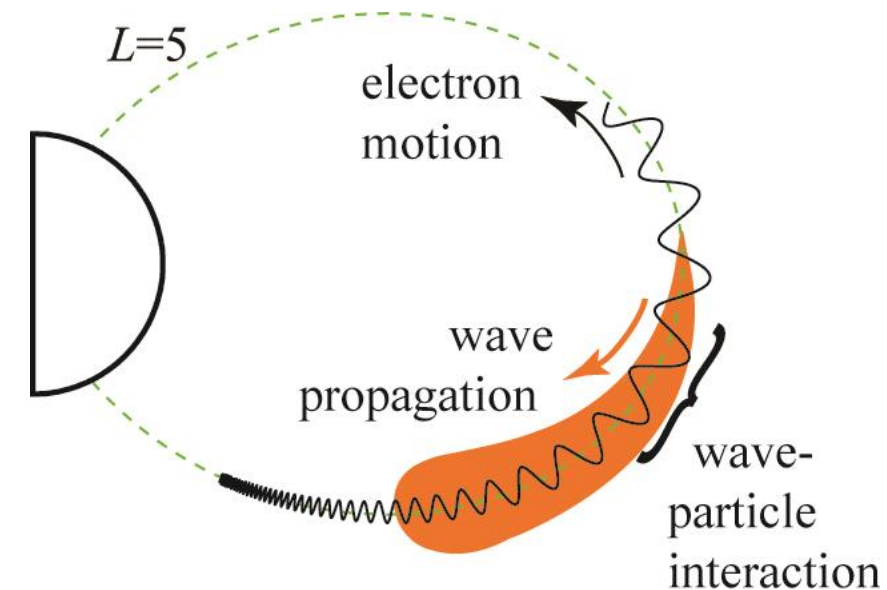
Magnetospheric convection, leading to magnetic storms

- 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



1 – 5 MeV electron at $L^* = 4.5$

Gyro-motion	0.1-1 <i>ms</i>	1 – 10 <i>kHz</i>
Bounce motion	0.5-1.5 <i>s</i>	1 <i>Hz</i>
Drift motion	2-10 <i>min</i>	1-8 <i>mHz</i>

(1) Magnetic moment

$$\mu = \frac{p_{\perp}}{2mB} \left[\frac{MeV}{G} \right]$$

(2) Longitudinal invariant

$$K = \int_{s_m}^{s_{m'}} [B_m - B(s)] ds$$

Kaufmann (1965)

(3) Total magnetic flux

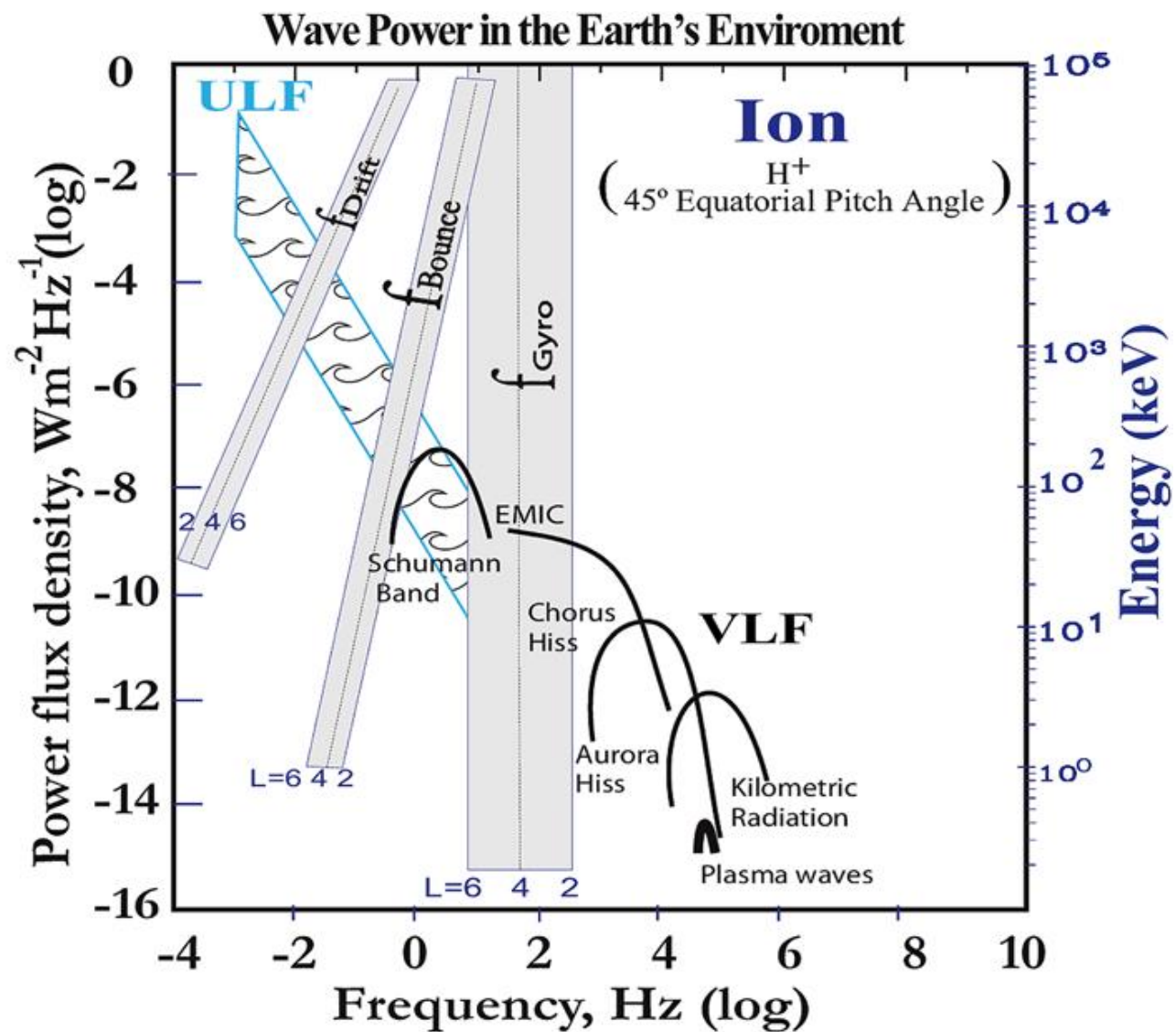
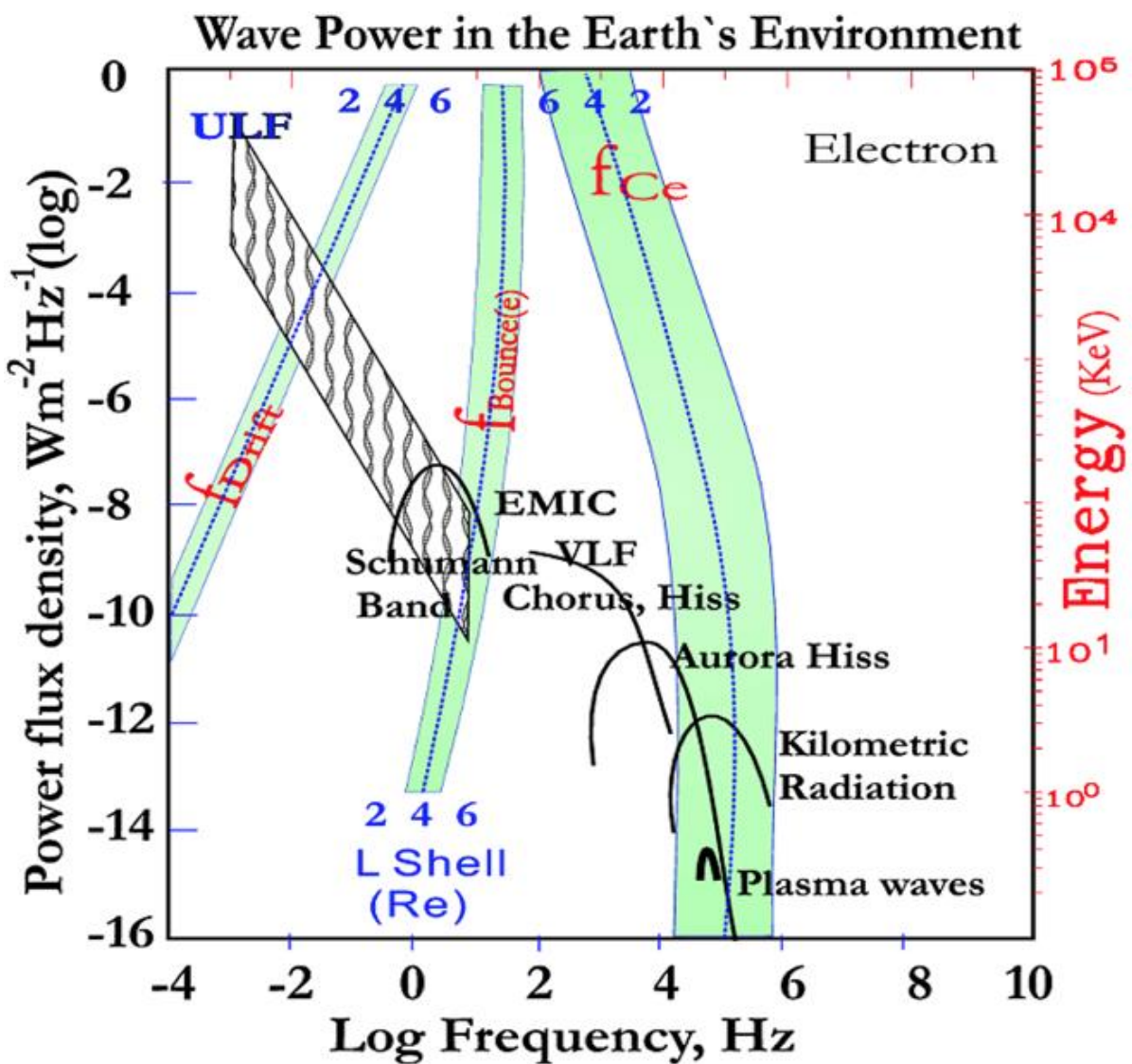
$$L^* = - \frac{2\pi M_E}{\Phi R_E}$$

Roederer (1972)

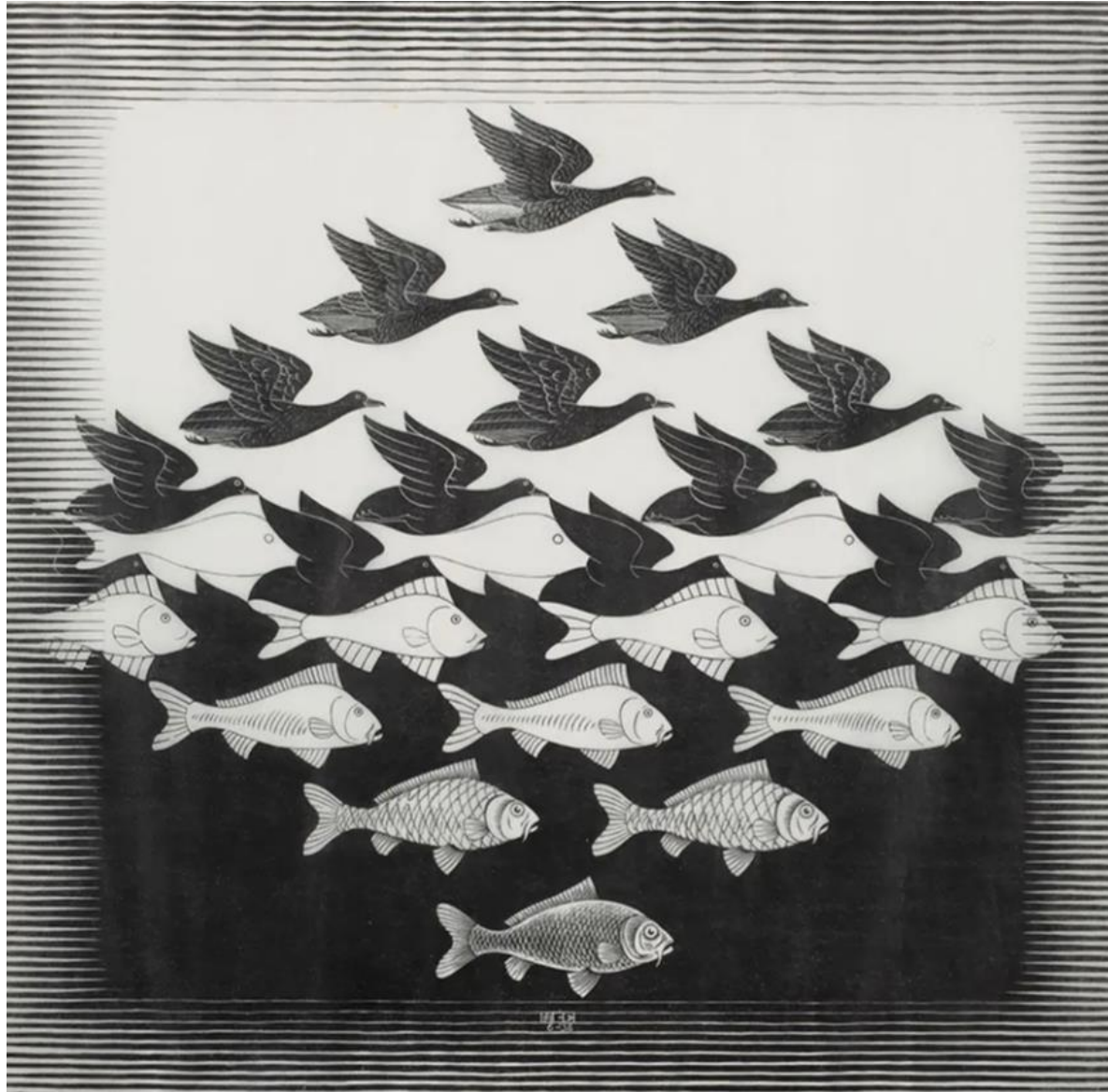
Condition for conservation

$$\left| \frac{1}{B} \frac{\partial B}{\partial t} \right| < \frac{1}{\tau}$$

$$\tau_c \ll \tau_b \ll \tau_d \ll \left| \frac{B}{\partial B / \partial t} \right|$$

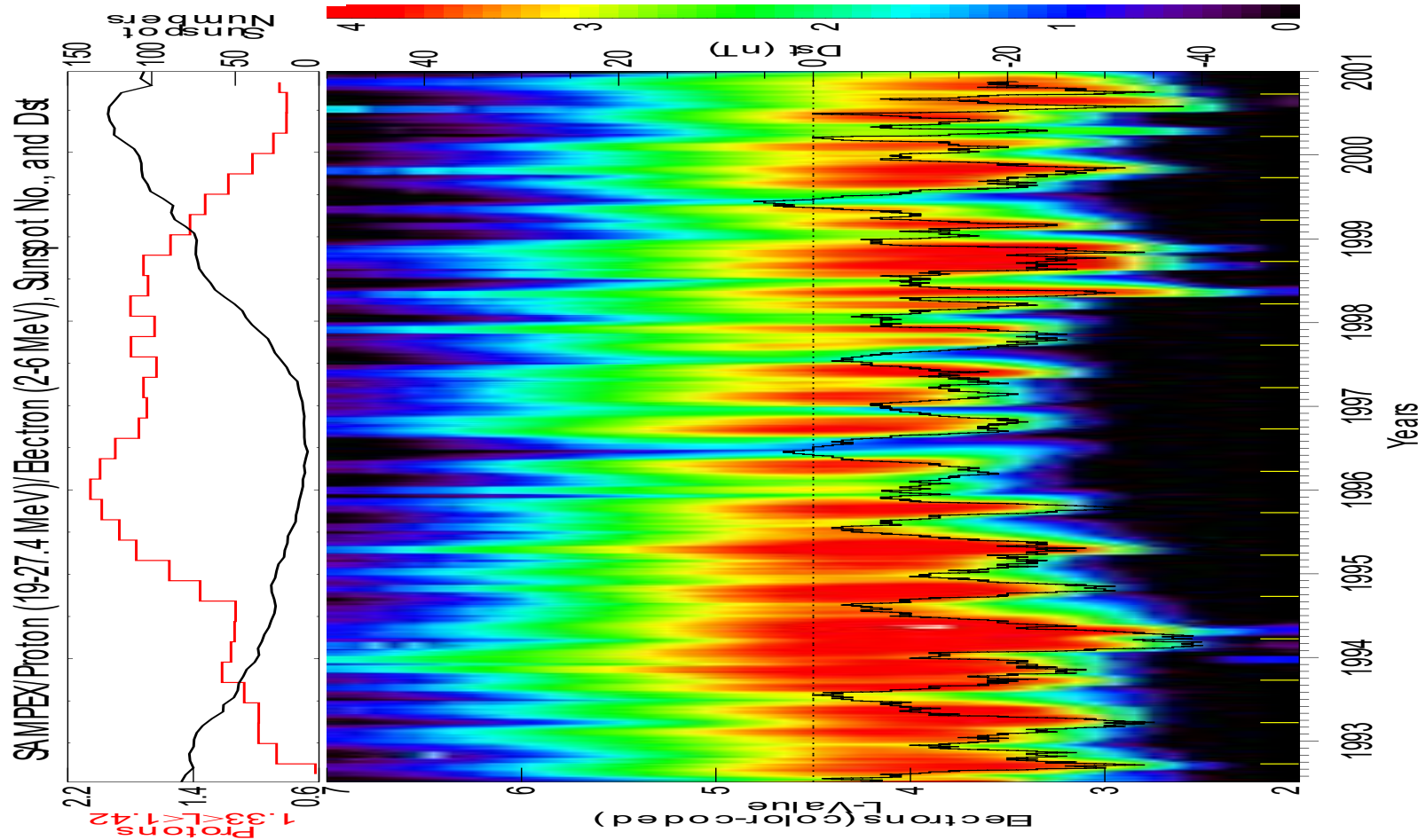


Let's go back to PATTERNS



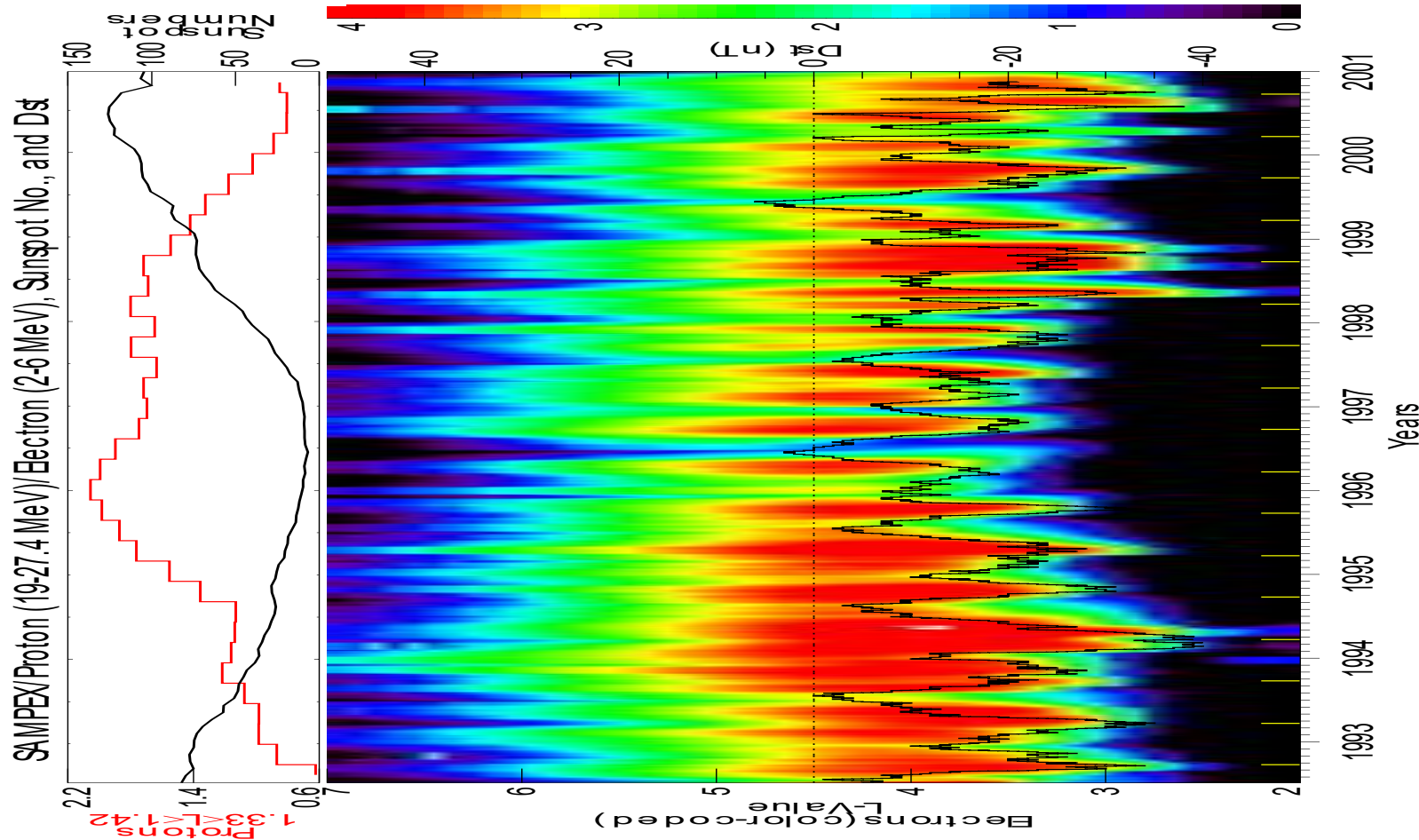
Maurits Cornelis Escher

Outer Van Allen belt multi-scale variability

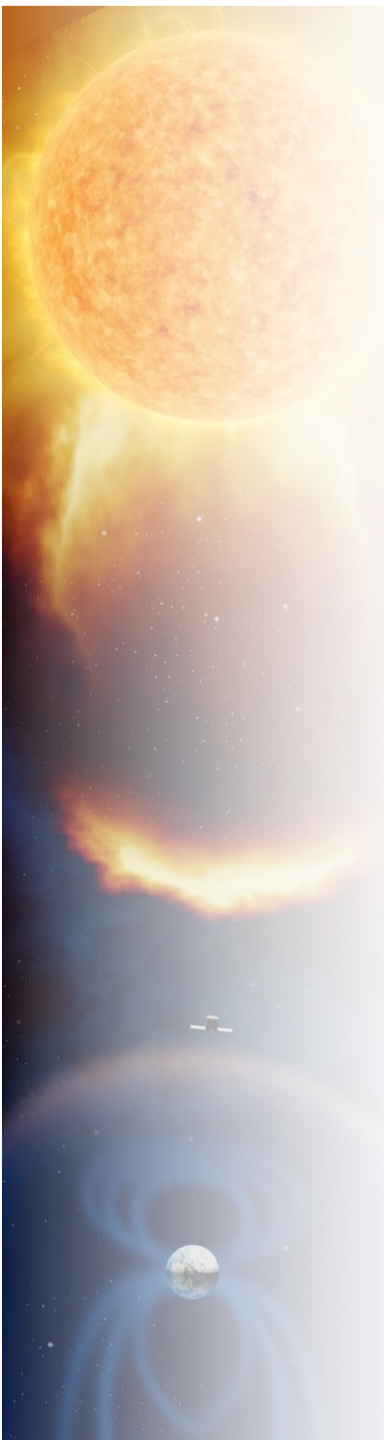


- Solar cycle: years
- Seasonal: Months
- Solar rotation: 27 (Earth) days = 1 Sun-day
- Storm recovery: days
- Storm main phase: hours
- SSC: minutes
- Wave-particle interactions: (sub)seconds

Outer Van Allen belt multi-scale variability



- Solar cycle:
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27 (Earth) days =
1 Sun-day
- Storm recovery:
days
- Storm main
phase: **hours**
- SSC: minutes
- Wave-particle
interactions:
(sub)seconds



The basic facts of the outer Van Allen belt variability

1. The Sun

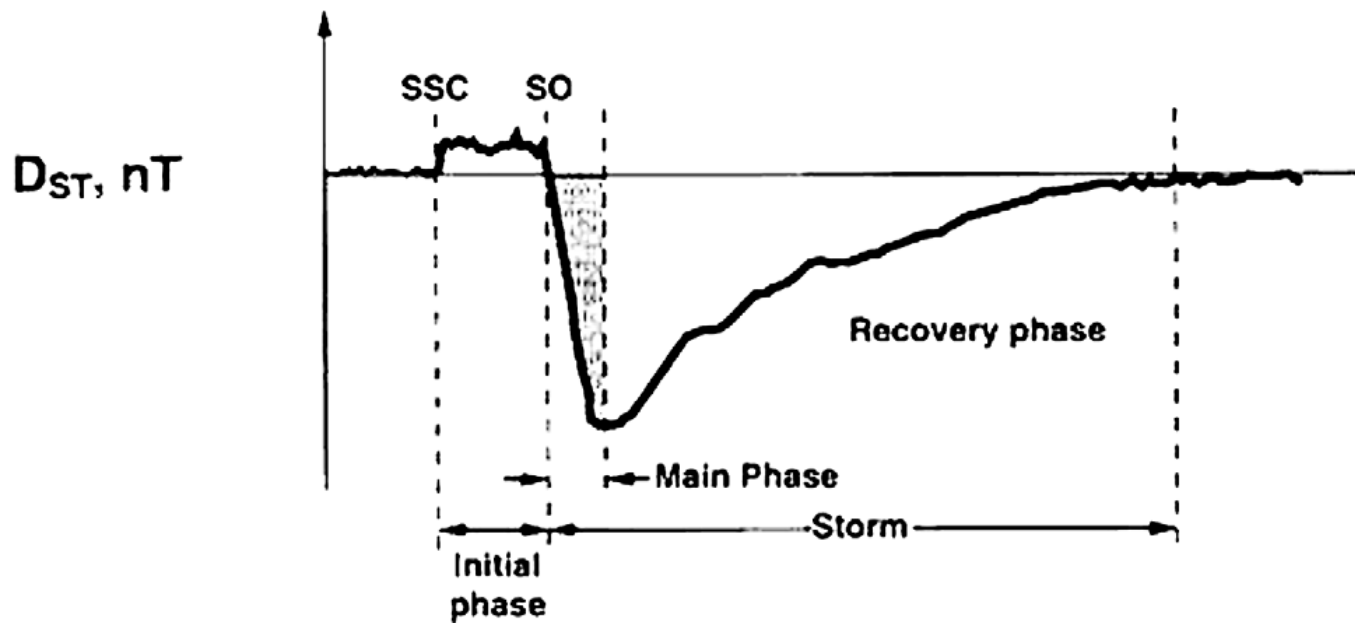
Occasional Coronal Mass Ejections

Occasional High-Speed Streams

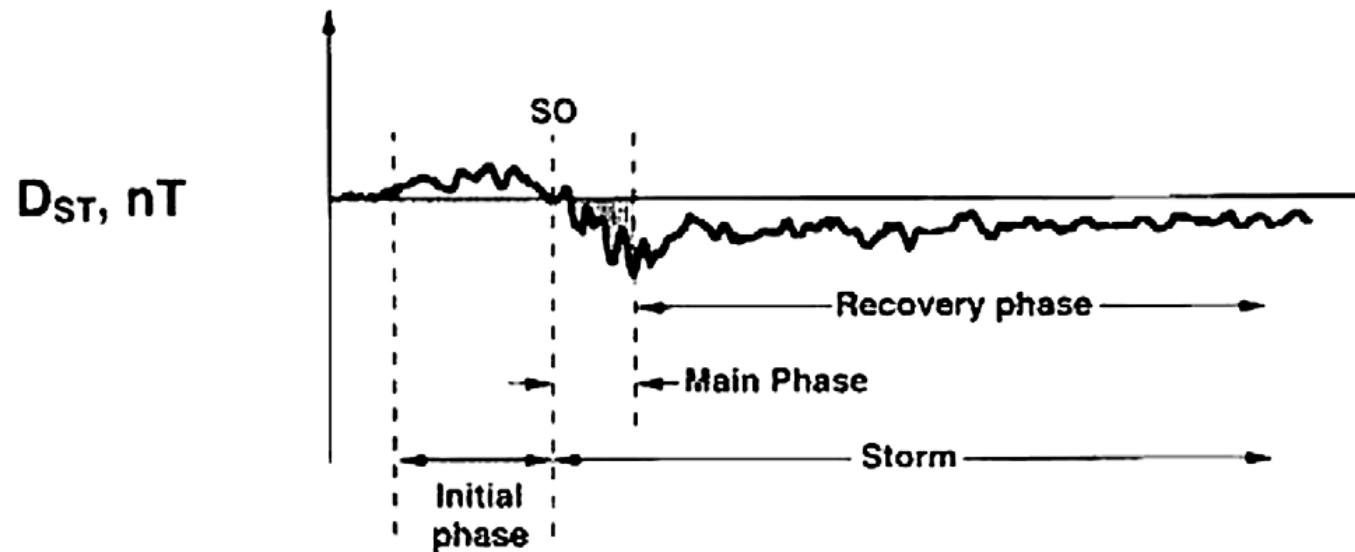
CIRs: Corotating Interaction Regions,
i.e., recurrent High-Speed Streams (every Sun-day)

All are geoeffective – in different ways

Solar Maximum (ICME) Storm

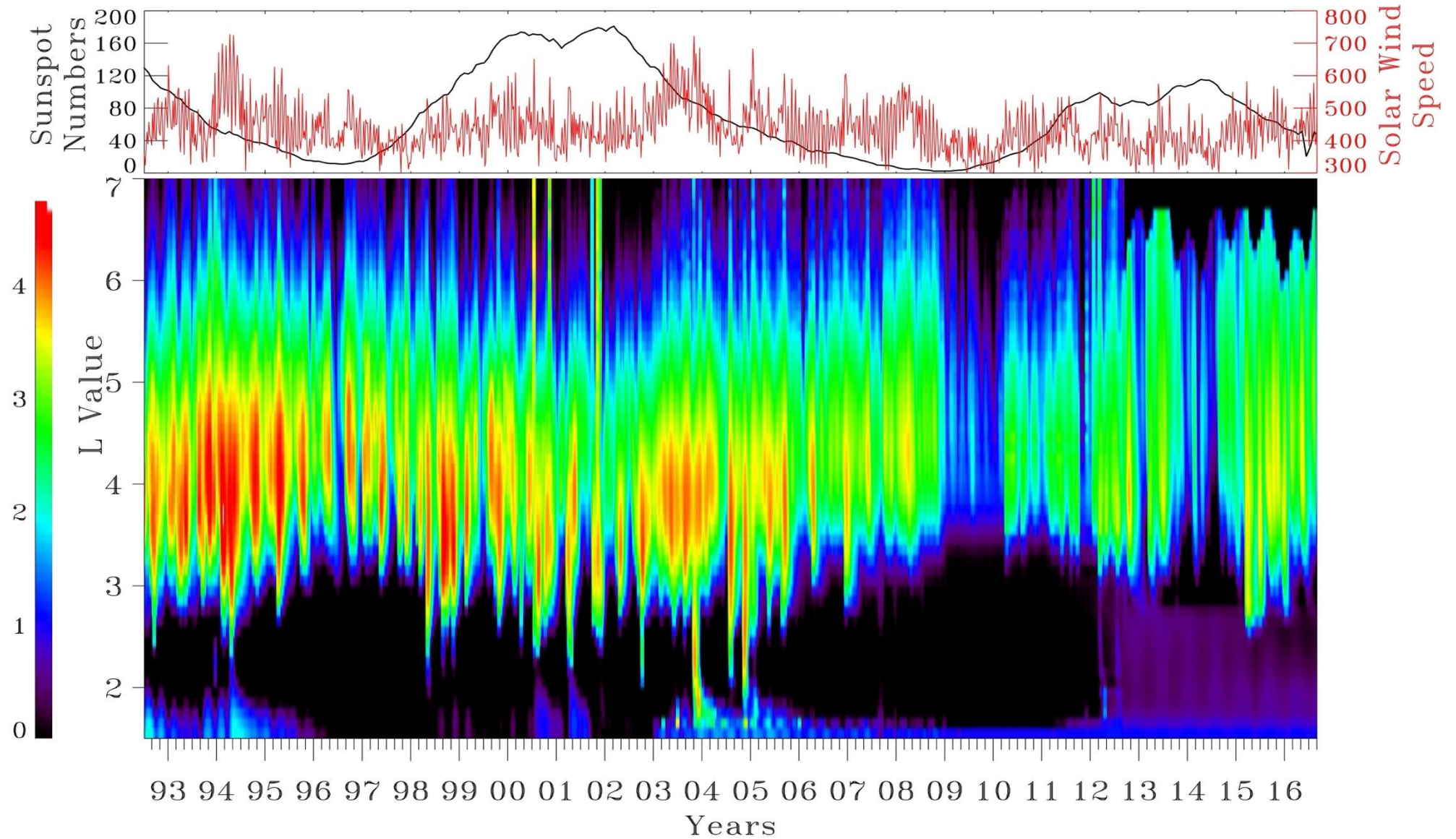


Solar Minimum (CIR) Storm



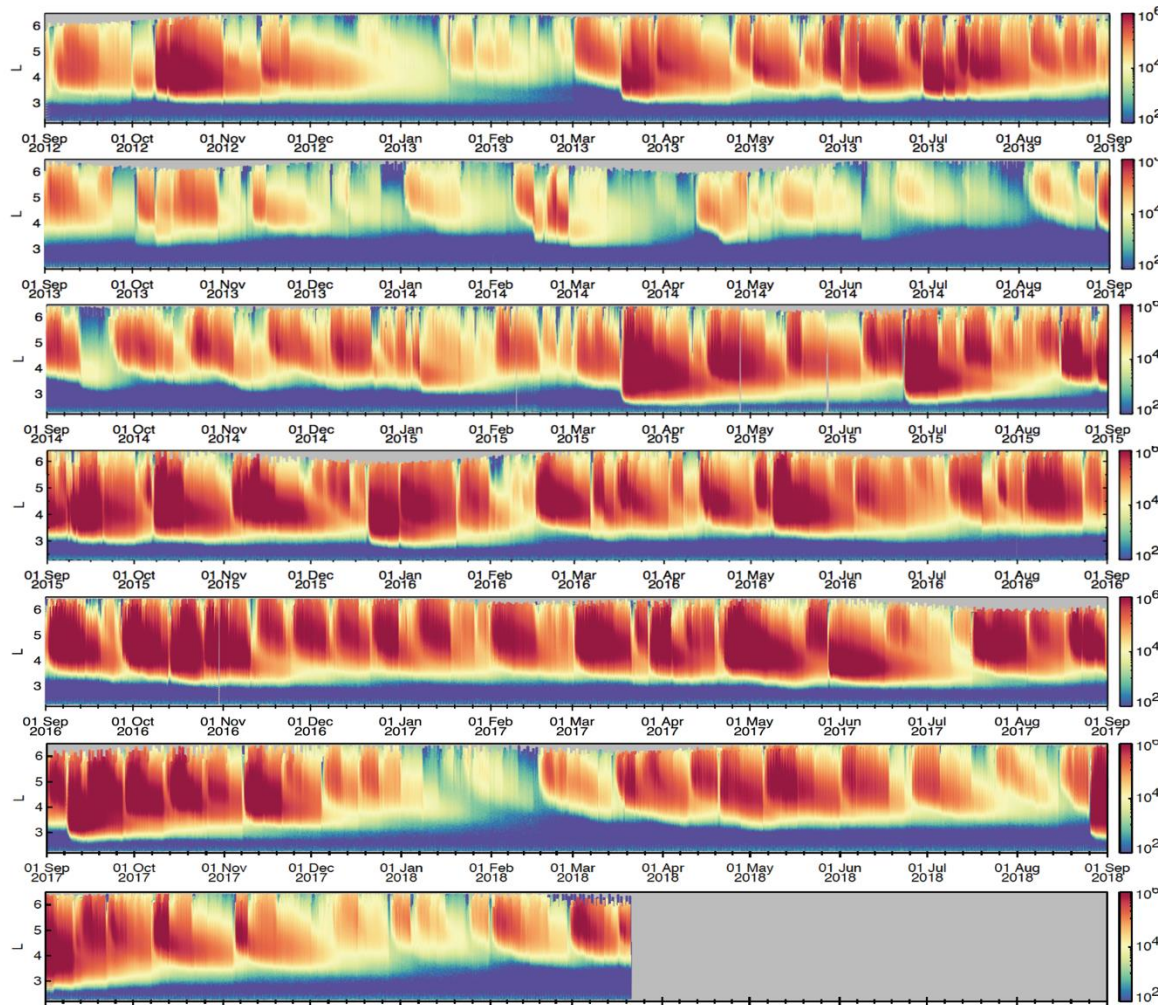
Basic facts of the outer belt variability

Phenomenological macroscopic dependence over 25 yrs: solar cycle

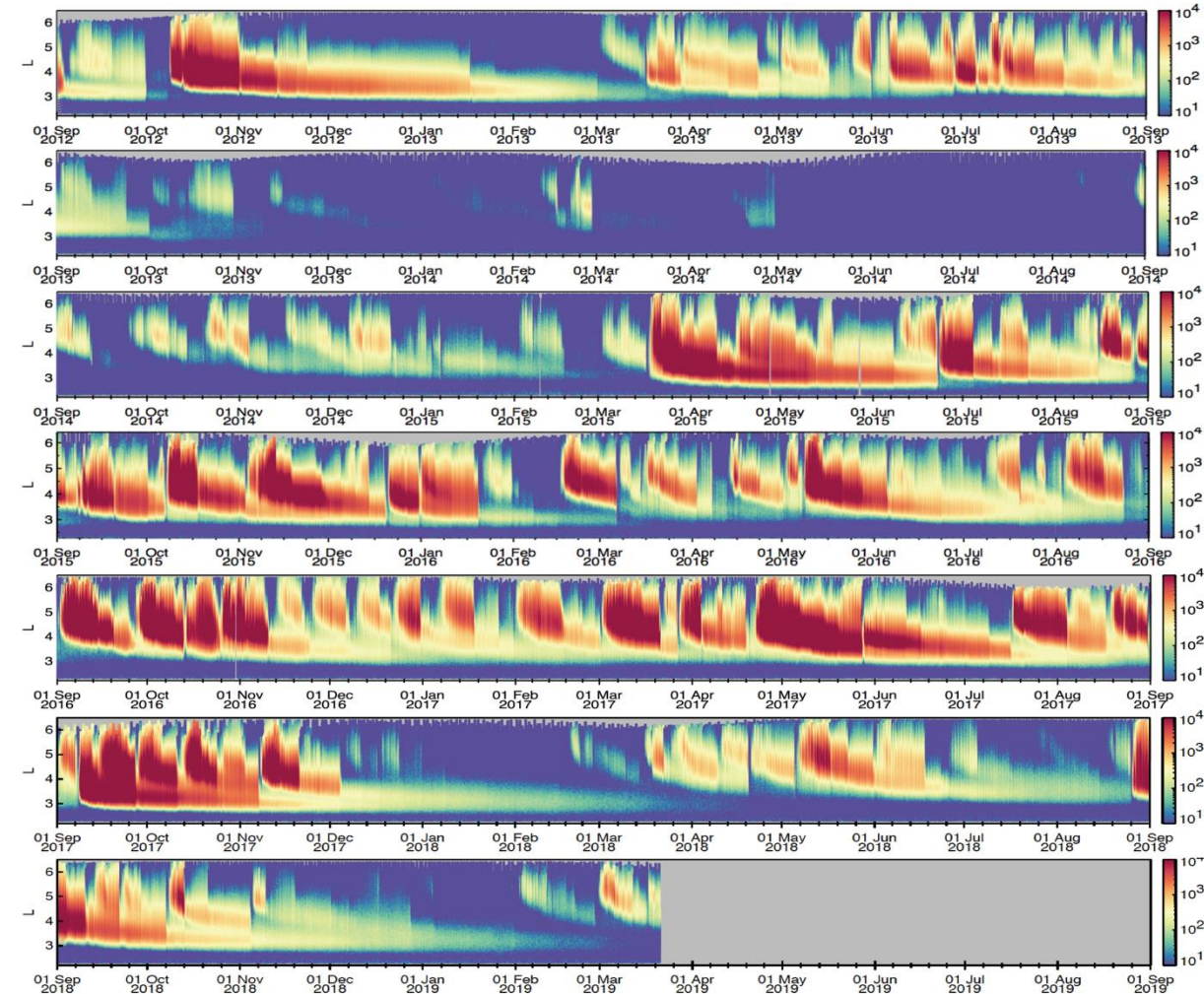


BUT ... (Van Allen Probes electron measurements)

REPT A & B 1.8 MeV Electrons

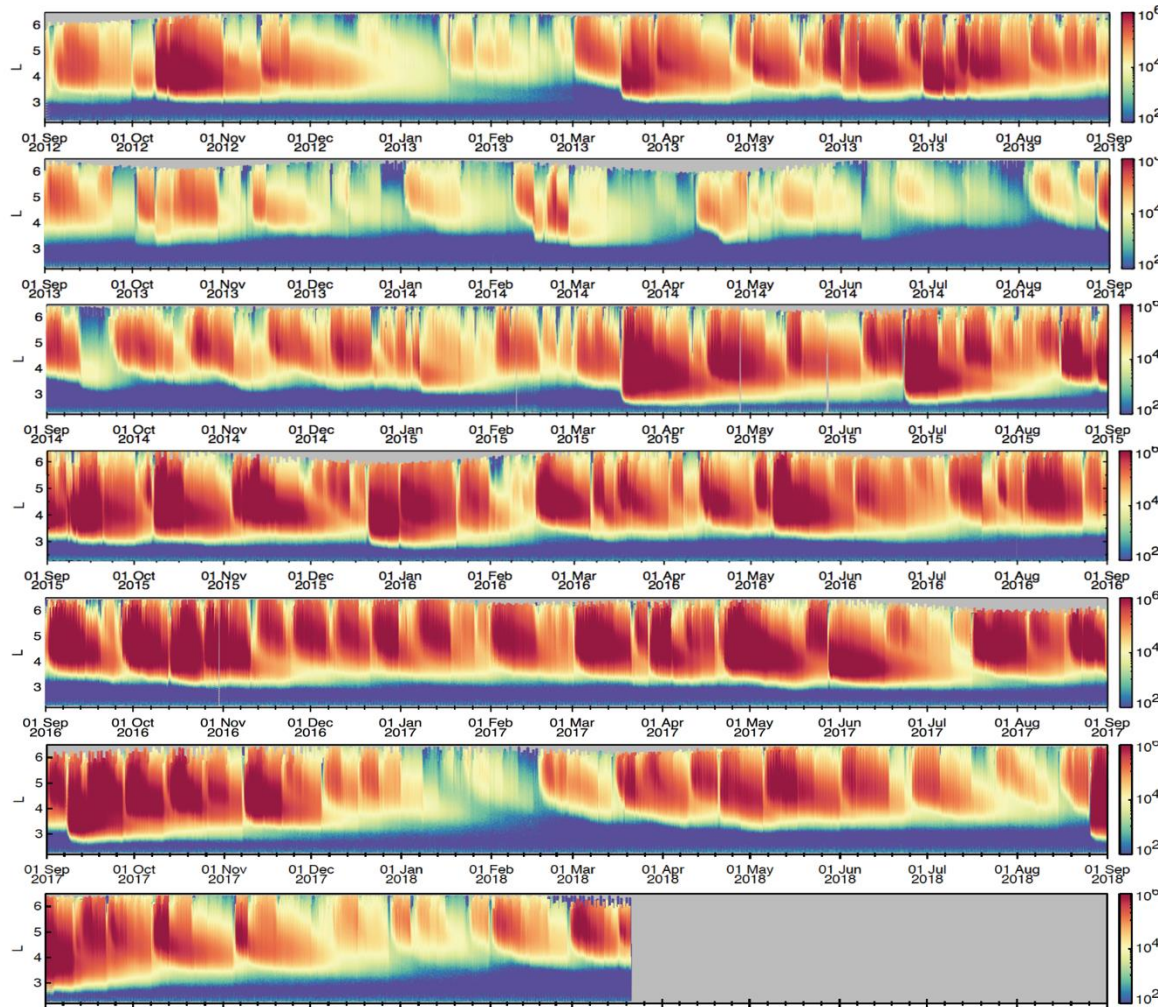


REPT A & B 4.2 MeV Electrons

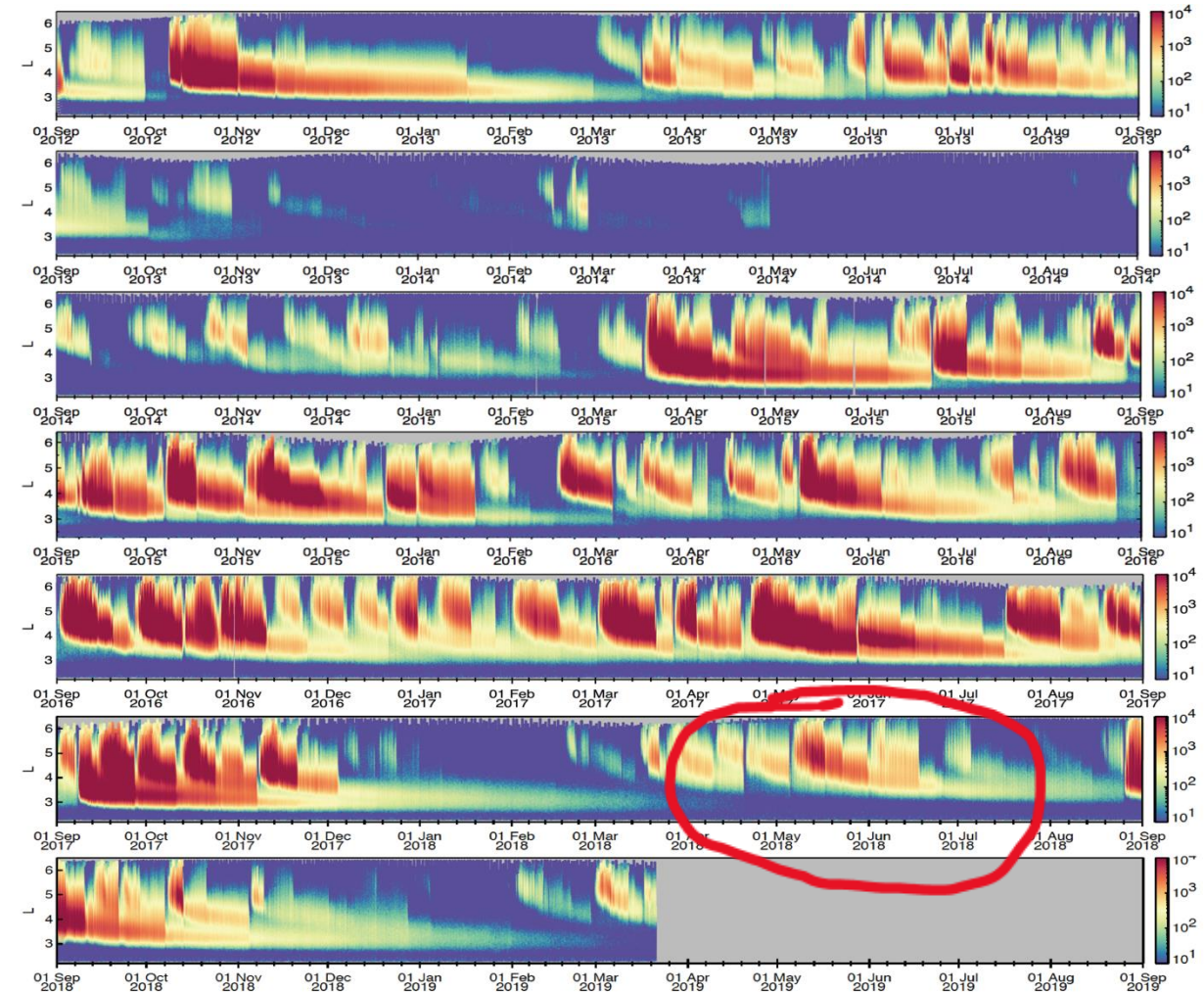


May 2018

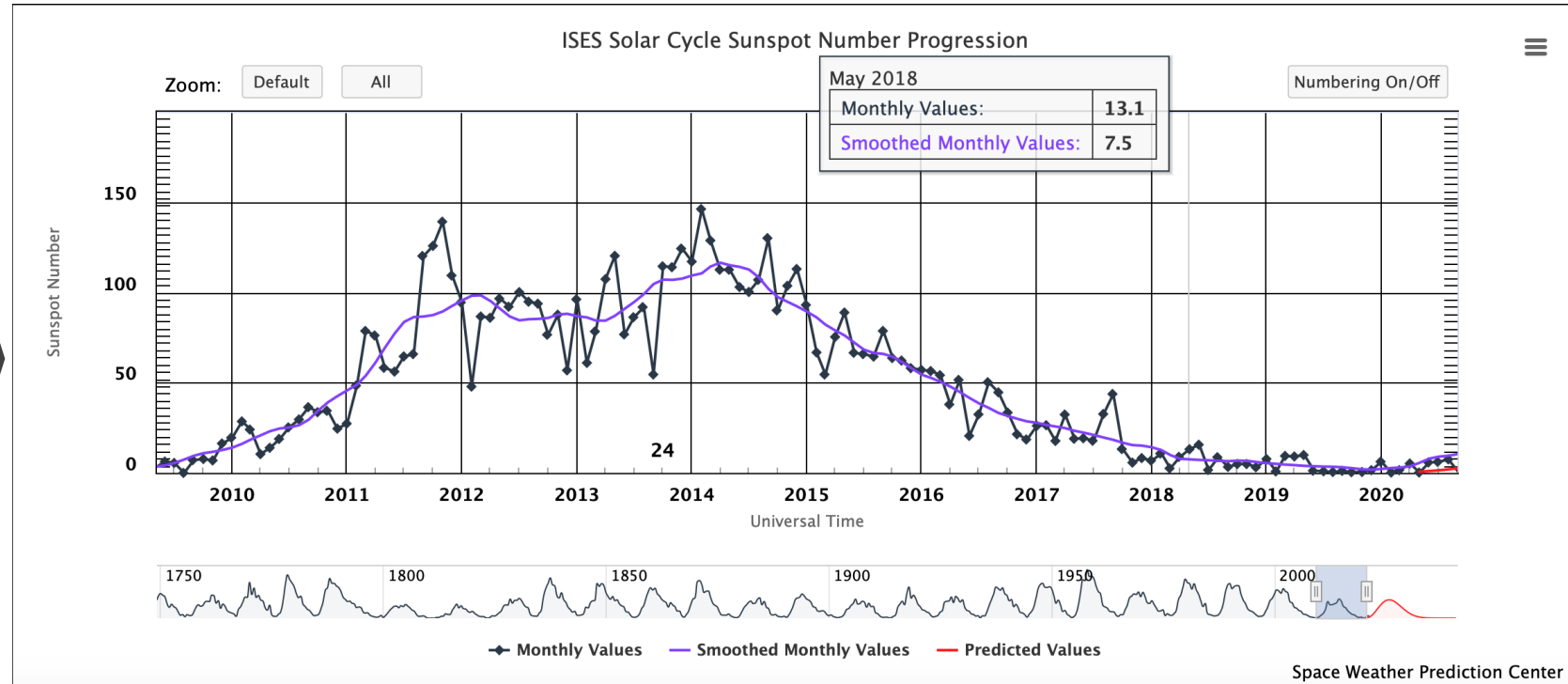
REPT A & B 1.8 MeV Electrons



REPT A & B 4.2 MeV Electrons



Clear
enhancement
at solar
minimum

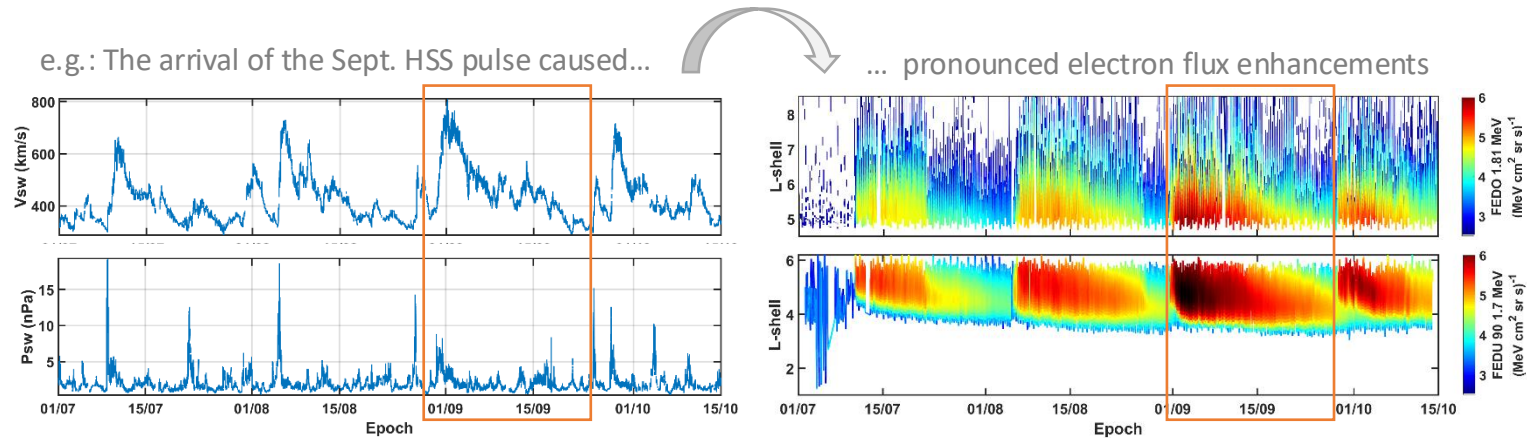


Recurrent HSSs

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.



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Geomagnetic &
Magnetospheric
parameters

ULF & VLF wave
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Electron flux

Electron Phase Space
Density (PSD)

NASA OMNIWEB and **SUPERMAG** databases

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Ultra-relativistic e (> 4 MeV)

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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**

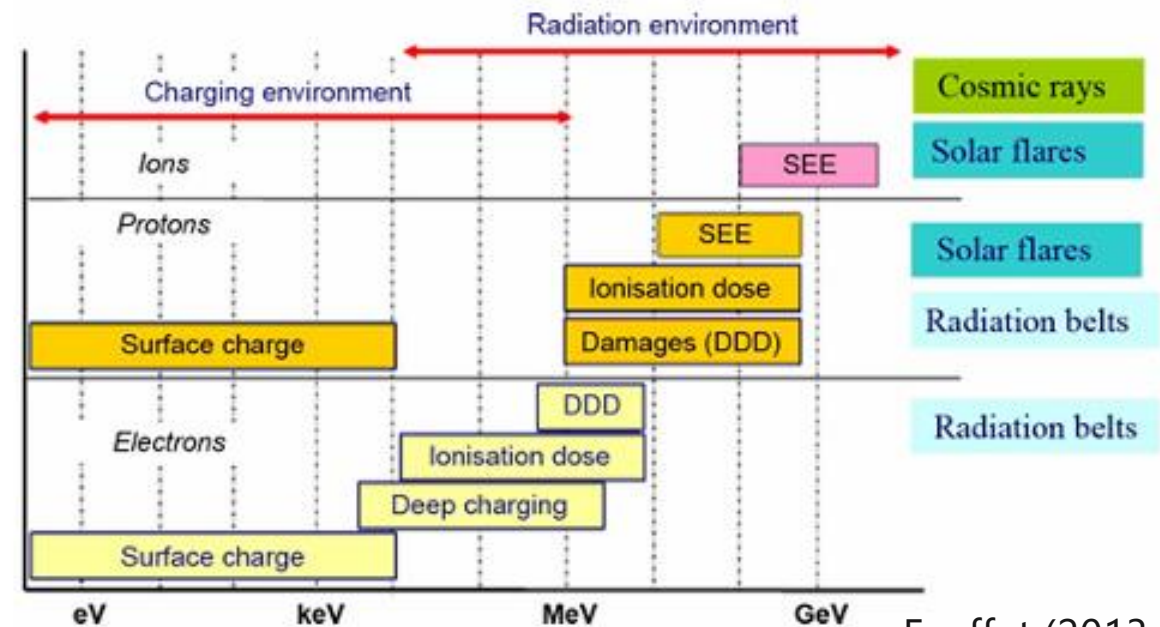
An unavoidable hazard leading to significant potential **risks**

No single acceleration process can do that

Space weather hazards

Impacts on satellites

- **Surface charging** from 10s to 100s keV electrons.
- **Internal charging** from >100s keV electrons (MeV).
- **Single Event Effects** (SEE) from >10MeV (mainly) protons and ions. (Destructive/ Non-destructive)
- **Total dosage effects:** Total Ionizing Dose (TID) & Displacement Damage Dose (DDD)



Ecoffet (2013)

Hazards and risks



Hazards and risks not the same?



Hazards and risks

$$\text{Risk} = \text{Hazard} \times \text{Vulnerability}$$



Hazards and risks

$$\text{Risk} = \text{Hazard} \times \text{Vulnerability} \times \text{Exposure}$$



Hazards and risks

Risk = Hazard x Vulnerability x Exposure

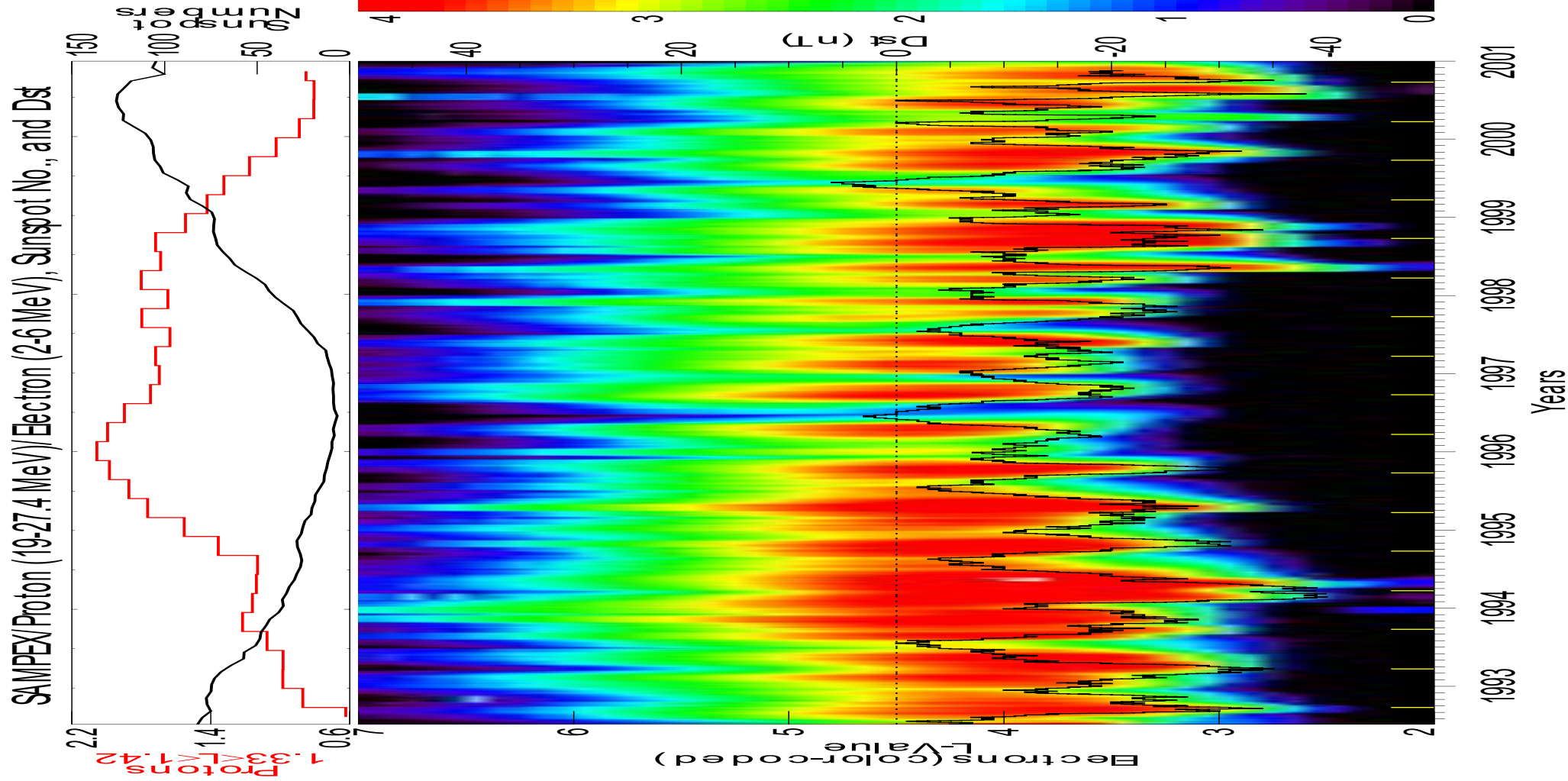
Minimize risk through:

- Reduction of exposure (e.g., GTO orbit, Jovian missions)
- Reduction of vulnerability (conditionally feasible)



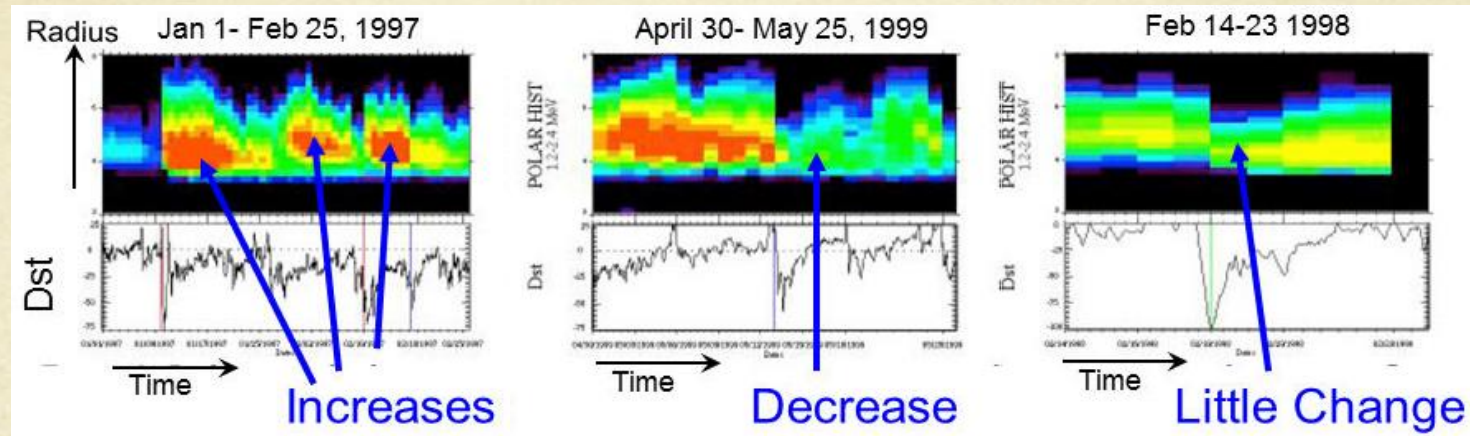
Basic facts of the outer belt variability

Phenomenological dependence: magnetic storms



Storms and RBs

Some storms are “more equal than others”



Reeves et al., 2003

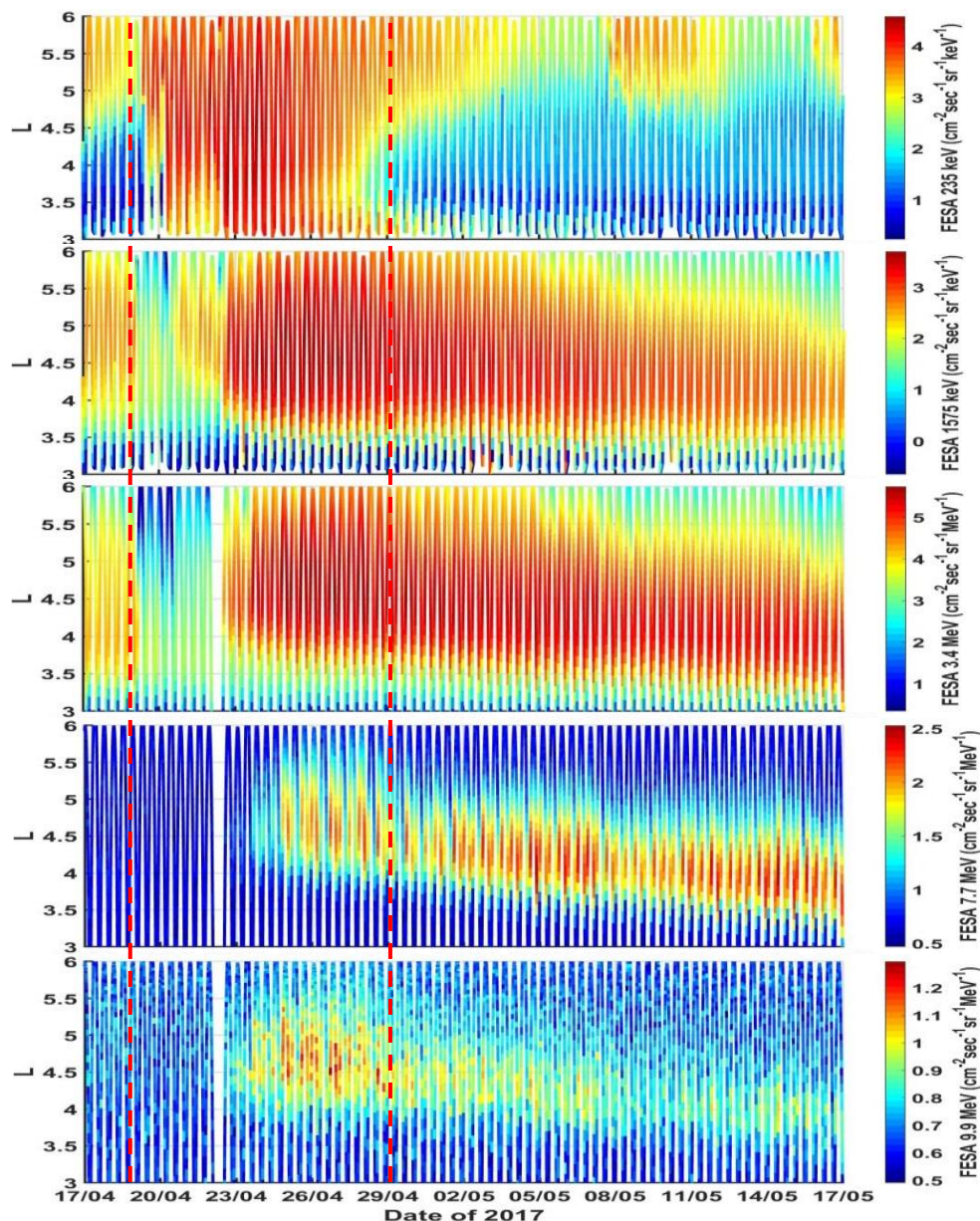
G. Orwell, 1945: **all animals are equal**, but **some animals are more equal** than others

G. Reeves, 2003: 276 moderate/intense storms, 1989-2000

Similar studies:

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

Impressive non-storm enhancement of ultra-relativistic electrons



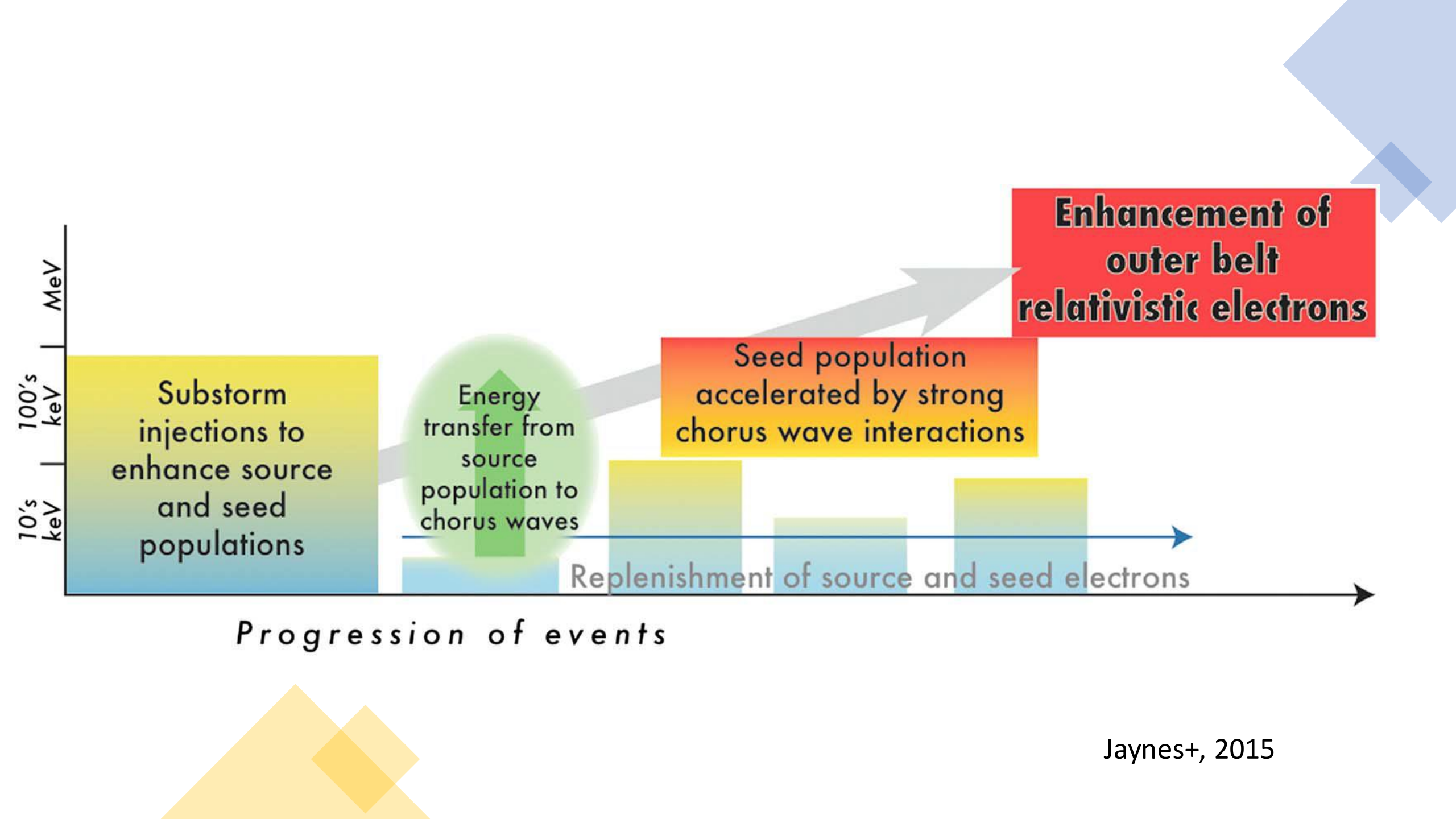
More than **three orders of magnitude** enhancement of **3.4 MeV** electron flux

Acceleration of electrons up to 9.9 MeV.

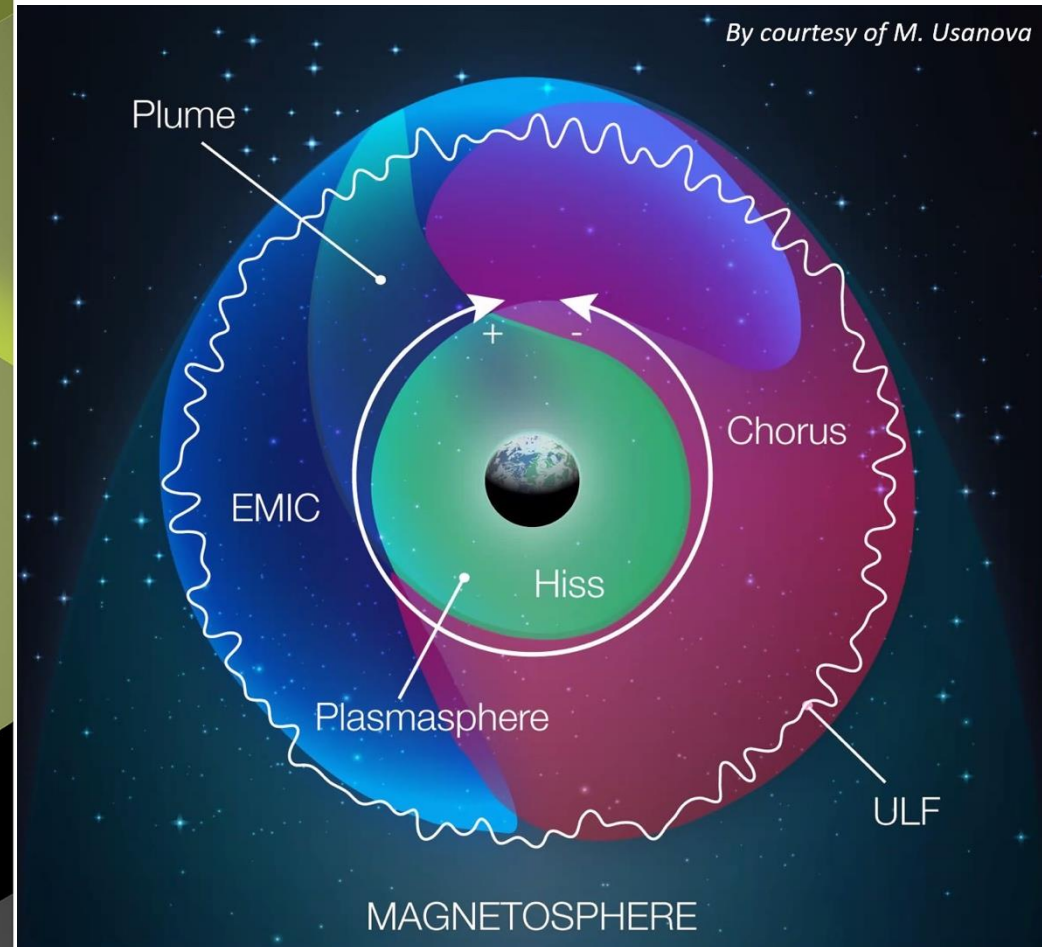
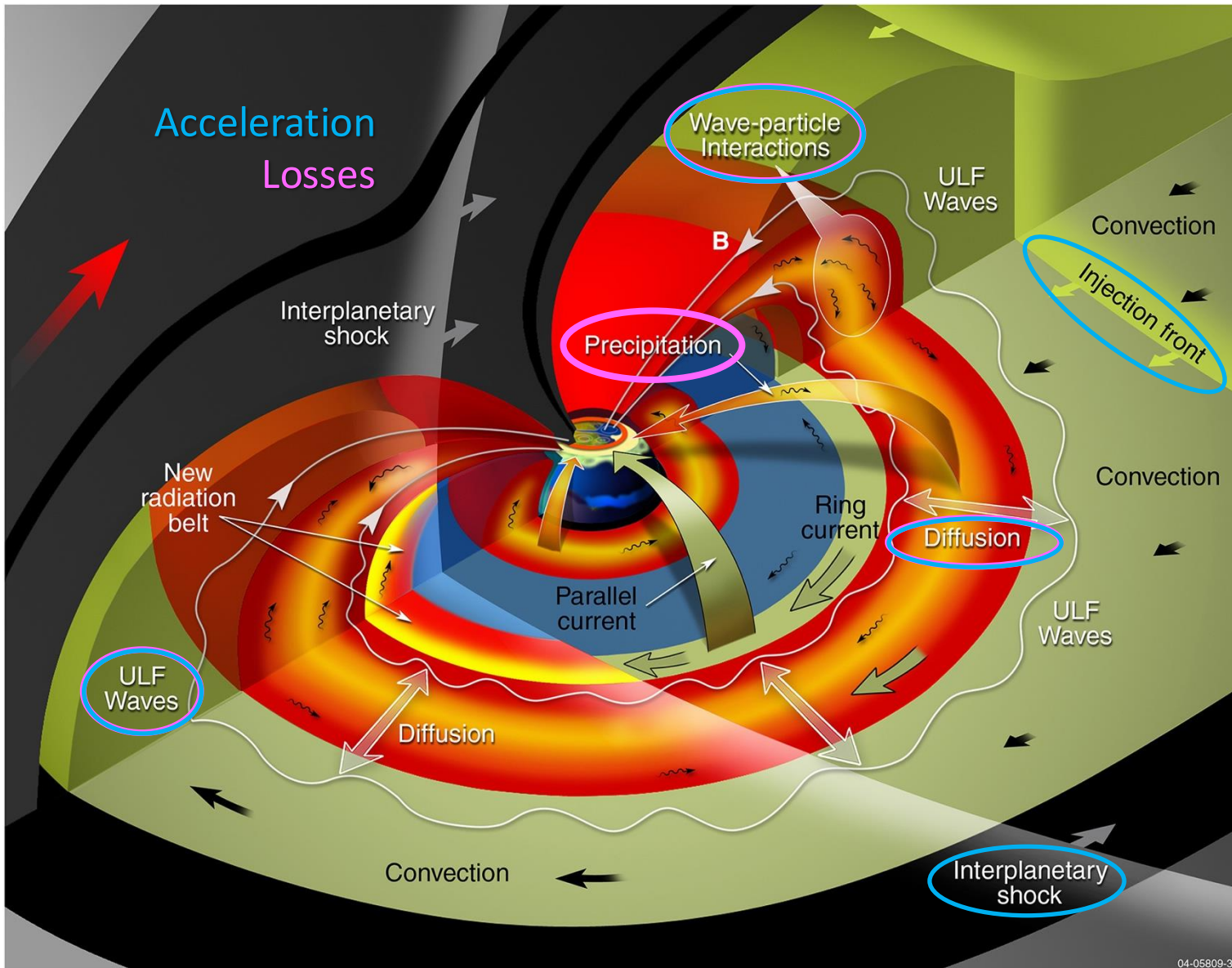
Enhancements are **energy-dependent**.

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

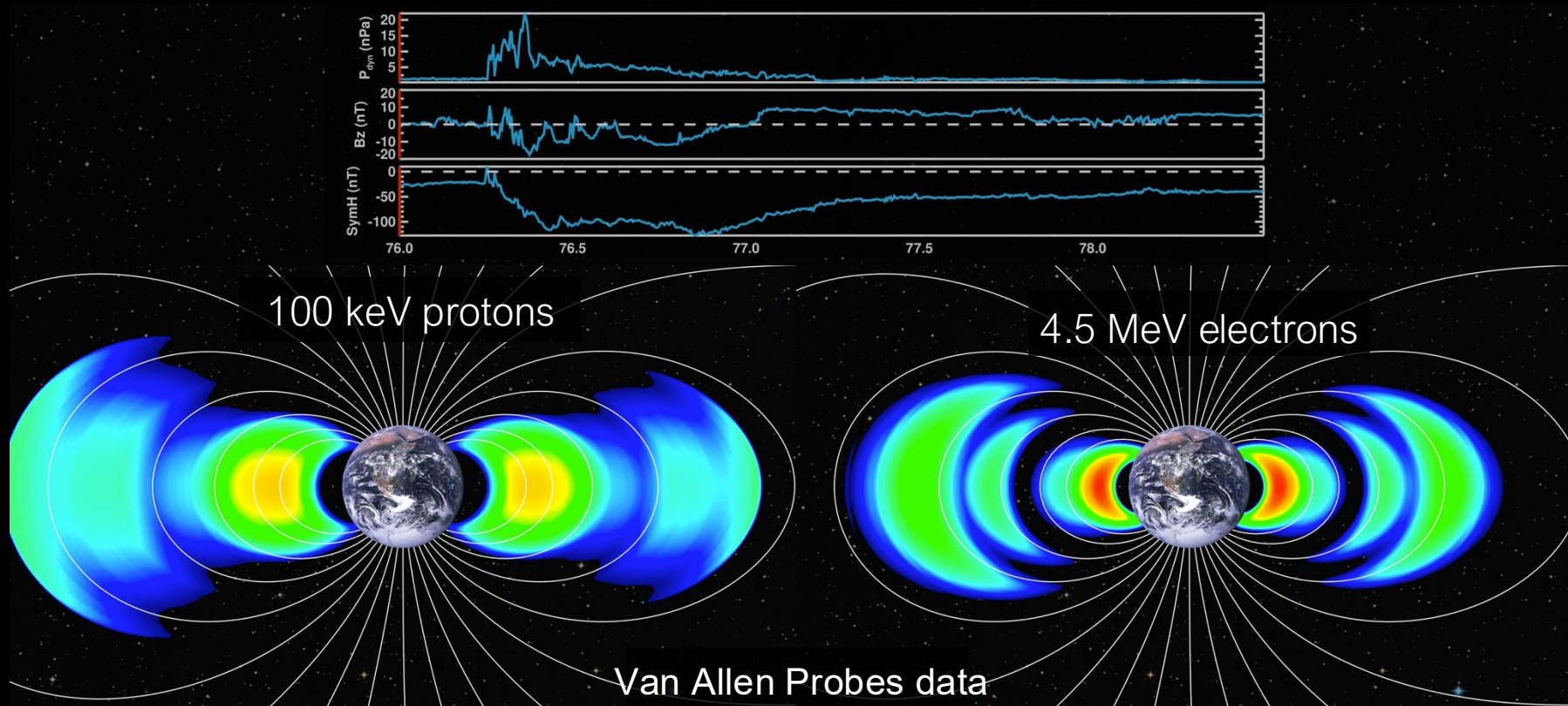
Katsavrias+, JGR2019



The Dynamic near-Earth Environment



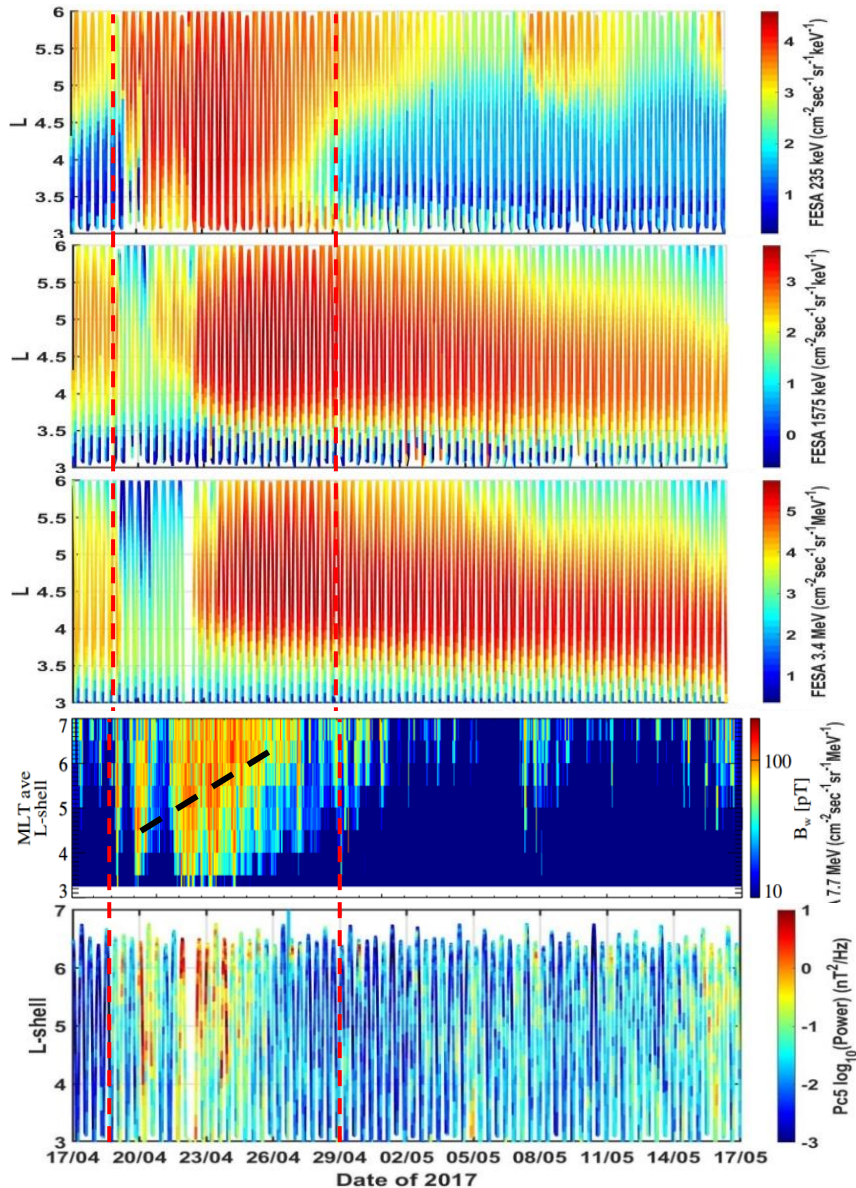
Radiation Belt Losses and Gains associated with the Ring Current variability driven geomagnetic field configuration changes



Courtesy of Grant Stephens

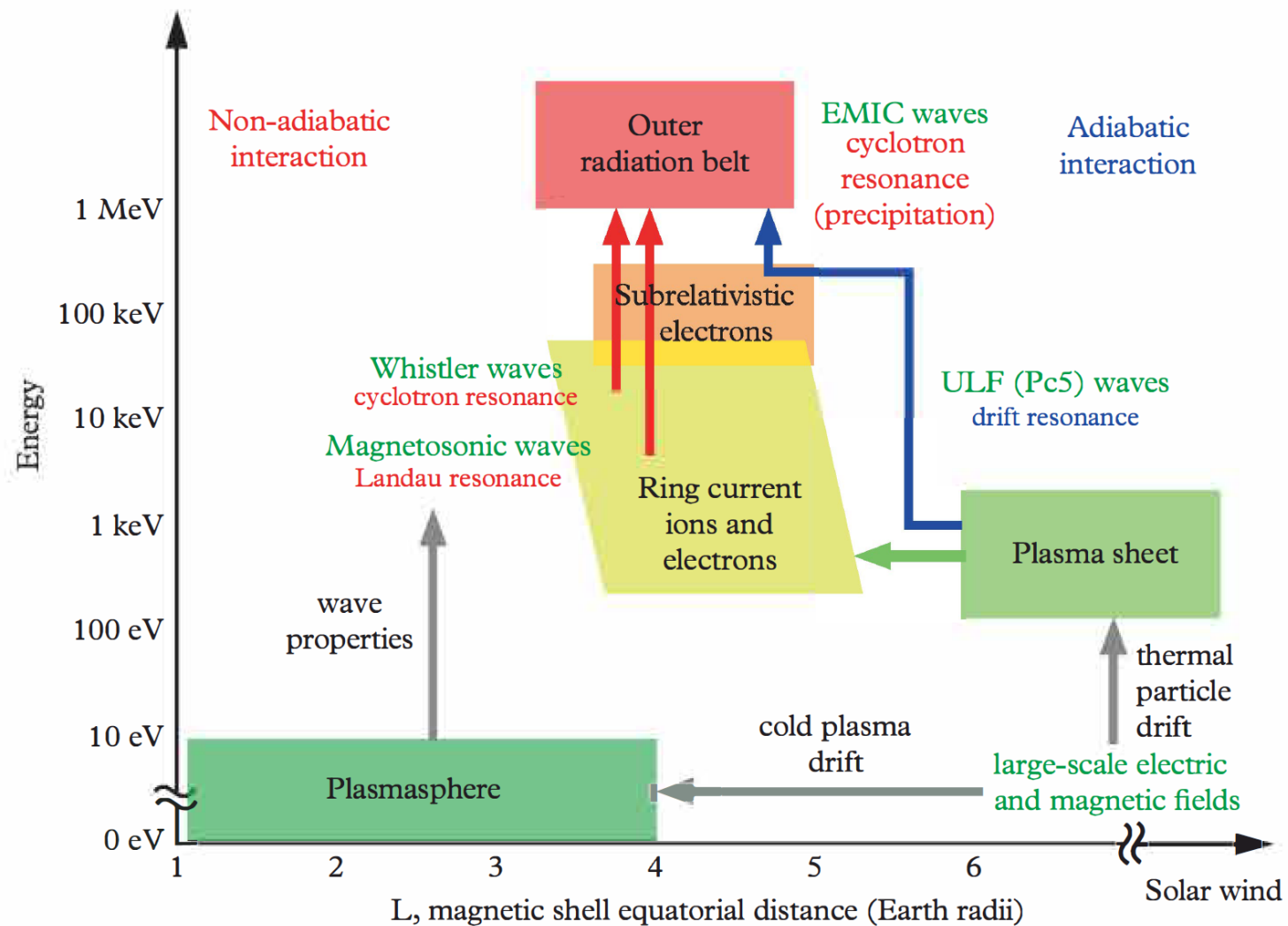
The distortion of the Earth's magnetic field in the inner magnetosphere due to the ring current formation, affects the transport and loss of radiation belt particles.

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**

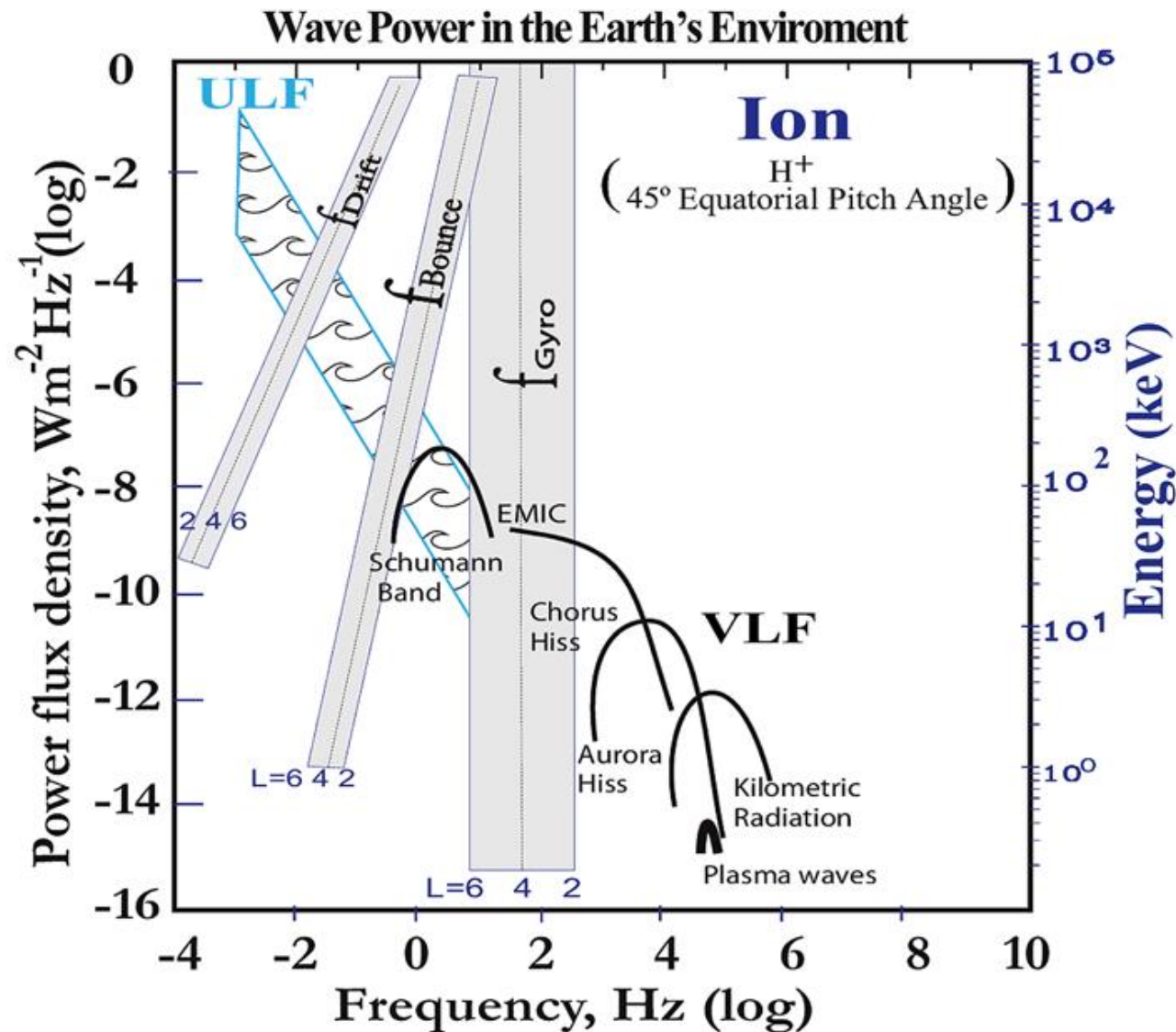
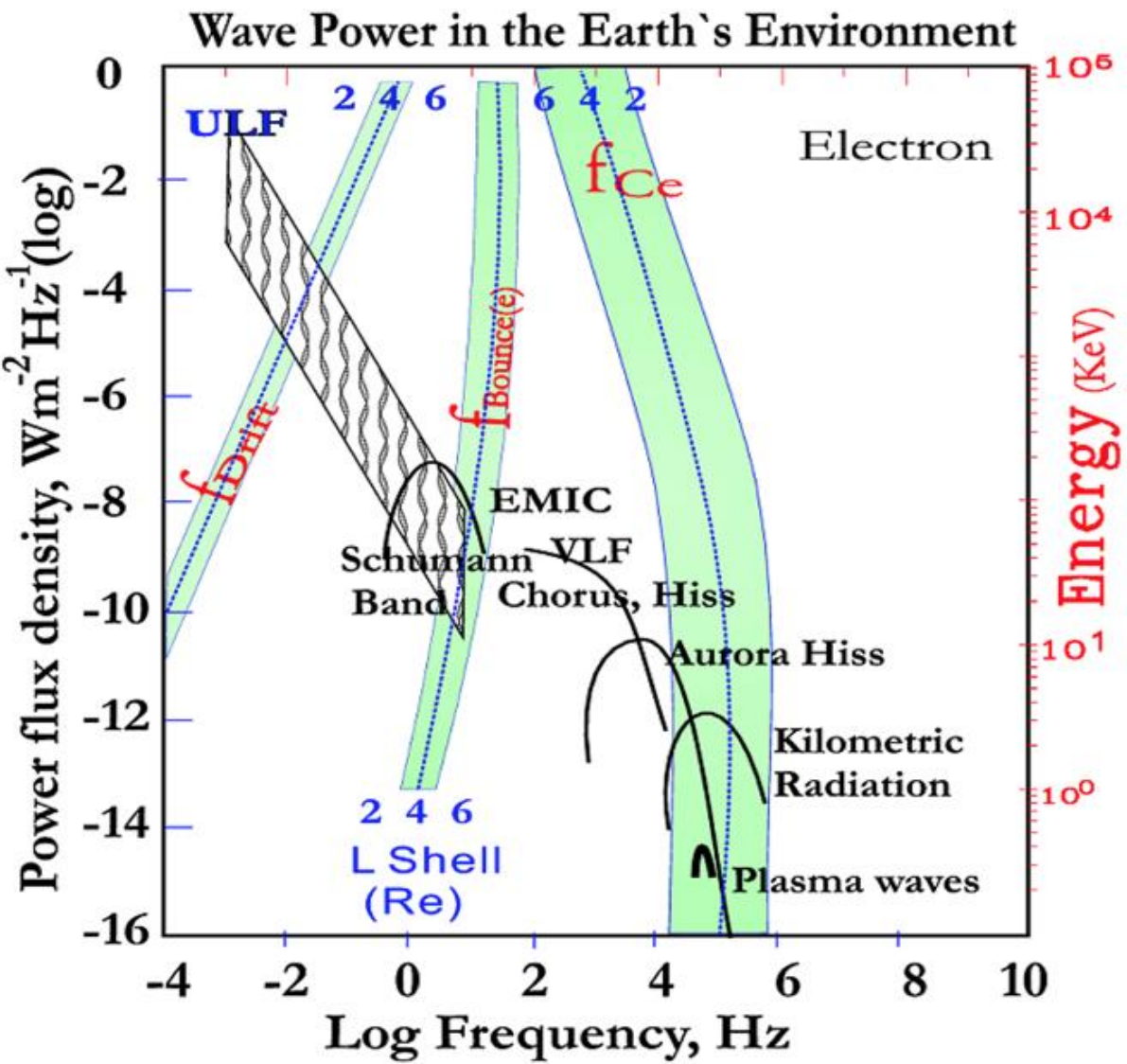
**More than 2 orders of magnitude
enhancement of Pc5 power**



Takahashi and Miyoshi, 2016

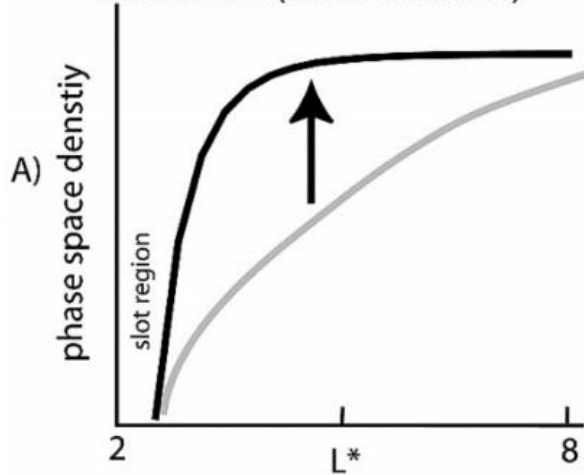
Interaction of various waves (in various ways)
with various particle populations during storms/substorms

Effects of wave-particle interactions depend on frequency-matching and (non-)conservation of adiabaticity

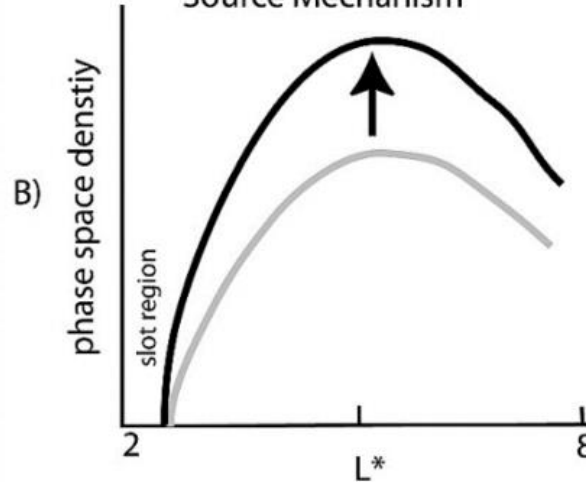


Variability of the Outer Belt - The basic mechanisms

Electron Acceleration by Radial Diffusion Mechanism (external source)



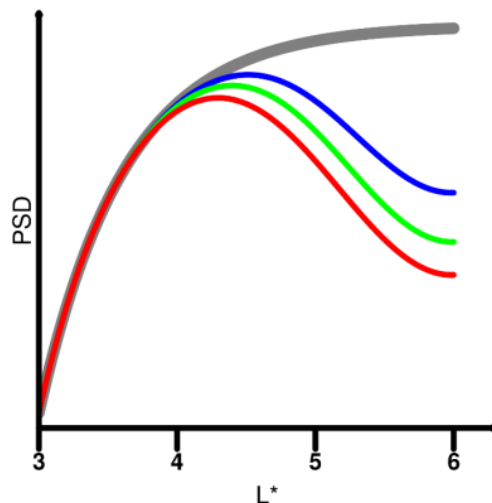
Electron Acceleration by Internal Source Mechanism



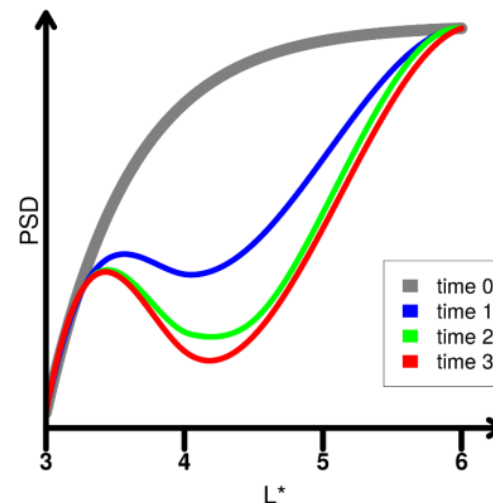
Acceleration Mechanisms

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

Outward diffusion



Fast local loss



Loss Mechanisms

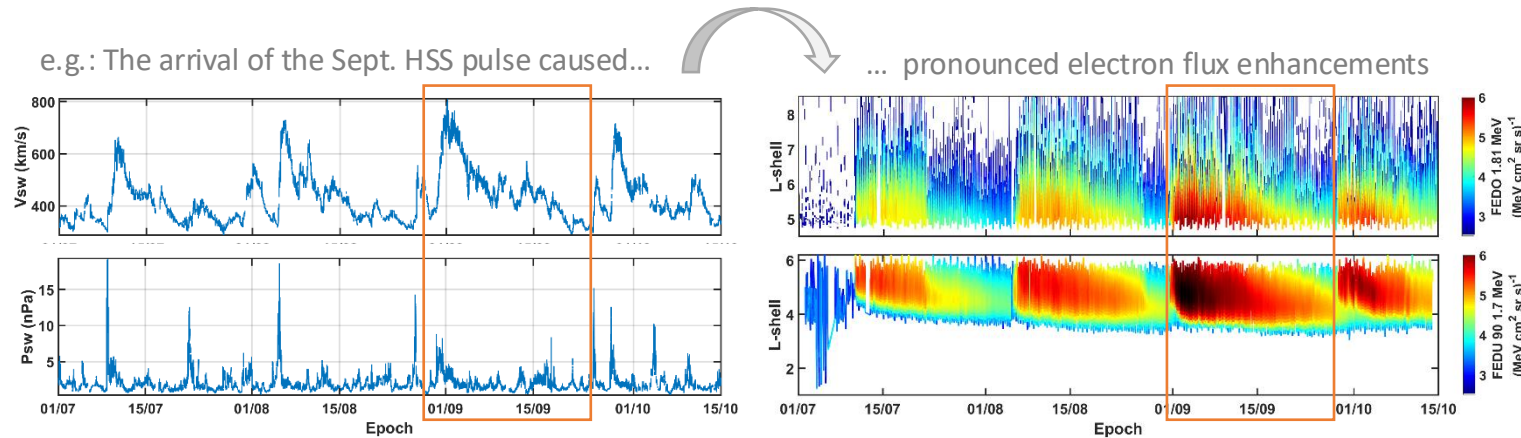
1. Outer boundary losses (magnetopause shadowing)
2. Atmospheric losses (whistler chorus mode, plasmaspheric hiss and EMIC waves)

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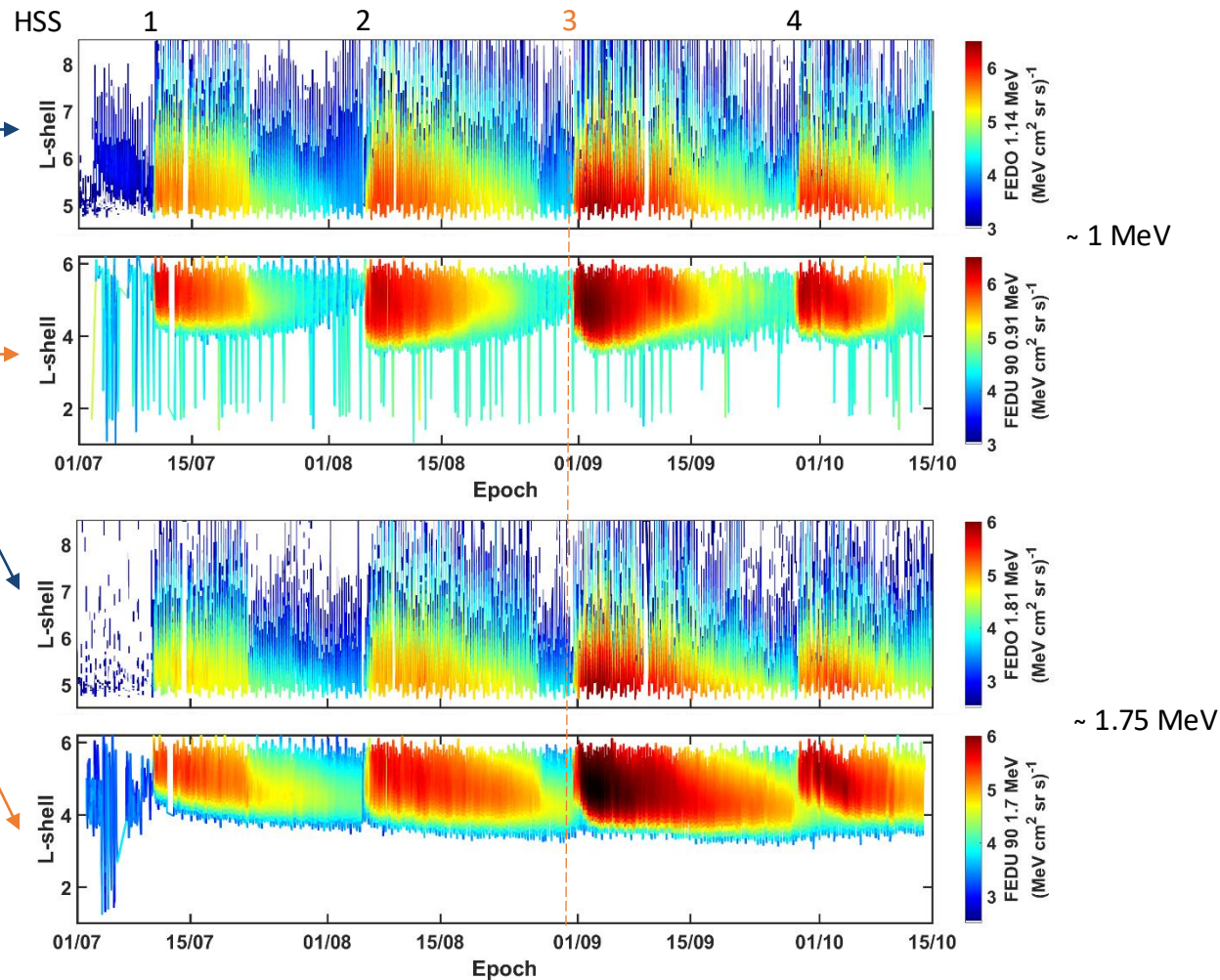
Flux intensity of relativistic electrons (1-2 MeV)

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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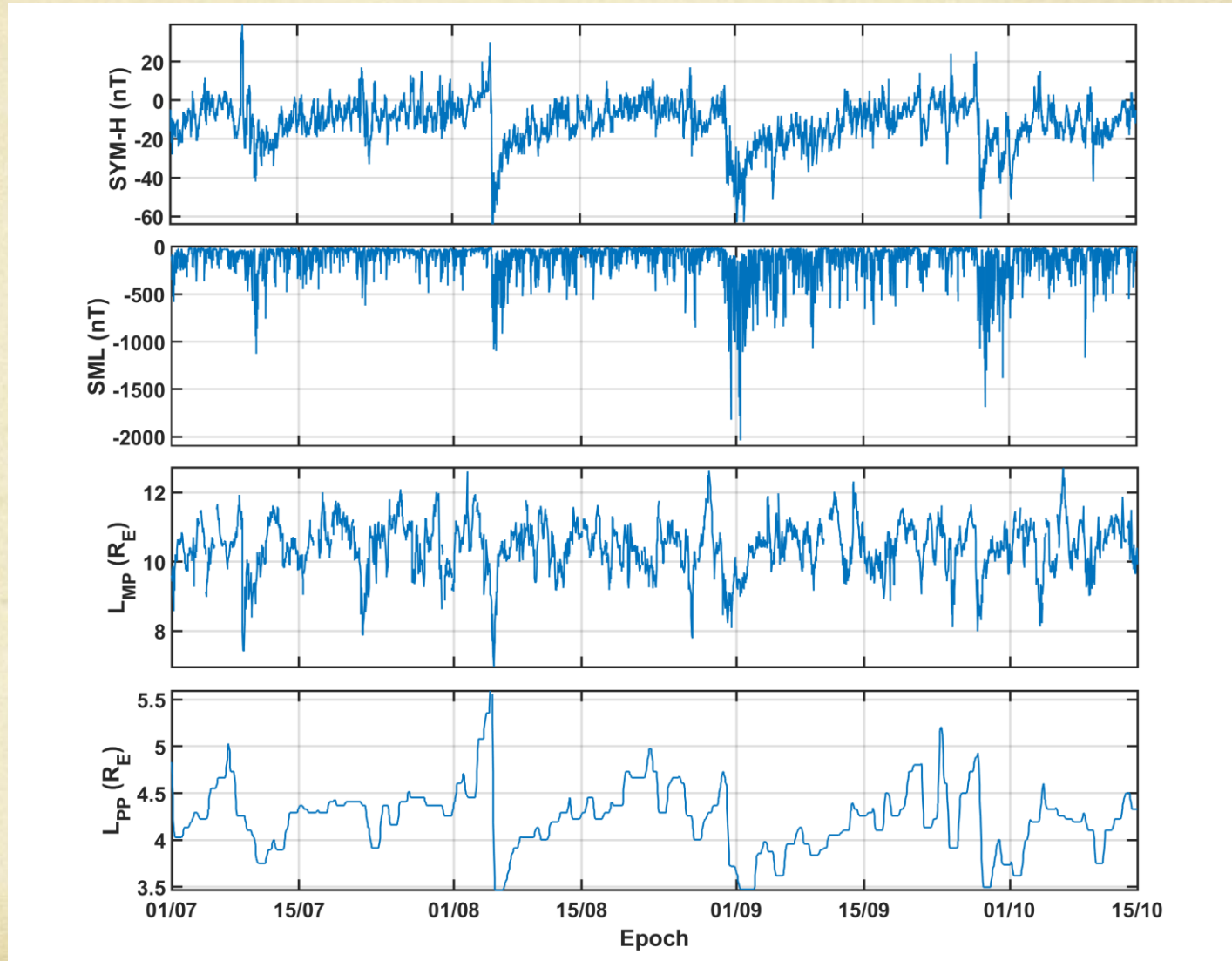
Ultra-relativistic e (> 4 MeV)

Electron Phase Space Density (PSD)

Conclusions

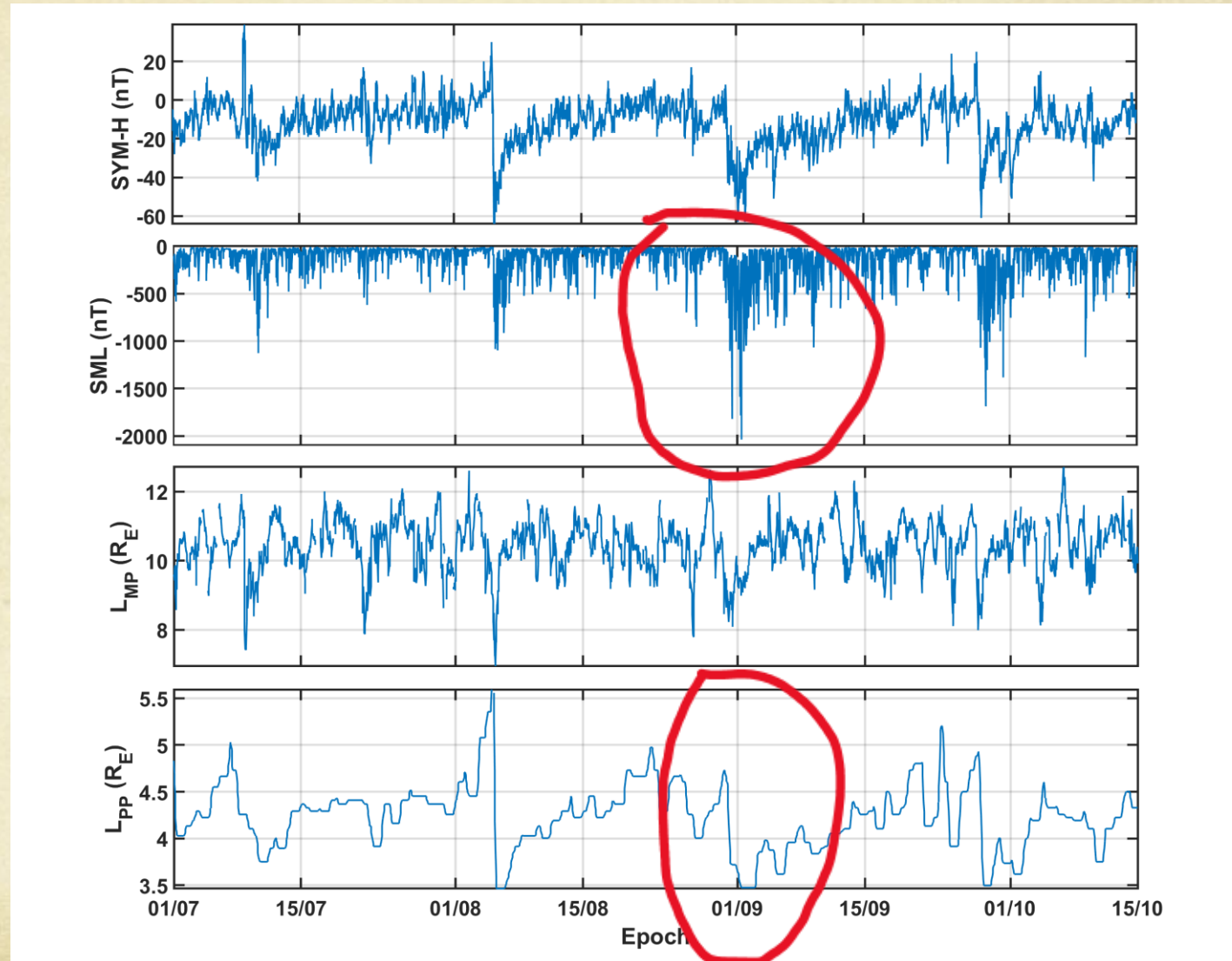
References

Substorms and plasmapause location



Nasi et al., *Frontiers in Astronomy and Space Sciences*, 2022

Substorms and plasmapause location

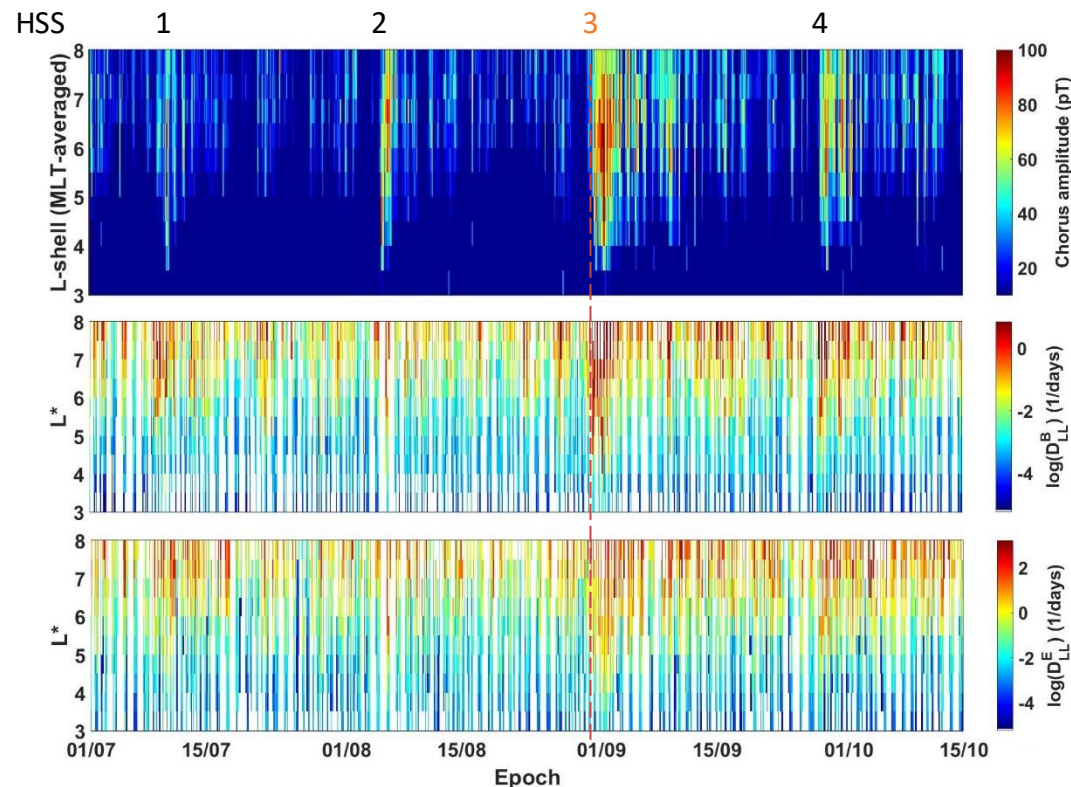


Nasi et al., *Frontiers in Astronomy and Space Sciences*, 2022

ULF & VLF wave parameters

The **third HSS pulse** was associated with:

- 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 us to believe that this will not significantly affect the nature of our results.

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

POES & MetOp

THEMIS

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

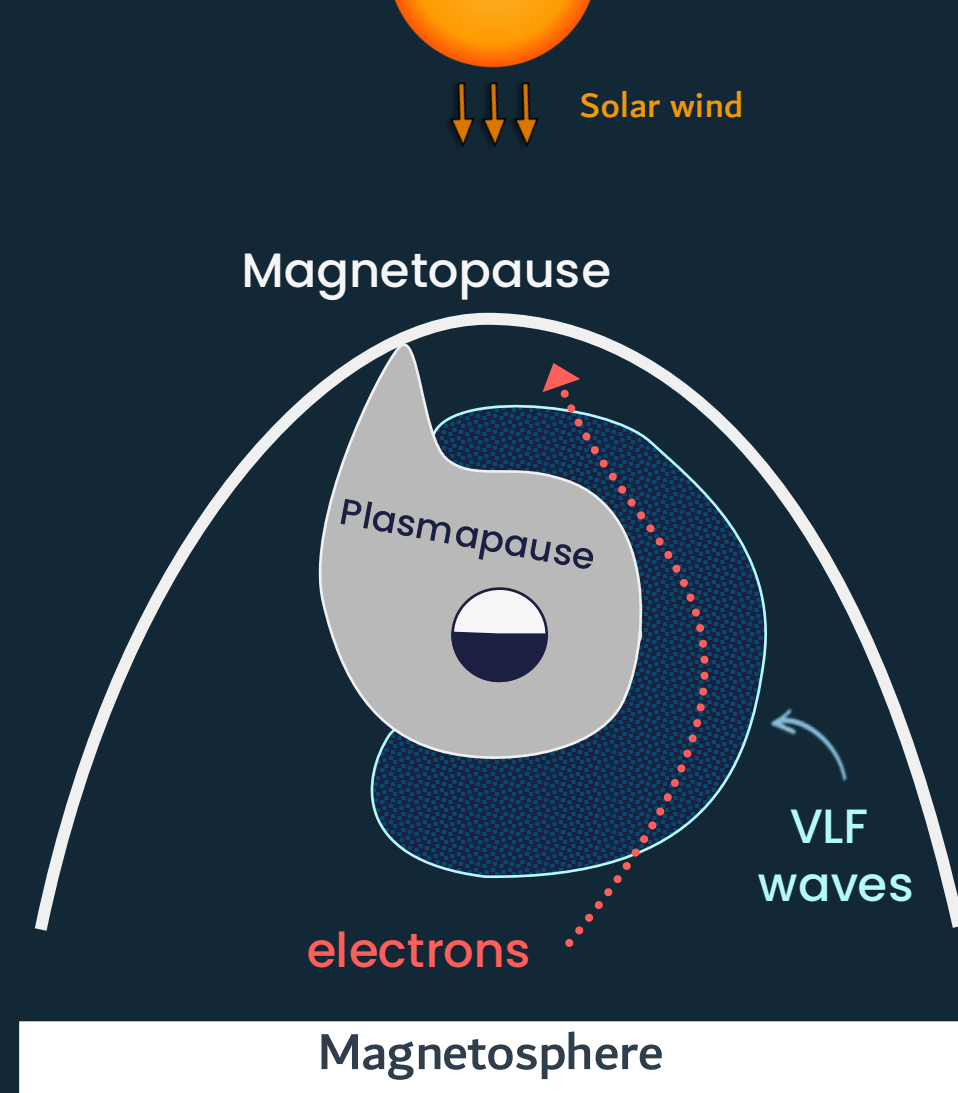
VLf WAVES

- Natural magnetospheric plasma waves
- Propagate in the whistler-mode
- Usually generated near geomagnetic equator

Helliwell 1965, 1967; Rycroft 1972, Barr+ 2000

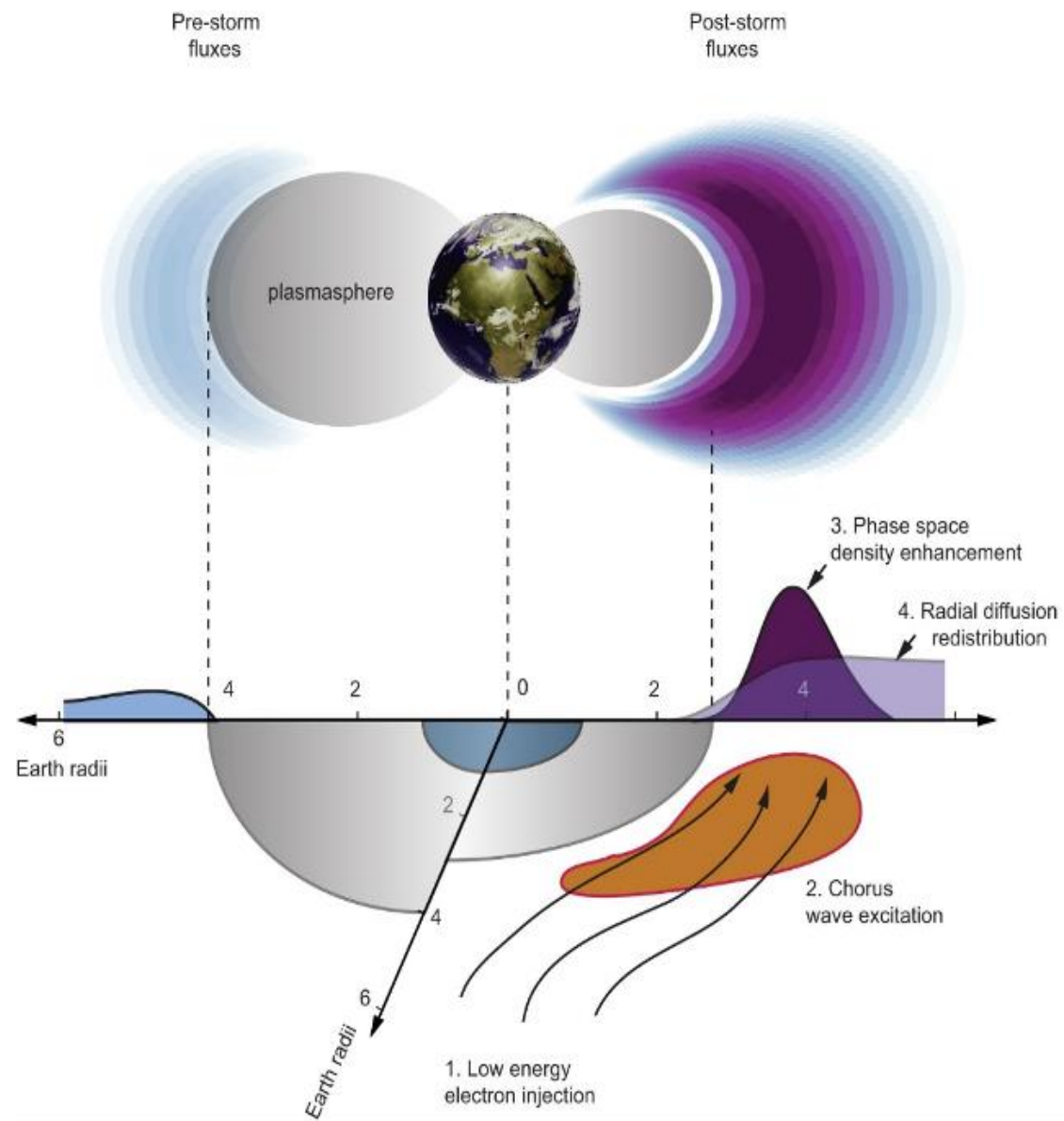
- Accelerate or scatter electrons through wave-particle interactions.
- Mediators for different energy populations

Major role in radiation belt dynamics!

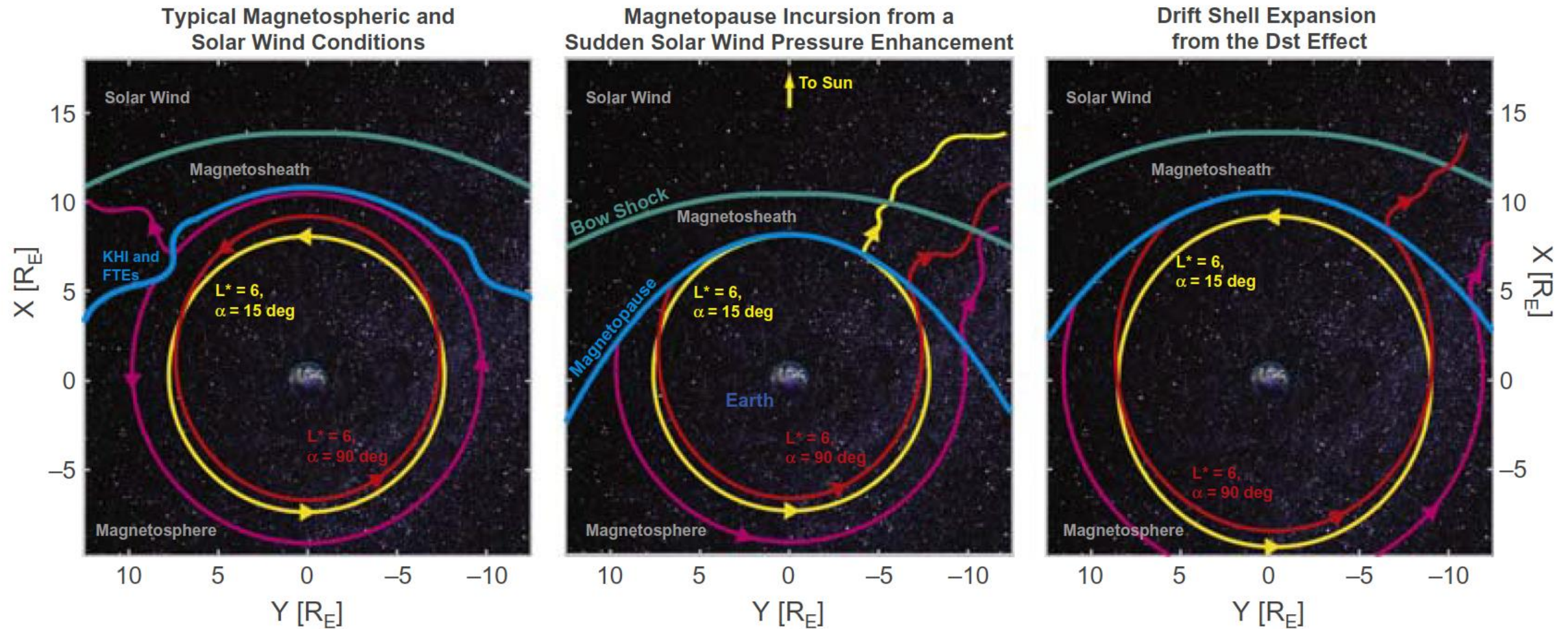


Adapted from [Reeves 2007]

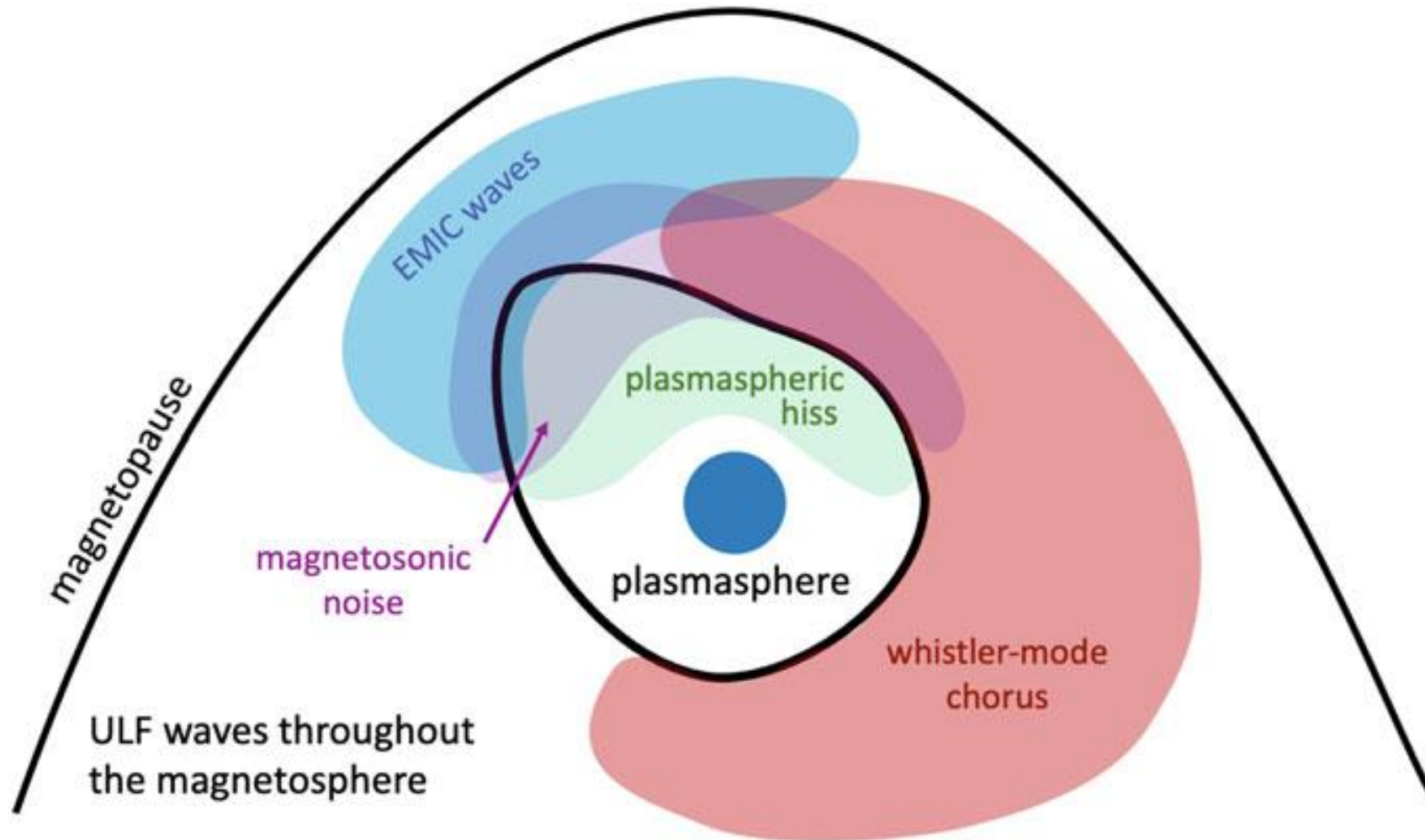
VLf waves in the magnetosphere



Outer radiation belt losses by magnetopause incursions and outward radial transport: new insight



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 ($\sim n_p, v_{ph}$)

**Thank you
for your
attention**

