複数衛星観測とシミュレーションデータ解析に基づくプラズマ波動の放射線帯変動への寄与

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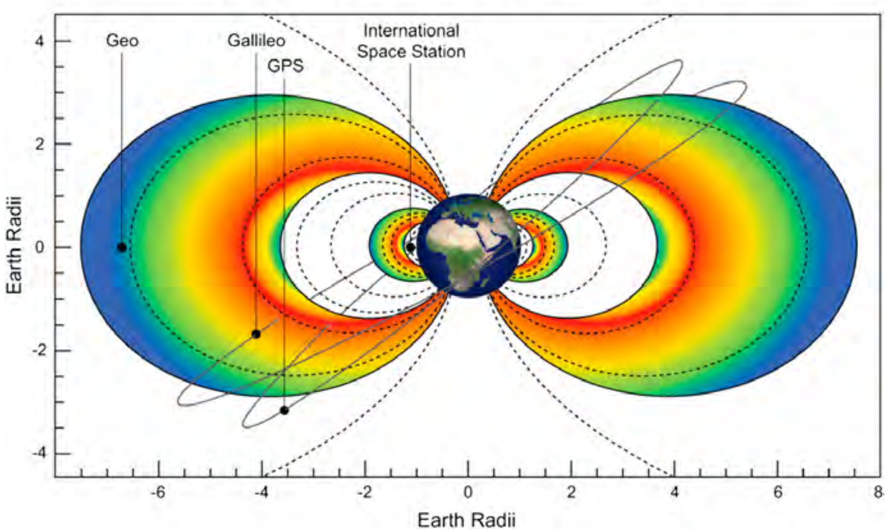
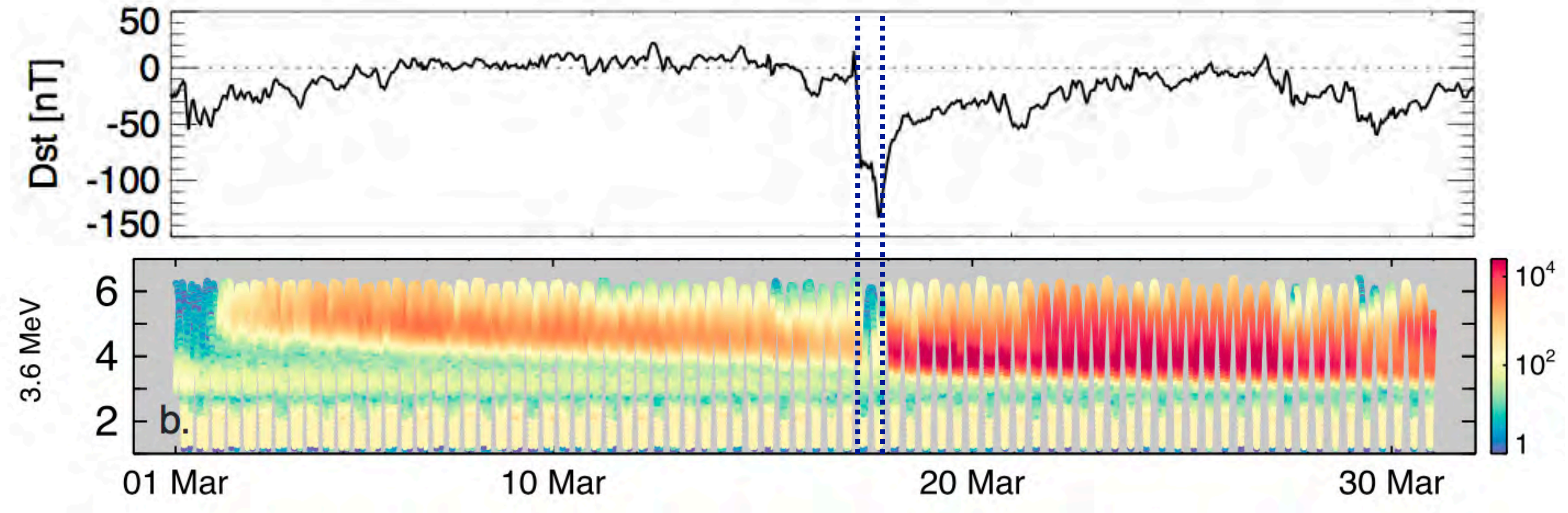
Radiation belt: MeV-energy particles are trapped

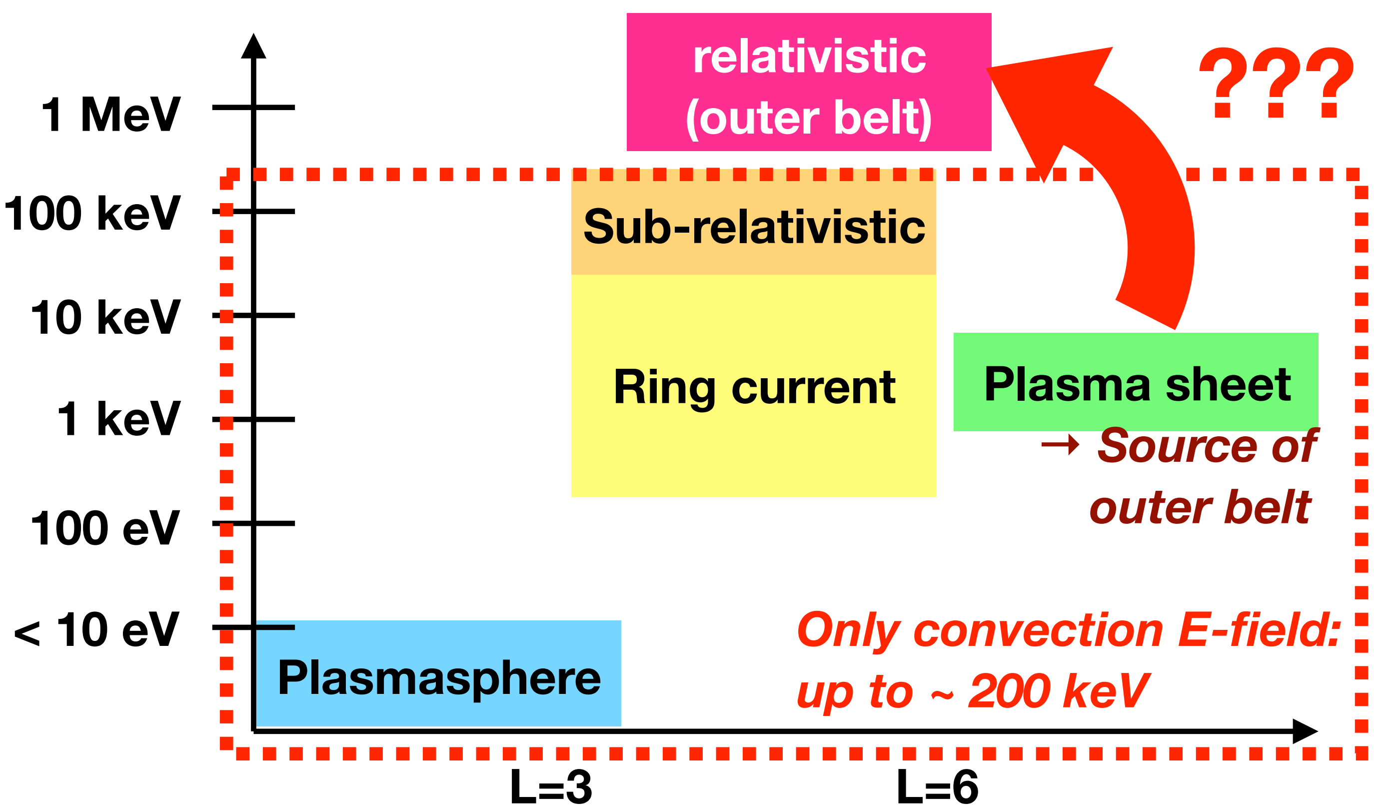
- MeV-electron fluxes enhance during the recovery phase of magnetic storm.



[Horne+2013]



[Modified from Baker+2014]



[Modified from Miyoshi+2012]

Question

How energetic particles accelerate up to relativistic energies?

Electromagnetic waves contributes to the particle acceleration

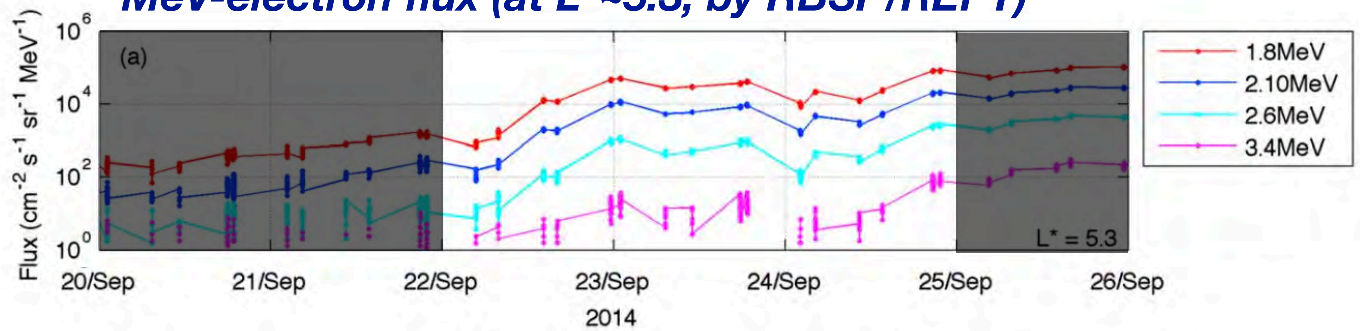
Contribution of waves to the particle acceleration

1. Radial diffusion by Pc5 ULF waves

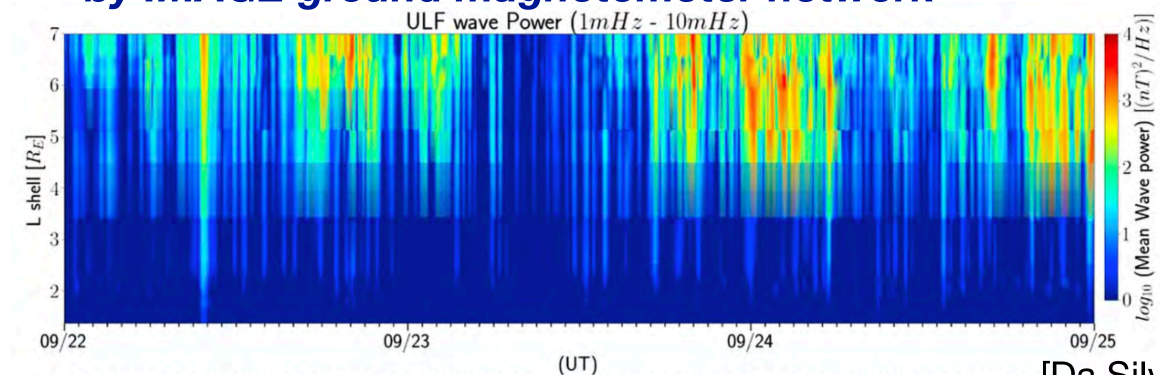
- Periodic waves with 1.6-6.7 mHz
- Pc5 ULF waves are globally seen.

- Source:
  - Magnetospheric compression by Psw
  - Kelvin-Helmholtz instability
  - ring current plasma by substorm injection

MeV-electron flux (at L*~5.3, by RBSP/REPT)



ULF wave power (1-10 mHz), by IMAGE ground magnetometer network



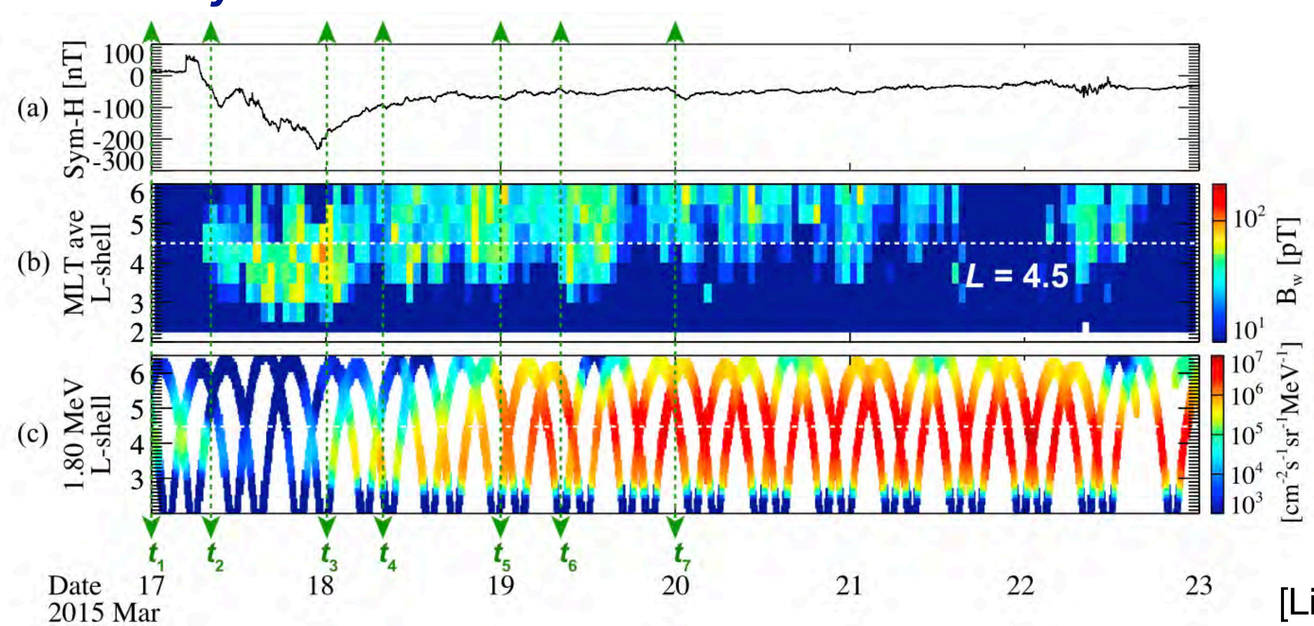
[Da Silva+2019]

2. Local acceleration by whistler-mode chorus waves (~0.1 f_{ce} - f_{ce})

- Chorus waves evolve due to the temperature anisotropy ($T_{perp}>T_{para}$)

- Source: 10s keV electrons

By Van Allen Probes



Chorus wave power

1.8 MeV flux

[Li+2016]

Purpose of this study

Electromagnetic waves play a crucial role in accelerating electrons up to relativistic energy.
However,…

how much these waves affect the radiation belt variation?
→ still few papers that compare between both contributions

- When, where, and how ULF and whistler-mode chorus waves contribute to the MeV-electron flux enhancement?
- Can ***the physical-based model (i.e., MHD model)*** reproduce global distributions of ULF and chorus waves?
- Can simulation parameters predict observed wave activity?

1. Global characteristics of ULF waves: March 2017 magnetic storm
2. ULF waves vs. Whistler-mode chorus waves: May 2017 magnetic storm

BATS-R-US + CRCM

[coupling method: Buzulukova et al., 2010; Glocer et al., 2013]

Global magnetosphere

BATS-R-US

(Block-Adaptive-Tree Solar-Wind Roe-Type Upwind Scheme)

- ***Ideal MHD equations***
  (continuity, momentum, Maxwell's equations)
- Cartesian grid
- Huge size of simulation box
  32 R_E (upstream) - 224 R_E (downstream)

[Powell et al., 1999; Toth et al., 2012]

magnetic field
temperature
density

Pressure

Inner magnetosphere

CRCM

(Comprehensive Ring Current Model)

- ***Bounce-averaged Boltzmann equation***
  → temporal variation in the phase space density of ring current species
- Assumption of gyrotropic & anisotropic conditions for the pressure tensor
- ***Magnetospheric electric field is self-consistently solved.***
- connect to the ionosphere (2.5 R_E)
  → Ionospheric potential is estimated by assuming the dipole field, which maps back to the magnetic equator.

[Fok et al., 2001]

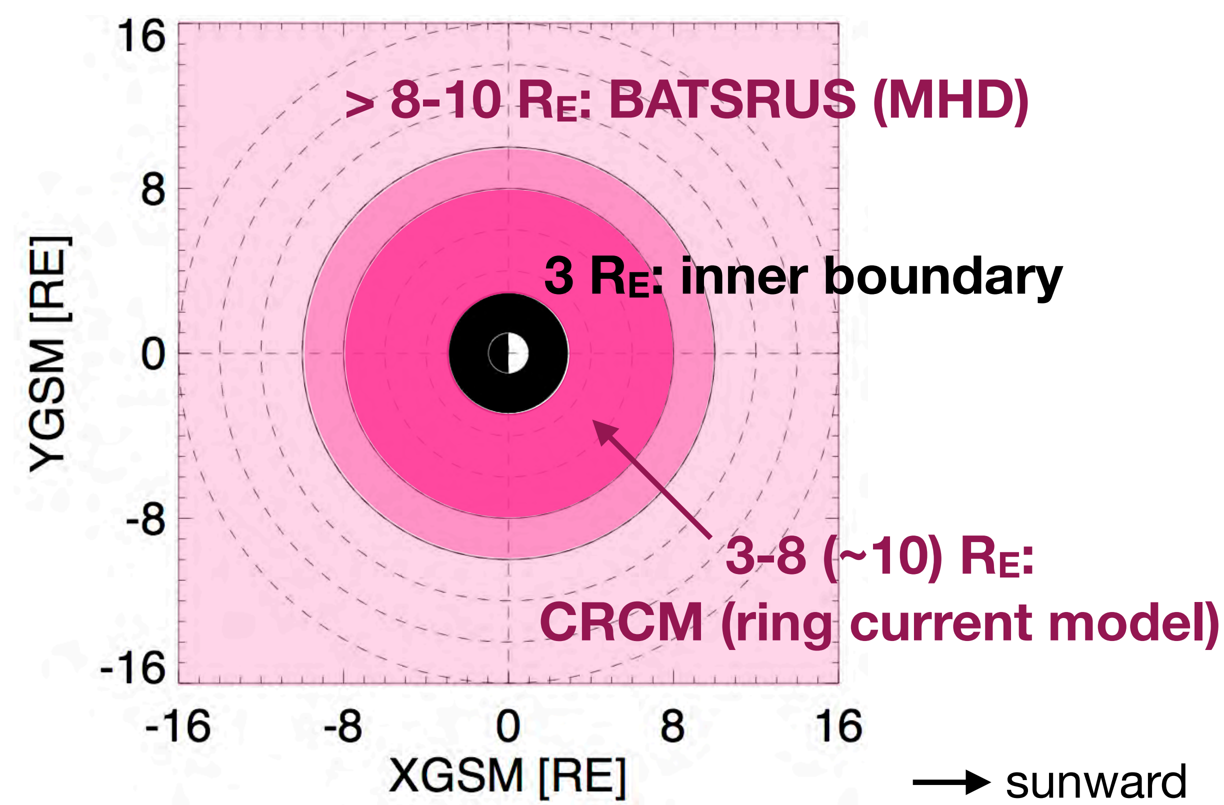
Initial condition

Solar wind input — For BATS-R-US

- Real solar wind parameters
- Only IMF Bx is fixed (average).
- The dipole tilt is included.

Particles — For CRCM

- ion: Maxwellian, electron: Kappa
- no temperature anisotropy (even boundary)



Resolution of output files

- Both time and spatial resolutions are increased only in the inner magnetosphere ($|x, y, z| \leqq 15$ R_E)
  - BATSRUS (MHD)
    5 seconds, 0.15 R_E at finest → to reproduce Pc5 ULF waves (1.7-6.7 mHz)
  - CRCM (ring current)
    10 minutes, 1/3 R_E

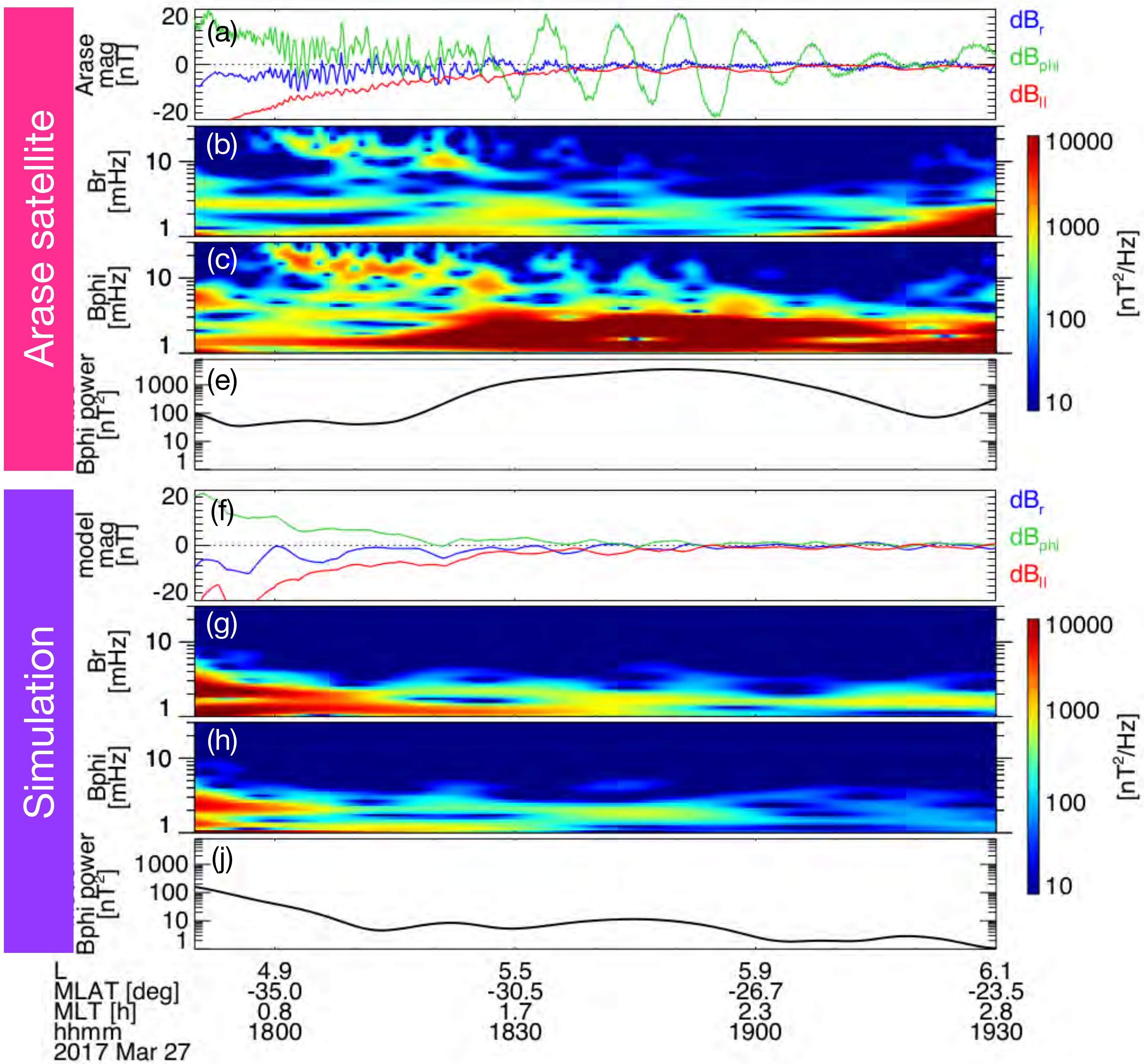
1. Global characteristics of ULF waves

Reference

Takahashi, N., Seki, K., Teramoto, M., Fok, M.-C., Zheng, Y., Matsuoka, A., et al. (2018). Global distribution of ULF waves during magnetic storms: Comparison of Arase, ground observations, and BATSRUS + CRCM simulation. Geophysical Research Letters, 45. https://doi.org/10.1029/2018GL078857

‘Local’ comparison: Simulation vs. Arase

The simulation can reproduce the enhancement of ULF waves in B_{phi} (frequency: 2-3 mHz). → **consistent with Arase**

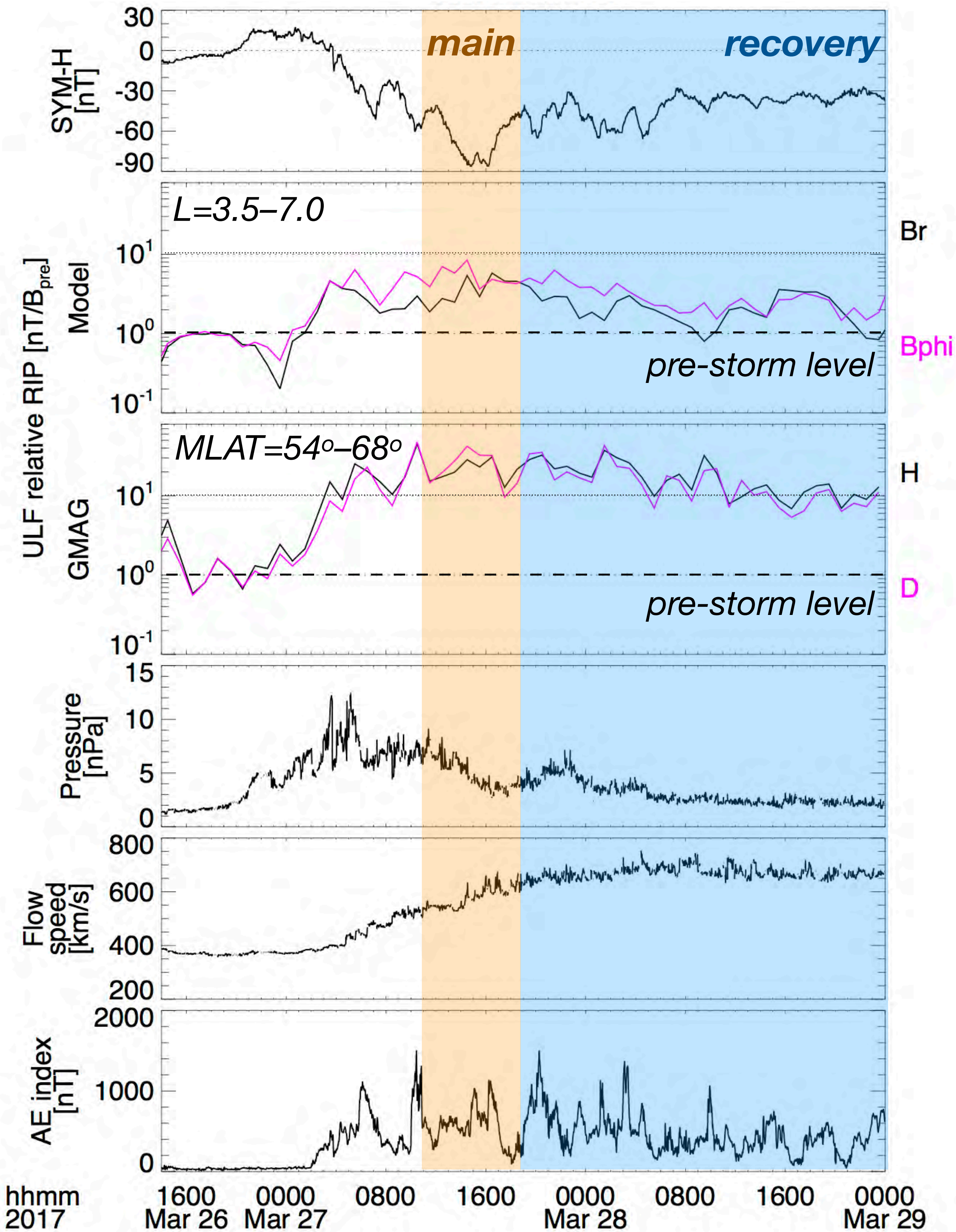


Discrepancies

- smaller amplitude of ULF waves
  → large numerical dissipation
- No higher-frequency waves (10-30 mHz)
  → low temporal resolution of solar wind input parameters (~1 min)

*background: 15-min running average

‘Global’ comparison: Relative ULF activity



Pc5-range ULF wave activity

	simulation	GMAG
main	high	high
	↓	↓
recovery	(relatively) low	high
relate to…	**pressure**	**pressure + V_{SW} & AE**

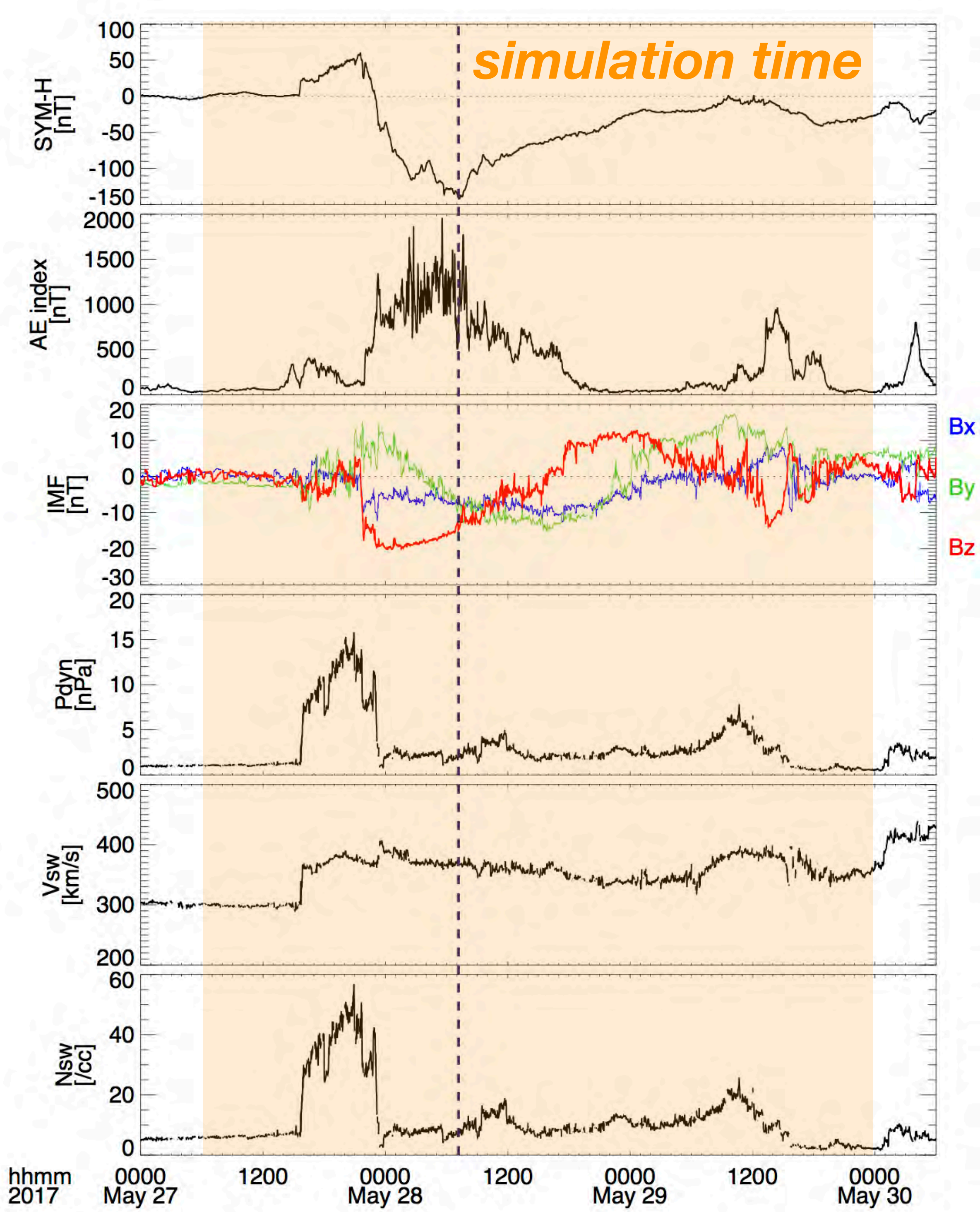
The simulated ULF wave activity is **strongly** affected by the solar wind dynamic pressure.

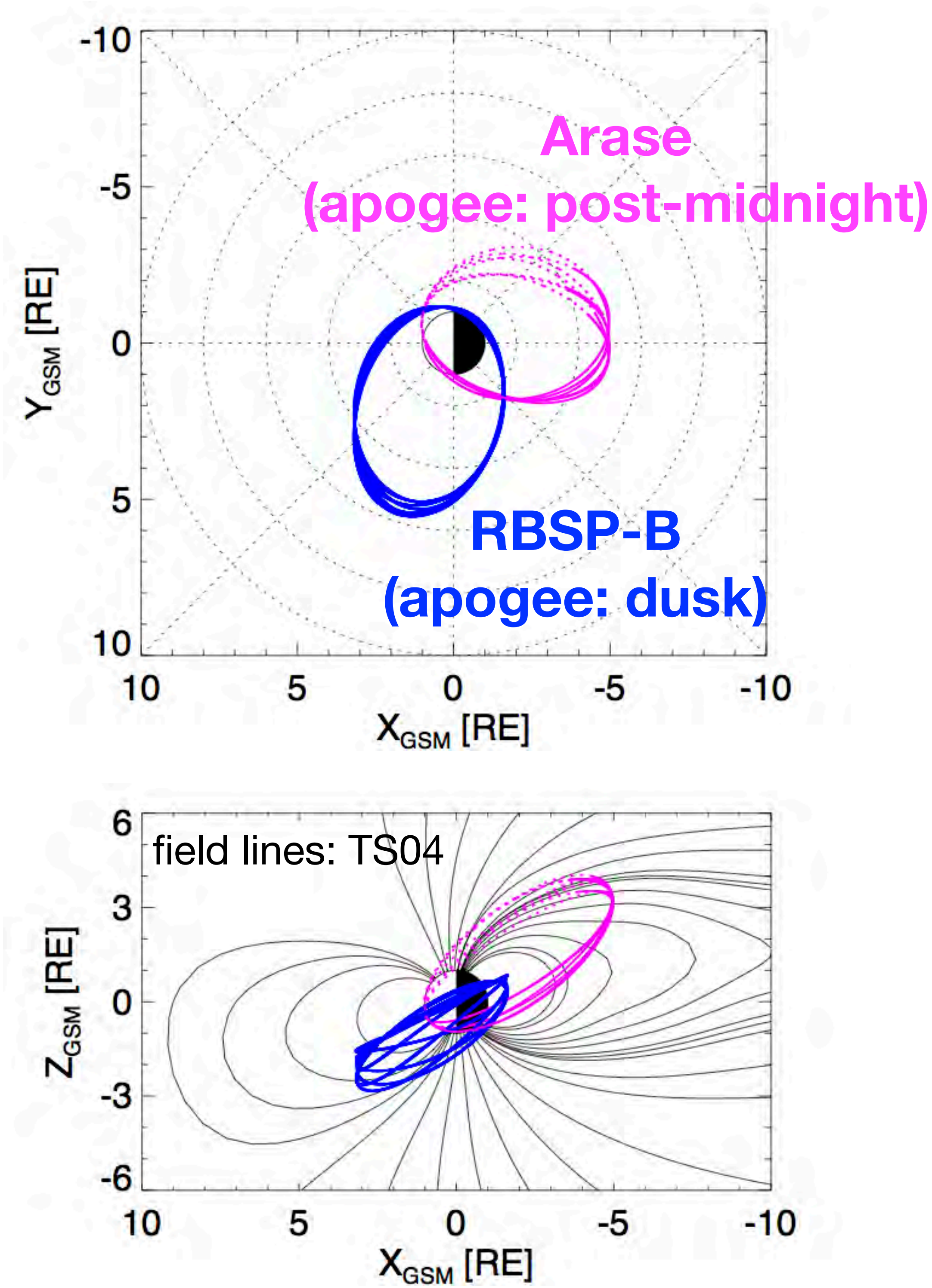
* ULF wave intensity:
normalized by 3-h average during the pre-storm

2. ULF waves vs. Whistler-mode chorus waves

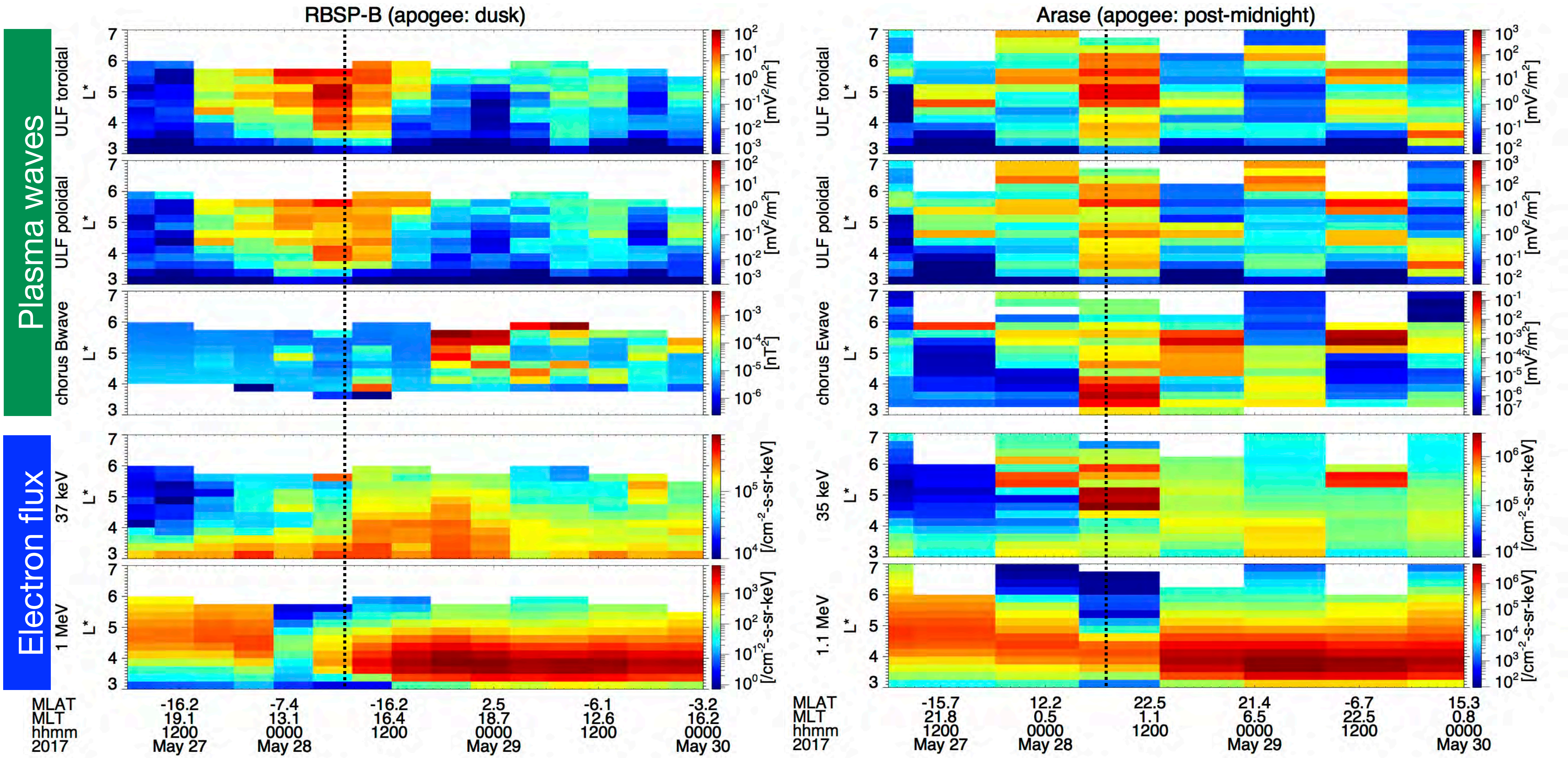
<u>Target event: May 2017 magnetic storm</u>

→ ***Suitable for understanding global characteristics of waves***





Observation: L-value dependence

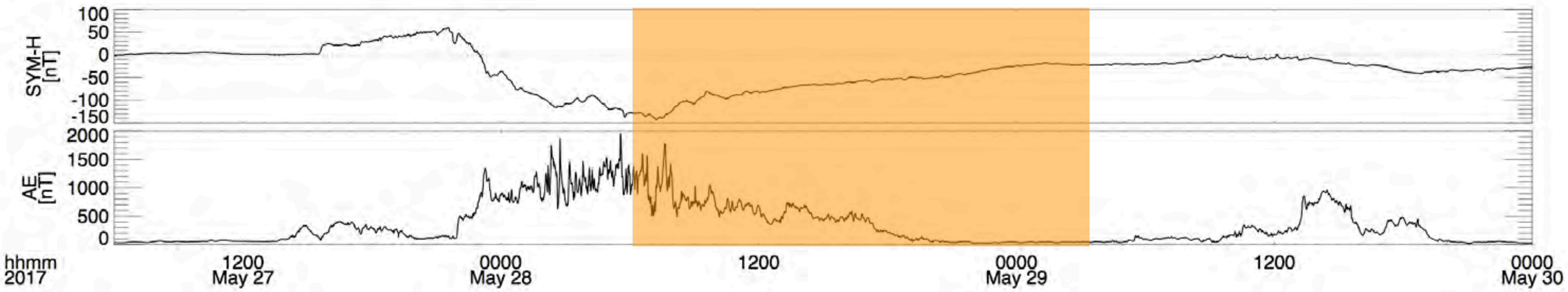


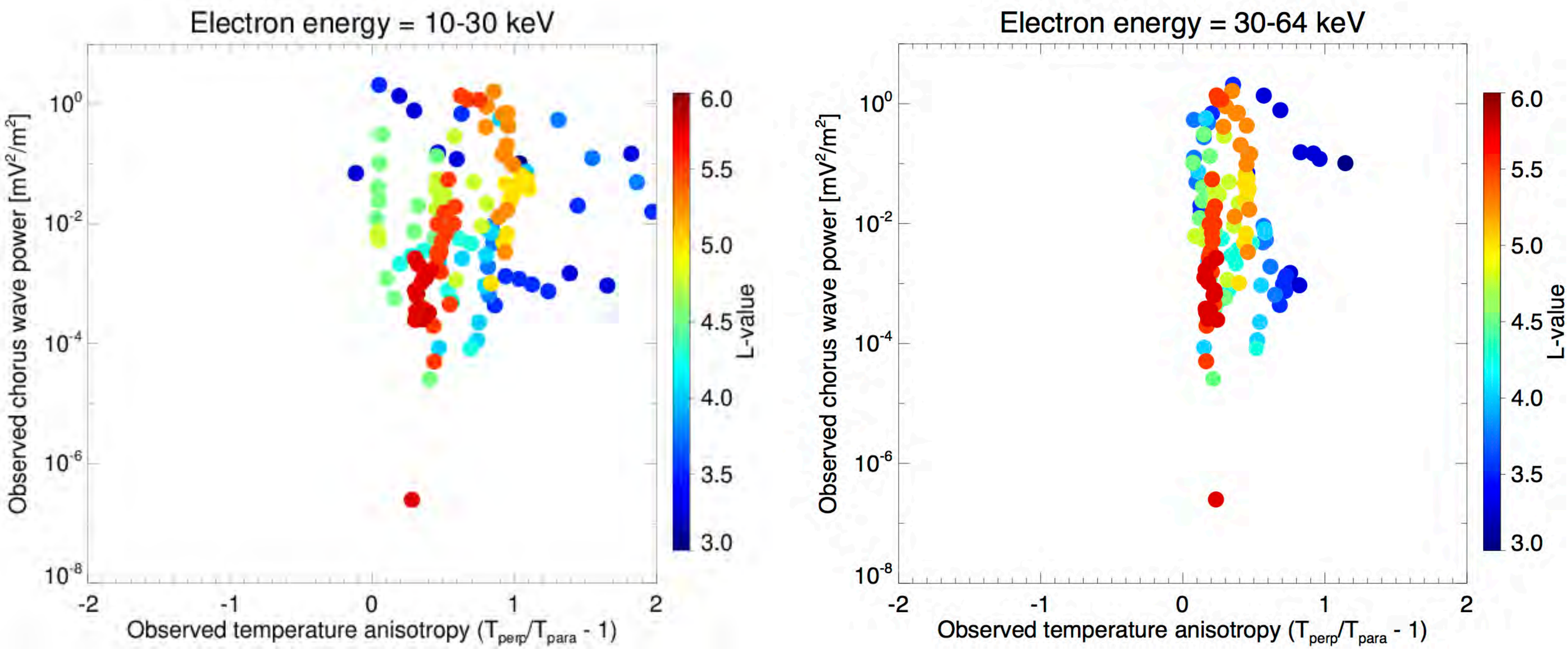
dotted line: minimum of Dst index

Arase: use only outbound-pass data due to high inclination in the inbound pass

- ULF: (main phase and) **early recovery** phase
- chorus: **late recovery** phase

Observation: Temperature anisotropy vs. chorus wave power

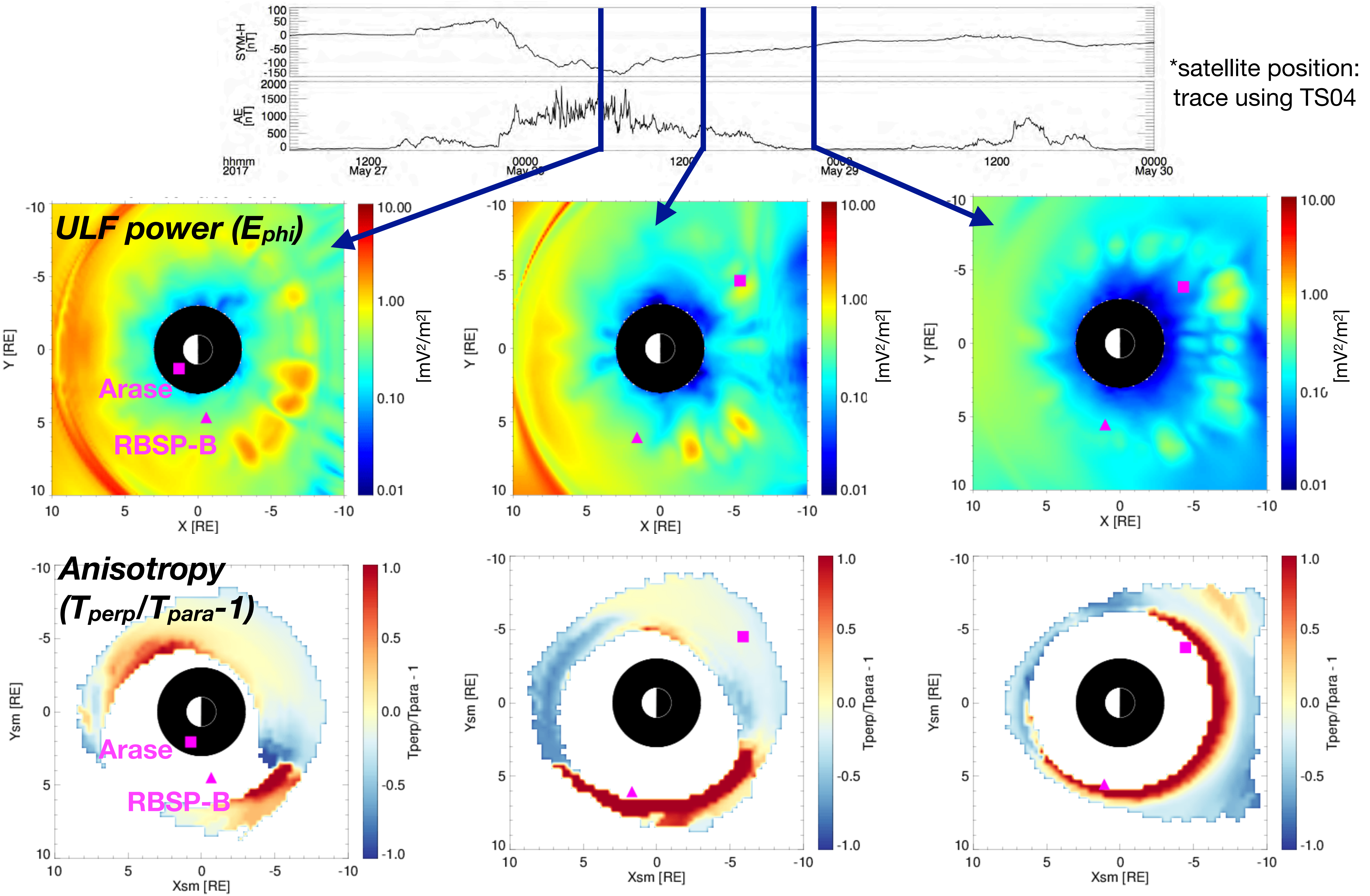




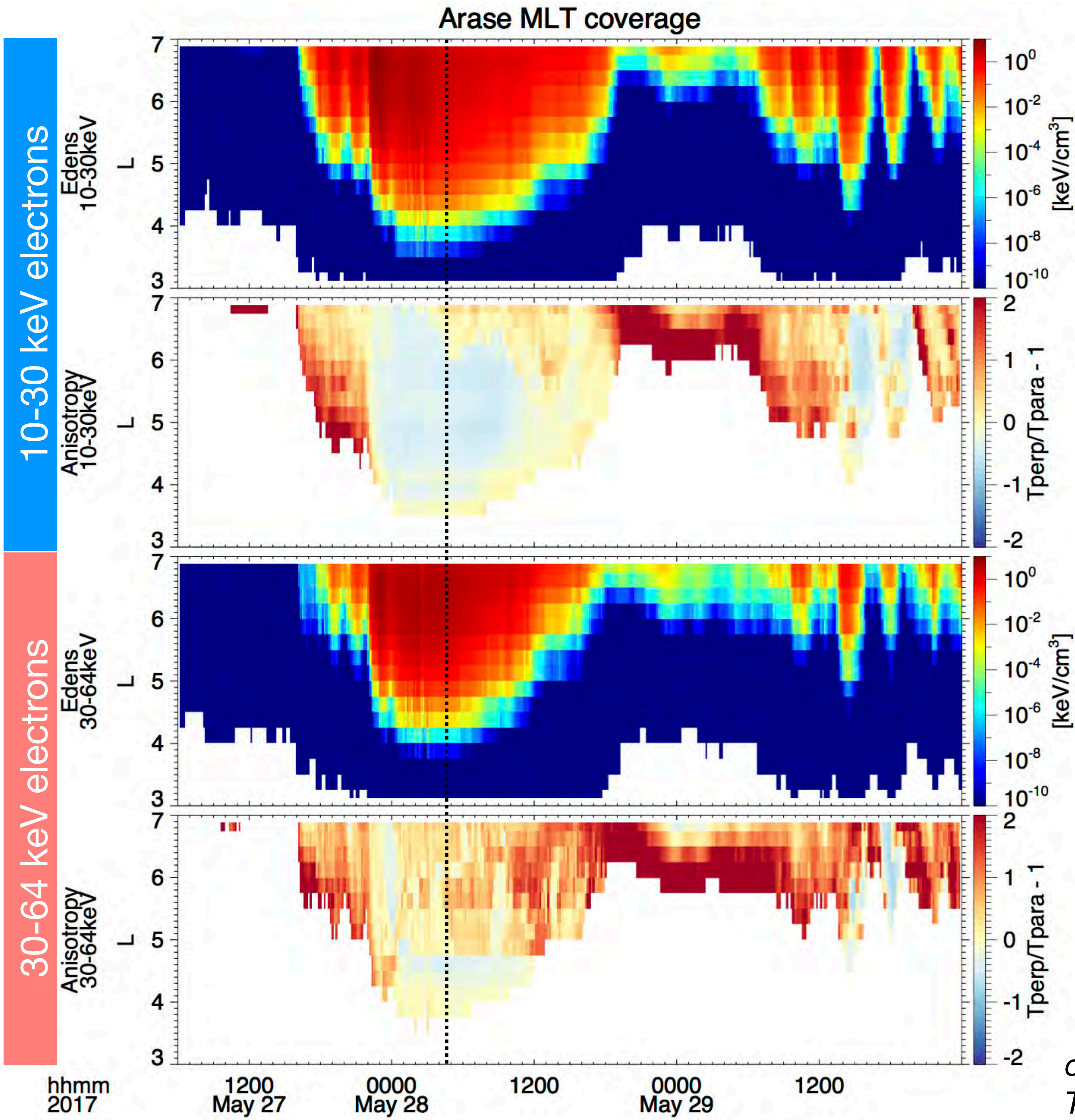
From MEP-e/Arase: Energy-dependent structure is seen.

- L~5.0 - 5.5: 10-30 keV
- L~3.5 - 4.0: 30-64 keV

Simulation: 2D map@magnetic equator



Can simulation predict observed chorus waves?



Energy-dependent structure is seen.

- L~5.0 - 5.5: 10-30 keV
- L~3.5 - 4.0: 30-64 keV

→ Consistent with observation

Recovery phase

- Quite low electron flux at low L-shell (why?)

dotted line: minimum of Dst index

Threshold: Energy density = 10^{-10} keV/cm^3

Summary

Physics-based simulation can qualitatively reproduce global characteristics of plasma waves.

For Pc5 ULF waves (= MHD waves)…

- Small wave power in the simulation
  → Large numerical dissipation
- Higher-frequency waves cannot be reproduced in the simulation.
  → low temporal resolution of solar wind input parameters (~1 min)
- No enhancement of simulated ULF wave power is seen during the main phase.
  → Simulation strongly affects to the solar wind dynamic pressure variation.

For whistler-mode chorus waves (=VLF waves)…

- Energy-dependent characteristics are seen.
- At low L-shell (L~4), the energy density of electrons is quite smaller than observation.