ULF wave observations in the inner magnetosphere

Michael Hartinger[1,2]

[1]Virginia Tech, [2]National Institute of Aerospace

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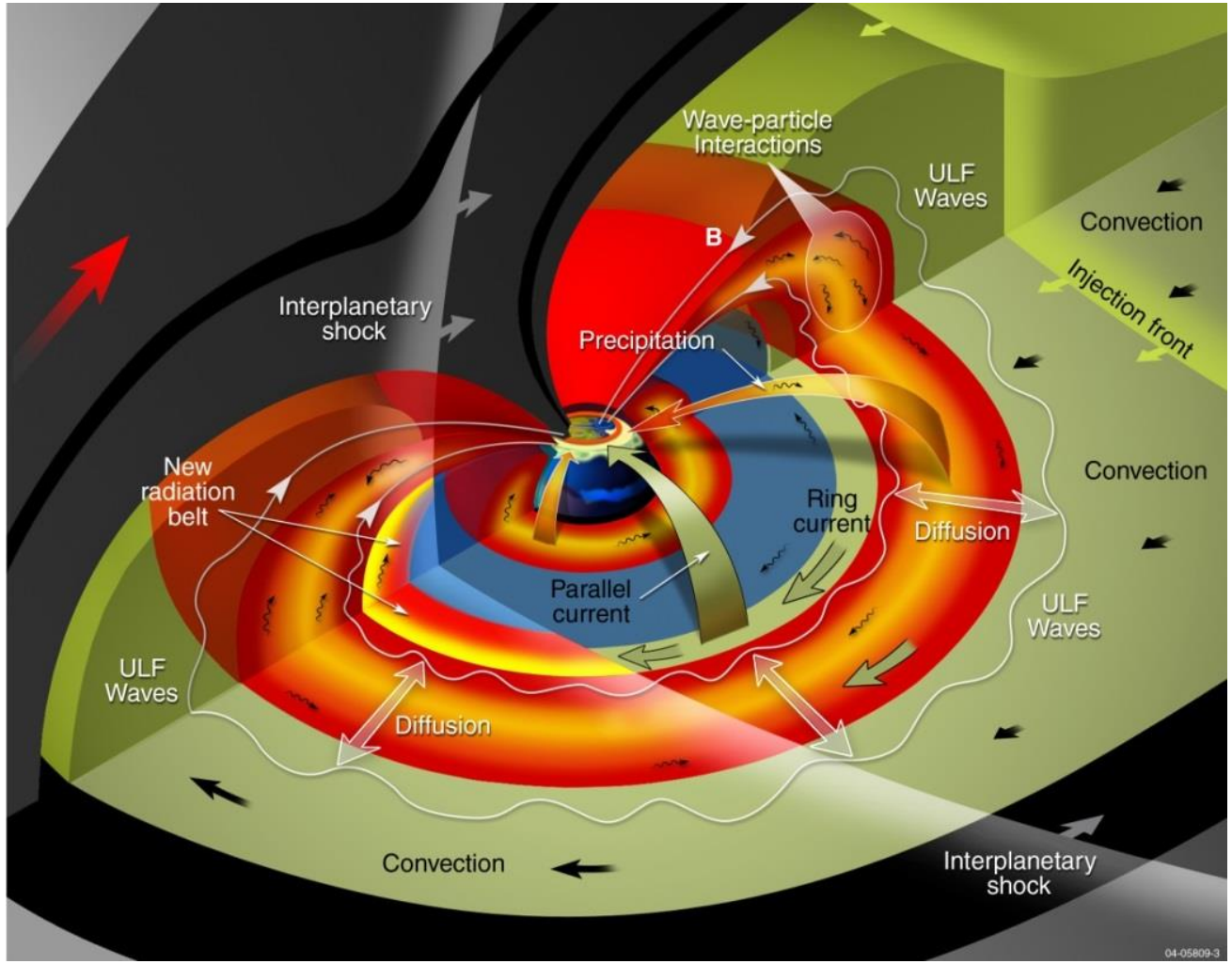
Ultra Low Frequency Waves

- Ultra Low Frequency (ULF) waves: plasma waves in the Earth's magnetosphere with absolute frequency less than 5 Hz (Jacobs et al., 1964)
- Largest wavelengths and lowest frequencies in system
- Space weather impacts including radiation belt/ring current interactions



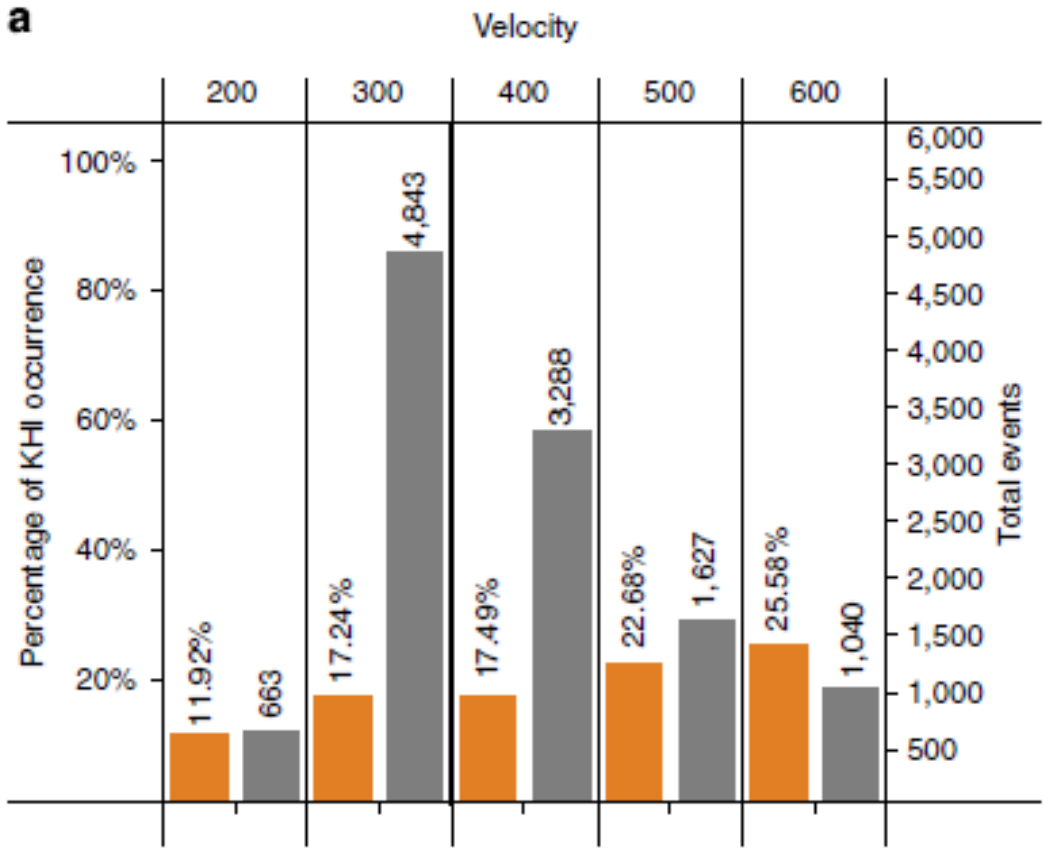
[Mauk et al., 2012]

“…the subject of hydromagnetic waves in the magnetosphere (or magnetospheres) is highly developed…” but
“…the subject is far from played out as a research field…”
Southwood and Hughes, [1983]

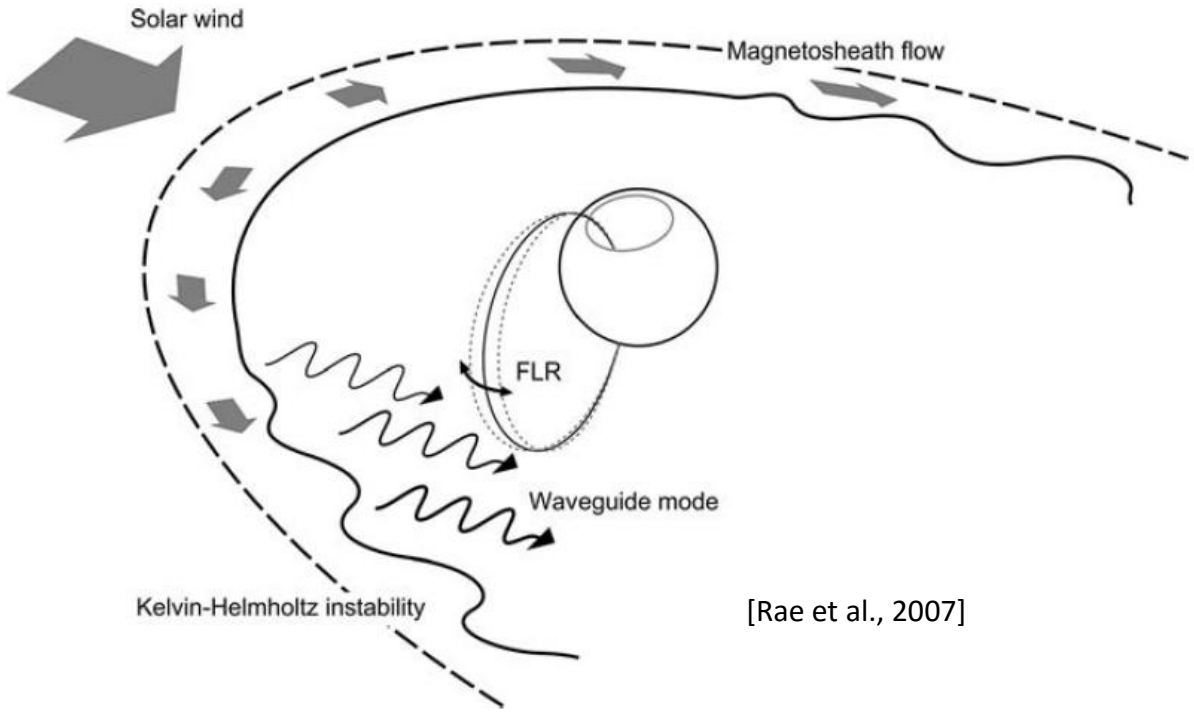
Outline

- Focus on recent advances, challenges, and open questions
- Focus on research related to over-arching questions:
  - What excites ULF waves?
  - How do ULF waves couple to the plasmasphere? Ring current? Radiation belts?
  - What is the role of ULF waves in Magnetosphere-Ionosphere Coupling?
- Introducing the new GEM focus group, “ULF wave modeling, effects, and applications”

What excites inner magnetosphere ULF waves?
Example: Magnetopause surface waves



[Kavosi and Raeder, 2015]

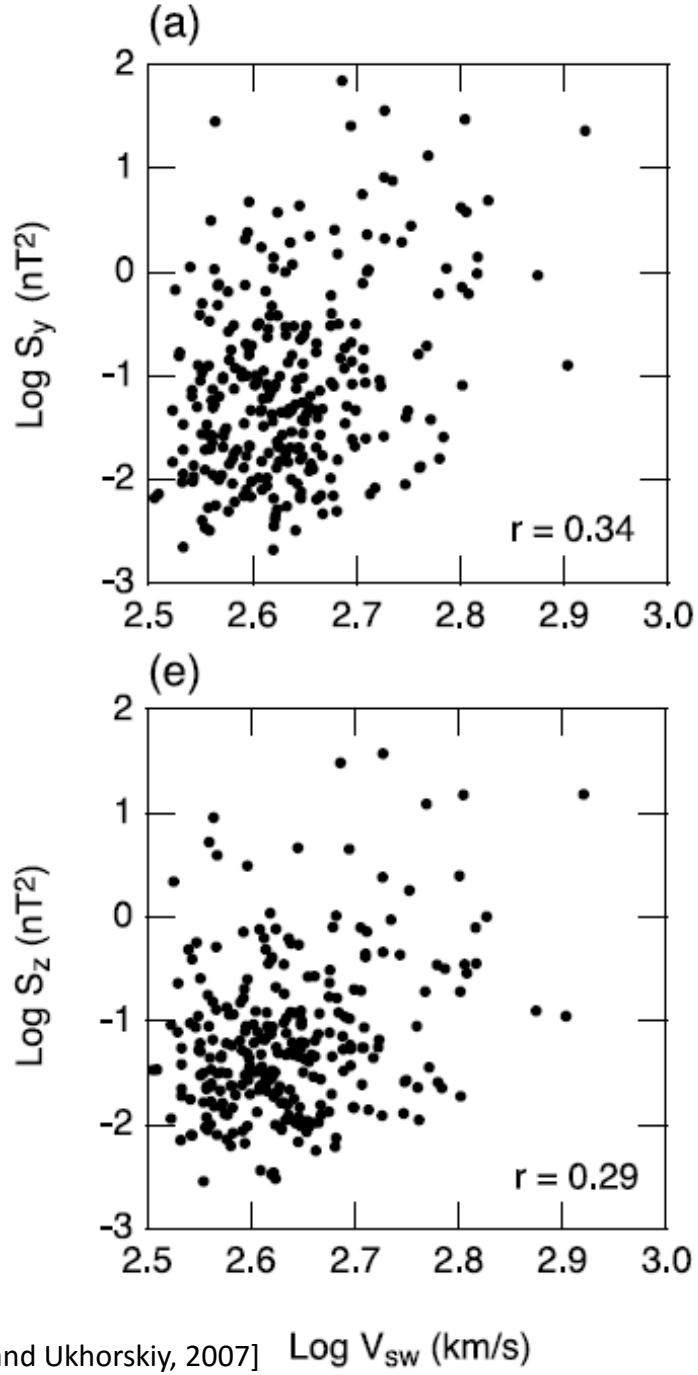


[Rae et al., 2007]

- Increasing availability of spacecraft observations near the magnetopause
- Statistics on magnetopause surface waves related to the Kelvin-Helmholtz instability - increased occurrence with increased flow shear
- These waves couple to inner magnetospheric ULF waves

What excites inner magnetosphere ULF waves? Example: Magnetopause surface waves

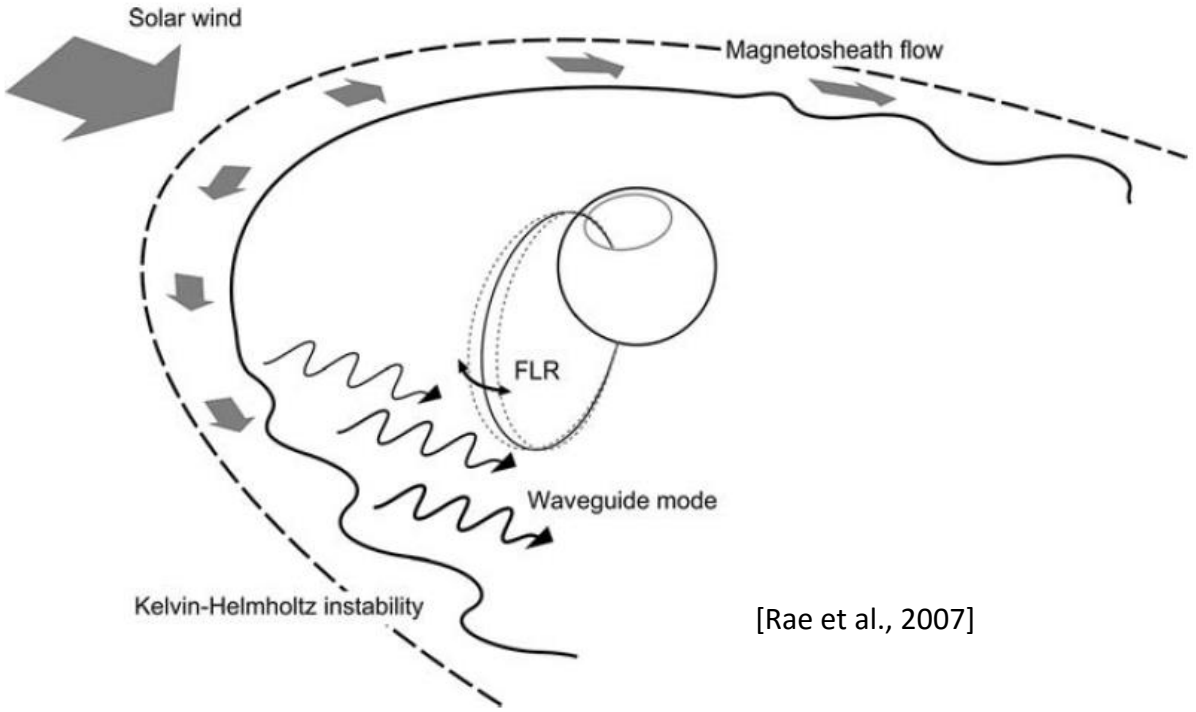
- Inner magnetospheric Pc5 (~2-7 mHz) ULF wave power and occurrence rate generally increase with solar wind flow speed in the flank magnetosphere
- Large amount of scatter in the trend



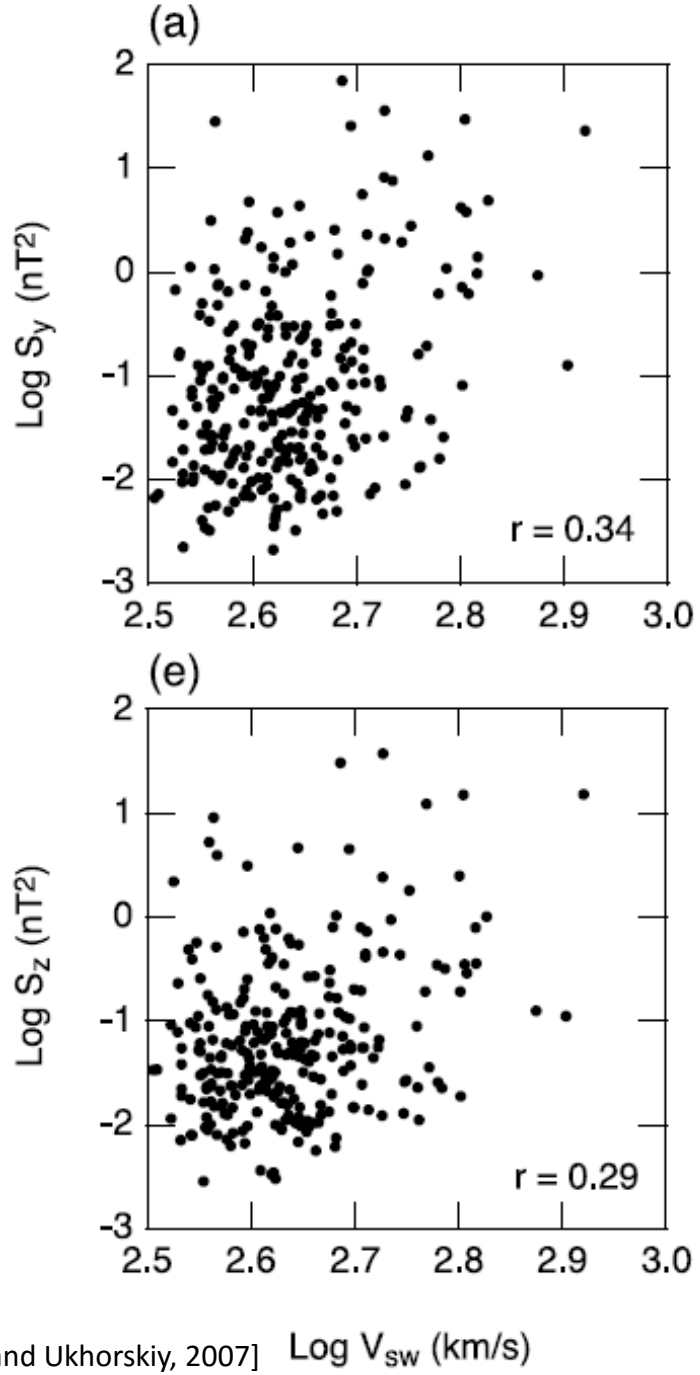
[Takahashi and Ukhorskiy, 2007]

What excites inner magnetosphere ULF waves? Example: Magnetopause surface waves

- Inner magnetospheric Pc5 (~2-7 mHz) ULF wave power and occurrence rate generally increase with solar wind flow speed in the flank magnetosphere
- Large amount of scatter in the trend
- Need more observations to explain scatter: role of seed fluctuations, magnetospheric Alfven speed and other factors



[Rae et al., 2007]



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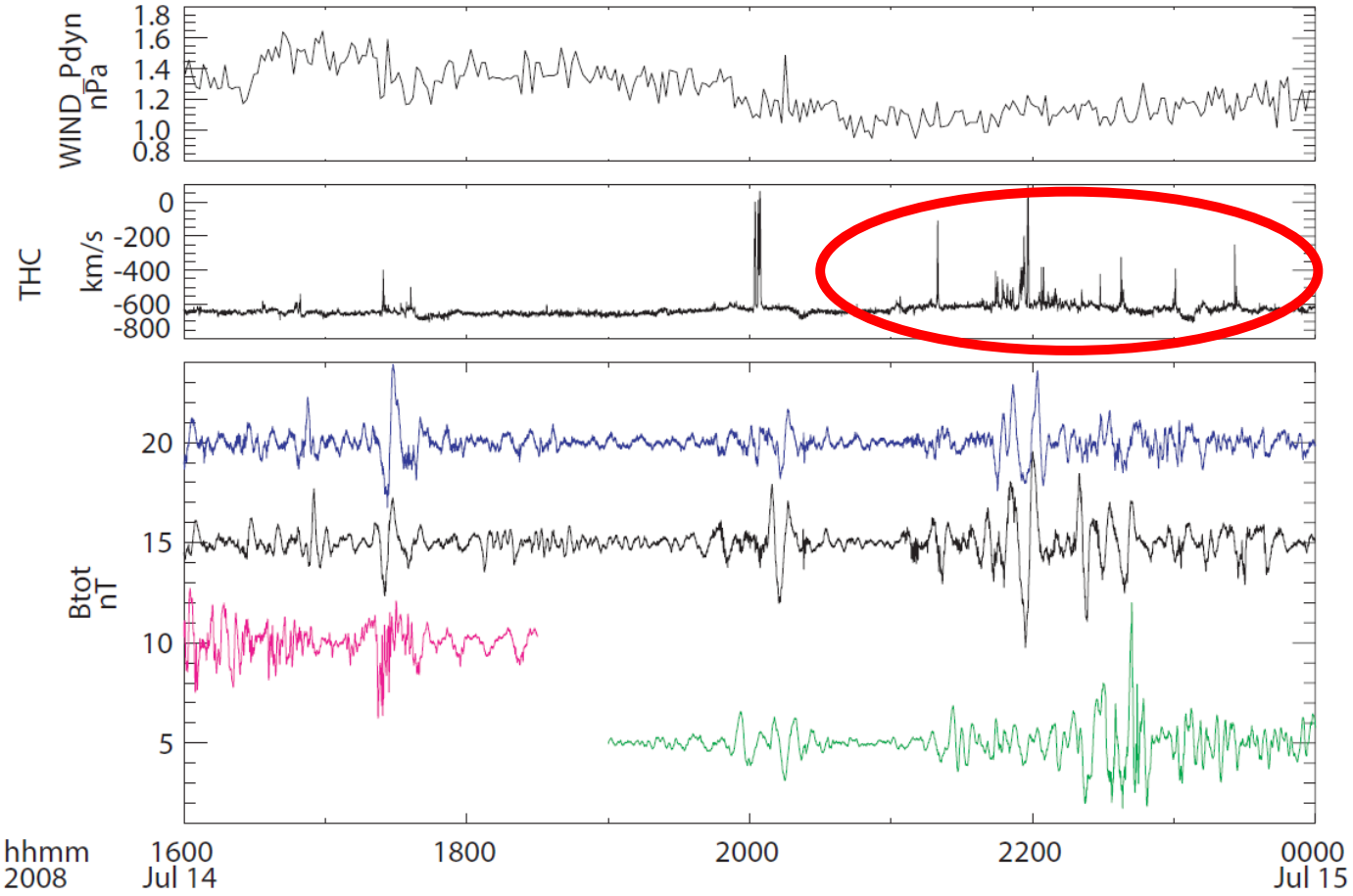
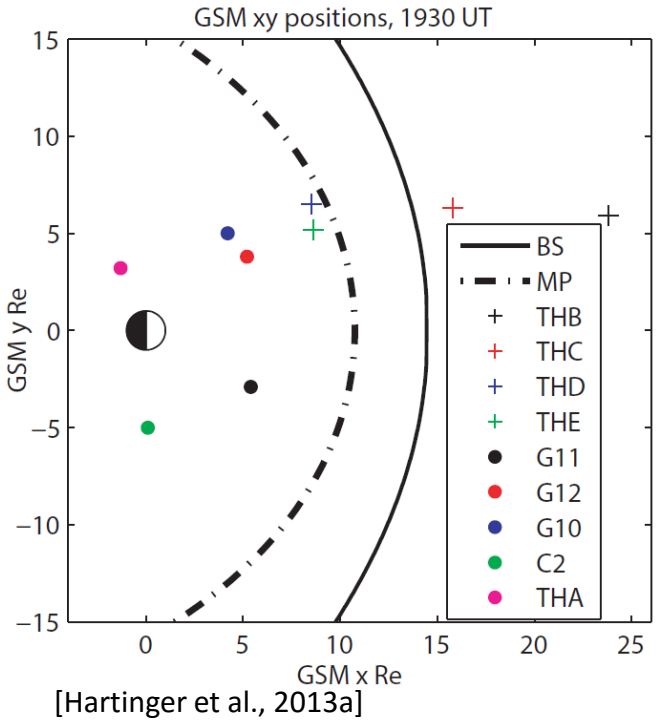
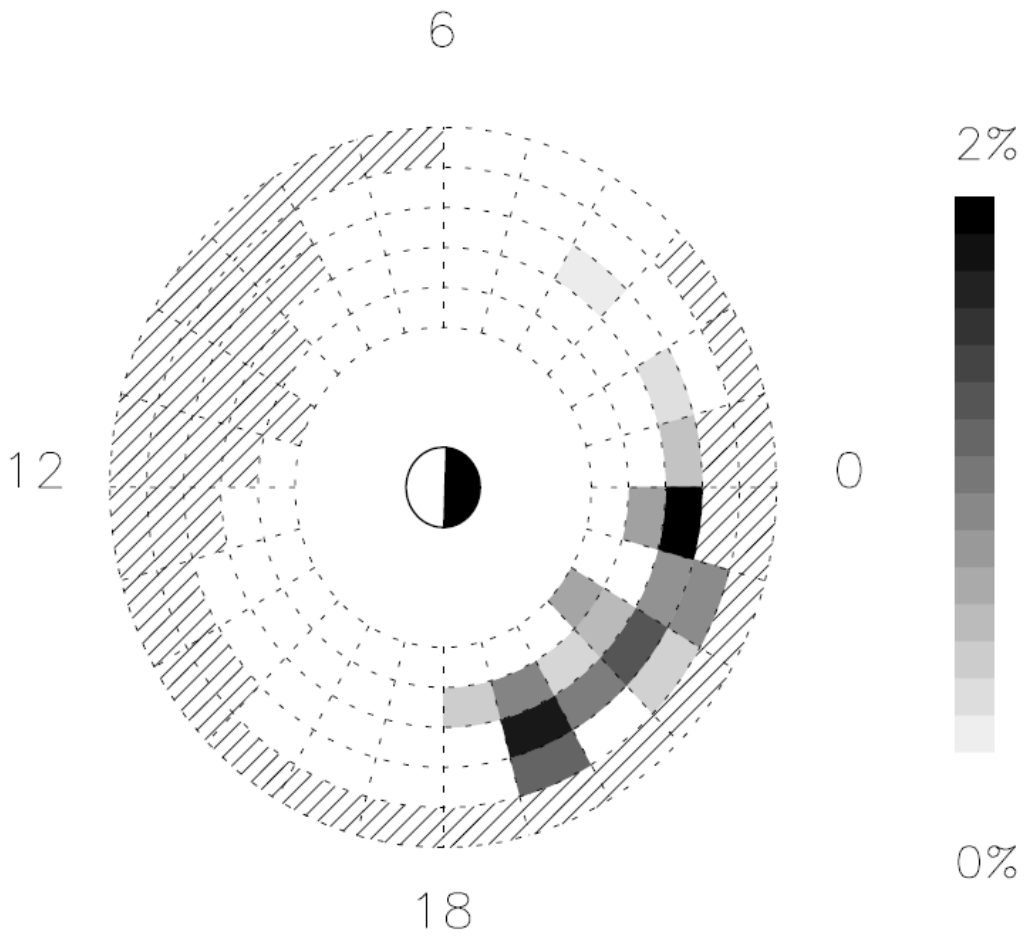




[Hartinger et al., 2013a]

- The ion foreshock can provide sporadic and/or nearly continuous impulses to seed the growth of magnetopause surface waves during high speed solar wind

What excites inner magnetosphere ULF waves? Example: Drift and Drift-bounce resonance



[Hudson et al., 2004]

- Inner magnetosphere second harmonic poloidal mode standing Alfven waves occur in the pre-midnight sector

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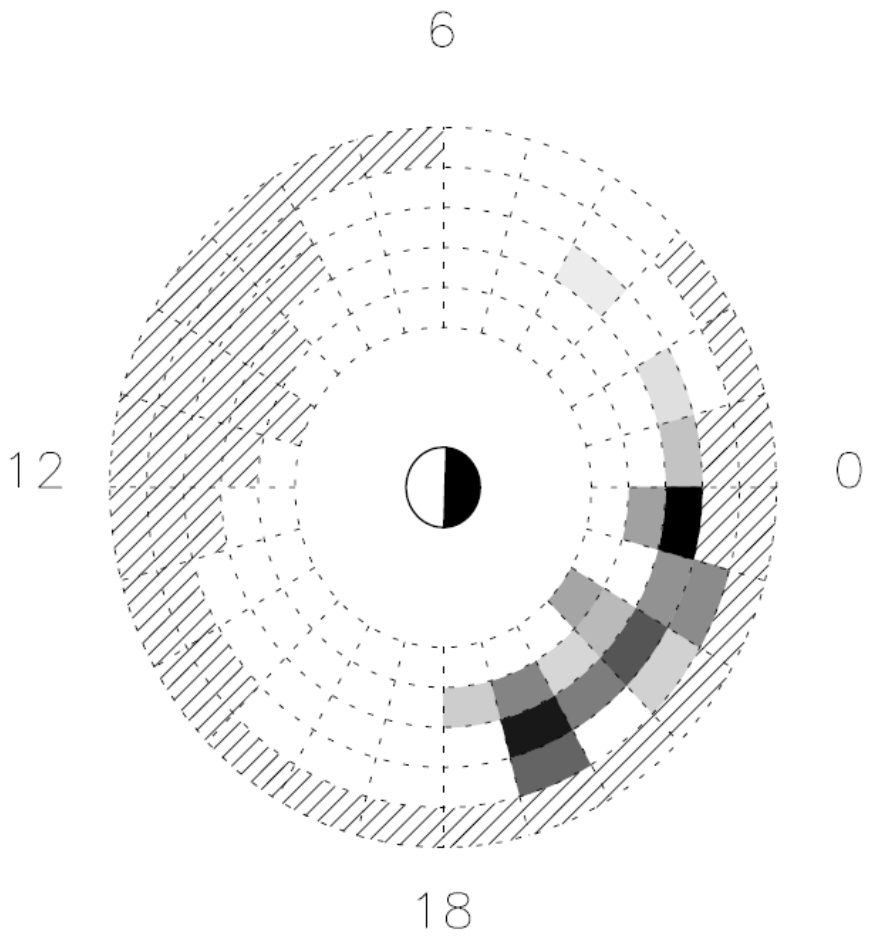

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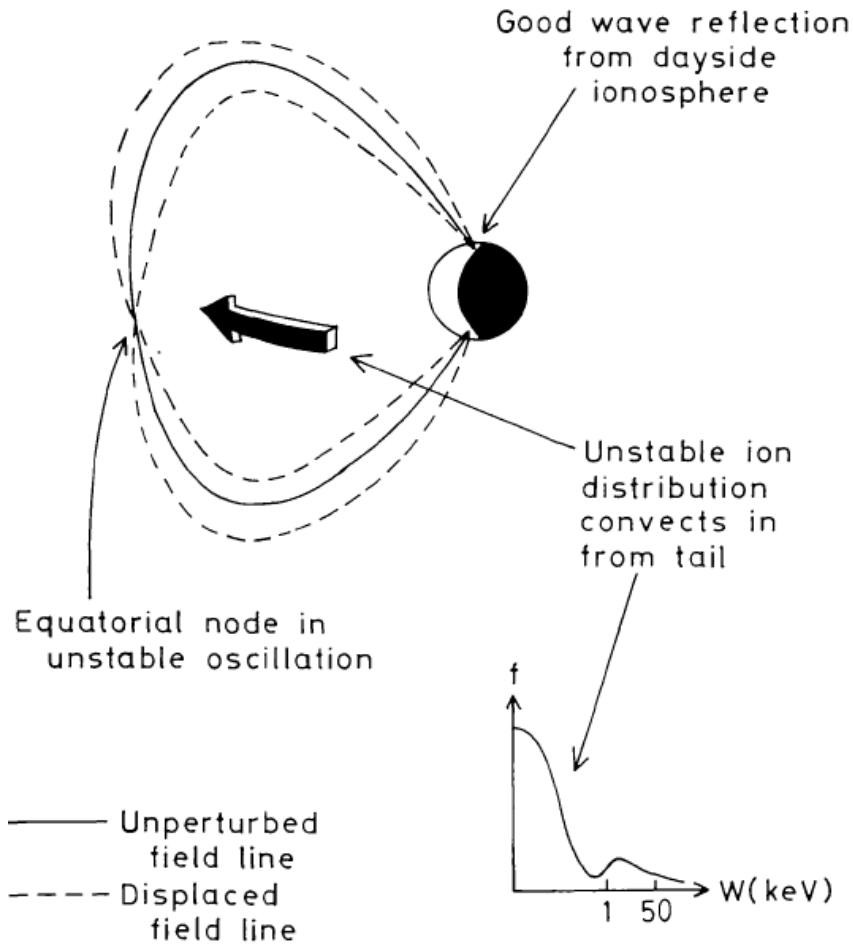
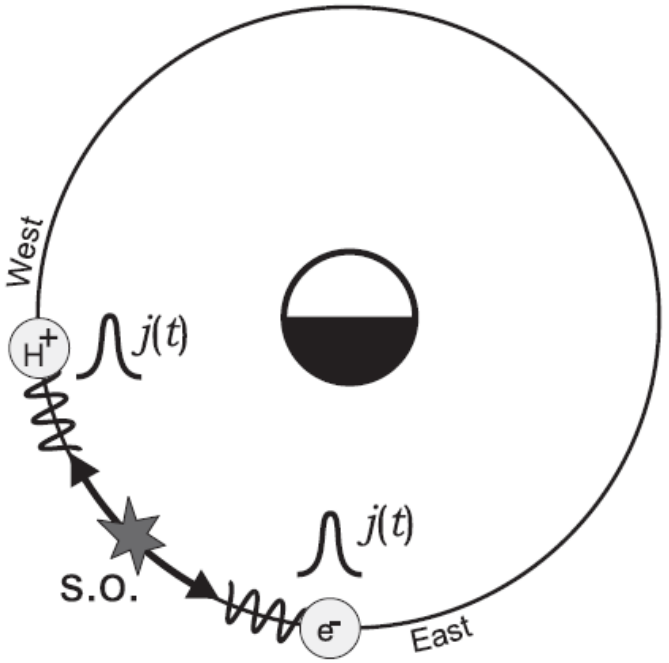


[Southwood and Hughes, 1983]

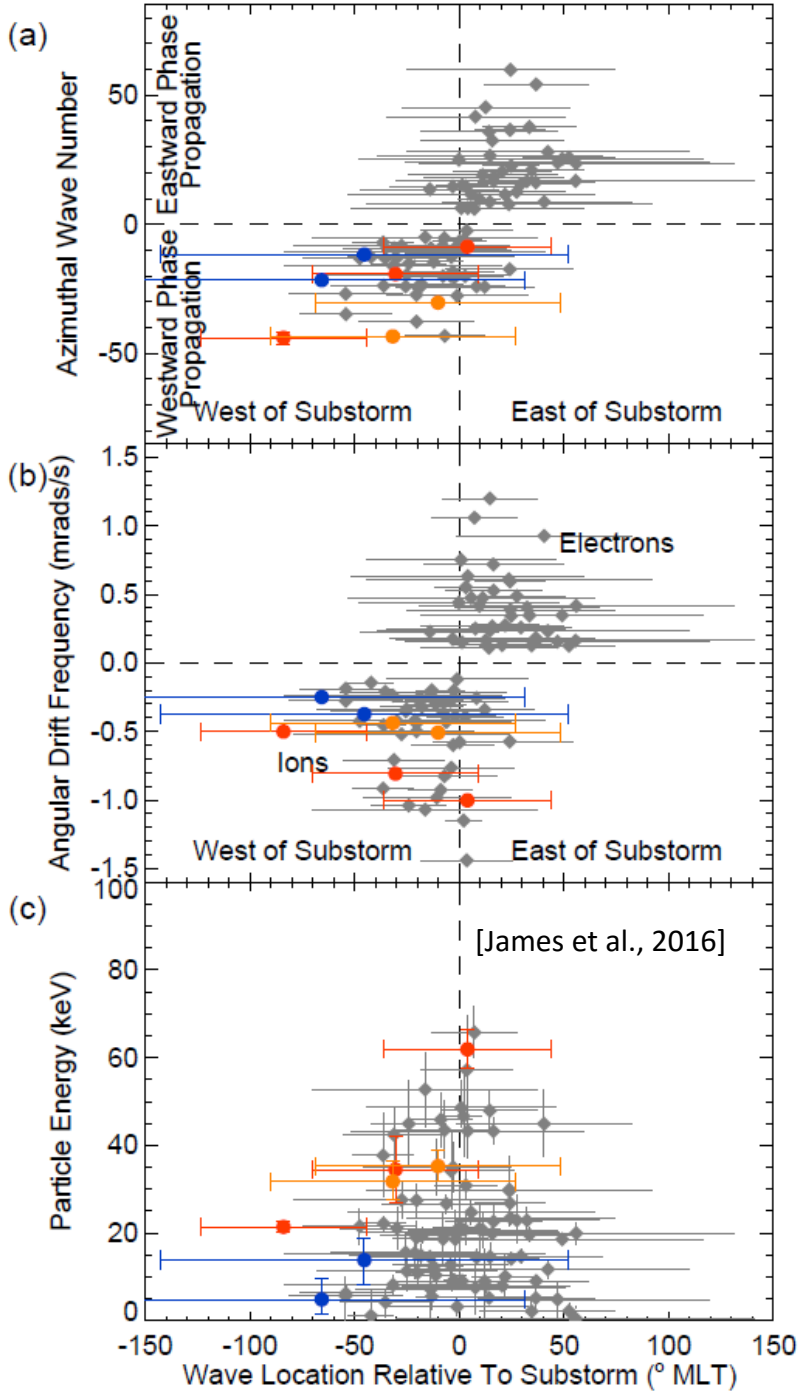
- Inner magnetosphere second harmonic poloidal mode standing Alfven waves occur in the pre-midnight sector
- Generally associated with ion injections
- Wave generation mechanisms include drift-bounce resonance

What excites inner magnetosphere ULF waves? Example: Drift and Drift-bounce resonance

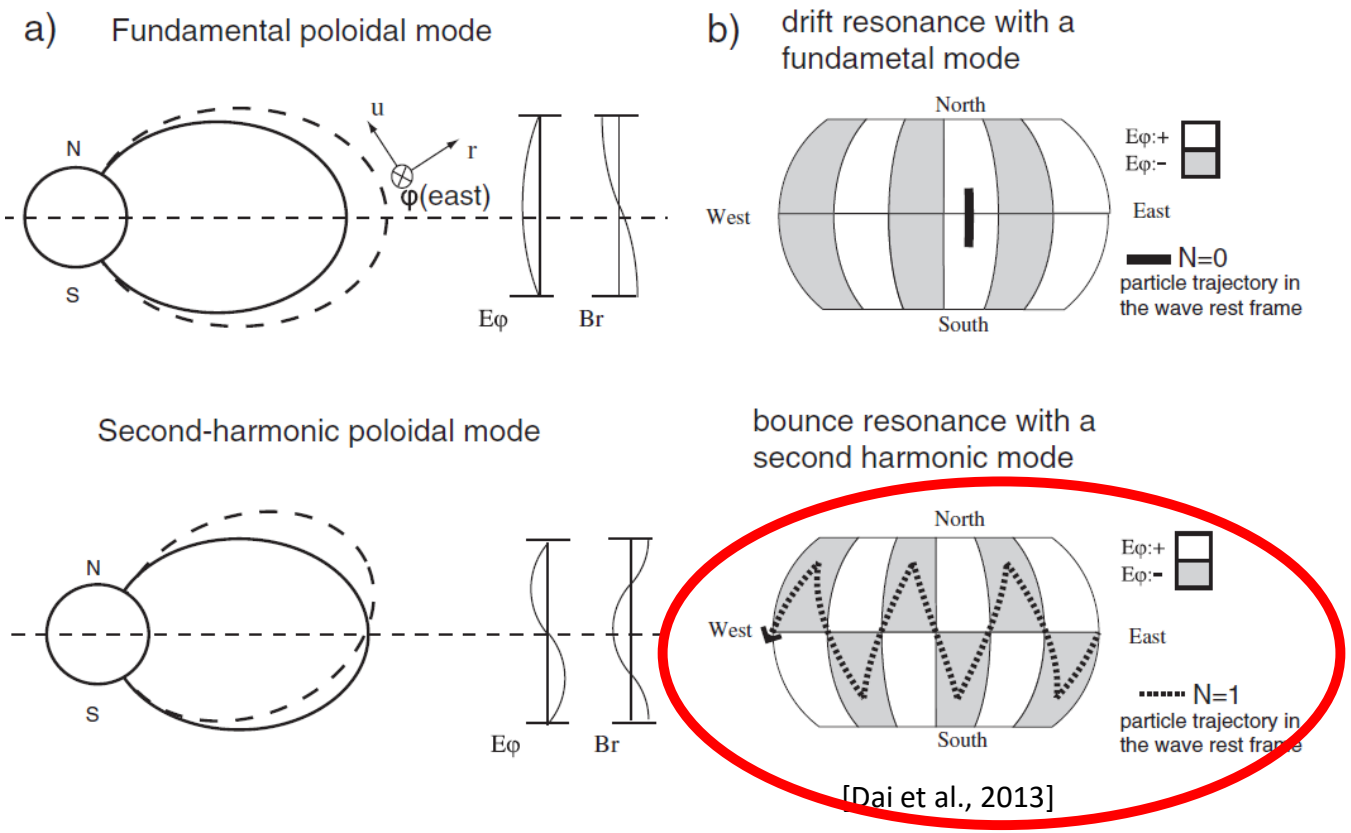
- Increasingly, sunward propagating ULF waves are observed in the post-midnight sector (e.g., Eriksson et al., 2008)
- Ground-based SuperDARN radar observations have provided excellent statistics on wave properties



[James et al., 2013]



How do ULF waves couple to the ring current? Example: Drift and Drift-bounce resonance



[Dai et al., 2013]

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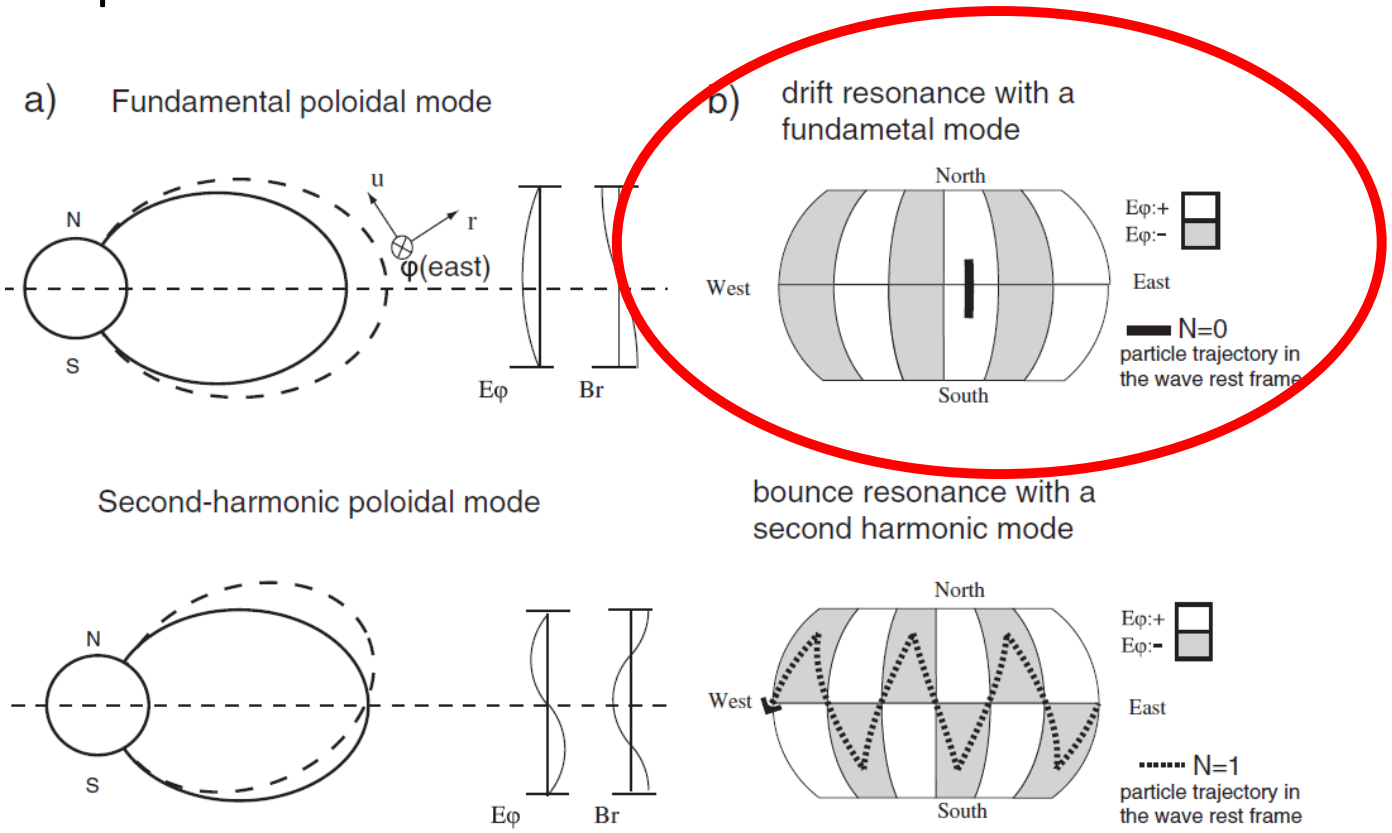

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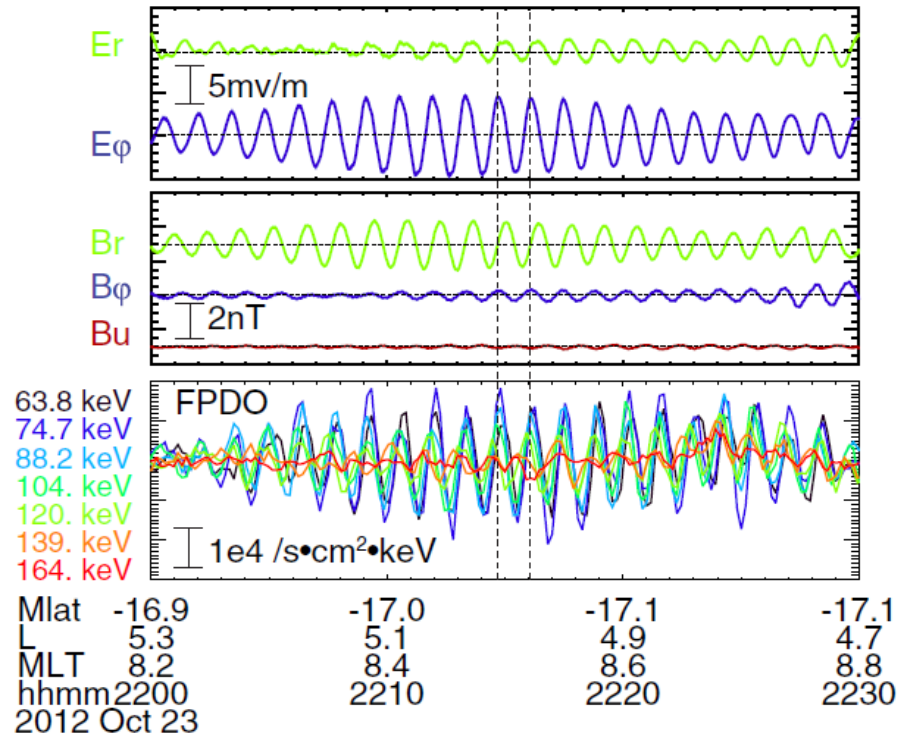

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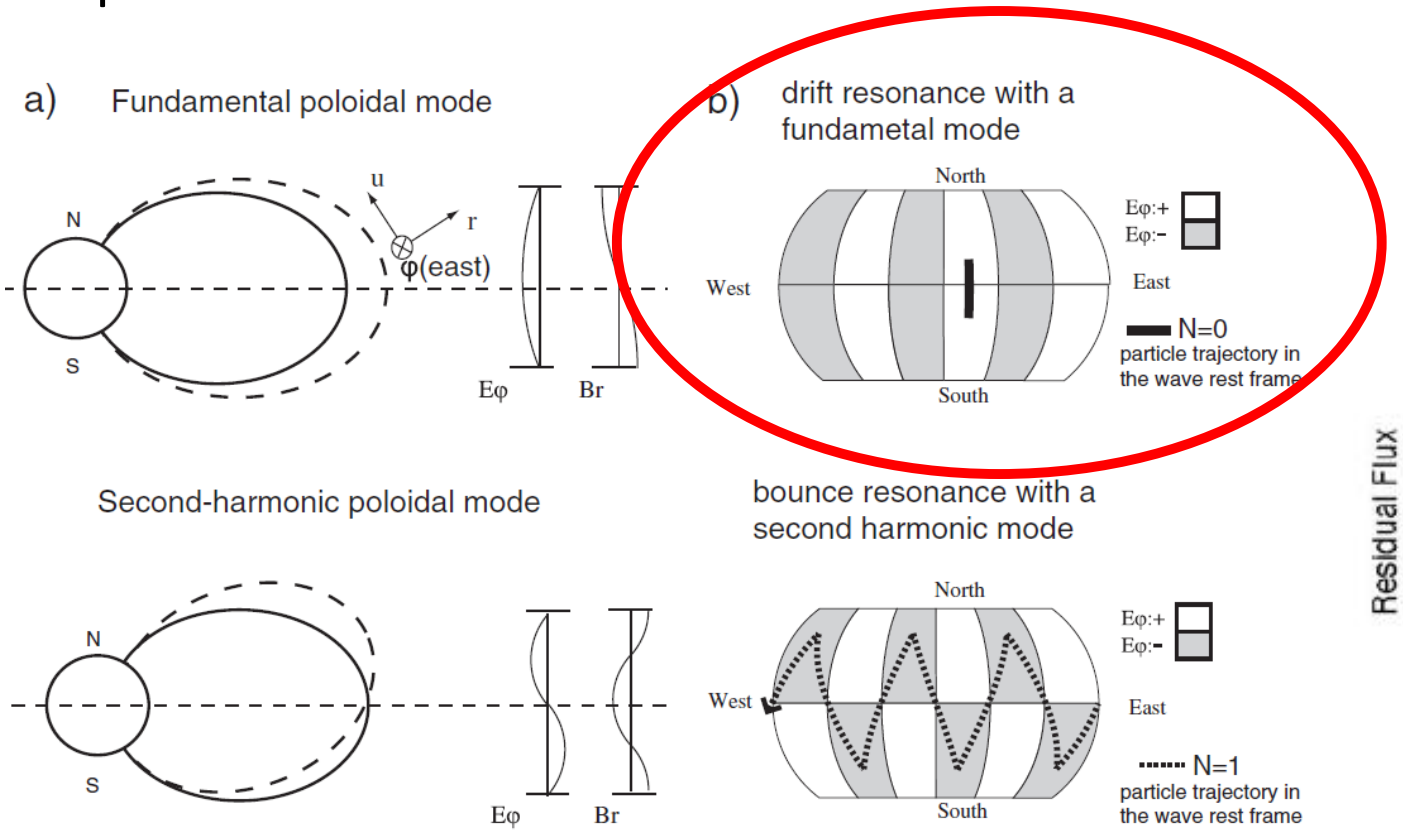
How do ULF waves couple to the ring current? Example: Drift and Drift-bounce resonance



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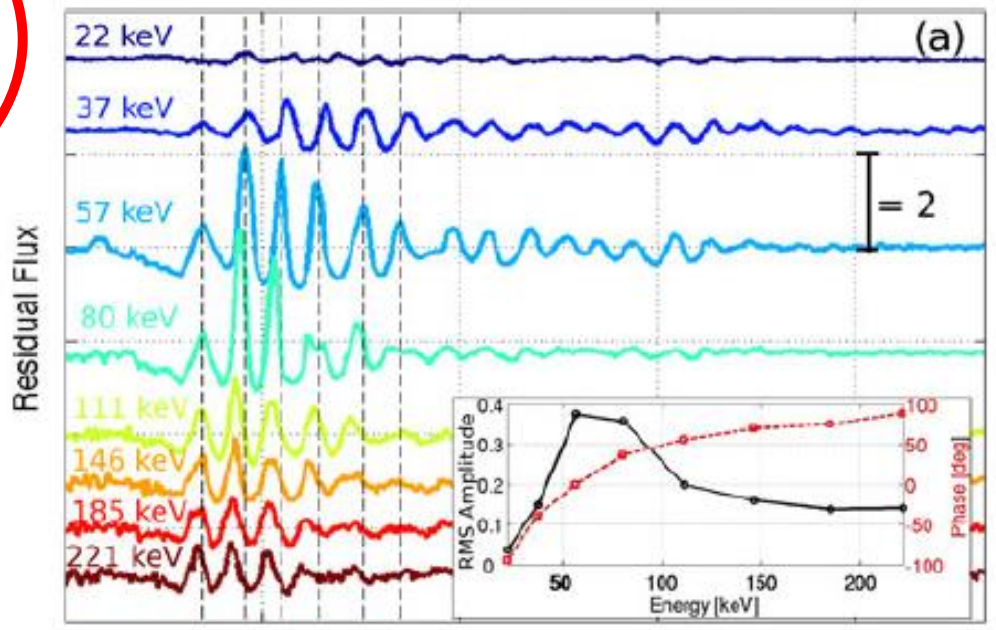
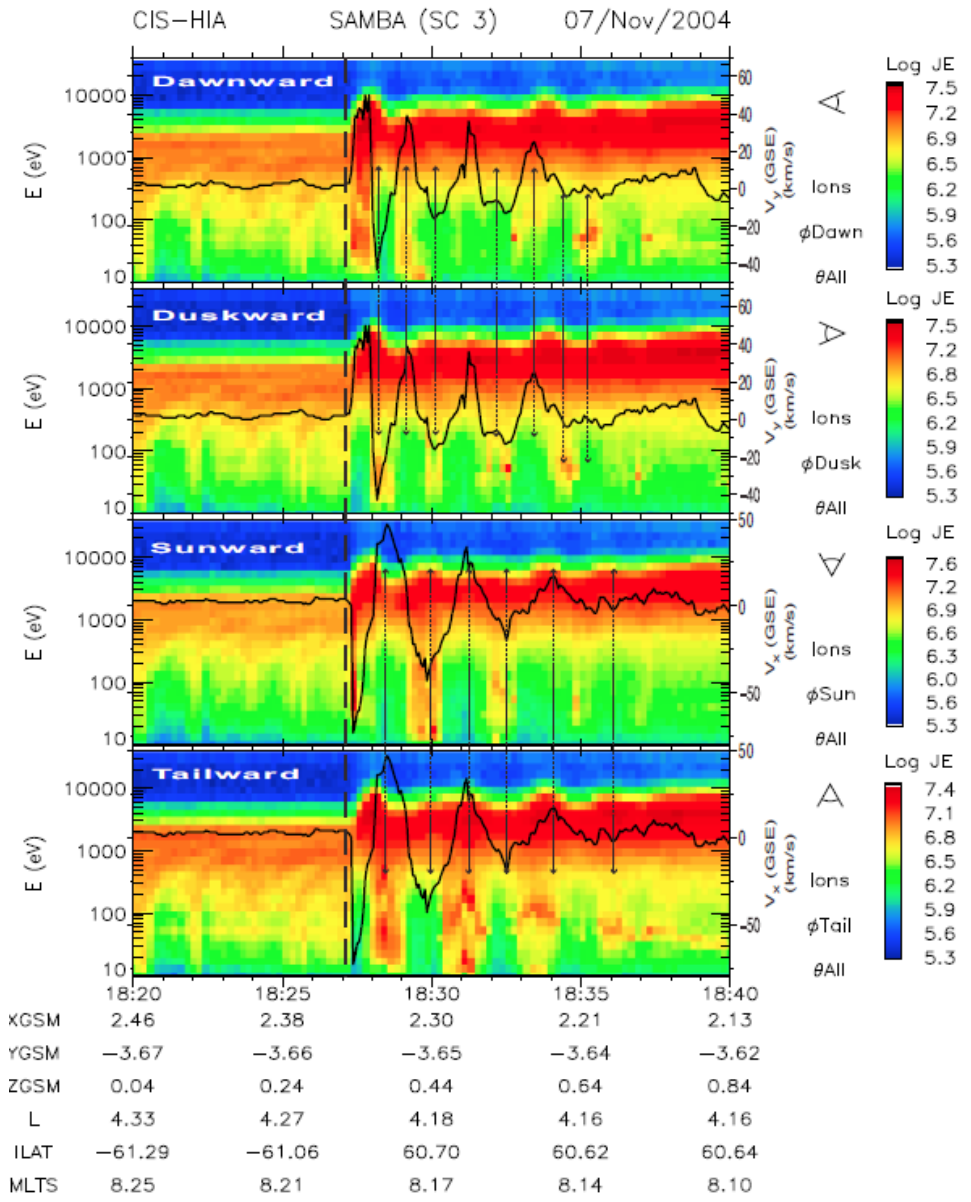


[Claudepierre et al., 2013]

- In situ particle data from Van Allen Probes have confirmed the operation of drift resonance with electrons →excitation of fundamental poloidal mode
- Associated with solar wind pressure increase

How do ULF waves couple to the ring current? Example: Drift and Drift-bounce resonance

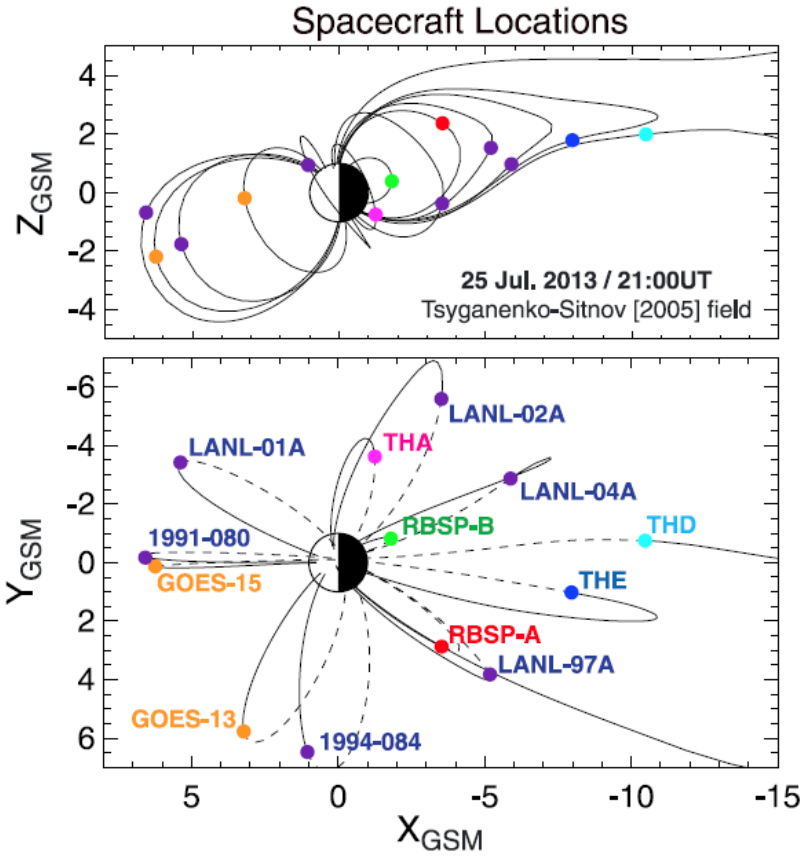
- These waves can affect the ring current
- Example: poloidal mode standing Alfven waves excited by interplanetary shocks rapidly accelerate hydrogen and oxygen ions [Zong et al., 2012]



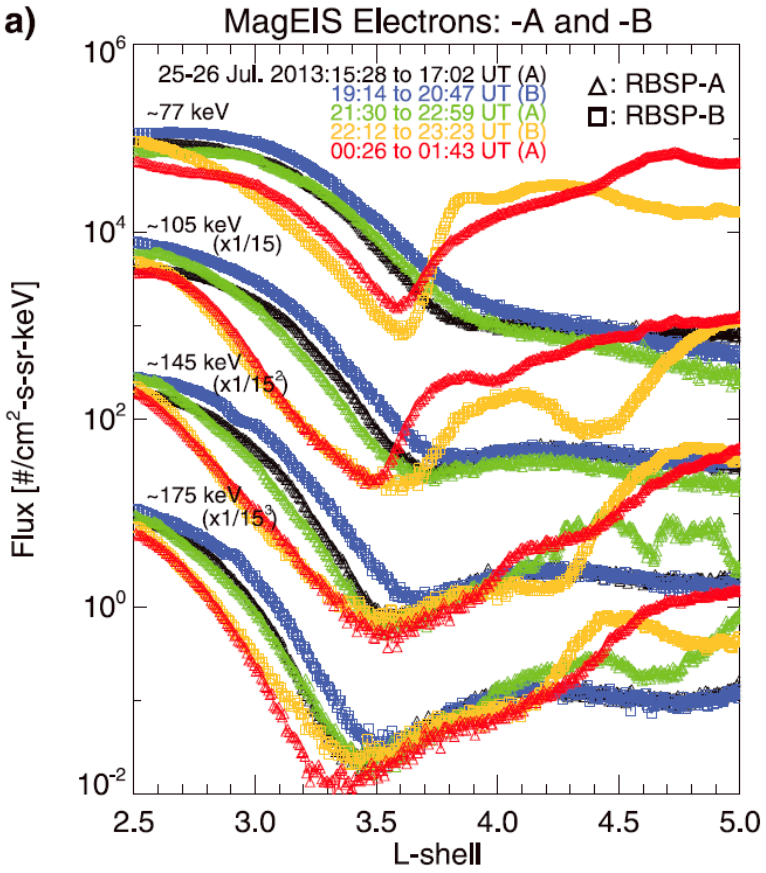
[Zong et al., 2012]

How do ULF waves couple to the ring current? Example: Particle injections

- During electron injection events, particles can be transported to extremely low L values

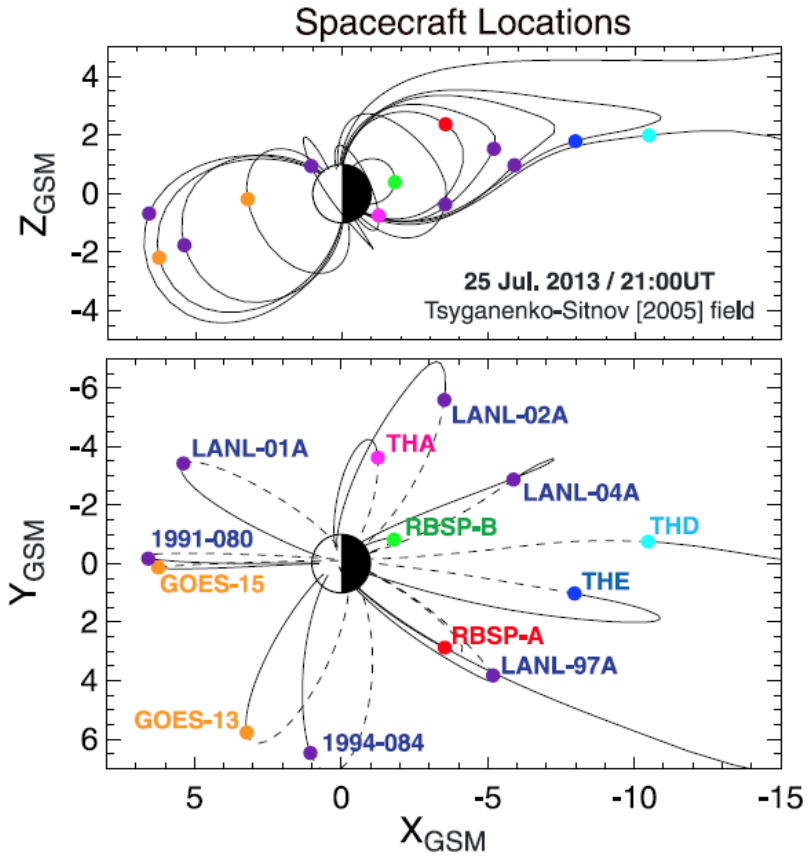


[Turner et al., 2015]



How do ULF waves couple to the ring current? Example: Particle injections

- During electron injection events, particles can be transported to extremely low L values
- Possible mechanism: rapid diffusion via plasmaspheric cavity mode waves



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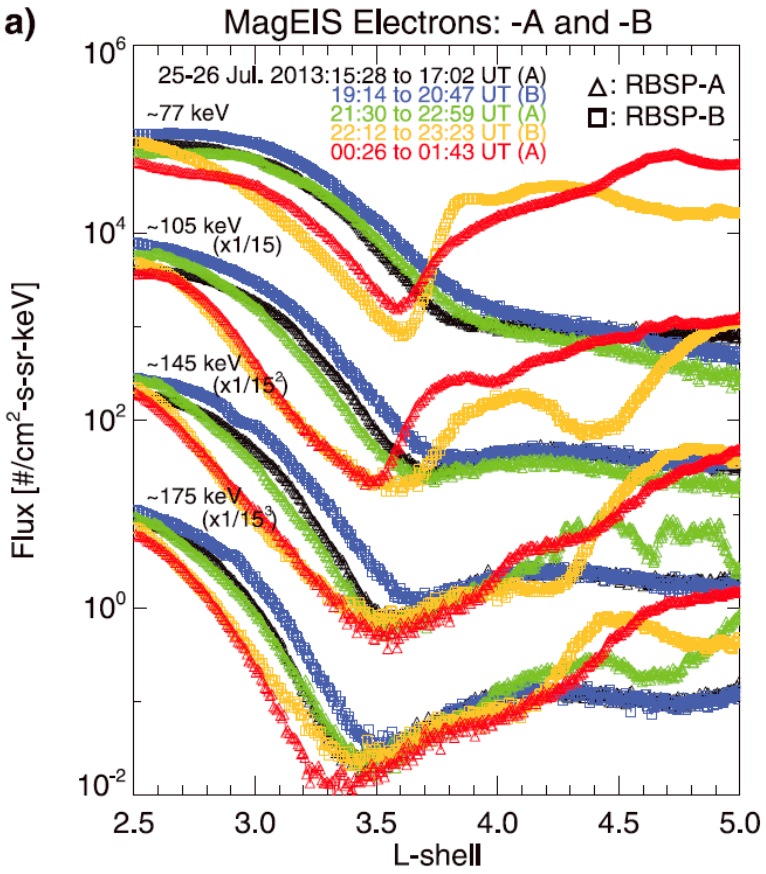
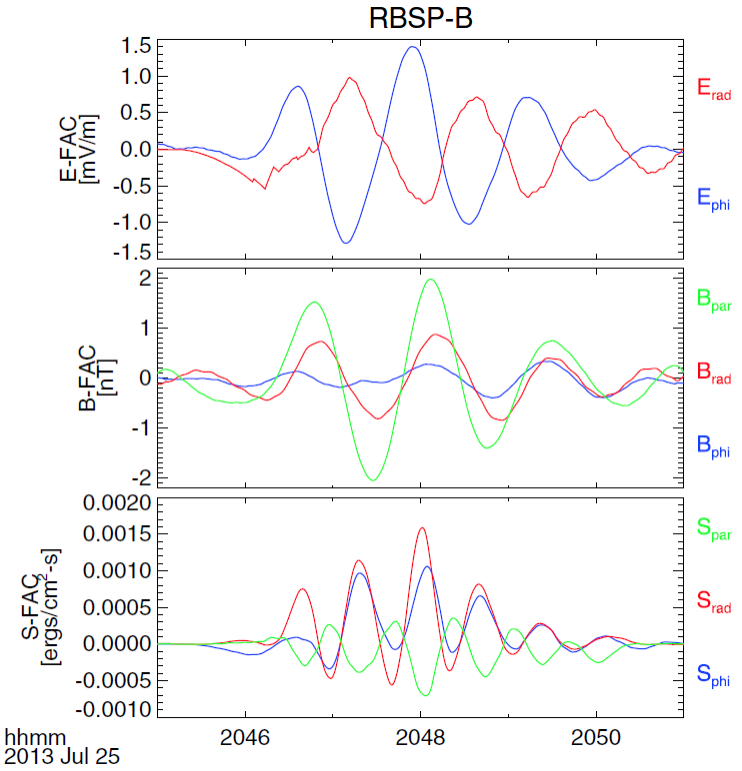
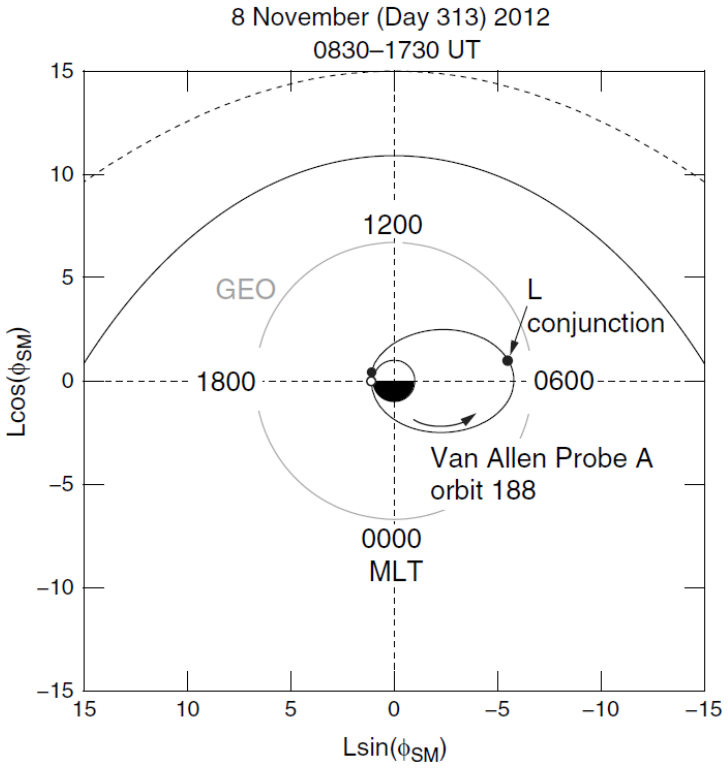
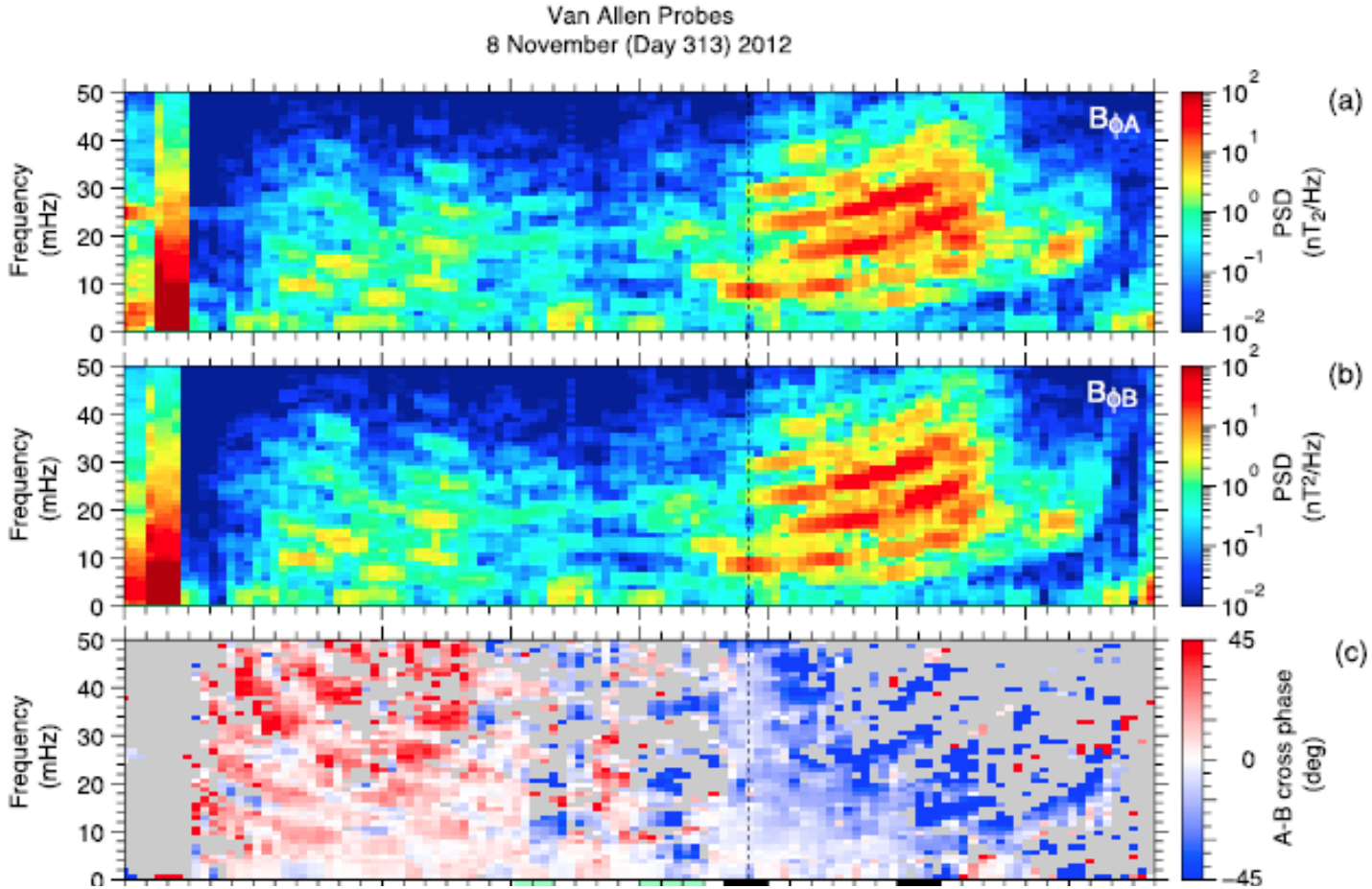




How do ULF waves couple to the plasmasphere? Example: Standing Alfven waves

- Multiple spacecraft distinguish between different wave modes
- Diagnostic for wave propagation, wave coherence scales in plasmasphere/outside plasmasphere

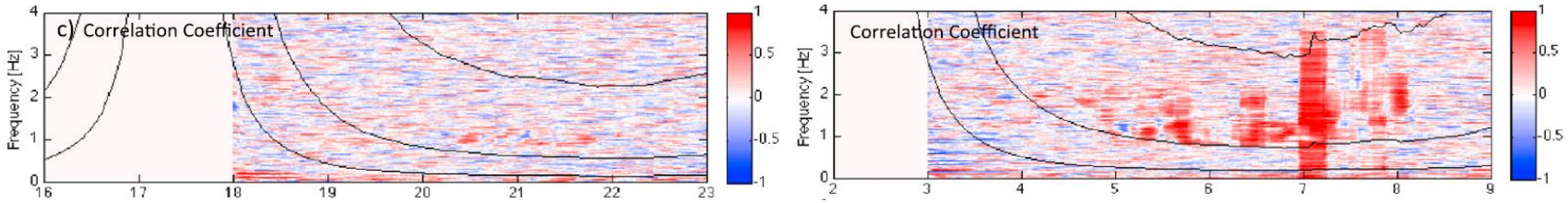




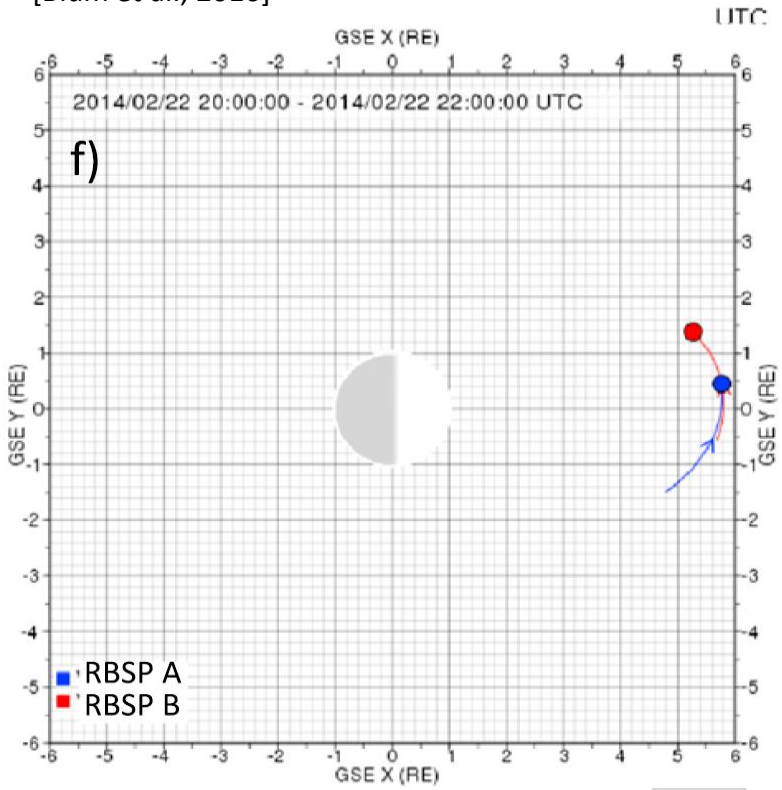
[Takahashi et al., 2015]

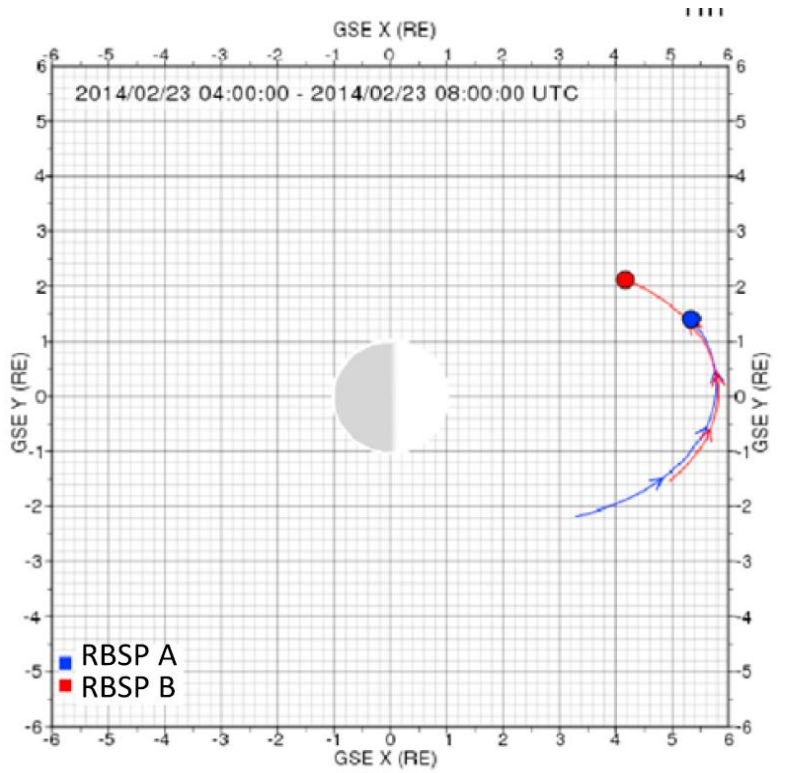
How do ULF waves couple to the plasmasphere? Example: EMIC waves

- Use multiple spacecraft to detect coherence scales for EMIC waves

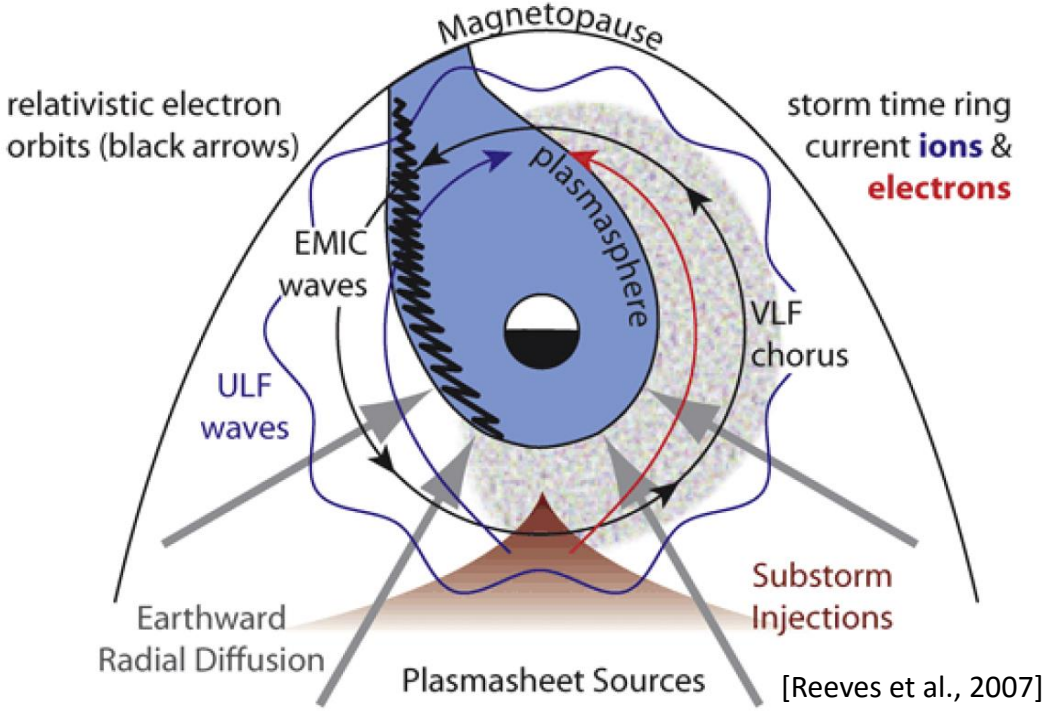


[Blum et al., 2016]



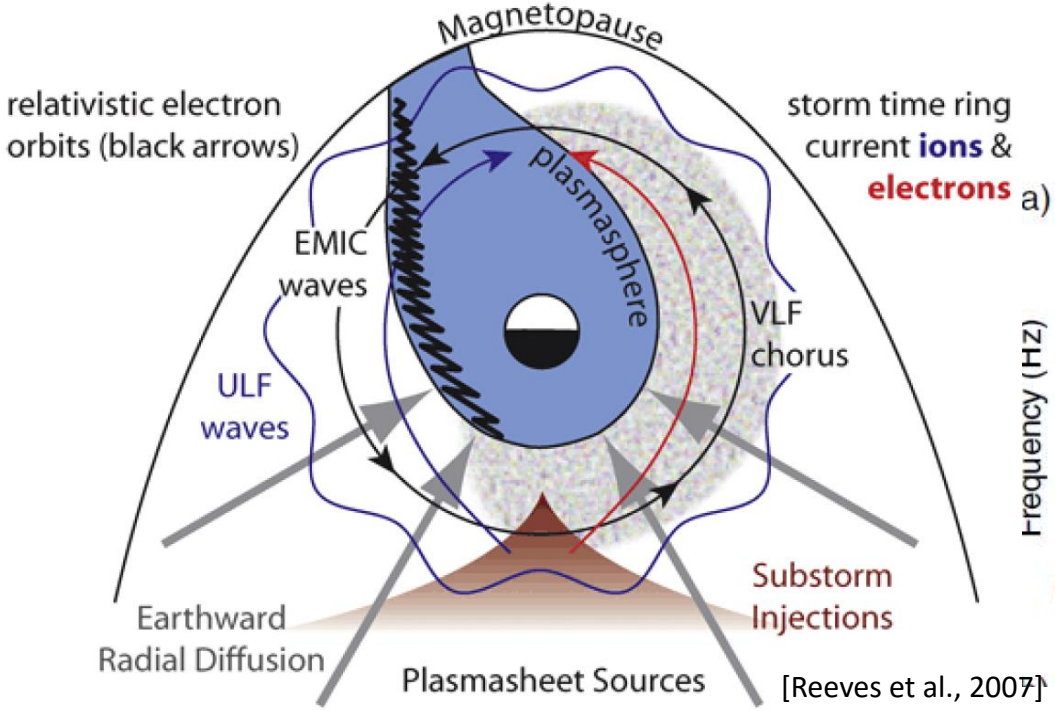


How do ULF waves couple to the plasmasphere? Example: EMIC wave growth



[Reeves et al., 2007]

How do ULF waves couple to the plasmasphere? Example: EMIC wave growth



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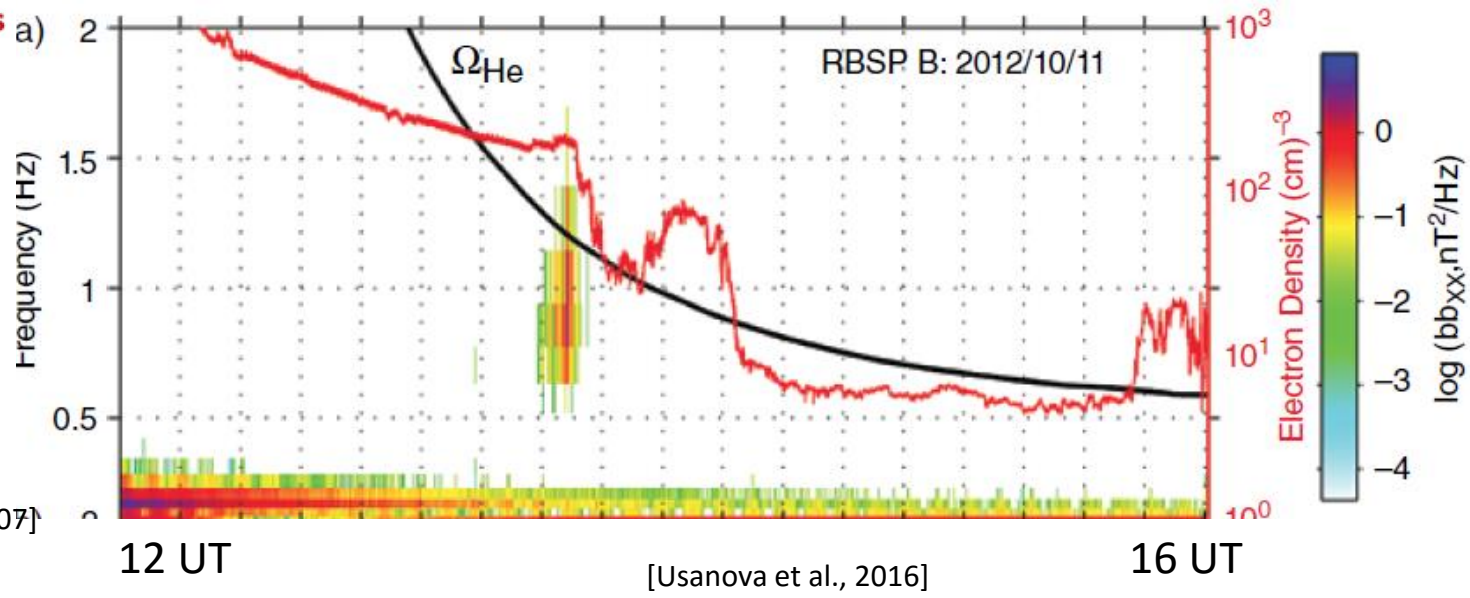

[Usanova et al., 2016]

- There is correspondence in some cases

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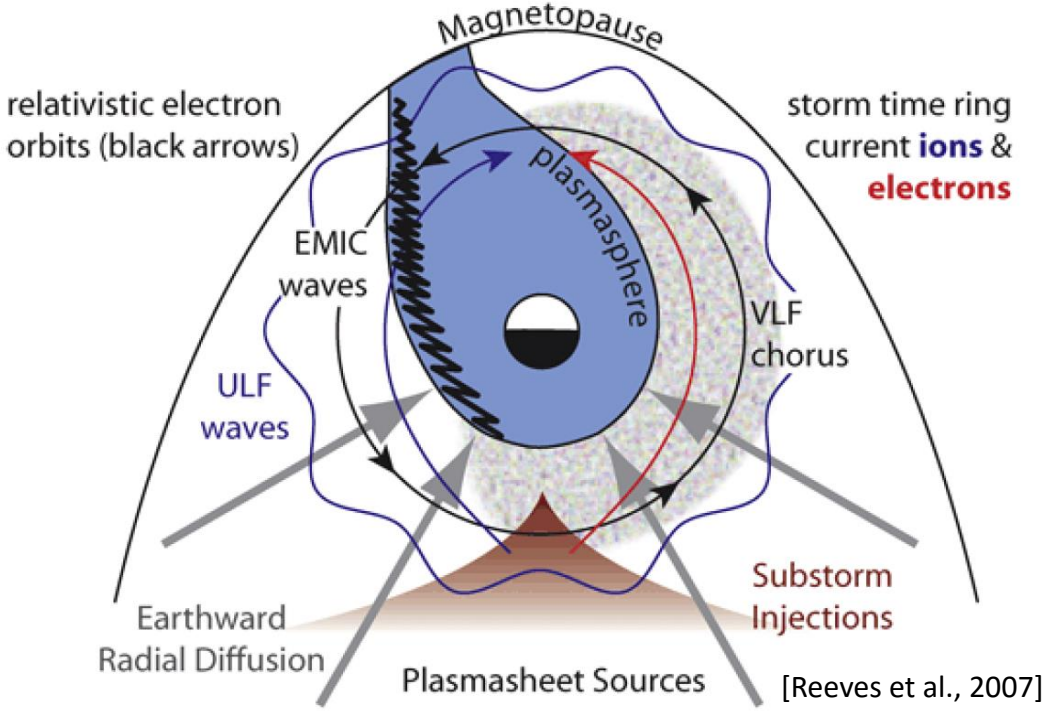

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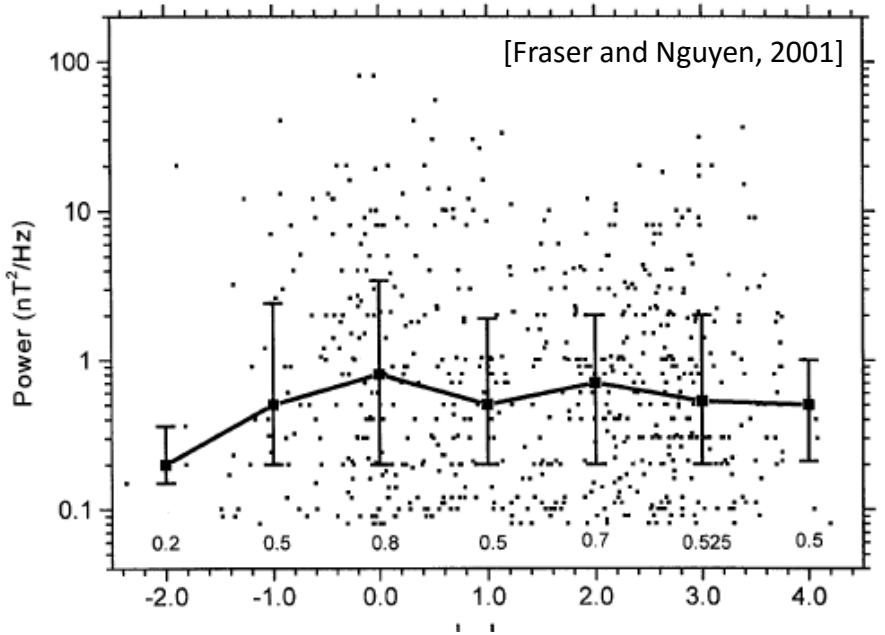
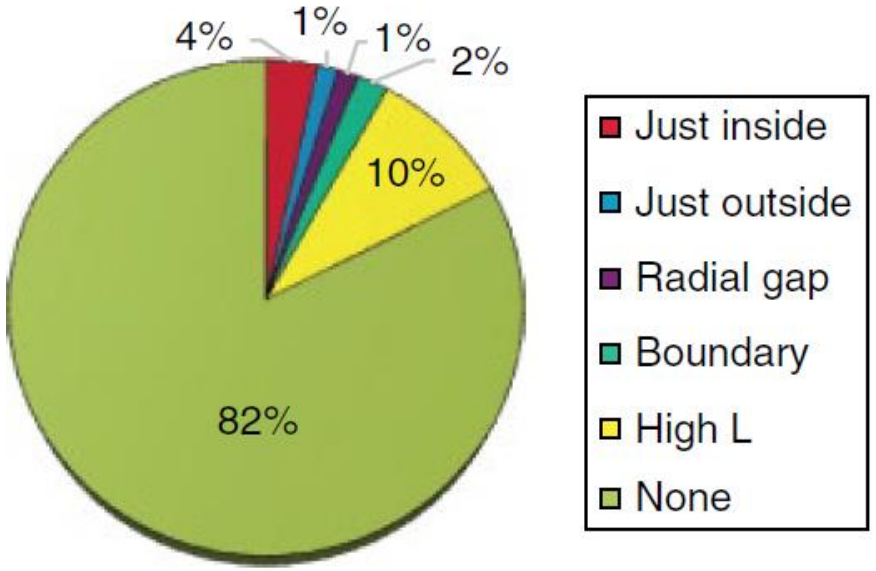
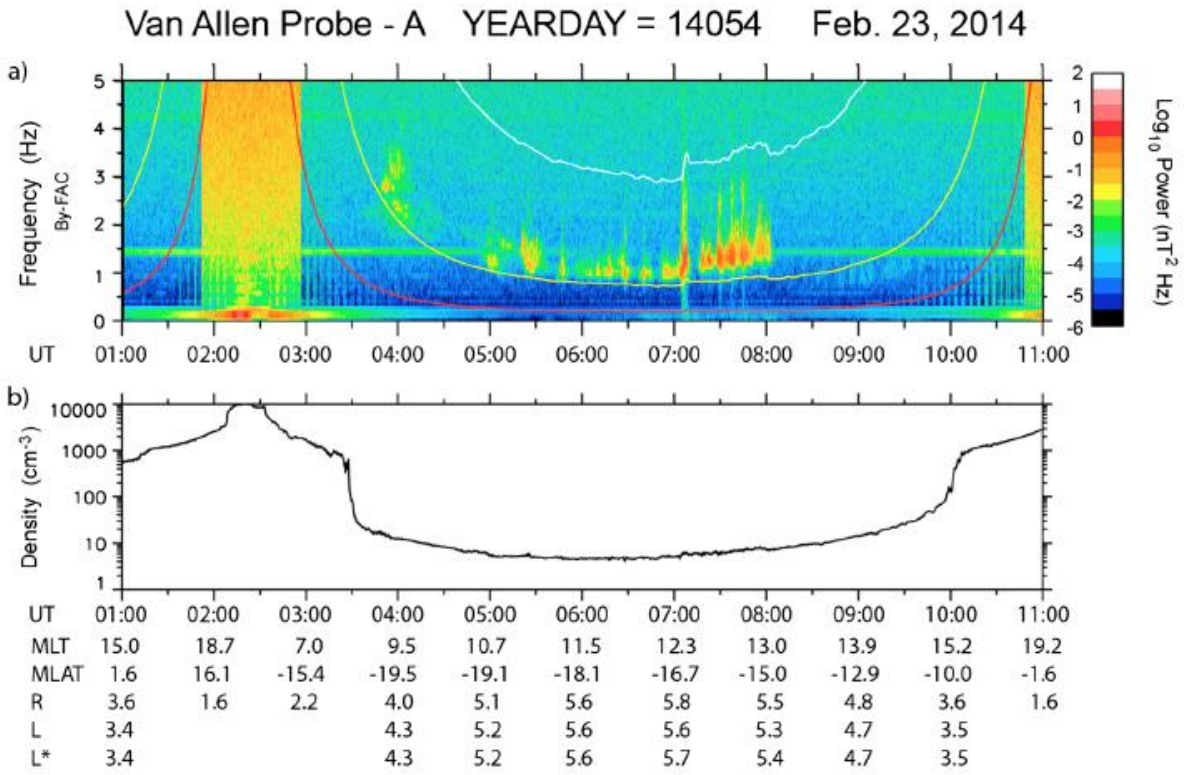




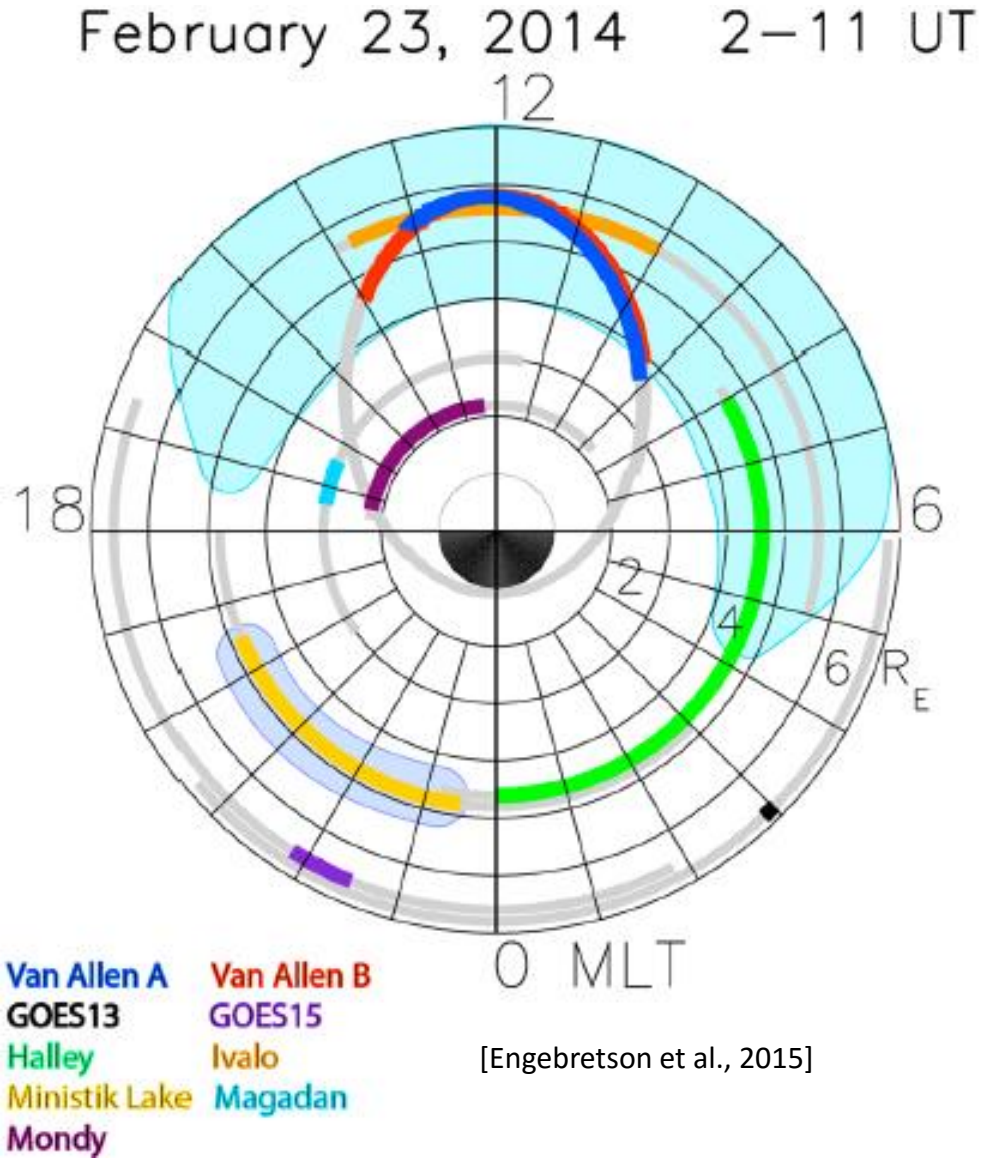
[Usanova et al., 2016]

- There is correspondence in some cases
- However, EMIC wave occurrence is not as closely tied to the plasmapause as previously thought

How do ULF waves couple to the plasmasphere? Example: EMIC wave growth

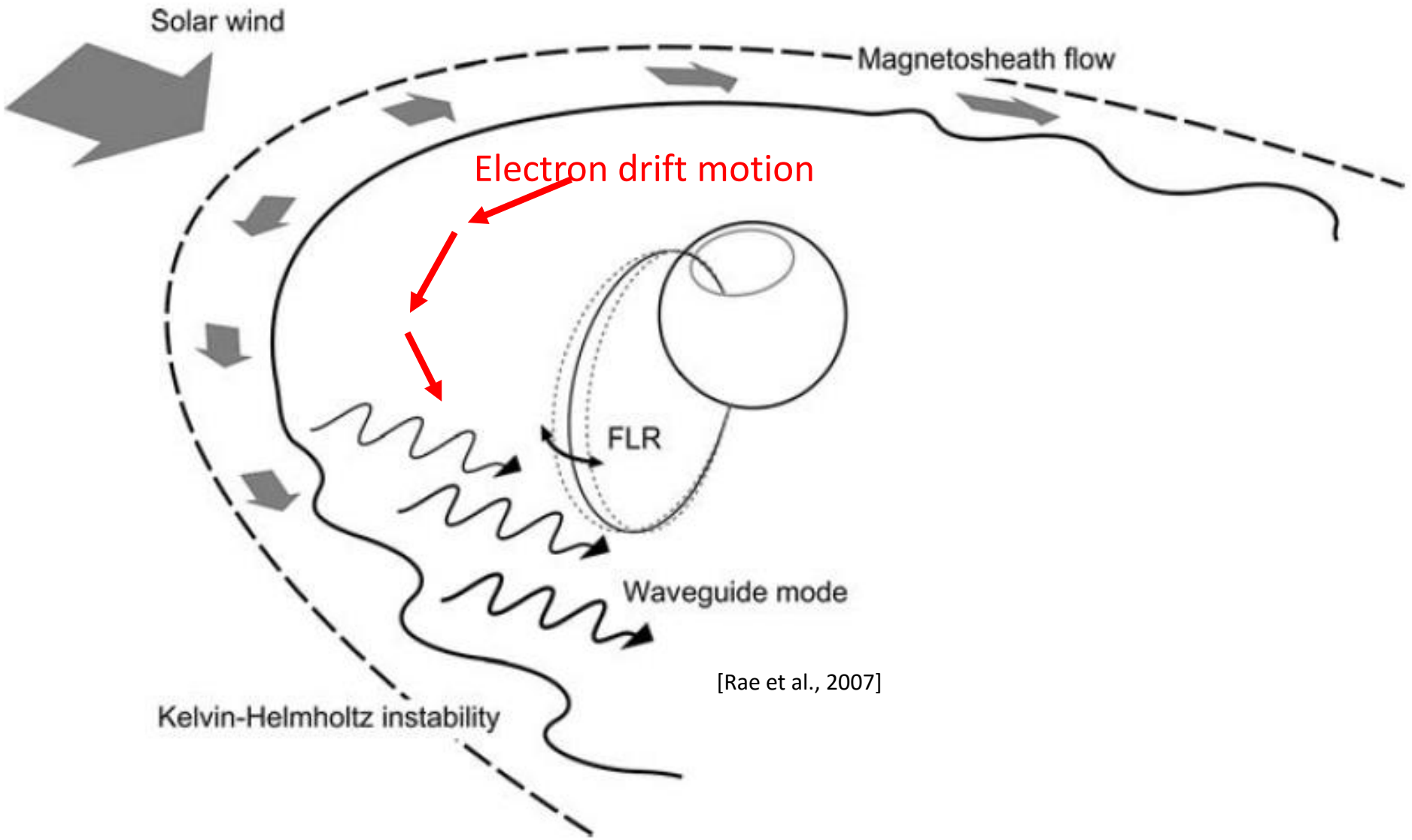


- In some cases, global observations show the plasmapause location matters very little for EMIC wave growth



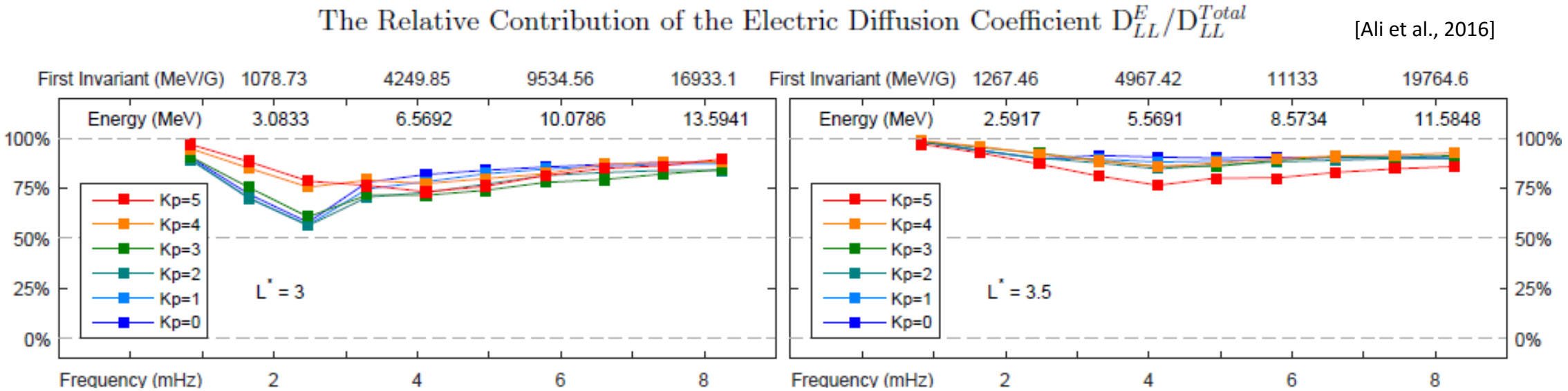
[Engebretson et al., 2015]

How do ULF waves couple to the radiation belts?



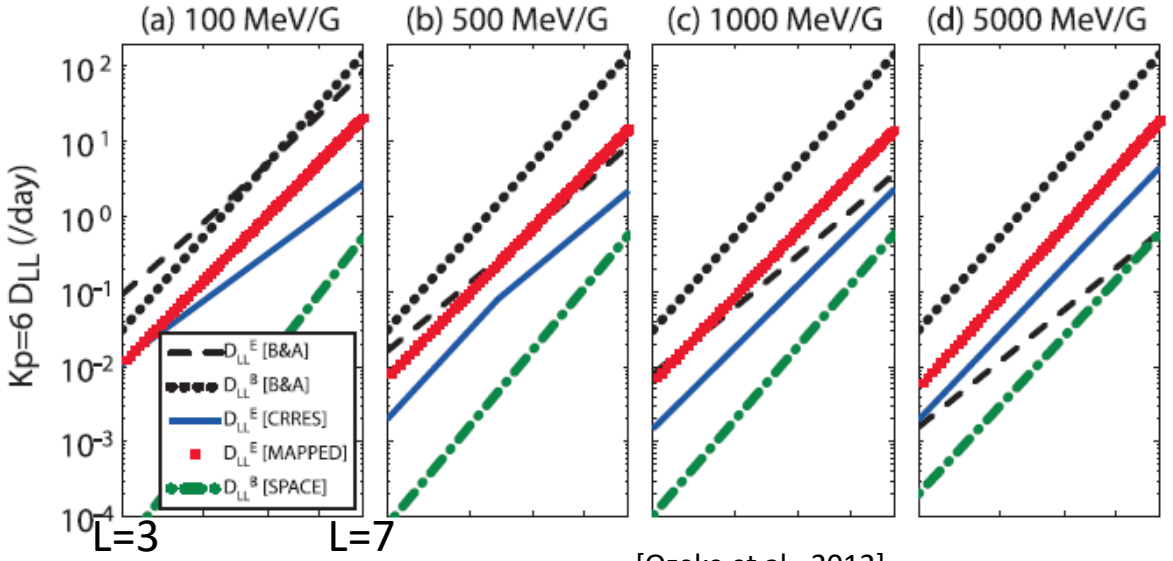
[Rae et al., 2007]

How do ULF waves couple to the radiation belts? Example: New diffusion coefficients (1)



[Ali et al., 2016]

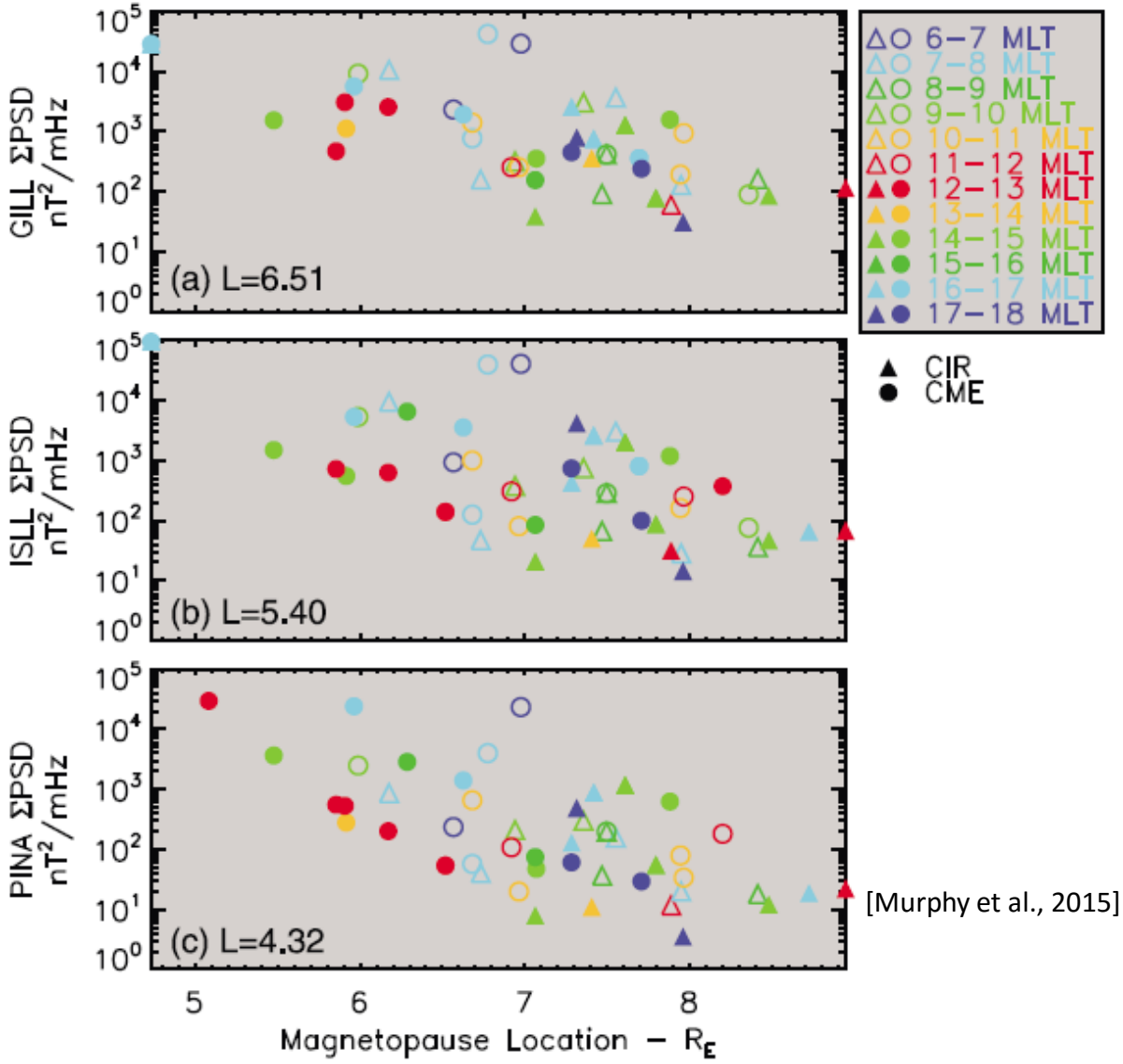
- New results from in situ measurements and ground-based magnetometers suggest the electric field diffusion coefficient is much more important than the magnetic field coefficient
- Contrary to previous results
- What will the effect be on models of diffusive transport via ULF waves



[Ozeke et al., 2012]

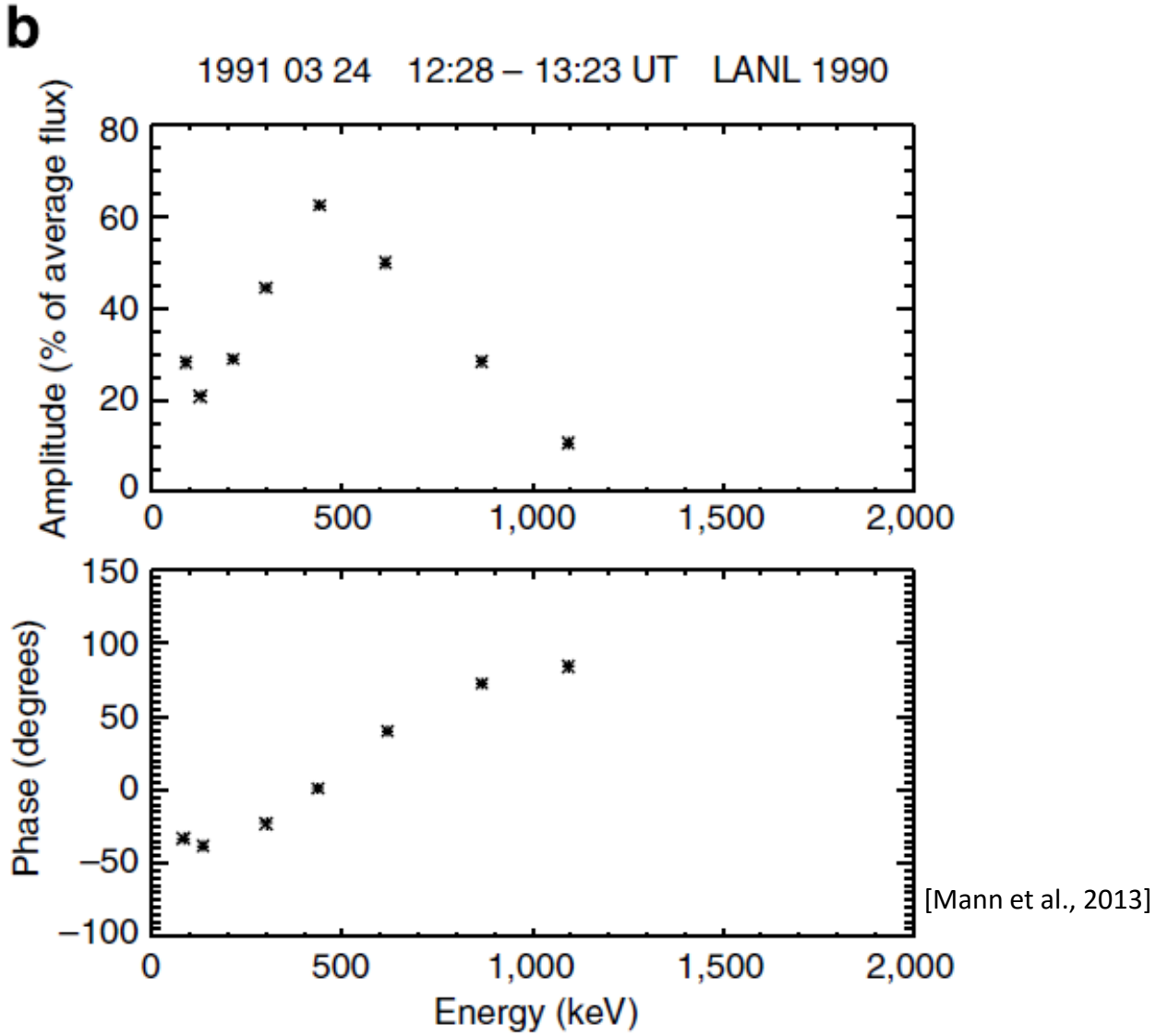
How do ULF waves couple to the radiation belts? Example: New diffusion coefficients (2)

- ULF wave amplitudes during storms depends strongly on position relative to magnetopause
- Diffusion coefficients during periods when the magnetosphere is compressed – e.g., during CIR/CME storms – can be substantially different
- Need parameterizations beyond Kp (e.g., Dimitrakoudis et al., 2015)



[Murphy et al., 2015]

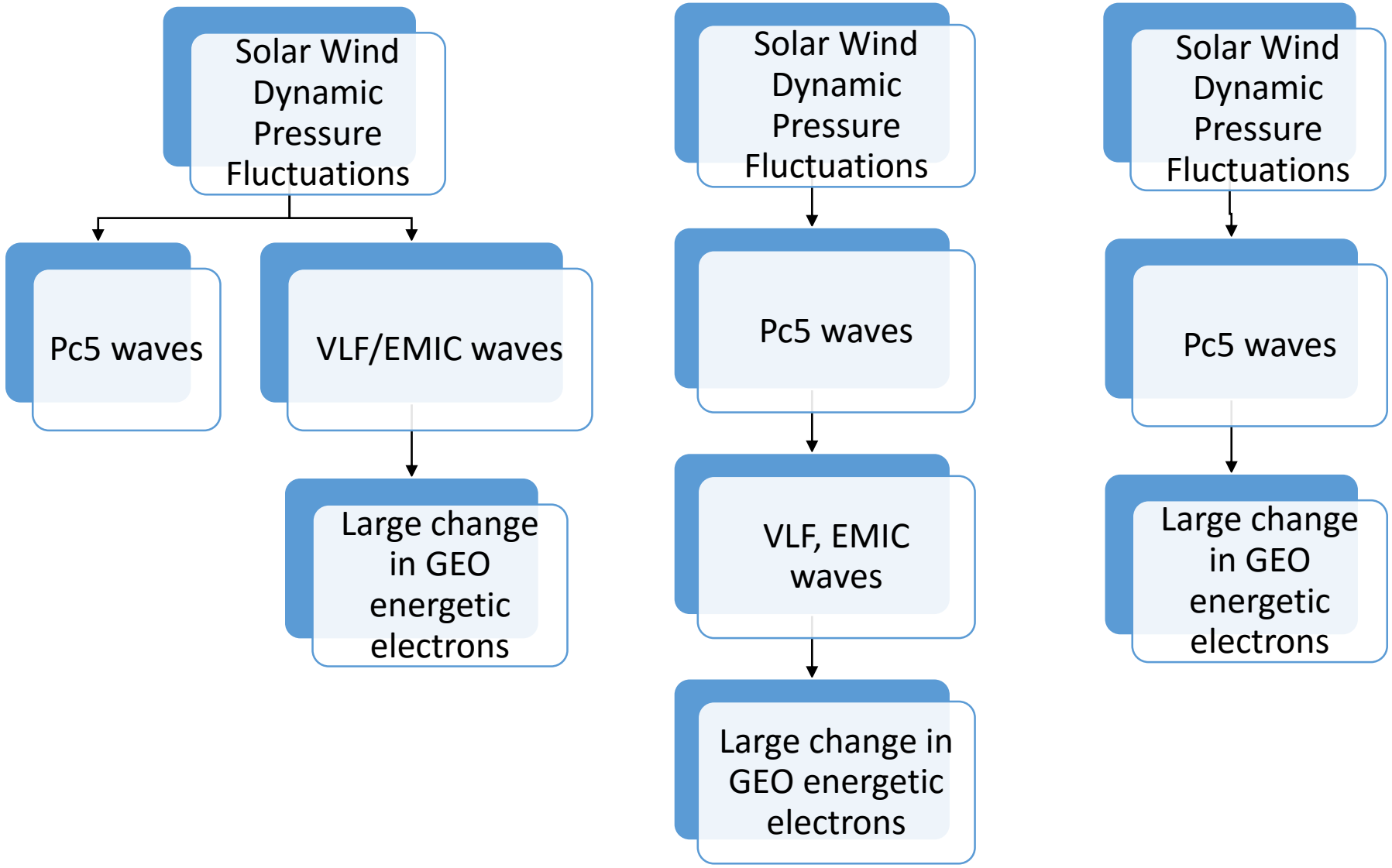
How do ULF waves couple to the radiation belts? Example: Drift resonance via Pc5 waves



[Mann et al., 2013]

- Drift resonance with electron energies ~500 keV
- Leads to rapid transport at select energy ranges

How do ULF waves couple to the radiation belts?
Example: When/where/how do Pc5 waves affect radiation belt dynamics



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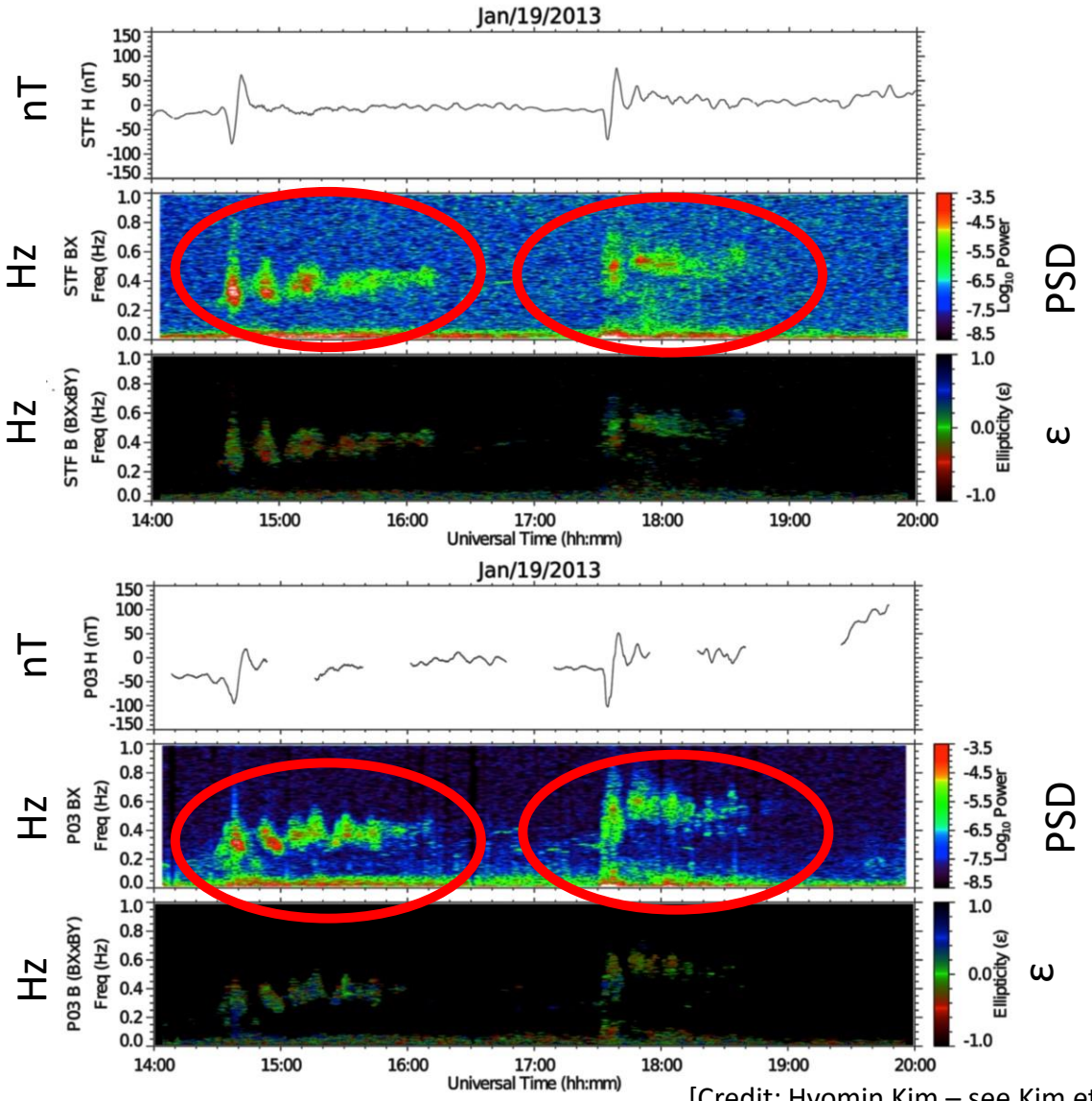
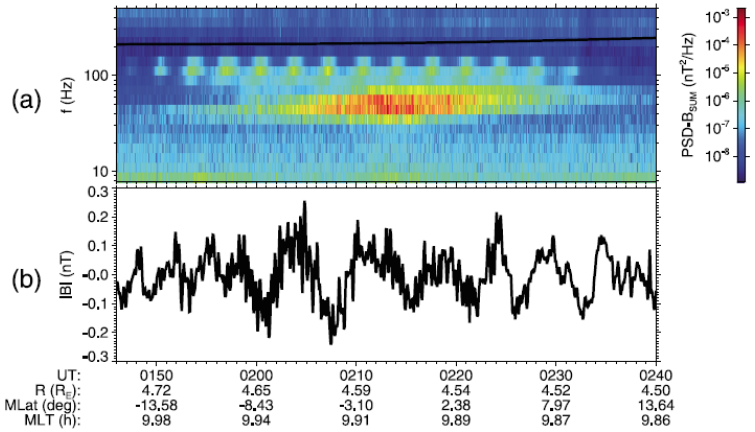


[Credit: Hyomin Kim – see Kim et al., 2015]

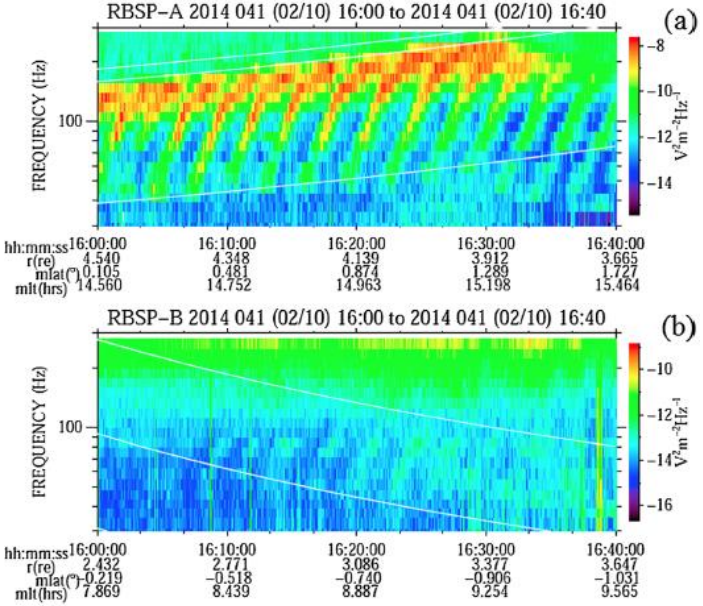
- Pc5 (2-7 mHz) wave amplitudes are anti-correlated with EMIC wave amplitudes in many cases (e.g., Loto'aniu et al., 2009 and previous studies)

How do ULF waves couple to the radiation belts?
Example: When/where/how do Pc5 waves affect radiation belt dynamics

Equatorial noise/magnetosonic



[Nemec et al., 2015]

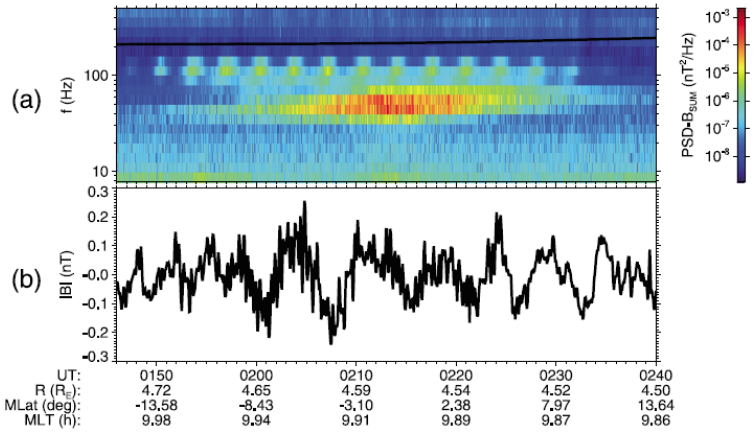


[Boardsen et al., 2014]

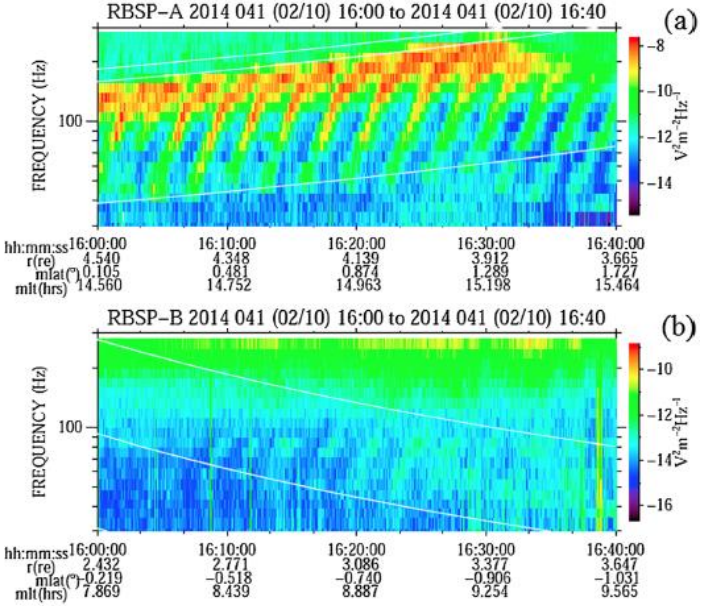
- In situ observations are shedding new light on previous ground-based observations/theory of ULF modulated VLF waves (QP)
- Many VLF wave modes have amplitudes that peak/dip at ULF frequencies – not all are necessarily linked to ULF waves, and more than one ULF wave mode is implicated

How do ULF waves couple to the radiation belts?
Example: When/where/how do Pc5 waves affect radiation belt dynamics

Equatorial noise/magnetosonic

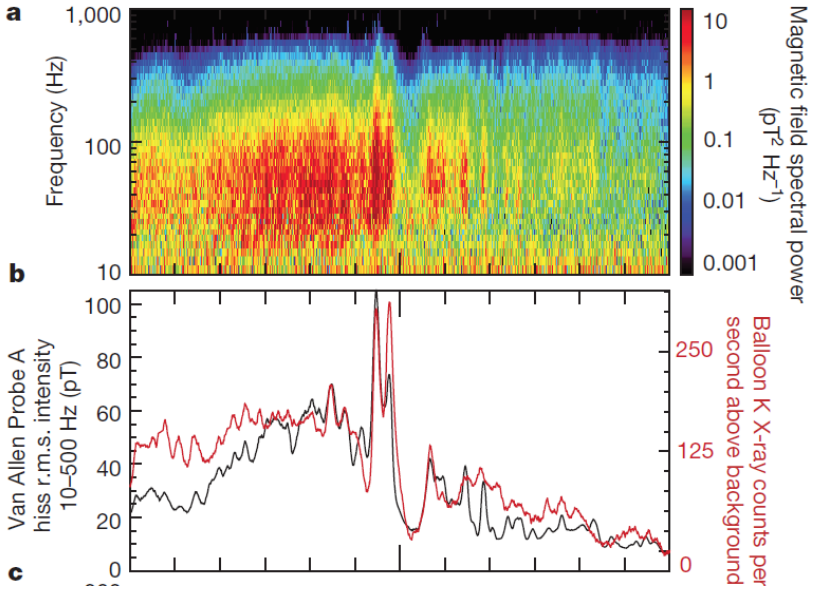


[Nemec et al., 2015]



[Boardsen et al., 2014]

Plasmaspheric Hiss



[Breneman et al., 2015]

- In situ observations are shedding new light on previous ground-based observations/theory of ULF modulated VLF waves (QP)
- Many VLF wave modes have amplitudes that peak/dip at ULF frequencies – not all are necessarily linked to ULF waves, and more than one ULF wave mode is implicated

How do ULF waves couple to the radiation belts?
Example: When/where/how do Pc5 waves affect radiation belt dynamics

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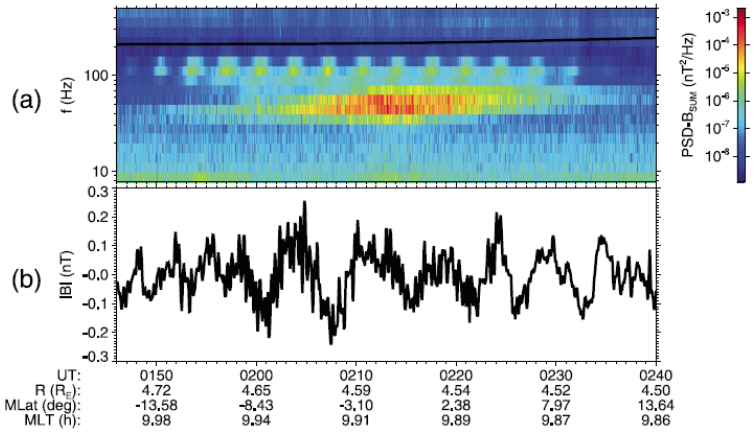
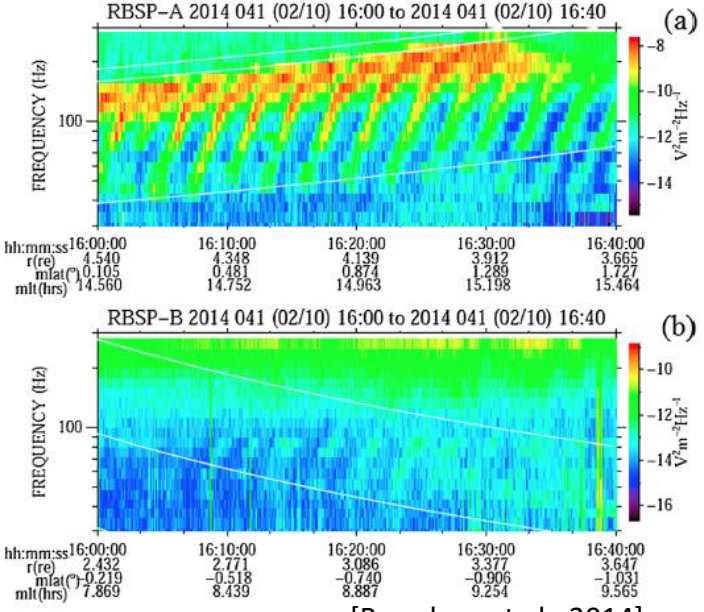


[Nemec et al., 2015]



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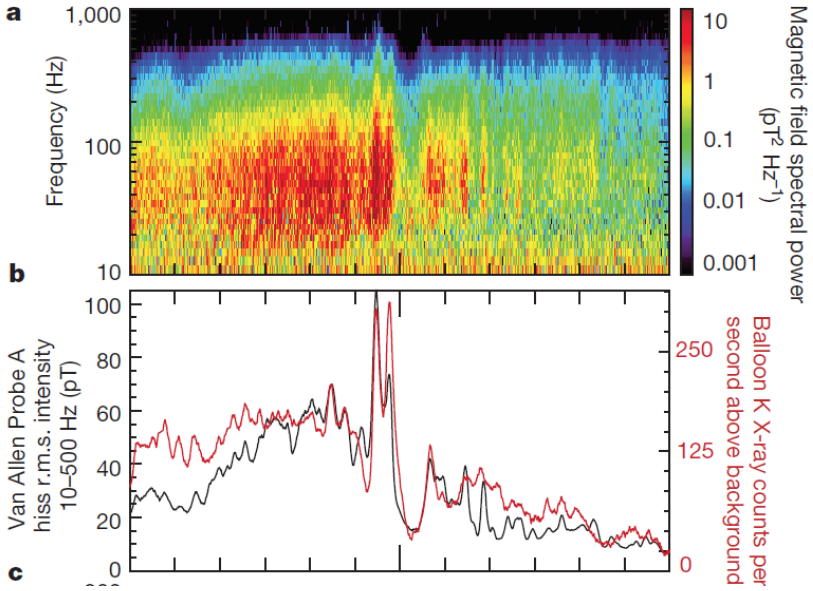
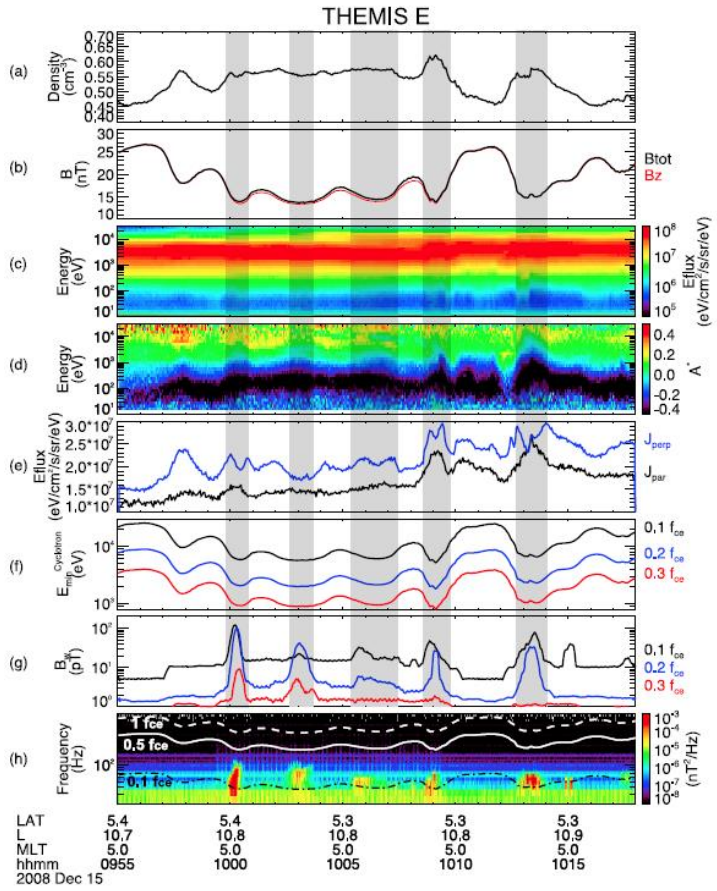


[Breneman et al., 2015]

Whistler-mode Chorus



[Li et al., 2011]

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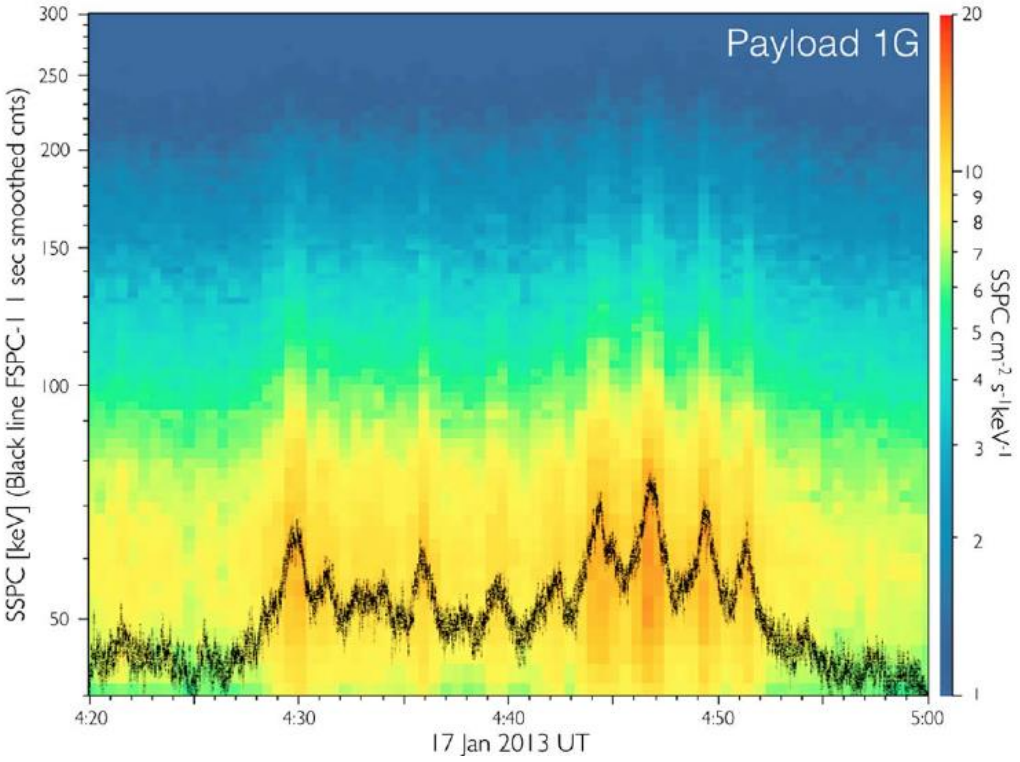
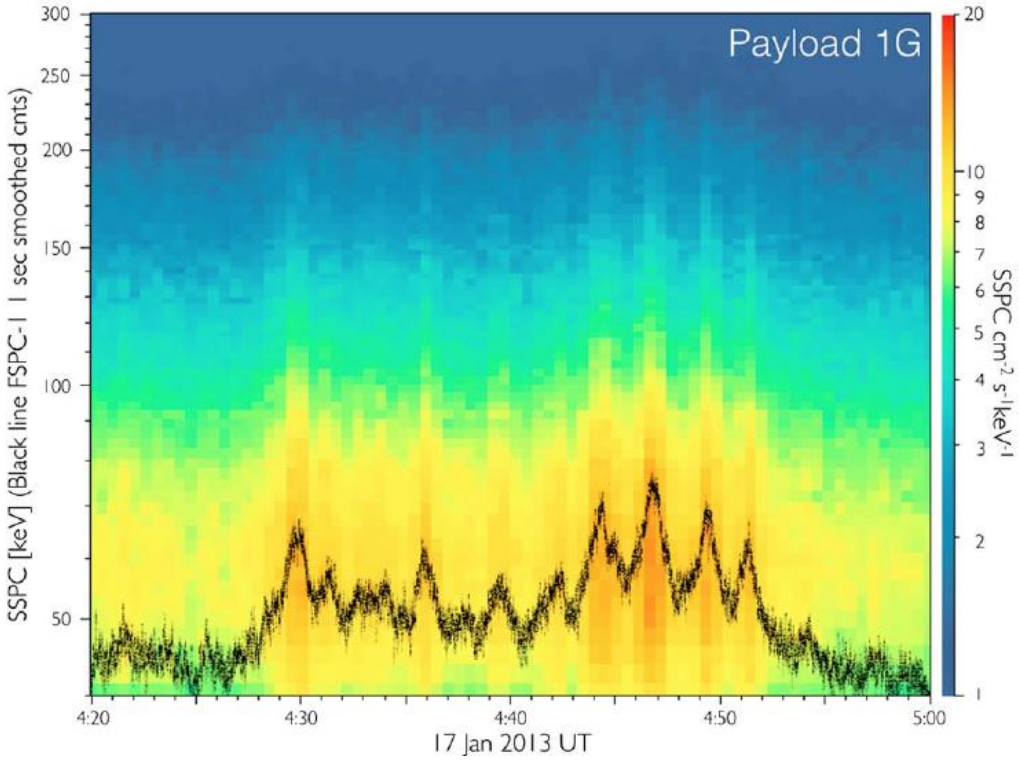
How do ULF waves couple to the radiation belts?
Example: When/where/how do Pc5 waves affect radiation belt dynamics



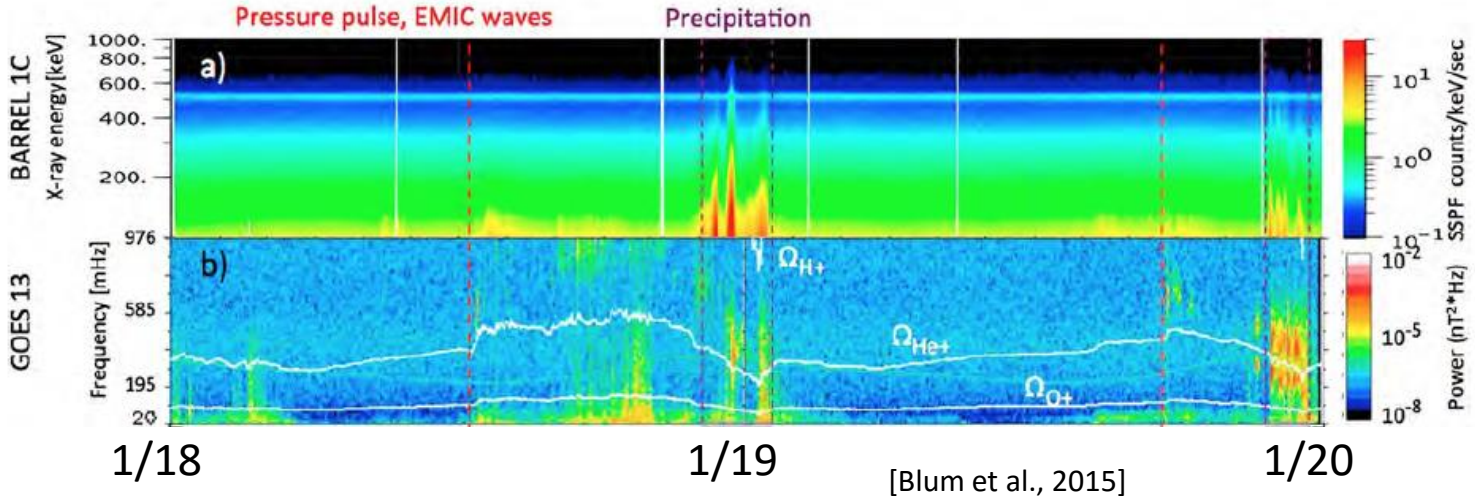
[Brito et al., 2015]

- ULF waves with frequencies <10 mHz have been linked to relativistic electron precipitation in the absence of VLF/EMIC waves (above, Brito et al., 2015)

How do ULF waves couple to the radiation belts?
Example: When/where/how do Pc5 waves affect radiation belt dynamics



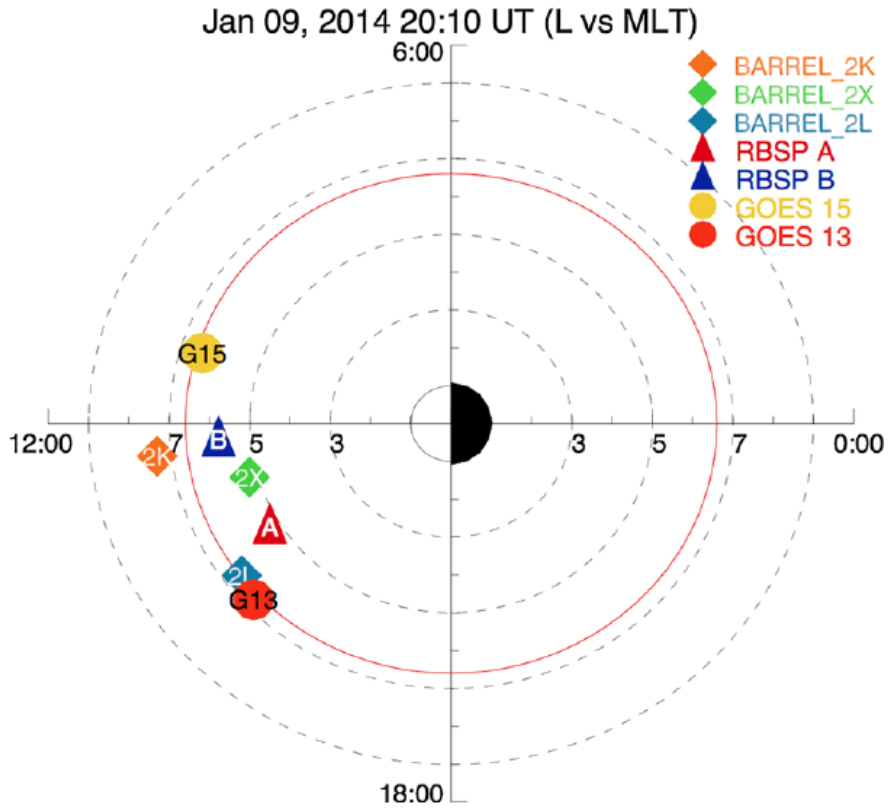
[Brito et al., 2015]

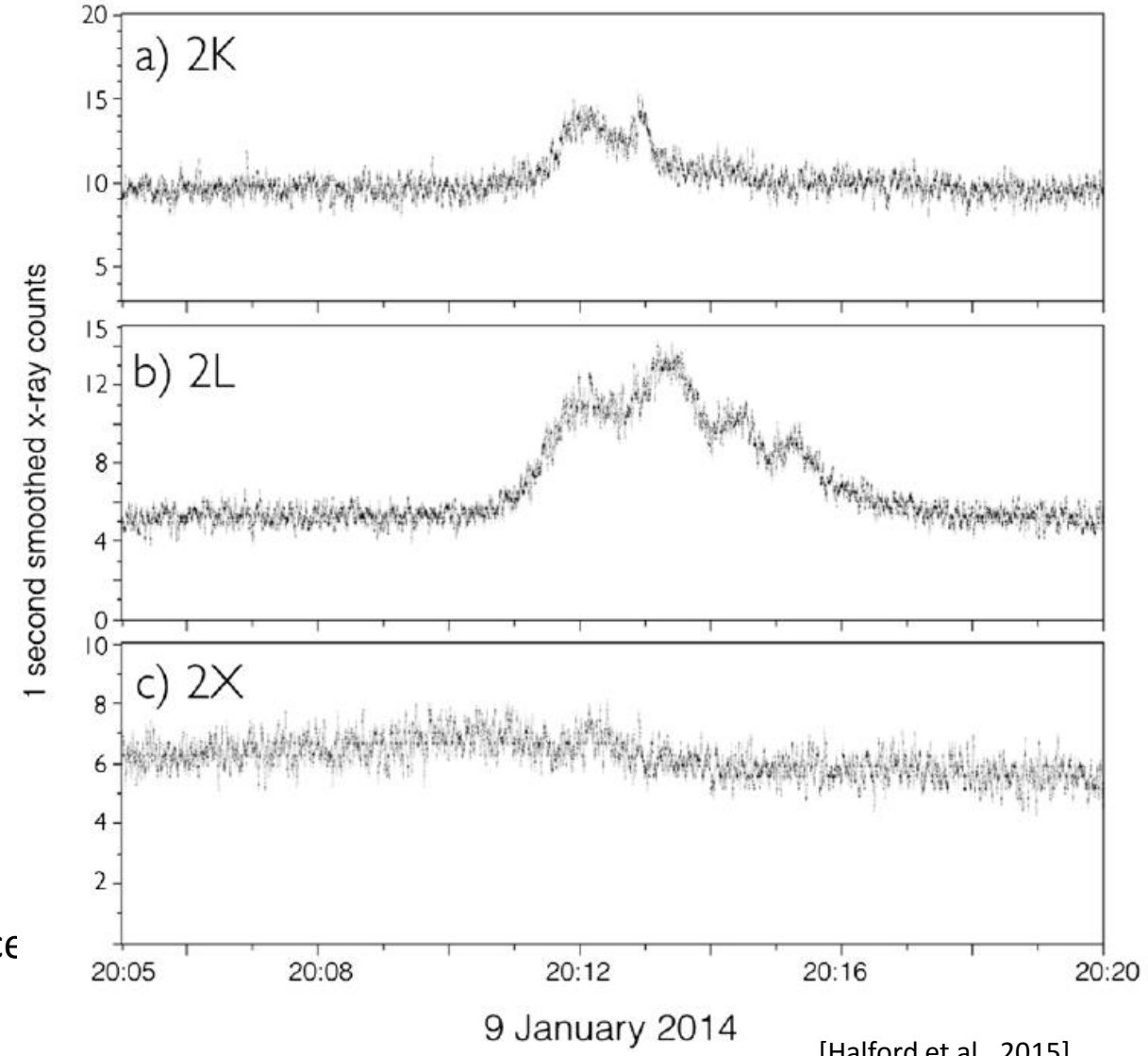


[Blum et al., 2015]

- ULF waves with frequencies <10 mHz have been linked to relativistic electron precipitation in the absence of VLF/EMIC waves (above, Brito et al., 2015)
- Recent BARREL observations are also providing strong evidence for direct links between EMIC waves and precipitation

How do ULF waves couple to the radiation belts?
Example: When/where/how do Pc5 waves affect radiation belt dynamics

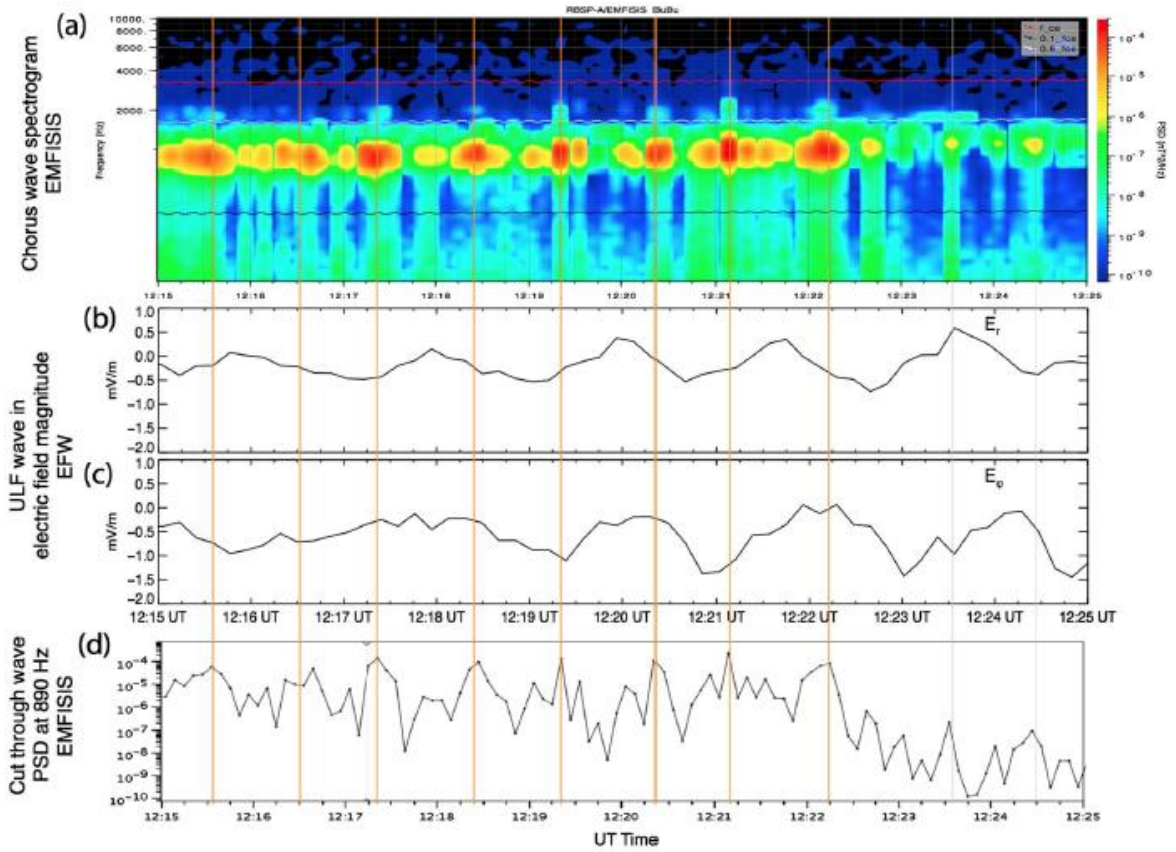




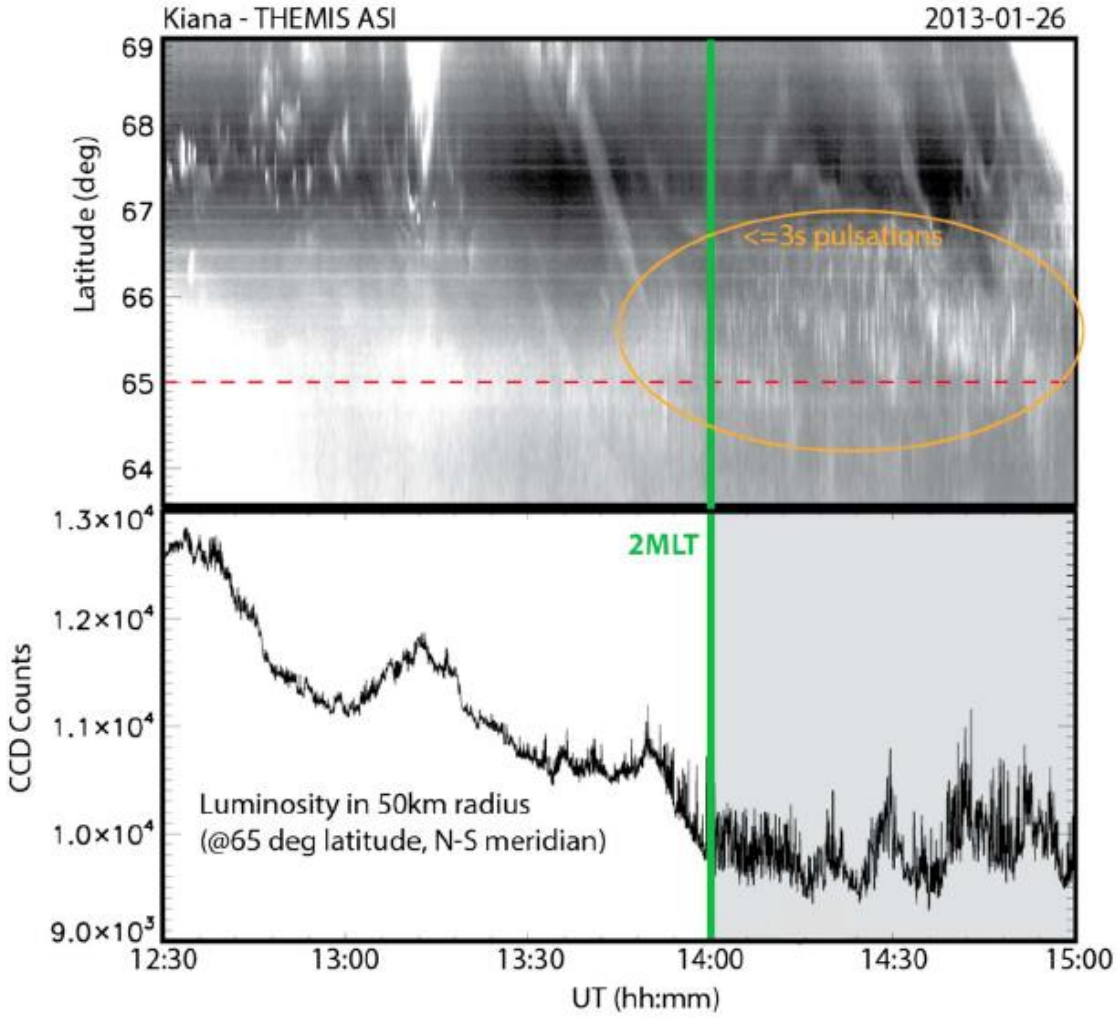
- Electron precipitation via VLF waves modulated by ULF waves (as well as electric field impulses)
- Recent BARREL observations are also providing strong evidence for direct links between ULF modulated-VLF waves and precipitation

[Halford et al., 2015]

What is the role of ULF waves in Magnetosphere-Ionosphere Coupling? Example: ULF modulation of auroral precipitation (1)



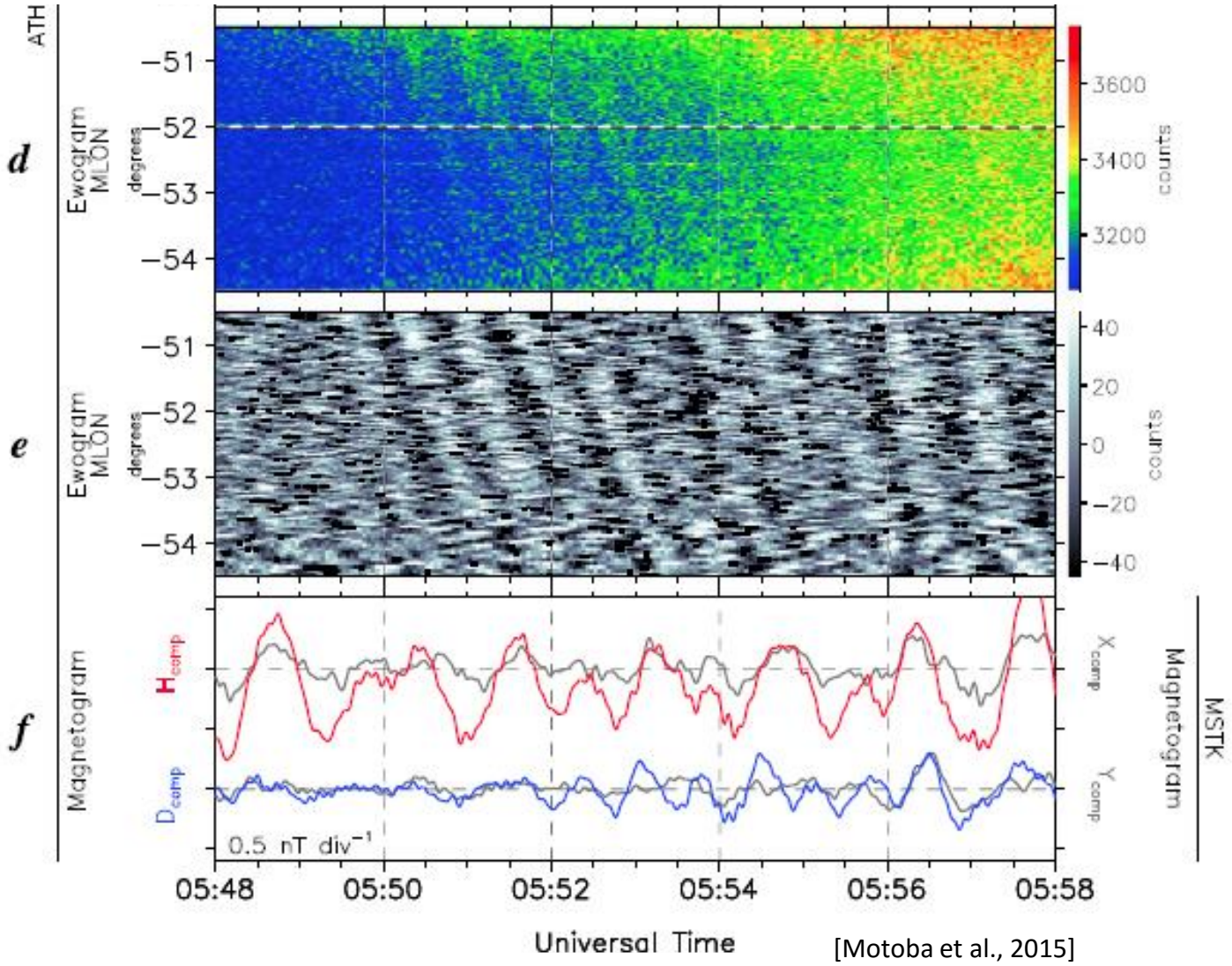
[Jaynes et al., 2015]



- Simultaneous observations of ULF wave properties, VLF wave properties, and auroral modulation
- ULF waves grow due to substorm injection, modulate chorus waves that in turn cause precipitation as they grow

What is the role of ULF waves in Magnetosphere-Ionosphere Coupling? Example: ULF modulation of auroral precipitation (2)

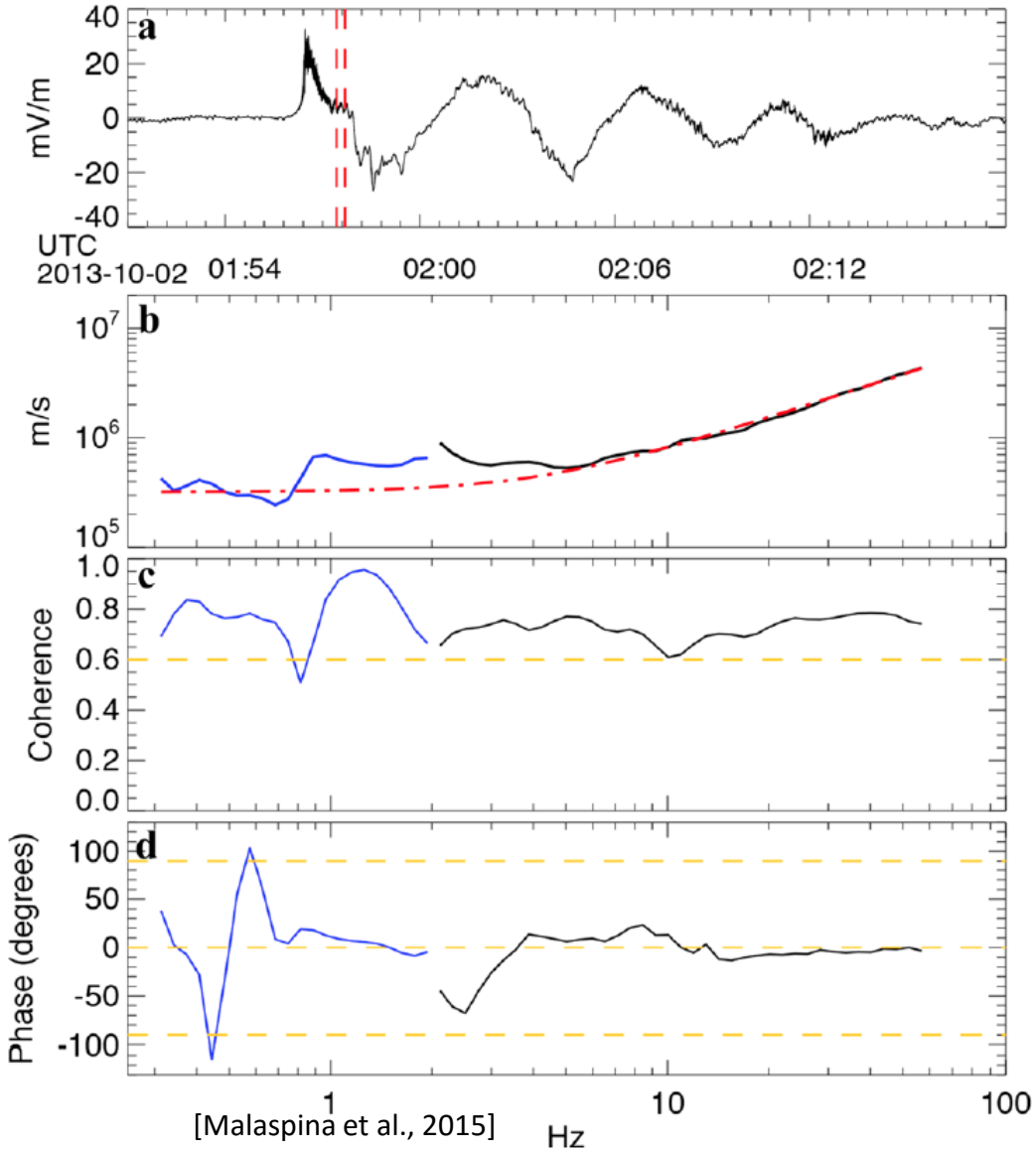
- ULF modulation of VLF waves leading to auroral structures
- Direct interaction with ULF waves can also cause auroral modulation



[Motoba et al., 2015]

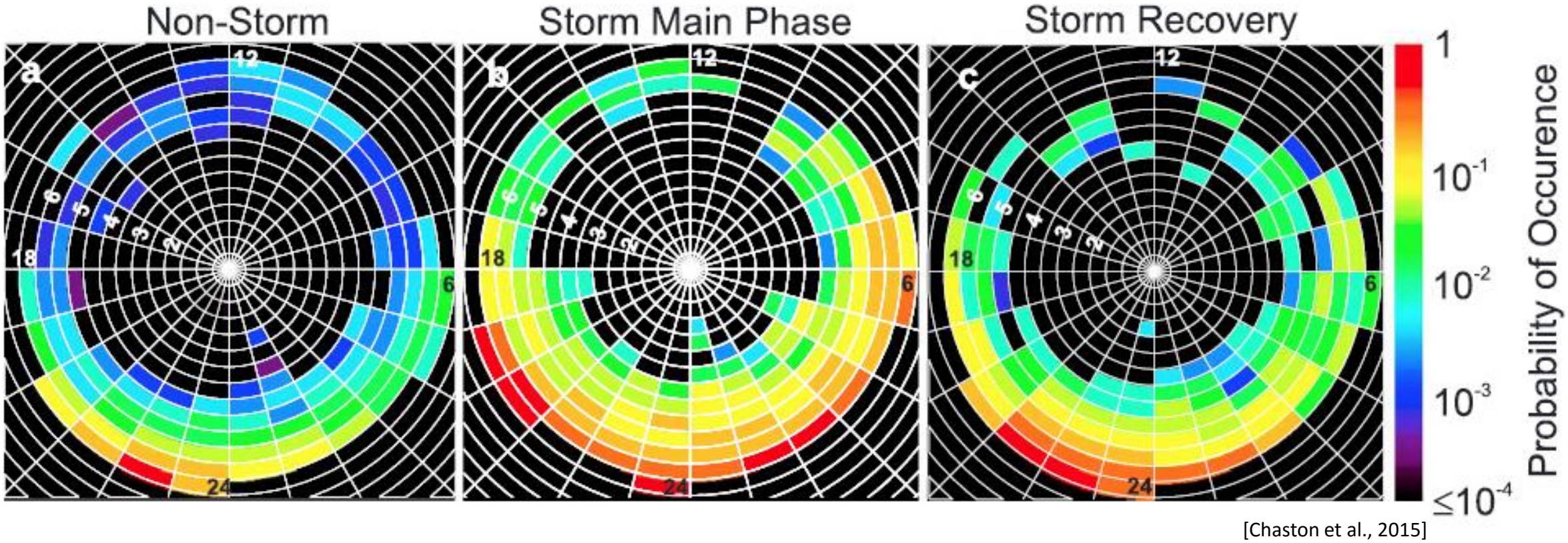
What is the role of ULF waves in Magnetosphere-Ionosphere Coupling? Example: Small scale, dispersive Alfven waves (1)

- There are an increasing number of observations of small scale, dispersive Alfven waves embedded within large wave fields – e.g., standing Alfven waves with Pc5 frequencies
- They are associated with parallel electric fields that cause particle acceleration
- They are part of the energy budget for the large scale structure



[Malaspina et al., 2015]

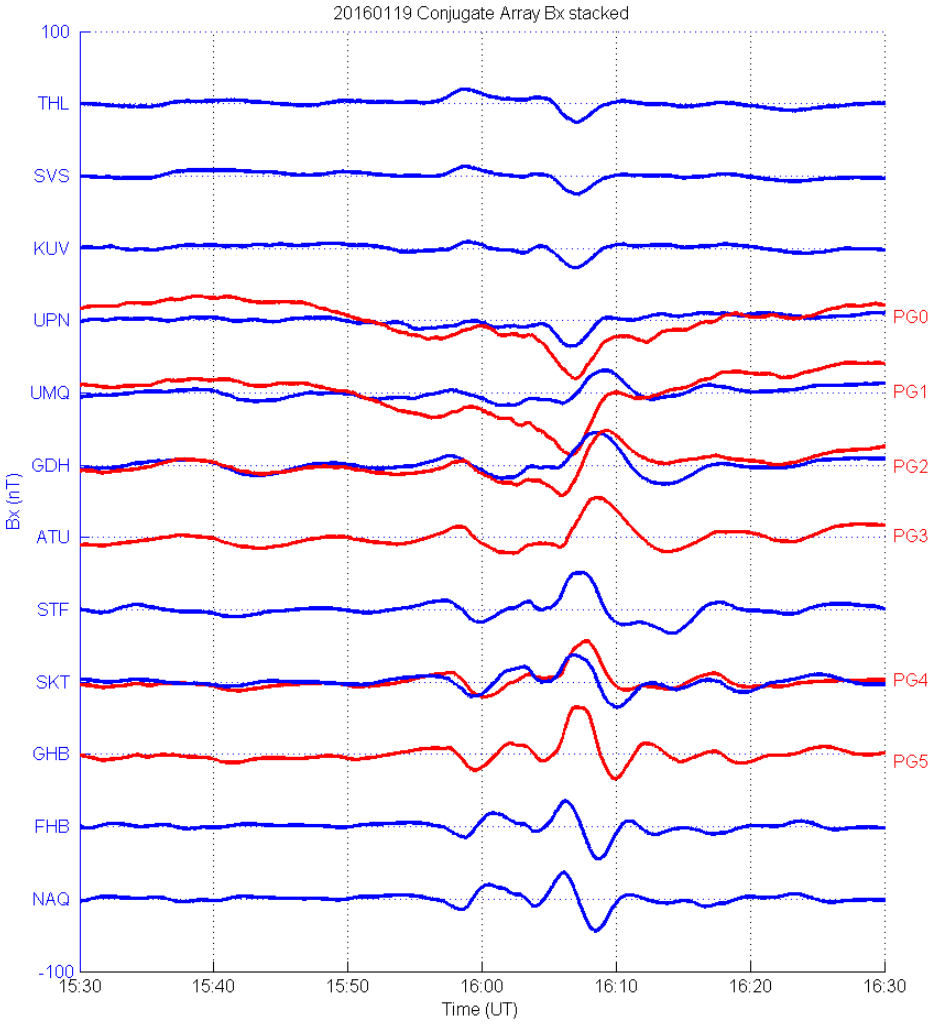
What is the role of ULF waves in Magnetosphere-Ionosphere Coupling? Example: Small scale, dispersive Alfven waves (3)

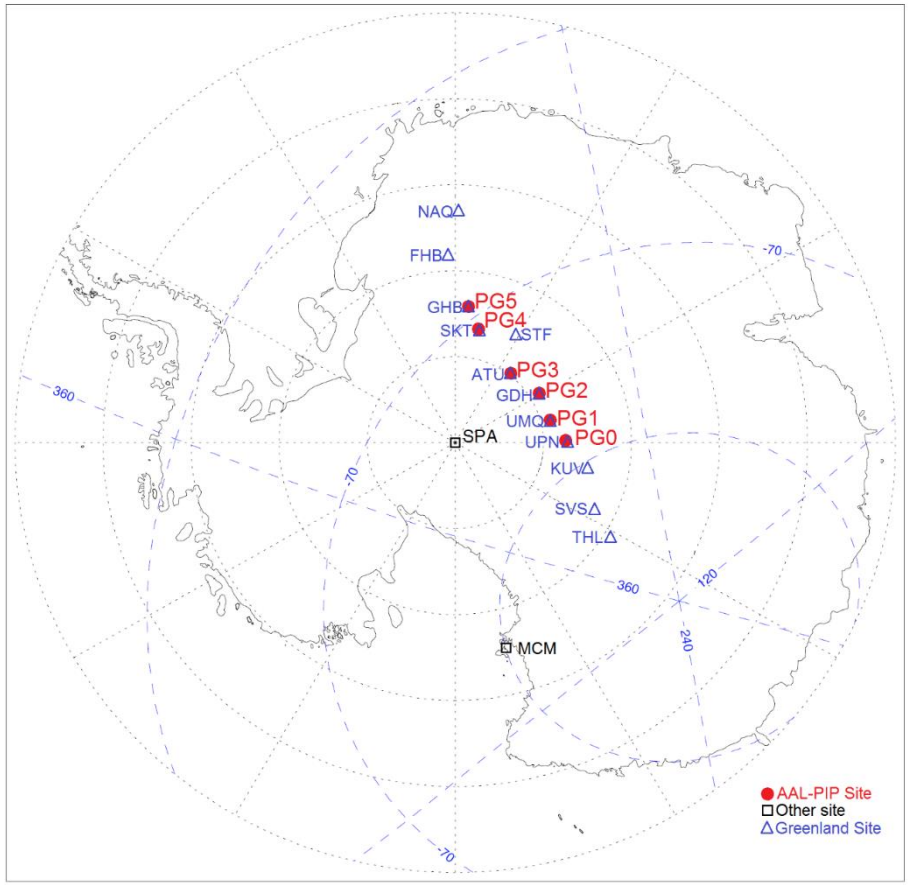


[Chaston et al., 2015]

- Dispersive Alfven waves are increasingly observed in the inner magnetosphere and may also affect higher energy radiation belt particles

What is the role of ULF waves in Magnetosphere-Ionosphere Coupling? Example: Explaining North-south asymmetries





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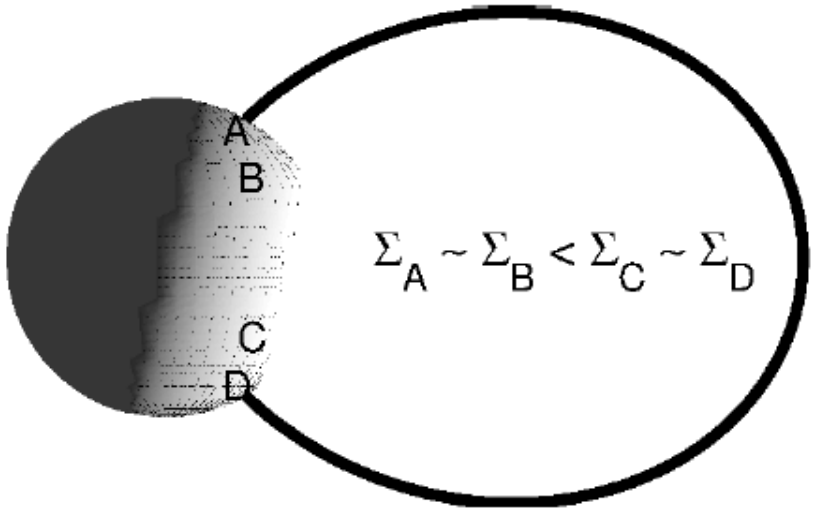
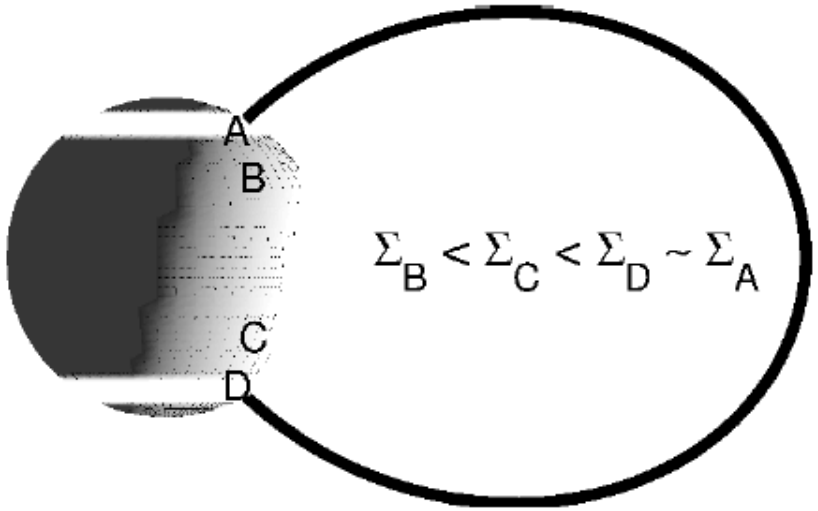
- ULF wave properties often differ between the north-south hemisphere at latitudes corresponding to the auroral oval/open-closed field line boundary

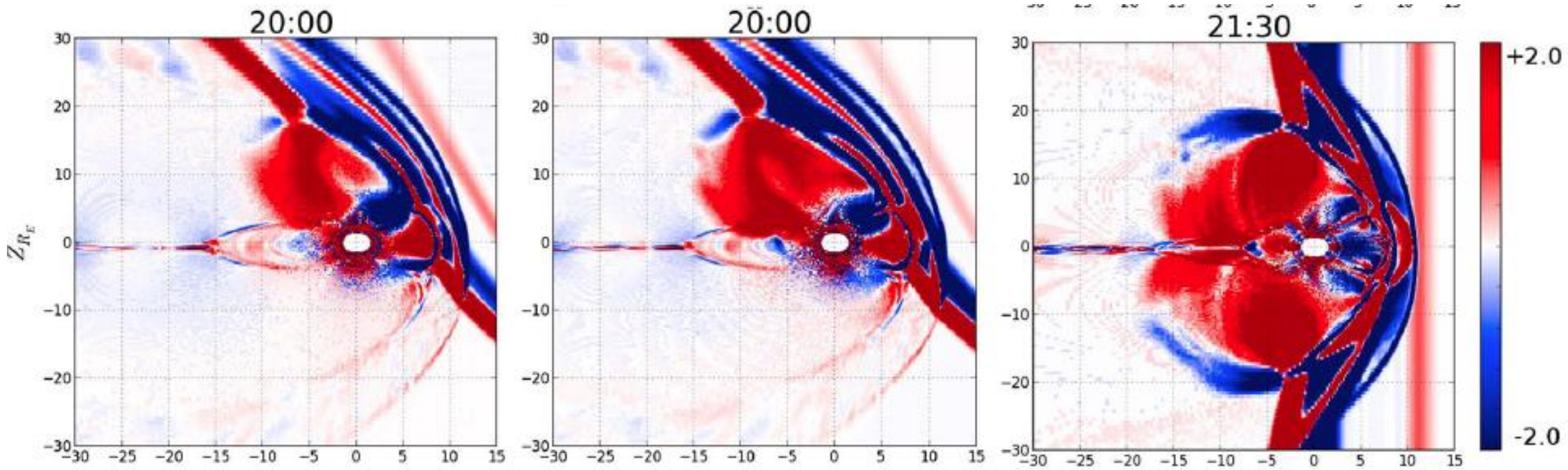
What is the role of ULF waves in Magnetosphere-Ionosphere Coupling? Example: Explaining North-south asymmetries





- Internal asymmetries affect ULF wave properties
- Large scale Alfven waves should vary according to the ionospheric conductivity and conductivity gradients

What is the role of ULF waves in Magnetosphere-Ionosphere Coupling? Example: Explaining North-south asymmetries



[Oliveira and Raeder, 2014, 2015]

- External asymmetries affect ULF wave properties
- The solar wind, ion foreshock, and magnetosheath energy sources for ULF wave excitation are not necessarily symmetric with respect to the magnetic equatorial plane
- Need more observations in southern hemisphere to explain north-south asymmetries

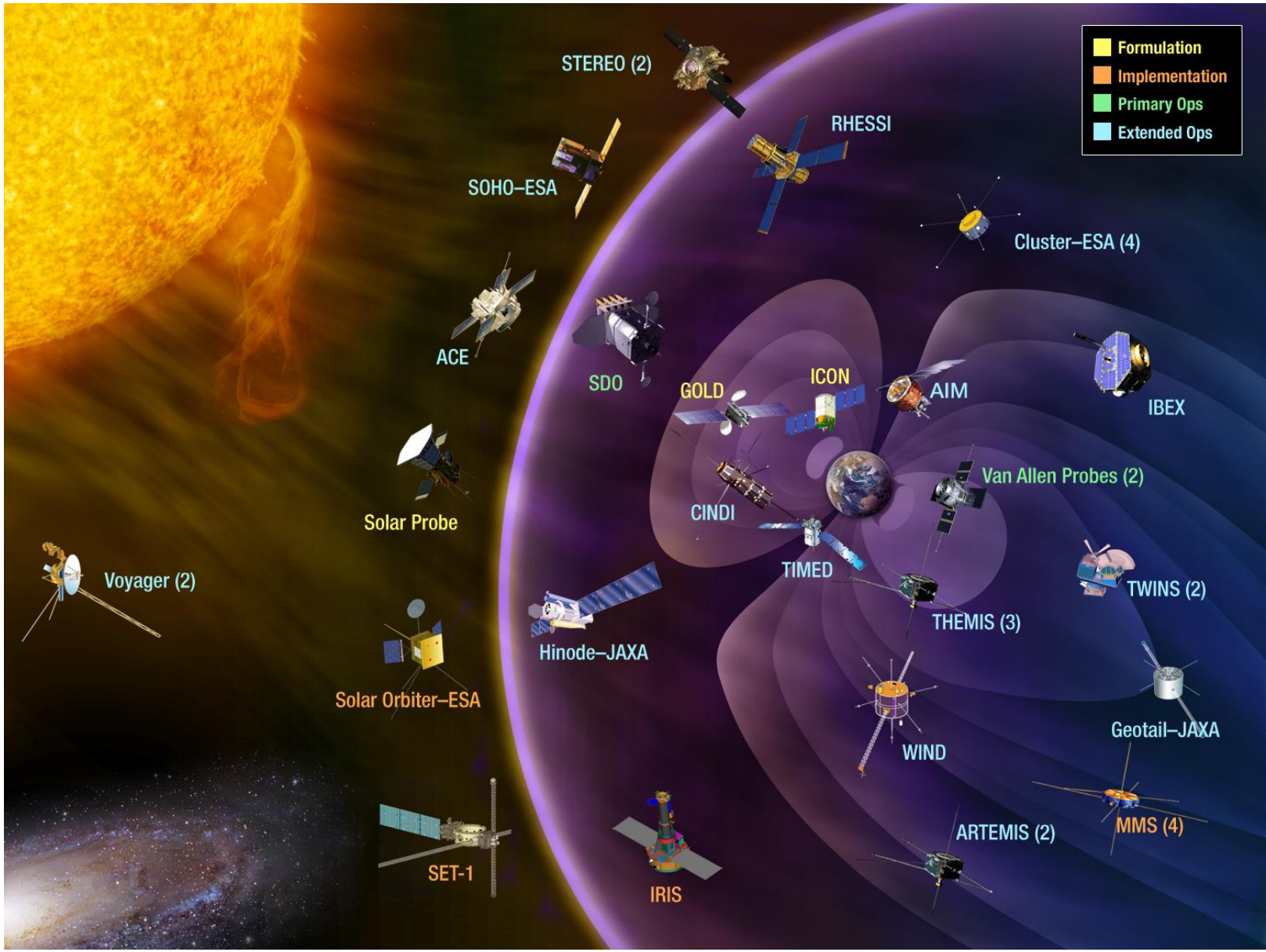
Summary of a few recent studies and new questions

- What excites ULF waves?
  - Magnetopause surface waves
  - Drift/drift-bounce resonance
- How do ULF waves couple to the ring current?
  - Drift/drift-bounce resonance
  - Particle injections to small radial distances
- How do ULF waves couple to the plasmasphere?
  - Standing Alfven waves
  - EMIC waves/EMIC wave growth
- How do ULF waves couple to the radiation belts?
  - New radial diffusion coefficients
  - Non-diffusive transport/drift resonance
  - Pc5 modulation of VLF waves and EMIC waves – when/where/how do Pc5 waves affect radiation belt dynamics?
- What is the role of ULF waves in MI coupling?
  - ULF modulation of auroral precipitation
  - Relation between large scale ULF waves and small scale, dispersive Alfven waves that can cause precipitation
  - Role of north-south asymmetries

New Observations and New Opportunities

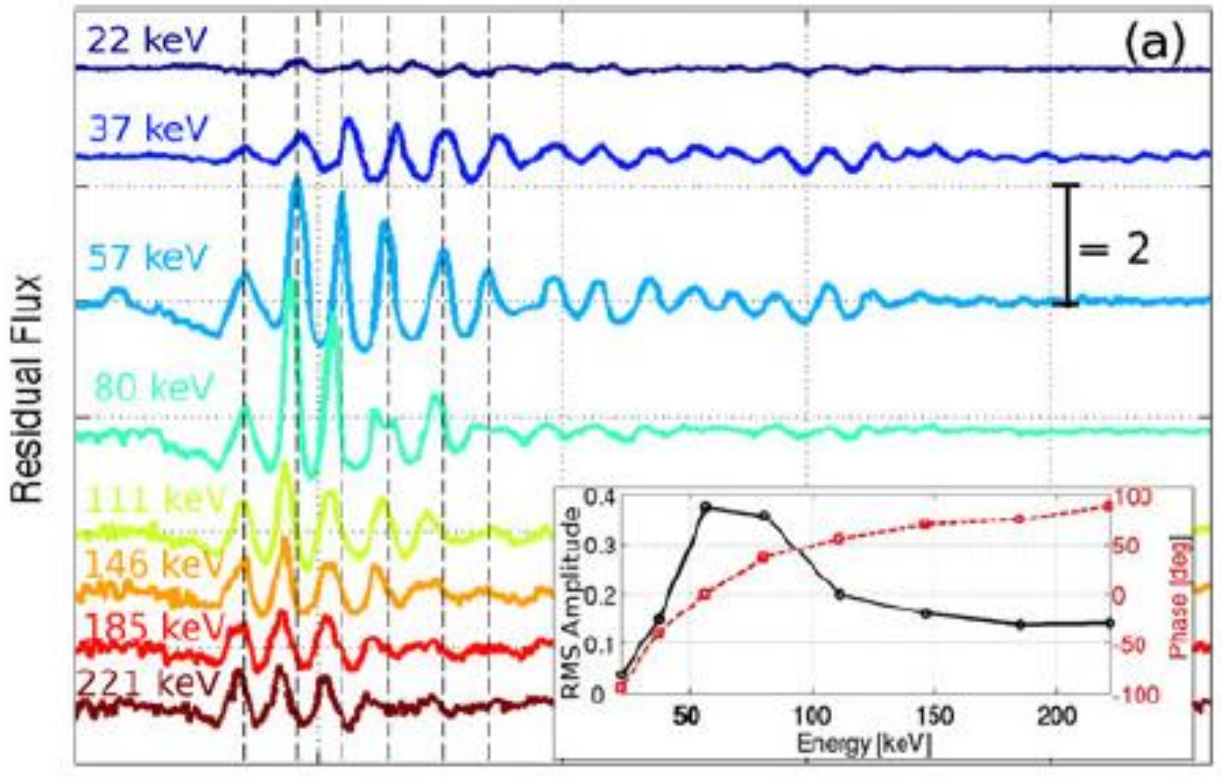
- Multiple satellite constellations
  - →Global wave properties

[NASA]



New Observations and New Opportunities

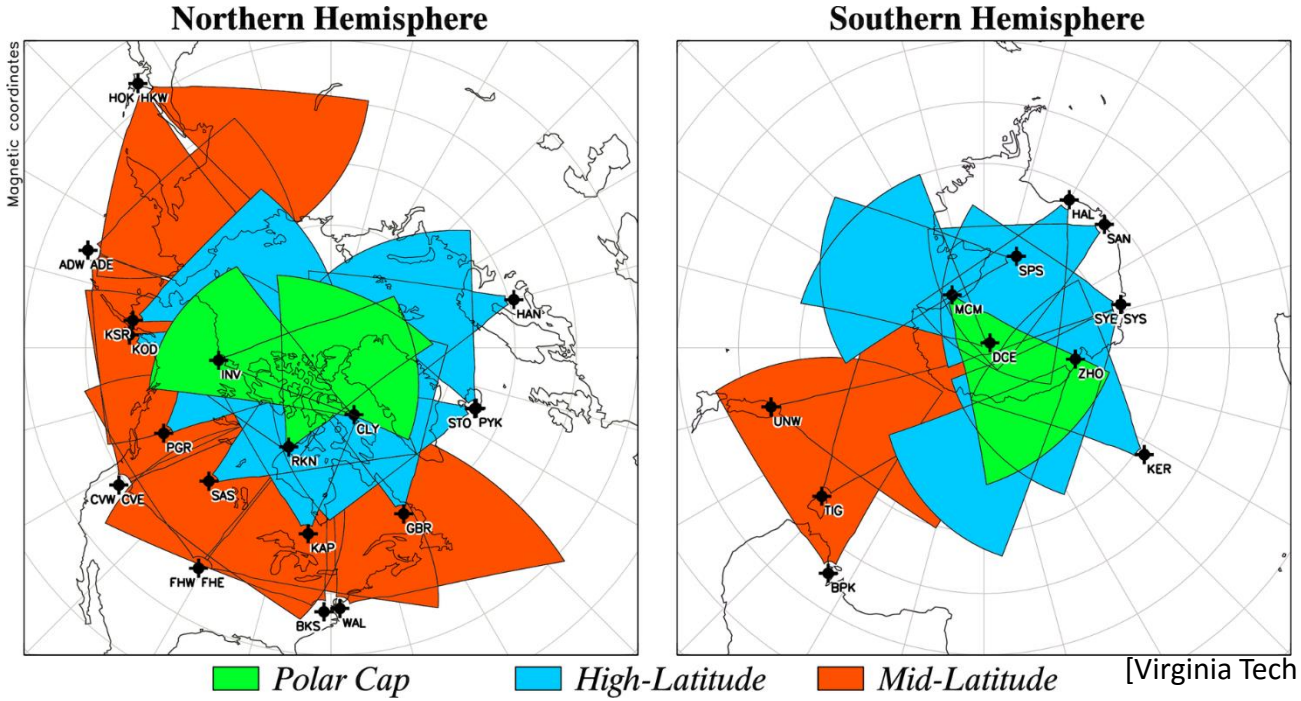
- Multiple satellite constellations
  - →Global wave properties
- High resolution particle and fields instruments
  - →Drift/drift-bounce resonance



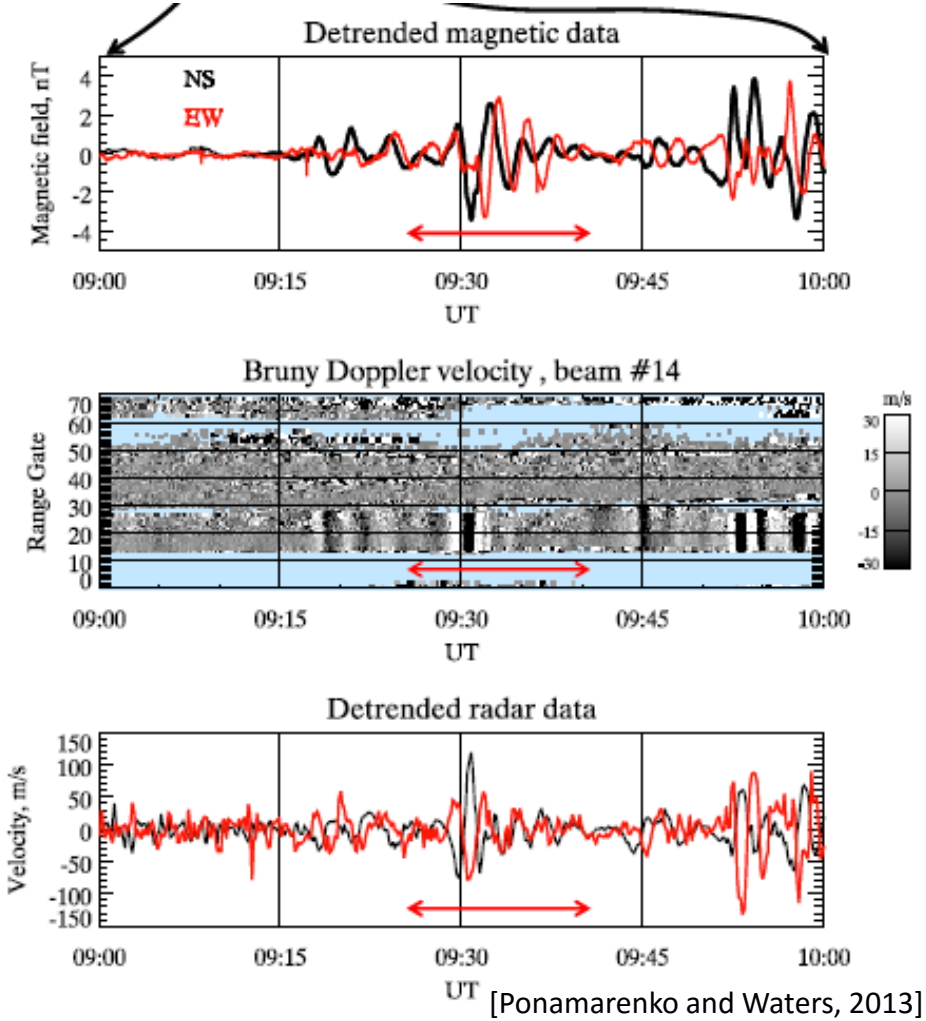
[Claudepierre et al., 2013]

New Observations and New Opportunities

- Multiple satellite constellations
  - →Global wave properties
- High resolution particle and fields instruments
  - →Drift/drift-bounce resonance
- Expanded ground-based arrays
  - →New information about ULF wave excitation and dissipation



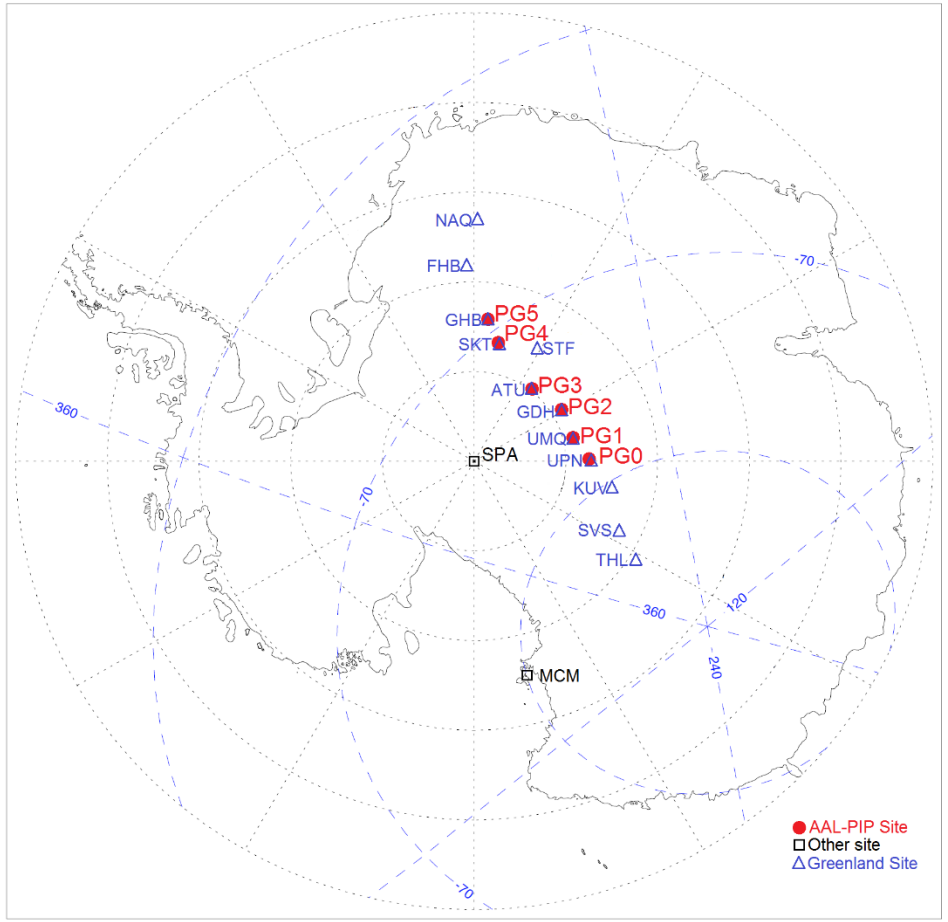
[Virginia Tech SuperDARN website]



[Ponamarenko and Waters, 2013]

New Observations and New Opportunities

- Multiple satellite constellations
  - →Global wave properties
- High resolution particle and fields instruments
  - →Drift/drift-bounce resonance
- Expanded ground-based arrays
  - →New information about ULF wave excitation and dissipation
- Coordinated instrument operation and data analysis
  - →North-south asymmetries, global wave properties and their impact on the ring current/radiation belts



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SuperMAG

Introducing the UMEA focus group: ULF wave modeling, effects, and applications

- ULF wave research spans many different research areas and focus groups
- UMEA aims to bring researchers in different areas together to address these questions:
  - What excites ULF waves?
  - How do ULF waves couple to the plasmasphere/ring current/radiation belts?
  - What is the role of ULF waves in Magnetosphere-Ionosphere coupling?
- This is an ideal time for such an effort: unprecedented availability of multi-point in situ and ground-based observations, high quality measurements of electric/magnetic fields and particles, and improved modeling capabilities

“…the subject of hydromagnetic waves in the magnetosphere (or magnetospheres) is highly developed…”
but
“…the subject is far from played out as a research field…”
Southwood and Hughes, [1983]

Thank you!