Nonlinear Whistler Waves in Earth's Radiation Belts: THEMIS Observations

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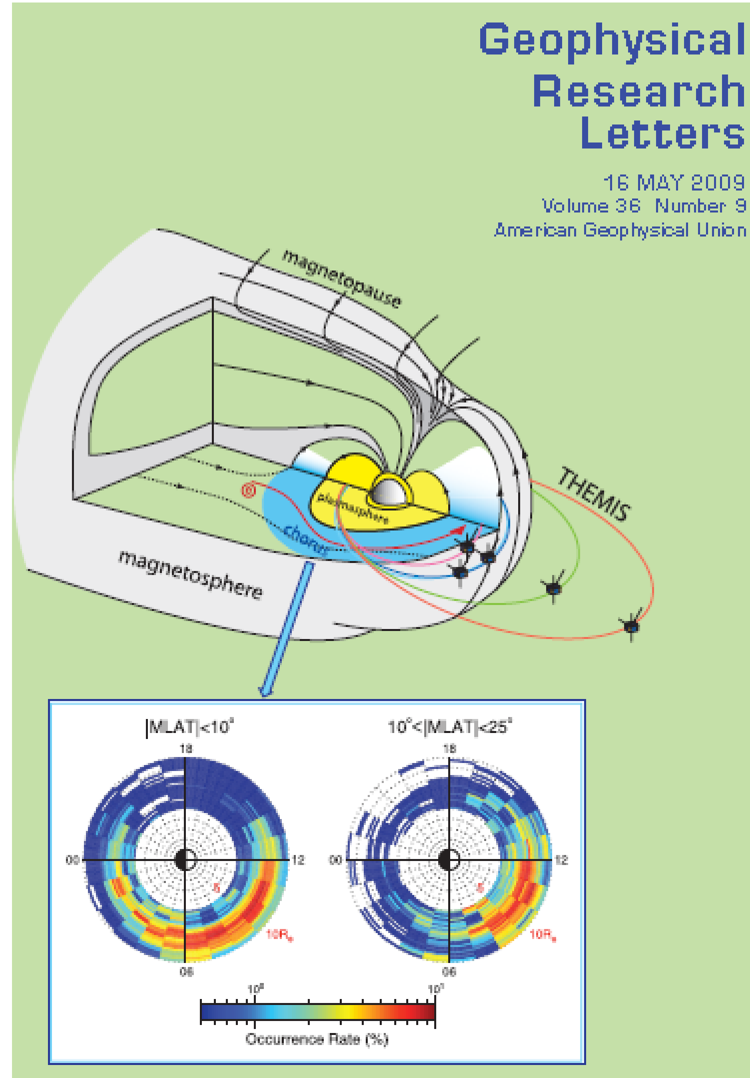
    - Alain Roux, Olivier LeContel
  - Fluxgate Magnetometer:
    - Karl-Heinz Glassmeier

Outline

- Early observation:
  - Larger E amplitudes than expected
- Event study
  - Where quasilinear theory works
  - Where nonlinear theory is required
    - Chorus sweep
      - Omura’s chorus generation mechanism
        - Experimental test
  - Cyclotron harmonic emissions

Background

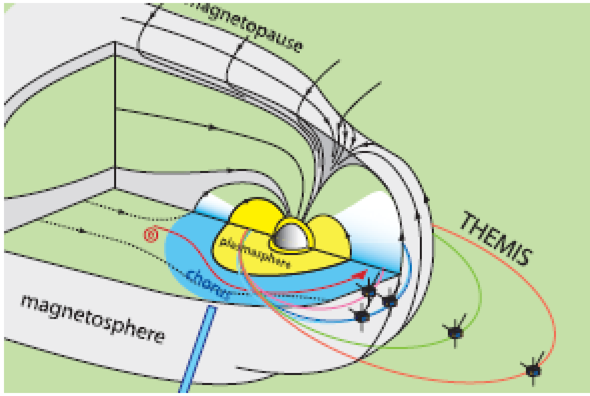
- Wave-particle interaction is a major controlling process in the Earth's radiation belts
  - Acceleration
  - Loss (scattering into loss cone)
- Whistler waves
  - Largely at dawn
  - Equatorial generation
  - Bursts of rising tones (chorus)



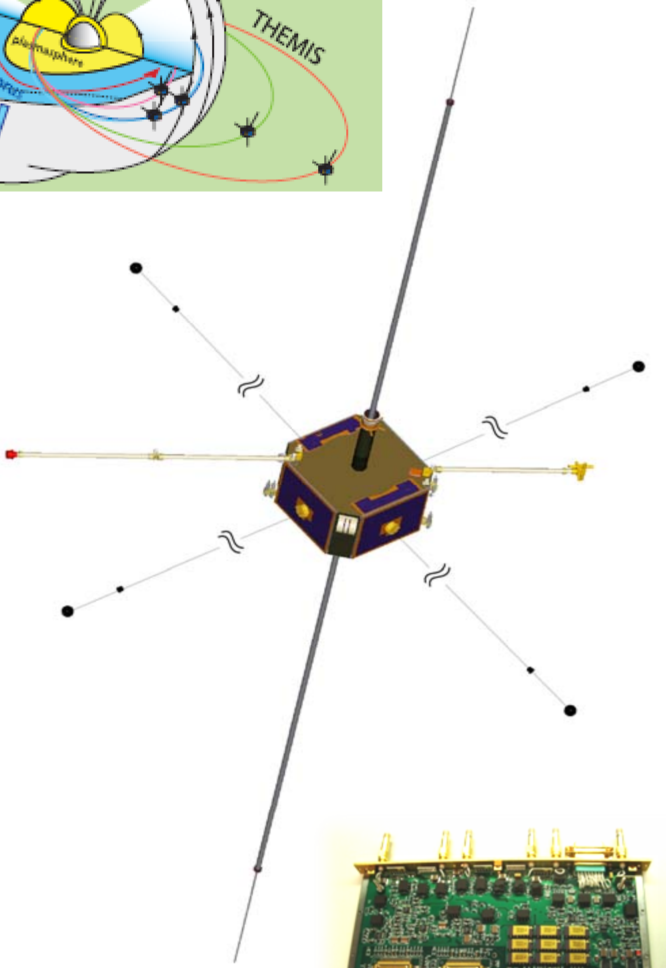
Li et al., GRL, 2009

Themis: nonlinear whistlers

Themis

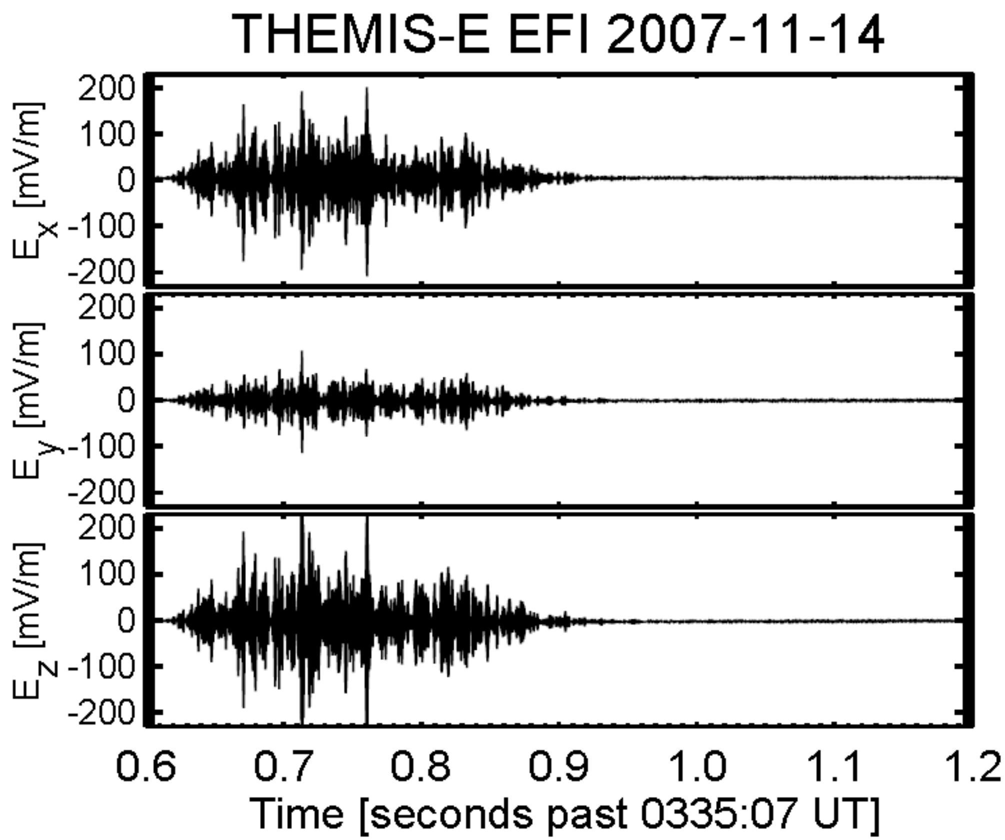


- 5 satellites in equatorial orbits
- Plasma instruments
  - Low energy (<30 keV) + high energy (<6 MeV) ions and electrons
  - Electric and magnetic fields



Unexpected amplitudes

- Early Themis result: Whistler electric fields larger than expected
- Heavy-tailed distribution
- >100 mV/m
  - Deterministic dynamics rather than stochastic
- Occur in large (hours of MLT) and persistent (days) region
- Agrees with other recent data (eg. STEREO)



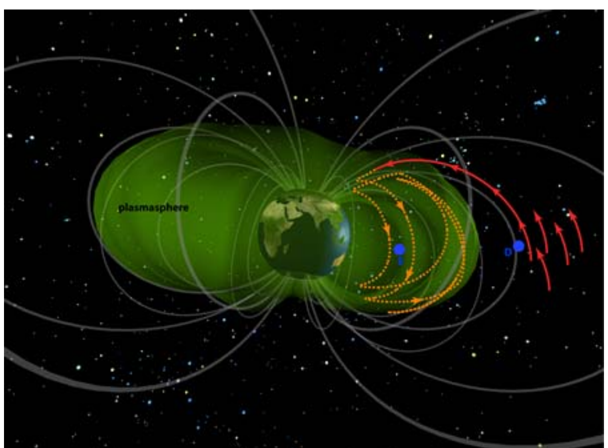
Cully et al, GRL, 2008

Themis: nonlinear whistlers

Themis: nonlinear whistlers

Oblique propagation

- Many of the largest amplitude events are obliquely propagating
  - Even near the equator
  - Lack the characteristic chorus chirp
- Propagation effect?



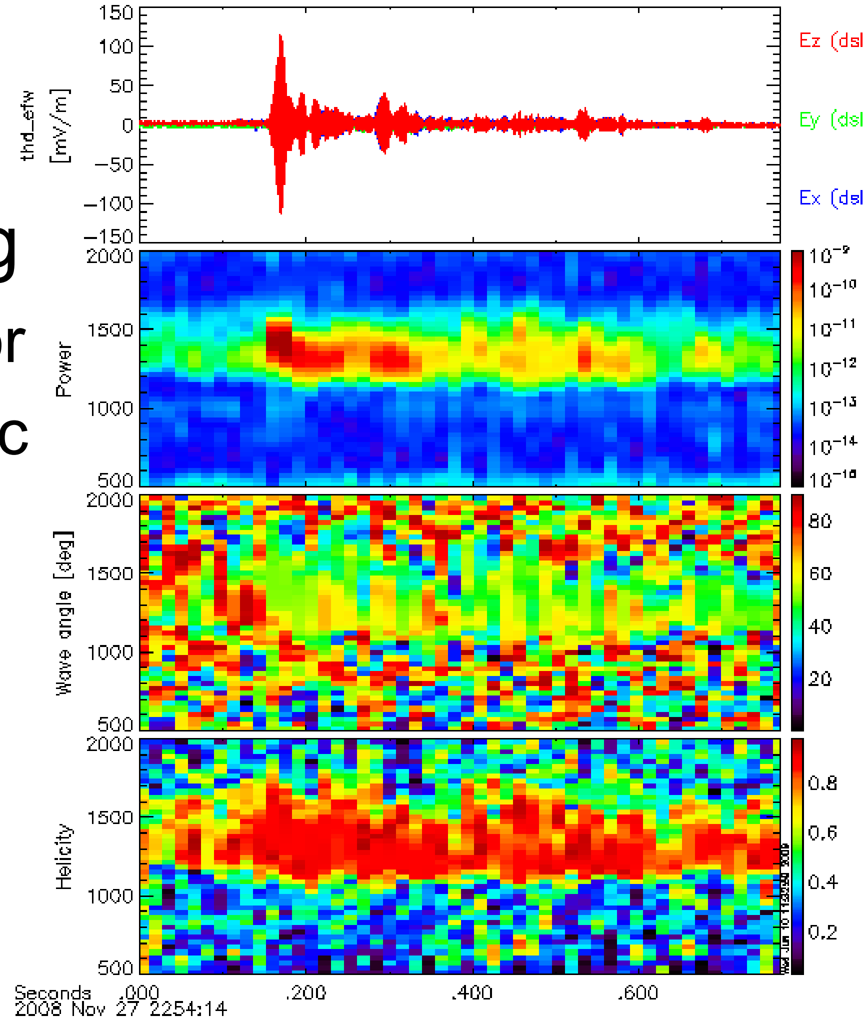


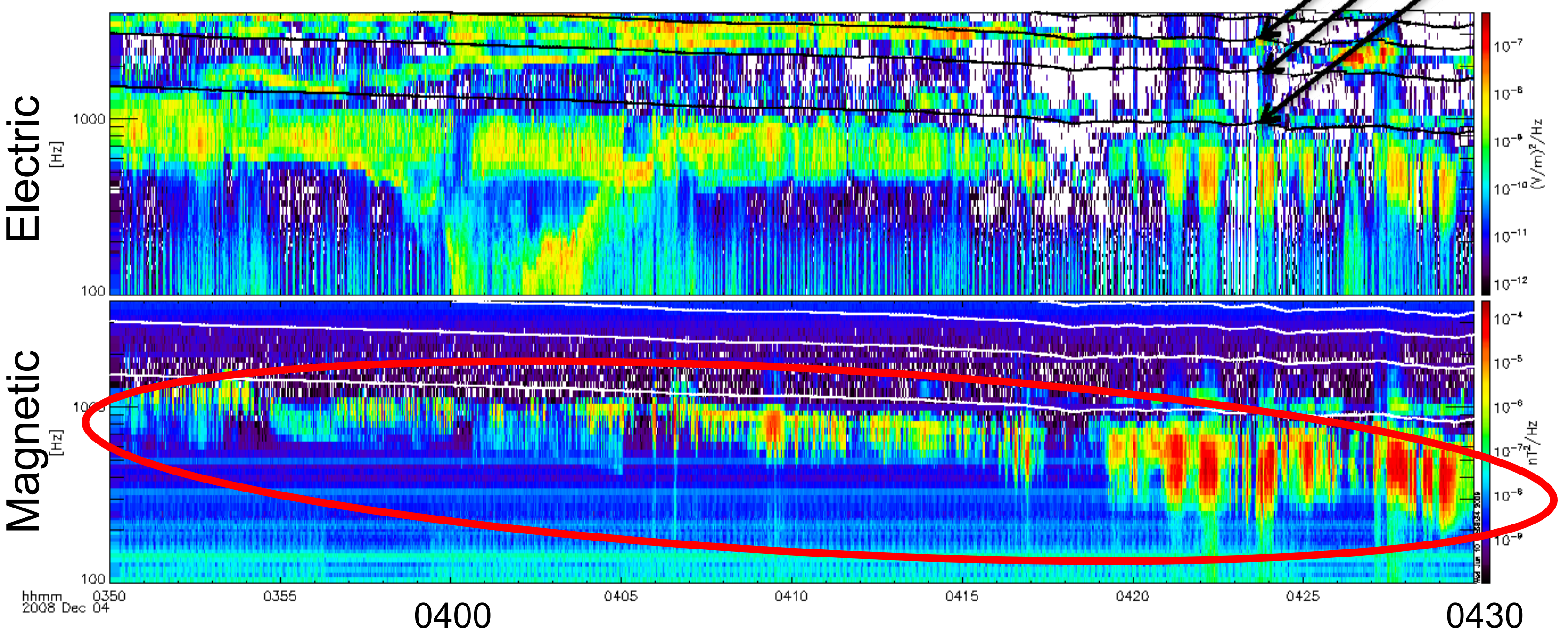
Image: NASA/Jacob Bortnik. See Bortik et al, Science, 2009.

CASE STUDY

Outline

- Early result:
  - Larger E amplitudes than expected
- Event study
  - Where quasilinear theory works
  - Where nonlinear theory is required
    - Chorus sweep
      - Omura's chorus generation mechanism
        - Experimental test
  - Cyclotron harmonic emissions

Event overview



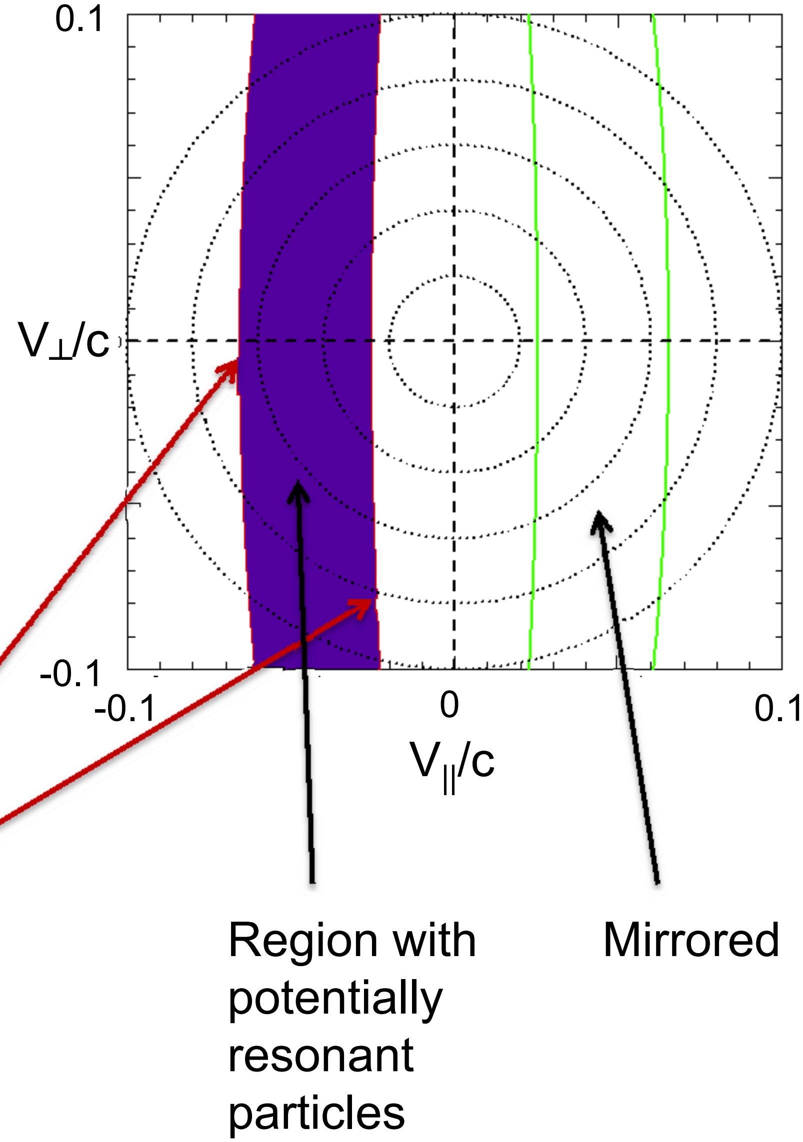
- Themis-D, L~5 R_E, MLAT~2°
- Bursts of whistler activity up to 0.5 f_{ce}
  - Gap at 0.5 f_{ce} (common)
  - Parallel propagation
- Strong cyclotron harmonics

Resonant ellipses

- Electrons moving counter to the wave motion at

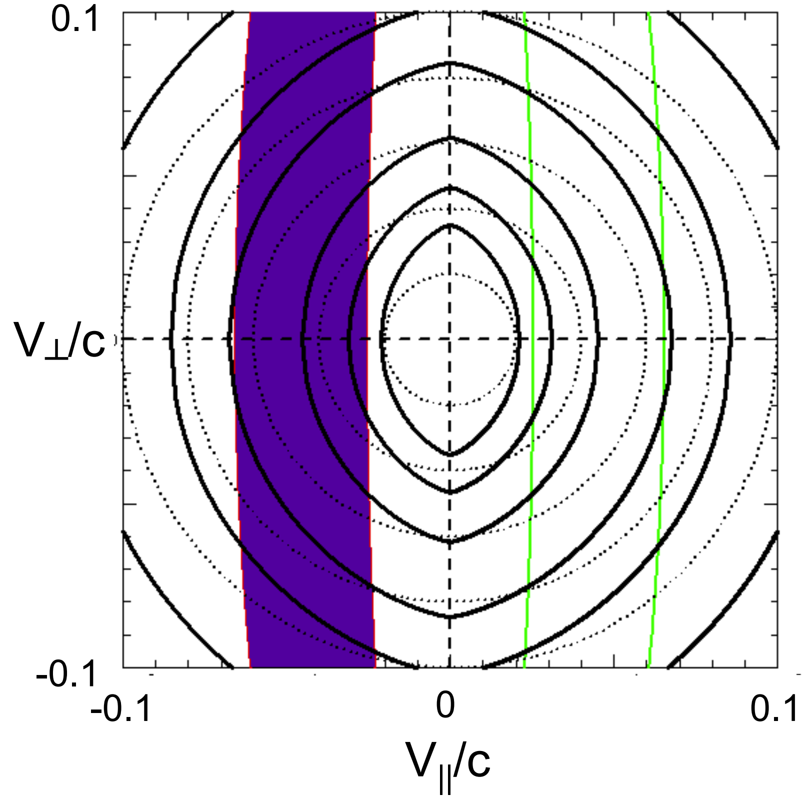
$$V_R = \frac{\omega}{k}\left(1 - \frac{\omega_{ce}}{\gamma\omega}\right)$$

  are cyclotron-resonant with the wave
- Ellipses at f=0.2 f_{ce} and f=0.5 f_{ce} demarcate interaction boundaries



Diffusion curves

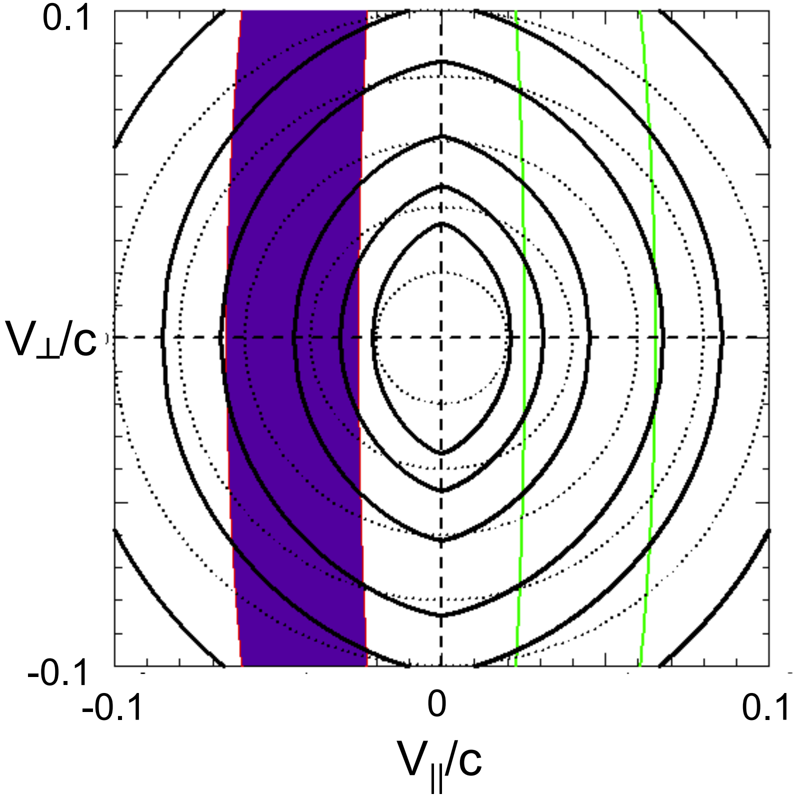
- Given broad spectrum of waves:
  - In frame moving with wave phase velocity, (relativistic) energy of resonant particle is conserved
  - As energy changes, particle resonates with different frequencies
- Result: diffusion curves shown
  - Hot, relativistic curves shown; cold and non-relativistic very similar



Summers, Thorne, Xiao, JGR, 1998
Horne and Thorne, GRL, 2003
Gendrin and Roux, JGR, 1980

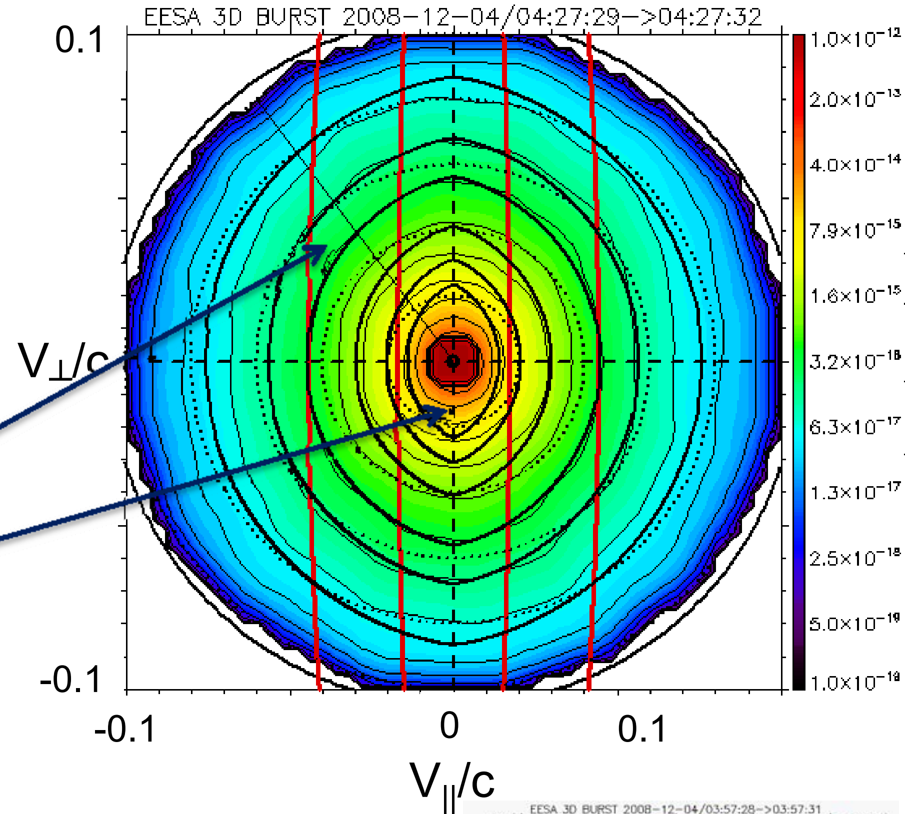
Experimental test

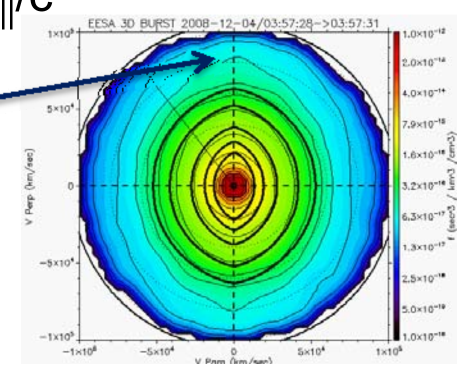
- Diffusion surface = phase space density iso-surface
  - Valid between the resonant ellipses for the observed wave spectrum
  - Marginal stability criterion



Diffusion curves: result

- Very good agreement with observed distribution function
- Diffusion curve=f iso-surface in interaction region
- Isotropic core
  - Resonant frequency above $f_{ce}/2$ (no wave power available)
- Sometimes see shoulder at $f_{ce}/2$

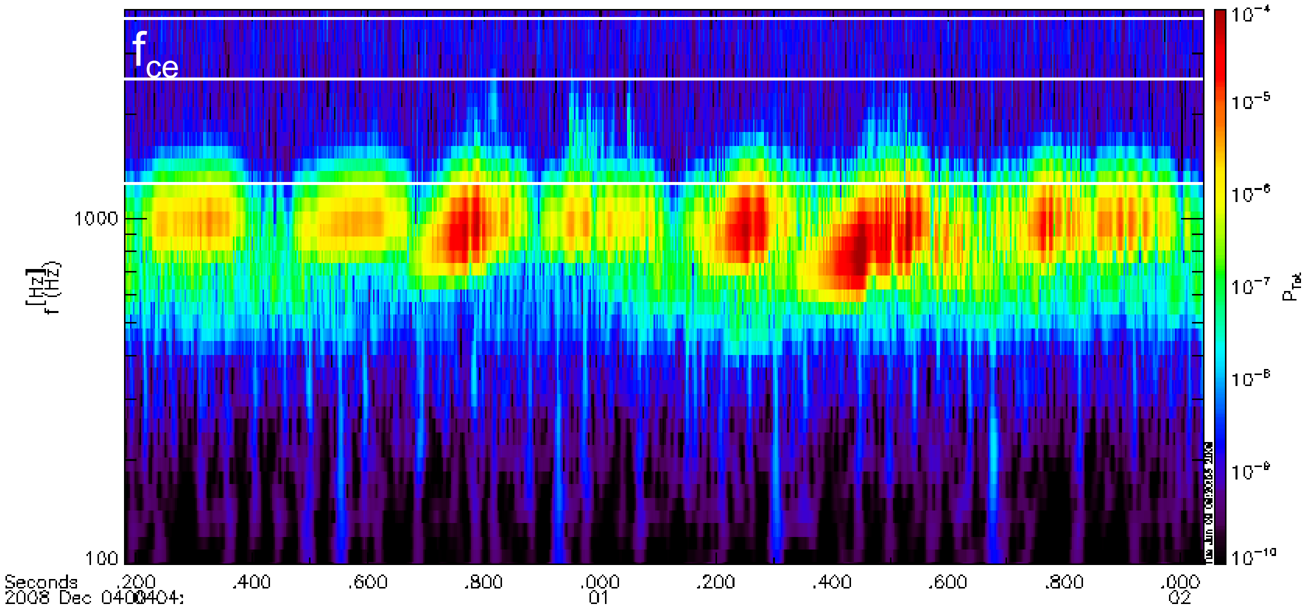




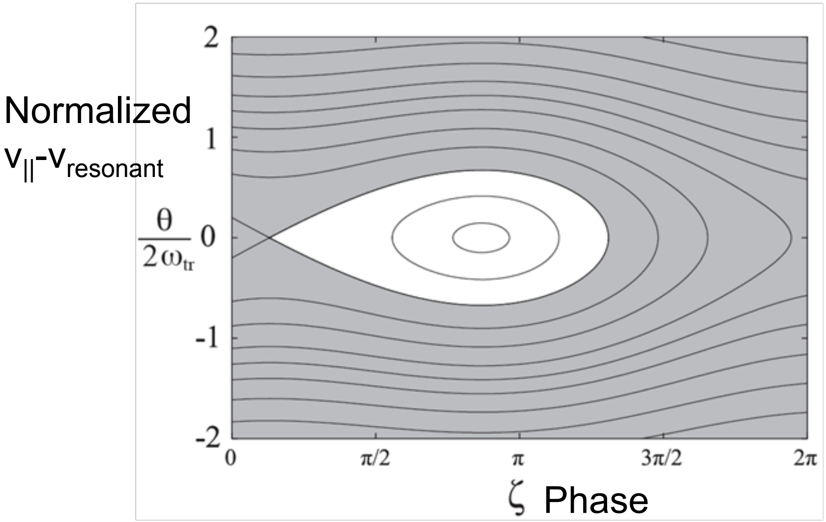
Nonlinear questions

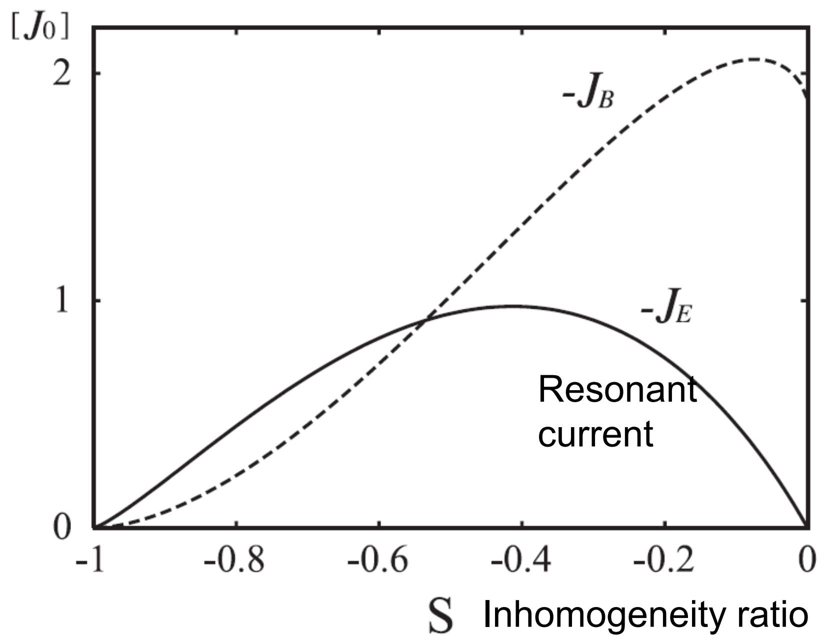
Linear theory predicts wave growth in a broad band up to f_{ce}. So:

1. Why does the chorus element chirp?
2. Why is the wave absorbed at $f_{ce}/2$?



Growth by nonlinear trapping

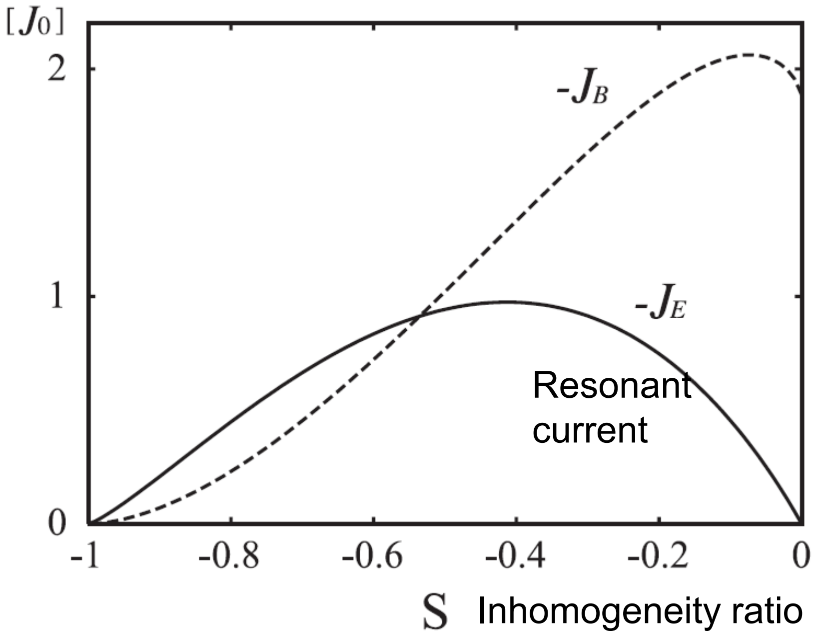




- Omura, Katoh and Summers, JGR, 2008
- Wave trapping results in electromagnetic phase space hole
- For specific conditions, resonant currents cause wave growth
  - Rising frequency
  - Quantified by inhomogeneity ratio S

Themis: nonlinear whistlers

Omura et al.'s prediction



- Fastest-growing wave is the one that maximizes the resonant current
  - Inhomogeneity ratio S ~ -0.4

$$S = -\frac{m_0}{k v_\perp e B_w \delta^2}\left\{\gamma\left(1-\frac{V_R}{V_g}\right)^2 \frac{\partial \omega}{\partial t} + \left[\frac{k\lambda v_\perp^2}{2\Omega_e} - \left(1+\frac{\delta^2}{2}\frac{\Omega_e-\gamma\omega}{\Omega_e-\omega}\right)V_R\right]\frac{\partial \Omega_e}{\partial h}\right\}$$

$$\delta^2 = 1 - \frac{\omega^2}{c^2 k^2}$$

Linear relation (if everything else constant and 1st term dominant)

Making it testable

- Need to eliminate some variables:

$$B_w = F\left(S, \frac{\partial \omega}{\partial t}, k, \omega, V_g, \Omega_e, \frac{\partial \Omega_e}{\partial h}, v_\perp, v_\parallel, V_R \right)$$

Making it testable

- Need to eliminate some variables:

$$B_w = F\left(S, \frac{\partial \omega}{\partial t}, k, \omega, V_g, \Omega_e, \frac{\partial \Omega_e}{\partial h}, v_\perp, v_\parallel, V_R\right)$$

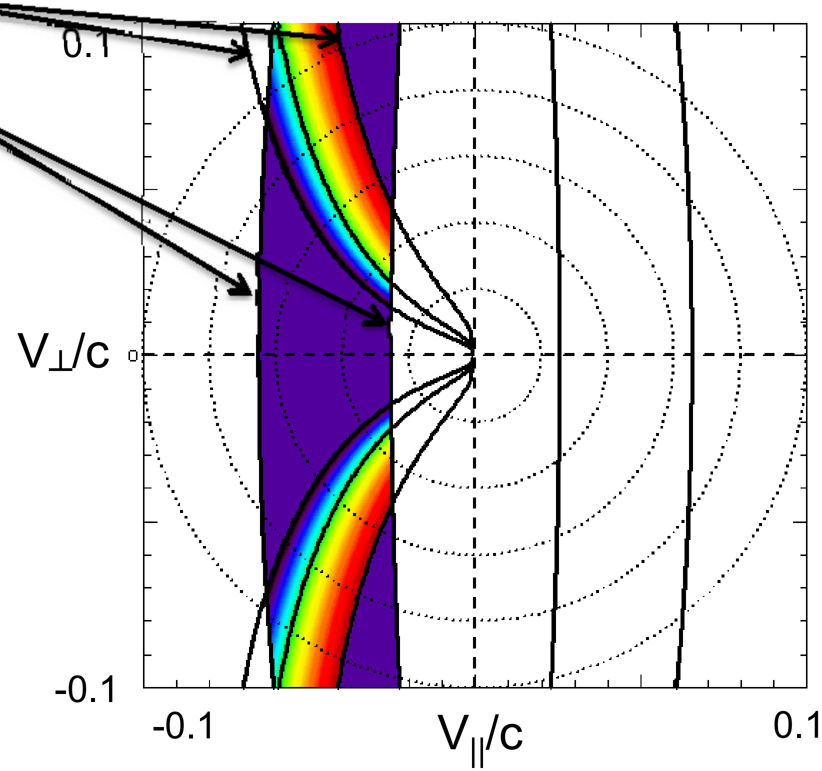
- Growth in range -0.6 < S < -0.2
- Dispersion relation (introduces ω_{pe})
- Growth in range 0.2 < f/f_{ce} < 0.5
- Resonance condition

$$\rightarrow B_w = G\left(\frac{\partial \omega}{\partial t}, \boxed{\Omega_e, \omega_{pe}, \frac{\partial \Omega_e}{\partial h}}, \boxed{v_\perp, v_\parallel}\right)$$

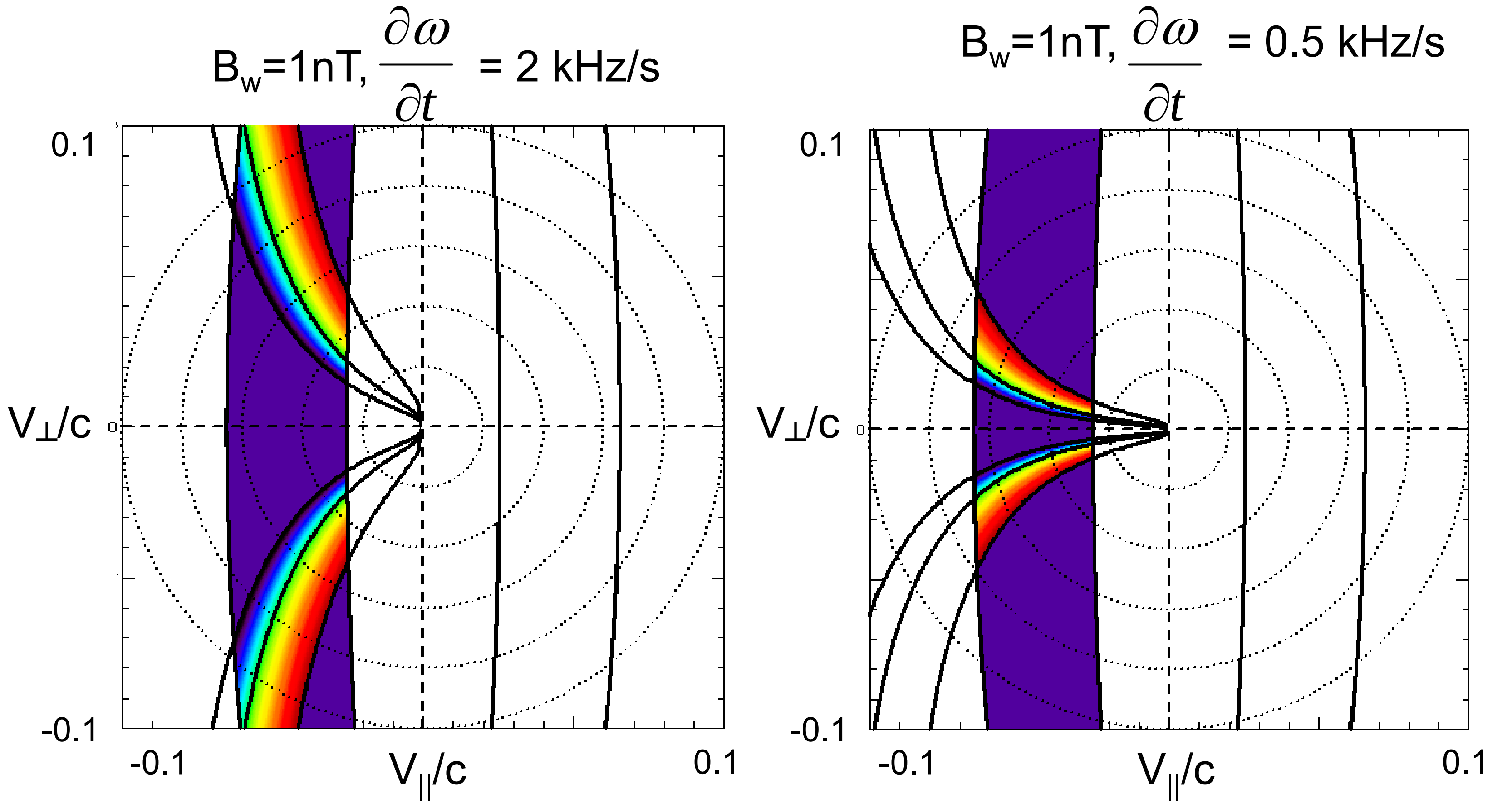
Plasma parameters
Velocities (???)

Maximization in velocity space

- Fastest-growing wave is the one that maximizes the resonant current
  - Maximize $n' = \int_C f \mathrm{d}^3 \mathrm{v}$ over domain bounded by:
    - $-0.6 < S < -0.2$
    - $0.2 < f/f_{ce} < 0.5$



Maximization in velocity space



- Integration domain depends on B_w and $\frac{\partial\omega}{\partial t}$ through S

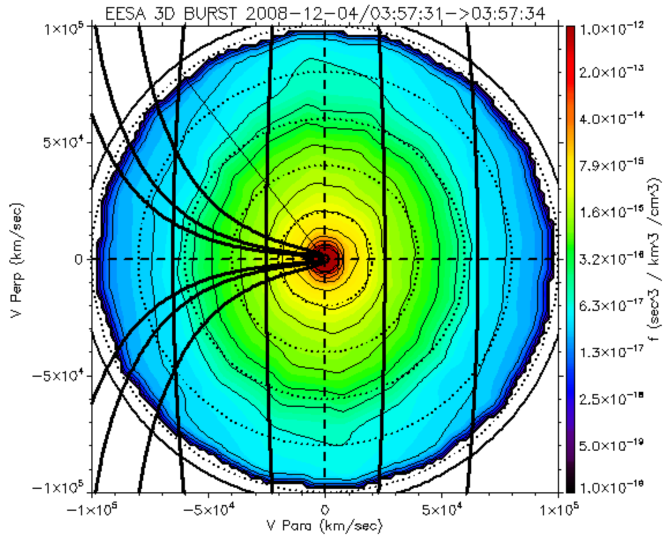
Themis: nonlinear whistlers

Testable result

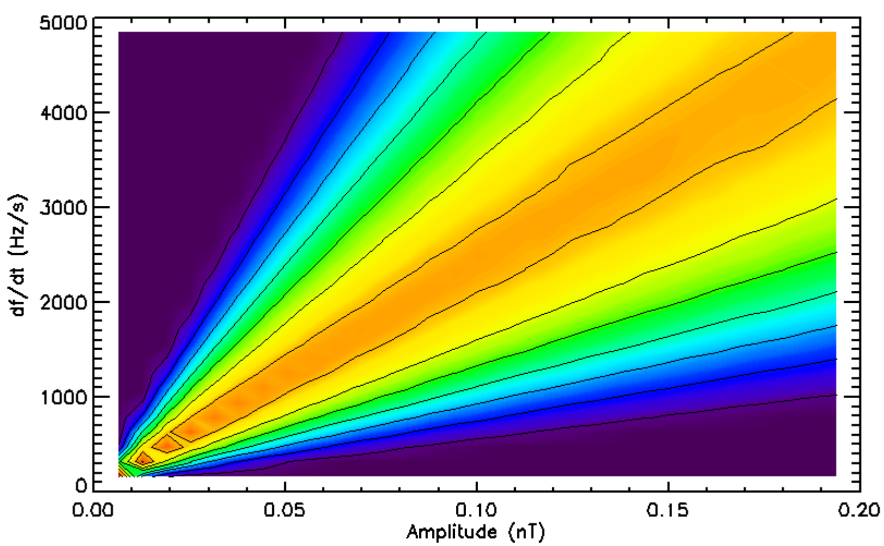
- By integrating over the observed particle distributions, arrive at

$$n' = F\left(\frac{\partial \omega}{\partial t}, B_w\right)$$

- Maximizing n' yields a very specific testable prediction:
  - Relationship between B_w and $\partial f/\partial t$
  - NO adjustable parameters!!

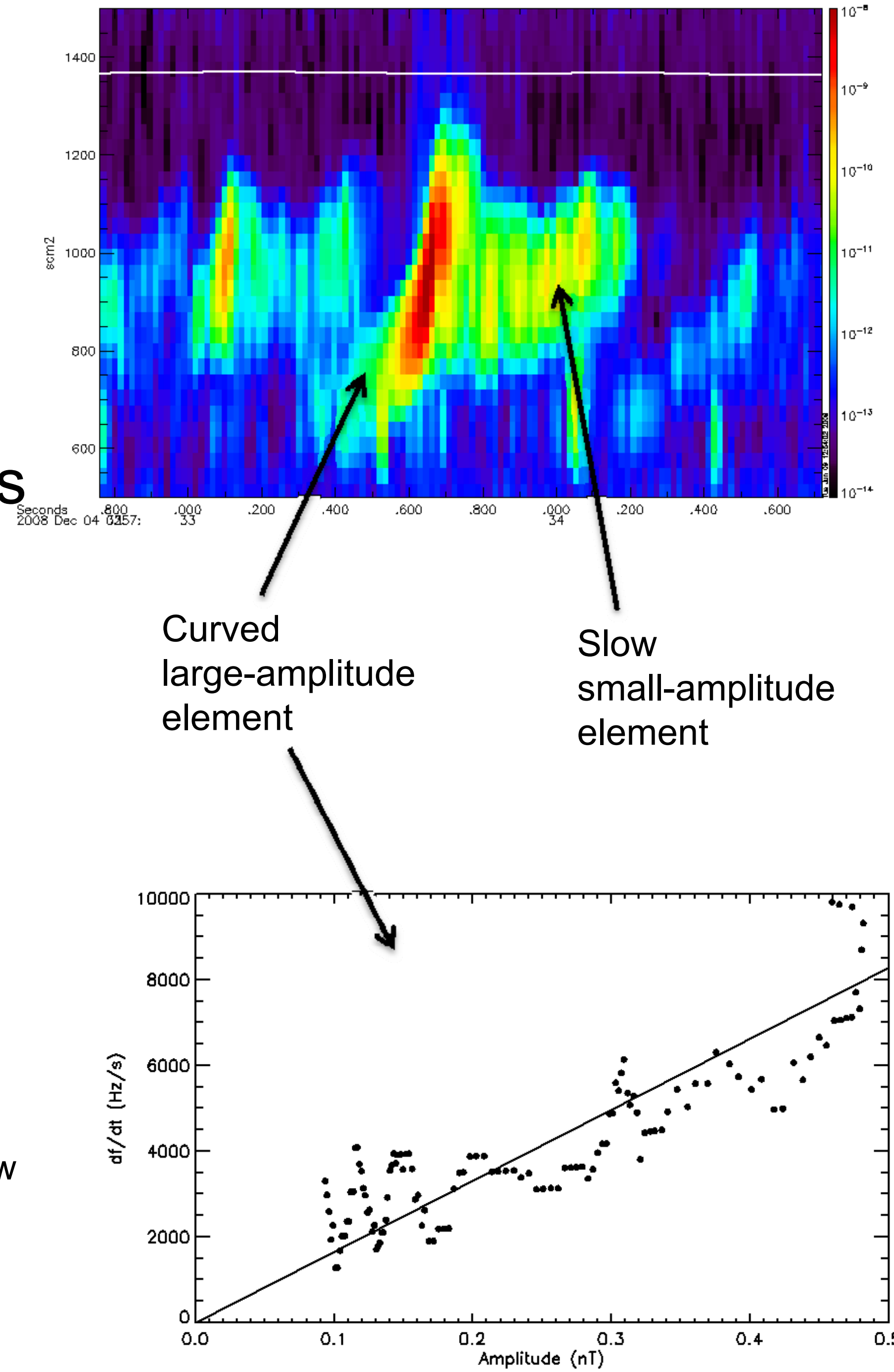


n'(B_w, ∂f/∂t)



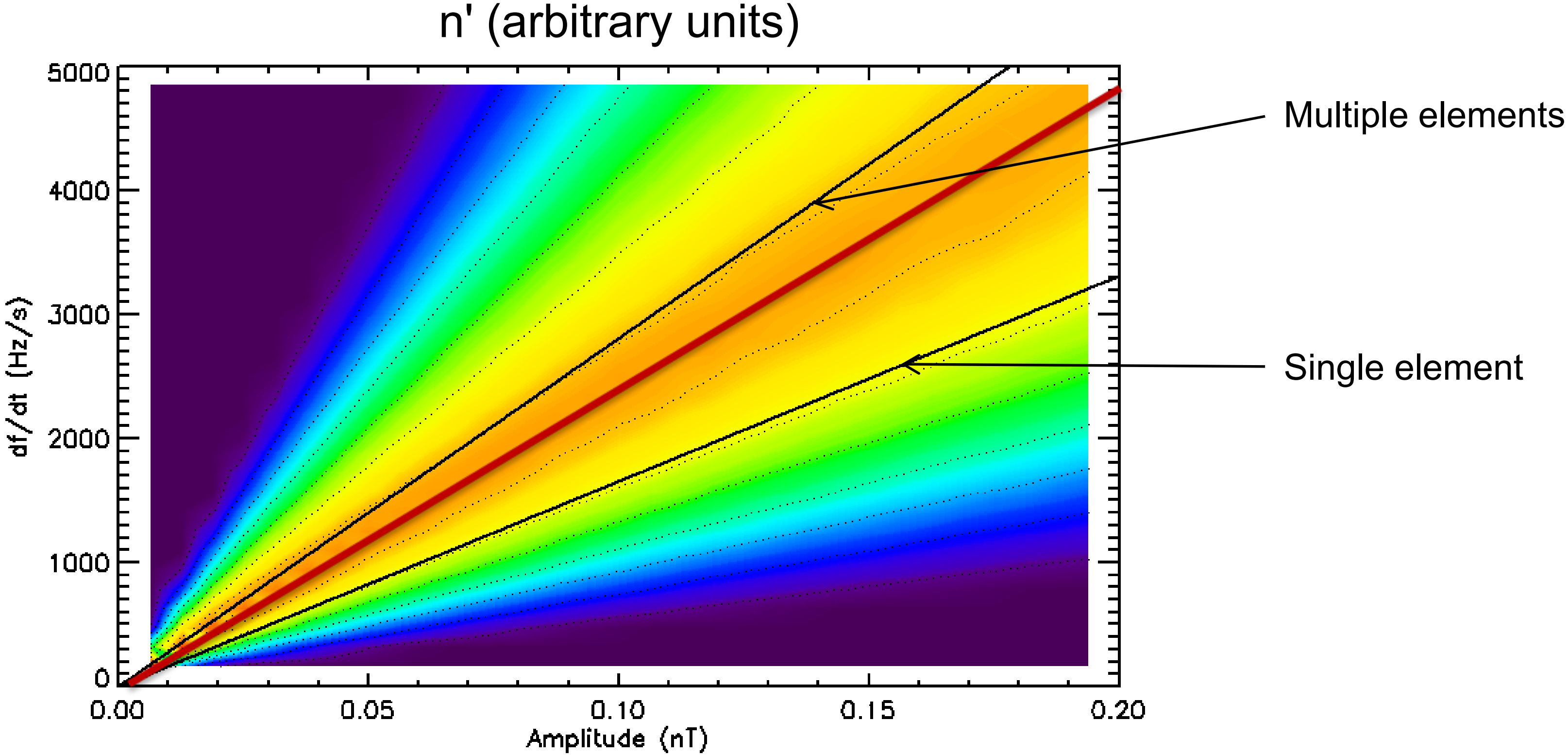
Testing it...

- Need B_w and $\partial f/\partial t$. Either:
  - Select multiple chorus elements, use average B_w and $\partial f/\partial t$ for each element
    - Amplitude and sweep rates vary throughout sweep
  - Select one element
    - Use zero crossings to get “instantaneous” B_w and frequency



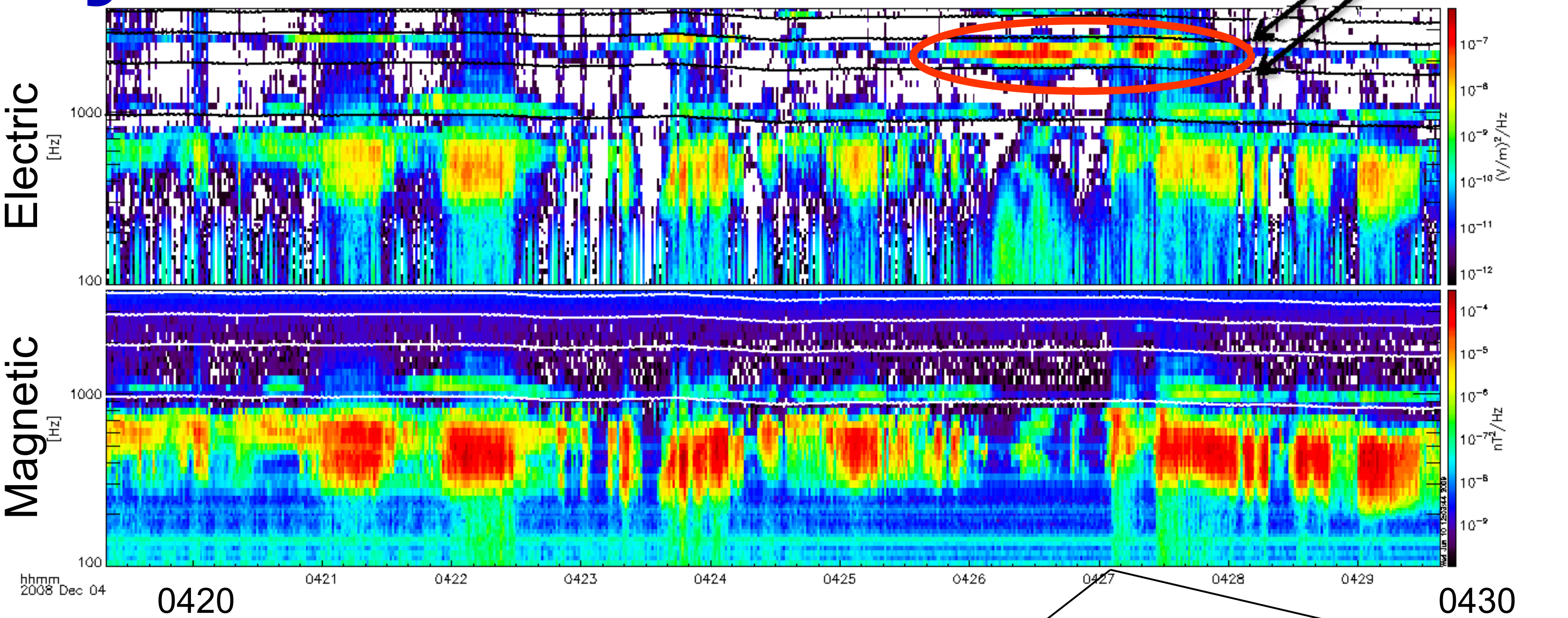
The result

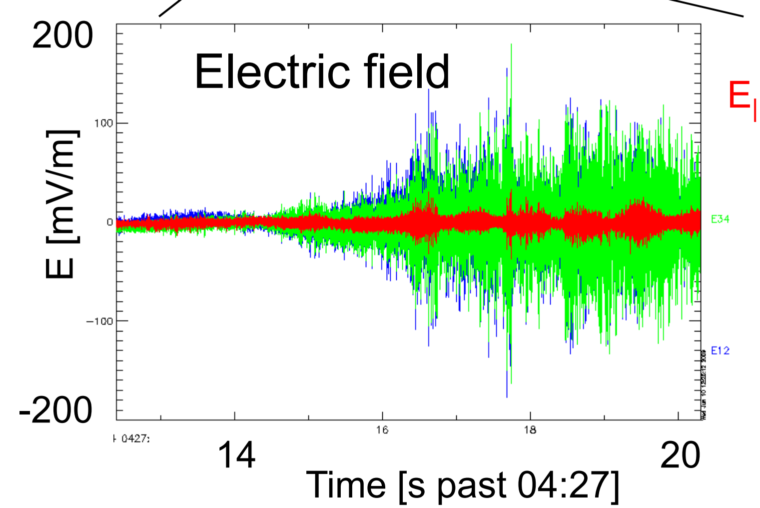
- Observed chorus elements **agree in detail** with the theoretical prediction
  - Lines should follow maximum in n’ (red)



Themis: nonlinear whistlers

Cyclotron harmonics

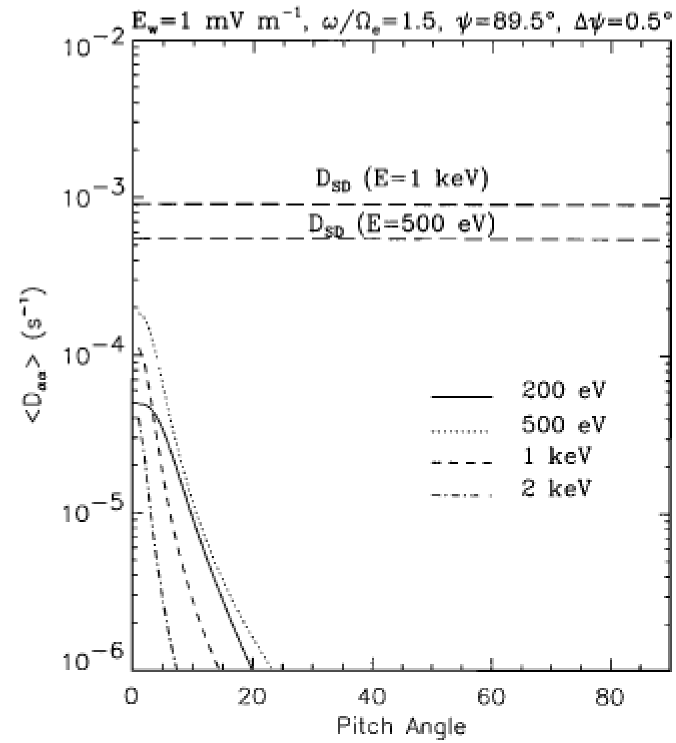




- Electrostatic wave between f_{ce} and $3/2\ f_{ce}$
  - Linear polarization
  - Perpendicular to B_0
- Amplitude ~100 mV/m
  - Greater than the whistlers
  - Greater than expected

ECH: Scattering rates

- Pitch angle diffusion rates for Electron Cyclotron Harmonic waves (ECH) calculated by Horne and Thorne.
- For 100 mV/m:
  - Strong scattering limit over several tens of degrees for ~keV particles
    - Loss cone filled on each bounce

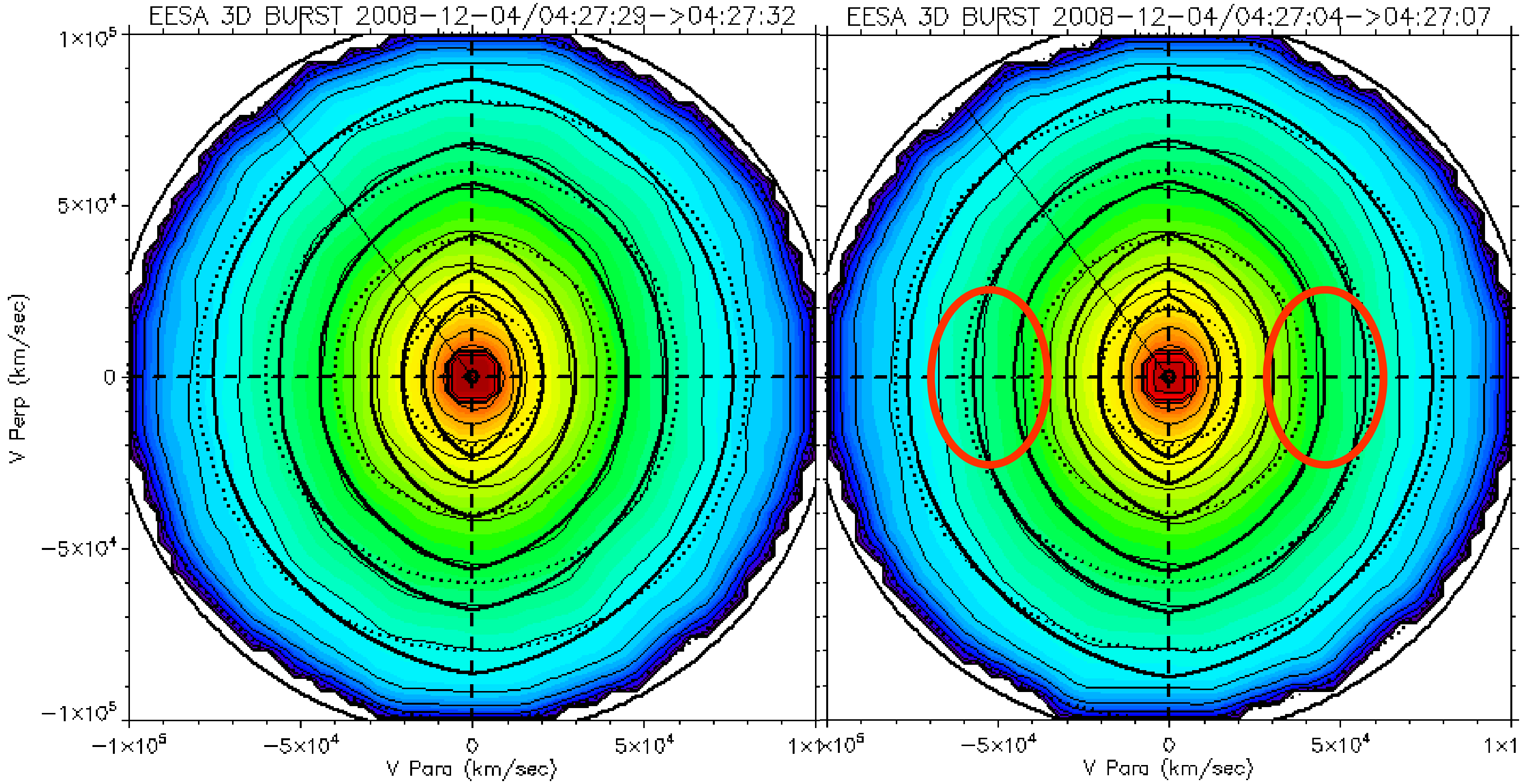


Horne and Thorne, JGR, 2000

Themis: nonlinear whistlers

ECH: effect

- ECH waves remove "extended" loss cone
- Whistler waves fill it back in



ECH inactive
Whistler active

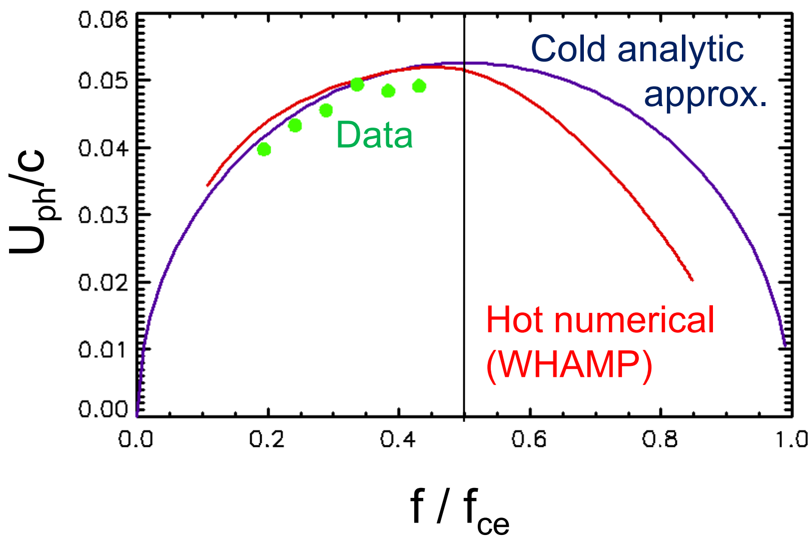
ECH active
Whistler inactive

Conclusions

- Observation: maximum electric field amplitudes larger than previously seen (>100 mV/m)
- Quasilinear theory:
  - Good fit to diffusion curves
  - Featureless spectrum up to f_{ce} not observed
- Nonlinear theory:
  - Amplitude vs. sweep rate (Omura)
    - Specific testable prediction verified
- Open (?):
  - What absorbs the waves at $f_{ce}/2$?
  - What causes the high-amplitude unstructured oblique whistlers?
  - Interaction between Electron Cyclotron Harmonic waves and chorus whistlers?

EXTRA SLIDES

Dispersion curves



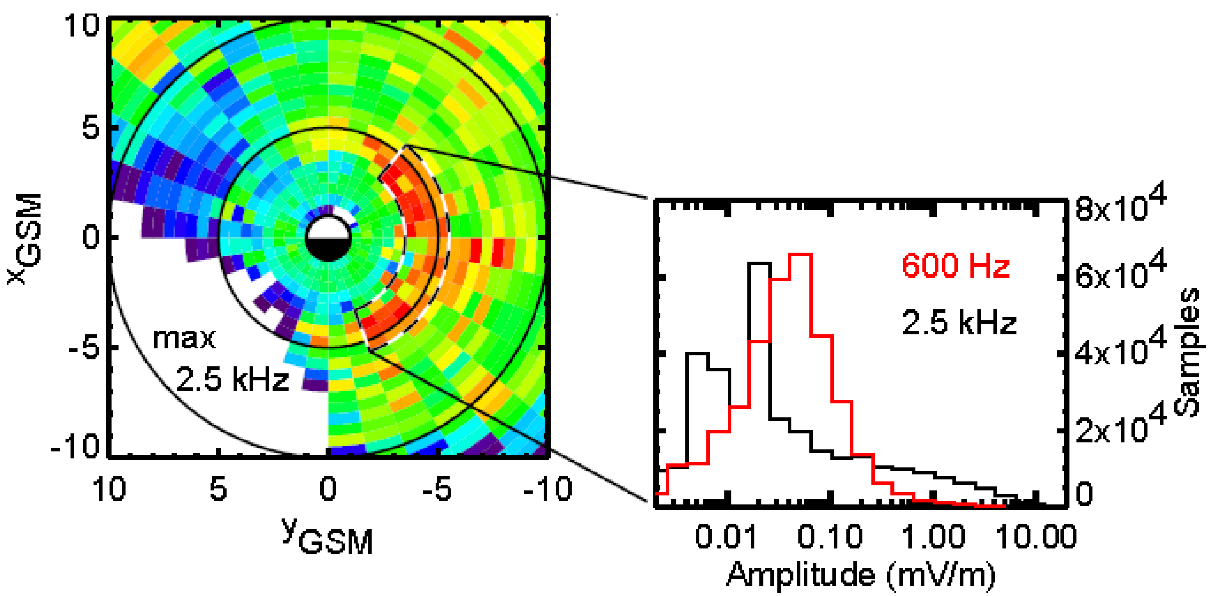
- 2-component plasma: cold isotropic core + hot anisotropic
- Good match to dispersion curve
  - Test of instrument performance

- Thermal effects not important below 0.5 f_{ce}
  - Wave power confined to range 0.2-0.5 f_{ce}

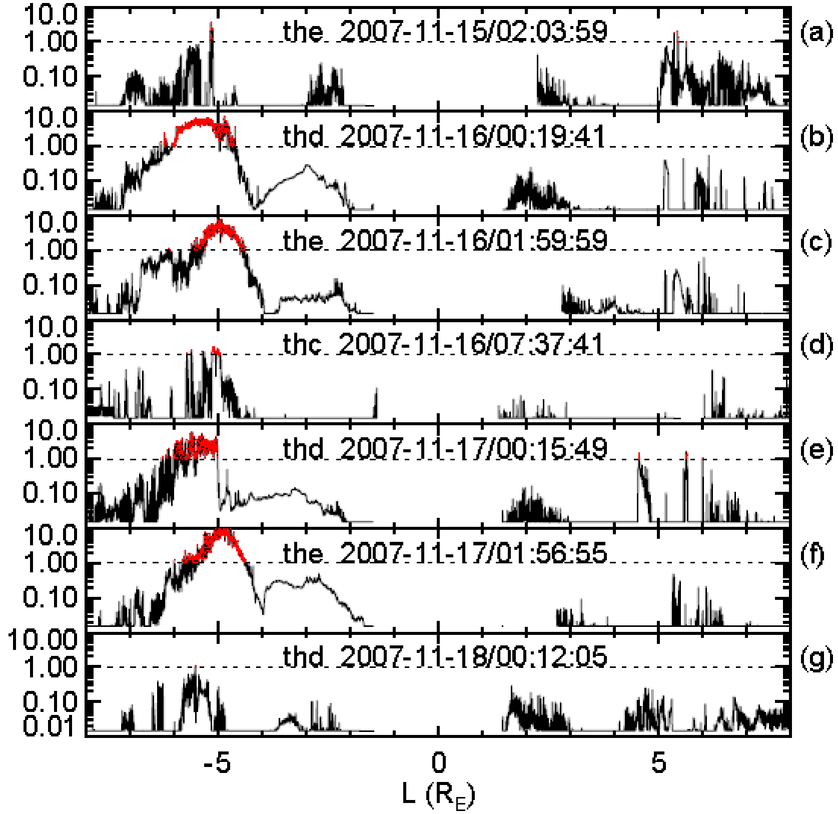
STATISTICAL RESULTS

Electric field amplitude distribution

- Probability distribution function is ”heavy”-tailed, with substantial probability out to tens of mV/m.
  - 4-s averaged data: values up to tens of mV/m
    - Instantaneous values much larger, but limited statistics



Spatial/temporal distribution



- Multiple satellites yield information on spatial and temporal distribution
- Enhanced activity can last for days
- Confined to a few hours of local time

Statistics: conclusions

- Whistler electric field amplitudes have a heavier tail than previously reported
  - > 100 mV/m bursts
  - High-amplitude regions are:
    - Spatially extended (several R_E)
    - Temporally persistend (several days)
  - Relevant for acceleration/loss processes
- Many of the highest-amplitude events are obliquely propagating
  - Even at magnetic latitudes < few degrees
  - Lack the characteristic chorus chirp