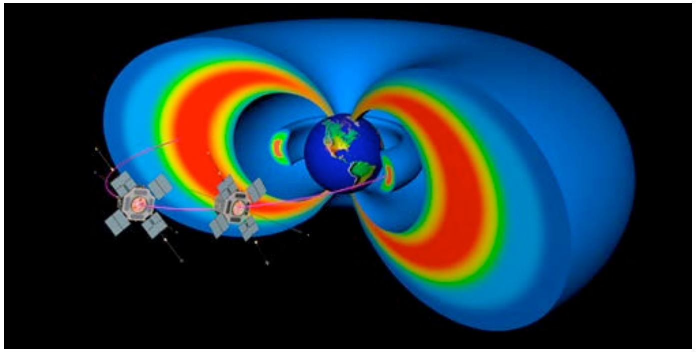
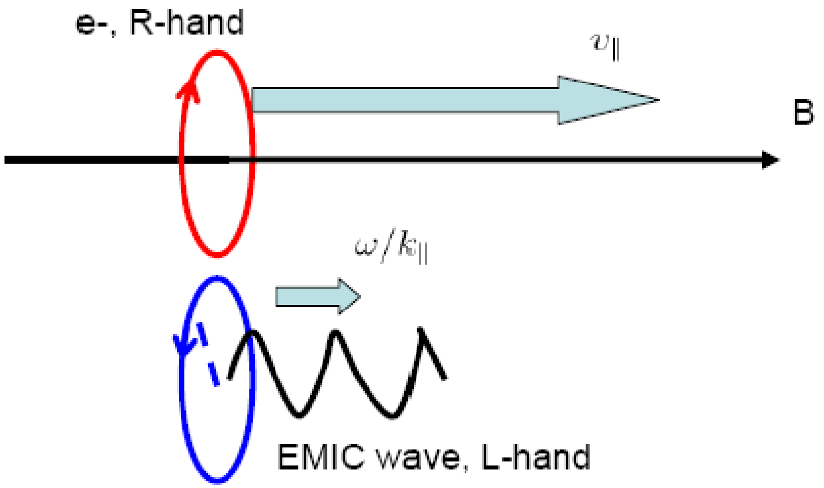


Van Allen Probes
Science Working Group
Iowa, August 16, 2013

Scattering of Radiation Belt Electrons by EMIC waves

Richard M. Thorne
Jacob Bortnik, Lunjin Chen,
Department of Atmospheric and Oceanic Sciences, UCLA

Resonant Scattering of Relativistic Electrons by EMIC Waves



Relativistic electron overtakes EMIC wave and reverses sense of wave polarization to R-mode in the electron rest frame allowing resonant scattering.

Resonant Cyclotron Interaction Condition

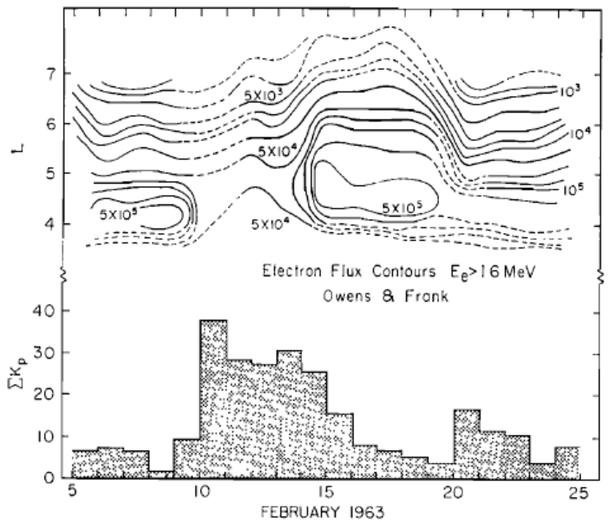
$$\omega - k_{ll}\, v_{ll} = -\,\Omega_{gyro}/\gamma$$

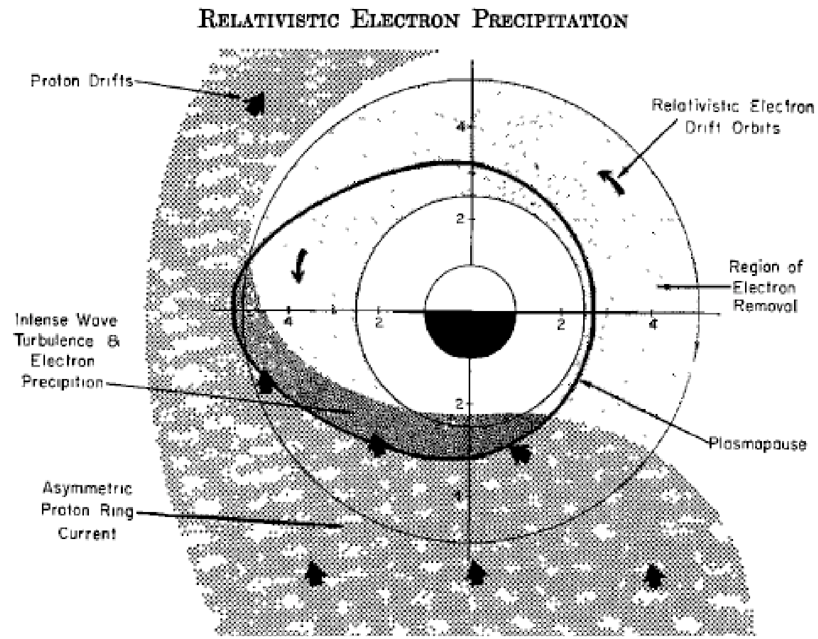
Motion of electron through the wave packet causes a Doppler shift in wave frequency to the relativistic electron gryrofrequency.

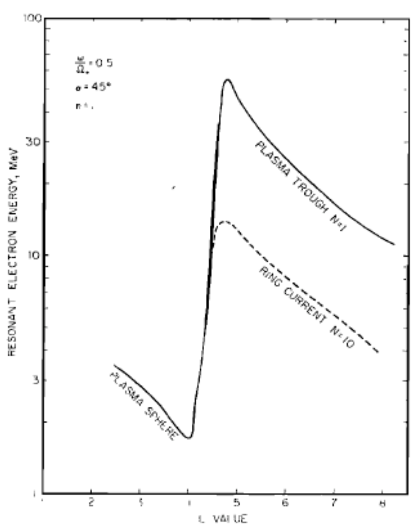
Resonant wave-particle interactions cause pitch-angle scattering (and ultimate loss to the atmosphere)

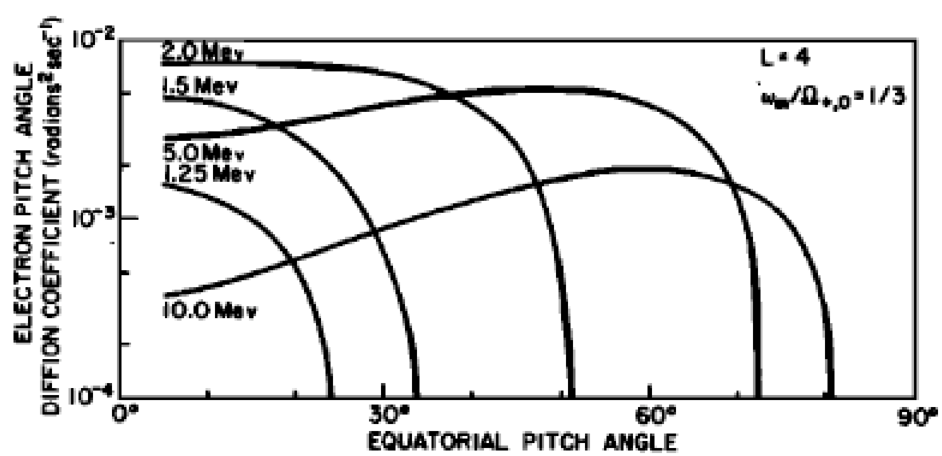
Quantifying Electron Scattering by EMIC waves

Thorne and Kennel, 1971

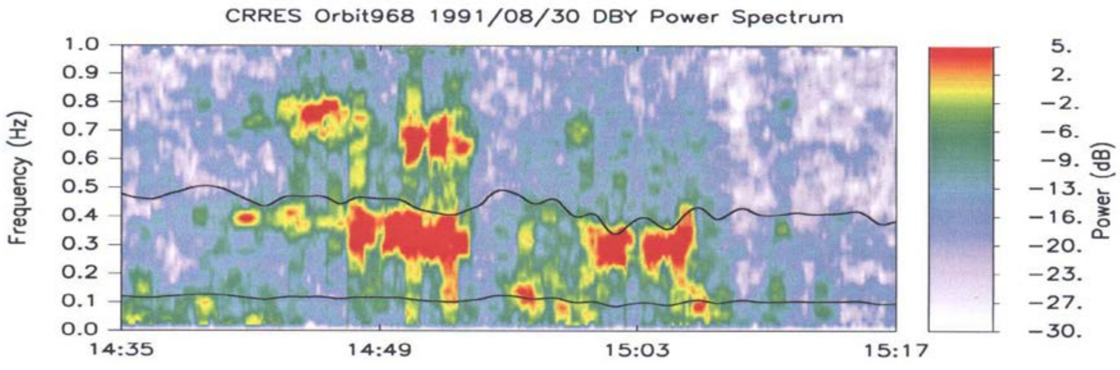


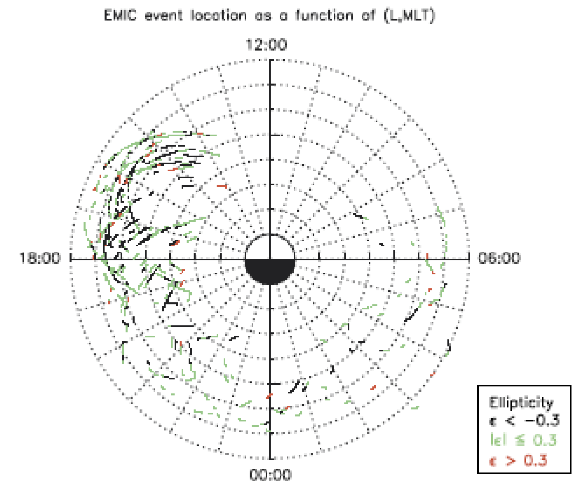




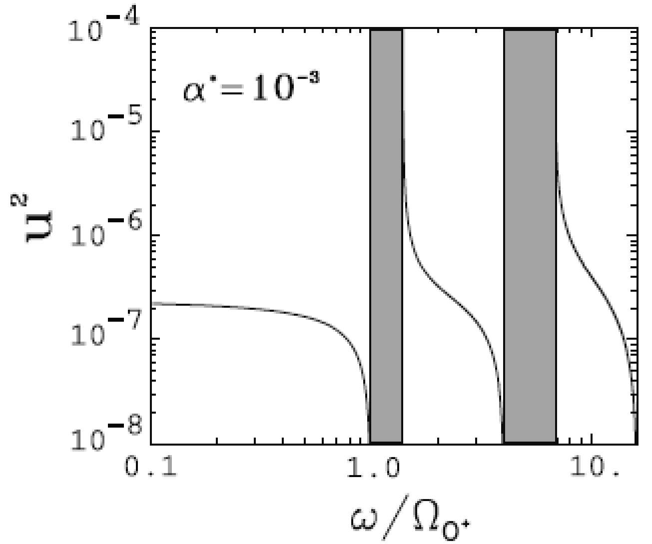


Excitation of Electromagnetic Ion Cyclotron Waves and their Effect on the Radiation Belts





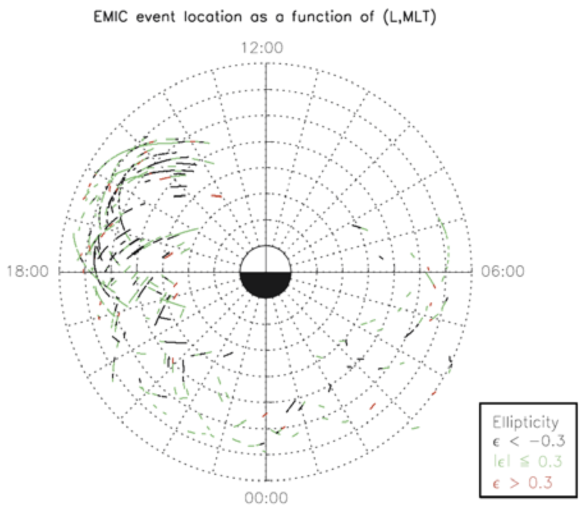
Left-hand polarized EMIC waves are excited during cyclotron resonant interactions with anisotropic ring current ions. They occur in bands between the ion gyrofrequencies.



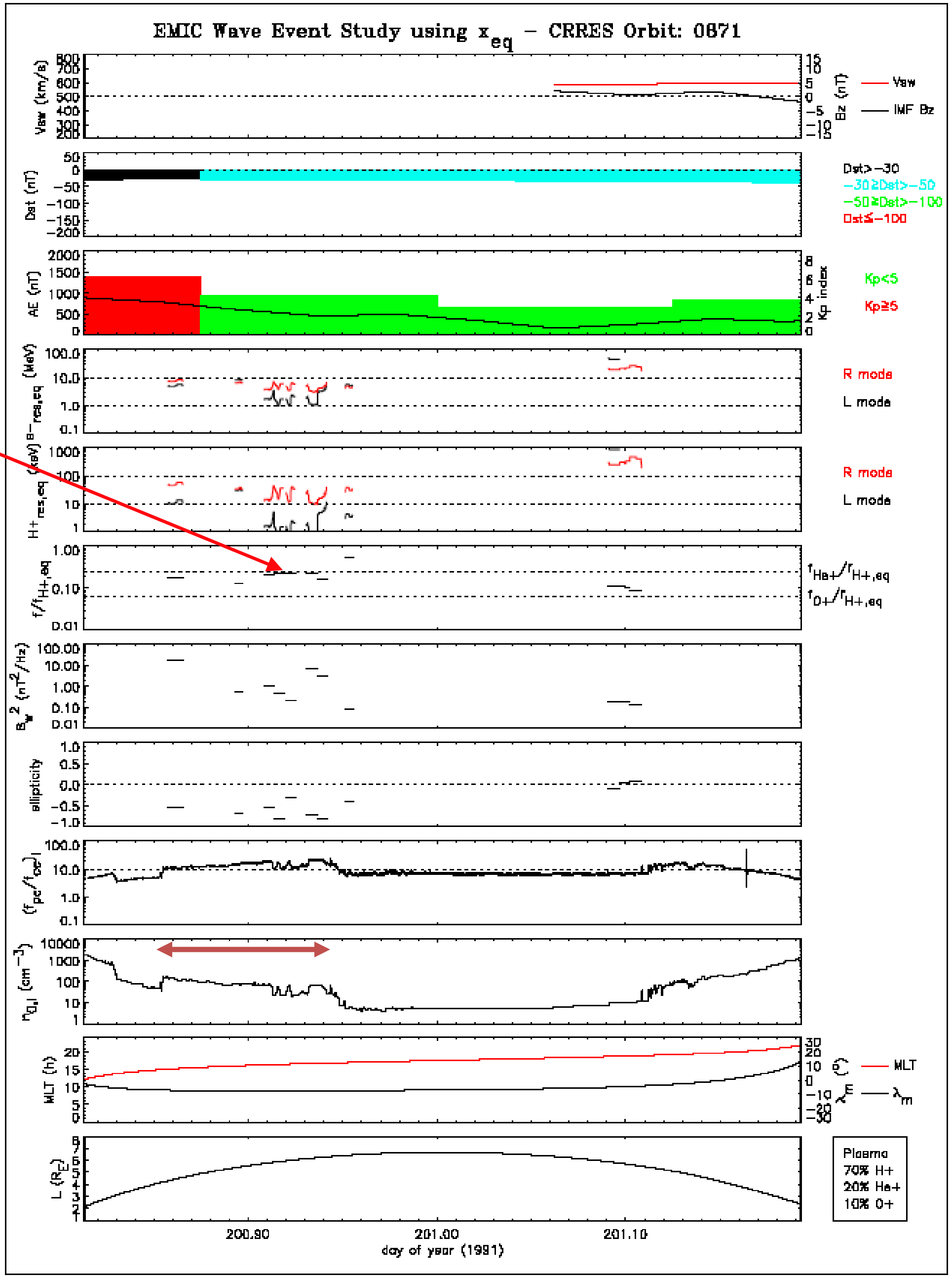
EMIC waves can also resonate with and scatter relativistic electrons

EMIC Waves Observed on CRRES Within a Plume

Intense (few nT) EMIC waves observed near 1600 MLT between L = 4.5-6.



Location of EMIC waves observed on CRRES

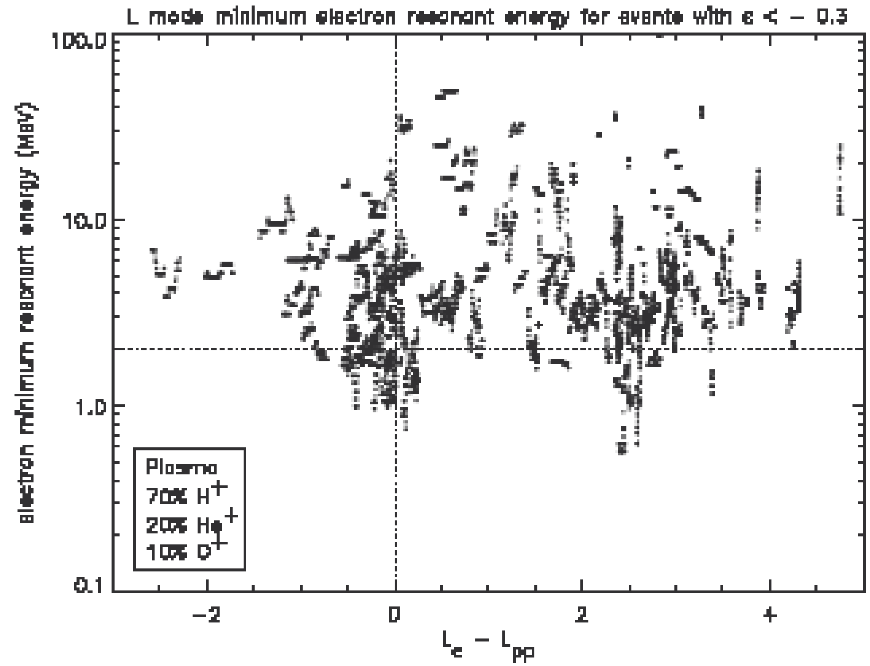


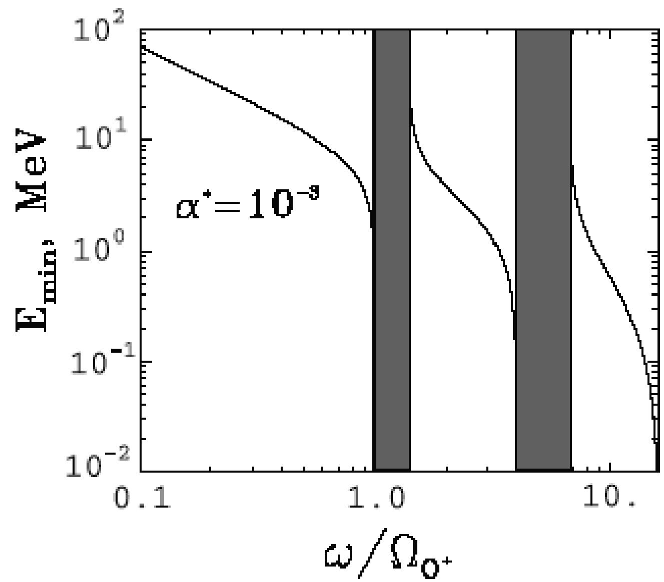
Resonant Electron Energies for EMIC Waves on CRRES

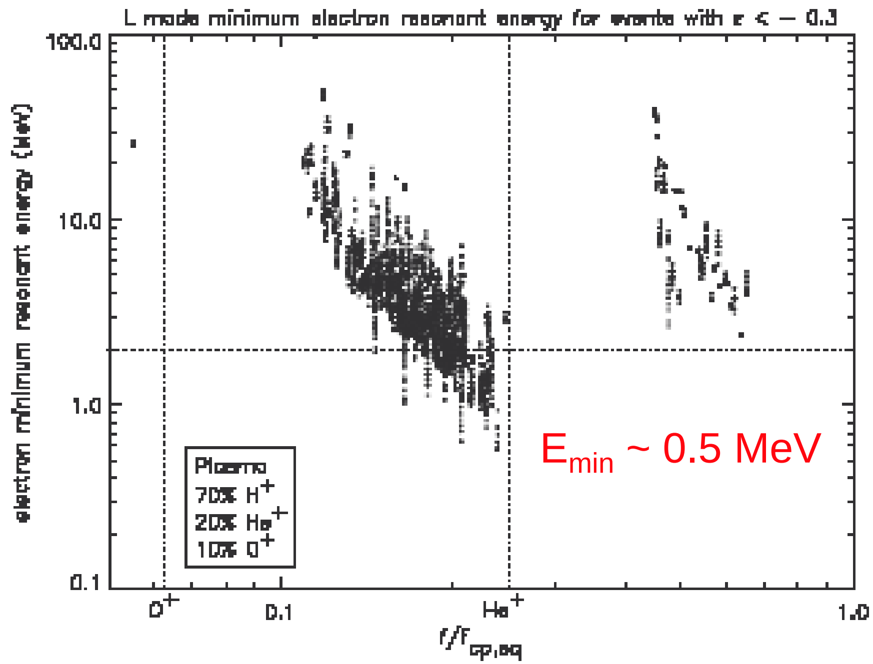
Meredith et al., JGR, 2003

Summers and Thorne, JGR, 2003

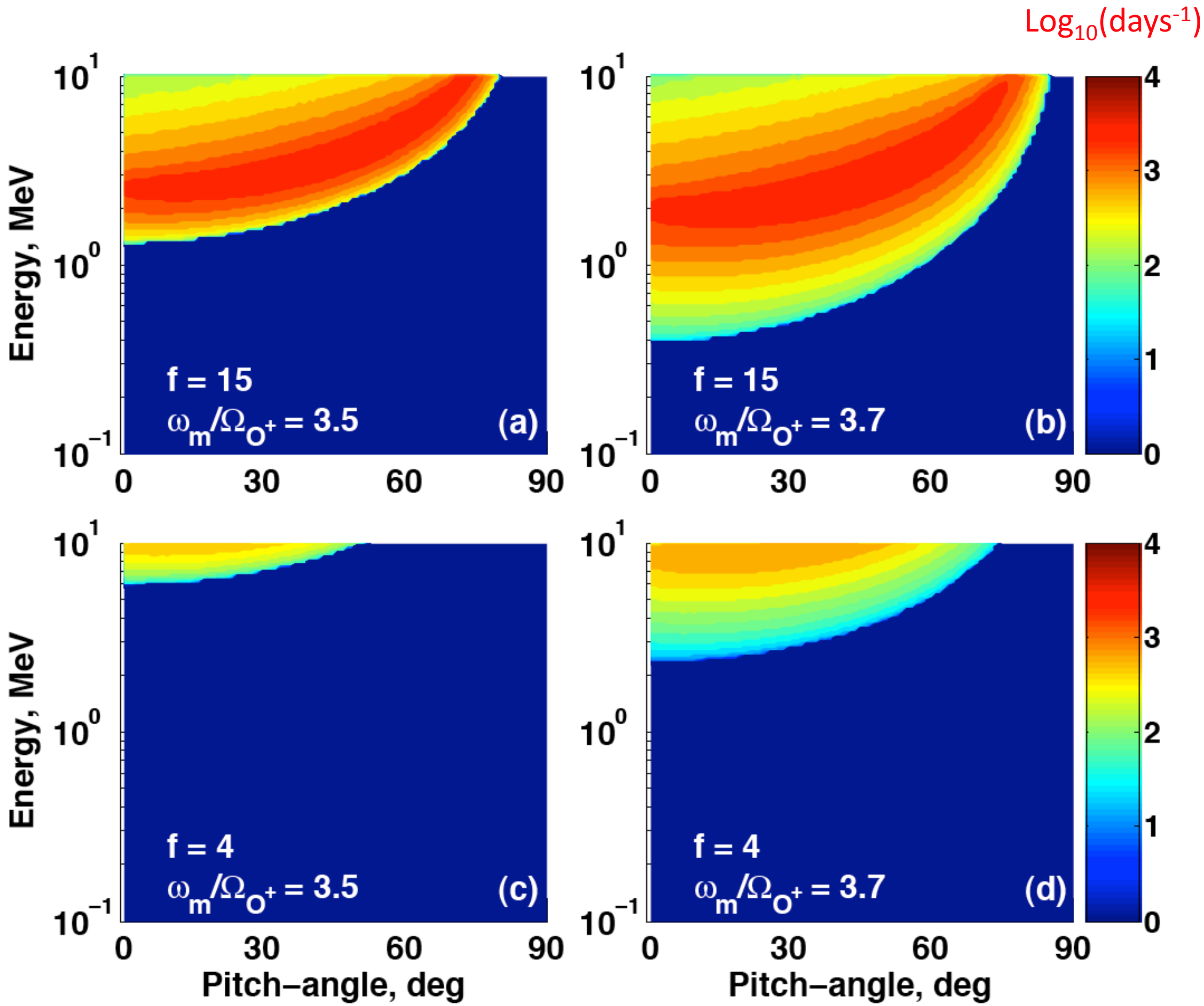
EMIC waves can scatter relativistic electrons near a few MeV inside the plasma-pause or within plumes.







Quasi-linear Pitch Angle Scattering Rates by EMIC waves

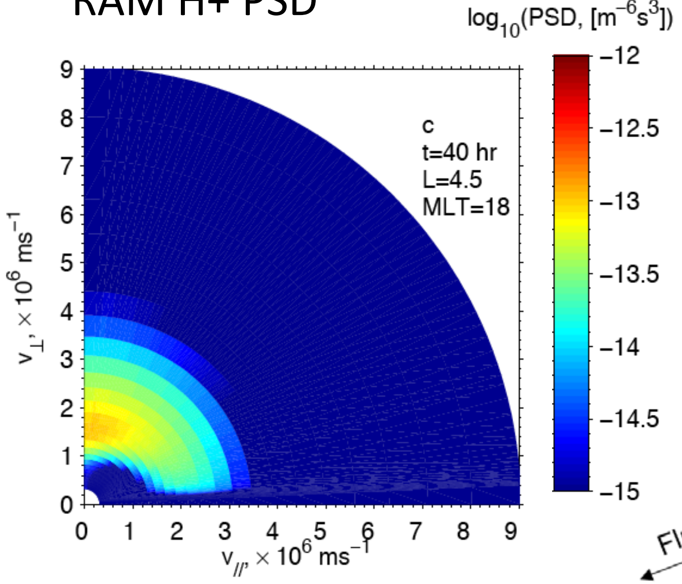


Li et al., JGR 2007

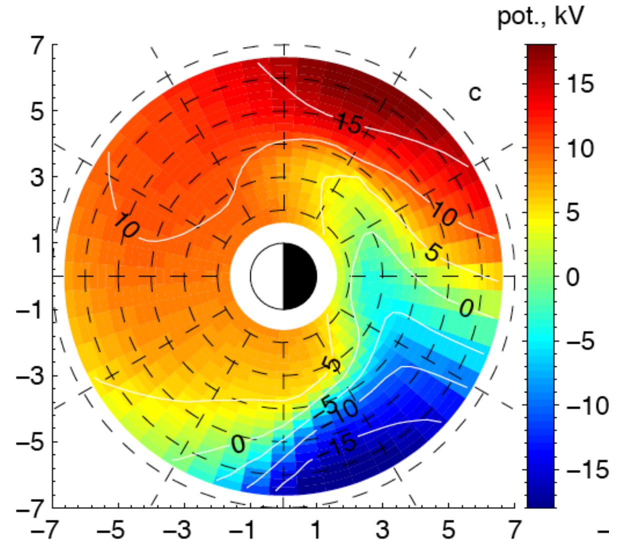
In a high density plume (f =fpe/fce) or inside the plasmapuase, resonant electron energies may drop below 1 MeV but only when waves lie near the He Gyro.

Resonant electron energies are well above an MeV for EMIC waves in the low density trough.

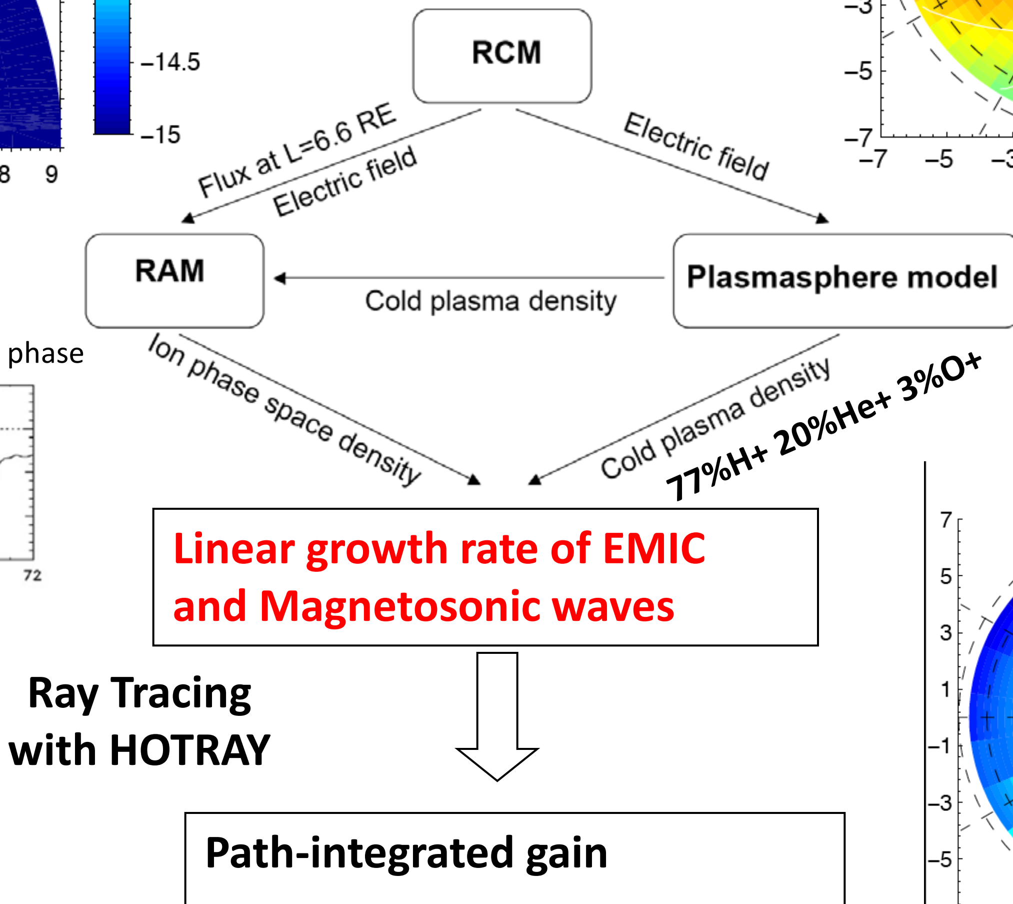
RAM H+ PSD



RCM
E-Potential



Wave Excitation by
Ring Current Ions



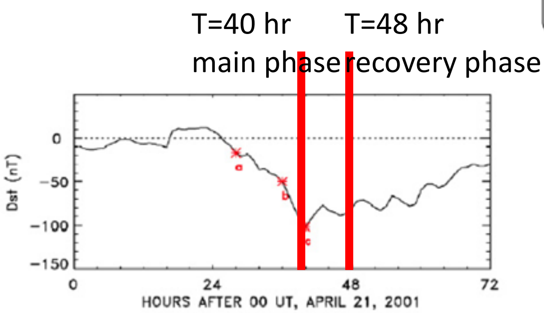
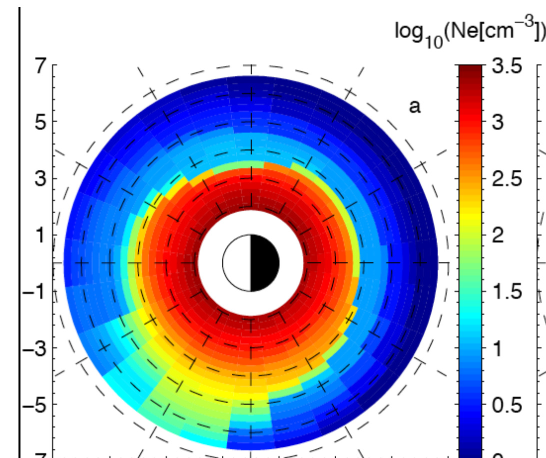


Figure 10: Dst profile for 2001 April 21st storm.



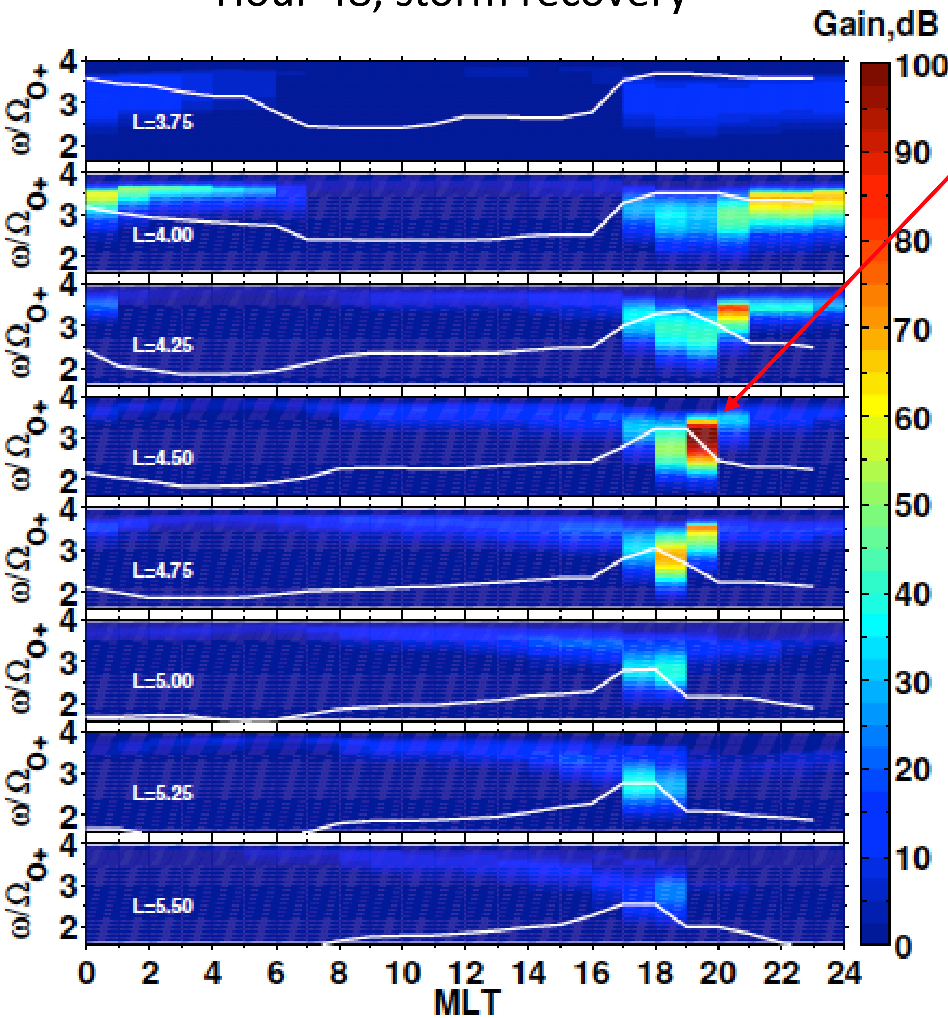
Cold electron density

Chen et al., 2010

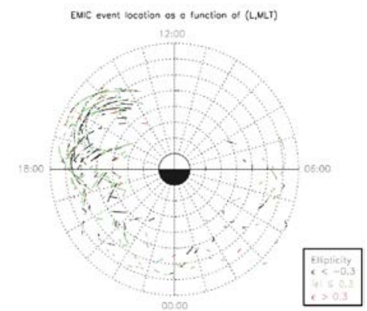
Path Integrated Gain and Spectral Properties of Excited EMIC Waves

Chen et al., 2010

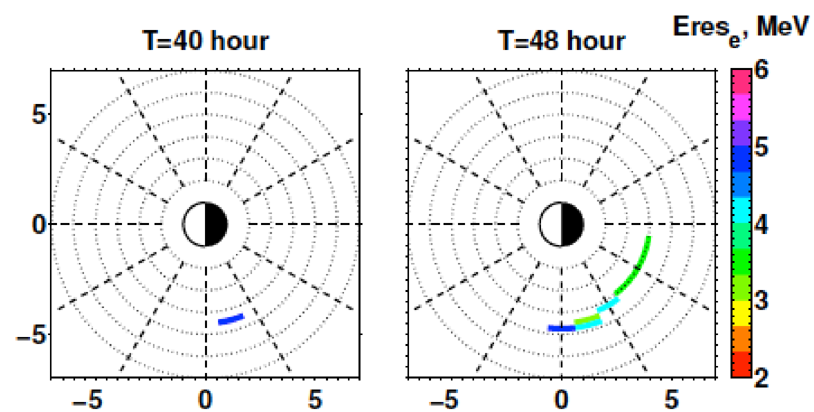
Hour 48, storm recovery



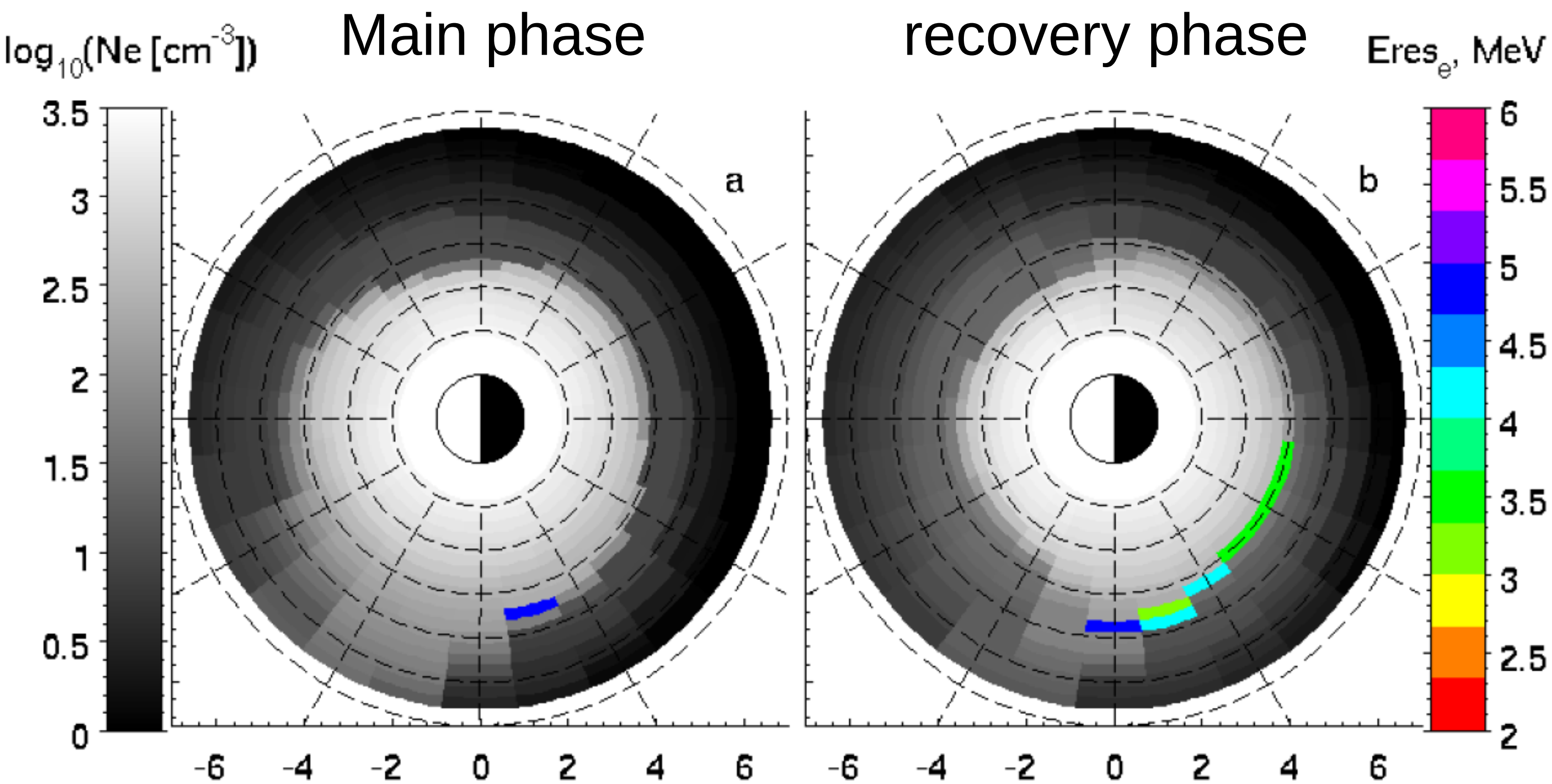
Strongest wave gain confined to the edge of the plume and nightside plasmapause



Electron minimum resonant energies with waves having more than 30 db gain near the equator.



Minimum electron cyclotron resonant energy with excited EMIC waves in the equatorial region (Gain >30 dB)



~ 5 MeV during main phase; > 3 MeV at recovery phase
But no fine scale density fluctuation is included.

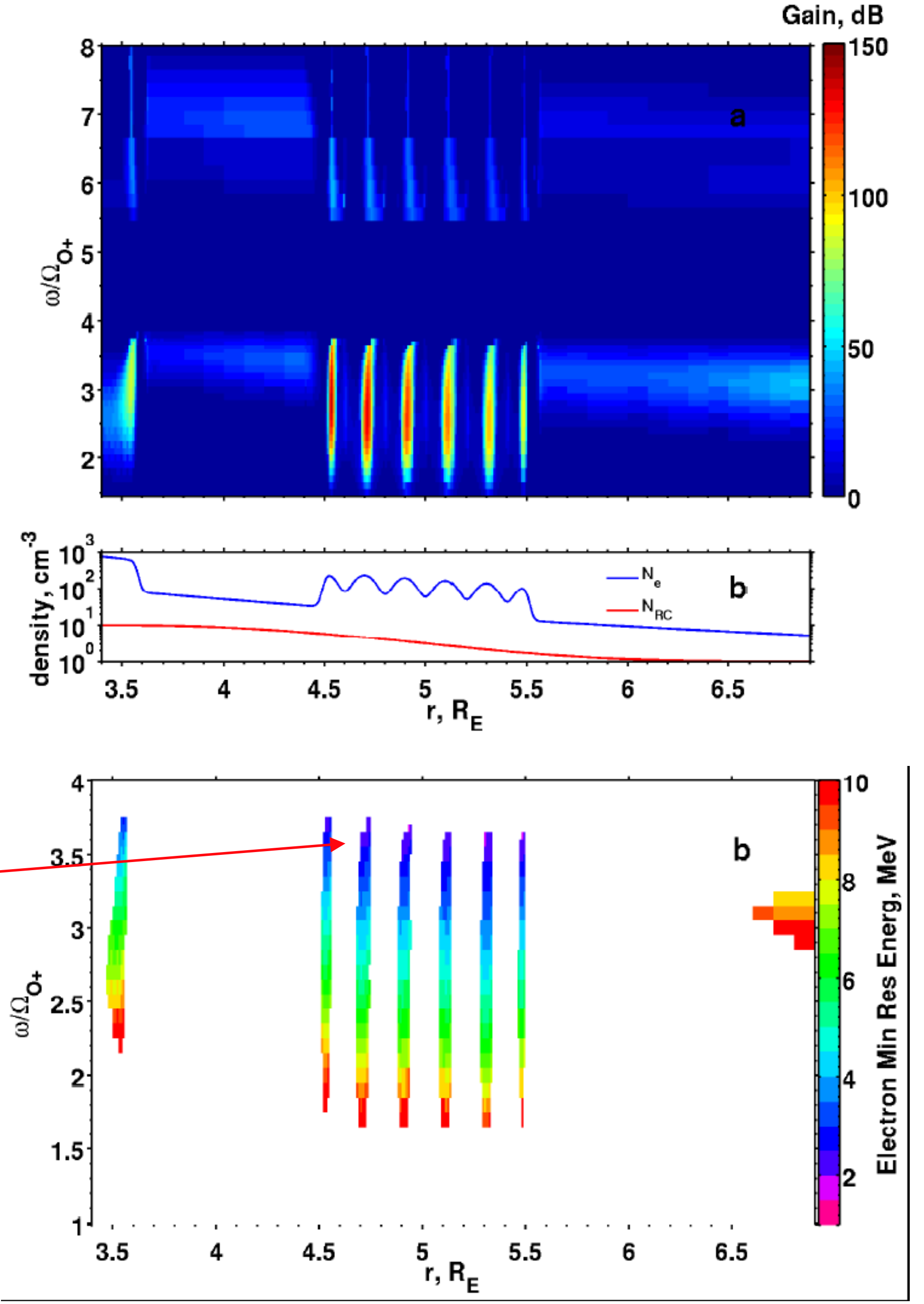
Effects of Density Variation In a Plume

Chen et al., JGR 2009

Density variation inside the plume play a important role in not only increasing the wave gain but also reducing the electron minimum resonant energy due to increase in the wave power close to He+ gyro-frequency.

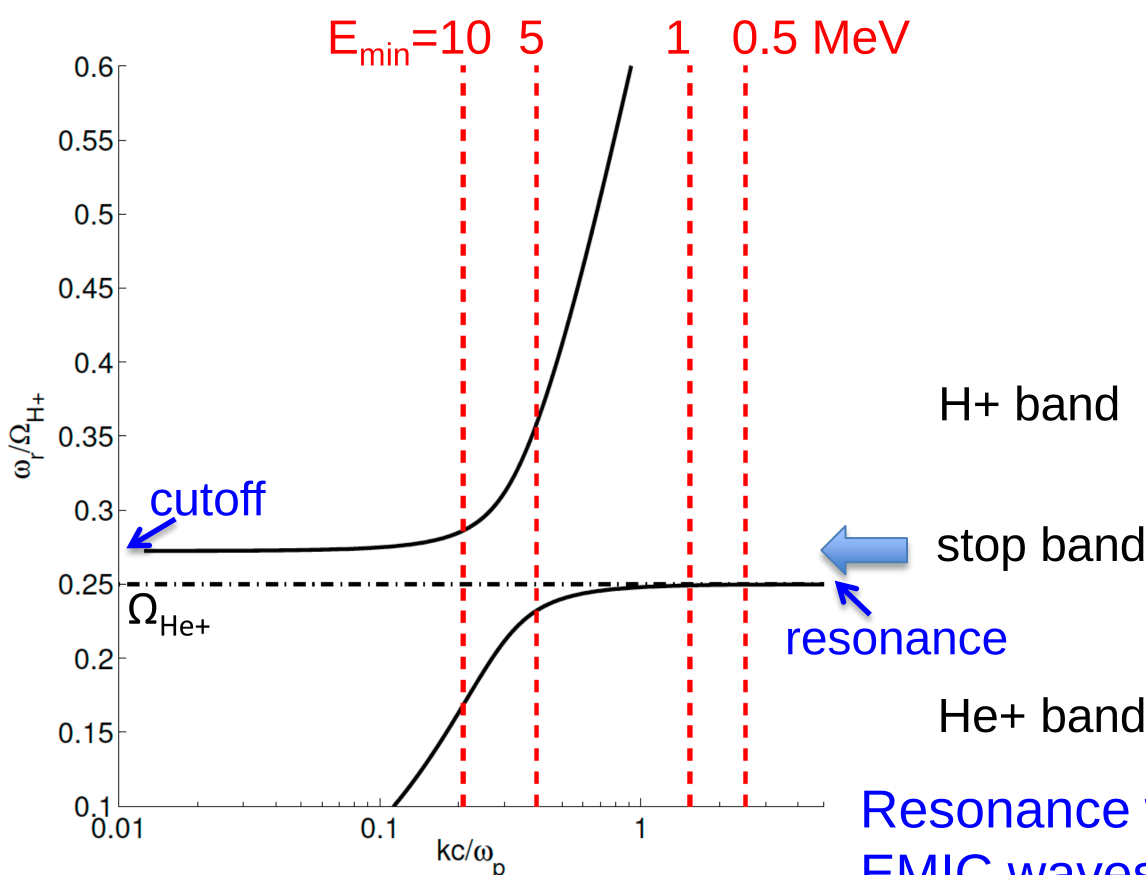
However, minimum resonant energies are ~ 2 MeV even under optimum conditions.

Could non-linear effects allow wave excitation closer to the He gyrofrequency and thus lower the resonant energy?

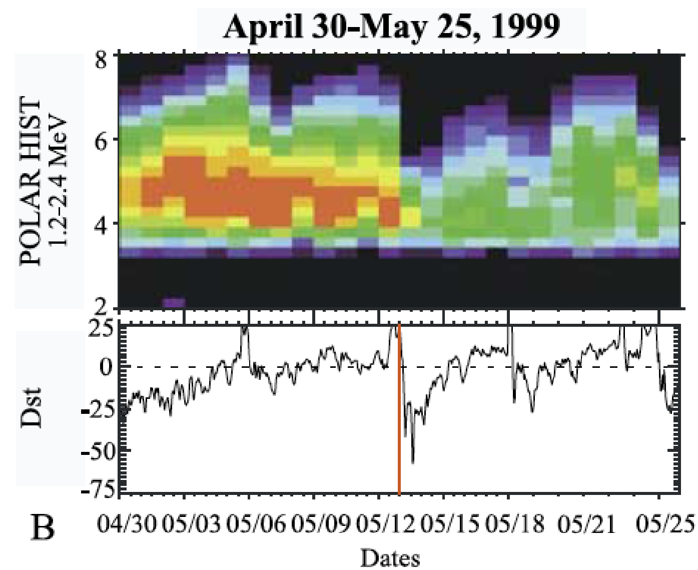


Dispersion Relation of EMIC waves in cold H+-He+ plasma

"cold": 1) thermal speed << wave phase speed
2) $\omega \neq \Omega$



Relativistic electron flux dropout during main phase
[Reeves et al., 2003]



Resonance with MeV electron requires EMIC waves with large wave numbers (very close to Ω_{He+} from cold plasma theory)

EMIC waves in warm H^+-He^+ plasma

Displacement current

Cold e-

Cold H+

Warm He+ (he)

$$y^2 = \boxed{(x/f)^2 m_e/m_{H+}} \boxed{-x} + \boxed{(1-\eta_{hh}-\eta_{he})\frac{x}{1-x}} + \boxed{\frac{\eta_{he}x}{4x-1}\zeta_{he}Z(\zeta_{he})}$$
$$+ \boxed{\eta_{hh}\left[A_{hh} + \left(A_{hh} + \frac{x}{x-1}\right)\zeta_{hh}Z(\zeta_{hh})\right]}, \qquad (1)$$

Anisotropic ring current H+ (hh)

$x = \omega/\Omega_{H+} = \omega_r/\Omega_{H+} + i\omega_i/\Omega_{H+}$ Complex wave frequency

$y = kc/\omega_p$ Wave number

Chen et al., 2011

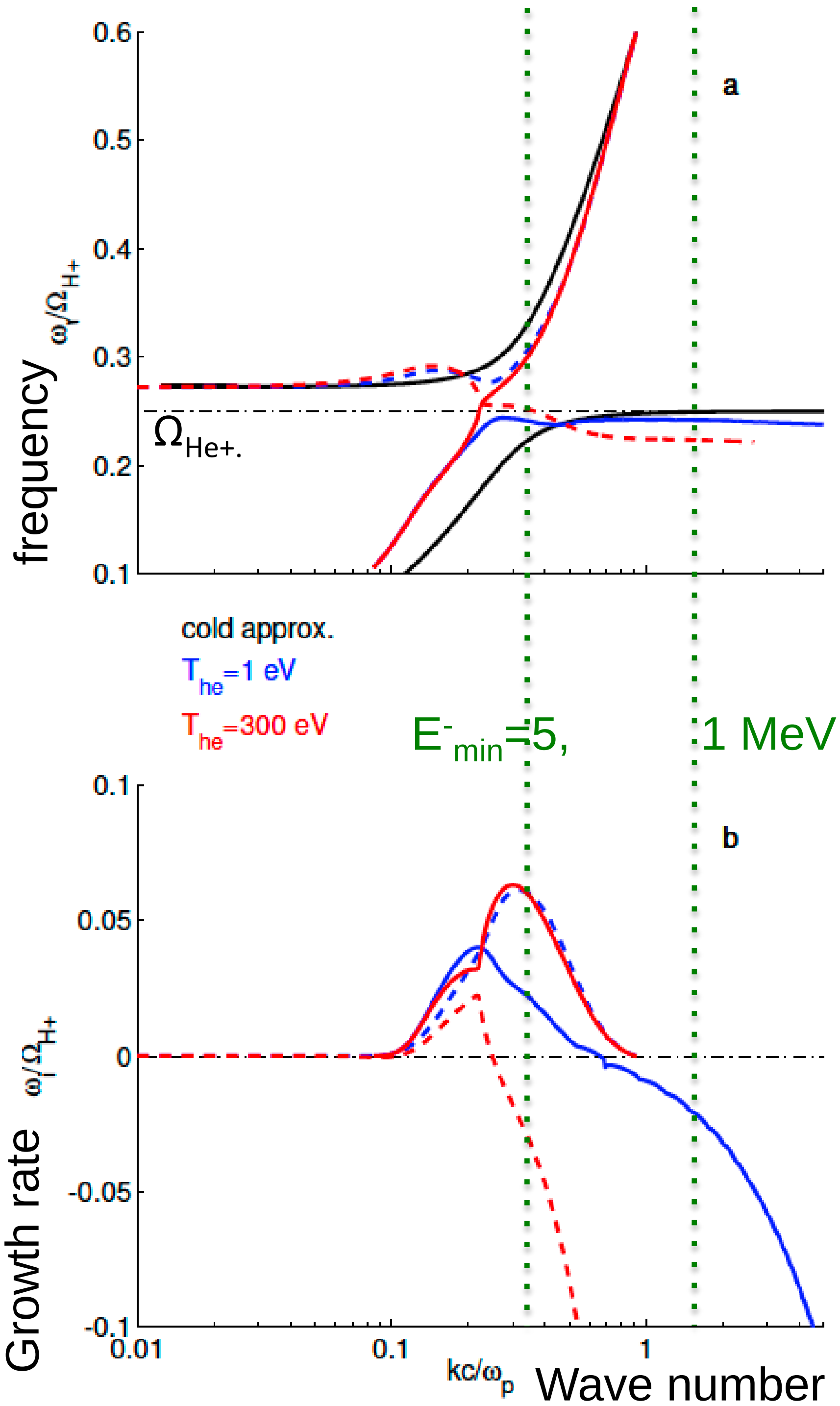
$f = \omega_{pe}/|\Omega_e|$

$\omega_p = \sqrt{N_e e^2/(\epsilon_0 m_{H+})}$

$A_{hh} = T_{hh\perp}/T_{hh\parallel} - 1$

Z plasma dispersion function [Fried and Conte, 1961]

$$D(x, y; f, \eta_{he}, T_{he}, \eta_{hh}, T_{hh\parallel}, A_{hh}) = 0$$



- ➢Hot plasma modification is pronounced, especially near Ω_{He+}. => important when evaluating relativistic electron scattering rate.

- ➢Instability of EMIC waves at Ω_{He+} and in "stop band" is due to the dominance of hot H^+ over warm He^+.

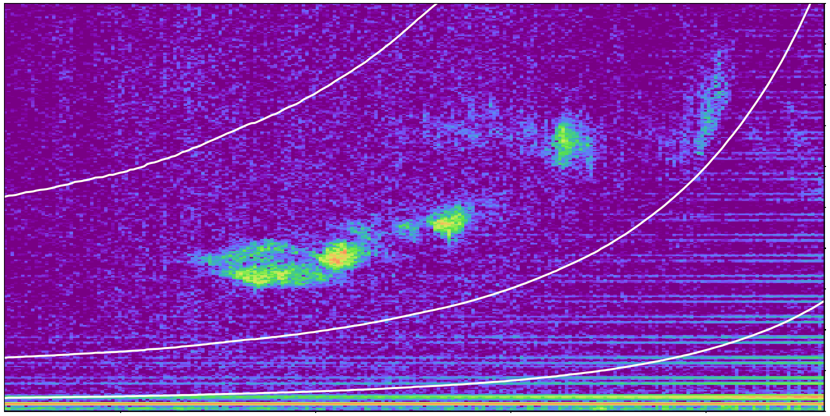
- ➢Extreme condition (e.g., at least ω_{pe}/Ω_e>~25, A_{hh}>1) is required to excite waves capable of resonating MeV electrons.

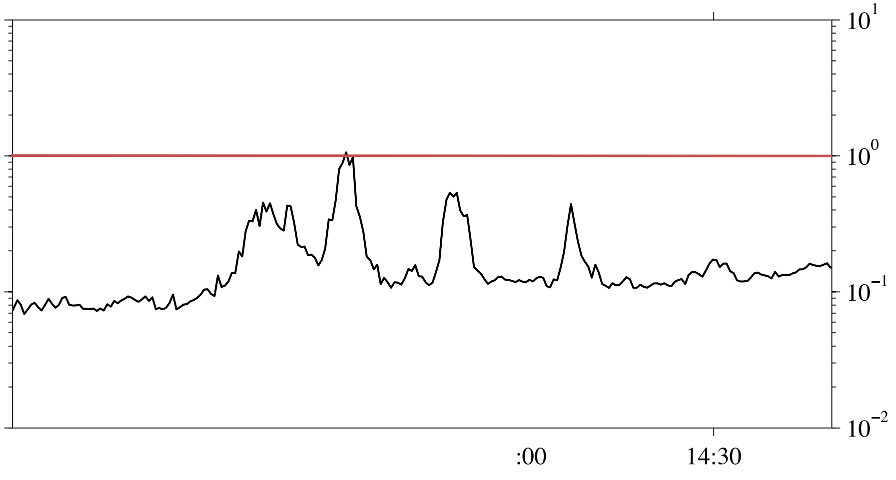
$$\omega_{pe}/|\Omega_e| = 10 \quad \eta_{he} = 3\%,$$
$$\eta_{hh} = 10\%,\ T_{hh\|} = 25\ \text{keV},\ A_{hh} = 1.5$$

EMIC waves

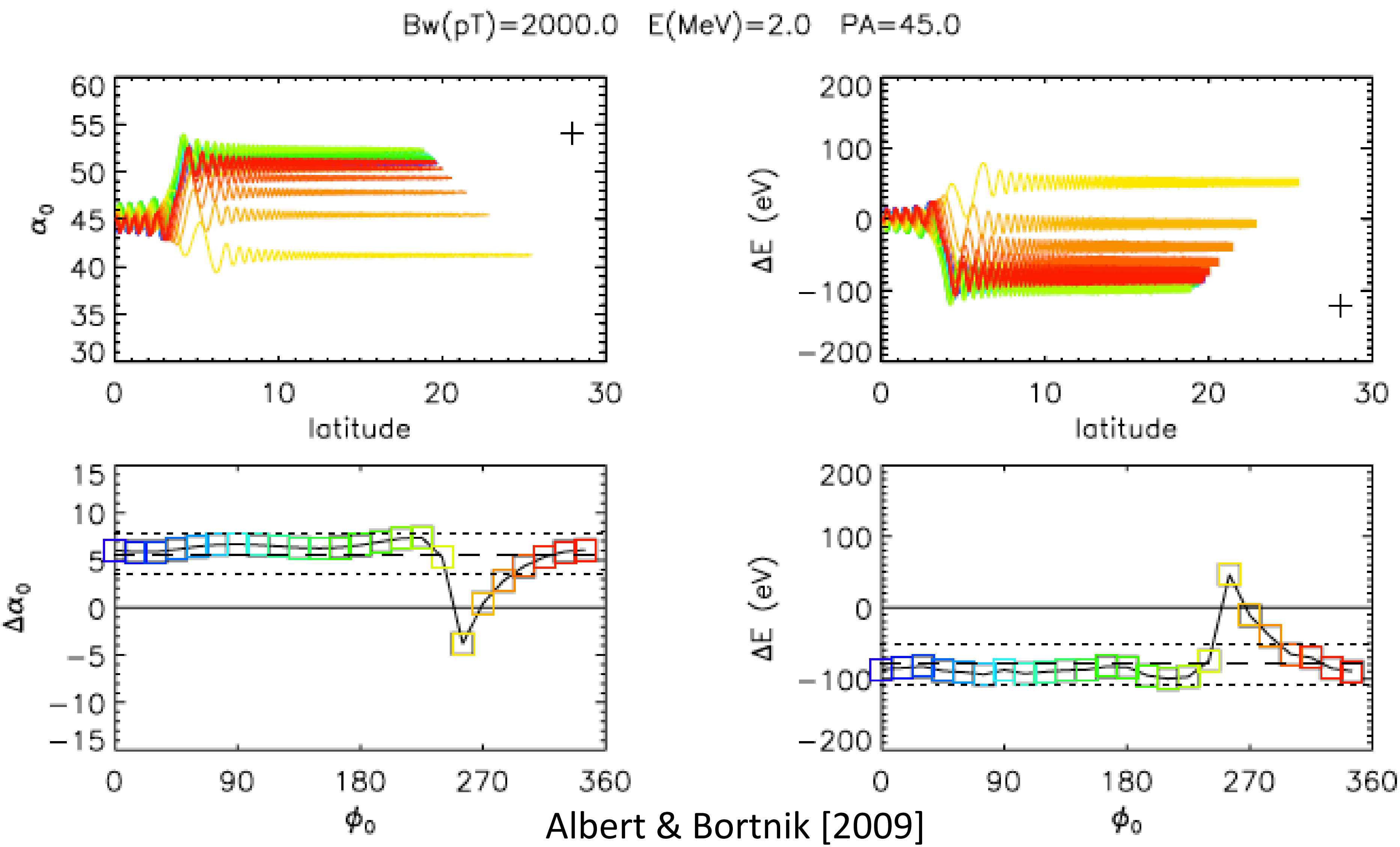
EMIC waves can be:

- Large, ~1-10 nT
- Banded: occurring between ion gyro-frequencies
- And spatially limited: generation region near equator





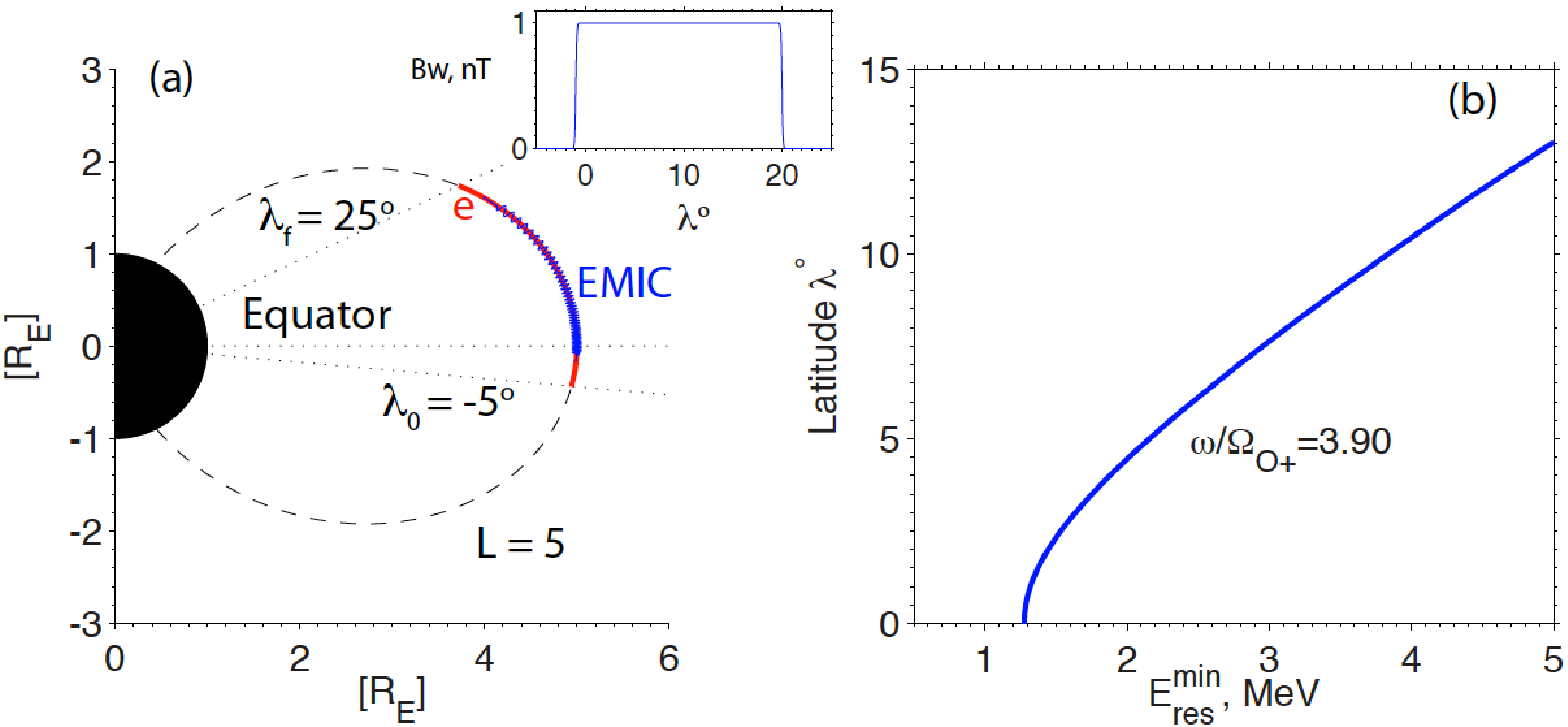
Nonlinear Test Particle Scattering by a Monochromatic Large Amplitude EMIC wave

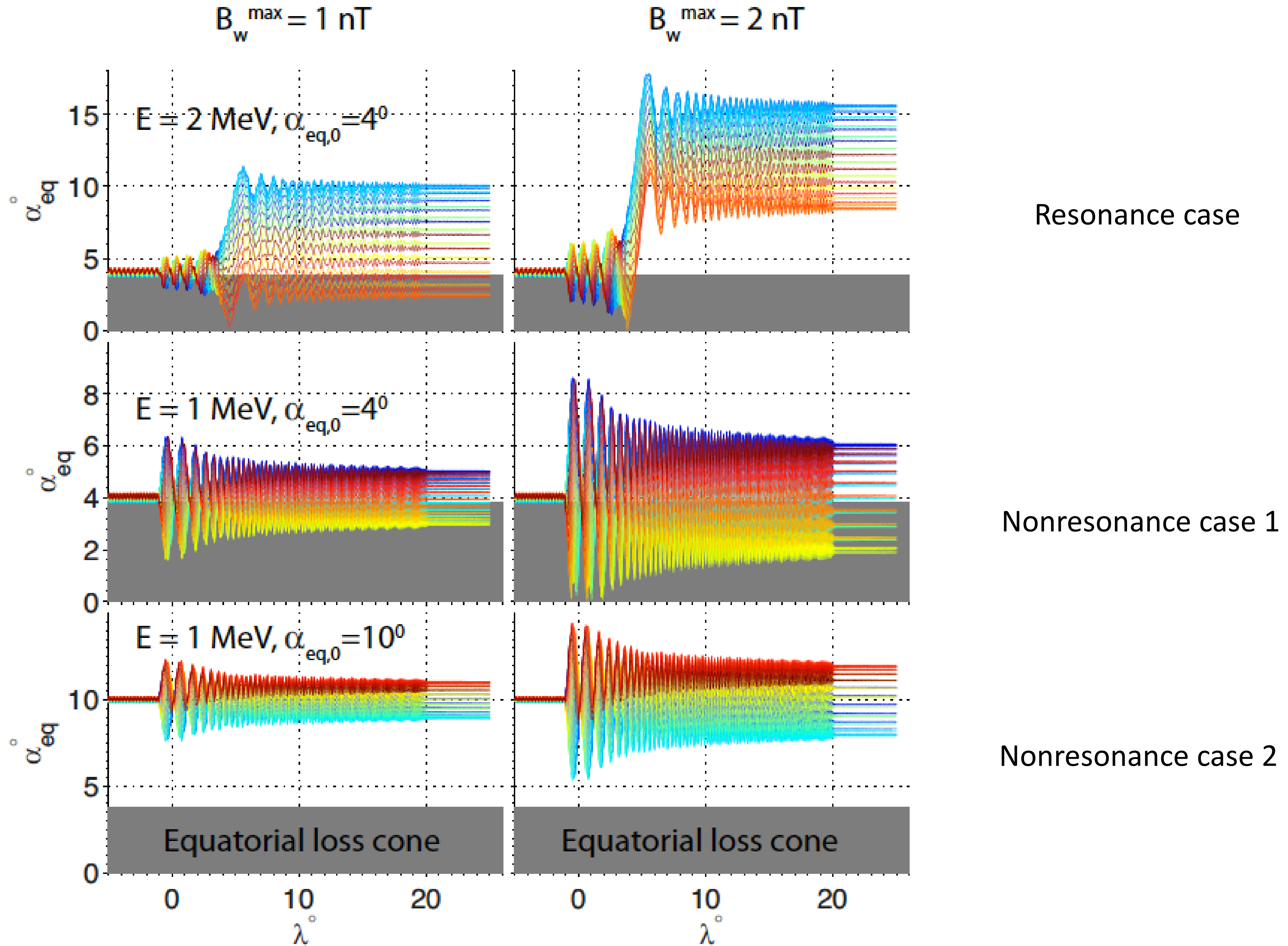


Albert & Bortnik [2009]

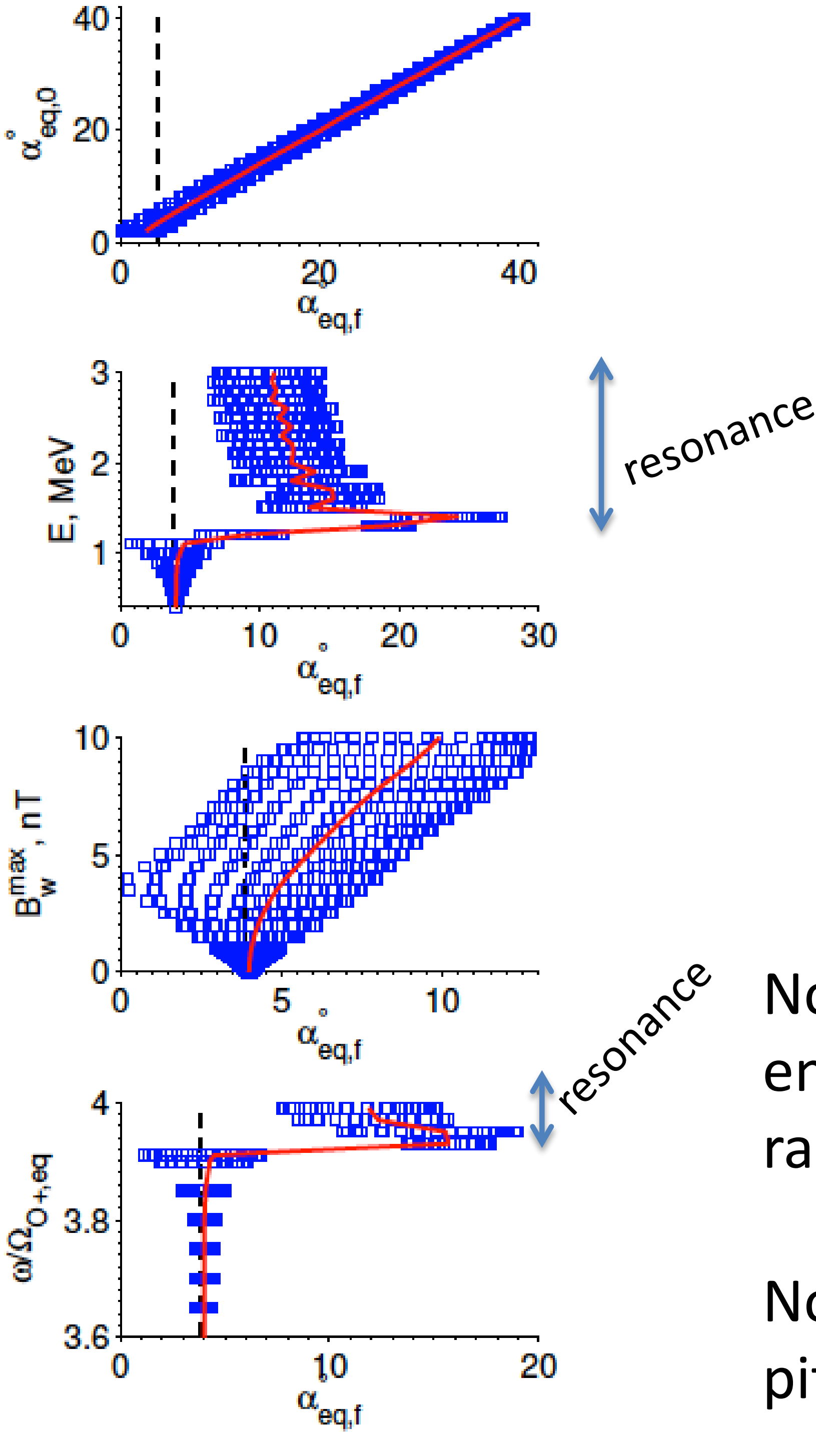
Can Nonresonant Electrons be Subject to Pitch Angle Scattering (into loss cone)?

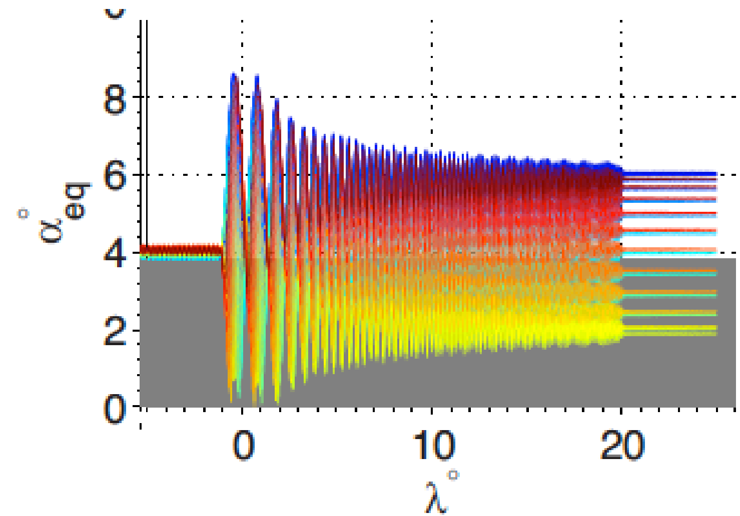
$$\omega_r - k_\parallel v_\parallel^e \neq \Omega_e/\gamma$$





$B_w^{max} = 1$ nT
$B_w^{max} = 2$ nT
E = 2 MeV, $\alpha_{eq,0}=4^0$
E = 1 MeV, $\alpha_{eq,0}=4^0$
E = 1 MeV, $\alpha_{eq,0}=10^0$
α_{eq}°
λ°
Equatorial loss cone
Equatorial loss cone
Resonance case
Nonresonance case 1
Nonresonance case 2



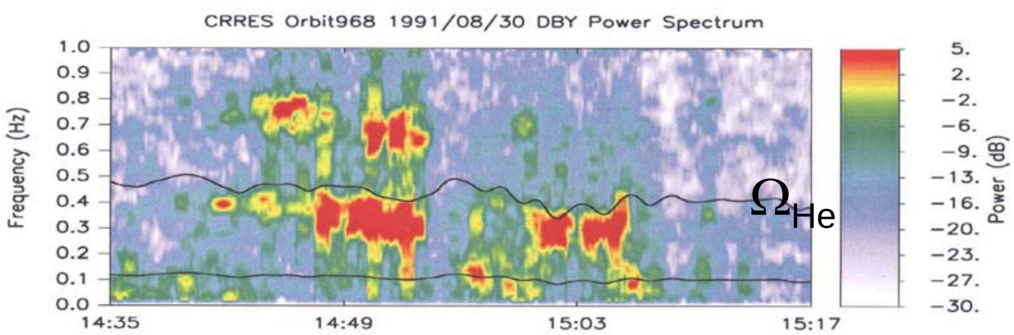


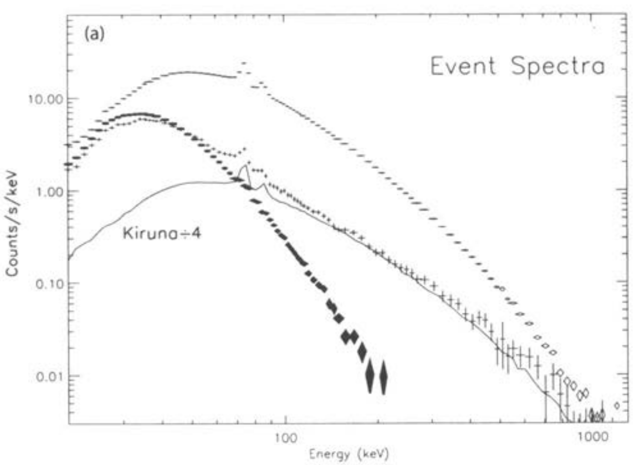
The nominal case:
Bw^{max}=2 nT, ω=3.9 Ω_{O+},
E=1 MeV, $\alpha_{eq0}=4^{o}$

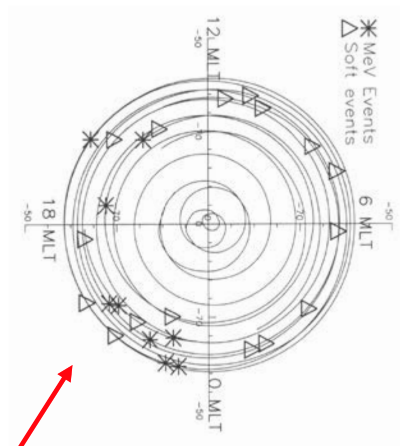
Nonresonant scattering can be effective for energy down to 100s keV, and over a broad range of pitch angles.

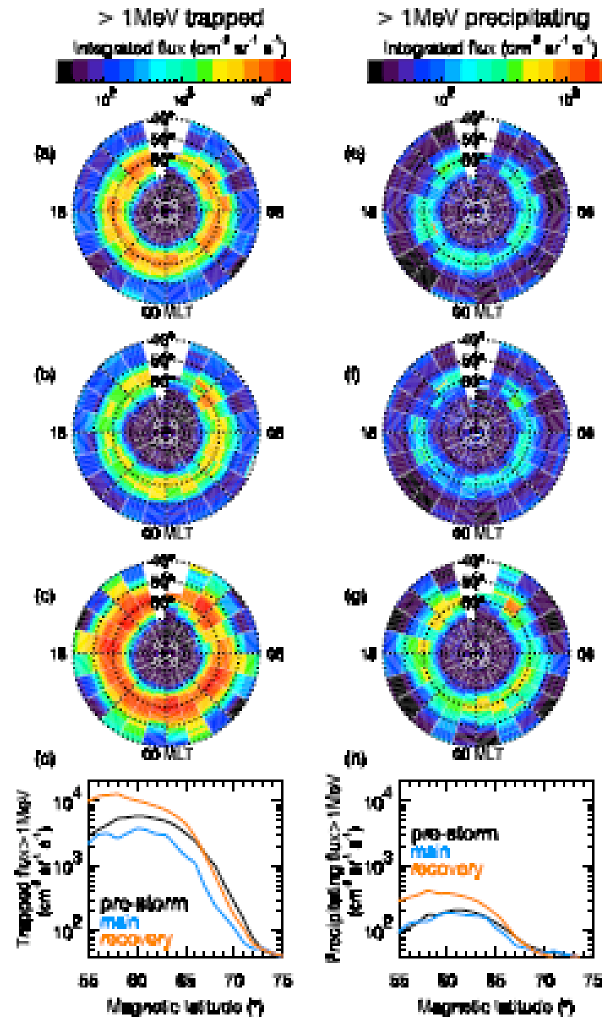
Nonresonant and resonant responses in pitch angle are quite different.

Evidence for Electron Precipitation Loss by EMIC Waves?









Extremely hard X-ray events observed on balloons: Millan et al., GRL 2002.

But where are the precipitating Electrons during the main phase dropouts? Horne et al., 2009.

Conclusions

- Quasi-linear scattering by EMIC waves can cause rapid electron scattering into the loss cone:
  - Resonance is usually limited to energies well above an MeV.
  - The range of resonant energies is lowered for waves just below the He gyrofrequency in a dense plasma.
  - Hot plasma effects limit the range of unstable k and limit resonance to energies > MeV even when the wave frequency is very close to the He gyrofrequency.

- Non-linear test particle scattering by EMIC:
  - Reproduce the stochastic scattering from QL theory for small EMIC amplitudes.
  - However for large amplitude waves (~ 1-10 nT) the resonant scattering is highly advective, away from loss cone
  - But for discrete wave packets with a spatial size comparable a few wave lenghts, nonresonant scattering can occur at energies down to ~ 100 keV, which can contribute to electron loss to the atmosphere.

Resonance with 1 MeV electrons

Solve $D(x, y; f, \eta_{he}, T_{he}, \eta_{hh}, T_{hh\|}, A_{hh}) = 0$

for x with a fixed y=15.4/f and a huge set (7×10^5) of plasma conditions:
f= 5, 10, …, 30; η_{he}= 2%, 4%, …, 30%; T_{he}=1, 3, 5, 10, …, 3000, 5000 eV
η_{hh}= 2%, 4%, …, 20%; T_{hh}=5, 10, 20, 30, …, 100 keV; A_{hh}=0.5, 1, …, 3.

and require that solutions of x must satisfy x_i>0.01.

Table 1. Necessary (but Not Sufficient) Plasma Conditions That Are Unstable to L-Mode Waves Capable of Resonating With Relativistic Electrons of Energy Down to 1 MeV[a]

A_{hh} \ f	15	20	25	30
1	X	X	$\eta_{he} \geq 28\%$, $\eta_{hh} \geq 20\%$, $T_{he} \leq 1$	$\eta_{he} \geq 6\%$, $\eta_{hh} \geq 12\%$, $T_{he} \leq 10$
	X	X	X	$\eta_{he} \leq 8\%$, $\eta_{hh} \geq 10\%$
1.5	X	X	$\eta_{he} \geq 6\%$, $\eta_{hh} \geq 12\%$, $T_{he} \leq 10$	$\eta_{hh} \geq 8\%$
	X	$\eta_{he} \leq 4\%$, $\eta_{hh} \geq 18\%$	$\eta_{he} \leq 18\%$, $\eta_{hh} \geq 8\%$	$\eta_{he} \leq 26\%$, $\eta_{hh} \geq 6\%$
2.0	X	$\eta_{he} \geq 18\%$, $\eta_{hh} \geq 18\%$, $T_{he} \leq 3$	$\eta_{hh} \geq 10\%$, $T_{he} \leq 10$	$\eta_{hh} \geq 4\%$
	X	$\eta_{he} \leq 20\%$, $\eta_{hh} \geq 10\%$	$\eta_{hh} \geq 6\%$	$\eta_{hh} \geq 4\%$
2.5	X	$\eta_{he} \geq 8\%$, $\eta_{hh} \geq 14\%$, $T_{he} \leq 10$	$\eta_{hh} \geq 8\%$	$\eta_{hh} \geq 4\%$
	$\eta_{he} \leq 8\%$, $\eta_{hh} \geq 16\%$	$\eta_{hh} \geq 6\%$	$\eta_{hh} \geq 4\%$	$\eta_{hh} \geq 4\%$
3	X	$\eta_{he} \geq 4\%$, $\eta_{hh} \geq 12\%$, $T_{he} \leq 50$	$\eta_{hh} \geq 6\%$	$\eta_{hh} \geq 4\%$
	$\eta_{he} \leq 20\%$, $\eta_{hh} \geq 12\%$	$\eta_{hh} \geq 6\%$	$\eta_{hh} \geq 4\%$	Full

x_r<=0.25

x_r>0.25

Most favorable plasma condition occurs only in the large f (>=15) and A_{hh} (>=1) regime.

For x_r<=0.25, a dense, hot H+, and a dense colder He+

For x_r>0.25, a dense, hot H+, tenuous He+