Wave fields of electromagnetic ion cyclotron and whistler waves in a two dimensional dipole magnetosphere and associated particle acceleration and pitch angle scattering

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and many others

Hybrid Equations

Fluid

$$\frac{\partial \vec{\mathbf{B}}}{\partial t} = -\vec{\nabla} \times \vec{\mathbf{E}}$$

$$\vec{\mathbf{J}} = \frac{1}{\mu_0}\vec{\nabla} \times \vec{\mathbf{B}}$$

$$\vec{\mathbf{E}} = -\vec{\mathbf{u}}_{ec} \times \vec{\mathbf{B}}$$

Particles

$$\frac{d\vec{\mathbf{x}}_m}{dt} = \vec{\mathbf{v}}_m$$

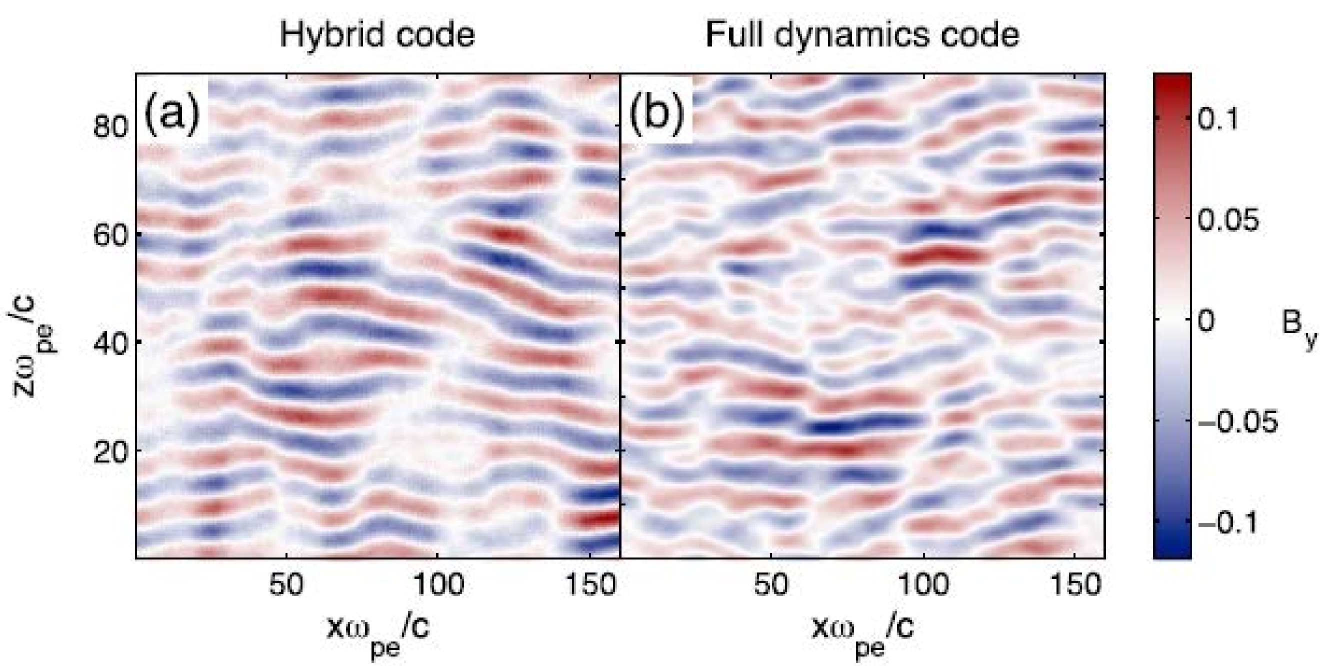
$$\frac{d\vec{\mathbf{v}}_m}{dt} = \frac{q_m}{m_m}(\vec{\mathbf{E}}_m + \vec{\mathbf{v}}_m \times \vec{\mathbf{B}}_m)$$

Coupling

$$\vec{\mathbf{J}} = -en_{ec}\vec{\mathbf{u}}_{ec} + \vec{\mathbf{J}}_{et}$$

$$n_{ec} + n_{et} = n_{\text{ion}}$$

Note: $E_{//} = 0$ even for whistler waves

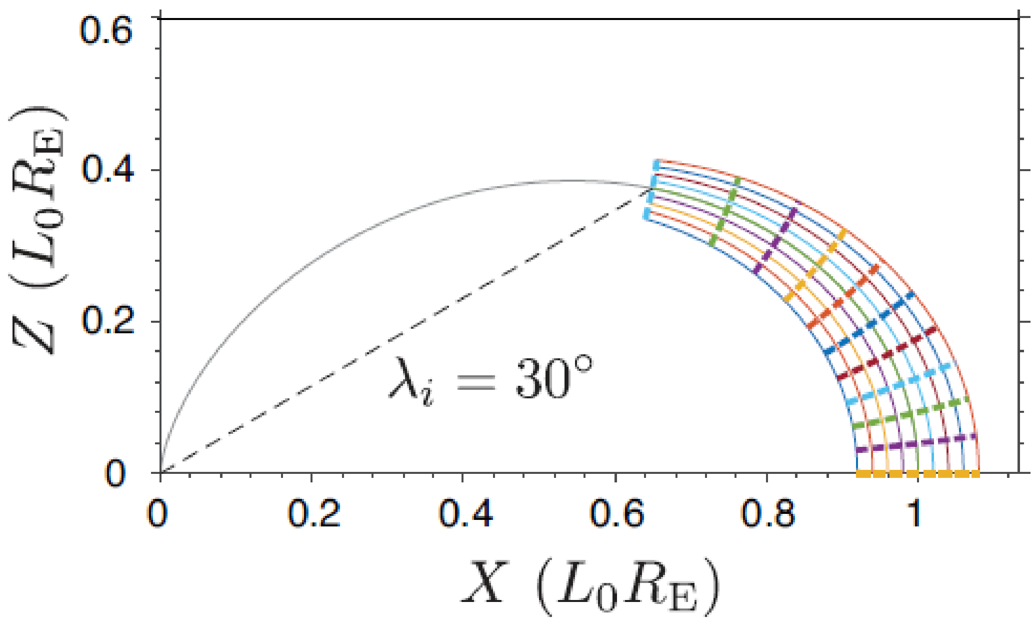


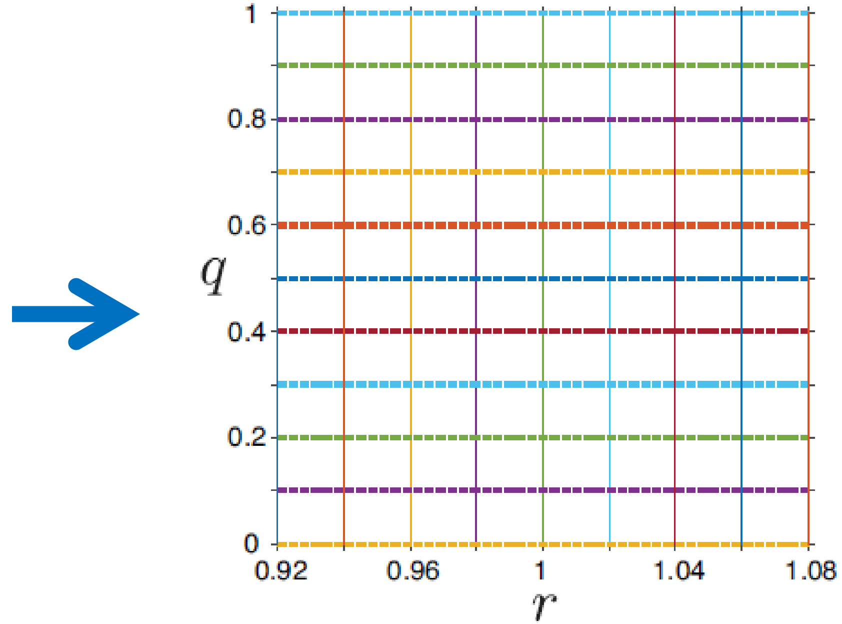
Whistler waves

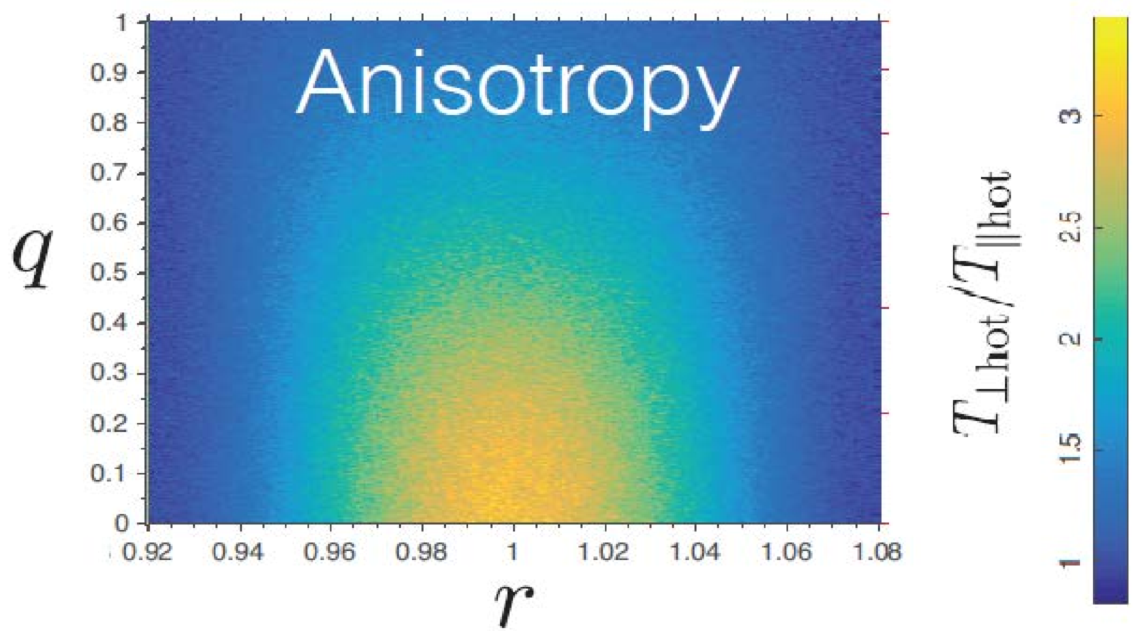
Note: good agreement with PIC

[Wu et al., JGR, 2015]

Dipole curvilinear coordinate system



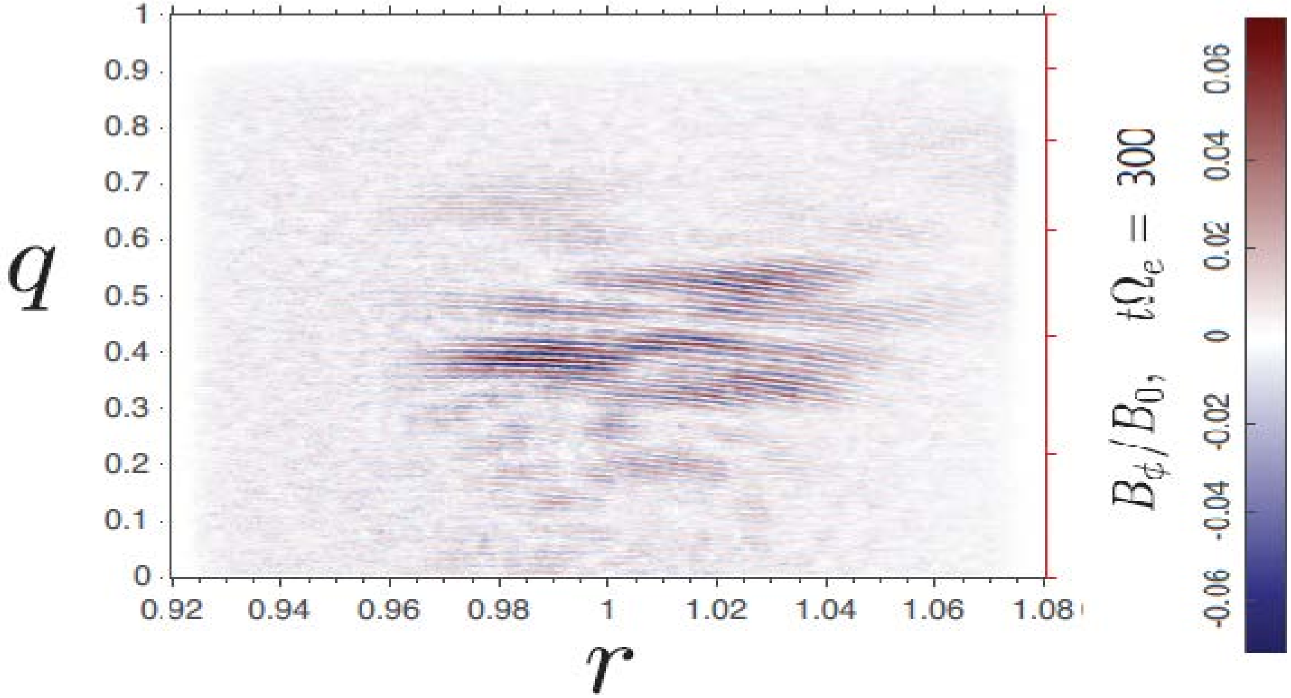




Wave B Fields

Whistler waves
Note: small (1/13) scale, so realistic waves would have even smaller wavelength

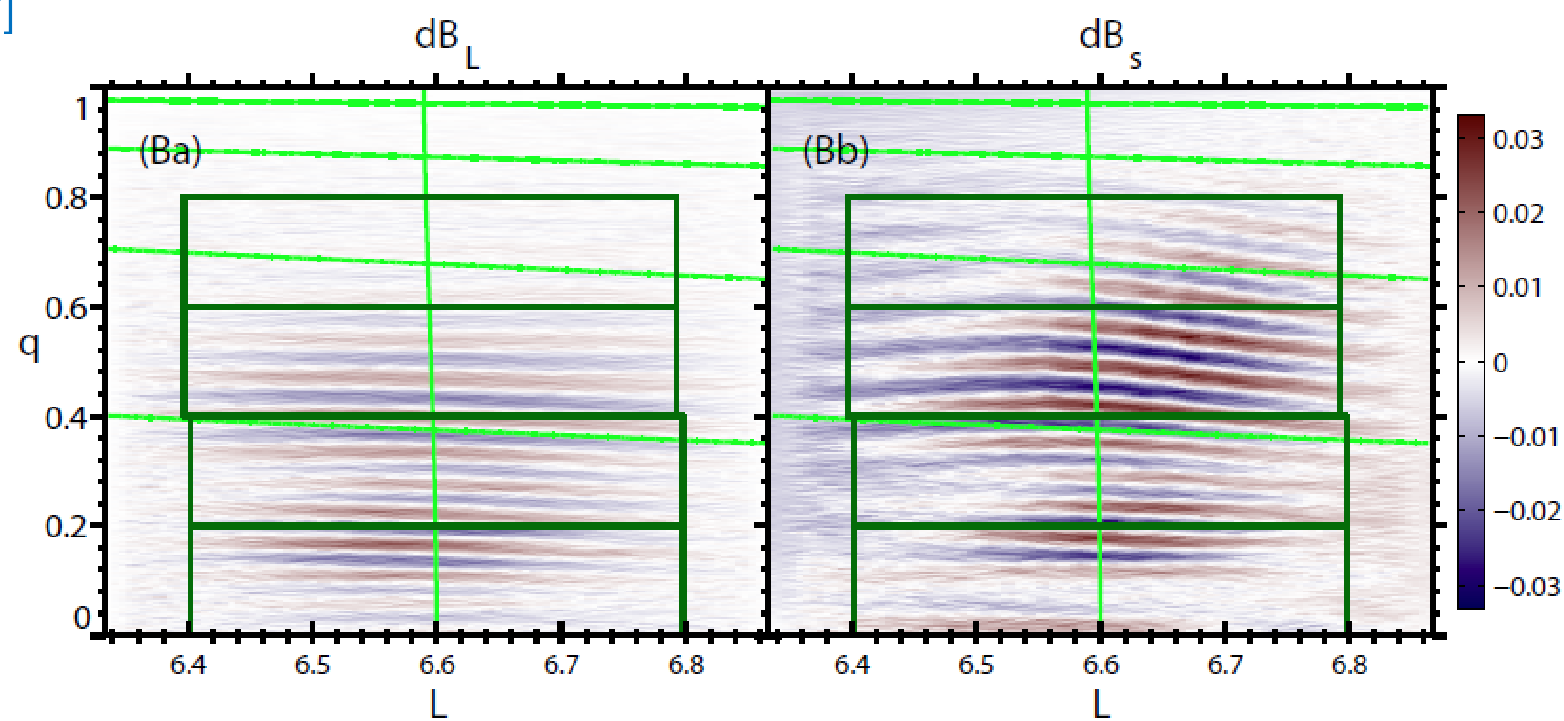
[da Silva et al., JGR, 2017]



EMIC

Full scale

[Denton, JGR, 2018]



Resonant interactions

Resonance Condition:

$$\omega - k_{\parallel} v_{\parallel} = n \frac{\Omega_e}{\gamma}$$

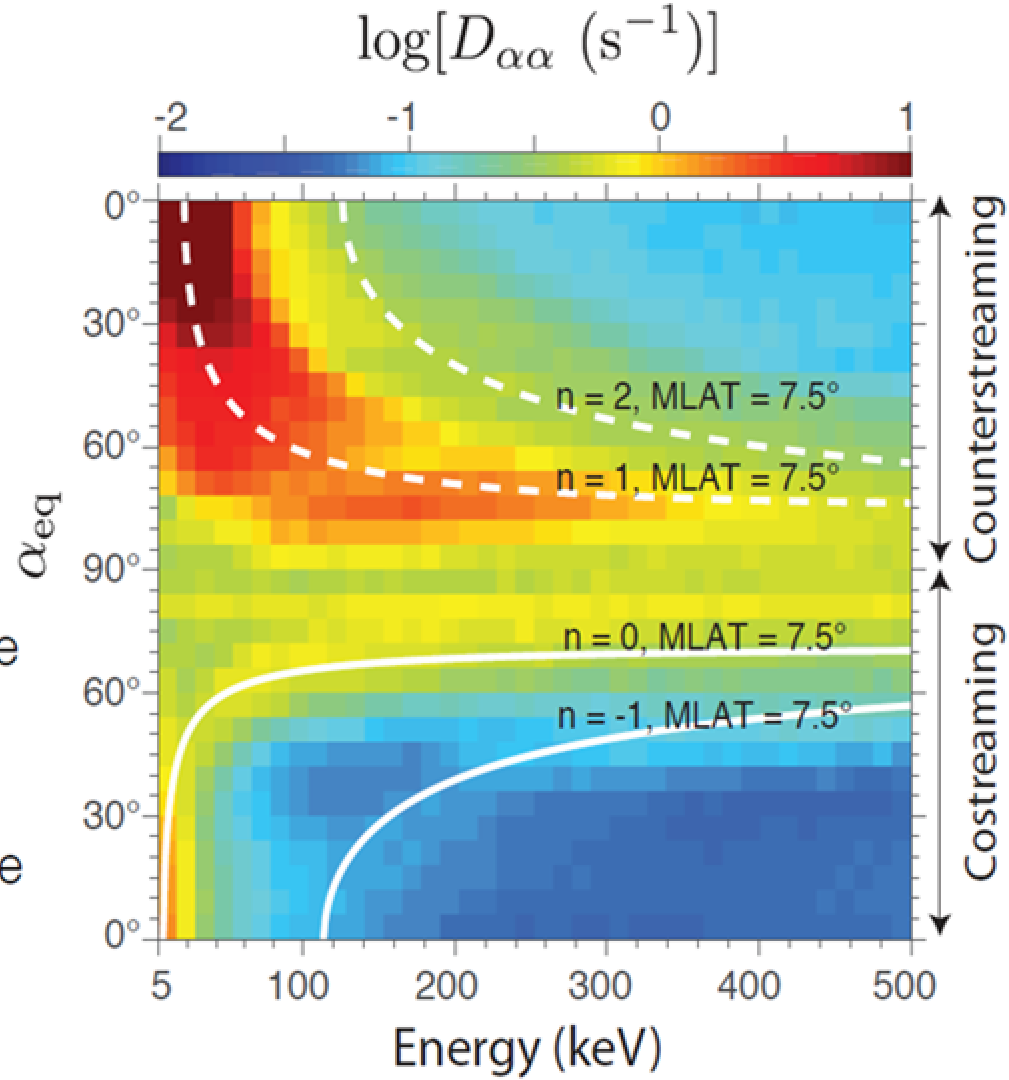
$$n = 0, \pm 1, \pm 2, \ldots$$

n=0: Landau Resonance

n=+1: Dominant Cyclotron Resonance for Counterstreaming Electrons

n=-1: Dominant Cyclotron Resonance for Costreaming Electrons

$$D_{\alpha\alpha} \equiv \frac{\langle \Delta \alpha_{\mathrm{eq}}^2 \rangle}{2 \Delta t}$$

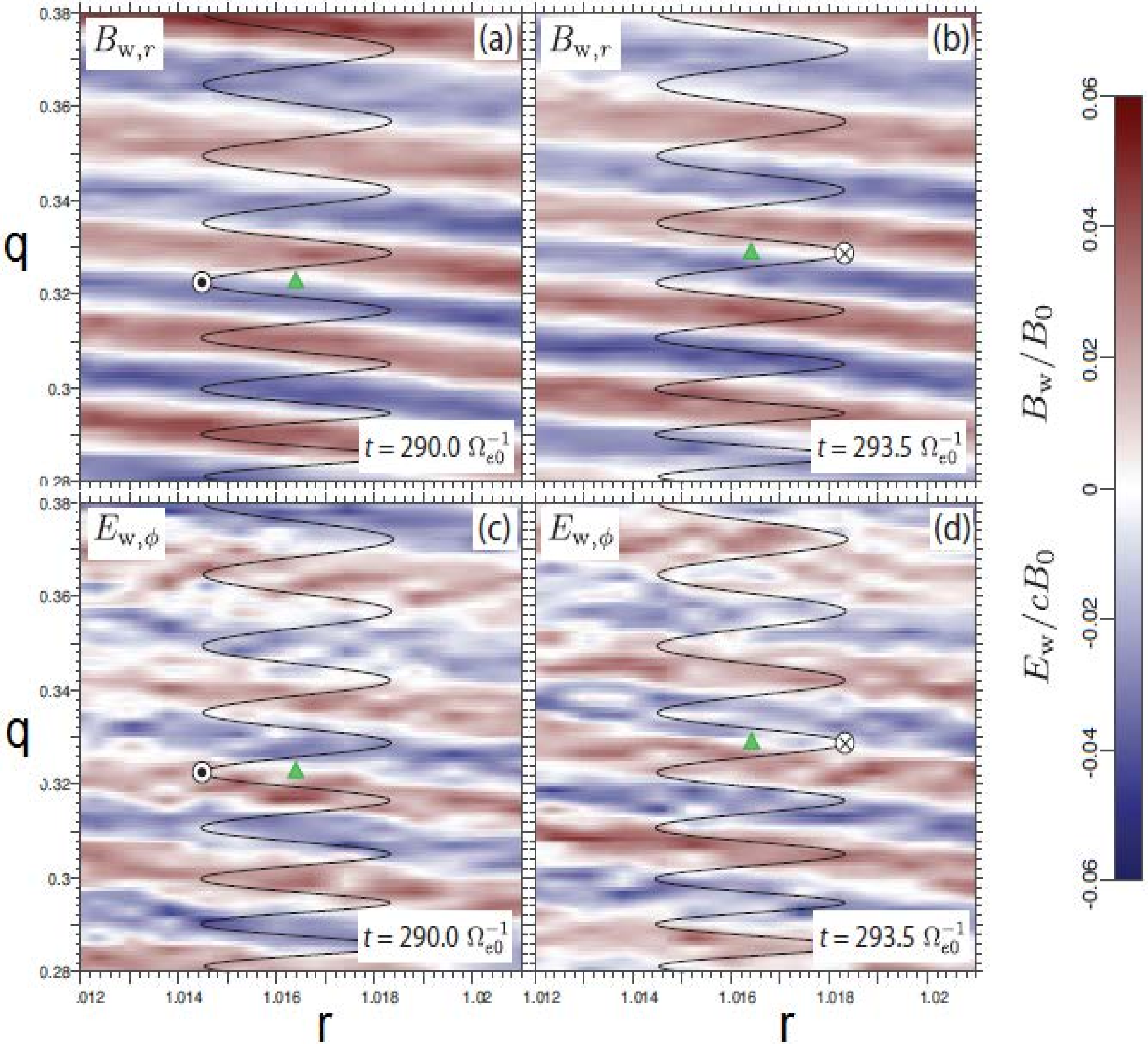


$$B_{\mathrm{w}} = 10^{-1} B_0$$

$$\Delta t = 250\text{–}300\ \Omega_{e0}^{-1}$$

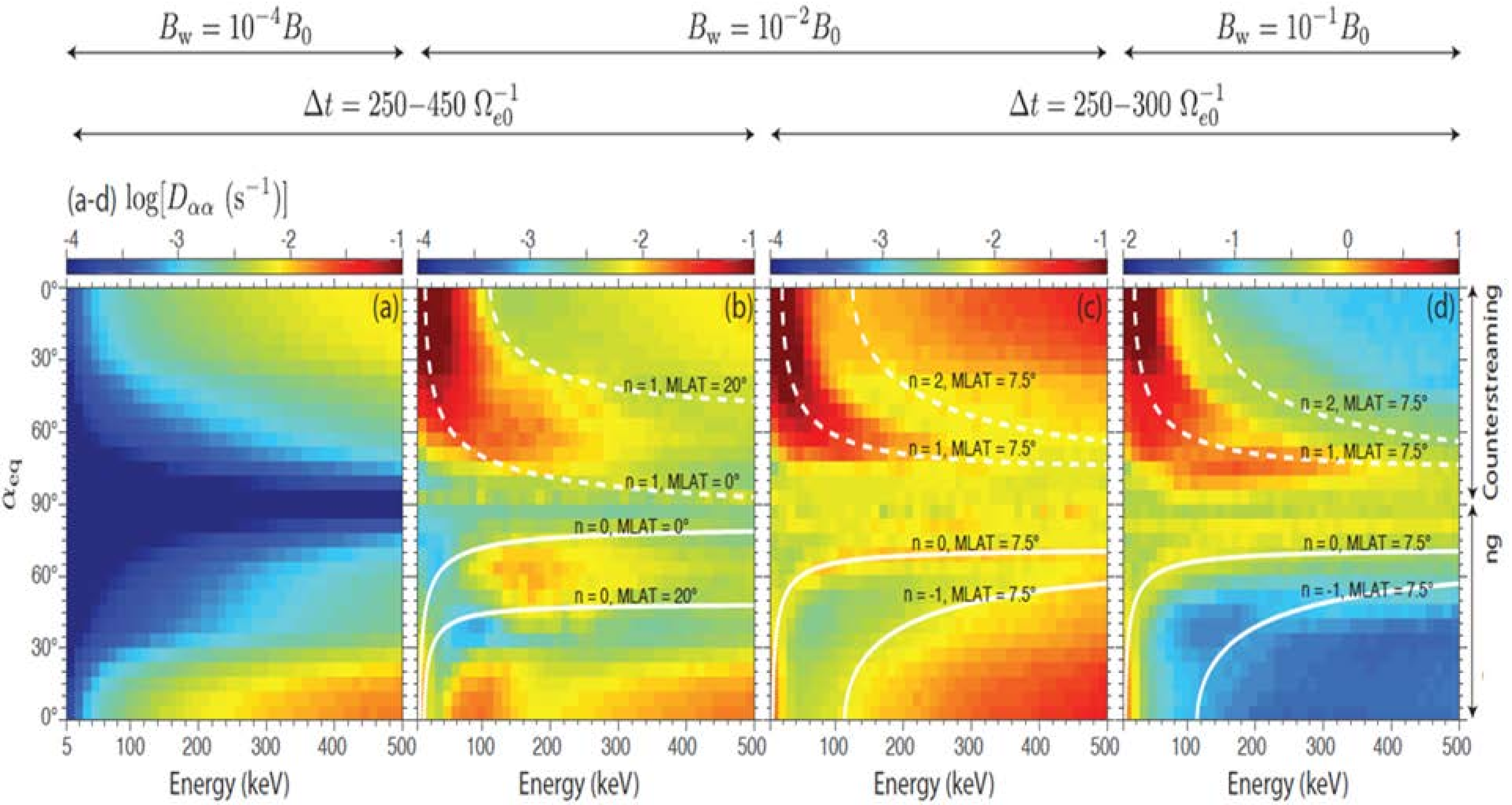
[da Silva et al., JGR, 2017]

Whistler Landau resonance



The gyrocenter at the green triangle moves with the wave node, but the particle Vs resonates with Br, leading to pitch angle scattering, and Vs resonates with Es, leading to energization, because of $k_\perp$ due to oblique propagation.

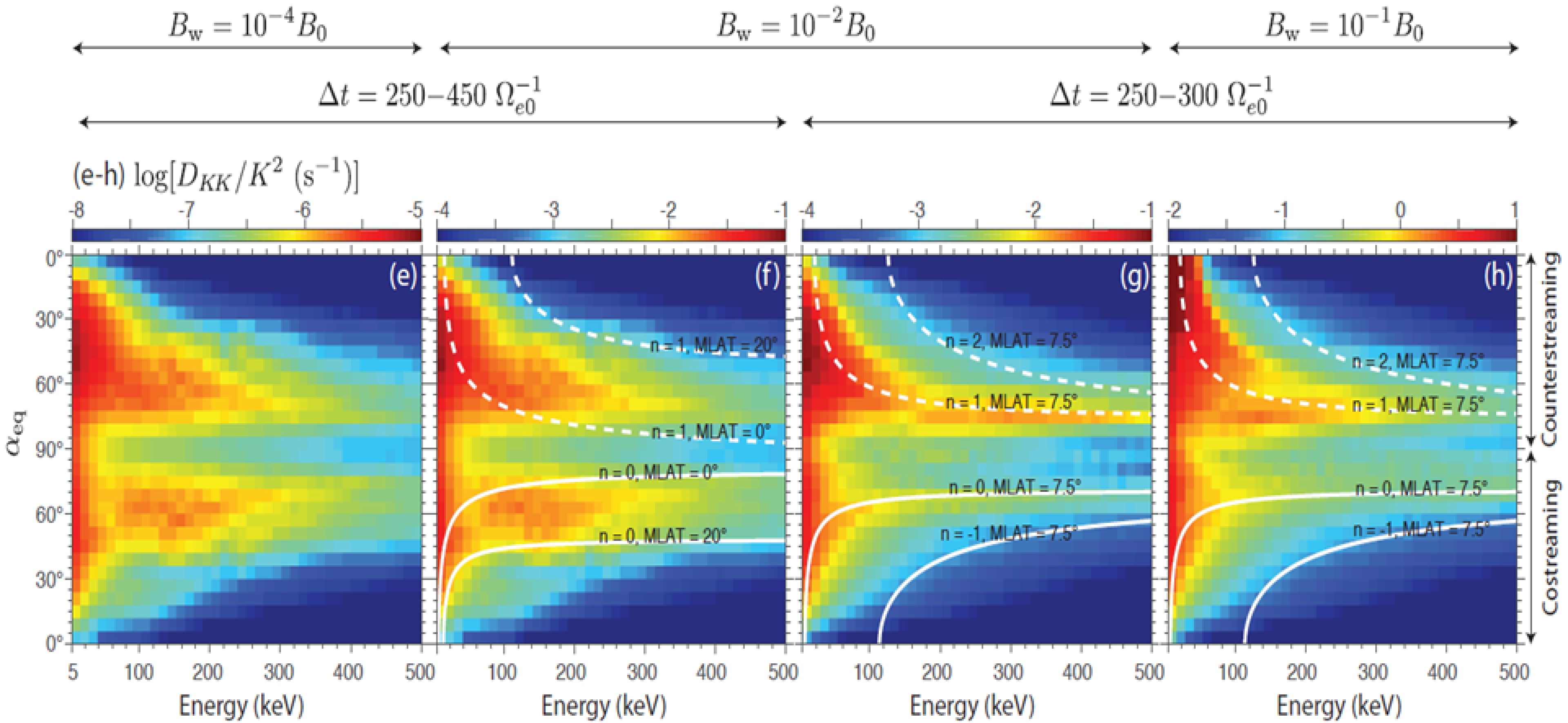
Whistler pitch angle diffusion



- Cyclotron resonance is more efficient for pitch-angle diffusion;
- Diffusion coefficients vary as $\propto B_w^2$

[da Silva et al, JGR, 2017]

Whistler energy diffusion

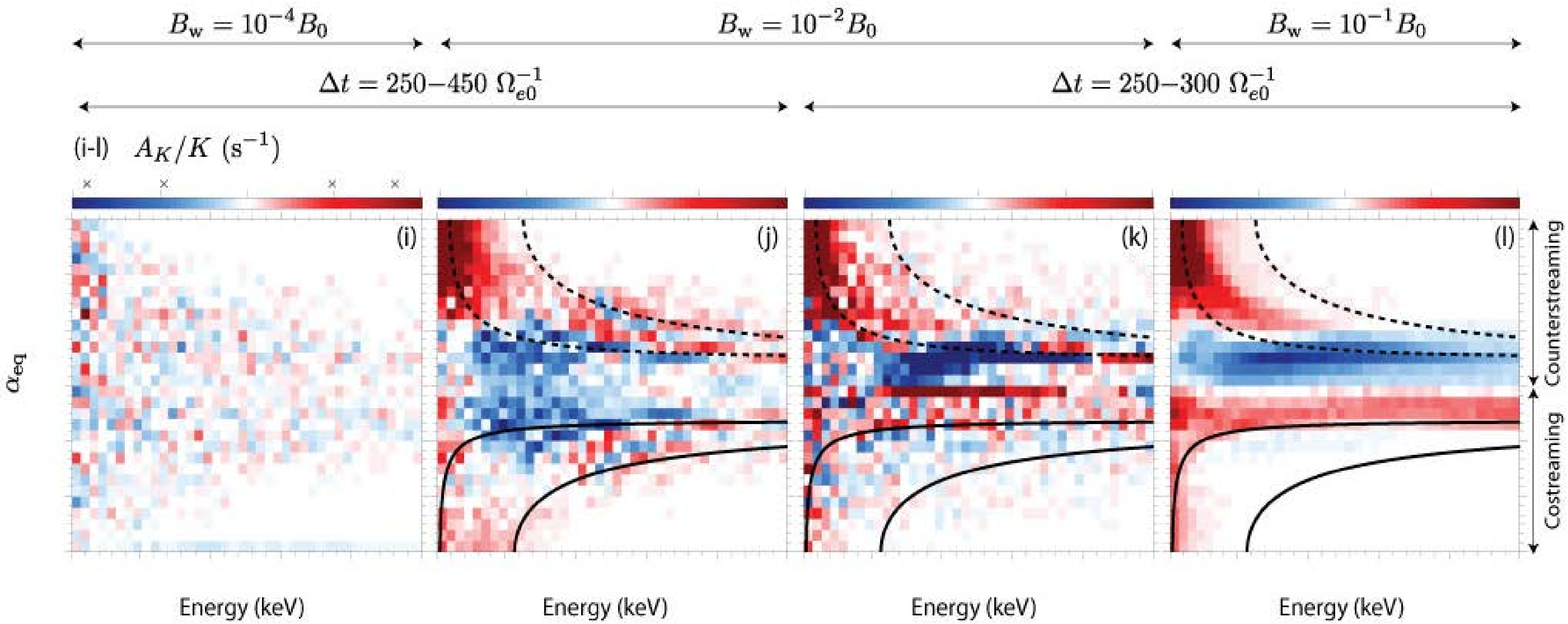


- Landau resonance is comparable to cyclotron for energy diffusion;
- Diffusion coefficients vary as $\propto B_w^2$

$$D_{KK} \equiv \frac{\langle \Delta K^2 \rangle}{2\Delta t}$$

[da Silva et al., JGR, 2017]

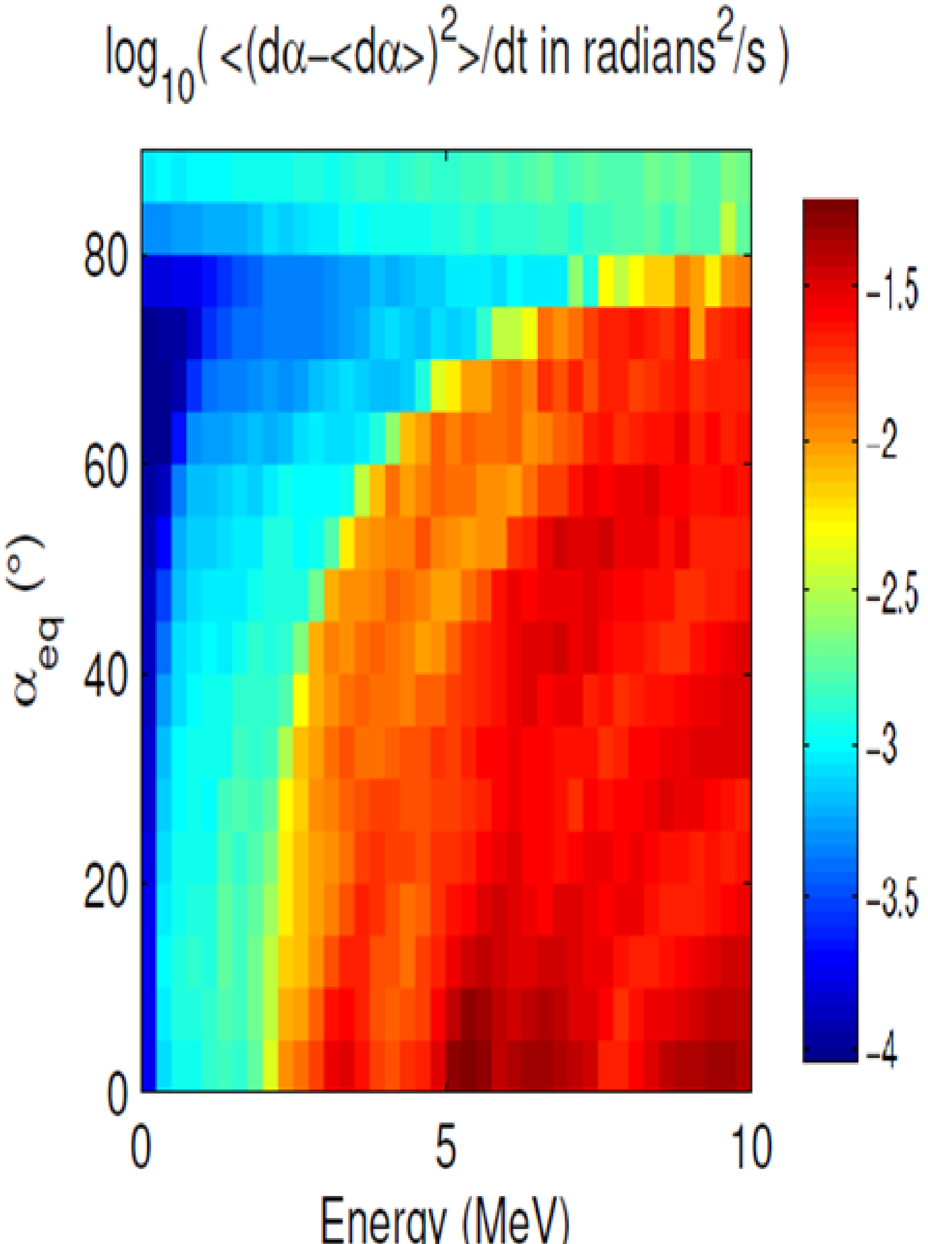
Whistler nonlinear energy advection

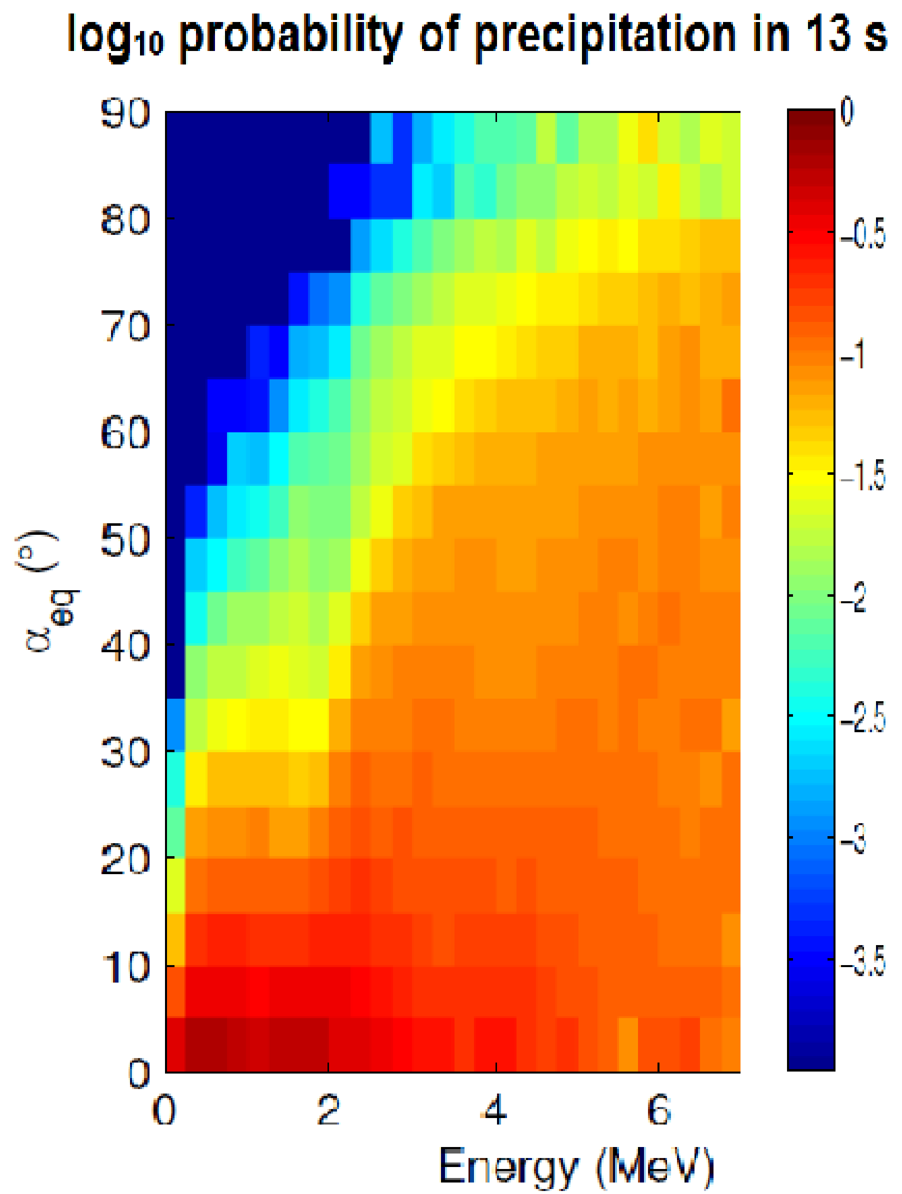


- Strong, systematic energy advection arises at high wave amplitudes
- Significant acceleration due to both cyclotron and Landau resonances

$$A_K \equiv \frac{\langle \Delta K \rangle}{\Delta t}$$

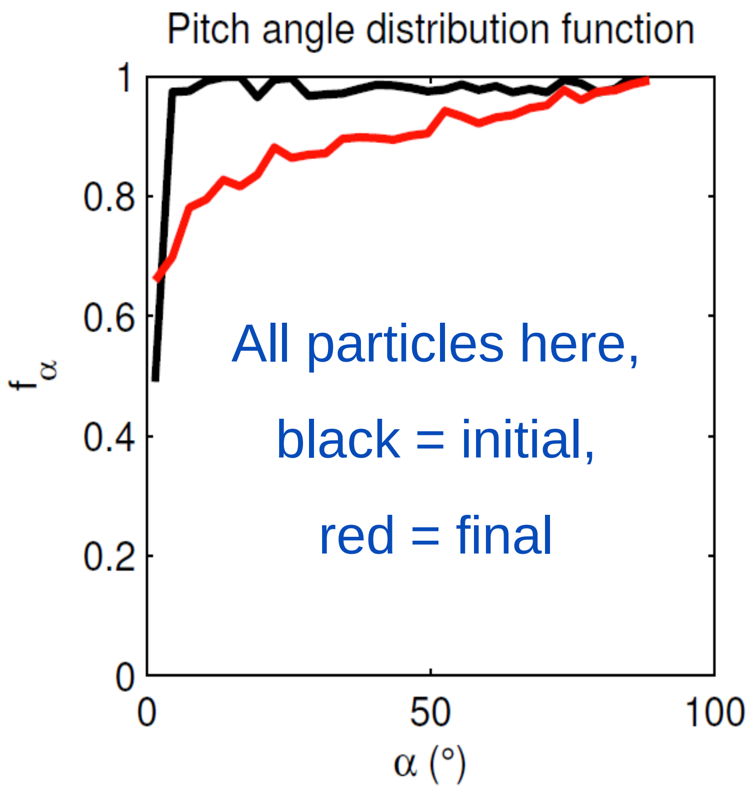
Strong EMIC pitch angle diffusion

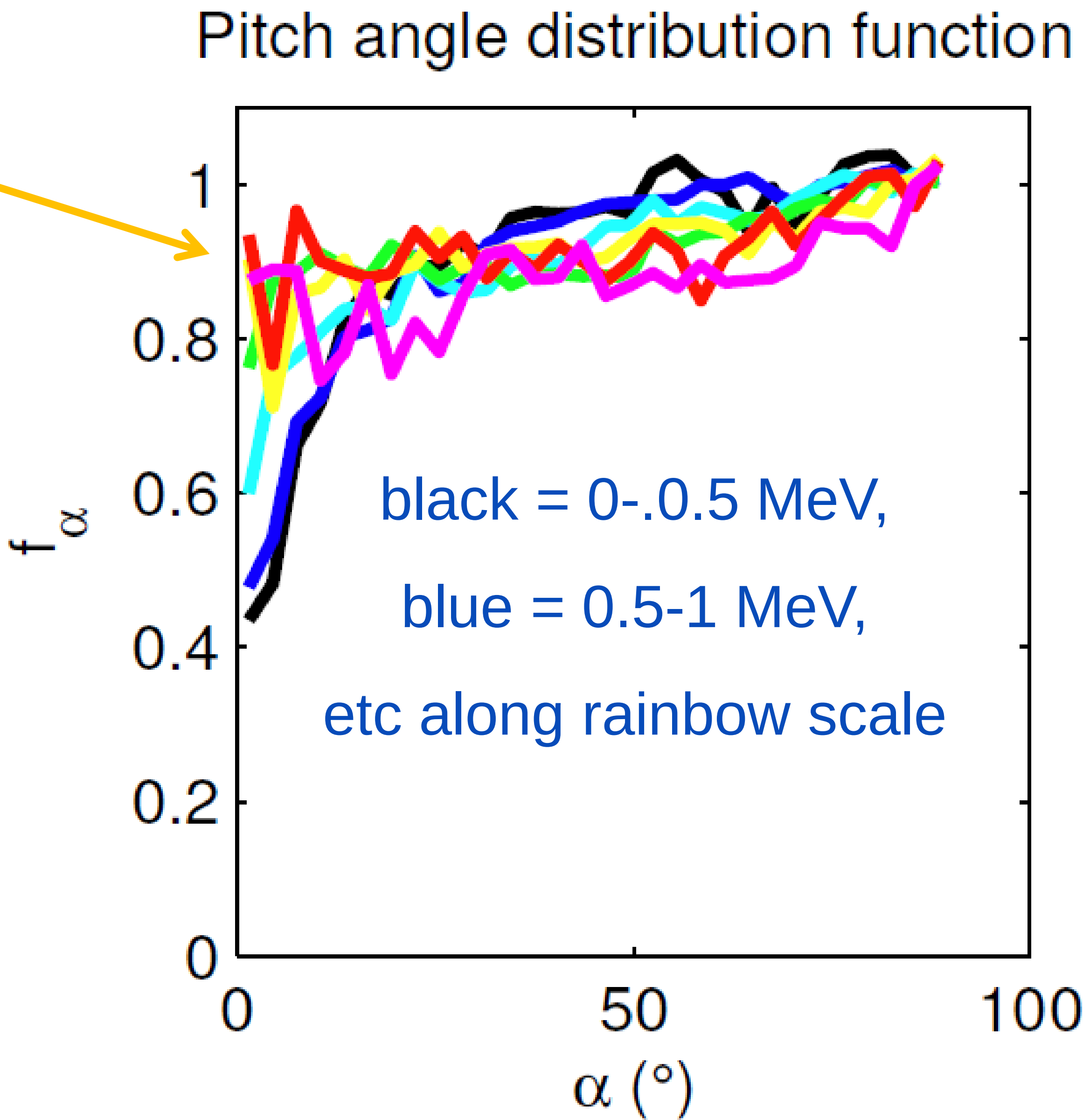




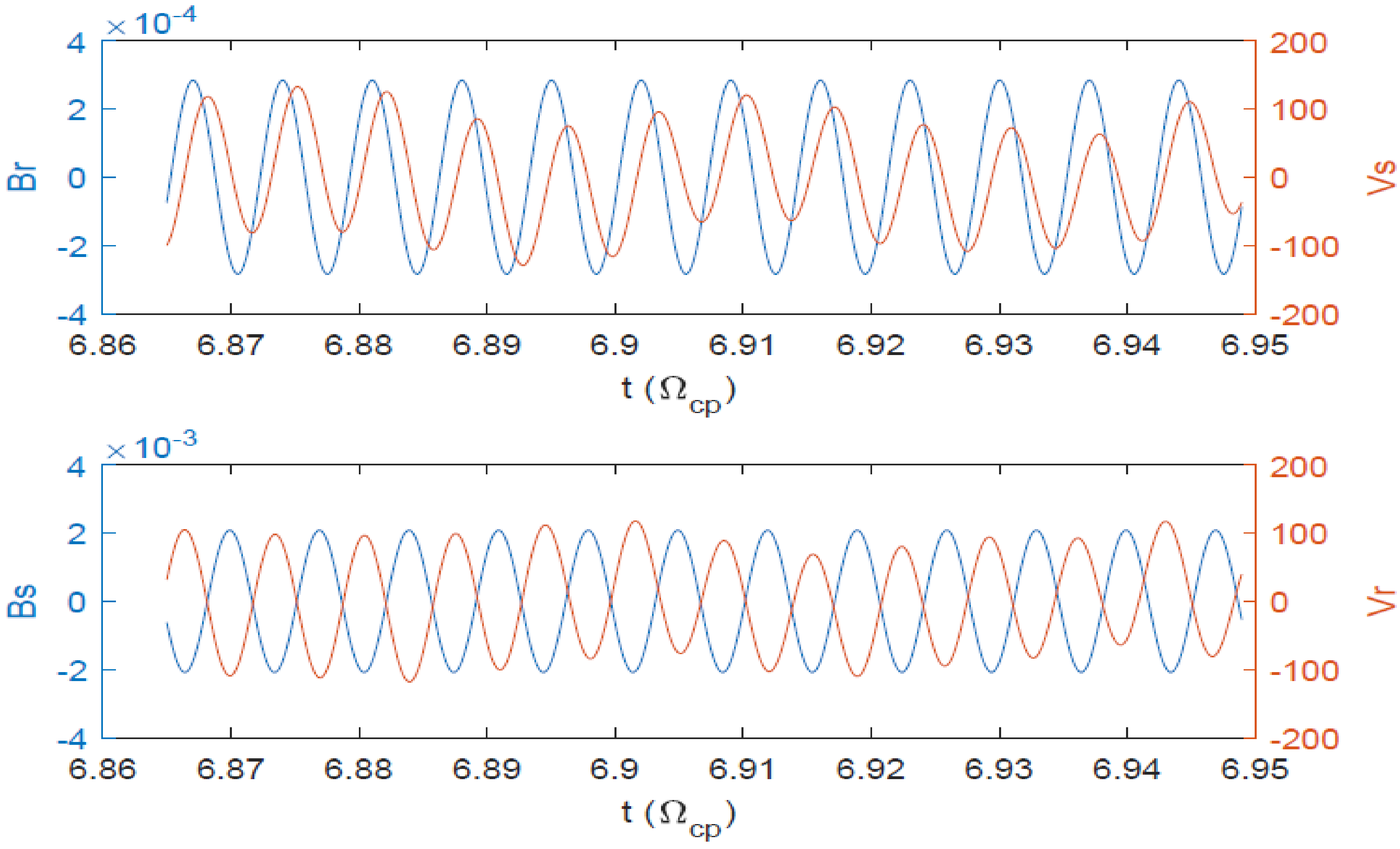
Change in pitch angle distribution from EMIC in 13s, even low energies affected

Low energy particles scattered more effectively at low pitch angles

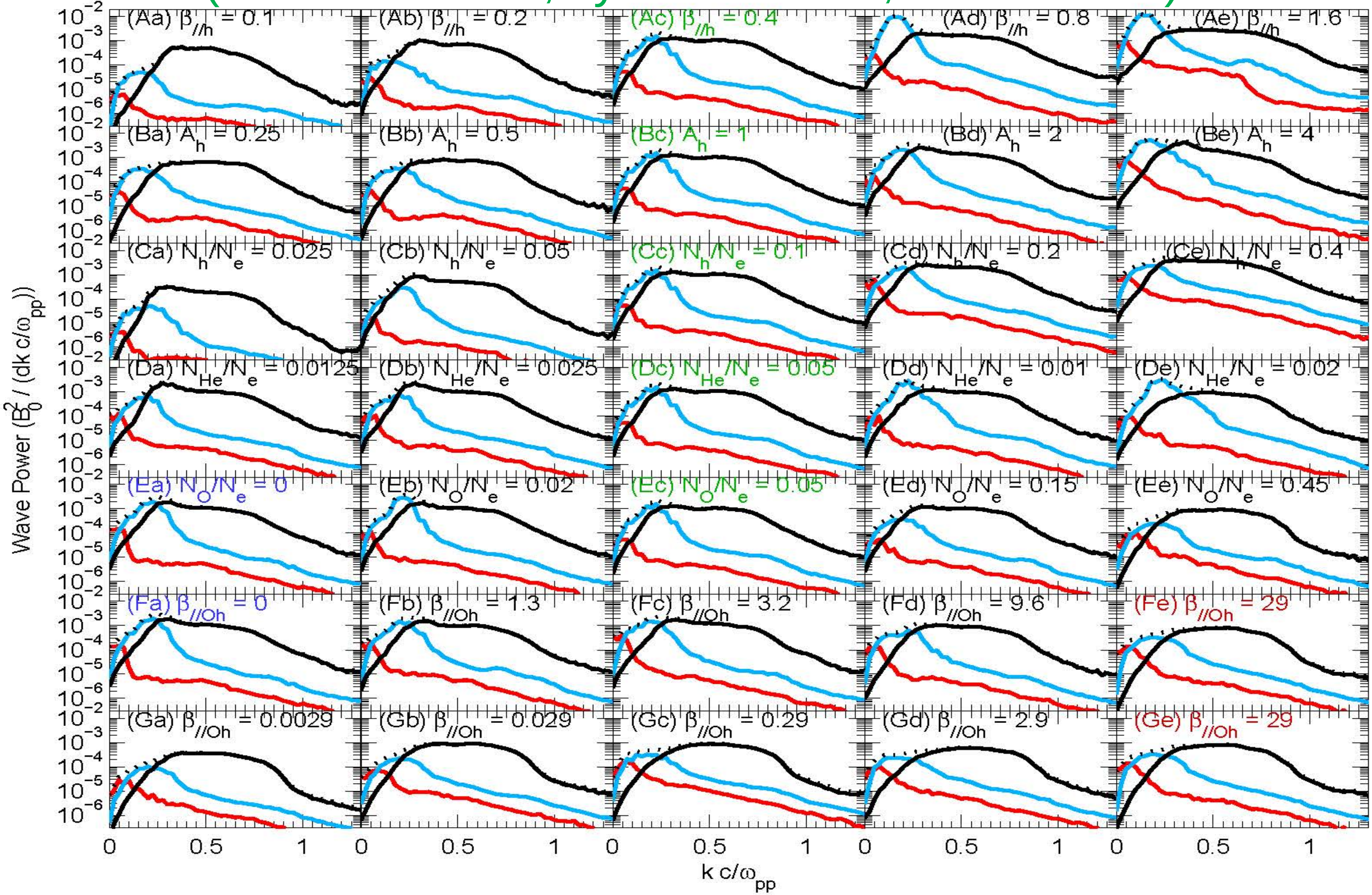




Resonance of band pass filtered Bs with Vr -> non-dominant high $k_{//}$ wave power causes pitch angle scattering of this relatively low energy relativistic electron



And for a wide range of (homogeneous) simulation parameters, the H band mode dominates EMIC wave power at high $k_{//}$ (black = H band, cyan=He band, red=O band)



Conclusions

- Whistler waves pitch angle scatter relativistic electrons predominately through the n = 1 cyclotron resonance
- Landau resonance can cause diffusion in both energy and pitch angle. Landau resonance can occur even without $E_{//}$ (as in our hybrid code system)
- Whistler diffusion consistent with quasilinear diffusion, but energy and pitch angle (not shown) advection is nonlinear, driving particles toward resonances
- EMIC waves can lead to strong pitch angle scattering of relativistic electrons
- Particles with energy below the resonant energy of the dominant waves can be scattered by H mode waves that extend to high $k_{//}$, even if the wave power at those $k_{//}$ values is small compared to the dominant waves. Particles with low pitch angle will be most strongly affected.

Another Conclusion

- Relativistic electron precipitation is often linked to He band EMIC events. But this study suggests that the wave power that causes precipitation of relativistic electrons with energy below the resonant energy is in the H band. Denton et al. [JGR, 2014] showed that the He band is often dominant when the plasma density is large. Large plasma density means that the normalization factor for k, ω_{pi}/c , is large, meaning that the wave numbers will be larger in real units (e.g., km^{-1}). This suggests that the best conditions for precipitation of relatively low energy relativistic electrons will occur when both the He mode (associated with high density) and the H mode (directly causing the pitch angle scattering) are present. A recent observational study by Murong Qin et al. (manuscript in progress) finds this very result.