Instabilities and wave-particle interactions associated with asymmetric magnetic reconnection

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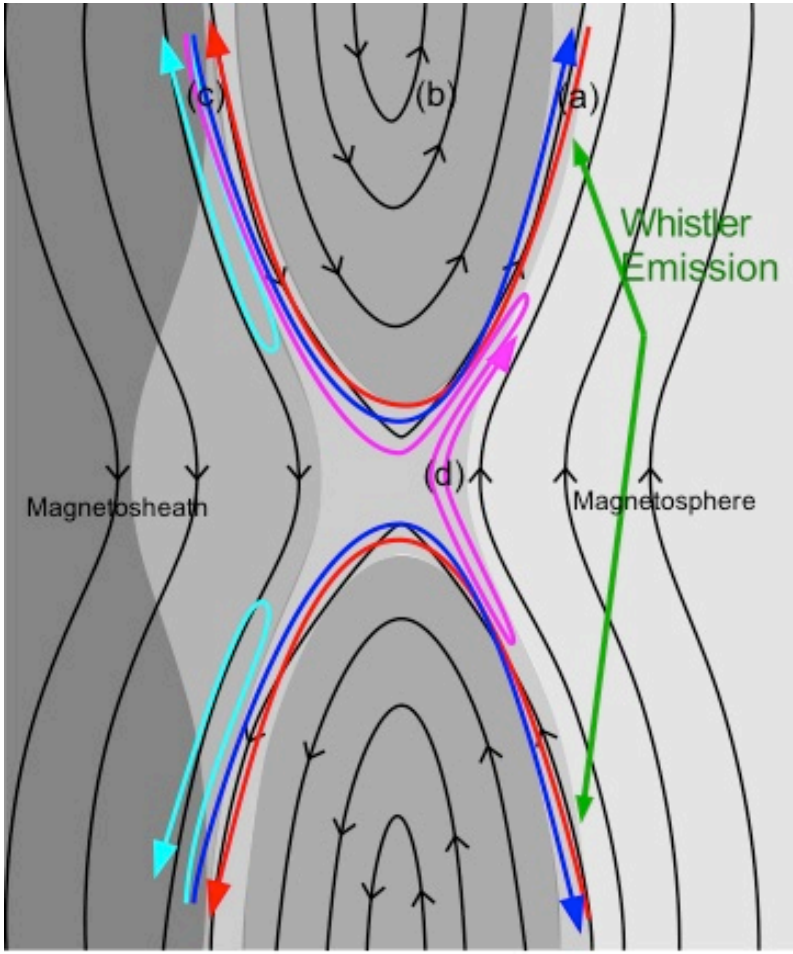
Outline

1. Electron distributions of asymmetric reconnection.
2. Whistler waves and reconnection
3. Electrostatic solitary waves and reconnection
4. Statistical properties of electrostatic solitary waves
5. Conclusions

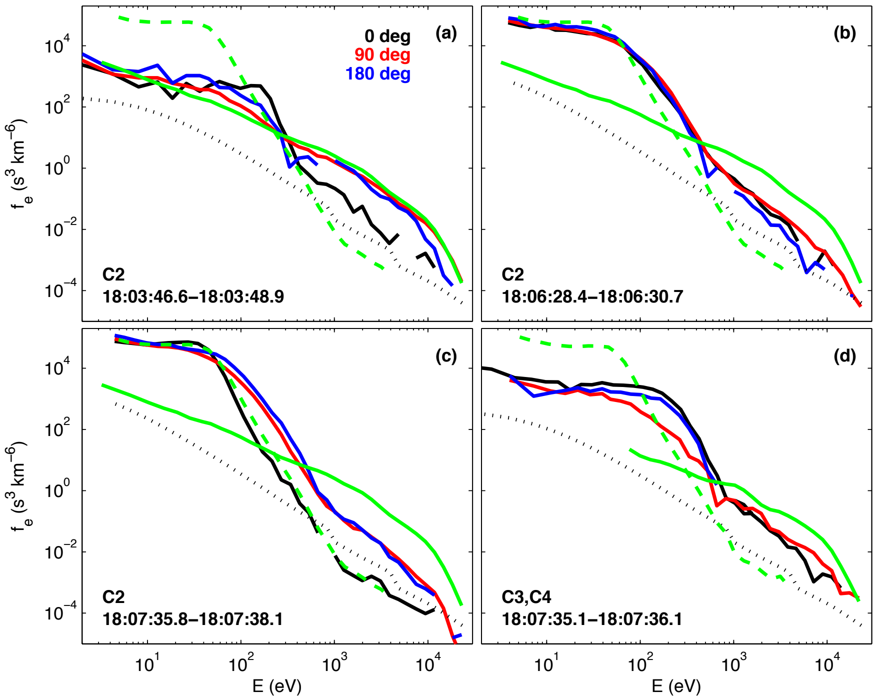
Electron distributions in asymmetric reconnection

Diagram of expected electron trajectories.



[Cf., Tanaka et al., 2008; Egedal et al., 2011; Graham et al., 2014].

- MS separatrices (a): Partial loss of MS electrons, and some incoming SH electrons.
- Outflow (b): Mixing of MS and SH electrons.
- SH separatrices (c): SH electrons and escaping MS electrons.
- Ion Diffusion region (d): Trapped SH electrons and reduced density of MS electrons. [e.g., Graham et al., 2014].



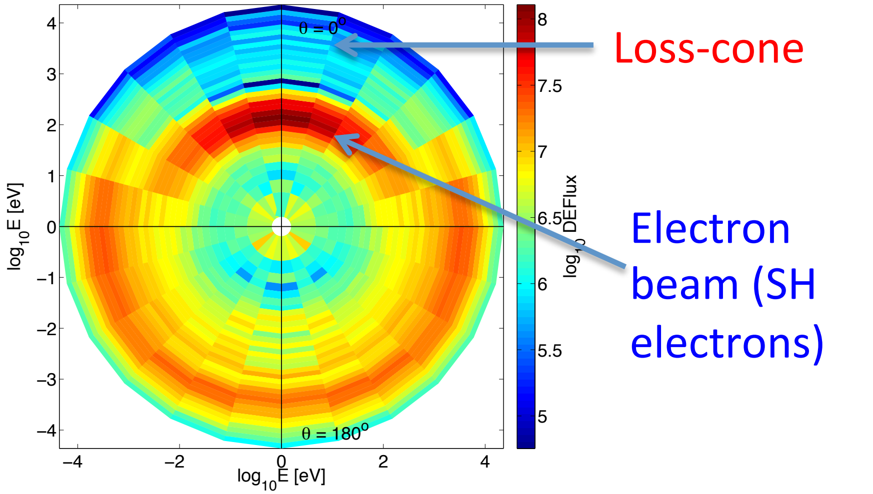
Green solid – background MS.

Green dashed – background SH.

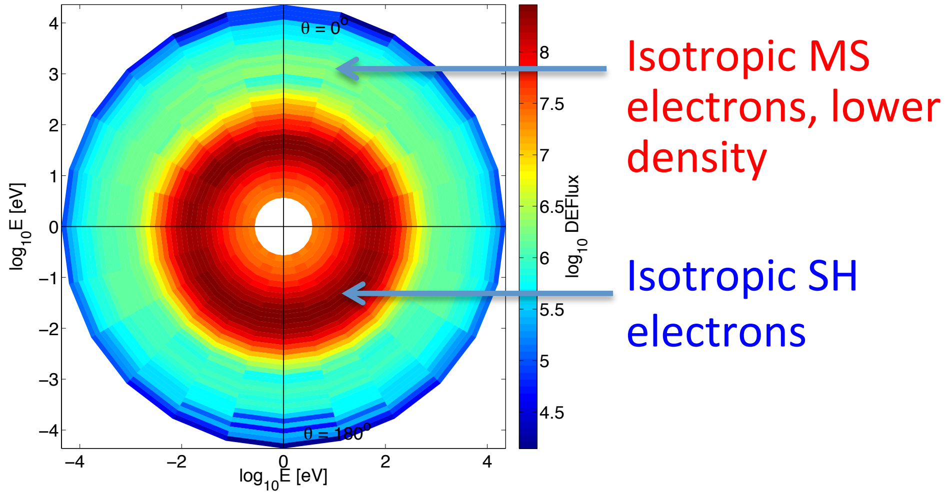
Dotted – Instrument one count level.

Electron Pitch-angle distributions

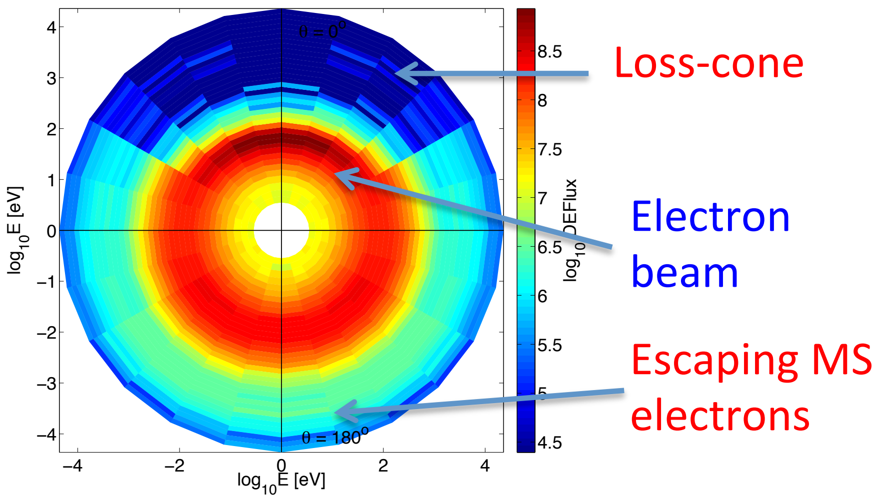
MS separatrix region



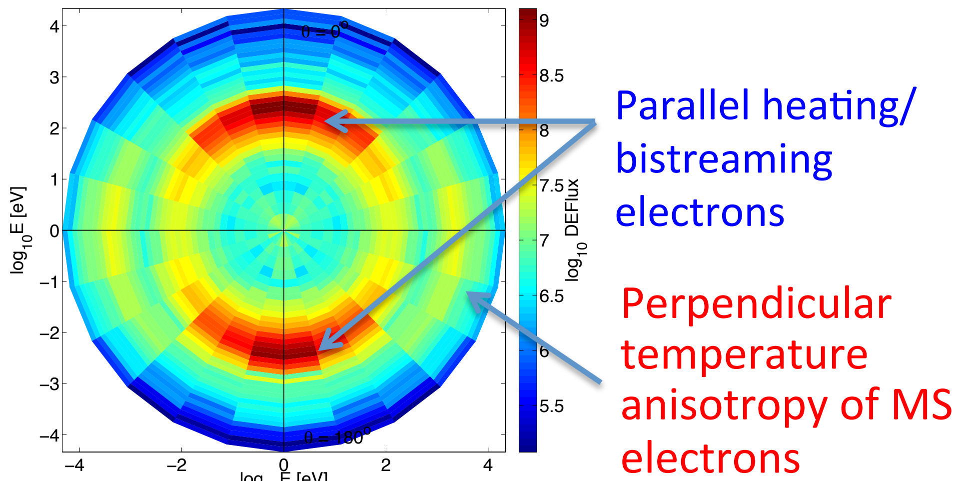
Outflow region (small guide field)



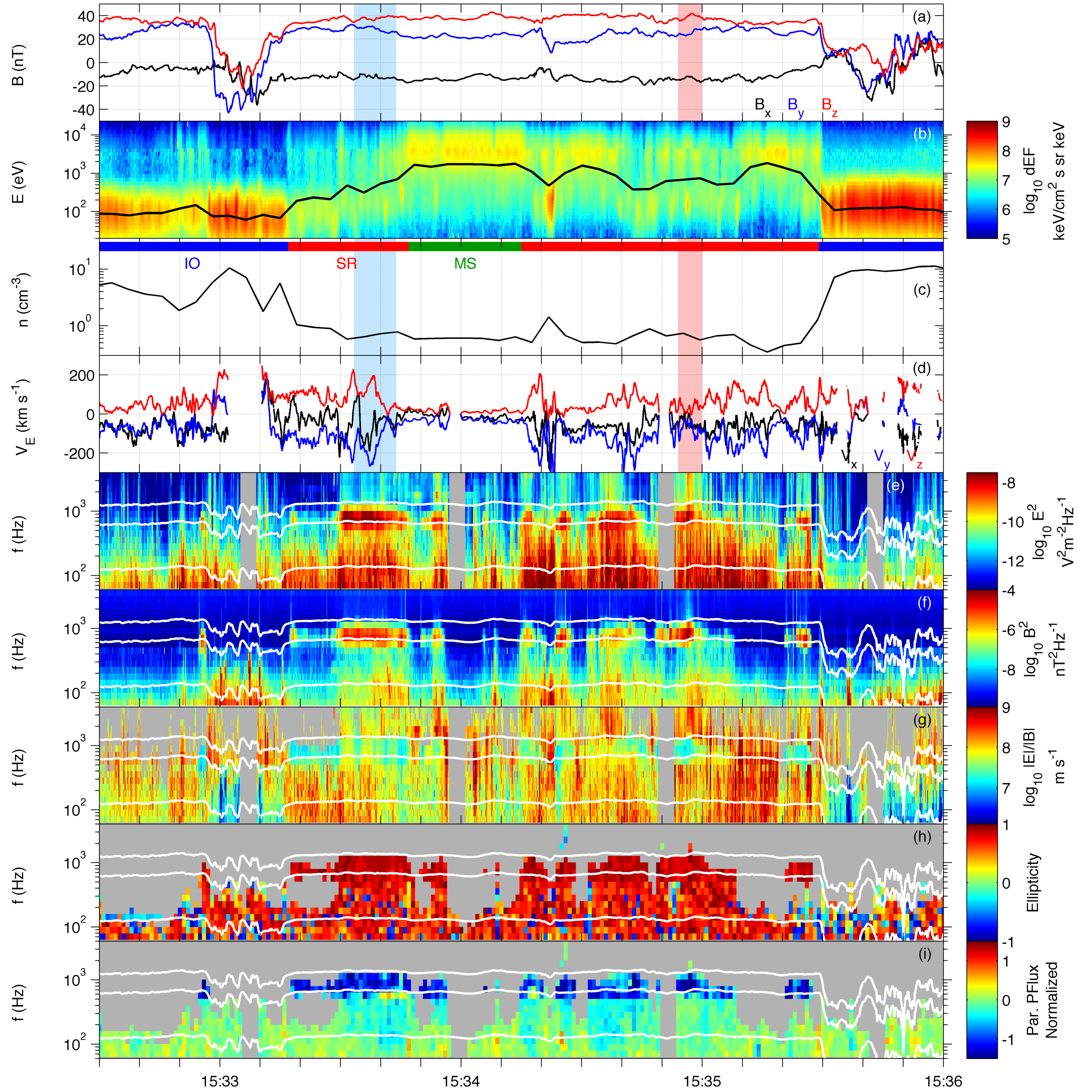
SH separatrix region

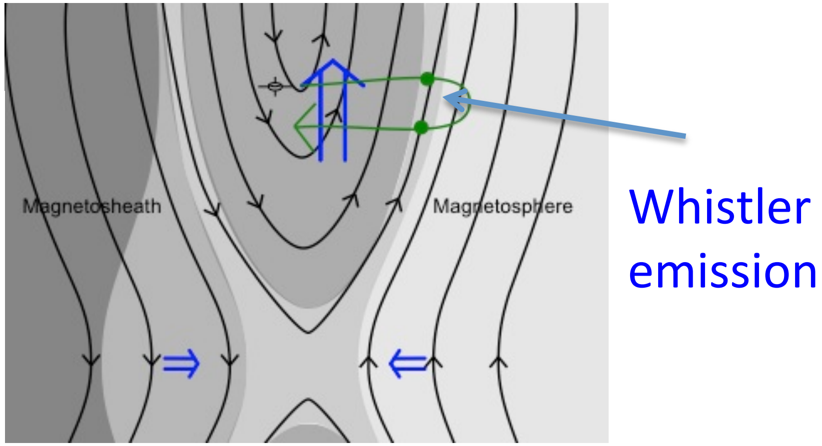


Ion diffusion region



Whistler emission - 17 April 2007, C2





Mixing of MS and SH electrons in MS separatrix regions.

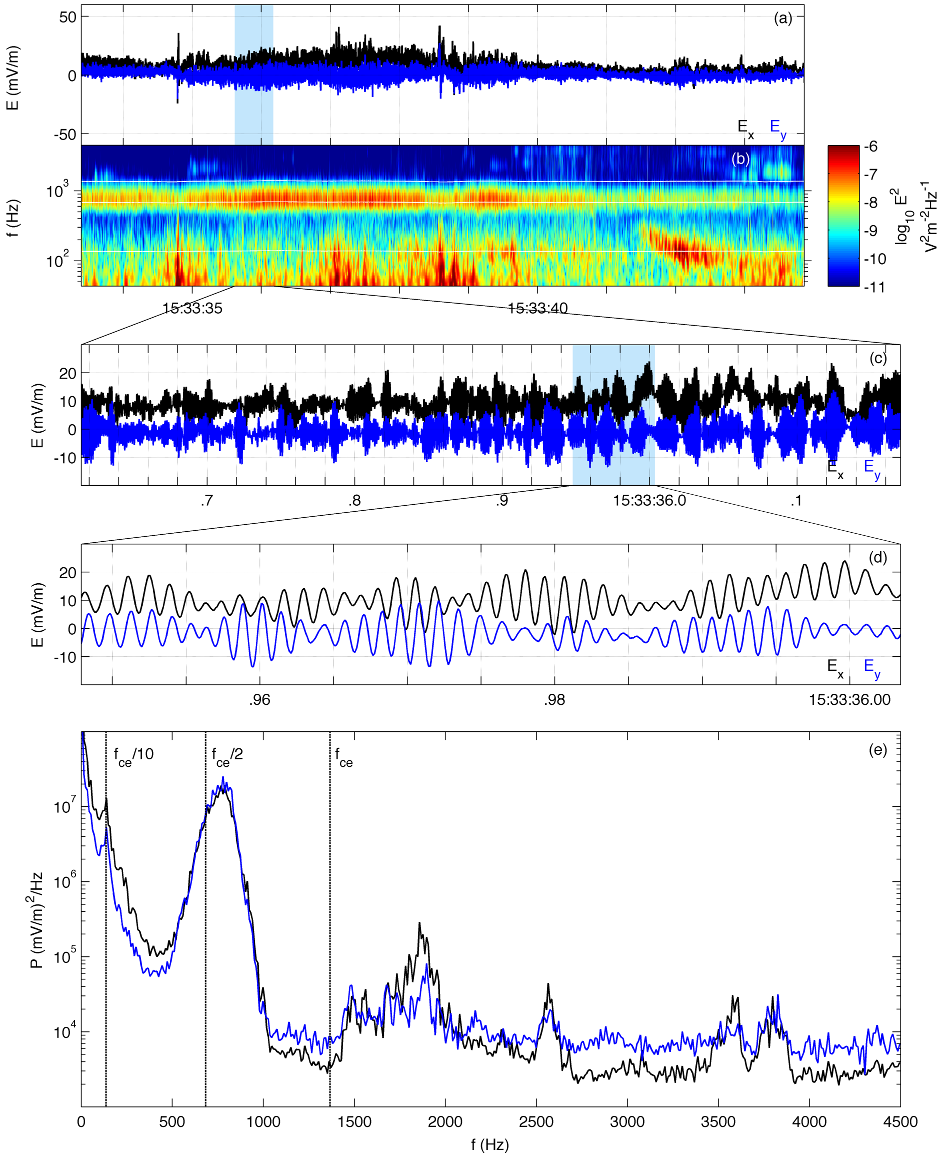
Whistler waves observed in the MS separatrix regions.

v_{ph} ~ 30,000 km/s.

Waves are right-hand circularly polarized.

Waves propagate antiparallel to **B**, toward X line.

Whistlers – blue interval



EFW's internal burst mode was activated, with 9000/s sampling rate.

Large-amplitude ~ 20 mV/m electric fields.

Whistlers have packet structure, which might be due to linear growth at a range of f and k.

Whistler generation

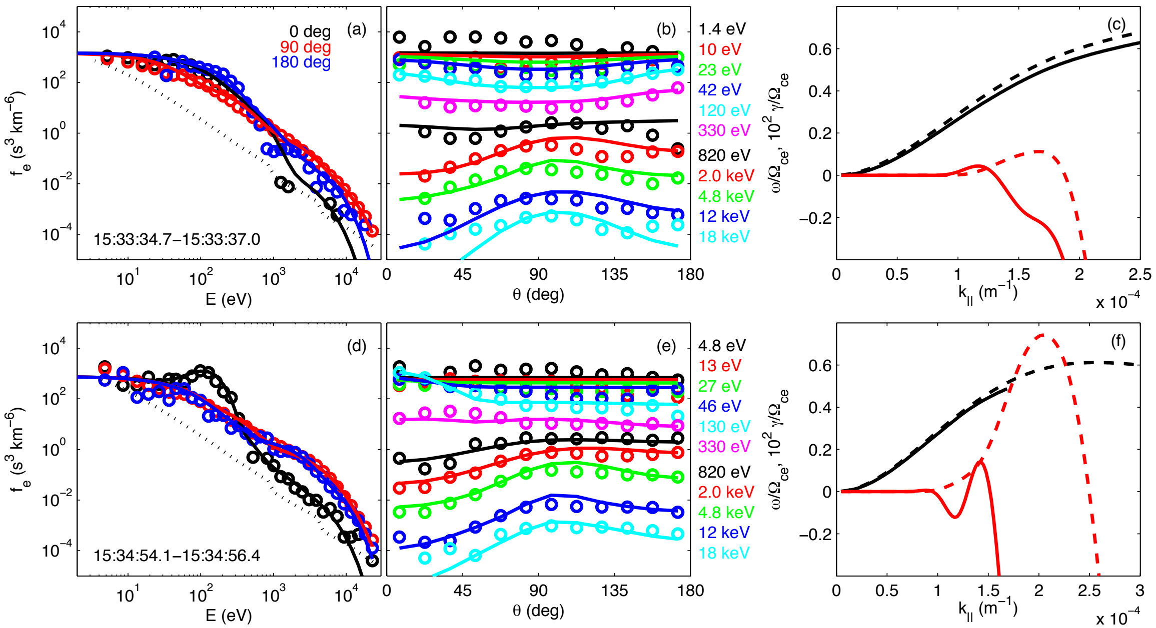
- $f_e(E)$ modeled using $f(v_\parallel, v_\perp) = \sum_j \frac{n_e^j}{(\sqrt{\pi} v_{th}^j)^3} \exp\left(-\left[\frac{v_\parallel - v_d^j}{v_{th}}\right]^2\right) \cdot \frac{T_\parallel^j}{T_\perp} \exp\left(-\left[\frac{v_\perp^2}{T_\perp / T_\parallel^j (v_{th}^j)^2}\right]\right)$
- Linear dispersion relations are found using WHAMP.
- Loss of MS electrons propagating away from the X line generates the observed whistler waves.

Blue Interval

Red Interval

o - data

Line - fits



Solid – Parallel to B (away from X line)

Dashed – Antiparallel to B (toward X line)

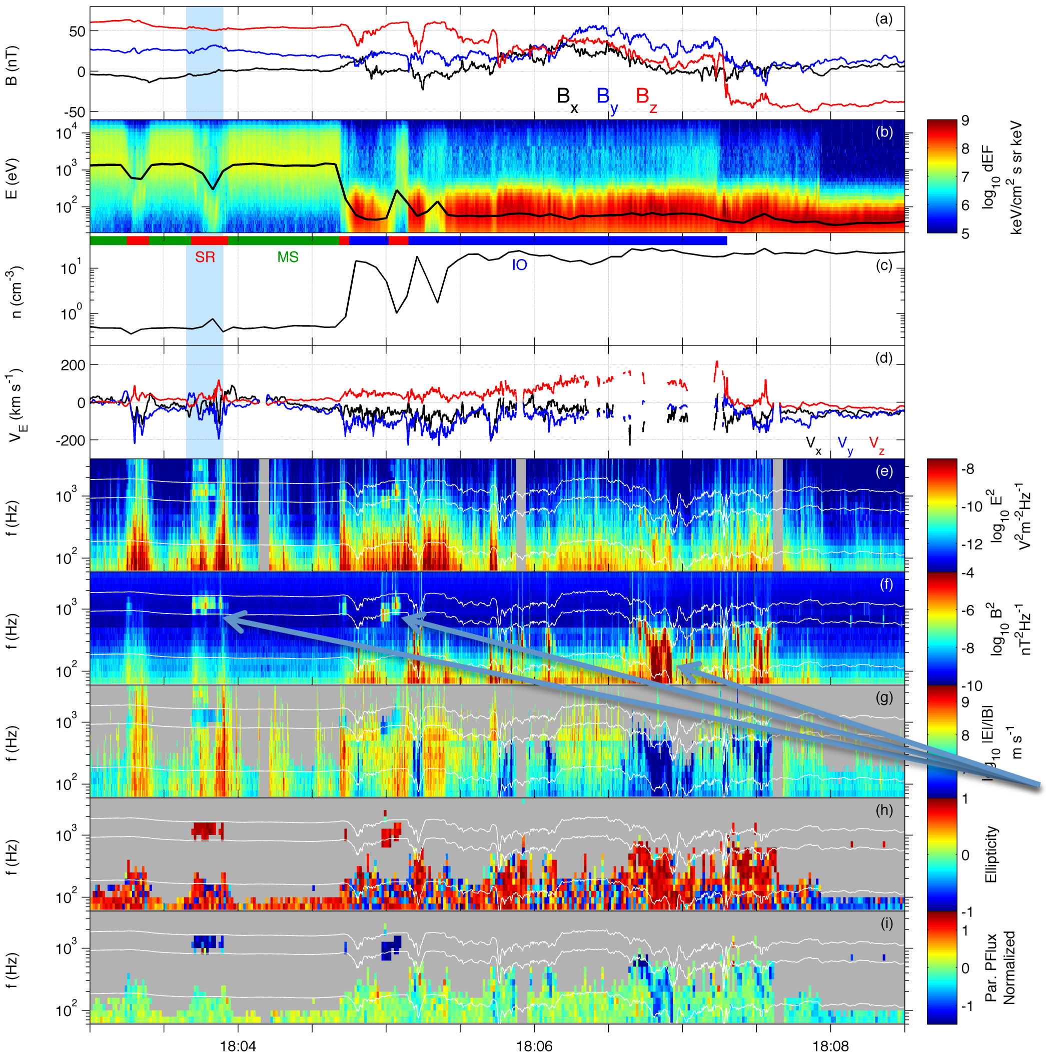
- Dispersion relation
- Growth rate

Growth rate is largest antiparallel to B, consistent with observations.

	Observed				Linear theory			
Event	f (Hz)	$k_\parallel$ (m^{-1})	$\lambda_\parallel$ (km)	v_{ph} ($km\,s^{-1}$)	f (Hz)	$k_\parallel$ (m^{-1})	$\lambda_\parallel$ (km)	v_{ph} ($km\,s^{-1}$)
17 April 2007 (blue)	775	1.1×10^{-4}	55	4.3×10^4	740	1.7×10^{-4}	37	2.7×10^4
17 April 2007 (red)	800	2.5×10^{-4}	25	2.0×10^4	750	2.0×10^{-4}	31	2.4×10^4

Excellent agreement between observations and linear theory.

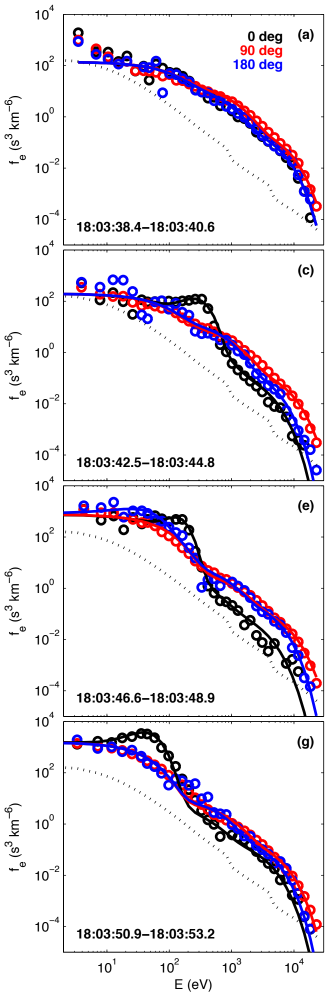
Whistler emission – 22 April 2008, C2



- Whistlers observed in separatrix regions, with $0.5f_{ce} < f < f_{ce}$.
- Whistler propagate toward X line.
- Qualitatively similar to 17 April 2007.

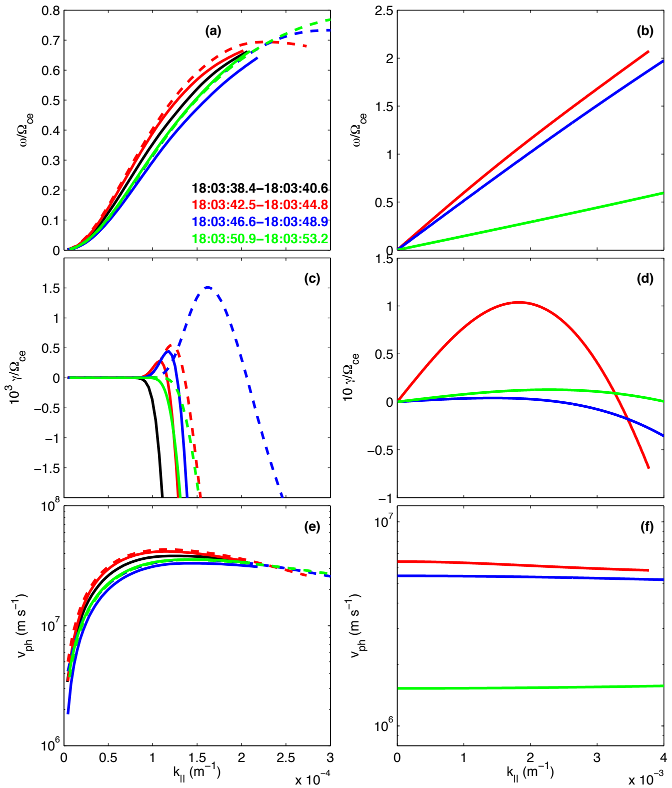
Whistler emission

Electron distributions and waves



Electron distributions from the blue shaded region.

Whistler | Beam mode



Solid – Parallel propagating (away from X line)
Dashed – Antiparallel propagating (toward X line)

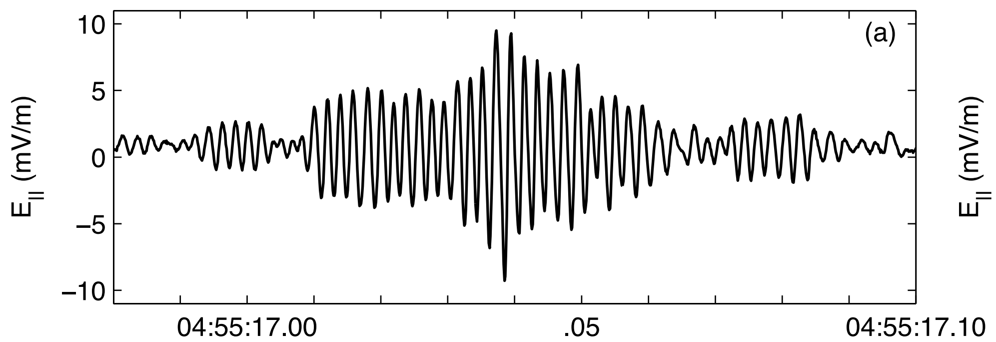
- Whistlers are generated by loss-cone distributions.
- Beam mode waves are produced by beams of magnetosheath electrons.
- Whistler and beam modes only cross near k=0 ➔ modes are independent of each other.

	Observed				Linear theory			
Event	$f(\mathrm{Hz})$	$k_{\parallel}(\mathrm{m}^{-1})$	$\lambda_{\parallel}(\mathrm{km})$	$v_{\mathrm{ph}}(\mathrm{km\,s}^{-1})$	$f(\mathrm{Hz})$	$k_{\parallel}(\mathrm{m}^{-1})$	$\lambda_{\parallel}(\mathrm{km})$	$v_{\mathrm{ph}}(\mathrm{km\,s}^{-1})$
22 April 2008 (blue)	1100	4.1×10^{-4}	15	1.7×10^{4}	920	1.6×10^{-4}	39	3.6×10^{4}

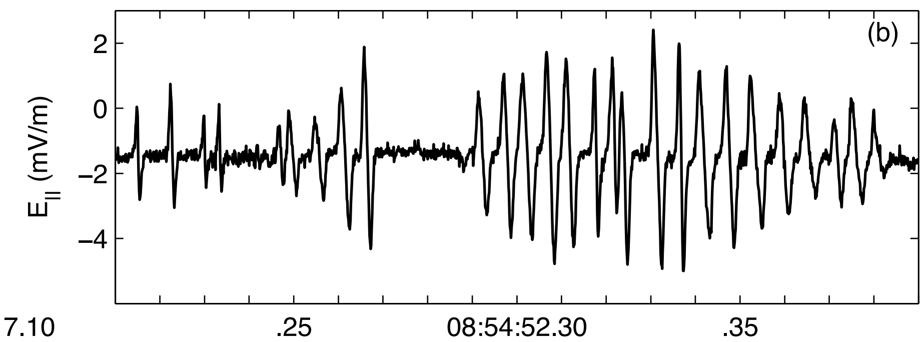
Electrostatic waves

- Electrostatic waves, in particular, electrostatic solitary waves (ESW) are associated with reconnection.
- They can couple different particle populations and can produce resistively.
- They can be produced by different instabilities: beam-plasma, Buneman, lower-hybrid, &c.

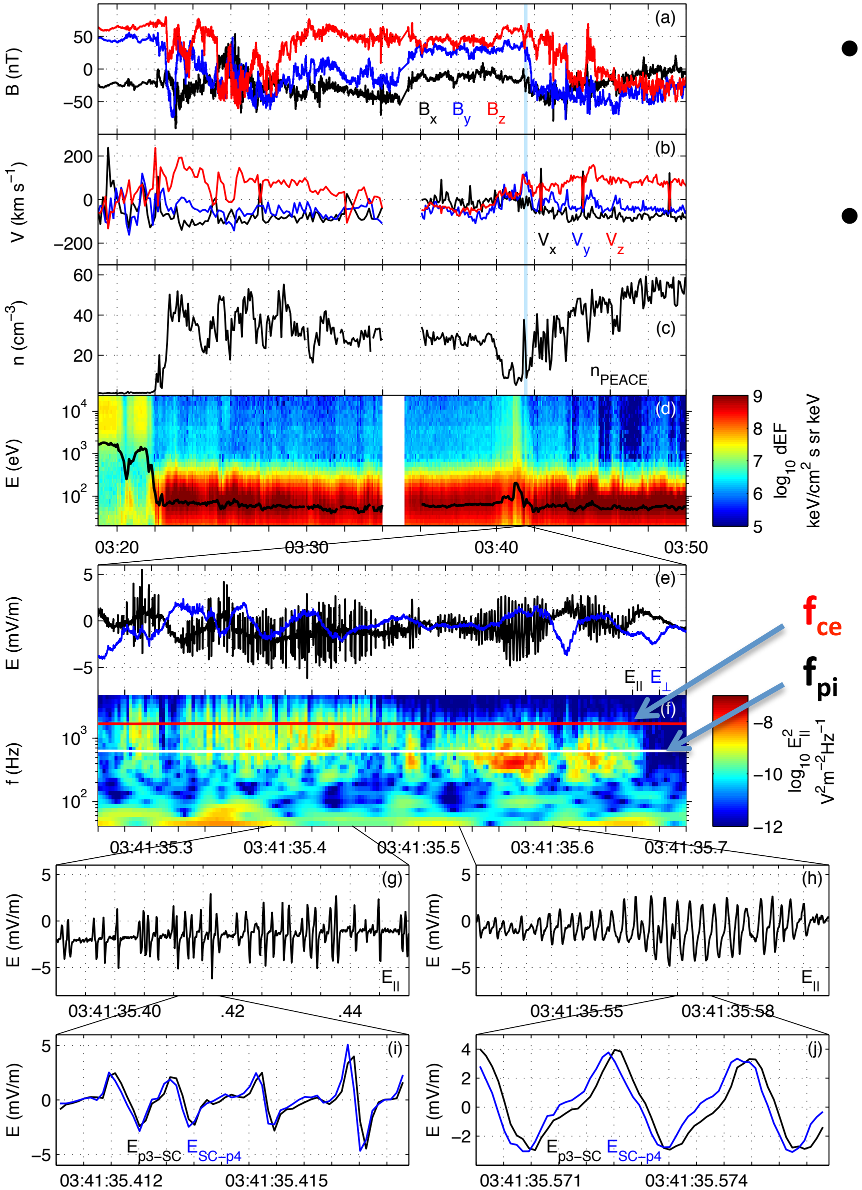
Electrostatic waves



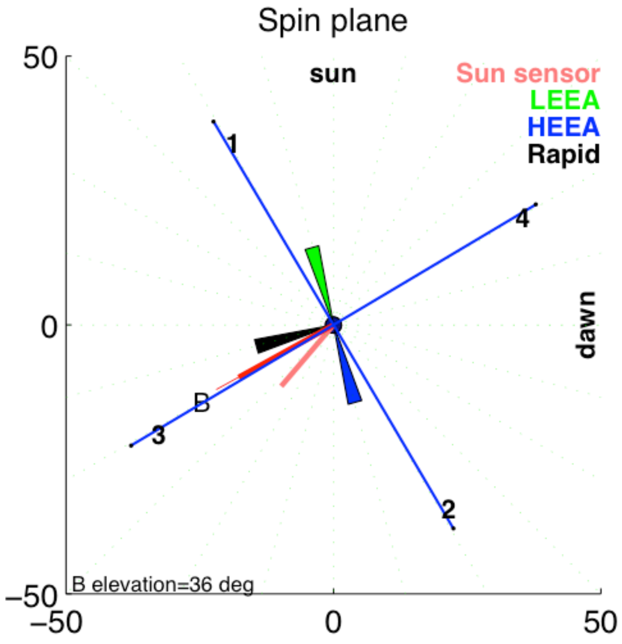
ESWs



ESWs - 28 April 2006, C4

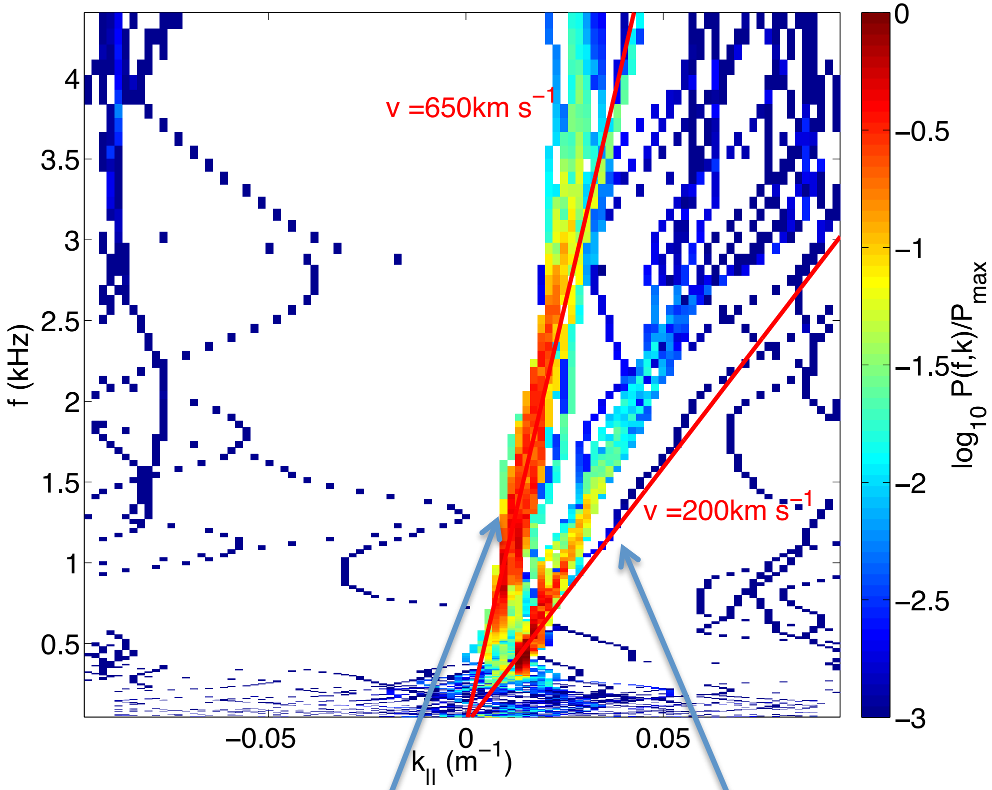


- ESW and ES wave speeds are observed near current sheet.
- Different time delays observed ➔ different speeds.



Probe orientation at the time the waves are observed.

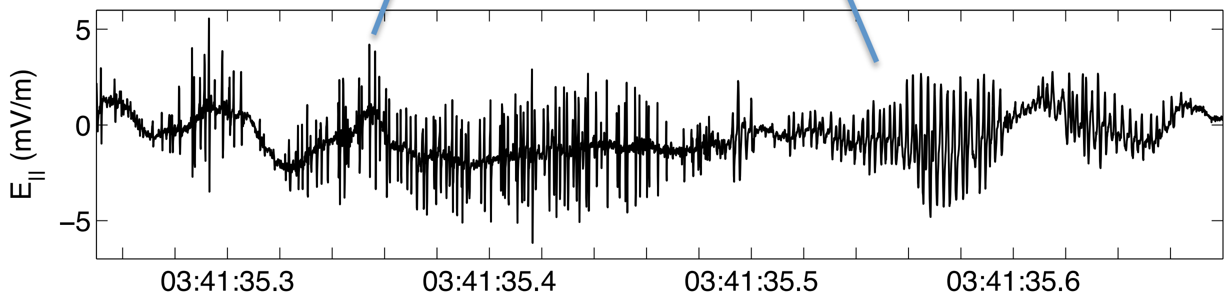
Wave properties



- Wave speeds are calculated using cross-spectral analysis.
- ESWs and ES waves have distinct dispersion relations.
- Speeds are distinct, but waves propagate in the same direction.

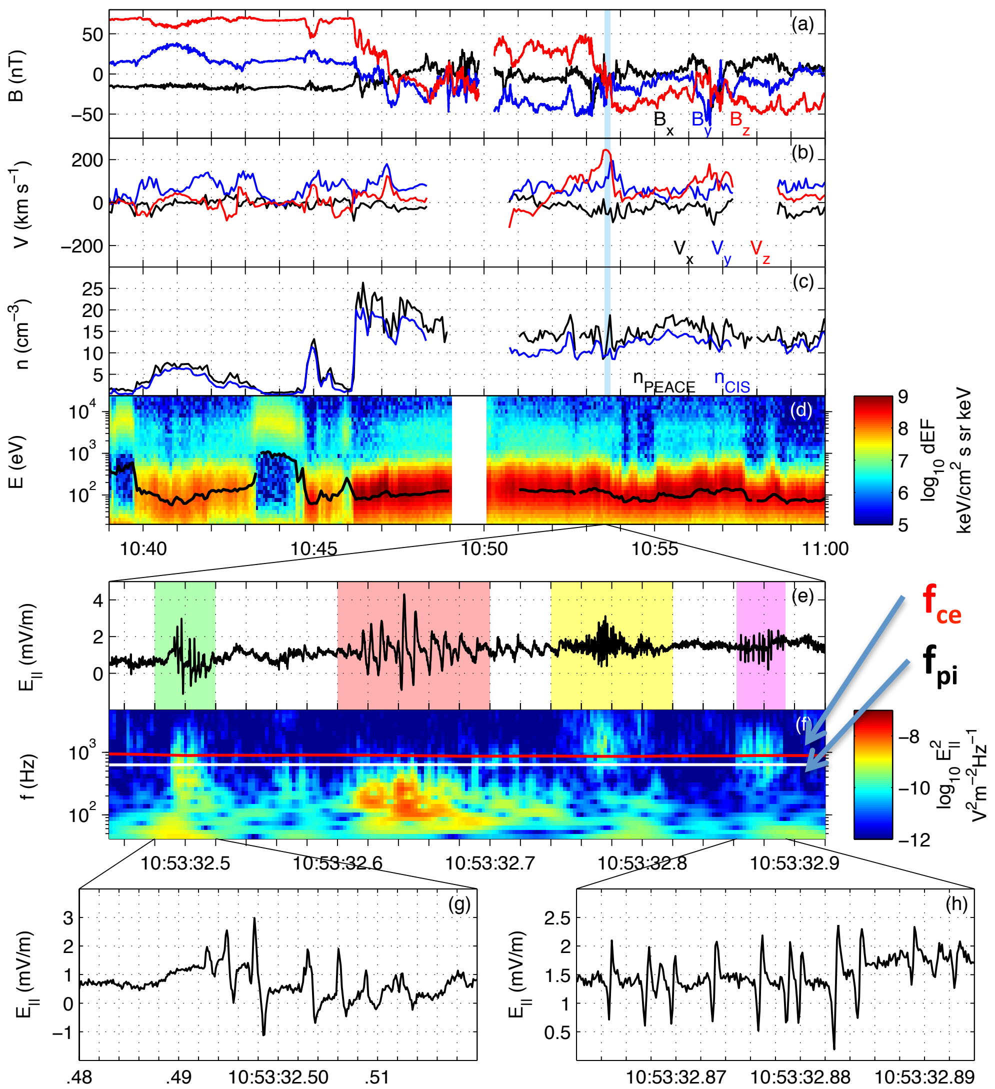
ESWs: v = 650 km/s, l_{pp} = 9 λ_D, ϕ = 0.7 V, v_T = 500 km/s.

ES waves: v = 200 km/s, $\lambda/2$ = 13 λ_D, ϕ = 0.3 V, v_T = 300 km/s.



ES waves can potentially couple electrons and ions.

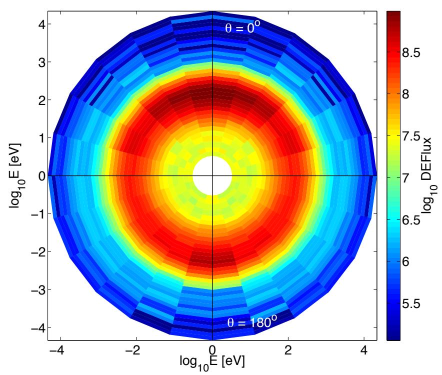
ESWs - 20 March 2008, C4



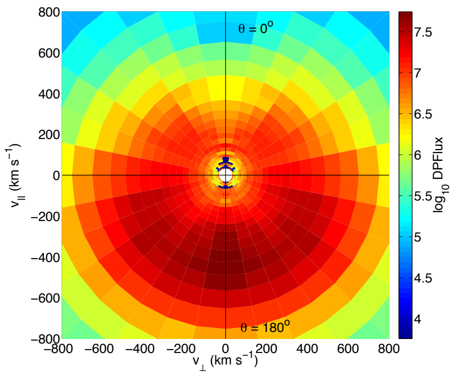
- ESWs and ES waves are observed near a current sheet associated with reconnection.
- Waves have distinct time scales.

[Graham et al., GRL, 2015]

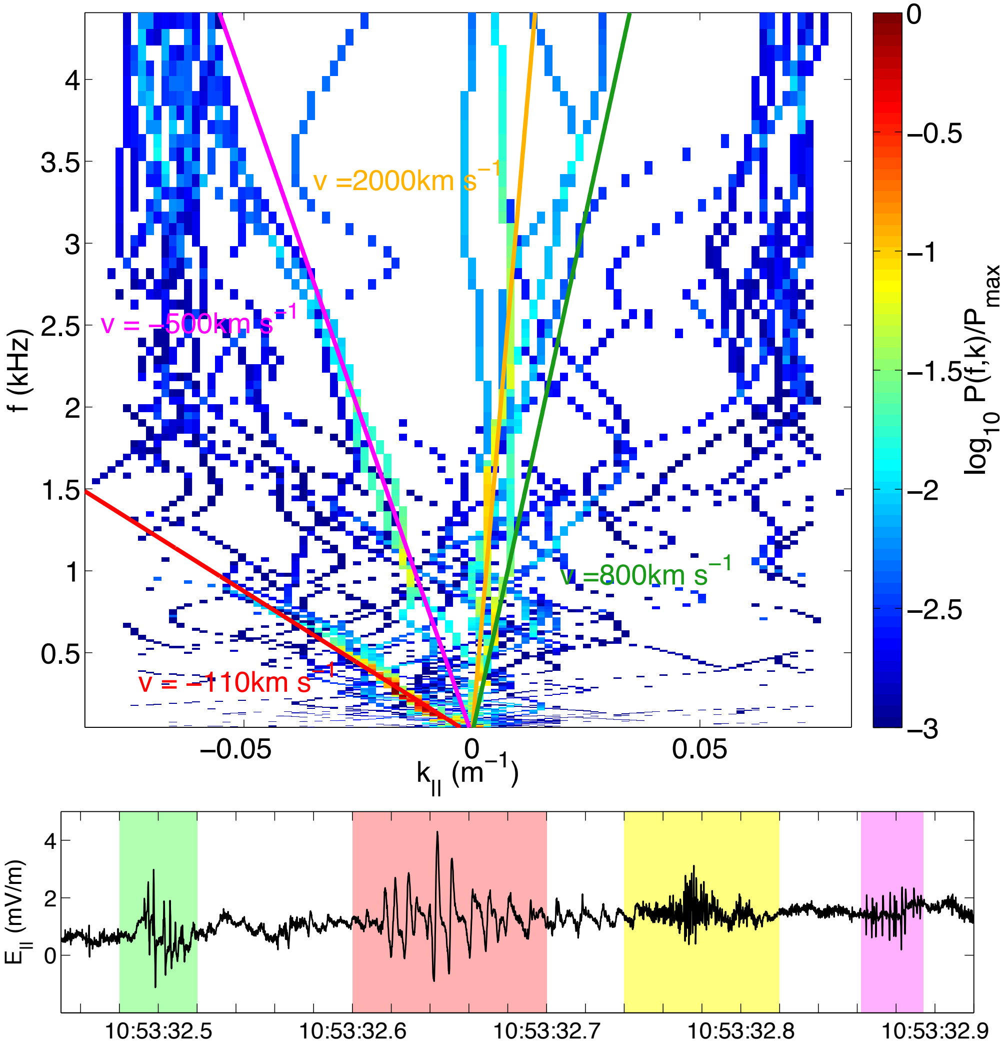
Electrons



Ions



Wave properties



[Graham et al., GRL, 2015]

- Four distinct dispersion relations are found.
- Waves have distinct speeds and propagation directions.
- Suggests dissipation occurs over a wide range of particle energies.

ESWs: v = 800 km/s, l_{pp} = 24 λ_D, ϕ = 1 V, v_T = 600 km/s.

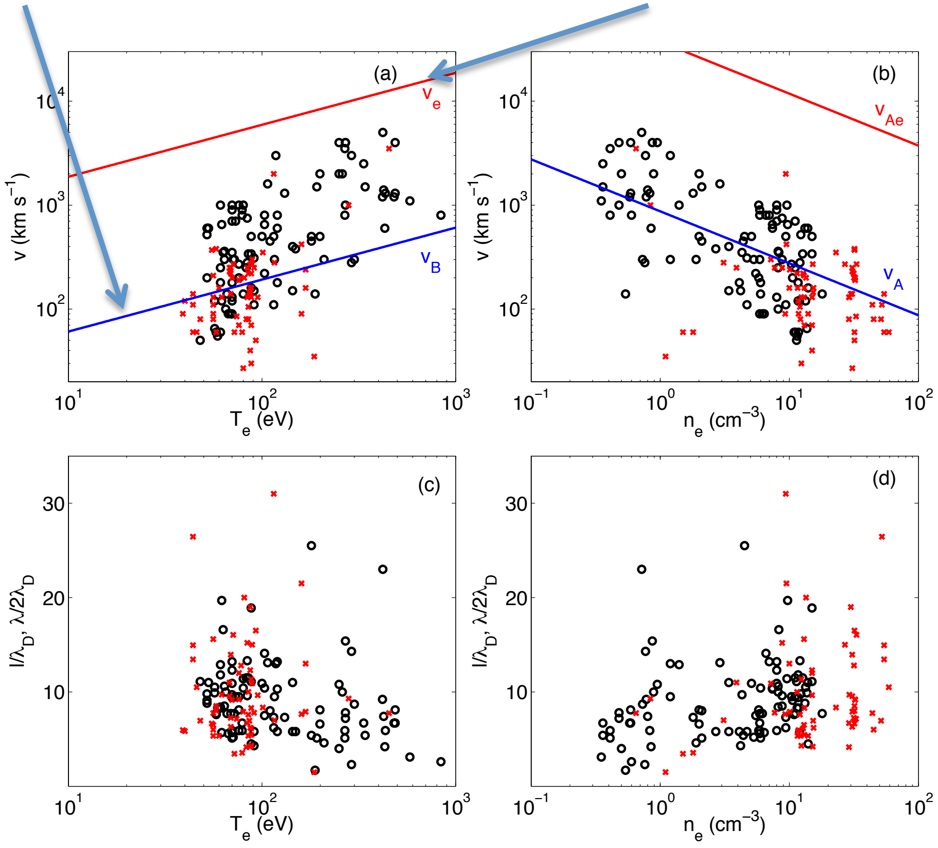
ESWs: v = -110 km/s, l_{pp} = 7.3 λ_D, ϕ = 0.4 V, v_T = 380 km/s.

Electrostatic waves: v = 2000 km/s, $\lambda/2$ ~ 30 λ_D, ϕ = 0.3 V.

ESWs: v = -500 km/s, l_{pp} = 6.2 λ_D, ϕ = 0.14 V, v_T = 220 km/s.

Statistics of ESWs

Approximate Buneman speed   Electron thermal speed



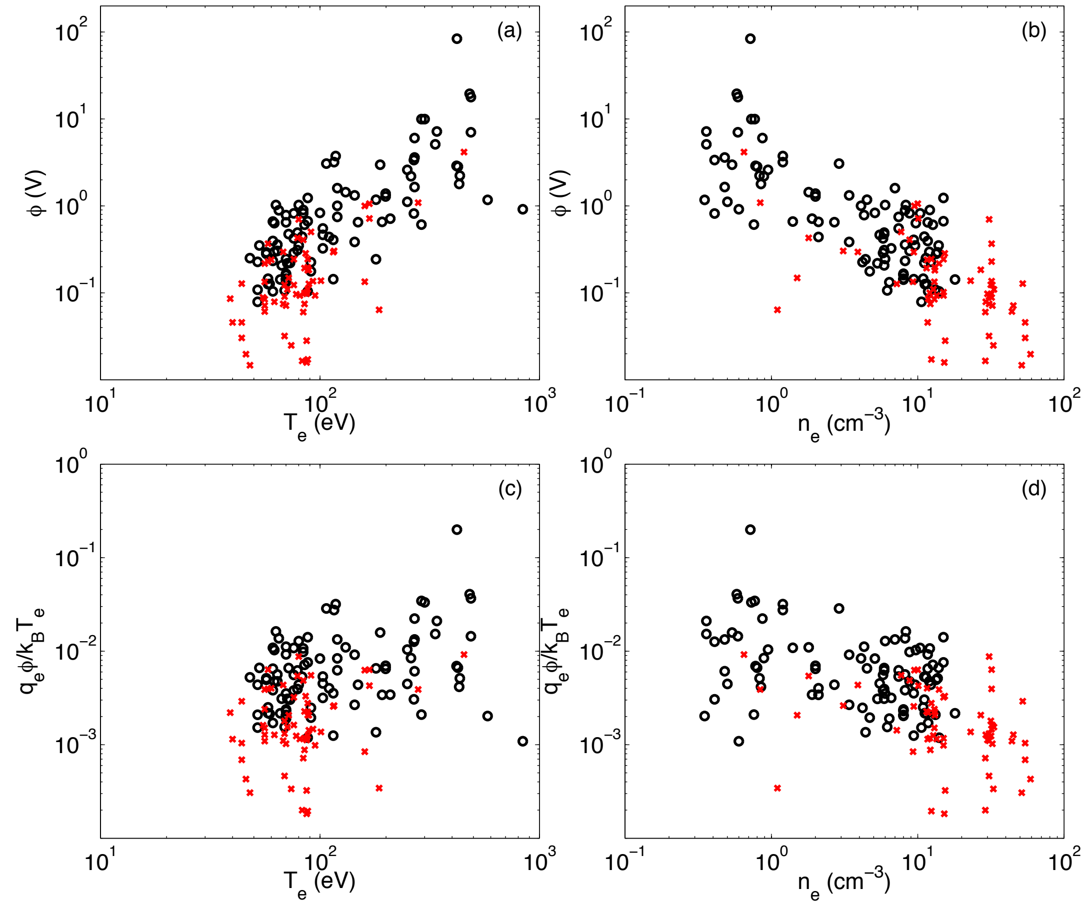
ESWs, electrostatic waves

- Large range of wave speeds observed.
- Length scales depend weakly on plasma conditions.
- Average peak-to-peak length scale = 9 λ_D.

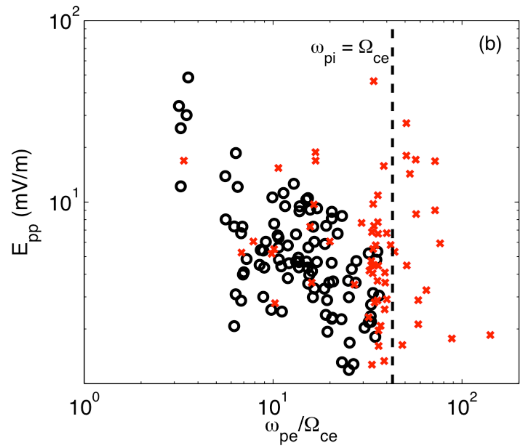
[Graham et al., JGR, 2015, submitted]

Wave amplitudes and potentials

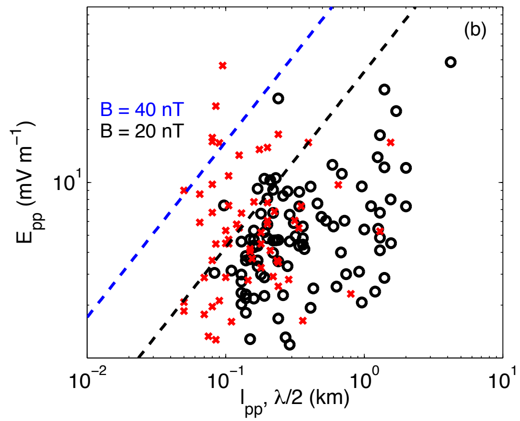
Potentials versus n_e and T_e.



ESWs, electrostatic waves



- ESW fields decrease as plasma become more weakly magnetized.



- ESWs must satisfy: $\omega_b < \Omega_{ce}$

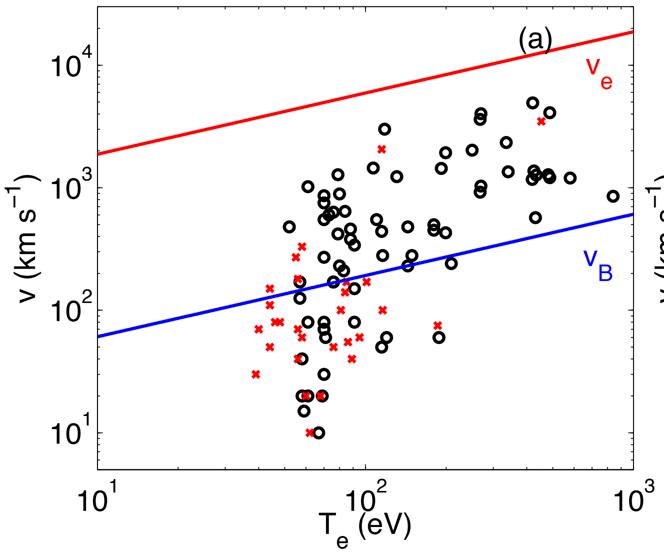
  or equivalently: $E_{pp} \lesssim \frac{e^{1/2} q_e B^2 l_{pp}}{m_e}$

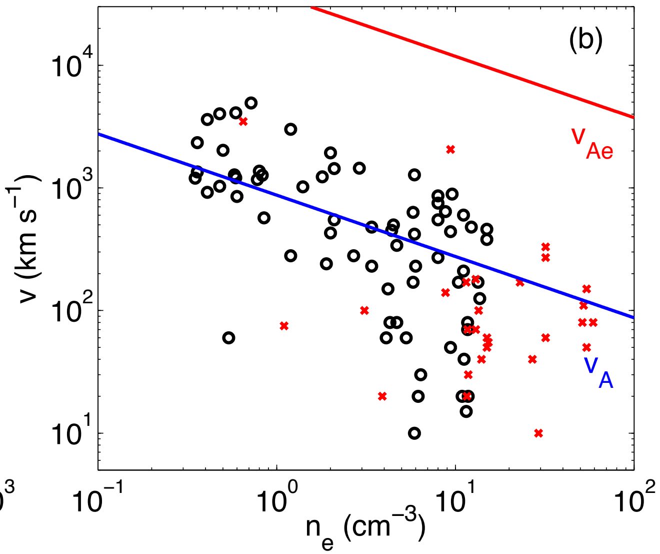
  [see Muschietti et al., 2000]

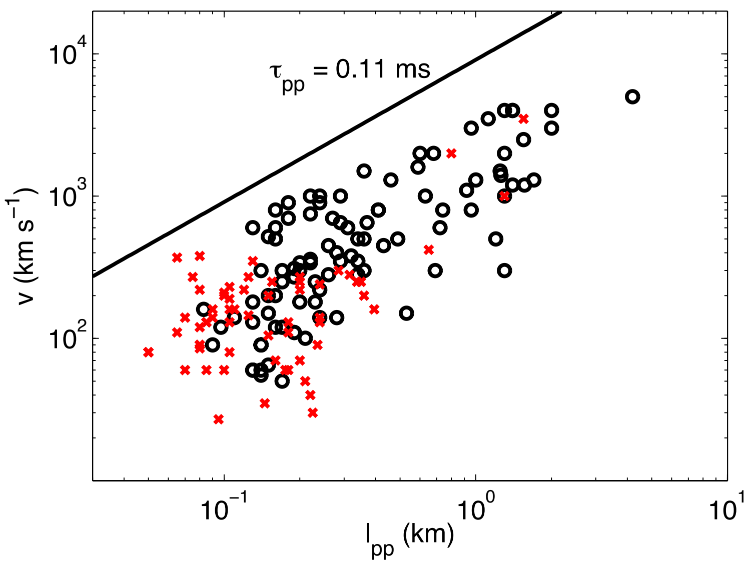
Conclusions

- Whistler emission is observed in the separatrix regions of reconnection. Produced by loss-cone distributions and propagate toward the X-line.
- ESWs and ES waves are observed in the separatrix regions, near the outflows, of reconnection.
- ESWs are observed with distinct speeds. Dissipation, heating, and scattering can occur over a wide range of particle energies.

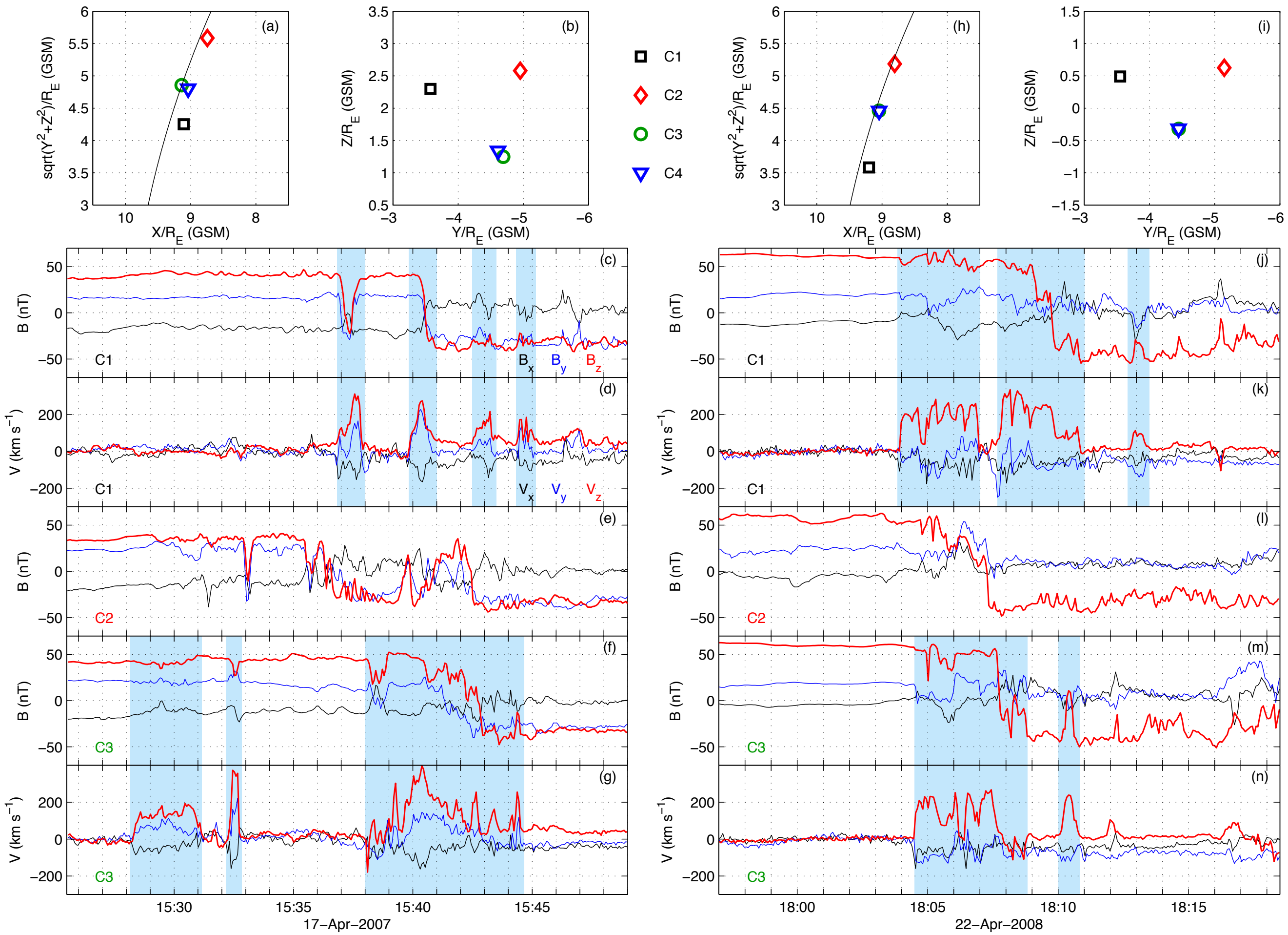
ESWs again


(a)
v_e
v_B
10^4
10^3
10^2
10^1
v (km s^{-1})
10^1
10^2
10^3
T_e (eV)

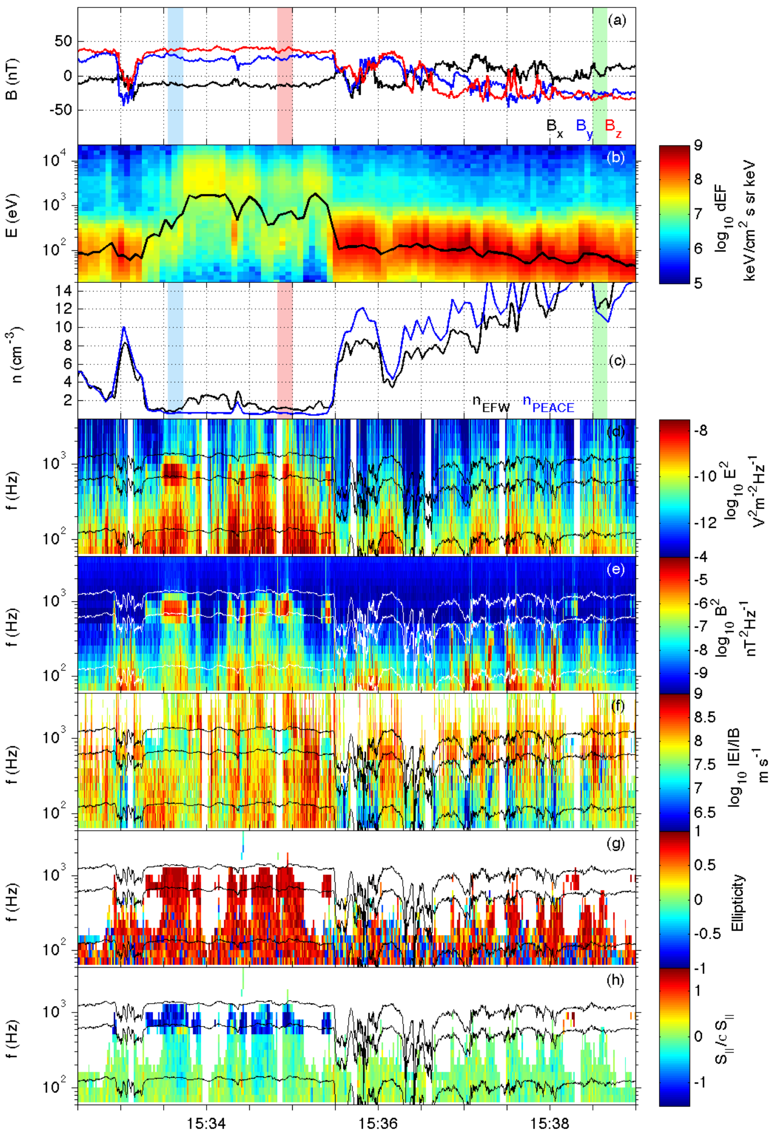

(b)
v_{Ae}
v_A
10^4
10^3
10^2
10^1
v (km s^{-1})
10^{-1}
10^0
10^1
10^2
n_e (cm^{-3})


τ_{pp} = 0.11 ms
10^4
10^3
10^2
v (km s^{-1})
10^{-1}
10^0
10^1
l_{pp} (km)

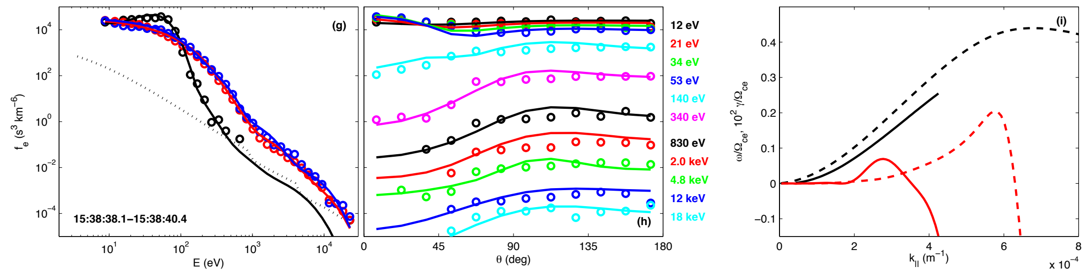
Outflows for whistler events



SH separatrix whistlers



SH separatrix distribution and associated whistler waves (green shaded region).



	Observed				Linear theory			
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17 April 2007 (red)	800	2.5×10^{-4}	25	2.0×10^{4}	750	2.0×10^{-4}	31	2.4×10^{4}
17 April 2007 (green)	350	4.3×10^{-4}	15	5.1×10^{3}	470	5.7×10^{-4}	11	5.2×10^{3}