Lower hybrid waves at magnetic reconnection sites

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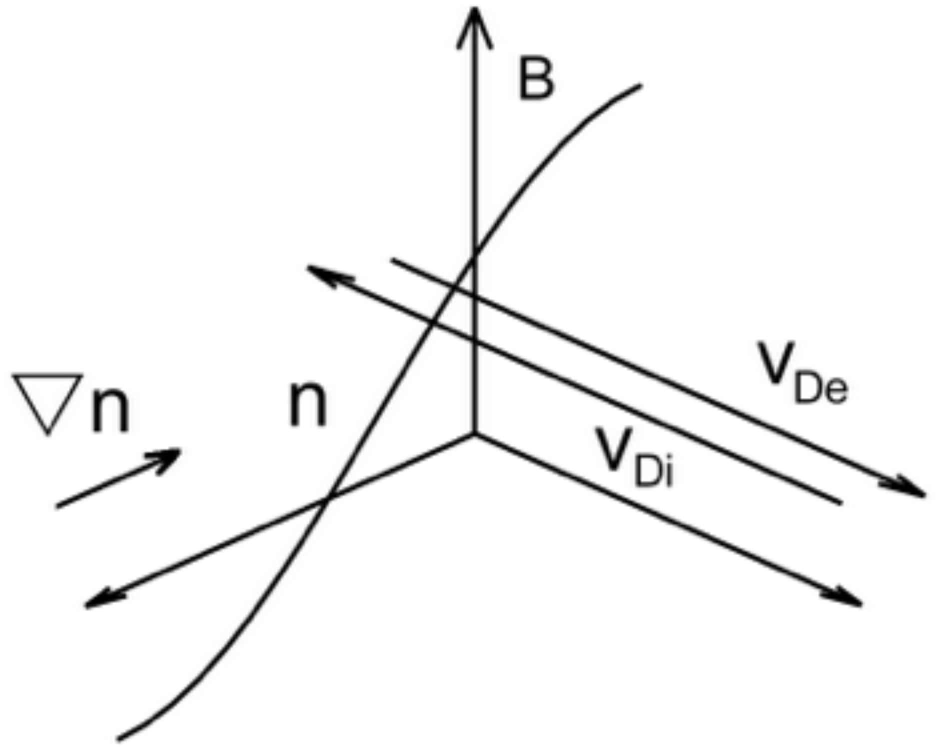
Lower hybrid waves

Lower hybrid waves are commonly excited at sharp boundaries where gradients in the density and magnetic fields are large.



$$k \cdot B = 0 \qquad k \cdot \nabla n = 0$$

$$k\rho_e \sim 1 \qquad \omega \sim \omega_{LH} \approx \sqrt{\omega_{ce}\omega_{ci}}$$

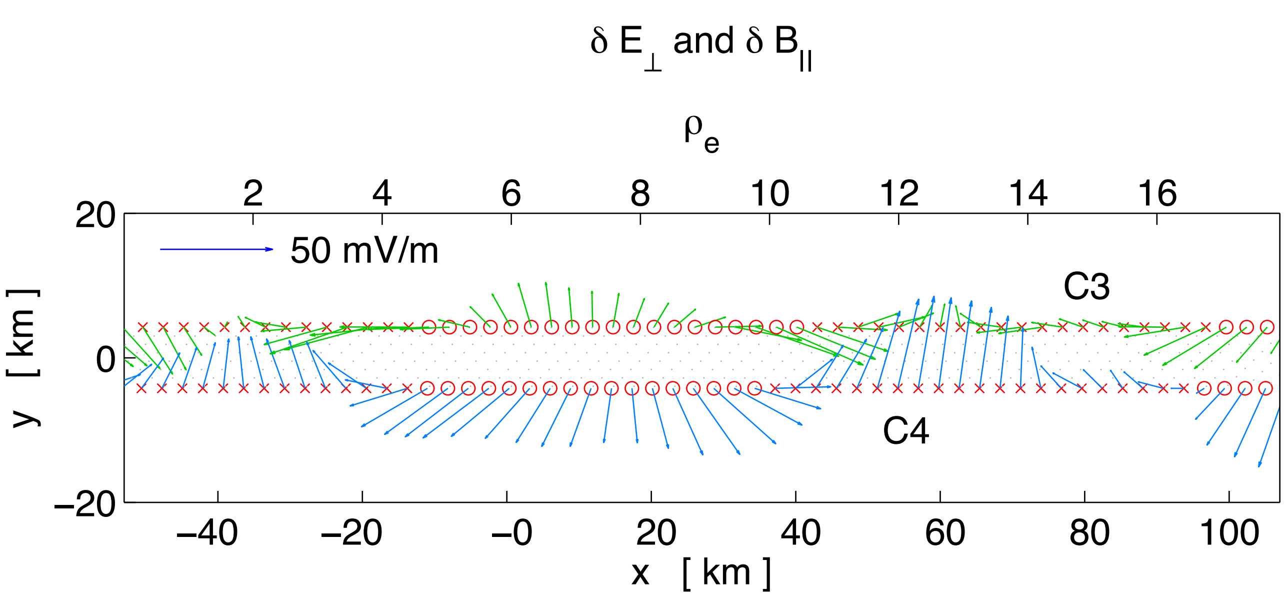
$$k\sqrt{\rho_e\rho_i} \sim 1$$

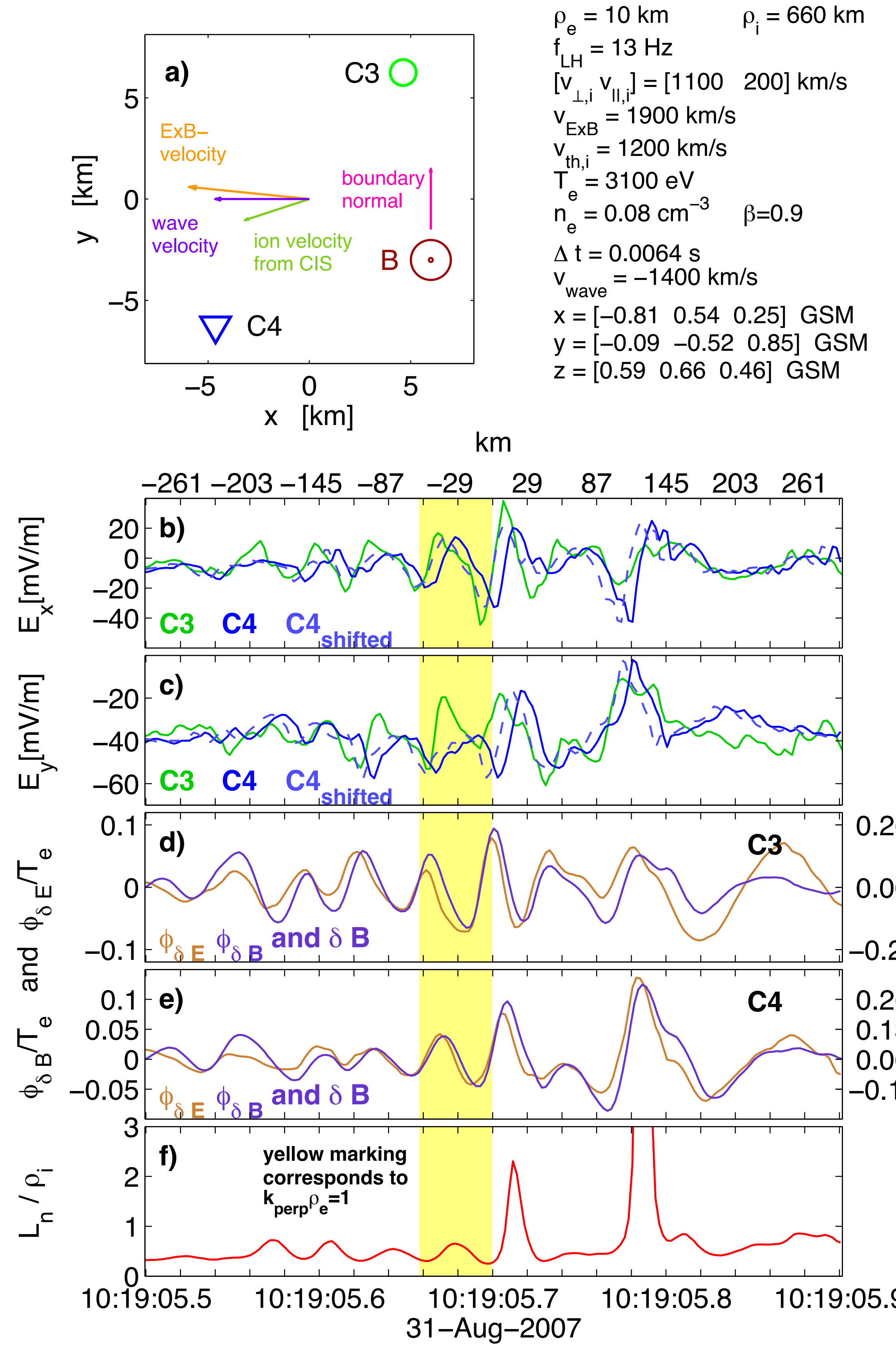
Lower hybrid waves

- Electrostatic mode located on edge of current layer/separatrix $k\rho_e \sim 1$
- Electromagnetic mode can penetrate deeper into the current sheet $k\sqrt{\rho_e \rho_i} \sim 1$
    - Change current sheet structure?

2 spacecraft

- Magnetotail crossing
  [-14 -4 2] R_E (GSM)
- Cluster is in burst mode
  (f_s=450 Hz for E and B)
- Wave at lower hybrid frequency located at strong gradient in density
- We find $\nabla n / |\nabla n|$ by minimum variance analysis





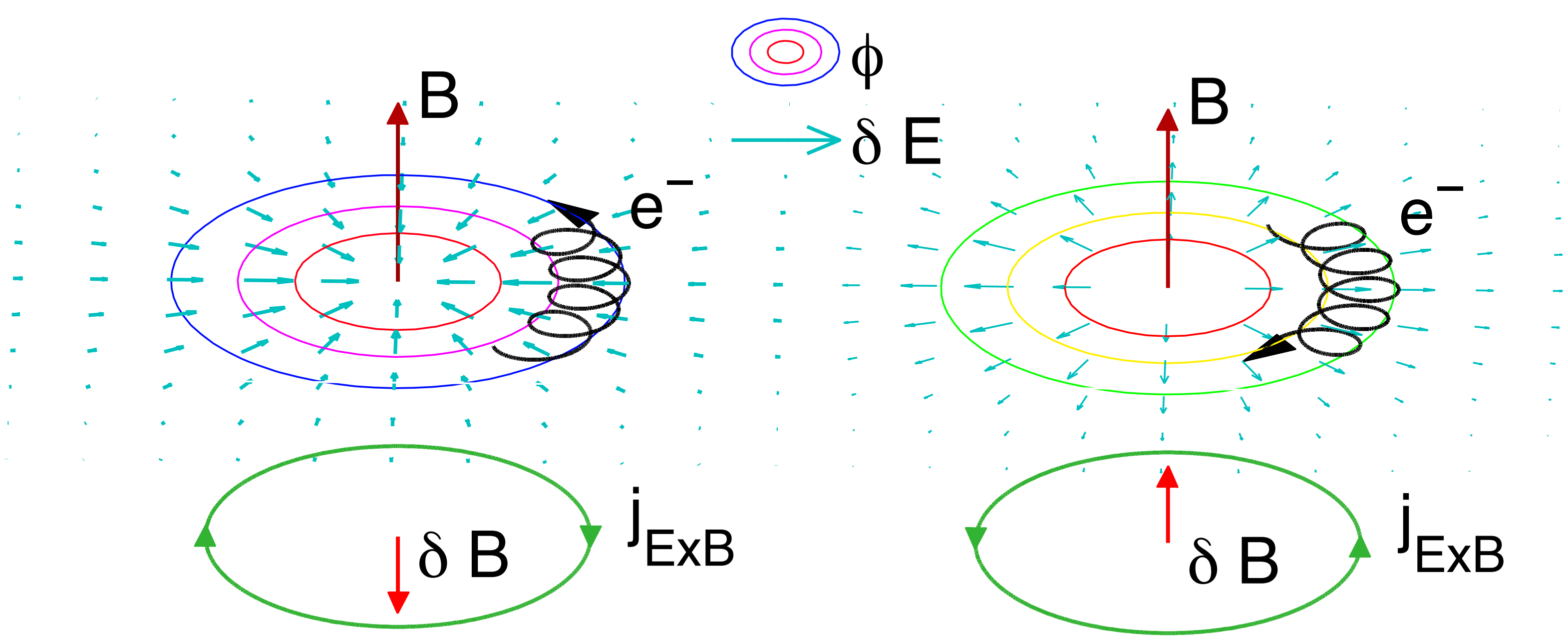
Norgren et al. 2012

Correlation of dE and dB

$$f_{ce} < f_{LH} \ll f_{ci} \qquad \lambda \sim 2\pi\rho_e$$

Electrons unmagnetized / Ions magnetized

$$\delta j_e = -ne\frac{\delta E \times B}{B^2}$$



Neglect displacement current and derivatives along the background magnetic field

$$\phi_{\delta B} = \frac{B}{\mu_0 ne}\delta B$$

The parallel magnetic wave field is proportional to the electrostatic potential!

From 2 to 1 spacecraft

Usual way to calculate potential

$$\phi_{\delta E} = \int \delta\vec{E} \cdot \vec{v}_{ph} dt$$

Another way using completely independent measurements

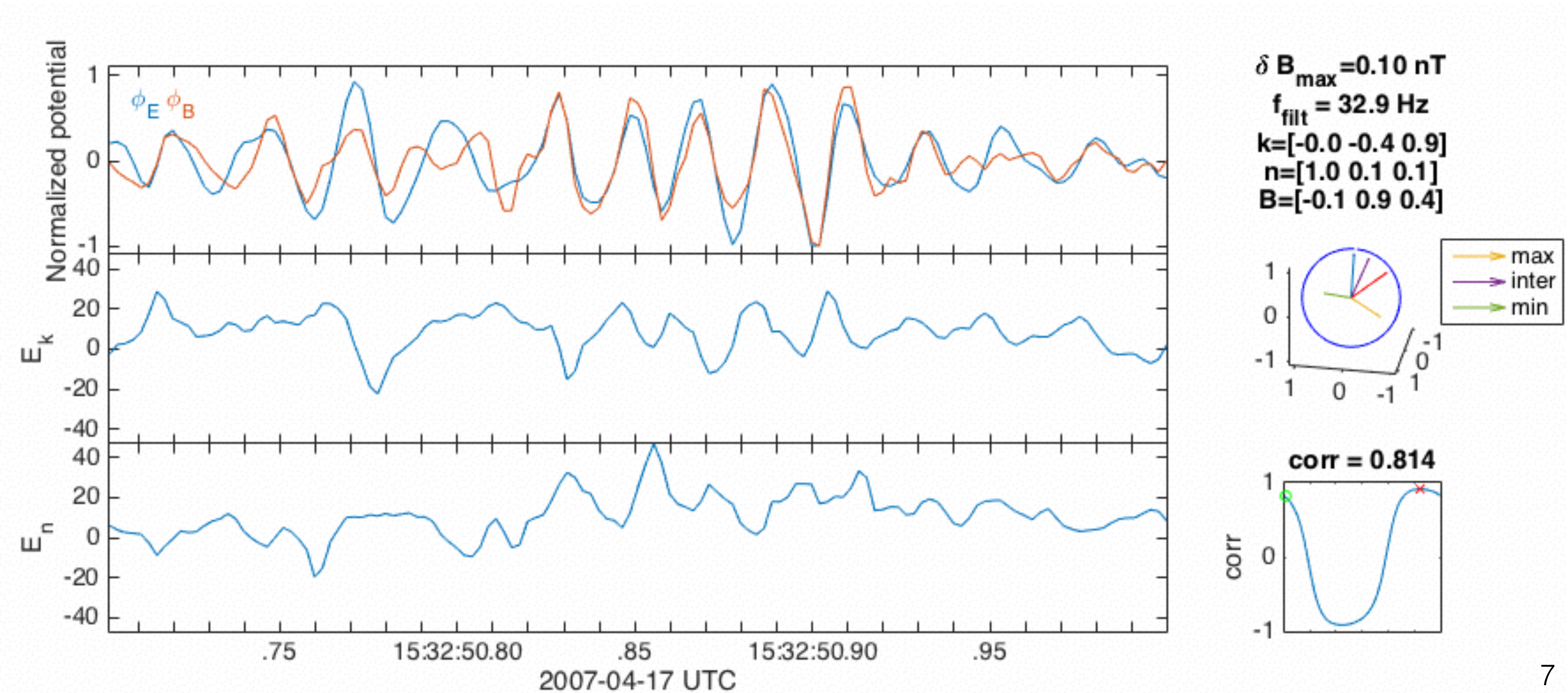
$$\phi_{\delta B} = \frac{B}{\mu_0 n e} \delta B_{||}$$

We need to find $\vec{v}_{ph}$ such that $\int \delta\vec{E} \cdot \vec{v}_{ph} dt = \frac{B}{\mu_0 n e} \delta B_{||}$

Example: Find propagation direction

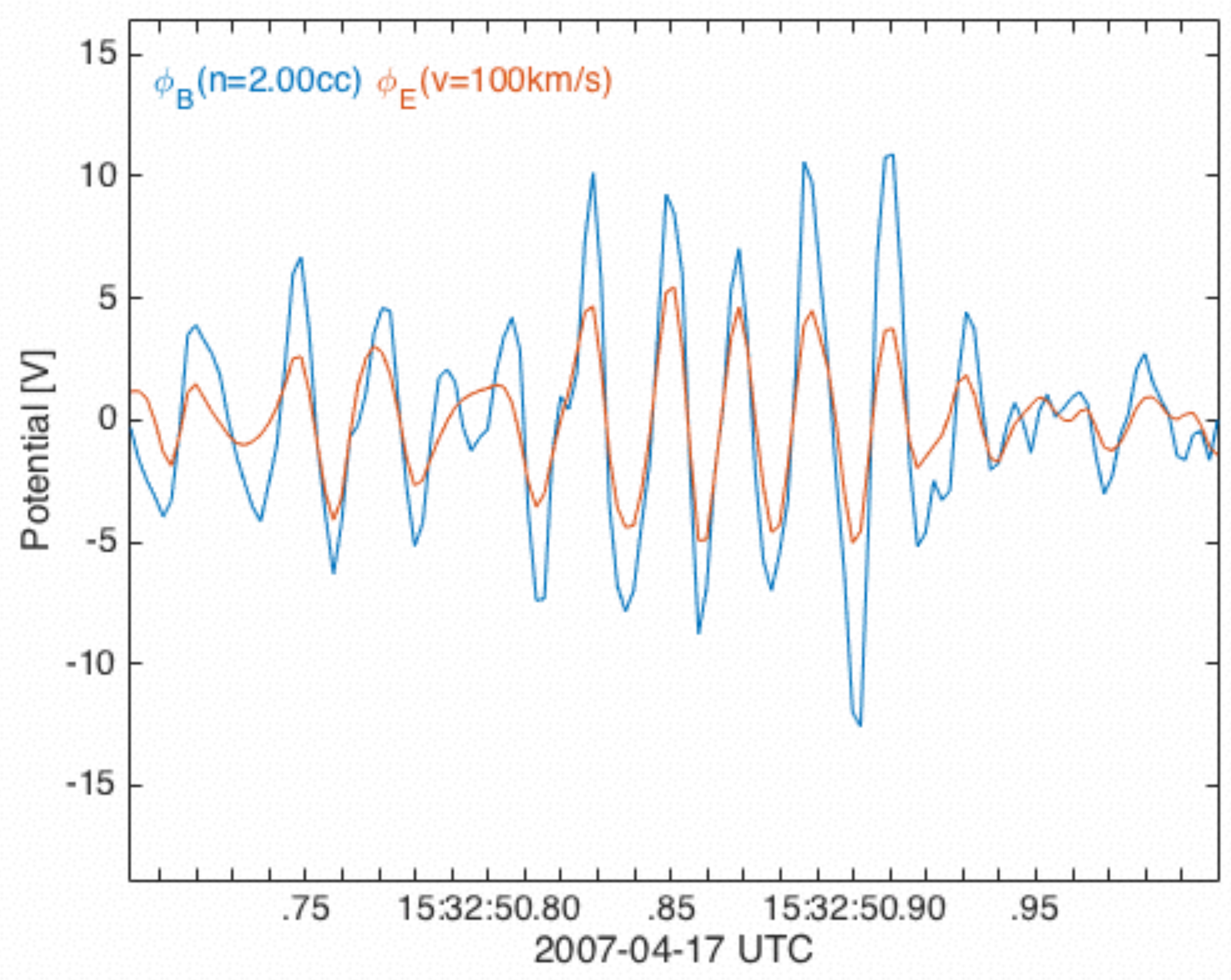
$\phi_{\delta E_\perp}$ is integrated in several different directions perpendicular to B

— shows the direction of maximum correlation

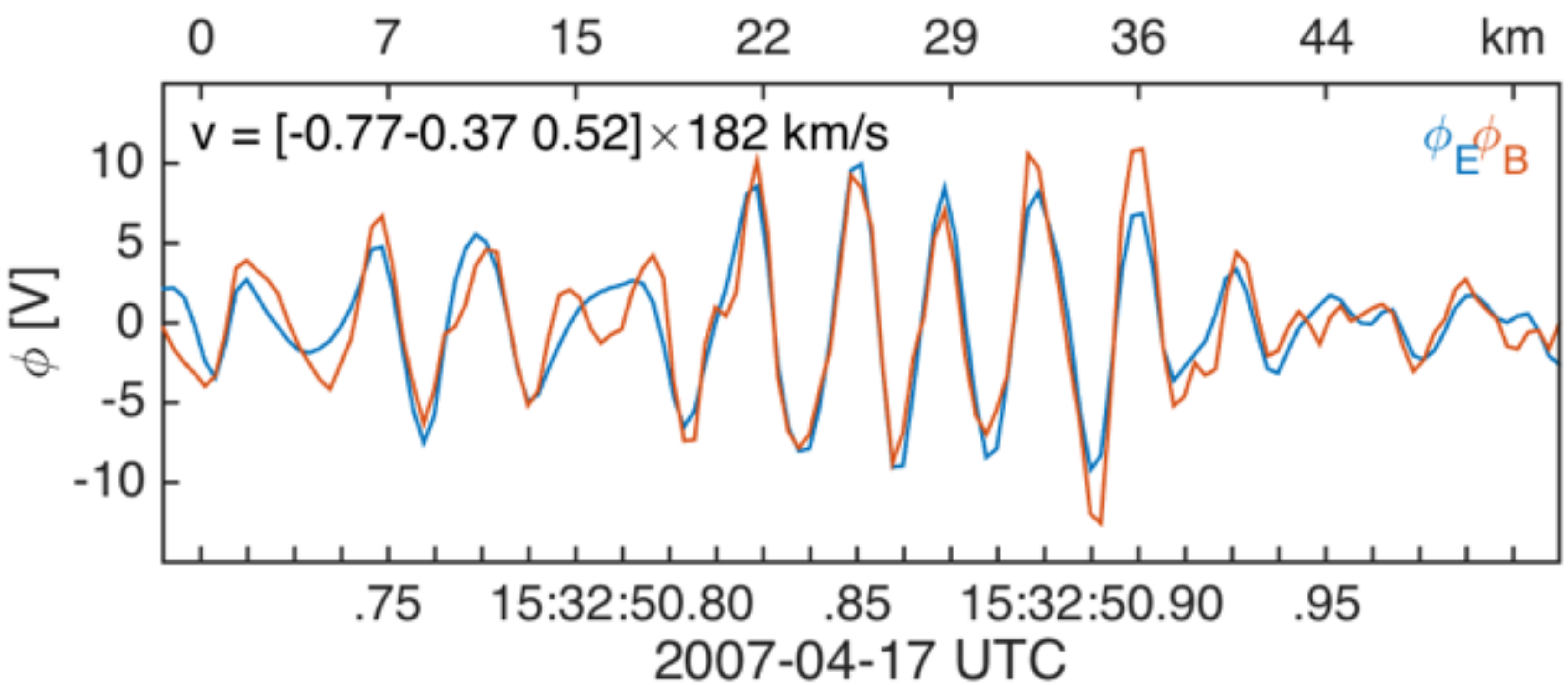


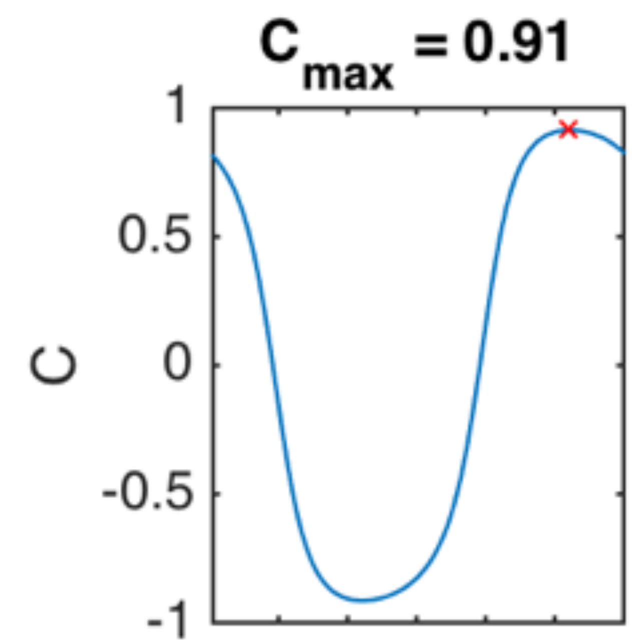
Example: Find propagation speed

We minimize the area between the two waveforms to find the speed.



Example: Results f_{filt}=33 Hz

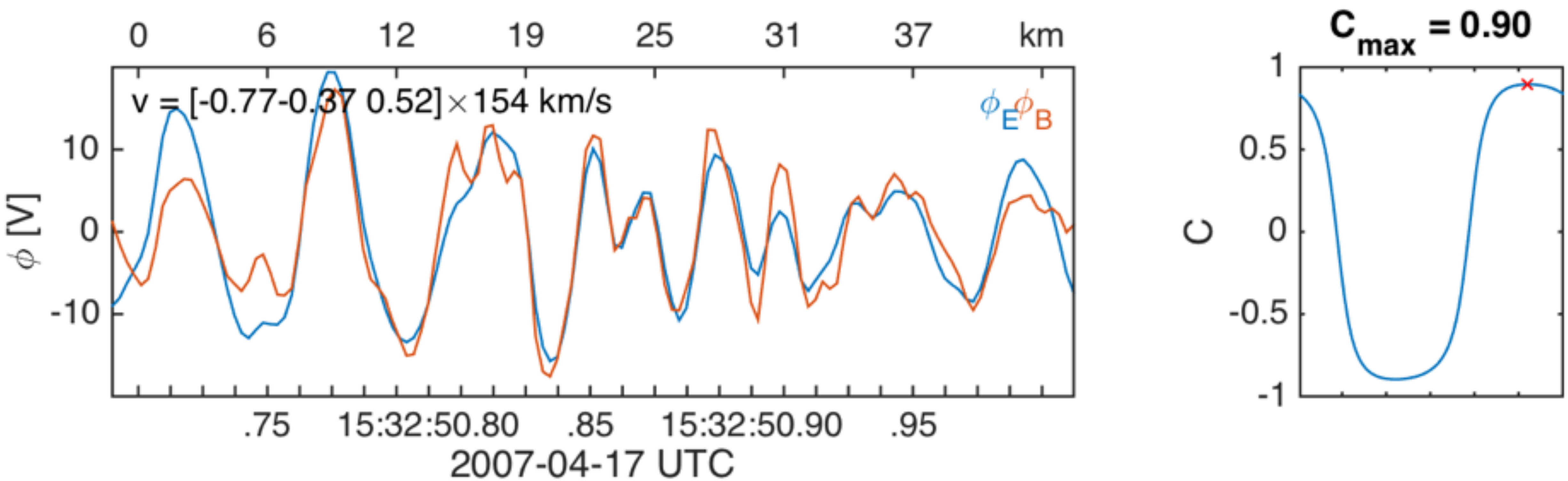




$$k\rho_e \sim 1 \quad \rho_e = 0.5\text{km} \Longrightarrow \lambda = 2\pi\rho_e \sim 3\text{km}$$

We can see small scale structure and motion of electric field!

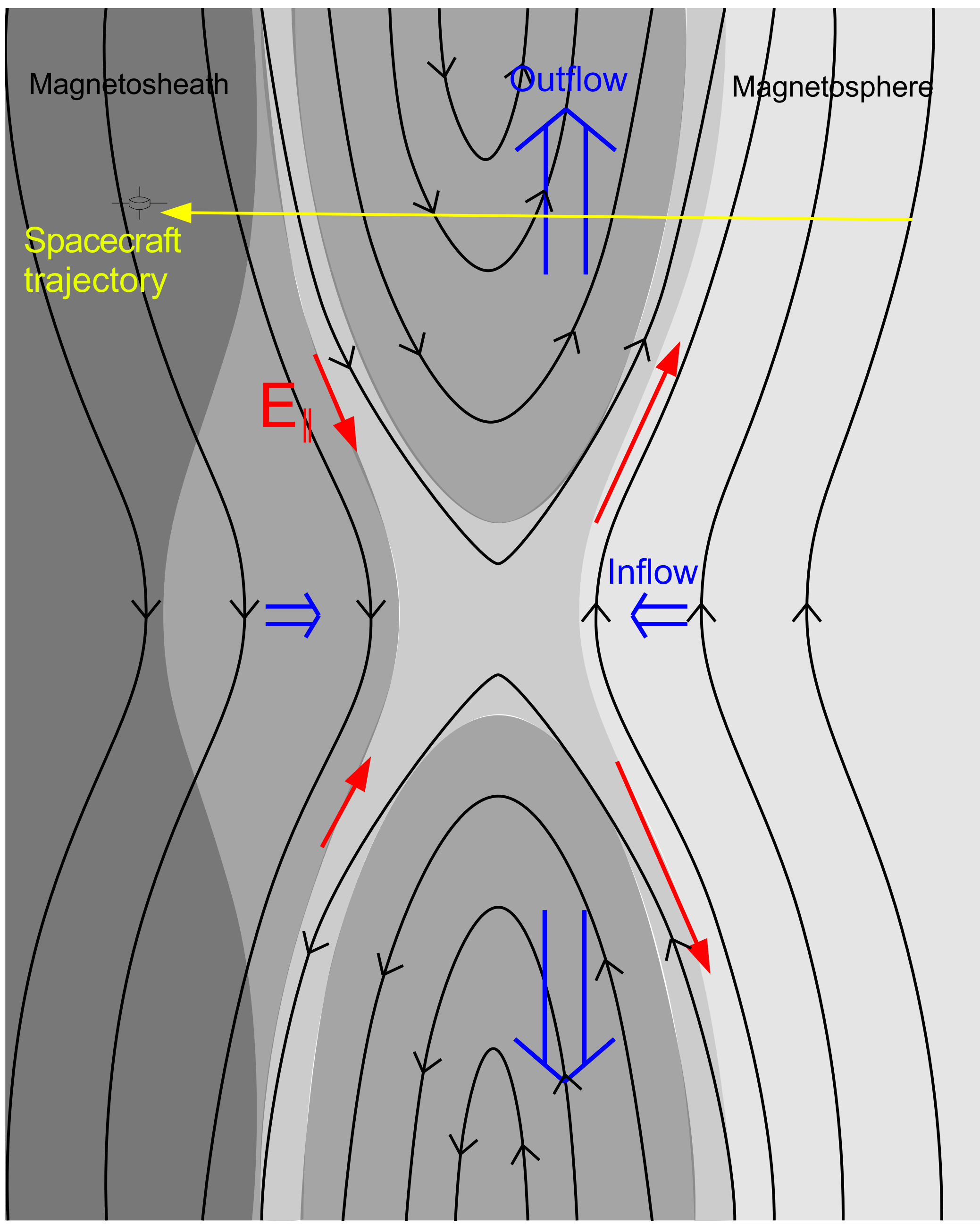
Example: Results f_{filt}=16 Hz



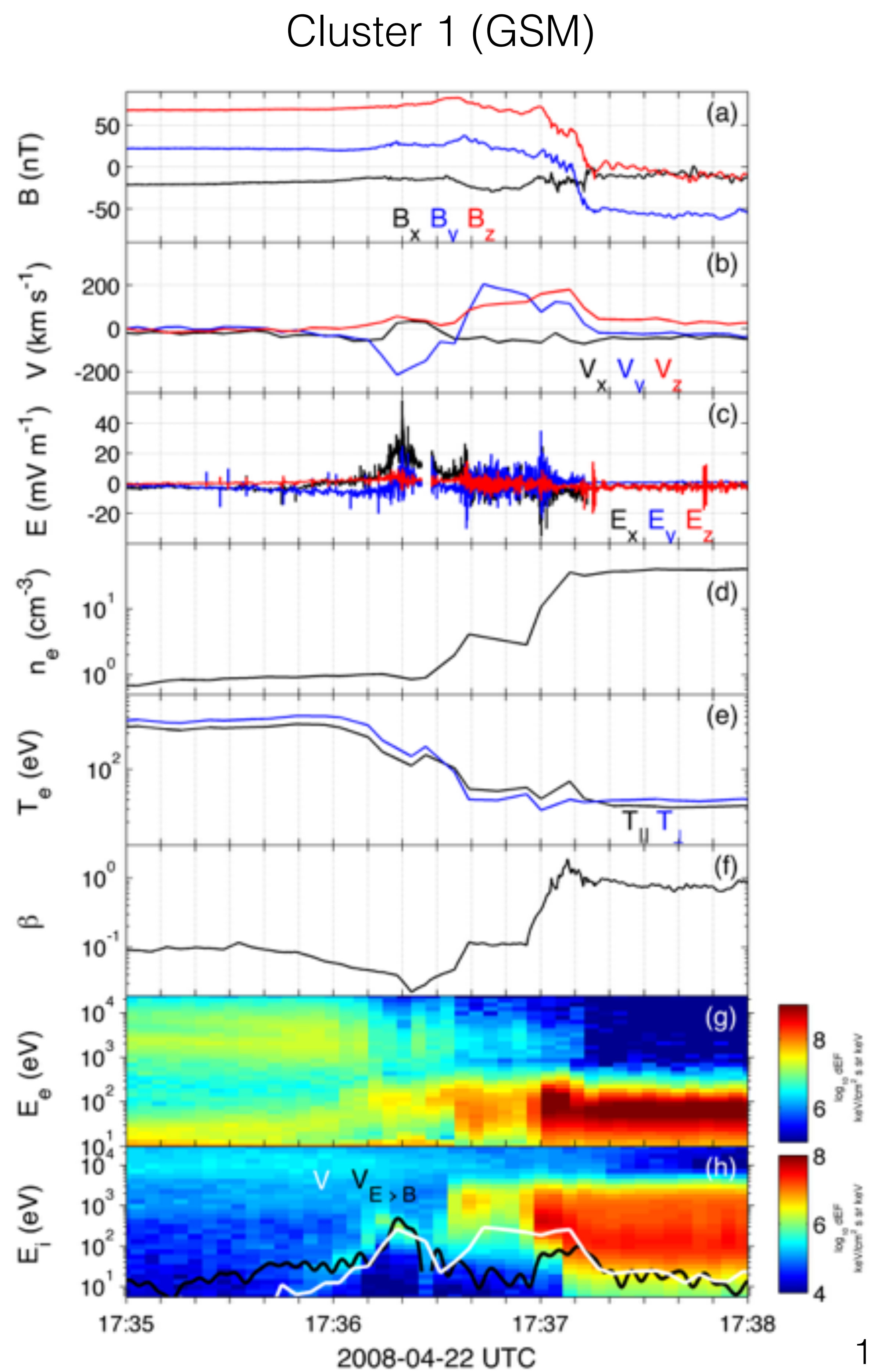
As the filtering frequency is lowered (33 Hz —>16 Hz), longer wavelength modes becomes visible.

$$\lambda \approx 7km$$

Magnetopause reconnection

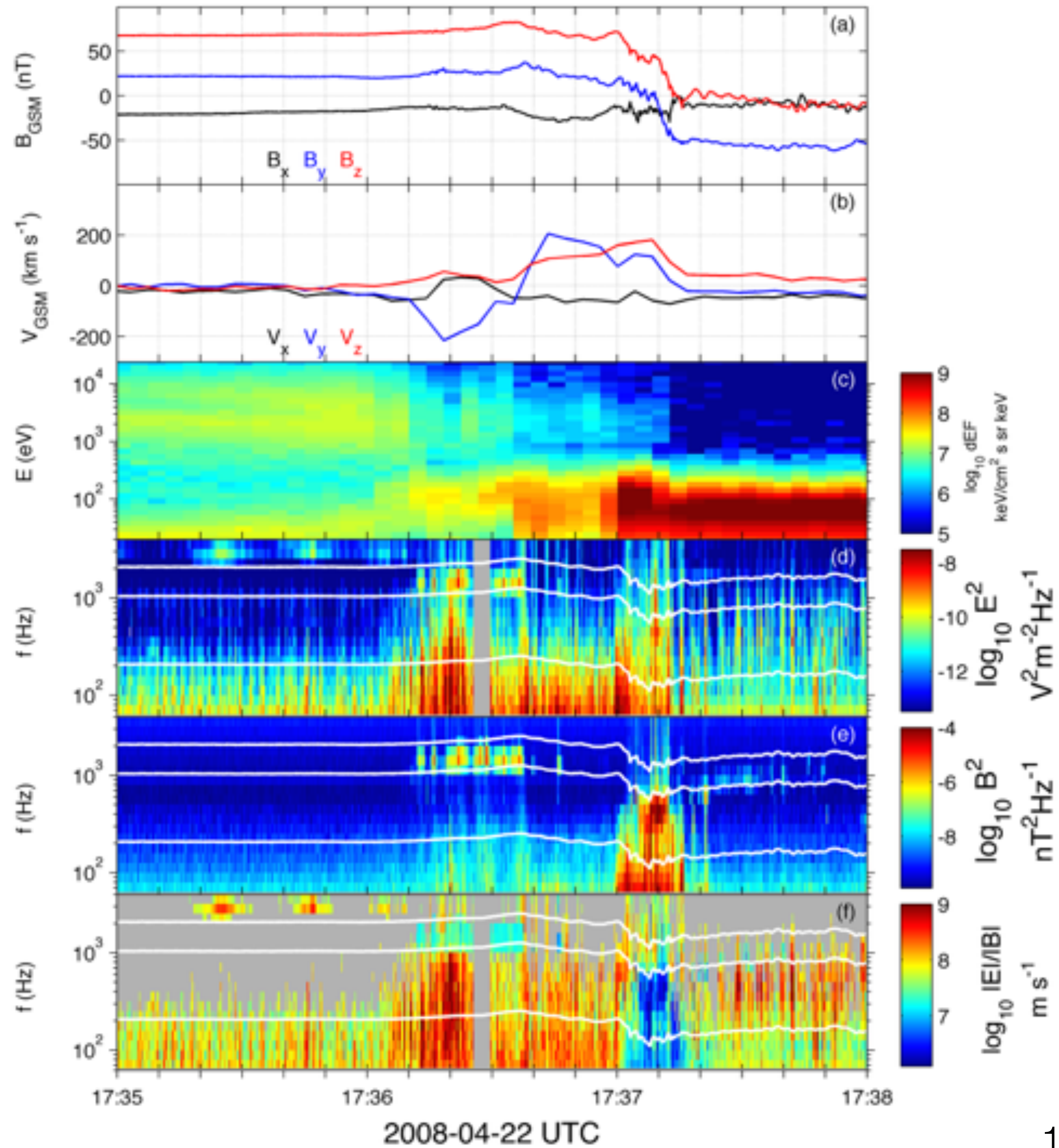


Graham et al., PRL 2014



Wave activity

- Whistler waves
- Lower hybrid waves
  - Electrostatic region
  - Electromagnetic region



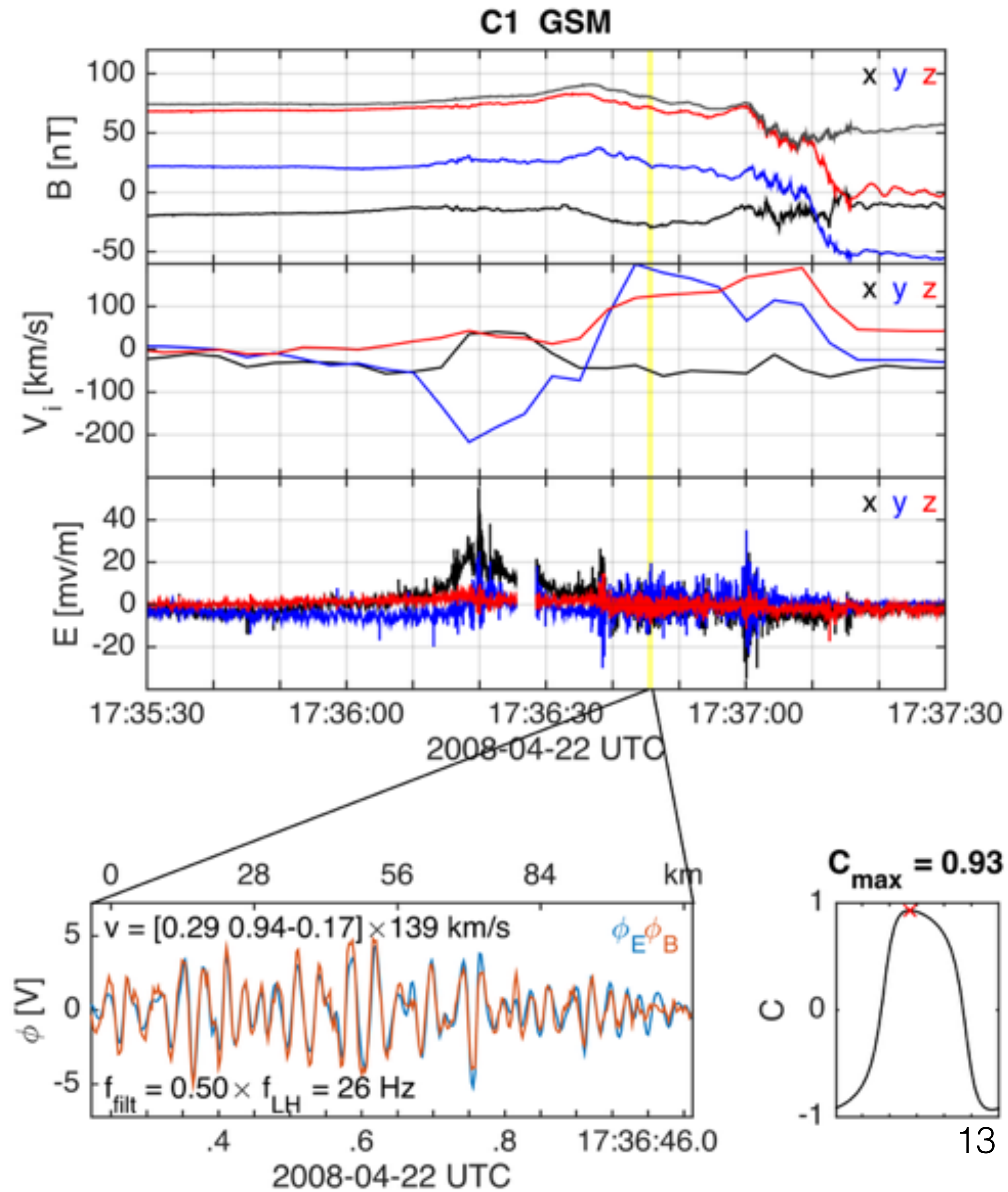
Low beta outflow

$$\lambda \approx 4.5 \text{ km}$$

$$2\pi\rho_e \approx 2 \text{ km}$$

➡ Wavelength a little bit longer than electrostatic mode

$$e\phi/k_B T_e \sim 0.1$$



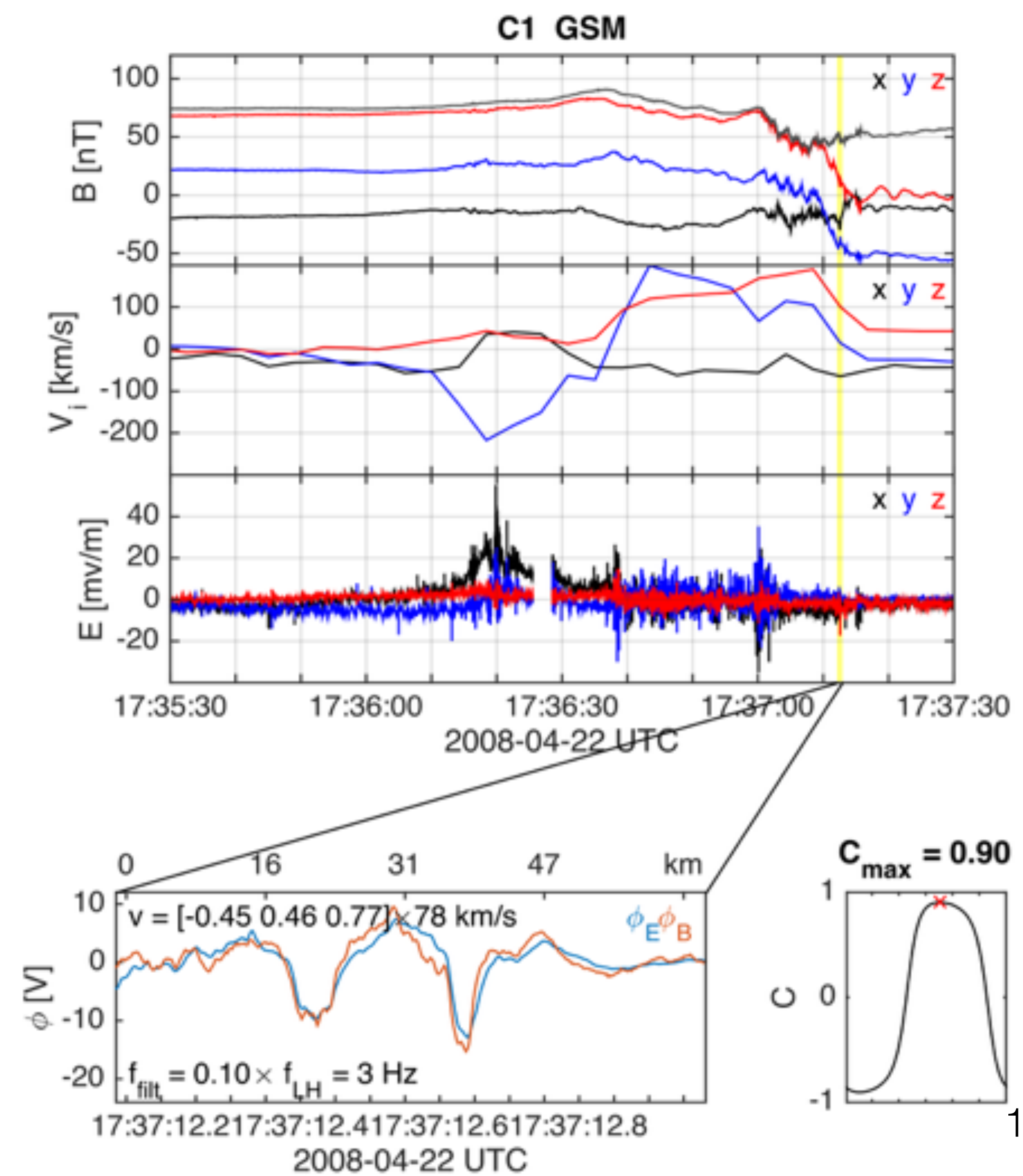
High beta outflow/ waves at small current layer

- The minimum variance direction [-0.46 0.49 0.74] and k coincide

➡ Estimate current layer thickness to 30 km

$$\delta B/\Delta B \sim 0.4$$

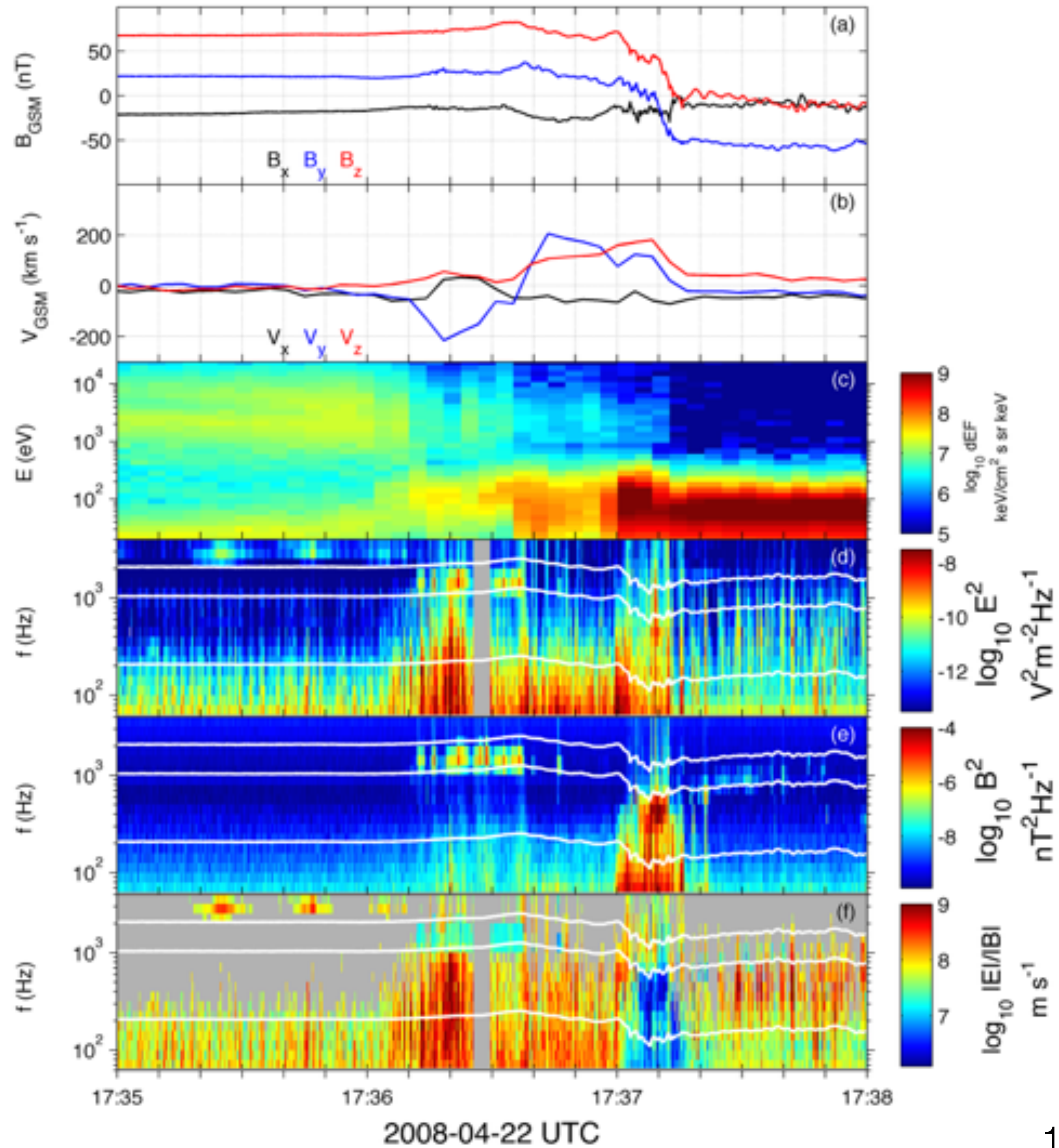
- $2\pi\sqrt{\rho_e \rho_i} \approx 24$ km
- $e\phi/k_B T_e \sim$ 0.3



General remarks

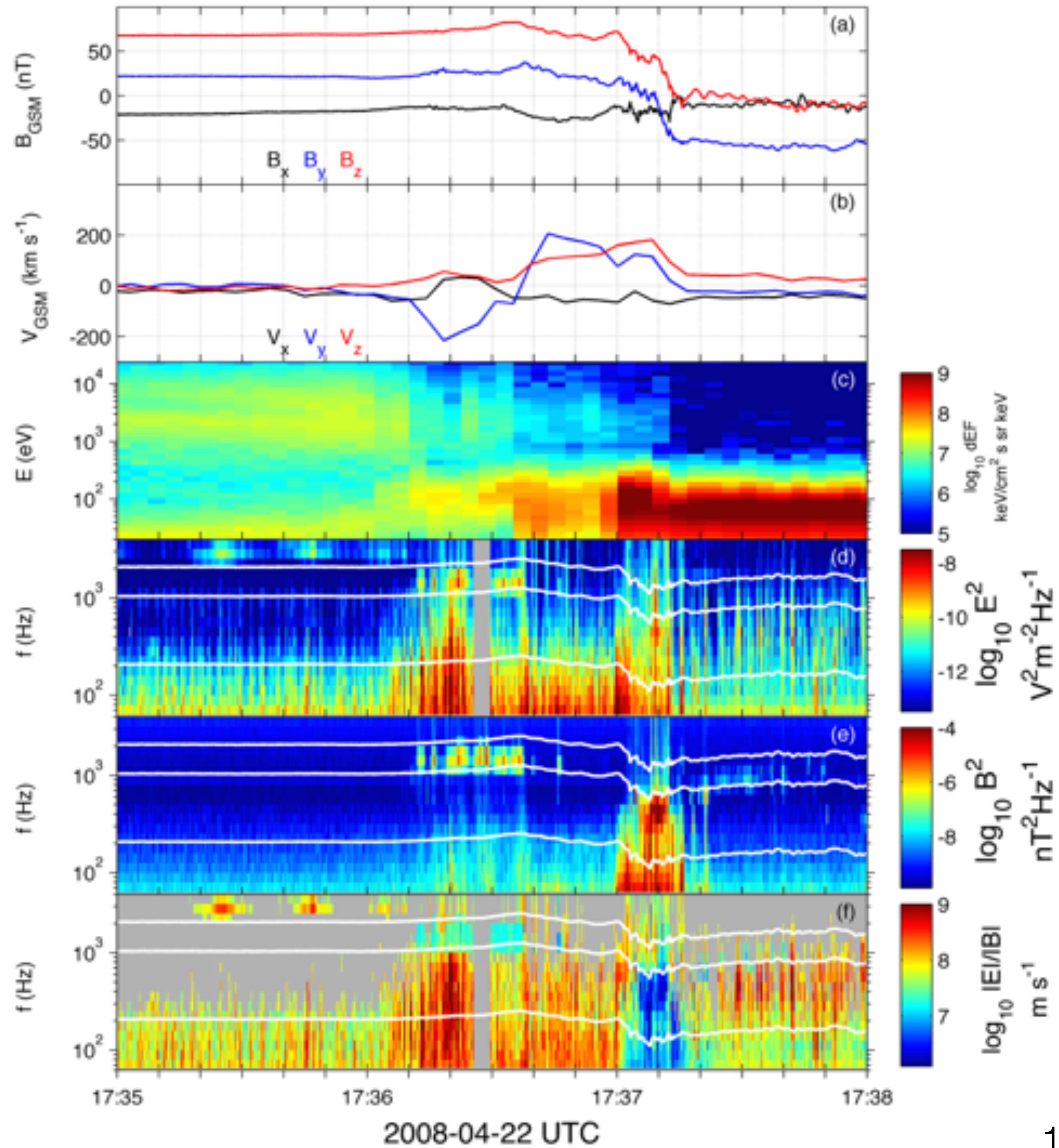
- v_{perp} ~ 100 km/s (lower in ExB frame)
- $$v_{||} = \left(\frac{m_i}{m_e}\right)^{1/2} v_{\perp}$$

  v_{par} ~ 5000 km/s (v_{te} ~4000-8000 km/s)
- Potential ~1-20 V (T_e ~50-200 eV)



General remarks

- Waves move in ExB frame
- Mixed scales
- Highest relative potentials are in high beta region



When can we use the method?

Short answer, when the structure is on electron scale and when $E \perp B \quad \text{and} \quad v \perp B$

Not only lower hybrid waves.

(+high sampling frequency)

Long answer is work in progress…

Summary

✓ We used two spacecraft to observe phase velocity and wavelength

✓ We go from two to one spacecraft and look at small scale wave structure in unprecedented detail

✓ We find strong waves in both high and low beta magnetic reconnection outflow region