

Electron anisotropy driven by kinetic Alfven waves in the Earth magnetotail

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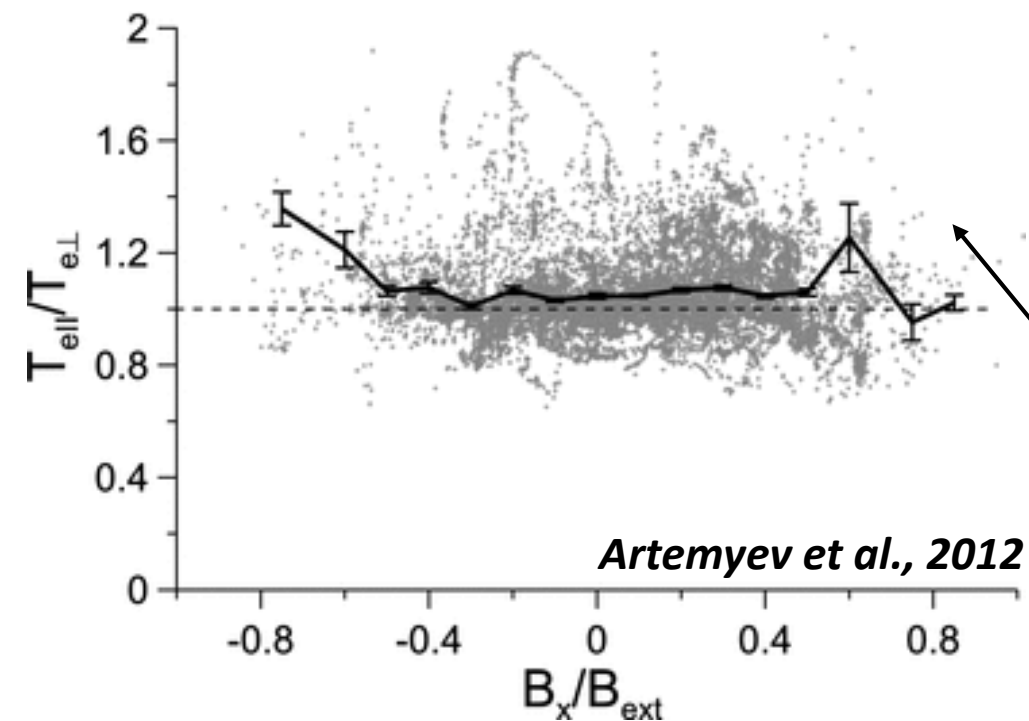


Abstract

Thermal and subthermal electron populations in the Earth's magnetotail are usually characterized by pronounced field-aligned anisotropy that contributes to generation of strong electric currents within the magnetotail current sheet. Formation of this anisotropy requires electron field-aligned acceleration, and thus likely involves field-aligned electric fields. Such fields can be carried by various electromagnetic waves generated by fast plasma flows interacting with ambient magnetotail plasma. In this presentation we consider one of the most intense observed wave emissions, kinetic Alfvén waves, that accompany all fast plasma flows in the magnetotail.

Using two tail seasons (2018, 2019) of MMS observations we have collected statistics of 80 fast plasma flows (or BBF) events with distinctive enhancement of intensity of broadband electromagnetic waves sharing properties of kinetic Alfvén waves. We show that a direct correlation the intensity of electric fields of kinetic Alfvén waves and electron anisotropy distribution: the parallel electron anisotropy significantly increases with magnitude of the wave parallel electric field. The energy range of this electron anisotropic population is well within the range of resonant energies for observed kinetic Alfvén waves. Our results show that kinetic Alfvén waves can significantly contribute to shaping the magnetotail electron population.

Electron anisotropy in the magnetotail

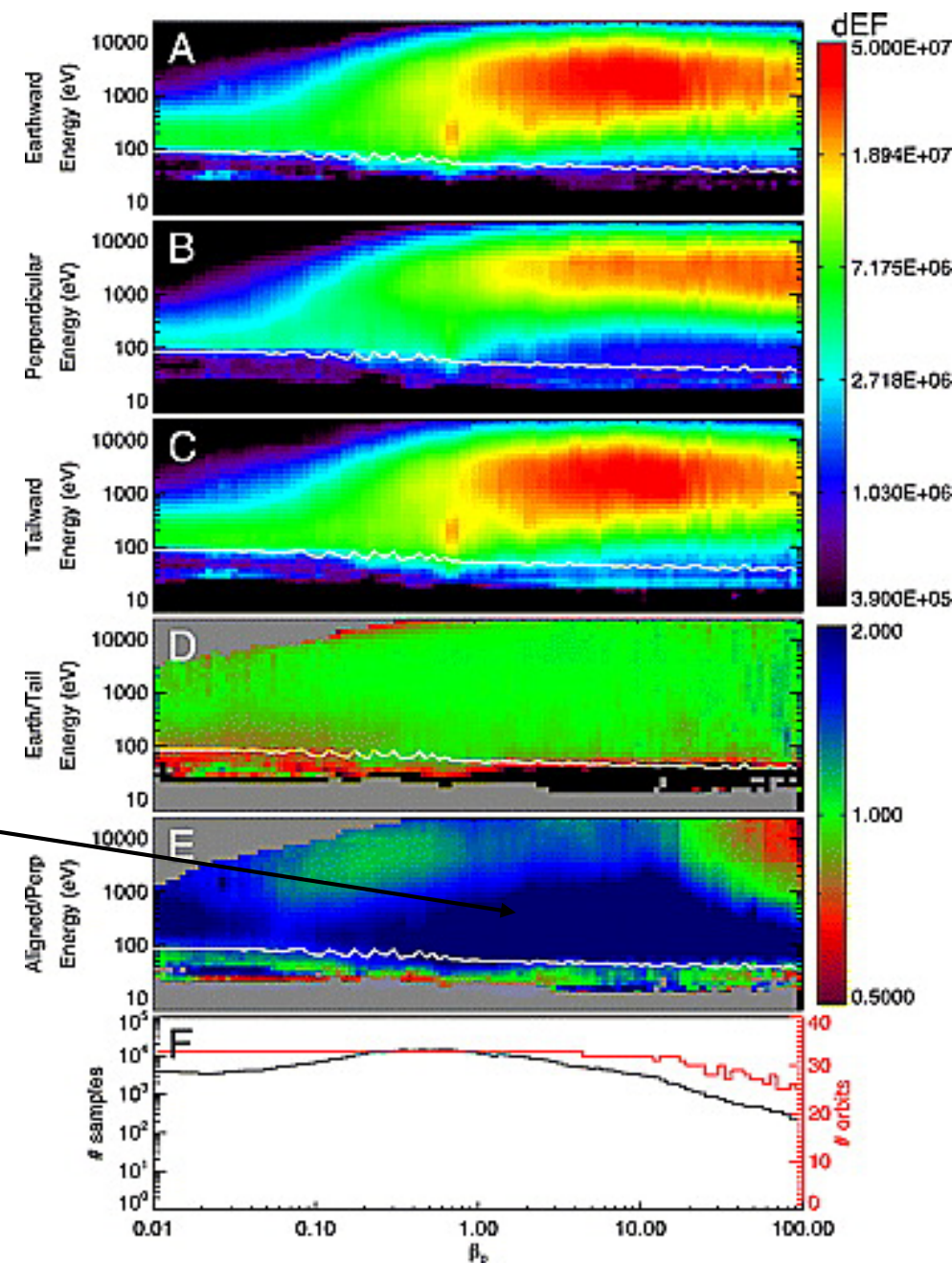


Artemyev et al., 2012

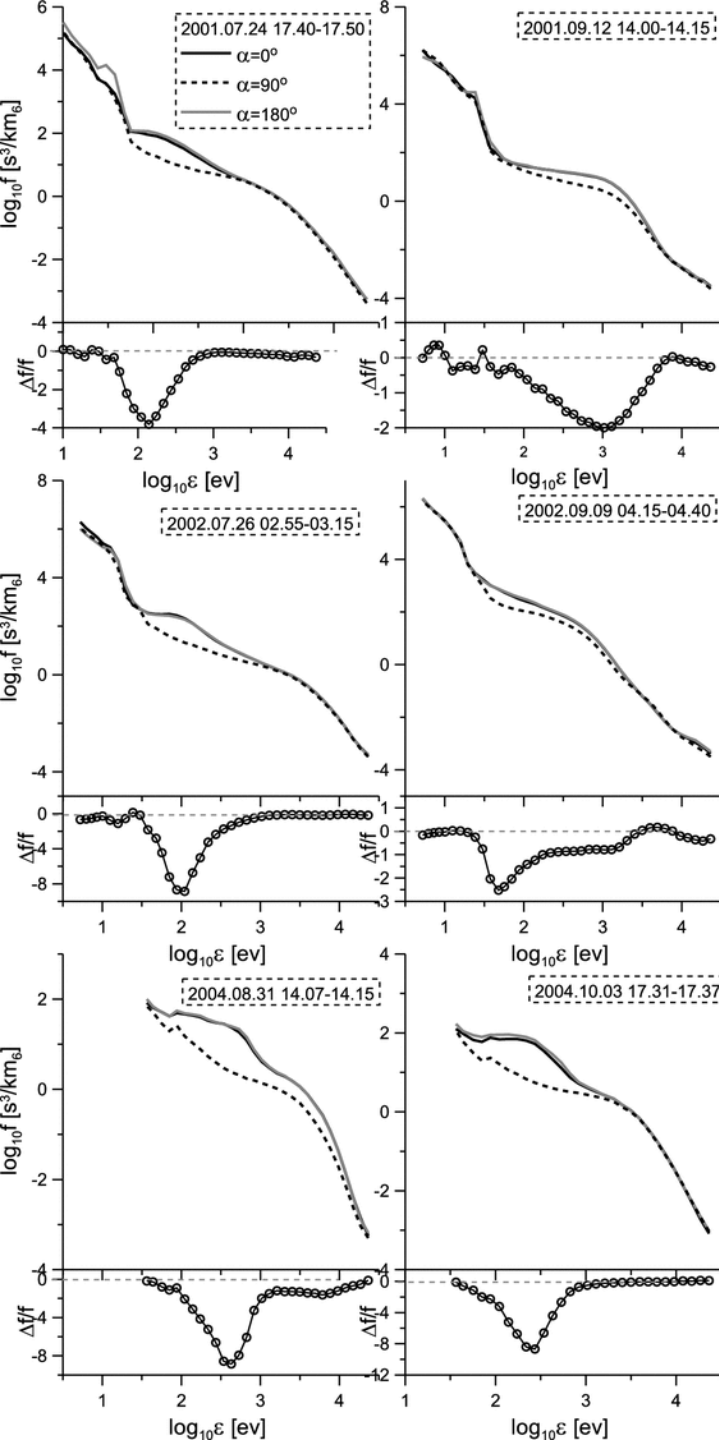
Strong parallel anisotropy is a typical state of the plasma sheet ($\beta > 1$)

Walsh et al., 2011

Electron differential flux (dEF) binned by β_p . (a) An Energy- β_p spectrogram of Earthward-directed field-aligned proton dEF, (b) perpendicular and (c) tailward dEF. (d) The ratio between Earthward and tailward dEF, and (e) the ratio between the mean of parallel dEF and the perpendicular dEF. The black trace on Figure 2f is the number of samples in each β_p bin and the red the number of orbits from which the data in each bin were taken.



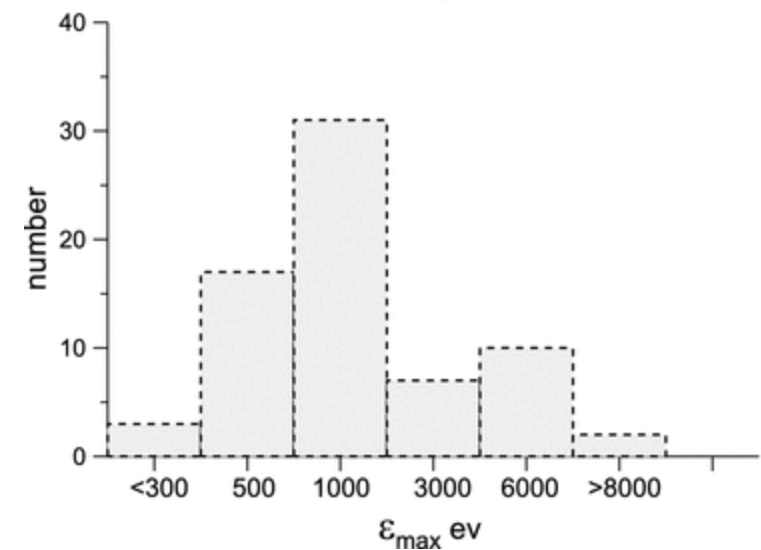
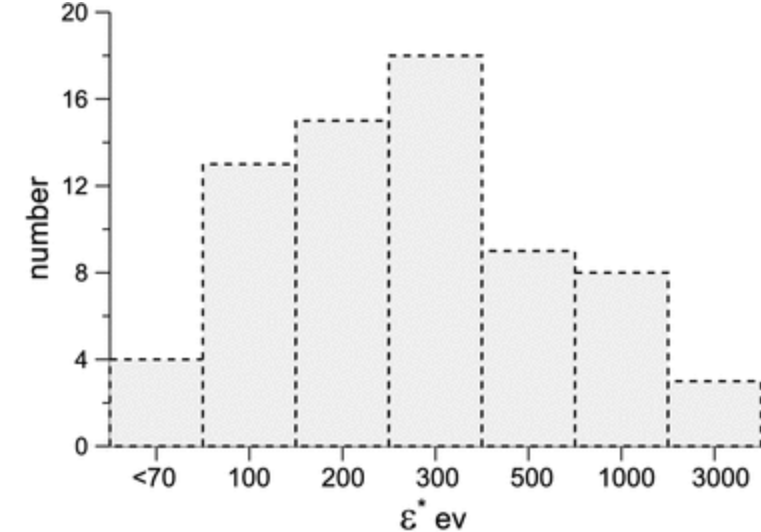
Anisotropy energy ranges



Typical electron spectra in the magnetotail plasma sheet: electron parallel anisotropy is mostly supported by subthermal population <1keV (electron temperature is ~1 keV)

ϵ^* is the energy of the peak flux ratio $f_{\parallel}/f_{\perp}$.

$\epsilon_{\max}$ is the maximum energy of anisotropic population with $f_{\parallel}/f_{\perp} > 1.5$



Artemyev et al., 2012

Possible mechanisms of anisotropy formation

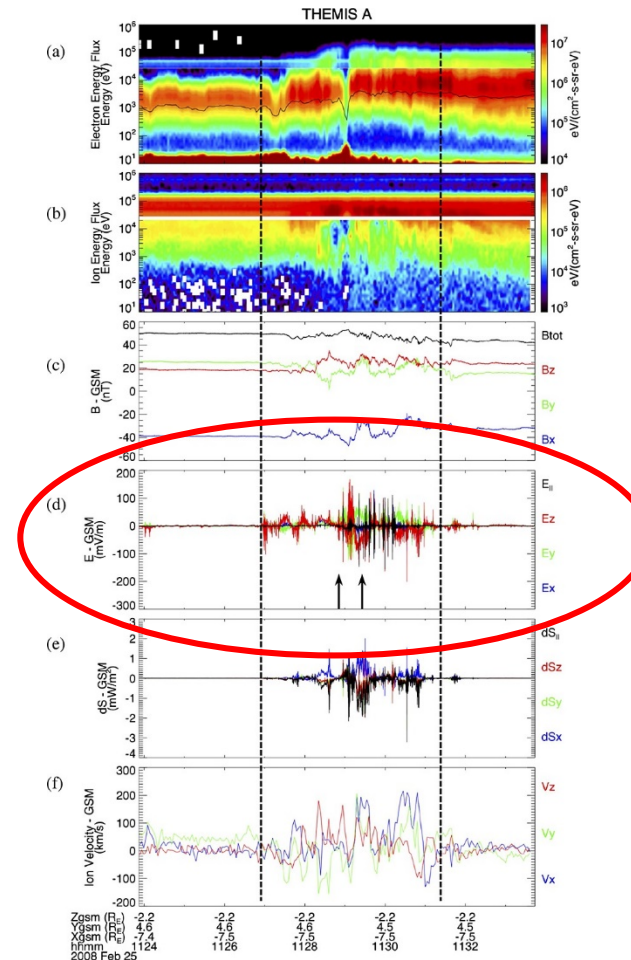


To shape electron distributions with field-aligned anisotropic populations we need to propose some acceleration mechanism, likely related to the field-aligned electric fields. There are several candidates:

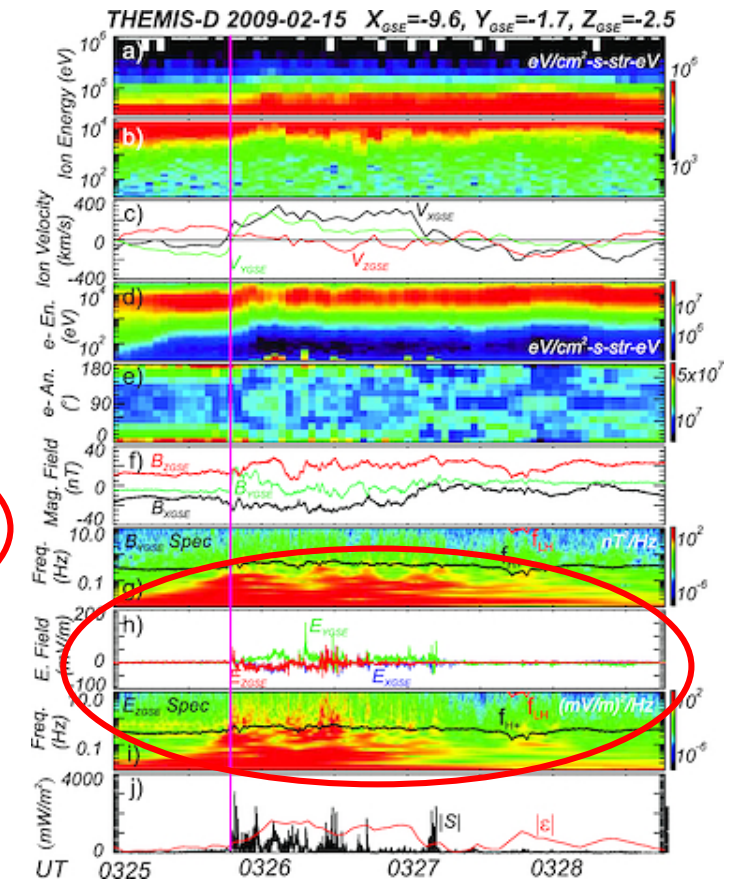
- Drift mode of lower-hybrid waves
- Very oblique whistler waves
- Kinetic Alfven waves

Kinetic Alfven Waves are the most intense and widespread type of wave emission at the magnetotail fast plasma flows:

- Electric fields are up to 100mV/m
- Broadband spectrum



Ergun et al., 2015



Chaston et al., 2012

Instruments

Value	Instrument	Time resolution
Magnetic field	Fluxgate Magnetometer	125 Hz
Electric field	Electric field Double Probe	1 kHz
Plasma moments	Fast Plasma Investigation (10 eV – 30 keV)	Electrons – 33.3 Hz Ions – 6.67 Hz

By definition:

- Parallel (field aligned) electrons (F_{par}): $0 - 24^\circ$
- Antiparallel (F_{anti}): $156 - 180^\circ$
- Transverse ($F_{\perp}$): $66 - 114^\circ$

KAW properties

Theoretical relations: $\mathbf{B}_0 \parallel \mathbf{z}$

In our study $\mathbf{B}_0$ is determined from lowpass filtering below 0.01 Hz. $\mathbf{B}_{wave} = \mathbf{B}_{observed} - \mathbf{B}_0$

Hereinafter: $\mathbf{B}_i, \mathbf{E}_i = \mathbf{B}_{wave\ i}, \mathbf{E}_{wave\ i} = CWT(\mathbf{B}_i, \mathbf{E}_i)$,

CWT – continuous Morlet wavelet transform

- $\frac{E_x}{B_y} = \frac{v_A(1+k_\perp^2\rho_i^2)}{\sqrt{1+k_\perp^2(\rho_i^2+\rho_s^2)}}$

Chaston et al 2008, 2013
Stasiewicz et al 2000

- $\frac{B_\parallel}{B_\perp} = -\frac{i\beta k_\perp v_A}{\omega_i \sqrt{1+k_\perp^2(\rho_i^2+\rho_s^2)}}$
- $k_\perp \sim \rho_i \sim \frac{\omega}{|v_i|}$

$$B_\perp = \sqrt{B_x^2 + B_y^2}$$

In our study:

- $B_\parallel, E_\parallel \parallel B_0$,
- $B_y = B_{\perp 1} \parallel v_{ion\perp}$
- $E_x = E_\perp \parallel cross(v_{i\perp}, B_0)$
- $k_\perp = \frac{\omega}{|v_i|}$

Example

Selection criteria:

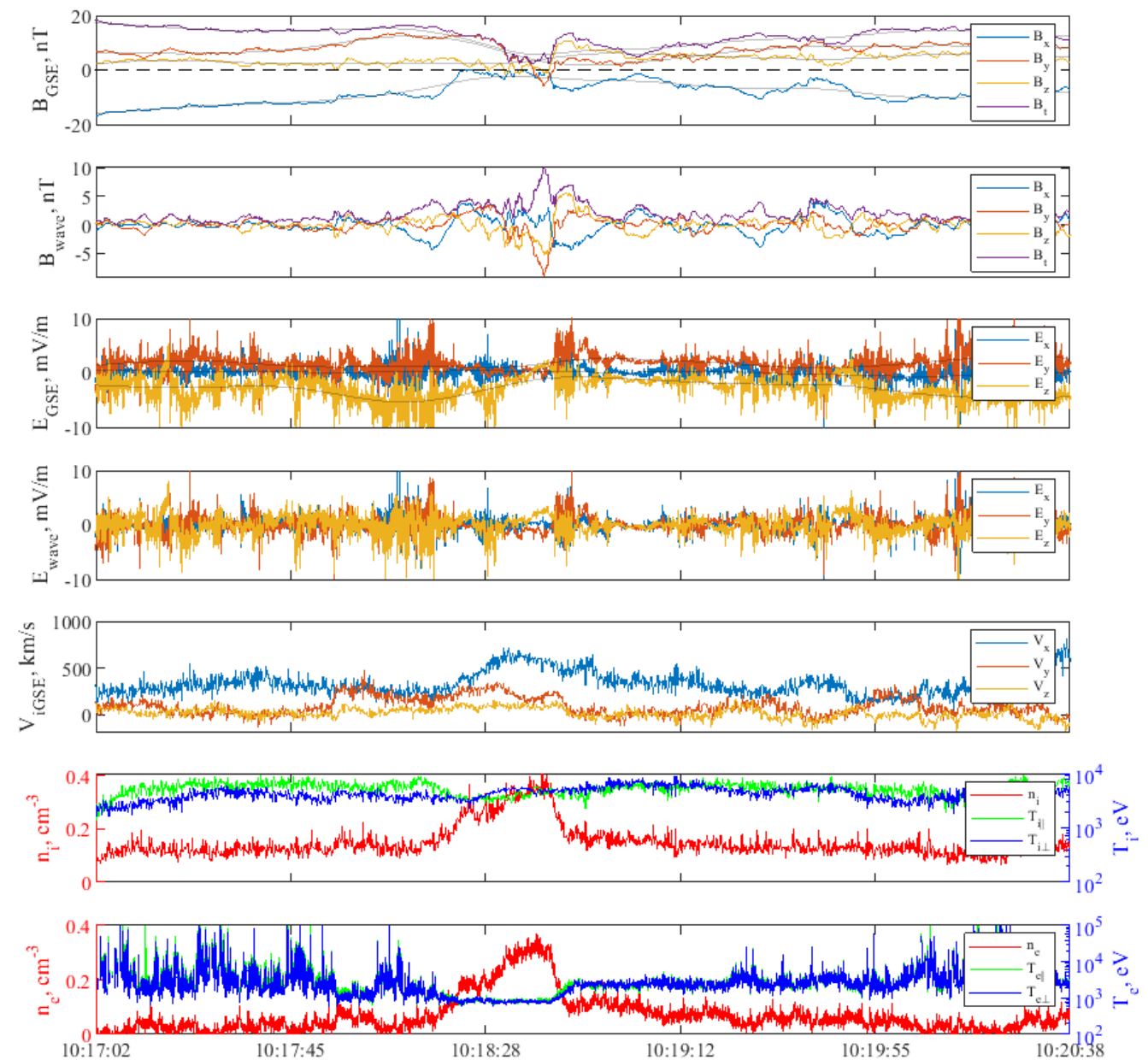
- $V_x \geq 200 \text{ km/s}$ during BBF
- Spacecraft are near the neutral plane
- Waves are electrostatic on high frequencies
- Observational spectra are close to theoretical

Summary:

Two years: 2018-2019

119 events

80 clear events



From top to bottom: GSE magnetic field, “wave” magnetic field, GSE electric field, “wave” electric field, ion bulk velocity, electron number density and temperatures, ion number density and temperatures. Gray curves show lowpass filtered magnetic and electric fields

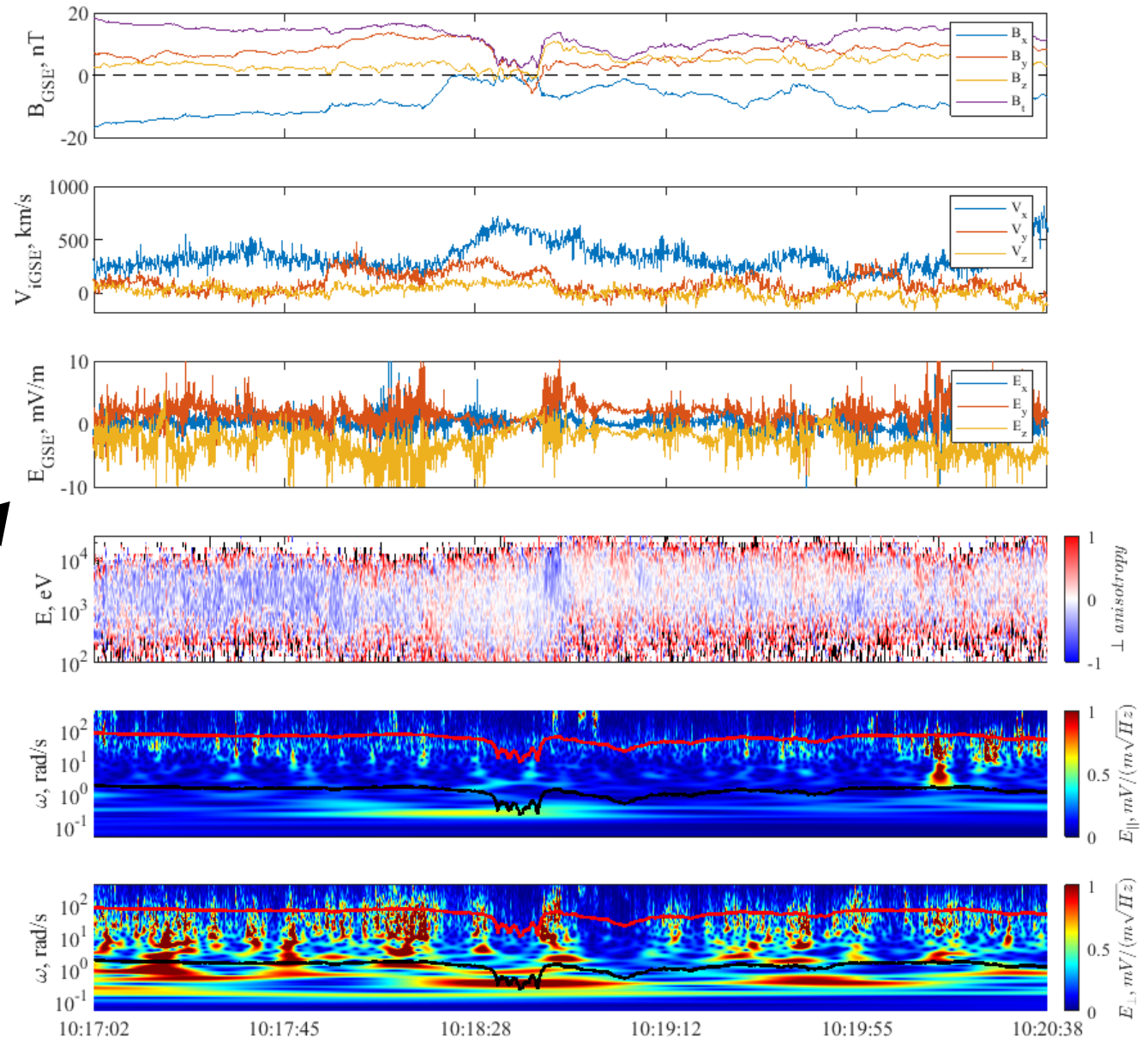
Anisotropy:

$$A_{\perp} = \frac{F_{\perp} - F_{\parallel}}{F_{\perp} + F_{\parallel}}, F_{\parallel} = \frac{F_{par} + F_{anti}}{2}$$

Parallel (field aligned) electrons (F_{par}): $0 - 24^{\circ}$

Antiparallel (F_{anti}): $156 - 180^{\circ}$

Transverse ($F_{\perp}$): $66 - 114^{\circ}$



From top to bottom: GSE magnetic field, ion bulk velocity, GSE electric field, electron perpendicular anisotropy, parallel and transverse electric field wavelet spectra. Black curve – ion cyclotron frequency, red curve – lower-hybrid frequency

Longitudinal and transverse wave numbers

We follow the work of Chaston et al 2008, 2013 and assume $k_{\perp} = k_y = \frac{\omega}{|v_i|}$ and $k_{\parallel} = k_z$ is defined from the following equation:

$$k_z^2 v_A^2 k_y^2 \rho_s^2 = \left(\omega^2 - \frac{k_z^2 v_A^2}{\xi_i} \right) \left(1 - \frac{k_z^2 v_s^2}{\omega^2} I_0(\alpha_i) e^{-\alpha_i} \right)$$

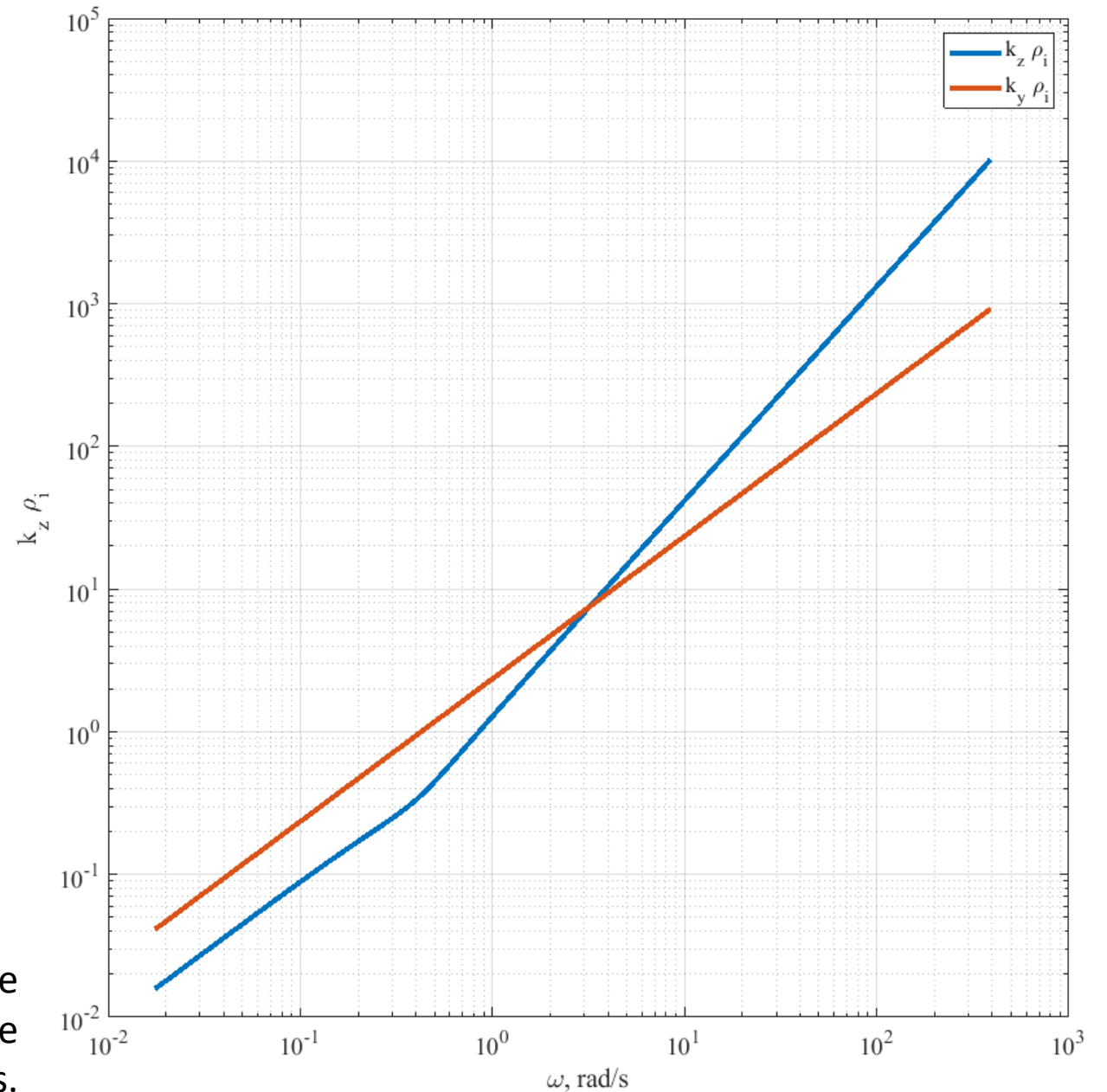
where $\alpha_i = k_y^2 \rho_i^2$

$$\xi_i = \frac{1 - I_0(\alpha_i) e^{-\alpha_i}}{\alpha_i}$$

v_s is ion acoustic speed

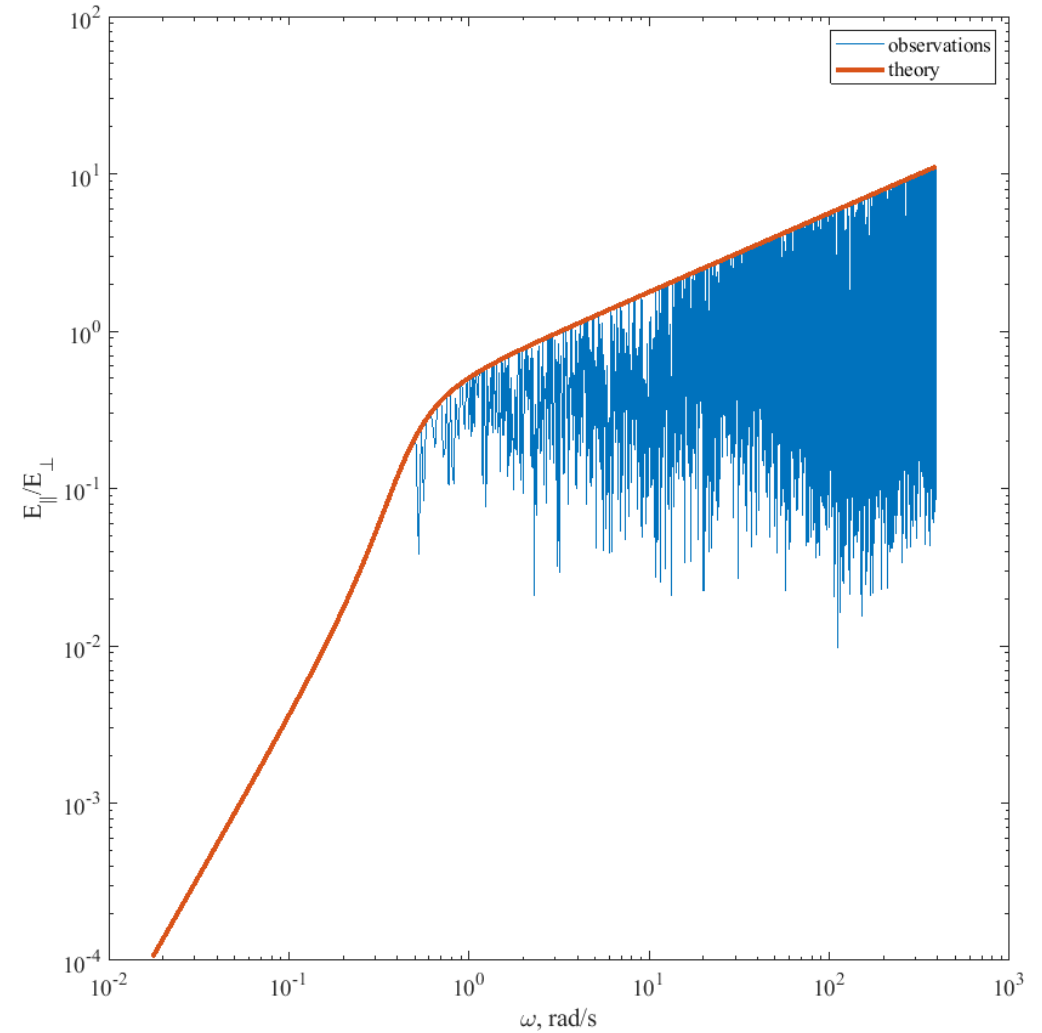
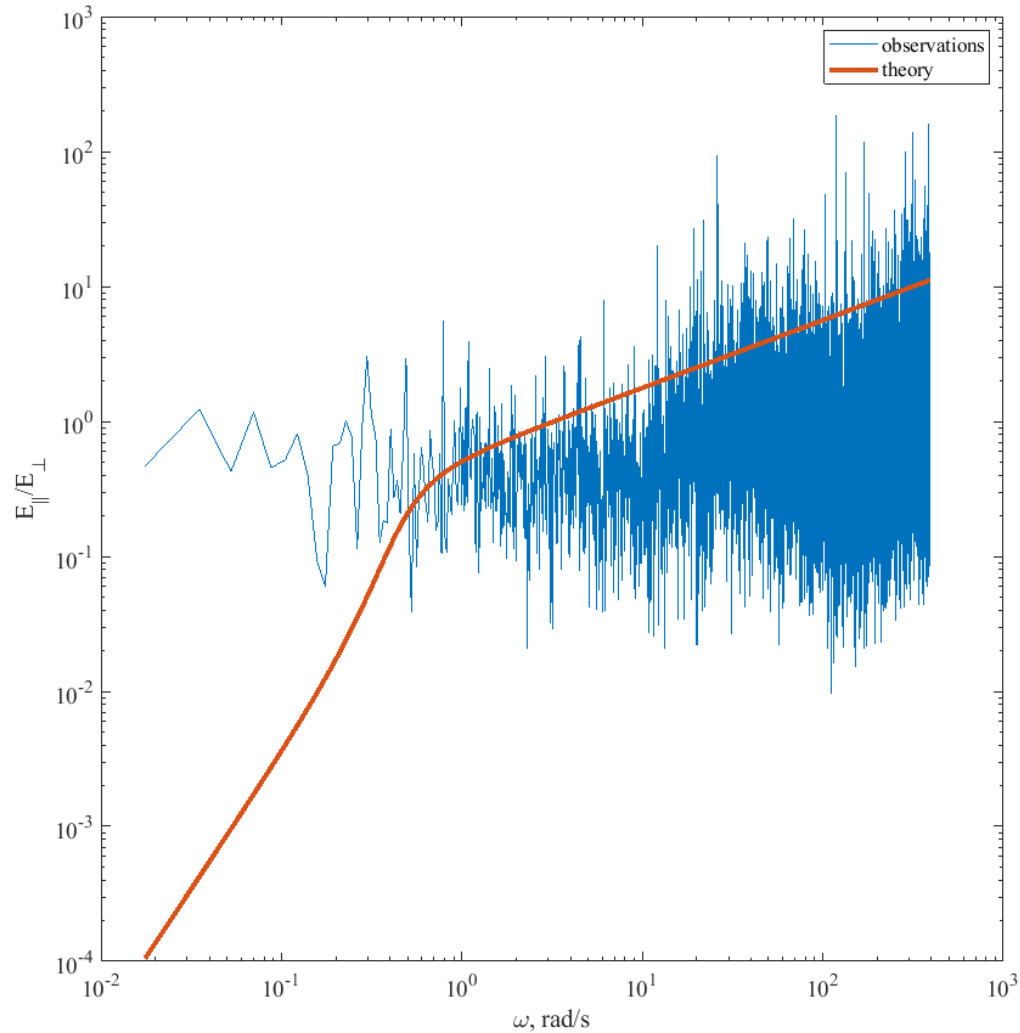
I_0 is the zero order modified Bessel function

Longitudinal and transverse wave numbers multiplied by mean value of ion thermal gyroradius.



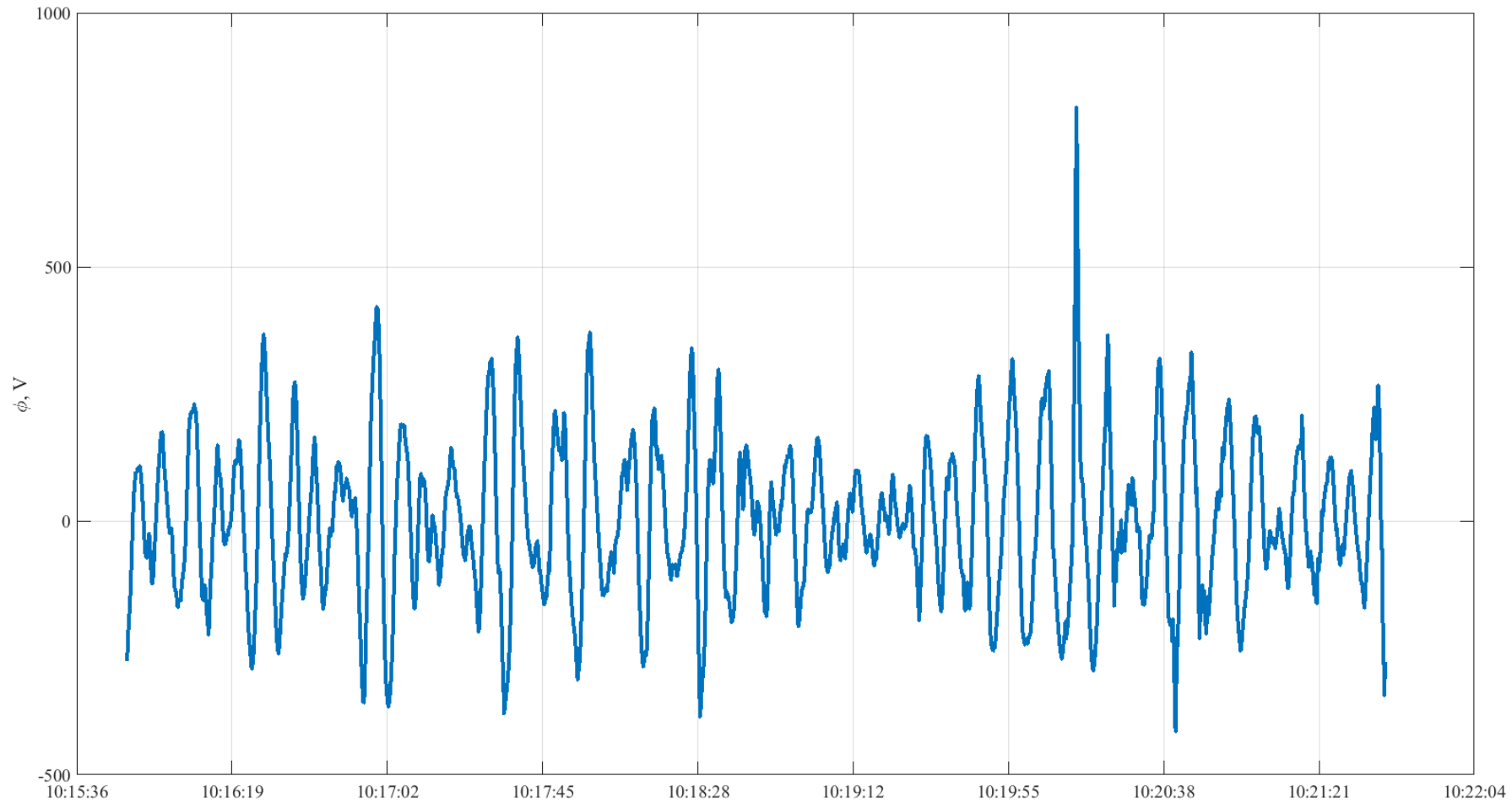
To exclude strong electrostatic fields we change the Fourier transform of the parallel wave electric field component and then restore it using inverse transform.

$$\frac{E_z}{E_y} = - \frac{k_z k_y \rho_s^2 \xi_i}{1 - \frac{I_0(\alpha_i) e^{-\alpha_i} k_z^2 v_s^2}{\omega^2}}$$



We can also restore the electric potential using
calculated longitudinal wave number:

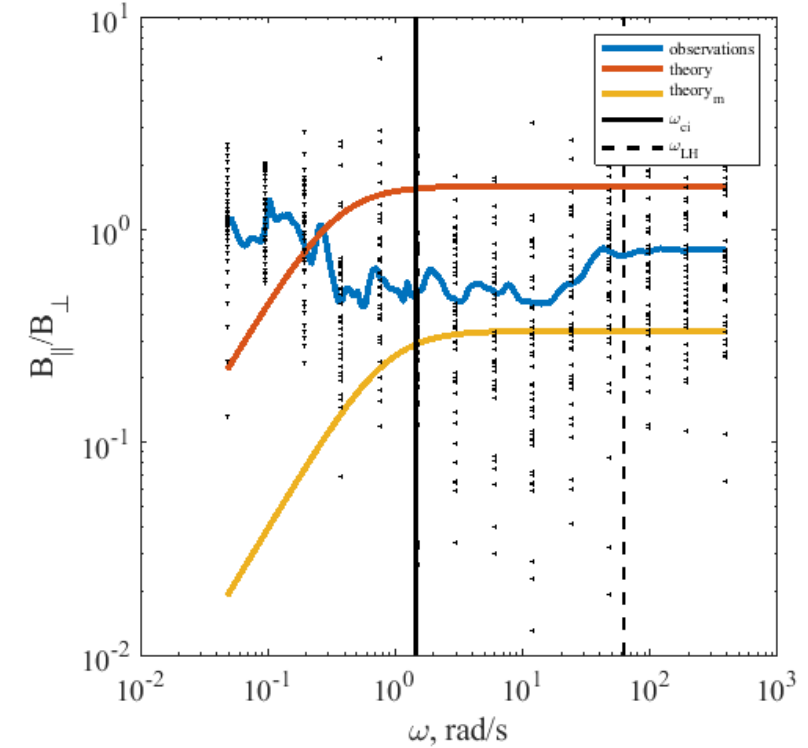
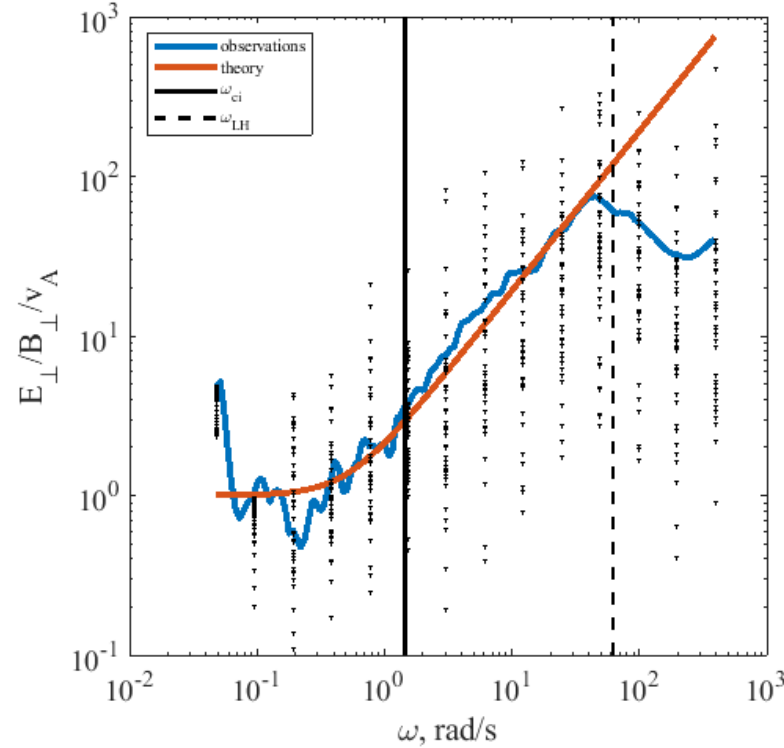
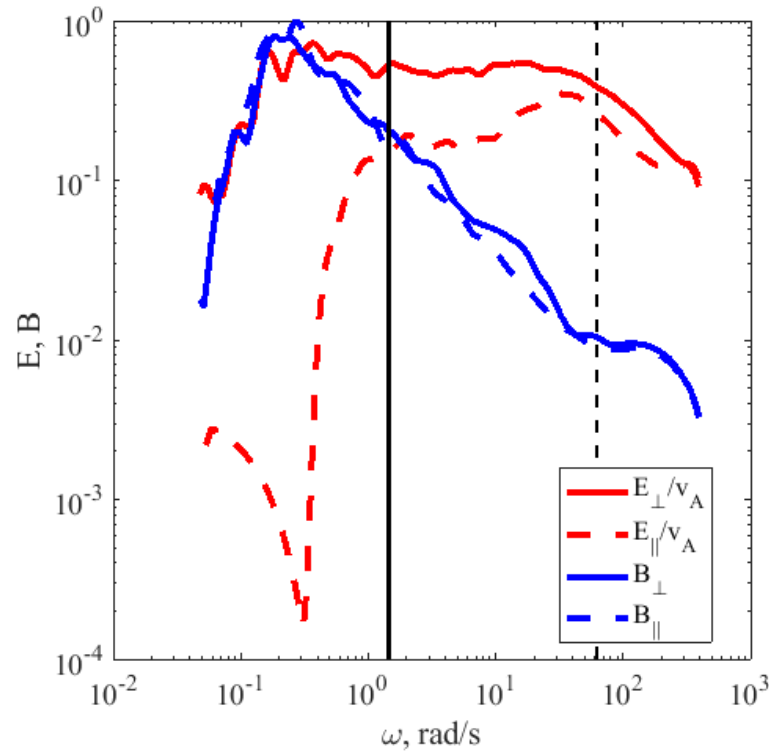
$$\phi(t) = \int E_{\parallel}(\omega)/k_z(\omega)e^{i\omega t}d\omega$$



Spectra ratios

$$\frac{E_x}{B_y} = \frac{v_A(1 + k_{\perp}^2 \rho_i^2)}{\sqrt{1 + k_{\perp}^2(\rho_i^2 + \rho_s^2)}}$$

$$\frac{B_{\parallel}}{B_{\perp}} = -\frac{i\beta k_{\perp} v_A}{\omega_i \sqrt{1 + k_{\perp}^2(\rho_i^2 + \rho_s^2)}}$$

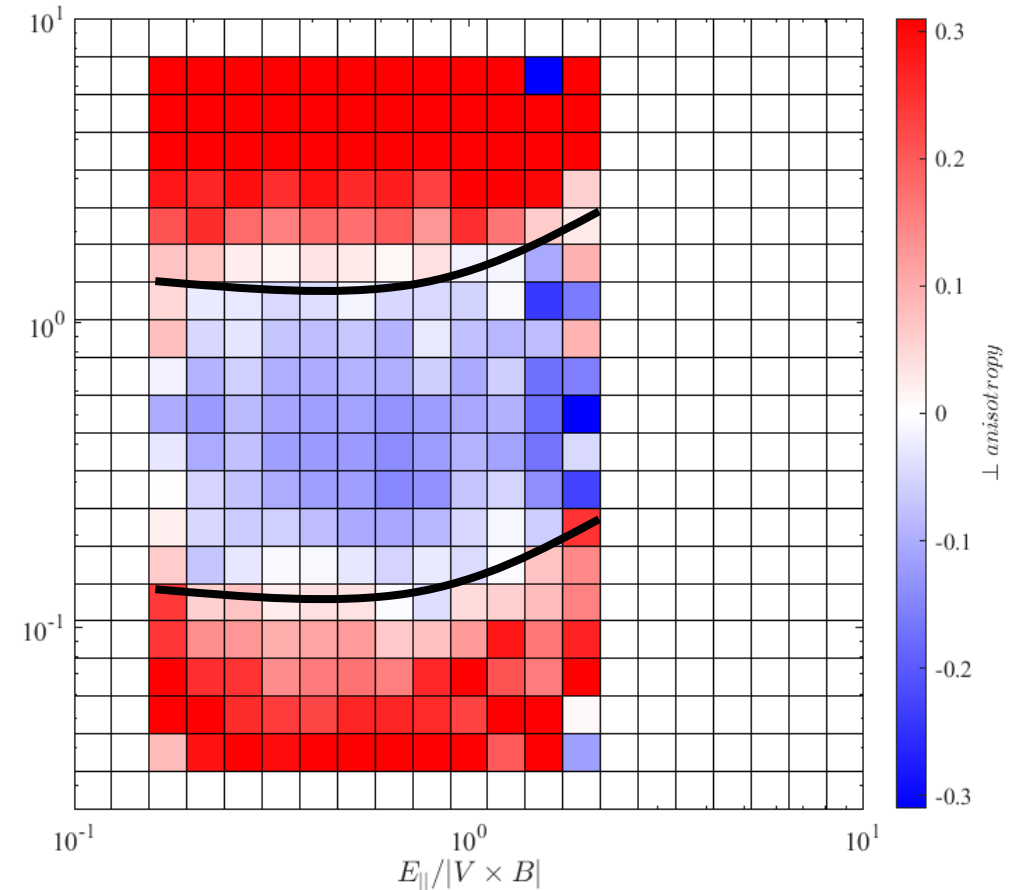
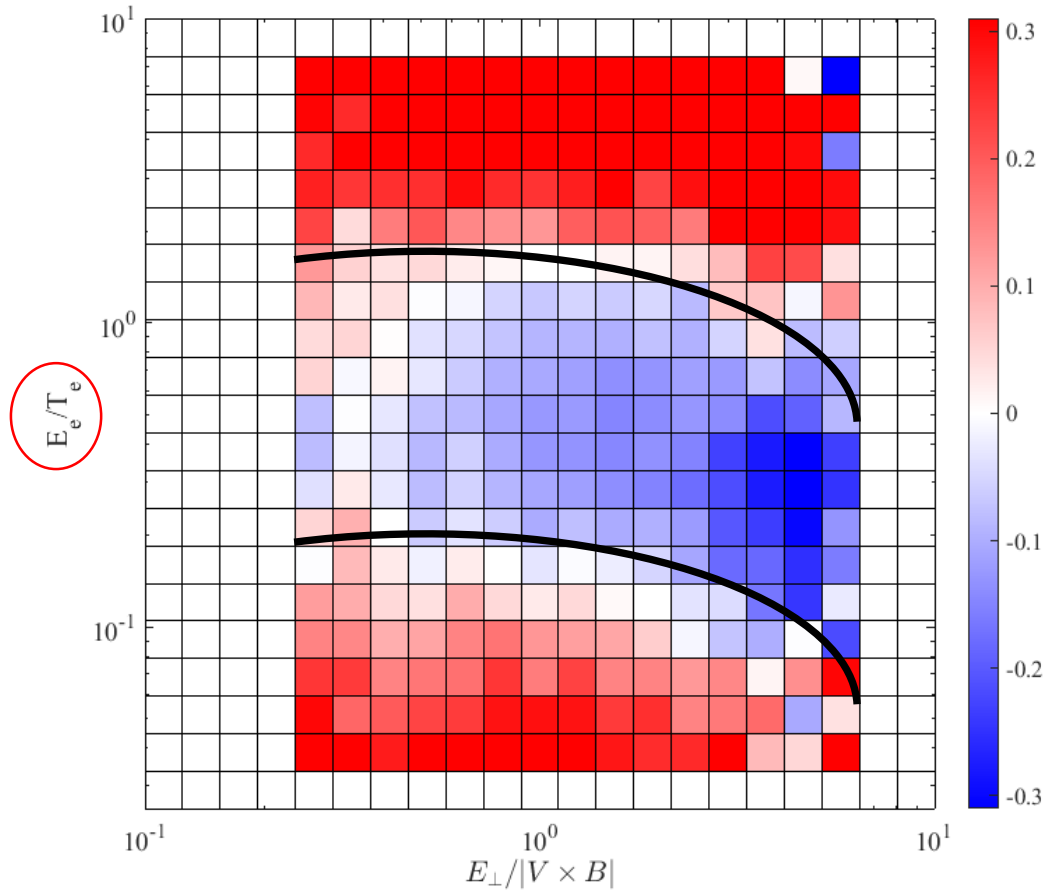


Time averaged CWT spectra. Middle and right panels show CWT spectra ratios. Right panel – yellow line shows theory curve obtained from the pressure balance: $p_{MF} = 0.7(p_{MF} + p_{thermal}) = 0.7p_{lobe}$

Anisotropy

For this picture we integrate wavelet spectra of the electric field components up to lower-hybrid frequency

Electron energy is normalized by mean temperature



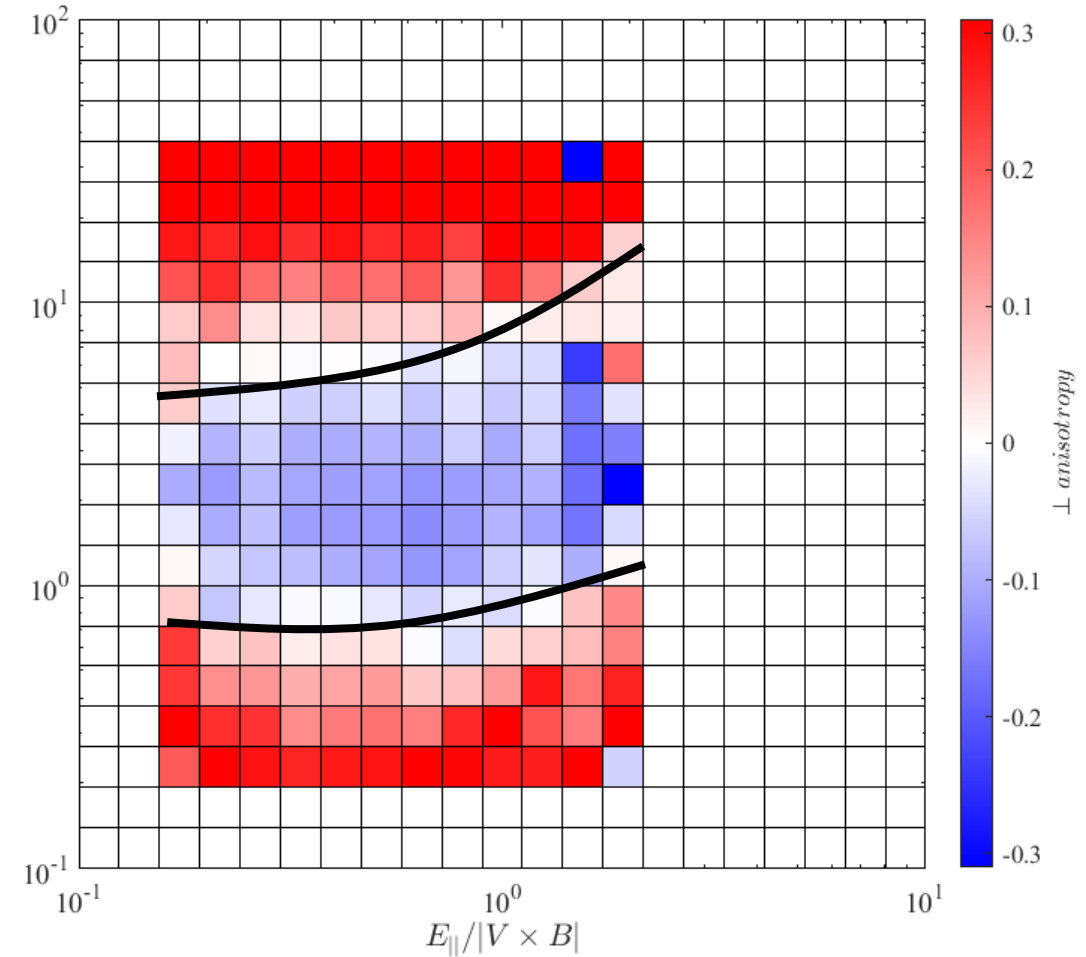
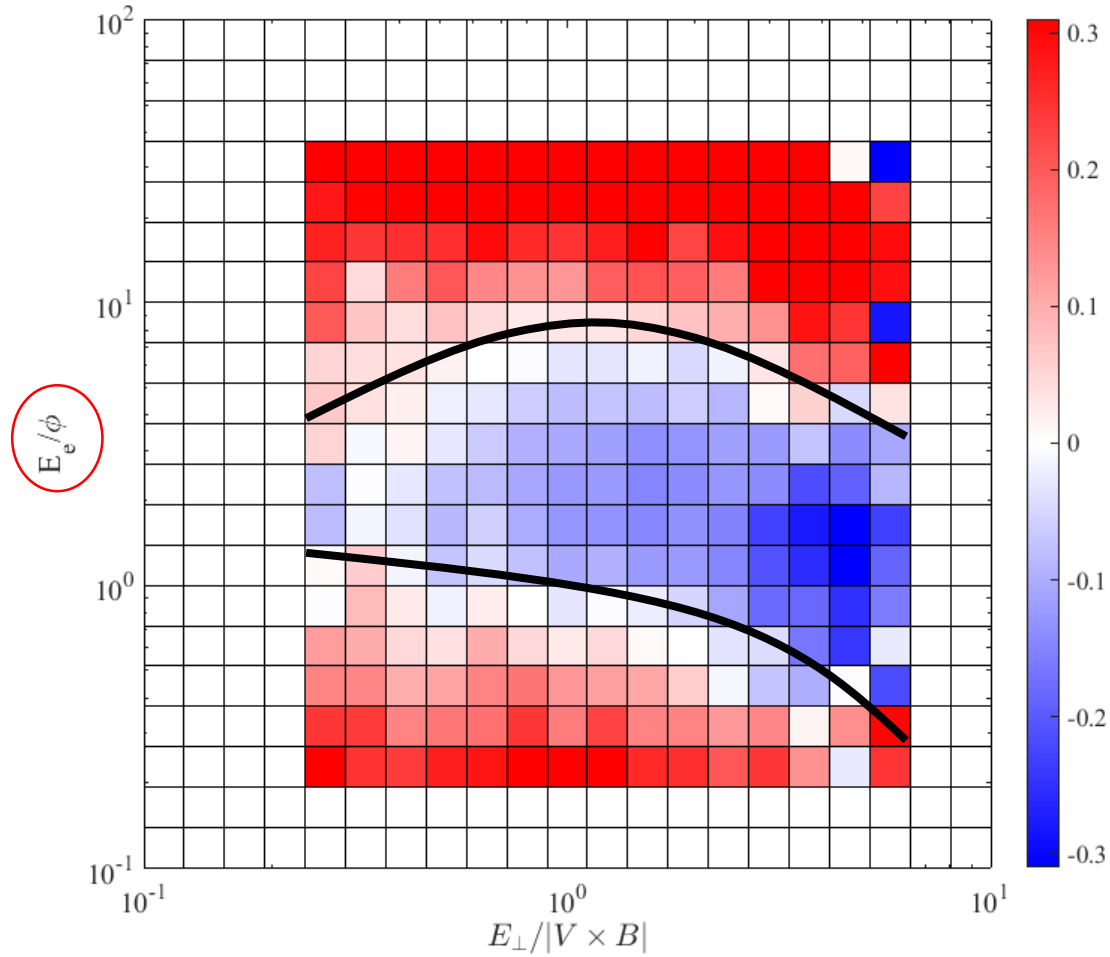
Anisotropy $A_{\perp} = \frac{F_{\perp} - F_{\parallel}}{F_{\perp} + F_{\parallel}}$ as function of $E_{\perp}$ and $E_{\parallel}$ normalized magnitudes (magnitudes are normalized by mean value of $|V \times B|$ electric field).

Strong perpendicular anisotropy above $\frac{E_e}{T_e} \sim 1$ is associated with betatron mechanism.

Perpendicular anisotropy at $\frac{E_e}{T_e} \leq 0.1$ are due to spacecraft potential.

Increase in parallel anisotropy with parallel electric field magnitude for $\frac{E_e}{T_e} \sim [0.1, 1]$ is (probably) associated with KAWs.

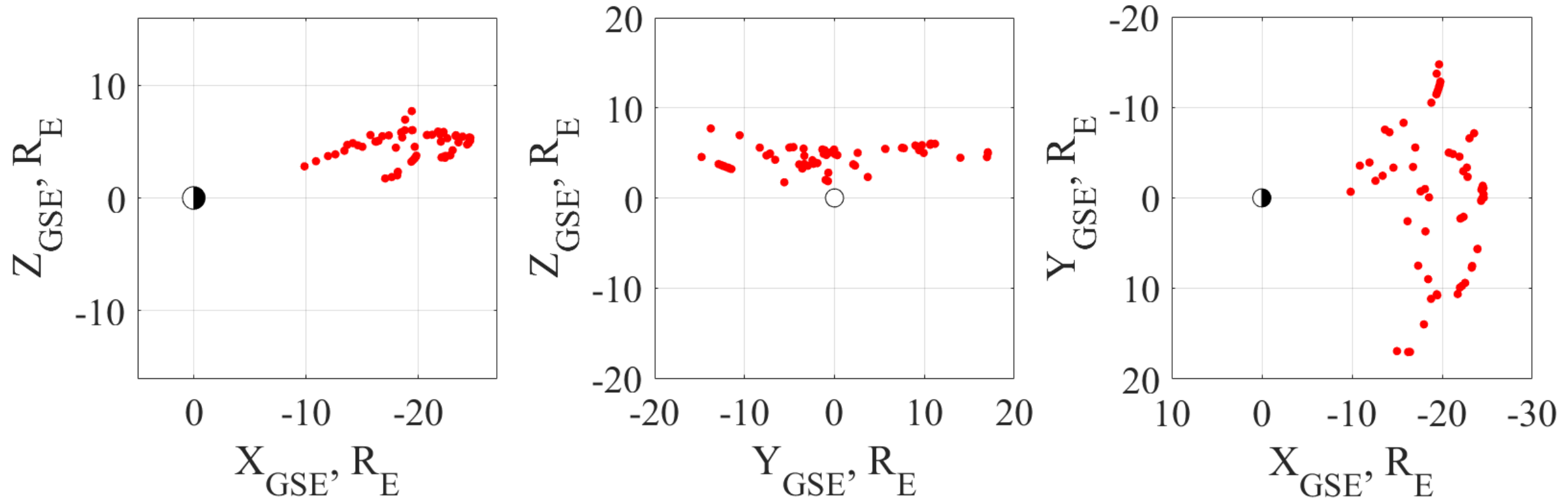
Electron energy is normalized by maximum value of the electric potential

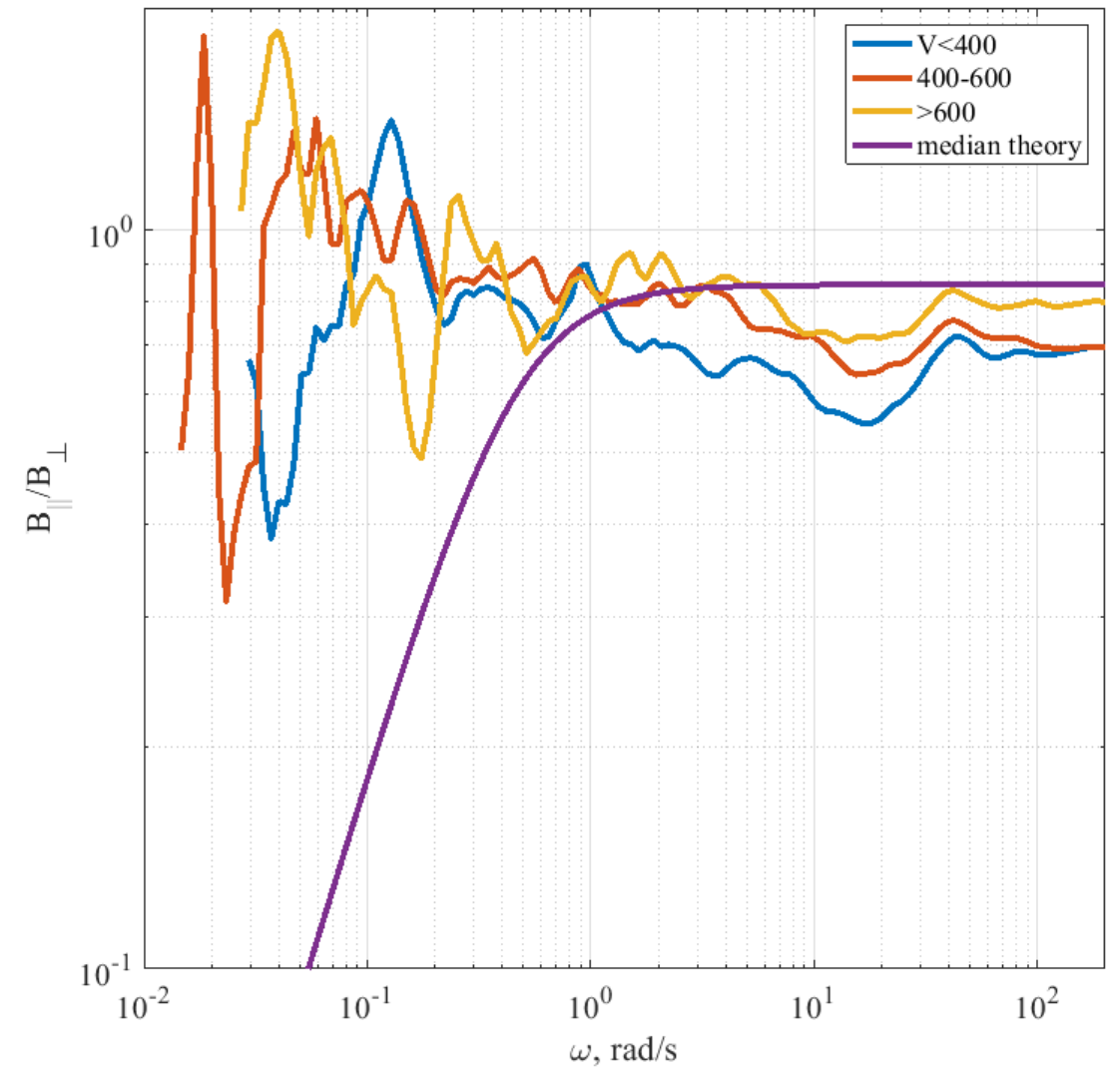
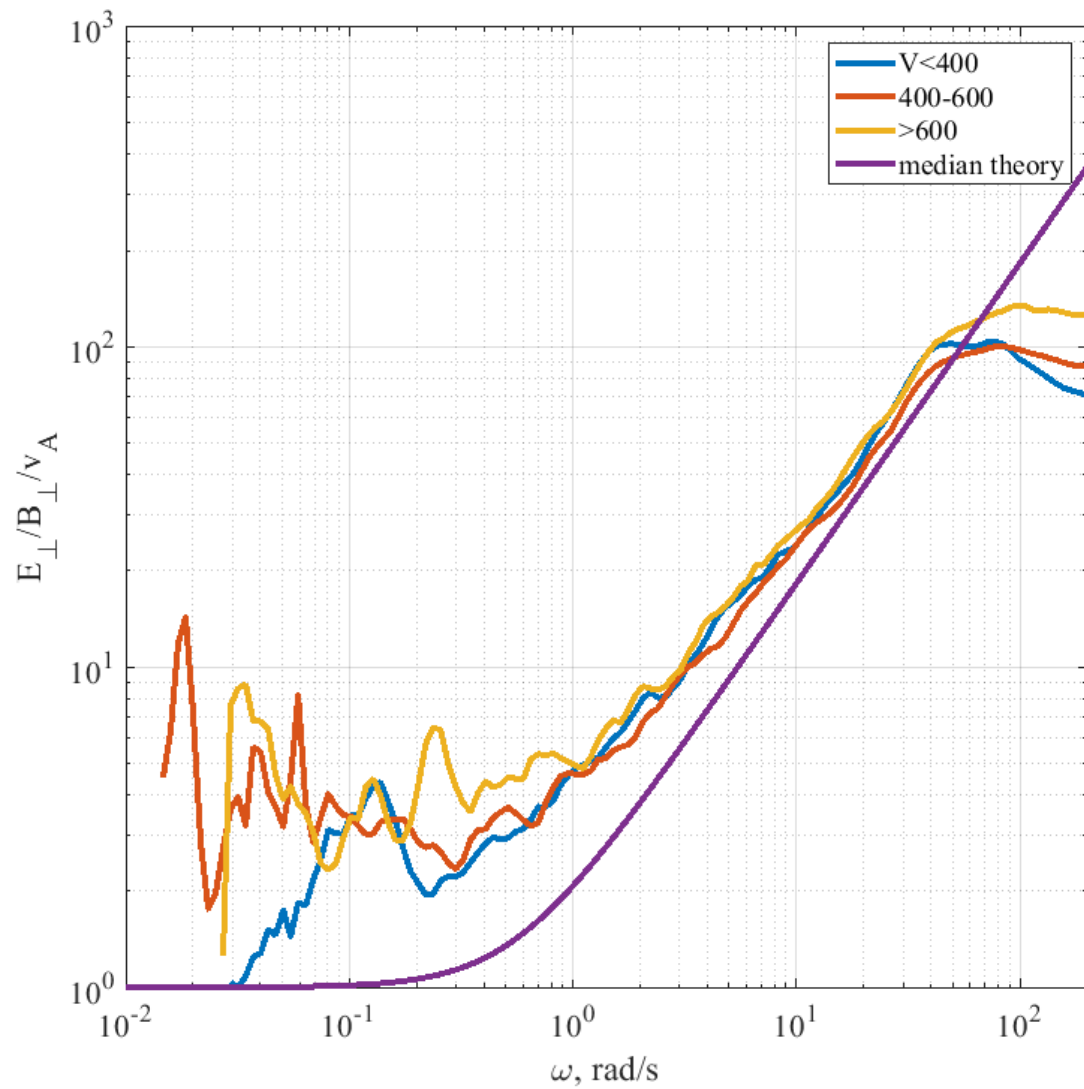


Anisotropy $A_{\perp} = \frac{F_{\perp} - F_{\parallel}}{F_{\perp} + F_{\parallel}}$ as function of $E_{\perp}$ and $E_{\parallel}$ normalized magnitudes ((magnitudes are normalized by mean value of $|V \times B|$ electric field)).

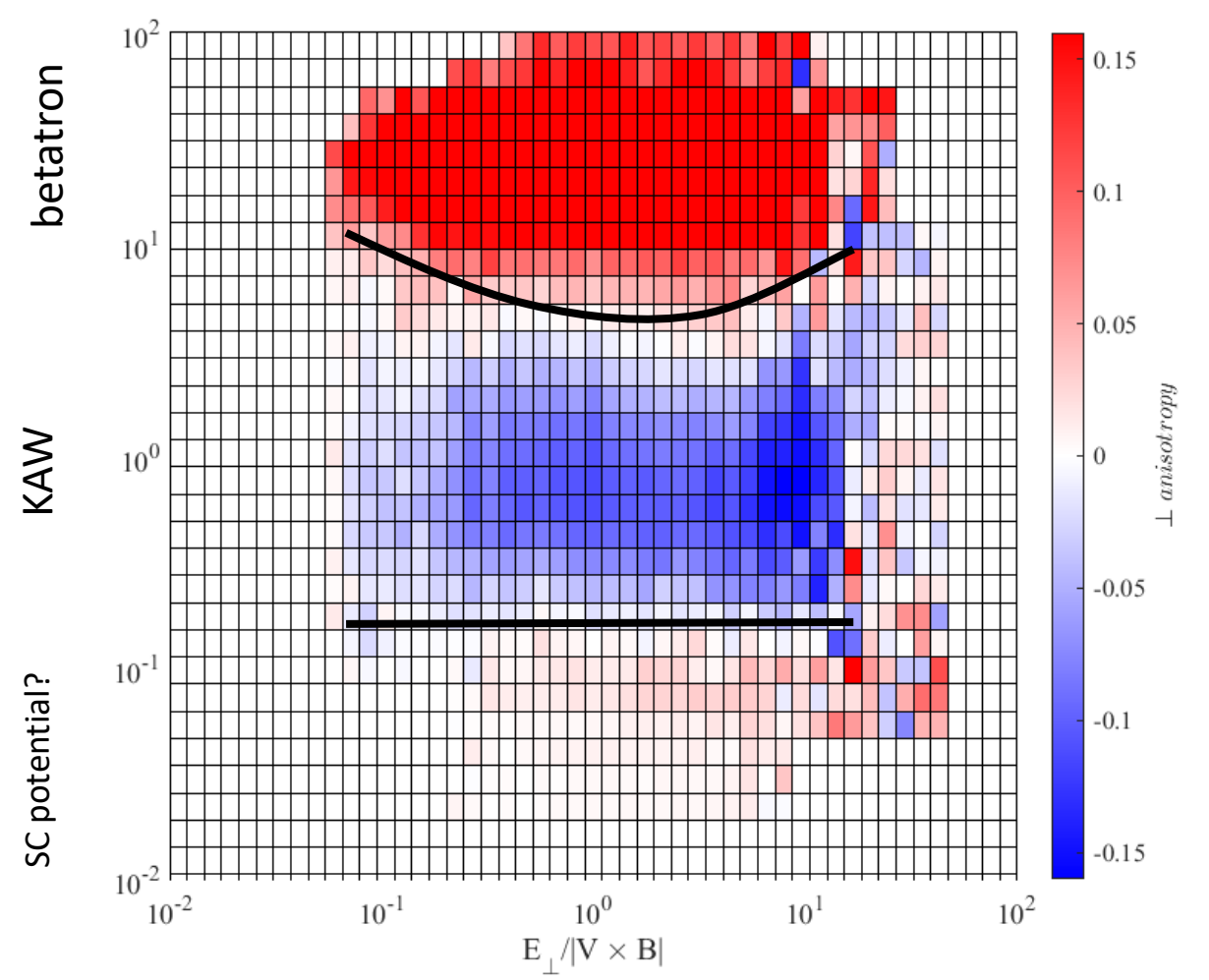
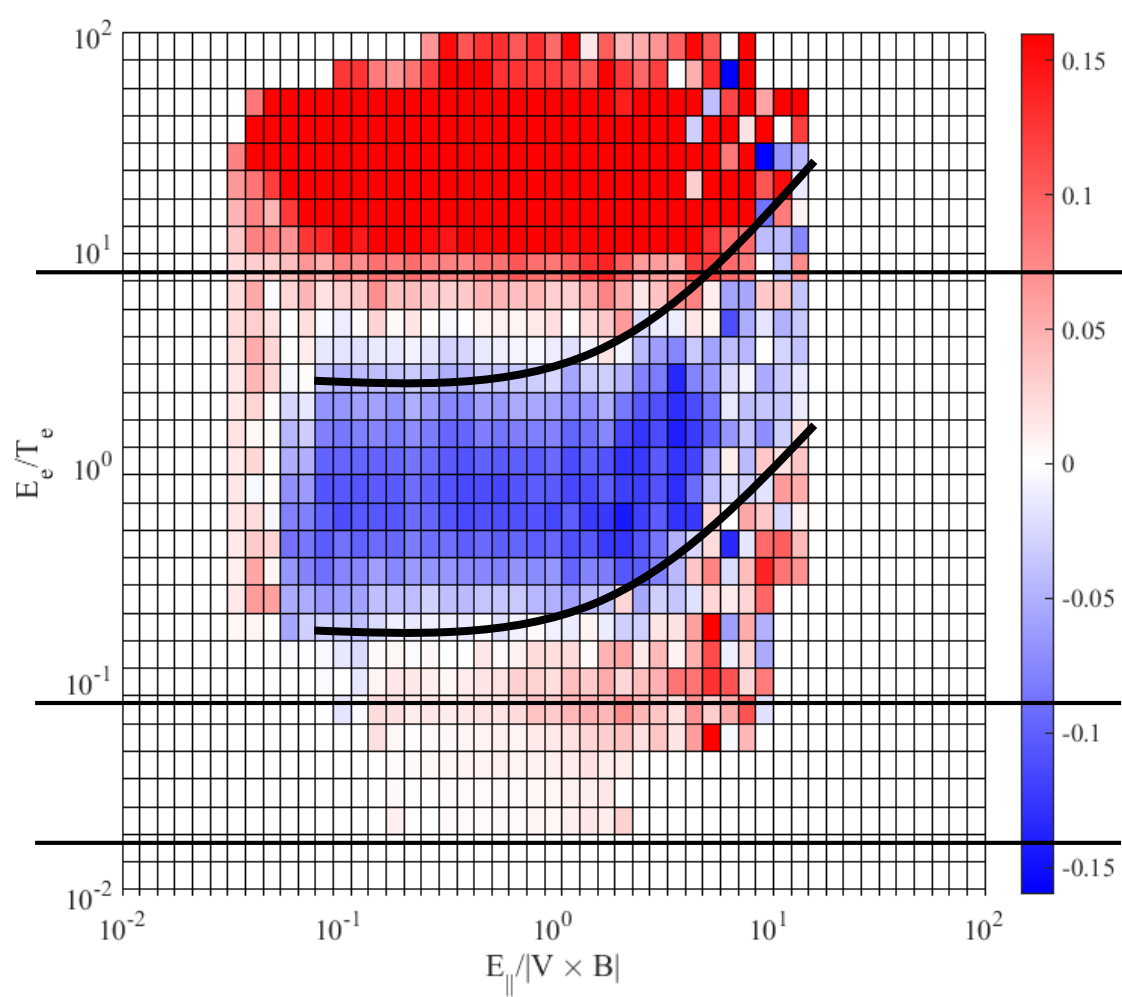
Statistics

80 events (2018-2019)

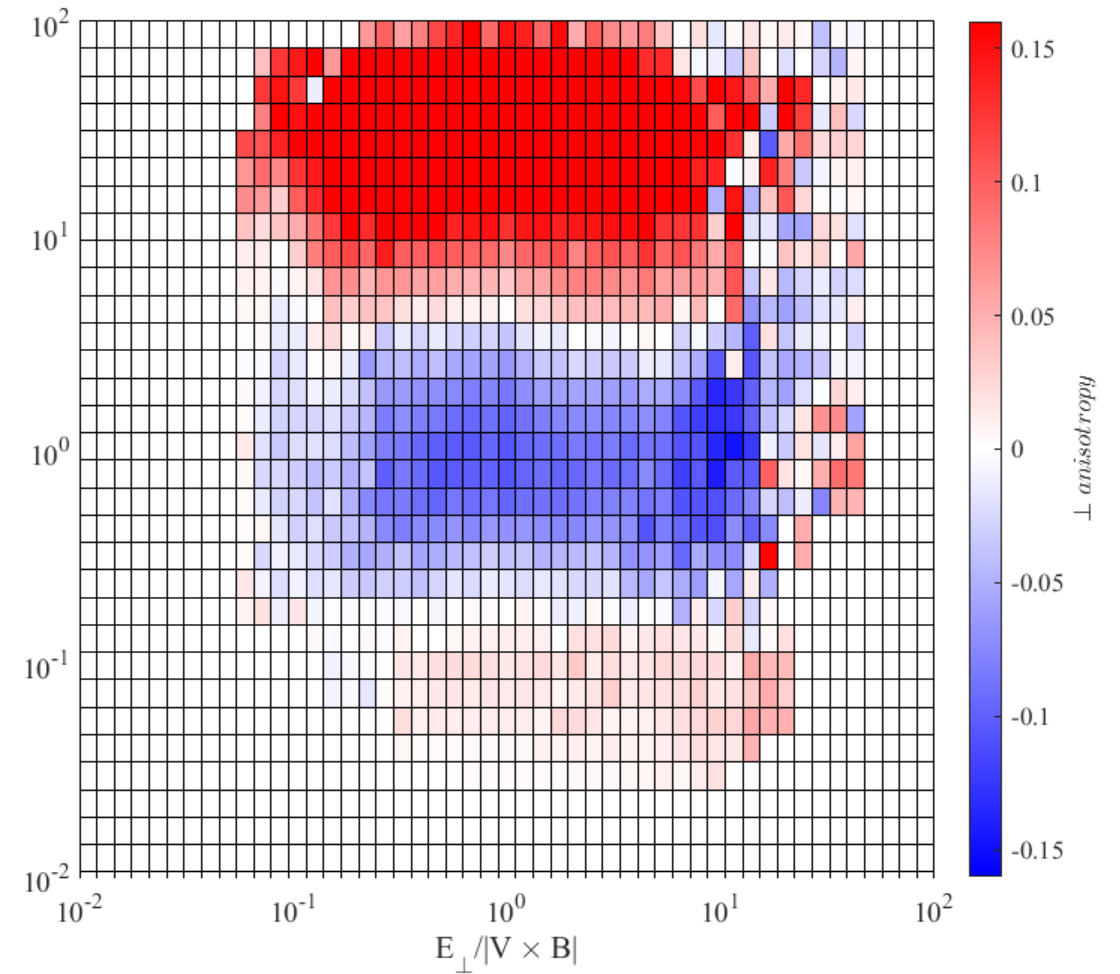
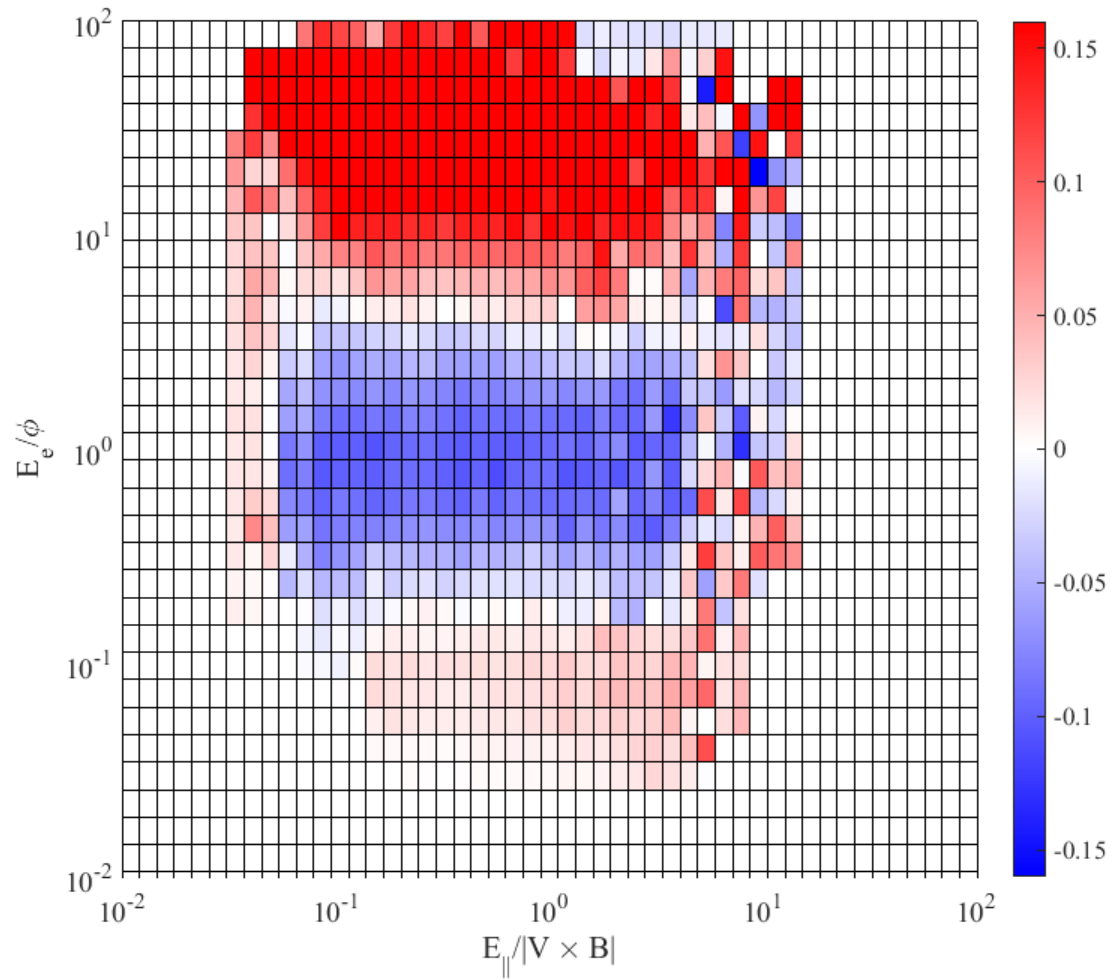




Averaged spectra divided into 3 ion bulk velocity bins. There are additional wave modes in small frequency range.



Anisotropy $A_{\perp} = \frac{F_{\perp} - F_{\parallel}}{F_{\perp} + F_{\parallel}}$ as function of $E_{\perp}$ and $E_{\parallel}$ normalized magnitudes (magnitudes are normalized by mean value of $|V \times B|$ electric field).



Anisotropy $A_{\perp} = \frac{F_{\perp} - F_{\parallel}}{F_{\perp} + F_{\parallel}}$ as function of $E_{\perp}$ and $E_{\parallel}$ normalized magnitudes (magnitudes are normalized by mean value of $|\mathbf{V} \times \mathbf{B}|$ electric field).

Results and conclusion

- Using two years of MMS observations we have collected 80 clear BBF events during which electromagnetic wave spectra represent KAW properties in frequency range of $\sim 0.1 - 10 \text{ Hz}$.
- There is a correlation between the intensity of KAWs and increase in electron parallel anisotropy.