Large-amplitude high-frequency waves at Earth's magnetopause

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[Graham, D. B., Vaivads, A., Khotyaintsev, Yu. V., Andre, M., et al. (2018). Large-amplitude high-frequency waves at Earth's magnetopause. Journal of Geophysical Research: Space Physics, 123.https://doi.org/10.1002/2017JA025034]

Outline

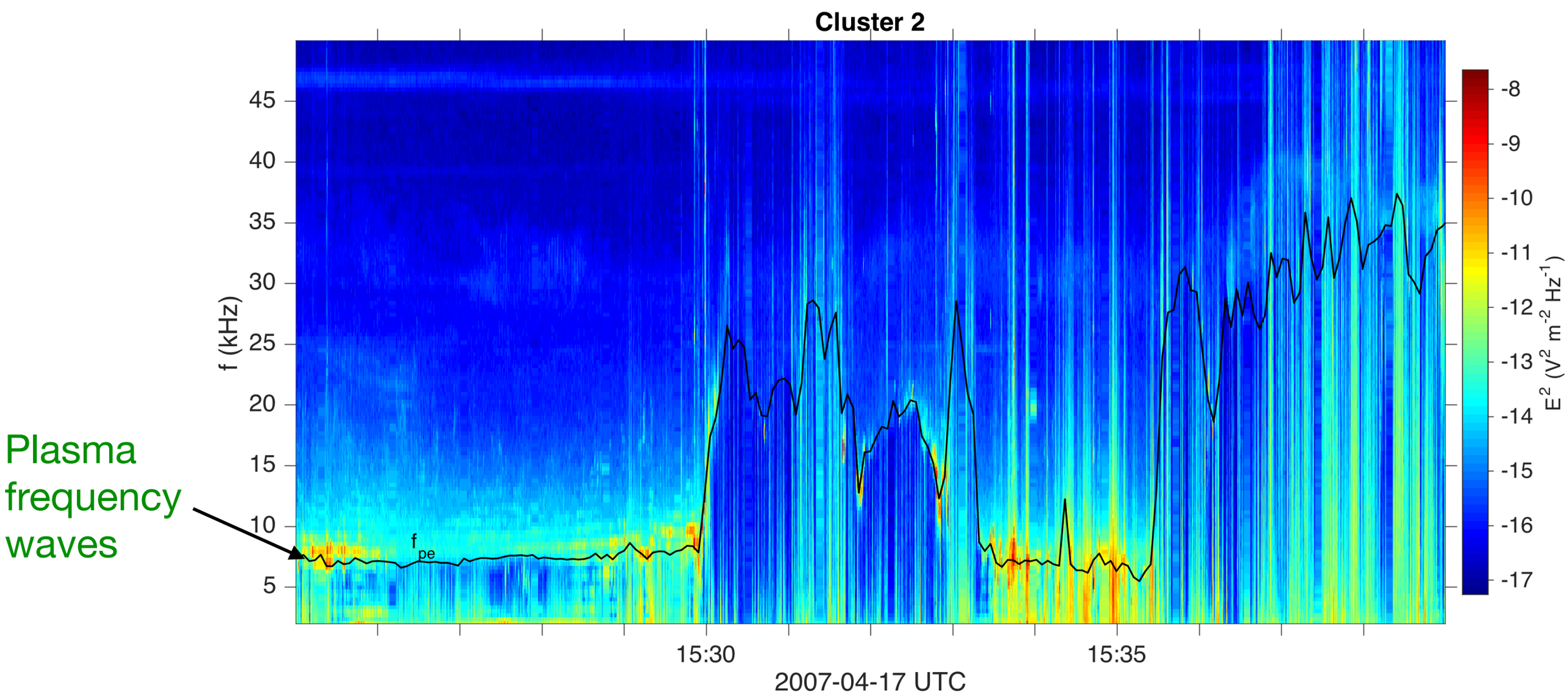
- Background and motivation
- Theory
- Wave observations
- Statistical results
- Conclusions

Background and motivation

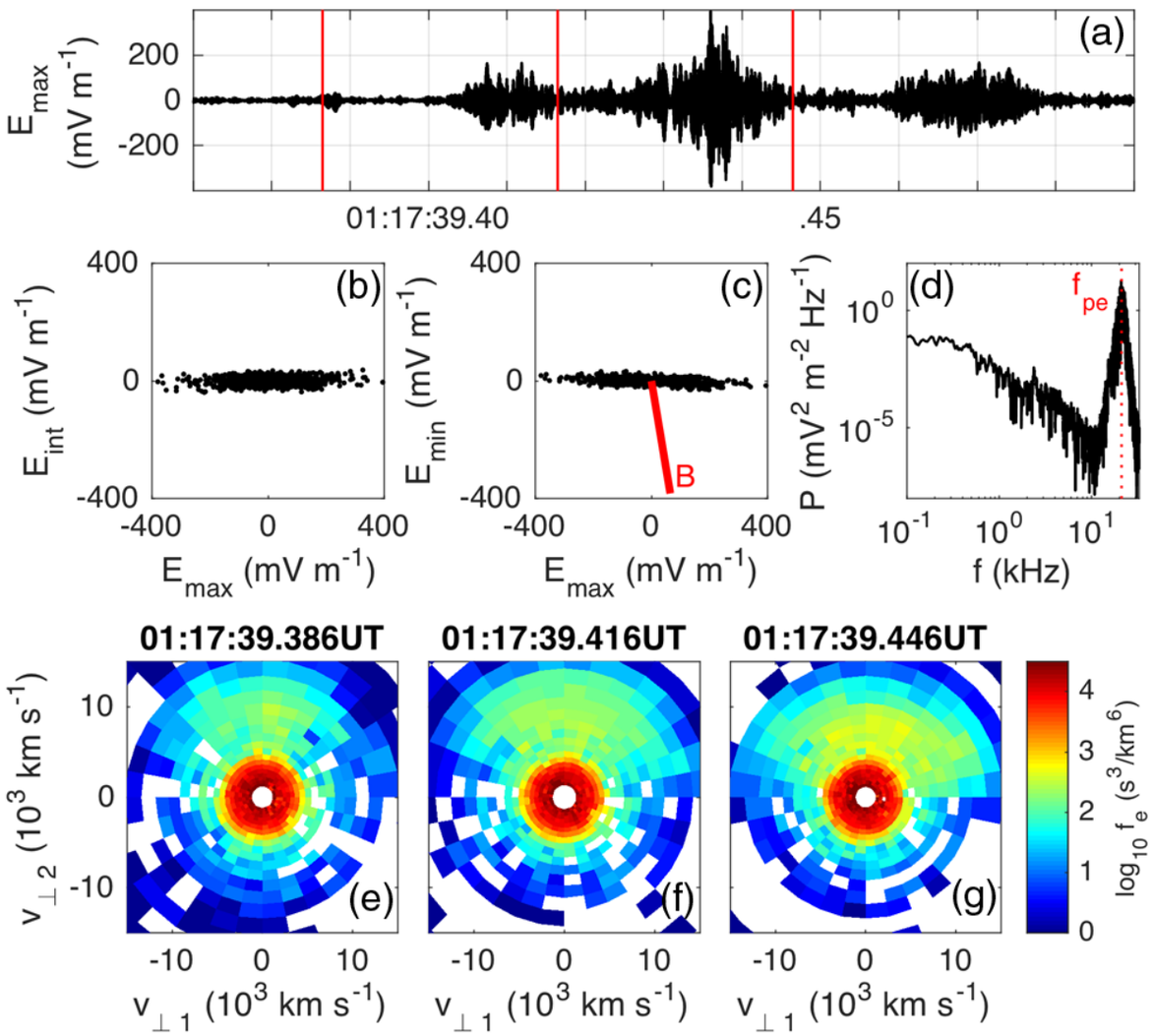
- Langmuir ($k_{\parallel} >> k_{\perp}$) and/or upper hybrid ($k_{\parallel} << k_{\perp}$) waves have been reported at Earth's magnetopause.

[e.g., Gurnett et al., 1978; Anderson et al., 1982]

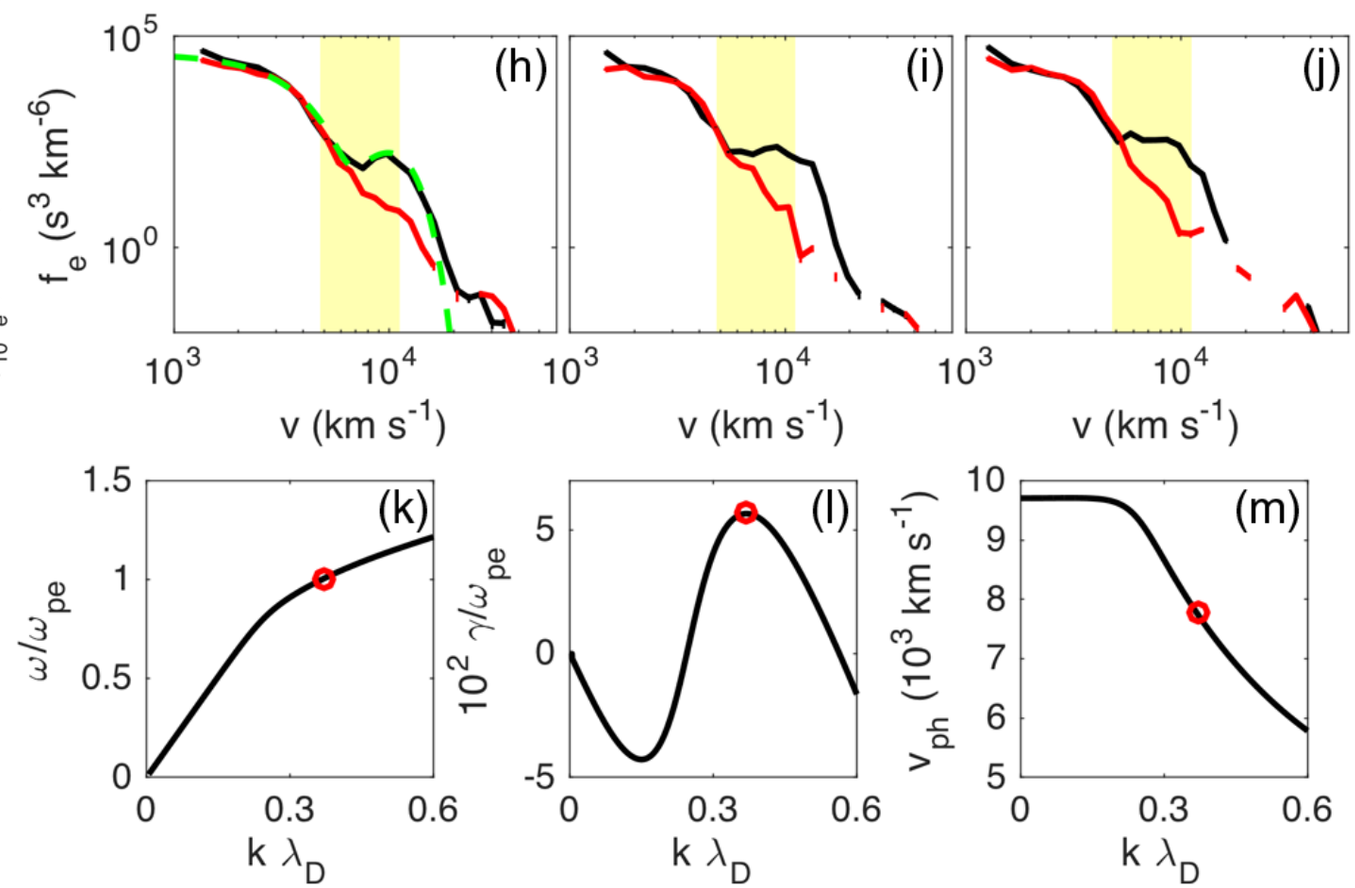
Waves at the magnetopause



Magnetic reconnection



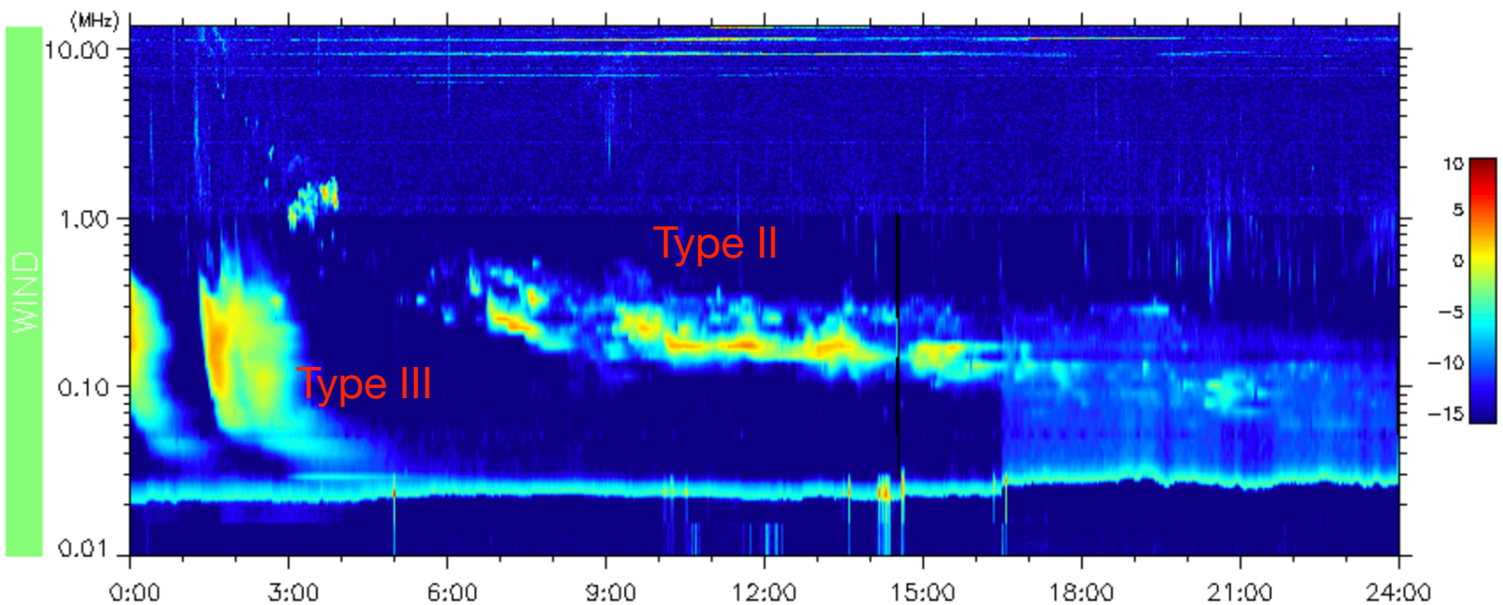
- Plasma frequency waves generated near a reconnection electron diffusion region.



- Waves are generated by an agyrotropic electron beam.

[Graham et al., 2017]

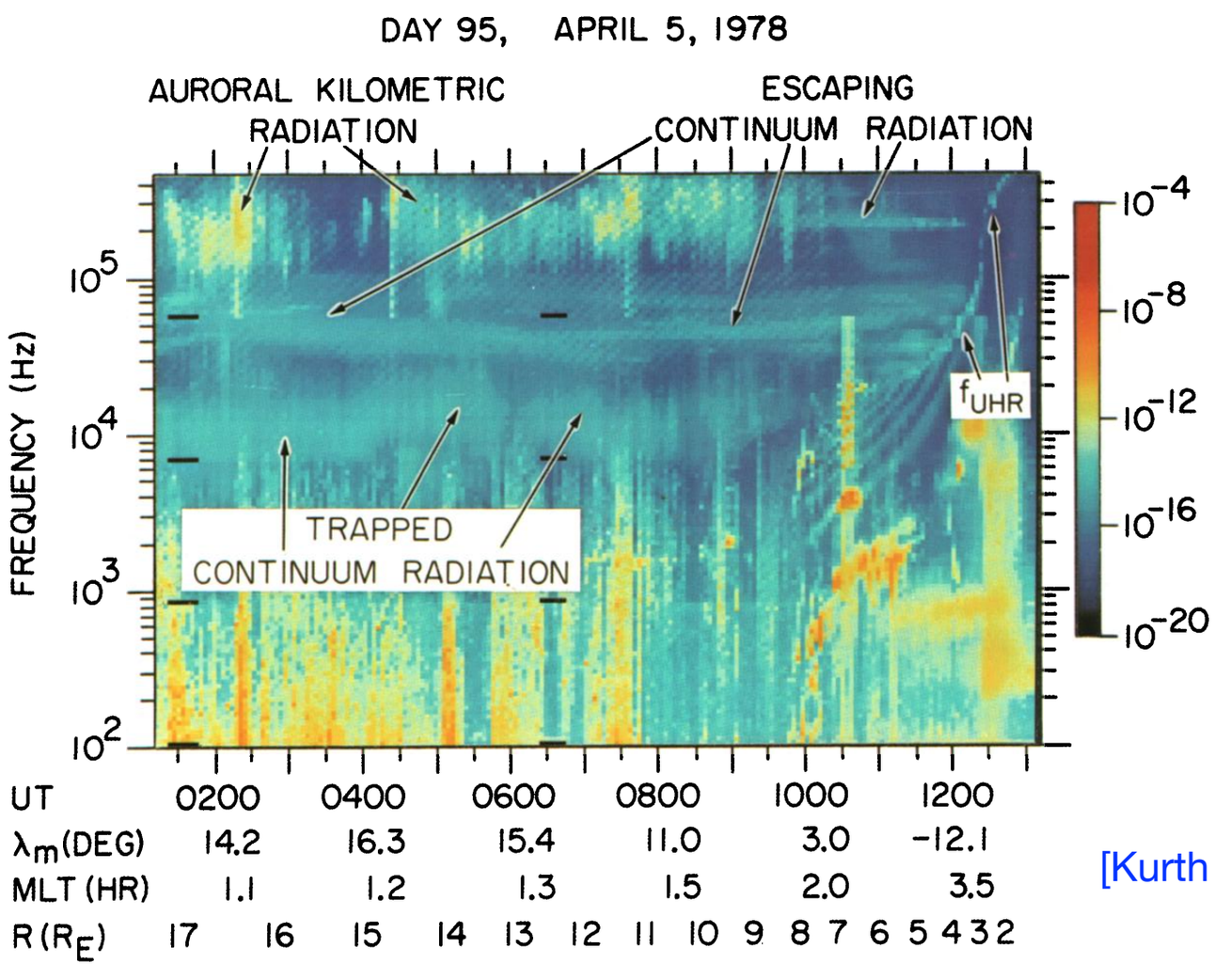
Radio emission



- Type II and type III radio bursts (Wind data).

2017 July 14

- Langmuir and UH waves can generate radio waves by linear or nonlinear processes.



- Continuum radio emission and AKR.

[Kurth et al., 1981]

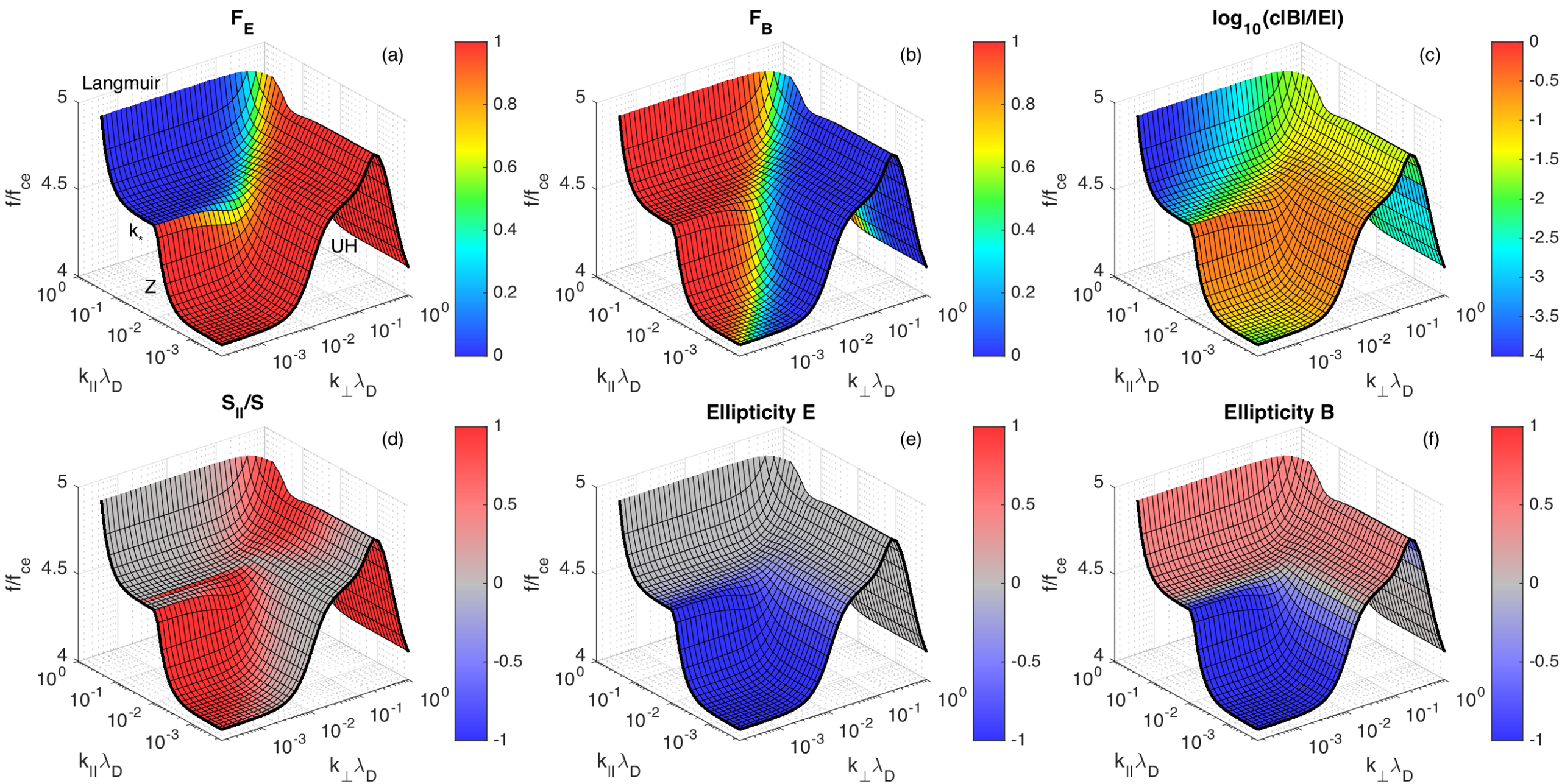
Langmuir/UH dispersion surface

- Single electron Maxwellian distribution.

$$F_E = \frac{\sum E_\perp(t)^2}{\sum E_\perp(t)^2 + \sum E_\parallel(t)^2}.$$

$$F_B = \frac{\sum B_\perp(t)^2}{\sum B_\perp(t)^2 + \sum B_\parallel(t)^2}.$$

T_e = 200 eV; n_e = 0.5 cm^{-3}; B_0 = 50 nT



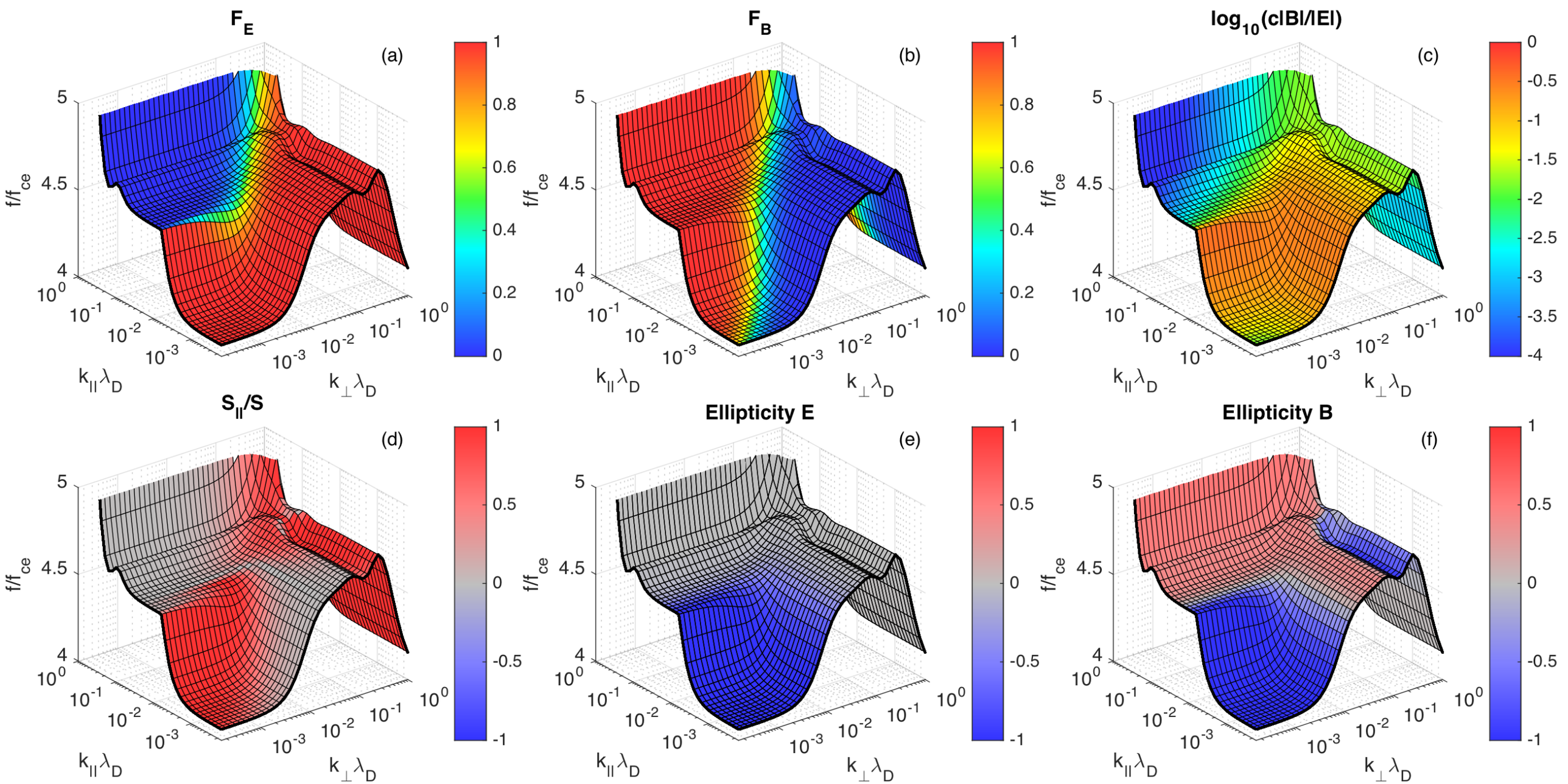
Langmuir/UH dispersion surface

- Hot and cold electron Maxwellian distributions

n_e = 0.5 cm^{-3}; n_{ec} = 0.95n_e; n_{eh} = 0.05ne;
T_{ec} = 100 eV; Teh = 2keV; B_0 = 50 nT

$$F_E = \frac{\sum E_\perp(t)^2}{\sum E_\perp(t)^2 + \sum E_\parallel(t)^2}.$$

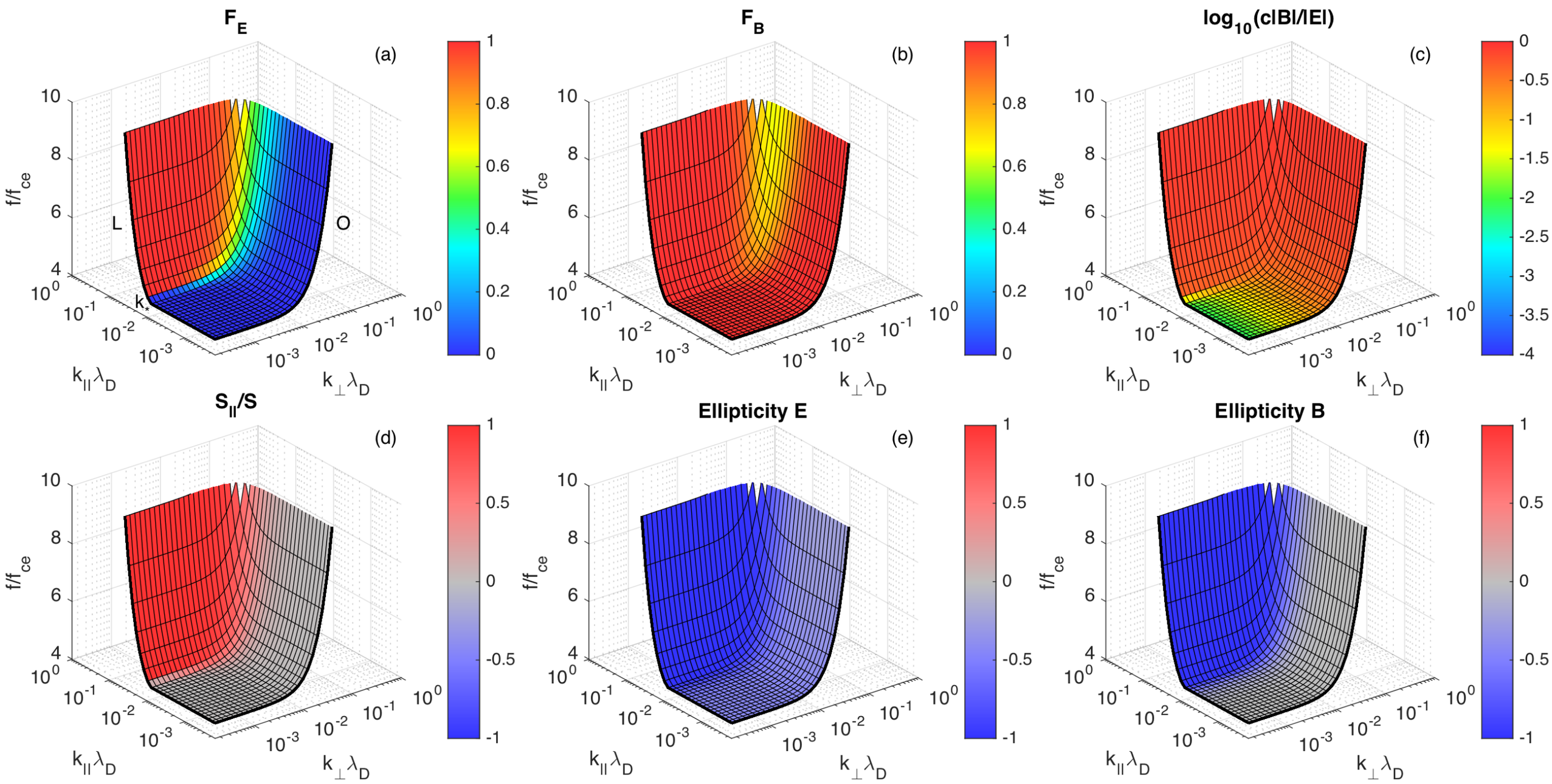
$$F_B = \frac{\sum B_\perp(t)^2}{\sum B_\perp(t)^2 + \sum B_\parallel(t)^2}.$$



L-O surface

$$F_E = \frac{\sum E_\perp(t)^2}{\sum E_\perp(t)^2 + \sum E_\parallel(t)^2}.$$

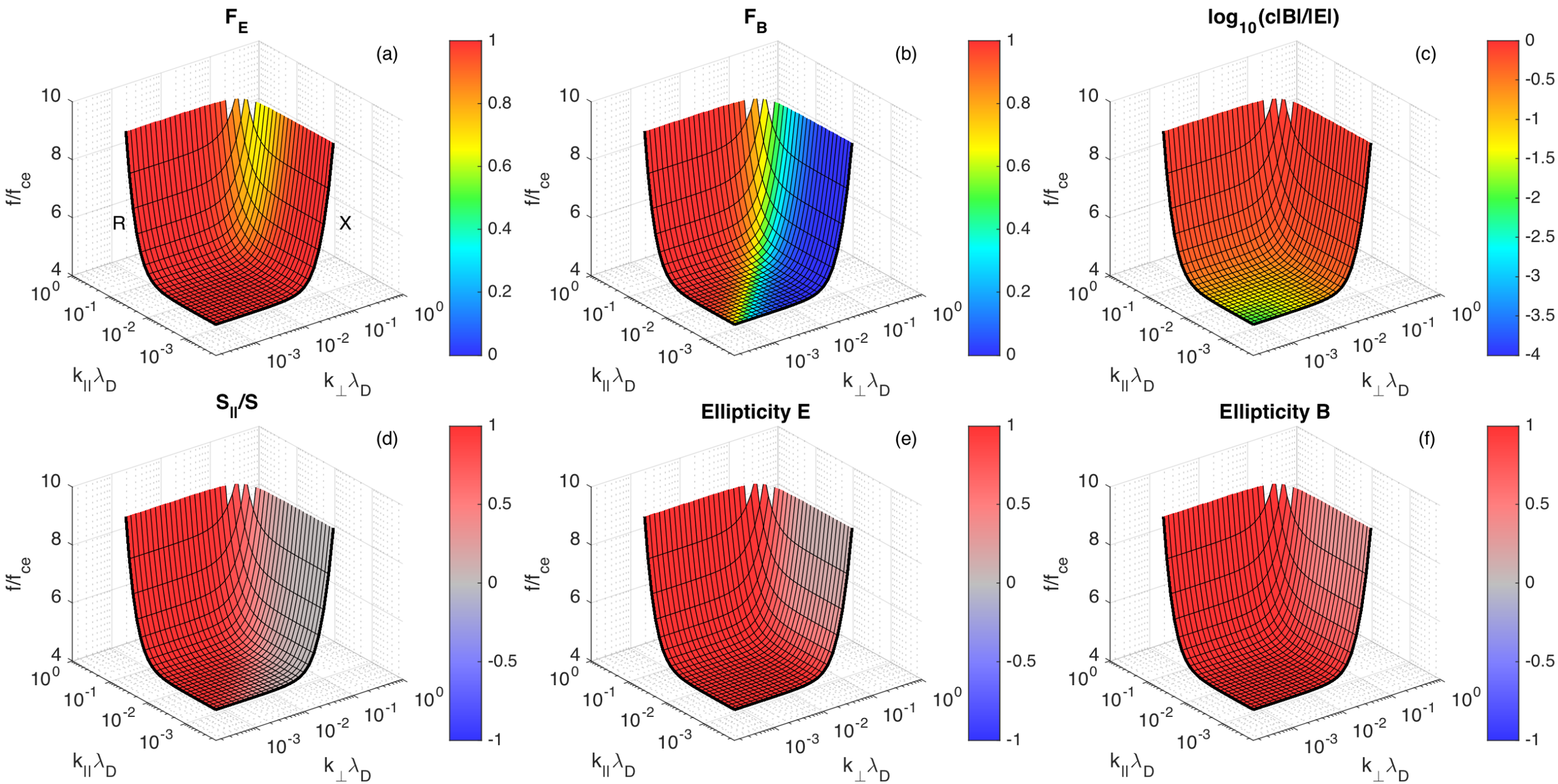
$$F_B = \frac{\sum B_\perp(t)^2}{\sum B_\perp(t)^2 + \sum B_\parallel(t)^2}.$$



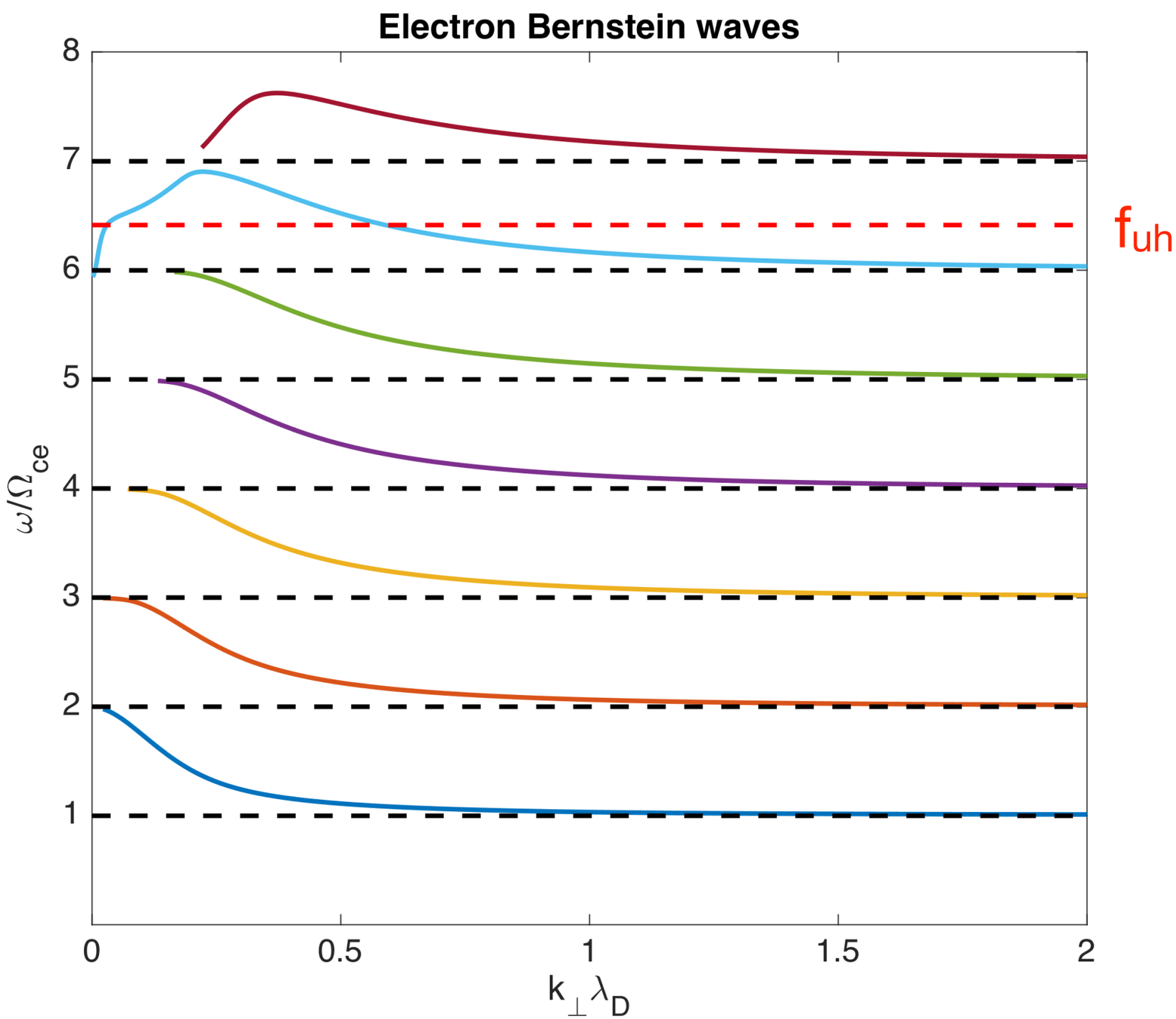
R-X surface

$$F_E = \frac{\sum E_\perp(t)^2}{\sum E_\perp(t)^2 + \sum E_\parallel(t)^2}.$$

$$F_B = \frac{\sum B_\perp(t)^2}{\sum B_\perp(t)^2 + \sum B_\parallel(t)^2}.$$



Electron Bernstein waves

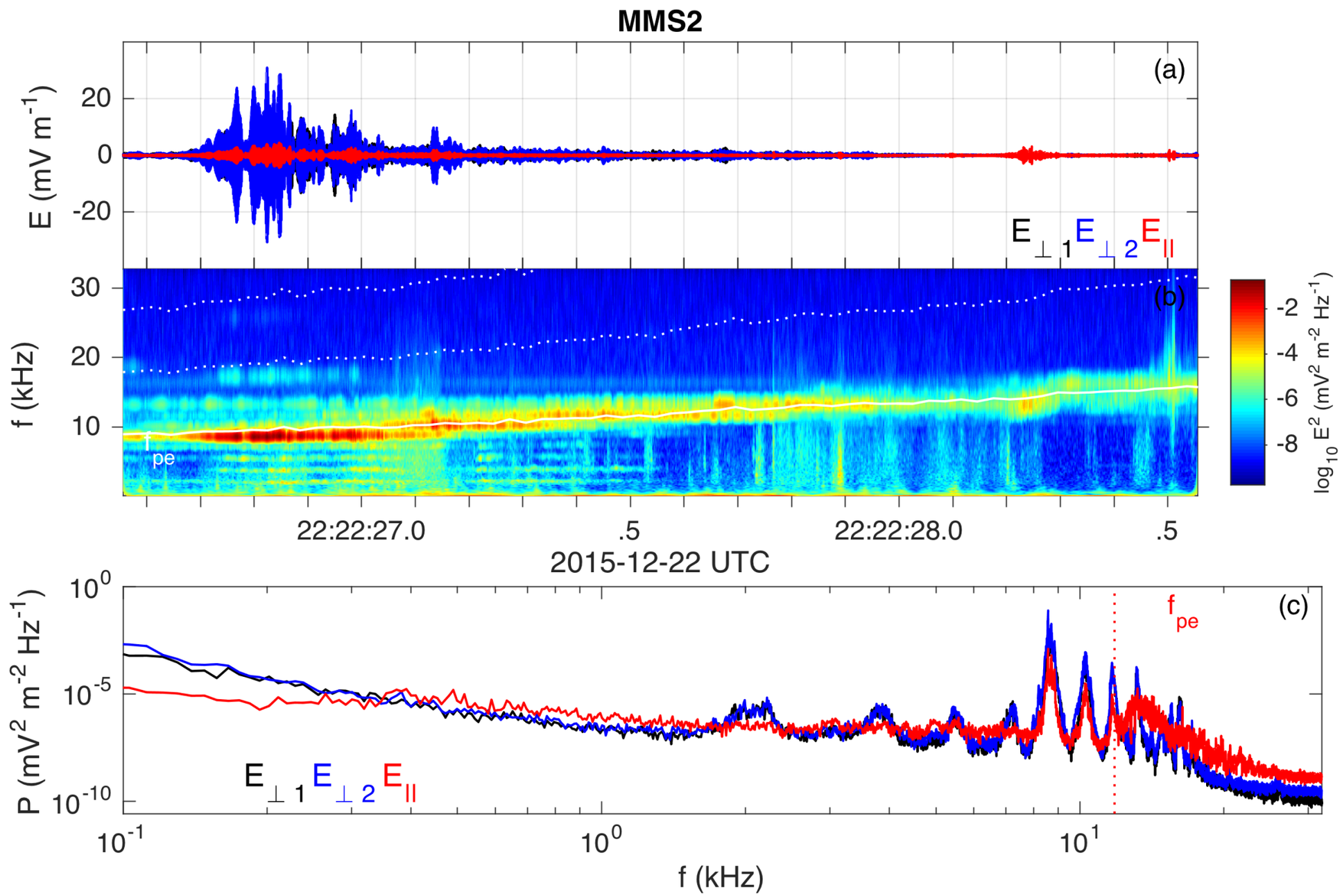


- In addition to the three dispersion surfaces near f_{pe}, electron Bernstein waves can develop between f_{ce} harmonics.

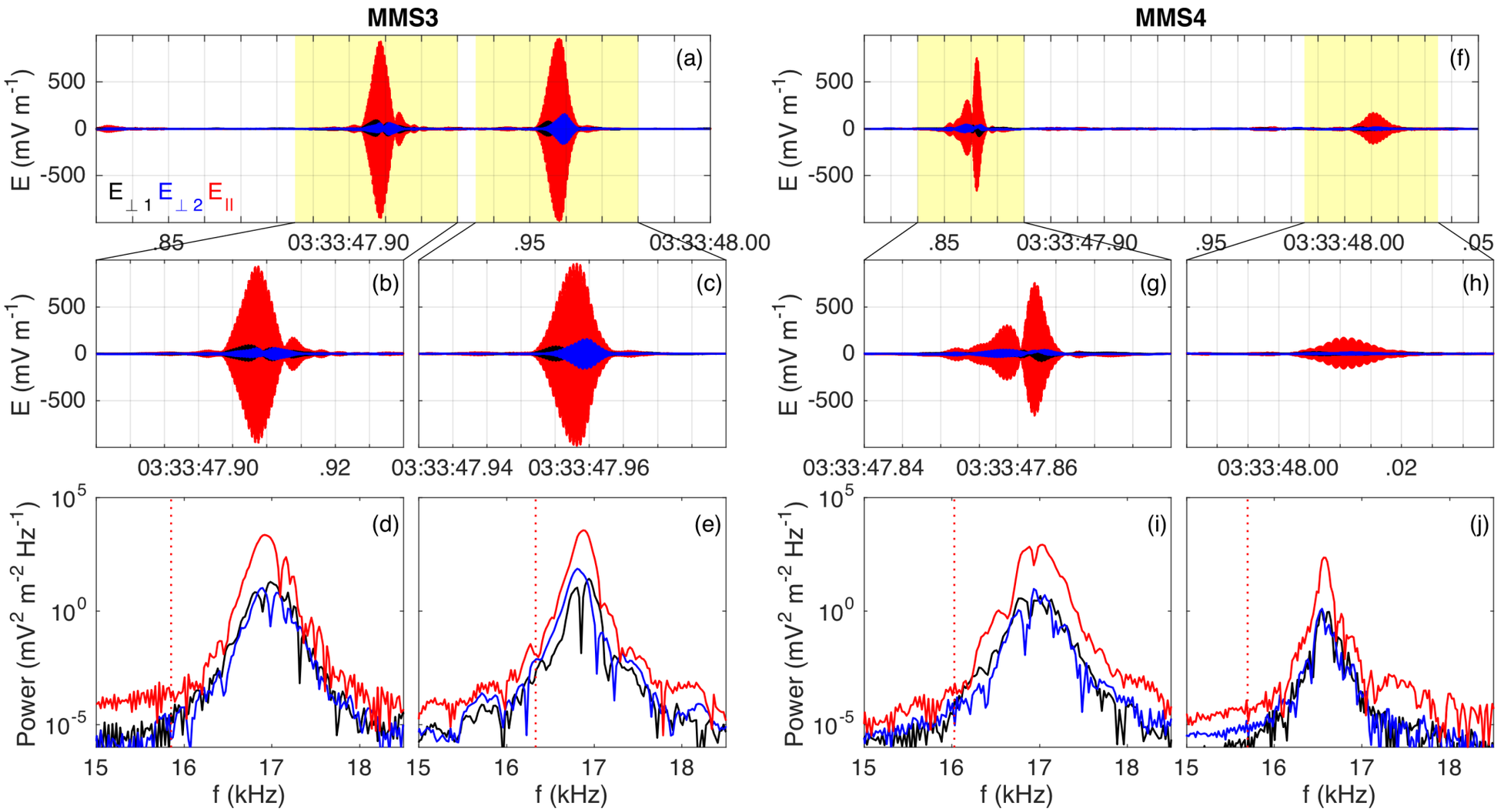
MMS data

- We search through high-resolution electric field data for large-amplitude waves near f_{pe} (E_{max} > 20 mV m^{-1}).
- From MMS magnetopause phases we find 8837 wave events (most near the MP, some near the foreshock).

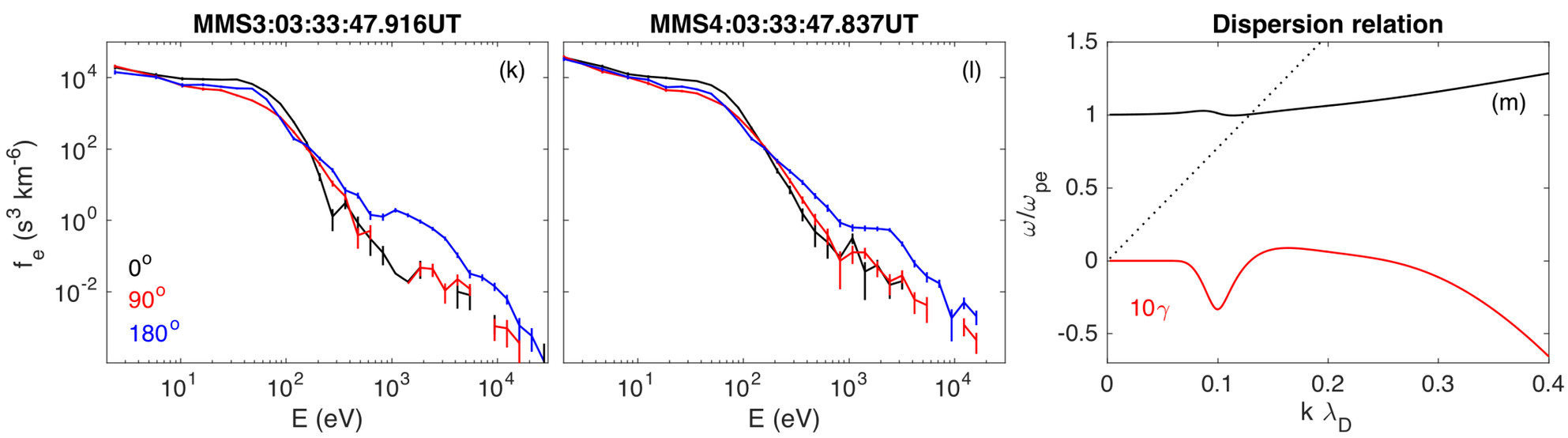
Example wave event near the magnetopause



Langmuir waves (1)

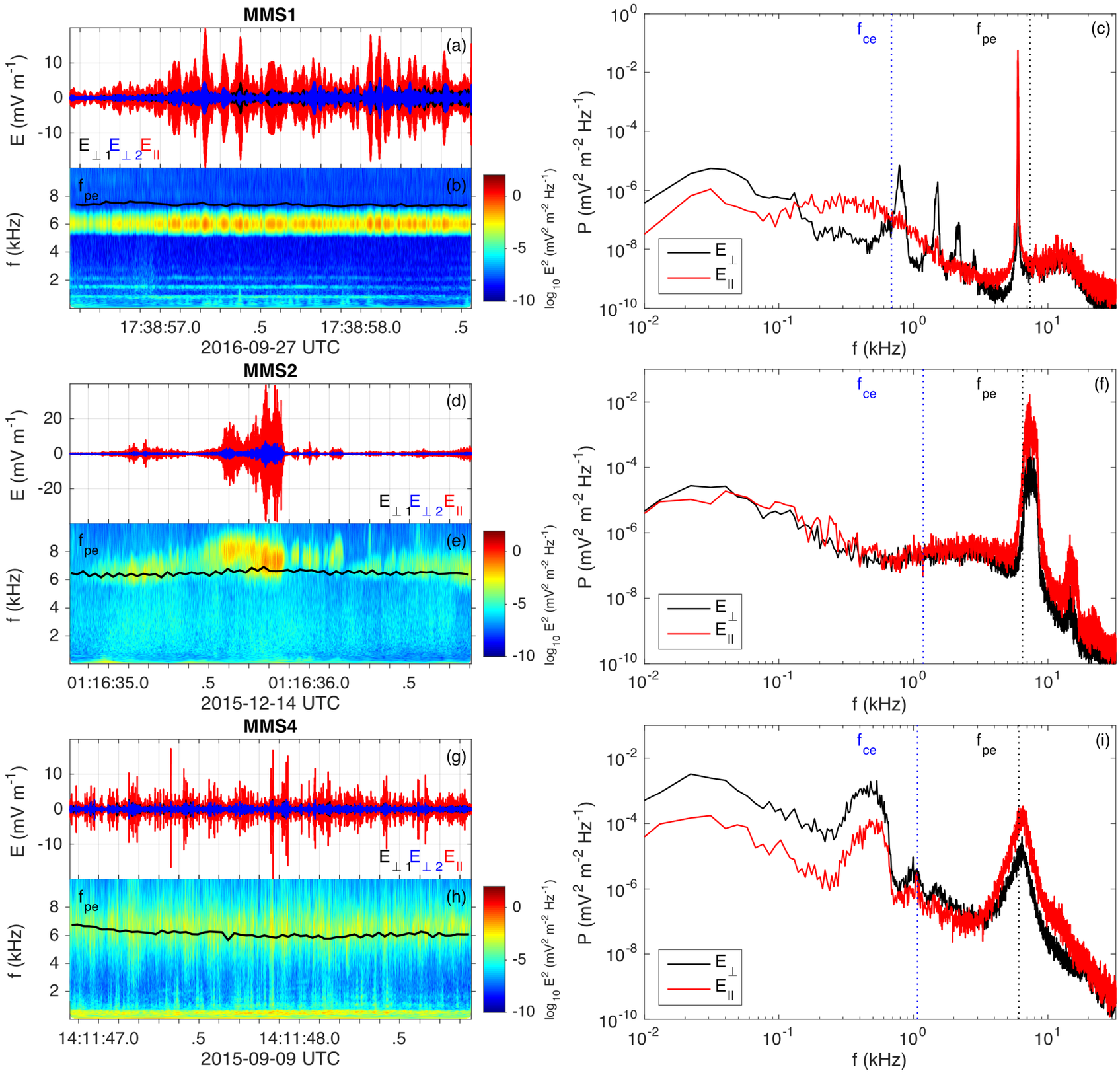


- $E_{\parallel} >> E_{\perp}$



- Langmuir waves are driven by the bump-on-tail instability.

Langmuir waves (2)



- Three examples of Langmuir waves

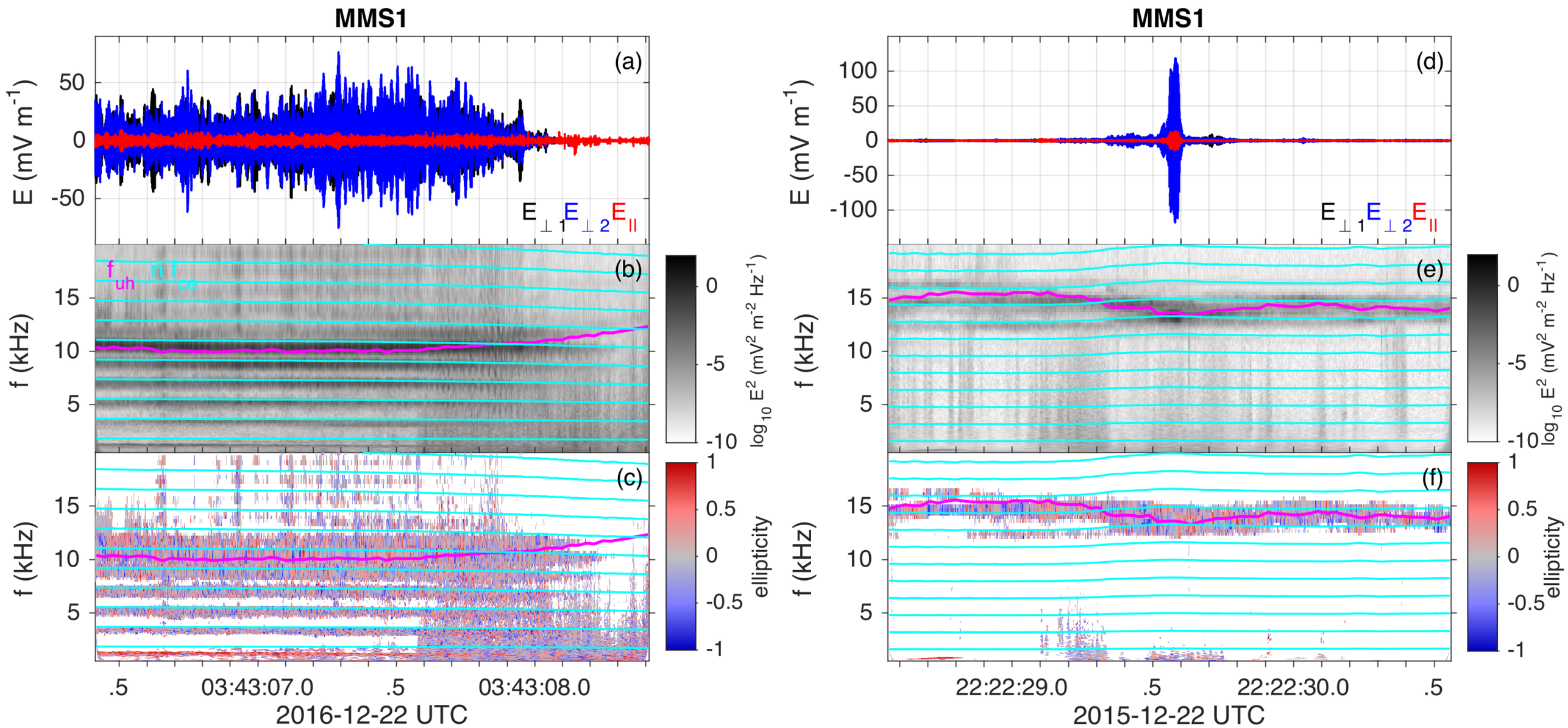
Very narrow spectral peak and Bernstein waves.

Broader spectral peak Langmuir waves.

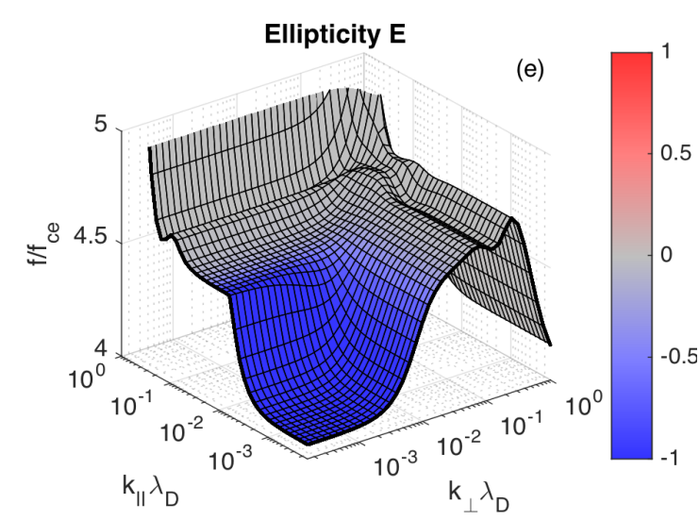
Broad spectral peak Langmuir waves and whistler waves.

[cf., Reinleitner et al.1982]

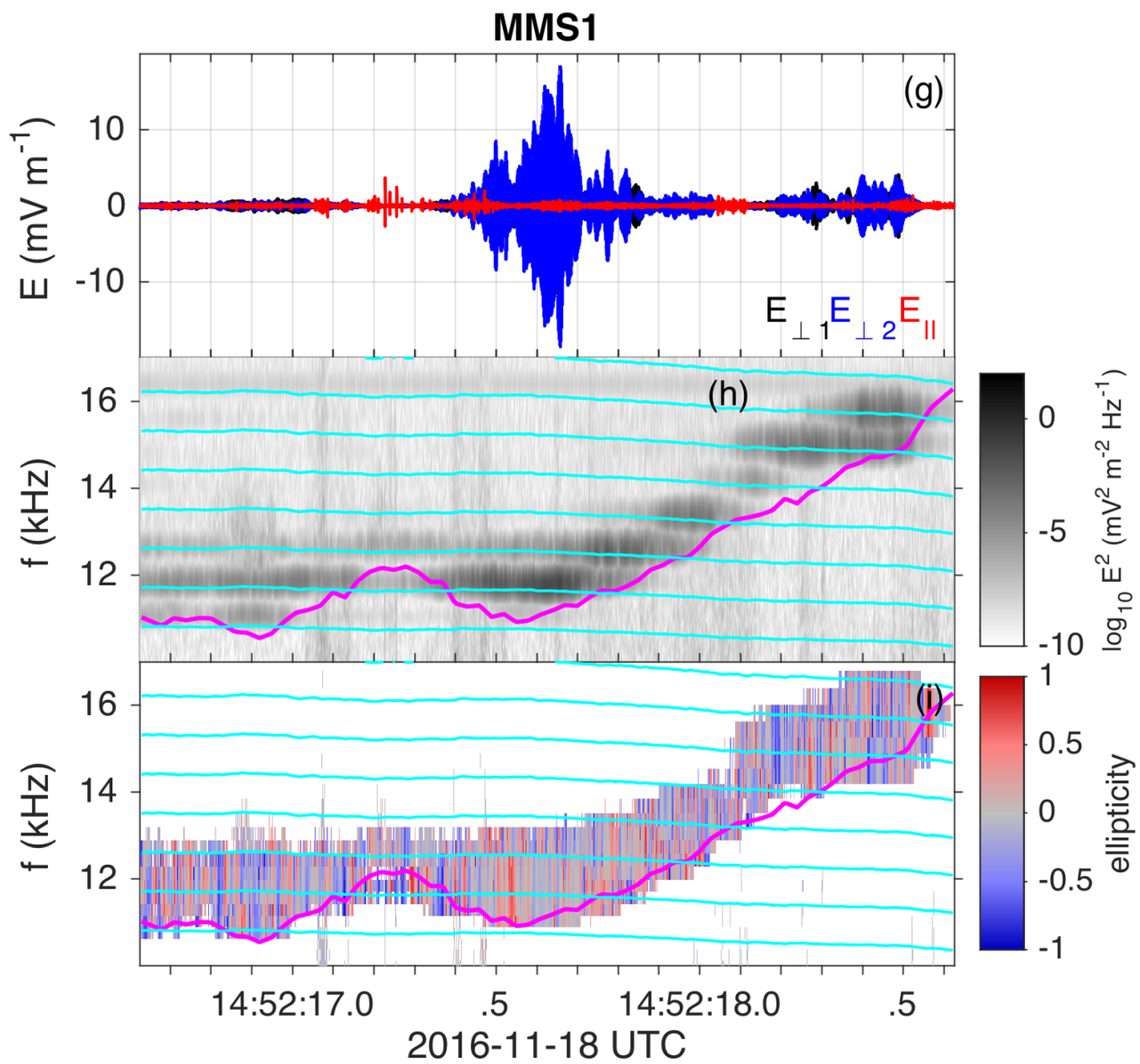
UH waves (1)

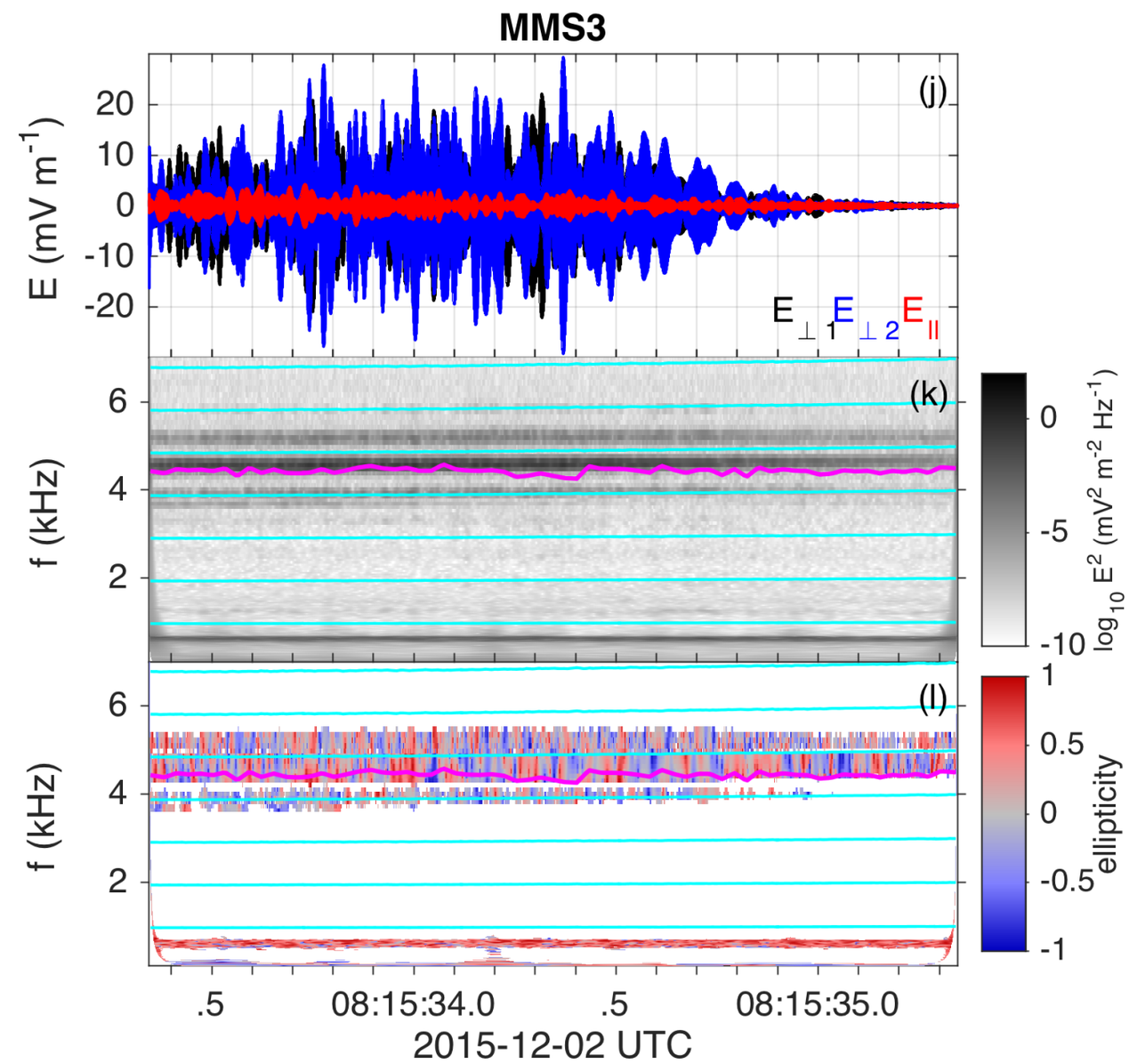


- $E_{\parallel} << E_{\perp}$.
- UH waves are can be simultaneously observed with Bernstein waves and whistlers.



UH waves (2)





- $E_{\parallel} << E_{\perp}$.
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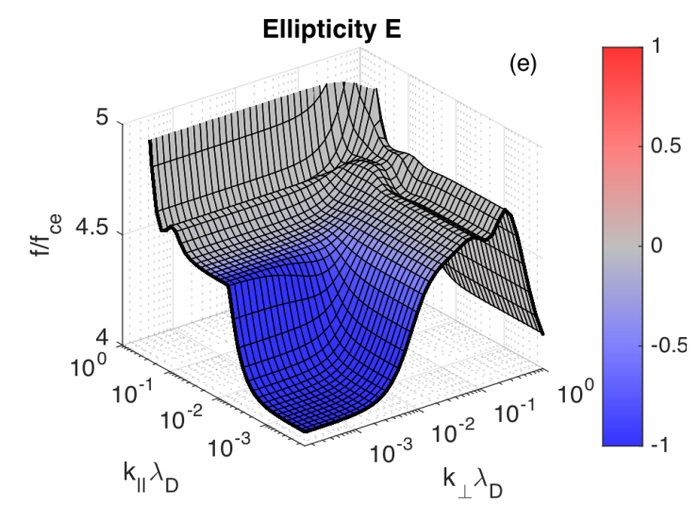
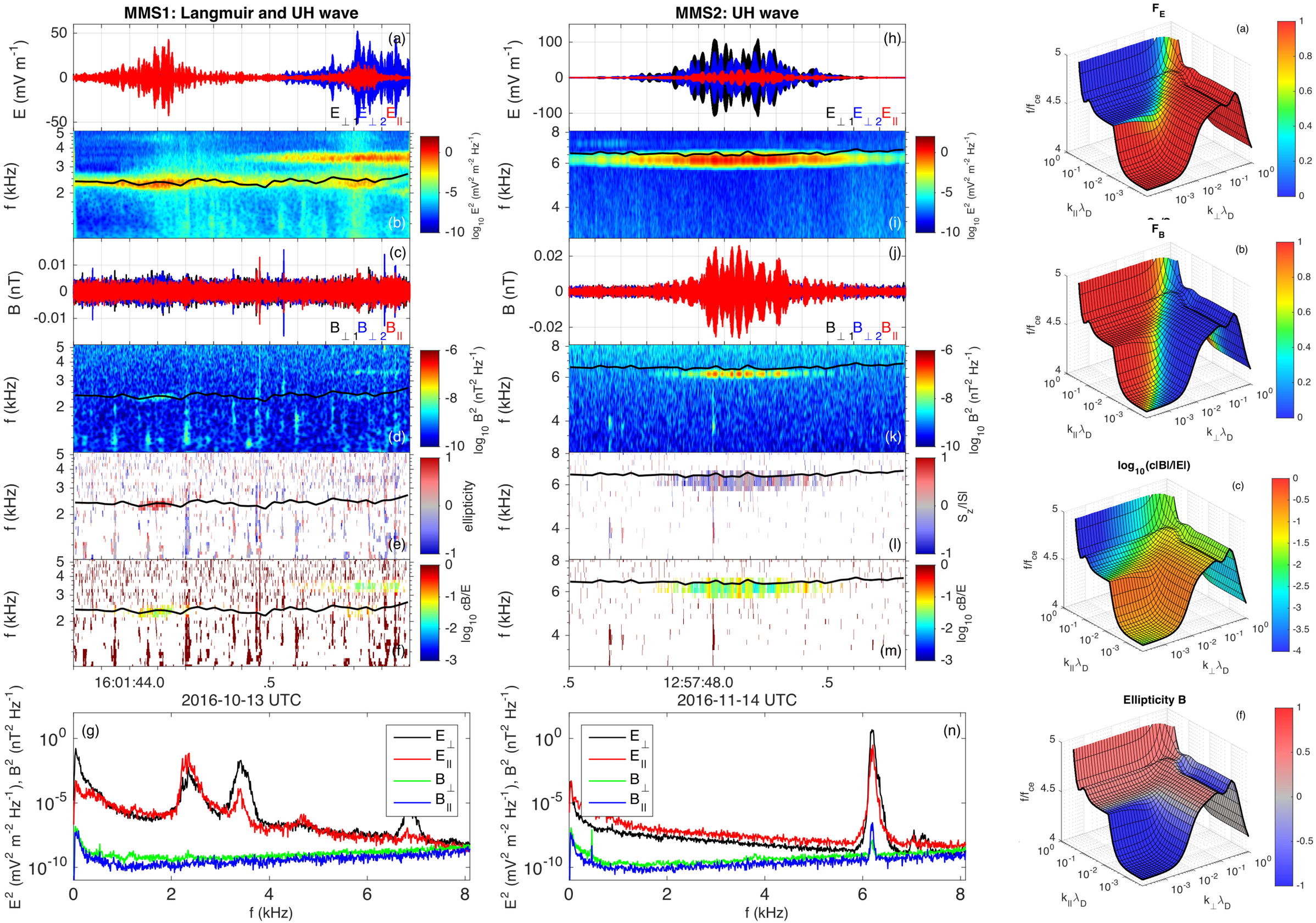
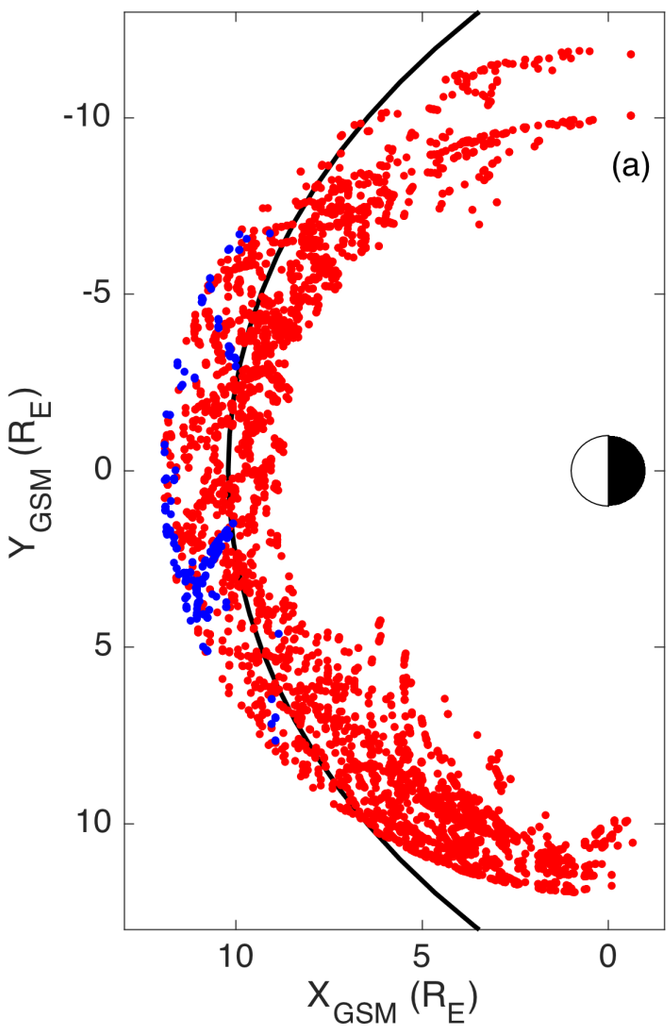
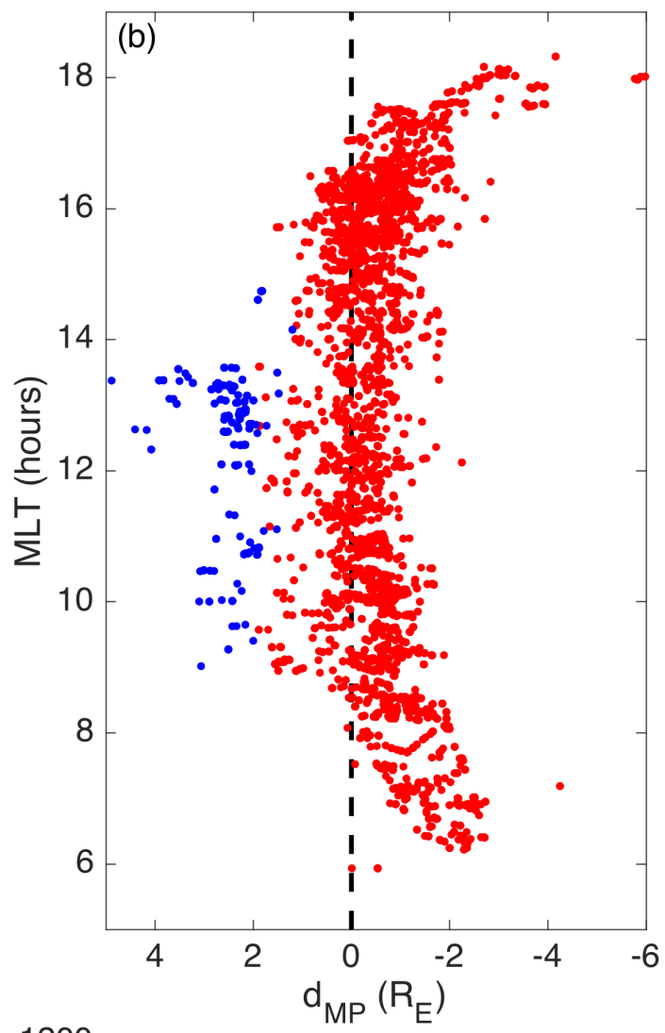


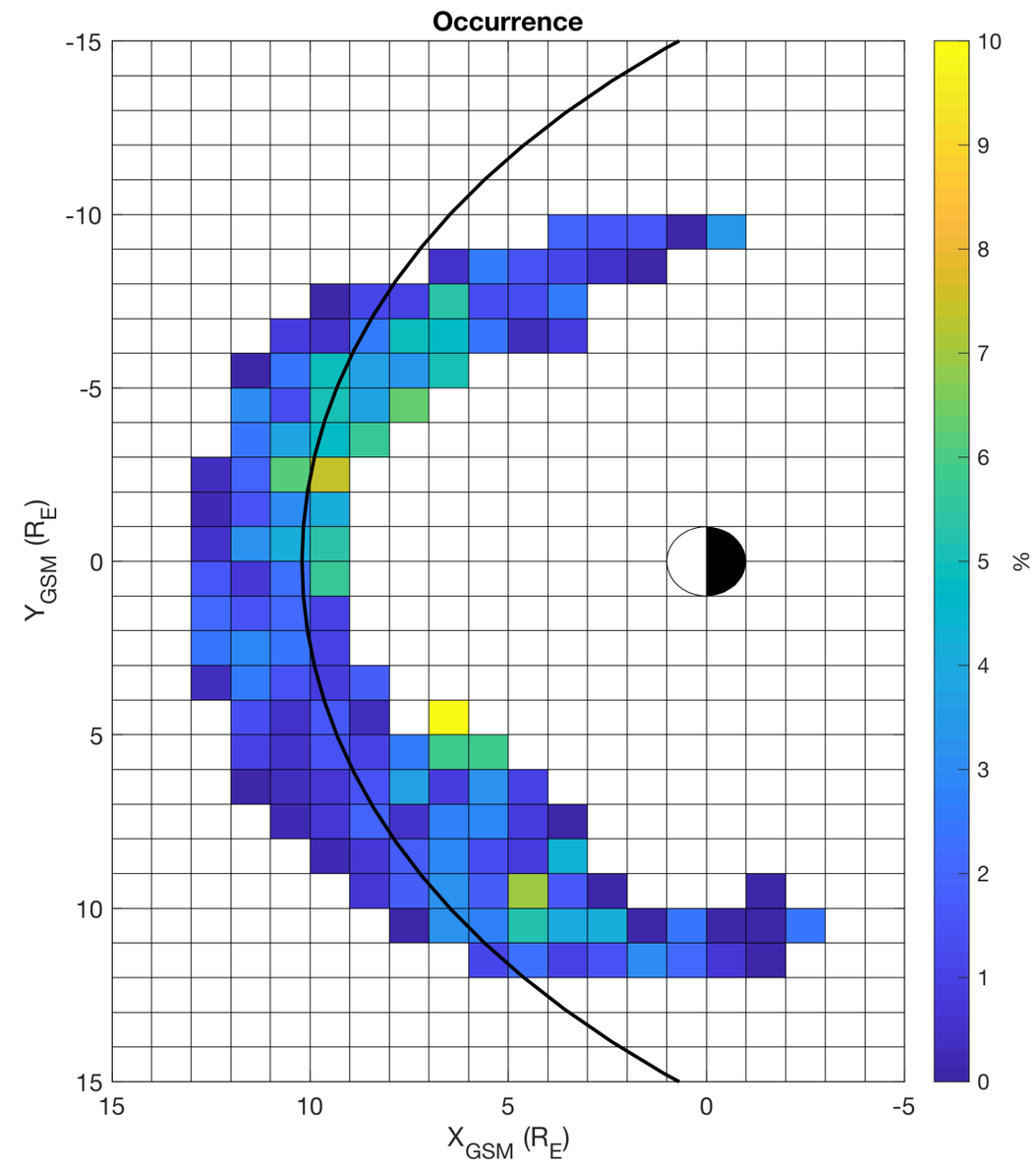
Electromagnetic properties

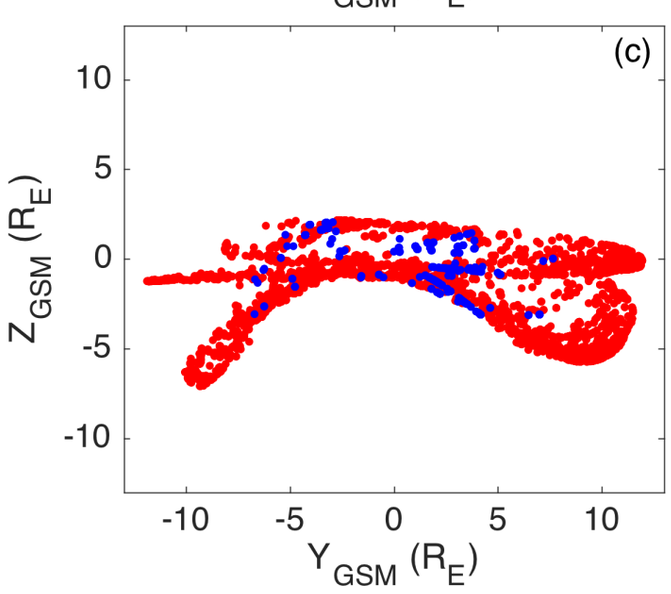


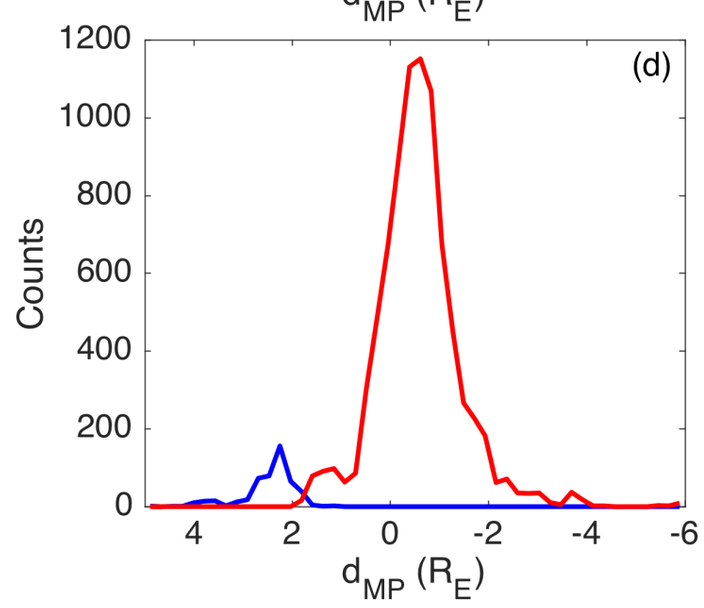
Wave locations











- Average occurrence rate for > 20 mV/m waves is 2.3 %.

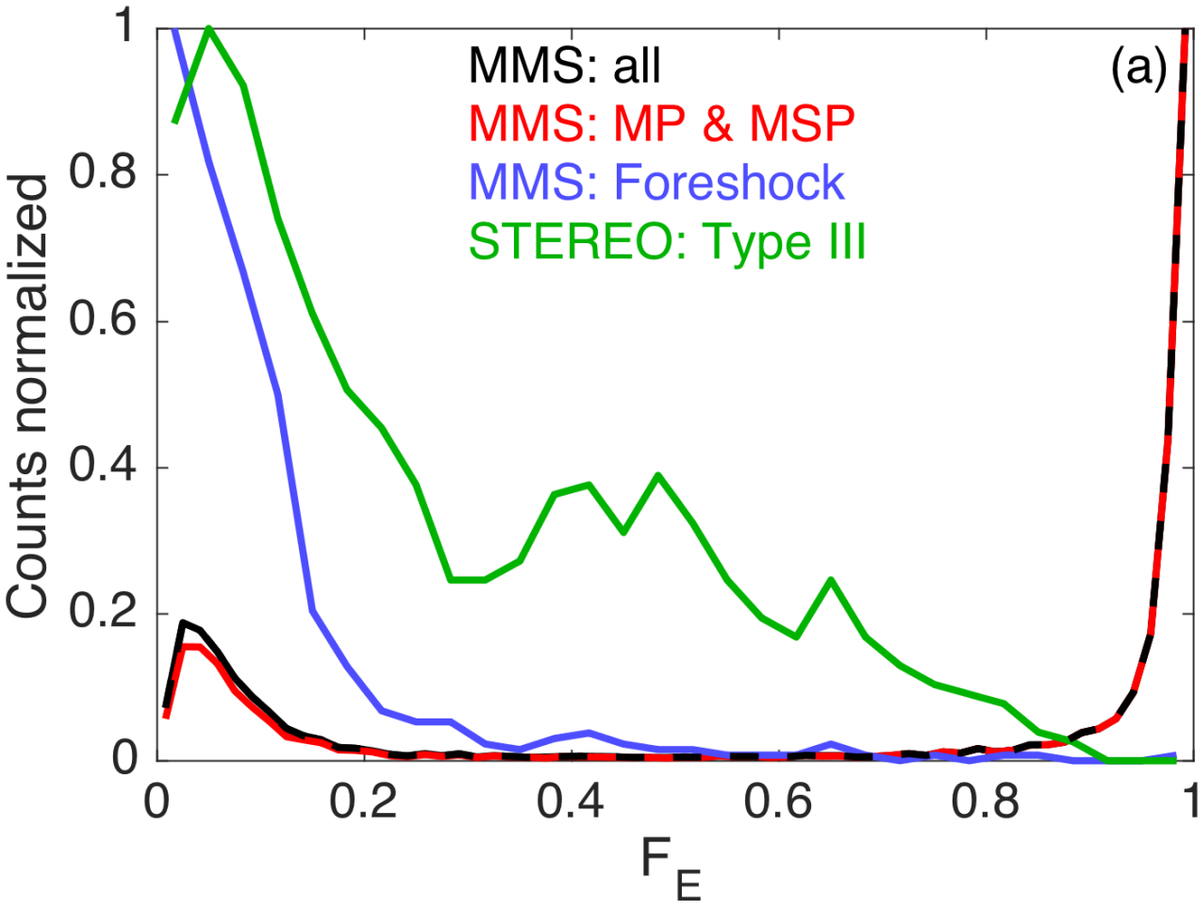
MP waves
Foreshock waves

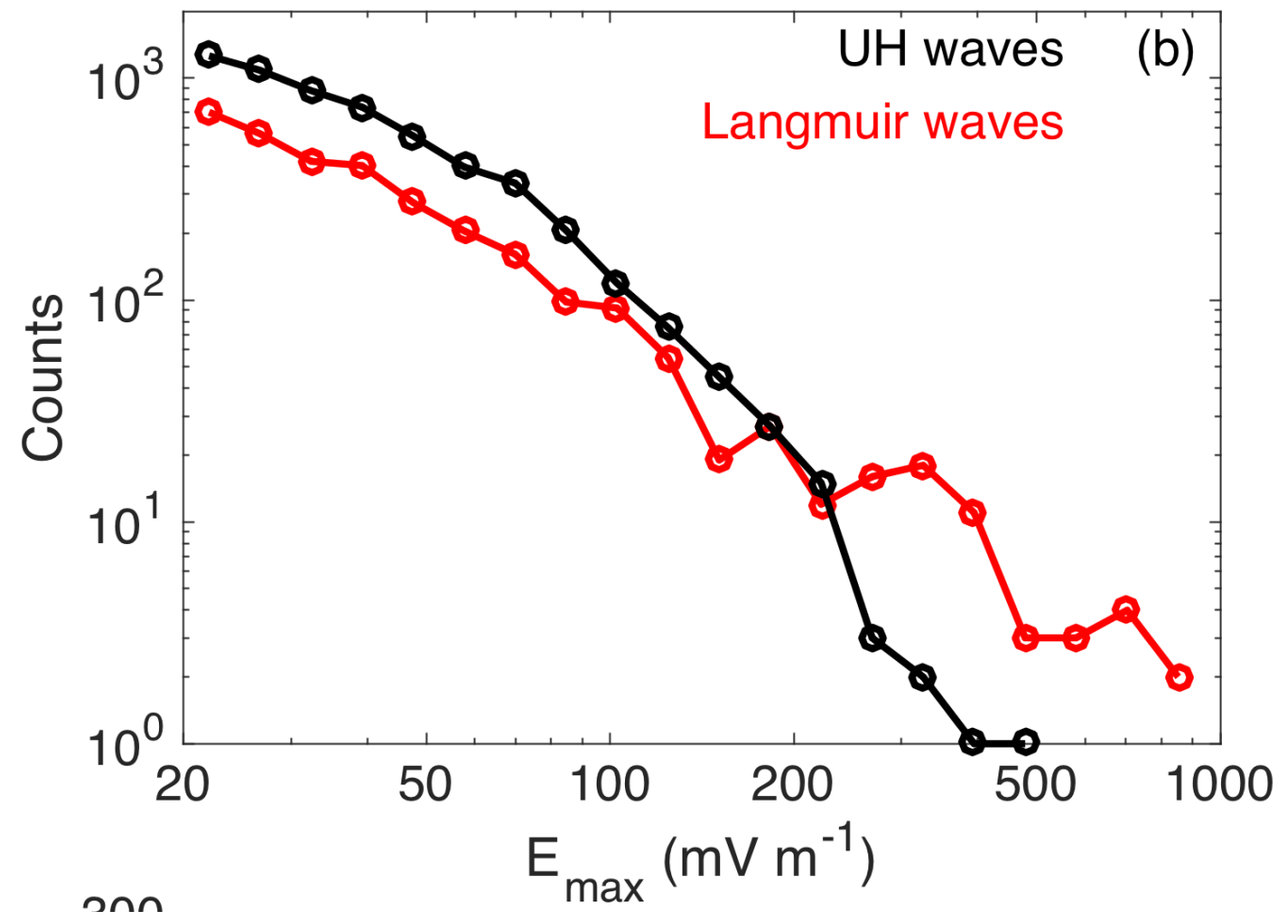
Wave properties (1)

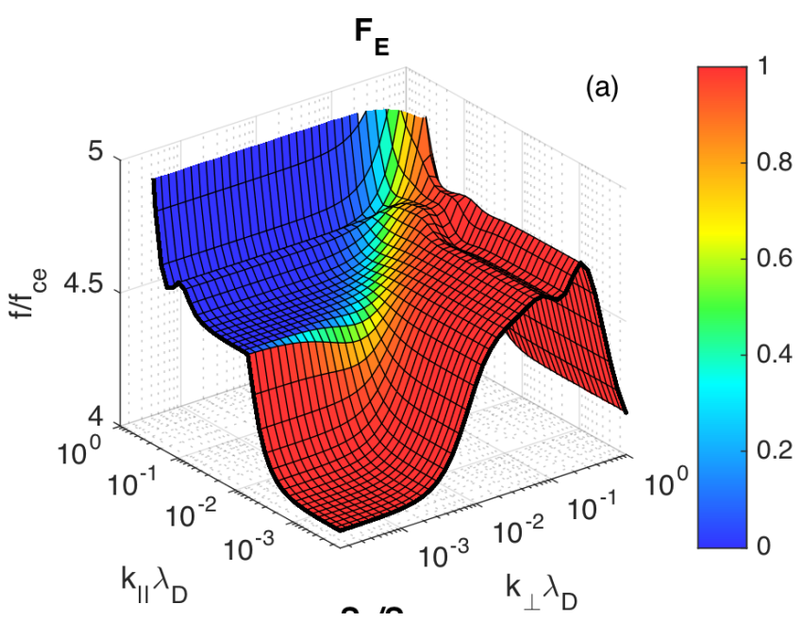
Langmuir waves

$$F_E = \frac{\sum E_\perp(t)^2}{\sum E_\perp(t)^2 + \sum E_\parallel(t)^2}.$$

UH waves

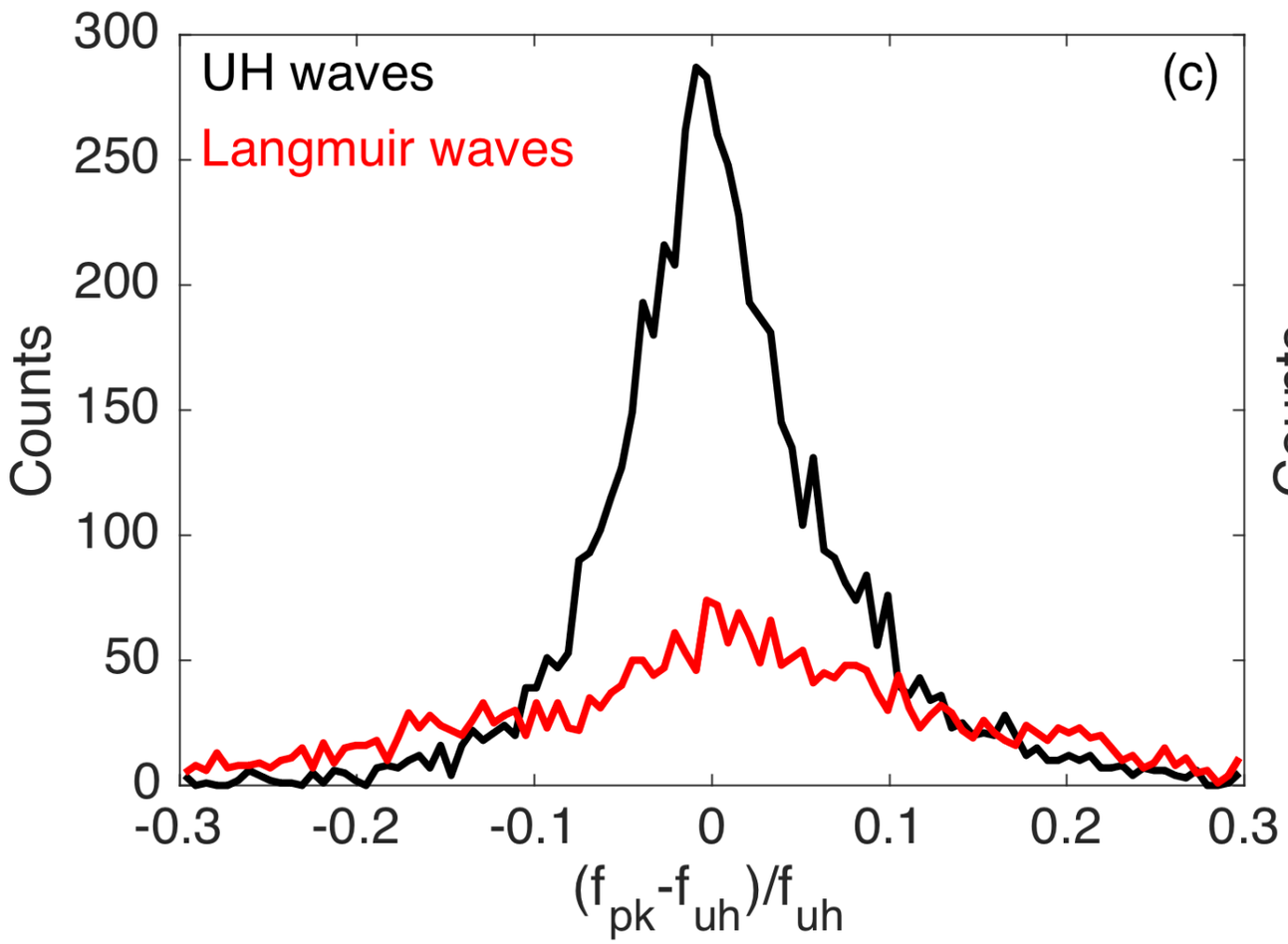


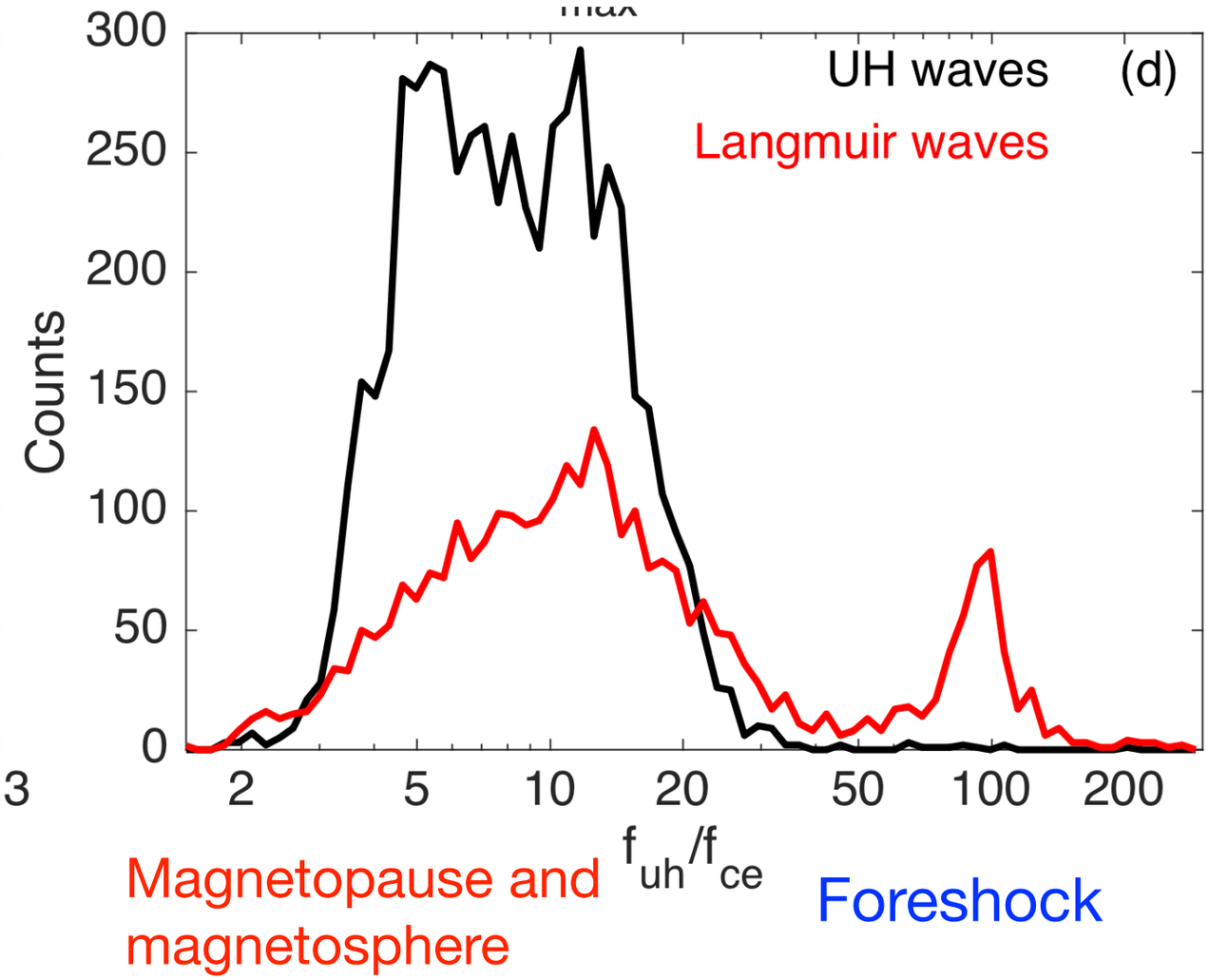




F_E histogram changes depending on region.

Wave properties (2)



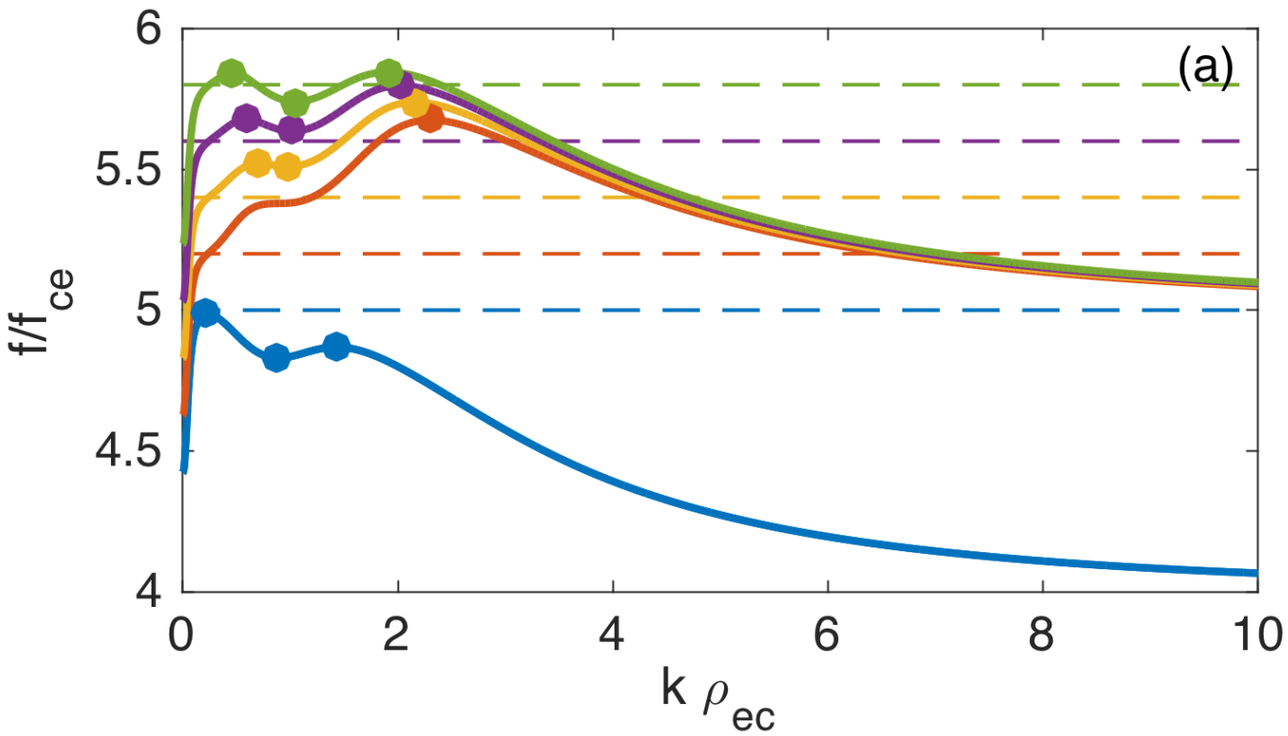


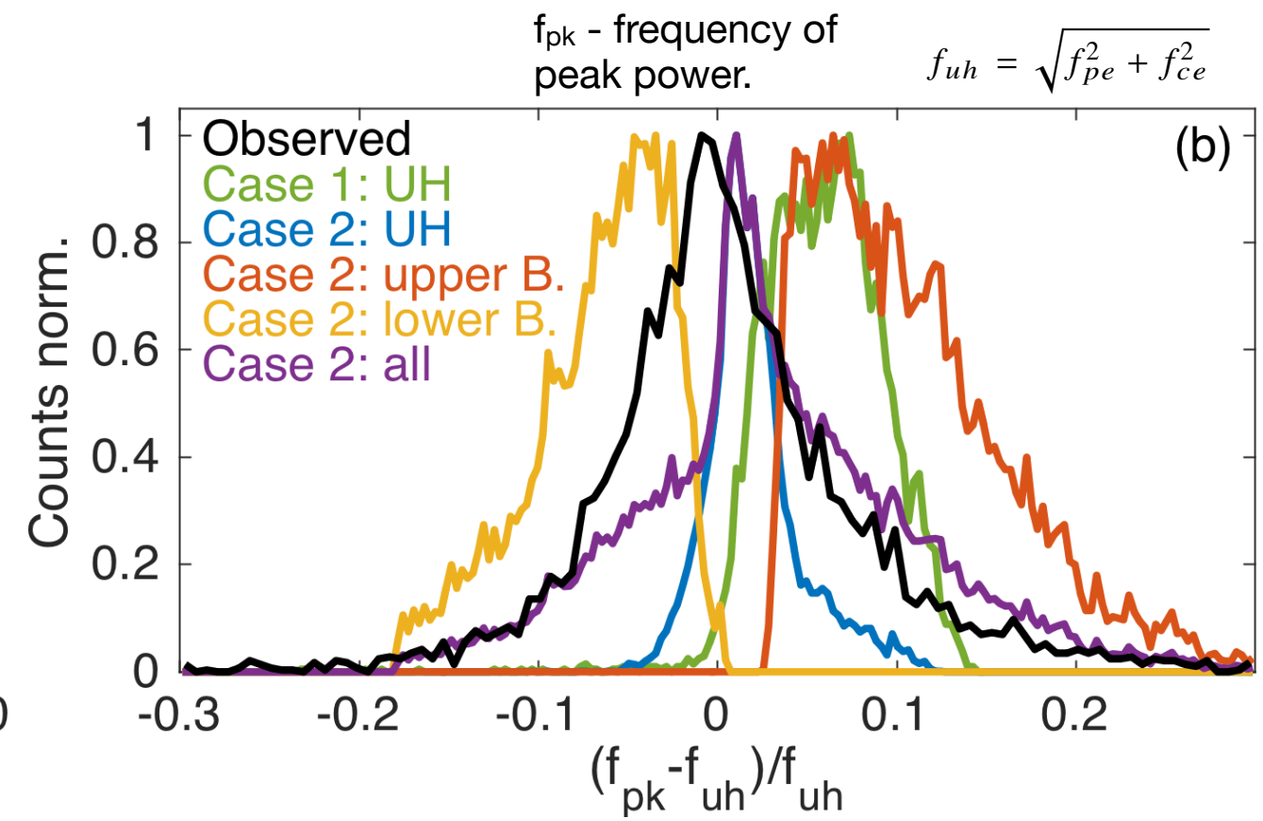
$$f_{uh} = \sqrt{f_{pe}^2 + f_{ce}^2}$$

f_{pk} - frequency of peak power.

- UH waves are more likely to be found than Langmuir waves at the magnetopause.

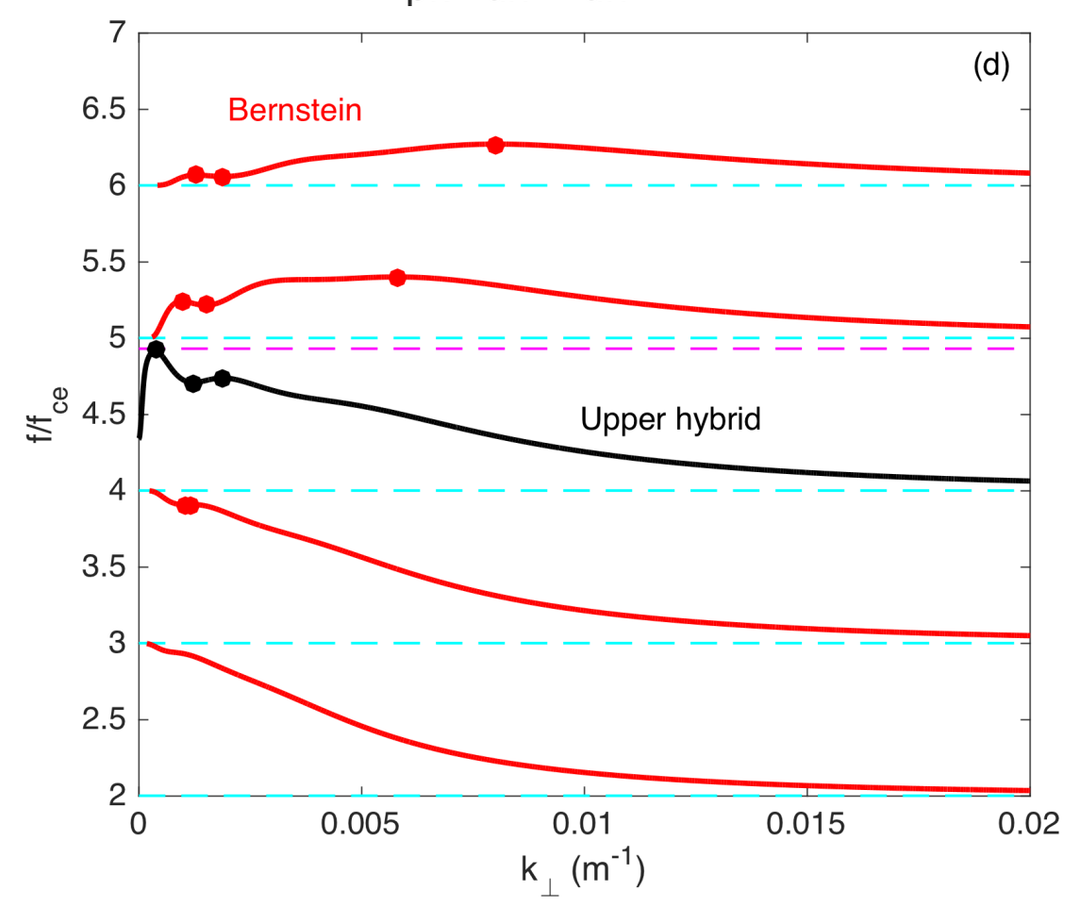
Comparison with kinetic theory





- Case 1: Single Maxwellian - using measured parameters
- Case 2: Hot and Cold Maxwellians - measured B and n.

We assume f_{pk} occurs where $v_g = 0$.

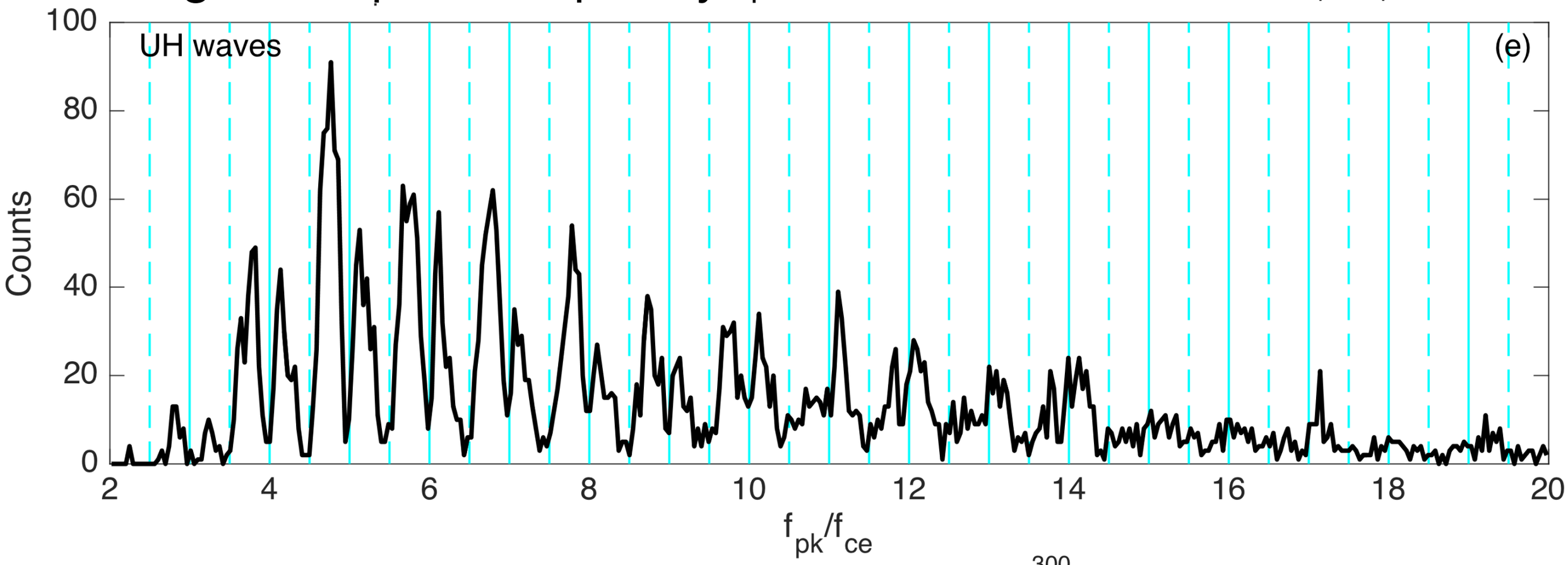


- Case 1 waves do not agree well with observations.
- Case 2 agrees well with observations.

Wave properties (3)

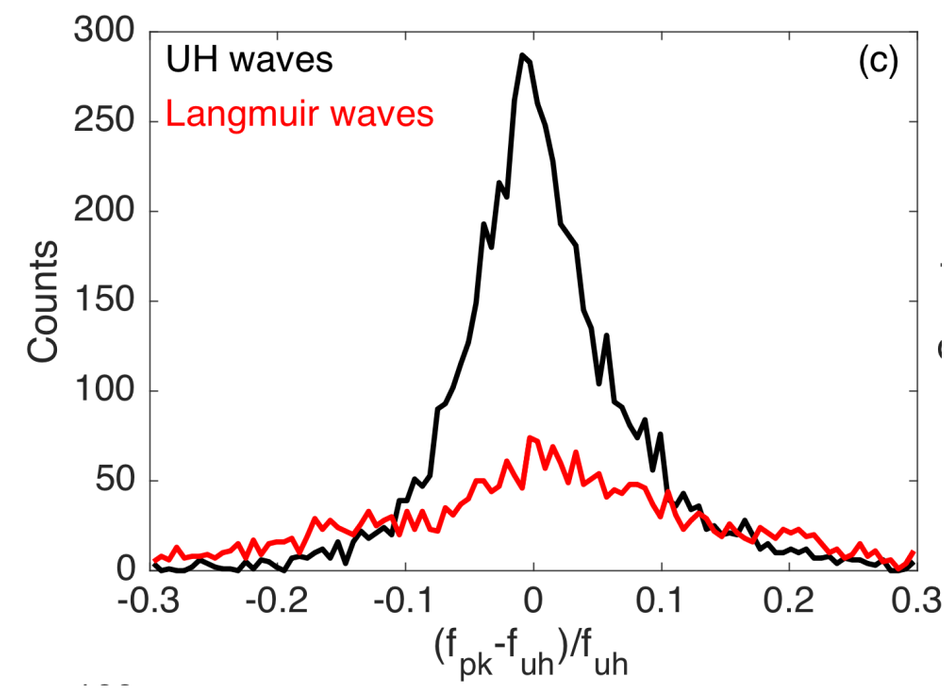
Histogram of peak frequency f_{pk}/f_{ce} for UH waves

f_{pk} - frequency of peak power.



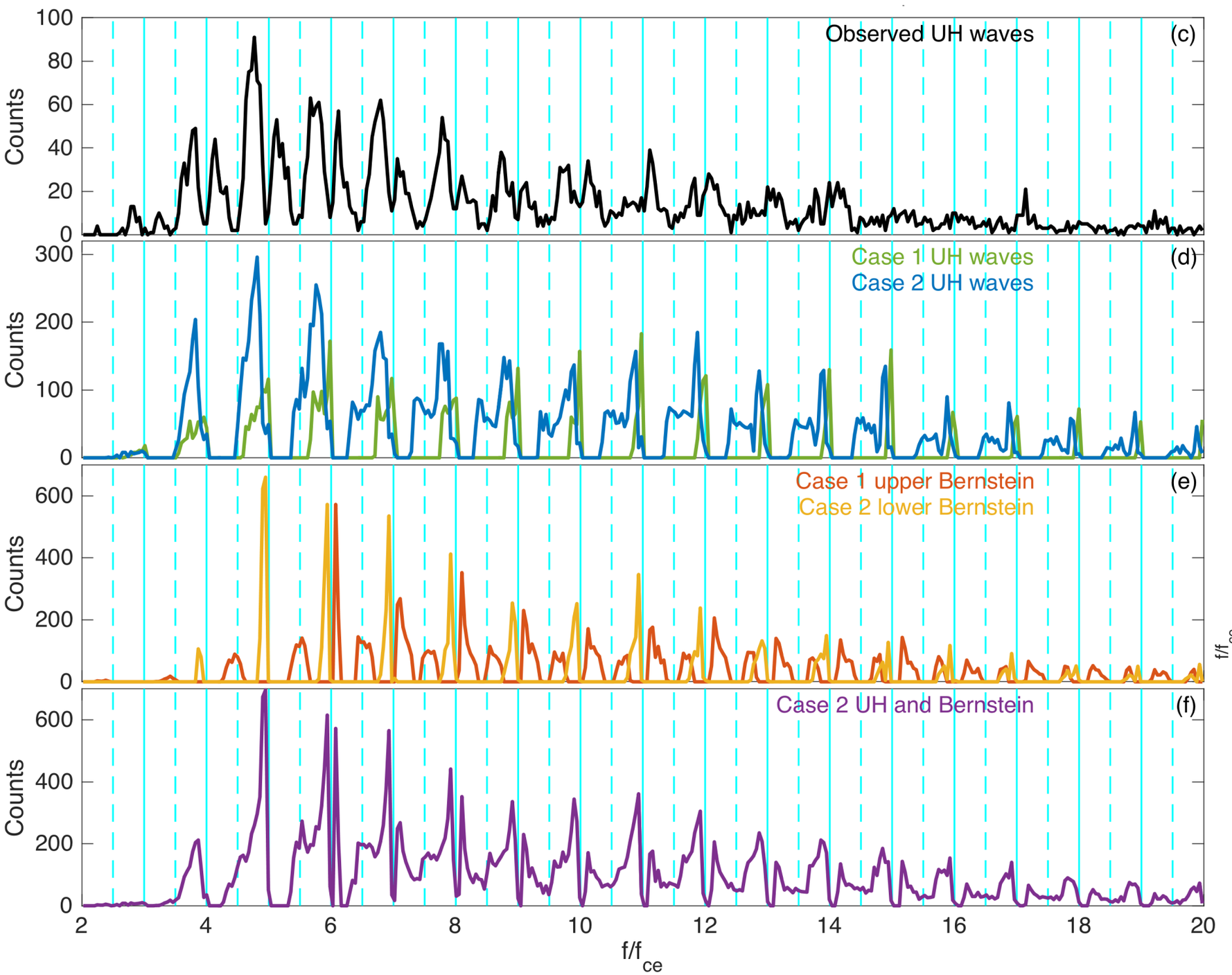
- Peak frequencies of UH waves tend to avoid nf_{ce} and $(n+1/2)f_{ce}$.

This behavior can explain some of the spread in $(f_{pk} - f_{uh})/f_{uh}$.

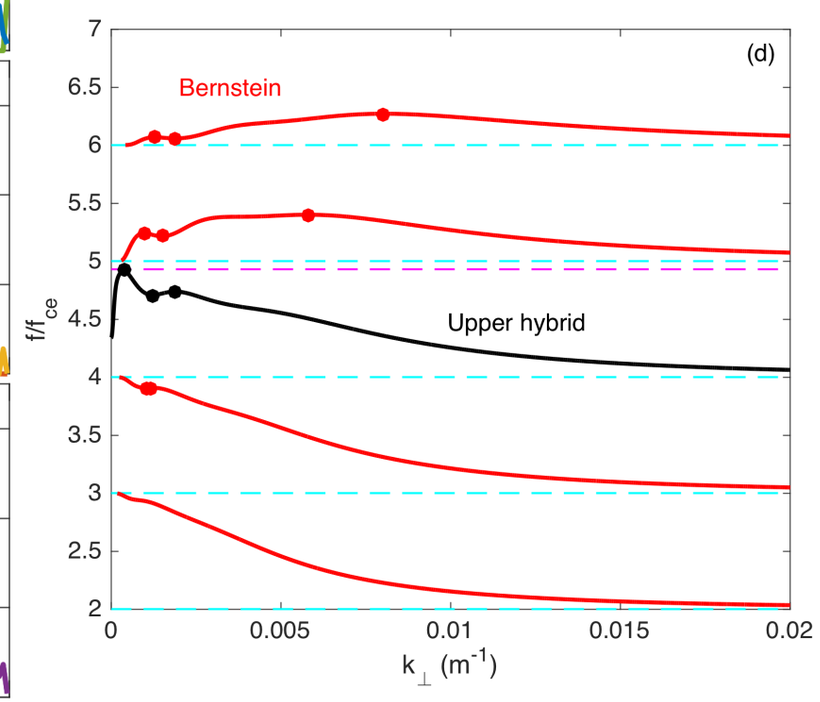


Comparison with kinetic theory

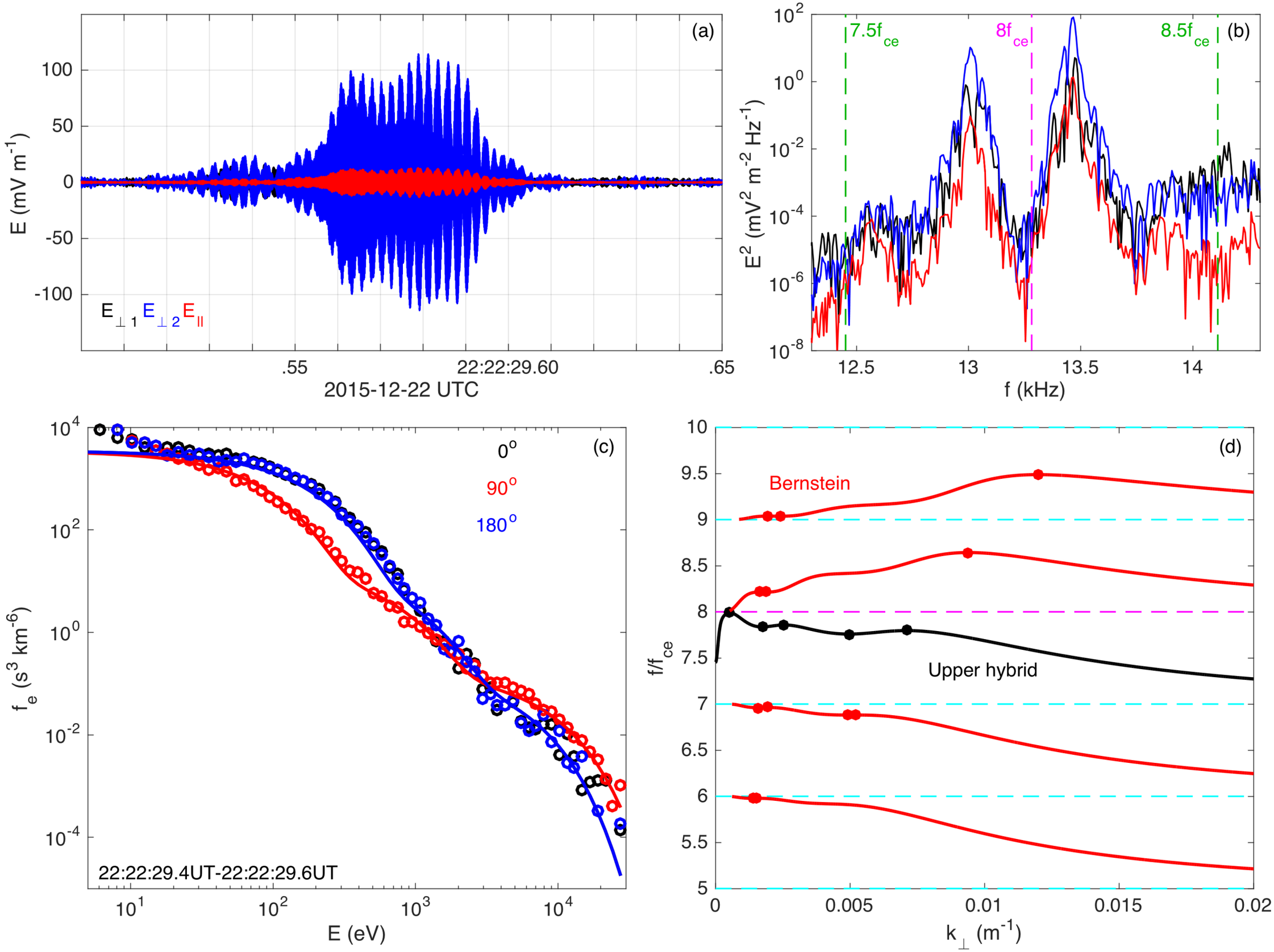
- Case 1: Single Maxwellian
- Case 2: Hot and Cold Maxwellians



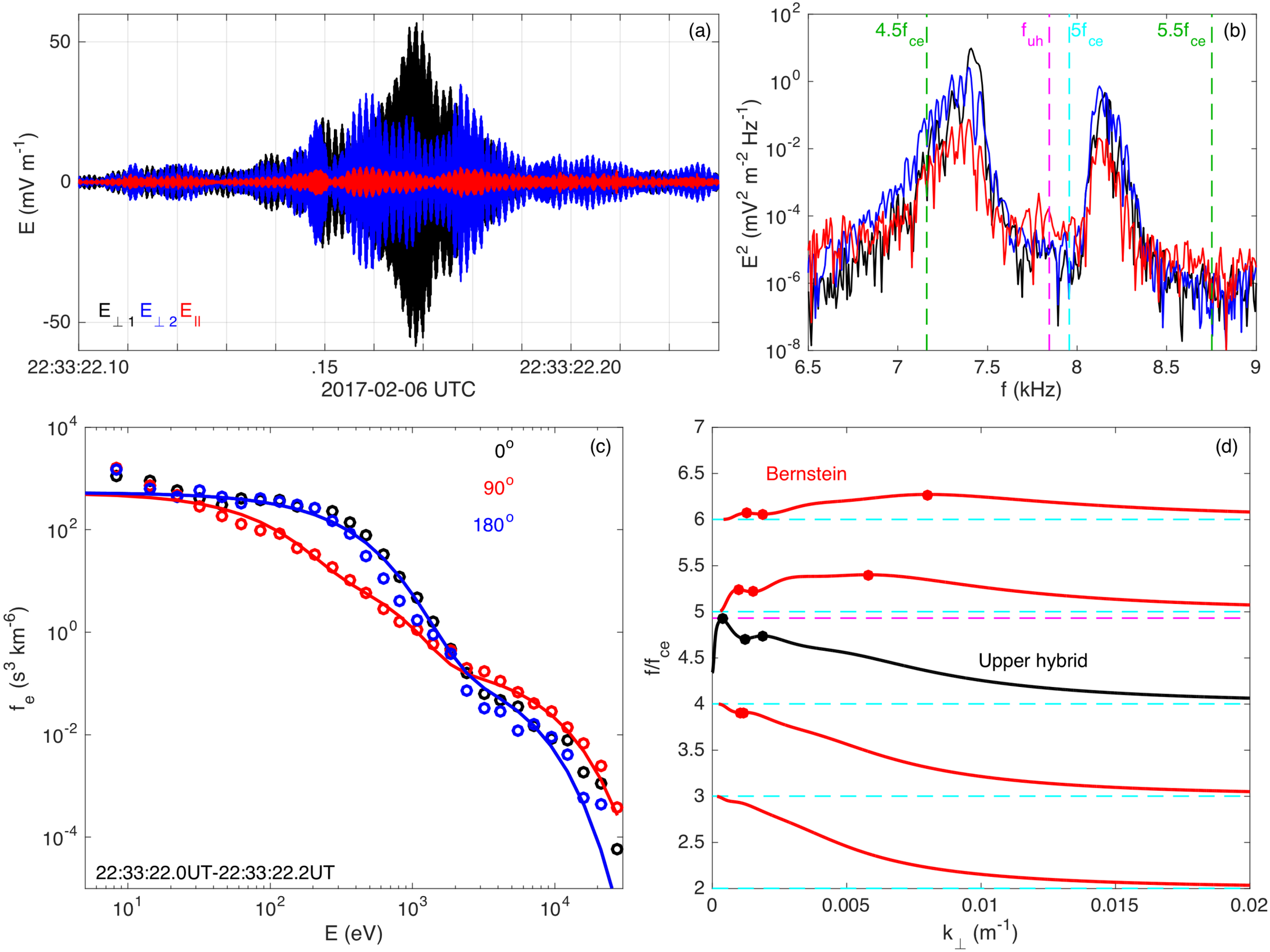
- Case 2 provides better agreement with observations.



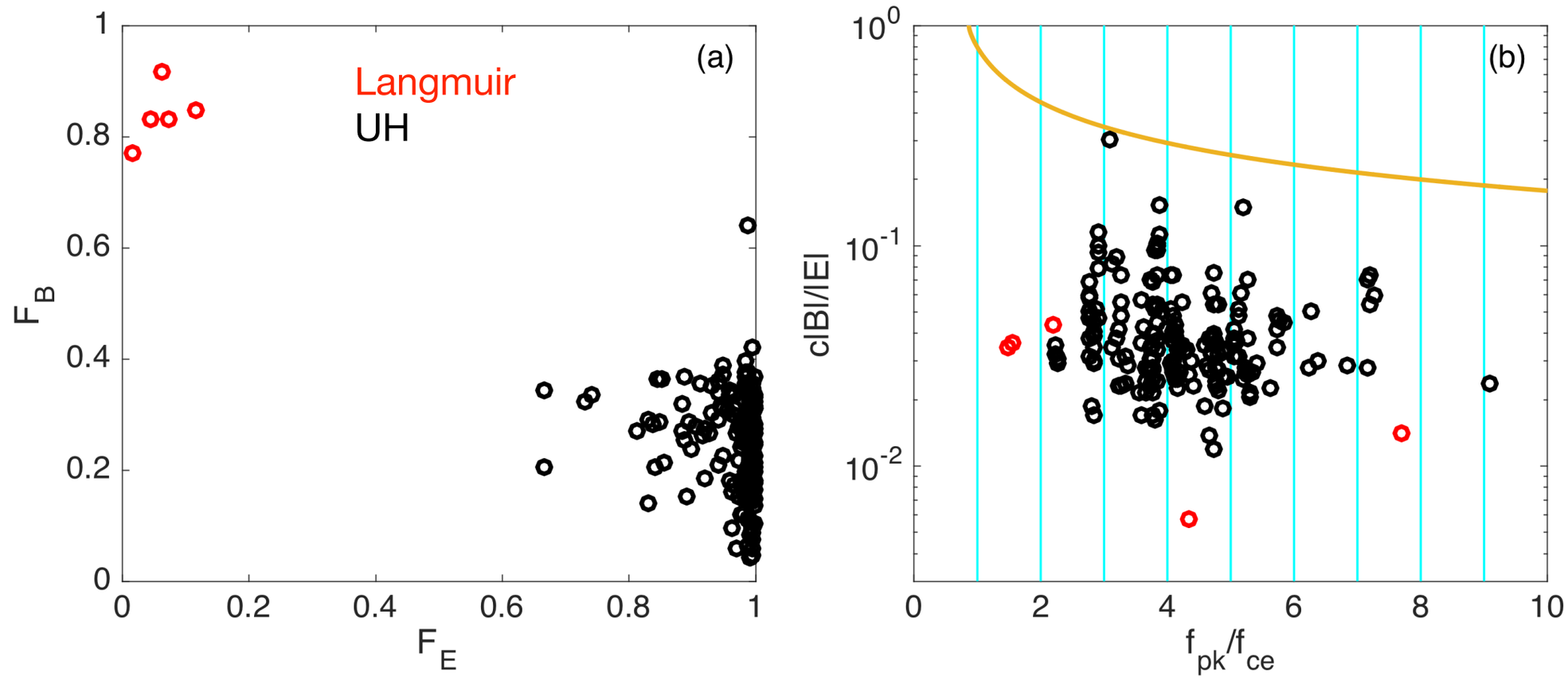
Example 1

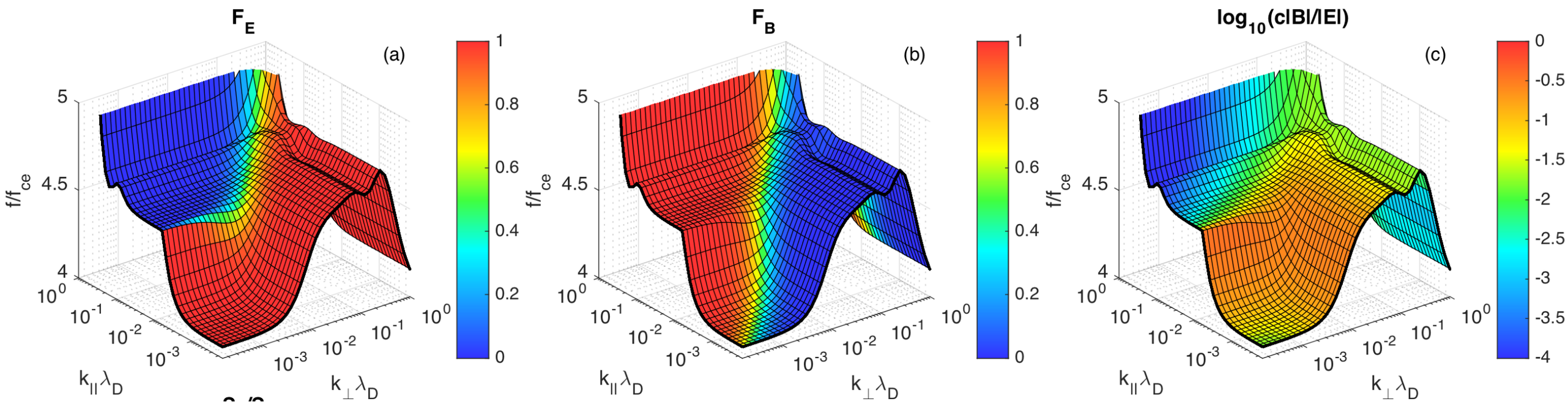

(a)
E (mV m-1)
100
50
0
-50
-100
E⊥1 E⊥2 E∥
.55
22:22:29.60
.65
2015-12-22 UTC
(b)
7.5fce
8fce
8.5fce
E2 (mV2 m-2 Hz-1)
f (kHz)
12.5
13
13.5
14
(c)
0o
90o
180o
fe (s3 km-6)
22:22:29.4UT-22:22:29.6UT
E (eV)
(d)
Bernstein
Upper hybrid
f/fce
k⊥ (m-1)

Example 2


(a)
E (mV m^{-1})
50
0
-50
$E_{\perp 1}$ $E_{\perp 2}$ $E_{\parallel}$
22:33:22.10
.15
22:33:22.20
2017-02-06 UTC
(b)
$4.5f_{ce}$
f_{uh}
$5f_{ce}$
$5.5f_{ce}$
E^2 (mV^2 m^{-2} Hz^{-1})
10^2
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
6.5
7
7.5
8
8.5
9
f (kHz)
(c)
0°
90°
180°
f_e (s^3 km^{-6})
10^4
10^2
10^0
10^{-2}
10^{-4}
22:33:22.0UT-22:33:22.2UT
10^1
10^2
10^3
10^4
E (eV)
(d)
Bernstein
Upper hybrid
f/f_{ce}
7
6.5
6
5.5
5
4.5
4
3.5
3
2.5
2
0
0.005
0.01
0.015
0.02
$k_{\perp}$ (m^{-1})

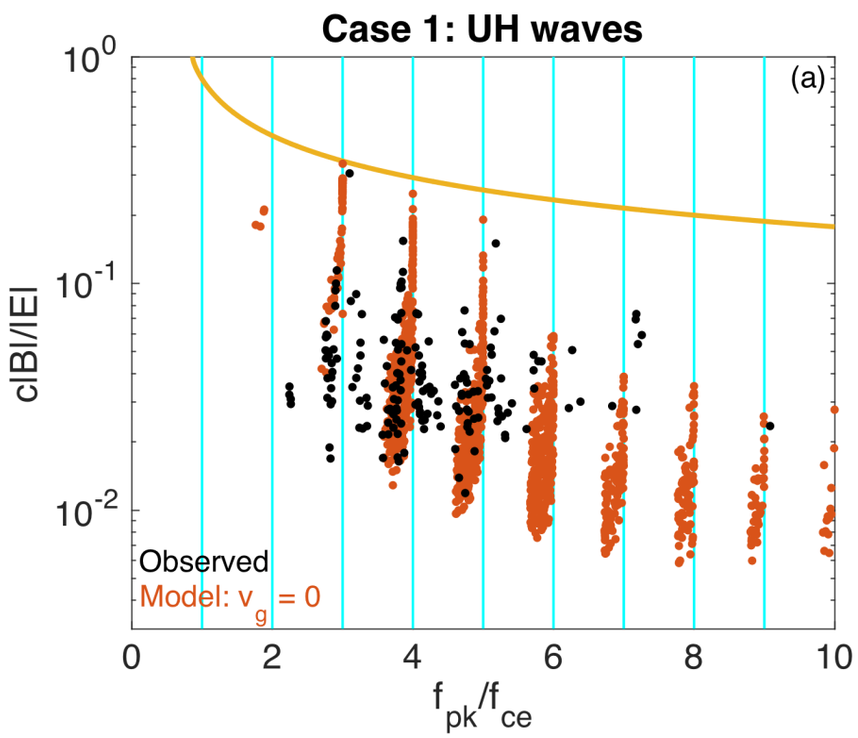
Electromagnetic properties

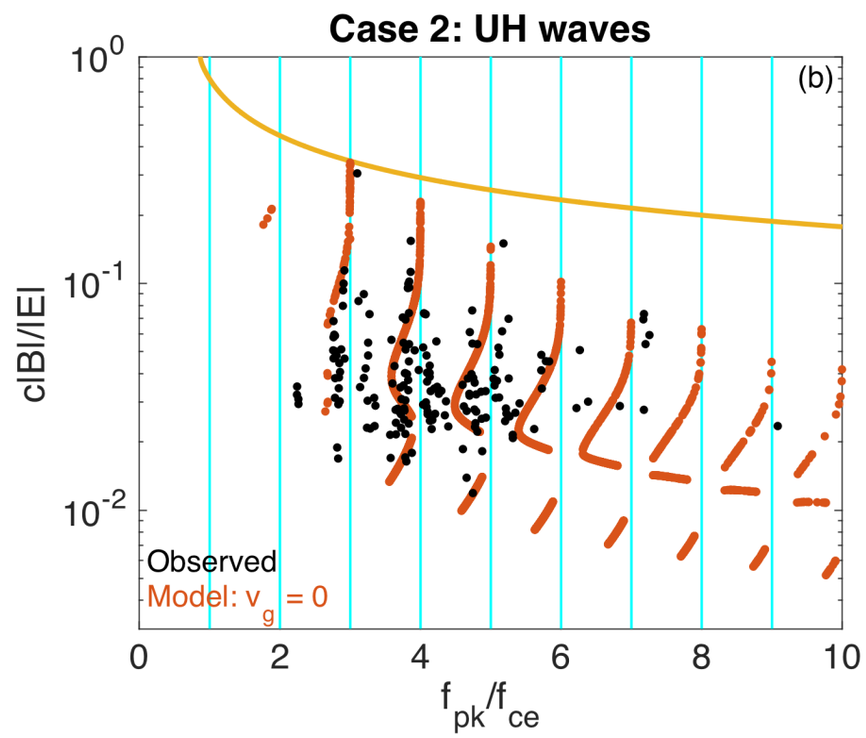


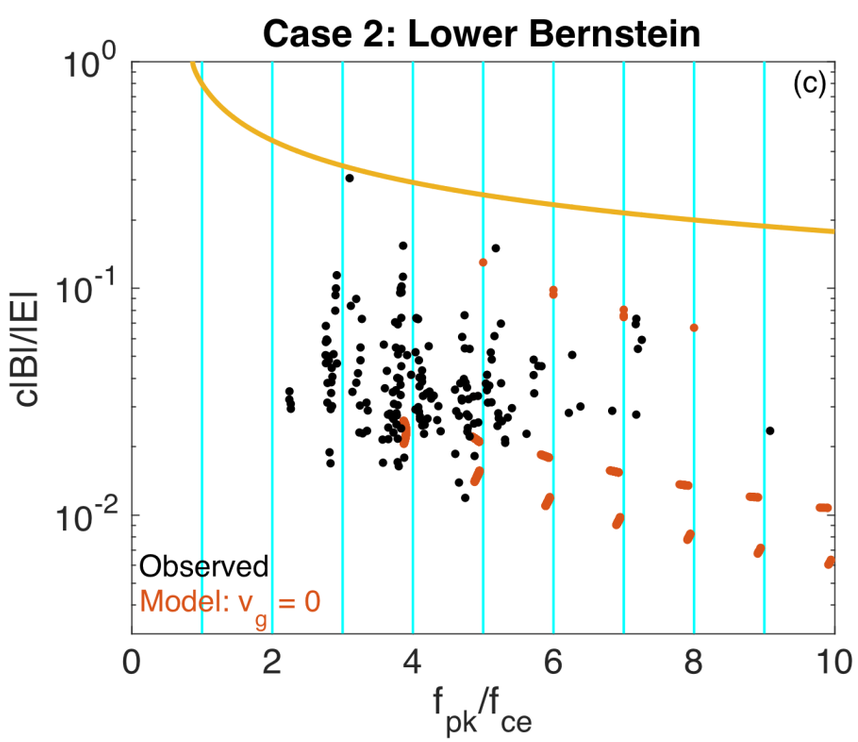


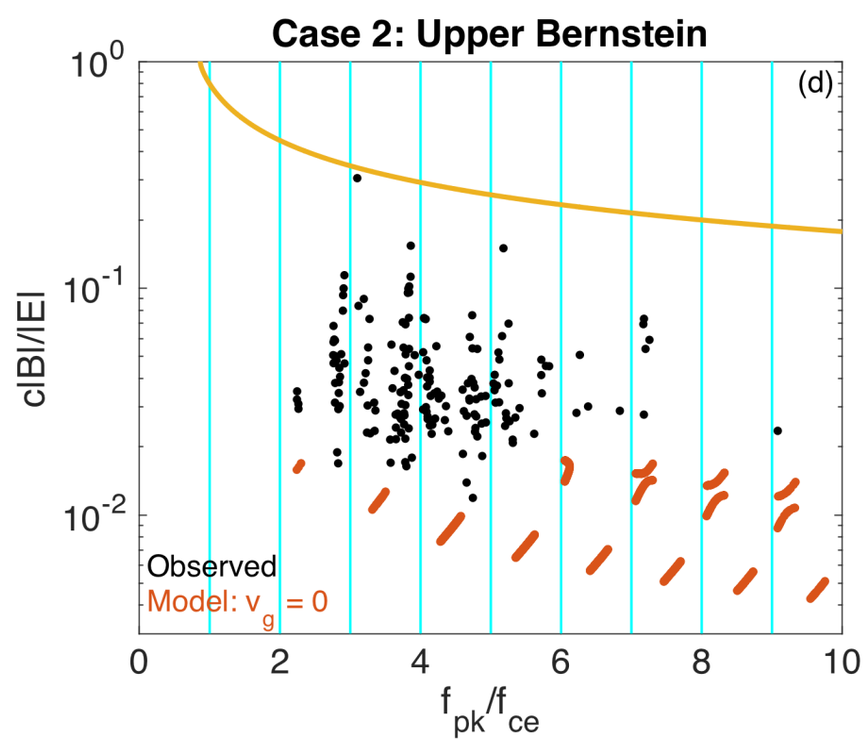
Comparison with kinetic theory

- Case 1: Single Maxwellian
- Case 2: Hot and Cold Maxwellians



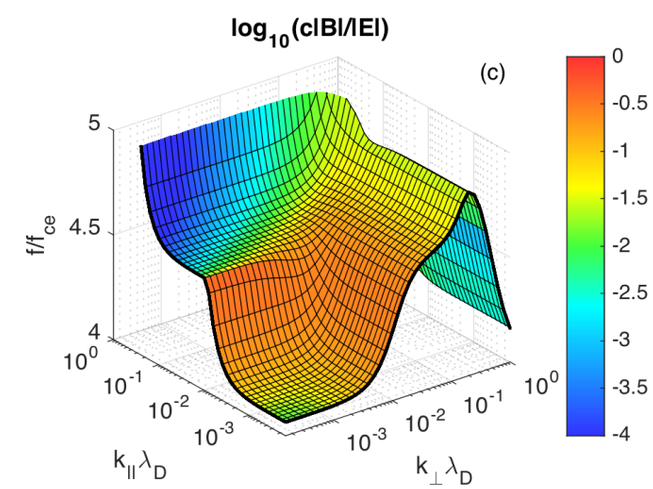




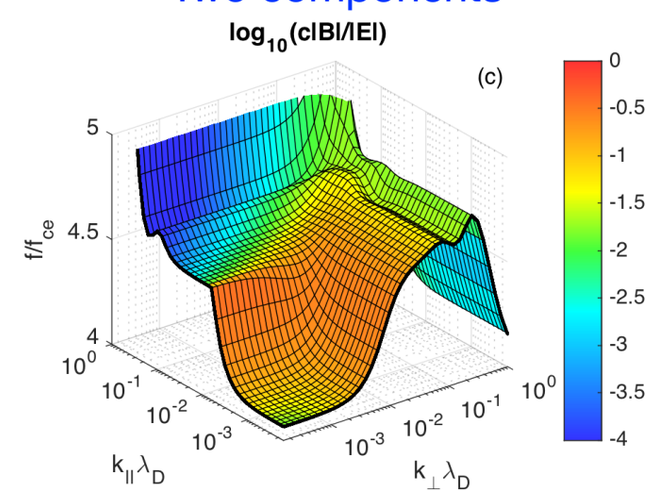


- EM properties are consistent with UH waves rather than Bernstein waves.

One component



Two components



Conclusions

- Large-amplitude Langmuir and UH waves are frequently observed at Earth's magnetopause.
- The electrostatic and electromagnetic properties of the waves are consistent with kinetic theory.