Effects of large-amplitude Langmuir waves on the spacecraft potential

D. B. Graham

Swedish Institute of Space Physics, Uppsala, Sweden

Background

- Spacecraft potential is determined by currents to the spacecraft.
- The spacecraft potential tends to scale with density, and can be used as a density estimate.
- Spacecraft potentials can be measured at much higher cadences than particle distributions.
- This makes high cadence measurements of density theoretically possible.

Spacecraft potential

- Spacecraft potential is determined by:

$$I_e + I_i + I_{\mathrm{ph}} + I_{\mathrm{2nd}} + I_{\mathrm{ASPOC}} + I_{\mathrm{EDI}} + I_{\mathrm{misc.}} = 0,$$

- Often thermal and photo-electron currents are dominant:

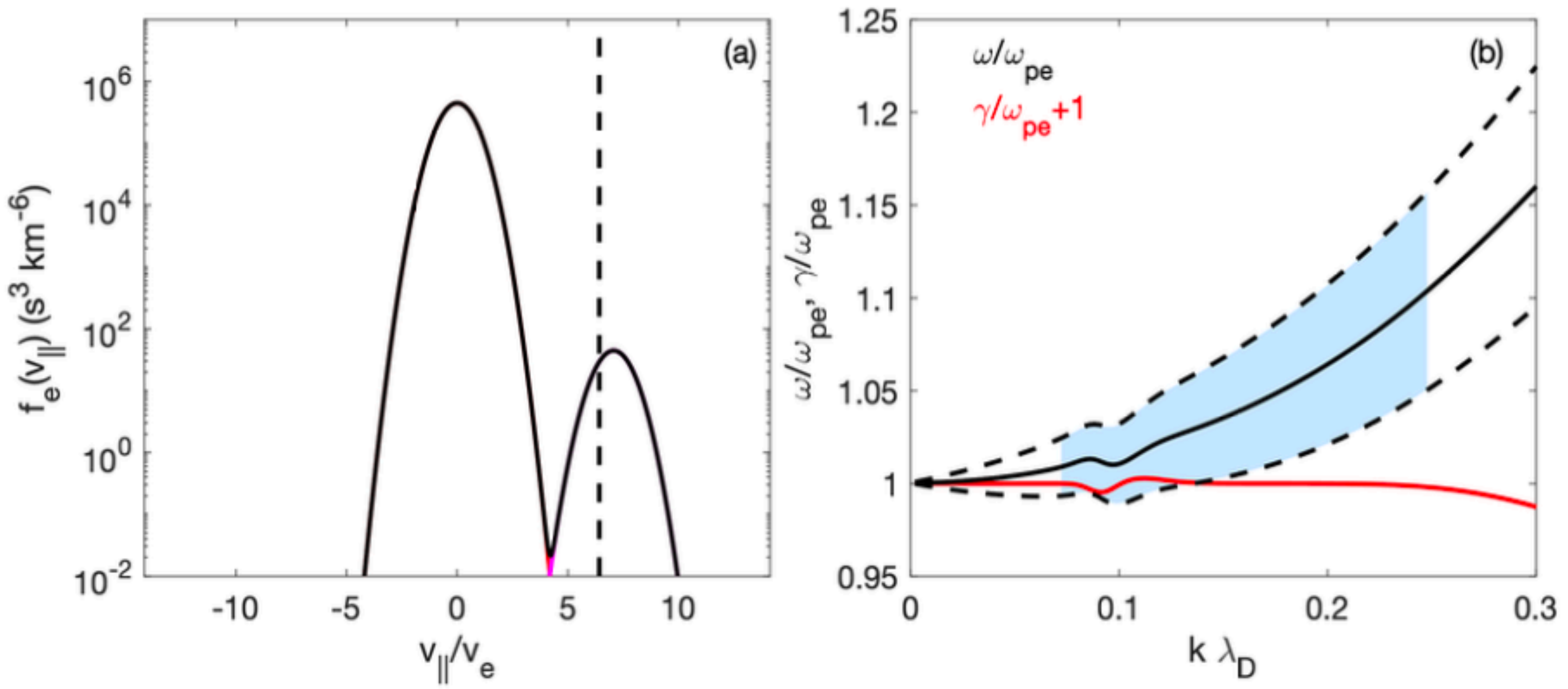
$$I_e = -en_eS\left(\frac{k_BT_e}{2\pi m_e}\right)^{1/2}\left(1+\frac{eV_{\mathrm{SC}}}{k_BT_e}\right),$$

$$I_{\mathrm{ph}} = I_{\mathrm{ph0}}\exp\left(\frac{-eV_{\mathrm{SC}}}{k_BT_{\mathrm{ph0}}}\right) + I_{\mathrm{ph1}}\exp\left(\frac{-eV_{\mathrm{SC}}}{k_BT_{\mathrm{ph1}}}\right),$$

- This leads to density given by:

$$n_{\mathrm{SC}} = \frac{1}{eS}\left(\frac{2\pi m_e}{k_BT_e}\right)^{1/2}\left(1+\frac{eV_{\mathrm{SC}}}{k_BT_e}\right)^{-1}\left[I_{\mathrm{ph0}}\exp\left(\frac{-eV_{\mathrm{SC}}}{k_BT_{\mathrm{ph0}}}\right) + I_{\mathrm{ph1}}\exp\left(\frac{-eV_{\mathrm{SC}}}{k_BT_{\mathrm{ph1}}}\right)\right]$$

Role of density fluctuations

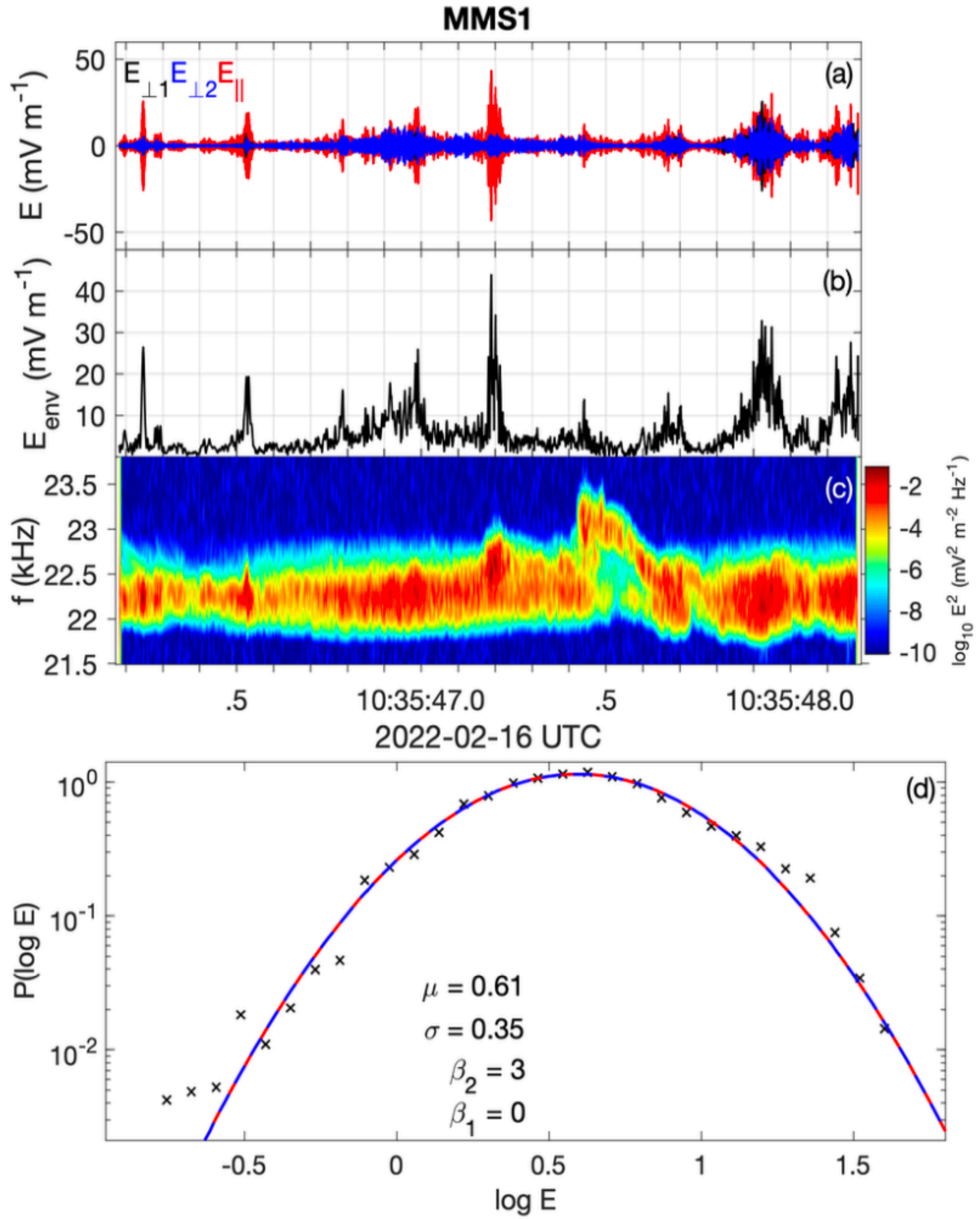


- Density perturbations play in important role in Langmuir wave evolution:

$$\omega \approx \omega_{pe}\left(1+\frac{\delta n}{2n}+\frac{3k^2v_e^2}{2\omega_{pe}^2}\right)$$

- Density perturbations result in clumpy Langmuir waves.

[e.g., Robinson, 1992;
Voshchepynets et al., 2015]



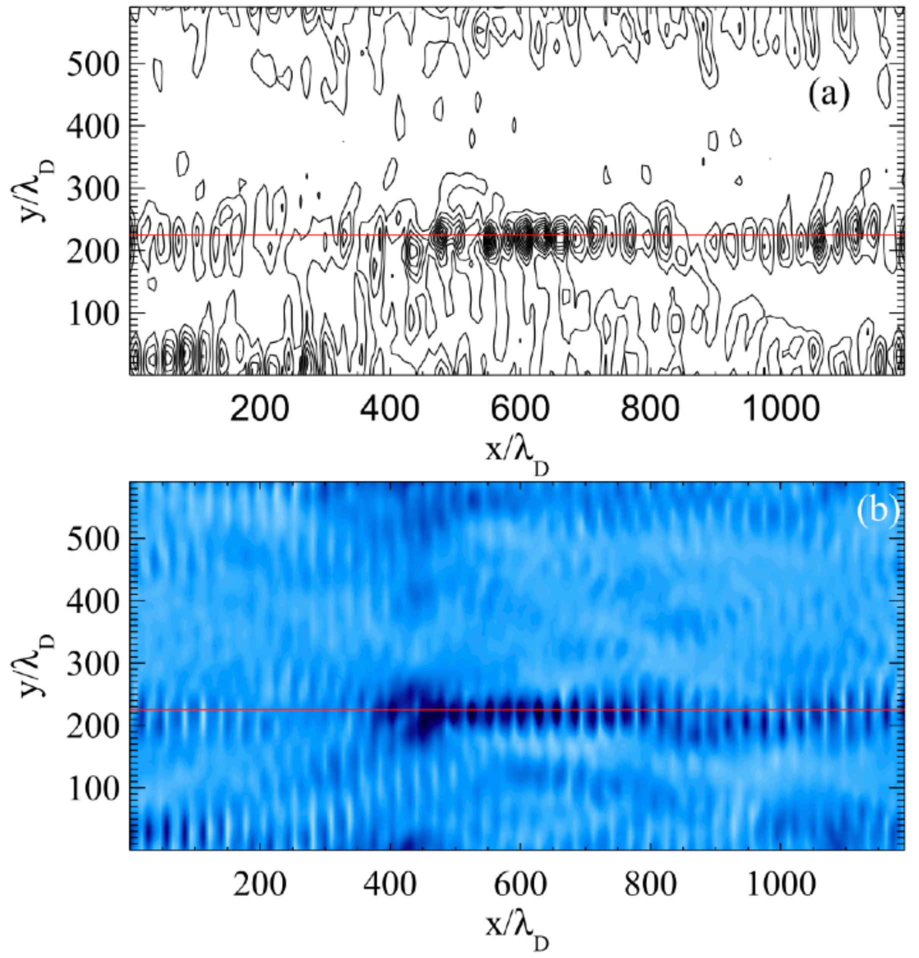
Nonlinear Processes

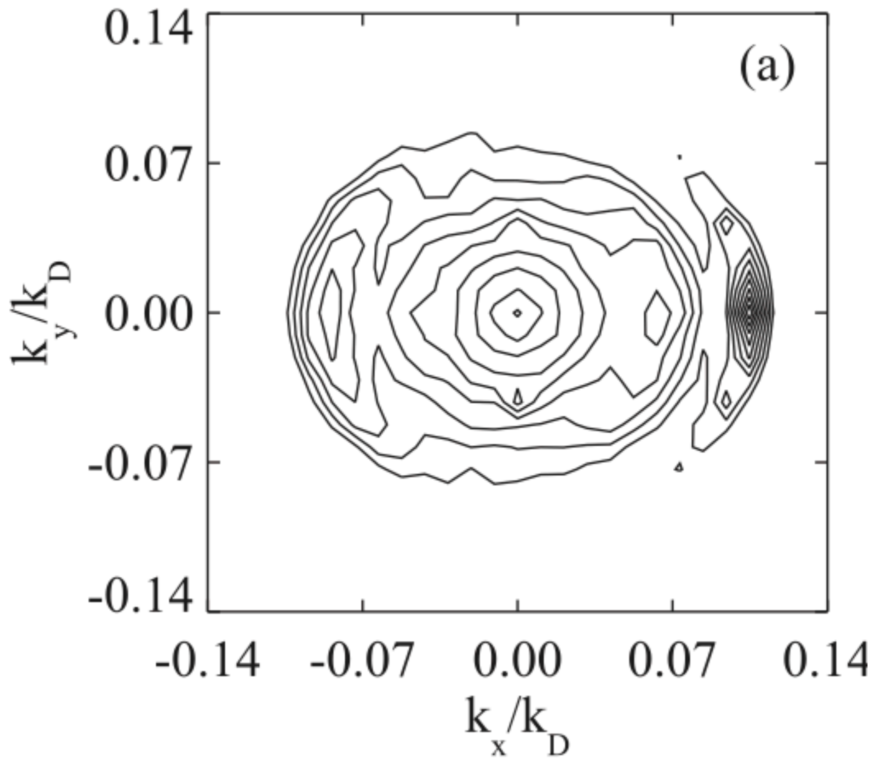
Three-wave decay

$$L(\omega_L, \mathbf{k}_L) \rightarrow L'(\omega_{L'}, \mathbf{k}_{L'}) + S(\omega_S, \mathbf{k}_S),$$

W

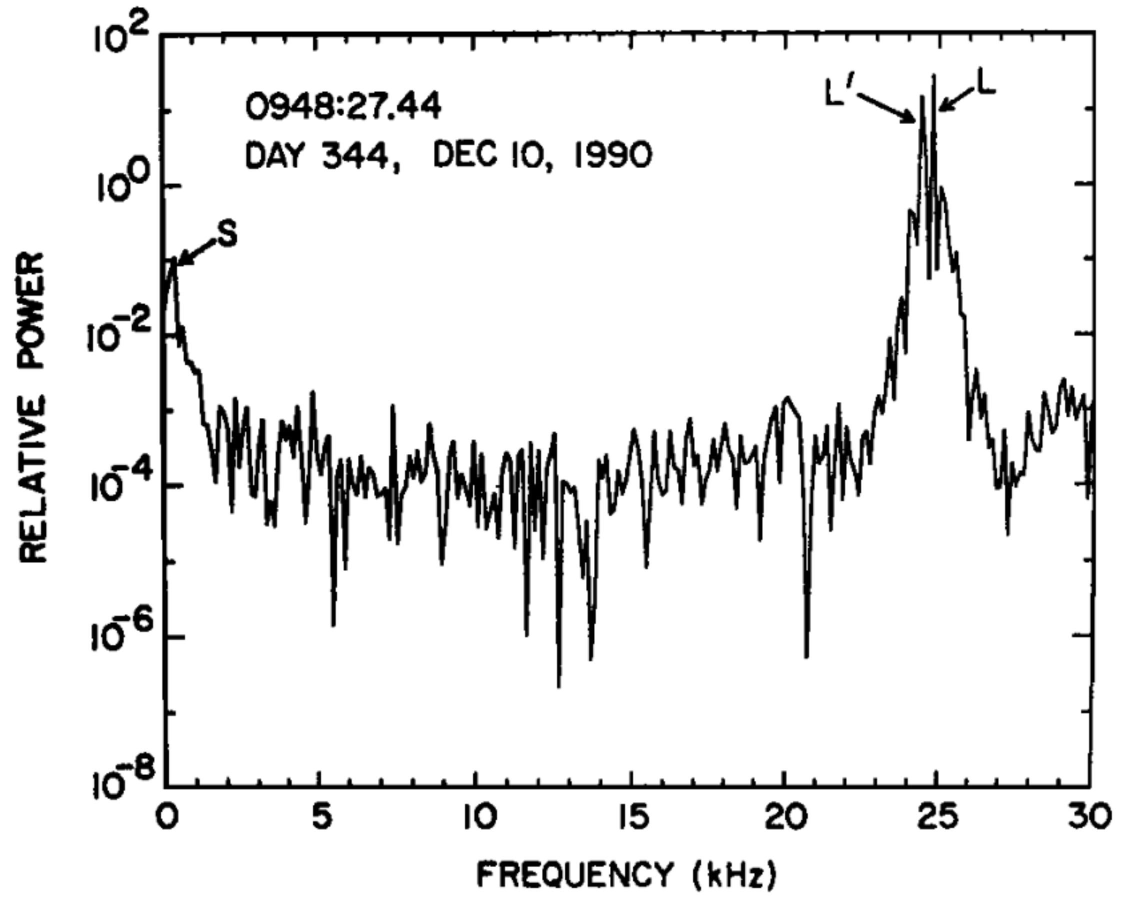
δn/n





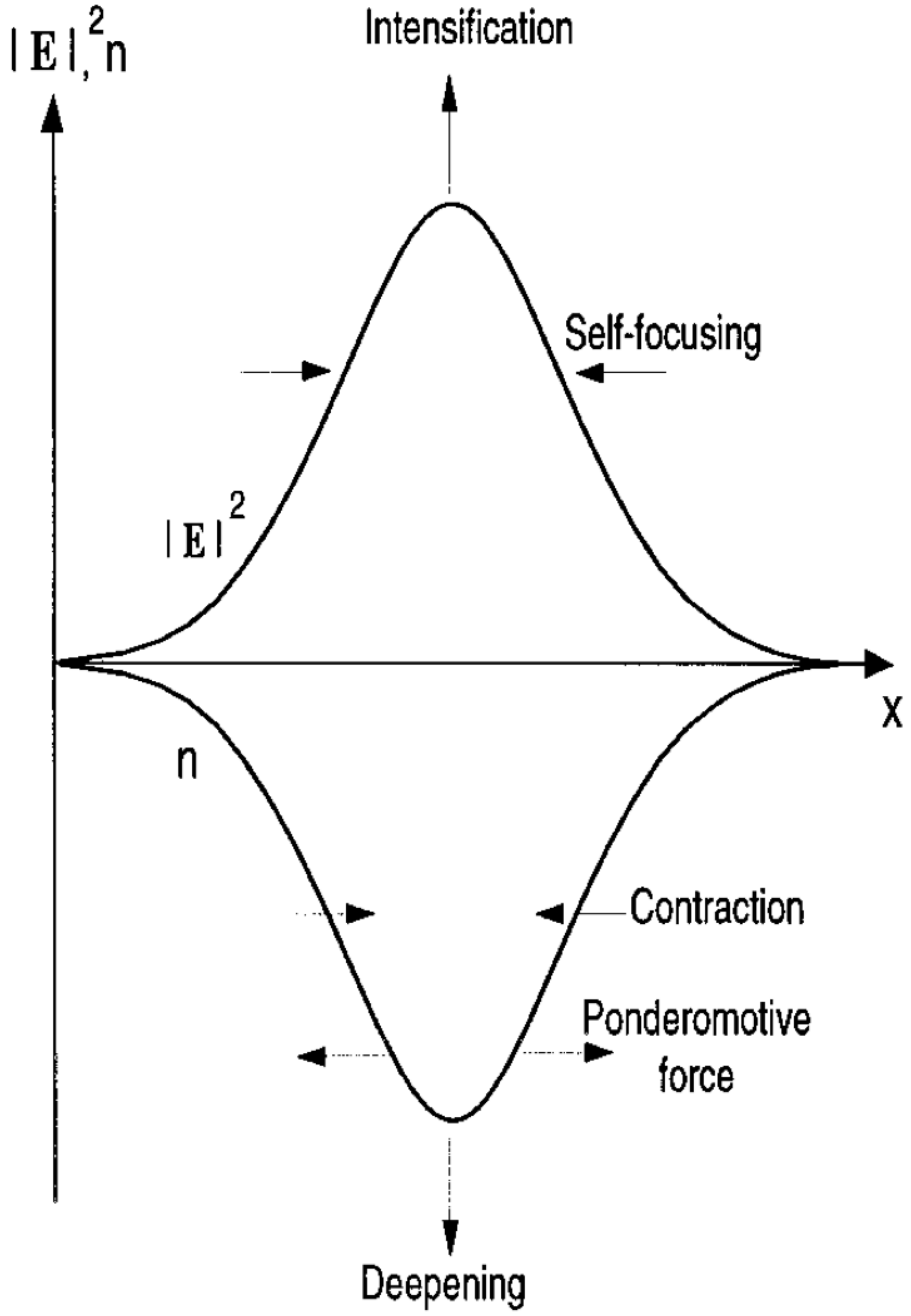
[Graham et al., 2012]

Nonlinear Langmuir wave processes can produce density perturbations.



[Hospodarsky & Gurnett, 1995]

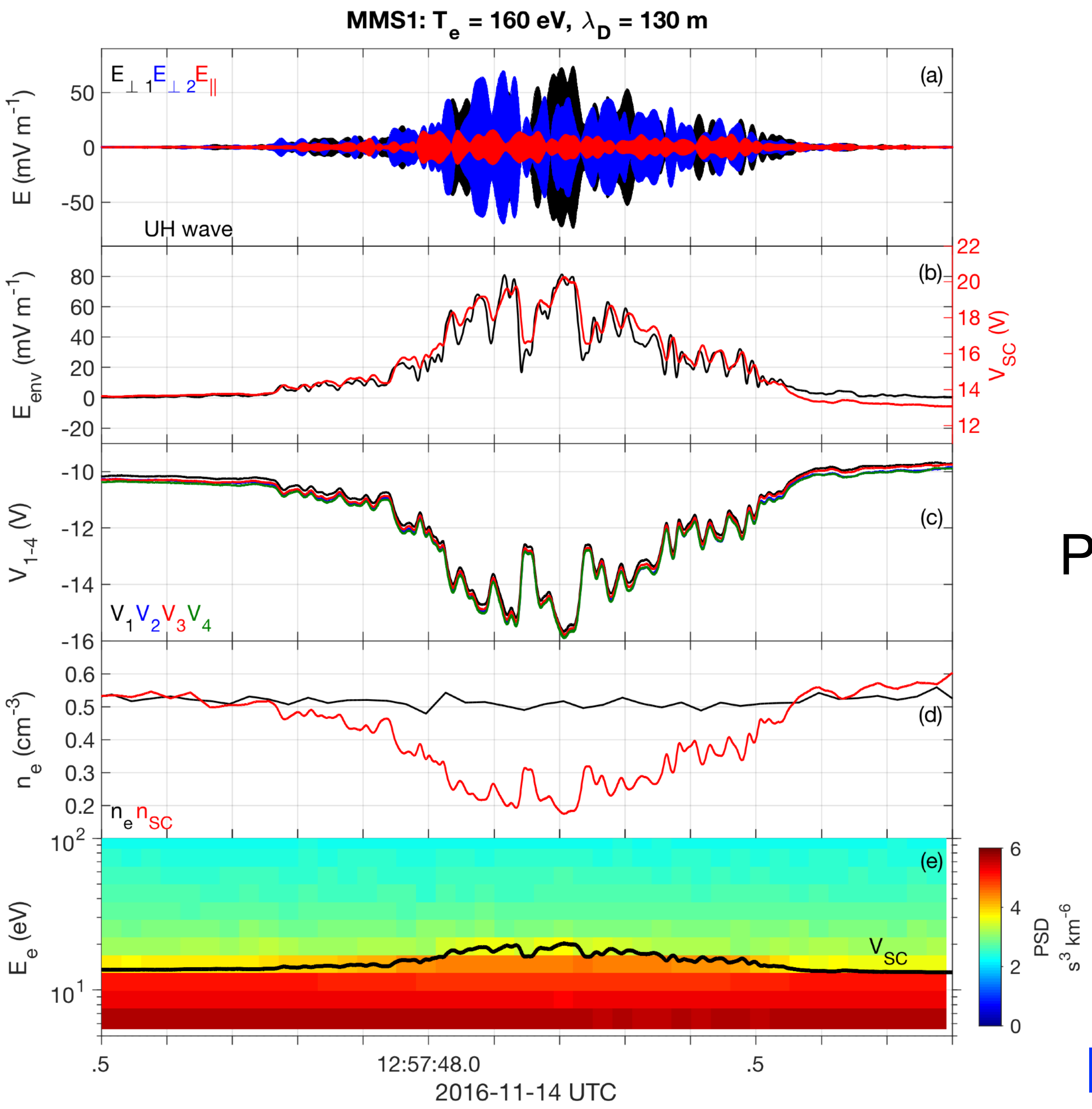
Ponderomotive force



$$\mathbf{F}_P = -\frac{q^2}{4m\omega_p^2}\nabla|\mathbf{E}|^2 \qquad \frac{\delta n}{n} \sim W$$

[Robinson, 1997]

MMS observations



Upper-hybrid waveform

E-field envelope and spacecraft potential

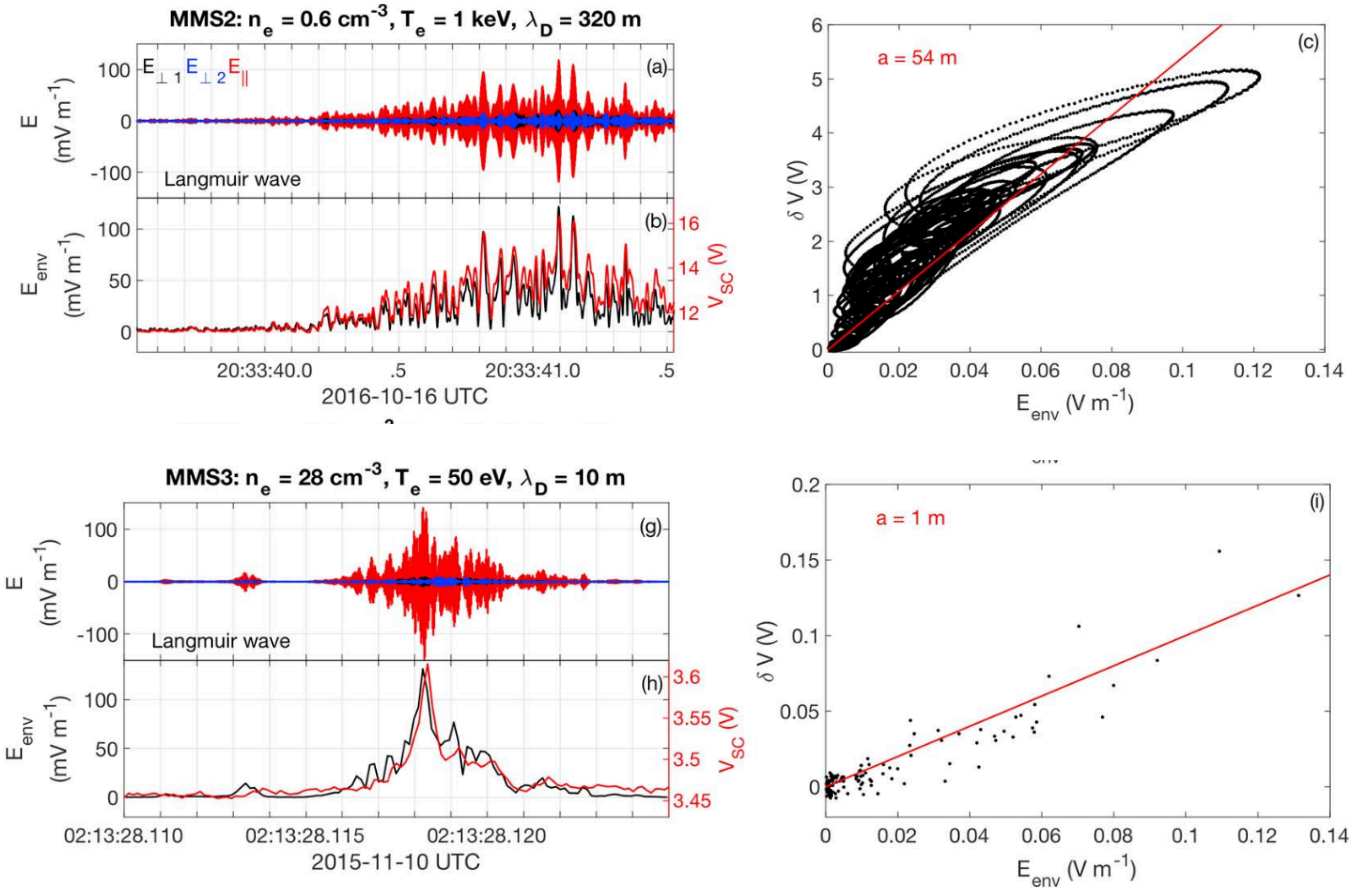
Probe-to-spacecraft potentials

Electron number densities

Spacecraft photoelectrons

[Graham et al., 2018]

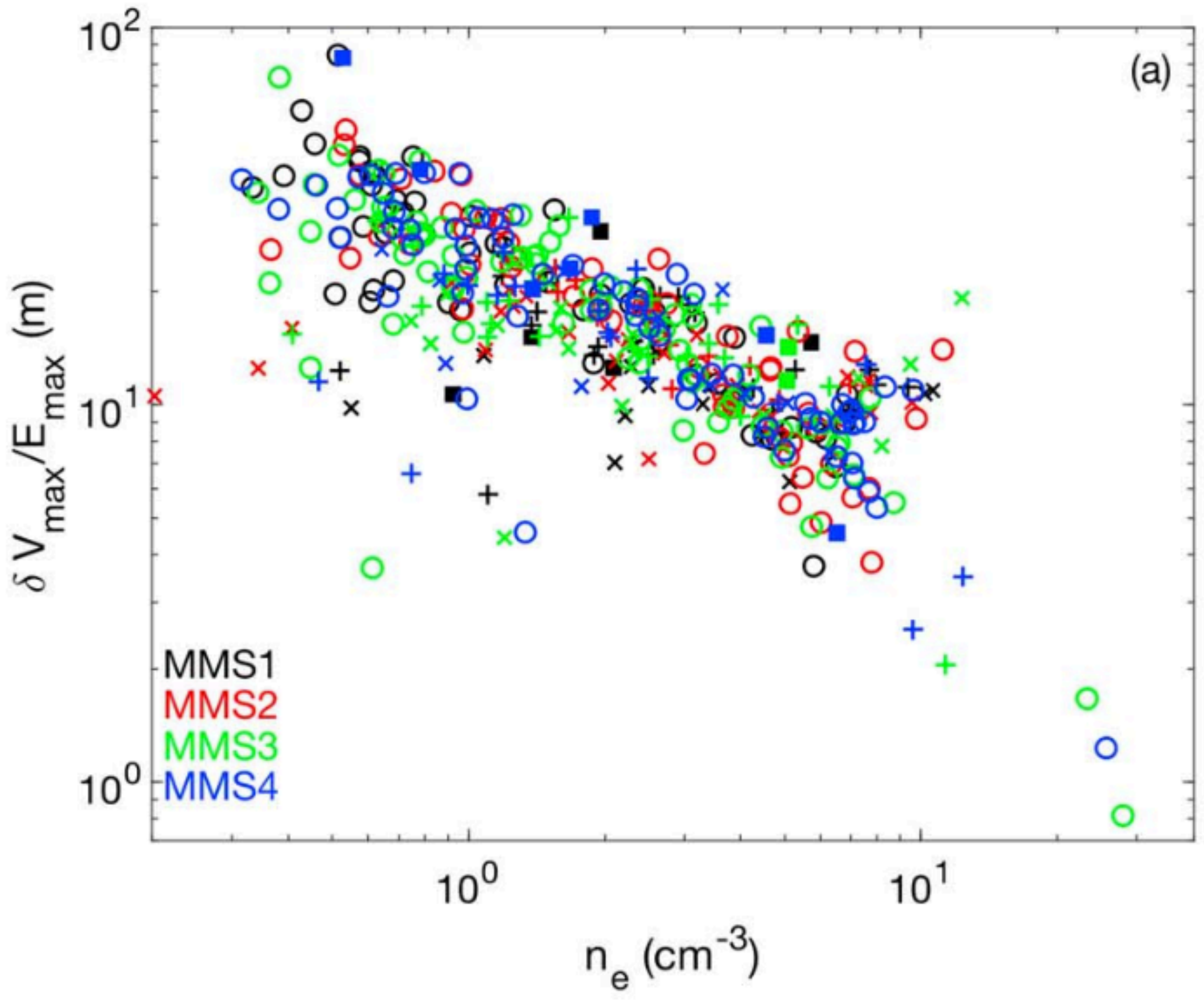
Effect of plasma conditions

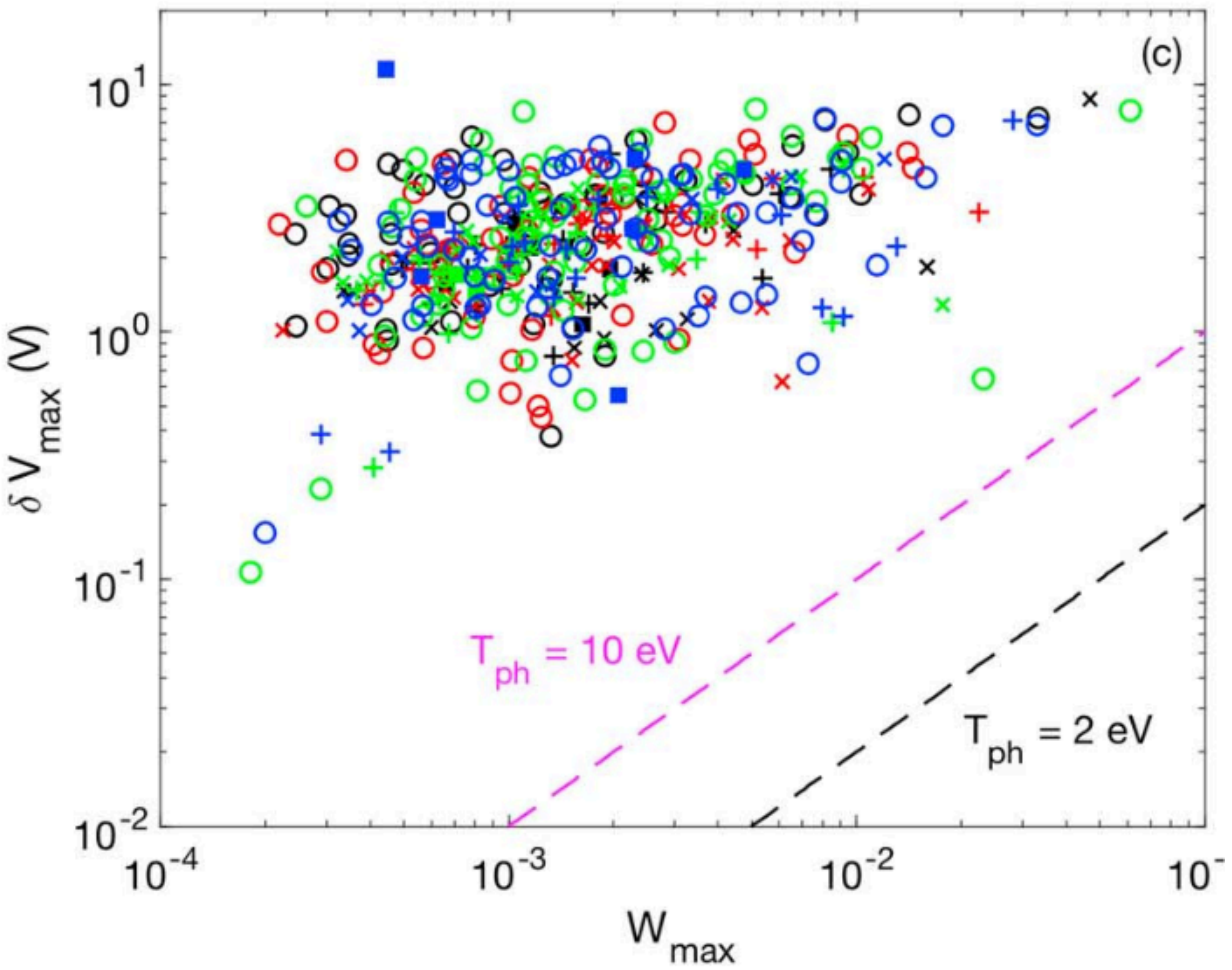


- The magnitude of spacecraft potential perturbations appears to depend on density (or wave frequency).

[Graham et al., 2018]

Statistical Results





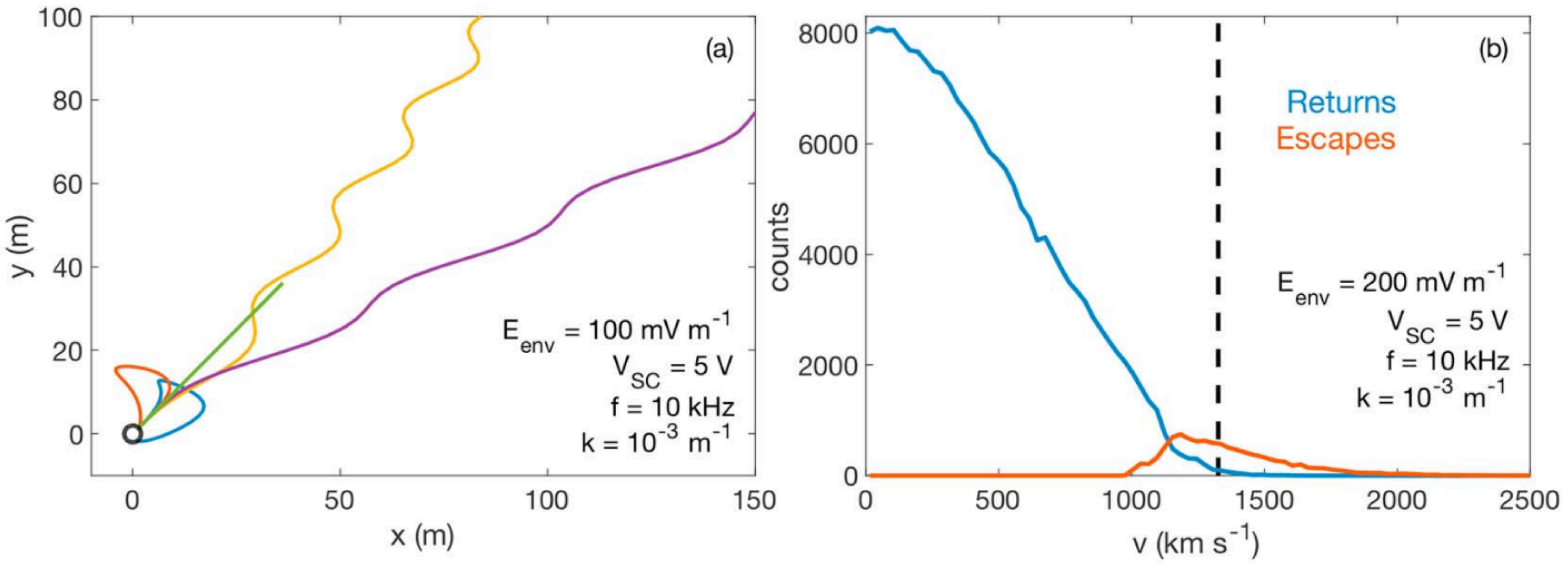
- Relative changes in spacecraft potential decrease as density increases.

- Potential changes are too large to be explained by ponderomotive force.

$$W = \epsilon_0 E_{env}^2/(4 n_e k_B T_e)$$

[Graham et al., 2018]

Numerical Results

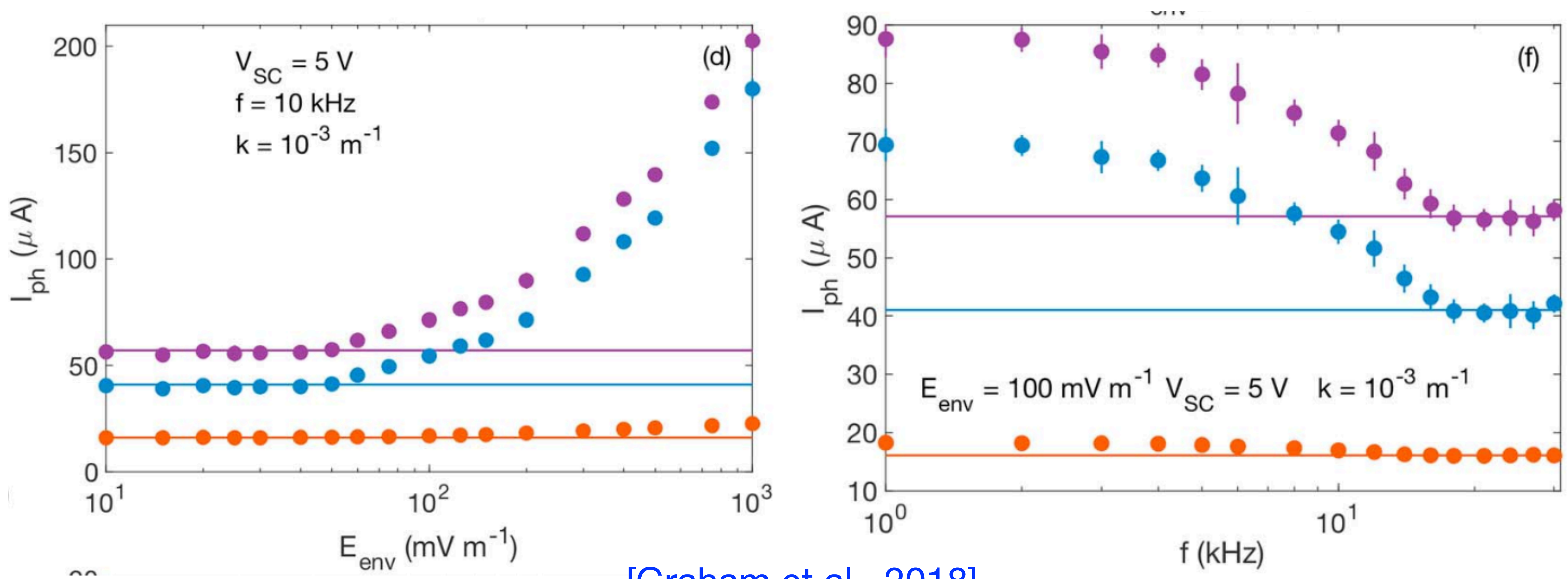


$$\Phi(x,y,z) = \frac{V_0 R_0}{r} \; : \; r > R_0,$$

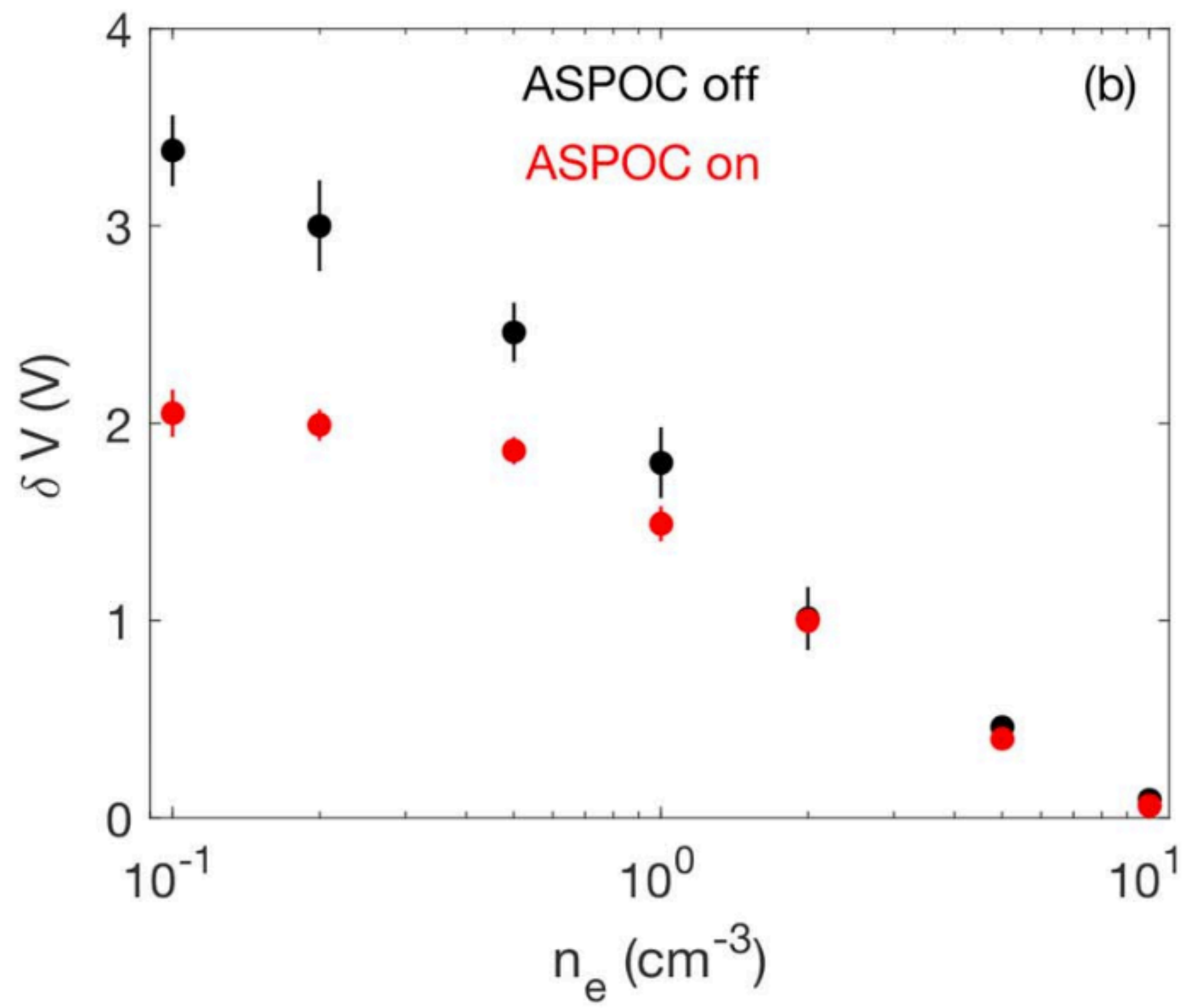
$$\mathbf{E}(x,y,z) = \frac{V_0 R_0 \mathbf{x}}{r^3} + \mathbf{E}_{\text{env}} \cos(kx - 2\pi f t + \phi),$$

$$I_{\text{ph}} = I_{\text{ph0}} \frac{\sum v_{0,\text{esc}}}{\sum v_0},$$

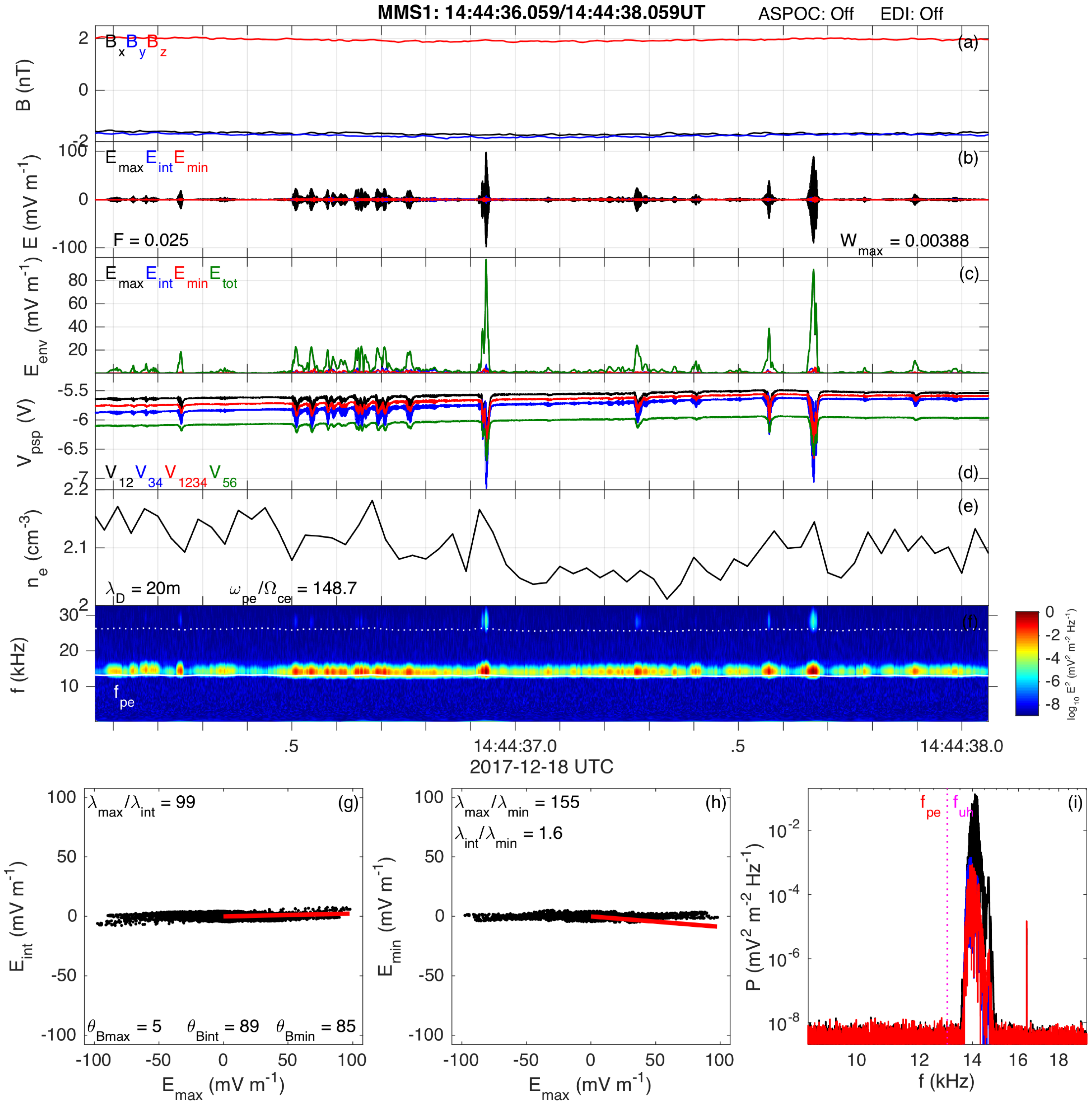
- Test-particle model shows that more photoelectrons escape due to external electric field.



[Graham et al., 2018]



Foreshock Langmuir waves



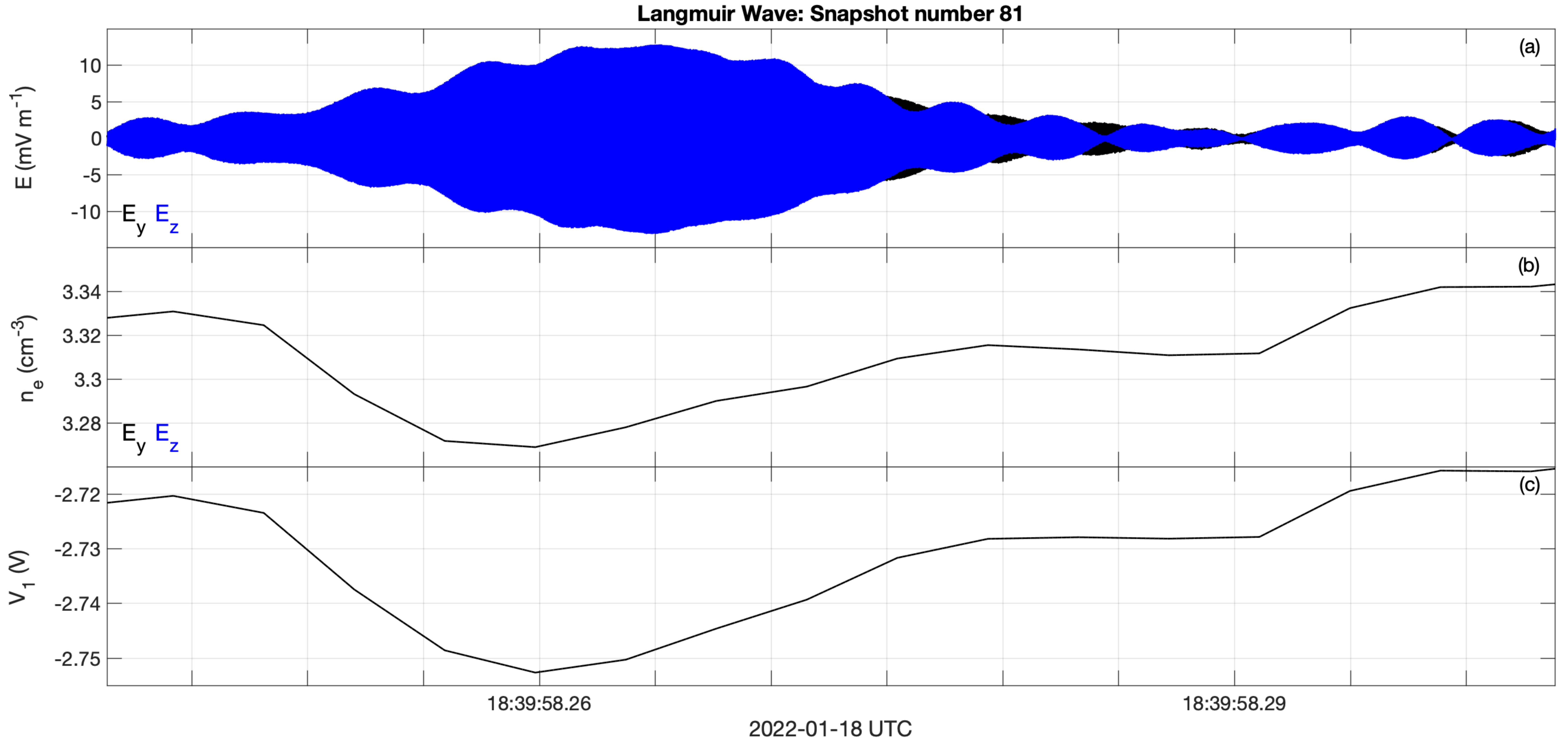
- Significant potential changes are observed for Langmuir waves in the solar wind.

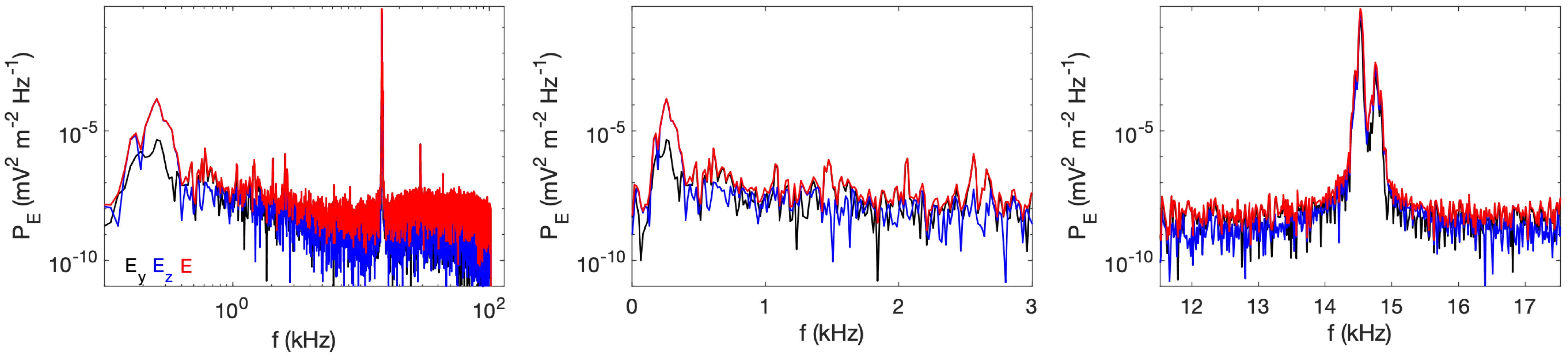
Application to Solar Orbiter

- Possible approaches to look at high-resolution potentials:
  - Use TDS and LFR burst mode (256 s^{-1}).
  - Compare TDS-MAMP with LFR burst mode.
  - Use Fields and potential from TDS (similar to STEREO).

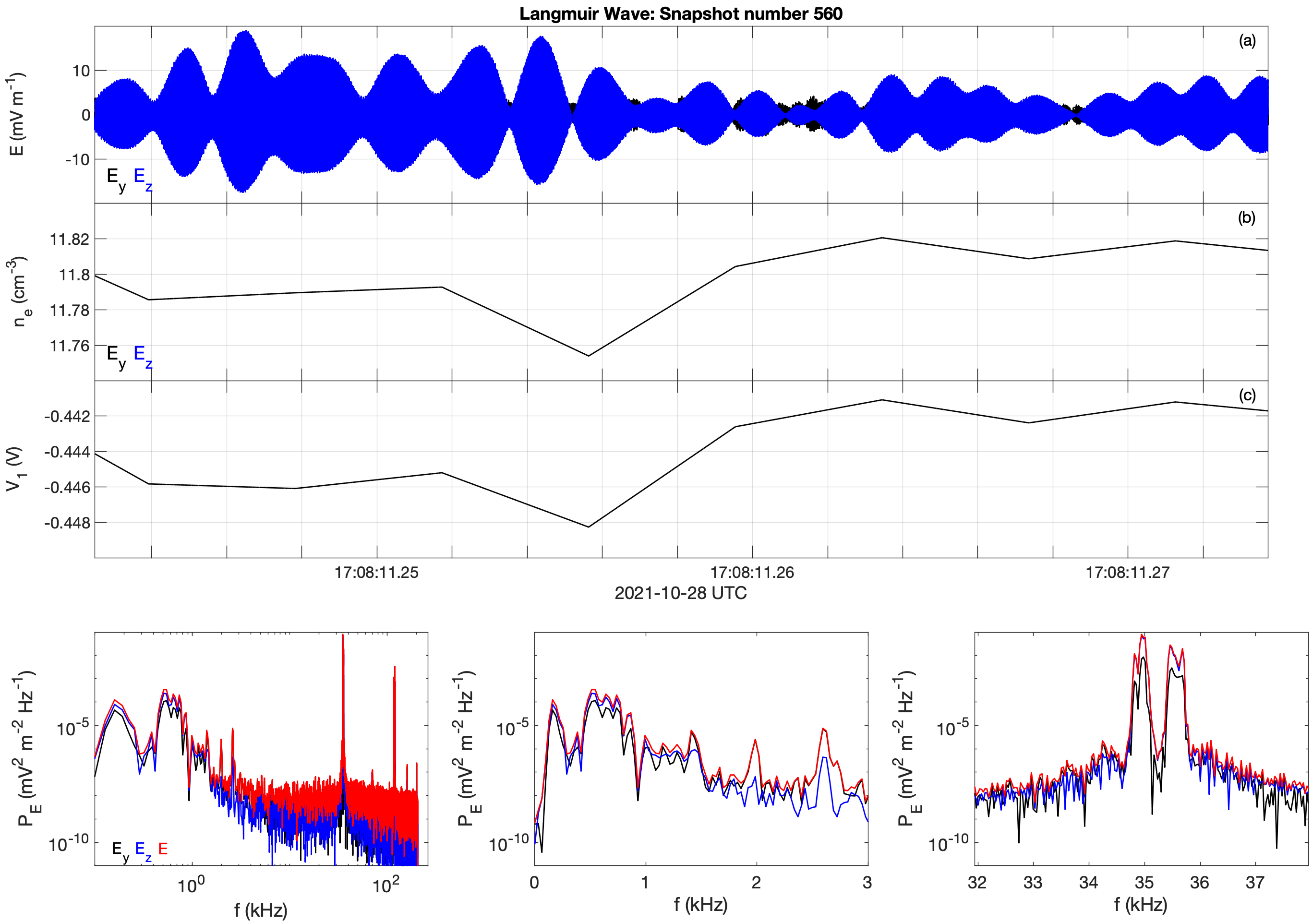
[Henri et al., 2011]

Comparison with LFR

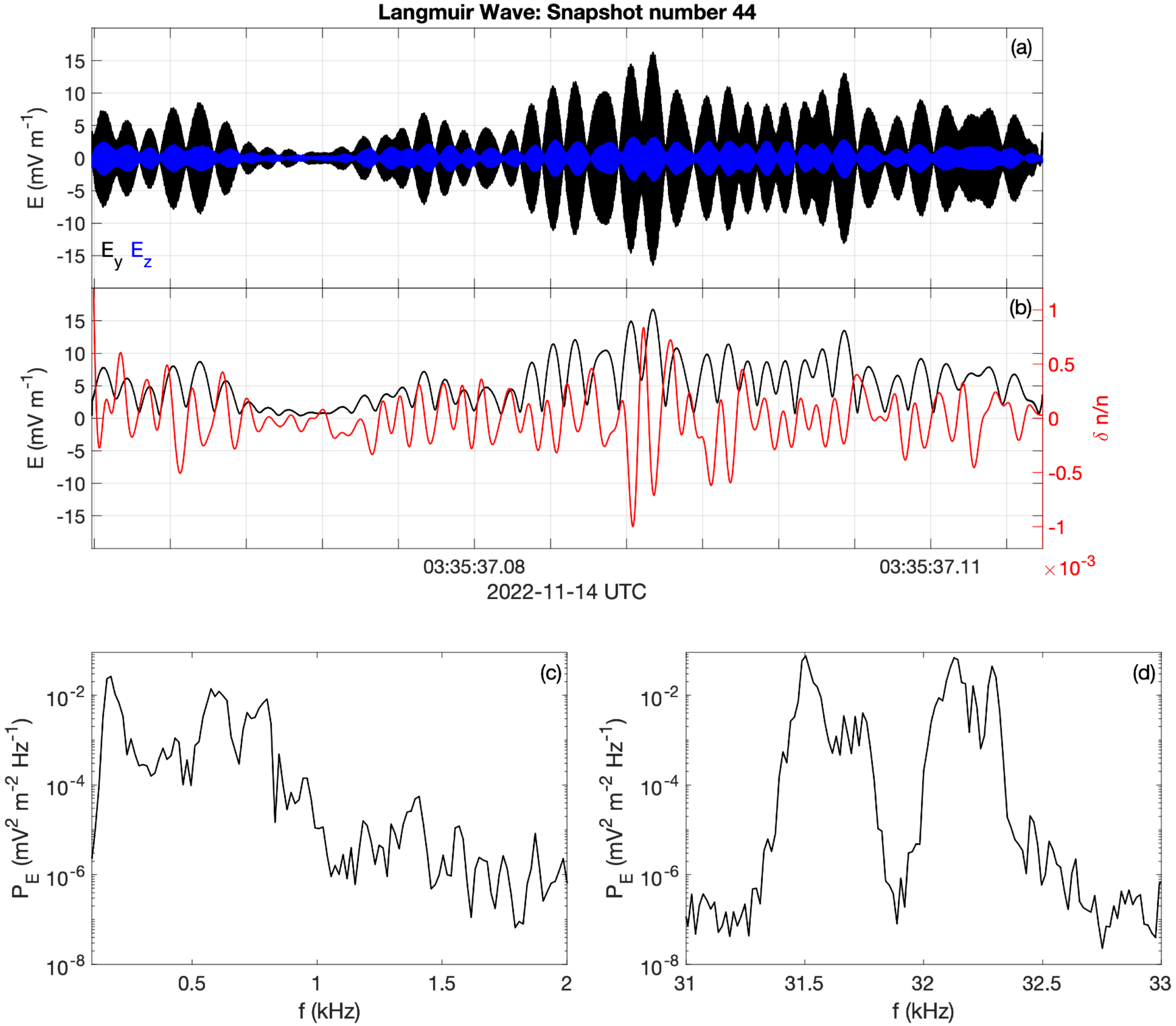


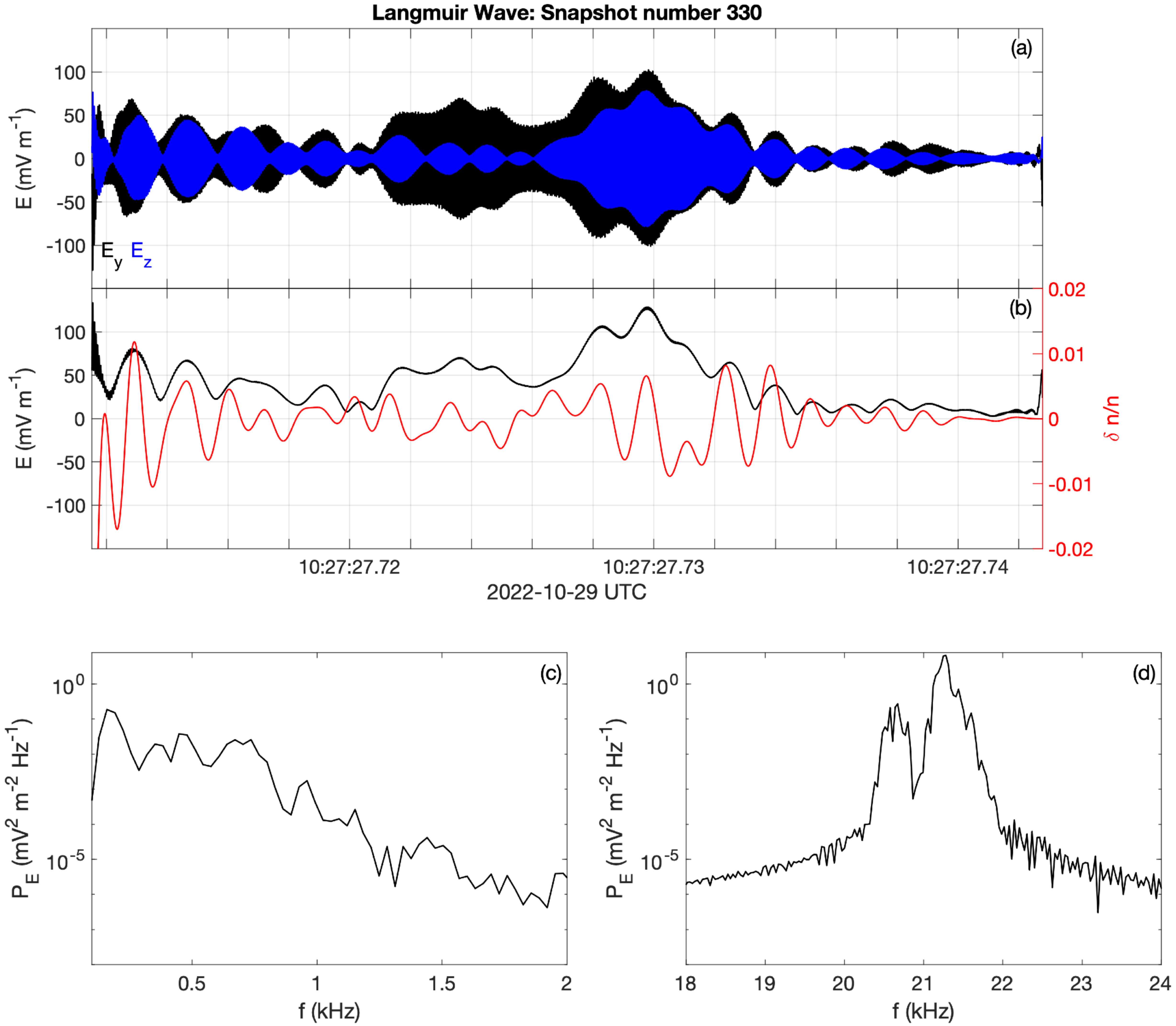


Comparison with LFR



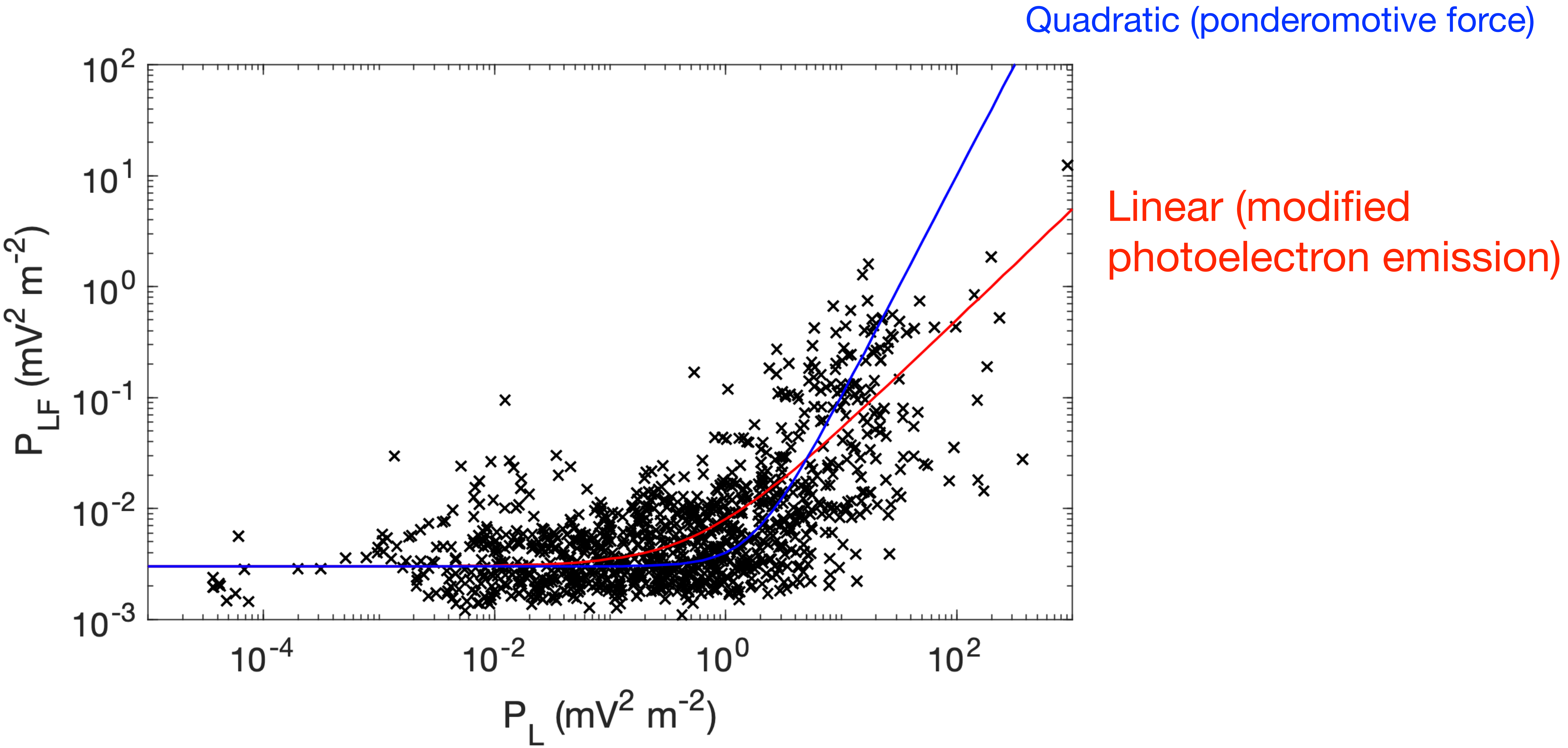
Low-frequency response from TDS





Statistics

- Low-frequency potential response versus Langmuir wave power.



LFR-TDS comparison

Conclusion

- Spacecraft potential can potentially be used to estimate high-cadence density.
- Electric fields of Langmuir waves can modify spacecraft potential by enhancing photoelectron emission.
- Difficult to quantify this effect on Solar Orbiter.