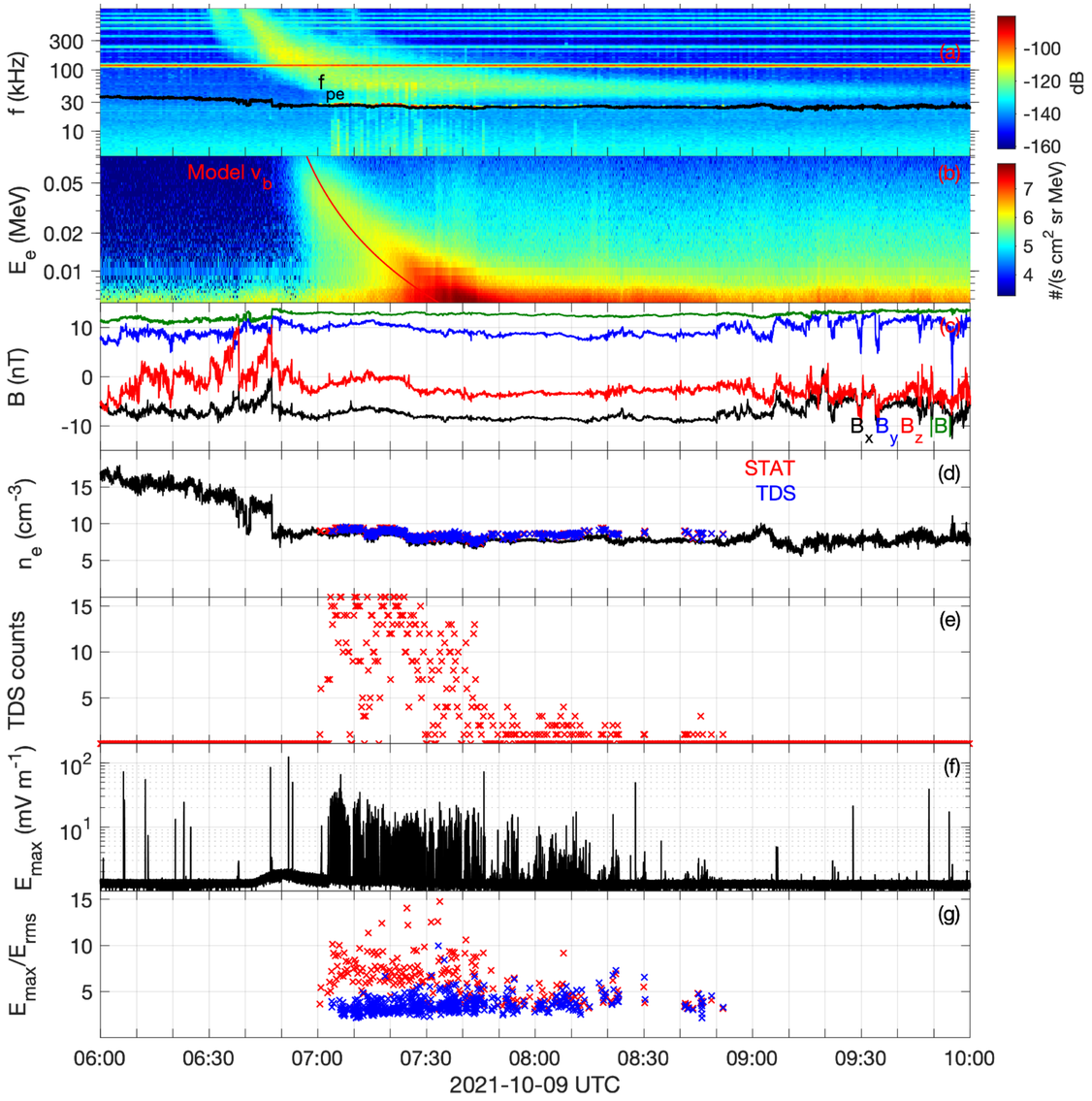
Langmuir waves in the solar wind: Research Topics

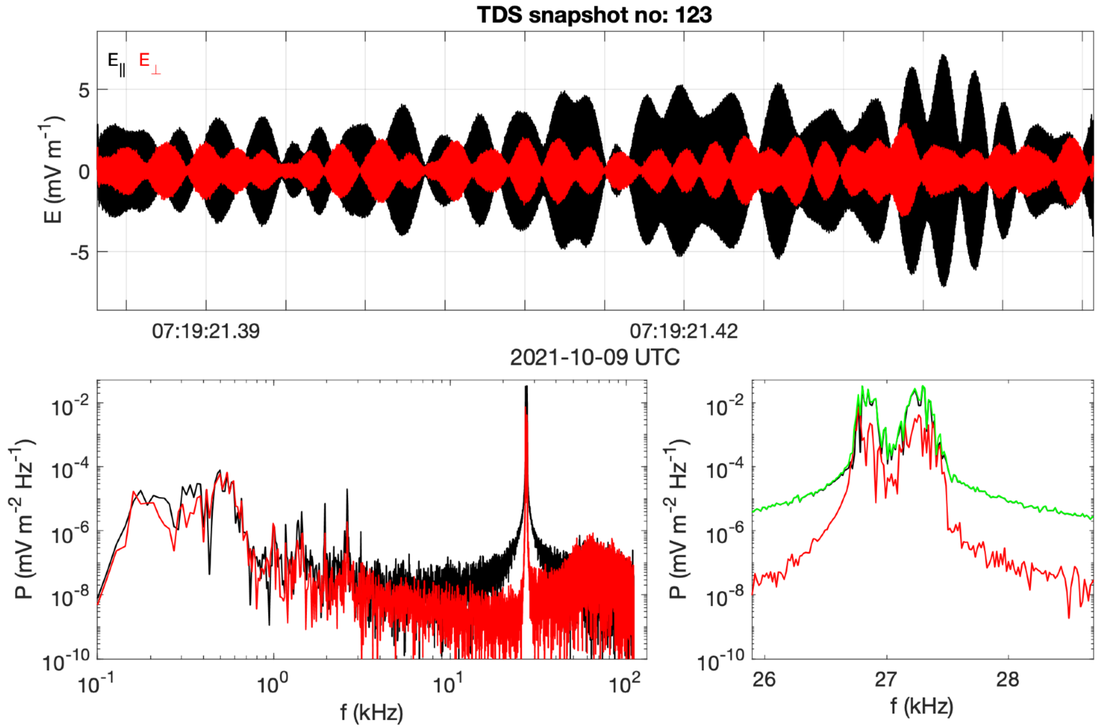
D. B. Graham

Swedish Institute of Space Physics, Uppsala, Sweden

Type III source regions



Example of a type III Source region observed by Solar Orbiter



Langmuir waveform from type III source region

Properties

- In type III source regions:
- vb/ve ~ 5-40
- nb/ne ~ 1e-5

[e.g., Lin et al., ApJ, 1981, 1986; Ergun et al., ApJ, 1998; Malaspina et al., GRL, 2011]

- Magnetic reconnection
- vb/ve ~ 1-10
- nb/ne ~ Up to a few %

[e.g., Fujimoto, GRL, 2014; Graham et al., JGR, 2023]

- Electron foreshock of Earth
- vb/ve ~ 1-40
- nb/ne ~ 1e-5-1e-2

[e.g., Filbert & Kellogg, JGR, 1979; Fitzenreiter et al., GRL, 1984; Fuselier et al., JGR, 1985; Cairns, JGR, 1987; Soucek et al., JGR, 2019]

Strong Turbulence

- Described by Zakharov equations:

Electrostatic

$$\nabla\cdot\left(i\frac{\partial}{\partial t}+\nabla^2+i\hat{\gamma}_L\right)\mathbf{E}=\nabla\cdot(n\mathbf{E}),$$

$$\left(\frac{\partial^2}{\partial t^2}+2\hat{\gamma}_S c_S\frac{\partial}{\partial t}-c_S^2\nabla^2\right)n=\nabla^2|\mathbf{E}|^2,$$

[Zakharov 1972; Zakharov et al., 1985]

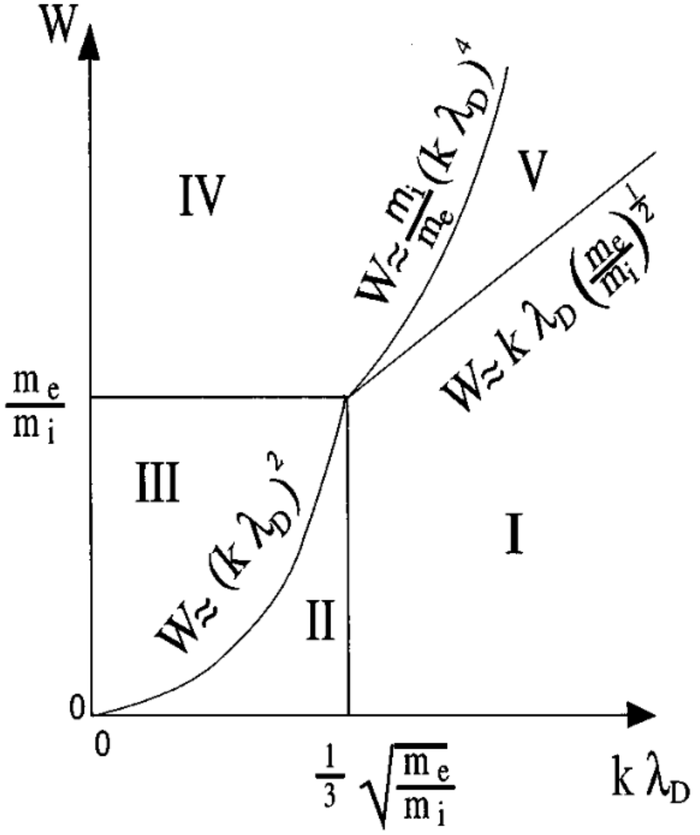
Electromagnetic

$$i\frac{\partial\mathbf{E}}{\partial t}=\left(\frac{v_T^2}{3v_L^2}\nabla\times\nabla\times-\nabla\nabla.-i\hat{\gamma}_L-i\hat{\gamma}_T+\delta n\right)\mathbf{E},$$

$$\left(\frac{\partial^2}{\partial t^2}+2\hat{\gamma}_S\frac{\partial}{\partial t}-C_S^2\nabla^2\right)\delta n=\nabla^2|\mathbf{E}|^2,$$

[e.g., Melatos et al., PoP, 2007; Jenet et al., PoP, 2007]

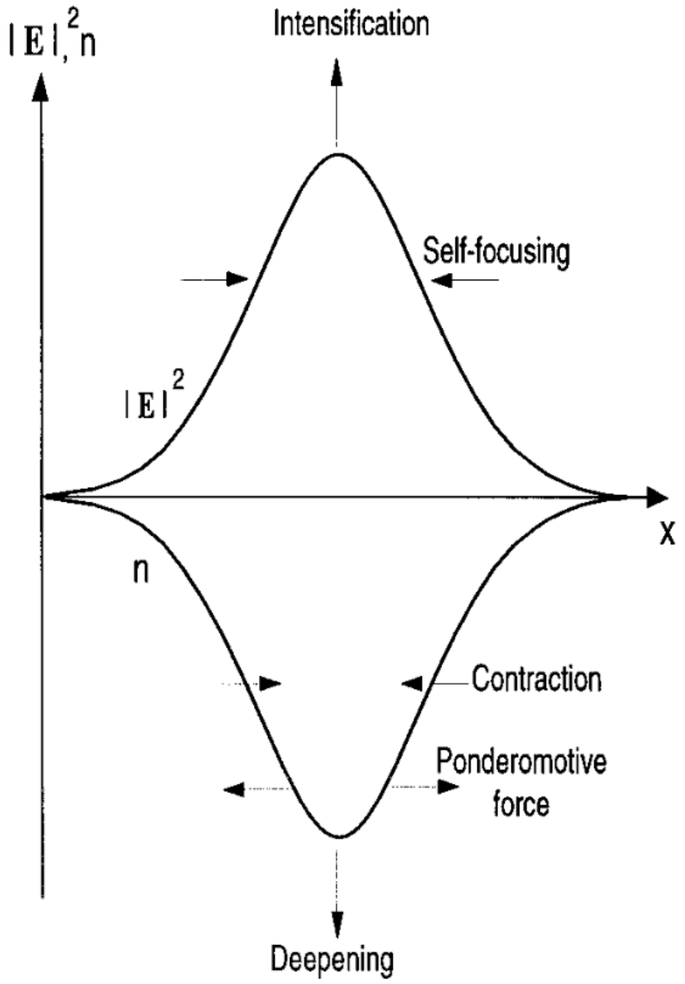
- For monochromic wave
- tens mV/m



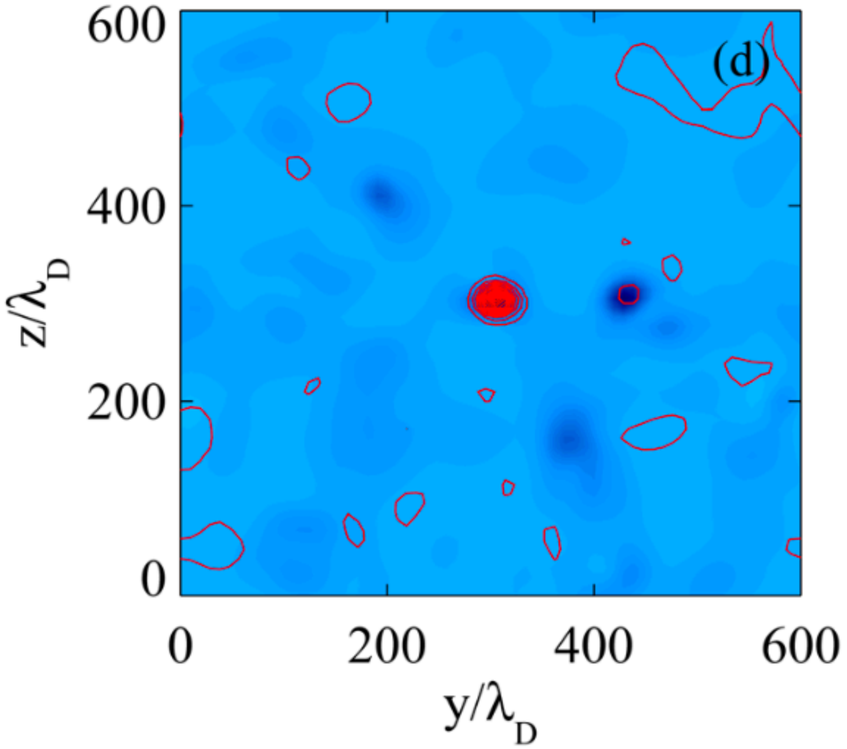
- vb/ve ~ 140

[Zakharov 1972; Zakharov et al., 1985; Robinson, Rev. Mod. Phys., 1997]

Strong turbulence

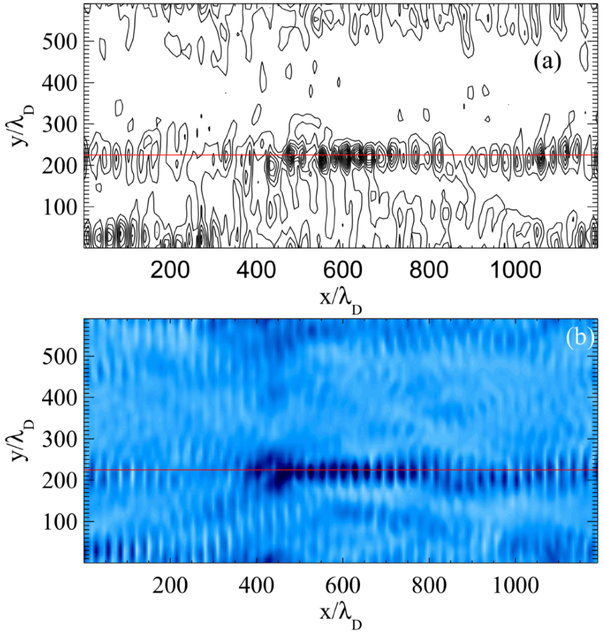


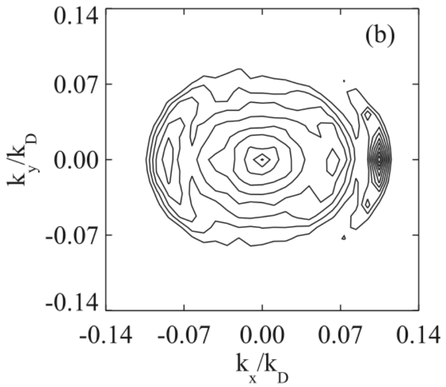
[Robinson, Rev. Mod. Phys., 1997]



- Consists of freely propagating waves and trapping collapsing wave packets.

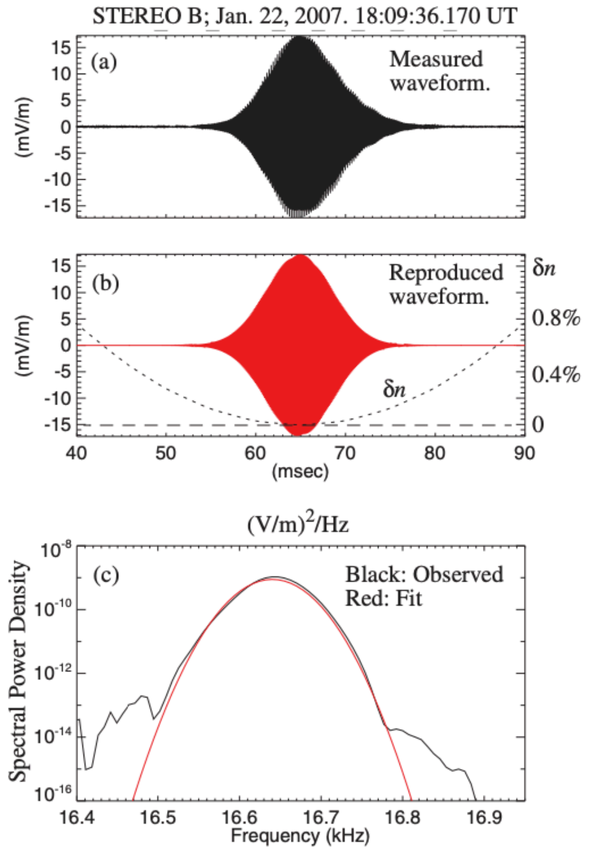
[Robinson & Newman, Phys. Fluids B, 1990a,b]

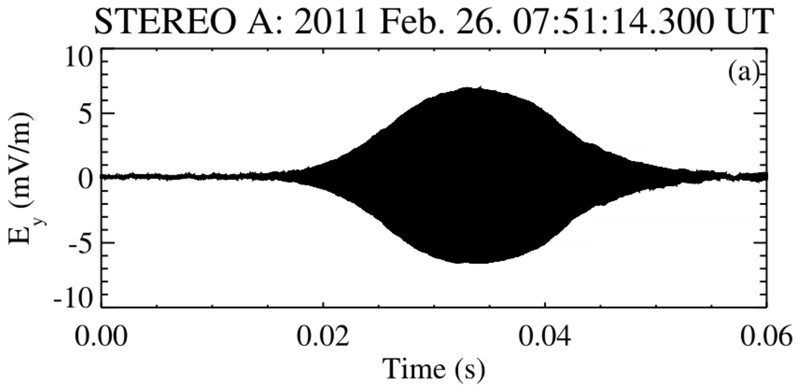


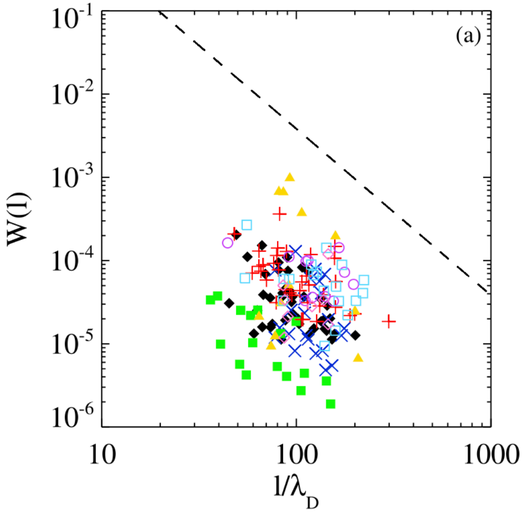


[Images from Graham et al., PoP, 2012a,b]

Localized Langmuir waves



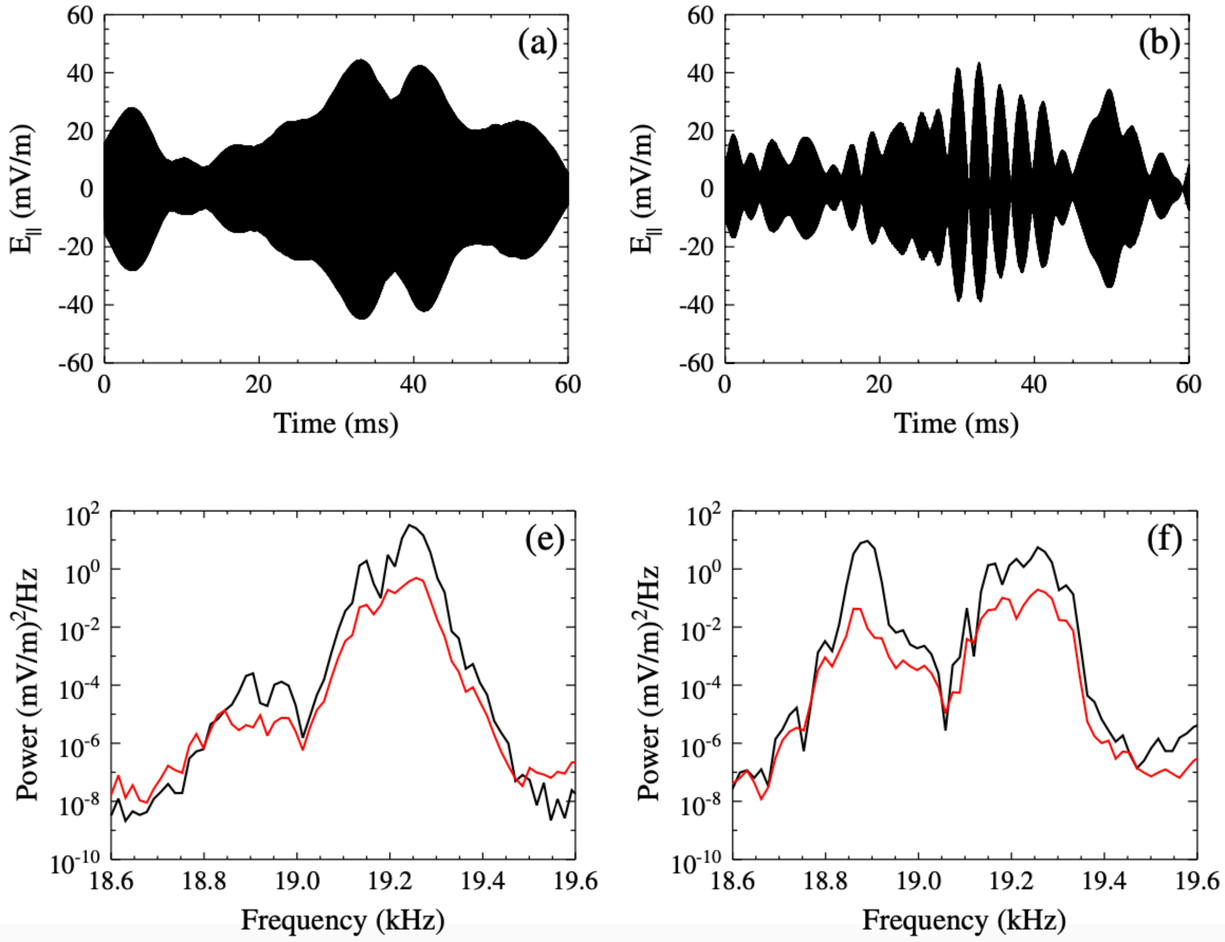




- Too low amplitude for wave packet collapse. [Nulsen et al., JGR, 2007; Graham et al., JGR, 2012; and others]

- Interpreted as localized eigenmodes of density cavities. [Ergun et al., PRL, 2008; Malaspina et al., 2009; and others]

Three-wave decay

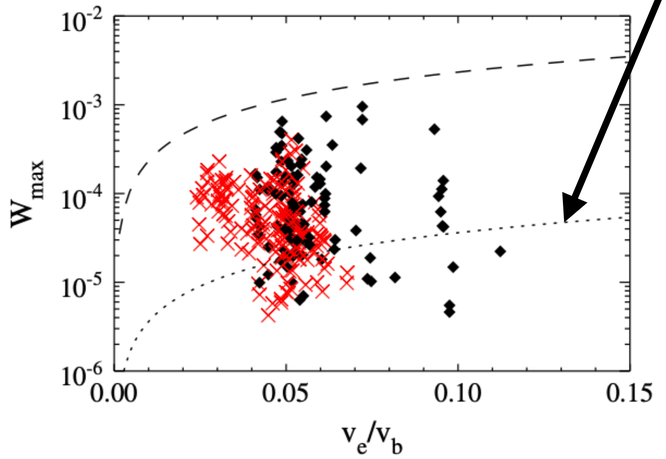


Example of Langmuir wave forms with single spectral peak and two spectra peaks (counter propagating waves)

[Images from Graham & Cairns, JGR, 2013]

- Estimated threshold: [Robinson et al., ApJ, 1993; Robinson & Cairns, GRL, 1995]

$$W_{\max} \gtrsim W_{\mathrm{thr}} = \frac{3}{8\pi\gamma^{3/2}} \sqrt{\frac{m_i}{m_e}} \frac{\gamma_{L'}}{\omega_p} \frac{\Delta v_b}{v_b} \frac{v_e}{v_b},$$



- Often waveforms satisfy predictions for ES decay.

  [E.g., Graham & Cairns, JGR, 2013; cf. Henri et al., JGR, 2009]

- Others argue that reflection off density gradients is more important.

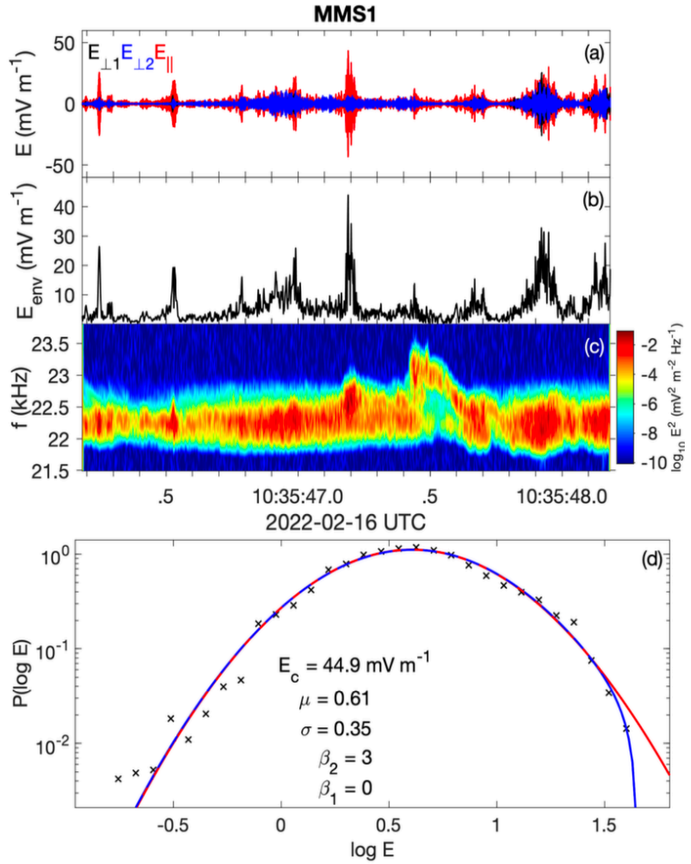
  [e.g., Krasnoselskikh et al., Ann. Geo., 2011]

Field statistics

- Langmuir waveforms are highly complex and bursty.
- Stochastic Growth Theory predicts a log-normal distribution:

$$P(\log E) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(\log E - \mu)^2}{2\sigma^2}\right)$$

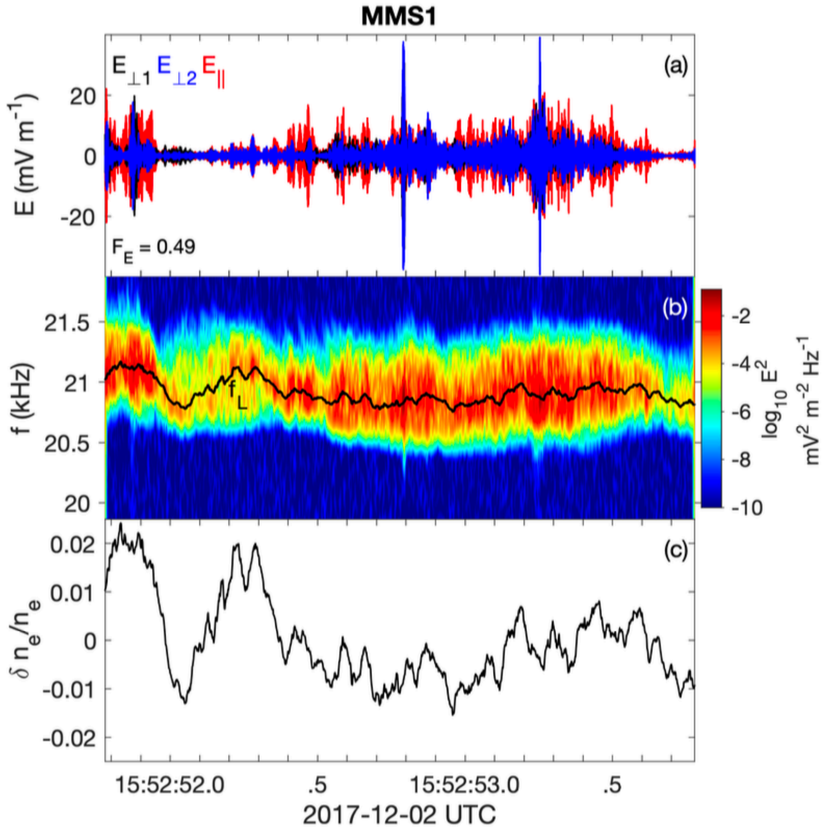
[Robinson, Sol. Phys., 1992]



[Langmuir waves in Earths electron foreshock; from Graham et al., 2026 in prep.]

- Distributions of electric field envelope can be important for investigating Langmuir wave evolution and processes or occurring.

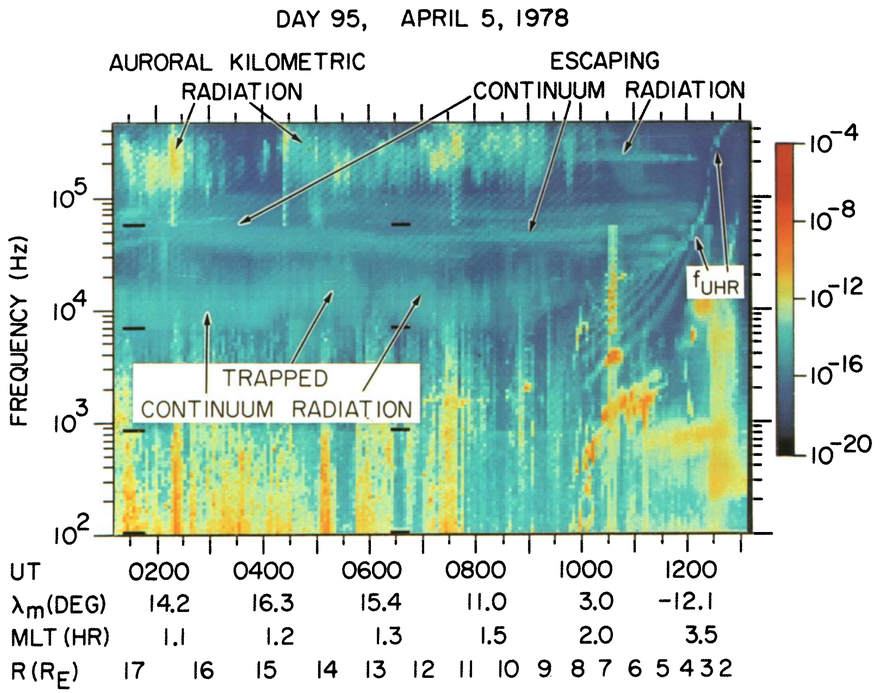
[e.g., Robinson et al, ApJ., 1993; Cairns & Menietti, JGR, 2001; Krasnoselskikh et al., JGR, 2007; Cairns et al., Adv. Space Phys., 2026]



Small scale density fluctuations are important for wave evolution [Smith & Sime, ApJ, 1979; Celnikier et al., A&A, 1987]

Radio wave emission

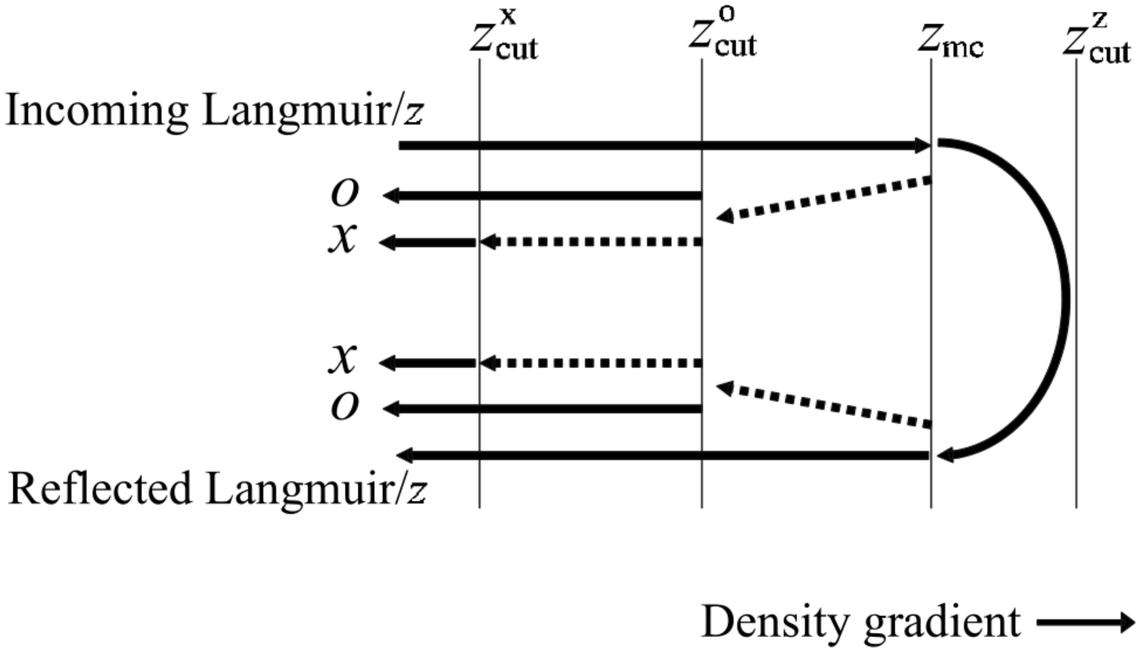
- Suggested processes:
  - Electromagnetic decay
  - Electrostatic decay and coalescence
  - Linear mode conversion
  - Antenna mechanisms



- Continuum radio emission and AKR.

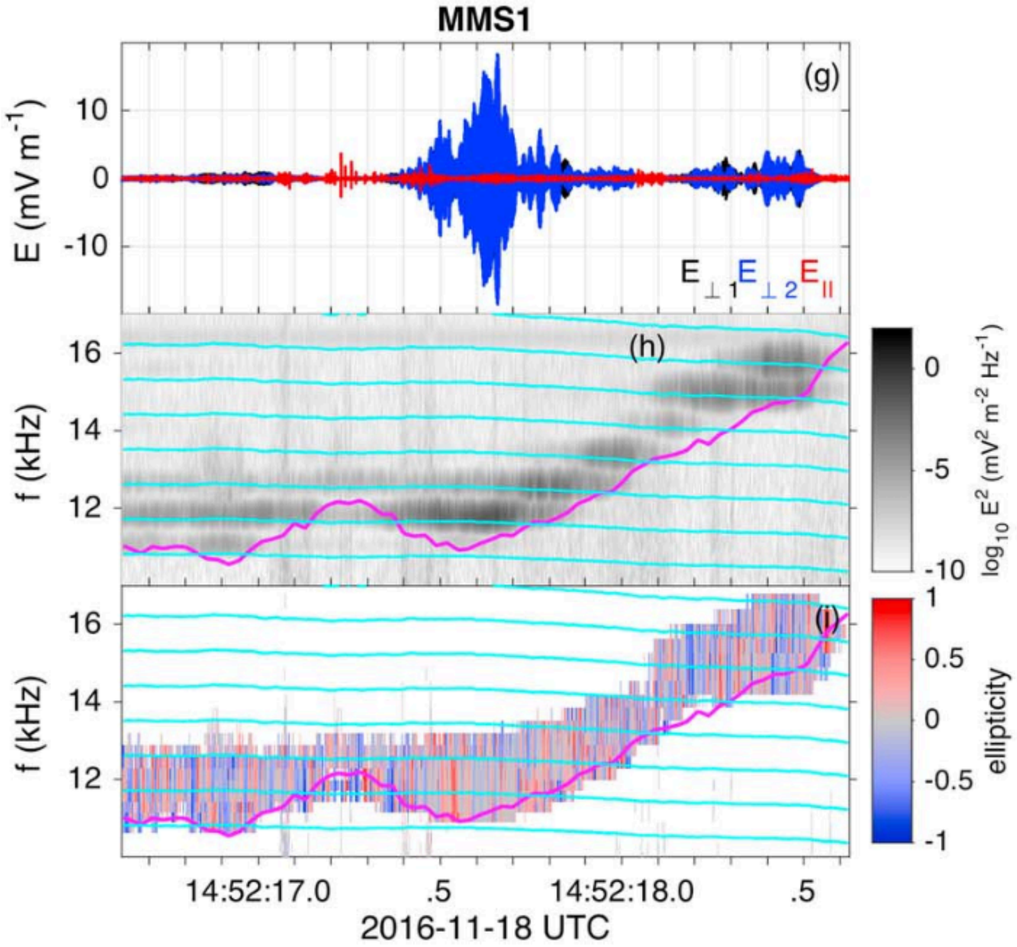
[Kurth et al., JGR, 1981]

Linear mode conversion



- Schematic of linear mode conversion

  [Kim et al., PRL, 2007, PoP, 2008; Schleyer et al., JGR, 2014]



- Upper hybrid waves at a density gradient

  [From Graham et al., JGR, 2018]

Ongoing questions

- What is the role of small scale density turbulence (dn/n ~ 0.01, l 10^3-10^5 λ_D) on Langmuir wave evolution?
- Are localized Langmuir waves eigenmodes of density cavities?
- Do laboratory plasmas produce similar waveforms or field statistics as observations?
- Relatively importance of radio emission processes (e.g., mode conversion versus EM decay, ES decay and coalescence)?
- What is the conversion efficiency of linear mode conversion at a density gradient?