

Evidence of Langmuir/ Z -mode Wave Decay into Z -mode Electromagnetic Radiation in the Solar Wind



Francisco J. Polanco-Rodríguez, C. Krafft & P. Savoini

Laboratoire de Physique des Plasmas, Palaiseau, France.

ATST Conference, June, 2026, Biarritz, France.



INSTITUT
POLYTECHNIQUE
DE PARIS

université
PARIS-SACLAY



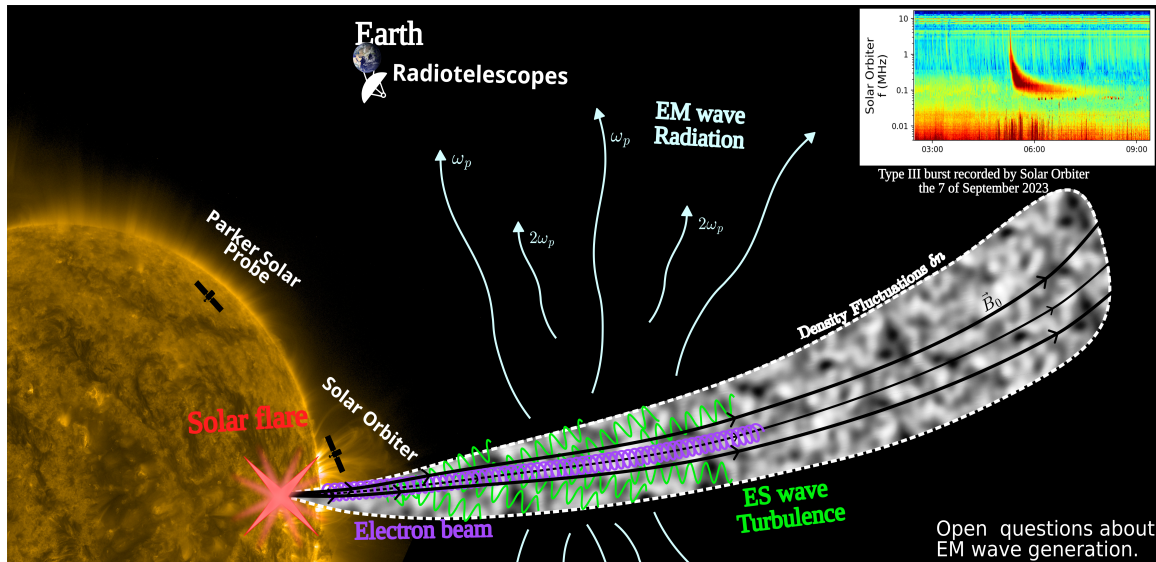
SORBONNE
UNIVERSITÉ



institut
universitaire
de France

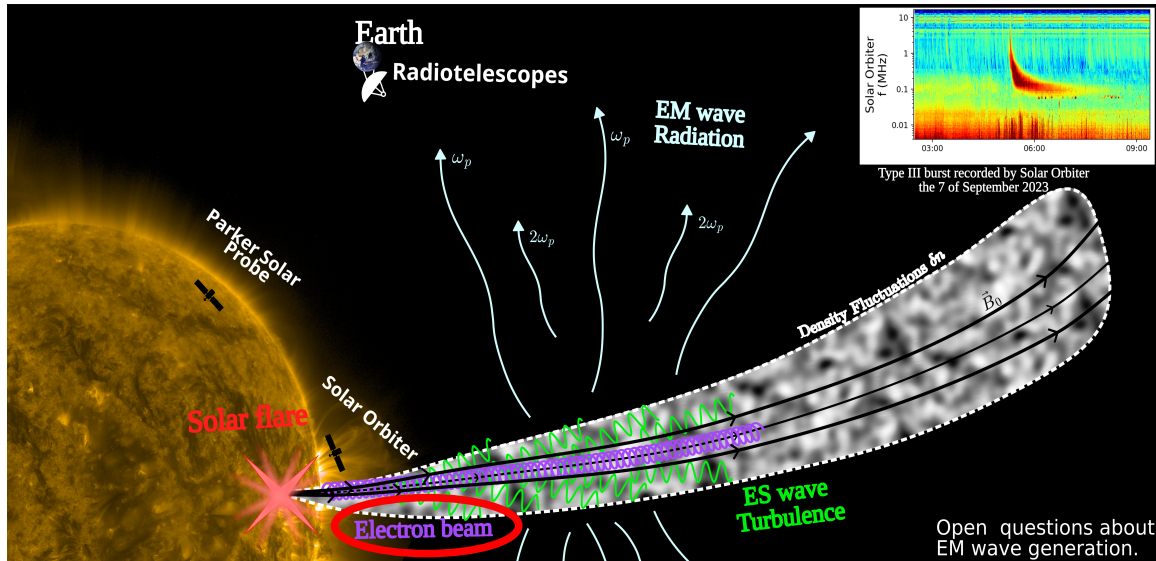
Context

Type III Solar Radio Bursts



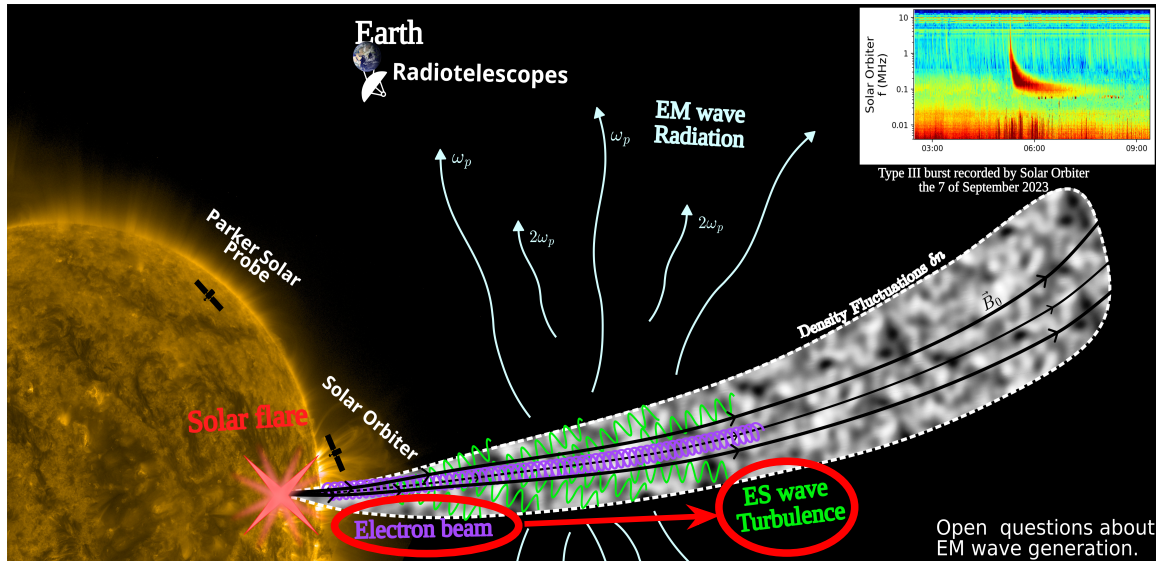
Open questions about
EM wave generation.

Type III Solar Radio Bursts



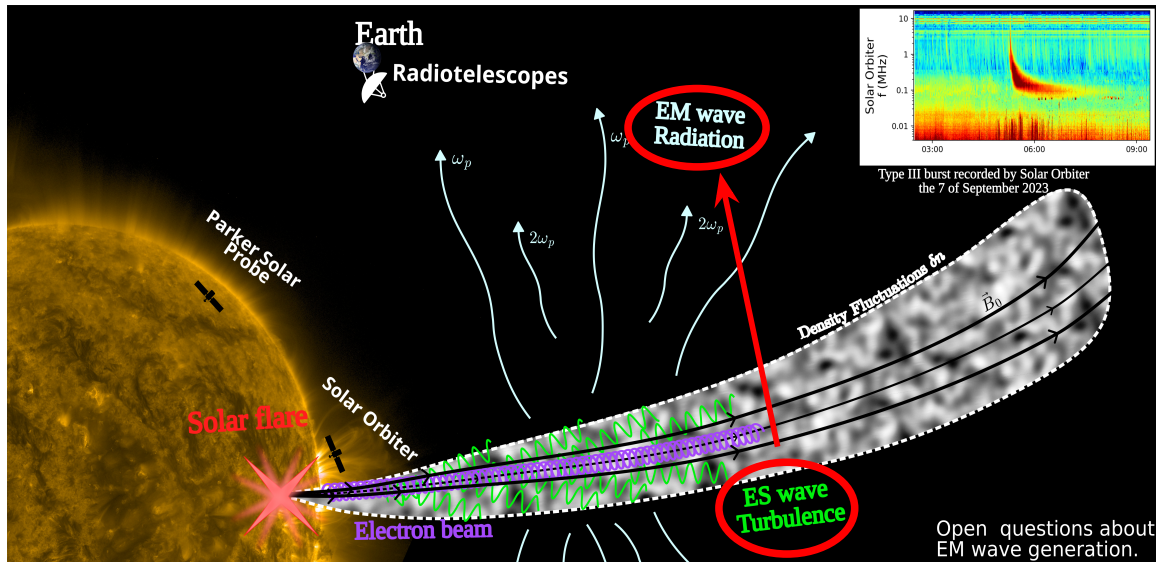
Open questions about
EM wave generation.

Type III Solar Radio Bursts



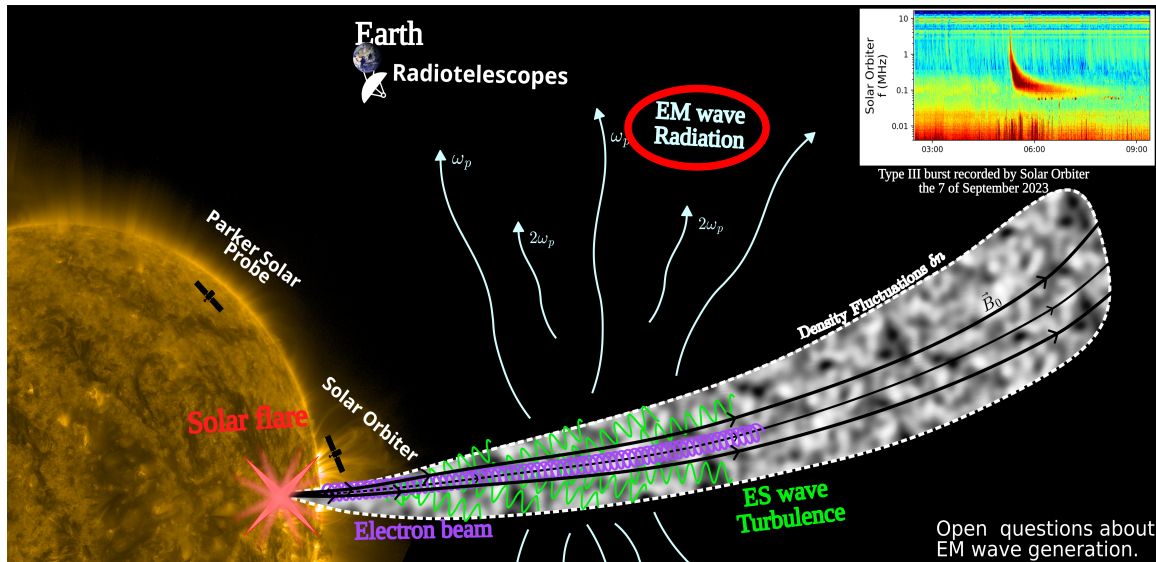
Open questions about
EM wave generation.

Type III Solar Radio Bursts



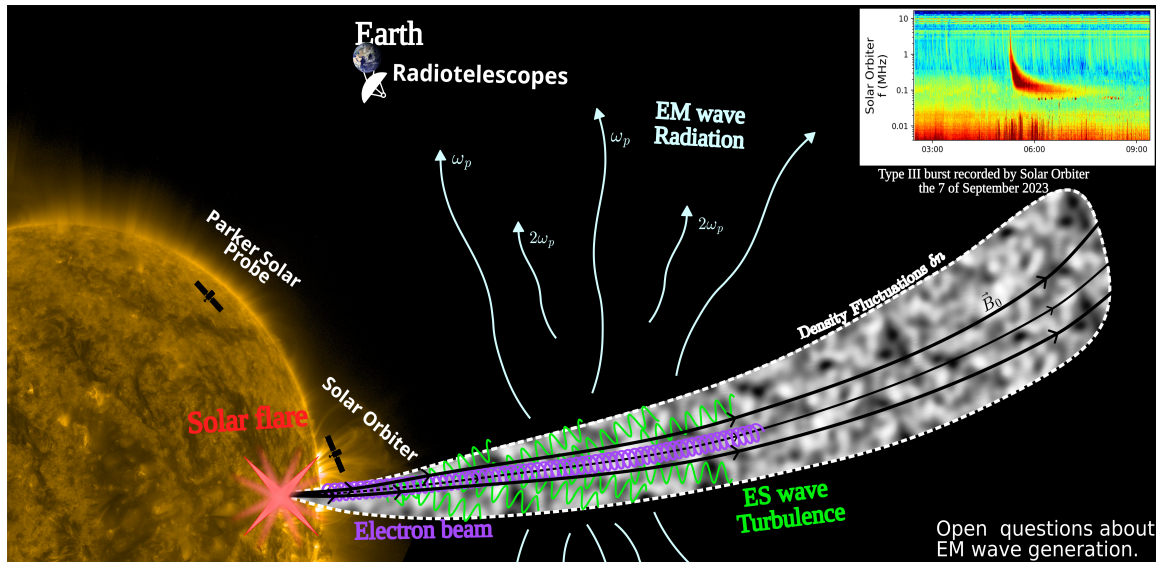
Open questions about
EM wave generation.

Type III Solar Radio Bursts



Open questions about
EM wave generation.

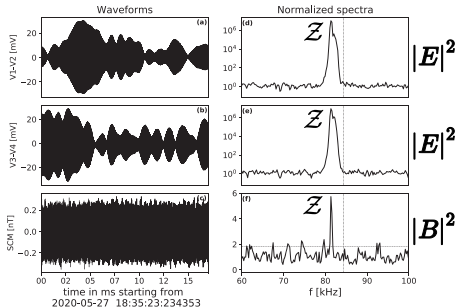
Type III Solar Radio Bursts



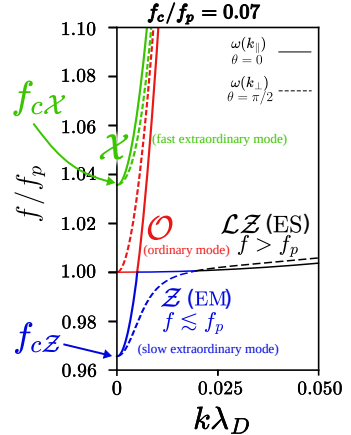
Open questions about
EM wave generation.

The electromagnetic $\mathcal{Z}$ mode

- ▶ Z-mode waves have been searched for in the solar wind for decades (e.g. Bale et al. 1998, GRL, 25, 9)
- ▶ High-resolution magnetic field waveforms are available only since the **P**arker **S**olar **P**robe spacecraft launch (2018)
- ▶ First observation of a Z-mode wave by **PSP** (Larosa et al. 2022, ApJ, 927, 95)

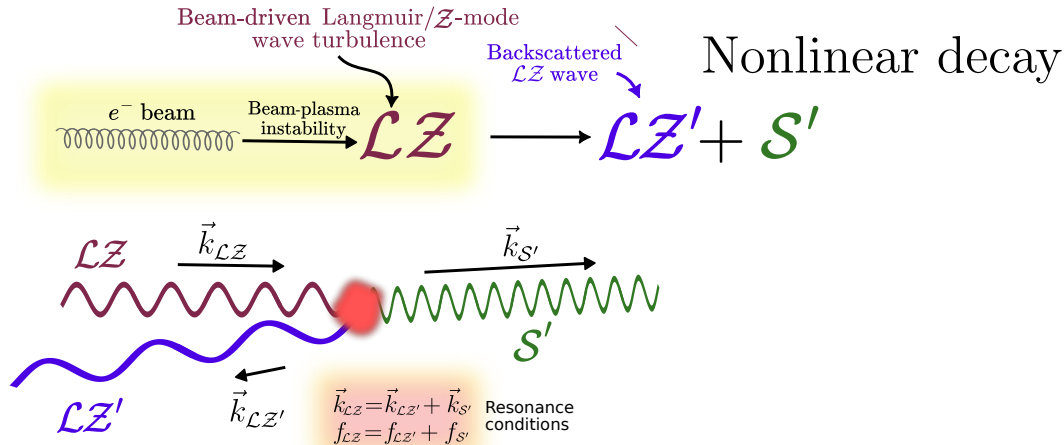


HF wave dispersions In weakly magnetized plasmas

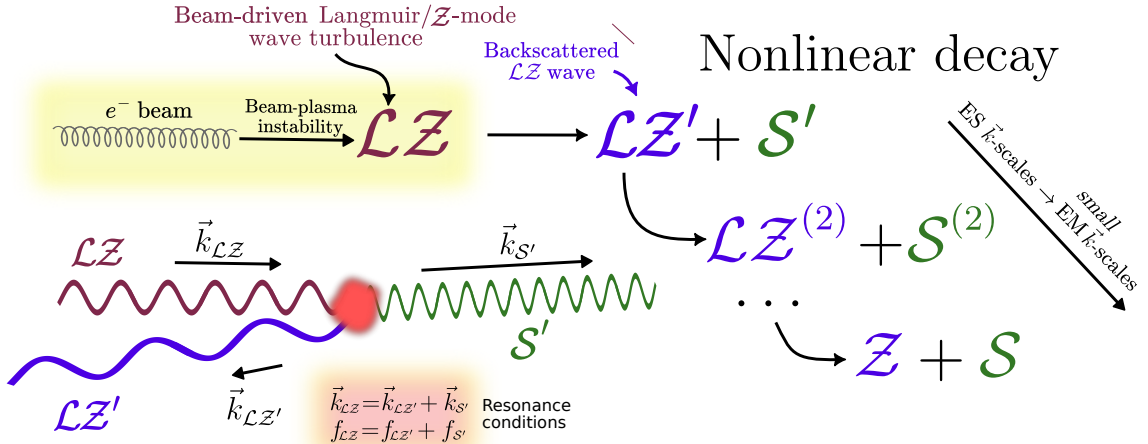


The decay of $\mathcal{LZ}$ waves

The decay of $\mathcal{LZ}$ waves

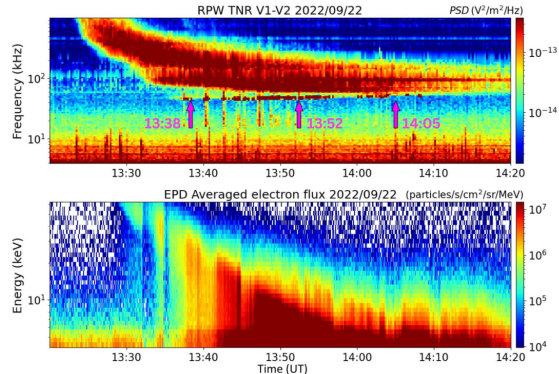


The decay of $\mathcal{LZ}$ waves



Solar Orbiter observation of decay
to Z-mode waves

Solar Orbiter observation on the 22 September 2022



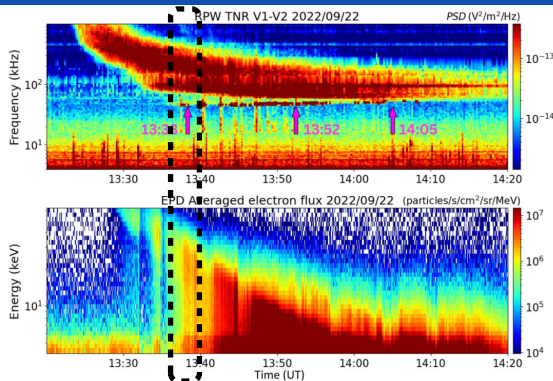
Credit:Formánek et al 2025, ApJL, 985, L29

Solar Orbiter (RPW) detected LZ waveforms, associated with a type III burst. The corresponding electron beam was simultaneously observed.

Solar Orbiter observation on the 22 September 2022

- Measurement of plasma and beam VDFs at 13:38 and 14:05.

	13:38	14:05
E_b	23.9keV	Decelerated
T_e	11.7eV	11.9eV



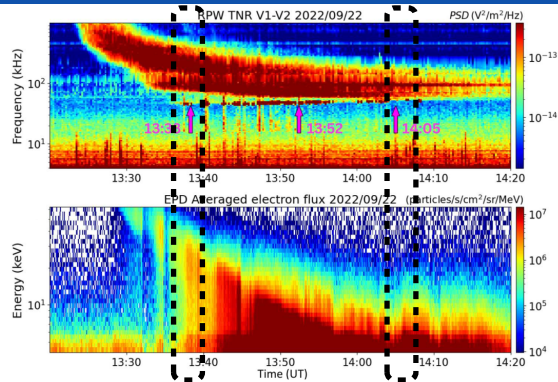
Credit:Formánek et al 2025, ApJL, 985, L29

Solar Orbiter (RPW) detected LZ waveforms, associated with a type III burst. The corresponding electron beam was simultaneously observed.

Solar Orbiter observation on the 22 September 2022

- Measurement of plasma and beam VDFs at 13:38 and 14:05.

	13:38	14:05
E_b	23.9keV	Decelerated
T_e	11.7eV	11.9eV



Credit:Formánek et al 2025, ApJL, 985, L29

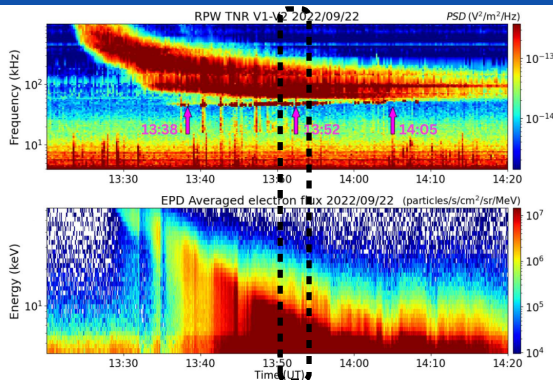
Solar Orbiter (RPW) detected LZ waveforms, associated with a type III burst. The corresponding electron beam was simultaneously observed.

Solar Orbiter observation on the 22 September 2022

- Measurement of plasma and beam VDFs at 13:38 and 14:05.

	13:38	14:05
E_b	23.9keV	Decelerated
T_e	11.7eV	11.9eV

- **Magnetized LZ wave identified** at 13:52. Linear calculations reveal that $k \simeq 10^{-3} \lambda_D^{-1} \ll k_b \simeq \omega_p / v_b$ (i.e. not beam-driven).



Credit:Formánek et al 2025, ApJL, 985, L29

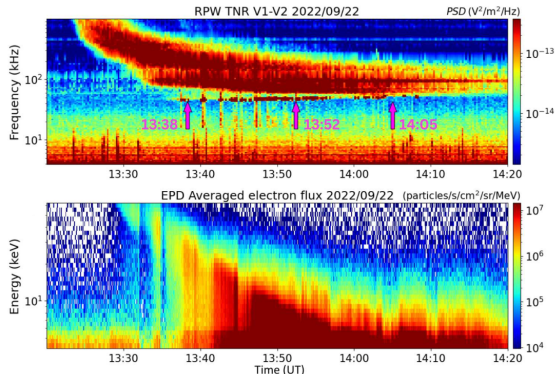
Solar Orbiter (RPW) detected LZ waveforms, associated with a type III burst. The corresponding electron beam was simultaneously observed.

Solar Orbiter observation on the 22 September 2022

- ▶ Measurement of plasma and beam VDFs at 13:38 and 14:05.

	13:38	14:05
E_b	23.9keV	Decelerated
T_e	11.7eV	11.9eV

- ▶ **Magnetized LZ wave identified** at 13:52. Linear calculations reveal that $k \simeq 10^{-3} \lambda_D^{-1} \ll k_b \simeq \omega_p/v_b$ (i.e. not beam-driven).
- ▶ **What mechanism is producing Z-mode waves?**

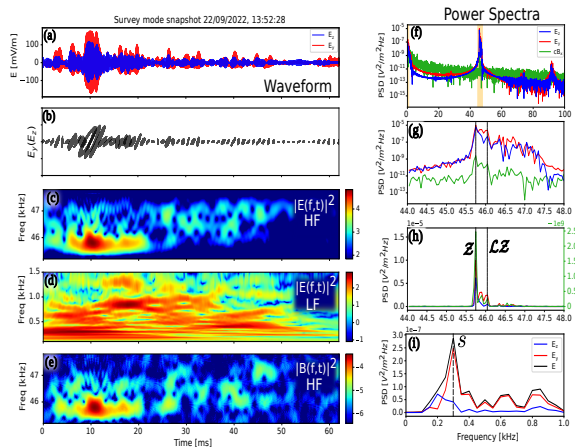


Credit:Formánek et al 2025, ApJL, 985, L29

Solar Orbiter (RPW) detected LZ waveforms, associated with a type III burst. The corresponding electron beam was simultaneously observed.

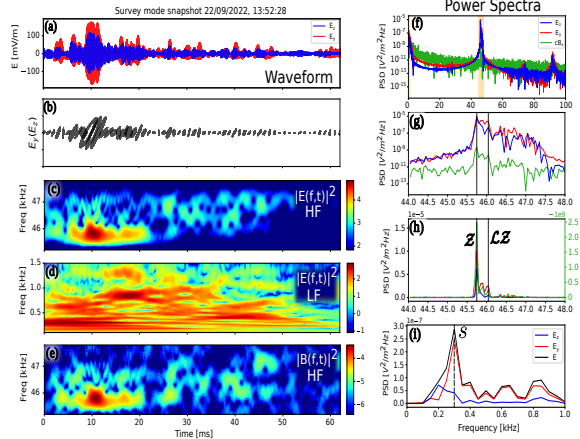


- Amplitude up to $|\mathbf{E}| \simeq 150 \text{ mV/m}$.



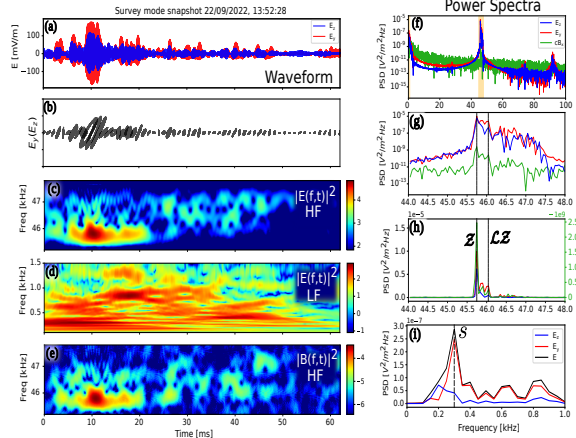


- **Amplitude** up to $|\mathbf{E}| \simeq 150 \text{ mV/m}$.
- **Elliptic polarization** and important magnetic signature $((cB/E)^2 \simeq 10^{-4})$.



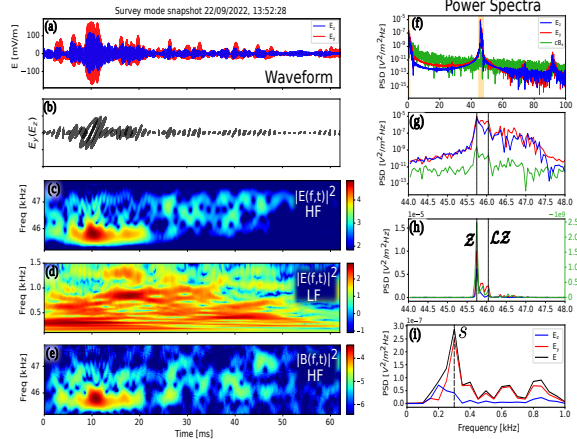


- **Amplitude** up to $|E| \simeq 150 \text{ mV/m}$.
- **Elliptic polarization** and important magnetic signature ($(cB/E)^2 \simeq 10^{-4}$).
- E and B spectrograms peak at $f \sim 45.5 \text{ kHz}$ and $t \sim 10 \text{ ms}$.



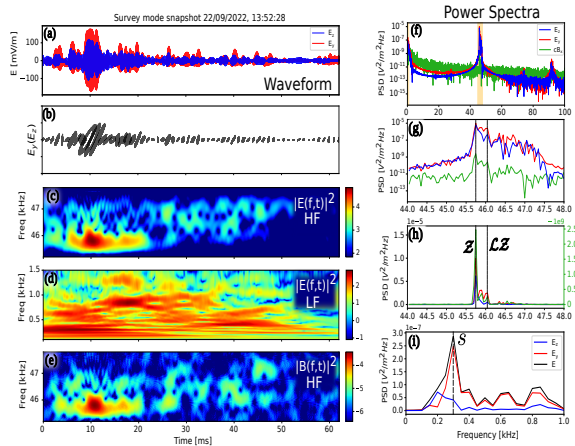


- **Amplitude** up to $|\mathbf{E}| \simeq 150 \text{ mV/m}$.
- **Elliptic polarization** and important magnetic signature ($(cB/E)^2 \simeq 10^{-4}$).
- E and B spectrograms peak at $f \sim 45.5 \text{ kHz}$ and $t \sim 10 \text{ ms}$.
- **Low-frequency** E spectrogram shows waves at $f \sim 0.3 \text{ kHz}$ and $t \sim 10 \text{ ms}$.



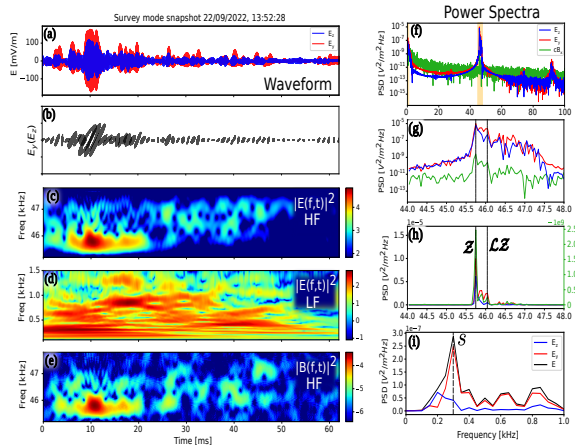


- ▶ **Amplitude** up to $|\mathbf{E}| \simeq 150 \text{ mV/m}$.
- ▶ **Elliptic polarization** and important magnetic signature ($(cB/E)^2 \simeq 10^{-4}$).
- ▶ E and B spectrograms peak at $f \sim 45.5 \text{ kHz}$ and $t \sim 10 \text{ ms}$.
- ▶ Low-frequency E spectrogram shows waves at $f \sim 0.3 \text{ kHz}$ and $t \sim 10 \text{ ms}$.
- ▶ Three peaks can be measured in spectra, at $f = 45.74 \text{ kHz}$, $f = 46.04 \text{ kHz}$ and $f = 0.3 \text{ kHz}$.





- ▶ **Amplitude** up to $|E| \simeq 150 \text{ mV/m}$.
- ▶ **Elliptic polarization** and important **magnetic signature** ($(cB/E)^2 \simeq 10^{-4}$).
- ▶ E and B spectrograms peak at $f \sim 45.5 \text{ kHz}$ and $t \sim 10 \text{ ms}$.
- ▶ **Low-frequency** E spectrogram shows waves at $f \sim 0.3 \text{ kHz}$ and $t \sim 10 \text{ ms}$.
- ▶ **Three peaks** can be measured in spectra, at $f = 45.74 \text{ kHz}$, $f = 46.04 \text{ kHz}$ and $f = 0.3 \text{ kHz}$.



Observations suggest that the decay of $\mathcal{LZ} \rightarrow S + Z$ is the mechanism at play.

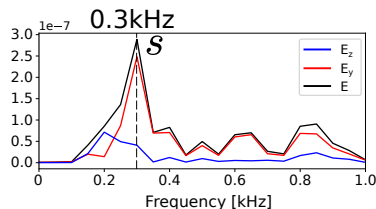
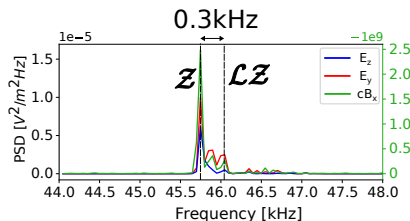


List of Arguments

1 Resonance conditions fulfilled

$$f_{\mathcal{LZ}} = f_Z + f_S$$

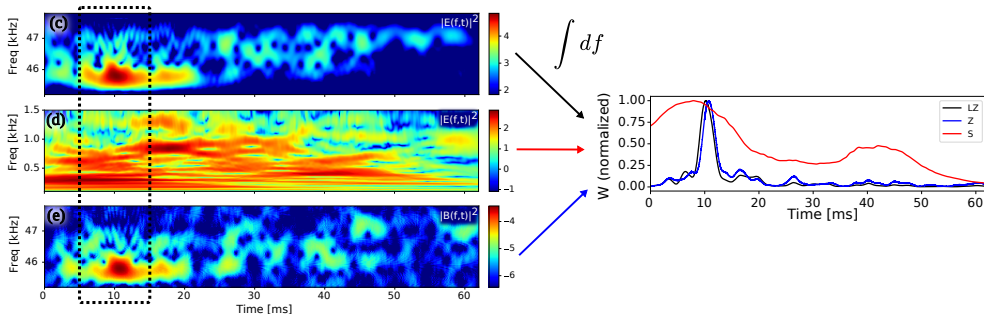
▷ f Doppler-shifted $\Rightarrow$ resonance in (f, k) .





List of Arguments

- 1 **Resonance conditions** fulfilled
 $f_{\mathcal{LZ}} = f_Z + f_S$
▷ f Doppler-shifted $\Rightarrow$ resonance in (f, k) .
- 2 **Time coincidence** of HF and LF modes.





List of Arguments

- 1 **Resonance conditions** fulfilled
 $f_{\mathcal{LZ}} = f_Z + f_S$
▷ f Doppler-shifted $\Rightarrow$ resonance in (f, k) .
- 2 **Time coincidence** of HF and LF modes.
- 3 **Decay kinematics** predicts a single cascade to a Z -mode wave with
 $k_Z \sim 10^{-3} \lambda_D^{-1}$.

Polanco-Rodríguez et al. 2025, ApJL, 982, L24



List of Arguments

① **Resonance conditions** fulfilled

$$f_{\mathcal{LZ}} = f_Z + f_S$$

▷ f Doppler-shifted $\Rightarrow$ resonance in (f, k) .

② **Time coincidence** of HF and LF modes.

③ **Decay kinematics** predicts a single

cascade to a Z -mode wave with

$$k_Z \sim 10^{-3} \lambda_D^{-1}.$$

Polanco-Rodríguez et al. 2025, ApJL, 982, L24

④ **Turbulence parameter**

$$W = \varepsilon_0 E^2 / 4 n_0 k_B T_e \simeq 3.5 \cdot 10^{-4},$$

▷ **threshold** for decay is **overcome**,

▷ **no strong turbulence** expected.

(given that $k_{\mathcal{LZ}} \simeq 0.023 \lambda_D^{-1}$)



List of Arguments

① **Resonance conditions** fulfilled

$$f_{\mathcal{LZ}} = f_Z + f_S$$

▷ f Doppler-shifted $\Rightarrow$ resonance in (f, k) .

② **Time coincidence** of HF and LF modes.

③ **Decay kinematics** predicts a single cascade to a Z -mode wave with $k_Z \sim 10^{-3} \lambda_D^{-1}$.

Polanco-Rodríguez et al. 2025, ApJL, 982, L24

④ **Turbulence parameter**

$$W = \varepsilon_0 E^2 / 4 n_0 k_B T_e \simeq 3.5 \cdot 10^{-4},$$

- ▷ **threshold** for decay is **overcome**,
- ▷ **no strong turbulence** expected.

(given that $k_{\mathcal{LZ}} \simeq 0.023 \lambda_D^{-1}$)

⑤ **Other wave processes** excluded



List of Arguments

- ❶ **Resonance conditions** fulfilled
 $f_{\mathcal{LZ}} = f_Z + f_S$
 - ▷ f Doppler-shifted $\Rightarrow$ resonance in (f, k) .
- ❷ **Time coincidence** of HF and LF modes.
- ❸ **Decay kinematics** predicts a single cascade to a Z -mode wave with $k_Z \sim 10^{-3} \lambda_D^{-1}$.

Polanco-Rodríguez et al. 2025, ApJL, 982, L24
- ❹ **Turbulence parameter**
 $W = \varepsilon_0 E^2 / 4 n_0 k_B T_e \simeq 3.5 \cdot 10^{-4}$,
 - ▷ **threshold** for decay is **overcome**,
 - ▷ **no strong turbulence** expected.
(given that $k_{\mathcal{LZ}} \simeq 0.023 \lambda_D^{-1}$)
- ❺ **Other wave processes excluded**
- ❻ **Second SOLO event** easily identified with similar decay scenario.



List of Arguments

1 Resonance conditions fulfilled

$$f_{\mathcal{LZ}} = f_Z + f_S$$

▷ f Doppler-shifted $\Rightarrow$ resonance in (f, k) .

2 Time coincidence of HF and LF modes.

3 Decay kinematics predicts a single cascade to a Z -mode wave with $k_Z \sim 10^{-3} \lambda_D^{-1}$.

Polanco-Rodríguez et al. 2025, ApJL, 982, L24

4 Turbulence parameter

$$W = \varepsilon_0 E^2 / 4 n_0 k_B T_e \simeq 3.5 \cdot 10^{-4},$$

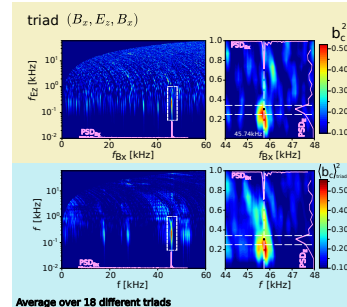
- ▷ **threshold** for decay is **overcome**,
- ▷ **no strong turbulence** expected.

(given that $k_{\mathcal{LZ}} \simeq 0.023 \lambda_D^{-1}$)

5 Other wave processes excluded

6 Second SOLO event easily identified with similar decay scenario.

7 Strong phase coherence between the 3 waves (cross-bicoherence diagnostic)





List of Arguments

❶ **Resonance conditions** fulfilled

$$f_{\mathcal{LZ}} = f_Z + f_S$$

▷ f Doppler-shifted $\Rightarrow$ resonance in (f, k) .

❷ **Time coincidence** of HF and LF modes.

❸ **Decay kinematics** predicts a single cascade to a Z -mode wave with $k_Z \sim 10^{-3} \lambda_D^{-1}$.

Polanco-Rodríguez et al. 2025, ApJL, 982, L24

❹ **Turbulence parameter**

$$W = \varepsilon_0 E^2 / 4 n_0 k_B T_e \simeq 3.5 \cdot 10^{-4},$$

- ▷ **threshold** for decay is **overcome**,
- ▷ **no strong turbulence** expected.

(given that $k_{\mathcal{LZ}} \simeq 0.023 \lambda_D^{-1}$)

❺ **Other wave processes** excluded

❻ **Second SOLO event** easily identified with similar decay scenario.

❼ **Strong phase coherence** between the 3 waves (cross-bicoherence diagnostic)

❽ **Decay scenario** is closely **reproduced by PIC simulations** (all 6 field components and 3 densities, beam-plasma parameters)

Comparison between observations and simulations



Virtual satellites record **waveforms** of E and B field components as well as of ion and electron densities.

LZ Wave turbulence

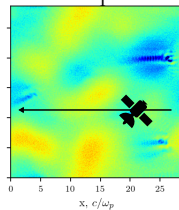
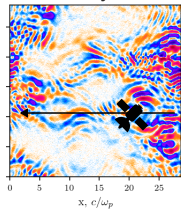
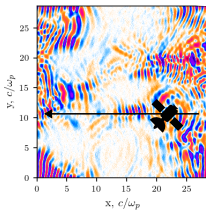
$t \cdot \omega_p = 2084.40$

E_x

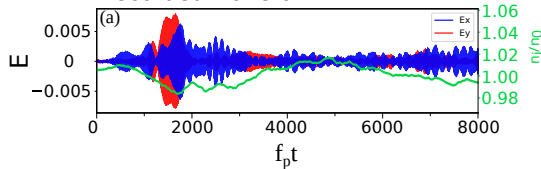
E_y

Density turbulence

n_i



Recorded waveform





Virtual satellites record **waveforms** of E and B field components as well as of ion and electron densities.

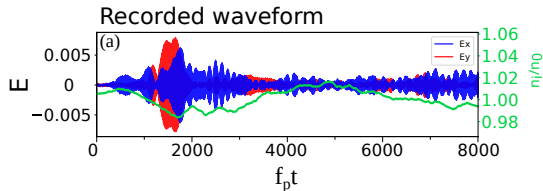
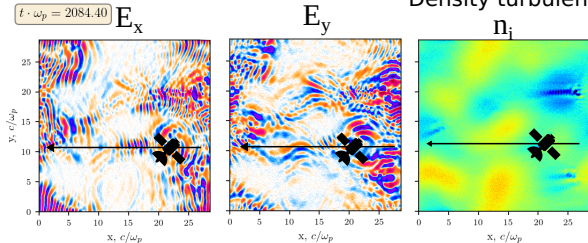
Simulation parameters as close as possible to Solar Orbiter observations' conditions.

Average level of density fluctuations
 $\Delta N = \sqrt{\langle \delta n^2 / n_0^2 \rangle}$

Physical parameters		Numerical parameters
$f_c/f_p = 0.02$	$v_b = 0.25c$	$N_x \times N_y = 1024^2$
$\Delta N = 0.025$	$(v_b = 12.7 v_T)$	$t_{tot} = 15\,000 f_p^{-1}$
$T_e/T_i = 10$	$n_b = 5 \cdot 10^{-4} n_0$	$N_{part}/cell = 5400$

LZ Wave turbulence

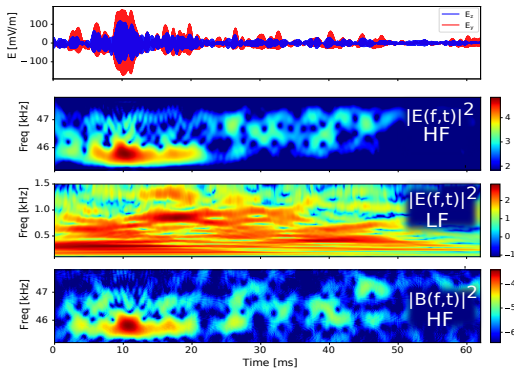
Density turbulence



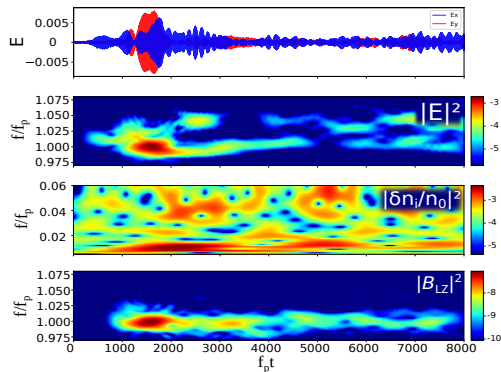


Decay confirmed in the simulation with characteristics very similar to SOLO observations.

Solar Orbiter



simulation



Conclusion

- ▶ **Solar Orbiter observations** of intense Langmuir/ Z -mode wavepackets associated with a type III electron beam are analyzed

- ▶ **Solar Orbiter observations** of intense Langmuir/ $\mathcal{Z}$ -mode wavepackets associated with a type III electron beam are analyzed $\Rightarrow$ **Evidence of nonlinear decay** $\mathcal{L}\mathcal{Z} \rightarrow \mathcal{S} + \mathcal{Z}$.
 - ▶ Resonance conditions satisfied (f, k) .
 - ▶ Time coincidence of modes.
 - ▶ Phase coherence (high cross-bicoherence).
 - ▶ No strong turbulence effects.
 - ▶ Consistent with decay kinematics $(k_{\mathcal{Z}} \sim k_*(\theta))$.
 - ▶ Decay threshold is overcome.
 - ▶ Second SOLO event found.
 - ▶ Exclusion of other wave processes.

- ▶ **Solar Orbiter observations** of intense Langmuir/ $\mathcal{Z}$ -mode wavepackets associated with a type III electron beam are analyzed $\Rightarrow$ **Evidence of nonlinear decay** $\mathcal{L}\mathcal{Z} \longrightarrow \mathcal{S} + \mathcal{Z}$.
 - ▶ Resonance conditions satisfied (f, k) .
 - ▶ Time coincidence of modes.
 - ▶ Phase coherence (high cross-bicoherence).
 - ▶ No strong turbulence effects.
 - ▶ Consistent with decay kinematics $(k_{\mathcal{Z}} \sim k_*(\theta))$.
 - ▶ Decay threshold is overcome.
 - ▶ Second SOLO event found.
 - ▶ Exclusion of other wave processes.
- ▶ **PIC simulations** strongly support observational analysis.

- ▶ **Solar Orbiter observations** of intense Langmuir/ $\mathcal{Z}$ -mode wavepackets associated with a type III electron beam are analyzed $\Rightarrow$ **Evidence of nonlinear decay** $\mathcal{L}\mathcal{Z} \longrightarrow \mathcal{S} + \mathcal{Z}$.
 - ▶ Resonance conditions satisfied (f, k) .
 - ▶ Time coincidence of modes.
 - ▶ Phase coherence (high cross-bicoherence).
 - ▶ No strong turbulence effects.
 - ▶ Consistent with decay kinematics $(k_{\mathcal{Z}} \sim k_*(\theta))$.
 - ▶ Decay threshold is overcome.
 - ▶ Second SOLO event found.
 - ▶ Exclusion of other wave processes.
- ▶ **PIC simulations** strongly support observational analysis.

Thank you for your attention

Supplementary material



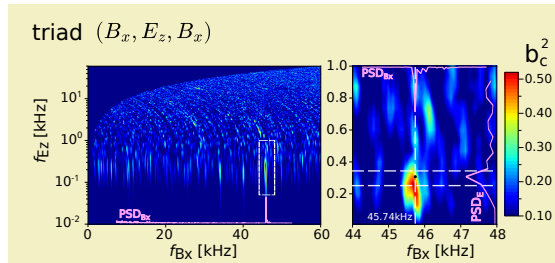
Cross-Bicoherence

The cross-bicoherence diagnostic is defined as:

$$b_c(f_1, f_2) = \frac{|\langle X^n(f_1) Y^n(f_2) Z^{n*}(f_1 + f_2) \rangle_n|}{\sqrt{\langle |X^n(f_1)|^2 |Y^n(f_2)|^2 \rangle_n \langle |Z^n(f_1 + f_2)|^2 \rangle_n}}.$$

$\langle \rangle_n$ = averaging on time window n

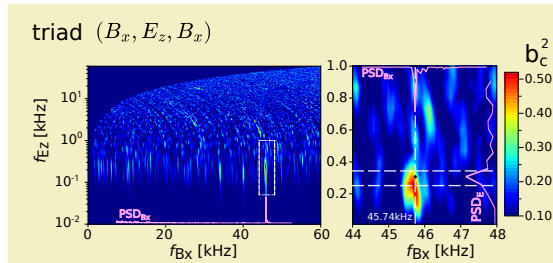
It measures the phase coherence between three waves participating in nonlinear wave-wave interaction at f_1 , f_2 and $f_3 = f_1 + f_2$ (resonance condition).





Cross-Bicoherence

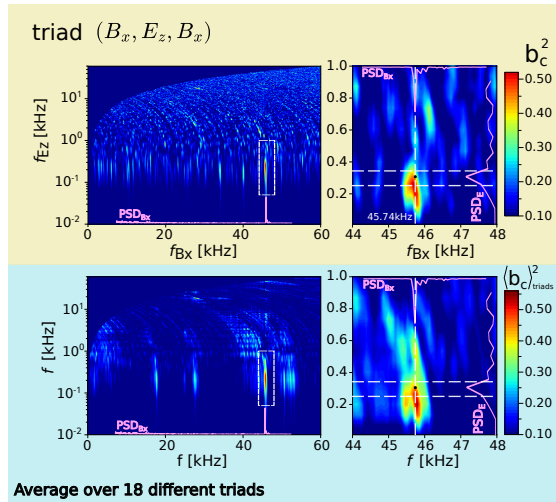
- ▶ Strong level of cross-bicoherence ($b_c \simeq 0.7$) for a single triad (B_x, E_z, B_x)
 - ▷ High b_c at resonance condition $f_1, f_2, f_3 = f_1 + f_2$.
 - ▷ No other comparable extremum.
 - ▷ As the triad is (B_x, E_z, B_x) , unlikely due to sheath effects.





Cross-Bicoherence

- ▶ Strong level of cross-bicoherence ($b_c \simeq 0.7$) for a single triad (B_x, E_z, B_x)
 - ▷ High b_c at resonance condition $f_1, f_2, f_3 = f_1 + f_2$.
 - ▷ No other comparable extremum.
 - ▷ As the triad is (B_x, E_z, B_x) , unlikely due to sheath effects.
- ▶ After averaging over b_c (18 triads used)
 - ▷ b_c maximum unaffected.
 - ▷ 3-waves interaction confirmed at the observed frequencies.



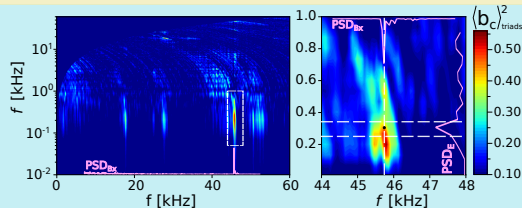
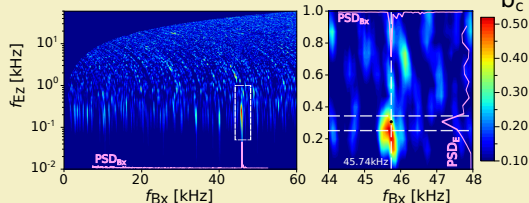


Cross-Bicoherence

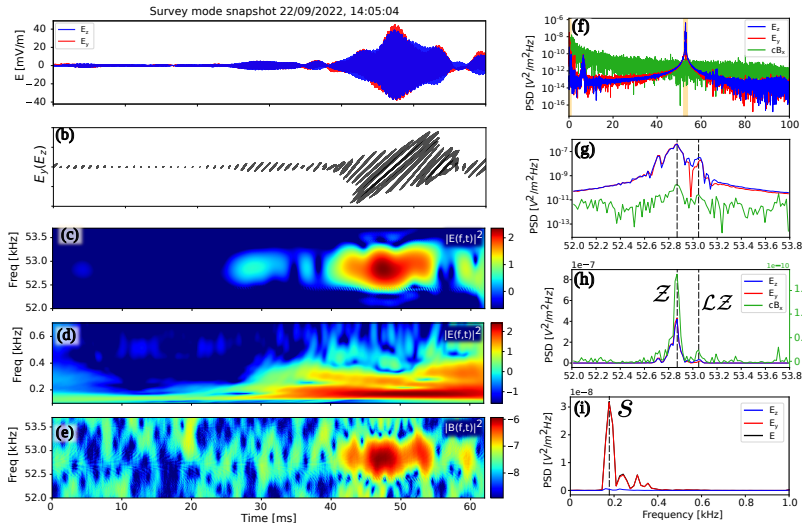
- ▶ Strong level of cross-bicoherence ($b_c \simeq 0.7$) for a single triad (B_x, E_z, B_x)
 - ▷ High b_c at resonance condition $f_1, f_2, f_3 = f_1 + f_2$.
 - ▷ No other comparable extremum.
 - ▷ As the triad is (B_x, E_z, B_x), unlikely due to sheath effects.
- ▶ After averaging over b_c (18 triads used)
 - ▷ b_c maximum unaffected.
 - ▷ 3-waves interaction confirmed at the observed frequencies.

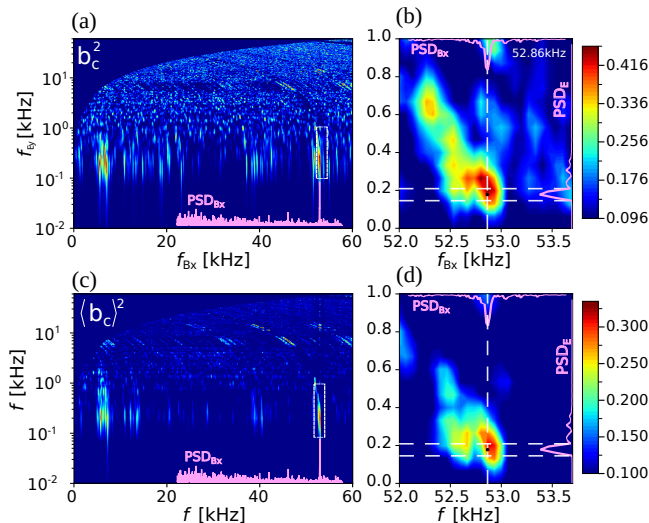
Very strong evidence for the decay process $\mathcal{LZ} \rightarrow \mathcal{S} + \mathcal{Z}$.

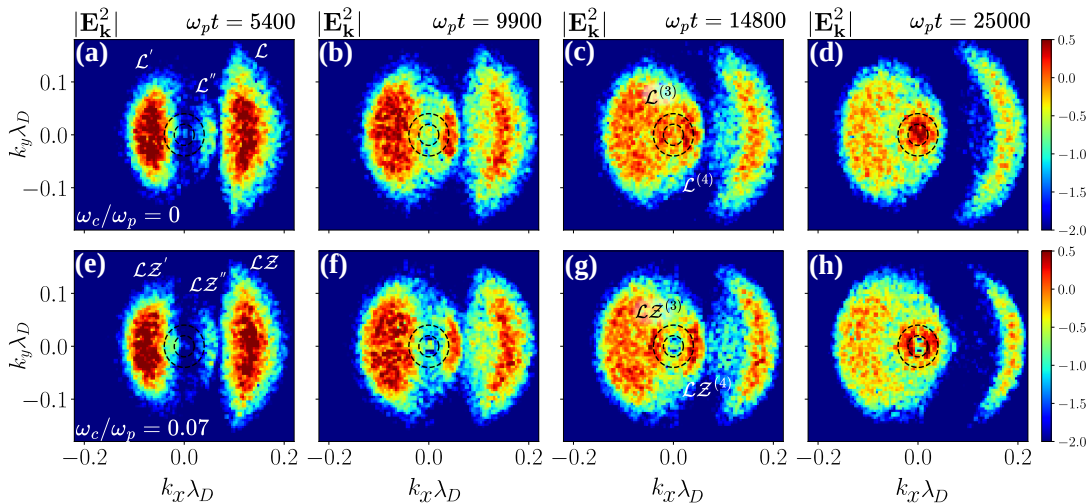
triad (B_x, E_z, B_x)

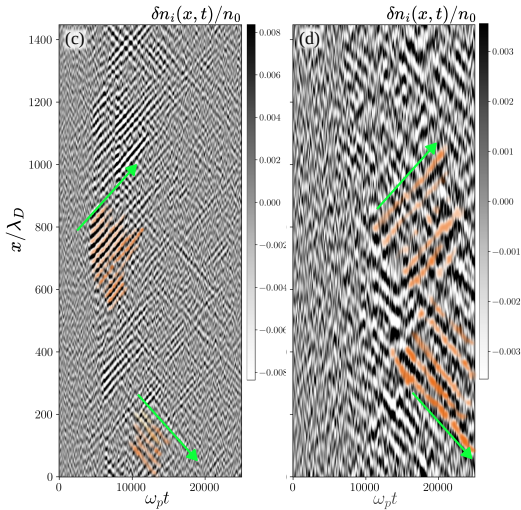
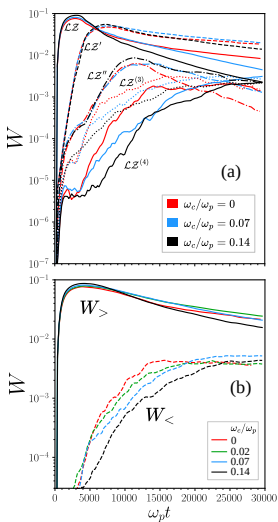


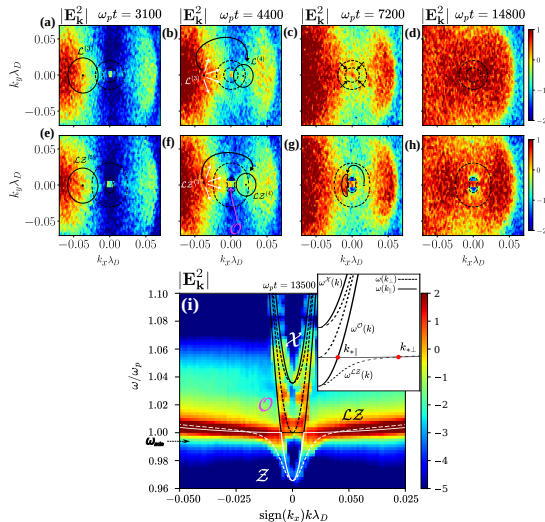
Average over 18 different triads

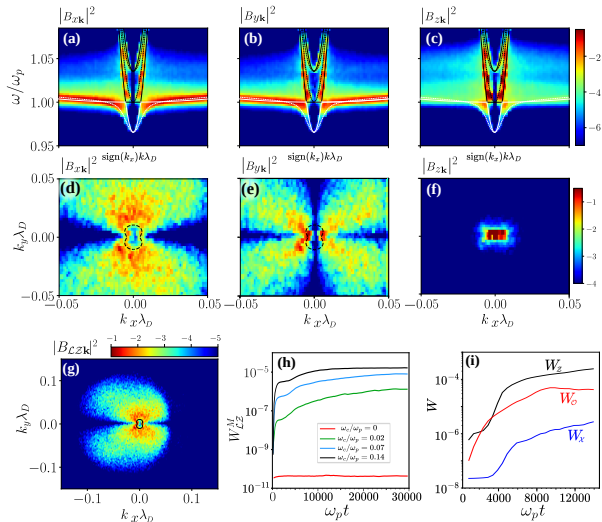


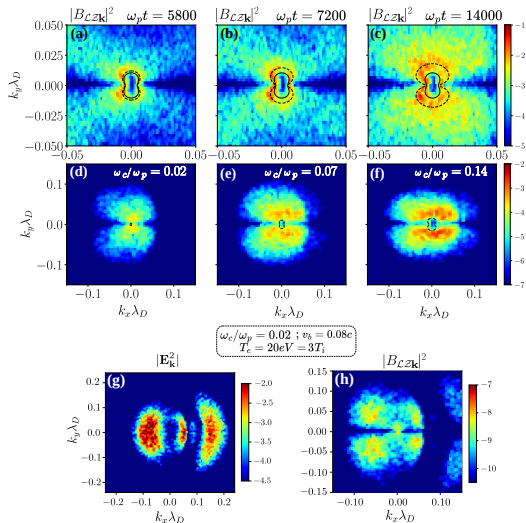


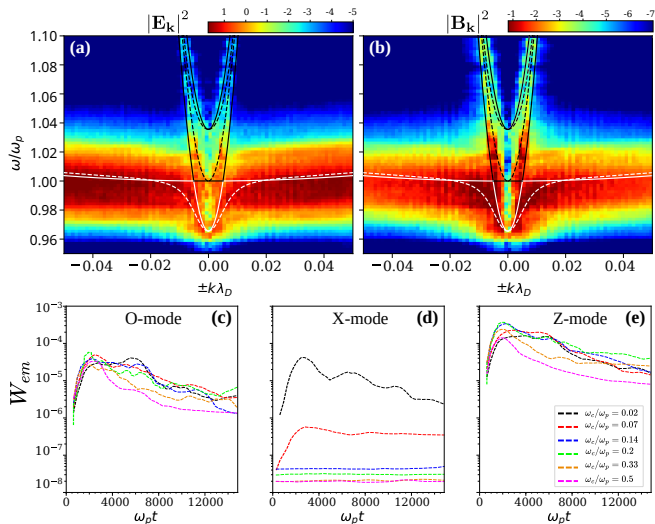




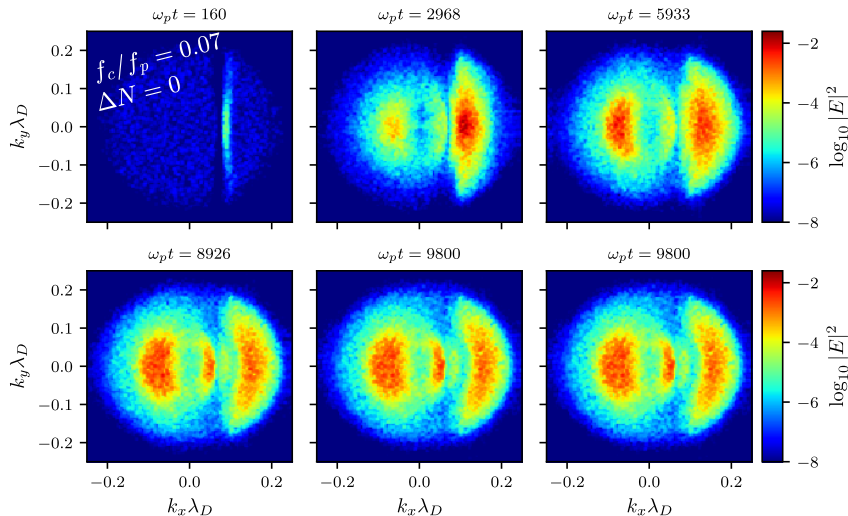




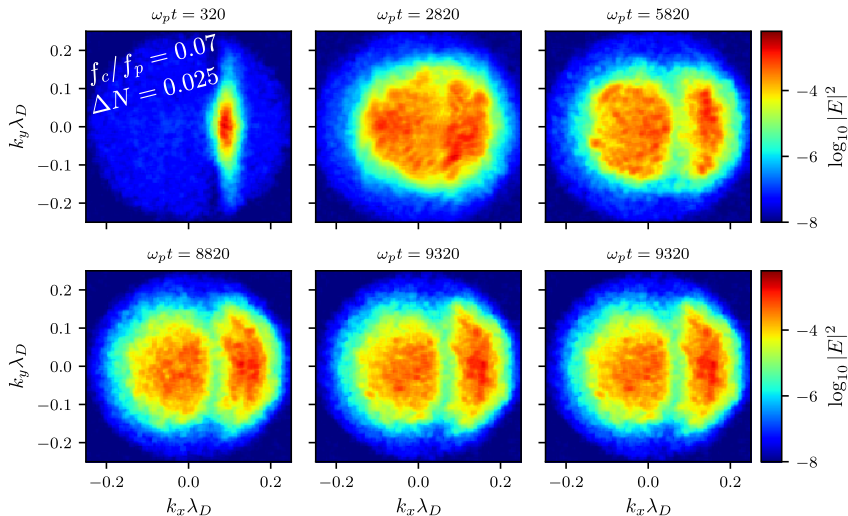




Spectrum of simulation with $T_e = 20\text{eV}$: homogeneous case



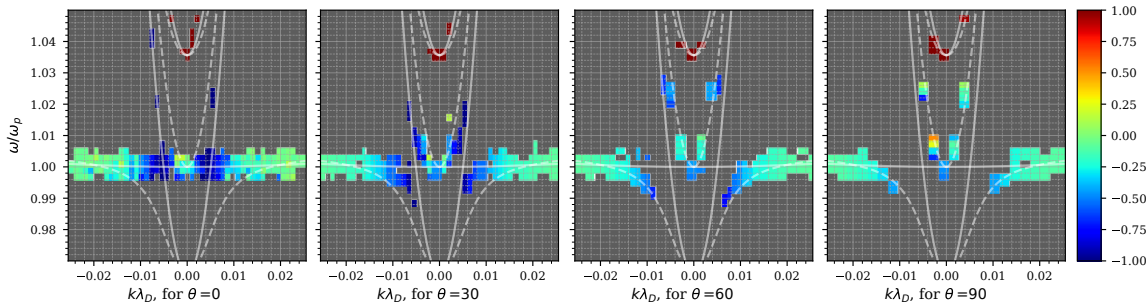
Spectrum of simulation with $T_e = 20\text{eV}$: inhomogeneous case



Polarization of waves in Fourier space. $\Delta N = 0$

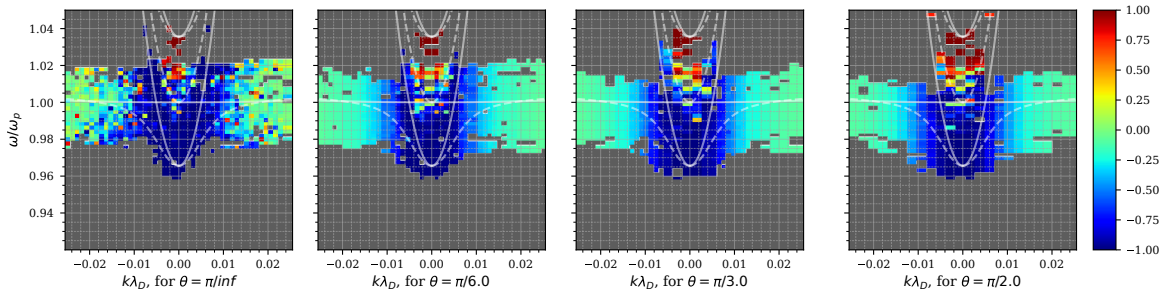
- Stokes parameter $V/I = -2\text{Im}(E_{\perp 1}E_{\perp 2}^*)/\sqrt{|E_{\perp 1}|^2 + |E_{\perp 2}|^2}$ in the $\omega - \mathbf{k}$ Fourier space for waves propagating at $\theta = 60^\circ$ ($\mathbf{B}_0 \cdot \mathbf{k} = B_0 k \cos \theta$). Simulation with $\omega_c/\omega_p = 0.07$ and initially, $\Delta N = \sqrt{\langle \delta n^2/n_0^2 \rangle} = 0$.

$$12000 \leq \omega_p t \leq 15000$$



Polarization of waves in Fourier space. $\Delta N = 0.025$

- Stokes parameter $V/I = -2\text{Im}(E_{\perp 1}E_{\perp 2}^*)/\sqrt{|E_{\perp 1}|^2 + |E_{\perp 2}|^2}$ in the $\omega - \mathbf{k}$ Fourier space for waves propagating at $\theta = 60^\circ$ ($\mathbf{B}_0 \cdot \mathbf{k} = B_0 k \cos \theta$). Simulation with $\omega_c/\omega_p = 0.07$ and initially, $\Delta N = \sqrt{\langle \delta n^2 / n_0^2 \rangle} = 0.025$.



Polarization of waves, linear solutions

- Linear solution for the ellipticity (V/I) and other physical quantities of Langmuir/ Z mode in a magnetized plasma

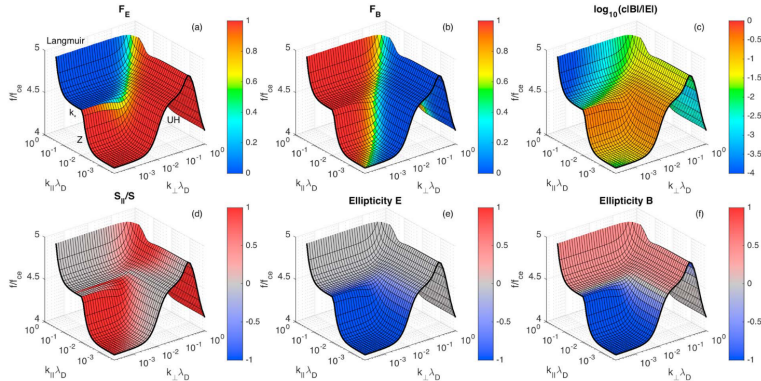


Figure 1. Langmuir/ Z mode and upper hybrid dispersion surface. (a) F_E . (b) F_B . (c) $c|B|/|E|$. (d) $S_{\parallel}/S$. (e) Ellipticity of $\mathbf{E}$. (f) Ellipticity of $\mathbf{B}$. The dispersion surface is computed from a single-electron Maxwellian distribution for parameters $n_e = 0.5 \text{ cm}^{-3}$, $T_e = 200 \text{ eV}$, and $B_0 = 50 \text{ nT}$. The wave numbers k are normalized to the Debye length λ_D .

Graham et al. 2018, JGR,123, 2630

Polarization of waves, linear solutions

- Linear solution for the ellipticity (V/I) and other physical quantities of $\mathcal{O}$ -mode in a magnetized plasma

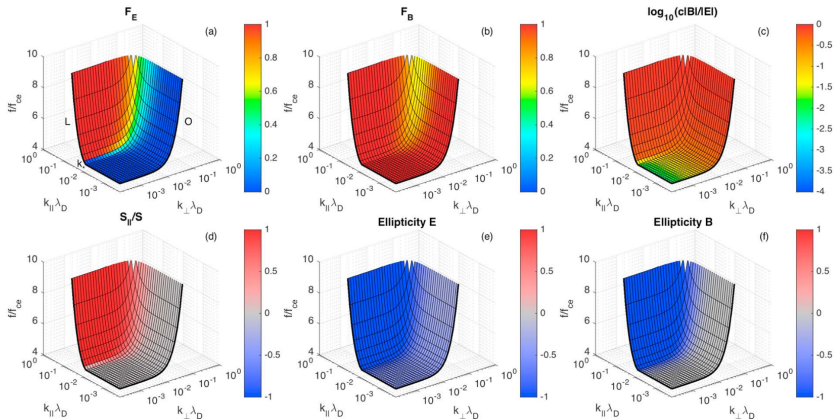


Figure 2. L-O mode dispersion surface. (a) F_E . (b) F_B . (c) $c|B|/|E|$. (d) $S_{\parallel}/S$. (e) Ellipticity of $\mathbf{E}$. (f) Ellipticity of $\mathbf{B}$.

Graham et al. 2018, JGR,123, 2630

Polarization of waves, linear solutions

- Linear solution for the ellipticity (V/I) and other physical quantities of $\mathcal{X}$ -mode in a magnetized plasma

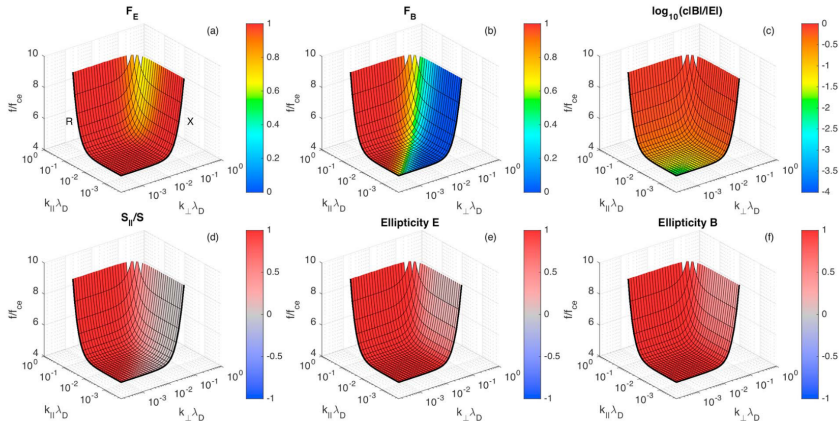


Figure 3. R-X mode dispersion surface. (a) F_E . (b) F_B . (c) $c|B|/|E|$. (d) $S_{\parallel}/S$. (e) Ellipticity of $\mathbf{E}$. (f) Ellipticity of $\mathbf{B}$.

Graham et al. 2018, JGR,123, 2630