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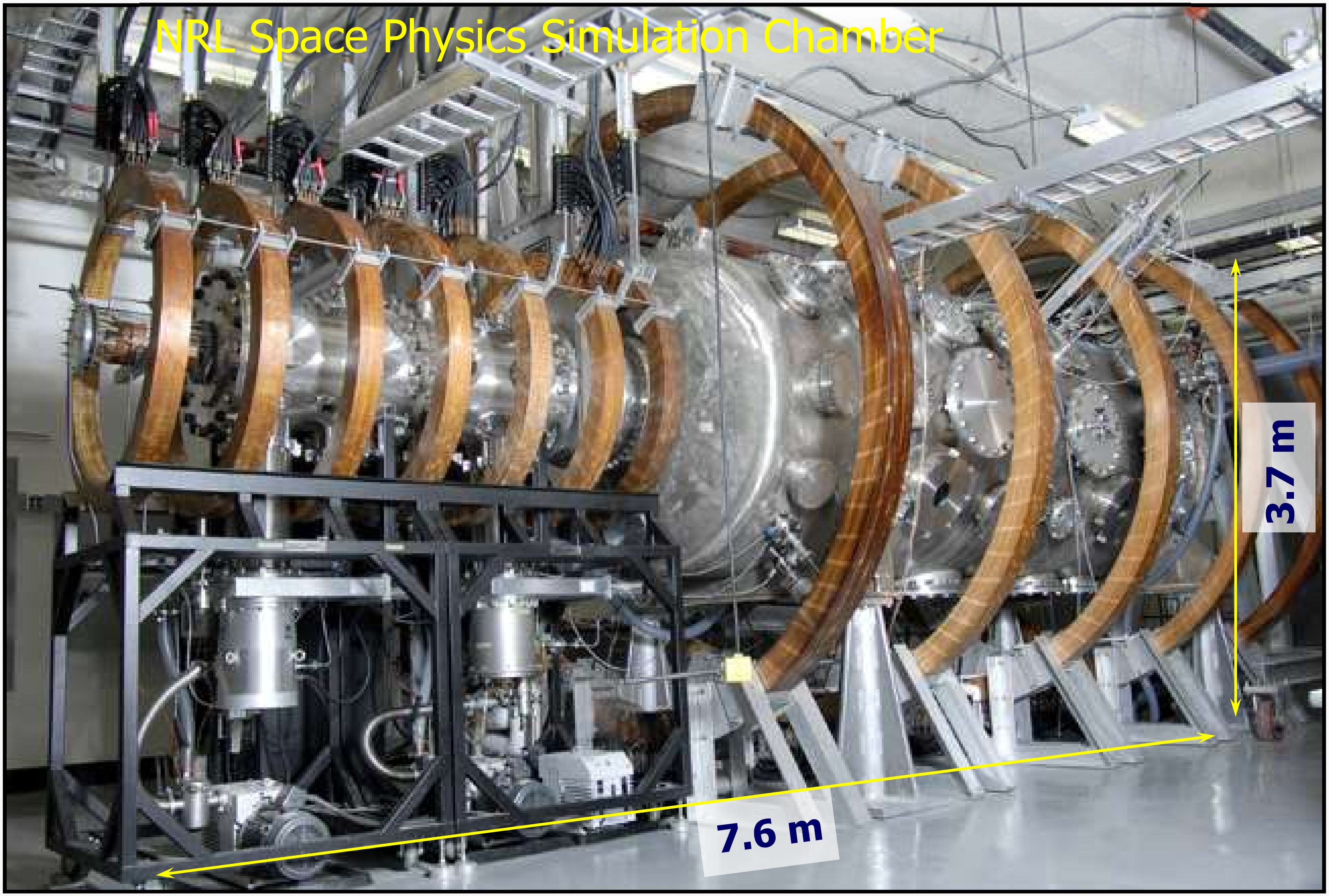
Scaled Experiments in NRL SPSC for Satellite Measurements

Erik Tejero
erik.tejero@nrl.navy.mil
Plasma Physics Division, Naval Research Laboratory


NRL Space Physics Simulation Chamber
3.7 m
7.6 m

Dimensionless Parameter Covered in SPSC

NRL PPD

Space Plasma - Space Chamber Parameter Comparison

parameter	ionosphere	RB (L = 2)	NRL SPSC
plasma density (cm^{-3})	$10^3 – 10^6$	~10^3	$10^4 – 10^{12}$
electron temp. (eV)	~0.3	~1	0.1 – 4
ion temp. (eV)	~0.3	0.3	0.05
magnetic field strength (G)	~0.3	~0.04	up to 750 G (SC) & 250 G (MC)
plasma freq. (Hz)	10^5 - 10^7	5×10^5	$10^6 – 10^{10}$
ion gyrofrequency (Hz)	~30 (O^+)	3.8×10^4 (H^+)	~10^3- 10^5 (Ar^+)
electron gyrofrequency (Hz)	~10^6	10^5	$10^6 – 10^9$
ω_{pe}/Ω_e	0.1 – 10	5	0.01 - 50
ω/ν_{en}	> 1	>> 1	~5 - 600
β	$10^{-7} – 10^{-4}$	10^{-5}	$10^{-7} – 10^{-3}$

Velocity Shear-Driven Instabilities

NRL PPD

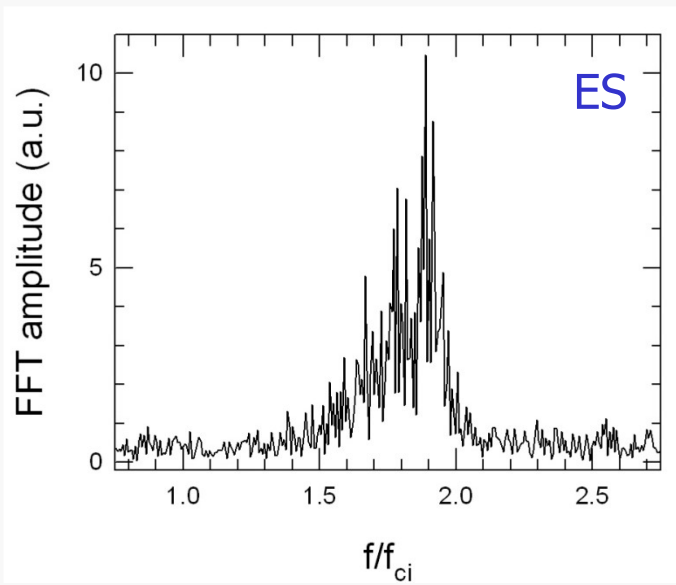
- Nonuniform Transverse Electric Fields
- Transverse Electric Field Gradients

ρ_i / L_E decreasing

$\rho_i \ll L_E \rightarrow$ Kelvin-Helmholtz Instability $(\omega \ll \Omega_i)$

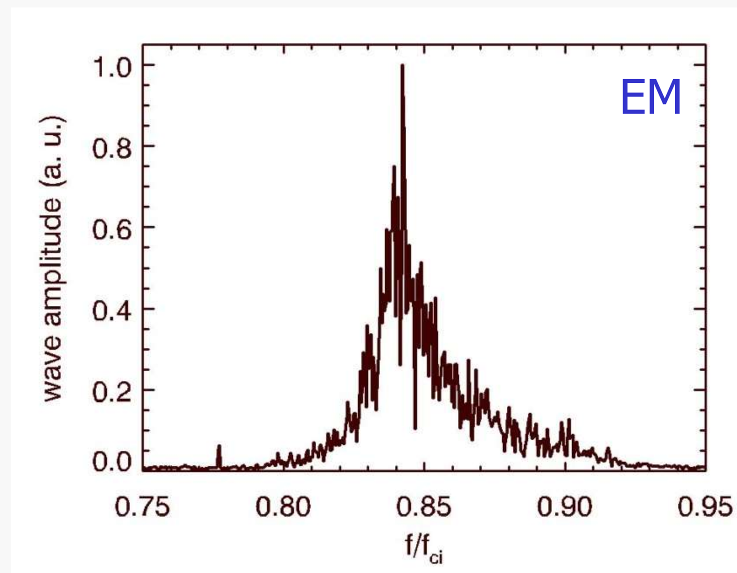
$\rho_i \sim L_E \rightarrow$ IEDDI $(\omega \sim \Omega_i)$

Amatucci et al., PRL (1996)



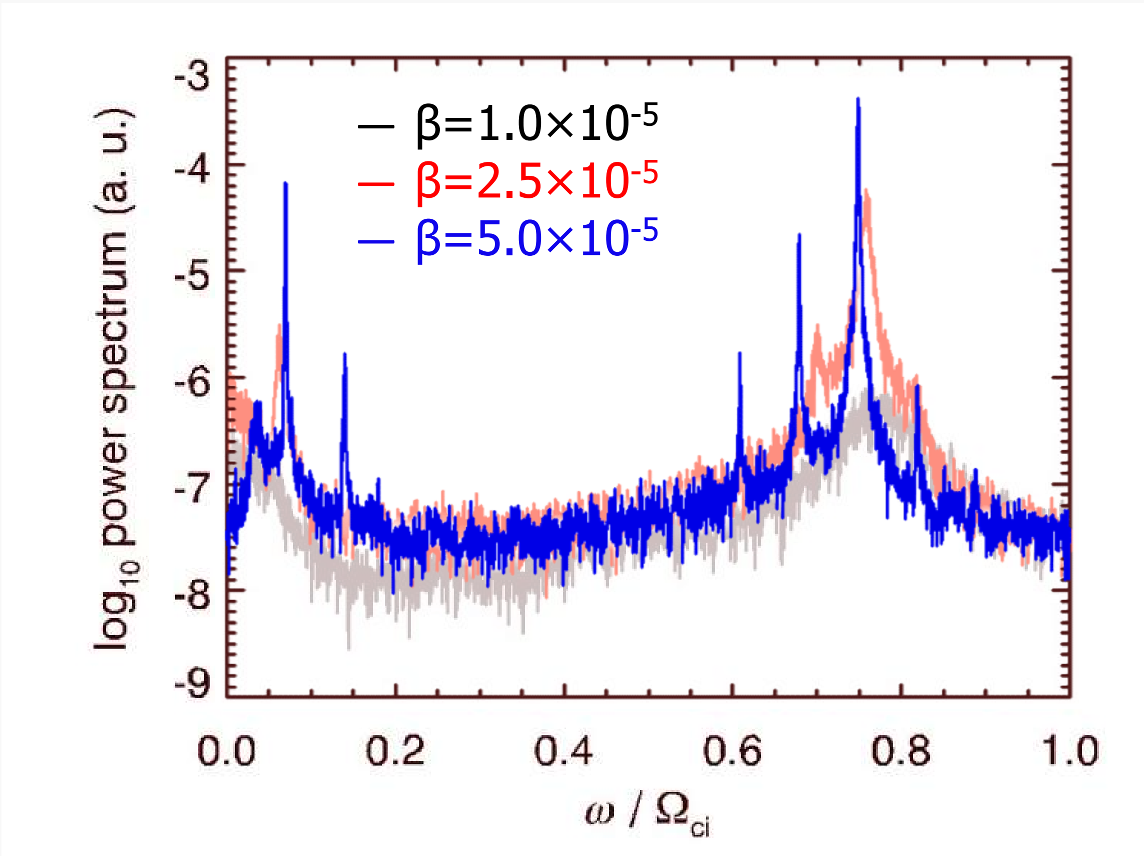
$\beta > \frac{m_e}{m_i}$

Tejero et al., PRL (2011)

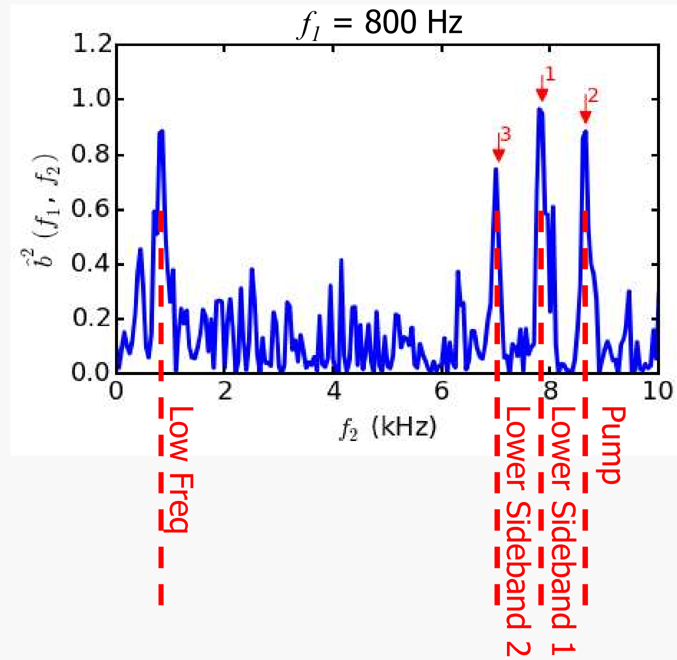


$\rho_i > L_E \rightarrow$ EIH $(\Omega_i < \omega < \Omega_e)$

Plasma β Also Controls Nonlinear Decay



$$\hat{b}^2(f_1, f_2) = \frac{|\langle X(f_1)X(f_2)X^*(f_1+f_2)\rangle|^2}{\langle |X(f_1)X(f_2)|^2\rangle\langle |X(f_1+f_2)|^2\rangle}$$



1) Three Wave Decay of Pump

2) Coalescence Leading to Upper Sideband

3) Three Wave Decay of Lower Sideband

Velocity Shear-Driven Instabilities

- Nonuniform Transverse Electric Fields
- Transverse Electric Field Gradients

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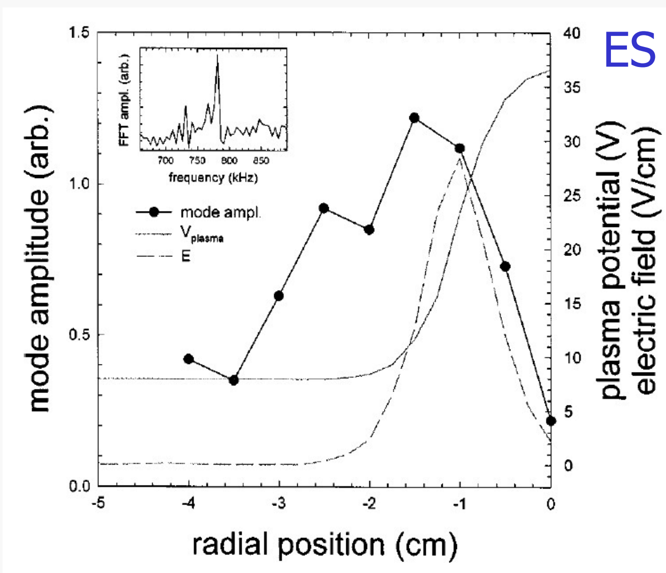
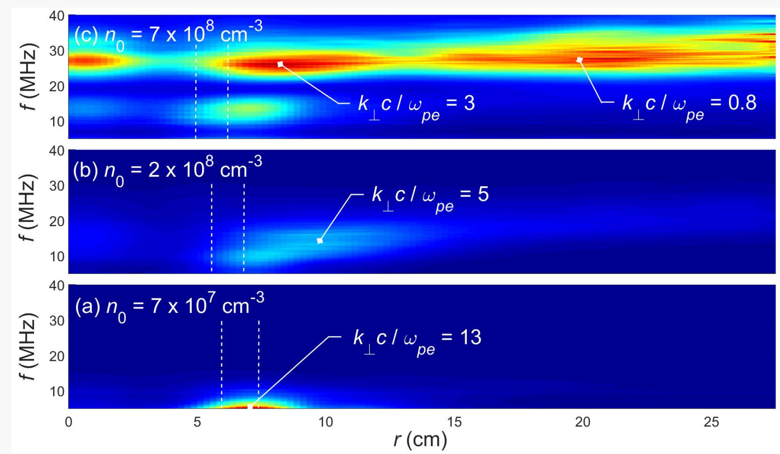
$\rho_i \sim L_E \rightarrow$ IEDDI $(\omega \sim \Omega_i)$

$\rho_i > L_E \rightarrow$ EIH $(\Omega_i < \omega < \Omega_e)$

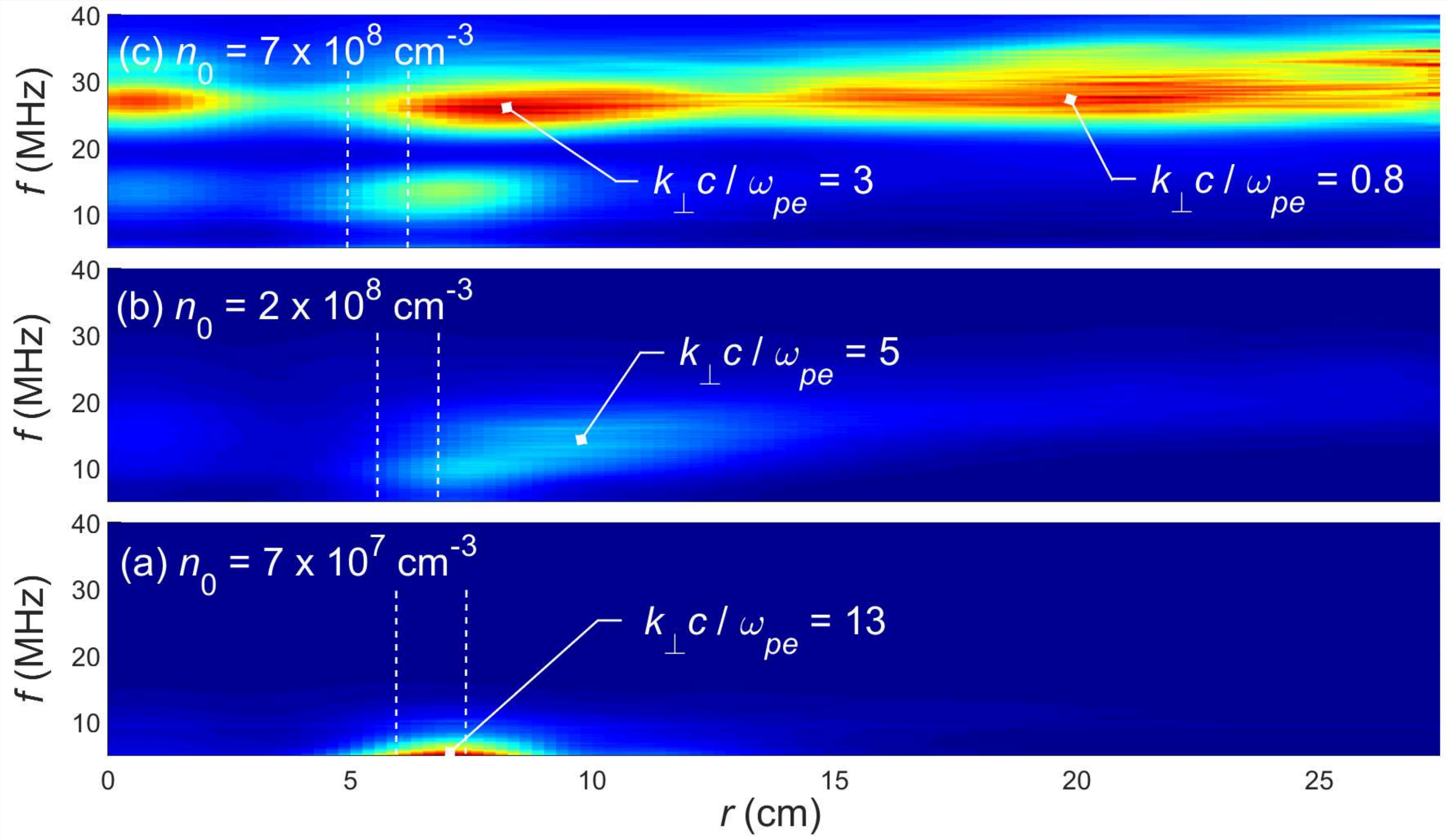
Amatucci et al., PoP (2003)



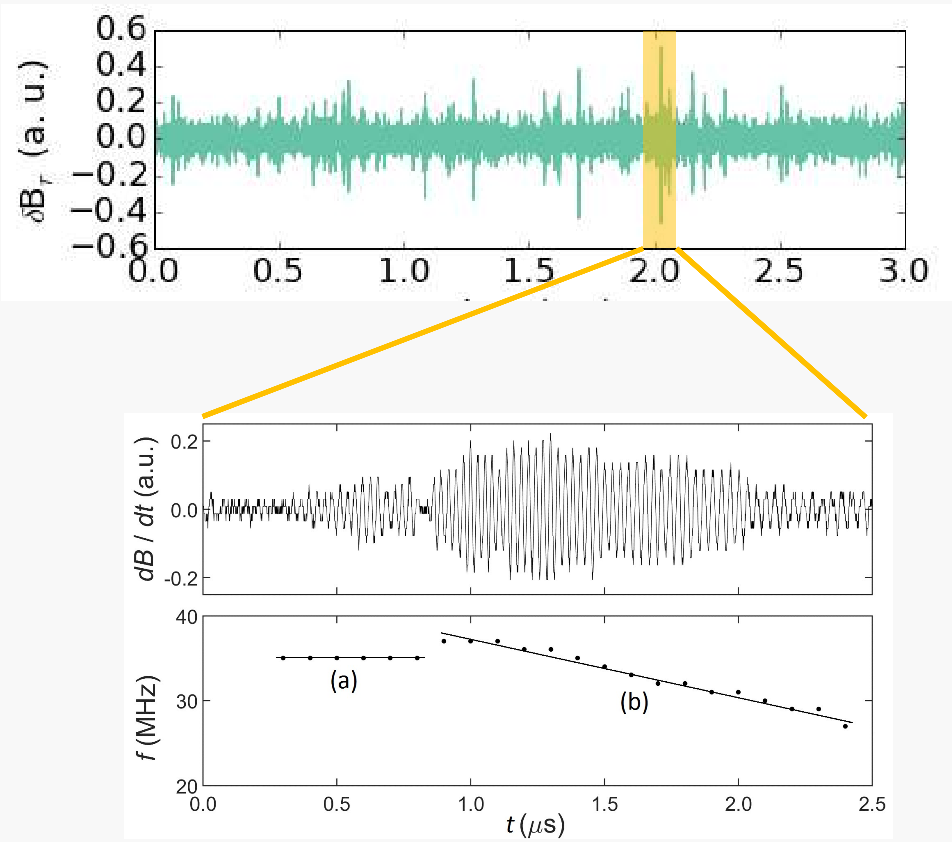
Enloe et al., PoP (2017)

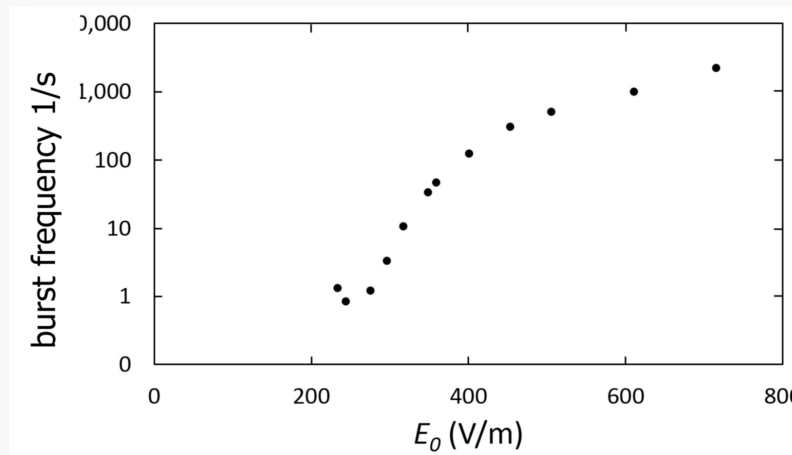


Whistler Waves Can Also Be Driven by Sheared Flows



Whistler Waves Are Bursty, Chirping Waves





Studying the Building Blocks of Weak Turbulence

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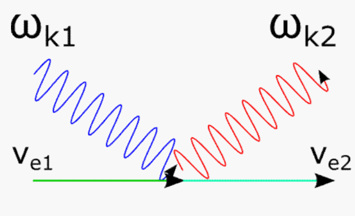
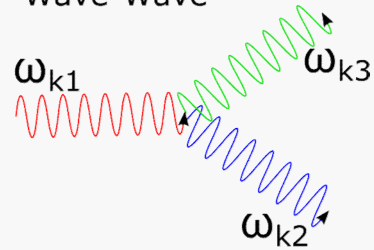
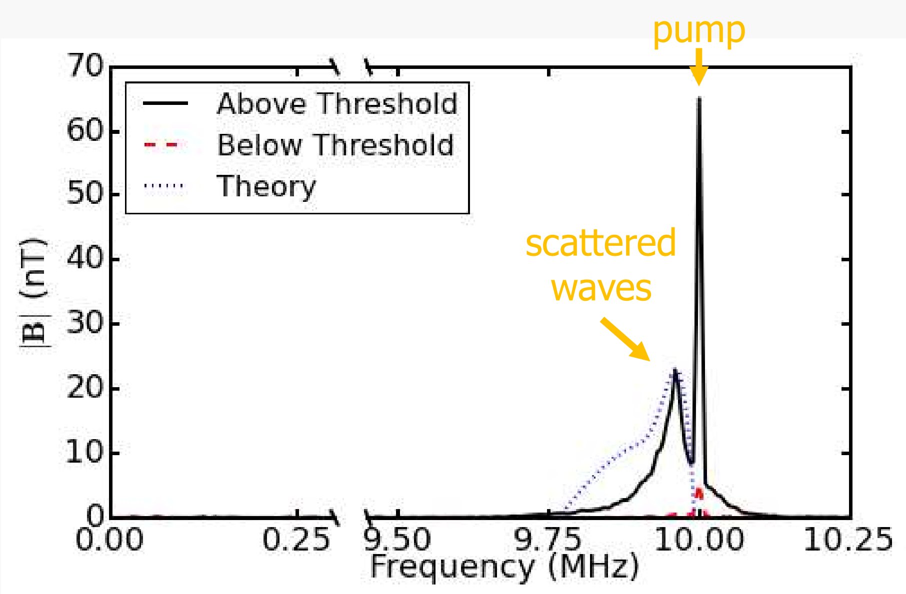


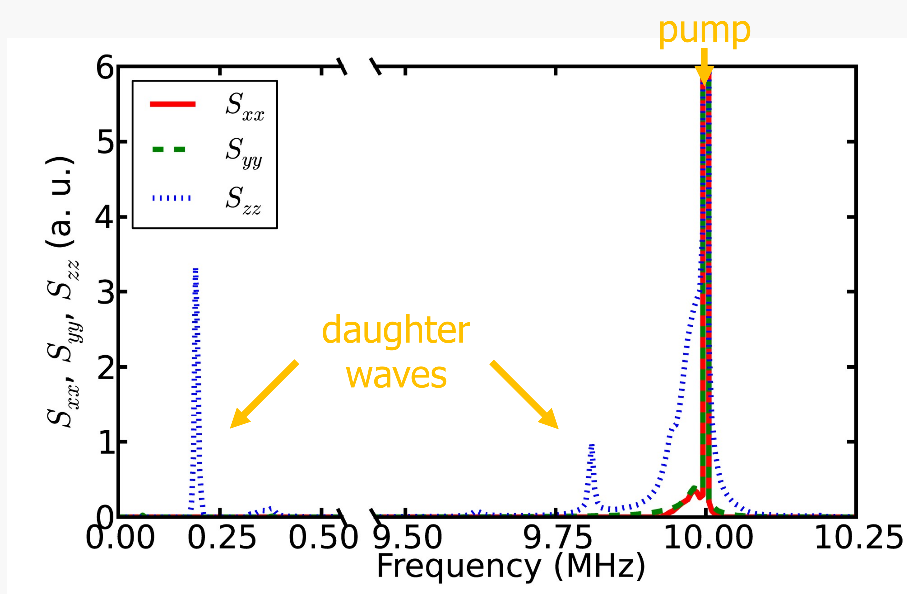
Non-Linear
Scattering

Wave-Wave





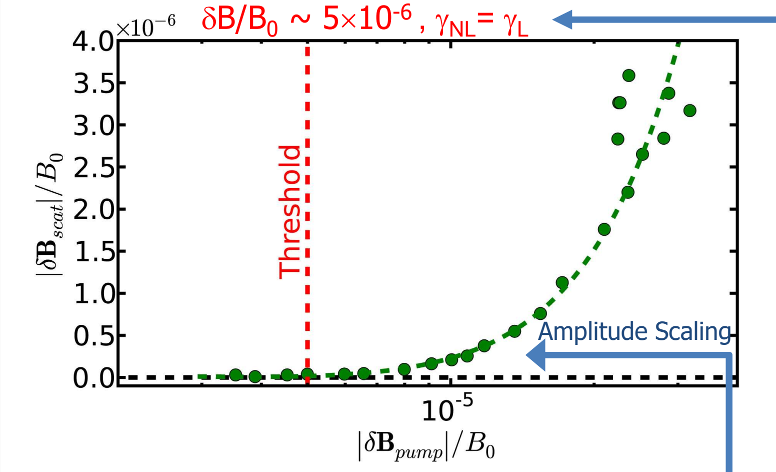
Nonlinear Scattering



Parametric Decay

Tejero *et al.*, *Phys. Plasmas*, **22**, 091503 (2015)

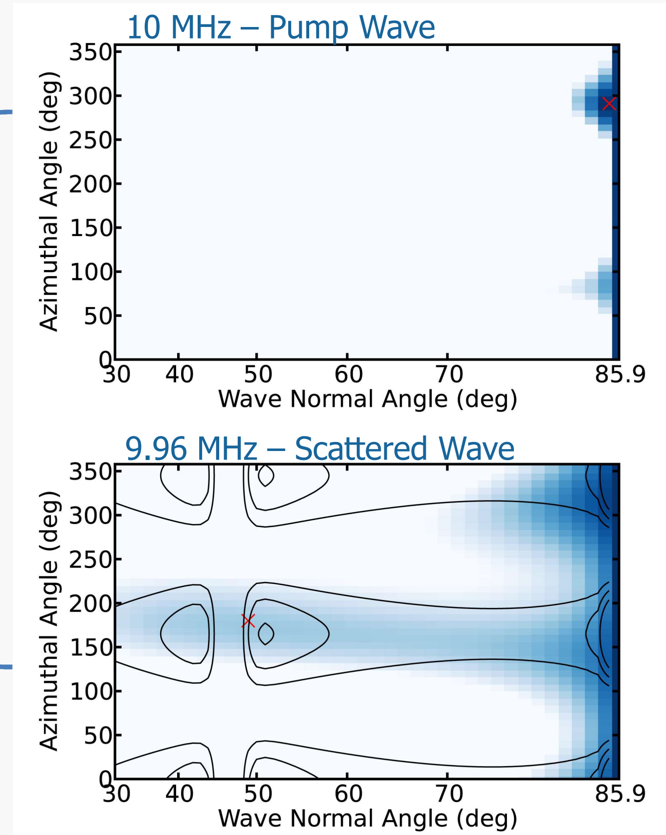
Verification of Nonlinear Conversion of ES to EM



Threshold

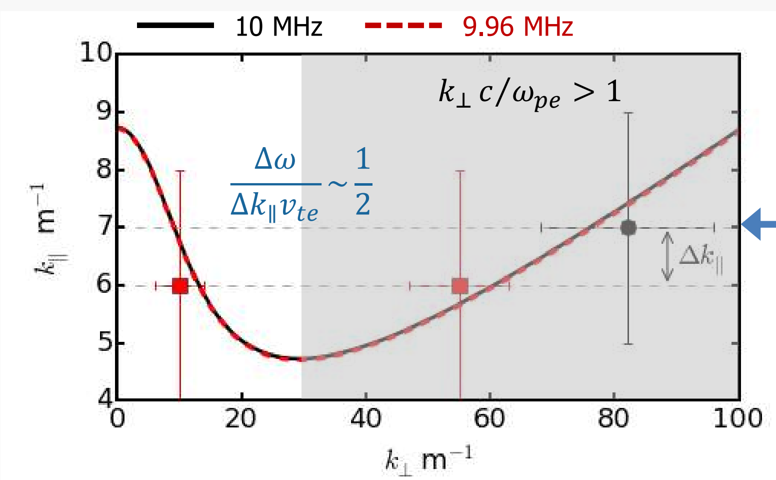
$$\gamma_L(k,\omega) = \gamma_{NL}(k,\omega,W)$$

90° turning



$$\gamma_{NL}^{k1\to k2} \sim \frac{\omega_{pe}^2}{\omega_{k2}} \frac{\bar{k}_2^2}{1+\bar{k}_2^2} \sum_{k1} \frac{W_{k1}}{n_0 T} \frac{(\vec{k}_1\times\vec{k}_2)_\parallel^2}{k_{\perp1}^2 k_{\perp2}^2} \zeta_e \,\mathrm{Im}\, Z\left(\frac{\omega_{k2}-\omega_{k1}}{\left|k_{\parallel2}-k_{\parallel1}\right| v_{te}}\right)$$

Resonance Condition



Experiment agrees with theory in detail

Tejero *et al.*, *Sci. Rep.*, **5**, 17852 (2015) and Tejero *et al.*, *Phys. Plasmas*, **23**, 055707 (2016)

Wave Distribution Function Technique Validated

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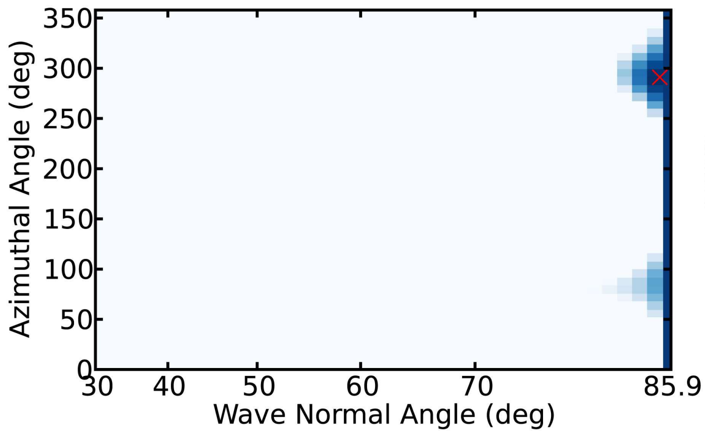
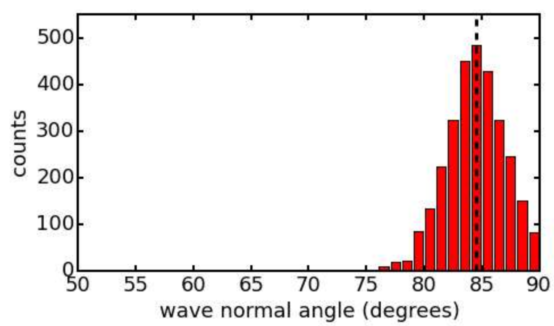
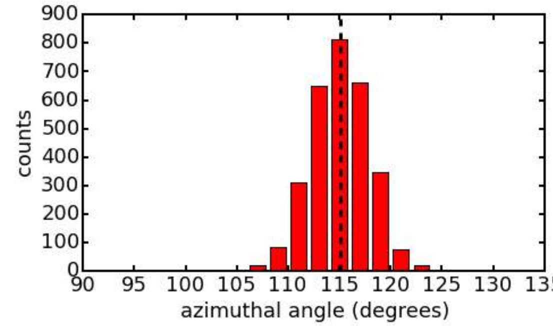
10 MHz – Pump Wave

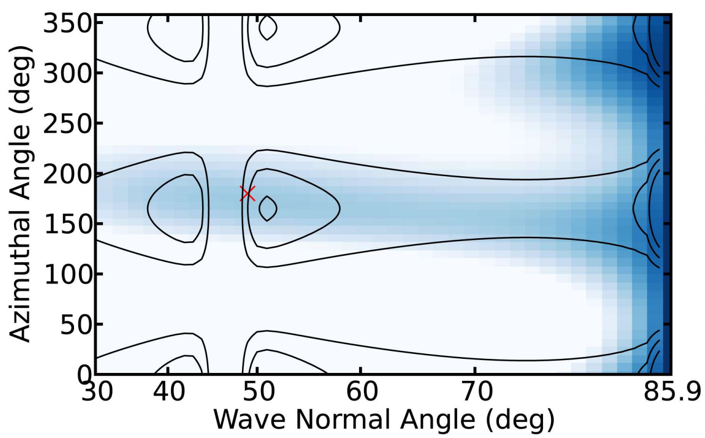


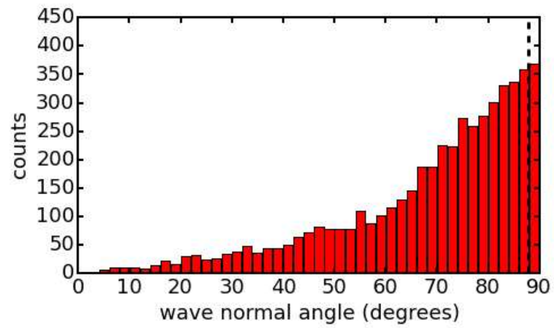


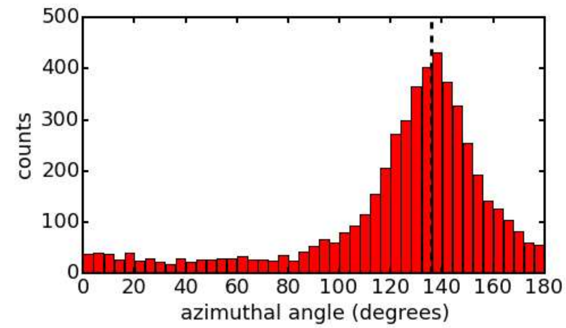


Histogram Results Using Spectral Techniques (SVD)

9.96 MHz – Scattered Wave







Results from WDF and spectral techniques are consistent with laboratory *k* measurements.

Tejero *et al.*, *Phys. Plasmas*, **22**, 091503 (2015)

Triggered Emission Observed in Laboratory

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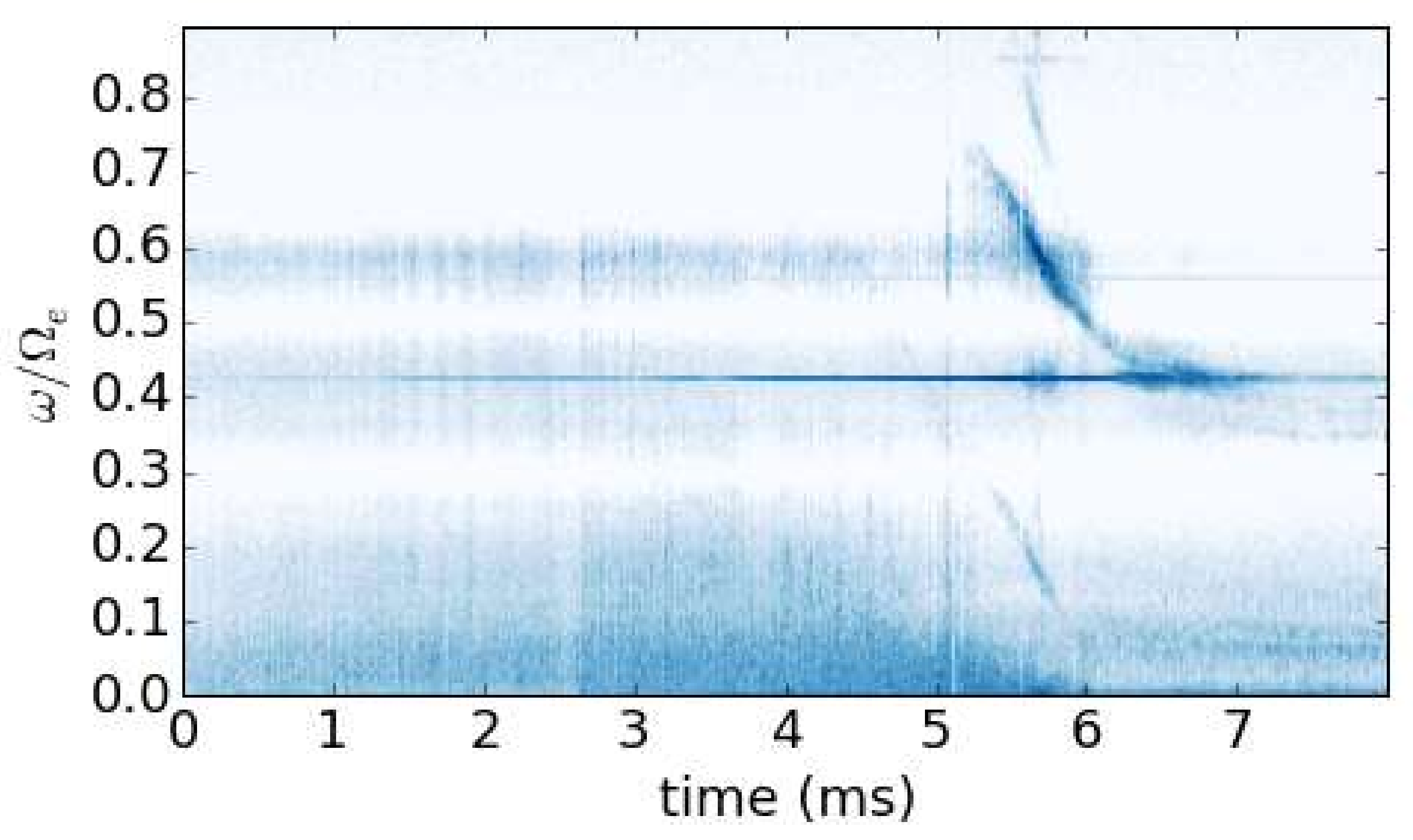
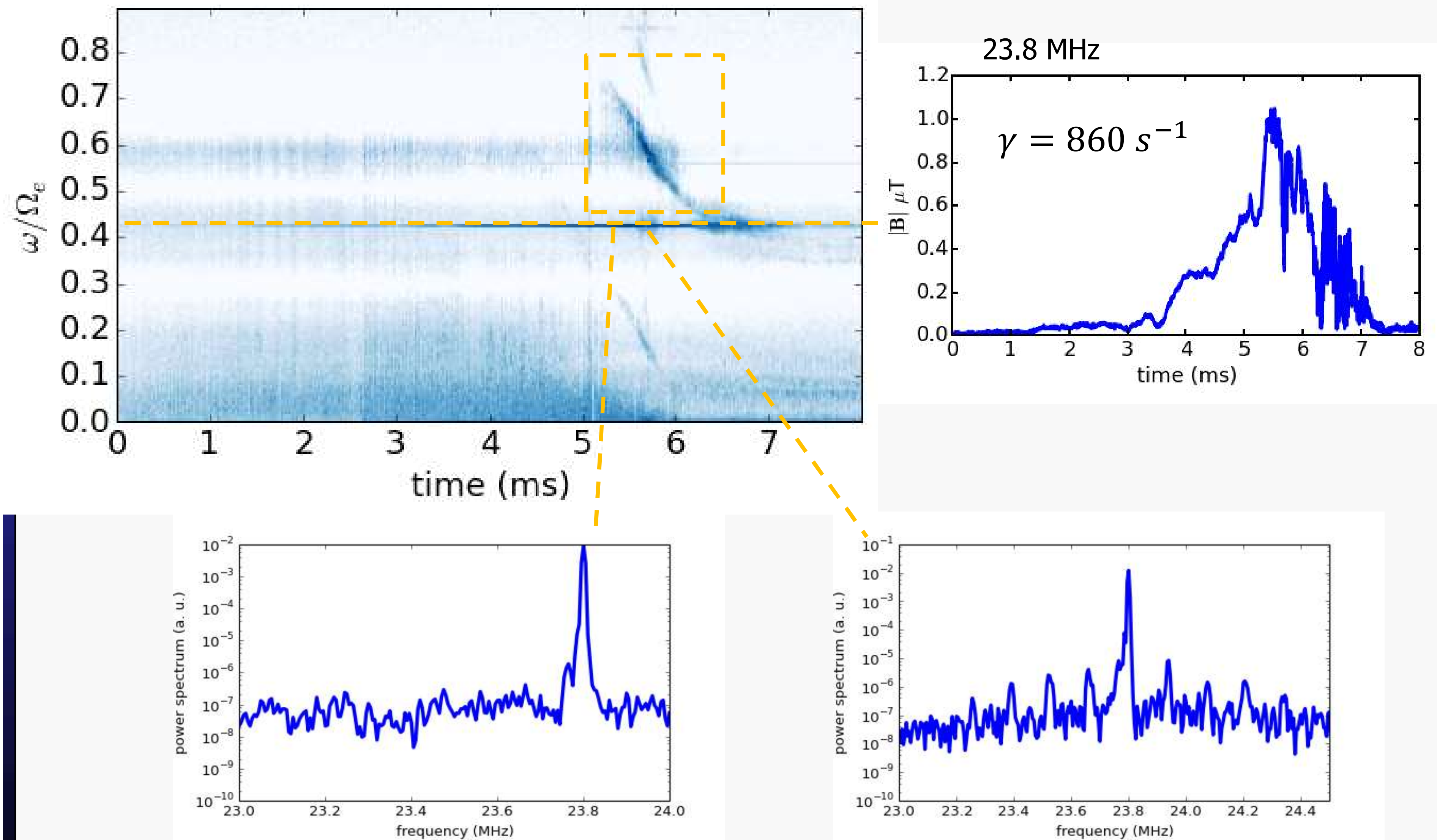


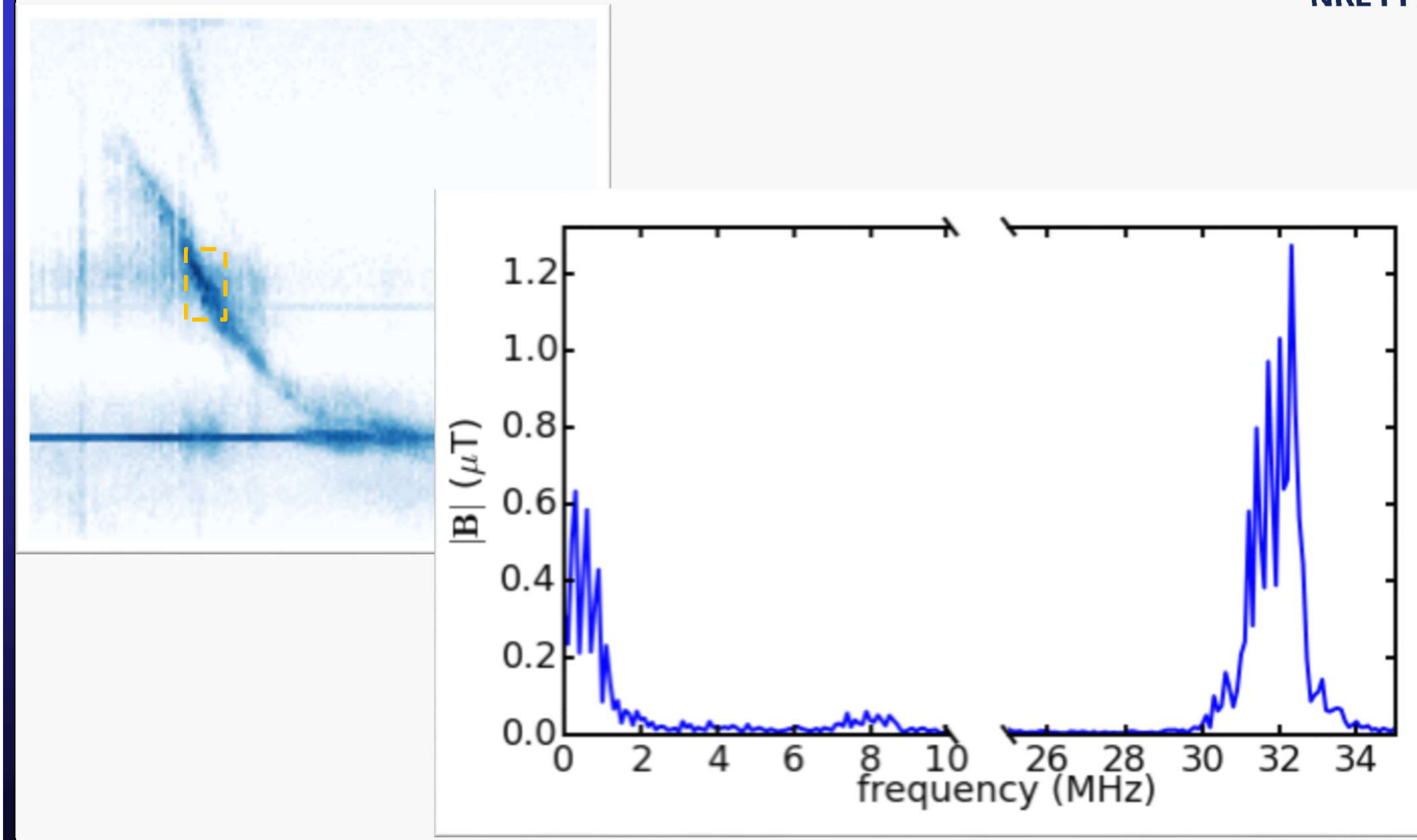
$E_b = 1.8\ keV$ $\quad I_b = 20\ mA \rightarrow\ n_b/n_0 = 0.5 - 13\%$ $\quad \alpha = 40°$

$\omega_{pe}/\Omega_e = 1.75 - 9.2$ $\quad \omega_0/\Omega_e = 0.425$

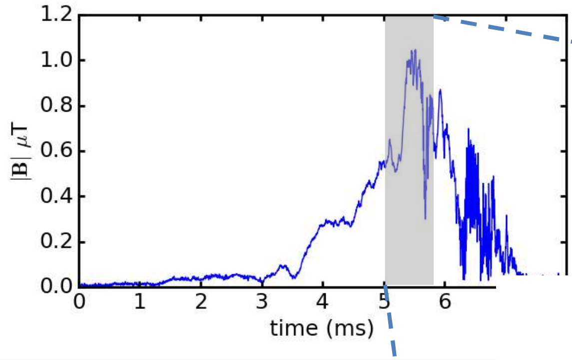
Nonlinear Scattering in Triggered Emission Data

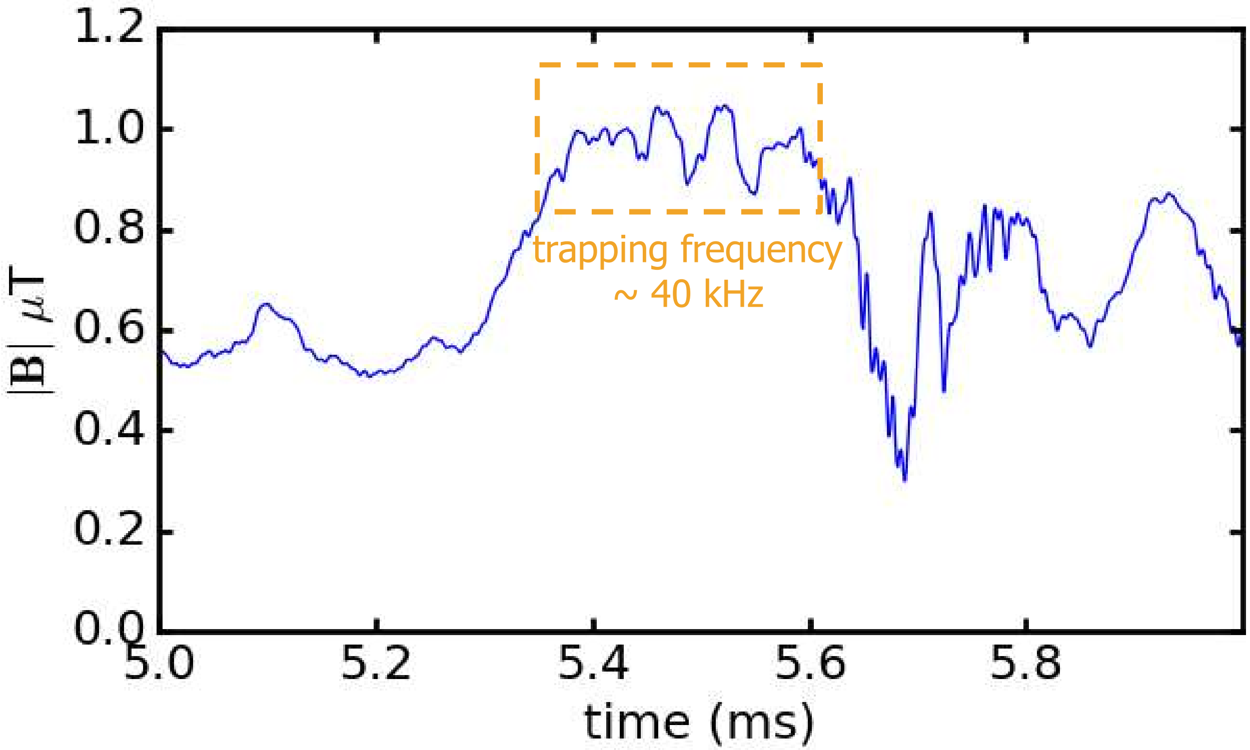


Three Wave Decay in Triggered Emission Data



Trapping Frequency Observed in Saturated Pump Wave





Chorus-like Emissions Exhibit Subpacket Structure

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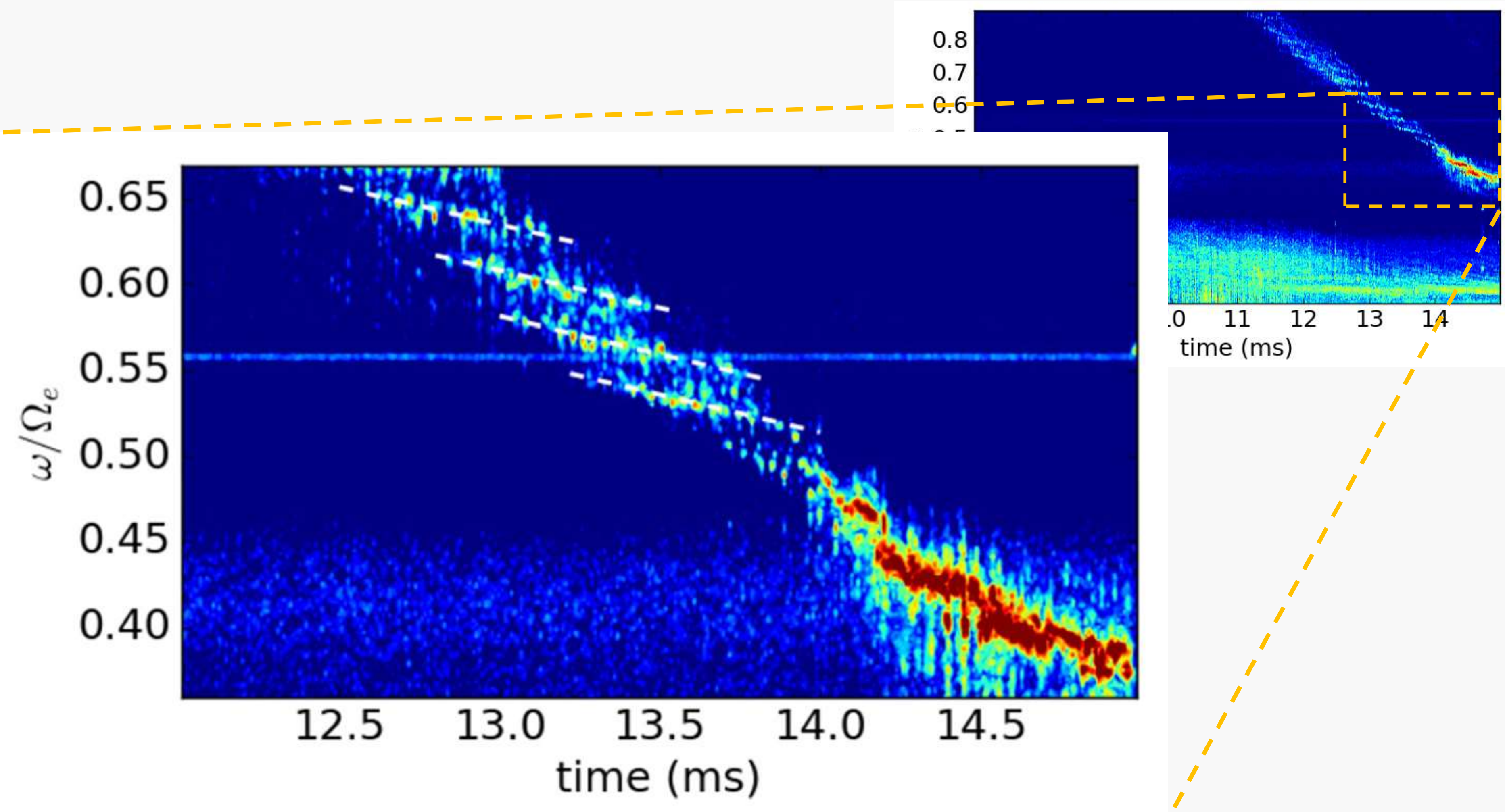

Chorus-like emissions observed in laboratory experiments.

Case Study: EIH in Space Boundary Layers

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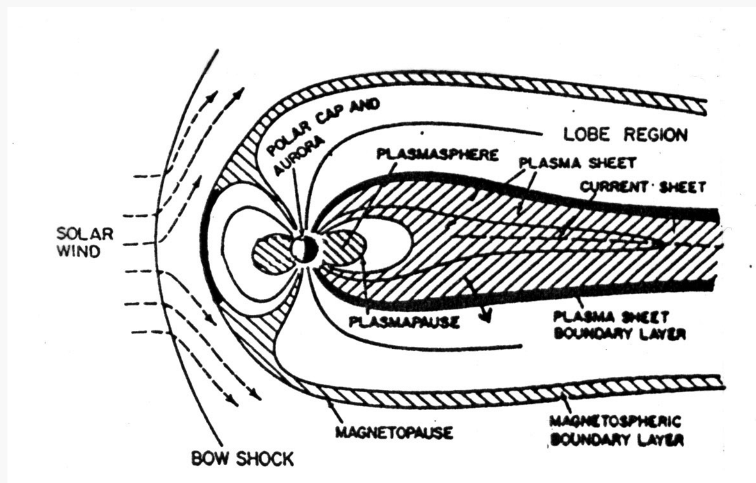
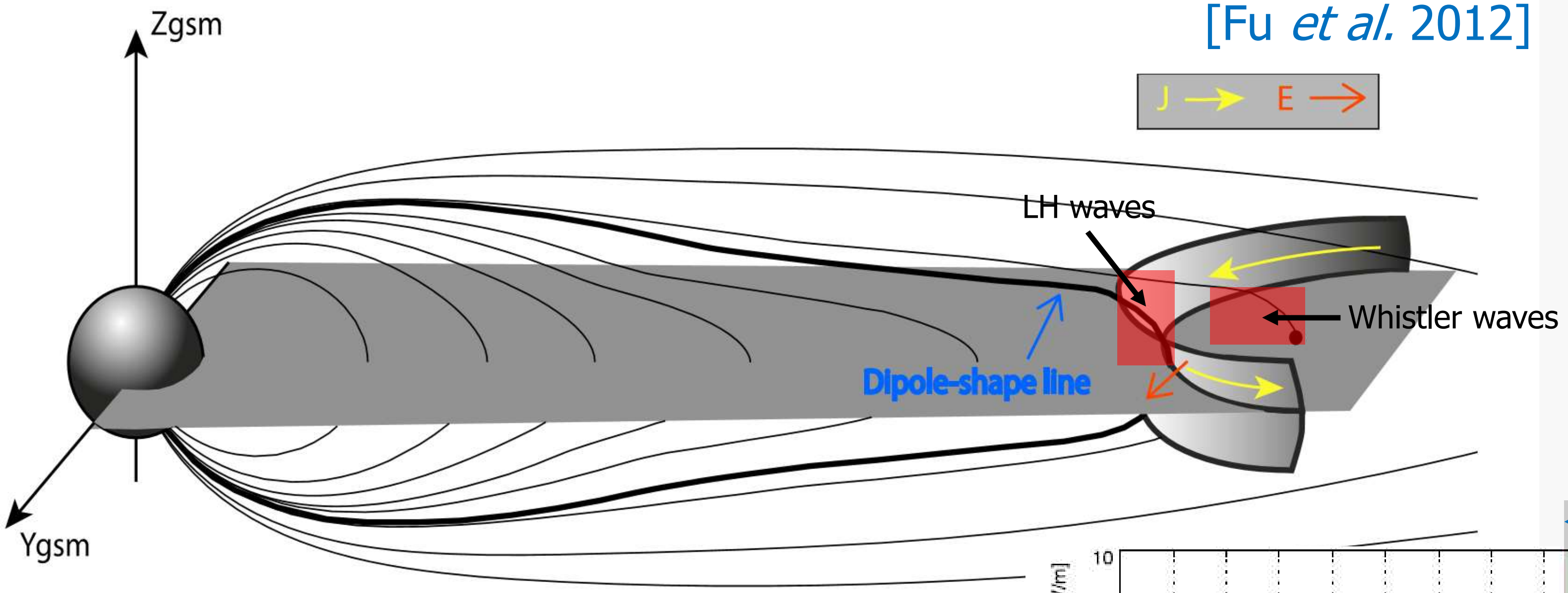
- 1988 — Ganguli *et al.* develop EIH theory
- 1992 — Peyser *et al.* applied EIH to laser plasma expansions
- 1993 — Romero and Ganguli PIC simulations and applied to PSBL
- 2003 — Amatucci *et al.* validated theory in lab
- 2017 — NASA effort to search for EIH in dipolarzation fronts

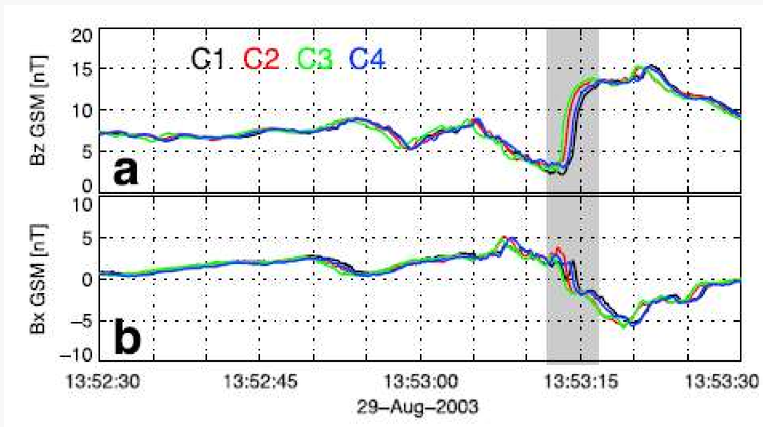


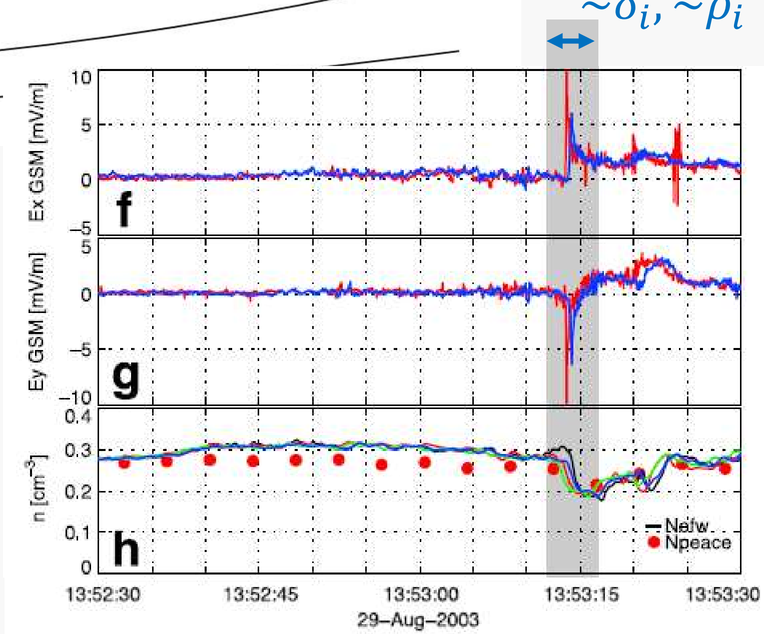
- Malaspina *et al.*, JGR 2015 – Up to 95% of boundaries showed broadband waves
- Divin *et al.*, JGR 2015 – Detailed analysis of LH waves at a dipolarization front

In Situ Observations of Dipolarization Fronts

[Fu *et al.* 2012]

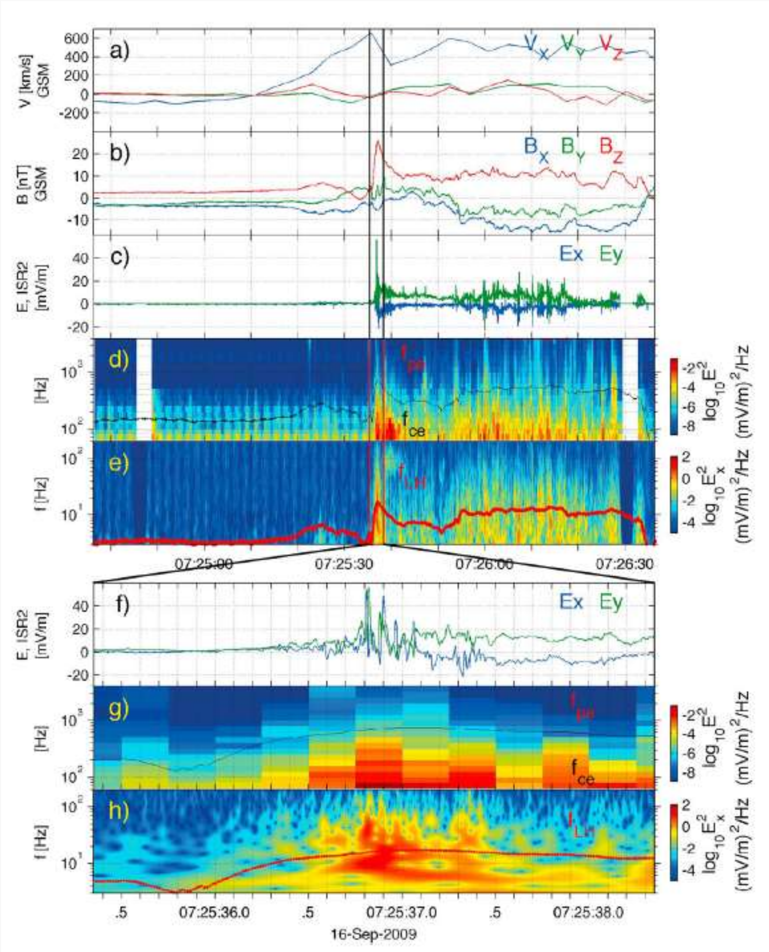




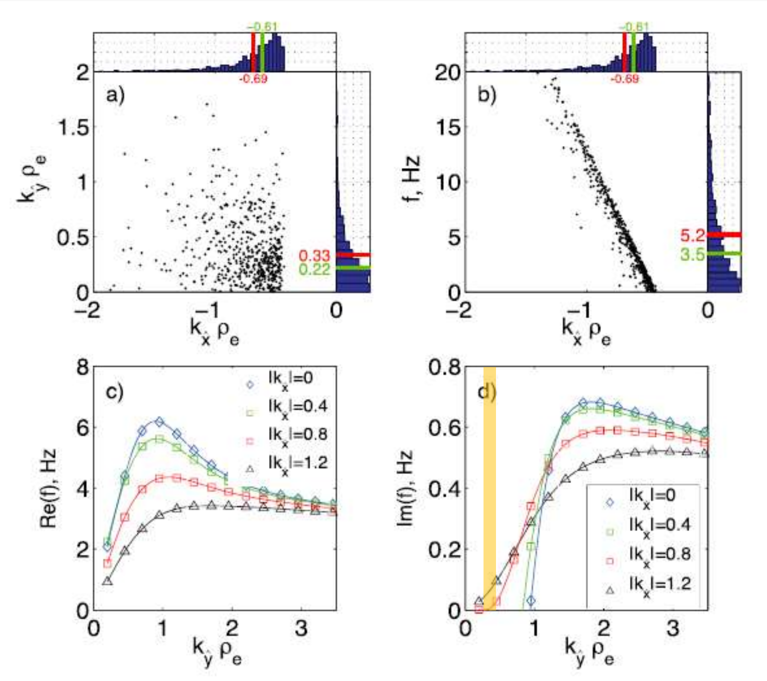


Divin *et al.* Identified Lower Hybrid Drift Instability as Source of Observed Lower Hybrid Waves

NRL PPD



[Divin *et al.* 2015]



- $(k_{\hat{x}}\rho_e, k_{\hat{y}}\rho_e) \sim (-0.6, 0.3)$
- LHDI modes should be damped

Local Approximation Predicts Instability Threshold

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$$\bar{\omega}^3 + \left(2\frac{\delta^2}{1+\delta^2}\frac{\bar{V}_0}{\bar{k}_y} - \bar{k}_y\bar{V}_0\right)\bar{\omega}^2 - \bar{\omega} + \bar{k}_y\bar{V}_0 = 0$$

$$\bar{\omega} = \frac{\omega}{\omega_{LH}}, \delta = \frac{\omega_{pe}}{\Omega_e}, \bar{V}_0 = \frac{v_E}{\omega_{LH}L_E}, \bar{k}_y = k_y L_E$$

$$ax^3 + bx^2 + cx + d = 0$$

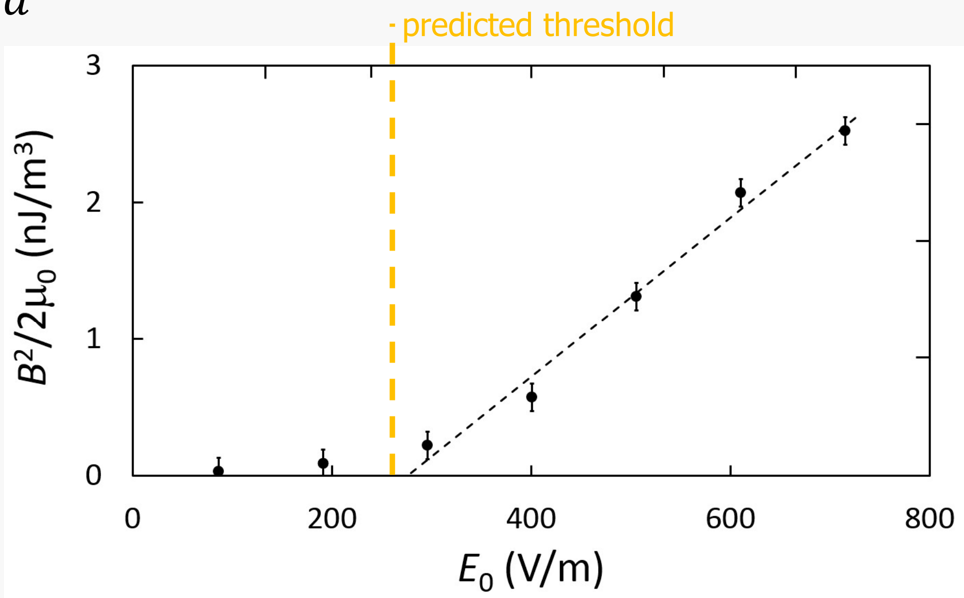
$$\Delta = 18abcd - 4b^3d + b^2c^2 - 4ac^3 - 27a^2d^2$$

Diamagnetic Drift Frequency: $\omega_{De,i} = kv_{De,i}$

Shear Frequency: $\omega_s = \frac{dv_E}{dx}$

If $\Delta < 0$, then 1 real solution and two complex conjugate solutions

Effects of Nonuniform B on EIH
- Increased growth rate
- No effect on wavelength



Reanalysis Shows that Sheared Flows Can Drive Observed Lower Hybrid Waves

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Relevant Parameters

Density	$n = 3.8 \times 10^5 \text{ m}^{-3}$
Magnetic Field	$B_z = 26 \text{ nT}$
Ion Diamagnetic Drift	$V_{Di} = 1.9 \times 10^5 \text{ m/s}$
Electric Field	$E_x = -20 \text{ mV/m}$
E×B Drift	$v_E = 1.7 \times 10^6 \text{ m/s}$
Electric Field Gradient Scale Length	$L_E = 54 \text{ km}$
Wave Vector in E×B Direction	$k_y = 3 \times 10^{-5} \text{ m}^{-1}$

Analysis Results

$\omega_s = 8.5 \text{ vs } \omega_{Di} = 8.7$

- LHDI: $k_y \rho_e \sim 1$
- EIH: $k_y L_E \sim 1$

$k_y \rho_e = 0.3 \text{ vs } k_y L_E = 1.6$

$\Delta = -9.3$

- Propagates in E×B direction

Conditions above threshold to drive EIH and wavelength scaling more consistent with EIH.