Eigenmode Structure in Solar Wind Langmuir Waves

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STEREO SWG
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TDS Langmuir waveforms from SWAVES

What determines

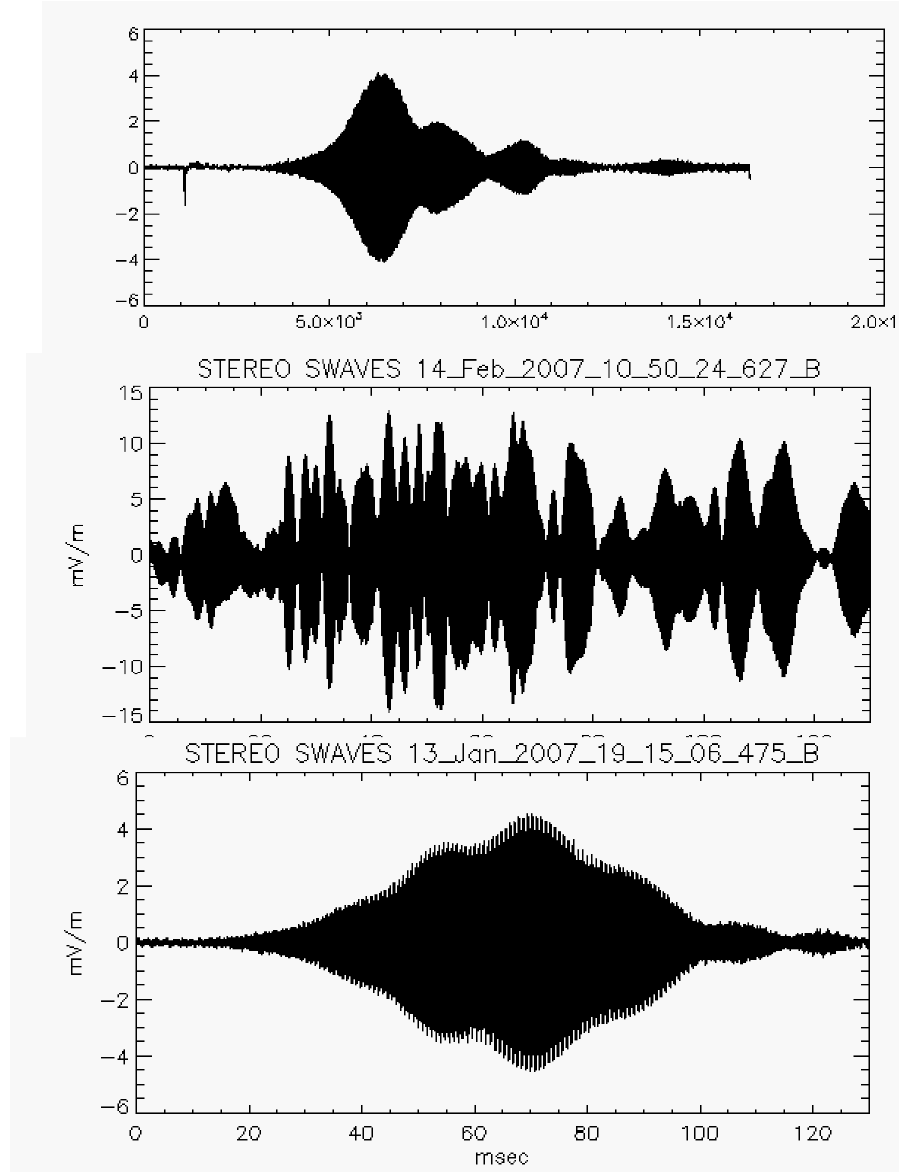
- **modulation ?**
- **amplitudes ?**
- **packing ?**
- **growth / maintenance ?**

Similar Waveforms seen by

- **Wind**
- **Ulysses**
- **Galileo**
- **ISEE3**

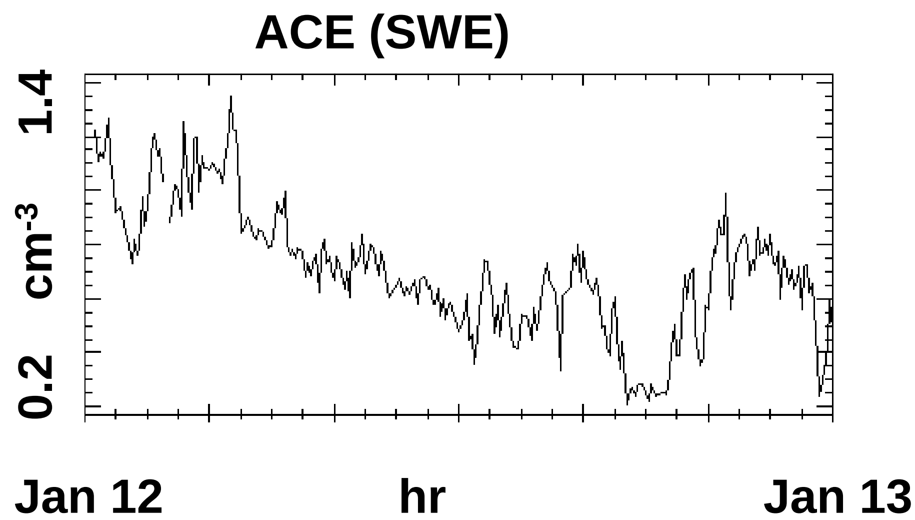
Many Theories:

(Ginzburg and Zheleznyakov 1958)
(Bardwell and Goldman 1976)
(Lin et al. 1981)
(Li, Robinson, and Cairns 2006)
(many,many others…)



Parameterize Turbulent Solar Wind

- **Density cavities pre-exist at all dist / time scales (ACE / WIND / ISEE / etc.)**



- **Zakharov Equations couple Langmuir waves to density perturbations (Zakharov 1972)**

$$\nabla \cdot \left(i\frac{\partial}{\partial t} + \frac{3V_{\mathrm{e}}^2}{2\omega_{\mathrm{p}}}\nabla^2 + i\hat{\gamma}_{\mathrm{L}} \right)\mathbf{E} = \nabla \cdot \left(\frac{\omega_{\mathrm{p}}\delta n_{\mathrm{e}}}{2n_{\mathrm{e}}}\mathbf{E} \right)$$

$$n = n_0(1 + \Delta n)$$

- **Parameterize density by curvature (assume parabolic well)**

$$\Delta n = n_0 \frac{x^2}{L^2}$$

Eigenmode Solutions for Langmuir Electric field

$$E(x,t) = \sum_n^{\infty} A_n E_n$$

Envelope

Plasma Oscillation

$$\boxed{E_n = H_n(Qx)e^{-\frac{(Qx)^2}{2}} e^{i(k+\Delta k)x - i(\omega+\Delta\omega)t+\phi}}$$

$$Q^2 = \frac{\omega_{plasma}}{\sqrt{3} v_e L} \qquad v_e = \sqrt{\frac{k_b T_e}{m_e}} \qquad \Delta k = -\frac{\omega_{plasma} v_\Delta}{3 v_e^2}$$

$$v_\Delta = v_{group} - v_{sound} \qquad \Delta\omega = \frac{(2n+1)\sqrt{(3)}v_e}{2L} - \frac{v_\Delta^2 \omega_{plasma}}{6 v_e^2}$$

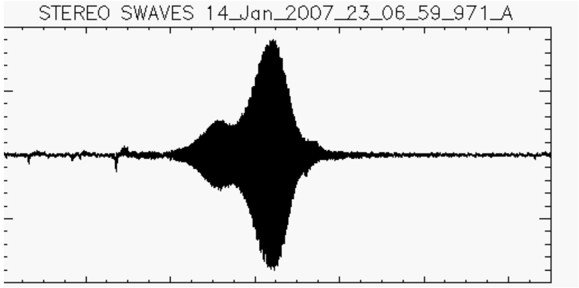
Quantization condition

Selecting ILS Events for Eigenmode Description

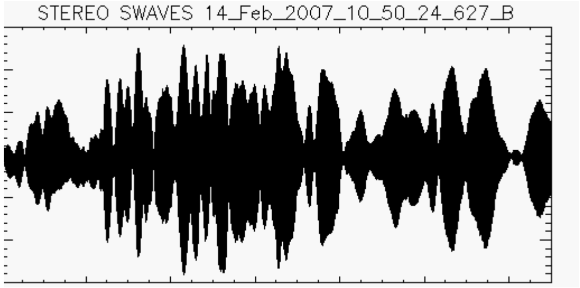
1172 Total Langmuir events during Jan - Jul '07

204 ILS (Intense Langmuir Solitons) (one waveform within 130 msec)

968 Multiple burst events



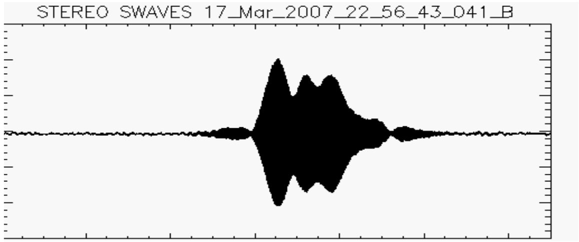
0 (msec) 130



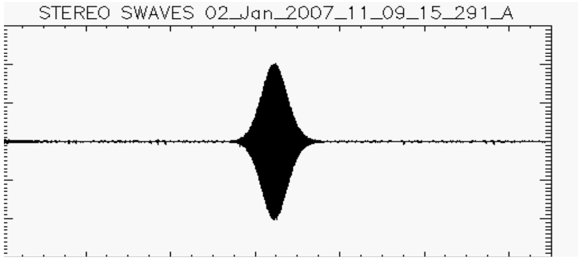
0 (msec) 130

95 with complex waveforms (mode 3 - 12 dominant)

109 simple waveforms (mode 0 - 2 dominant)

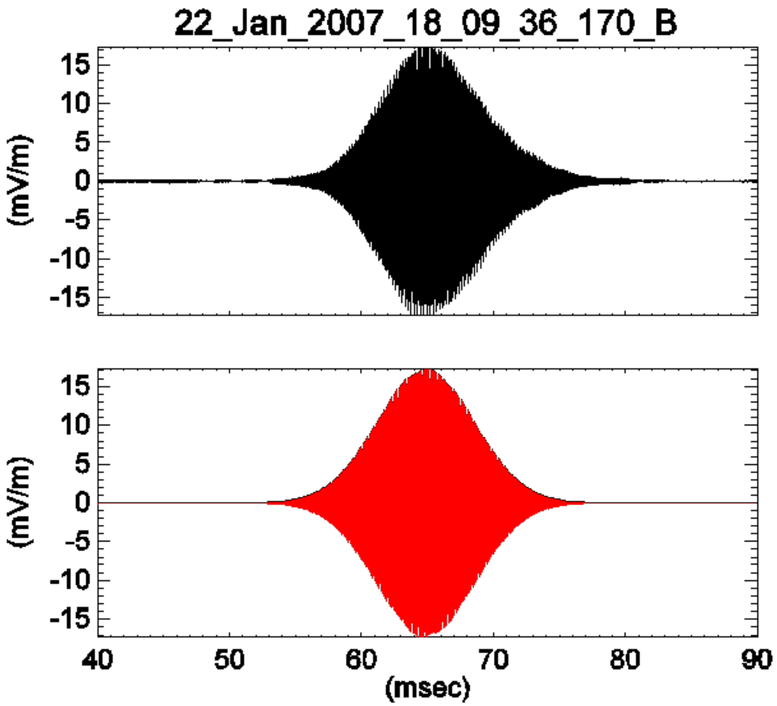


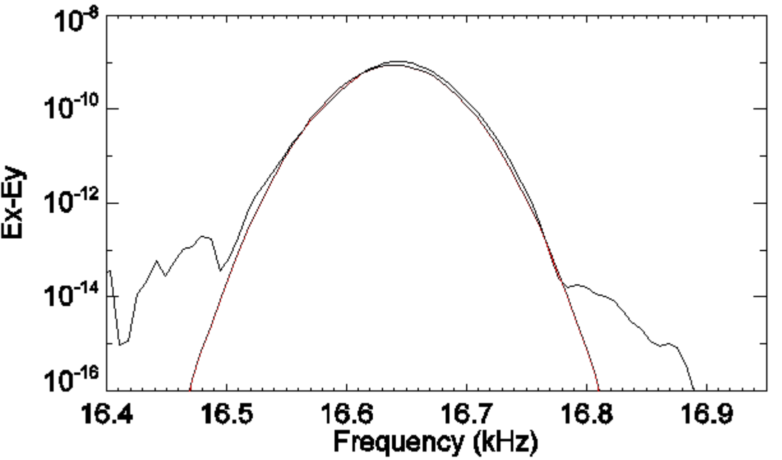
0 (msec) 130



0 (msec) 130

Case Study Fits (Simple Case)

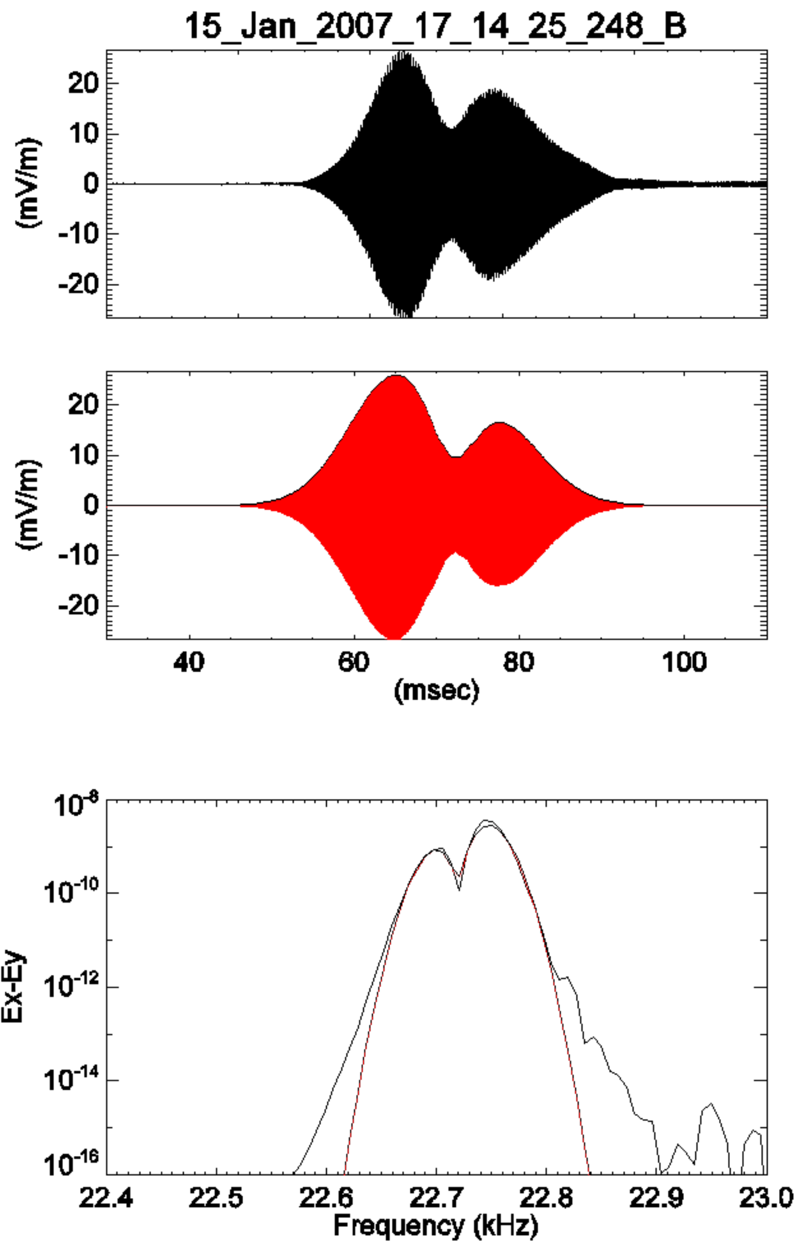




mode	An
0	1

Param.	Val.	Unit
Vb	**0.09*c**	**m/s**
Vsw * B/|B|	**344**	**km/s**
Q	**0.0008**	**1/m**
Te	**7.3e4**	**K**
fp	**16.7**	**kHz**
Length	5.2	km
Vg	143	km/s
Ve	1053	km/s
W	3.6e-4	
k/Q	3.94	

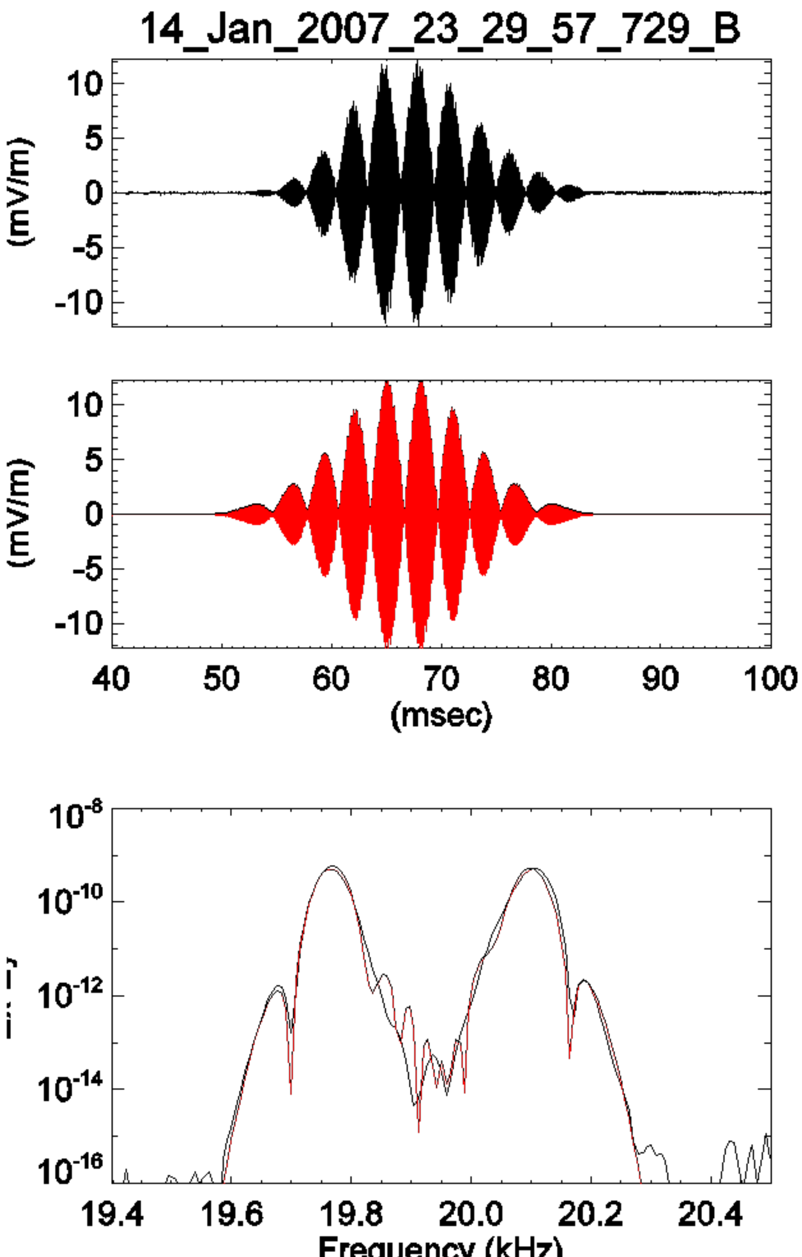
Case Study Fits (More Complex)



mode	An
0	0.45
1	0.5
2	0.05

Param.	Val.	Unit
Vb	0.24*c	m/s
Vsw * B/|B|	600	km/s
Q	0.0002	1/m
Te	4.9e5	K
fp	22.8	kHz
Length	15.8	km
Vg	311	km/s
Ve	2733	km/s
W	5e-5	
k/Q	7.43	

Case Study Fits (Very Complex)



mode	An
1	-0.06
2	-0.0006
3	-0.222
5	0.35
7	-0.26
8	-0.0013
9	-0.0059
11	0.097

Param.	Val.	Unit
Vb	0.2*c	m/s
Vsw * B/|B|	280	km/s
Q	0.0012	1/m
Te	7091 *(2-4)	K
fp	20.2	kHz
Length	3.31	km
Vg	6	km/s
Ve	328	km/s
W	1e-3	
k/Q	4.99	

Modulation Conclusions

Hermite-Gauss Eigenmode solutions describe Langmuir packet modulation <u>(few modes!!)</u>

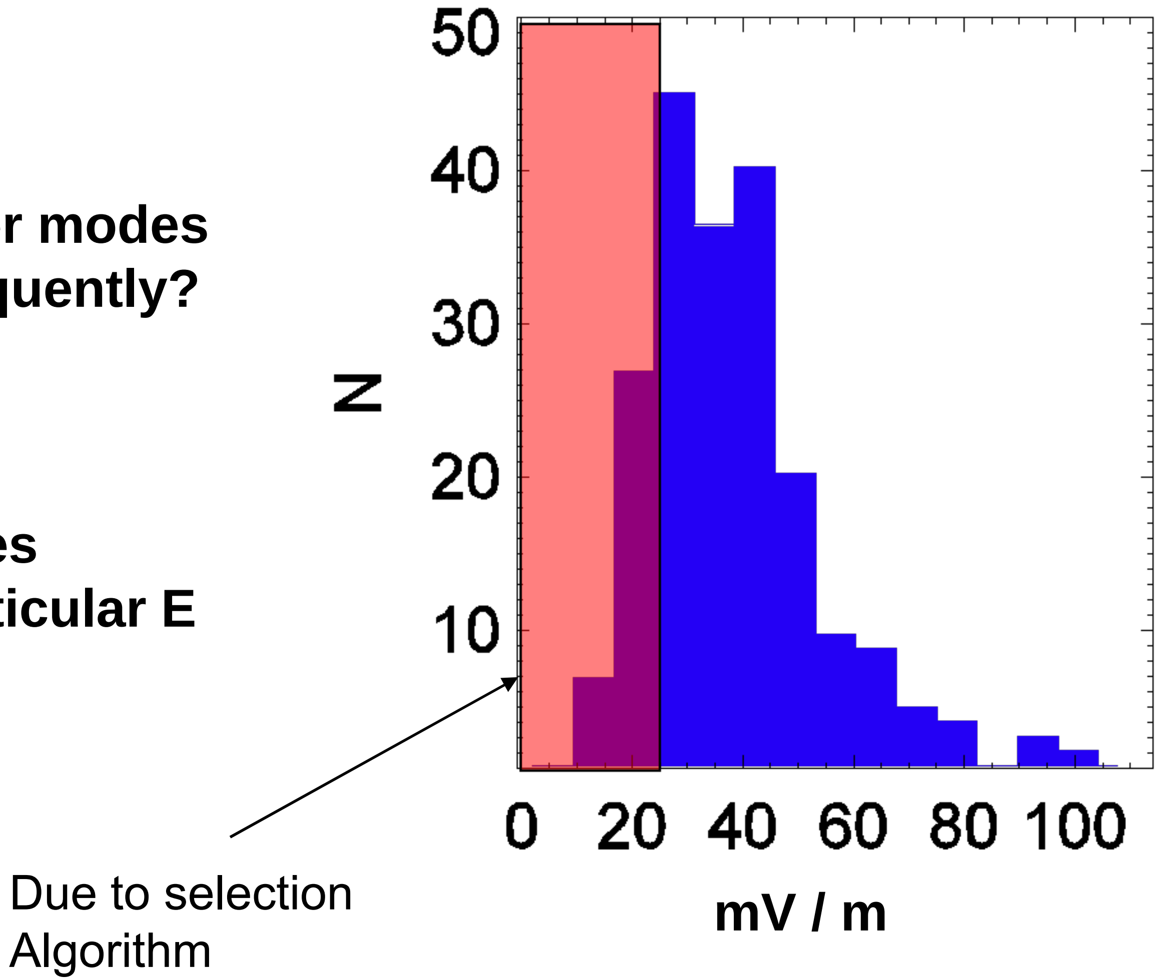
<u>1D physics dominates</u> in many cases (polarization and B field measurements support)

Beams interact with density cavities <u>only</u> when density cavity is the proper curvature for a given beam wave number

Eigenmode Growth

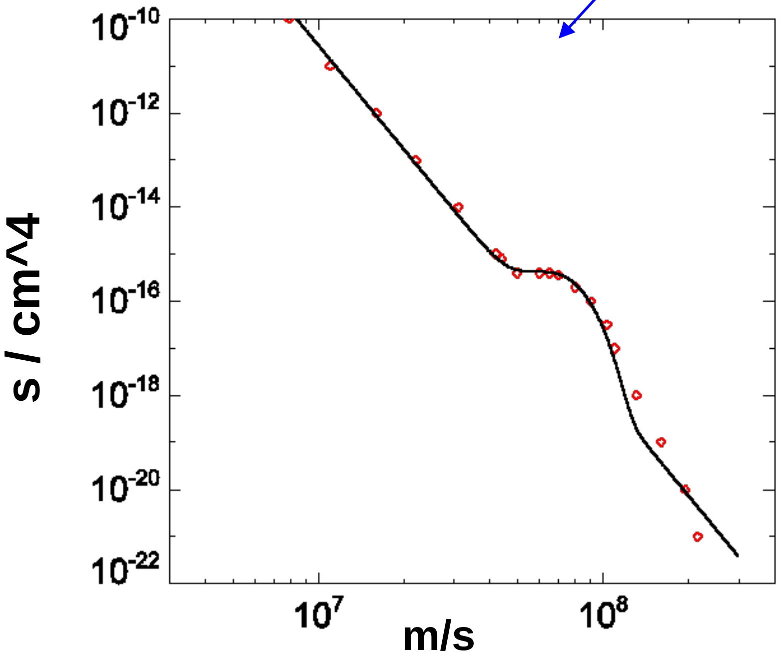
- What determines relative mode powers?
- Why are low order modes observed more frequently?
- Why should waves saturate at any particular E field value?

ILS Peak to background RMS

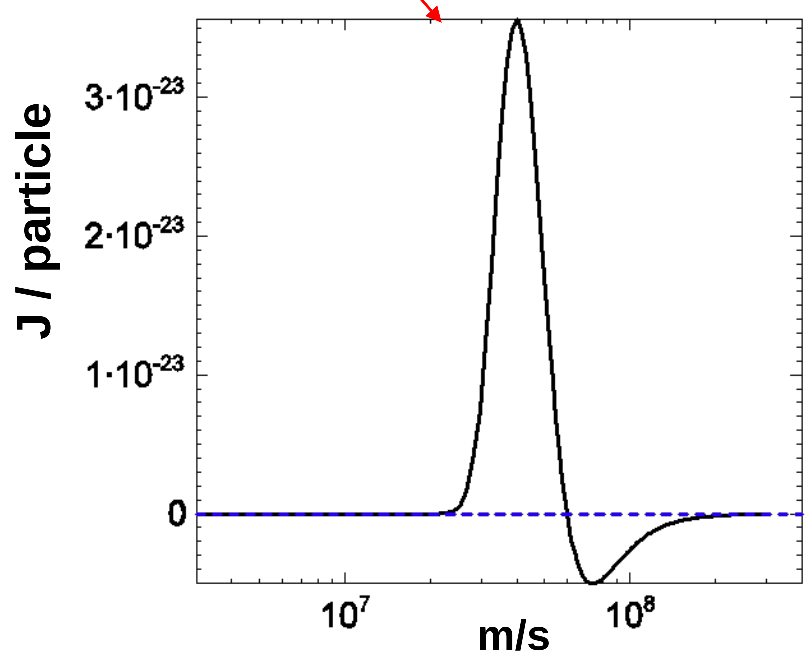


Transit Time Simulations

$$\frac{E_{transit} = \int f v G \, dv}{E_{packet} = \int \frac{\epsilon_o E^2}{2} \, dx} = 2\gamma$$



Distribution Function

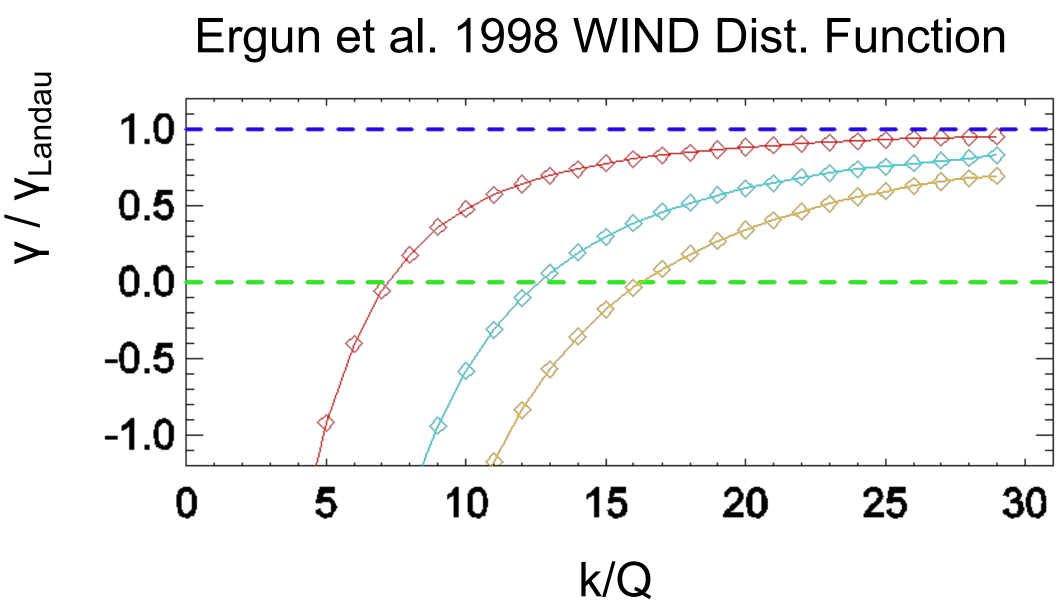


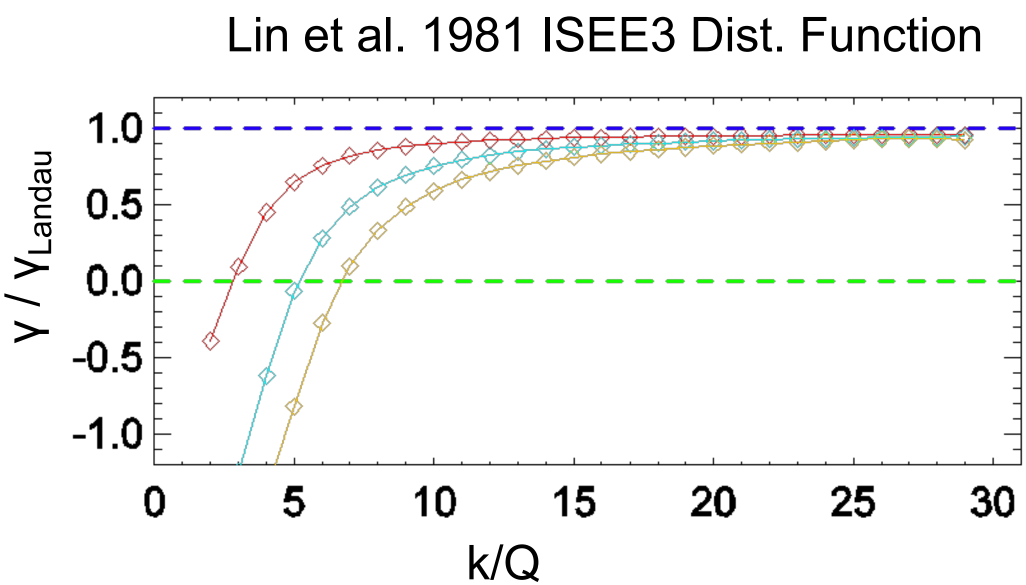
Growth Function

Eigenmode Growth Results

Parameter		Effect	
Mode	↑	γ	↓
k/Q	↑	γ	↑
Slope	↑	γ	↑
E_o	↑	γ	↓
Width f(v)	↑	γ	↑

- Minimum k/Q !
- Low order modes grow first
- Saturates naturally (~120 mV/m)
- Wider plateaus => higher modes





Conclusions

1D ILS Langmuir wave modulation <u>well described</u> as trapped Eigenmodes of parabolic density well

(what about 2D and 3D?)

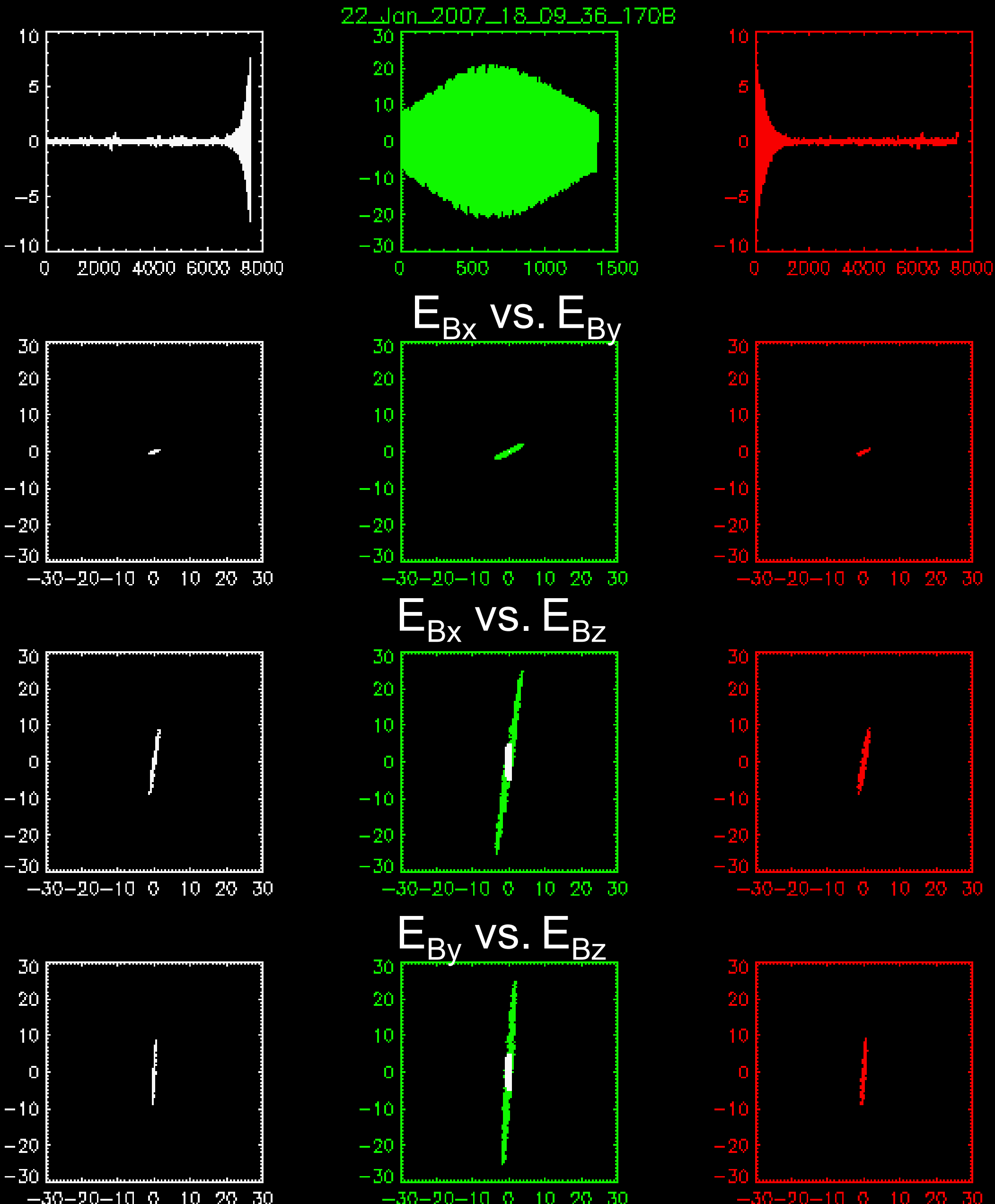
Eigenmode growth by transit time effects <u>consistent with observed saturation and mode structure</u>

<u>(nonlinear effects?)</u>

Zakharov + Vlasov simulation results (preliminary) show Langmuir localization to shallow density wells

(very preliminary)

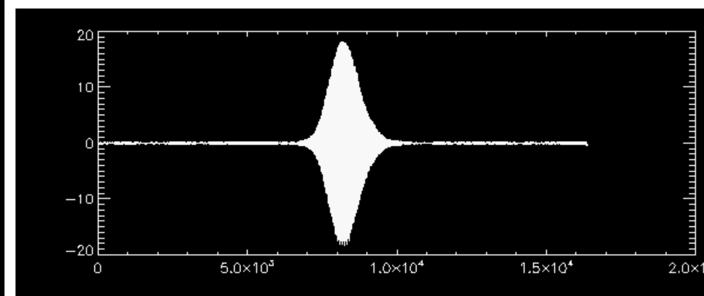
Field Aligned 3D Polarization

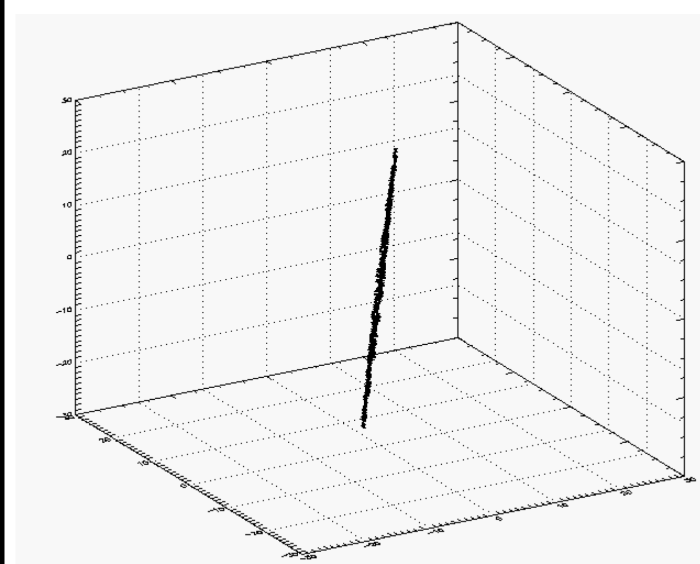


70% ILS Waveforms

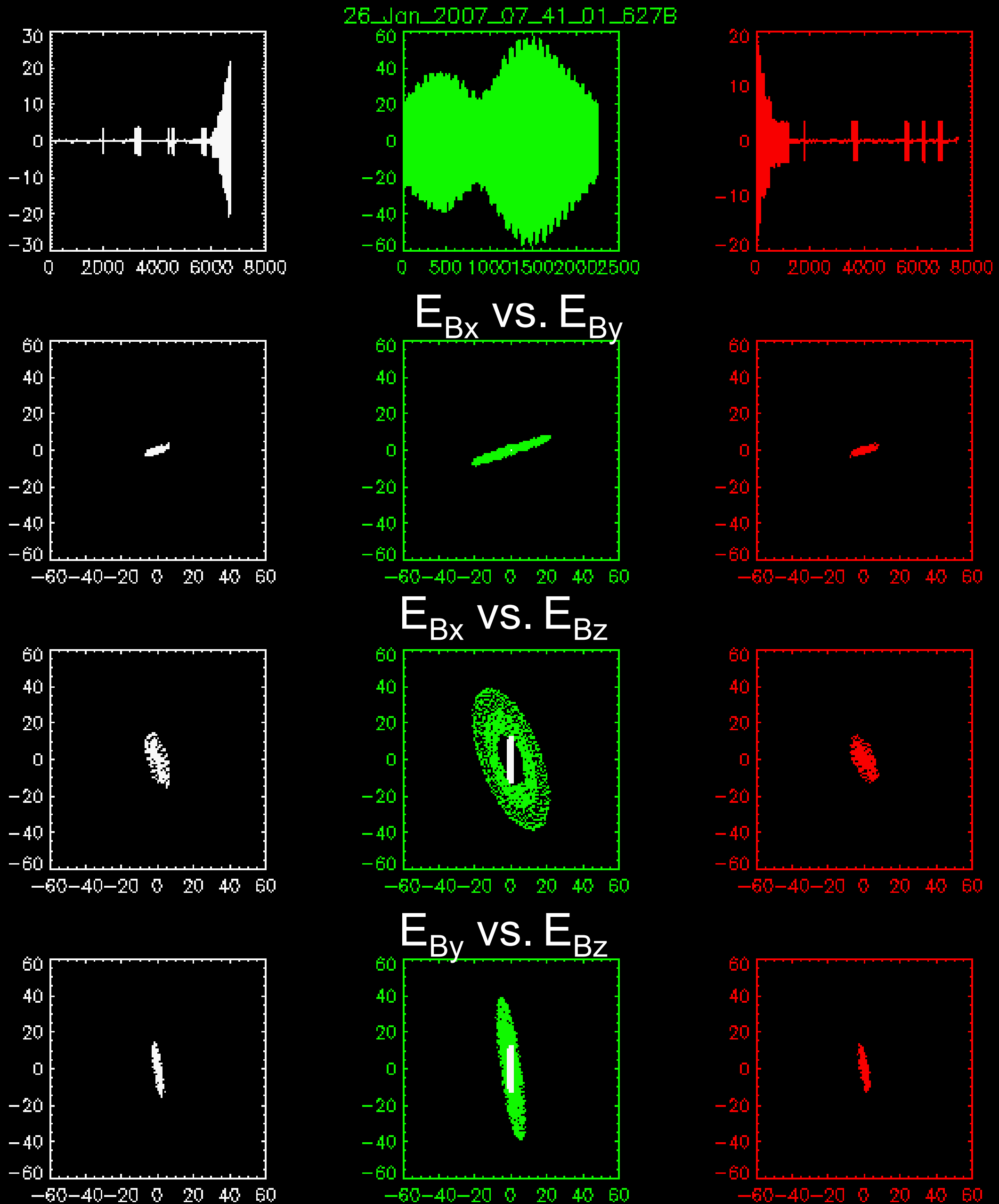
Linearly Polarized

Along B





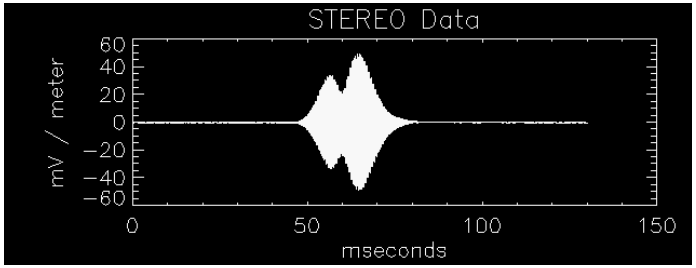
Field Aligned 3D Polarization

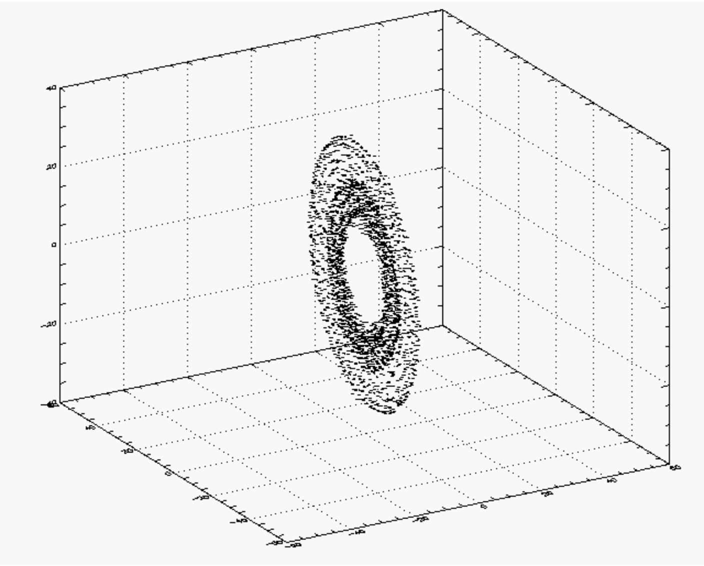


20% ILS Waveforms

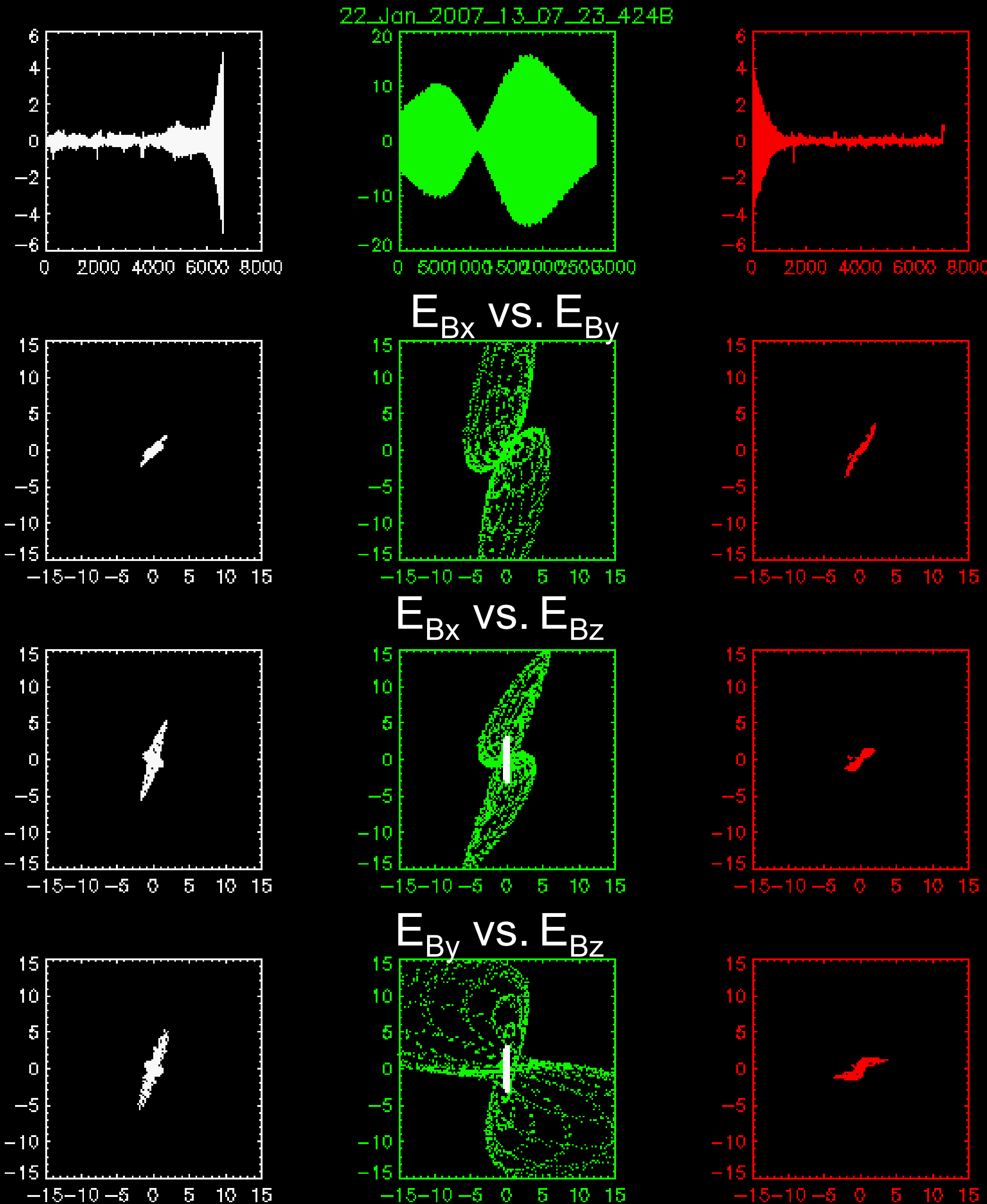
2D Polarized

Long Axis Along B





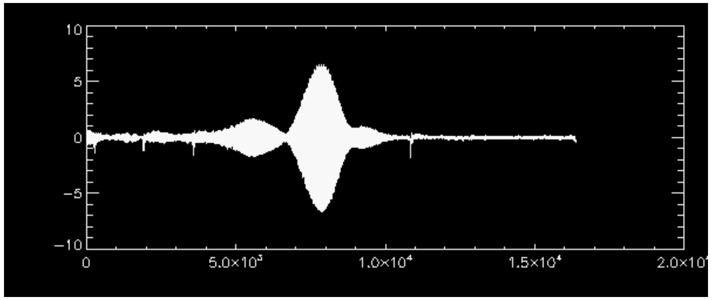
Field Aligned 3D Polarization

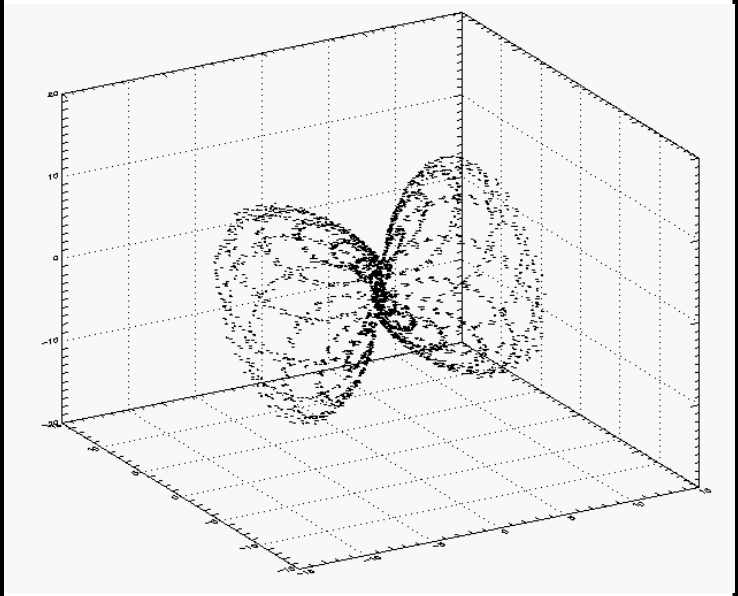


10% ILS Waveforms

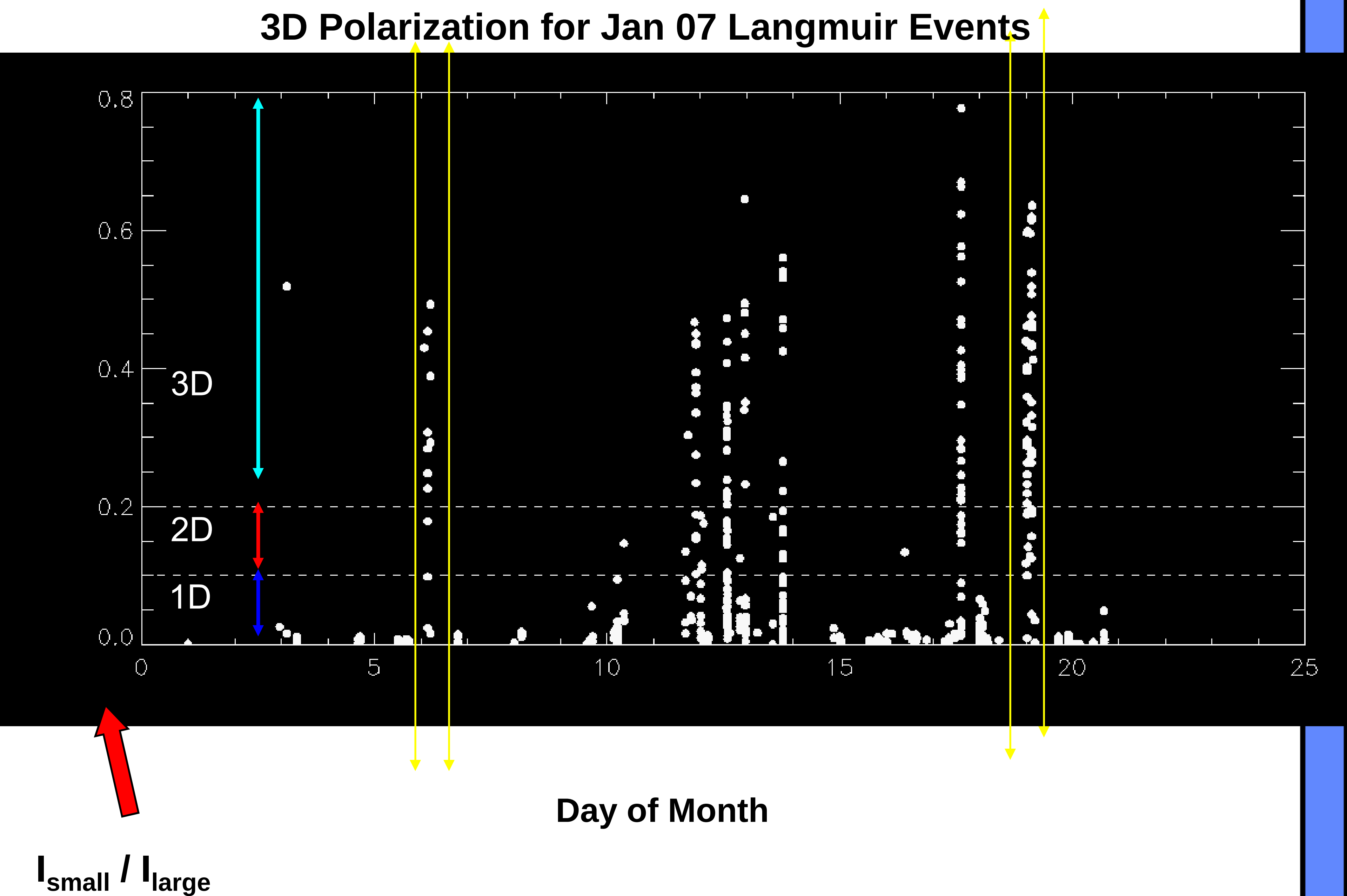
3D Polarized

Random(?) wrt B





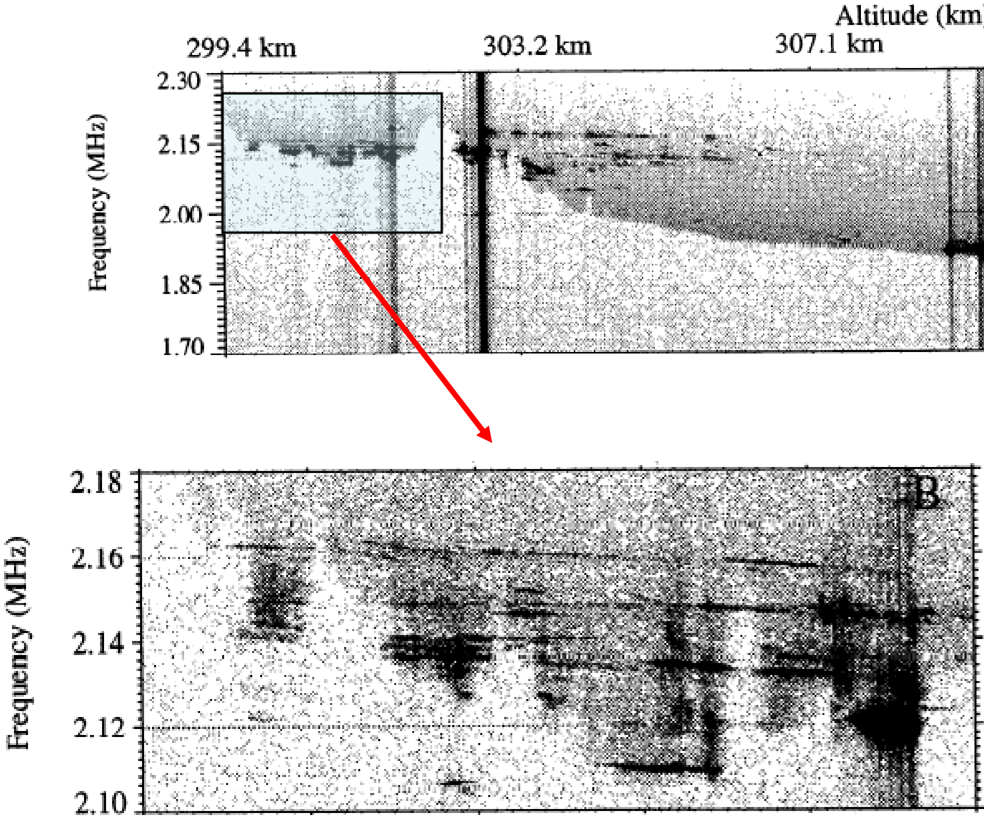
Polarization For Distinct Type III Events

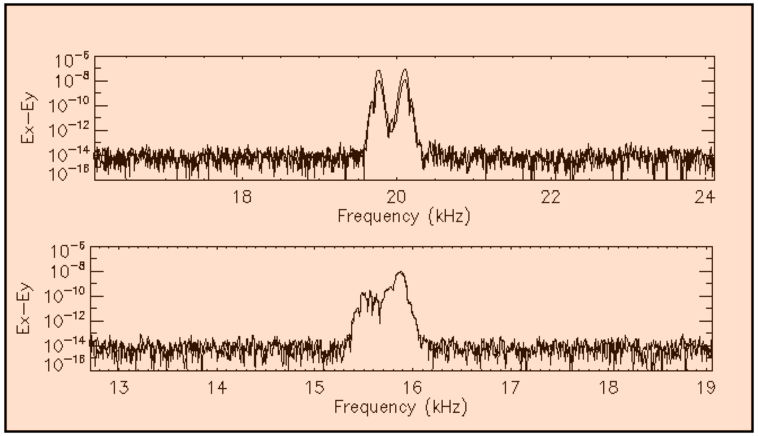


Eigenmodes

- Frequency structure observations near the w_p interpreted as eigenmode structure in the ionosphere
 (McAdams and LaBelle 1999 / McAdams, Ergun and LaBelle 2000)

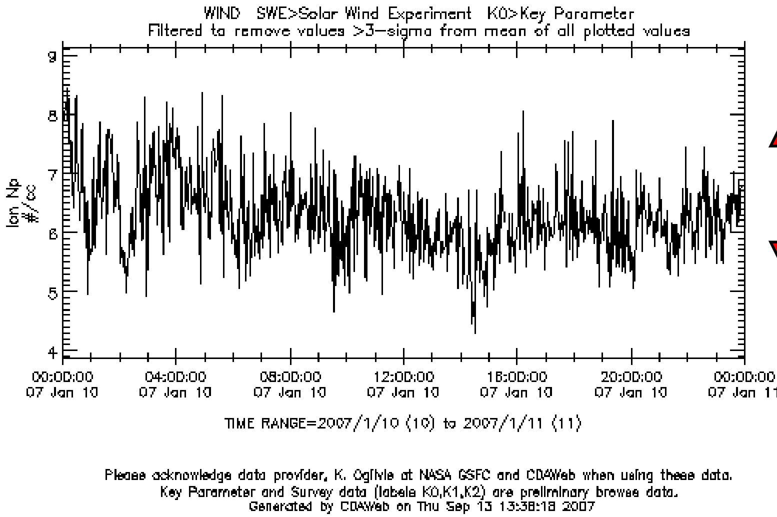
- Similar to freq structure in STEREO observations





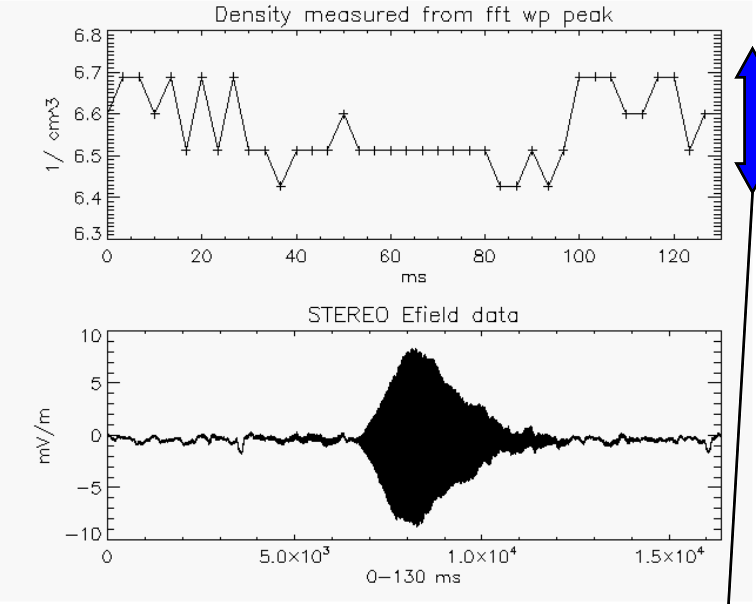
Density Variation

Hourly Variation from WIND

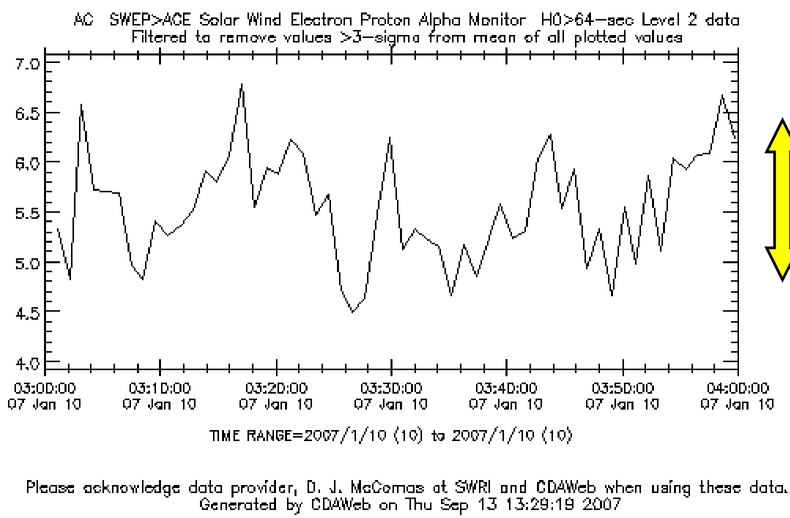


30% variation

Millisecond Variation from STEREO



Minute Variation from ACE



15% variation

1% or < variation

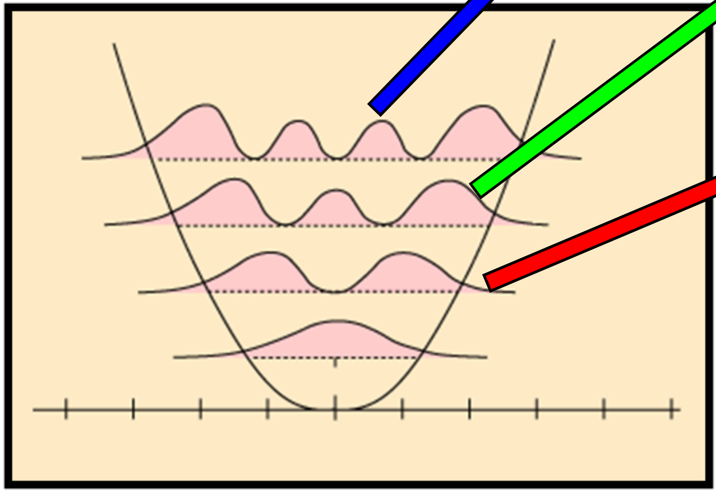
Yet More Sanity Check

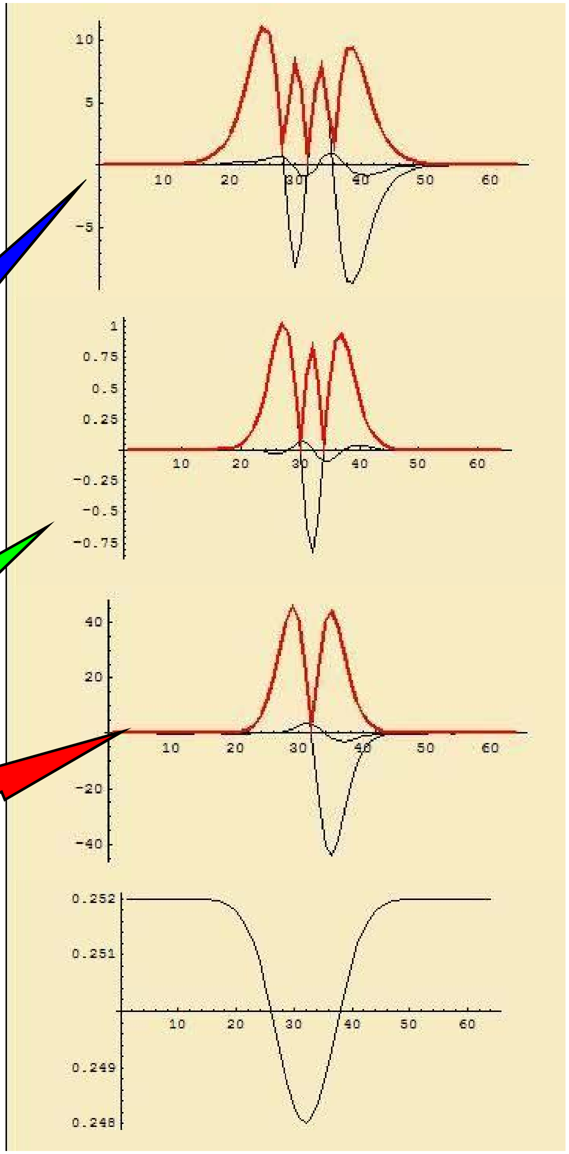
Solving Zakharov equation with assumed density well as eigenvalue problem

(Code by David Newman, based on Buneman Instability eigenvalue solver)

- Growing eigenmodes in parabolic wells can be Hermite solutions

- High frequency density ripples are ignored by growing eigenmode when ripple scale << well size (but wave-wave interactions not considered explicitly)





N=3

N=2

N=1

n

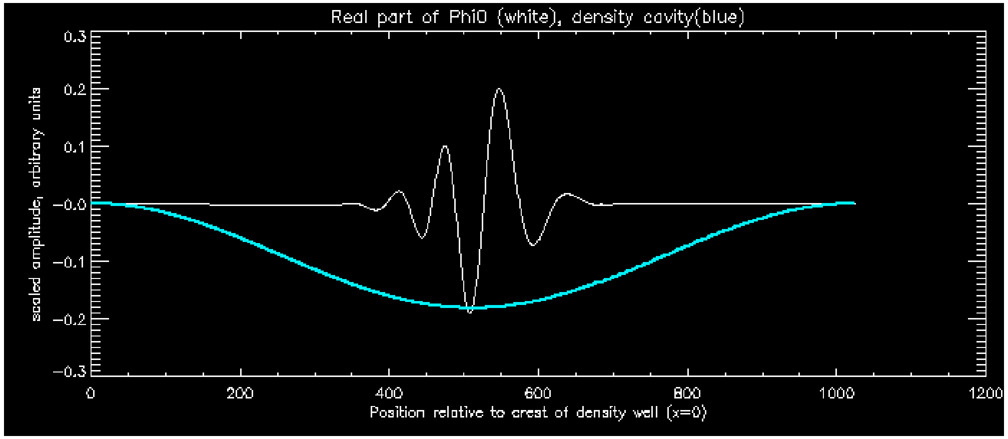
Sanity Check

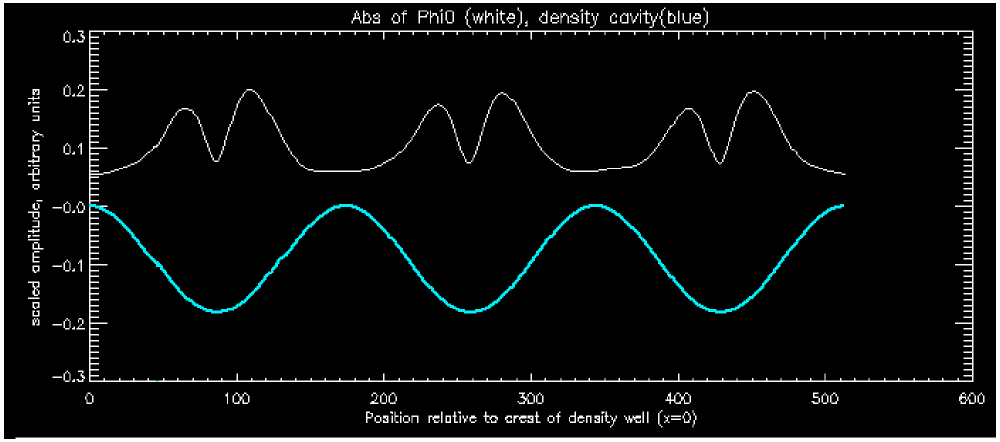
Using 2D Zakharov code reduced to 1D (Newman et al. 1990)

- Langmuir waves will grow in cavities, (when plane wave solutions absent)

- Waves travel with moving density wells (stay coherent)

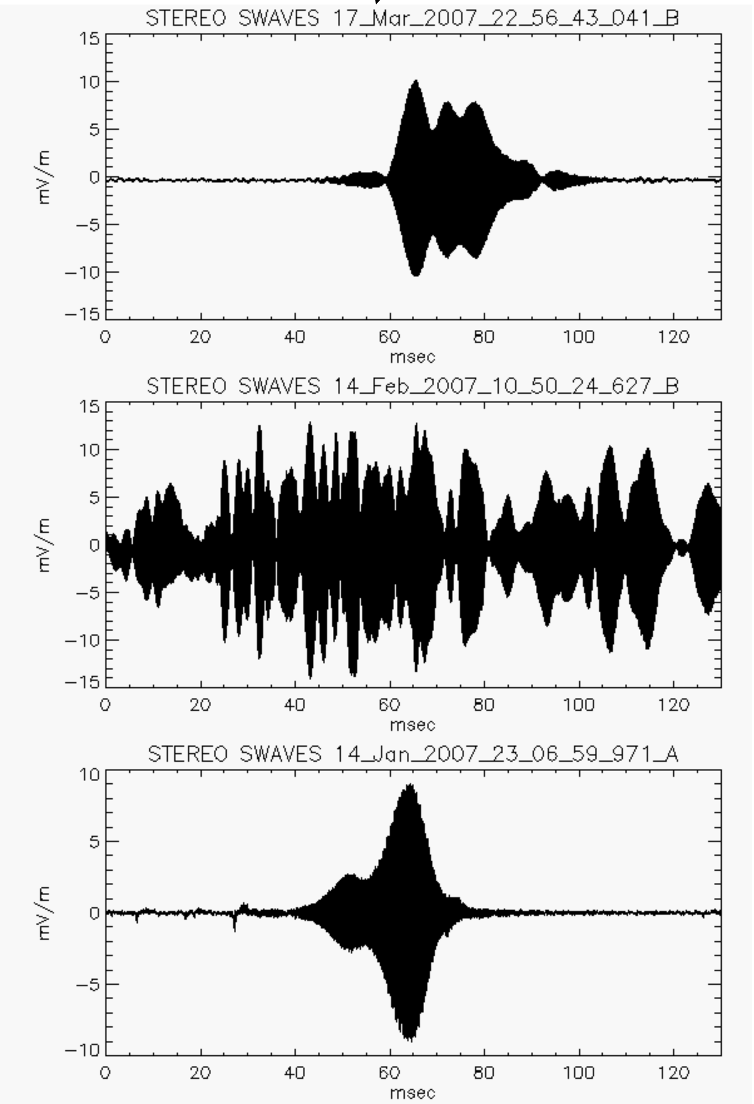
- Waves will selectively grow in wells of certain sizes, depending on e- beam driving k



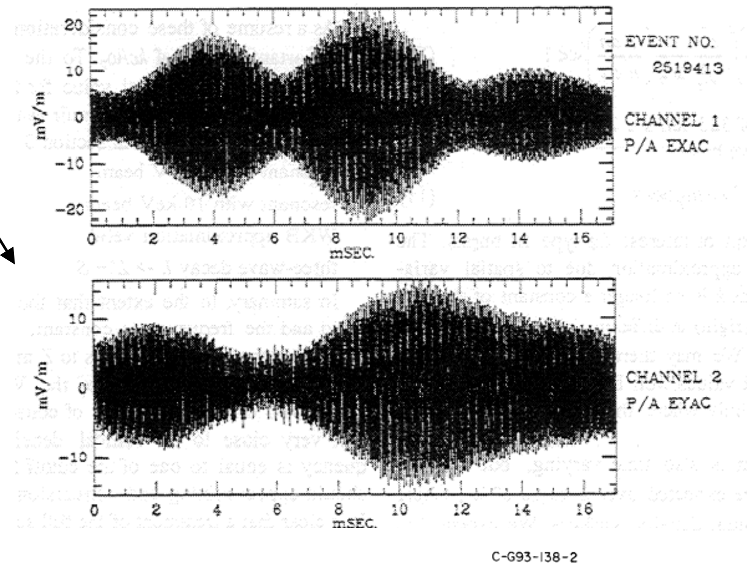


Langmuir Wave Profiles

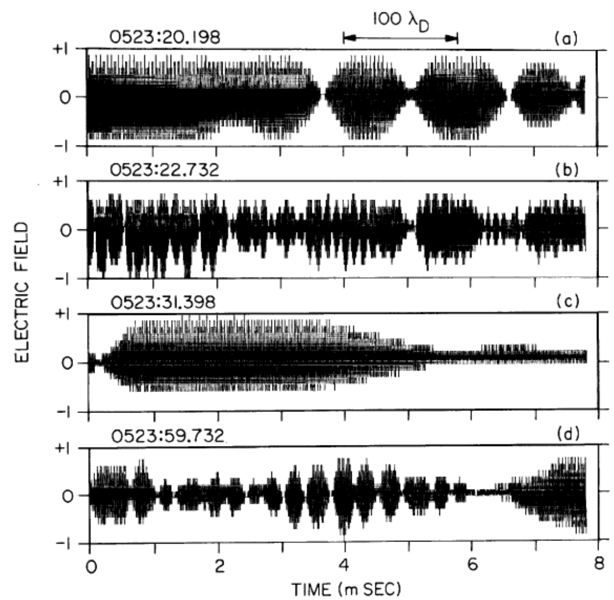
STEREO



WIND



Galileo



GALILEO-VENUS, DAY 41, FEB. 10, 1990