Exploring waves through their effects on particle velocity distributions for ions and electrons

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Outline

1. Ion motion in ion acoustic waves
2. Electron motion in Alfven waves

Electrostatic waves at ion frequencies

$$E = -\nabla\Phi$$

$$n_e \approx n_i$$

Quasi-neutral $\lambda >> \lambda_d$

$$\frac{\tilde{n}_{e1}}{n_{e0}} \approx e^{\frac{e\Phi}{\kappa T_e}}$$

Low frequency $\omega << \omega_{pi}$

$$\frac{\partial f}{\partial t} + \mathrm{v}\frac{\partial f}{\partial z} + \frac{e}{m} E \frac{\partial f}{\partial \mathrm{v}} = 0$$

Small amplitude

$$E = E_1$$

$$f = f_0 + f_1$$

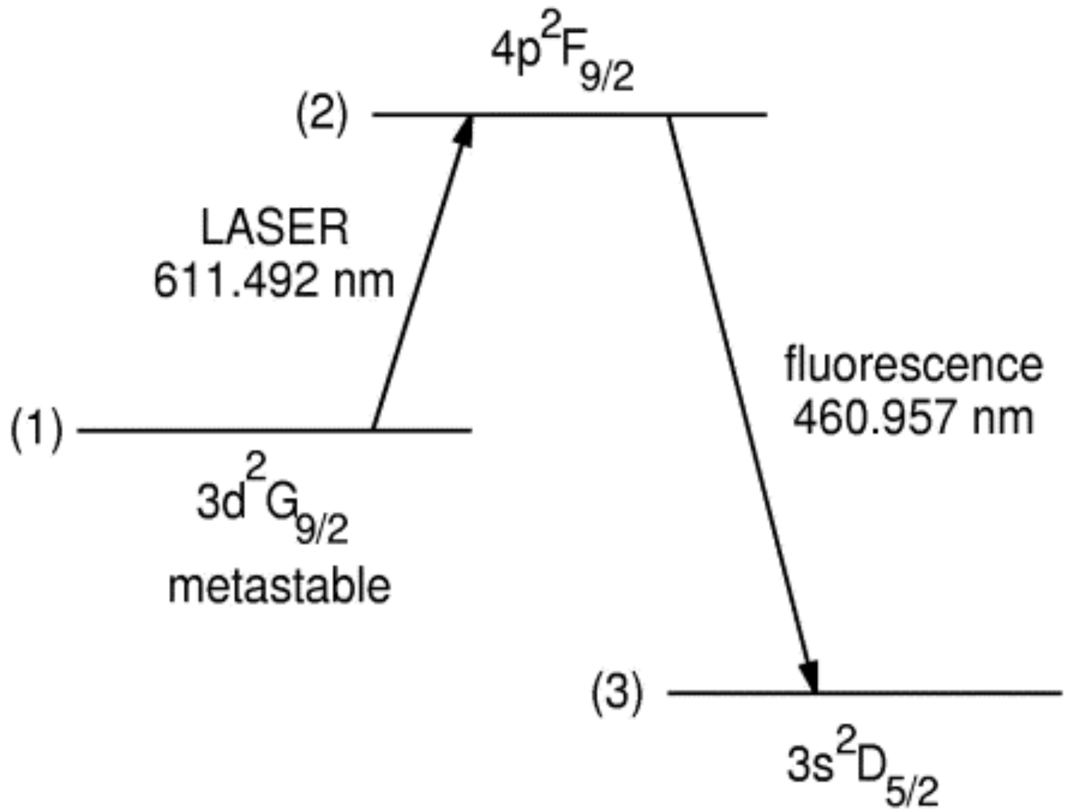
Kinetic Dispersion Relation

$$1 - C_s^2 \frac{1}{n_0} G\left(\frac{\partial f}{\partial v_{\mathrm{P}}}\right) = 0$$

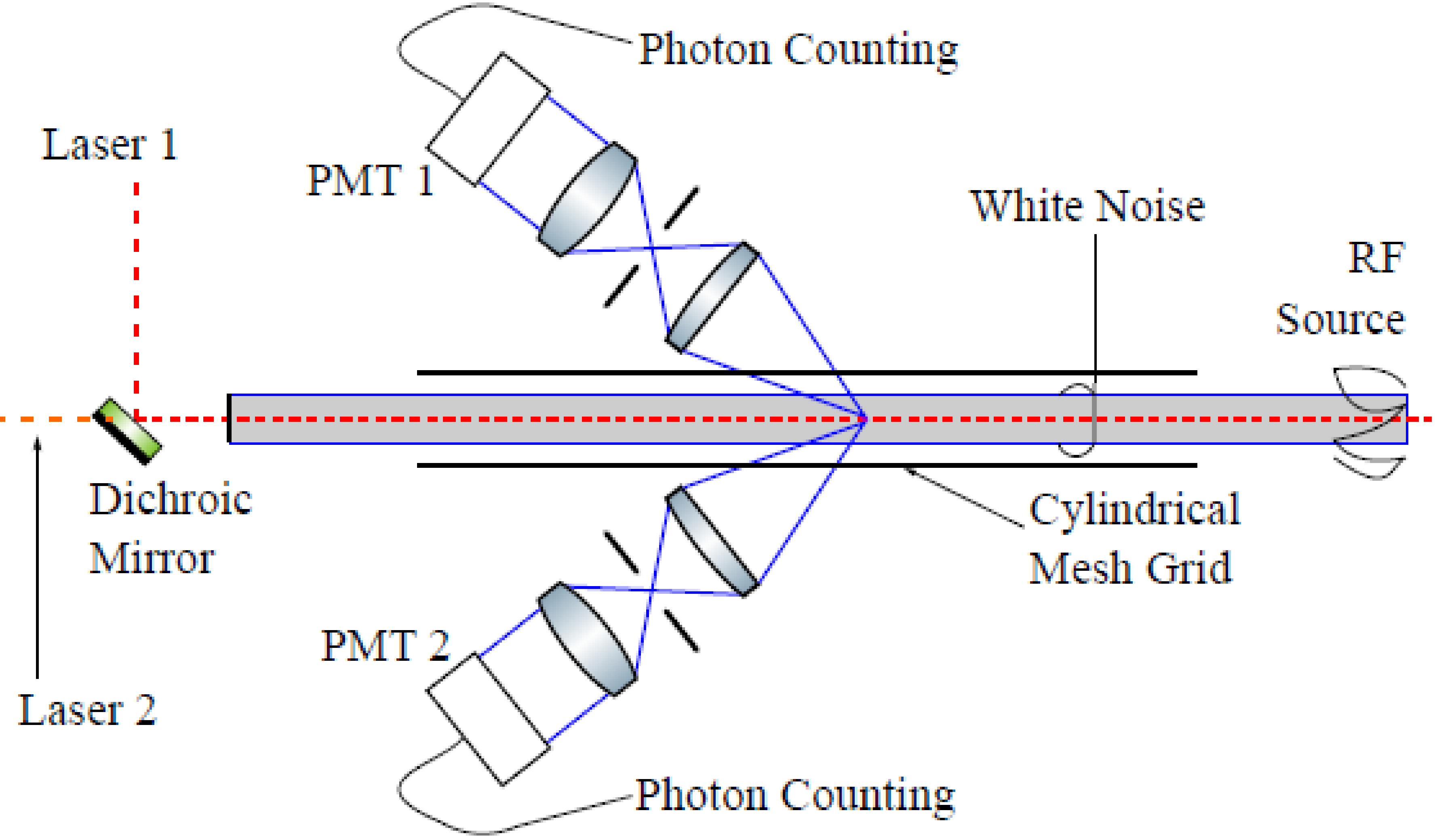
$$G(h(v))_u = p\int_{-\infty}^{\infty} \frac{h(v)}{v-u}\,dv + i\pi h(u)$$

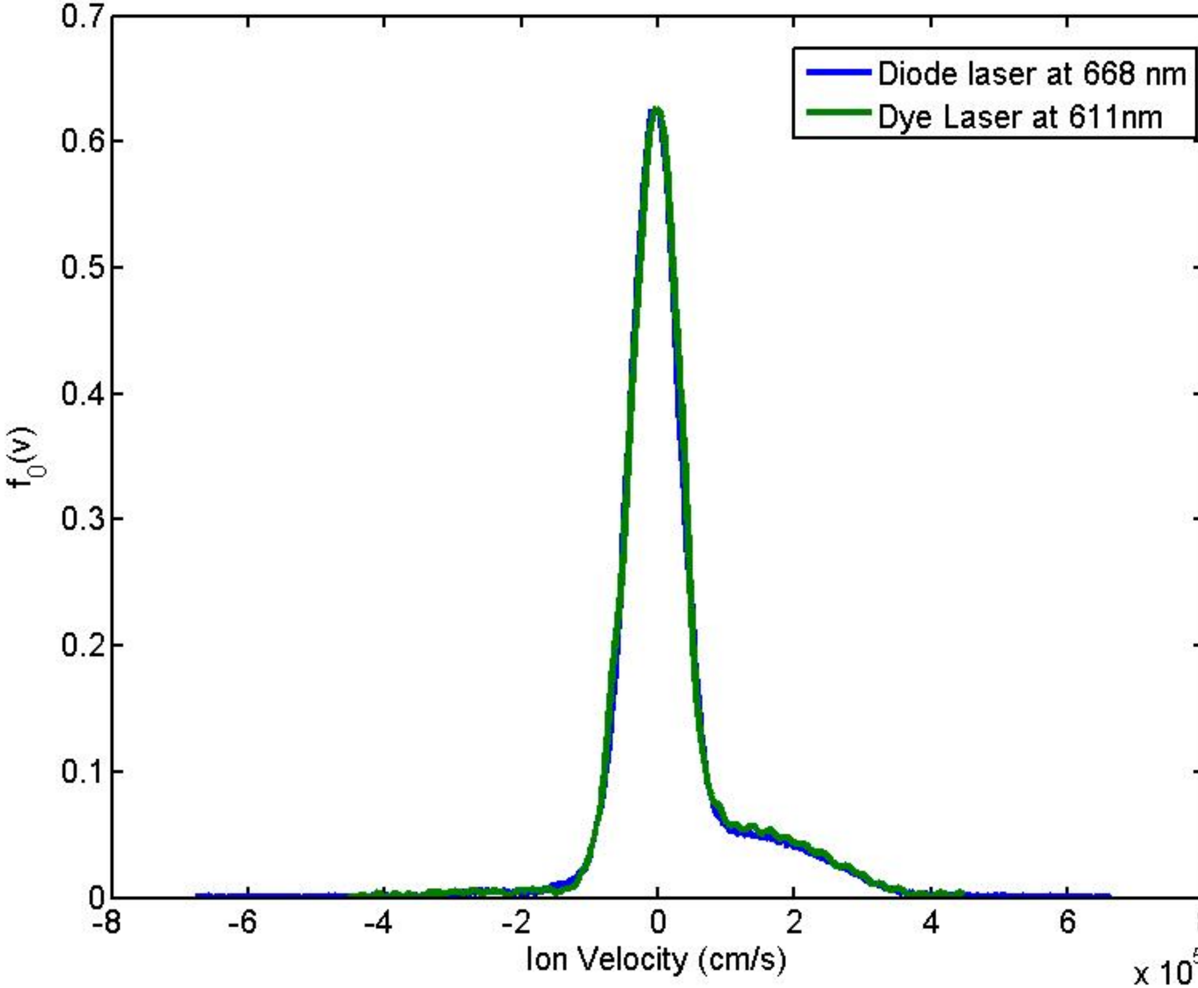
$$G\left(\frac{\partial f}{\partial v_{\mathrm{P}}}\right)_{u=\frac{\omega}{k_{\mathrm{P}}}} \longrightarrow n_0 Z(u / v_t)$$

(For the case of a maxwellian *f(v)*)

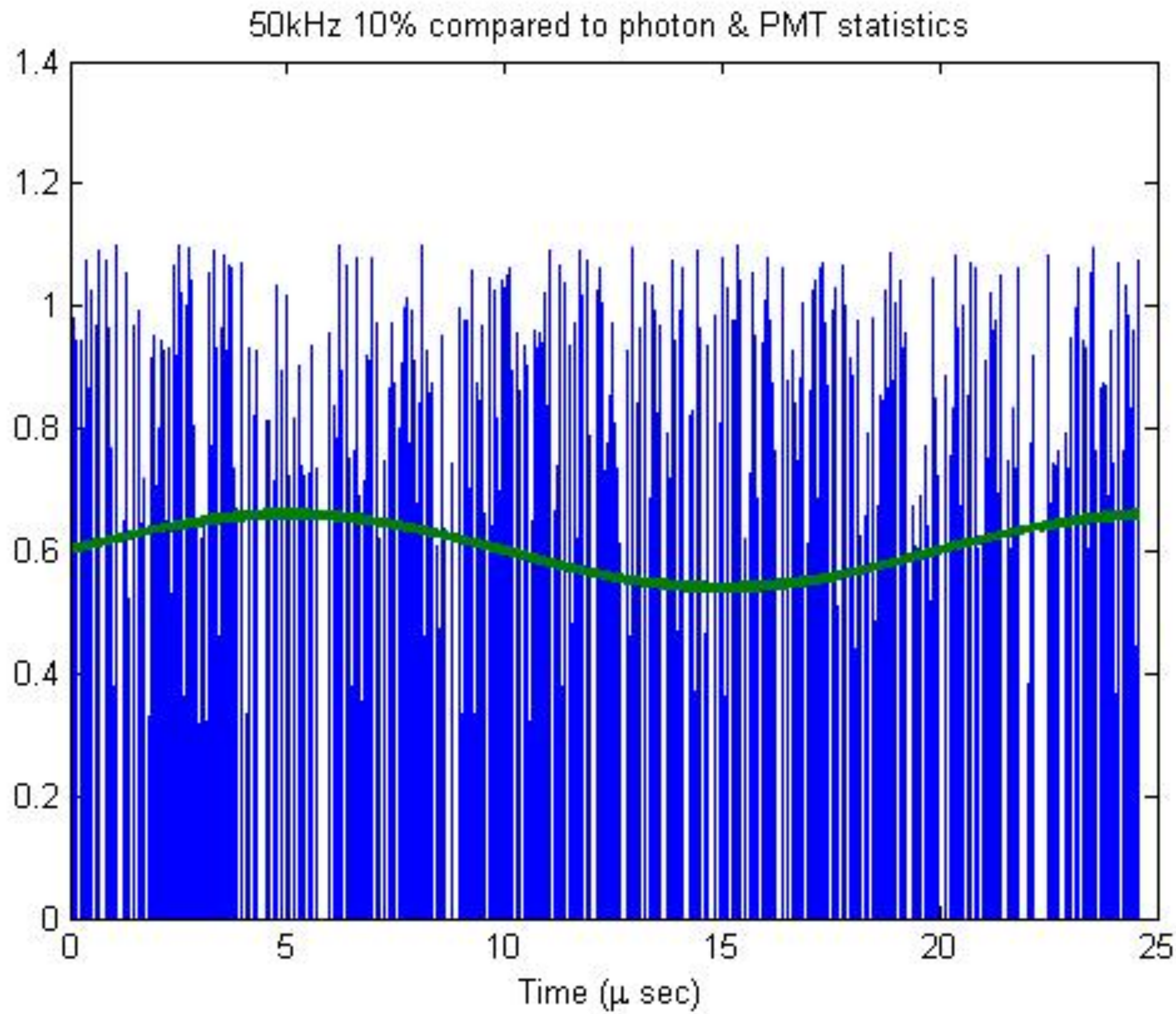


$4p\,^2F_{9/2}$
(2)
LASER
611.492 nm
fluorescence
460.957 nm
(1)
$3d\,^2G_{9/2}$
metastable
(3)
$3s\,^2D_{5/2}$

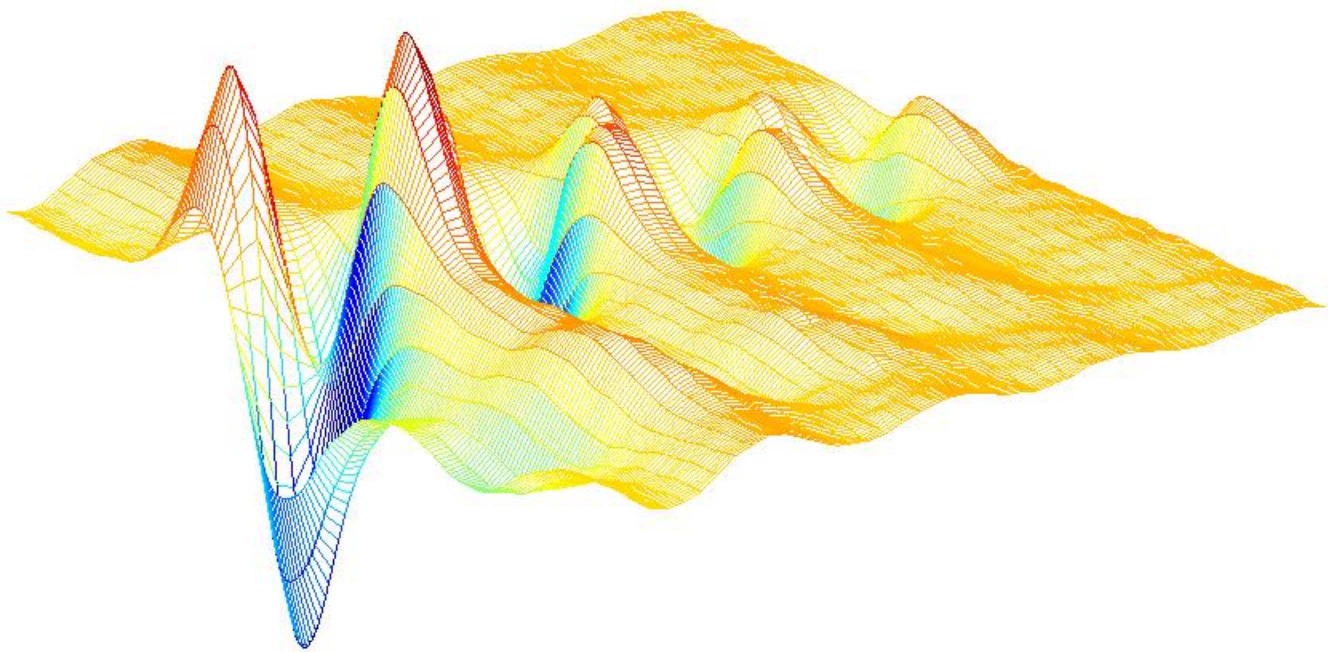

Photon Counting
Laser 1
PMT 1
White Noise
RF
Source
Dichroic
Mirror
Cylindrical
Mesh Grid
PMT 2
Laser 2
Photon Counting



Diode laser at 668 nm
Dye Laser at 611nm
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
$f_0(v)$
-8
-6
-4
-2
0
2
4
6
8
Ion Velocity (cm/s)
x 10^5



50kHz 10% compared to photon & PMT statistics
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
5
10
15
20
25
Time (μ sec)



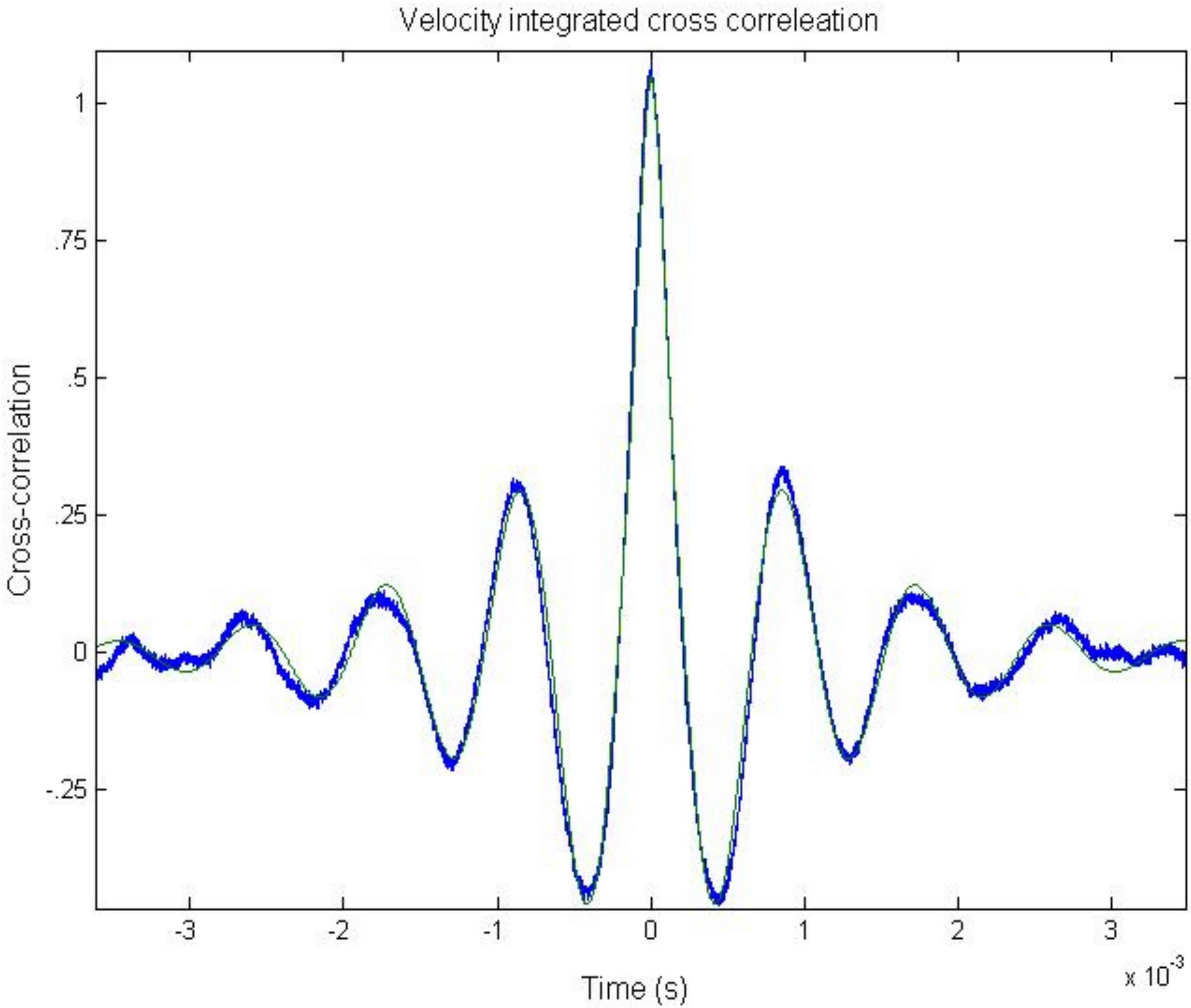
$$C = < \boldsymbol{g}(x, v, t)\boldsymbol{g}(x', v', t-\tau) >_t$$

Consider x=x'

$$C(v, v', \tau) = C(v', v, -\tau)$$

$$C(v, v', \omega) = C(v', v, \omega)^*$$

$$g \stackrel{\text{def}}{=} \sqrt{\frac{-mv}{\partial f_0 / \partial v}} f(x, v, t)$$

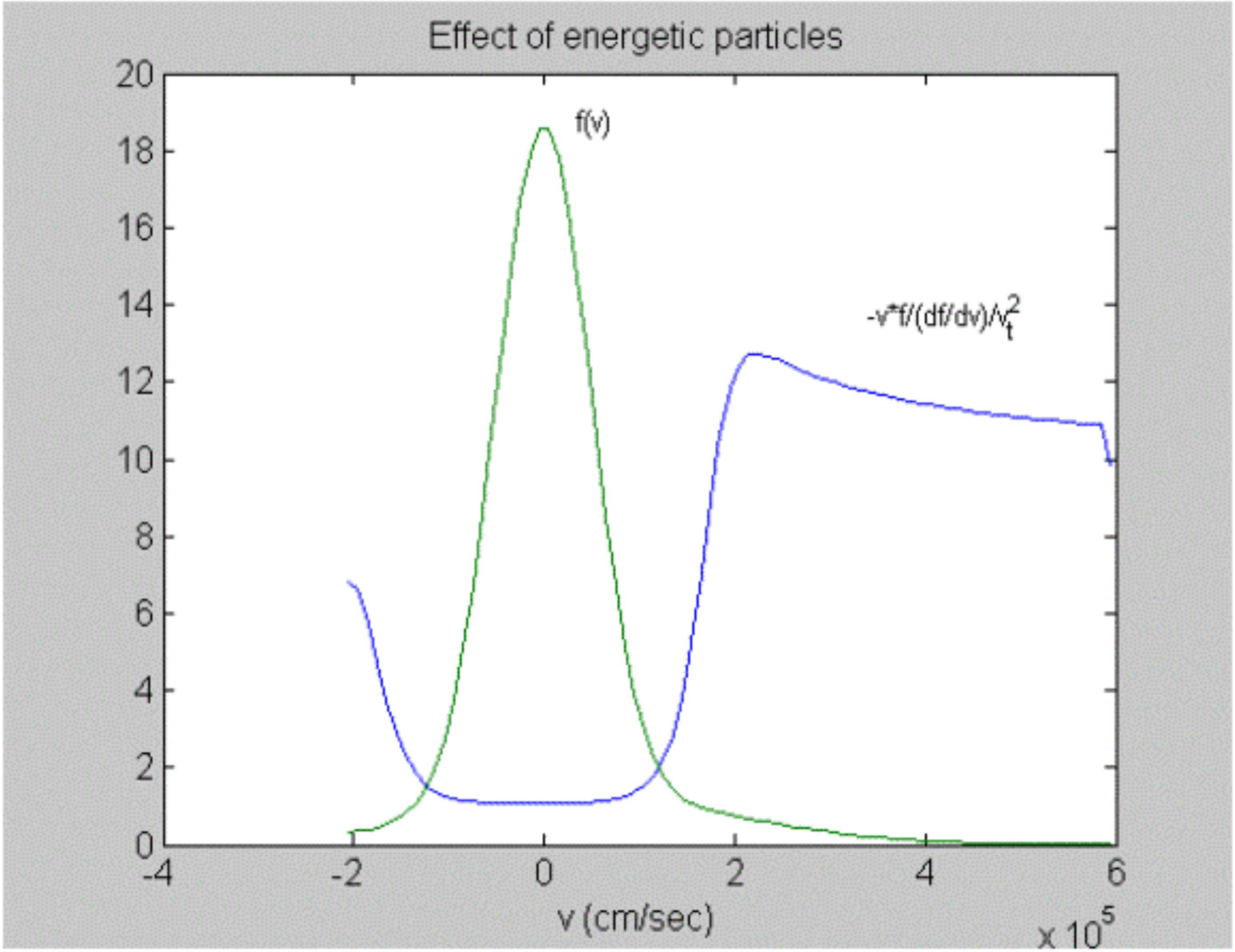


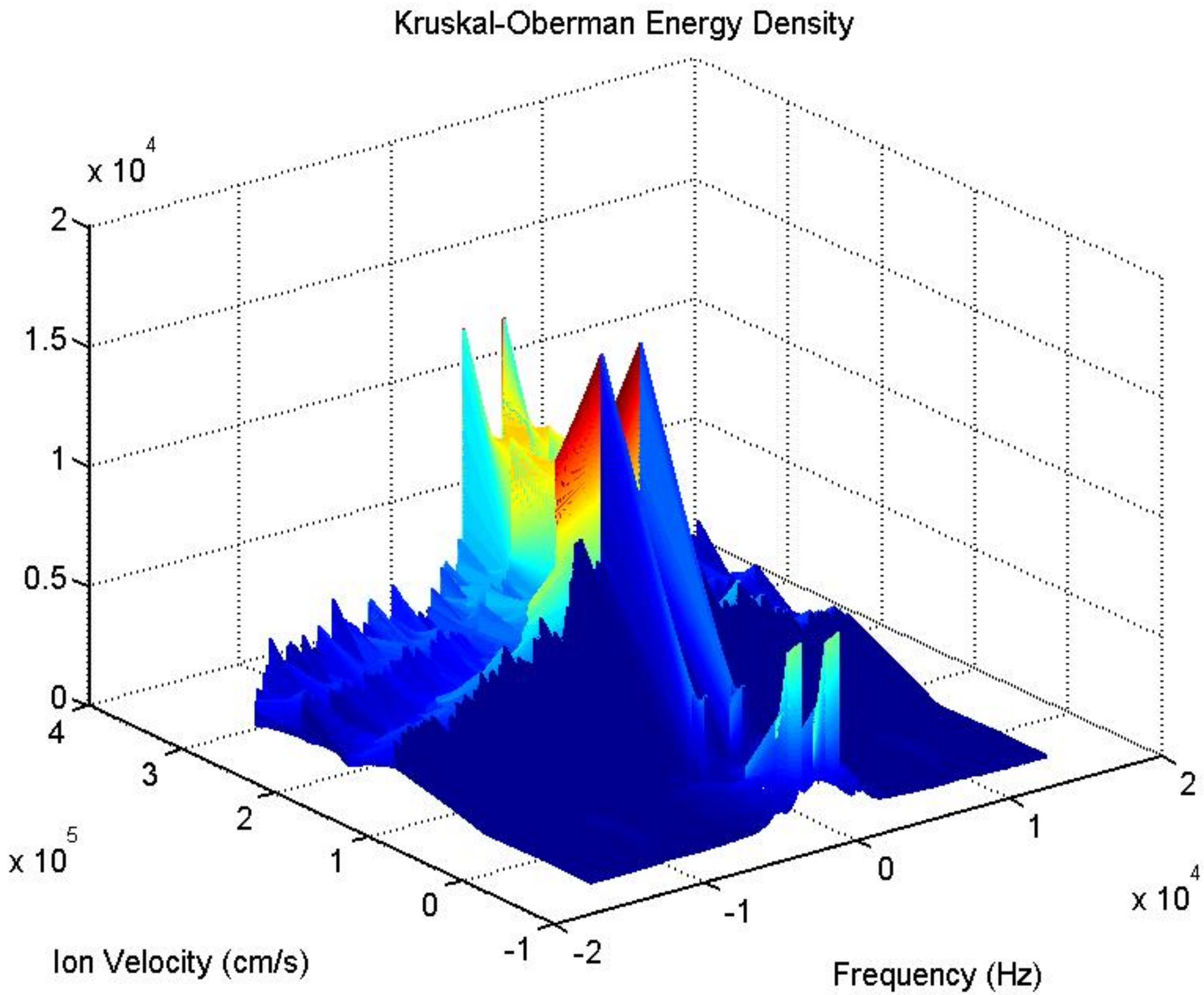
Velocity integrated cross correleation
Cross-correlation
1
.75
.5
.25
0
-.25
-3
-2
-1
0
1
2
3
x 10^-3
Time (s)

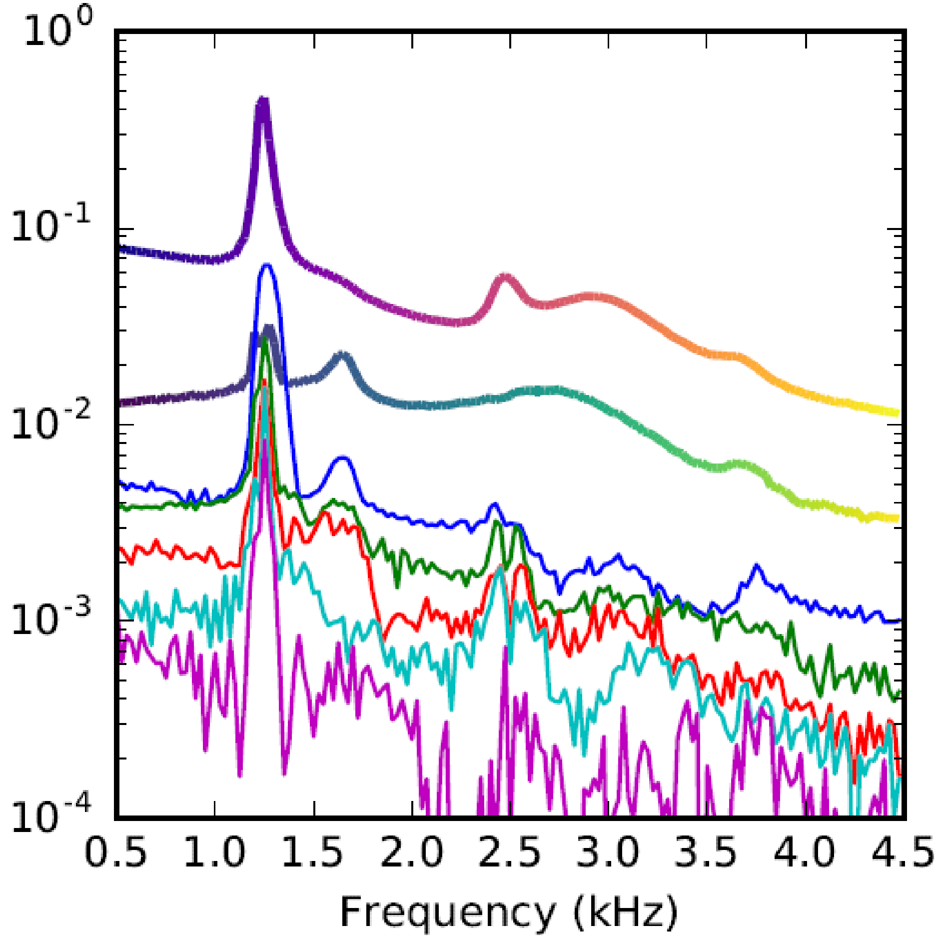
Electrostatic wave energy density

$$W = \tfrac{1}{4}\left[\frac{E^2}{4\pi} + \kappa T_e n_0 \left(\frac{n_1}{n_0}\right)^2 + \int \frac{mv}{\left(-\frac{\partial f_0}{\partial v}\right)} |f_1|^2 \, dv\right]$$

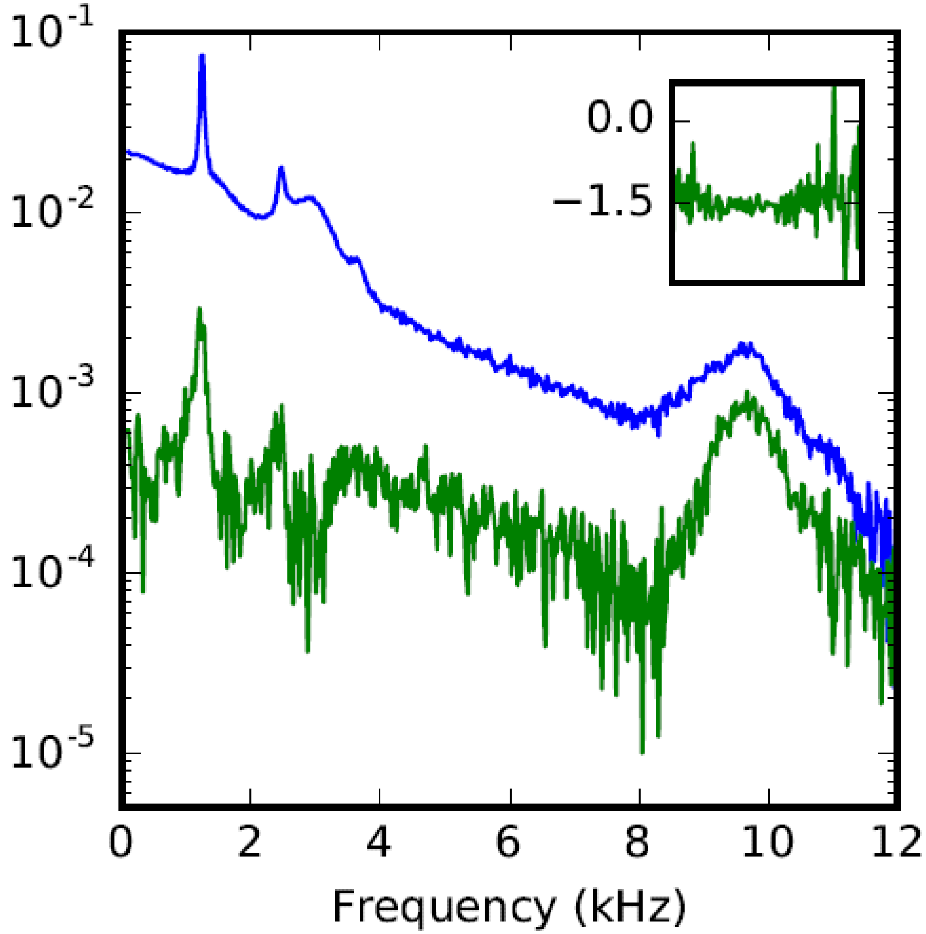
- Electric field (small due to quasi-neutrality).
- Electron compression
- Ion motion


Effect of energetic particles
f(v)
-v*f/(df/dv)/v_t^2
v (cm/sec)
x 10^5
20
18
16
14
12
10
8
6
4
2
0
-4
-2
0
2
4
6

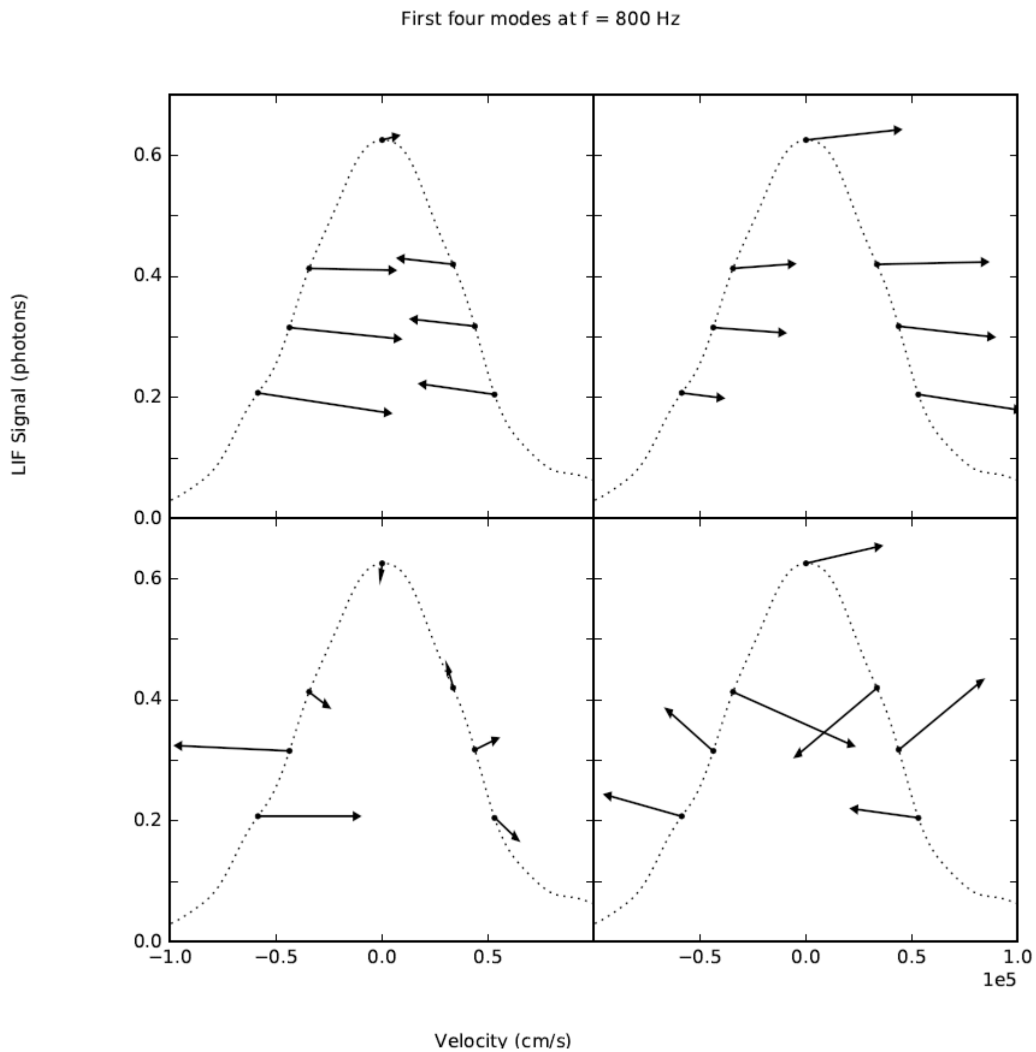

Kruskal-Oberman Energy Density
x 10^4
2
1.5
1
0.5
0
4
3
2
1
0
-1
x 10^5
Ion Velocity (cm/s)
-2
-1
0
1
2
x 10^4
Frequency (Hz)

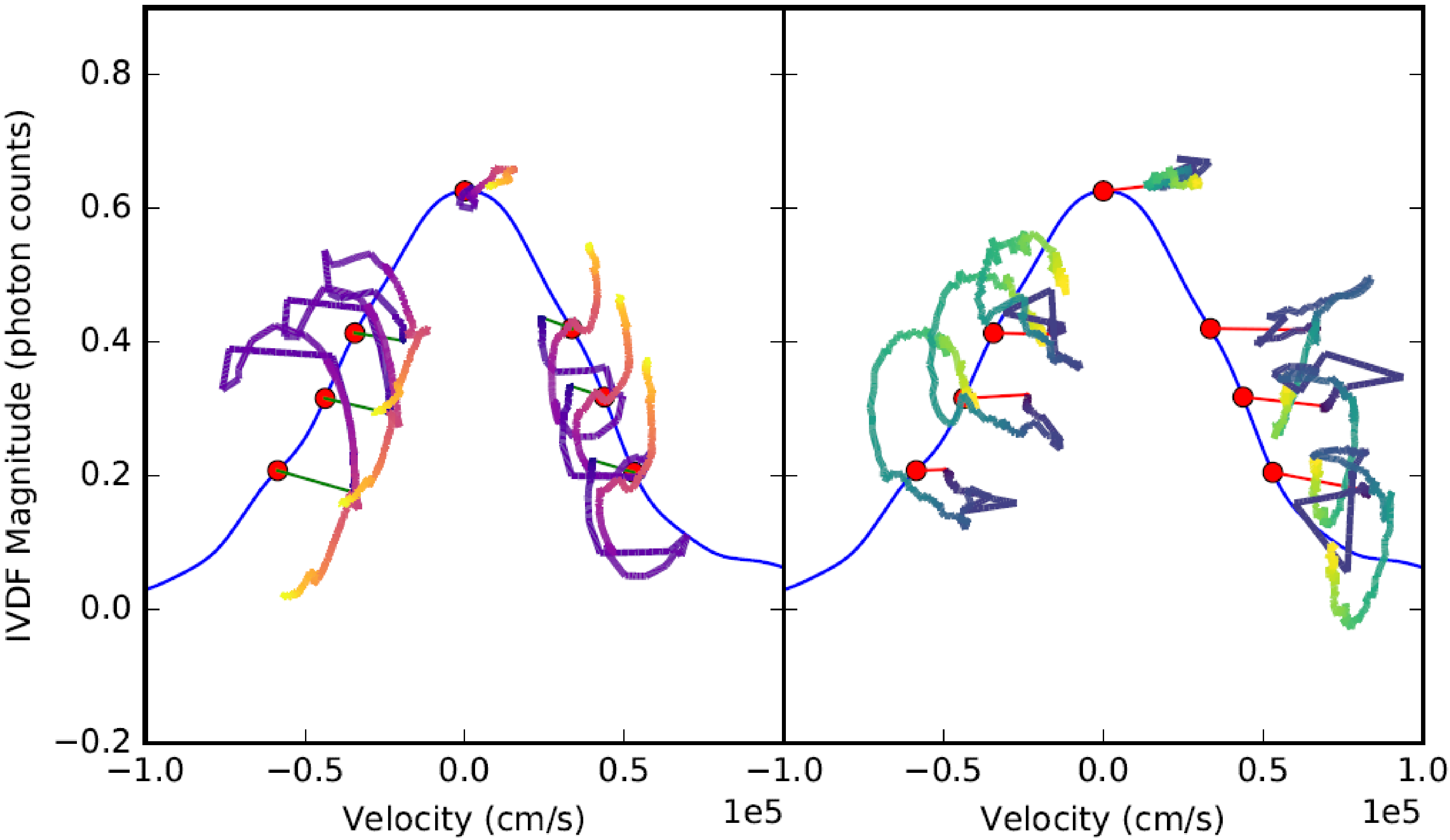


10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5
Frequency (kHz)



10^-1
10^-2
10^-3
10^-4
10^-5
0.0
−1.5
0
2
4
6
8
10
12
Frequency (kHz)

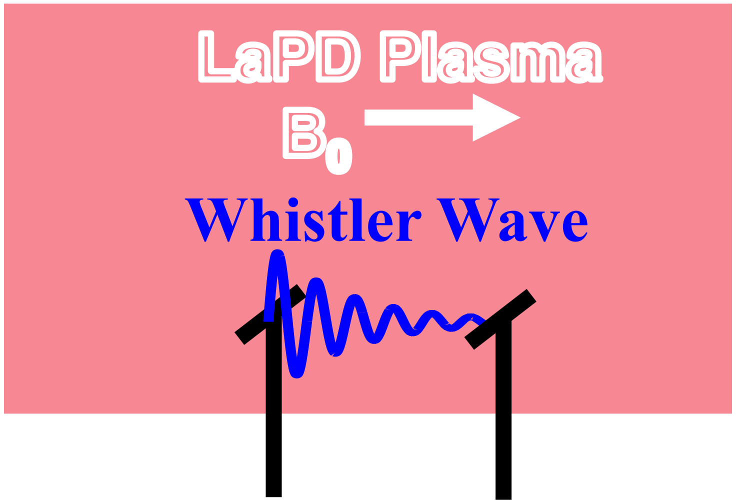

First four modes at f = 800 Hz
LIF Signal (photons)
0.0
0.2
0.4
0.6
−1.0
−0.5
0.0
0.5
1.0
1e5
Velocity (cm/s)

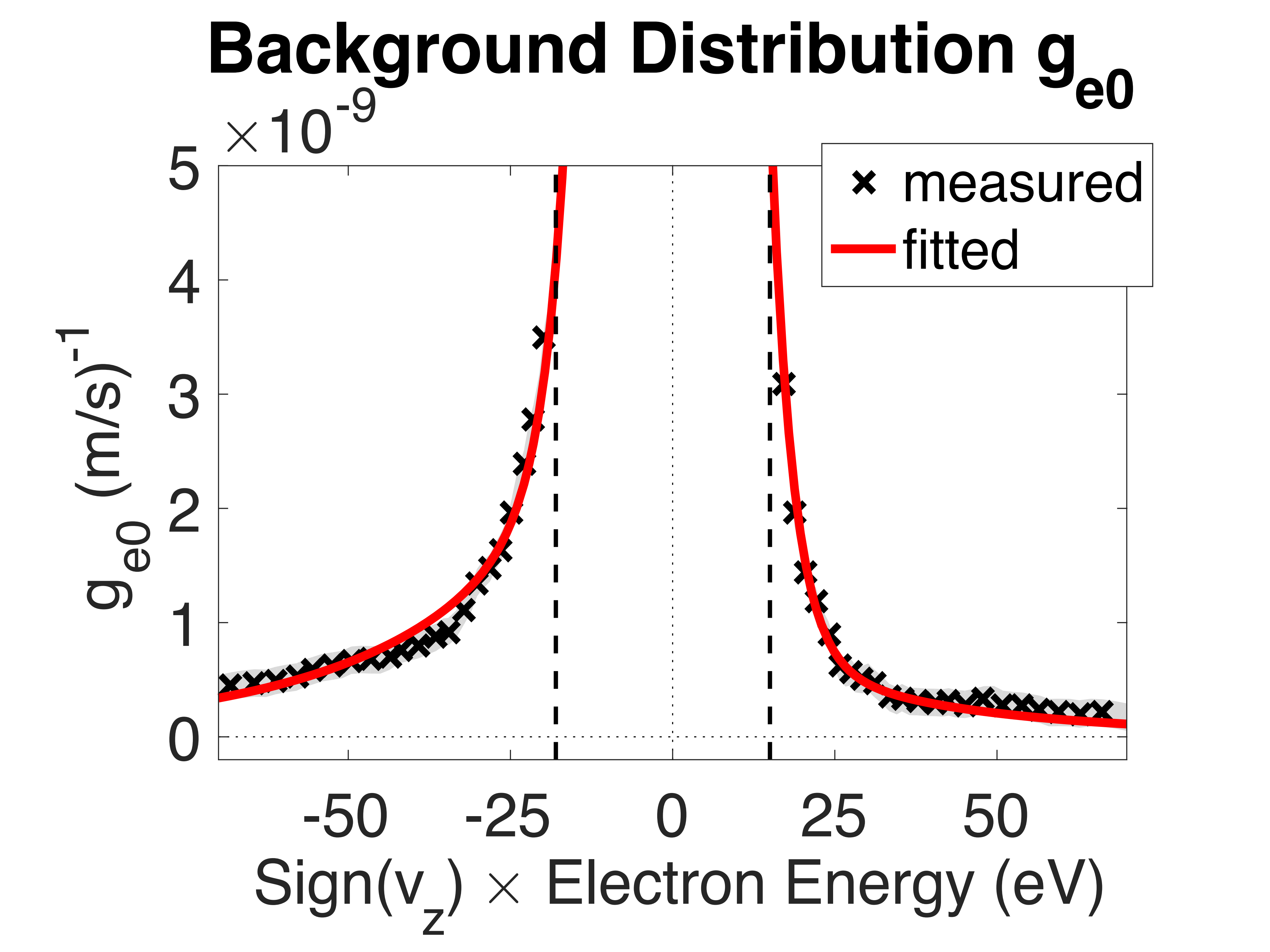


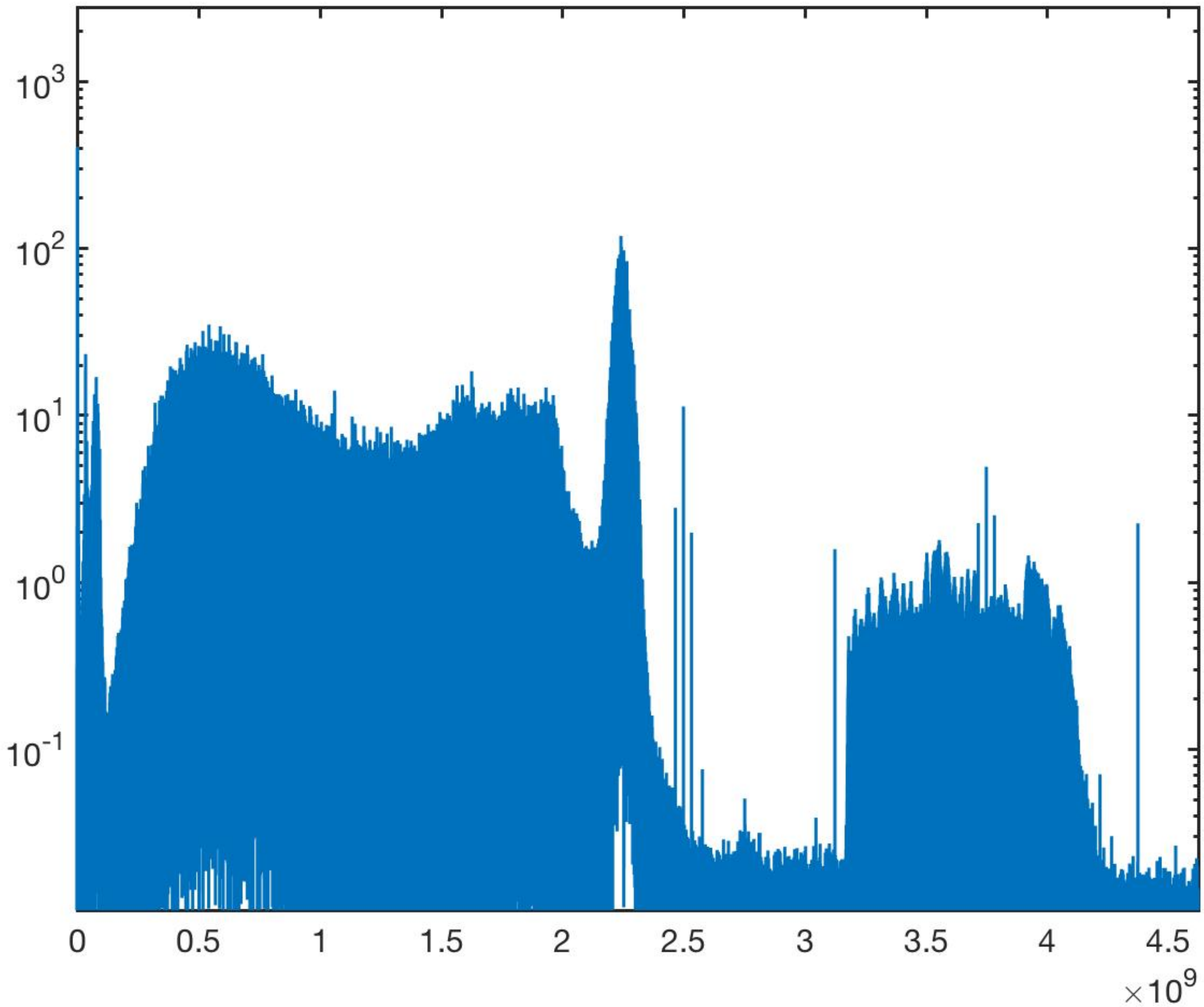
IVDF Magnitude (photon counts)
0.8
0.6
0.4
0.2
0.0
−0.2
−1.0
−0.5
0.0
0.5
1.0
Velocity (cm/s)
1e5
Velocity (cm/s)
1e5

The whistler-mode wave absorption diagnostic can capture suprathermal f(v) for electrons.

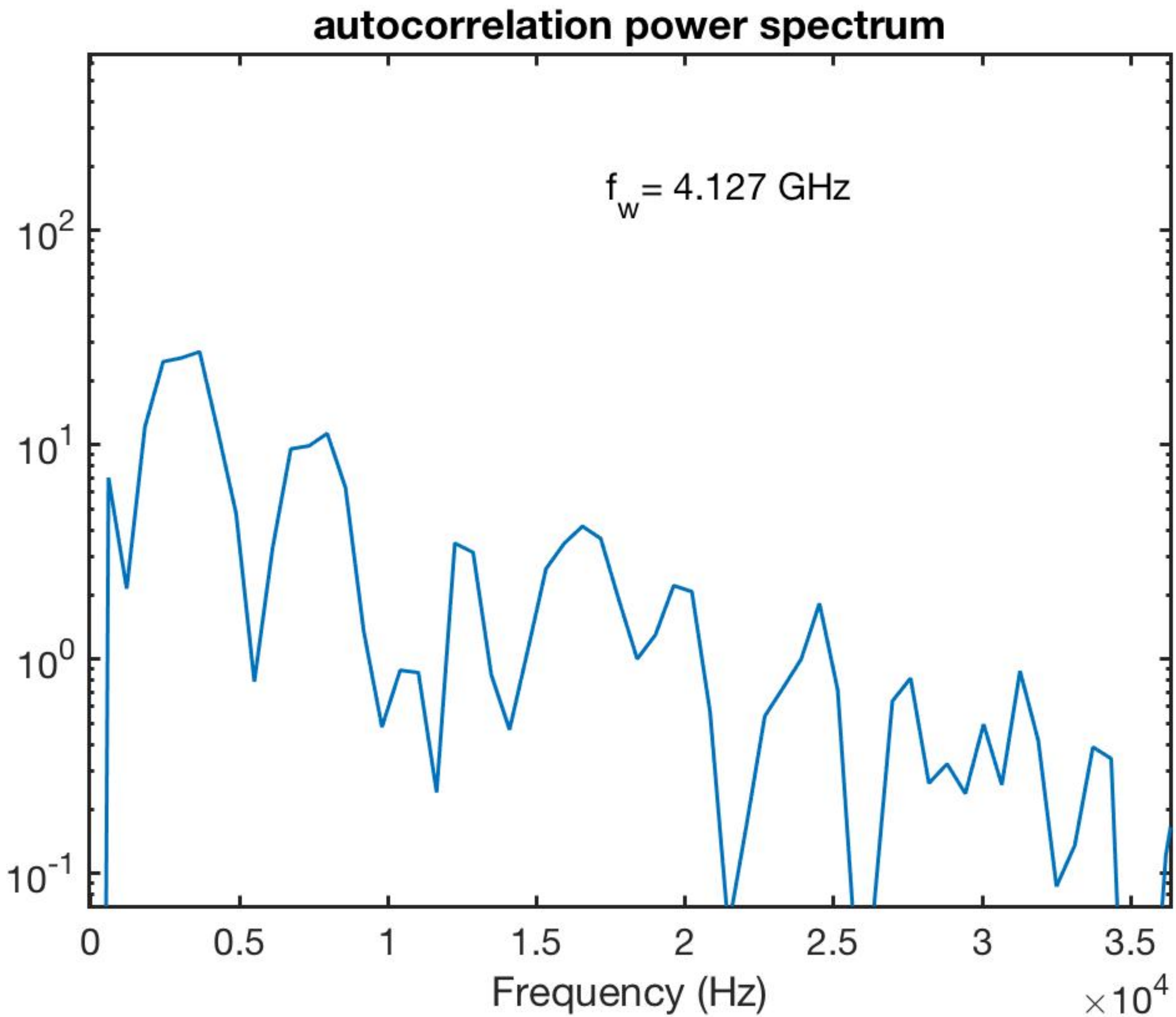
- Damping is measured between two 1” dipole antennas separated by ~30 cm.




Background Distribution g_{e0}
$\times 10^{-9}$
5
4
3
2
1
0
g_{e0} (m/s)$^{-1}$
measured
fitted
-50
-25
0
25
50
Sign(v_z) × Electron Energy (eV)



10^3
10^2
10^1
10^0
10^-1
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
×10^9



autocorrelation power spectrum
f_w= 4.127 GHz
10^2
10^1
10^0
10^-1
0
0.5
1
1.5
2
2.5
3
3.5
Frequency (Hz)
×10^4

Conclusions

- Kinetic degrees of freedom are generally active in weakly collisional plasma.
- The energetics of non-maxwellian plasmas is very sensitive.
- This is an area where the laboratory is catching up to what can be done in space.