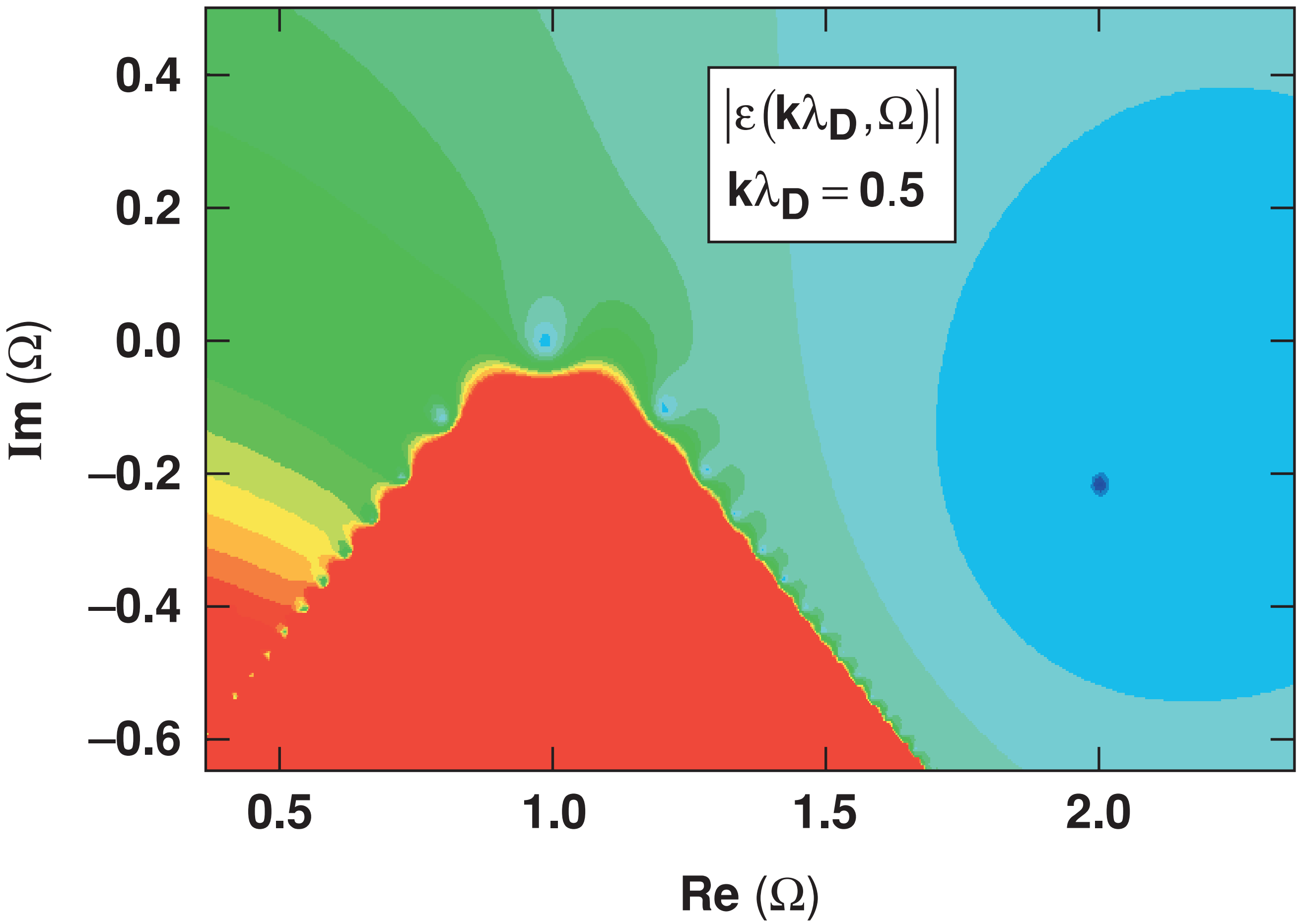
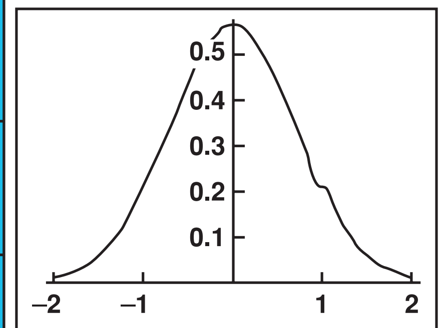
On the Role of Electron-Acoustic Waves in Two-Plasmon Decay





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Summary

A model based on electron-acoustic waves can account for otherwise enigmatic features of both TPD and SRS

- Why does the level of TPD activity depend on overlapped rather than single-beam intensities?
- Why does TPD respect the “Landau limit” on plasmon wave vector, while SRS does not?
- These observations imply the existence of plasma modes not described by the Bohm-Gross or Maxwellian Landau dispersion relations; electron-acoustic waves provide this “missing link.”

Outline

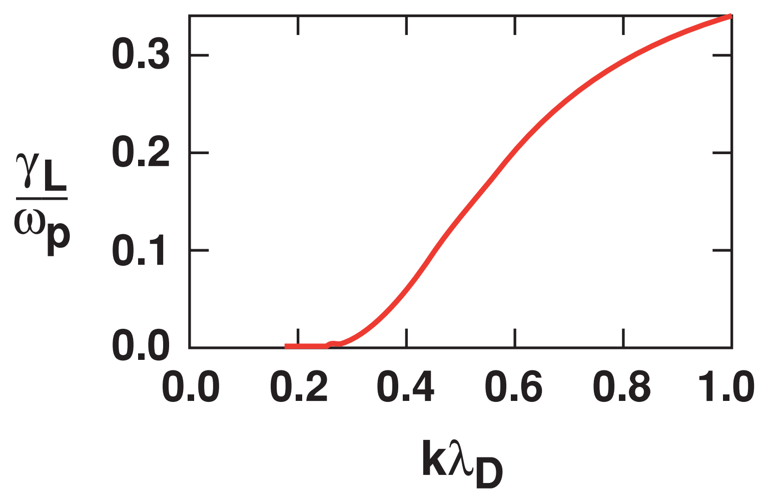
- The dependence of TPD on overlapped beam intensity implies the existence of new plasma modes
- How these modes (“almost” electron-acoustic modes) are produced
- Comparison with the SRS case
- Summary and conclusions

Landau damping limits the range of plasmon wave vectors participating in TPD

- The TPD growth rate is small at moderate intensities:

$$\frac{\gamma_0}{\omega_p} \cong \frac{\upsilon_0}{2c} \cong 1.5 \times 10^{-3}\, I_{14}^{1/2}$$

- Landau damping must be negligible to allow significant TPD growth:



Assuming negligible damping the TPD threshold is determined by the inhomogeneity

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- The inhomogeneity threshold is $\left(\frac{\upsilon_0}{\upsilon_T}\right)^2 > \frac{12}{k_0 L}$ or $6.7 \times 10^{-3} I_{14} L_\mu > T_{keV}$.

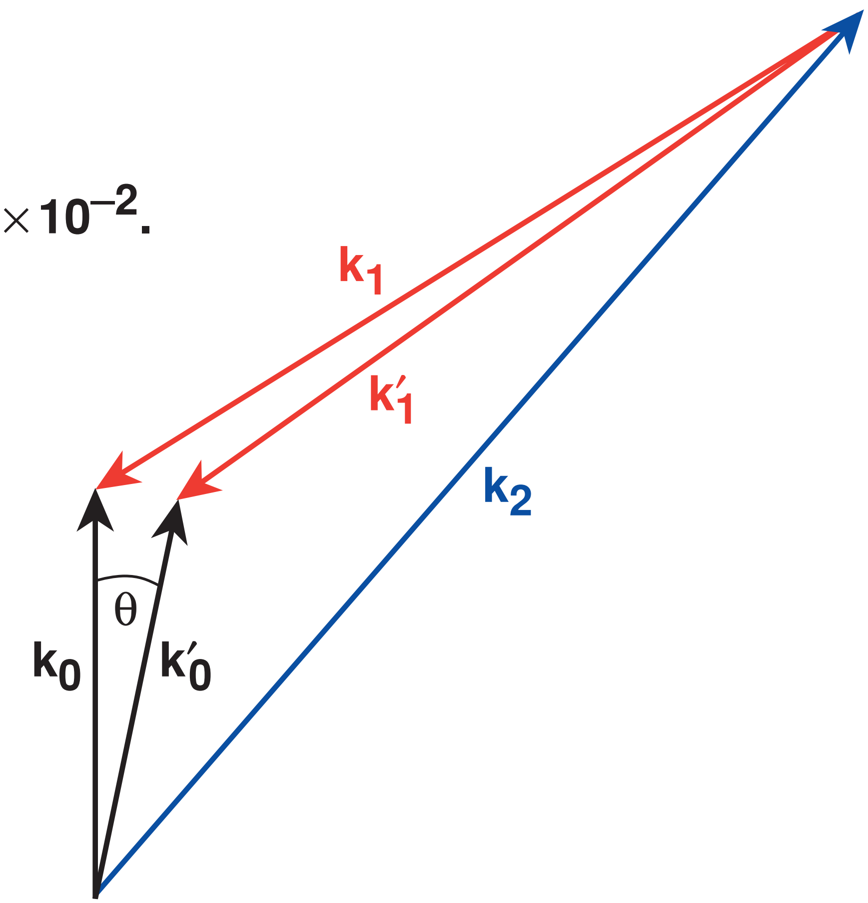
- For the low-intensity OMEGA experiments $L \cong 350\ \mu$ and $T_e \cong 2.5$ keV, so the threshold is $I_{14} \gtrsim 1.1$.

- The interaction length $\sqrt{2\pi/\kappa'} \cong 9\,\mu$ for $k\lambda_D \sim 0.3$ and $L_n \cong 350\,\mu$, while the interference structure between adjacent beams ~ 1.1 μ. So interbeam interference hot spots are unlikely to contribute to TPD, while intrabeam hot spots in overlapping beams do not in general overlap.

Two pump beams propagating at different angles will not in general drive the same plasmon in TPD

$$\frac{\Delta\omega}{\omega_p} \cong 3\left(k_0\lambda_D\right)^2 \left\{\frac{k_{2\parallel}}{k_0}\right\} \sin\theta.$$

For $\theta = 10°$, this gives $\frac{\Delta\omega}{\omega_p} \cong 1.2 \times 10^{-2}$.



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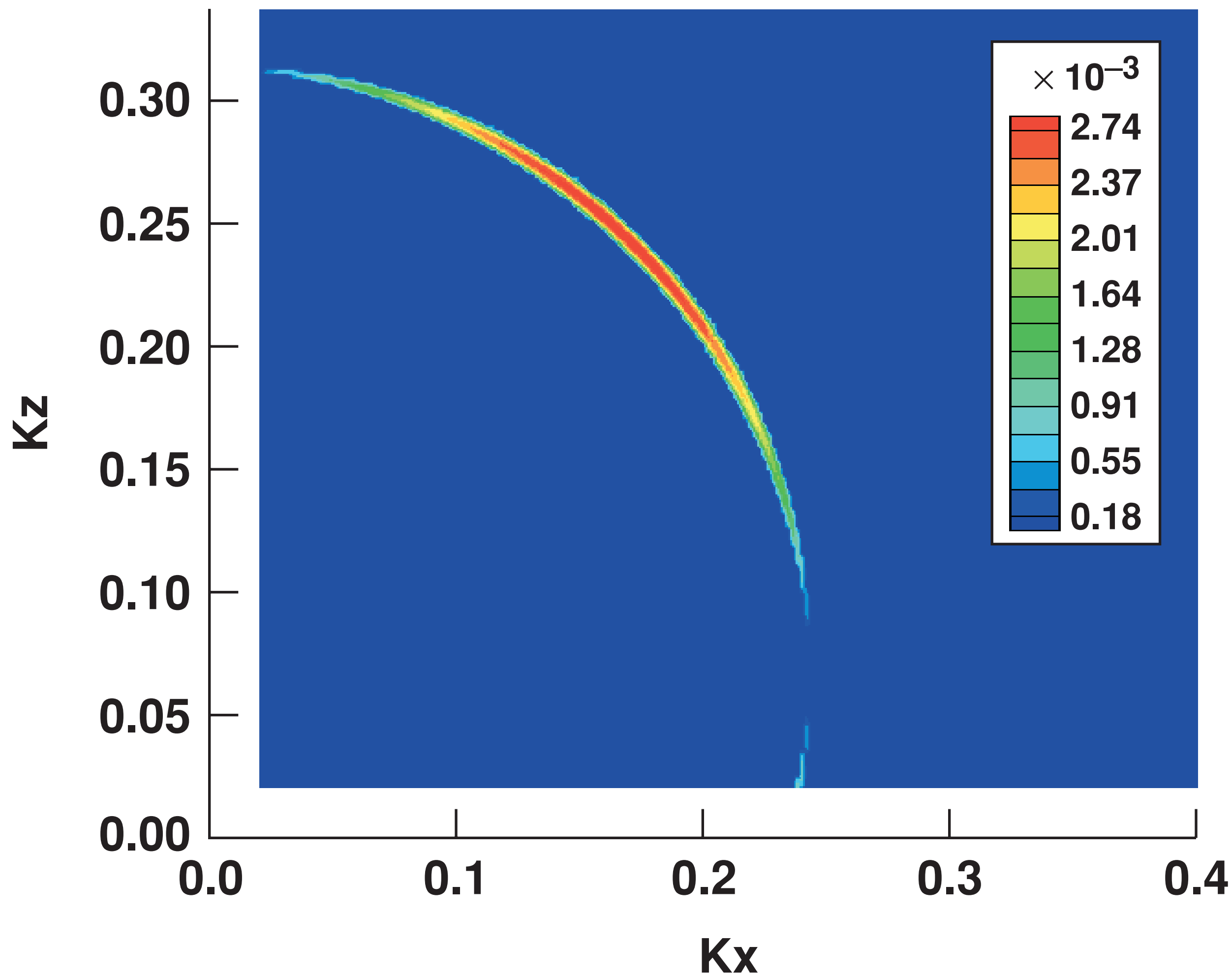
At moderate intensities the range of plasmon wave vectors driven by TPD is narrow

Growth rate γ/ω_p for single pump at 5×10^{14} W/cm^2

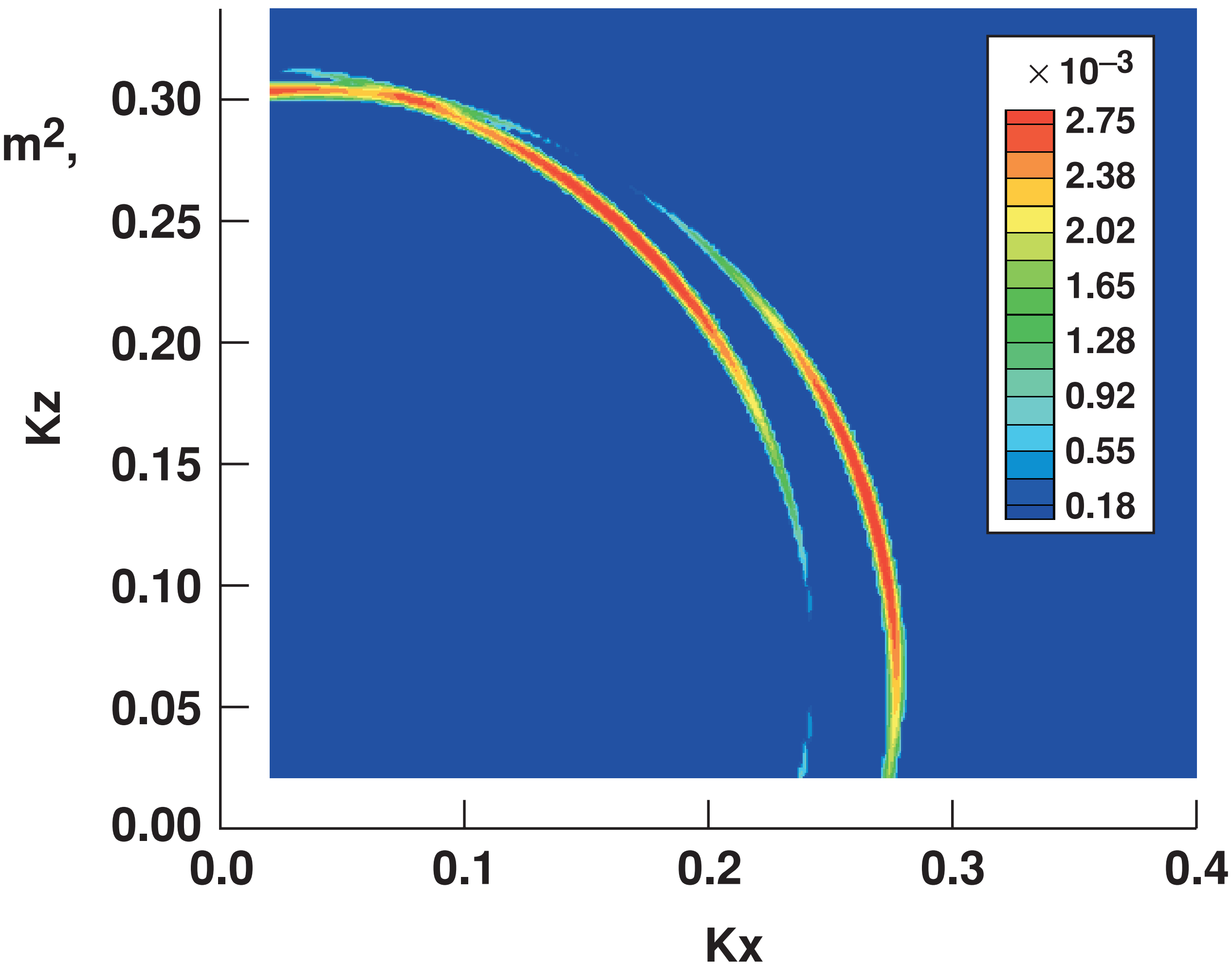
$n/n_c = 0.21$
$T_e = 2.5$ keV
$k_0\lambda_D \cong 0.12$



For two pumps differing by 30° the instability regions are well separated

Growth rate γ/ω_p for two pumps, each 5×10^{14} W/cm^2, separated by 30°

$n/n_c = 0.21$
$T_e = 2.5$ keV
$k_0\lambda_D \cong 0.12$



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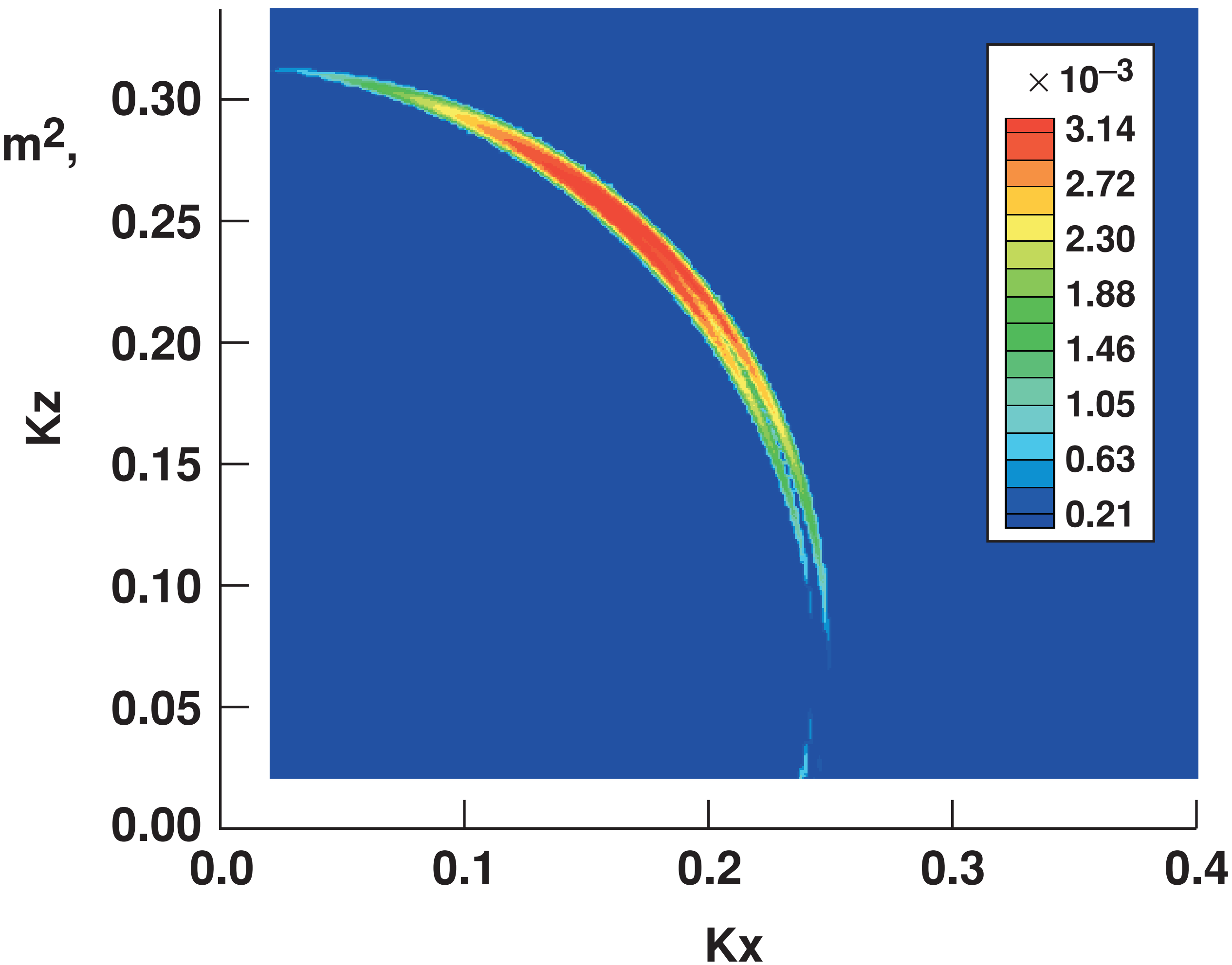
Even at only 5° separation there is little enhancement of the single-beam growth rate

Growth rate γ/ω_p for two pumps, each 5×10^{14} W/cm^2, separated by 5°



$n/n_c = 0.21$
$T_e = 2.5$ keV
$k_0\lambda_D \cong 0.12$

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Exceptional decay geometries with special symmetry seem inadequate to account for the observations

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- For special decay geometries, more than one pump (up to six on OMEGA) can couple resonantly to the same plasmon.
- However, this applies only in limited regions of the plasma and for a small range of decay wave vector space.
- Observed dependence on total intensity in spherical OMEGA experiments indicates more than a single hex involved.
- Thomson scattering experiments probe a single plasmon, which is observed to be driven by unsymetrically arranged pump beams.

In general, coupling multiple laser pumps to a plasmon through TPD requires new plasma modes

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- The problem: if a pump (k_0, ω_0) is resonantly coupled to "signal" wave (k_1, ω_1) by "idler" wave ($k_0 - k_1$, $\omega_0 - \omega_1$), then the idler wave ($k'_0 - k_1$, $\omega_0 - \omega_1$) required to link a second pump (k'_0, ω_0) to the signal (k_1, ω_1) is not in general a normal mode of the plasma.

- But it can become one: the driven (ponderomotive) response at ($k'_0 - k_1$, $\omega_0 - \omega_1$) is subject to Landau damping, and hence, locally flattens the distribution function at the phase velocity $\frac{(\omega_0 - \omega_1)}{(k'_0 - k_1)}$.

- Local flattening introduces new, lightly damped modes; these are (almost) electron-acoustic modes. They provide the missing link.

Local flattening of the distribution function introduces a family of new modes

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- **Electron-acoustic waves (Stix, 1962) are linear modes with frequencies and wave vectors satisfying $\mathrm{Re}\left[\varepsilon(\omega,\mathbf{k})\right]=0$ for real ω and *k*. When the distribution function is modified so that $\mathrm{Im}\left[\varepsilon(\omega,\mathbf{k})\right]=0$ these become true modes. Simplest way of getting $\mathrm{Im}\left[\varepsilon(\omega,\mathbf{k})\right]=0$ is local flattening of the distribution function at the phase velocity $\omega/\mathbf{k}$.**

- ***Exact* electron-acoustic modes are not much help because we need a *family* of modes at each phase velocity $\dfrac{(\omega_0-\omega_1)}{(k'_0-k_1)}$.**

- **Local flattening at velocity u_0 introduces such a one-parameter family (ω, k) with $\omega/k = u_0$; only the electron-acoustic mode is *completely* undamped, but the others are lightly damped.**

A model LFDF is analytic and can be arbitrarily close to a Maxwellian

- Small-amplitude electrostatic perturbations in a collisionless plasma are studied using the linearized Vlasov-Poisson equations.

- An analytic distribution function with zero slope at normalized velocity $u_0 = \upsilon_0 / \sqrt{2}\upsilon_T$ and second derivative $f''(u_0) = \beta$ is given by

$$f(u) = f_0(u) + f_1(u) + f_2(u),$$

$$\text{where } f_0(u) = \frac{1}{\sqrt{\pi}} e^{-u^2},$$

$$f_1(u) = -f_0'(u_0)(u - u_0) e^{-\frac{(u-u_0)^2}{(\Delta u)^2}}, \text{ and}$$

$$f_2(u) = \frac{1}{3}\left[\beta - f_0''(u_0)\right]\left[(u - u_0)^2 - \frac{1}{2}(\Delta u)^2\right] e^{-\frac{(u-u_0)^2}{(\Delta u)^2}}.$$

The resulting dielectric function is also analytic

- $\varepsilon(\mathbf{k},\omega) = 1 - \dfrac{1}{2(k\lambda_D)^2} \displaystyle\int_{-\infty}^{\infty} \dfrac{f'(u)}{u - \dfrac{\omega}{\sqrt{2}k\nu_T}}\, du$

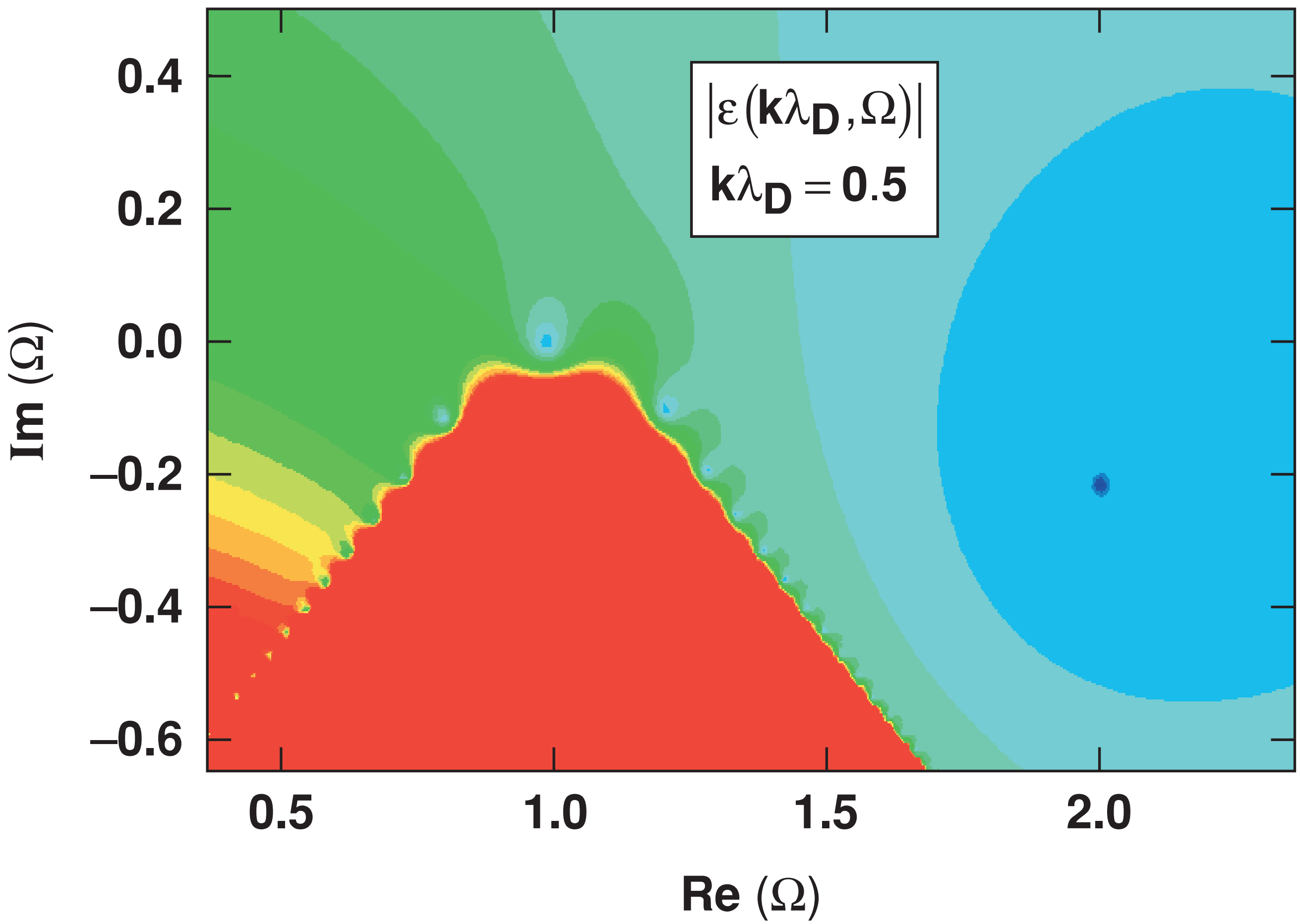
- As in the Maxwellian case, the dielectric function can be expressed in terms of the plasma dispersion function Z:

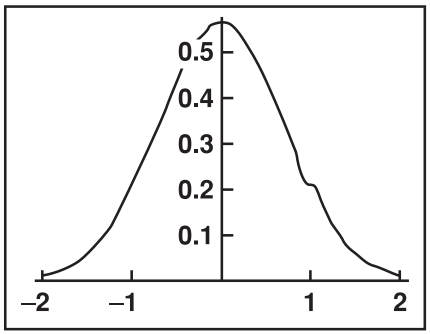
$$\varepsilon(\mathbf{k},\omega) = 1 + \frac{1}{(k\lambda_D)^2}\left[1 + \Omega Z(\Omega)\right] + \frac{u_0 e^{-u_0^2}}{(k\lambda_D)^2}\left[2y + \left(2y^2 - 1\right)Z(y)\right]$$

$$+ \frac{\Delta u}{(k\lambda_D)^2}\left[\frac{\sqrt{\pi}}{2}\beta + \left(1 - 2u_0^2\right)e^{-u_0^2}\right]\left[\frac{2}{3}\left(y^2 - 1\right) + \left(\frac{2}{3}y^3 - y\right)Z(y)\right],$$

where $\Omega \equiv \dfrac{\omega}{\sqrt{2}k\upsilon_T}$ and $y \equiv \dfrac{\Omega - u_0}{\Delta u}$.

Local flattening of the distribution function at u_0 introduces a family of modes at that phase velocity





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Multiple-pump modes in LDF's can be studied by solving the kinetic dispersion relation

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- **The kinetic dispersion relation for two-pump TPD is**

$$\frac{\varepsilon(\mathbf{k},\omega)}{1-\varepsilon(\mathbf{k},\omega)} = \frac{1-\varepsilon(\mathbf{k_0}-\mathbf{k},\omega_0-\omega)}{\varepsilon(\mathbf{k_0}-\mathbf{k},\omega_0-\omega)}\left\{\frac{(\mathbf{k}\bullet\mathbf{v_0})^2\left[(\mathbf{k_0}-\mathbf{k})^2-\mathbf{k}^2\right]^2}{4\omega_p^2\mathbf{k}^2(\mathbf{k_0}-\mathbf{k})^2}\right\}$$

$$+\frac{1-\varepsilon(\mathbf{k_0'}-\mathbf{k},\omega_0-\omega)}{\varepsilon(\mathbf{k_0'}-\mathbf{k},\omega_0-\omega)}\left\{\frac{(\mathbf{k}\bullet\mathbf{v_0'})^2\left[(\mathbf{k_0'}-\mathbf{k})^2-\mathbf{k}^2\right]^2}{4\omega_p^2\mathbf{k}^2(\mathbf{k_0'}-\mathbf{k})^2}\right\}$$

- **The local flattening makes $\varepsilon(\mathbf{k_0'}-\mathbf{k},\omega_0-\omega)$ resonant, so the second term contributes as much as the first.**

How does TPD differ from anomalous (large $k\lambda_D$) SRS?

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- In both cases the Landau damping of the beat of two lightly damped modes (pump and signal) generates local flattening and a new, lightly damped mode (idler) that did not exist in the original Maxwellian.
- In the SRS case both pump and signal are EM waves, essentially undamped for all *k*, so the idler can have large $k\lambda_D$.
- In the TPD case the signal is a plasma wave and must have $k_1\lambda_D < 0.25$ to be lightly damped. Since $k_0\lambda_D << k_1\lambda_D$ at the Landau cutoff, we must also have $k_2\lambda_D \lesssim 0.25$.
- So TPD is limited by the Landau cutoff, while SRS is not.

Summary/Conclusions

A model based on electron-acoustic waves can account for otherwise enigmatic features of both TPD and SRS

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- Why does the level of TPD activity depend on overlapped rather than single-beam intensities?
- Why does TPD respect the "Landau limit" on plasmon wave vector, while SRS does not?
- These observations imply the existence of plasma modes not described by the Bohm-Gross or Maxwellian Landau dispersion relations; electron-acoustic waves provide this "missing link."
- Future work will elucidate the limits of this process and suggest feasible experimental tests.