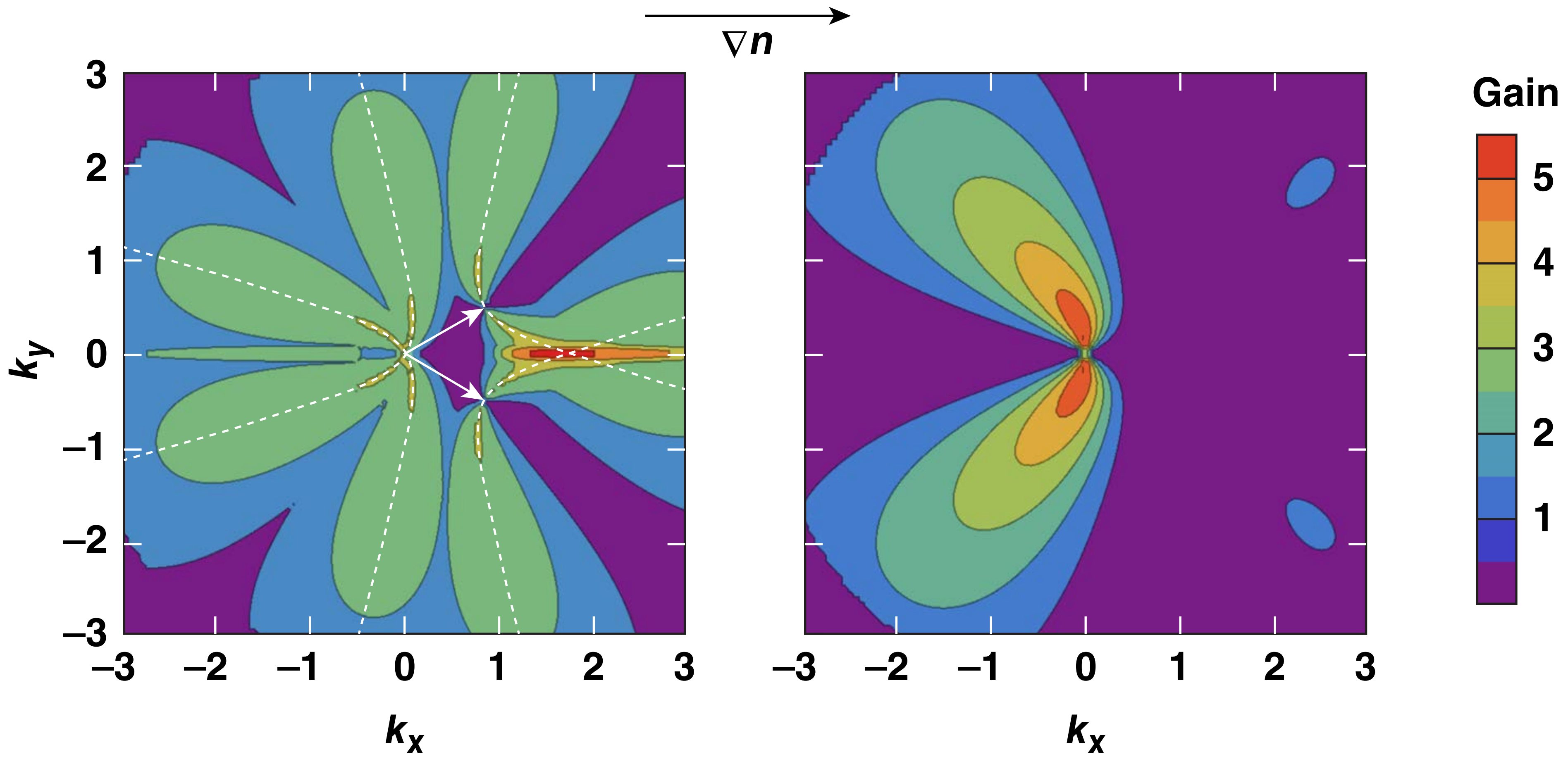
Absolute Two-Plasmon Decay and Stimulated Raman Scattering in Direct-Drive Irradiation Geometries



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Summary

In general, both stimulated Raman scattering (SRS) and two-plasmon decay (TPD) will play a role in direct-drive laser–plasma interactions

- Absolute TPD and SRS thresholds have different dependencies on laser and plasma parameters, but are comparable
- The modes with lowest thresholds tend to be either SRS or TPD; mixed polarization modes seem unimportant
- Larger scale lengths and temperatures favor SRS; larger incidence angles favor TPD
- The analysis presented here is linear; however there is evidence that the absolute SRS/TPD it describes persists well into the nonlinear regime

The origin in *k* space corresponds to the plasma-wave turning point, allowing SRS and TPD to be absolute there

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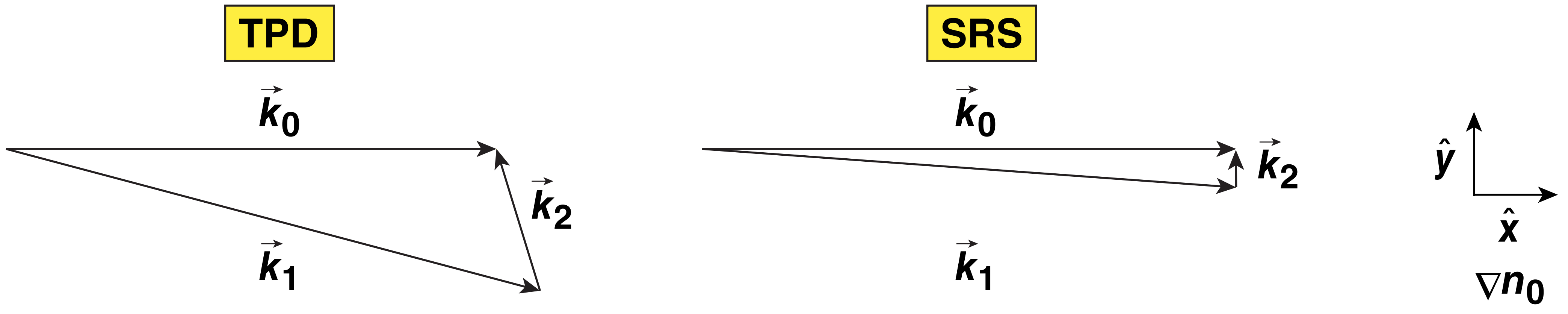
- In general, instabilities can only be convective in inhomogeneous plasmas*
- Near the turning point, however, there is a finite threshold for absolute instability**
- Enhanced multibeam convective gain near the origin in *k* space suggests the potential for absolute instability there
- Convective SRS occurs for $n/n_c \leq 1/4$; for absolute SRS, the electromagnetic (EM) decay wave must have $k \cong 0$ and originate at $n/n_c \cong 1/4$

*M. N. Rosenbluth, Phys. Rev. Lett. 29, 565 (1972).
**C. S. Liu, M. N. Rosenbluth, and R. B. White, Phys. Rev. Lett. 31, 697 (1973); A. Simon *et al*., Phys. Fluids 26, 3107 (1983).

TC11294a

Absolute SRS requires the component of *k* perpendicular to the density gradient to vanish



- The *y* components of the plasma-wave group velocity $v_g = 3v_T^2\, k / \omega$ are equal and opposite, so TPD is absolute in the *y* direction
- For SRS, $v_{g1y} = 3v_T^2\, k_{1y} / \omega$ and $v_{g2y} = c^2\, k_{2y} / \omega$, so SRS will be convective in *y* unless $k_{2y} \cong 0$

TC12199

For a single beam, the absolute TPD threshold* is lower than the Rosenbluth convective threshold

- The Simon threshold (adjusted for *s*-polarized oblique incidence) is $\eta \equiv \frac{I_{14} L_{\mu}}{233\, T_{\text{keV}} \cos\theta} > 1$

- The Rosenbluth convective gain is $G_{\text{R}} = \frac{2\pi\gamma_0^2}{\kappa' V_1 V_2} = \frac{I_{14} L_{\mu}}{53.6\, T_{\text{keV}} \cos\theta} \cong 4.35\,\eta$

- The nominal convective threshold is $G_{\text{R}} > 2\pi$ or $\eta > \frac{2\pi}{4.35} \cong 1.44$

- Therefore, the TPD absolute instability threshold lies below the convective instability threshold; this, in general, remains true for multiple beams

- The threshold for absolute SRS is comparable**

*A. Simon *et al.*, Phys. Fluids 26, 3107 (1983).
**C. S. Liu, M. N. Rosenbluth, and R. B. White, Phys. Fluids 17, 1211 (1974).

Fourier analysis of the time-independent TPD equations results in a set of first-order linear differential equations

- Absolute TPD and SRS occur near quarter-critical, so the local density profile may be approximated by a linear gradient
- Fourier transforming in space, the wave equations become first-order linear equations for the longitudinal and transverse components of the small-*k* decay wave
- The larger-*k* decay wave may be taken to be longitudinal
- For *N* beams there are therefore $3N + 1$ linear differential equations that are integrated from $k_x \rightarrow -\infty$ to $k_x \rightarrow +\infty$ to obtain the spatial gain
- Divergence of the gain indicates an onset of absolute instability; optimizing over ω gives the threshold and frequency

TC12200

Fourier analysis of the time-independent TPD equations results in a set of first-order linear differential equations

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- For a single beam, take the decay triangle in the x–y plane and normalize $\vec{k} \rightarrow c\vec{k}/\omega_0$, $\Delta \rightarrow \omega/\omega_0 - 1/2$, $L \rightarrow \omega_0 L/c$

$$\frac{\partial u_L}{\partial k_x} = iL\left(\frac{k_d}{k} - \frac{k}{k_d}\right)(k \cdot v_0)e^{-4iL\left\{2\Delta k_x - 3\frac{v_T^2}{c^2}\left(\frac{1}{3}k_x^3 + k_y^2 k_x\right) + 3\frac{v_T^2}{c^2}\left[\frac{1}{3}(k_x - k_{0x})^3 + (k_y - k_{0y})^2 k_x\right]\right\}} u_d$$

$$\frac{\partial u_T}{\partial k_x} = iL\frac{k_d}{k}\left[\left(k_x\hat{y} - k_y\hat{x}\right)\cdot v_0\right]e^{-4iL\left\{2\Delta k_x - \left[\frac{1}{3}k_x^3 + \left(\frac{ck_y}{\omega_0}\right)^2 k_y^2 k_x\right] + 3\frac{v_T^2}{c^2}\left[\frac{1}{3}(k_x - k_{0x})^3 + (k_y - k_{0y})^2 k_x\right]\right\}} u_d$$

$$\frac{\partial u_z}{\partial k_x} = iLk_d v_{0z} e^{-4iL\left\{2\Delta k_x - \left(\frac{1}{3}k_x^3 + k_y^2 k_x\right) + 3\frac{v_T^2}{c^2}\left[\frac{1}{3}(k_x - k_{0x})^3 + (k_y - k_{0y})^2 k_x\right]\right\}} u_d$$

$$\begin{aligned}\frac{\partial u_d}{\partial k_x} = {} & iL\left(\frac{k_d}{k} - \frac{k}{k_d}\right)\left(\frac{ck}{\omega_0}\cdot\frac{v_0}{c}\right)(k \cdot v_0)e^{4iL\left\{2\Delta k_x - 3\frac{v_T^2}{c^2}\left(\frac{1}{3}k_x^3 + k_y^2 k_x\right) + 3\frac{v_T^2}{c^2}\left[\frac{1}{3}(k_x - k_{0x})^3 + (k_y - k_{0y})^2 k_x\right]\right\}} u_L \\ & + iL\frac{k_d}{k}\left[\left(k_x\hat{y} - k_y\hat{x}\right)\cdot v_0\right]e^{4iL\left\{2\Delta k_x - \left[\frac{1}{3}k_x^3 + \left(\frac{cky}{\omega_0}\right)^2 k_y^2 k_x\right] + 3\frac{v_T^2}{c^2}\left[\frac{1}{3}(k_x - k_{0x})^3 + (k_y - k_{0y})^2 k_x\right]\right\}} u_T \\ & + iLk_d v_{0z} e^{4iL\left\{2\Delta k_x - \left(\frac{1}{3}k_x^3 + k_y^2 k_x\right) + 3\frac{v_T^2}{c^2}\left[\frac{1}{3}(k_x - k_{0x})^3 + (k_y - k_{0y})^2 k_x\right]\right\}} u_z\end{aligned}$$

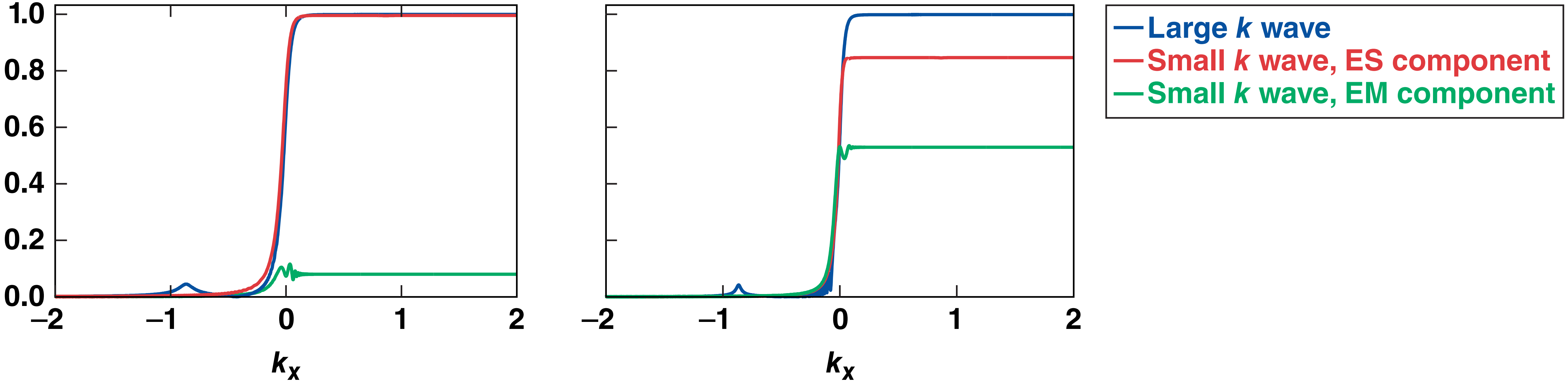
For smaller $k_\perp$, TPD decay waves become more transverse

- The optimal SRS mode has $k \cong 0$ and is almost entirely electromagnetic
- The optimal TPD mode is almost entirely electrostatic (ES); for smaller $k_\perp$, the EM component and the threshold increase

$k_\perp = 0.06$
Threshold $I_{14} = 1.54$

$k_\perp = 0.02$
Threshold $I_{14} = 1.85$

$L(\mu) = 300$
$T_{\mathrm{keV}} = 2.0$



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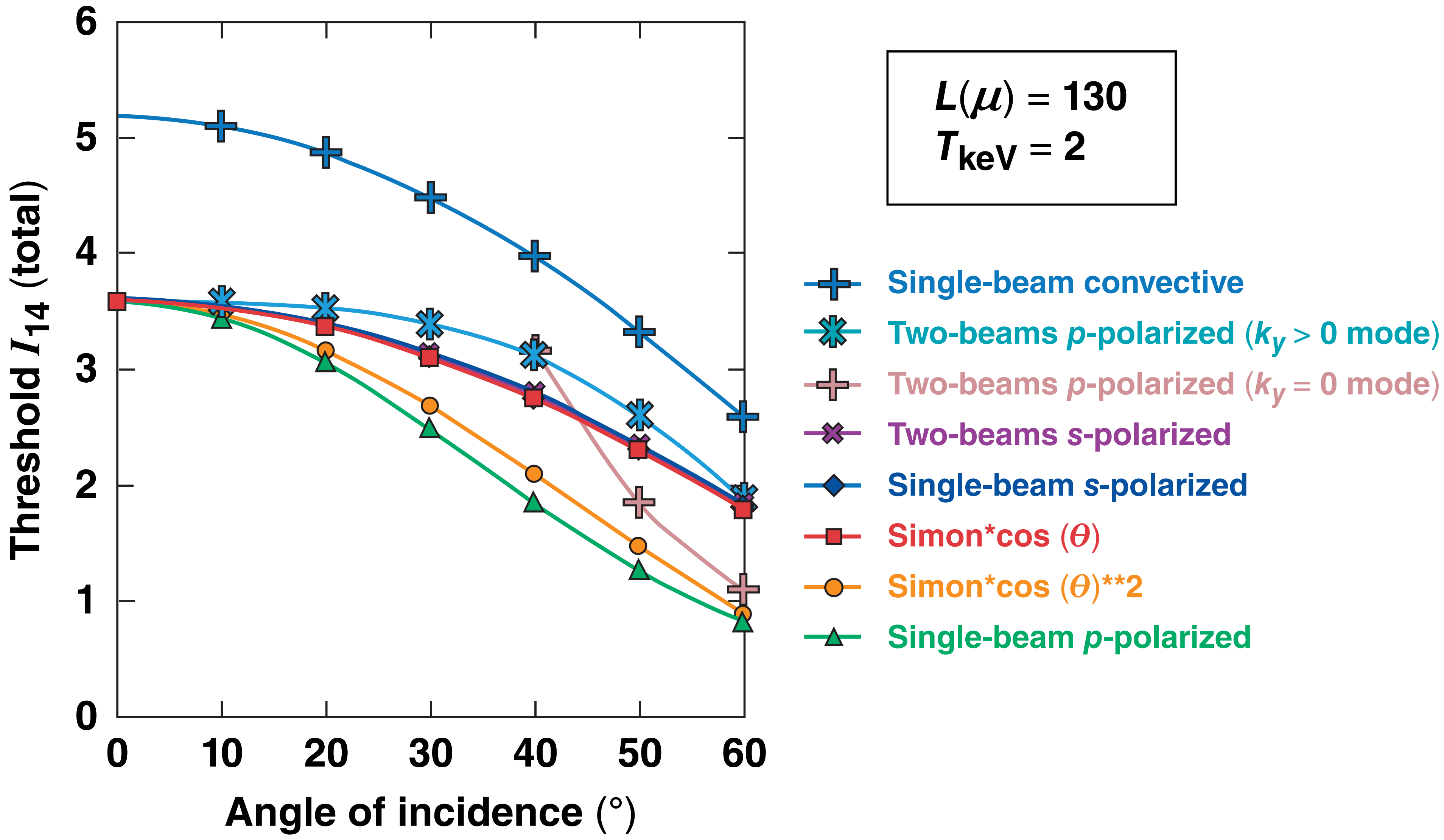
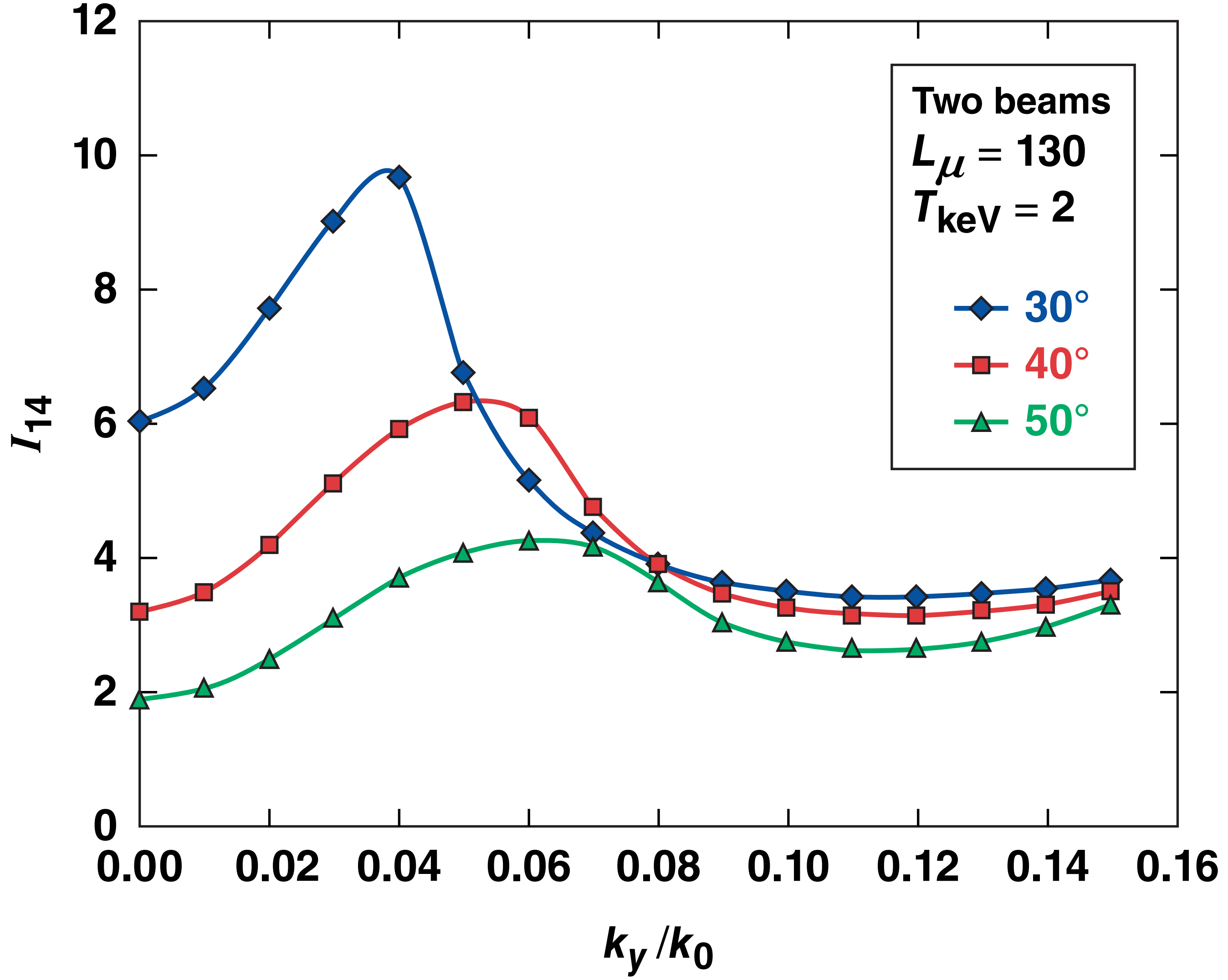
The absolute threshold for TPD depends on angle of incidence and polarization



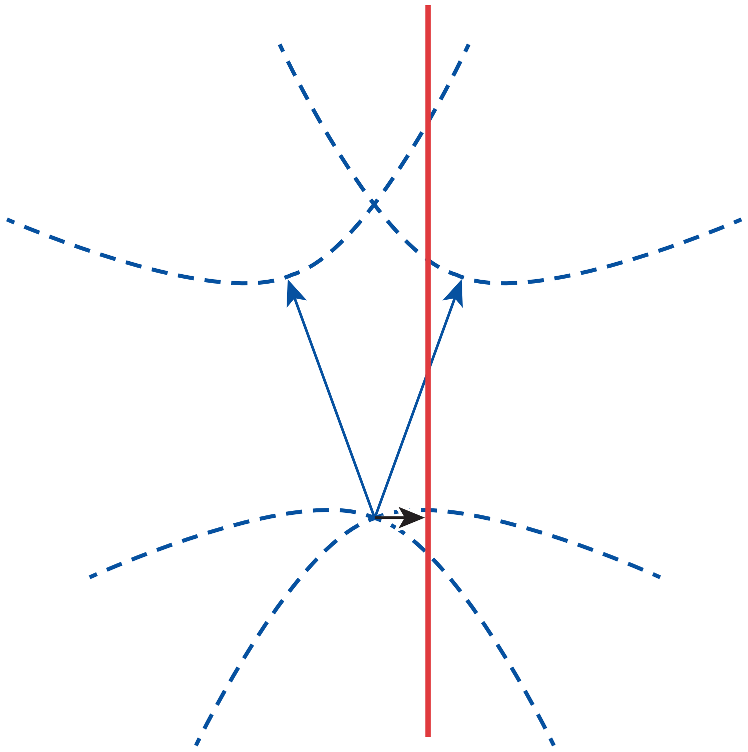
TC10640I

For two *p*-polarized beams, an on-axis TPD mode ($k_y = 0$) has the lowest threshold at larger incidence angles

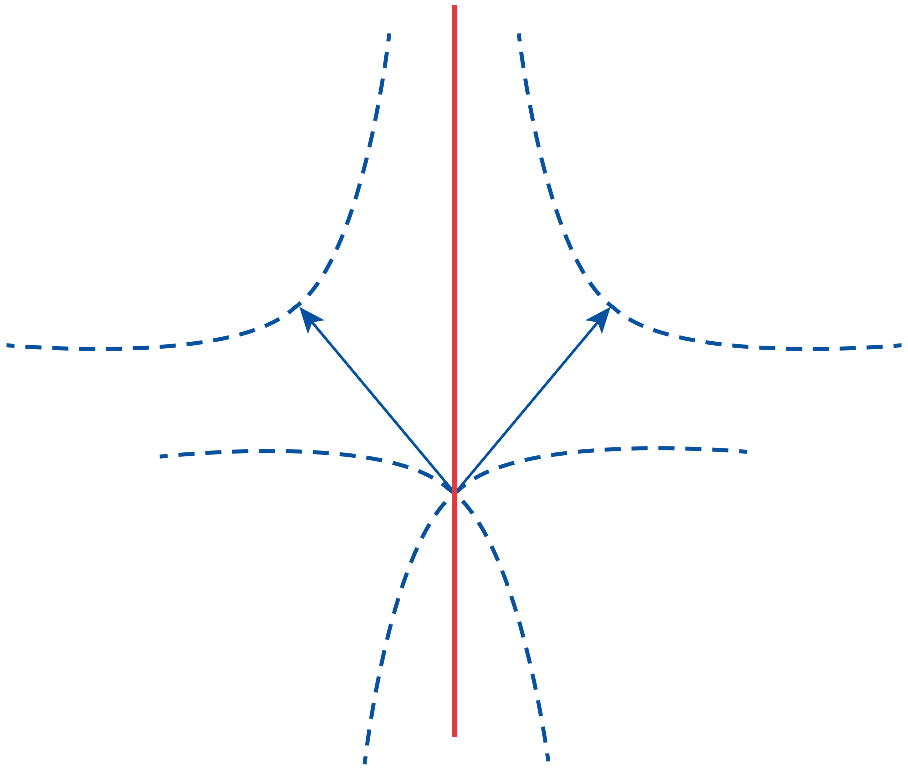


TC10643a

At larger angles, the on-axis mode is closer to the hyperbolas than the off-axis modes



$\theta = 20°$



$\theta = 40°$

TC10644b

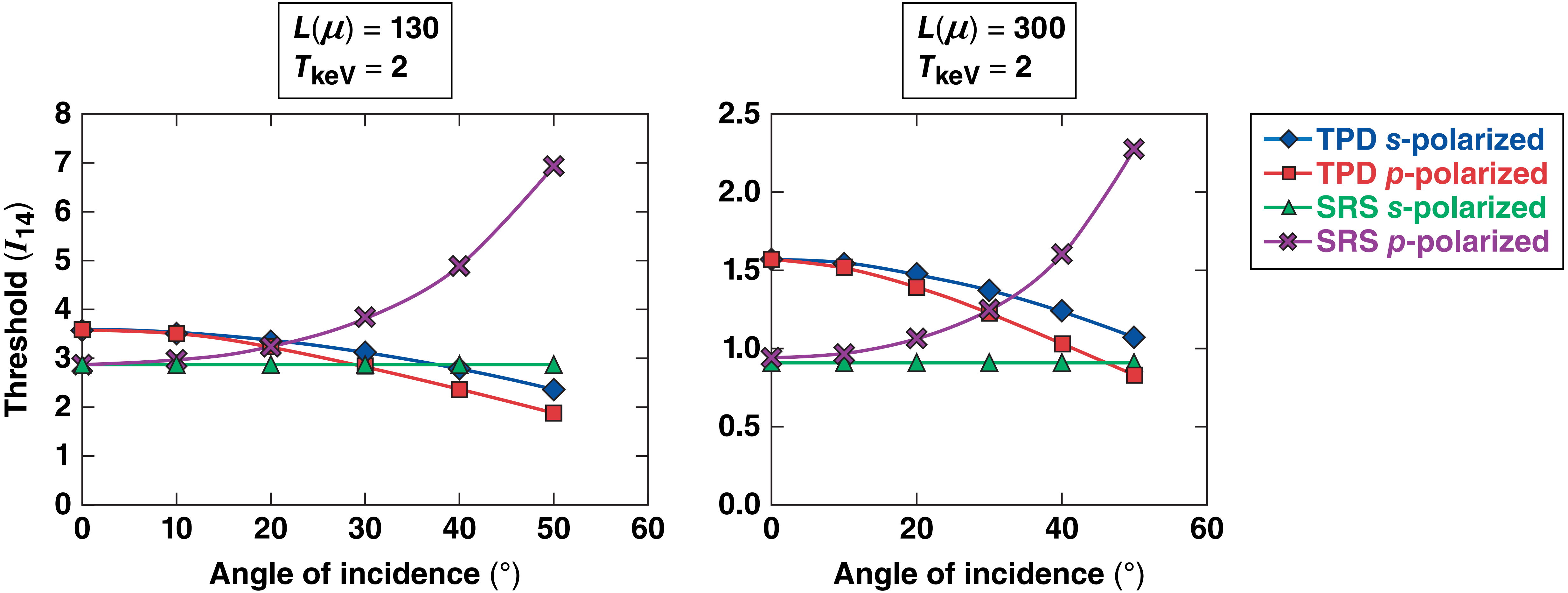
Light from absolute SRS will be emitted along the density gradient

- The much-higher group velocity of the EM wave means the instability must be absolute in the direction perpendicular to the density gradient, i.e., $k_y \sim k_z \sim 0$ and the wave is purely transverse
- Phase matching, and therefore threshold, will be insensitive to temperature
- The spectrum of the emitted light will have the same dependence on temperature as for TPD
- For *s*-polarization the threshold will be independent of pump incidence angle; for *p*-polarization the coupling is reduced for oblique incidence and the threshold increases with angle
- Analysis of the *k*-space equations for a normally incident beam gives a threshold of $I_{14} > \frac{1995}{L_{\mu}^{4/3}}$, close to the Liu, Rosenbluth, and White result

TC12171

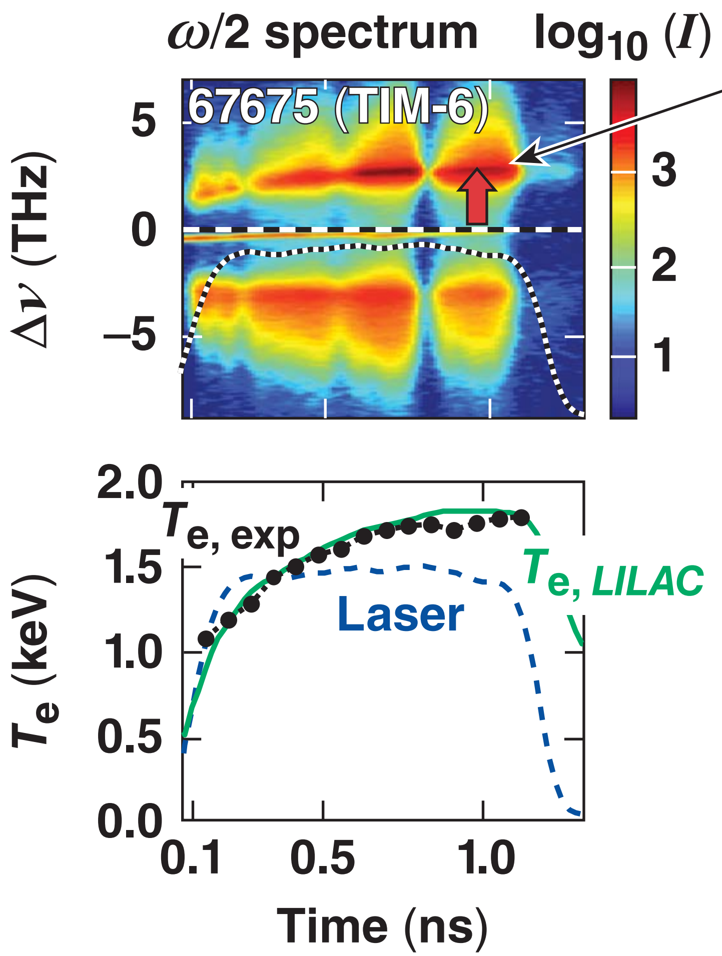
For oblique incidence, TPD and SRS behave differently as a function of incidence angle

- **Increasing temperatures and scale lengths favor SRS; increasing incidence angles favor TPD**



TC12172

The spectral signature of the absolute instability near $n_c/4$ is a sharp red-shifted feature that can be used for T_e measurements



$\Delta\lambda_{nm} = 4.4 \times 10^{-3}\ T_{e,\,keV}$

At $I \lesssim 5 \times 10^{14}$ $T_{e,\,keV} \sim T_{e,\,LILAC}$

$I_{14} = 5.6$

- Although the absolute instability is obtained from linear analysis, it can remain the most-intense TPD mode in the nonlinear regime, persisting throughout the pulse

E22225a

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