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The destabilising effect of dynamical friction on beam-driven waves in a near-threshold non-linear regime

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Collisionality

Marginal stability $\left(|\gamma_l - \gamma_d| \ll \gamma_l, \gamma_d\right)$ has been previously analysed using Krook and diffusive collision operators

$$\left.\frac{dF}{dt}\right|_{coll} = \beta\left(F - F_0\right) \qquad \left.\frac{dF}{dt}\right|_{coll} = \nu^3\left(\frac{\partial^2 F}{\partial v^2} - \frac{\partial^2 F_0}{\partial v^2}\right)$$

For very fast particles the effect of drag may need to be included

$$\left.\frac{dF}{dt}\right|_{coll} = \alpha^2\left(\frac{\partial F}{\partial v} - \frac{\partial F_0}{\partial v}\right)$$

The cubic equation

Near marginal stability the amplitude (A) of an unstable mode evolves according to the following equation

$$\frac{dA}{d\tau} = A(\tau) - \frac{1}{2}\int_0^{\tau/2} dz\, z^2 A(\tau - z) \int_0^{\tau-2z} dx\, e^{-\hat{\nu}_k^3 z^2 (2z/3+x) - \hat{\beta}_k (2z+x) + i\hat{\alpha}_k^2 z(z+x)} \times A(\tau - z - x) A^*(\tau - 2z - x)$$

$\hat{\nu}_k$ - Diffusion coefficient

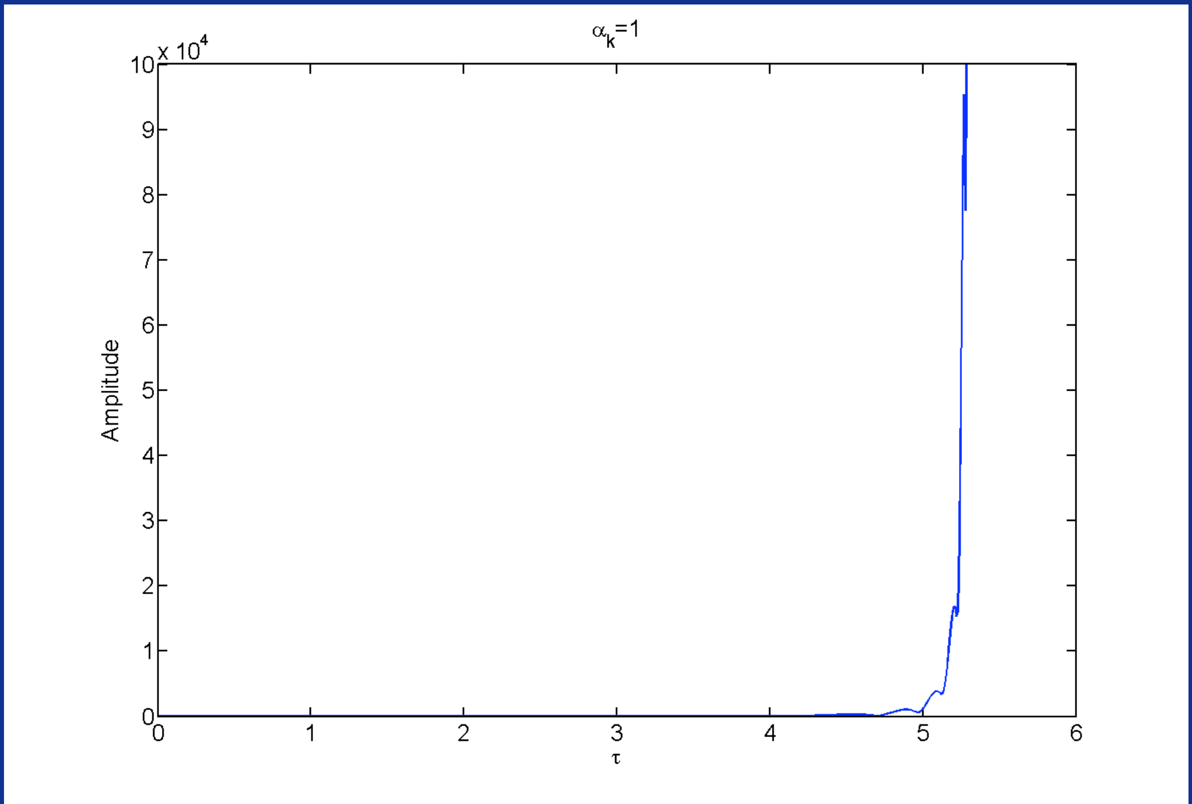
$\hat{\beta}_k$ - Krook coefficient

$\hat{\alpha}_k$ - Drag coefficient

Drag adds oscillatory behaviour, in contrast to the Krook and diffusive cases.

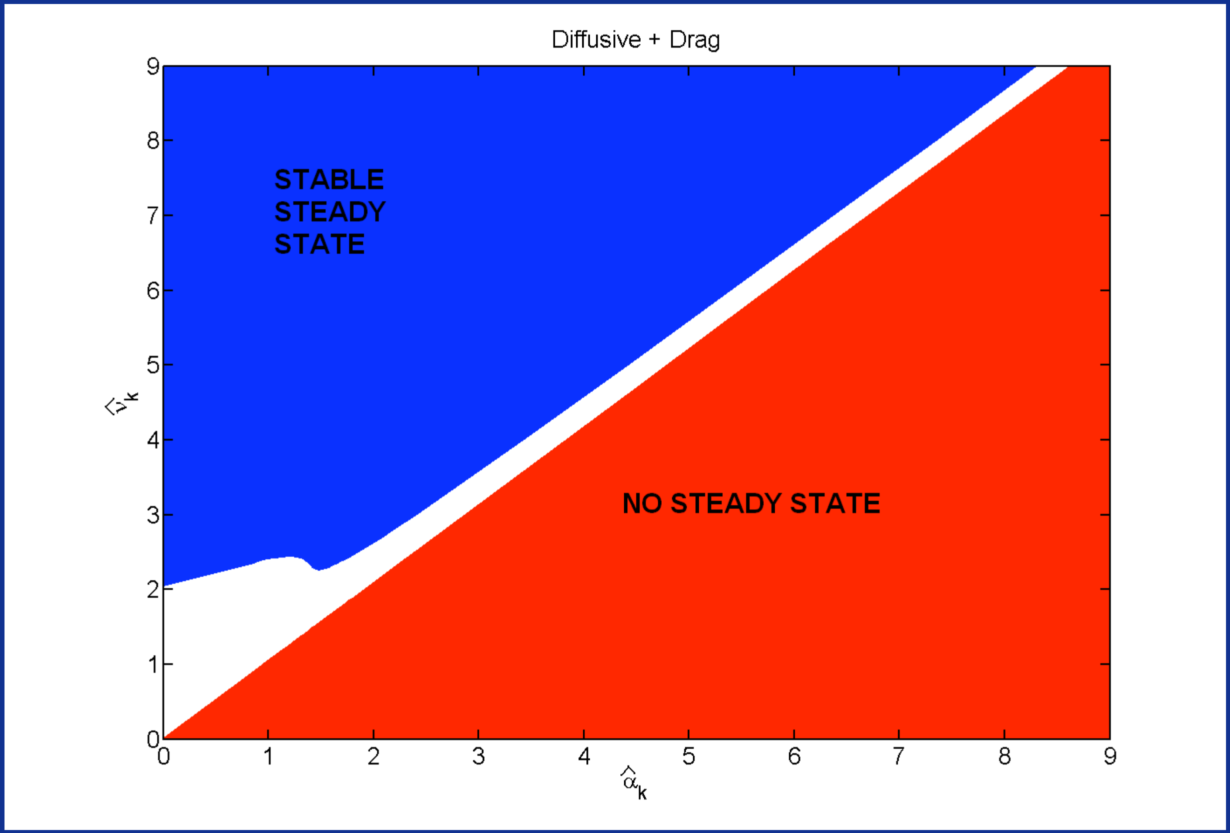
Pure drag

- For pure drag $(\hat{v}_k = \hat{\beta}_k = 0)$ there are no steady state solutions in contrast to the diffusive and Krook cases.
- Therefore when drag completely dominates we always enter an explosive regime even in the marginal case.



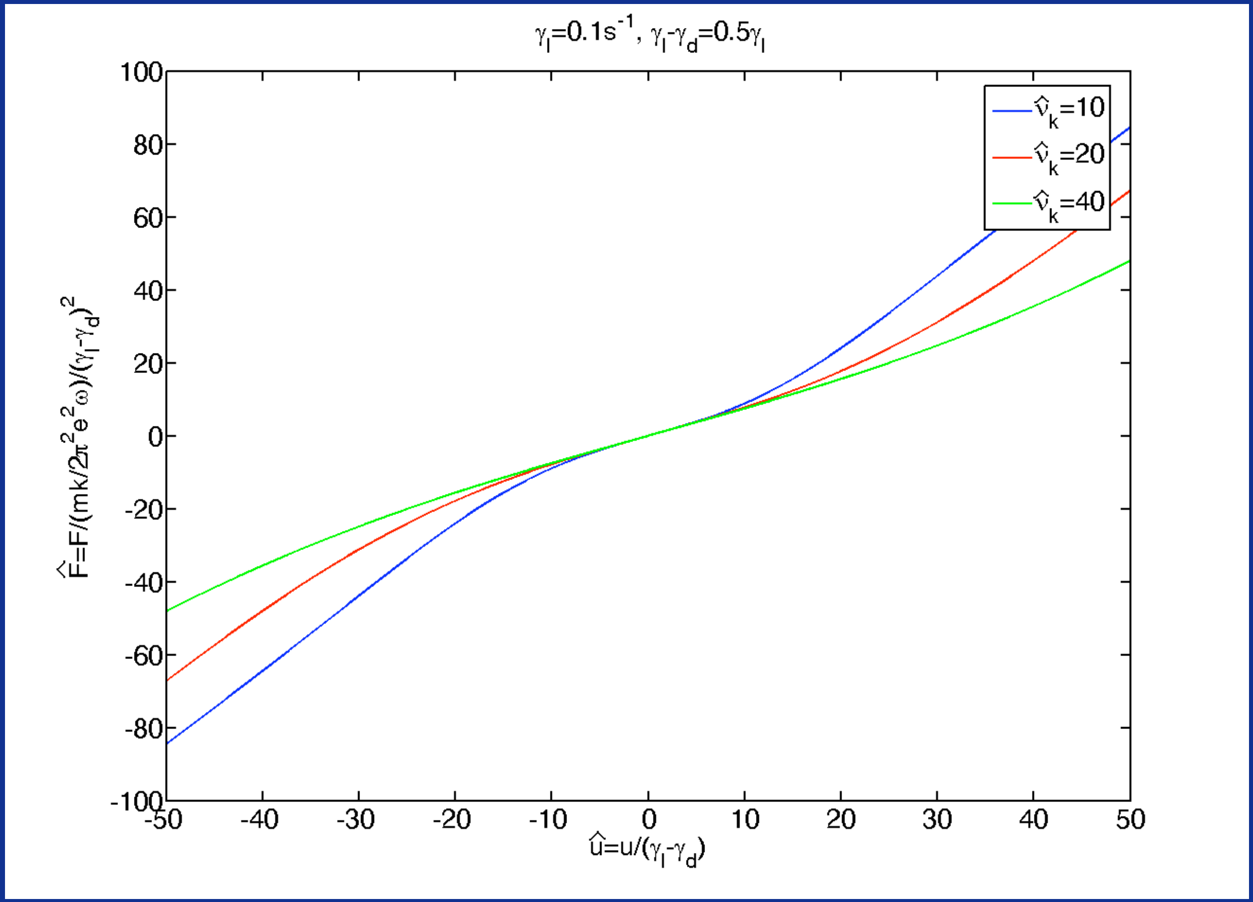
Diffusion + drag $\left(\hat{\beta}_k = 0\right)$

- For diffusion drag steady state solutions do exist
- For an appreciable amount of drag these solutions become unstable (pitch fork splitting etc.)
- Explosive solutions again when drag dominates



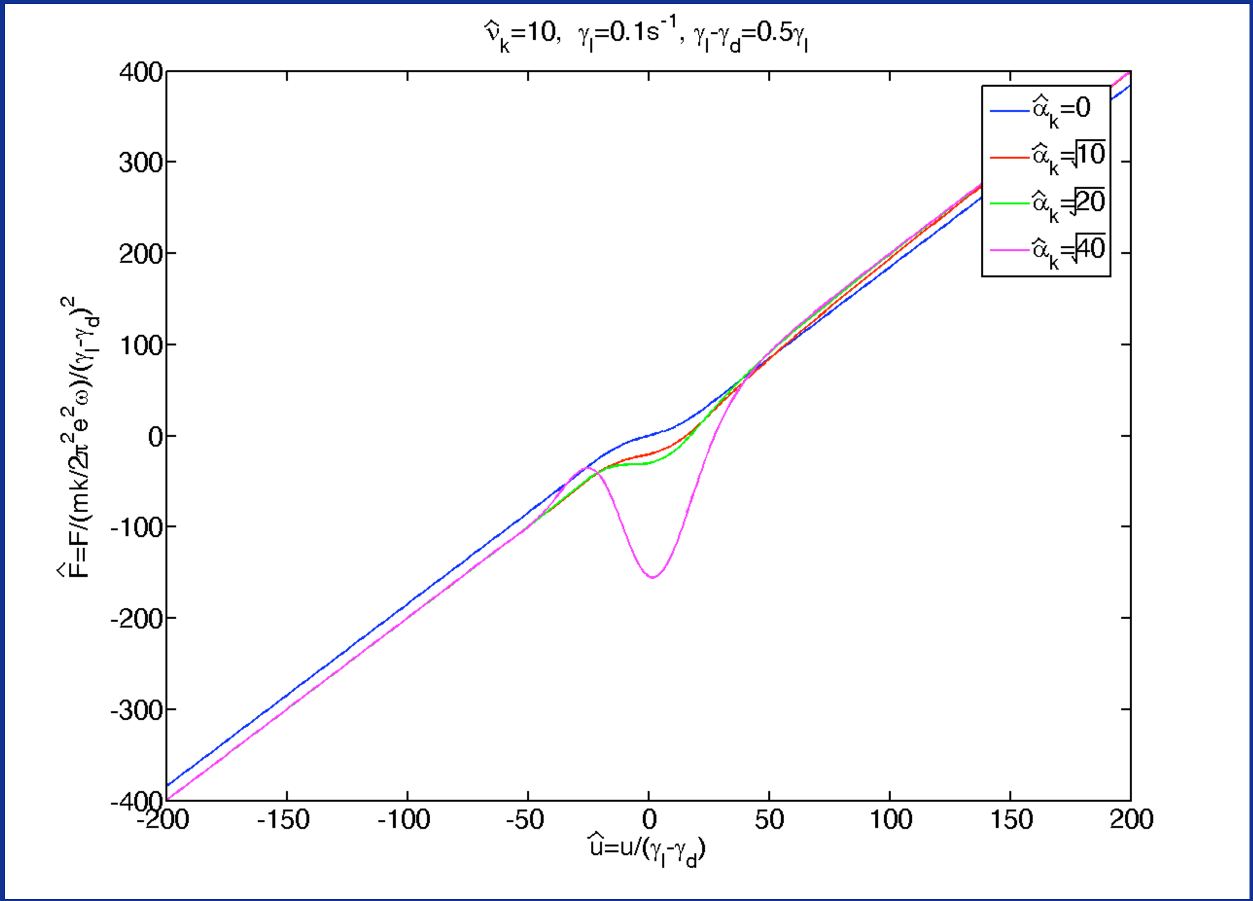
Diffusion + drag $\left(\hat{\beta}_k = 0\right)$

- For pure diffusion the distribution function does not become significantly perturbed.



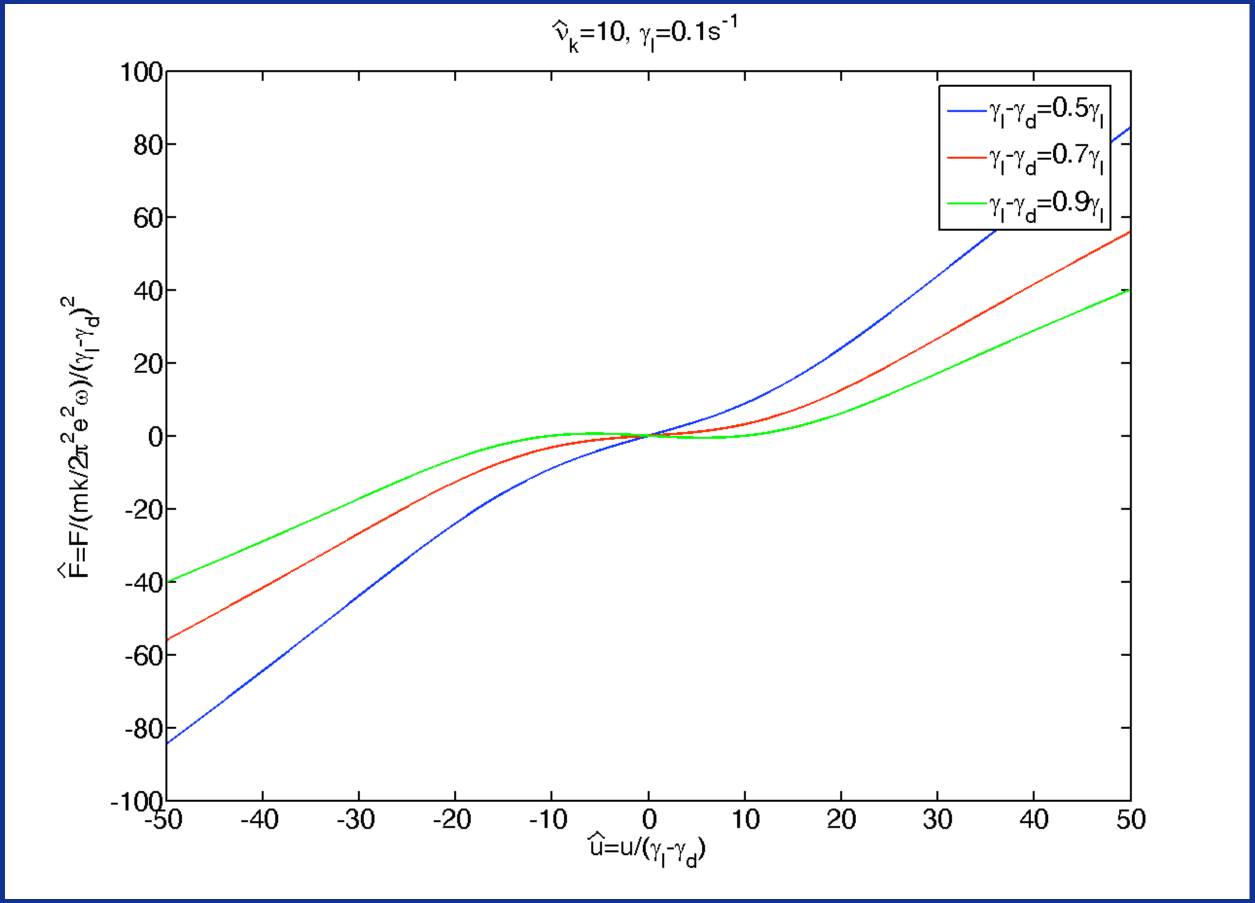
Diffusion + drag $\left(\hat{\beta}_k = 0\right)$

- Adding slowing down creates large asymmetric perturbations in the distribution function.



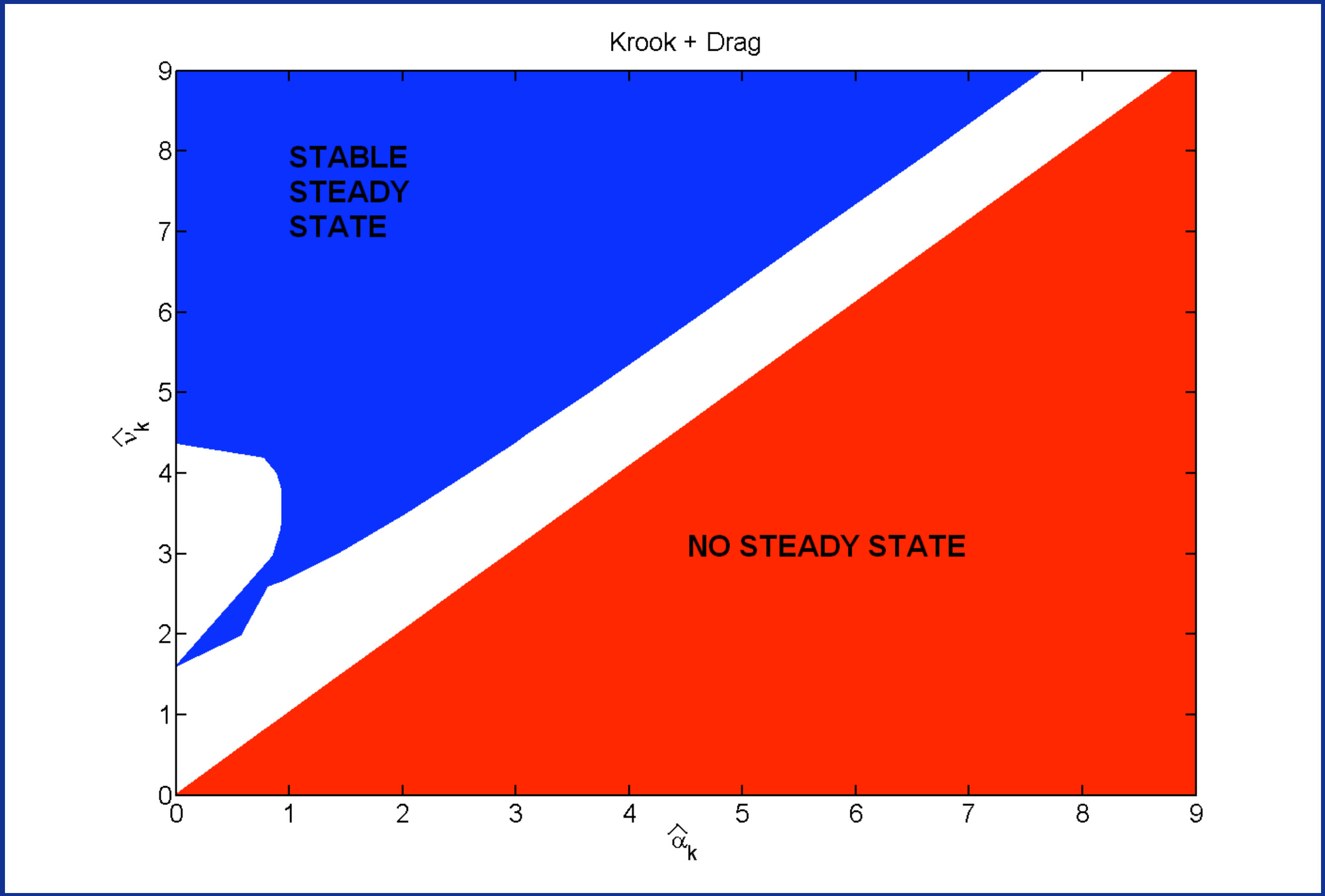
Diffusion + drag $\left(\hat{\beta}_k = 0\right)$

- Compare to pure diffusion with an increasing growth rate. This implies slowing down is creating a more unstable system



Krook + drag $(\hat{v}_k = 0)$

- Krook + drag behaves very similarly to the diffusive + drag case.
- Note that there are subtleties for low values of β



Experimental comparison NBI vs. ICRH (TAEs)

- Compare diffusion to drag for TAEs

$$\frac{\partial}{\partial \mathbf{v}} \cdot \mathbf{D} \cdot \frac{\partial f}{\partial \mathbf{v}} = \left\langle \frac{\partial P_\varphi}{\partial \mathbf{v}} \cdot \mathbf{D} \cdot \frac{\partial P_\varphi}{\partial \mathbf{v}} \right\rangle \left(\frac{\partial \Omega}{\partial P_\varphi} \right)^2 \frac{\partial^2 f}{\partial \Omega^2} \qquad \frac{\partial}{\partial \mathbf{v}} \mathbf{b} f = \left\langle \frac{\partial P_\varphi}{\partial \mathbf{v}} \cdot \mathbf{b} \right\rangle \left(\frac{\partial \Omega}{\partial P_\varphi} \right) \frac{\partial f}{\partial \Omega}$$

- The resonance width $\Delta\Omega$ can be estimated for deeply passing particles for MAST NBI parameters:

$$\frac{\left(\Delta\Omega_{\mathrm{Diff}}\right)^6}{\left(\Delta\Omega_{\mathrm{Drag}}\right)^6} \approx \omega_{*b} \tau S \frac{L_b}{r} \frac{{v_A}^2}{v_{Tb}^2} \left[\frac{T_e}{E_A} \left\{ \tilde{Z}_2 + \frac{4}{3\sqrt{\pi}} \frac{m_b}{m_e} \left(\frac{v_A}{v_e} \right)^3 \right\} \right.$$

$$\left. + \frac{\theta_{\mathrm{beam}}^2 Z_{\mathrm{eff}}}{2} \left(1 + \frac{4}{3\sqrt{\pi}} \frac{v_A}{v_e} \right) \right]^2 \left[\tilde{Z}_1 + \frac{4}{3\sqrt{\pi}} \frac{m_b}{m_e} \left(\frac{v_A}{v_e} \right)^3 \right]^{-3} \approx 0.2 - 1.6$$

Experimental comparison NBI vs. ICRH (TAEs)

NBI

- Theory – Drag can dominate → explosive
- Experiment – Bursting dominates

ICRH

- Theory – Wave diffusion → steady state, pitch fork etc.
- Experiment – steady state, pitch fork etc. dominates