Kinetic instabilities in burning inertial-confinement-fusion (ICF) plasmas

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ICF experiments are producing burning plasmas

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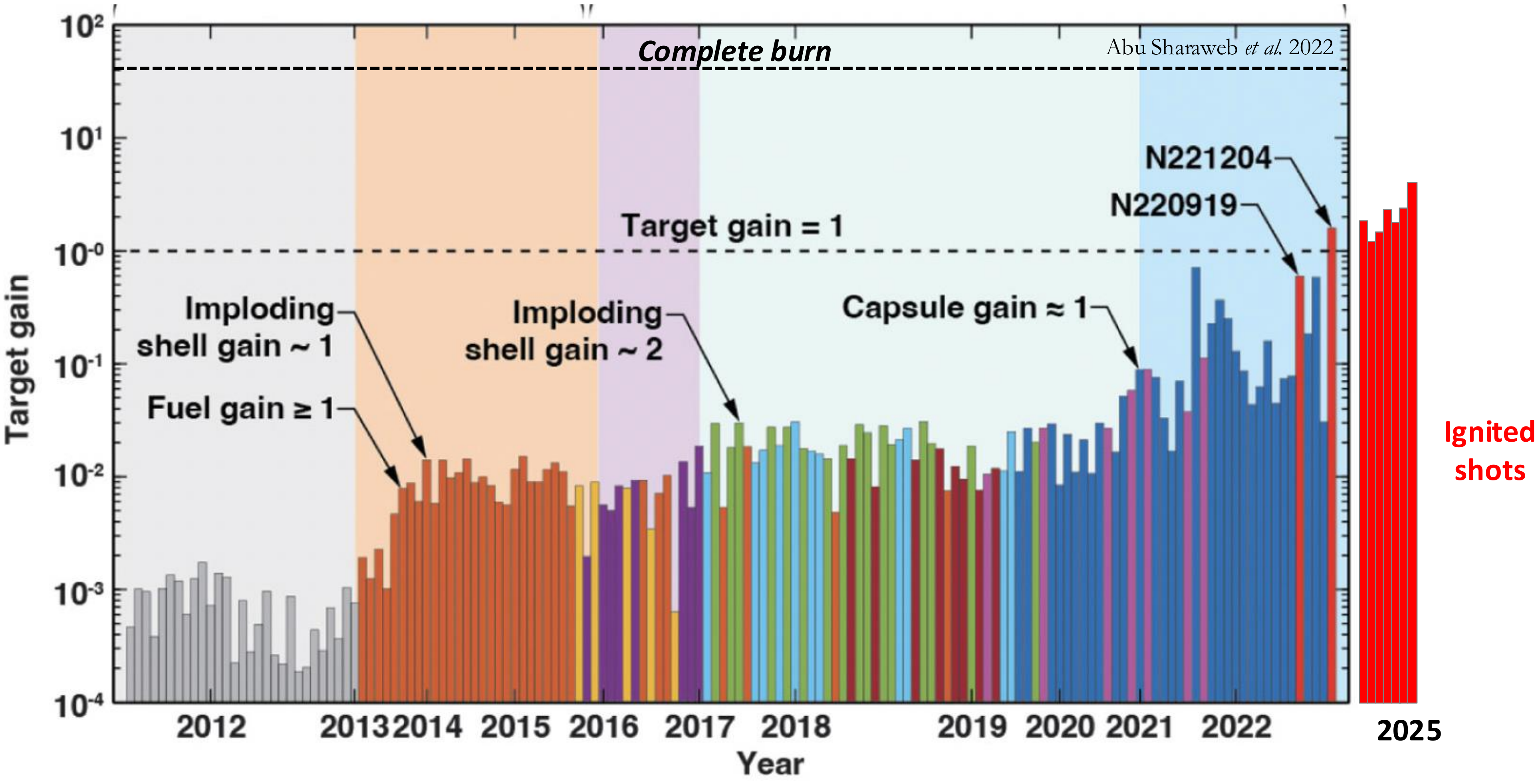
Significant improvements to fusion yields on the National Ignition Facility (NIF) over the last 15 years

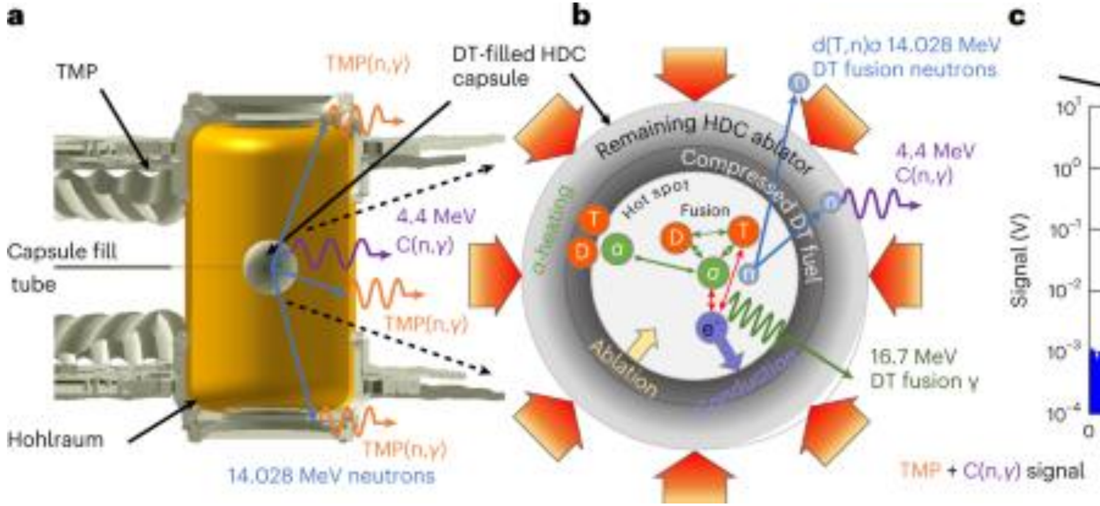


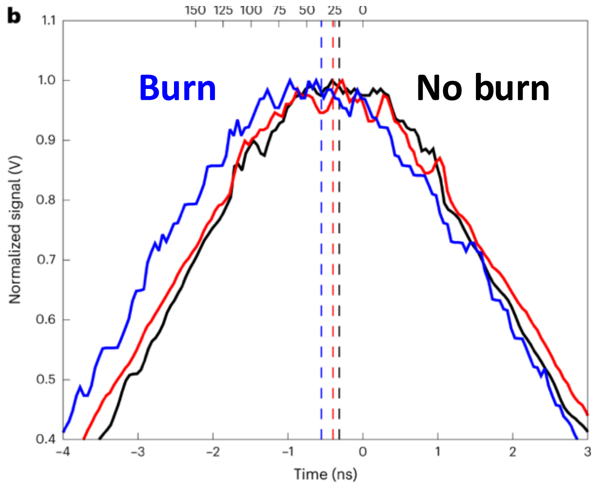
Most successful NIF experiment: $G_{\text{target}} \approx 4 \implies G_{\text{fuel}} \approx 400,\ Q_\alpha \gg Q_{\text{ext}}$

Why is kinetic theory relevant here?

Recent observational signatures of kinetic effects in burning ICF plasmas

- Traditional paradigm in ICF: kinetic physics is unimportant because of high collisionality ($\lambda_e, \lambda_i \ll L$)
- Recent experiments characterising burning plasmas (e.g. Hartouni et al. 2022) suggested otherwise…





- ➢ Temperature inferred from upward energy shift in neutron spectral peak ~2.5 times higher than measured value, assuming Maxwellian distribution of DT ions
- ➢ Most plausible explanation given other measurements: ***suprathermal DT ion populations***

nature physics

Plasma physics

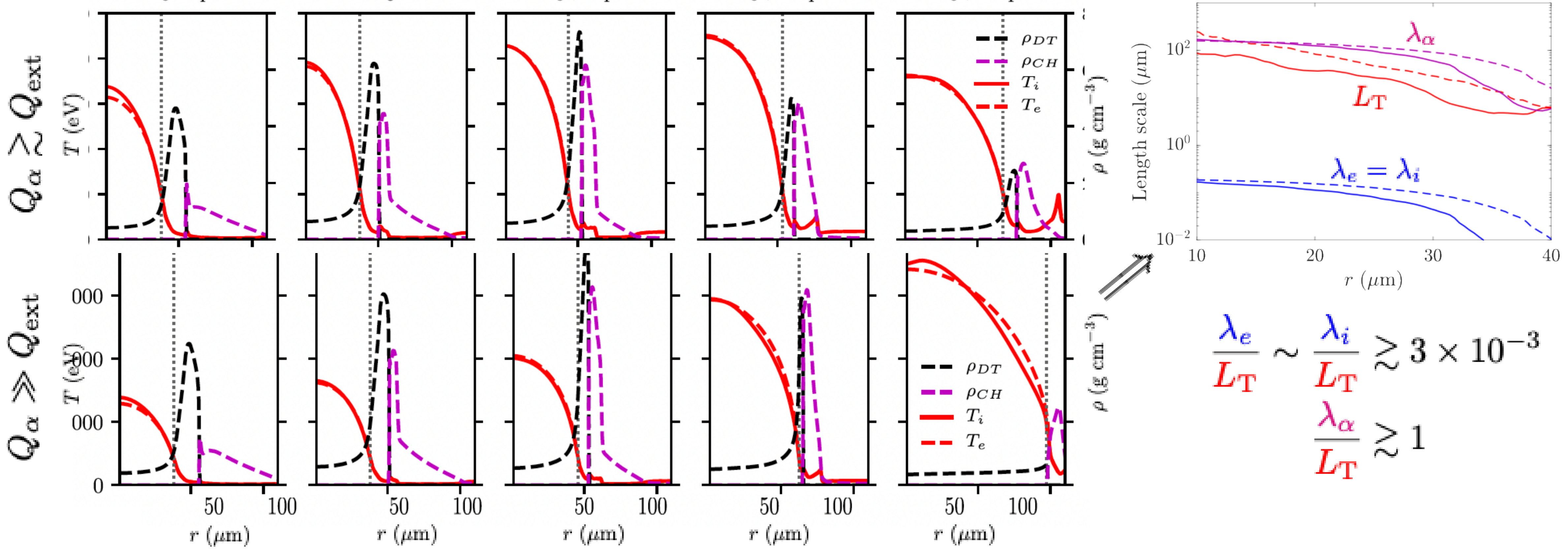
Burning plasma surprise

Stefano Atzeni

Conditions in burning ICF plasmas

To determine what kinetic processes might be relevant, consider (simulation-derived) temperature/density profiles of implosions in different regimes:

Tong *et al.* 2019



$$\frac{\lambda_e}{L_T} \sim \frac{\lambda_i}{L_T} \gtrsim 3 \times 10^{-3}$$

$$\frac{\lambda_\alpha}{L_T} \gtrsim 1$$

Hot-spot DT plasma is classical & collisional, with collisionless, sparse population of alpha particles

Burning ICF plasmas are weakly magnetised

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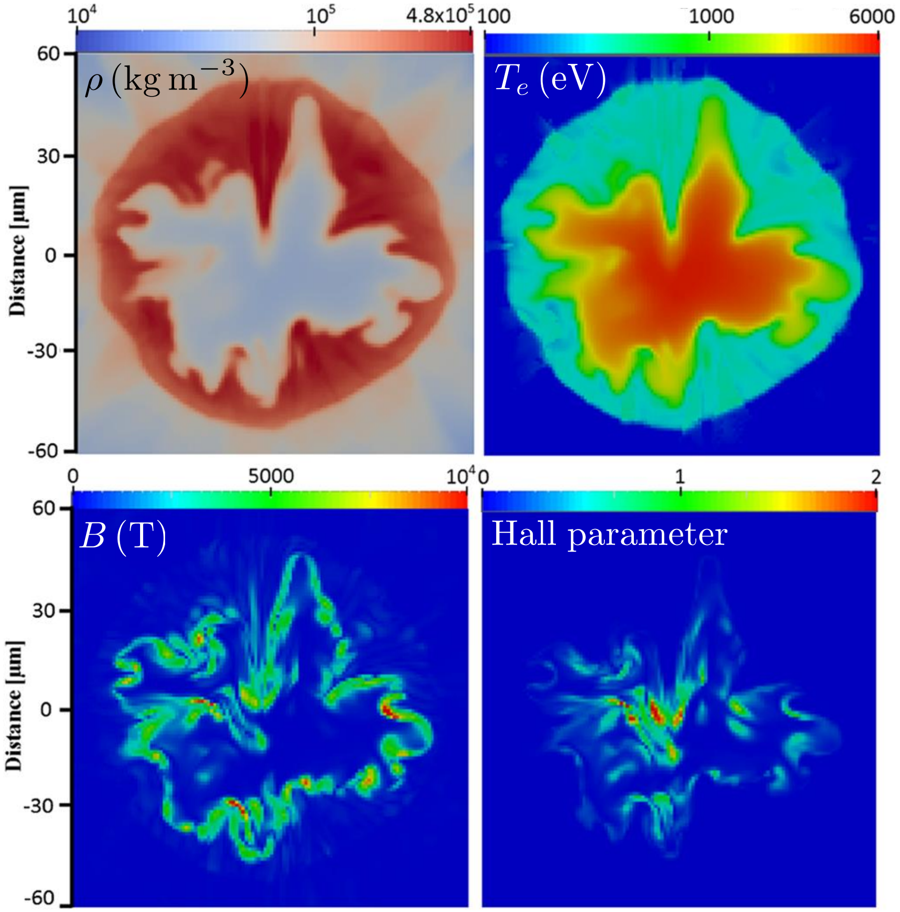
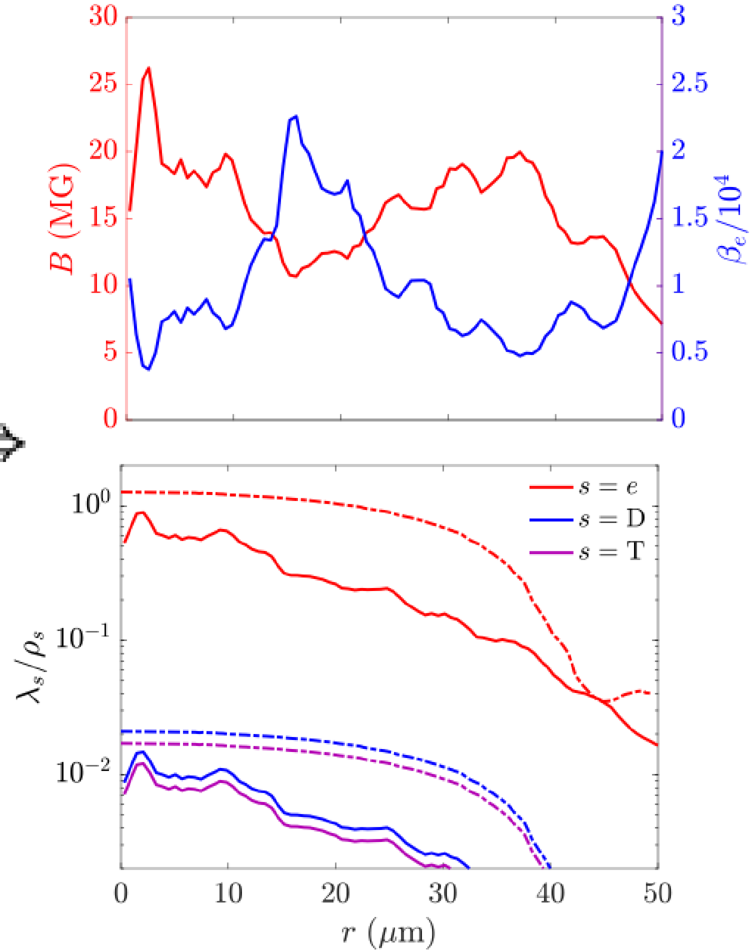
MHD simulations of NIF implosions with Braginskii transport find self-generated, stochastic magnetic fields



C. Walsh *et al.* 2017

$\Longrightarrow$



$$\beta_e \sim 10^4$$

$$\frac{\lambda_D}{\rho_D} \sim \frac{\lambda_T}{\rho_T} \ll \frac{\lambda_e}{\rho_e} \sim 1$$

Weak magnetisation places significant constraints on possible instability candidates

Kinetic instabilities in weakly collisional plasmas

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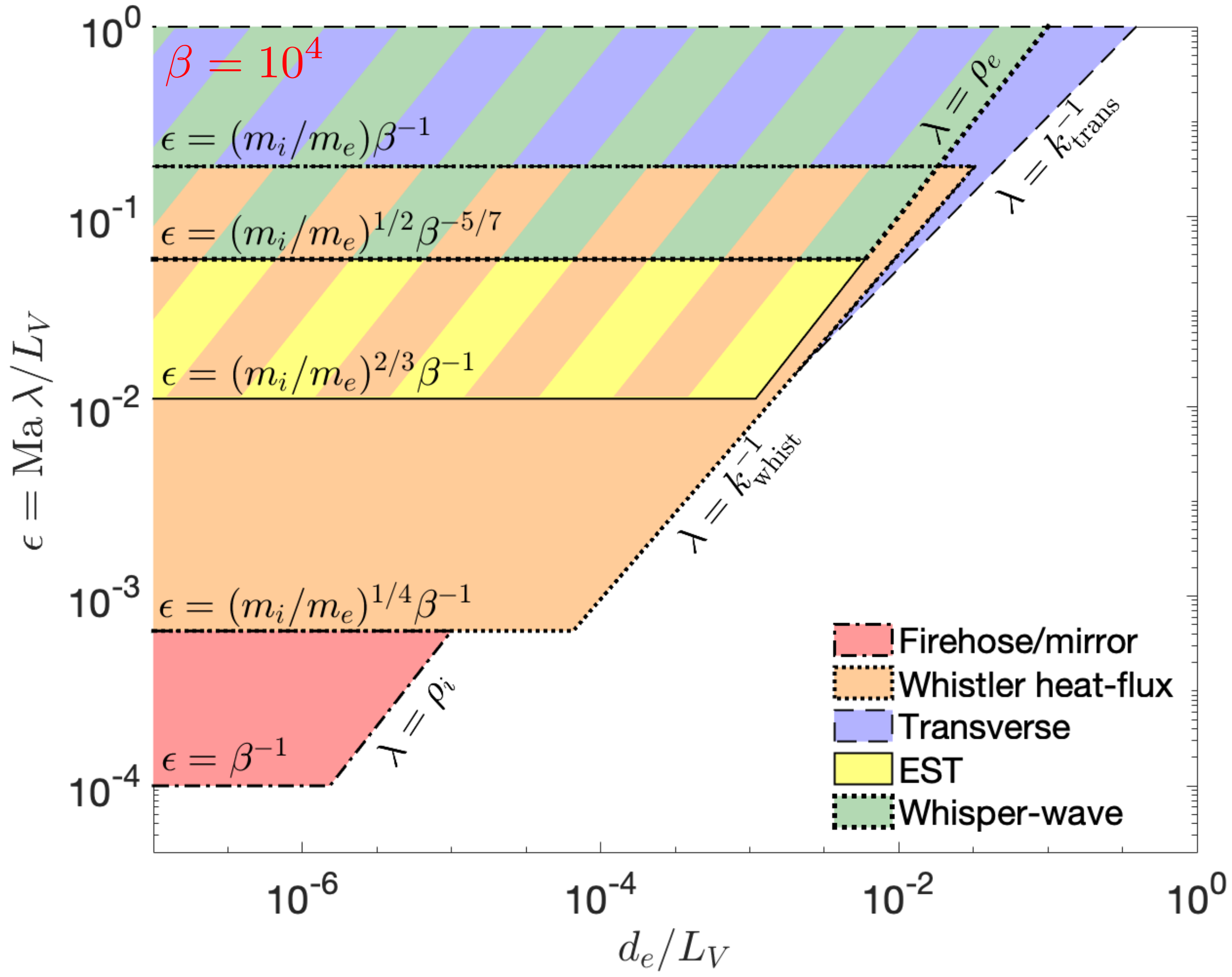
Weakly collisional plasmas are kinetically unstable at sufficiently large β



Bott et al. (2024) considered kinetic stability of

$$f_e = f_{\rm Me}\left[1 - \frac{\lambda_e}{L_{\rm T}}\frac{v_\|}{v_{\rm the}}\left(\frac{v^2}{v_{\rm the}^2} - \frac{5}{2}\right)\right],$$

finding fast-growing kinetic instabilities when

$$\beta_e \gg L_{\rm T}/\lambda_e,\ \lambda_e \gg \rho_e.$$

Whistler heat-flux instability (WHFI) fastest growing of heat-flux-driven instabilities

Problem: calculation not valid in plasmas with moderate collisionality ($\rho_e \lesssim \lambda_e$), so not strictly applicable to ICF applications

Are there instabilities in this regime?

Linear theory with moderate collisionality

To make life easier, let's make a few assumptions, based on properties of the WHFI…

1. Static ions
2. Circularly polarised modes with a wavevector parallel to macroscopic magnetic field: $\bar{\boldsymbol{B}} = B_0 \hat{\boldsymbol{z}},\ \boldsymbol{k} = k\hat{\boldsymbol{z}}.$
3. Equilibrium close to Maxwellian: $\bar{f}_e = f_{\mathrm{Me}}(v) + \frac{\lambda_e}{L_{\mathrm{T}}} v_{\|} \bar{f}_{e1}(v),\ \frac{\lambda_e}{L_{\mathrm{T}}} \ll 1.$
4. Assume collisions can be modelled as Lorentz scattering operator (with non-trivial velocity dependence)
5. In addition to usual linearisation, I will adopt following ordering of parameters:

$$\frac{\omega}{k v_{\mathrm{the}}} \sim \frac{v_{\mathrm{the}} |\delta \boldsymbol{E}|/c}{|\delta \boldsymbol{B}|} \sim \frac{1}{\beta_e} \sim \frac{\lambda_e}{L_T} \sim \frac{\Omega_e}{L_T} \ll 1,\ k\rho_e \sim 1.$$

I will sketch derivation…!

Summary of key steps I

1. Start from linearised Vlasov-Fokker-Planck equation plus Maxwell's equations (neglecting displacement current):

$$\nabla \times \delta \boldsymbol{E} = -\frac{1}{c}\frac{\partial \delta \boldsymbol{B}}{\partial t}, \quad \nabla \times \delta \boldsymbol{B} = -\frac{4\pi}{c} e \int \mathrm{d}^3\boldsymbol{v}\, \boldsymbol{v}\, \delta f_e,$$

$$\cancel{\frac{\partial \delta f_e}{\partial t}} + \boldsymbol{v} \cdot \nabla \delta f_e - \frac{e}{m_e}\frac{\boldsymbol{v} \times \bar{\boldsymbol{B}}}{c} \cdot \frac{\partial}{\partial \boldsymbol{v}} \delta f_e - \nu_{ei}(v)\mathcal{L}(\delta f_e) = \frac{e}{m_e}\left(\delta \boldsymbol{E} + \frac{\boldsymbol{v} \times \boldsymbol{B}}{c}\right) \cdot \frac{\partial \bar{f}_e}{\partial \boldsymbol{v}}.$$

2. Substitute circularly polarised eigenmode:

$$\delta \boldsymbol{E} = \widehat{\delta E}\,(\hat{\boldsymbol{x}} - i\hat{\boldsymbol{y}}) \exp\left[i\left(kz - \omega t\right)\right], \quad \delta \boldsymbol{B} = \widehat{\delta B}\,(\hat{\boldsymbol{x}} - i\hat{\boldsymbol{y}}) \exp\left[i\left(kz - \omega t\right)\right].$$

$$\delta f_e = \widehat{\delta f}_e(\boldsymbol{v}) \exp\left[i\left(kz - \omega t\right)\right].$$

3. Expand perturbed distribution in spherical harmonics:

$$\widehat{\delta f}_e(\boldsymbol{v}) = \sum_{n=0}^{\infty} \sum_{m=-n}^{m=n} \widehat{\delta f}_{e,n}^{m}(v) P_n^m(\cos\theta) \exp\left(im\phi\right)$$

Summary of key steps II

4. Use orthogonality to show that

$$\frac{n-1}{2n-1}ikv\widehat{\delta f}^{1}_{e,n-1}(v) + \frac{n+2}{2n+3}ikv\widehat{\delta f}^{1}_{e,n+1}(v) + i\Omega_e\widehat{\delta f}^{1}_{e,n}(v) + \frac{n(n+1)}{2}\nu_{ei}(v)\widehat{\delta f}^{1}_{e,n}(v)$$
$$= \frac{\delta_{n1}}{2}\left[\frac{ie}{m_e}\widehat{\delta B}\frac{\lambda_e}{L_T}\bar{f}_{e1} - 2\frac{e}{m_e}\widehat{\delta E}\frac{v}{v_{\mathrm{the}}^2}f_{\mathrm{Me}}\right].$$

All other spherical harmonics vanish!

5. (After much algebra), deduce dispersion relation: $\omega = \frac{\lambda_e}{L_T}\frac{k\mathcal{I}_1}{\mathcal{I}_0} + \frac{1}{\beta_e}\frac{k^2\rho_e^2}{\mathcal{I}_0}$, where

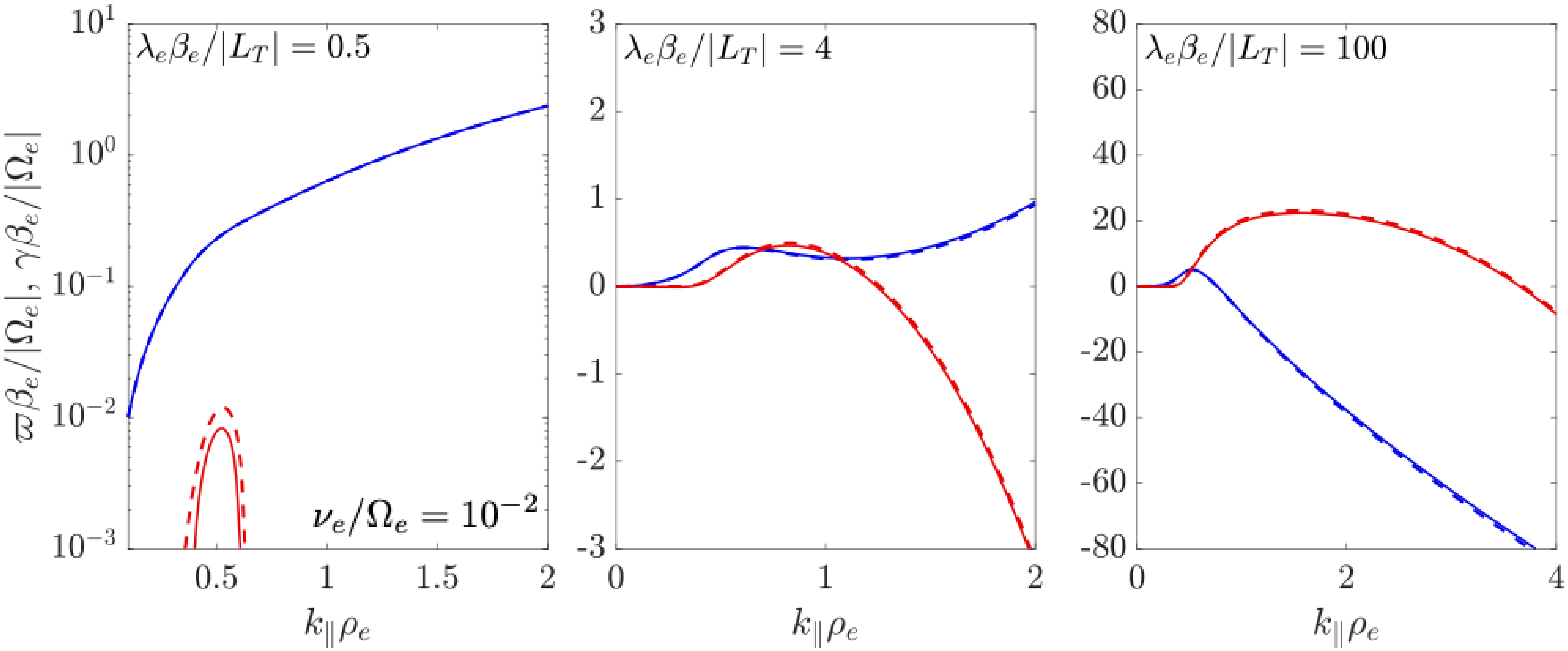
$$\mathcal{I}_0 = \frac{8}{3\sqrt{\pi}}\int_0^\infty \mathrm{d}v\, v^4\exp(-v^2)g_1^*, \quad \mathcal{I}_1 = \frac{4}{3\sqrt{\pi}}\int_0^\infty \mathrm{d}v\, v^7\left(\frac{v^2}{v_{\mathrm{the}}^2} - 4\right)\exp(-v^2)g_1^*,$$

and g_1 satisfies $\left(1 - \frac{in(n+1)}{2}\nu_{ei}(v)\right)g_n + \frac{n-1}{2n-1}ikvg_{n-1} + \frac{n+2}{2n+3}ikvg_{n+1} = \delta_{n1}$

General case solved by Bell et al (2020)…

Validating numerical implementation

First, a check: if $f_e = f_{\mathrm{M}e}\left[1 - \frac{\lambda_e}{L_{\mathrm{T}}}\frac{v_\parallel}{v_{\mathrm{th}e}}\left(\frac{v^2}{v_{\mathrm{th}e}^2} - \frac{5}{2}\right)\right]$, and $\nu_e/\Omega_e \ll 1$, do we recover previous results?

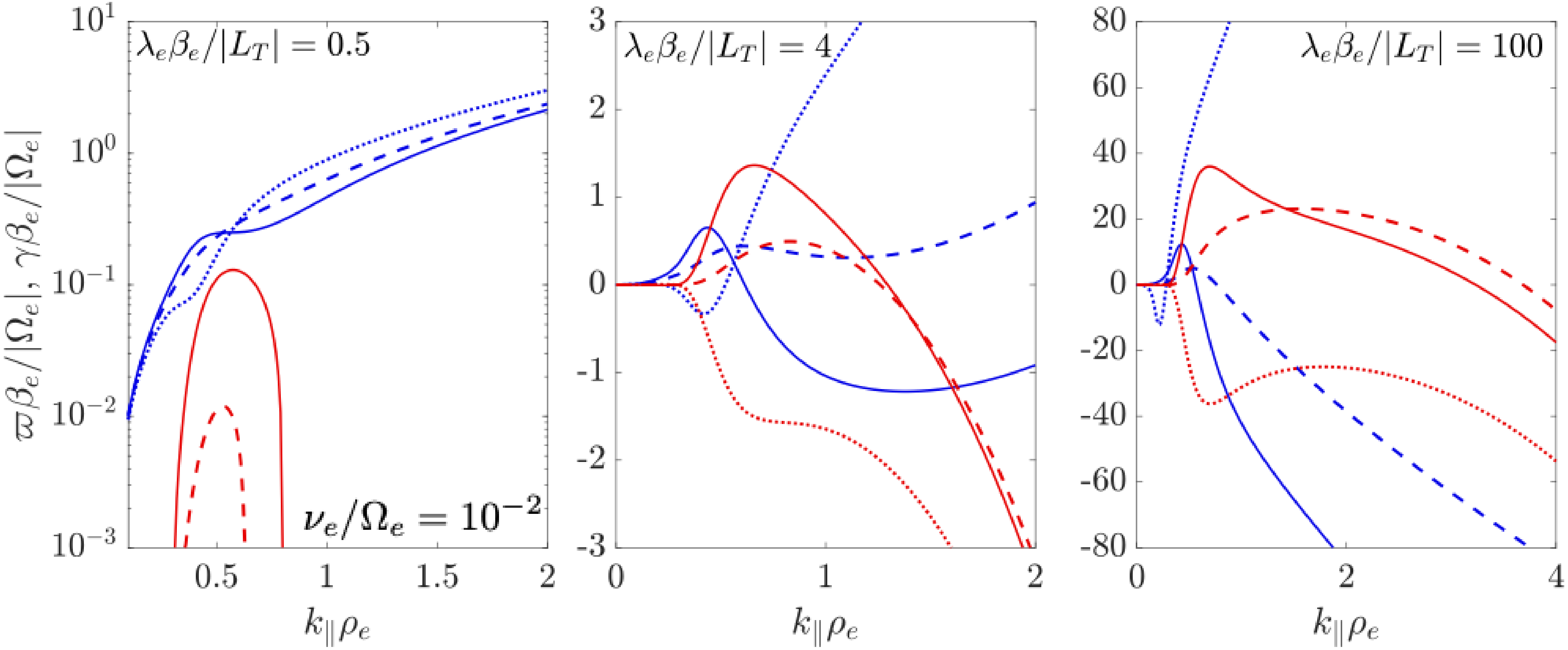


Close agreement with analytic expressions for frequency and growth rate of collisionless WHFI!

Krook vs. Lorentz collision operator

New method allows for calculating more realistic form for distribution functions (quasi)-analytically:

$$f_e = f_{\mathrm{M}e}\left[1 - \frac{\lambda_e}{L_\mathrm{T}}\frac{v_\parallel}{v_{\mathrm{th}e}}\left(\frac{v^2}{v_{\mathrm{th}e}^2} - \frac{5}{2}\right)\right] \quad \text{vs.} \quad f_e = f_{\mathrm{M}e}\left[1 - \frac{\lambda_e}{2L_\mathrm{T}}\frac{v_\parallel}{v_{\mathrm{th}e}}\frac{v^3}{v_{\mathrm{th}e}^3}\left(\frac{v^2}{v_{\mathrm{th}e}^2} - 4\right)\right]$$



Instability more potent if Lorentz collision operator adopted… and additional instability!

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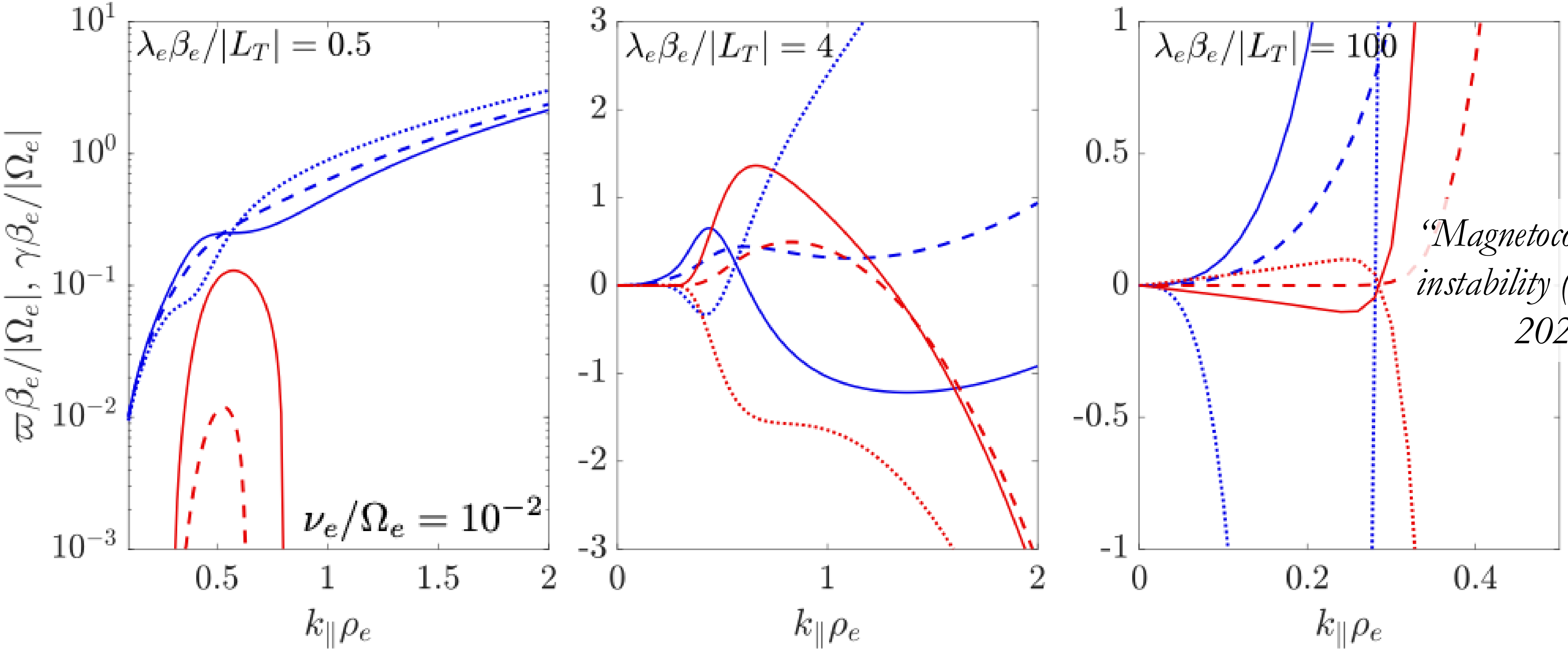
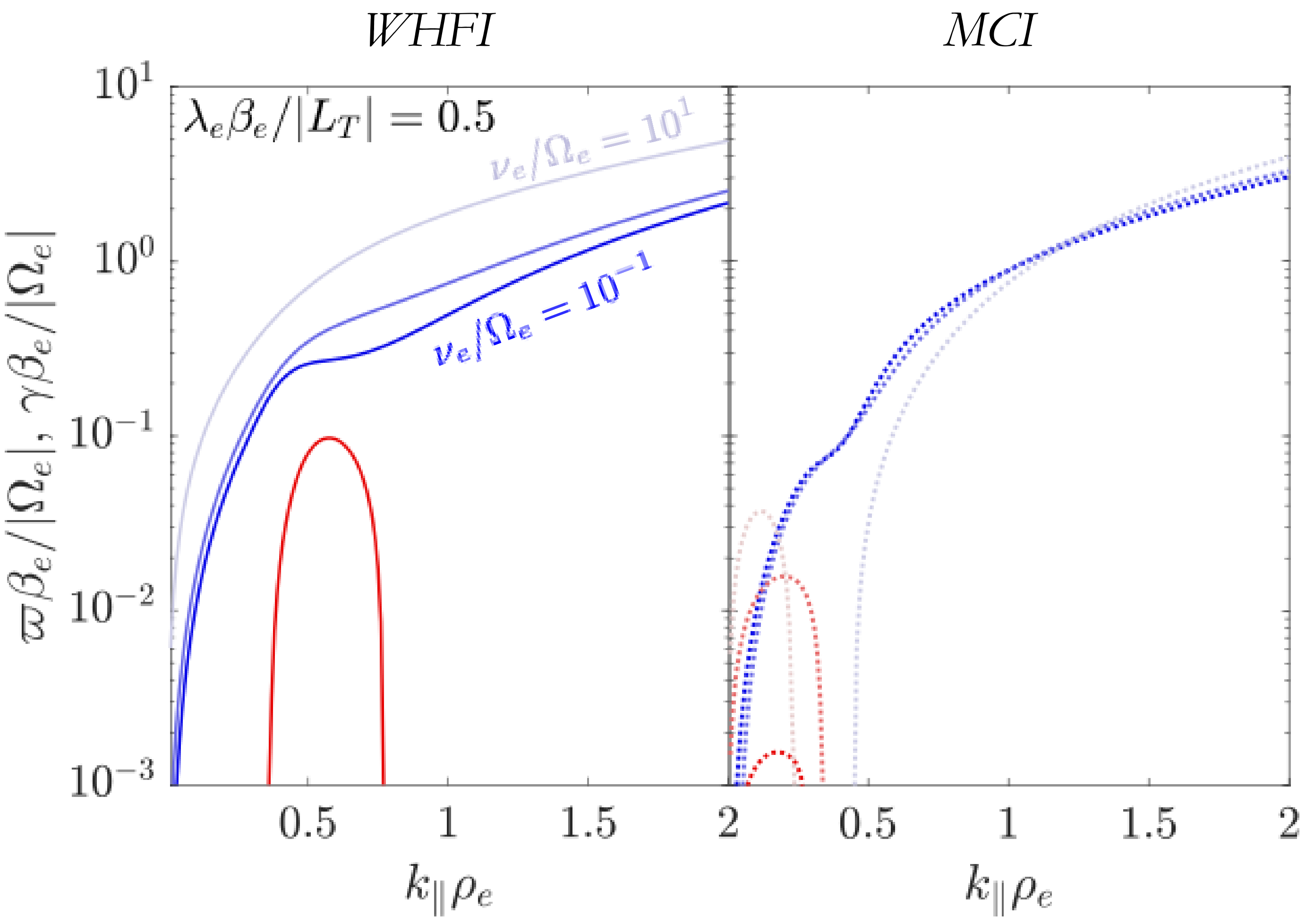


"Magnetocollisional" instability (Bell et al. 2020)

Instability more potent if Lorentz collision operator adopted… and additional instability!

Collisionality

Questions of primary interest: how do collisions affect WHFI? And when is MCI competitive?



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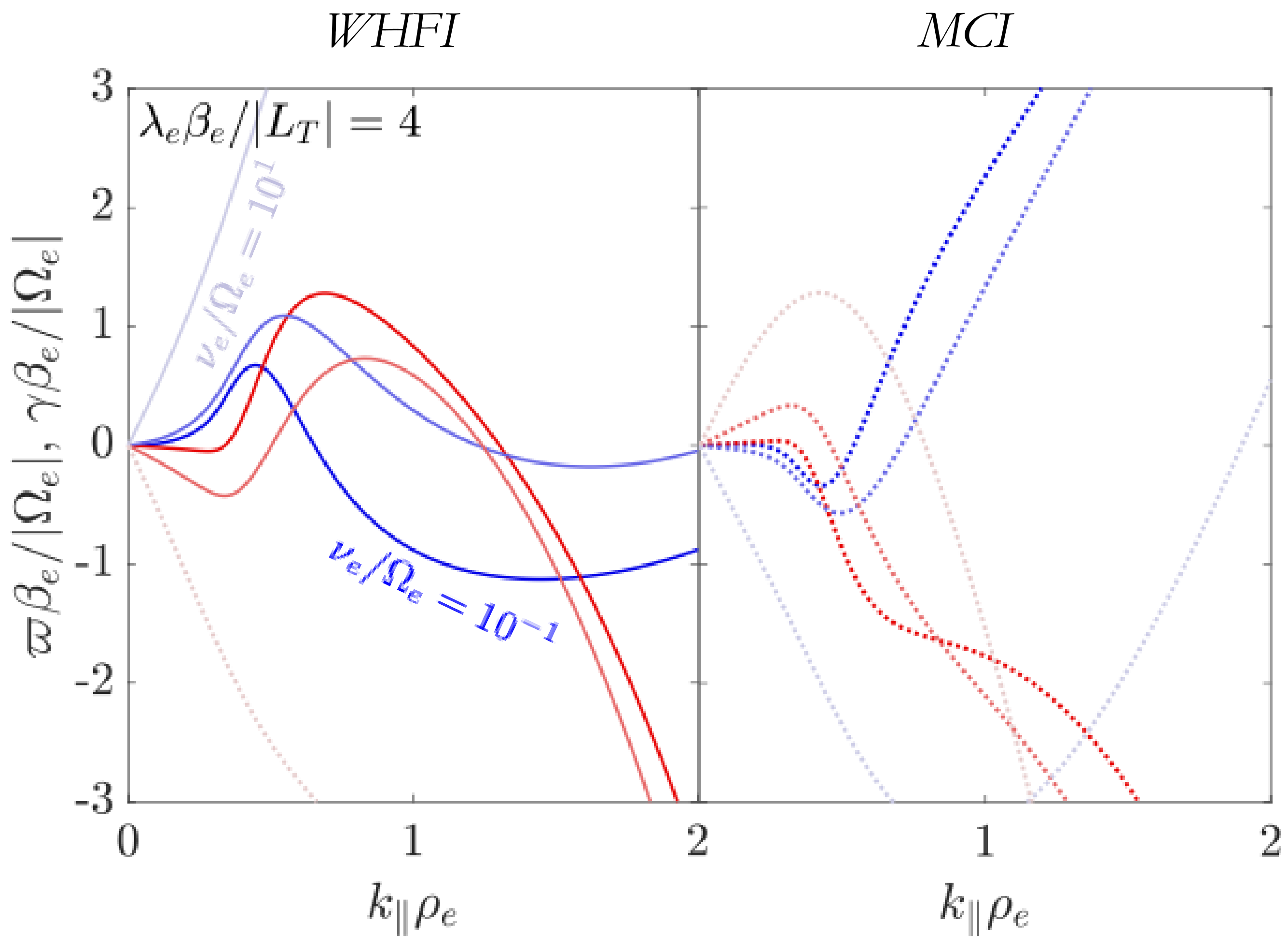

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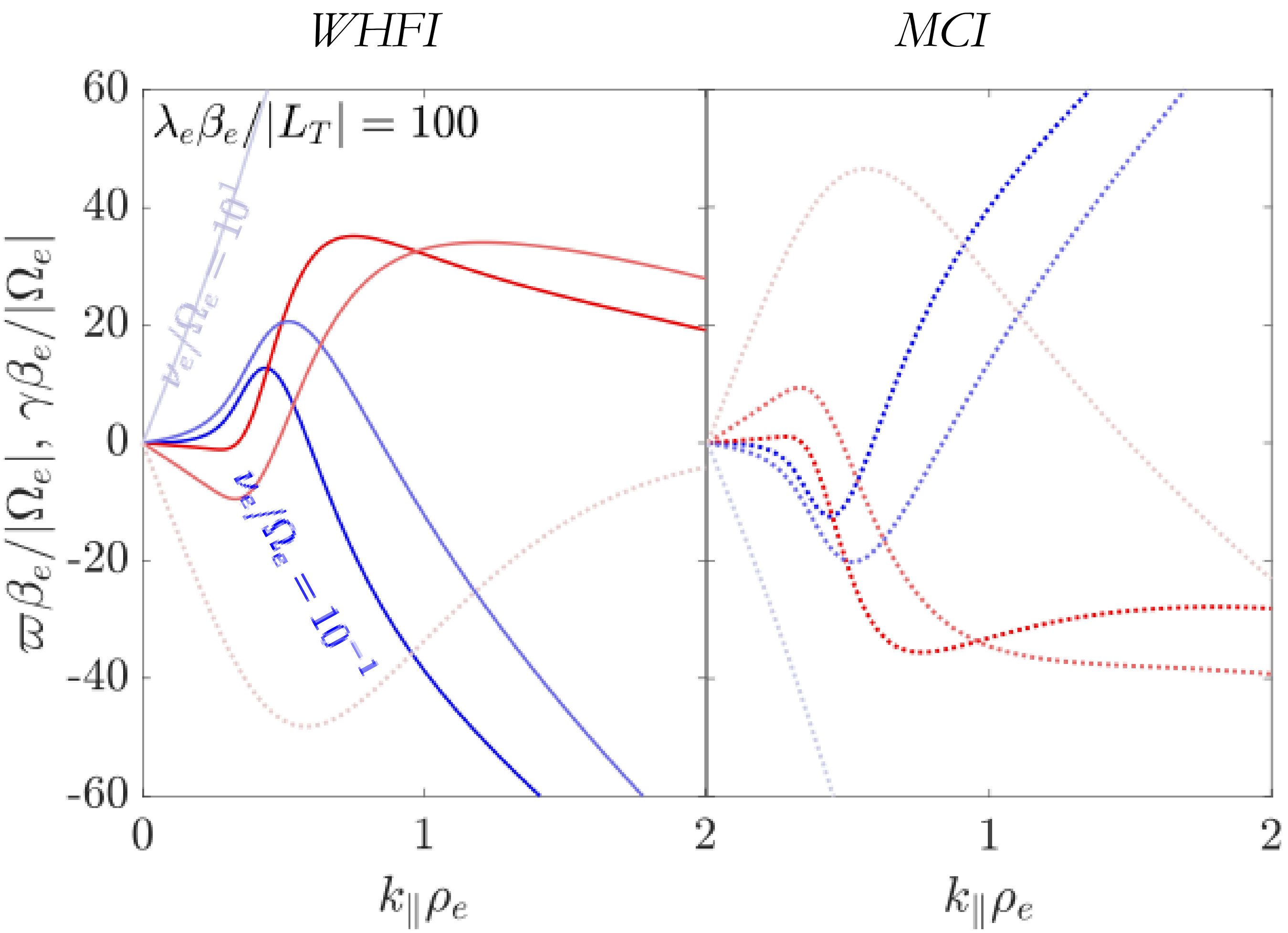


When $\nu_e \sim \Omega_e$, WHFI can still operate provided $\lambda_e\beta_e/L_\mathrm{T} \gtrsim 1$

- If $\lambda_e\beta_e/L_\mathrm{T} \gg 1$, then collisions don't affect WHFI much, and

$$\gamma_\mathrm{WHFI} \approx 0.36\frac{\lambda_e}{|L_\mathrm{T}|}\Omega_e,\ k_\mathrm{WHFI}\rho_e \sim 1.$$

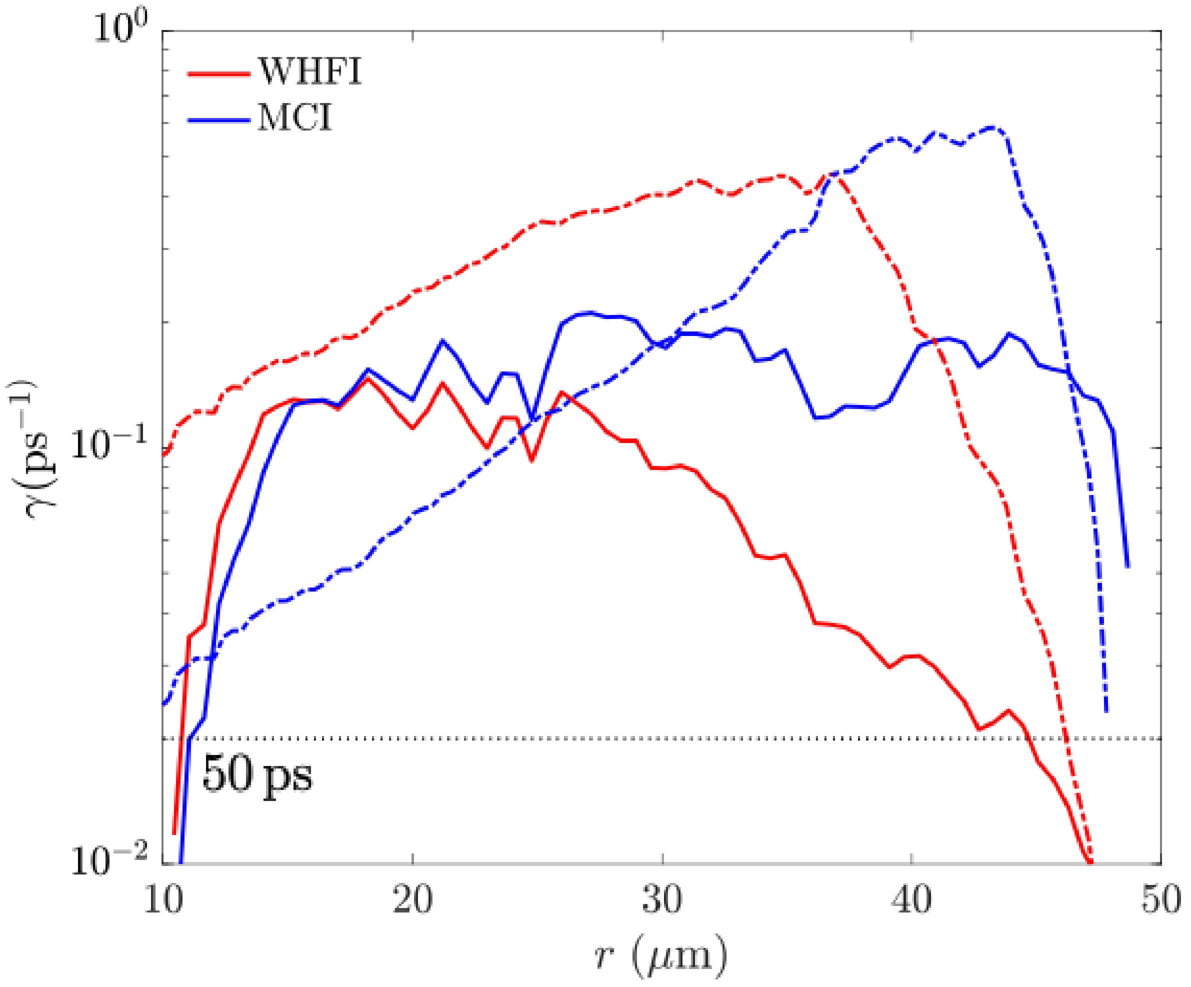
- For fixed $\lambda_e\beta_e/L_\mathrm{T}$, WHFI disappears at sufficiently high collisionality

MCI becomes dominant when $\nu_e \gtrsim \Omega_e$:

$$\gamma_\mathrm{MCI} \approx 0.11\frac{\nu_e}{|L_\mathrm{T}|}\Omega_e,\ k_\mathrm{WHFI}\rho_e < 1.$$

Are burning plasmas kinetically unstable?

Yes, to both the WHFI and the MCI!



- Inner part of hot-spot susceptible primarily to WHFI
- Outer part susceptible to MCI; fastest growth here
- Growth rate over an order of magnitude greater than macroscopic evolution rate for both instabilities
- In burning plasmas, expect WHFI instability to become increasingly important

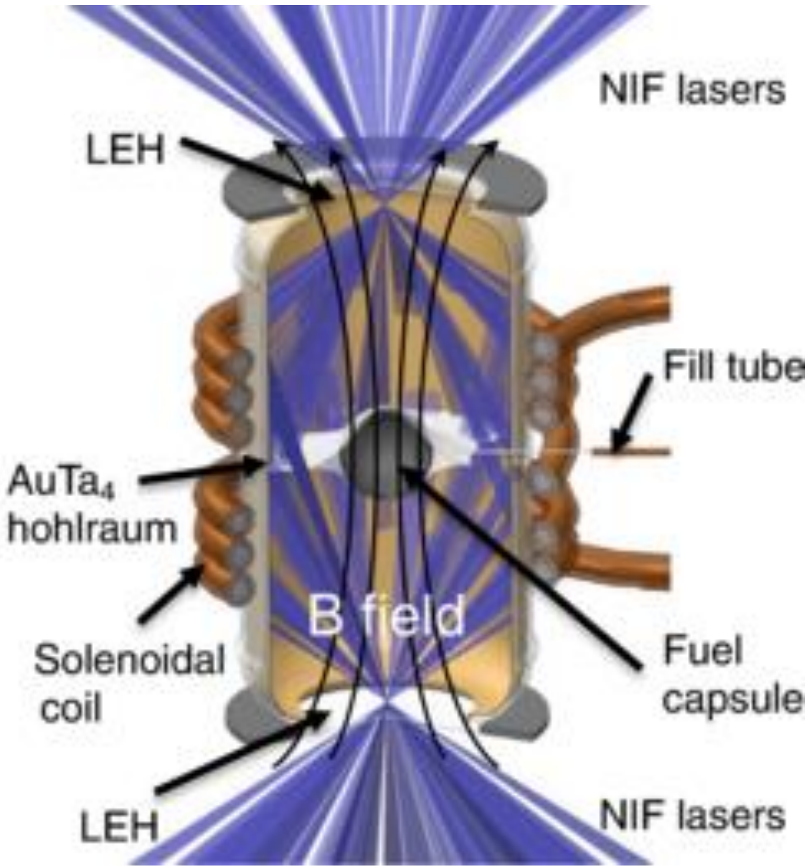
Next steps

1. Improved modelling of collisionality (beyond Lorentz operator)

2. Nonlinear (numerical) modelling of both WHFI and MCI instability saturation → determine heat fluxes

3. Understand implications for design of ICF capsules (including magnetised ICF)

4. Explore alpha-particle-flux-driven instabilities (can amplify the magnetic field) - what can be learned from MCF?



Moody *et al.* 2022