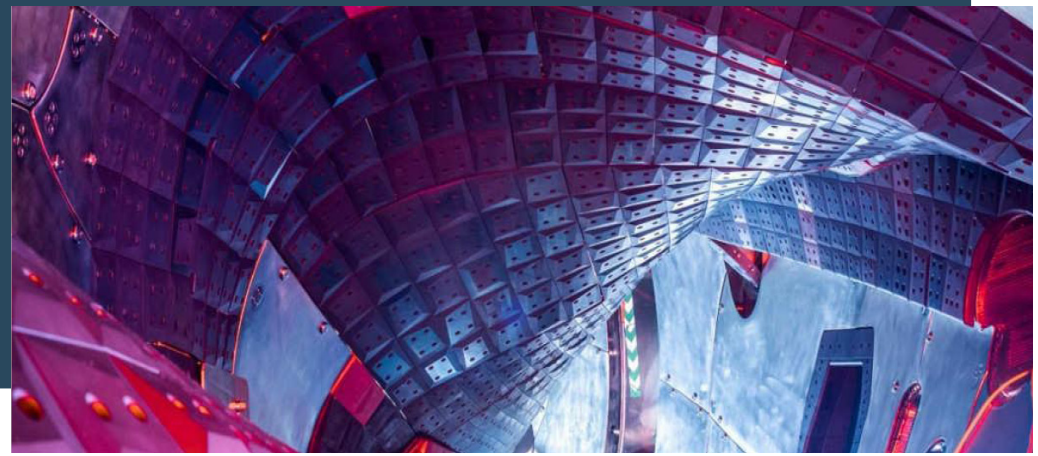
MAX-PLANCK-INSTITUT
FÜR PLASMAPHYSIK

Geometry effects on gyrokinetic instabilities and turbulence in W7-X

Wendelstein 7-X

Linda Podavini, Jan-Peter Bähner, Alejandro Bañon Navarro, Miklos Porkolab, Eric M. Edlund, Adrian von Stechow, Olaf Gurke, Alessandro Zocco and the W7-X Team



EUROfusion

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Introduction

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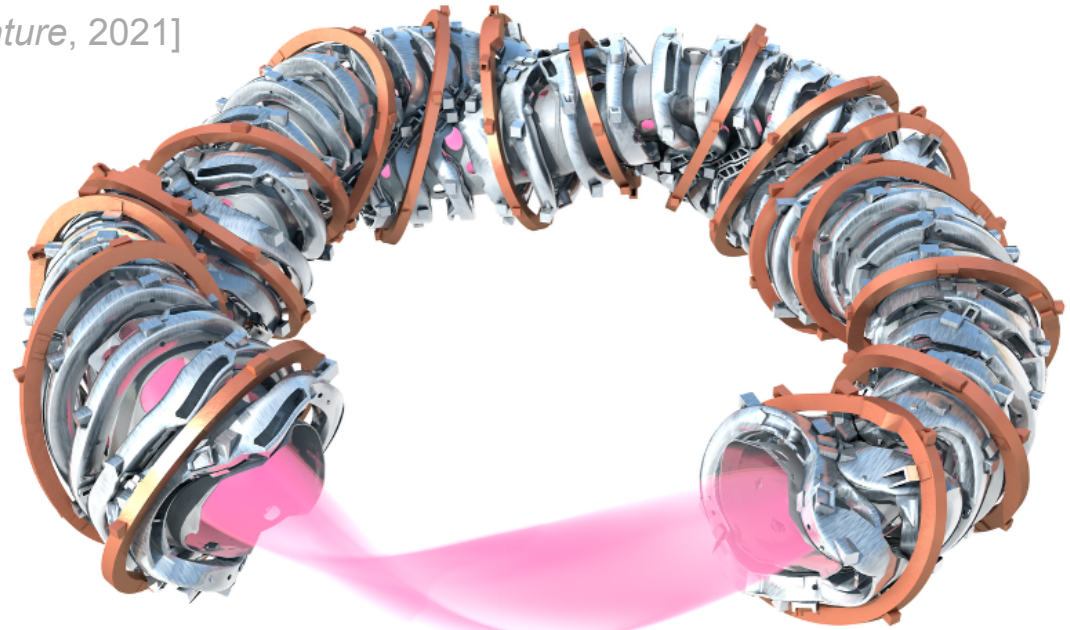

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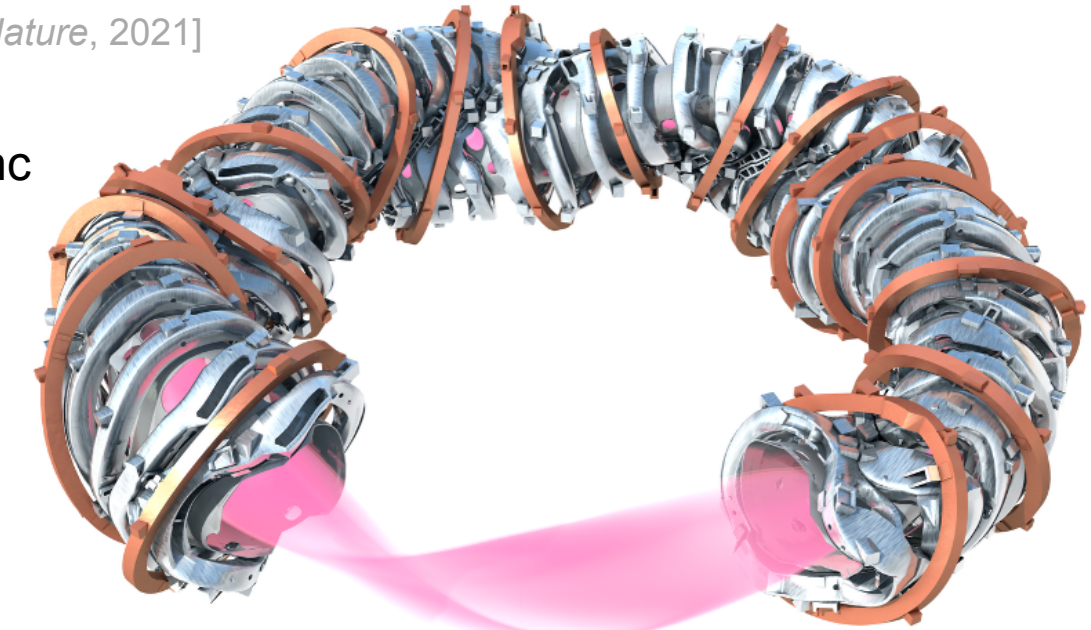
  [Bozhenkov *et al., NF,* 2020; Wappl *et al., PPCF,* 2025]



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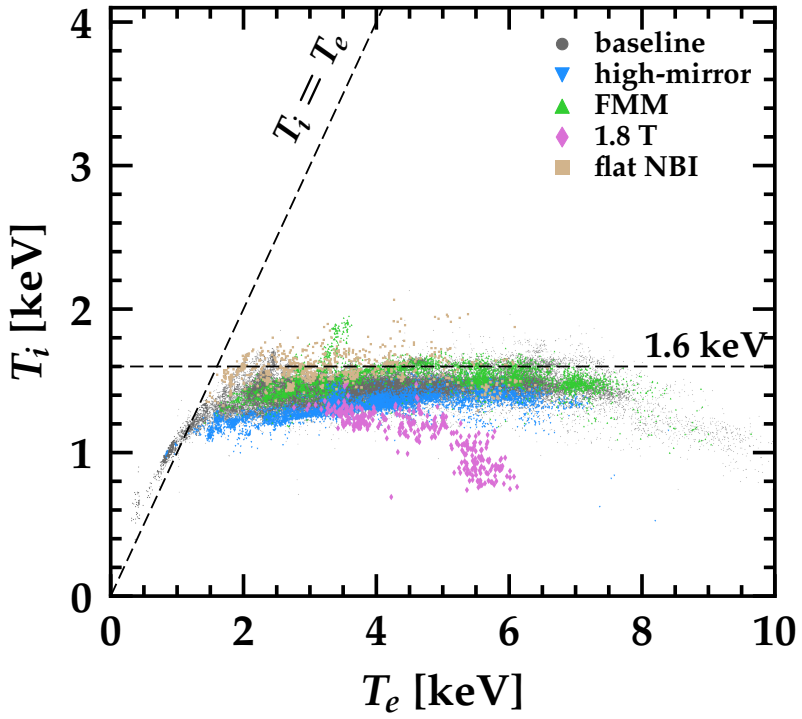
- **T_i clamping at 1.6 keV regardless of heating power:** inefficient electron-to-ion thermal coupling in an ITG-driven turbulence dominated regime with large T_e/T_i (as observed and reproduced in AUG) [Beurskens *et al., NF,* 2021; Bañon Navarro *et al., NF,* 2023]



Bozhenkov *et al., 51st EPS Vilnius,* 2025

Turbulence characterisation in W7-X

- **Density fluctuations relation to turbulence-relevant parameters consistent with ITG** (**P**hase **C**ontrast **I**maging — **PCI**) [Carralero *et al.*, *NF*, 2021; *PPCF*, 2022; Bähner, *PhD Thesis*, 2022]

- **Numerous gyrokinetic simulations predict ITG importance,** validated by experimental observations [Bähner *et al.*, *JPP*, 2021; González-Jerez *et al., NF,* 2024; Agapito Fernando *et al., submitted to PoP,* 2025]

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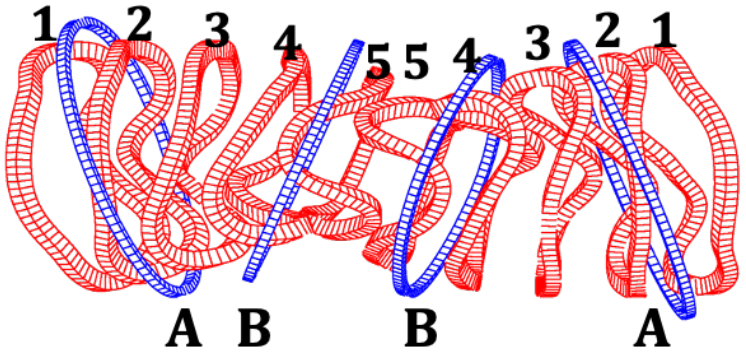
Key aspects of these questions addressed with:

➡ **Direct numerical comparison with W7-X data**

➡ **Gyrokinetic numerical experiments**

Magnetic configuration effects on W7-X turbulence



One field period of the W7-X coil system [courtesy of J. Geiger]

- Flexible coil current system allows large variety of configurations [Geiger et al., PPCF, 2015]

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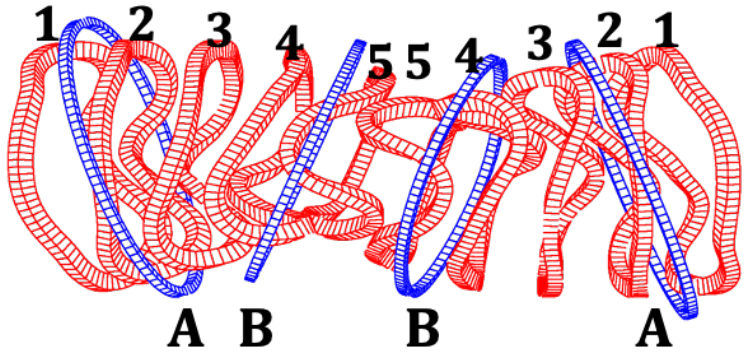

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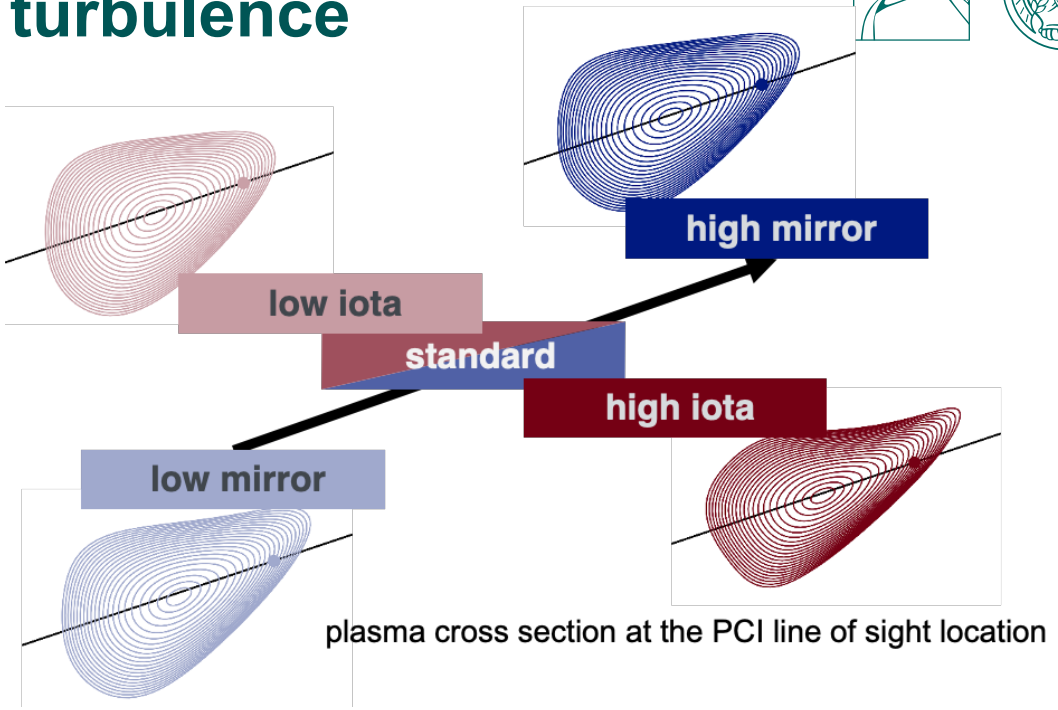

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- Possible to scan **rotational transform** $\iota = 1/q$ and **magnetic mirror ratio** (ratio of neighbouring local minima and maxima of $|B|$)

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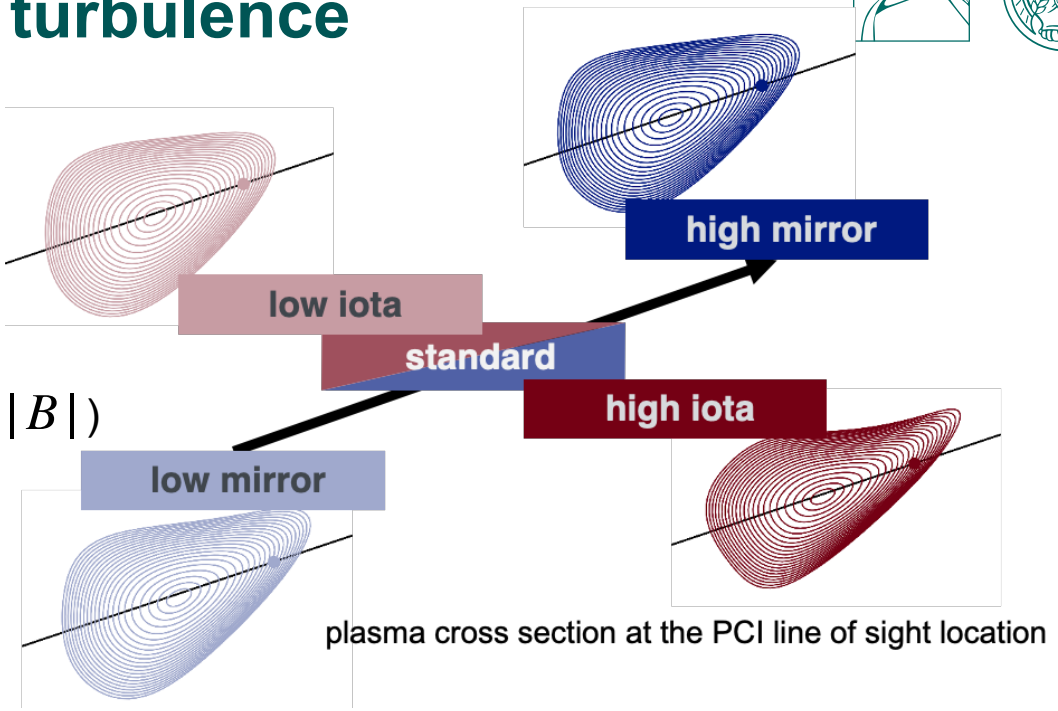
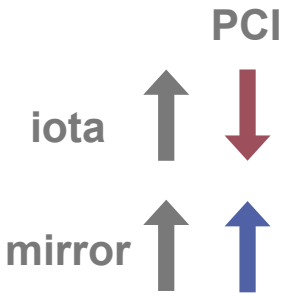
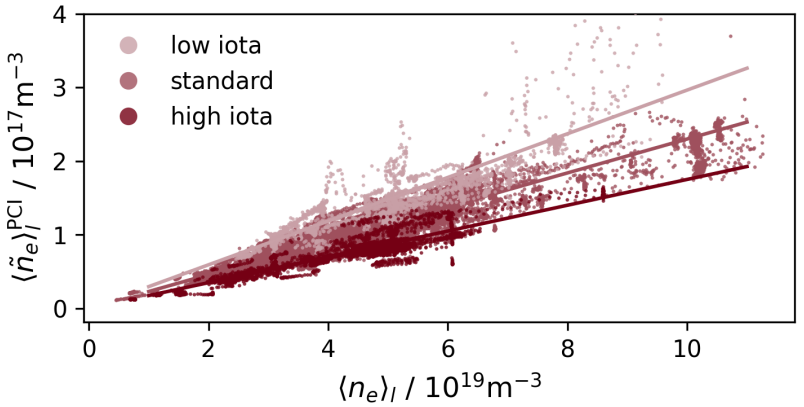
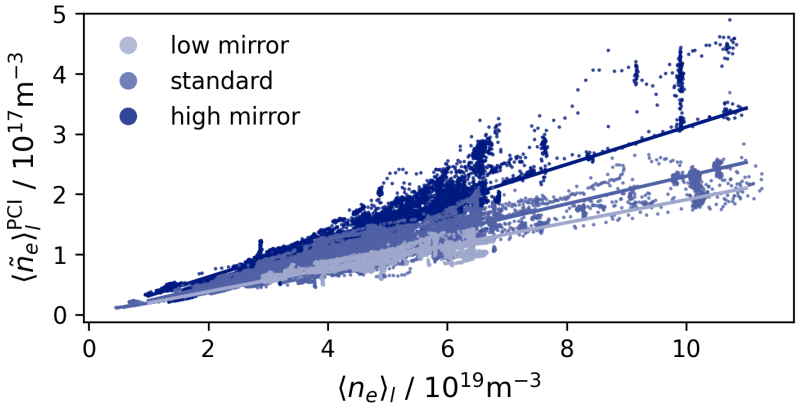


PCI measures reduction of density fluctuations in ECRH plasmas when increasing iota and decreasing mirror ratio [Bähner, Podavini *et al.*, *submitted to NF*, 2025]



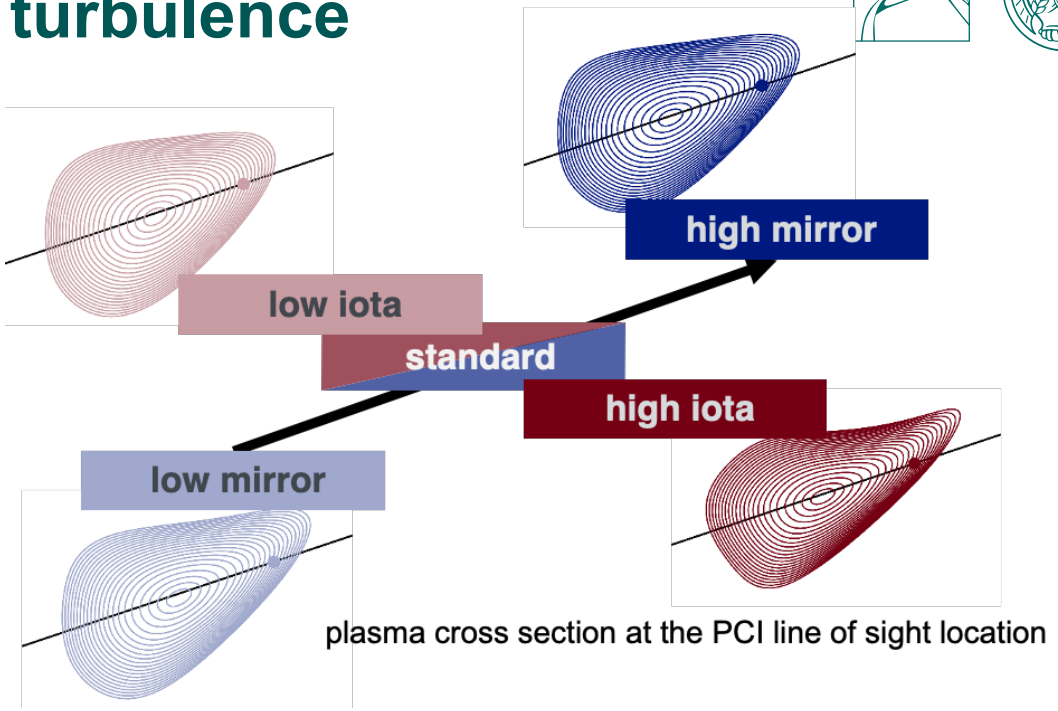




Magnetic configuration effects on W7-X turbulence

`stella` nonlinear flux-tube simulations:

- 6 flux-tubes crossing the PCI line of sight at $r_{eff}/a = 0.75$, ~ 1 poloidal turn long
- Assumption of **equal kinetic profiles to isolate geometry effects**
  fixed $a/L_{Ti} = -aT_i^{-1}dT_i/dr$ and $a/L_n = -an^{-1}dn/dr$
- Kinetic electrons included



plasma cross section at the PCI line of sight location

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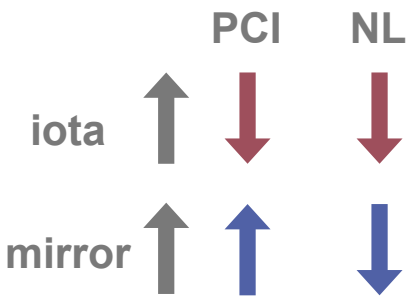
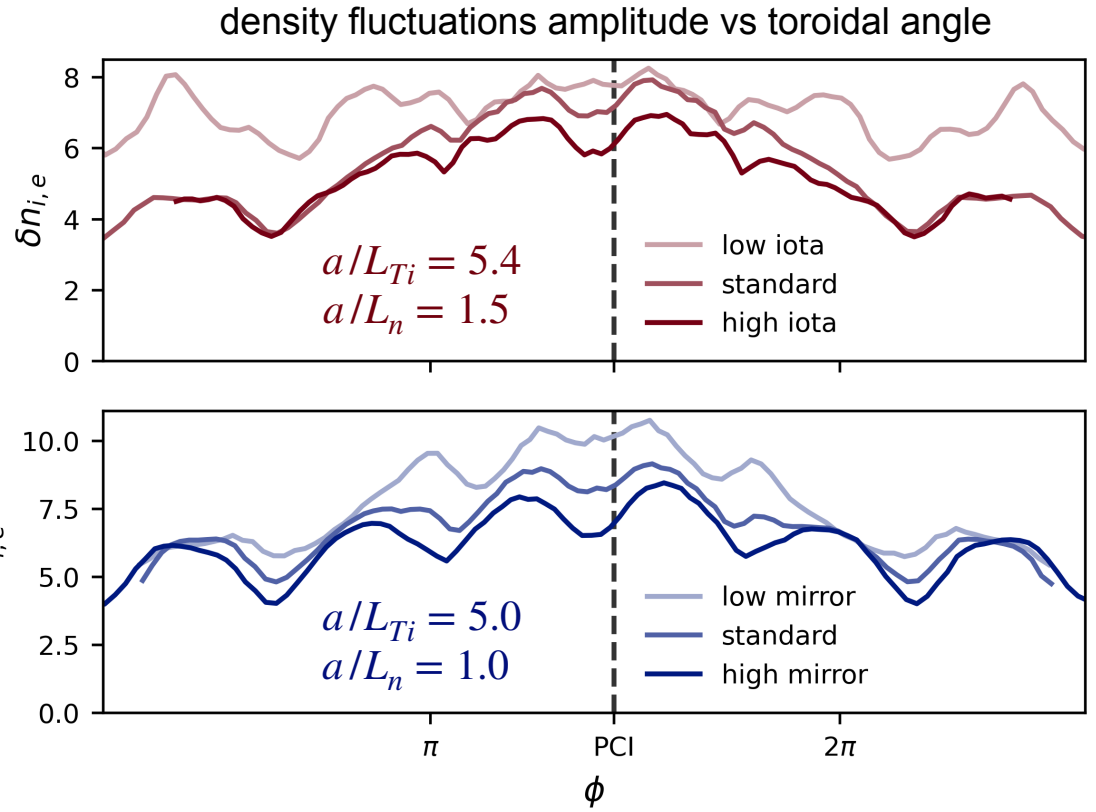


$\sim 10\,\%$ reduction
matches PCI

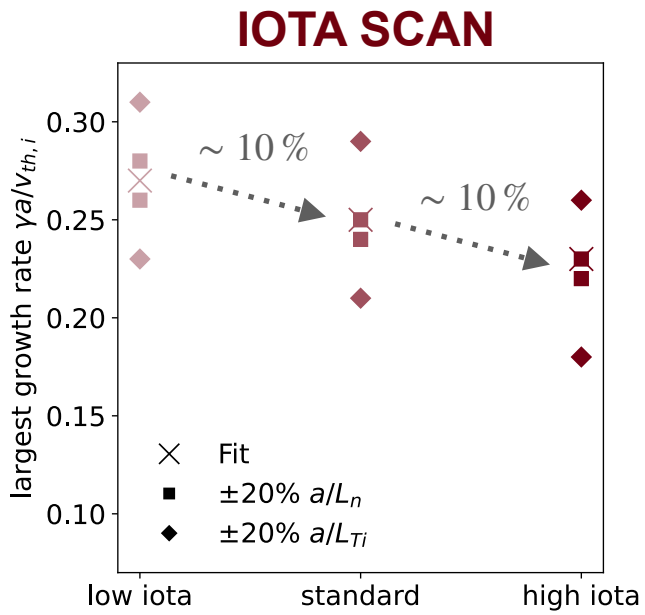
$\sim 20\,\%$ reduction
does not match PCI
(discrepancy not understood at present)

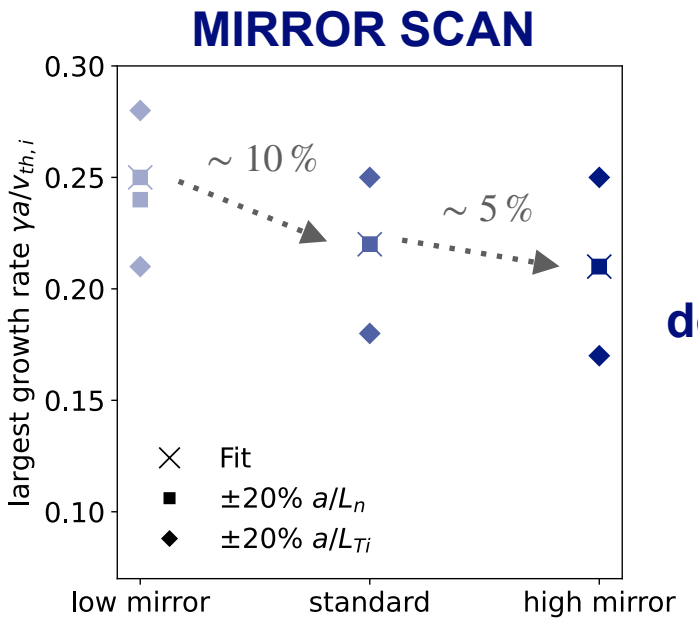


Magnetic configuration effects on W7-X turbulence

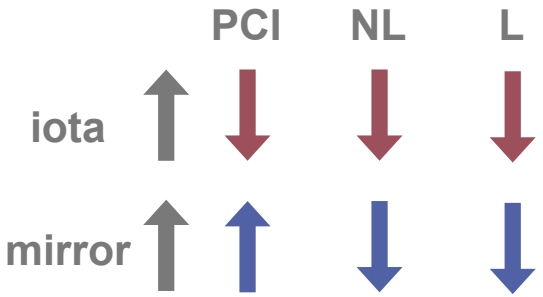
Linear simulations identify turbulence drive

matches PCI





does not match PCI



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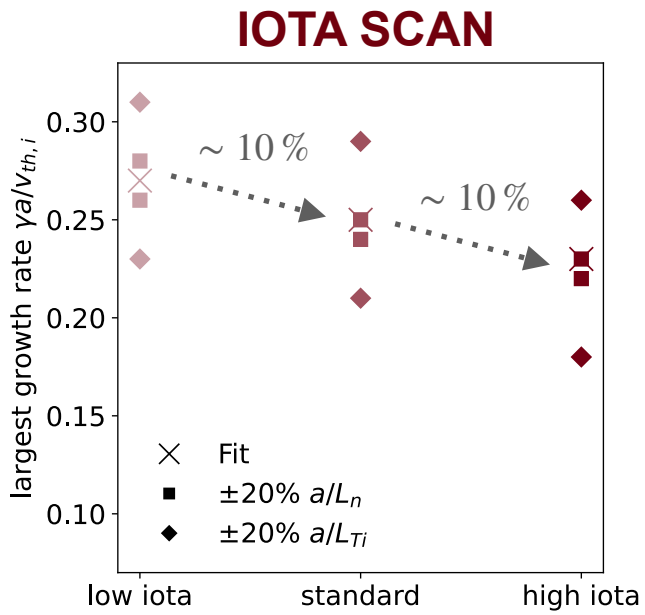

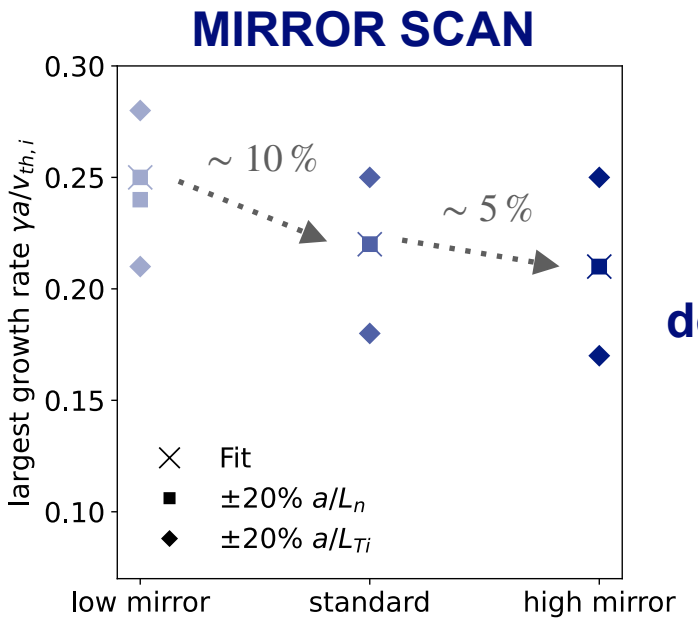

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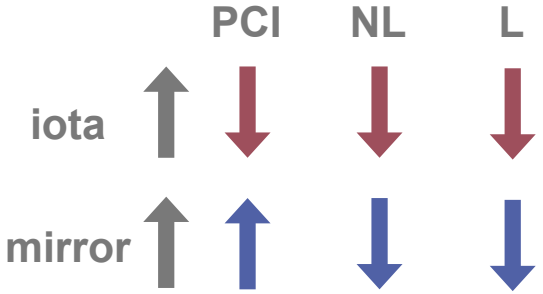
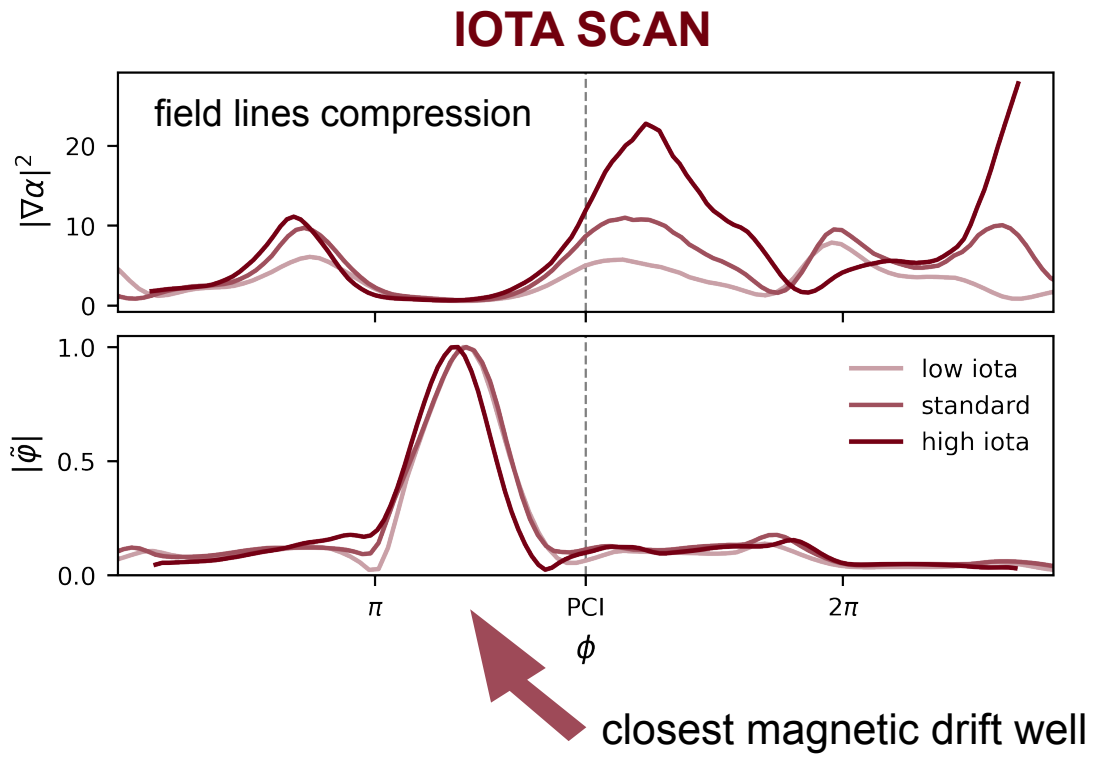


- **Same suppression trends as nonlinear simulations**
- Trend still visible with $\pm 20\,\%\, a/L_{Ti}$ variation
- $\pm 20\,\%\, a/L_n$ variation does not affect growth rate

} **turbulence is ITG dominated**

Magnetic configuration effects on W7-X turbulence

Parallel structure of electrostatic potential $|\tilde{\varphi}|$ vs geometry gives a hint on linear drive suppression mechanisms



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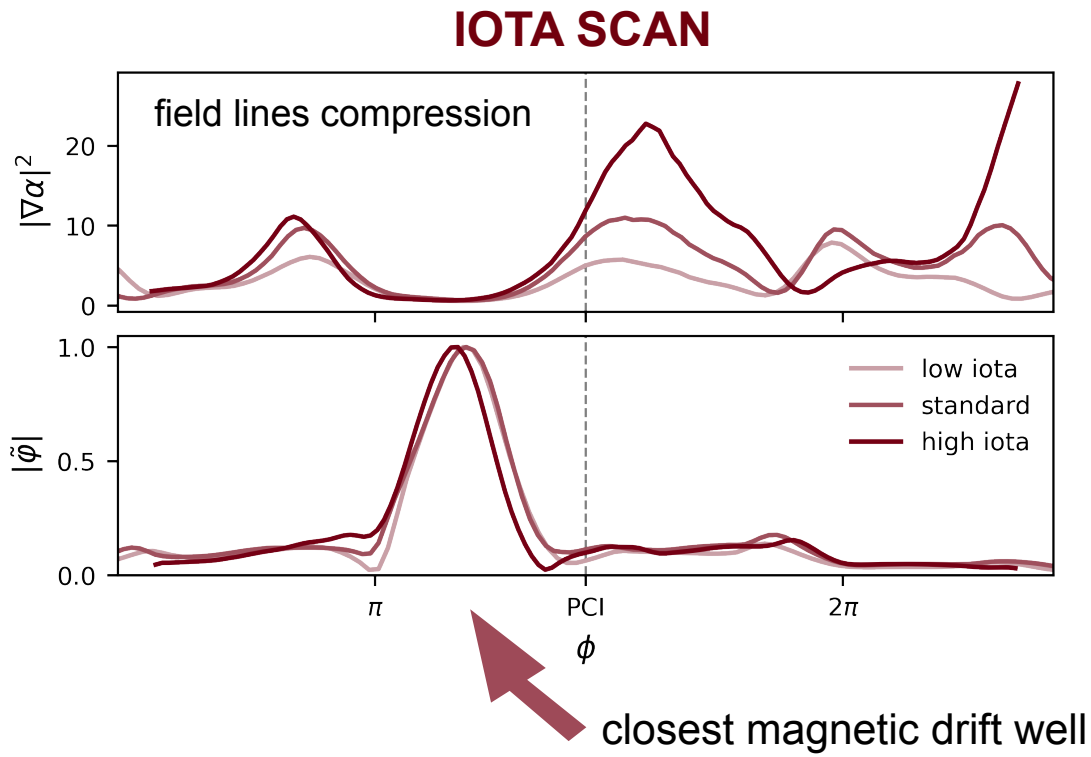

- **Increased local shear effect** ($\propto |\nabla\alpha|^2$) produces **FLR stabilisation** + marginal reduction of curvature drive with increasing ι
- Effect also exploited in critical gradient optimisation [Roberg-Clark *et al.*, *PRR*, 2023]

$$J_0\left(\frac{k_\perp v_\perp}{\Omega_i}\right) \approx J_0\left(\frac{k_\alpha |\nabla\alpha| v_\perp}{\Omega_i}\right)$$

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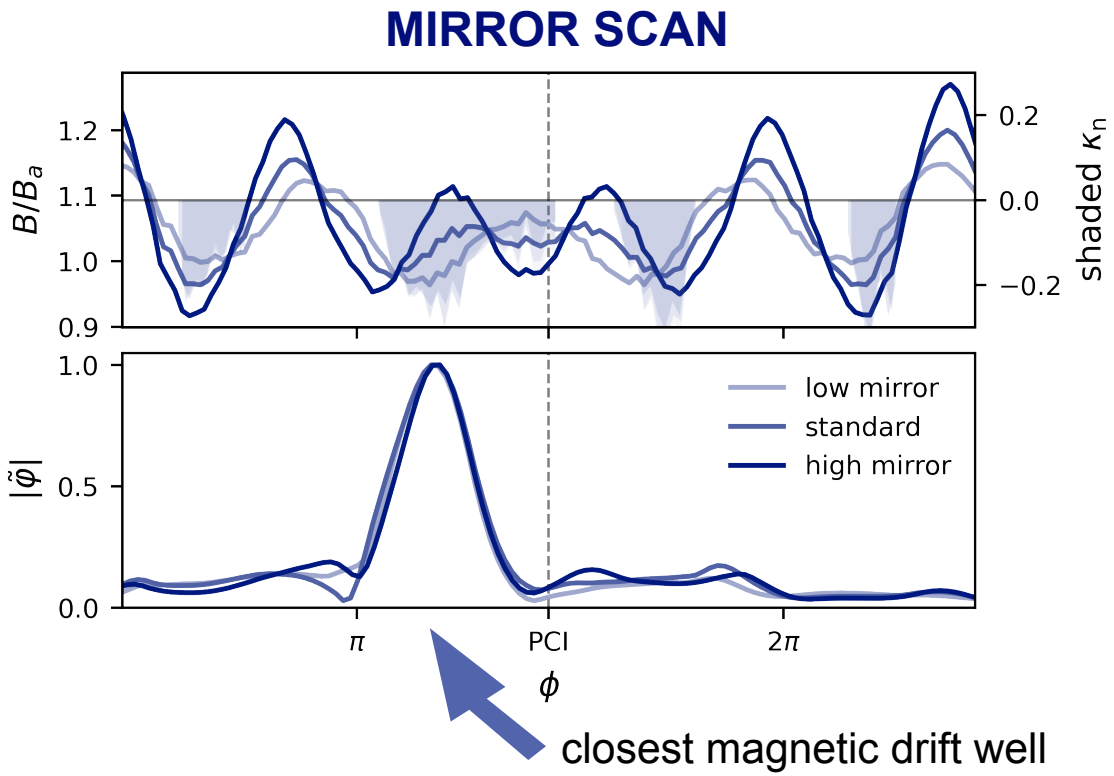

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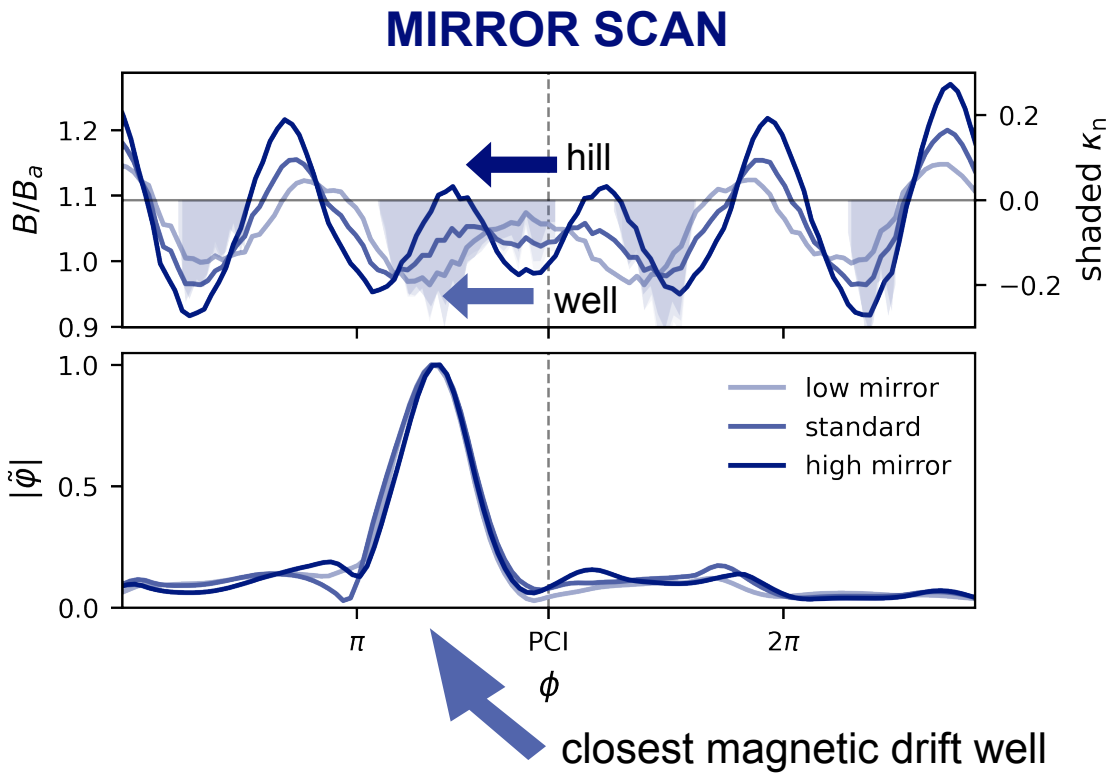


- **Displacement of magnetic wells** from bad curvature regions – more robust reduction of curvature drive but no significant $|\nabla\alpha|^2$ change
- Trapped particles can further stabilise/destabilise ITG [Costello *et al., JPP,* 2024]

Magnetic configuration effects on W7-X turbulence

Nonlinear global GENE-3D simulations including all effects:

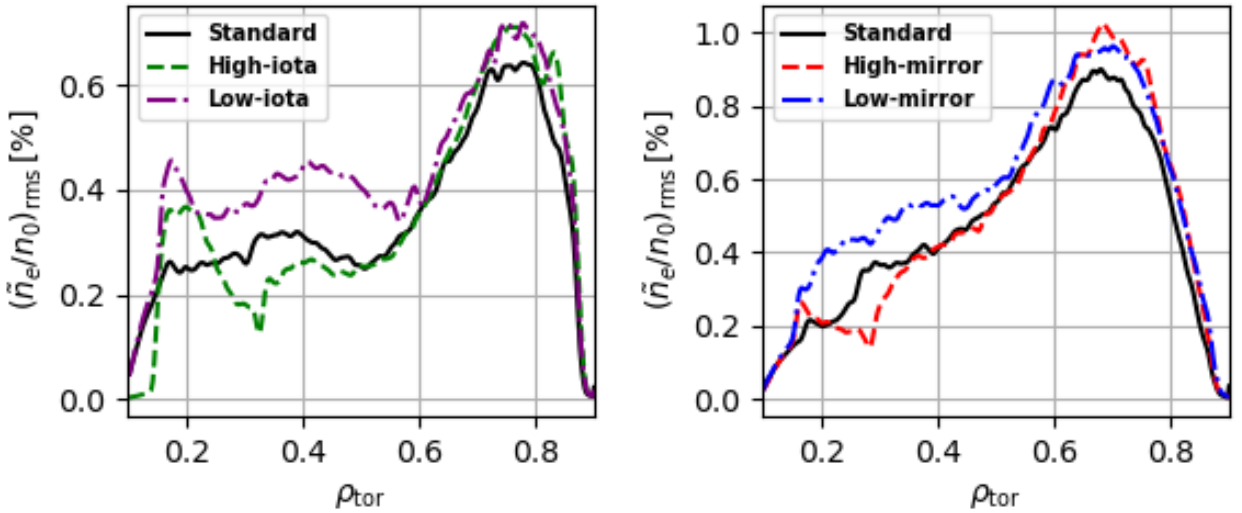
➡ E_r profiles from neoclassical transport calculations

➡ Electromagnetic

➡ Kinetic electrons

➡ Collisions

density fluctuations vs normalised radius



[Courtesy of A. Bañon Navarro]

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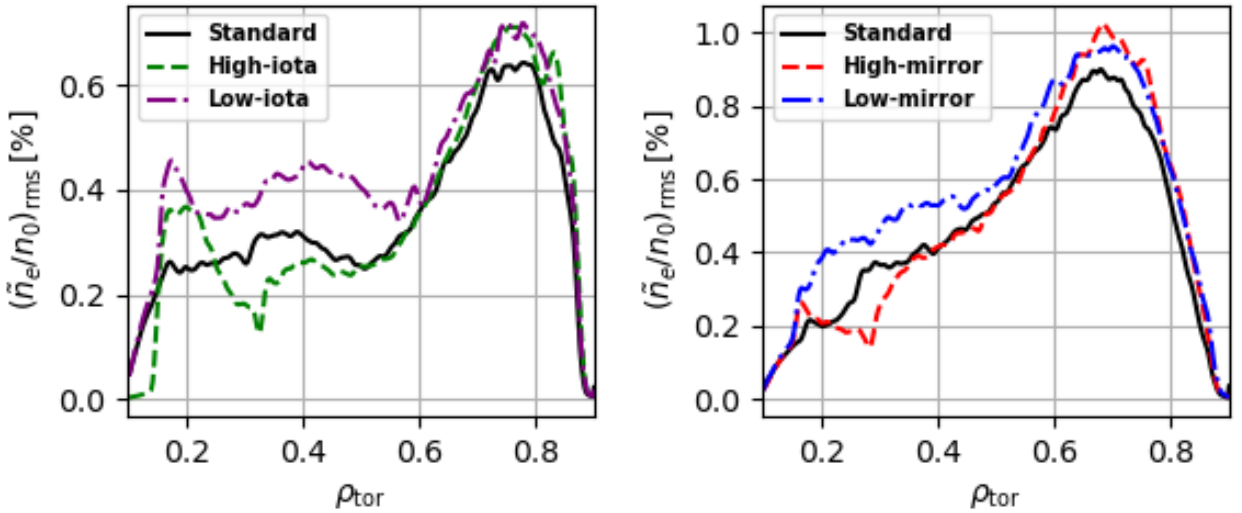

[Courtesy of A. Bañon Navarro]

- Global results align with the flux-tube simulations, though effects are less pronounced
- Trends are not radially unique
- **Future work:** evaluate impact on confinement and address unresolved disagreement for mirror ratio scan

Tailoring ι for turbulence control

- Experimentally, the dependence of turbulence on the global value of ι can be studied

- **What about the shape of ι?**
  - ➡ Can be used to reduce turbulence in near-marginal or high performance discharges

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  - ➡ **Behaviour of ITG close to critical threshold?**

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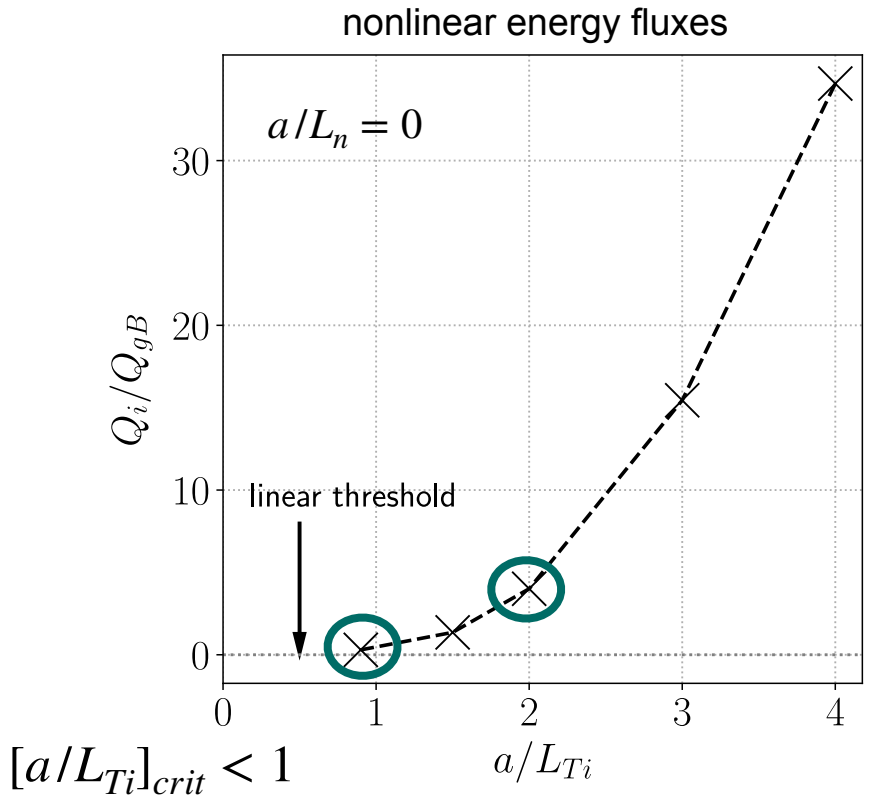
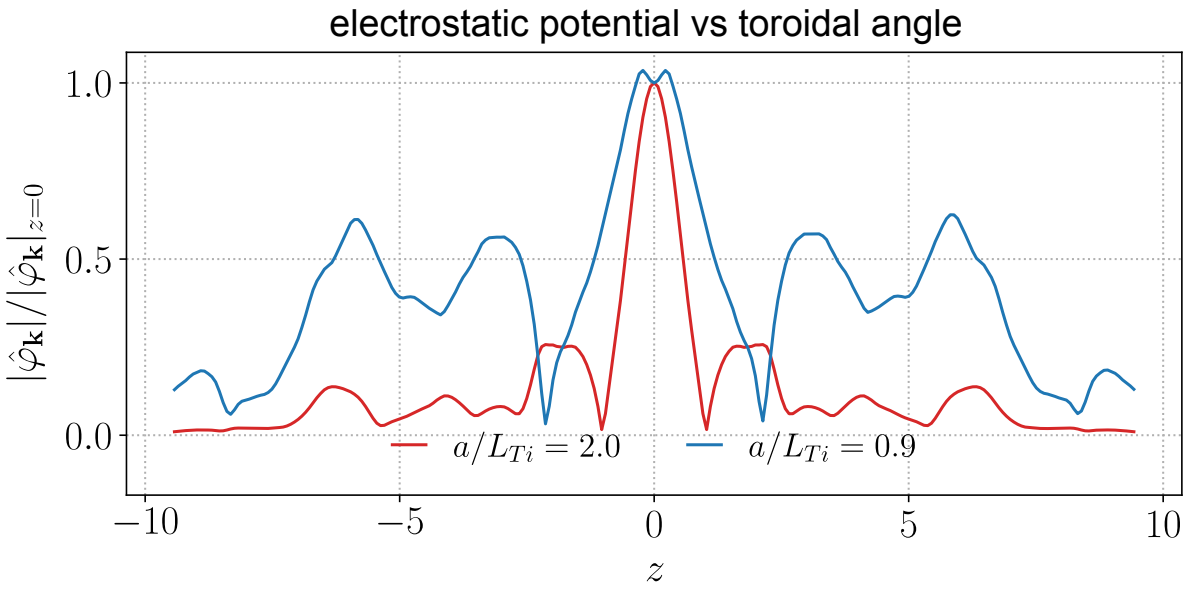
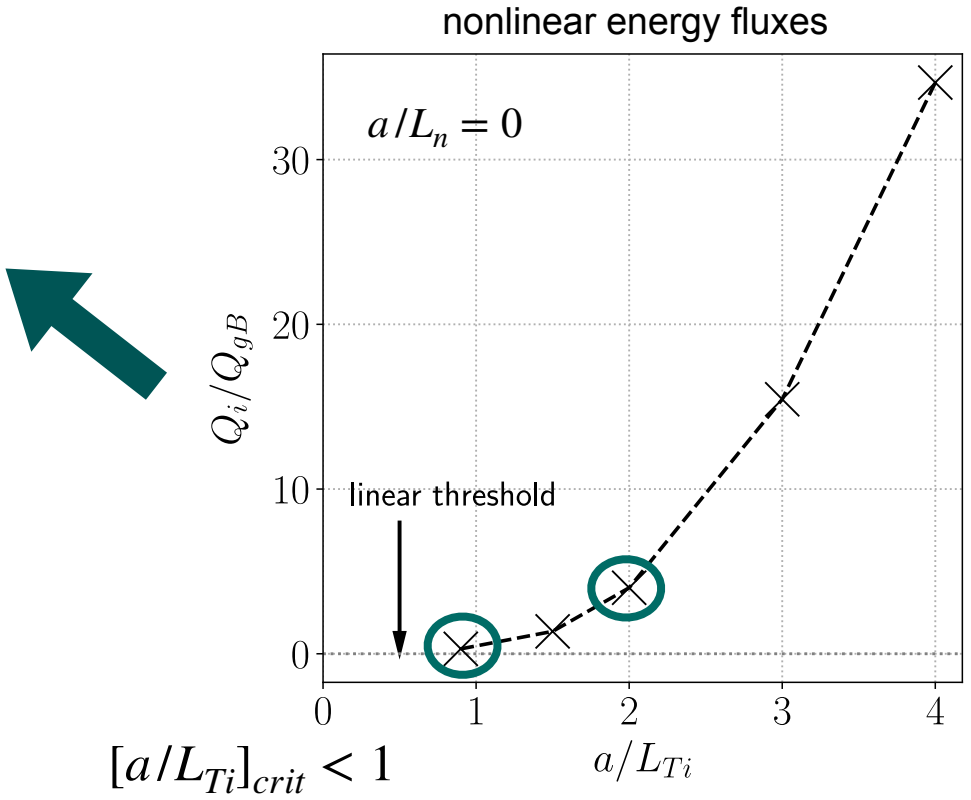
W7-X suffers from (linear and nonlinear) small critical threshold for ITG destabilisation

[Zocco *et al., PPCF,* 2015; *JPP,* 2018; *PRE*, 2022; Podavini *et al., JPP,* 2024]



High-performance discharges in W7-X



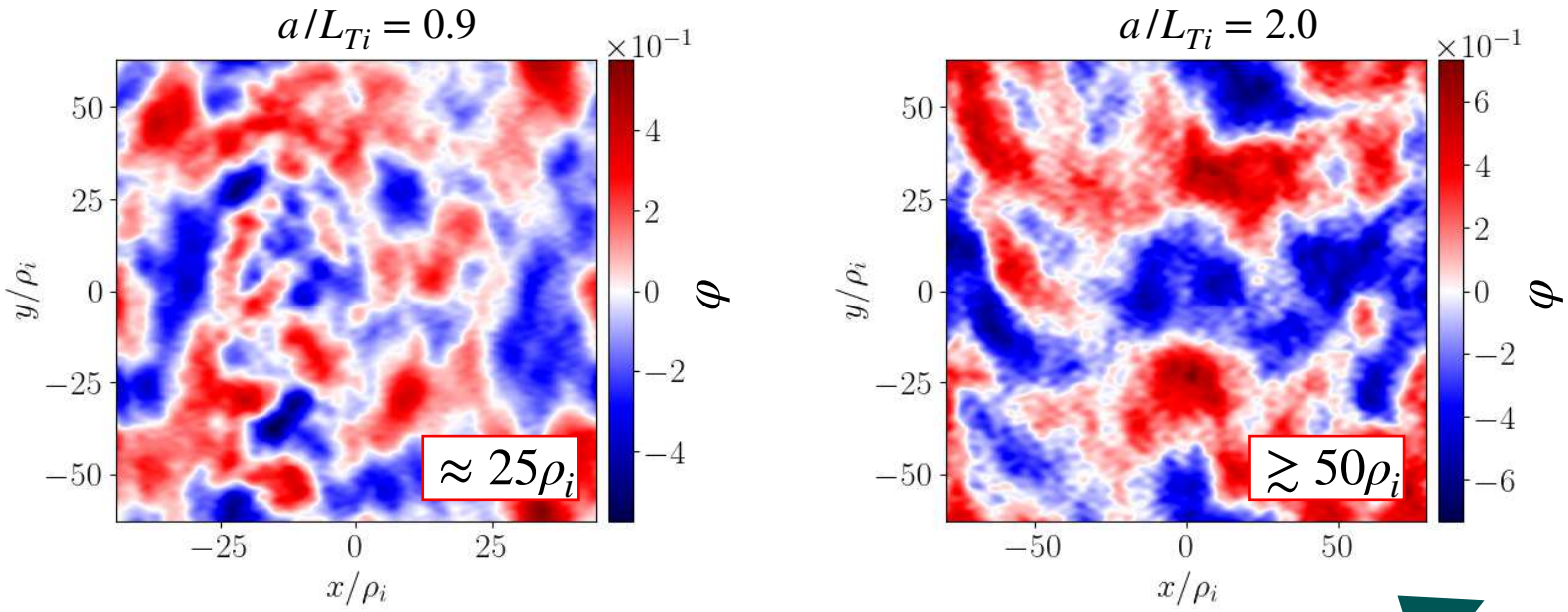


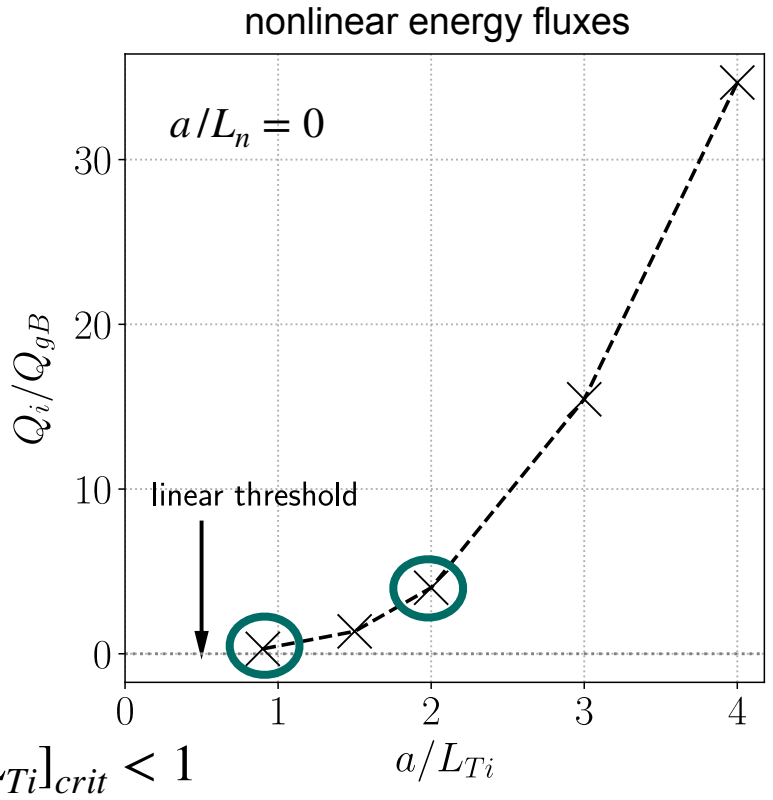
Extended (Floquet-like) modes

dominate close to the threshold

[Zocco *et al., PPCF,* 2015; *JPP,* 2018; *PRE*, 2022; Podavini *et al., JPP,* 2024]

High-performance discharges in W7-X





Small but finite energy flux due to smaller radial structure of fluctuations

[Zocco et al., PPCF, 2015; JPP, 2018; *PRE*, 2022; Podavini *et al., JPP,* 2024]

Tailoring ι for turbulence control

- **Expected dependence of transport on the ι-profile**, as experimentally observed in tokamaks
  - ➡ **Can ι tailoring be used to suppress extended modes?**

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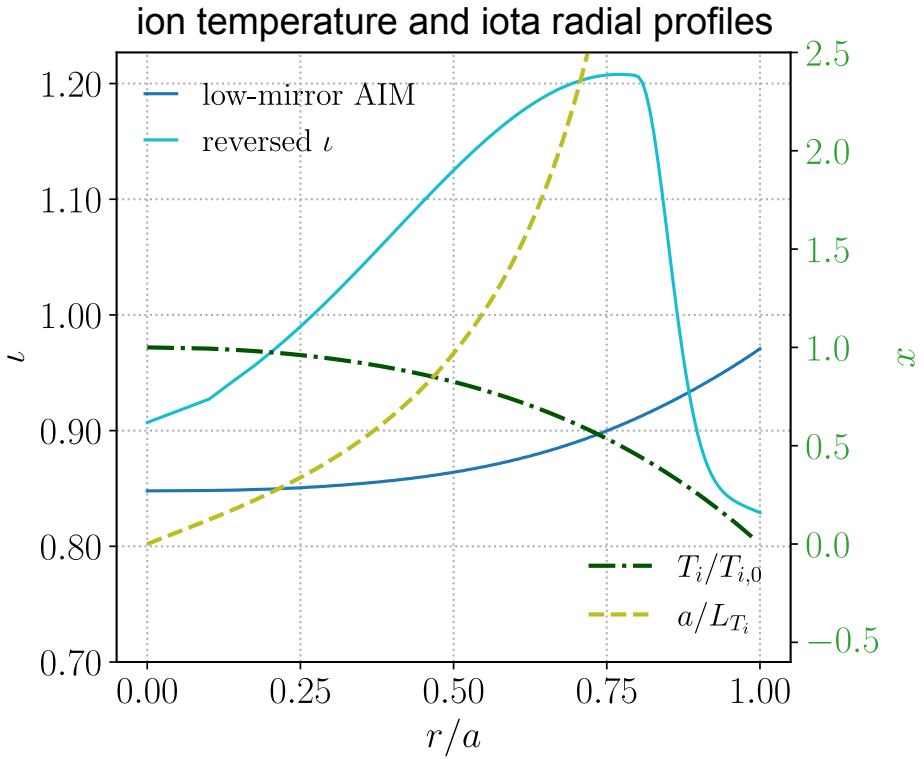
  - ➡ **Can ι tailoring be used to suppress extended modes?**

- ι-profile distortion more experimentally challenging for W7-X, but can achieved through **E**lectron **C**yclotron **C**urrent **D**rive (**ECCD**) — already used for bootstrap current control [Zanini *et al., NF*, 2020; *NF*, 2021; Geiger *et al., PPCF,* 2015]

Tailoring ι for turbulence control

- Unrealistic but not unphysical ι **tailoring where normalised ion temperature gradient is largest**



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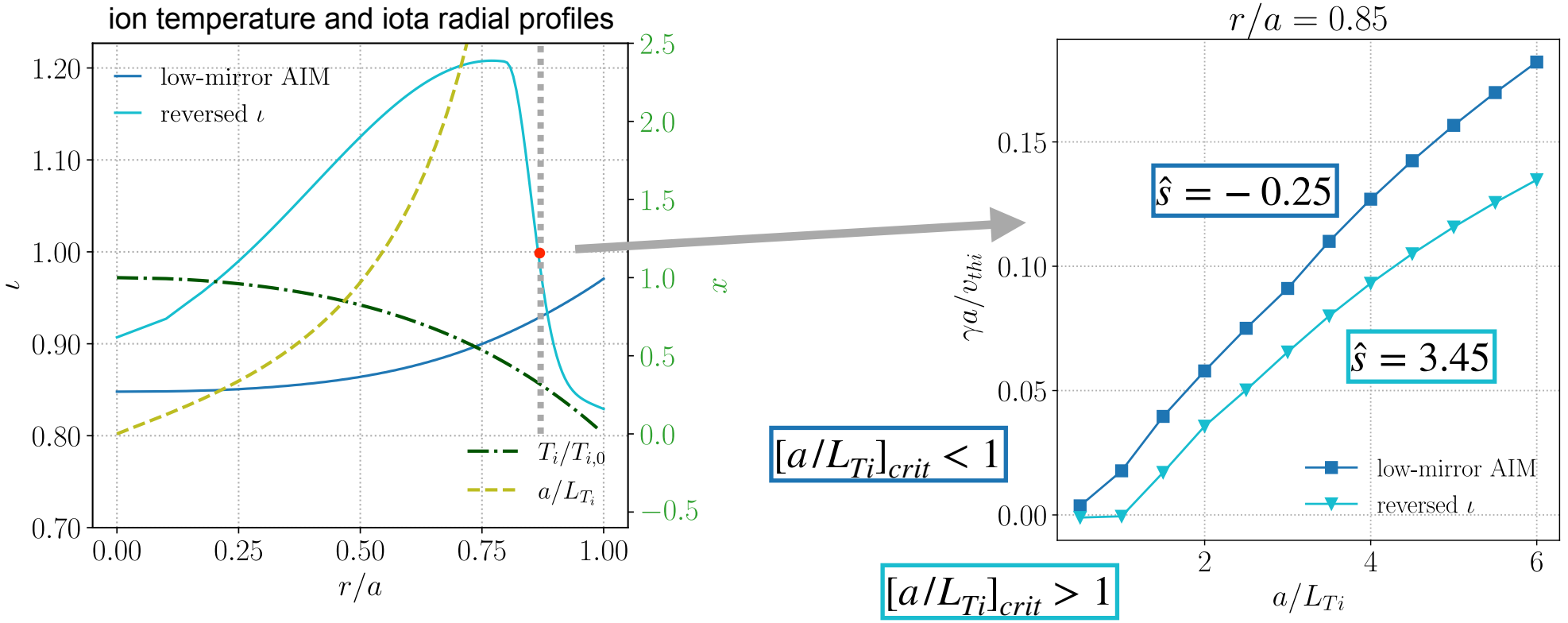


Large magnetic global shear $\hat{s}$ can suppress extended modes and increase the threshold

Conclusions

- Turbulence modelling of W7-X important to **understand confinement and improve performances**

- **Dependence on magnetic configuration** is small but both predicted by gyrokinetics and experimentally observed

- 3D geometry makes turbulence studies difficult, but it can be exploited, e.g.

  ➡ **FLR suppression** of ITG achieved via local or global shear

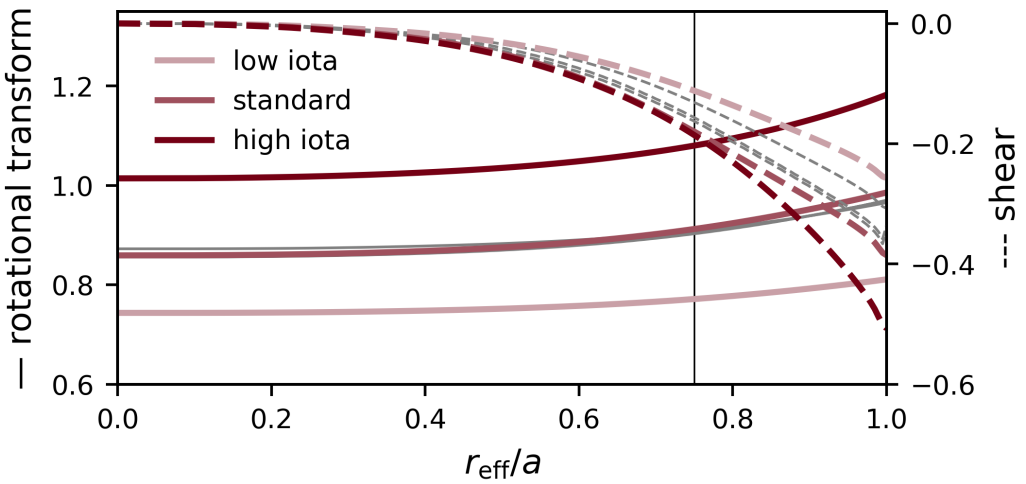
  ➡ **Displacement of trapped particles** from regions of bad curvature

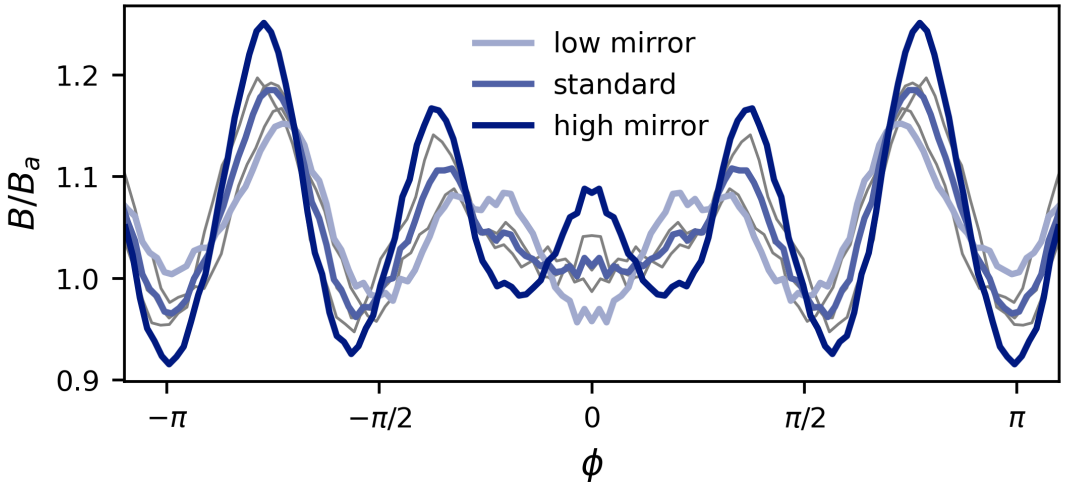
  } **new W7-X configuration with better performance?**

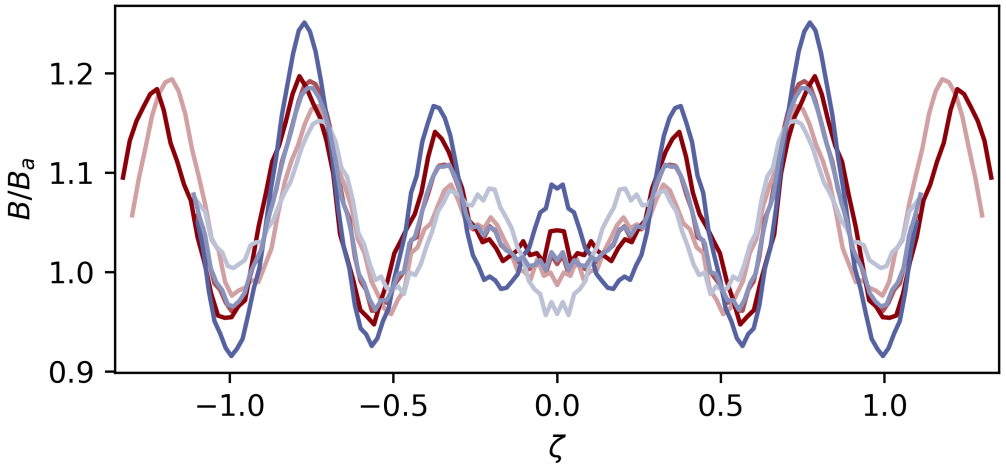
  ➡ New operational scenarios, exploiting ι **tailoring**, to increase the pathologically small critical gradient in W7-X

Additional material

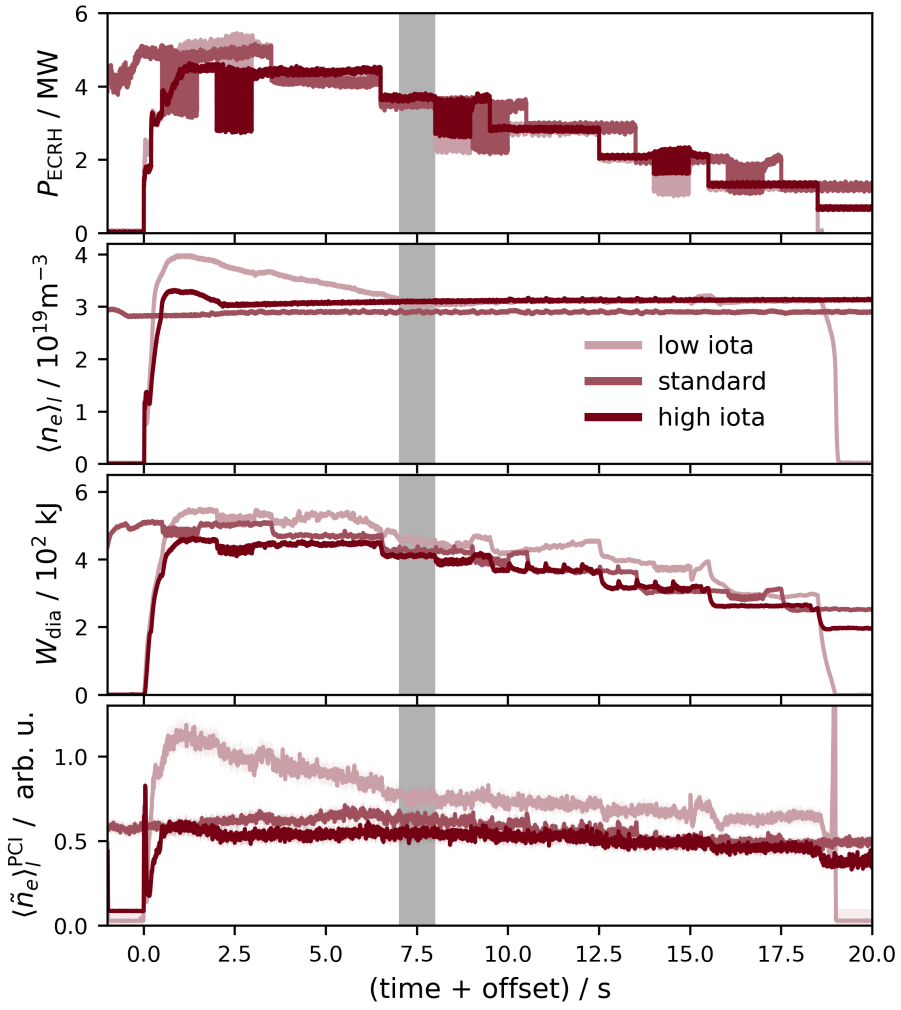
Geometry

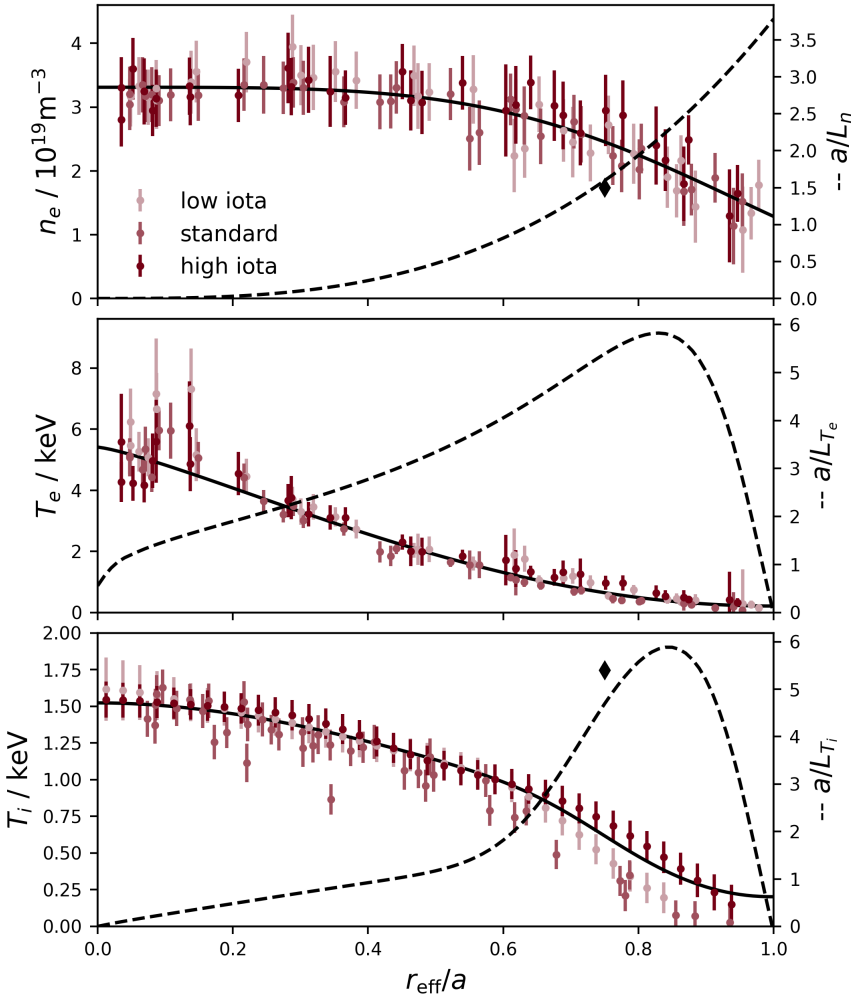

low iota
standard
high iota
— rotational transform
--- shear
r_{eff}/a


low mirror
standard
high mirror
B/B_a
ϕ

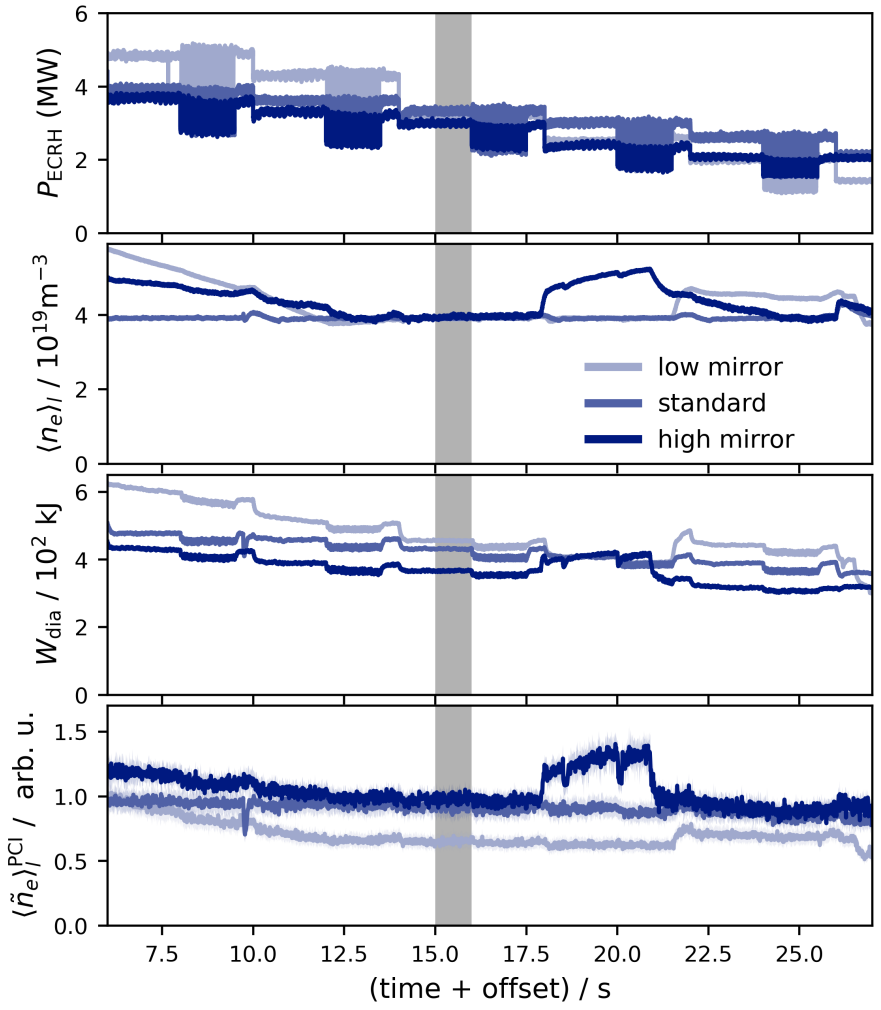

B/B_a
ζ

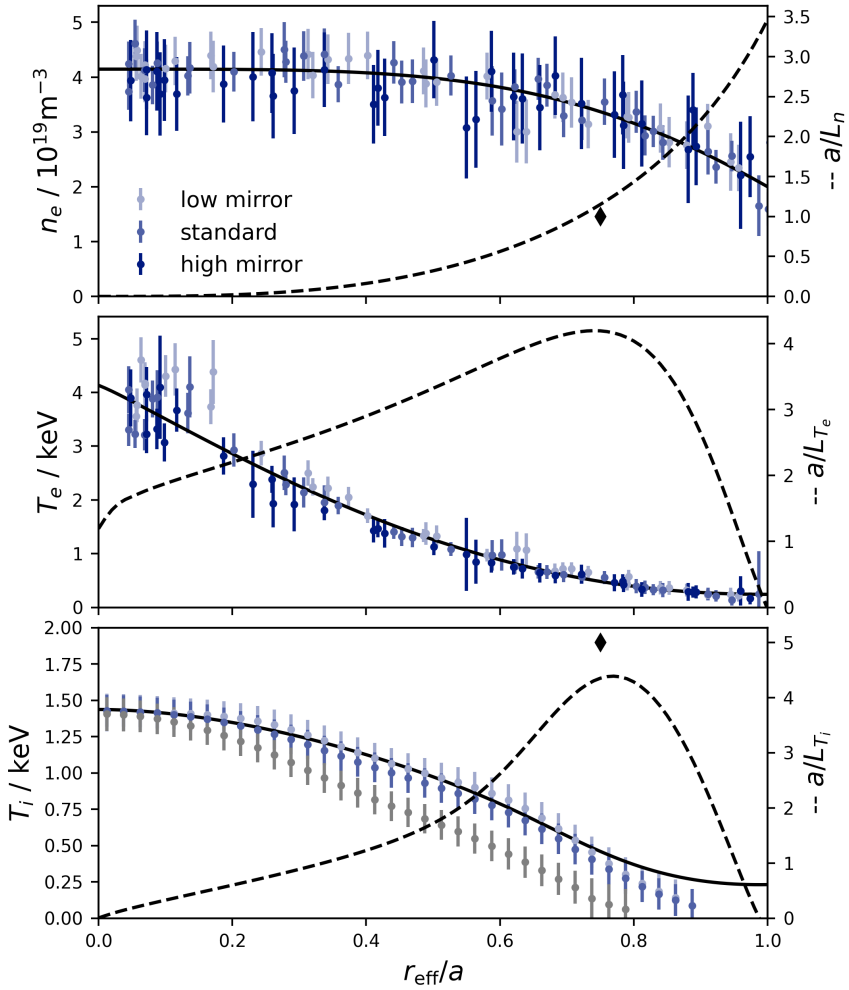
Plasma discharges and kinetic profiles - iota scan



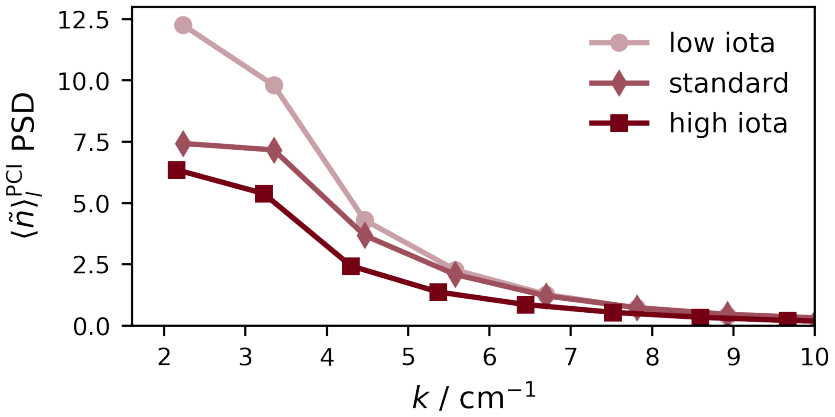


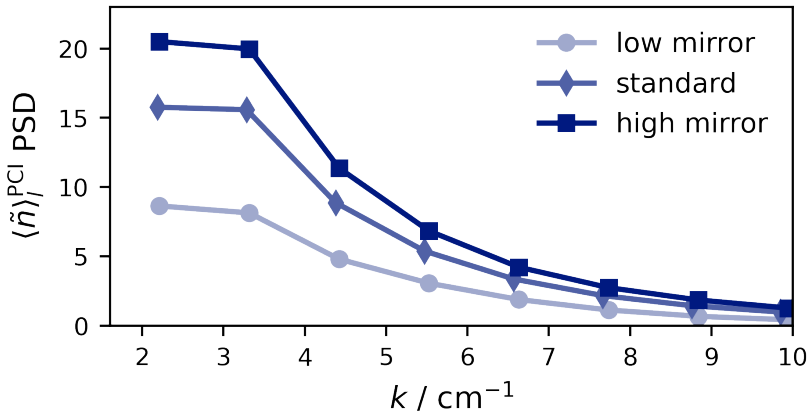
Plasma discharges and kinetic profiles - mirror scan

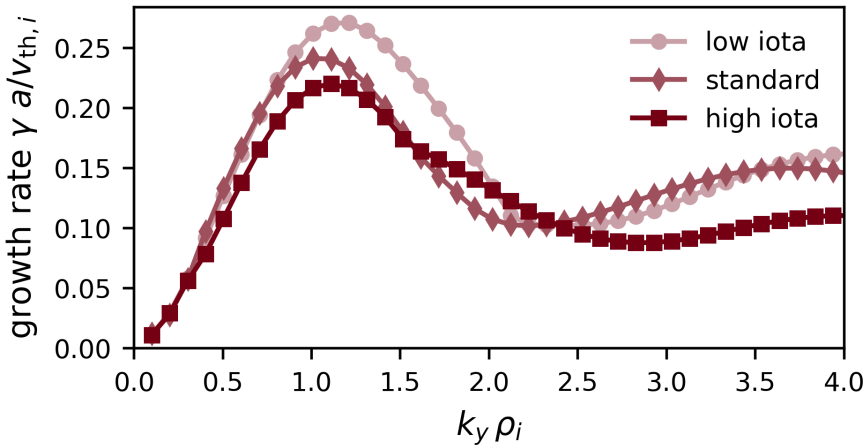


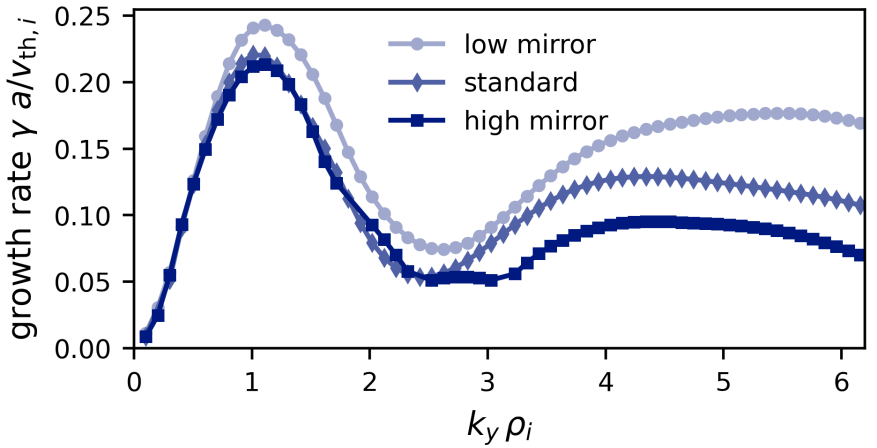


PCI density fluctuations spectra + linear $k_x \rho_i = 0$ spectra

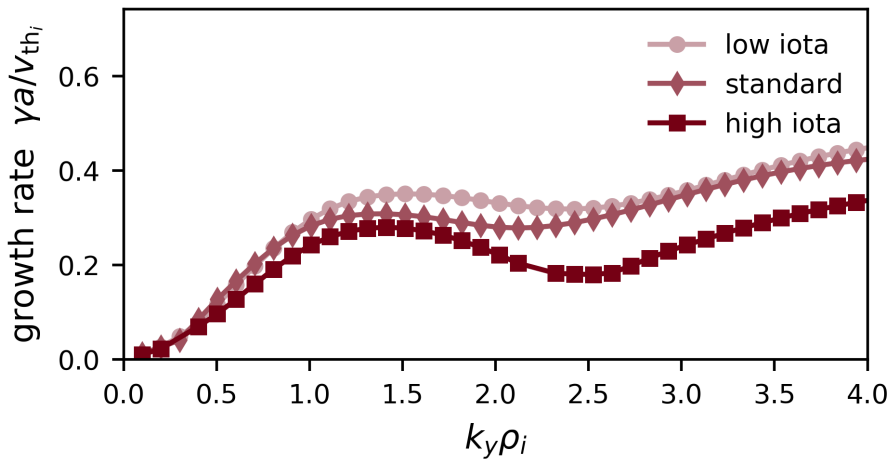


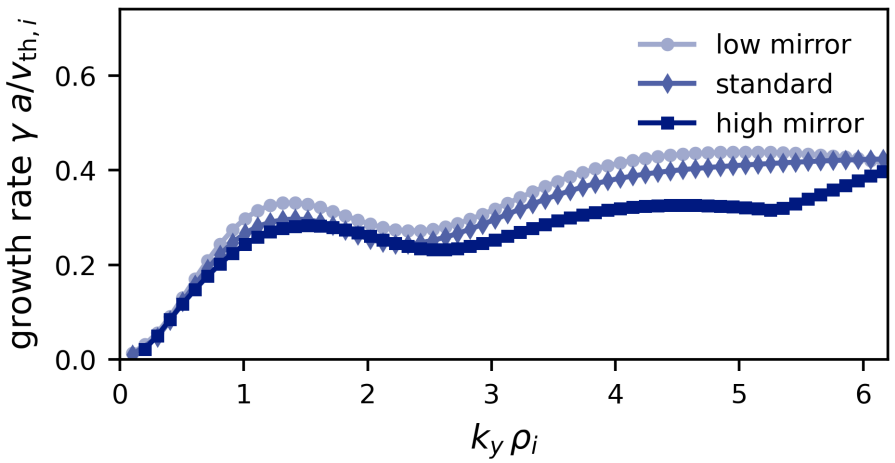






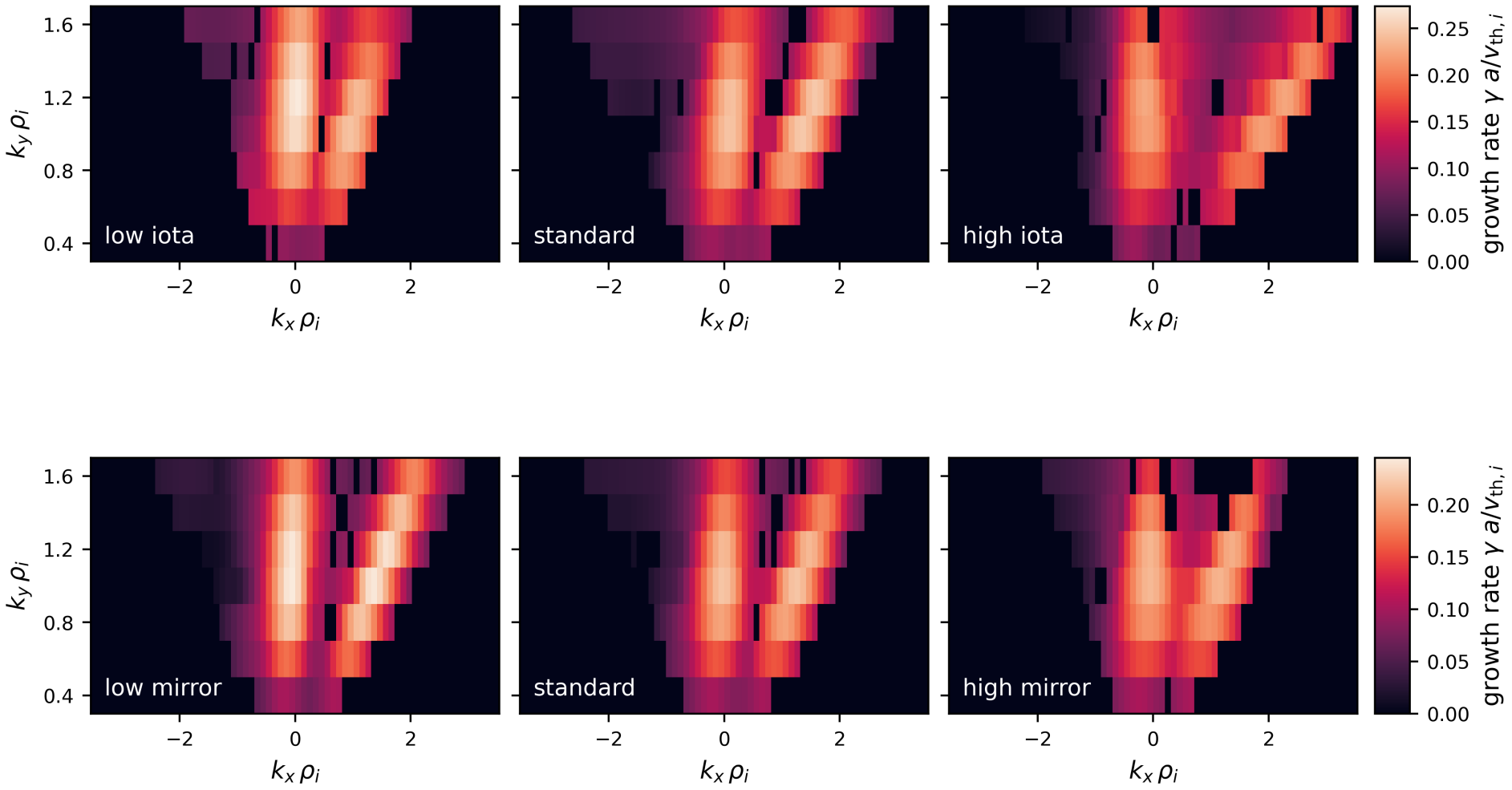
Linear $k_x\rho_i = 0$ spectra w/ $a/L_{Te} = a/L_{Ti}$



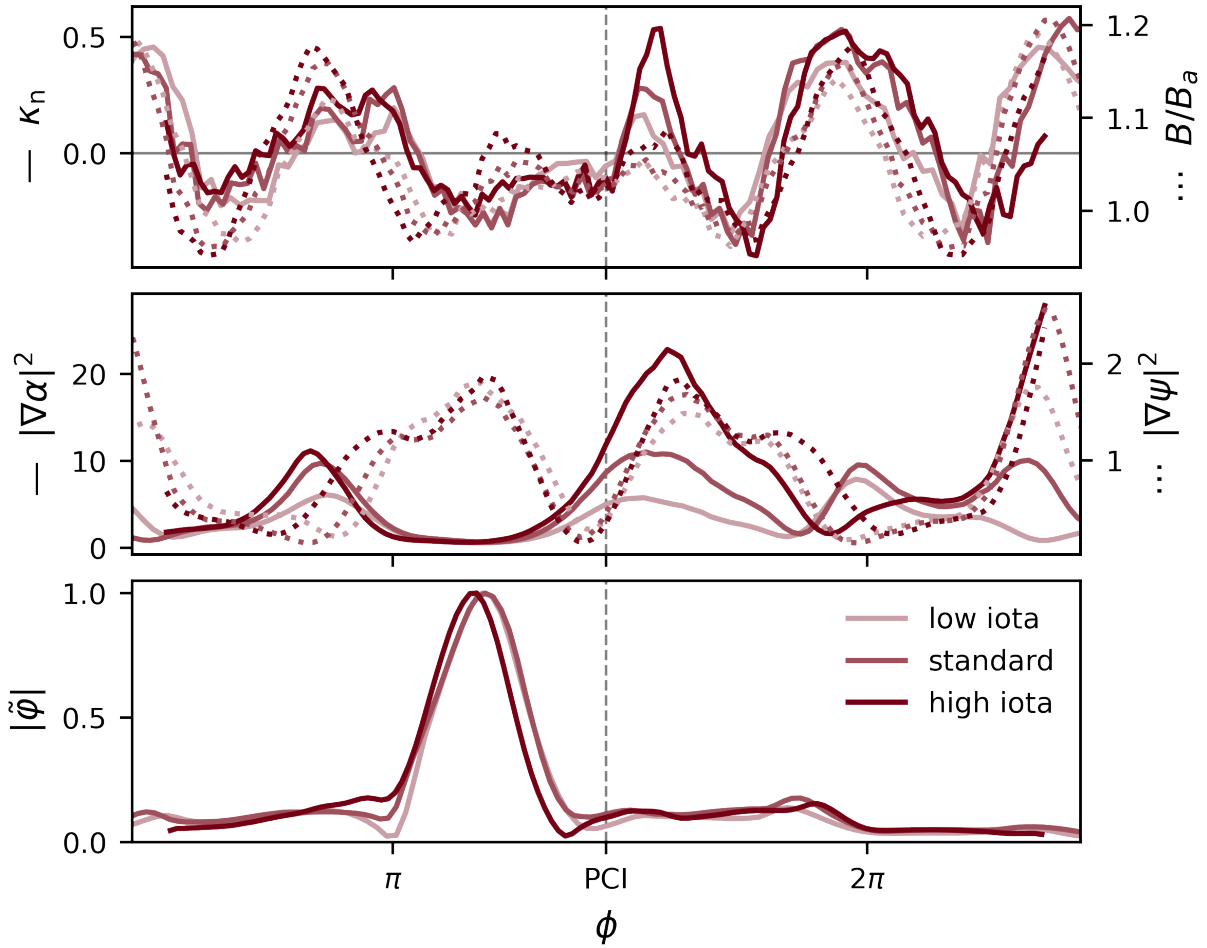


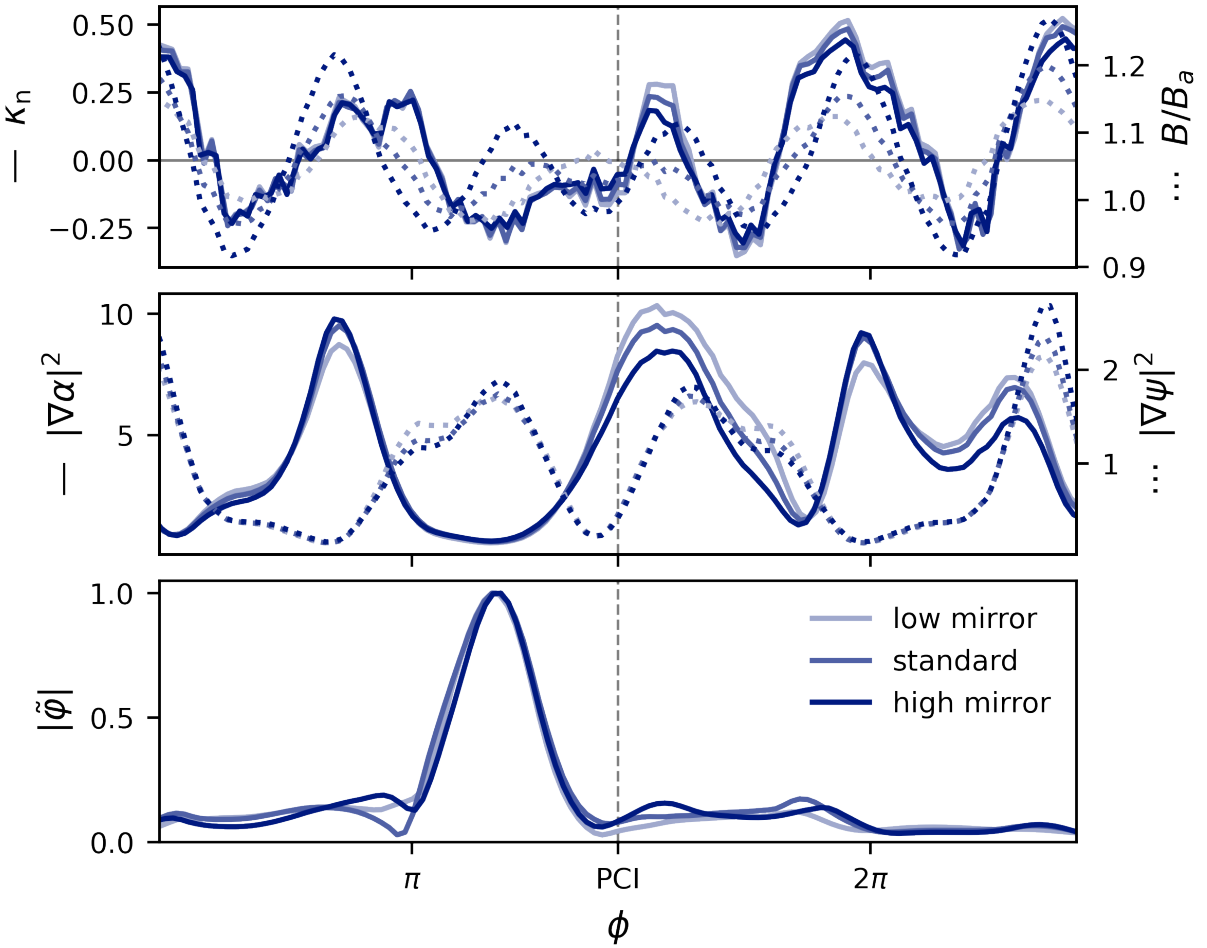
Everything more unstable but turbulence drive qualitatively equal

Linear (k_x, k_y) scans



Eigenfunctions vs geometry





ITG modes inertia

Pure ITG with bounce-averaged electrons but no source of electron free energy, drift-kinetic limit

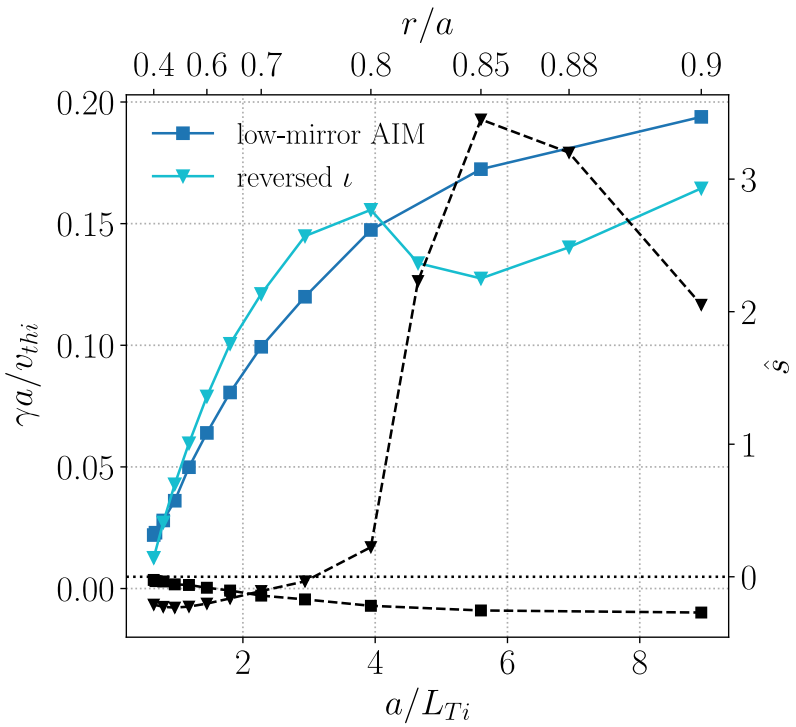
$$\omega = \pm\sqrt{-\omega_{*i}\eta_i \int_{-\infty}^{+\infty} \hat{\omega}_{di}(l)|\delta\phi|^2 \frac{\mathrm{d}l}{B}} \Bigg/ \left(\tau \int_{-\infty}^{+\infty} |\delta\phi|^2 \frac{\mathrm{d}l}{B} - \frac{\tau}{2}\sum_j \int_{1/B_{\max}}^{1/B_{\min}} \tau_{B,j}|\overline{\delta\phi}_j|^2 \,\mathrm{d}\lambda\right)^{\frac{1}{2}},$$

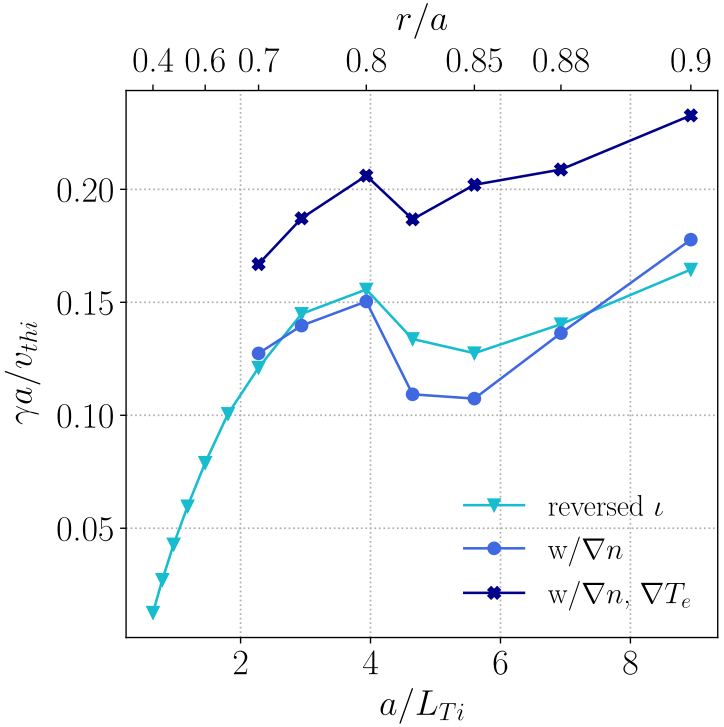
average of $\omega_{*i}\eta_i\hat{\omega}_{di}|\delta\phi|^2$ must be positive, $\delta\phi$ has large amplitudes in regions of bad curvature

trapped electron contribution decreases the denominator magnitude, destabilising the ITG

Iota tailoring

Consistent linear simulations





Iota tailoring

- Eigenfunctions at $r/a = 0.85$ with global shear effect on $|\nabla\alpha|^2$ and localisation
- Nonlinear results of Q_i/Q_{GB}

r/a	AIM	reversed iota
0.75	4.9	6.7
0.85	15	2