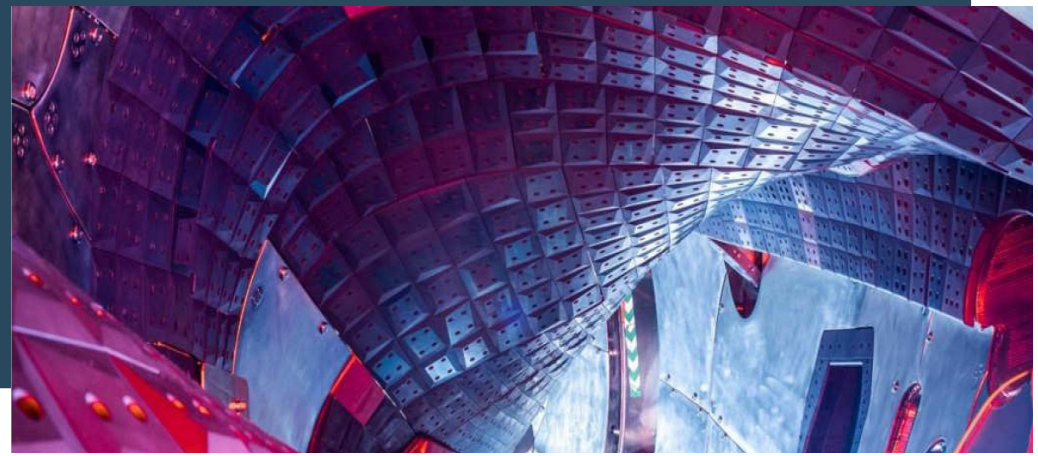
MAX-PLANCK-INSTITUT
FÜR PLASMAPHYSIK

Gyrokinetic core turbulence simulations on the magnetic configuration effects in W7-X

Wendelstein 7-X

Linda Podavini



EUROfusion

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Motivation

- Database study on **Phase Contrast Imaging (PCI)** data from OP2.1 reveals **density fluctuations dependence** on W7-X magnetic configuration

  ➡ **What does PCI measure?** Line-of-sight (*los*)-averaged density fluctuations at a specific toroidal location $\zeta = 4.55$

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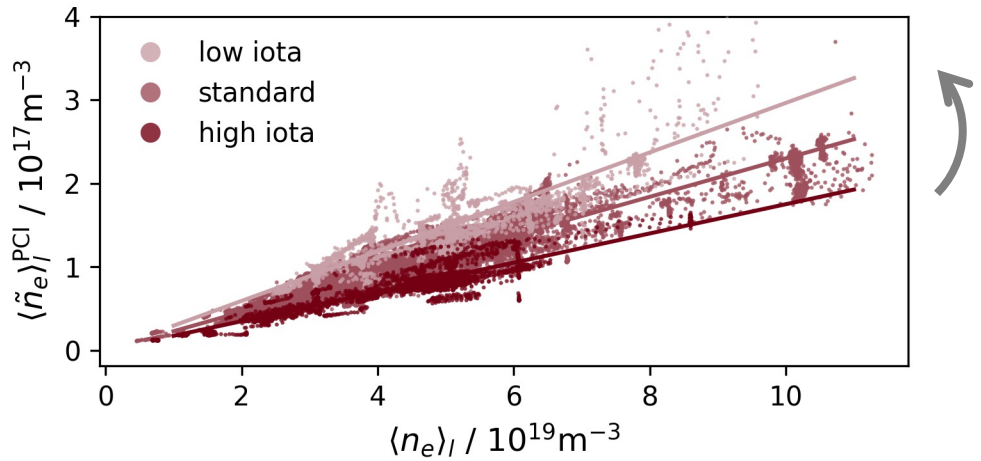
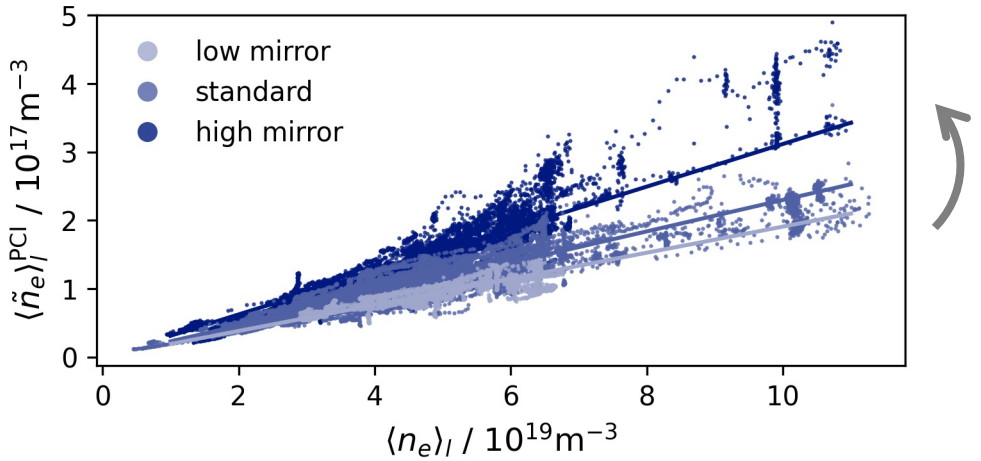
  ➡ **What does PCI measure?** Line-of-sight (*los*)-averaged density fluctuations at a specific toroidal location $\zeta = 4.55$

- Trend is visible from line-averaged density fluctuations **versus line-averaged density** [1]

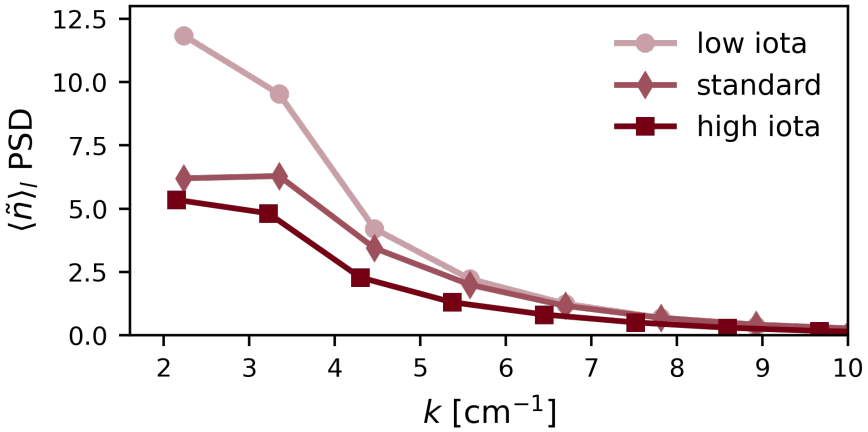




[1] Bähner, J-P., et al., *49th EPS Conference on Plasma Physics*. European Physical Society, 2024

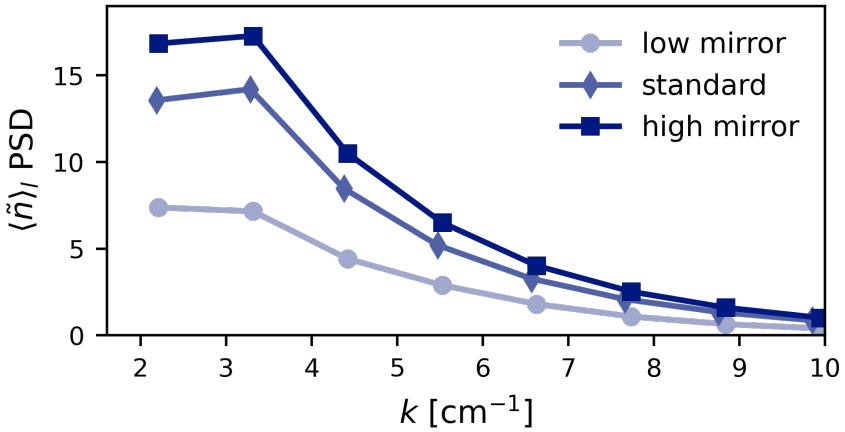
Motivation

- And also from line-averaged fluctuations spectra



Difference observed at **low wavenumbers**

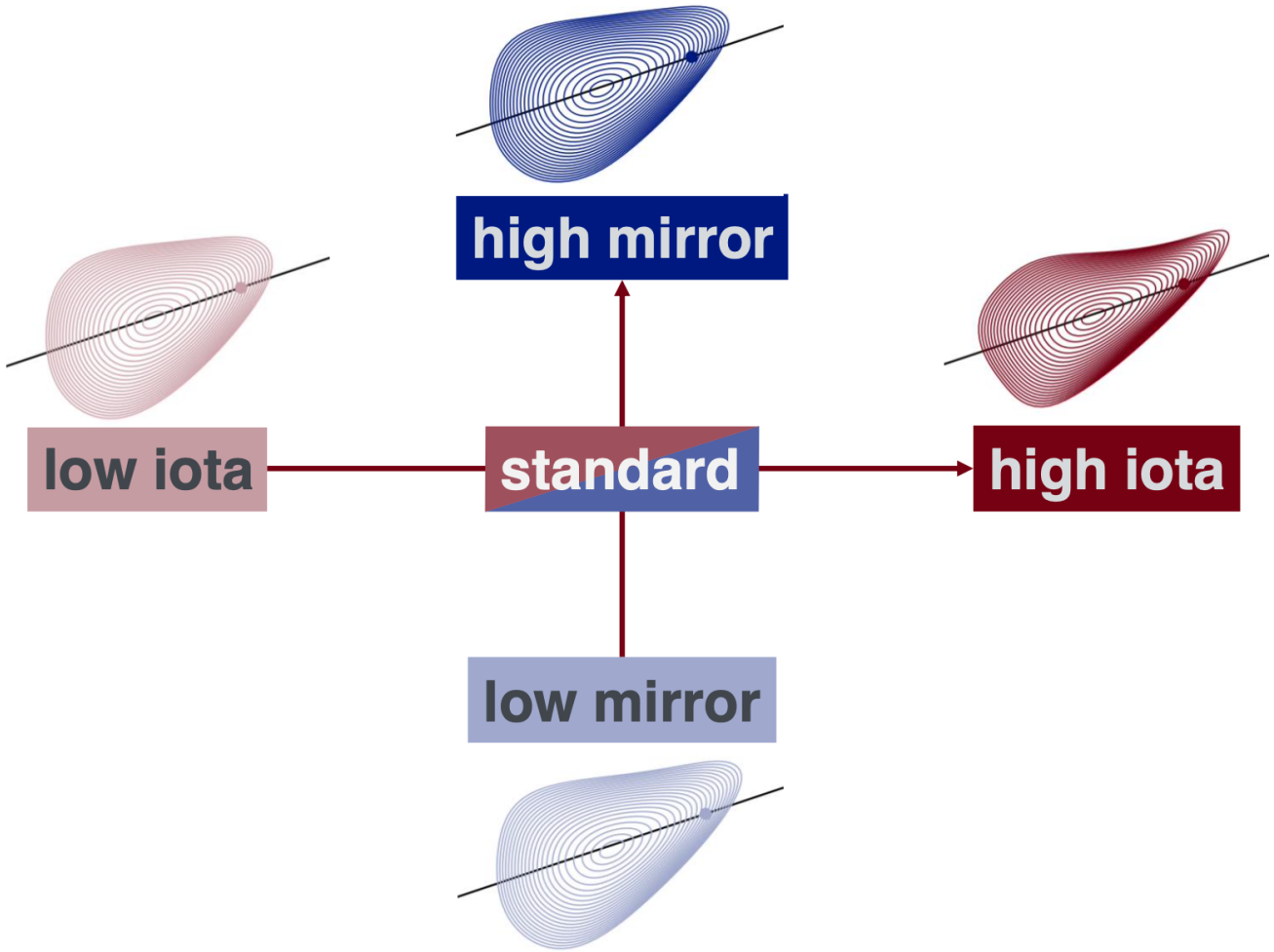
➡ predominant role of ITG expected

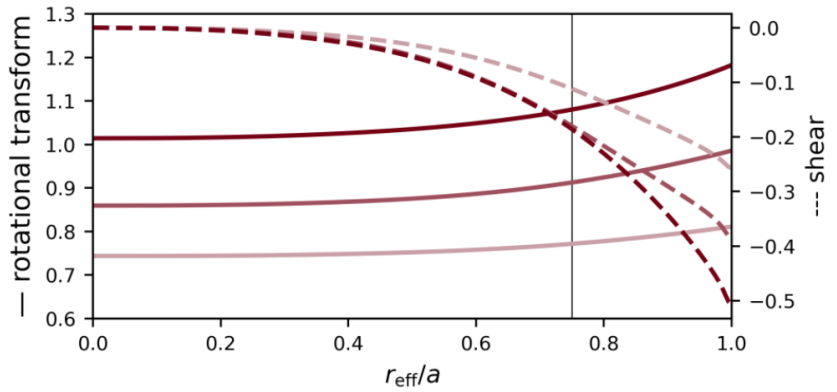


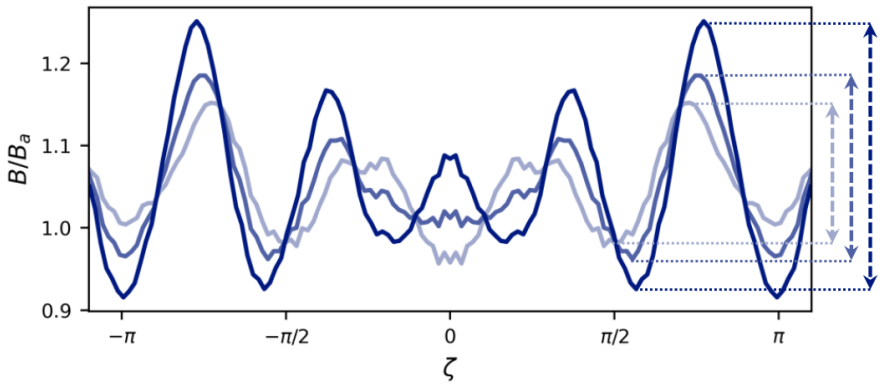
Difference observed at **higher wavenumbers too**

➡ larger role of trapped electrons expected

Magnetic configurations







Simulations setup

- Electrostatic, collisionless, flux tube simulations with gyrokinetic code `stella`, kinetic e^-
- **6 configurations**, flux tube chosen so to cross PCI *los* at $r_{eff}/a = 0.75$, where previous simulations highlighted peak of density fluctuations [2]
- Fixed a/L_{Ti} and a/L_n to **isolate geometry effects**
- Gradients extracted from fit that matches all configurations:
  - $a/L_{Ti} = 5.4$ and $a/L_n = 1.5$ for ι scan
  - $a/L_{Ti} = 5.0$ and $a/L_n = 1.0$ for mirror scan

Configuration	Type (VMEC ID)	θ^*	ι	α
low iota	DBM (19)	0.23	0.77	-3.278
standard	EJM (352)	0.13	0.91	-4.025
high iota	FTM (311)	0.17	1.08	-4.746
low mirror	AIM (22)	0.14	0.90	-3.961
standard	EJM (169)	0.15	0.90	-3.975
high mirror	KKM (339)	0.16	0.91	-3.982

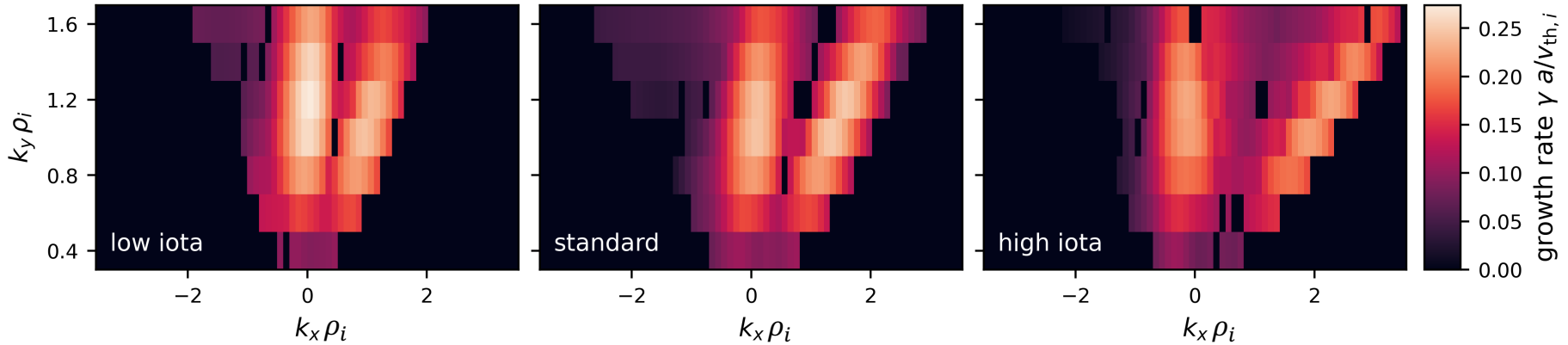
*θ varies with configuration because *los* is not normal to flux surfaces

- ~1 poloidal turn simulated, $N_z \times N_{v_\parallel} \times N_\mu = 128 \times 64 \times 24$
- Linear: $k_y\rho_i \in [0.1,10]$, $k_x\rho_i \in [-5.0,5.0]$
- Nonlinear: $N_y \times N_x = 177 \times 180$, $y_0 = 20$

[2] Bähner, J-P., et al., *JPP*, 2021

Linear results – $k_x k_y$ scan

$(k_y\rho_i, k_x\rho_i, \gamma a/v_{th,i}) = (1.2, 0.05, \mathbf{0.27})$ $(1.1, 1.46, \mathbf{0.25})$ $(1.1, -0.05, \mathbf{0.23})$



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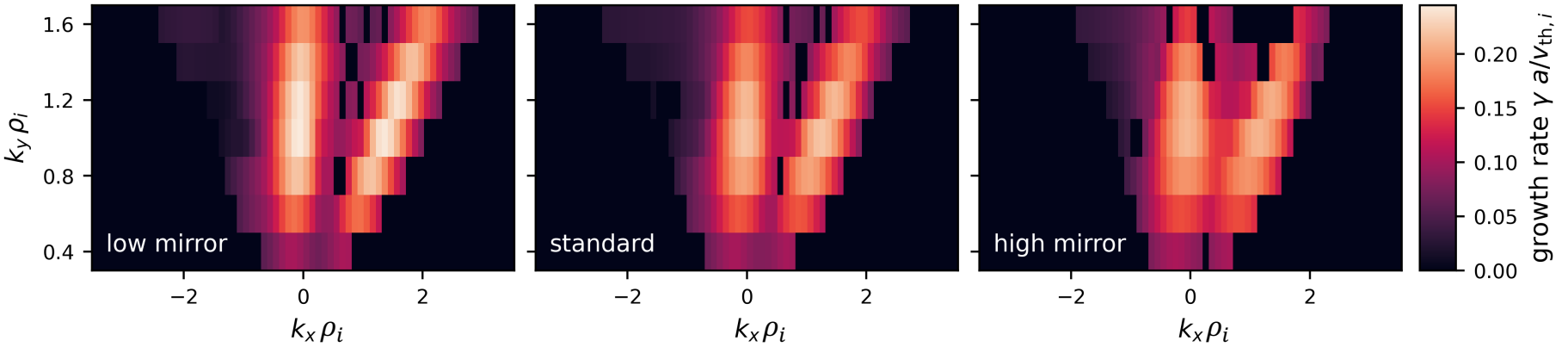

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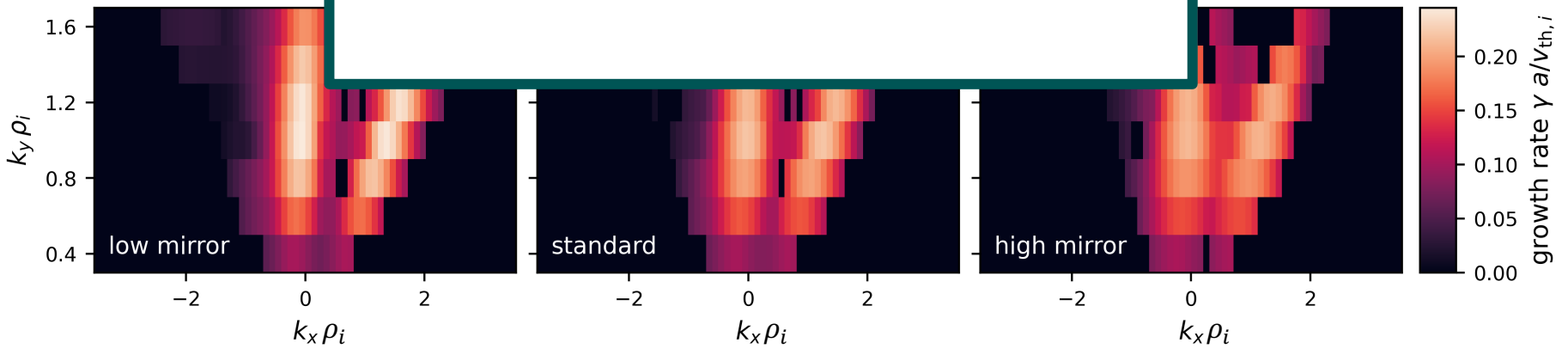
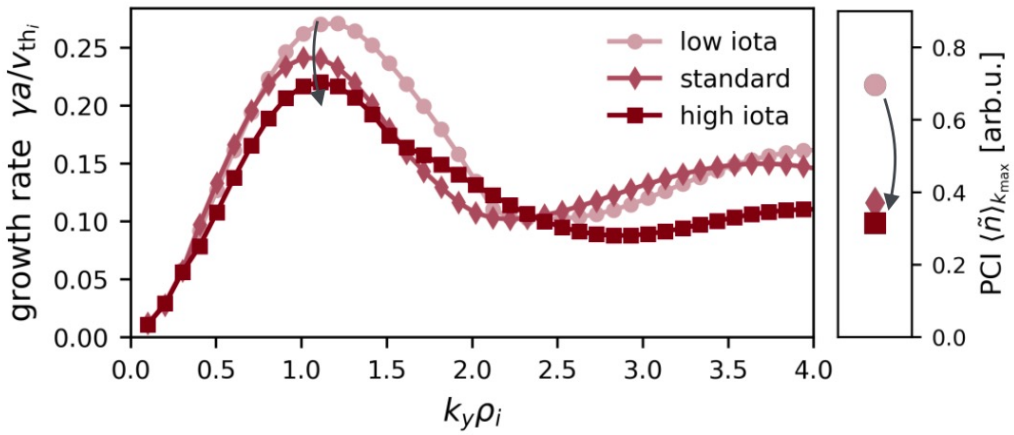
~10% difference between configurations

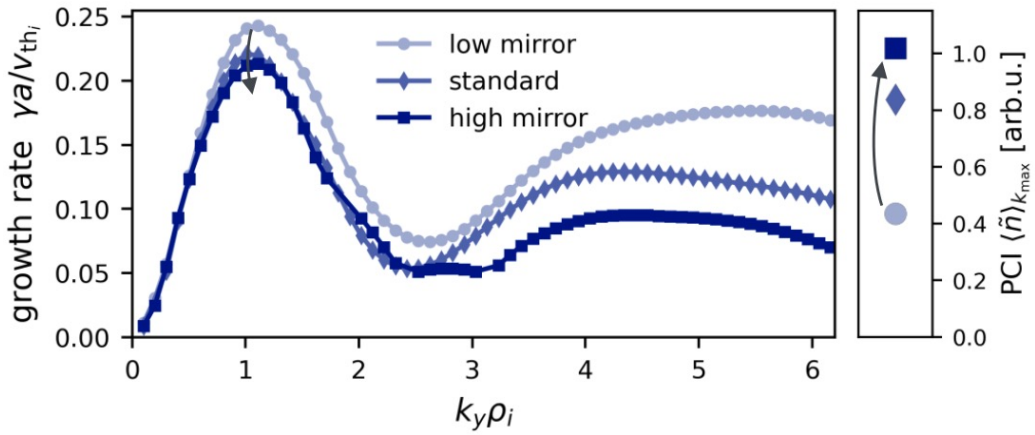
$(k_y\rho_i, k_x\rho_i, \gamma a/v_{th,i}) = (1.1, -0.0$ $0.05, \mathbf{0.21})$



Linear results – $k_y\rho_i$ scan, $k_x\rho_i = 0$



- Fastest growing mode trend **matches** PCI observations



- Fastest growing mode trend **does not match** PCI observations

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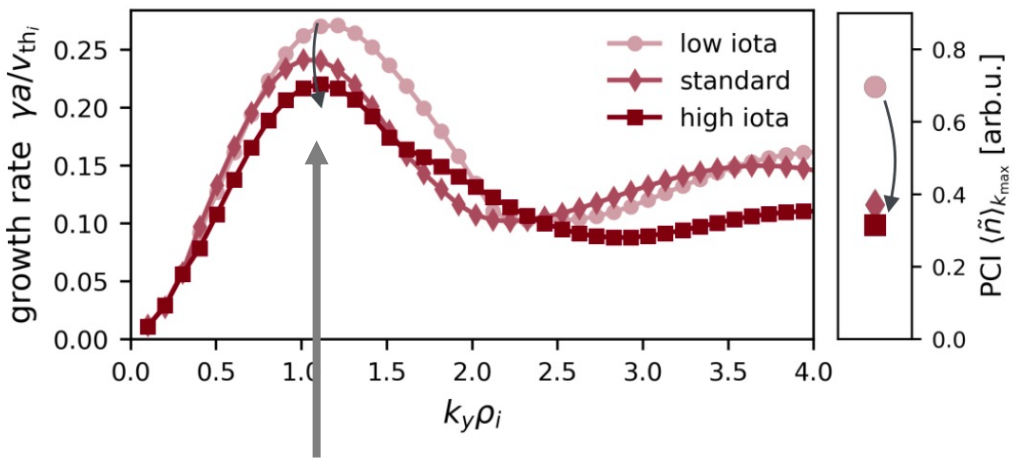

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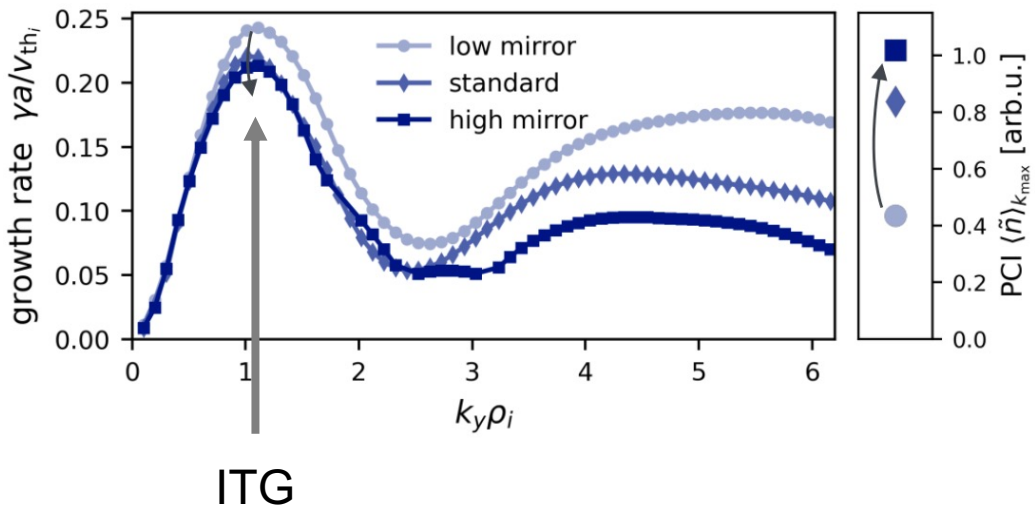

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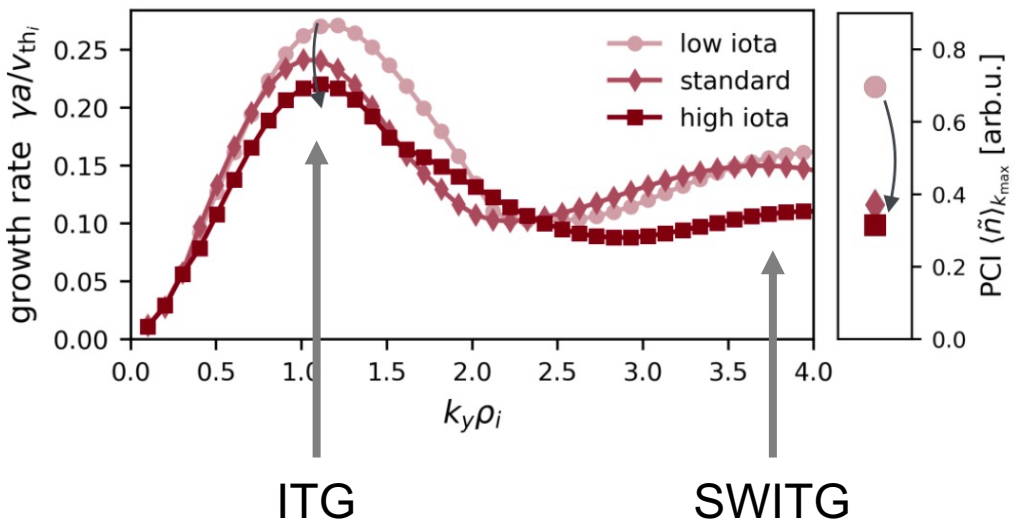

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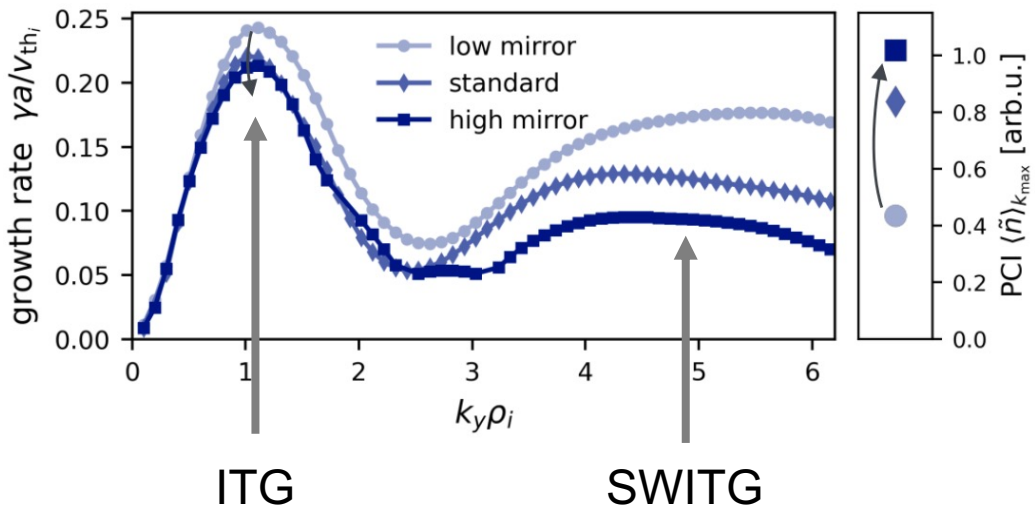

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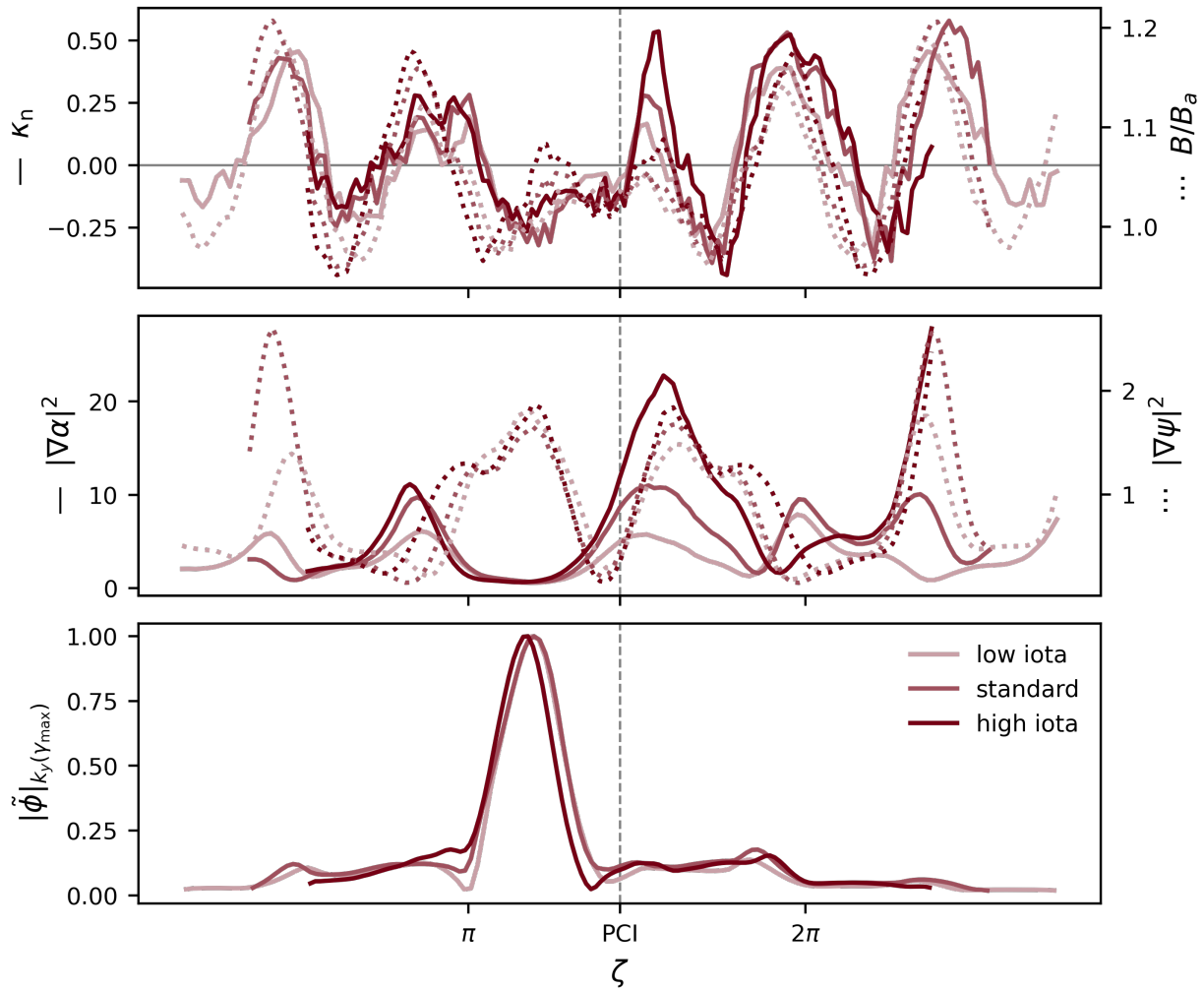
Linear results – ι scan eigenfunctions vs geometry



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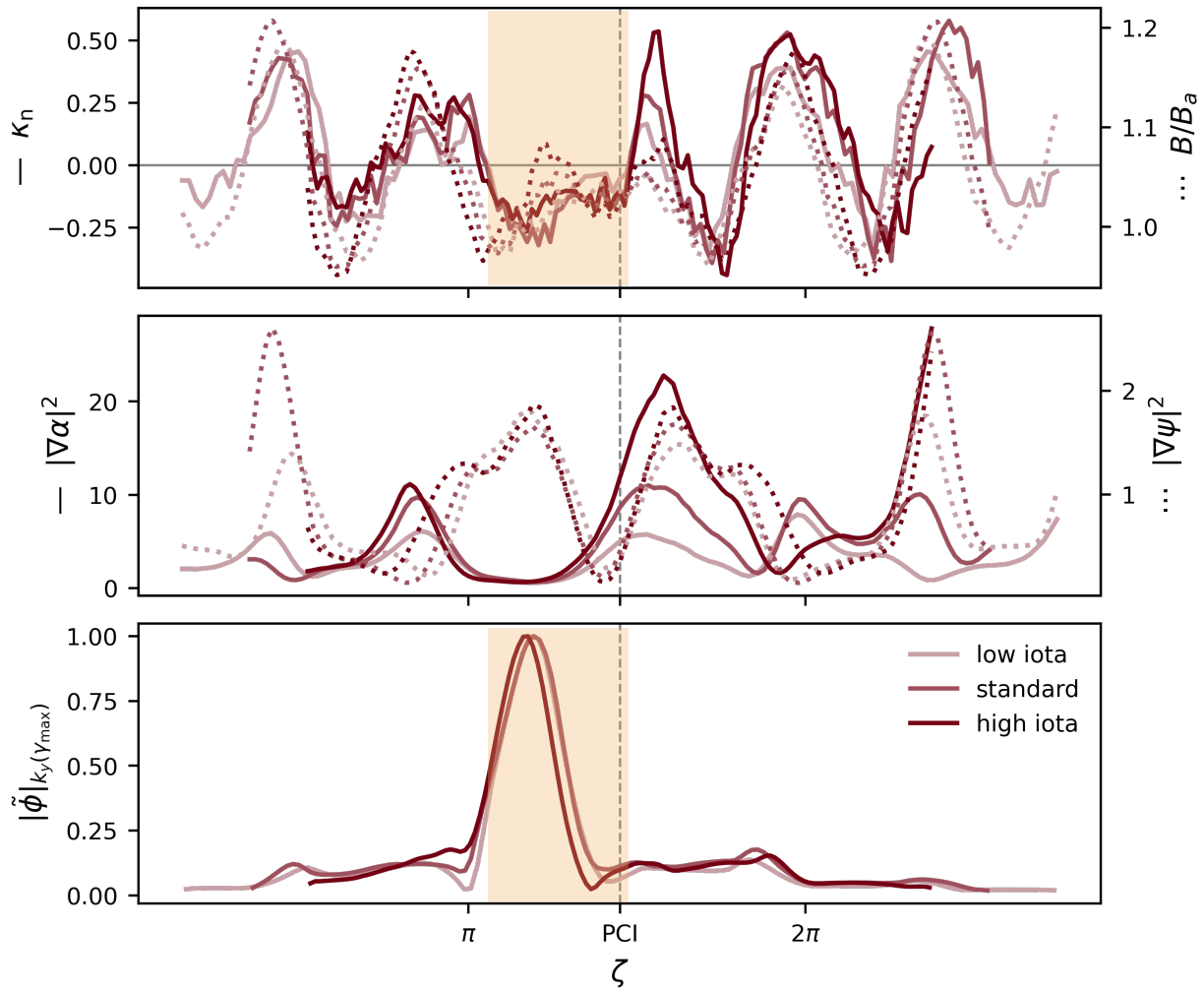

- Eigenfunctions peak at **bad curvature region** corresponding to bean-shaped cross section

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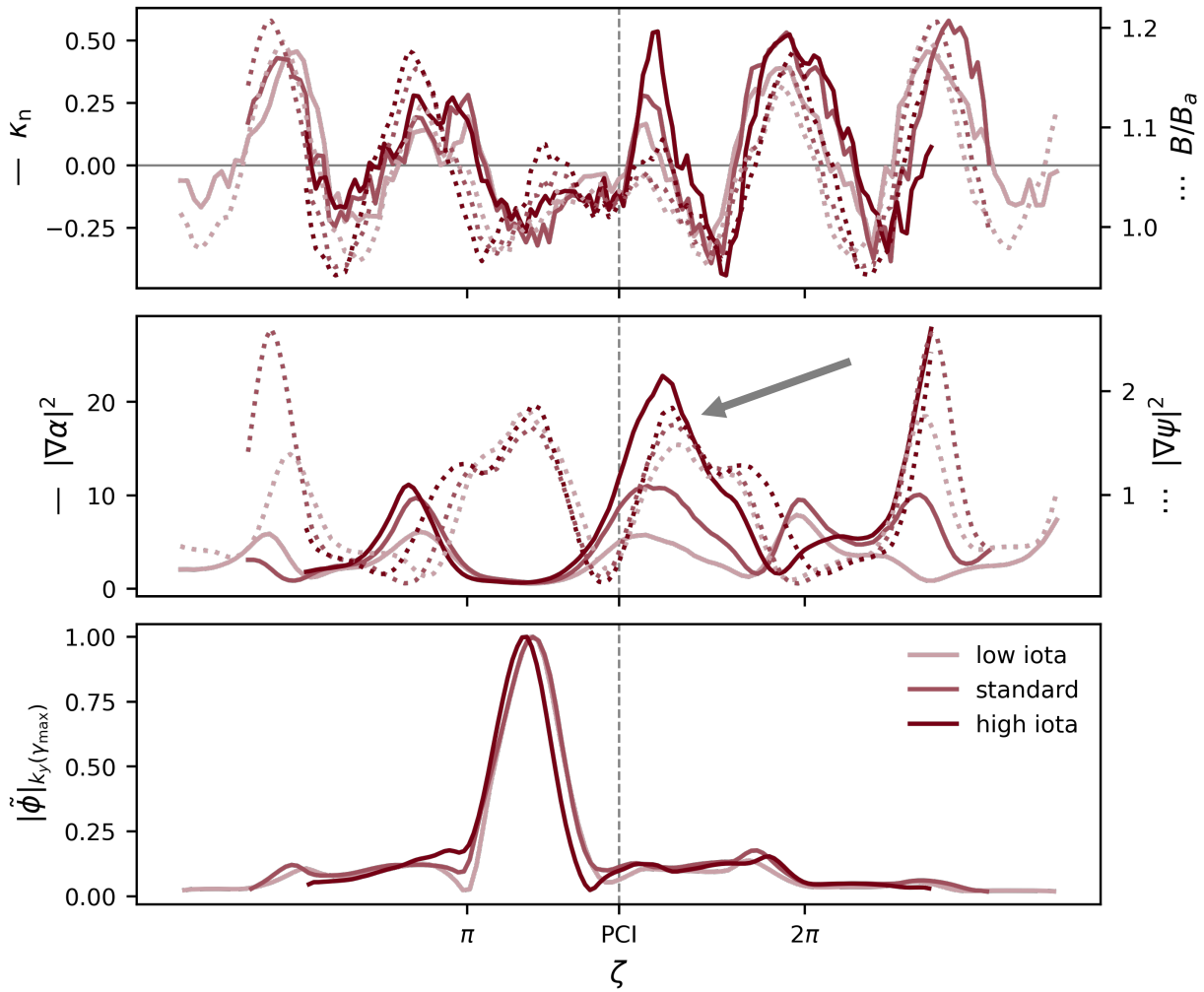
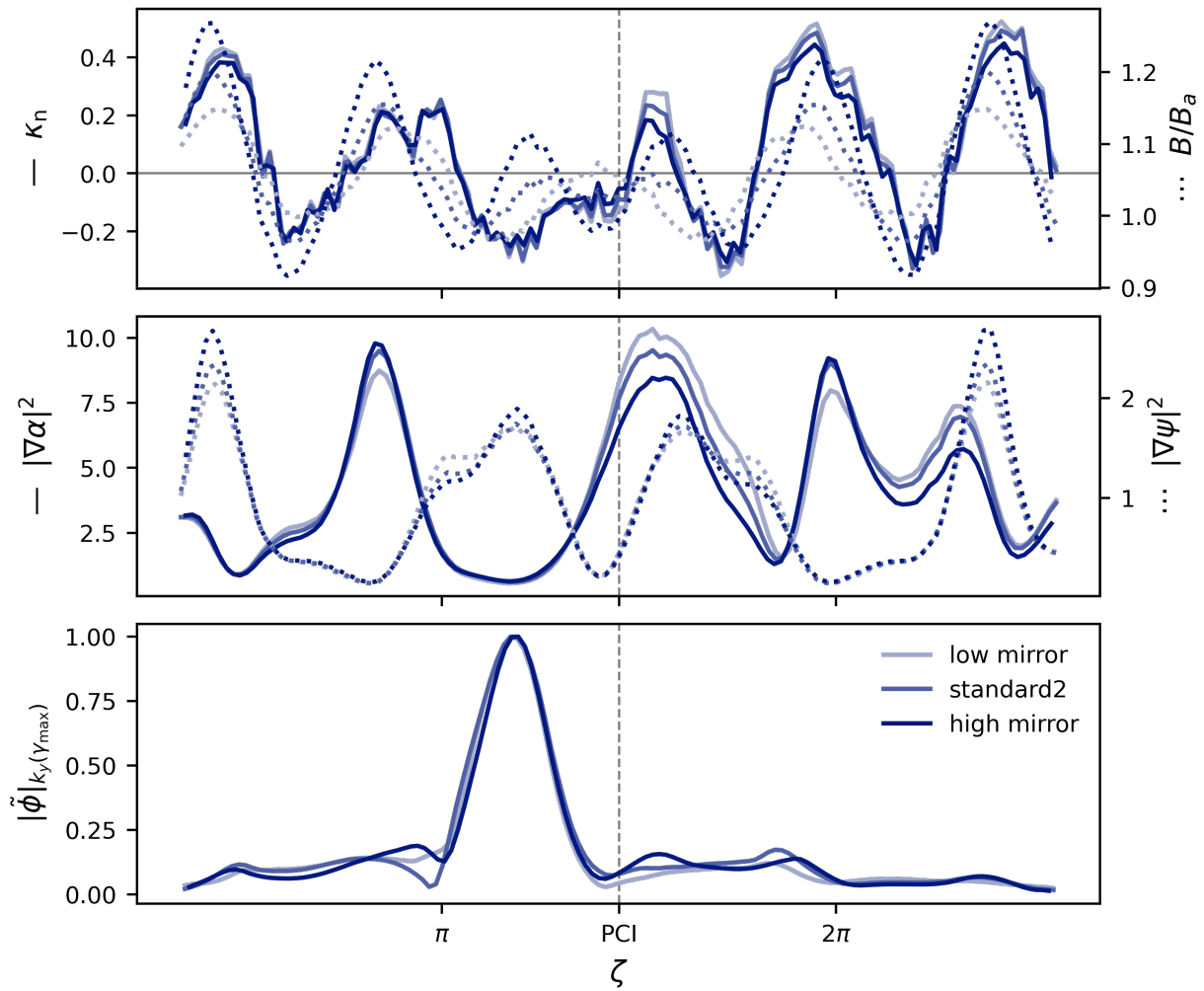


- Eigenfunctions peak at **bad curvature region** corresponding to bean-shaped cross section
- Growth rate suppression related to **increased local shear effect** with increasing ι
- FLR effect related to increased $|\nabla\alpha|^2$ already predicted to have an effect in W7-X [3] and used for critical gradient optimisation [4]

[3] Plunk G. G., et al., *Phys. Plasmas*, 2014

[4] Roberg-Clark G. T., et al., *PRR*, 2023

Linear results – mirror scan eigenfunctions vs geometry



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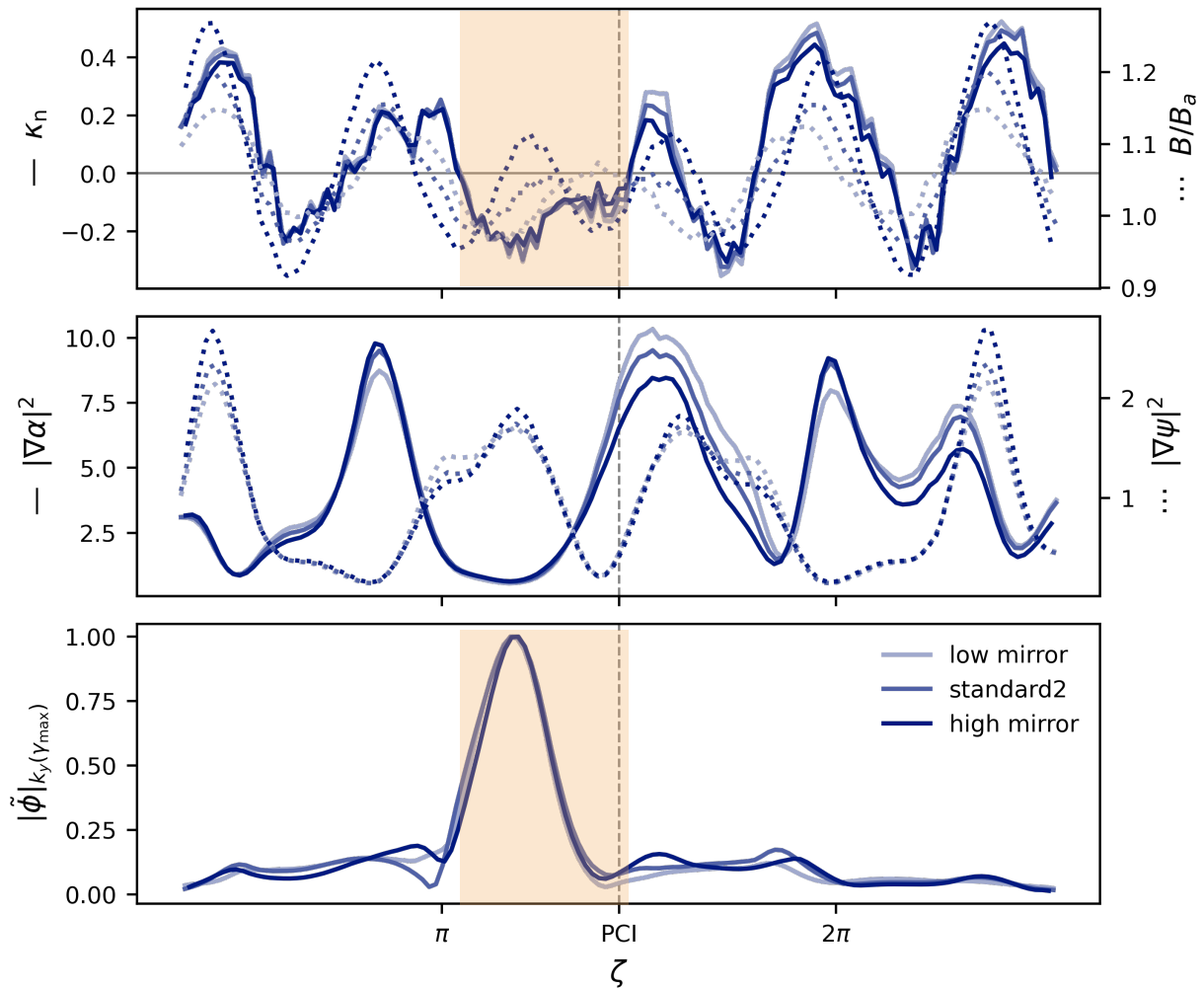

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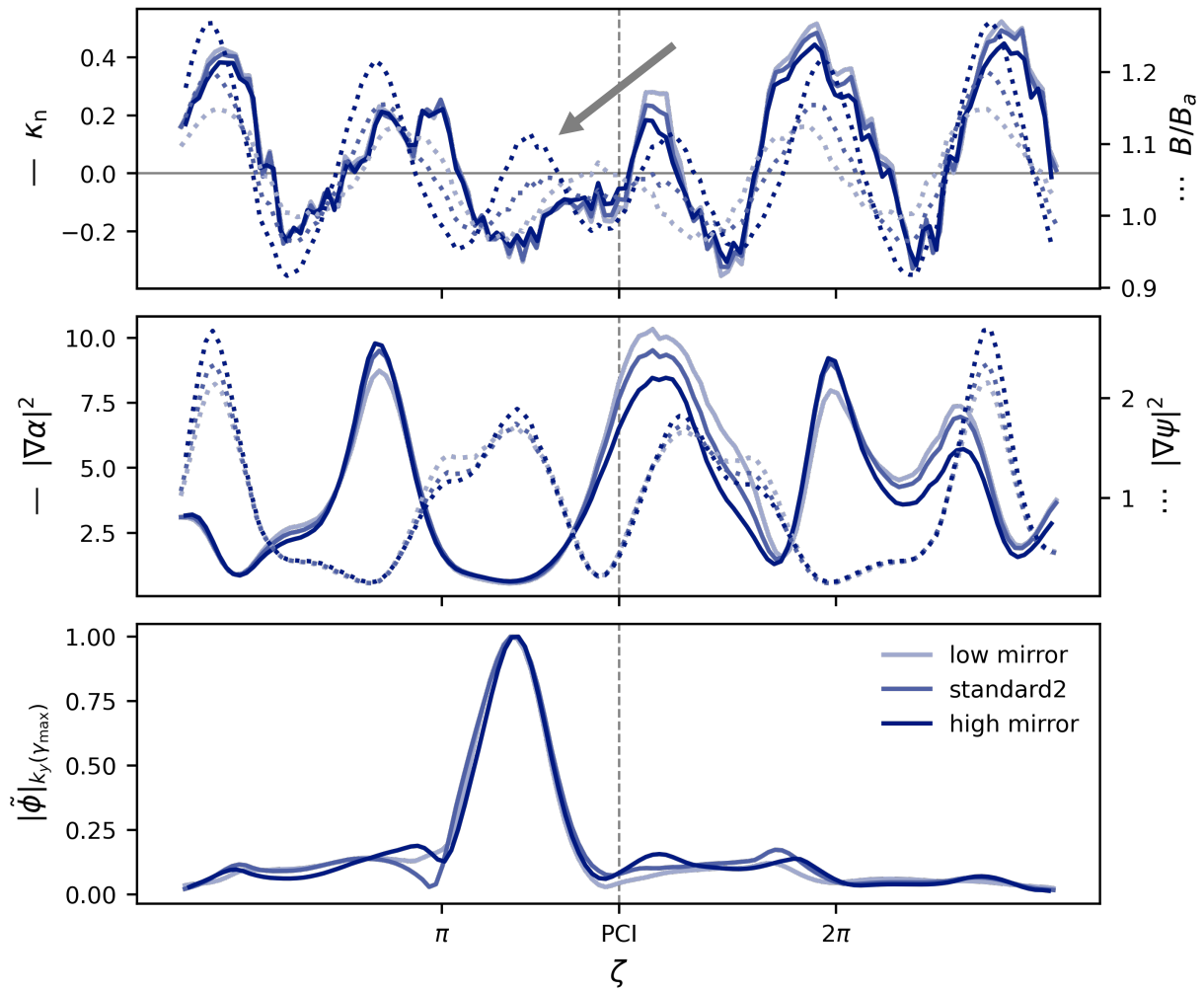
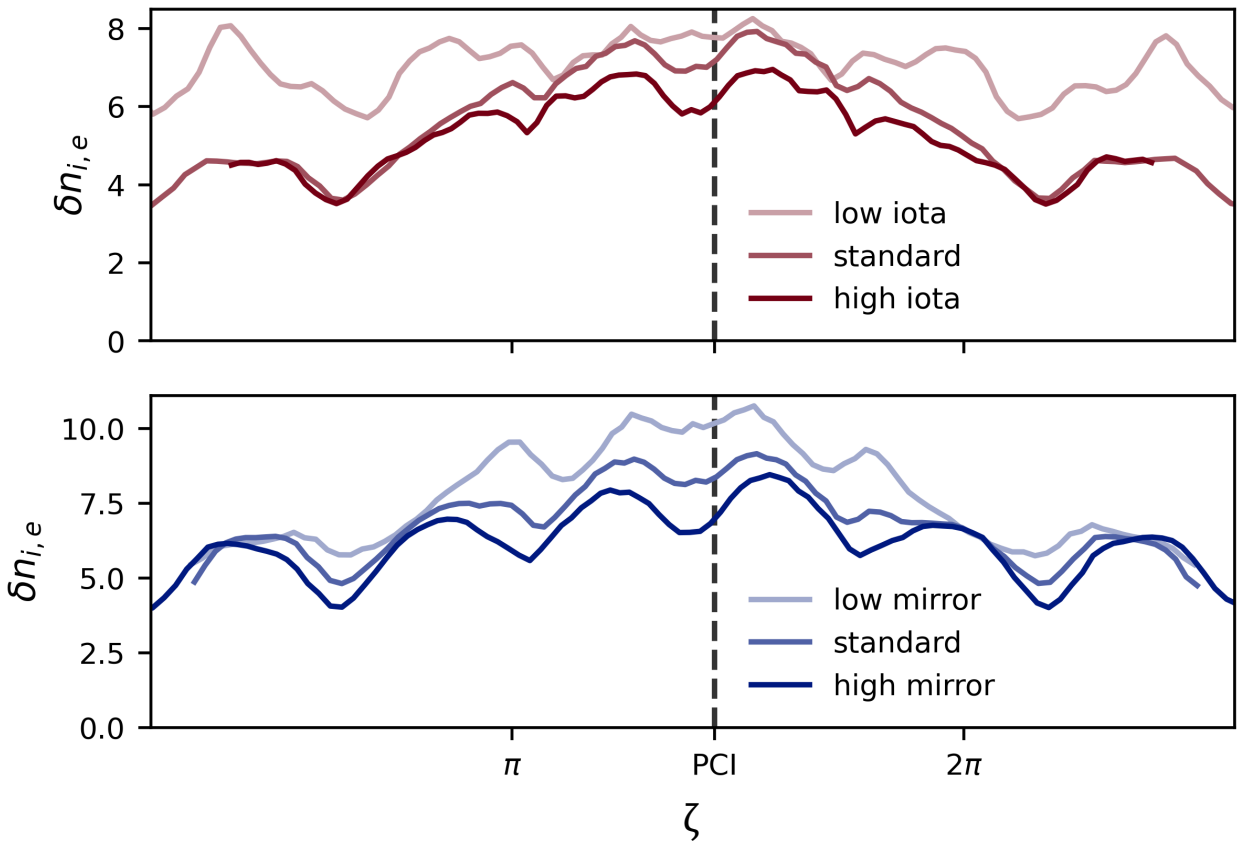


- Eigenfunctions peak at **bad curvature region** corresponding to bean-shaped cross section
- Growth rate suppression related to **displacement of magnetic wells** from bad curvature regions
- Effect previously observed for TEMs and linked to **maximum-*J* property** [5]
- Trapped particles can further destabilise ITG and the effect is larger the more trapped particles the modes “see” [6]

[5] Alcusón J. A., et al., *Plasma Phys. Control. Fusion*, 2020

[6] Costello P. J., et al., *JPP*, 2024, submitted

Nonlinear results – density fluctuations



$\delta n_{i,e}\big|_{\zeta=4.55}$

low iota	standard	high iota
7.78	7.18	6.13

- Trend **matches** PCI observations
- $\geq 10\%$ difference

$\delta n_{i,e}\big|_{\zeta=4.55}$

low mirror	standard	high mirror
10.18	8.35	6.97

- Trend **does not match** PCI observations
- $\sim 20\%$ difference

Conclusions

- `stella` flux tube linear and nonlinear simulations reproduce **effect with magnetic configuration**
- Relative difference **matches** experimentally observed difference
- However, mirror ratio trend is **opposite** to what experimentally observed, and difference is **larger** than what linearly observed ➡ nonlinear effect of mirror ratio?

Future work:

- Further analyse nonlinear simulations: zonal component, density fluctuations spectra, low-k_y modes
- Understand reason behind disagreement simulations-experimental data for mirror ratio scan

BACKUP SLIDES

Trapped electrons effect on ITG growth rate

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

$$\omega = \pm\sqrt{-\omega_{*i}\eta_i \int_{-\infty}^{+\infty} \hat{\omega}_{di}(l)|\delta\phi|^2 \frac{\mathrm{d}l}{B}} \Bigg/ \left(\tau \int_{-\infty}^{+\infty} |\delta\phi|^2 \frac{\mathrm{d}l}{B} - \frac{\tau}{2}\sum_j \int_{1/B_{\min}}^{1/B_{\max}} \tau_{B,j}|\overline{\delta\phi}_j|^2 \,\mathrm{d}\lambda\right)^{\frac{1}{2}}, \quad (8.2)$$

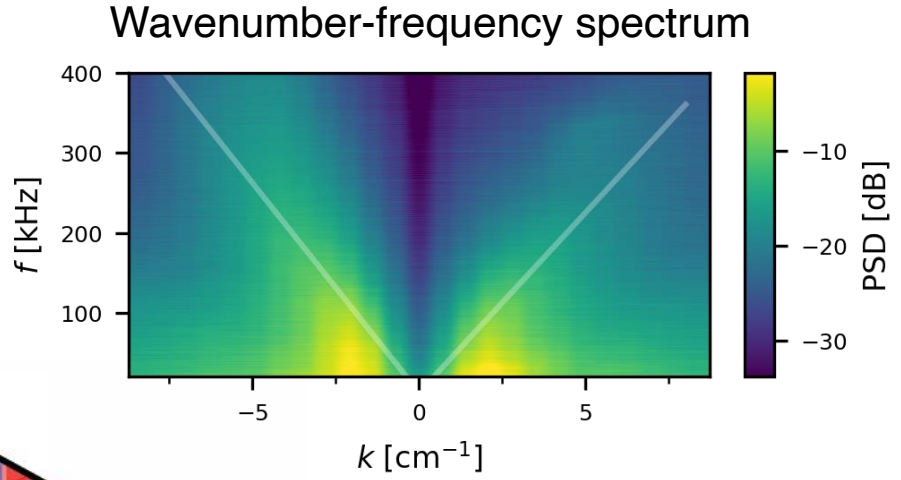
average of $\omega_{*i}\eta_i\widehat{\omega}_{di}|\delta\phi|^2$ must be positive, $\delta\phi$ has large amplitudes in regions of bad curvature

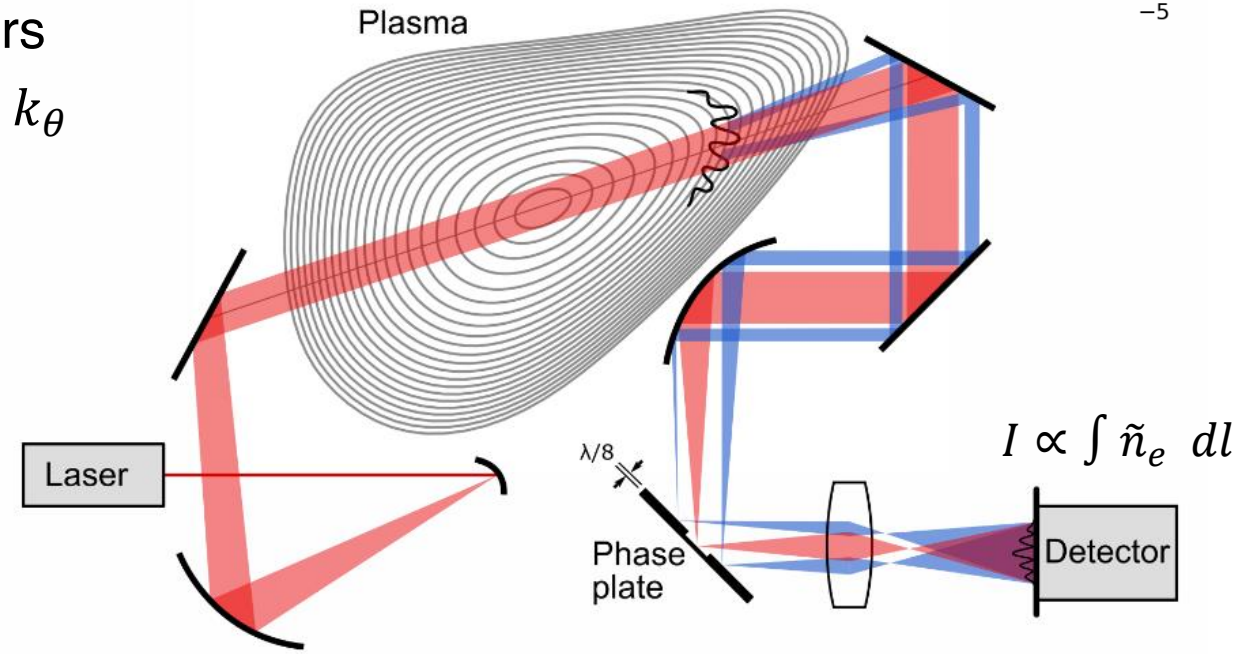
trapped electron contribution decreases the denominator magnitude, destabilising the ITG

[6] Costello P. J., et al., *JPP*, 2024, submitted

Phase Contrast Imaging at Wendelstein 7-X
Measuring turbulent density fluctuations

- infrared CO_2 laser scatters on density fluctuations
- image at detector is directly proportional to $\int \tilde{n}_e \; dl$
- online sound wave calibration
  → absolute fluctuation amplitude
- two 32 channel detectors
  → resolution in f and k_θ





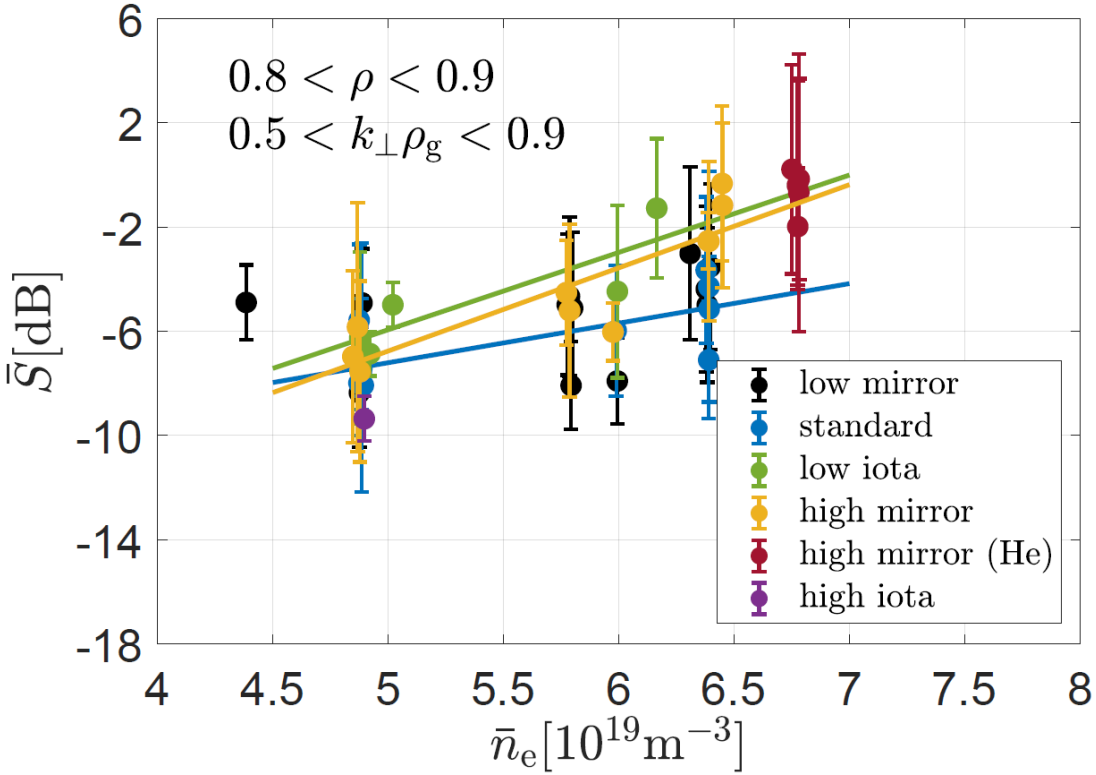
$$I \propto \int \tilde{n}_e \; dl$$

Doppler Reflectometry measurements confirm observed differences between configurations

Doppler reflectometers measure density fluctuations in the edge and core of W7-X

- fluctuation level towards the edge ($0.8 < \rho < 0.9$) shows qualitatively similar trends as PCI
- stronger fluctuations in low iota and high mirror

E. Maragkoudakis, D. Carralero, T. Estrada, T. Windisch and the W7-X team



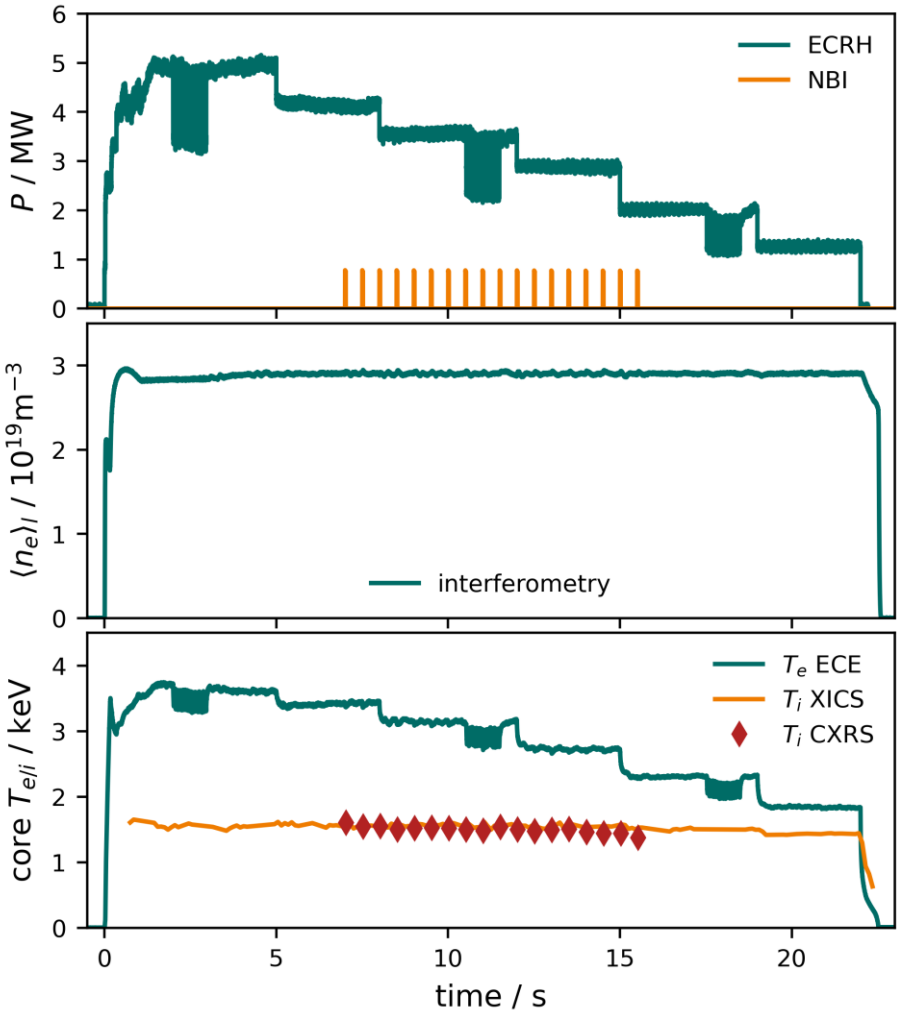
courtesy of E. Maragkoudakis (PhD thesis)

- more detailed analysis? → dedicated programs

Dedicated experiment programs enable direct comparison of magnetic configurations

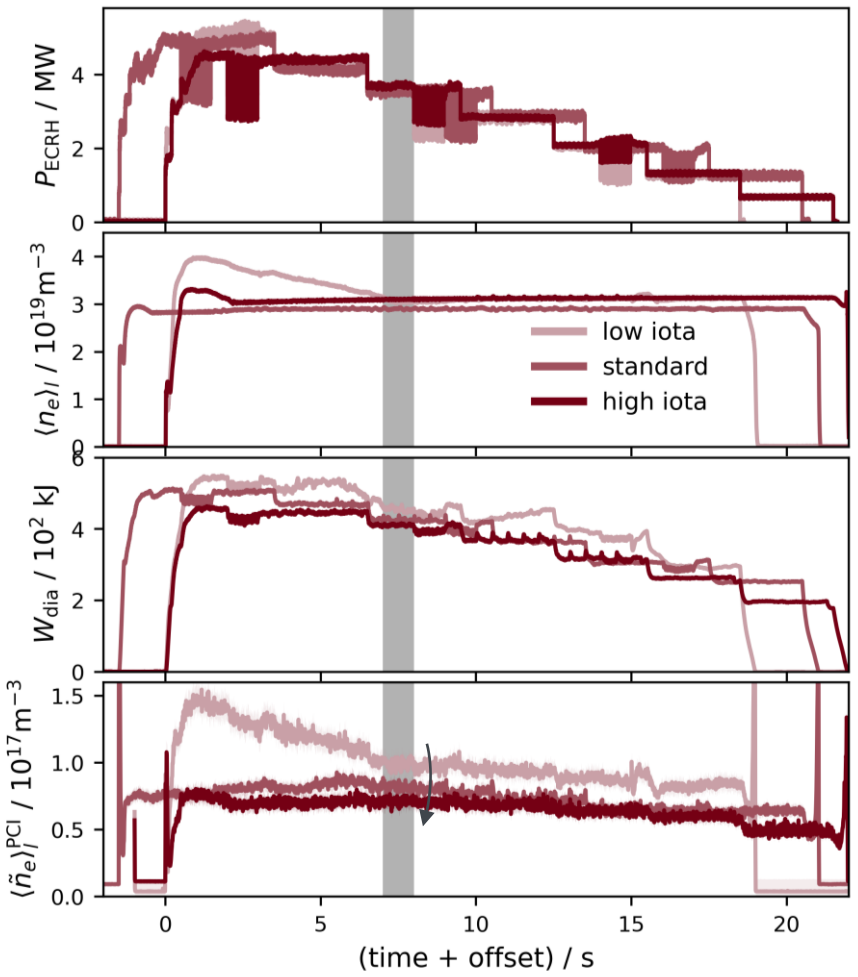
- power-step programs at different densities were performed in all magnetic configurations
- enables **direct comparison at identical conditions**
- overall 9 scenarios at 3 different densities and 3 different power levels were analysed for 5 magnetic configurations
- results are qualitatively reproduced in every scenario

  → robust observations

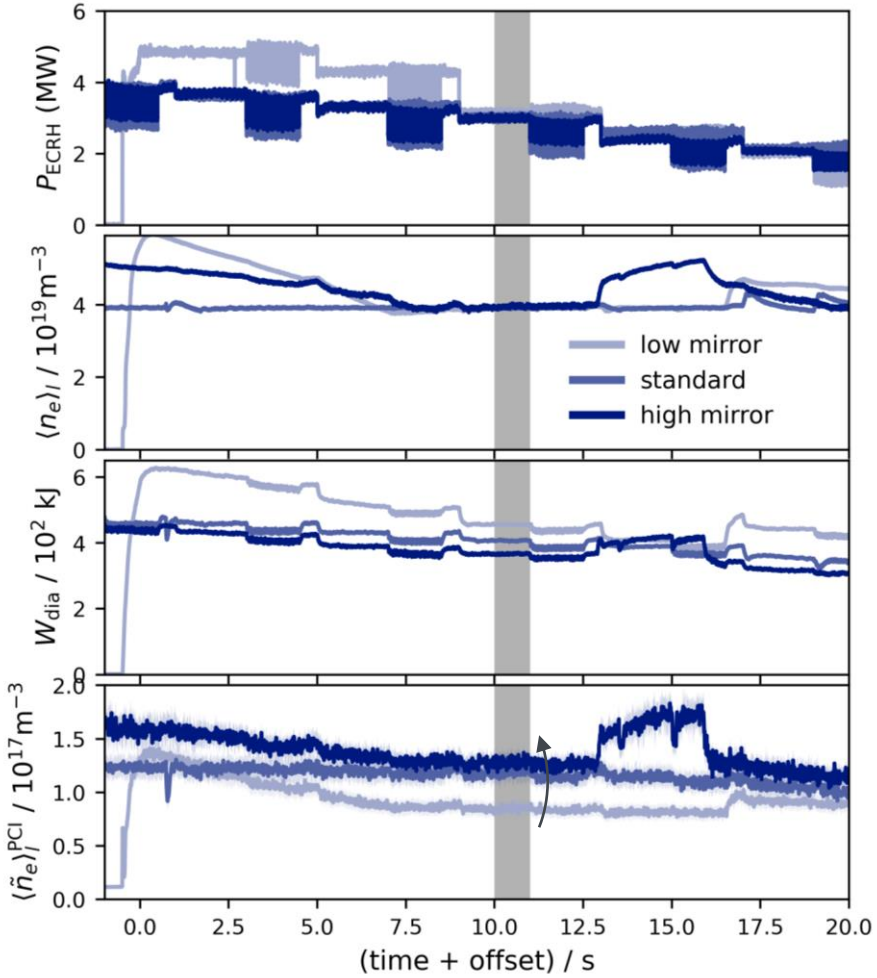


Dedicated experiment programs
Select time window to match power step

low to high iota



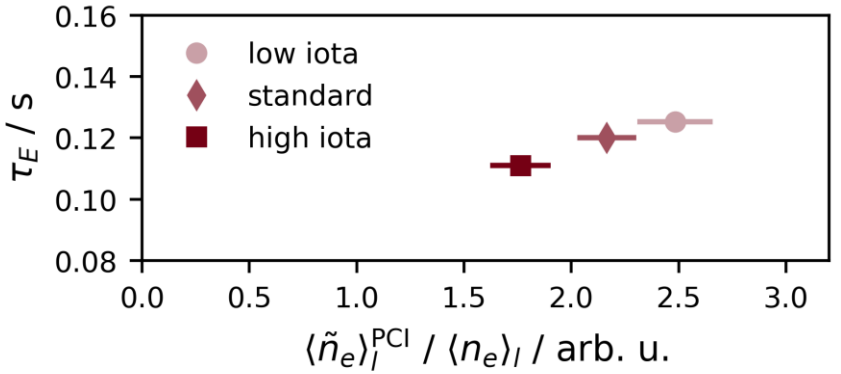
low to high mirror



Relation to global confinement
Differences are small and not always consistent

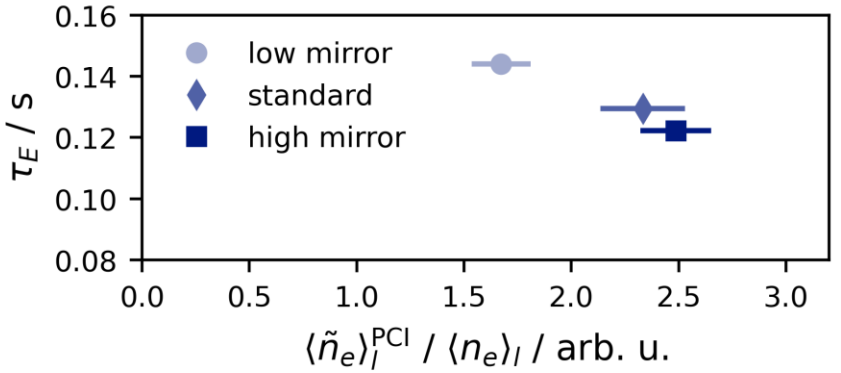
low-high iota

- confinement time *increase* with increasing density fluctuation amplitudes
- might be related to large differences in SOL physics



low-high mirror

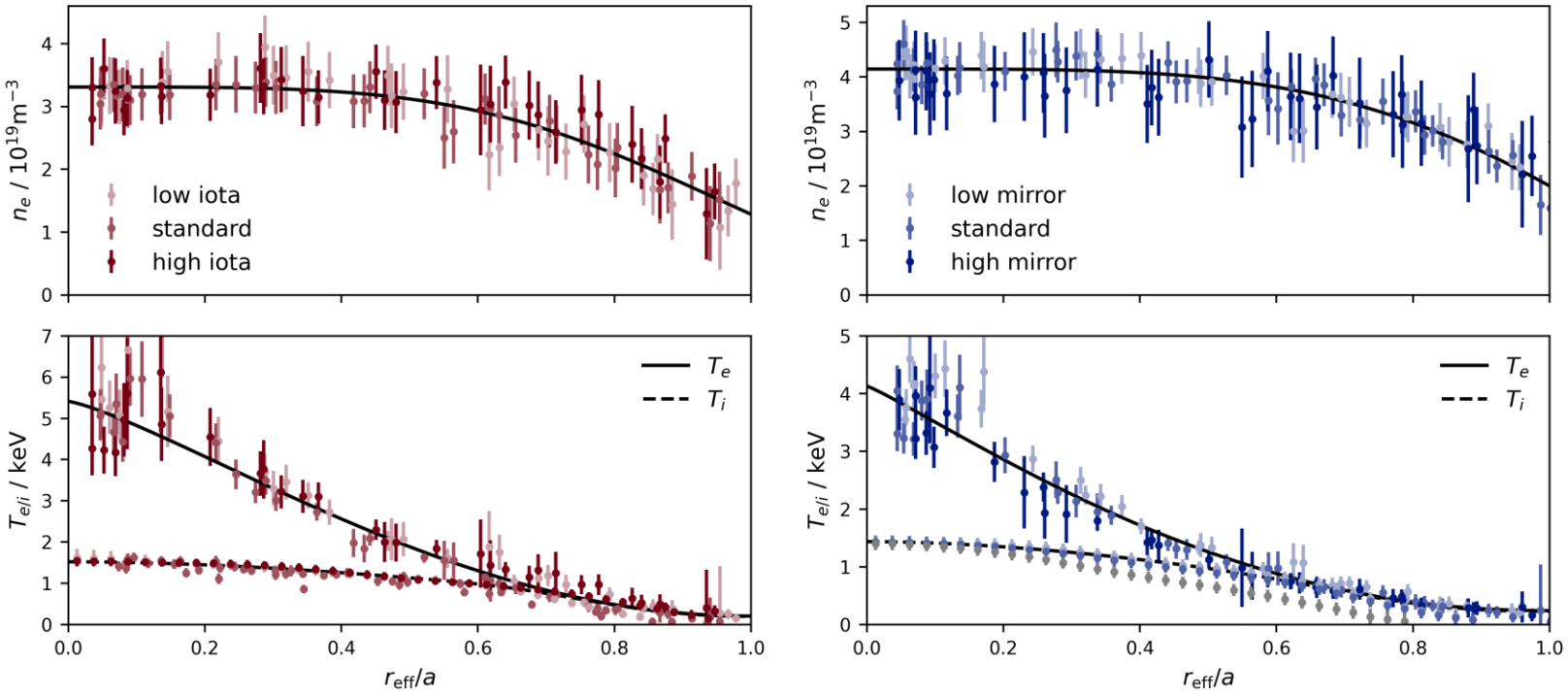
- confinement time *decreases* with increasing density fluctuation amplitudes



- differences in τ_E are small – effect on global transport is reproducible but minor, which is reflected by profiles

Kinetic Profiles
show no variation beyond measurement uncertainties

- differences between profiles at (almost) identical heating power and line-averaged density are within measurement uncertainties
- generate fit to match all configurations – take as **representative model profiles**



Gobal simulations with GENE-3D
Most rigorous simulations available support FT results

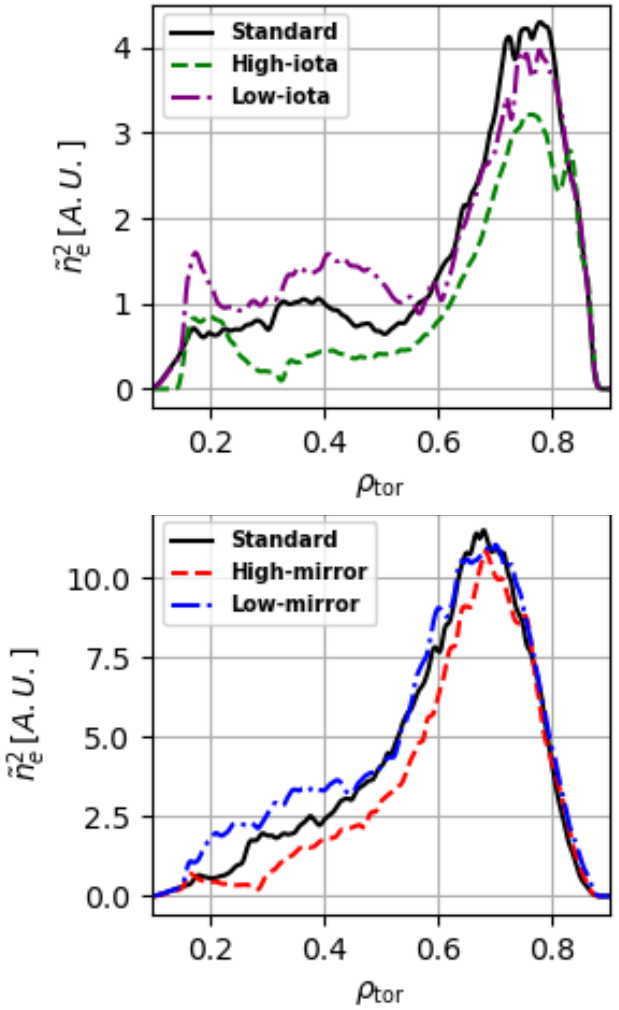
- global, nonlinear, electromagnetic, include kinetic electrons & collisions
- input: model profiles and E_r-profiles from neoclassical transport calculations

Results:

- largely support picture from FT simulations
- overall, differences in density fluctuations heat fluxes are small
- observed trends are not radially unique
- radially global effects do not qualitatively change results

Ongoing work:

- apply synthetic diagnostics to GENE-3D data
- evolve profiles in GENE-KNOSOS-TANGO framework



courtesy of A. Bañón Navarro

A. Bañón Navarro *et al.*, *24th International Stellarator Heliotron Workshop, Sep. 9th* 2024, Hiroshima, Japan

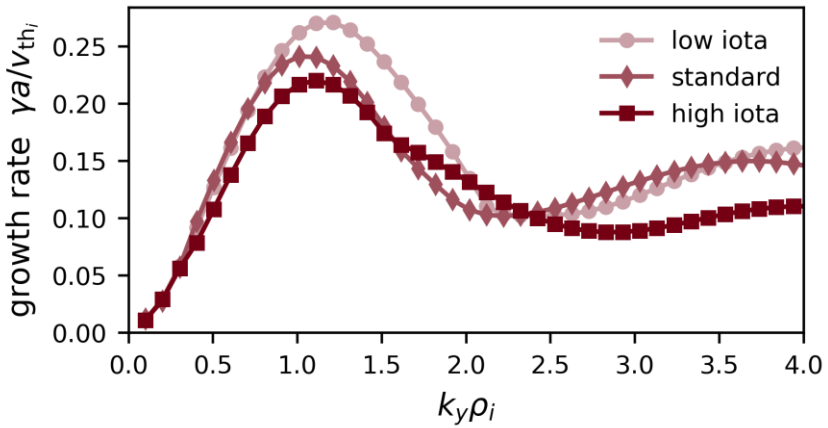
Overview of linear stella simulations

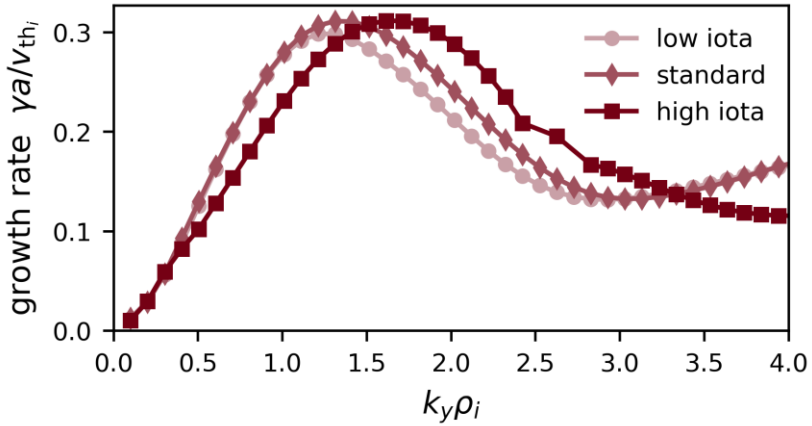
low to high iota

PCI FT

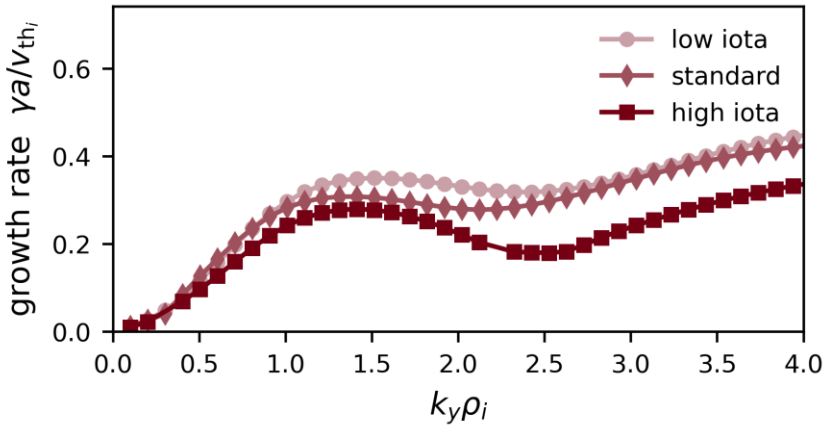
bean FT

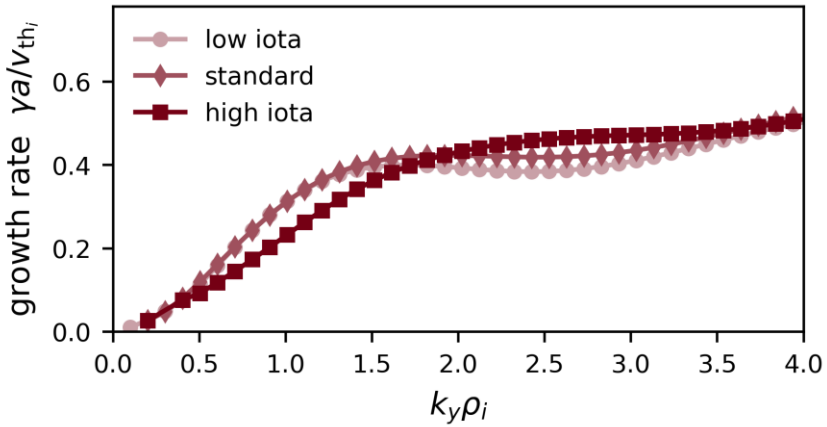
$a/L_{T_e} = 0$





$a/L_{T_e} = a/L_{T_i}$





Overview of linear stella simulations

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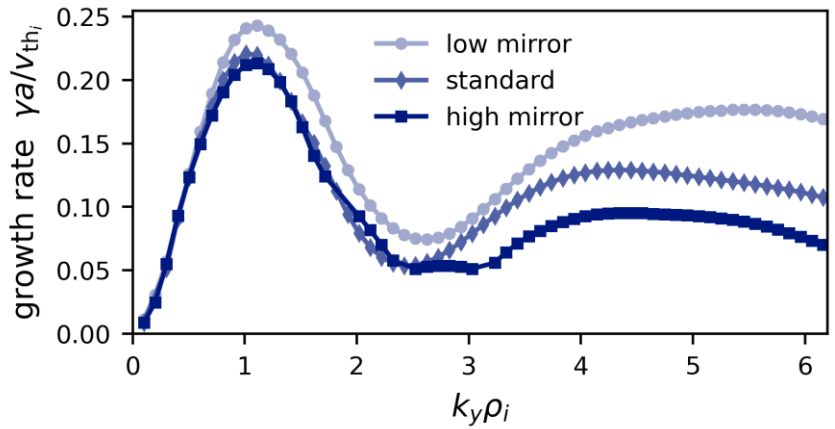
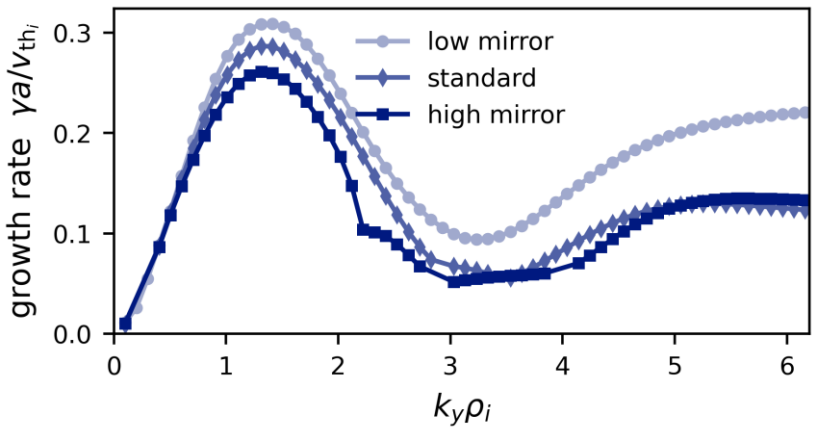
$a/L_{T_e} = 0$





$a/L_{T_e} = a/L_{T_i}$