First insights into ITB physics

A progress report for TSVV1 workshop

Arnas Volčokas
Justin Ball, Stephan Brunner

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Outline

- Internal and edge transport barriers
- Internal transport barrier formation
- Milestones and deliverables
- Turbulent self-interaction
- Preliminary results:
  - Linear simulations
  - Nonlinear simulations
- Current work

Internal and edge transport barriers

<u>H-mode (edge transport barrier)</u>

- Transport bifurcation
- Gradient steepening
- **ExB shearing flow**
- High magnetic shear

<u>Internal transport barrier (ITB)</u>

- Transport bifurcation
- Gradient steepening
- **ExB shearing flow**
- Low or negative magnetic shear

References: K Ida and T Fujita 2018 *Plasma Phys. Control. Fusion* **60** 033001

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Core region – easier to investigate numerically

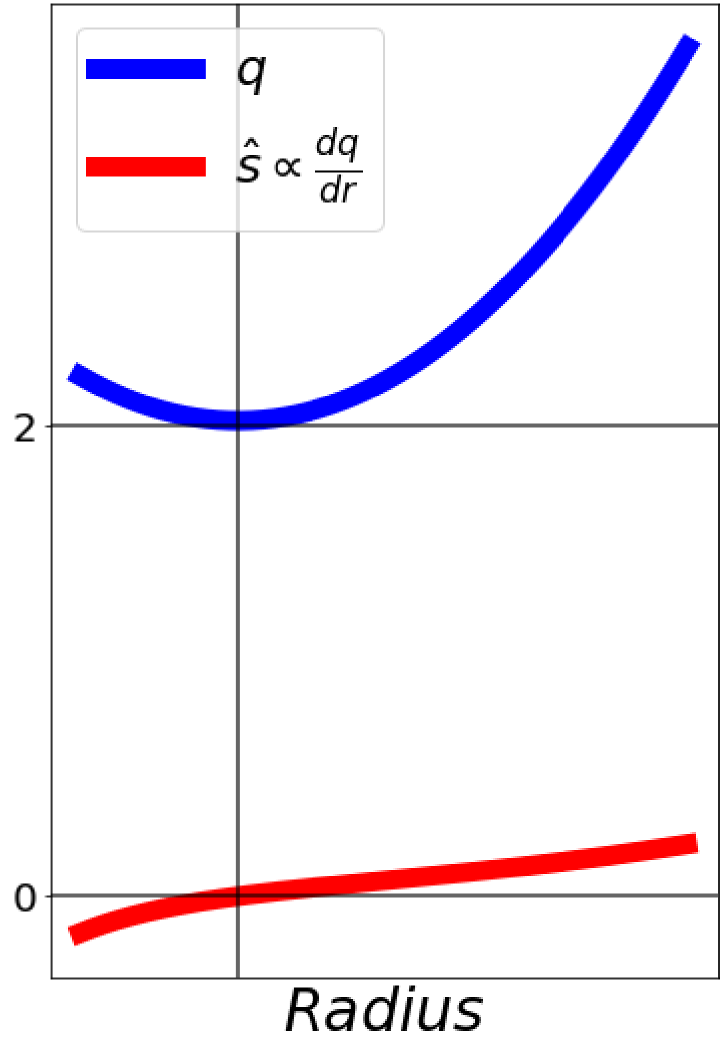
- No coupling to scrape-off layer;
- Relatively simple geometry;
- Low collisionality;
- Low fluctuation levels;
- No neutrals.

ITB formation

- Low or negative magnetic shear $\hat{s}$ is crucial;
- ITBs are often localized around rational q;
- Presence of **integer minimum *q*** seems to be especially favourable for ITB formation

Additionally:

- Heating power threshold



References:

- K Ida and T Fujita 2018 Plasma Phys. Control. Fusion 60 033001
- J.W. Connor et al. 2004 Nucl. Fusion 44 R1
- X. Garbet et al. 2010 Nucl. Fusion 50 043002

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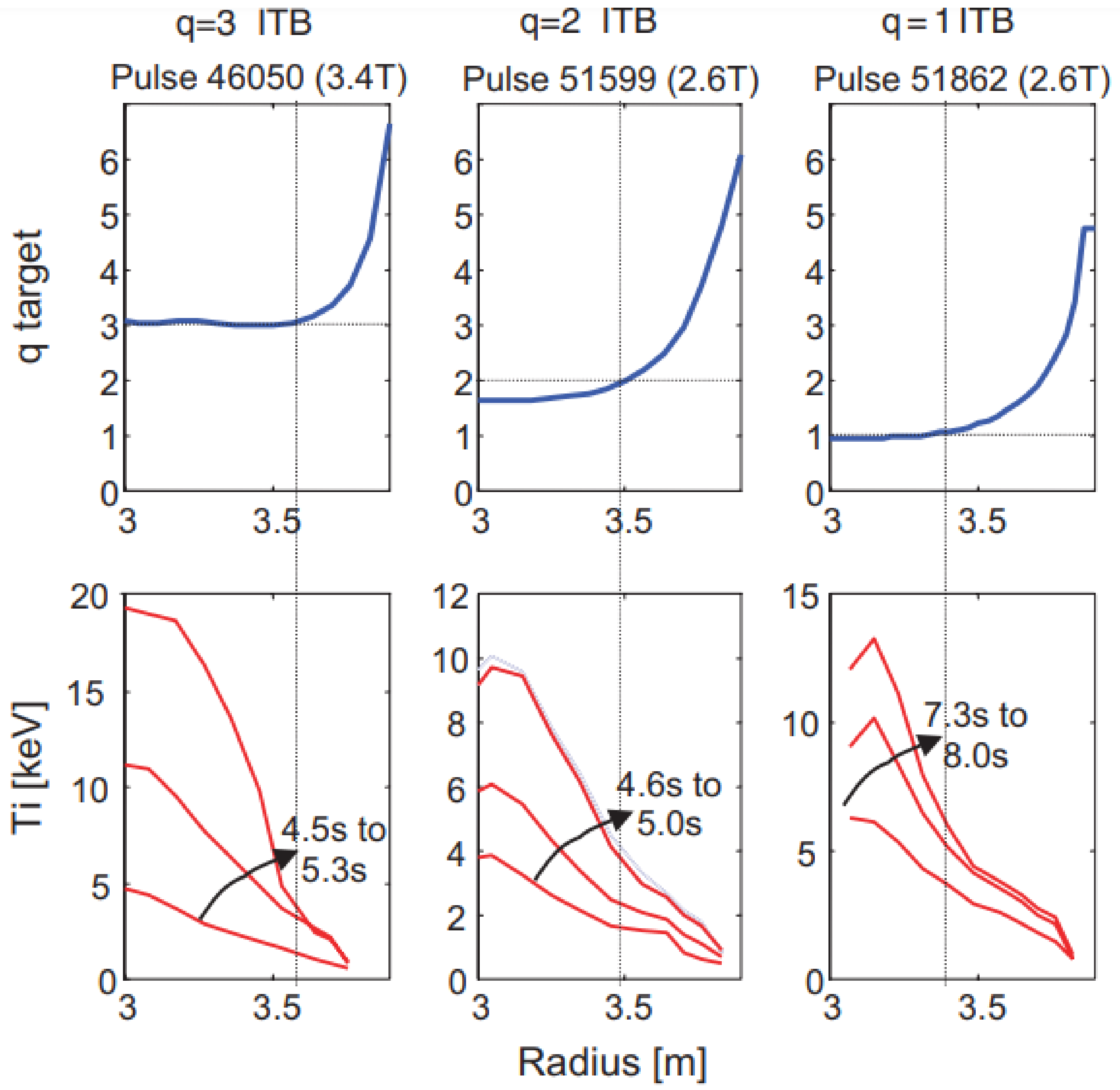

E Joffrin et al 2002 *Plasma Phys. Control. Fusion* **44** 1739

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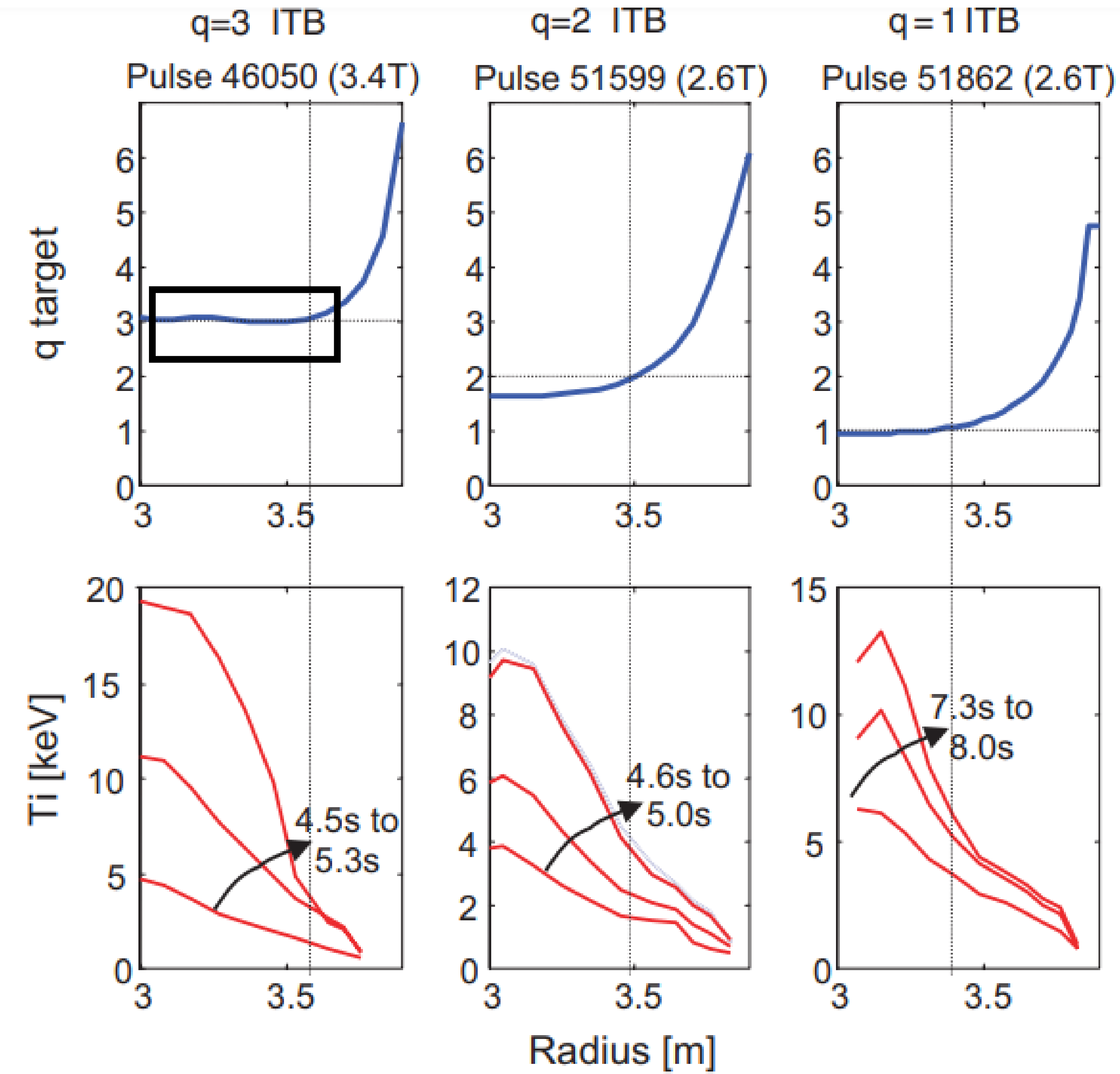

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Deliverables and milestones 1

D4.1 Quantification of ITB momentum drive from rational vs irrational surfaces and comparisons to plasma edge	Target date 02/2022
M4.1 Quantify momentum drive from rational vs irrational surfaces in ITBs and compare to momentum drive at plasma edge and determine relationship of parallel correlation length with magnetic shear.	Target date 12/2021

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The proposed plan has not changed substantially and we are on track, working towards the milestones.

Internal transport barrier investigation in local gyrokinetic simulations

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Turbulent self-interaction

On low order rational surfaces (q=2,2.5,3,…)

Magnetic field lines exactly close on themselves

Strong parallel self-interaction

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References:

- J. Ball *et al.* 2020 *Journal of Plasma Physics* **86(2)**, 905860207
- Ajay CJ, Studying the effect of non-adiabatic passing electron dynamics on microturbulence self-interaction in fusion plasmas using gyrokinetic simulations, Thesis EPFL Lausanne, 2020

Self-interaction

- Self-interaction alters fluctuation behaviour both linearly and non-linearly
- Turbulent self-interaction can be visualized **in real space as “eddy biting its own tail”**

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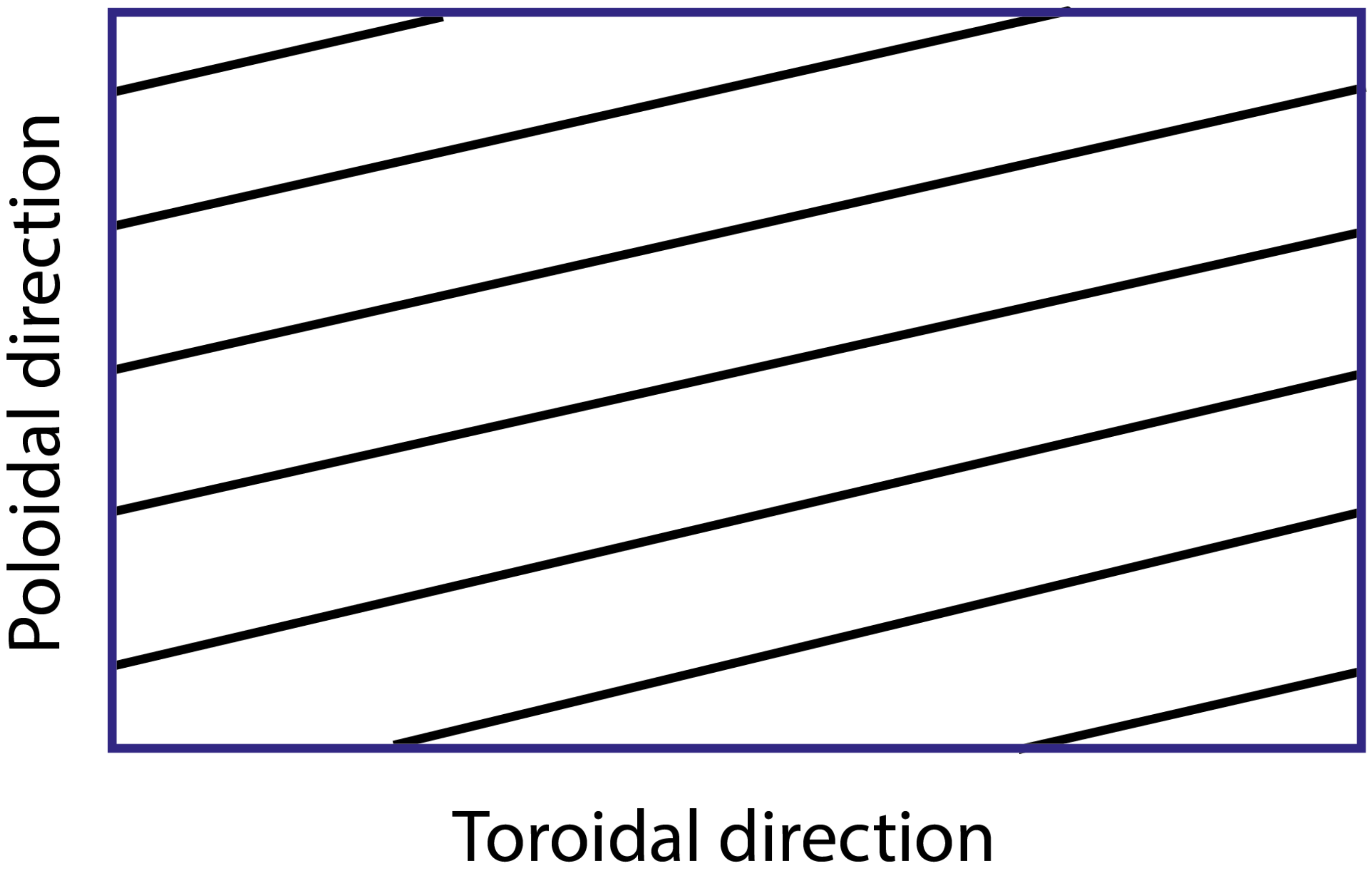
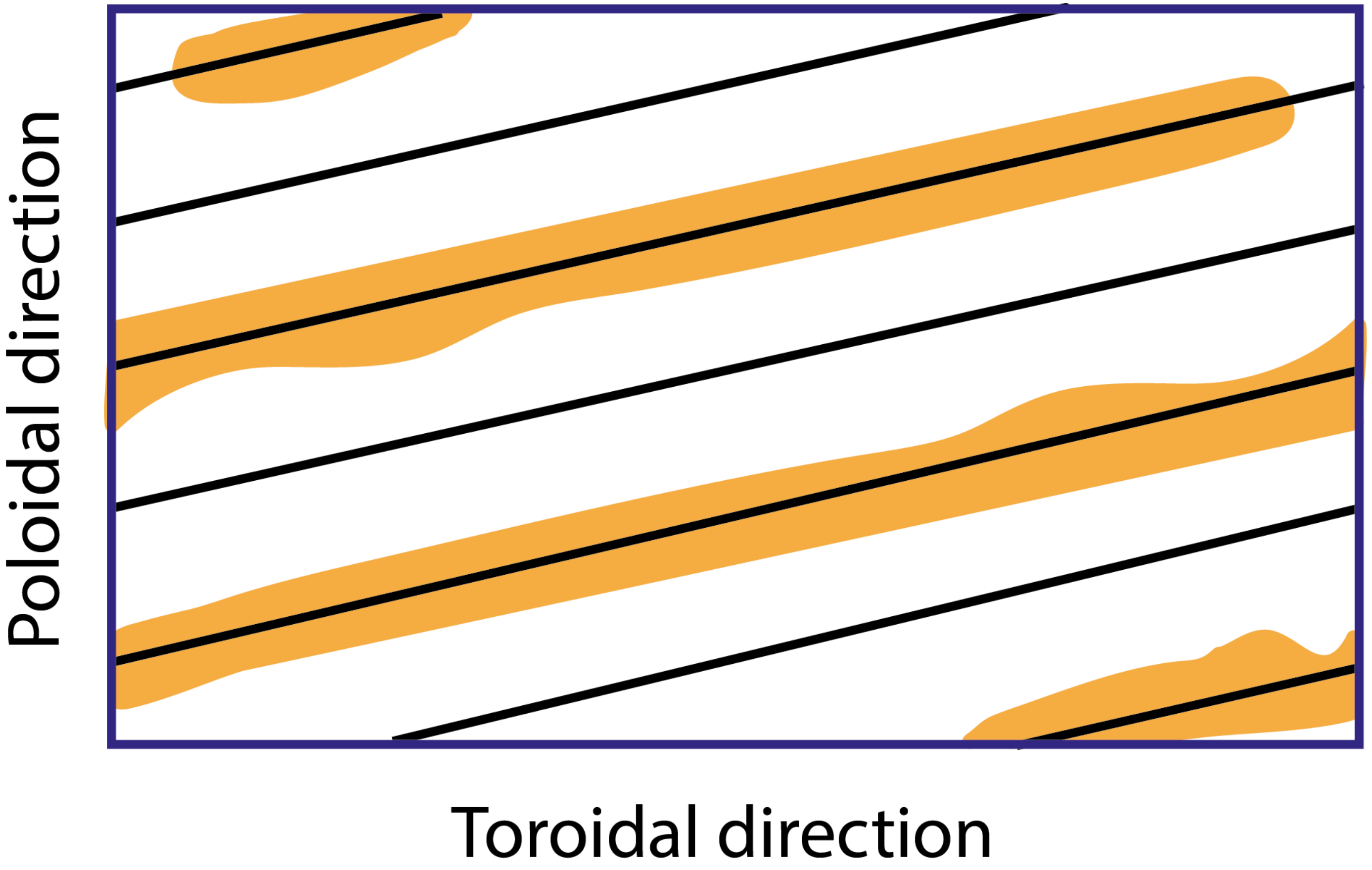
Self-interaction



$q = 2.5$

Self-interaction



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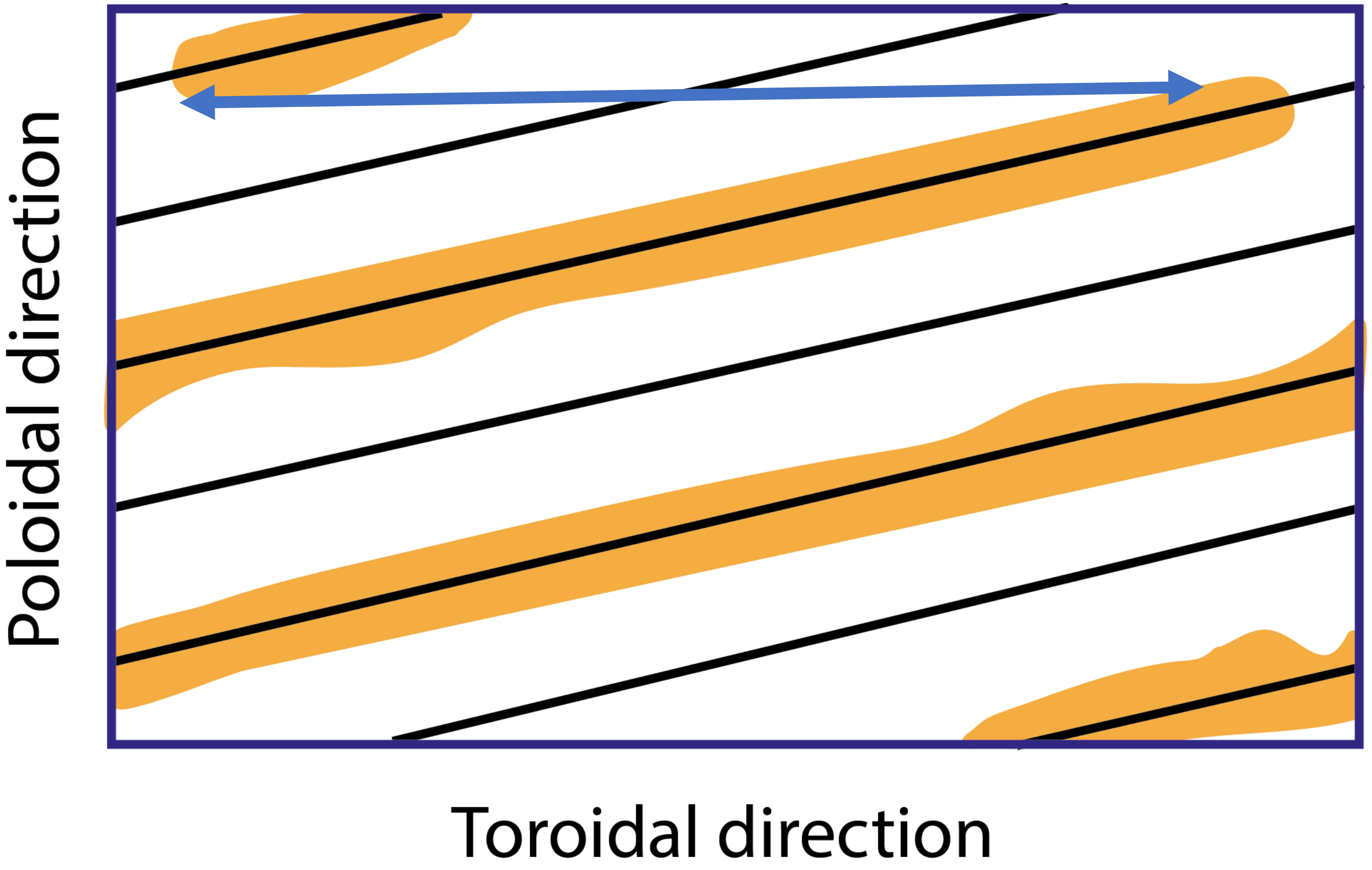

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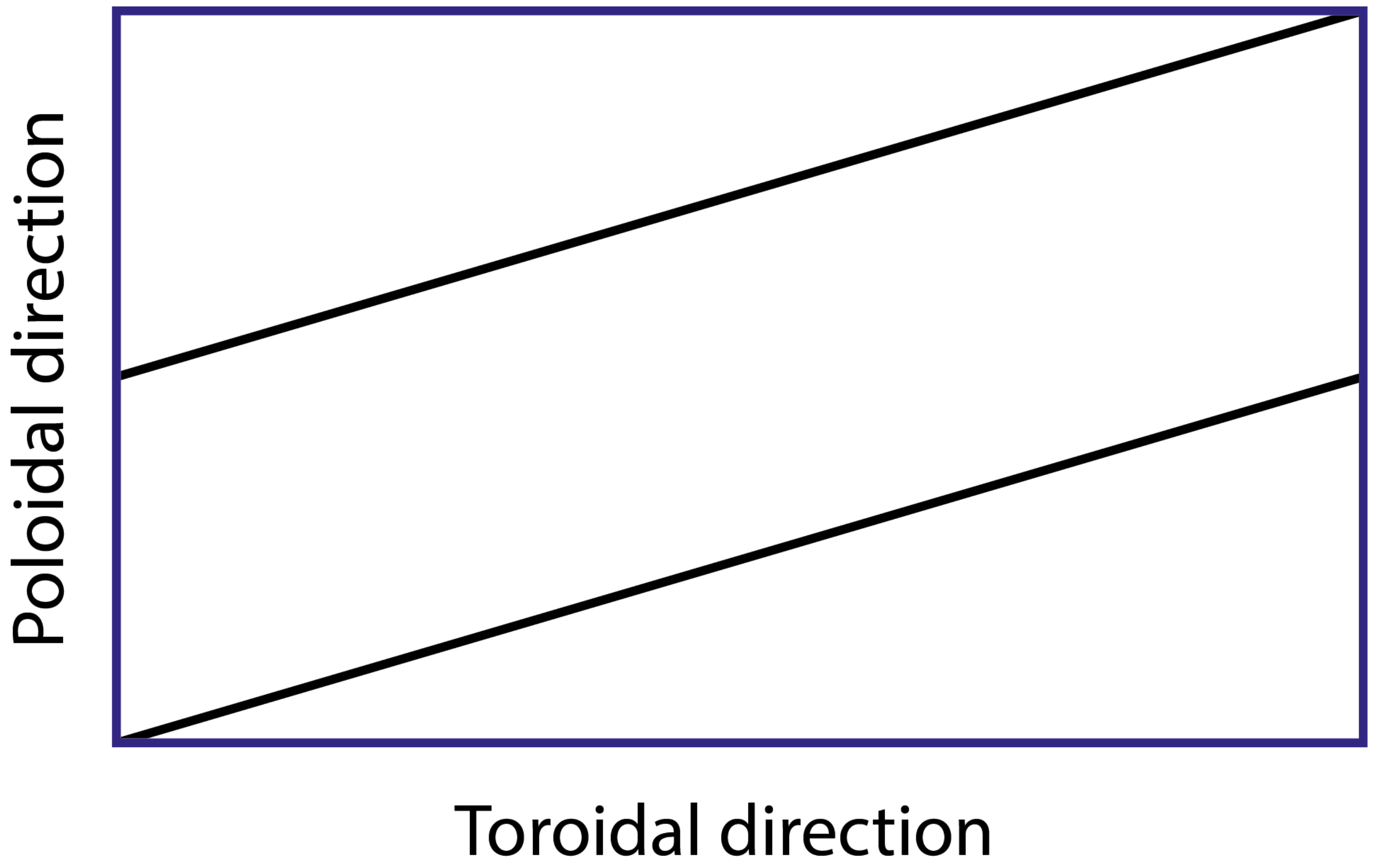

$$q = 2$$

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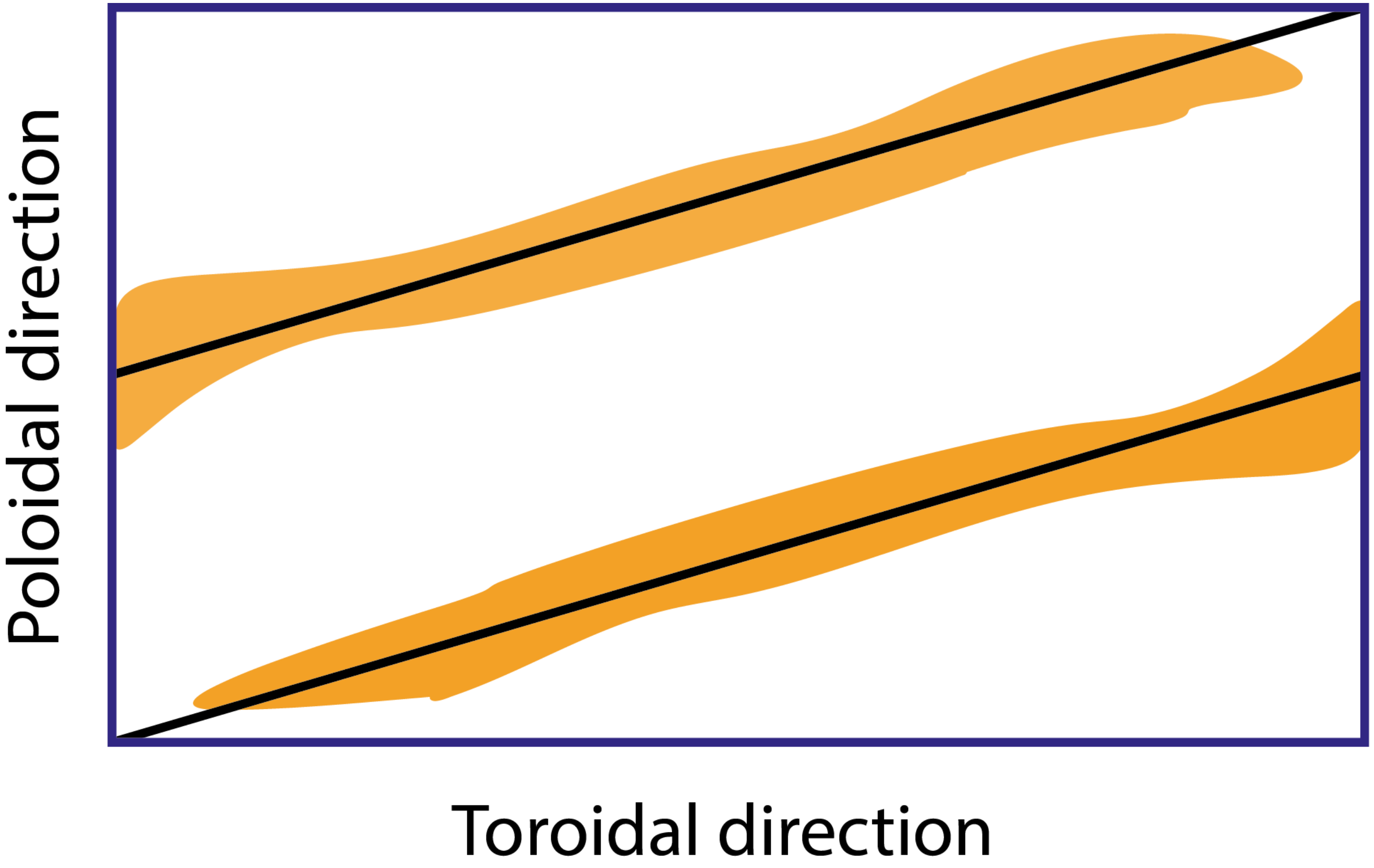
Self-interaction



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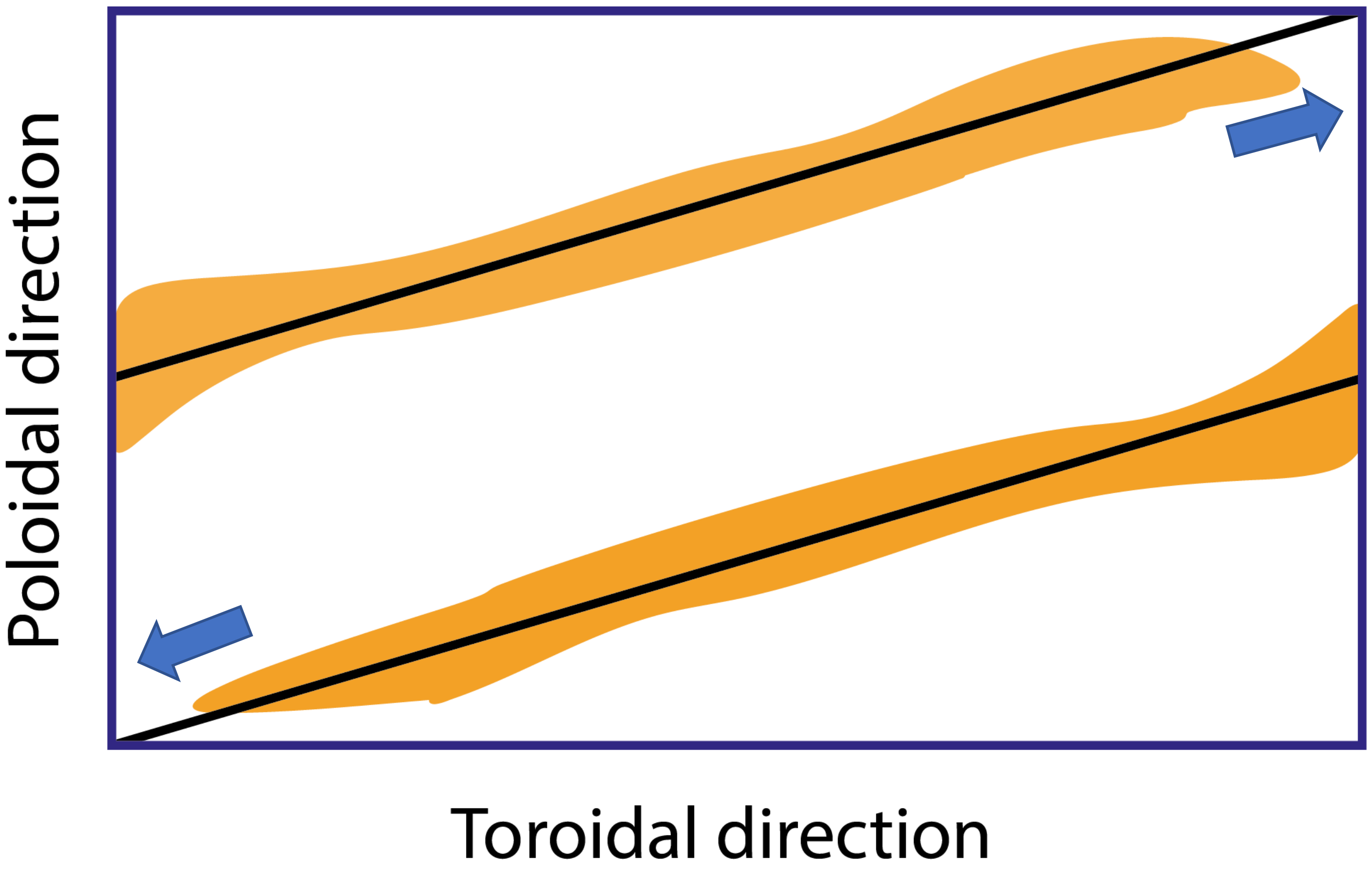

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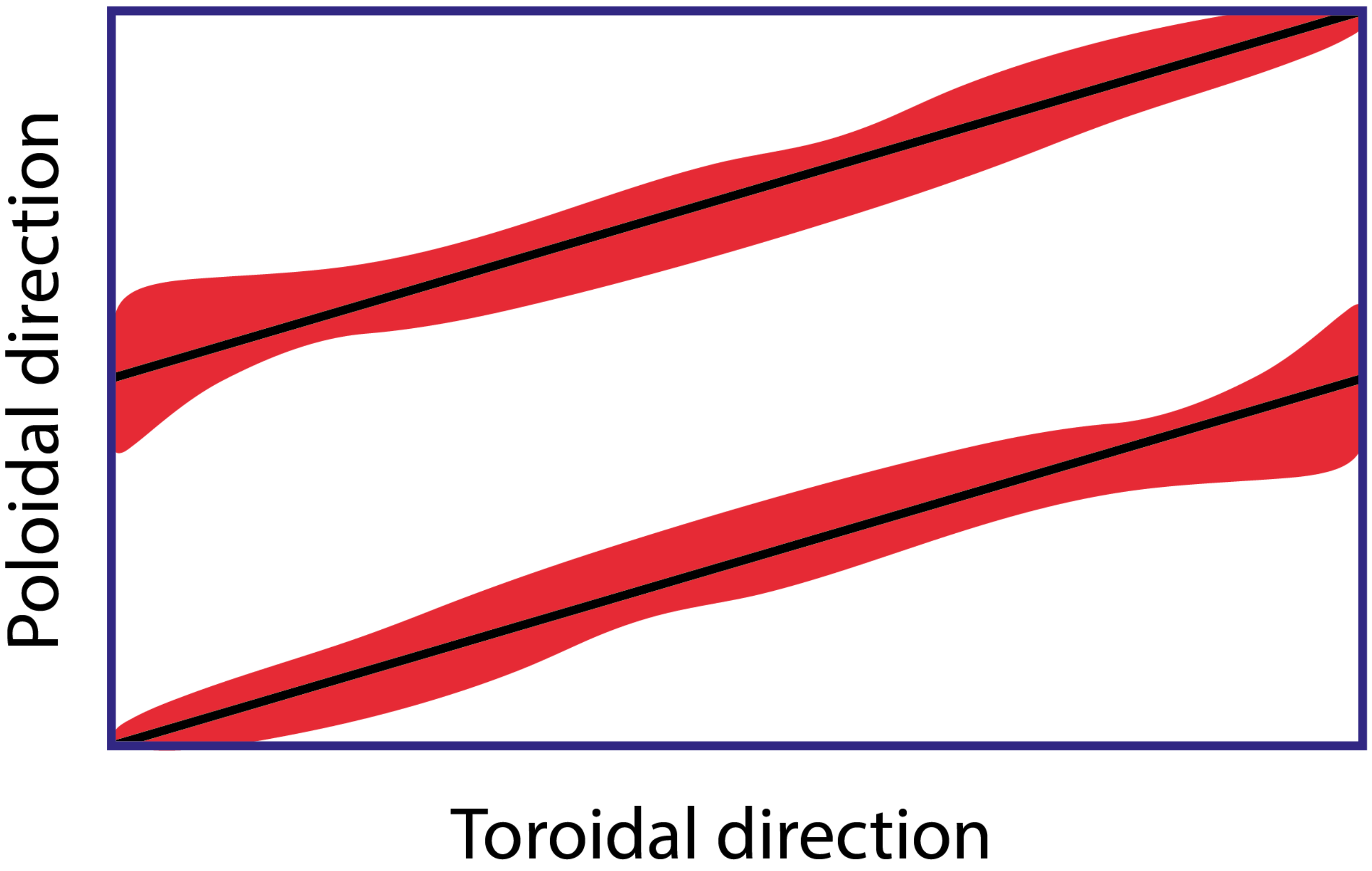
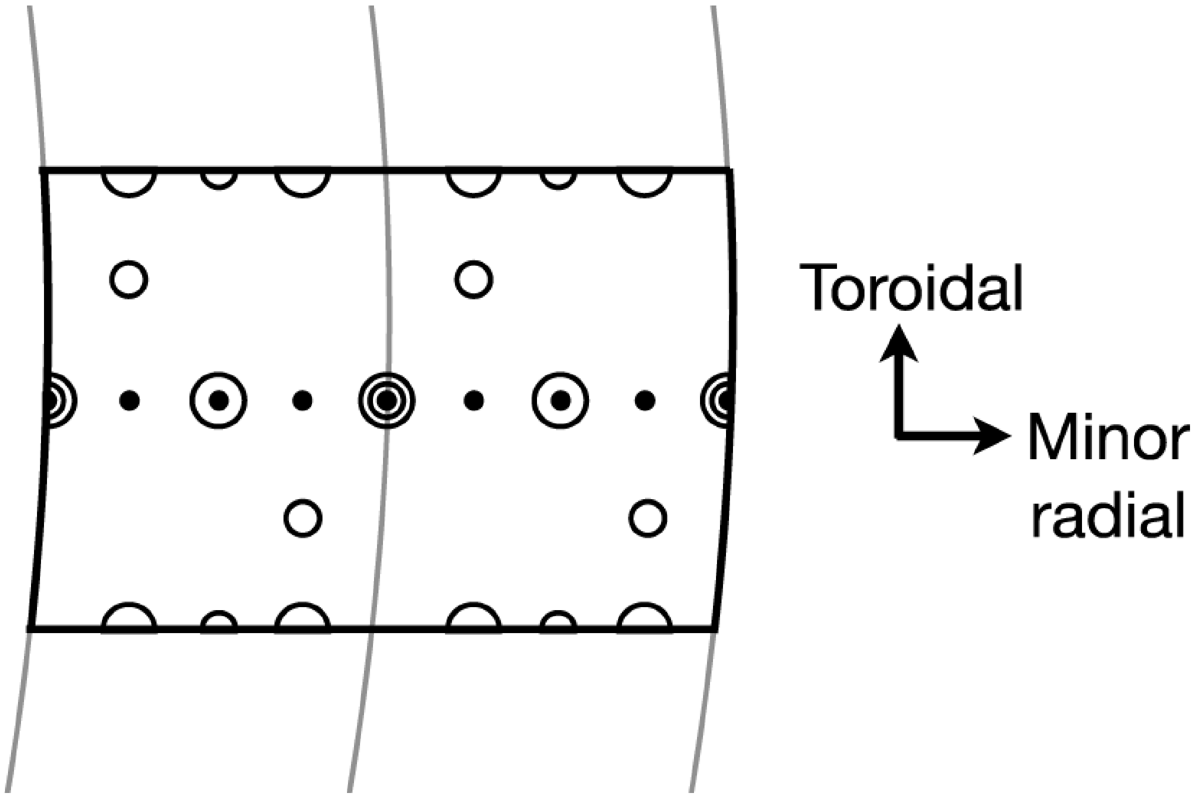


$q = 2$

Flux-tube

- Simulations using local flux-tube GENE code (Eulerian δf code)

- Twist and shift parallel boundary condition -> special radial locations



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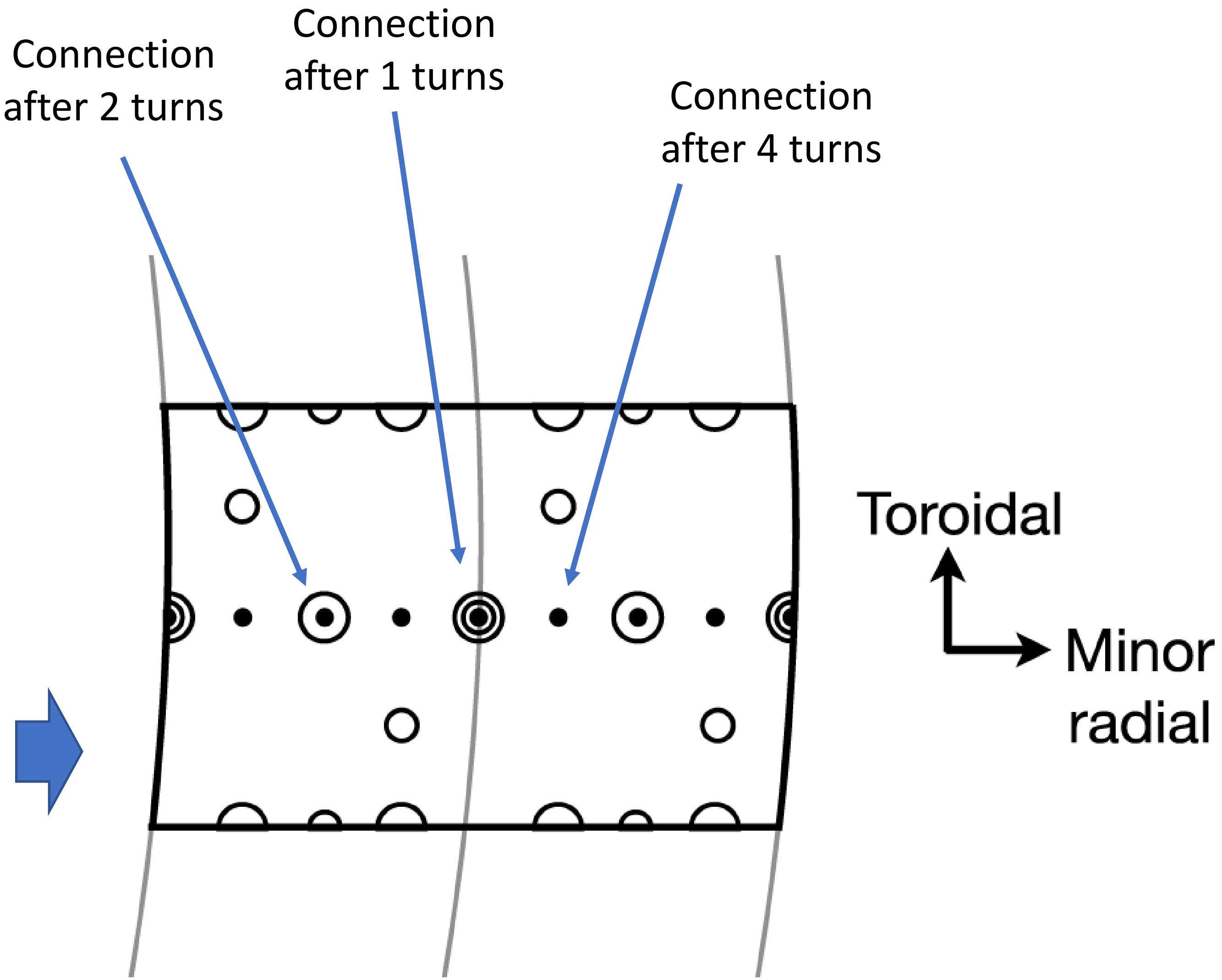

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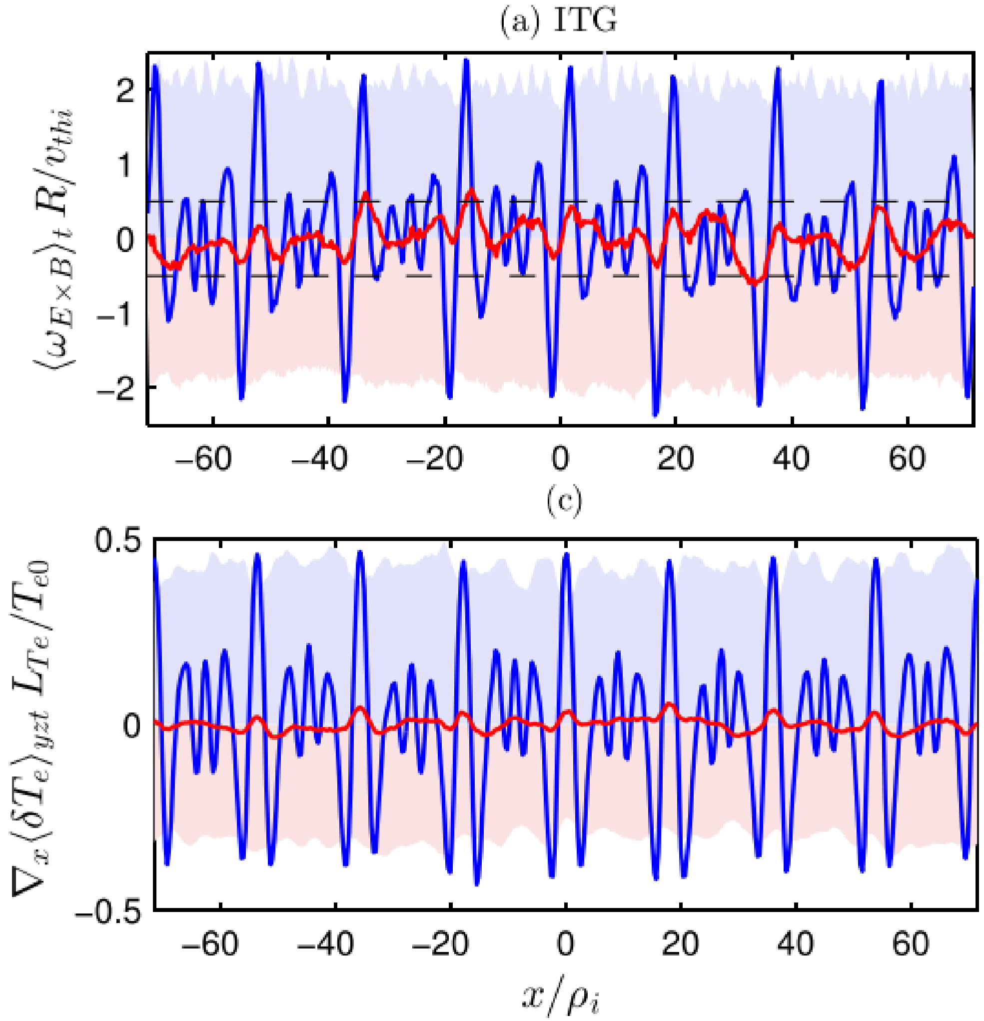
Turbulent self-interaction

Drives ExB shear flow around rational surfaces



J. Dominski *et al.* 2015 *Physics of Plasmas* **22**, 062303

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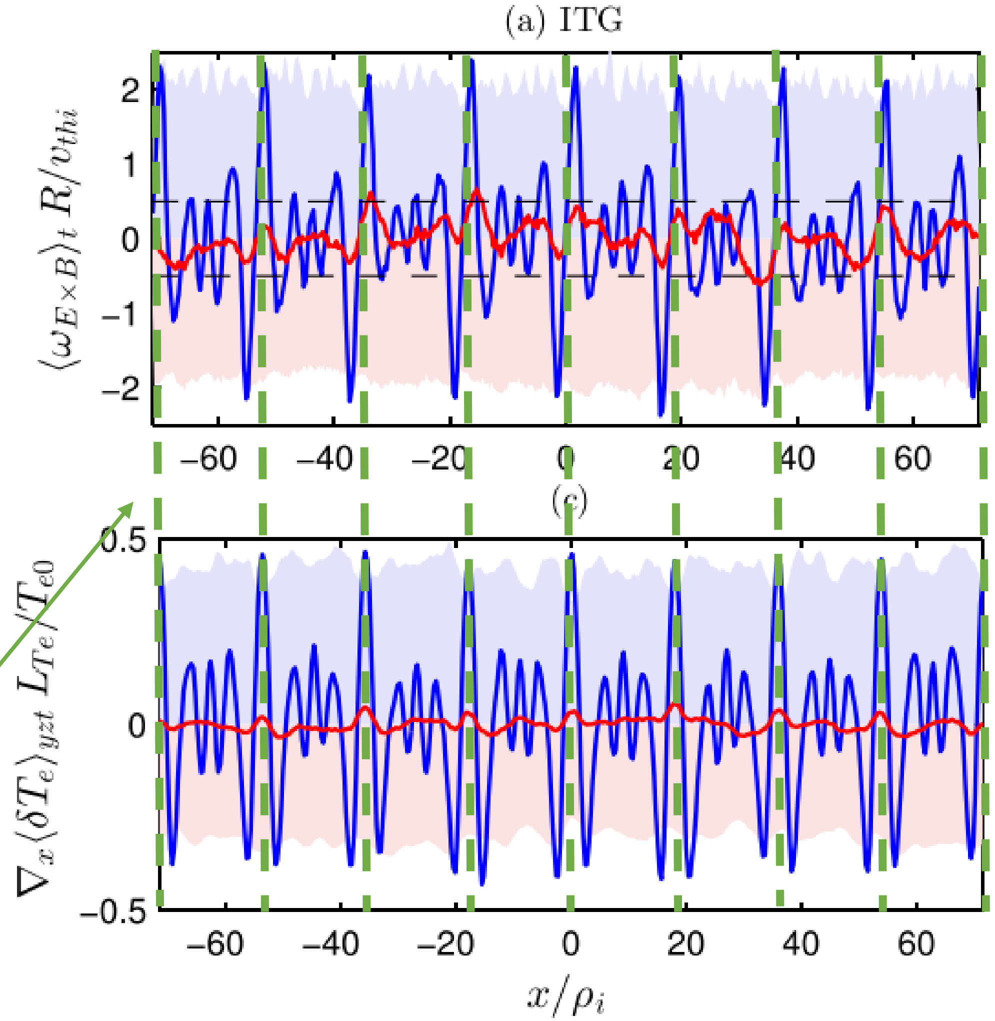

Lowest order rational surfaces

J. Dominski *et al.* 2015 *Physics of Plasmas* **22**, 062303

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ITB triggering

- Low magnetic shear important for ITB formation
- Integer (or low order rational) surfaces important for ITB formation
- Turbulent self-interaction strongest around rational surfaces
- Turbulent self-interaction seems to be stabilizing

Low magnetic shear + self-interaction = ITB ?

Preliminary study

- Linear low and zero shear simulations
- Nonlinear low and zero shear simulations
- Simulations with **kinetic electrons**
- Starting point – Cyclone Base Case (CBC) parameters

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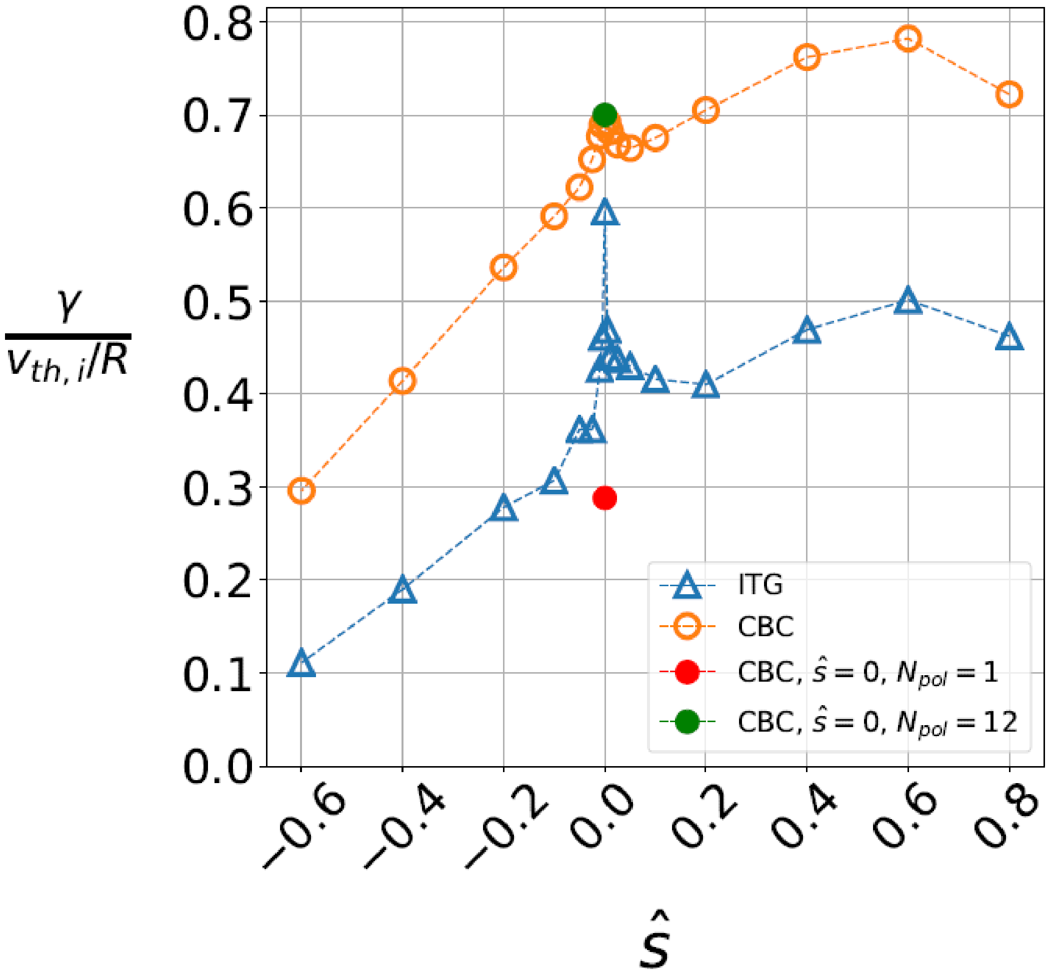
References: Dimits et al. 2000, Physics of Plasmas **7**, 969

Linear study with kinetic electrons



We believe we observe **transition from toroidal to slab ITG mode** as magnetic shear approaches zero.

$k_y \rho_i = 0.45$

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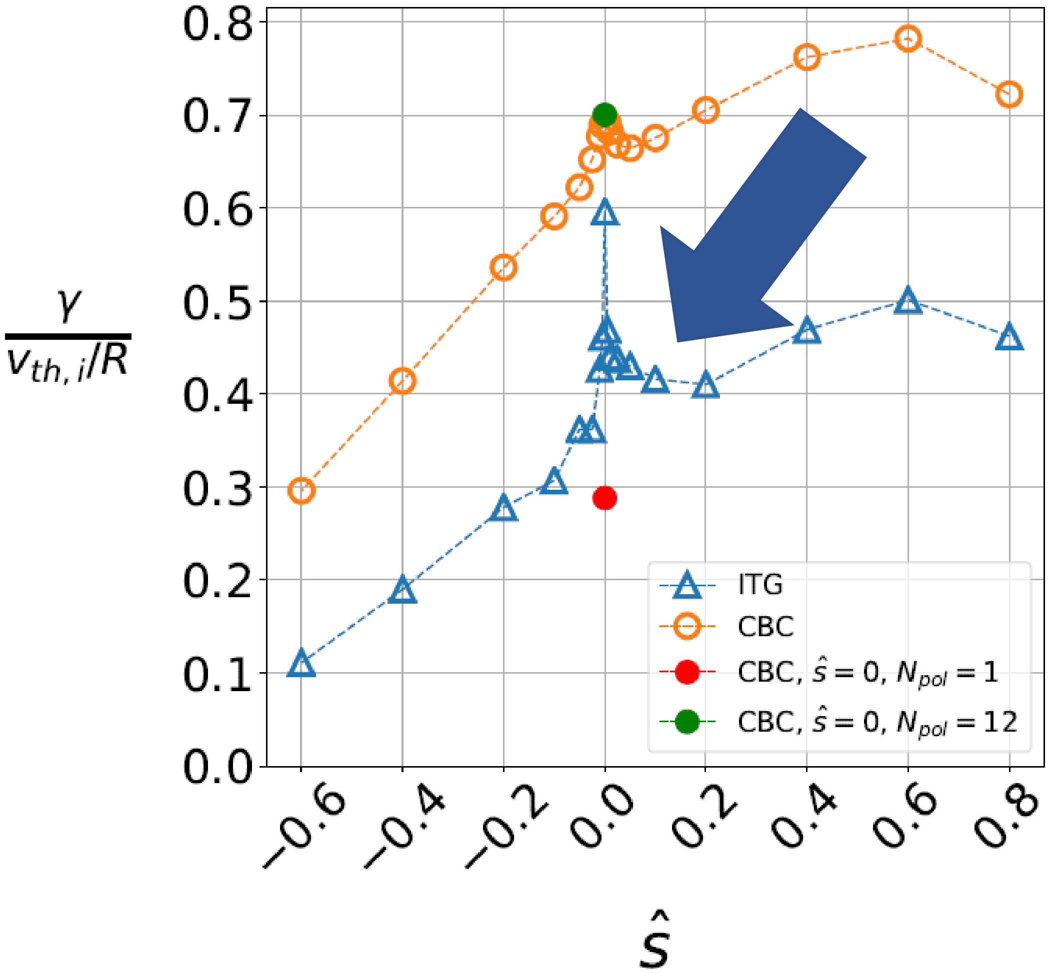
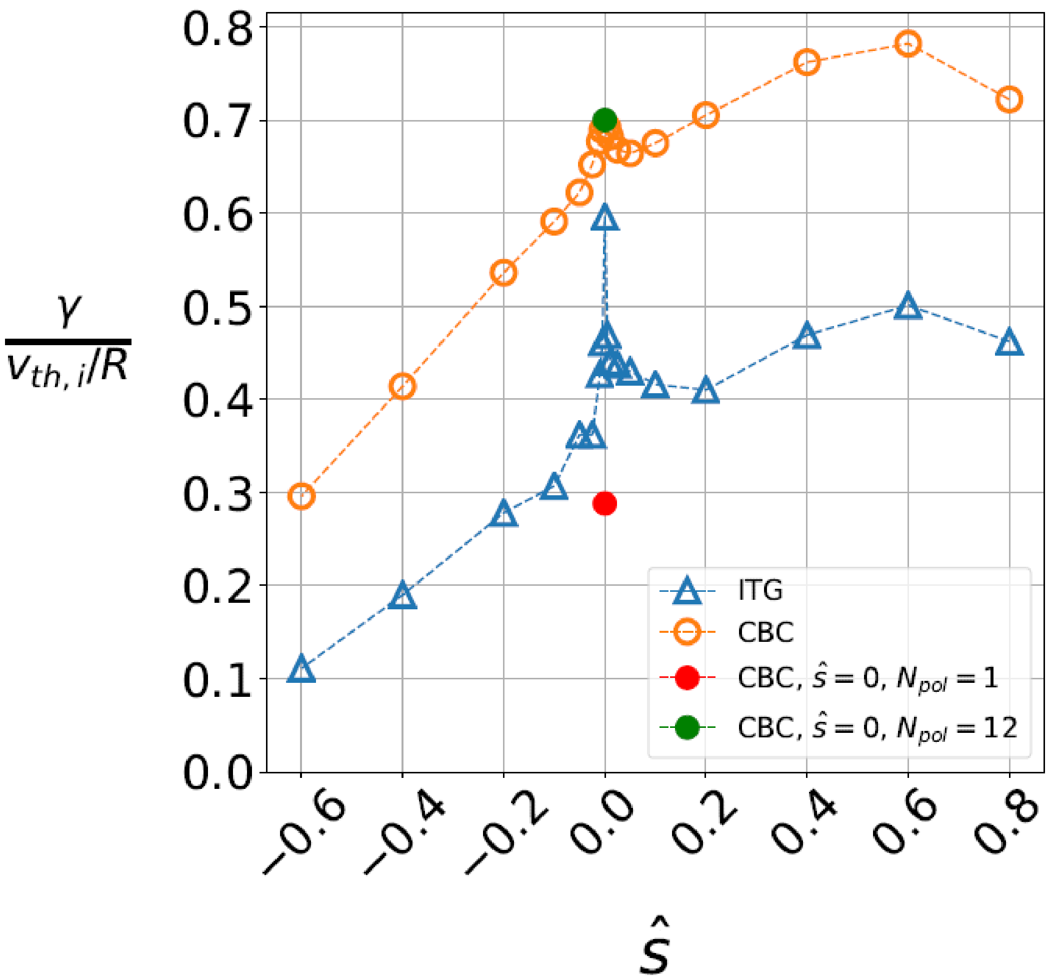
Linear study with kinetic electrons

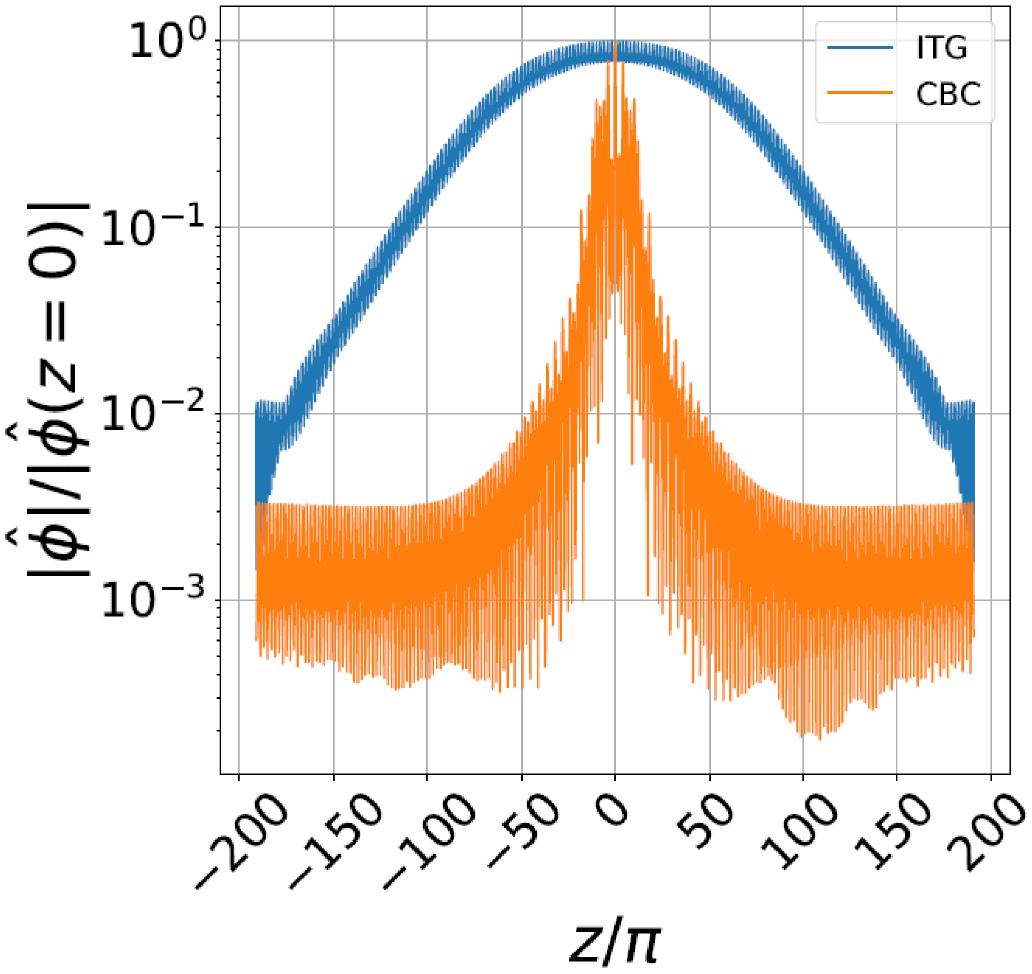


Slab ITG to toroidal ITG for purely ITG drive

$k_y \rho_i = 0.45$

EPFL Linear study with kinetic electrons





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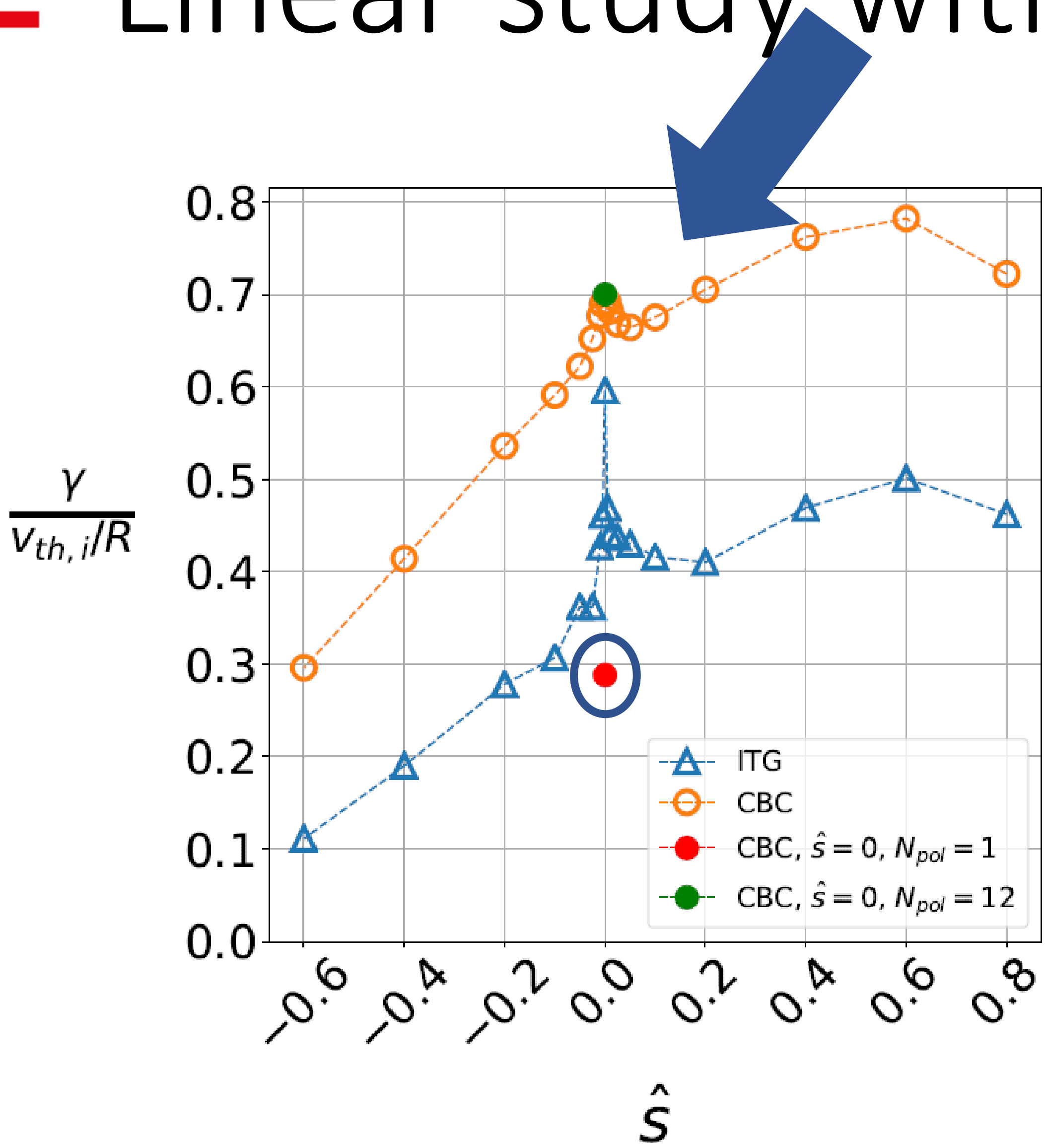

$k_y \rho_i = 0.45$

With CBC drive discontinuity at s=0

Toroidal ITG growth rate reduced by self-interaction at s=0

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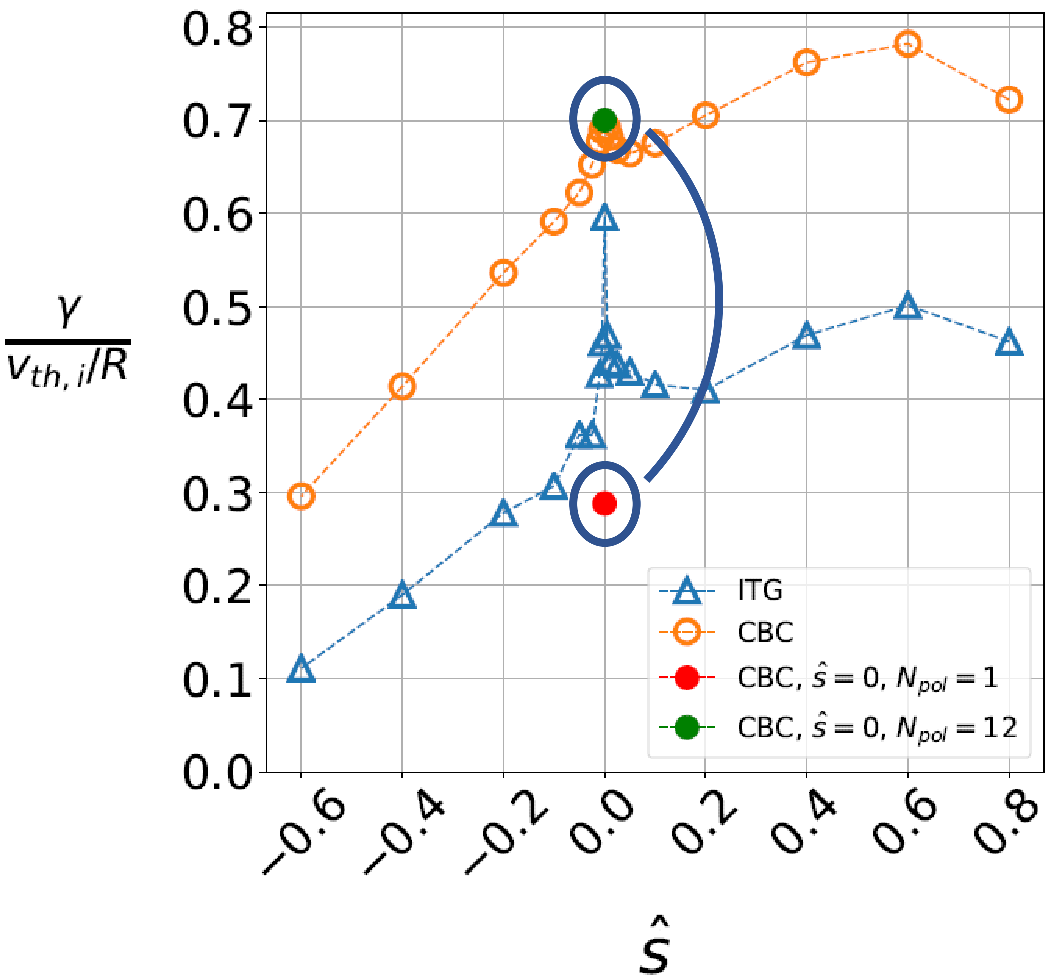
Linear study with kinetic electrons



$k_y \rho_i = 0.45$

Continuity recovered if number of poloidal turns is increased

Number of poloidal turns does not affect purely ITG driven s=0 simulation

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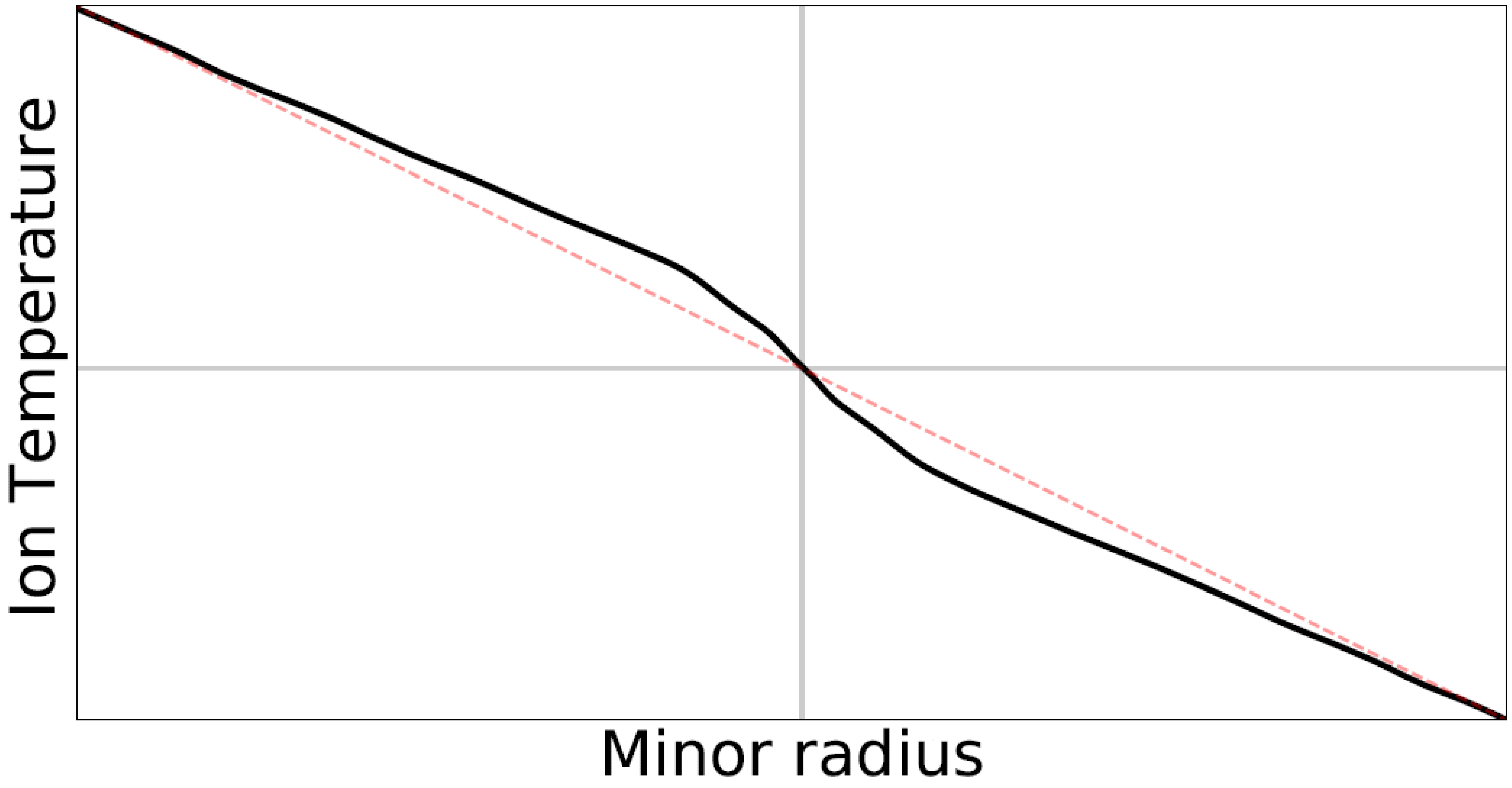
Key linear results

So far the main takeaway from linear studies is that at low magnetic shear there can be a transition to slab ITG.

- The linear growth rate of toroidal ITG was strongly reduced by self-interaction unlike slab ITG;
- Slab ITG extends further along magnetic field lines;
- This transition could be very important for turbulent self-interaction.

Nonlinear study

For s=0.1 we see **a strong corrugation in the plasma profiles** when compared to background gradients



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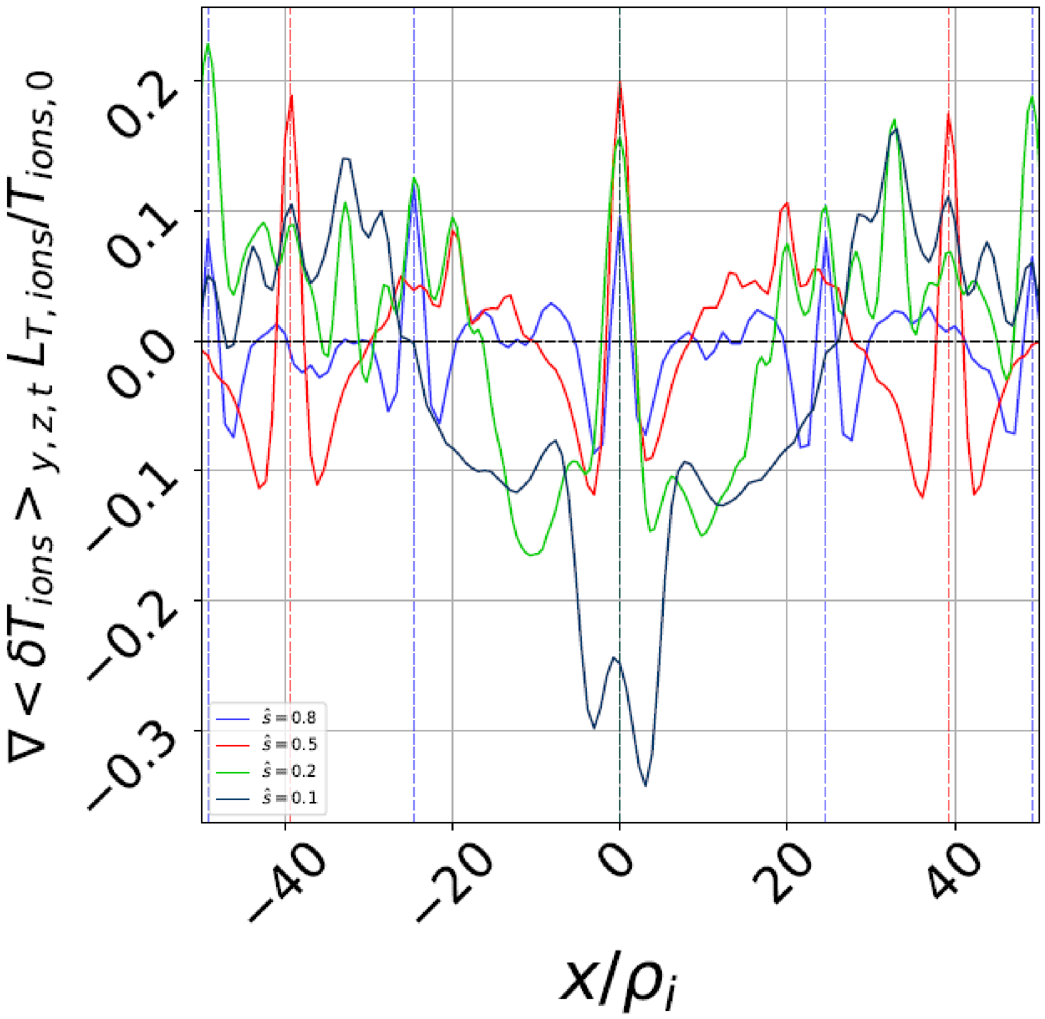
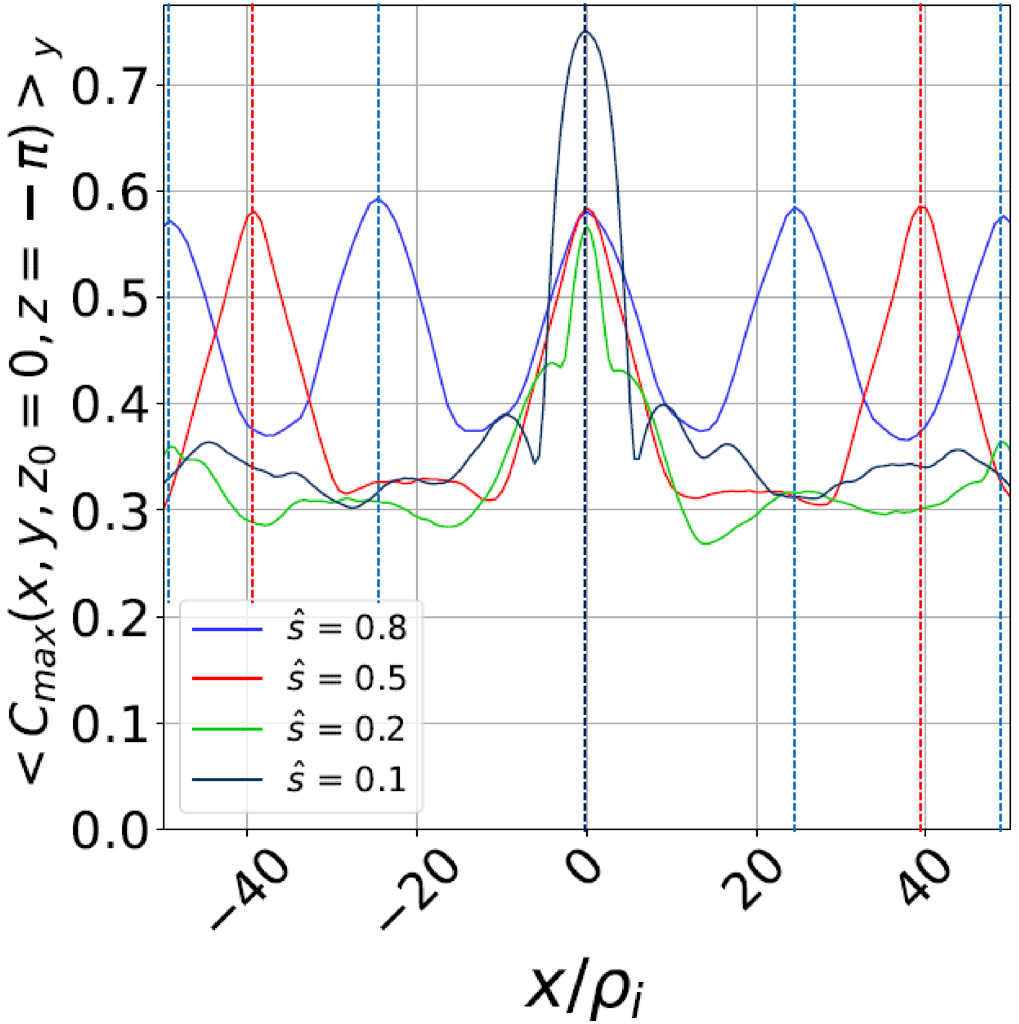
Temperature gradients and auto-correlation





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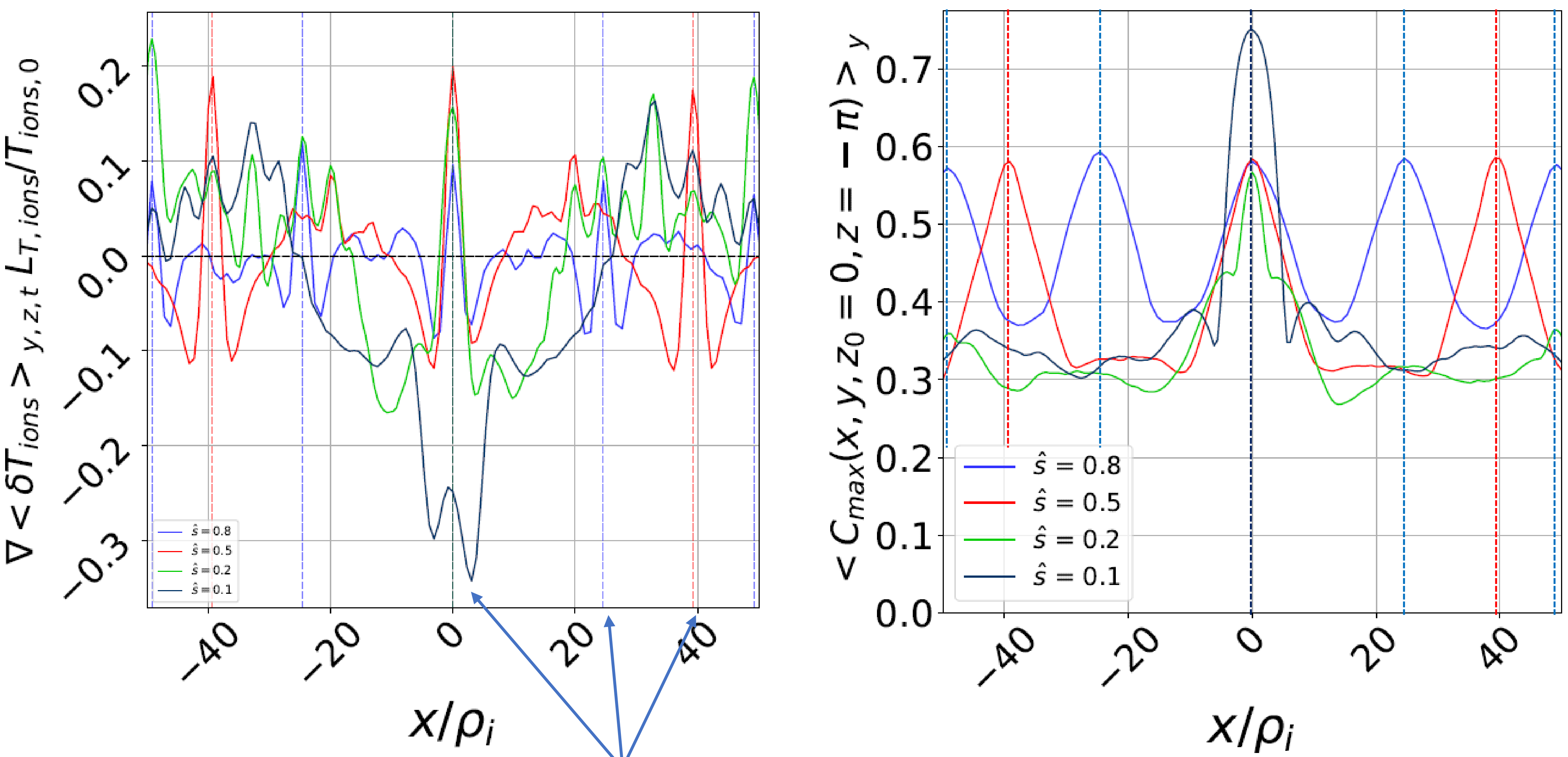
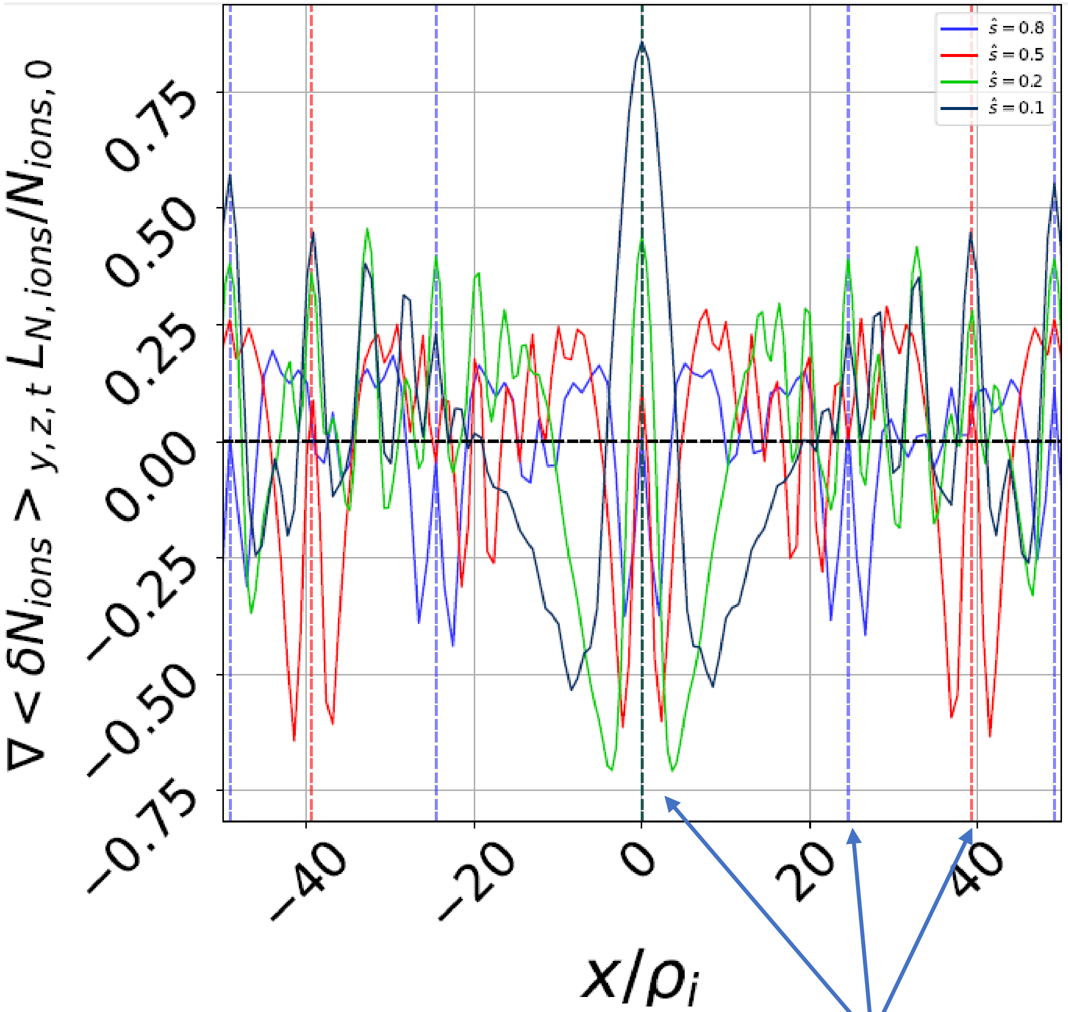
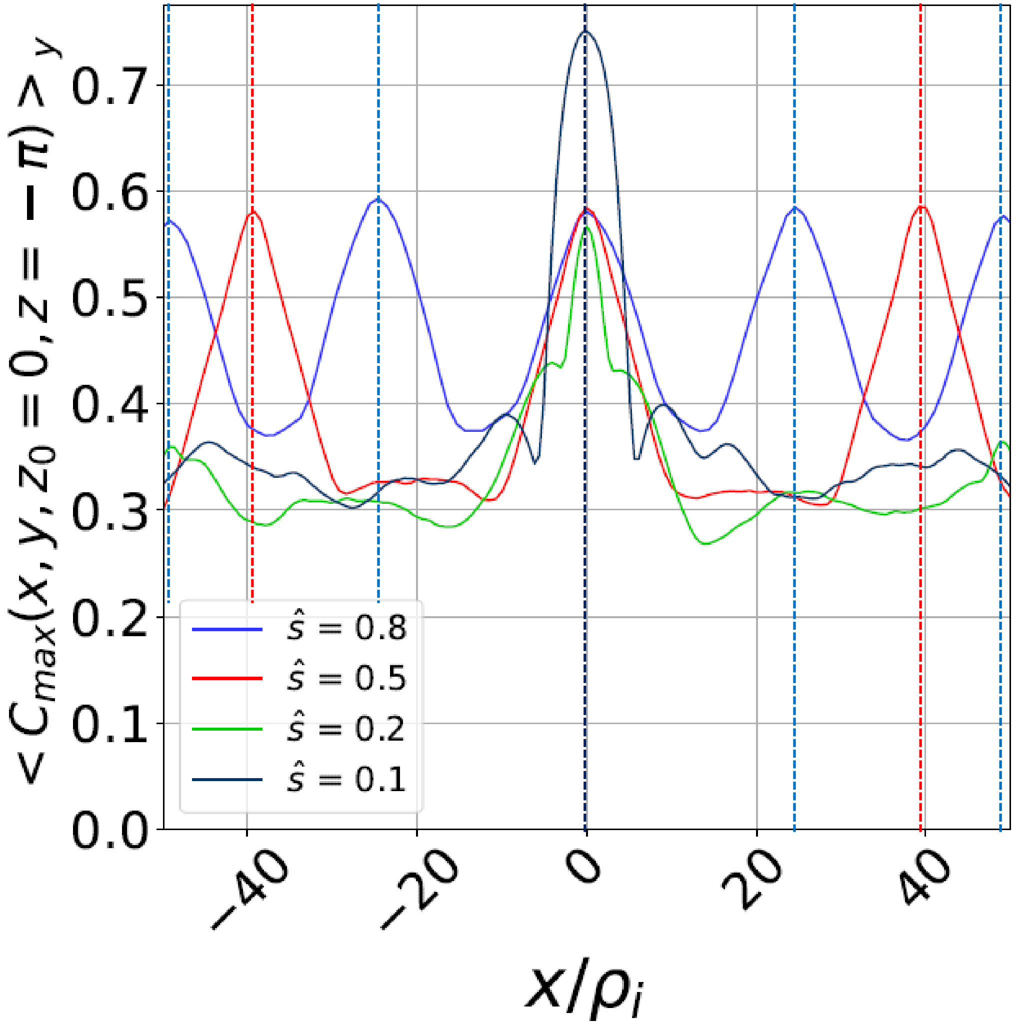


Rational surface location

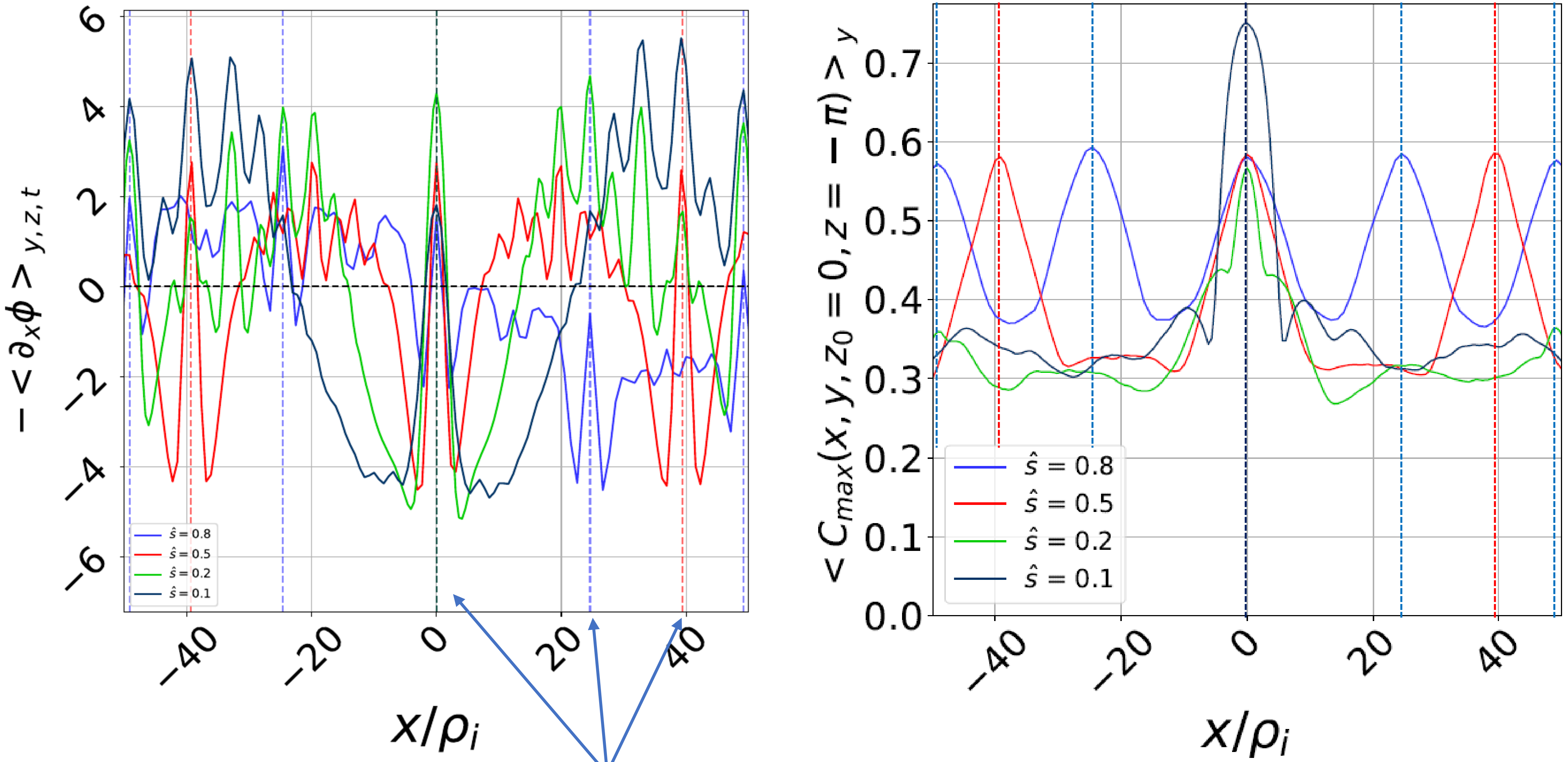
Density gradients and auto-correlation





Rational surface location

Electric field and auto-correlation



Rational surface location

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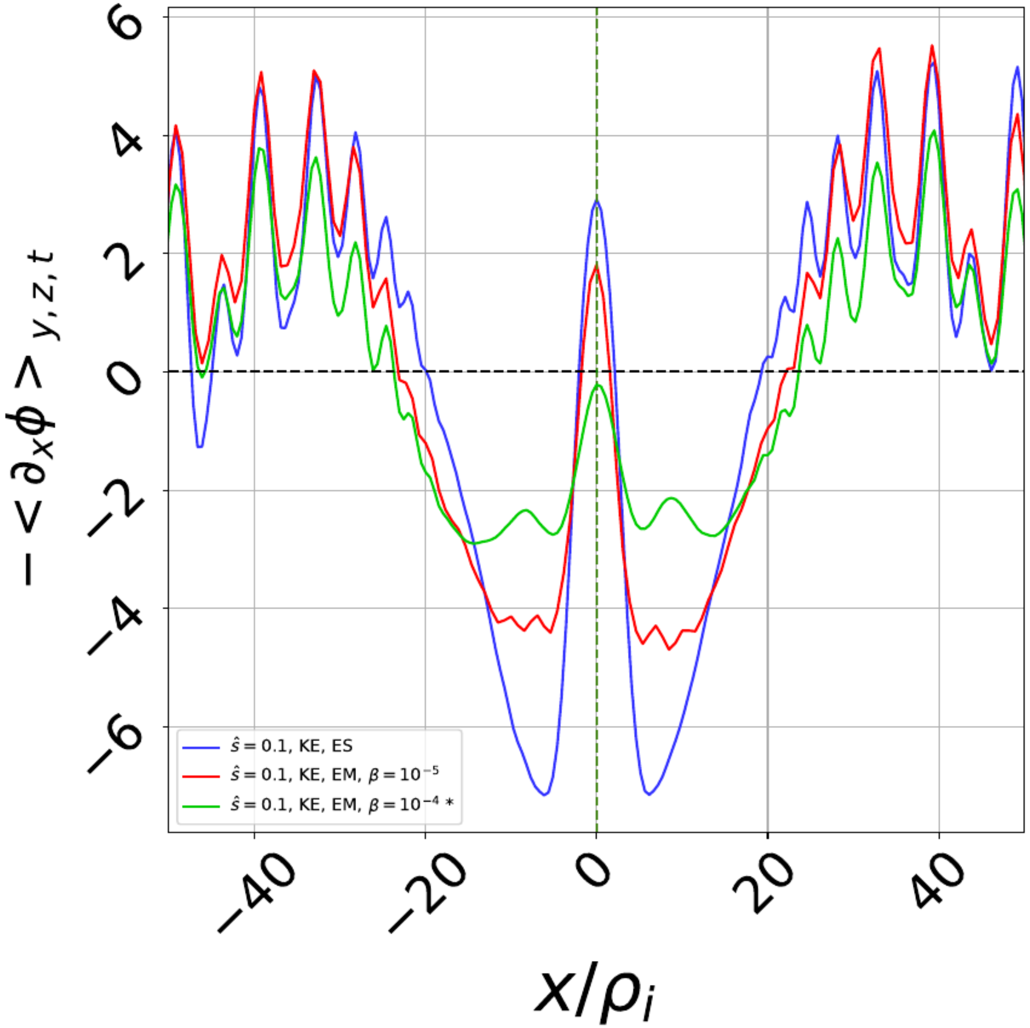
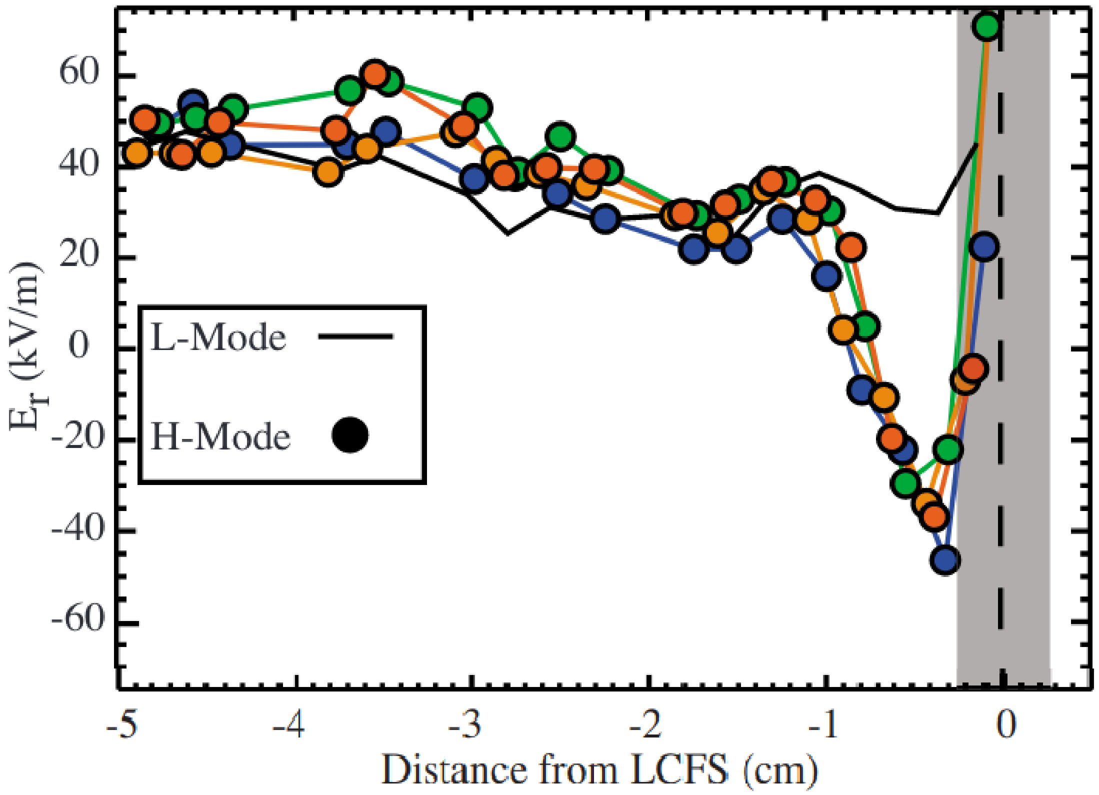
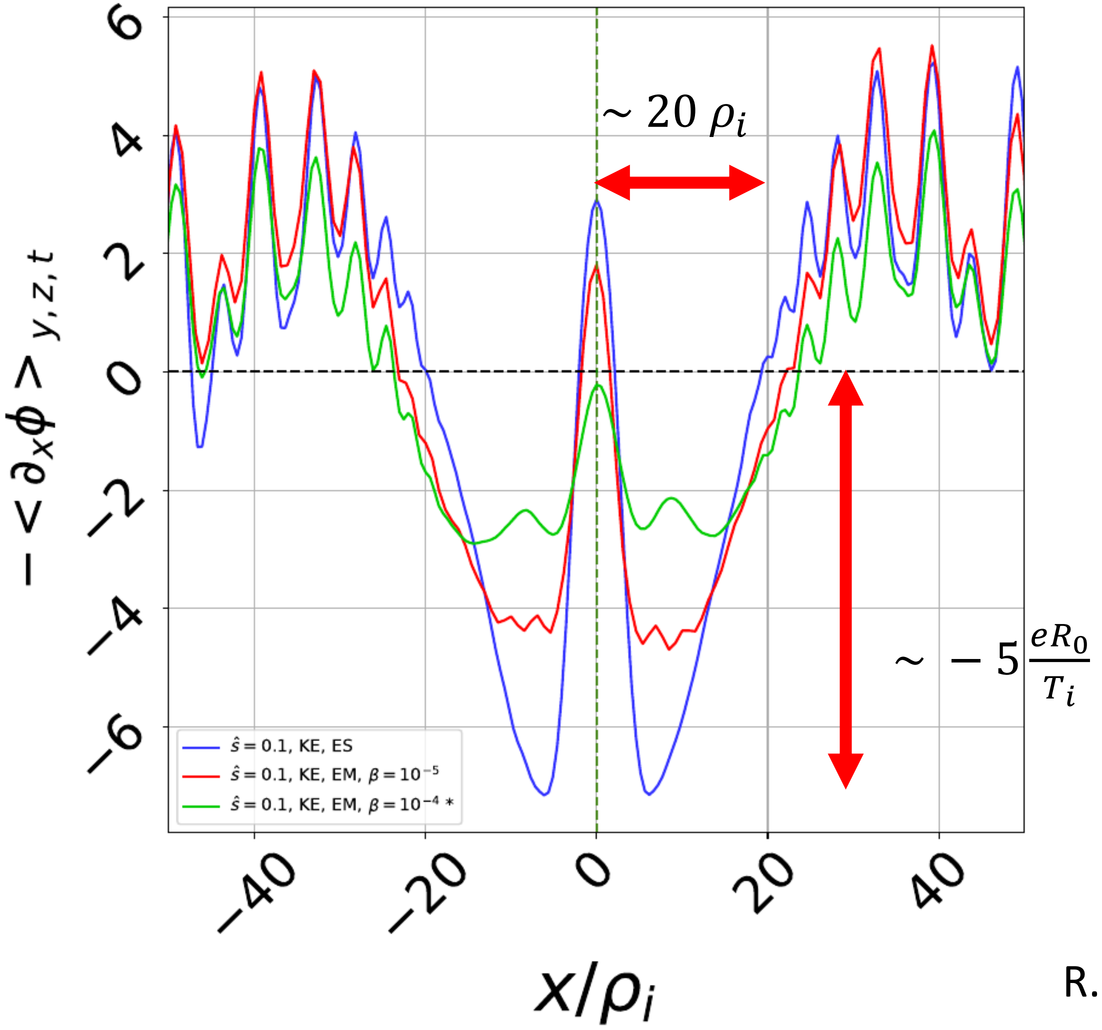
Radial Electric field well at the edge

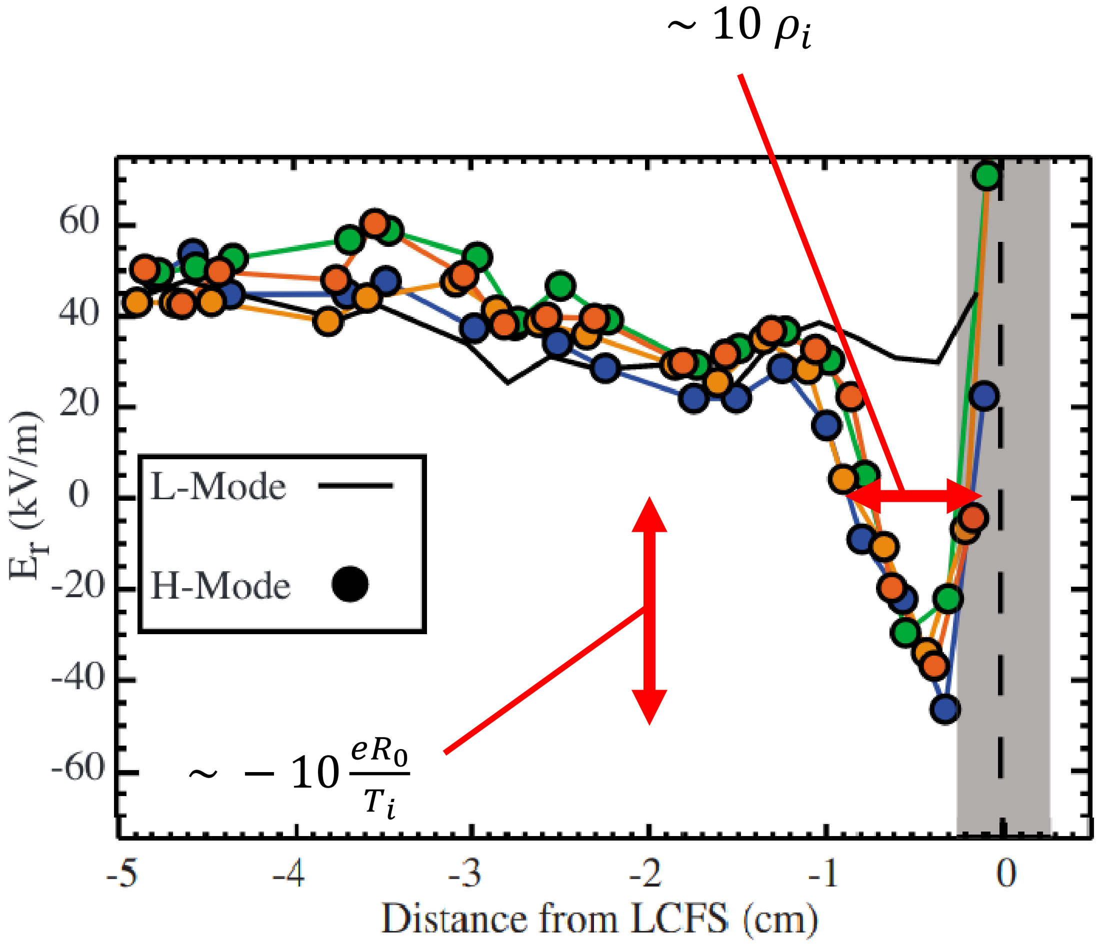




R. M. McDermott *et al.,* Phys. Plasmas 16, 056103 (2009)

Radial Electric field well at the edge





R. M. McDermott *et al.*, Phys. Plasmas 16, 056103 (2009)

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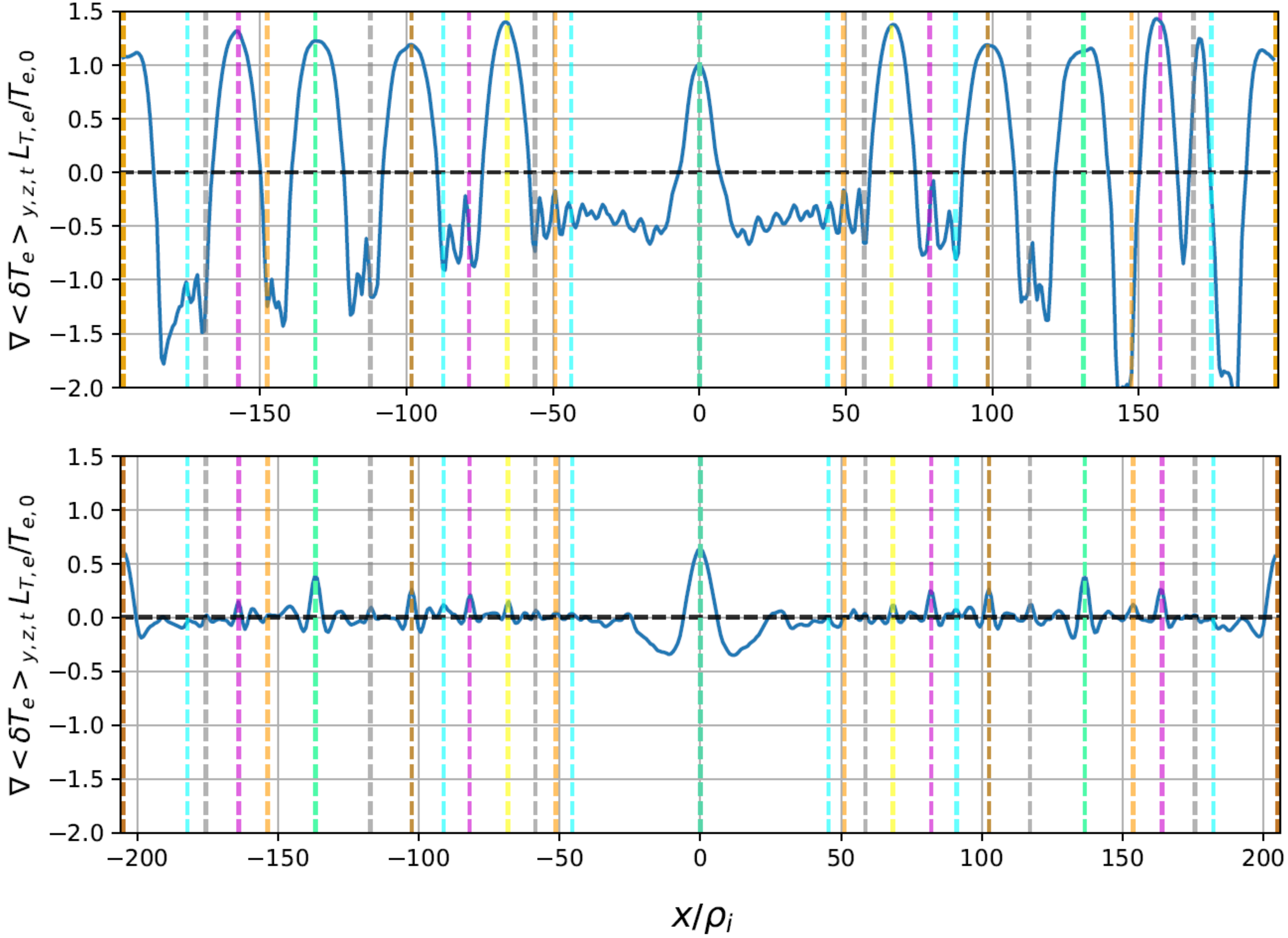
Effects of N_{pol} on corrugations

Number of poloidal turns N_{pol} has a large impact on profile corrugation due to reduction of self-interaction

s=0.05

$N_{pol} = 1$

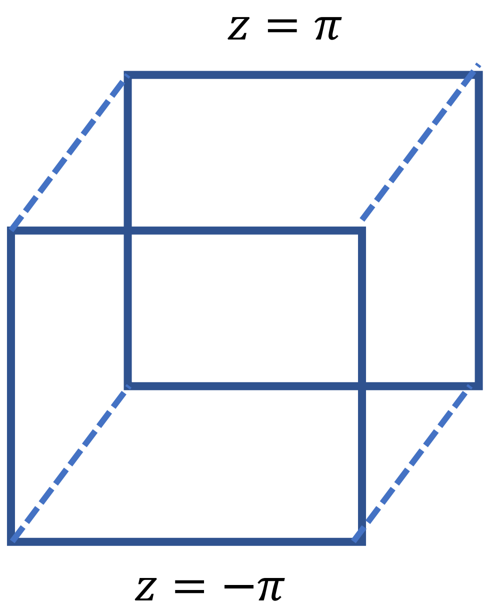
$N_{pol} = 3$

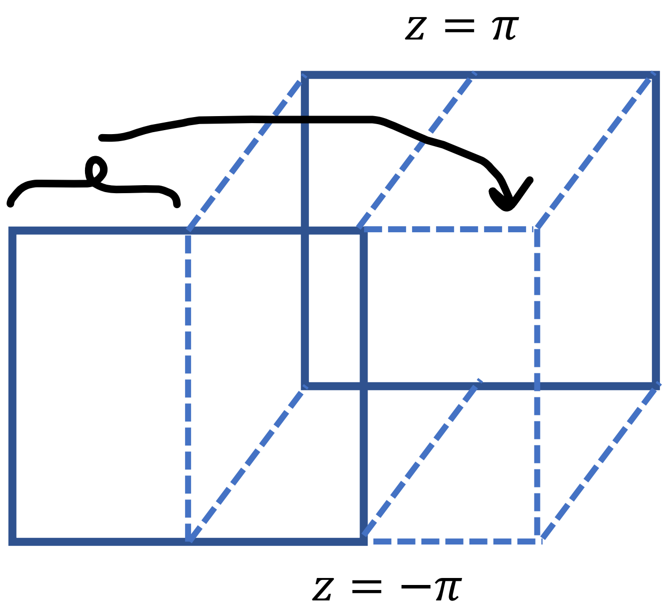


s=0 boundary

In the s=0 case

- Linear growth rates change slowly with q
- Periodic parallel boundary with a shift





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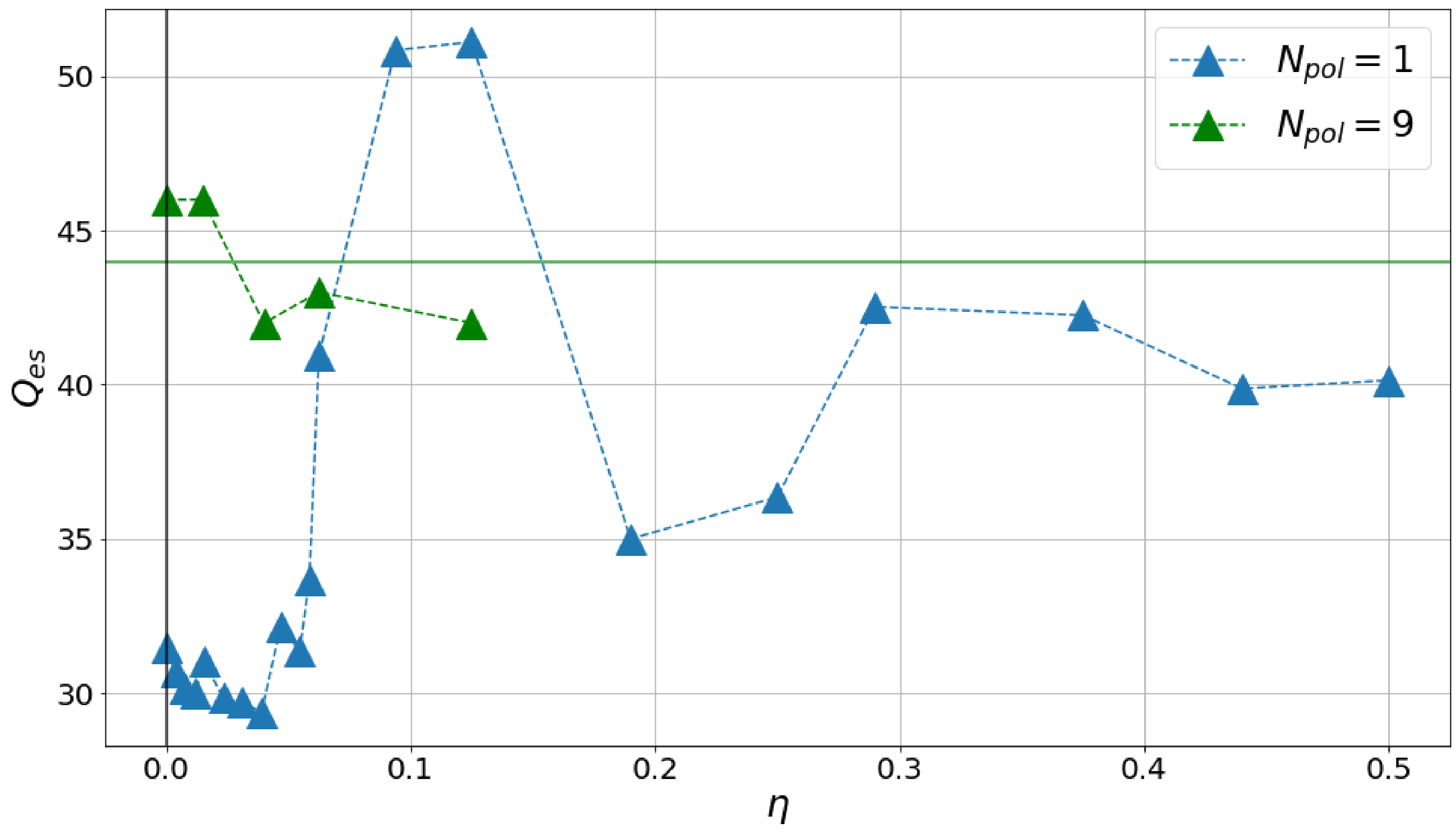
Nonlinear simulations with adiabatic electrons



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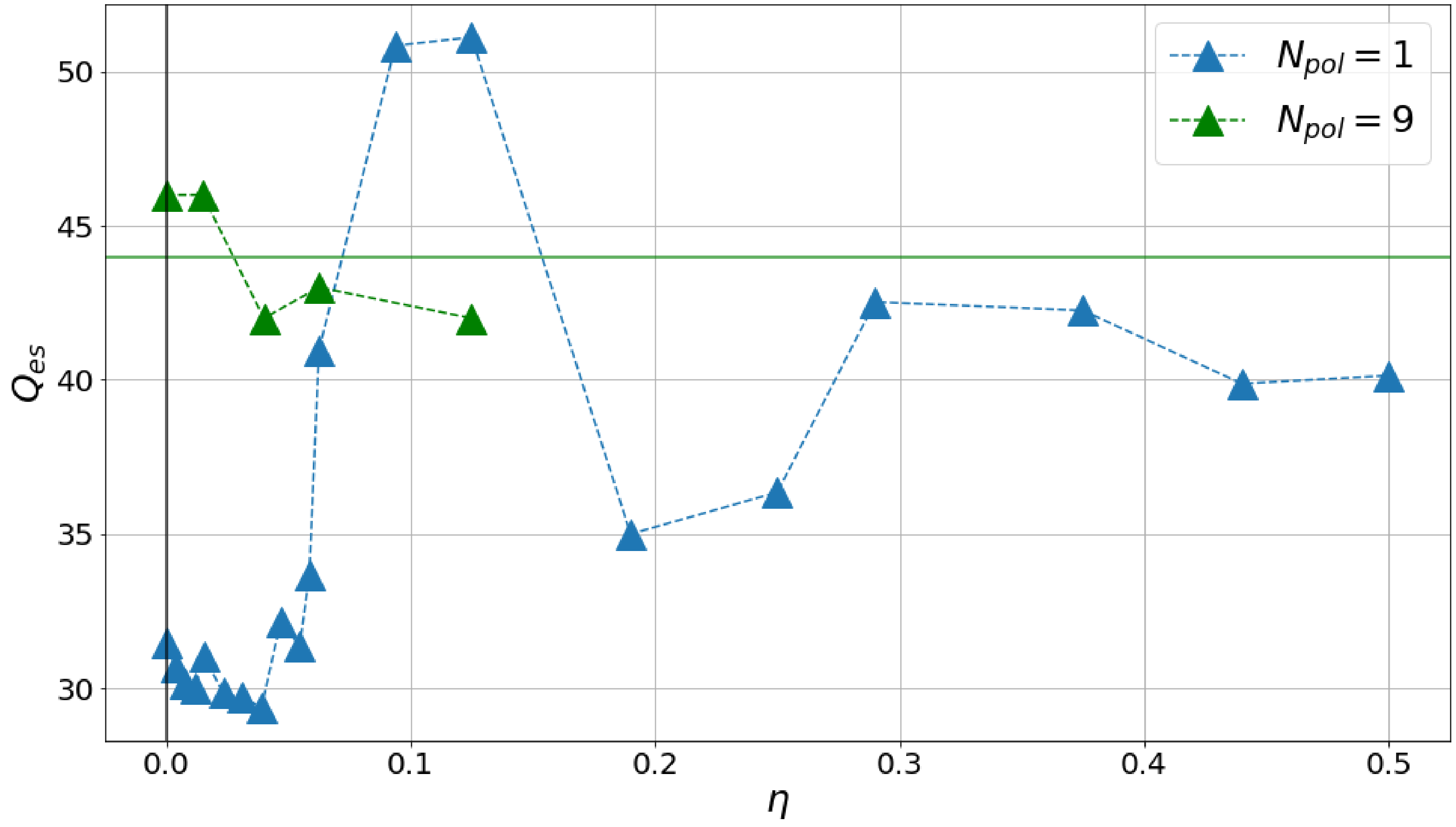

Preliminary simulations with **kinetic electrons** also show sharp change with varying η but require further study

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Key nonlinear results

Significant changes in the turbulent behaviour in simulations with low magnetic shear

- Strong stationary corrugations around low order rational surfaces that are comparable to the background profile gradients;
- We believe that this is a consequence of strong turbulent self-interaction in the parallel direction;
- Turbulent self-interaction seems to be stabilizing;
- Started comparisons between radial electric fields in the core with observed radial electric field wells at the plasma edge

Currently outstanding questions

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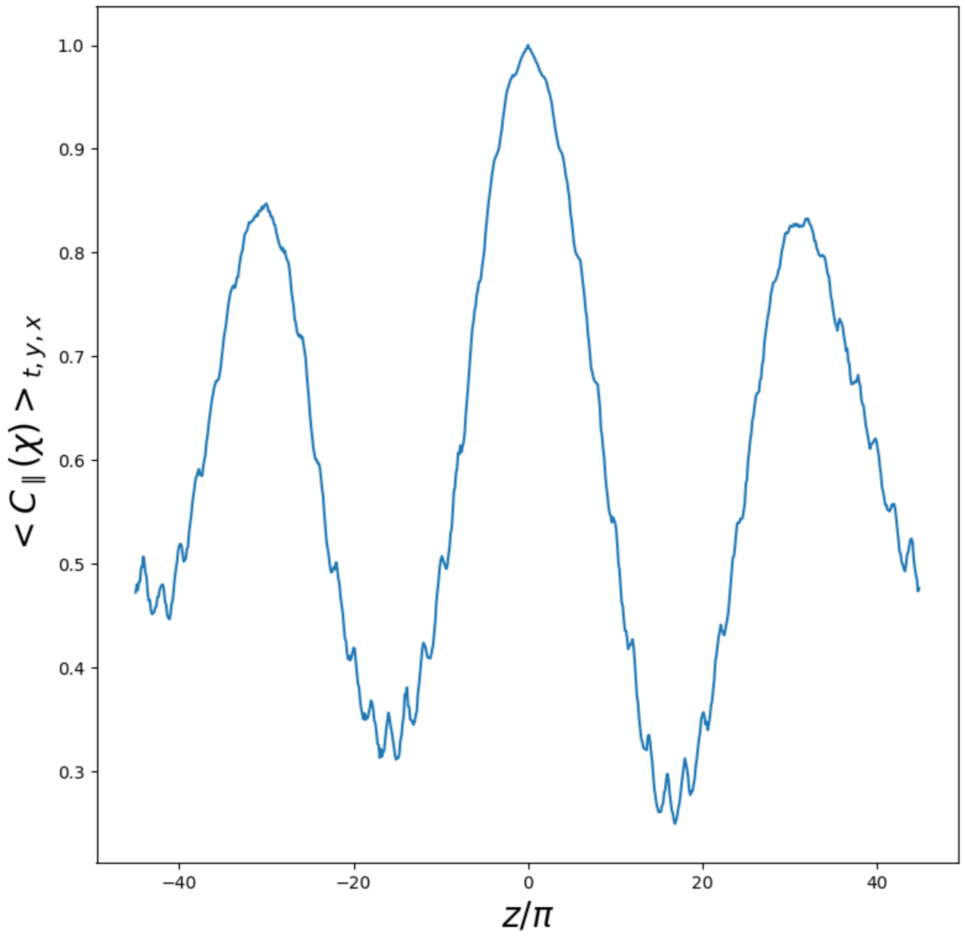
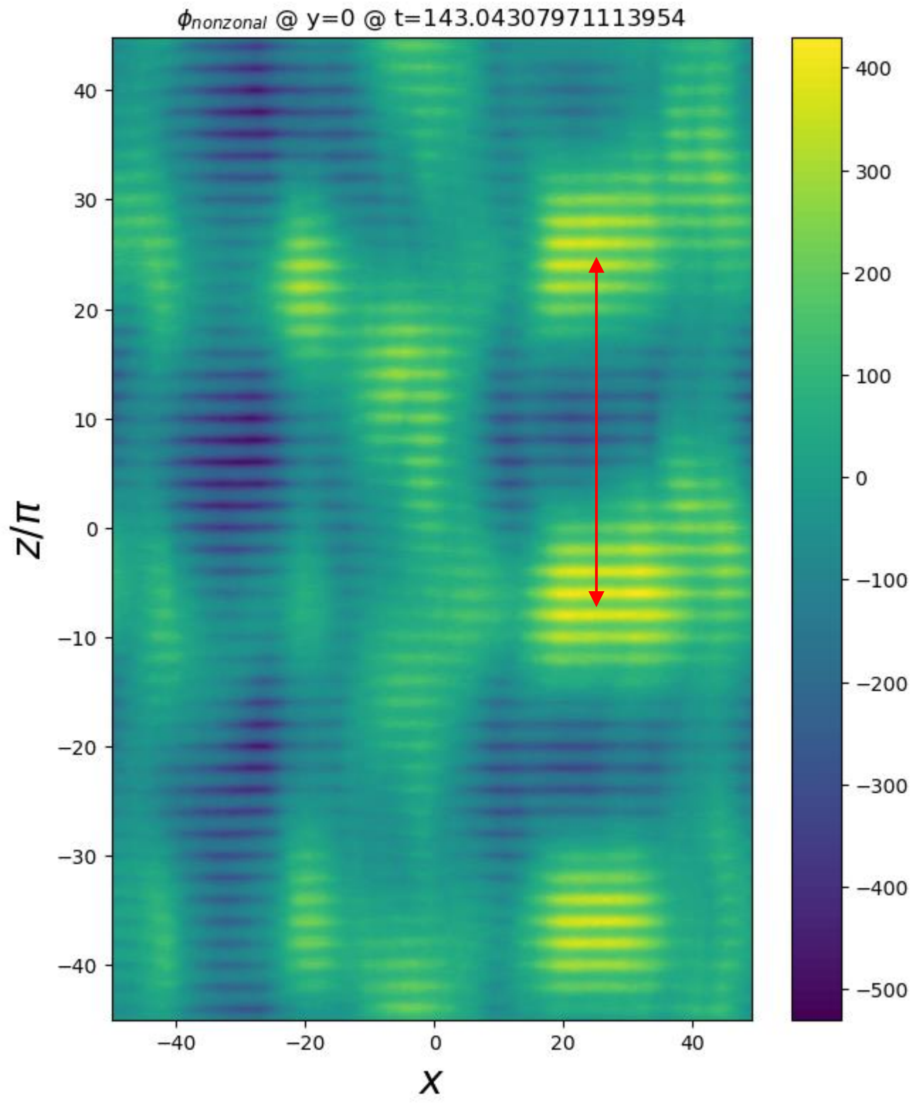
s=0 long wavelength parallel wave





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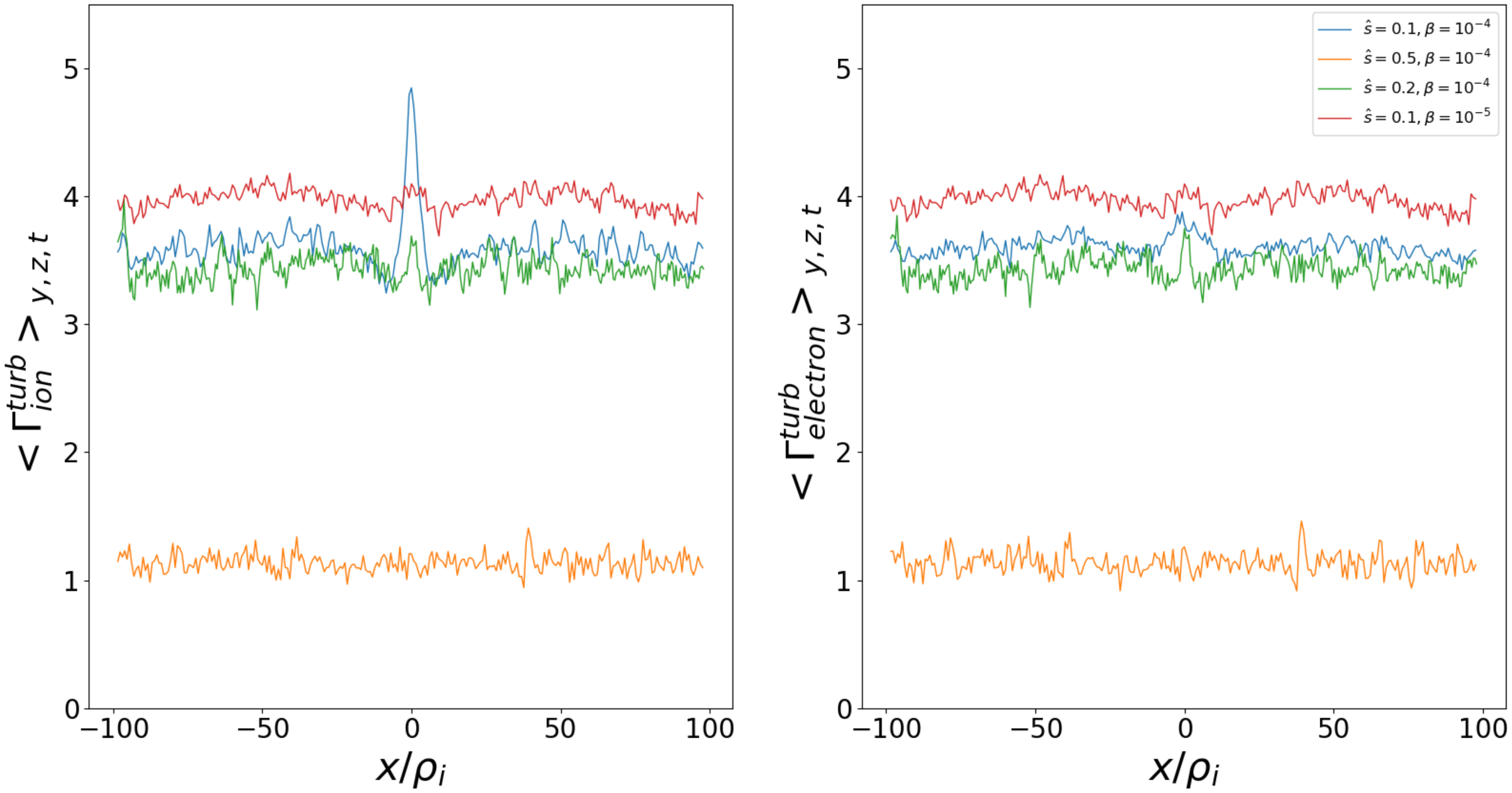
$N_{pol} = 45$

Radial particle flux

$$\Gamma(x) = < nv_r >_{FS}$$

$$\Gamma(x) = -< \frac{c}{\tilde{C}} \frac{\partial \phi_1}{\partial y} M^{00}(\mathbf{x}) + \frac{1}{\tilde{C}} \frac{\partial A_{1,\parallel}}{\partial y} M^{01}(\mathbf{x}) >_{FS}$$



References: Hauke Doerk, Gyrokinetic Simulation of Microtearing Turbulence, Universität Ulm, 2012

Radial particle flux

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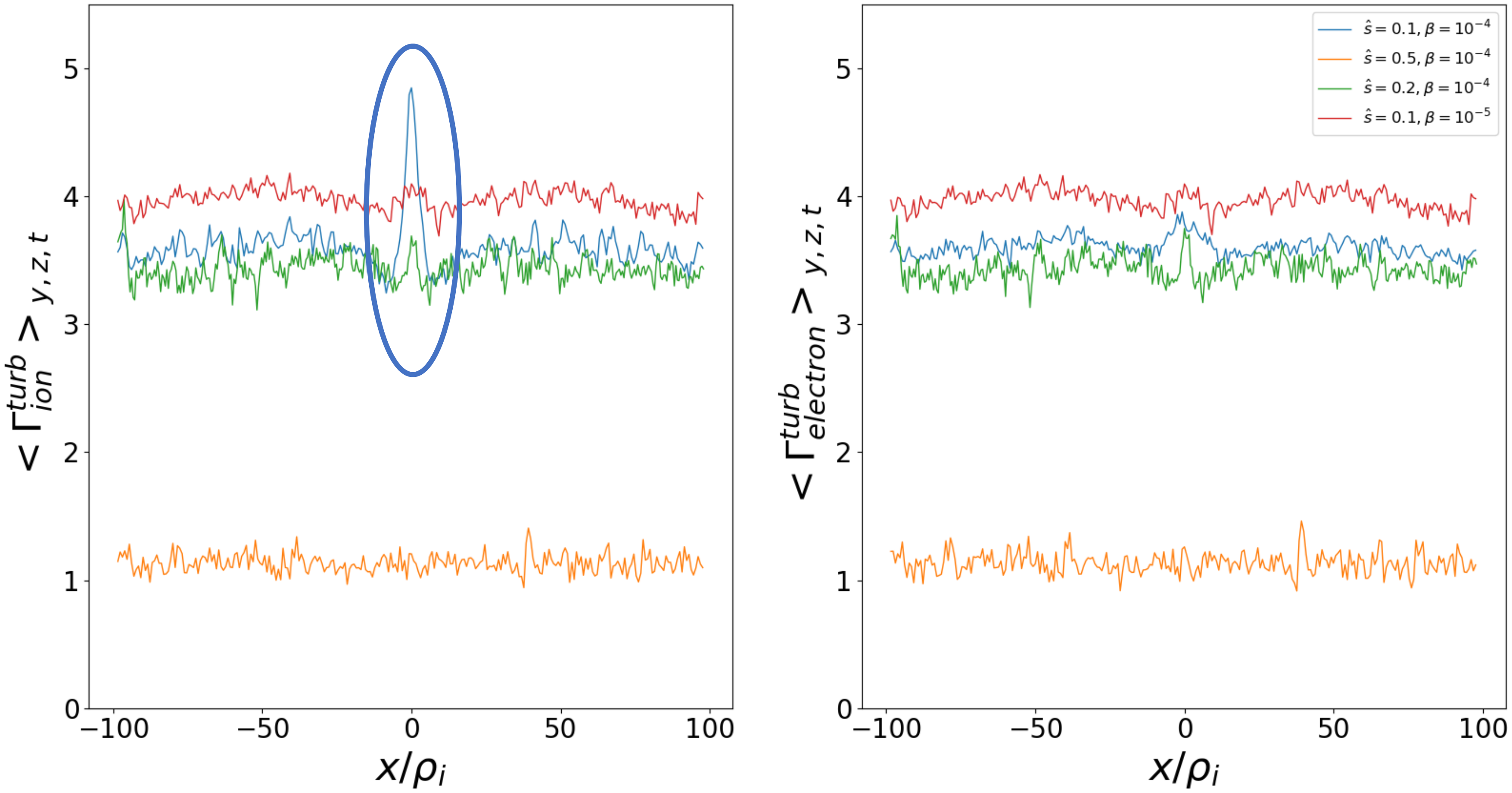

References: Hauke Doerk, Gyrokinetic Simulation of Microtearing Turbulence, Universität Ulm, 2012

Summary

- Transition between slab and toroidal ITG modes in linear study identified;
- M4.1: Found strong plasma profile (i.e. $\phi_1, \nabla n_1, \nabla T_1$) corrugations around rational surfaces for $\hat{s} \leq 0.1$;
- M4.1: Preliminary ITB simulations display a normalized E_r well that is comparable to experimental measurements in pedestal (pedestal E_r well is roughly 2 times narrower and 2 deeper);
- M4.1: Parallel correlation of turbulent eddies become much longer when $\hat{s} \leq 0.1$ and very long wavelength modes appear for $\hat{s} = 0$

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Thank you for your attention