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EUROfusion

Ultra long turbulent eddies, magnetic topology, and the triggering of internal transport barriers in tokamaks

EFTC 2023

Arnas Volčokas, Justin Ball, Stephan Brunner

05/10/2023

Swiss Plasma Center

Outline

- Motivation and background
- Methods
- Numerical results:
  - Low magnetic shear simulations
  - Ultra-long turbulent eddies $\hat{s} = 0$
  - Non-uniform magnetic shear simulations
- Conclusions

EPFL Outline

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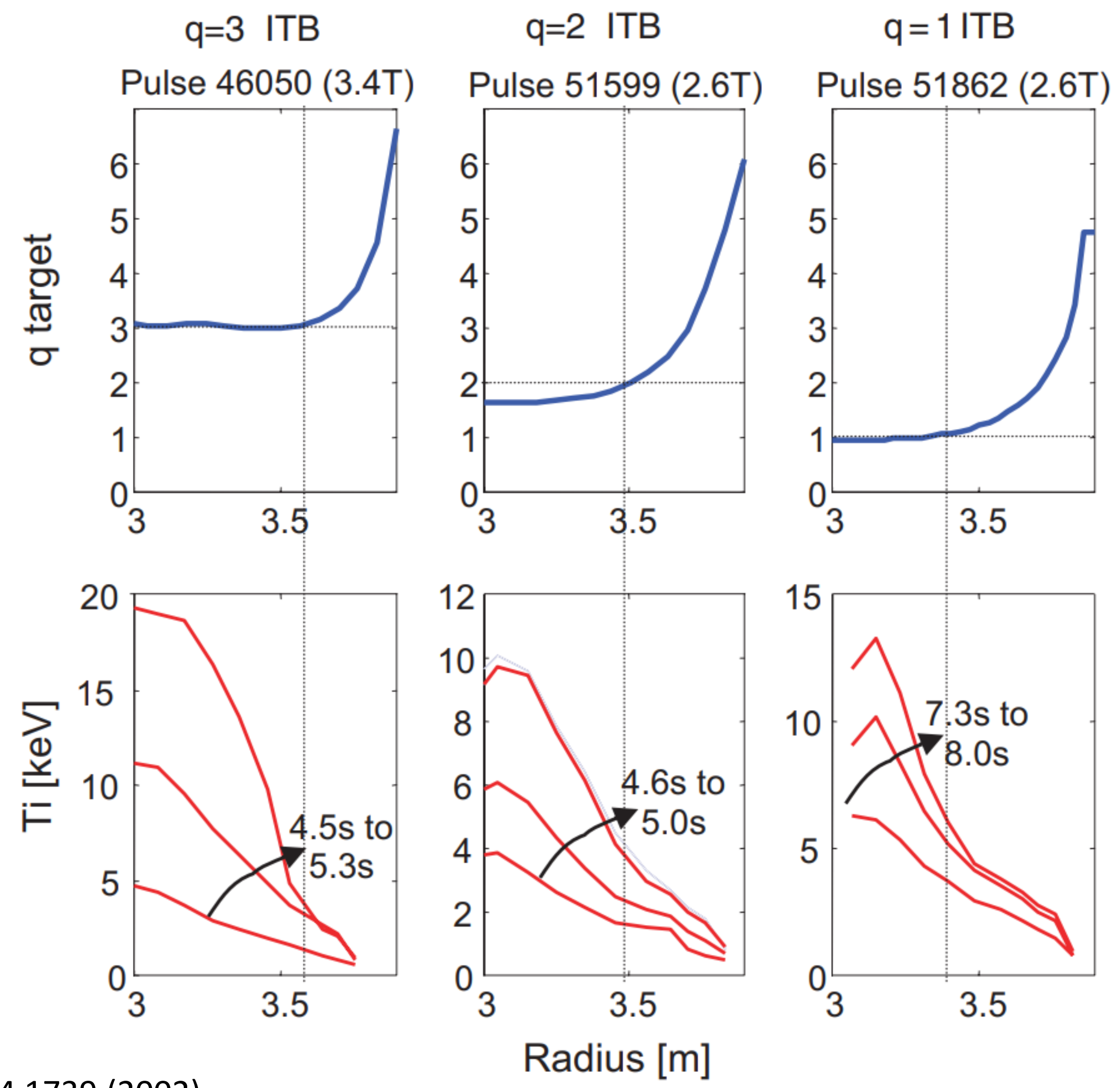
Internal Transport Barriers (ITBs)



Examples from JET

- E Joffrin et al Plasma Phys. Control. Fusion 44 1739 (2002)

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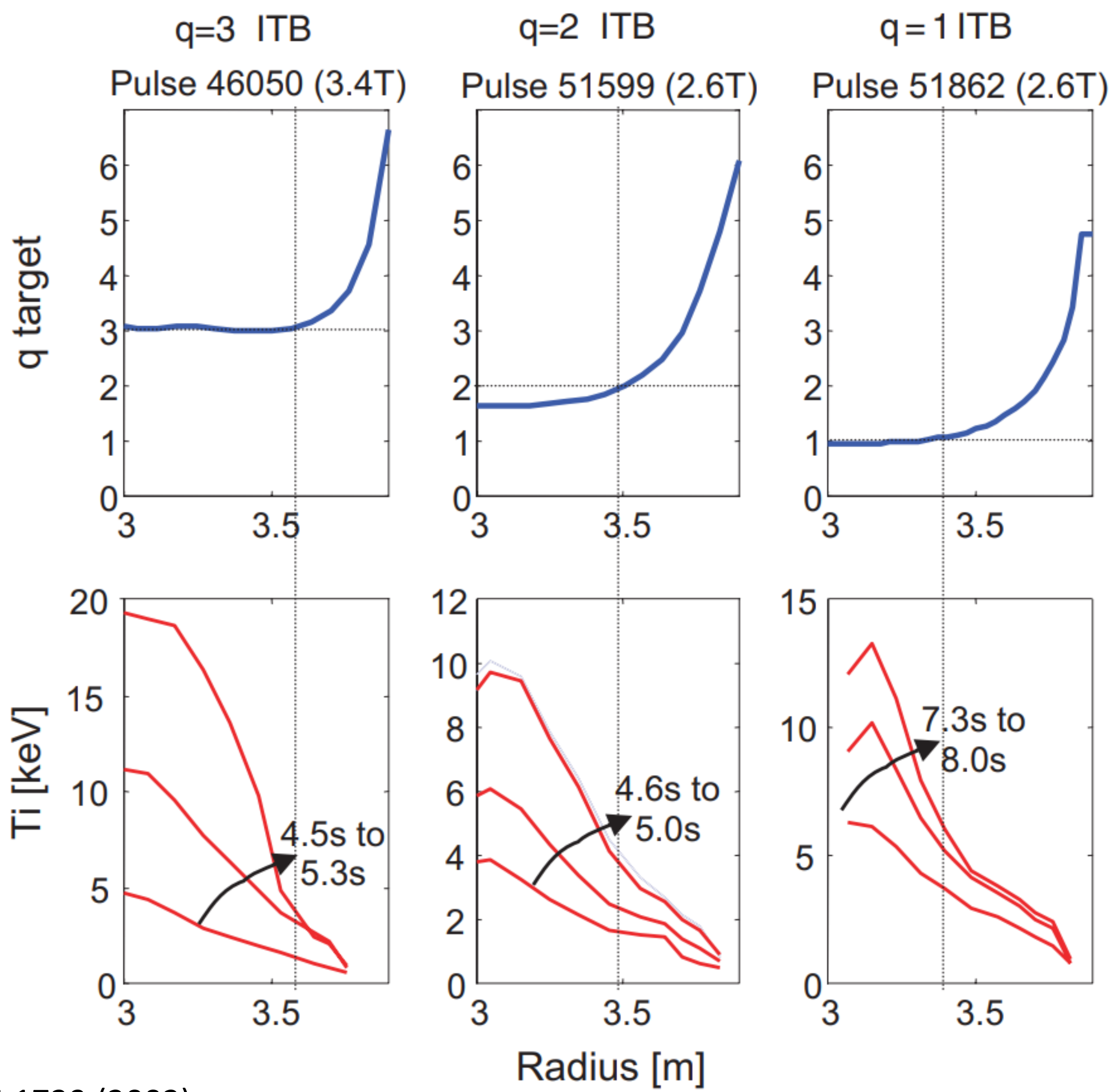
Internal Transport Barriers (ITBs)

ITBs are formed when:

- Low magnetic shear $\hat{s} \approx 0$ is present



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Internal Transport Barriers (ITBs)

ITBs are formed when:

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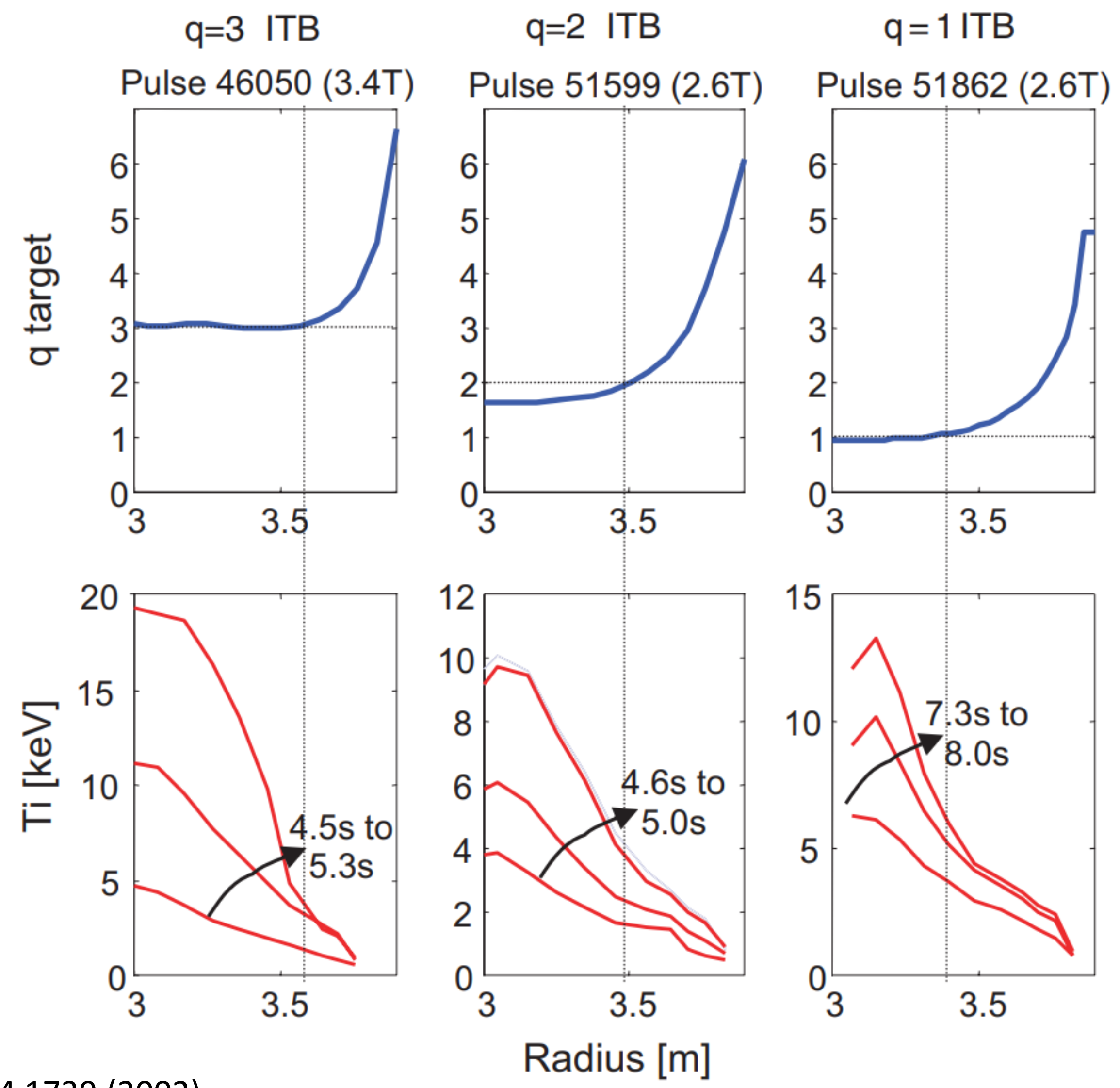
- Facilitated by integer or low order rational $q = M/N$ with $\hat{s} \approx 0$



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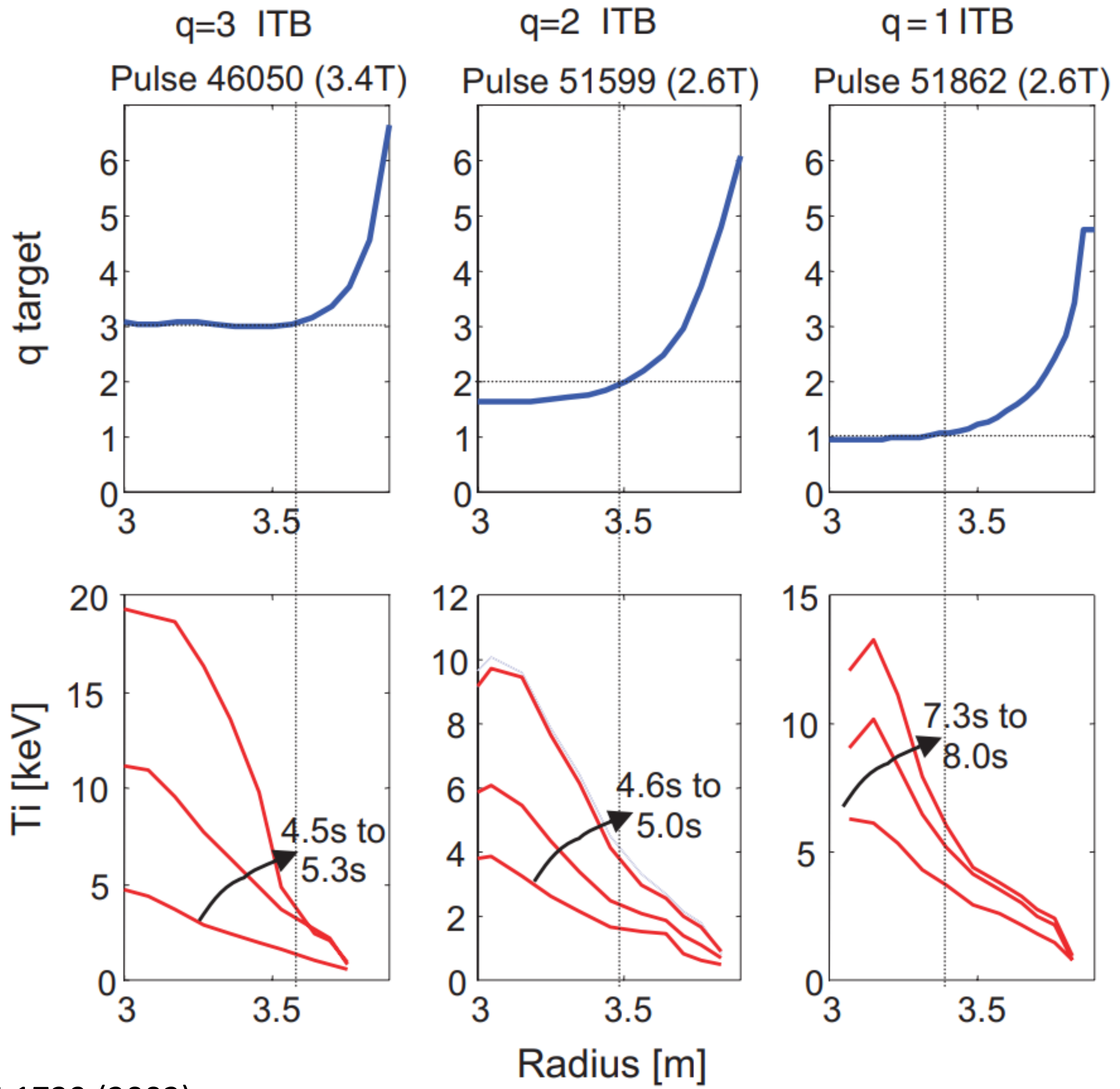

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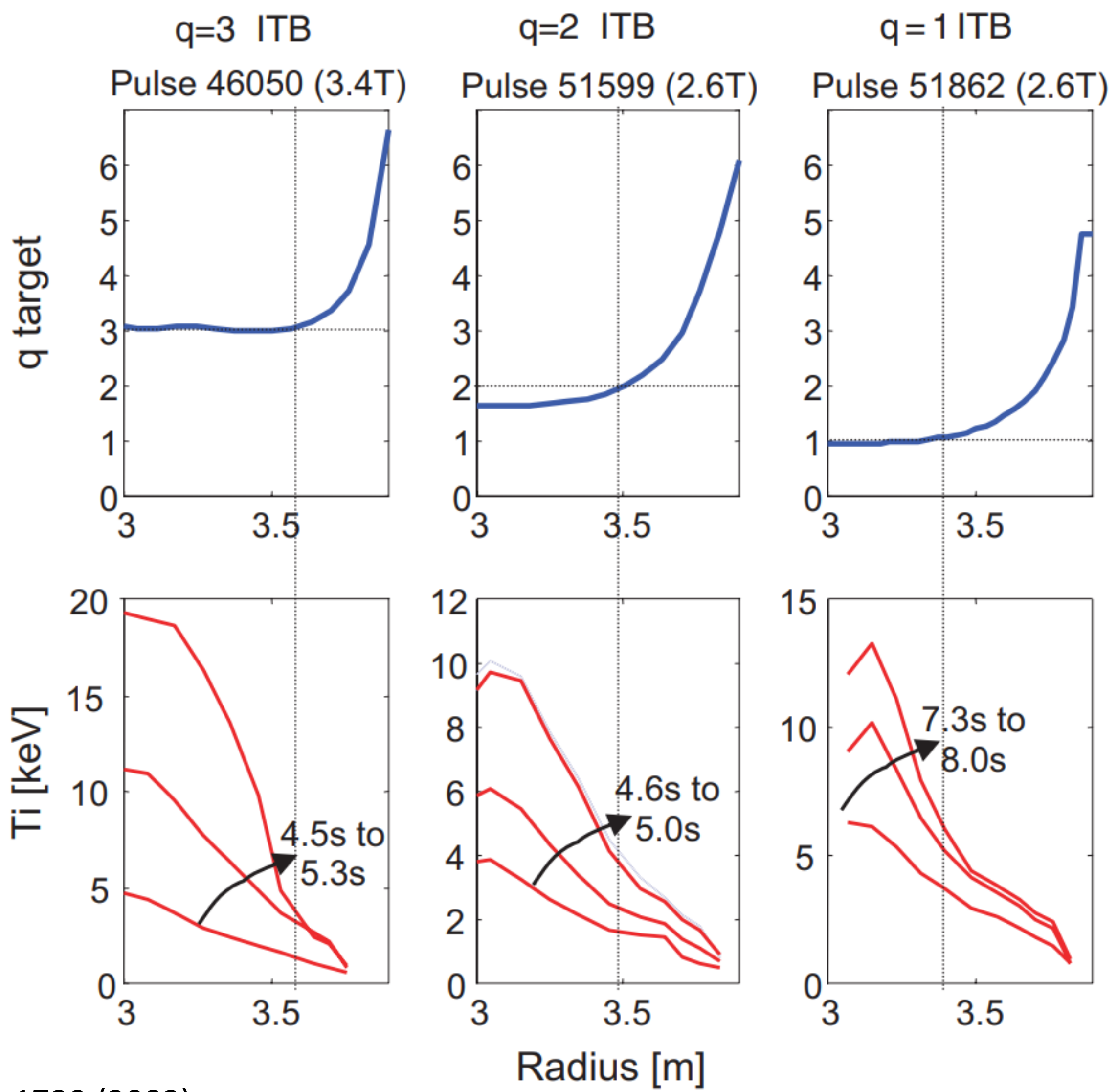

Examples from JET

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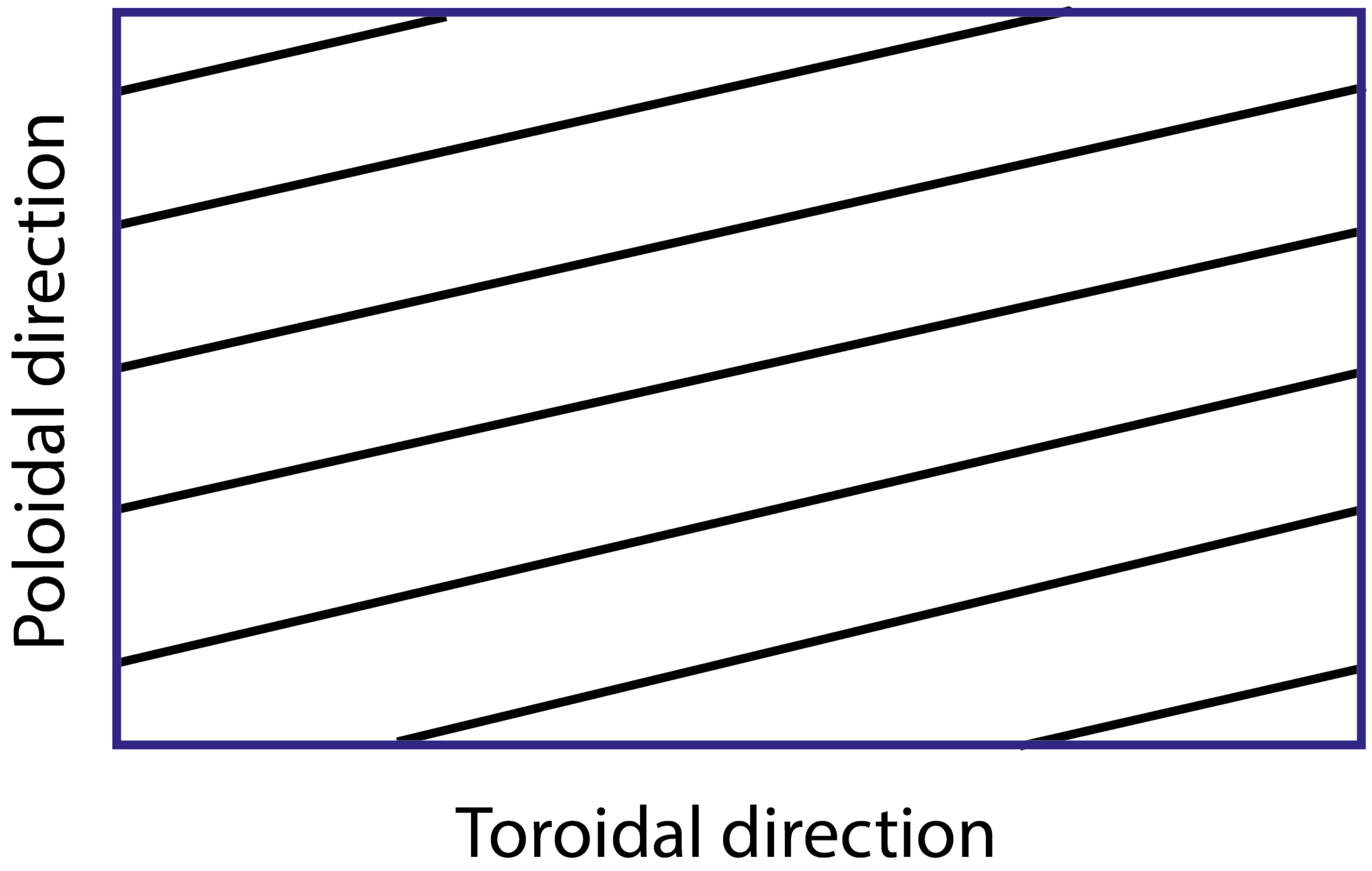
What is the role of turbulent self-interaction in ITB formation?

Self-interaction – the nonlinear interaction of turbulent eddy with itself

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

No self-interaction



$q = 2.5$

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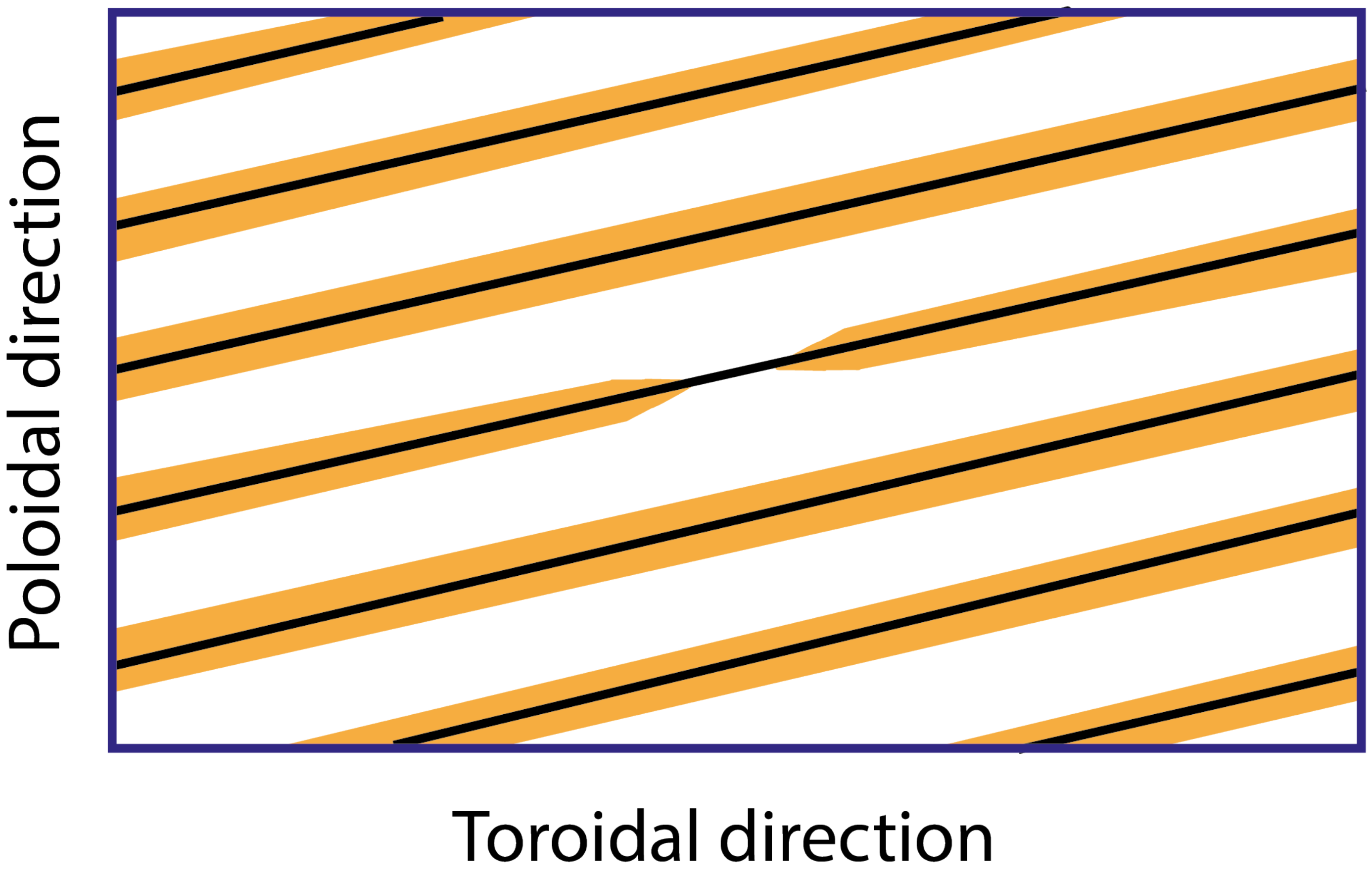
No self-interaction



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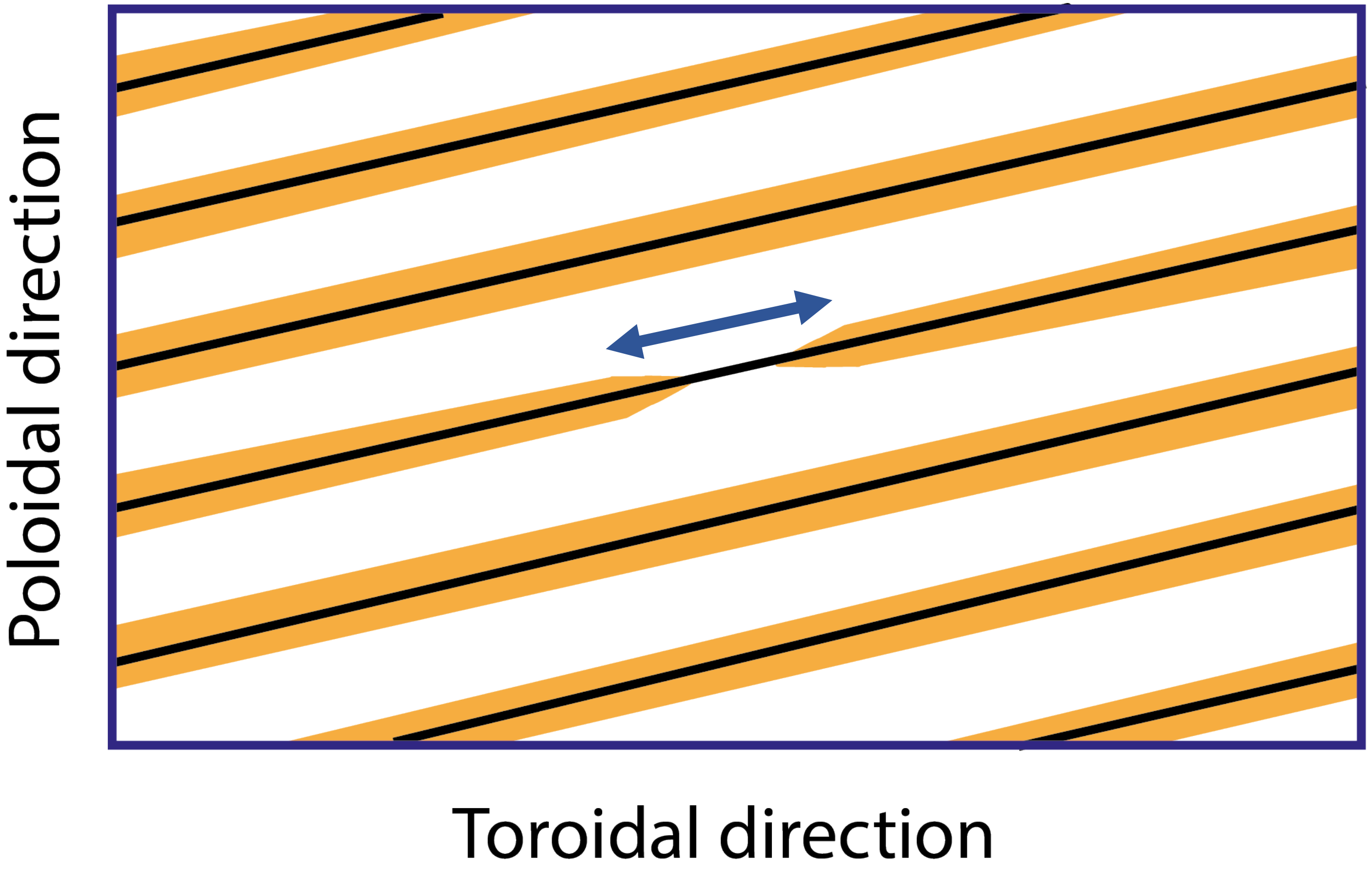

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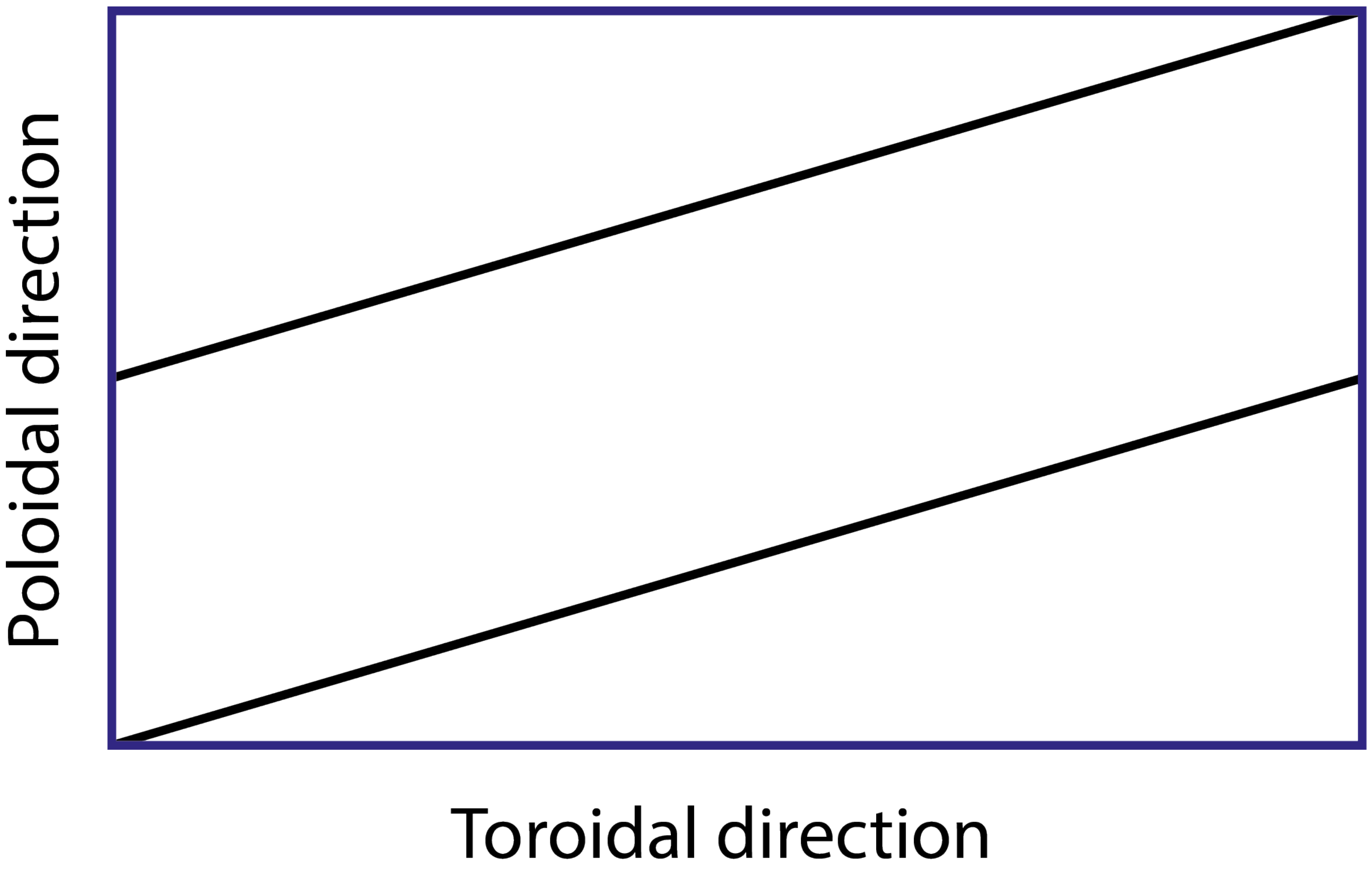
Self-interaction



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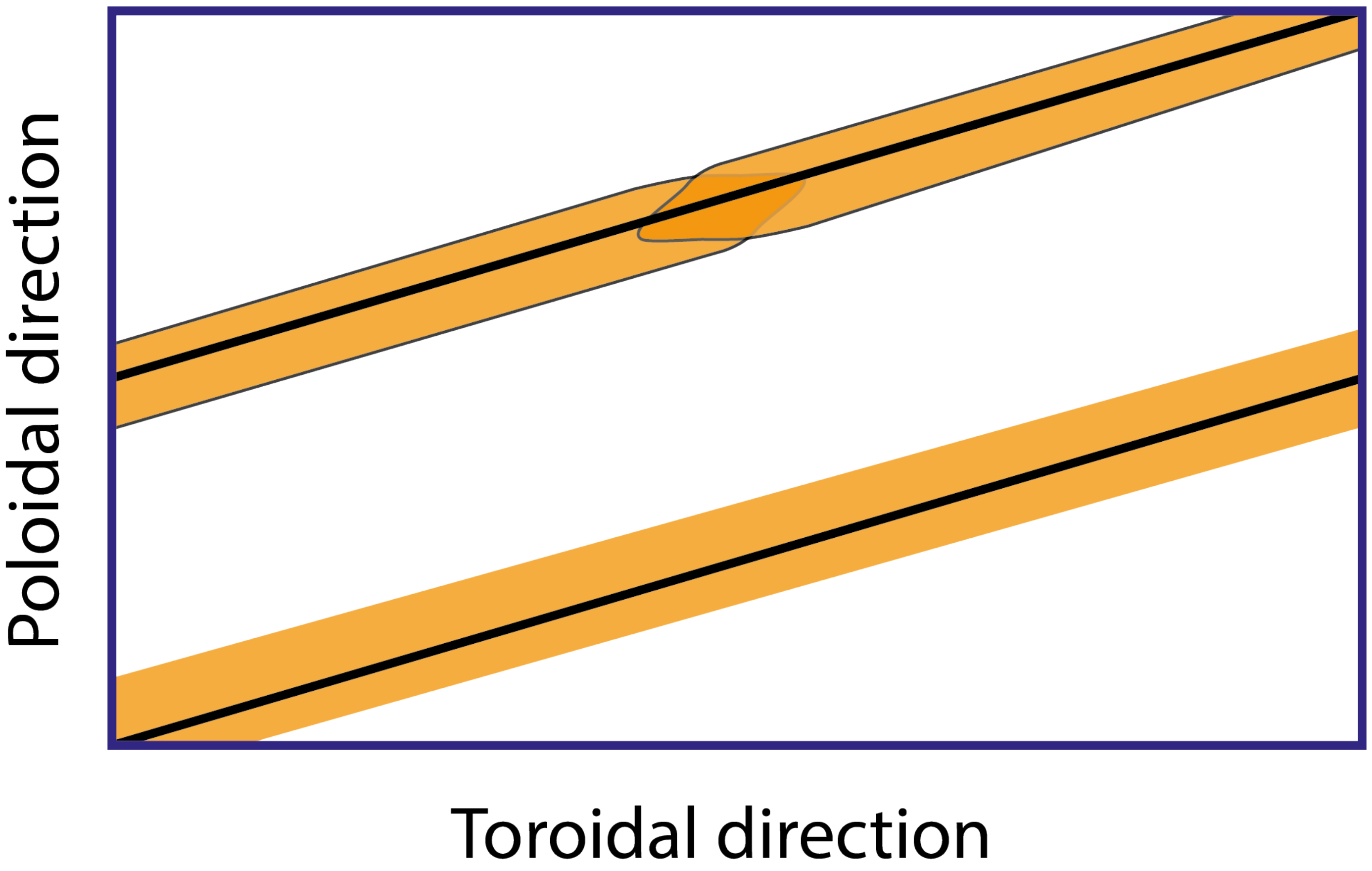
Self-interaction



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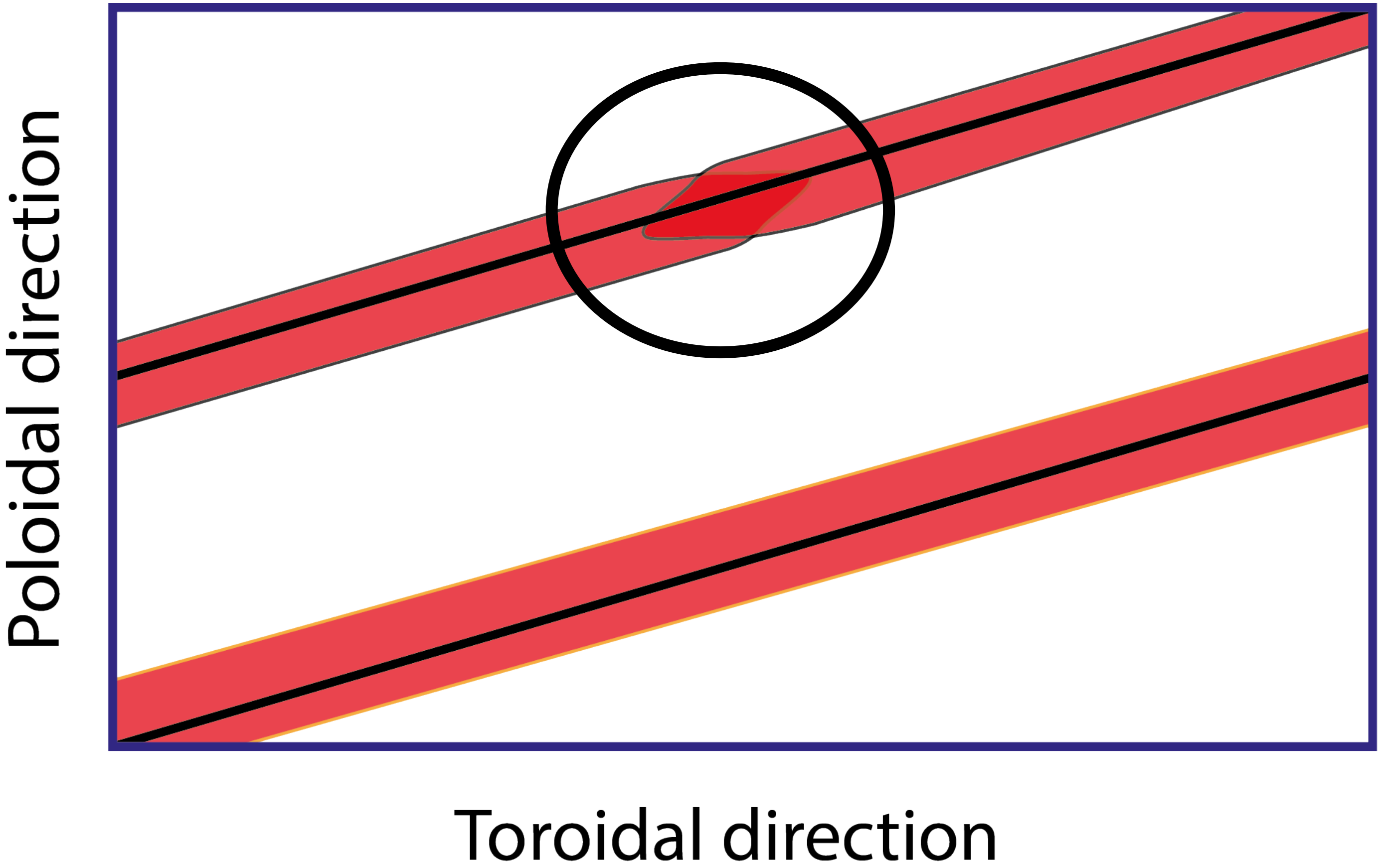
Self-interaction



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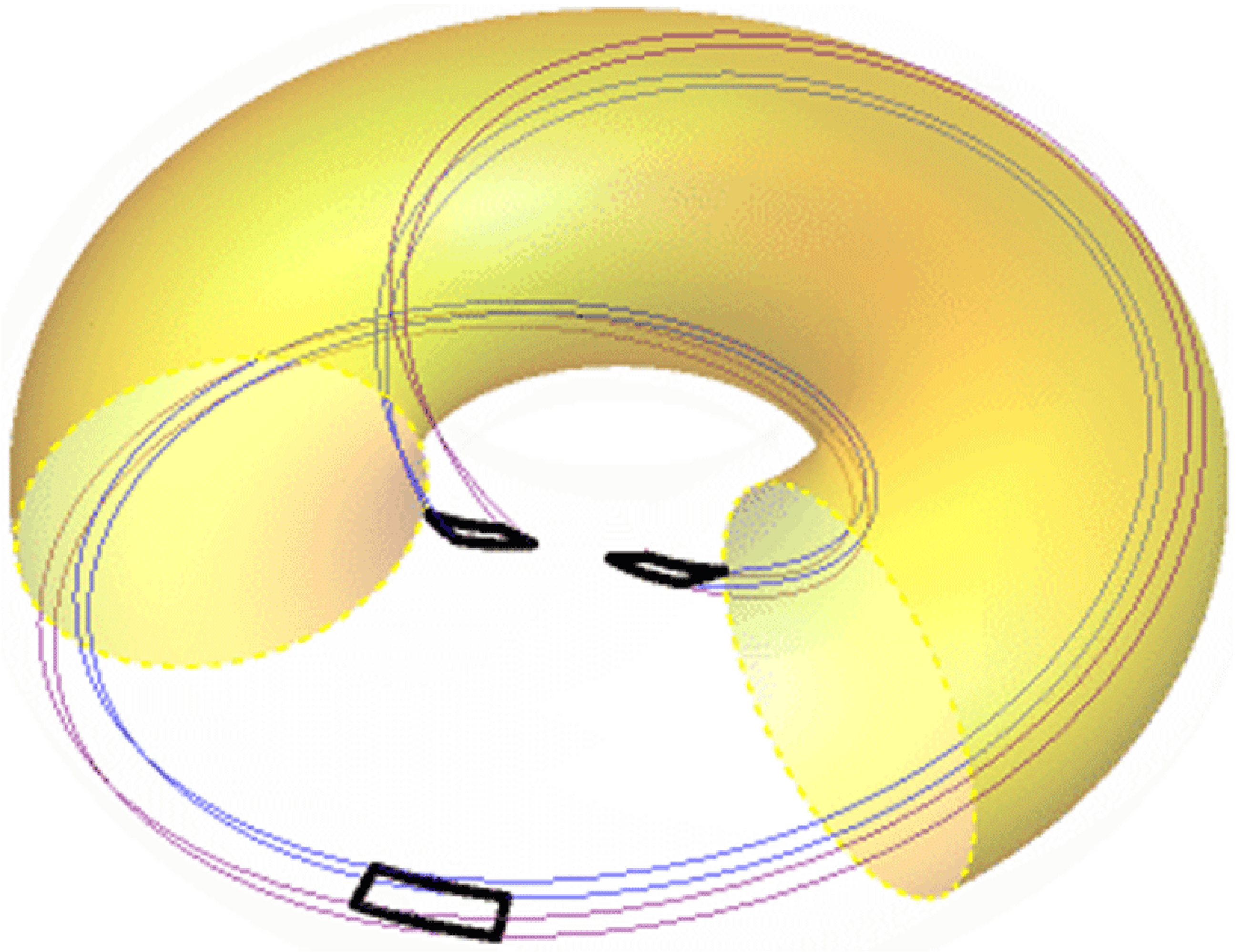
GENE flux-tube simulations



$N_{pol} = 1$

Gyrokinetic
Electromagnetic
Numerical
Experiment-
Eulerian δf code

N_{pol} - number of poloidal turns

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- J. Ball *et al.* 2020 *Journal of Plasma Physics* **86(2)**, 905860207

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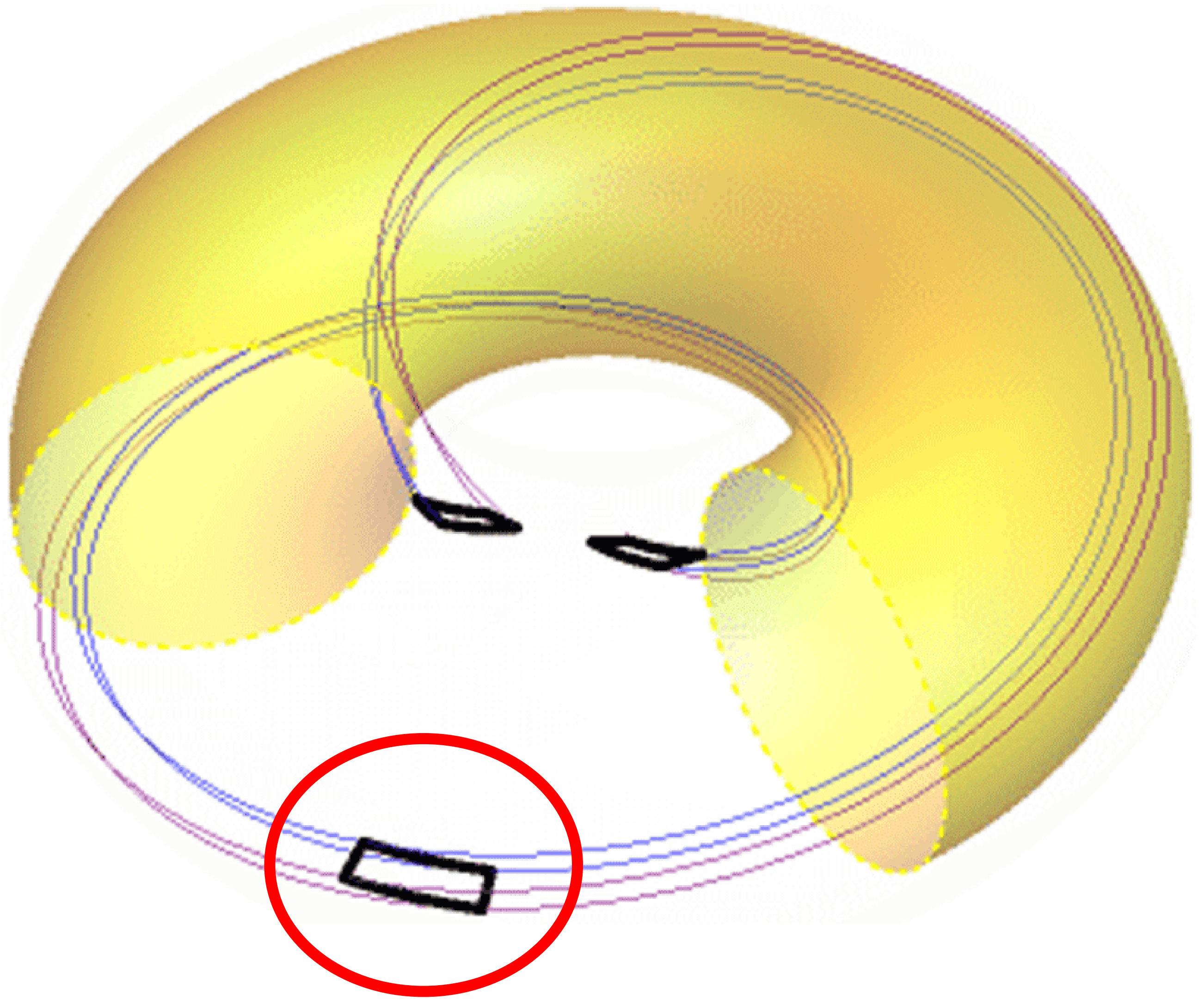

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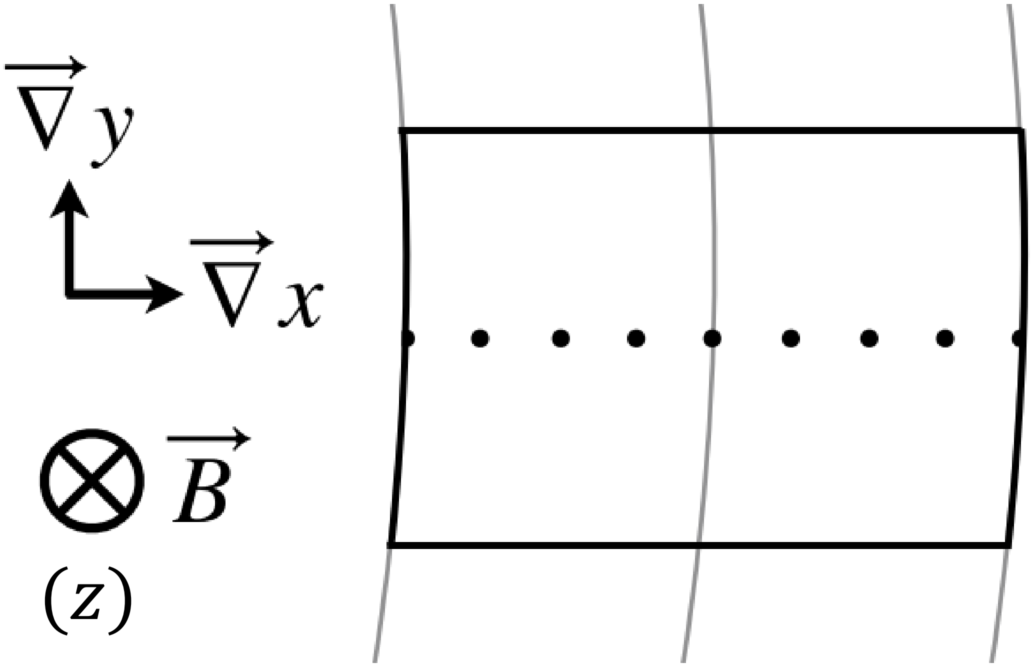
Twist-and-shift $\hat{s} \neq 0$



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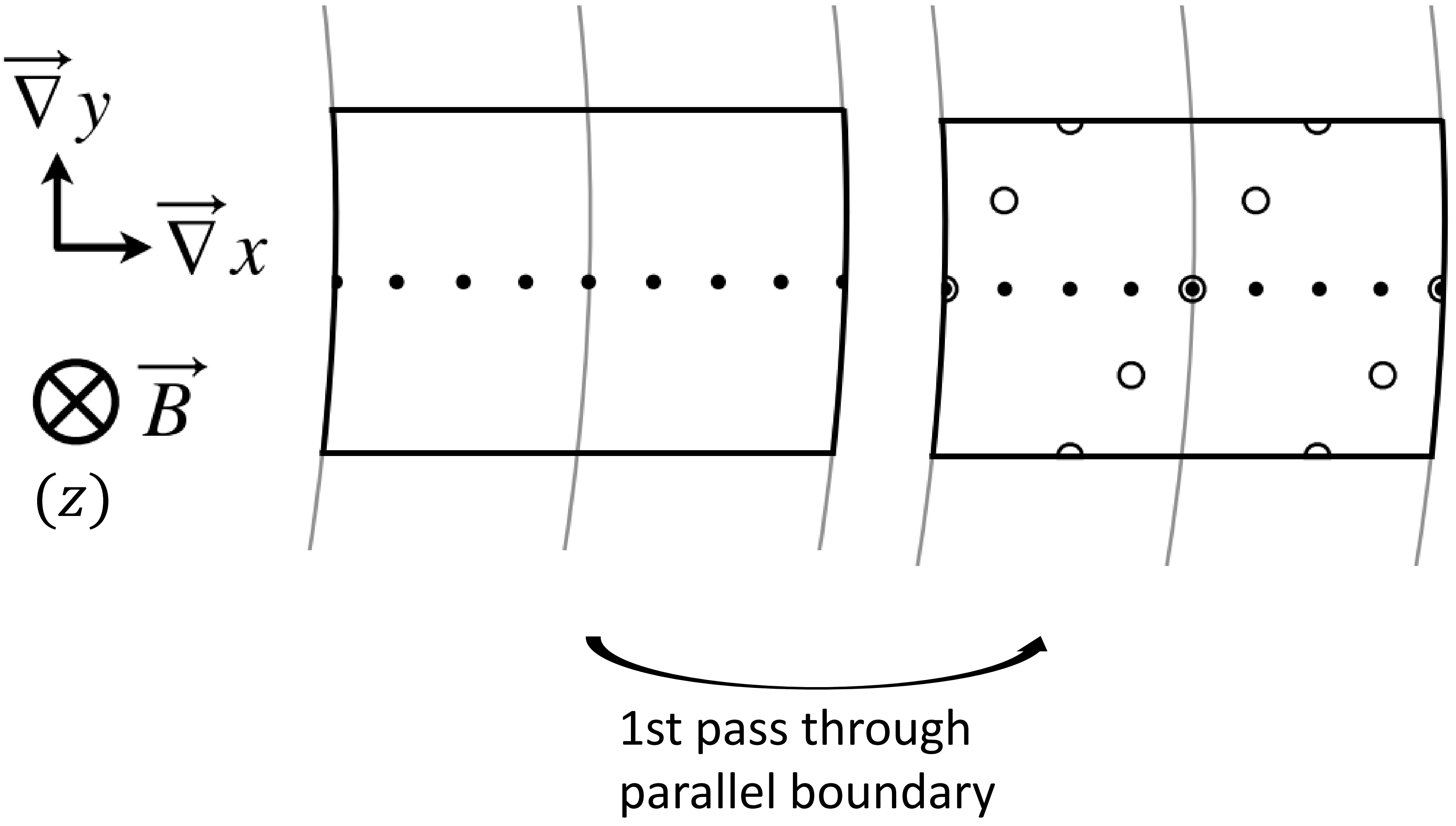

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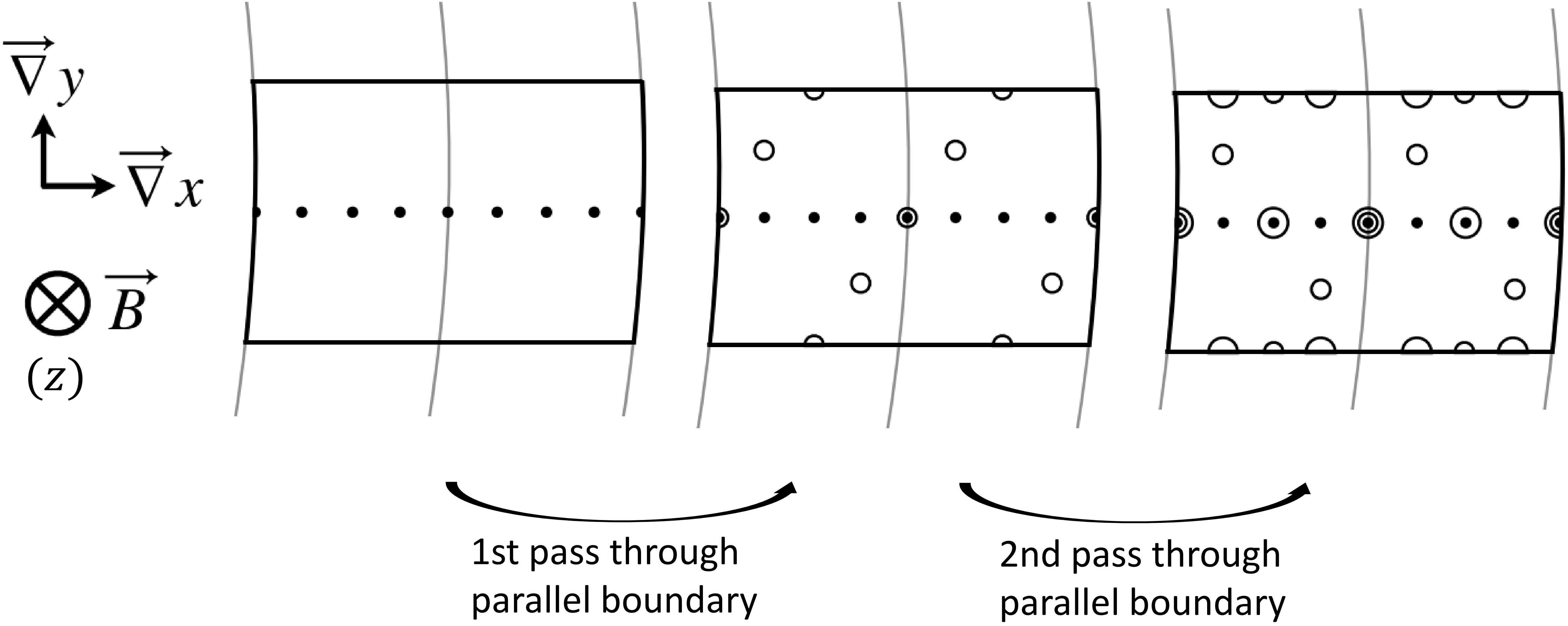

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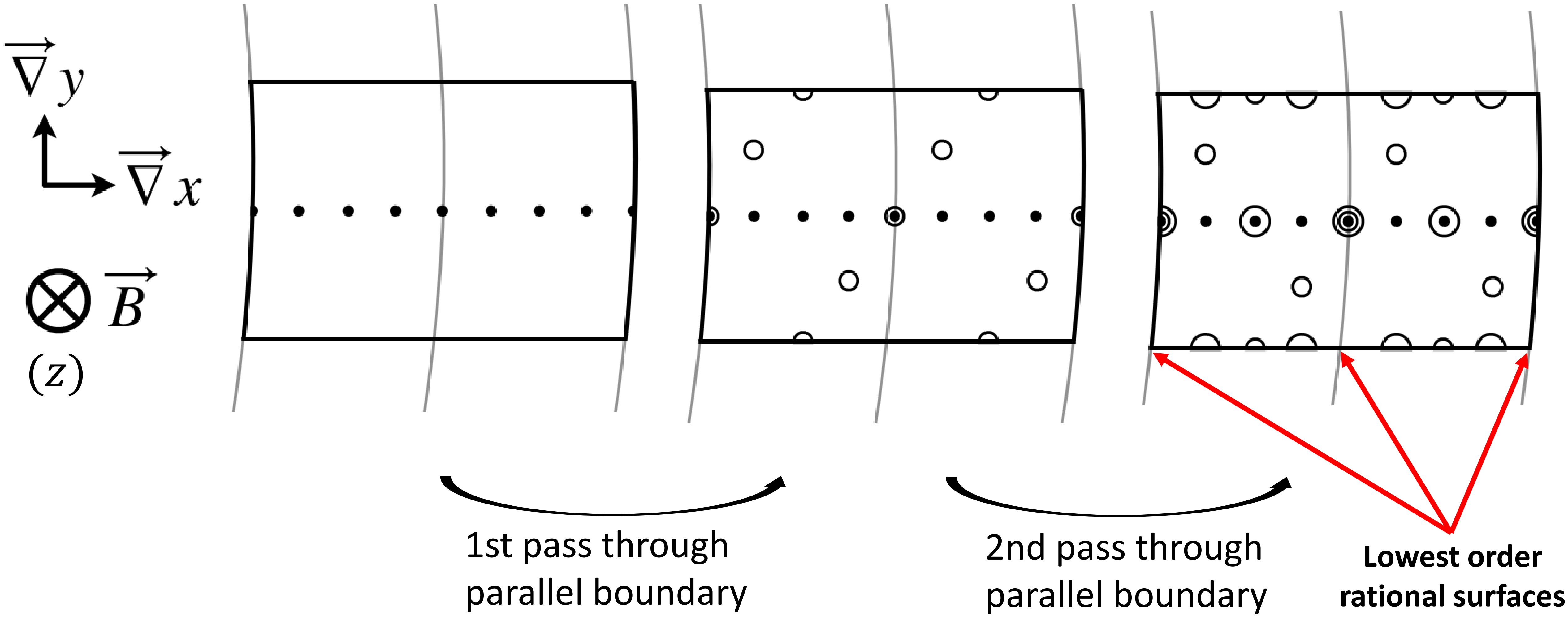

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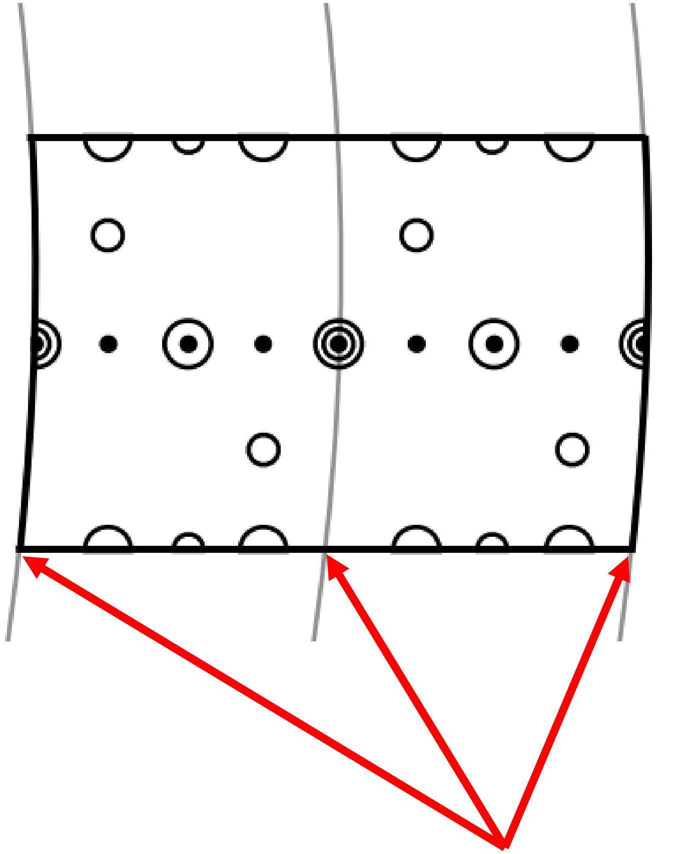
- J. Ball *et al.* 2020 *Journal of Plasma Physics* **86(2)**, 905860207

N_{pol} - adjusted to safety factor

$$q = 2 = \frac{2}{1} \rightarrow N_{pol} = 1$$

$$q = 2.5 = \frac{5}{2} \rightarrow N_{pol} = 2$$

$$q = 2.125 = \frac{17}{8} \rightarrow N_{pol} = 8$$



Lowest order rational surfaces

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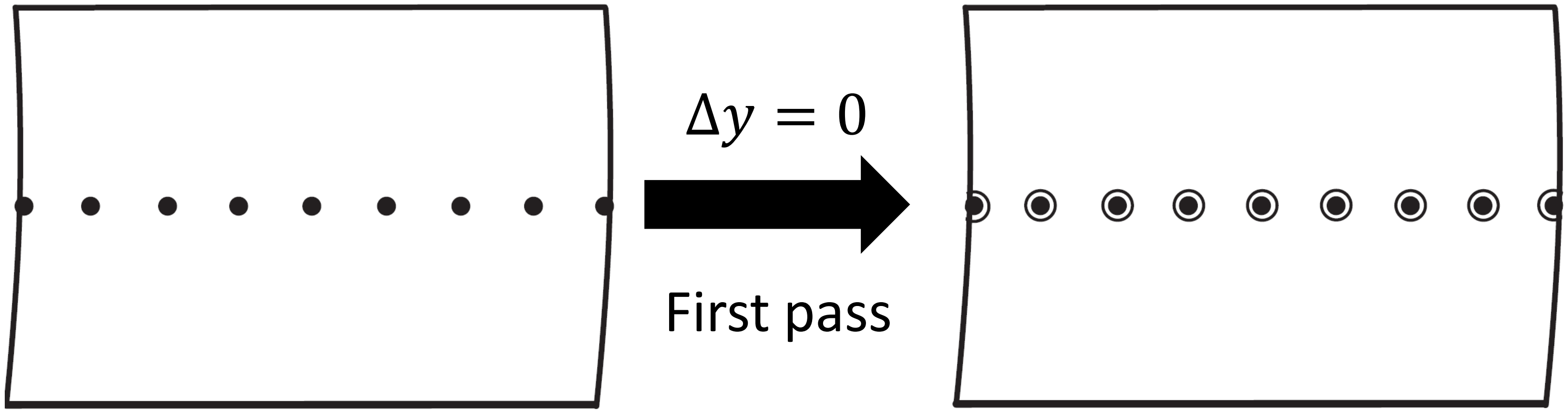
- J. Ball *et al.* 2020 *Journal of Plasma Physics* **86(2)**, 905860207

Parallel boundary $\hat{s} = 0$

Boundary condition: $\hat{A}_{k_x,k_y}(z) = C(\Delta y)\hat{A}_{k_x,k_y}(\mathrm{z}+2\pi)$

Phase factor: $C(\Delta y) \neq 1$

Shift: Δy



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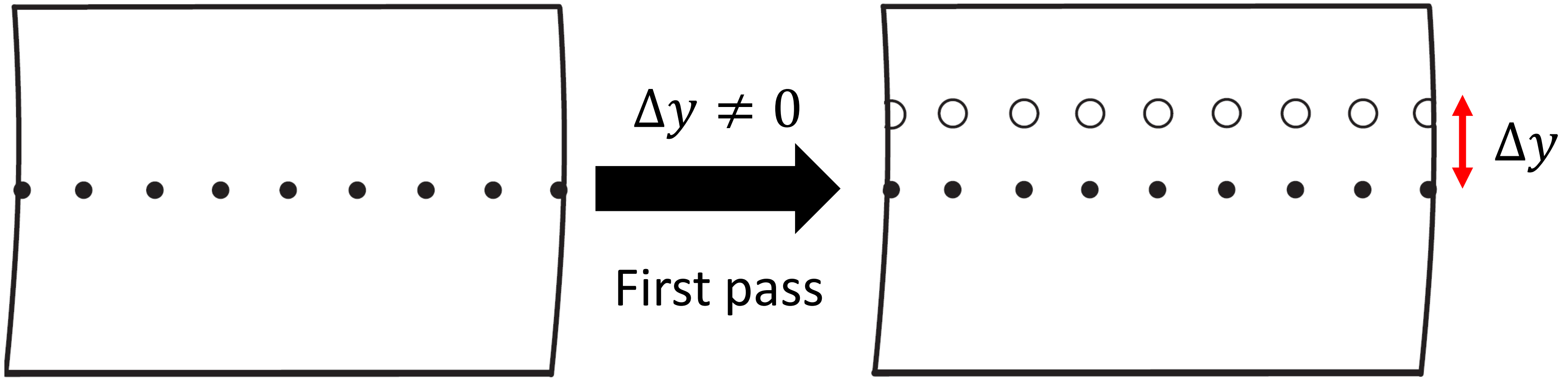

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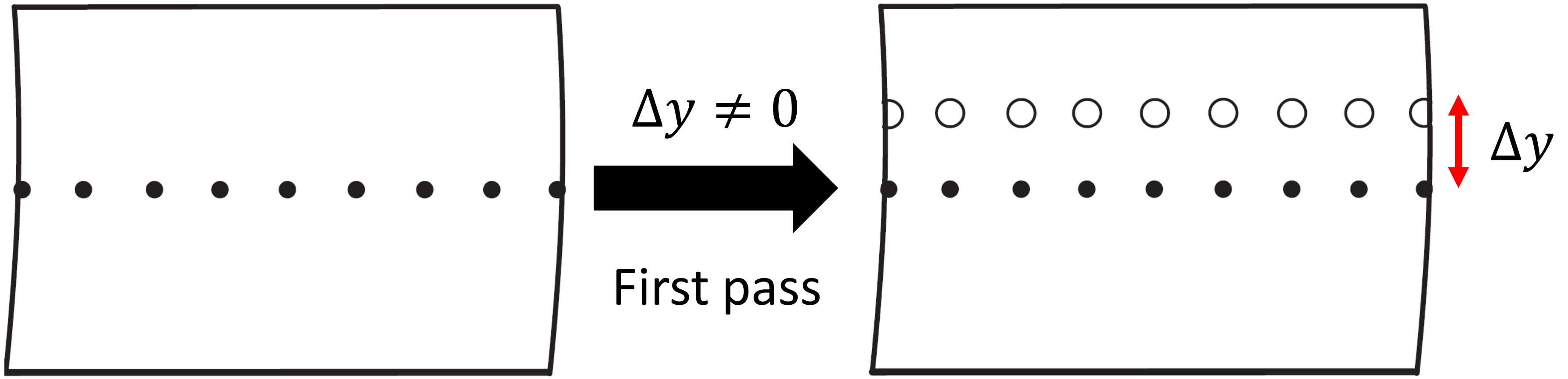

$$q \Leftrightarrow N_{pol}\ and\ \Delta y$$

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Usual simulation parameters

- $\beta = 10^{-4}$
- **Kinetic electrons (!)**
- Two cases – **Cyclone Base Case (CBC)** or **pure ITG (pITG)** drive

Cyclone Base Case (CBC):

- $T_e = T_i$
- $R/L_T = 6.96$
- $R/L_n = 2.22$
- $q = 1.4$

pure ITG (pITG):

- $T_e = T_i$
- $R/L_{T,i} = 6.96$
- $R/L_{T,e} = 0$
- $R/L_n = 0$
- $q = 1.4$

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

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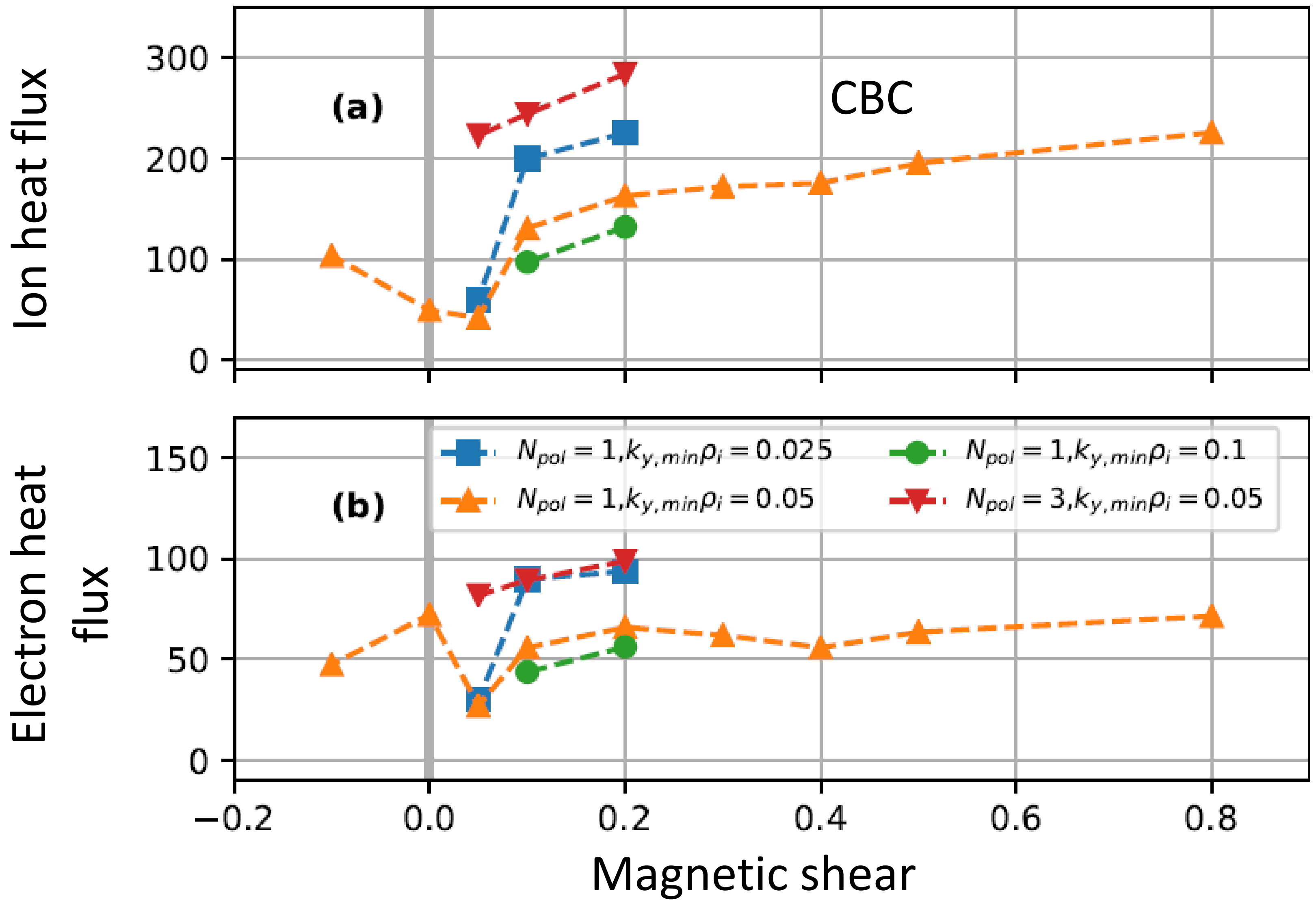
Heat flux at finite shear



Self-interaction trends at low shear agree with previous study at $\hat{s} = 0.8$

- J. Ball *et al.* 2020 *Journal of Plasma Physics* **86(2)**, 905860207

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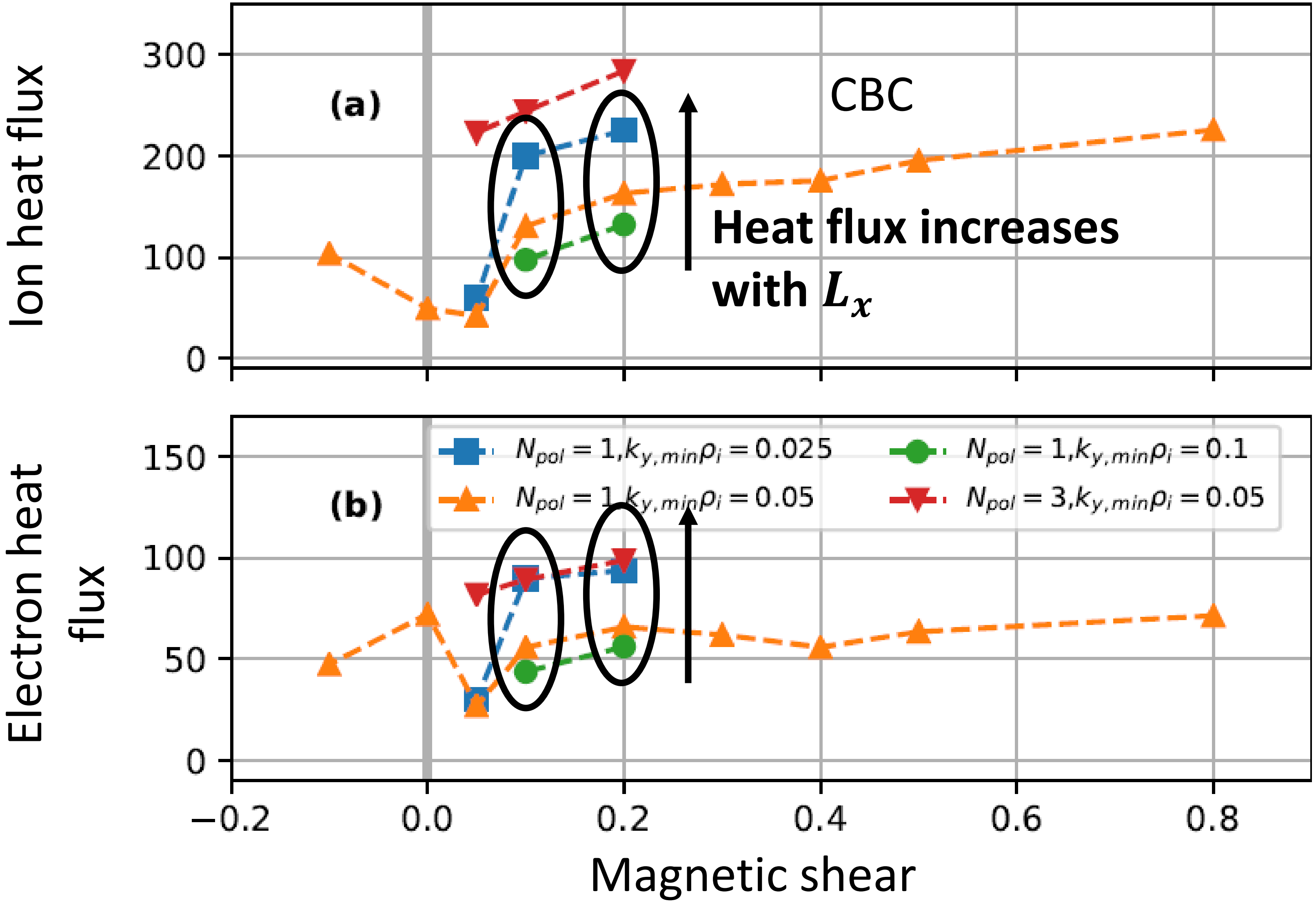
By spacing out integer surfaces



$$L_x \propto (k_{y,min}\hat{s})^{-1}$$

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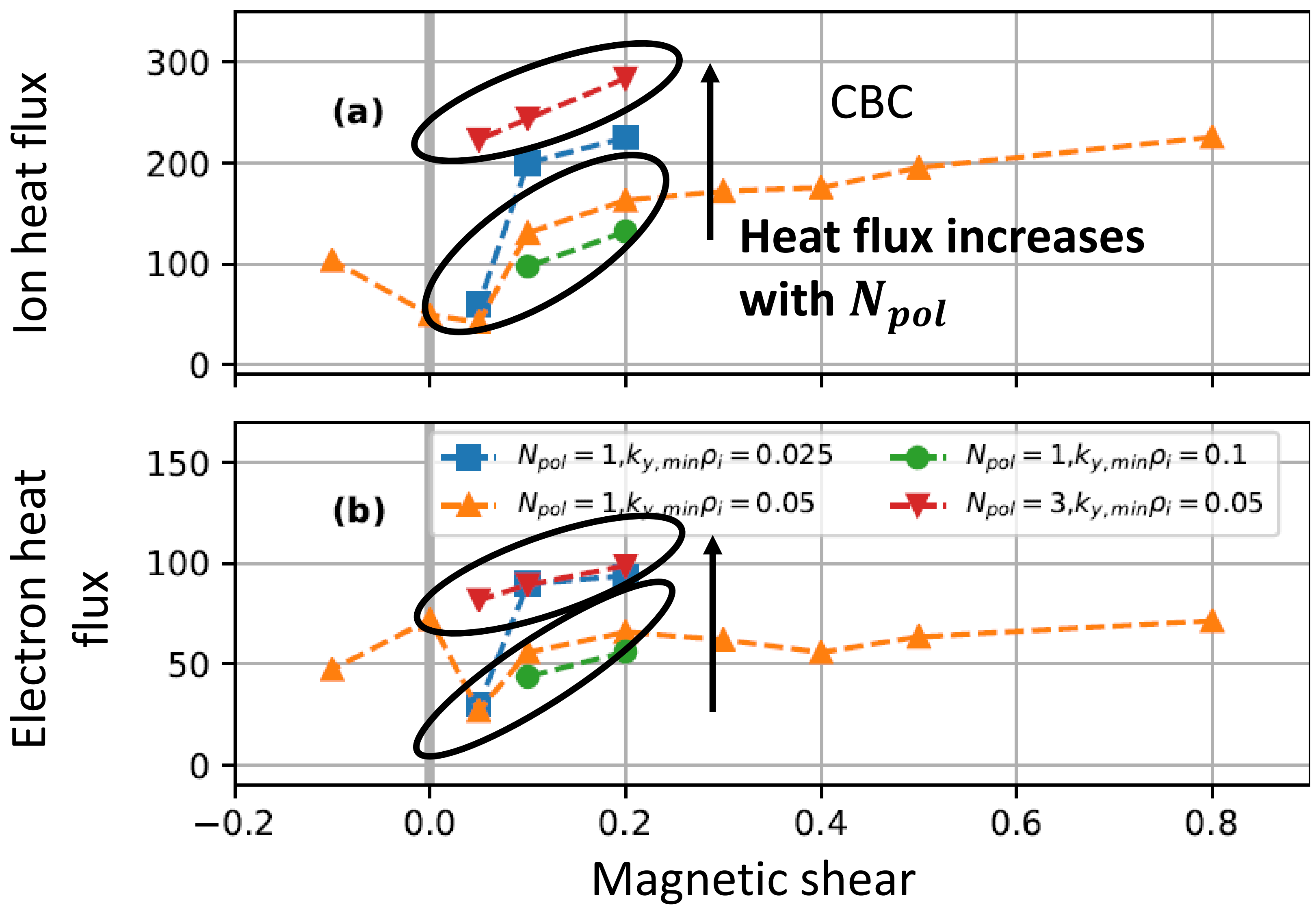
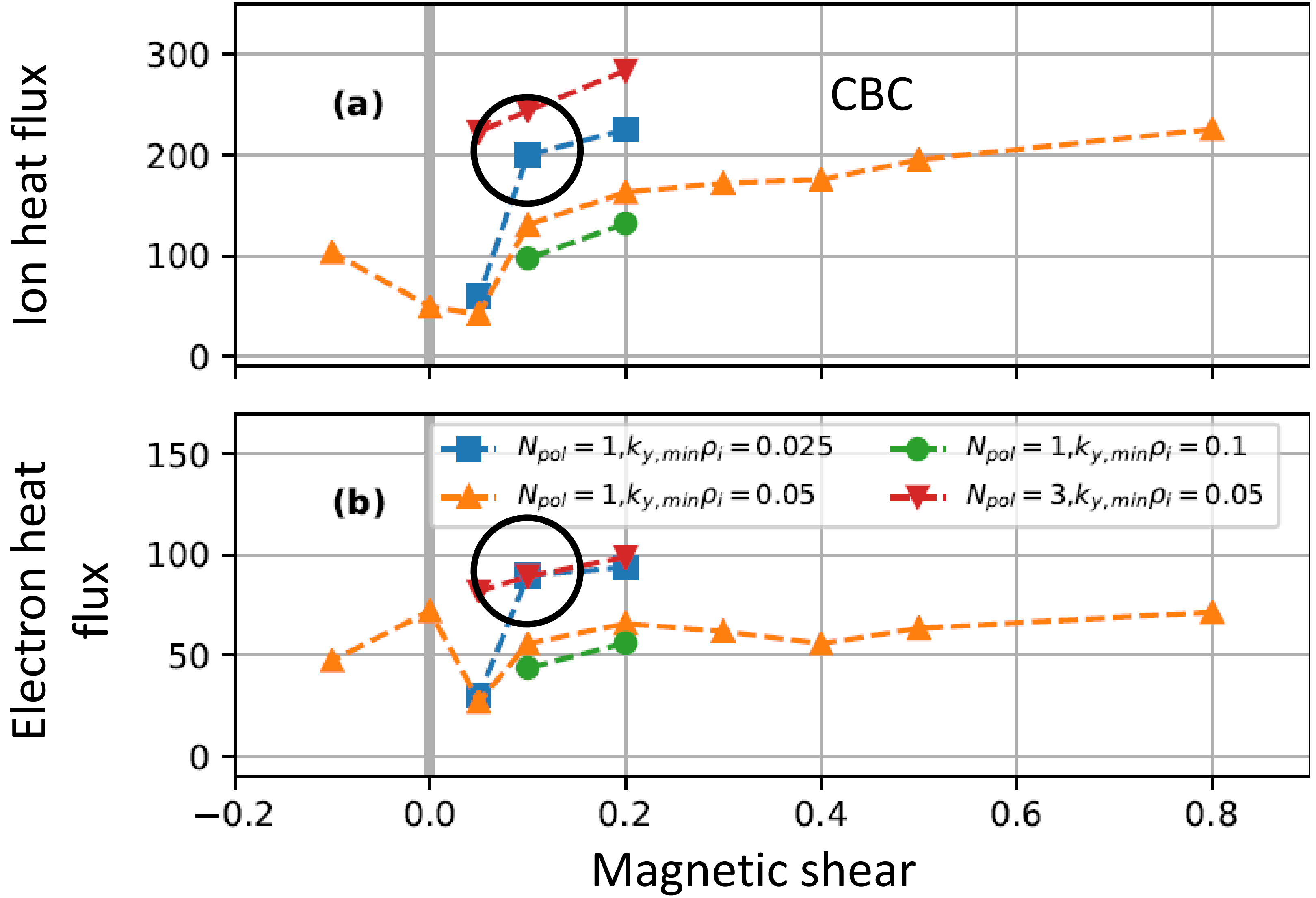
By increasing domain length



Due to finite eddy length

Radial plasma profiles at $\hat{s} = 0.1$



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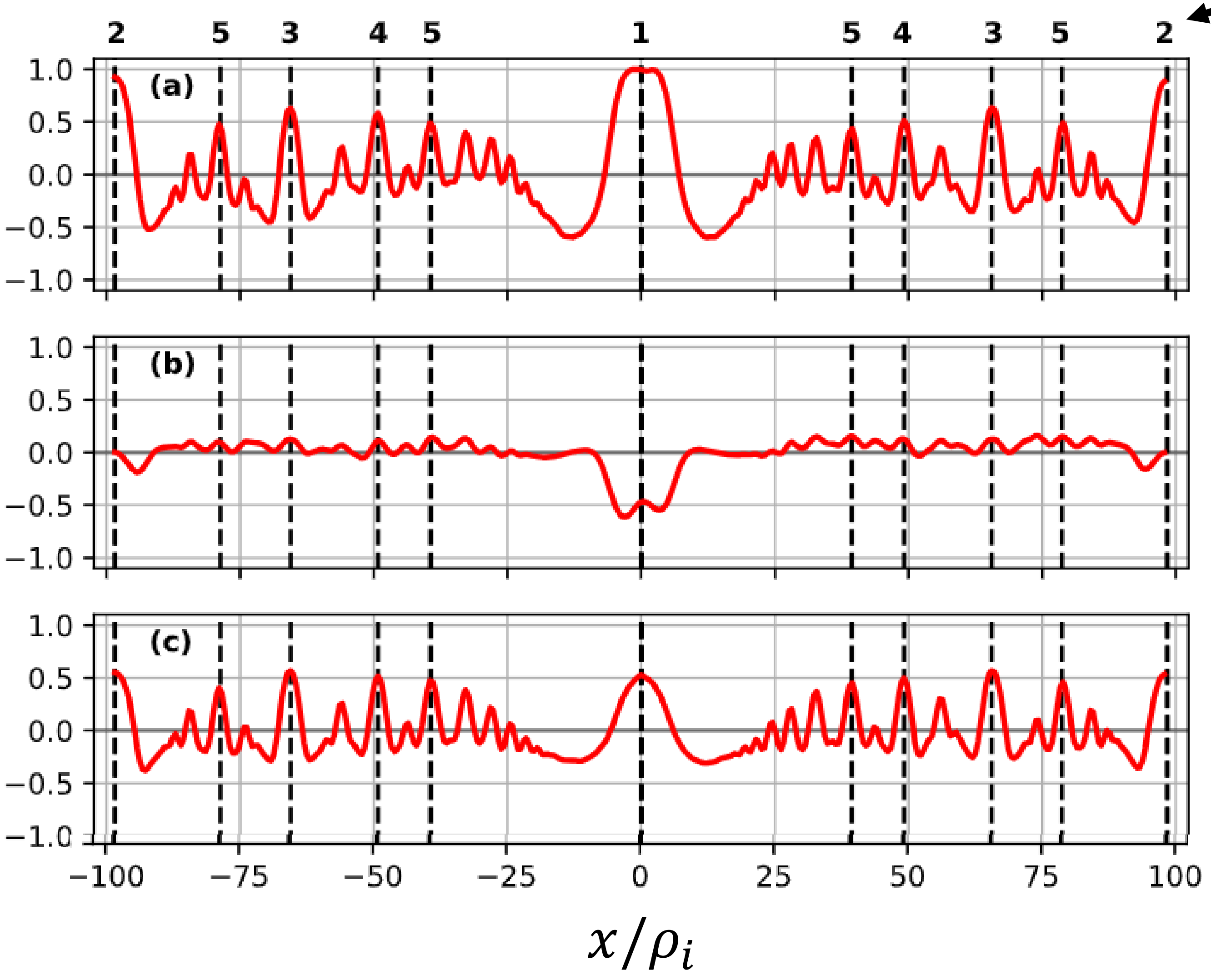
Profile corrugations

Perturbed density gradient

Perturbed ion temperature gradient

Perturbed electron temperature gradient



Order of rational surface

$\propto \partial_x \langle \delta n \rangle_{y,z,t}$

$\hat{s} = 0.1$
$N_{pol} = 1$

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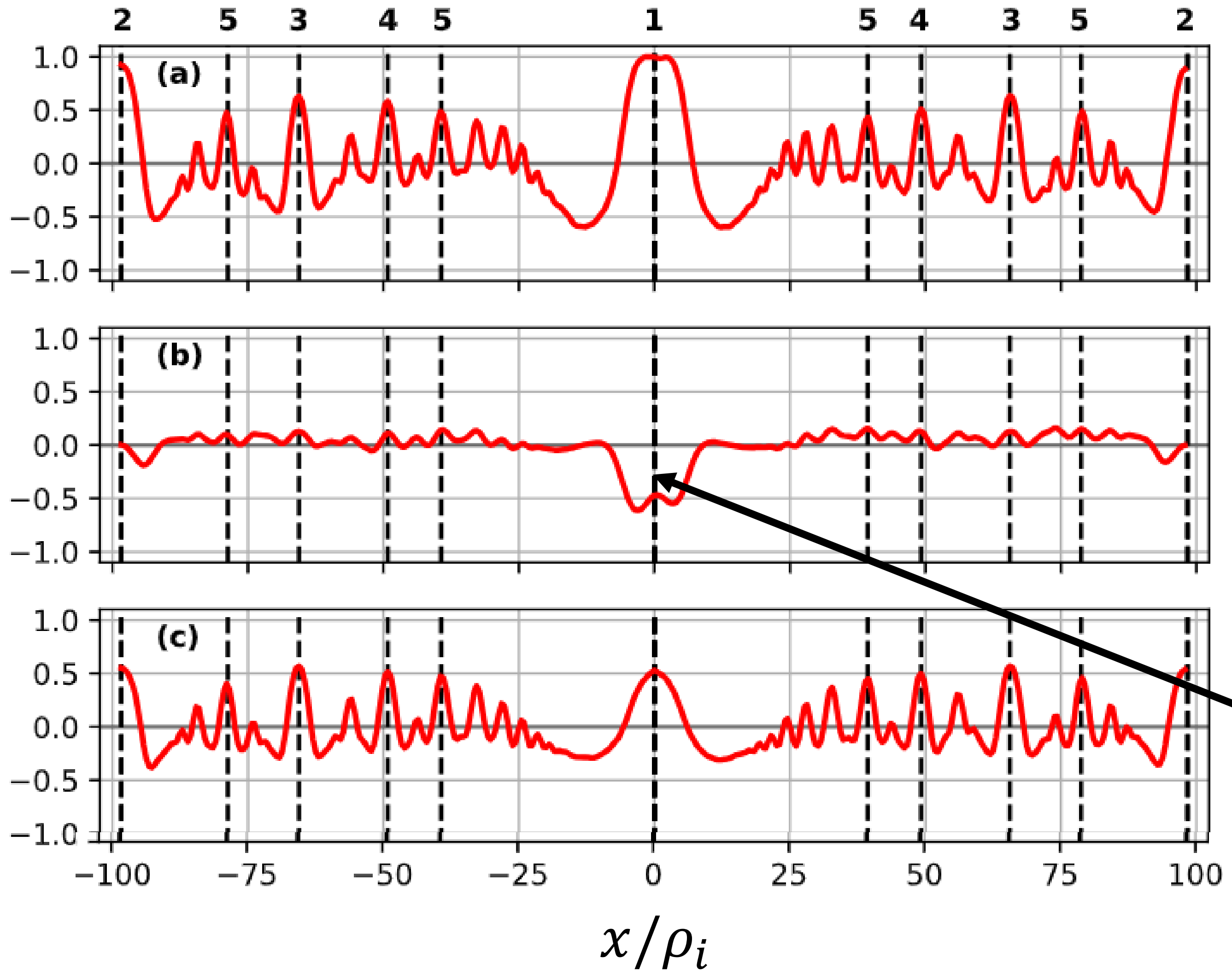

Positive → flattening
Negative → steepening

$\hat{s} = 0.1$
$N_{pol} = 1$

Profile steepening by 50 %

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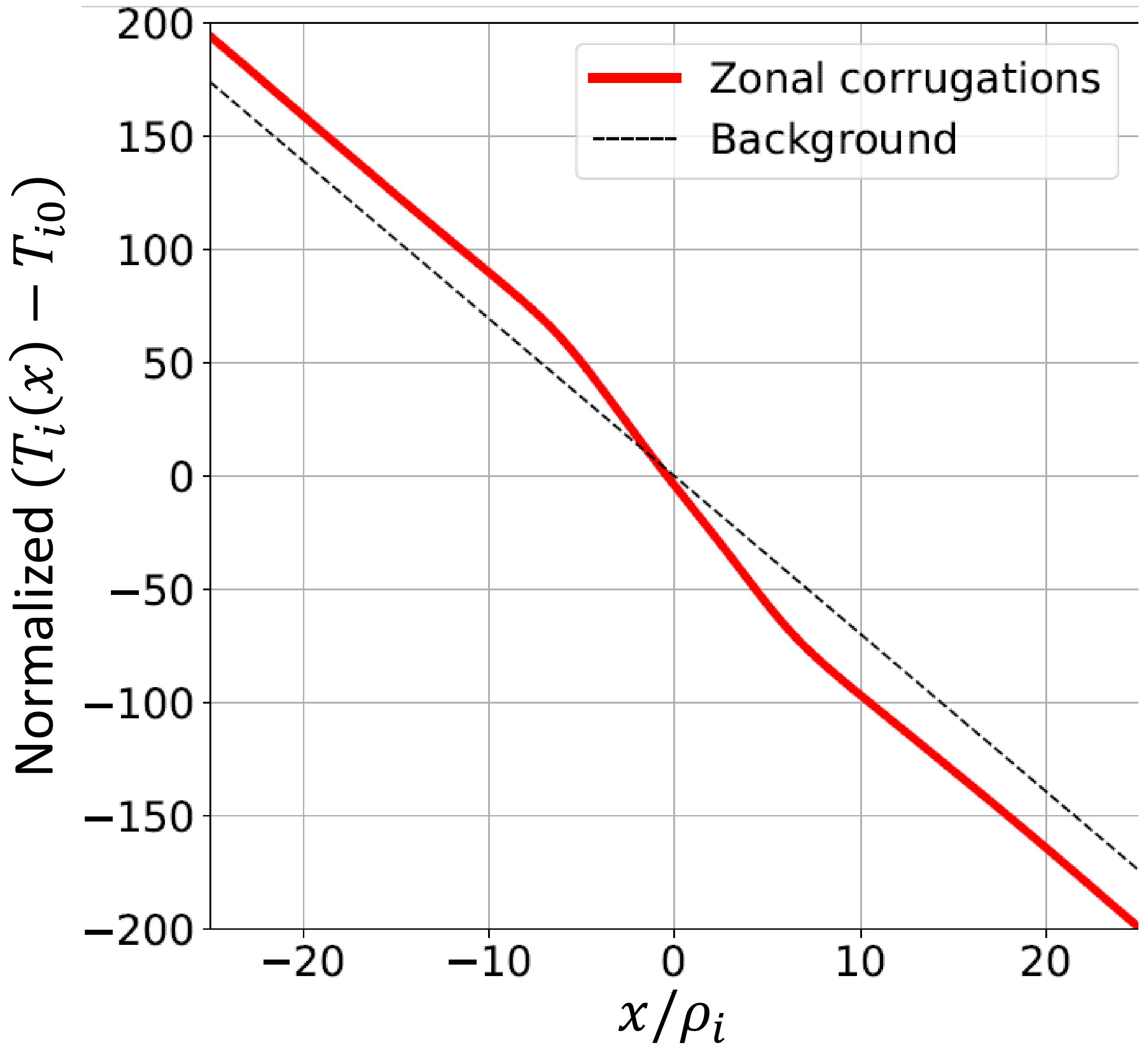
Profile steepening at integer surface



$\hat{s} = 0.1$
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Estimate of eddy length with $\hat{s}$

Perturbed density gradient

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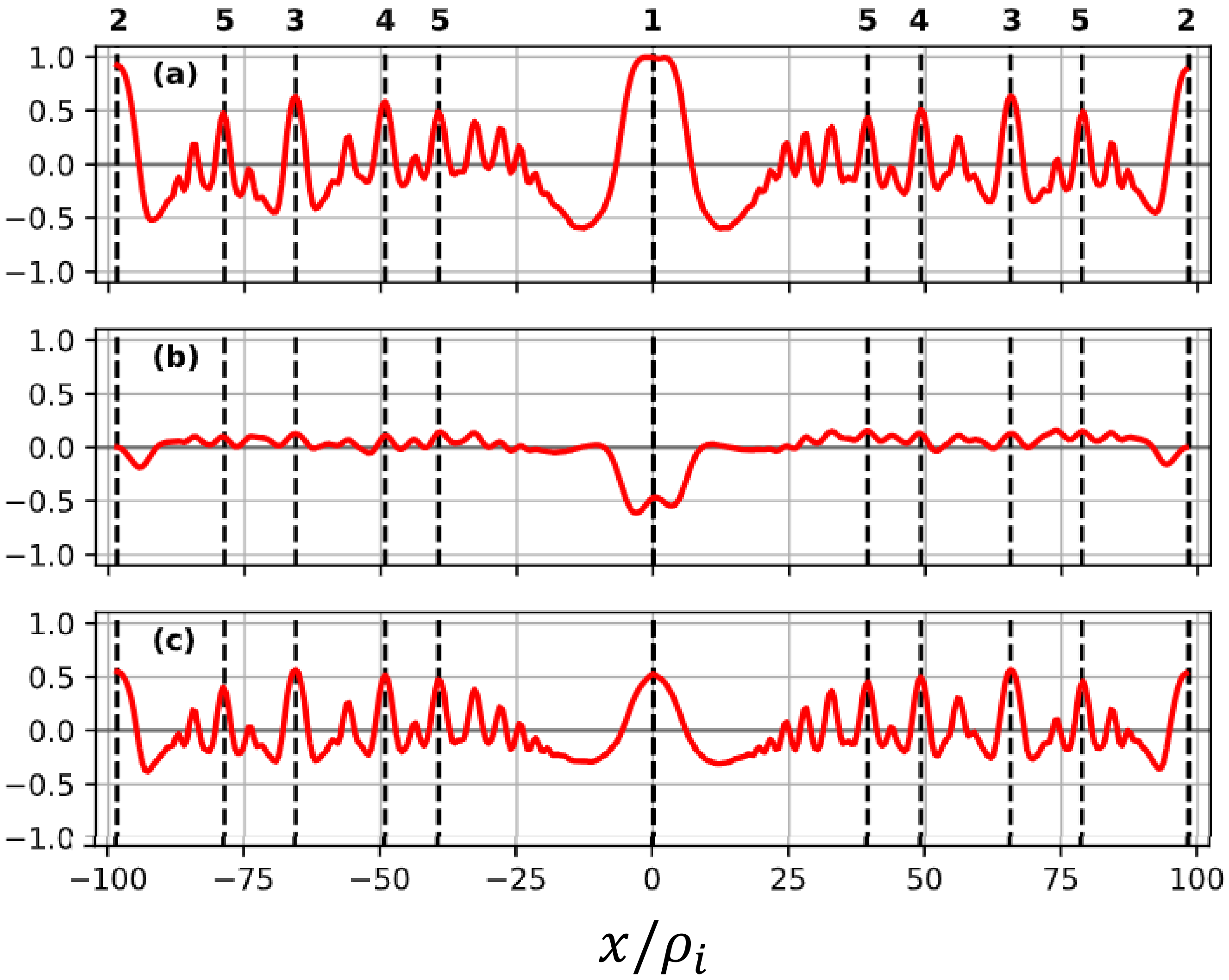
Perturbed electron temperature gradient



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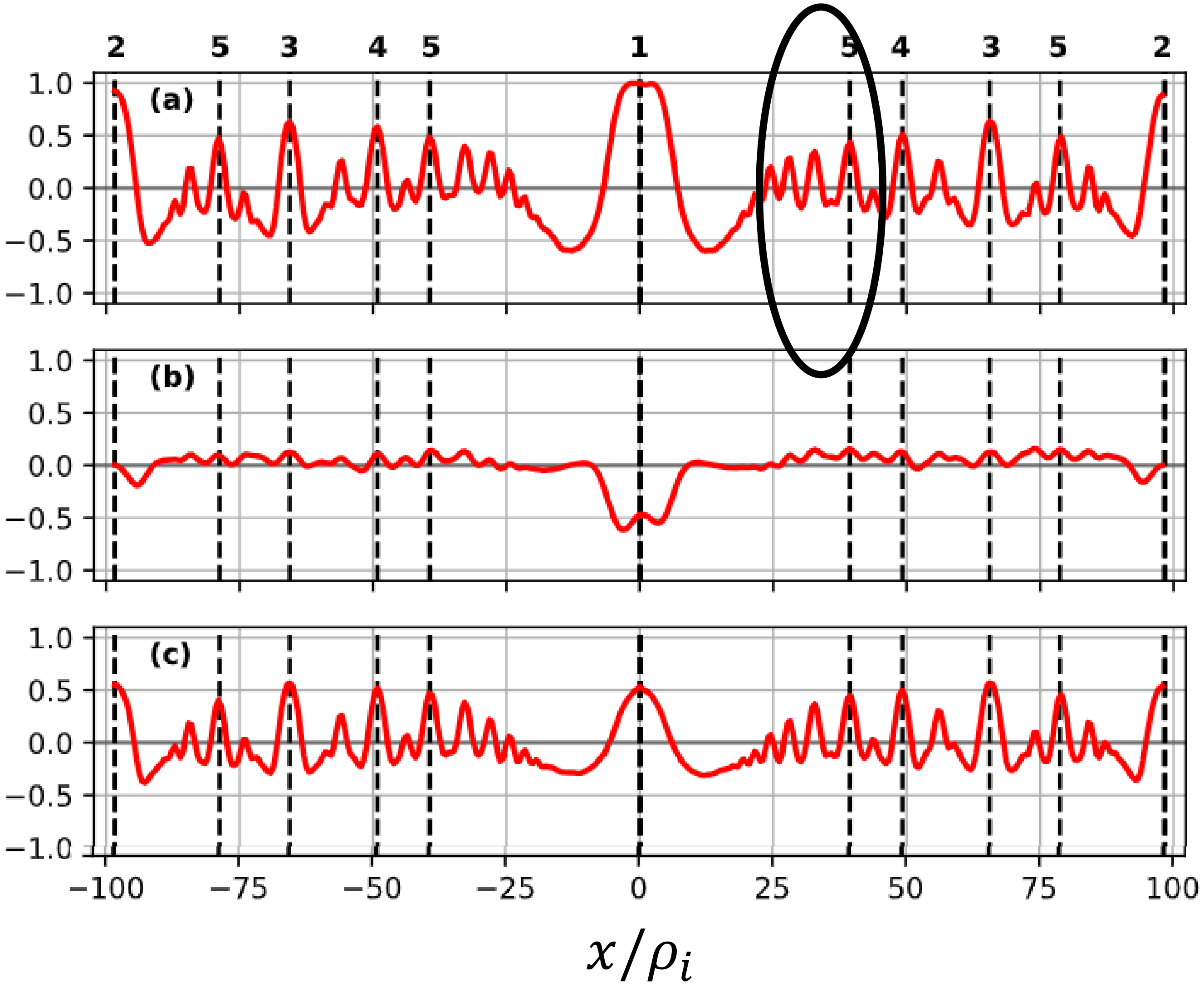

Based on the highest order rational surfaces with significant zonal structures

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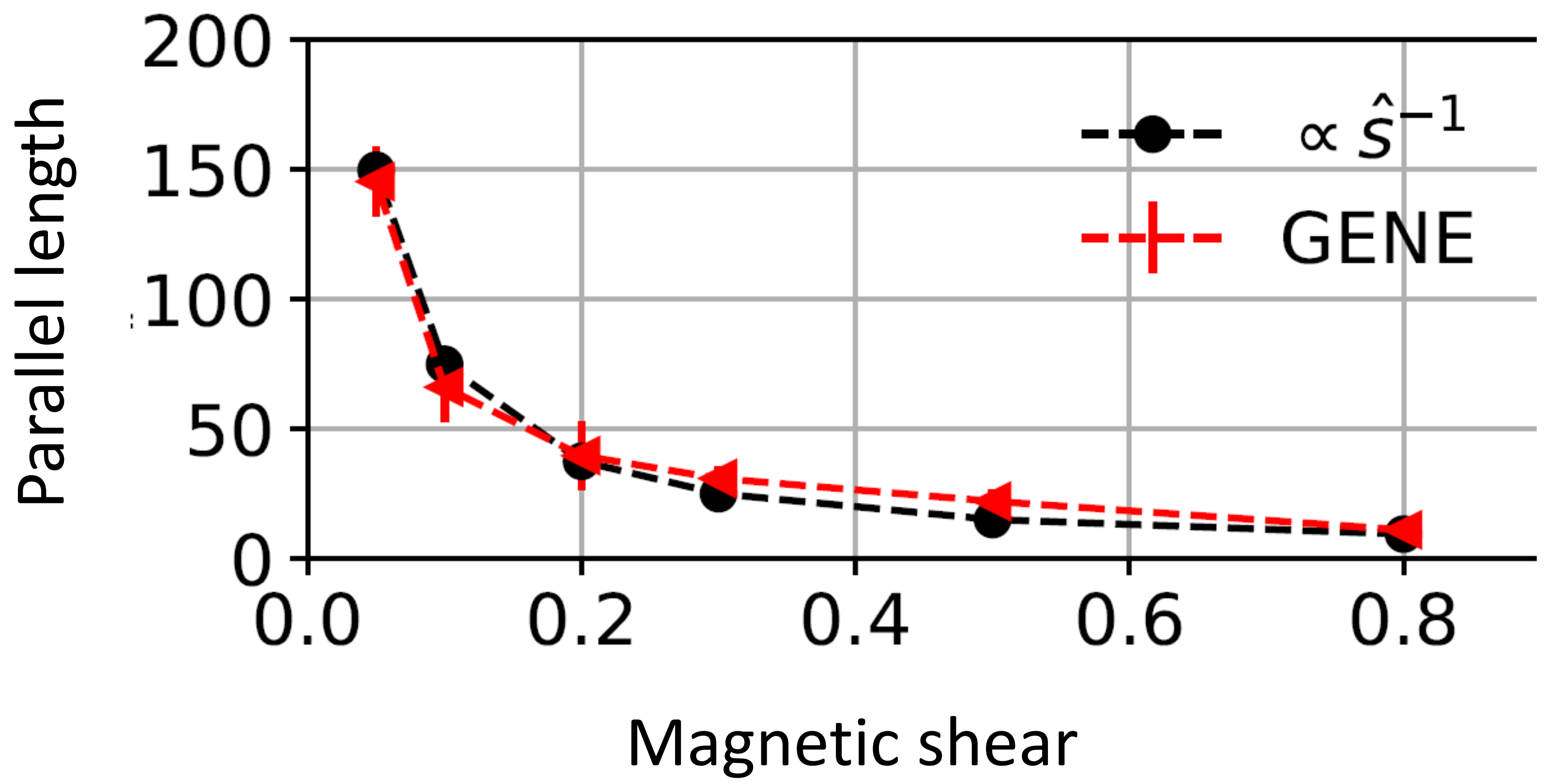

Based on the highest order rational surfaces with significant zonal structures

Due to **magnetic drifts** and **FLR effects** parallel eddy length scales like $\hat{s}^{-1}$

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Summary: Finite shear study

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- Self-interaction follows the same paradigm as established in previous work

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EPFL

Summary: Finite shear study

- Self-interaction follows the same paradigm as established in previous work
- Eddies extend in the parallel direction when shear is reduced as $\hat{s}^{-1}$
- Profile corrugations appear at multiple rational surfaces
- Simulations become computationally expensive as shear is reduced $[L_x \propto (k_y \hat{s})^{-1}]$

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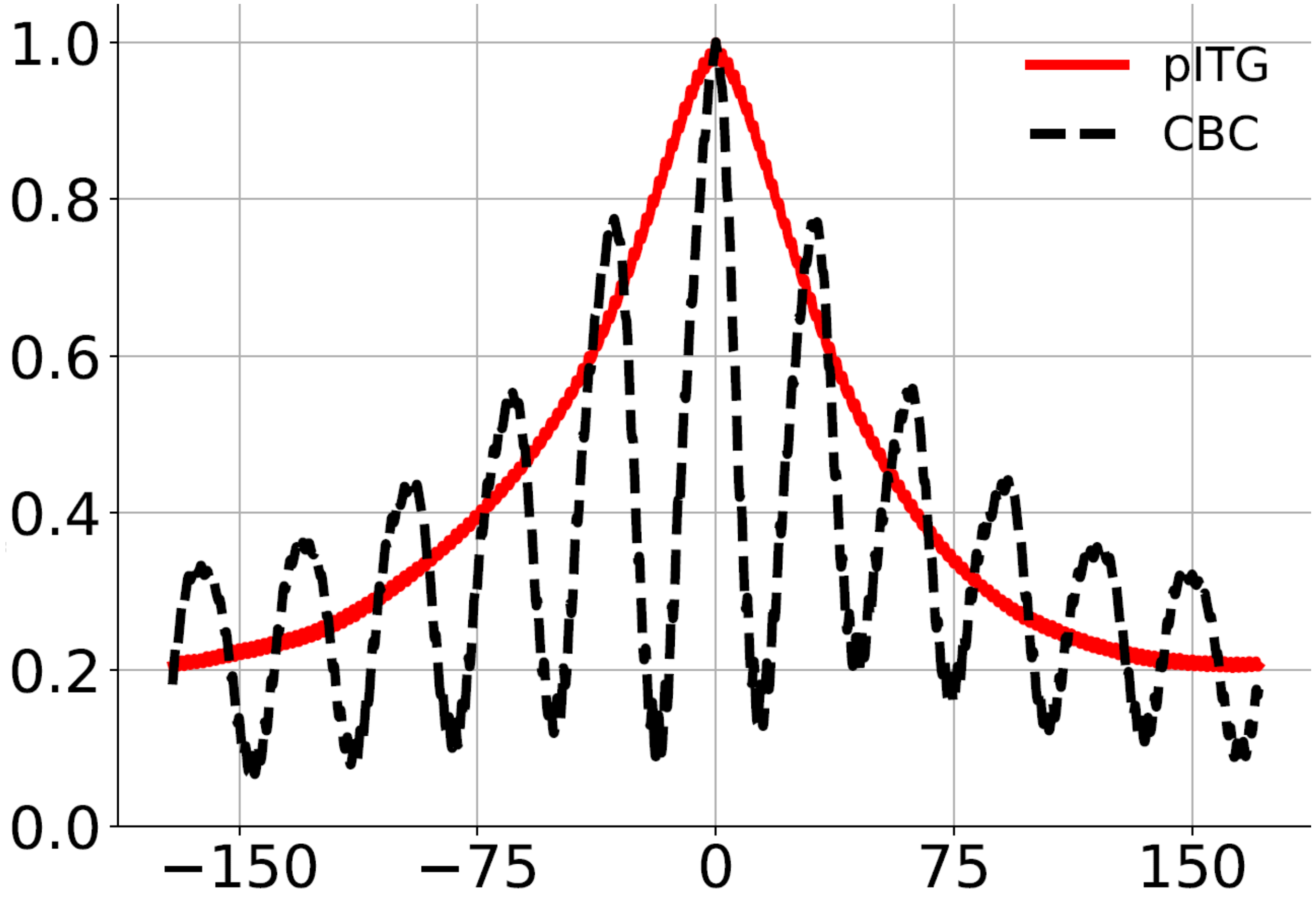
EPFL Ultra-long turbulent eddies $\hat{s} = 0$

Parallel correlation along field lines

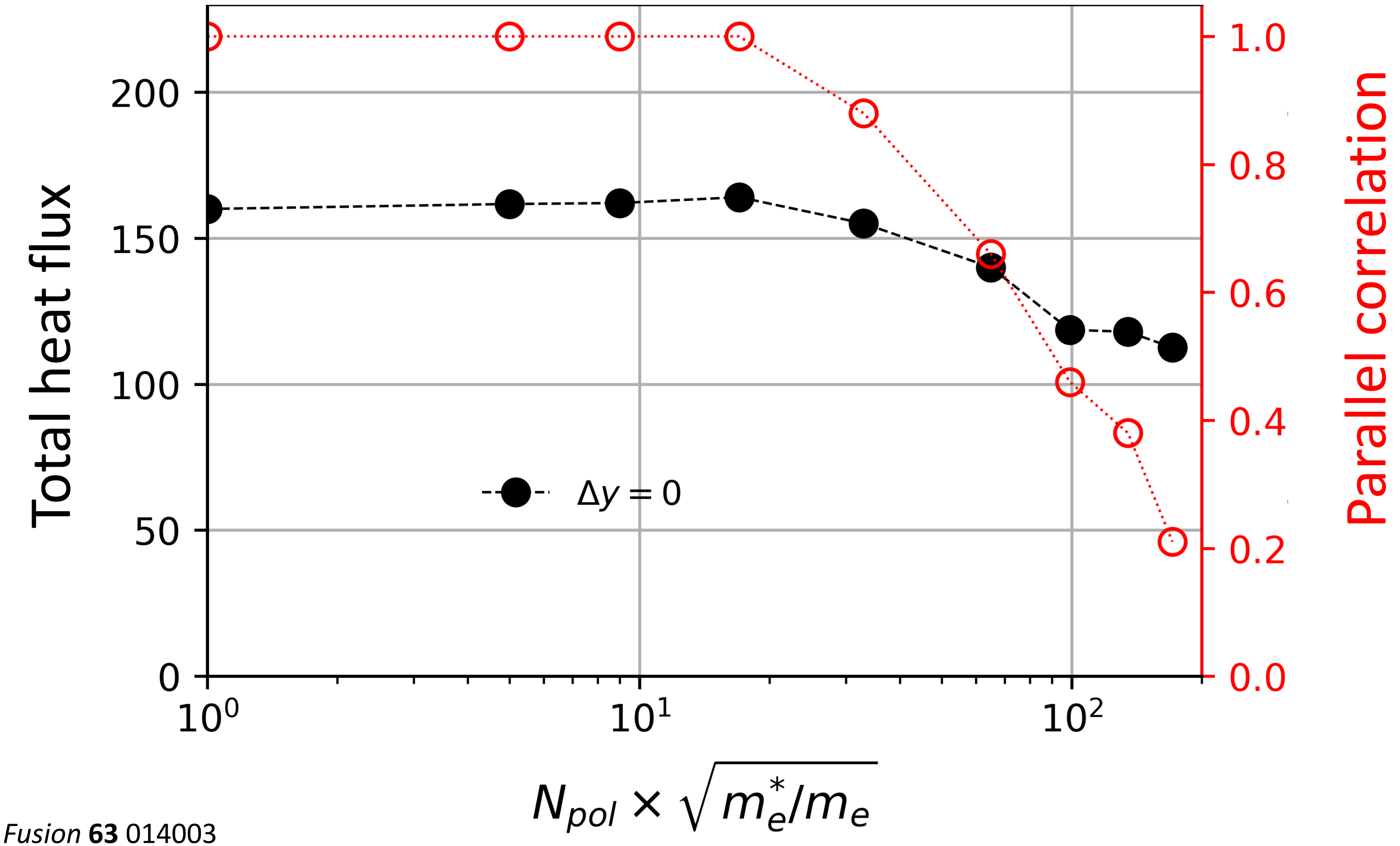


$z\ /\ \pi$

$N_{pol} = 171$

- A. Volčokas *et al.* 2023 *Nucl. Fusion* **63** 014003

pITG heat flux and correlation



Periodic parallel boundary condition ($\Delta y = 0$)

- A. Volčokas *et al.* 2023 *Nucl. Fusion* **63** 014003

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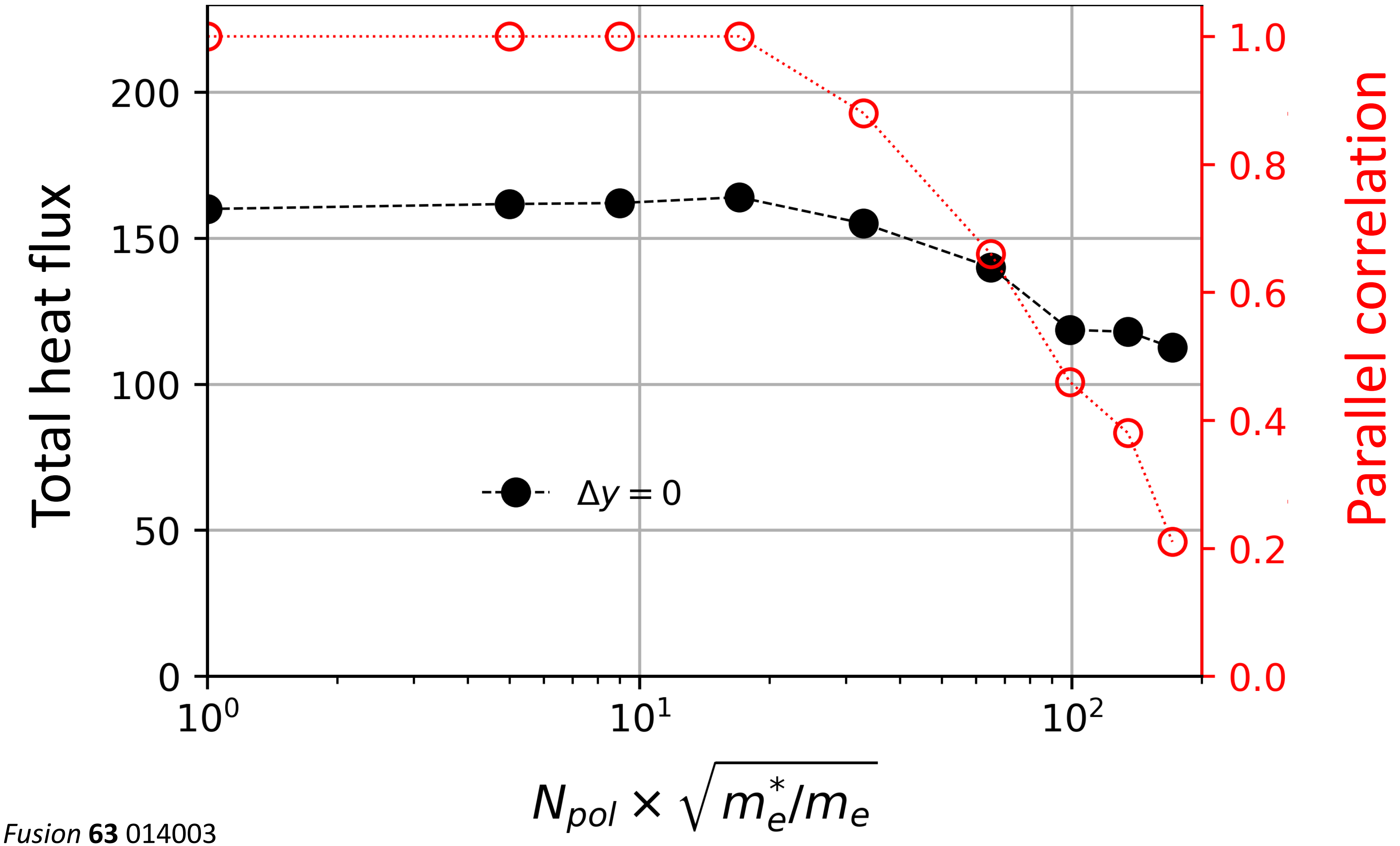
pITG heat flux and correlation

Kinetic electrons are key

Periodic parallel boundary condition ($\Delta y = 0$)



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- A. Volčokas *et al.* 2023 *Nucl. Fusion* **63** 014003

Electrons set eddy length

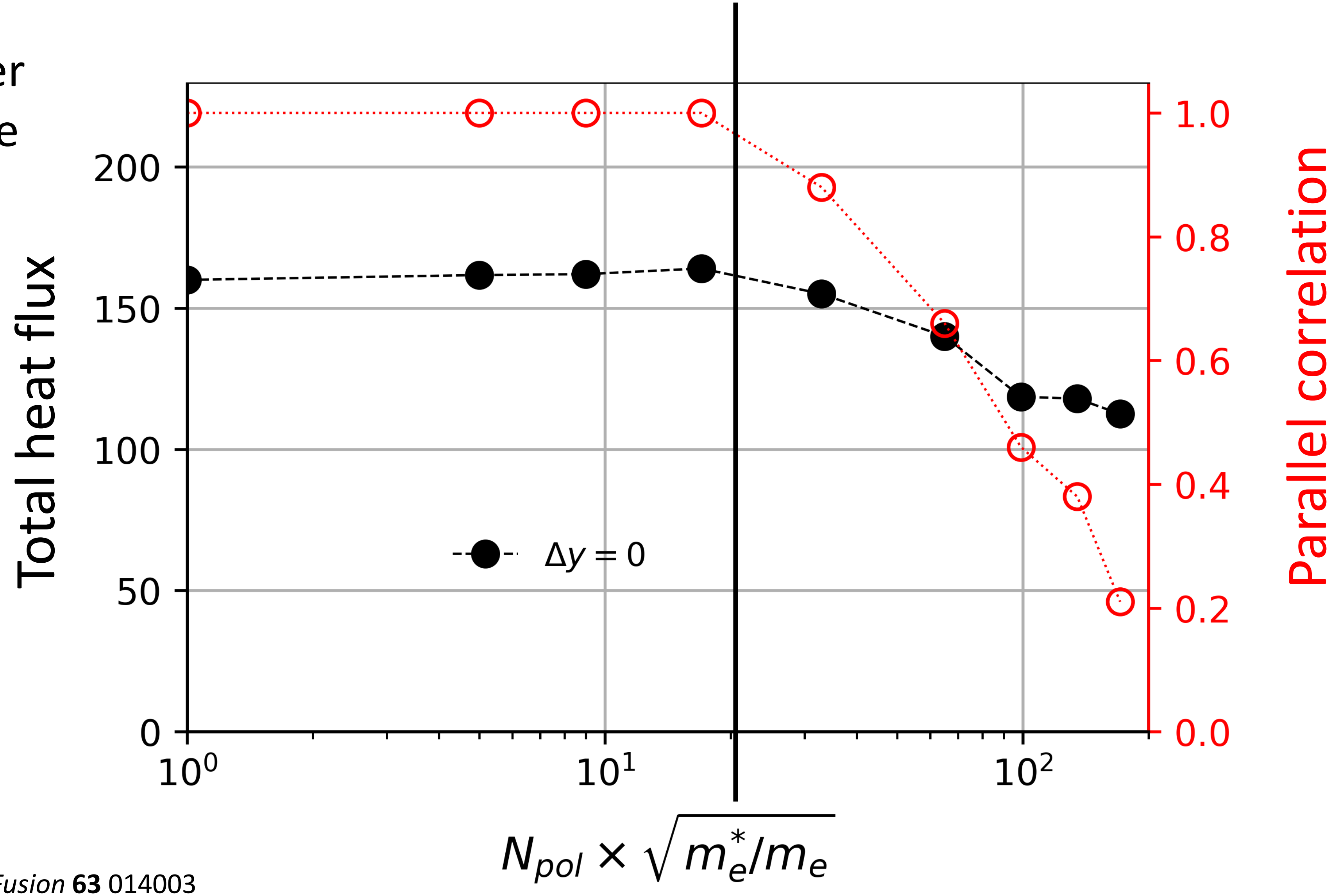
How far **electrons** travel over turbulent time scale sets the parallel eddy size.

$$\sqrt{m_i/m_e} \approx 60$$

$$\tau_{turb} \approx 3\,R/c_i$$

$$L_\parallel \approx \; v_{th,e}\tau_{turb}$$

$$\frac{L_\parallel}{L_{N_{pol}=1}} \approx 20$$



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- A. Volčokas *et al.* 2023 *Nucl. Fusion* **63** 014003
- M. Barnes, F. I. Parra, and A. A. Schekochihin, Phys. Rev. Lett. 107, 115003 (2011)

Check with heavier electrons

How far **electrons** travel over turbulent time scale sets the parallel eddy size.

$$\sqrt{m_i/m_e} \approx 60$$

$$\tau_{turb} \approx 3\, R/c_i$$

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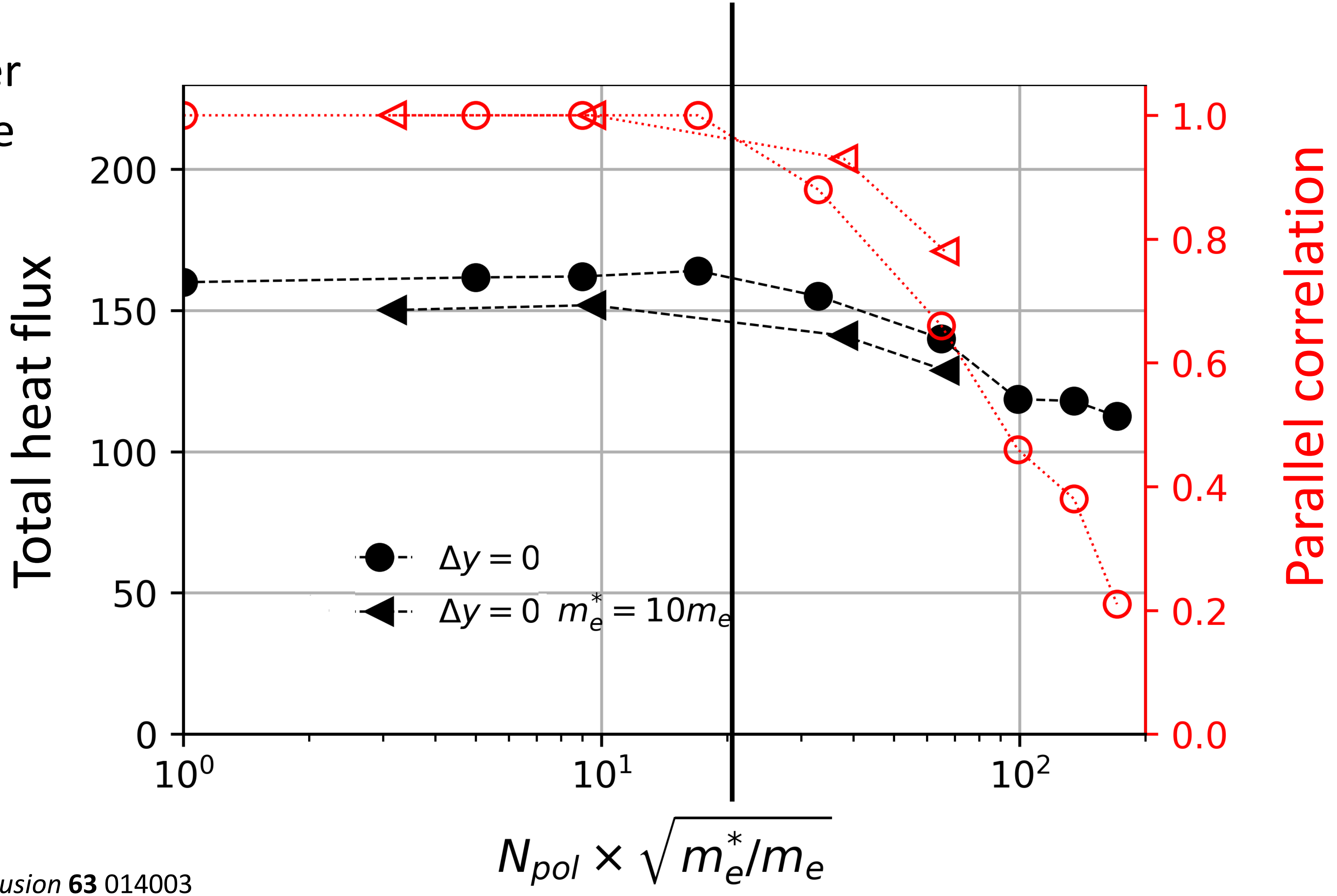

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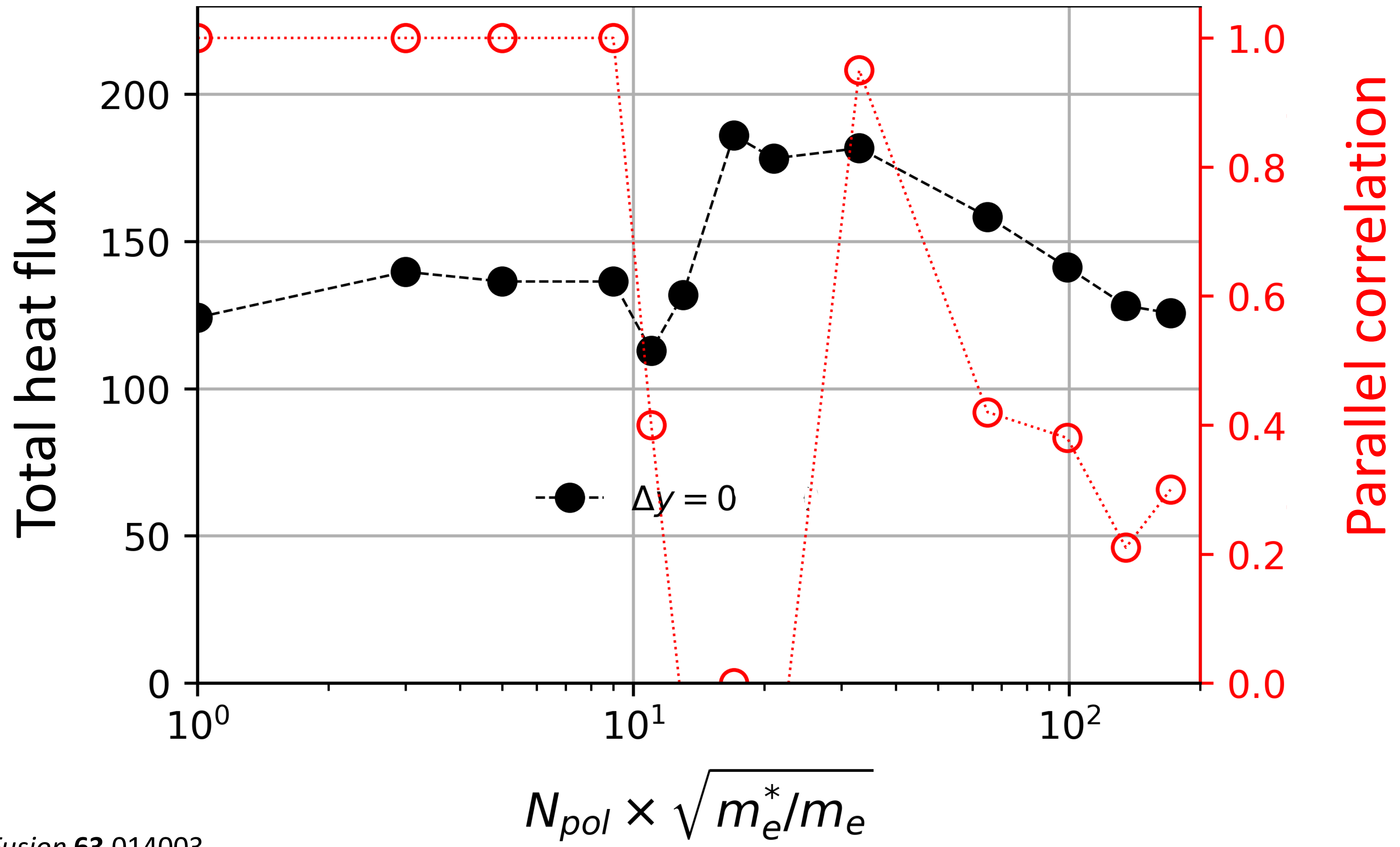
- M. Barnes, F. I. Parra, and A. A. Schekochihin, Phys. Rev. Lett. 107, 115003 (2011)

CBC heat flux and correlation

Similar picture to pITG



- A. Volčokas *et al.* 2023 *Nucl. Fusion* **63** 014003

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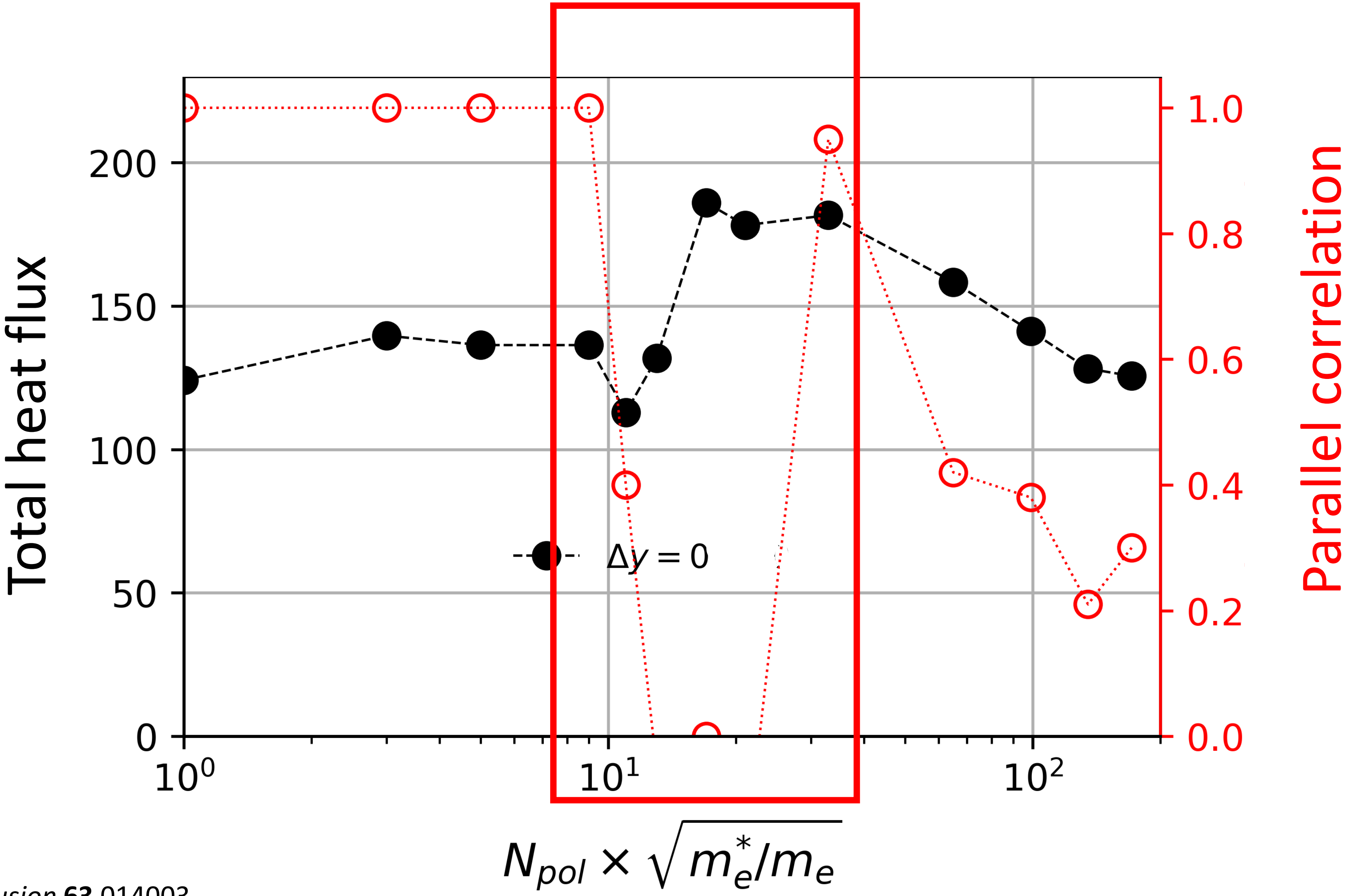
Parallel waves

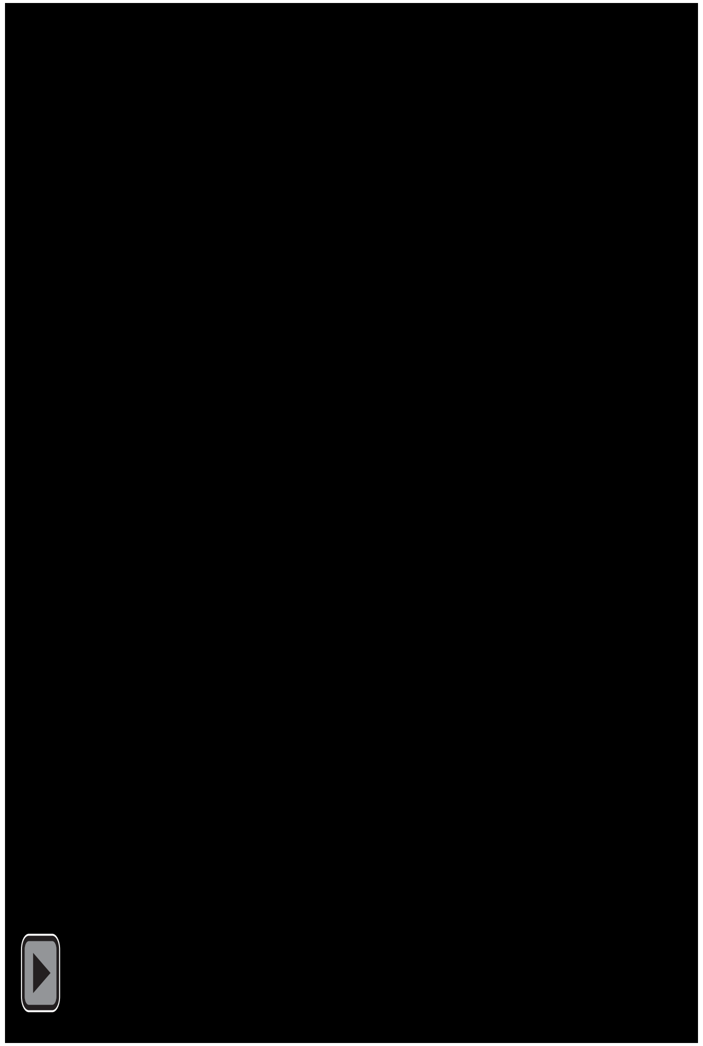
Long parallel waves
$\lambda \approx 20\ N_{pol}$ appear

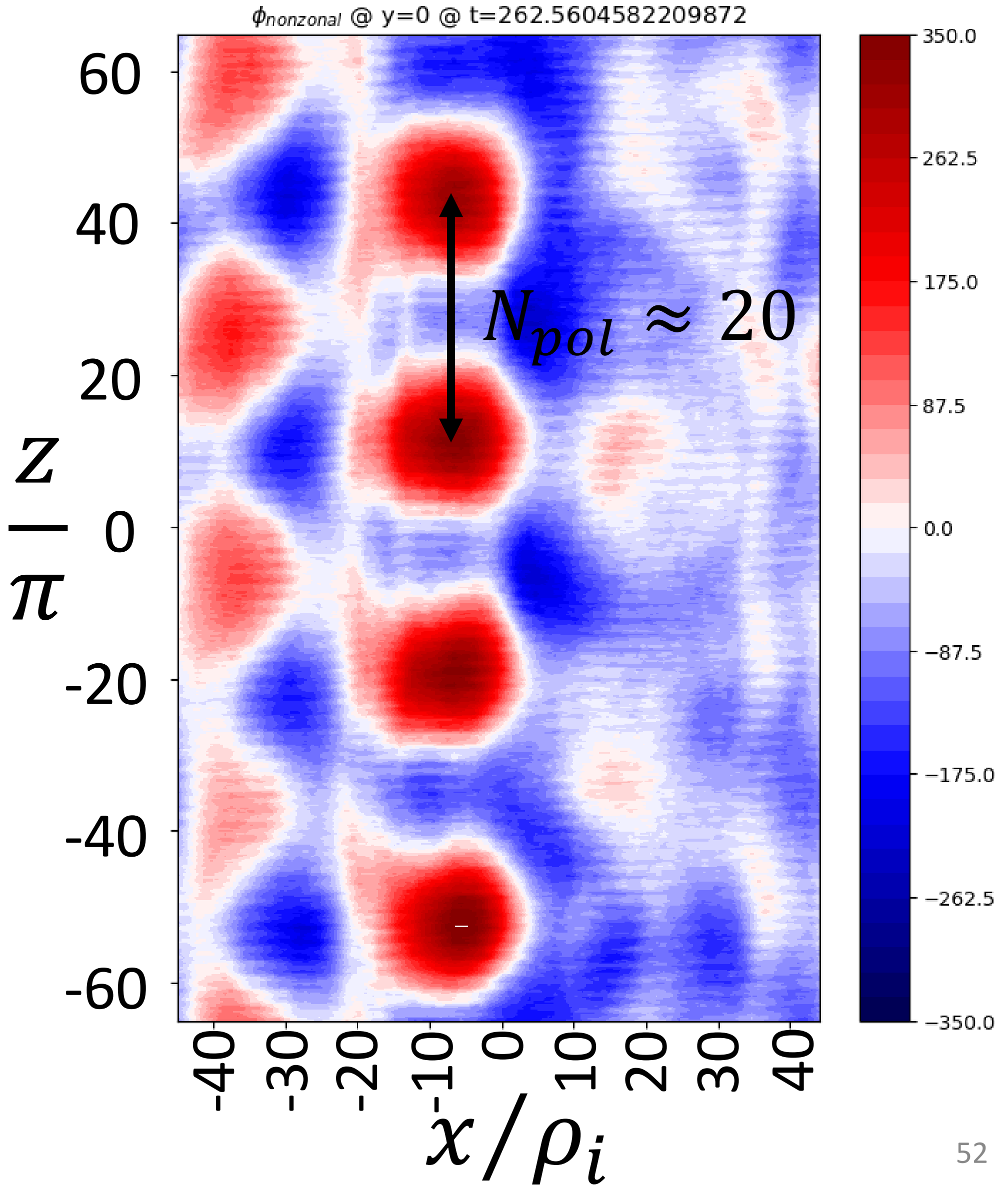


- A. Volčokas *et al.* 2023 *Nucl. Fusion* **63** 014003

Long parallel wave-like structures

$N_{pol} = 65$





Robustness of ultra-long turbulent eddies

- **Collisions** do not reduce ultra-long eddy length but eliminate parallel waves
- No **plasma shaping** (elongation or triangularity) effects on ultra-long eddies

➢ Ultra-long eddies seem to **be a robust plasma feature** at low magnetic shear $\hat{s} \ll 1$.

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Summary: Eddy parallel length study

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- Simulations with kinetic electrons at zero magnetic shear **require hundreds of poloidal turns** to achieve convergence

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- Heat flux is reduced when eddies are unable to self-interact

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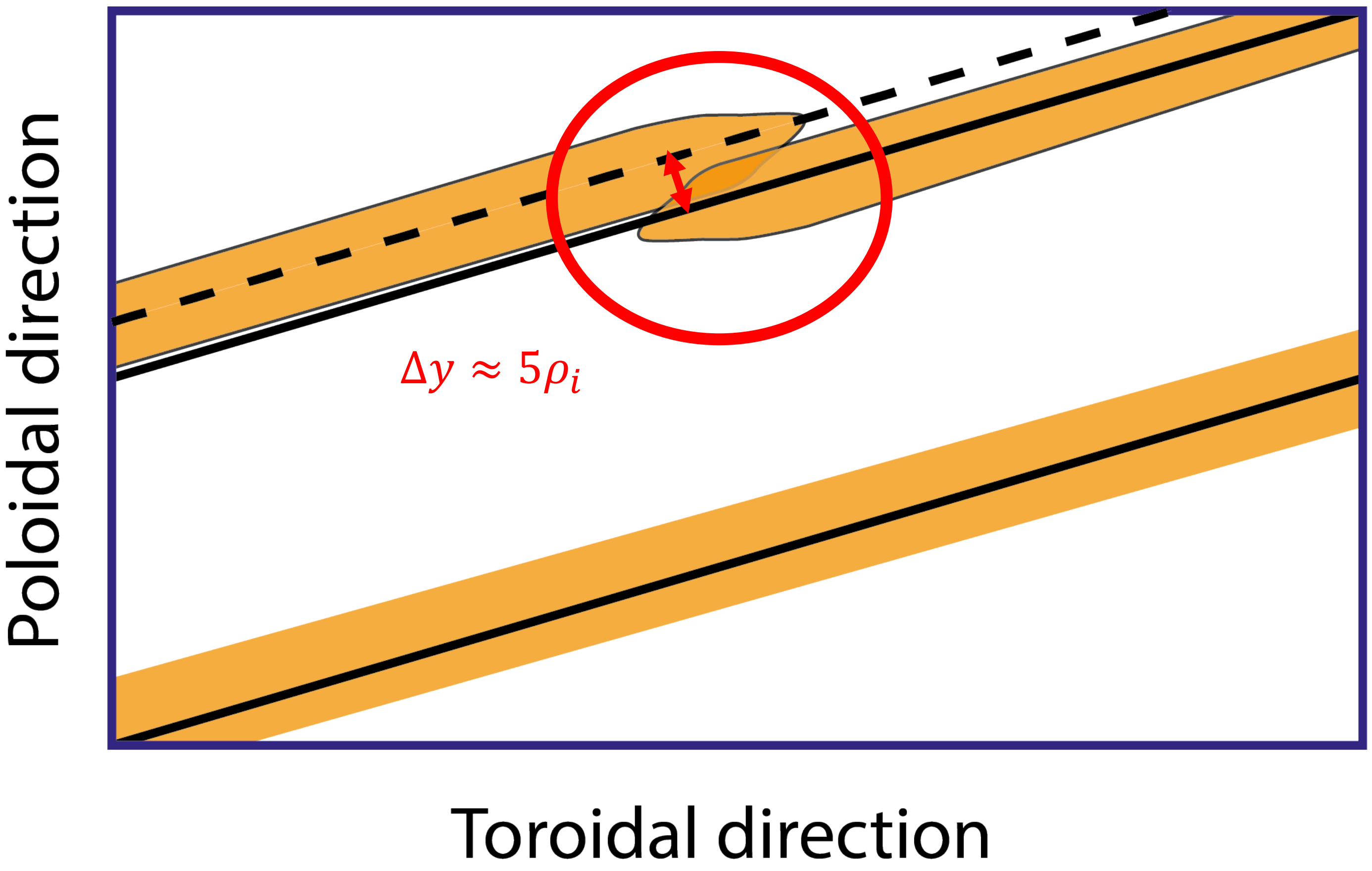
Summary: Eddy parallel length study

- Simulations with kinetic electrons at zero magnetic shear **require hundreds of poloidal turns** to achieve convergence
- **Kinetic electrons** set the parallel turbulence length scale
- Heat flux is reduced when eddies are unable to self-interact
- In simulations with electron temperature gradient long parallel waves emerge

Parallel boundary shift



$q = 2.01$

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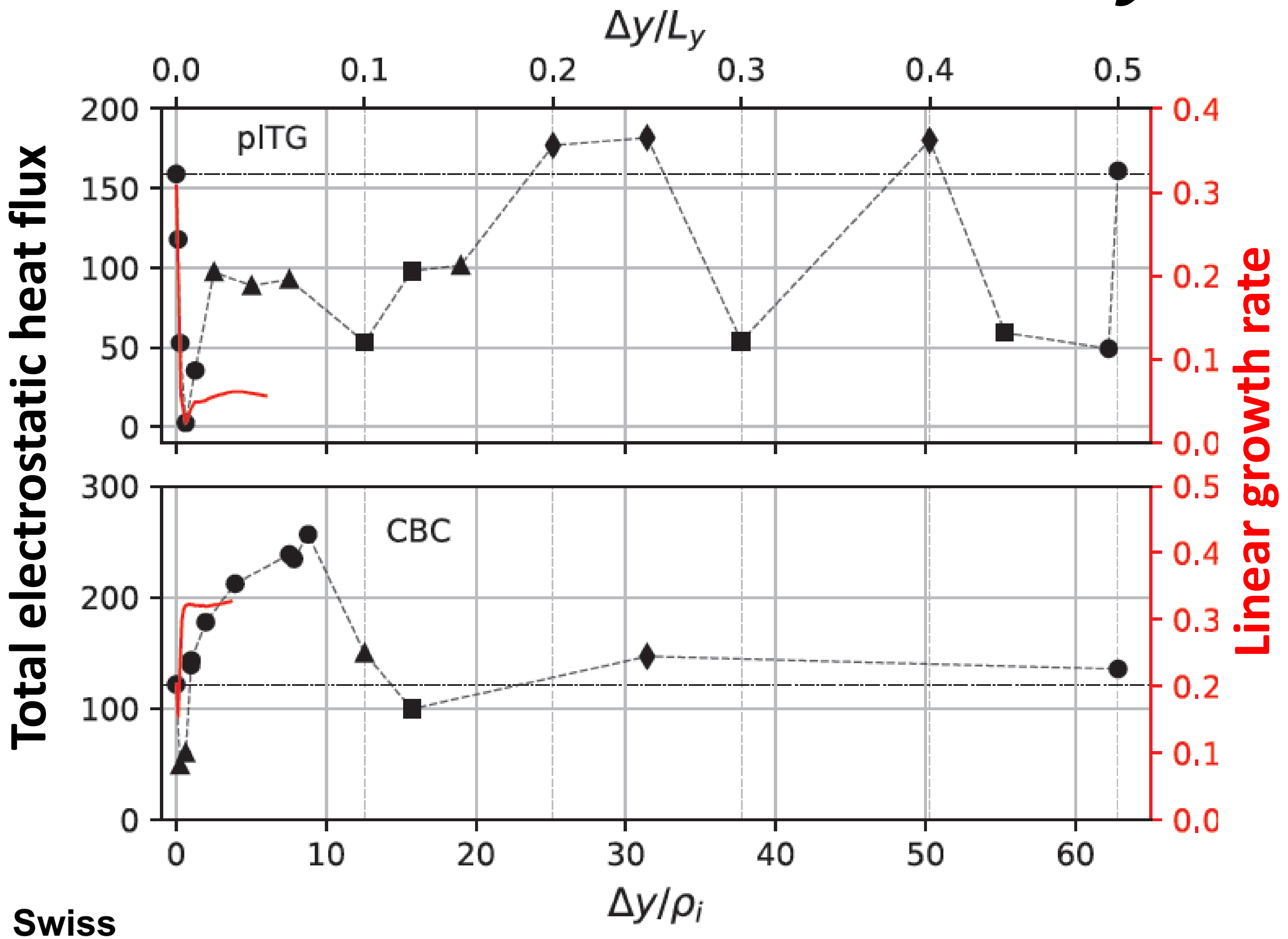
EPFL Binormal shift Δy when $\hat{s} = 0$



- Turbulence can be strongly affected by the magnetic field topology, leading **to complete stabilization** in some cases.

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$$N_{pol} = 1$$

- A. Volčokas *et al.* 2023 *Nucl. Fusion* **63** 014003
- D. St-Onge *et al.* 2023 *Plasma Phys. Control. Fusion* **65** 015016

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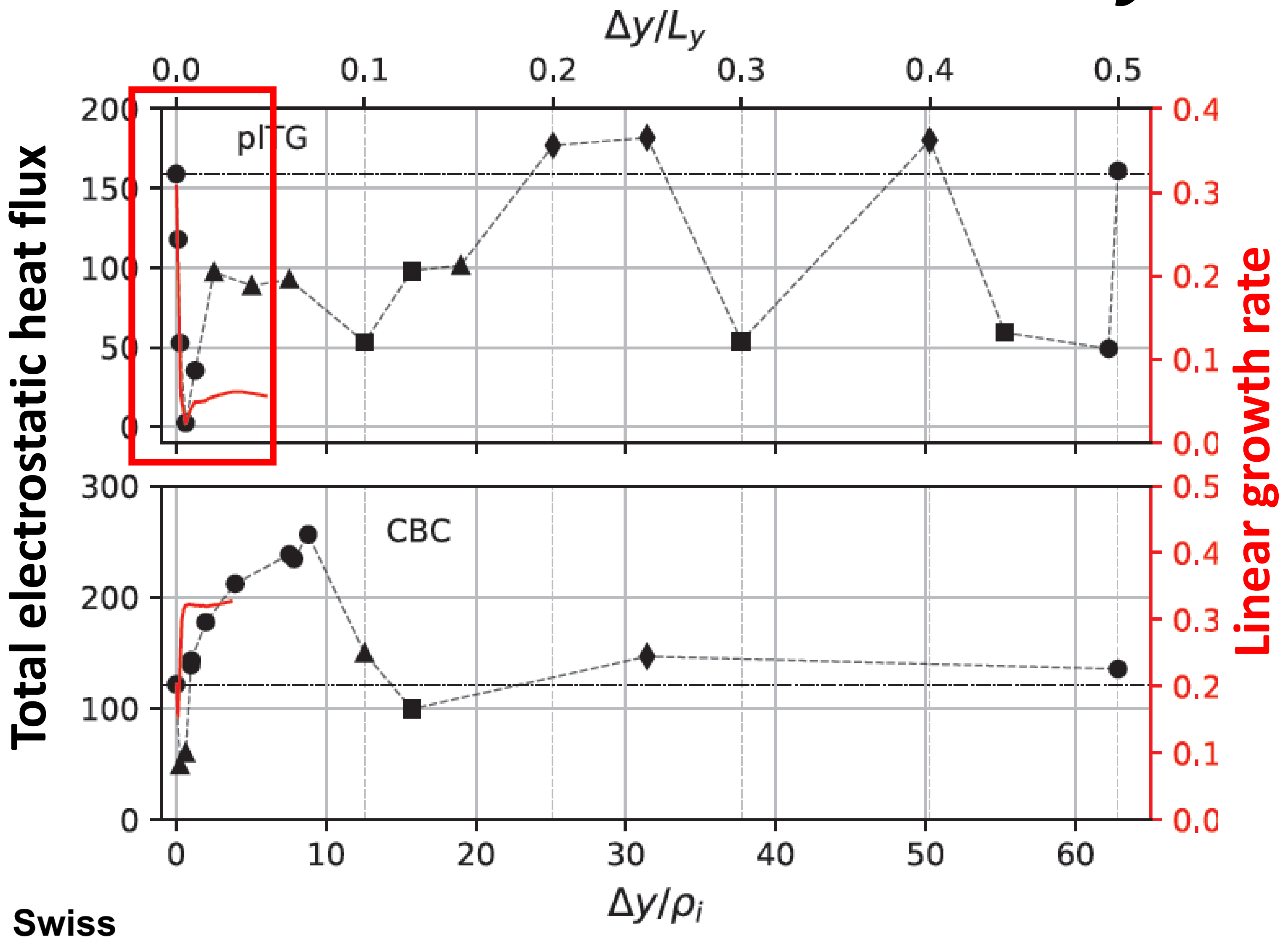

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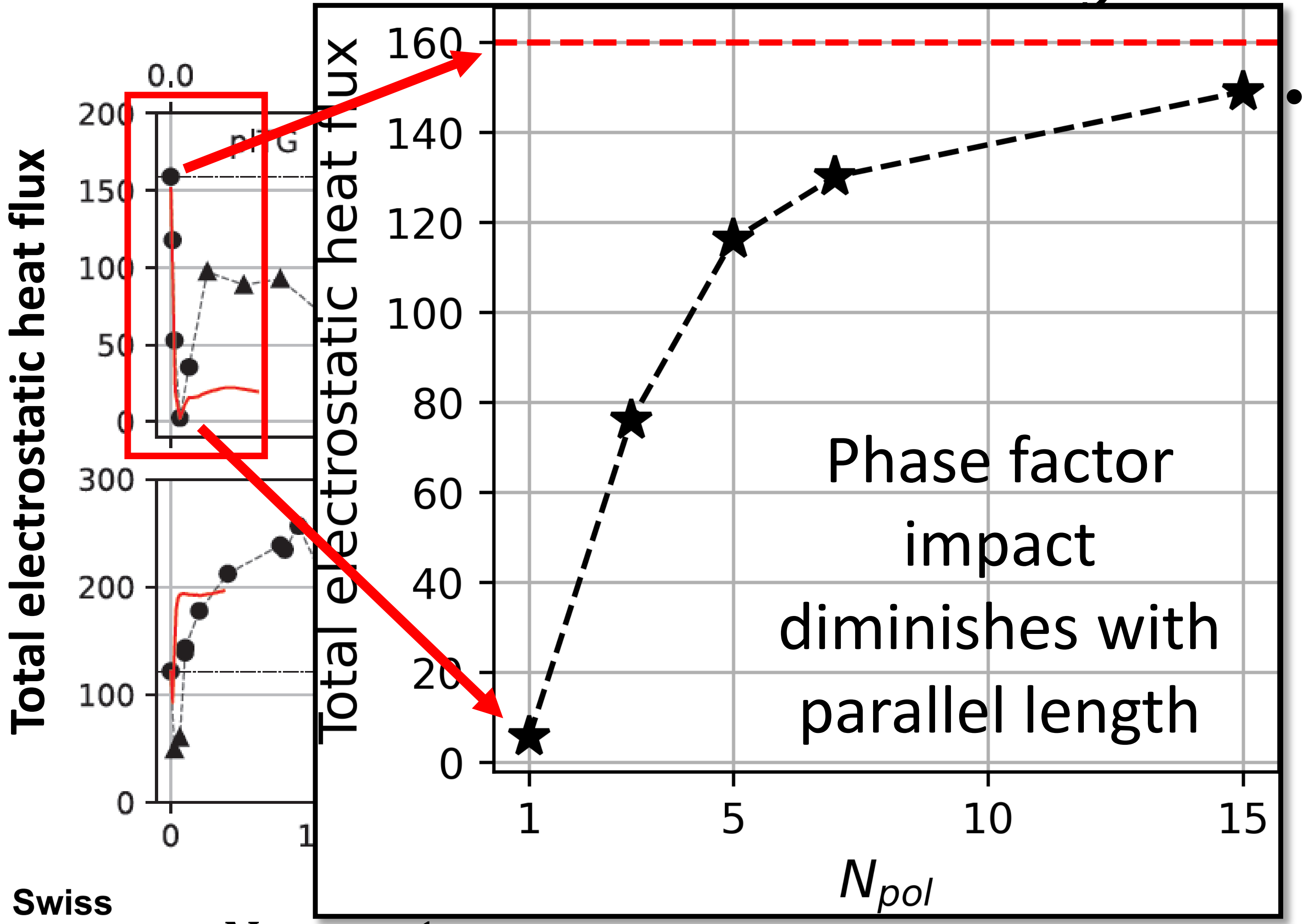
Binormal shift $\Delta\, y$ when $\hat{s} = 0$



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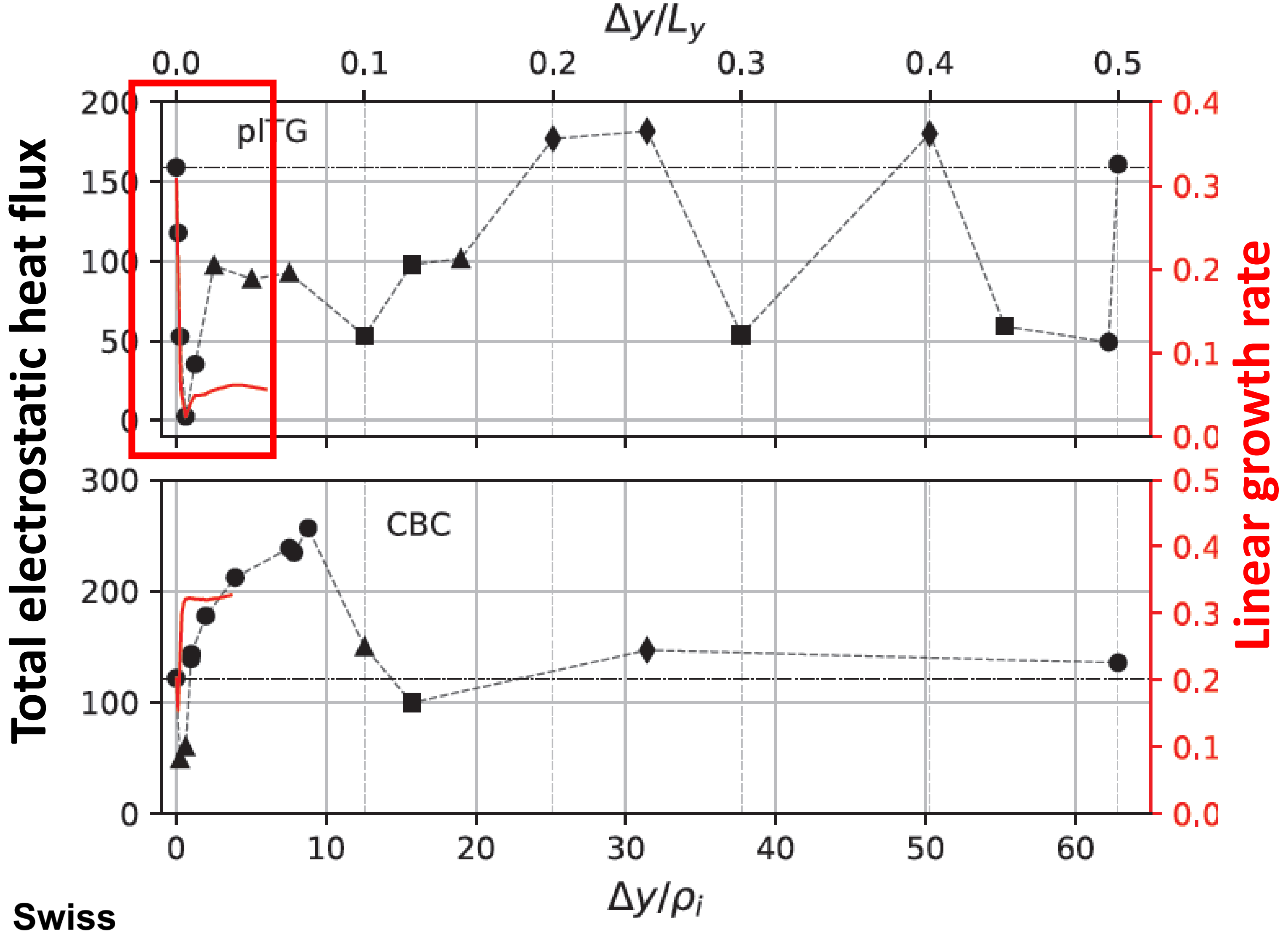

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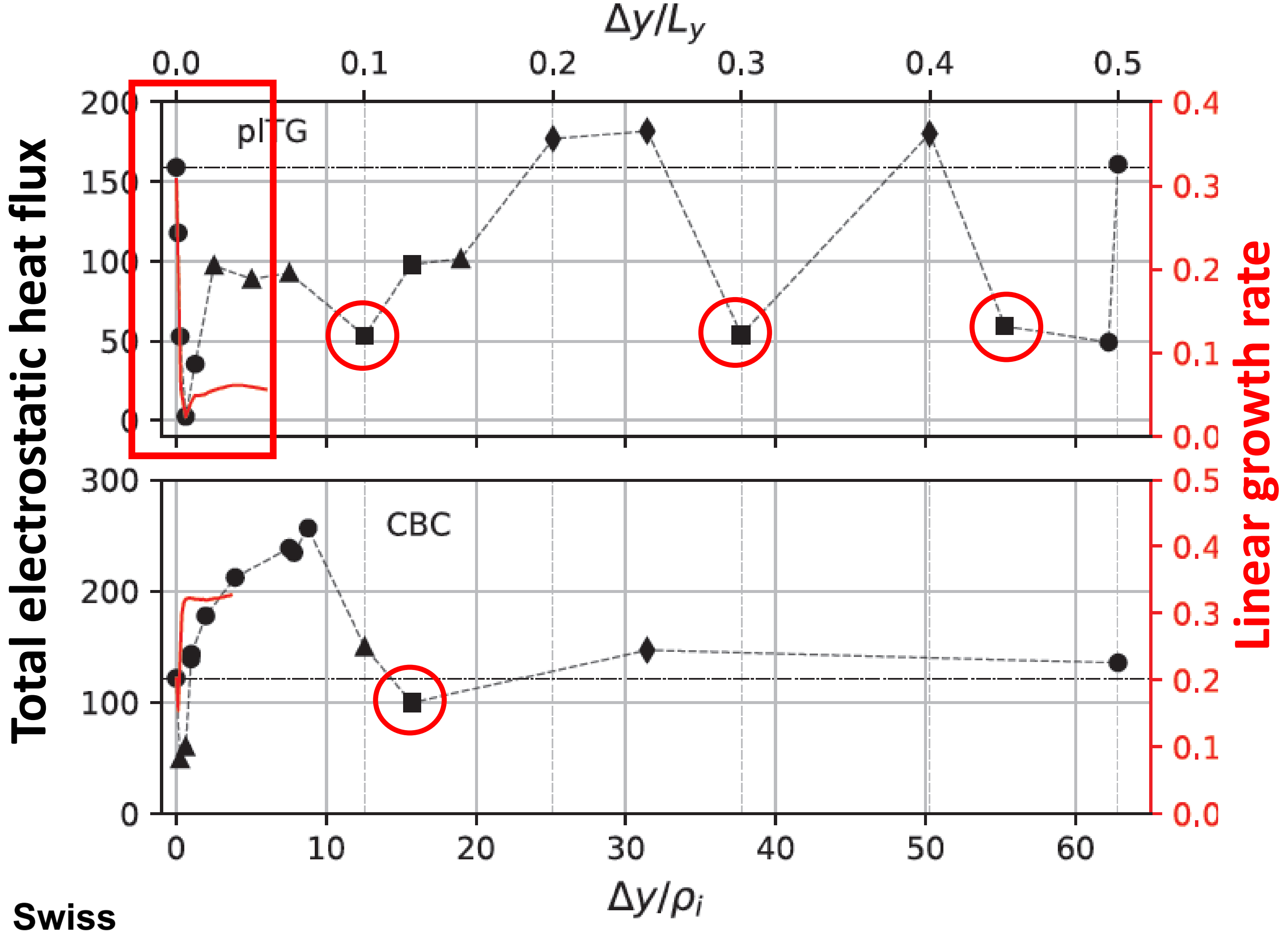

- Turbulence can be strongly affected by the magnetic field topology, leading **to complete stabilization** in some cases.
- A single eddy can cover an entire flux surface leading to reduced flux

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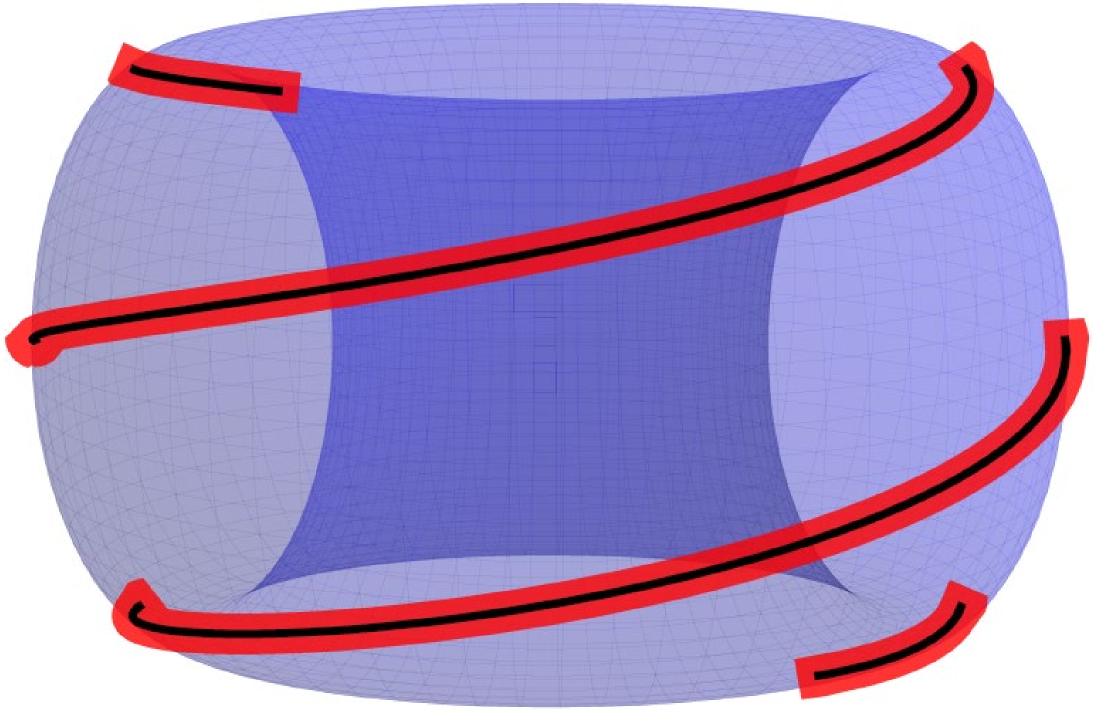
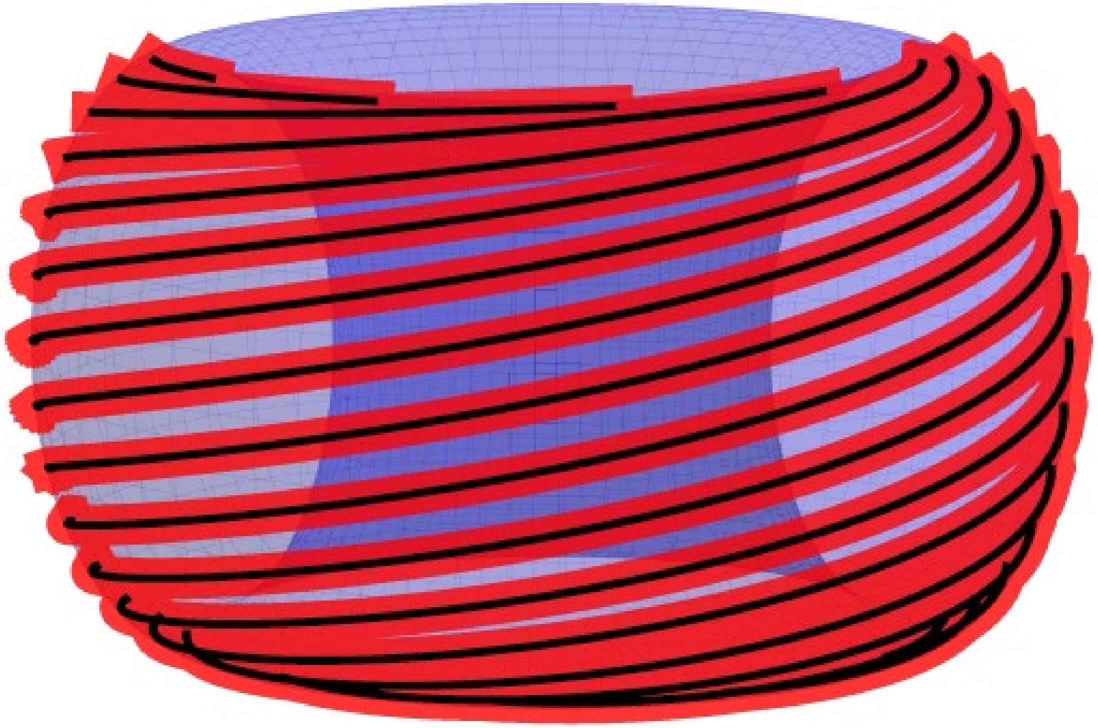
“Eddy squeezing”

Perpendicular self-interaction



q=2.5

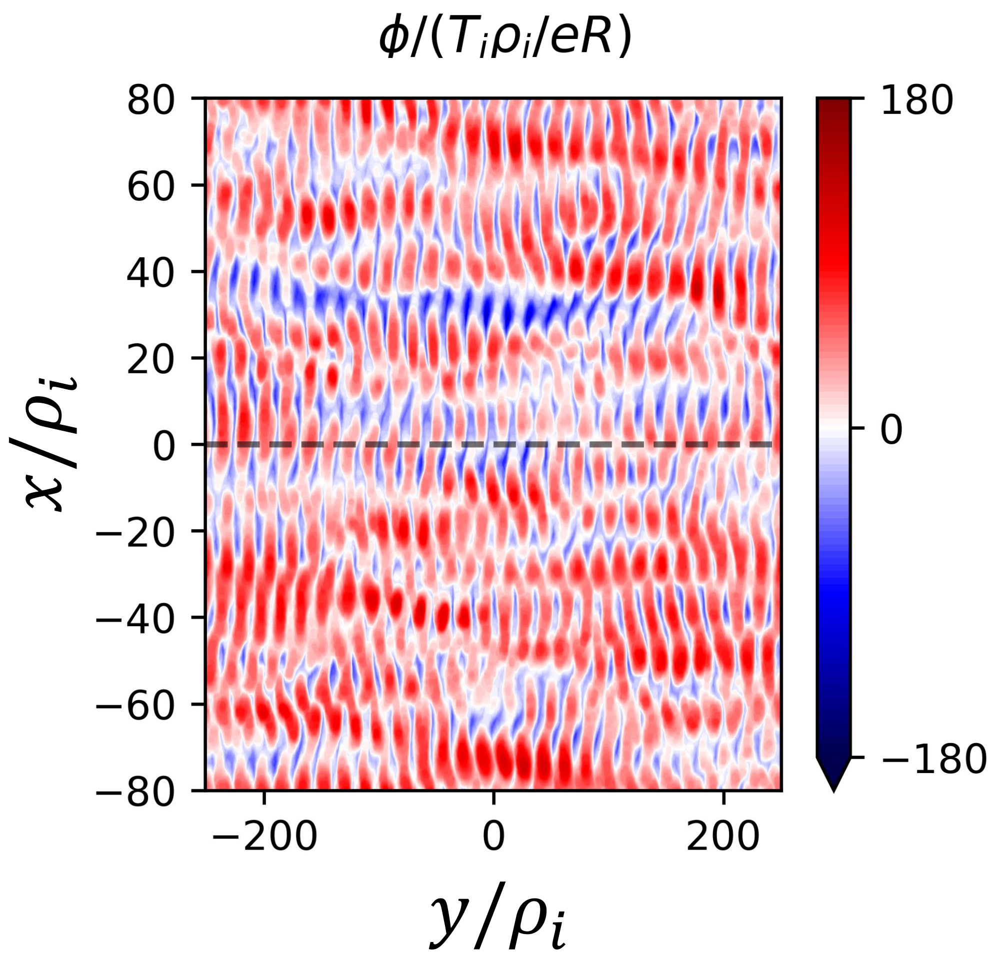


q=2.7

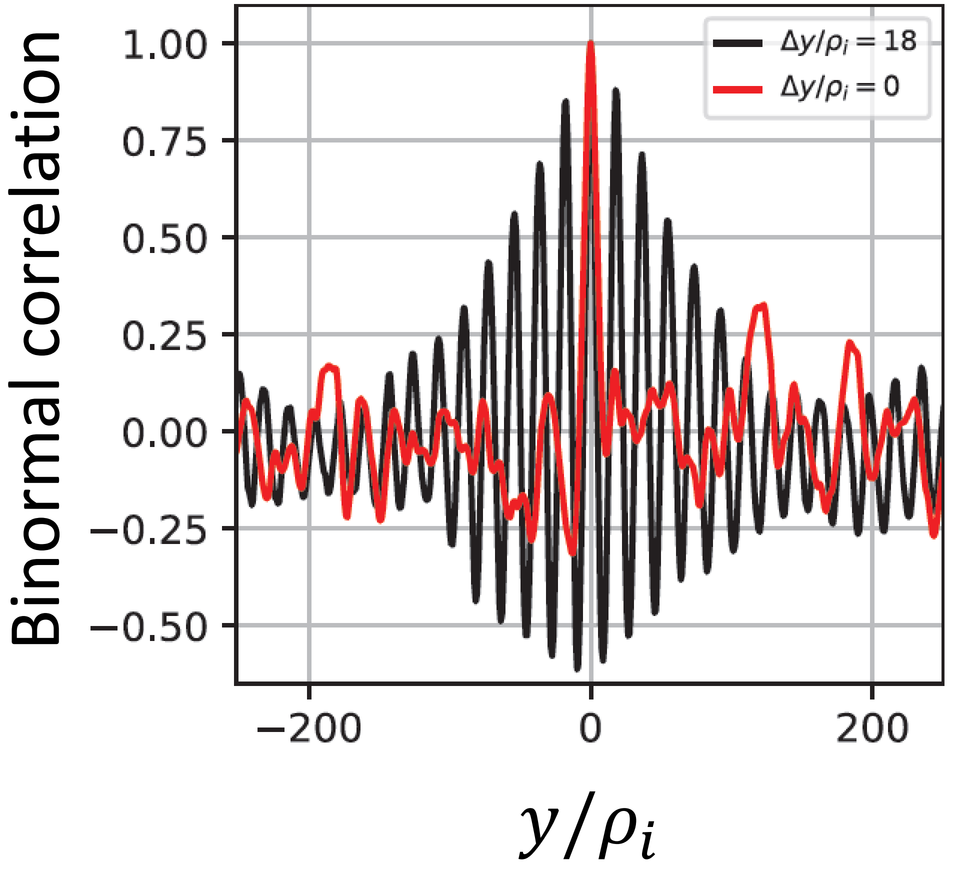
$\hat{s} = 0$

Potential and binormal correlation

- Increased electron mass
- $k_{y,min}\rho_i = 0.0125$
- **Two-fold change in the heat flux**



$@t = 200\ R/c_i$



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Summary: Binormal shift study $\hat{s} = 0$

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- Allows to study self-interaction at irrational q values and **in particular close to rational-q**
- Small changes in q can have a large impact on the fluxes
- Different behaviour depending on the turbulence drive
- Provides experimentally testable predictions regarding turbulence self-organization in tokamak core

EPFL Outline

- Motivation and background
- Methods
- Numerical results:
  - Low magnetic shear simulations
  - Ultra-long turbulent eddies $\hat{s} = 0$
  - **Non-uniform magnetic shear simulations** 
- Conclusions

Non-uniform magnetic shear formalism

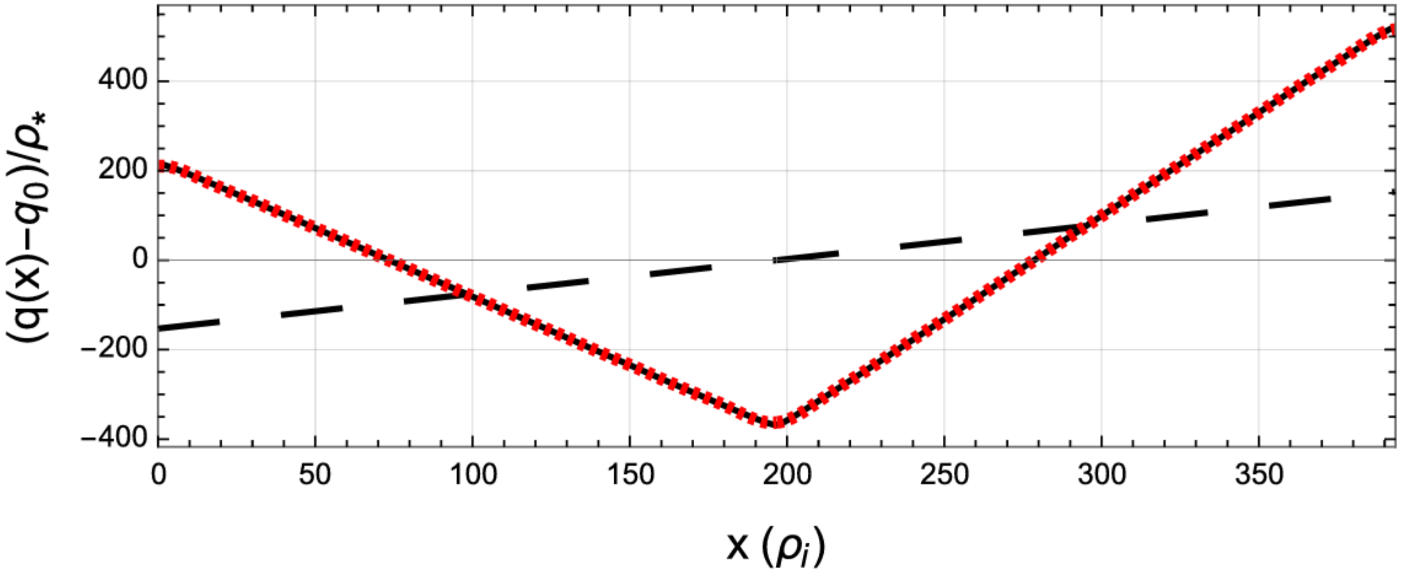
Key idea:

Create a safety factor profile that varies on the gyroradius-scale, which is rigorously derived from a current drive source inspired by ECCD

$$\tilde{q}(r) = \sum_{n=1}^{\infty} \left[\tilde{q}_n^C \cos\left(\frac{2\pi n}{L_r}(r - r_0) \right) + \tilde{q}_n^S \sin\left(\frac{2\pi n}{L_r}(r - r_0) \right) \right] .$$

(2

- The simulations are no longer “local” but still performed in a flux tube domain



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- J. Ball and S. Brunner 2023 *Plasma Phys. Control. Fusion* **65** 014004

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Goals

- Increase realism
- Investigate electromagnetic effects
- Investigate extremely low magnetic shear
- Include safety factor curvature effects

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Simulate the minimum in the safety factor profile

Full safety factor profile

Safety factor profile

$$\frac{\bar{q} - q_0}{\rho_*} = \frac{r}{q_0}\hat{s}x$$

Linear shear part

Full safety factor profile

Safety factor profile

Non-uniform shear part

$$\frac{\bar{q} - q_0}{\rho_*} = \frac{r}{q_0}\hat{s}x + \tilde{q}(x)$$

Linear shear part

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Non-uniform shear part

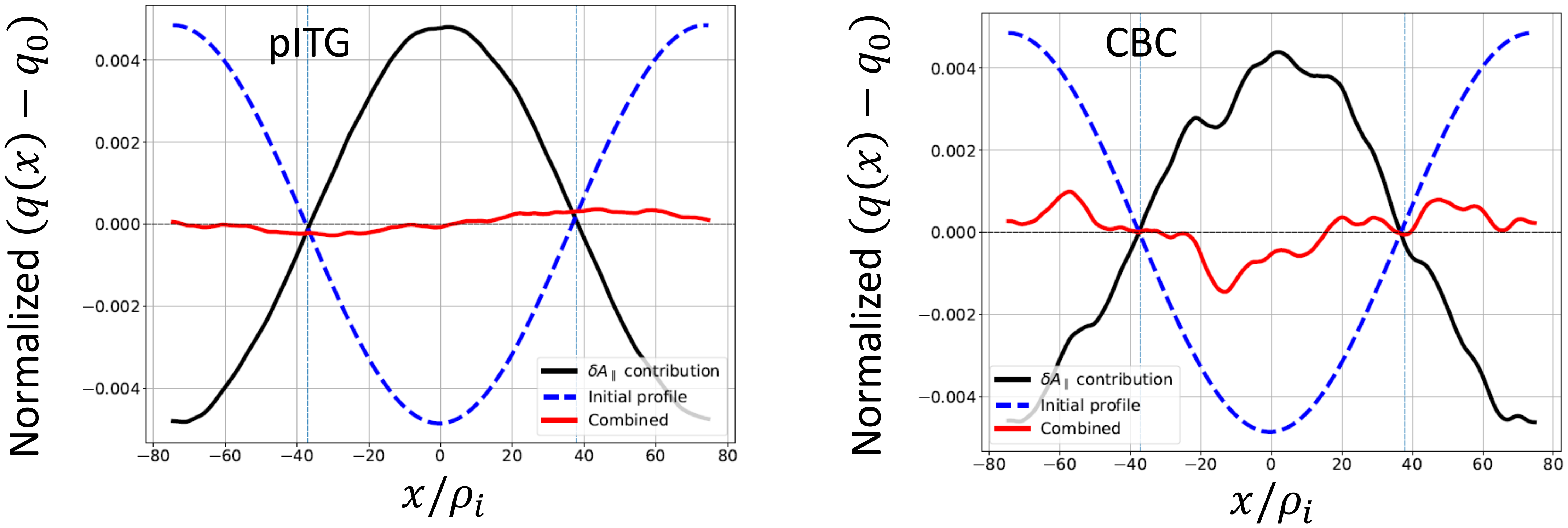
$\delta \boldsymbol{B} = \nabla \times \delta A$

$$\frac{\bar{q} - q_0}{\rho_*} = \frac{r}{q_0}\hat{s}x + \tilde{q}(x) + \boxed{\tilde{q}_{\delta A_{\parallel}}(x)}$$

Linear shear part

Correction due to zonal part of the magnetic potential

Full flattening of q profile



- $\beta = 0.001$
- $\hat{s}_S^1 = -0.004$

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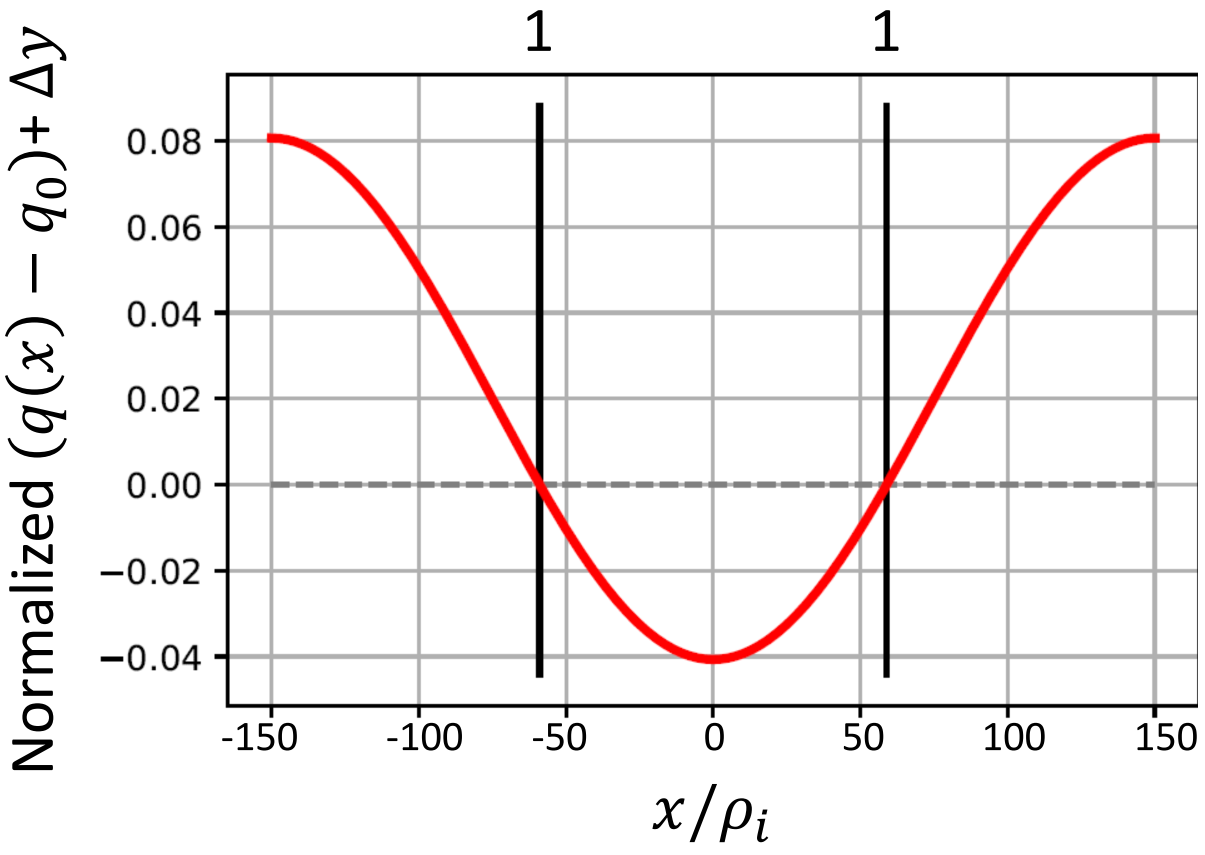
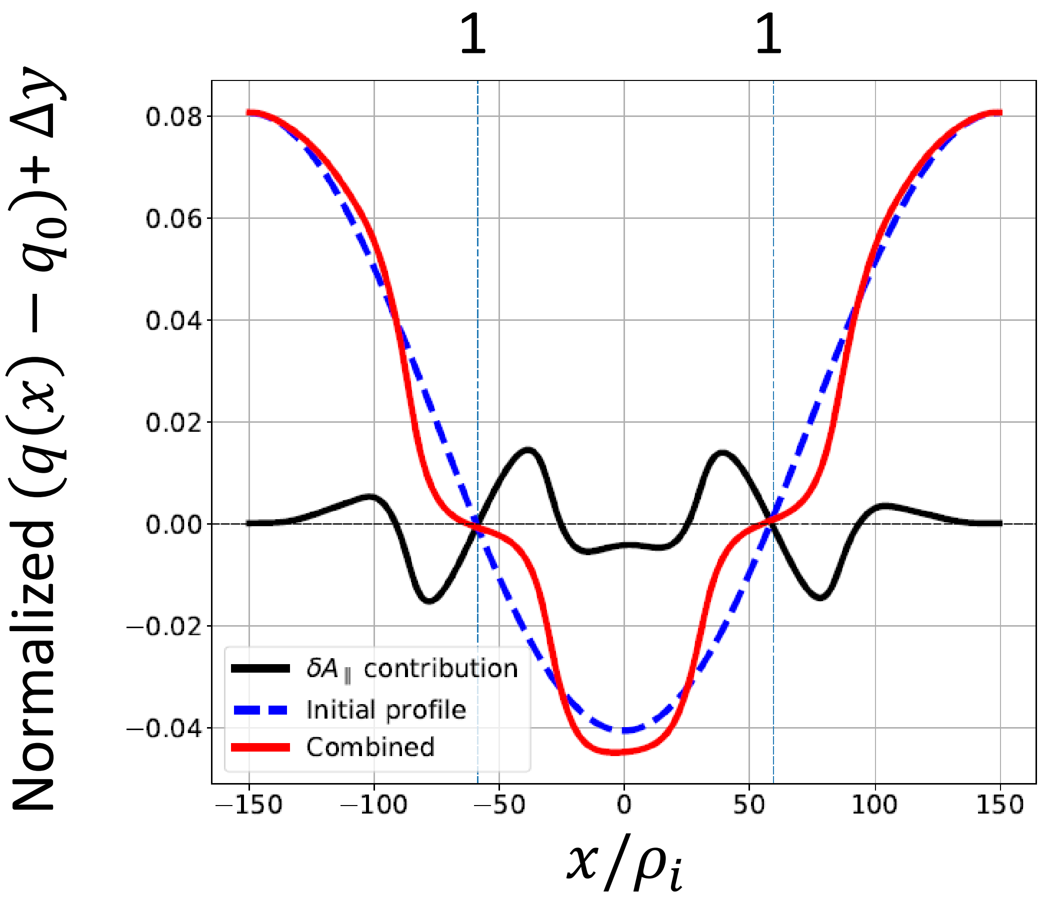
Two integer surfaces





- $\beta = 0.0001$
- $\hat{s}_S^1 = -0.025$

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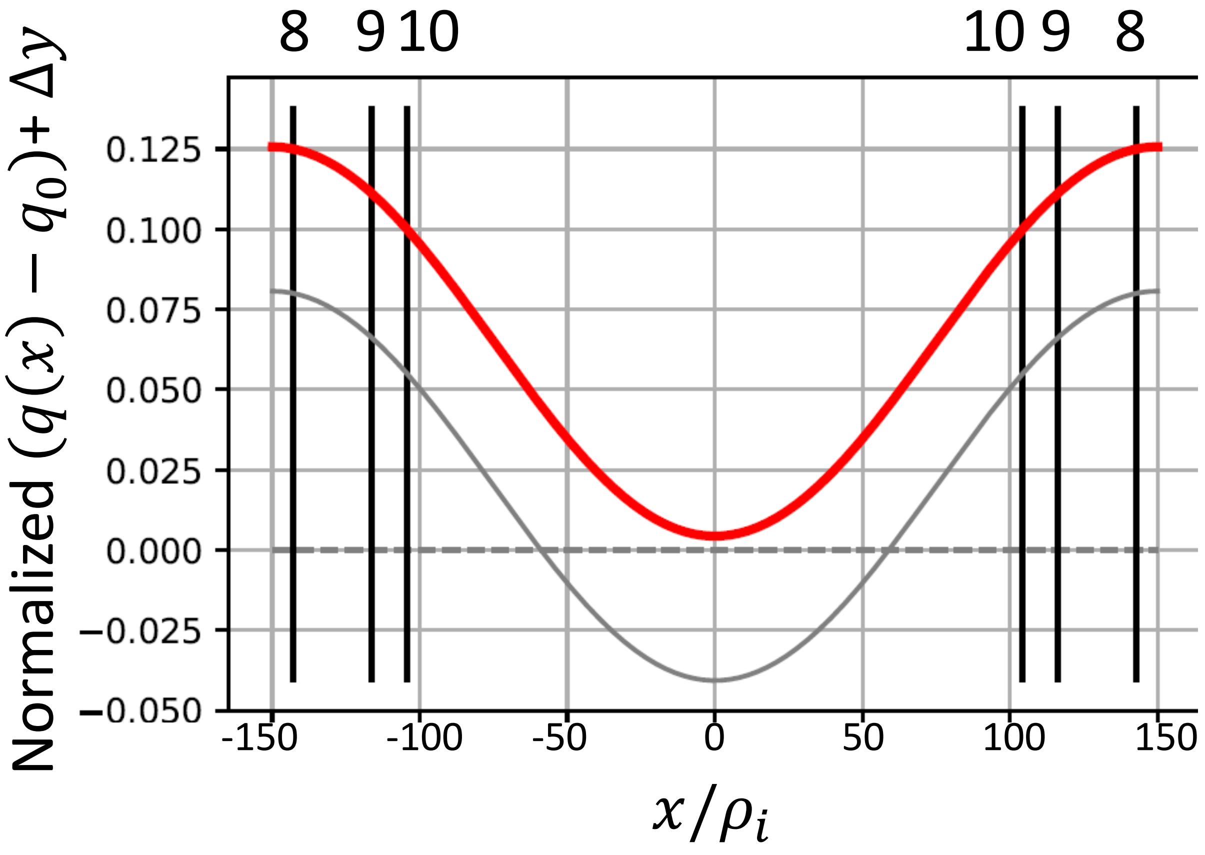
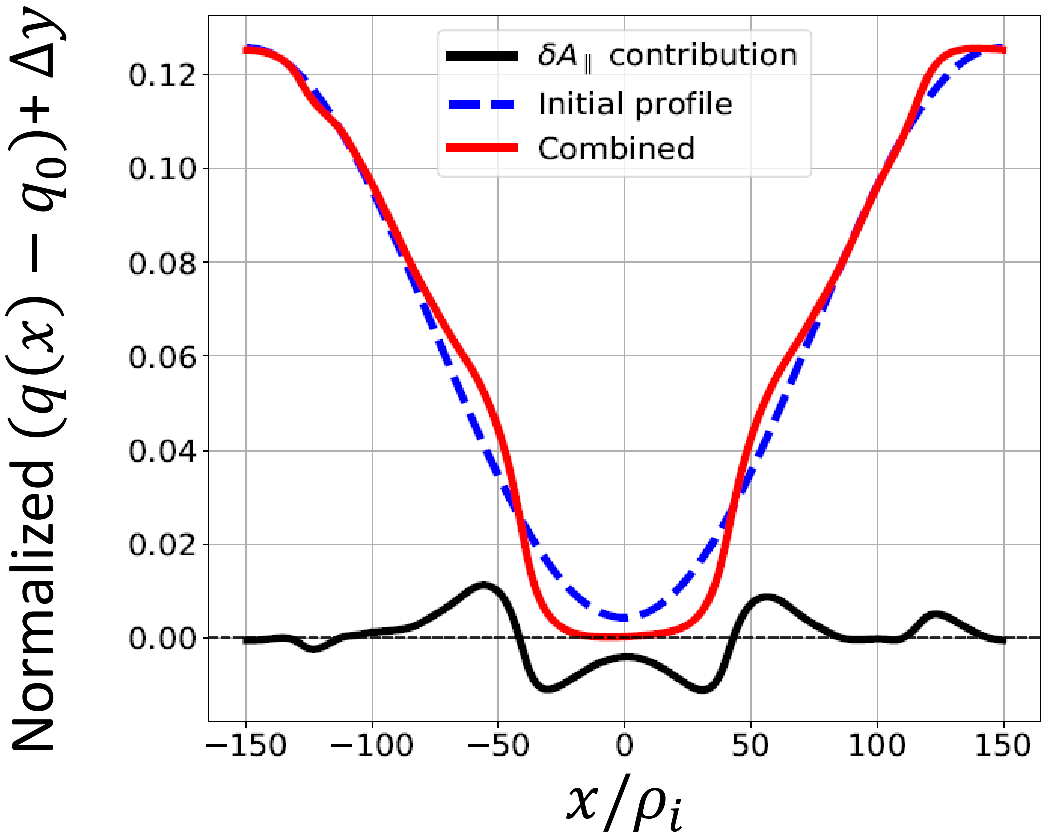
Close to an integer surface





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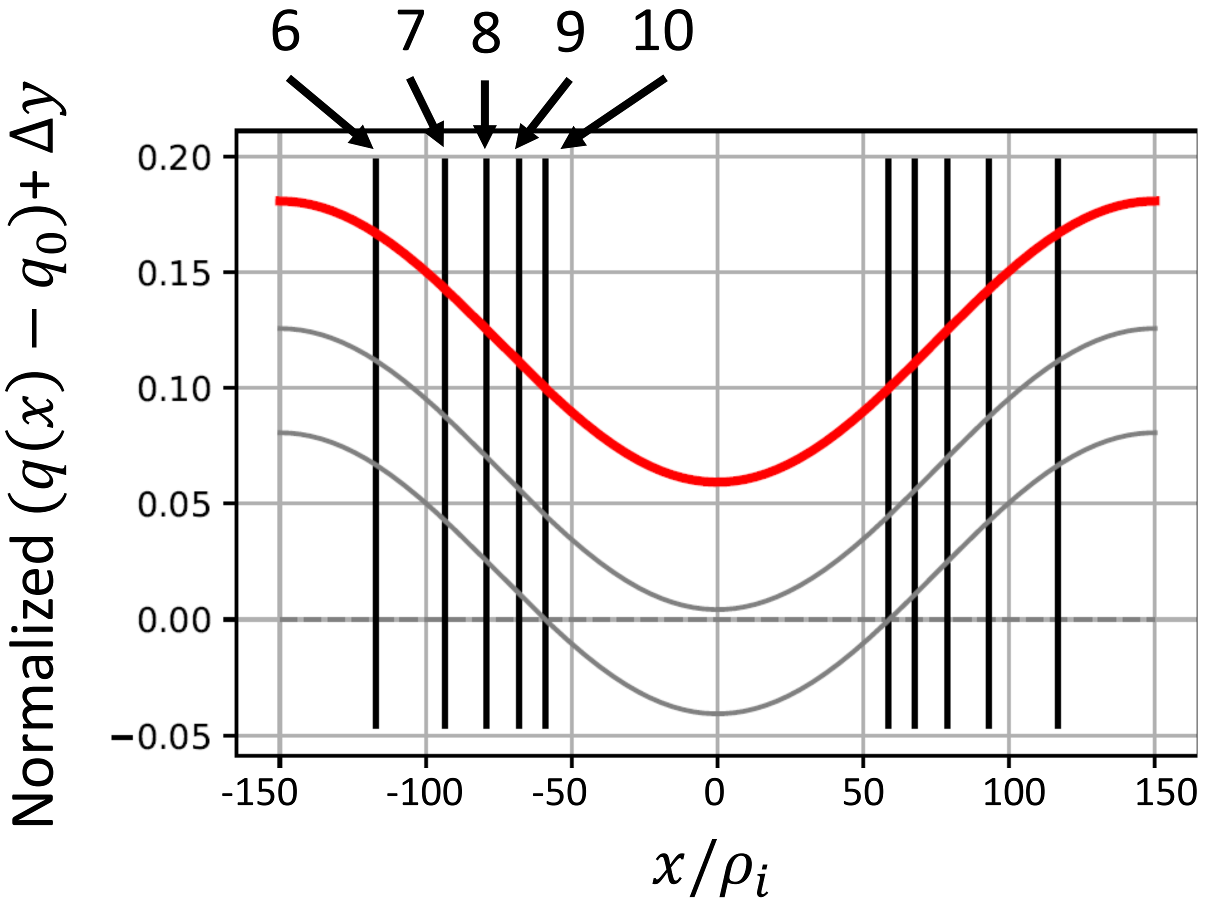
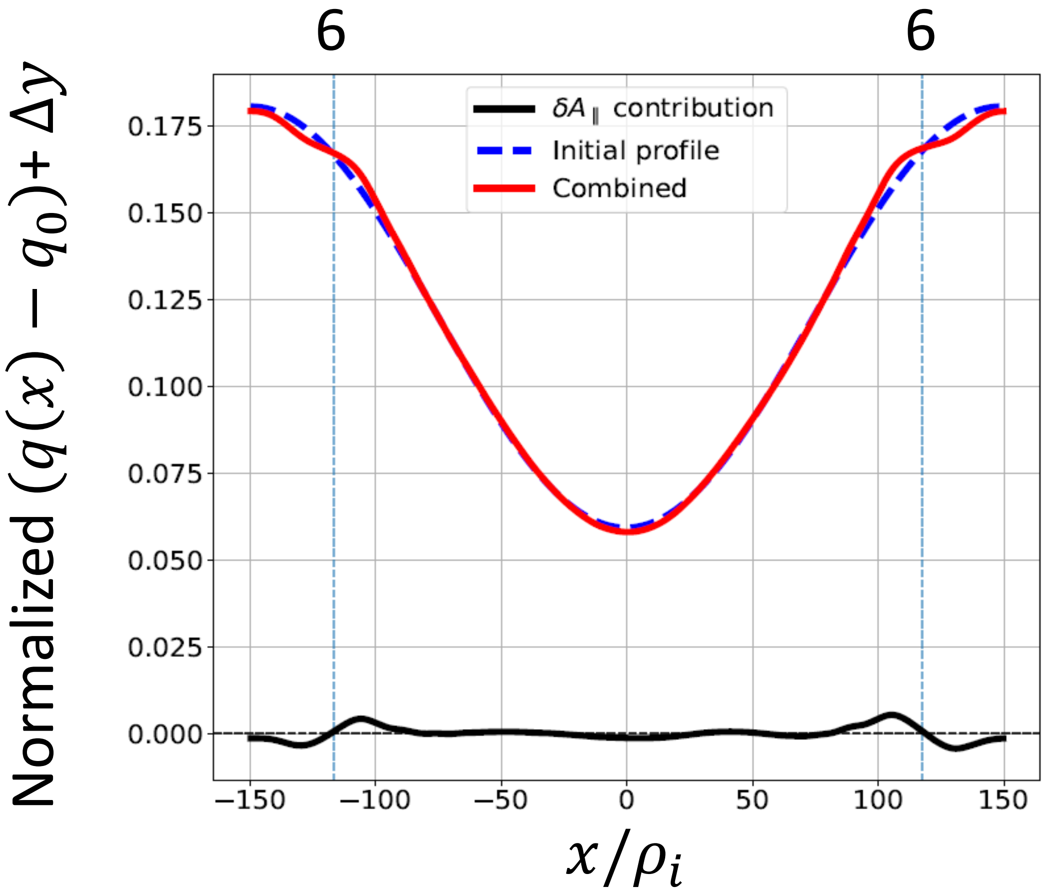
EPFL Away from an integer surface





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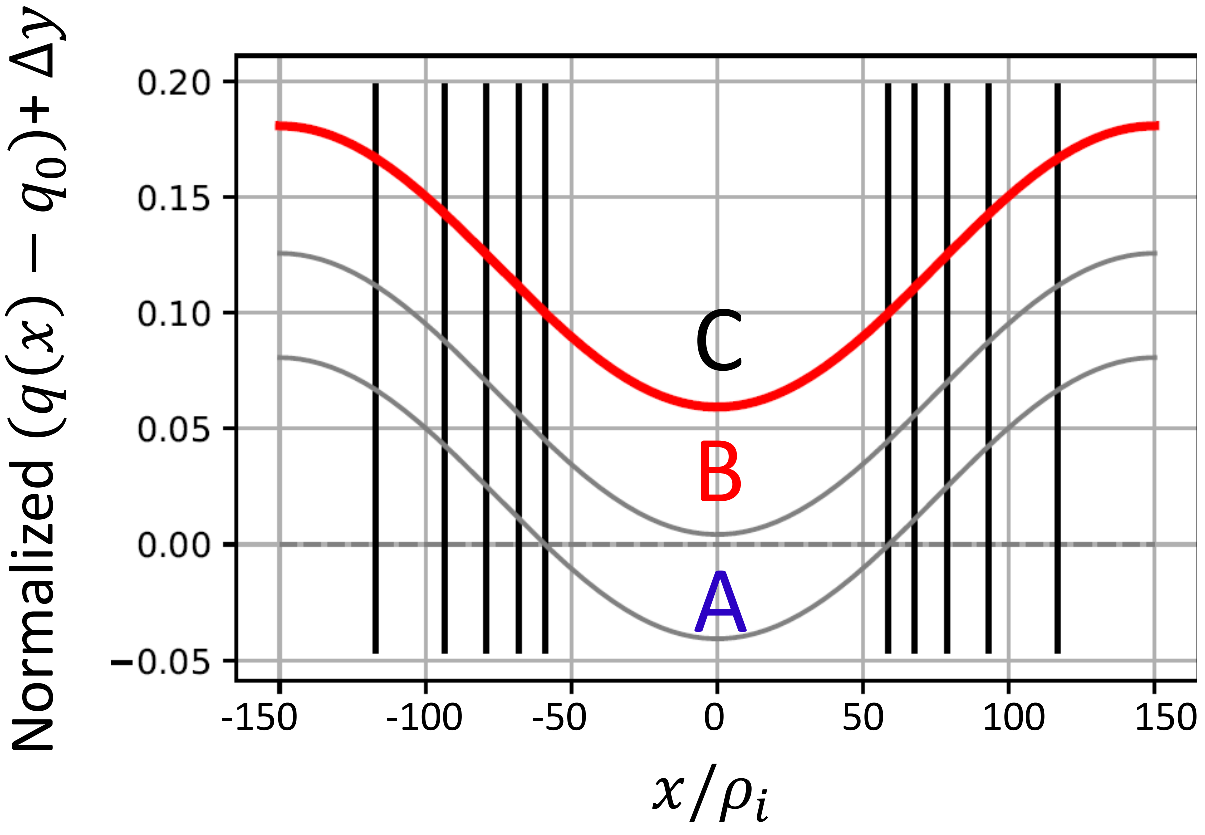
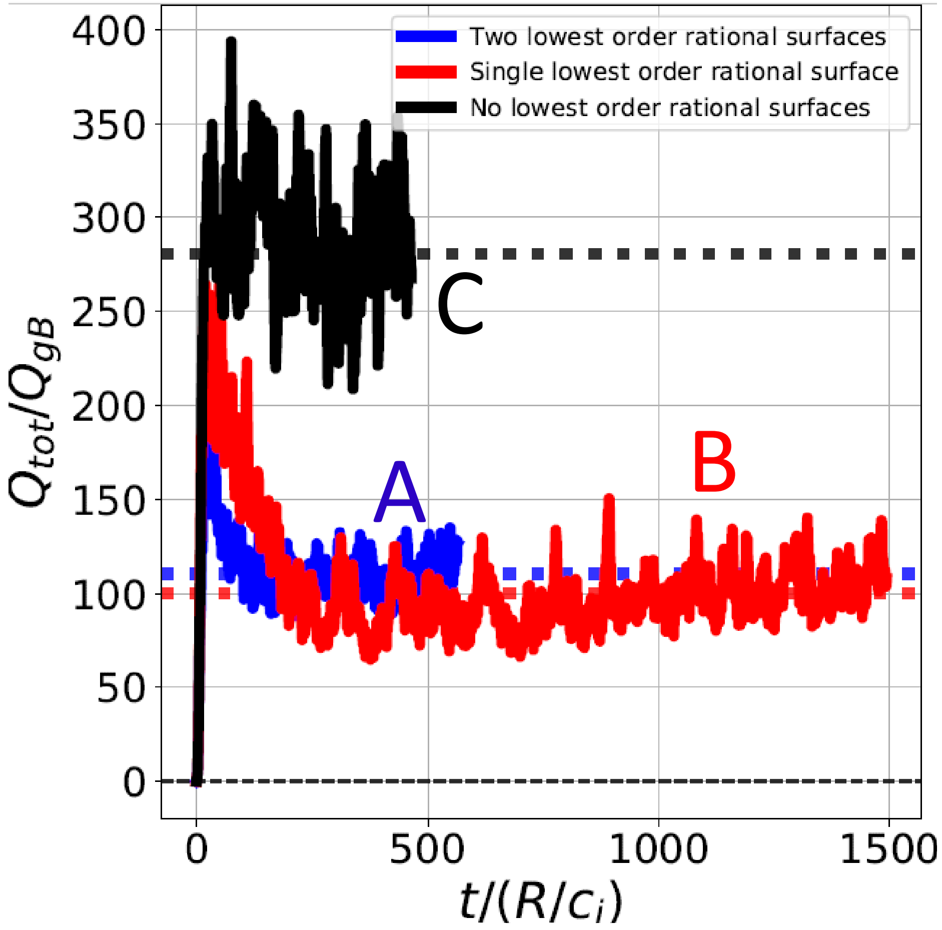
q profile impact on heat flux





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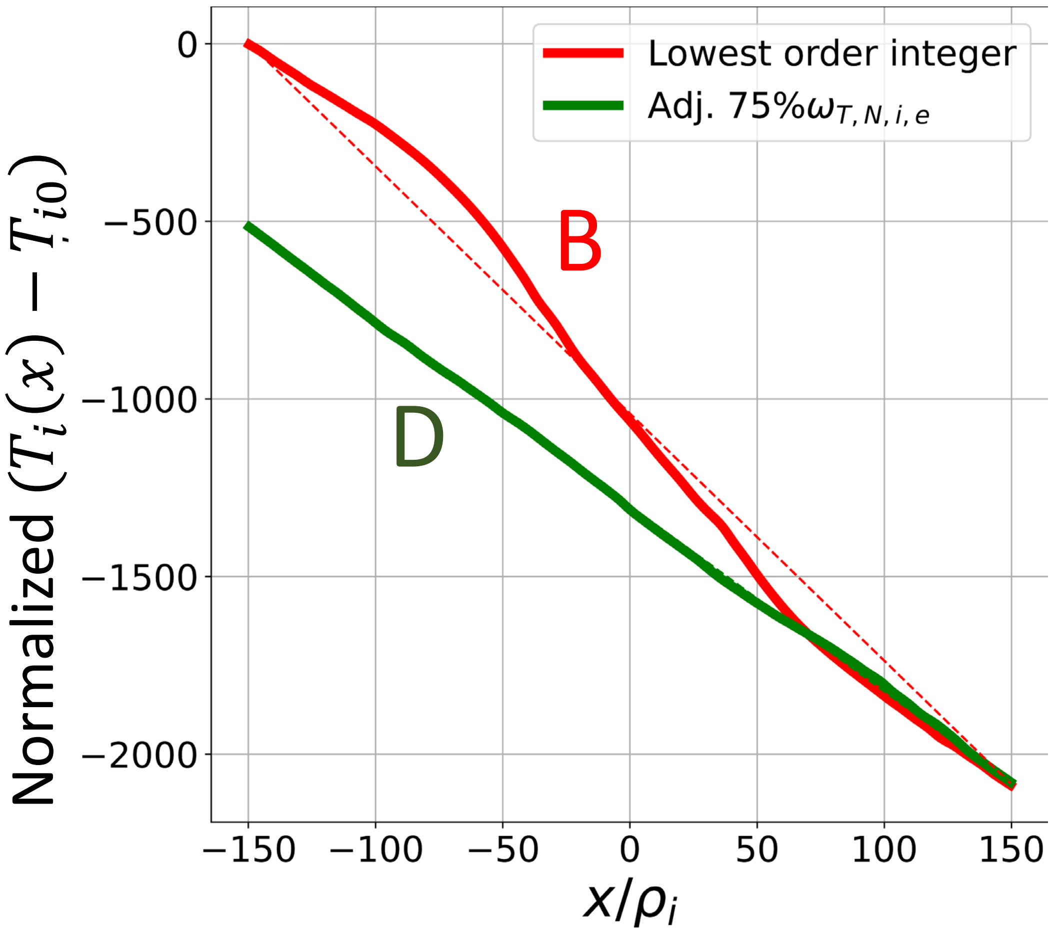
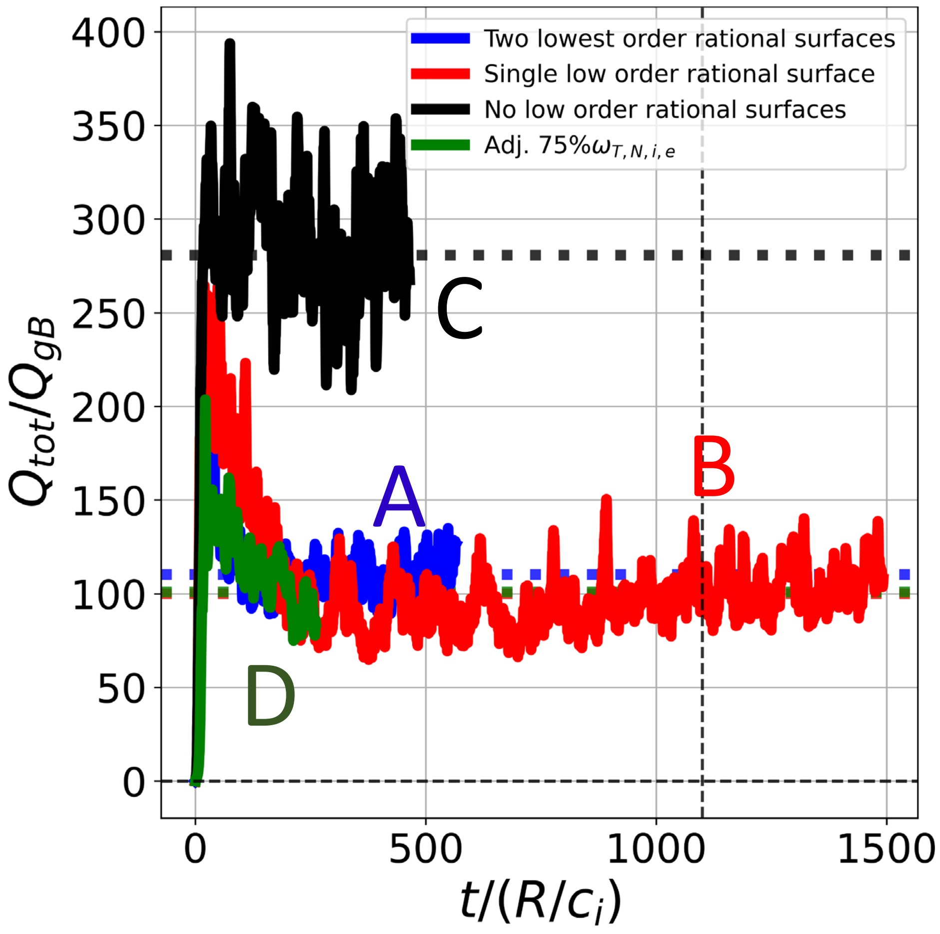
Profile steepening





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Thank you for your attention!