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Ultra Long Turbulent Eddies, Magnetic Topology, and the Triggering of Internal Transport Barriers in Tokamaks

TSVV1 Workshop 2022

Arnas Volčokas, Justin Ball, Stephan Brunner

27/09/2022

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https://arxiv.org/abs/2208.06159

Outline

- Motivation and background
- Methods
- Ultra-long turbulent eddies
- Binormal shift at the parallel boundary
- Low magnetic shear simulations
- TSVV1 deliverables
- Conclusions

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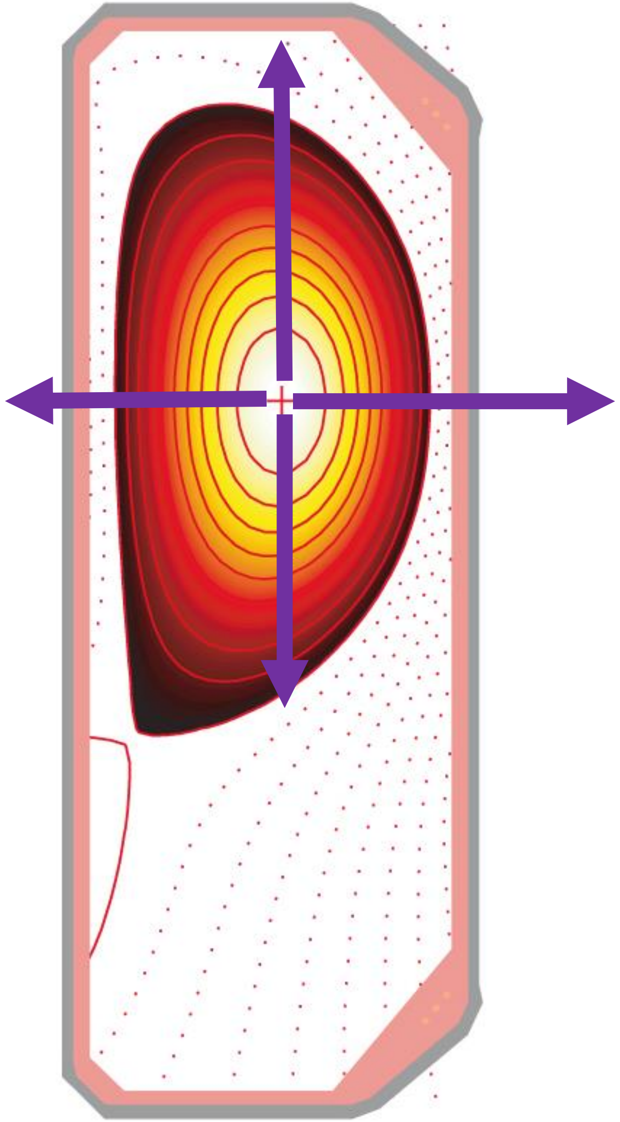
Turbulence transport problem

- Transport is dominated by turbulent transport
- Reducing cross-field energy/particle transport is critical in achieving fusion
- One way to reduce turbulent transport is with **internal transport barriers (ITBs)**



- X. Garbet et al. 2010 Nucl. Fusion 50 043002
- M. Kikuchi, M. Azumi. Frontiers in Fusion Research II. 2015

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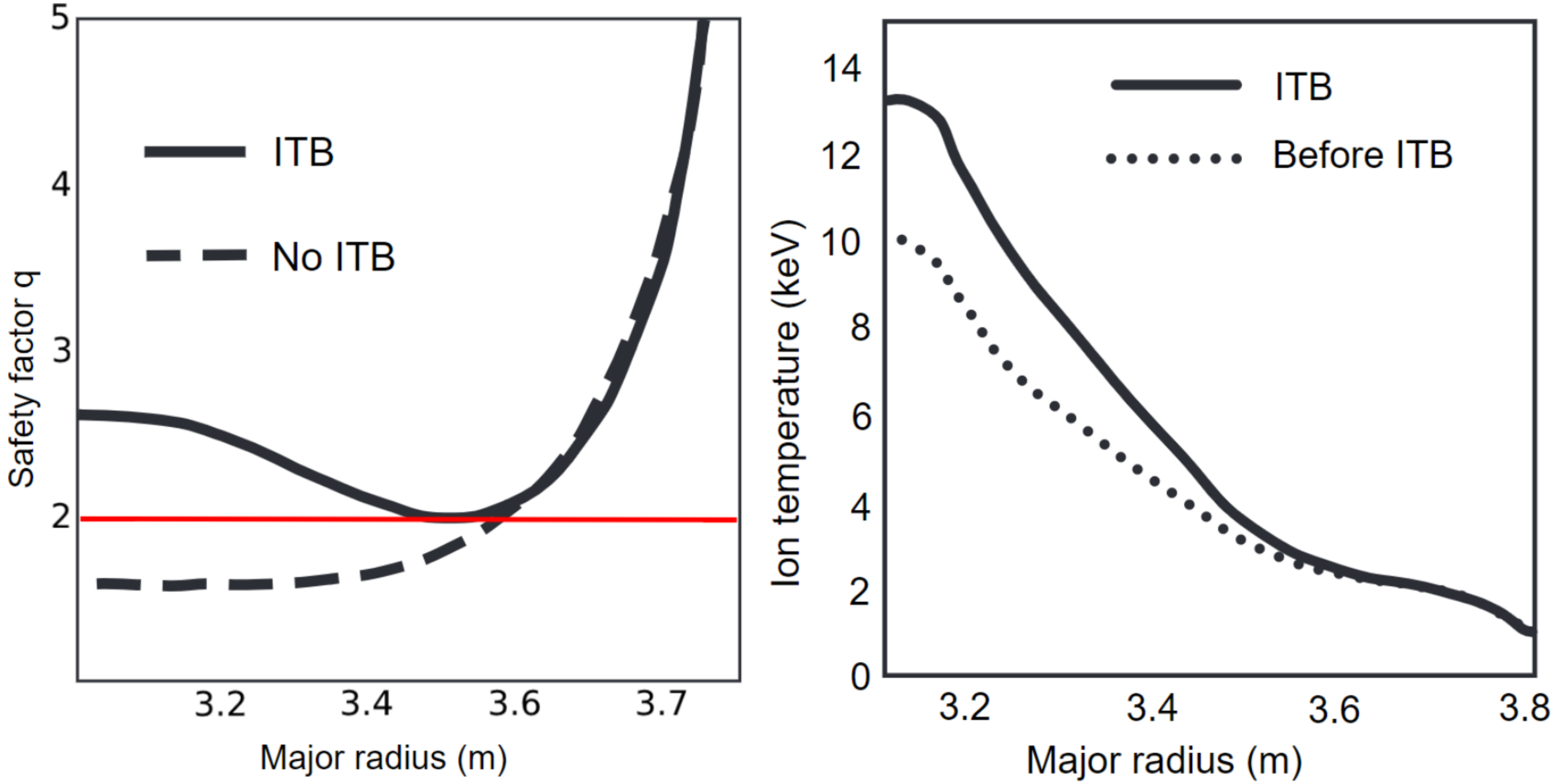
ITBs from at minimum q

ITBs are formed when:

- A power threshold is exceeded
- Low magnetic shear $\hat{s} \approx 0$ is present
- Facilitated by integer or low order rational $q =$ M/N with $\hat{s} \approx 0$



- L.-G. Eriksson et al., Phys. Rev. Lett. 88, 145001 (2002)
- K Ida and T Fujita 2018 Plasma Phys. Control. Fusion 60 033001

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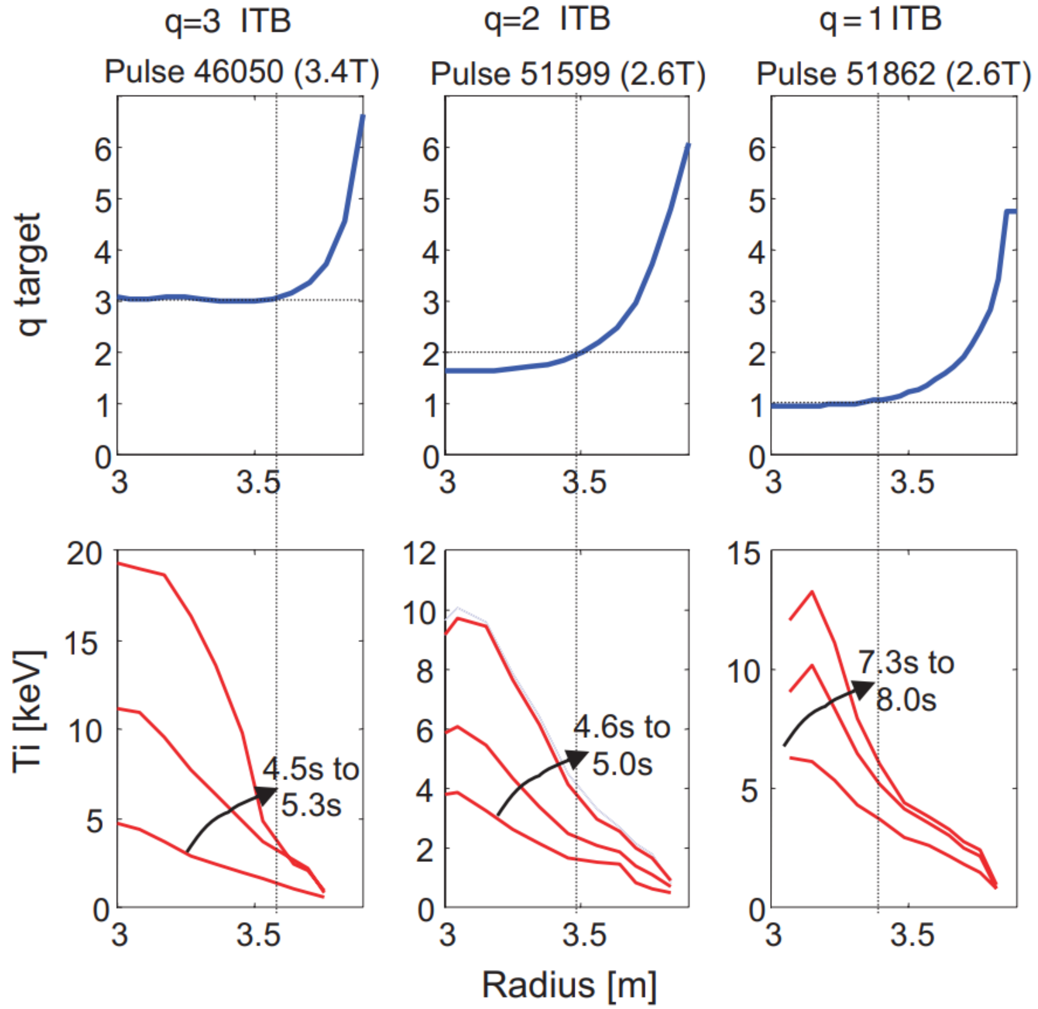
Example of strong ITBs at JET

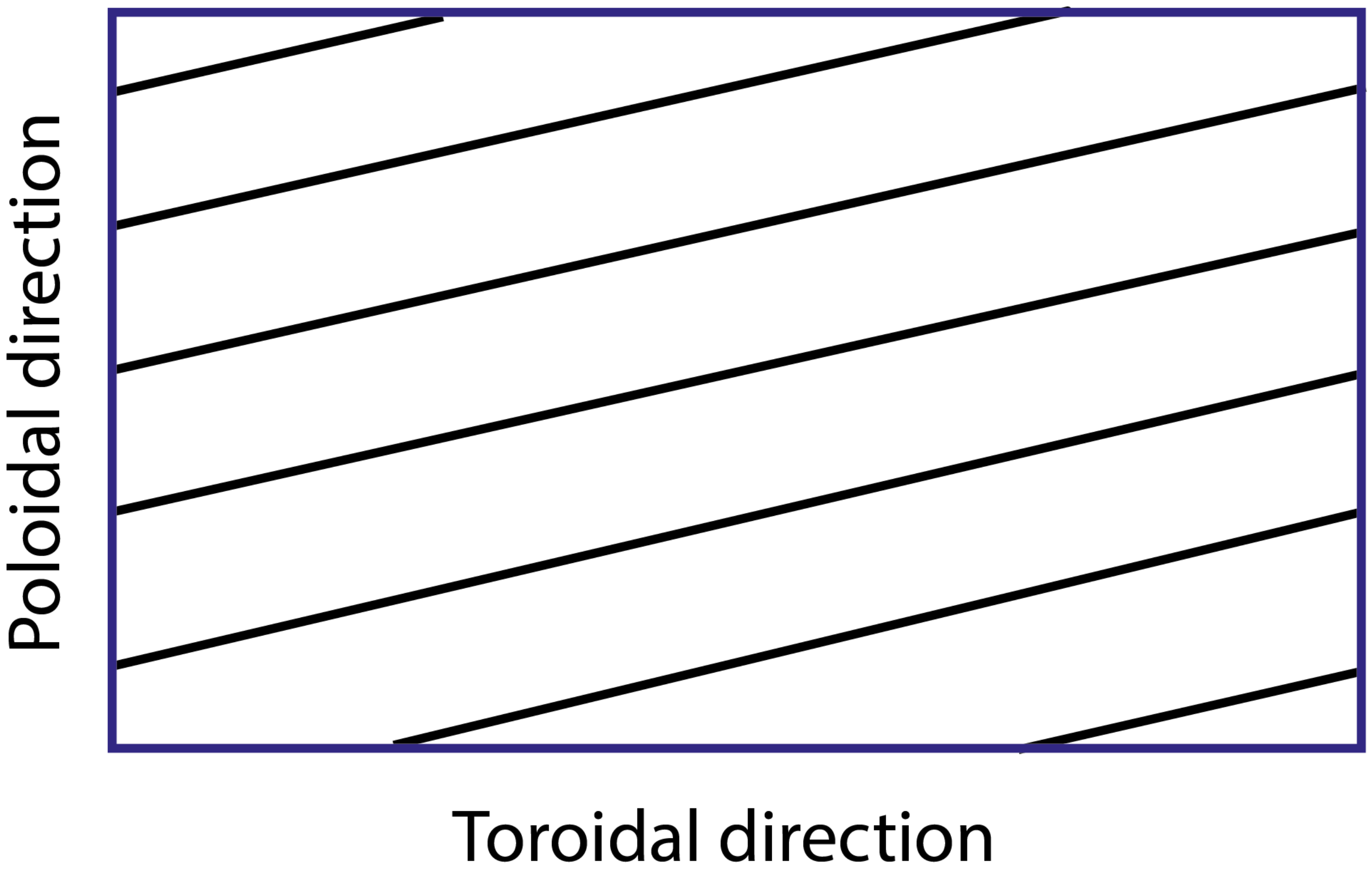


- E Joffrin et al 2002 Plasma Phys. Control. Fusion 44 1739

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

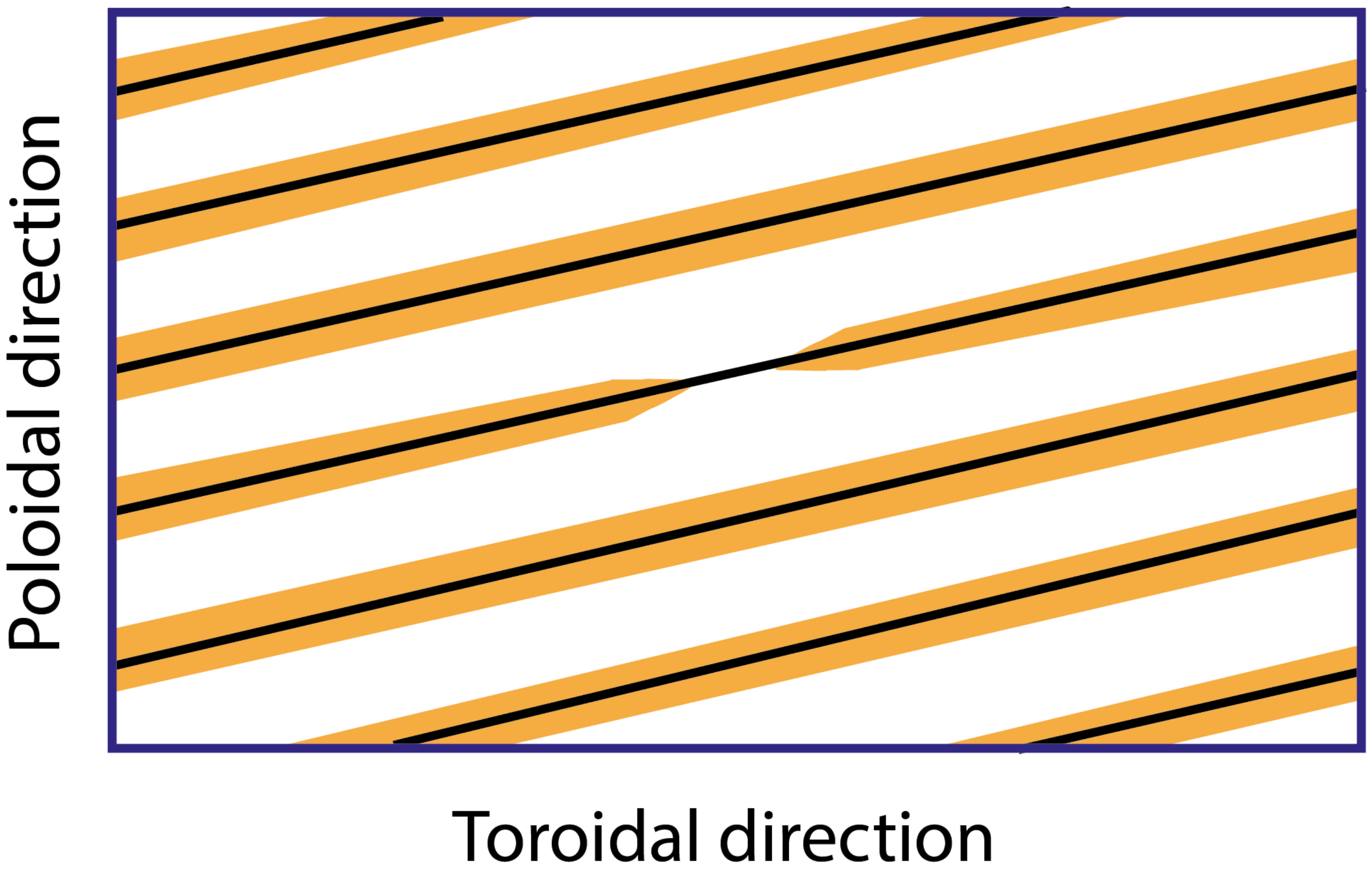
- J. Ball *et al.* 2020 *Journal of Plasma Physics* **86(2)**, 905860207
- Ajay CJ, Studying the effect of non-adiabatic passing electron dynamics on microturbulence self-interaction in fusion plasmas using gyrokinetic simulations, Thesis EPFL Lausanne, 2020
- J. Dominski *et al.* 2015 *Physics of Plasmas* **22**, 062303

No self-interaction



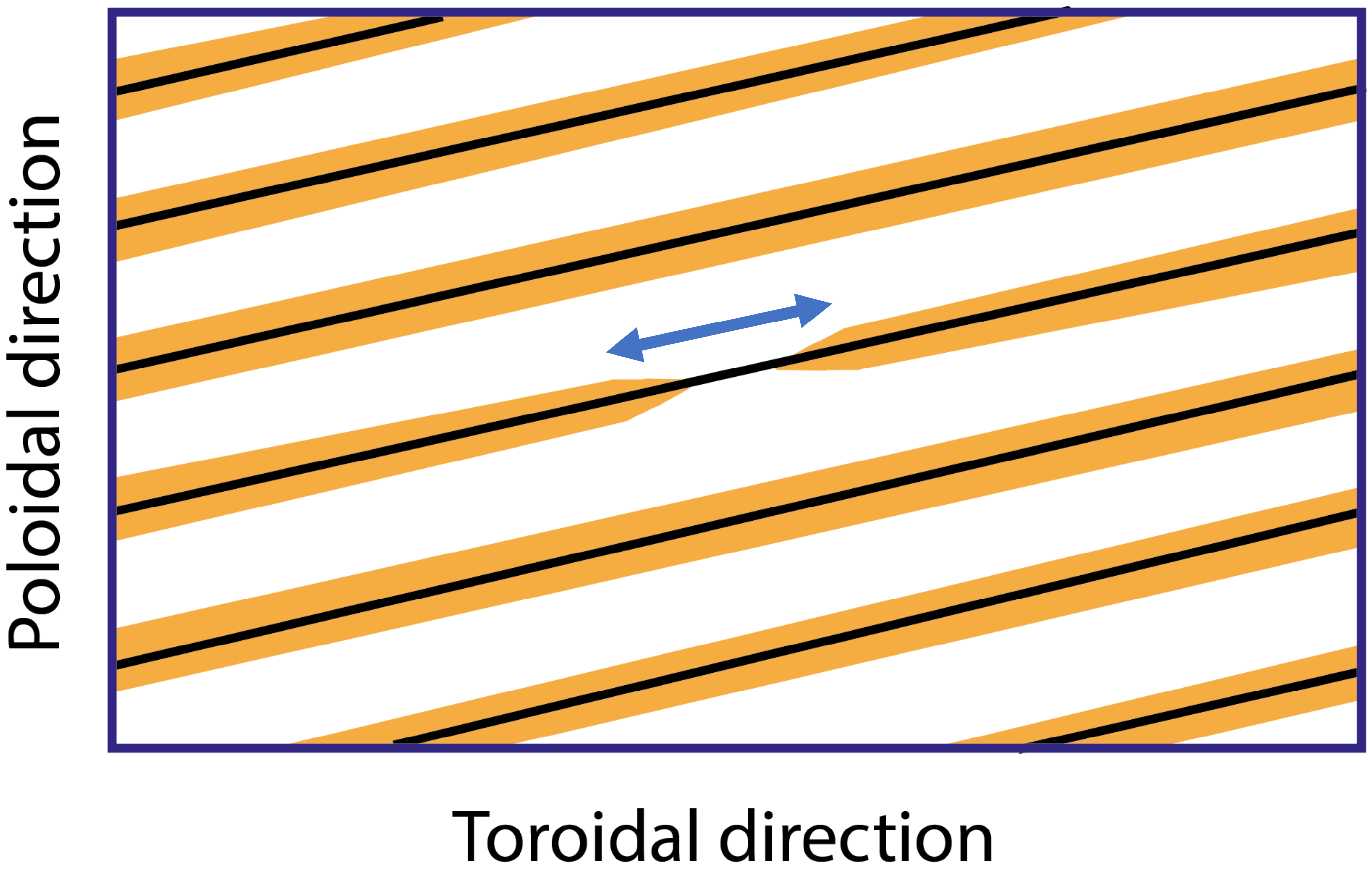
$q = 2.5$

No self-interaction



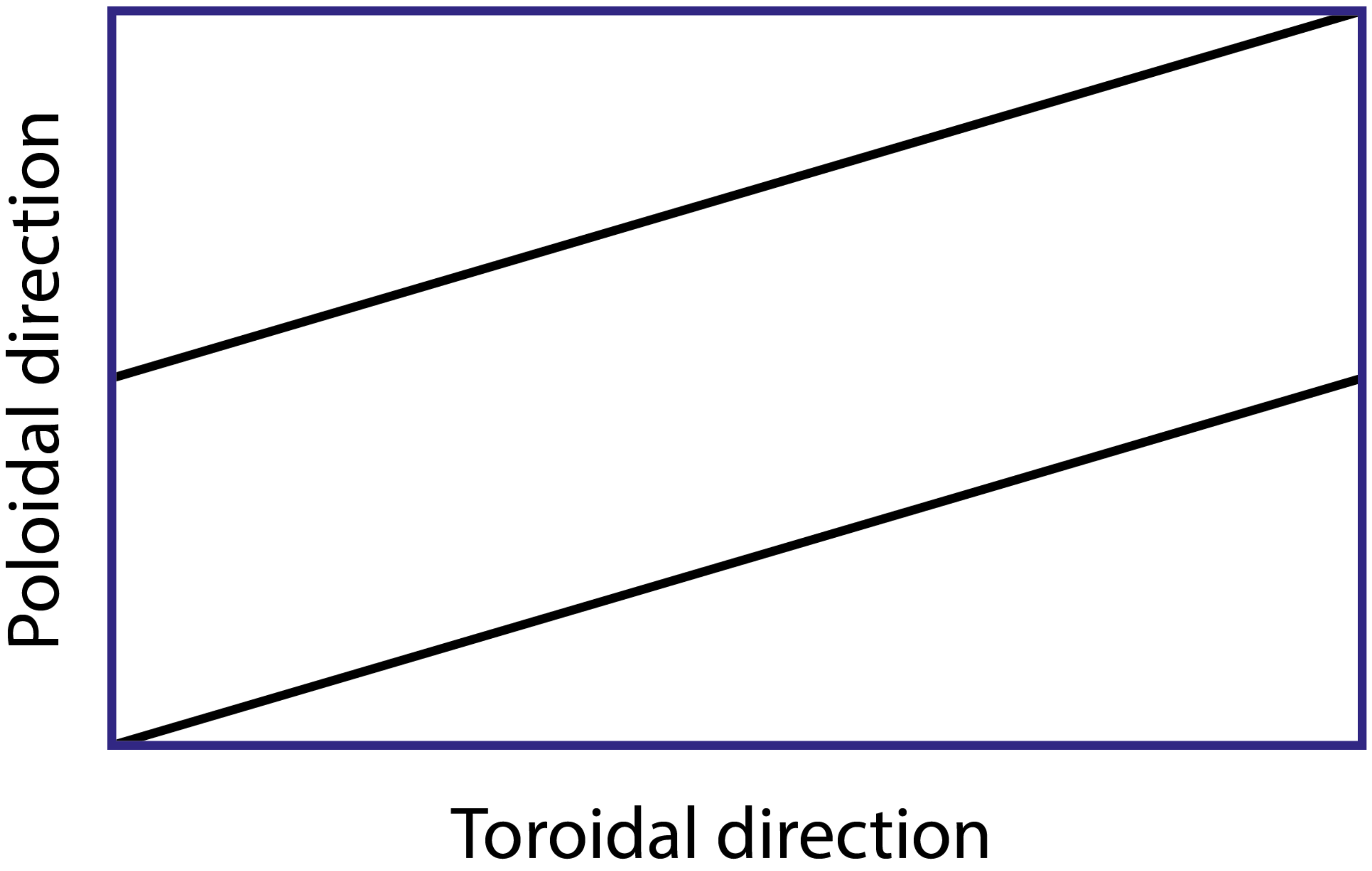
$$q = 2.5$$

No self-interaction



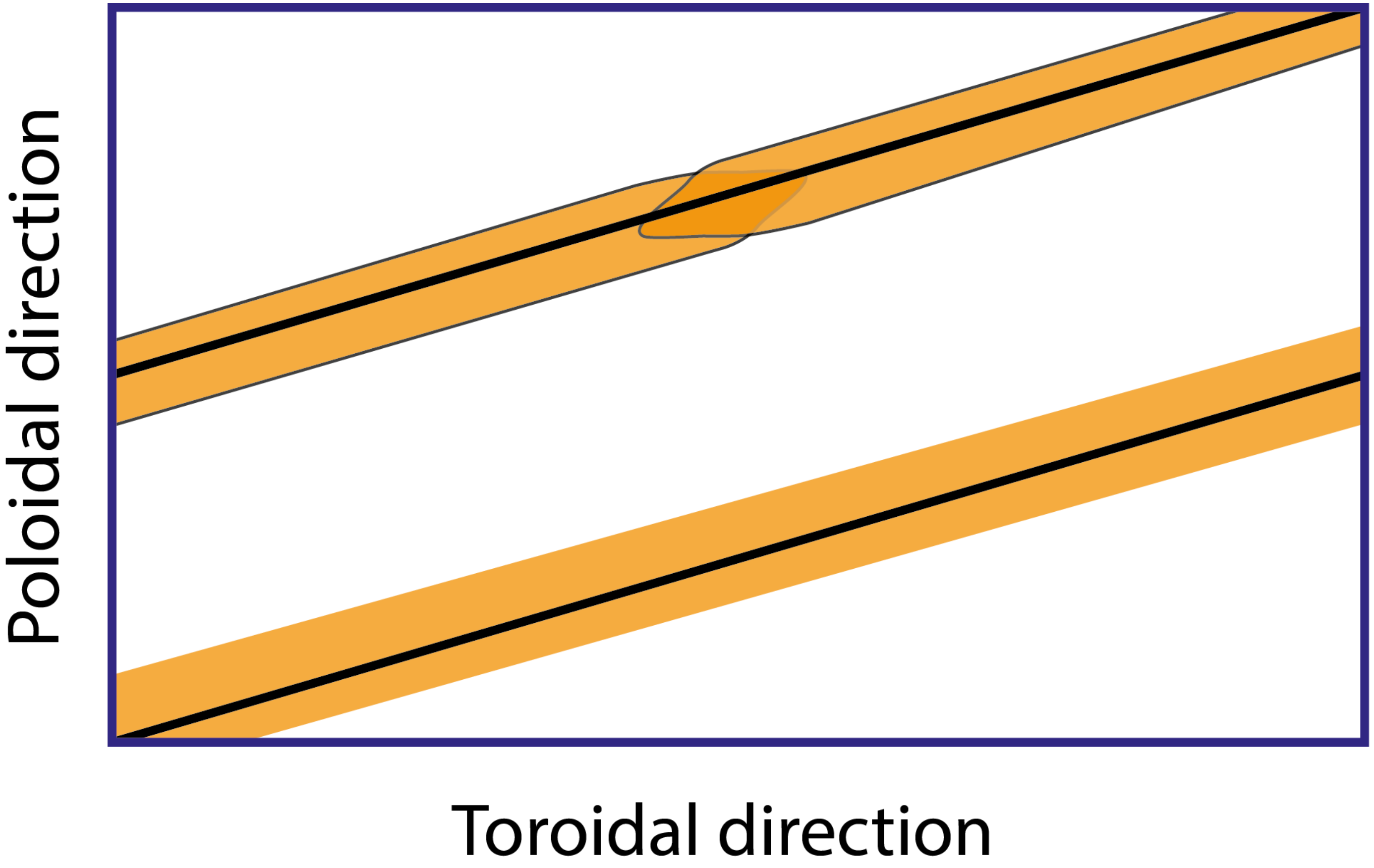
$q = 2.5$

Self-interaction



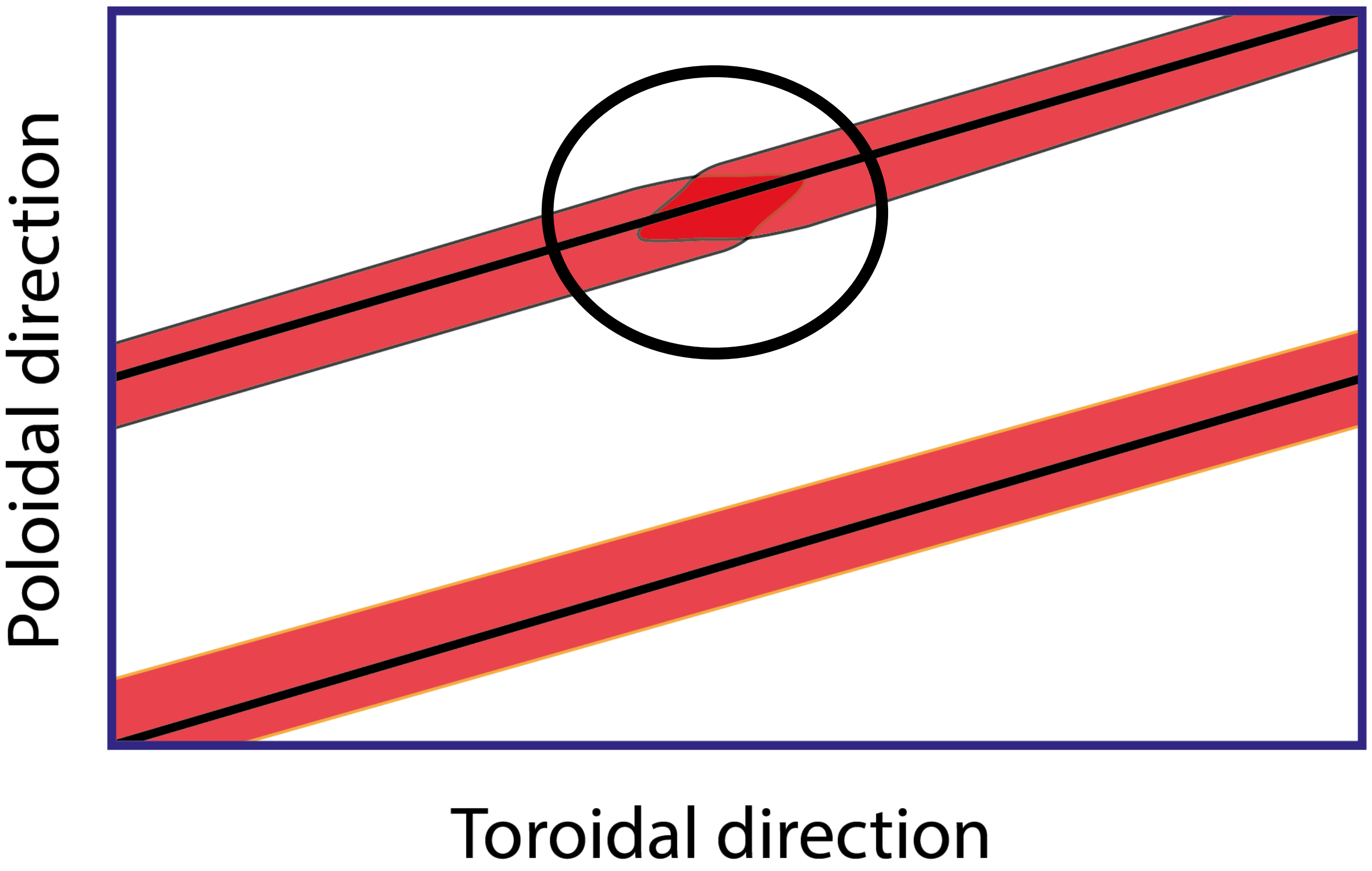
$$q = 2$$

Self-interaction



$q = 2$

Self-interaction



$q = 2$

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EPFL Self-interaction triggers ITBs?

Low magnetic shear + integer q

↓

Strong self-interaction

↓ ?

ITB

- 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
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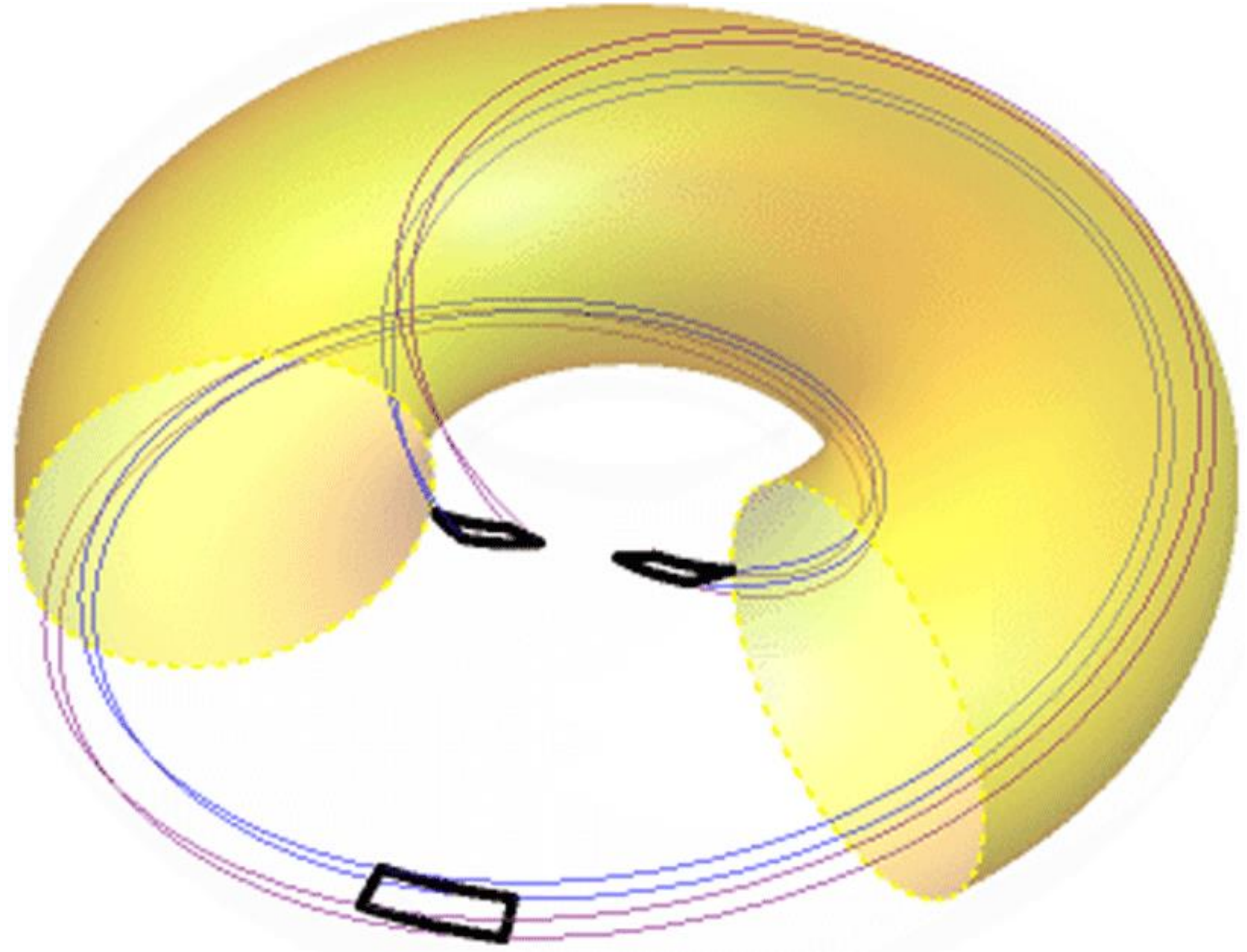
GENE flux-tube simulations



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

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Zero magnetic shear simulations

- Electrostatic ($\beta = 10^{-5}$) and collisionless
- Simulations with adiabatic and **kinetic electrons**
- Two cases – Cyclone Base Case (CBC) or pure ITG drive

Cyclone Base Case (CBC):

- $T_e = T_i$
- $R/L_T = 6.96$
- $L_T/L_n = 0.321$
- $q = 1.4$
- $\hat{s} = 0$

Pure ITG drive:

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

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

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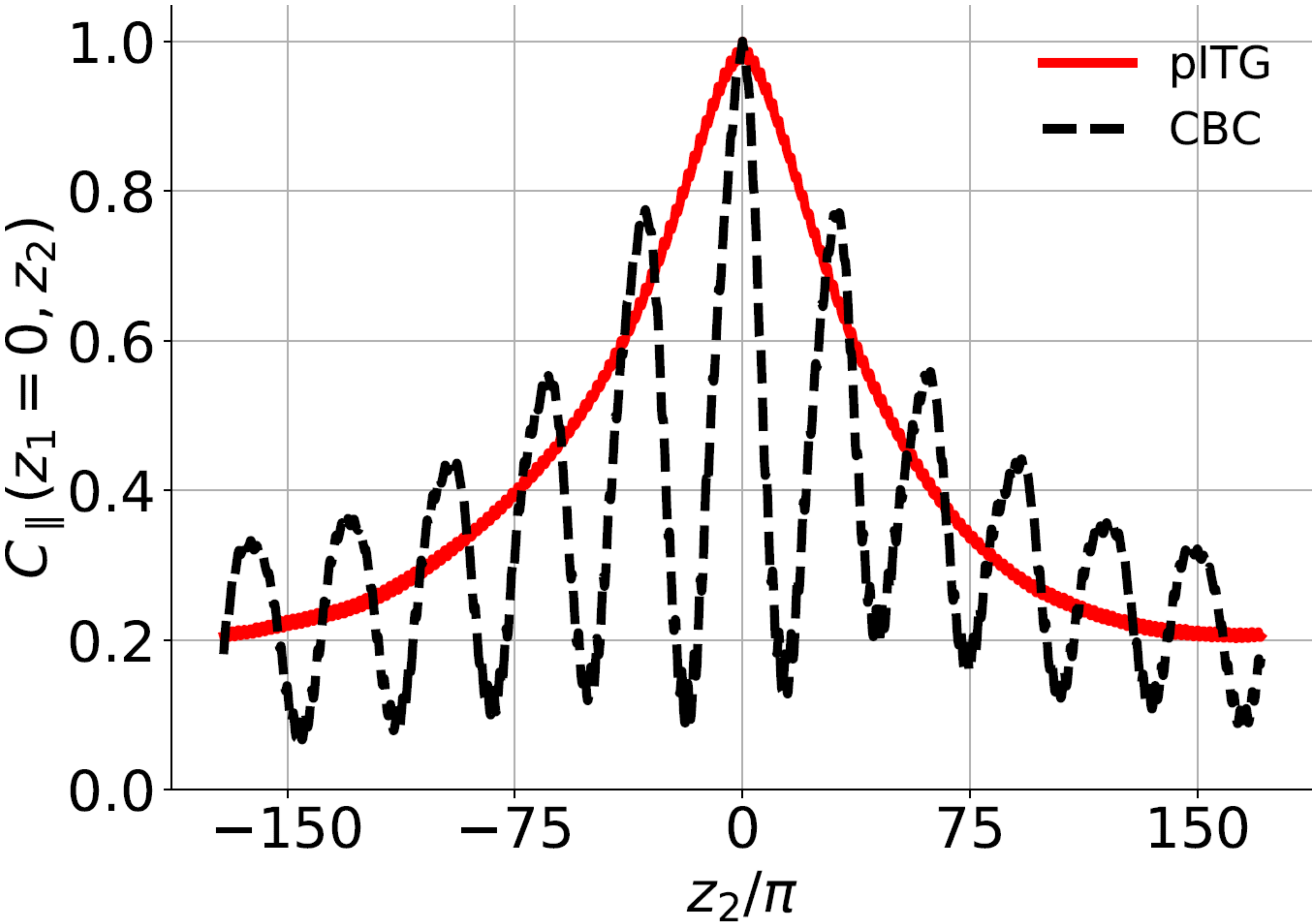
Ultra-long turbulent eddies

$N_{pol} = 171$



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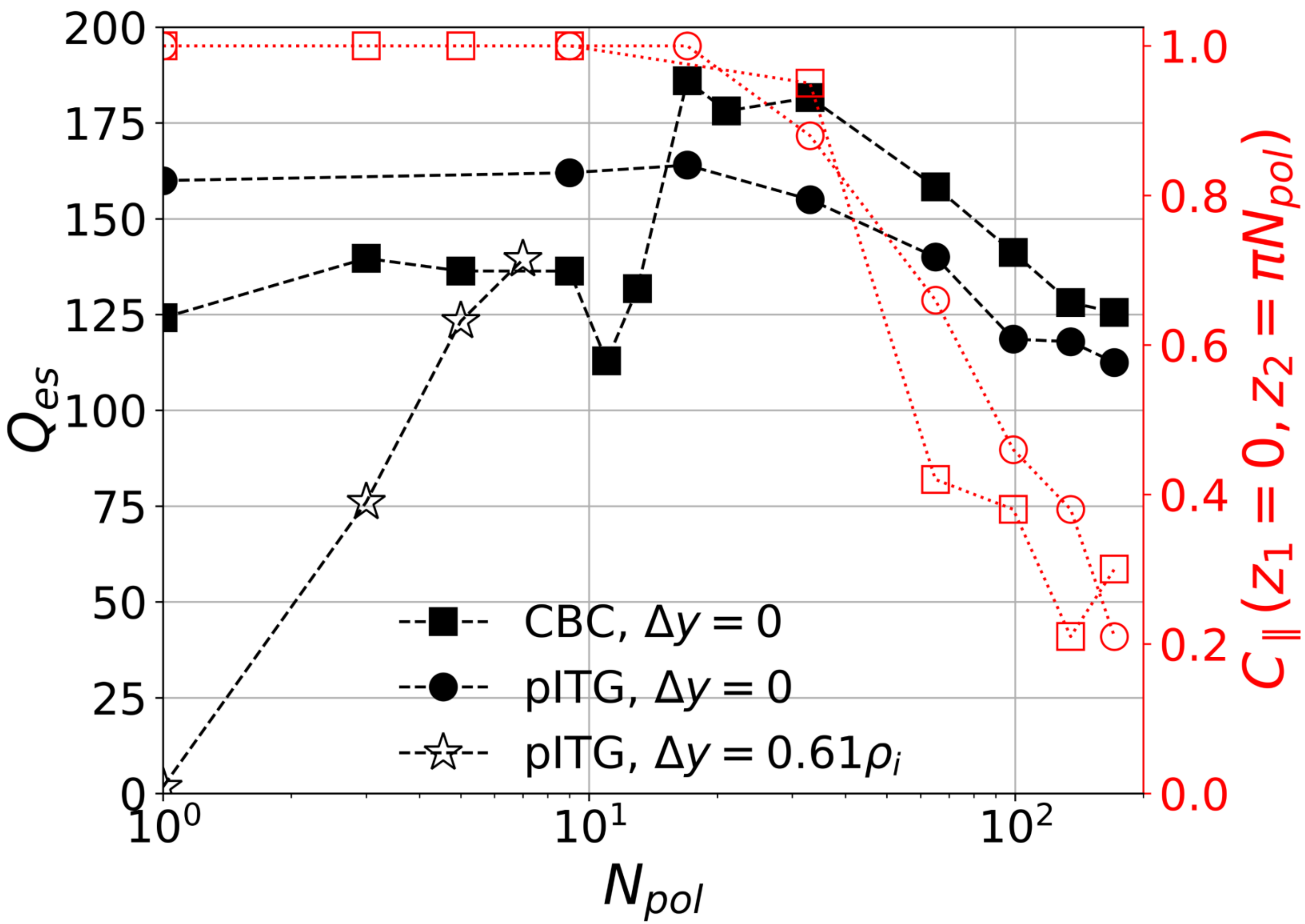
Heat flux and correlation



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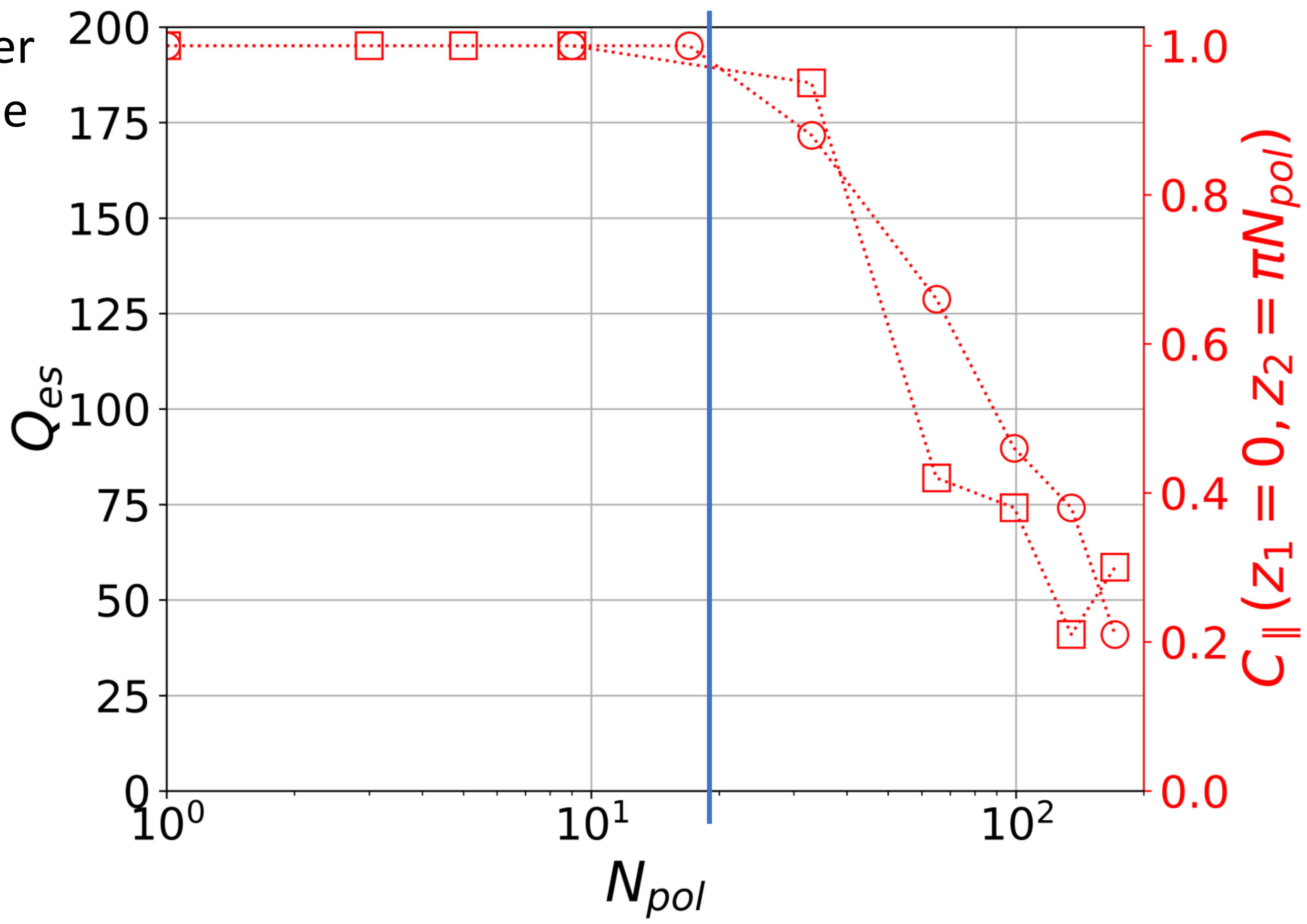
Parallel correlation

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

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

$$\tau_{turb,KE} \approx 3\frac{R}{c_i}$$

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



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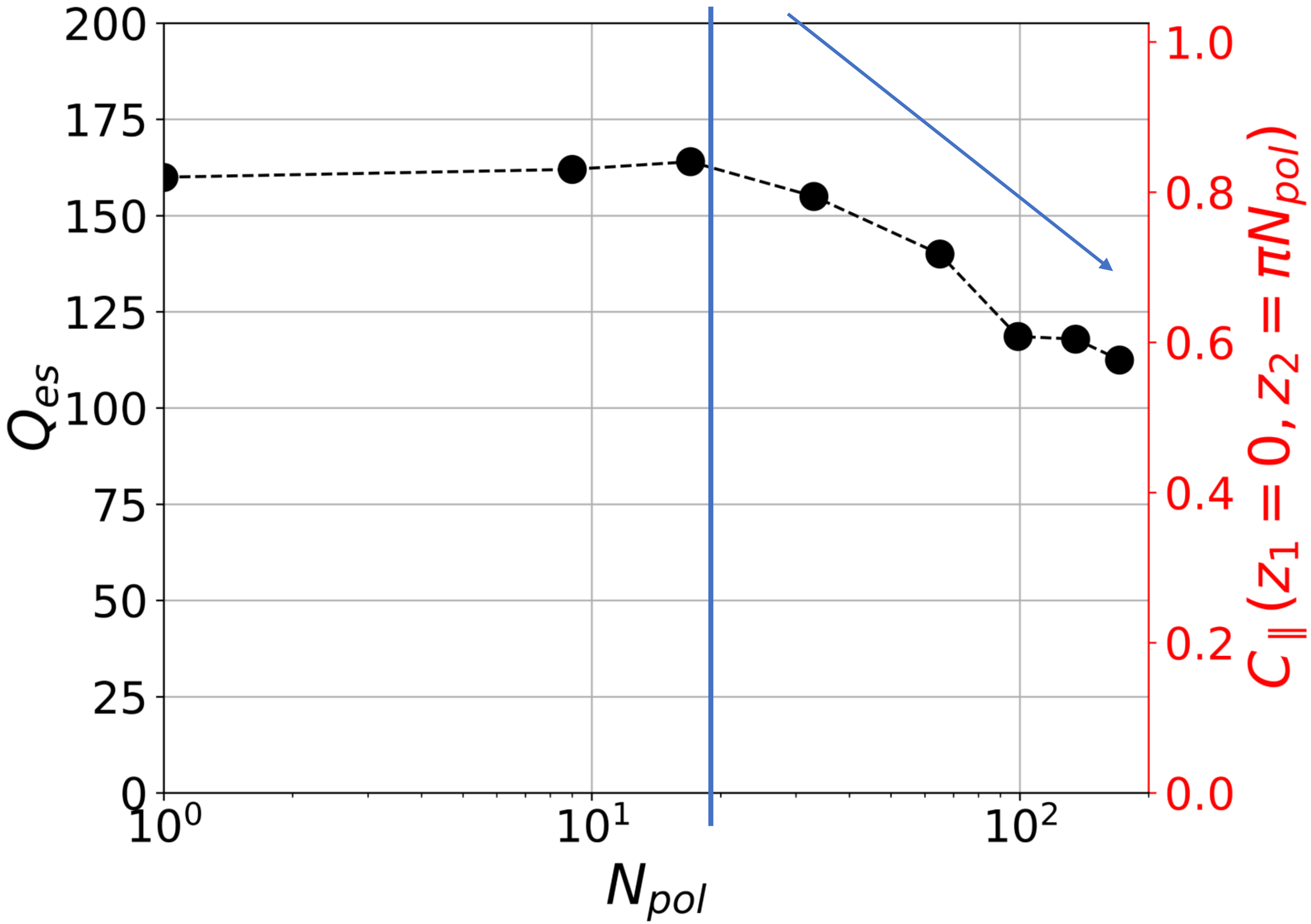
pITG heat flux

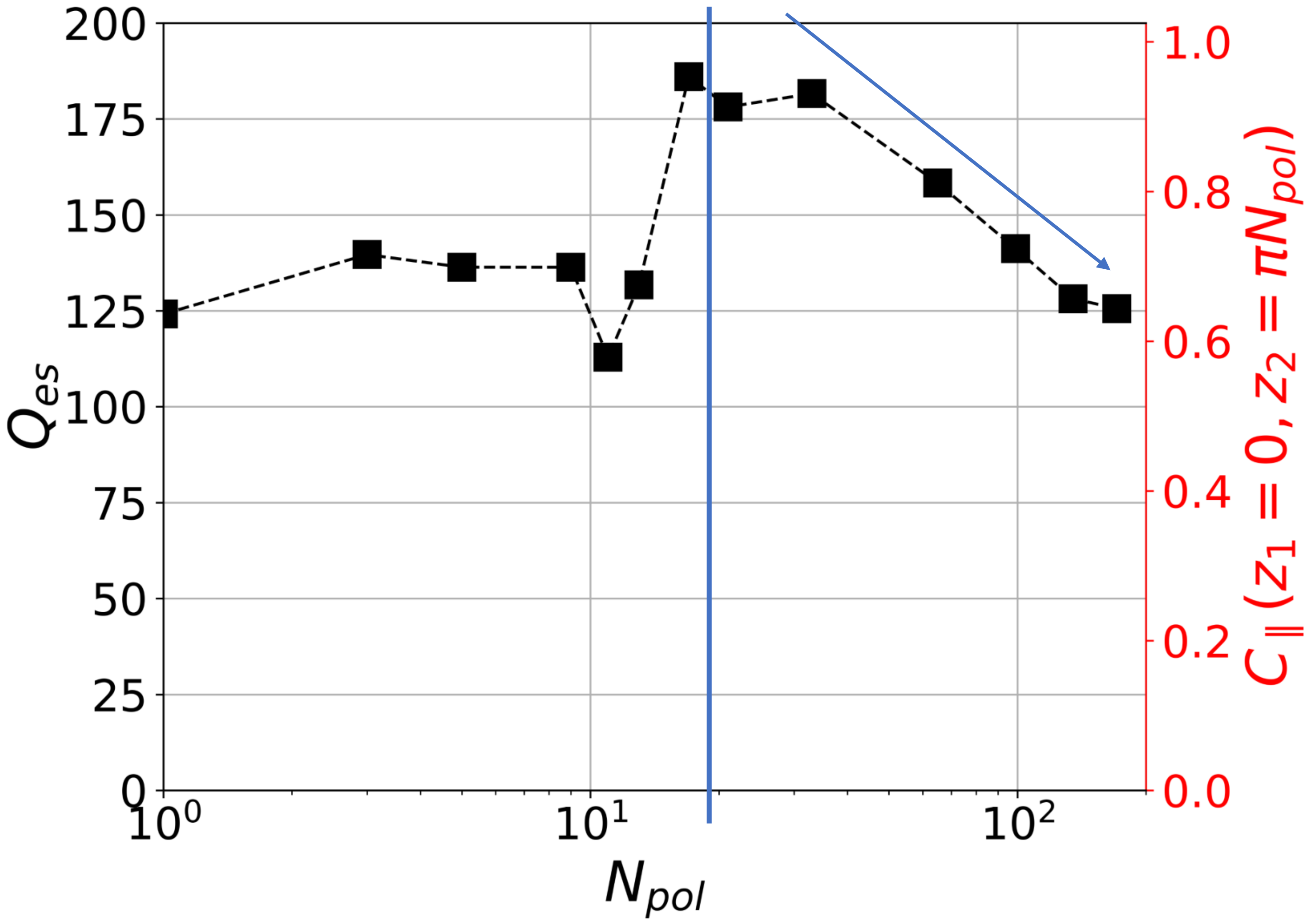
Heat flux decreases due to interference between different parallel eddies



CBC-like heat flux

Heat flux decreases due to interference between different parallel eddies

Long parallel waves appear in the system



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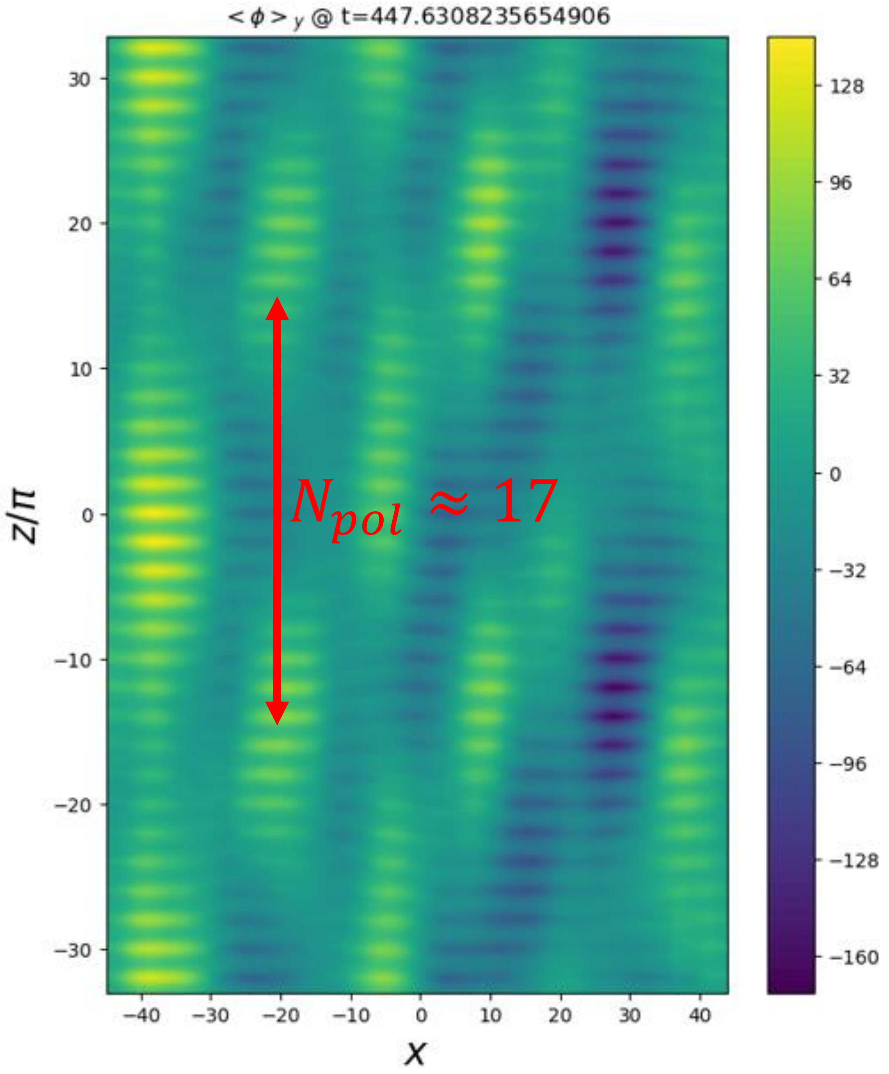
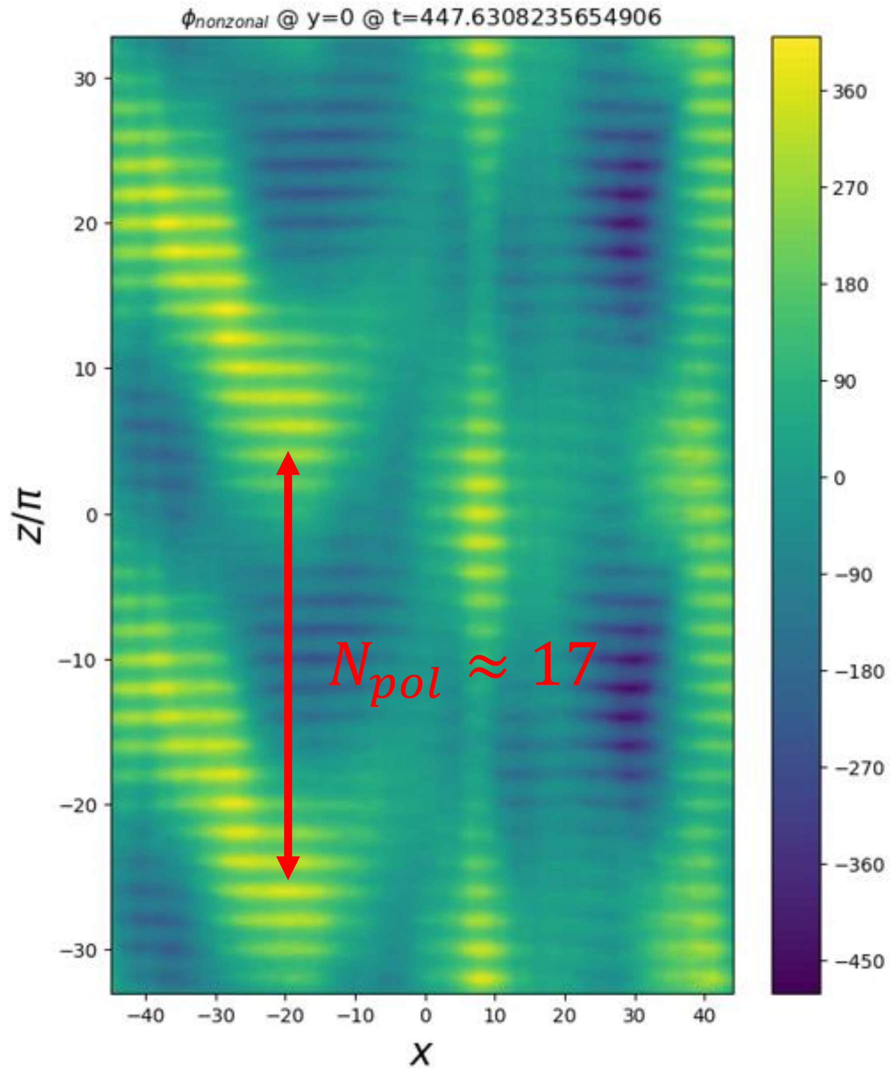
Long parallel wave-like structures





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Par. and perpendicular scales

Adiabatic electrons

$$\tau_{turb,AE} \approx 9\frac{R}{c_i}$$

$$L_{\perp,AE} \approx O(10)\rho_i$$

$$L_{\parallel,AE} \approx v_{th,i}\tau_{turb,AE}$$

Kinetic electrons

$$\tau_{turb,KE} \approx 3\frac{R}{c_i}$$

$$L_{\perp,KE} \approx O(10)\rho_i$$

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

Par. and perpendicular scales

Adiabatic electrons

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Ion thermal velocity

Kinetic electrons

$$\tau_{turb,KE} \approx 3\frac{R}{c_i}$$

$$L_{\perp,KE} \approx O(10)\rho_i$$

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

Electron thermal velocity

N_{pol} study conclusions

- Simulations with kinetic electrons at zero magnetic shear require hundreds of poloidal turns to achieve convergence
- **Kinetic electrons** set the parallel length scale
- In simulations with electron temperature gradient long parallel waves emerge
- Different behaviour in simulations with pure ITG drive vs a mixed ITG/TEM drive.

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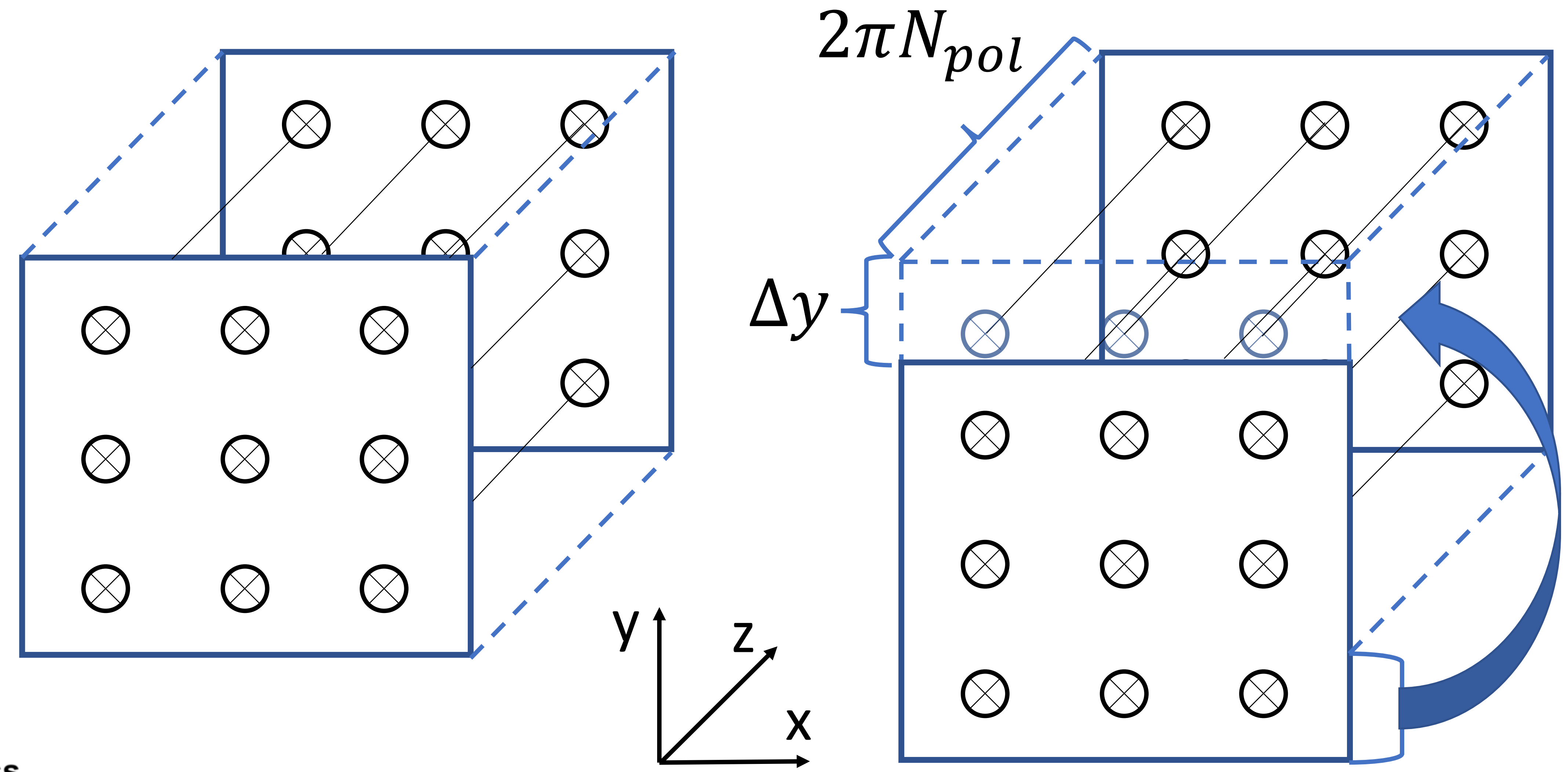
Parallel boundary shift



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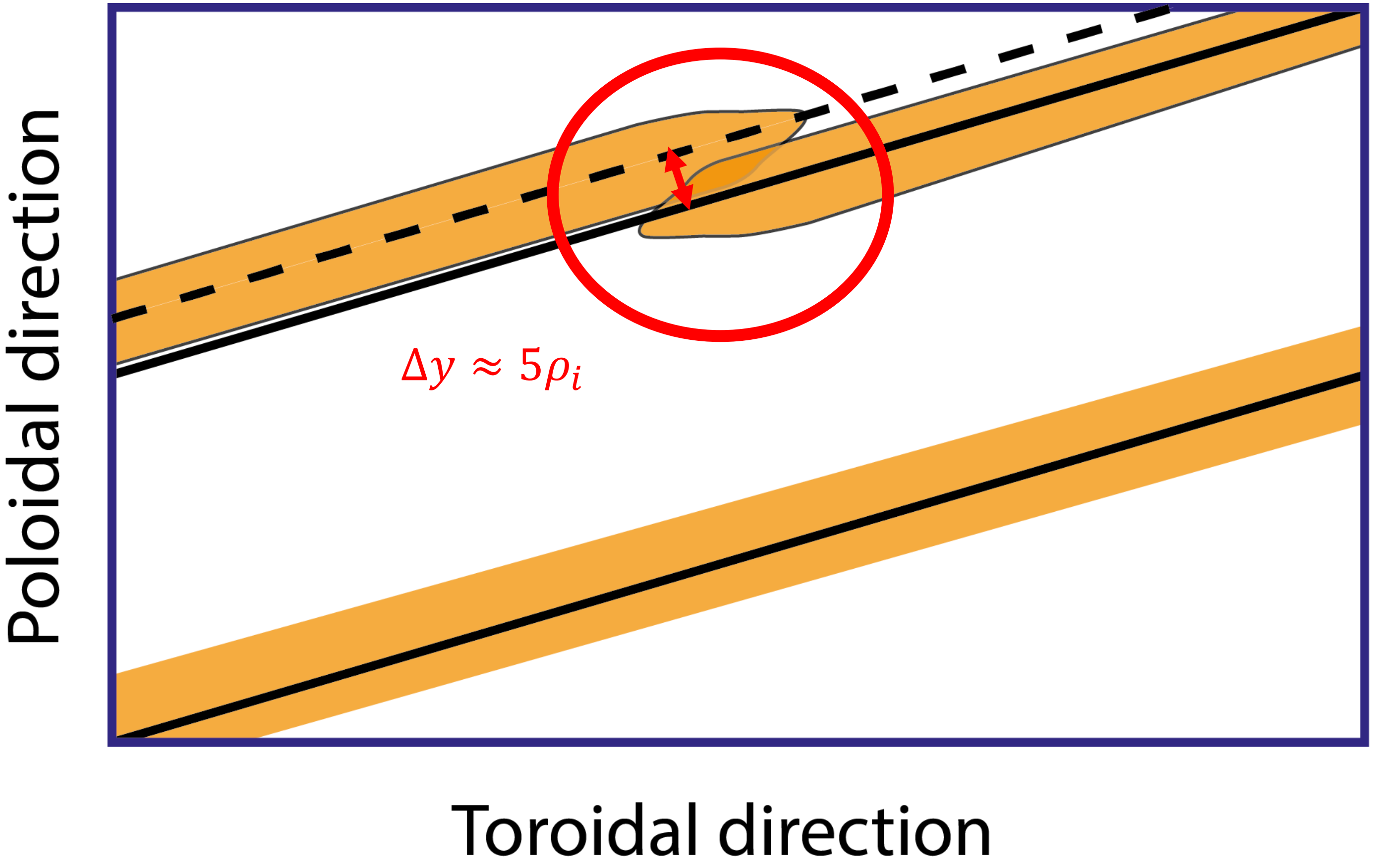
Parallel boundary shift



$q = 2.01$

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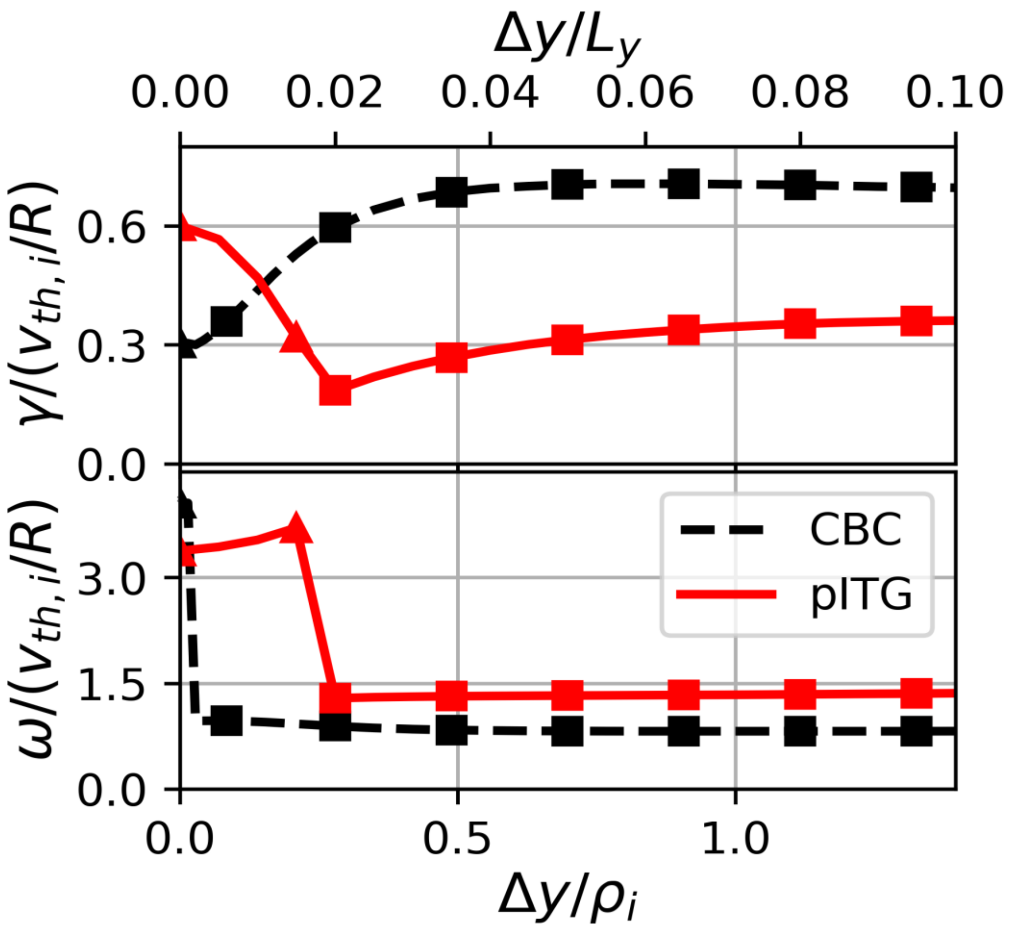
$N_{pol} = 1, \Delta y$ scan

Different behaviour between CBC and pITG drives



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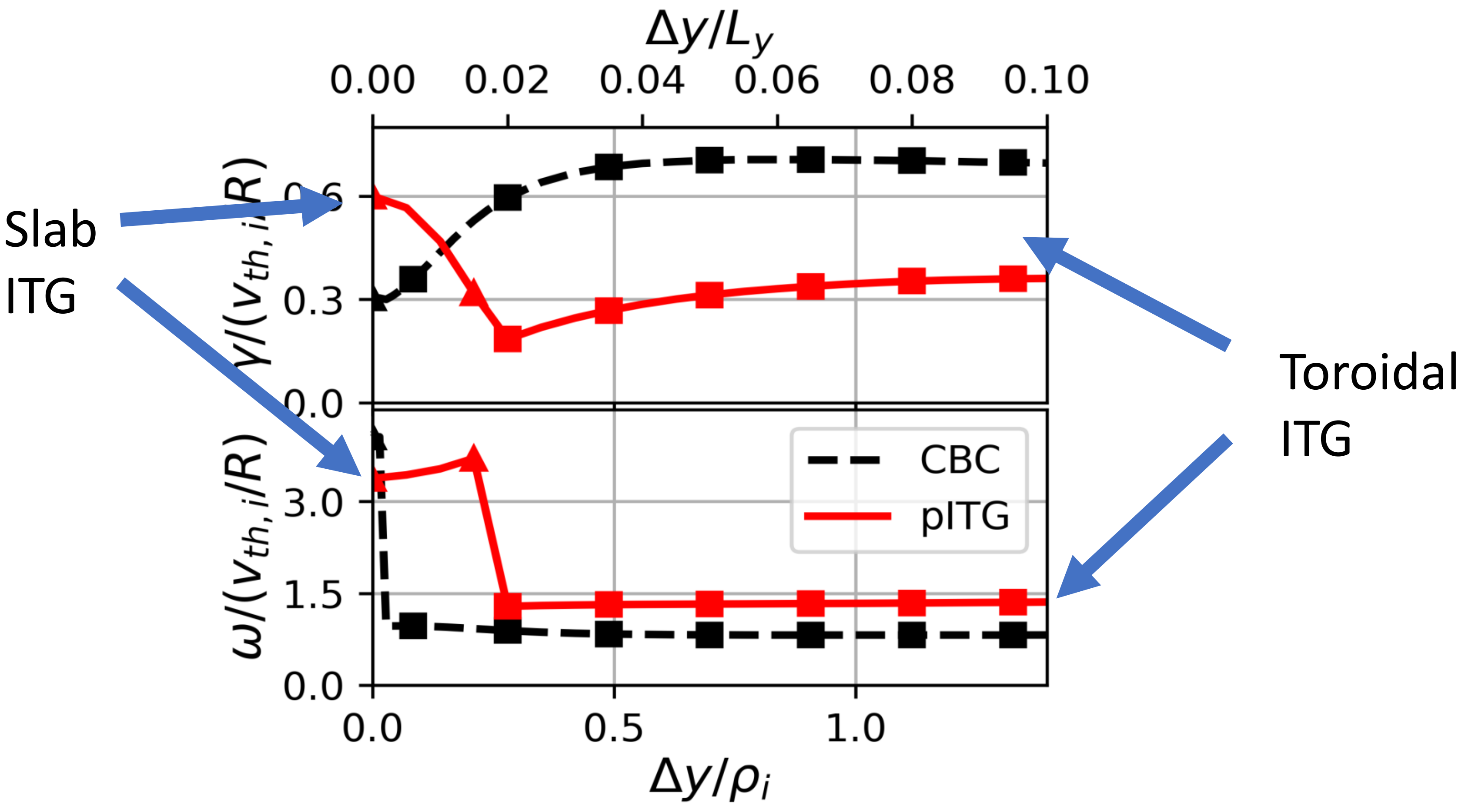
EPFL $N_{pol} = 1, \Delta y$ scan

Different behaviour between CBC and pITG drives

Transition from slab to toroidal ITG

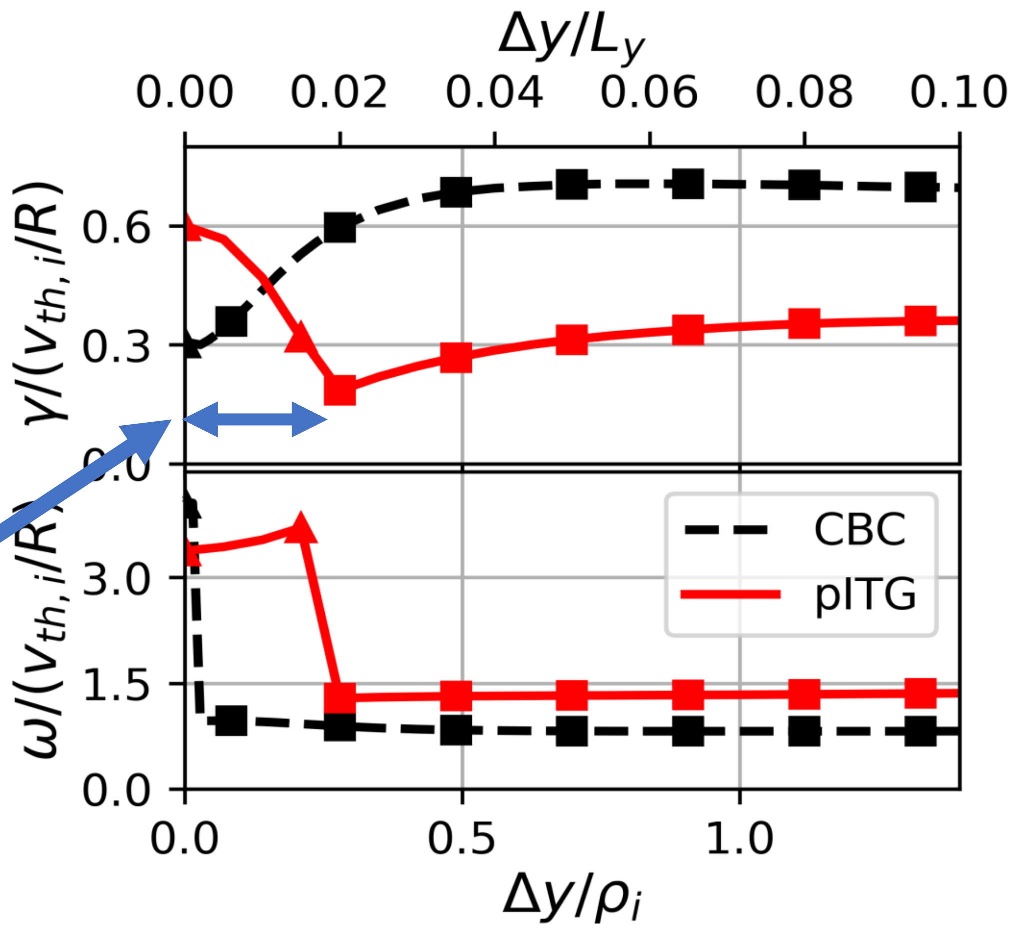


EPFL $N_{pol} = 1, \Delta y$ scan

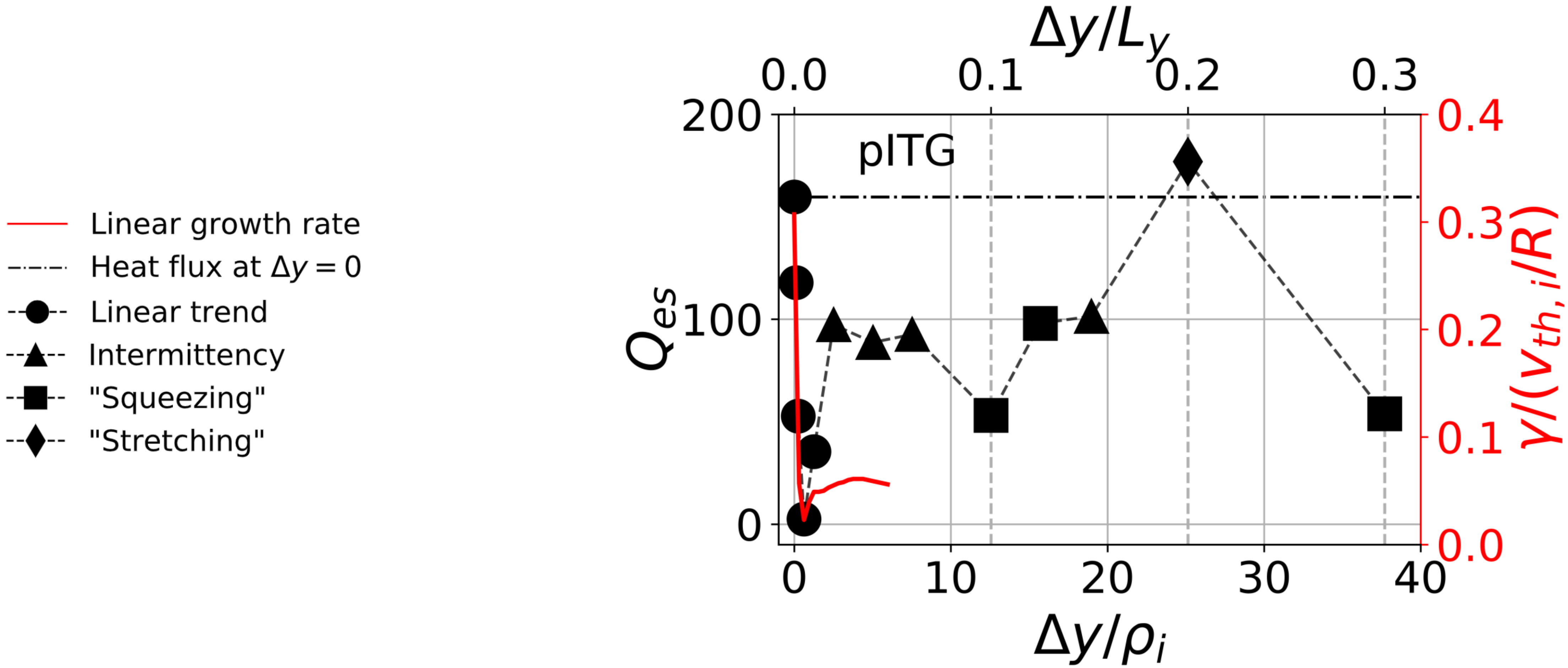
Different behaviour between CBC and pITG drives

Transition from slab to toroidal ITG

Width scales with electron mass



pITG heat flux



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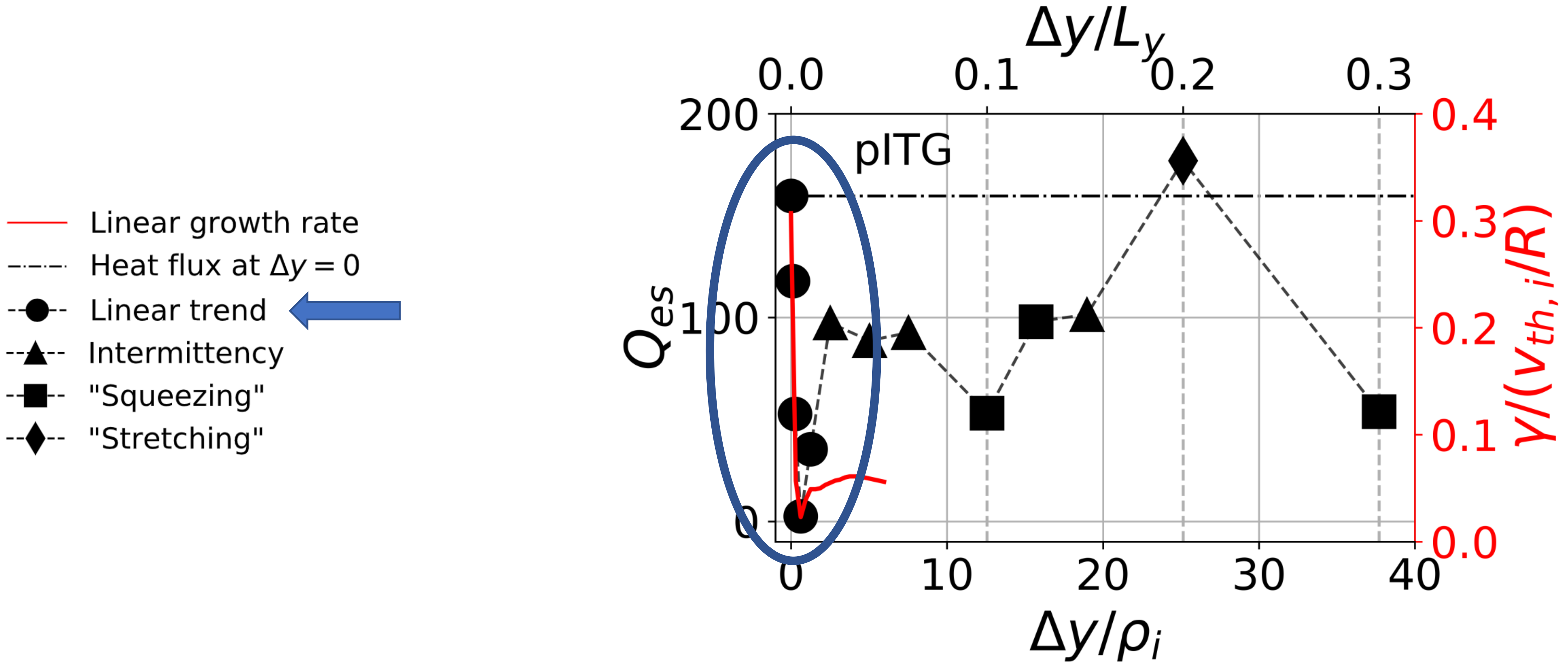
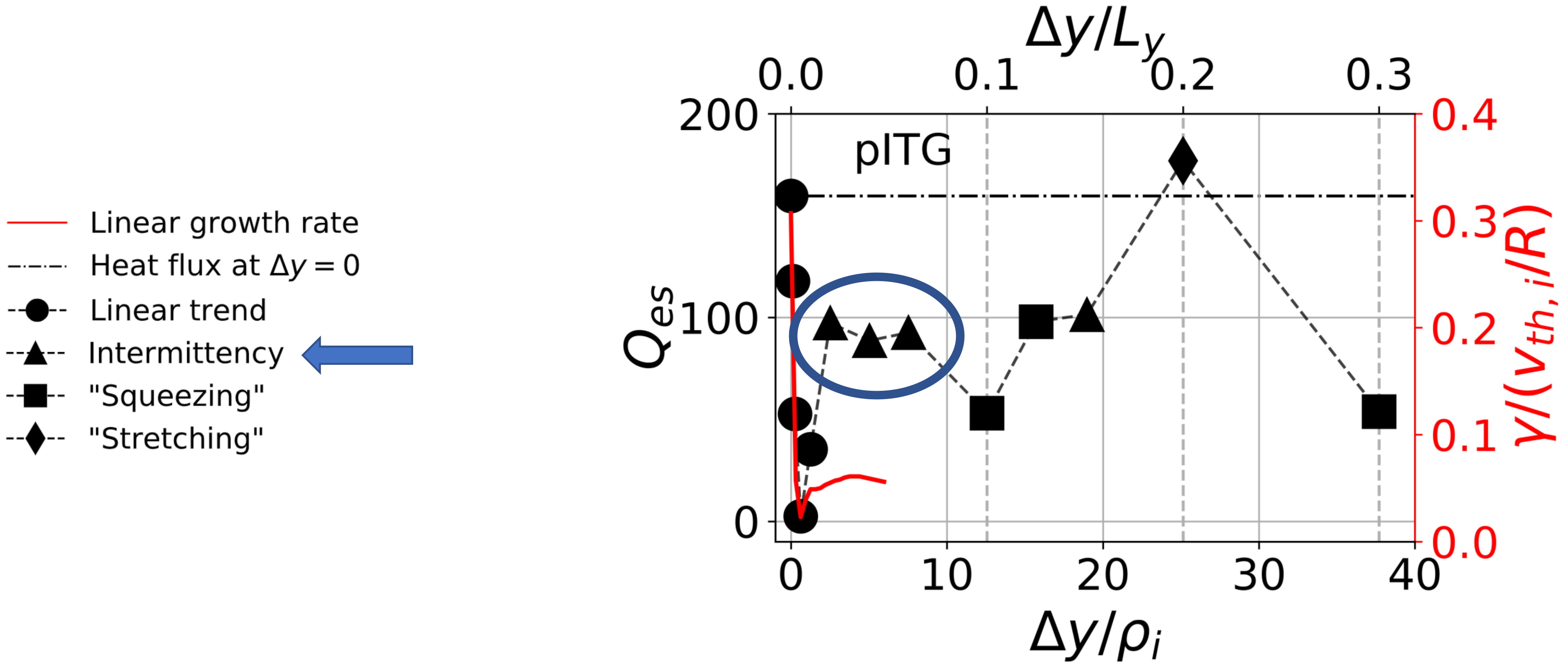
pITG heat flux



pITG heat flux



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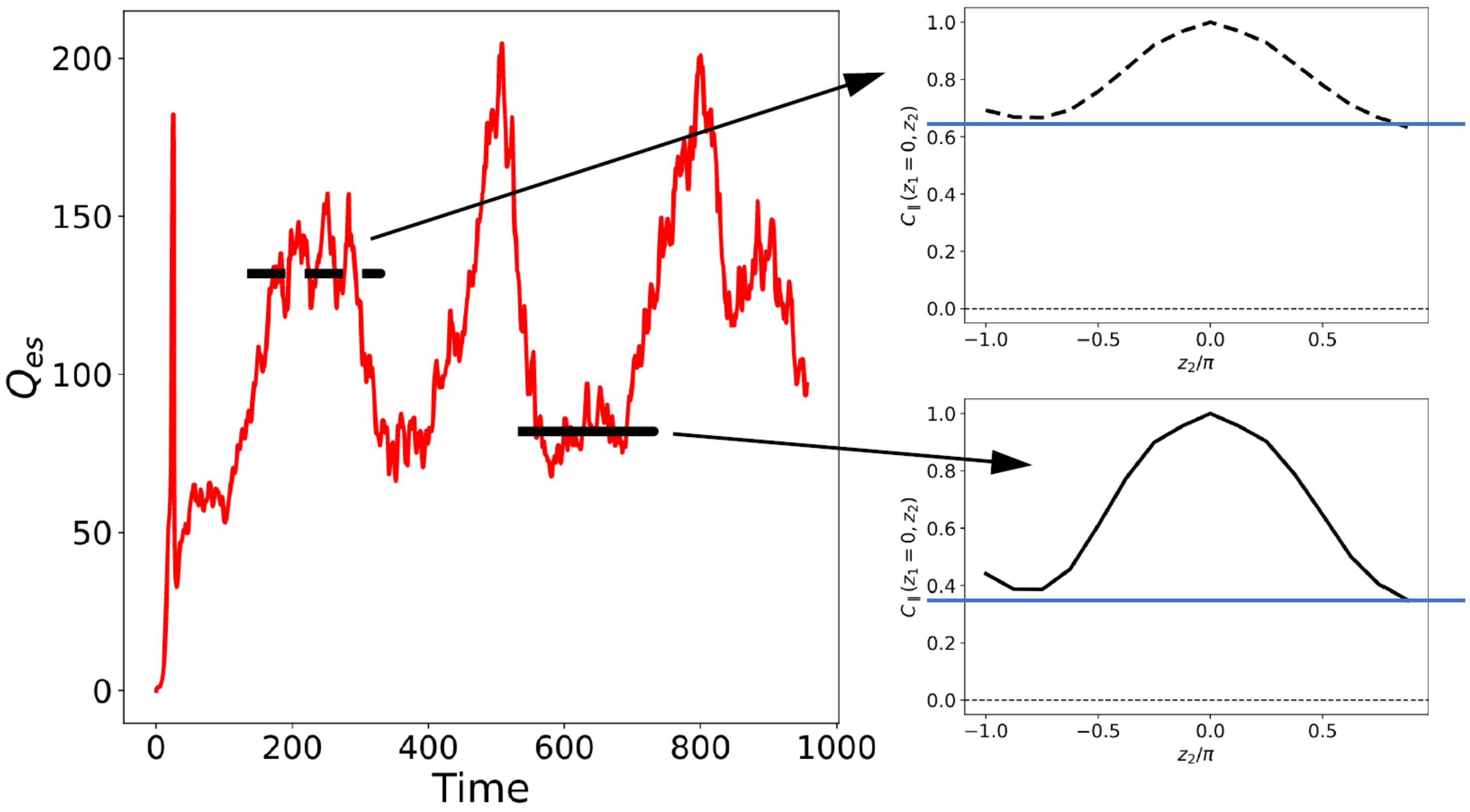
Intermittency

- Linear growth rate
- Heat flux at $\Delta y = 0$
- Linear trend
- Intermittency
- "Squeezing"
- "Stretching"



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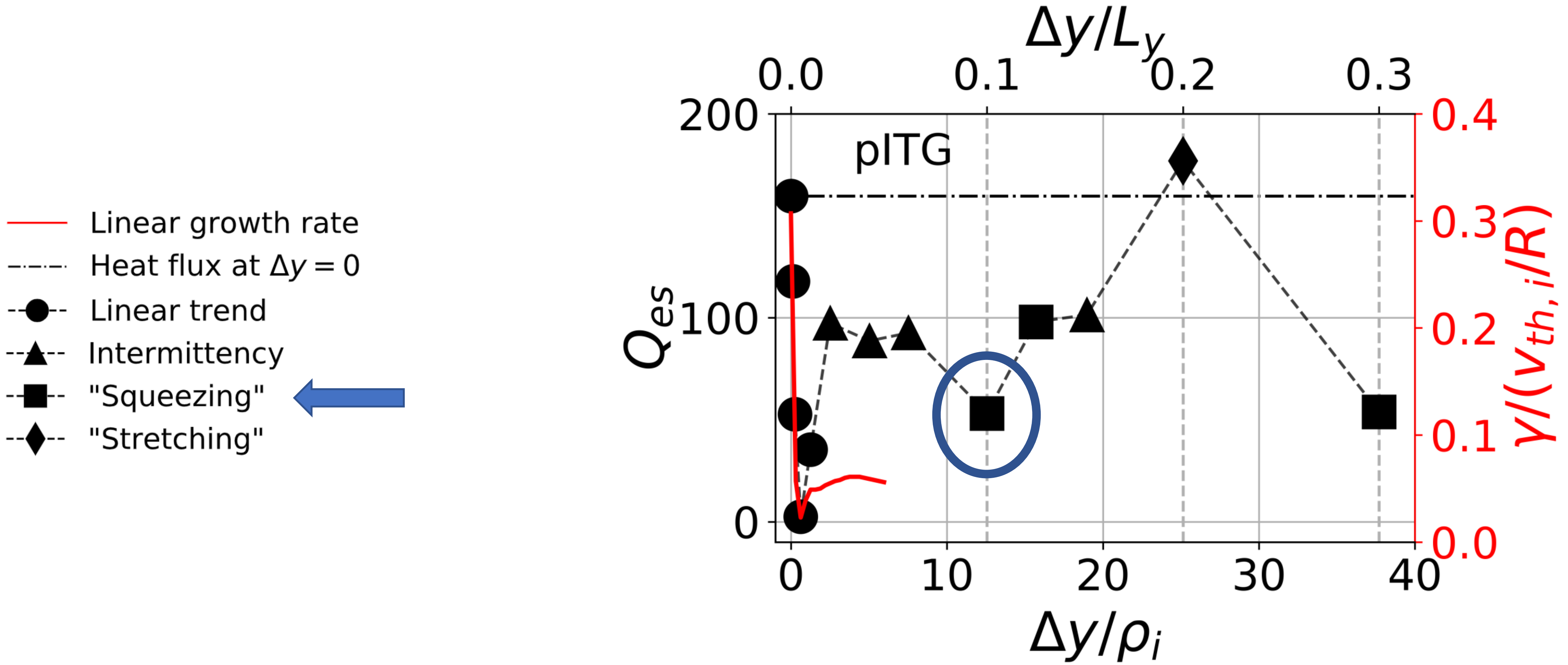
pITG heat flux



“Squeezing”

Linear growth rate
Heat flux at $\Delta y = 0$
Linear trend
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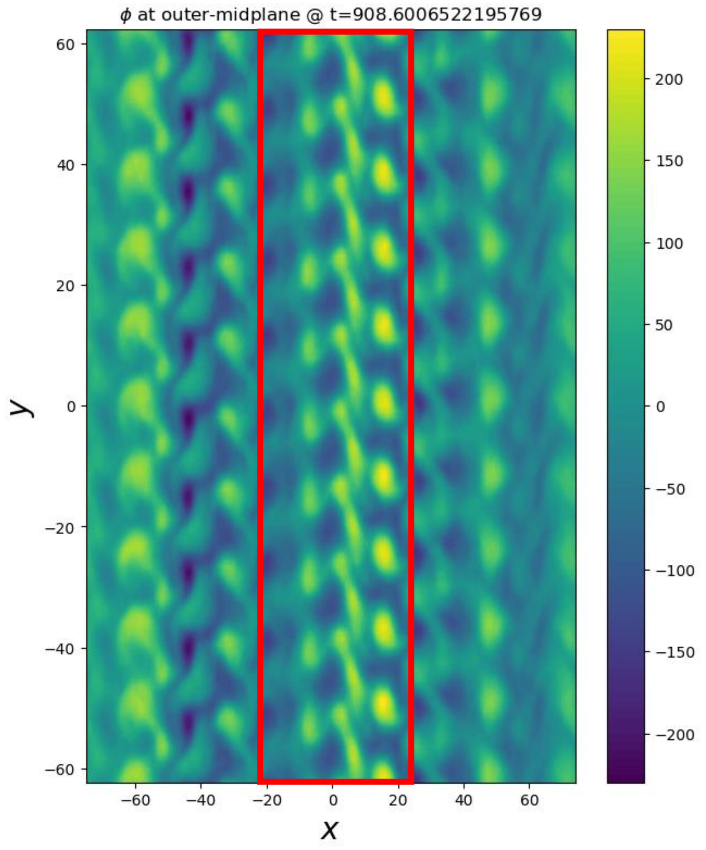
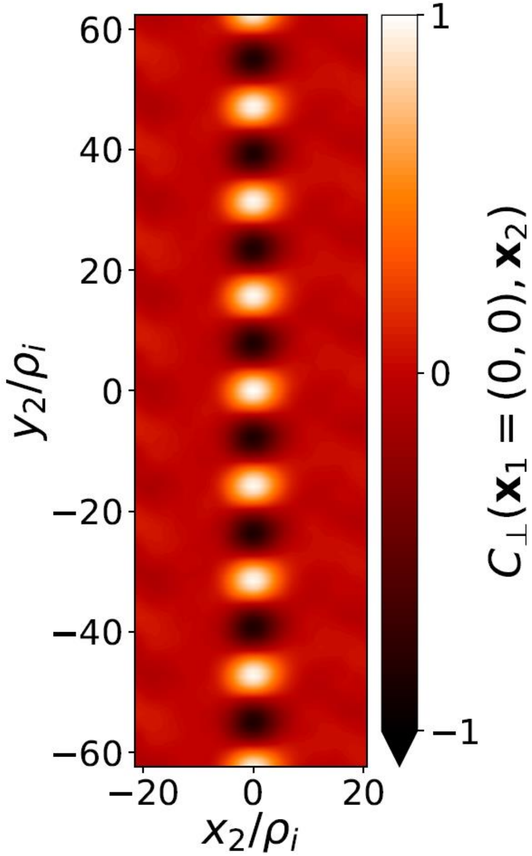


Snapshot



Correlation

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“Squeezing”

- Linear growth rate
- Heat flux at $\Delta y = 0$
- Linear trend
- Intermittency
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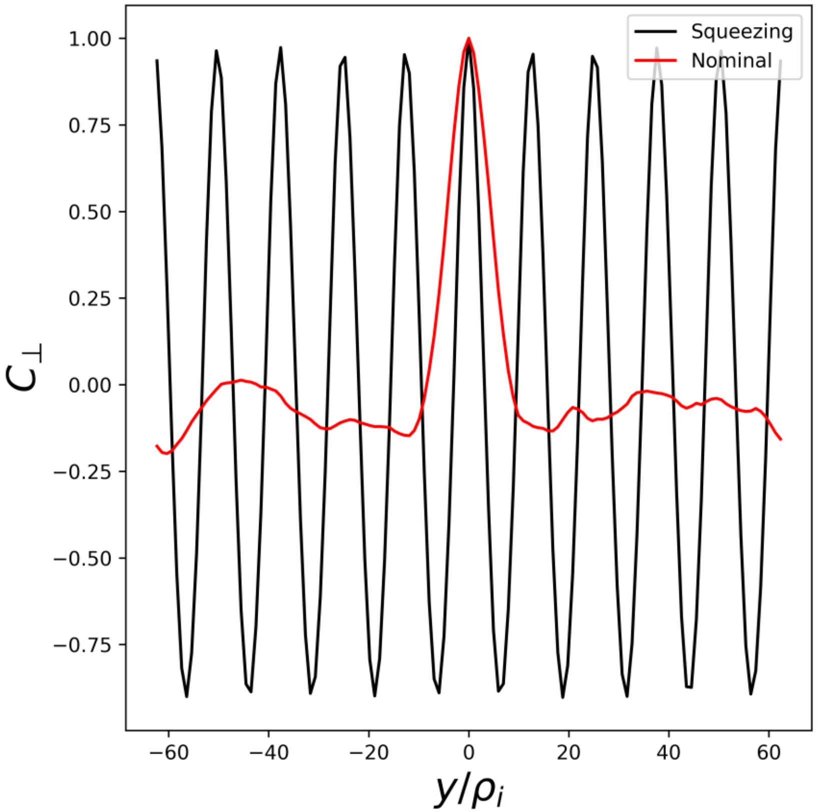
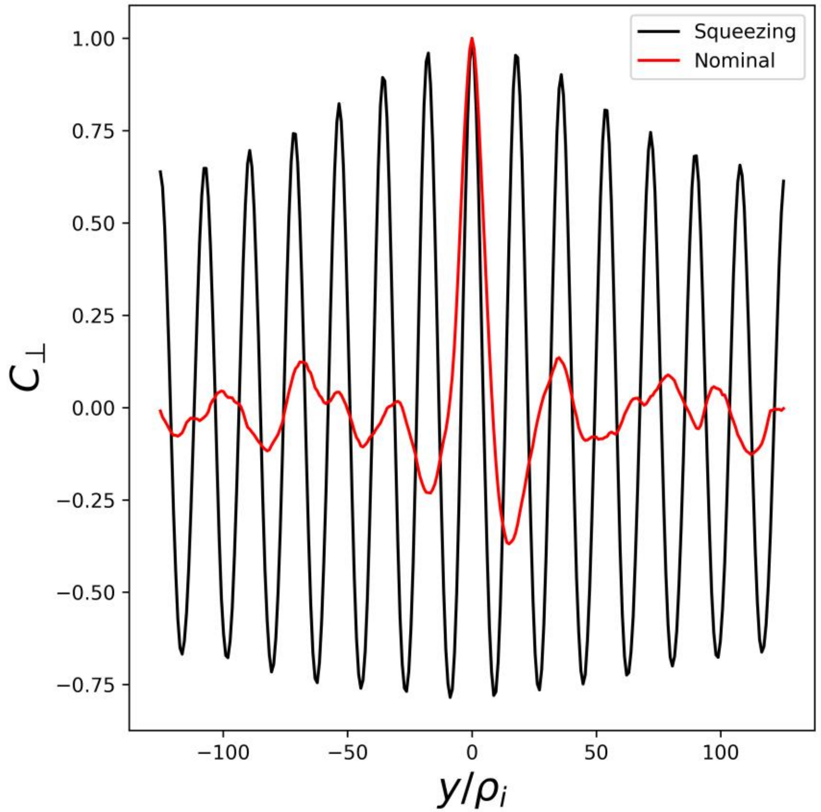
- "Stretching"



$$\frac{m_e}{m_i} = \frac{1}{3672}$$



$$\frac{m_e}{m_i} = \frac{10}{3672}$$

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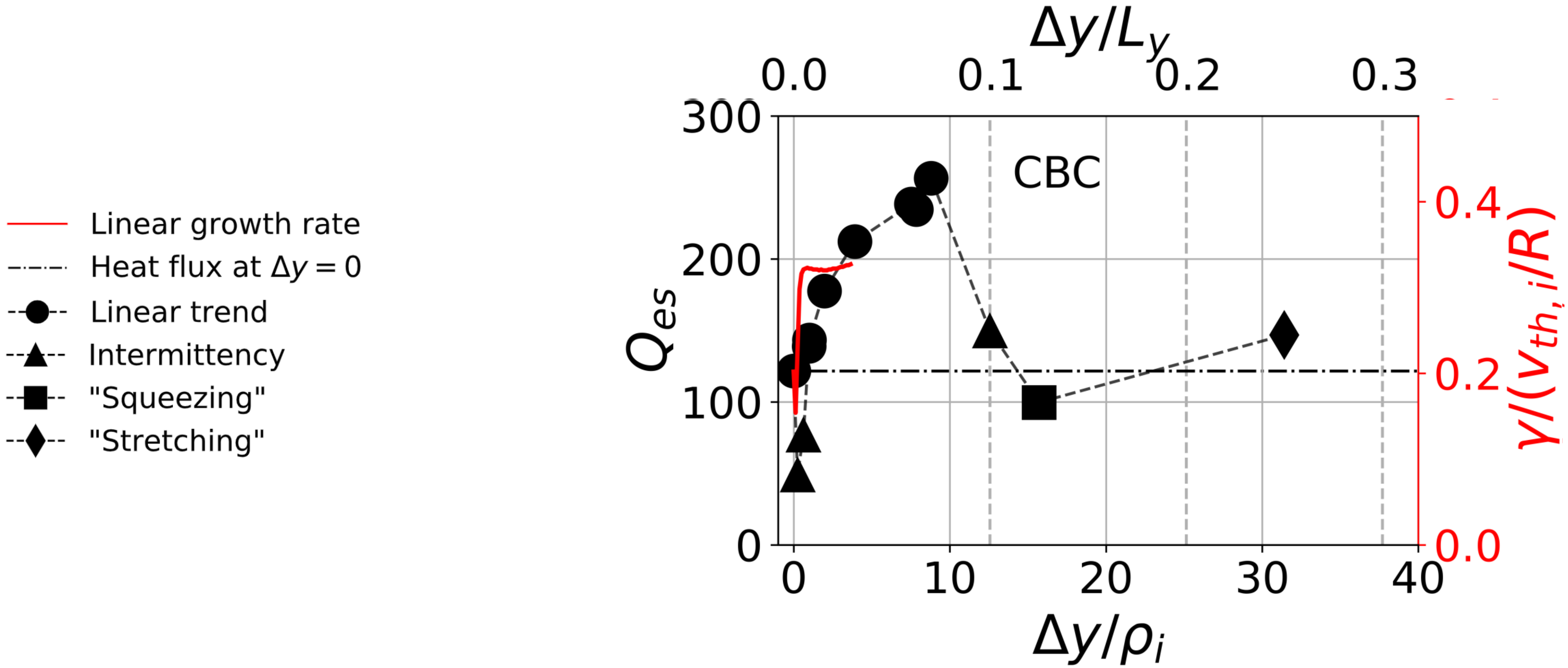
CBC-like heat flux



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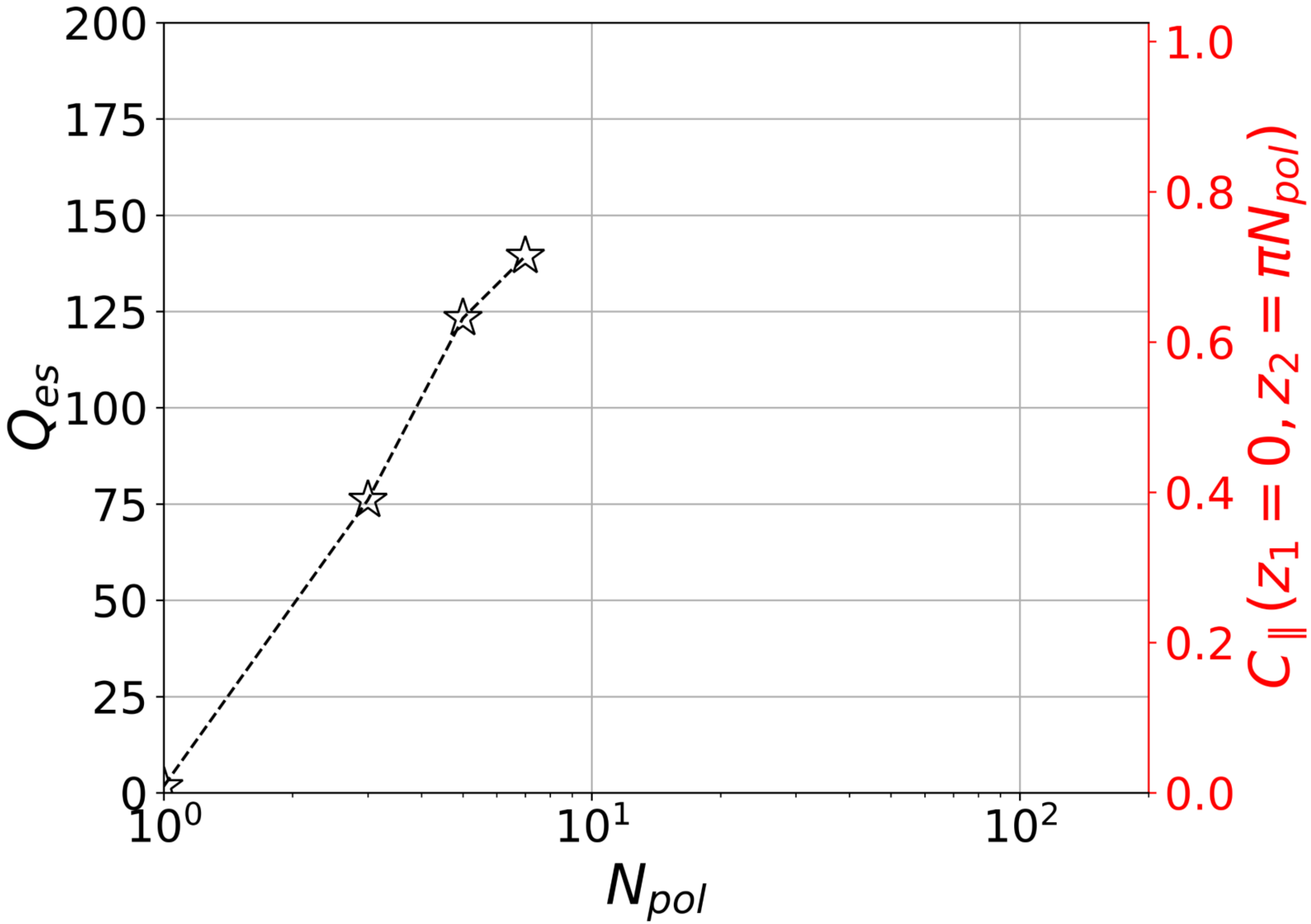
pITG heat flux with fixed $\Delta y = 0.61\ \rho_i$

Strongest reduction in transport near integer or low-order rational surfaces



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Binormal shift study

- Allows to study self-interaction in a region close to rational-q
- Proximity to a rational surface has a large impact on the heat flux
- Different behaviour in simulations with pure ITG drive vs a mixed ITG/TEM drive.

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Linear shear scan

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Gradients and auto-correlation

Profile corrugations

Side note: low shear eddy length

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EPFL Deliverables and milestones

Conference contribution and a paper under review:
Ultra Long Turbulent Eddies, Magnetic Topology, and the Triggering of Internal Transport Barriers in Tokamaks
A. Volčokas, J. Ball, S. Brunner, arXiv:2208.06159

• M1.6 As a simple intermediate step towards the L-H transition, investigate the ability of standard, existing flux-tube simulations to model ITBs; if successful, validate against experiment as a proof of principle.	Target date 06/2022
• D1.2 ITB physics studied and key elements that could be transferred to edge transport barriers identified	Target date 09/2022
• 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
• D4.1 Quantification of ITB momentum drive from rational vs. irrational surfaces and comparisons to plasma edge	Target date 02/2022

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

Conclusions

- Kinetic electrons necessary for accurately modelling low magnetic shear simulations
- Electron velocity sets the parallel length scale of turbulent eddies
- At low magnetic shear turbulent transport is very sensitive to exact q value
- Significantly different behaviour in simulations with pure ITG drive vs a mixed ITG/TEM drive
- Time stationary ITB-like plasma profile corrugations around rational surface in simulations with low magnetic shear

Future work

- Increase realism, e.g. including finite collisions, plasma shaping and **electromagnetic effects**
- Investigate TEM and ETG regimes
- Extend this work to stellarators where global shear tends to be very small
- Possibility of deriving **reduced self-interaction models**
- Attempt to **measure ultra long eddies** in experiments
- More detailed low but finite shear simulations

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Thank you for your attention

Theory, Simulation, Verification and Validation

Research is being caried out in the framework of TSVV1:

Physics of the L-H Transition and Pedestals

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Additional slides