

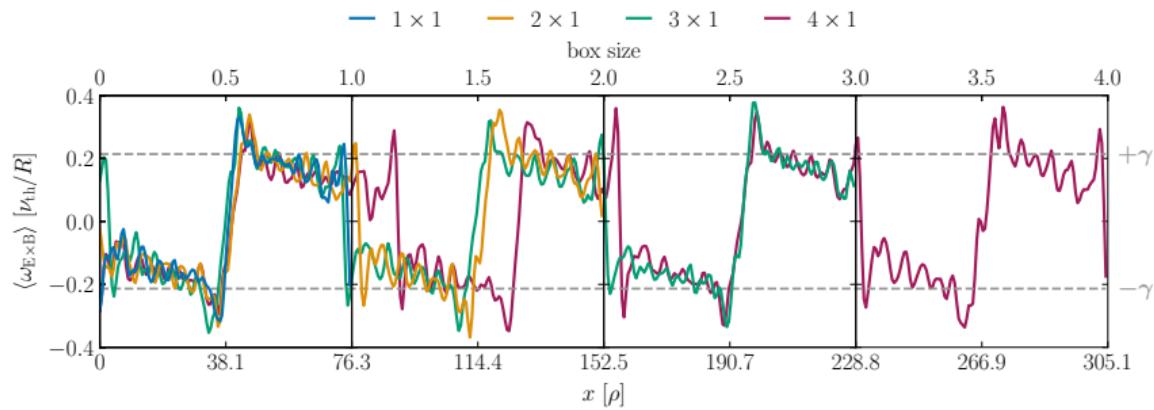


SIZE CONVERGENCE OF THE $E \times B$ STAIRCASE PATTERN IN FLUX TUBE SIMULATIONS OF ION TEMPERATURE GRADIENT-DRIVEN TURBULENCE

June 23, 2023

Manuel Lippert

Theoretical Physics V



MOTIVATION

MOTIVATION

- Zonal flow pattern formation on mesoscales in ion temperature gradient-driven turbulence

MOTIVATION

- Zonal flow pattern formation on mesoscales in ion temperature gradient-driven turbulence
- Patterns are called $E \times B$ staircase structures

MOTIVATION

- Zonal flow pattern formation on mesoscales in ion temperature gradient-driven turbulence
- Patterns are called $E \times B$ staircase structures
- Pattern formation observed in **local/global flux/gradient-driven** studies

MOTIVATION

- Zonal flow pattern formation on mesoscales in ion temperature gradient-driven turbulence
 - Patterns are called $E \times B$ staircase structures
 - Pattern formation observed in **local/global flux/gradient-driven** studies
-
- **Global studies:** Multiple radial repetitions of staircase structures with a typical pattern size of several ten Larmor radii

MOTIVATION

- Zonal flow pattern formation on mesoscales in ion temperature gradient-driven turbulence
 - Patterns are called $E \times B$ staircase structures
 - Pattern formation observed in **local/global flux/gradient-driven** studies
-
- **Global studies:** Multiple radial repetitions of staircase structures with a typical pattern size of several ten Larmor radii
 - **Local studies:** Radial size of $E \times B$ staircase structures always converge to the radial box size

MOTIVATION

- Zonal flow pattern formation on mesoscales in ion temperature gradient-driven turbulence
 - Patterns are called $E \times B$ staircase structures
 - Pattern formation observed in **local/global flux/gradient-driven** studies
-
- **Global studies:** Multiple radial repetitions of staircase structures with a typical pattern size of several ten Larmor radii
 - **Local studies:** Radial size of $E \times B$ staircase structures always converge to the radial box size

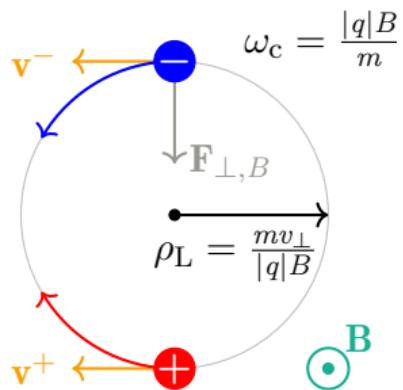
Does the basic pattern size always converges to the box size, or is there a typical mesoscale size inherent to staircase structures also in a local flux-tube description?

CHARGED PARTICLE MOTION

CHARGED PARTICLE MOTION

Lorentz force

$$F_{\perp,B} = |q|v_{\perp}B$$



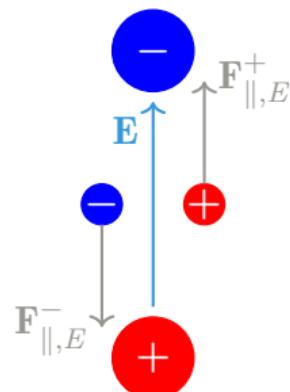
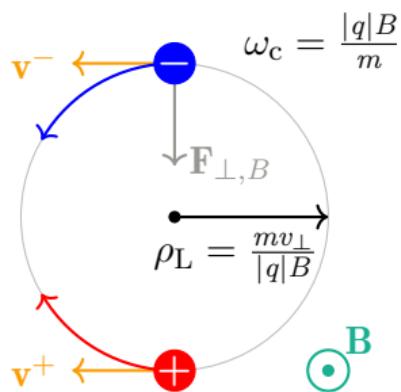
CHARGED PARTICLE MOTION

Lorentz force

$$F_{\perp,B} = |q|v_{\perp}B$$

Electric force

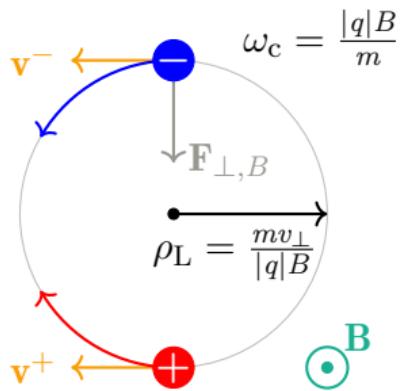
$$F_{\parallel,E} = qE_{\parallel}$$



CHARGED PARTICLE MOTION

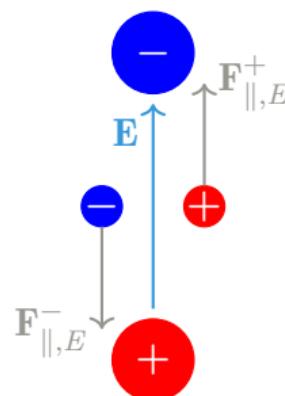
Lorentz force

$$F_{\perp,B} = |q|v_{\perp}B$$



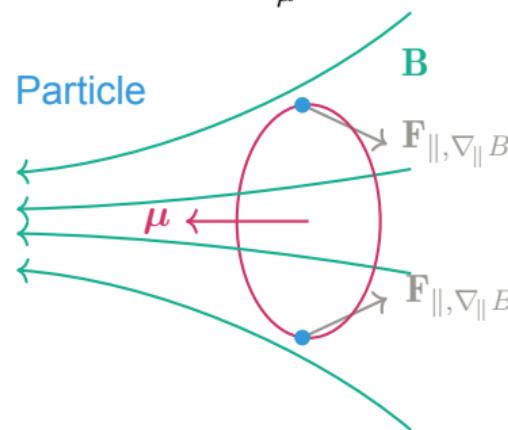
Electric force

$$F_{\parallel,E} = qE_{\parallel}$$



Inhomogeneous magnetic field

$$F_{\parallel,\nabla_{\parallel}B} = - \underbrace{\frac{mv_{\perp}^2}{2B}}_{\mu} \nabla_{\parallel}B$$

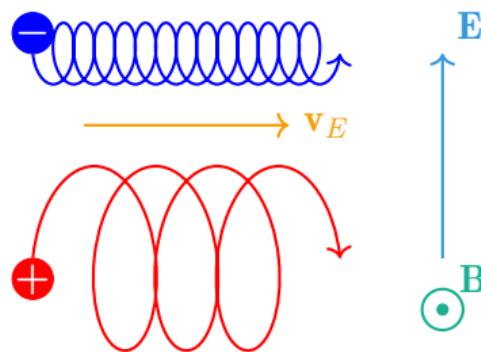


DRIFT IN THE GYROCENTER

DRIFT IN THE GYROCENTER

E × B Drift

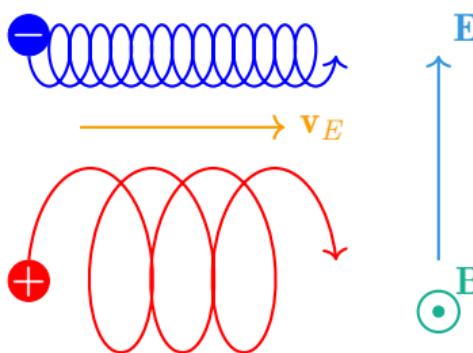
$$\mathbf{v}_E = \frac{\mathbf{E} \times \mathbf{B}}{B^2}$$



DRIFT IN THE GYROCENTER

$E \times B$ Drift

$$\mathbf{v}_E = \frac{\mathbf{E} \times \mathbf{B}}{B^2}$$

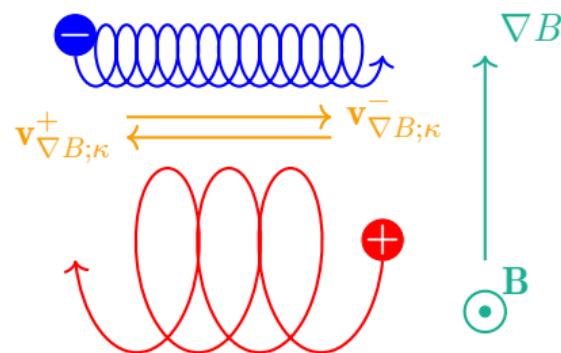


∇B Drift

$$\mathbf{v}_{\nabla B} = \frac{mv_{\perp}^2}{2q} \frac{\mathbf{B} \times \nabla B}{B^3}$$

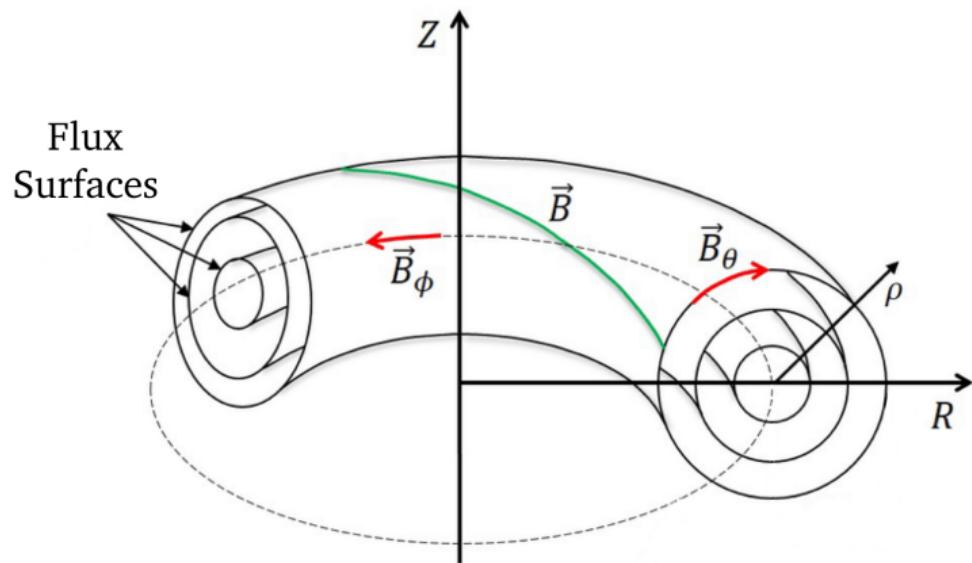
Curvature Drift

$$\mathbf{v}_{\kappa} = \frac{mv_{\parallel}^2}{qB^2} \mathbf{B} \times \underbrace{\kappa}_{\frac{\nabla B}{B}} = \frac{mv_{\parallel}^2}{q} \frac{\mathbf{B} \times \nabla B}{B^3}$$



MAGNETIC CONFINEMENT IN TOKAMAK

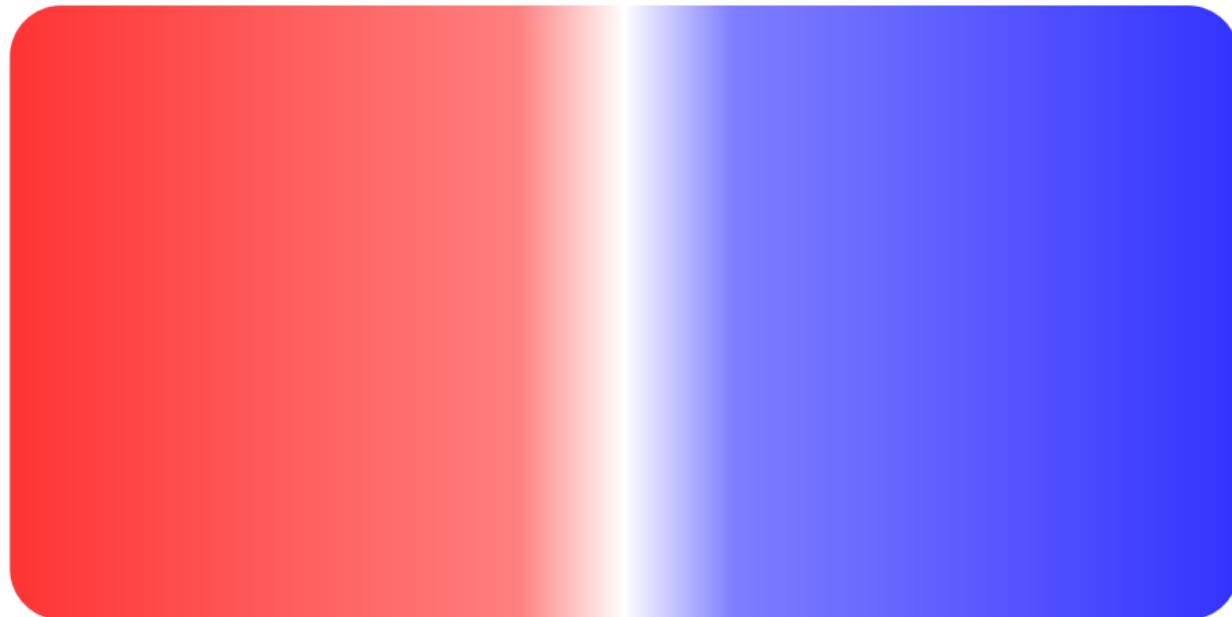
MAGNETIC CONFINEMENT IN TOKAMAK



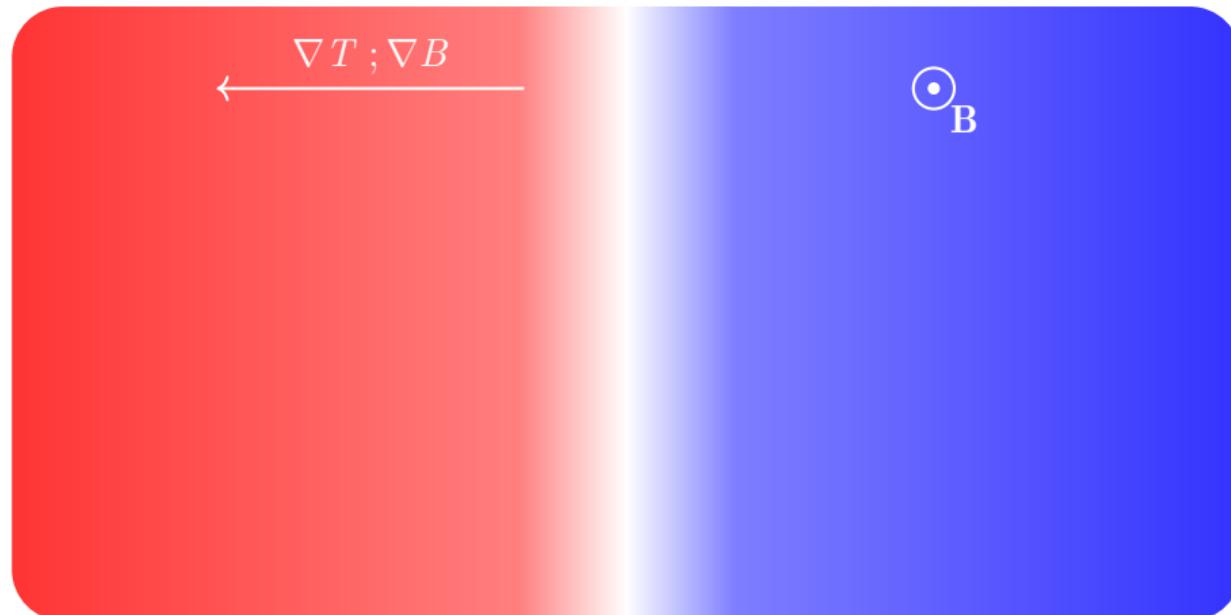
$$\beta = \frac{nT}{\mu_0 B^2/2}$$

ION TEMPERATURE GRADIENT (ITG)-DRIVEN INSTABILITY

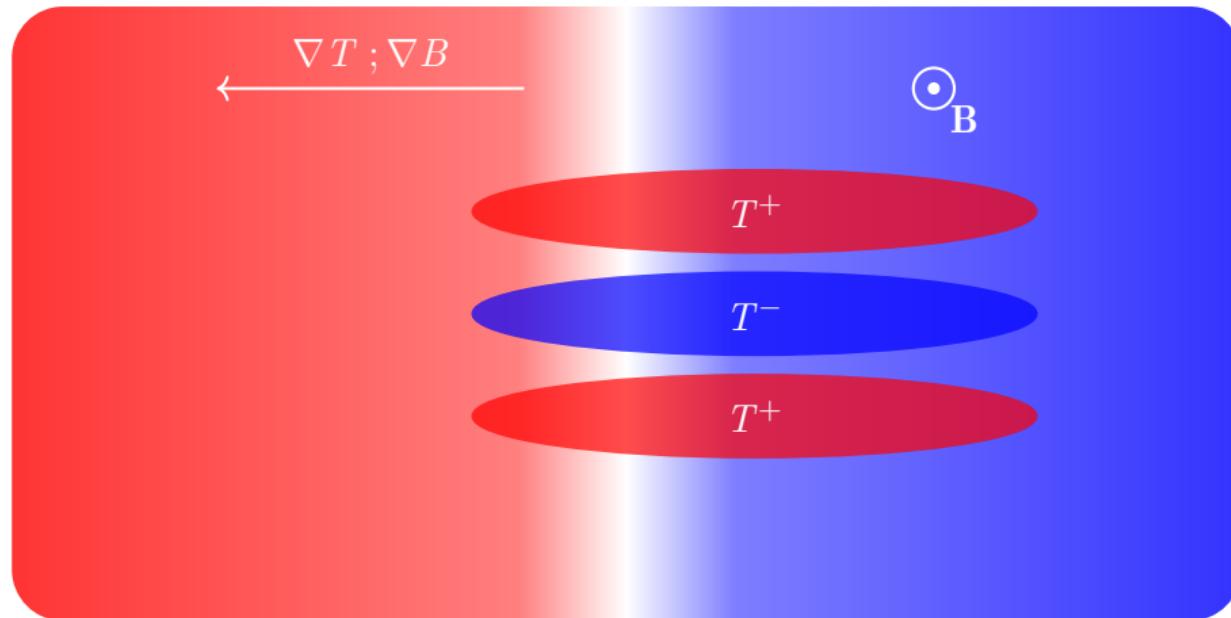
ION TEMPERATURE GRADIENT (ITG)-DRIVEN INSTABILITY



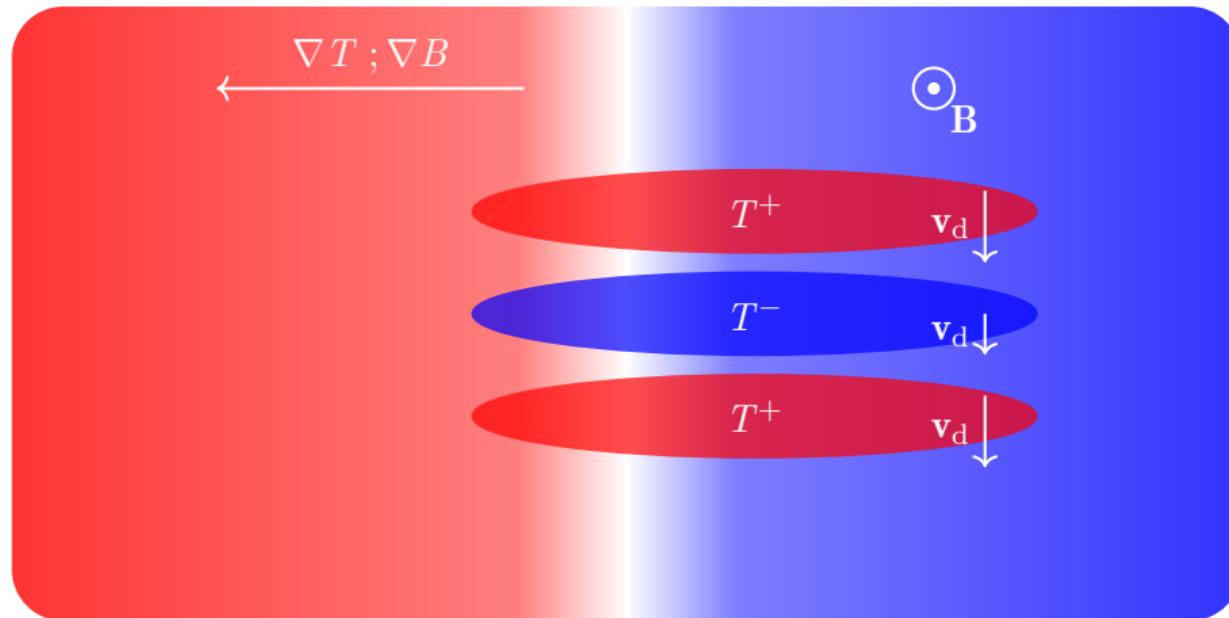
ION TEMPERATURE GRADIENT (ITG)-DRIVEN INSTABILITY



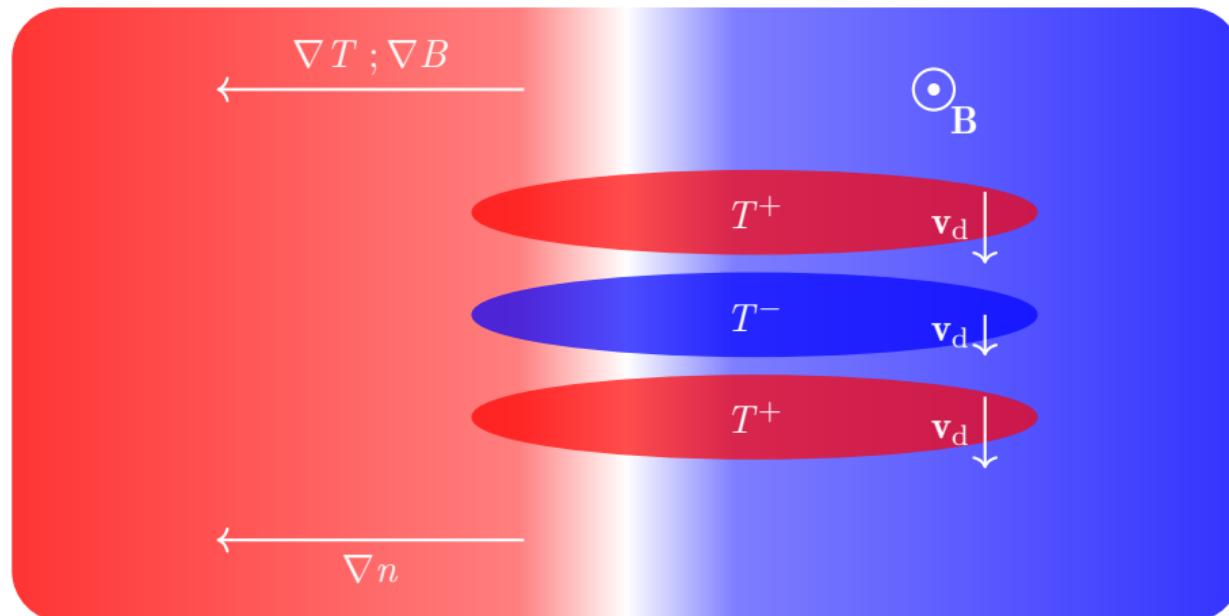
ION TEMPERATURE GRADIENT (ITG)-DRIVEN INSTABILITY



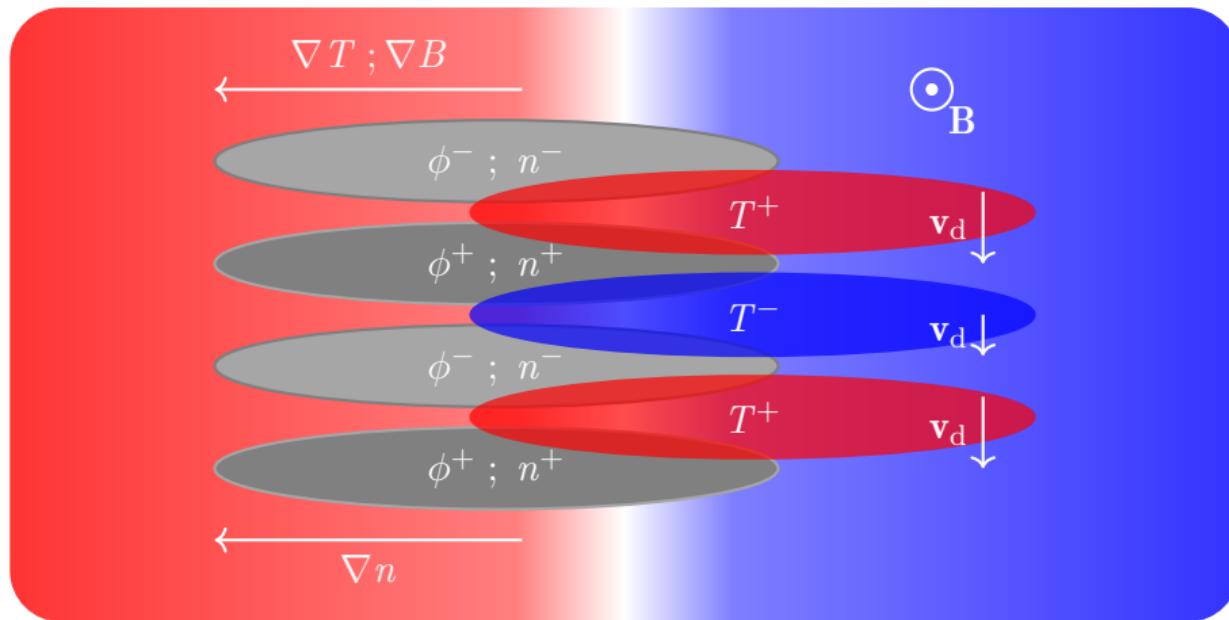
ION TEMPERATURE GRADIENT (ITG)-DRIVEN INSTABILITY



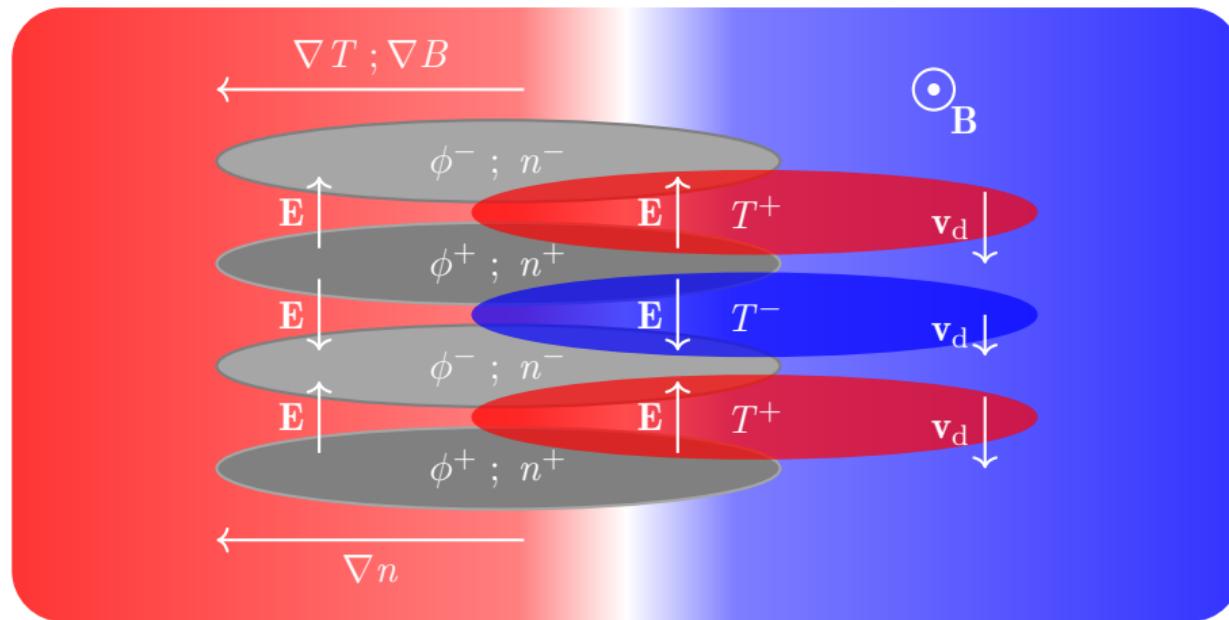
ION TEMPERATURE GRADIENT (ITG)-DRIVEN INSTABILITY



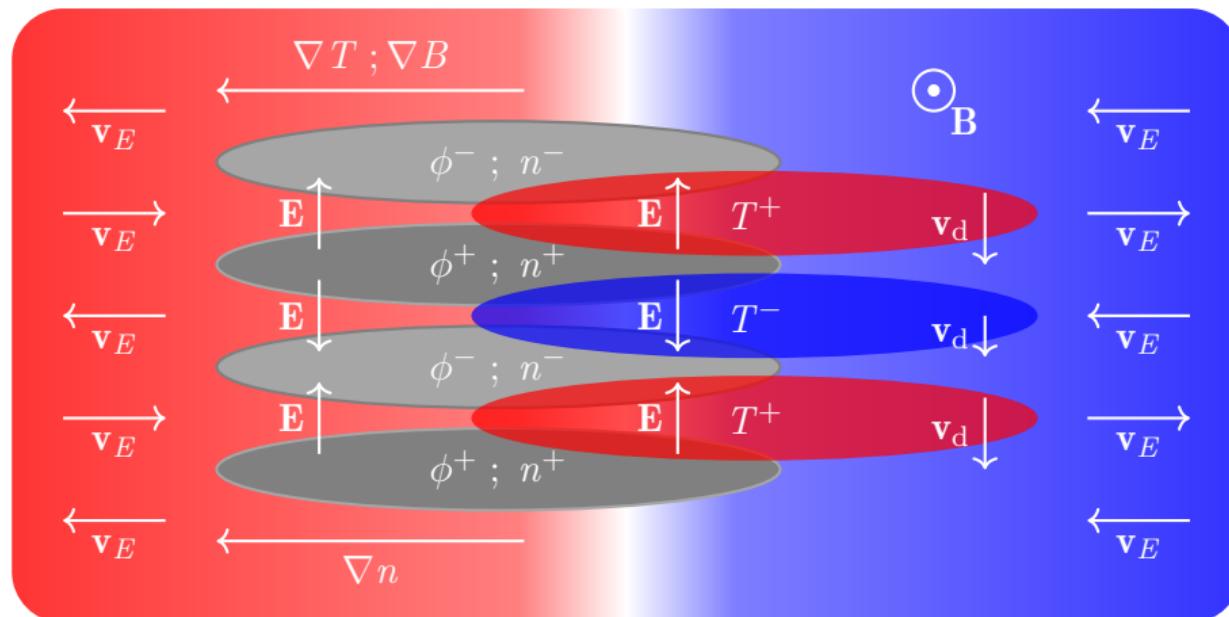
ION TEMPERATURE GRADIENT (ITG)-DRIVEN INSTABILITY



ION TEMPERATURE GRADIENT (ITG)-DRIVEN INSTABILITY

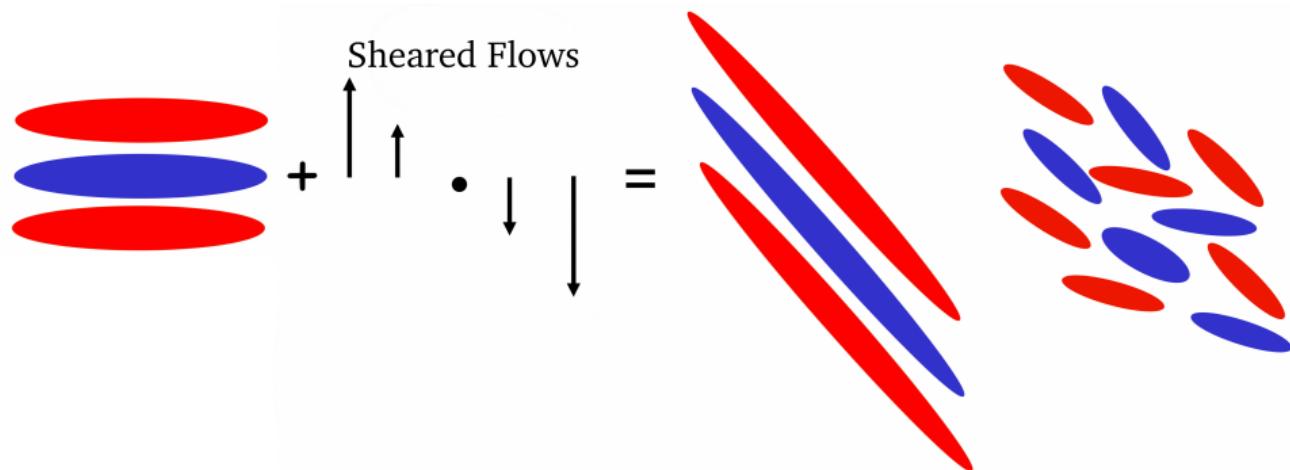


ION TEMPERATURE GRADIENT (ITG)-DRIVEN INSTABILITY



ZONAL FLOWS

ZONAL FLOWS



SHEARING RATE

SHEARING RATE

Pattern formation occurs in the stabilized tokamak plasma the so-called $E \times B$ staircase structure.

SHEARING RATE

Pattern formation occurs in the stabilized tokamak plasma the so-called $E \times B$ staircase structure.

Properties:

SHEARING RATE

Pattern formation occurs in the stabilized tokamak plasma the so-called $E \times B$ staircase structure.

Properties:

- (1) *Radial mesoscale* of order of $\rho_L < 10 \rho < R$

SHEARING RATE

Pattern formation occurs in the stabilized tokamak plasma the so-called $E \times B$ staircase structure.

Properties:

- (1) *Radial mesoscale* of order of $\rho_L < 10 \rho < R$
- (2) *Quasi stationary* in space

SHEARING RATE

Pattern formation occurs in the stabilized tokamak plasma the so-called $E \times B$ staircase structure.

Properties:

- (1) *Radial mesoscale* of order of $\rho_L < 10 \rho < R$
- (2) *Quasi stationary* in space
- (3) Time scales much longer than the typical turbulence time scales

SHEARING RATE

Pattern formation occurs in the stabilized tokamak plasma the so-called $E \times B$ staircase structure.

Properties:

- (1) *Radial mesoscale* of order of $\rho_L < 10 \rho < R$
- (2) *Quasi stationary* in space
- (3) Time scales much longer than the typical turbulence time scales
- (4) *Typical amplitude* of the order of $10^{-1} v_{th}/R$.

SHEARING RATE

Pattern formation occurs in the stabilized tokamak plasma the so-called $E \times B$ staircase structure.

Properties:

- (1) *Radial mesoscale* of order of $\rho_L < 10 \rho < R$
- (2) *Quasi stationary* in space
- (3) Time scales much longer than the typical turbulence time scales
- (4) *Typical amplitude* of the order of $10^{-1} v_{th}/R$.
- (5) Turbulent transport strongly linked to the local $E \times B$ shearing through *avalanches*

SHEARING RATE

Pattern formation occurs in the stabilized tokamak plasma the so-called $E \times B$ staircase structure.

Properties:

- (1) *Radial mesoscale* of order of $\rho_L < 10 \rho < R$
- (2) *Quasi stationary* in space
- (3) Time scales much longer than the typical turbulence time scales
- (4) *Typical amplitude* of the order of $10^{-1} v_{th}/R$.
- (5) Turbulent transport strongly linked to the local $E \times B$ shearing through *avalanches*

$$\omega_{E \times B} = \frac{1}{2} \frac{\partial^2 \langle \phi \rangle}{\partial x^2} \quad \langle \phi \rangle = \frac{1}{L_y} \int_0^{L_y} dy \phi(x, y, s=0)$$

GYROKINETICS

GYROKINETICS

$$\frac{\partial f}{\partial t} + \frac{\partial f}{\partial \mathbf{x}} \cdot \frac{d\mathbf{x}}{dt} + \frac{\partial f}{\partial \mathbf{v}} \cdot \frac{d\mathbf{v}}{dt} = 0 \quad f(\mathbf{x}, \mathbf{v}, t)$$

Vlasov Equation

GYROKINETICS

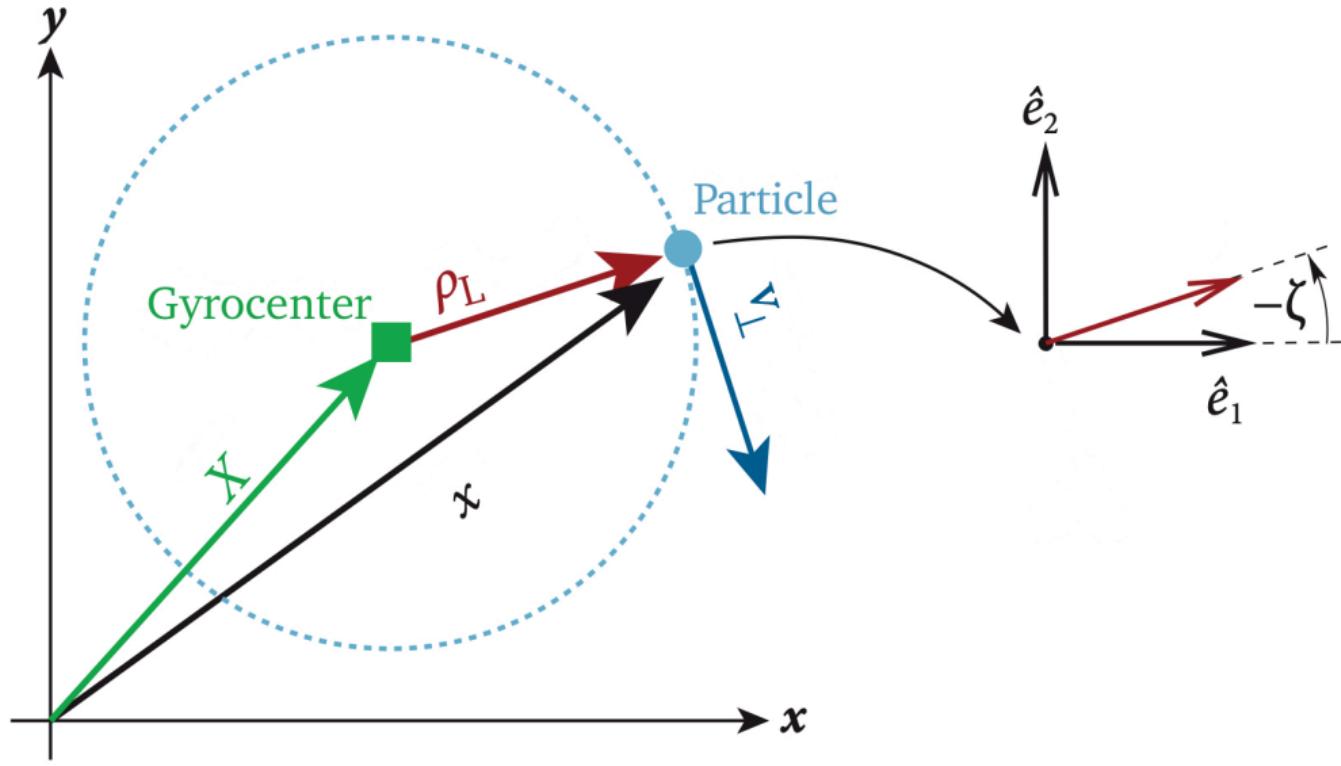
$$\frac{\partial f}{\partial t} + \frac{\partial f}{\partial \mathbf{x}} \cdot \frac{d\mathbf{x}}{dt} + \frac{\partial f}{\partial \mathbf{v}} \cdot \frac{d\mathbf{v}}{dt} = 0 \quad f(\mathbf{x}, \mathbf{v}, t)$$

Vlasov Equation

$$\Downarrow \quad \frac{\omega}{\omega_c} \sim \frac{k_{\parallel}}{k_{\perp}} \sim \frac{\rho}{L_n} \sim \frac{\delta n}{n_0} \sim \frac{\delta B}{B_0} \sim \frac{v_d}{v_{th}} \sim \epsilon_g$$

Gyrokinetic Ordering

GYROKINETICS



GYROKINETICS

$$\frac{\partial f}{\partial t} + \frac{\partial f}{\partial \mathbf{x}} \cdot \frac{d\mathbf{x}}{dt} + \frac{\partial f}{\partial \mathbf{v}} \cdot \frac{d\mathbf{v}}{dt} = 0 \quad f(\mathbf{x}, \mathbf{v}, t)$$

Vlasov Equation

$$\Downarrow \quad \frac{\omega}{\omega_c} \sim \frac{k_{\parallel}}{k_{\perp}} \sim \frac{\rho}{L_n} \sim \frac{\delta n}{n_0} \sim \frac{\delta B}{B_0} \sim \frac{v_d}{v_{th}} \sim \epsilon_g$$

Gyrokinetic Ordering

$$\frac{\partial f}{\partial t} + \frac{\partial f}{\partial \mathbf{X}} \cdot \frac{d\mathbf{X}}{dt} + \frac{\partial f}{\partial v_{\parallel}} \cdot \frac{dv_{\parallel}}{dt} = 0 \quad f(\mathbf{X}, v_{\parallel}, \mu) ; \frac{d\mu}{dt} = 0$$

Gyrokinetic Formalism

GYROKINETICS

$$\frac{\partial f}{\partial t} + \frac{\partial f}{\partial \mathbf{x}} \cdot \frac{d\mathbf{x}}{dt} + \frac{\partial f}{\partial \mathbf{v}} \cdot \frac{d\mathbf{v}}{dt} = 0 \quad f(\mathbf{x}, \mathbf{v}, t)$$

Vlasov Equation

$$\Downarrow \quad \frac{\omega}{\omega_c} \sim \frac{k_{\parallel}}{k_{\perp}} \sim \frac{\rho}{L_n} \sim \frac{\delta n}{n_0} \sim \frac{\delta B}{B_0} \sim \frac{v_d}{v_{th}} \sim \epsilon_g$$

Gyrokinetic Ordering

$$\frac{\partial f}{\partial t} + \frac{\partial f}{\partial \mathbf{X}} \cdot \frac{d\mathbf{X}}{dt} + \frac{\partial f}{\partial v_{\parallel}} \cdot \frac{dv_{\parallel}}{dt} = 0 \quad f(\mathbf{X}, v_{\parallel}, \mu) ; \frac{d\mu}{dt} = 0$$

Gyrokinetic Formalism

$$\Downarrow \quad f = f_0 + \delta f$$

δf Approx & Local Limit

GYROKINETICS

$$\frac{\partial f}{\partial t} + \frac{\partial f}{\partial \mathbf{x}} \cdot \frac{d\mathbf{x}}{dt} + \frac{\partial f}{\partial \mathbf{v}} \cdot \frac{d\mathbf{v}}{dt} = 0 \quad f(\mathbf{x}, \mathbf{v}, t) \quad \text{Vlasov Equation}$$

$$\Downarrow \quad \frac{\omega}{\omega_c} \sim \frac{k_{\parallel}}{k_{\perp}} \sim \frac{\rho}{L_n} \sim \frac{\delta n}{n_0} \sim \frac{\delta B}{B_0} \sim \frac{v_d}{v_{th}} \sim \epsilon_g \quad \text{Gyrokinetic Ordering}$$

$$\frac{\partial f}{\partial t} + \frac{\partial f}{\partial \mathbf{X}} \cdot \frac{d\mathbf{X}}{dt} + \frac{\partial f}{\partial v_{\parallel}} \cdot \frac{dv_{\parallel}}{dt} = 0 \quad f(\mathbf{X}, v_{\parallel}, \mu); \quad \frac{d\mu}{dt} = 0 \quad \text{Gyrokinetic Formalism}$$

$$\Downarrow \quad f = f_0 + \delta f \quad \delta f \text{ Approx & Local Limit}$$

$$\frac{\partial g}{\partial t} + \mathbf{v}_{\chi} \cdot \nabla g + (v_{\parallel} \mathbf{b} + \mathbf{v}_D) \cdot \nabla (\delta f) - \frac{\mu B}{m} \frac{\mathbf{B} \cdot \nabla B}{B^2} \frac{\partial (\delta f)}{\partial v_{\parallel}} = S \quad \text{Gyrokinetic Equation}$$

$$g \sim (f_0 + \delta f) \quad S \sim (f + f_0) \quad \mathbf{v}_D \sim \nabla B \quad \mathbf{v}_{\chi} \sim \mathbf{E} \times \mathbf{B} \quad f(x, y, s, v_{\parallel}, \mu)$$

SIMULATION SETUP

SIMULATION SETUP

- Non-linear flux tube version of Gyrokinetic Workshop (GKW)

SIMULATION SETUP

- Non-linear flux tube version of Gyrokinetic Workshop (GKW)
- Circular concentric flux surfaces

SIMULATION SETUP

- Non-linear flux tube version of Gyrokinetic Workshop (GKW)
- Circular concentric flux surfaces
- Standard resolution with 6th order (S6)

	N_m	N_x	N_s	$N_{\nu_{ }}$	N_μ	D	ν_d	$D_{\nu_{ }}$	D_x	D_y	Order	$k_y \rho$	$k_x \rho$
S6	21	83	16	64	9	1	$ \nu_{ } $	0.2	0.1	0.1	6	1.4	2.1

SIMULATION SETUP

- Non-linear flux tube version of Gyrokinetic Workshop (GKW)
- Circular concentric flux surfaces
- Standard resolution with 6th order (S6)
- Cyclone Base Case (CBC) parameters $R/L_T = 6.0$

	N_m	N_x	N_s	$N_{\nu_{ }}$	N_μ	D	ν_d	$D_{\nu_{ }}$	D_x	D_y	Order	$k_y \rho$	$k_x \rho$
S6	21	83	16	64	9	1	$ \nu_{ } $	0.2	0.1	0.1	6	1.4	2.1

SIMULATION SETUP

- Non-linear flux tube version of Gyrokinetic Workshop (GKW)
- Circular concentric flux surfaces
- Standard resolution with 6th order (S6)
- Cyclone Base Case (CBC) parameters $R/L_T = 6.0$
- Turbulence level is quantified by the turbulent heat conduction coefficient χ (normalized by $\rho^2 v_{\text{th}}/R$ ($v_{\text{th}} = \sqrt{2T/m}$ and $\rho = \frac{mv_{\text{th}}}{|q|B}$))

	N_m	N_x	N_s	$N_{\nu_{ }}$	N_μ	D	ν_d	$D_{\nu_{ }}$	D_x	D_y	Order	$k_y\rho$	$k_x\rho$
S6	21	83	16	64	9	1	$ \nu_{ } $	0.2	0.1	0.1	6	1.4	2.1

SIMULATION SETUP

- Non-linear flux tube version of Gyrokinetic Workshop (GKW)
- Circular concentric flux surfaces
- Standard resolution with 6th order (S6)
- Cyclone Base Case (CBC) parameters $R/L_T = 6.0$
- Turbulence level is quantified by the turbulent heat conduction coefficient χ (normalized by $\rho^2 v_{\text{th}}/R$ ($v_{\text{th}} = \sqrt{2T/m}$ and $\rho = \frac{mv_{\text{th}}}{|q|B}$))
- Quantities ρ , R , T , v_{th} and m are referenced quantities

	N_m	N_x	N_s	$N_{\nu_{\parallel}}$	N_{μ}	D	ν_d	$D_{\nu_{\parallel}}$	D_x	D_y	Order	$k_y\rho$	$k_x\rho$
S6	21	83	16	64	9	1	$ \nu_{\parallel} $	0.2	0.1	0.1	6	1.4	2.1

SIMULATION SETUP

- Non-linear flux tube version of Gyrokinetic Workshop (GKW)
- Circular concentric flux surfaces
- Standard resolution with 6th order (S6)
- Cyclone Base Case (CBC) parameters $R/L_T = 6.0$
- Turbulence level is quantified by the turbulent heat conduction coefficient χ (normalized by $\rho^2 v_{\text{th}}/R$ ($v_{\text{th}} = \sqrt{2T/m}$ and $\rho = \frac{mv_{\text{th}}}{|q|B}$))
- Quantities ρ , R , T , v_{th} and m are referenced quantities
- Standard box size $(L_x, L_y) = (76.3, 89.8) \rho$

	N_m	N_x	N_s	$N_{\nu_{ }}$	N_μ	D	ν_d	$D_{\nu_{ }}$	D_x	D_y	Order	$k_y \rho$	$k_x \rho$
S6	21	83	16	64	9	1	$ \nu_{ } $	0.2	0.1	0.1	6	1.4	2.1

DIAGNOSTICS

DIAGNOSTICS

$$\omega_{E \times B} = \sum_{k_{ZF}} \hat{\omega}_{E \times B}(k_{ZF}, t) \exp(i k_{ZF} x)$$

$$k_{ZF} = 2\pi n_{ZF} / L_x$$

$$|\hat{\omega}_{E \times B}|_{n_{ZF}} = 2 |\hat{\omega}_{E \times B}(k_{ZF}, t)|$$

DIAGNOSTICS

$$\omega_{E \times B} = \sum_{k_{ZF}} \hat{\omega}_{E \times B}(k_{ZF}, t) \exp(i k_{ZF} x)$$

$$k_{ZF} = 2\pi n_{ZF} / L_x$$

$$|\hat{\omega}_{E \times B}|_{n_{ZF}} = 2 |\hat{\omega}_{E \times B}(k_{ZF}, t)|$$

- Zonal flow mode that dominates the staircase pattern are called **basic mode**

DIAGNOSTICS

$$\omega_{E \times B} = \sum_{k_{ZF}} \hat{\omega}_{E \times B}(k_{ZF}, t) \exp(i k_{ZF} x)$$

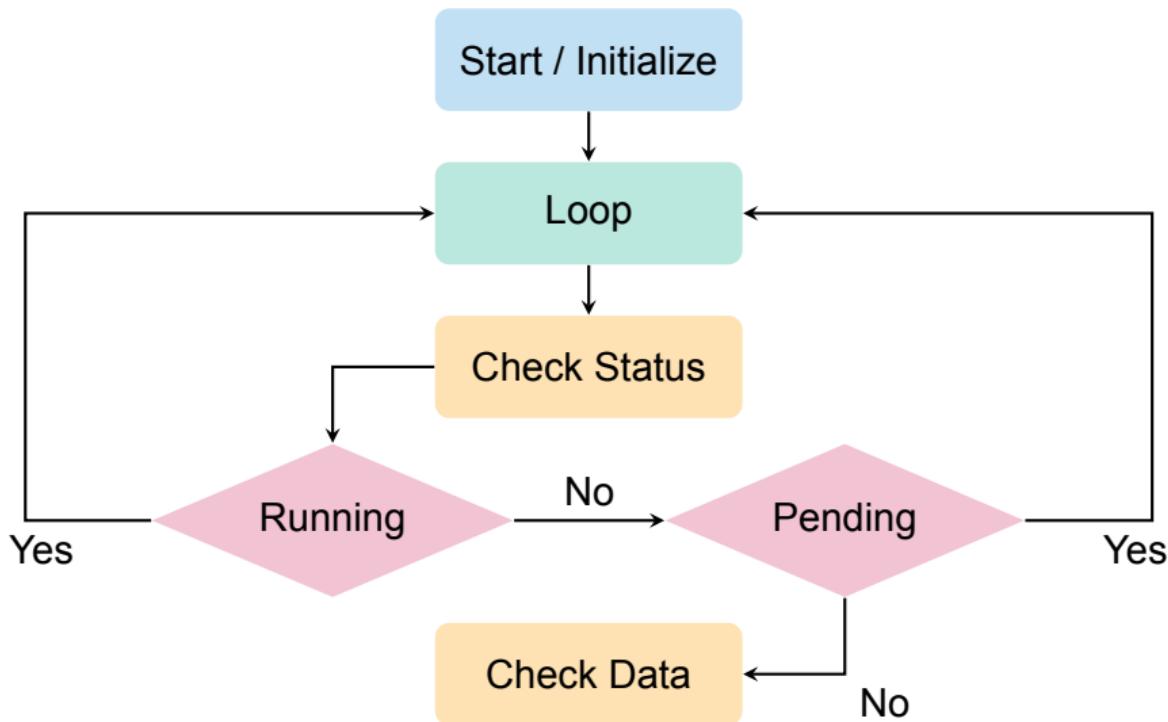
$$k_{ZF} = 2\pi n_{ZF} / L_x$$

$$|\hat{\omega}_{E \times B}|_{n_{ZF}} = 2 |\hat{\omega}_{E \times B}(k_{ZF}, t)|$$

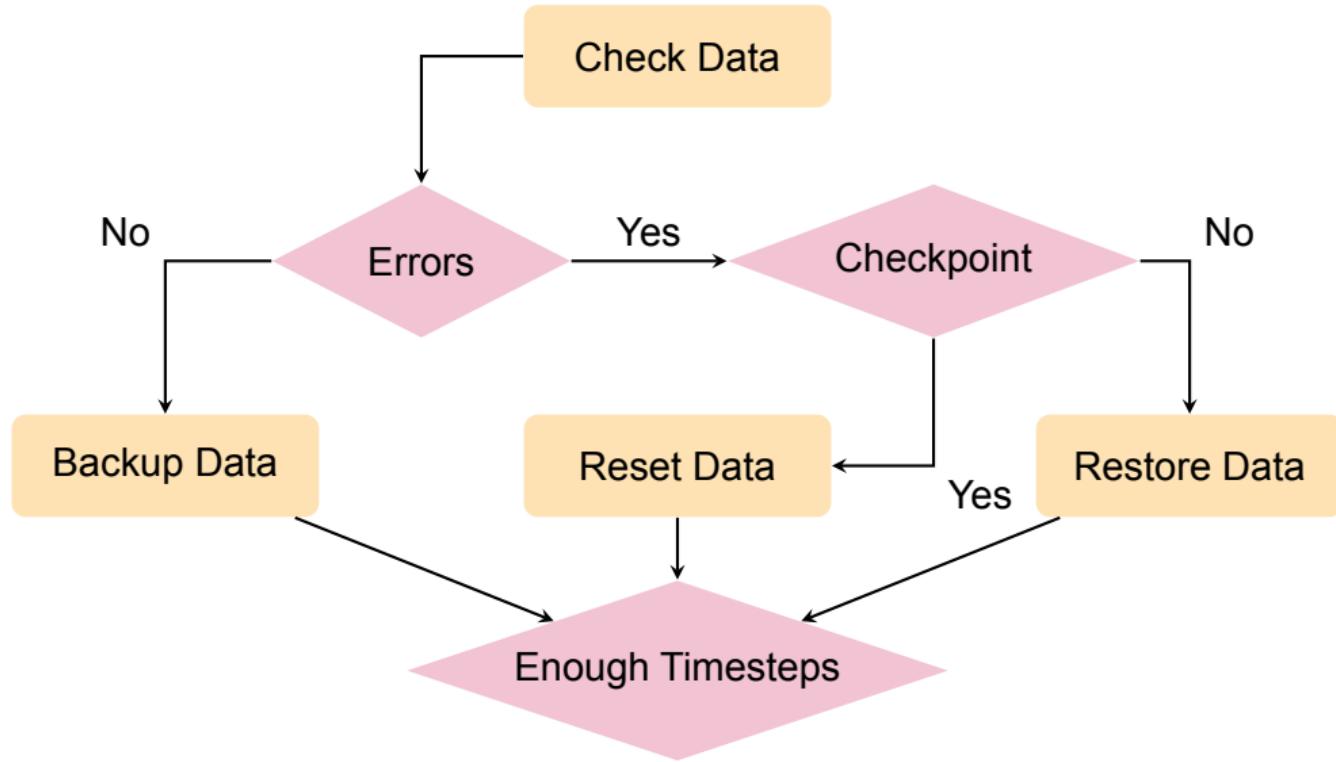
- Zonal flow mode that dominates the staircase pattern are called **basic mode**
- The basic mode exhibits the maximum amplitude in the spectrum $|\hat{\omega}_{E \times B}|_{n_{ZF}}$

RESTART SCRIPT

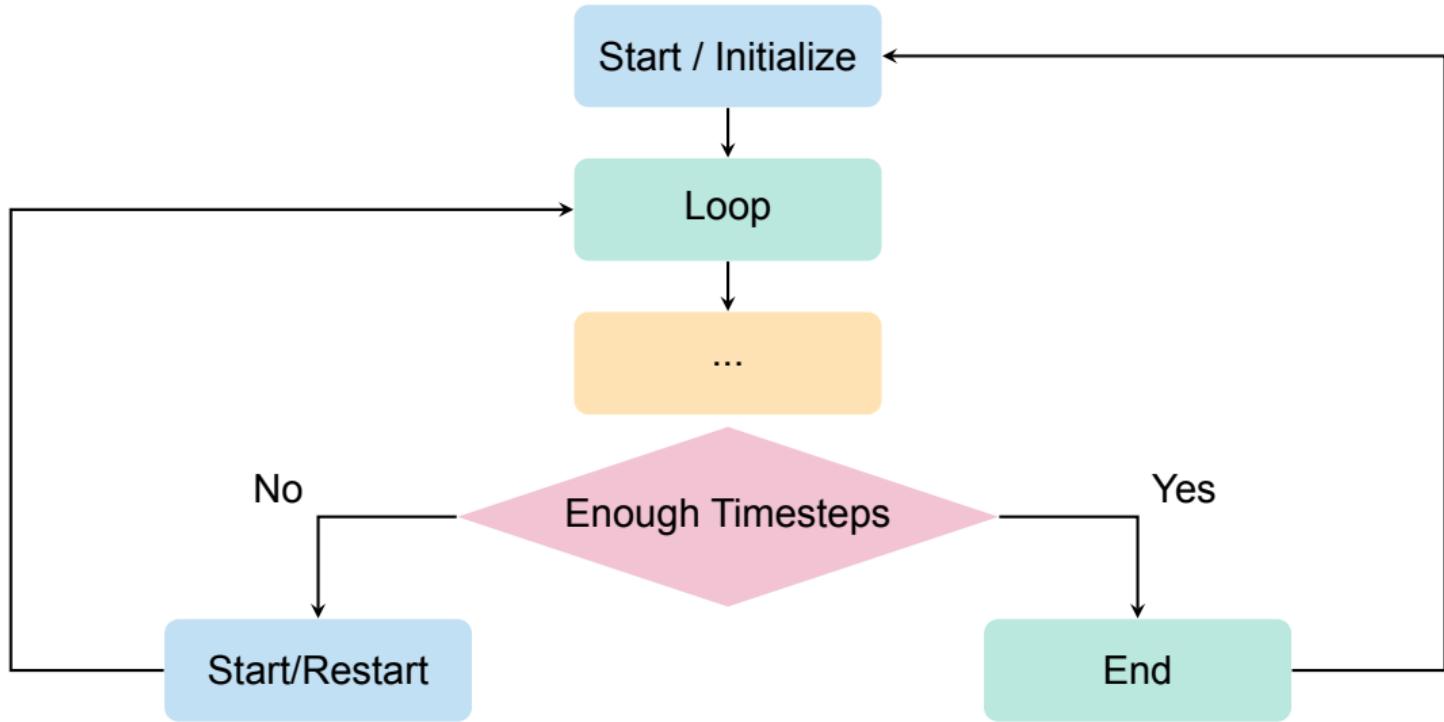
RESTART SCRIPT



RESTART SCRIPT



RESTART SCRIPT



VARIATION OF COMPUTATIONAL RESOLUTION

VARIATION OF COMPUTATIONAL RESOLUTION

Goals:

- Estimate the minimal resolution without numerical dissipation
- Reduce **calculation time** and **costs** of the simulation

VARIATION OF COMPUTATIONAL RESOLUTION

Goals:

- Estimate the minimal resolution without numerical dissipation
- Reduce **calculation time** and **costs** of the simulation

Criteria:

- (1) Subdued turbulence after **short** time periods
- (2) Stability for **long** time periods

VARIATION OF COMPUTATIONAL RESOLUTION

Goals:

- Estimate the minimal resolution without numerical dissipation
- Reduce **calculation time** and **costs** of the simulation

Criteria:

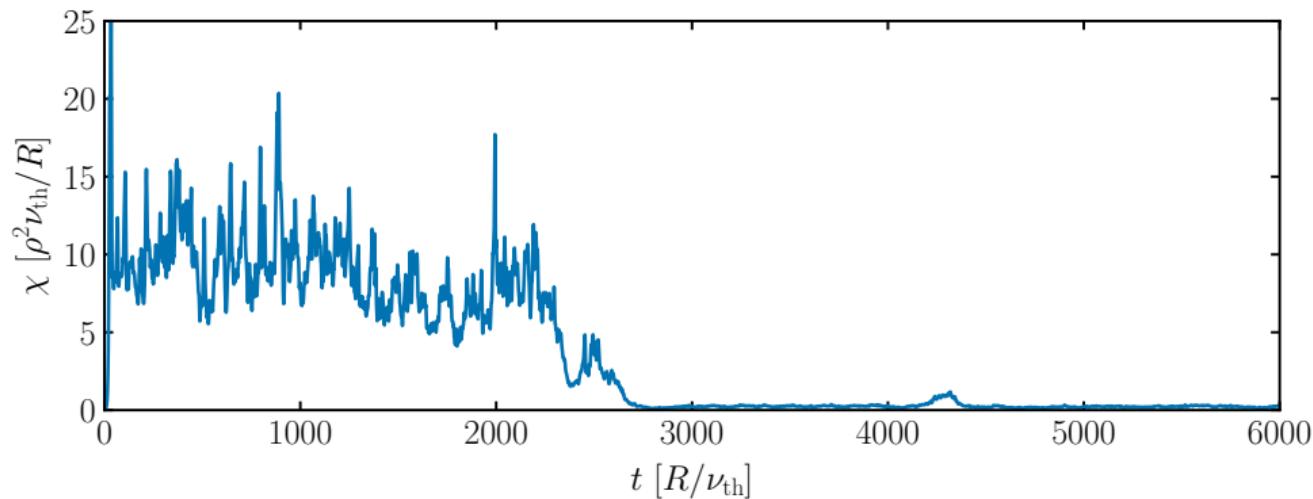
- (1) Subdued turbulence after **short** time periods
- (2) Stability for **long** time periods

Verification:

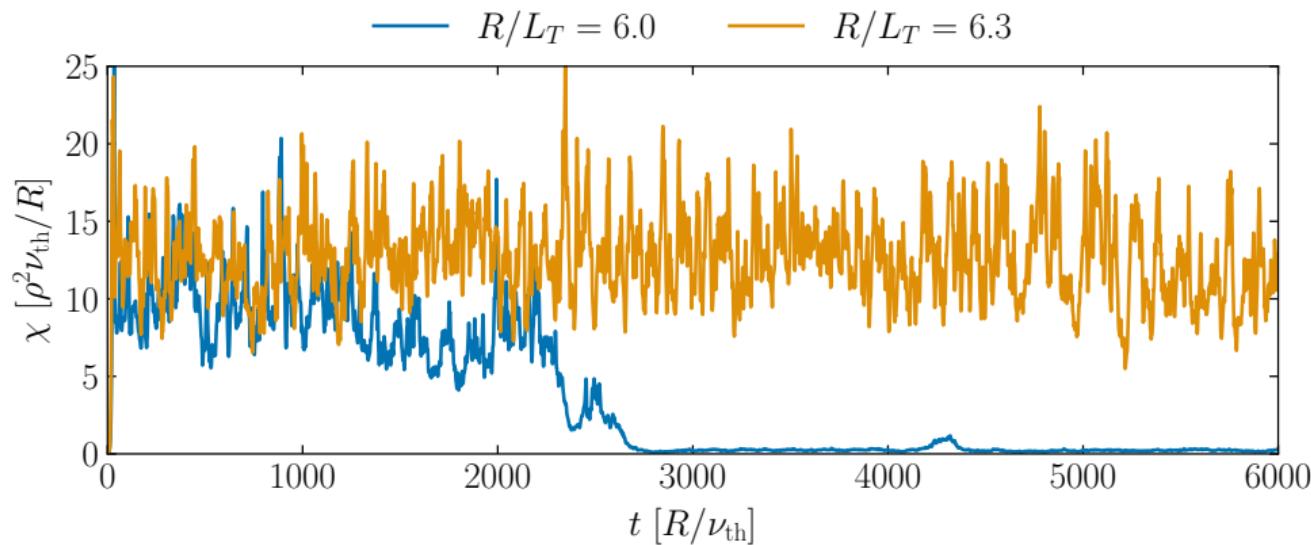
1. Reduce only one number of grid points and look if criterias (1), (2) are satisfied
2. Reduce to known the minimum number of grid points to verify result in general.

BENCHMARK

BENCHMARK

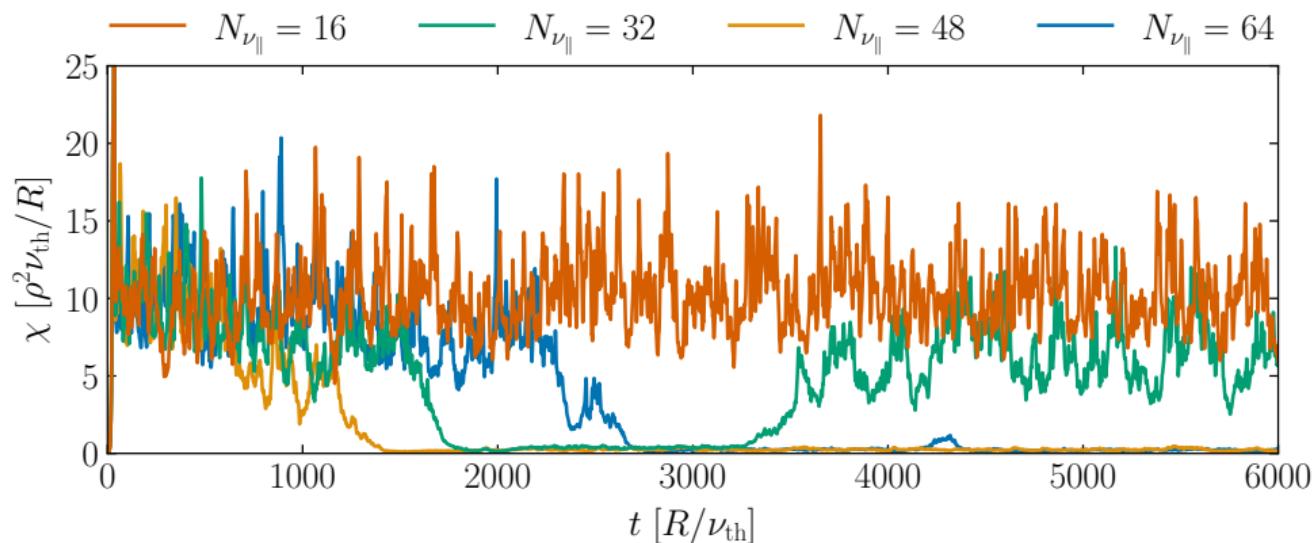


BENCHMARK

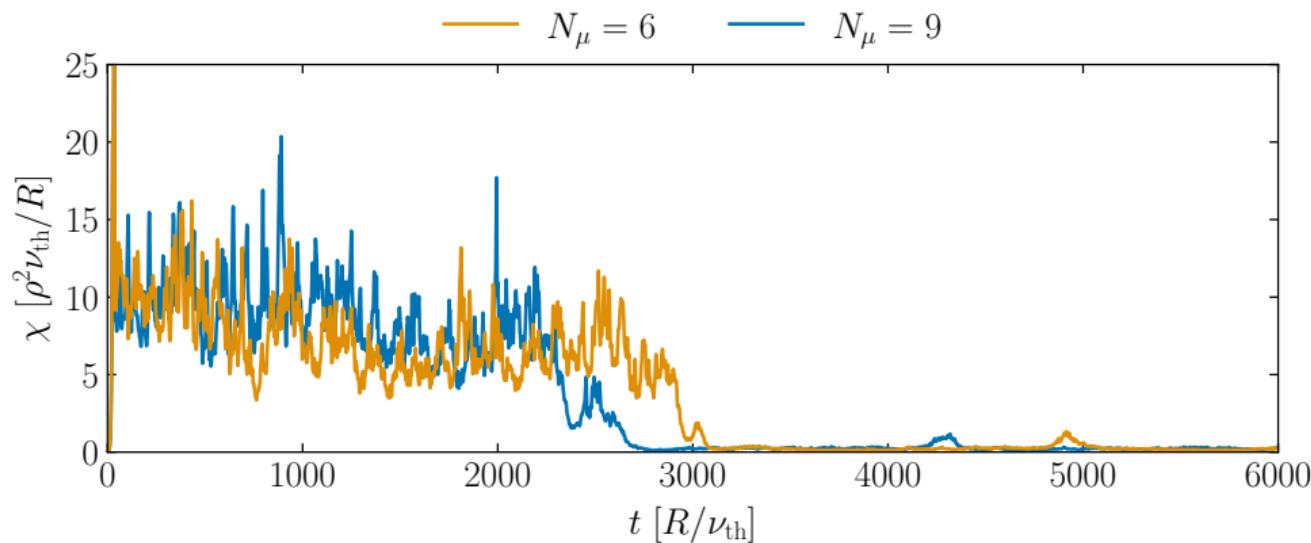


REDUCTION OF GRID POINTS

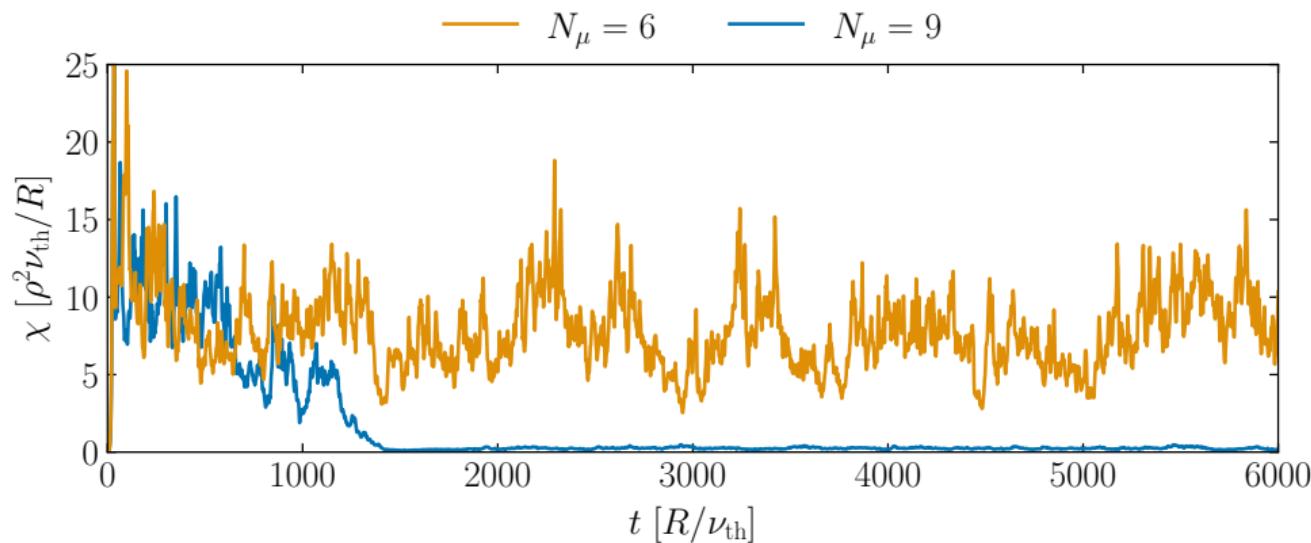
REDUCTION OF GRID POINTS



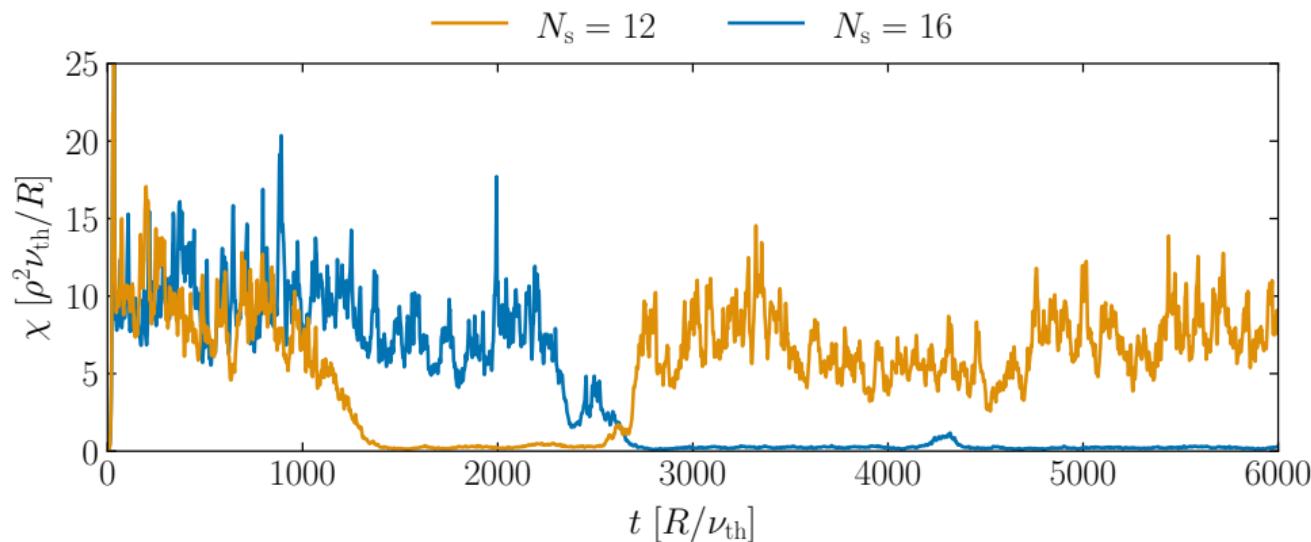
REDUCTION OF GRID POINTS



REDUCTION OF GRID POINTS



REDUCTION OF GRID POINTS



REDUCTION OF GRID POINTS

Final Resolution

	N_m	N_x	N_s	$N_{\nu_{ }}$	N_μ	D	ν_d	$D_{\nu_{ }}$	D_x	D_y	Order	$k_y \rho$	$k_x \rho$
S6	21	83	16	48	9	1	$ \nu_{ } $	0.2	0.1	0.1	6	1.4	2.1

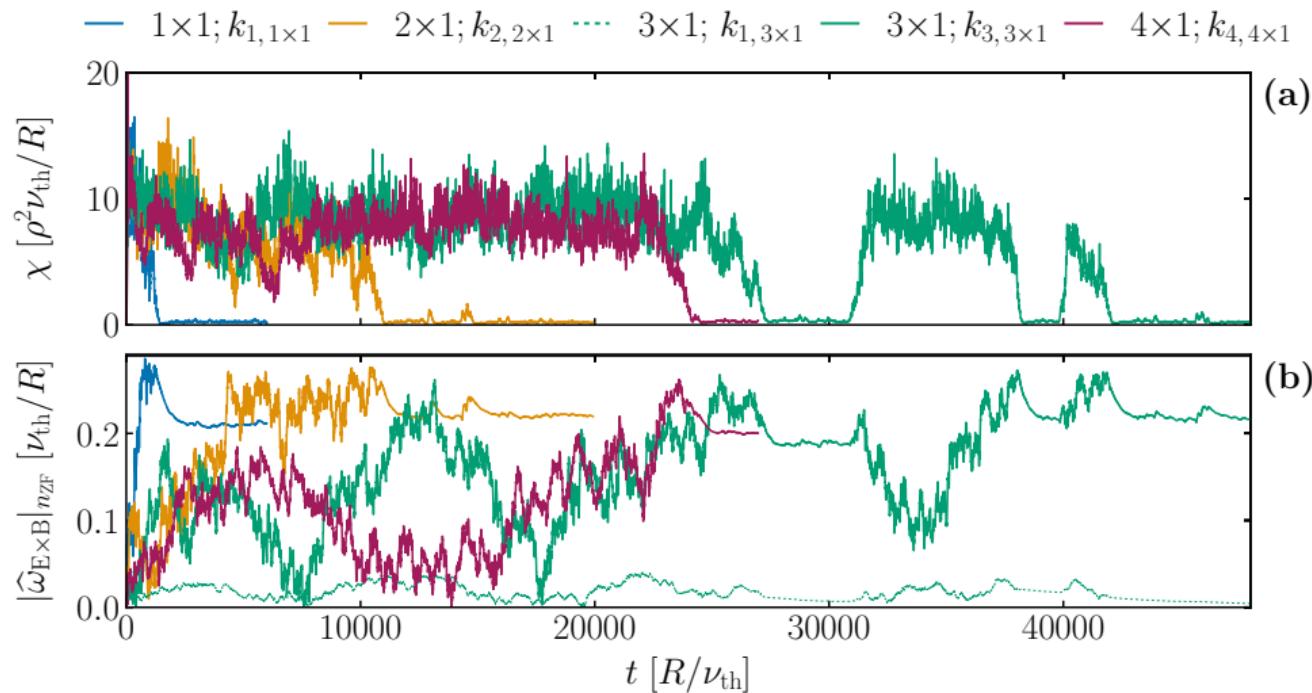
SIZE CONVERGENCE OF E × B STAIRCASE PATTERN

SIZE CONVERGENCE OF E × B STAIRCASE PATTERN

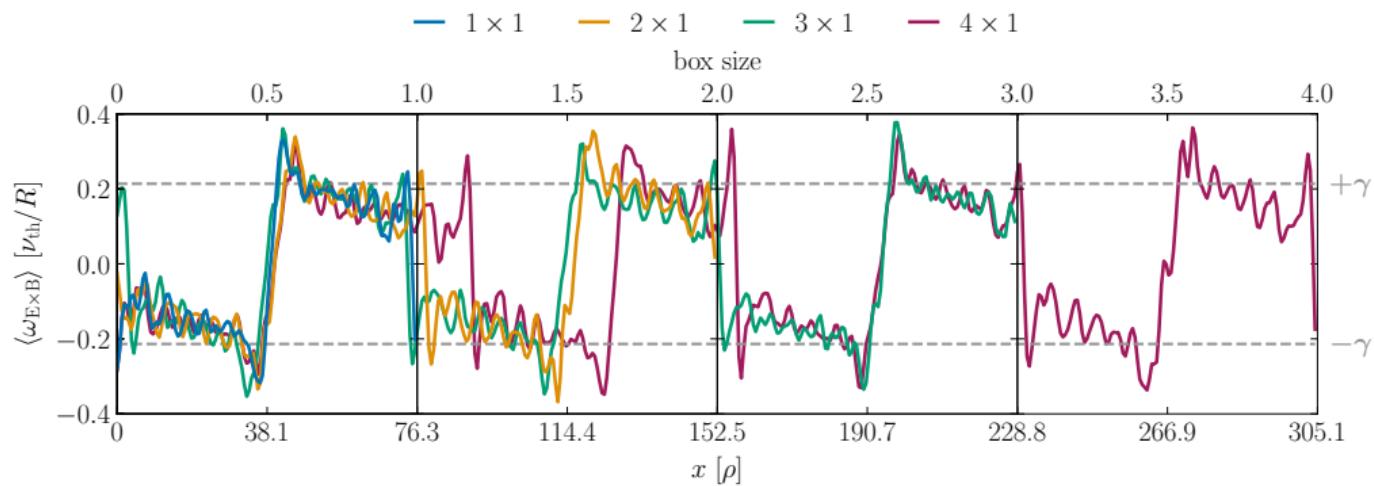
(1) Radial

$$N_R \times N_B \in [1 \times 1, 2 \times 1, 3 \times 1, 4 \times 1]$$

SIZE CONVERGENCE OF $E \times B$ STAIRCASE PATTERN



SIZE CONVERGENCE OF $E \times B$ STAIRCASE PATTERN

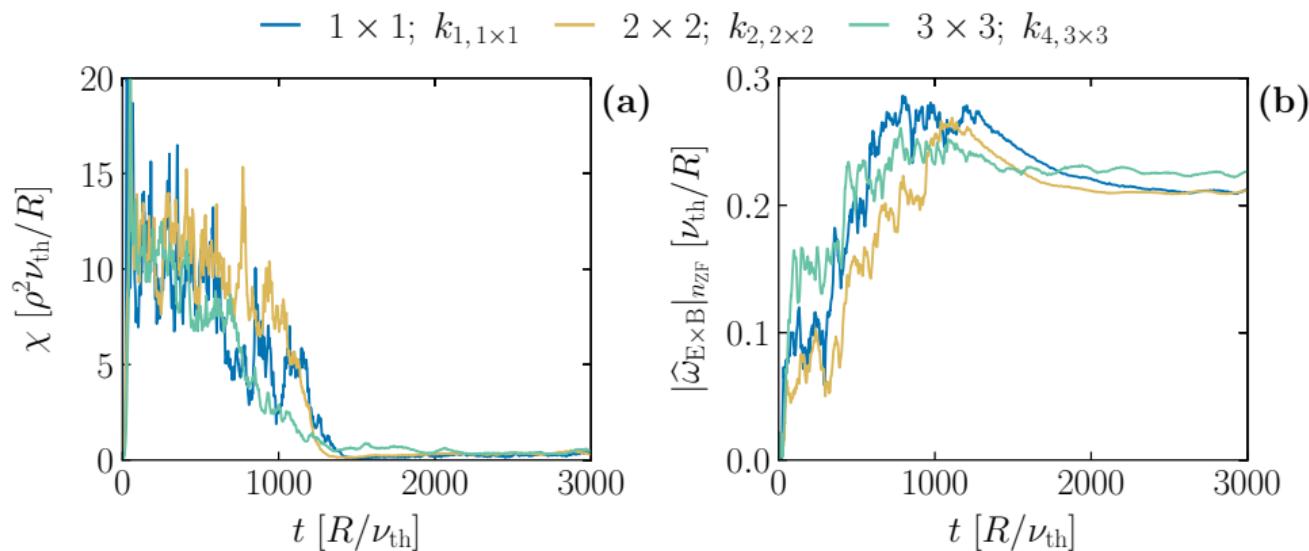


SIZE CONVERGENCE OF E × B STAIRCASE PATTERN

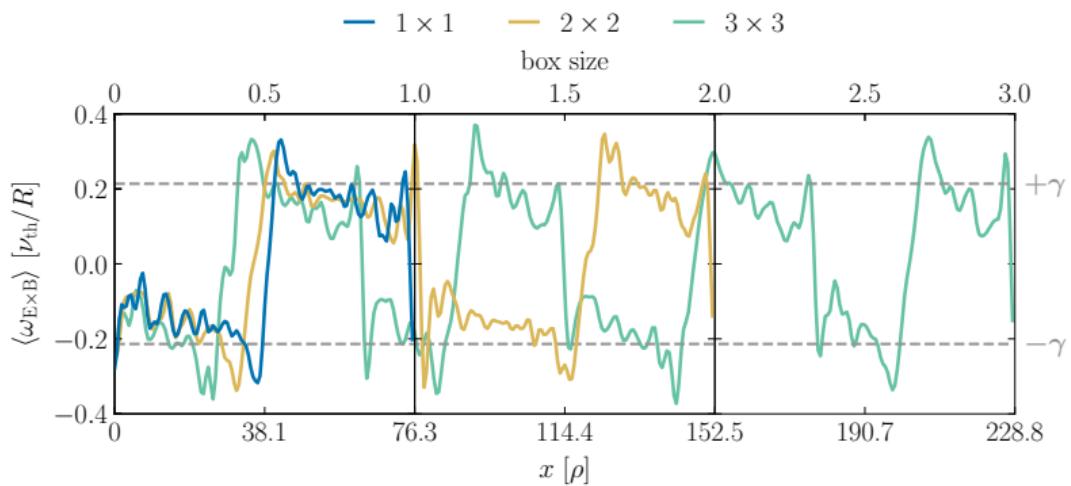
(2) Isotropic

$$N_R \times N_B \in [1 \times 1, 1.5 \times 1.5, 2 \times 2, 2.5 \times 2.5, 3 \times 3]$$

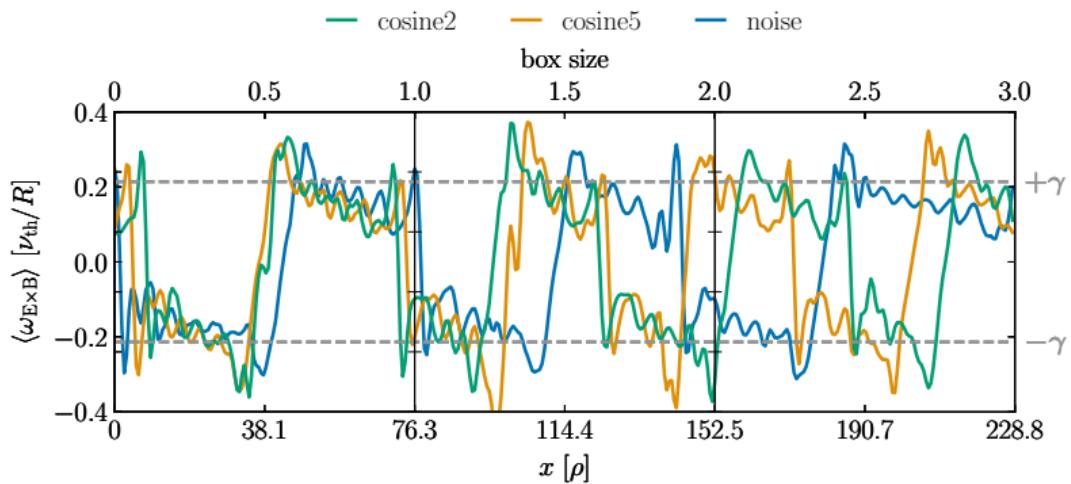
SIZE CONVERGENCE OF $E \times B$ STAIRCASE PATTERN



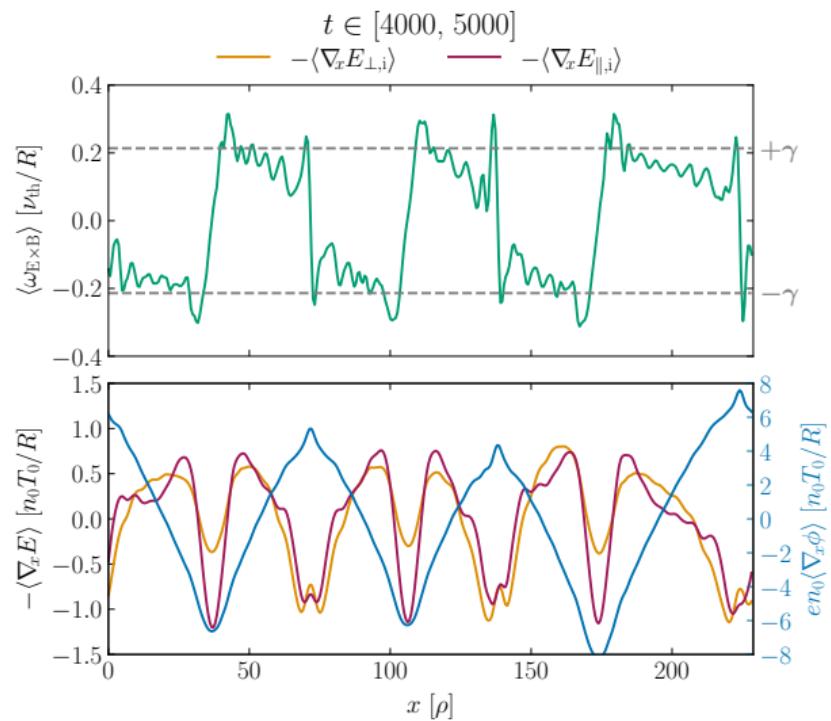
SIZE CONVERGENCE OF $E \times B$ STAIRCASE PATTERN



SIZE CONVERGENCE OF $E \times B$ STAIRCASE PATTERN



SIZE CONVERGENCE OF $E \times B$ STAIRCASE PATTERN

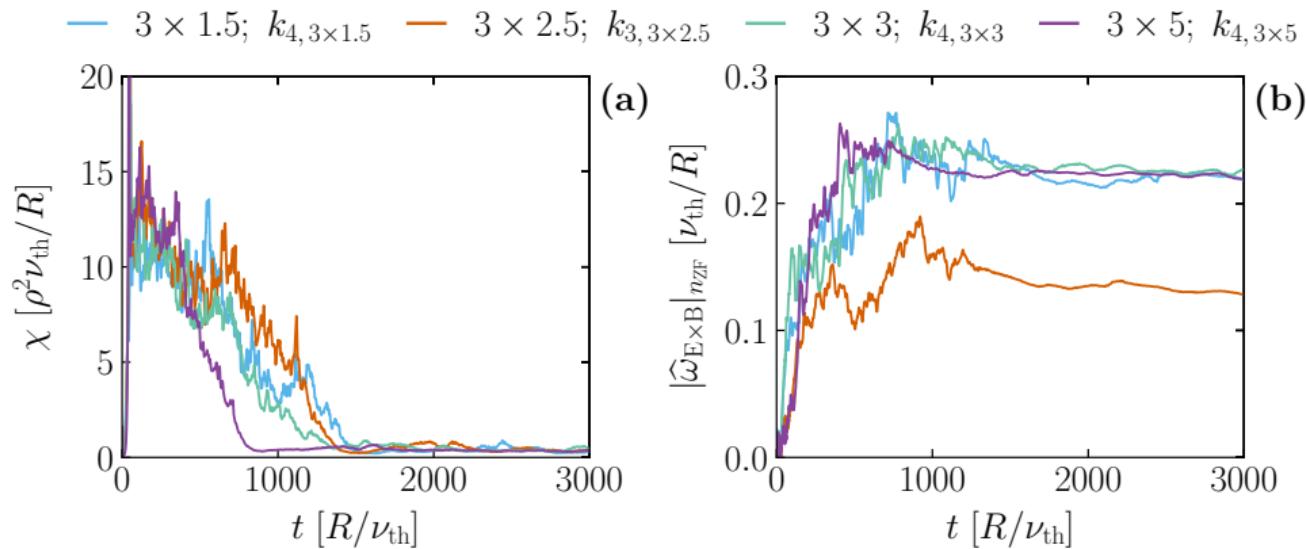


SIZE CONVERGENCE OF E × B STAIRCASE PATTERN

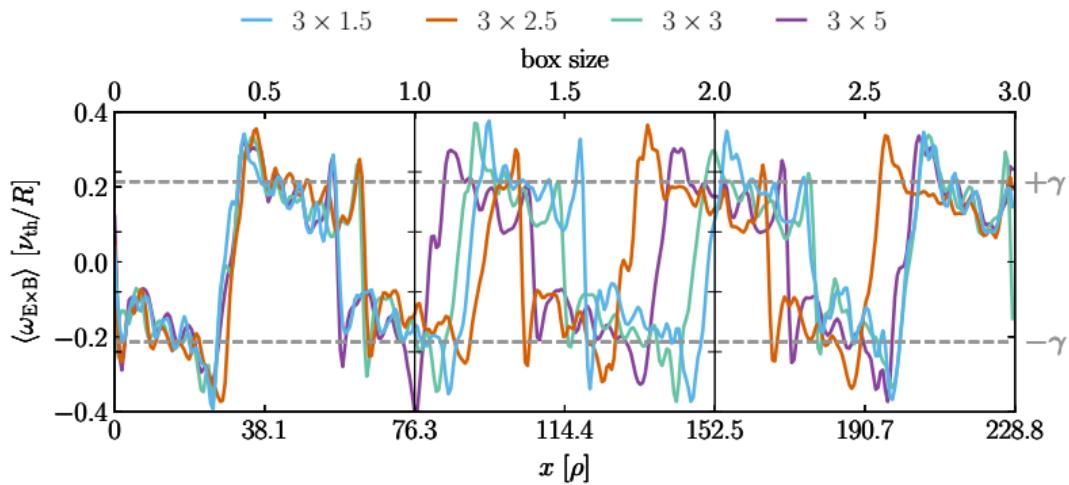
(3) Binormal

$$N_R \times N_B \in [3 \times 1.5, 3 \times 2.5, 3 \times 3, 3 \times 5]$$

SIZE CONVERGENCE OF $E \times B$ STAIRCASE PATTERN



SIZE CONVERGENCE OF $E \times B$ STAIRCASE PATTERN



SIZE CONVERGENCE OF E × B STAIRCASE PATTERN

SIZE CONVERGENCE OF $E \times B$ STAIRCASE PATTERN

Does the basic pattern size always converges to the box size, or is there a typical mesoscale size inherent to staircase structures also in a local flux-tube description?

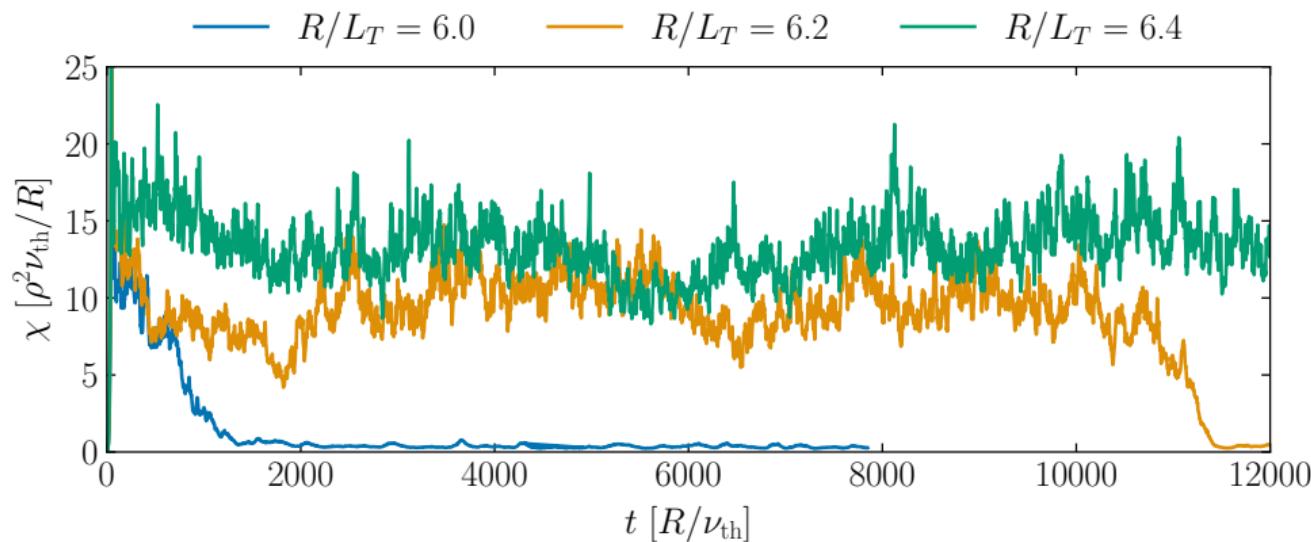
⇒ Mesoscale pattern size of:

$$\sim 57 - 76 \rho$$

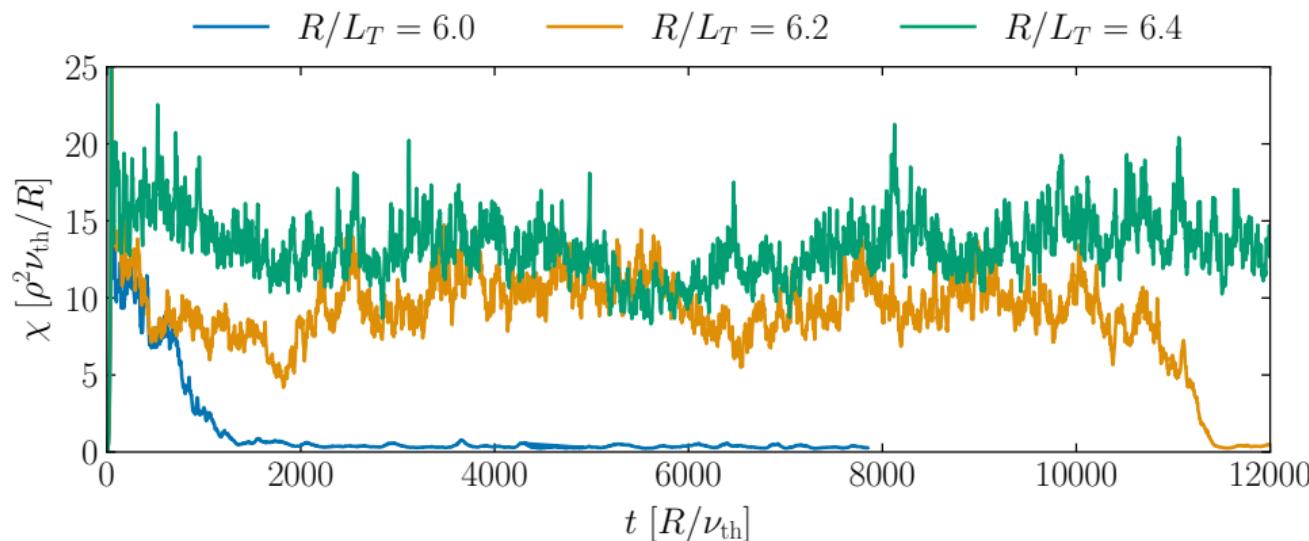
- Non-locality is inherent to ITG-driven turbulence
- Avalanches are spatially organized by the $E \times B$ staircase pattern

THE FINITE HEAT FLUX THRESHOLD

THE FINITE HEAT FLUX THRESHOLD



THE FINITE HEAT FLUX THRESHOLD



$$\Rightarrow \boxed{R/L_T|_{\text{finite}} = 6.3 \pm 0.1}$$

CONCLUSION

CONCLUSION

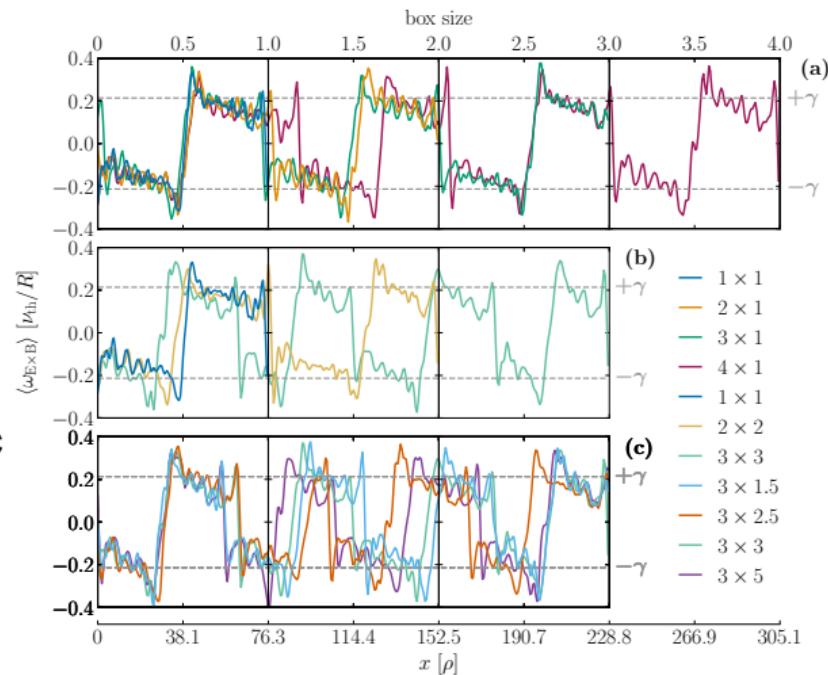
- Parallel velocity $N_{\nu_{||}}$ could be reduced from 64 to 48, which halved the time until suppression of turbulence

CONCLUSION

- Parallel velocity $N_{\nu_{||}}$ could be reduced from 64 to 48, which halved the time until suppression of turbulence
- Restart Script with `python` led to further convenience during the task of performing simulations

CONCLUSION

- Parallel velocity $N_{\nu_{||}}$ could be reduced from 64 to 48, which halved the time until suppression of turbulence
- Restart Script with python led to further convenience during the task of performing simulations
- Mesoscale pattern size of $\sim 57 - 76 \rho$ is found to be intrinsic to ITG-driven turbulence for Cyclone Base Case parameters



CONCLUSION

- Parallel velocity $N_{\nu_{||}}$ could be reduced from 64 to 48, which halved the time until suppression of turbulence
- Restart Script with python led to further convenience during the task of performing simulations
- Mesoscale pattern size of $\sim 57 - 76 \rho$ is found to be intrinsic to ITG-driven turbulence for Cyclone Base Case parameters
- Finite heat flux threshold is located at $R/L_T|_{\text{finite}} = 6.3 \pm 0.1$

