

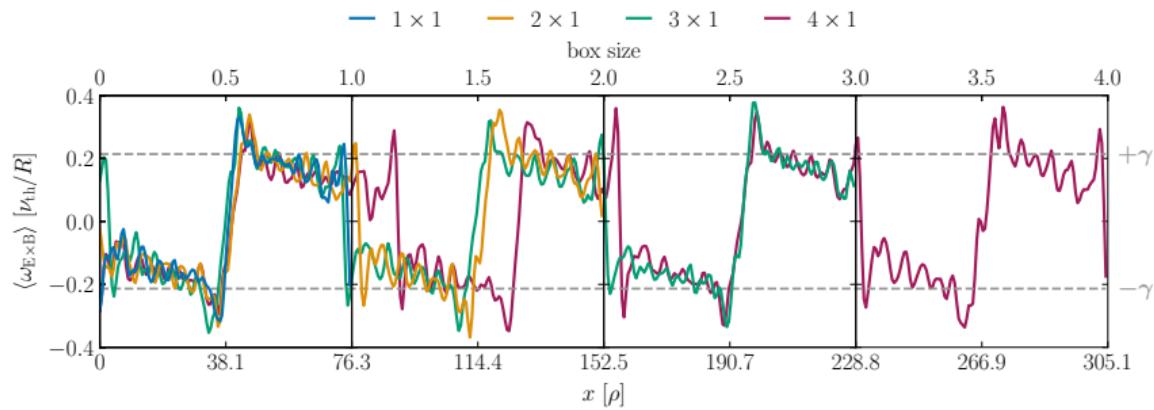


# SIZE CONVERGENCE OF THE $E \times B$ STAIRCASE PATTERN IN FLUX TUBE SIMULATIONS OF ION TEMPERATURE GRADIENT-DRIVEN TURBULENCE

June 22, 2023

Manuel Lippert

Theoretical Physics V



# MOTIVATION

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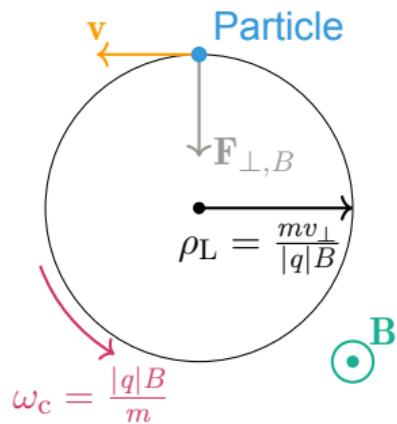
**Does the basic pattern size always converges to the box size, or is there a typical mesoscale size inherent to staircase structures also in a local flux-tube description?**

# CHARGED PARTICLE MOTION

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## Lorentz force

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



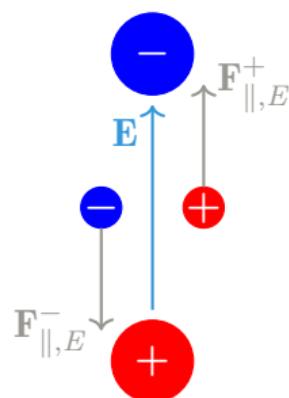
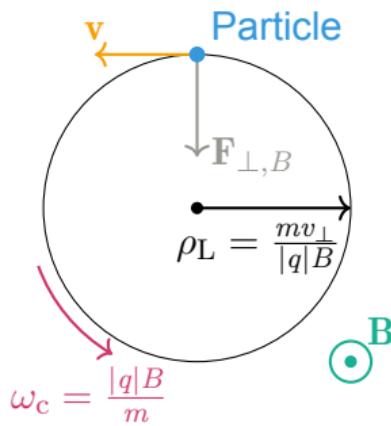
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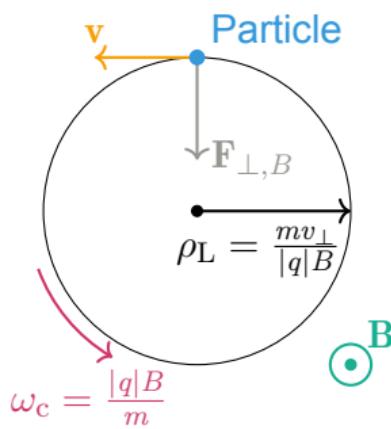
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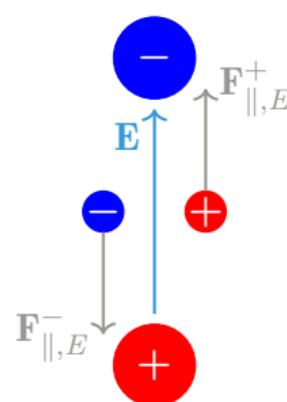
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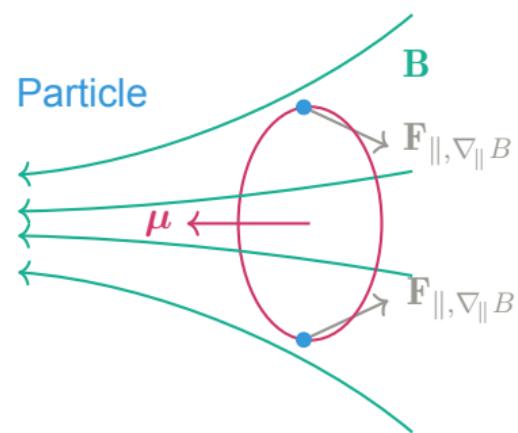
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## Inhomogeneous magnetic field

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

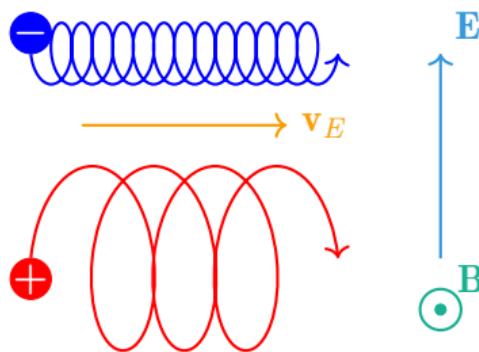


# DRIFT IN THE GYROCENTER

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## **E × B Drift**

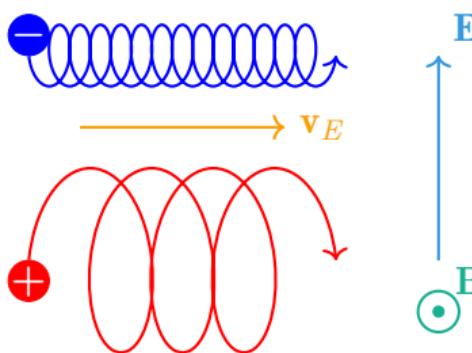
$$\mathbf{v}_E = \frac{\mathbf{E} \times \mathbf{B}}{B^2}$$



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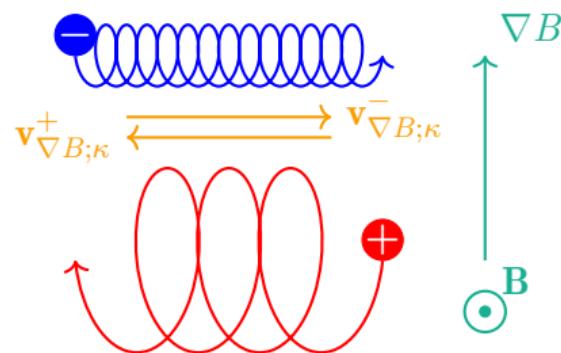


## **$\nabla B$ Drift**

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

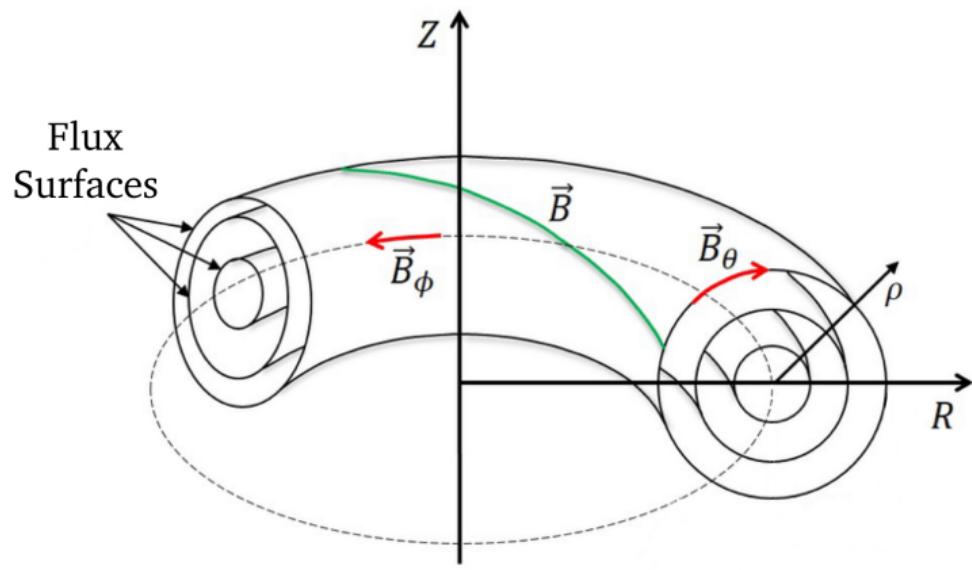
## **Curvature Drift**

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



# MAGNETIC CONFINEMENT IN TOKAMAK

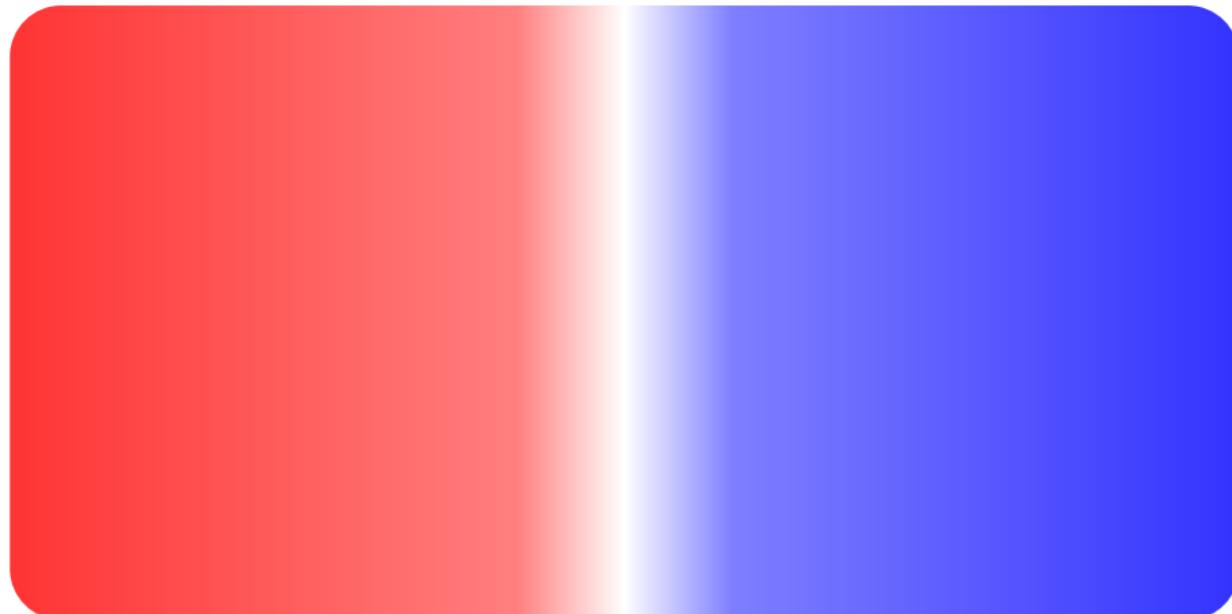
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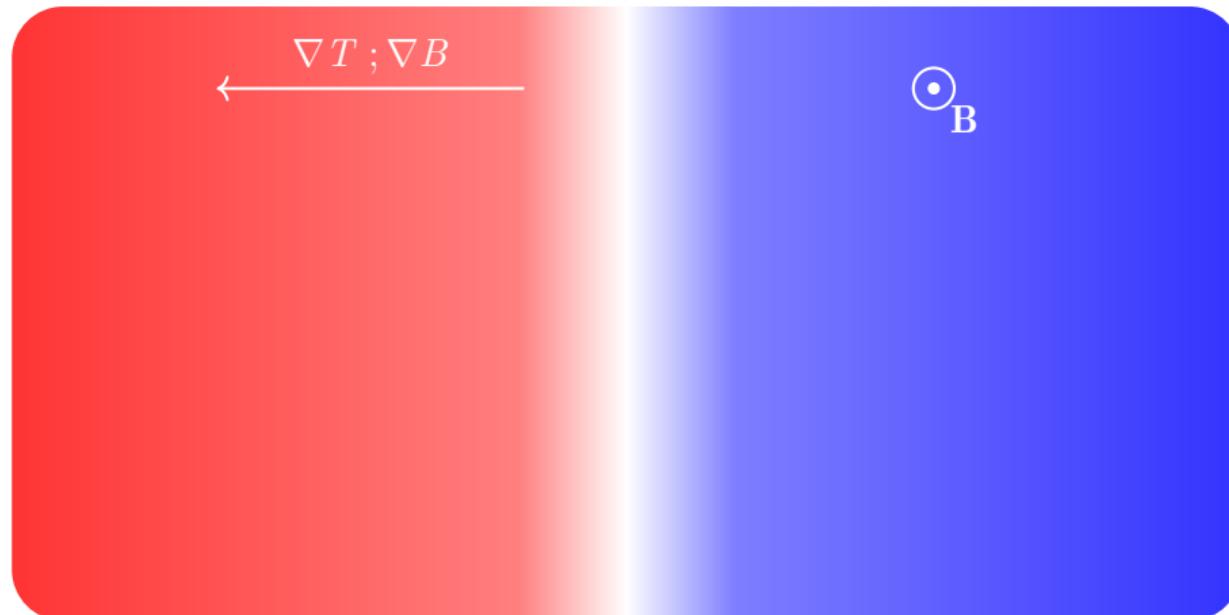
$$\beta = \frac{nT}{\mu_0 B^2/2}$$

# ION TEMPERATURE GRADIENT (ITG)-DRIVEN INSTABILITY

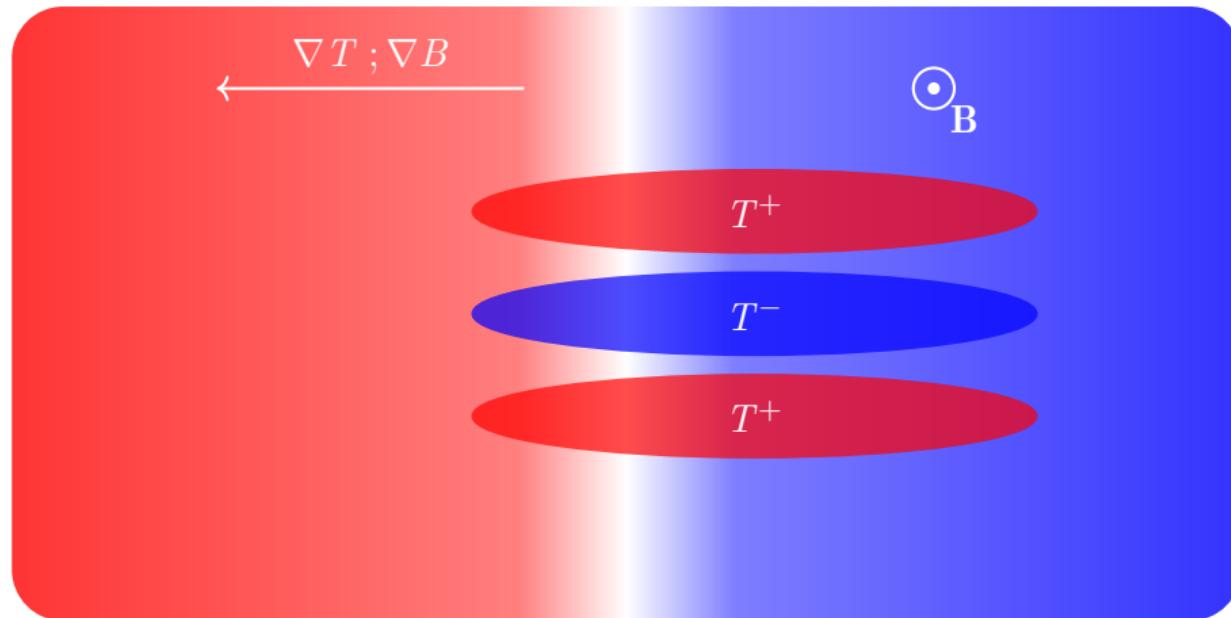
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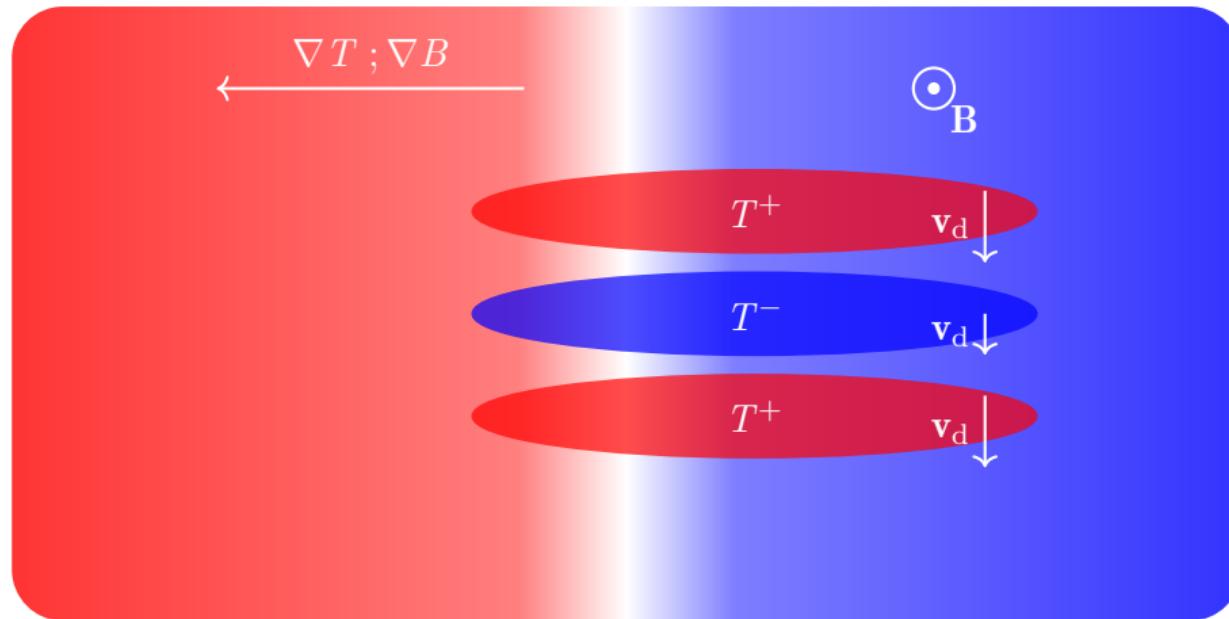
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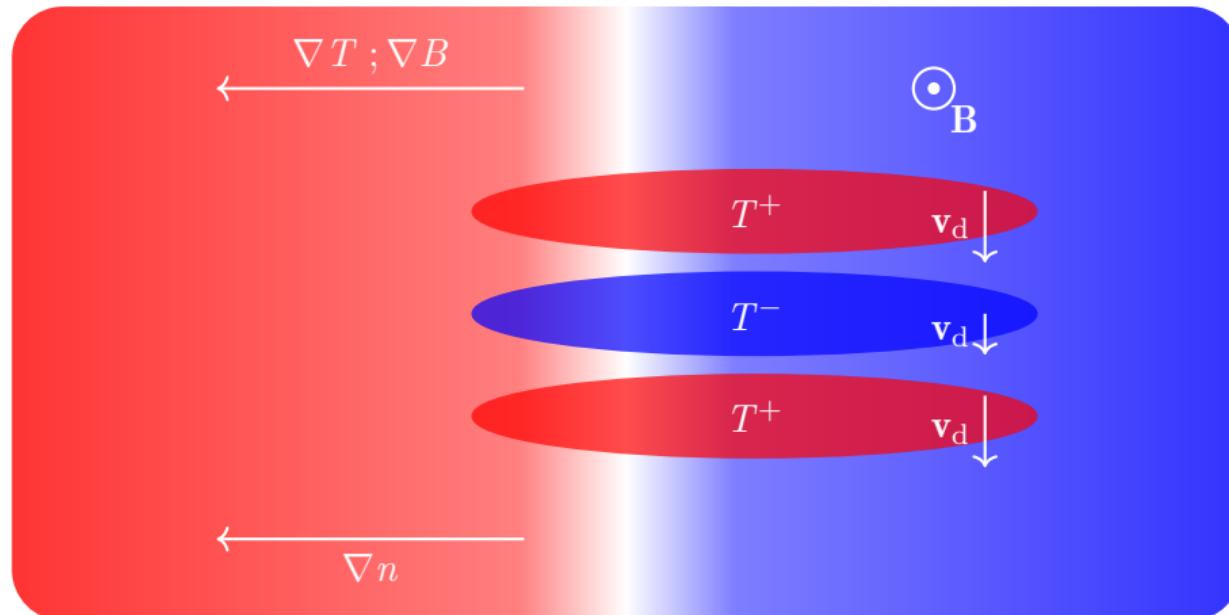
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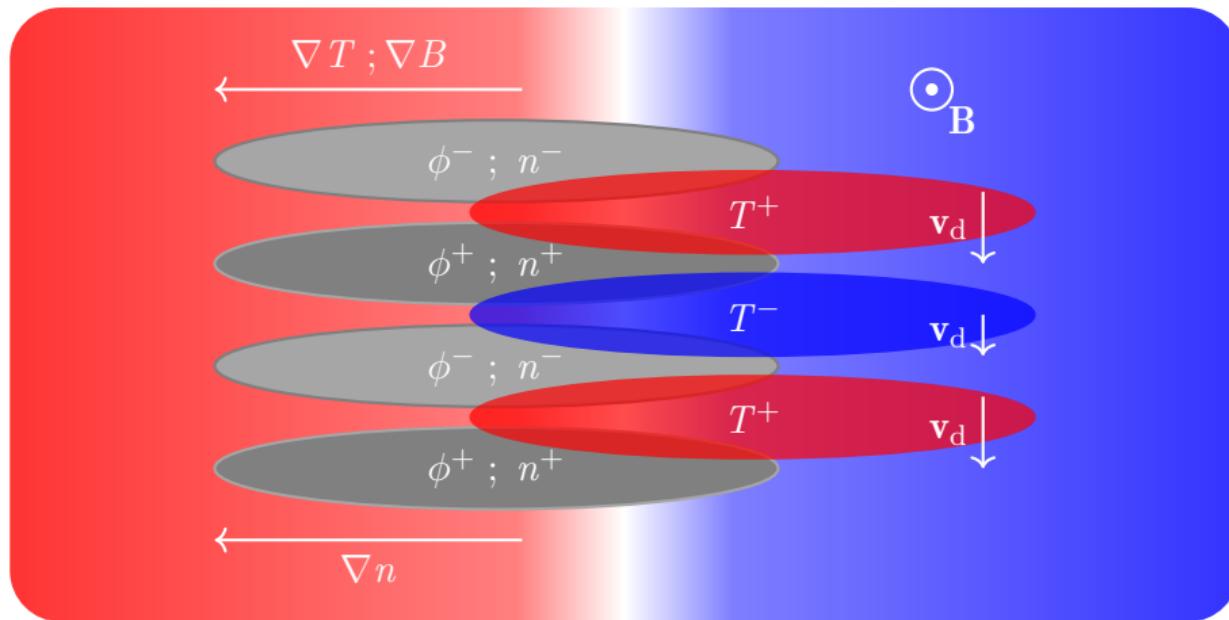
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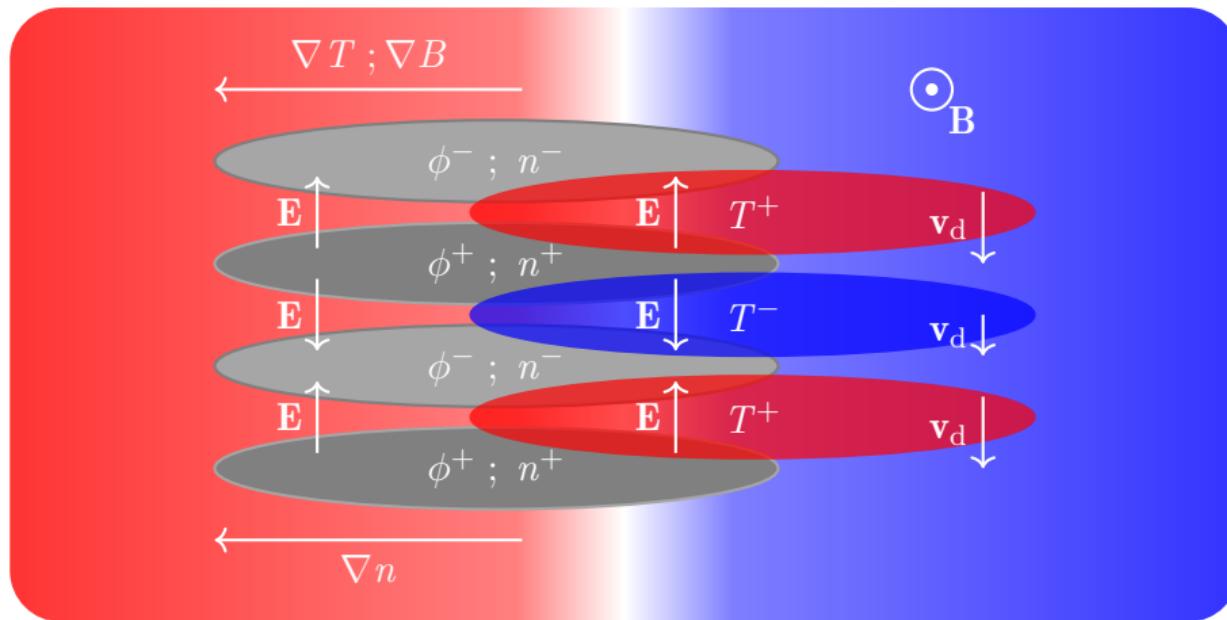
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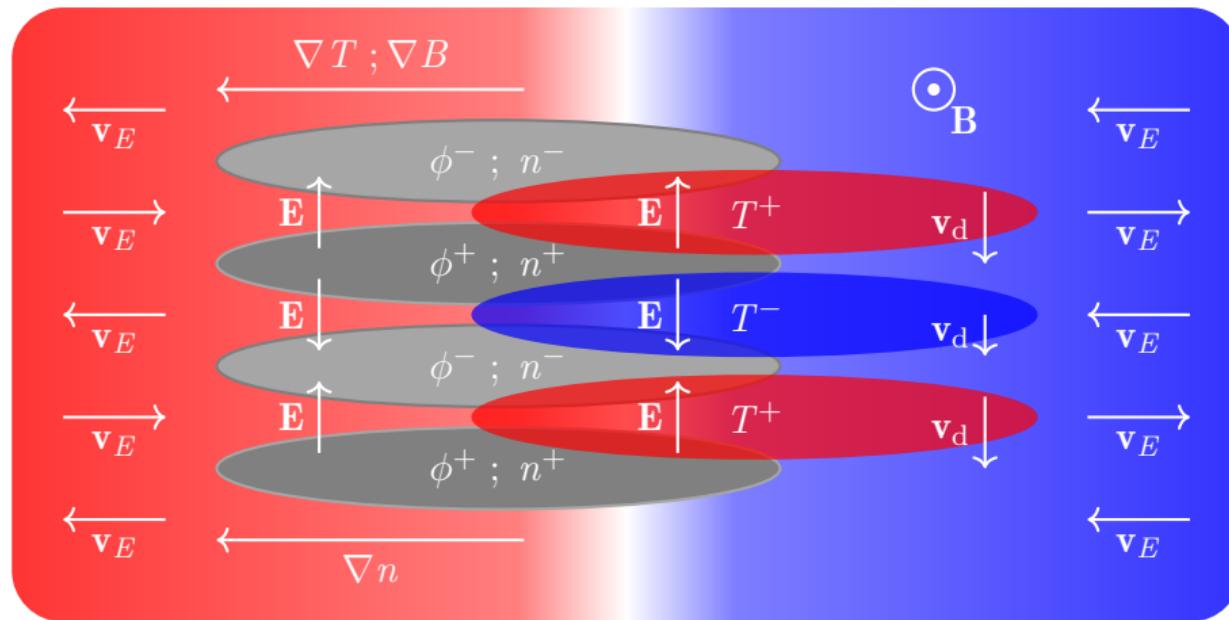
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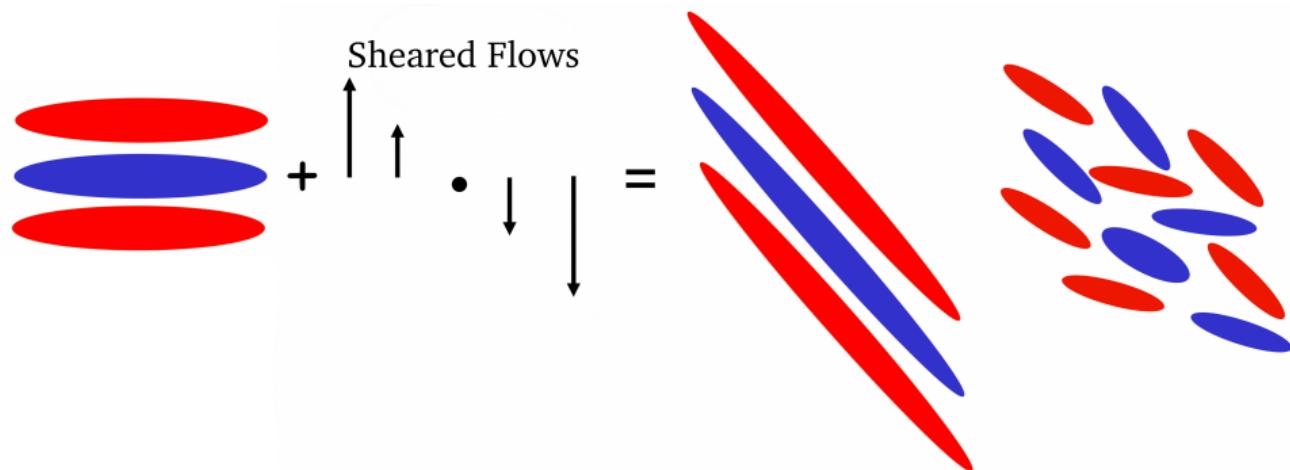


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$$\omega_{E \times B} = \frac{1}{2} \frac{\partial^2 \langle \phi \rangle}{\partial x^2} \quad \langle \phi \rangle = \frac{1}{L_y} \int_0^{L_y} dy \phi(x, y, s=0)$$

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

Vlasov Equation

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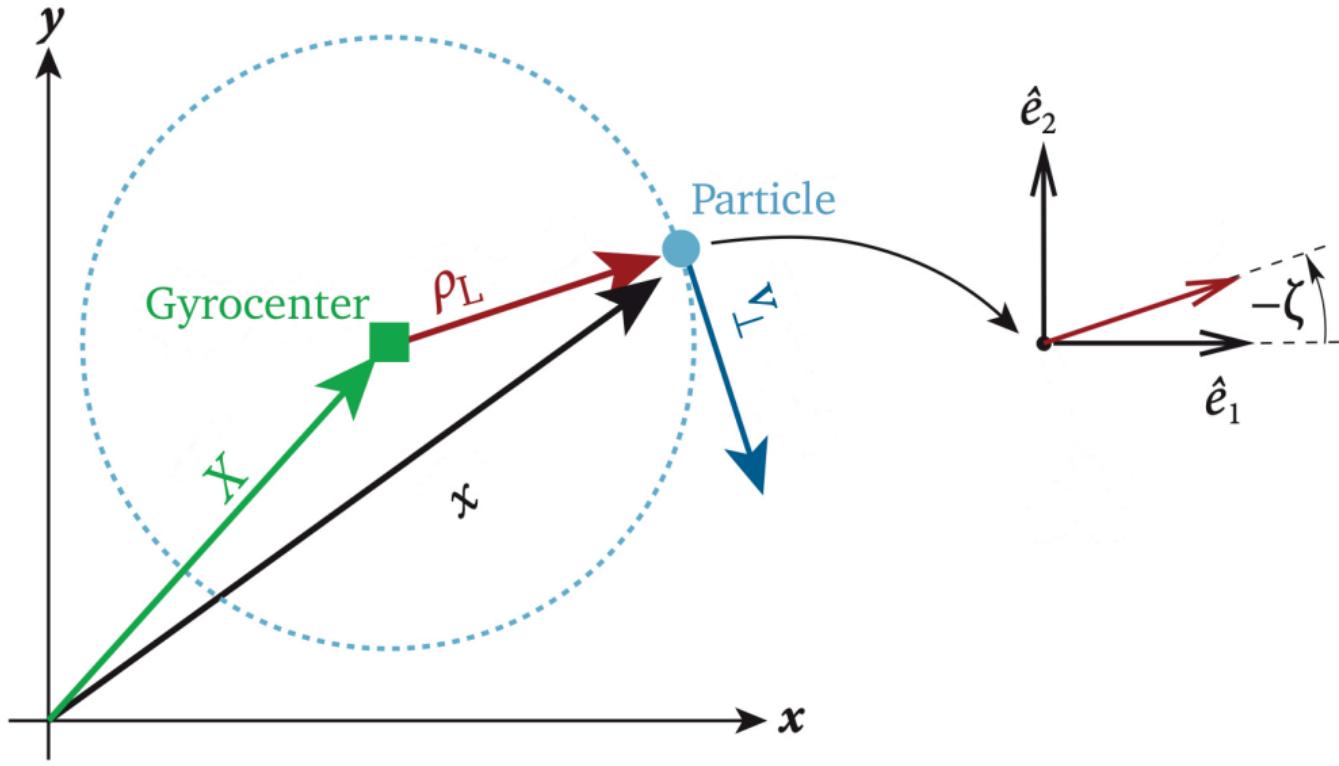
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$$\frac{\partial g}{\partial t} + \mathbf{v}_{\chi} \cdot \nabla g + (v_{\parallel} \mathbf{b} + \mathbf{v}_D) \cdot \nabla (\delta f) - \frac{\mu B}{m} \frac{\mathbf{B} \cdot \nabla B}{B^2} \frac{\partial (\delta f)}{\partial v_{\parallel}} = S \quad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

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

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	$N_m$	$N_x$	$N_s$	$N_{\nu_{  }}$	$N_\mu$	$D$	$\nu_d$	$D_{\nu_{  }}$	$D_x$	$D_y$	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

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- Quantities  $\rho$ ,  $R$ ,  $T$ ,  $v_{\text{th}}$  and  $m$  are referenced quantities
- Standard box size  $(L_x, L_y) = (76.3, 89.8) \rho$

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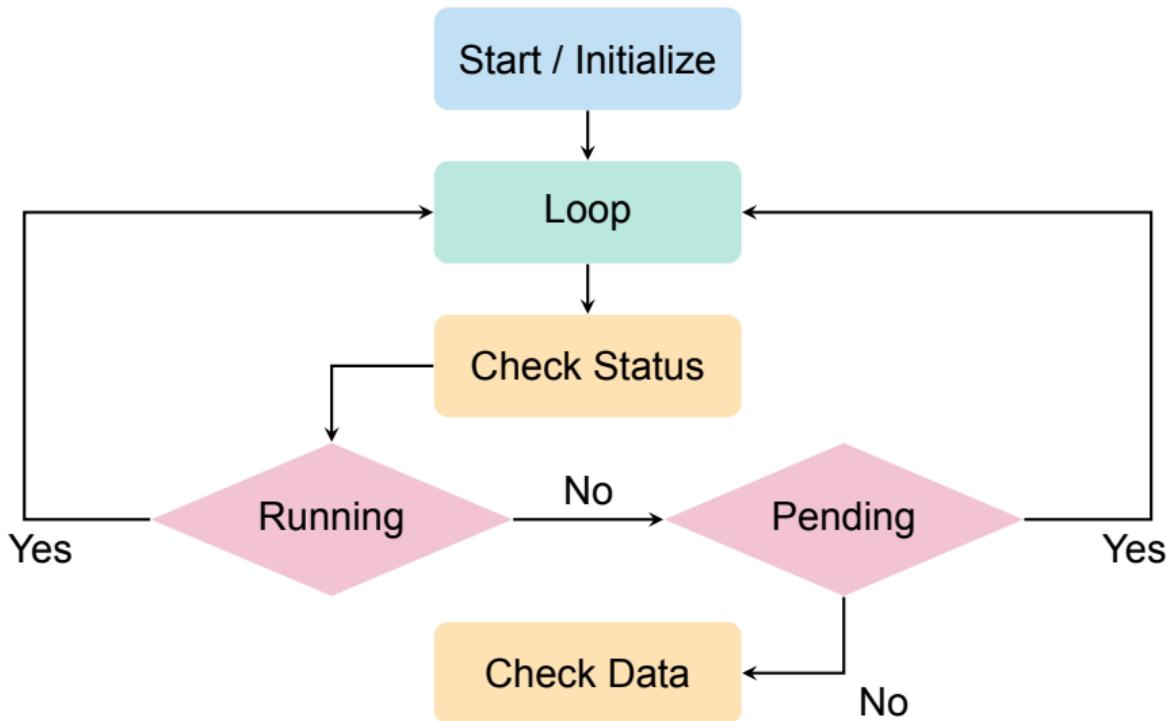
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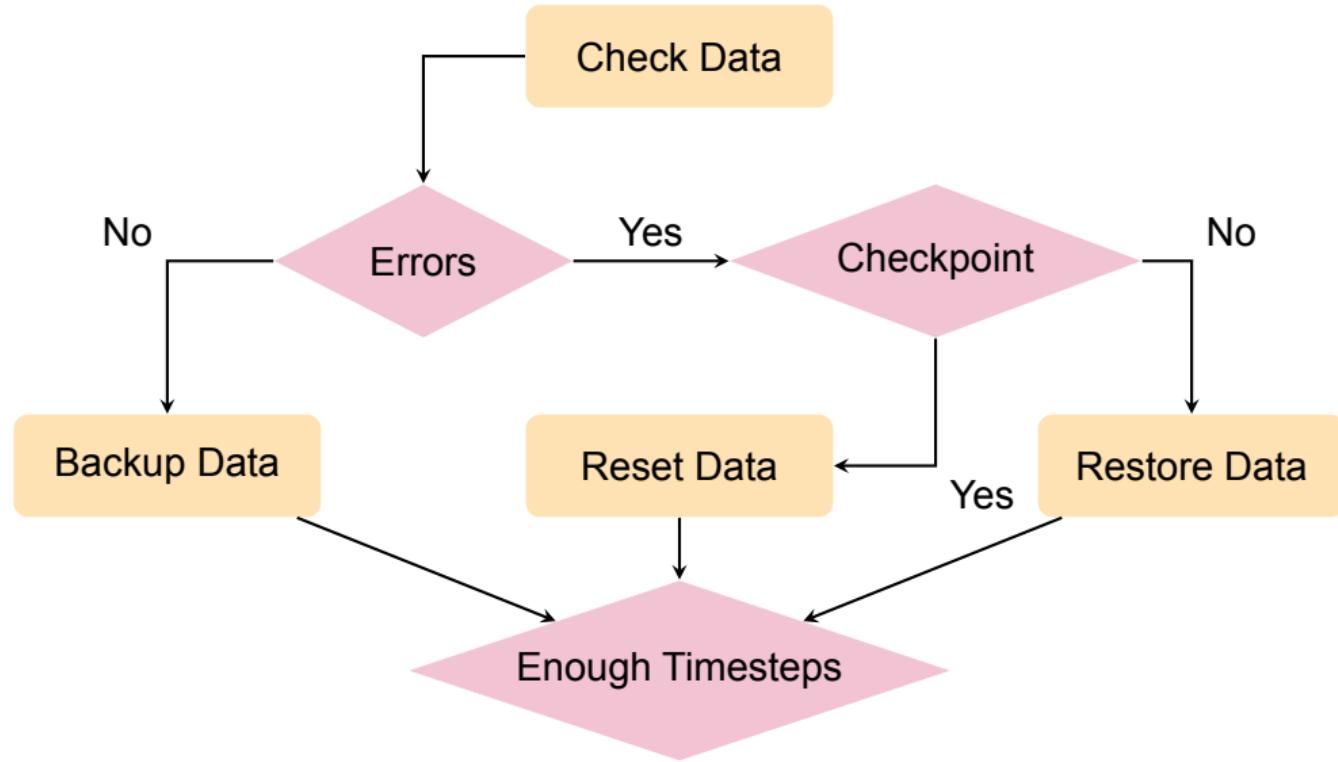
- Zonal flow mode that dominates the  $E \times B$  staircase pattern are called **basic mode**
- The basic mode exhibits the maximum amplitude in the spectrum  $|\hat{\omega}_{E \times B}|_{n_{ZF}}$

# RESTART SCRIPT

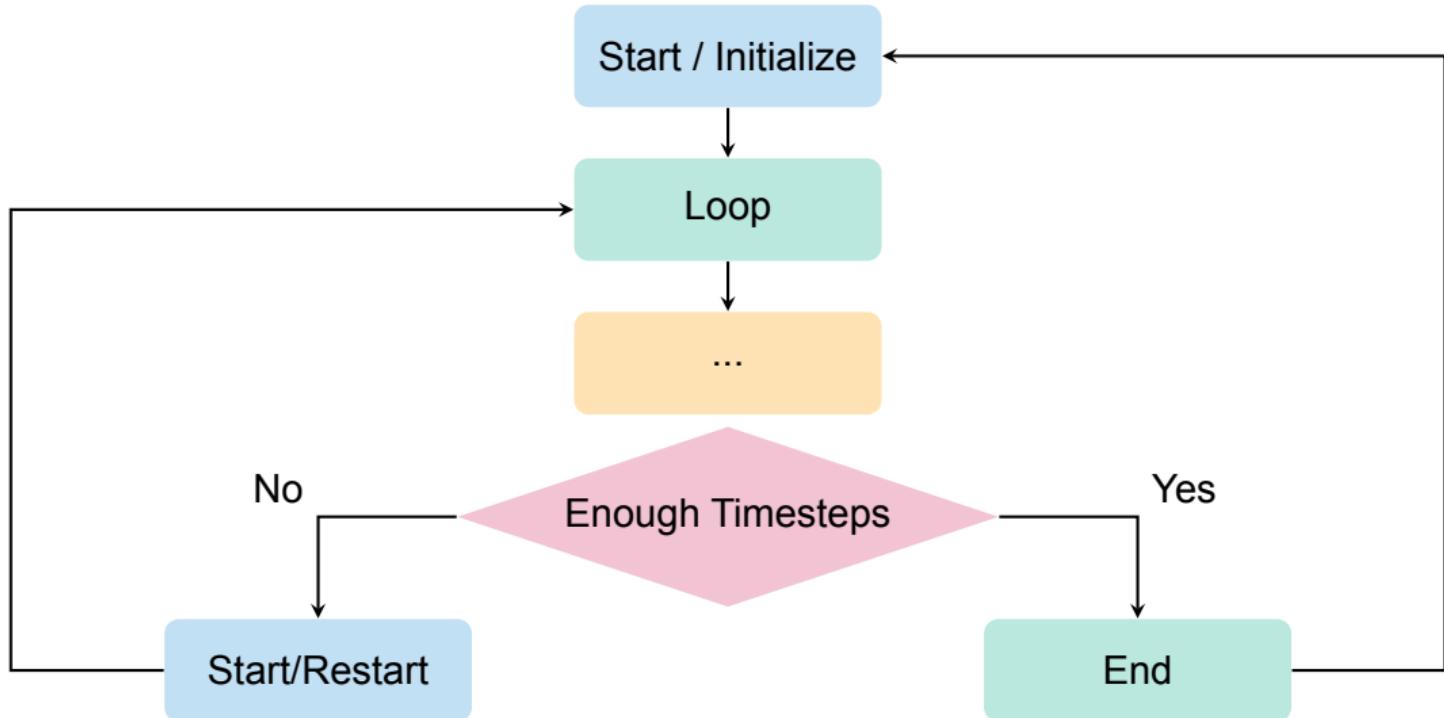
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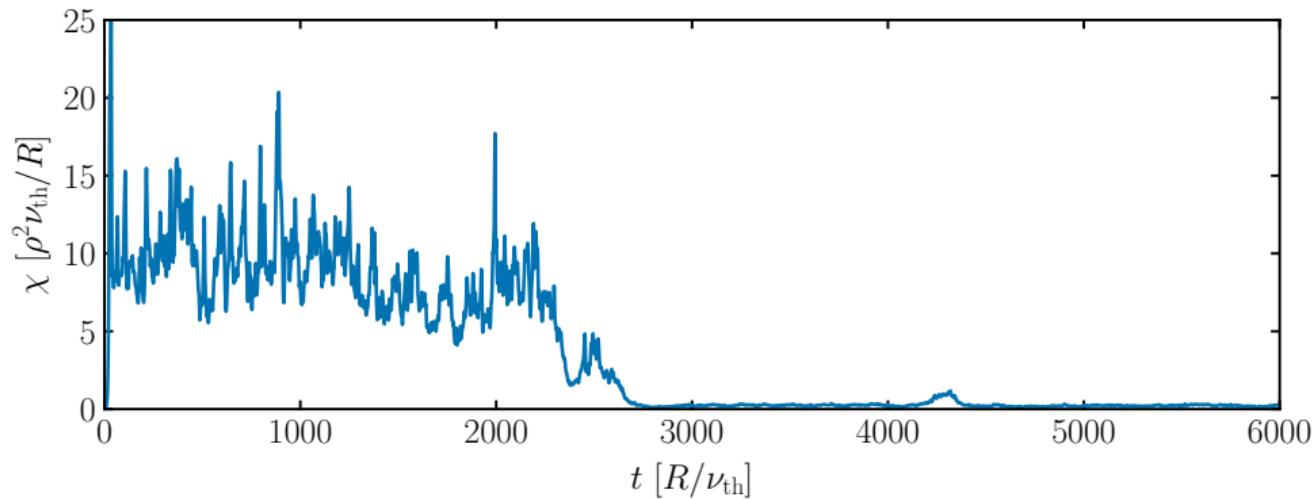
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## Verification:

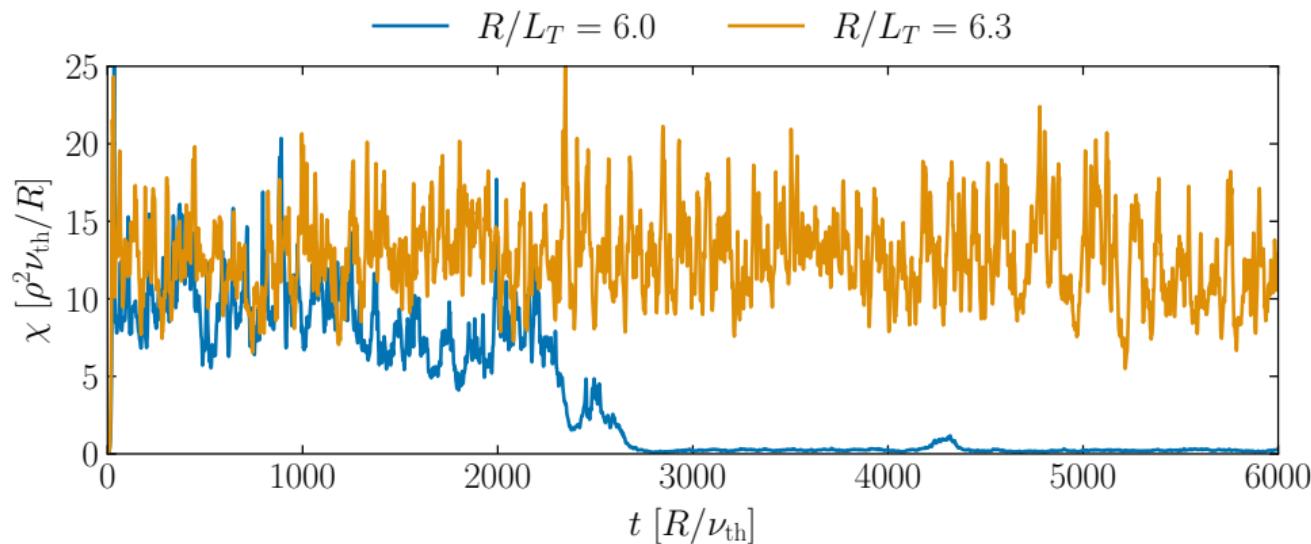
1. Reduce only one number of grid points and look if criterias (1), (2) are satisfied
2. Reduce to known the minimum number of grid points to verify result in general.

# BENCHMARK

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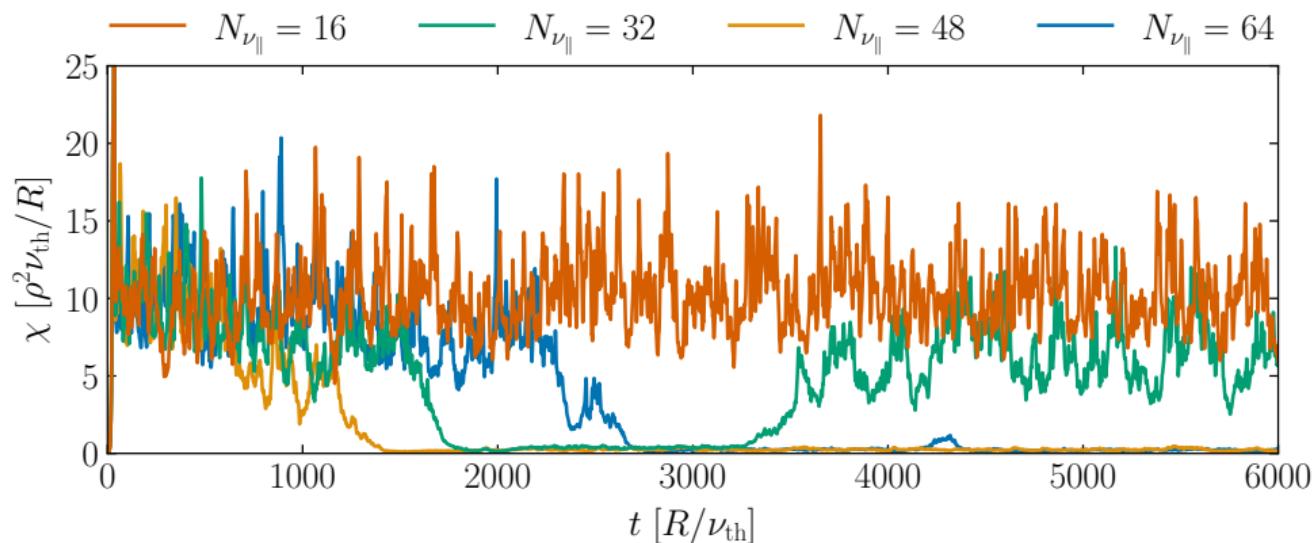


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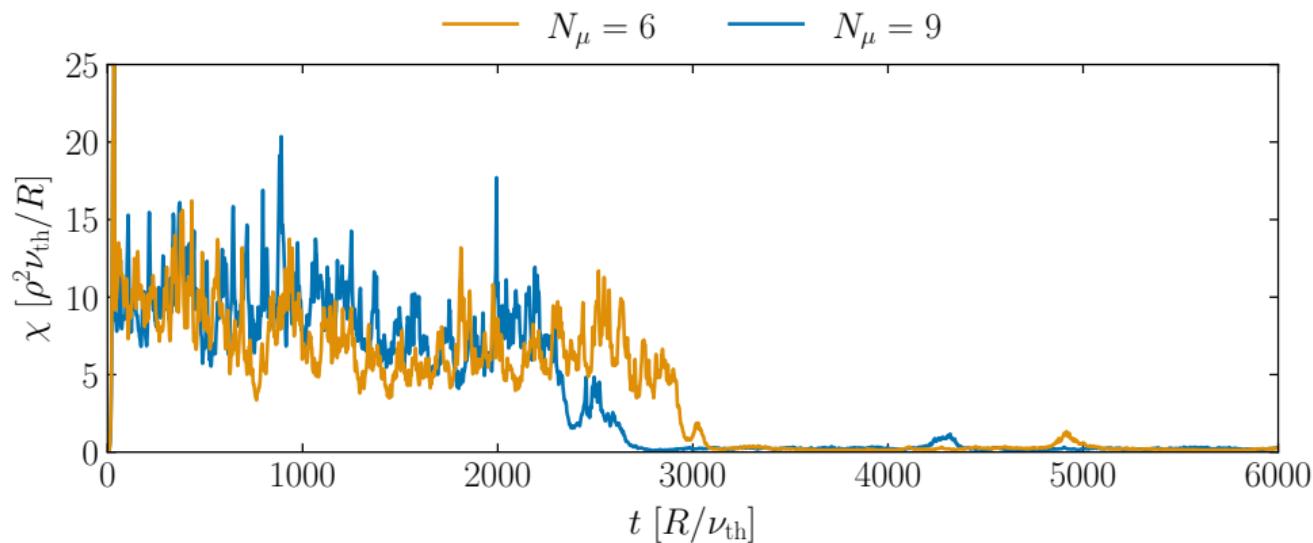


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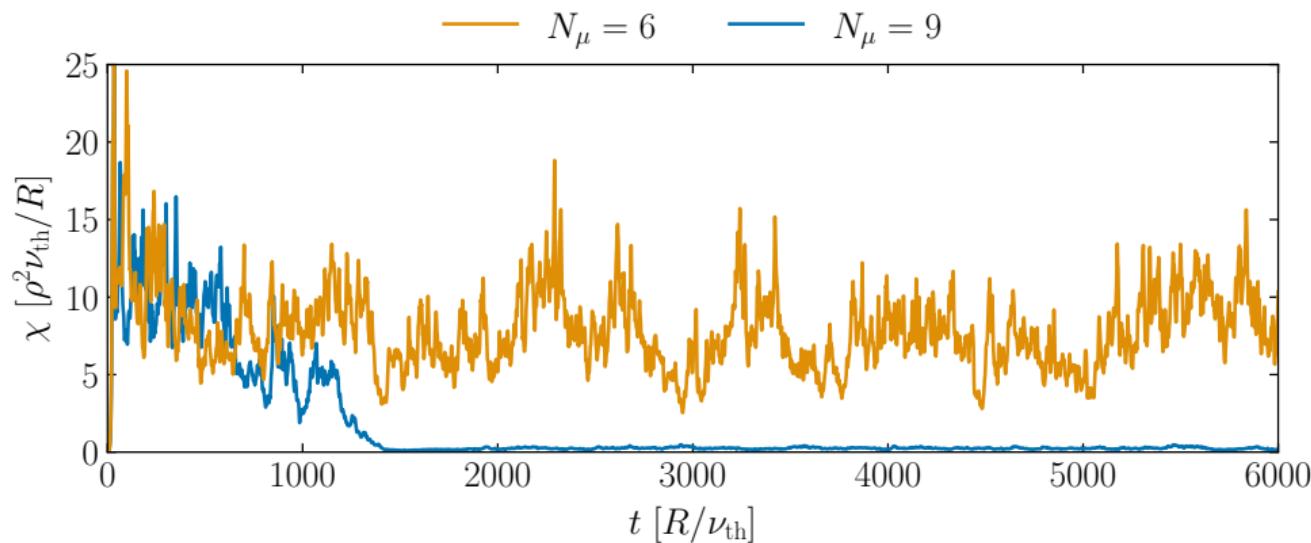
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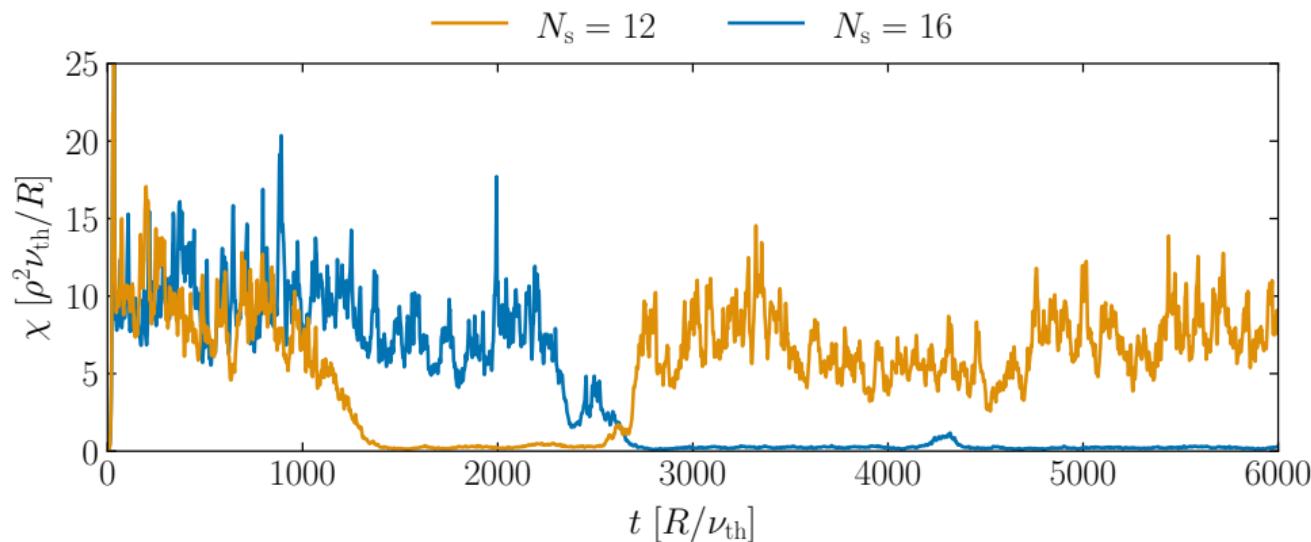
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## Final Resolution

	$N_m$	$N_x$	$N_s$	$N_{\nu_{  }}$	$N_\mu$	$D$	$\nu_d$	$D_{\nu_{  }}$	$D_x$	$D_y$	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

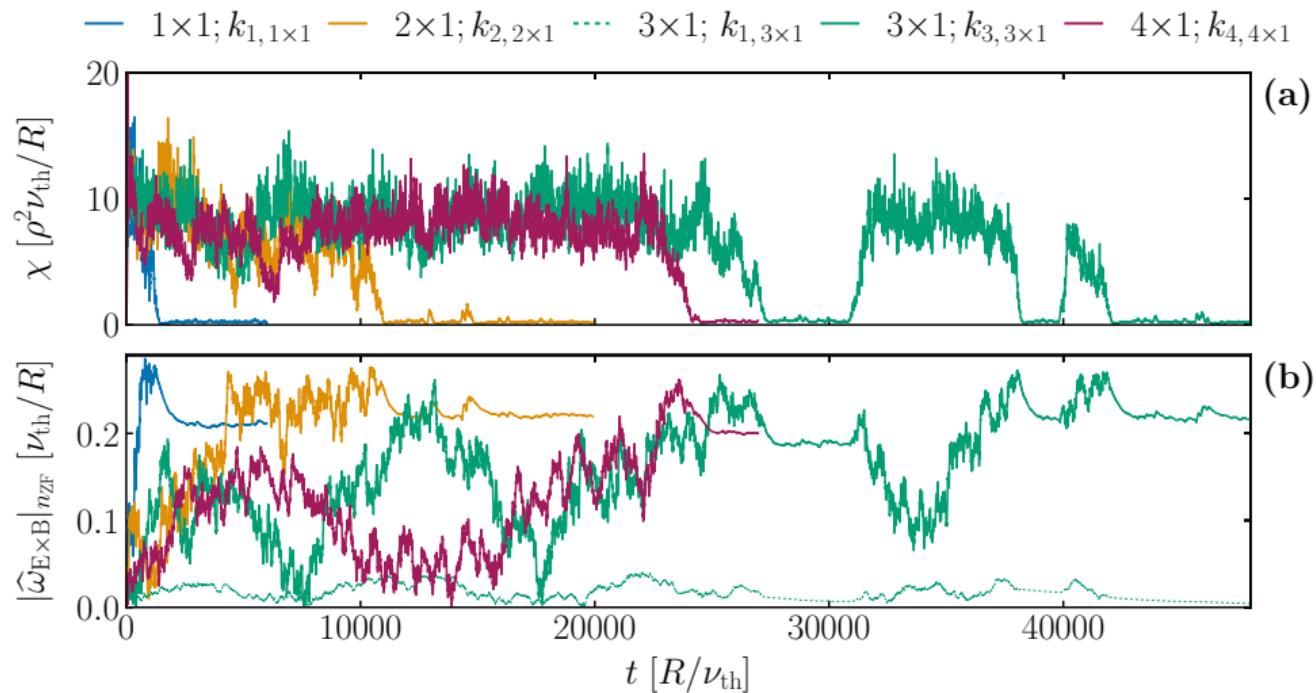
# SIZE CONVERGENCE OF E × B STAIRCASE PATTERN

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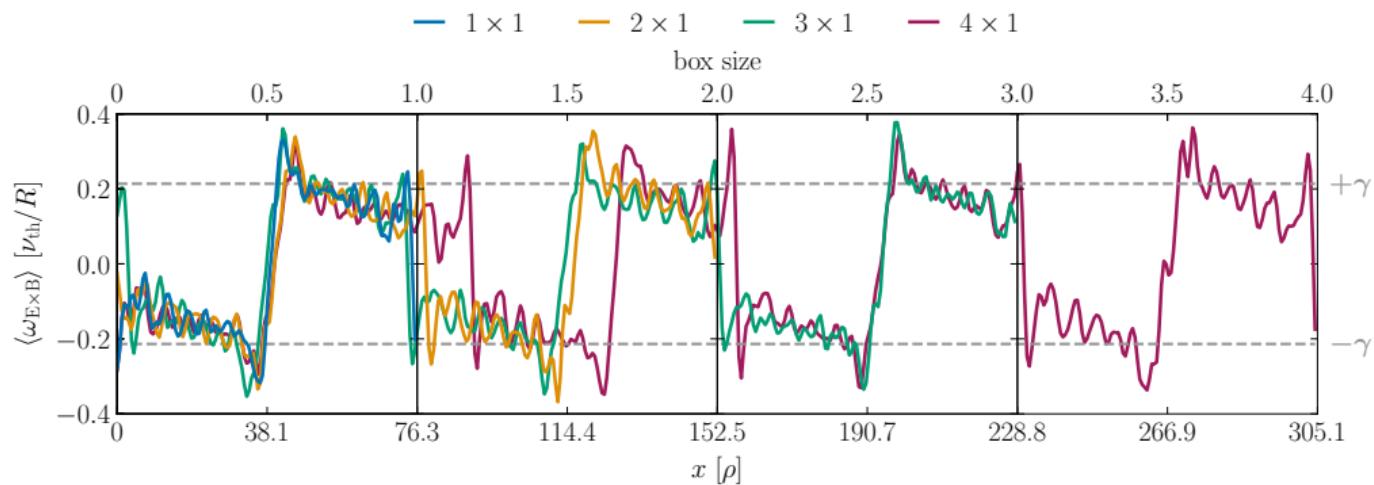
## (1) Radial

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

# SIZE CONVERGENCE OF $E \times B$ STAIRCASE PATTERN



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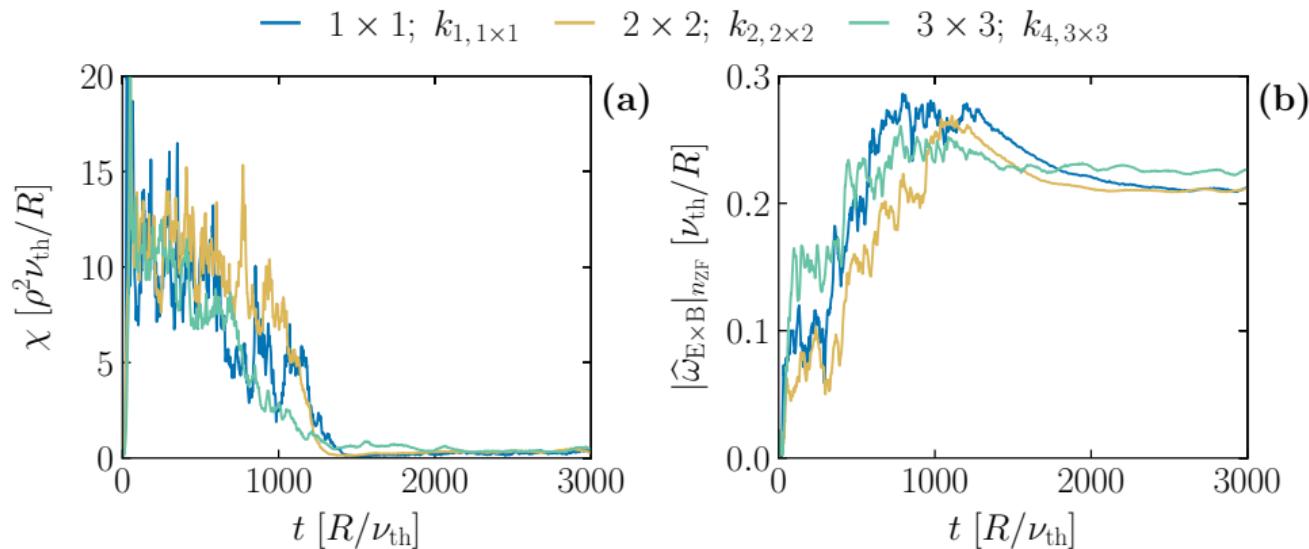


# SIZE CONVERGENCE OF E × B STAIRCASE PATTERN

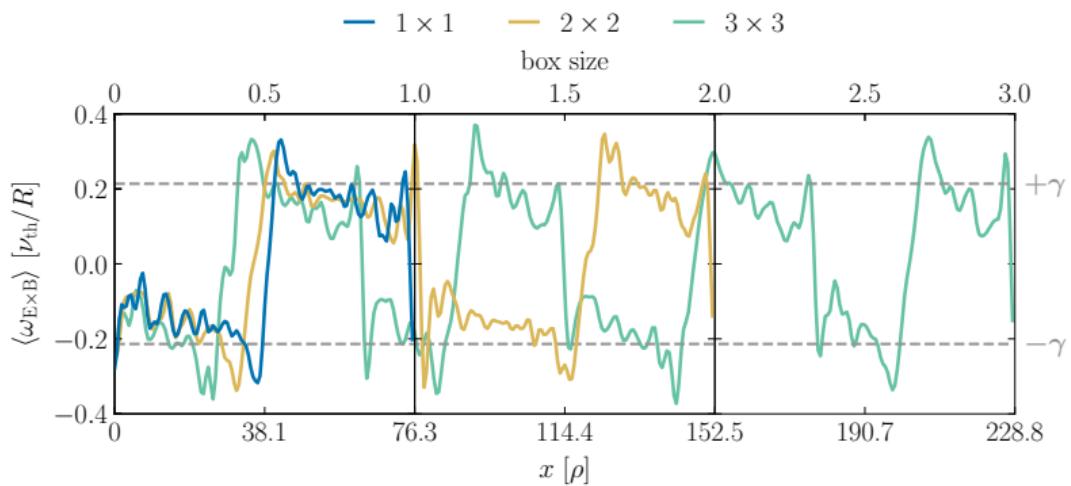
## **(2) Isotropic**

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

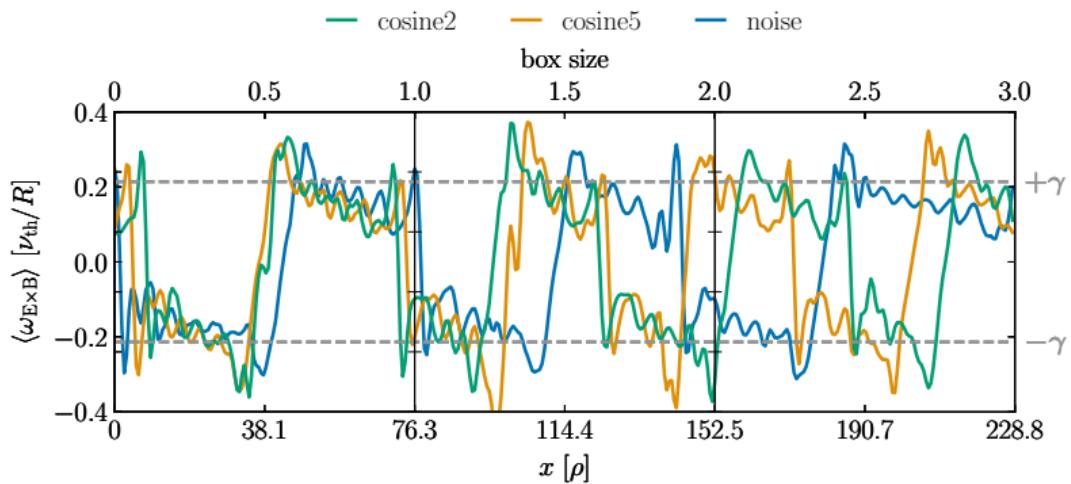
# SIZE CONVERGENCE OF $E \times B$ STAIRCASE PATTERN



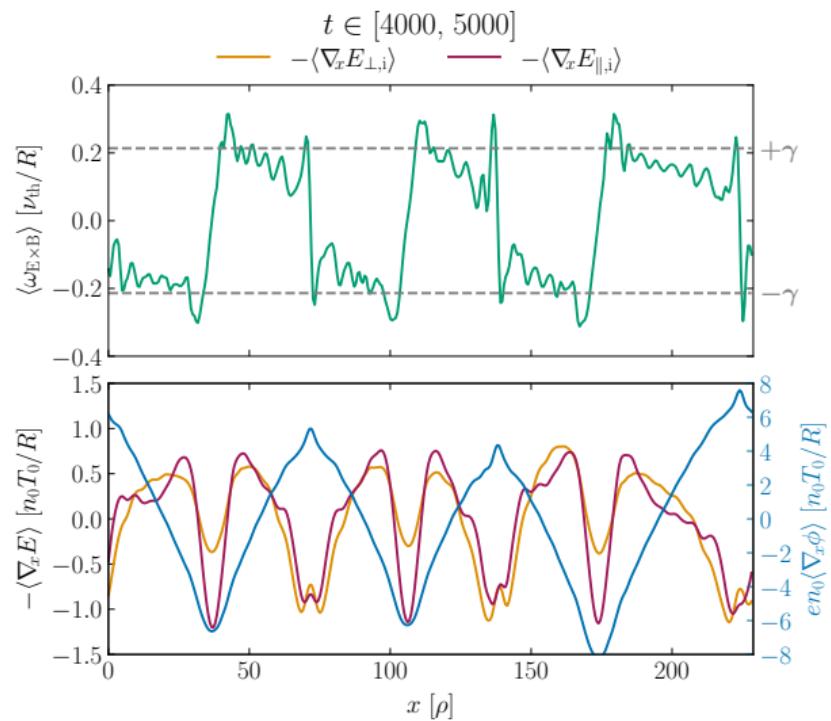
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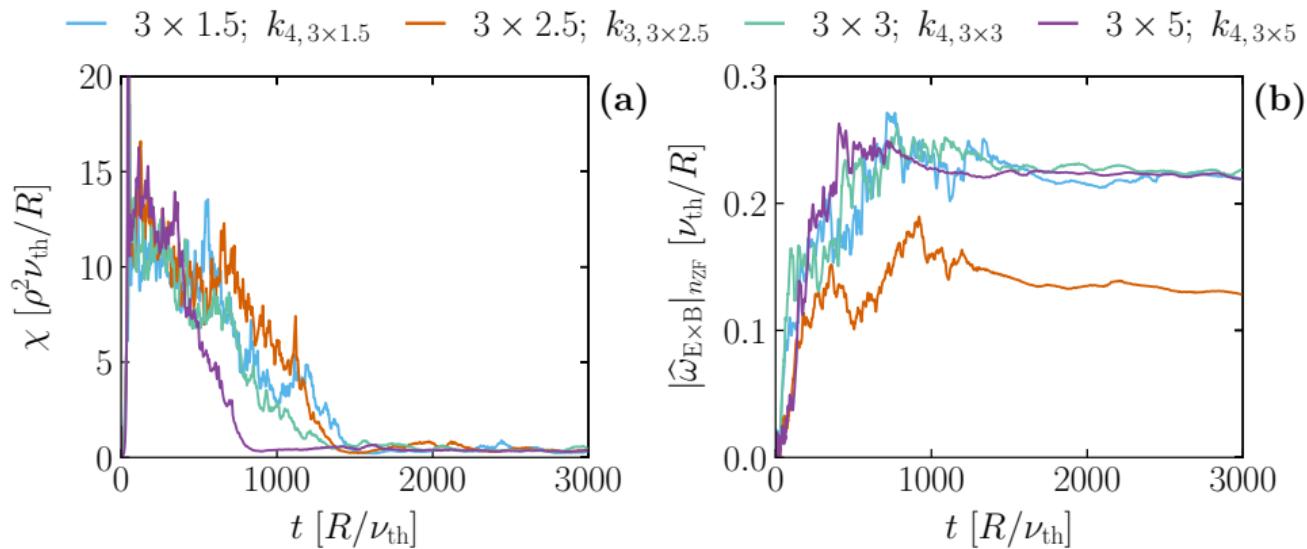


# SIZE CONVERGENCE OF E × B STAIRCASE PATTERN

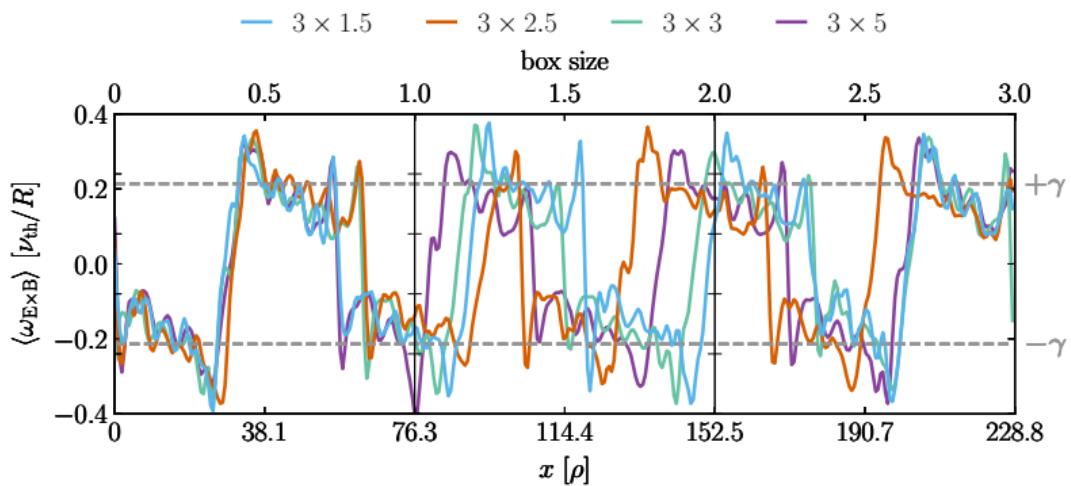
## **(3) Binormal**

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

# SIZE CONVERGENCE OF $E \times B$ STAIRCASE PATTERN



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## SIZE CONVERGENCE OF E × B STAIRCASE PATTERN

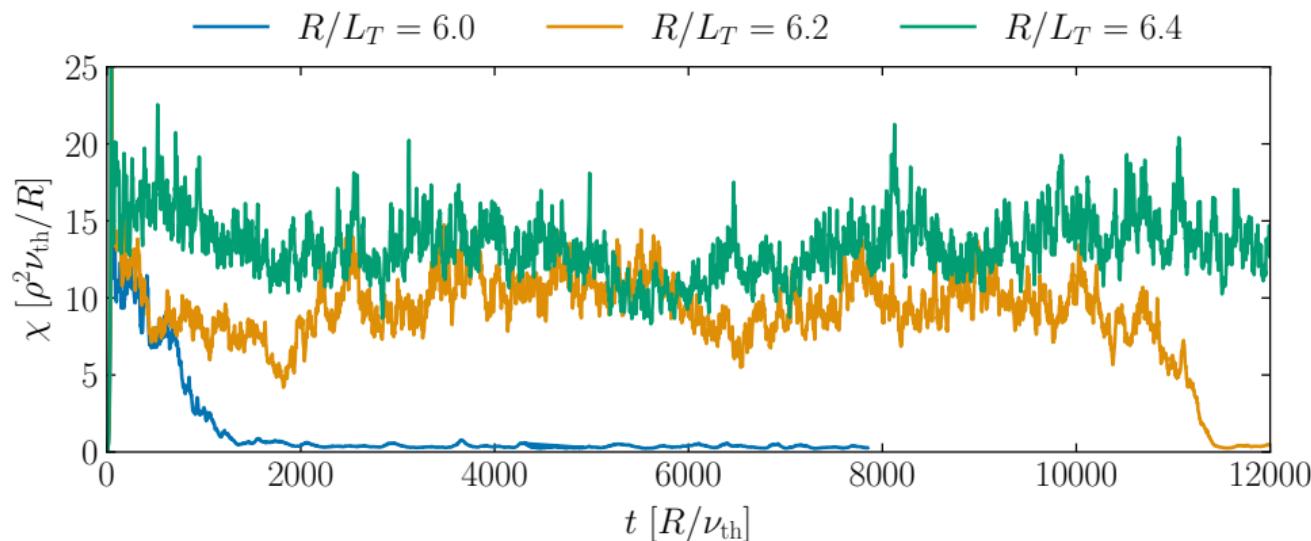
⇒ Mesoscale pattern size of:

$$\sim 57 - 76 \rho$$

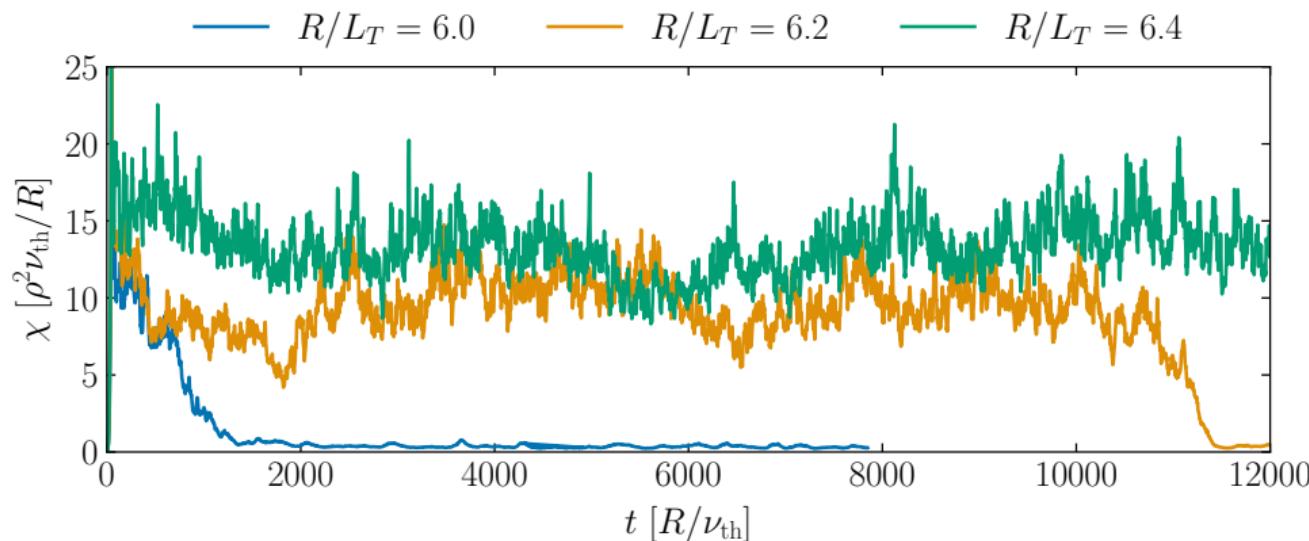
- Non-locality is inherent to ITG-driven turbulence
- Avalanches are spatially organized by the E × B staircase pattern

# THE FINITE HEAT FLUX THRESHOLD

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

# CONCLUSION

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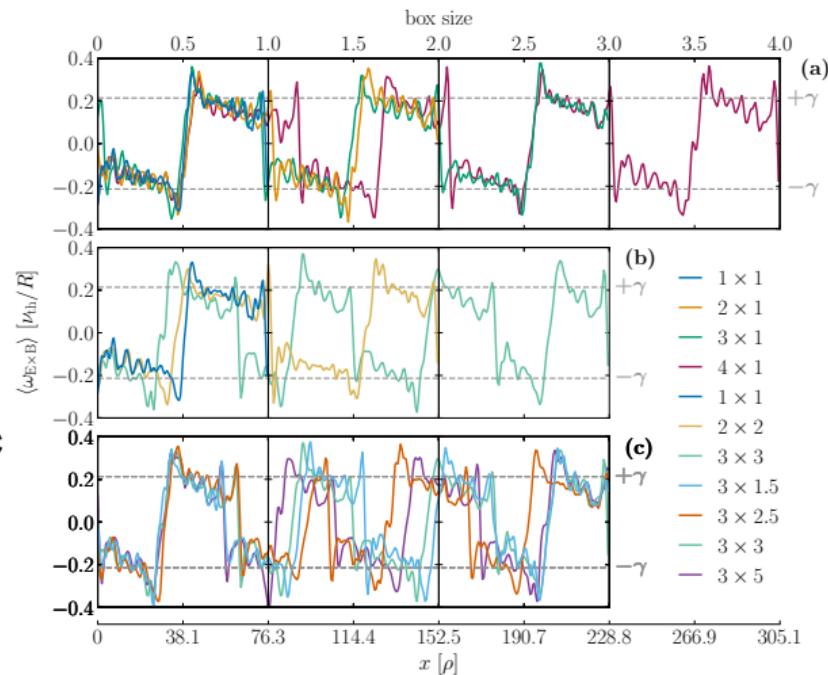
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- Finite heat flux threshold is located at  $R/L_T|_{\text{finite}} = 6.3 \pm 0.1$

