Ion Heat and Parallel Momentum Transport by Stochastic Magnetic Fields and Turbulence

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Outline

- Introduction

  Transport of momentum and ion heat in stochastic magnetic field .

- Model & Calculation

- Results

  a. In strong turbulence regime, the mean flow is driven by stochastic-turbulent scattering.

  b. Stochastic lines and parallel ion flow gradient drives a net electron particle flux, in additional to the Maxwell force contribution.

- Conclusions

Why we study stochastic fields in fusion device?

Shear Flow

↓

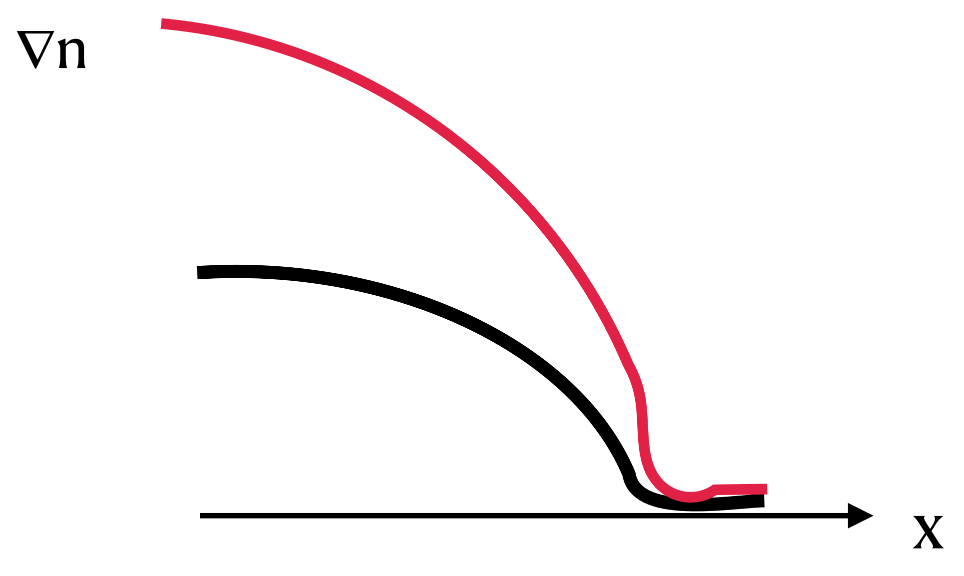
Quench Turbulence

↓

Pedestal Formation

↓

Edge-Localized Mode (ELM)



Boundary Control: Resonant Magnetic Perturbation (RMP)

Suppress (by inducing magnetic perturbation)

Edge-Localized Mode (ELM)

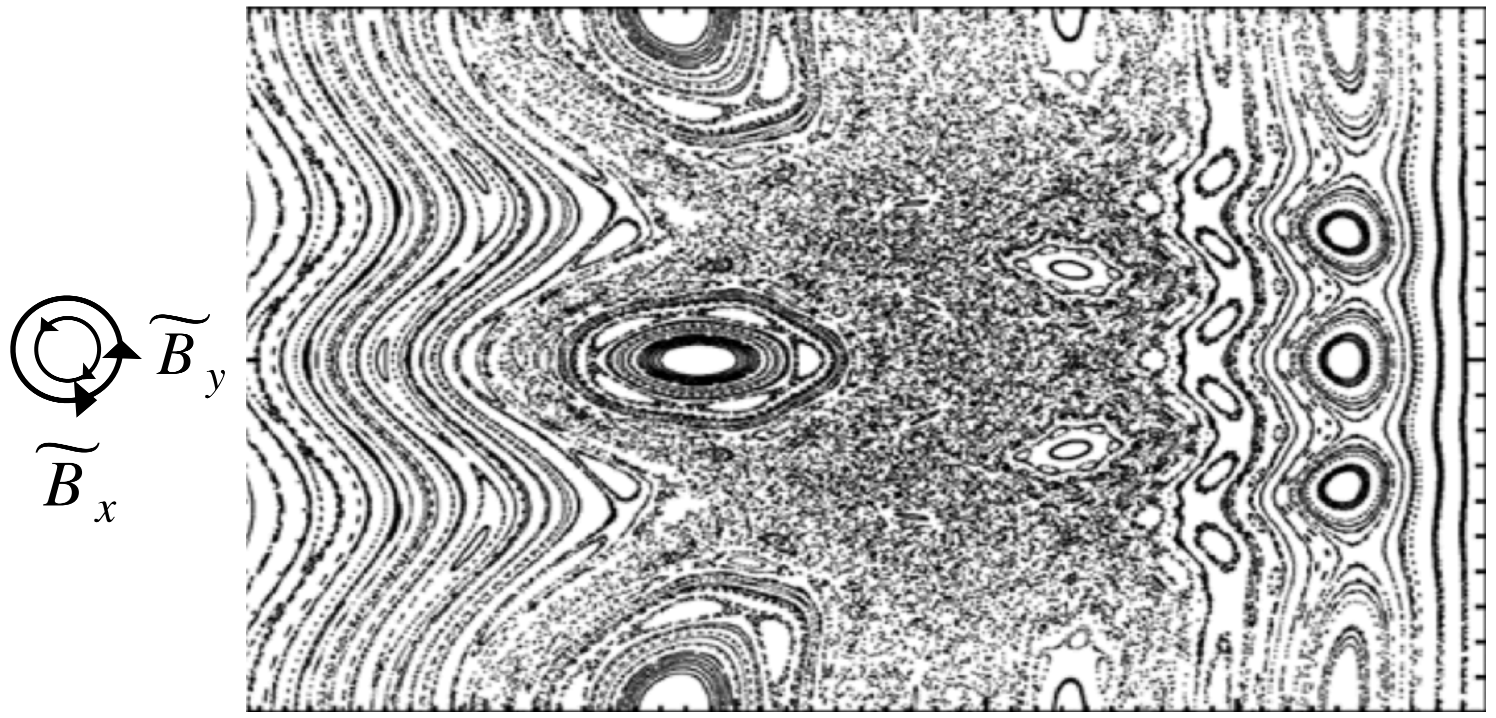
Trade off: RMPs controls gradients and mitigates ELM, but raise the **power threshold**.

- ELMs are quasi-periodic relaxation events occurring at edge pedestal in H-mode plasma.
- ELMs can damage wall components of a fusion device.

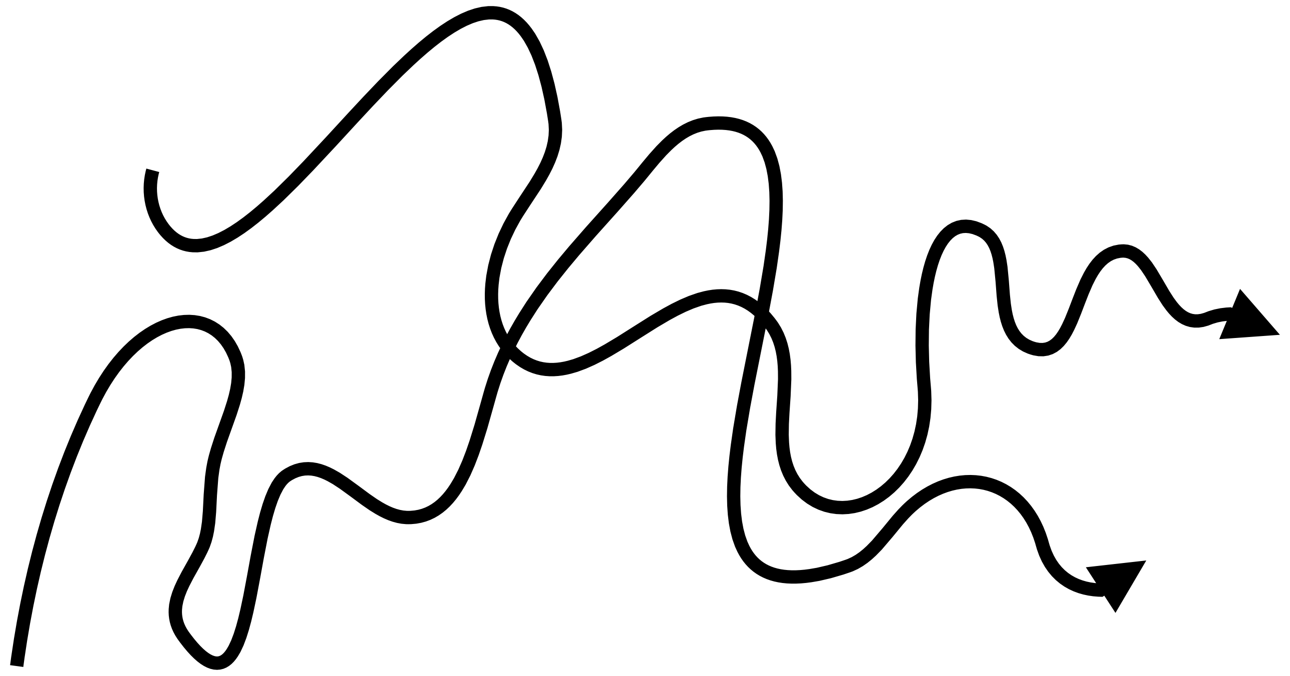
The **transport of parallel momentum** and **pressure** in presence of stochastic field is important in studies of fusion plasma.

Coexistence of Stochastic Field and Turbulence

Before L-H transition, L-mode plasma with RMP:



Magnetic islands overlapping forms stochastic fields



Strong electrostatic turbulence

Both **stochastic field** and **turbulence** enter the cross-phase $\langle \widetilde{b}\widetilde{p} \rangle$, $\langle \widetilde{b}\widetilde{u}_{\|} \rangle$, and hence enter the dephasing mechanism.

Key question:

How does stochastic fields influence on the response of parallel flow and pressure in strong/weak turbulence regime?

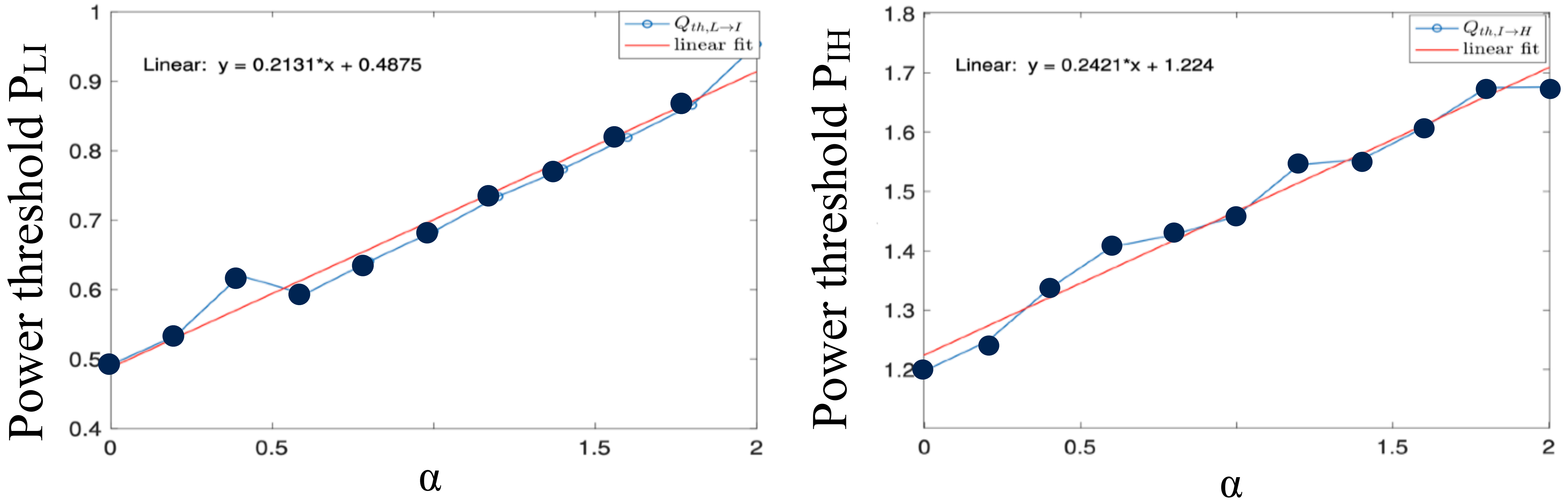
We analyze the dephasing effect of stochastic field in strong and weak electrostatic turbulence—how they *together* drives transport.

Previous Works

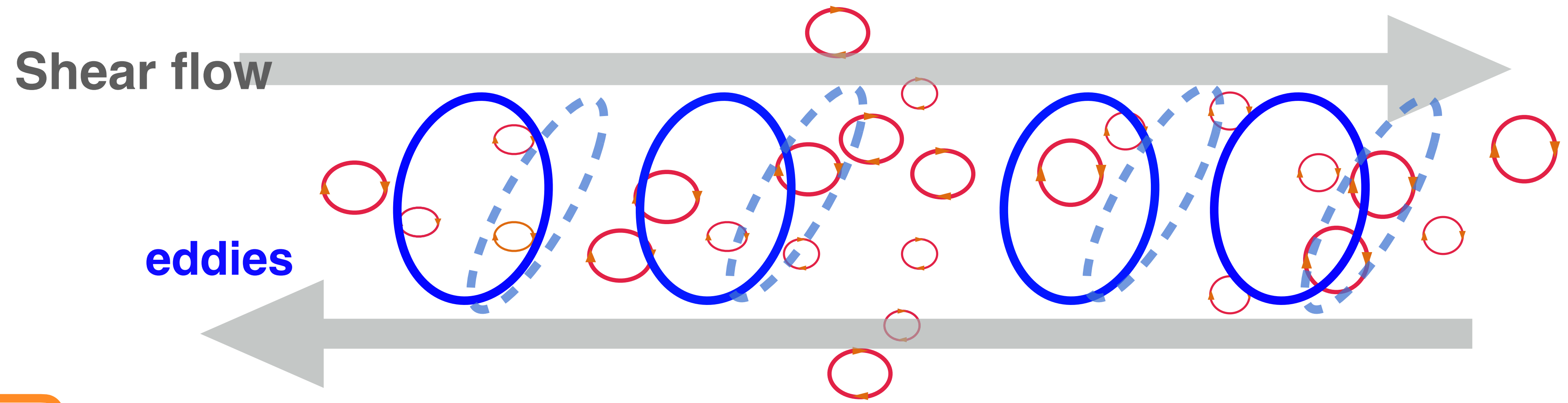
Stochastic field effect on Reynolds Stress and the Power Threshold

Chen et al.,PoP **28**, 042301 (2021):

- b^2 shift L-H threshold to higher power, in proportional to $\alpha \equiv \frac{b^2}{\sqrt{\beta}\rho_*^2}\frac{q}{\epsilon}$.



- Dephasing effect caused by stochastic fields quenches poloidal Reynolds stress—the **mean $E \times B$ shear** is suppressed by this effect. However, observe



$$\frac{\partial}{\partial t}\langle u_{E\times B}\rangle = \boxed{D_{PV}}\frac{\partial}{\partial x}\langle\zeta\rangle - \boxed{F_{res}}\kappa\frac{\partial}{\partial x}\langle p\rangle$$

$$\langle E_r\rangle = \frac{\nabla\langle p_i\rangle}{ne} - \langle \mathbf{u}\rangle \times \langle \mathbf{B}\rangle$$

Ion heat/ particle transport

Parallel momentum transport

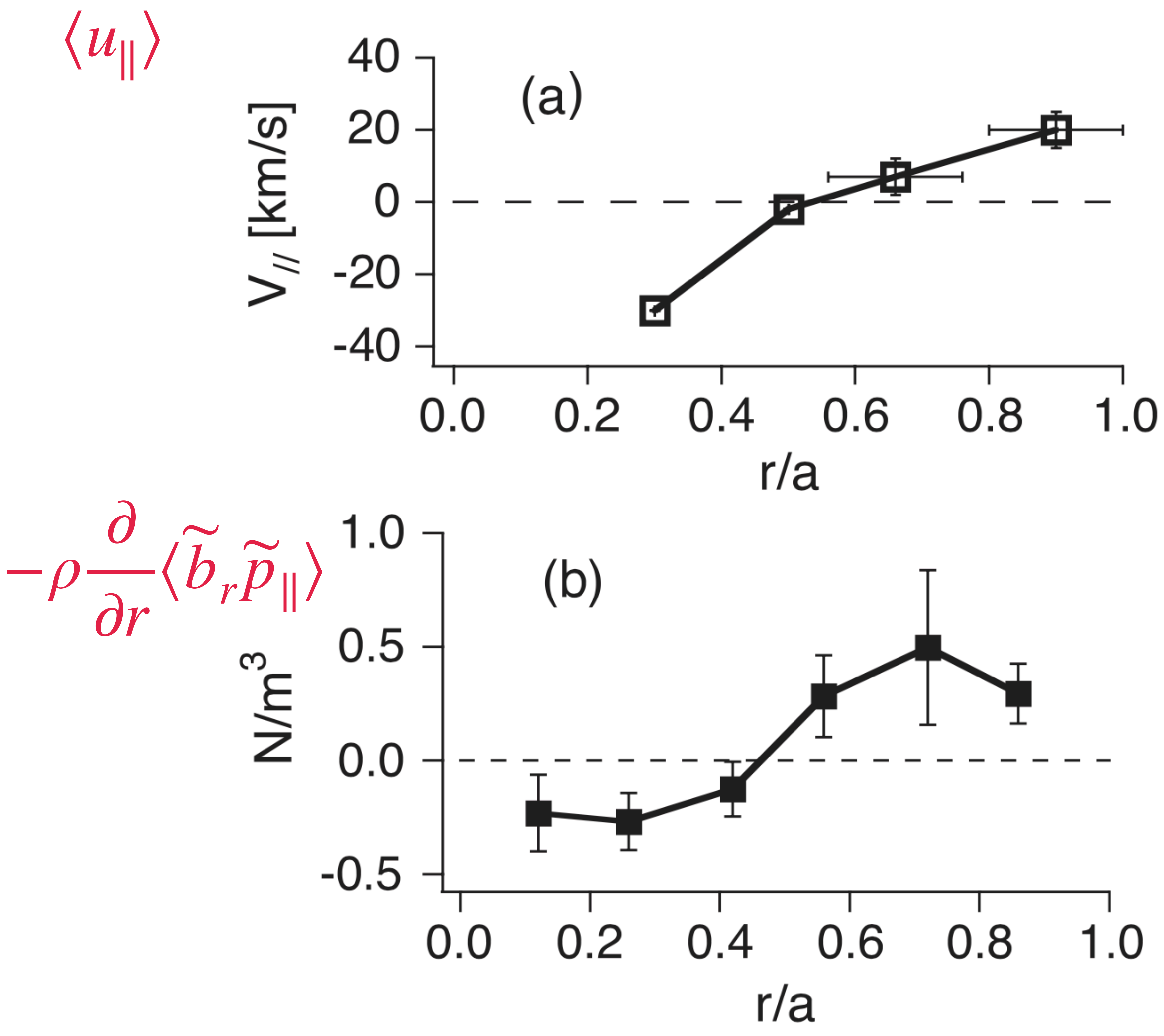
Key question:

How stochastic fields influence the ion heat and the parallel momentum transport?

We examine the physics of stochastic fields interaction with the ion pressure and the parallel flow.

Example

Experimental Result of Madison Symmetric Torus (MST)



(Ding et al., PRL **110**, 065008 (2013))

Macroscopic parallel flow dynamics.

Nonlinear momentum transport

Microscopic effect measured from the fluctuations of the pressure and the stochastic field.

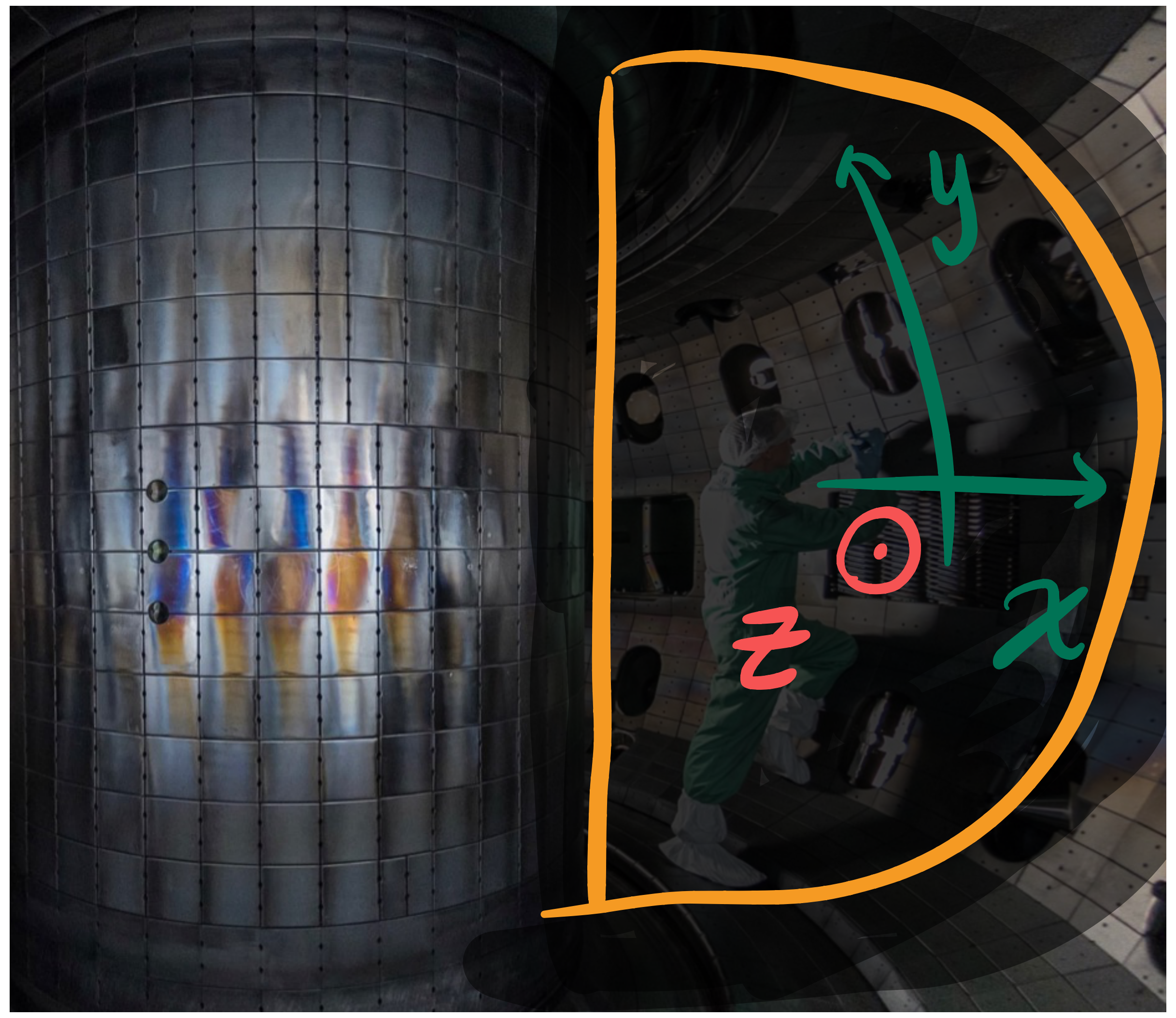
MST Experimental results: demonstrated the similarity of the kinetic stress to the parallel flow.

Model

1. Cartesian coordinate: strong mean field B_0 is in z direction (3D).
2. Rechester & Rosenbluth (1978): waves, instabilities, and transport are studied in the presence of **external excited, static, stochastic fields.**
3. $\underline{k} \cdot \underline{B} = 0$ (or $k_{\|} = 0$) **resonant at rational surface in third direction, and** Kubo number: $Ku_{mag} = l_{ac} | \widetilde{\mathbf{B}} | / \Delta_{\perp} B_0$).
4. Equations:

   (a) Pressure equation: $\frac{\partial}{\partial t} p + (\mathbf{u} \cdot \nabla) p = -\gamma p (\nabla_z \cdot \mathbf{u}_z)$

   (b) Parallel flow equation: $\frac{\partial}{\partial t} u_z + (\mathbf{u} \cdot \nabla) u_z = -\frac{1}{\rho} \nabla_z p$



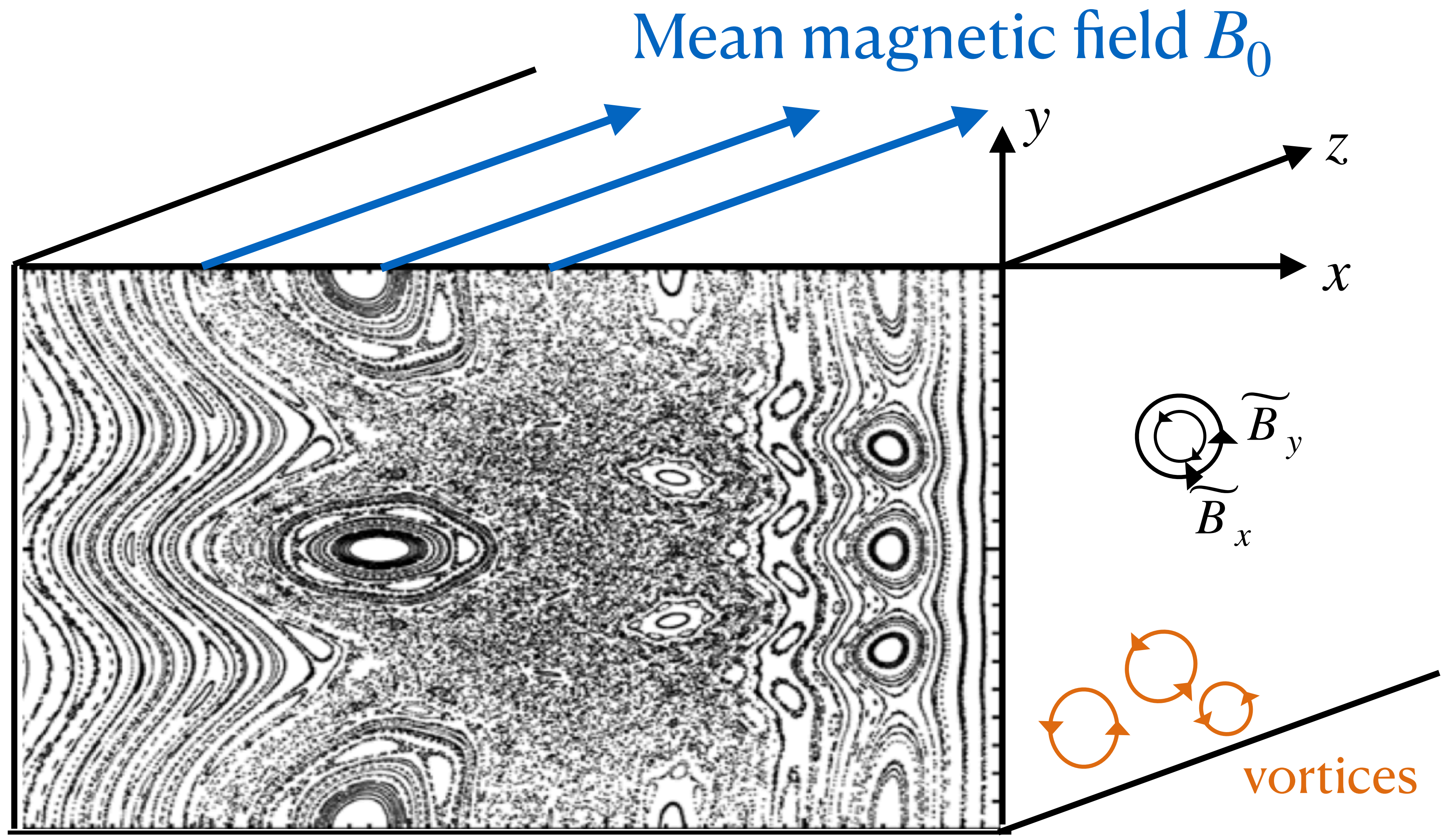
We use mean field approximation: $\nabla_z = \nabla_z^{(0)} + \tilde{b} \cdot \nabla_{\perp}$

$p = \langle p \rangle + \boxed{\tilde{p}}$, Perturbations produced by turbulences

$where \;\; \langle \; \rangle = \frac{1}{L_{\|}} \int dL_{\|} \frac{1}{2\pi r} \int r d\theta$

ensemble average over the symmetry direction

We define rms of normalized stochastic field $\tilde{b} \equiv \sqrt{\langle \widetilde{B}^2 \rangle / B_0^2}$



Magnetic islands overlapping forms stochastic

Heuristics

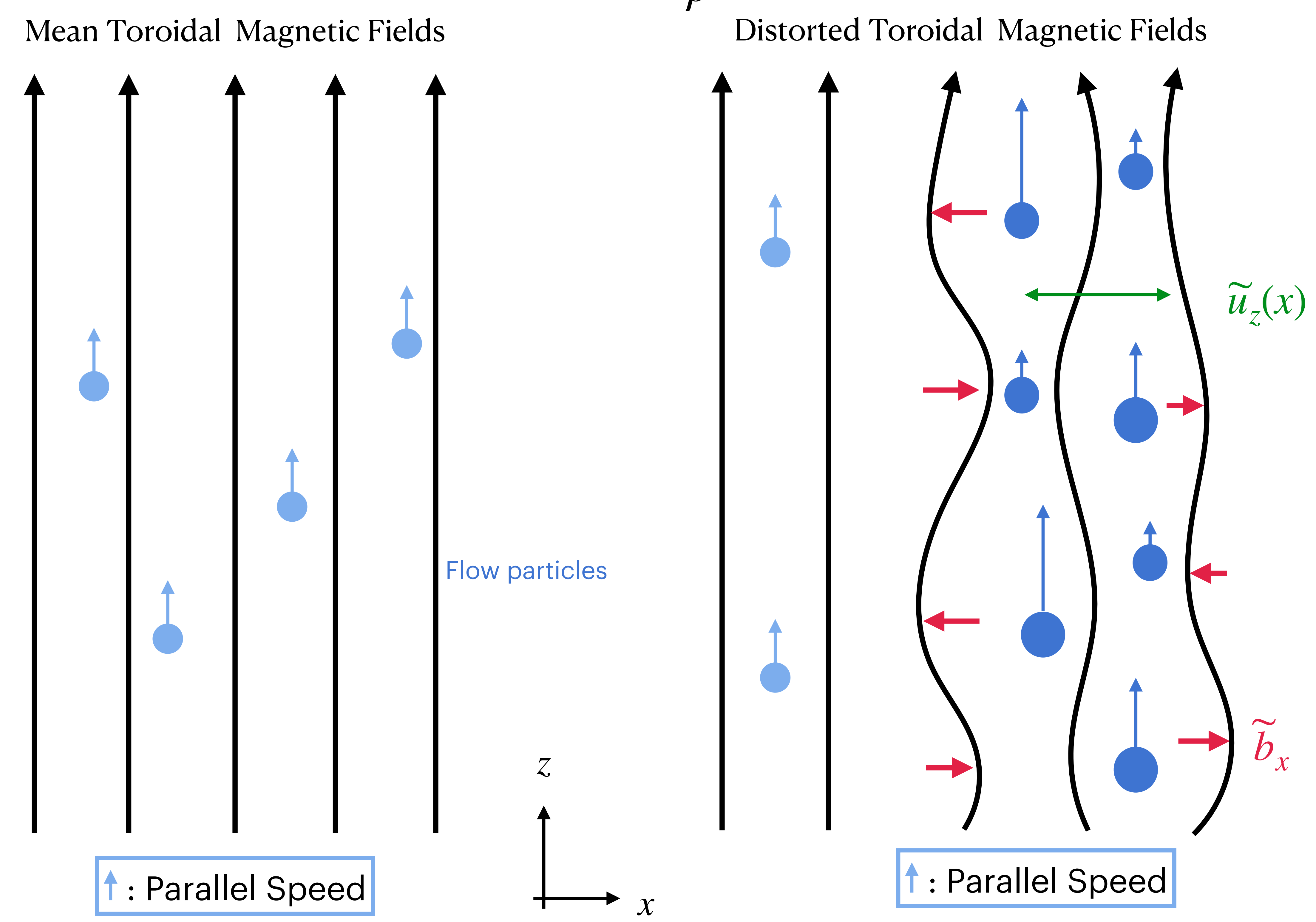
Physical Picture of Pressure Response

Local **pressure excess** ($\tilde{b}_r \partial_r \langle p \rangle$) caused by magnetic perturbation is balanced by: ($u_{\parallel}$ response in the same way)

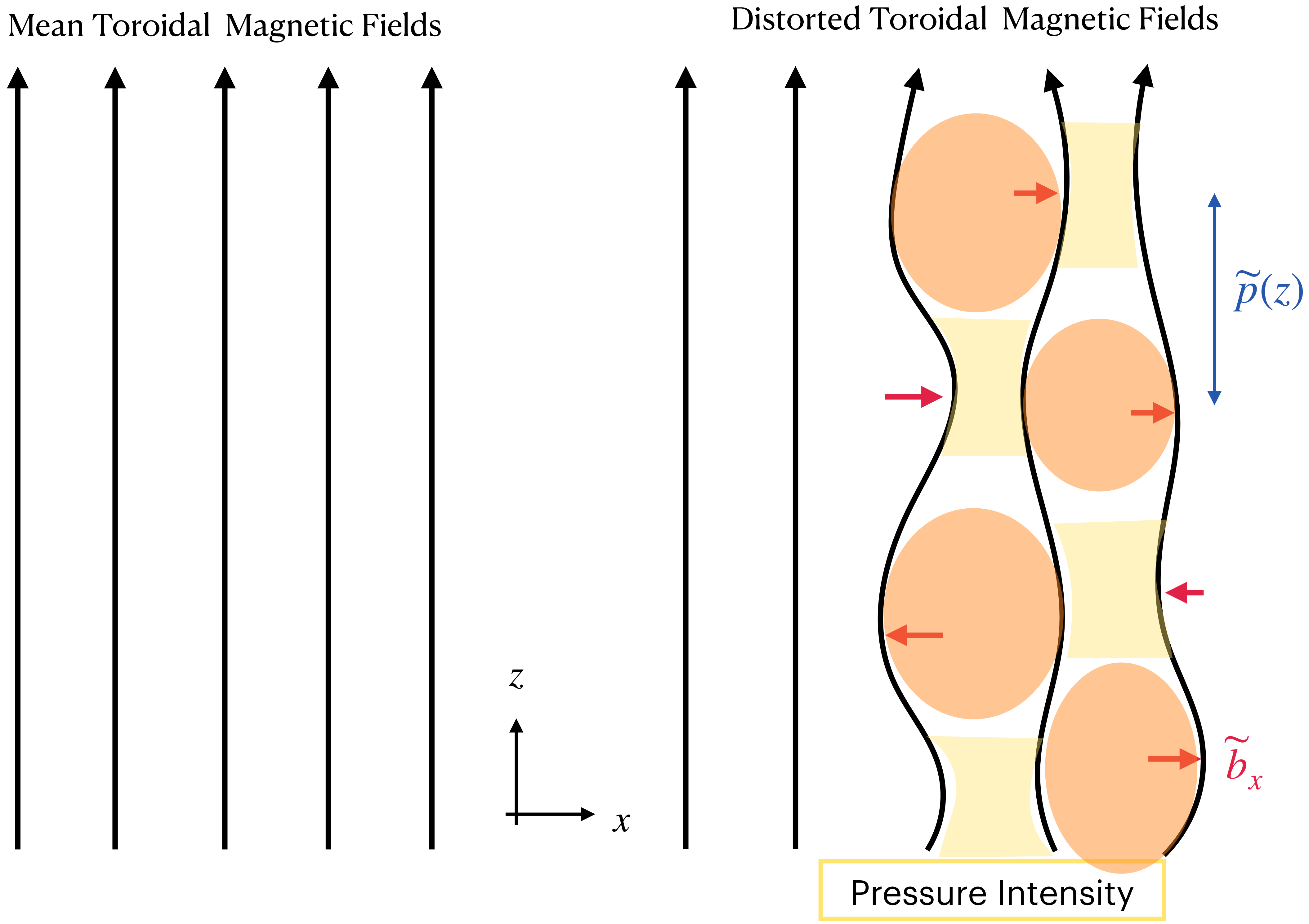
... by parallel flow perturbation, which is damped by turbulent viscosity.

... by parallel pressure gradient. → Finn et al., PoP **4**, 1152 (1992)

1 Strong Turbulence: $\tilde{b}_r \nabla_r \frac{\langle p \rangle}{\rho} \simeq D_T \nabla_\perp^2 \tilde{u}_z$



2 Weak Turbulence: $\tilde{b}_r \nabla_r \langle p \rangle \simeq -\nabla_z \tilde{p}$ $(\mathbf{B} \cdot \nabla p = 0)$.



Rate of turbulent (i.e. viscous) mixing $D_T/l_\perp^2$ > other rate: turbulent viscosity will dissipate the parallel flow.

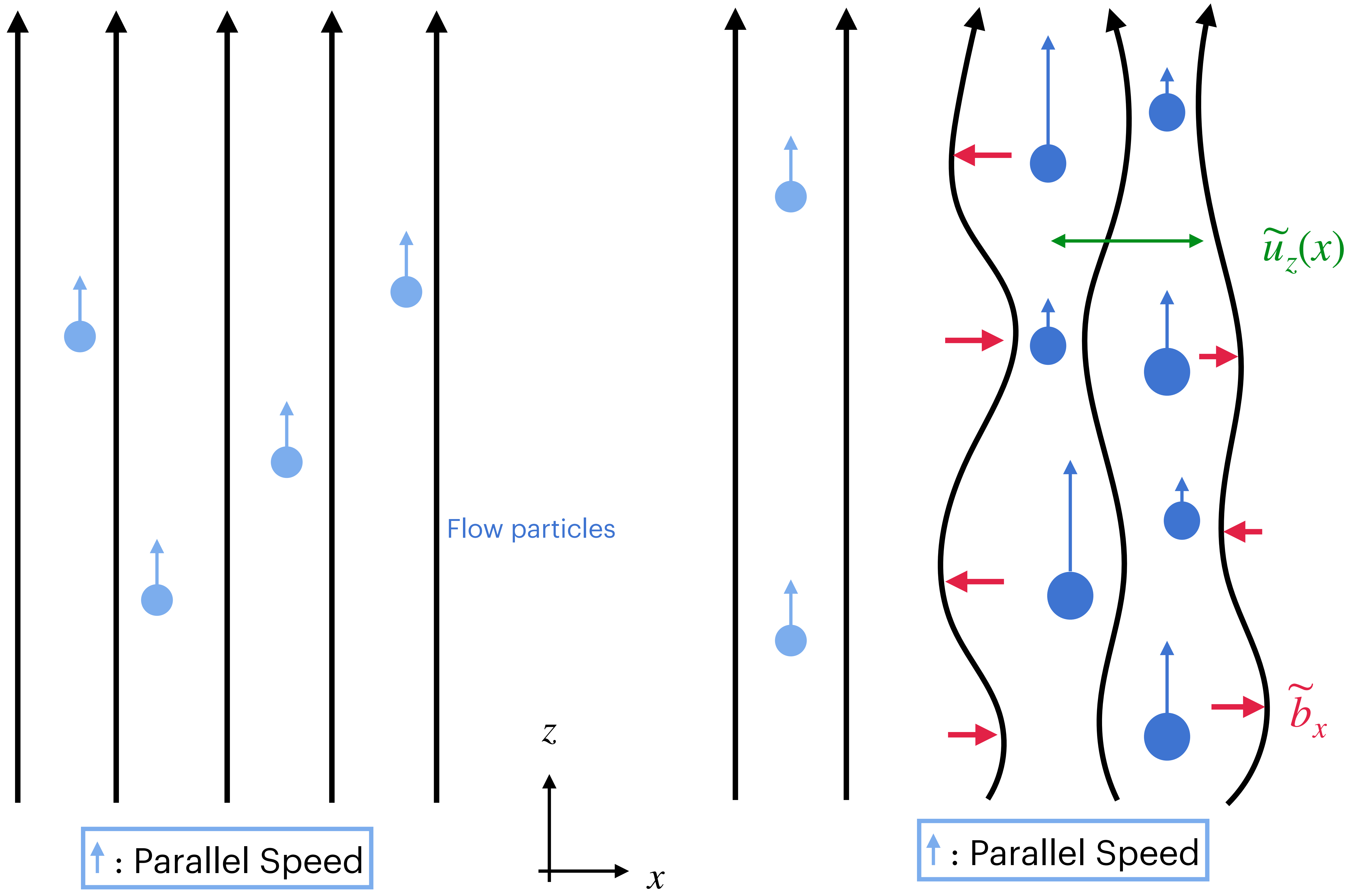
Rate of sound propagation $c_s/l_\parallel$ > other rate: pressure gradient builds up parallelly.

Only the Strong Turbulence Regime is Relevant

Strong Turbulence: $\widetilde{b}_r \nabla_r \frac{\langle p \rangle}{\rho} \simeq D_T \nabla_\perp^2 \widetilde{u}_z$

Mean Toroidal Magnetic Fields

Distorted Toroidal Magnetic Fields



$(D_T / l_\perp^2$ > other rates).

In reality, the rate of turbulent (i.e. viscous) mixing of the parallel flow response is large.

Only strong turbulent cases are relevant!

Kinetic Stress and Compressible Energy Flux

Mean field equation for parallel flow and the pressure equation:

$$\frac{\partial}{\partial t}\langle u_z\rangle + \frac{\partial}{\partial x}\langle \tilde{u}_x\tilde{u}_z\rangle = -\frac{1}{\rho}\frac{\partial}{\partial x}\langle \tilde{b}_x\tilde{p}\rangle \equiv -\frac{\partial}{\partial x}K,$$ where the **kinetic stress** $K \equiv \frac{1}{\rho}\langle \tilde{b}_x\tilde{p}\rangle$

$$\frac{\partial}{\partial t}\langle p\rangle + \frac{\partial}{\partial x}\langle \tilde{u}_x\tilde{p}\rangle = -\rho c_s^2\frac{\partial}{\partial x}\langle \tilde{b}_x\tilde{u}_z\rangle \equiv -\frac{\partial}{\partial x}H,$$ where the **compressible heat flux** $H \equiv \rho c_s^2\langle \tilde{b}_x\tilde{u}_z\rangle$ (or, ion heat density flux)

Perturbed equation with **Riemann variables** $f_\pm \equiv \tilde{u}_{z,k\omega} \pm \frac{\tilde{p}_{k\omega}}{\rho c_s}$:

$$-i\omega\frac{\tilde{p}}{\rho c_s} + c_s i k_z\tilde{u}_z + \tilde{u}_\perp\nabla_\perp\frac{\tilde{p}}{\rho c_s} = -\tilde{u}_x\frac{\partial}{\partial x}\frac{\langle p\rangle}{\rho c_s} - \tilde{b}_x c_s\frac{\partial}{\partial x}\langle u_z\rangle$$

$$-i\omega\tilde{u}_z + c_s i k_z\frac{\tilde{p}}{\rho c_s} + \tilde{u}_\perp\nabla_\perp\tilde{u}_z = -\tilde{u}_x\frac{\partial}{\partial x}\langle u_z\rangle - \tilde{b}_x c_s\frac{\partial}{\partial x}\left(\frac{\langle p\rangle}{\rho c_s}\right)$$

→

$$(\pm i c_s k_z + i k_\perp\tilde{u}_\perp)f_{\pm,k} = -\tilde{b}_x c_s\left(\frac{\partial}{\partial x}\frac{\langle p\rangle}{\rho c_s} \pm \frac{\partial}{\partial x}\langle u_z\rangle\right)$$

$$\tilde{u}_\perp\nabla_\perp \equiv -\nabla_\perp\cdot \underline{\underline{D_T}}\cdot\nabla_\perp$$

turbulent fluid diffusivity

$$D_T \equiv \sum_k |\tilde{u}_{\perp,k}|^2\tau_{ac} \simeq 1/k_\perp^2\tau_{c,k}$$

Decorrelation time due to turbulent scattering

→

$$K = \frac{1}{\rho}\langle \tilde{b}_x\tilde{p}\rangle = \frac{1}{\rho}\sum_{k_y,k_z}|\tilde{b}_{x,k}|^2\frac{-1}{k_\perp^4D_T^2+k_z^2c_s^2}\times\left[\rho c_s^2k_\perp^2D_T\frac{\partial}{\partial x}\langle u_z\rangle - ik_zc_s^2\frac{\partial}{\partial x}\langle p\rangle\right]$$

$$H \equiv \rho c_s^2\langle \tilde{b}_x\tilde{u}_z\rangle = \rho c_s^2\sum_{k_y,k_z}|\tilde{b}_{x,k}|^2\frac{-1}{k_\perp^4D_T^2+k_z^2c_s^2}\left[k_\perp^2D_T\frac{\partial}{\partial x}\frac{\langle p\rangle}{\rho} - ik_zc_s^2\frac{\partial}{\partial x}\langle u_z\rangle\right]$$

The propagator $1/(k_\perp^4D_T^2 + k_z^2c_s^2)$ contains the turbulent mixing ($k_\perp^4D_T^2$) and the magnetic shear effect ($k_z^2c_s^2$).

Magnetic shear Effect

Consider the propagator $\frac{1}{(k_\perp^4 D_T^2 + k_z^2 c_s^2)}$:

$$k_z^2 c_s^2 = (\frac{k_y x}{L_s})^2 c_s^2$$

Magnetic shear length

$$L_s = (\frac{q' r_0}{q^2 R_0})^{-1}$$

+

Summation:

$$\sum_{k_y k_z} = \int dm \int dn = \int dm \int dx \frac{|m|}{q^2} q' = r_0 \int dk_y \int dx \frac{|k_y|}{q} \hat{s}$$

Magnetic shear $\hat{s} = \frac{r_0}{q}\frac{dq}{dr}$

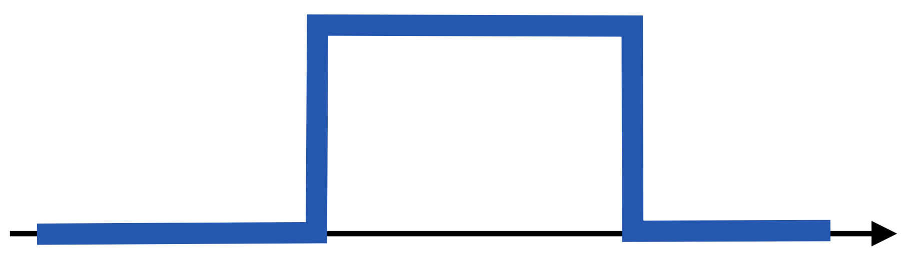
$\rightarrow$

$$\sum_{k_y,k_z} |\tilde{b}_{x,k}|^2 \frac{1}{k_\perp^4 D_T^2 + k_z^2 c_s^2} = \int dk_y \frac{k_y r_0^2 q'}{q^2} \int dx |\tilde{b}_{x,k}|^2 \frac{\tau_{c,k}^2}{1 + (k_y x/L_s)^2 c_s^2 \tau_{c,k}^2}$$

Consider competition between the stochastic field and turbulence:

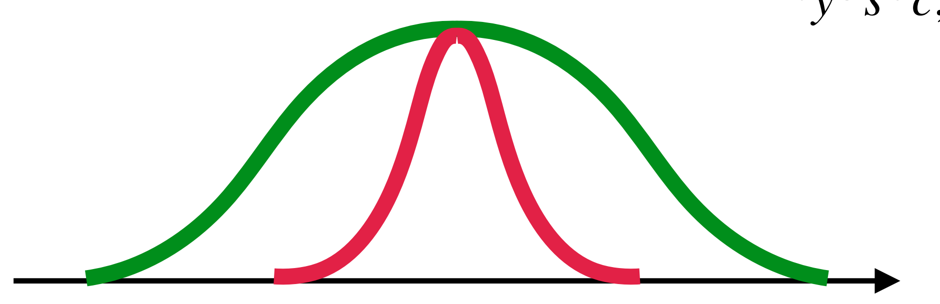
$$\langle \tilde{b}_x \tilde{p} \rangle = \overset{①}{\int dk_y \frac{k_y r_0^2 q'}{q^2} \int dx |\tilde{b}_{x,k}|^2 \frac{\tau_{c,k}}{1 + (k_y x/L_s)^2 c_s^2 \tau_{c,k}^2} \left(-\rho c_s^2 \frac{\partial}{\partial x} \langle u_z \rangle \right)} + \overset{②}{\int dk_y \frac{k_y r_0^2 q'}{q^2} \int dx |\tilde{b}_{x,k}|^2 \frac{1}{(k_\perp^2 D_T)^2 + k_z^2 c_s^2} \left(i k_z c_s^2 \frac{\partial}{\partial x} \langle p \rangle \right)}$$

$$|\tilde{b}_{x,k}|^2 = CS(k_y) \underline{F(x/w_k)}$$



Define the acoustic width: $x_s \equiv \frac{L_s}{k_y c_s \tau_{c,k}}$

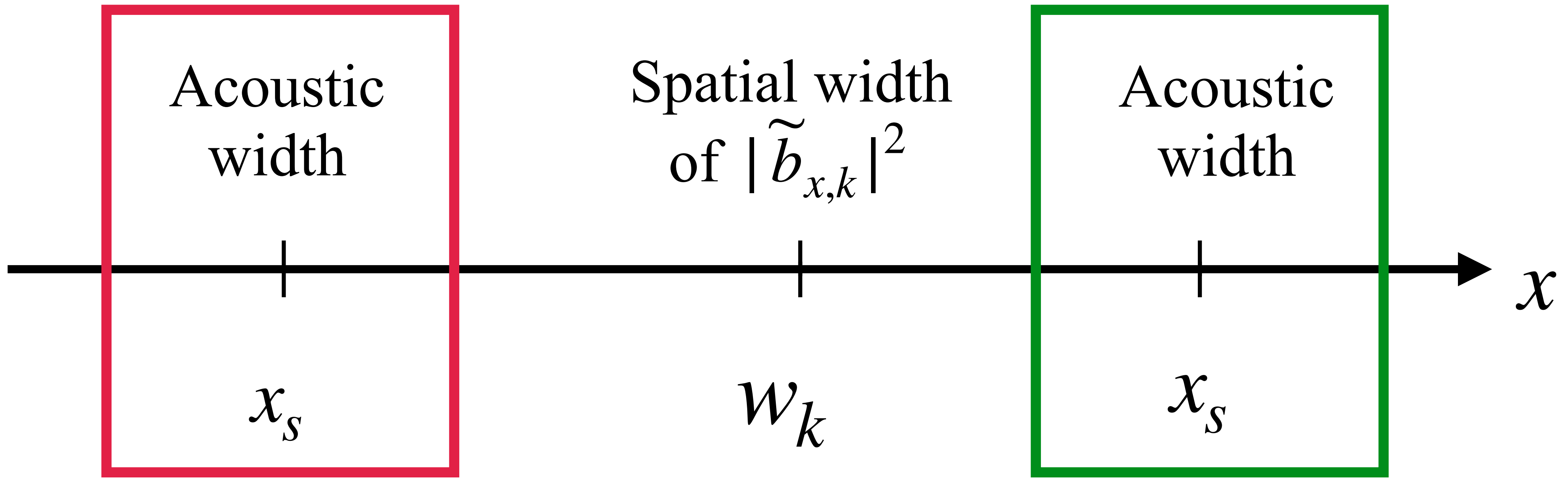
$$\frac{1}{1 + (k_y x/L_s)^2 c_s^2 \tau_{c,k}^2} \equiv \frac{1}{1 + \underline{(x/x_s)}^2}$$



Acoustic width x_s : the spatial width of turbulent flow

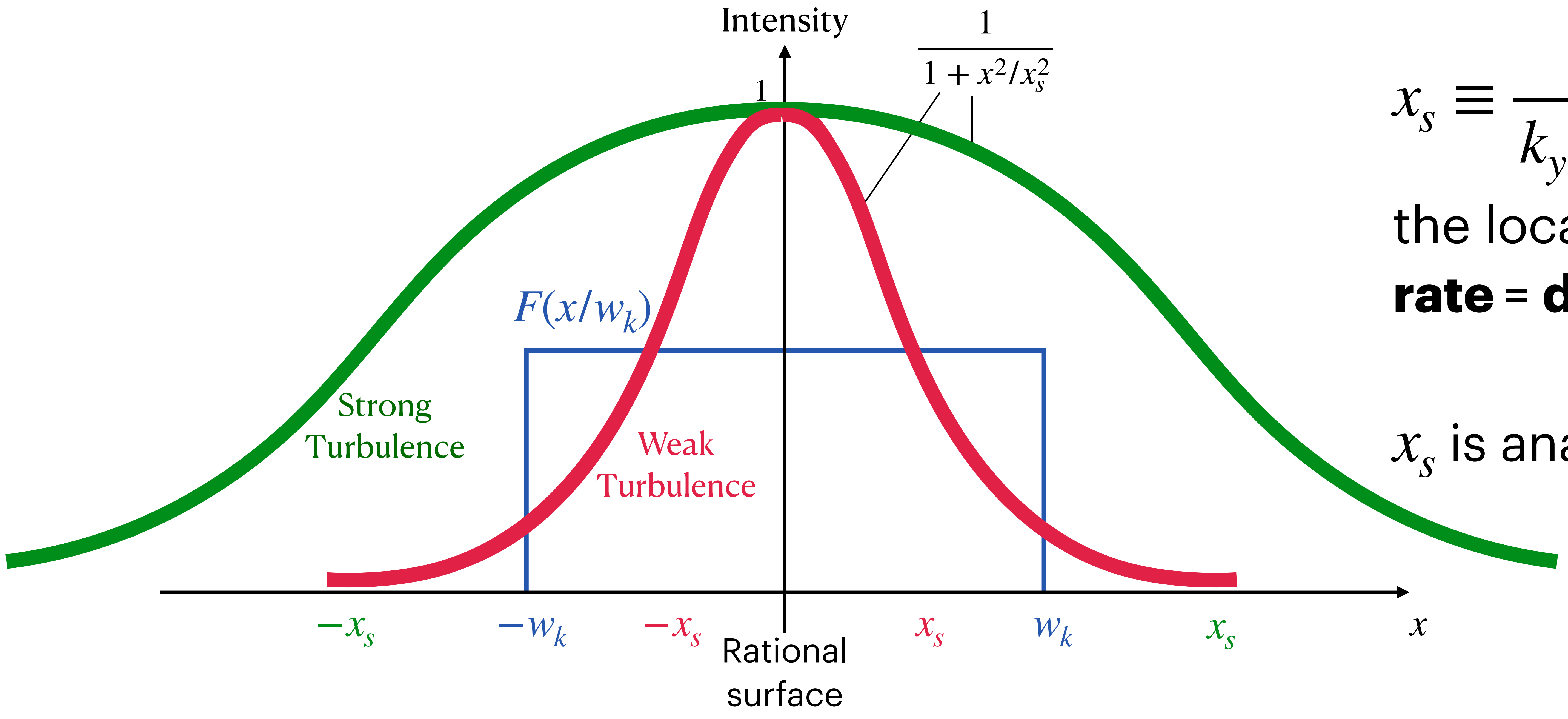
Scales

We consider length scales:



Weak turbulence regime

Strong turbulence regime



$x_s \equiv \dfrac{L_s}{k_y c_s \tau_{c,k}}$ is the **acoustic width**—x_s defines the the location where the **parallel acoustic streaming rate** = **decorrelation rate.**

x_s is analogous to ion Landau resonant point.

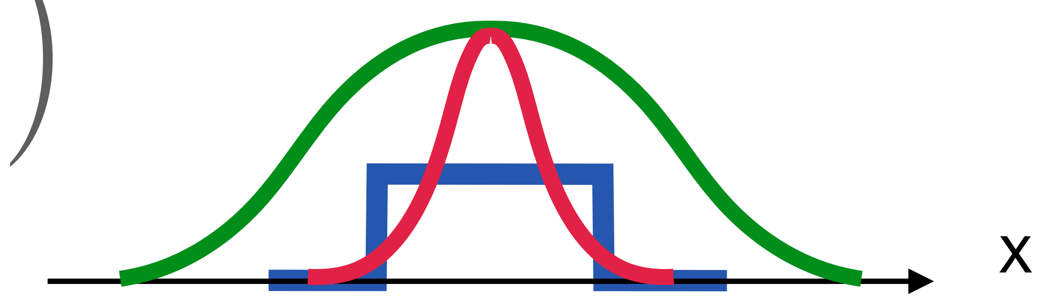
Dimensionless Ratio and Regimes

Dimensionless parameter (λ) that defines the competition between the stochastic-field and turbulent effect: $\lambda \equiv \dfrac{x_s}{w_k}$

$$\langle \tilde{b}_x \tilde{p} \rangle = \int dk_y \frac{k_y r_0^2 q'}{q^2} \int dx \, |\tilde{b}_{x,k}|^2 \frac{\tau_{c,k}}{1 + (k_y x/L_s)^2 c_s^2 \tau_{c,k}^2} \left(-\rho c_s^2 \frac{\partial}{\partial x} \langle u_z \rangle \right) \quad (1)$$

$$+ \sum_{k_y, k_z} |\tilde{b}_{x,k}|^2 \frac{1}{(k_\perp^2 D_T)^2 + k_z^2 c_s^2} \left(i k_z c_s^2 \frac{\partial}{\partial x} \langle p \rangle \right) \quad (2)$$

$$\rightarrow \int^{x = w_k \ or \ x_s} dx F(x/w_k) \cdot \frac{1}{1 + (x/x_s)^2}$$



In strong turbulence:

$\dfrac{x_s}{w_k} > 1$, the cutoff length in the integral is $x = w_k$

In weak turbulence:

$\dfrac{x_s}{w_k} < 1$, the cutoff length in the integral is $x = x_s$

1 $= -\rho D_{st} \dfrac{\partial}{\partial x} \langle u_z \rangle$ > 2

Relevant in reality

2 $= -D_M \dfrac{\partial}{\partial x} \langle p \rangle$ > 1

Results—Strong Turbulence Regime

In strong turbulence ($k_\perp^2 D_T \gg k_z c_s$ or $\lambda > 1$):

$$\underline{K} \equiv \frac{1}{\rho}\langle \tilde{b}_x \tilde{p} \rangle \simeq -D_{st}\frac{\partial}{\partial x}\langle u_z \rangle \text{ , where}$$

$$D_{st} = D_{st}(x) = \sum_{k_y k_z} \boxed{|\tilde{b}_{x,k}|^2} \frac{c_s^2}{\boxed{k_\perp^2 D_T}}$$

Stochastic B field

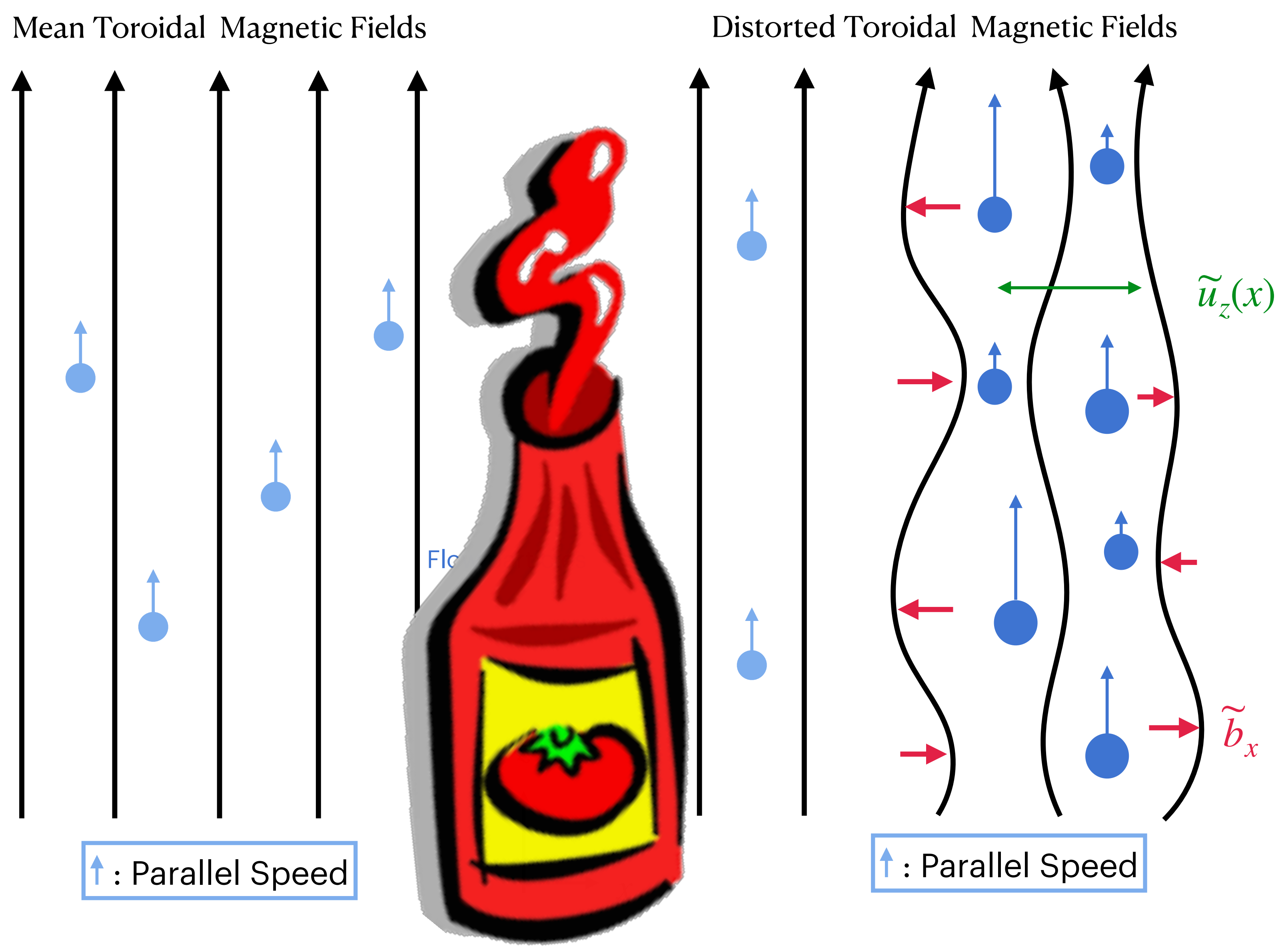
Turbulent scattering decorrelation rate

Turbulent fluid diffusivity $D_T \equiv \sum_k |\tilde{u}_{\perp,k}|^2 \tau_{ac}$

D_{st} : the **hybrid turbulent diffusivity**—explain how the kinetic stress is scattered by stochastic B fields and turbulence.

$$\underline{H} \equiv \rho c_s^2 \langle \tilde{b}_x \tilde{u}_z \rangle \simeq -D_{st}\frac{\partial}{\partial x}\langle p \rangle$$

Strong Turbulence: $\tilde{b}_r \nabla_r \frac{\langle p \rangle}{\rho} \simeq D_T \nabla_\perp^2 \tilde{u}_z$



Pressure gradient $\partial\langle p \rangle/\partial x$ due to $\tilde{b}$ is balanced by turbulent mixing of parallel flow $\nabla_\perp^2 \tilde{u}_z$.

The pressure gradient in presence of tilted B lines balances with the *hybrid* turbulent diffusion.

Rare in practice

Results — Weak Turbulence Regime

In weak turbulence ($k_\perp^2 D_T \ll k_z c_s$ or $\lambda > 1$):

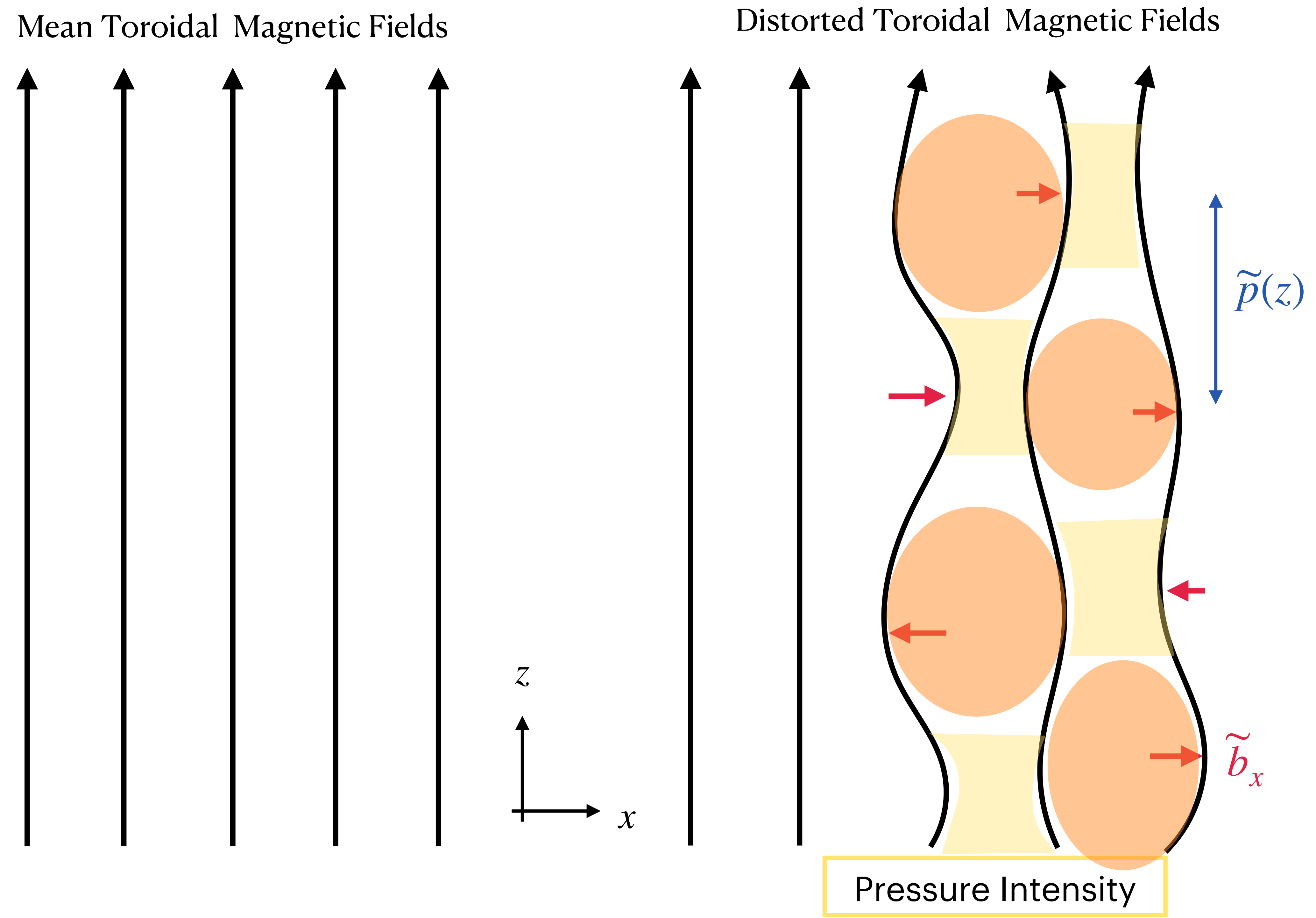
$$\underline{K} \equiv \frac{1}{\rho}\langle \tilde{b}_x \tilde{p}\rangle \simeq -\frac{1}{\rho} D_M \frac{\partial}{\partial x}\langle p\rangle \text{ , where}$$

$$D_M = D_M(x) \equiv \sum_{k_y,k_z} |\tilde{b}_{x,k}|^2 \tau_{d,k} c_s$$

D_M is the magnetic diffusivity.

$$\underline{H} \equiv \rho c_s^2 \langle \tilde{b}_x \tilde{u}_z\rangle \simeq -\rho c_s^2 D_M \frac{\partial}{\partial x}\langle u_z\rangle$$

Weak Turbulence: $\tilde{b}_r \nabla_r \langle p\rangle \simeq -\nabla_z \tilde{p}$



For weak scattering, momentum and energy transport occur only through stochastic B fields, with familiar transport coefficient $c_s D_M$.

Pressure gradient $\partial\langle p\rangle/\partial x$ due to $\tilde{b}$ is balanced by the parallel pressure gradient

Results — Mean Evolution of Parallel Flow and Pressure

	Strong Turbulence (λ>1)	Weak Turbulence (λ <1)
Kinetic Stress $K \equiv \langle \tilde{b}_x \tilde{p} \rangle / \rho$	$K = -D_{st} \frac{\partial}{\partial x} \langle u_z \rangle$	$K = -\frac{1}{\rho} D_M \frac{\partial}{\partial x} \langle p \rangle$
Compressive energy flux $H \equiv \rho c_s^2 \langle \tilde{b}_x \tilde{u}_z \rangle$	$H = -D_{st} \frac{\partial}{\partial x} \langle p \rangle$	$H = -\rho c_s^2 D_M \frac{\partial}{\partial x} \langle u_z \rangle$
Mean evol. of parallel flow	$\frac{\partial}{\partial t} \langle u_z \rangle = -\frac{\partial}{\partial x} \langle \tilde{u}_x \tilde{u}_z \rangle + \frac{\partial}{\partial x} D_{st}(x) \frac{\partial}{\partial x} \langle u_z \rangle$	$\frac{\partial}{\partial t} \langle u_z \rangle \simeq -\frac{\partial}{\partial x} \langle \tilde{u}_x \tilde{u}_z \rangle + \frac{\partial}{\partial x} \frac{D_M(x)}{\rho} \frac{\partial}{\partial x} \langle p \rangle$
Mean evol. of pressure	$\frac{\partial}{\partial t} \langle p \rangle = -\frac{\partial}{\partial x} \langle \tilde{u}_x \tilde{p} \rangle + \frac{\partial}{\partial x} D_{st}(x) \frac{\partial}{\partial x} \langle p \rangle$	$\frac{\partial}{\partial t} \langle p \rangle = -\frac{\partial}{\partial x} \langle \tilde{u}_x \tilde{p} \rangle + \frac{\partial}{\partial x} \rho c_s^2 D_M(x) \frac{\partial}{\partial x} \langle u_z \rangle$

hybrid turbulent diffusivity: $D_{st} = \sum_{k_y k_z} |\tilde{b}_{x,k}|^2 \frac{c_s^2}{k_\perp^2 D_T}$ $\quad D_T \equiv \sum_k |\tilde{u}_{\perp,k}|^2 \tau_{ac}$

Strong turbulence regime: Mean flow (macroscopic) is driven by the stochastic-turbulent scattering (microscopic).

Electron Particle Flux

Motivated by Finn et al., PoP **4**, 1152 (1992):

$$\frac{\partial \tilde{v}_\parallel}{\partial t} = -\frac{c_s^2}{n}\hat{\mathbf{b}}\cdot\nabla\tilde{n},$$

$$\frac{\partial \tilde{n}}{\partial t} = -n\hat{\mathbf{b}}\cdot\nabla\tilde{v}_\parallel .$$

Then, writing $u = \tilde{v}_\parallel/c_s + \tilde{n}/n$, $v = \tilde{v}_\parallel/c_s - \tilde{n}/n$, we obtain

$$\frac{\partial u}{\partial t} + c_s\hat{\mathbf{b}}\cdot\nabla u = 0,$$

$$\frac{\partial v}{\partial t} - c_s\hat{\mathbf{b}}\cdot\nabla v = 0. \qquad (6)$$

Consider equation of parallel flow and electron density:

Mean Field Theory

$$n_e = \langle n_e\rangle + \widetilde{n}_e$$

→

$$\langle n_e\rangle\frac{\partial}{\partial t}\langle u_z\rangle = -c_s^2\frac{\partial}{\partial x}\langle\widetilde{b}_x\widetilde{n}_e\rangle$$

$$\frac{\partial}{\partial t}\langle n_e\rangle = -\langle n_e\rangle\frac{\partial}{\partial x}\langle\widetilde{b}_x\widetilde{u}_z\rangle$$

→

Riemann-like variables

$$h_\pm \equiv \frac{\widetilde{u}_z}{c_s} \pm \frac{\widetilde{n}_e}{\langle n_e\rangle}$$

$$\langle\widetilde{b}_x\widetilde{n}_e\rangle = -D_M\frac{\partial}{\partial x}\langle n_e\rangle$$

$\langle\widetilde{b}_x\widetilde{n}\rangle$ gives an residual stress

$$\langle\widetilde{b}_x\widetilde{u}_z\rangle = -D_M\frac{\partial}{\partial x}\langle u_z\rangle$$

$\langle\widetilde{b}_x\widetilde{u}_z\rangle$ gives an off-diagonal convective flux

→

$$\frac{\partial}{\partial t}\frac{\langle u_z\rangle}{c_s} = \frac{\partial}{\partial x}c_s D_M\frac{\partial}{\partial x}\frac{\langle n_e\rangle}{n_0} \qquad \frac{\partial}{\partial t}\langle n_e\rangle = \frac{\partial}{\partial x}D_M\frac{\partial}{\partial x}\langle u_z\rangle$$

Fluxes are non-diffusive (off-diagonal)

This is overlooked by Finn et al. since their analysis never convert back from Riemann-like variables.

How is this related to the particle transport?

Electron Particle Flux

Consider electron density evolution:

$$\boxed{\frac{\partial \langle n_e \rangle}{\partial t} - \frac{\partial}{\partial x}\frac{\langle \tilde{b}_x \tilde{J}_{z,e} \rangle}{|e|} = 0} + \boxed{\begin{array}{c}\text{Ampère's Law}\\ -\nabla_\perp^2 A_z = \mu_0 (J_{z,e} + J_{z,i})\end{array}} \rightarrow \frac{\partial \langle n_e \rangle}{\partial t} = -\frac{1}{\mu_0 |e|}\frac{\partial}{\partial x}\underbrace{\langle \tilde{b}_x \nabla_\perp^2 \tilde{A}_{z,e} \rangle}_{\text{Total current contribution}} - n_{0,i}\frac{\partial}{\partial x}\underbrace{\langle \tilde{b}_x \tilde{u}_{z,i} \rangle}_{\text{Ion current contribution}}$$

$$\langle \tilde{b}_x \tilde{u}_z \rangle = -D_M \frac{\partial}{\partial x}\langle u_z \rangle$$

$$D_M \equiv \sum_{k_y k_z} |\tilde{b}_{x,k}|^2 \tau_{d,k} c_s$$

Dispersal timescale of an acoustic wave packet along the stochastic magnetic field

$$\rightarrow \frac{\partial \langle n_e \rangle}{\partial t} = -\frac{\partial}{\partial x}\Gamma_{e,s}$$

Electron particle flux

$$= \frac{\partial}{\partial x}\underbrace{\frac{B_0}{\mu_0 |e|}\frac{\partial}{\partial x}\langle \tilde{b}_x \tilde{b}_y \rangle}_{\text{Familiar div. Maxwell stress}} + \frac{\partial}{\partial x}\underbrace{n_0 D_M \frac{\partial}{\partial x}\langle u_{z,i} \rangle}_{\text{Ion flow along the tilted B line}}$$

Stochastic lines and parallel ion flow gradient drives a net electron particle flux, in additional to the Maxwell force contribution.

Conclusions

- We calculate the ***explicit form*** of the stochastic-field-induced transports—kinetic stress K and the compressive energy flux H—have different mechanisms in presence of strong/weak electrostatic turbulence.
- In practice, ***only* strong turbulent cases** ($k_\perp^2 D_T \gg k_z c_s$ or $\lambda > 1$) **are relevant**. We found mean parallel flow and mean pressure are driven via the ***hybrid diffusivity*** that involves effect of stochastic field and turbulent scattering:

$$D_{st} = D_{st}(x) = \sum_{k_y k_z} |\tilde{b}_{x,k}|^2 \frac{c_s^2}{k_\perp^2 D_T}$$

Stochastic B field

Turbulent scattering decorrelation rate

Future Works

- Magnetic drift—effect of stochastic field and turbulence upon geodesic acoustic modes.
- One should include the effect of $\langle \tilde{b}\,\tilde{\phi} \rangle \neq 0$ in the future (Cao & Diamond 2021).
- Relevant problems: cosmic ray acceleration and propagation.