Intrinsic plasma flows in straight magnetic fields

Jiacong Li

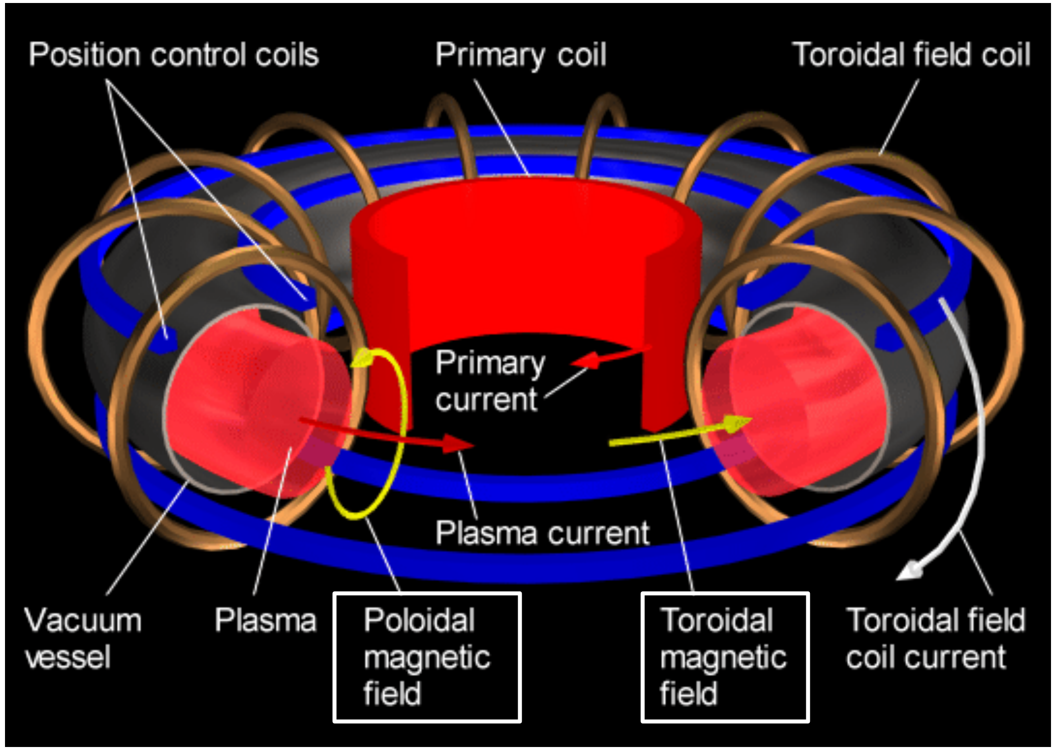
Advisor: Pat Diamond

Fusion and Astrophysical Plasma Physics Group, UC San Diego
fapp.ucsd.edu

Plasma, Fusion, and Tokamaks

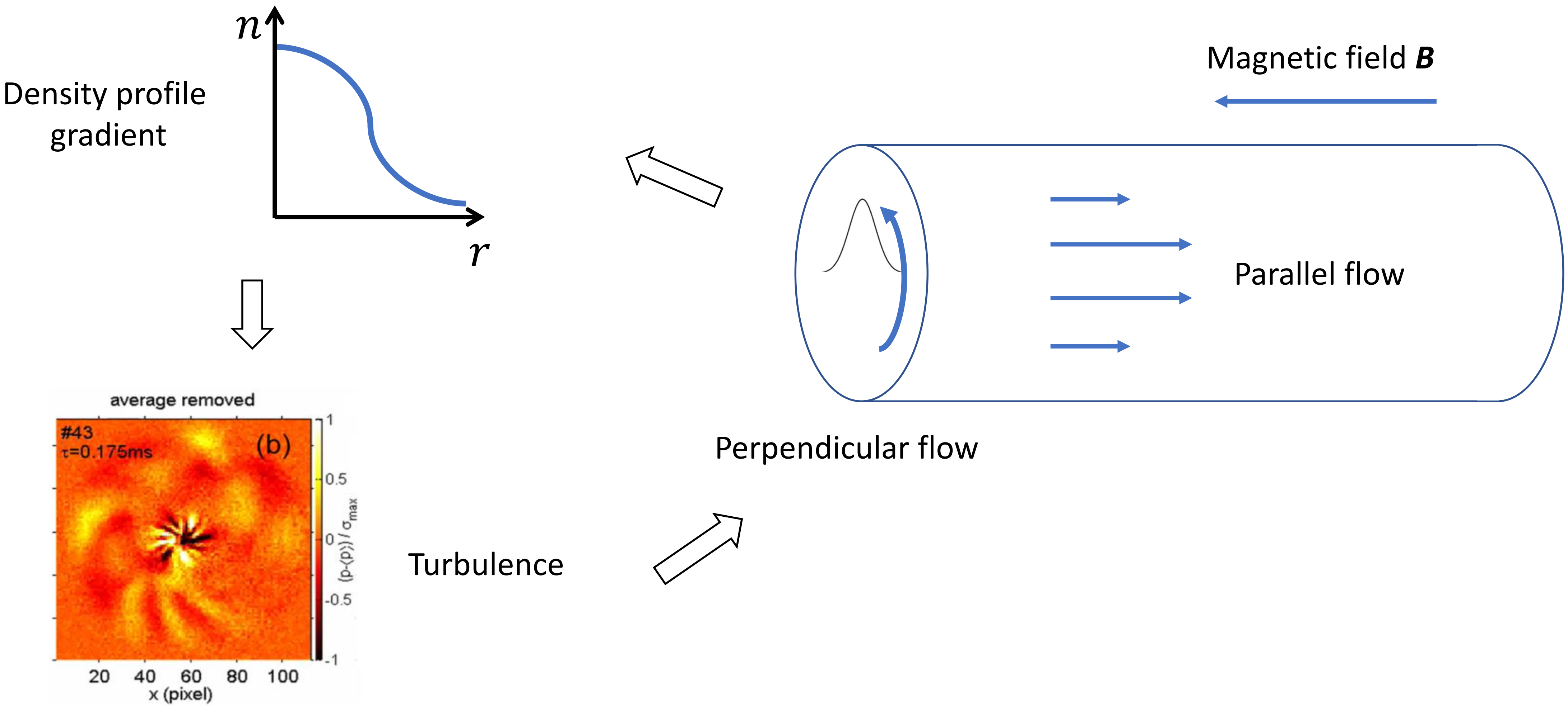
- Nuclear Fusion
  - Typically, deuterium—tritium (D—T) reaction is designed to be used for fusion energy
  - Require extremely high temperature
    - 14 keV or 160 million K
  - Neutral gas → hot plasma
- Tokamak
  - Main magnetic field in toroidal direction
  - Turbulent transport reduces energy confinement
  - Self-organization of turbulence mitigates transport
    - ***Turbulence-driven plasma flows in both toroidal and poloidal directions***

  → Control knob to manipulate turbulence state?

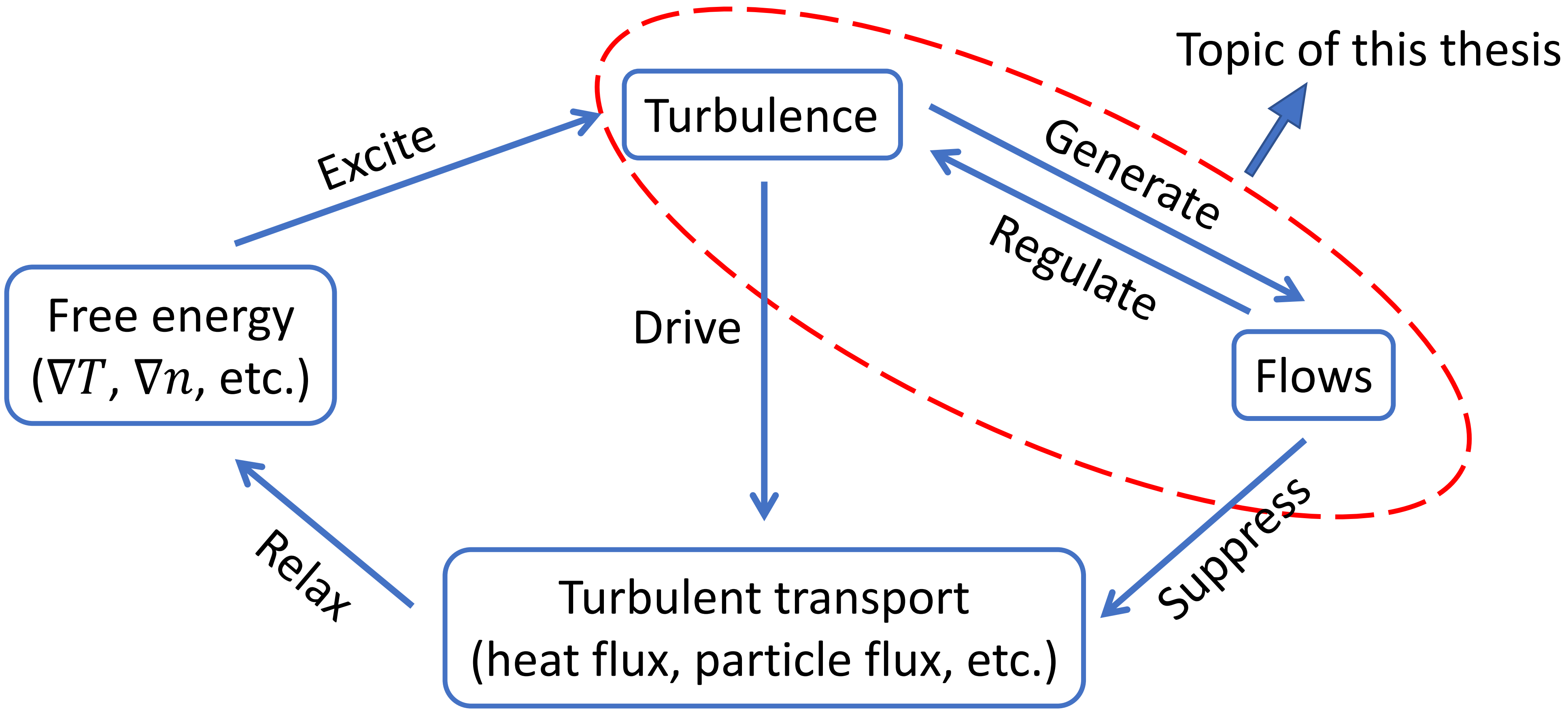


Schematic of a tokamak plasma

Plasma turbulence and flows in a cylinder

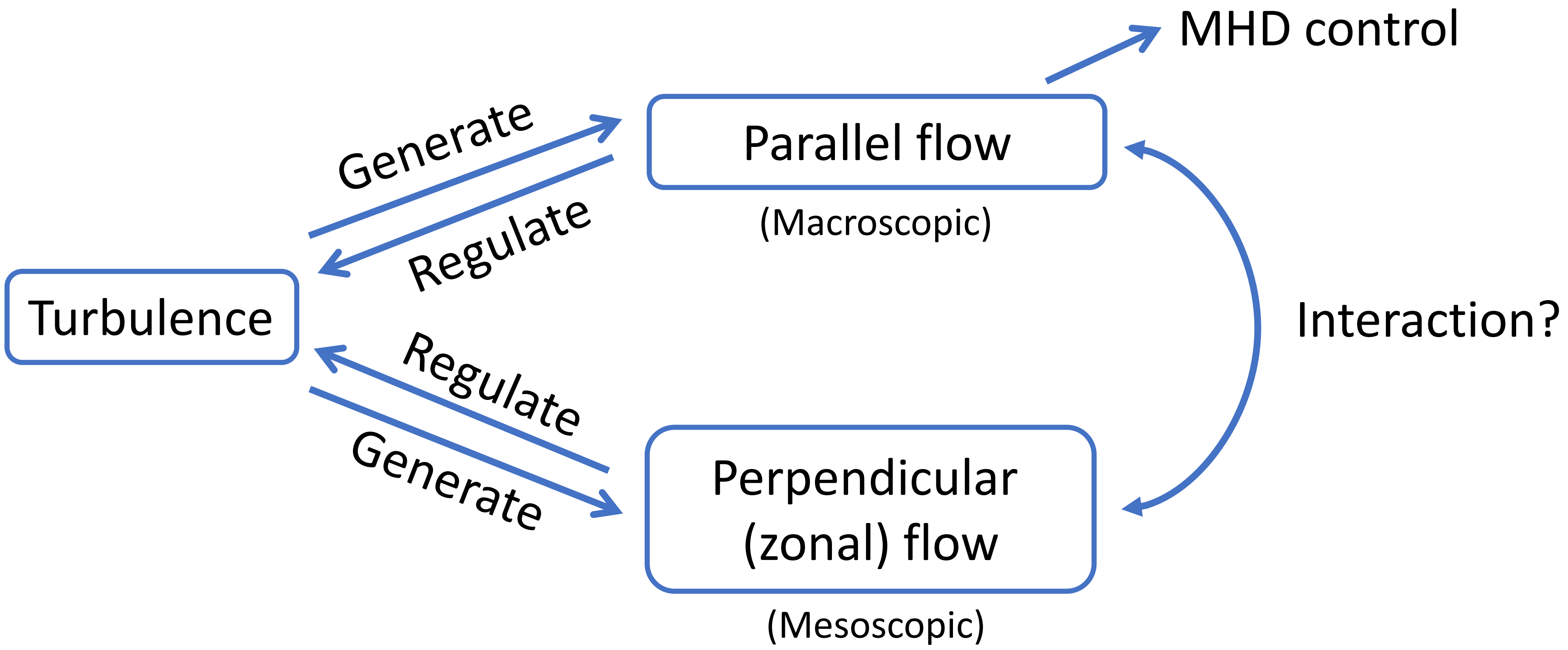


Self-organization of a turbulence—flow system



Turbulence-generated flows in fusion plasmas

- In magnetic fusion plasmas, turbulence generates flows in both parallel and perpendicular directions to the magnetic field



Motivation of this thesis

- **Turbulence-generated parallel flows + weak magnetic shear**

  → better confinement of fusion plasmas, e.g., JET experiments

- Conventional mechanisms of intrinsic parallel flow generation usually rely on geometrical mechanisms for symmetry breaking (i.e., related to magnetic shear, toroidicity, etc.)

  → How does turbulence generate parallel flows at weak to zero magnetic shear?

- Turbulence generates flows in orthogonal directions (i.e., parallel and perpendicular to magnetic fields)

  → What couples the intrinsic parallel and perpendicular flows (in absence of magnetic shear)?

Overview of results in this thesis

- New mechanism to generate intrinsic parallel flows in simple, straight geometry
  - Develop the new theory for flow generation by both electron drift wave turbulence and ITG (ion temperature gradient) turbulence
- These theoretical results motivate detailed measurements in a linear device with uniform magnetic fields (i.e., CSDX), including:
  - Dynamical symmetry breaking in turbulence
  - Generation of macroscopic axial flows

  → Experimental measurements support the theory
- Coupling of intrinsic axial and azimuthal flows in CSDX via turbulent production and Reynolds forces
- Also: frictionless saturation of zonal flows

Publications

- **Intrinsic axial flow generation and saturation in CSDX**:
  - J. C. Li, P. H. Diamond, X. Q. Xu, and G. R. Tynan, "Dynamics of intrinsic axial flows in unsheared, uniform magnetic fields", *Physics of Plasmas*, 23, 052311, 2016.
  - J. C. Li and P. H. Diamond, "Negative viscosity from negative compressibility and axial flow shear stiffness in a straight magnetic field", *Physics of Plasmas*, 24, 032117, 2017.
- **Phenomenology of intrinsic flows in CSDX**:
  - R. Hong, J. C. Li (joint first author), R. J. Hajjar, S. Chakraborty Thakur, P. H. Diamond, G. R. Tynan, "Generation of Parasitic Axial Flow by Drift Wave Turbulence with Broken Symmetry: Theory and Experiment", submitted to *Physics of Plasmas*.
- **Interaction of intrinsic axial and azimuthal flows in CSDX**:
  - J. C. Li and P. H. Diamond, "Interaction of turbulence-generated azimuthal and axial flows in CSDX", manuscript in preparation.
- **Frictionless zonal flow saturation**:
  - J. C. Li and P. H. Diamond, "Frictionless Zonal Flow Saturation by Vorticity Mixing", submitted to *Physical Review Letters*.
  - J. C. Li and P. H. Diamond, "Another Look at Zonal Flow Physics: Resonance, Shear Flows and Frictionless Saturation", submitted to *Physics of Plasmas*.

Outline

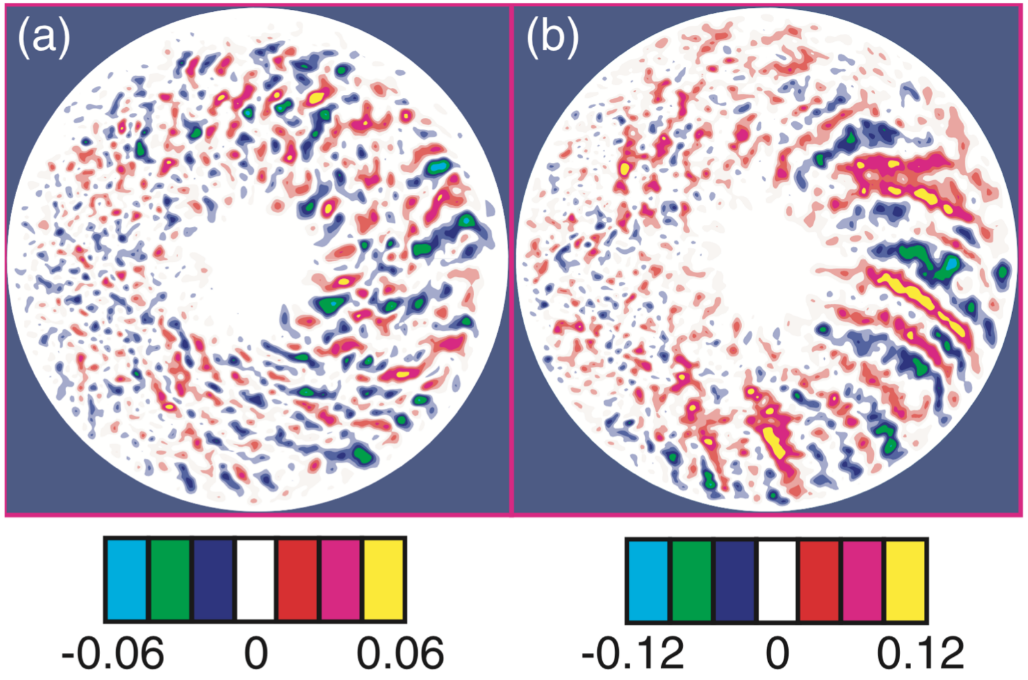
- Background
    - Flows and intrinsic rotation in fusion plasmas
    - Flows in a linear device CSDX
- Main content:
    - Intrinsic axial flow generation in CSDX
    - Interaction of intrinsic axial and azimuthal flows in CSDX
    - Lessons learned and future direction
- Also: frictionless zonal flow saturation

Zonal (poloidal) flow

- Mesoscopic shear flow layers driven by turbulence
- Occurs in a wide range of fluid systems
- Decorrelate the turbulent eddies by shearing

  → Reduce turbulence and transport in tokamaks

Zonal flows (bands) in atmosphere of Jupiter

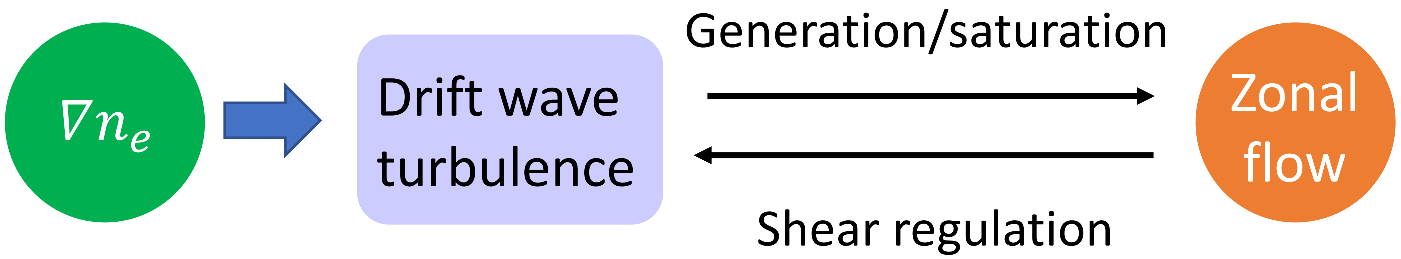


Zonal flow shearing reduces eddy size in tokamak simulation: (a) with zonal flow, (b) no zonal flow

[Diamond et al, PPCF 2005]

Theoretical understanding of zonal flows

- Schematic of predator—prey model for zonal flows



Zonal flow (predator):

$$\frac{dV'^2}{dt} = \alpha V'^2 E - \mu_L V'^2 - \mu_{NL}\left(V'^2\right)V'^2$$

Drift wave (prey):

$$\frac{dE}{dt} = -\alpha V'^2 E + \gamma_L E - \varepsilon_c E^{\frac{3}{2}}$$

[Diamond et al, PRL, 1994]

Intrinsic toroidal rotation

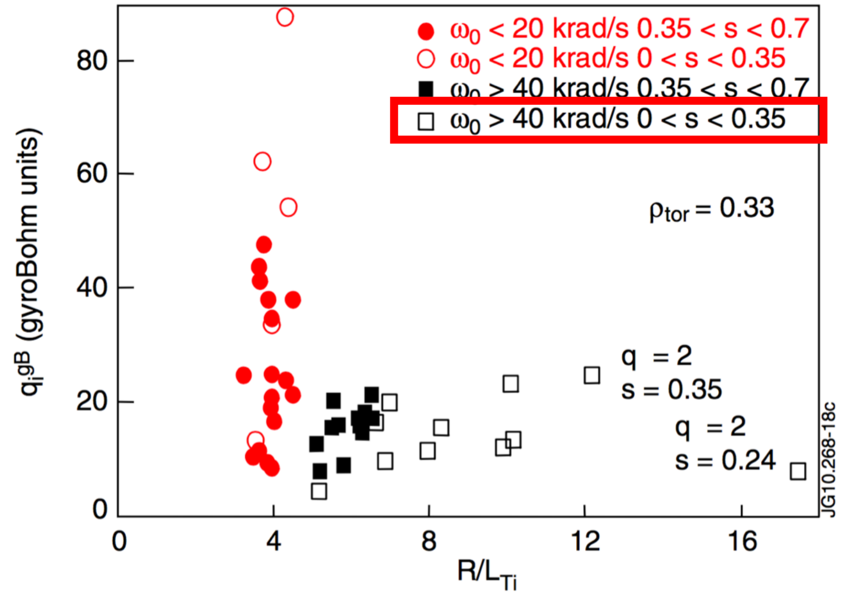
- Macroscopic shear flows in the direction parallel to the main (toroidal) magnetic field in a tokamak
- External torque insufficient to spin up plasma of larger size (e.g., ITER) → Intrinsic torque is desired
- Weak magnetic shear **AND** toroidal rotation → de-stiffened heat flux profile vs. ∇T
- So need understand: **intrinsic rotation in weak shear regimes**

- Important for:
  - Calculate total effective torque

$$\tau = \tau_{ext} + \tau_{intr}$$

  - Contribution to $V'_{E\times B}$

→ enhance confinement



[Mantica et al, PRL, 2011]

FIG. 4 (color online). q_i^{GB} vs R/L_{T_i} at $\rho_{tor} = 0.33$ for similar plasmas with different rotation and s values.

Generation of intrinsic parallel flow

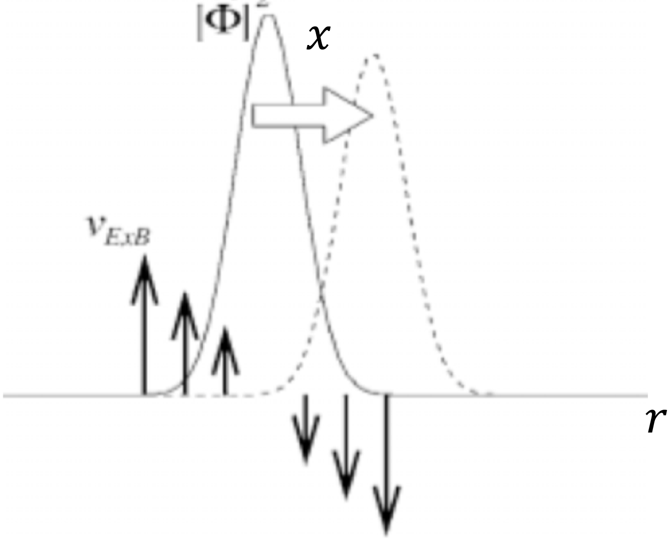
- Heat engine analogy

	Car	Intrinsic Rotation
Fuel	Gas	Heating → $\nabla T, \nabla n_0$
Conversion	Burn	$\nabla T, \nabla n_0$ driven turbulence
Work	Cylinder	Symmetry breaking → residual stress
Result	Wheel rotation	Flow

- Intrinsic parallel flow is driven by Reynolds force: $\partial_t V_\parallel \sim -\partial_r \langle \tilde{v}_r \tilde{v}_\parallel \rangle$
- Reynolds stress: $\langle \tilde{v}_r \tilde{v}_\parallel \rangle = -\chi_\parallel V_\parallel' + \Pi_{r\parallel}^{Res}$
- Residual stress requires symmetry breaking: $\Pi_{r\parallel}^{Res} \sim \langle k_\theta k_\parallel \rangle = \sum_k k_\theta k_\parallel |\phi_k|^2$

Problem of conventional wisdoms of intrinsic parallel flow generation

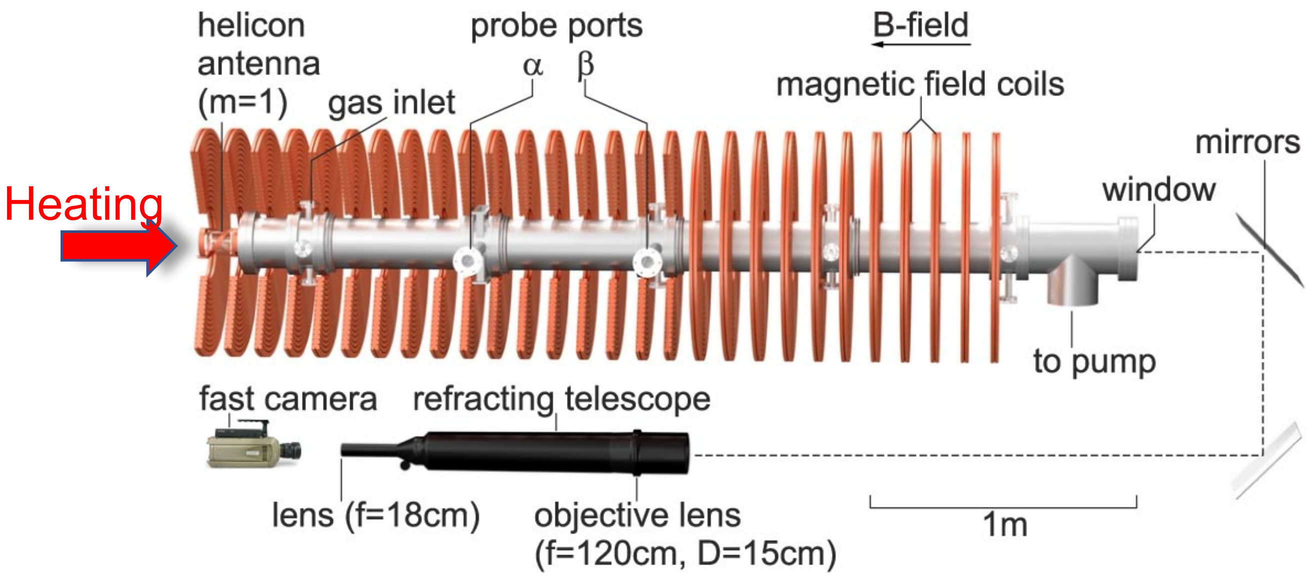
- Conventional wisdom of intrinsic parallel flow generation
  - $\Pi_{r\parallel}^{Res} \sim \langle k_\theta k_\parallel \rangle$ requires symmetry breaking in $k_\theta - k_\parallel$ spectrum
  - In tokamaks, with finite magnetic shear:
    $k_\parallel = k_\theta\, x/L_s \rightarrow \langle k_\theta k_\parallel \rangle \sim k_\theta^2 \langle x \rangle / L_s$
  - $\langle x \rangle$: averaged distance from mode center to rational surface
  - $\langle x \rangle$ is set, in simple models, by E_r', I', etc.
- What of weak shear?
  - $L_s \rightarrow \infty$, so $\langle k_\theta k_\parallel \rangle \sim k_\theta^2 \langle x \rangle / L_s \rightarrow 0$



[Gurcan et al, PoP, 2007]

CSDX: Controlled Shear Decorrelation Experiment

- Goal: study intrinsic parallel flow generation at zero magnetic shear
  - What breaks the symmetry in turbulence?
- Device characteristics:
  - **Straight, uniform magnetic field** in axial direction → magnetic shear = 0
  - Diagnostics: Combined Mach and Langmuir probe array
  - Argon plasma produced by RF helicon source at 1.8 kW and 2 mtorr
  - Insulating endplate avoid strong sheath current

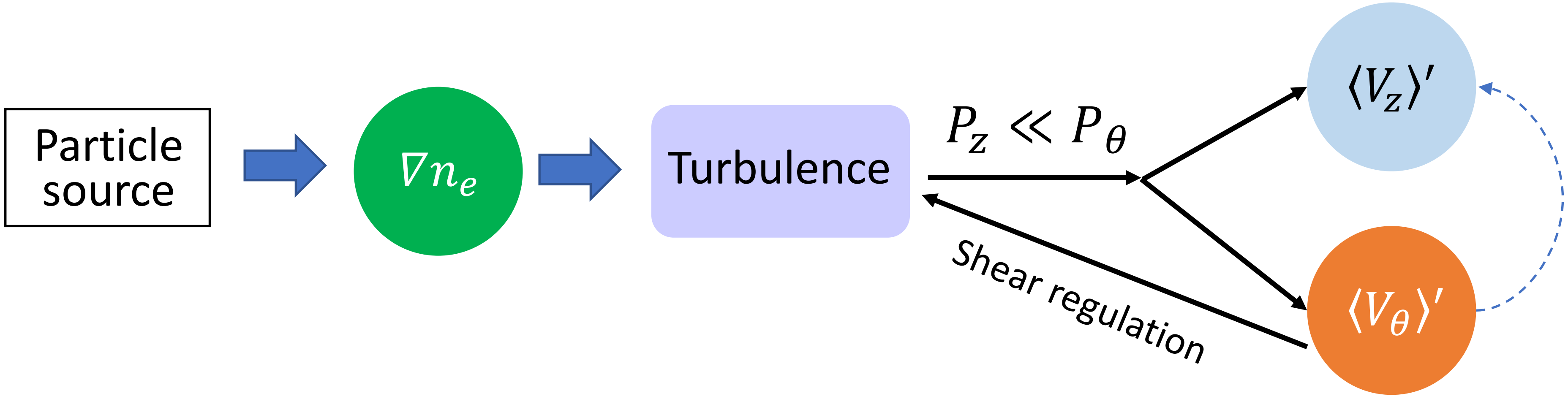


CSDX correspondence to tokamaks

- Parameters similar to SOL region of tokamaks
- Intrinsic axial (↔ toroidal) and azimuthal (zonal) flows
- Testbed to study drift wave—zonal flow—axial flow ecology

Parameters	Tokamak Boundary	CSDX
$\rho_* = \rho_s / L_n$	~ 0.1	~ 0.3
$k_\parallel^2 v_{te}^2 / \omega \nu_e$	$\sim 0.5 - 5$	$\gtrsim 1$
λ_{ei} / L_{conn}	$\lesssim 1$	$\sim 0.1 - 0.3$
l_{cor} / ρ_s	$\lesssim 1$	~ 1

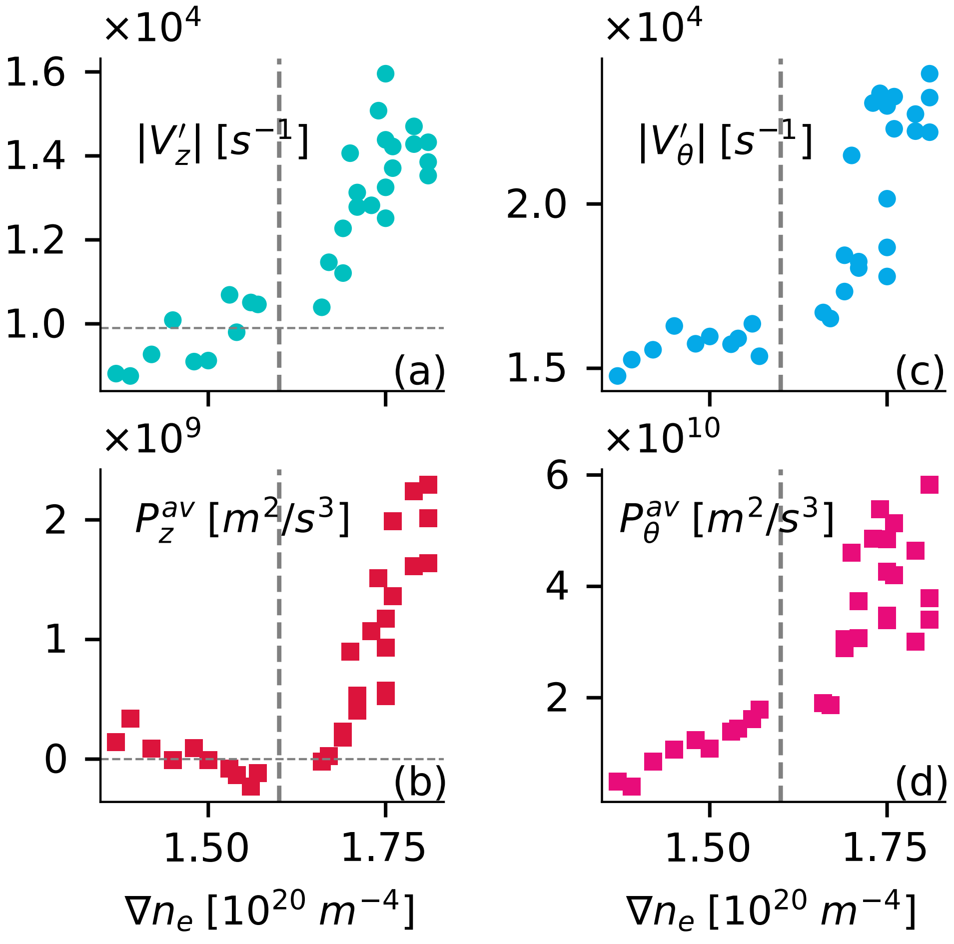
Characterization of turbulence—flow ecology in CSDX



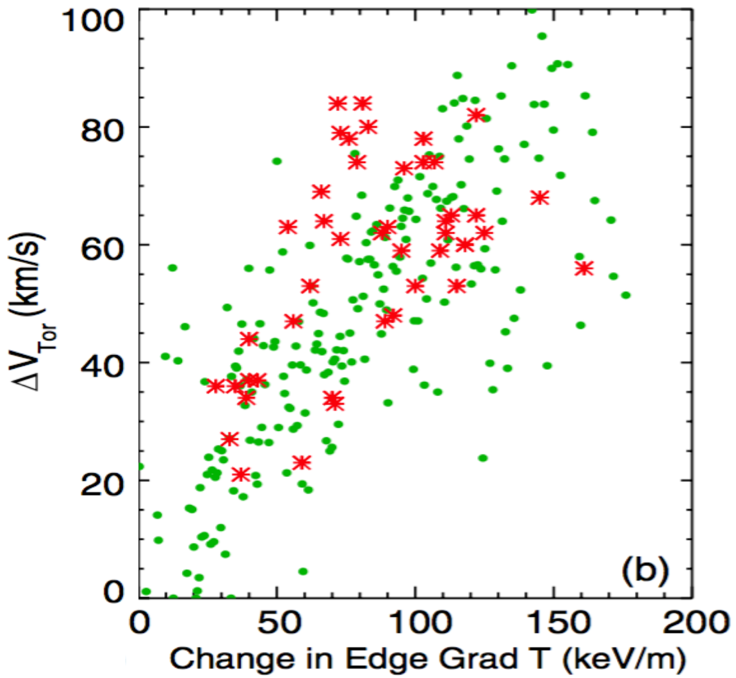
- Heat engine analogy for intrinsic flow generation
  - Branching ratio of intrinsic axial and azimuthal (zonal) flows

    → Ratio of Reynolds power P_z/P_θ, where $P_z = -\langle \tilde{v}_r \tilde{v}_z \rangle' V_z$, $P_\theta = -\langle \tilde{v}_r \tilde{v}_\theta \rangle' V_\theta$
- Parasitic axial flow riding on drift wave–zonal flow system
  - Zonal flow regulates turbulence
  - $|k_z V_z'| \ll |k_\theta V_\theta'|$ → Weak coupling between axial and azimuthal flows

Intrinsic flows in CSDX: phenomenology



- $V_z', V_\theta' \sim \nabla n$ → **Rice-type scaling**: $\Delta\langle v_\phi\rangle \sim \nabla T$
- Reynolds power:
  $P_z = -\langle\tilde{v}_r\tilde{v}_z\rangle' V_z,\ P_\theta = -\langle\tilde{v}_r\tilde{v}_\theta\rangle' V_\theta$



[Rice et al, PRL, 2011]

Issues and relevant questions

- What generates the axial flow absent magnetic shear?
  - Conventional theories are often tied to finite magnetic shear
    → need a new mechanism
- How does the axial flow saturate?
  - Interplay of new generation mechanism and conventional ones
  - Stiffness of $V_{\parallel}'$ profile vs. ∇T
- How does axial flow interact with azimuthal flow?
  - Coupling of intrinsic parallel and perpendicular flows absent geometrical coupling
  - Branching ratio of intrinsic axial and azimuthal flows

Intrinsic axial flow generation and saturation in drift wave turbulence

Key takeaways

- Dynamical symmetry breaking in drift wave turbulence:
  - A seed axial flow shear breaks the spectral symmetry in $k_\theta k_z$ space
  - Resulting residual stress induces a negative viscosity increment
  - When total viscosity turns negative, the seed shear is reinforced by modulational instability
- Modulational growth of axial flow shear is limited by PSFI (parallel shear flow instability) saturation → V_z' saturates at or below PSFI threshold
- Measurement of symmetry breaking of microscopic fluctuation spectrum confirms this new theory

Equations for Electron Drift Wave

- System equations:

$$\frac{D}{Dt}n_e - \frac{\nabla n_0}{n_0}\frac{1}{r}\frac{\partial \phi}{\partial \theta} + \frac{\partial v_{e,z}}{\partial z} = 0$$

$$\frac{D}{Dt}\nabla_\perp^2 \phi = \frac{\partial}{\partial z}\left(v_z - v_{e,z}\right)$$

$$\frac{D}{Dt}v_z - \langle v_z \rangle' \frac{1}{r}\frac{\partial \phi}{\partial \theta} = -\frac{\partial n_e}{\partial z}$$

$$\left(\frac{D}{Dt} = \frac{\partial}{\partial t} + \mathbf{v}_E \cdot \nabla\right)$$

- Non-adiabatic electrons: $n_e \cong (1 - i\delta)\phi$

$$\delta \cong \frac{\nu_{ei}(\omega_* - \omega)}{k_z^2 v_{The}^2}, \text{ where } 1 < \frac{k_z^2 v_{The}^2}{\nu_{ei}\omega} < \infty \qquad \omega_* = k_\theta \rho_s c_s \frac{|\nabla n_0|}{n_0}$$

- Growth rates of linear modes are calculated using the dispersion relation:

$$1 + k_\perp^2 \rho_s^2 - i\delta - \frac{\omega_*}{\omega} + \frac{k_\theta k_z \rho_s c_s \langle v_z \rangle'}{\omega^2} - (1 - i\delta)\frac{k_z^2 c_s^2}{\omega^2} = 0$$

- How does a seed axial flow shear affect the growth rate?

Dynamical Symmetry Breaking

- Drift wave growth rate ~ frequency shift:

$$\omega_k \cong \frac{\omega_*}{1+k_\perp^2\rho_s^2} - \frac{k_\theta k_z \rho_s c_s \langle v_z\rangle'}{\omega_*}$$

$$\gamma_k \cong \frac{\nu_{ei}}{k_z^2 v_{The}^2}\frac{\omega_*^2}{(1+k_\perp^2\rho_s^2)^2}\left(\frac{k_\perp^2\rho_s^2}{1+k_\perp^2\rho_s^2} + \frac{k_\theta k_z \rho_s c_s \langle v_z\rangle'}{\omega_*^2}\right)$$

- Spectral imbalance:

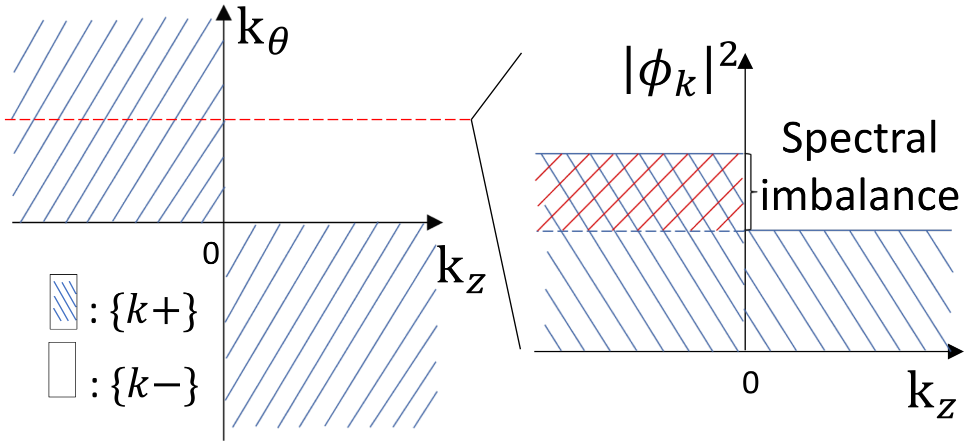
Infinitesimal test axial flow shear, e.g. $\delta\langle v_z\rangle' < 0$

Modes with $k_\theta k_z < 0$ grow faster than other modes,

$\gamma_k|_{k_\theta k_z<0} > \gamma_k|_{k_\theta k_z>0}$

Spectral imbalance in $k_\theta k_z$ space

$\langle k_\theta k_z\rangle < 0 \rightarrow \Pi_{rz}^{Res} < 0$



$\{k\pm\}$: Domains where modes grow faster/slower

Spectral imbalance

Residual stress induces a negative viscosity increment

- Self-steepening of seed flow shear → negative viscosity phenomena
- Reynolds stress: $\langle \tilde{v}_r \tilde{v}_z \rangle = -\chi_\phi \langle v_z \rangle' + \Pi_{rz}^{\mathrm{Res}}$
- Turbulent viscosity driven by drift waves:

$$\chi_\phi = \sum_k \frac{\nu_{\mathrm{ei}}}{k_z^2 v_{\mathrm{The}}^2} \frac{k_\perp^2 \rho_s^2}{1 + k_\perp^2 \rho_s^2} k_\theta^2 \rho_s^2 |\phi_k|^2$$

- Residual stress → Negative viscosity ***increment***
- $\delta \Pi_{rz}^{Res} = |\chi_\phi^{Inc}| \delta \langle v_z \rangle'$ ➡ $\delta \Pi_{rz}^{\mathrm{Res}} = \frac{\nu_{\mathrm{ei}} L_n^2}{v_{\mathrm{The}}^2} \sum_k (1 + k_\perp^2 \rho_s^2)(4 + k_\perp^2 \rho_s^2) |\phi_k|^2 \delta \langle v_z \rangle'$

⬇

Total viscosity: $\chi_\phi^{tot} = \chi_\phi - |\chi_\phi^{Inc}|$

Modulational enhancement of $\delta\langle v_z\rangle'$

- $\delta\langle v_z\rangle'$ amplifies itself via modulational instability

- Dynamics of $\delta\langle v_z\rangle'$:

$$\frac{\partial}{\partial t}\delta\langle v_z\rangle' + \frac{\partial^2}{\partial r^2}\left(\delta\Pi_{rz}^{Res} - \chi_\phi \delta\langle v_z\rangle'\right) = 0$$

- Growth rate of flow shear modulation

$$\gamma_q = -q_r^2\left(\chi_\phi - \left|\chi_\phi^{Inc}\right|\right)$$

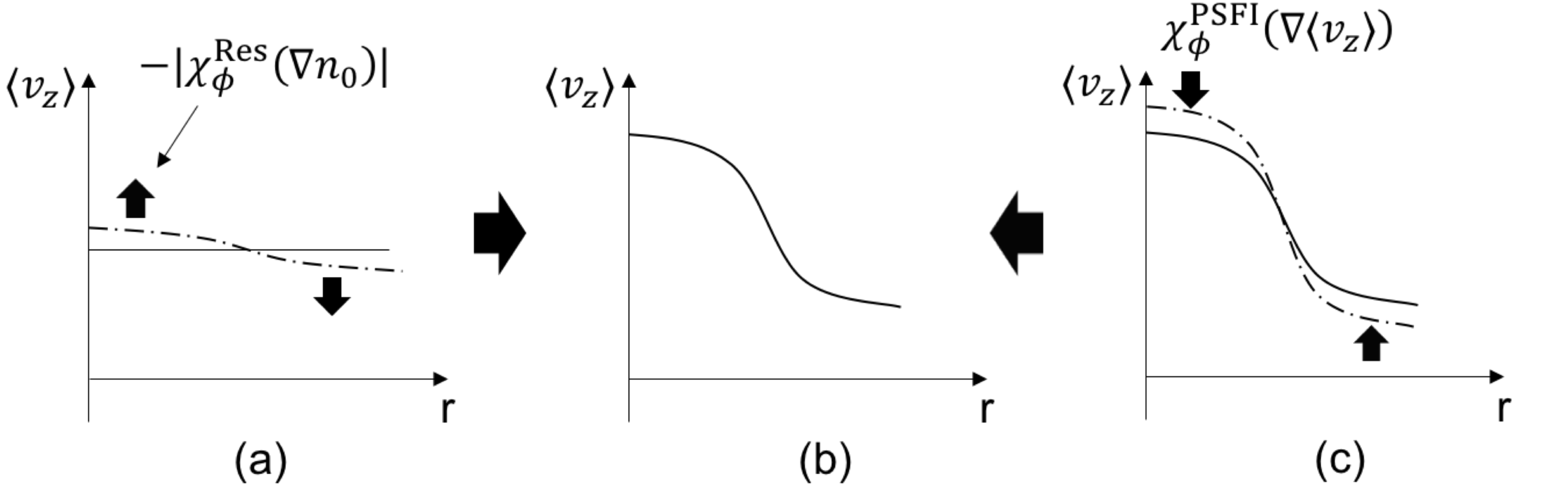
- $\chi_\phi^{tot} = \chi_\phi - \left|\chi_\phi^{Inc}\right| < 0$ → Modulational growth of $\delta\langle v_z\rangle'$

- Feedback loop: $\delta\langle v_z\rangle'$ → $\delta\Pi_{rz}^{Res}$ → $-\left|\chi_\phi^{Inc}\right|$

Self-steepending of $\langle v_z \rangle'$ limited by PSFI

- Parallel shear flow instability (PSFI) keeps χ_ϕ^{tot} positive

  → limit modulational growth of seed flow shear



$$\chi_\phi^{tot} = \chi_\phi^{DW} - |\chi_\phi^{Inc}| < 0$$

$$\chi_\phi^{tot} = \chi_\phi^{DW} + \chi_\phi^{PSFI} - |\chi_\phi^{Inc}| > 0$$

$$\chi_\phi^{tot} = \chi_\phi^{DW} + \chi_\phi^{PSFI}\Theta(\langle v_z \rangle' - \langle v_z \rangle'_{crit}) - |\chi_\phi^{Inc}|$$

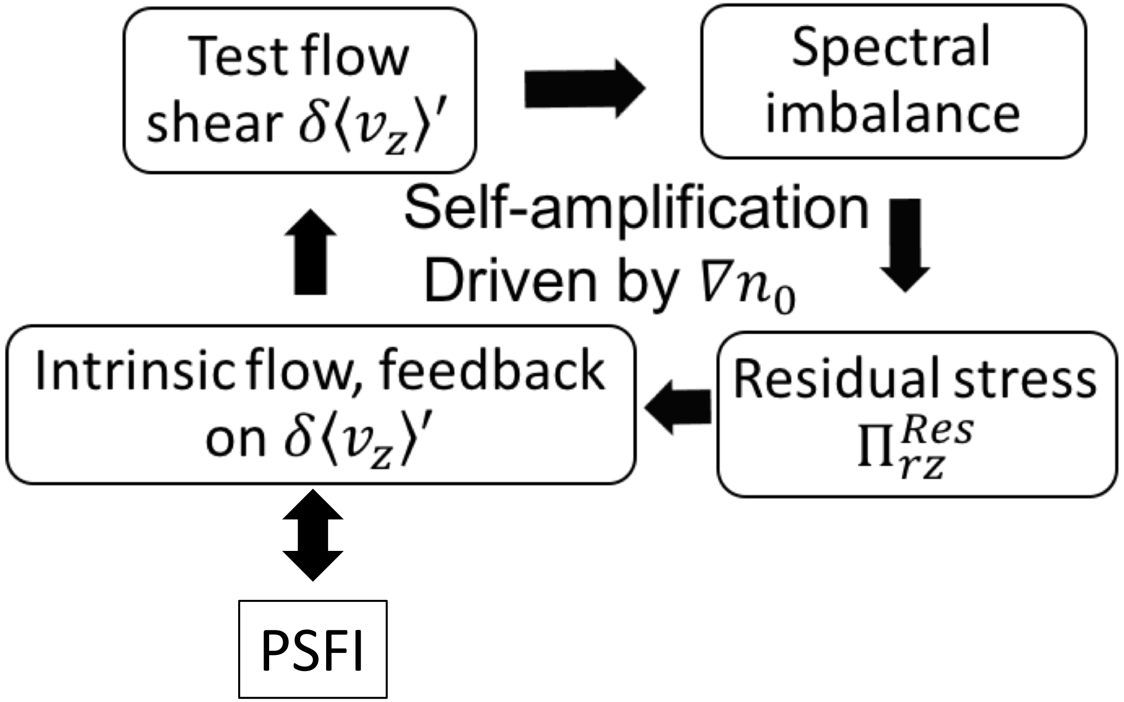
Compare new mechanism to conventional models

- Feedback Loop:

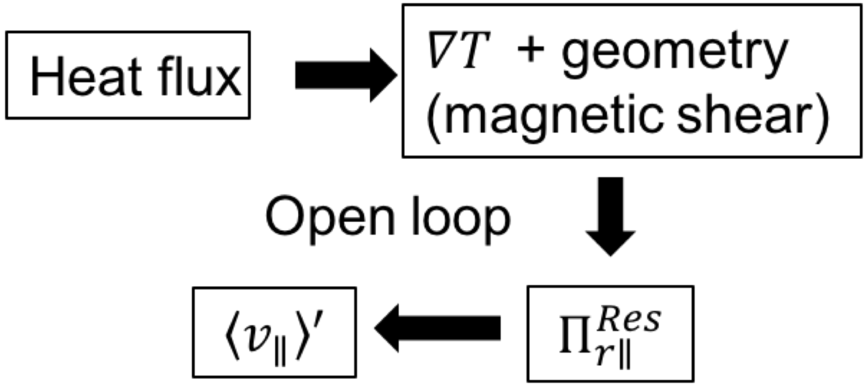
vs.

- Open Loop:

Dynamical Symmetry Breaking

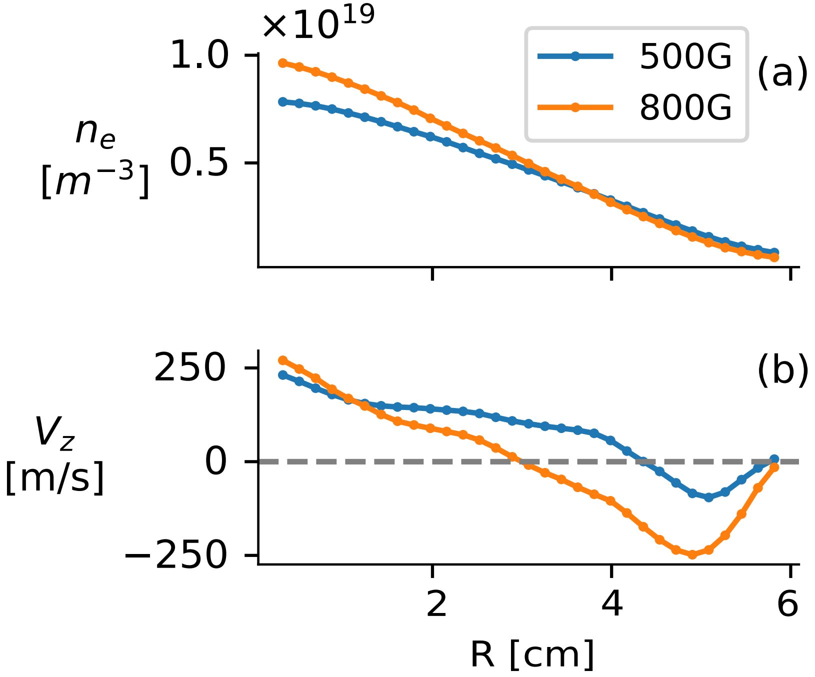


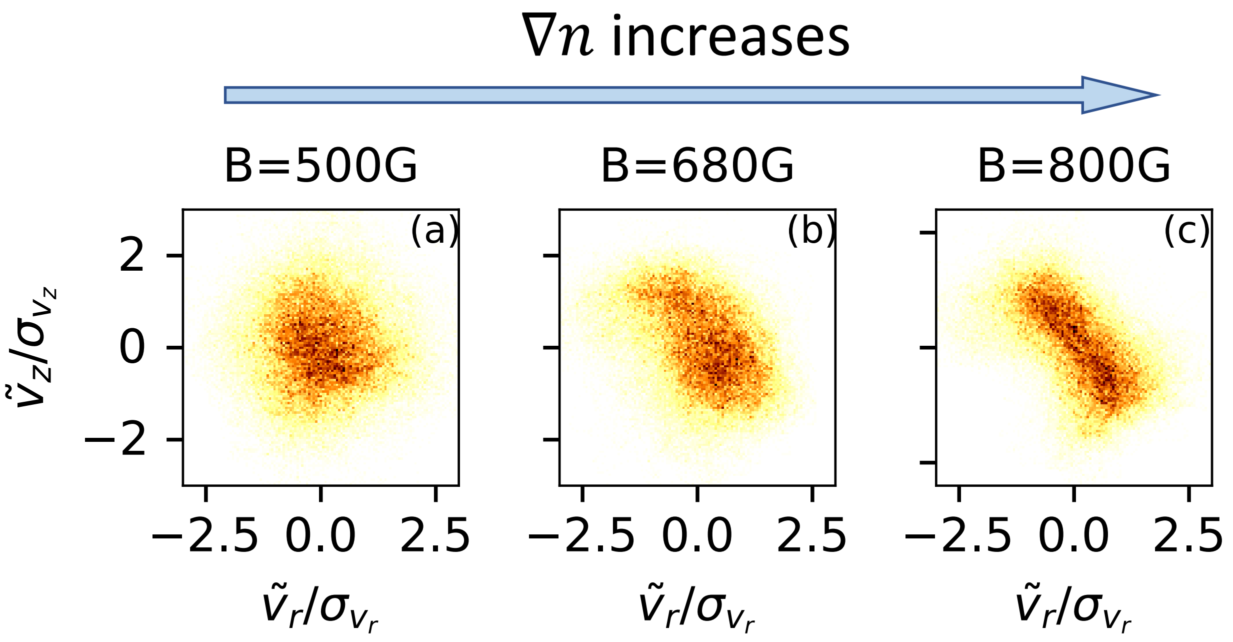
Conventional Models



Measurement of symmetry breaking in CSDX

- Motivated by theoretical findings on symmetry breaking
- Joint PDF $P(\tilde{v}_r, \tilde{v}_z)$ empirically represents spectral correlator $\langle k_\theta k_z \rangle$
  - $\tilde{v}_r \sim \partial_\theta \tilde{\phi} \sim k_\theta \tilde{\phi}$ and $\tilde{v}_z \sim \partial_z \tilde{p} \sim k_z \tilde{\phi}$
- Spectral asymmetry → $\langle k_\theta k_z \rangle \neq 0$ → residual stress $\neq 0$





Partial summary: intrinsic axial flow generation absent magnetic shear

- For drift wave turbulence in CSDX:
  - Seed flow shear $\delta\langle v_z\rangle'$ → **Negative viscosity increment** induced by Π_{rz}^{Res}
  - $\delta\Pi^{Res} = |\chi_\phi^{Res}|\delta\langle v_z\rangle'$ → Total viscosity: $\chi_\phi^{tot} = \chi_\phi - |\chi_\phi^{Res}|$
  - $\chi_\phi^{tot} < 0$ → Modulational growth of $\delta\langle v_z\rangle'$
- Axial pressure gradient (plasma hot near the source and cold near the outlet)

  → Seed axial flow shear → Self-amplification → Saturated by PSFI
- Measurements on CSDX confirm this new mechanism

Results not presented here

- Stationary axial flow shear profile
  - Momentum budget of a pipe flow
- Effects of neutral flows
  - Impact of boundary dynamics on the intrinsic axial flow profile
- Related papers:
  - J. C. Li, P. H. Diamond, X. Q. Xu, and G. R. Tynan, “Dynamics of intrinsic axial flows in unsheared, uniform magnetic fields”, *Physics of Plasmas*, 23, 052311, 2016.
  - R. Hong, J. C. Li (joint first author), R. J. Hajjar, S. Chakraborty Thakur, P. H. Diamond, G. R. Tynan, “Generation of Parasitic Axial Flow by Drift Wave Turbulence with Broken Symmetry: Theory and Experiment”, submitted to *Physics of Plasmas*.

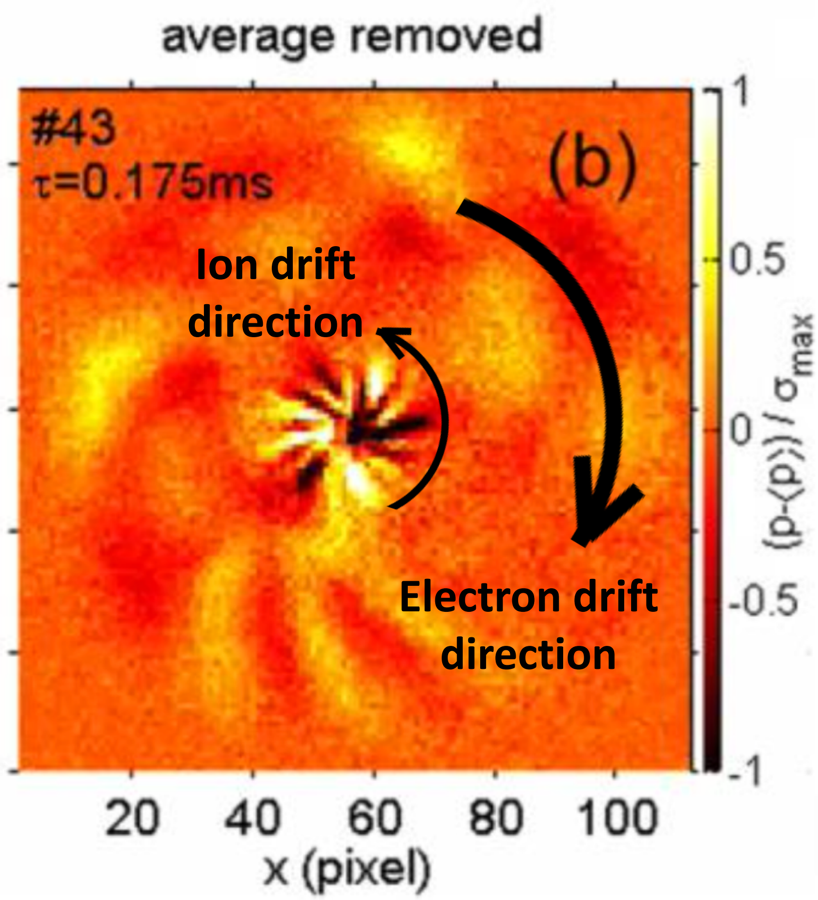
Intrinsic axial flow generation and saturation in ITG turbulence

Why study ITG turbulence?

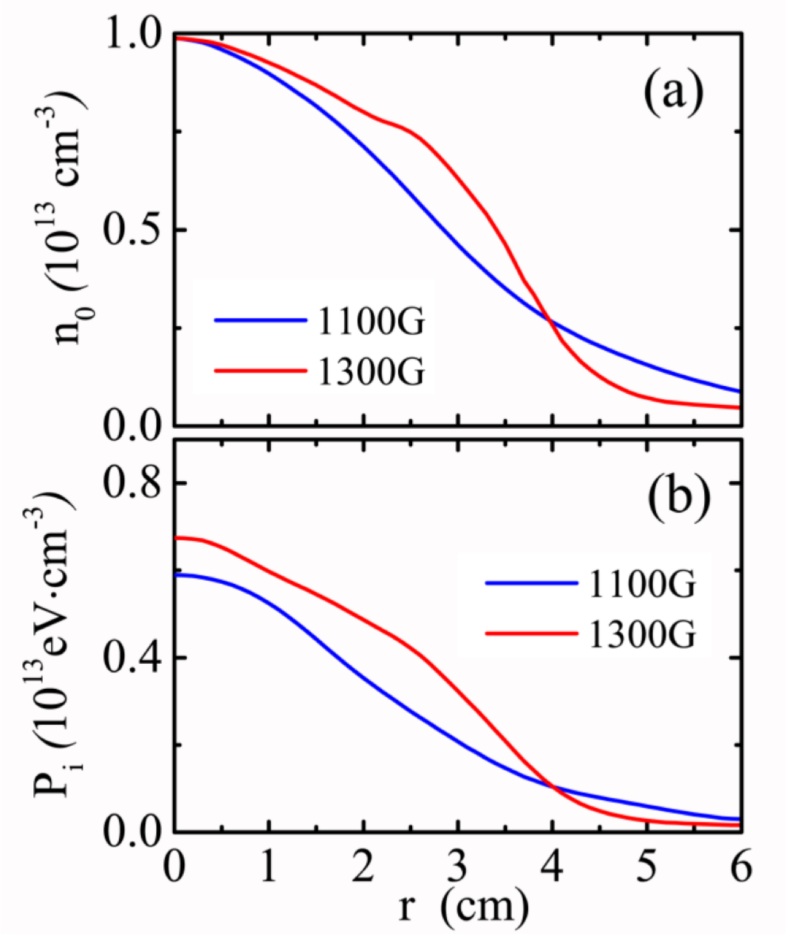
- ITG = ion temperature gradient
- ITG is the major turbulence type in confinement devices
  - Major contributor to momentum transport
- Ion features in CSDX observed (not necessarily ITG turbulence)
  - Fluctuations propagating in ion drift direction

Ion Features in CSDX

- Coexistence of ion and electron features

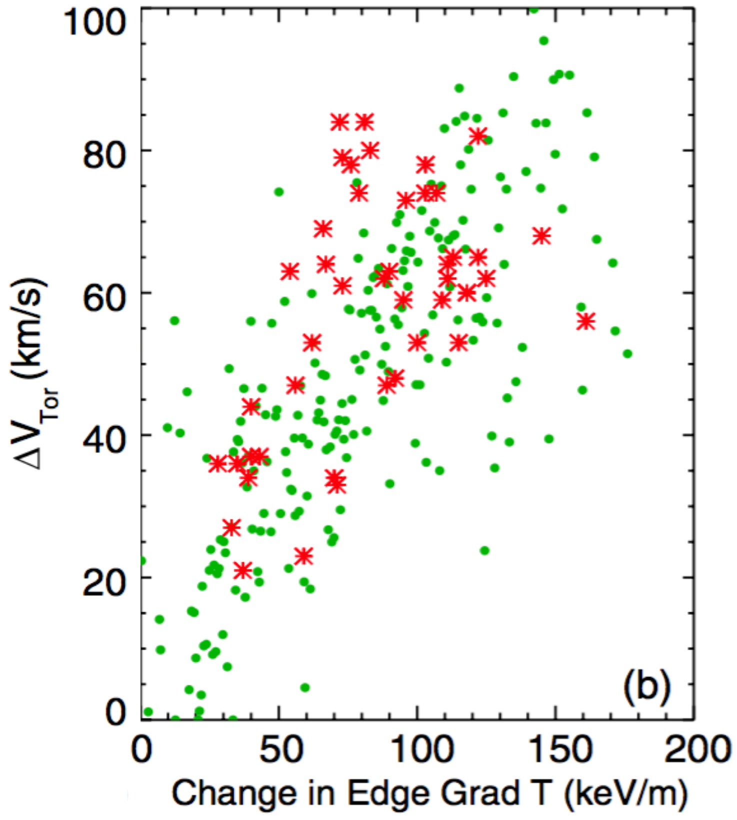


- T_i profile steepening



Issues of intrinsic axial flow in ITG regime

- Intrinsic axial flow in ITG (ion temperature gradient) turbulence at zero magnetic shear?
  - Does ITG turbulence induce negative viscosity?
  - Can seed axial flow shear amplify via modulational instability?
- How does $V_\parallel'$ saturate in ITG turbulence?
  - What is the profile stiffness, i.e., $V_\parallel' \sim (\nabla T_i)^\alpha$?
  - How is it compared to the case where $\alpha = 1$, i.e., Rice-like scaling?



Key takeaways

- Dynamical symmetry breaking does not drive intrinsic axial flow in ITG turbulence with zero magnetic shear
  - Total viscosity is positive definite
  - Seed flow shear cannot reinforce itself
- In ITG turbulence, axial flow shear can saturate significantly above the linear threshold for PSFI
  - $\nabla V_{\parallel} \sim (\nabla T_i)^{2/3}$ as compared to Rice-type scaling $\nabla V_{\parallel} \sim \nabla T_i$

Model of ITG turbulence

- Fluid model of ITG turbulence

$$\frac{d}{dt}(1-\nabla_\perp^2)\phi + \mathbf{v}_E \cdot \frac{\nabla n_0}{n_0} + \nabla_\parallel \tilde{v}_\parallel = 0,$$

$$\frac{d\tilde{v}_\parallel}{dt} + \mathbf{v}_E \cdot \boxed{\nabla V_\parallel} = -\nabla_\parallel \phi - \nabla_\parallel \tilde{p}_i,$$

$$\frac{d\tilde{p}_i}{dt} + \frac{1}{\tau}\mathbf{v}_E \cdot \boxed{\frac{\nabla P_0}{P_0}} + \frac{\Gamma}{\tau}\nabla_\parallel \tilde{v}_\parallel + \nabla_\parallel Q_\parallel = 0.$$

- 2 free energy sources: $\nabla V_\parallel$ and ∇T_i
- Magnetic shear = 0
  → No correlation between parallel and perpendicular directions
- Landau damping closure: $Q_{\parallel,k} = -\chi_\parallel n_0 i k_\parallel \tilde{T}_{i,k}$

  (Hammett and Perkins, PRL, 1995) $\chi_\parallel = 2\sqrt{2} v_{Thi} / (\sqrt{\pi} |k_\parallel|)$

$\nabla V_\parallel$ and ∇T_i are coupled nonlinearly → Coexistence of PSFI and ITG instability

Negative viscosity induced by ITG turbulence

- In ITG turbulence, $\delta V_{\parallel}'$ **cannot** self-amplify
  - Negative viscosity increment: $\chi_{\phi}^{Res} < 0$
  - Total viscosity positive: $\chi_{\phi}^{tot} = \chi_{\phi}^{ITG} - |\chi_{\phi}^{Res}| = \frac{2}{3}\chi_{\phi}^{ITG} > 0$
  - Evolution of a test flow shear set by
    $\partial_t \delta V_{\parallel}' = \chi_{\phi}^{tot} \partial_r^2 \delta V_{\parallel}' \rightarrow \gamma_q = -\chi_{\phi}^{tot} q_r^2 < 0 \rightarrow \delta V_{\parallel}'$ cannot reinforce itself!

	ITG turbulence	Drift Wave turbulence
Sign of residual stress	$\langle k_\theta k_\parallel \rangle V_\parallel' > 0$	$\langle k_\theta k_\parallel \rangle V_\parallel' > 0$
Viscosity increment	$\chi_{\phi}^{Res} < 0$	$\chi_{\phi}^{Res} < 0$
Total viscosity	$\chi_{\phi}^{tot} > 0$	χ_{ϕ}^{tot} can be negative
Self-amplification of $\delta V_\parallel'$	No	Can exist

Intrinsic flow profiles driven by ITG turbulence

- $\Pi_{r\parallel}^{Res}$ set by conventional models
- Intrinsic flow profile: $V_{\parallel}' \sim \Pi_{r\parallel}^{Res}/\chi_{\phi}^{tot}$
  - $\delta V_{\parallel}' \rightarrow \delta \Pi_{r\parallel}^{Res} \rightarrow \chi_{\phi}^{Res}$
  - Thus, total viscosity:

$$\chi_{\phi}^{tot} = \chi_{\phi}^{ITG} + \chi_{\phi}^{PSFI} + \chi_{\phi}^{Res}$$

- Regimes in $\nabla V_{\parallel}$–∇T_i space:

(1) Marginal regime: $\gamma_k \gtrsim 0$

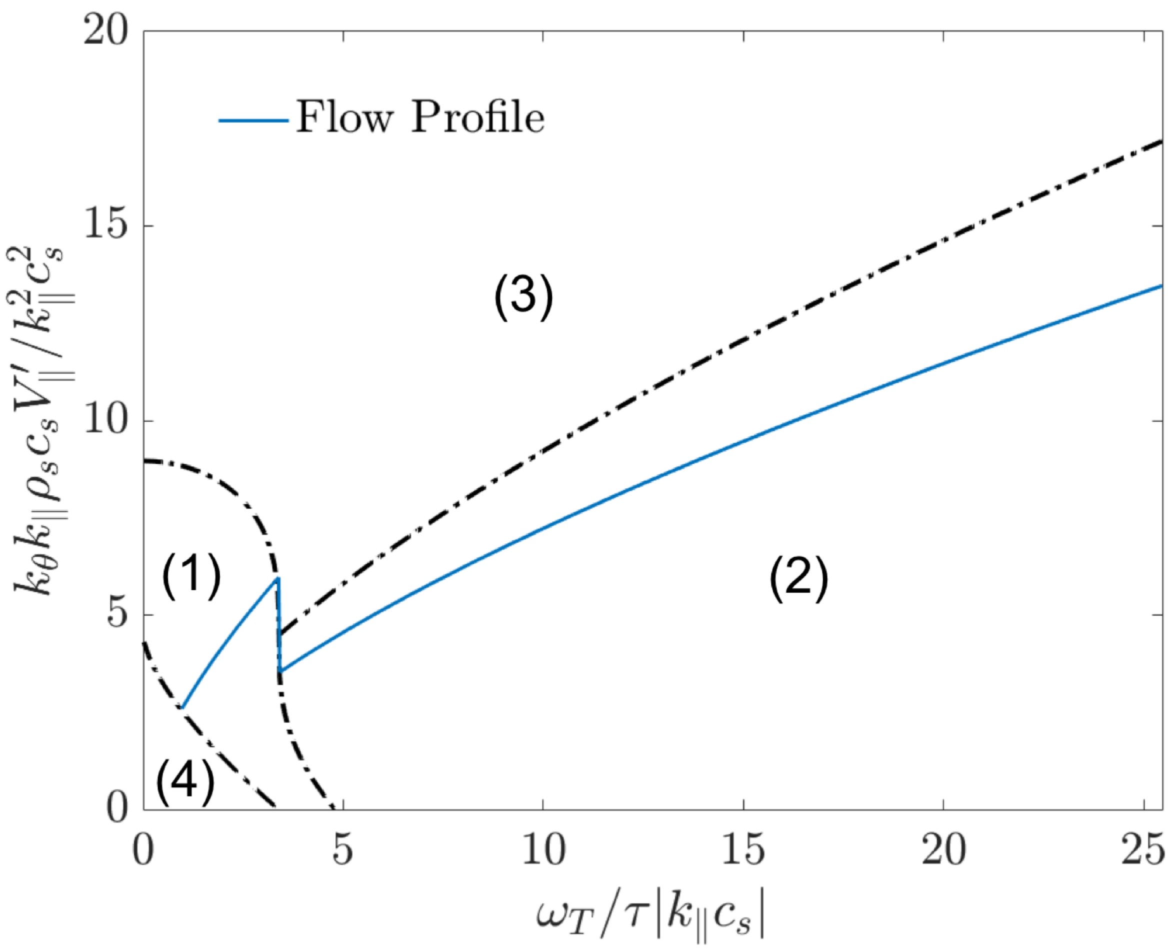
(2) ITG dominant regime

$$\frac{\left(|k_{\parallel}|L_T\right)^{2/3}}{|k_{\parallel}|L_V} < \frac{3}{2^{2/3}} \frac{c_s}{V_{\parallel}} \frac{\mathrm{A}^{1/3}}{(k_{\theta}\rho_s)^{1/3}\tau^{1/3}}$$

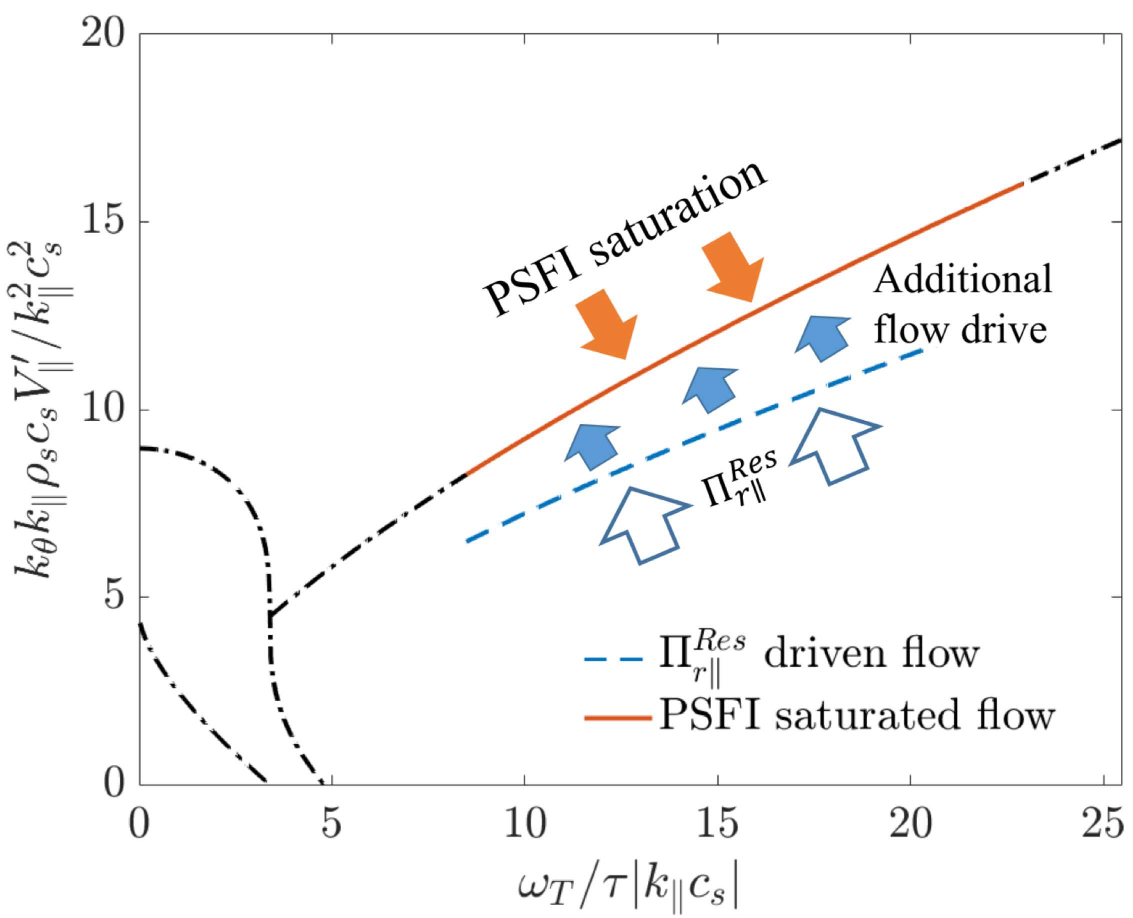
(3) PSFI dominant regime

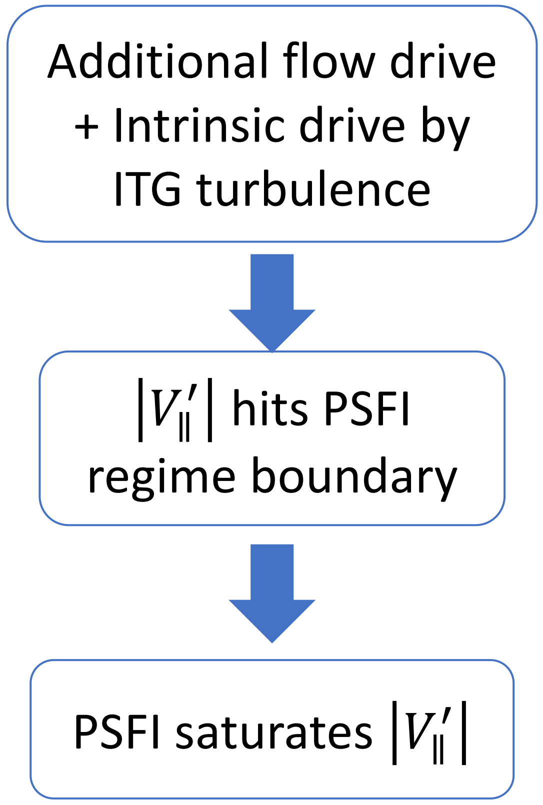
$$\frac{\left(|k_{\parallel}|L_T\right)^{2/3}}{|k_{\parallel}|L_V} > \frac{3}{2^{2/3}} \frac{c_s}{V_{\parallel}} \frac{\mathrm{A}^{1/3}}{(k_{\theta}\rho_s)^{1/3}\tau^{1/3}}$$

(4) Stable regime: $\gamma_k < 0$



$|V_\parallel'|$ profile saturated by PSFI

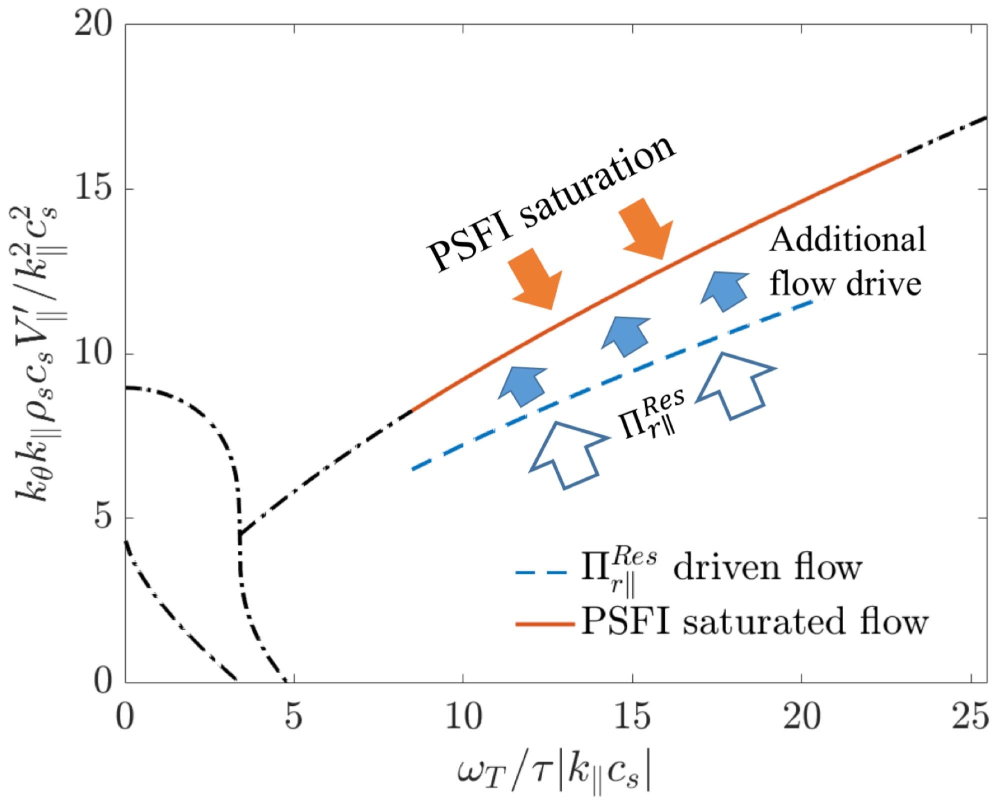




$\nabla V_\parallel \sim (\nabla T_i)^{2/3}$

Partial summary: axial flow generation and saturation in ITG turbulence

- Negative viscosity increment by ITG smaller than turbulent viscosity
  - Total viscosity positive, i.e.,
    $$\chi_\phi^{Tot} = \chi_\phi^{ITG} - |\chi_\phi^{Res}| > 0$$
    → No intrinsic rotation by ITG turbulence
- Flow saturation by PSFI
  - $\nabla V_\parallel$ saturates **above** PSFI linear threshold
  - **Generalized Rice scaling**: $\nabla V_\parallel \sim (\nabla T_i)^{2/3}$



Results not presented

- What happens to marginal regime?
  - ITG turbulence is usually marginal in the edge region of tokamak
- How does $\nabla V_{\parallel}$ affect the ITG turbulence?
  - Both parallel shear flow instability and ITG instability are negative compressibility phenomena → $\nabla V_{\parallel}$ enhances ITG turbulence
- Related paper:
  - J. C. Li and P. H. Diamond, "Negative viscosity from negative compressibility and axial flow shear stiffness in a straight magnetic field", *Physics of Plasmas*, 24, 032117, 2017.

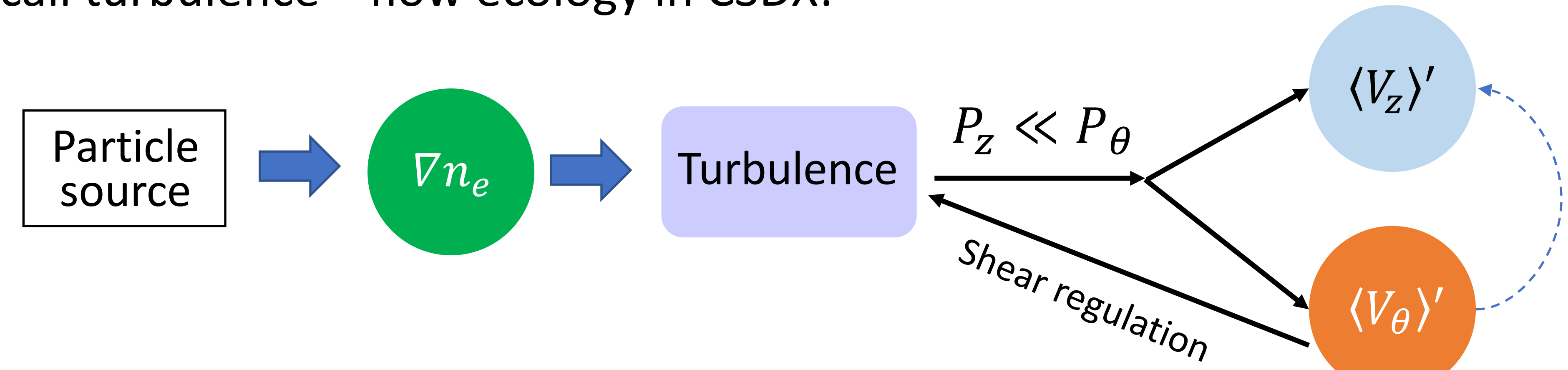
Interaction of intrinsic axial and azimuthal flows in CSDX

Interaction of axial and azimuthal flows

- Motivation:
  - (1) Heat engine analogy → **Branching ratio** P_z^R / P_θ^R?
  - (2) Parasitic V_z, $|k_z V_z'| \ll |k_\theta V_\theta'|$

    → How does V_θ' affect intrinsic V_z generation?

- Recall turbulence—flow ecology in CSDX:



Key takeaways

- Intrinsic axial and azimuthal flows interact through turbulent production and axial residual stress
  - Azimuthal flow shear reduces axial residual stress
  - Intrinsic axial flow saturates below PSFI threshold

    → Consistent with measurements in CSDX

    → Turbulent diffusion of axial momentum saturates the axial Reynolds power

Method: incremental study

- Drift wave + azimuthal flow shear (V_y') + axial flow shear (V_z'):

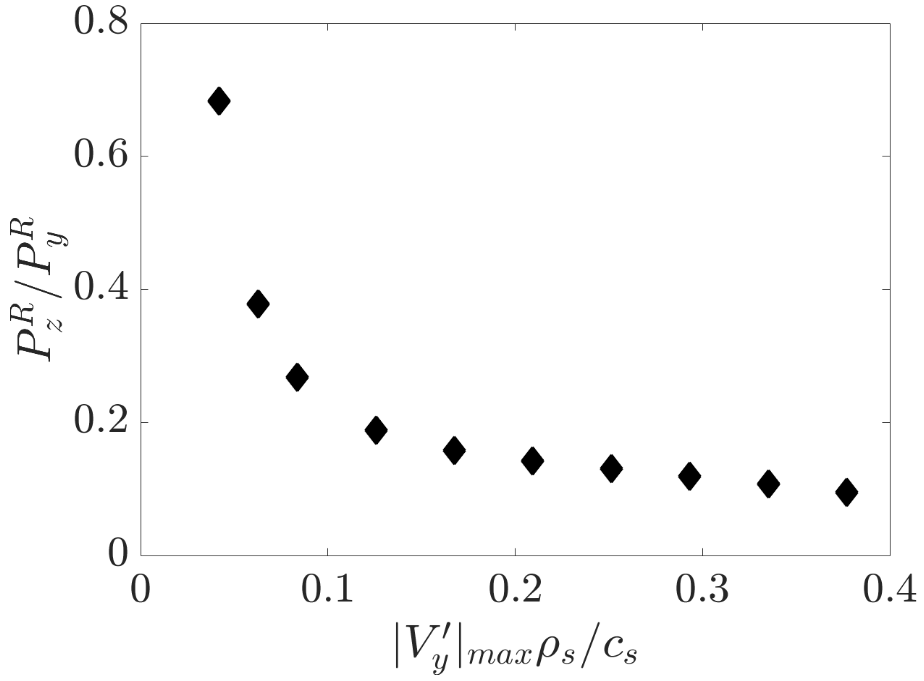
$$\frac{D}{Dt}n + v_x\frac{\nabla n_0}{n_0} = D_\parallel \partial_z^2(n-\phi)$$
$$\frac{D}{Dt}\nabla_\perp^2\phi + v_x V_y'' = D_\parallel \partial_z^2(n-\phi)$$
$$\frac{D}{Dt}v_z + v_x V_z' = -\partial_z n$$

$$\left(\frac{D}{Dt} = \frac{\partial}{\partial t} + V_y\partial_y + V_z\partial_z\right)$$

- Analogous to perturbation experiments
  - External flows: ignore feedback of turbulence-generated flows on the flow shear profile
  - Fix one flow shear and increase the other → solve for eigenmode
  - Calculate ratio of Reynolds powers $P_z\ /P_y$ for a single eigenmode

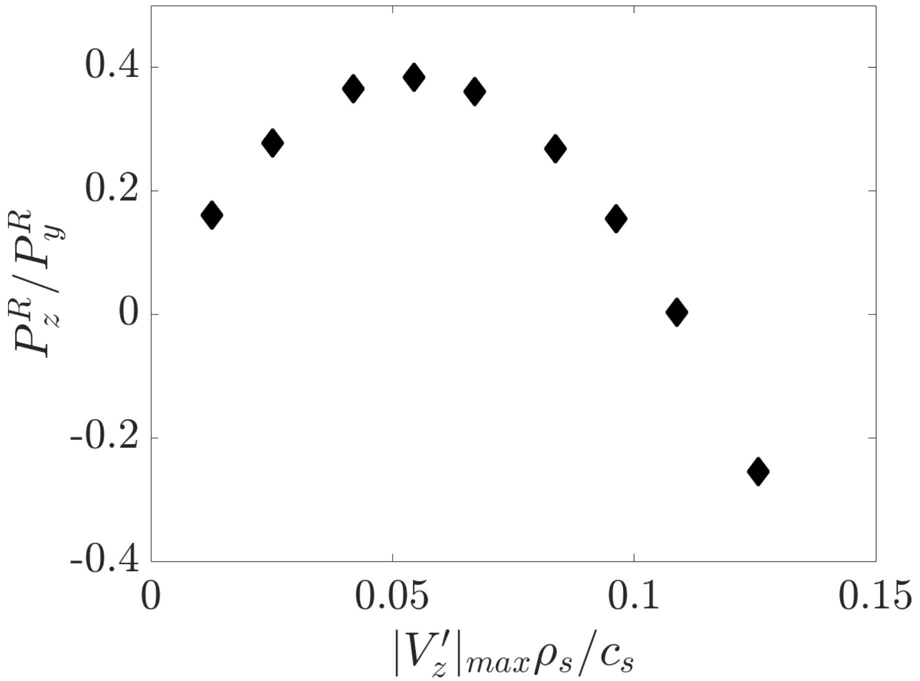
Result (1): V_y' reduces generation of intrinsic V_z

- Ratio $P_z\ /P_y$ decreases with V_y'
  → V_y' reduces generation of V_z, i.e., $\langle \tilde{v}_x \tilde{v}_z \rangle \sim |V_y'|^{-2}$
  → ***Competition*** between V_y and V_z



Result (2): Intrinsic V_z saturates below PSFI threshold

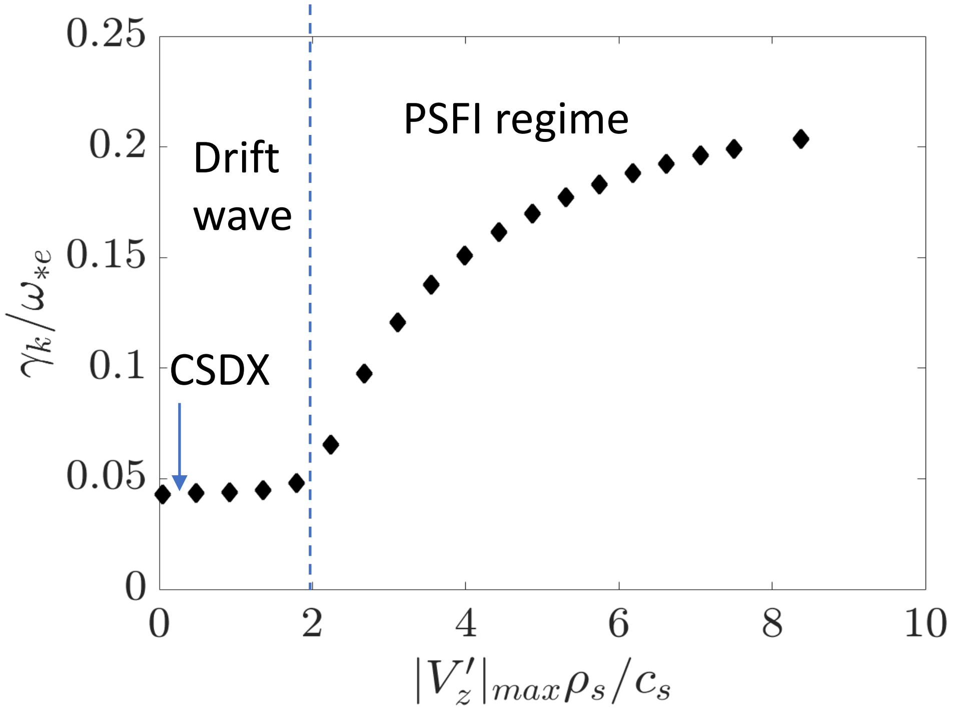
- Increase V_z' → P_z $/P_y$ first increases and then decreases
  - → Turnover because $-\chi_z V_z'$ contribution increases faster than Π_{xz}^{Res} contritution
  - → $P_z \sim \langle \tilde{v}_x \tilde{v}_z \rangle V_z' = \Pi_{xz}^{Res} V_z' - \chi_z |V_z'|^2$
  - → Intrinsic V_z saturates ***below*** PSFI threshold



Drift wave is the primary turbulence population

- Other potential drives:
  - V_y'' → Kelvin-Helmholtz (KH) instability
  - ∇V_z → Parallel shear flow instability (PSFI)

- KH is negligible
  - V_y'' drive weaker than ∇n_0 drive → $|k_y \rho_s^2 V_y''| \ll \omega_{*e}$



- ∇V_z in CSDX is well below the PSFI linear threshold

→ ***PSFI stable*** in CSDX

Results not presented here

- Effects of azimuthal flow shear on the intrinsic axial flow
  - V_y' reduces the modulational growth of seed axial flow shear
  - V_y' does **not** affect the stationary axial flow profile, to leading order
    - V_y' reduces both Π_{xz}^{Res} and χ_z by the same factor ($|V_y'|^{-2}$)
    - $V_z' = \Pi_{xz}^{Res}/\chi_z$, to leading order → V_y' effect cancels
- Related paper:
  - J. C. Li and P. H. Diamond, "Interaction of turbulence-generated azimuthal and axial flows in CSDX", manuscript in preparation.

Conclusion: summary and look forward

Lessons learned (1)

- Self-amplification of seed axial flow shear driven by drift wave turbulence
  - No requirement for magnetic shear

    → effective in cases with and without magnetic shear
  - Axial flow saturates **below** PSFI threshold
  - Confirmed by measurements of symmetry breaking and axial flow generation in CSDX
- For ITG turbulence:
  - Seed flow shear cannot self-amplify → no intrinsic parallel flow at zero magnetic shear
  - With other flow drives → $V_{\parallel}'$ steepens

    → $V_{\parallel}'$ saturates significantly **above** PSFI threshold

    → PSFI dominates over ITG turbulence → generalized Rice scaling: $\nabla V_{\parallel} \sim (\nabla T_i)^{2/3}$

Lessons learned (2)

- Interaction of intrinsic axial and azimuthal flows in CSDX
  - V_z' and V_y' couple through residual stress and turbulent production
  - V_y' reduces the production (i.e., Reynolds power) of V_z'
  - V_z' saturates **below** the PSFI threshold

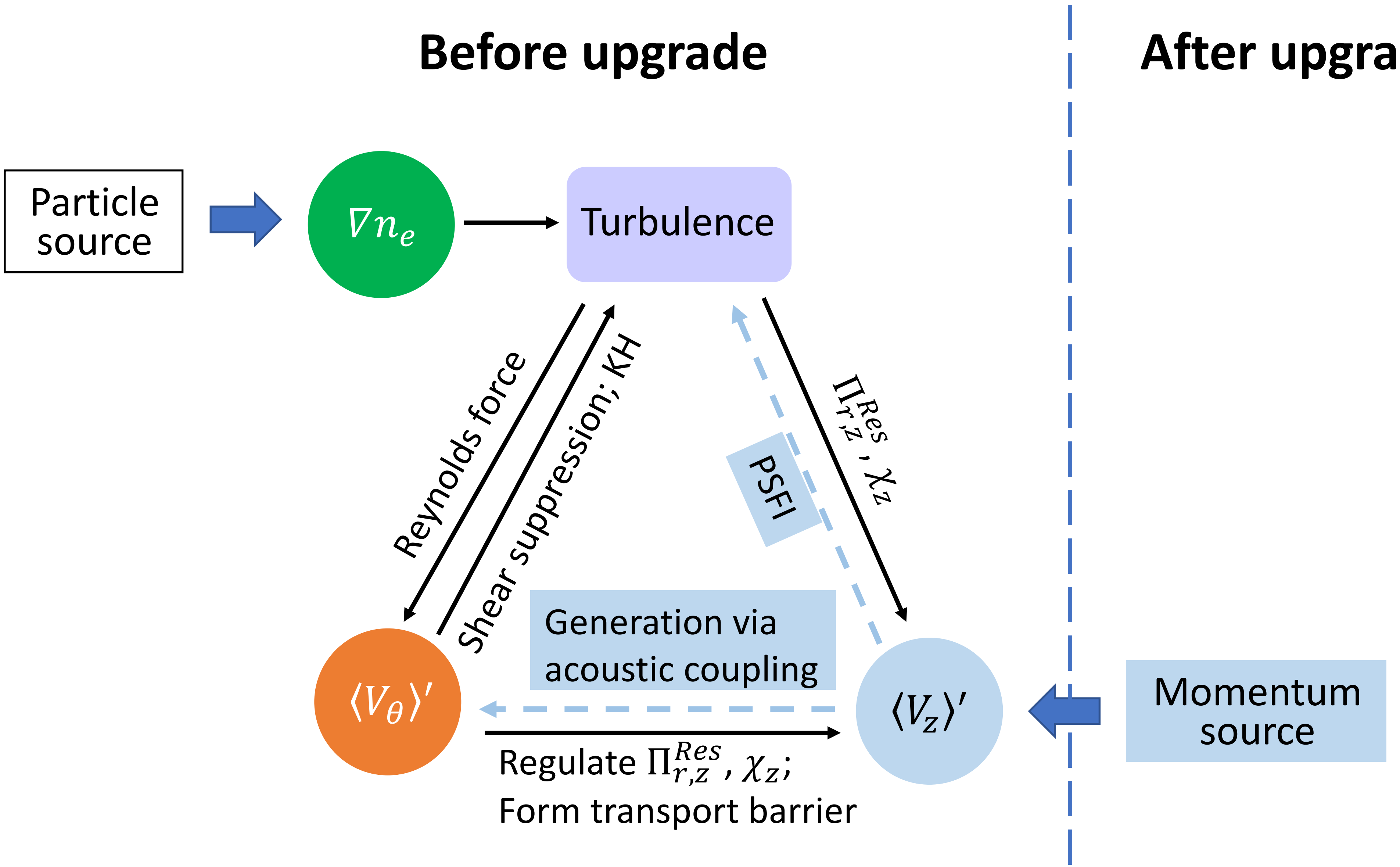
    → consistent with theoretical prediction and experimental measurements

Future direction for CSDX:

- Current: weak coupling between intrinsic axial flow and zonal flow
  - Because $|k_z V_z'| \ll |k_y V_y'|$, zonal flow regulates turbulence
  - Parasitic axial flow rides on drift wave–zonal flow system
- Future:
  - Axial momentum source:
    - Strong externally driven axial flow → $|k_z V_z'| \sim |k_y V_y'|$ → $\frac{\partial}{\partial t} + V_y \partial_y + V_z \partial_z \sim \omega - k_y V_y' \Delta_x - k_z V_z' \Delta_x$

      → significant V_z' effects on drift wave and zonal flow
    - Strong coupling of axial and azimuthal flows
    - Transport barrier formation
  - Pulsed source → avalanching and its effects on transport
  - Heat the ion → ITG regime → coexisting ITG and electron drift wave turbulence?

Future direction: drift wave—V_θ'—$V_z{}'$ ecology in CDSX



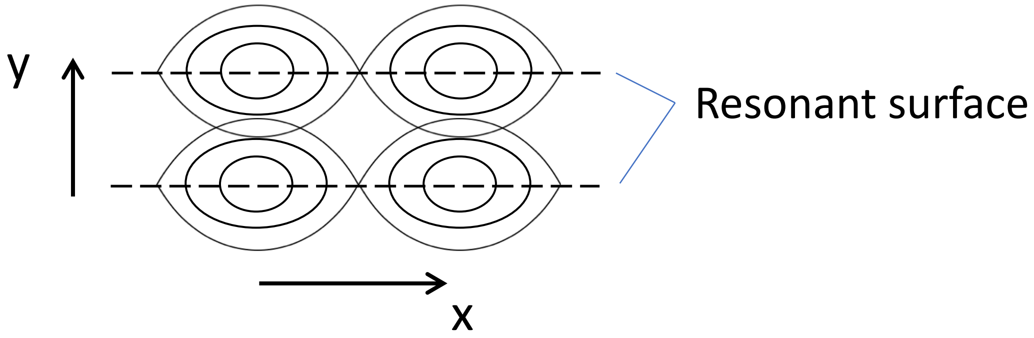
Frictionless zonal flow saturation

- J. C. Li and P. H. Diamond, “Frictionless Zonal Flow Saturation by Vorticity Mixing”, submitted to *Physical Review Letters*.
- J. C. Li and P. H. Diamond, “Another Look at Zonal Flow Physics: Resonance, Shear Flows and Frictionless Saturation”, submitted to *Physics of Plasmas*.

Zonal flow saturation absent frictional drag

- Motivation: physics of Dimits up-shift regime
  → collisionless regime with near-marginal turbulence

- Tertiary instability not effective
  – Severely damped by magnetic shear
  – Observed mean flow shear is always below the threshold for tertiary instability excitation
- Solution: wave—flow resonance $\omega_k - k_\theta V_\theta' \Delta_x$
  – Resonant scattering of vorticity saturates zonal flows



Overlapped islands
→ stochastic trajectories
→ irreversibility

Overview of results

- Resonance effects on linear stability
  - Wave—flow resonance suppresses instability
  - V_θ' weakens resonance → V_θ' ***enhances*** instability via resonance
  - Contradicting conventional shear suppression models
  - Wave—flow resonance is important at least in some regimes
- Resonant scattering of vorticity saturates zonal flow in frictionless regime
  - Resonant PV mixing → turbulent diffusion of vorticity → zonal flow saturation
  - Extended predator—prey model including this resonant regulation effect

Results

- Zonal flow shear and scale are directly calculated from this model
  - Mesoscopic flow scale: $L_{ZF} \sim \rho_s^{5/8} l_0^{3/8}$ → $\rho_s \ll L_{ZF} \ll l_0$
  - $l_0 \sim L_n$ is the base state mixing length at zero flow shear
  - Strong flow shear: $V'_{ZF} \sim \frac{c_s}{L_n}\left(\frac{l_0}{\rho_s}\right)^{3/8}$
- Implication for gyro-Bohm breaking: $D = D_B \rho_*^{1/4} \left(\frac{l_0}{L_n}\right)^{3/4} \sim D_B \rho_*^{1/4}$
- Extended predator—prey model → turbulence energy $\sim \gamma_L^2 / \varepsilon_c^2$, not $\sim \gamma_L$
- Flow independent of turbulence level → effective in regulating frictionless marginal turbulence

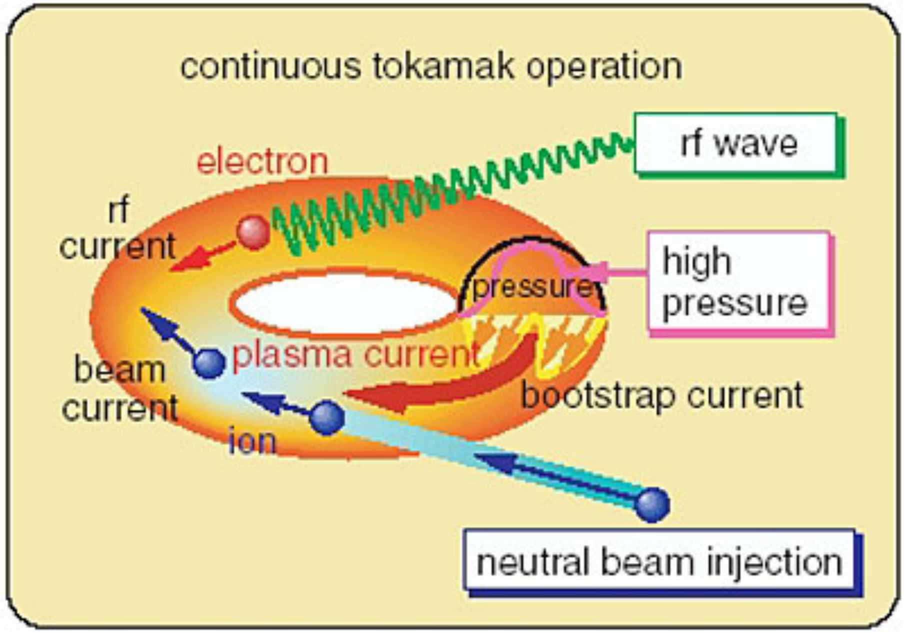
Thank you!

The research presented in this dissertation was supported by the U.S. Department of Energy, Office of Science, Office of Fusion Energy Sciences, under Award Nos. DE-FG02- 04ER54738 and DE-AC52-07NA27344, and CMTFO Award No. DE-SC0008378.

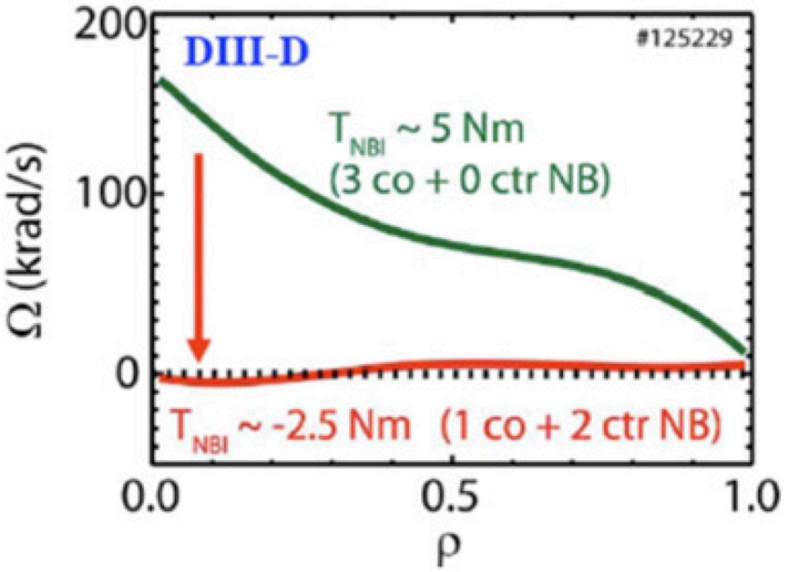
Appendix

Intrinsic toroidal rotation: phenomenology

- Cancellation experiment
  - Neutral Beam Injection (NBI) → External torque
  - 1 co + 2 ctr NB = 0 total torque → **Intrinsic torque = 1 co NB**
  - “co” and “ctr”: toroidal direction same as/opposite to plasma current direction



NBI and plasma current directions



Total rotation profile for different NB configurations

Parallel shear flow instability

- Growth rate and resulting turbulent momentum diffusivity:

$$\gamma_k^{PSFI} \cong \sqrt{\frac{k_\theta k_z \rho_s c_s \left(\langle v_z \rangle' - \langle v_z \rangle'_{crit}\right)}{1 + k_\perp^2 \rho_s^2}}$$

$$\chi_\phi^{PSFI} \cong \sum_k |\phi_k|^2 k_\theta^2 \rho_s^2 \frac{4(1 + k_\perp^2 \rho_s^2)^2}{\omega_*^2} \sqrt{\frac{k_\theta k_z \rho_s c_s \left(\langle v_z \rangle' - \langle v_z \rangle'_{crit}\right)}{1 + k_\perp^2 \rho_s^2}}$$

- $\langle v_z \rangle'$ hits PSFI threshold → χ_ϕ^{PSFI} nonlinear in $\nabla \langle v_z \rangle$ → $\chi_\phi^{tot} > 0$
- $\delta \langle v_z \rangle'$ → Π^{Res} → $\delta \langle v_z \rangle'$ growth ← Saturated by PSFI

$$\chi_\phi^{tot} = \chi_\phi^{DW} - \left|\chi_\phi^{Inc}\right| < 0$$

$$\chi_\phi^{tot} = \chi_\phi^{DW} + \chi_\phi^{PSFI} - \left|\chi_\phi^{Inc}\right| > 0$$

Nonlinear Model: *Resonant* PV Mixing

- Density: $$\frac{\partial}{\partial t}\langle n\rangle = \frac{\partial}{\partial x} D_{n,\mathrm{turb}} \frac{\partial}{\partial x}\langle n\rangle + D_c \nabla^2 \langle n\rangle,$$
- Vorticity: $$\frac{\partial}{\partial t}\langle \rho\rangle = \frac{\partial}{\partial x}\left[(D_{n,\mathrm{turb}} - D_q^{\mathrm{res}})\frac{\partial}{\partial x}\langle n\rangle + D_q^{\mathrm{res}}\frac{\partial}{\partial x}\langle \rho\rangle\right] - \mu_c\langle\rho\rangle - \mu_{NL}\langle\rho\rangle + \chi_c\nabla^2\langle\rho\rangle,$$
- Potential enstrophy: $$\frac{\partial}{\partial t}\Omega = D_\Omega \frac{\partial}{\partial x}\Omega + D_q^{\mathrm{res}}\left[\frac{\partial}{\partial x}(\langle n\rangle - \langle\rho\rangle)\right]^2 - \varepsilon_c \Omega^{3/2} + \gamma_L \Omega. \qquad \Omega \equiv \langle \tilde{\rho}^2\rangle$$

- $\mu_{NL} = \mu_{NL}(\langle v_y\rangle)$: nonlinear damping rate driven by tertiary mode ← ***Irrelevant*** **to most cases we have encountered**

- D_c, μ_c, χ_c: collisional particle diffusivity, flow damping, vorticity diffusivity → vanishing in collisionless regime

Extended Predator—Prey Model

- Mean flow energy:

$$\frac{L_{ZF}^2}{2}\frac{dV''^2}{dt} = \alpha_1|V''|E - \alpha_2 V''^2 E - \gamma_{NL}V''^2 - \mu_c V''^2.$$

Resonant diffusion of vorticity

Collisional Damping

new

Production by residual vorticity flux

Nonlinear damping by tertiary modes

- Turbulence energy (potential enstrophy):

$$\frac{dE}{dt} = -\alpha_1|V''|E + \alpha_2 V''^2 E - \varepsilon_c E^{3/2} + \gamma_L E.$$

Forward cascade of PE

Linear instability

Turbulence and flow states

- Compare by regime:

Regime	Frictionless	Weakly Frictional	Strongly Frictional
Frictional Damping Strength	$\mu_c \ll \alpha_2 E$	$\alpha_2 E \ll \mu_c \ll 4\gamma_L \alpha_1^2/\varepsilon_c^2$	$\mu_c \gg 4\gamma_L \alpha_1^2/\varepsilon_c^2$
Flow $\lvert V'' \rvert$	$\frac{\alpha_1}{\alpha_2}$	$\frac{\alpha_1 \gamma_L^2}{\mu_c \varepsilon_c^2}$	$\frac{\gamma_L}{\alpha_1}$
Turbulence Energy E	$\frac{\gamma_L^2}{\varepsilon_c^2}$	$\frac{\gamma_L^2}{\varepsilon_c^2}$	$\frac{\gamma_L \mu_c}{\alpha_1^2}$

- Frictionless = friction drag$\rightarrow 0$
- Frictionless saturation compared to usual frictional damping:
  - Turbulence energy determined by linear stability and small scale dissipation
    → Different from usual models, where turbulence energy ~ flow damping
  - Flow state basically independent of stability drive
    → There can be flows in nearly marginal turbulence