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Low momentum diffusivity regime in toroidal tokamak plasmas

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Outline

- **Introduction to microturbulence in tokamaks**
- **Flow shear suppression of turbulence**
- **Low Momentum Diffusivity (LMD) regime & up-down asymmetry**
- **Quasilinear model for momentum transport**

Microturbulence in tokamaks

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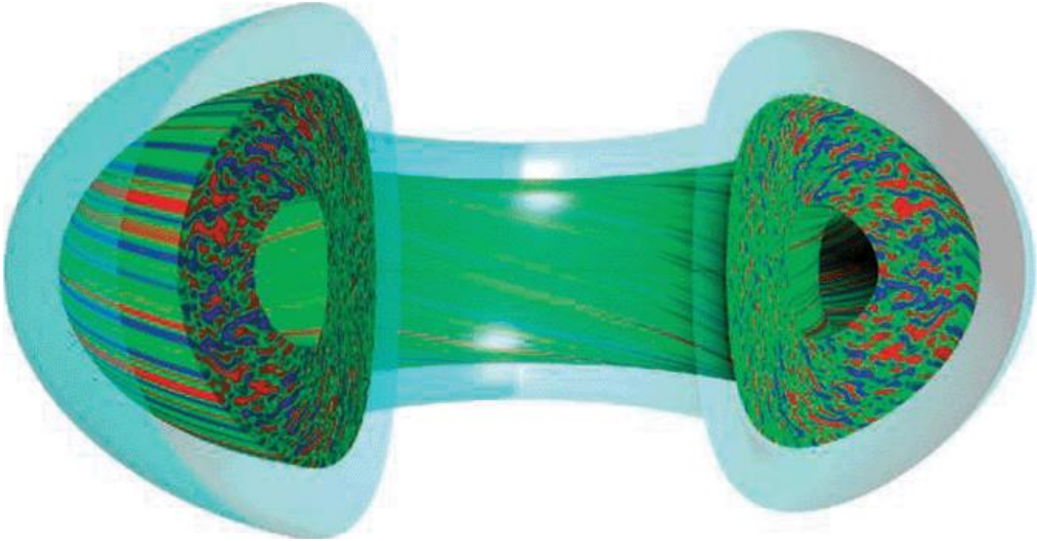
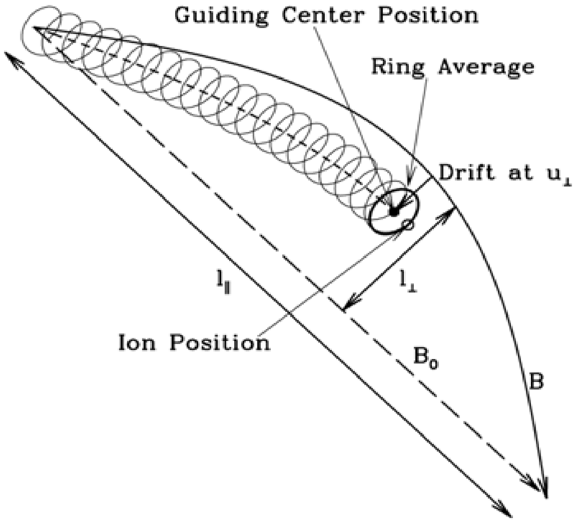
Ion scale turbulence

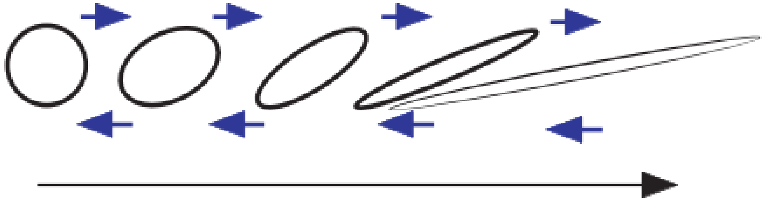


Microturbulence causes more than 90% of energy loss in tokamaks

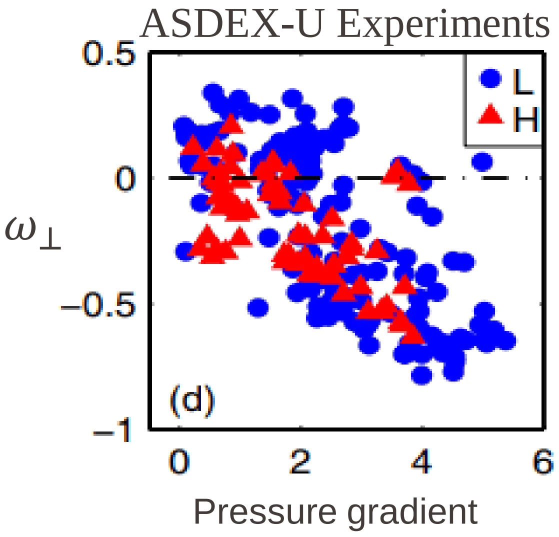
1. **Turbulence is highly anisotropic**
2. **Electromagnetic turbulence**
3. **Weakly collisional**
4. **Gyrokinetic simulation is needed to simulate such turbulence**



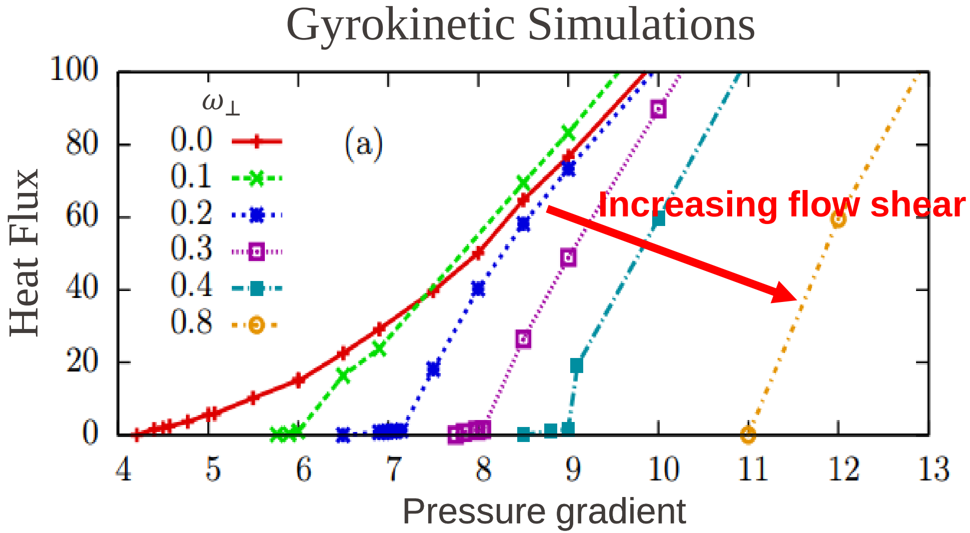
Suppression of turbulence by flow shear



Flow shear $\omega_{\perp} \sim \partial V / \partial r$ twists turbulence eddies into smaller spatial scale, reducing their amplitude



[Angioni et al., PRL, 2011]



[Highcock, PhD thesis, 2012]

Experiments and simulations have shown that flow shear can stabilize turbulence, improving tokamak performance

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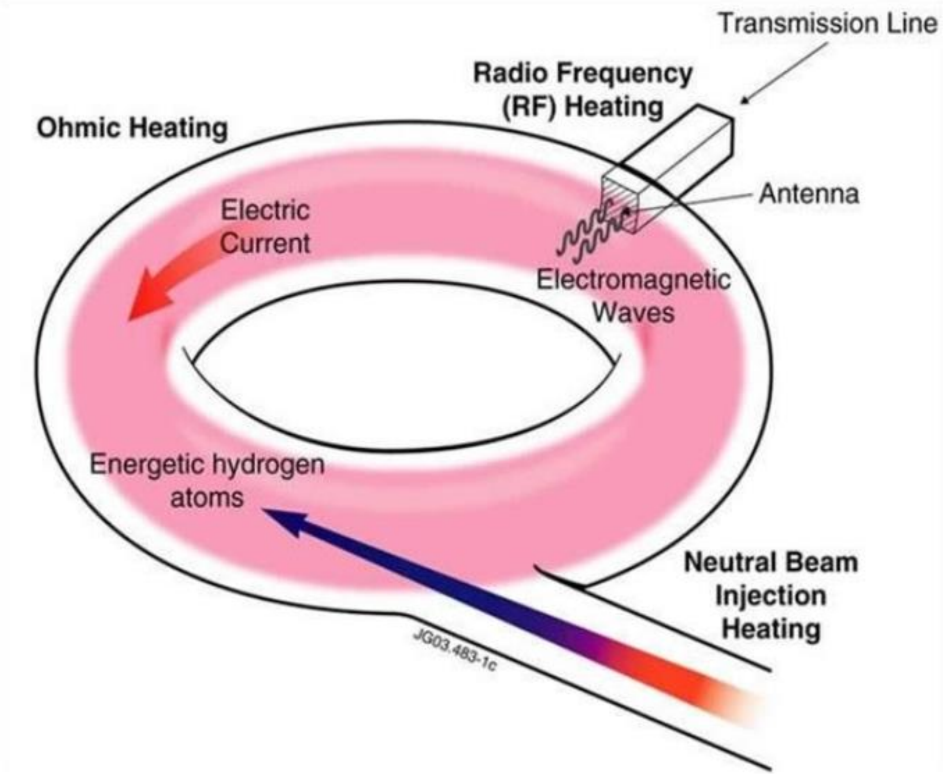
Generating flow shear using neutral beam/radio frequency waves

[Liu et al., Nuclear Fusion, 2004]



Flow shear is usually generated from external momentum sources such as NBI or RF waves.

External injections does not scale well to large devices

ITER: $\omega_{\perp} < 0.02 v_A / R_0$

Alternatives?

Generate flow shear using up-down asymmetry

Typical expression for momentum flux

$$\Pi_i = \Pi_{i,intrinsic} - D_{\Pi_i}\frac{dV_i}{dr}$$

In steady state: $\Pi_i = 0$, so we have

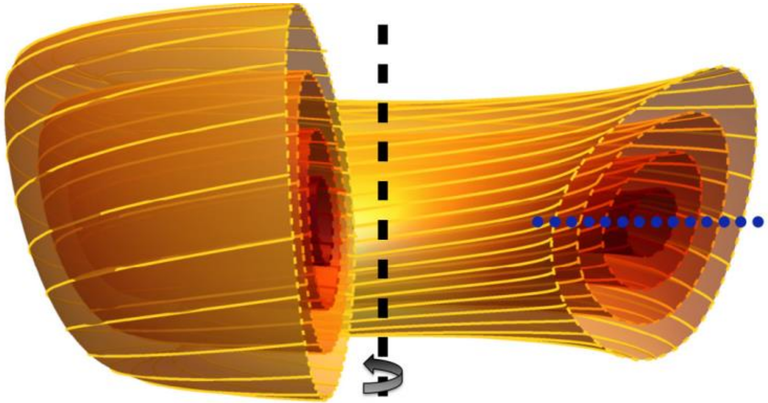
$$\Pi_{i,intrinsic} = D_{\Pi_i}\frac{dV_i}{dr}$$

$$Q_i = -D_{Q_i}\frac{dT_i}{dr}$$

Define Prandtl number: $Pr_i = \frac{D_{\Pi_i}}{D_{Q_i}}$

Most important source of intrinsic rotation: up/down asymmetry of magnetic equilibrium.

[Ball et al., Nuclear Fusion, 2018]



Low Pr_i regime? → Flow shear generated? → Suppress turbulence?

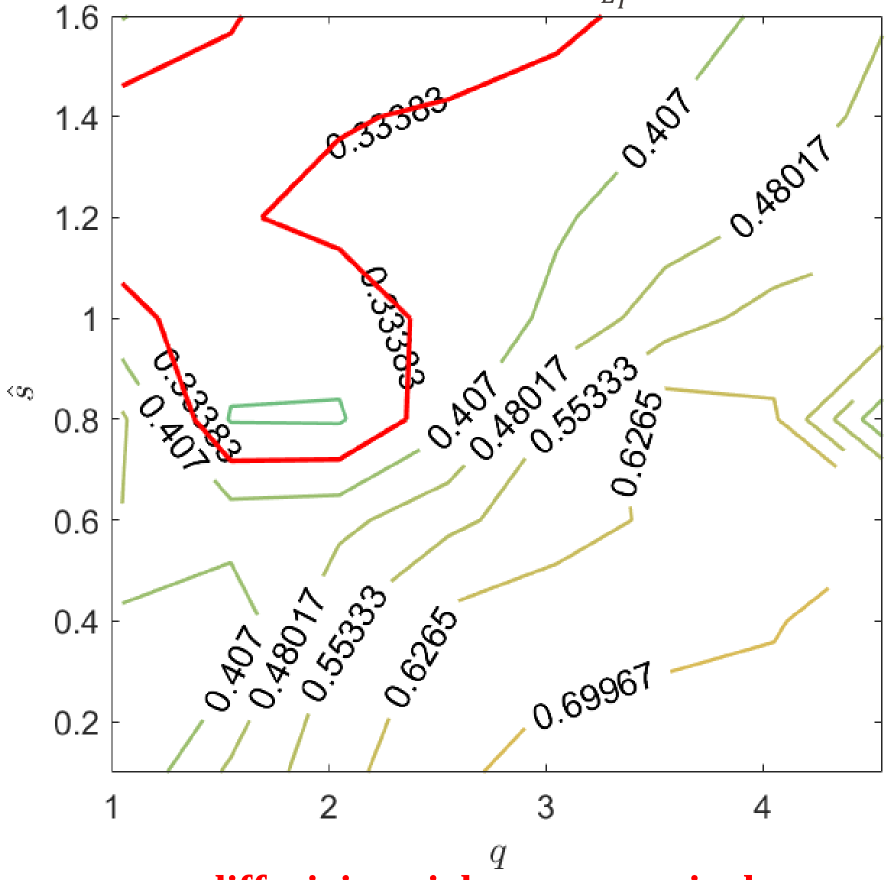
Gyrokinetic simulations

Quasilinear model

Heat flux at zero Π_i

Low Momentum Diffusivity (LMD) regime

Contours of constant Pr_i at $\frac{R_0}{L_T} = 10.96$

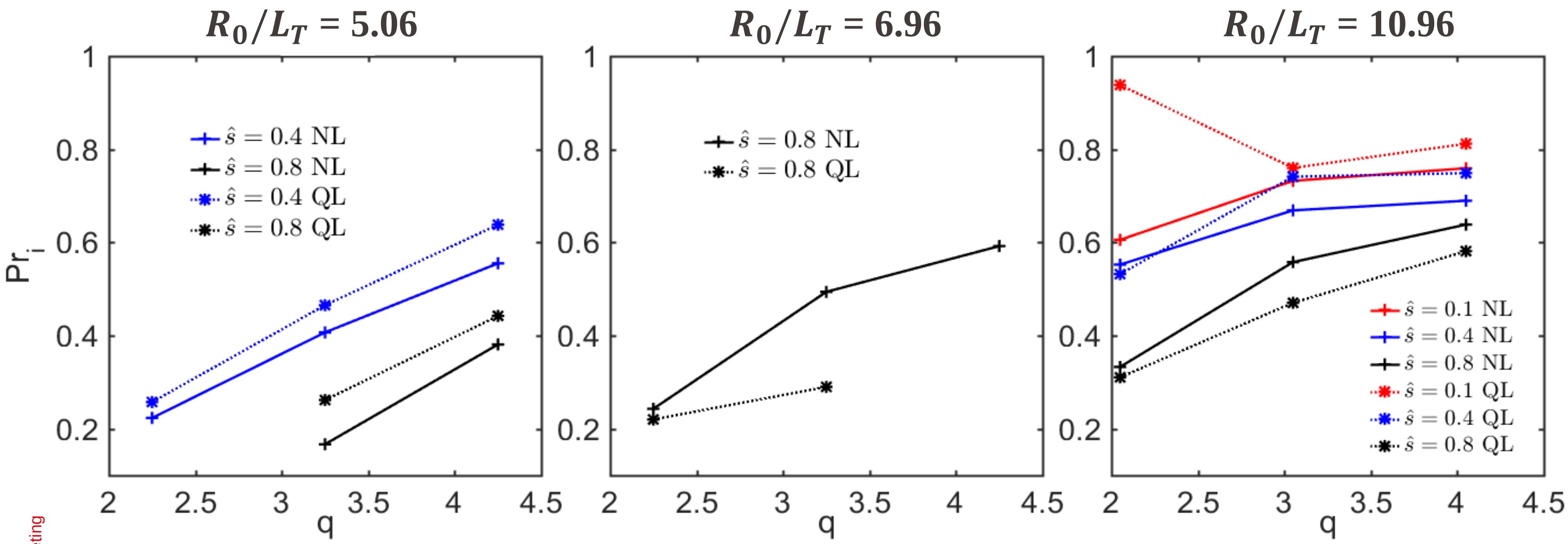


[McMillan & Dominski, Journal of Plasma Physics, 2019]

Low momentum diffusivity: tight aspect ratio, low q, normal to high $\hat{s}$.

A new quasilinear (QL) model for momentum transport

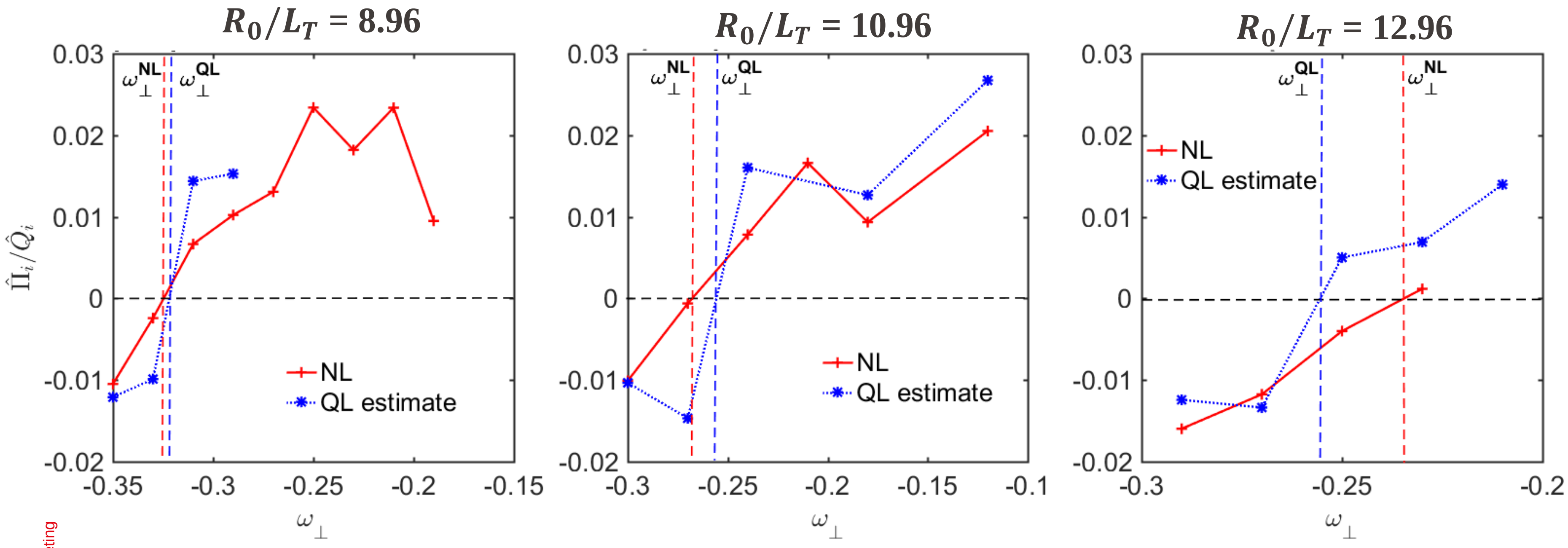
Momentum flux drive: $\Pi_i = -D_{\Pi_i} \partial \Omega_i / \partial r$



The model predicts the momentum transport well (paper in preparation)

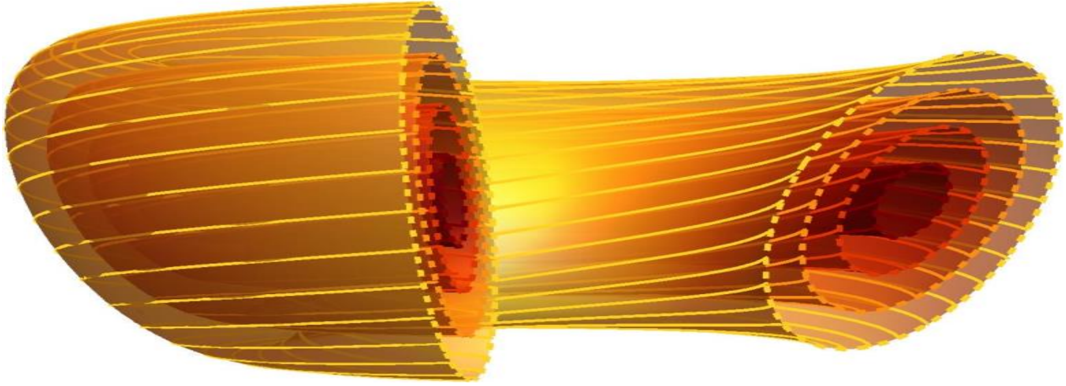
Using QL model to estimate flow shear at equilibrium

Up-down asymmetry with $\kappa = 1.5, \theta_\kappa = \pi/8$

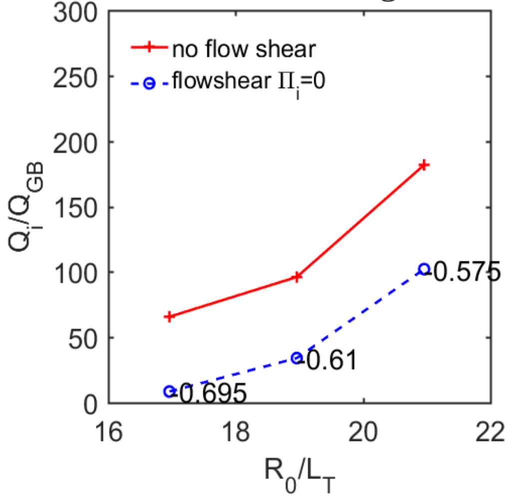


The model predicts the steady-state flow shear well

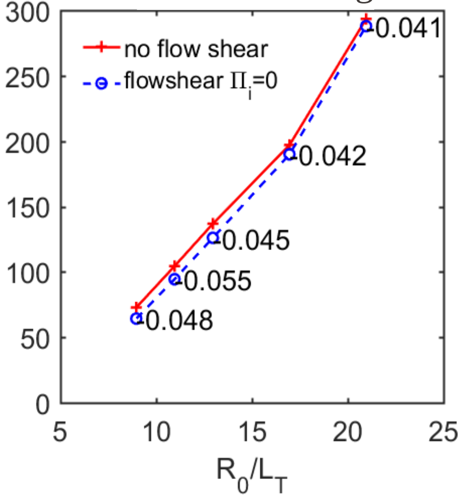
Combining LMD regime with up-down asymmetry



In the LMD regime



Out of the LMD regime



In the LMD: strong flow shear, significant suppression of turbulence especially near marginal stability

Out of the LMD: weak flow shear, nearly no effect on heat transport

Conclusions

- The Low Momentum Diffusivity (LMD) regime is enabled by tight aspect ratio, low safety factor and normal to high magnetic shear
- Combining the LMD regime with up-down asymmetry generates a large intrinsic flow shear, which can significantly reduce the turbulent heat flux
- A new quasilinear model is proposed to estimate the momentum transport, which agrees well with nonlinear simulations even in the presence of flow shear and up-down asymmetric geometry

$Pr_i = 0.5$ manifold $\epsilon = 0.36$