The role of flow shear in tokamak transport barriers

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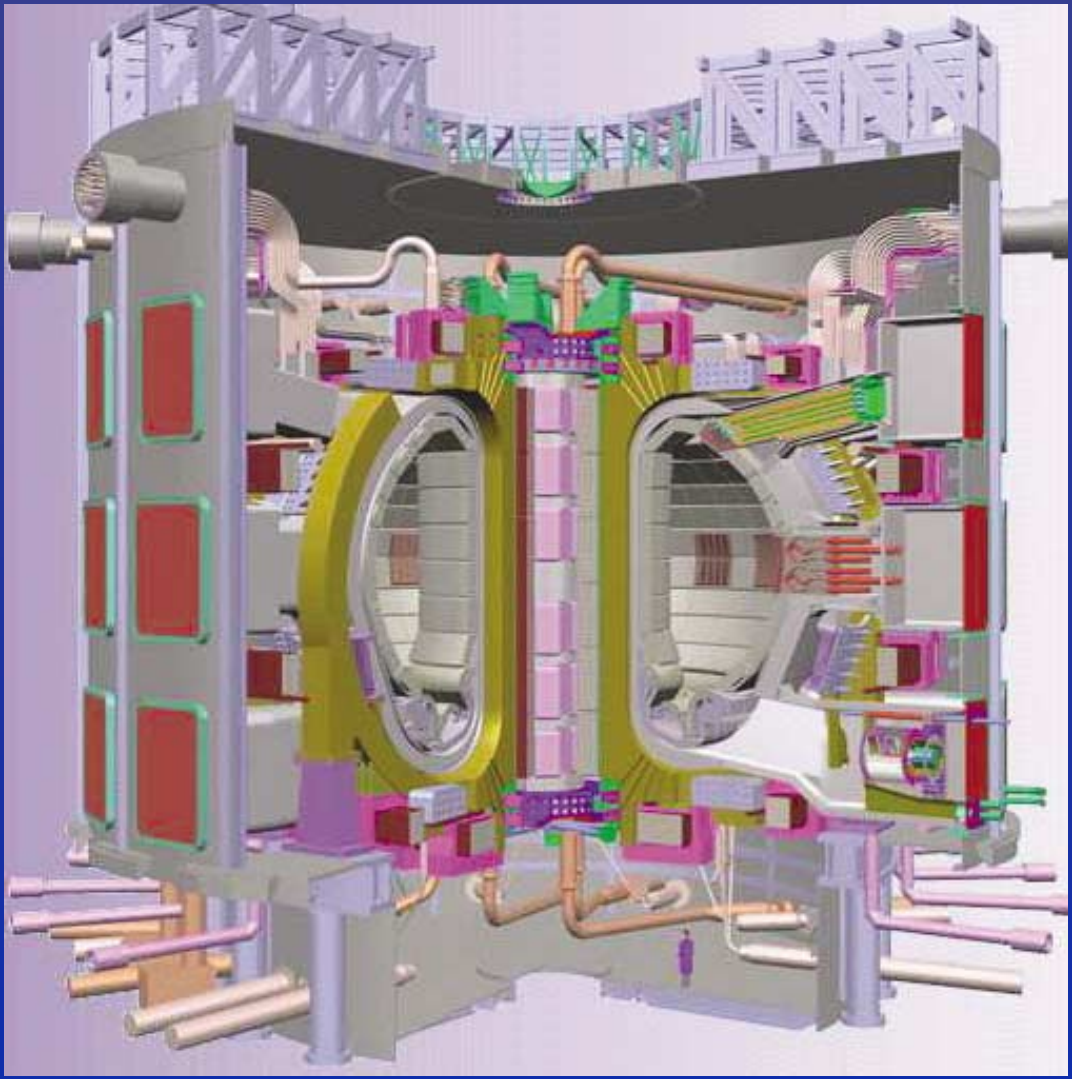
Overview

- Motivation
- Evidence for shear flow suppression of turbulence and ITBs
- Characteristics of turbulent fluxes in presence of shear flow
- Implications for mean profiles (ITB formation?)
- Conclusions

Magnetic confinement fusion



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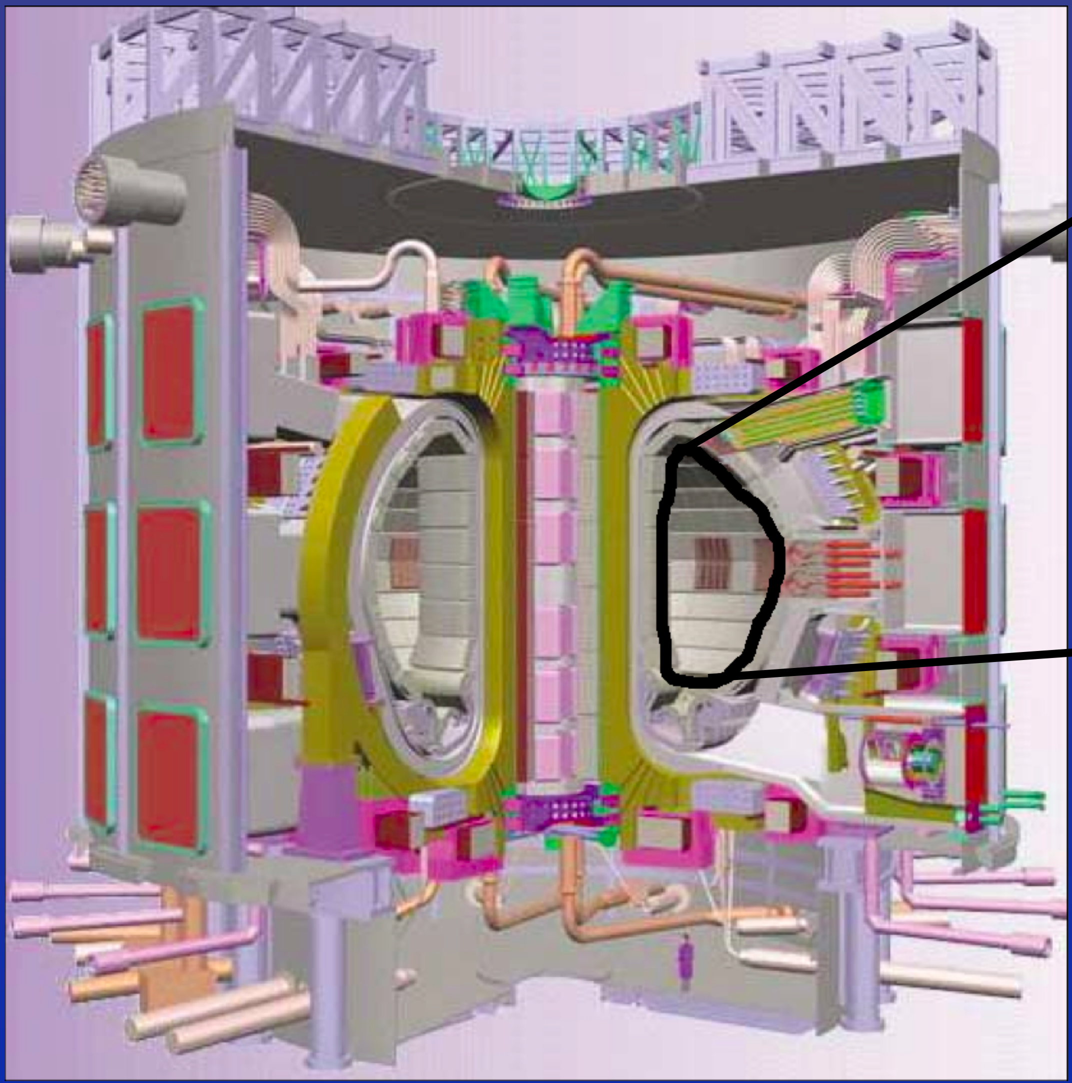
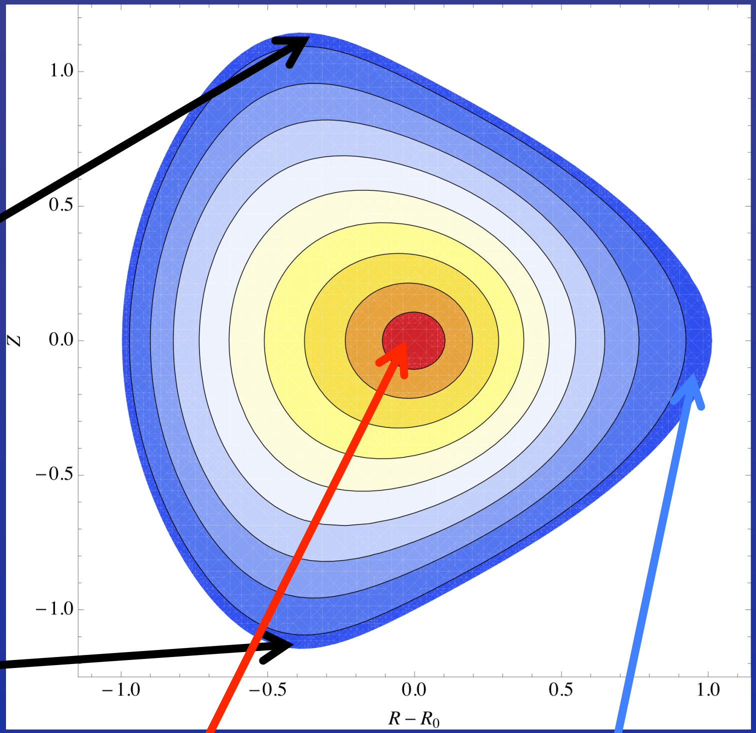
Magnetic confinement fusion





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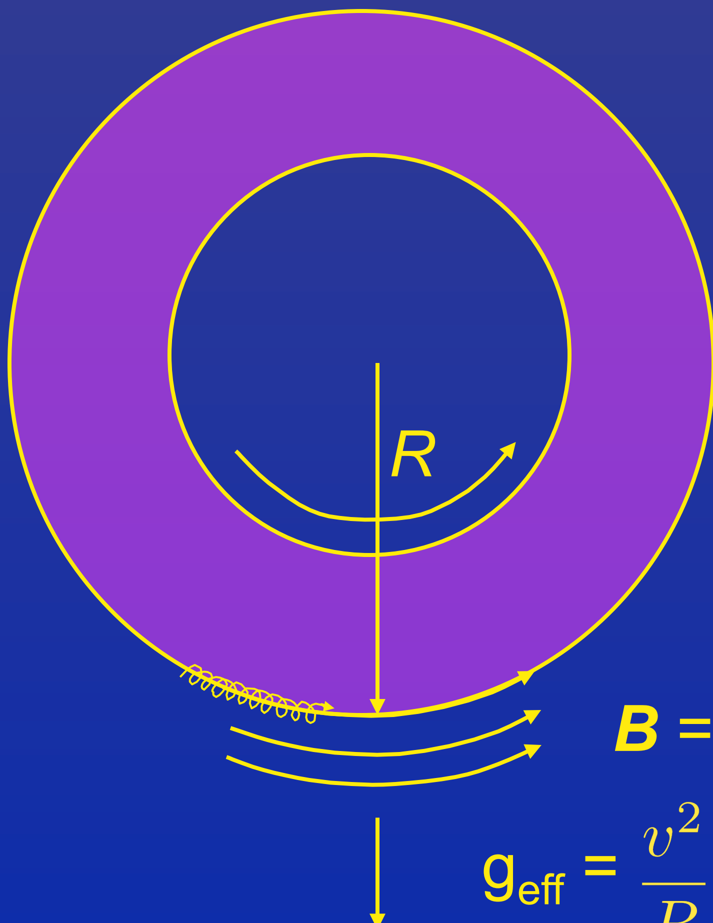
Simple picture of instability

Top view of toroidal plasma:



plasma = heavy fluid

B = "light fluid"

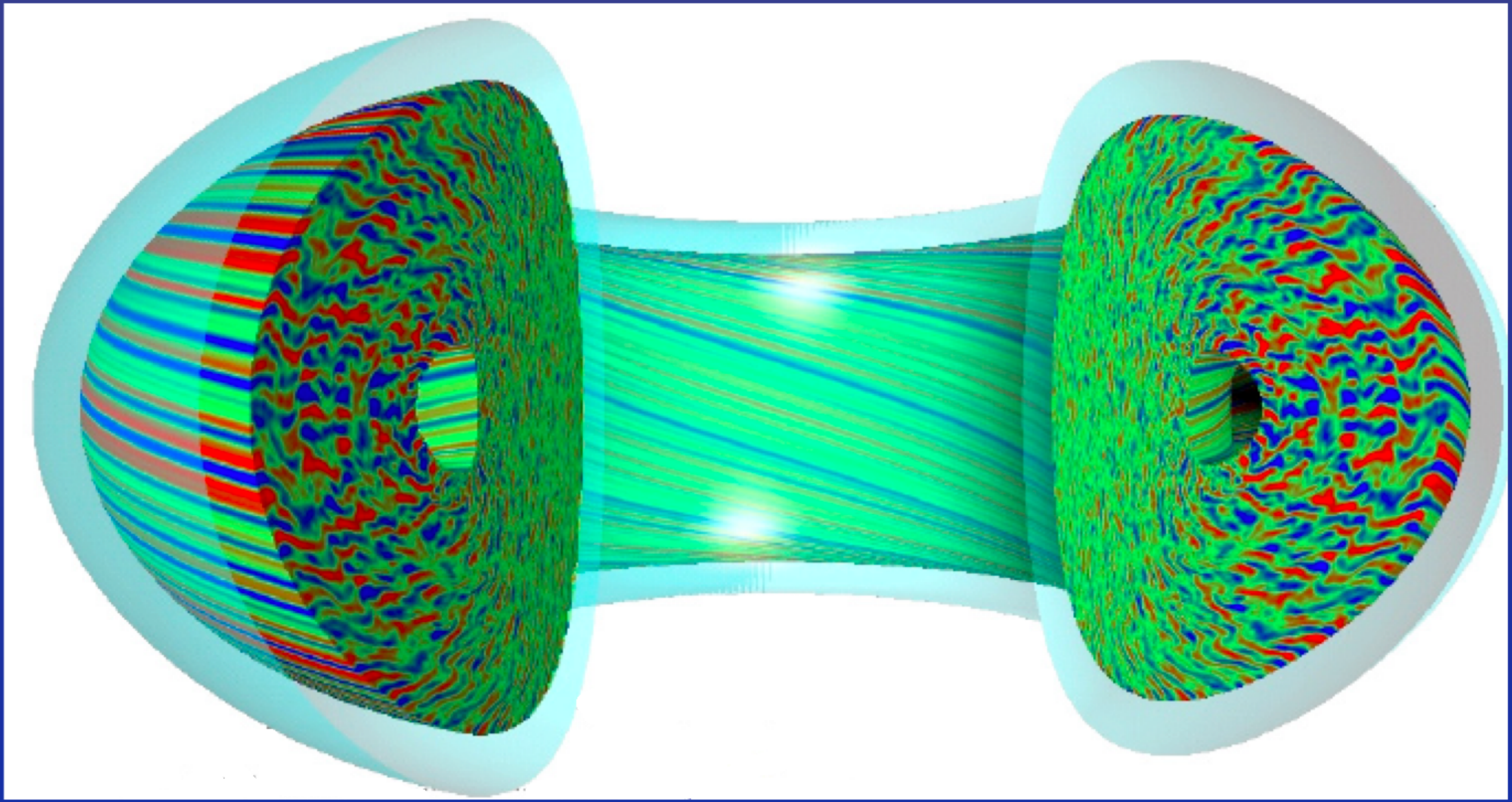
$g_{\text{eff}} = \dfrac{v^2}{R}$ centrifugal force

Growth rate:

$$\gamma = \sqrt{\frac{g_{\text{eff}}}{L}} = \frac{v_t}{\sqrt{RL}}$$

Instability mechanism similar to Rayleigh-Taylor

Resultant turbulence



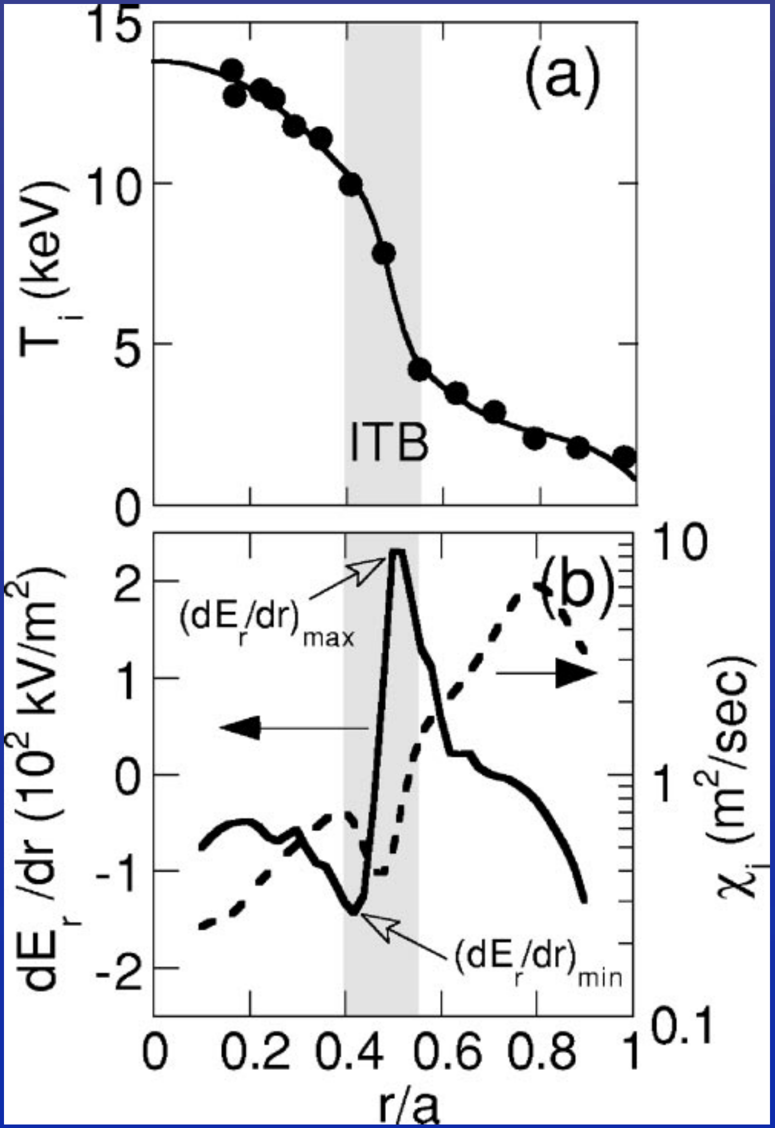
Turbulence-driven heat fluxes limit core plasma temperature

Mean flow in tokamak plasmas

- Two types of sheared flow:
  1) Zonal flows (generated by turbulence, radial wavelength ~ Larmor radius)
  2) Mean toroidal flows (evolve on transport time scale, system space scale)
- Both affect turbulent fluctuations, but here we consider mean flows
- Note toroidal flow has components along and across mean magnetic field
  - Perpendicular flow = $\mathbf{v}_E = (c/B^2)\mathbf{E} \times \mathbf{B}$

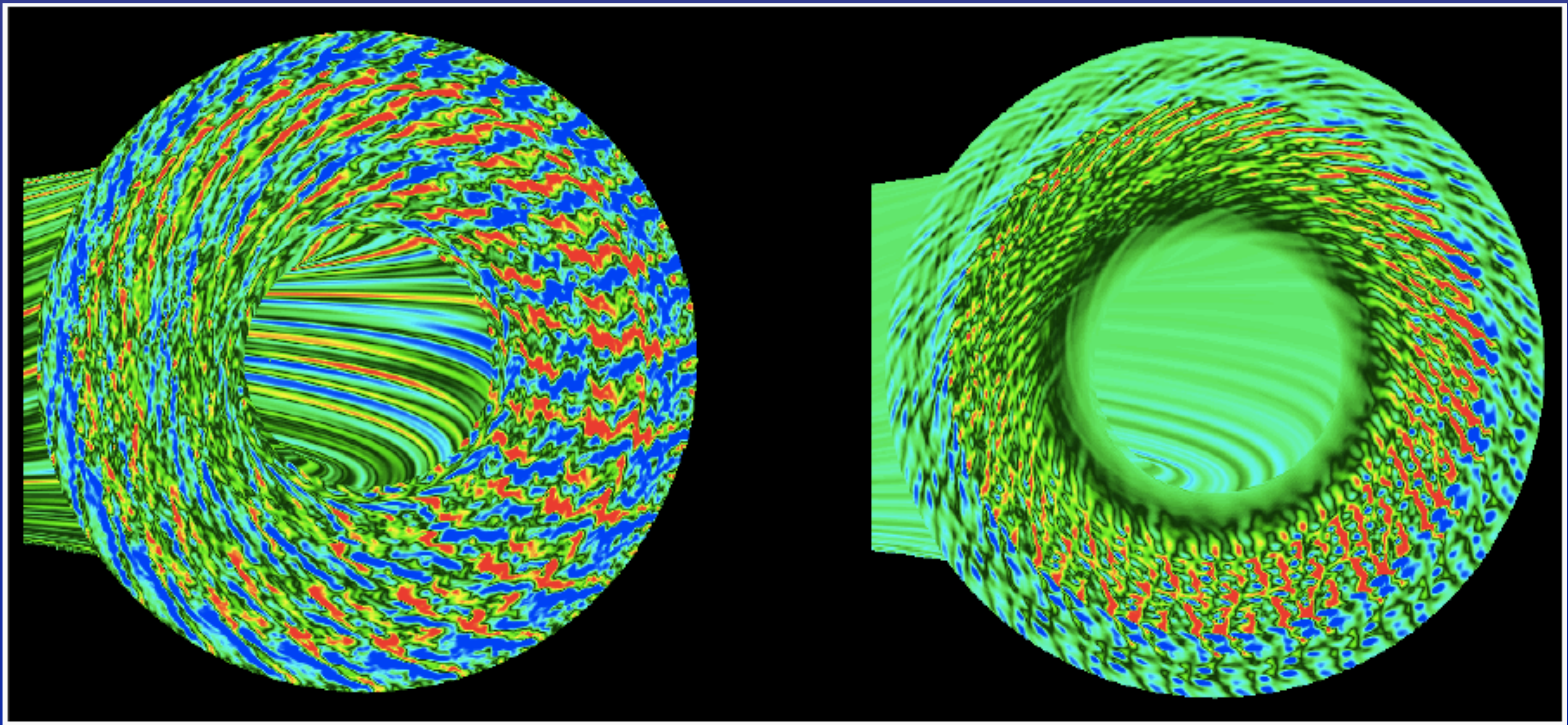
Shear flow suppression of turbulence

- "Internal Transport Barriers" (ITBs) observed in wide range of fusion devices
- Often accompanied by strong velocity shear
- Important ITB issues: limitations, residual transport mechanisms, control mechanisms



JT-60U data. Y. Miura, *et al.,* 10:1809:2003

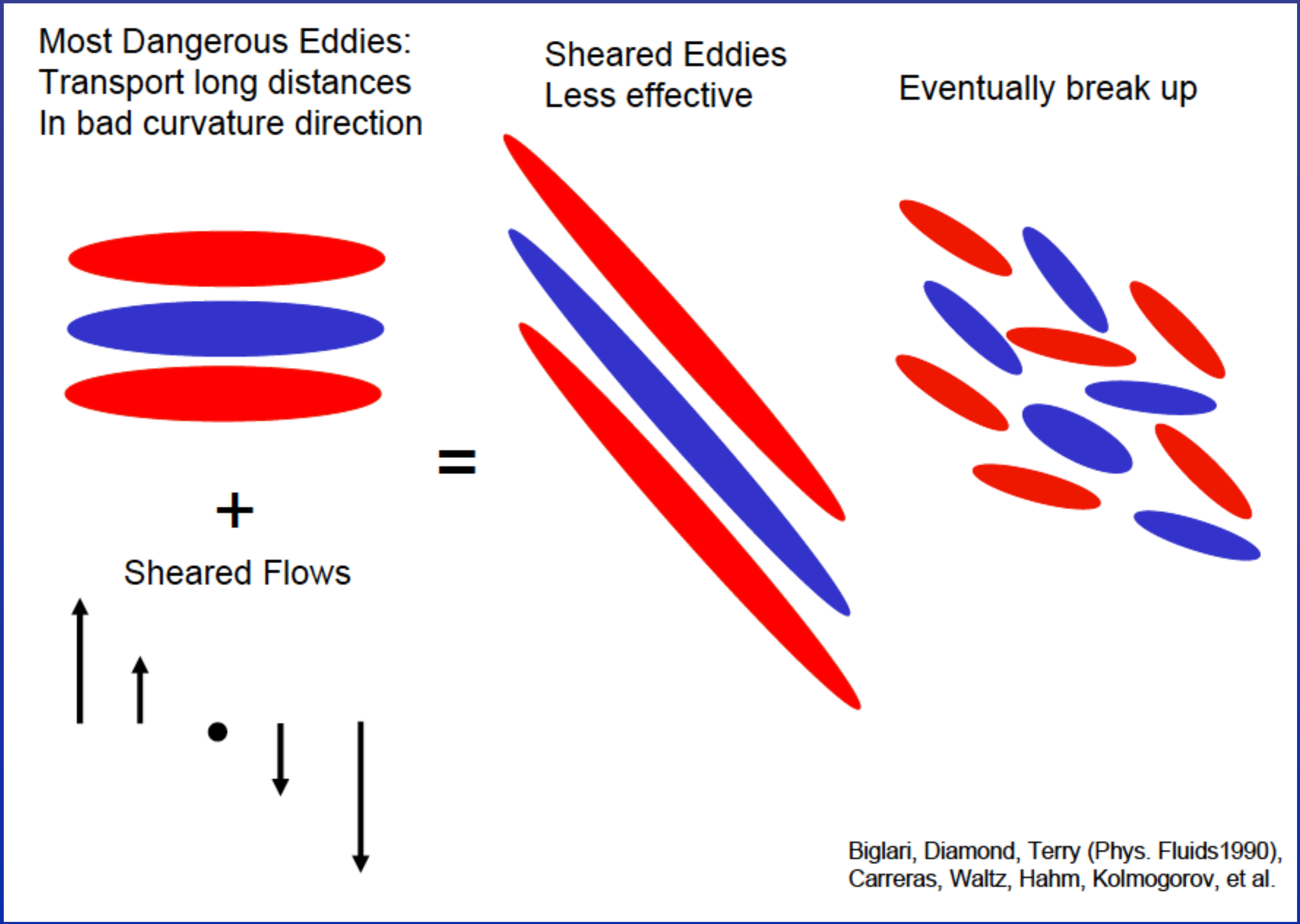
Simulations of turbulence suppression



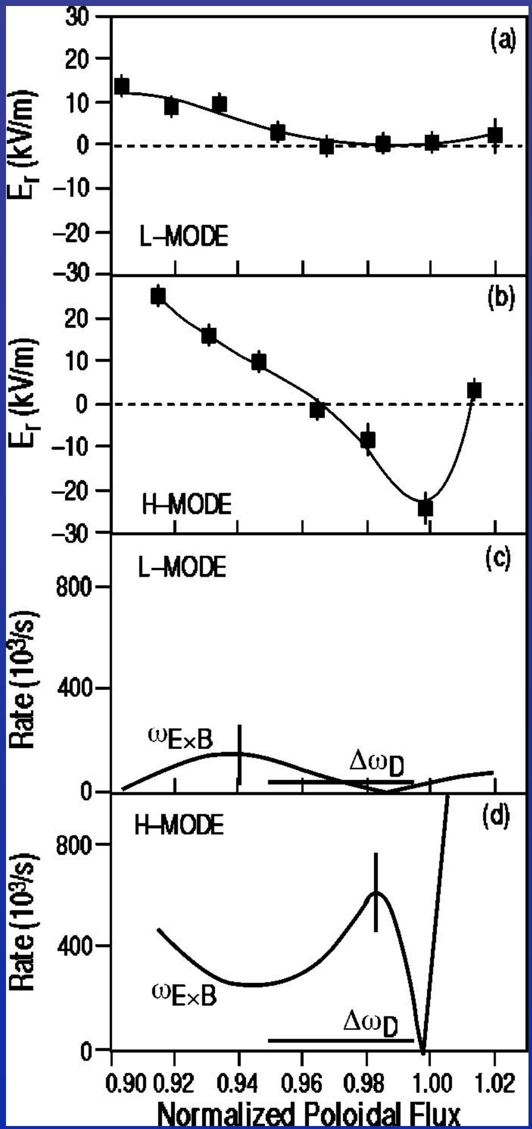
No mean shear flow

With mean shear flow

Simple physical intuition



Heuristic "quench rule"



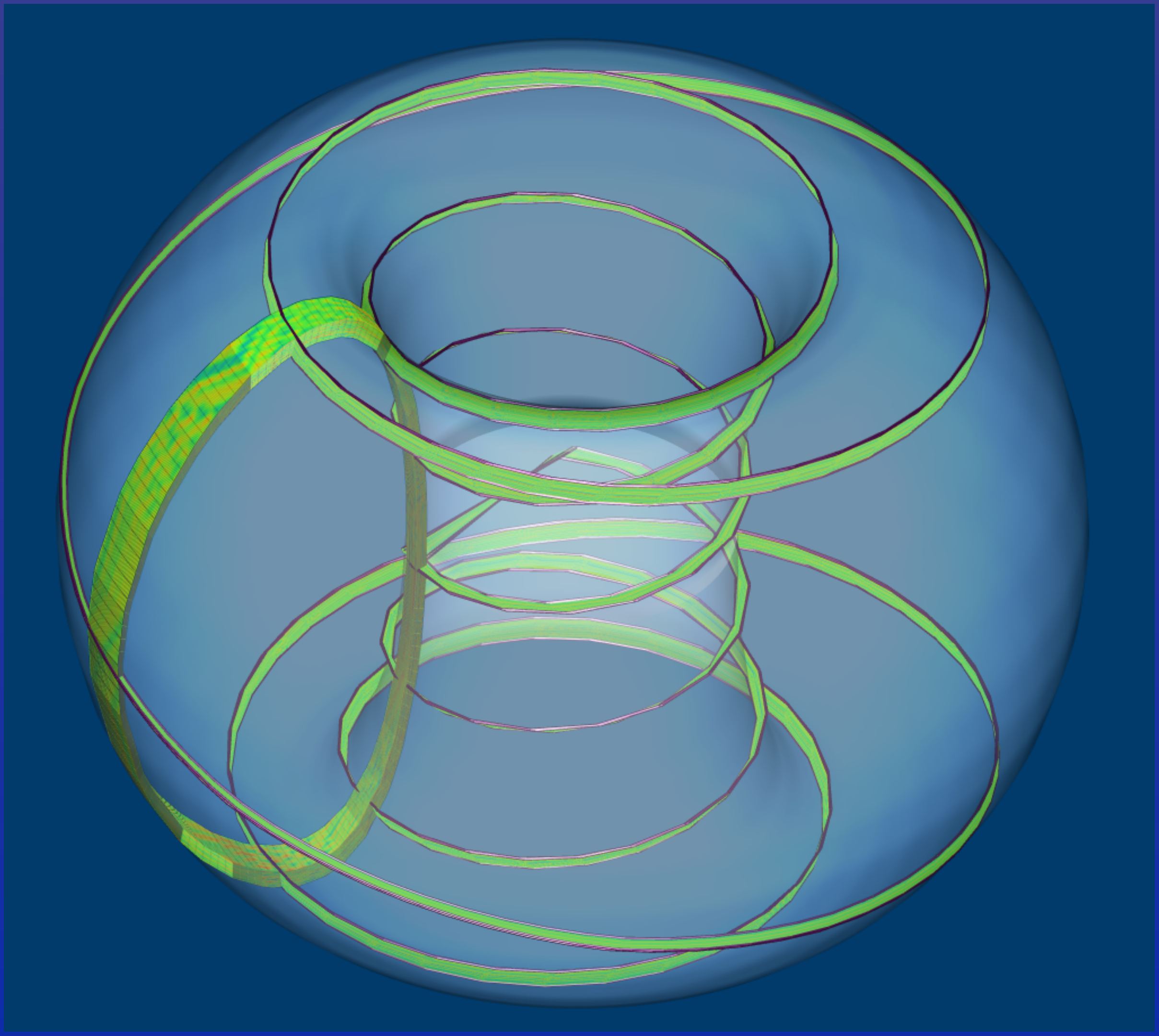
DIII-D data. K H Burrell, PoP 6:4418:1999

- When the confinement is high quality ("H-mode") there is a clear shear layer.
- The shear in this layer is larger than the turbulence decorrelation rate.
- When the confinement is low quality ("L-mode") the shear is at best comparable to the turbulence.
- **Two important questions:**
  1) How do shear layers self-organize?
  2) How do they affect turbulent transport?

Numerical model (gyrokinetics)

- High temperature, so long mean free path

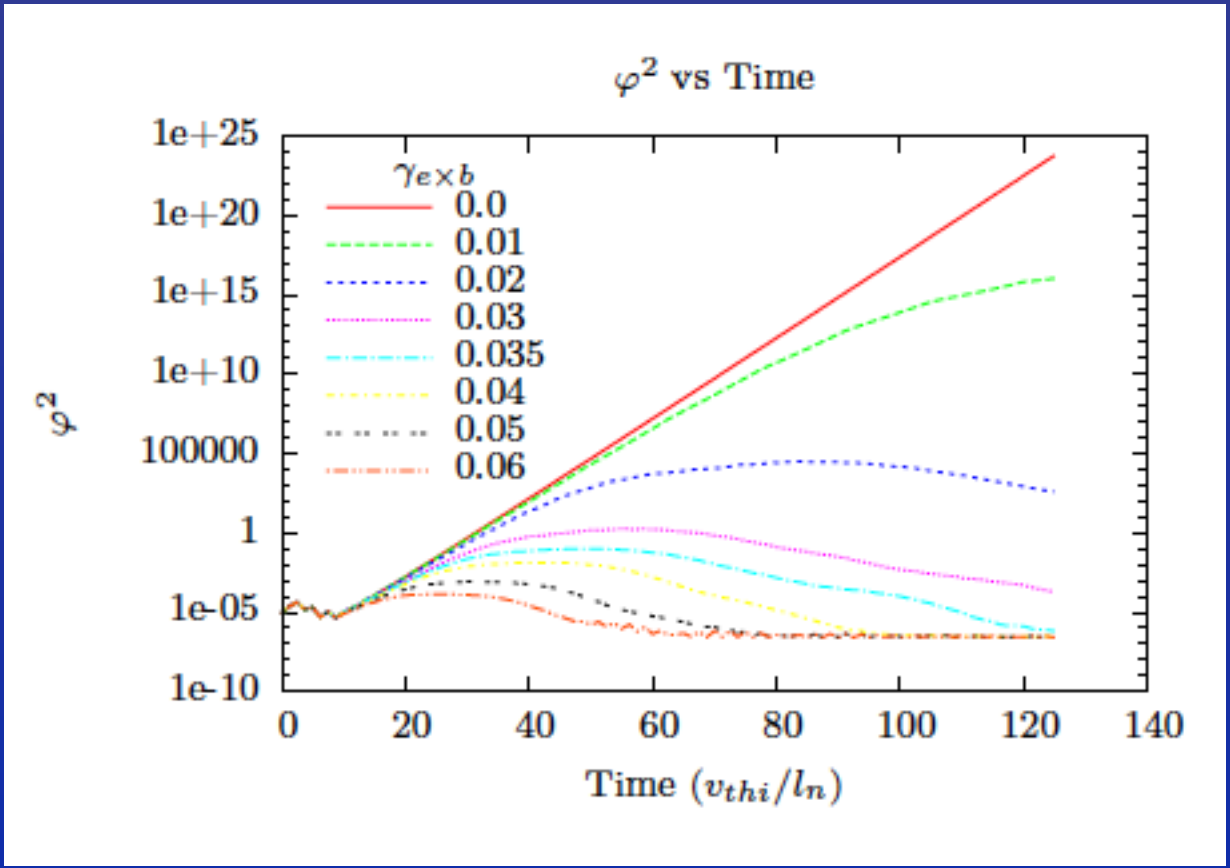
  ⇒ kinetic theory
- Low frequency (compared to Larmor frequency) limit with anisotropic fluctuations (gyrokinetics)



Simple tokamak geometry

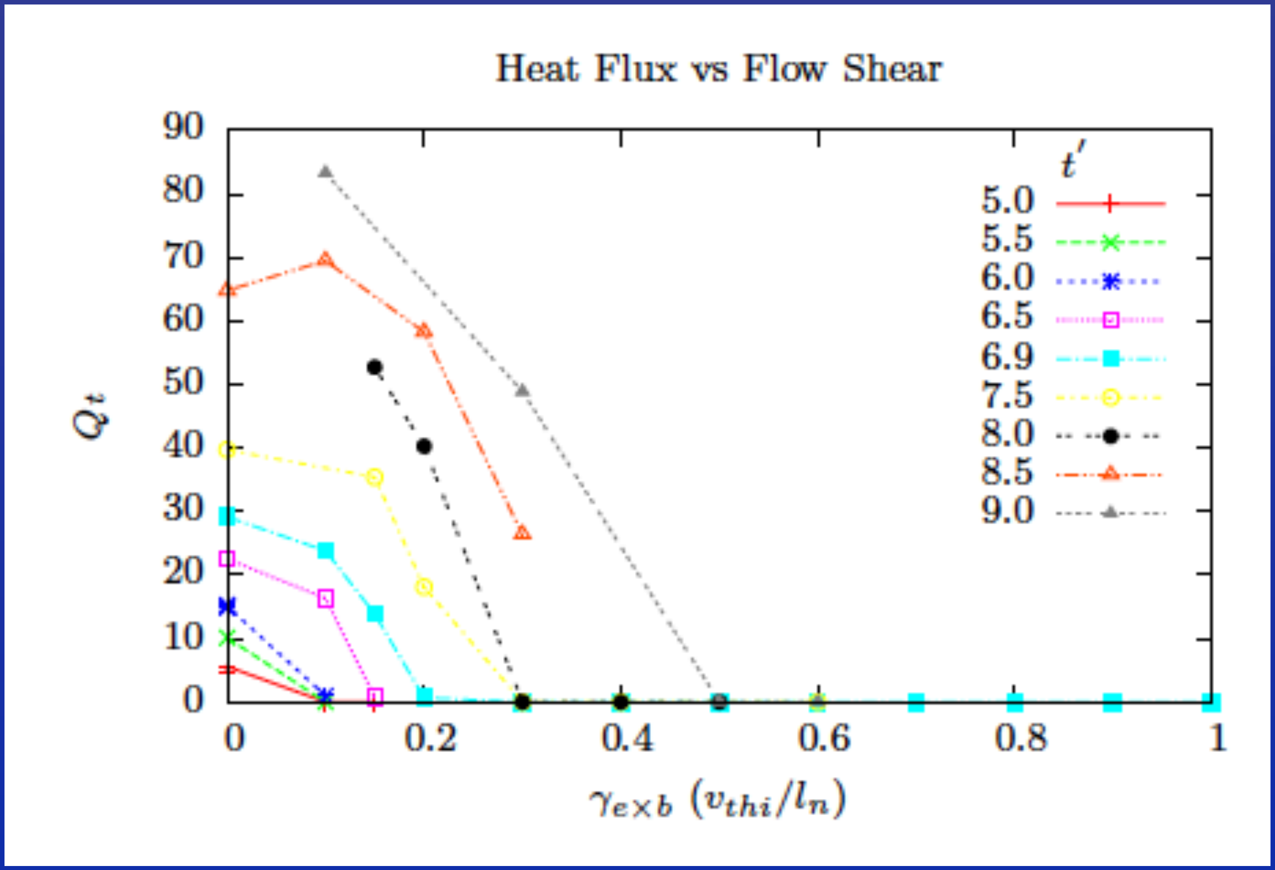
- Consider widely benchmarked tokamak plasma equilibrium with concentric, circular flux surfaces
- We simulate a specialized region of parameter space for which the pitch of the mean magnetic field is locally independent of radius (i.e. magnetic shear is zero)
- The case of zero magnetic shear is observed experimentally to be favorable for the formation of transport barriers

Linear transient growth



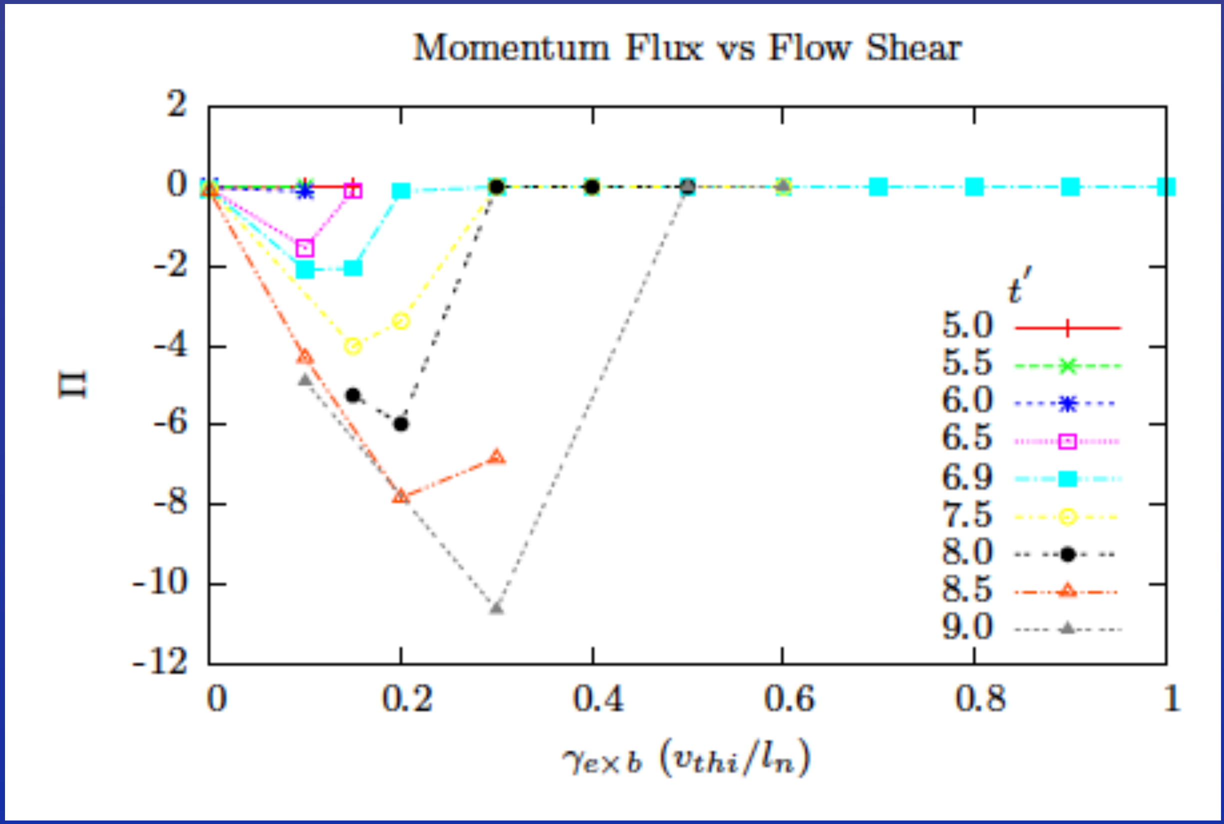
- Only transient linear instability for finite values of flow shear
- Transient growth time (and amplitude) decreases with increasing flow shear

Heat flux suppression



- Transient growth drives finite heat turbulent heat flux
- Sufficiently large flow shear suppresses heat flux for all temperature gradients

Momentum flux suppression

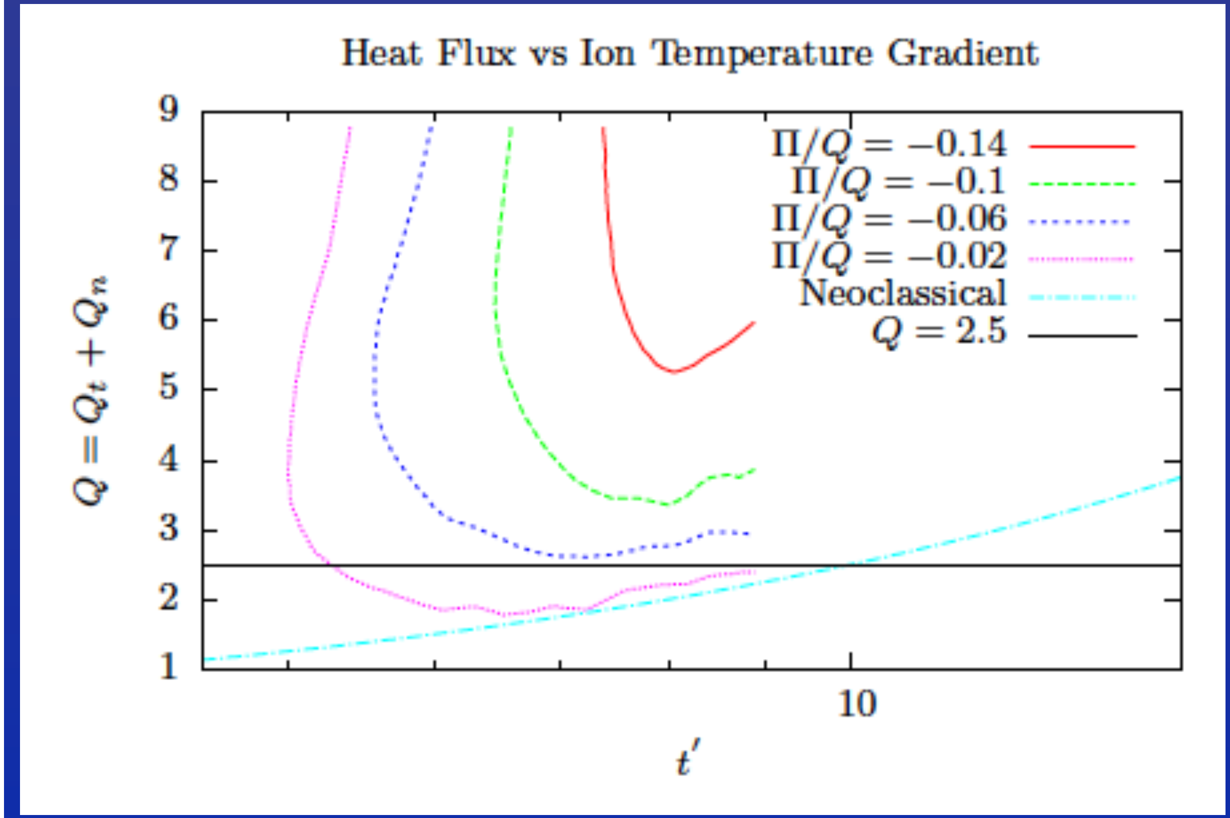


- Indicates possibility of bifurcation in flow shear and temperature gradient

Temperature gradient bifurcation

- But things are not quite so simple…
- Relevant control parameters in experiment are momentum and heat injection, which are the same as the momentum and heat fluxes in steady state
- Need to consider fixed heat and momentum fluxes
- Also need to include small collisional thermal diffusivity and viscosity (as they dominate when turbulent transport is eliminated)

Temperature gradient bifurcation



- At fixed values for heat and momentum injection, two possible solutions for temperature gradient
- Possible sudden increase in temperature gradient

Conclusions and future directions

- Mean flow shear can fully suppress turbulence in tokamak plasmas (in certain parameter regimes)
- Turbulence suppression can give rise to bifurcation in flow shear and temperature gradient
- Such bifurcations are candidates for thermal transport barriers in core of tokamak experiments
- Still a lot of work to be done in understanding underlying theory and determining parametric dependencies
- Need self-consistent treatment including back-reaction of turbulence on mean flow (evolution of mean profiles)