Fusion Reactor Technology I
(459.760, 3 Credits)

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Contents

Contents

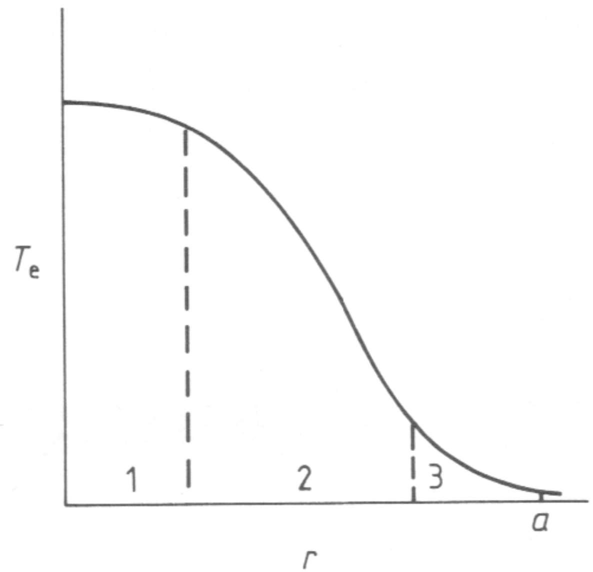
Tokamak Transport

- **Profile consistency (or profile resilience or stiffness)**

- The observation that profiles (of temperature, density, and pressure) often tend to adopt roughly the same shape (in tokamaks), regardless of the applied heating and fueling profiles. B. Coppi, "*Nonclassical Transport and the "Principle of Profile Consistency""*, Comments Plasma Phys. Cont. Fusion **5** 6 261-270 (1980)
  → tendency of profiles to stay close to marginal stability
- Due to plasma self-organisation, i.e., the feedback mechanism regulating the profiles (by turbulence) is often dominant over the various source terms.

Tokamak Transport

- **Profile consistency (or profile resilience or stiffness)**



- Three zones in which transport processes play the dominant part

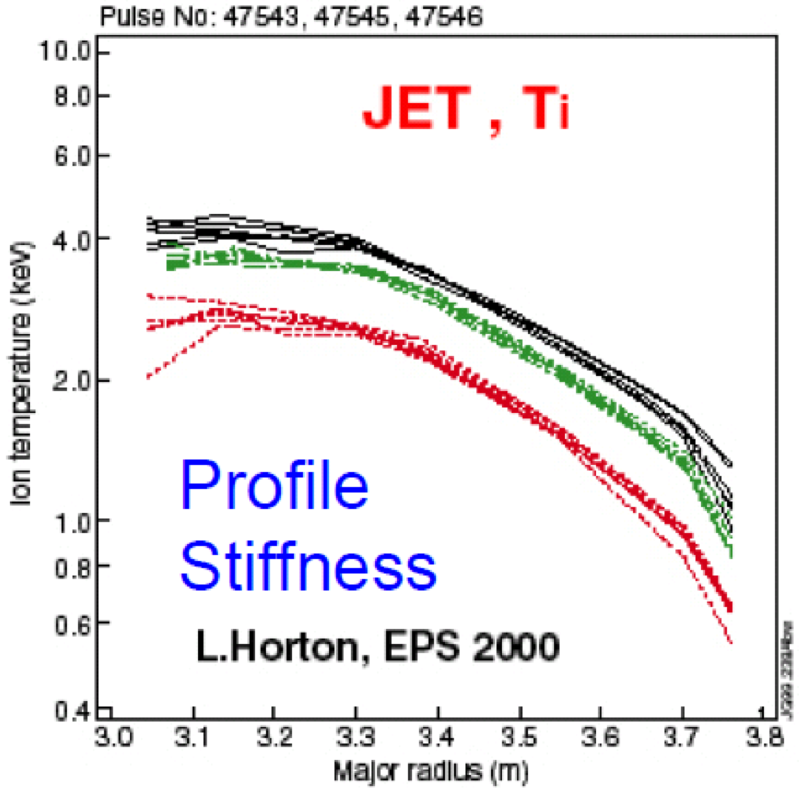
1: sawtooth oscillations - volume depending on the inversion radius which depending on q_a

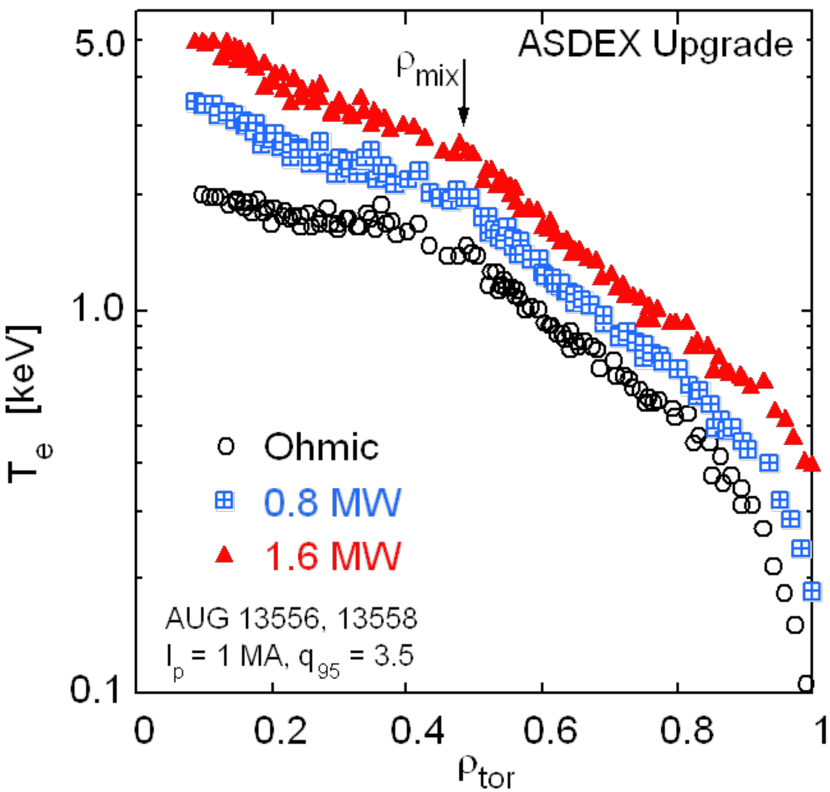
2: heat transfer - responsible for magnetic confinement

3: atomic processes

Tokamak Transport

- Profile consistency (or profile resilience or stiffness)

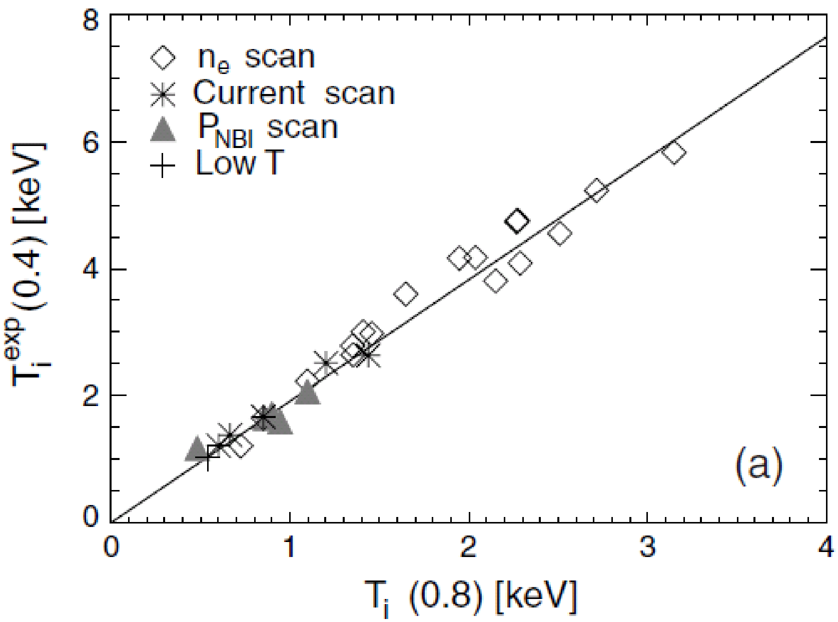




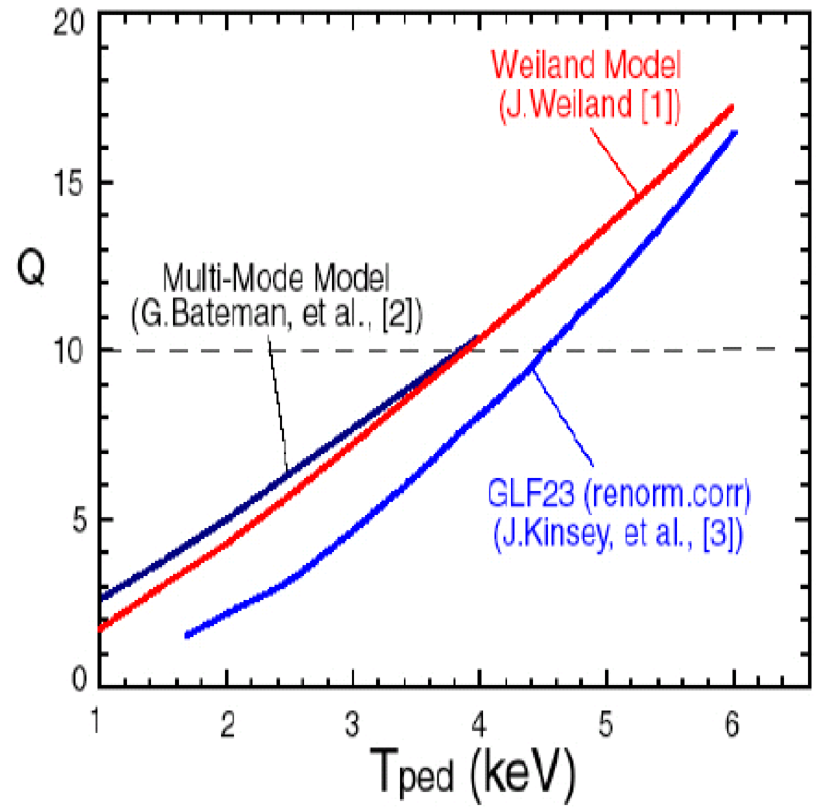
Tokamak Transport

- **Profile consistency (or profile resilience or stiffness)**

*G. Tardini et al, NF **42** 258 (2002)*

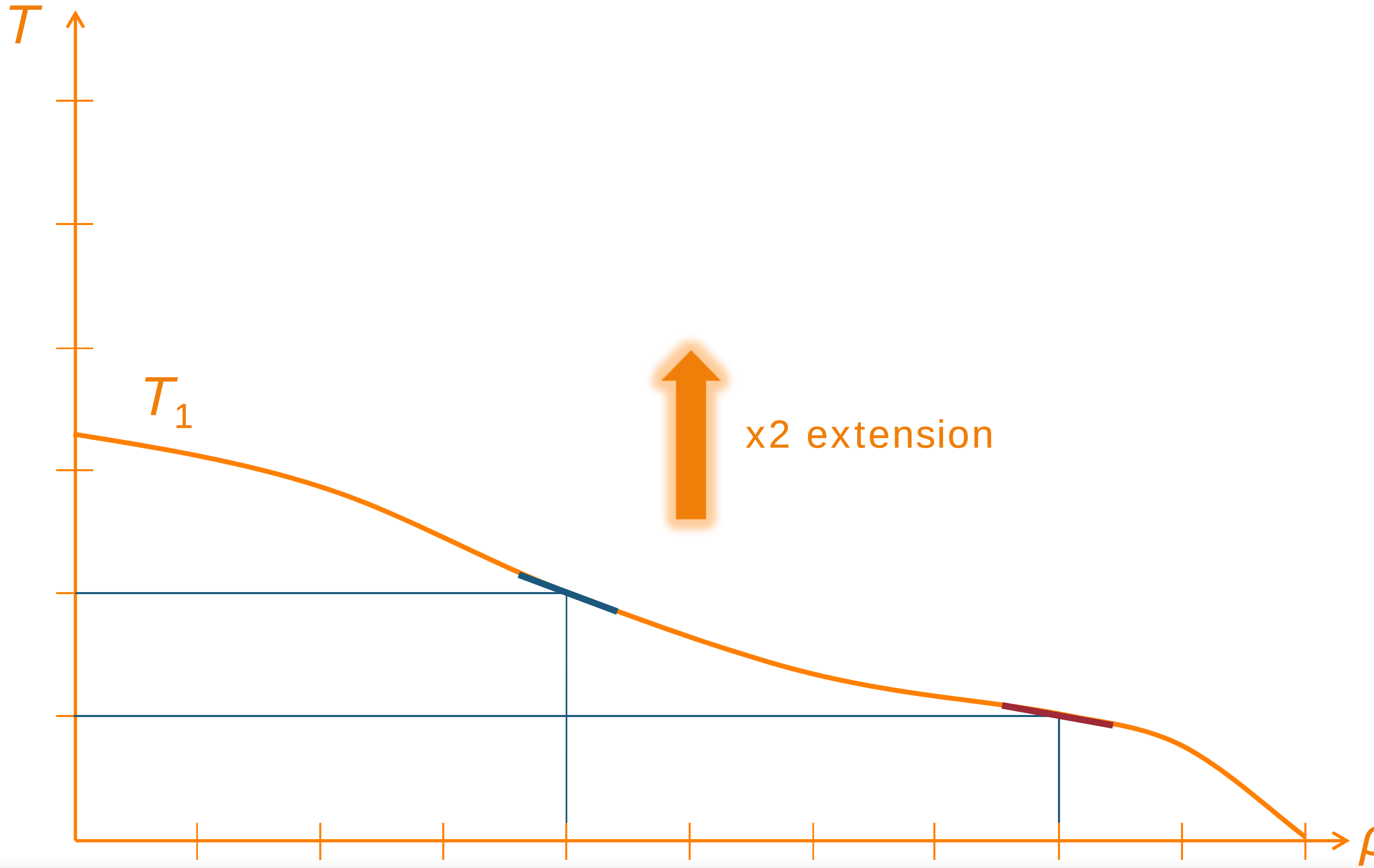


ITER: I=15MA; P_{aux}=40MW; n=0.85n_G



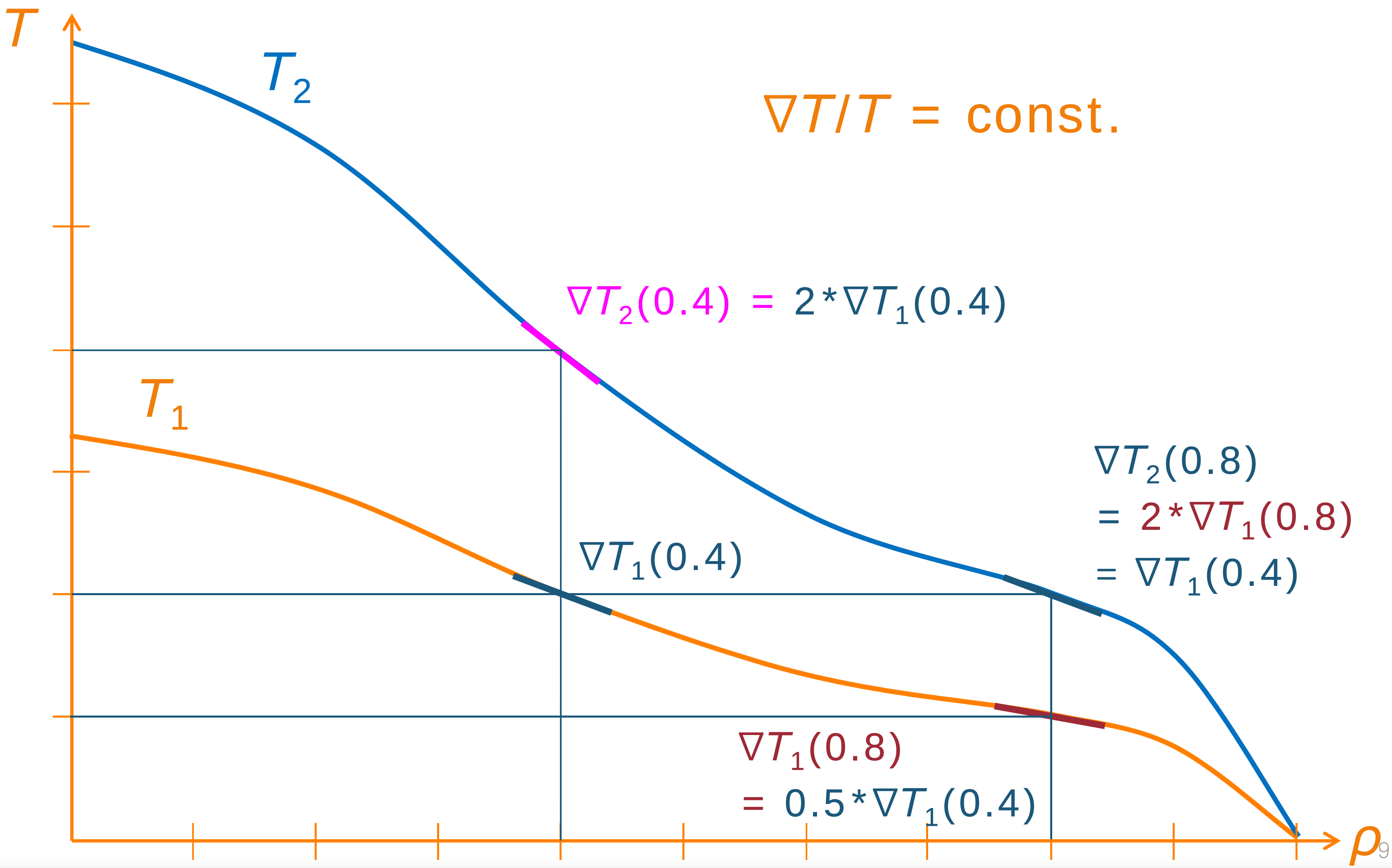
Tokamak Transport

- **Profile consistency (or profile resilience or stiffness)**



Tokamak Transport

- **Profile consistency (or profile resilience or stiffness)**



Tokamak Transport

- **Anomalous Transport - Microinstabilities**

$$D^{\exp} = D^{NC} + D^{anomalous} > D^{NC}$$

$$\chi^{\exp} = \chi^{NC} + \chi^{anomalous} > \chi^{NC}$$

- Plasma waves and their associated instabilities

Electron drift wave: ‘Universal’, trapped electron

Sound wave: Ion temperature gradient

Alfven wave: Micro-tearing

Tokamak Transport

- **Anomalous Transport - Microinstabilities**

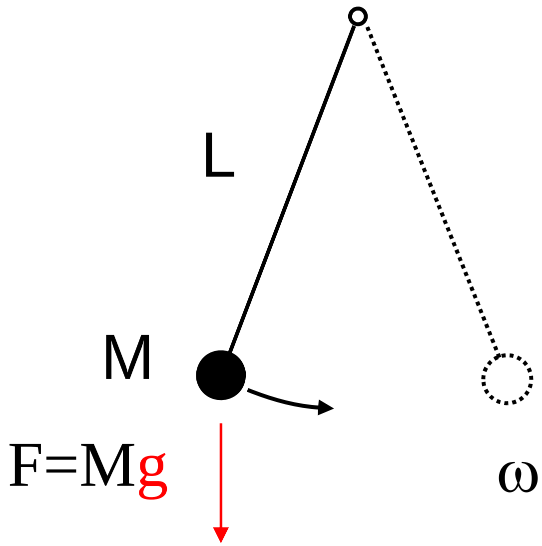
- Electrostatic instabilities: drift wave instabilities
  perturbations of the magnetic field are ignored,
  so that only the perturbed electric field matters.
  Assumption appropriate if the plasma beta is lower than the
  instability threshold for electromagnetic interchange modes
  (called ‘kinetic ballooning modes’)
    Passing particle instabilities
    Trapped particle instabilities
    Ex. Ion Temperature Gradient (ITG) modes,
        Trapped Electron Modes (TEM)
- Electromagnetic instabilities: micro-tearing modes

Tokamak Transport

- **Anomalous Transport**

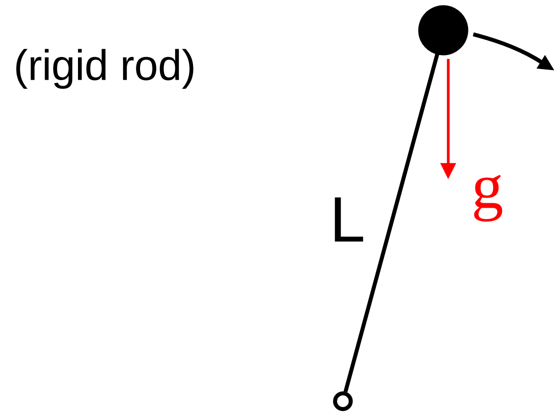
- Main instabilities are interchange modes.

Stable Pendulum



$\omega=(g/L)^{1/2}$

Unstable Inverted Pendulum

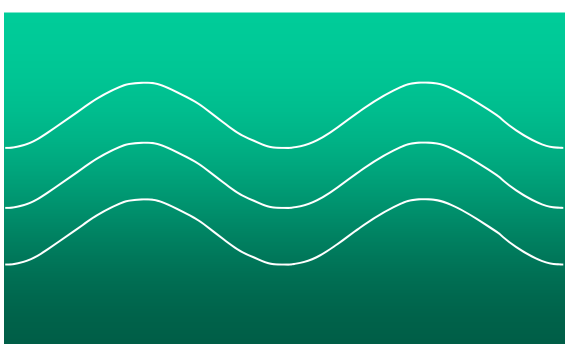


$\omega= (-g/|L|)^{1/2} = i(g/|L|)^{1/2} = i\gamma$

Instability

Density-stratified Fluid

$\rho=\exp(-y/L)$

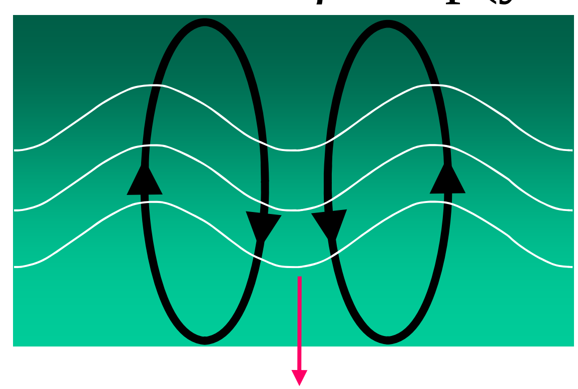


stable $\omega=(g/L)^{1/2}$

Inverted-density fluid

$\Rightarrow$Rayleigh-Taylor Instability

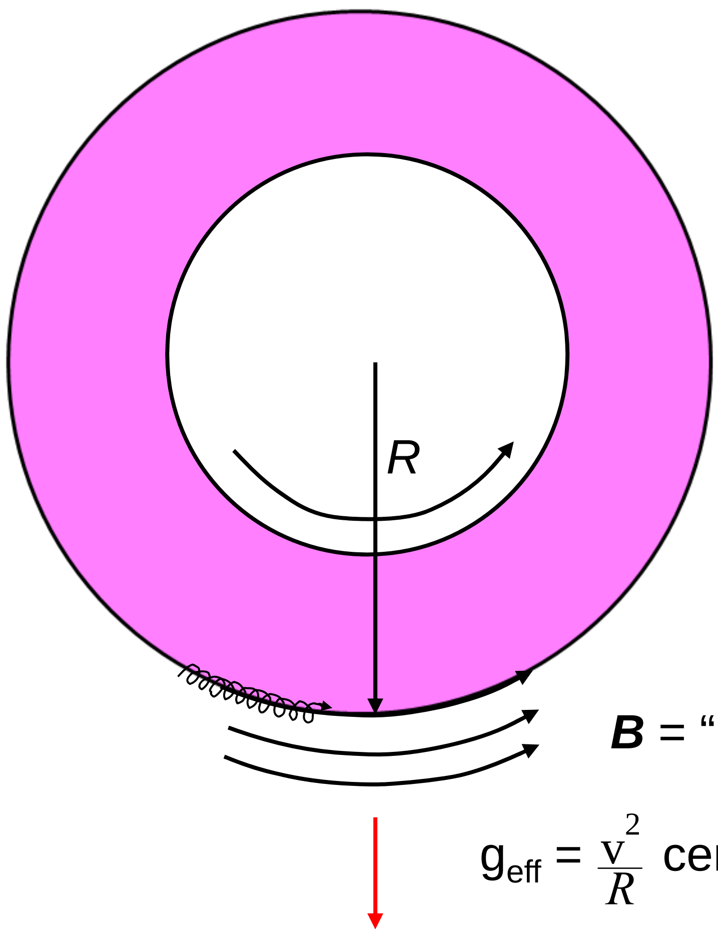
$\rho=\exp(y/L)$



Max growth rate $\gamma=(g/L)^{1/2}$

“Bad Curvature” instability in plasmas
≈ Inverted Pendulum / Rayleigh-Taylor Instability

Top view of toroidal plasma:



plasma = heavy fluid

B = “light fluid”

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

Growth rate:

$$\gamma = \sqrt{\frac{g_{eff}}{L}} = \sqrt{\frac{\mathbf{v}_t^2}{RL}} = \frac{\mathbf{v}_t}{\sqrt{RL}}$$

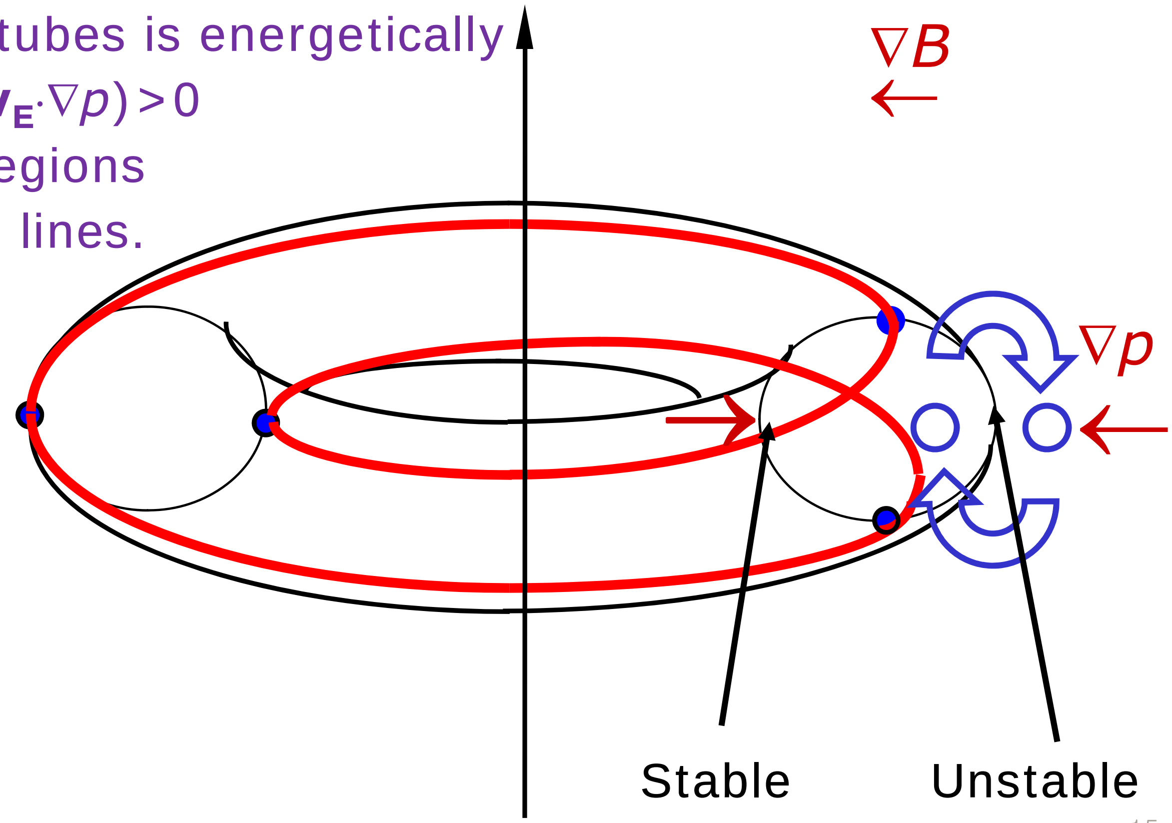
Similar instability mechanism
in MHD & drift/microinstabilities

$1/L = \nabla p/p$ in MHD,
$\propto$ combination of ∇n & ∇T
in microinstabilities.

Tokamak Transport

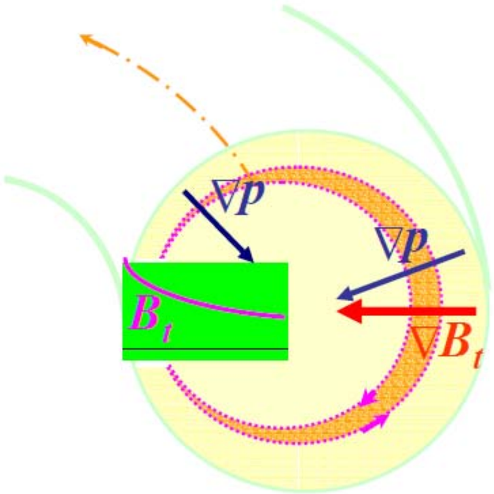
- **Anomalous Transport**

- Main instabilities are interchange modes.
- The exchange of two flux tubes around a field line releases free energy.
- Exchange of two flux tubes is energetically favourable if $(\mathbf{v}_E \cdot \nabla B)(\mathbf{v}_E \cdot \nabla p) > 0$
- Stable and unstable regions are connected by field lines.



Tokamak Transport

- **Anomalous Transport**



Unstable region: $\nabla B_t \cdot \nabla p > 0$

- Trapped particles are localised on the low field side, as this corresponds to the zone of minimum field along the field lines.
→ Trapped particles are expected to play a prominent role in the interchange process.

Tokamak Transport

- **Anomalous Transport – ITG/TEM**

- Unstable in the limit of large wavelengths: $k_\perp \rho_i < 1$
- Electron and/or ion modes are unstable above a threshold.
- Underlie particle, electron and ion heat transport: interplay between all channels

- ITG: For a given q-profile, the threshold of a pure ion mode (i.e., when the electron response follow a Bolzmann law) appears as a critical ion temperature logarithmic gradient $-R\nabla T_i/T_i$ that depends on the logarithmic density gradient $-R\nabla n_i/n_i$, and on the ratio of electron to ion temperature T_e/T_i.
  An ion mode usually rotates in the ion diamagnetic direction.
- TEM: usually rotate in the electron diamagnetic direction and are mainly driven through a resonant interaction of the modes with trapped electrons at the precession frequency.
  The threshold is a critical value of $-R\nabla T_e/T_e$ that depends on $-R\nabla n_e/n_e$ and the fraction of trapped electrons f_t.

Tokamak Transport

- **Anomalous Transport – ITG/TEM**

- Unstable in the limit of large wavelengths: $k_{\perp}\rho_i < 1$
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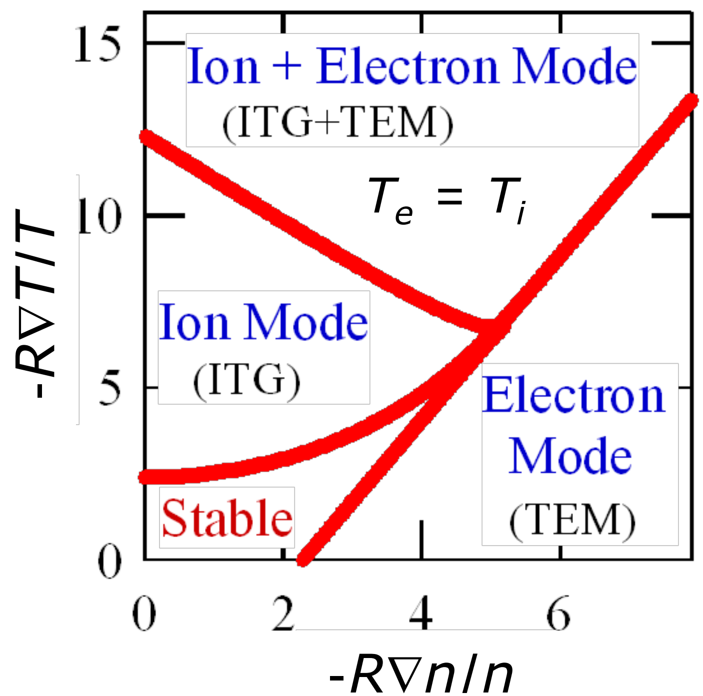


Stability diagram
(Weiland model)

Tokamak Transport

- **Anomalous Transport**

- Fluctuations of **E**x**B** drift velocity produce turbulent transport.

- **E**x**B** drift

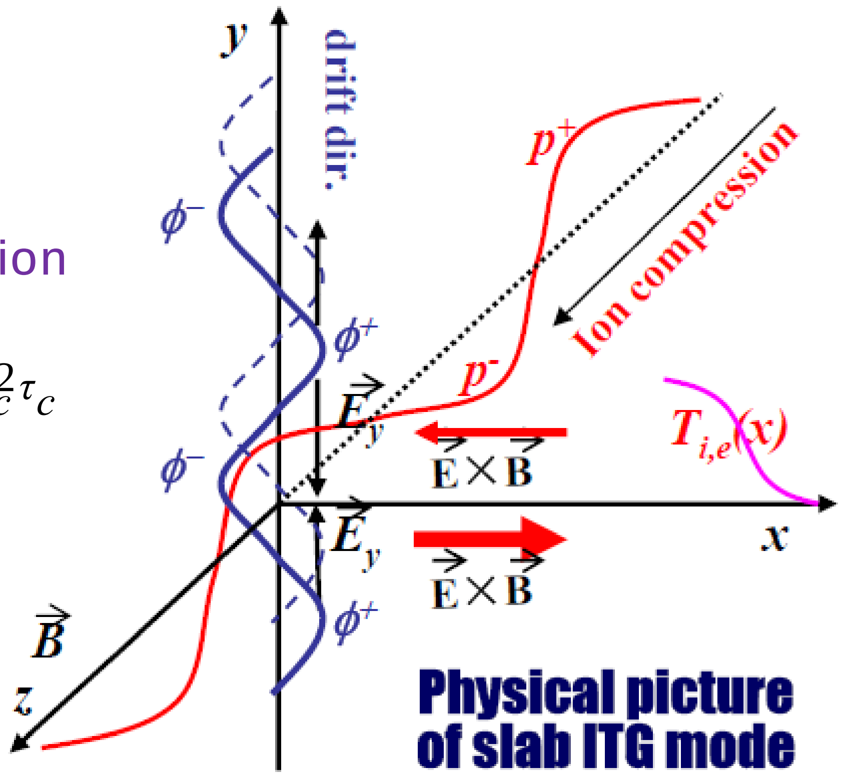
$$v_E = \frac{B \times \nabla \phi}{B^2}$$

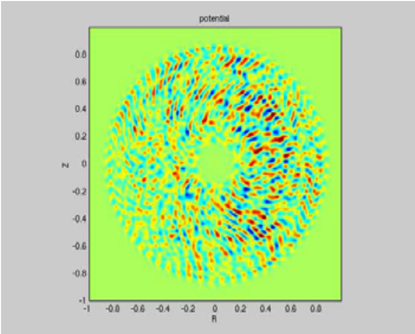
- Turbulent diffusion

$$D_{turb} \propto |v_E|^2 \tau_c \propto L_c^2 \tau_c$$

- Turbulent flux

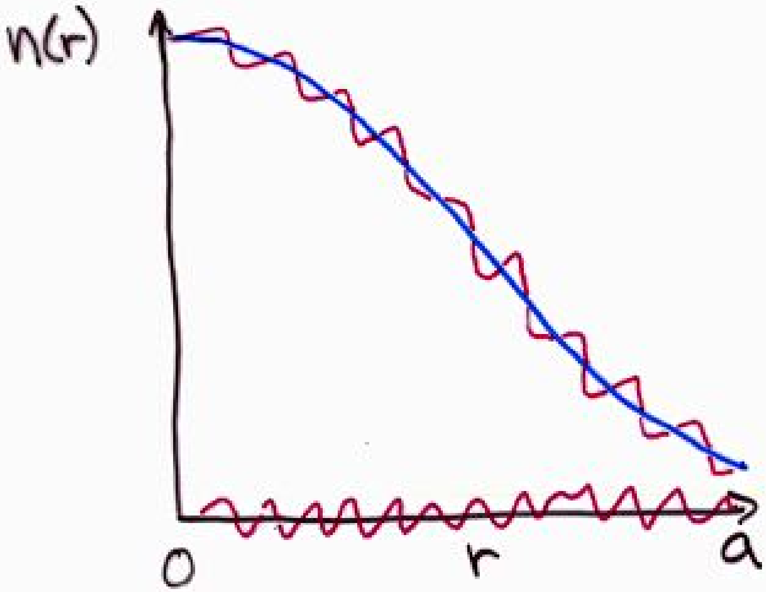
$$\phi_E = \frac{3}{2}\langle p v_E \rangle$$





Contour lines of electric potential ϕ (TRB simulation)

Microinstabilities are small-amplitude but still nonlinear



$$n = n_0(r) + \tilde{n}(\underset{\sim}{x}, t)$$

$$n_0 \gg \tilde{n}$$

$$\text{but} \quad \nabla n_0 \sim \nabla \tilde{n}$$

Can locally flatten or reverse total gradient that was driving instability.

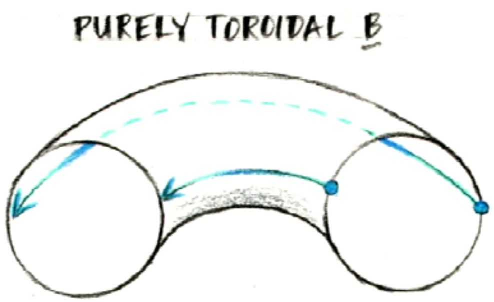
* Turbulence causes loss of plasma to the wall, but confinement still $\times 10^5$ better than without $\underset{\sim}{B}$.

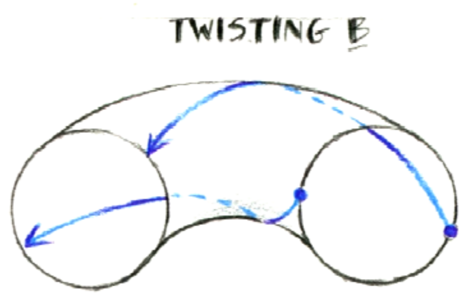
If no $\underset{\sim}{B}$, loss time $\sim \frac{a}{v_t} \sim 1\ \mu\text{sec}$

with $\underset{\sim}{B}$, expts. measure $\sim 0.1 - 1.0$ sec.

The Secret for Stabilizing Bad-Curvature Instabilities

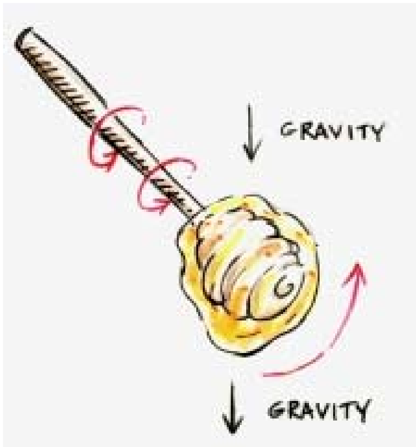
Twist in ***B*** carries plasma from bad curvature region to good curvature region:





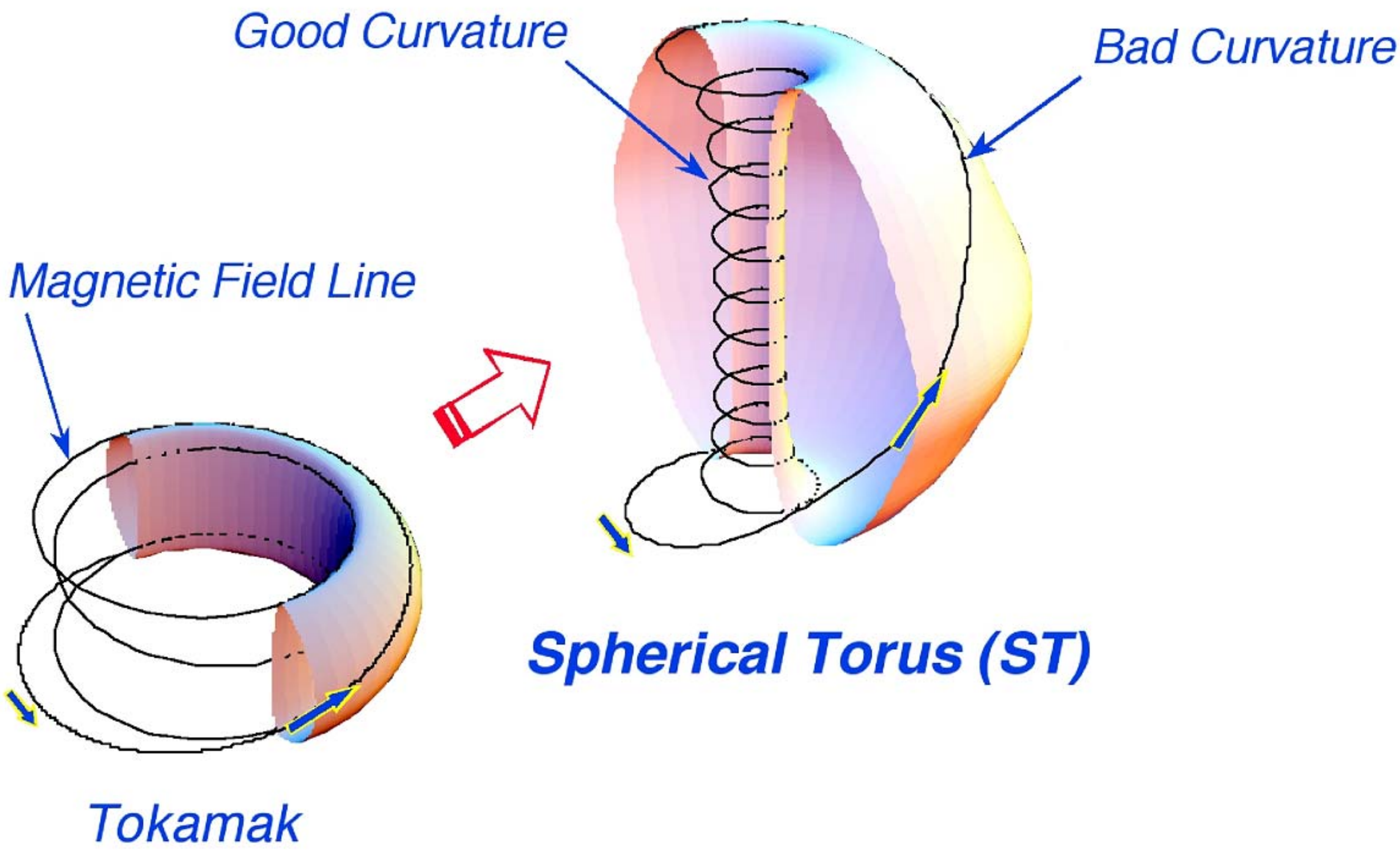
Unstable

Stable



Similar to how twirling a honey dipper can prevent honey from dripping.

Spherical Torus has improved confinement and pressure limits (but less room in center for coils)



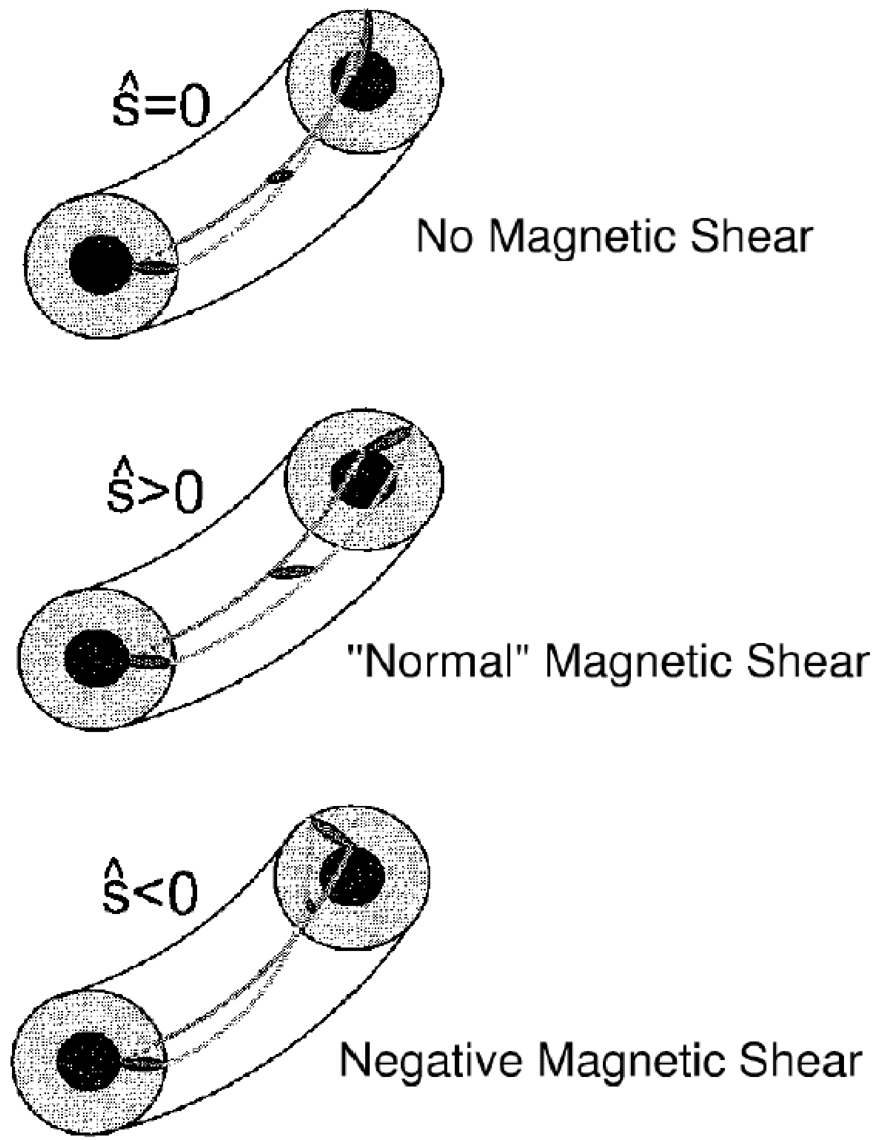
Simple picture of reducing turbulence by negative magnetic shear

Particles that produce an eddy tend to follow field lines.

Reversed magnetic shear twists eddy in a short distance to point in the ``good curvature direction".

Locally reversed magnetic shear naturally produced by squeezing magnetic fields at high plasma pressure: ``Second stability" Advanced Tokamak or Spherical Torus.

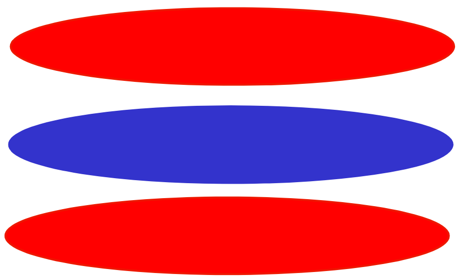
Shaping the plasma (elongation and triangularity) can also change local shear



Antonsen, Drake, Guzdar et al. Phys. Plasmas 96
Kessel, Manickam, Rewoldt, Tang Phys. Rev. Lett. 94

Sheared flows can suppress or reduce turbulence

Most Dangerous Eddies:
Transport long distances
In bad curvature direction



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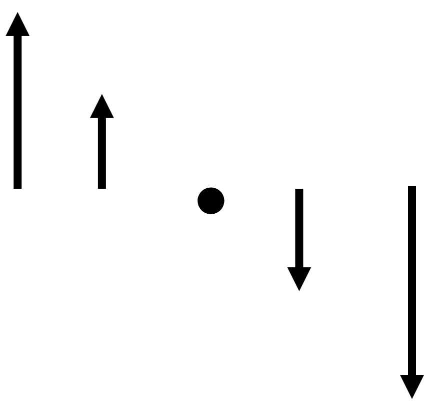
Sheared Flows



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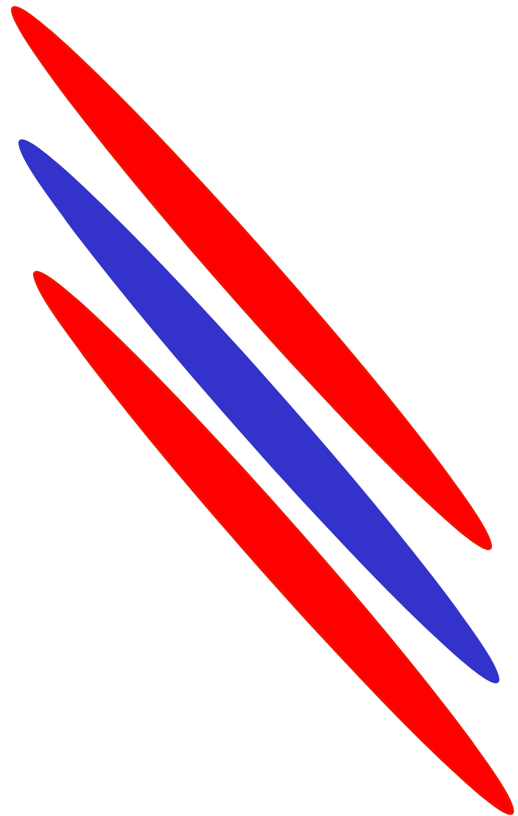
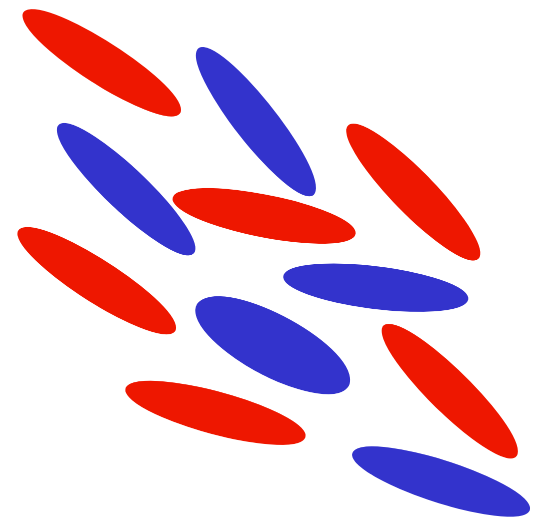
Sheared Eddies
Less effective

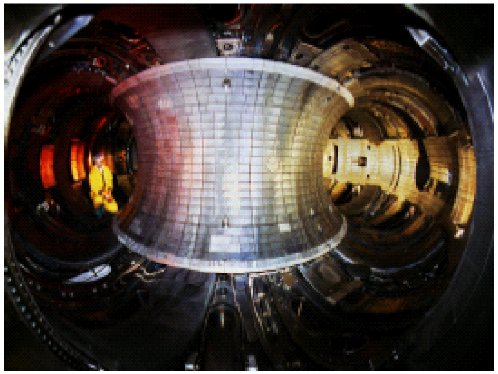


Eventually break up



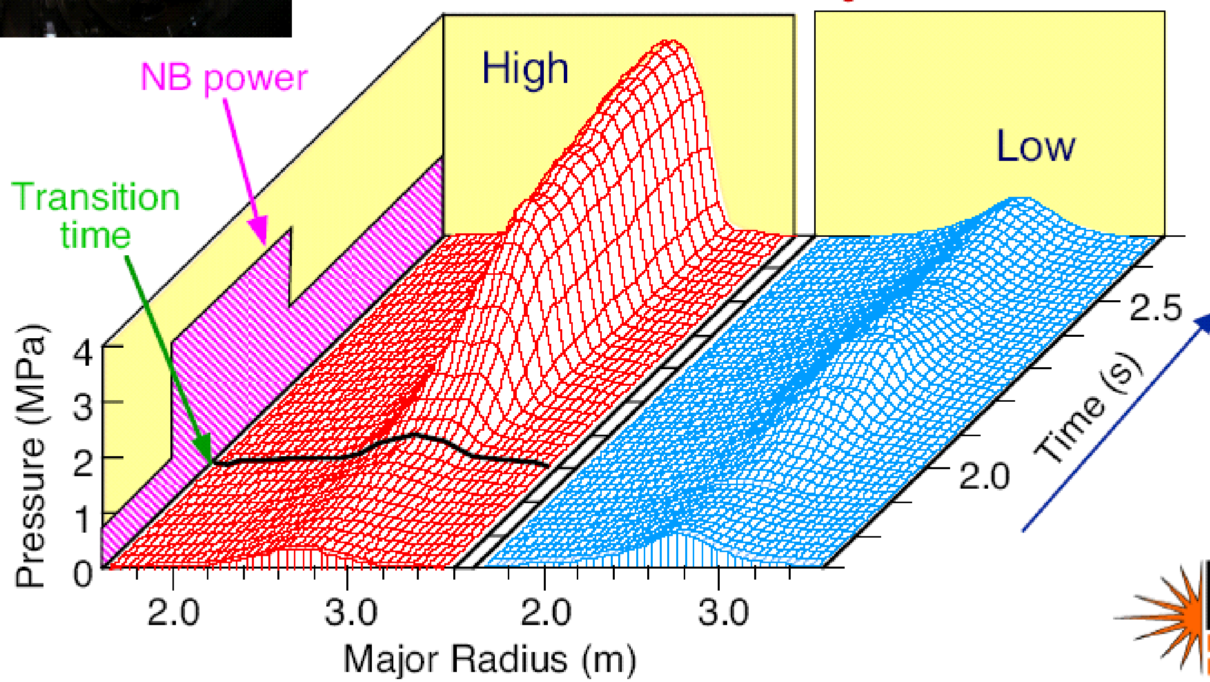
Biglari, Diamond, Terry (Phys. Fluids1990),
Carreras, Waltz, Hahm, Kolmogorov, et al.

Fascinating Diversity of Regimes in Fusion Plasmas. What Triggers Change? What Regulates Confinement?



TFTR

- Two regimes with very different confinement for similar initial conditions and neutral beam heating
- Access depends on plasma heating and reducing current density on axis
- Can we attribute a difference in turbulence to these two different confinement regimes?



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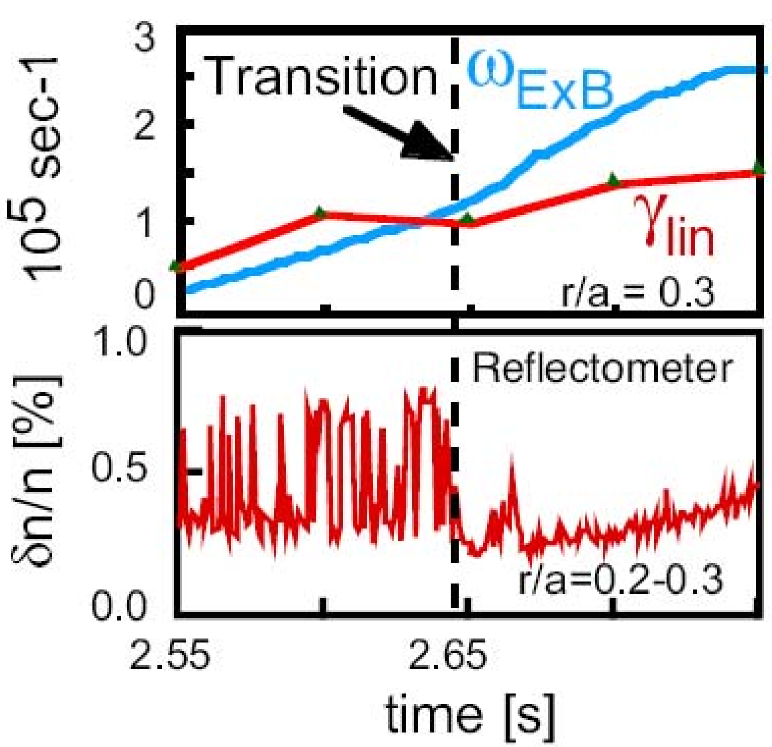
PRINCETON PLASMA PHYSICS LABORATORY

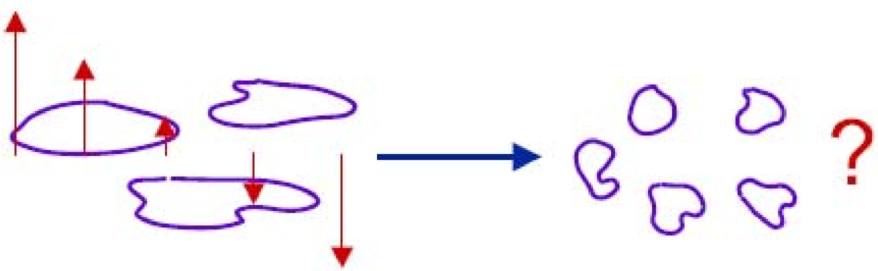
R. Nazikian et al.

Transition to Enhanced Confinement Regime is Correlated with Suppression of Core Fluctuations in TFTR



- Theory predicts fluctuation suppression when rate of shearing (ω_{ExB}) exceeds rate of growth (γ_{lin})

- Outstanding issue:
  Is suppression accompanied by radial decorrelation?



- Similar suppression observed on JET (X-mode reflectometer) and DIII-D (FIR Scattering)

Hahm, Burrell, Phys. Plas. 1995, E. Mazzucato et al., PRL 1996.

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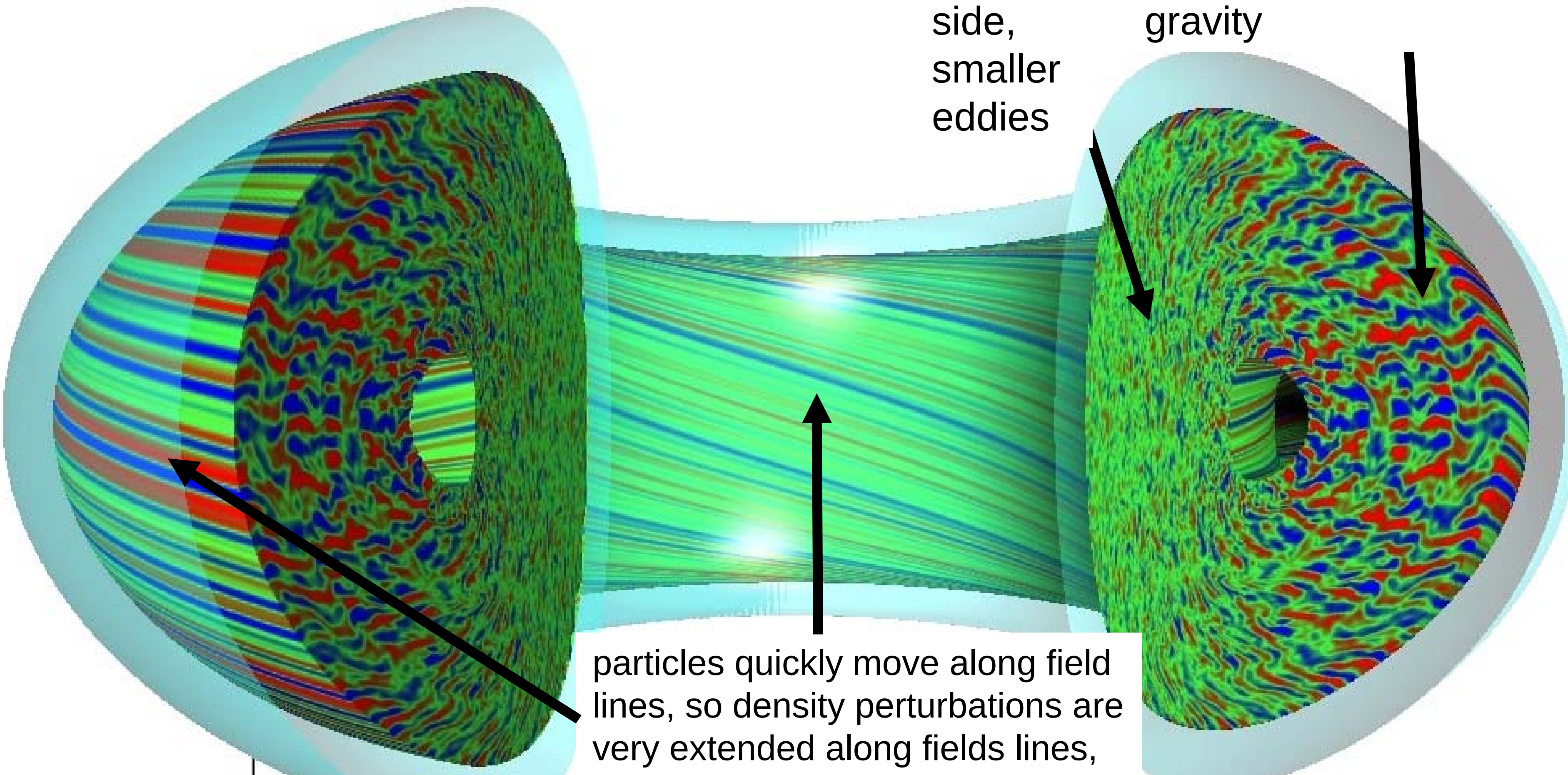
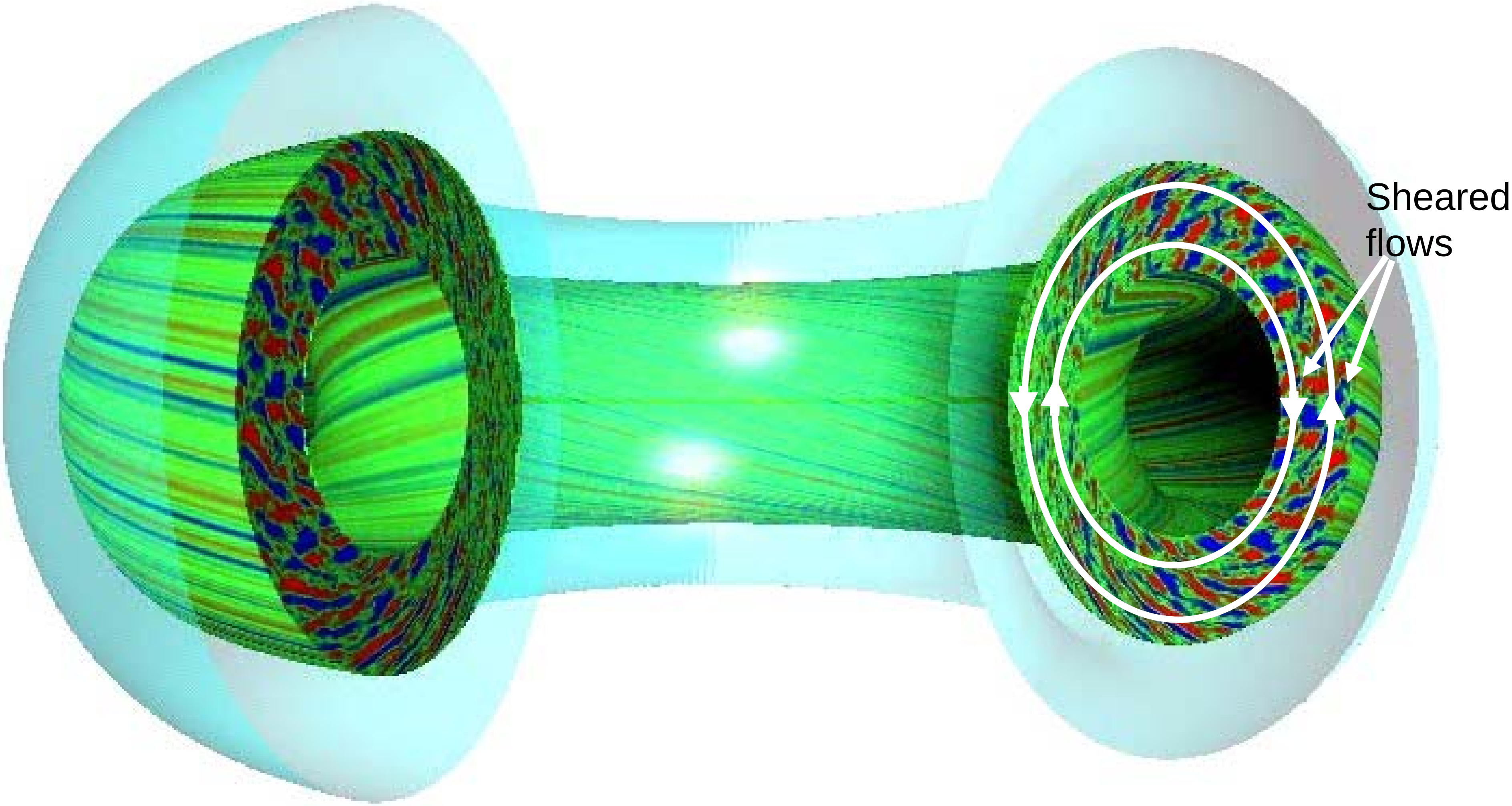
R. Nazikian et al.

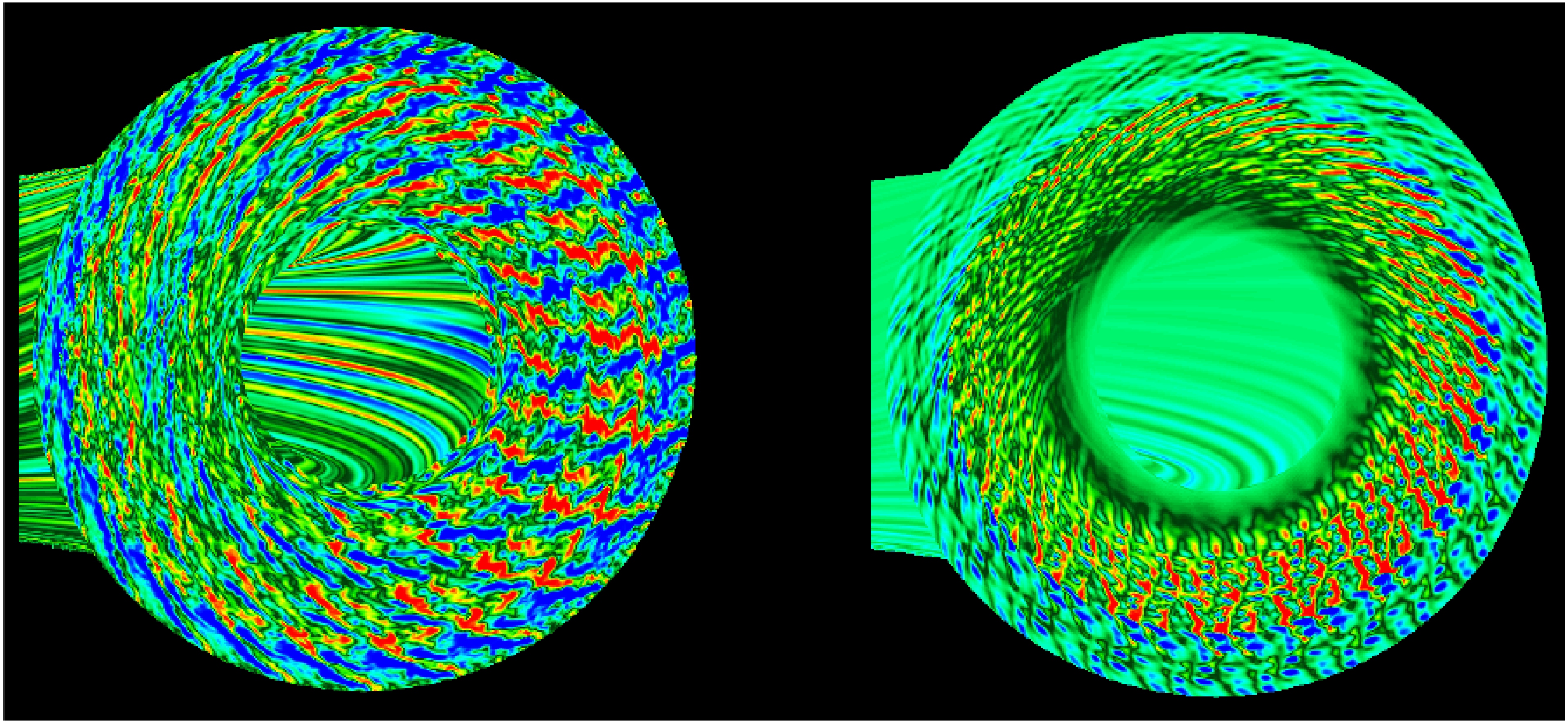
These physical mechanisms can be seen in gyrokinetic simulations and movies



Movie http://fusion.gat.com/THEORY/images/3/35/D3d.n16.2x_0.6_fly.mpg from http://fusion.gat.com/theory/Gyromovies shows contour plots of density fluctuations in a cut-away view of a GYRO simulation (Candy & Waltz, GA). This movie illustrates the physical mechanisms described in the last few slides. It also illustrates the important effect of sheared flows in breaking up and limiting the turbulent eddies. Long-wavelength equilibrium sheared flows in this case are driven primarily by external toroidal beam injection. (The movie is made in the frame of reference rotating with the plasma in the middle of the simulation. Barber pole effect makes the dominantly-toroidal rotation appear poloidal..) Short-wavelength, turbulent-driven flows also play important role in nonlinear saturation.



Sheared ExB Flows can regulate or completely suppress turbulence (analogous to twisting honey on a fork)



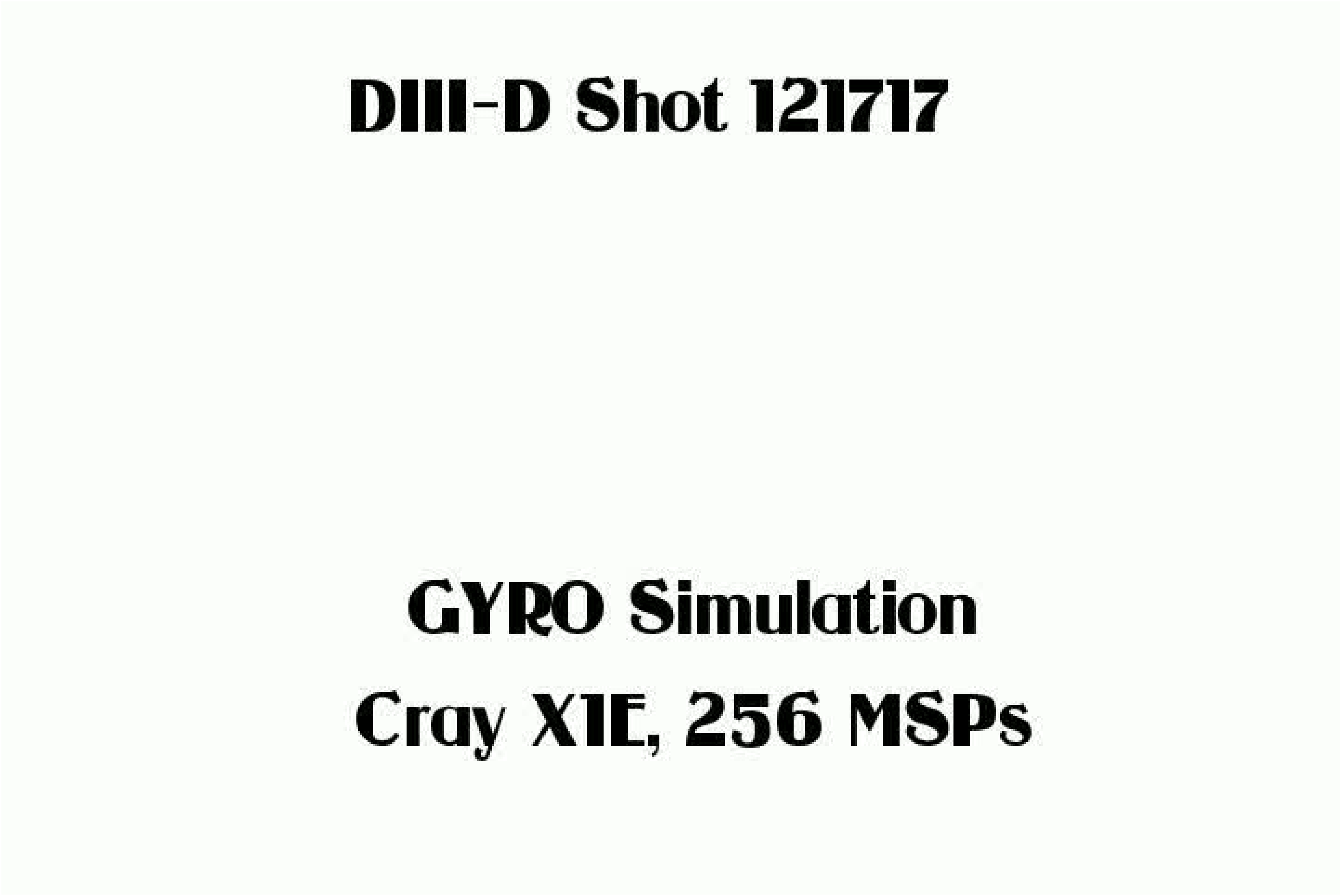
Dominant nonlinear interaction between turbulent eddies and $\pm\theta$-directed zonal flows.

Additional large scale sheared zonal flow (driven by beams, neoclassical) can completely suppress turbulence

Waltz, Kerbel, Phys. Plasmas 1994 w/ Hammett, Beer, Dorland, Waltz Gyrofluid Eqs., Numerical Tokamak Project, DoE Computational Grand Challenge

Tokamak Transport

- **Anomalous Transport**



- Ion density fluctuations in the DIII-D tokamak for discharge 121717

Tokamak Transport

- **Anomalous Transport**

Code: **GYRO**

Authors: Jeff Candy and Ron Waltz

- Evolution of potential fluctuations in a plasma very similar to DIII-D 101381/101391. Simulation is centered at $r/a = 0.6$. Note the strong equilibrium sheared rotation, which leads to a strong reduction in transport. This landmark simulation from 2002 includes kinetic electrons at finite-beta, along with the equilibrium **E**x**B** variation.

Tokamak Transport

- **Anomalous Transport**

- Transport modelling e.g. Weiland, GLF23
- Simplified version is a critical gradient model

$$\chi \approx \gamma_{lin} L_c^2$$

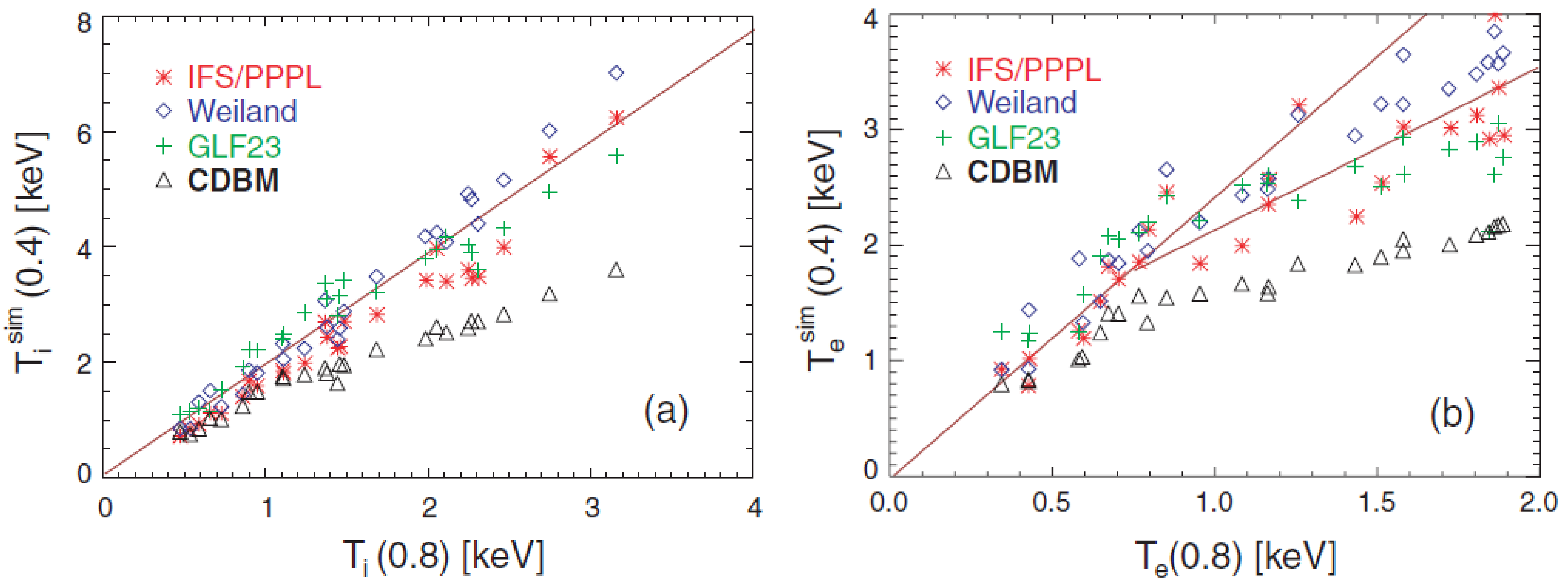
$$\gamma_{lin} = \underbrace{\chi_s}_{\text{Stiffness number}} \frac{c_s}{R} \left(\frac{-R\partial_r T}{T} - \kappa_c \right)$$

$$L_c \propto \rho_c$$

Tokamak Transport

- **Anomalous Transport**

G. Tardini et al, NF ***42*** *258 (2002)*



References

- *X. Garbet, "Physics of Transport in Tokamaks", EPS (2004)*
- *Greg Hammett (PPPL), "Status of Research on Fusion Energy and Plasma Turbulence", University of Ottawa, Physics Dept. Seminar (Nov. 29, 2007)*
- *https://fusion.gat.com/theory/Gyromovies*