Fusion Reactor Technology I

(459.760, 3 Credits)

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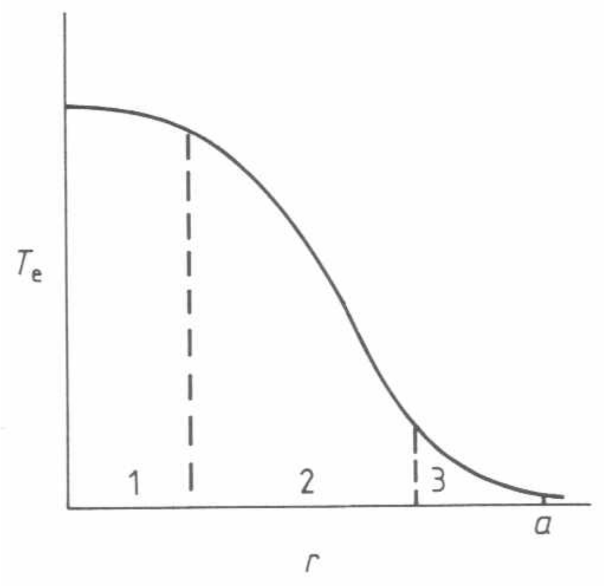
Tokamak Transport

- **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

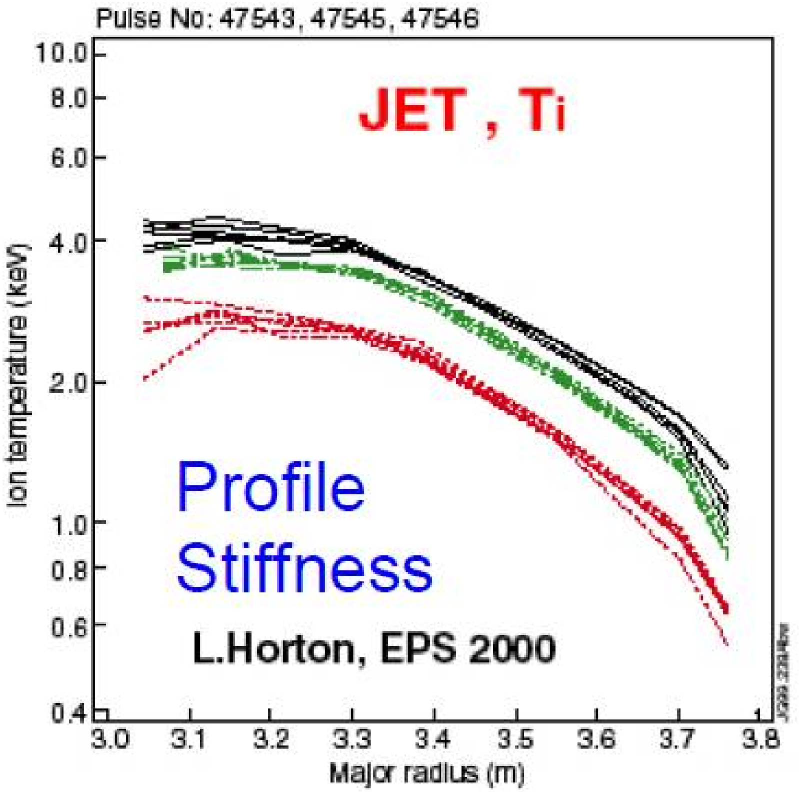
1: sawtooth oscillations - volume depending on the inversion radius which depending on q_a

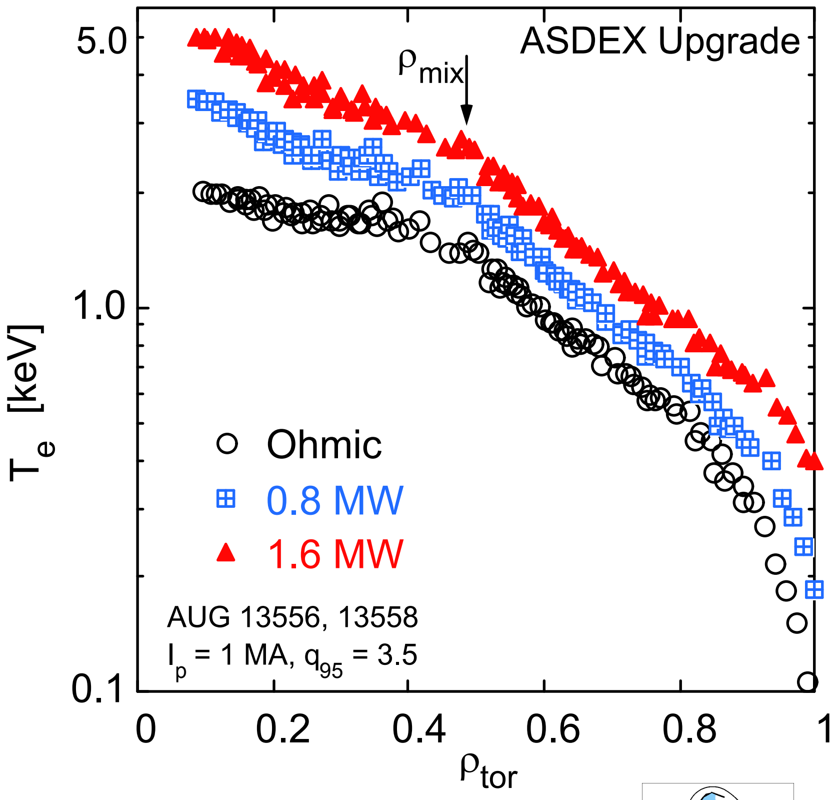
2: heat transfer - responsible for magnetic confinement

3: atomic processes

Tokamak Transport

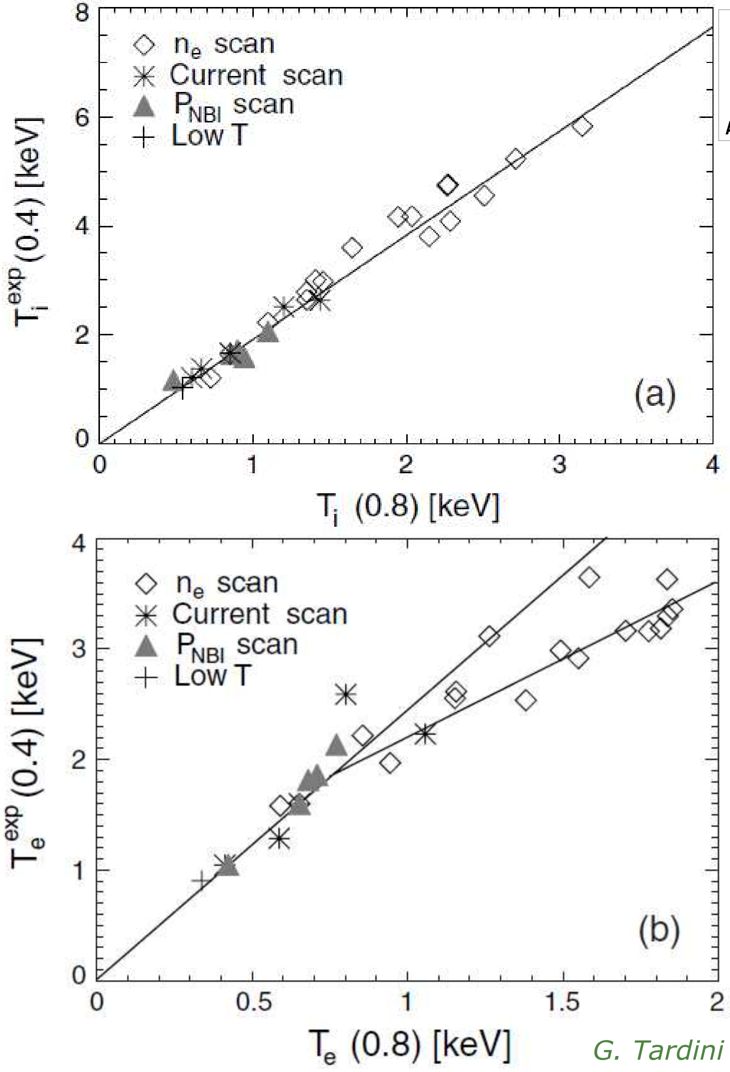
- **Profile consistency (or profile resilience or stiffness)**

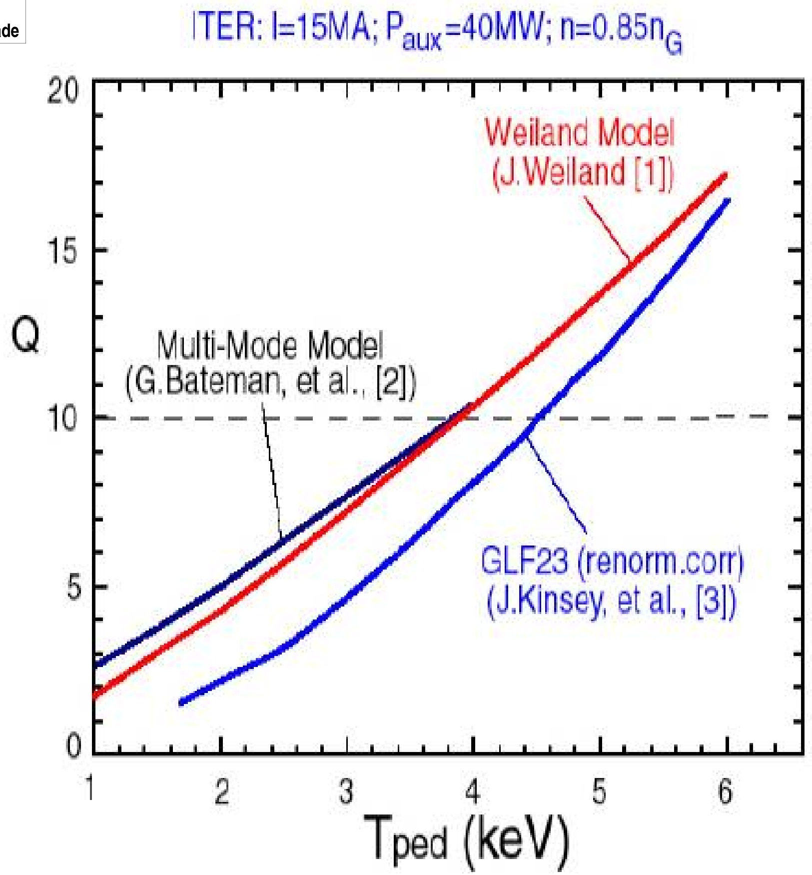




Tokamak Transport

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

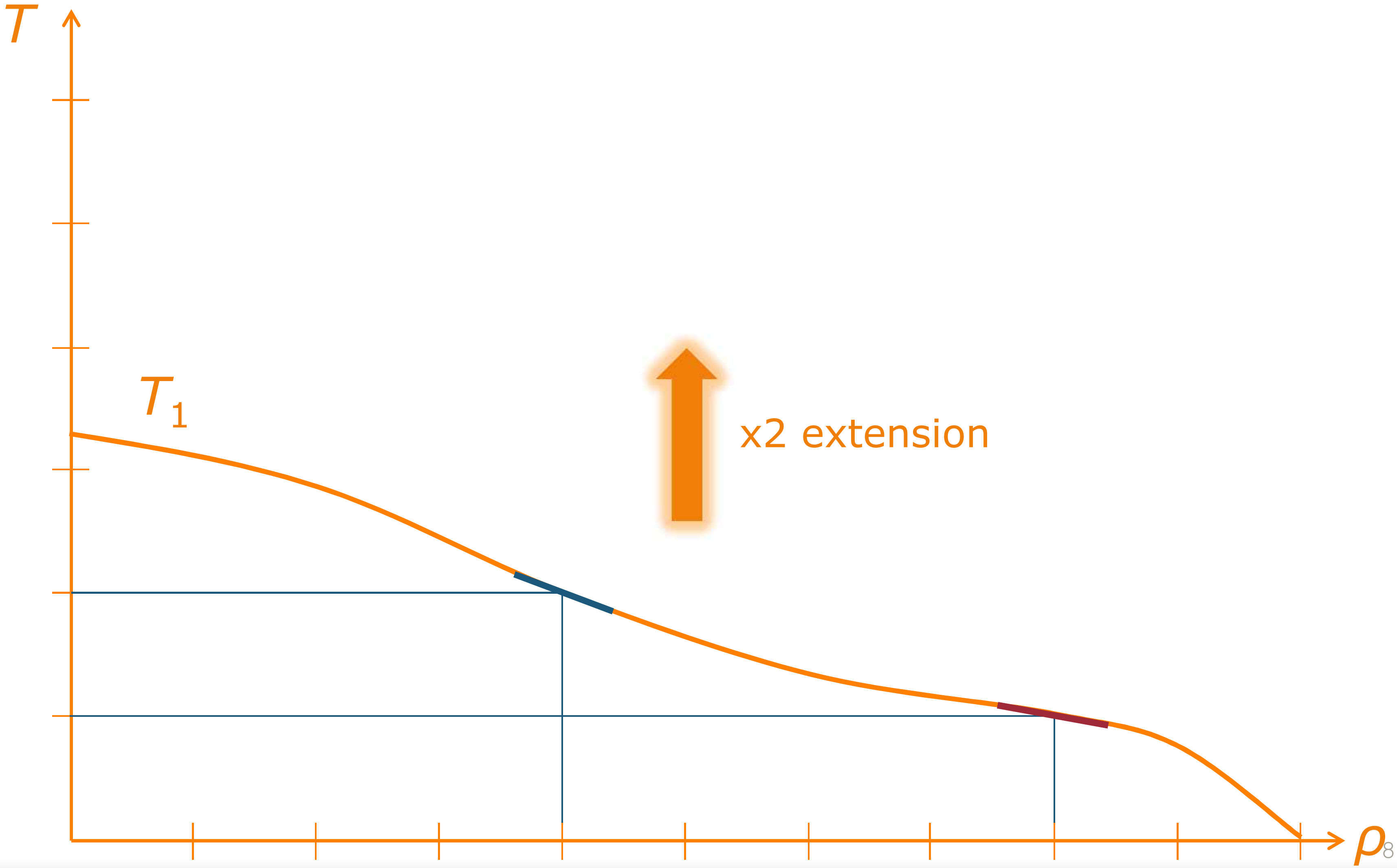




*G. Tardini et al, NF **42** 258 (2002)*

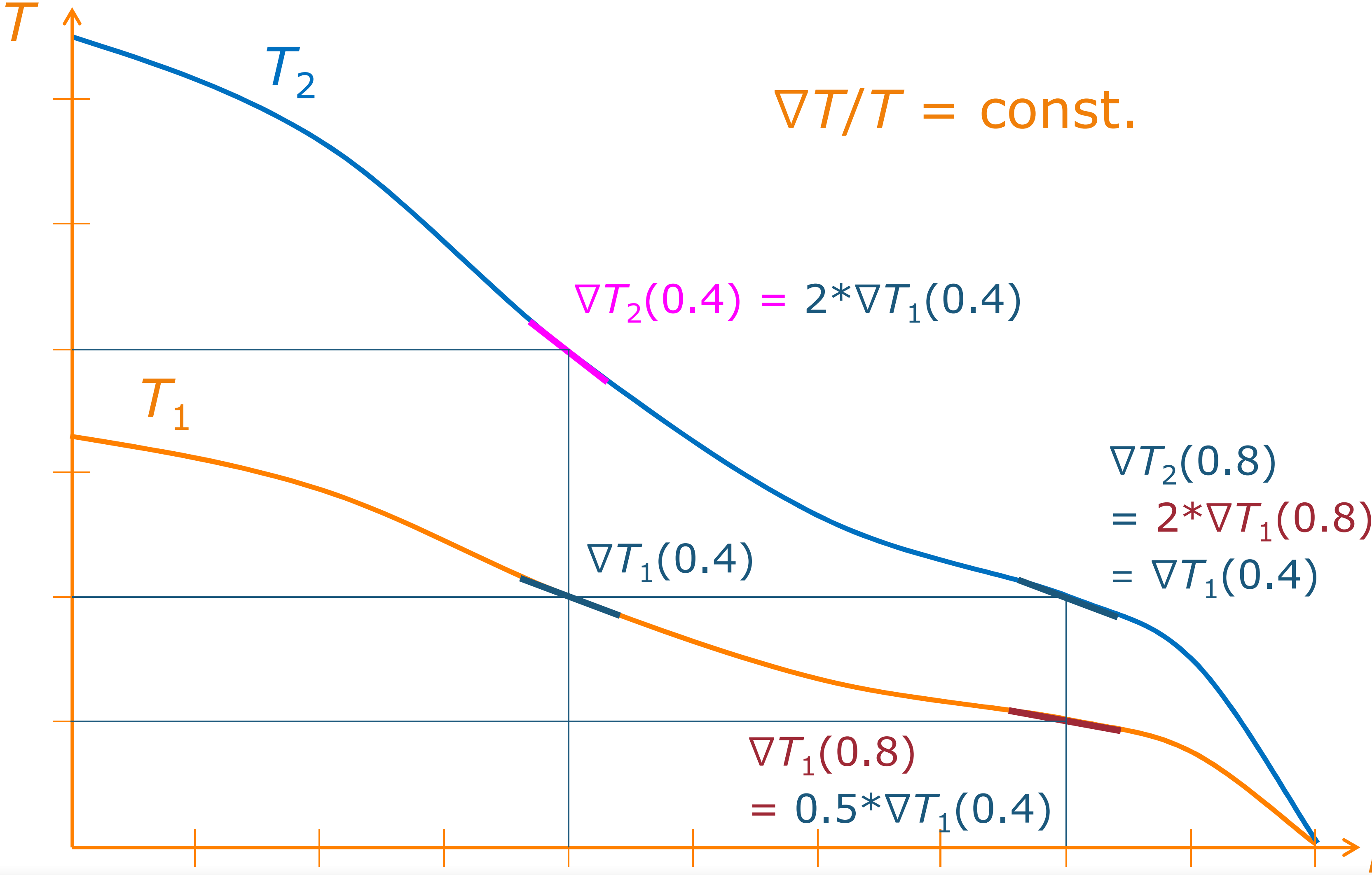
Tokamak Transport

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



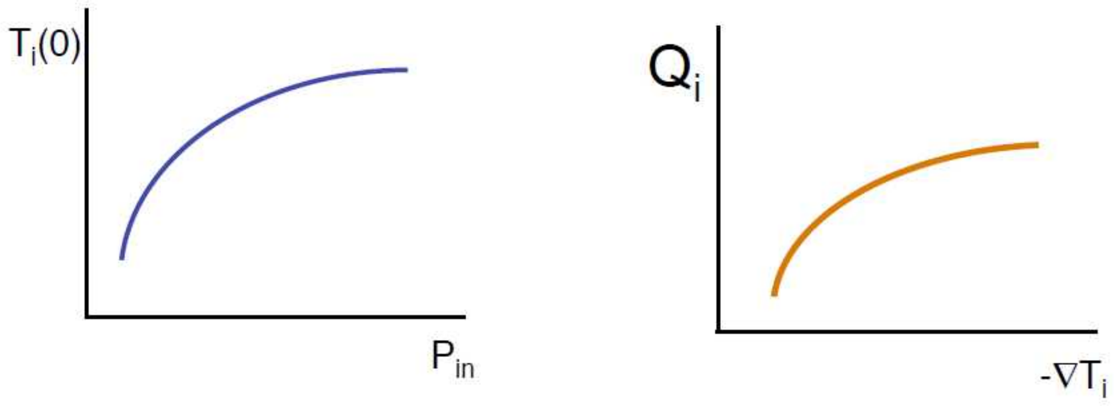
Tokamak Transport

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



Tokamak Transport

- **Flux-Gradient Relation**



Generalization of Fick's Law:

$$\begin{pmatrix} Q_i \\ Q_e \\ \Gamma \\ \Gamma_\phi \end{pmatrix} = -\begin{bmatrix} \chi_i & \cdots & \cdots & \cdots \\ \cdots & \chi_e & \cdots & \cdots \\ \cdots & \cdots & D & \cdots \\ \cdots & \cdots & \cdots & \chi_\phi \end{bmatrix} \begin{pmatrix} \nabla T_i \\ \nabla T_e \\ \nabla n \\ \nabla U_\phi \end{pmatrix}$$

Tokamak Transport

Ch. P. Ritz et al, PRL ***62*** *1844 (1989)*
X. Garbet, C.R. Physique ***7*** *573 (2006)*

- **Transport dominated by turbulence**

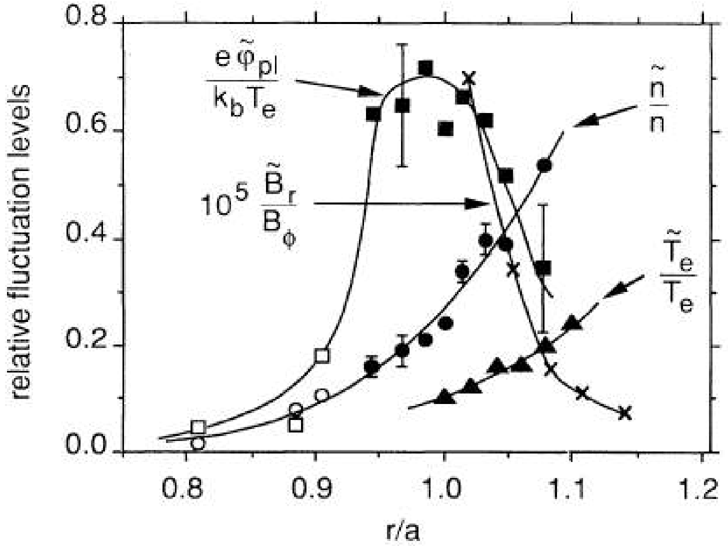


FIG. 1. Relative fluxuation levels of density $\tilde{n}/n$, plasma potential $e\tilde{\varphi}_{\mathrm{pl}}/k_B T_e$, electron temperature $\tilde{T}_e/T_e$, and magnetic field $\tilde{B}_r/B_\phi$, as functions of radius. Filled symbols represent data from Langmuir probes, and open symbols from the HIBP.

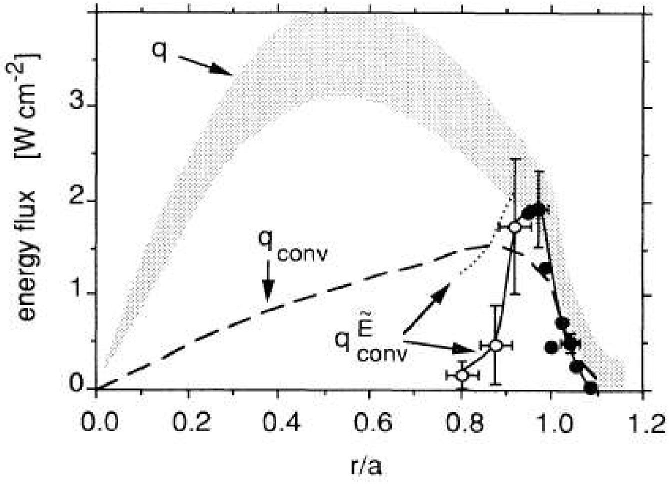


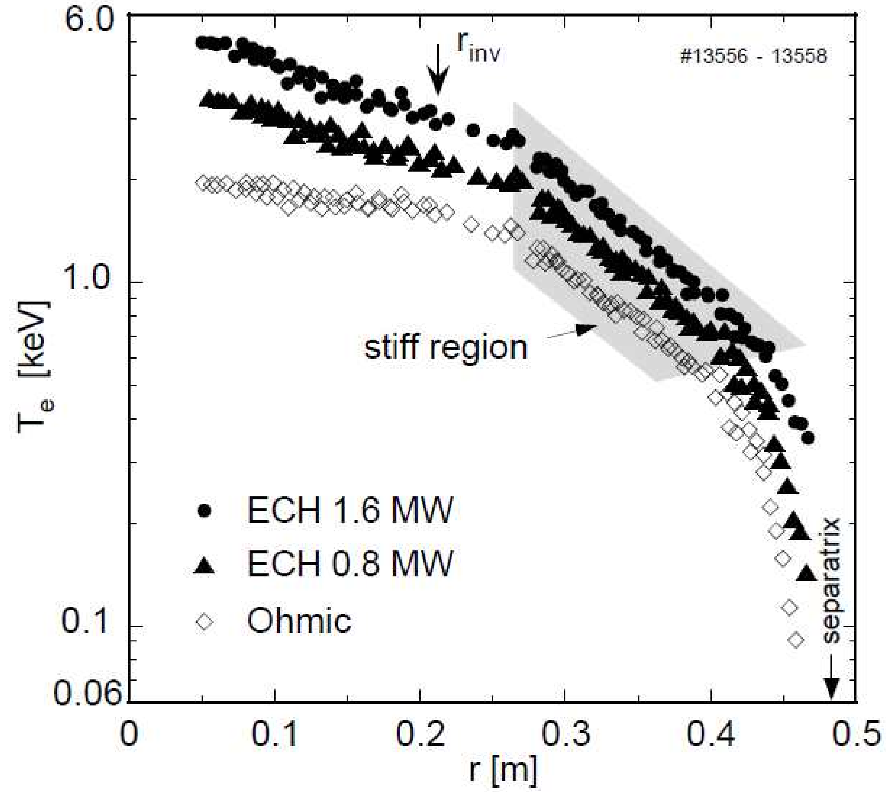
FIG. 2. Radial profiles of the total electron and ion energy flux $q = q_e + q_i$ from power balance (shaded area, defined by the standard deviation), the fluctuation-induced convected flux $q^{\tilde{E}}_{\mathrm{conv}}$ (filled circles from Langmuir probes, and open circles from HIBP; dotted line is upper bound in presence of η_i mode), and the total convected energy flux $q_{\mathrm{conv}}(r)$ from a neutral-penetration code and H_α measurements.

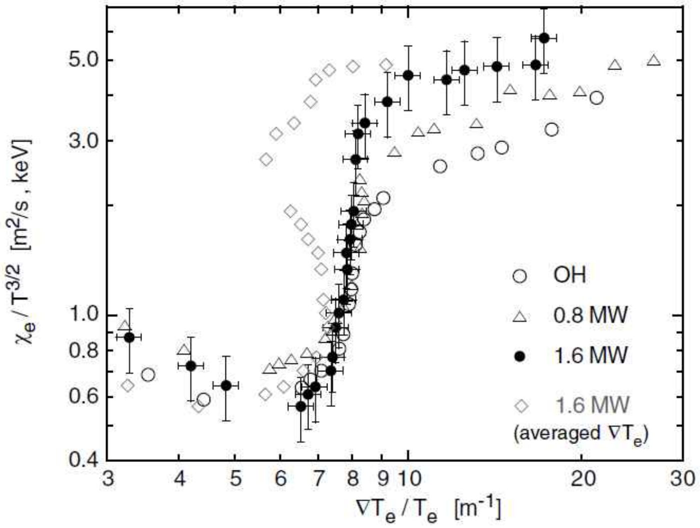
- It was proved that in edge plasmas, turbulence particle and energy fluxes agree with the fluxes deduced from particle and heat balance (i.e., integral of the particle and heating sources). Since then, several studies have confirmed the close connection between turbulence and transport. In particular, a reduction of the fluctuation level is observed when a transport barrier is formed.

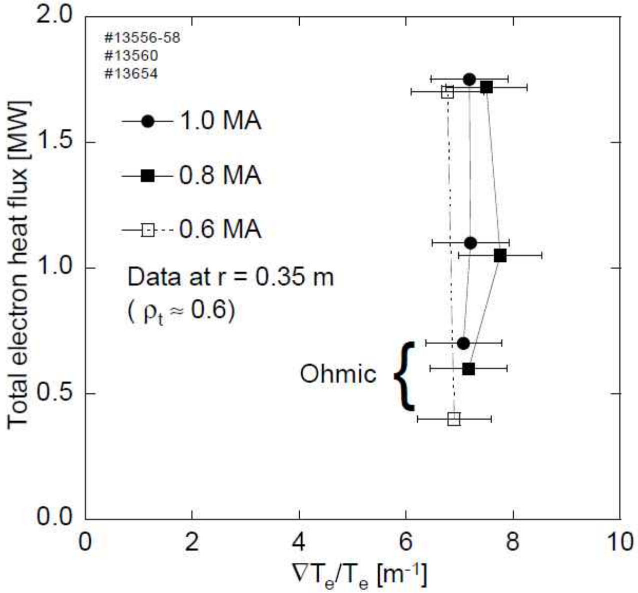
Tokamak Transport

- **Anomalous Transport**

ASDEX Upgrade





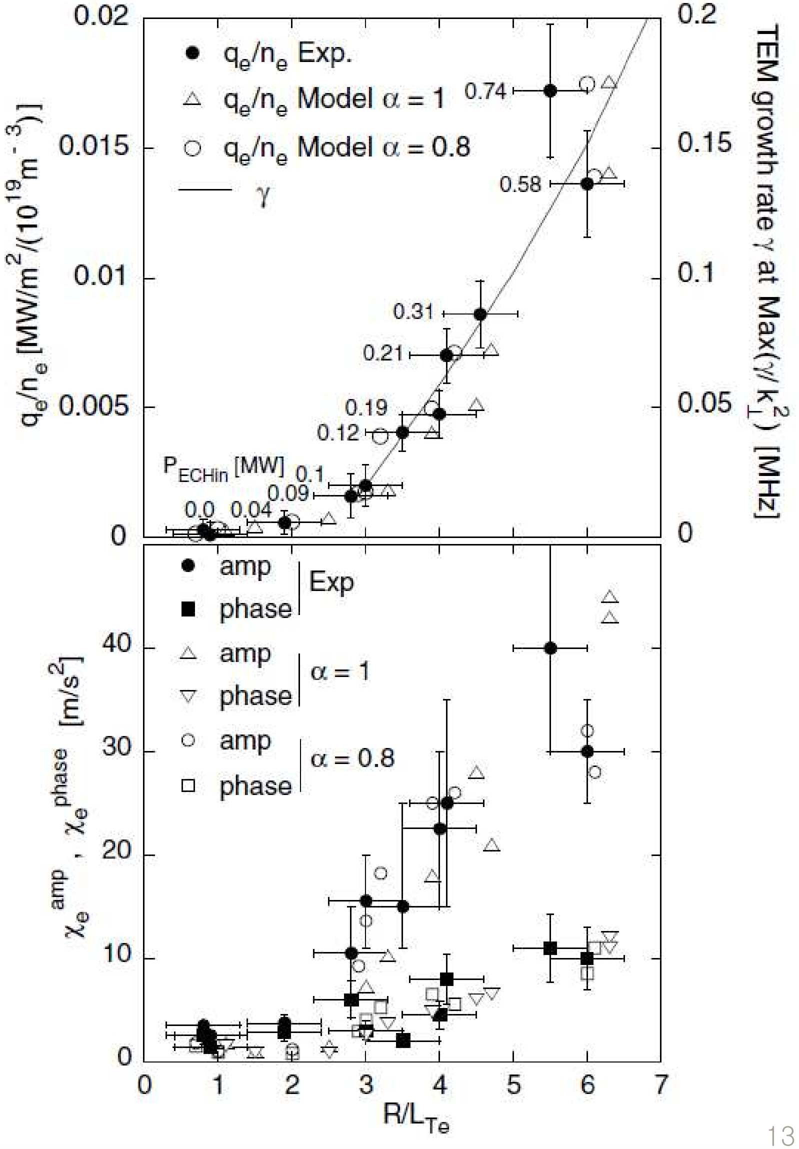


*F. Ryter et al, PRL **86** 2325 (2001),*
*PRL **86** 5498 (2001), NF **41** 537 (2001)*

Tokamak Transport

- **Anomalous Transport**

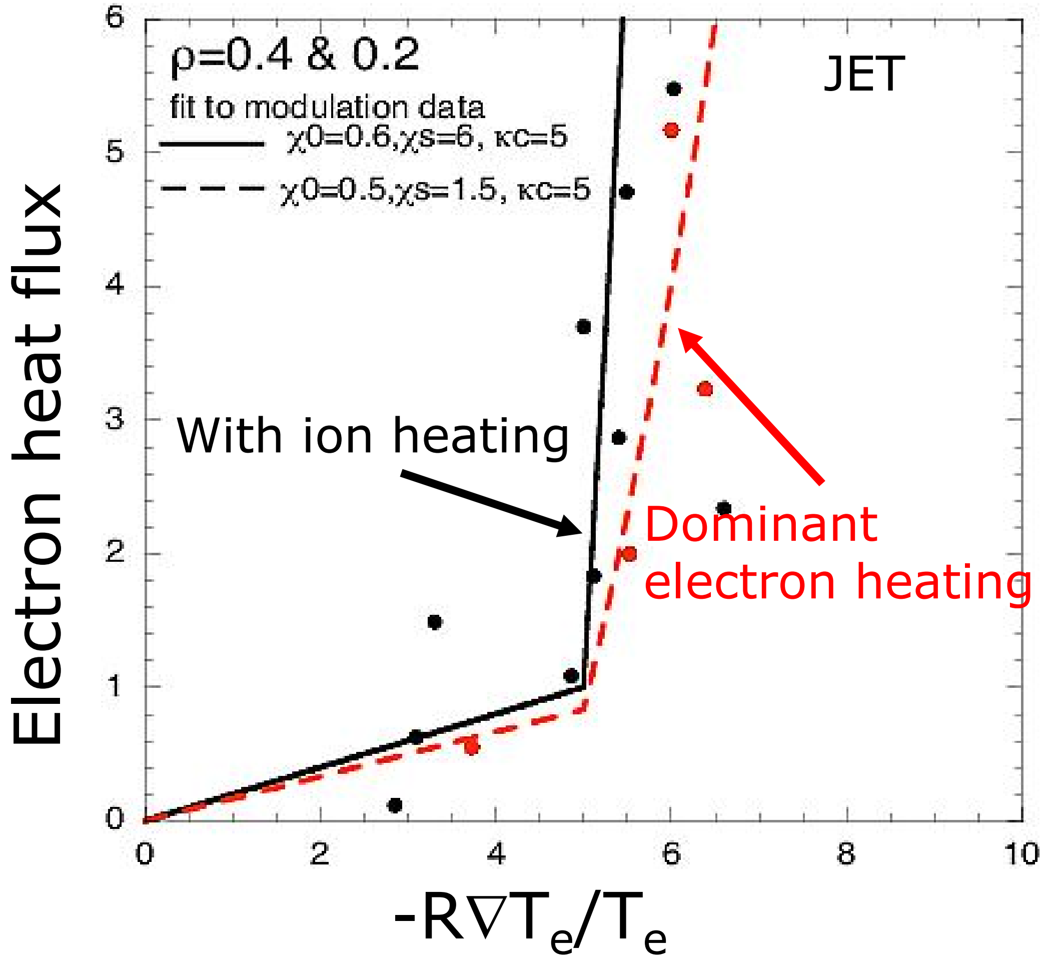
- Trapped electron modes are one of the candidates to explain turbulence driven electron heat transport observed in tokamaks.
- This instability has two characteristics: a threshold in normalized gradient and stabilization by collisions.
- Experiments using modulated ECH in the ASDEX Upgrade tokamak demonstrate explicitly the existence of the threshold.



*F. Ryter et al, PRL **95** 085001 (2005)*

Tokamak Transport

- **Anomalous Transport**



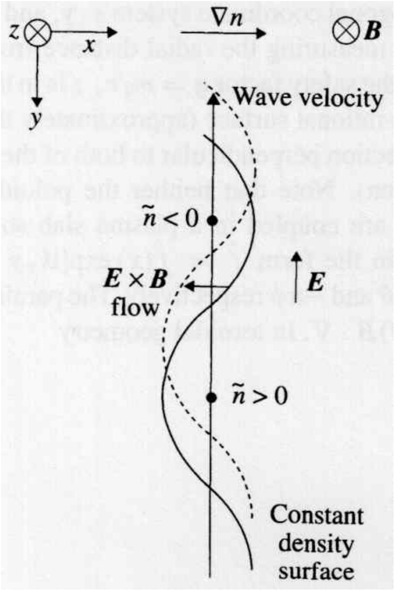
Tokamak Transport

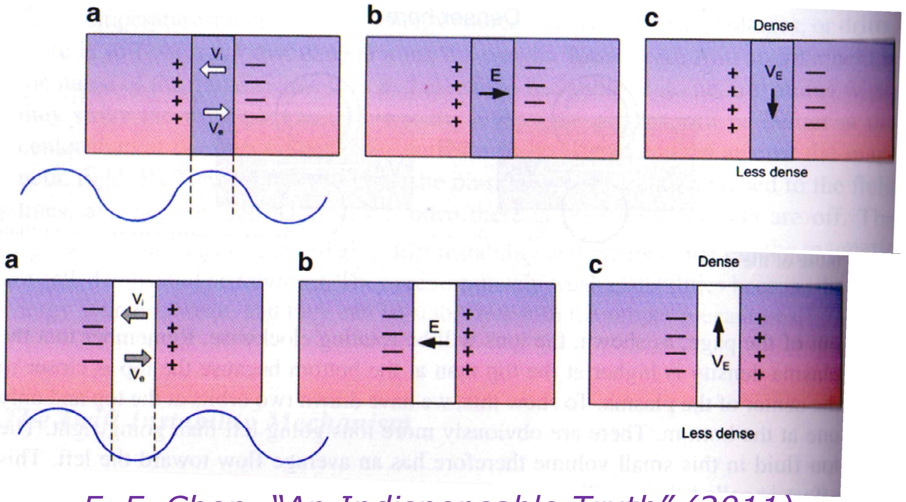
- **Anomalous Transport - Microinstabilities**

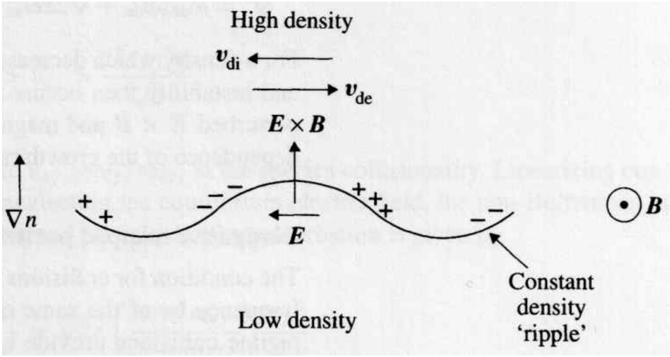
$$D^{\exp} = D^{NC} + D^{anomalous} > D^{NC}$$

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

- Plasma waves and their associated instabilities
  - Electron drift wave: ‘Universal’, trapped electron
  - Sound wave: Ion temperature gradient
  - Alfven wave: Micro-tearing







F. F. Chen, “An Indispensable Truth” (2011)
J. Wesson, “Tokamaks” (2009)

Tokamak Transport

- **Anomalous Transport - Microinstabilities**

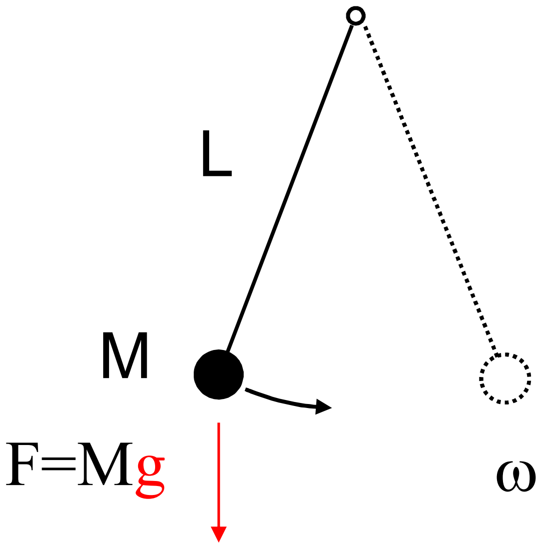
- Electrostatic instabilities: drift wave instabilities
  perturbations of the magnetic field are ignored,
  so that only the perturbed electric field matters.
  Assumption appropriate if the plasma beta is lower than the instability threshold for electromagnetic interchange modes (called ‘kinetic ballooning 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**

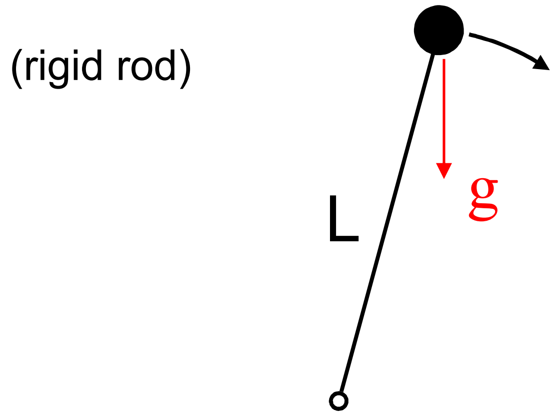
- Main instabilities are interchange modes.

Stable Pendulum



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

Unstable Inverted Pendulum

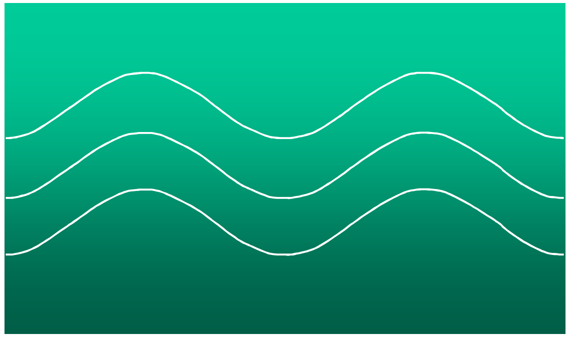


$\omega= (-g/|L|)^{1/2} = i(g/|L|)^{1/2} = i\gamma$

Instability

Density-stratified Fluid

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

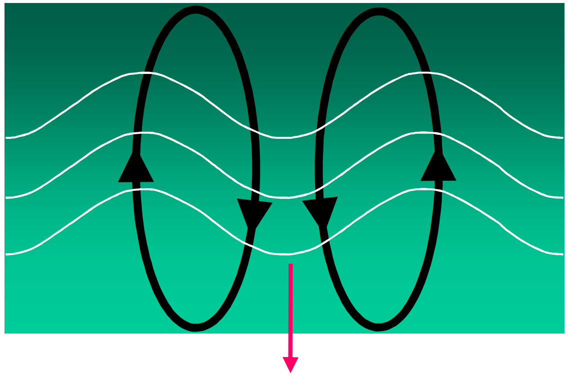


stable $\omega=(g/L)^{1/2}$

Inverted-density fluid

⇒Rayleigh-Taylor Instability

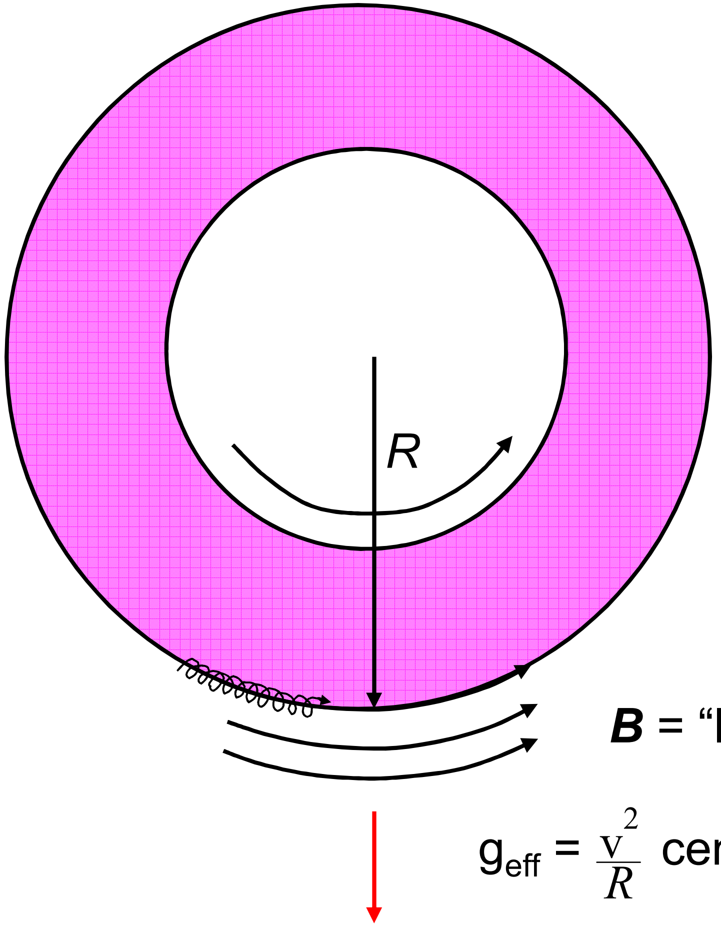
$\rho=\exp(y/L)$



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:

$$\gamma = \sqrt{\frac{g_{eff}}{L}} = \sqrt{\frac{V_t^2}{RL}} = \frac{V_t}{\sqrt{RL}}$$

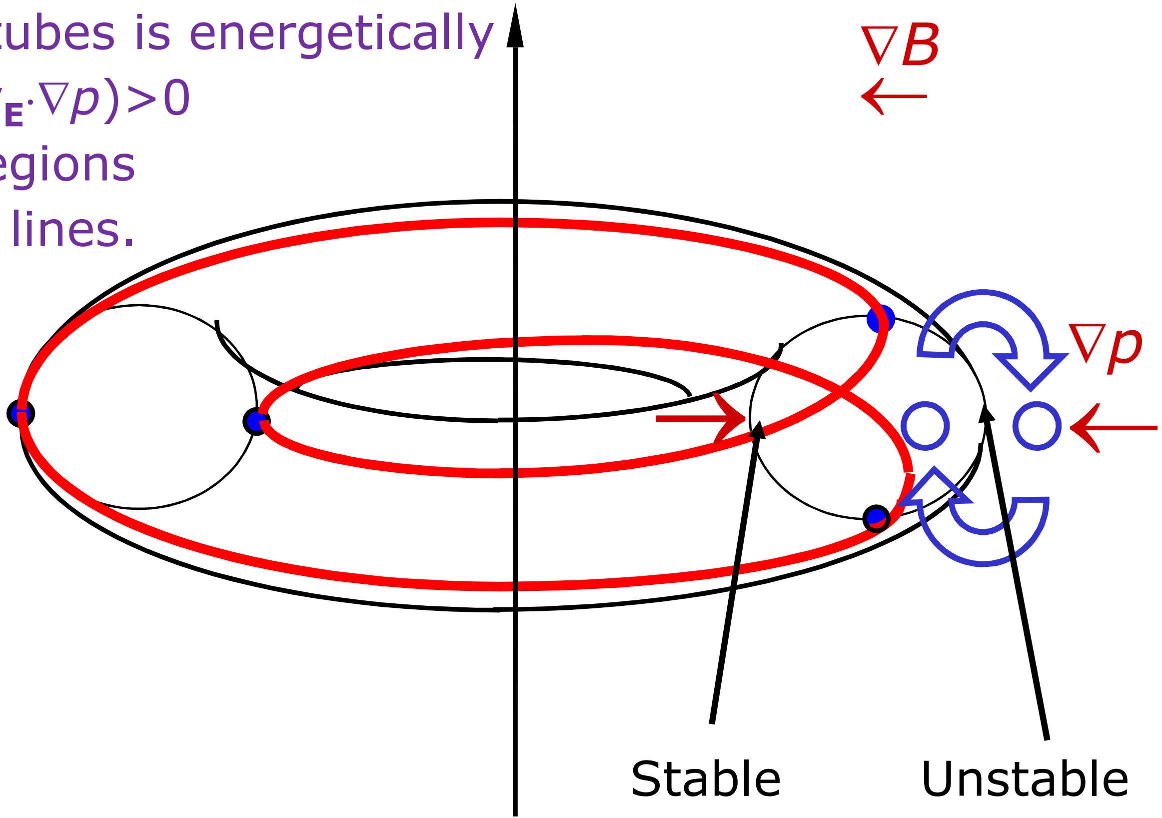
Similar instability mechanism in MHD & drift/microinstabilities

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

Tokamak Transport

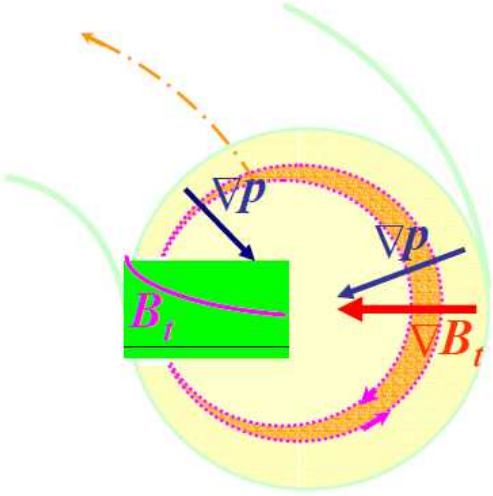
- **Anomalous Transport**

- 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**

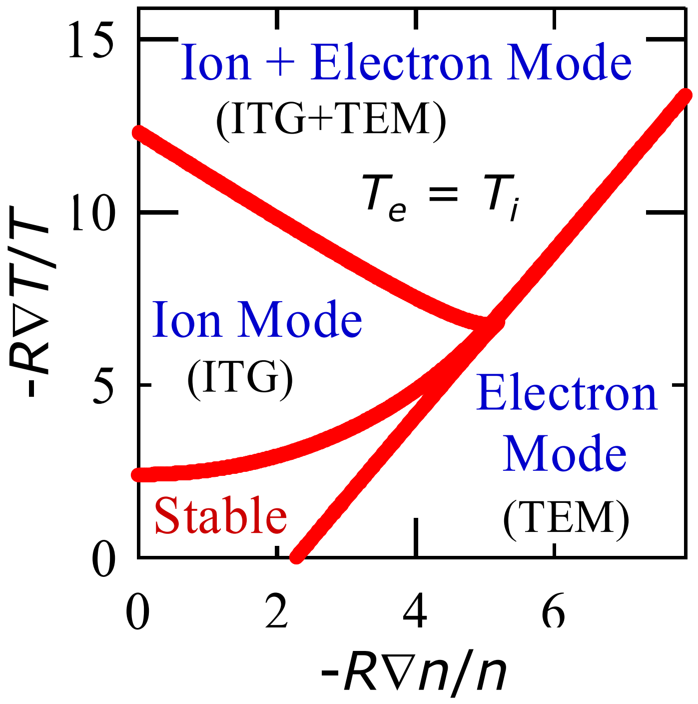
- Unstable in the limit of large wavelengths: $k_\perp \rho_i < 1$
- Electron and/or ion modes are unstable above a threshold.
- Underlie particle, electron and ion heat transport: interplay between all channels

- 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: $k_{\perp}\rho_i < 1$
- Electron and/or ion modes are unstable above a threshold.
- Underlie particle, electron and ion heat transport: interplay between all channels



Stability diagram
(Weiland model)

Tokamak Transport

- **Anomalous Transport**

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

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

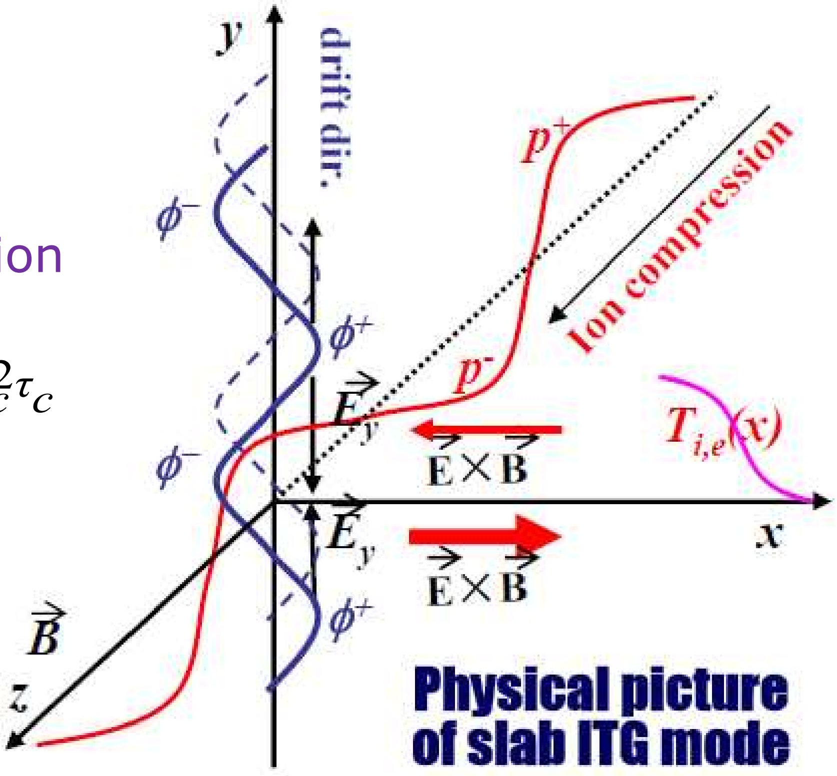
$$v_E = \frac{B \times \nabla \phi}{B^2}$$

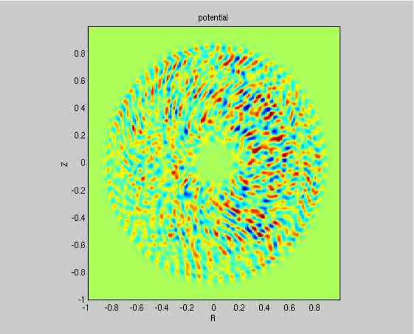
- Turbulent diffusion

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

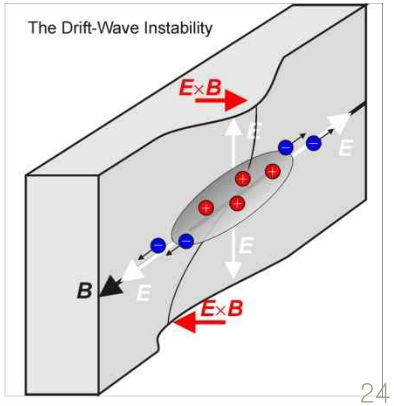
- Turbulent flux

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



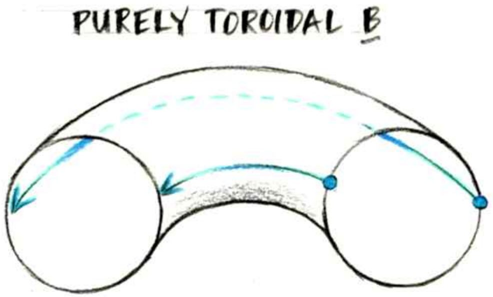


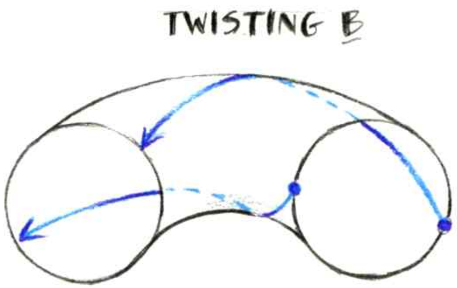
Contour lines of electric potential ϕ (TRB simulation)



The Secret for Stabilizing Bad-Curvature Instabilities

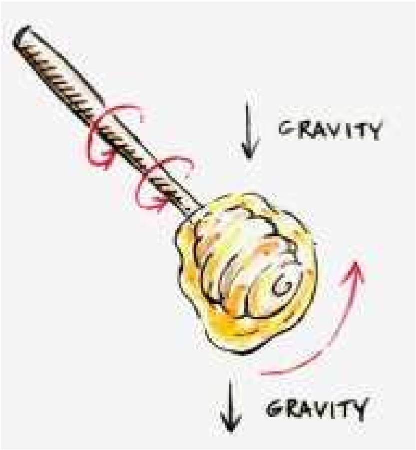
Twist in ***B*** carries plasma from bad curvature region to good curvature region:





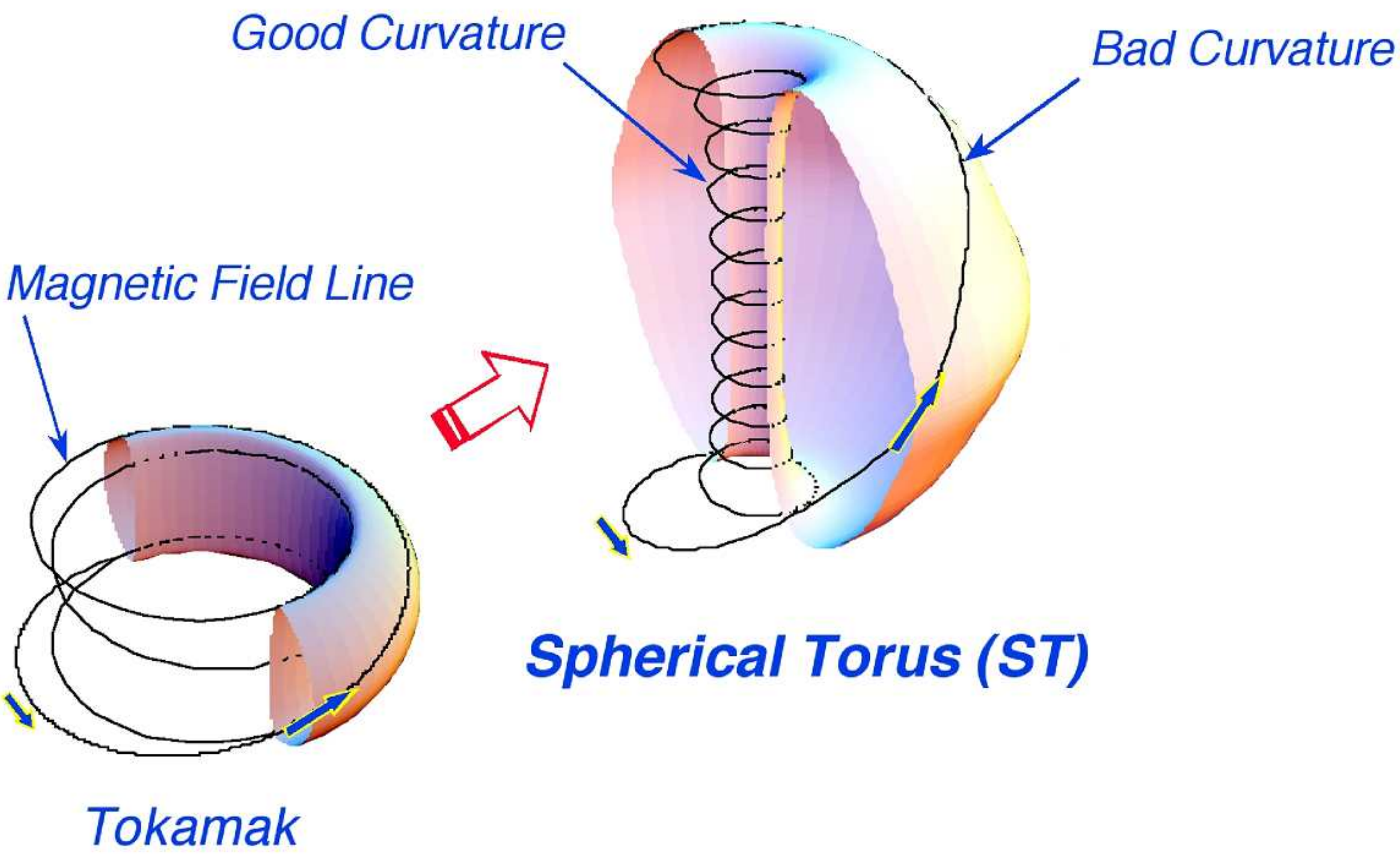
Unstable

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)



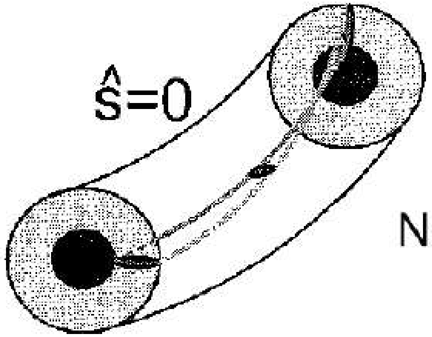
Simple picture of reducing turbulence by negative magnetic shear

Particles that produce an eddy tend to follow field lines.

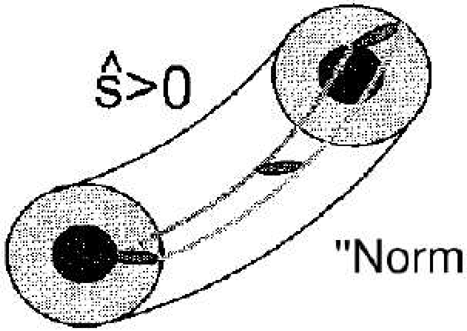
Reversed magnetic shear twists eddy in a short distance to point in the ``good curvature direction''.

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

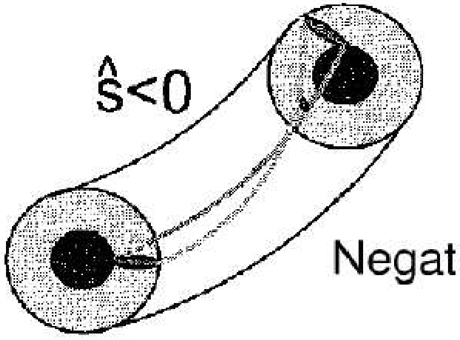
Shaping the plasma (elongation and triangularity) can also change local shear



No Magnetic Shear



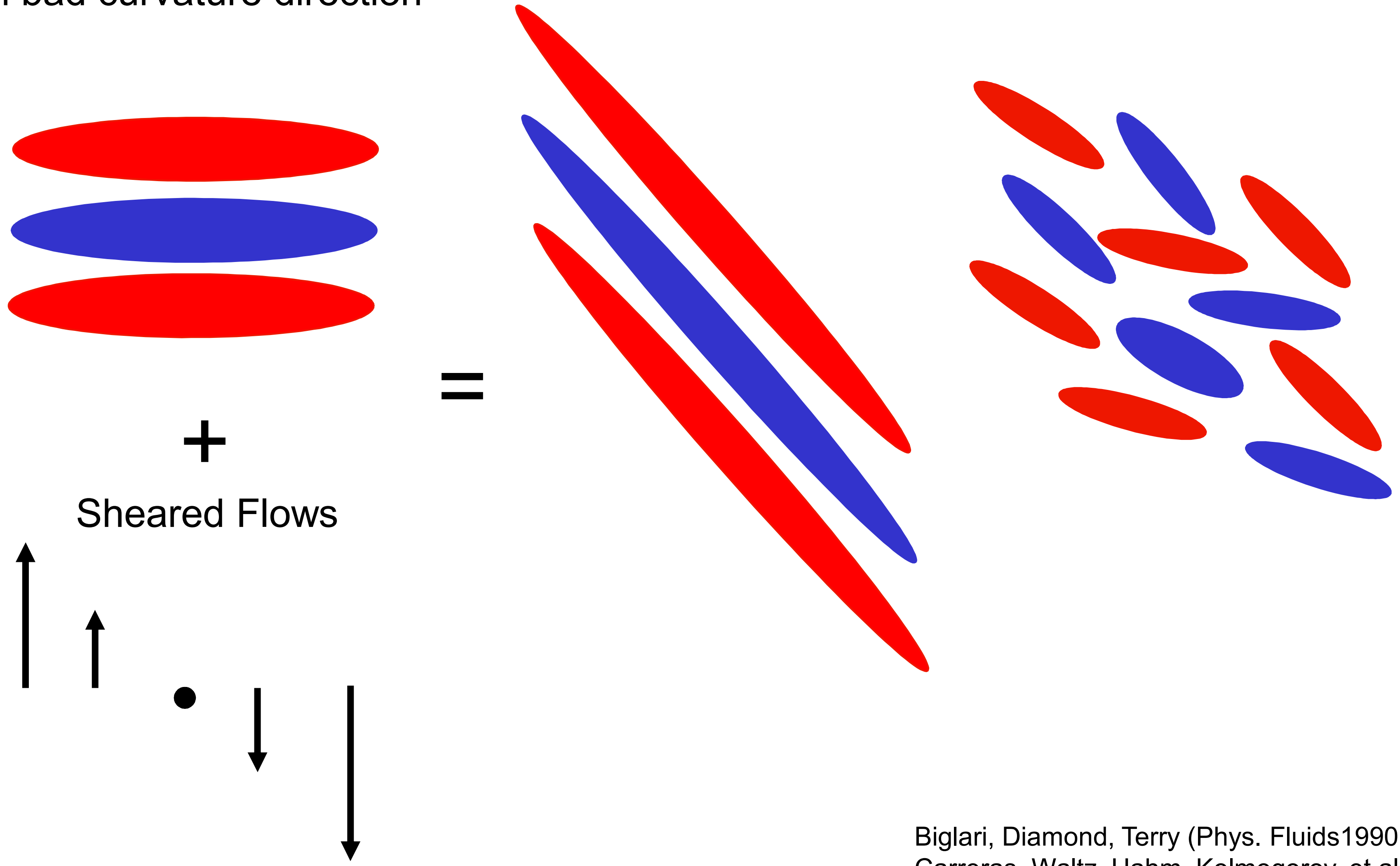
"Normal" Magnetic Shear



Negative Magnetic 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

+

Sheared Flows

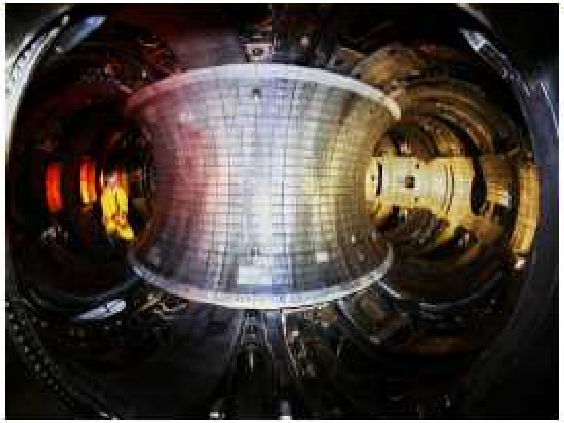
=

Sheared Eddies
Less effective

Eventually break up

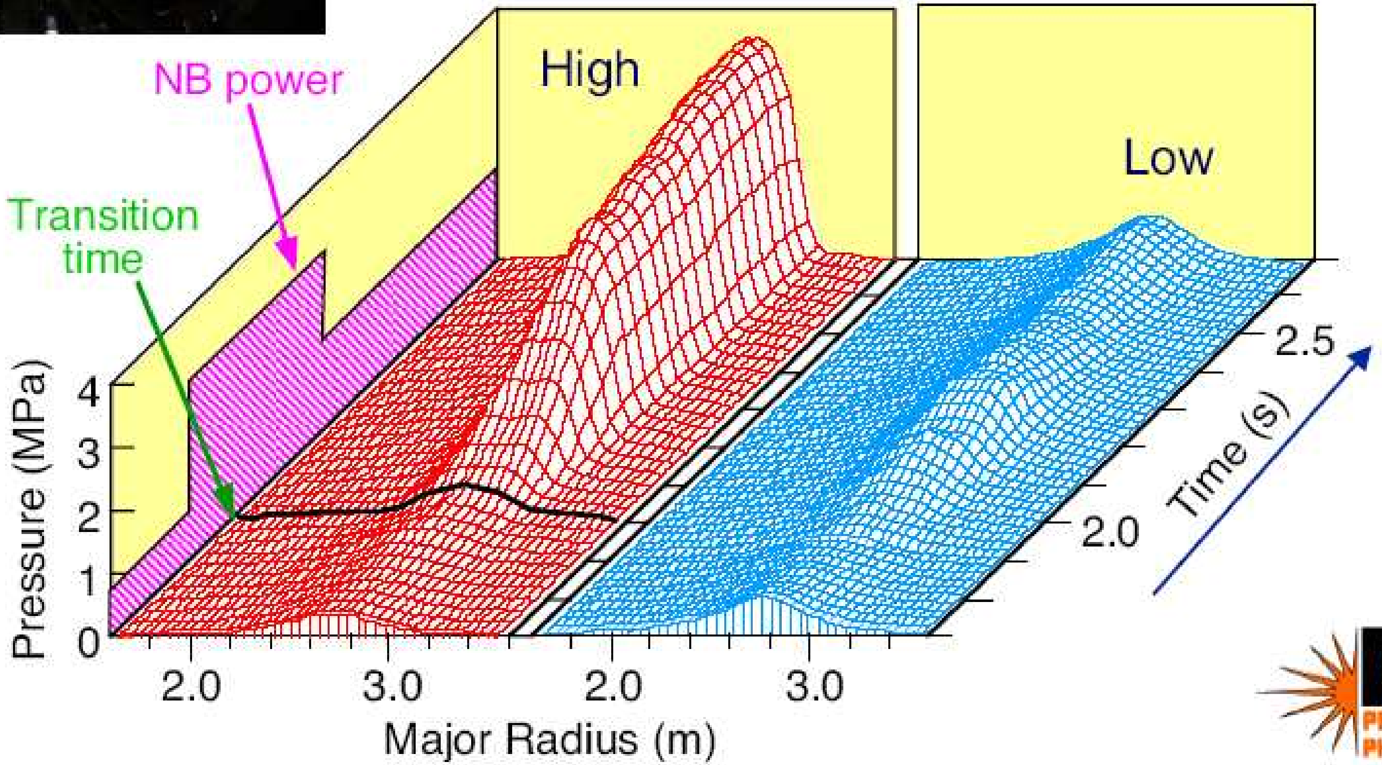
Biglari, Diamond, Terry (Phys. Fluids1990),
Carreras, Waltz, Hahm, Kolmogorov, et al.

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



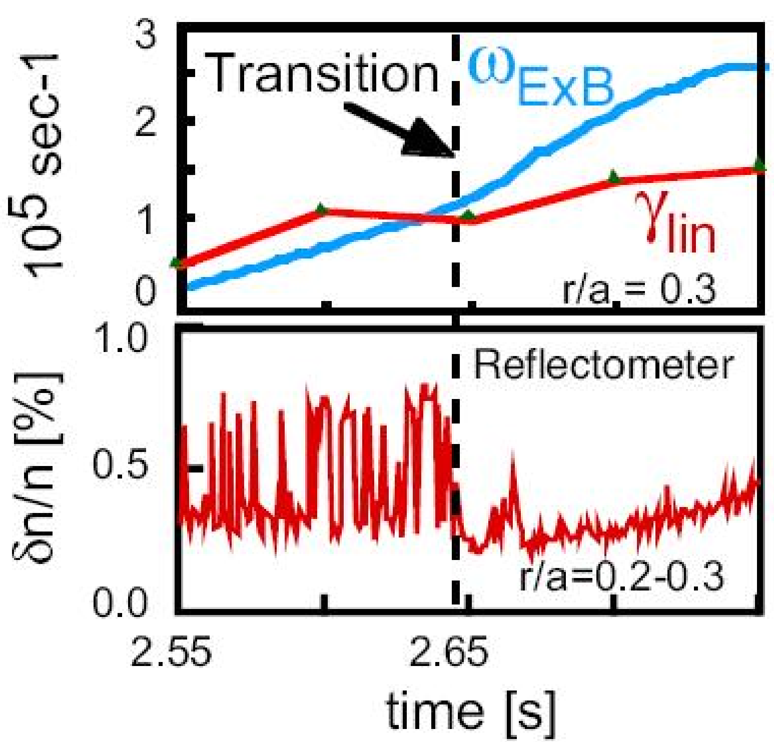
TFTR

- 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?



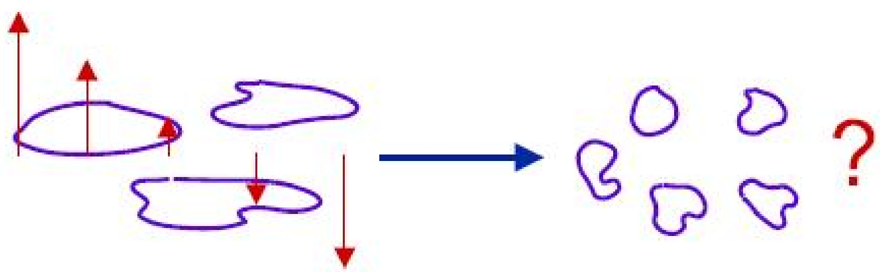
PPPL
PRINCETON PLASMA PHYSICS LABORATORY
R. Nazikian et al.

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)

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

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PRINCETON PLASMA PHYSICS LABORATORY

Tokamak Transport

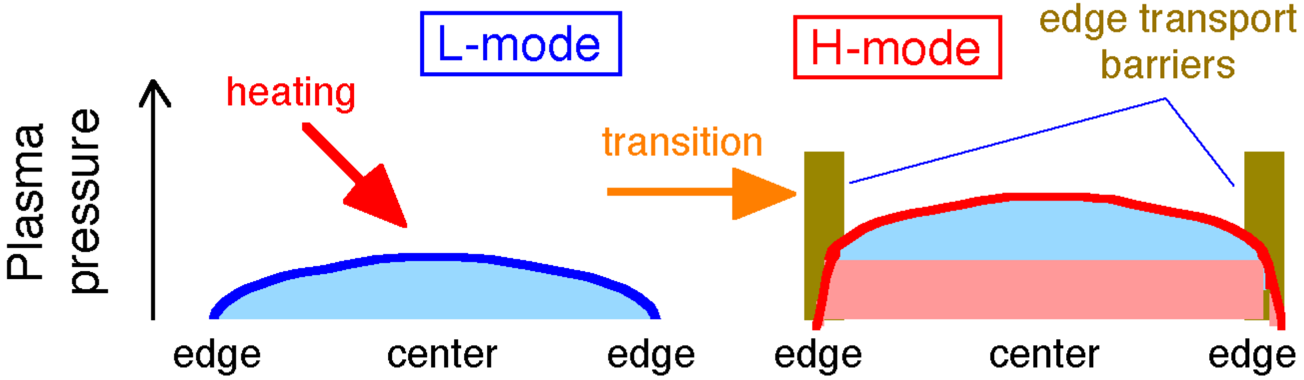
- **Anomalous Transport**

*F. Ryter et al, PRL **86** 2325 (2001),*
*PRL **86** 5498 (2001), NF **41** 537 (2001)*

$$\chi = T^{3/2}\left[\xi_0 + \xi_{TG} G\left(R/L_T - R/L_{T,c}\right)\right]$$

- ξ_0: transport when TG turbulence is not active
- $\xi_0 G$: transport caused by TG turbulence
- $T^{3/2}$: reflecting the gyro-Bohm assumption
- $G = 0$ for $L_T \geq L_{T,c}$ but increases strongly when $L_T < L_{T,c}$ and eventually saturates. When $L_T < L_{T,c}$ transport is high to keep L_T close to $L_{T,c}$, providing the stiffness.

Confinement scaling



$\tau_E^{ITER89P} = 0.048 M^{0.5} I_p^{0.85} B_t^{0.2} R^{1.2} a^{0.3} \kappa^{0.5} n_{20}^{0.1} P^{-0.5}$ **M for DT mixture?**

$$\chi \sim \frac{a^2}{\tau_E} \sim \chi_{Bohm} (\rho^*)^{\mu} F(\beta, \nu^*)$$: nearly “Bohm” scaling (μ ~ 0)

Why?

$$\chi_{Bohm} = \frac{cT}{eB}$$

$\tau_{E,th}^{IPB98(y)} = 0.0365 M^{0.2} I_p^{0.97} B_t^{0.08} R^{1.7} a^{0.23} \kappa_a^{0.67} n_{19}^{0.41} P^{-0.63}$

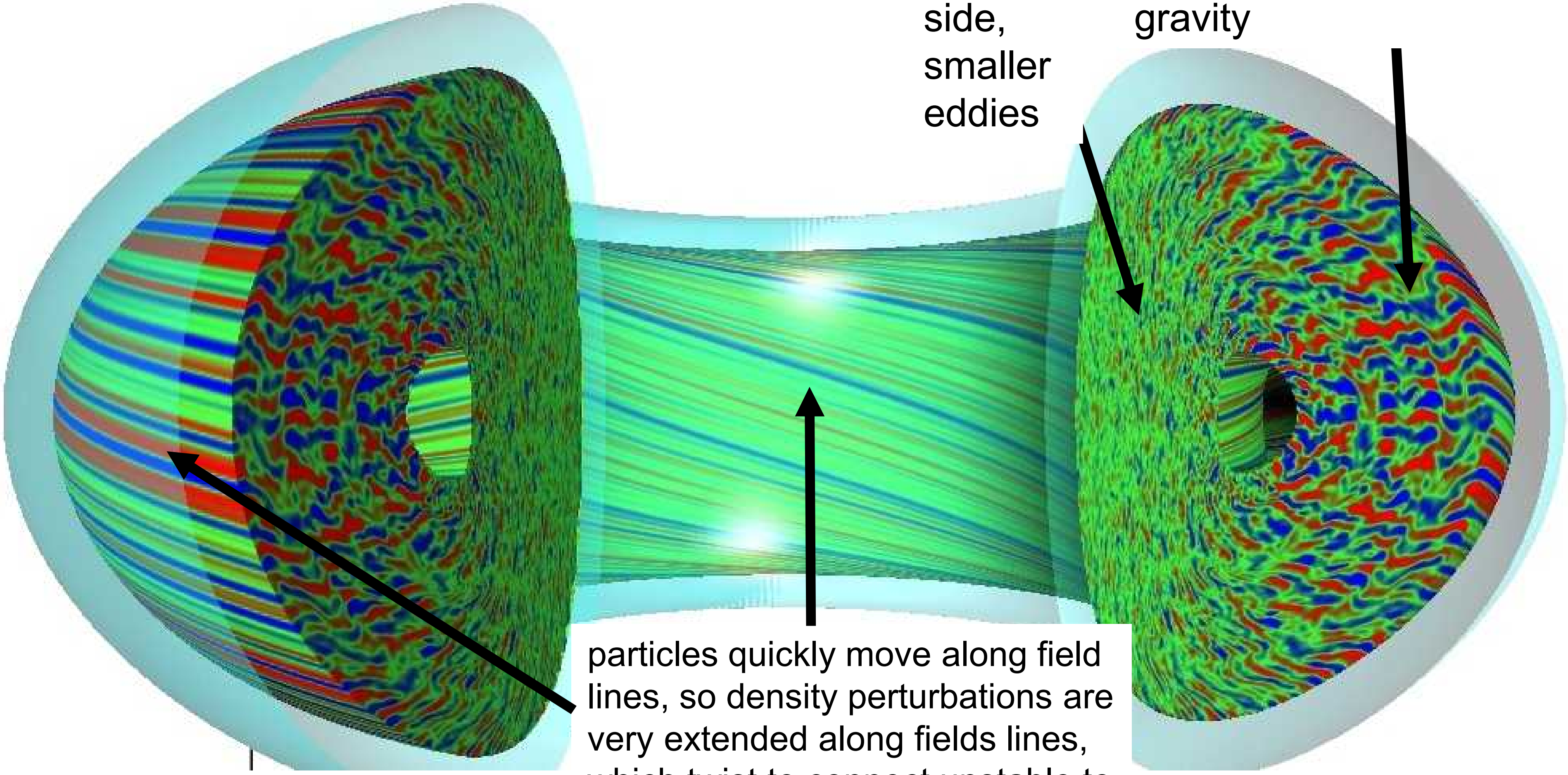
$\propto \tau_B \rho^{*-0.83} \beta^{-0.50} \nu^{*-0.10} M^{0.97} q^{-2.52} \varepsilon^{-0.55} \kappa_a^{2.72}$

$$\chi \sim \frac{a^2}{\tau_E} \sim \chi_{Bohm} (\rho^*)^{\mu} F(\beta, \nu^*)$$: close to “gyroBohm” scaling (μ ~ 1, $\tau_E/\tau_B \propto \rho^{*-1}$)

$$\chi \sim \left(\frac{\rho_i}{L}\right)\left(\frac{cT_i}{eB}\right) \qquad \left(\frac{\rho_i}{L}\right) << 1$$

XGC1 turbulence simulation

These physical mechanisms can be seen in gyrokinetic simulations and movies

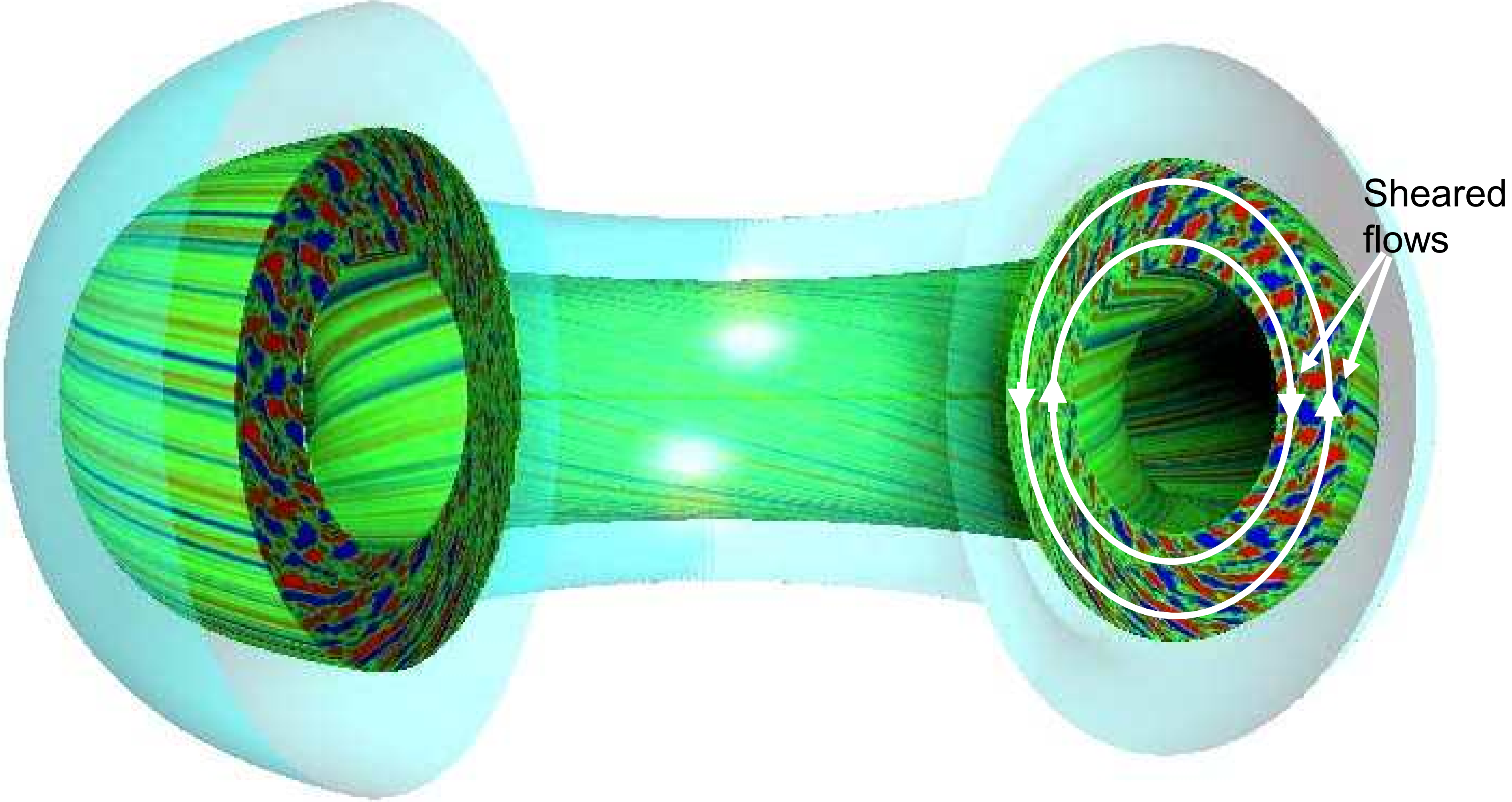


Stable side, smaller eddies

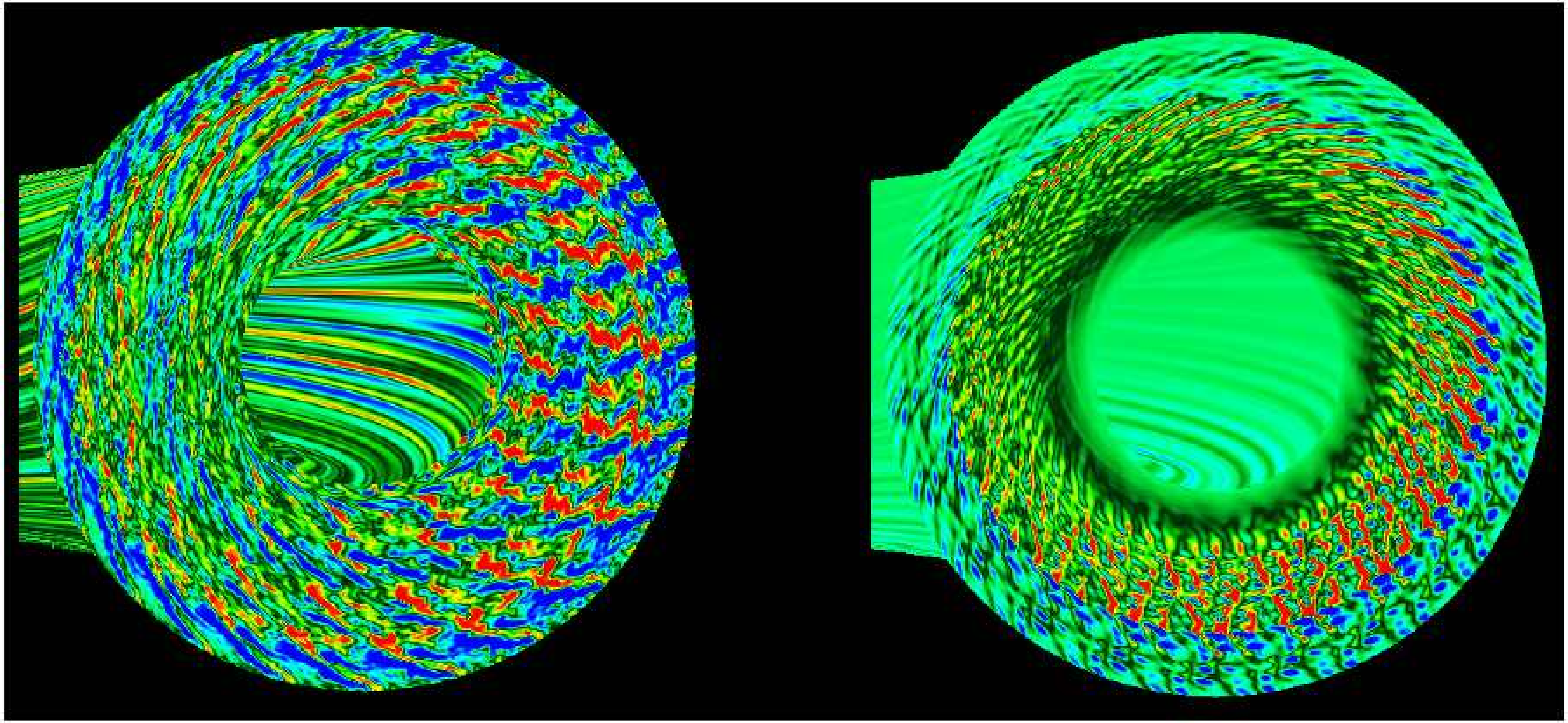
Unstable bad-curvature side, eddies point out, direction of effective gravity

particles quickly move along field lines, so density perturbations are very extended along fields lines, which twist to connect unstable to stable side

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**

DIII-D Shot 121717

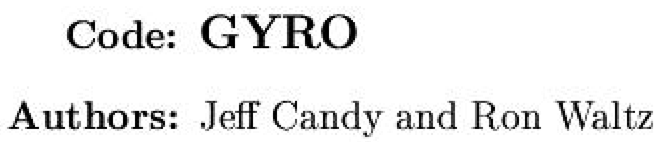
GYRO Simulation

Cray X1E, 256 MSPs

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

Tokamak Transport

- **Anomalous Transport**



Code: **GYRO**

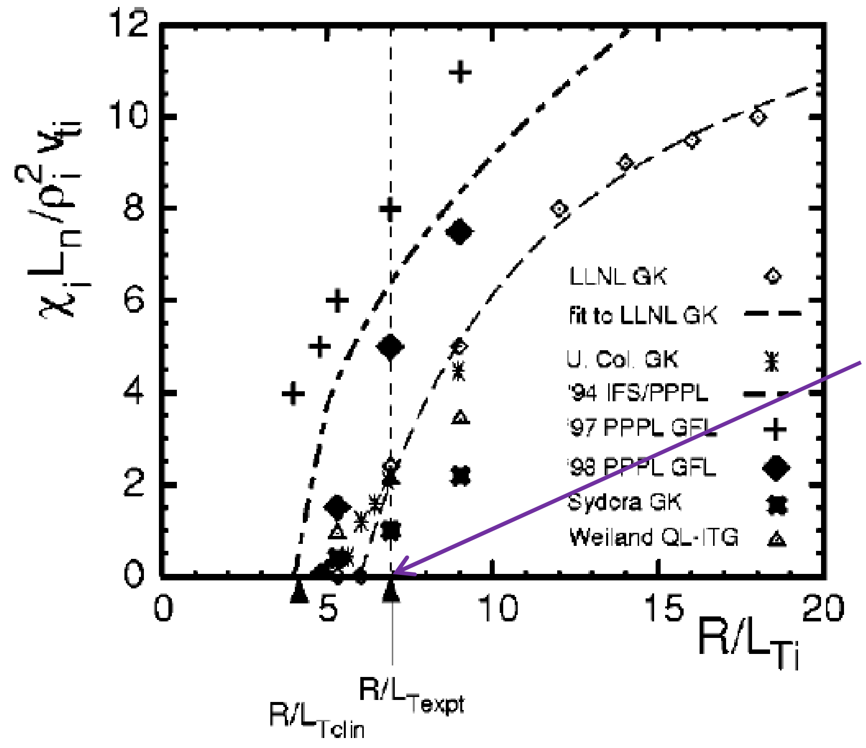
Authors: Jeff Candy and Ron Waltz

- 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**

*A. M. Dimits et al, PHP **7** 969 (2000)*



Dimits shift due to nonlinear effect

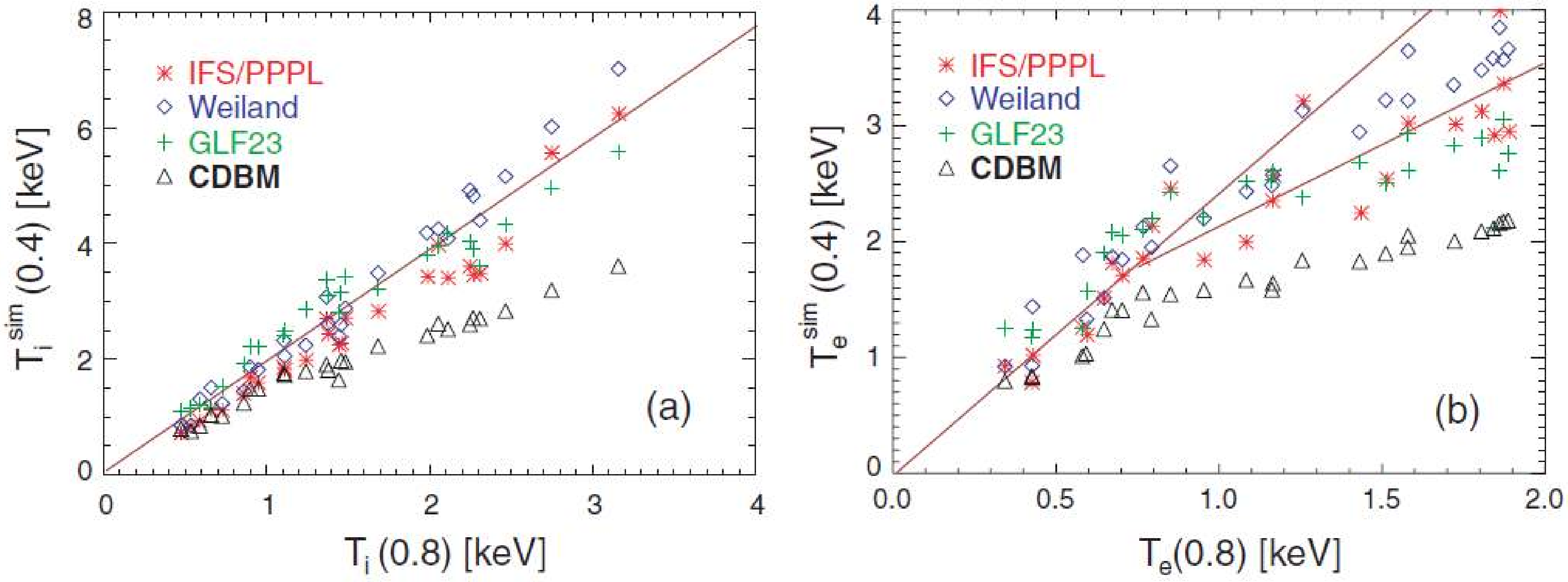
(turbulence stabilisation by zonal flows)

- χ_i vs R/L_T from the gyrofluid code using the 1994 "thesis closure", an improved 1998 gyrofluid closure, the 1994 IFS-PPPL model, the LLNL and U. Colorado flux-tube and UCLA (Sydora) global gyrokinetic codes, and the MMM model for the DIII-D base case.

Tokamak Transport

- **Anomalous Transport**

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



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

$$\gamma_{lin} = \underset{\downarrow \text{ Stiffness number}}{\chi_s} \frac{c_s}{R}\left(\frac{-R\partial_r T}{T} - \kappa_c\right) \qquad L_c \propto \rho_c$$

Tokamak Transport

- **Anomalous Transport**

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Stiffness number

$$L_c \propto \rho_c$$

Diffusion and pinch velocity

- Particle flux

$$\Gamma_e = -D\frac{dn_e}{dr} + Vn_e$$

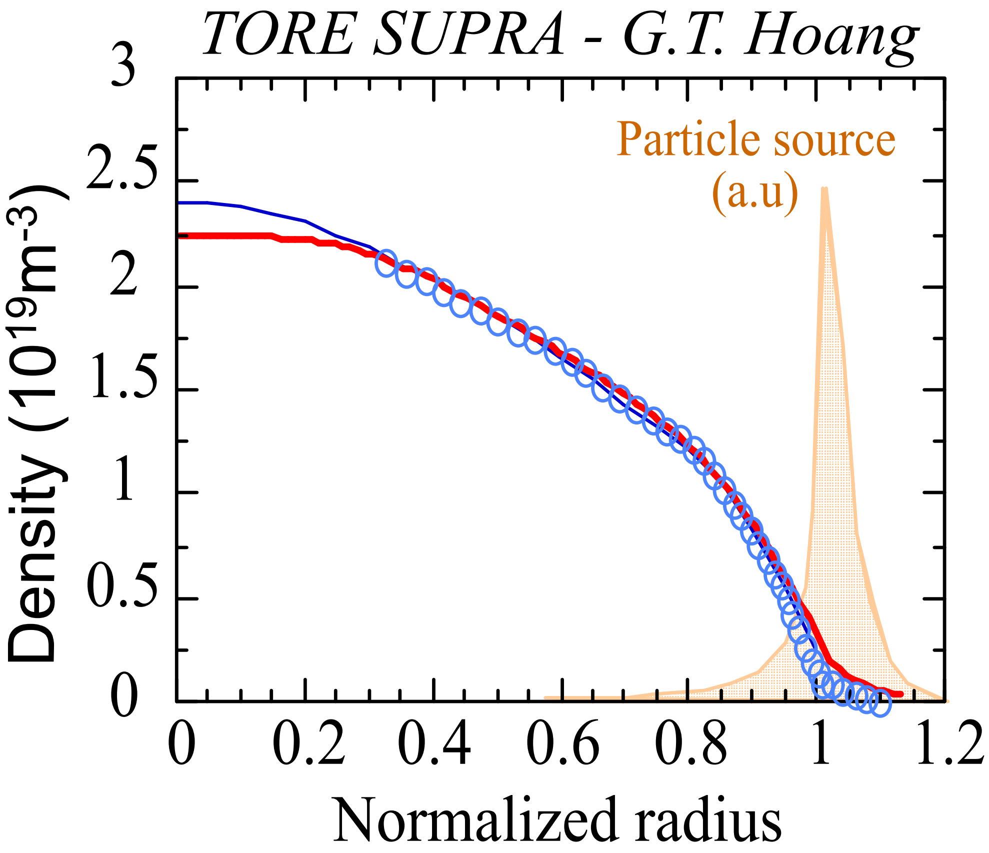
- Diffusion is turbulent

$$D = D_{turb}$$

- pinch velocity=

collisions + turbulenc

$$V = V_{coll} + V_{turb}$$


TORE SUPRA - G.T. Hoang

- In a reactor:

- ionisation source localised in the edge → Γ_e=0

-V_{coll}~V_{Ware}=0. Turbulent pinch V_{turb} → density peaking?

Density and safety factor profiles are correlated in L-mode

- Combined heating and current drive :

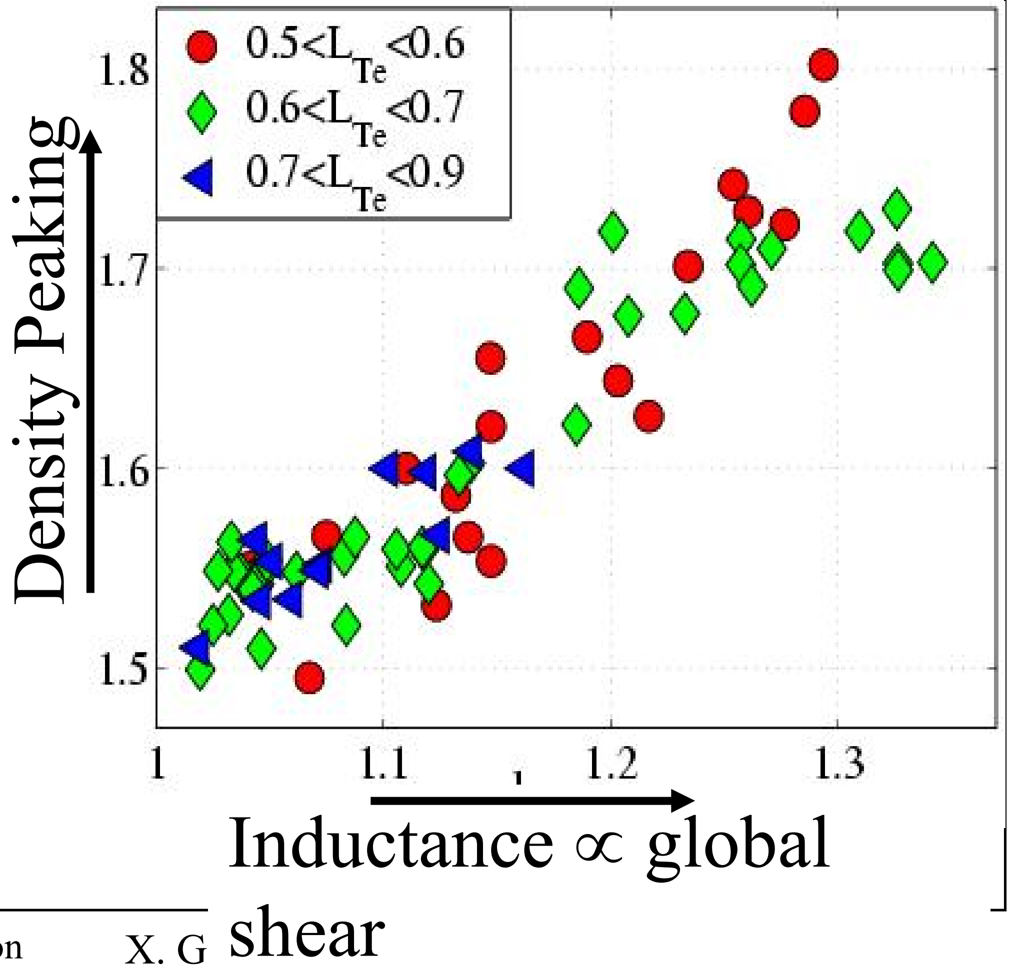
- consistent with curvature pinch

- no indication of thermodiffusion:

e/ion-mode transition'

→ density and q profiles are correlated in JET, DIIID, TCV, TS...

JET- H. Weisen, A.Zabolotsky



References

- *T. S. Hahm, “Turbulent Transport in Tokamaks”, Lecture at NFRI and SNU (2009)*
- *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*