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Turbulent Transport in Fusion Plasmas: Scaling Laws, Transport Models and Barriers

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CEA Cadarache

Transport will be an important part of the ITER scientific programme

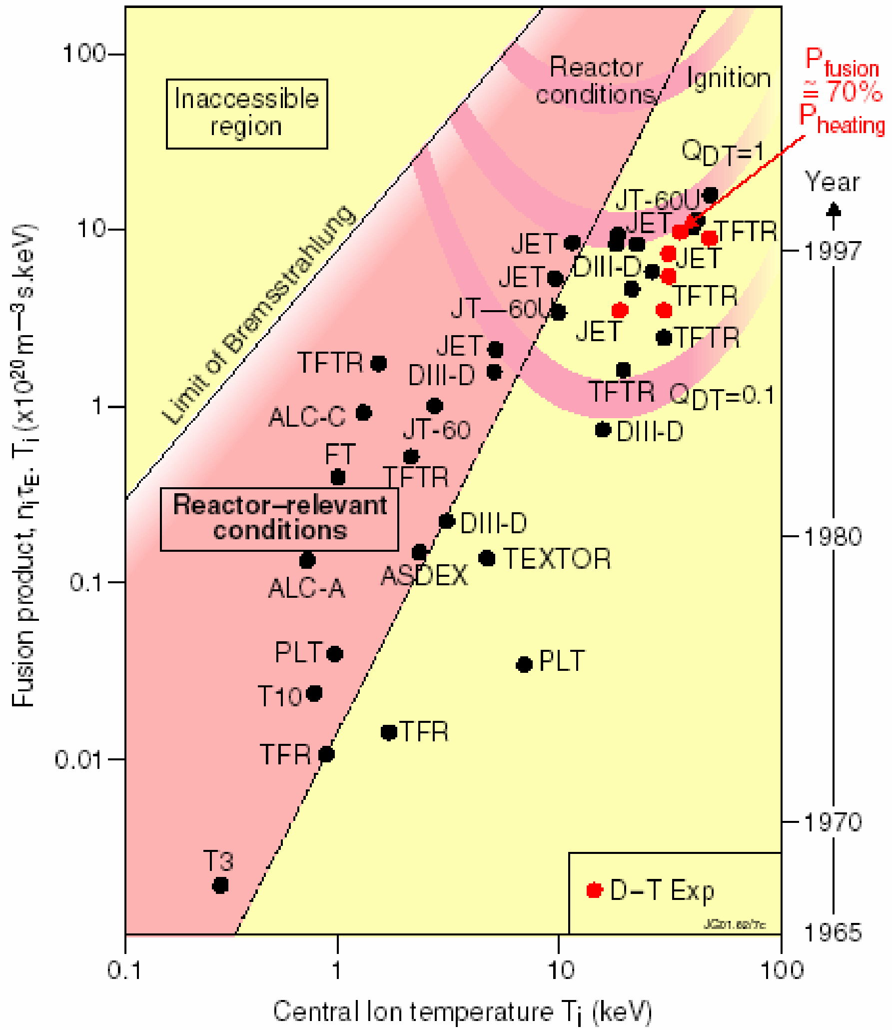
- Lawson criterion for ignition

$n_D T_D \tau_E = 3\ 10^{21} m^{-3}.keV.s$

- Confinement

$$\tau_E = \frac{\text{Energy content}}{\text{Power losses}}$$

→ Transport

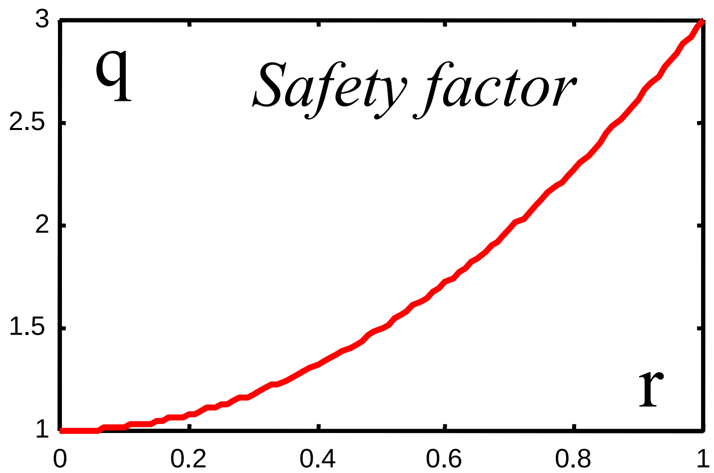


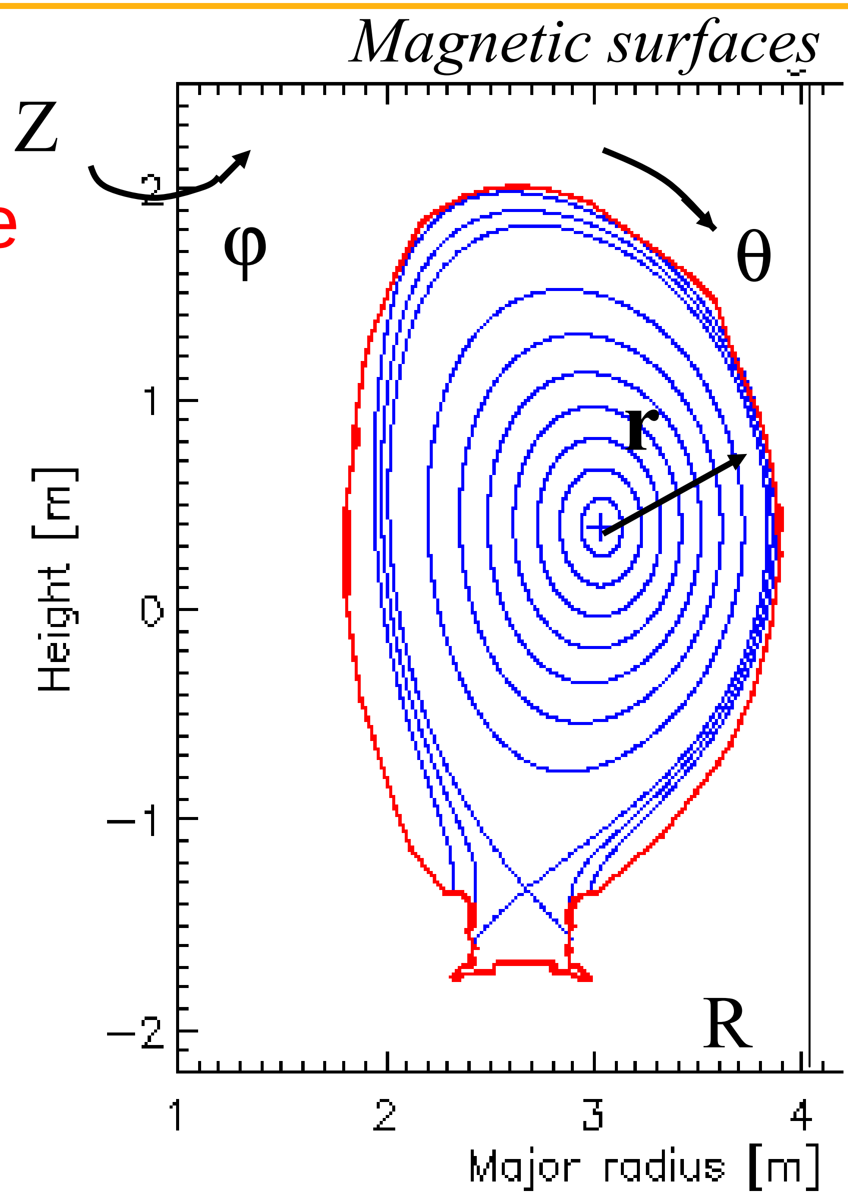
Outline

- Basics of turbulent transport : a reminder …
- Dimensionless scaling laws
- Building a transport model: mixing-length estimate, profile stiffness and modulation experiments.
- Improved confinement, physics of Internal Transport Barriers.

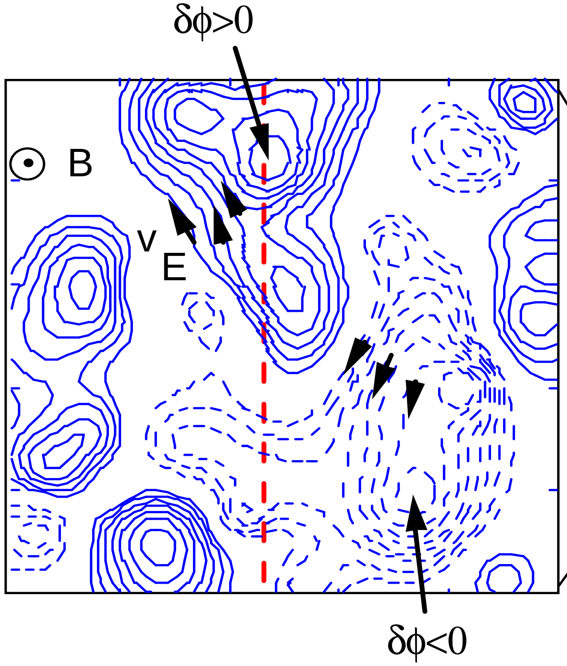
Geometry

- Helicoidal field lines generate magnetic surfaces.
- Safety factor : $q(r) = \frac{d\varphi}{d\theta}$
- Density and temperature are constant on magnetic surfaces.

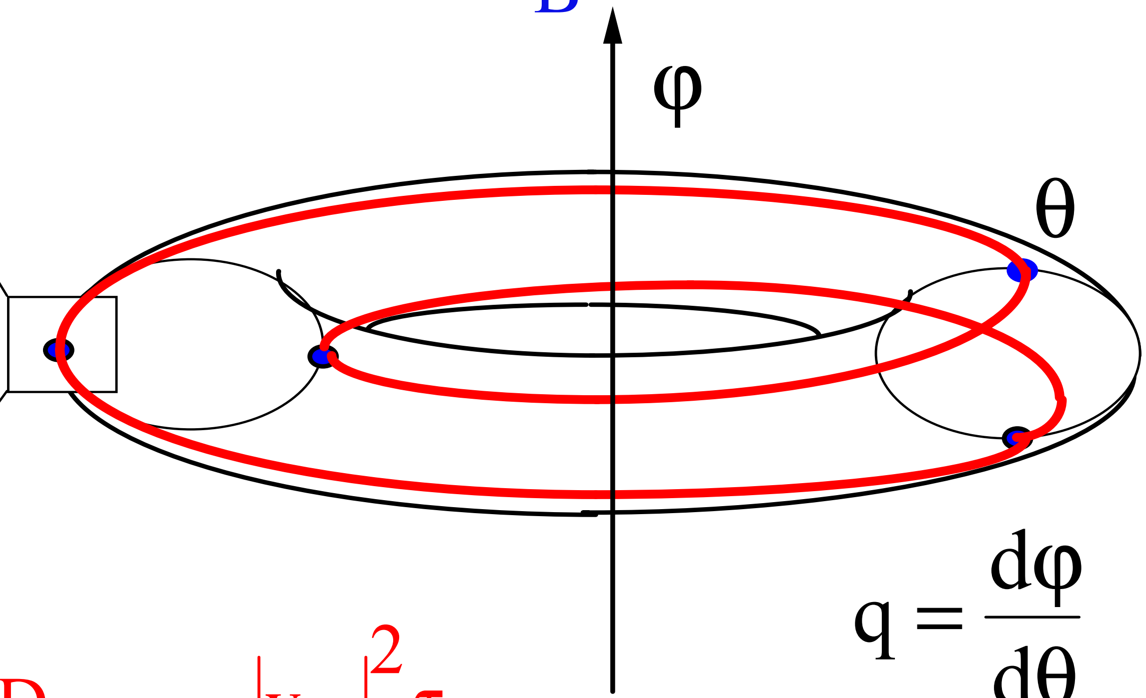




Fluctuations of ExB drift velocity produce turbulent transport



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



$$q = \frac{d\varphi}{d\theta}$$

$$D_{turb.} \approx |v_E|^2 \tau_c$$

Random walk process

- ExB drift

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

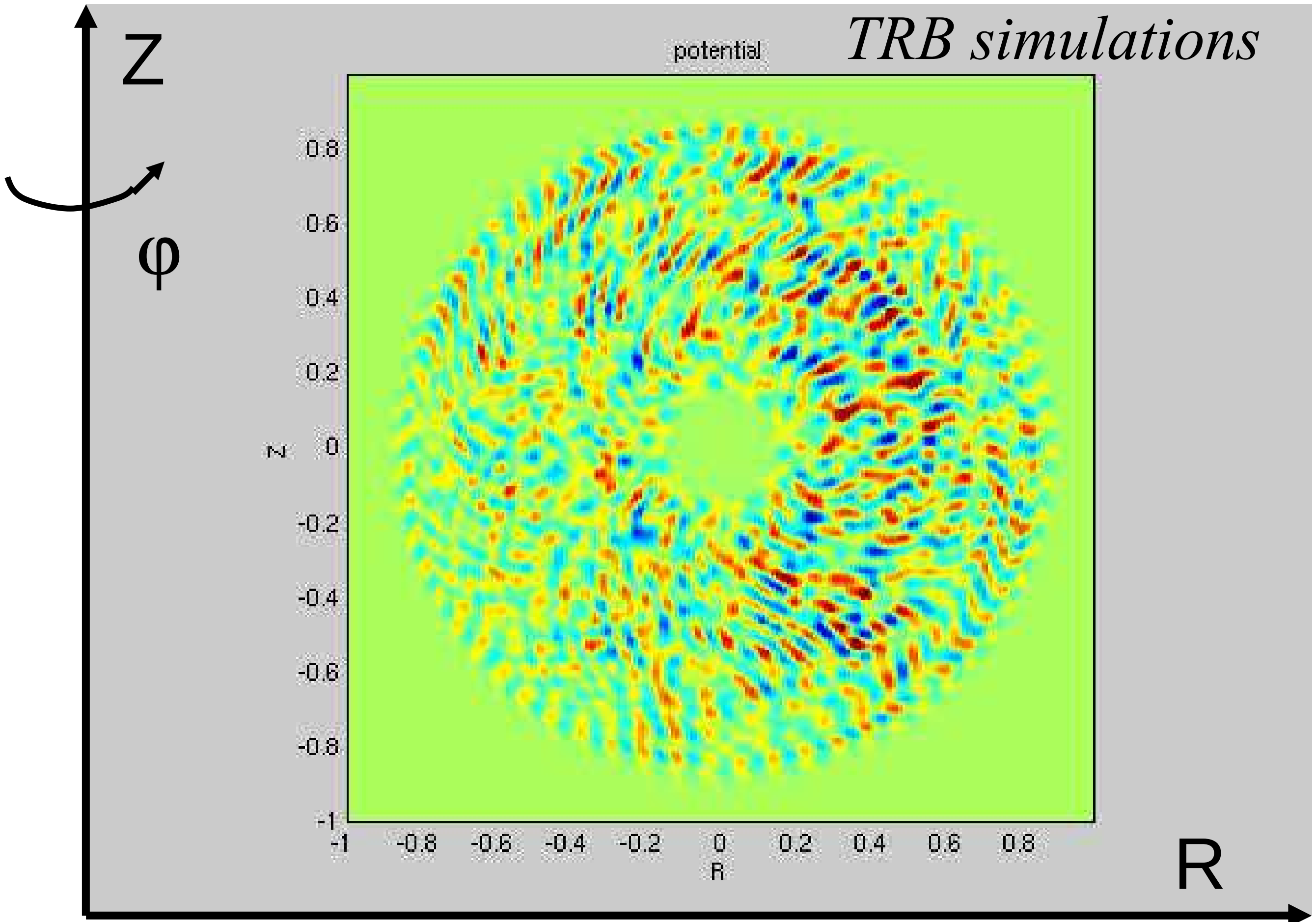
- Turbulent diffusion

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

$$\propto L_c^2 / \tau_c$$

- Turbulent flux

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



Contour lines of electric potential ϕ.

Electrostatic vs Magnetic Transport

	Electrostatic Low β	Magnetic High β
Test Particles	$\chi_{es} \approx \|\delta v_E\|^2 \tau_c$	$\chi_m \approx \|\delta B/B\|^2 L_c v_{//}$
Fluid	$q_r = 3/2<\delta p \delta v_E>$	$q_r = <\delta Q_{//} \delta B/B>$
Transport channels	All	Electron heat

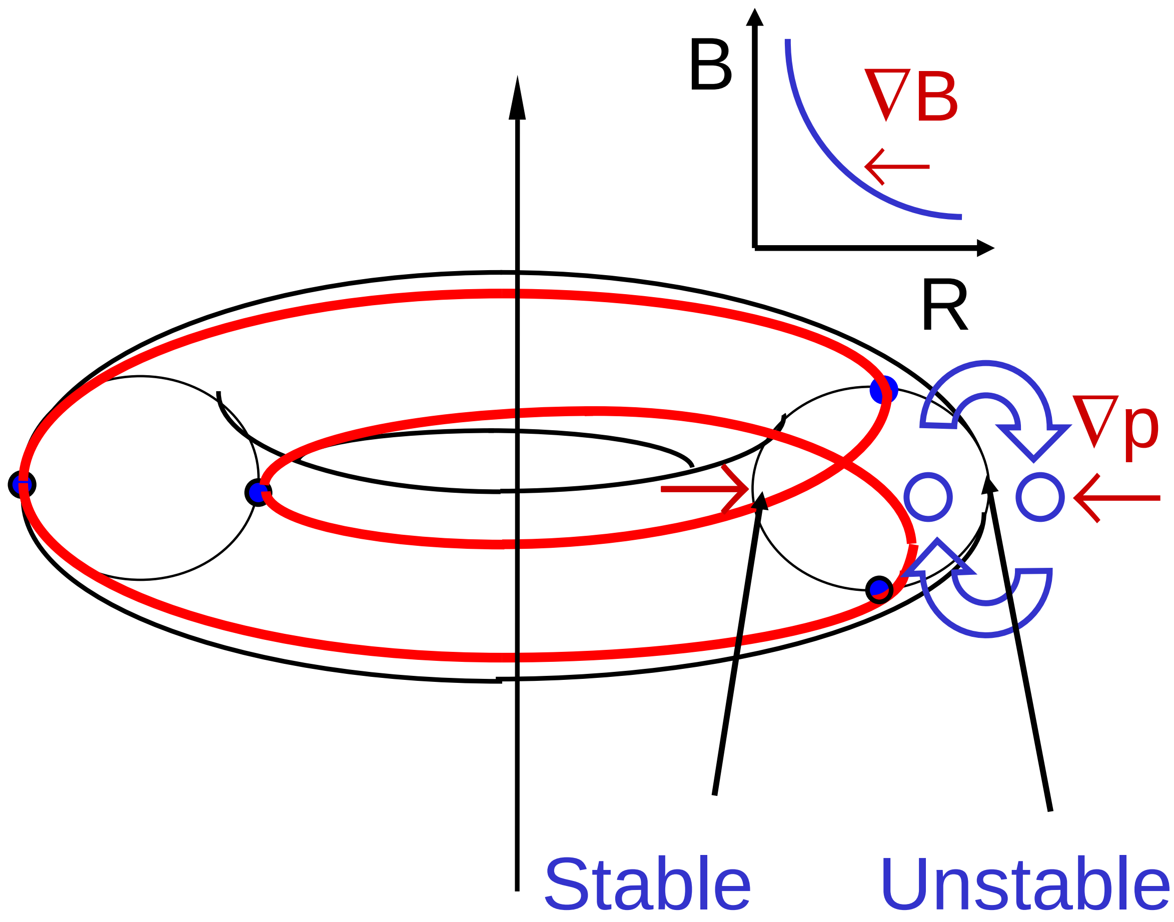
$\chi_m << \chi_{es}$ except at high β

Main instabilities are interchange modes

- Exchange of two flux tubes is energetically favourable if

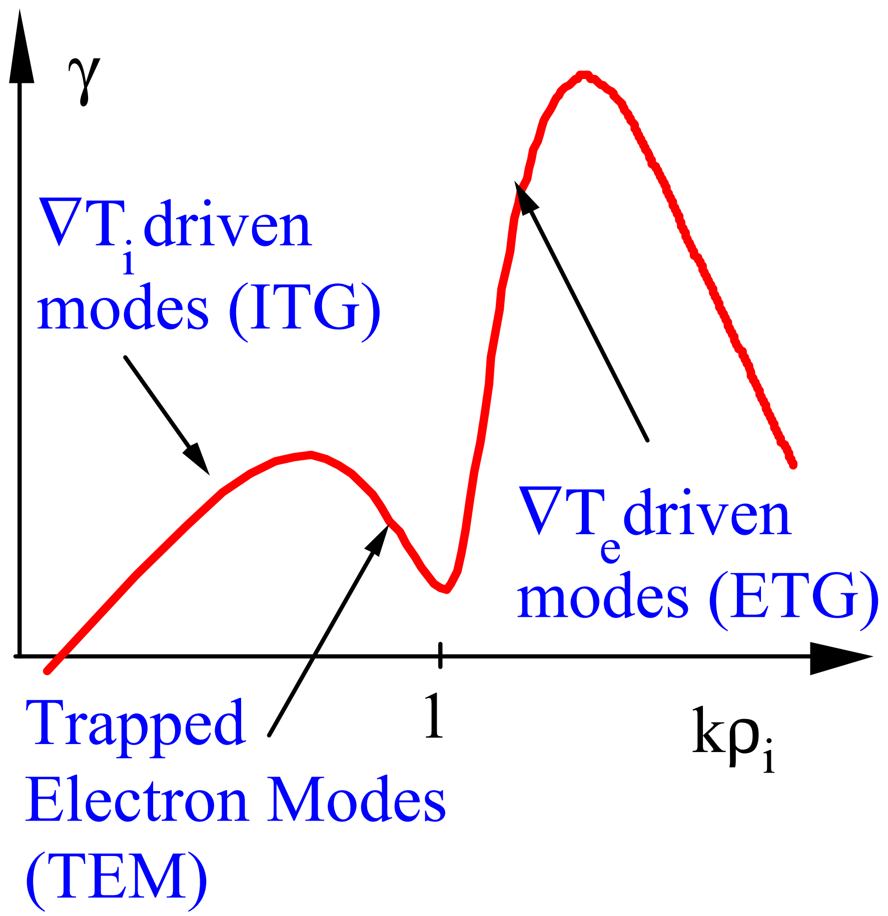
$(v_E \cdot \nabla B)(v_E \cdot \nabla p) > 0$

- Stable and unstable regions are connected by field lines.



Several branches are potentially unstable

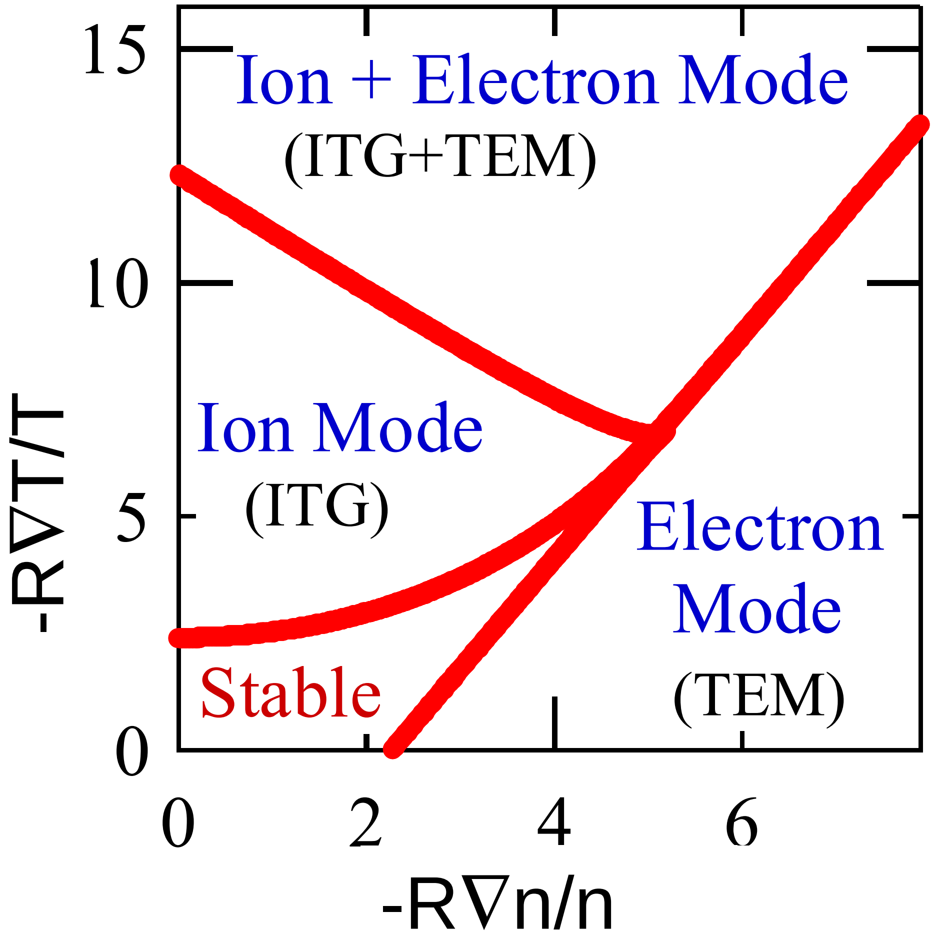
- Ion Temperature Gradient modes: driven by passing ions, interchange + “ slab ”
- Trapped Electron Modes: driven by trapped electrons, interchange type.
- Electron Temperature Gradient modes: driven by passing electrons
- Ballooning modes at high β



Electron and/or ion modes are unstable above a threshold

- Instabilities → turbulent transport
- Appear above a threshold κ_c.
- Underlie particle, electron and ion heat transport : interplay between all channels.

Stability diagram -Weiland model



Similarity principle

- Basics
- Scaling with normalized gyroradius
- Scaling with collisionality and β.

Dimensionless numbers

Kadomtsev '75

- Numbering of dimensionless parameters for a given set of plasma parameters
- 8 numbers for a pure e-i plasma

I. $\nu^* = qR/\lambda_{mfp} \quad \rho^* = \rho_c/a \quad \beta = 2\mu_0 p/B^2$

II. $A = R/a \quad \tau = T_e/T_i \quad q$

III. $\mu = m_e/m_i \quad N = n_e \lambda_d^3$

- Implications on confinement time, II and III given

$$\omega_c \tau_E = \overline{\tau}(\rho^*, \beta, \nu^*)$$

Scale invariance

Connor&Taylor '77

- Analysis of scale invariance of Fokker-Planck equation coupled to Maxwell equations $\rightarrow$ local relations.

- If geometry, profiles, and boundary conditions are fixed, plasma is neutral, then

$$\chi = \frac{T}{eB}\overline{\chi}(\rho^*, \beta, \nu^*)$$

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Dimensionless scaling is a powerful tool to predict transport in a next step device

Similarity principle

$\omega_c\tau_E=F(\rho_*, \beta,\nu_*)$

Normalised gyroradius:

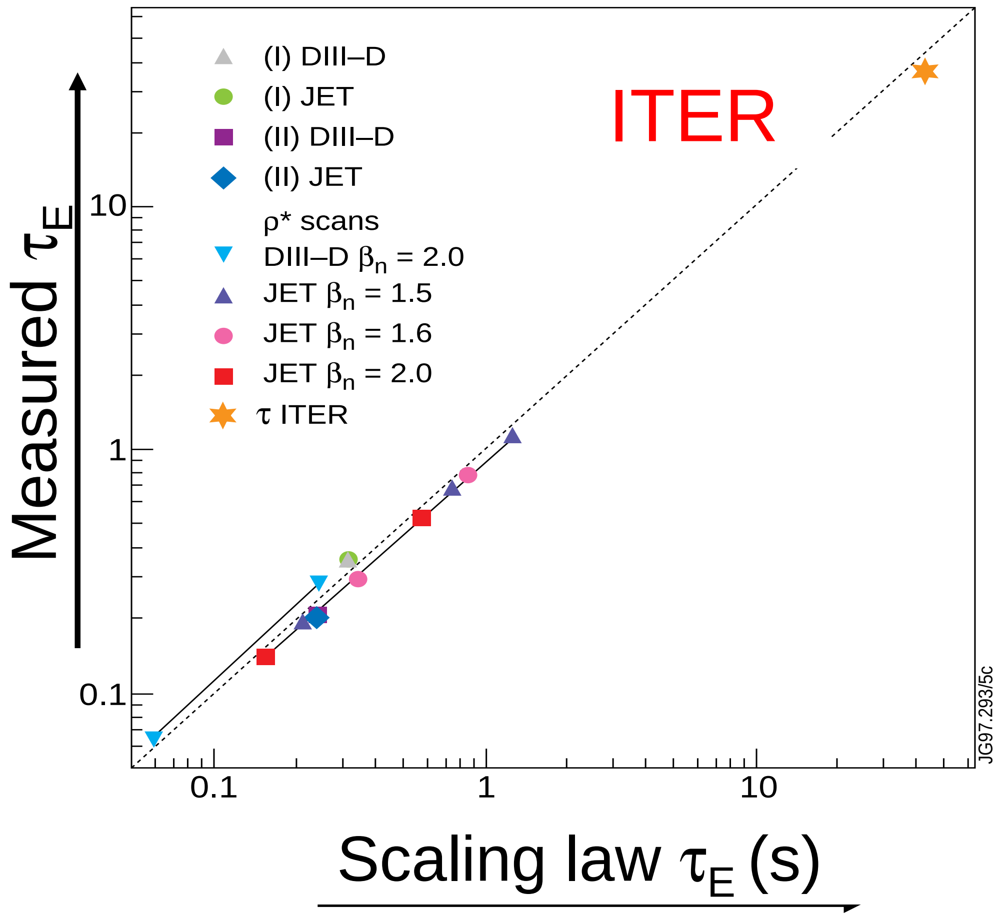
$$\rho_* = \frac{\rho_c}{a}$$

beta: $$\beta = \frac{p}{B^2/2\mu_0}$$

collisionality:

$$\nu_* = \frac{\nu_{coll}}{c_s/R}$$

Measured τ_E vs fit, ITPA



β has a weak influence on confinement

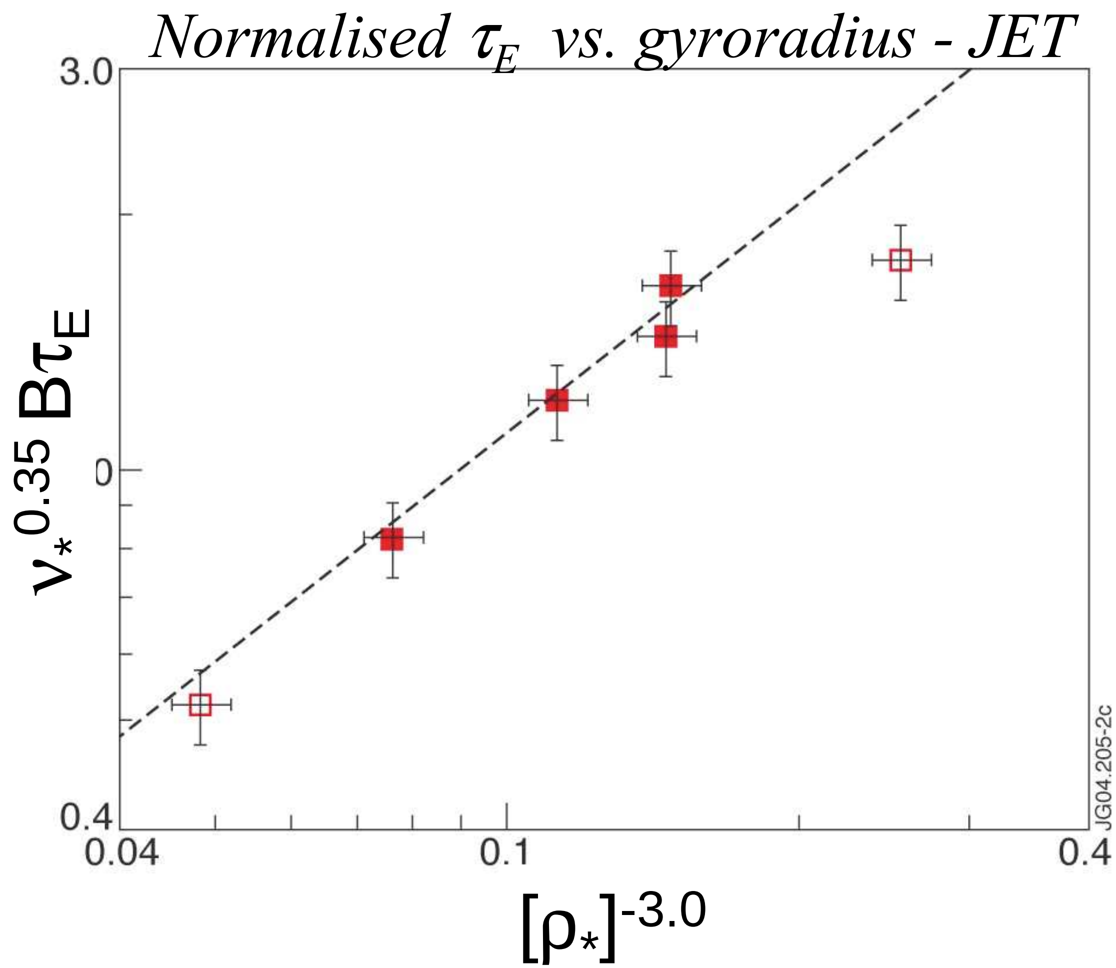
- Experiments on DIIID and JET

$\omega_c \tau_E \equiv \rho_*^{-3.0} \beta^{0.0} \nu_*^{-0.35}$

- Consistent with electrostatic turbulent transport :

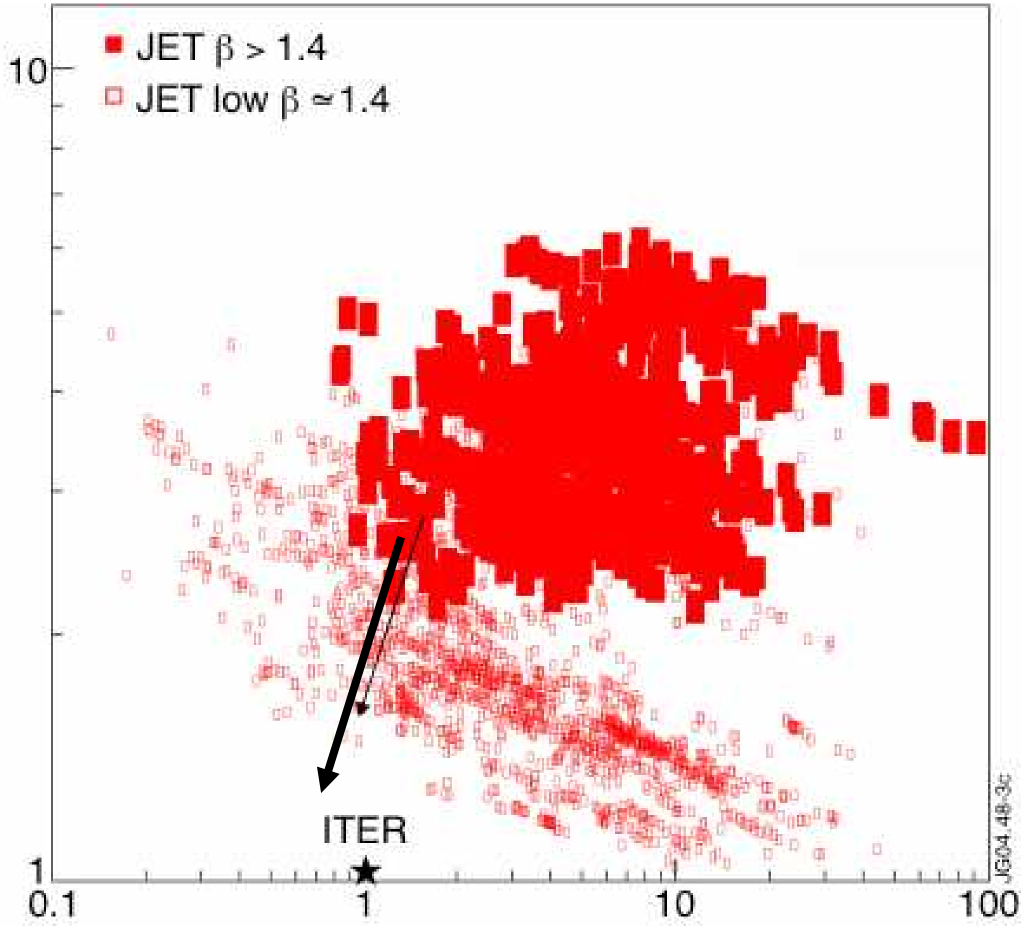
$L_c \equiv \rho_c$ and $\tau_c \equiv R/c_s$

$\omega_c \tau_E \equiv \rho_*^{-3.0} \beta^{0.0} \nu_*^{?}$



ρ_* and ν_* will be smaller in ITER

ρ_* / ρ_{*ITER}



ν_* / ν_{*ITER}

Important for transport models

- At fixed β and ν^*,

$$\frac{L_c}{a} \equiv [\rho_*]^{\frac{\alpha+1}{2}} \qquad \gamma \equiv \frac{c_s}{a} \rightarrow \qquad \chi \equiv \frac{T}{eB}[\rho_*]^{\alpha}$$

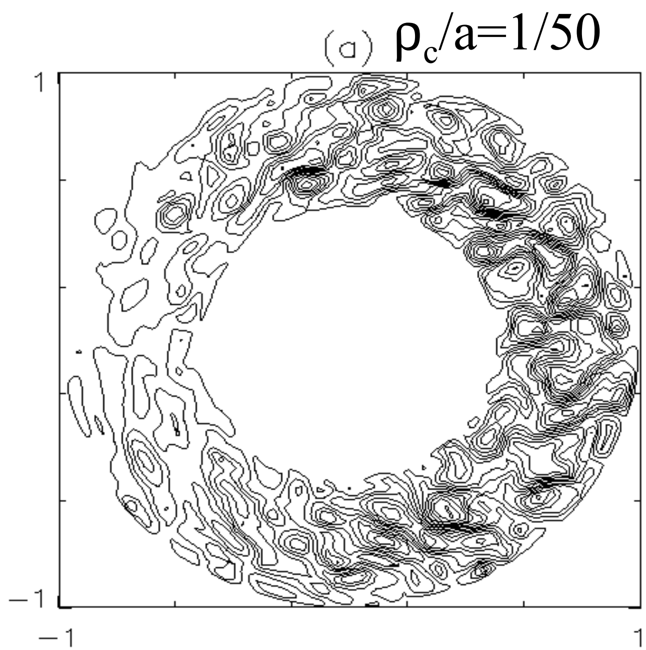
- Two main cases: $\alpha=1$ (gyroBohm) and $\alpha=0$ (Bohm).

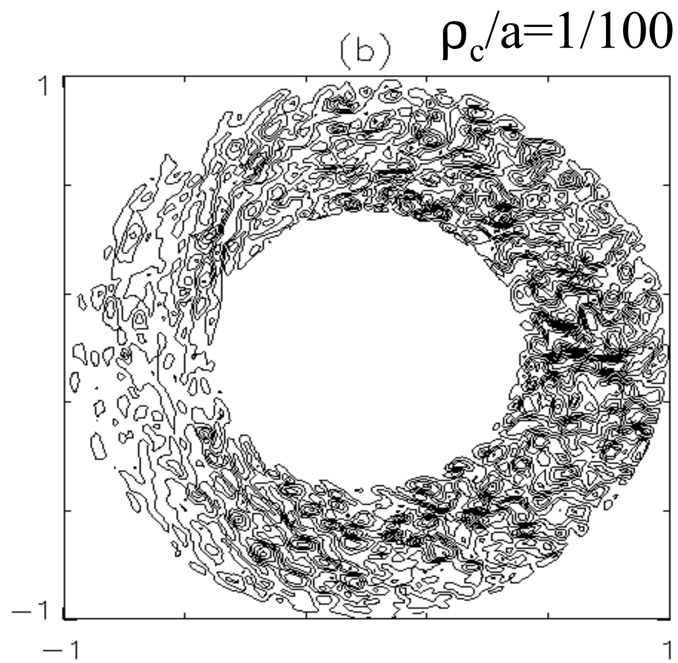
- Theory predicts that when $\rho_* \rightarrow 0$, the scaling is gyroBohm

$$\chi \equiv \frac{T}{eB}\rho_*$$

An example of gyroBohm scaling

- Simulations where the scale ρ* is changed by a factor 2
- Agree with $L_c \equiv \rho_c$ and $D \equiv (T/eB)\,\rho_c/a \rightarrow \omega_c \tau_E \equiv \rho_*^{-3} F(\beta, \nu_*)$

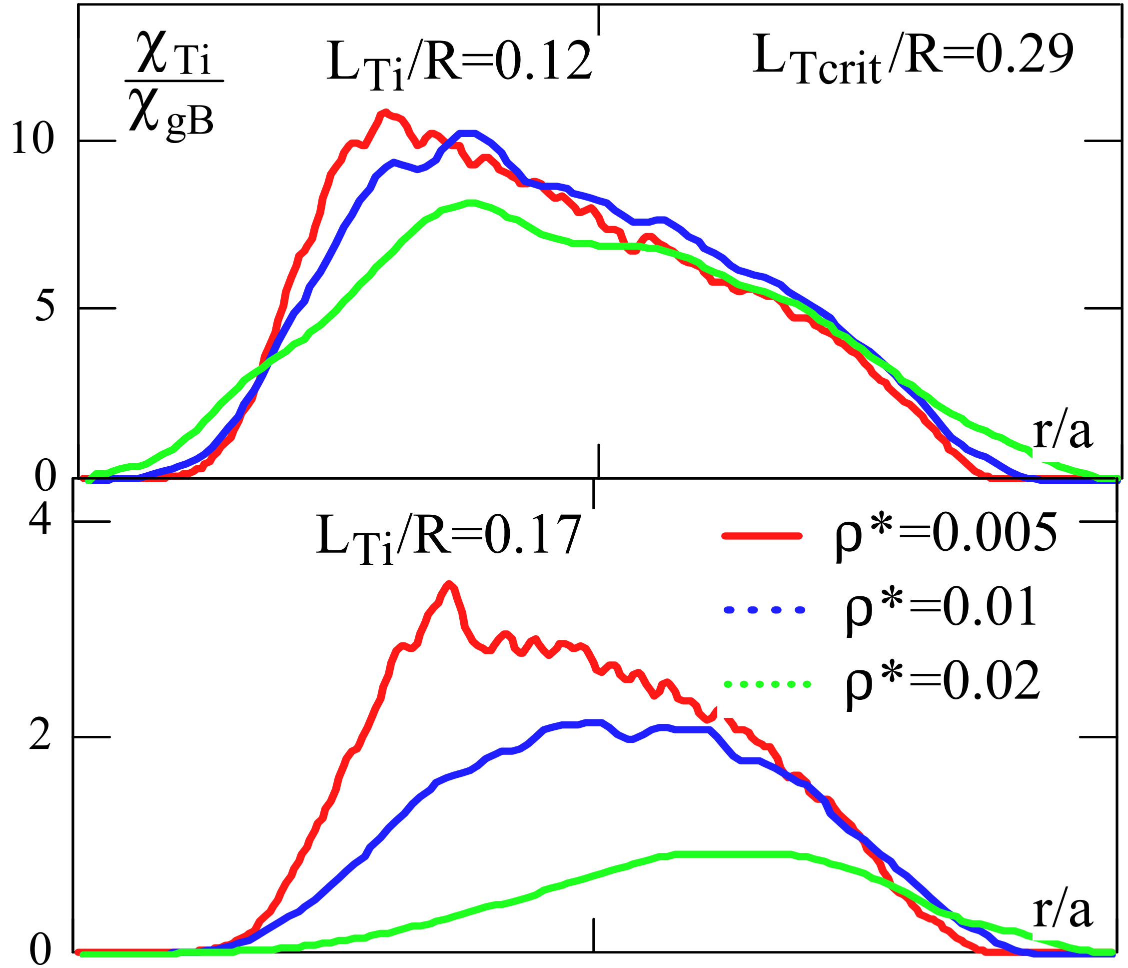




Ottaviani 99

Investigating scaling laws

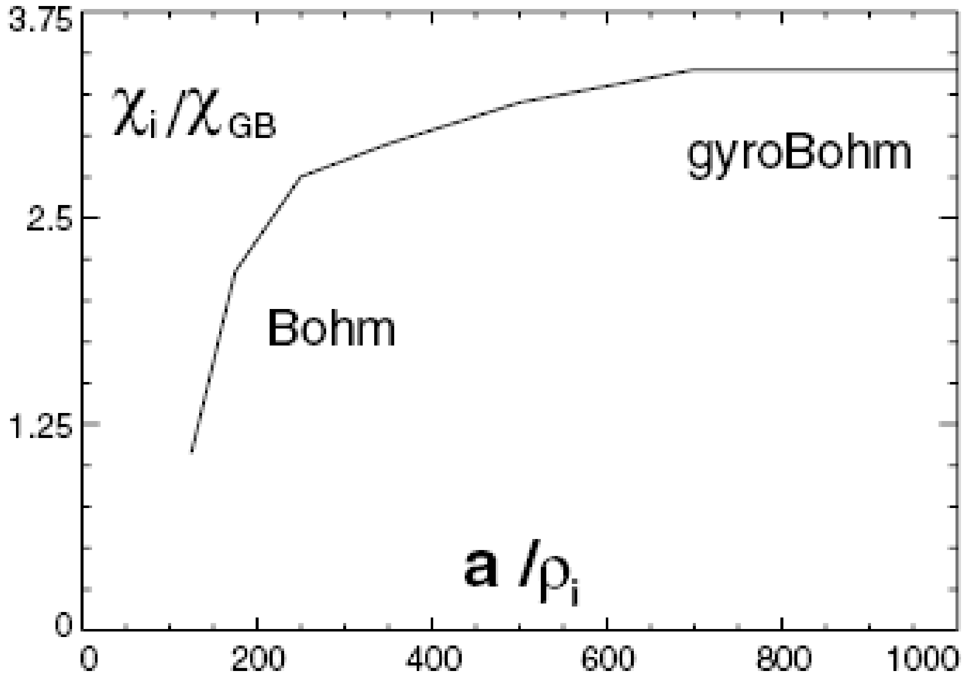
- When $\rho_* \to 0$, scaling is found to be gyroBohm
- Some departure from gyroBohm is found for $\rho_* > 10^{-2}$
- gyroBohm is the most favorable scaling



Scaling is gyroBohm when $\rho^* \to 0$

- Gyrokinetic and fluid simulations find that the scaling is gyroBohm when $\rho^* \to 0$

- The transition value of ρ^* is still subject to debate.



Lin 02

GyroBohm scaling law is favorable for ITER

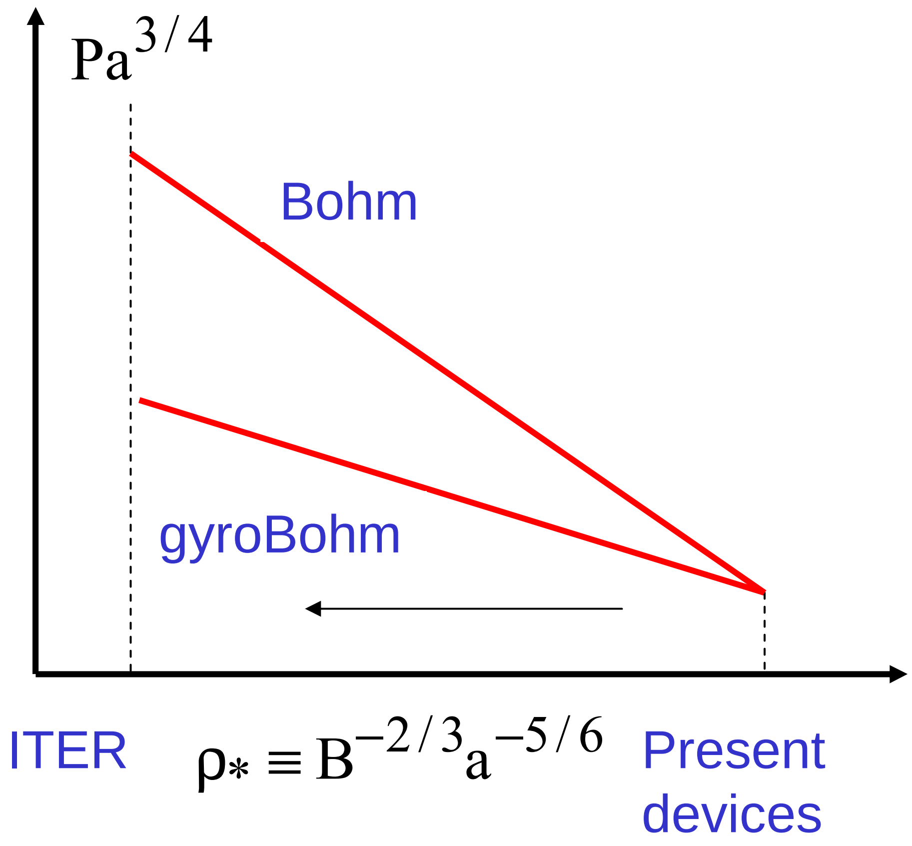
- At constant β and ν^* the normalised loss power $Pa^{3/4}$ is a function of

$$\rho_* \equiv B^{-2/3} a^{-5/6}$$

only

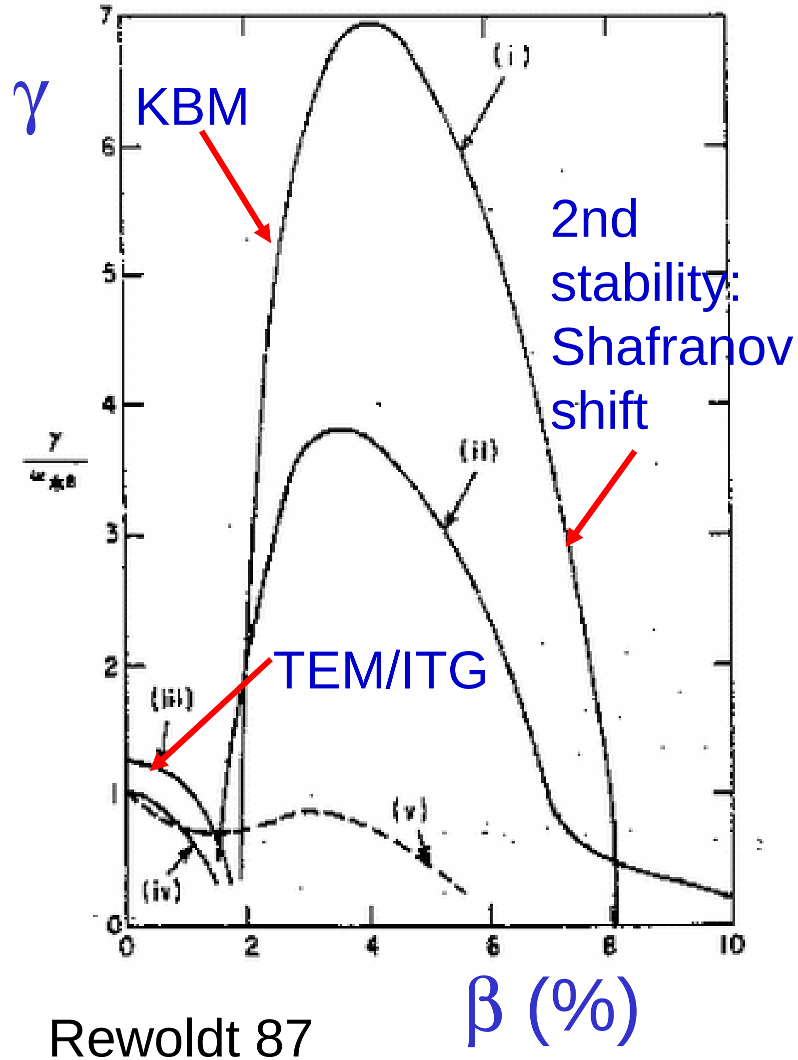
$$Pa^{3/4} \equiv [\rho_*]^{\alpha - 5/2}$$

- GyroBohm scaling corresponds to the lowest losses.



β scaling

- β controls the effects of magnetic fluctuations.
- β also controls the Shafranov shift (2nd stability).
- Linear stability combines these 2 effects.



Rewoldt 87

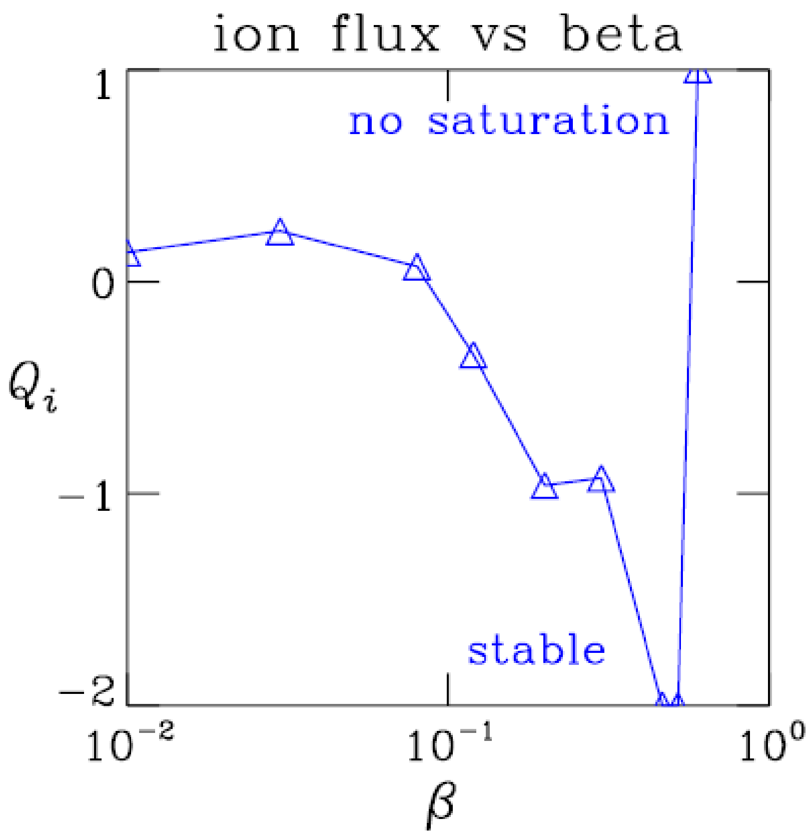
β scaling (cont.)

- Strong degradation expected at high β

Camargo 96, Snyder 01 , Scott 01 & 06

- Critical β for transition debated.
- No β dependence observed on DIII-D, JET and TS, but seen on JT-60U and AUG.

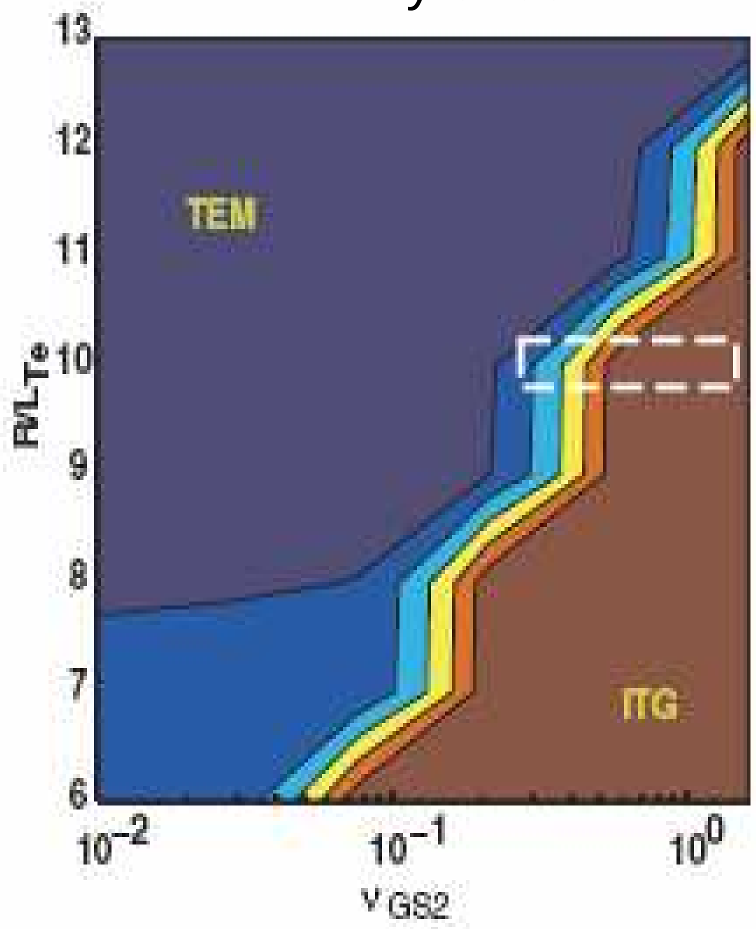
Scott 06



ν* scaling: trapped electrons

- Collisionality stabilizes TEM → $\omega_c\tau_E$ should be an increasing function of ν* .
- Should affect χ_e more than χ_i → might be invisible on τ_E .

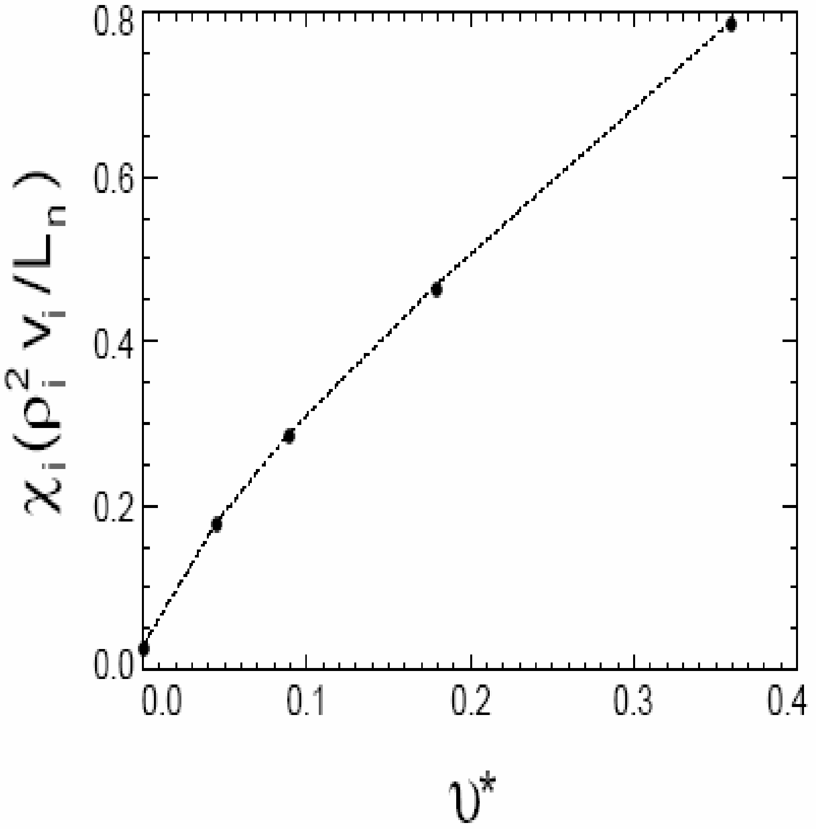
Ryter 05



ν* scaling: zonal flows

- Collisions damp zonal flows $\rightarrow$ $\omega_c \tau_E$ should be a decreasing function of ν*
- Found in numerical simulations
  Lin '98 , Falchetto '05
- Compete with effect on trapped electrons.

Lin 98



No a definite scaling with ν^*

- $\omega_c\tau_E$ is a decreasing function of ν^*

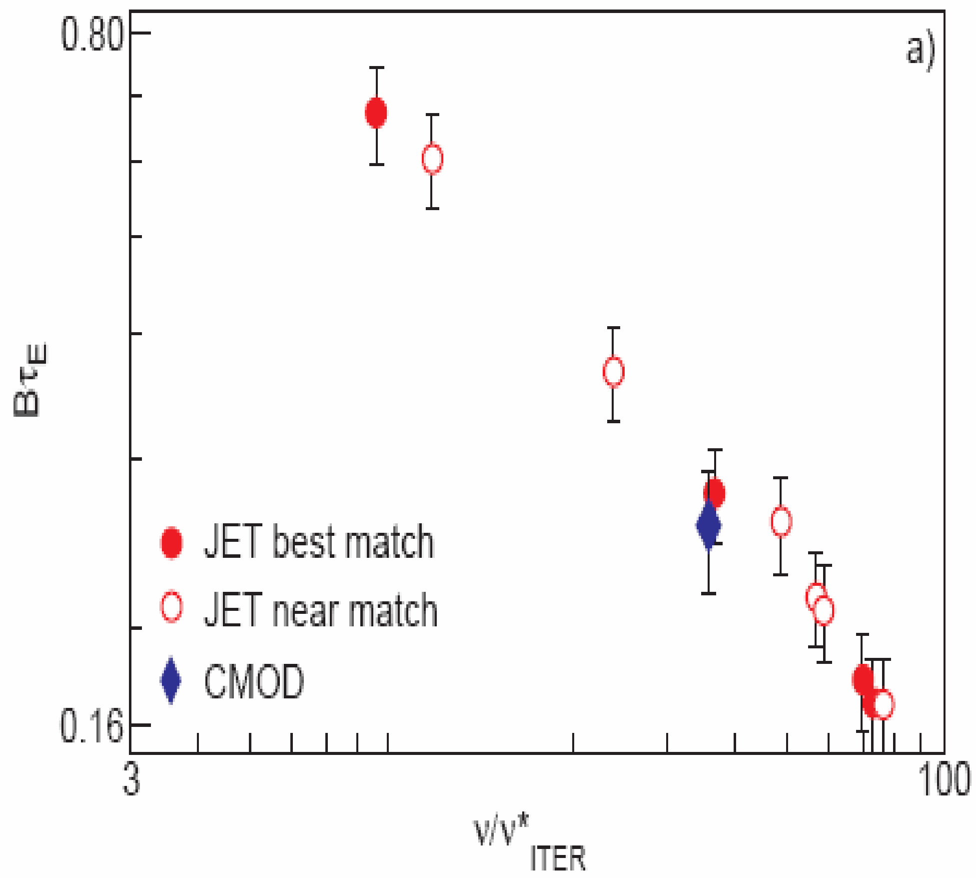
- Not a definite scaling

$\omega_c\tau_E \equiv [\nu^*]^{-0.3}$ at low ν^*

$\omega_c\tau_E \equiv [\nu^*]^{-0.8}$ at high ν^*

- May reflect competing effects.

McDonald 06



Building a Transport Model

- Mixing Length Estimate.
- Combining similarity and mixing-length estimate
- A simplified model: critical gradient model

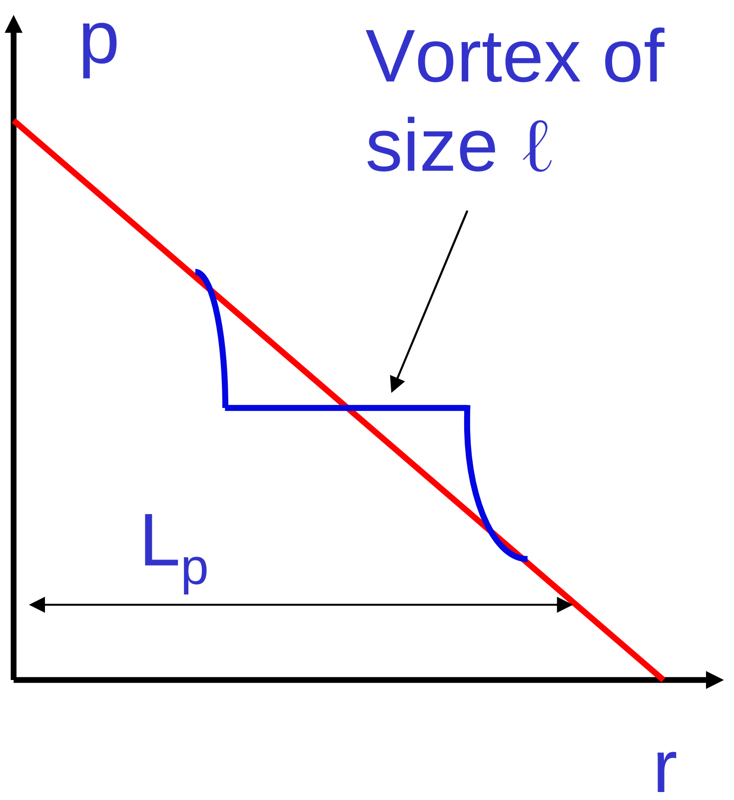
Mixing-length estimate : level of fluctuations

- Mixing of the pressure profile by vortex of size ℓ

$$\frac{\delta p_\ell}{p} \approx \frac{\ell}{L_p}$$

- With a bit of cooking …

$$\frac{e\phi_k}{T} \approx \frac{\delta p_k}{p} \approx \frac{\gamma_k}{\omega_k^2 + \gamma_k^2} \frac{1}{k_\perp L_p}$$



Mixing-length estimate : diffusion

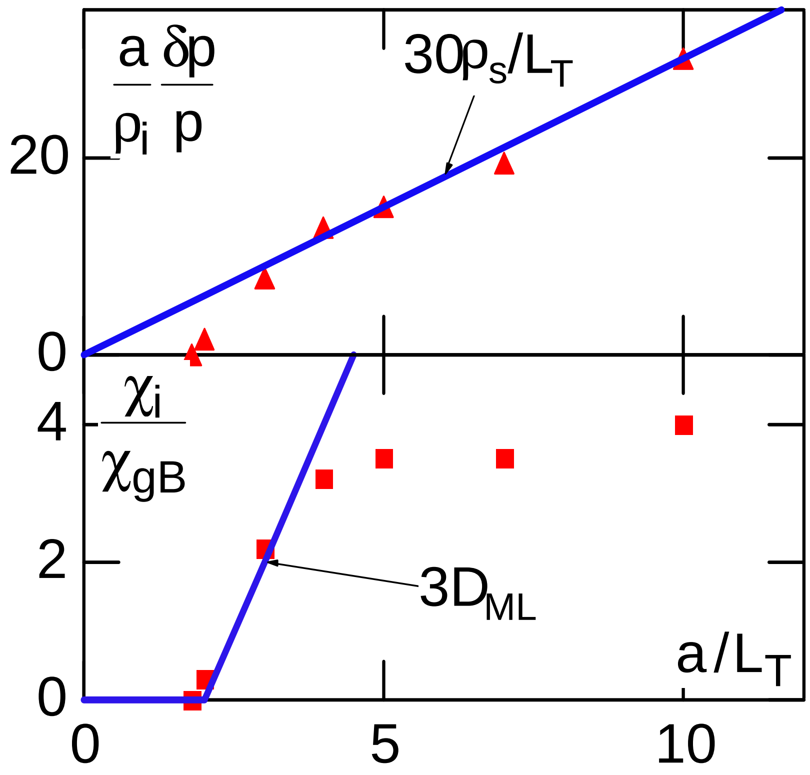
- Quasi-linear diffusion

$$D = \sum_k |v_{Ek}|^2 \tau_{ck}$$

- Combining with mixing-length estimate

$$D = \sum_k \frac{\gamma_k}{k_\perp^2}$$

Waltz 1994



Critical Gradient Model

- Rules for correlation length and time :

$$L_c \equiv \rho_s \qquad \gamma \equiv \frac{c_s}{R}\left(\left|\frac{RdT}{Tdr}\right| - \kappa_c\right)^{\sigma}$$

- Mixing length estimate :

$$\chi_T = \chi_s \left(\frac{T}{eB}\frac{\rho_s}{R}\right)\left(\left|\frac{RdT}{Tdr}\right| - \kappa_c\right)^{\sigma}$$

Stiffness GyroBohm Threshold

- Can be extended to more complex models$\rightarrow$ Weiland and GLF23 models.

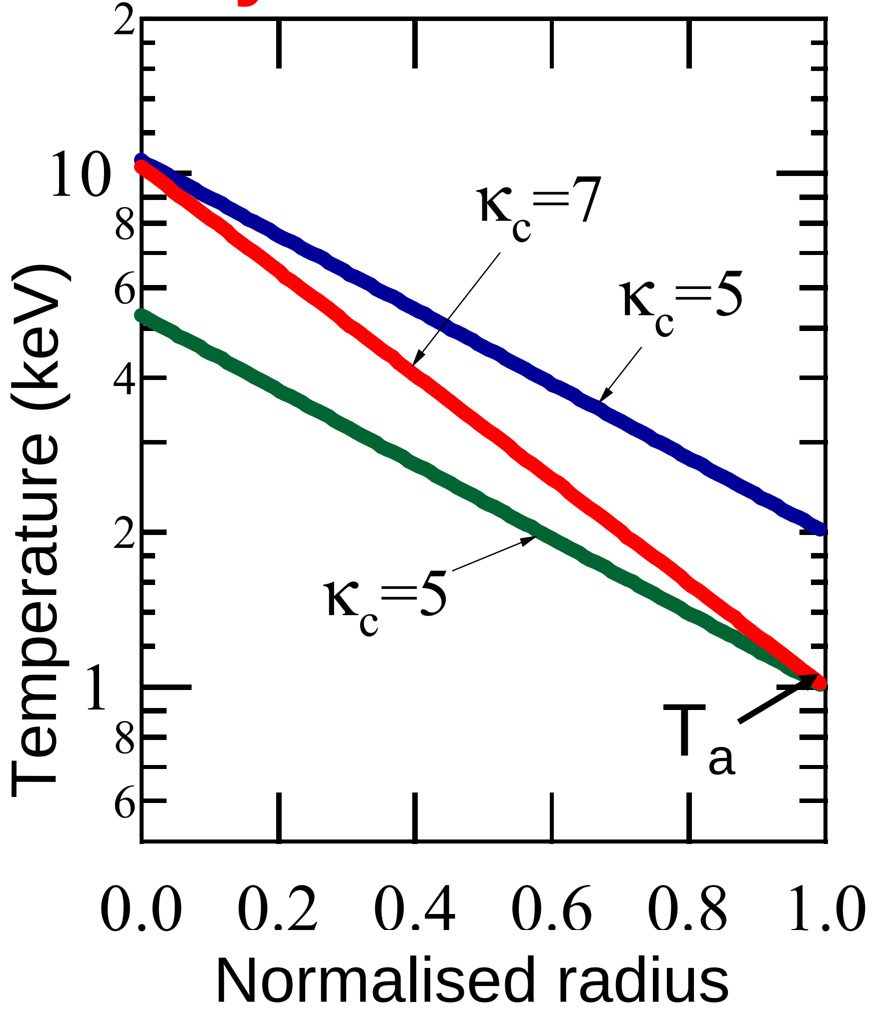
A useful, but controversial, concept : marginal stability

- Marginally stable profile

$$T = T_a e^{\kappa_c \frac{a-r}{R}}$$

- Stiffness: tendency of profiles to stay close to marginal stability.
- Central temperature is improved if

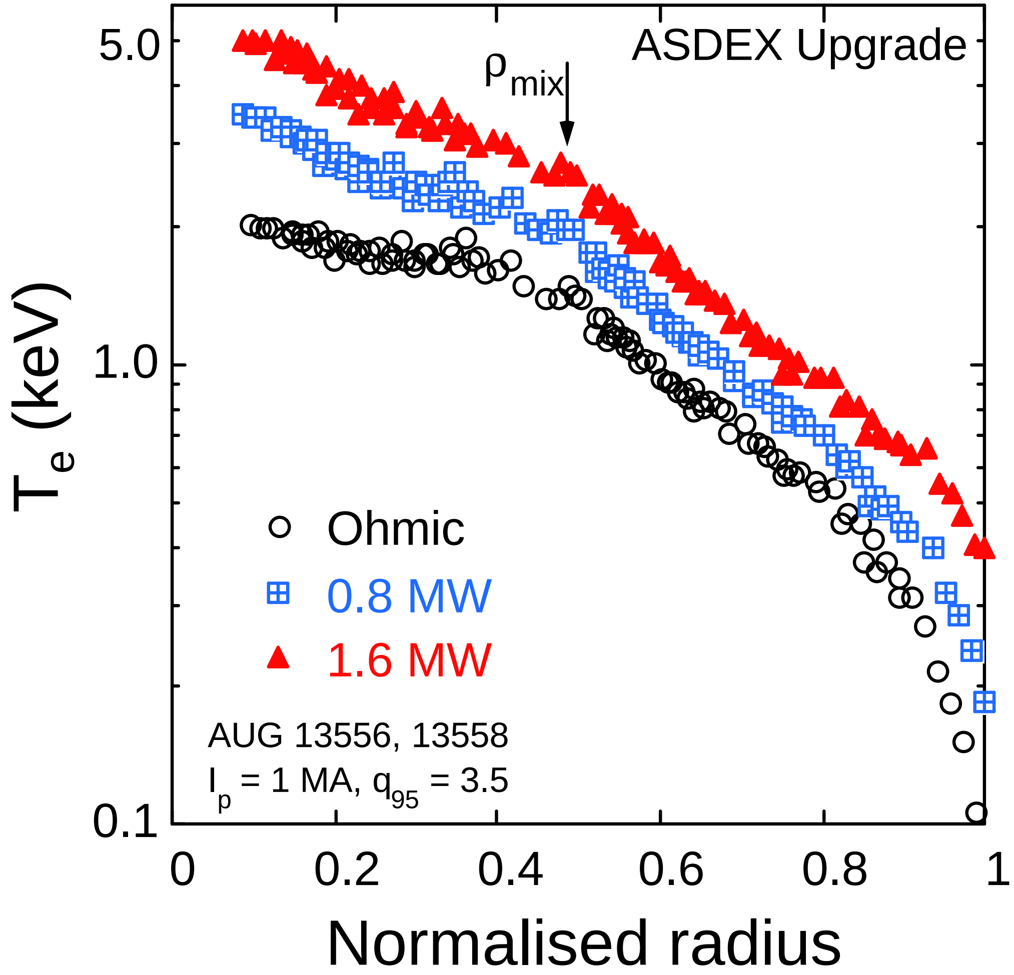
- threshold κ_c is larger
- edge pedestal T_a is higher.



Profiles are not marginally stable everywhere

- Edge plasma gets closer to the threshold for high T_{edge}

- Core plasma is subcritical.



Modulation experiments provide a stringent test of transport models

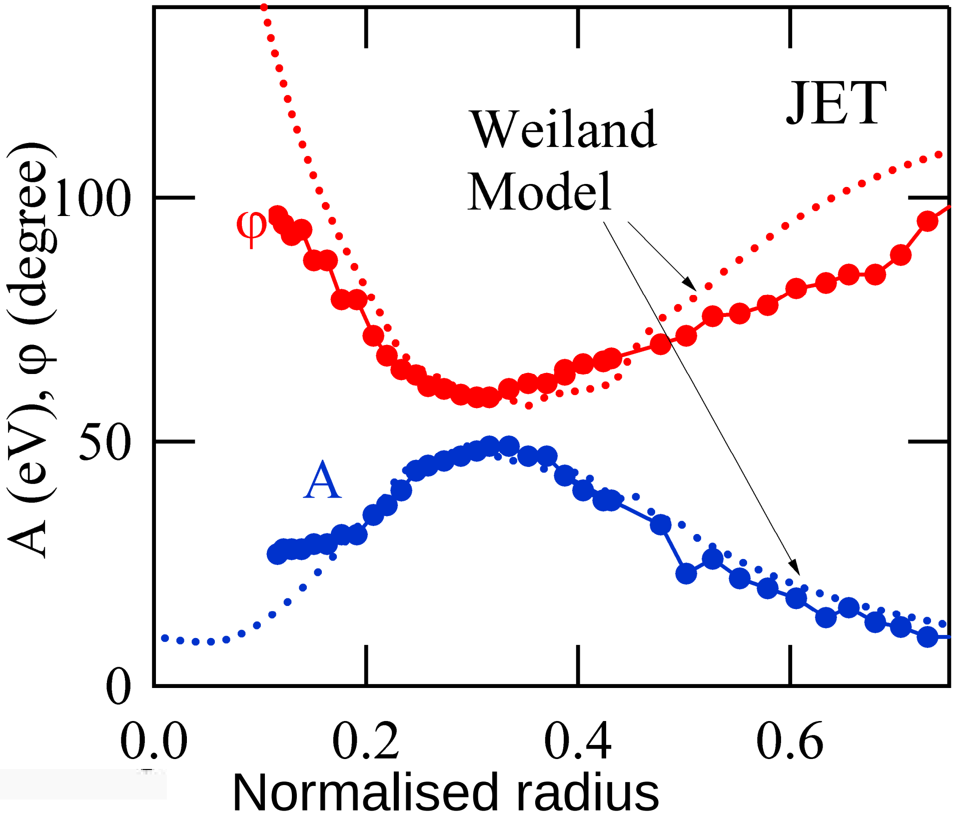
- Localised electron heat modulation.
- Slope $\sim 1/[\chi_{hp}]^{1/2}$

$$\chi_{hp} = \chi + \nabla T \partial\chi/\partial\nabla T$$

→ Assessment of transport models.

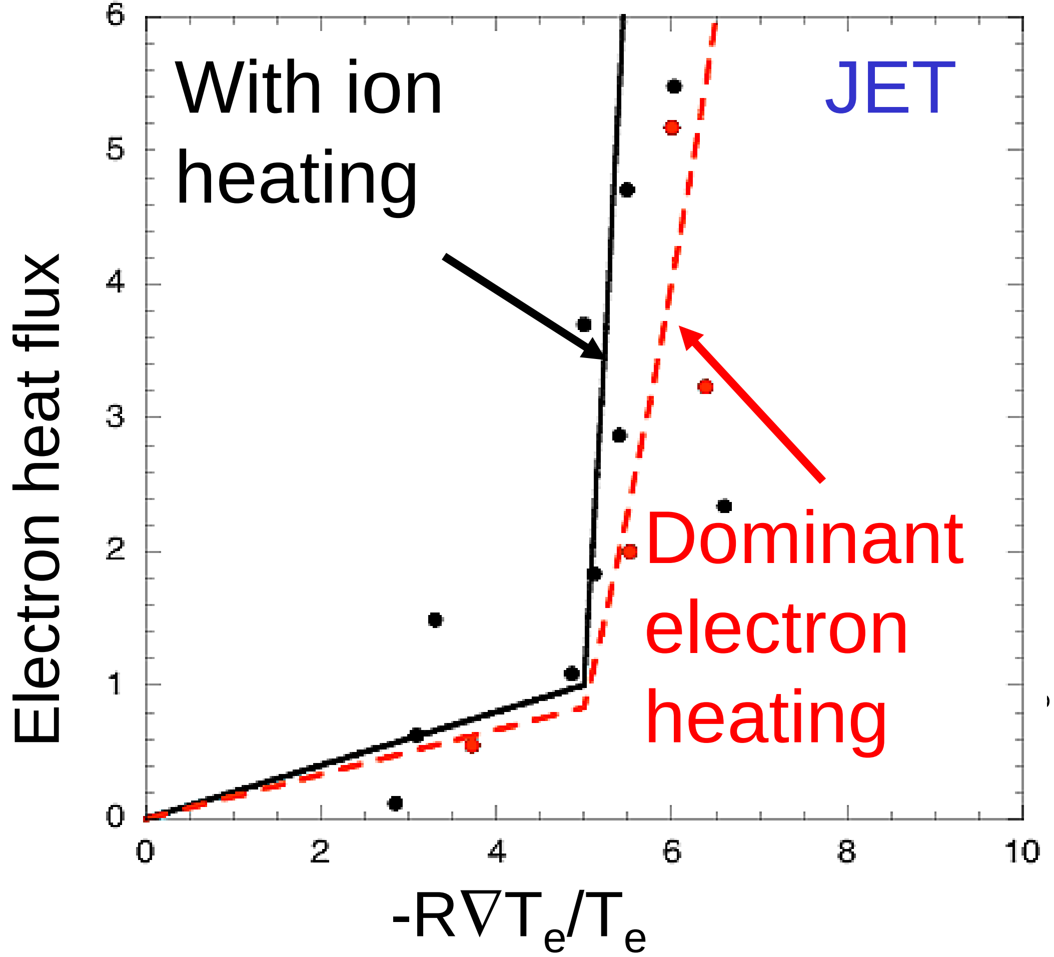
→ stiffness χ_s and threshold κ_c.

Phase and amplitude vs radius



Stiffness is found to be highly variable

- Critical gradient model:
- threshold as expected.
- large variation of stiffness.
- Reproduced by transport modeling and stability analysis
- Transition from electron to ion turbulence is key issue.

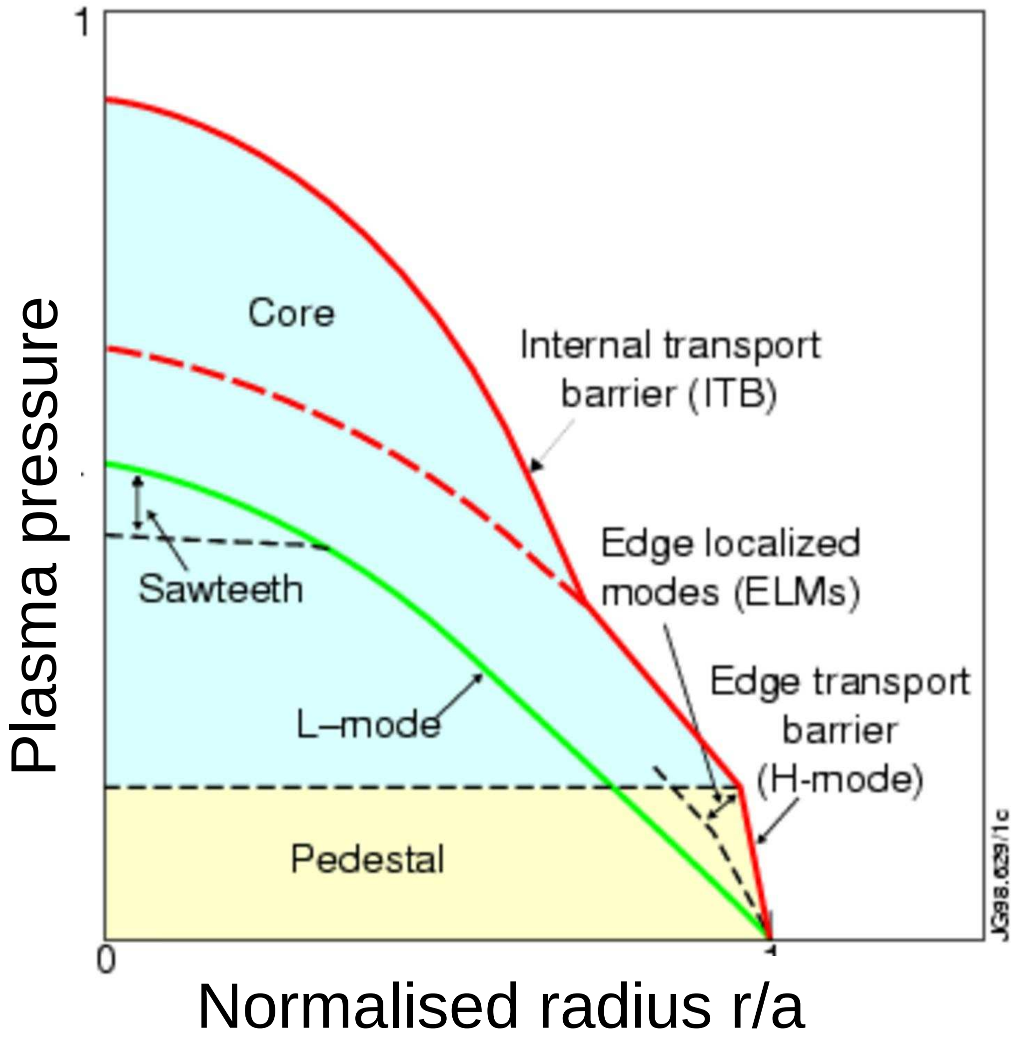


Improved confinement

- Shear flow
- Negative magnetic shear
- Transport barriers
- Consequences

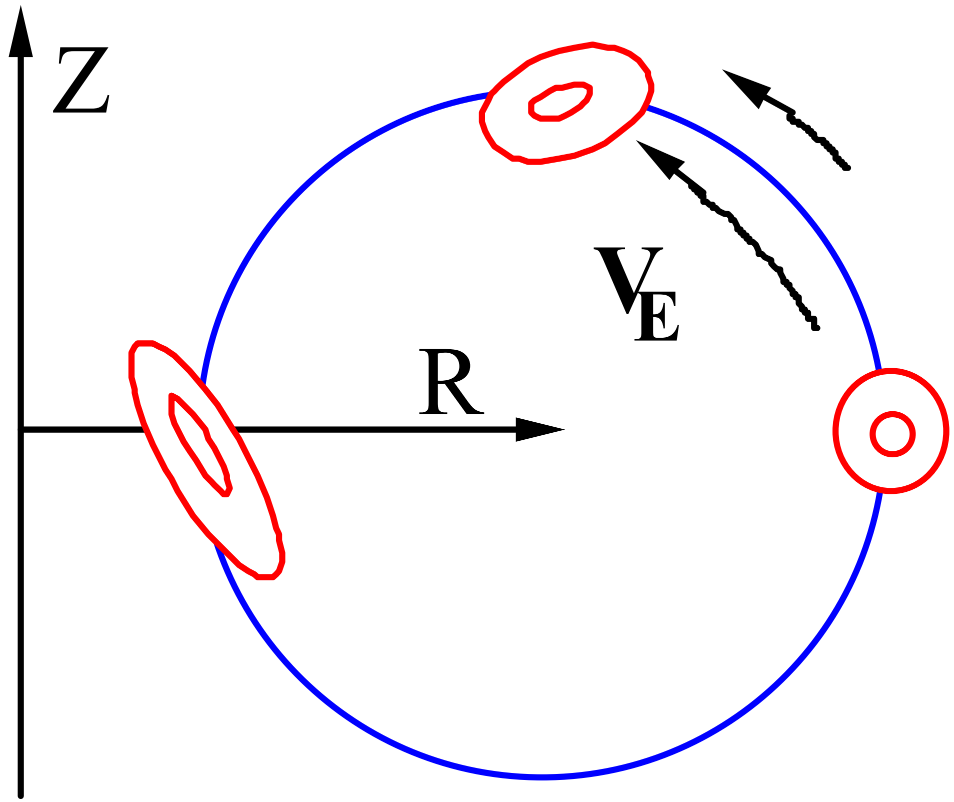
Several “regimes” in a tokamak plasma

- L-mode: basic plasma, turbulence everywhere.
- H-mode: low turbulent transport in the edge, formation of a pedestal.
- Internal Transport Barrier: low turbulent transport in the core, steep profiles.



Several mechanisms may lead to improved confinement

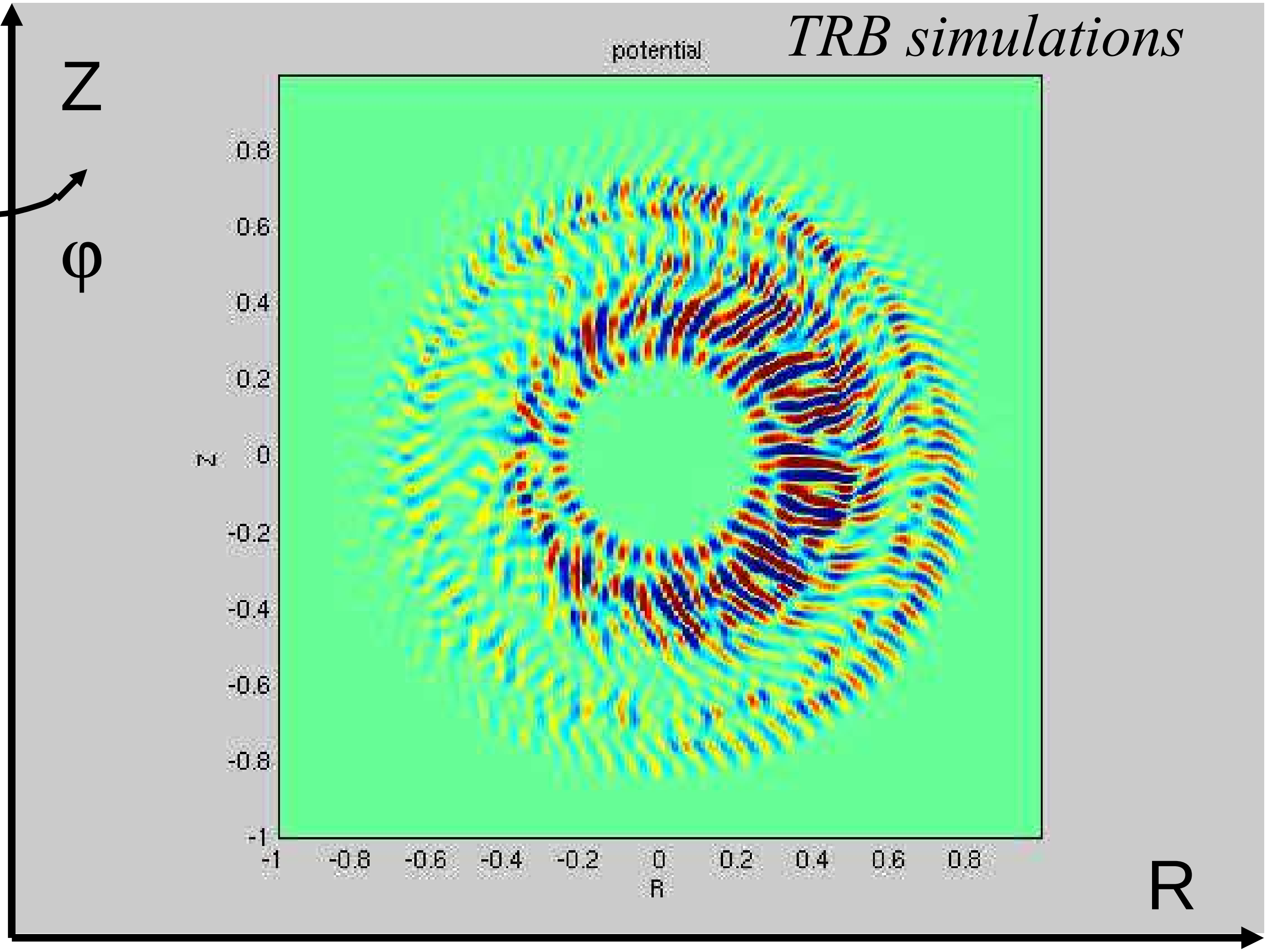
- Flow shear
- Magnetic shear
- T_e/T_i, Z_{eff}, density gradient, fast particles… : not generic



Shear flow is stabilising

- E×B velocity shear tears apart large scale vortices

- Very generic mechanism.



Contour lines of electric potential.

Flow Shear Stabilization

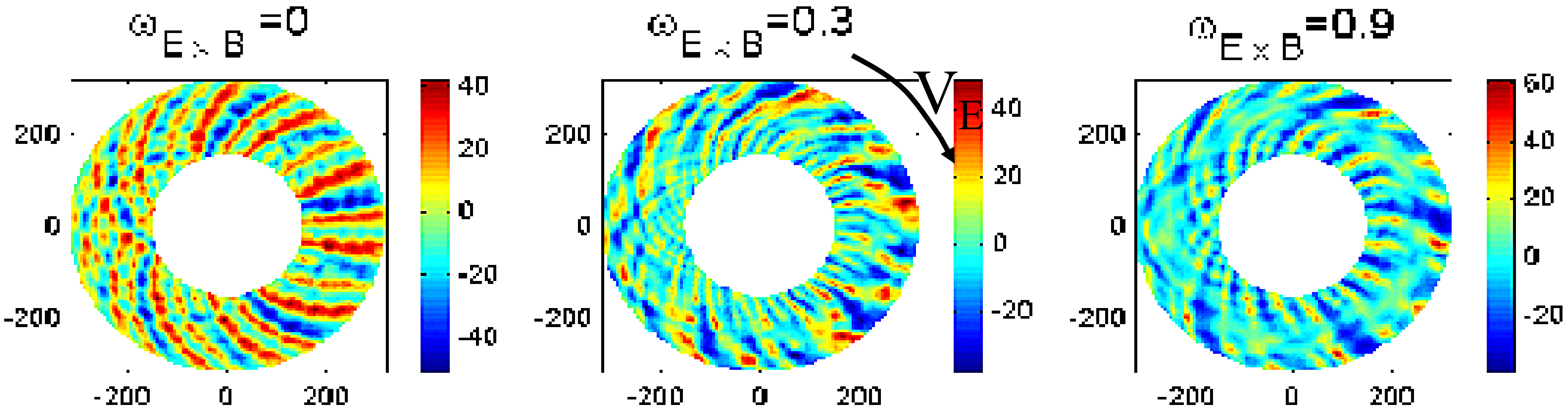
- Shear rate $V_E^{'} = \frac{dV_E}{dr}$
- Approximate criterion for stabilization

$$\left(Dk_\theta^2 V_E^{'2}\right)^{1/3} > \tau_c^{-1}$$

Biglari-Diamond-Terry 90

$$V_E^{'} > \gamma_{lin}$$

Waltz 94



Beyer 03

Controlling the Flow

- Force balance equation

$$E_r = \frac{T_i dn_i}{e_i n_i dr} + (1 - k_{neo})\frac{dT_i}{e_i dr} + V_{Ti} B_p$$

Fuelling — Heating — Toroidal momentum

$\rightarrow$ power threshold!

- Flow generation

$$\partial_t V_\theta = -\nabla_r \langle \tilde{V}_{Er} \tilde{V}_{E\theta} \rangle - \nu_{neo}\left(V_\theta - V_{eq}\right)$$

Implementation in a transport model

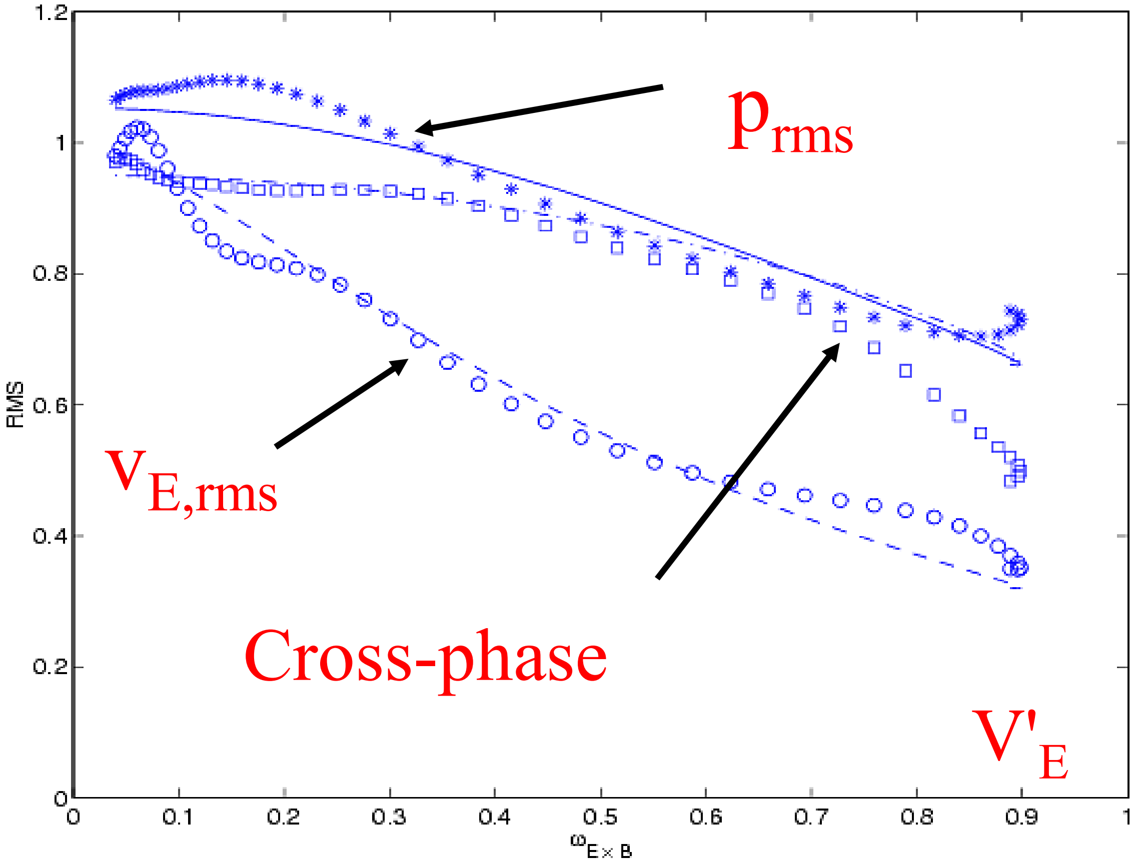
- Form factor $F(\gamma_E)$

$$F = \frac{1}{1 + [\gamma_E]^2}$$

or

$$F = 1 - \frac{\gamma_E}{\gamma_{max}}$$

Figarella 03



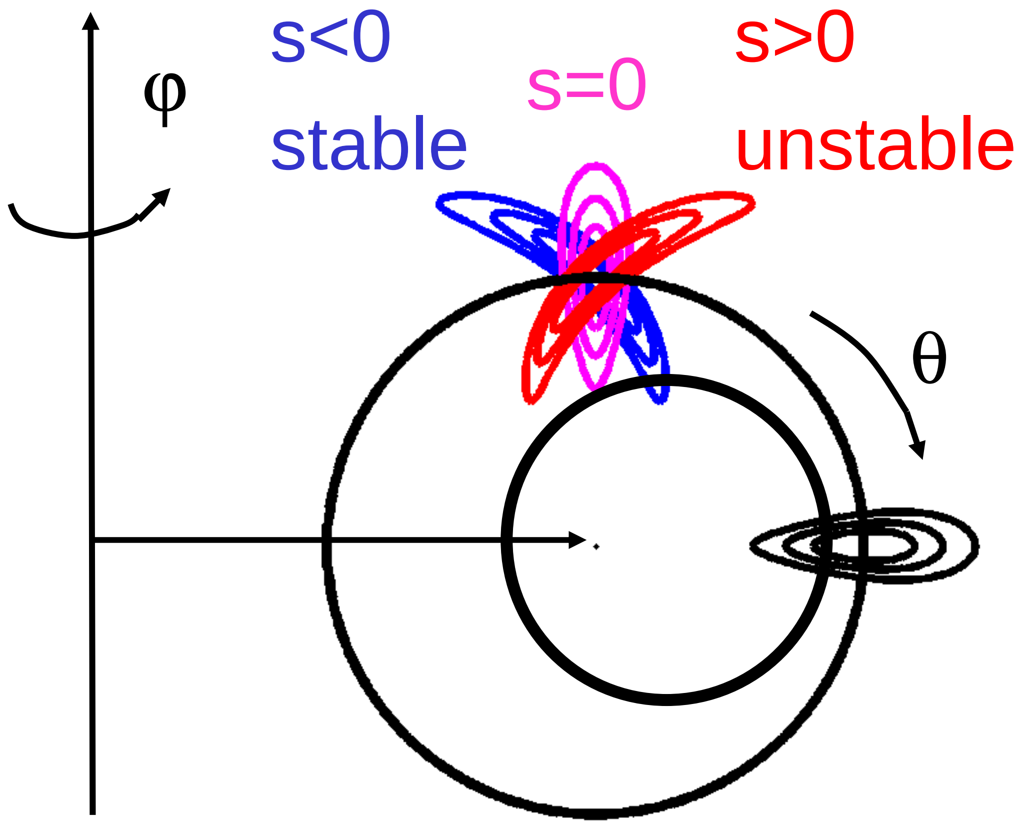
Negative magnetic shear is stabilising

- Magnetic shear :

$$s = \frac{r}{q}\frac{dq}{dr}$$

- s<0 : favourable average of interchange drive $(v_E \cdot \nabla B)(v_E \cdot \nabla p)$ along field lines.
- Enhanced by geometry effect.

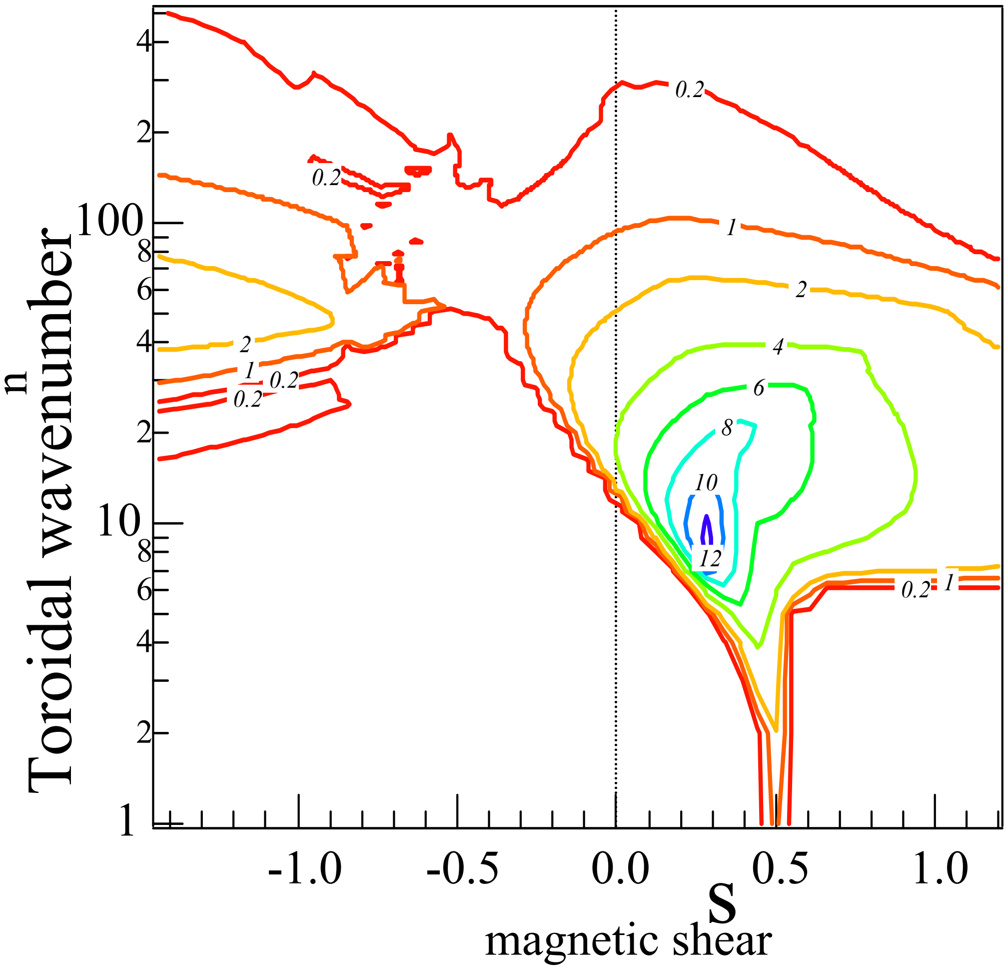
B.B.Kadomtsev, J.Connor, M.Beer, J.Drake, R.Waltz, A.Dimits, C.Bourdelle…



Vortex distorsion

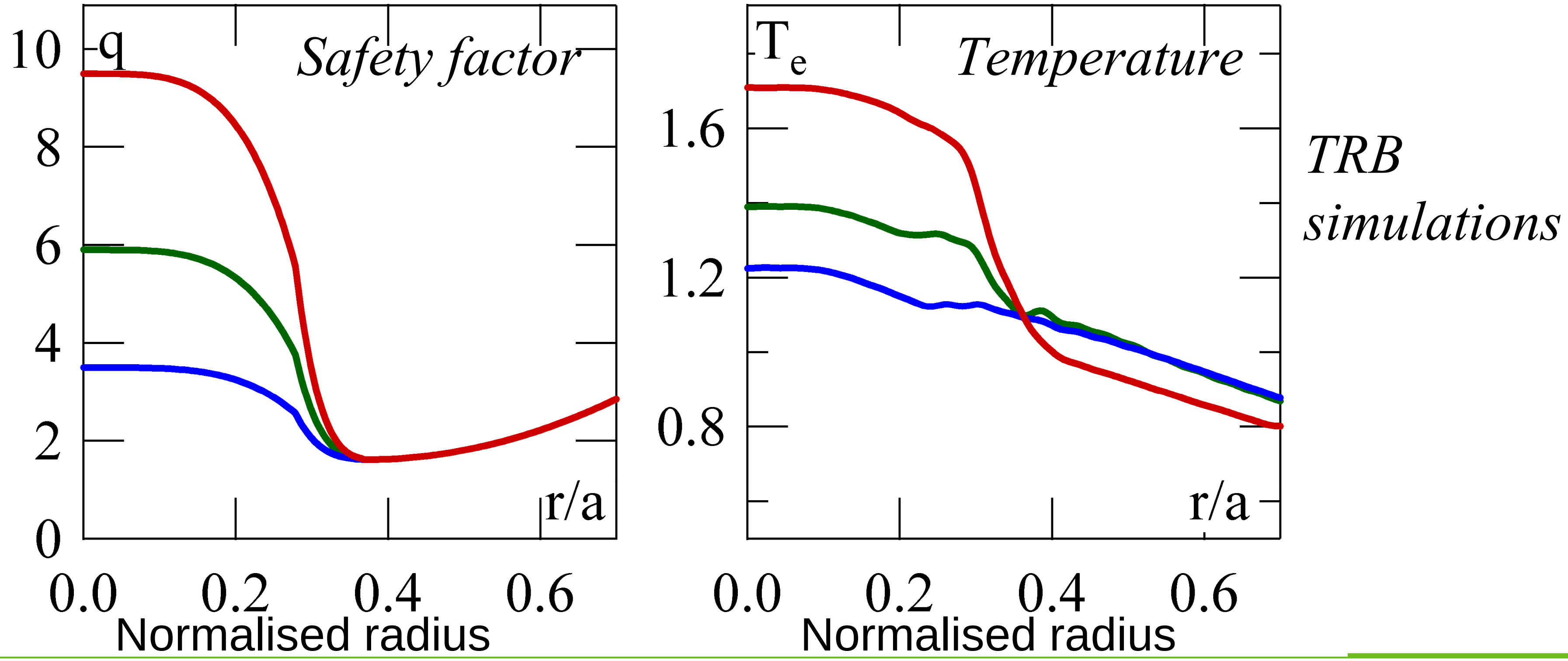
Magnetic shear: linear stability

- ITG modes are stabilized by average curvature effect
- TEM stabilization occurs via reversal of precession frequency with negative s.



Negative magnetic shear is a robust effect

- Turbulence simulations : stabilisation for s<-0.5
- Agrees with experiment (TORE SUPRA, TCV, FTU, JET, AUG …)



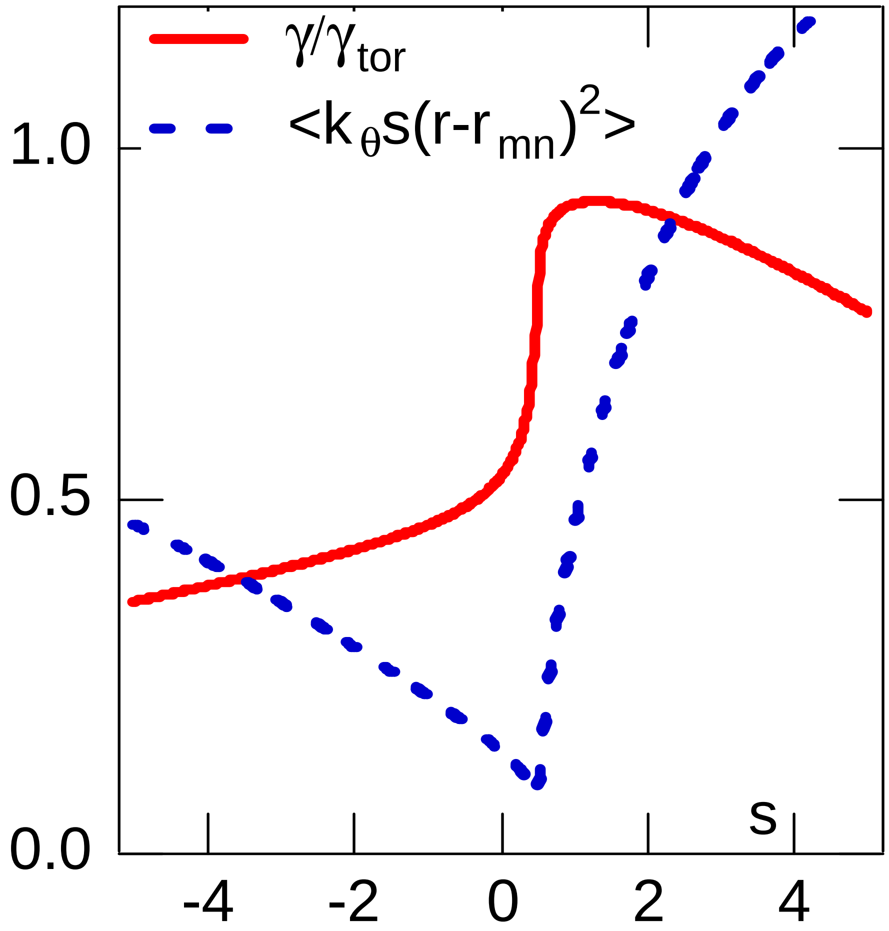
Implementation in a Transport Model

- Mixing-length estimate with actual growth rates.

- Form factor F(s)

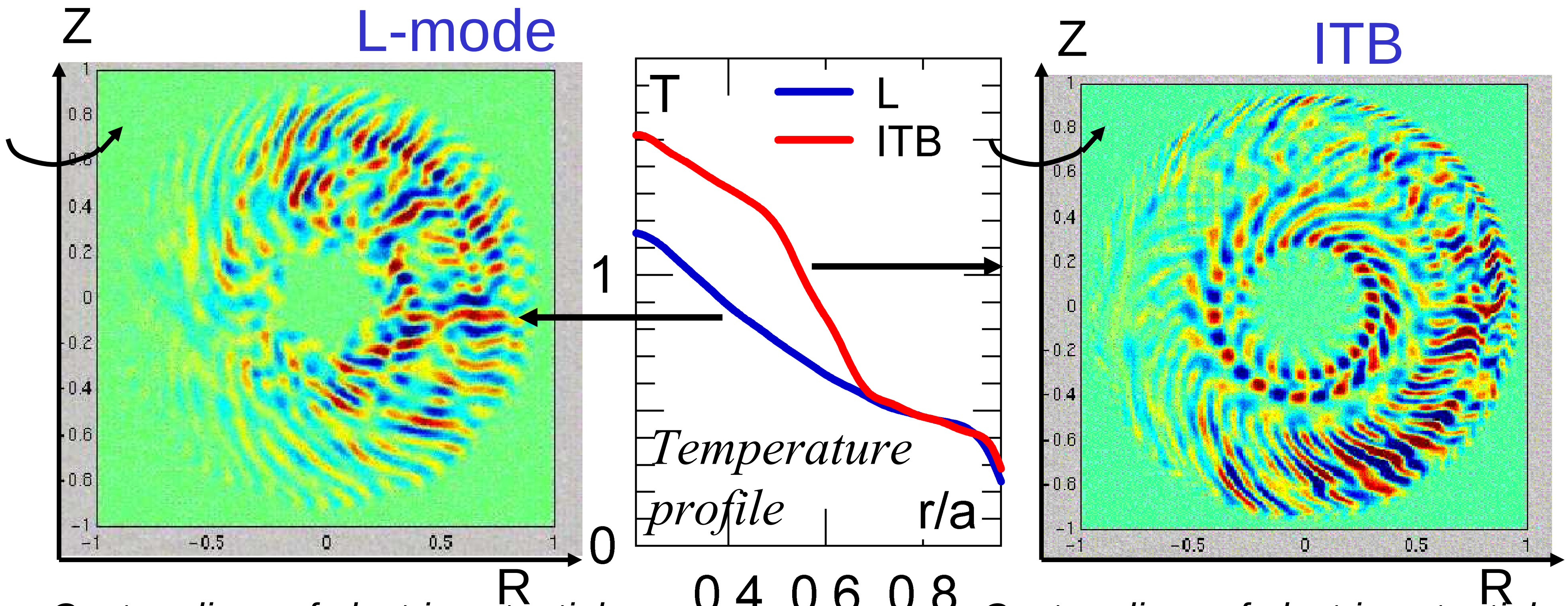
$$\chi_T = F(s)\chi_T(\text{noshear})$$

- Power threshold?



Internal Transport Barriers

- Transport barriers are layers of plasma where turbulent transport is reduced.
- Requires a minimum amount of power → triggering?



Contour lines of electric potential. *Contour lines of electric potential.*

Synergy between magnetic shear and shear flow at transition

- Force balance equation

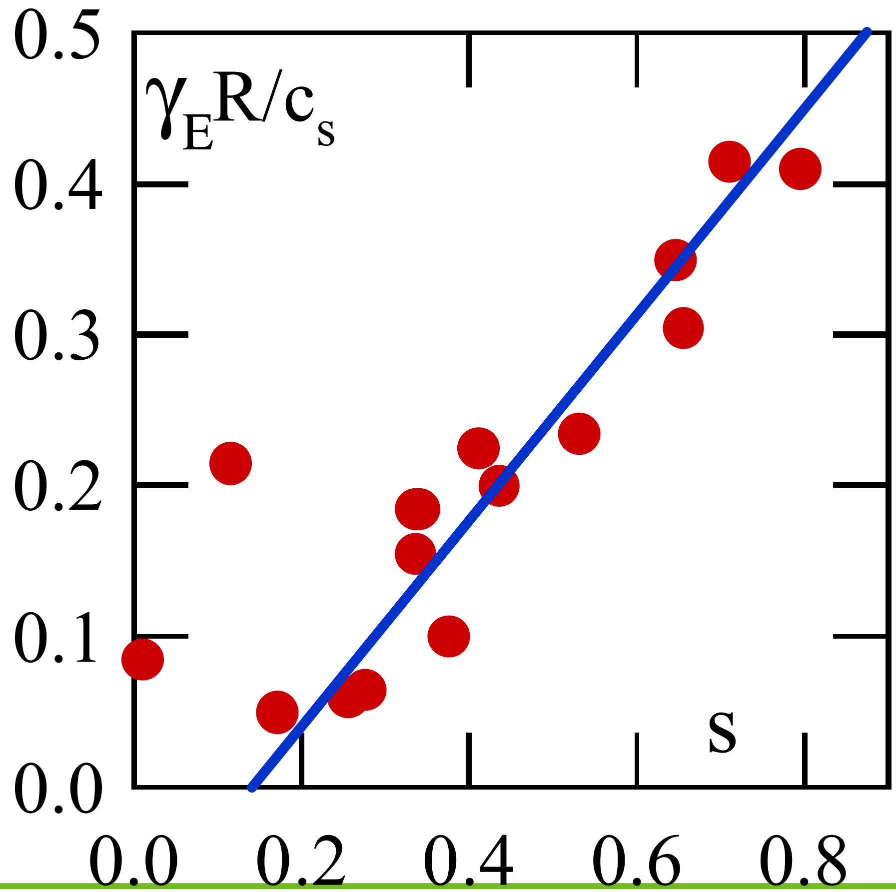
$$n_i e_i(\mathbf{E}+\mathbf{V}\times\mathbf{B})-\nabla p_i=0$$

→ in a reactor plasma

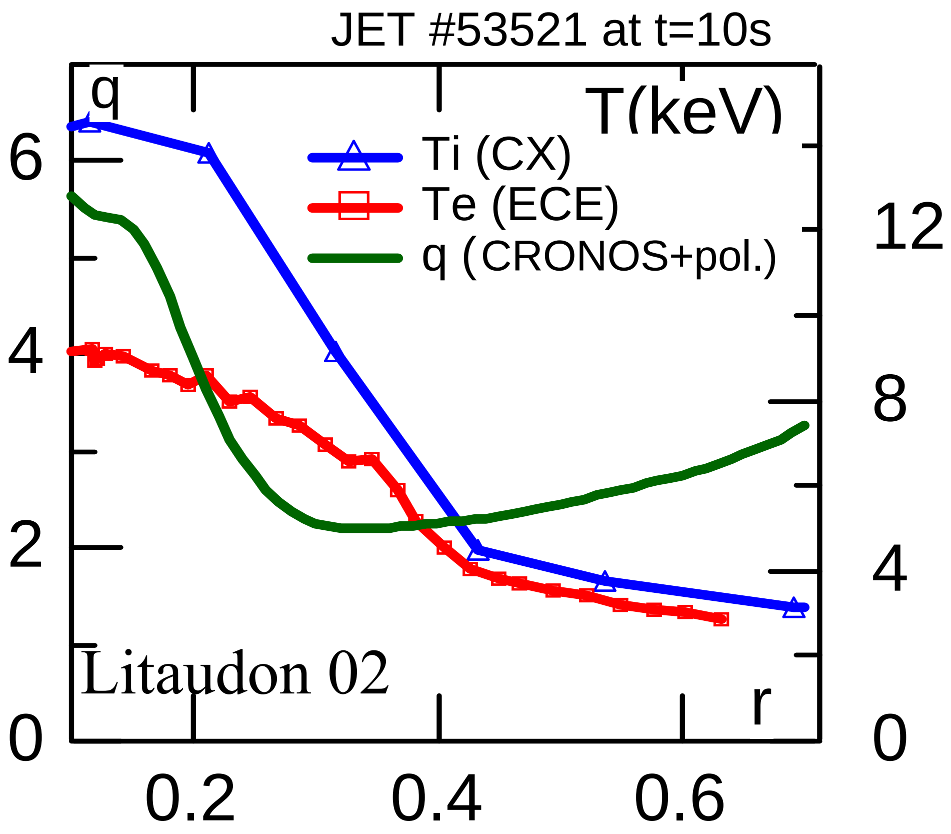
$$\gamma_E/\gamma_{lin}\approx\rho_*<<1$$

→ adjustement of magnetic shear s to lower γ_{lin}.

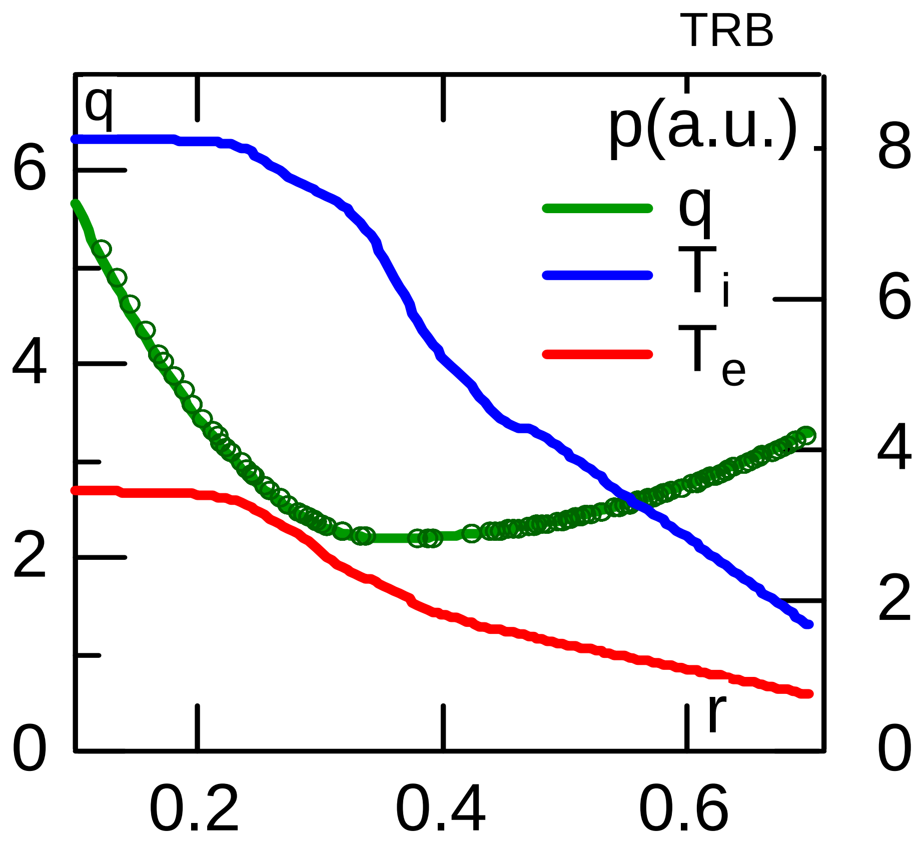
Shear flow rate vs. magnetic shear
JET Tala 00



Turbulence simulations reproduce some of the barrier features

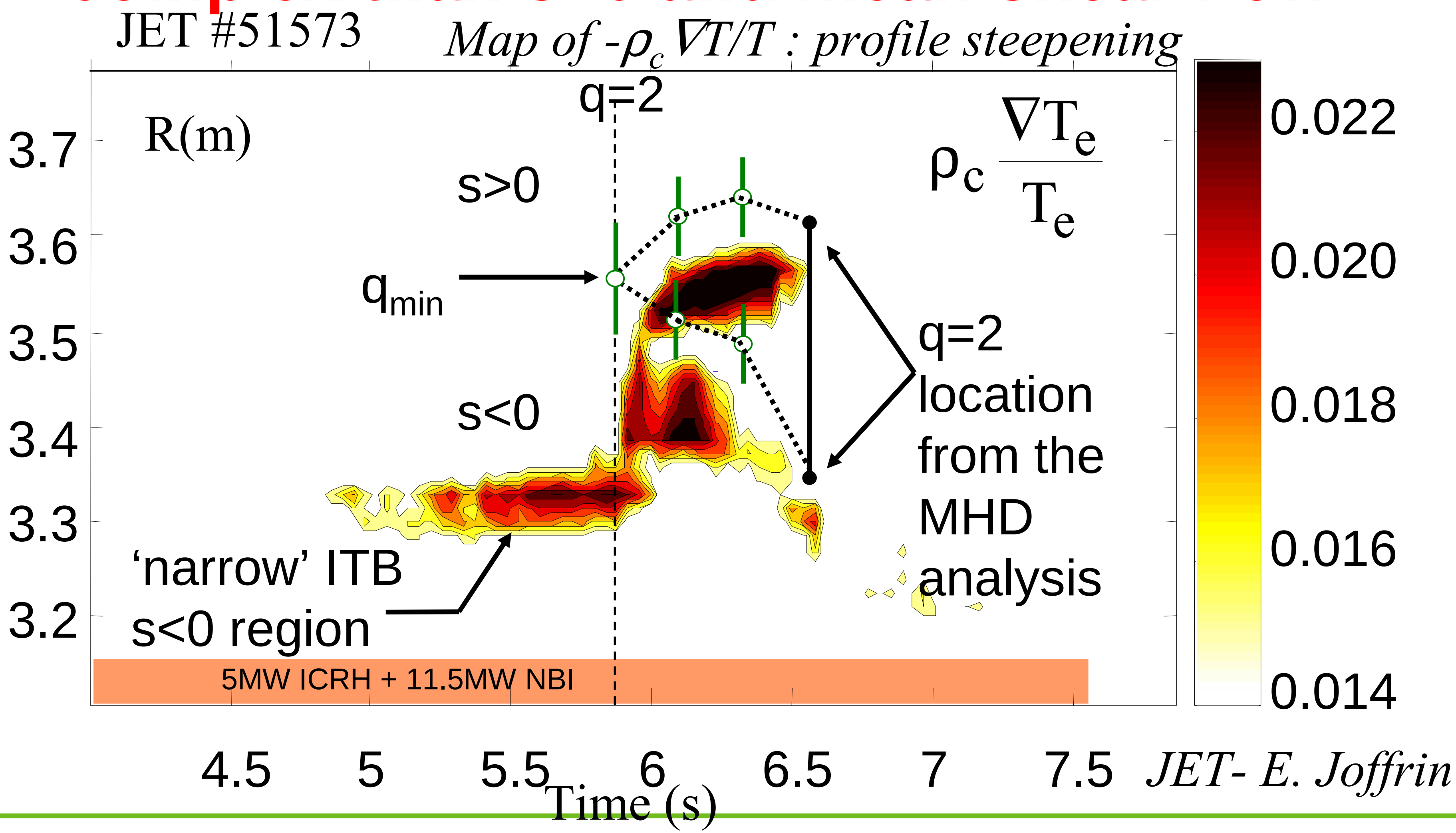


Measured temperature



Turbulence simulation

Dynamics of transport barriers is more complex than s<0 and mean shear flow



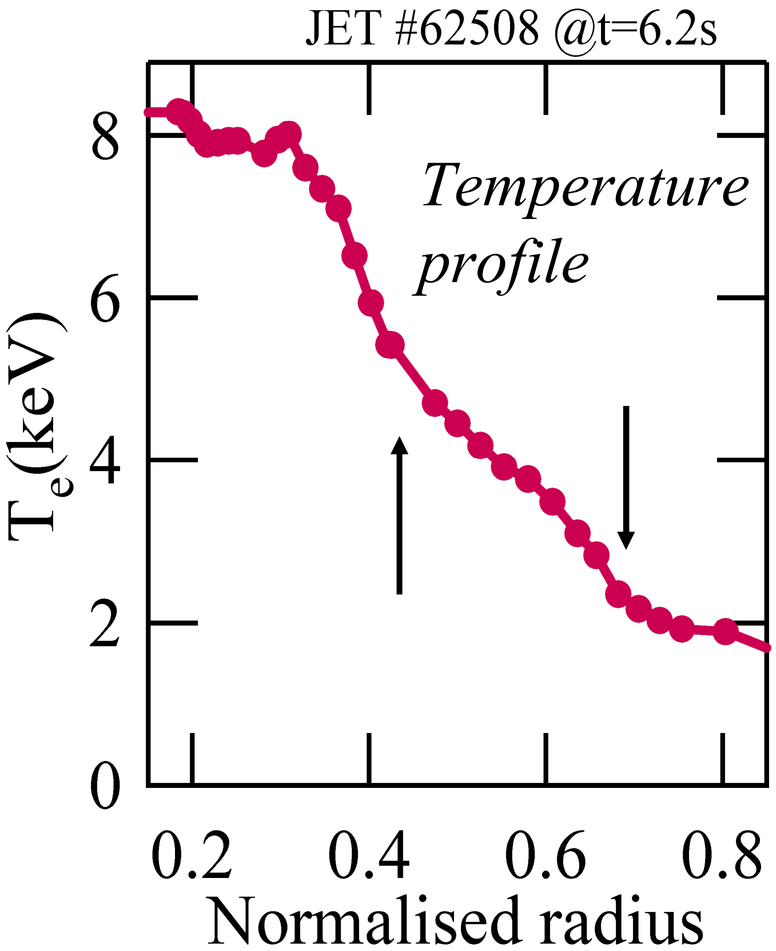
Role of low order rational q_{min} surfaces and onset of double barriers

- Persistent feature in JET plasmas.
- Possible explanations:
- MHD activity Joffrin 02
- Special role of s=0 in turbulence

→ density of rational surfaces ? Romanelli 93, Garbet 01.

→large scale flows? Waltz 05, Diamond 06.

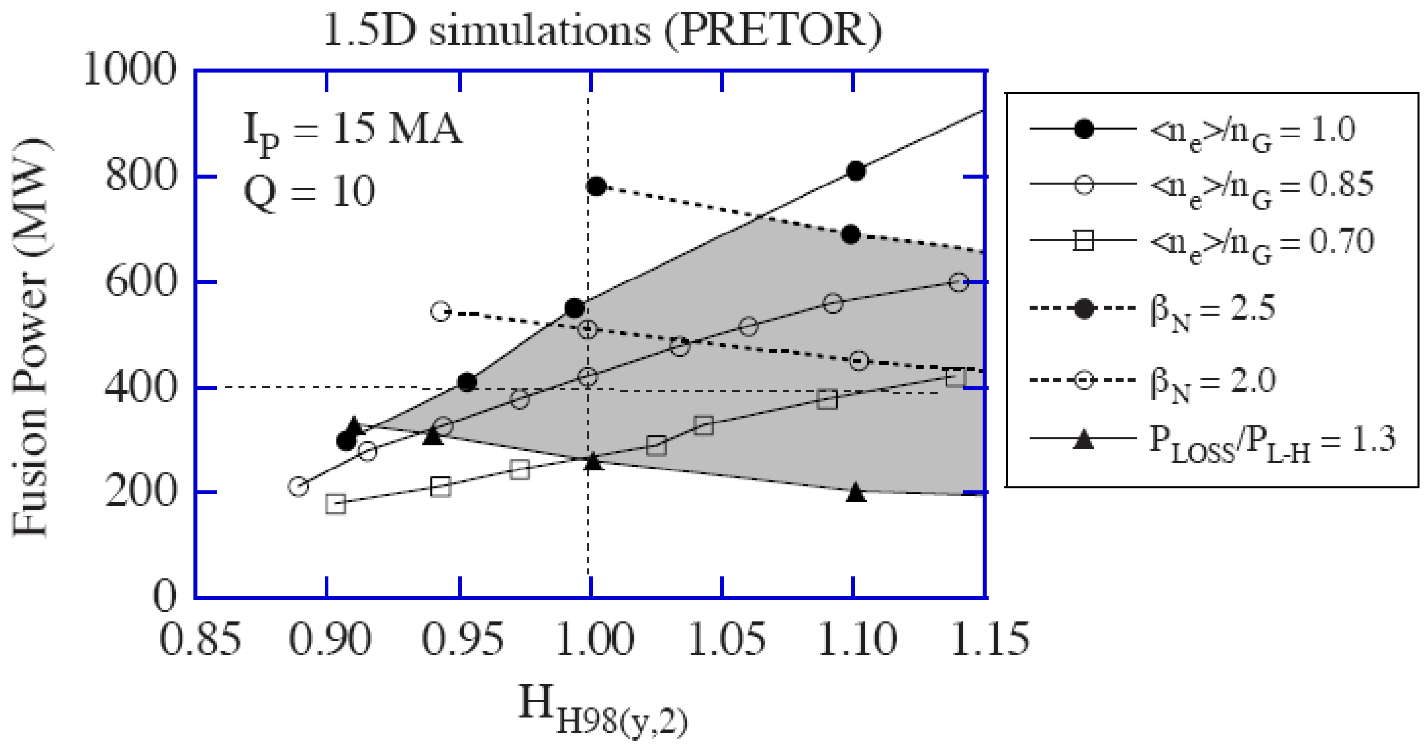
- Barriers stick to rational q's → multiple barriers



Consequences for ITER: H-mode

- The standard scenario is an H-mode : external transport barrier

- Q=10 is reached at I_p=15MA if the confinement is as expected

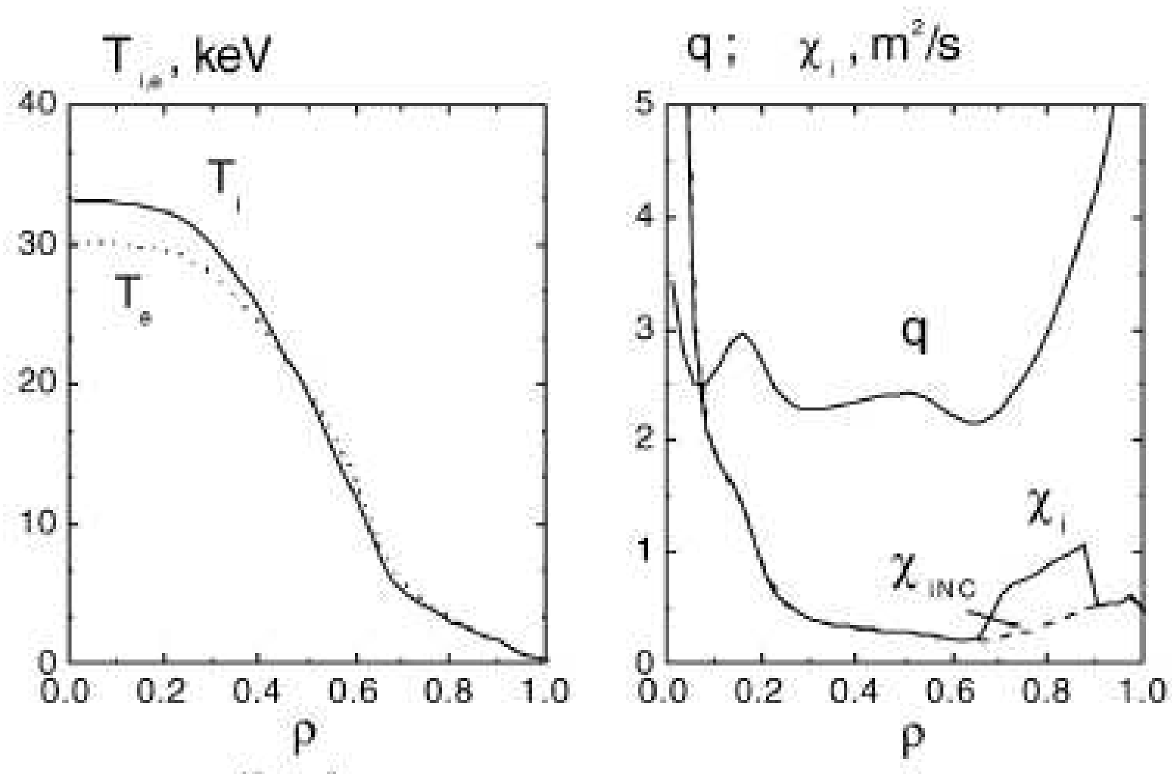


Consequences for ITER: advanced scenarios

Advanced scenarios are foreseen in a second phase.

- The objective is to reach a steady-state regime

- Requires an ITB



Conclusions

- Dimensionless scaling laws have proved to be an efficient tool for predicting the confinement in ITER.
- Still uncertainties remain concerning the dependences on ν^* and β .
- Transport models can be built based on quasi-linear theory and mixing length estimate.
- However the accuracy of most transport models does not exceed 20%
- Improved models on the basis of a better statistical theory (to be done) or direct use of simulations of turbulence?

Conclusions (cont.)

- Shear flow and magnetic topology optimization provide generic mechanisms to control turbulent transport $\rightarrow$ improved confinement.
- Turbulence simulations have tested the validity of various theoretical ideas for turbulence quench.
- Provide a solid basis for ITER scenarios.
- Still many issues remain unresolved, in particular the determination of power thresholds for barrier formation.