Inter-linkage of transports and its bridging mechanism

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OUTLINE

1 Introduction

2 particle pinch and impurity exhaust

3 spontaneous rotation

4 T and ∇T dependence of heat transport

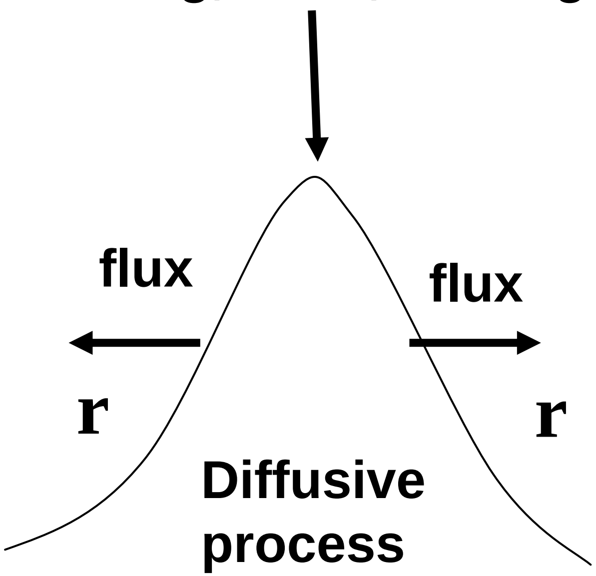
5 Non-local transport phenomena

6 Summary

Transport in plasma

Plasma

Fueling, drive, heating



density profile

Velocity profile

Temperature profile

10 Radial Fluxes

particle fluxes 2

momentum fluxes 3x2=6

heat fluxes 2

Radial flow is negligible

$V_r^e = 0$

$V_r^i = 0$

equilibrium

$$j^{\perp} \times B = \nabla\left(p_i + p_e\right)$$

Am bipolar condition

$$\Gamma_i = \Gamma_e$$

6 radial fluxes are determined by transport

Transport matrix

$$\begin{array}{l} \text{particle} \\ \text{toroidal momentum} \\ \text{Poloidal momentum} \\ \text{ion heat} \\ \text{electron heat} \end{array}
\begin{pmatrix} \Gamma \\ P_\phi \\ P_\theta \\ Q_{i,} \\ Q_{e,} \end{pmatrix}
=
\begin{pmatrix} D & - & - & - & - \\ - & \mu_\phi n m_i & - & - & - \\ - & - & \mu_\theta n m_i & - & - \\ - & - & - & n\chi_{i,} & - \\ - & - & - & - & n\chi_e \end{pmatrix}
\begin{pmatrix} \nabla n_e \\ \nabla V_\phi \\ \nabla V_\theta \\ \nabla T_i \\ \nabla T_e \end{pmatrix}
\begin{array}{l} \longrightarrow \text{Non-Diffusive} \\ \longrightarrow \text{Non-Diffusive} \\ \\ \longrightarrow \text{Diffusive} \\ \longrightarrow \text{Diffusive} \end{array}$$

6 radial fluxes are expressed by 5 x 5 transport Matrix + Current diffusion equation

5 Diagonal coefficients are determined by turbulence

$\Gamma = D\nabla n$

$P_\phi/(m_i n_i) = \mu_\phi \nabla V_\phi$

$P_\theta/(m_i n_i) = \mu_\theta \nabla V_\theta$

$Q_e/n_e = \chi_e \nabla T_e$

$Q_i/n_i = \chi_i \nabla T_i$

particle, momentum and heat transport

simplified

There is no need for plasma physicist because physics is simple

realistic

1 Linear + diffusive + local transport model (simple!)

$\Gamma = D\nabla n$ $\quad$ $P/(n_i m_i) = \mu \nabla V$ $\quad$ $Q/n = \chi \nabla T$

2 Add Non-linearity

$\Gamma = D(n,\nabla n)\ \nabla n$ $\quad$ $Q/n = \chi(T,\nabla T)\ \nabla T$

Non-liner dependence → stiffness

3 Add Non-diffusivity (inter-linkage between flux)

$\Gamma = D(n,\nabla n)\nabla n + D^N(n/T)\ \nabla T +$

Non-diffusive term → particle inward/outward pinch

$P_\phi/(n_i m_i) = \mu_\phi(\nabla E)\nabla V_\phi + \mu^N(V_{th}/T)\ \nabla T +$

Non-diffusive term → spontaneous rotation

4 Add non-locality (inter linkage in space)

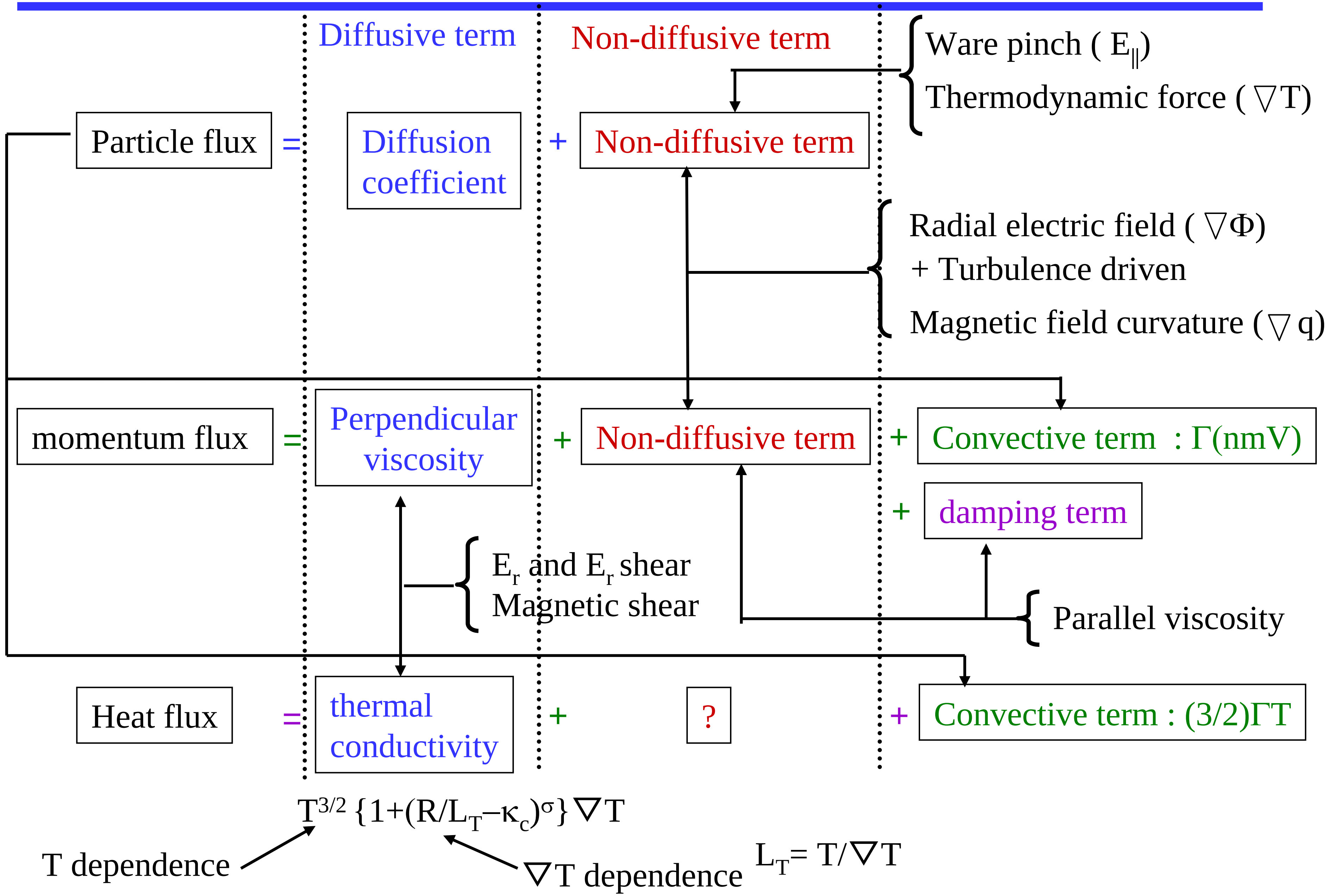
$\Gamma = D\ (n,\nabla n\ )\ \nabla n + D^N(n/T)\nabla T + \int f(n,\nabla n,\nabla T,\ ,\ ,\ )d\rho\ +$

Non-local term

complicated

unrealistic

Diffusive and non-diffusive transport



Particle transport

Ware pinch ($E_{\|}$)

2. Thermodynamic force (∇T)

Particle flux = diffusion + Non-diffusive term

1. T dependence

Radial electric field ($\nabla\Phi$)

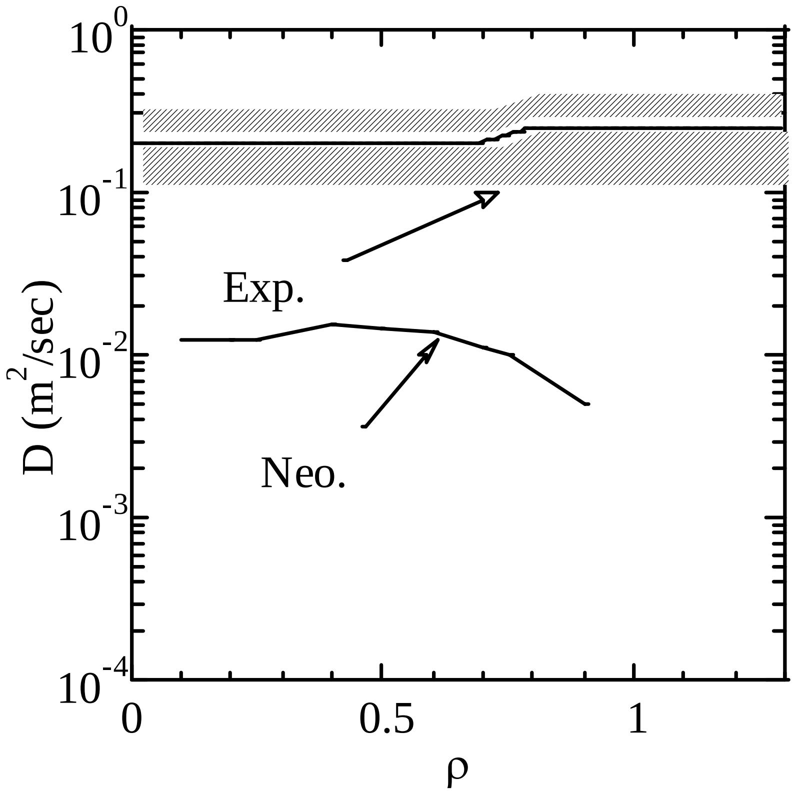
Turbulence driven

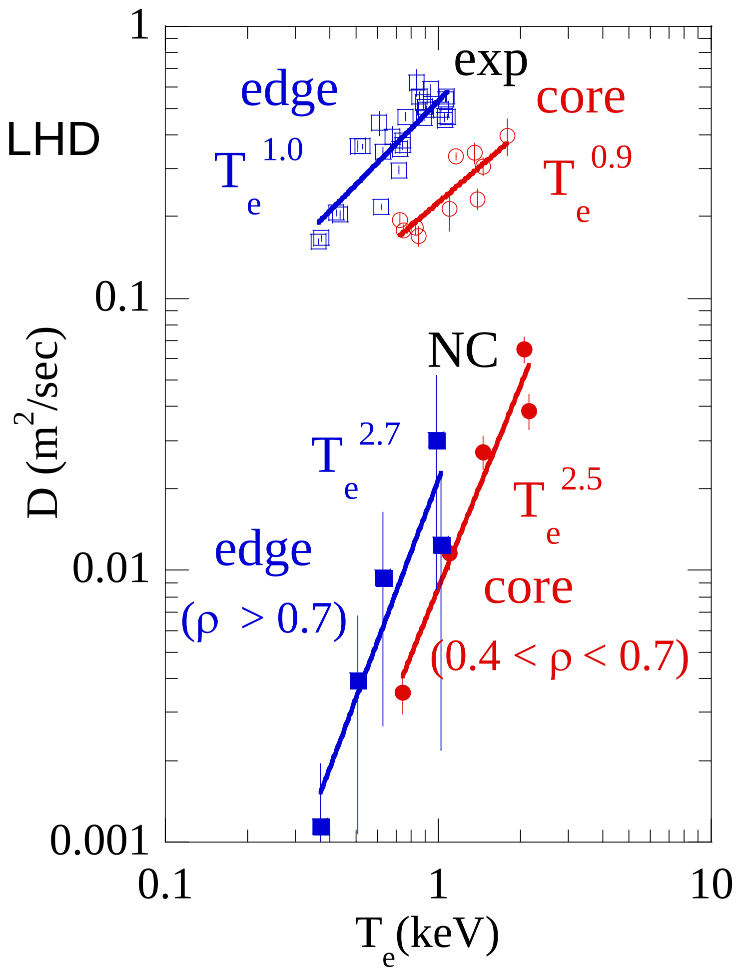
3. Magnetic field curvature (∇q)

Convective term

Convective term

Particle transport diffusive term





Diffusion coefficient is much larger than the neoclassical values and particle transport is dominated by turbulent transport. It has temperature dependence of T^α where $\alpha \sim 1$.

K.Tanaka Nucl. Fusion 46 (2006) 110

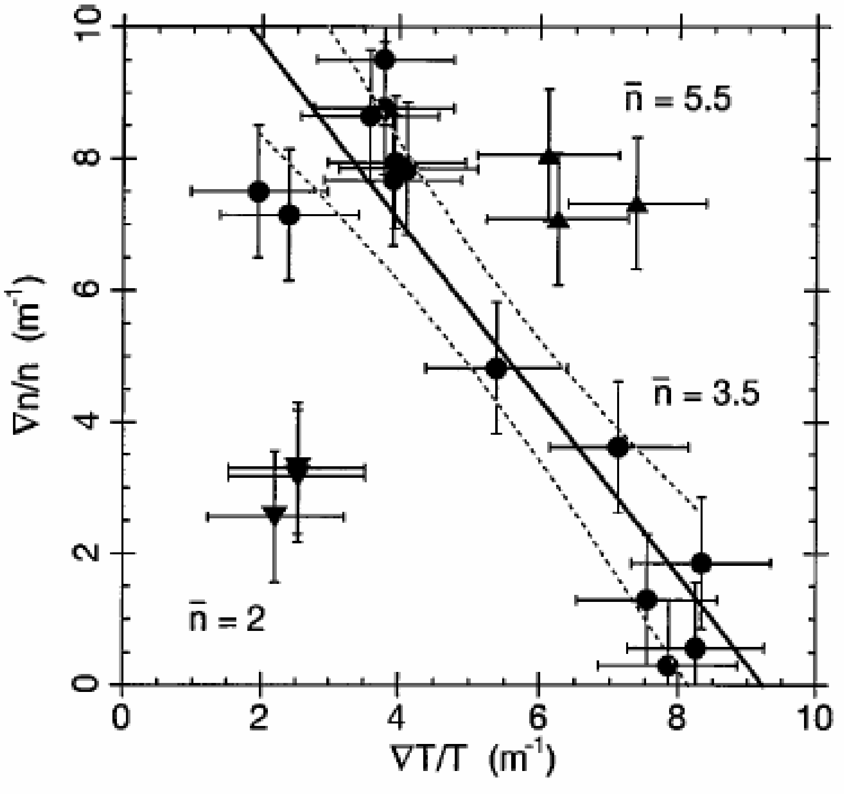
Non-diffusive term of particle flux

Diffusion

pinch

$$\Gamma_e = -n_e\left(D_{11}\,\frac{\nabla_r n_e}{n_e} + D_{12}\,\frac{\nabla_r T_e}{T_e} - u\right),$$

Thermo diffusion



Wendelstein 7-AS

Thermo diffusion term is comparable to diffusion term D_{12}/D_{11}=1.4

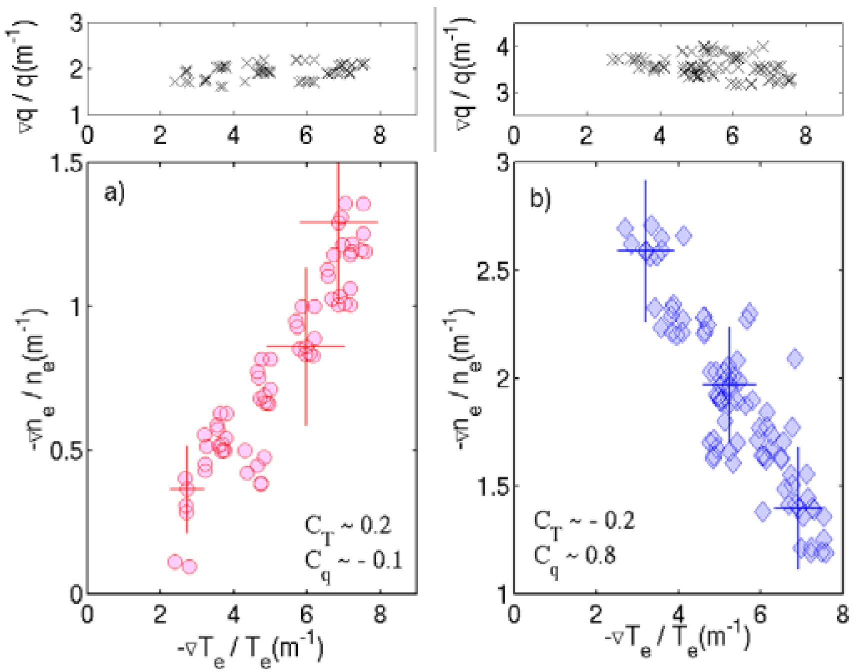
Inward Pinch term is significant u/D_{11} = -12.5 m^{-1}

U.Stroth Phys. Rev. Lett. 82 (1999) 928

Magnetci field curvature pinch

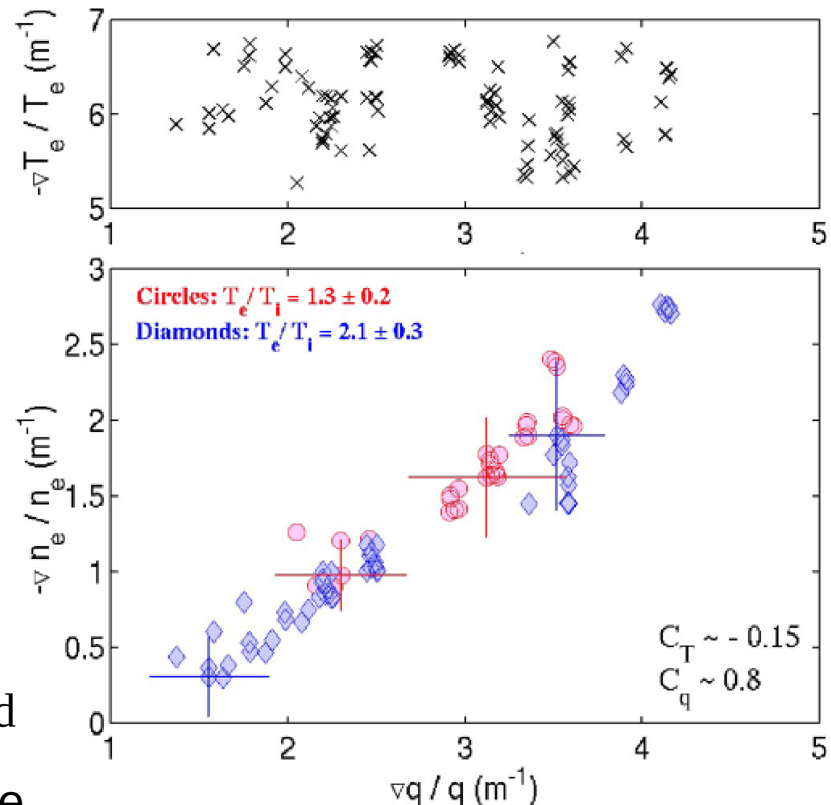
$$\nabla n_e/n_e = -C_q\nabla q/q + C_T\nabla T_e/T_e.$$

Thermo diffusion flux



ρ < 0.3 : inward   0.35 < ρ < 0.6 : outward

Magnetic field curvature Inward pinch

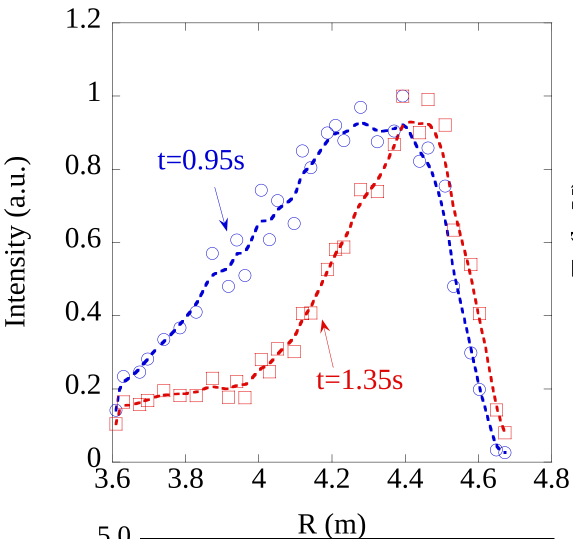


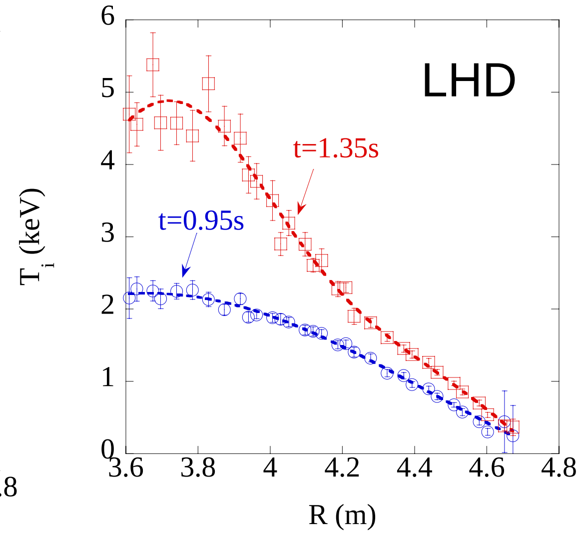
▽T term changes it sign between in and core

Particle pinch due to magnetic shear is observed

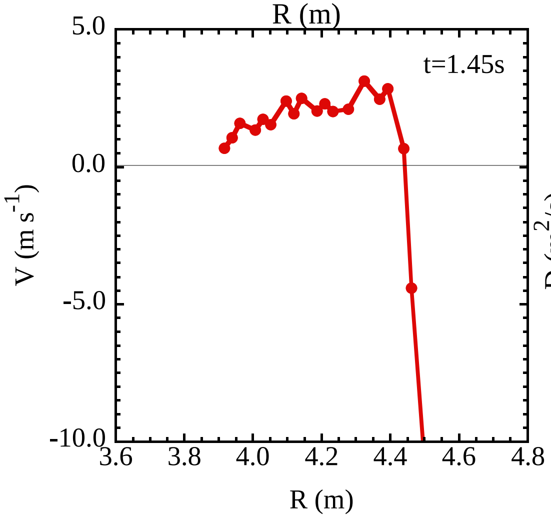
G.T.Hoang, Phys. Rev. Lett. 93 (2004) 135003

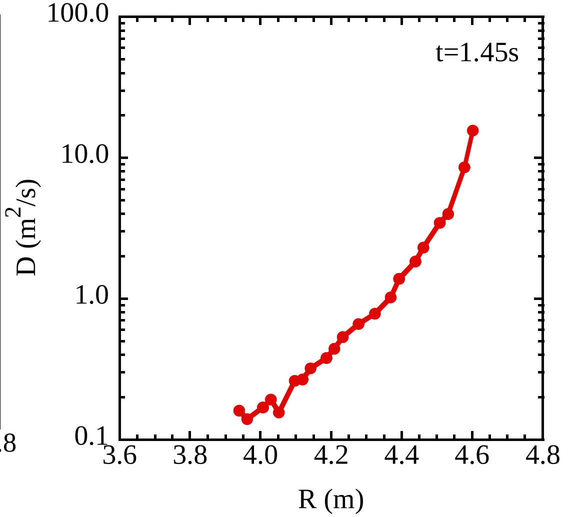
Impurity hole
evidence of strong outward flux due to Ti gradient?





Carbon profile becomes hollow associated with the peaking of ion temperature profile

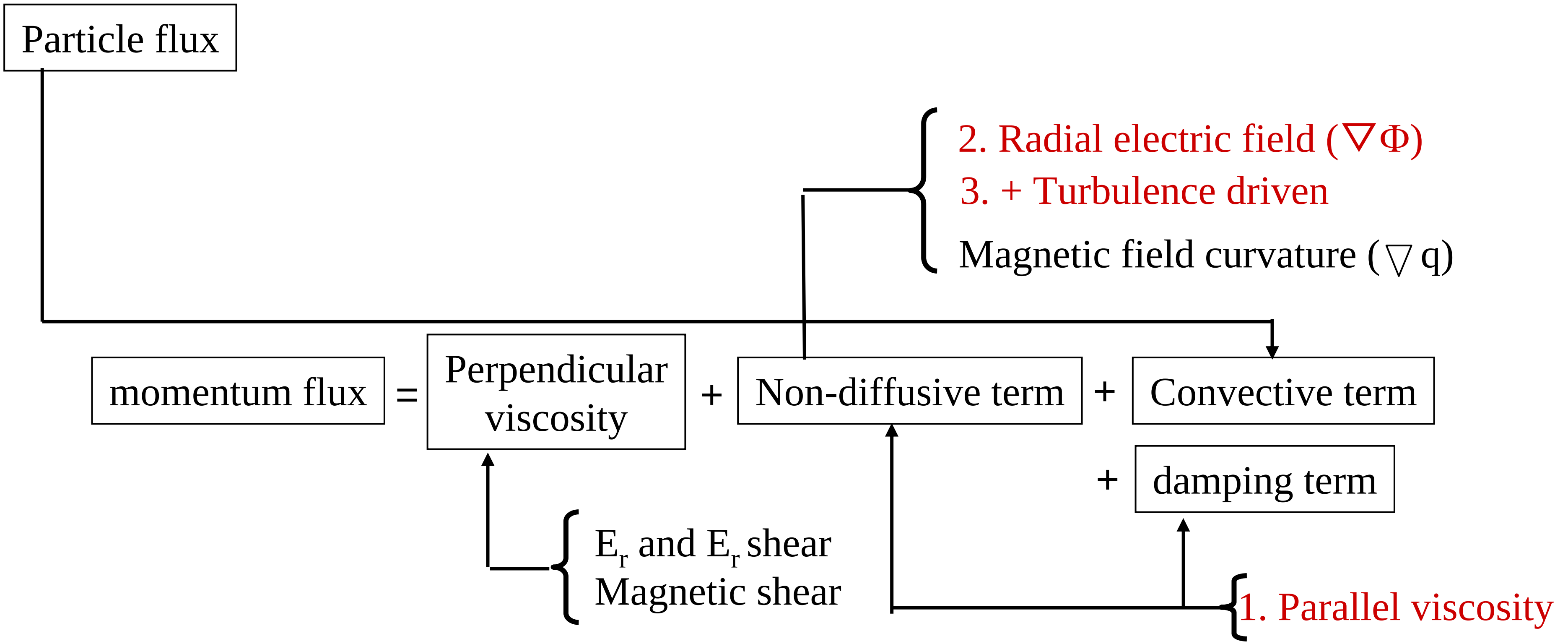




The transport analysis shows strong outward convective flow and low diffusivity in the core region.

Impurity hole is observed in the plasma with peaked ion temperature
→ Suggest a strong coupling between Ti gradient and impurity outward flux

Momentum transport



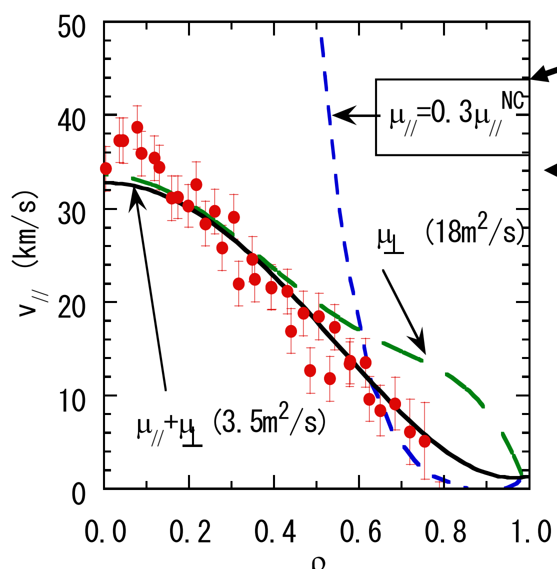
Parallel and perpendicular viscosity (diffusive term)

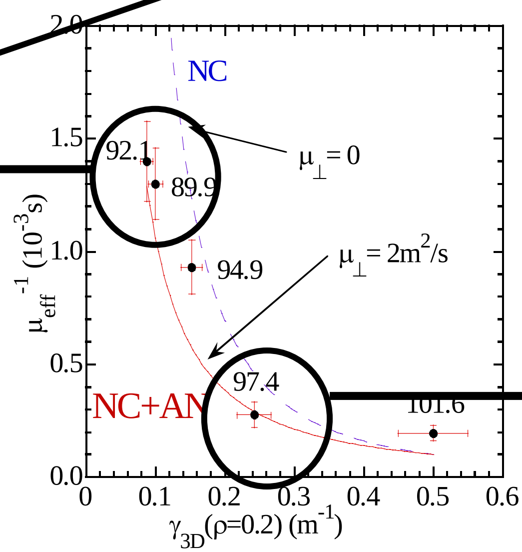
$$\Gamma_M = m_i n_i[- \mu_\perp^D\, dv_\phi /dr + \mu^N (v_{th} /T_i)(eE_r) - \mu_{||}\, v_\phi\,]$$

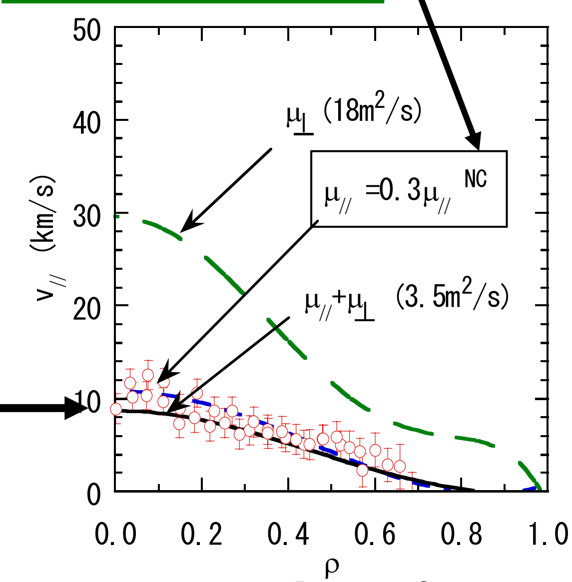
Anomalous perpendicular viscosity

Non-diffusive term

Neoclassical parallel viscosity







Small ripple configuration

→ $V_{mes} << V_{cal(NC)}$

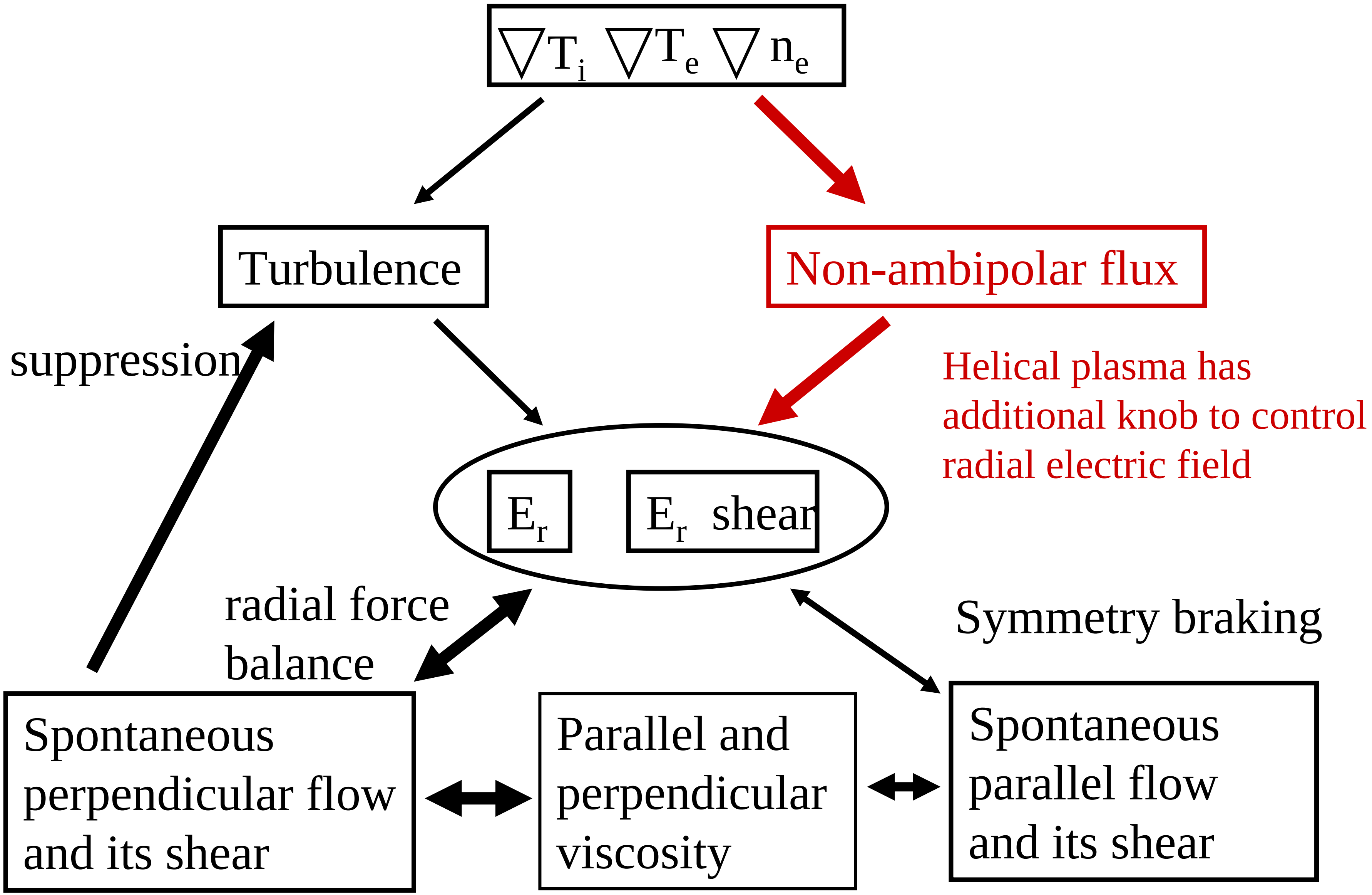
Large ripple configuration

→ $V_{mes} \sim V_{cal(NC)}$

In the configuration of small ripple the anomalous perpendicular viscosity is dominant in the plasma core ($\rho < 0.6$) even in helical plasmas

K.Ida Phys. Rev. Lett. 67 (1991) 58

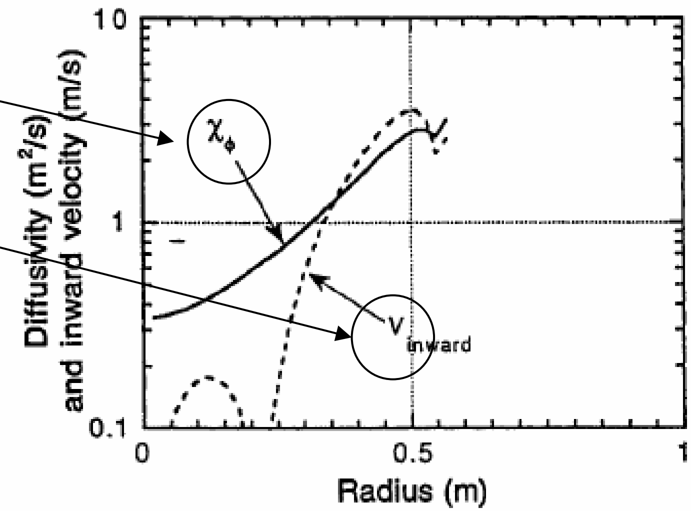
Physical mechanism determining spontaneous flows



Non-diffusive momentum transport in tokamak

Momentum Flux

$$\Gamma_M = m_i n_i[- \chi_\phi \, dv_\phi /dr + V_{inward} V_\phi]$$



$$\Gamma_M = m_i n_i[- \mu^D \, dv_\phi /dr + \mu^N (v_{th} /T_i)(eE_r)]$$

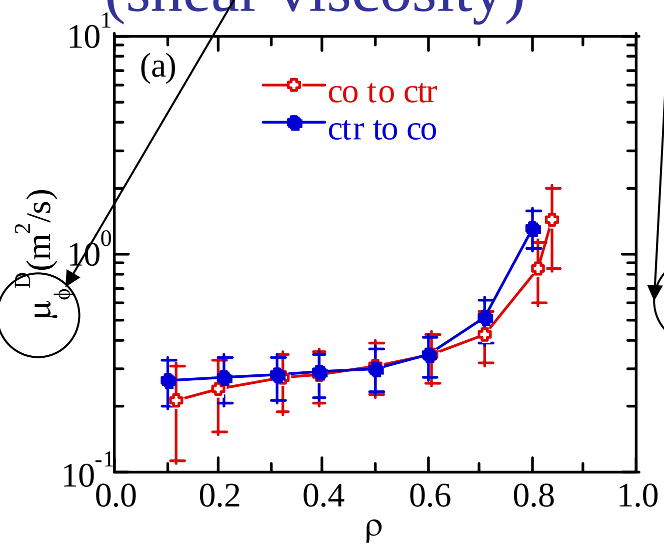
eE_r = dTi/dr

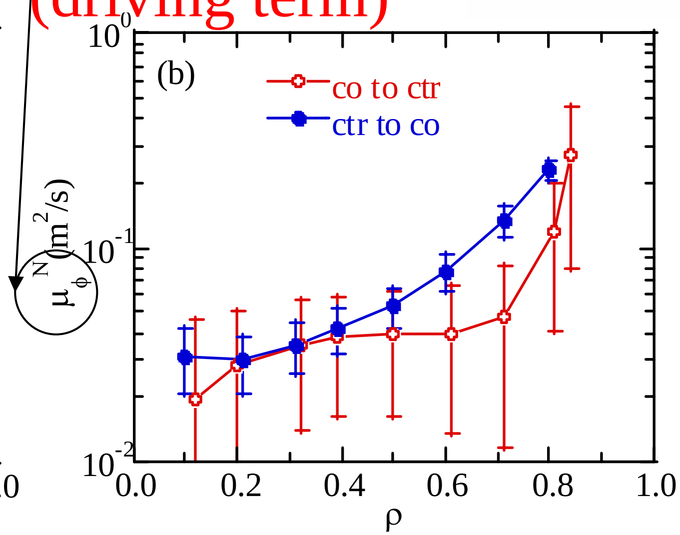
diffusive

(shear viscosity)

non-diffusive

(driving term)





Finite dV_ϕ/dr can be non-zero for $\Gamma_M = 0$ because of the existence of non-diffusive term

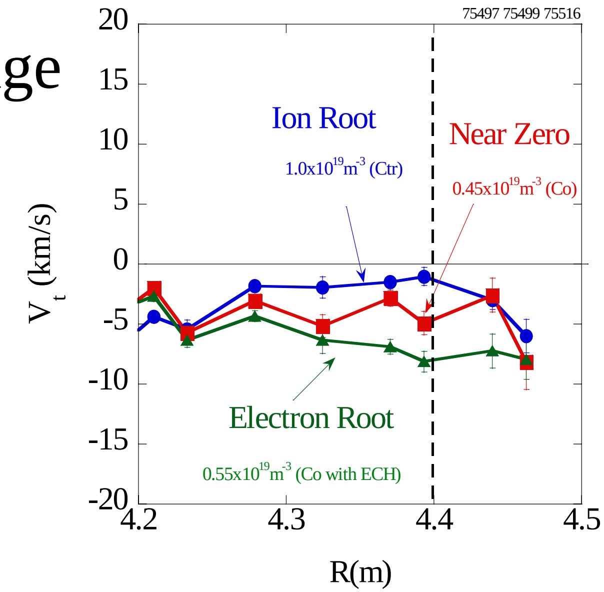
Spontaneous rotation was observed as a non-diffusive term of momentum transport.

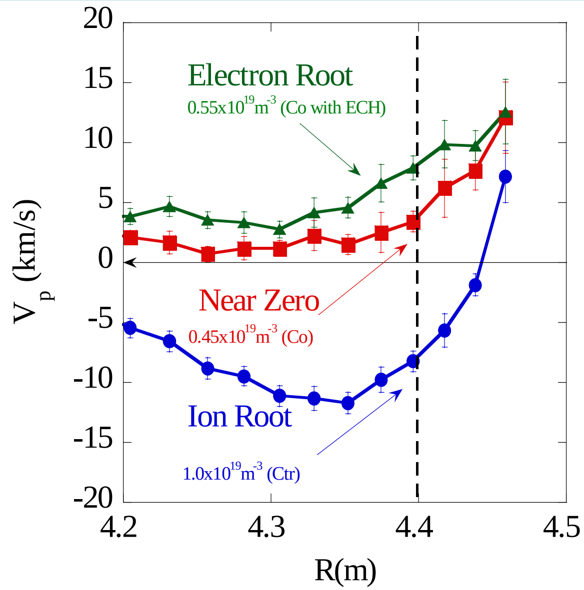
K.Nagashima, Nucl Fusion 34 (1994) 449

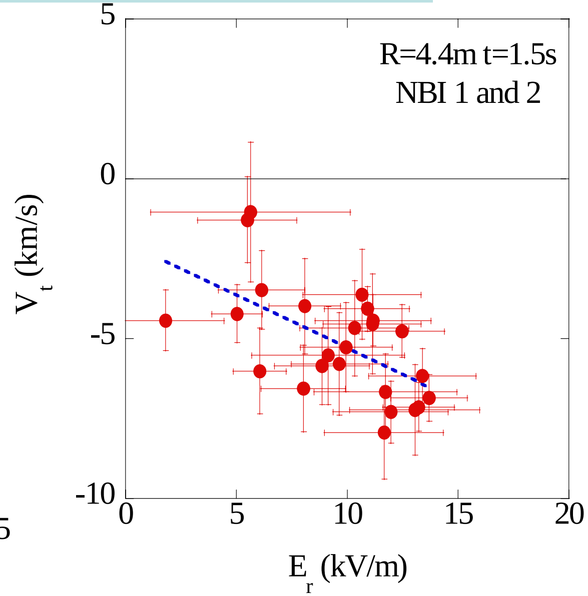
K.Ida , Phys Rev Lett 74 (1995) 1990, J.Phys.Soc.Jpn 67 (1998) 4089

Spontaneous toroidal at edge and core

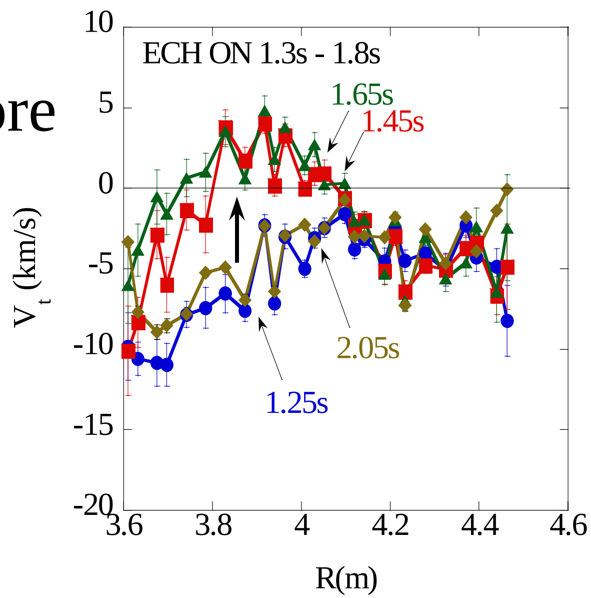
edge







core

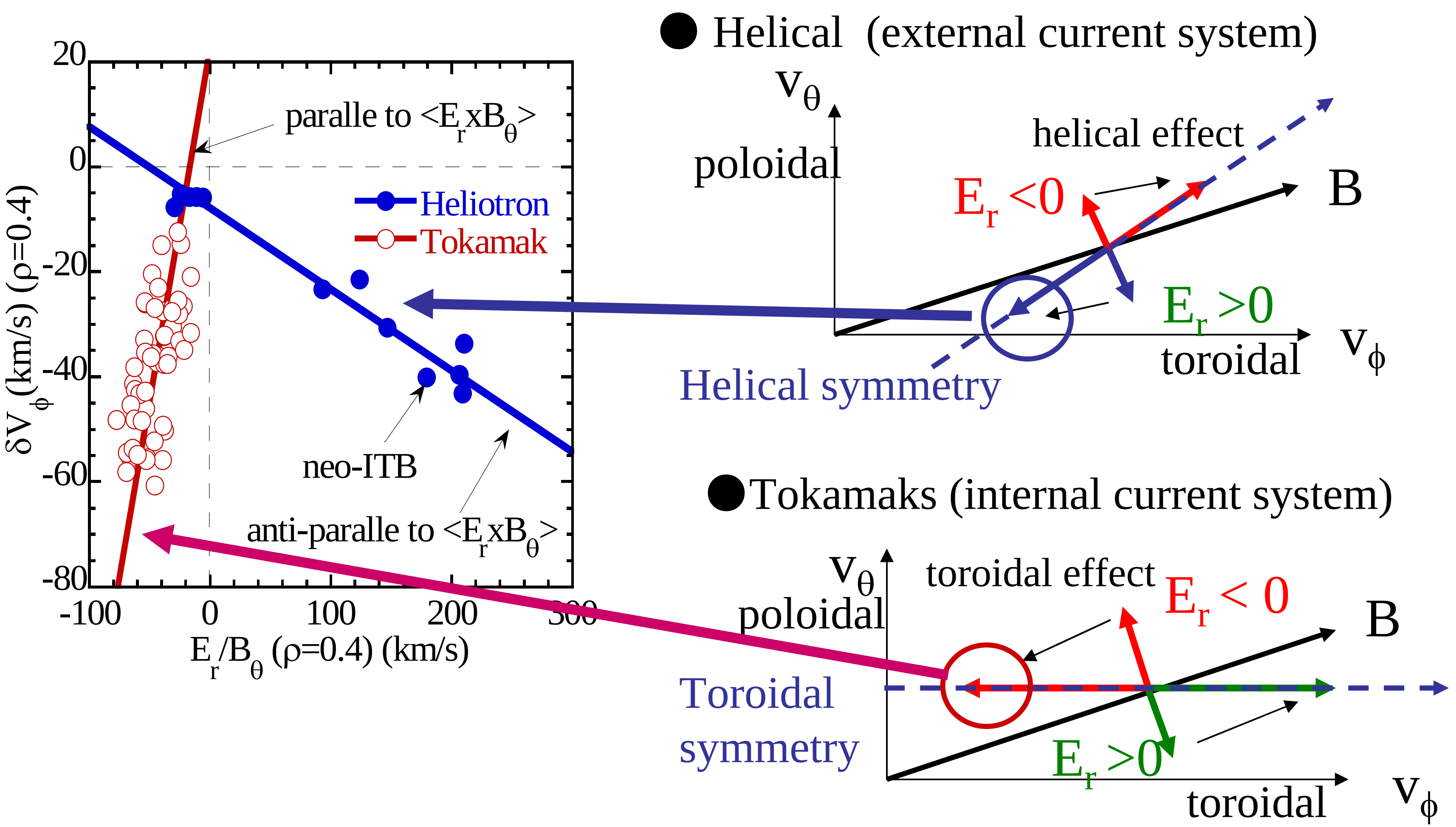


Coupling between poloidal and toroidal rotaion is observed

Edge (helical symmetry dominant)
→ ctr rotation for $E_r>0$
Core (toroidal effect dominant)
→ co rotation for $E_r>0$

M.Yoshinuma ITC17 O -12 Friday

Sign of non-diffusive viscosity



Tokamak : negative E_r → counter spontaneous flow $V=1.3E_r/B_\theta$

Helical : positive Er → counter spontaneous flow $V=0.16E_r/B_\theta$

K.Ida , Plasma Phys. Control. Fusion 44 (2002) 362

Why the spontaneous rotation depends on E_r in tokamak

Why the non-diffusive terms has E_r dependence?

$$\boldsymbol{\Gamma_M = m_i n_i[-\mu^D\, dv_\phi/dr + \mu^N (v_{th}/T_i)(eE_r)] = -(1/r)\int f_\phi\, r\, dr}$$

Non-diffusive term can be expressed as toroidal force which proportional to E_r shear

$$\boldsymbol{\mu^N = c_{sym}(1/B_\theta) = c_{sym} qR/(rB_\phi)}$$

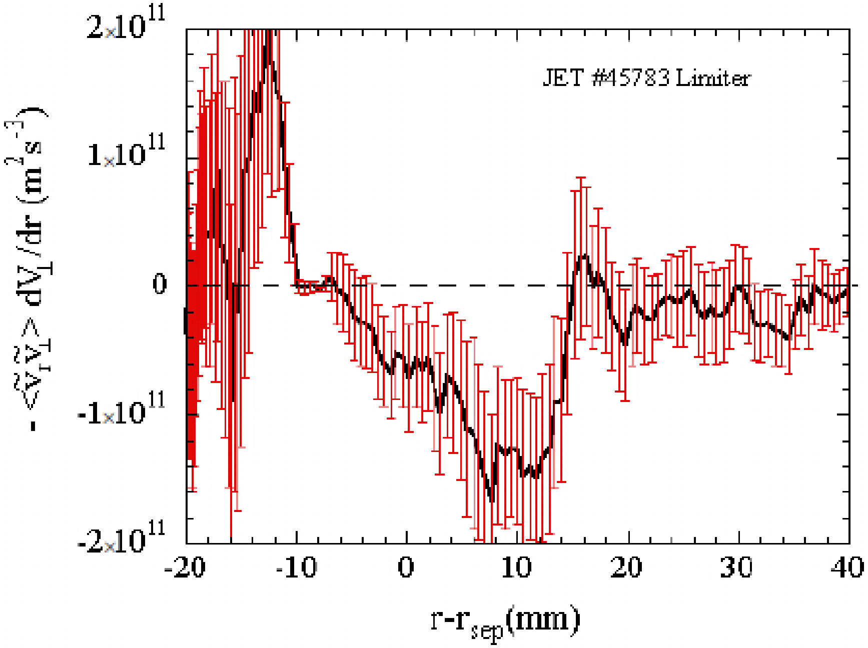
$$f_\phi^{spon} = (c_{sym} eqR/B_\phi)(v_{th}/T_i)(1/r)(dE_r/dr)$$
$$\sim (c_{sym} eqRv_{th}/T_i)(d\omega_{ExB}/dr)$$

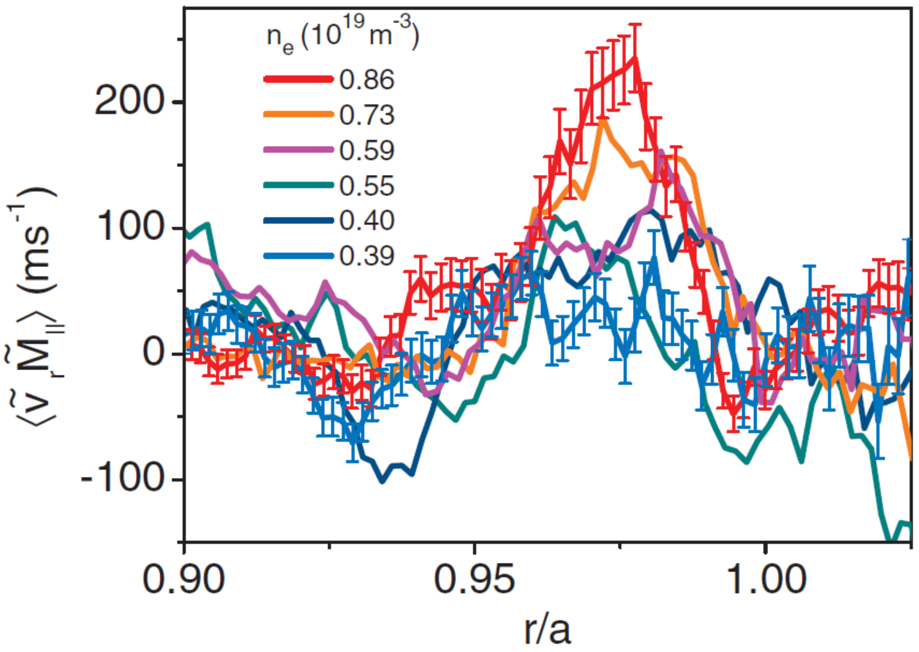
In tokamak
Toroidal momentum is produced by symmetry breaking of non-zero <k||>.

In stellarator
Because of the asymmetry of magnetic field, E_r and spontaneous flow are produced by ripple loss too.

O.D.Gurcan Phys. Plasmas 14 (2007) 042306

Evidence of turbulence driven perpendicular and parallel Reynolds stress





Radial-poloidal component of the Reynolds stress due to turbulence is observed in JET

C.Hidalgo, Plasma Phys. Control. Fusion 48 (2006) S169

In TJ-II stellarator, significant radial-parallel component of the Reynolds stress, which drives spontaneous parallel flow is observed

B.Concalves, Phys. Rev. Lett. 96 (2006) 145001

Heat transport

Particle flux = diffusion + Non-diffusive term

1. E_r and E_r shear Zonal flow (Itoh's talk)

Magnetic shear

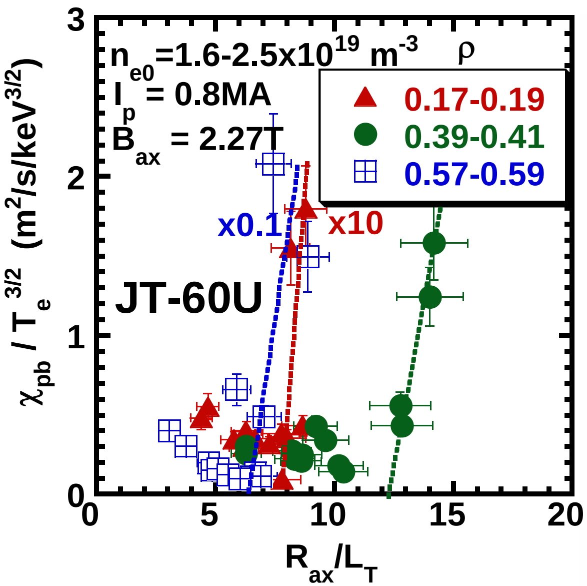
Energy flux = thermal diffusivity + Convective term

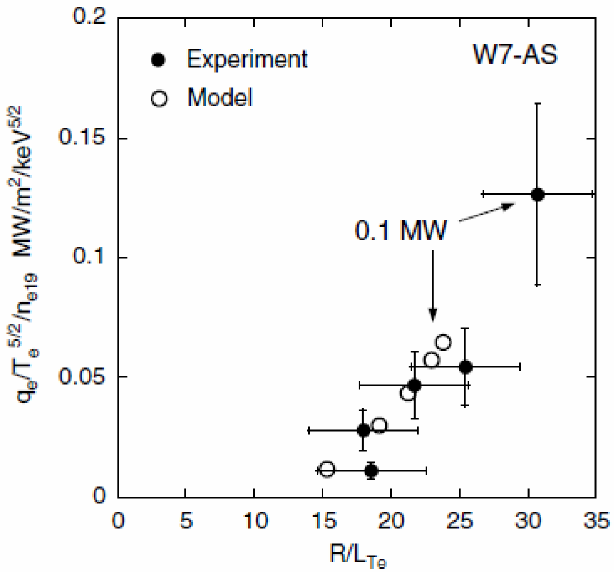
$$T^{3/2}\,(1+(R/L_T-\kappa_c)^{\sigma})\ \ \nabla T$$

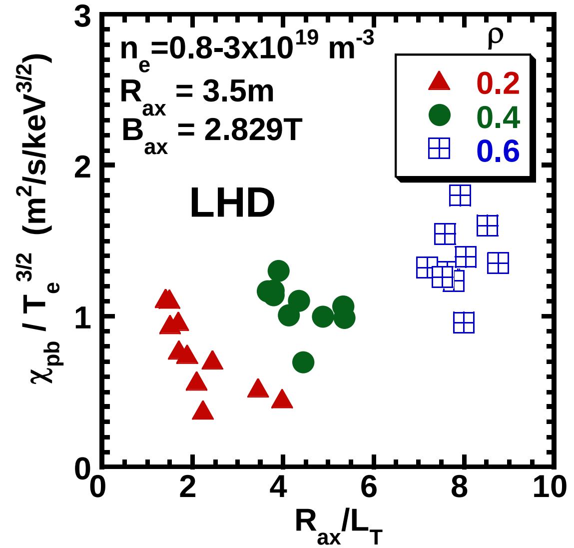
3. T dependence

2. ∇T dependence

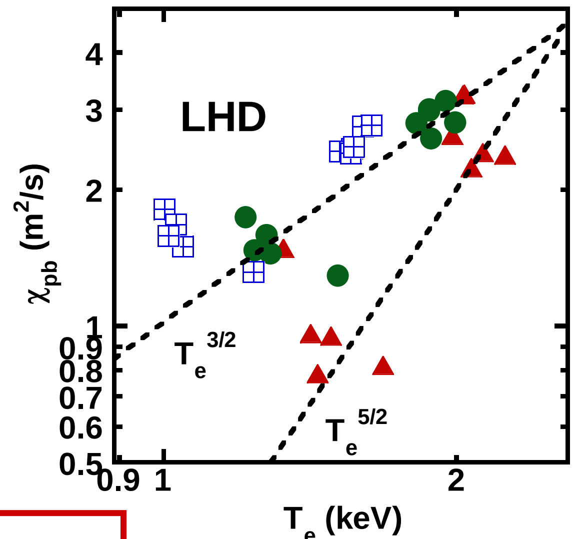
T_e and grad-T_e dependence of transport in axisymmetric and non-axisymmetric system







JT-60U tokamak
W7AS helical
→ Clear scale length threshold
No clear T_e dependence



LHD Helical → No scale length threshold
clear T_e dependence
Gyro Bohm type $T_e^{1.5}$ in L-mode

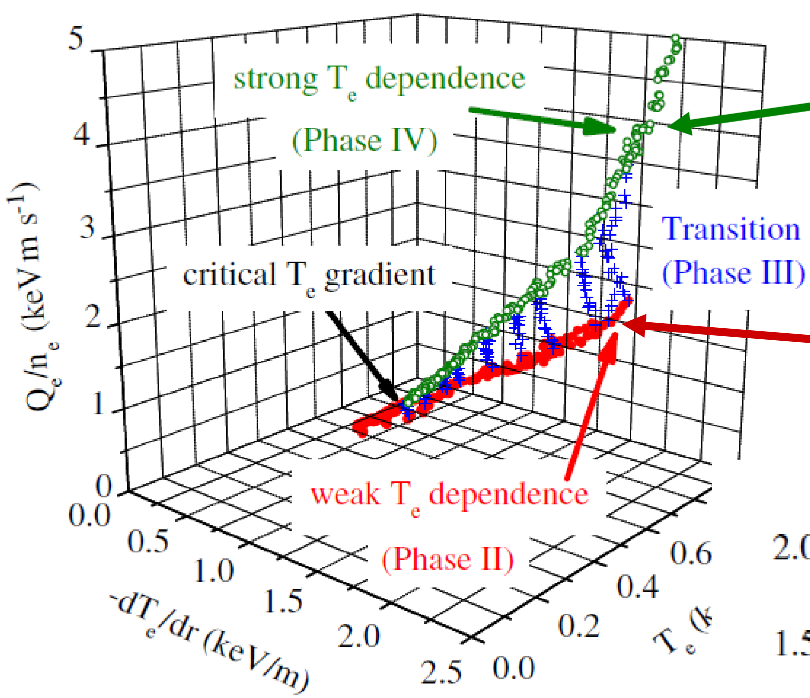
$$Q \propto T^{3/2}\{1+(R/L_T-\kappa_c)^\sigma\}\nabla T$$

Electron ITB appears below the scale length threshold in LHD

F Ryter et. al., Plasma Phys. Control. Fusion 48 (2006) B453

S.Inagaki, Nucl. Fusion 46 (2006) 133

Bifurcation of transport between week and strong T_e dependence

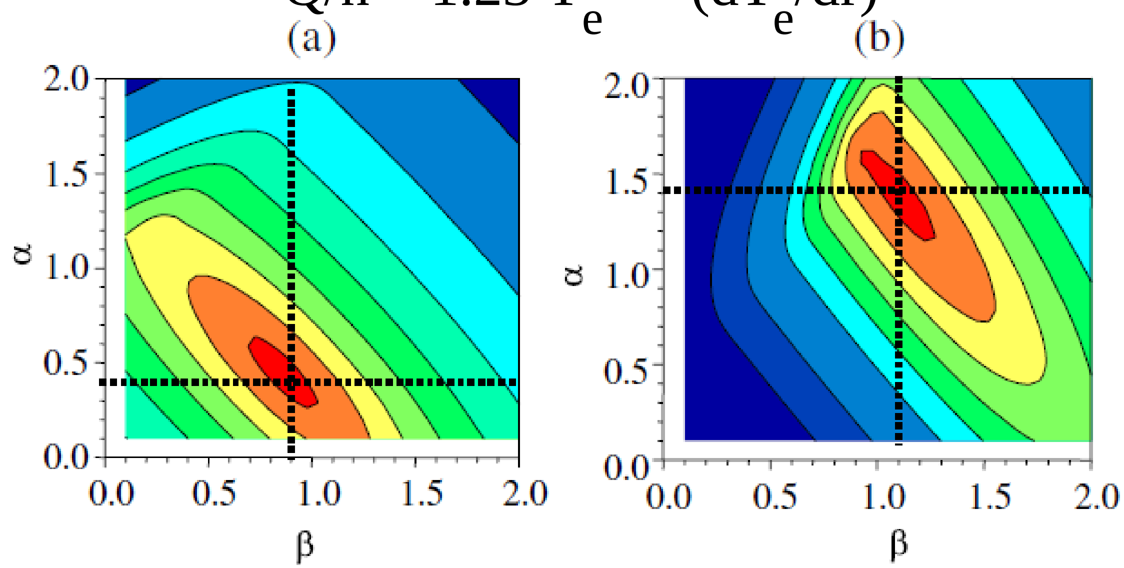


Gyro-Bohm T_e dependence

$$Q/n = 2.49\, T_e^{1.4} (dT_e/dr)^{1.1}$$

Weak T_e dependence

$$Q/n = 1.23\, T_e^{0.4} (dT_e/dr)^{0.9}$$



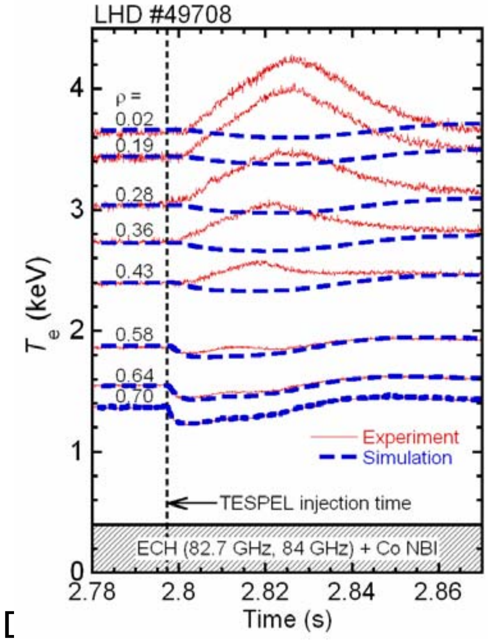
Contour of χ^2

$$\chi^2 = \sum \left(Q_e / n_e - T_e^{\alpha} \nabla T_e^{\beta} \right)^2$$

T_e dependence changes
but no change in grad-T_e dependence

K.Ida, Phys. Rev. Lett. 96 (2006) 125006

non-local transport



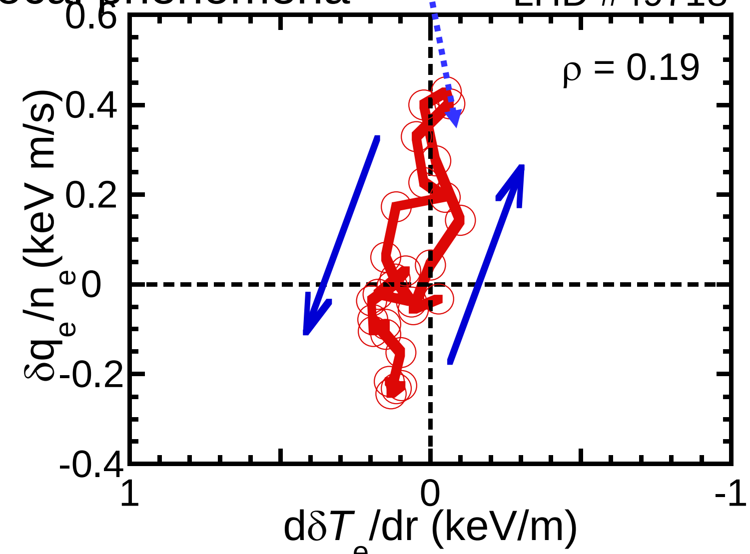
Hear flux

Diffusive term

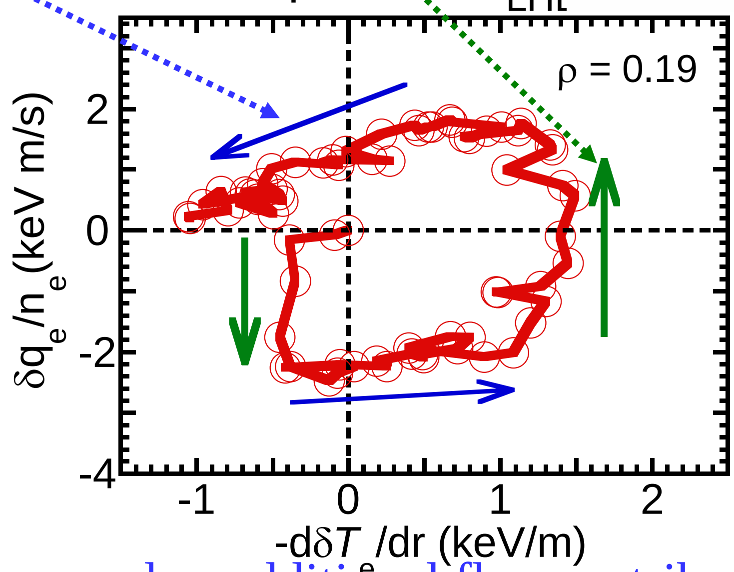
Additional term

$$Q = \chi(T, \nabla T)\,\nabla T + \int f(\nabla T, \ , \ , \ )\, d\rho\ +$$

local phenomena



Non-local phenomena



→ Non-local transport can be expressed as additional flux contributed by the ∇T at different radii

→ Suggest strong coupling of turbulence between at the two location separated through meso-scale flow

N.Tamura,, Nucl. Fusion 47, (2007) 4495

Summary

The transport between particle, momentum and heat fluxes are liked through the non-diffusive term of transport

1 Non-diffusive term of particle transport is driven by ∇Te , ∇T_i (with strong relation with E_r) and magnetic field curvature.

2 Non-diffusive term of momentum transport, which drive spontaneous rotation, is driven by E_r shear and viscosity tensor. Therefore the direction of spontaneous flow depends on sign of E_r, magnetic field symmetry and type of responsible turbulence

3 Diffusive term of heat transport is affected by E_r shear and E_r itself in stellarator (through the reduction of collisional flow damping of Zonal flow). It mainly depends on T_e rather than ∇T_e in LHD (because of the formation of ITB below the threshold)

The transport between different location are liked through meso-scale flow and causes non-local transport phenomena

4 Non-local transport is characterized as additional flux due to the gradient of different radii

Remarks

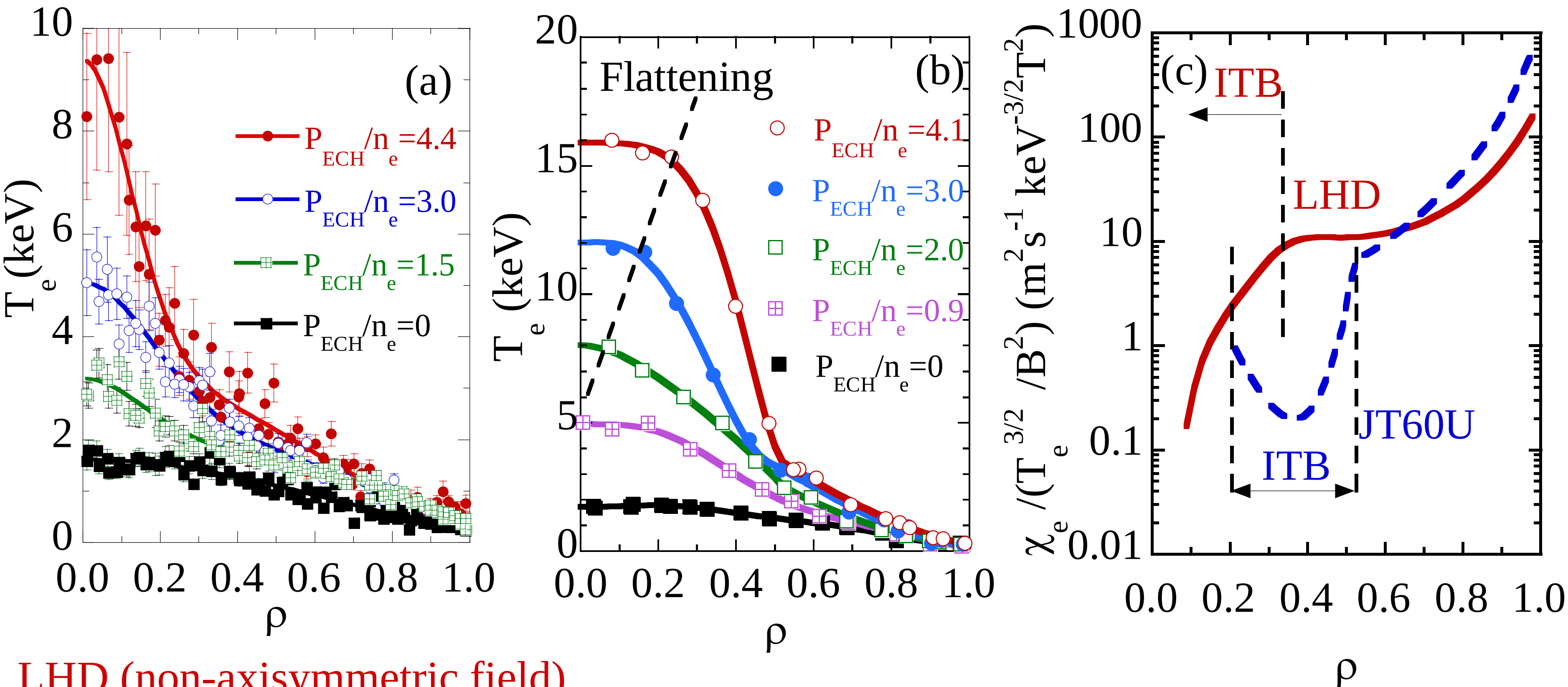
Good news

3N (non-linearity, non-diffusivity, non-locality) of transport give us interesting physics to be investigated (and gave me a chance for tutorial talk in this conference)

Bad news

Because of the recent significant progress of transport study in experiment and in theory, the X-day (all the transport physics will be understood and all the transport physicist will lose their job) is coming soon.

Comparison of radial structure of electron ITB between axisymmetric and non-axisymmetric devices



LHD (non-axisymmetric field)

→ reduction of χ_e is extended to the plasma core (weak E_r hear)

JT-60U (axisymmetric field)

→ reduction of χ_e is localized in the narrow E_r shear region

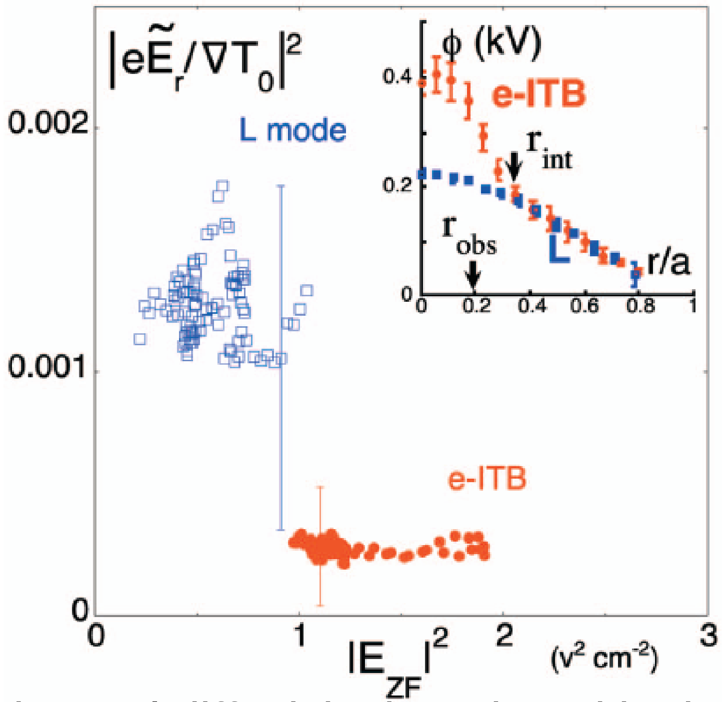
K

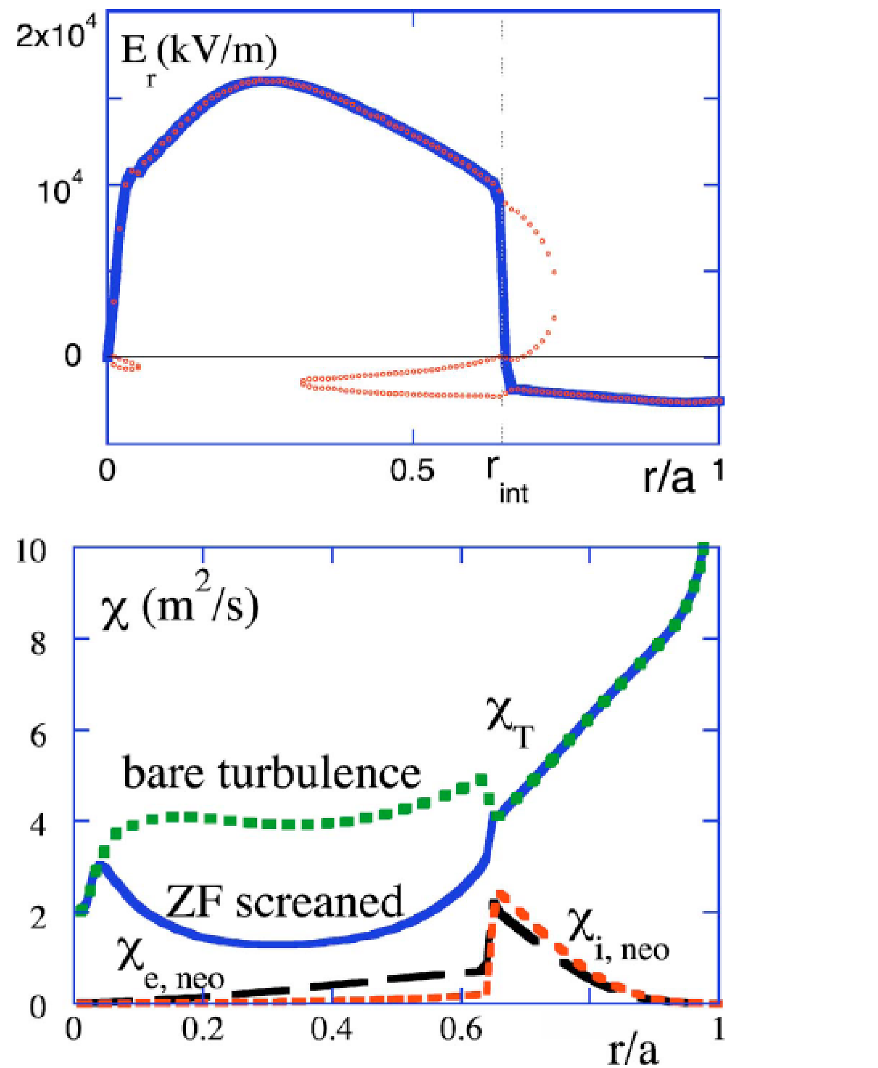
K.Ida, Plasma Phys. Control. Fusion 46 (2004) A45

Role of mean ExB flow on turbulence transport

L-mode → small Er → large ZF damping
→ small zonal flow → large turbulence

Electron ITB → large Er → small ZF damping
→ large zonal flow → small turbulence





Thermal diffusivity is reduced in the region with small E_r shear by ZF effect

K.Itoh, Phys. Plasmas 14 (2007) 020702