NON-LINEAR FLUID SIMULATIONS of THE EFFECT of ROTATION on ION HEAT TURBULENT TRANSPORT in TOKAMAK PLASMAS

G.L.Falchetto, M.Ottaviani, X.Garbet

Association EURATOM-CEA

CEA/DSM/DRFC Cadarache, France

OUTLINE

- **The model: 3D global fluid model of flux-driven electrostatic ITG turbulence in the plasma core**
- **Theoretical issue and impact**
- **Turbulent generation of poloidal rotation**
  - impact of collisionally damped zonal flows (ZF) on ion thermal transport
  - key role of ZF shear
- **Turbulent generation of toroidal rotation**
  - quasi-linear theory
  - preliminary results in a cylindrical case
- **Summary and discussion**

1) Turbulent generation of poloidal rotation

Zonal flow generation:

balance between Reynolds' stress drive **[Diamond et al.,1991]**

and damping by ion-ion collisions **[Rosenbluth-Hinton, 1998]**

The MODEL: 3D FLUID GLOBAL ELECTROSTATIC

Continuity eq. + parallel momentum + ion pressure evolution eq. including **curvature**, poloidal flow damping [Hinton-Rosenbluth '99], Landau damping closure and **flux driven** boundary conditions.

$$\left(\frac{d}{dt}+\vec{\mathbf{v}}_E\cdot\nabla\right)w-2\,\varepsilon\,\omega_d\,(\Phi+p_i)+A\nabla_{\|}v=\boxed{-A\,\gamma_{pfd}<w>}+D_w\nabla^2 w$$

$$\left(\frac{d}{dt}+\vec{\mathbf{v}}_E\cdot\nabla\right)v-4\,\varepsilon\,\omega_d\,v+A\nabla_{\|}(\Phi+p_i)=D_v\nabla^2 v$$

$$\left(\frac{d}{dt}+\vec{\mathbf{v}}_E\cdot\nabla\right)p_i-2\Gamma\,\varepsilon\,\omega_d\,(2\,p_i+<\Phi>)+\Gamma A\nabla_{\|}v=-\gamma_L|\nabla_{\|}|\,p_i+D_p\nabla^2 p_i$$

$$w=\Phi-<\Phi>-\rho_*^2\nabla^2\Phi$$

GC ion density

main parameter

$$\boxed{\gamma_{pfd}=\frac{2}{3}\,\nu^*\,\frac{\varepsilon^{1/2}}{q}}$$

ZONAL FLOW SELF-GENERATION & FEEDBACK

Perpendicular flow shears are effective in turbulence suppression **[e.g Hahm-Burrell. 1995]**

Impact of ion-ion collisions on zonal flows and tranport:

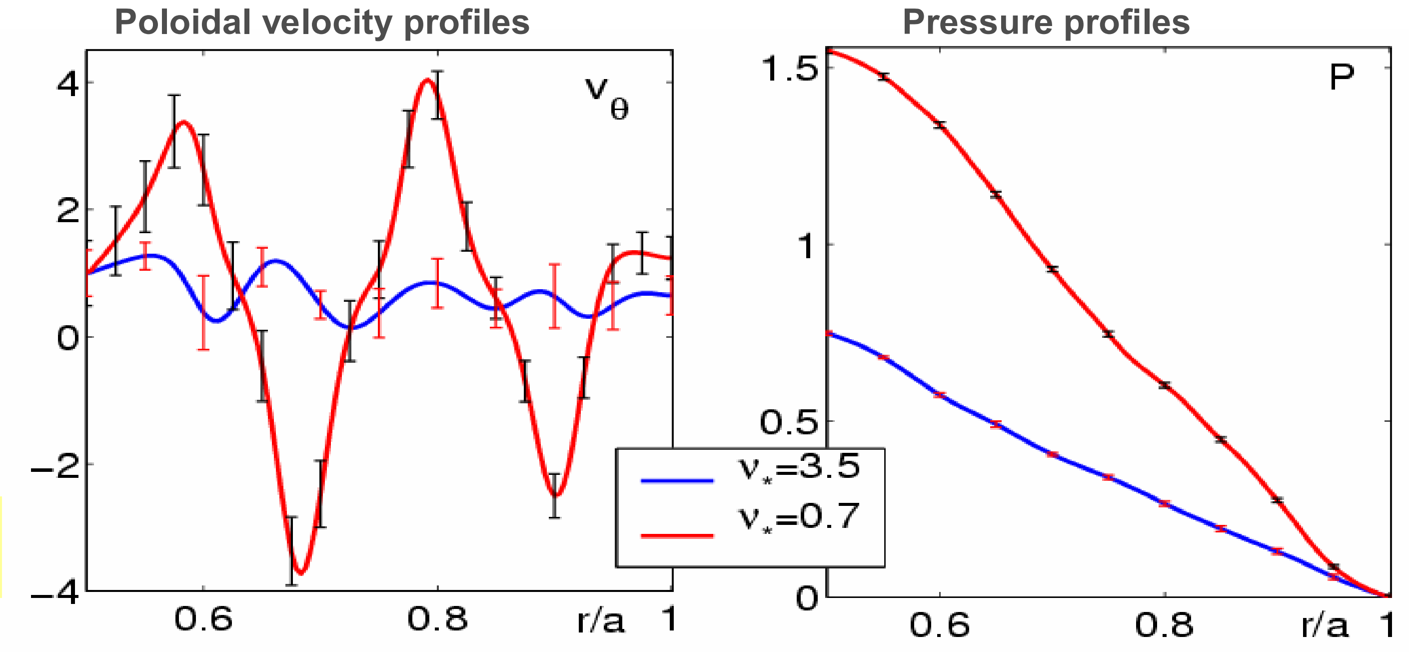
low collisionality ν^* = ZF less damped ➔ decrease of turbulent fluctuation amplitudes ➔ reduced radial turbulent flux

➔ **improved energy confinement at low collisionality ν^***

Mechanism of turbulence stabilization via **zonal flow damping:** reduction of collisionality ➔ self-generation of larger amplitude and higher **shear** ZF ➔ upshift of effective temperature threshold for ITG instability ➔ decrease of effective ion heat conductivity **[G.L. Falchetto&M. Ottaviani, PRL 92, 2004]**

EFFECT OF LOW COLLISIONALITY ON STEADY-STATE PROFILES

**$\rho^* = 0.01$
Fin=0.025**



"frozen" zonal flow

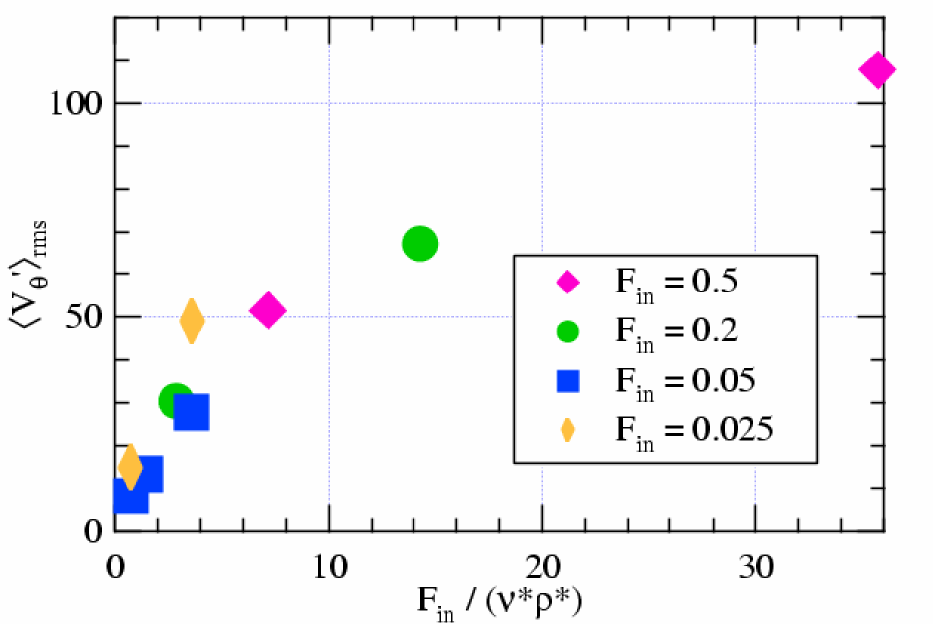
self-generated localised zonal flows
with increased amplitude & shear
persisting for over a confinement time

steepening
of pressure profile

! constantly injected
heat flux

KEY ROLE of MEAN ZONAL FLOW SHEAR in REGULATING TURBULENT TRANSPORT

zonal flow mean shear
depends on collisionality and input power
$\langle v_\theta' \rangle \nearrow$ with $\nu^* \searrow$ $F_{in} \nearrow$



increase of ZF shear

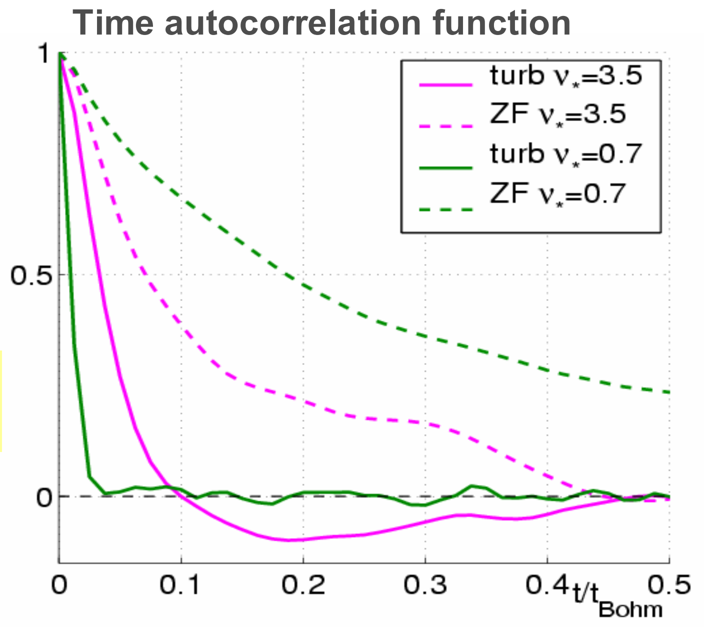
⇓

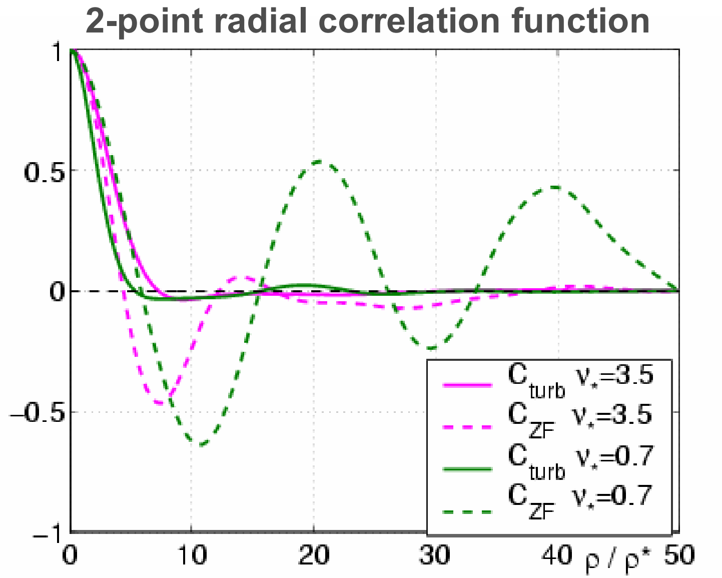
upshift of ∇T_{eff}
ITG threshold

ZF mean shear plays key role in the regulation of turbulence

AUTOCORRELATION FUNCTIONS

$\rho^* = 0.01$
Fin=0.025



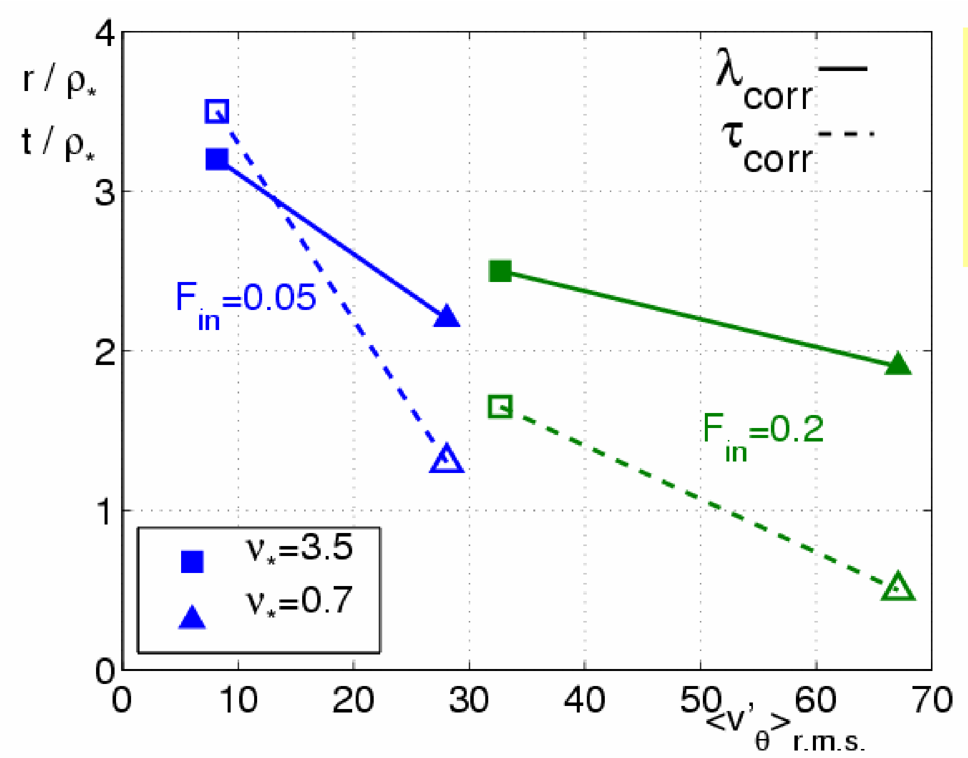


ZF evolution much slower than ambient turbulence'
➔ *"frozen" ZF*

ν^* ↘ $\lambda_{\text{corr turb}}$ ↘
$\lambda_{\text{corr ZF}}$ ↗

$\tau_{ZF} \sim t_{Bohm}$ $\tau_{turb} \sim 10^{-2}\, \tau_{ZF}$

ZONAL FLOW SHEAR EFFECT ON TURBULENCE CORRELATION LENGHTS AND TIMES



$\rho^* = 0.02$

correlation lengths **decrease**
with increased
ZF shear and injected flux
$\lambda_{\mathbf{corr\ turb}}$ ↘ $< \mathbf{v}_\theta' >$ ↗ F_{in} ↗

strong reduction of
turbulence correlation times
with increased mean ZF shear
$\tau_{\mathbf{turb}}$ ↘ $< \mathbf{v}_\theta' >$ ↗

⇓

agreement with criteria of
turbulence stabilisation
by decorrelation
due to velocity shearing

2) Turbulent generation of toroidal rotation

THEORETICAL AND EXPERIMENTAL CONTEXT

The effect of parallel flow shear has not been well investigated

Experimental facts:

- ✓ Large toroidal velocities without external torque observed in many tokamaks (Alcator C-mod, JET, Tore-Supra). **[J.Rice, Nucl.Fus.1998; L.G. Eriksson, Nucl.Fus. 2001; PRL 2003]**
- ✓ Dynamical coupling between parallel flows and turbulent transport observed in JET **[C. Hidalgo, B. Gonçalves et al., PRL 2003]**
- ✓ Following H-mode transition, toroidal momentum is observed to propagate inward from the plasma edge (Alcator C-mod). Momentum redistribution linked to edge physics phenomenon. **[J.Rice et al., Nucl.Fus.44 / IAEA 2004]**

Various theoretical interpretations

TURBULENT GENERATION of TOROIDAL ROTATION

- **Turbulence driven mechanism**

Similarly to the well known generation of perpendicular flow, turbulence can generate a parallel flow **via the parallel Reynold's stress** component

[Dominguez & Staebler 1993; P.Diamond et al., 1994; B.Coppi, 2002; X. Garbet et al., 2002]

$$\Pi_{//} = < \tilde{v}_{Er} \tilde{v}_{//} >$$

! Few numerical simulations available to test this effect

ANOMALOUS TOROIDAL ROTATION - CYLINDRICAL CASE

Parallel momentum equation, flux-surface averaged

$$\partial_t < v > + \frac{1}{r}\, \partial_r \boxed{< -\frac{1}{r}\, (\partial_\theta \phi)\; v >} = D_v\, \frac{1}{r}\; \partial_r\, (r \partial_r < v >)$$

$\pi_{//}$ Reynolds stress

Quasi-linear analysis:
parallel Reynold's stress = anomalous viscosity + source term

$$F^D_{Q.L.} = \int_0^t d\tau \sum_{m,n} \left[{k_\theta}^2\, \tilde{\phi}(r,t)\; \tilde{\phi}^*(r,\tau)\; e^{im\, \omega_0 (t-\tau)} \right] \partial_r < v(r,\tau) >$$

$$F^S_{Q.L.} = \int_0^t d\tau \sum_{m,n} \left[A\, k_\theta\, k_\parallel\, \tilde{\phi}(r,t)\; \left(\tilde{\phi}^*(r,\tau) + \tilde{p}^*(r,\tau) \right)\; e^{im\, \omega_0 (t-\tau)} \right]$$

ANOMALOUS TOROIDAL ROTATION - CYLINDRICAL CASE

In the absence of shear flow, fluctuations are symmetric around rational surfaces

! no net parallel velocity is produced

$$F^S_{Q.L.} = \int_0^t d\tau \sum_{m,n} \left[A\, k_\theta\, \overset{\downarrow}{k_\parallel}\, \tilde{\phi}(r,t) \;\left(\tilde{\phi}^*(r,\tau) + \tilde{p}^*(r,\tau) \right)\; e^{im\,\omega_0(t-\tau)} \right]$$

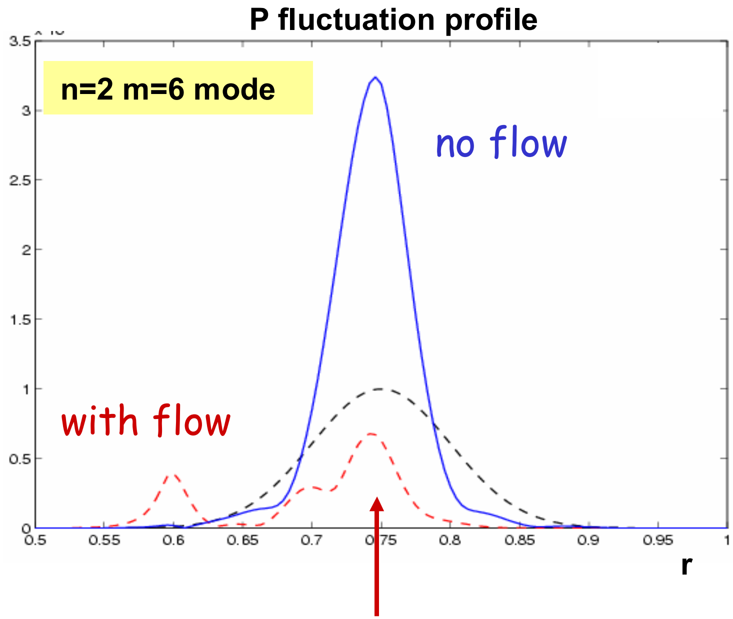
➔ for parallel velocity generation a de-symmetrization of the parallel flow is needed

➢ e.g. imposed strong constant shear flow

PRELIMINARY RESULTS - CYLINDRICAL CASE

Test simulation
one mode cylindrical case
with imposed constant
shear flow

$$v_{\theta 0}(r) = const.$$

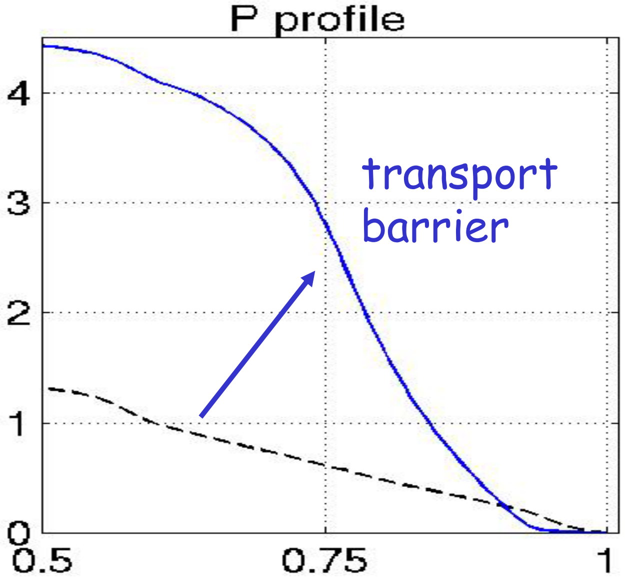


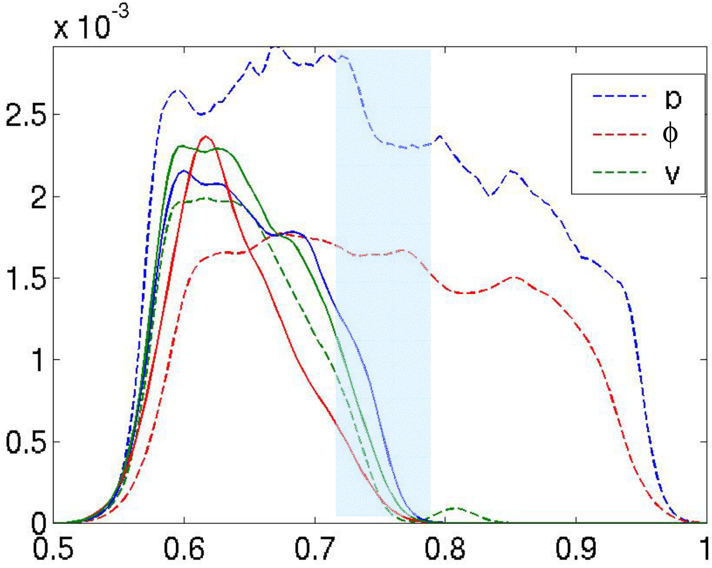
de-symmetrization of mode structure
with imposed flow

PRELIMINARY RESULTS - CYLINDRICAL CASE

Cylindrical case with zero initial velocity and profile

- ✓ strong shear flow triggers a transport barrier
- ✓ complete stabilization of fluctuations by imposed ExB shear





$\rho^* = 0.01$
Fin=0.05

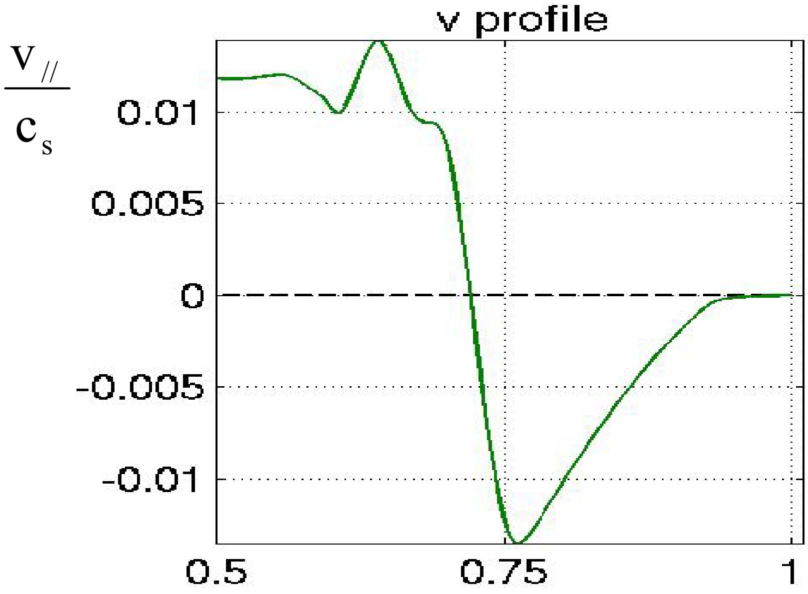
stabilization of fluctuations induced by shear flow outside the barrier

PRELIMINARY RESULTS - CYLINDRICAL CASE

De-symmetrization induced by the shear flow →

finite parallel velocity generation in region internal to the barrier !

HOWEVER low amplitude of generated velocity

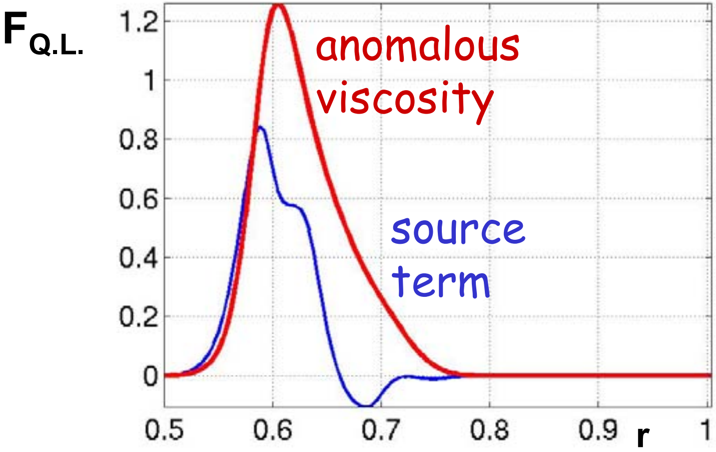


DISCUSSION

! Low level of fluctuations ➔ weak generation inside the barrier

! The turbulent source is small outside the barrier

✓ parallel Reynold's stress quasi-linear components, **diffusion** and **source**, are asymmetric and small outside the barrier



➢ further investigate to better understand generation mechanism

SUMMARY and CONCLUSIONS

3D fluid global non-linear simulations of flux-driven electrostatic ITG turbulence in a tokamak core

✓ **Effect of poloidal rotation on turbulence**

main trigger parameter: collisionality ν^*

- ✓ low ν^* : self-generation of *"frozen"* zonal flows of large amplitude and shear ➔ shearing of convective cells, upshift of ITG threshold & steepening of steady-state pressure profiles ➔ improved confinement
- ✓ key role of ZF mean shear in decorrelating turbulence: stronger ZF shear (at low ν^*) ➔ shorter turbulence correlation lenghts and times

➢ **interplay with geodesic curvature modes**

SUMMARY and CONCLUSIONS

✓ Turbulent generation of toroidal rotation

preliminary reults - cylindrical case with imposed strong poloidal flow shear :

- ✓ there is a source of parallel momentum due to a de-symmetrization of the turbulent flow
- ✓ finite parallel velocity generation but SMALL with an imposed shear flow because of turbulence quench