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# Interplay between magnetic braking and turbulent stress tensor regarding plasma flow

R. Varennes<sup>1</sup>

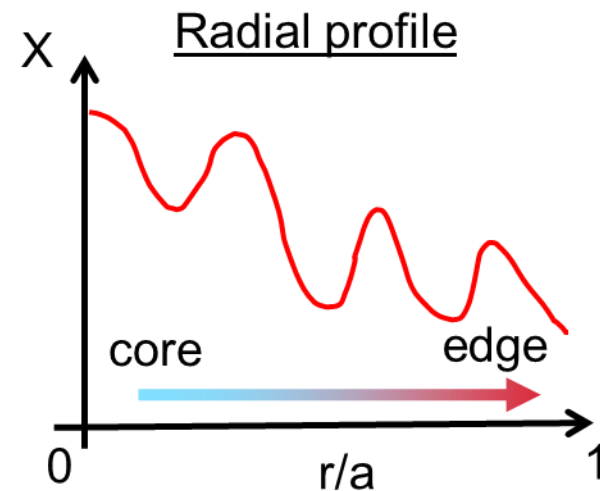
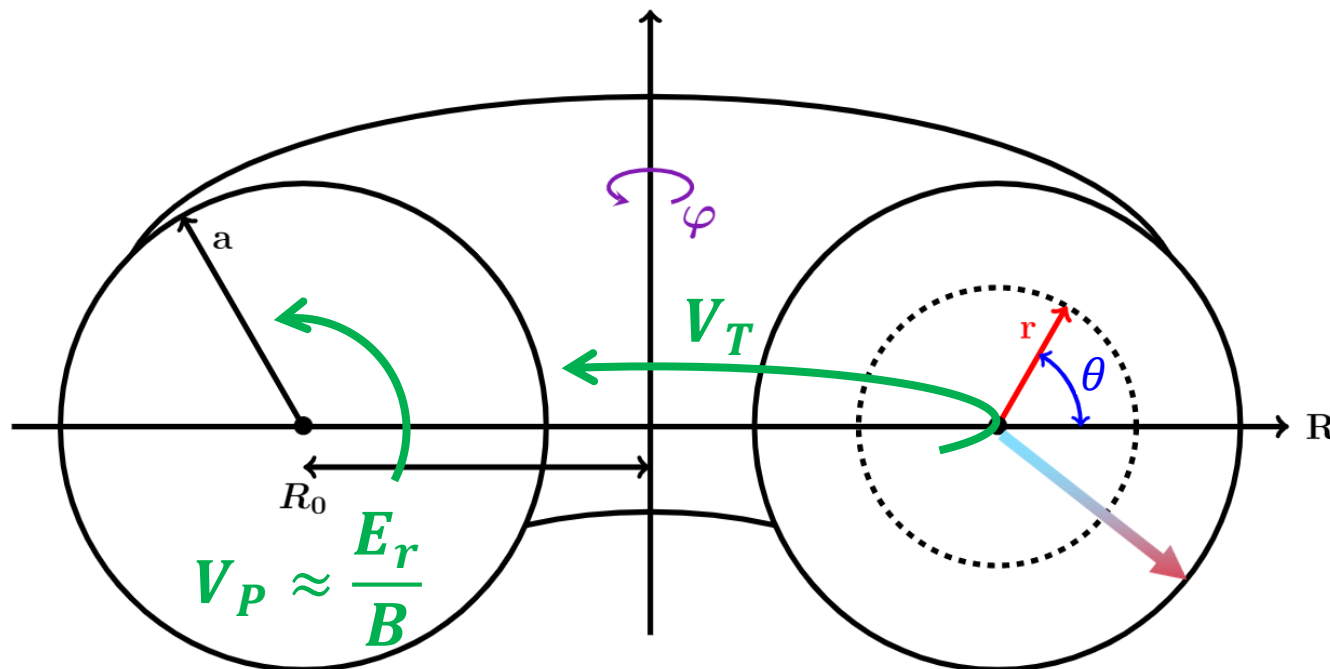
## Acknowledgments:

L. Vermare<sup>2</sup>, X. Garbet<sup>1</sup>, Y. Sarazin<sup>1</sup>, V. Grandgirard<sup>1</sup>, G. Dif-Pradalier<sup>1</sup>, P. Gendrih<sup>1</sup>, P. Donnel<sup>1</sup>, M. Peret<sup>2</sup>

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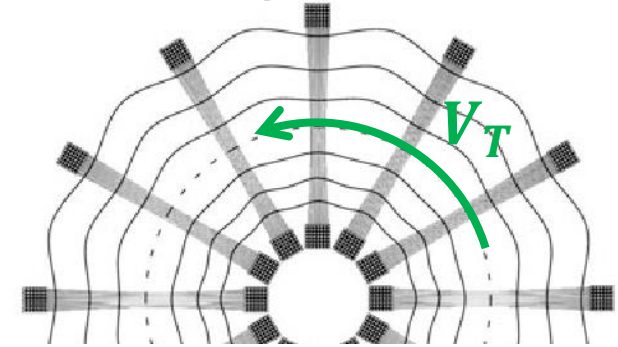
- Tokamak: magnetic configuration often considered axisymmetric
- Interest of 3D magnetic configuration: effect on the LH transition threshold, optimization of plasma stability and confinement, impact on the rotation

[J.-K. Park - PRL 2021]

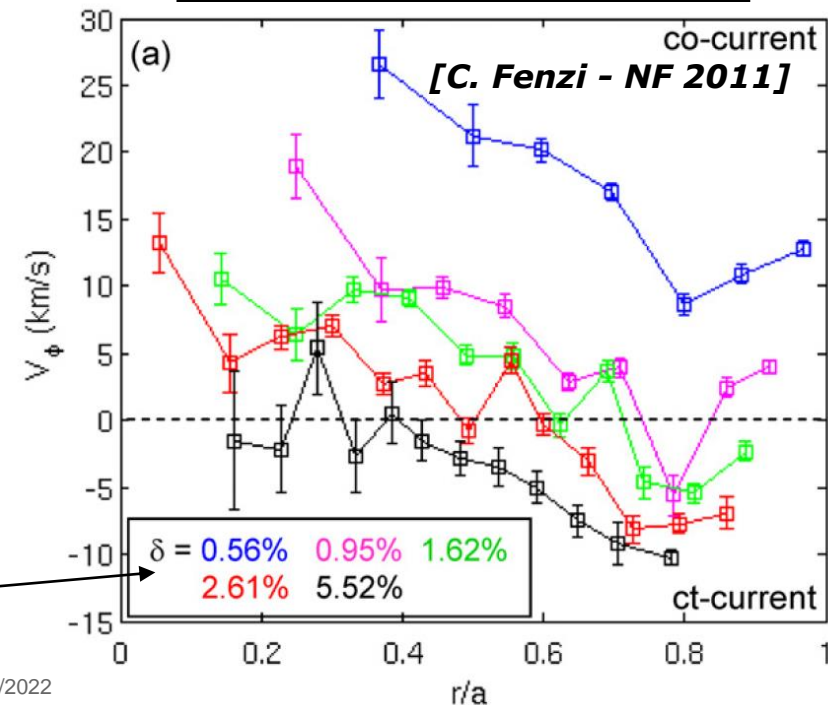
[M. Landreman - PRL 2022]

# Plasma rotation → competition between magnetic braking and turbulence

## Rippled magnetic field lines



## Plasma rotation in Tore Supra without momentum input



### Plasma toroidal rotation $V_T$ :

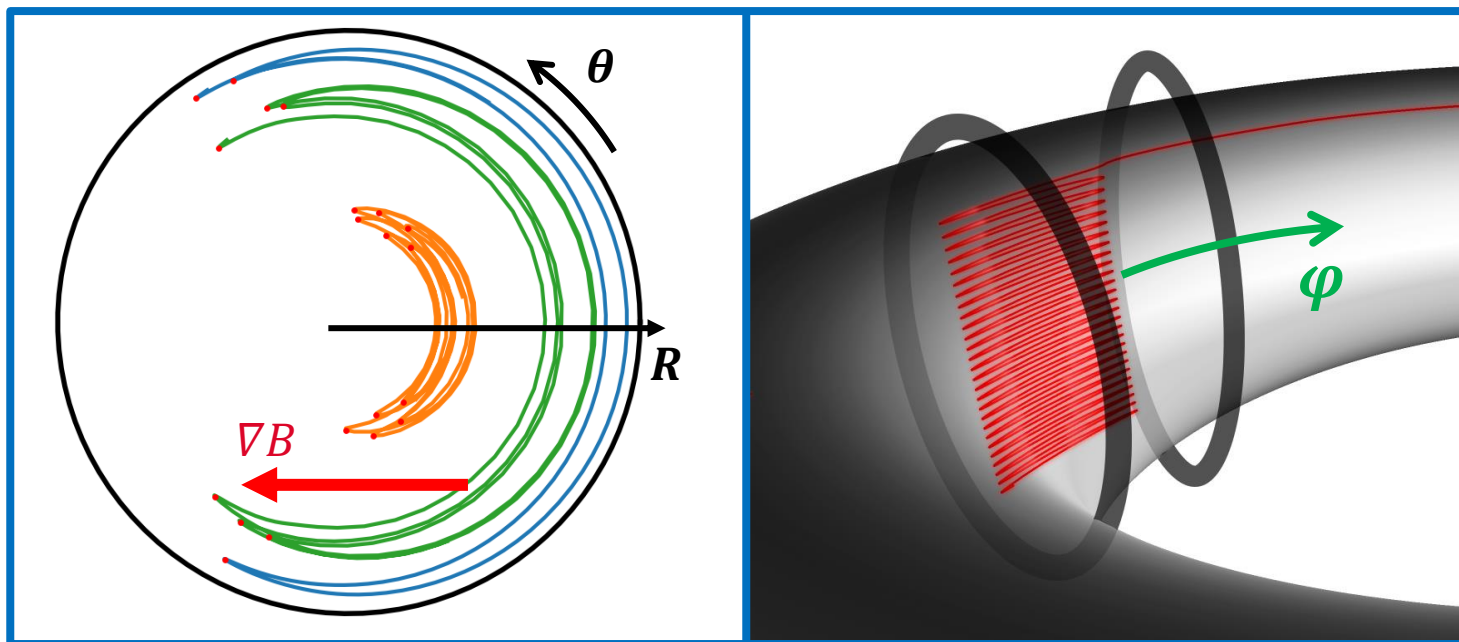
- Plays a key role in confinement
- Challenging to control in reactor-sized tokamak (e.g. ITER)
- Flows rather governed by **intrinsic rotation**
- Governed by **turbulent momentum drive** and **magnetic braking** (RMP, ripple, ...)

Ripple amplitude →

- 1) Reduced model for the intrinsic rotation**
- 2) Validation with gyrokinetic simulations**
- 3) Synergy between turbulent drive and magnetic braking**

- 1) Reduced model for the intrinsic rotation**
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## Trapped trajectories in presence of ripple



Magnetic braking:  $m = -v_{\text{col}}(V_T - V_{\text{col}})$

↑
↑

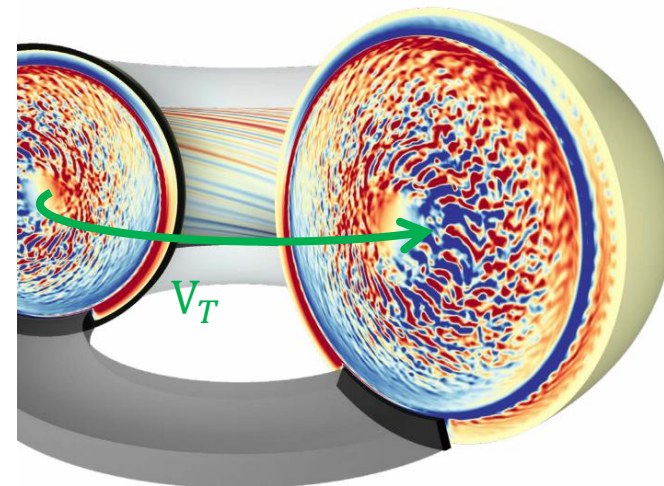
Collisional friction                  Equilibrium velocity

*[J. W. Connor - NF 1973]*  
*[K. C. Shaing - PoF 1986]*  
*[P.N. Yushmanov - NF 1983]*  
*[L. M. Kovrizhnykh - NF 1984]*  
*[X. Garbet - PoP 2010]*

## Turbulence:

- Small-scale fluctuations of the electric potential leading to macroscopic transport
- Turbulence forces rotation to finite value via wave/particle momentum transfer
- Expression of the exerted force:  $-\nabla \cdot \Pi$

## Turbulent structures in a tokamak



[O. Gürcan - PRL 2008]  
[T. S. Hahm - PoP 2007]  
[P.H. Diamond - NF 2009]  
[A. Peeters - PRL 2007/ NF 2011]  
[B. Chouli - PPCF 2015]

Toroidal Reynolds stress:  $\Pi = \langle \tilde{v}_r \tilde{v}_\varphi \rangle = -\chi \partial_r V_T + \mathcal{V} V_T + \Pi_{\text{res}}$

↑
↑
↑

Turbulent viscosity
Pinch
Residual stress → Sets the equilibrium velocity



$$\Pi = -\chi \partial_r V_T + \mathcal{V} V_T + \Pi_{res}$$

Turbulent drive:

$$-\nabla \cdot \Pi \approx -\nu_{turb} (V_T - V_{turb})$$

$$-\frac{\partial_r^2 V_T}{V_T} \chi + \frac{\partial_r V_T}{V_T} \mathcal{V}$$

“Effective” turbulent friction

$$\frac{\Pi_{res}}{\nu_{turb}}$$

Equilibrium velocity

# A critical ripple amplitude rules the toroidal rotation

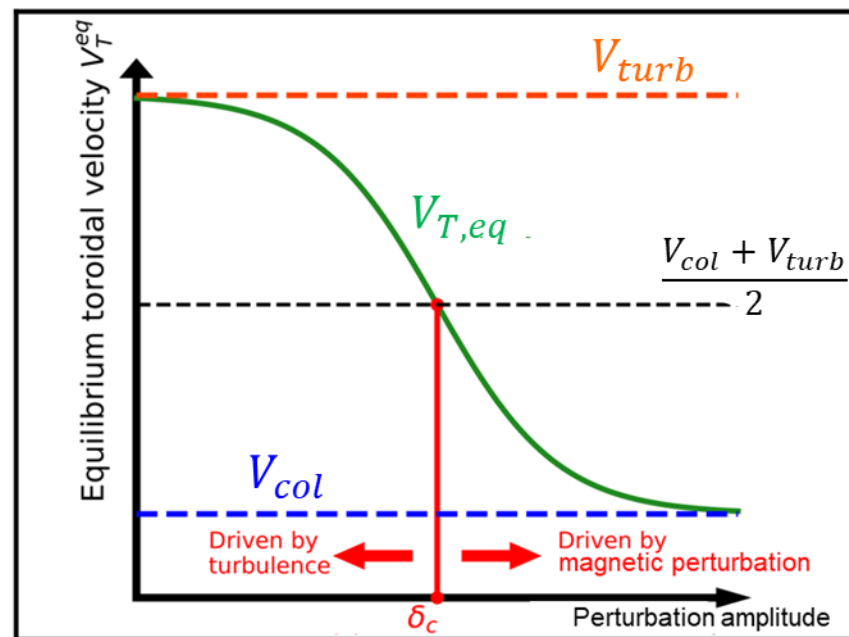
## Turbulence and ripple:

Theoretical model:  $\partial_t V_T = m - \nabla \cdot \Pi$

$$\partial_t V_T = -(v_{col} + v_{turb})V_T + v_{col}V_{col} + v_{turb}V_{turb}$$

Dominating drive depends on a **critical ripple amplitude**  $\delta_c$  such that

$$v_{col}(\delta_c) = v_{turb}$$



[R. Varennes - PRL 2022]

Rule of thumb:  $\delta_c \sim \frac{\rho_i}{R_0} \sqrt{N_c} \left(\frac{R}{L_T}\right)^{-3/2}$

Labels: Ion Larmor radius ( $\rho_i$ ), Coils number ( $N_c$ ), Temperature gradient length ( $L_T$ ).

## Application at $r/a = 0.8$ :

- Tore Supra typical discharge  $\rightarrow \delta_c \approx 0.4\%$
- Same with ITER geometry  $\rightarrow \delta_c \approx 0.15\%$

- 1) **Reduced model for the intrinsic rotation**
- 2) **Validation with gyrokinetic simulations**
- 3) **Synergy between turbulent drive and magnetic braking**

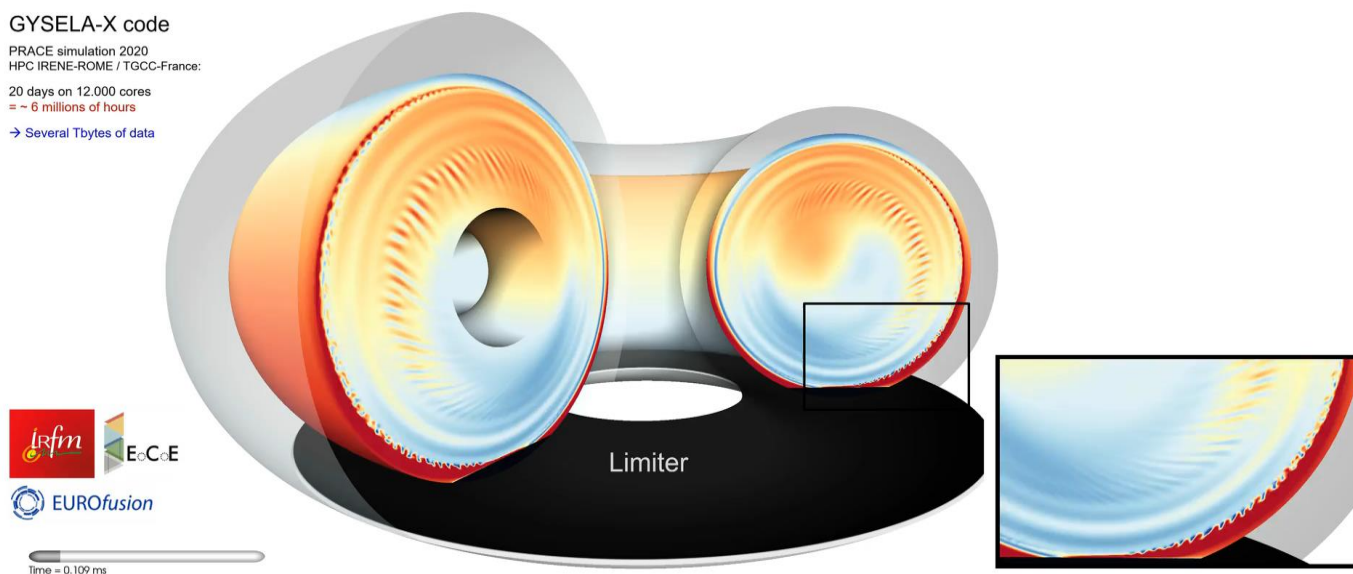
# Validating the model requires gyrokinetic simulations

- GYSELA: kinetic code solving

Fokker-Planck:  $\frac{dF}{dt} = C(F)$

Poisson:  $\epsilon_R \nabla^2 \phi = -\sum_{\text{species}} e \int F d^3v$

GYSELA-X code  
PRACE simulation 2020  
HPC IRENE-ROME / TGCC-France:  
20 days on 12,000 cores  
= ~ 6 millions of hours  
→ Several Tbytes of data



$$v_{\text{col}}(\delta_c) \approx v_{\text{turb}}$$

[V. Grandgirard – CPC 2016]

Requires 3D magnetic perturbation to be implemented

Determined for one turbulence

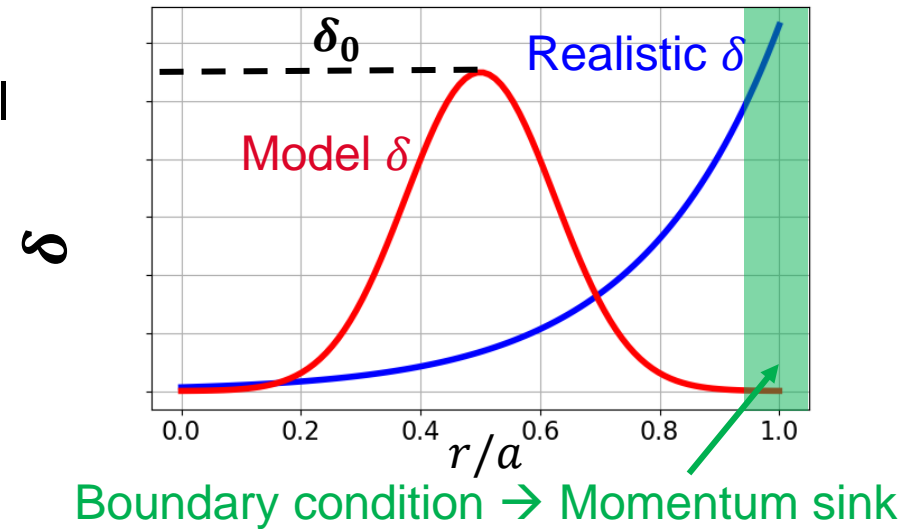
■ Boundary conditions (realistic/simulated)

→ momentum sink not included in the model

■ Solution: radially gaussian ripple

amplitude

## Ripple amplitude profile



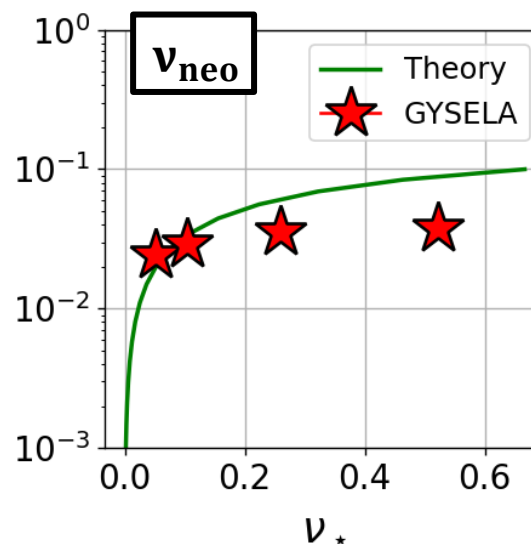
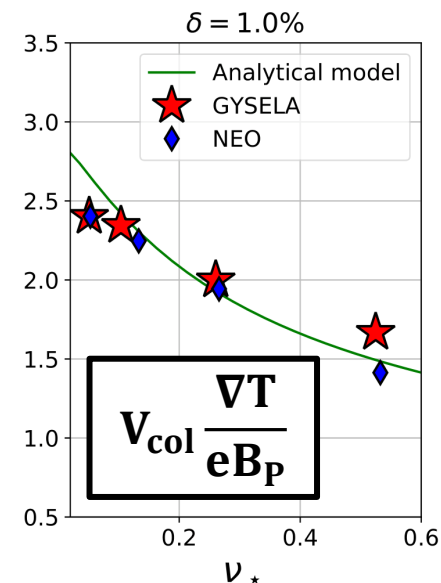
# Thorough benchmark of the ripple implementation

$$m = -v_{col}(V_T - V_{col})$$

Depend on the collisionality  $\nu_*$  and ripple amplitude  $\delta$

- Toroidal momentum is conserved
- $V_{col} \rightarrow$  good agreement GYSELA / NEO
- Collisional friction  $v_{col} \rightarrow$  good

agreement between GYSELA and the theory



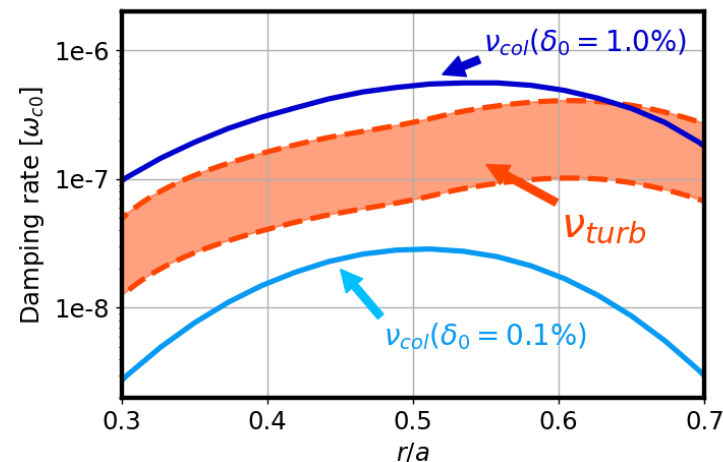
[R. Varennes - Submitted to PPCF]

# The estimated critical ripple amplitude validated through simulations

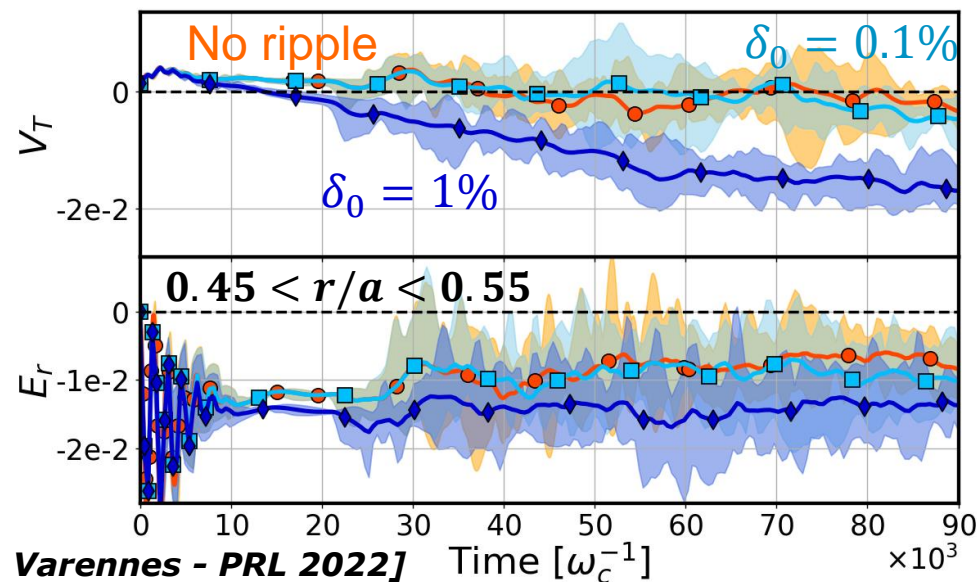
- Cases with  $\delta \gg \delta_c$  and  $\delta \ll \delta_c$
- No significant difference between  $\delta \ll \delta_c$  case and the **no ripple** case
- $\delta \gg \delta_c$  case dominated by magnetic braking  $\rightarrow$  similar in some experiments (TS, JET and JT60)

[H. Urano - NF 2011]  
[M.F.F Nave - PRL 2010]  
[C. Fenzi - NF 2011]

## Radial profiles of $\nu_\phi$ and $\chi$



## Time evolution of $V_T$ and $E_r$



[R. Varenes - PRL 2022]

- 1) **Reduced model for the intrinsic rotation**
- 2) **Validation with gyrokinetic simulations**
- 3) **Synergy between turbulent drive and magnetic braking**



Synergy observed in simulations:

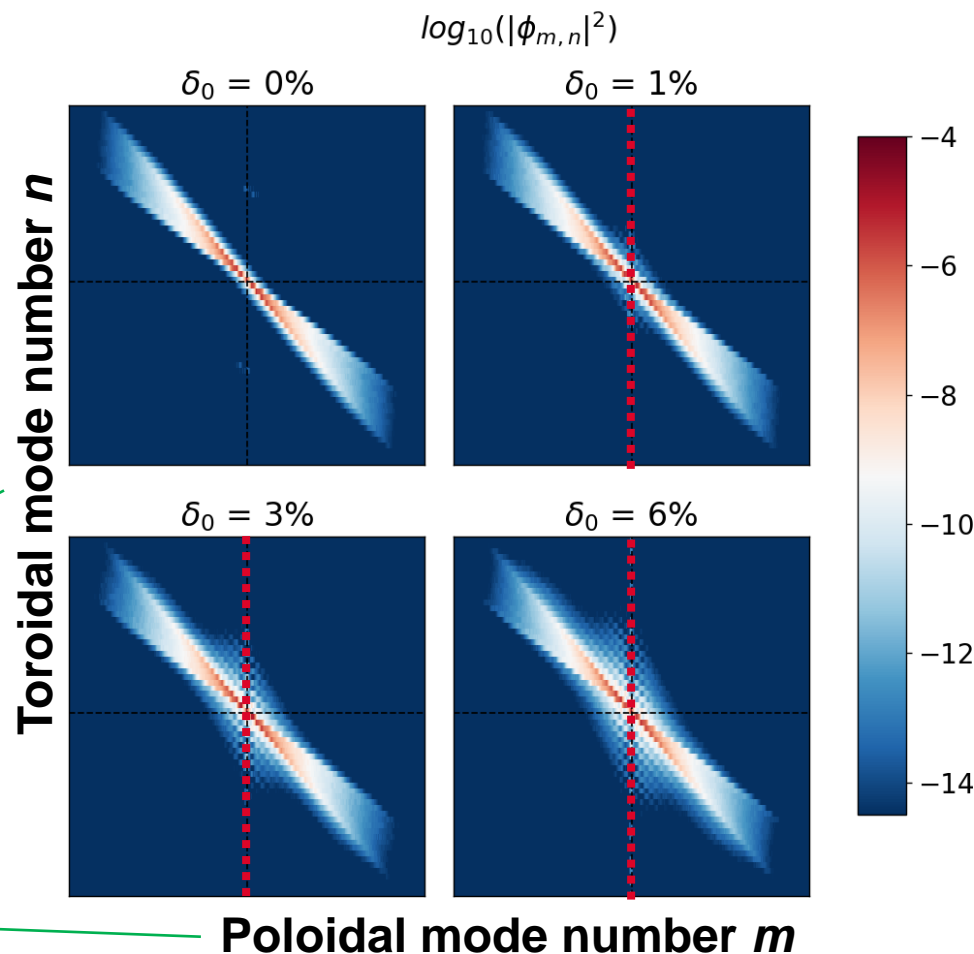
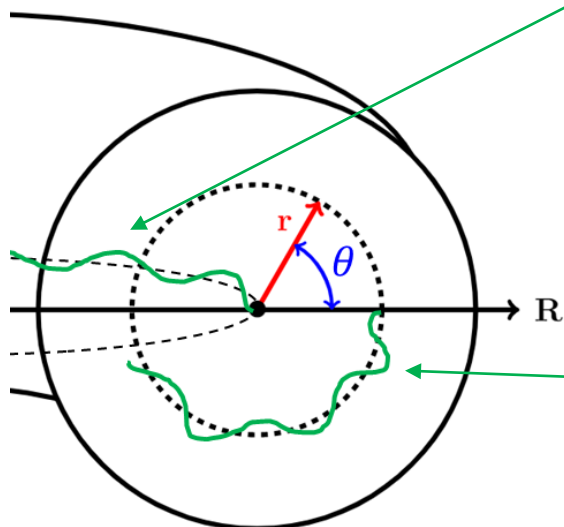


## ■ Possible synergy mechanisms:

- Up-down asymmetry of magnetic surfaces ✗ [Y. Camenen - PRL 2009]
- Stochasticity of magnetic field lines ✗ [C.-C Chen - PoP 2021]
- Modification of the turbulent intensity radial shear ✓ [O. Gürçan - PRL 2008]
- Modification of the  $E_r$  radial shear ✓ [P.H. Diamond - IAEA Vienna 1994]

# Ripple changes turbulence intensity through mode-coupling

- Turbulent intensity defined as  $I = \frac{e\tilde{\phi}}{T}$
- Ripple  $\rightarrow \cos(N_c\varphi)$  perturbation magnetic field  $\rightarrow$  reflects on electric potential  $\phi$
- With turbulence, mode-coupling modifies the turbulent spectra

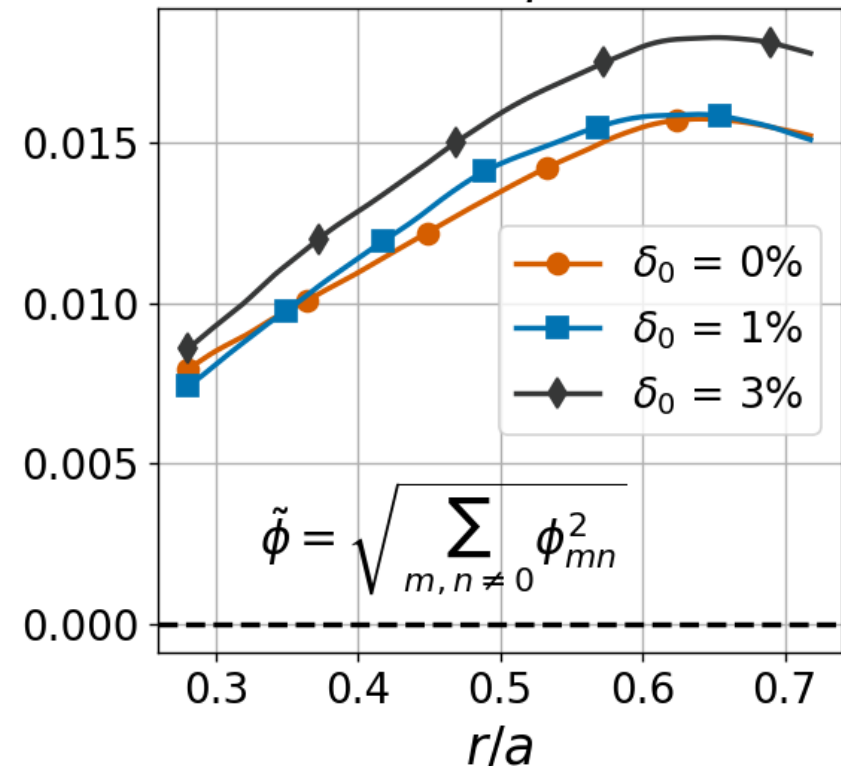


➤ Spectral coupling → well described by the simulation code

➤ However, weak effect of the ripple on the turbulent intensity

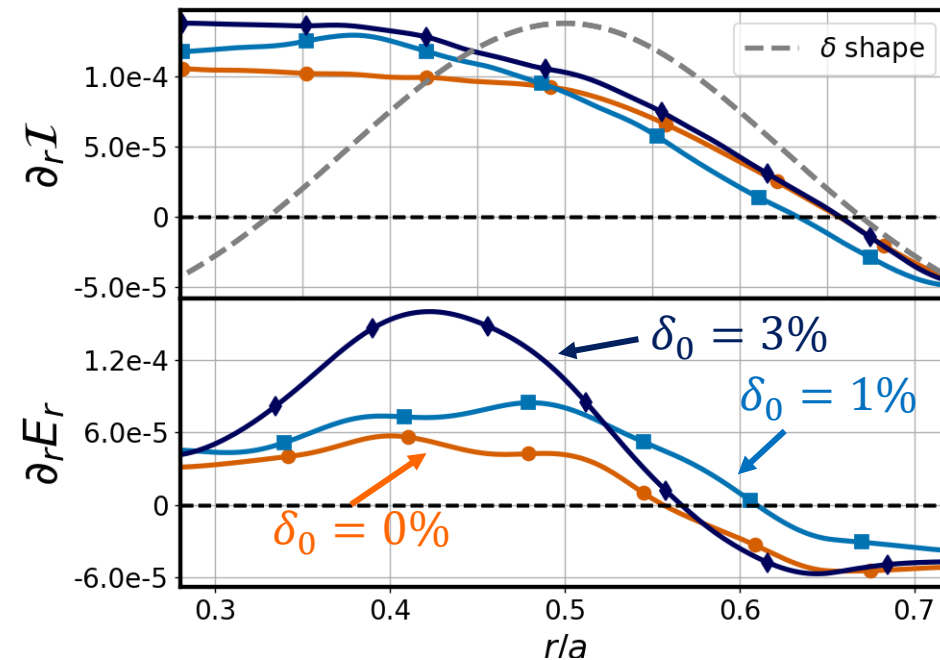
## Coarse-grained turbulent intensity

$$I = e\tilde{\phi}/T$$



- $\partial_r E_r$  expected to impact  $\Pi$
- Ripple  $\rightarrow E_r$  enhancement through collisional processes
- Increasing of  $\Pi$  associated with an increase in  $\partial_r E_r$  in simulations

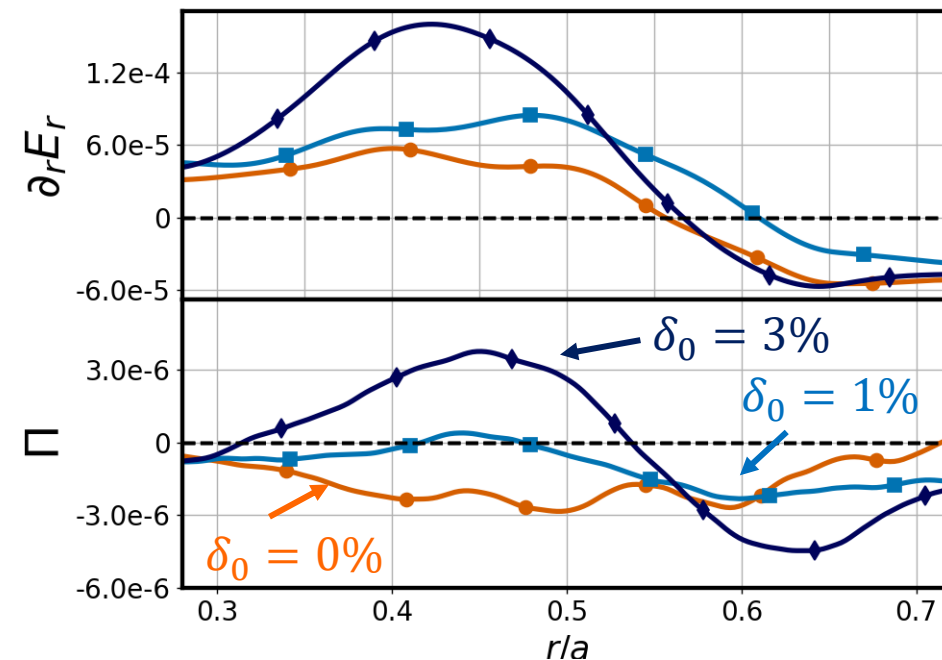
## Coarse-grained profiles



[R. Varennes - PRL 2022]

- $\partial_r E_r$  expected to impact  $\Pi$
- Ripple  $\rightarrow E_r$  enhancement through collisional processes
- Increasing of  $\Pi$  associated with an increase in  $\partial_r E_r$  in simulations

## Coarse-grained profiles



[R. Varennes - PRL 2022]

- Plasma rotation → driven by a **competition** between **turbulence** and **magnetic braking**
- Magnetic braking overcomes turbulence above a **critical amplitude** of magnetic ripple
- Toroidal Reynold stress → **strongly impacted by ripple**
- Synergy mechanism → **Enhancement of  $\partial_r E_r$  due to ripple** which in turn modifies  $\Pi$

*[R. Varennes - PRL 2022]*

*[R. Varennes - Submitted to PPCF]*

# Backup slides

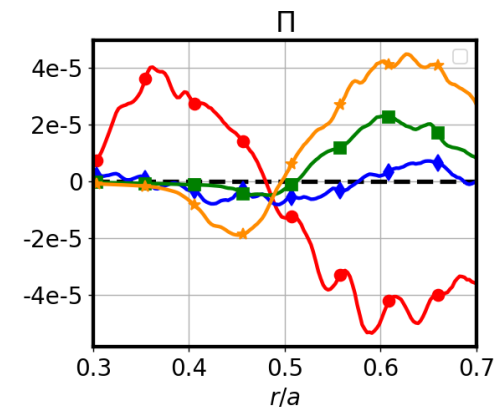
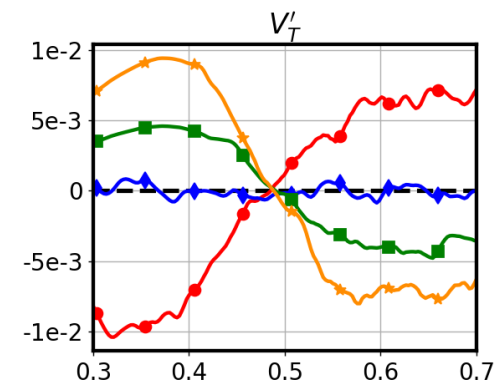
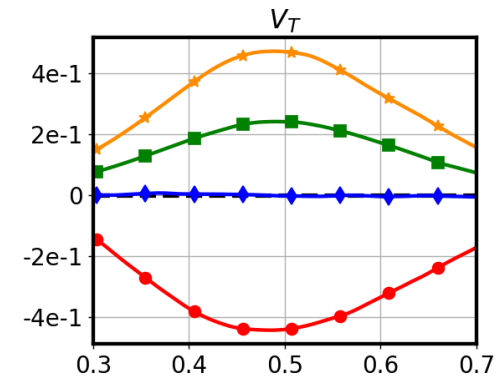
# Evaluating the turbulent viscosity with gyrokinetic code

$$\Pi = -\chi \partial_r V_T + \mathcal{V} V_T + \Pi_{res}$$

Unknowns

GYSELA outputs

- Simulations of ITG turbulence with different initial  $V_T$
- Enough equation to deconvolve  $\chi$ ,  $\mathcal{V}$  and  $\Pi_{res}$
- Pinch  $\mathcal{V}$  found negligible





# A simple expression for the critical ripple amplitude

$$\delta_c \text{ defined by } v_\varphi(\delta_c) = |\lambda_v| \underbrace{\left( \chi + \frac{\kappa_v}{\lambda_v} \mathcal{V} \right)}_{\chi_{\text{eff}}}$$

Toroidal harmonic of the perturbation  $\rightarrow$  Thermal velocity

- Ripple-plateau regime (relevant for most tokamaks):  $v_\varphi \sim \frac{N_c V_{\text{th}}}{R} \delta^2$  (robust)

Ion Larmor radius  $\rightarrow$

- Gyrobohm scaling:  $\chi_{\text{eff}} \sim \chi_{\text{GB}} = \frac{\rho_i^2 V_{\text{th}}}{L_T}$  (debatable, but verified in our simulations)

Temperature gradient length  $\rightarrow$

- $\lambda_v = -\frac{(r\chi V_{\text{Teq}})'}{r\chi V_{\text{Teq}}} \sim L_T^{-2}$  (ok in order of magnitude)

$$\Rightarrow \delta_c \sim \frac{\rho_i}{R} \sqrt{N_c} \left( \frac{R}{L_T} \right)^{-3/2}$$

Application with magnetic ripple at  $r/a = 0.8$ :

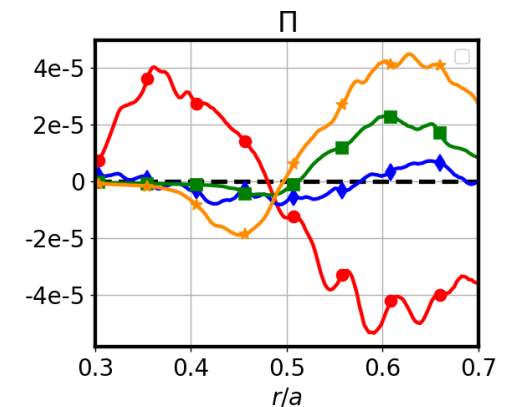
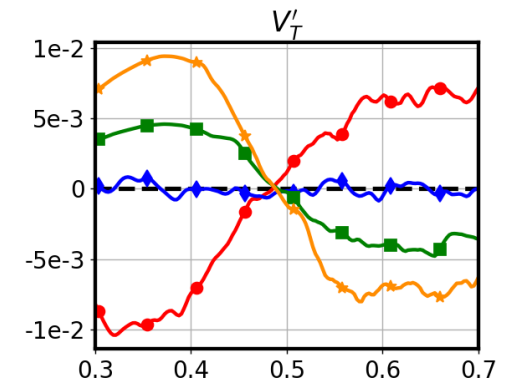
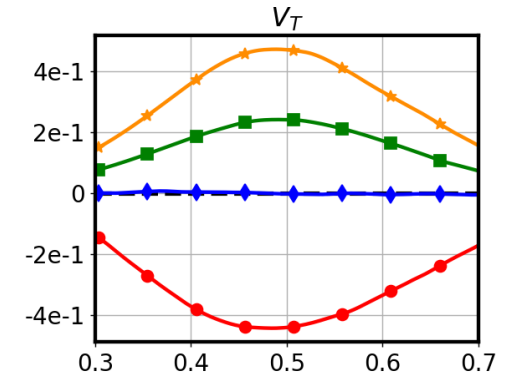
- Tore Supra typical discharge  $\rightarrow \delta_c \approx 0.4\%$
- Same with ITER geometry  $\rightarrow \delta_c \approx 0.15\%$

# Evaluating the turbulent viscosity with gyrokinetic code

$$\Pi = -\chi \partial_r V_T + \mathcal{V} V_T + \Pi_{res}$$

Unknowns

GYSELA outputs



- Simulations with different initial  $V_T \rightarrow$  get enough equation to deconvolve  $\chi$ ,  $\mathcal{V}$  and  $\Pi_{res}$
- ITG turbulence with adiabatic  $e^-$
- Pinch  $\mathcal{V}$  found negligible  $\rightarrow$  already observed adiabatic  $e^-$

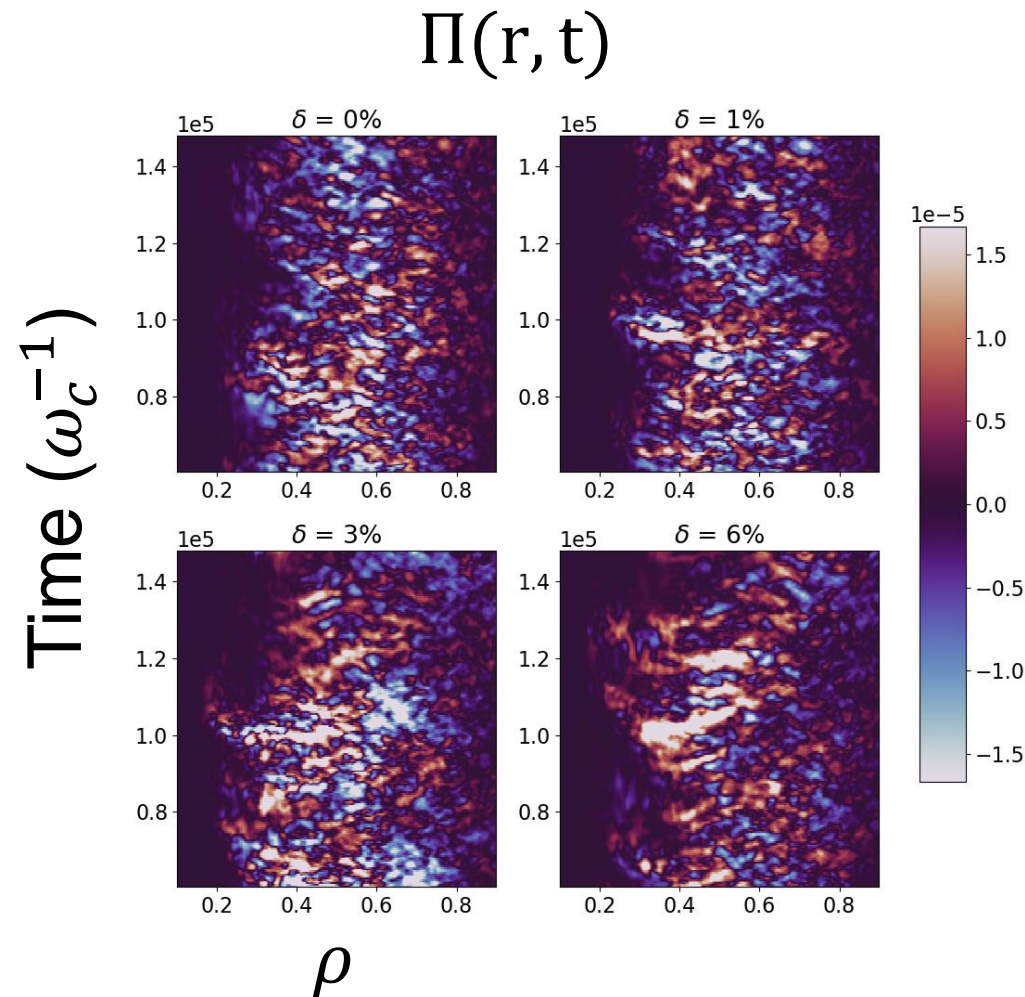
[A. Peeters - NF 2011]

## Synergy between ripple and turbulence:

- Turbulence impact on magnetic braking found negligible (not tested with RMPs)
- However magnetic braking strongly modifies  $\Pi$

## Mechanisms considered:

- 1) Modification of the turbulent intensity shear
- 2) Modification of the  $E \times B$  shear



- Toroidal symmetry → degeneracy on  $E_r$  and  $V_T$  (linked by force balance)
- Ripple → toroidal magnetic braking / friction

Drift kinetic equation :  $(\mathbf{v}_{\parallel} + \mathbf{v}_D) \cdot \nabla (F_{eq} + \delta F) = \mathcal{C}(\delta F)$

Annotations: **Ripple** (red arrow from  $\mathbf{v}_D$  to  $\delta F$ ), **Banana** (green arrow from  $\delta F$  to  $\mathbf{v}_D$ ),  **$\nabla B$**  (green arrow from  $\mathbf{v}_D$  to  $\mathbf{v}_{\parallel}$ ), **Local trapping** (red arrow from  $\delta F$  to  $\mathbf{v}_{\parallel}$ )

→ Drifting banana  
→ Magnetic wells

⇒ 
$$\begin{matrix} \text{Particle flux} \rightarrow \\ \text{Magnetic braking} \rightarrow \\ \text{Heat flux} \rightarrow \end{matrix} \begin{pmatrix} \frac{\Gamma}{N} \\ \frac{\mathcal{M}}{NeB_p} \\ \frac{Q}{NT} \end{pmatrix} = \underbrace{\begin{pmatrix} d_{NN} & d_{NV} & d_{NT} \\ d_{VN} & d_{VV} & d_{VT} \\ d_{TN} & d_{TV} & d_{TT} \end{pmatrix}}_{\text{Depends on}} \begin{pmatrix} \frac{dN}{Ndr} - \frac{eE_r}{T} \\ \frac{eB_p}{T} V_T \\ \frac{dT}{Tdr} \end{pmatrix}$$

Depends on  $\begin{cases} \delta : \text{ripple amplitude} \\ \varepsilon : \nabla B \text{ amplitude} \\ \nu^* : \text{collisionnality} \end{cases}$

[J. W. Connor 1973]  
[K. C. Shaing 1986]  
[P.N. Yushmanov 1987]  
[A. B. Mikhailovskii 1995]  
[L. M. Kovrizhnykh 1998]  
[X. Garbet 2010]

(Also valid for RMPs !)

- Neoclassical non-axisymmetric toroidal momentum conservation :

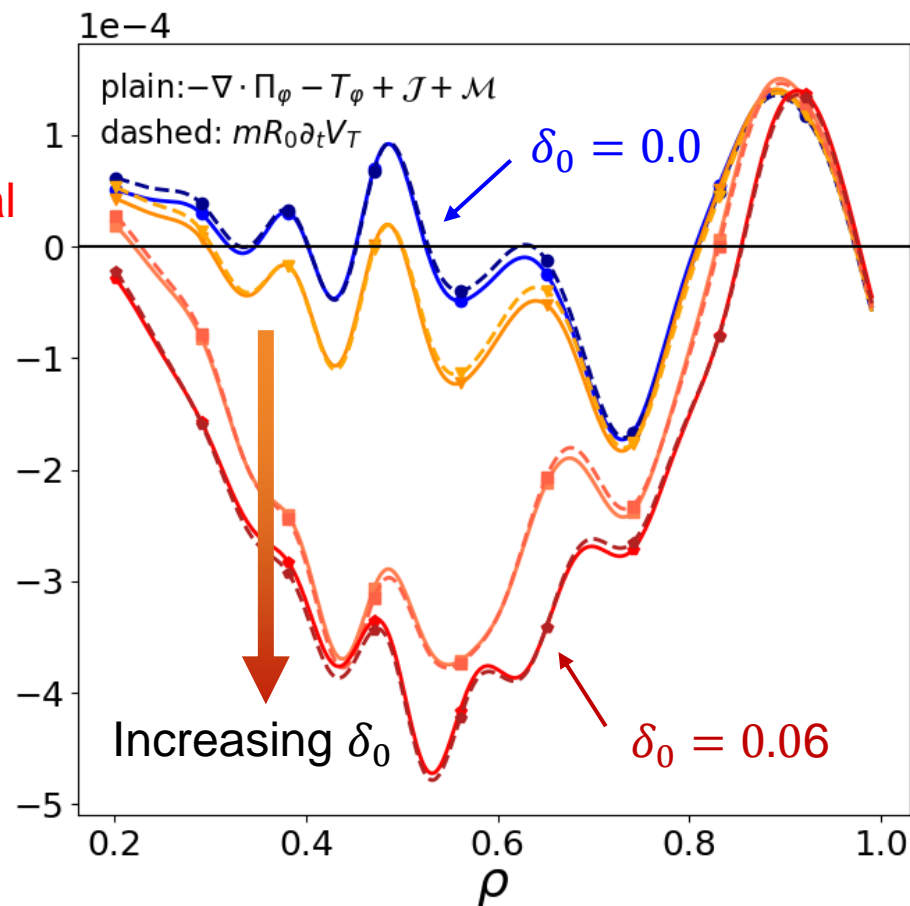
$$NmR_0 \frac{\partial V_T}{\partial t} = \underbrace{-\nabla \cdot \Pi_{turb}}_{\text{Turbulence (=0)}} - \underbrace{T_\varphi}_{\text{Polarization}} + \underbrace{J}_{\text{Current}} + \underbrace{\mathcal{M}}_{\text{Neoclassical Toroidal Viscosity}}$$

[J. Abiteboul 2011]

$$\mathcal{M} = - \int \frac{d\theta d\varphi}{4\pi^2} \int \mathbf{d}\mathbf{v} F \left\{ \mu \frac{\partial \tilde{B}}{\partial \varphi} \right\}$$

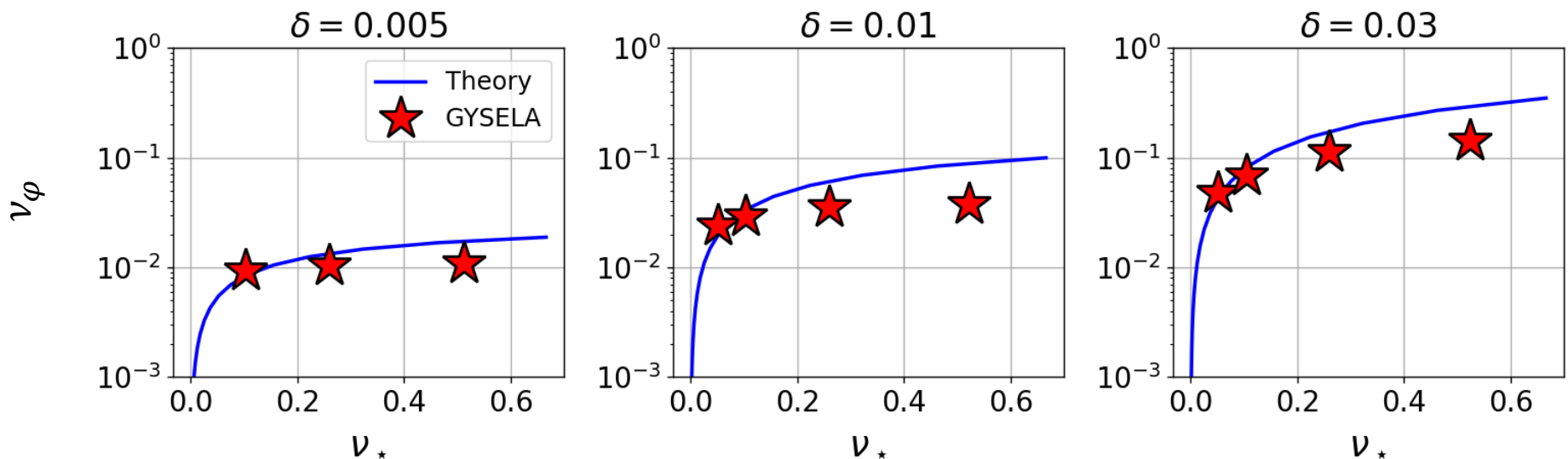
$$\mathcal{M} \text{ dominating} \rightarrow NmR_0 \frac{\partial V_T}{\partial t} \approx \mathcal{M}$$

## Radial profile of the LHS and RHS of the conservation of $L$



- Toroidal momentum with magnetic braking is conserved
- Neoclassical target velocity  $V_{neo}$  in good agreement between GYSELA and NEO
- Neoclassical friction  $v_\phi$  in good agreement between GYSELA and the theory

## Neoclassical friction vs ripple amplitude and collisionality



## Magnetic braking:

- Resulting force coming from B inhomogeneity on particle magnetic moments  $\mu$
- Magnetic braking force expression:  $m = -\int d^3v \left( \mu \frac{\partial B}{\partial \varphi} F \right)$
- 3D magnetic perturbations in tokamaks  $\rightarrow$  external, magnetic ripple
- Constrains the particle trajectories  $\rightarrow$  results in finite plasma toroidal velocity  $V_T$

$$\Pi_{\text{res}} = \sum_k k_{\parallel} k_{\theta} \left| \frac{e\phi_k}{T} \right|^2 \tau_k$$