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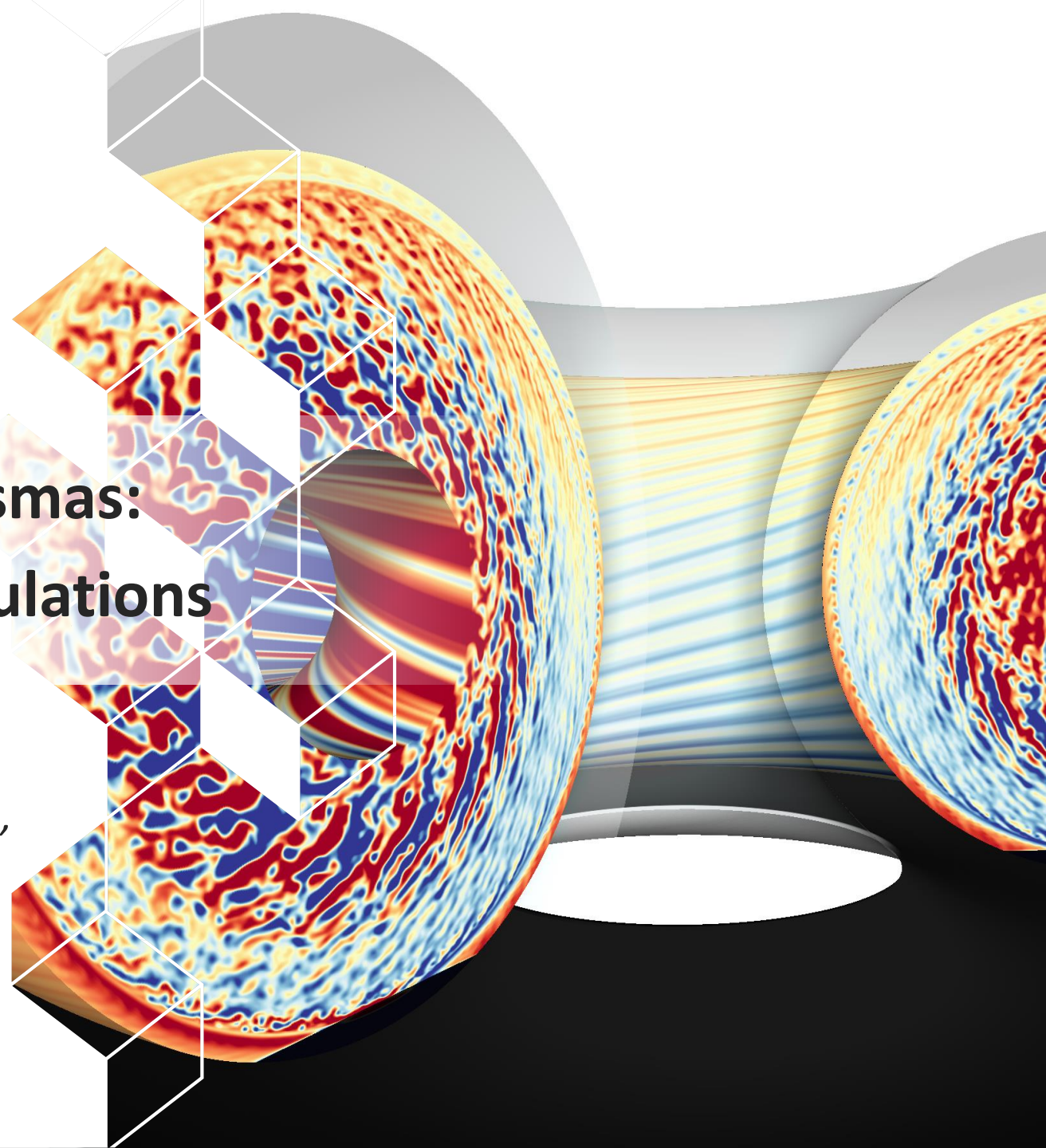
# The edge $E_r$ well in L-mode plasmas: Experiments & gyrokinetic simulations

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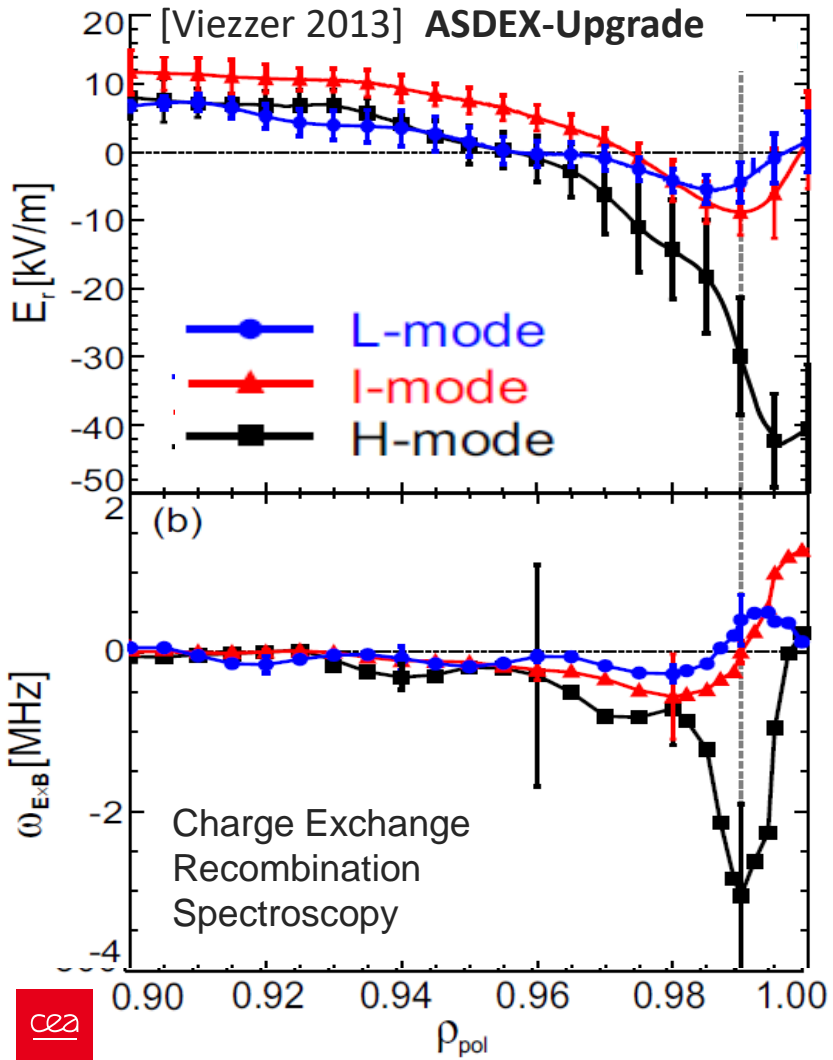
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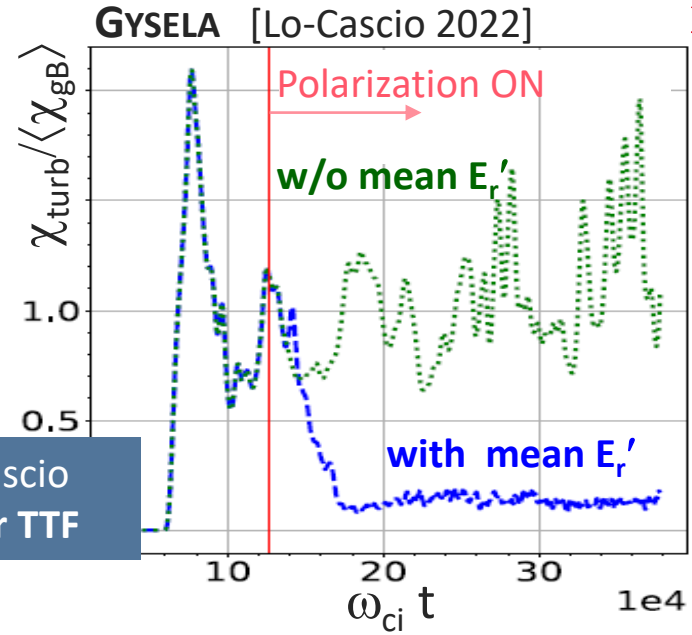


# Motivation – Outline

- Shear of  $v_{E\theta} = -E_r/B \rightarrow$  turbulence regulation  
 $\rightarrow$  transport barrier [Biglari-Diamond-Terry 1990; Waltz 1994; Hahm-Burrell 1995]



Lo-Cascio  
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- $E_r$  well key player in H-mode [Wagner 1982, Itoh 1988]
  - Experimentally observed close to separatrix [Groebner 1990, Burrell 1992, ...]
  - Deepens when bifurcating from L- to H-mode
  - Some evidence of causal role of turbulence [Moyer 2001]
- This talk:
  - Competition between collisions & turbulence in flow dynamics
  - Dependence on safety factor (plasma current)

# Heuristic dynamical equation on $\langle E_r \rangle$

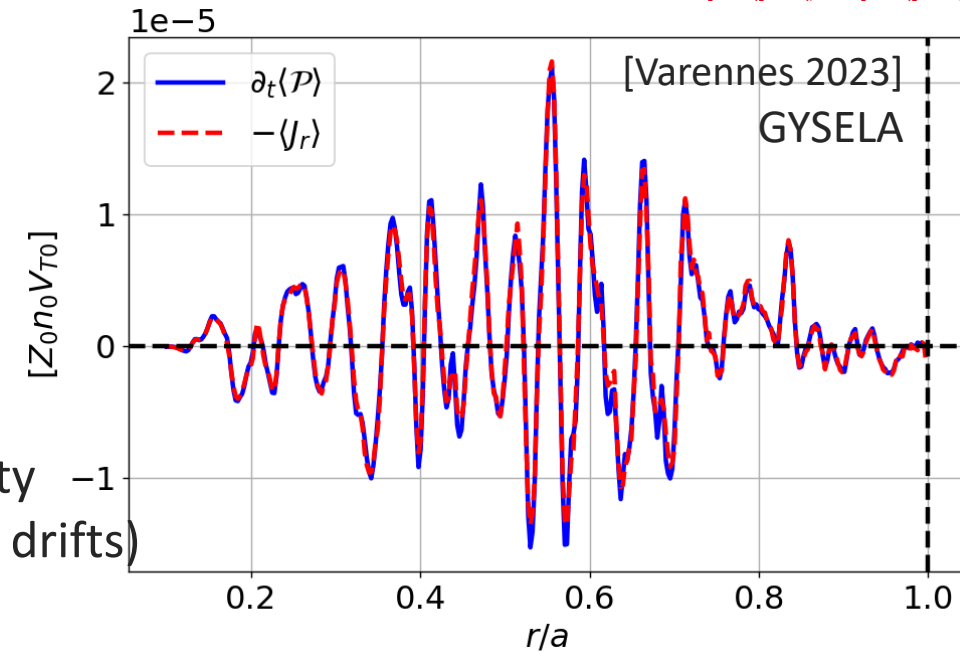
- Poisson equation → **exact** dynamical equation for polarization field at small  $k_{\perp} \rho_i$  [Parra 2009, Abiteboul 2011]

$$\frac{\partial}{\partial t} \sum_s \epsilon_{pol,s} \left( E_r - \frac{1}{2e_s N_s} \frac{dP_{\perp,s}}{dr} \right) = - \sum_s J_{r,s}$$

Polarization

Radial current density  
(electric & magnetic drifts)

Permittivity =  $\frac{N_s m_s}{B^2}$   $\frac{\partial P_{\perp,s}}{\partial t}$  governed by heat eq.



- Leads to a **heuristic equation** for  $\langle V_{E\theta} \rangle = -\langle E_r \rangle / B$  → in banana regime  $\nu_* = \frac{\nu_{ii} q R}{v_T \epsilon^{3/2}} \ll 1$ :

$$(1 + \underbrace{Cq^2}) \frac{\partial \langle V_{E\theta} \rangle}{\partial t} = -\nu_{neo} (\langle V_{E\theta} \rangle - V_{E\theta,neo}) - \nabla_r \langle \Pi_{r\theta} \rangle$$

Renormalized inertia depends on collisionality

[Gianakon 2002, Chôné 2014]

Turbulent Reynolds stresses (Taylor's identity)

$$C \simeq \frac{1.6}{\epsilon^{3/2}} \text{ (banana regime)}$$

$$\simeq \frac{0.7 q^2}{\epsilon^{3/2}} \nu_{ii}$$

$$-\frac{T}{eB} \left\{ \frac{\nabla_r N}{N} + \left( 1 - \frac{B_{\varphi}}{B} K_{neo} \right) \frac{\nabla_r T}{T} \right\} - \frac{B_{\theta}}{B} V_{\varphi}$$

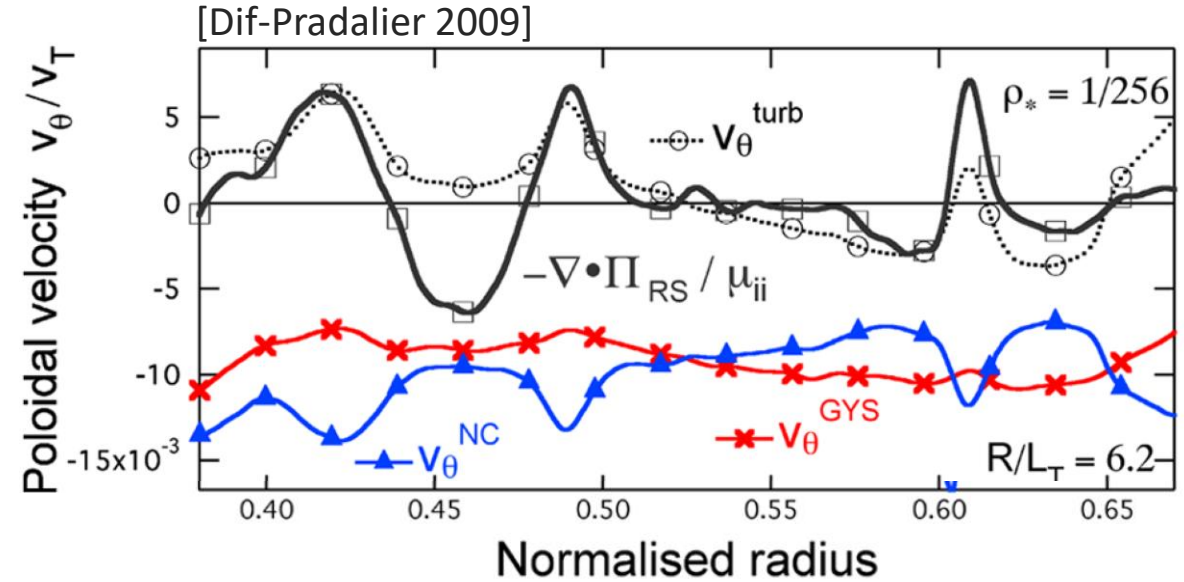
# Heuristic prediction for $\langle v_{E\theta} \rangle$ – some evidence in experiments

- Prediction at equilibrium: **balance between turbulence & collisions**

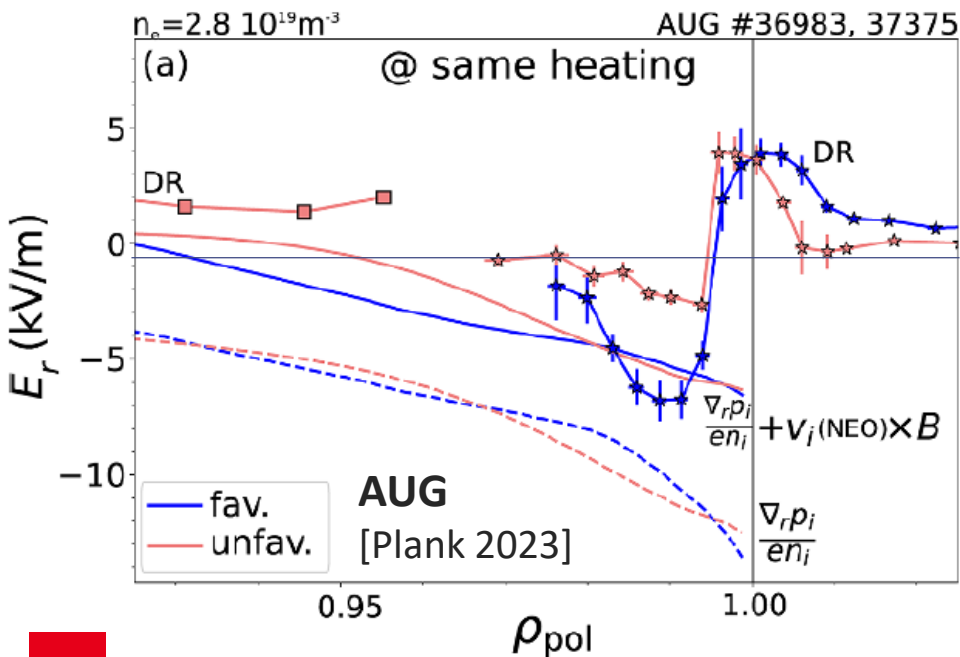
$$\langle V_{E\theta} \rangle = V_{E\theta,neo} - \frac{\nabla_r \langle \Pi_{r\theta} \rangle}{\nu_{neo}}$$

Fair agreement in the core

Important role of turbulence at staircase locations



- Experiments yield contradictory information in core [Bell 1998, Crombé 2005, Grierson 2013] & edge [Viezza 2014, Plank 2023]
- Radial force balance (with  $V_{\theta,neo}$ ) not always sufficient to recover experimental measurement of  $E_r$
- Other mechanisms than turb. possibly at play in edge:
  - Orbit squeezing [Shaing 1992, Kagan 2009, Landreman 2010]
  - Ion orbit losses [De Grassie 2011, Chang 2017, Brzozowski 2019]



# Turbulent RS not only electric → diamagnetic component $\Pi^*$

- Two distinct components of Reynolds stress:

$$\Pi_{r\theta} = \Pi + \Pi^*$$

$$\Pi = \tilde{v}_{Er} \tilde{v}_{E\theta} = -\frac{\nabla_{\theta}\tilde{\phi}}{B} \frac{\nabla_r\tilde{\phi}}{B}$$

$$\Pi^* = \tilde{v}_r^* \tilde{v}_{E\theta} = -\frac{\nabla_{\theta}\tilde{p}_{\perp i}}{eNB} \frac{\nabla_r\tilde{\phi}}{B}$$

[Smolyakov 2000;  
McDevitt 2010;  
Ajay JPP 2020]

In ITG turbulence  
(adiab. & kin. electrons)

$\Pi$  &  $\Pi^*$  are in phase

$\Pi^* \approx 2 \times \Pi$

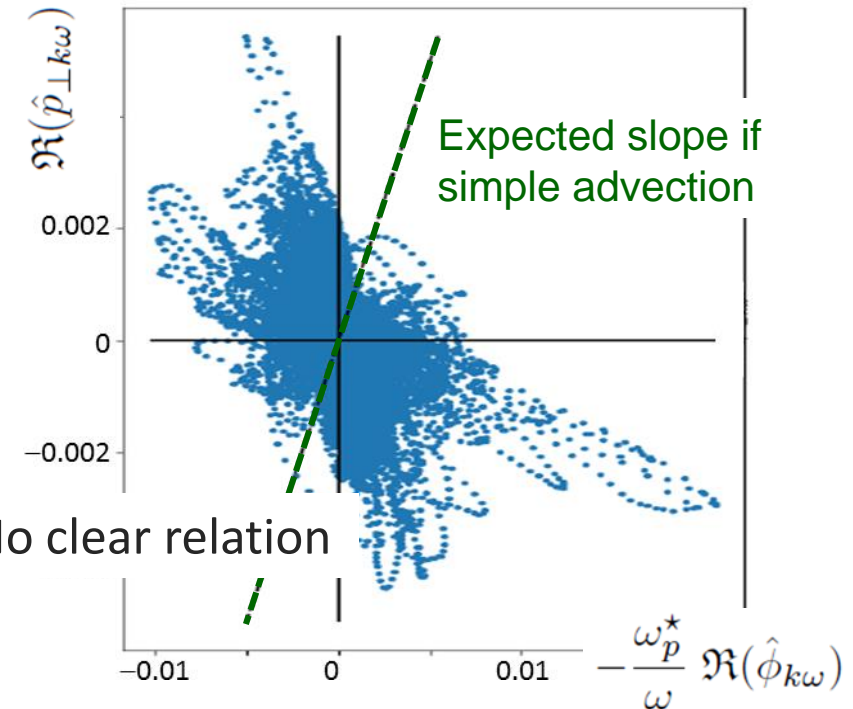
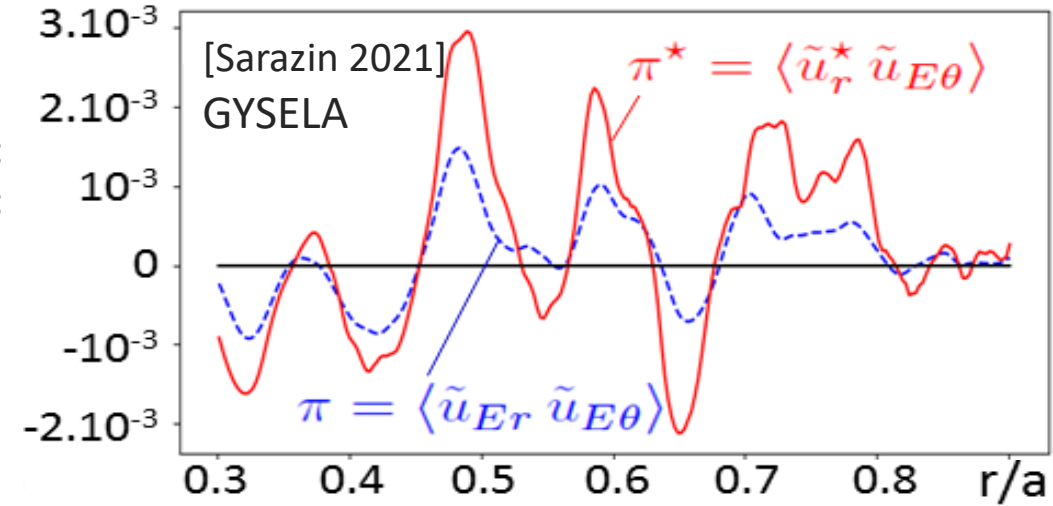
[Sarazin 2021]

- Exp. evidence: something missing beyond  $\Pi \rightarrow \Pi^*$  ?  
[Gerrú 2019]

- Csq: Pressure is NOT simply advected by ExB flow

- Indeed:  $\partial_t p_{\perp} + \mathbf{u}_E \cdot \nabla p_{\perp} = 0 \Rightarrow \langle \Pi^* \rangle / \langle \Pi \rangle < 0$
- Drift ITG:  $\hat{p}_{\perp k, \omega} = - \left\langle \frac{\omega^* - \omega_d - k_{\parallel} v_{\parallel}}{\omega - \omega_d - k_{\parallel} v_{\parallel}} \mu B F_M \right\rangle_v \hat{\phi}_{k, \omega}$
- Can be captured in reduced transport models

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# Core-edge GK simulations with immersed boundary → plasma-wall interaction

- Flux driven global GK simulation – adiab. electrons

Modelling **confined  $r/a < 1$**   
& **unconfined  $r/a > 1$**  regions

- Poloidally localized limiter when  $r/a > 1$

- Immersed boundary conditions

$$\frac{Df}{Dt} = C_{coll} + S_{heat} - \nu M_{Lim}(r, \theta) (f - f_{Lim})$$

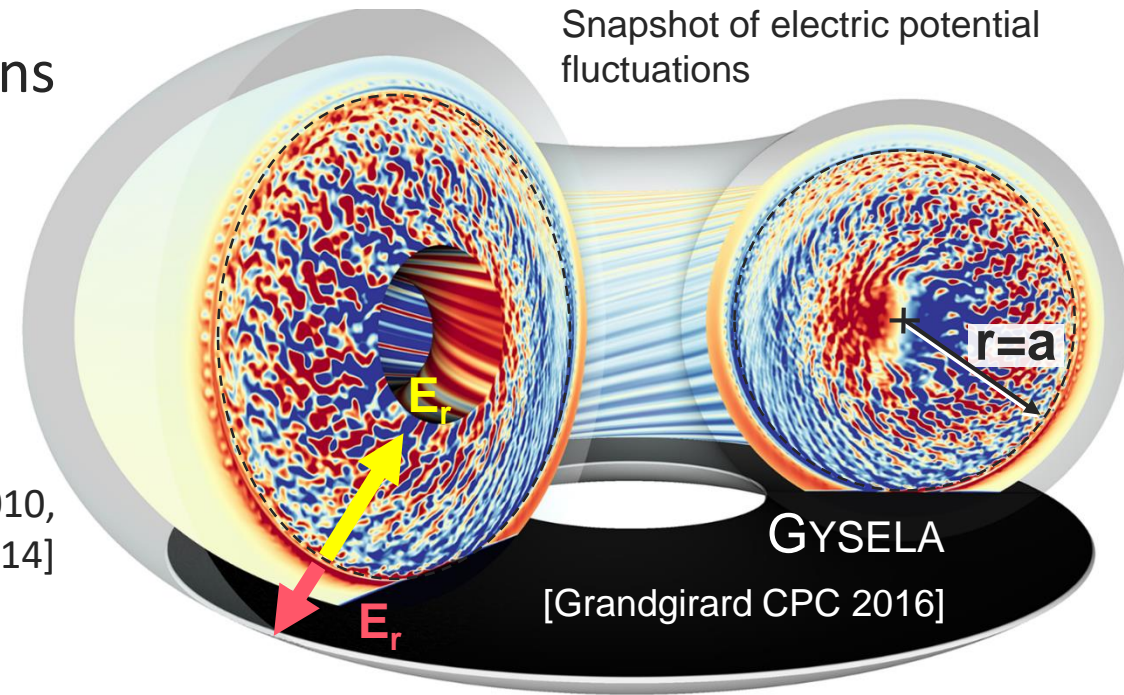
Strength of  
restoring force

**Mask = {0,1}**  
→ localized limiter

Centered Maxwellian at **low  $T_{ure}$**   
→ momentum & energy sink

- Modified quasi-neutrality condition for  $r/a > 1$  with Boltzmann electrons<sup>\*\*</sup>:

Enforced plasma-wall // condition →  $\delta n_e / n_e = e\phi / T_e - \Lambda$

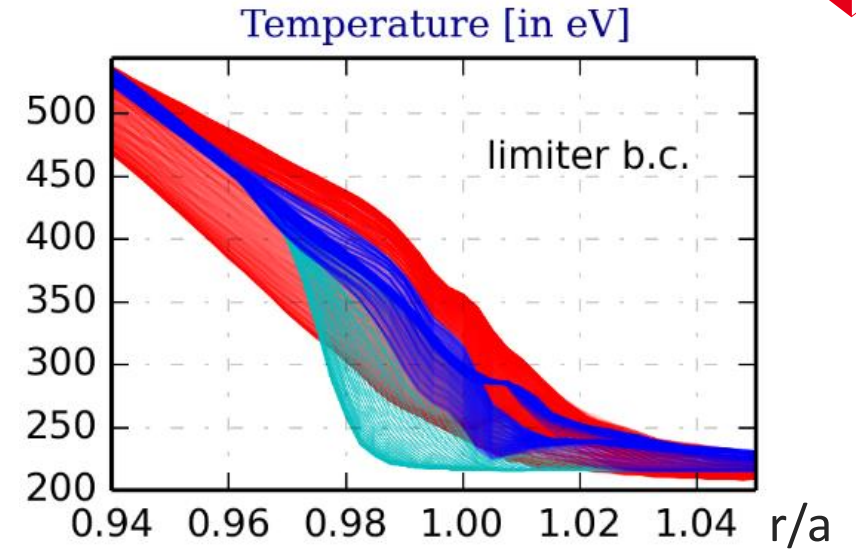
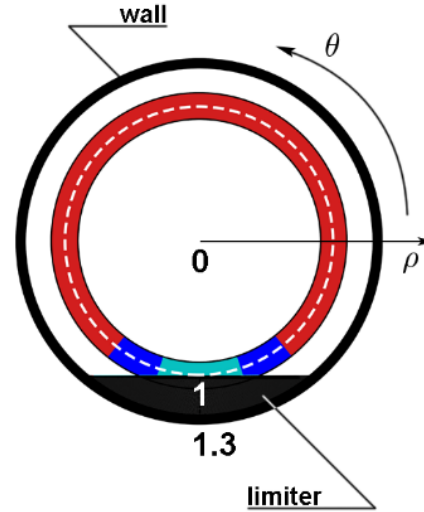


[Isoardi JCP 2010,  
Paredes JCP 2014]

# Steep gradients associated to sheared $E_r$

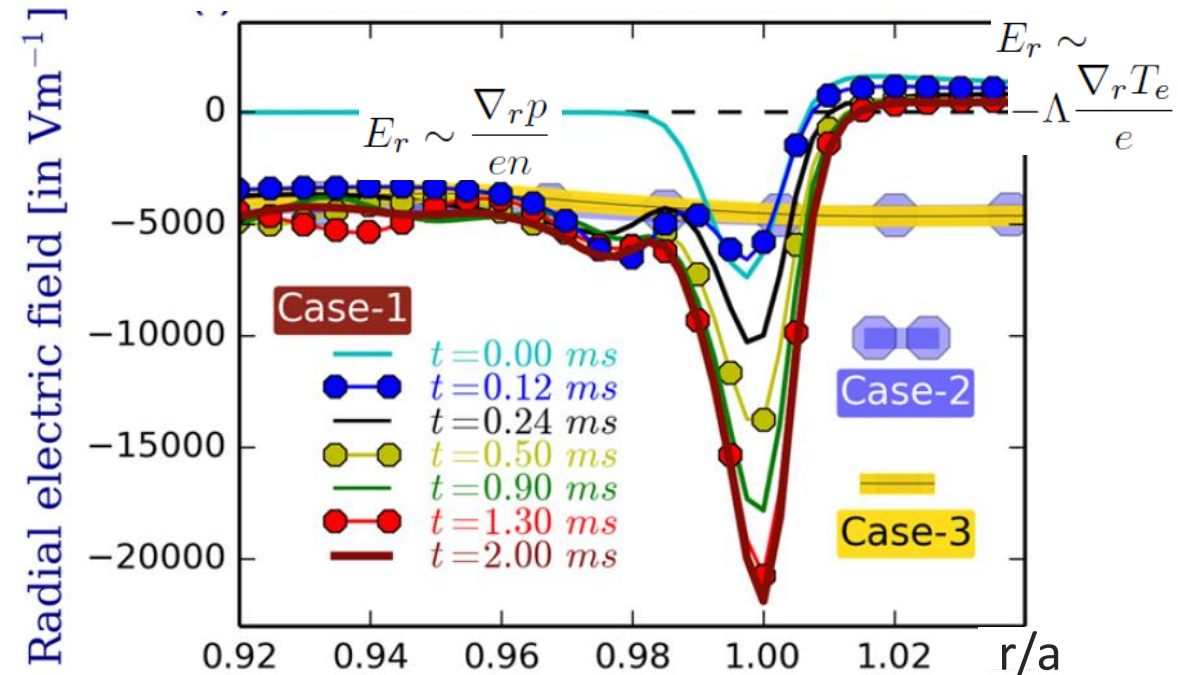
- Steep gradients in the vicinity of the separatrix @  $r/a=1$ 
  - Localized poloidally

[Dif-Pradalier 2022]



## ■ Radial electric field $E_r$

- Negative in core ( $r/a < 1$ )  $\rightarrow$  radial force balance
- Positive in SOL ( $r/a > 1$ )  $\rightarrow$  plasma-wall interaction physics
- **Well at the edge  $r \approx a$**   $\rightarrow$  strong shear





# Build up of $E_r$ well dynamically resolved

- Dynamics of toroidally averaged radial vorticity (shear of  $E_r$ ):

Other terms count for few % during  $E_r$  build-up

$$\partial_t \langle \Omega_r \rangle \approx -\nabla_r \left( \langle v_{Er} \Omega_r \rangle + \langle v_r^* \Omega_r \rangle - \langle v_\theta^* \nabla_\theta E_r \rangle \right)$$

$-\partial_t \nabla_r E_r(r, \theta, t)$       **Electric Reynolds force**      **Diamagnetic Reynolds force**      **Poloidal entrainment**

[Smolyakov 2000, McDevitt 2010, Ajay JPP 2020]

$$\nabla_r(\dots) = \frac{1}{r} \partial_r [r(\dots)]$$

$$\nabla_\theta(\dots) = \frac{1}{r} \partial_\theta(\dots)$$

$$\langle \dots \rangle = \int_0^{2\pi} \frac{d\varphi}{2\pi} \dots$$

$$v_r^* = -\nabla_\theta p / enB^2$$

$$v_\theta^* = \partial_r p / enB^2$$

- “Transfer Entropy” → causality (directional net flow of information):

[Schreiber 2000, Van Milligen 2014, Nicolau 2018, Dif-Pradalier 2021]

- $E_r$  well born at limiter poloidal location
- **Diamagnetic Reynolds force dominant initially**
- **Poloidal entrainment** ensures poloidal homogenization
- **Electric Reynolds force** dominant downstream & at later time

[Dif-Pradalier 2022]

# Incidence of plasma current $I_p$ on confinement... and $E_r$

- Confinement improves with plasma current  $I_p$  [Goldston 1984, Petty 2004]

→ Turbulence intensity  $I_{turb}$  increases with  $q \sim 1/I_p$  at constant  $\rho_*$ ,  $v_*$ ,  $\beta$

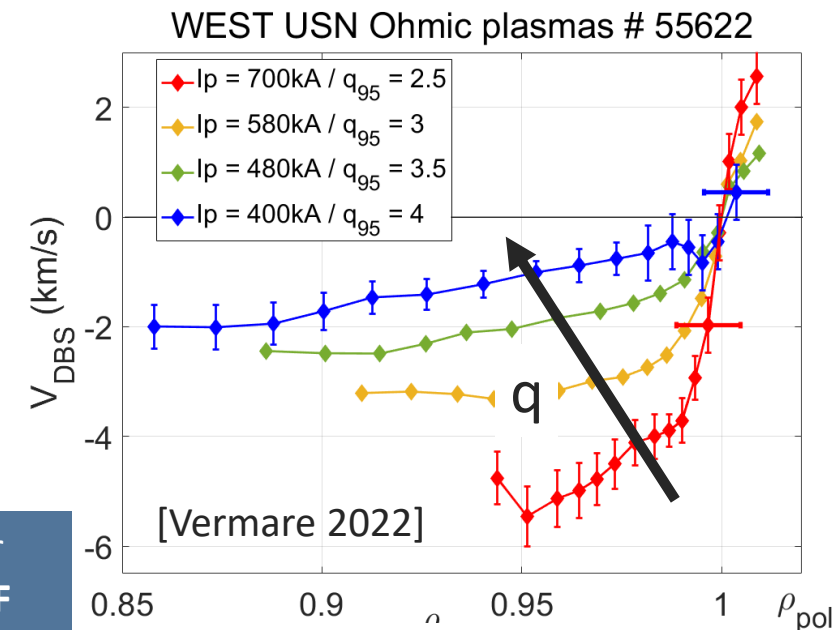
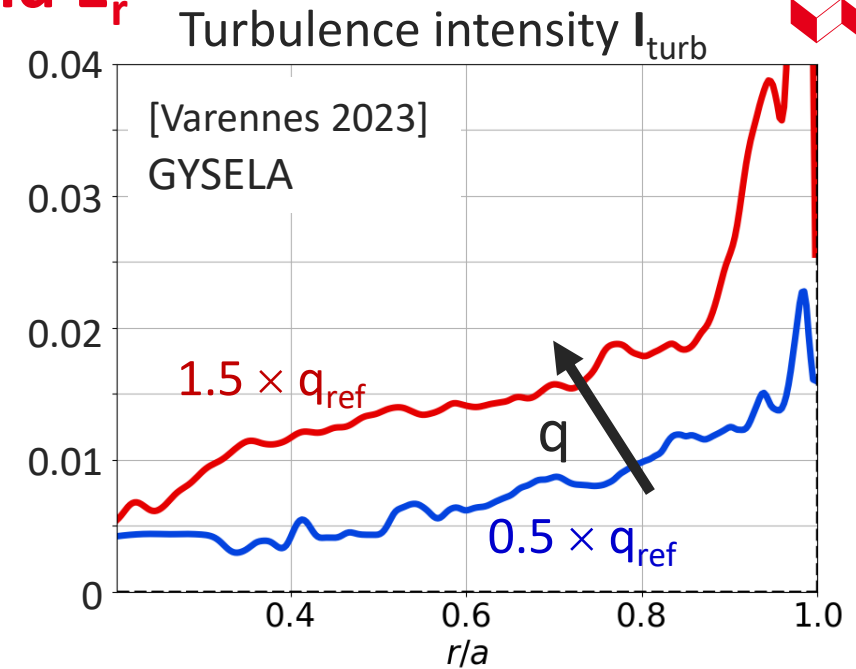
- Possible explanations:

- Growth rate increases with  $q$  [Waltz 1995]
- Threshold  $\sim s/q$  [Fourment 2003]
- Change in wave nb spectrum [Ottaviani 1997, Dannert 2005]
- Effect of GAMs [Angelino 2006]

- Experimentally: edge  $E_r$  well less deep when  $q$  increases

- L-mode (WEST data) [Vermare 2022]
- H-mode low density branch [Ryter 2014, Bilato 2020, Plank 2023]

→ How does it compare to heuristic prediction?



# $q \sim 1/I_p$ dependence of $E_r$ well $\rightarrow$ different dependence on $q$ of turb. drive & neo. viscosity

## ■ $E_r$ well less deep when increasing $q$

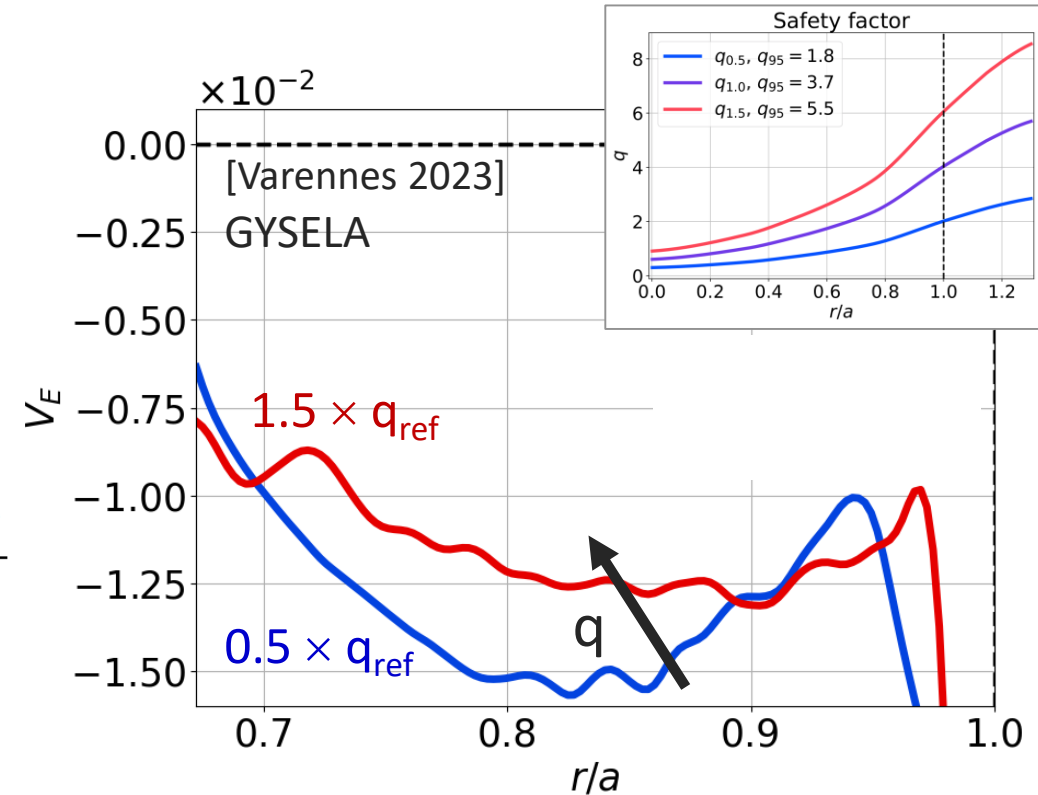
- Qualitatively consistent with experiments
- Not observed w/o turbulence (neo. only)
- Although turbulent intensity  $\uparrow$  with  $q$

## ■ Present understanding: $\langle V_{E\theta} \rangle = V_{E\theta,neo} - \frac{\nabla_r \langle \Pi_{r\theta} \rangle}{\nu_{neo}}$

- $V_{E\theta,neo}$  almost independent of  $q$
- $\nu_{neo}$  scales like  $q^2$
- $\nabla_r \langle \Pi_{r\theta} \rangle$  scales like  $q^\alpha$  with  $\alpha < 2$  (turb. heat flux  $\sim q^{1.3}$ )

[Gianakon 2002]

$\Rightarrow$  Balance between turbulence drive (Reynolds stresses) and neoclassical viscosity



# Conclusions

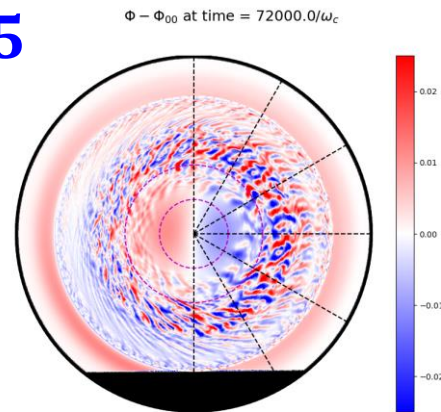
- Shear of  $E_r$  regulates turbulence
- **$E_r$  well at the edge**
  - Deepens when H-mode transport barrier
  - Sometimes inconsistent with neoclassical prediction
    - Points towards turbulence, ion orbit losses, ...
- Heuristic  **$E_r$  prediction** from **balance between turb. drive  $\Pi_{\text{turb}}$  & coll. Viscosity  $\nu_{\text{neo}}$**
- Turbulence drive = **electric + diamagnetic Reynolds stresses** (in phase in ITG turb.)
- **Diamagnetic Reynolds stress** key to the **build-up of  $E_r$  well at limiter**
- Experimental  **$q$ -dependence of edge  $E_r$  well** qualitatively recovered with GYSELA: different dependence on  $q$  of  $\Pi_{\text{turb}}$  and  $\nu_{\text{neo}}$
- **Next** : impact of kinetic electrons & of the nature of turbulence ITG/TEM?



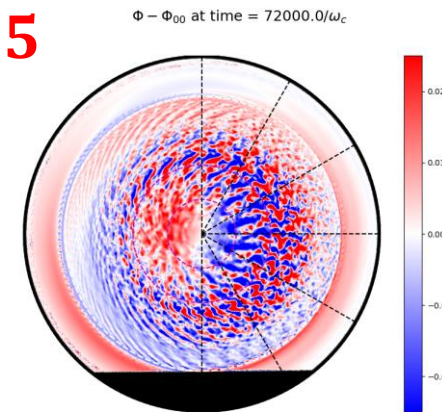
# Back up slides



$q_{ref} \times 0.5$



$q_{ref} \times 1.5$



Electrostatic potential fluctuations

Time evolution of  $E_r$

