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

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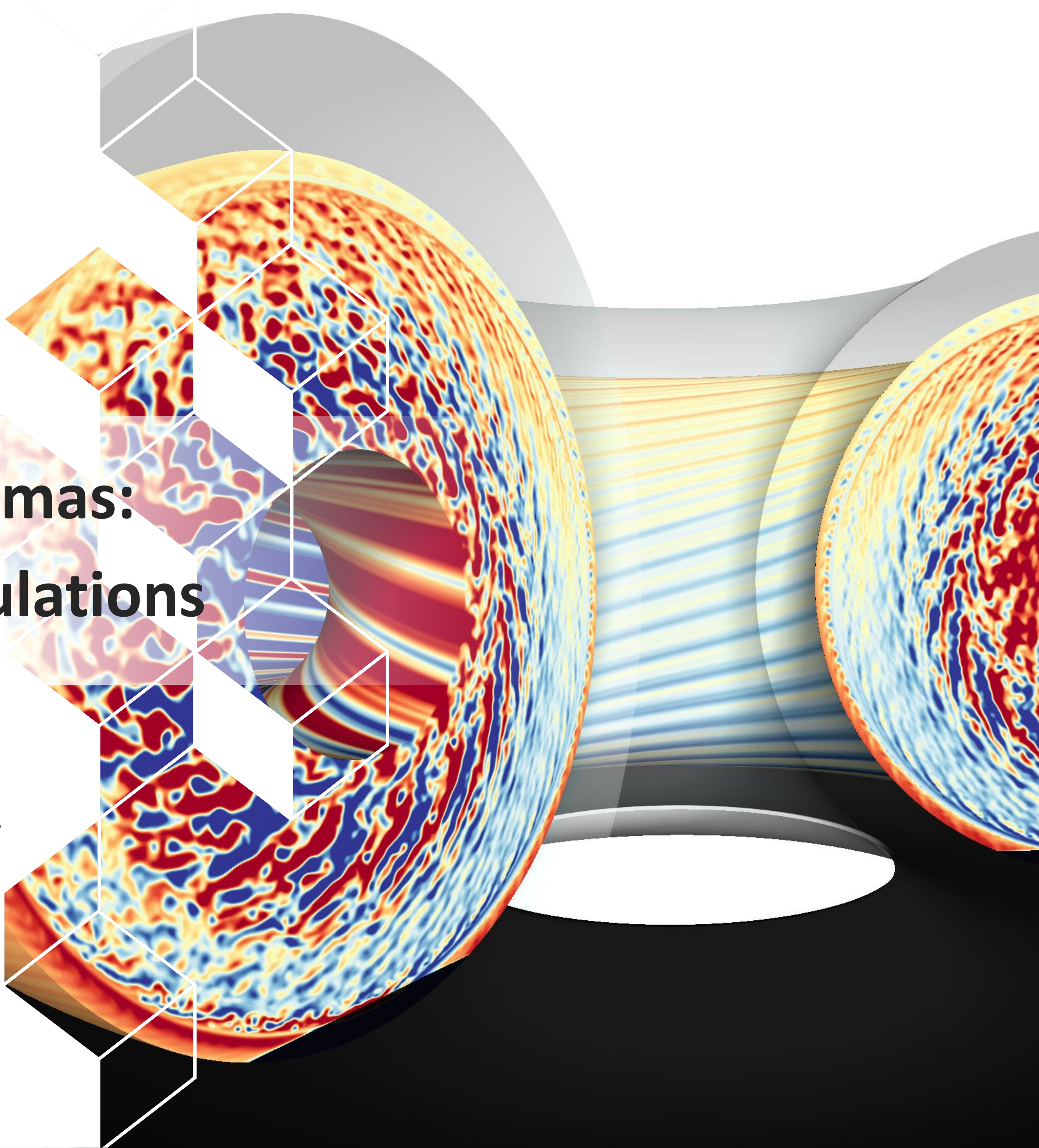
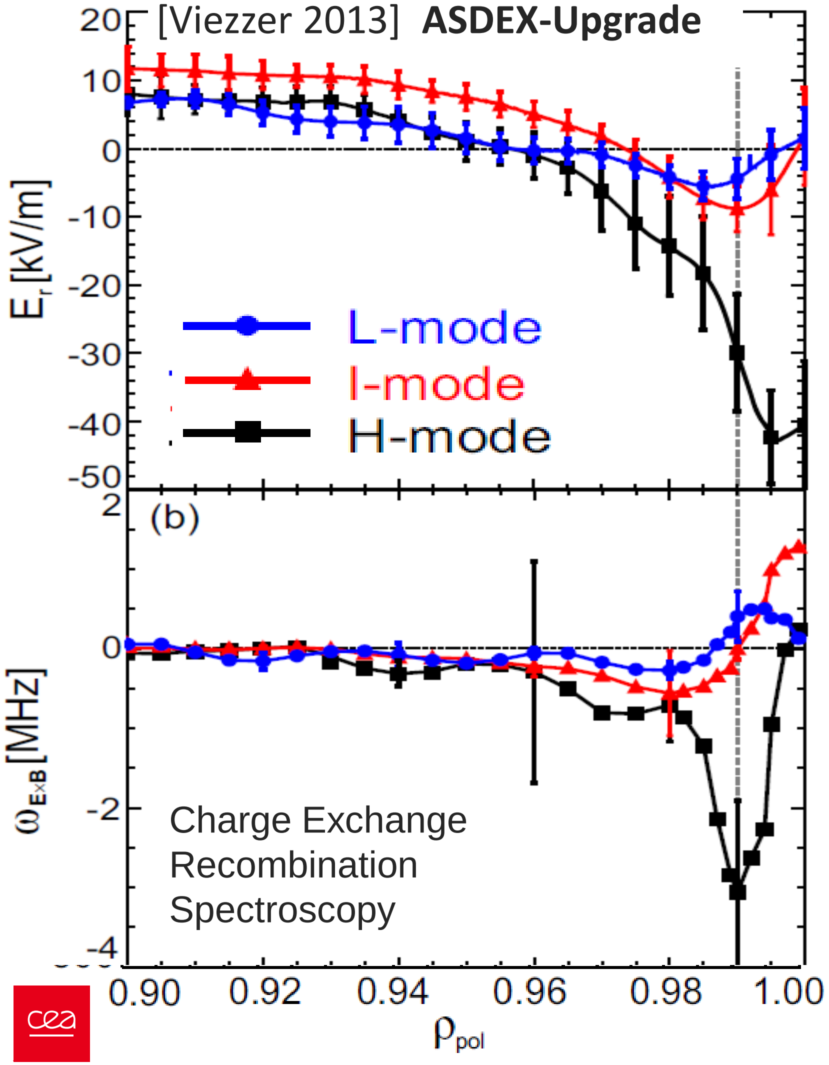
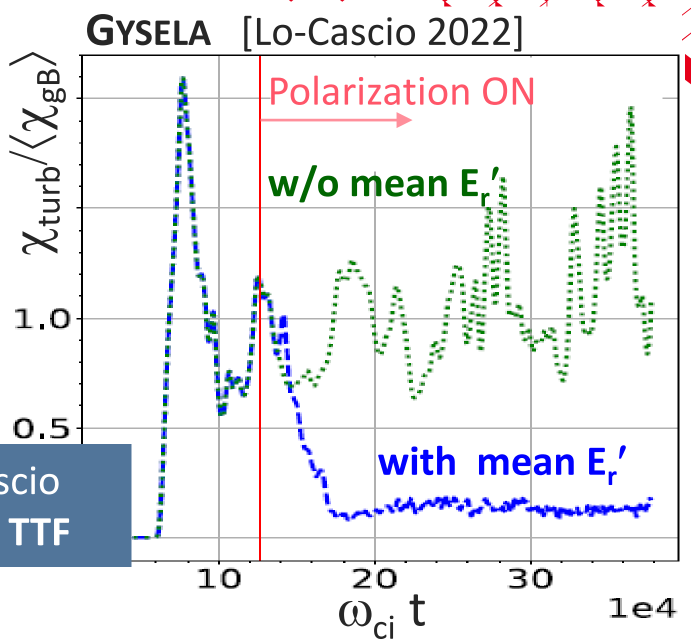


EU-US TTF workshop, Nancy, 2023-09-12

Motivation – Outline

- Shear of $v_{E\theta}=-E_r/B$ → turbulence regulation
  → 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 $\rightarrow$ **exact** dynamical equation for polarization field at small $k_\perp \rho_i$ [Parra 2009, Abiteboul 2011]

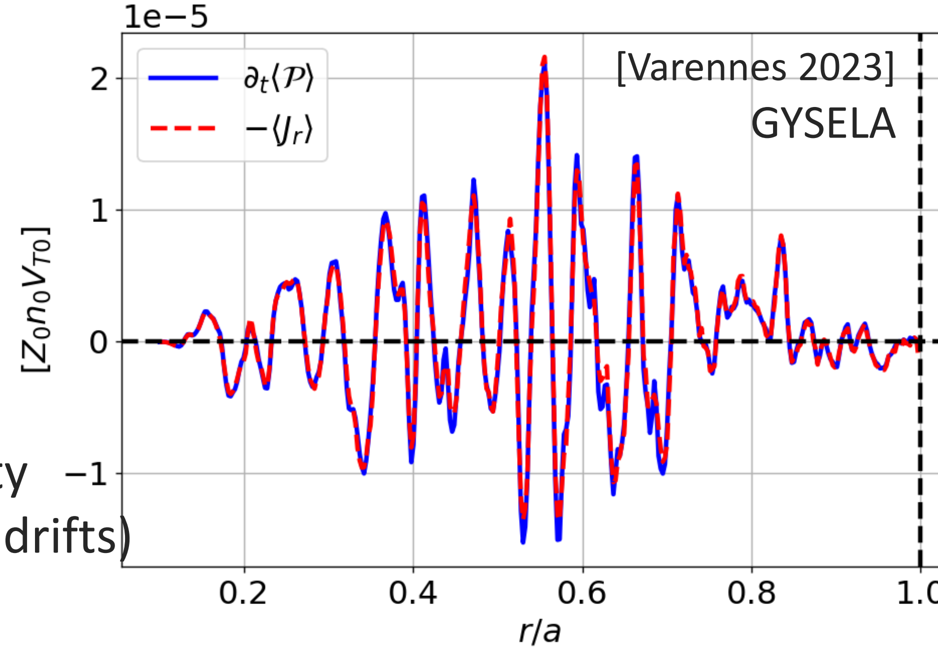
$$\frac{\partial}{\partial t}\sum_s \varepsilon_{pol,s}\left(E_r - \frac{1}{2e_s N_s}\frac{\mathrm{d}P_{\perp,s}}{\mathrm{d}r}\right) = -\sum_s J_{r,s}$$

Polarization

Permittivity $= \dfrac{N_s m_s}{B^2}$

$\dfrac{\partial P_{\perp,s}}{\partial t}$ governed by heat eq.

Radial current density (electric & magnetic drifts)



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

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

Renormalized inertia
depends on collisionality

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

[Gianakon 2002, Chôné 2014]

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

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

Turbulent Reynolds stresses (Taylor's identity)

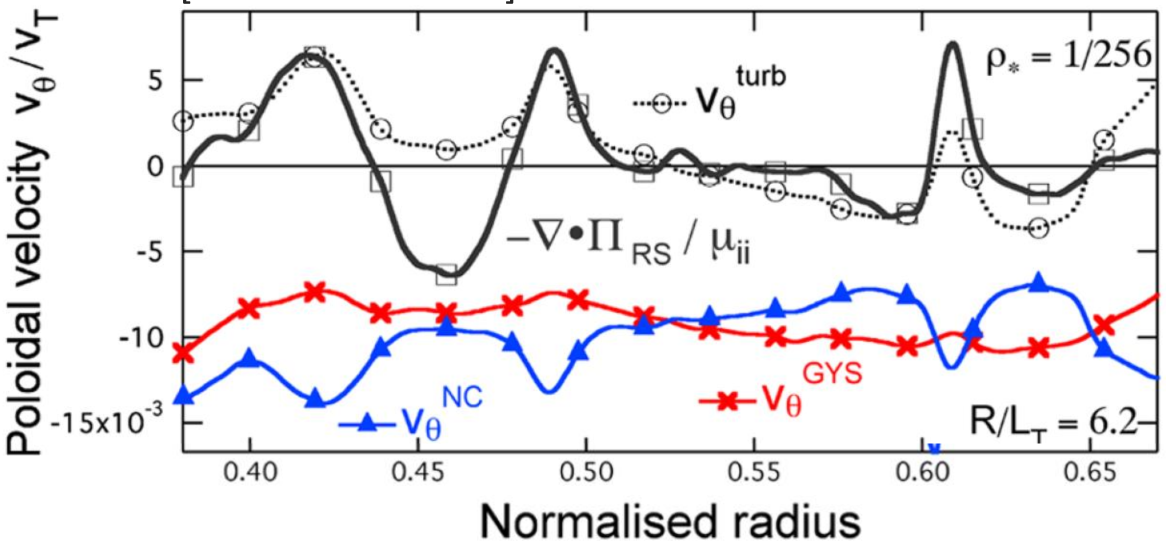
Heuristic prediction for $\langle v_{E\theta} \rangle$ – some evidence in experiments

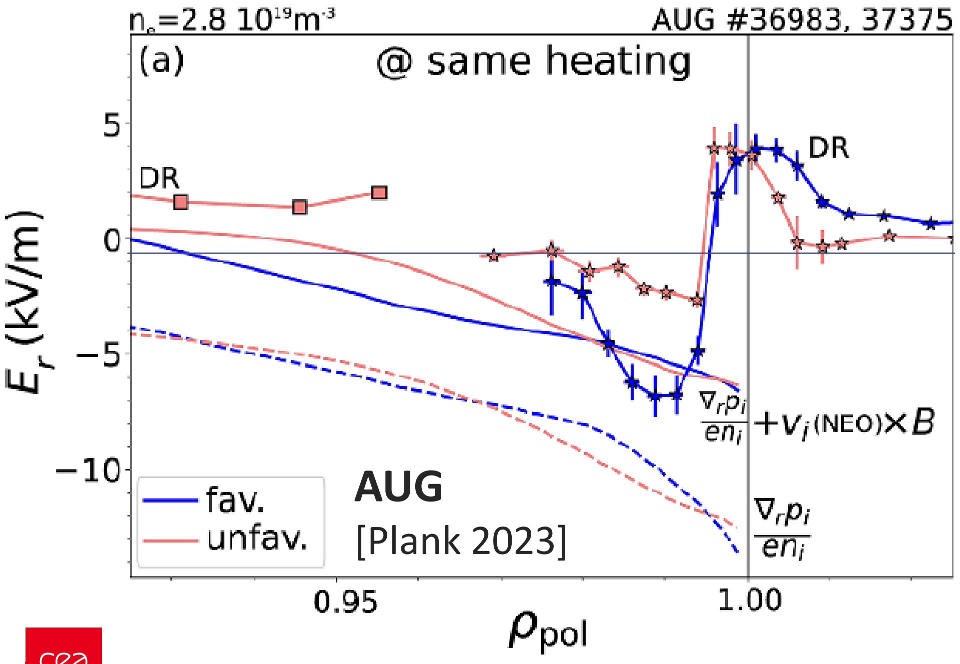
- Prediction at equilibrium: **balance between turbulence & collisions**

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

> Fair agreement in the core
>
> Important role of turbulence at staircase locations

[Dif-Pradalier 2009]





- Experiments yield contradictory information in core [Bell 1998, Crombé 2005, Grierson 2013] & edge [Viezzer 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]

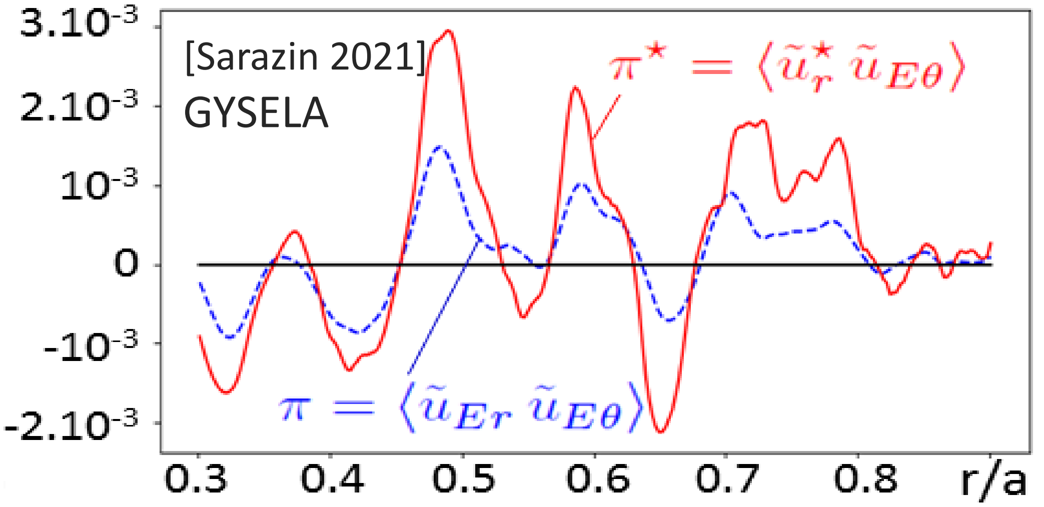
Turbulent RS not only electric → diamagnetic component Π^*

- Two distinct components of Reynolds stress:

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

[Smolyakov 2000; McDevitt 2010; Ajay JPP 2020]

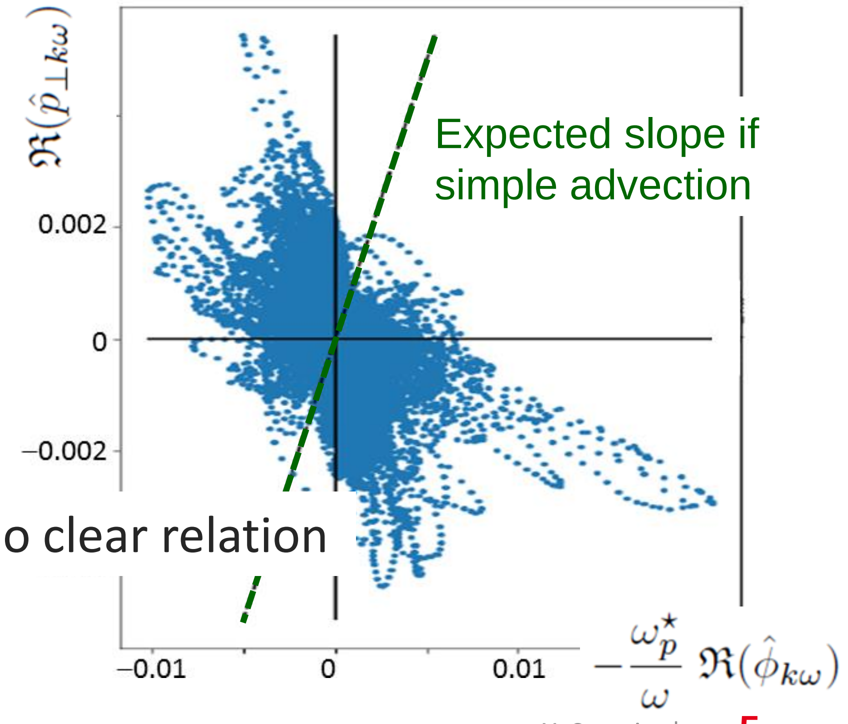
$$\Pi = \tilde{v}_{Er}\,\tilde{v}_{E\theta} = -\frac{\nabla_\theta\tilde{\phi}}{B}\frac{\nabla_r\tilde{\phi}}{B} \qquad \Pi^* = \tilde{v}^*_r\,\tilde{v}_{E\theta} = -\frac{\nabla_\theta\tilde{p}_{\perp i}}{eNB}\frac{\nabla_r\tilde{\phi}}{B}$$



In ITG turbulence (adiab. & kin. electrons) | Π & Π^* 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: $\partial_t p_\perp + \mathbf{u}_E.\boldsymbol{\nabla} p_\perp = 0 \Rightarrow \langle\Pi^*\rangle / \langle\Pi\rangle < 0$
  - Drift ITG: $\hat{p}_{\perp k,\omega} = -\left\langle \frac{\omega^\star - \omega_d - k_\parallel v_\parallel}{\omega - \omega_d - k_\parallel v_\parallel}\,\mu B\,F_M \right\rangle_v \hat{\phi}_{k,\omega}$ → No clear relation
  - Can be captured in reduced transport models



Panico Poster TTF

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

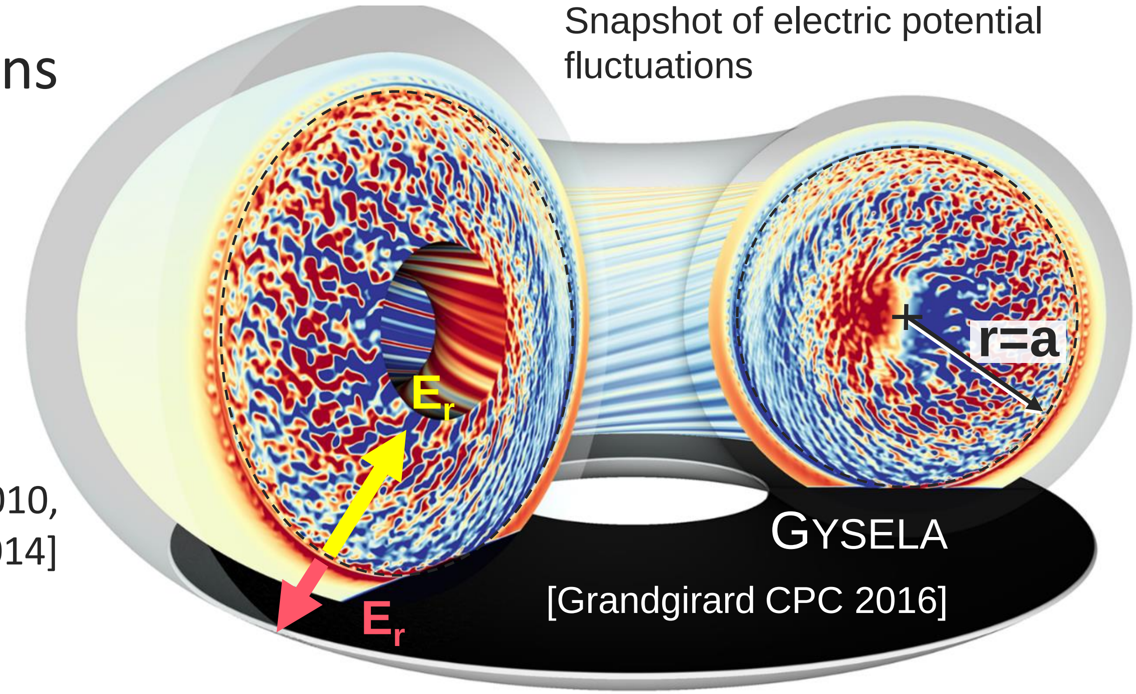
[Isoardi JCP 2010, Paredes JCP 2014]

$$\frac{Df}{Dt} = \mathcal{C}_{coll} + \mathcal{S}_{heat} - \nu\, \mathrm{M}_{Lim}(r,\theta)\,(f - f_{Lim})$$

Strength of restoring force

Mask = {0,1} → localized limiter

Centered Maxwellian at **low Tᵘʳᵉ** → momentum & energy sink



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

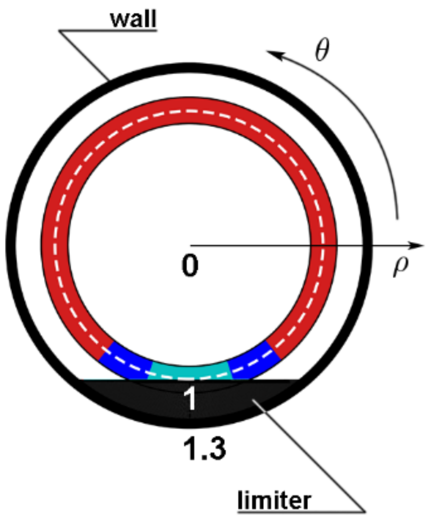
  Enforced plasma-wall // condition → $\delta n_e/n_e = e\phi/T_e - \Lambda$

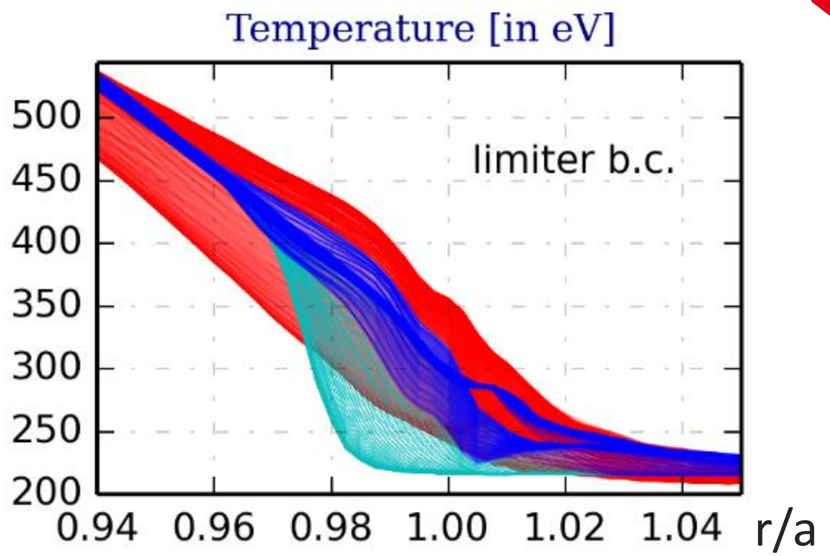
**Ongoing work to include kinetic electrons [Munschy 2023]

Steep gradients associated to sheared E_r

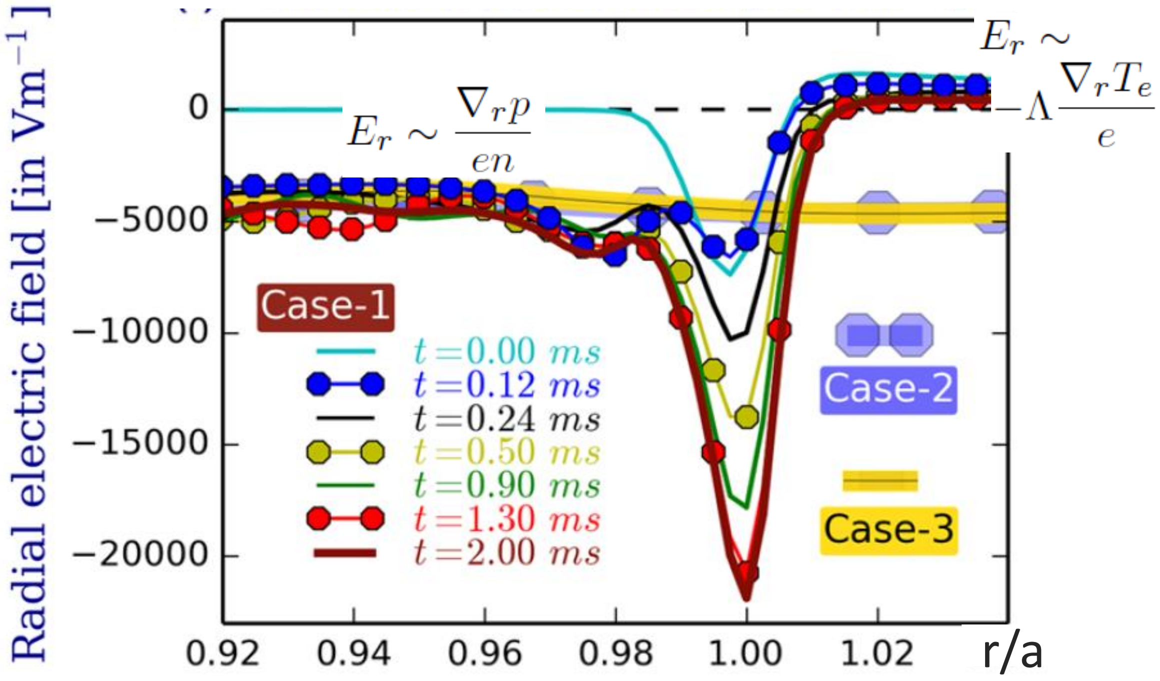
- Steep gradients in the vicinity of the separatrix @ r/a=1
  - Localized poloidally

[Dif-Pradalier 2022]





- **Radial electric field E_r**
  - Negative in core (r/a<1) → radial force balance
  - Positive in SOL (r/a>1) → plasma-wall interaction physics
  - **Well at the edge** r≈a → 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

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

$$-\partial_t \nabla_r E_r(r,\theta,t)$$

Electric Reynolds force — **Diamagnetic** Reynolds force — Poloidal entrainment

[Smolyakov 2000, McDevitt 2010, Ajay JPP 2020]

$$\nabla_r(\ldots) = \frac{1}{r}\partial_r[r(\ldots)]$$
$$\nabla_\theta(\ldots) = \frac{1}{r}\partial_\theta(\ldots)$$
$$\langle \ldots \rangle = \int_0^{2\pi} \frac{\mathrm{d}\varphi}{2\pi} \ldots$$
$$v_r^* = -\nabla_\theta p / enB^2$$
$$v_\theta^* = \partial_r p / enB^2$$

- "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 [Dif-Pradalier 2022]
  - Poloidal entrainment ensures poloidal homogenization
  - **Electric** Reynolds force dominant downstream & at later time

Incidence of plasma current I_p on confinement… and E_r

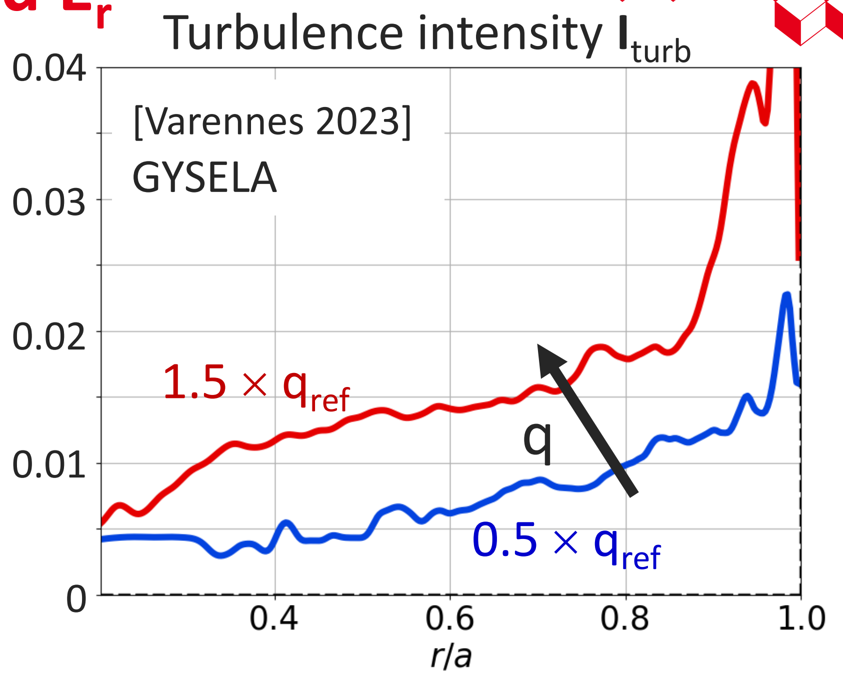
- **Confinement improves with plasma current I_p** [Goldston 1984, Petty 2004]]

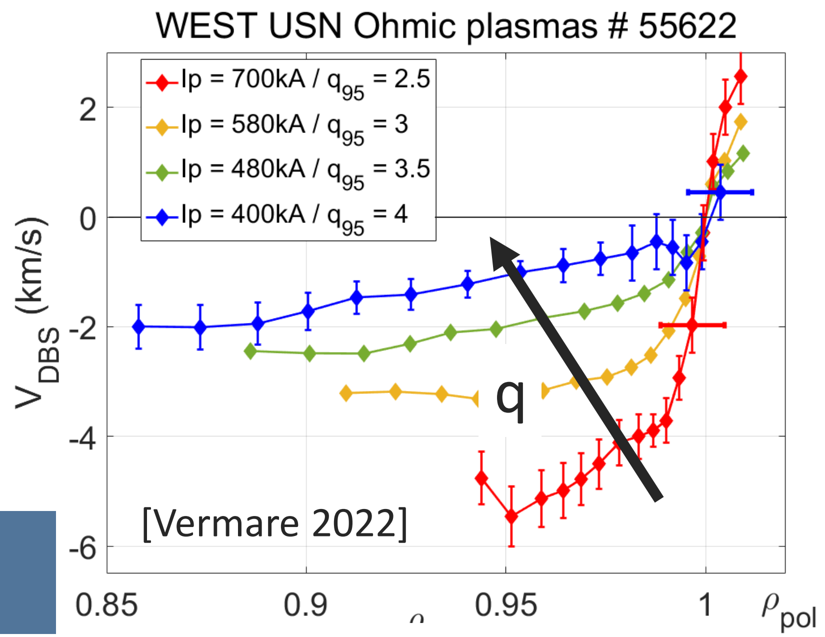
  → **Turbulence intensity I_{turb} increases with q** $\sim 1/I_p$ at constant ρ_*, ν_*, β

- 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?





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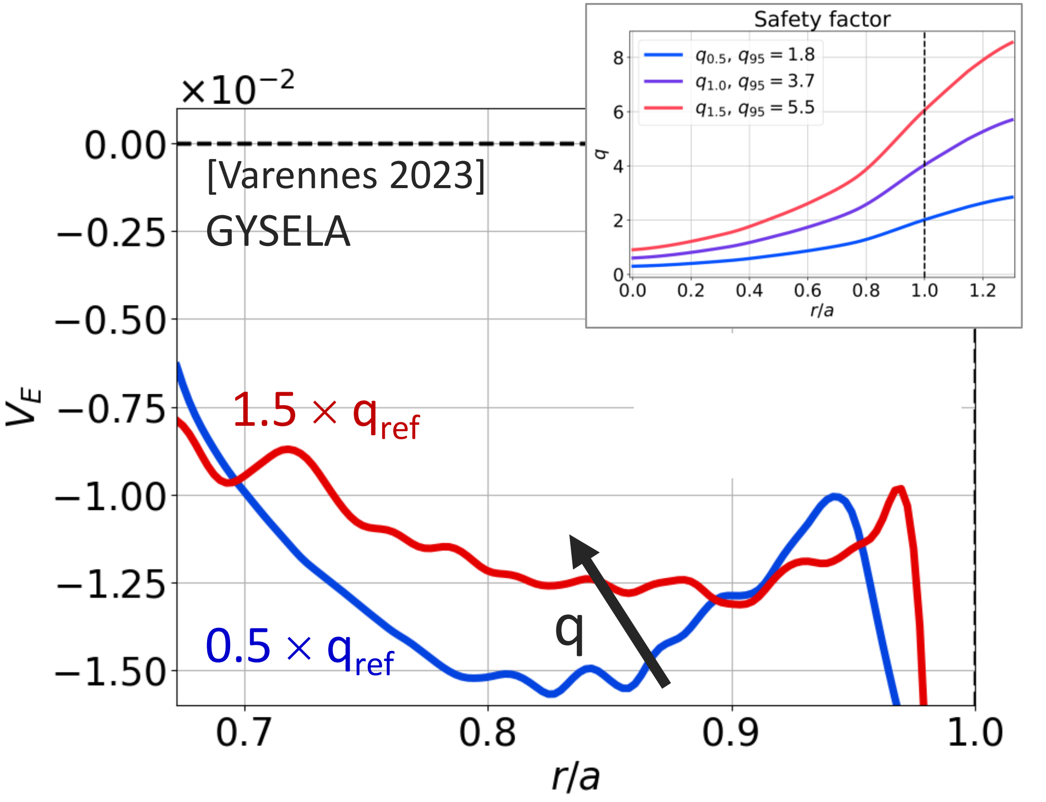
$q \sim 1/I_p$ dependence of E_r well $\rightarrow$ different dependence on q of turb. drive & neo. viscosity

- E_r well less deep when increasing q
  - Qualitatively **consistent with experiments**
  - Not observed w/o turbulence (neo. only)
  - Although turbulent intensity ↑ with q



- Present understanding: $\langle V_{E\theta} \rangle = V_{E\theta,neo} - \dfrac{\nabla_r \langle \Pi_{r\theta} \rangle}{\nu_{neo}}$
  - $V_{E\theta,neo}$ almost independent of q
  - ν_{neo} scales like q^2 [Gianakon 2002]
  - $\nabla_r \langle \Pi_{r\theta} \rangle$ scales like q^α with $\alpha < 2$ (turb. heat flux ~ $q^{1.3}$)

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

Conclusions

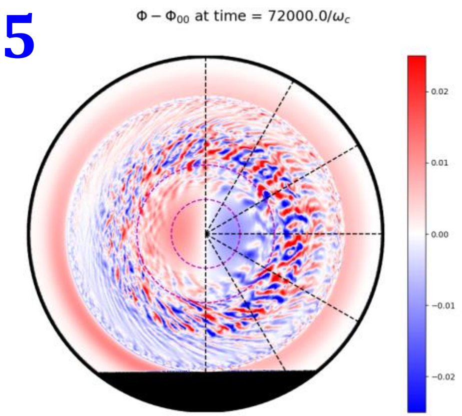
- Shear of E_r regulates turbulence
- **E_r well at the edge**
  - Deepens when H-mode transport barrier
  - Sometimes inconsistent with neoclassical prediction

    $\rightarrow$ Points towards turbulence, ion orbit losses, …

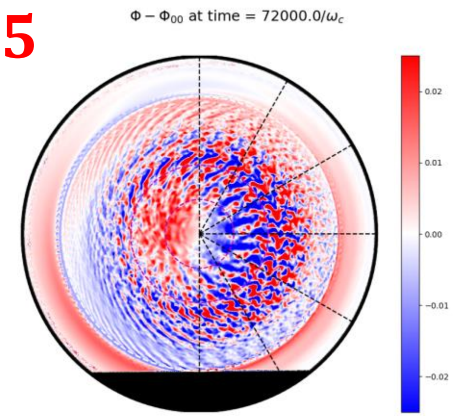
- Heuristic **E_r prediction** from balance between turb. drive Π_{turb} & coll. Viscosity ν_{neo}
- Turbulence drive = electric + diamagnetic Reynolds stresses (in phase in ITG turb.)
- Diamagnetic Reynolds stress key to the build-up of E_r well at limiter
- Experimental q-dependence of edge E_r well qualitatively recovered with GYSELA: different dependence on q of Π_{turb} and ν_{neo}
- **Next** : impact of kinetic electrons & of the nature of turbulence ITG/TEM?

Back up slides

$q_{\mathrm{ref}} \times 0.5$



$q_{\mathrm{ref}} \times 1.5$



Electrostatic potential fluctuations

Time evolution of E_r