Plasma–Boundary Interplay: incidence on edge turbulence organisation & barrier formation

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A major motivation: describe and understand whereby bifurcations to improved confinement occur

- spontaneous transitions come in many flavours: ITBs, yy-modes
  yy $\in \{H; I; QH; VH; \dots\}$
- common grounds: self-reinforcing feedback
  - onset of differential rotation
  - steepening of ∇p_i
  - electric field well (or hill) ➞ shear-induced bifurcation [Biglari PF 90, ...]
- narrow region, especially plasma edge ➞ **boundary conditions**

Global impact of localised boundary interactions is a classical problem

- fluids: Prandtl ; swirling flows [torque vs. velocity [Saint-Michel PRL 13]] $\leftrightarrow$ **forcing**
- MFE: upstream [core & edge] impact of magn. connection to bound. [SOL/wall]
  [known importance of wall conditioning, recycling, etc.]

➤ this work: propagation of information? core $\leftrightarrow$ edge $\leftrightarrow$ SOL? mechanisms? relevance to global confinement? *[Spoiler: there is a strong interplay]*

Our goal: understand turbulence dynamics in L-mode edge

[from where bifurcation to H-mode occurs]

this talk understand turbulence dynamics in L-mode edge
↳ important prerequisite for understanding edge bifurcation(s)

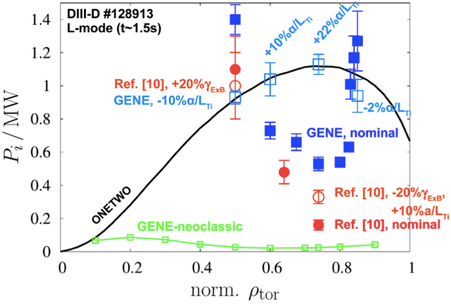
➤ Several (related) conundrums

❶ is there an intrinsic problem [NM'sL?] with the plasma edge?

↳ where does edge turb. come from?
↳ propagation/contamination?

❷ important turb. properties: all locally-determined?

❸ what presides over the onset of edge transport barrier? Mechanism(s)?



[Gorler PoP 14]

What desirable/minimal set of ingredients?

- equil. gradient length $\sim$(few ρ_i) $\Rightarrow$ **<u>scale separations break down</u>** near edge
  (gradient scale $\leftrightarrow F_{eq}$) $\not\gg$ (turb.scale $\leftrightarrow \delta f \equiv F - F_{eq}$)

- profiles $\equiv$ **<u>large uncertainties</u>** in edge; **<u>poorly known</u>** in SOL
  ↳ flux-driven desirable | $\Rightarrow$ propagation of information on global scales
  $\Rightarrow$ add. symm.-breaking mechanisms edge turb.

- magnetic connection to **<u>material boundaries</u>**
  ↳ expect E_r shear ($\nabla p/n$ vs. $-\nabla T_e$) $\Rightarrow$ incidence on transp. barrier onset?

Framework: "minimally" relevant model to understand turbulence dynamics in L-mode edge?

Framework $\equiv$ GYSELA [Grandgirard JCP 06 & CPC 16 ; Caschera JPCS 18]

- $\frac{\mathrm{D}\, F_s}{\mathrm{D}t} = \mathrm{C}\,(F_s) + \mathrm{S}_{\mathrm{heat}}(F_s) - \nu\, \mathrm{M}_{\mathrm{lim}}\,(F_s - F_{\mathrm{lim}})$ & $\Sigma_i Z_i\, \delta n_i = \delta n_e$

- flux-driven profile evolution
- global domain $0 \leqslant r/a \leqslant 1.3$
- poloidally-localised toroidal limiter
  $1 \leqslant r/a \leqslant 1.3$

  ↳ penalisation technique $\equiv$ Krook op. in gyrokinetic eq. rhs [Isoardi JCP 10]

- ~~kinetic trapp. elec~~ ➞ adiab. elec.

  ↳ modified QN eq. in SOL

Bohm cond. forced: $\delta n_e / n_e \to e\phi / T_e - \Lambda$

- no transport of mass
- transport of energy & momentum

➞ "minimal state" / "baseline" instab.

Framework: "minimally" relevant model to understand turbulence dynamics in L-mode edge?

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Bohm cond. forced: $\delta n_e / n_e \to e\phi / T_e - \Lambda$

- circular **B** geometry; electrostatic; $\rho_\star = 1/300$; with collisions

Systematic comparison TS#45511

Flux-Driven & limiter

↕

Flux-Driven & poloidally symm.
$M_{lim} \to 0$

↕

Gradient-Driven & poloidally symm.
$S_{heat} \to 0$
$M_{lim} \to 0$
$\forall r, t \quad F_s \to cst \equiv F_{\#2}$

How do steady states compare?

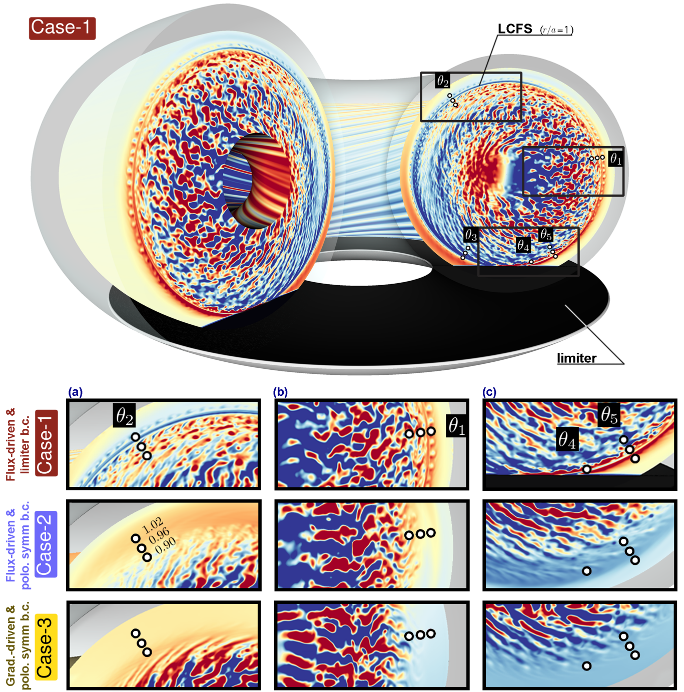
[Dif-Pradalier, under review]

❶ poloidal (a)symmetry

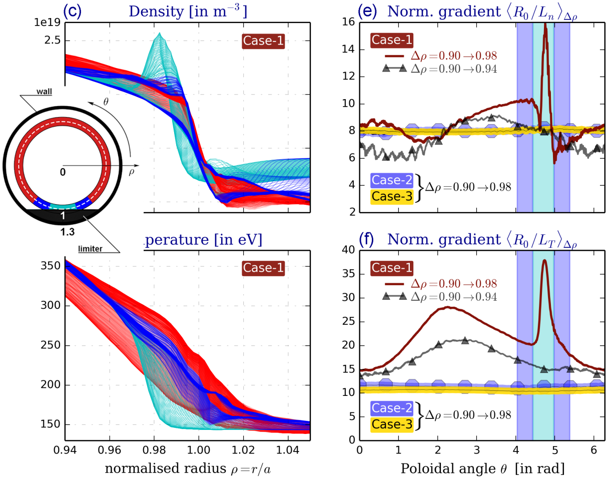
❷ “linear”

❸ NM’sL

❹ transport barrier [vorticity dyn.]



Edge unconditionally stable, destabilised by limiter



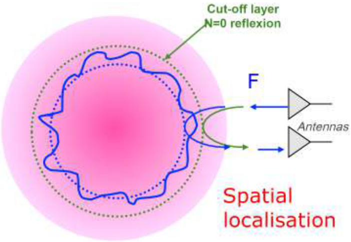
linear analysis of GYSELA profiles with local GKW

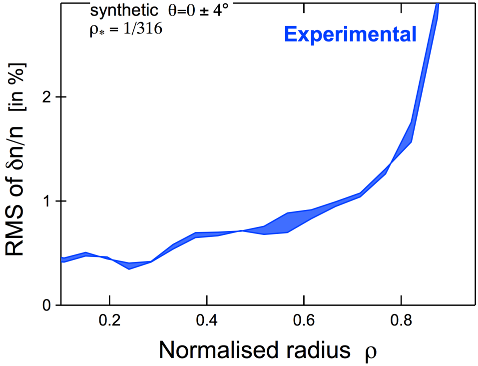
[Peeters CPC 09]

- edge **unconditionally stable** without limiter
- edge **destabilised** locally (r, θ) with limiter

➤ interesting situation: turbulence organisation in edge? investigate $\delta n/n$

Turbulence organisation in the plasma edge?





- quality fast-swept reflectometry measurements [Clairet RSI 2011]
- mimic conditions TS #45511 → synth. diag. for GYSELA: $\theta = 0 \pm 4^\circ$

Turbulence organisation in the plasma edge?

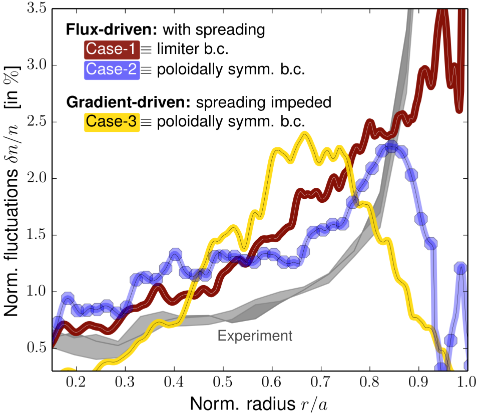
forcing & boundary conditions key

- reasonable trend with limiter;
- shortfall without;
- spreading ["contamination"] key

[Mattor; Garbet; Hahm; . . . ; Singh]

➤ sensitivity scans → robust concl.

➤ explain fluct. levels with limiter?



Wave-energy budget to quantify self-advection of turb. patches

- wave energy budget: conserved quantity $(n \cdot I)$

  [the fewer the oscillators, the larger the oscillations] [Mattor PRL 94; Gurcan NF 13; Gillot JPP 20]

$$\left(\frac{\partial}{\partial_t} + \overline{\mathbf{v}}_{E,\theta}\frac{\partial}{\partial_\theta}\right)(nI) + \nabla \cdot \Gamma_I = \mathrm{Inj} - \mathrm{Diss.}$$

- wave-energy flux: kinetic proxy for spatial turbulence spreading

$$\Gamma_I(r,\theta,t) \equiv \left\langle \int \mathrm{d}^3 v (\mathbf{v}_{ExB} \cdot \nabla r) \frac{\tilde{f}^2}{F_M} \right\rangle$$

procedure:

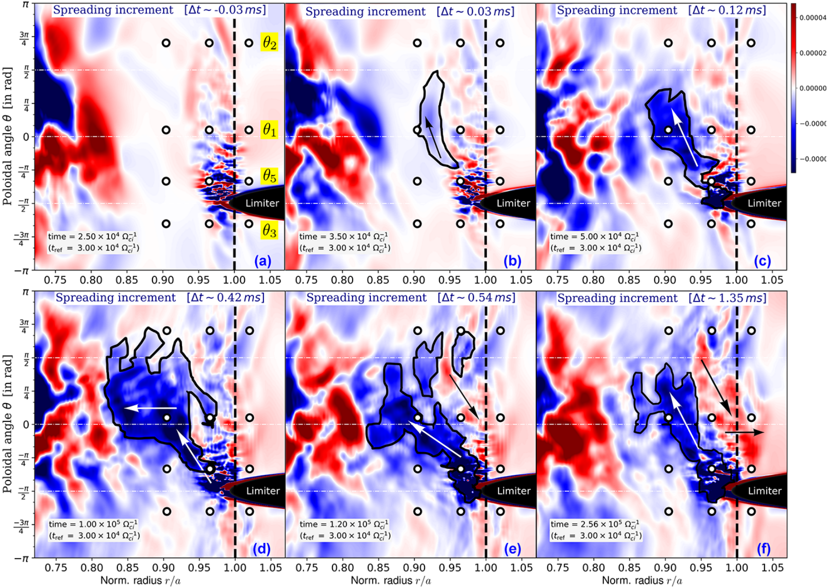
- limiter-borne poloidal asymm. → growing patches of turb. intensity near LCFS.
- chose nonlin. time reference t_{ref}

  ↳ investigate systematic spreading increments $\Delta S \equiv \Gamma_I(r,\theta,t) - \Gamma_I(r,\theta,t_{\mathrm{ref}})$
- times series of poloidal cross-sections of ΔS

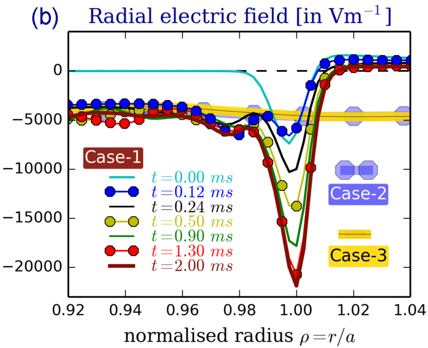
  $\Delta S \geqslant 0$ → radially-outward fluxes of turbulence intensity

  $\Delta S \leqslant 0$ → inward fluxes of turb. intensity

<u>Limiter-borne</u> fluctuations contaminate outer edge in staged polo. sequence; then LCFS[in]–core[out] cyclic equilibration



Persistent transport barrier @ closed–open field line interface
→ mechanism? assess causality?

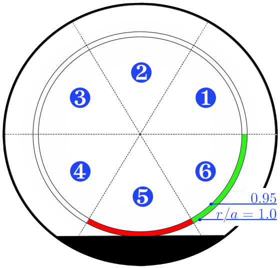


Spontaneous E_r **build-up** & sustainment

↳ (r, θ) vorticity balance [Sarazin PPCF 21]

$$\partial_t \langle \Omega_r \rangle + \underbrace{\partial_r \langle v_{Er} \Omega_r \rangle}_{\text{Reynolds force}} + \underbrace{\partial_r \langle v_{\star r} \Omega_r \rangle}_{\text{diamagn.}} + \ldots \approx 0$$

with $\Omega_r = -E'_r$; $v_{\star r} = -\frac{1}{r} \partial_\theta p_\perp$



- Mechanisms/causality? → *Transfer Entropy*

  [Schreiber PRL 00;. . . VanMilligen NF 14; Nicolau PoP 18]

- $\langle v_{\star r} \Omega_r \rangle$ → Ω_r **dominant flow of information**

  ↳ pressure θ-inhomog. & FLR [Dif-Pradalier, submitted]

Conclusions: evidence for SOL–edge–core interplay enlightens "shortfall conundrum" & transp. barrier onset/sustainment

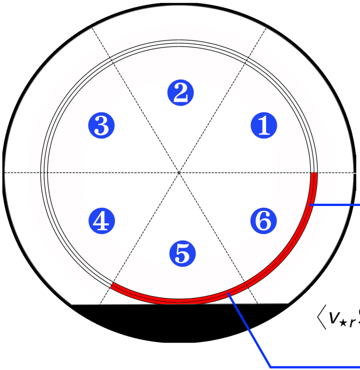
- penalised limiter ➞ simplified SOL   miss e^- $\|$ dynamics; convection & neutrals
- interplay SOL, edge & core
  - ➞ spontaneous persistent **transport barrier** $\equiv E_r$ build-up;
  - ➞ **with limiter:** **no "shortfall"** $\equiv$ clarifies spreading controversy
    - ❶ poloidal asymmetry (cold region. . .)
    - ❷ edge-to-core then ❸ cyclic edge→core & core→edge
  - ➞ **w/o limiter:** edge stable & **strong "shortfall"** in NM'sL
- Turbulence **not only locally driven** by local gradients but 'nonlocally' controlled by **fluxes of turb. activity**, primarily (though not exclusively) coming **from the edge** & mediated thru **interplay with material bound.**
- early transp. barrier build-up ➞ $\langle v_{Er}\Omega_r\rangle$ & $\langle v_{\star r}\Omega_r\rangle$ **key to E_r growth**

,

Assess flow of information in early stages of transp. barrier build-up → FLR effects & limiter-borne $\nabla p(\theta)$ are key players

$$TE_{Y\to X}(k) = \sum p(x_{n+1}, x_{n-k}, y_{n-k}) \log\left(\frac{p(x_{n+1}|x_{n-k}, y_{n-k})}{p(x_{n+1}|x_{n-k})}\right)$$

- **directional:** net flow of information $\Delta_{X,Y}(TE) \equiv TE_{Y\to X} - TE_{X\to Y}$
- time series $X, Y \in \{\Omega_r,\ \langle v_{Er}\Omega_r\rangle,\ \langle v_{\star r}\Omega_r\rangle,\ \ldots\}$



$\langle v_{\star r}\Omega_r\rangle \to \Omega_r$ &

$\langle v_{Er}\Omega_r\rangle \to \Omega_r$

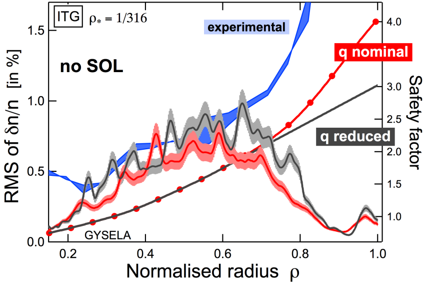
$\langle v_{\star r}\Omega_r\rangle \to \Omega_r \to \langle v_{\star r}\Omega_r\rangle$

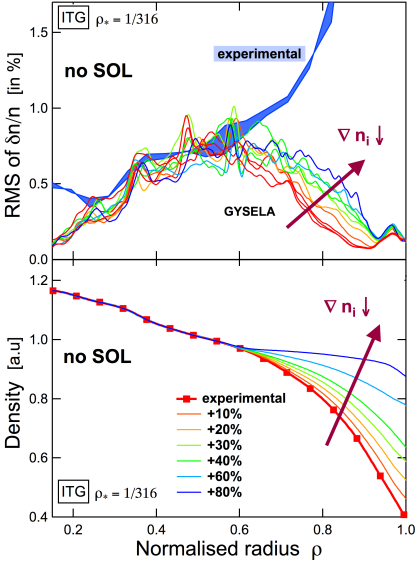
$\searrow \langle v_{Er}\Omega_r\rangle \to \langle v_{\star\theta}\partial_\theta v_{E\theta}\rangle$

W/o limiter: shortfall in stable edge not cured through combination of core spreading ⊕ modif. of local params.

No cure observed with:

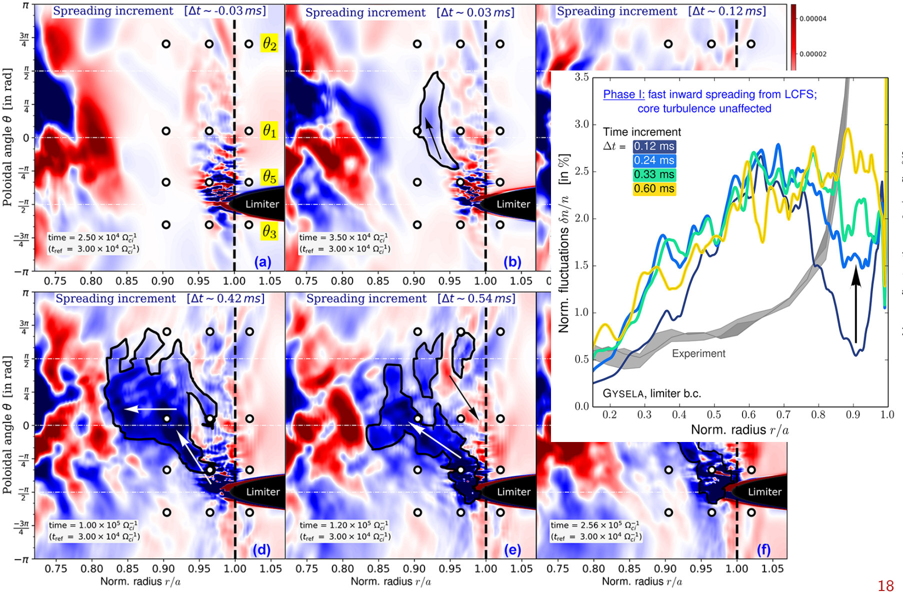
- increased resolution
- ↗ T_e/T_i ratio
- ↘ safety factor q [↘ magn. shear]
- ↘ ∇n_i





How to explain fluct. levels with limiter?

Limiter-borne fluctuations contaminate outer edge in staged polo. sequence; then LCFS[in]–core[out] cyclic equilibration



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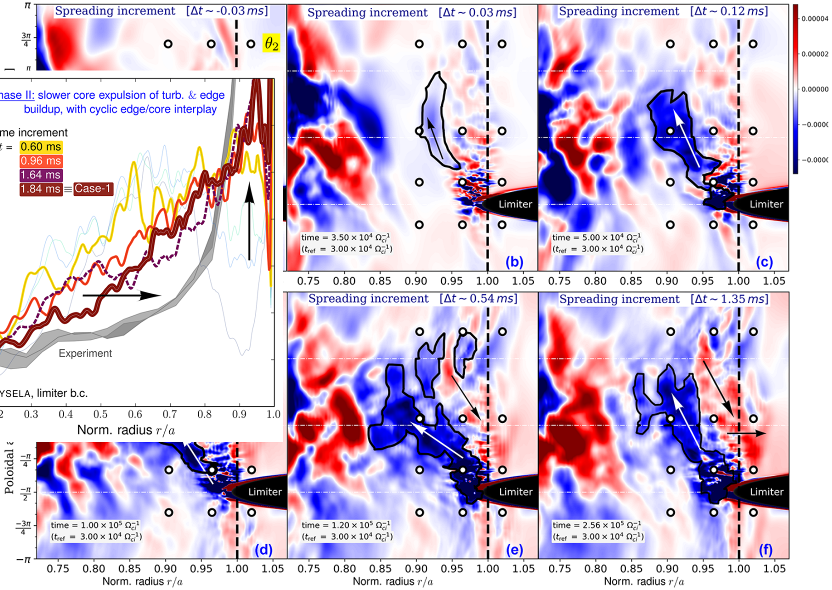
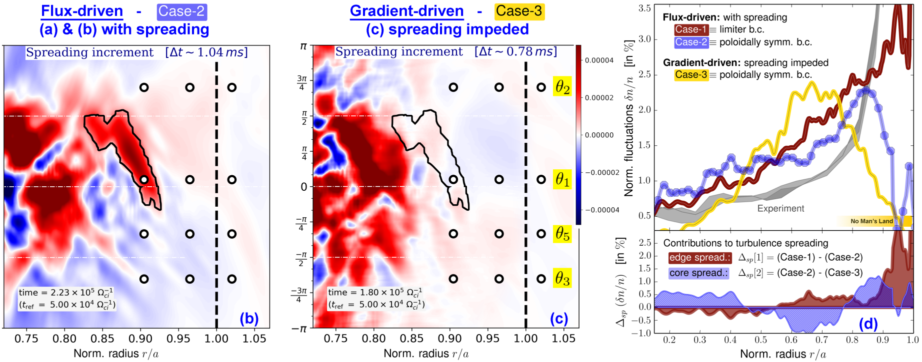


Disentangling all contrib.: weight of limiter-borne fluct.; edge → core & core → edge spreading

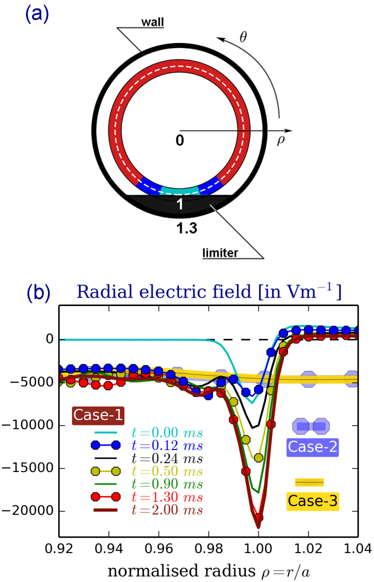


❶ - ❷ ≡ importance of near-LCFS turbulence & outside–in spreading

❷ - ❸ ≡ importance of inside–out spreading, amplified "beach effect"

- overpredict turb. activity $0.55 \leqslant r/a \leqslant 0.75$ → GD impedes redistribution $r/a \geqslant 0.8$ & $r/a \leqslant 0.4$
- redistribution of turb. intensity bridges free energy injection near limiter → upstream confined core

Spontaneous & persistent transport barrier @ closed–open field line interface → mechanism?



Detailed (r, θ) vorticity balance to probe mechanisms for E_r build-up & sustainment mechanisms

- start from GK equation + $\mathbf{E} \times \mathbf{B}$ velocity + gyroaverage

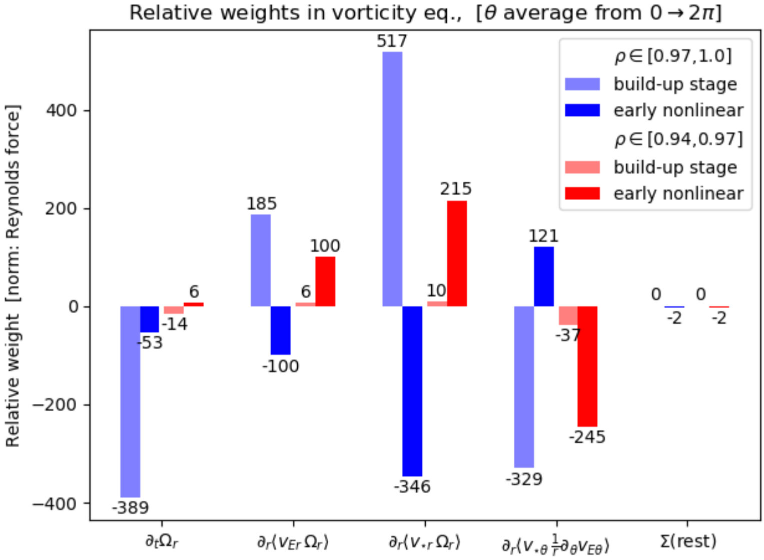
$$\partial_t \langle \Omega \rangle + \nabla \cdot \langle \Gamma \rangle = rhs$$

$$\partial_t \langle \Omega_r \rangle + \underbrace{\partial_r \langle v_{Er} \Omega_r \rangle}_{\text{Reynolds force}} + \underbrace{\partial_r \langle v_{\star r} \Omega_r \rangle}_{\text{diamagn.}} + \underbrace{\partial_r \left\langle v_{\star\theta} \frac{1}{r} \partial_\theta v_{E\theta} \right\rangle}_{\text{polo. tilt}} =$$

$$- \partial_t \langle \Omega_\theta \rangle - \frac{1}{r} \partial_\theta \langle (v_{E\theta} + v_{\star\theta}) \Omega_\theta \rangle - \partial_r \frac{1}{2r} \partial_\theta \langle v_{E\theta}^2 \rangle$$

$$+ \frac{1}{2r^3} \partial_\theta \partial_r \langle r^2 v_{Er}^2 \rangle - \frac{1}{r} \partial_\theta \left\langle v_{\star r} \frac{1}{r} \partial_\theta v_{E\theta} \right\rangle + rhs$$

Persistent transport barrier @ closed–open field line interface → mechanism?



Active mechanism for persistent transport barrier @ LCFS: $\langle v_{\star r}\Omega_r \rangle \equiv$ diamagn. currents sign-discriminate vortices advected