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Transport in Fusion Plasmas: Is the Tail Wagging the Dog?

#1: edge transport: new light on “shortfall” conundrum

#2: spontaneous confinement transition @separatrix

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Ackn.: Festival de Théorie, Aix-en-Provence

- ▶ spontaneous transitions come in many flavours: ITBs, $\{H; I; \dots\}$ -modes
- ▶ common grounds: **turbulence** & self-reinforcing feedback
 - onset of differential rotation
 - steepening of ∇p_i
 - electric field well (or hill) \rightarrow shear-induced bifurcation [Biglari PF 90, ...]
- ▶ robustly observed (Tokamak, stellarator, ...) upon modifications of edge/SOL operating **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.]

take a step back \rightarrow focus on **low-confinement "L-mode" edge**

\hookrightarrow **prerequisite** to understand **edge bifurcation(s)**

[Spoiler: interplay SOL \leftrightarrow edge \leftrightarrow core]

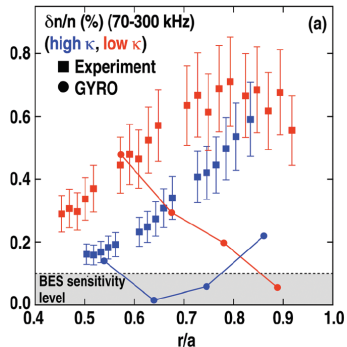
➤ Several (related) conundrums

① intrinsic problem [shortfall?] @plasma edge?

↳ edge often **linearly stable**

↳ where does edge turb. come from?

↳ propagation/contamination?



[Holland PoP 11]

➤ Several (related) conundrums

① intrinsic problem [shortfall?] @plasma edge?

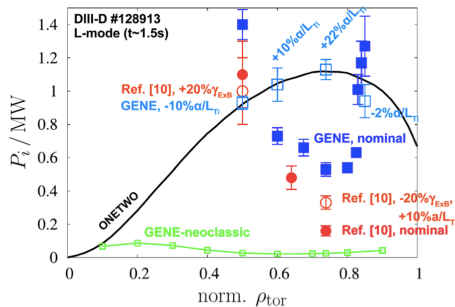
↳ edge often **linearly stable**

↳ where does edge turb. come from?

↳ propagation/contamination?

② important turb. properties:
all **locally-determined**?

③ what presides over the onset of edge transport barrier? Mechanism(s)?



[Gorler PoP 14]

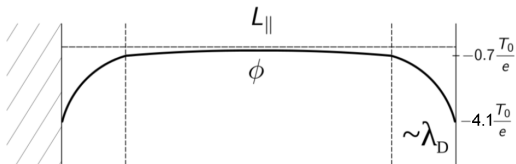
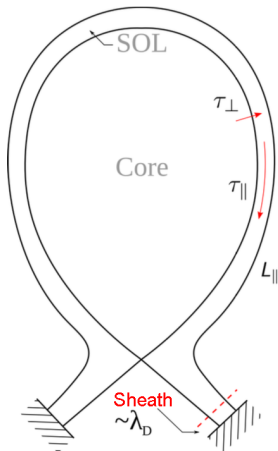
- equil. gradient length \sim (few ρ_i) \Rightarrow **scale separations debatable** in edge
(gradient scale $\leftrightarrow F_{eq}$) $\not\Rightarrow$ (turb.scale $\leftrightarrow \delta f \equiv F - F_{eq}$)
- profiles \equiv **large uncertainties** in edge; **poorly known** in SOL
 \hookrightarrow **flux-driven** desirable $\left\{ \begin{array}{l} \Rightarrow$ propagation of information on **global scales** \\ \Rightarrow add. **symm.-breaking mechanisms** edge turb. \end{array} \right.
- magnetic connection to **material boundaries**
 \hookrightarrow expect E_r shear ($\nabla p/n$ vs. $-\nabla T_e$) \Rightarrow incidence on **transp. barrier onset?**

► this work: global organisation core \leftrightarrow edge \leftrightarrow SOL? [Spoiler: strong interplay]

① **whereby edge transitions to / sustains a turbulent state?**

② **spontaneous transport barrier @separatrix**

\hookrightarrow mechanisms whereby such bifurcations occur? causality?



$$\Delta\phi^{\text{sheath}} \underset{\substack{\uparrow \\ \text{fluid}}}{\approx} \frac{T_e}{e} \frac{1}{2} \ln \left[\frac{m_e}{m_i} \left(1 + \frac{T_i}{T_e} \right) \right] \underset{\substack{\uparrow \\ \text{(D)}}}{\approx} -4.1 \frac{T_e}{e}$$

[eg. Stangeby 2000]

Path followed:

simplified SOL physics within flux-driven GK...
...without resolving sheath (subgrid) & neutrals

- ▶ simplified limiter geom.
- ▶ simplified adiabatic electron response
- ▶ penalised approach

$$\left\{ \begin{array}{l} \bullet F_s \rightarrow \mathbb{G}_{\text{cold}} \\ \bullet \phi \rightarrow \Delta\phi^{\text{sheath}} \end{array} \right.$$

[Isoardi JCP10; Caschera Varenna 18]

$$\bullet \frac{d\bar{F}_s}{dt} = \mathcal{C} + \mathcal{S} + \mathcal{D} - \nu \mathcal{M}^{\text{mat}}(r, \theta) [\bar{F}_s - \mathbb{G}_{\text{cold}}]$$

$$\bullet \Delta n_e = \rho + \frac{1}{n_{e0}} \sum_s Z_s \nabla_{\perp} \cdot \left(\frac{n_{s0}}{B \Omega_s} \nabla_{\perp} \phi \right)$$

with $\frac{T_e}{e} \Delta n_e = \phi - \lambda \left[1 - \mathcal{M}^{\text{SOL}}(r) \right] \langle \phi \rangle_{\mathcal{J}\mathcal{S}}$

$$- \lambda \frac{e}{T_e} \Delta \phi^{\text{sheath}} \left[\mathcal{M}^{\text{SOL}}(r) - \mathcal{M}^{\text{mat}}(r, \theta) \right] (T_e - T_e^{b.c.})$$

$$- \left[\mathcal{M}^{\text{mat}}(r, \theta) - \mathcal{M}^{\text{wall}}(r) \right] \phi^{\text{bias}}$$

with $\rho(\mathbf{x}, t) = \frac{1}{n_{e0}} \sum_s Z_s \int d^3v \mathcal{J} \cdot (\bar{F}_s - \bar{F}_{s,eq})$

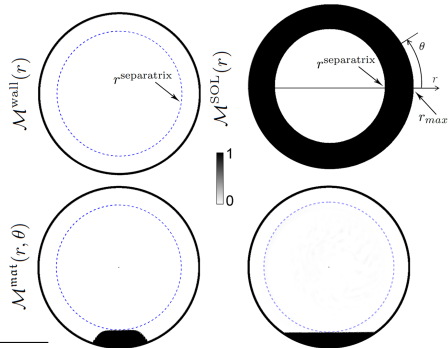
- ▶ global domain: $0 \leq r/a \leq 1.3$
- ▶ Tore Supra #45511
- ▶ $\rho_{*} \approx 1/300 \rightarrow$ in the "local limit"

- no transport of mass
- transport of energy & momentum

→ "baseline" instab. ITG+PVG; extension to TKEs

[see P. Donnel, [this conference](#)]

Tokamak volume	Mask
All plasma	$1 - \mathcal{M}^{\text{mat}}(r, \theta)$
Closed field lines	$1 - \mathcal{M}^{\text{SOL}}(r)$
Scrape-Off Layer	$\mathcal{M}^{\text{SOL}}(r) - \mathcal{M}^{\text{mat}}(r, \theta)$
Material boundaries	$\mathcal{M}^{\text{mat}}(r, \theta)$
Limiter only	$\mathcal{M}^{\text{mat}}(r, \theta) - \mathcal{M}^{\text{wall}}(r)$
Wall only	$\mathcal{M}^{\text{wall}}(r)$



$$\bullet \frac{d\bar{F}_s}{dt} = \mathcal{C} + \mathcal{S} + \mathcal{D} - \nu \mathcal{M}^{\text{mat}}(r, \theta) [\bar{F}_s - \mathbb{G}_{\text{cold}}]$$

$$\bullet \Delta n_e = \rho + \frac{1}{n_{e0}} \sum_s Z_s \nabla_{\perp} \cdot \left(\frac{n_{s0}}{B\Omega_s} \nabla_{\perp} \phi \right)$$

with $\frac{T_e}{e} \Delta n_e = \phi - \lambda \left[1 - \mathcal{M}^{\text{SOLO}}(r) \right] \langle \phi \rangle_{\mathcal{FS}}$

$$- \lambda \frac{e}{T_e} \Delta \phi^{\text{sheath}} \left[\mathcal{M}^{\text{SOLO}}(r) - \mathcal{M}^{\text{mat}}(r, \theta) \right] (T_e - T_e^{\text{b.c.}})$$

$$- \left[\mathcal{M}^{\text{mat}}(r, \theta) - \mathcal{M}^{\text{wall}}(r) \right] \phi^{\text{bias}}$$

with $\rho(\mathbf{x}, t) = \frac{1}{n_{e0}} \sum_s Z_s \int d^3v \mathcal{J} \cdot (\bar{F}_s - \bar{F}_{s,eq})$

- global domain: $0 \leq r/a \leq 1.3$
- Tore Supra #45511
- $\rho_{\star} \approx 1/300 \rightarrow$ in the "local limit"

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→ "baseline" instab. ITG+PVG; extension to TKEs
[see P. Donnel, [this conference](#)]

Systematic comparison TS#45511

#1 Flux-Driven & limiter



#2 Flux-Driven & poloidally symm.

$$\mathcal{M}^{\text{mat}}, \mathcal{M}^{\text{SOLO}}, \mathcal{M}^{\text{wall}} \rightarrow 0$$

$$\forall t, r/a \geq 1 \quad \bar{F}_s \rightarrow \text{cst} \equiv F_{\#1}$$

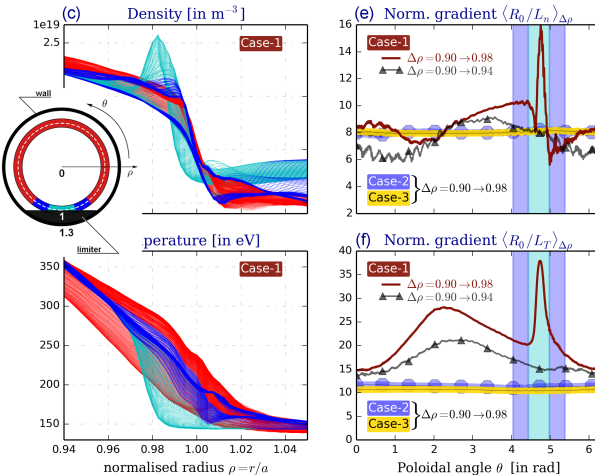


#3 Gradient-Driven & poloidally symm.

$$\mathcal{M}^{\text{mat}}, \mathcal{M}^{\text{SOLO}}, \mathcal{M}^{\text{wall}} \rightarrow 0$$

$$\mathcal{S} \rightarrow 0$$

$$\forall r, t \quad \bar{F}_s \rightarrow \text{cst} \equiv F_{\#2}$$



linear analysis of GYSELA
profiles with local GKW
[Peeters CPC 09]

w/o Limiter

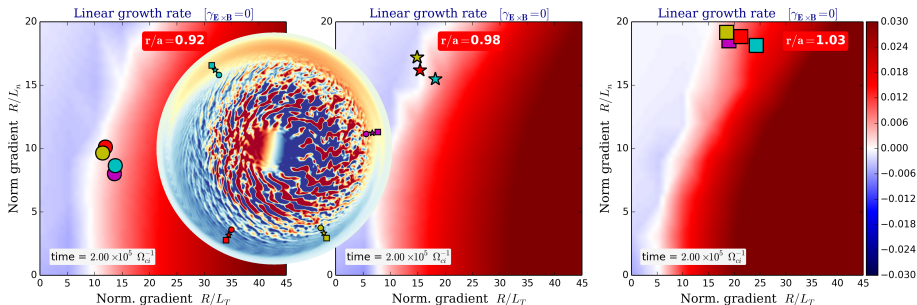
$\rho \leq .92$: ITG/TEM unstable
 $\rho \geq .92$: outer edge stable

with Limiter

- narrow (r, θ) region DW/interchange unstable
- rest of edge is stable

► interesting situation: turbulence organisation in edge?

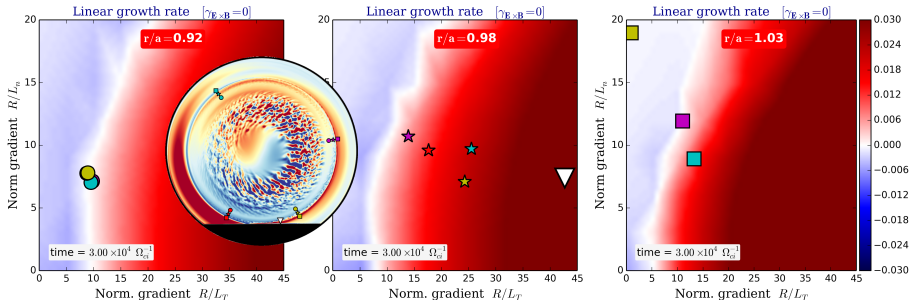
No Limiter \equiv polo. symmetric cases



major caveats: $\mathbf{E} \times \mathbf{B} = 0$ & poloidally (parallel) homogeneity

long story short: ITG & TEM unstable $r/a \leq 0.92$; outer edge stable $r/a \geq 0.92$

WITH Limiter \equiv (large) localised free energy sources



when edge instab. starts: *profiles ~same @LFS midplane w/ or w/o limiter*

- narrow (r, θ) region DW/interchange unstable ; PVG marginally unstable
- rest of edge is stable [marginally-unstable @steady-state]

➡ interesting situation: turbulence organisation in edge? investigate

$\delta n/n$

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

[Mattor; Garbet; Hahn; . . . ; Singh]

Proxy for spatial turb. spreading:

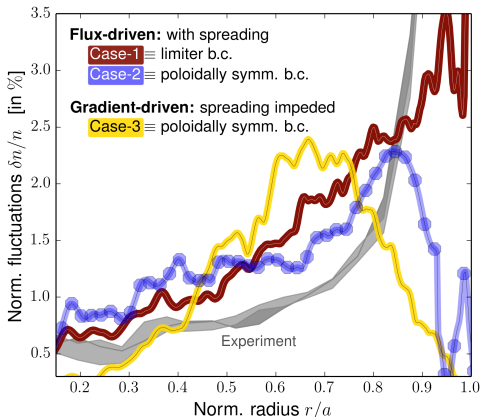
$$\left(\frac{\partial}{\partial t} + \bar{\mathbf{v}}_{E,\theta} \frac{\partial}{\partial \theta} \right) (nl) + \nabla \cdot \Gamma_I = \mathcal{P} - \mathcal{D}$$

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

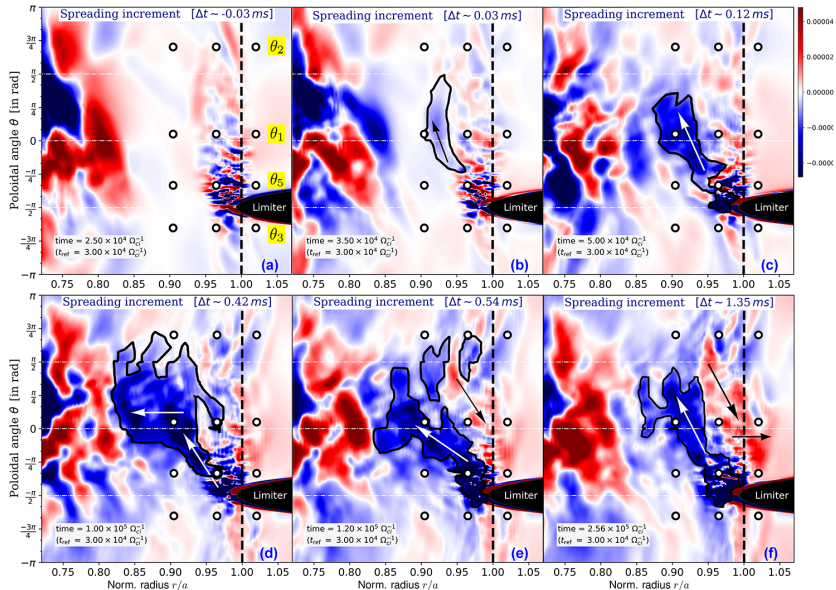
↳ investigate systematic spreading increments $\Delta S \equiv \Gamma_I(r, \theta, t) - \Gamma_I(r, \theta, t_{ref})$

$\Delta S \geq 0 \rightarrow$ radially-outward fluxes of turbulence intensity

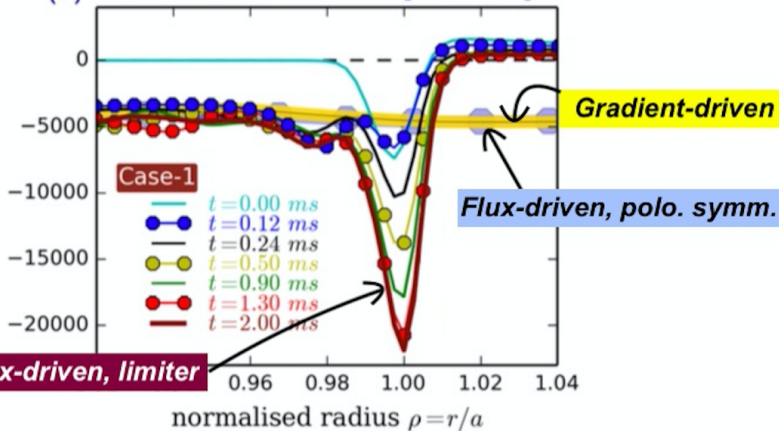
$\Delta S \leq 0 \rightarrow$ inward fluxes of turb. intensity



Limiter-borne fluctuations contaminate → edge & core then LCFS ↔ core cyclic equilibration



(b) Radial electric field [in Vm^{-1}]



- track vorticity production [GK eq. + $\mathbf{E} \times \mathbf{B}$ velocity + gyroaverage [eg. Sarazin PPCF 2021]]

$$\partial_t \langle \Omega_r \rangle + \frac{1}{r} \partial_r r \left[\langle v_{Er} \Omega_r \rangle + \langle v_{*r} \Omega_r \rangle - \left\langle v_{*\theta} \frac{1}{r} \partial_\theta E_r \right\rangle \right] = r.h.s$$

$$r.h.s \approx -\partial_t \langle \Omega_\theta \rangle - \frac{\partial_\theta}{r} \langle (v_{E\theta} + v_{*\theta}) \Omega_\theta \rangle - \partial_r \frac{\partial_\theta}{2r} \langle v_{E\theta}^2 \rangle + \frac{\partial_\theta}{2r^3} \partial_r \langle r^2 v_{Er}^2 \rangle - \frac{\partial_\theta}{r} \left\langle v_{*r} \frac{1}{r} \partial_\theta v_{E\theta} \right\rangle$$

$$\Omega_r \approx -\partial_r E_r \quad \& \quad \Omega_\theta = \partial_\theta^2 \phi / r^2$$

$$v_{Er} = -\partial_\theta \phi / r \quad \& \quad v_{E\theta} = \partial_r \phi = -E_r$$

$$v_{*r} = -\partial_\theta p_\perp / r \quad \& \quad v_{*\theta} = \partial_r p_\perp$$

- track vorticity production [GK eq. + $\mathbf{E} \times$

$$\partial_t \langle \Omega_r \rangle + \frac{1}{r} \partial_r r \left[\langle v_{Er} \Omega_r \rangle + \langle v_{*r} \Omega_r \rangle - \langle v_{*r} \Omega_r \rangle \right]$$

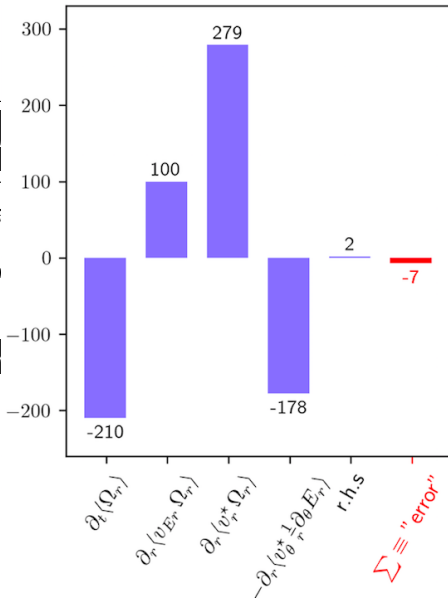
$$r.h.s \approx -\partial_t \langle \Omega_\theta \rangle - \frac{\partial_\theta}{r} \langle (v_{E\theta} + v_{*\theta}) \Omega_\theta \rangle - \hat{c}$$

$$\Omega_r \approx -\partial_r E_r \quad \& \quad \Omega_\theta = \partial_\theta^2 \phi / l$$

$$v_{Er} = -\partial_\theta \phi / r \quad \& \quad v_{E\theta} = \partial_r \phi$$

$$v_{*r} = -\partial_\theta p_\perp / r \quad \& \quad v_{*\theta} = \partial_r p_\perp$$

- accurate vorticity balance



- track vorticity production [GK eq. + $\mathbf{E} \times \mathbf{B}$ velocity + gyroaverage [eg. Sarazin PPCF 2021]]

$$\partial_t \langle \Omega_r \rangle + \frac{1}{r} \partial_r r \left[\langle v_{Er} \Omega_r \rangle + \langle v_{\star r} \Omega_r \rangle - \left\langle v_{\star \theta} \frac{1}{r} \partial_\theta E_r \right\rangle \right] = r.h.s$$

$$r.h.s \approx -\partial_t \langle \Omega_\theta \rangle - \frac{\partial_\theta}{r} \langle (v_{E\theta} + v_{\star \theta}) \Omega_\theta \rangle - \partial_r \frac{\partial_\theta}{2r} \langle v_{E\theta}^2 \rangle + \frac{\partial_\theta}{2r^3} \partial_r \langle r^2 v_{Er}^2 \rangle - \frac{\partial_\theta}{r} \left\langle v_{\star r} \frac{1}{r} \partial_\theta v_{E\theta} \right\rangle$$

$$\Omega_r \approx -\partial_r E_r \quad \& \quad \Omega_\theta = \partial_\theta^2 \phi / r^2$$

$$v_{Er} = -\partial_\theta \phi / r \quad \& \quad v_{E\theta} = \partial_r \phi = -E_r$$

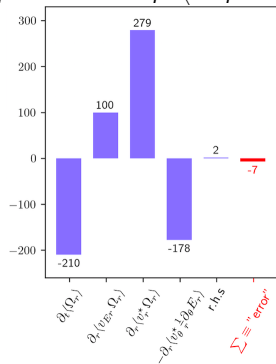
$$v_{\star r} = -\partial_\theta p_\perp / r \quad \& \quad v_{\star \theta} = \partial_r p_\perp$$

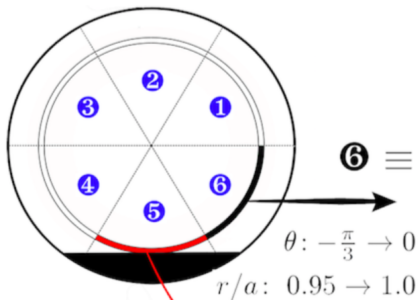
- accurate vorticity balance

- But...
 - no statement about dynamical relevance
 - assess causality in barrier build-up?

- "Transfer Entropy"** \equiv net directional flow of information

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





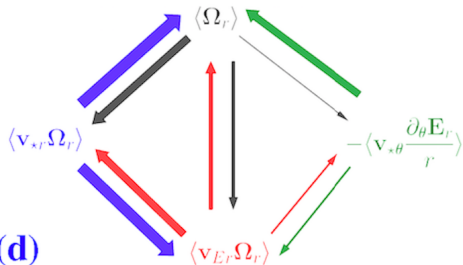
(b)

no fluctuations

5 \equiv

$\theta: -\frac{2\pi}{3} \rightarrow -\frac{\pi}{3}$
 $r/a: 0.95 \rightarrow 1.0$

(d)



- ▶ penalised limiter → **simplified SOL** miss e^- || dynamics; convection & neutrals
 ↳ free energy injection in narrow region → turb. redistribution key

- ▶ **interplay SOL, edge & core**

[Dif-Pradalier, Communications Physics 2022]

- spontaneous persistent **transport barrier** $\equiv E_r$ build-up;
- **with limiter: no “shortfall”** \equiv clarifies spreading controversy
 - ① poloidal asymmetry (cold region...)
 - ② edge-to-core then ③ 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.**

- ▶ transp. barrier build-up → $\langle v_{Er} \Omega_r \rangle$, $\langle v_{*r} \Omega_r \rangle$ & $\langle v_{*\theta} \frac{\partial_\theta E_r}{r} \rangle$ **key to E_r growth**