DE LA RECHERCHE À L'INDUSTRIE

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The Plasma E × B Staircase: Turbulence Self-Regulation through Spontaneous Flow Patterning

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Ackn.: • Festival de théorie, Aix-en-Provence 2011 & 2013
• KITP, Santa Barbara, 2014 & 2015

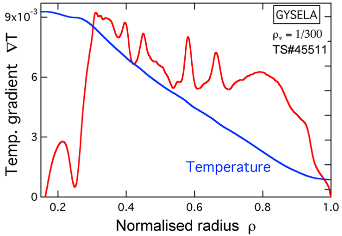
Spontaneous & robust trends in plasma turbulence

- T corrugations
- mean $\mathbf{E} \times \mathbf{B}$ shear
- flow patterning ➠ depart neoclass.
- set of quasi-regularly spaced weak transport barriers

- robust with $\rho_\star$ ➠ beneficial for conf.
- robust with $\nu_\star$
- observed so far near ITG threshold

large machines : $\frac{\text{intern. energy}}{\text{ext. heating}} \nearrow$

understand turb. self-organisation?



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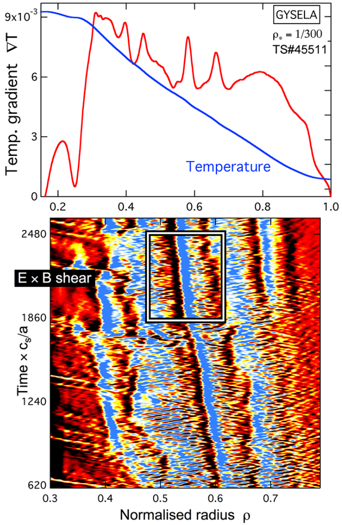

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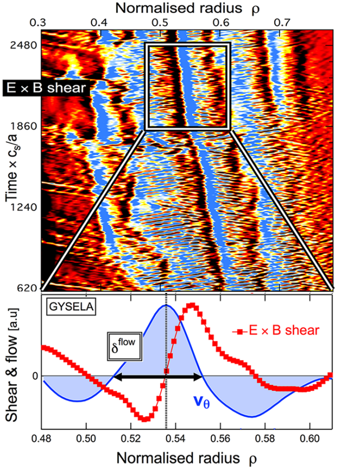

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[Dif-Pradalier PRE 10 & PRL 15]

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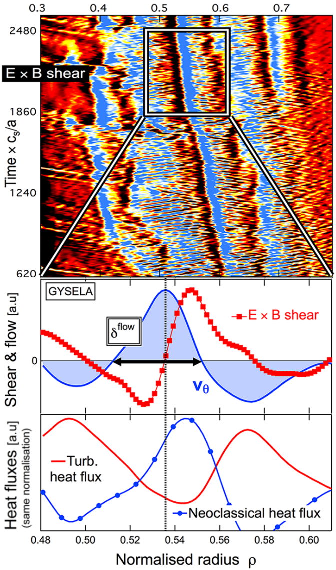
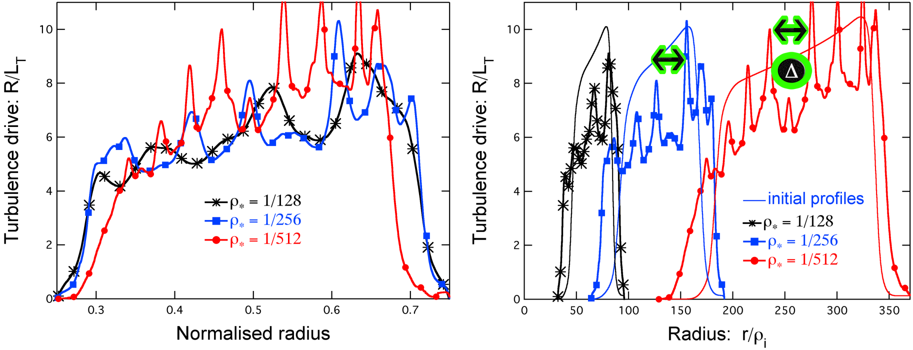
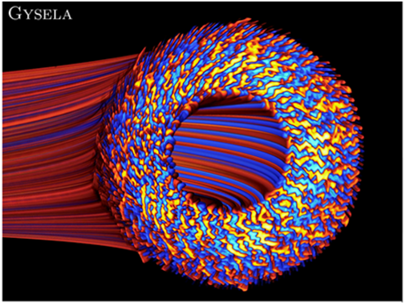


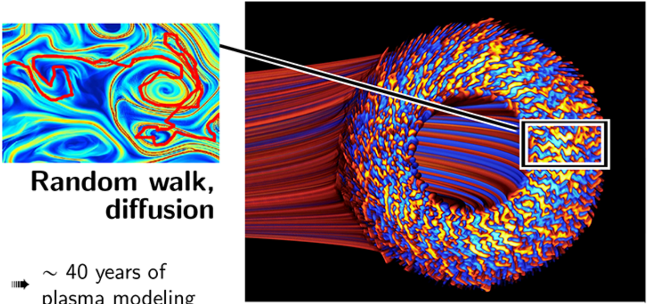
Spontaneous emergence of a meso-scale $\Delta \sim 30\rho_0$



- # shear layers $\nearrow$ as machine size $\nearrow$ ➠ beneficial for confinement
  - ↳ spacing saturates past $\rho_\star \sim 1/300$
  - ↳ expect 3-5 in a medium-size [$\rho_\star \sim 1/300$] tokamak

underlying physics for this mesoscale ?


GYSELA



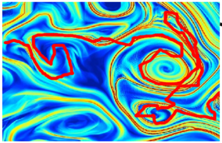
Random walk, diffusion

➠ $\sim$ 40 years of plasma modeling

- density/temp. gradients
- bath of turbulent eddies
- magnetic geometry

magnetic geom. $\rightarrow$ "pinned" turbulent eddies $\rightarrow$ random walk transport $\rightarrow$ **diffusion** $Q = -n\chi\nabla T$

➠ three generic trends for turb. self-organisation



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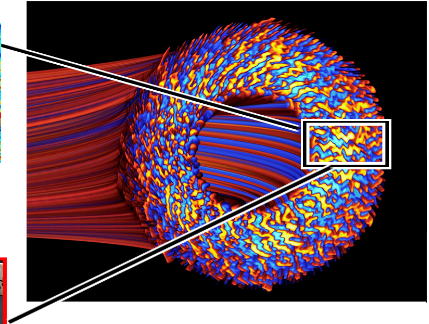
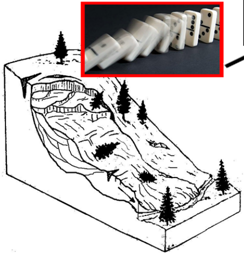




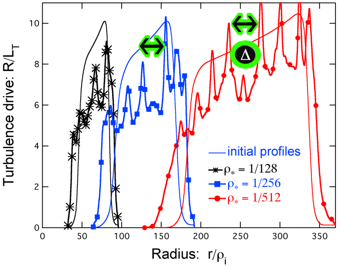
Avalanches (detrimental)

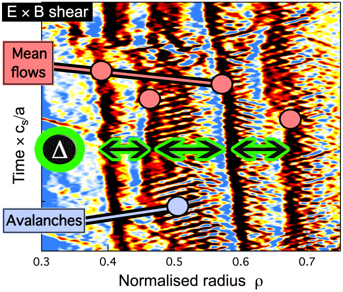
- non-local & non-diffusive
- self-consistent **profile dynamics**

➠ hindered in **"usual" turb. modeling**

[flux-tube, local or gradient-driven]

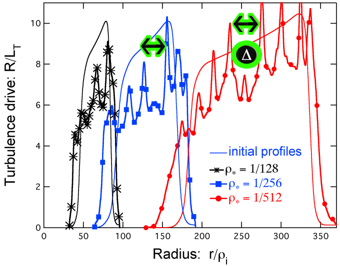
➠ need **flux-driven** approaches

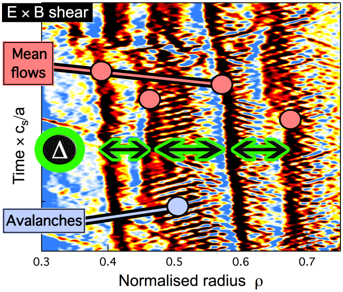




$$Q = -n\chi(r)\nabla T \quad \Rightarrow \quad Q = -\int \mathcal{K}(r, r')\nabla T(r')\,\mathrm{d}r'$$

$$\Rightarrow \quad \mathcal{K}(r, r') = \frac{S}{\pi}\,\frac{\Delta/2}{(\Delta/2)^2 + (r - r')^2}$$





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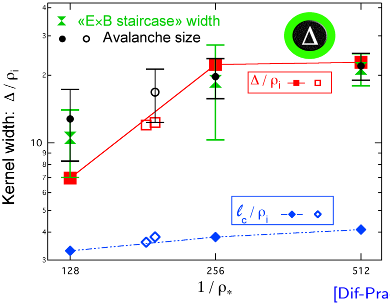
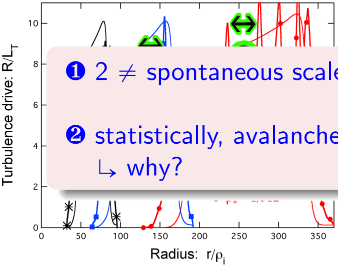


[Dif-Pradalier PRE 10]

at scales $\sim \ell_c$ $\equiv$ diffusive-like transport

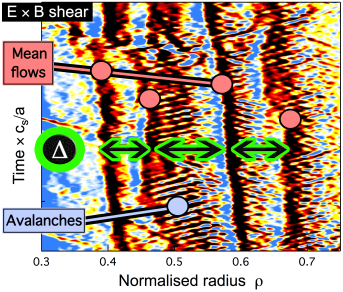
at scales $\in [\ell_c; \Delta]$ $\equiv$ scale-invariant, avalanche-mediated, non-local, non-diffusive transp.

The mesoscale Δ is the outer scale of the avalanche distribution ["non-local scale"]



❶ 2 ≠ spontaneous scales in the plasma

❷ statistically, avalanches are NOT scale-free
↳ why?



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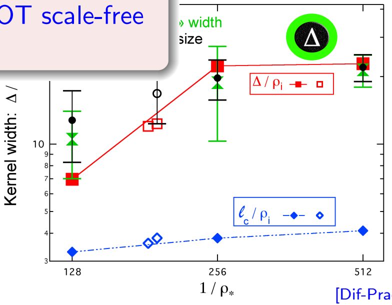

[Dif-Pradalier PRE 10]

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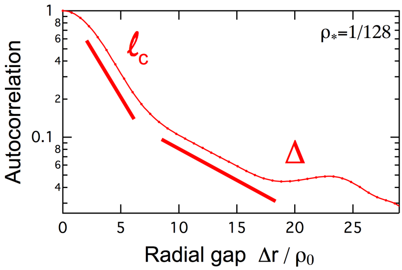
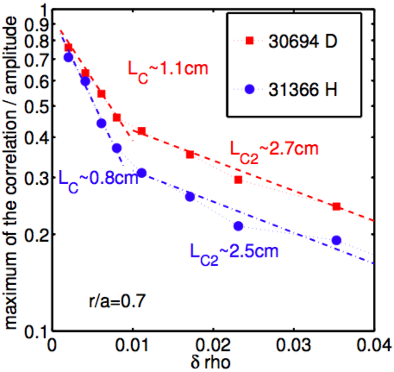
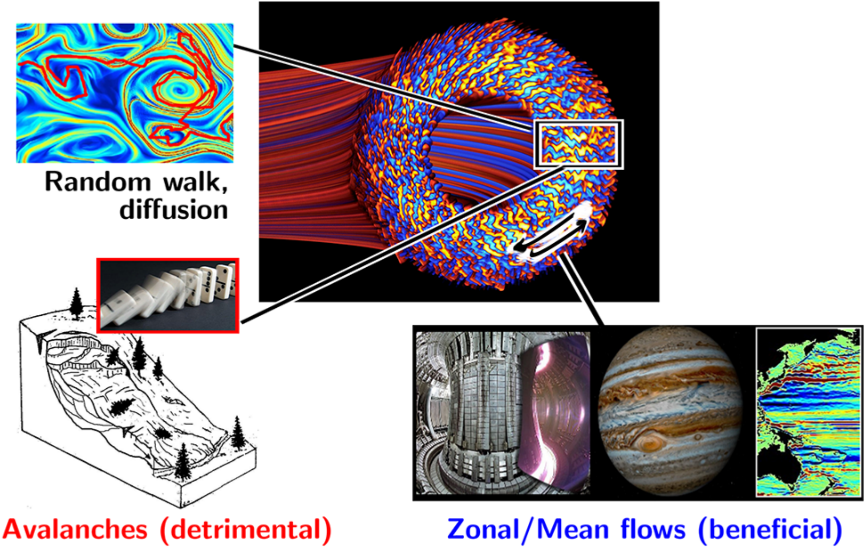
❶— Two spontaneous scales for the plasma: $\ell_c \equiv$ diffusive step & $\Delta \equiv$ avalanche extension



[Hennequin EPS 15]



❷— Why are avalanches not scale-invariant?
➠ three generic trends for turb. self-organisation



Problem: two mutually-exclusive natural trends for the plasma dynamics

The conundrum: two spontaneous patterning trends. . .yet mutually-exclusive

- avalanches: correlated over-turnings ➟ extended, intermittent transport
- zonal flows: limit the turbulent mixing, regulates transport via shearing

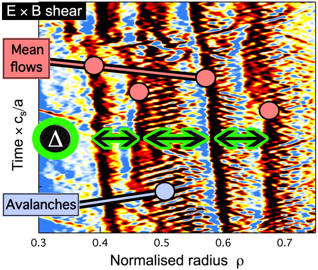
How can they coexist?

❶ they do not: both exist in different regions of parameter space?

❷ separation in time: both exist alternately?

❸ separation in space ➟ the **"E × B staircase"**

[Dif-Pradalier PRE 10 ; Kosuga PRL 13 ; Dif-Pradalier PRL 15]



the **E × B** staircase

- ZFs concentrate into thin layers & endure ➟ mean flows (MFs)
- MFs organise into a lattice of quasi-regularly spaced transp. barriers
- avalanches propagate in-between

A lot to understand still...

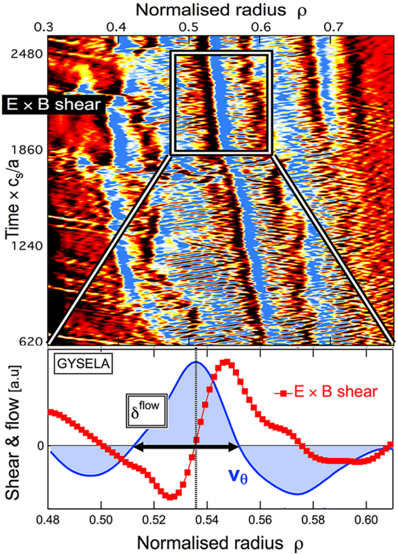
➥ what predictions? [a large dataset from Gysela]

Goal: provide figures for the experimental characterisation of the structure

- radial resolution $\delta^{\text{flow}} \sim 10\rho_i \sim 1\text{cm}$ [$\sim$ 1.5cm, Fujisawa PRL 04]
- radial extension: $2 - 3$ layers $\sim 60 - 100\rho_i$
- long-lived mean flows $\geqslant 10\text{ms}$... [$\sim$ 1.5ms, Fujisawa PRL 04]
- ... yet fast meandering $\sim 1\text{ms}$

needed: profiles, fast & high-res. [Hornung, following]

Turbulence-borne $\boxed{\sim \text{cm}}$ mean poloidal flows

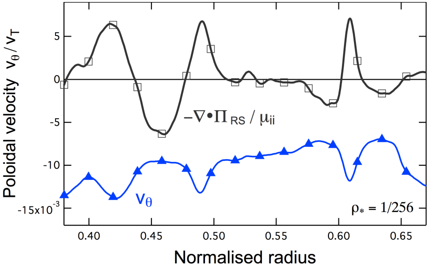


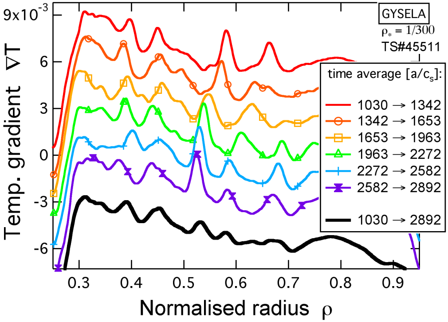
➥ $\delta^{\text{flow}} \sim 10\rho_i \sim 1\text{cm}$ [Dif-Pradalier, PRL15]

see G. Hornung

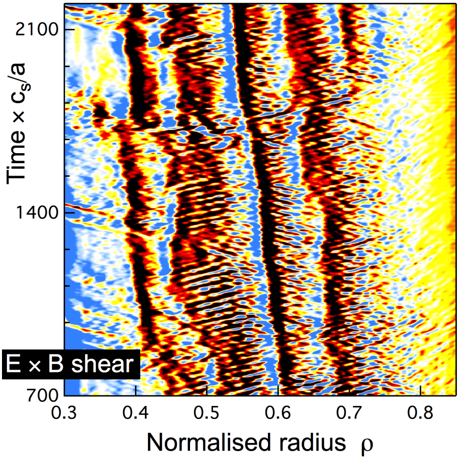
➥ local deviation from neoclassical prediction

[Bell PPCF 98, Crombé PRL 05, Dif-Pradalier PRL 09]





[∼ 5ms]



no fast-sweep ➠ no exp. observation

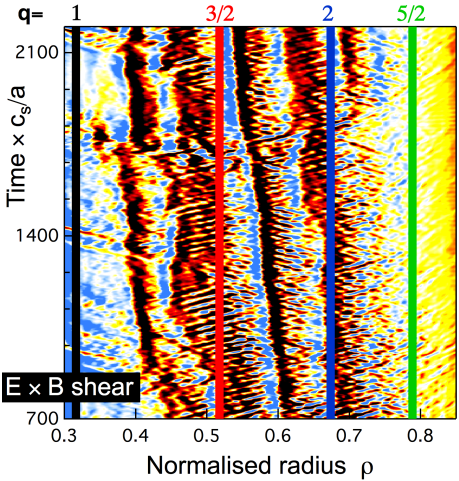
No clear connection to low-order q rationals

[experimentally. . .actually good news]

- spacing: regular, staircase: dynamical
- not pinned to a precise location
  - ↳ meanders, disappears, reforms
  - ↳ not linked to low-order q rationals

see G. Hornung

[∼ 5ms]



in a nutshell: 3 – 5 steps in medium size tokamak

resolve: ∼ms range & ∼cm range over ∼ 10's cm

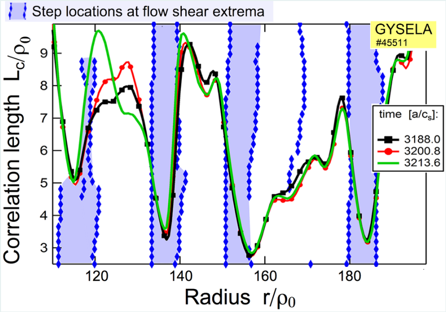
"straightforward" is uneasy

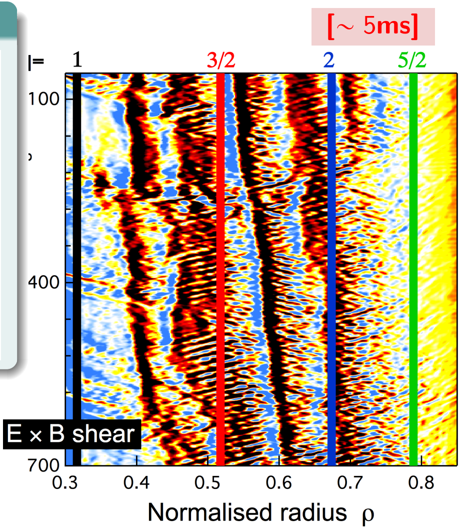
↳ "higher order" ≡ **correl. meas.**

No clear connection to low-order q rationals

[experimentally. . .actually good news]

Radial correlation length of turb. fluct.





in

tokamak

resolve: ~ms range & ~cm range

over ~ 10's cm

"straightforward" is uneasy

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Conclusions: the E × B staircase as a novel form of turbulence self-organisation

- **Turb.-borne long-lived & localised polo. flows ≠ neoclass.** [Dif-Pradalier PRL 09]
- **Identification of the E × B staircase** [Dif-Pradalier PRE 10]
  - ➥ nonlocal transport & stochastic avalanches
  - ➥ mesoscales are key ➠ 2 typical correlation lengths [Hennequin, this conference]
- **Model for staircase emergence** [Kosuga PRL 13 ; PoP 14]
  - ➥ clustering instability through a time-delay between flux & gradient
  - ➥ staircase with mesoscale step
- **Predictions v.s. experiments** [Dif-Pradalier PRL 15]
  - ➥ no link to low-order q rationals
  - ➥ radial turb. correlations ➠ observation on ToreSupra & predictions
- **Experimental characterisation of the E × B staircase** [Hornung, in preparation]

NB: may imply important **changes in common** (diffusive-based) **turb. models**

[Nakata NF 13 ; Villard PPCF 13 ; Norscini, Varenna 14 ; Cartier-Michaud, Varenna 14 ; Imadera, IAEA 15]

Additional material

Ab-initio **gyrokinetics, no scale separation** [full–f, flux-driven & global] $\equiv$ GYSELA

(i) Gyrokinetic equation for the gyrocenters $\bar{f}(\mathbf{x}_g, v_{\parallel,g}, \mu)$

$$\frac{\partial \bar{f}}{\partial t} + (\mathbf{v}_{\mathbf{E}\times\mathbf{B}} + \mathbf{v}_D)\cdot\nabla\bar{f} + v_\parallel \nabla_\parallel \bar{f} + \frac{\mathrm{d}v_\parallel}{\mathrm{d}t}\partial_{v_\parallel}\bar{f} = \mathcal{C}(f) + \mathcal{S}(f)$$

$$\mathbf{v}_{\mathbf{E}\times\mathbf{B}} = \frac{1}{B_\parallel^*}\mathbf{b}\times\nabla\bar{\phi} \qquad m\frac{\mathrm{d}v_\parallel}{\mathrm{d}t} = -\left(\mu\nabla B + e\nabla\bar{\phi}\right)\frac{\mathbf{B}^*}{B_\parallel^*}$$

$$\mathbf{v}_D = \frac{mv_\parallel^2 + \mu B}{eB_\parallel^*}\mathbf{b}\times\frac{\nabla B}{B} \qquad \mathbf{B}^* = \mathbf{B} + \frac{mv_\parallel}{e}\nabla\times\mathbf{b}$$

(ii) Quasi-neutrality equation for the particles

$$\frac{\delta n_e}{n_{eq}} = \frac{\delta n_i}{n_{eq}}$$

$$\frac{e}{T_e(r)}\left(\phi - \langle\phi\rangle\right) = \frac{2\pi B}{mn_0}\iint d\mu\, dv_\parallel J_0\left(f - f_{init}\right) - \frac{1}{n_0(r)}\boldsymbol{\nabla}_\perp\cdot\left[\frac{n_0}{B\,\omega_c}\boldsymbol{\nabla}_\perp\phi\right]$$

(*i*) Gyrokineti

$$\frac{\partial \bar{f}}{\partial t} + (\mathbf{v}_{\mathbf{E}\times\mathbf{B}}$$

$$\mathbf{v}_{\mathbf{E}\times\mathbf{B}} = \frac{1}{B_\parallel^*}\mathbf{b}$$

$$\mathbf{v}_D = \frac{mv_\parallel^2 + \mu B}{eB_\parallel^*}$$

(*ii*) Quasi-neu

$$\frac{e}{T_e(r)}\left(\phi - \langle\phi\rangle\right.$$

The GYSELA framework in a nutshell

- full–f $\equiv$ no scale separation in space & time
  [Grandgirard '06]
- flux-driven $\equiv$ sources of heat, momentum & vorticity
  - open system, known sources
  - self-consistent force balance E_r, ∇p, v_θ & v_φ
  - stiffness of the mean profiles
  - locality & non-locality $\equiv$ on equal footing
  [. . ., Dif-Pradalier '10, Ghendrih '12, Gurcan '13, Kosuga '13]
- adiabatic electrons & electrostatic

self-organising framework ➠ what transport to be expected?

Conclusions: the $\mathbf{E} \times \mathbf{B}$ staircase as a novel form of turbulence self-organisation

❶ what we do know

Globally-organised pattern spontaneous & weak transport barriers

[Dif-Pradalier PRL 15]

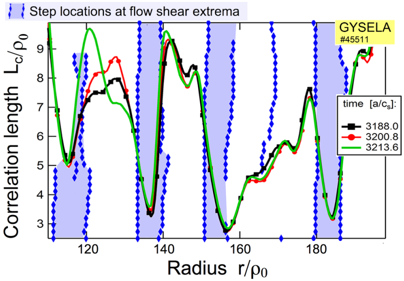
Visible on	$\gamma_{\mathbf{E}\times\mathbf{B}}, \nabla p, L_c, v_\theta, v_\parallel, \langle \tilde{v}_{Er}\tilde{v}_{E\theta}\rangle, \langle \tilde{v}_{Er}\tilde{v}_\parallel\rangle$
$\rho_\star = \rho_i/a$	$1/75 \rightarrow 1/512$
Step spacing	Outer scale of avalanche distribution constant [$\sim 20 - 30\rho_0$] for $\rho_\star \leq 1/300$ [1]
No. of steps	$1 \rightarrow 2[\rho_\star = 1/75]; 3 \rightarrow 5[\rho_\star = 1/300];$ $5 \rightarrow 7[\rho_\star = 1/512]$
Flow thickness	$\delta^{\text{flow}} \sim 10\rho_0$
Collisionality $\nu_\star$	$0.001 \rightarrow 1$
$\langle\langle R/L_T \rangle\rangle$	$4 \rightarrow 8$
$\langle\langle R/L_n \rangle\rangle$	$1 \rightarrow 4$
$\eta = L_n/L_T$	$2 \rightarrow 8$
Meandering	Stay at $\sim$ constant drive, follow $\nabla p(t)$
Strength	$\lvert\gamma_{\mathbf{E}\times\mathbf{B}}\rvert \sim$ constant for $\rho_\star \geq 1/300$
Resonant q	No correlation with low-order rationals

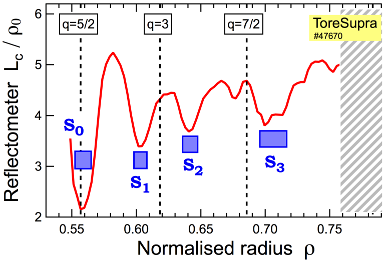
❷ what is still [somewhat] unknown

- mechanism whereby large-scale org. occurs [Kosuga PoP 14]
- robustness & domain of existence [Hornung, in prep.]
- impact on macro-transport properties & modeling

❸ why (we should) care?

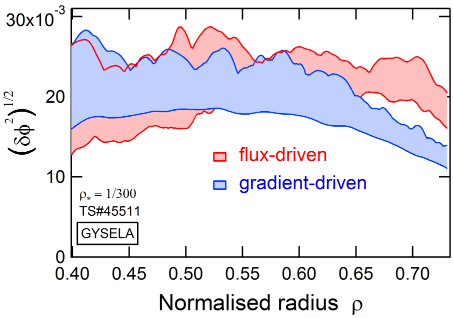
- because quite robust in flux-driven modeling [Dif-Pradalier PRE 10 ; Nakata NF 13 ; Villard PPCF 13 ; Norscini Varenna 14 ; Cartier-Michaud Varenna 14 ; Imadera, this conf.]
- because near-critical self-organisation may be key to next-gen. tokamaks
- GFD staircase "**the vein and arteries of the weather system**" [McIntyre, Festival 09]
- **because it exists!** prediction leads to exp. discovery [Dif-Pradalier PRL 15 ; Hornung, in prep.]

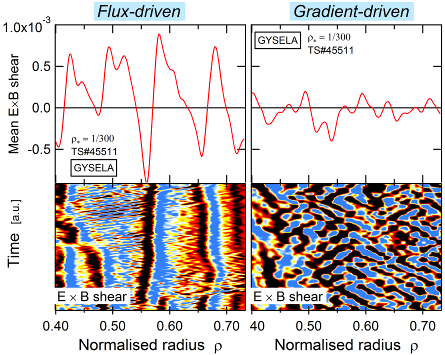




- may point towards important changes in current turbulence models

Ongoing: impact of scale separation [≡ forcing & bound. conditions]





- similar turbulence level
- mean shear pattern is lost : isotropisation of the fluctuations.
  ↳ ongoing : global impact on transport

Conclusions: the $\mathbf{E} \times \mathbf{B}$ staircase as a novel form of turbulence self-organisation

what we do know

Where staircases are observed in GYSELA

[Dif-Pradalier PRL 15]

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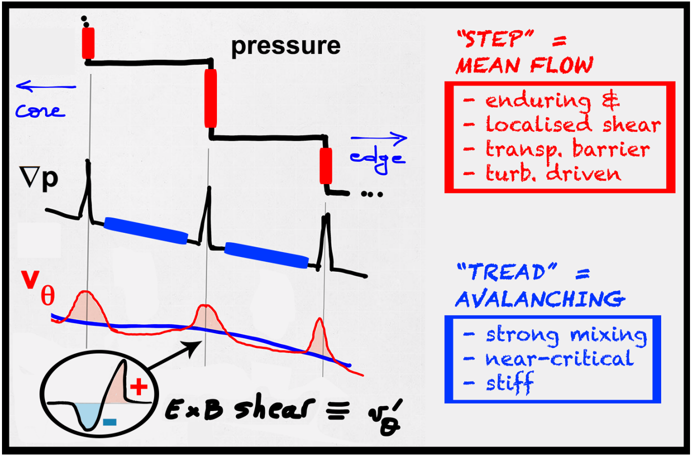
Strength	$\lvert\gamma_{\mathbf{E}\times\mathbf{B}}\rvert \sim$ constant for $\rho_\star \geq 1/300$
Resonant q	No correlation with low-order rationals



- avalanches interspersed between mean zonal flow layers
- shear flow layers associated to mean profile corrugations [$\equiv \nabla p$ or ∇f_s]

Global & dynamic pattern predicted on all turbulent fields

global & dynamic pattern

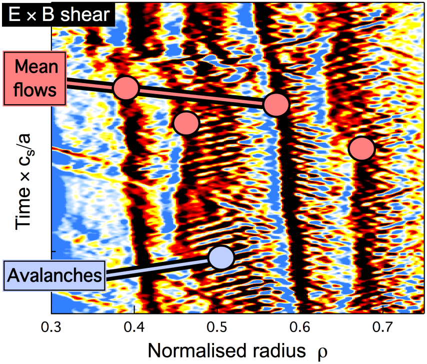
➥ impacts all turbulent fields

- $\mathbf{E}\times\mathbf{B}$ shear $v'_{E,\theta} = r\partial_r(E_r/rB)$
- Heat flux ; $v_{E,\theta}$; $\langle v_{Er} v_{E\theta}\rangle$, ...

predicted figures:

- radial res. $\delta^{\text{flow}} \sim 10\rho_i \sim 1\text{cm}$
- inter-shear layer: mesoscale $\sim 30\rho_i$
- long-lived mean flows $\gtrsim 10\text{ms}$...
- ... yet fast meandering $\sim 1\text{ms}$
- no link to low-order q rationals

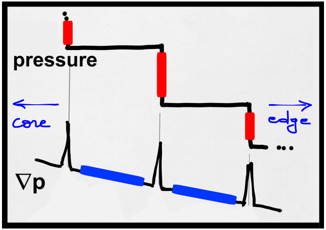
[~ 2ms]

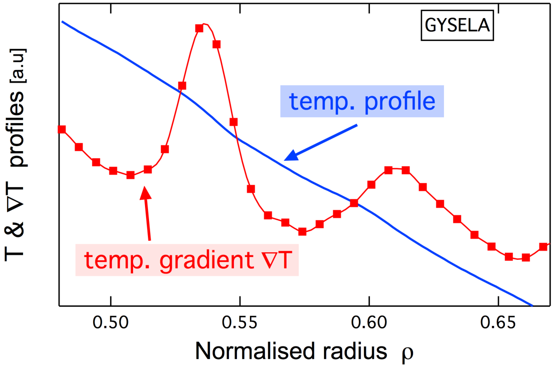


Legitimate concerns:

➥ does it really exist? [Dif-Pradalier '10 ; Nakata '13 ; Villard '13 ; Norscini '14 ; Cartier-Michaud '14 ; Imadera, this conf.]

➥ can we observe it? why never observed? [Dif-Pradalier PRL 15 ; Hornung, in prep.]



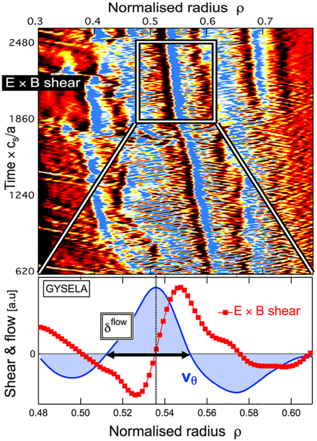


- unambiguous on the mean gradients
- difficult to characterise on the profile itself

  ➥ characterisation through fluctuation measurements

❶st choice: directly measure the mean flows

- regularly-spaced poloidal $\mathbf{E} \times \mathbf{B}$ shear flow layers
  - ➥ local deviation from neoclassical prediction
    [Bell PPCF 98, Crombé PRL 05, Dif-Pradalier PRL 09]
  - ➥ experimentally: a difficult measurement
    [C impurities, Doppler reflectometry, HIBP, . . .]



- radial resolution $\delta^{\text{flow}} \sim 10\rho_i \sim 1\text{cm}$
  [$\sim$ 1.5cm, Fujisawa PRL 04]
- radial extension: $2 - 3$ layers $\sim 60 - 100\rho_i$
- long-lived mean flows $\gtrsim 10\text{ms}$. . .
  [$\sim$ 1.5ms, Fujisawa PRL 04]
- . . . yet fast meandering $\sim 1\text{ms}$

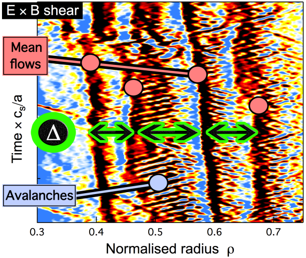
need **fast, high-res.** flow measur. ➽ **direct charact.** through flows **impractical**

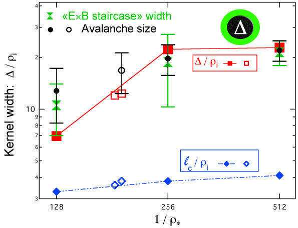
❷nd choice: characterise avalanching/transport

- $\rho_\star$ dependence ➠ break gyroBohm scaling?
  - **naive:** avalanching ≡ scale-independent → gBohm breaking → $\rho_\star$ dependence
  - **computation:** [Dif-Pradalier PRE 10] staircase ➠ mesoscale avalanching

$$Q = -\int \mathcal{K}(r,r')\nabla T(r')\,\mathrm{d}r' \quad ; \quad \mathcal{K} = \frac{1}{\pi}\frac{\Delta/2}{(\Delta/2)^2+(r-r')^2}$$

➥ **beneficial for conf.: spontaneous & mesoscale permeable/weak array of transp. barriers**



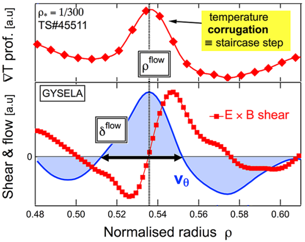


- direct obs. on fluctuations [Politzer PRL 00, Hornung PPCF 13]
  - high-res. temporal data
  - phase fluctuation ≠ dens. fluctuations
  - localisation: poloidal & radial

➥ **experimentally: a difficult measurement**

❸rd choice: through profile corrugations

Mean Flow ↔ staircase step ↔ mean prof. corrugation

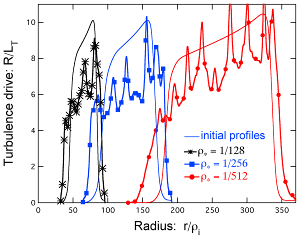


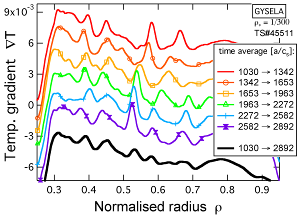
clear & systematic:

medium–large machines

- locally, large ∇p
- $\rho^{\mathrm{flow}} \sim$ constant
- $\Delta \sim$ constant
- near critical & stiff

[avalanches, SOC,. . .]





in a nutshell: 3 – 5 steps in medium size tokamak

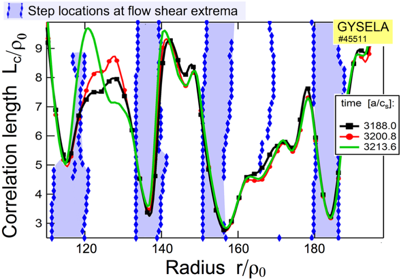
resolve: ∼ms range & ∼cm range over ∼ 10s cm

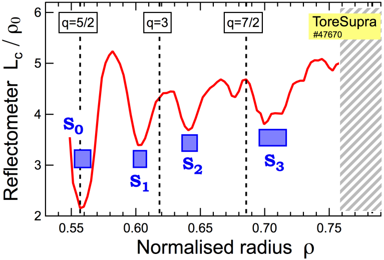
“straightforward” seems impractical

↳ “higher order” ≡ **correlation measurements**

- GYSELA: local minima turb. correlation lengths track staircase steps

[Ghendrih EPJD 14]



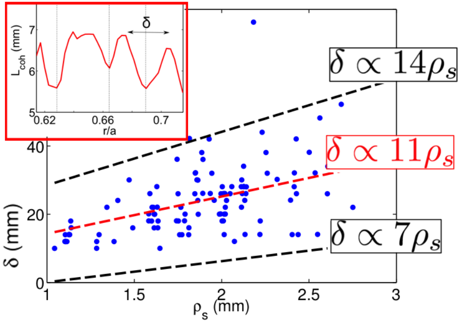


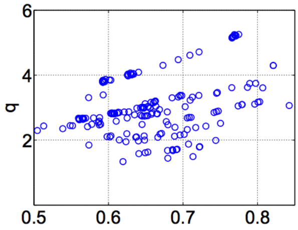
- Experiment: $L_c \equiv$ proxy for fluct. size [Dif-Pradalier PRL 15 & Hornung, in prep.]
  - L_c minima quasi-regularly spaced radially
  - reproducible: not random & robust w.r.t. definition of L_c
  - tilt consistent with flow shear around minima

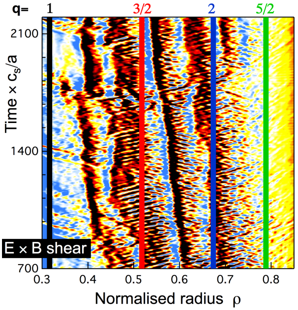
When **theoretical predictions** lead to **experimental discovery**

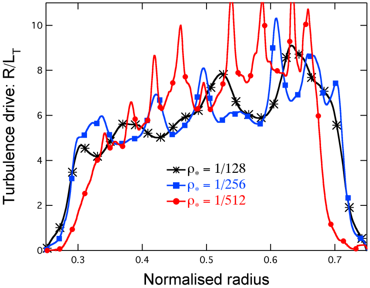
- flow width $\delta \sim 11\rho_i$ consistent with GYSELA obs. & ZF measurements
  [Fujisawa PRL 04]

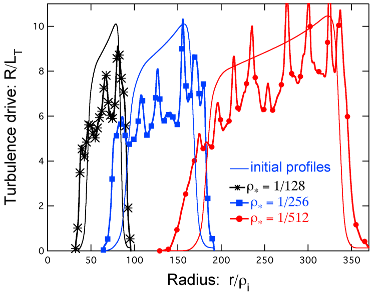
- turbulence-borne ➠ not MHD
  [Dif-Pradalier PRL 15 & Hornung, in prep.]



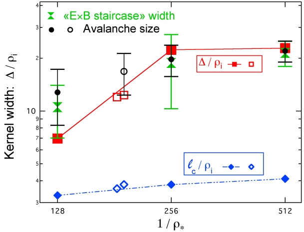


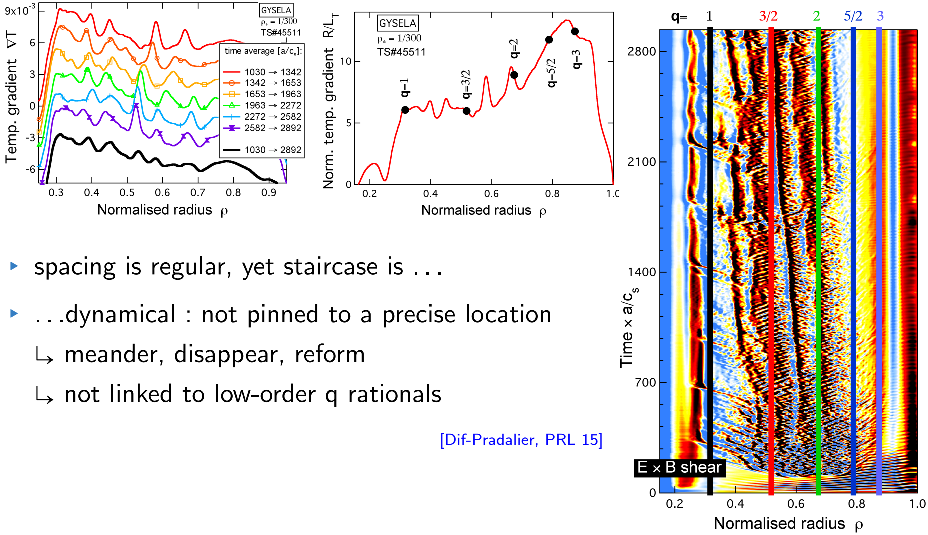






- how many shear layers ? ➠ depends on $\rho_\star$
- # shear layers ↗ as machine size ↗
  ↳ spacing saturates past $\rho_\star \sim 1/300$
  ↳ expect 3-5 in a medium-size tokamak

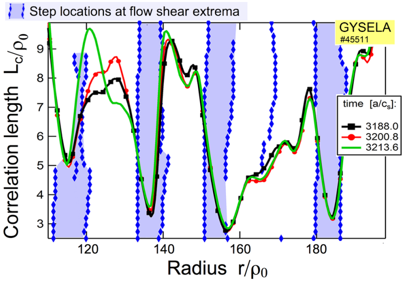


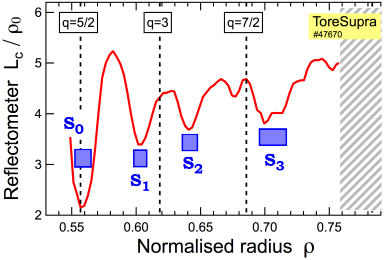


- spacing is regular, yet staircase is . . .
- . . .dynamical : not pinned to a precise location
  - ↳ meander, disappear, reform
  - ↳ not linked to low-order q rationals

[Dif-Pradalier, PRL 15]

Fast-sweeping reflectometry allows to identify the staircase structure in Tore Supra data

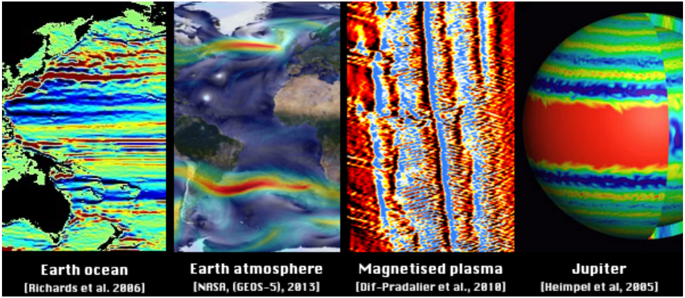




- structure difficult observe through direct profile measurements
- possible through turbulent fluctuation measurements [Hornung PPCF 13]

  ↳ radial profiles of turb. correlation lengths [Ghendrih EPJD 14, Dif-Pradalier PRL 15]

Strong on-going cross-field activity on "staircases" ➽ key to general principles of turb. self-organisation



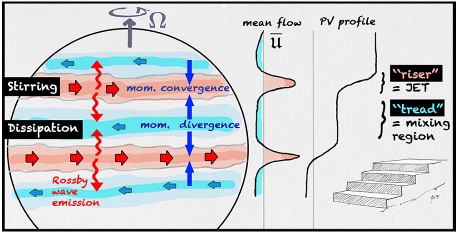
Atmospheric fluids: potential vorticity staircase, zonal flow structure from Rossby wave dynamics in quasigeostrophic turbulence ;

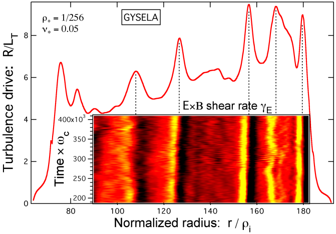
Magnetised plasma: $\mathbf{E} \times \mathbf{B}$ staircase, quasi-regular pattern of zonal flow layers co-located with profile corrugations interspersed by avalanching ;

Oceans: thermohaline staircase, alternately sharpened and flattened convection gradients driven by competing heat & salt gradients

A possibly **key structure** for confinement. . .
. . .yet **elusive to observe**

Why the name of "staircase"? analogy: "PV staircases" & atmospheric jets





[Festival de Théorie 2009 & 2011 ; Kavli Institute (KITP) 2014 & 2015]

Legitimate concern: **does it really exist?** [Dif-Pradalier '10 ; Nakata '13 ; Villard '13 ; Norscini '14 ; Cartier-Michaud '14 ; Imadera, this conf.]

why never observed? [Dif-Pradalier PRL 15 ; Hornung, in prep.]

- avalanches interspersed between mean zonal flow layers
- shear flow layers associated to mean profile corrugations [$\equiv \nabla(\mathrm{PV})$ or ∇p]
- other means to **characterise & observe the staircase?**