Self-Organized Edge Plasma Dynamics in Competing Drift-Wave and Interchange Turbulence

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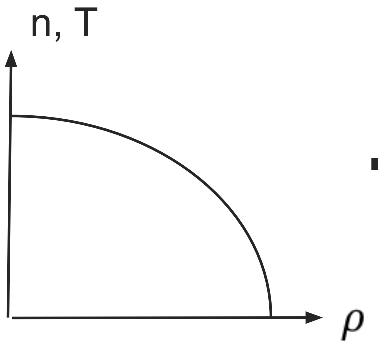
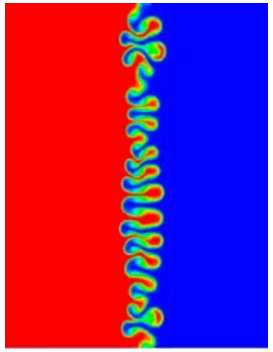
Turbulence governs the confinement

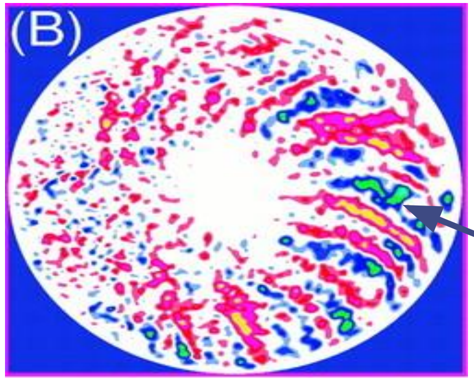
Gradients



Instabilities



Turbulence ⇒ Confinement time $\tau_E \downarrow$



Elec. Potential fluctuations $\tilde{\phi}$ [Lin 98]

Eddie size ℓ_c

How does turbulence saturate?

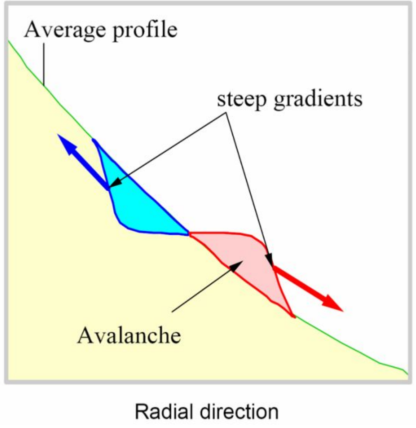
① Profile relaxation

② Energy transfer towards dissipative scales

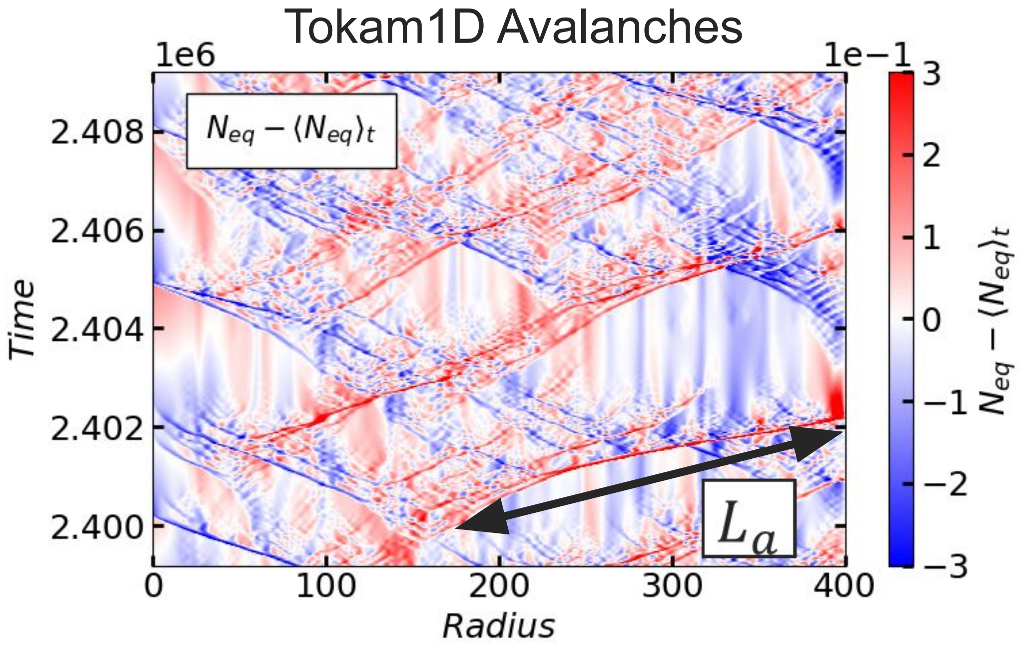
③ Structure generation

① Turb. saturation via profile relaxation

- **Turbulent flux** of heat / particles → $\Gamma_{turb} = \langle \tilde{n}\, \tilde{v} \rangle$
- Local profile relaxation can produce **avalanches**
  → ballistic events of transport



[Diamond 95; Garbet 98; Sarazin 98; Ghendrih 03; Politzer 00]

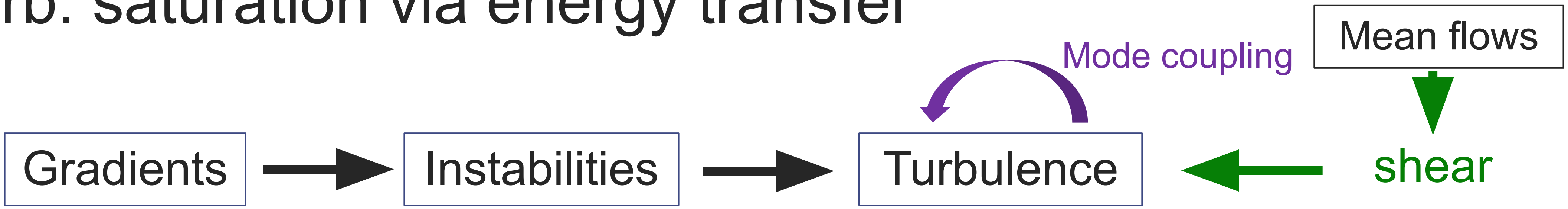


$\boxed{\text{Avalanches over large distance } (L_a \gg \ell_c) \rightarrow \text{degrade confinement}}$

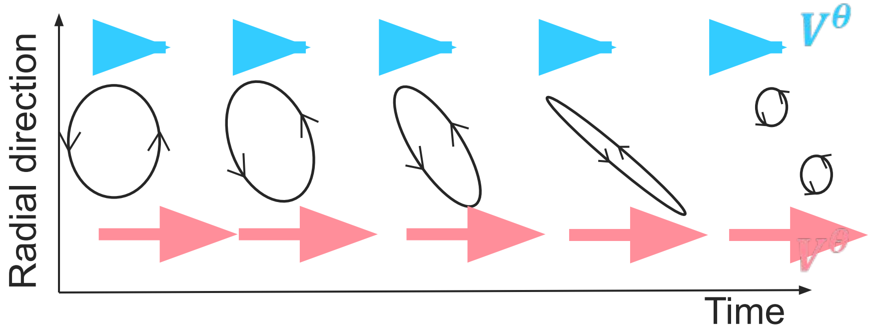
② Turb. saturation via energy transfer

- **Turbulent cascades** → Local (in k) energy transfer [Kolmogorov 41; Kraichnan 71]

② Turb. saturation via energy transfer



- **Turbulent cascades** → Local (in k) energy transfer [Kolmogorov 41; Kraichnan 71]
- **Sheared poloidal flow**
  - Stretching & decorrelation [Biglari 90, Manz 09]



$$V^\theta = v_E^\theta + v_{phase} \sim v_E^\theta$$

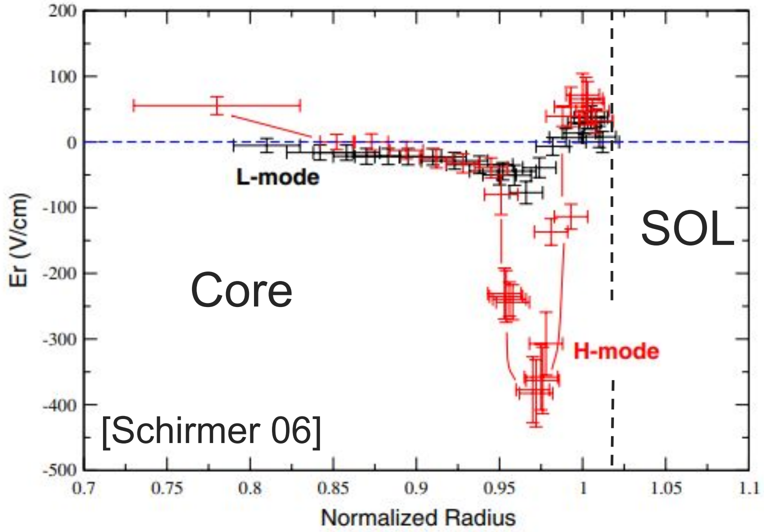
related to

$$\text{Electric: } v_E^\theta = \frac{\boldsymbol{E}\times\boldsymbol{B}}{B^2}\cdot e_\theta \sim -E_r/B$$

$$\text{Diamagnetic: } v_\star^\theta = \frac{\boldsymbol{B}\times\boldsymbol{\nabla}p_s}{n_e e_s B^2}\cdot e_\theta$$

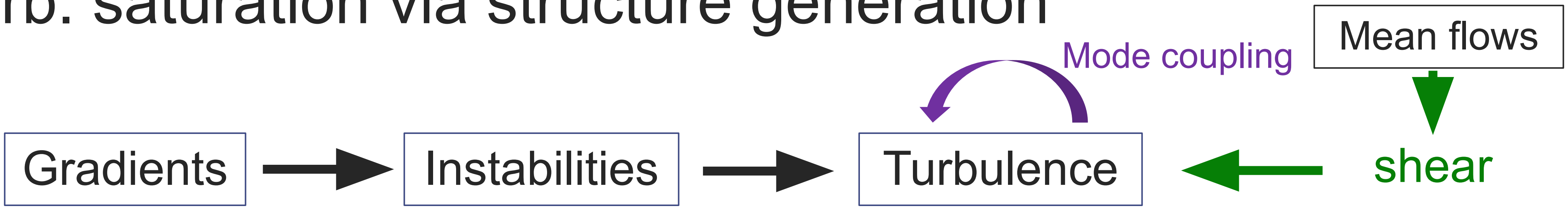
- Can lead to bifurcations (H-mode) → **transport barriers** [Wagner 82]

E_r well



[Schirmer 06]

③ Turb. saturation via structure generation



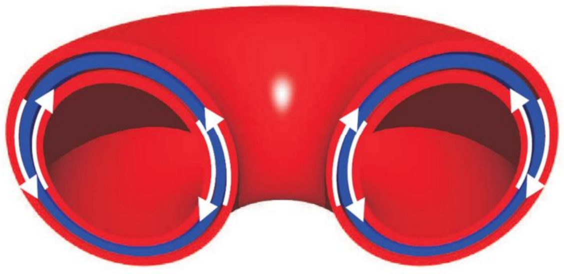
☞ **Zonal flows (ZFs)** [Hasegawa 79; Diamond 05]

- Constant on magnetic surfaces
- Excited nonlinearly by turbulence: **Reynolds stress** Π_{tot}

  Electric: $\Pi_E = \langle \tilde{v}_{Er}\, \tilde{v}_{E\theta} \rangle$ [Diamond 91]

  Diamagnetic: $\Pi_\star = \langle \tilde{v}_{\star r}\, \tilde{v}_{E\theta} \rangle$ [Smolyakov 00; Sarazin 21]
- Linearly stable: damped by **collisional friction** μ

Zonal flows



$V_{ZF} = -\langle E_r \rangle / B$

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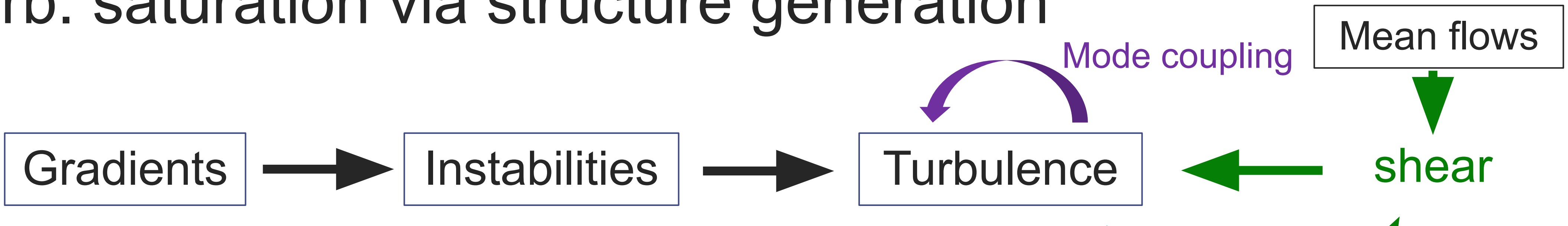

Mean flows

Mode coupling

Gradients → Instabilities → Turbulence ← shear

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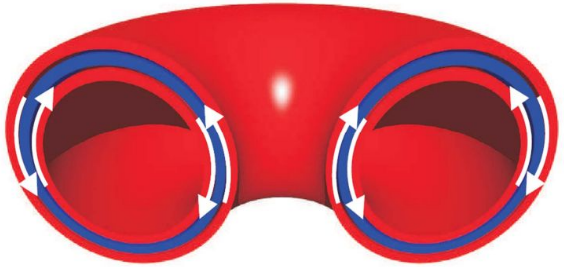
Zonal flows

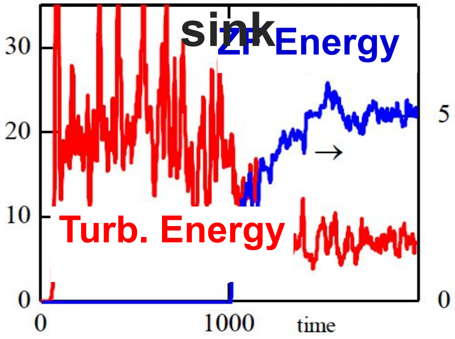


$V_{ZF} = -\langle E_r \rangle / B$

Radial structure

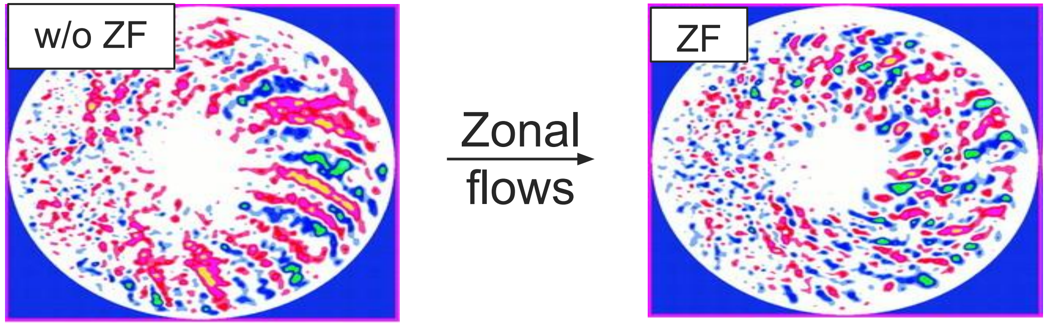
Staircases

Energy sink



[Beyer 04]

Shear turbulent eddies



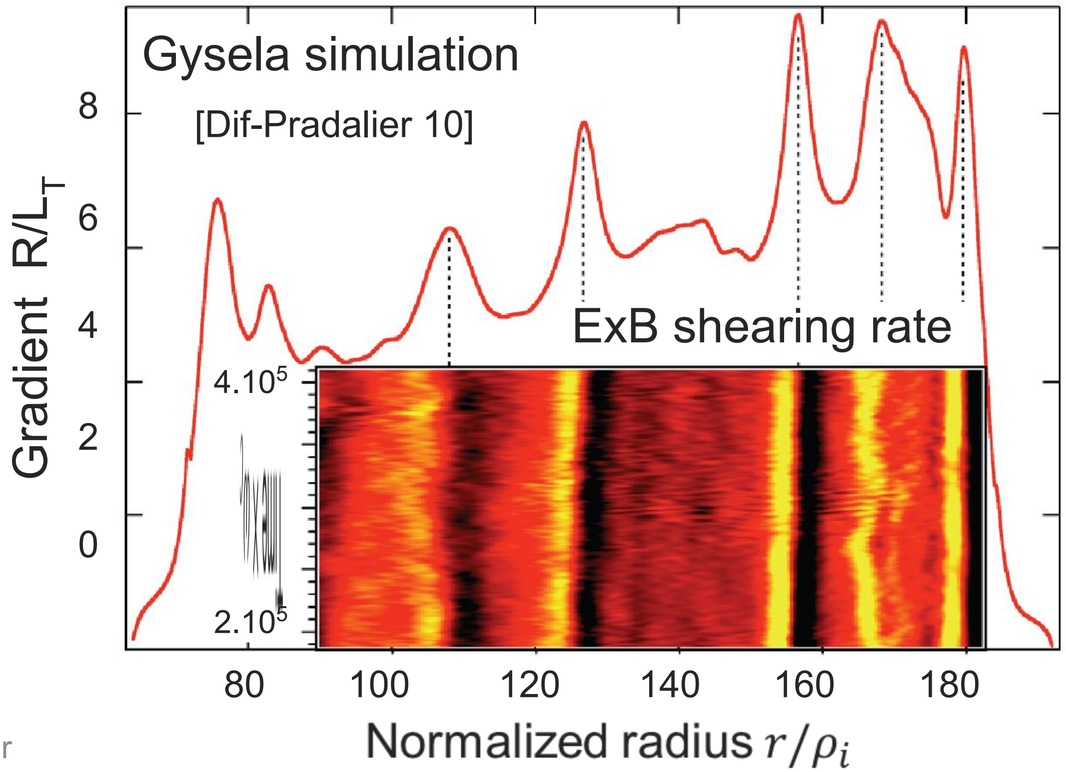
Elec. Potential fluctuations $\tilde{\phi}$ [Lin 98]

③ Turb. saturation via structure generation

☞ **Staircases:** radially localized sheared flows & corrugated pressure gradient

- Set of **microbarriers** → expected beneficial for confinement
- Well-established in **simulations**: first principle & reduced models [Dif-Pradalier 10, 15, 17]

E_r shear & temperature gradient



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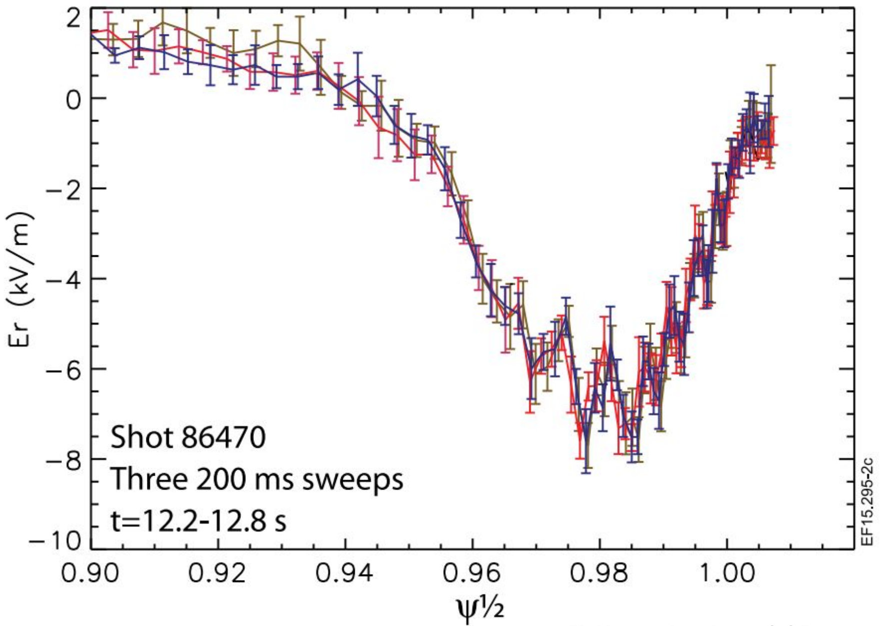
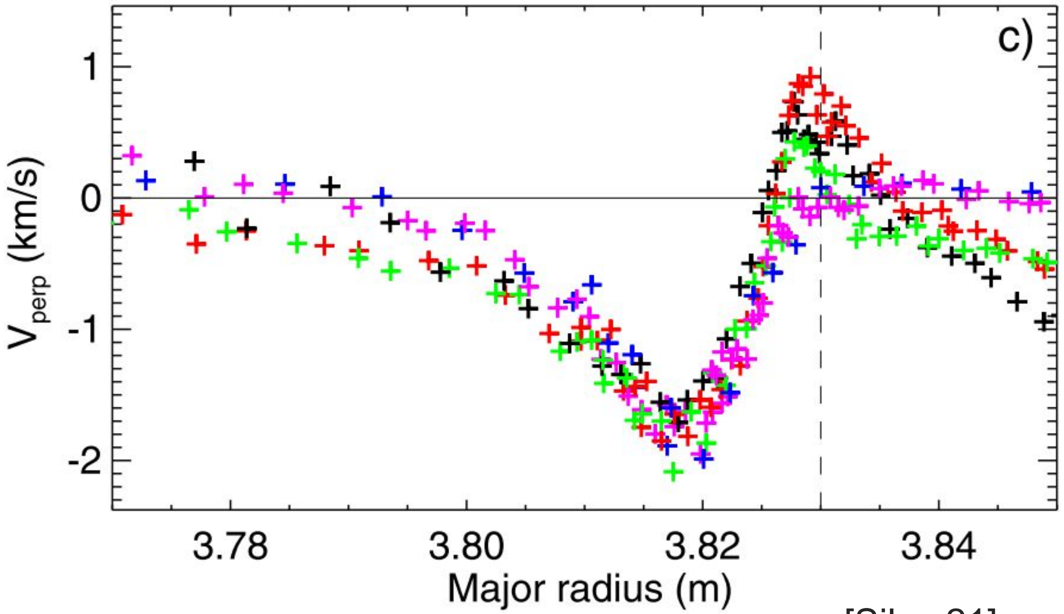
- **Difficult direct experimental characterization in tokamaks** [Hornung 16]

JET E_r with staircases



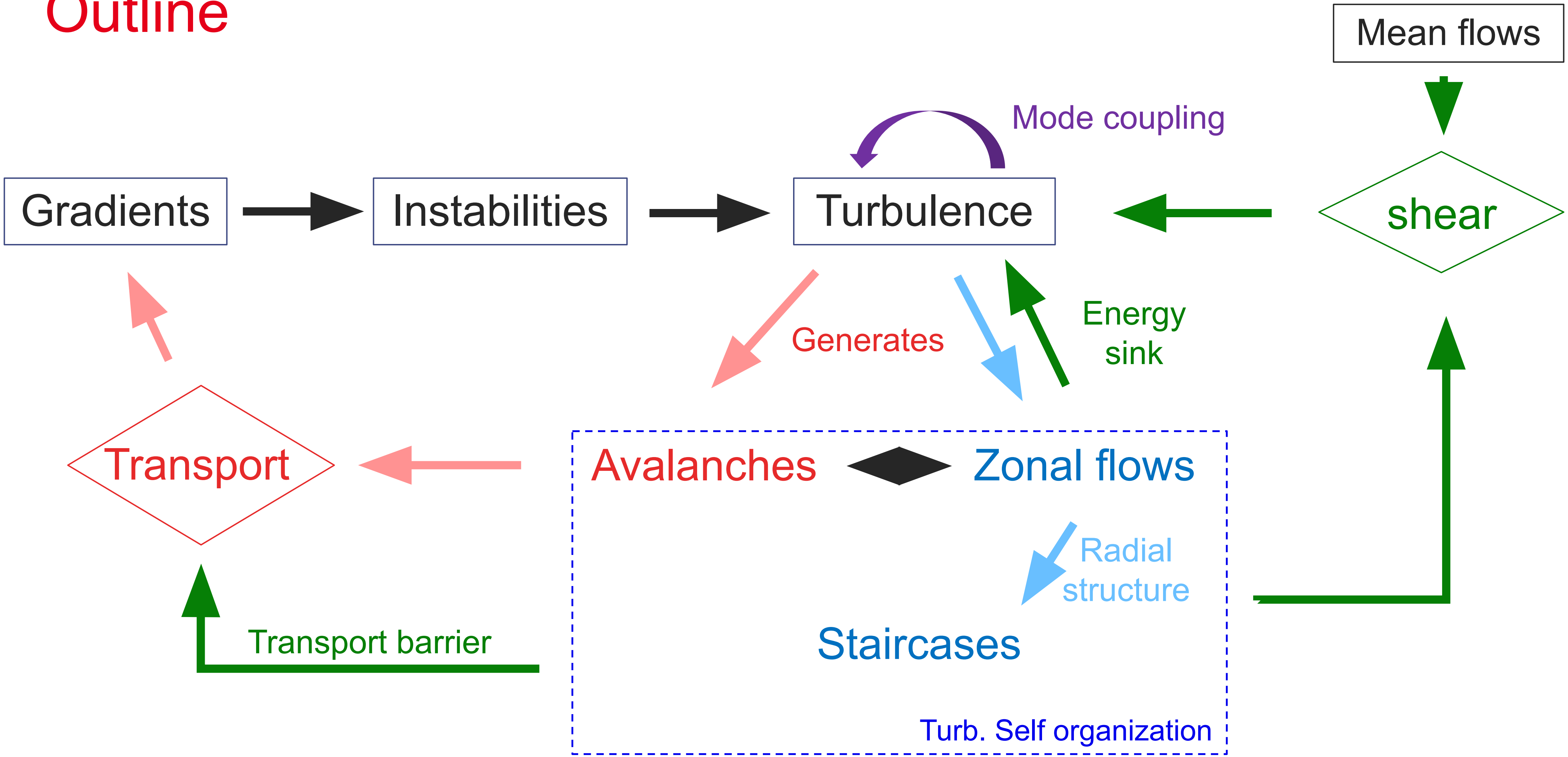
[Hillesheim 16]

JET E_r without staircases



[Silva 21]

Outline


Mean flows

Mode coupling

Gradients

Instabilities

Turbulence

shear

Generates

Energy sink

Transport

Avalanches

Zonal flows

Radial structure

Staircases

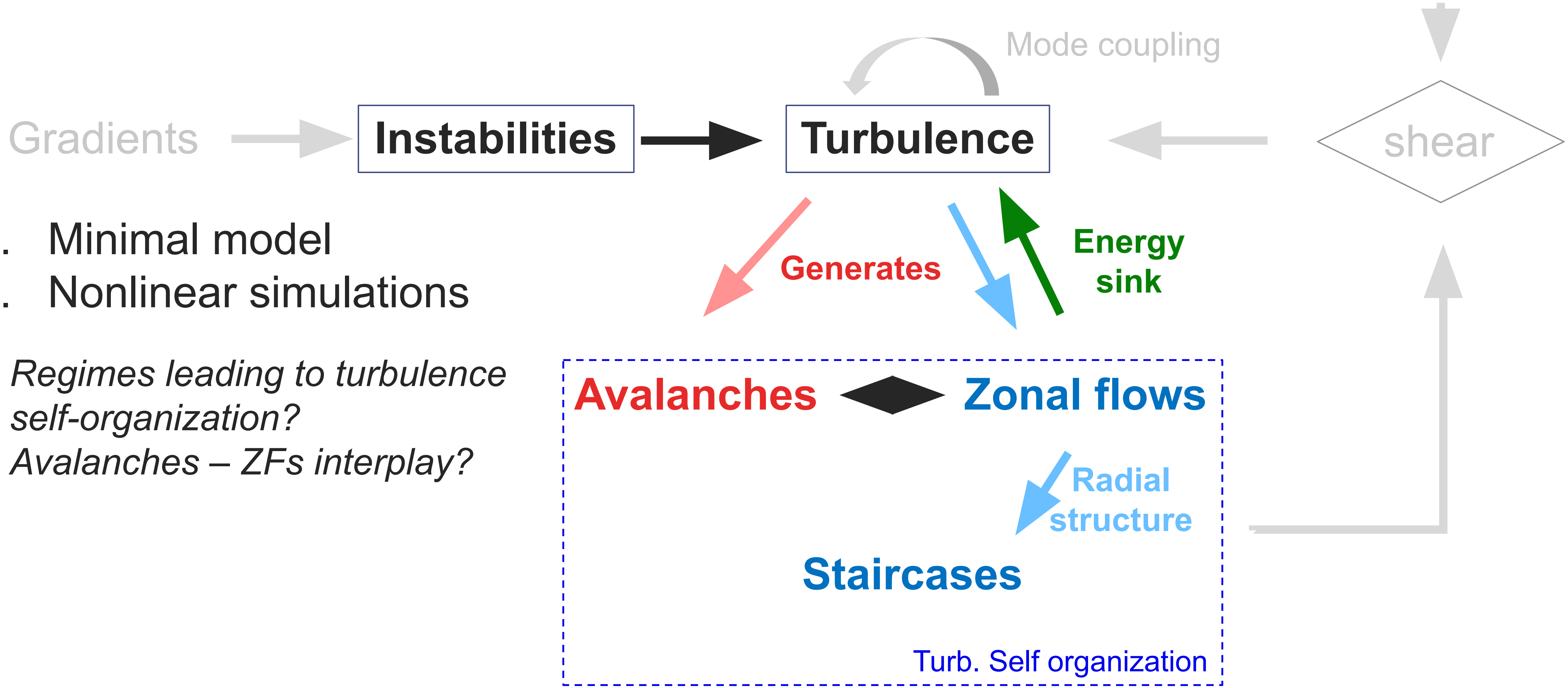
Transport barrier

Turb. Self organization

Outline

I. Minimal model
II. Nonlinear simulations

- *Regimes leading to turbulence self-organization?*
- *Avalanches – ZFs interplay?*



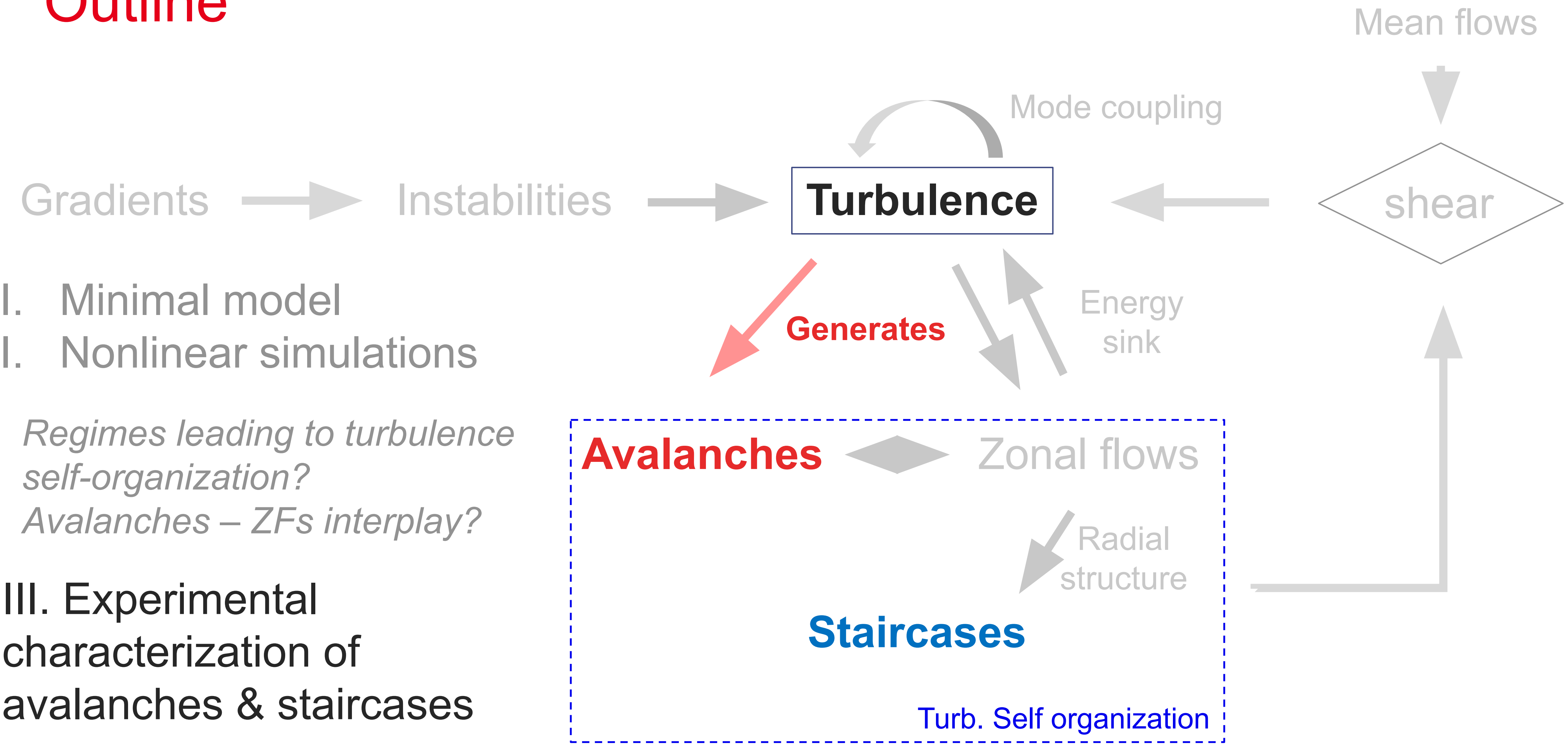
Outline

I. Minimal model

II. Nonlinear simulations

- *Regimes leading to turbulence self-organization?*
- *Avalanches – ZFs interplay?*

III. Experimental characterization of avalanches & staircases



Mean flows

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Turb. Self organization

I. Minimal model for turbulence self-organization

☞ Necessary features

[Scott 05; Bonanomi 19; Ghendrih 22]

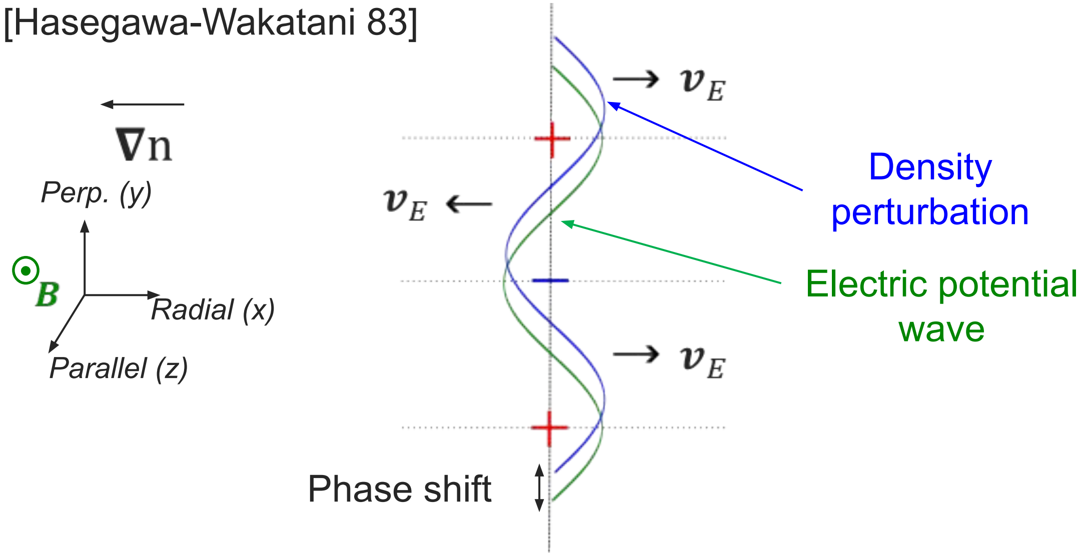
- Several intrinsic instabilities relevant in edge plasmas
- No scale separation → free evolution of profiles & fluctuations
- Self-generation of flows → both electric Π_E & diamagnetic $\Pi_\star$

Collisional drift waves (CDW)

Plasma **parallel conductivity**

Unstable due to phase shift between density & electric pot. fluctuations

[Hasegawa-Wakatani 83]

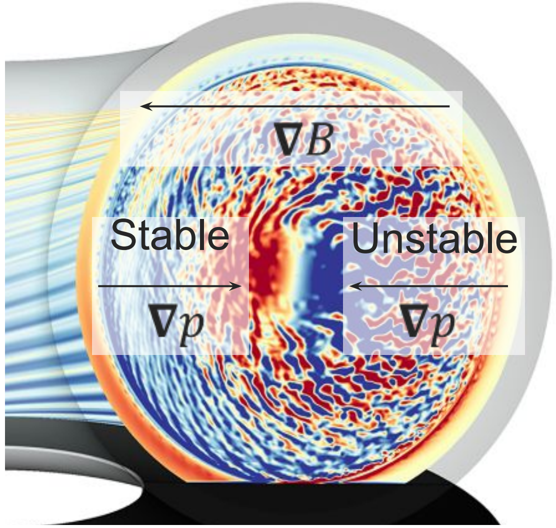


Interchange

Magnetic field **curvature**

~ Rayleigh-Bénard

Unstable where $\nabla p \cdot \nabla B > 0$



I. Minimal model for turbulence self-organization

☞ **Fluid** model with **isothermal** closure $\tau = T_i/T_e$

Electron conservation

$$\partial_t n + \boldsymbol{v}_E \cdot \boldsymbol{\nabla}\mathrm{n} + \mathrm{n}\boldsymbol{\nabla} \cdot \boldsymbol{v}_E + \boldsymbol{\nabla} \cdot (n\, \boldsymbol{v}_{\star e}) - \nabla_\parallel \left(\frac{j_\parallel}{e}\right) = S_n$$

Charge conservation

$$\boldsymbol{\nabla}_\perp \cdot \boldsymbol{j}_\star + \boldsymbol{\nabla}_\perp \cdot \boldsymbol{j}_{pol} + \nabla_\parallel j_\parallel = 0$$

Ohm's law

$$j_\parallel = \frac{enT_e}{m_e \nu_{ei}} \nabla_\parallel \left(\ln \frac{n}{n_0} - \frac{e\phi}{T_e} \right)$$

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Electron conservation

Compressibility terms

$$\partial_t n + \boldsymbol{v}_E \cdot \nabla \mathrm{n} + \mathrm{n}\nabla \cdot \boldsymbol{v}_E + \nabla \cdot (n\, \boldsymbol{v}_{\star e}) - \nabla_\parallel \left(\frac{j_\parallel}{e}\right) = S_n$$

Flux driven

Charge conservation

$$\nabla_\perp \cdot \boldsymbol{j}_\star + \nabla_\perp \cdot \boldsymbol{j}_{pol} + \nabla_\parallel j_\parallel = 0$$

↓

Polarisation current: $\boldsymbol{j}_{pol} = \dfrac{enm_i}{eB^2}\left[\partial_t + \boldsymbol{v}_E \cdot \nabla\right]\left(\nabla_\perp \phi + \dfrac{\tau T_e}{e}\dfrac{\nabla_\perp n}{n}\right)$

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Parallel conductivity $\sigma \propto 1/\nu_{ei}$

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☞ 3d model → **density** $N = \ln \hat{n}$ & **general vorticity** $\Omega = \nabla_\perp^2(\hat{\phi} + \tau N)$

$$\partial_t N + \{\hat{\phi}, N\} - \mathcal{G}[\hat{\phi} - N] = \sigma\, \nabla_\parallel^2 (N - \hat{\phi}) + D\, \nabla_\perp^2 N + S_n$$

$$\partial_t \Omega + (1+\tau)\mathcal{G}[N] + \nabla_{\perp,i} \{\hat{\phi}, \nabla_{\perp,i}\, (\hat{\phi} + \tau N)\} = \sigma\, \nabla_\parallel^2 (N - \hat{\phi}) + \nu \nabla_\perp^2 \Omega$$

Curvature operator

Parallel conductivity

Dimensionless fields

$$\hat{\phi} = \frac{e\phi}{T_e} \qquad \hat{n} = \frac{n}{n_0}$$

$$t = \omega_{ci}\, \hat{t} \qquad x = \hat{x}/\rho_s$$

Definitions

$$\omega_{ci} = \frac{eB}{m_i} \qquad \rho_s = \frac{\sqrt{m_i T_e}}{eB}$$

$$\{\phi, N\} = \partial_x \phi \partial_y N - \partial_y \phi \partial_x N$$

I. Minimal model for turbulence self-organization

☞ Reduction to 1D (x,t) by selecting single $(k_y, k_\parallel)$ for fluctuations

$$N = N_{eq} + \tilde{N}$$

Flux-surface avg $\in \mathbb{R}$

Fluctuations

$$\tilde{N} = N_k e^{i\,(k_y y + k_\parallel z)} + c.c$$

- No turbulent cascades
- Mode coupling through equilibrium fields interactions

☞ **Tokam1D** [Panico JPP 2025 (a)]

$$\partial_t N_{eq} = -\partial_x \Gamma_{turb} + D\,\partial_x^2 N_{eq} + S_N$$

Particle source

Turbulent flux: $\Gamma_{turb} = -2\,k_y |N_k||\phi_k| \sin \Delta\varphi$

Fluctuations amplitude

Density – electric potential fluctuations cross phase

$$\partial_t V_{eq} = -\partial_x \Pi_{tot} + \nu \partial_x^2 V_{eq} - \mu V_{eq}$$

Constant viscosity & friction coefficient

Reynolds stress: $\Pi_{tot} = \Pi_E + \Pi_*$

Electric

$$\Pi_E = -2k_y \Im(\phi_k^* \partial_x \phi_k)$$

Diamagnetic

$$\Pi_* = -2k_y \Im(\tau N_k^* \partial_x \phi_k)$$

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$$\partial_t V_{eq} = -\partial_x \Pi_{tot} + \nu \partial_x^2 V_{eq} - \mu V_{eq}$$

$$\partial_t N_k = \;... + i k_y g(\phi_k - N_k) + C(\phi_k - N_k) + D\,\nabla_\perp^2 N_k$$

$$\partial_t \Omega_k = \;... - i k_y g\,(1+\tau) N_k + C(\phi_k - N_k) + \nu \nabla_\perp^2 \Omega_k$$

$$V_{eq} = \partial_x \phi_{eq} = -\langle E_r \rangle$$
$$\Omega_k = (\partial_x^2 - k_y^2)(\phi_k + \tau N_k)$$

Interchange

Curvature parameter $g = \frac{2\rho_s}{R}$

CDW

Adiabatic param. $C = (k_\parallel \rho_s)^2 \sigma$

Ion to electron temperature ratio $\tau = T_i/T_e$

Particles source S_N

I. Minimal model for turbulence self-organization

☞ Re

☞ To

n only

$D\,\nabla_\perp^2 N_k$

$\nu\nabla_\perp^2\Omega_k$

aram.

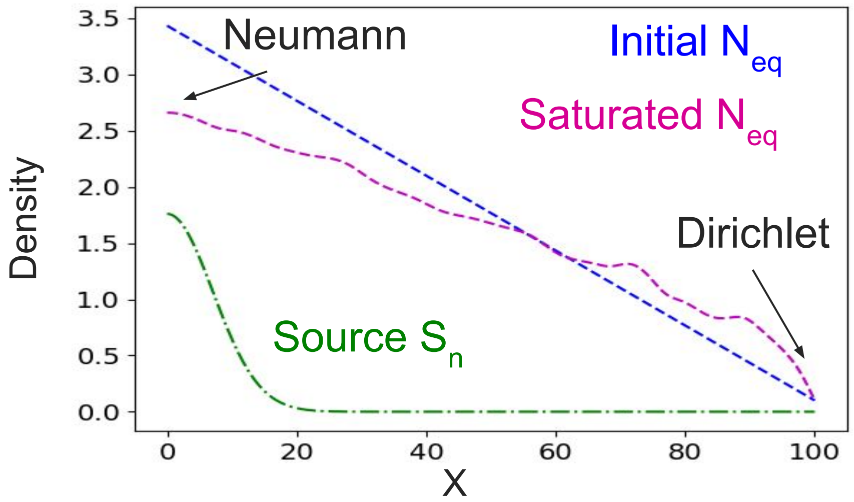
$^2\,\frac{\omega_{ce}}{\nu_{ei}}$

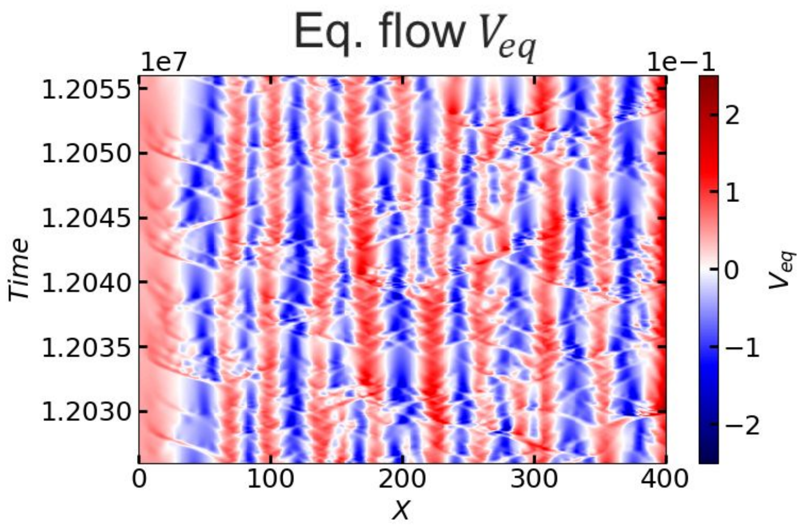
Numerics

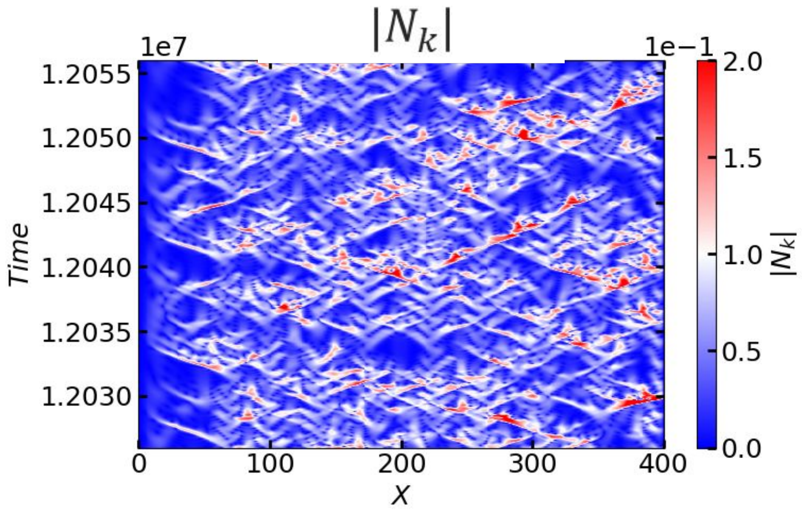
- Simulation on particle confinement time (~ 2 days)

$$\omega_{ci}\tau_p = \frac{\int N_{eq}dx}{\int S_n dx} > 10^6$$

- Resolve small turb. Scales:
  - $\omega_{ci}dt = 0.1$
  - $\rho_s^{-1}dx < 1$

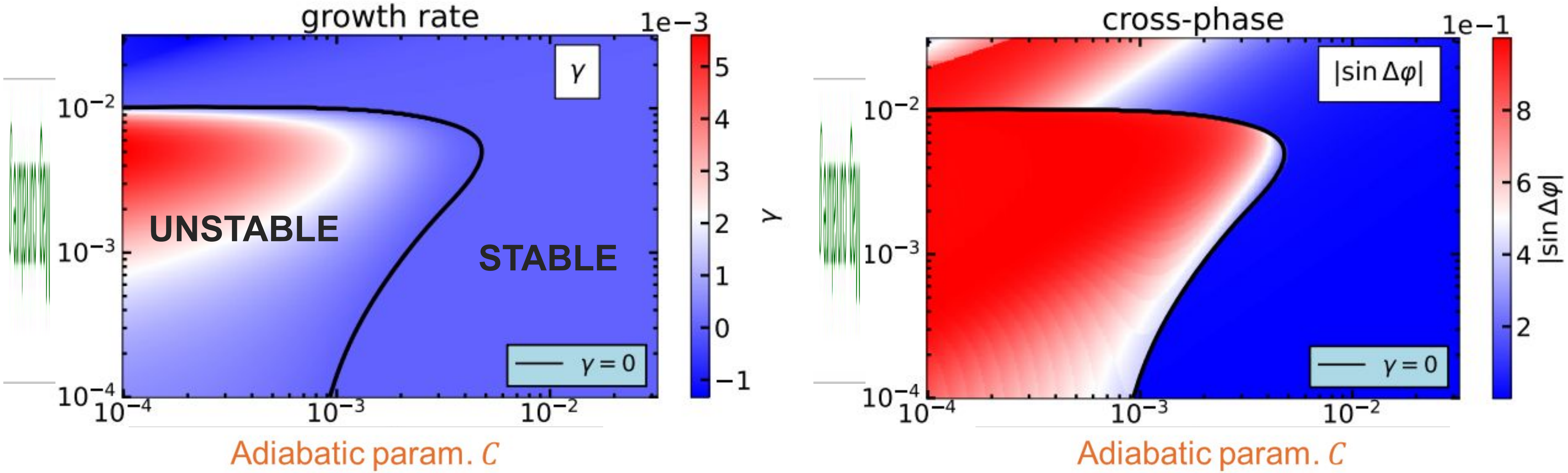






Characterization of the linear instabilities

- **Linear analysis**: dispersion relation at prescribed eq. parameters: $\partial_x N_{eq} = 1/100$; $D = \nu = 10^{-2}$
- Parameter dependencies:
  - Interchange → $g \sim T^{1/2}/RB$ [Sarazin 98]
  - Collisional drift waves → $C \sim (k_{\parallel}^2 T_e^{5/2})/nB$ [Hasegawa-Wakatani 83]



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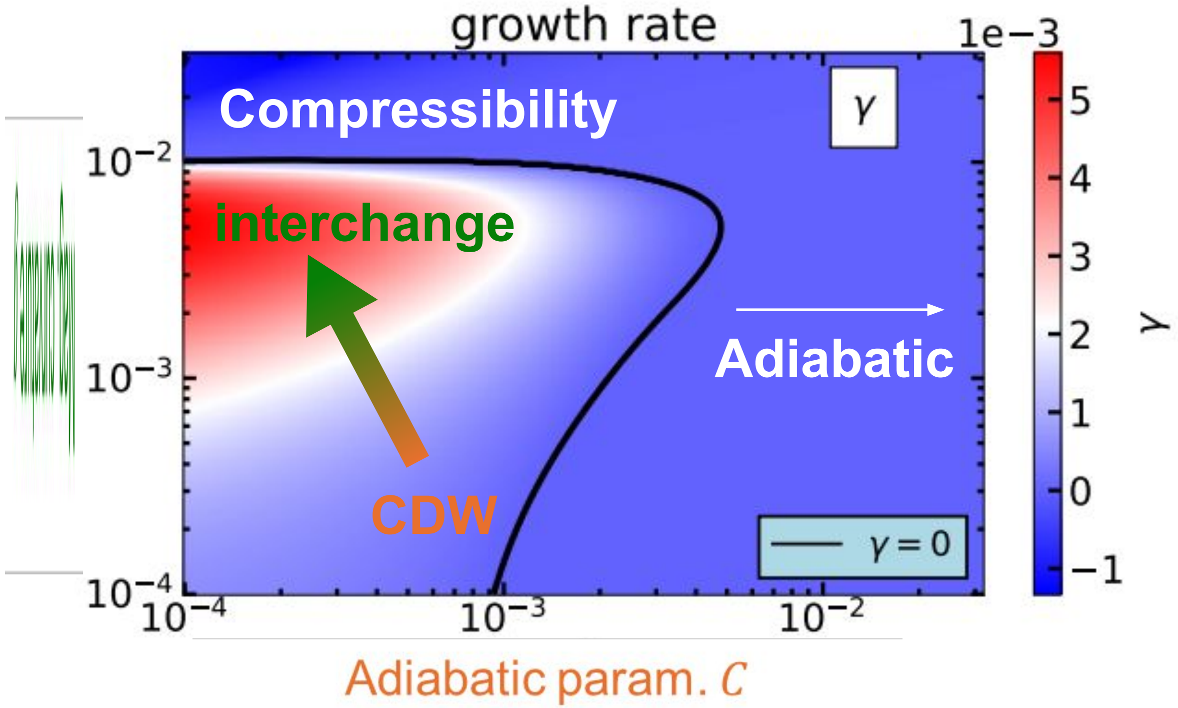
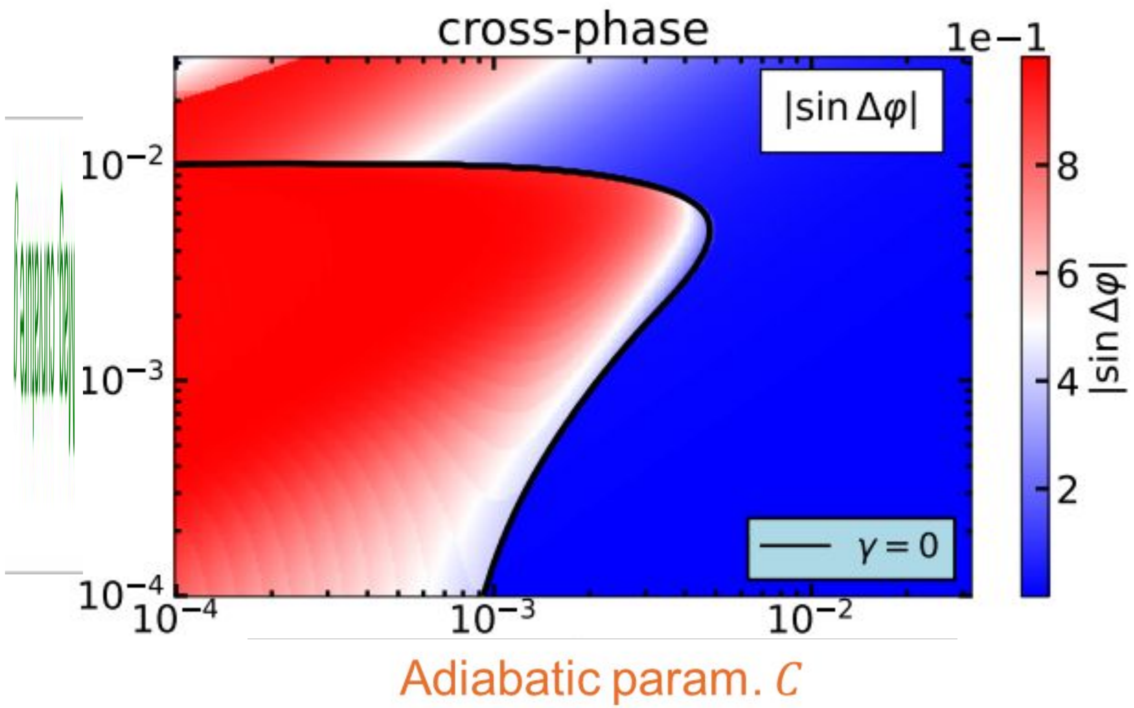
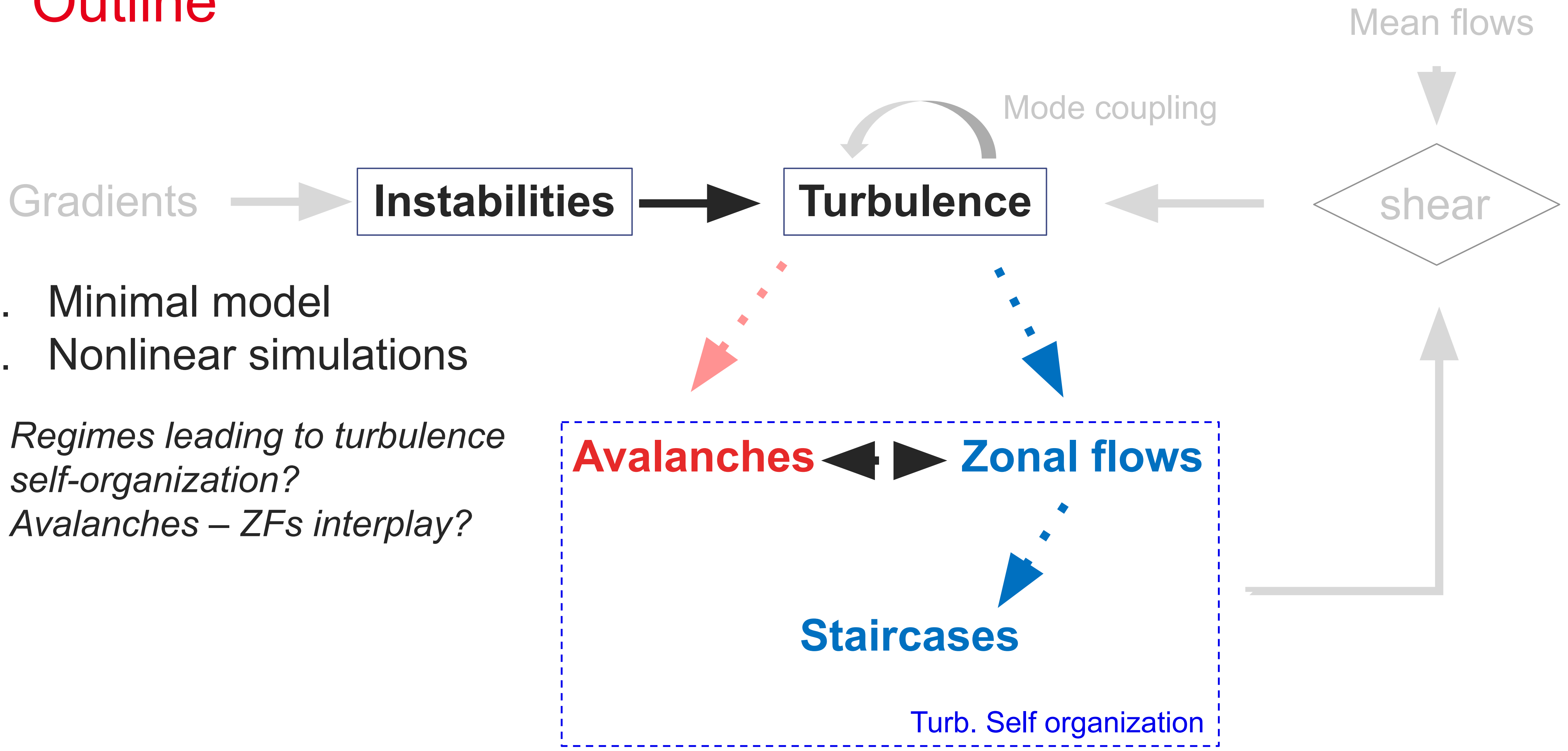




- Interchange → large growth rate & cross-phase
- Stabilisation → compressibility ($\nabla \cdot v_E$ & $\nabla \cdot (n v_\star)$) & adiabatic

Outline



I. Minimal model
II. Nonlinear simulations

- *Regimes leading to turbulence self-organization?*
- *Avalanches – ZFs interplay?*

II. Nonlinear simulations: explore ≠ turbulence regimes

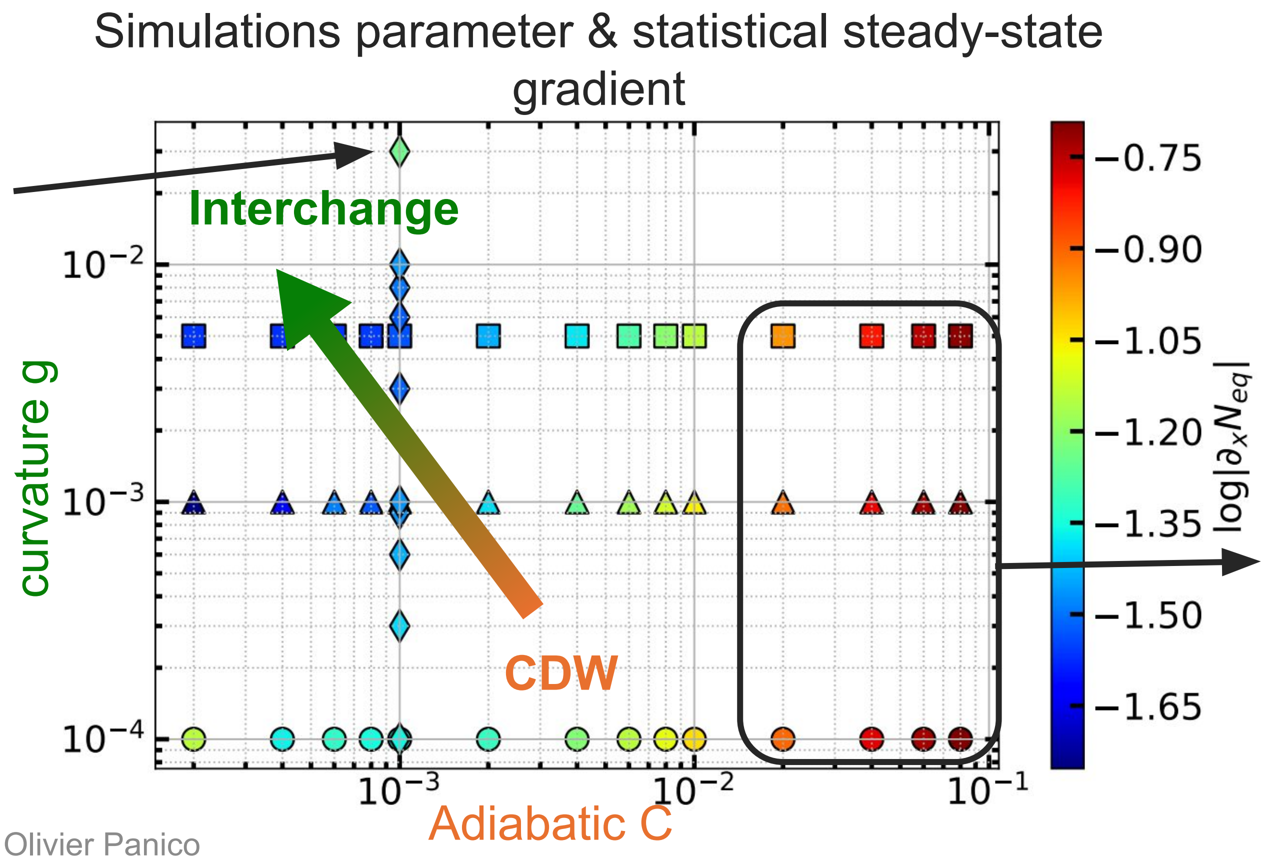
- Total of **120 simulations** on confinement times τ_p
- **Constant source** & diffusion coefficients
- Typical values of parameters for TCV →

$$g \sim T^{1/2}/RB \sim 10^{-3}$$

$$C \sim \ (k_\parallel^2 T_e^{5/2})/nB \ \sim 10^{-2} - 10^{-3}$$

[Panico JPP 2025 (b)]

Stabilisation at large g: **compressibility**



Stabilisation at large C: **adiabatic regime**

Flux-driven formulation crucial to ZF generation

☞ Turbulence flow partition:

Gradients

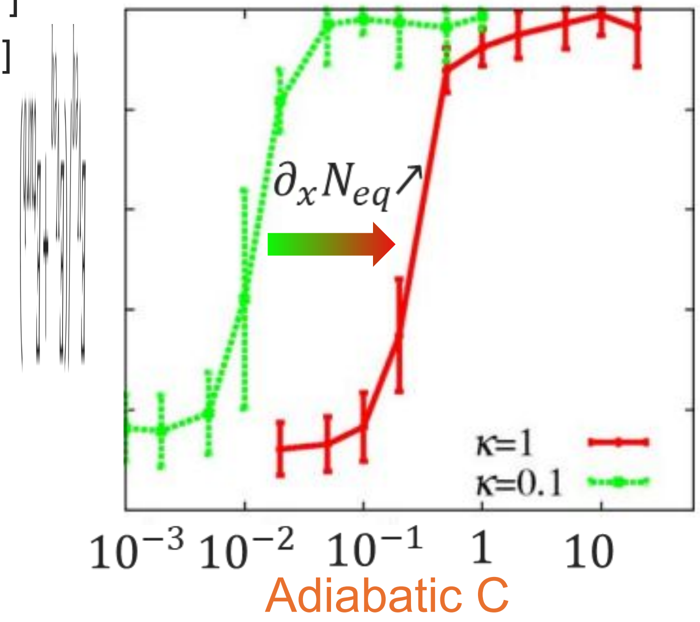
Turbulence E_{turb}

Zonal flows $E_{V_{eq}} = |V_{eq}|^2$

Drift waves only $(g = 0)$

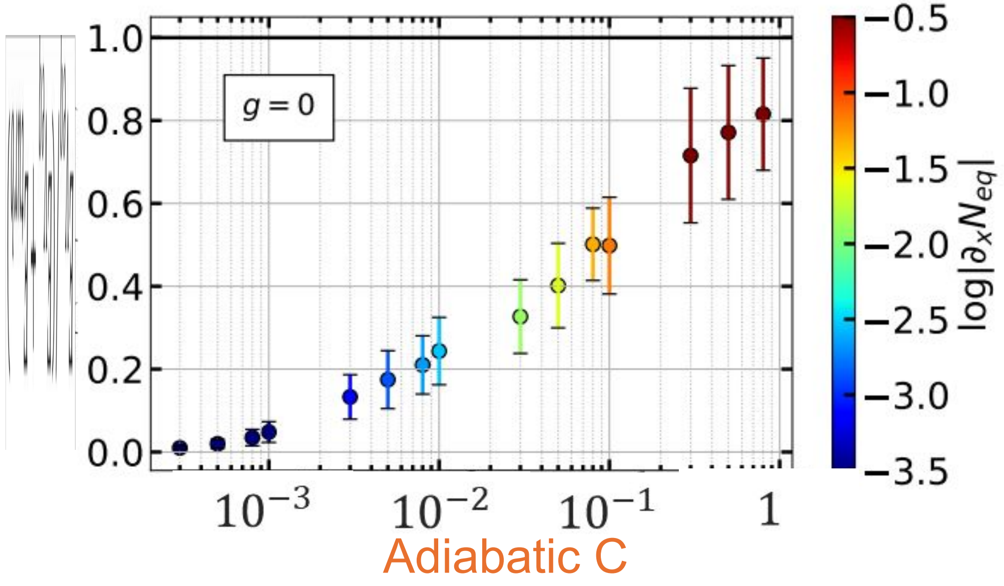
[Numata 07]
[Guillon 24]

Gradient driven



Flux driven

[Panico 24]



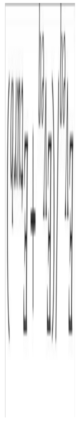
$C \propto \frac{1}{\nu_{ei}} \propto \frac{1}{N_{eq}} \rightarrow$ ZFs degraded at high density

No abrupt collapse of ZFs activity at low C in flux driven regime

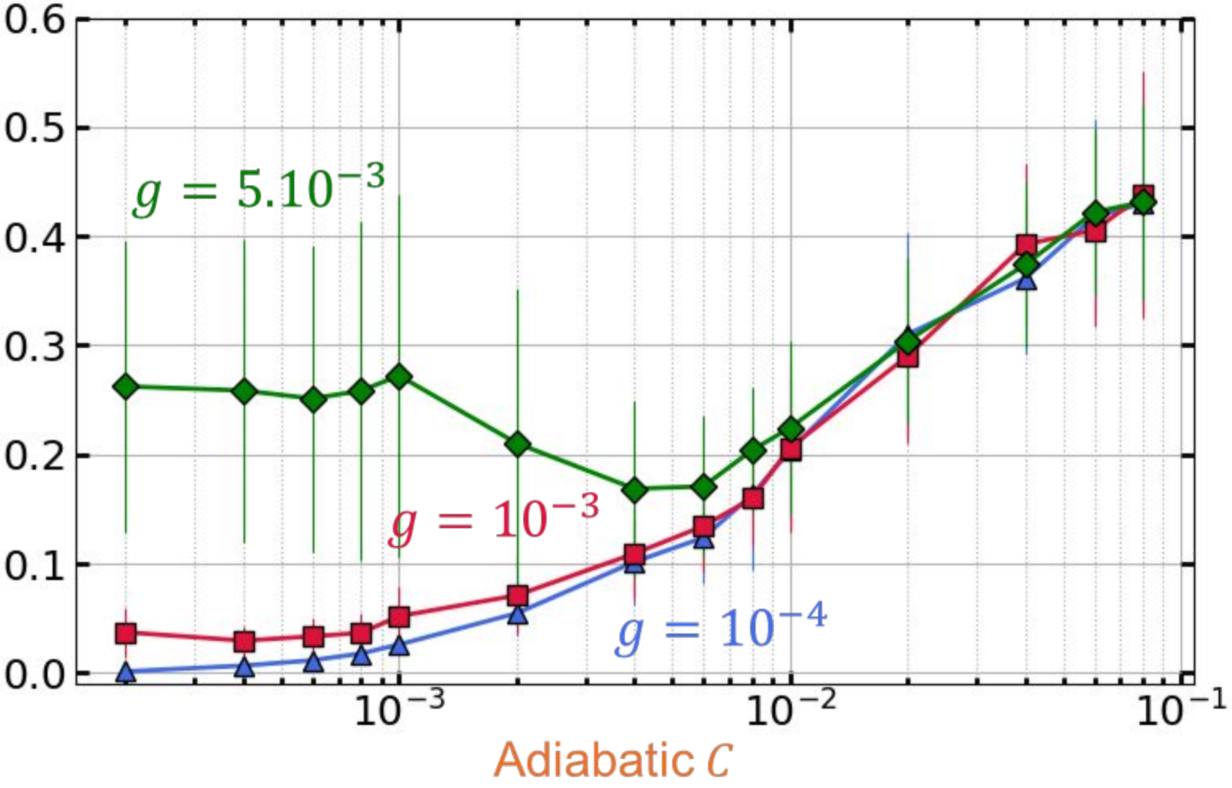
ZF also generated in interchange dominated turb.

☞ Turbulence flow partition:

Gradients → Turbulence E_{turb} ⇄ Zonal flows $E_{V_{eq}} = |V_{eq}|^2$



CDW-interchange turbulence



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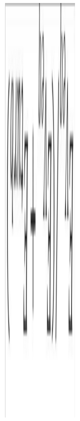
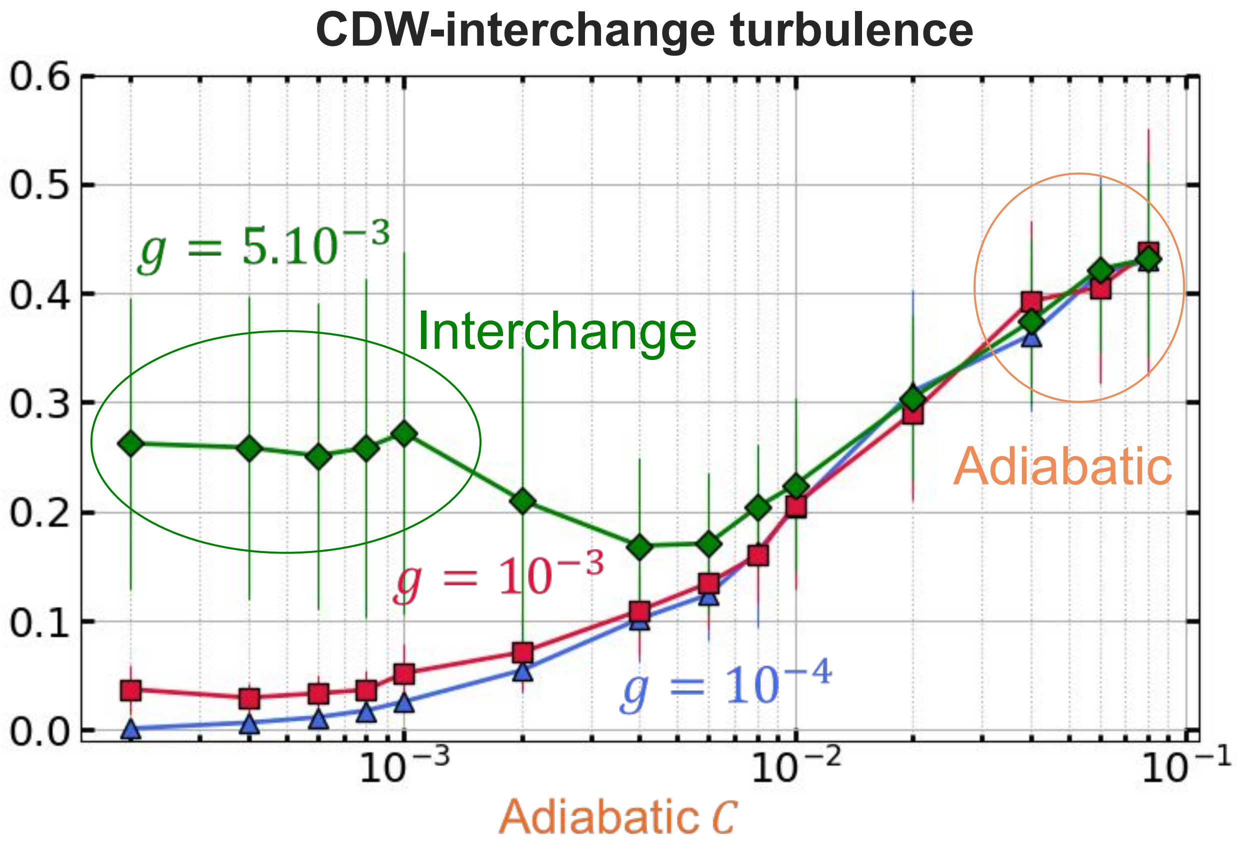
Zonal flows $E_{V_{eq}} = |V_{eq}|^2$



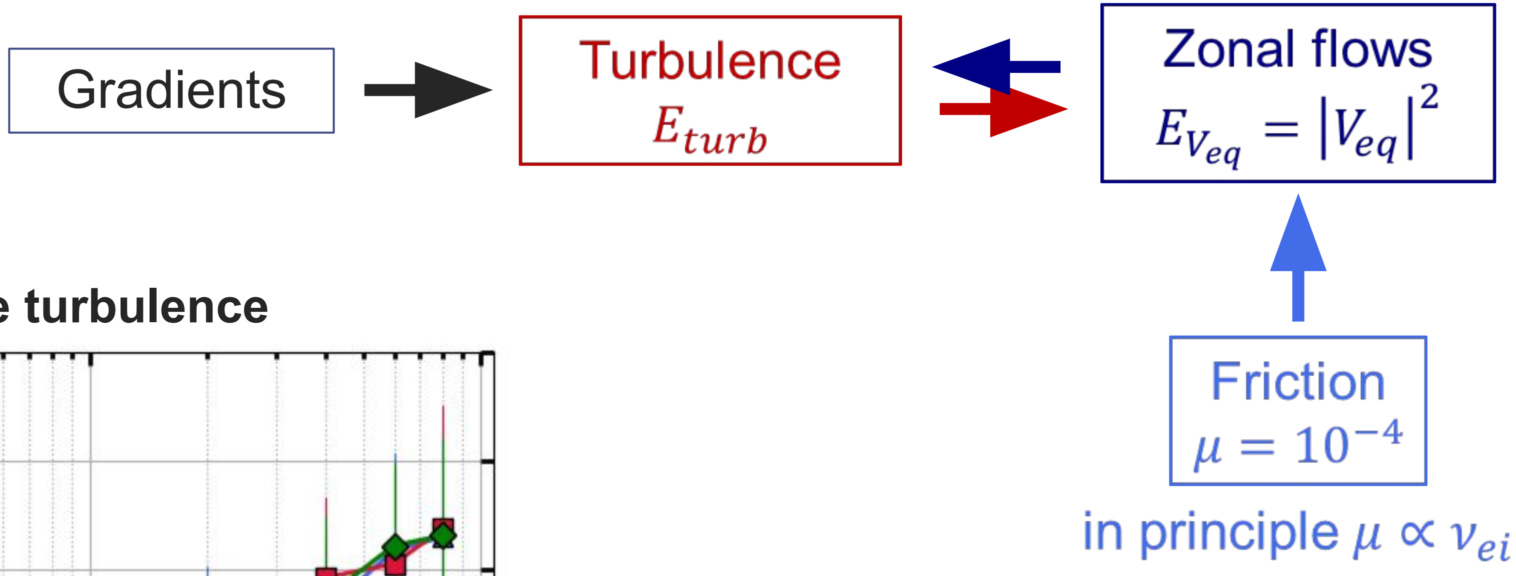


CDW-interchange turbulence

- 2 regimes with large flows: interchange & adiabatic

ZF also generated in interchange dominated turb.

☞ Turbulence flow partition:



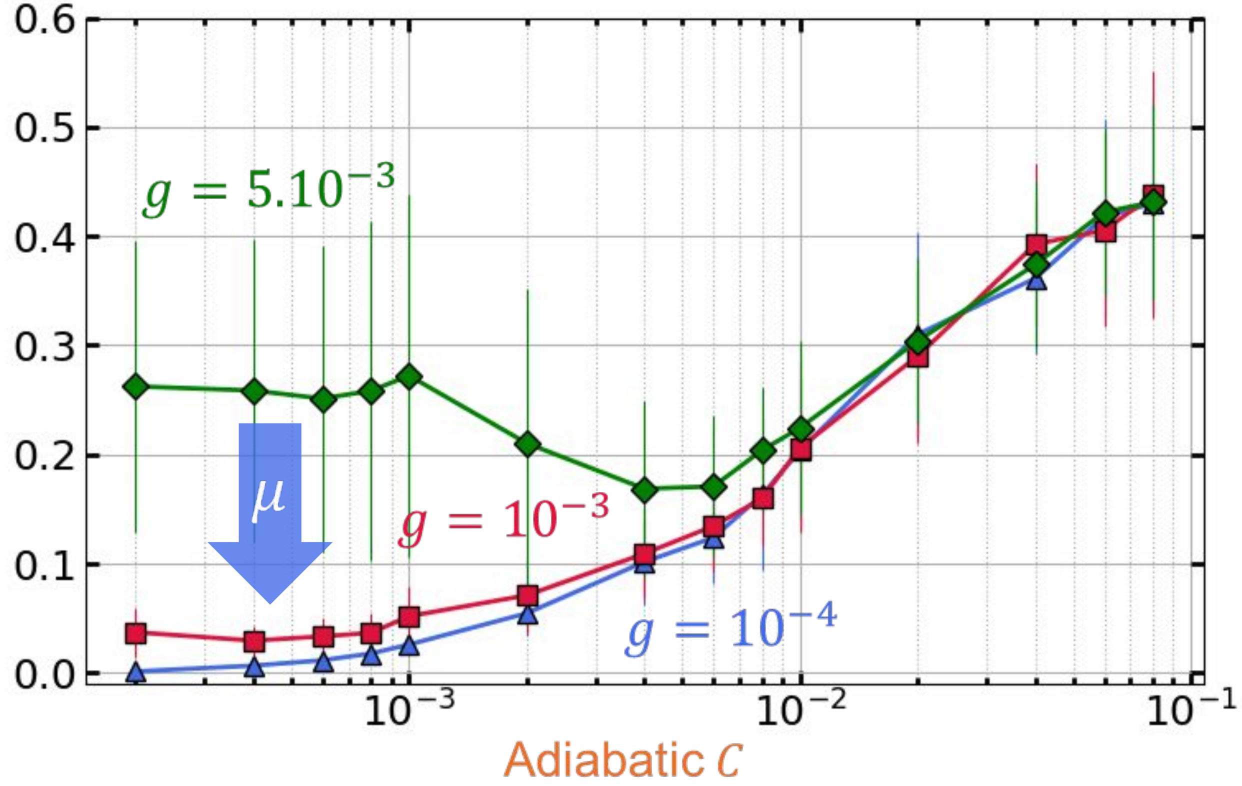
Gradients

Turbulence E_{turb}

Zonal flows $E_{V_{eq}} = |V_{eq}|^2$

Friction $\mu = 10^{-4}$

in principle $\mu \propto \nu_{ei}$


CDW-interchange turbulence

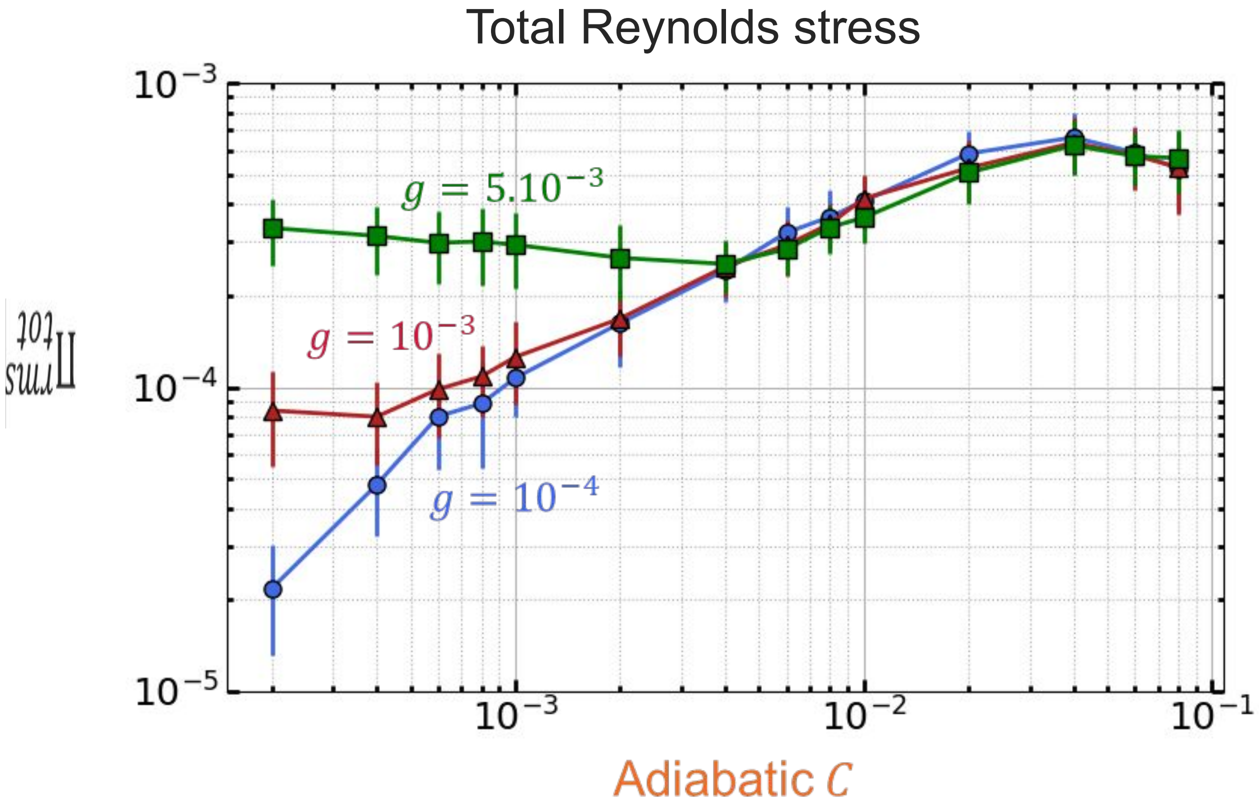
- 2 regimes with large flows: interchange & adiabatic
- Large N_{eq} → low C & large μ

$$\partial_t V_{eq} = -\partial_x \Pi_{tot} + \nu \partial_x^2 V_{eq} - \mu V_{eq}$$

Both Π_E & $\Pi_\star$ essential depending on turb. regime

☞ 2 regimes of large total Reynolds stress: interchange & adiabatic

$$\Pi_{tot} = \Pi_E + \Pi_*$$



Both Π_E & $\Pi_\star$ essential depending on turb. regime

☞ 2 regimes of large total Reynolds stress: interchange & adiabatic

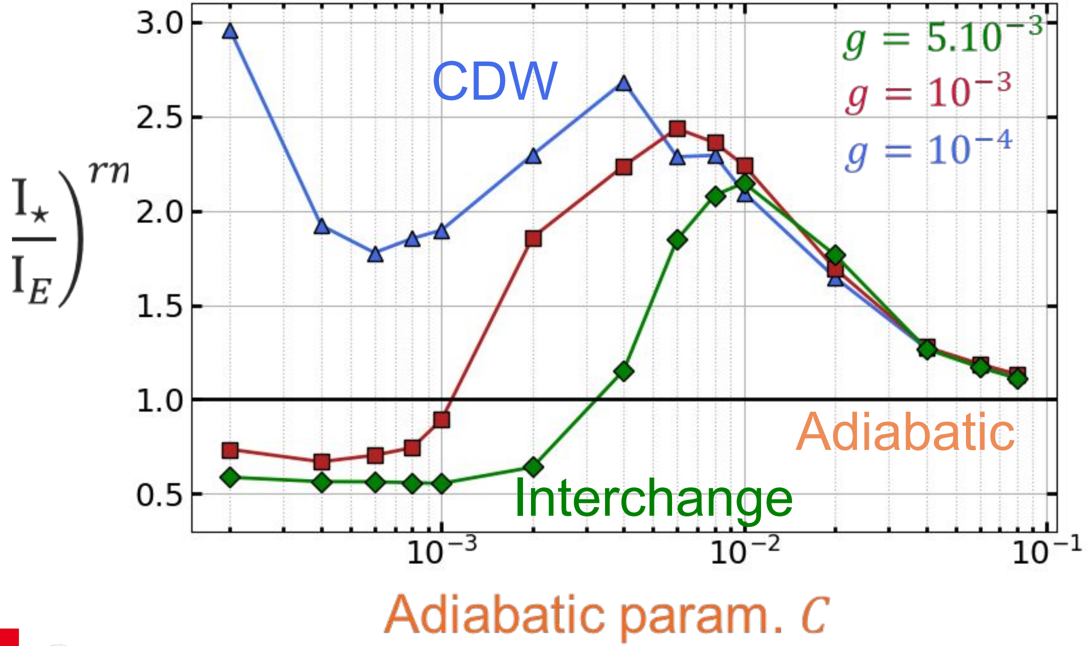
$$\Pi_{tot} = \Pi_E + \Pi_\star$$

$$\Pi_\star = \tau \left[\Pi_E \frac{|N_k|}{|\phi_k|} \cos \Delta\varphi + \Gamma_{turb} \partial_x (\log |\phi_k|) \right]$$

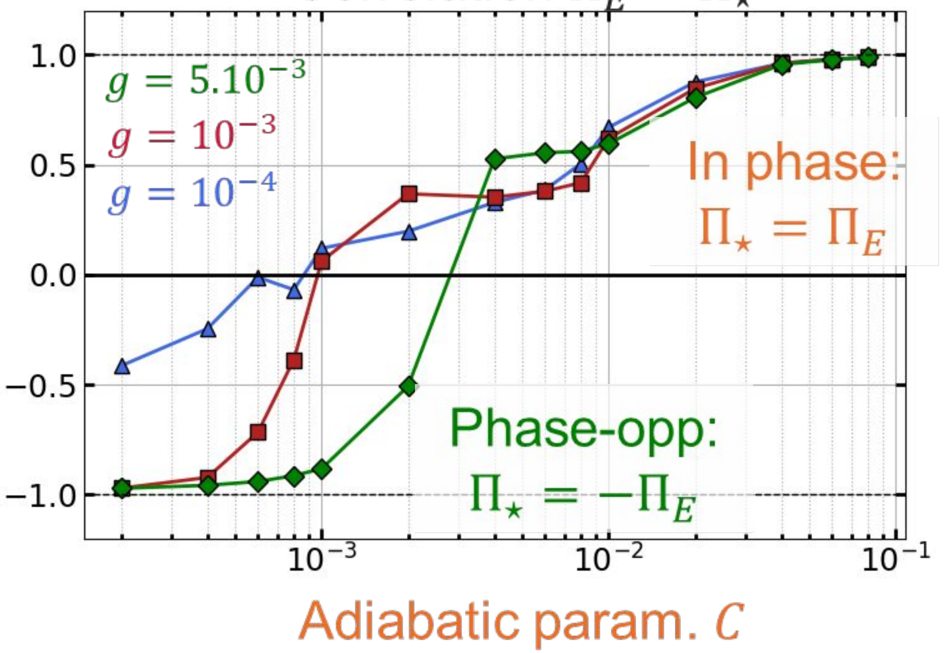
- $\Pi_E > \Pi_\star$ in interchange ($|\phi_k| \gg |N_k|$)
- $\Pi_\star$ in CDW ($|N_k| \gg |\phi_k|$)

- Phase opposition at low C
- In phase in adiabatic regime

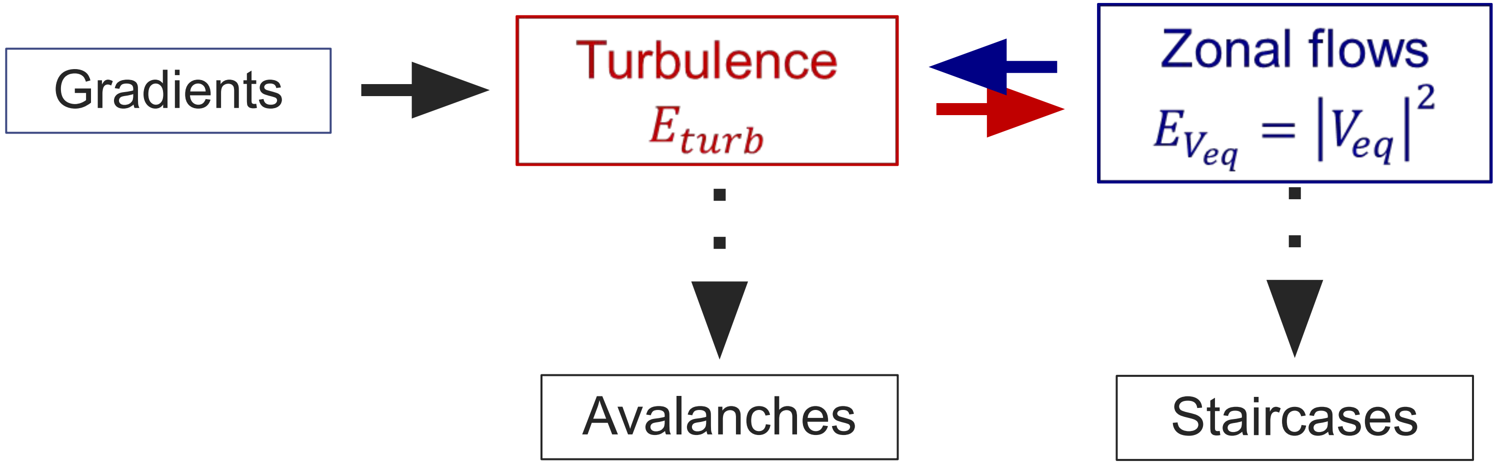
Relative amplitude



Correlation $\Pi_E - \Pi_\star$



Turbulence regimes leading to self-organization



Gradients

Turbulence

E_{turb}

Zonal flows

$E_{V_{eq}} = |V_{eq}|^2$

Avalanches

Staircases

Interchange

- Large flows
- $|\Pi_E| > |\Pi_\star|$ & phase opposition
- $|\phi_k| \gg |N_k|$

CDW

- Low / intermediate flows
- $|\Pi_\star| > |\Pi_E|$
- $|\phi_k| \gg |N_k|$

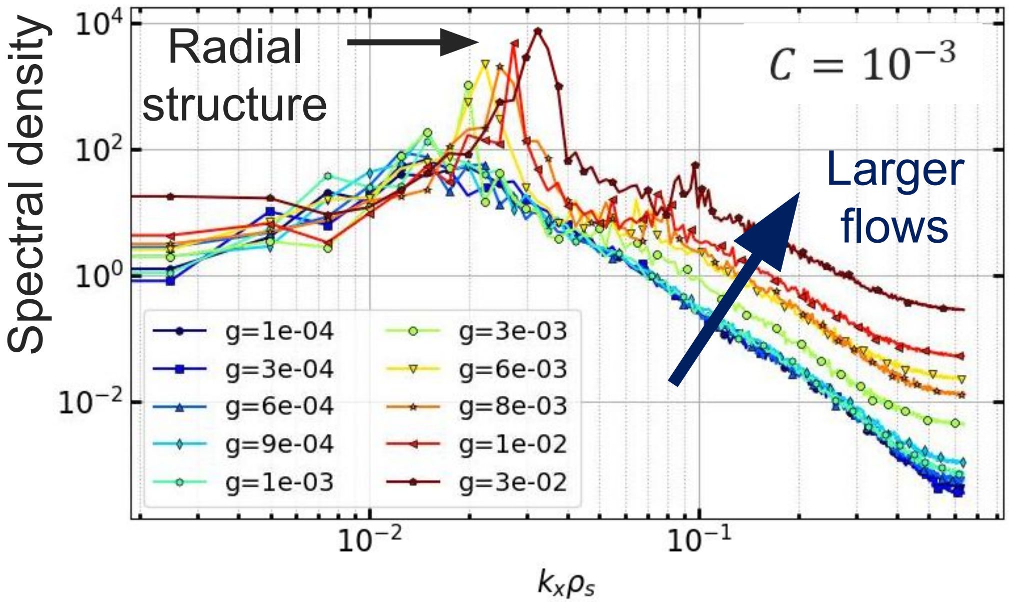
Adiabatic

- Large flows
- $\Pi_E \sim \Pi_\star$ & in phase
- $|\phi_k| \sim |N_k|$

ZFs structure into staircase in interchange

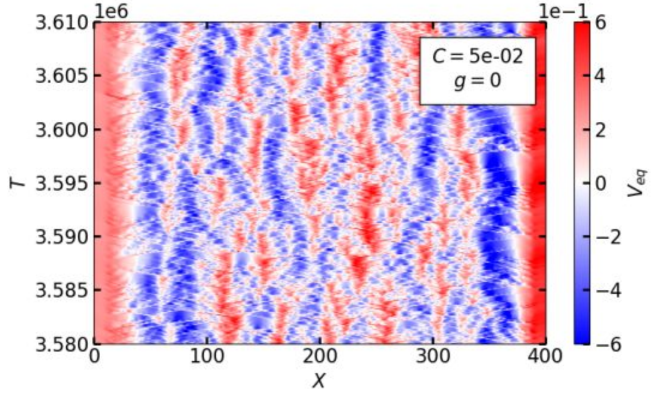
- Shear → second saturation mechanism induced by ZFs

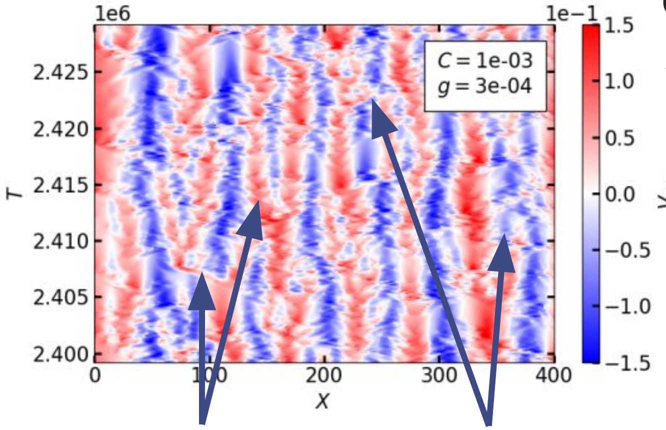
Radial Fourier transform of V_{eq}



ZFs structure into staircase in interchange

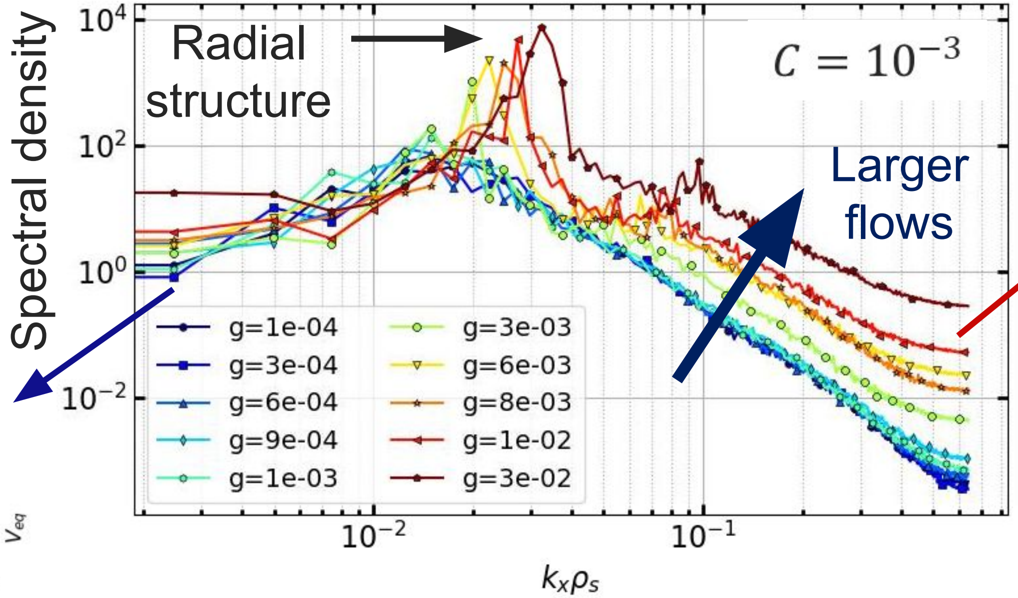
- Shear → second saturation mechanism induced by ZFs

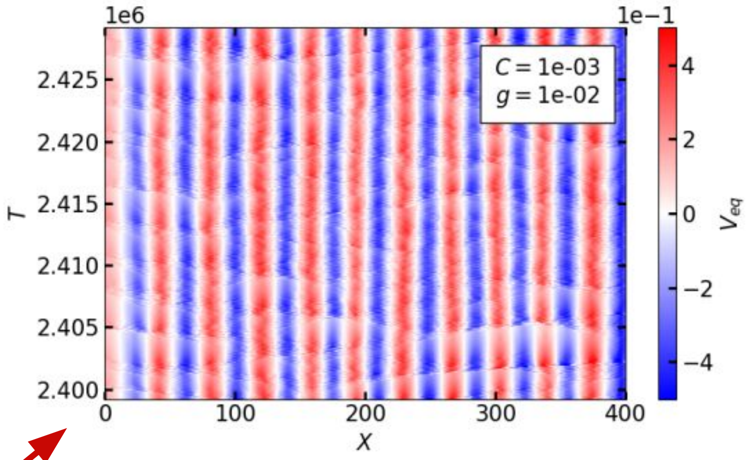




Splitting Merging

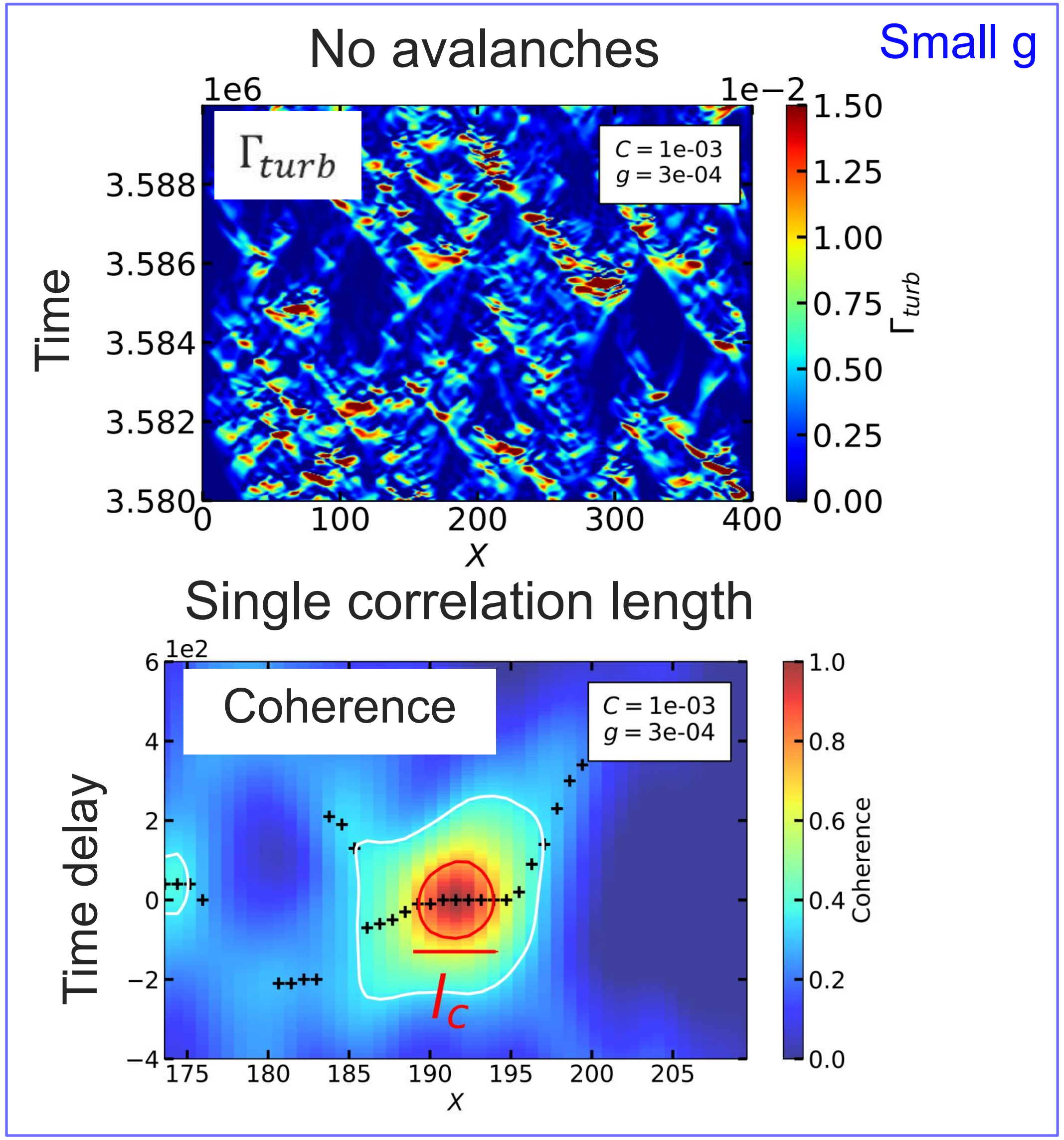
Radial Fourier transform of V_{eq}





- Challenging for experiments
- Interchange → radially structured zonal flows → staircases
- (not shown) distance to threshold also matters → more flows energy & radial structure

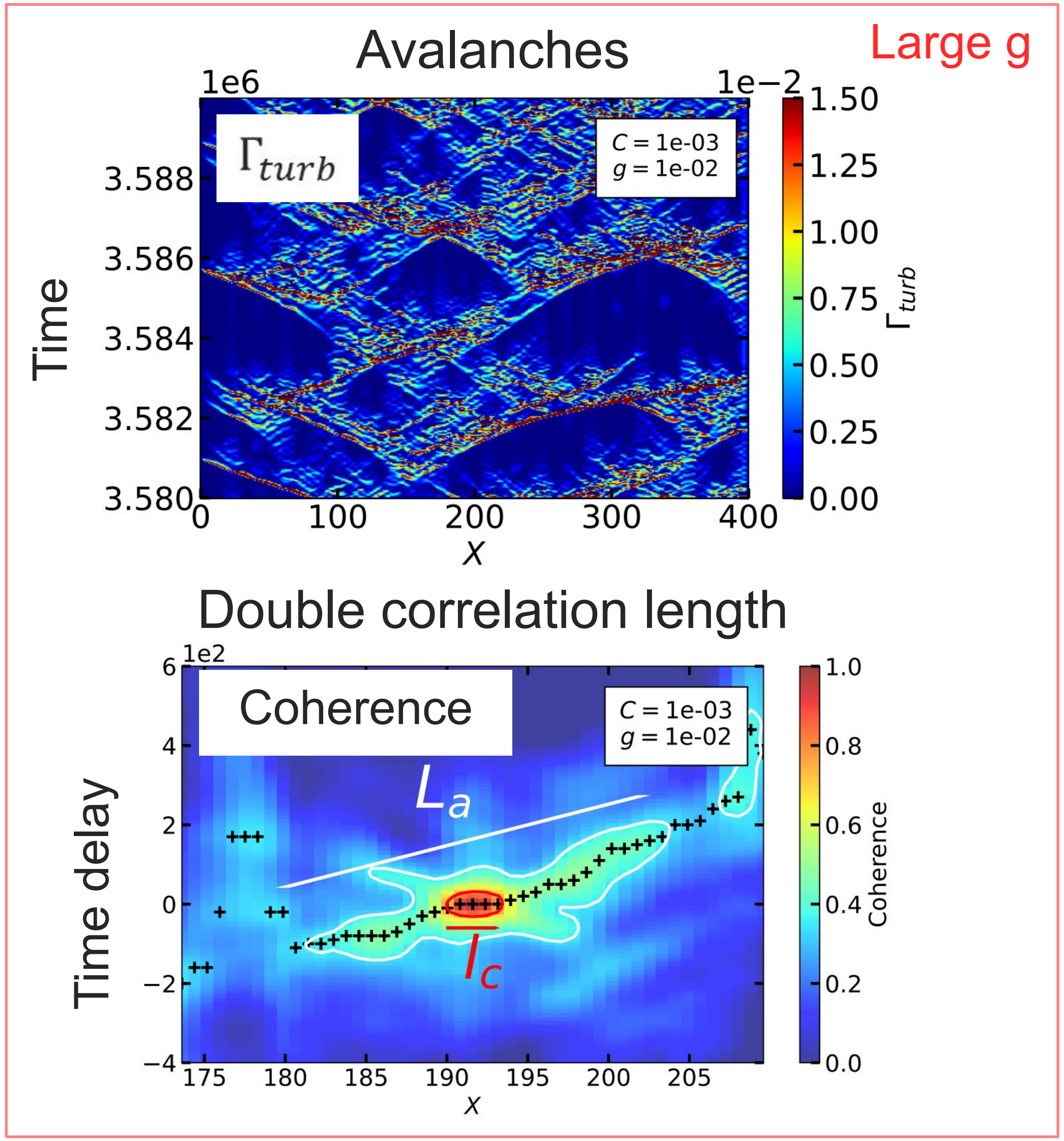
Avalanches in interchange driven turb.



No avalanches

Small g

Single correlation length



Avalanches

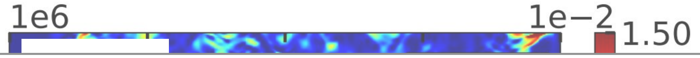
Large g

Double correlation length

Avalanches in interchange driven turb.

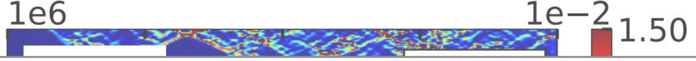
No avalanches

Small g



Avalanches

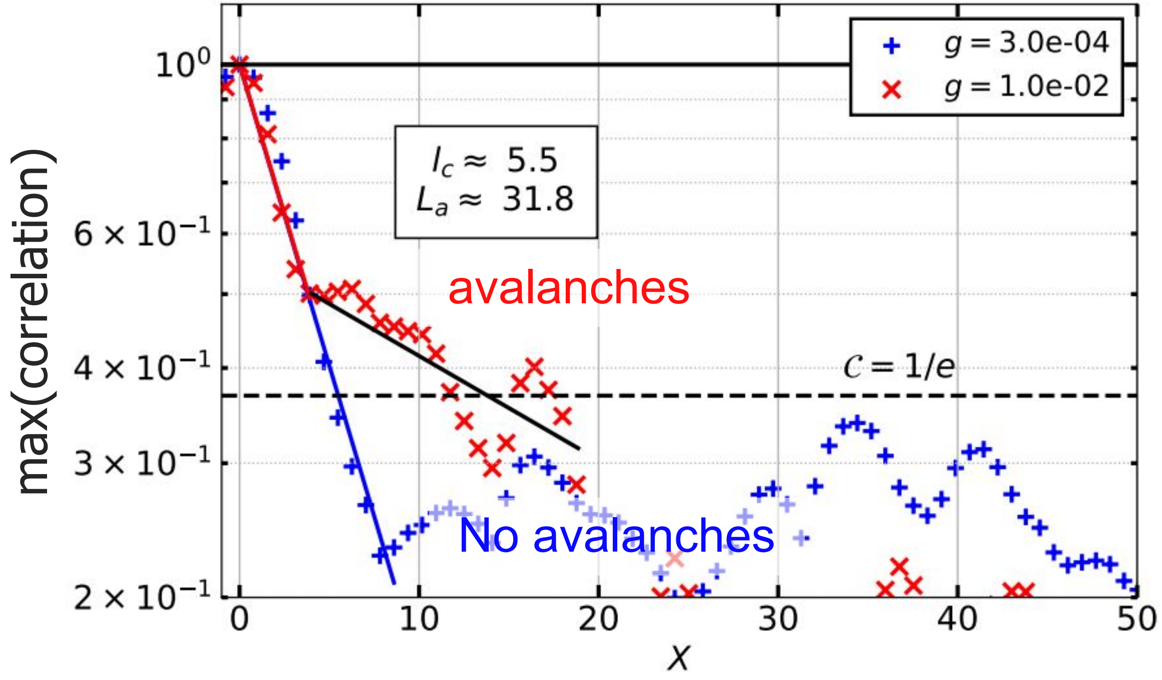
Large g

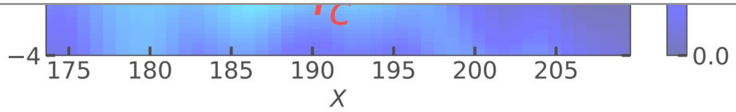


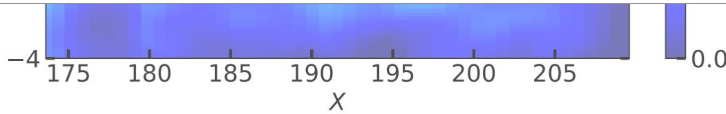
Signature for experiments

2 slopes for the radial correlation function of density fluctuations:

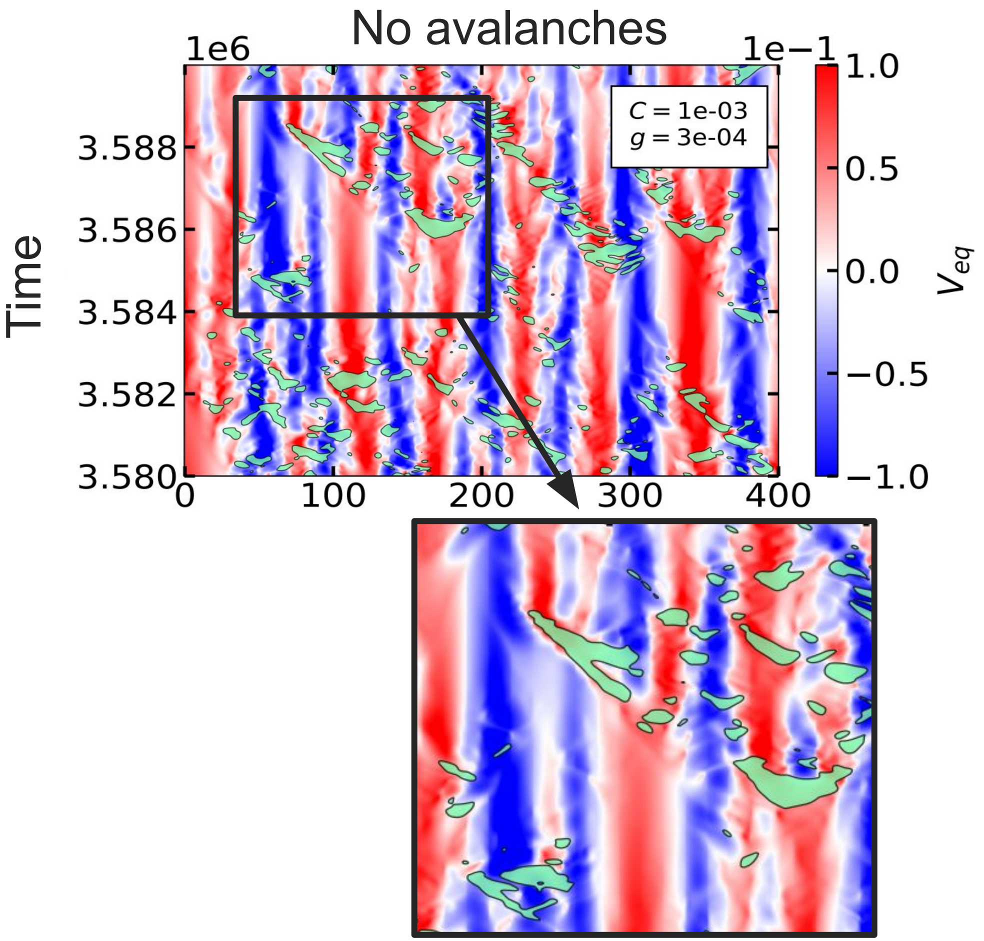
- **Short distance → eddie** size ℓ_c
- **Long distance → avalanche** extent L_a



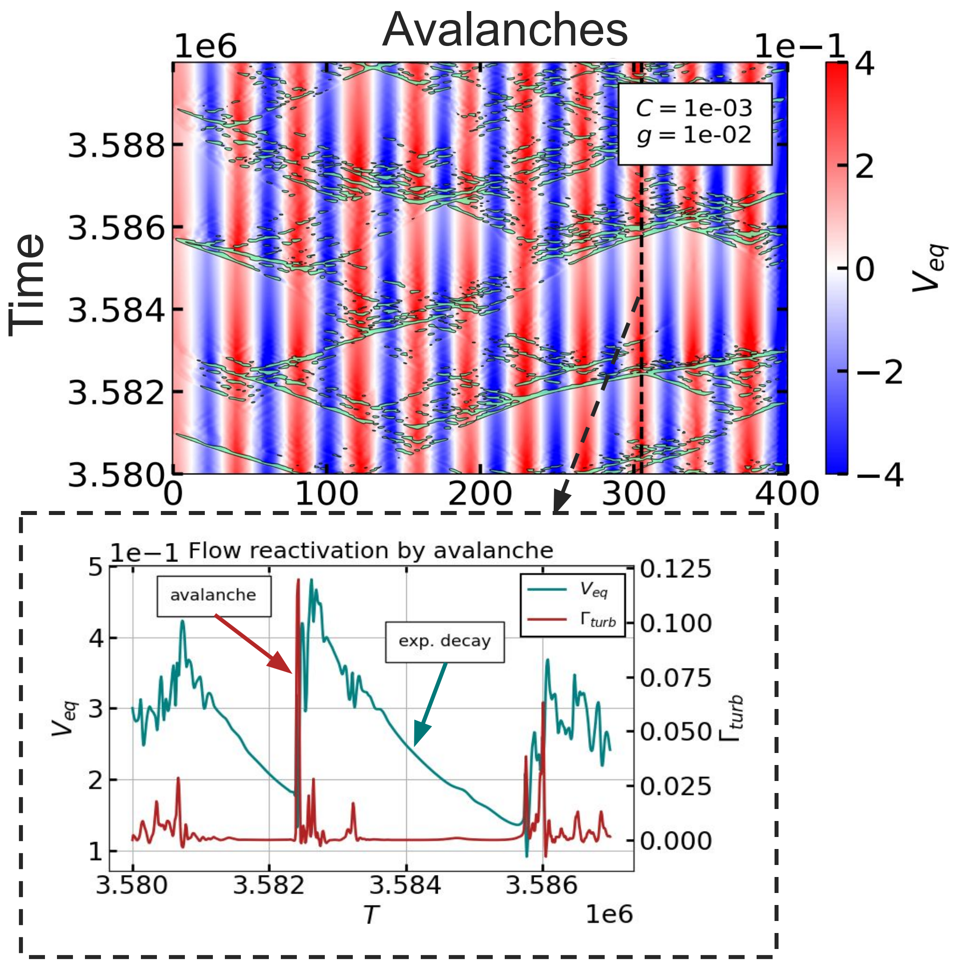




Complex interplay between turbulent flux & flows



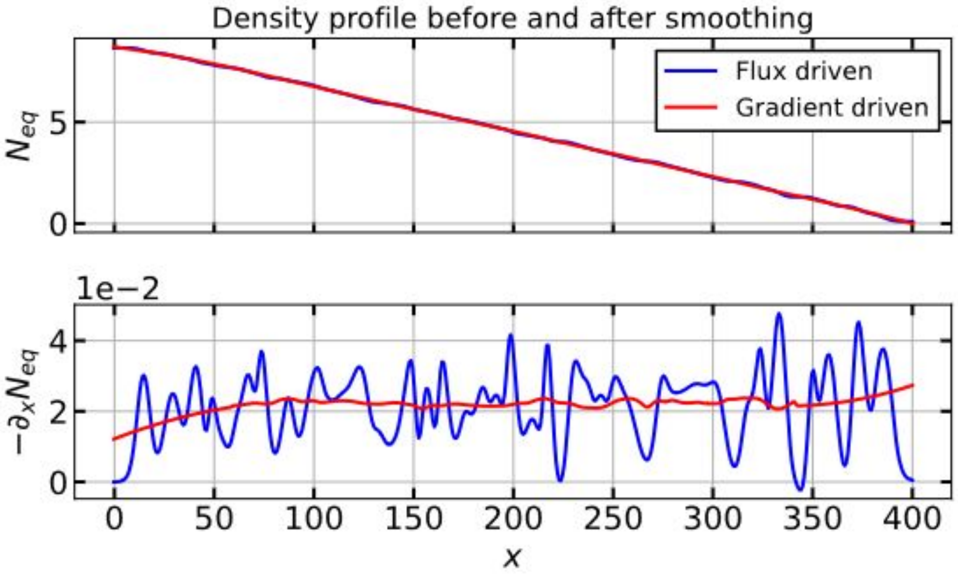
Turbulent flux changes the flow topology



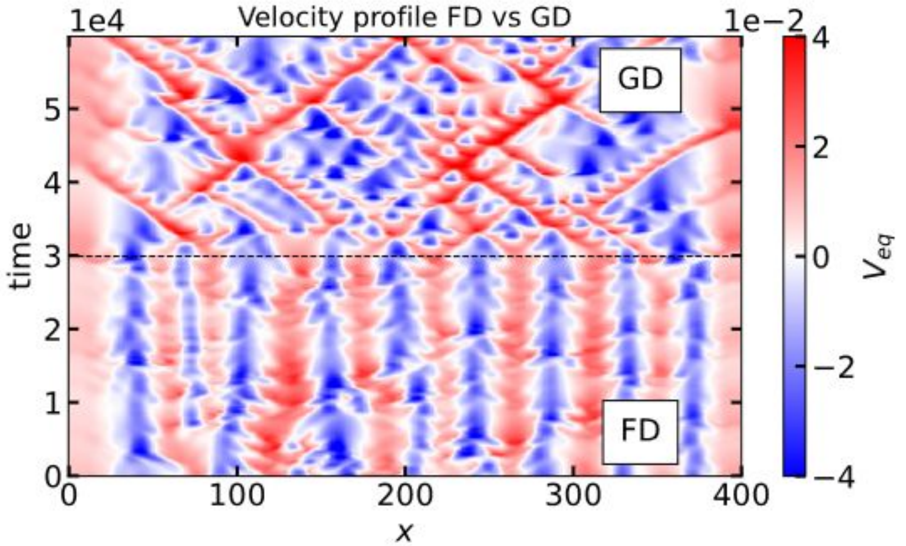
Avalanches reactivate standing zonal flow structures

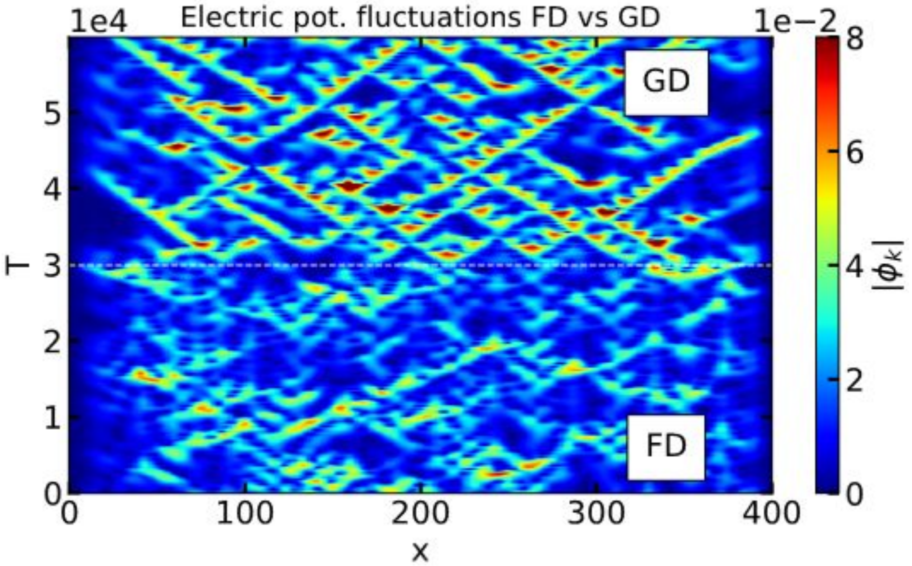
Freezing the gradient → no staircases

☞ ‘Hard’ gradient driven (GD) restart:
  - Smoothed at steady state
  - Constant in time

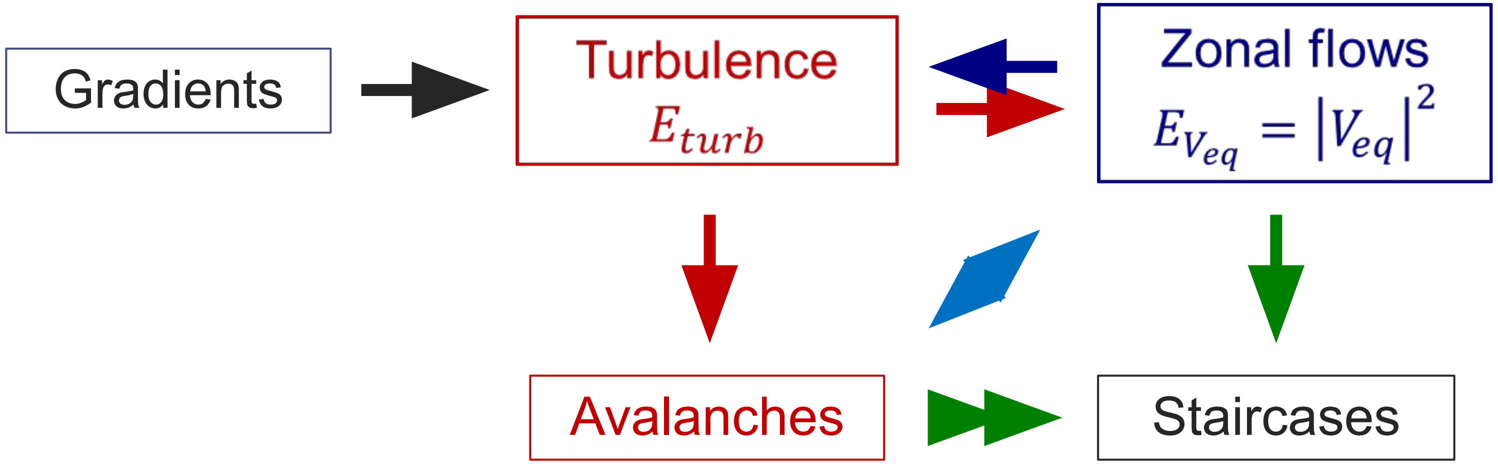


- Staircase structure lost
- Avalanches still present in GD





Turbulence regimes leading to self-organization



Gradients

Turbulence
E_{turb}

Zonal flows
$E_{V_{eq}} = |V_{eq}|^2$

Avalanches

Staircases

Interchange

- Large flows
- $|\Pi_E| > |\Pi_\star|$ & phase opposition
- $|\phi_k| \gg |N_k|$
- Radially structured ZFs
- Avalanches reactivate ZFs structures

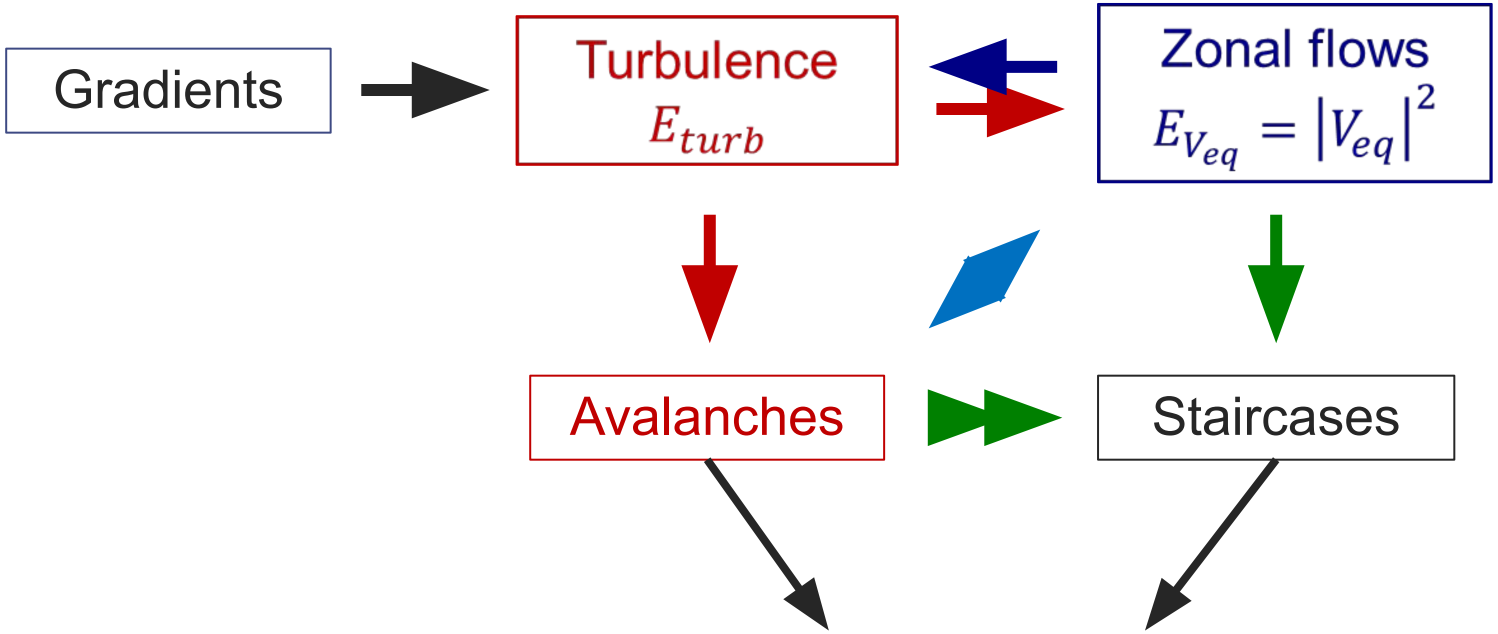
CDW

- Low / intermediate flows
- $|\Pi_\star| > |\Pi_E|$
- $|\phi_k| \gg |N_k|$
- Large turbulence flux disturbs ZFs structures

Adiabatic

- Large flows
- $\Pi_E \sim \Pi_\star$ & in phase
- $|\phi_k| \sim |N_k|$

Turbulence regimes leading to self-organization



Gradients

Turbulence

E_{turb}

Zonal flows

$E_{V_{eq}} = |V_{eq}|^2$

Avalanches

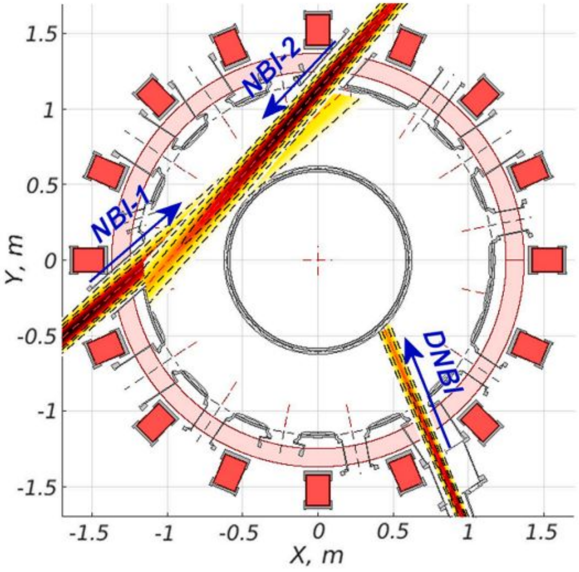
Staircases

III. Experimental investigation of
avalanches & staircases

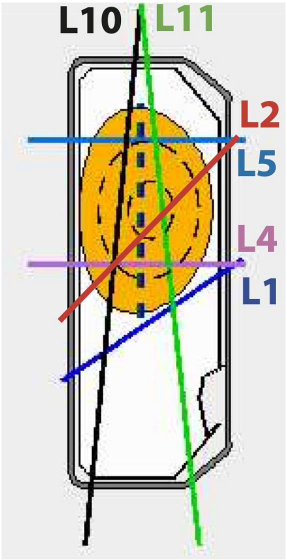
III. Experimental investigation of avalanches & staircases at TCV

☞ The **Tokamak à Configuration Variable** (TCV)

- Neutral beam heating (NBH) & Electron cyclotron heating (ECH)



NBH top view [Karpushov 23]



ECH launchers [SPC wiki]

- Radial correlation measurements with 2-channel Doppler backscattering
- Modification of edge turbulence with NBH / ECH power

☞ **Objectives**

- Measure avalanches & staircases
- Different turbulence regime

Doppler backscattering (DBS) → fluctuations & $v_\perp$

☞ Measuring with a DBS

- Backscattered signal → Fourier transform of density fluctuations

$$E_s \propto \int_V n\, e^{i\,\boldsymbol{k}_\perp \cdot \boldsymbol{r}} dr$$

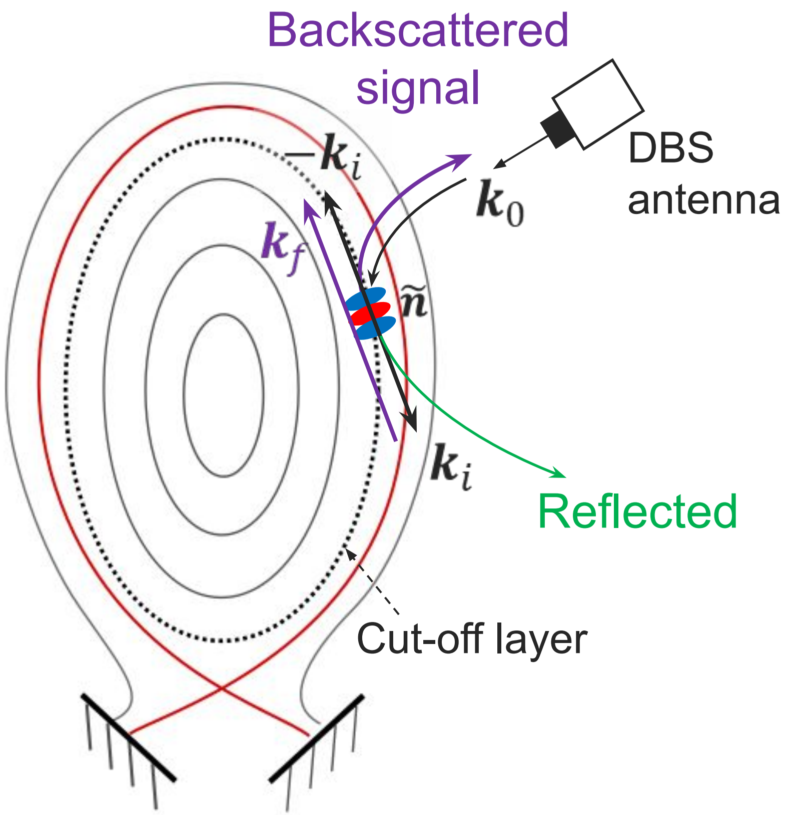
- Wavenumber $\boldsymbol{k}_\perp$ selected from angle w.r.t. cutoff
→ Beamtracing code for spatial localization & k estimation

- Doppler shift $\Delta\omega$ → fluctuations perpendicular velocity $v_\perp$

$$\frac{\Delta\omega}{k_\perp} = v_\perp = v_E + v_\varphi \approx v_E$$

☞ At TCV

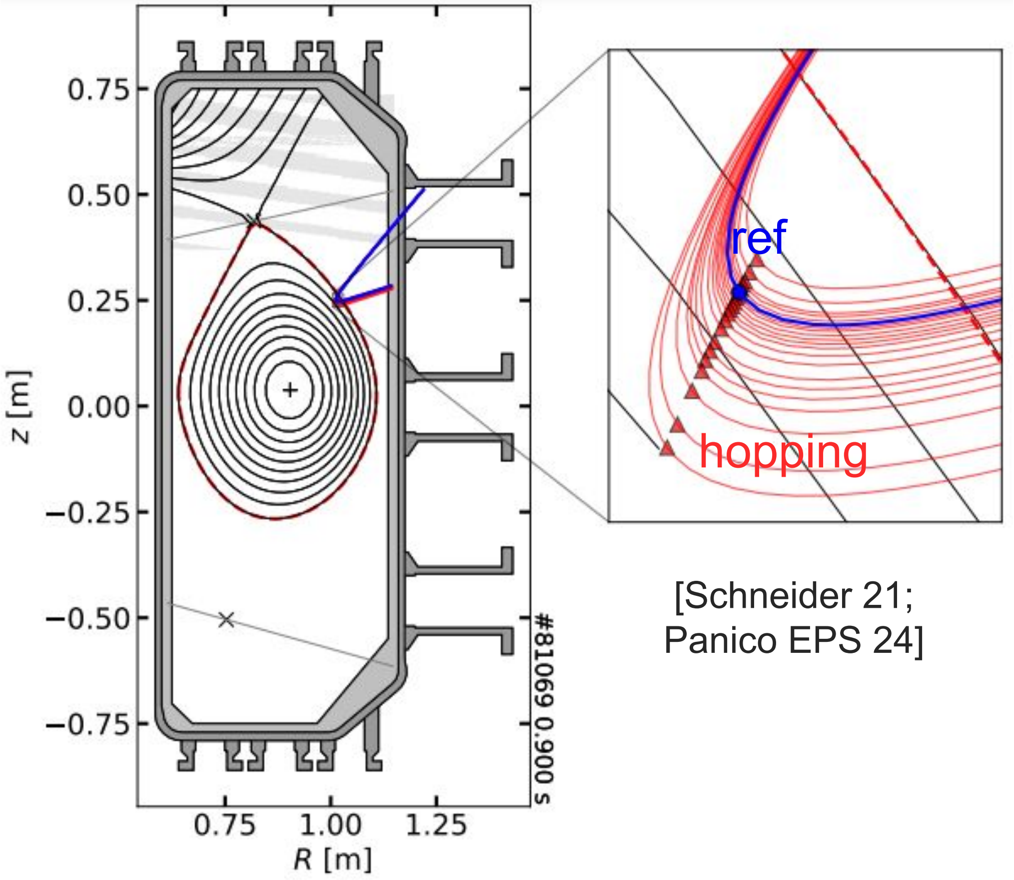
- Dual V-band X-mode → access $\rho \in [0.7\ - 1]$
- $k_\perp \in [4 - 15]\ cm^{-1} \sim [0.3 - 1.5]\ \rho_i^{-1}$



DBS principle

Correlation found at both short & large scale

Hopping channel scans around a reference channel

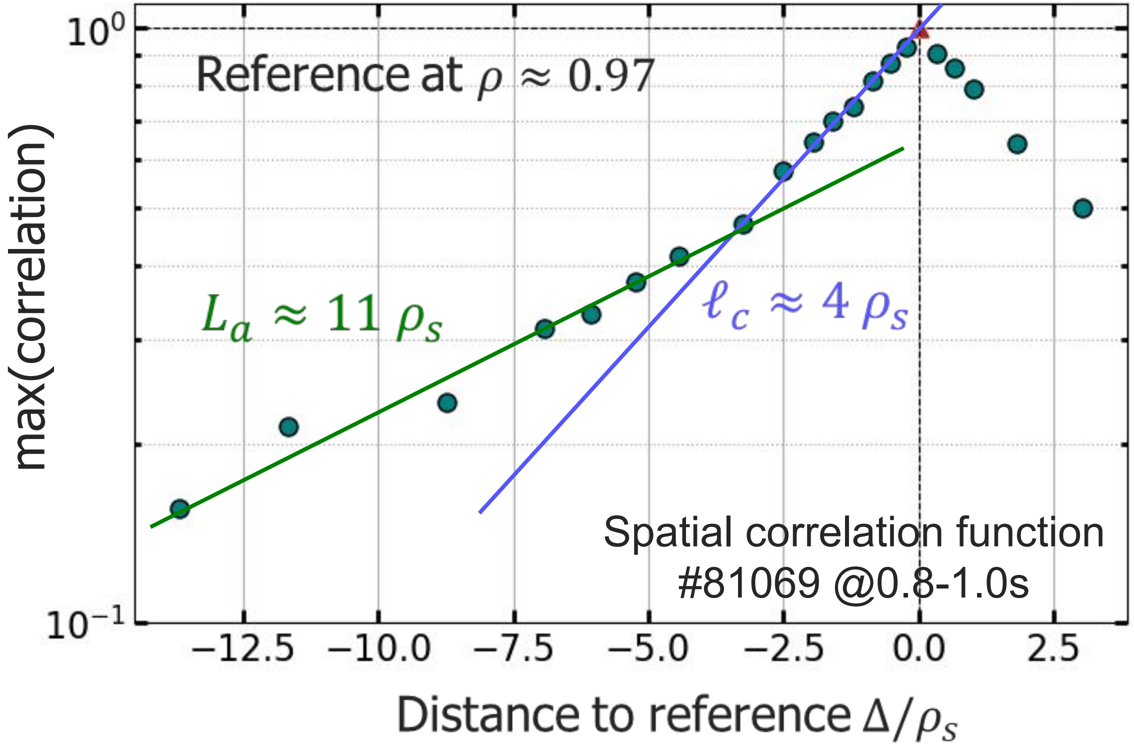


[Schneider 21; Panico EPS 24]

2-slopes (semi-log) on radial correlation when avalanches

ℓ_c: turbulence correlation length

L_a: avalanche extension

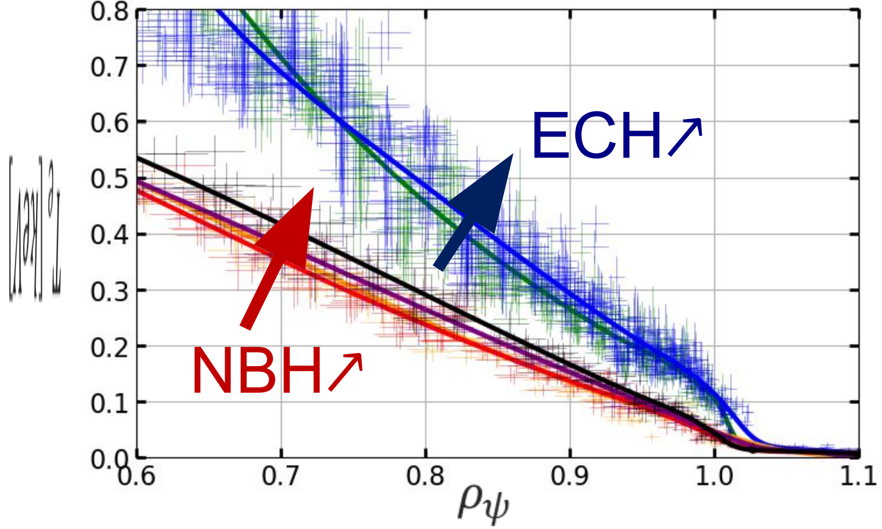


Spatial correlation function #81069 @0.8-1.0s

Design of the experiments

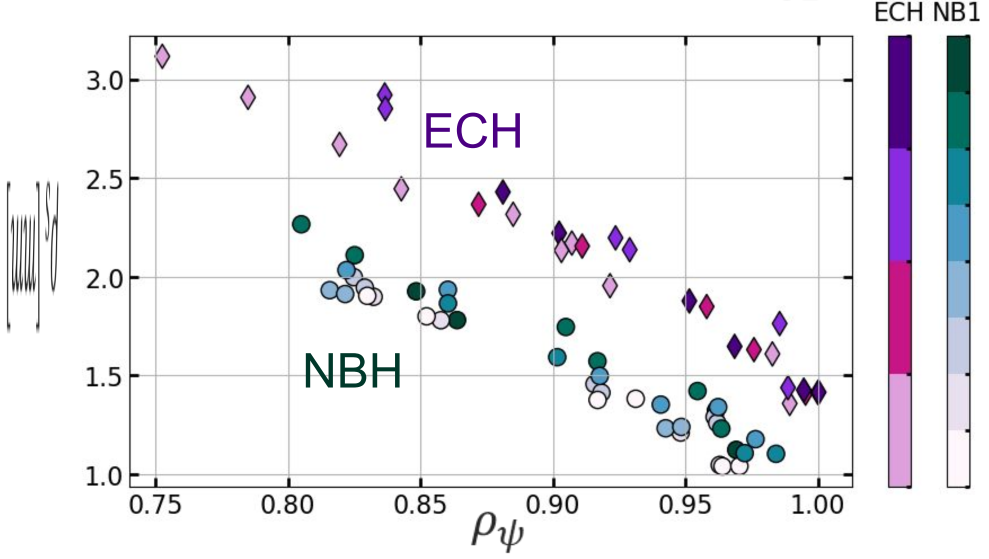
- **Constraints** for correlation DBS
  - Significant statistics on density fluctuations → L-mode
  - Probes from upper port → Upper single null configuration
- Turbulence parameters (8 shots used / 30 performed):
  - ECH: 590 – 1180 kW
  - NBH: 140 – 500 kW

Electron temperature



- **Stiff** edge profiles

Hybrid Larmor radius $\rho_s = \frac{\sqrt{m_i T_e}}{eB}$

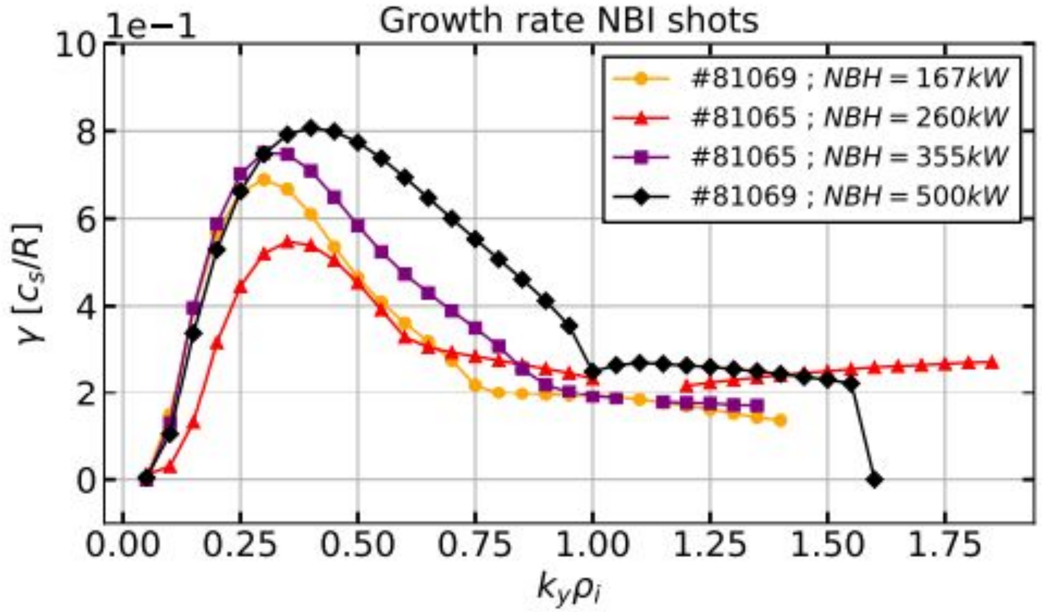


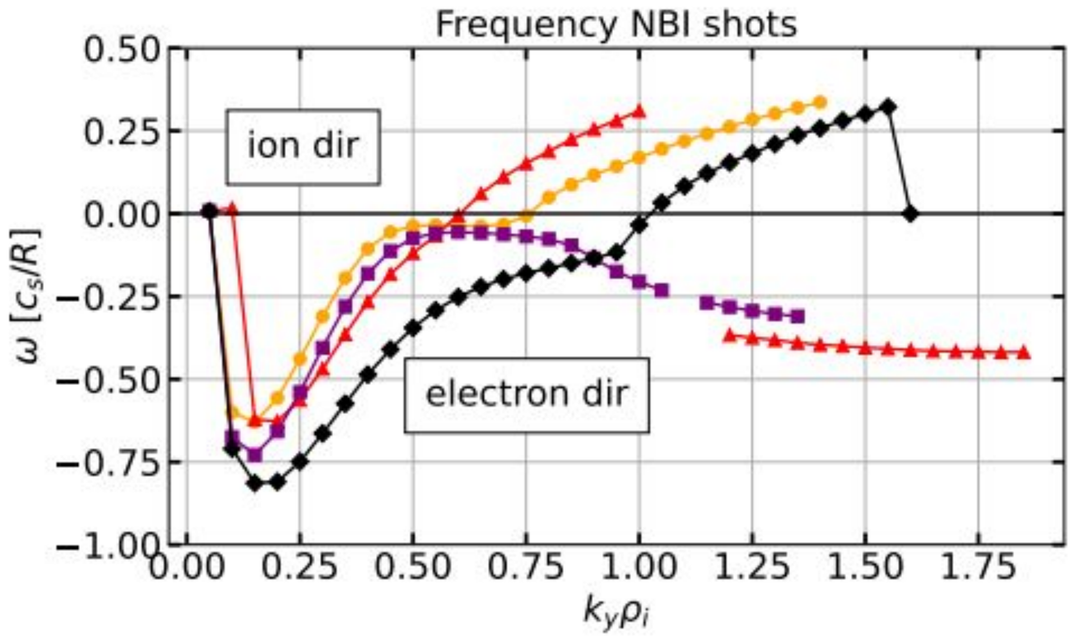
- 67 correlation measurements: $\rho = 0.75 - 1$
- Normalized to hybrid-Larmor radius

Large stiffness prevents exploration of turb. regimes

- Profiles analyzed with linear gyrokinetics (GENE) by A. Balestri
  - Local, flux-tube, initial value solver → provides most unstable mode

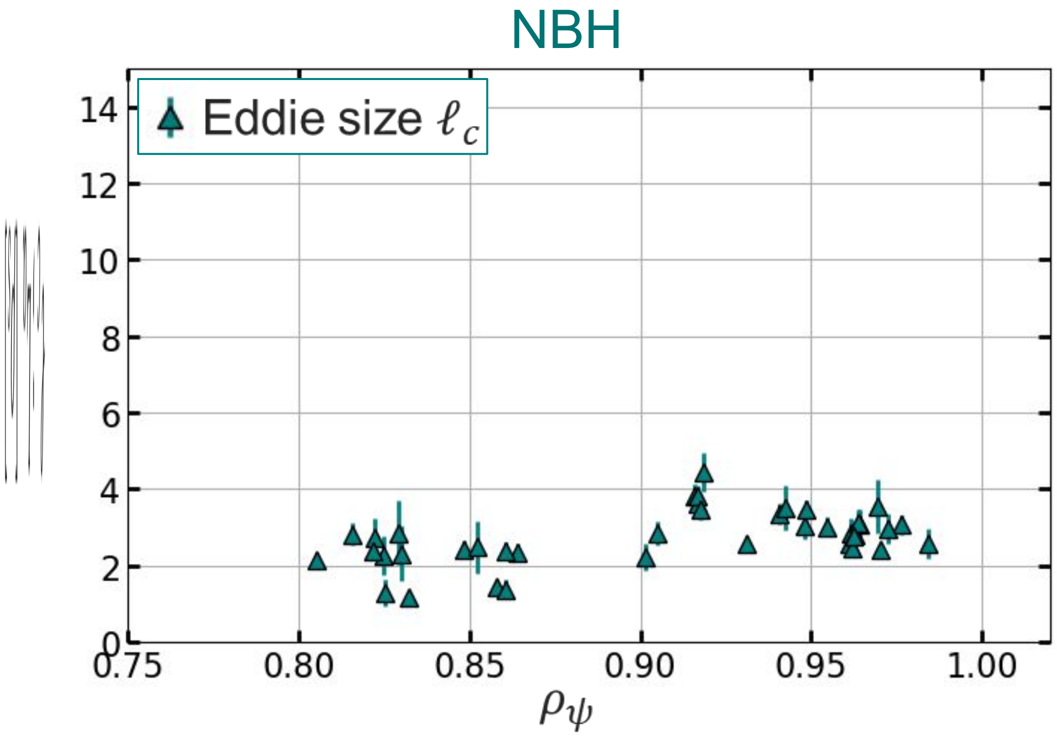
- Dominant instability:
  - driven by electrons → likely trapped electron modes (TEM)
  - No significant effect of heating

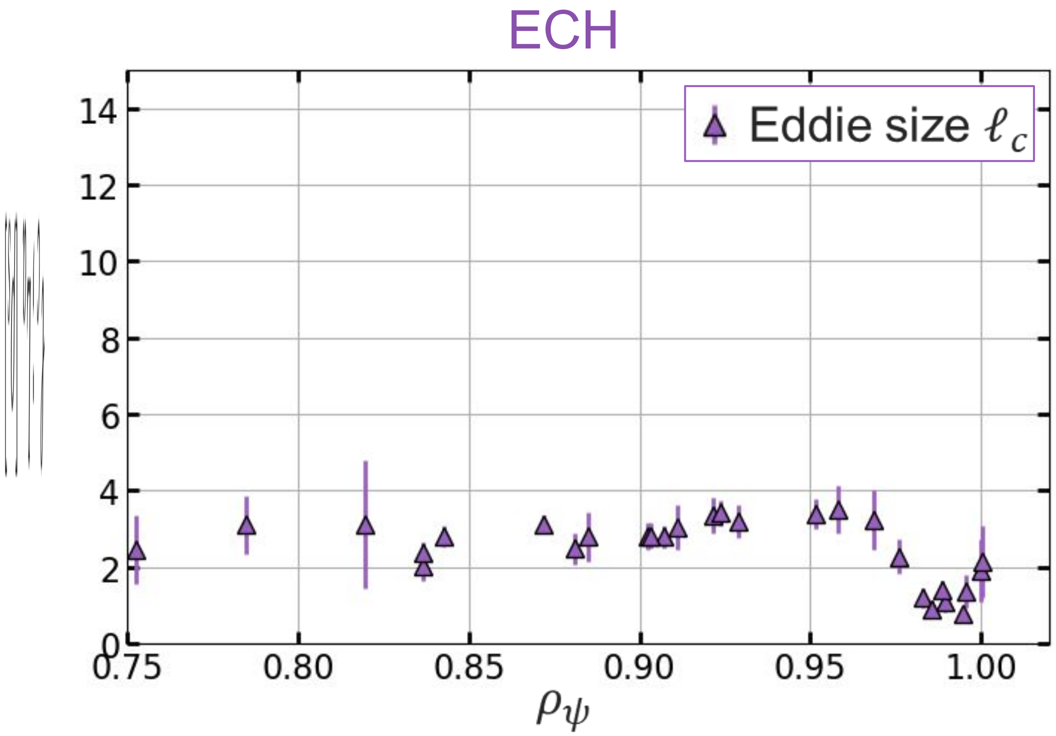




Spatial structure of turbulence

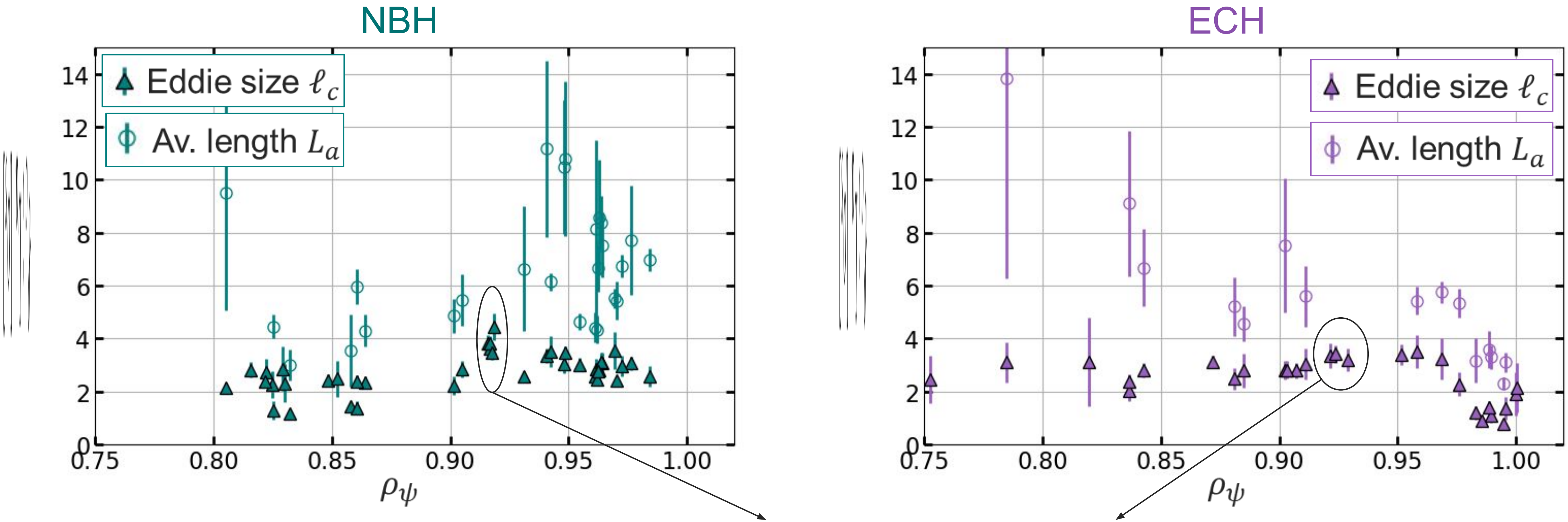
- Reliable short scale measurement → $\ell_c \approx 3 \pm 1\, \rho_s$





Spatial structure of turbulence

- Reliable short scale measurement → $\ell_c \approx 3 \pm 1\ \rho_s$
- Large variability for second slope → $L_a \approx 4 - 15\ \rho_s$



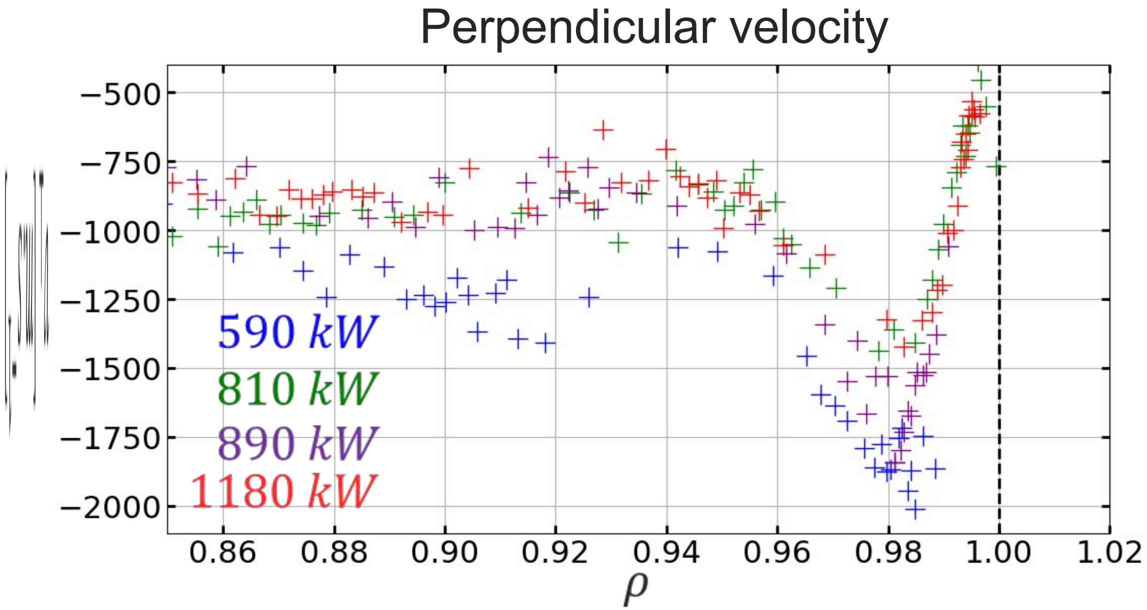
- Larger variability in NBH
- Density difficult to control

Avalanches not always present

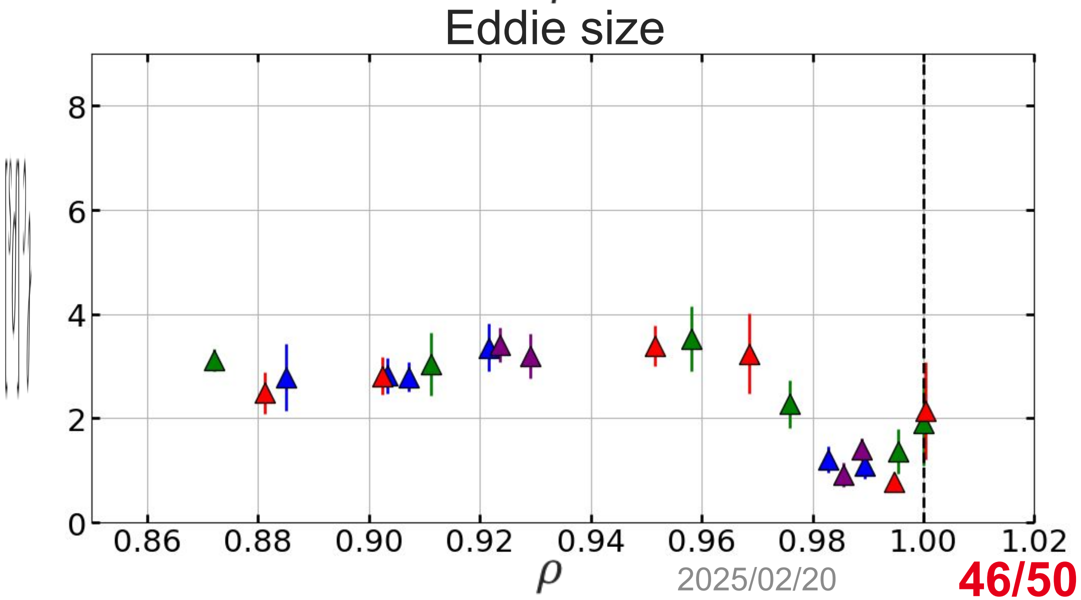
Smaller structures in large shear regions (E_r well)

☞ ECH cases: velocity & correlation in E_r well

→ Marginal dependance on heating power


Perpendicular velocity

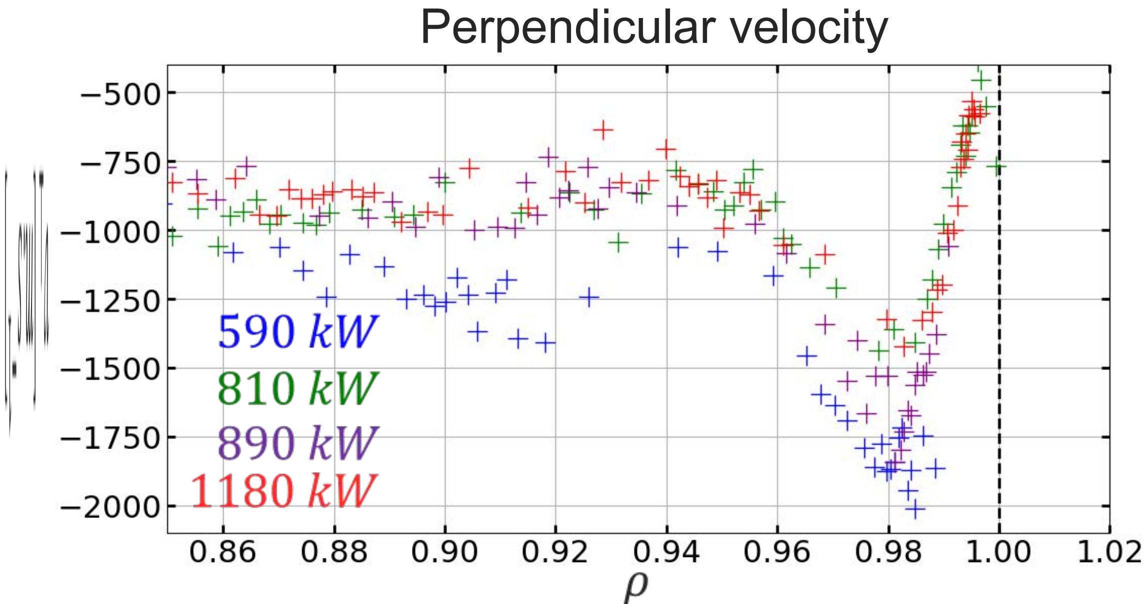
Reduced turb. Structures in E_r well
$\ell_c \sim 3 \ \rightarrow 1.5 \ \rho_s$

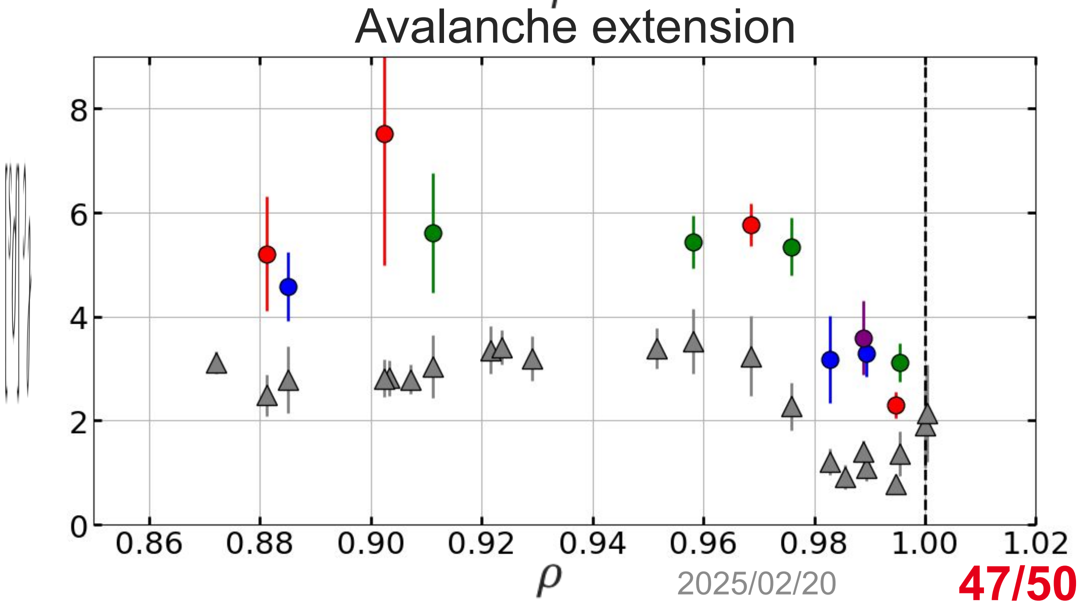

Eddie size

Smaller structures in large shear regions (E_r well)

☞ ECH cases: velocity & correlation in E_r well

→ Marginal dependance on heating power


Perpendicular velocity


Avalanche extension

Reduced turb. Structures in E_r well
$\ell_c \sim 3 \ \rightarrow 1.5 \ \rho_s$

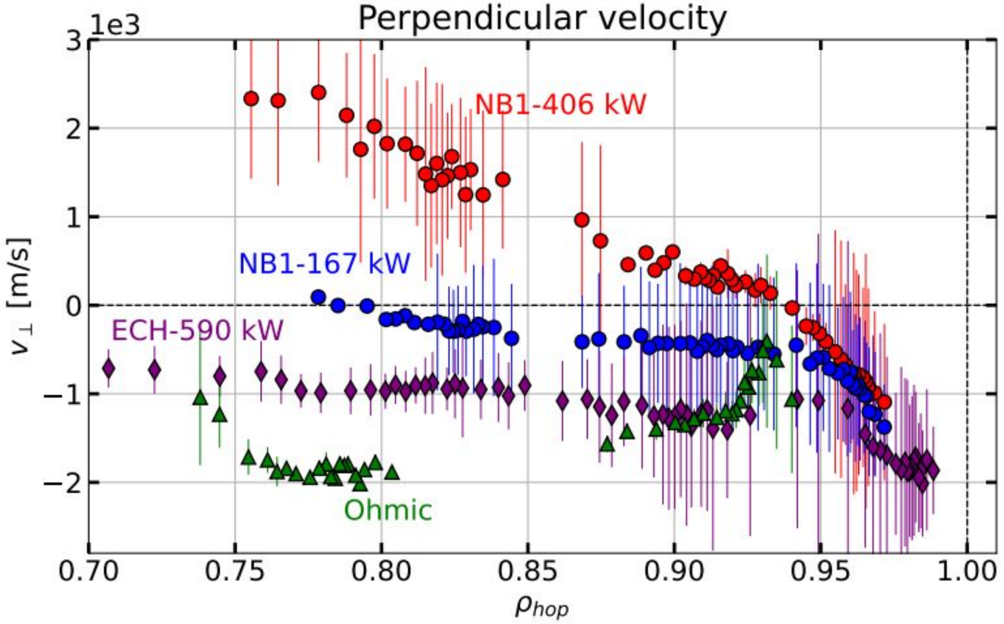
Reduced avalanches in E_r well
$L_a \sim 5 - 6 \ \rightarrow \ 3 \ \rho_s$

No corrugations in the perp. velocity profiles

- Perpendicular velocity with ≠ heating schemes
  - **No corrugations in $v_\perp$ profile**

Low amplitude

Not stable over
~ 100ms



- Link with turbulence regime?
  - Turb. driven by TEM
  - ∇T_e driven TEM not efficient in driving zonal flows

[Lang 08 ; Garbet AAPPS 24]

Conclusion

- ***Tokam1D***: *flux-driven model for turbulence self-organization*
    - Self-consistent generation of flows, avalanches & staircases

- *Identification of **regimes** prone to **turbulence self-organization***
    - Interchange & adiabatic regime → energy stored in ZFs
    - Interchange → **avalanches** (ℓ_c & L_a) & structured flows (**staircases**)
    - Avalanches → disturb ZF / reactivate staircases

- *Experimental measurements of avalanches & staircases*
    - 2-channel DBS for turbulence **correlation length** & **avalanches** measurement
    - **Shear reduces size** of turb. structures & avalanches

Panico O, Sarazin Y, Hennequin P, et al. **On the importance of flux-driven turbulence regime to address tokamak plasma edge dynamics**. Journal of Plasma Physics. 2025;91(1):E26. doi:10.1017/S0022377824001624

Panico O, Sarazin Y, Hennequin P, et al. **Generation of zonal flows and impact on transport in competing drift waves & interchange turbulence** (submitted to JPP)

Panico O, **Indirect evidence of avalanche-like transport in TCV plasmas backed by 1D nonlinear simulations**, EPS Salamnca 2024

What reduced models offer to 1st principle codes & experiments?

- **Guide to explore large landscapes of parameters**
  → Turbulence regimes (CDW/Interchange)
  perspectives: temperature gradient modes, **electromagnetism**

- **Informs on underlying physical mechanisms**
  → role of Reynolds stress, nonlinear interaction between avalanche & zonal flows
  perspectives: role of force balance flows, SOL physics

- **Experimental signatures**
  → Two slopes radial correlation
  perspectives: explore ≠ **turb. regimes**

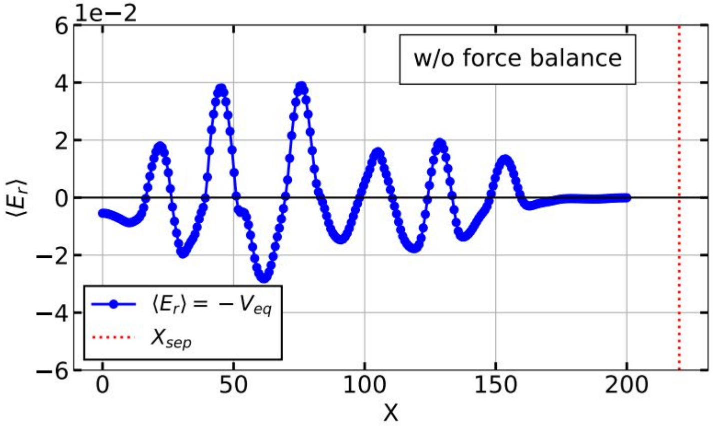
Backup slides

☞ **Derivation of Tokam1D**

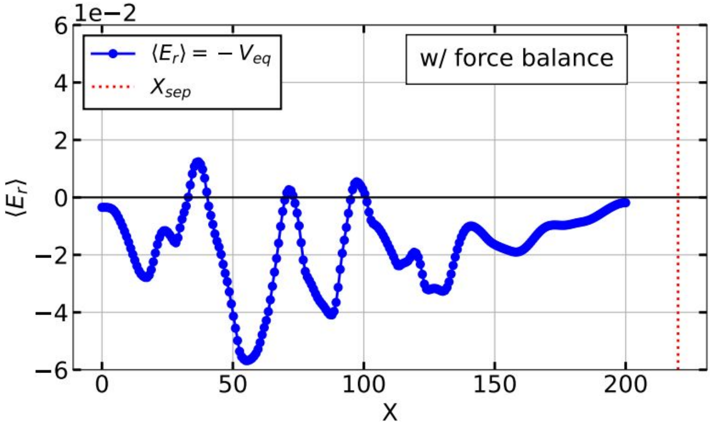
- Radial electric field in the different versions of Tokam1D
- Force balance flow
- Scrape-off layer
- Electromagnetic
- Energetics

Radial electric field in the different version of Tokam1D

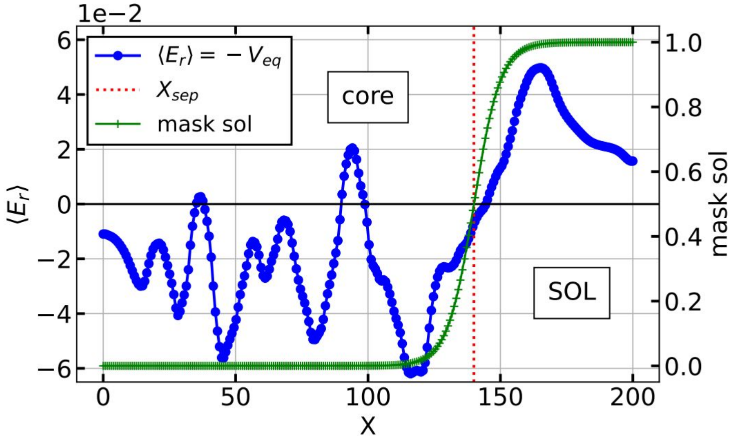
Tokam1D core



Force balance



Crossing the separatrix



Towards an electromagnetic model

Tokam1D - Force balance flow

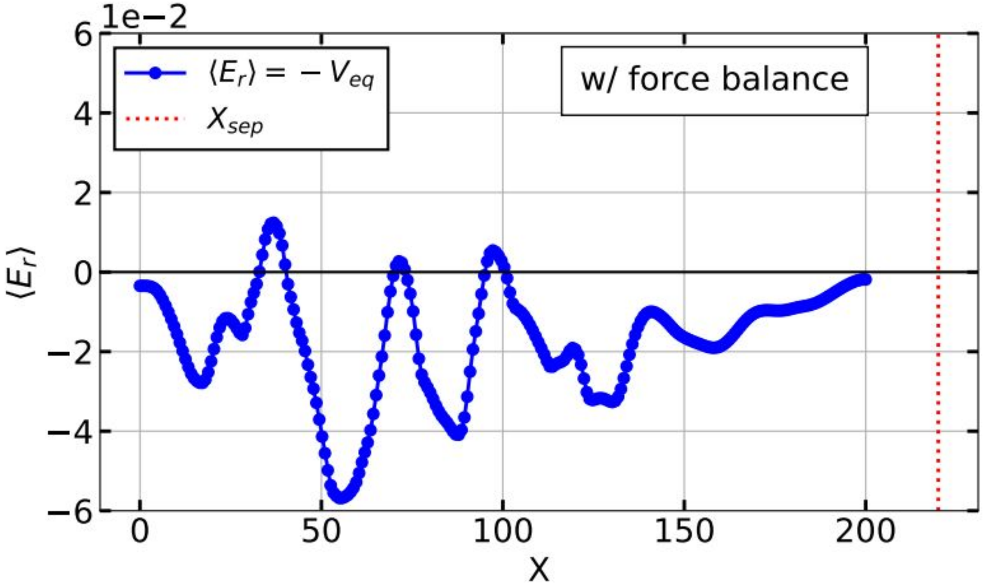
Velocity relaxes towards force balance equilibrium [Choné 15]

$$\partial_t V_{eq} = -\partial_x \Pi_{tot} + \nu \partial_x^2 V_{eq} - \mu (V_{eq} - V_{eq}^{FB})$$

$$\mu(x) = \left(\frac{q}{\varepsilon}\right)^2 \frac{0.452 f_T \nu_{i0} n_{eq}}{\left(1+1.03\sqrt{\nu_{\star i0} n_{eq}} + 0.31 \nu_{\star i0} n_{eq}\right)\left(1+0.66 \nu_{\star i0} n_{eq} \varepsilon^{3/2}\right)}$$

$$V_{eq}^{FB} = v_\theta - \tau \partial_x N$$

[Gianakon 02]



Density gradient → negative E_r in the core

Tokam1D – Scrape-off layer

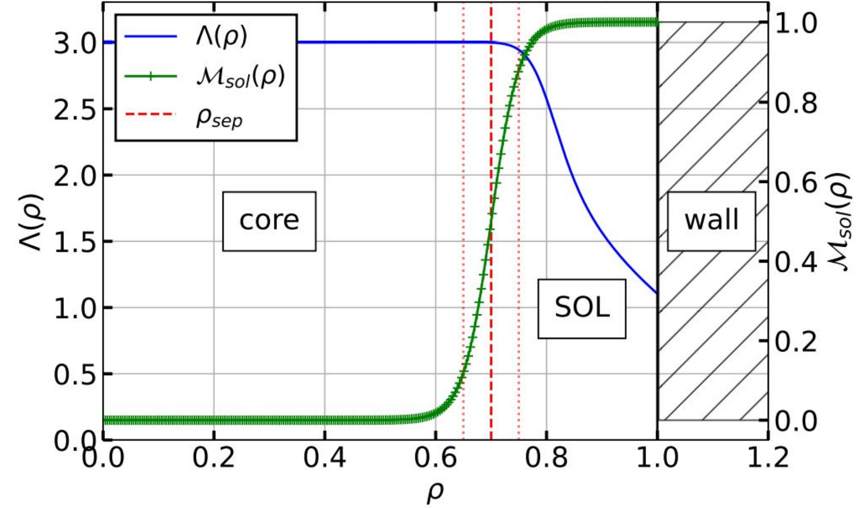
Transition from core to sol using a mask

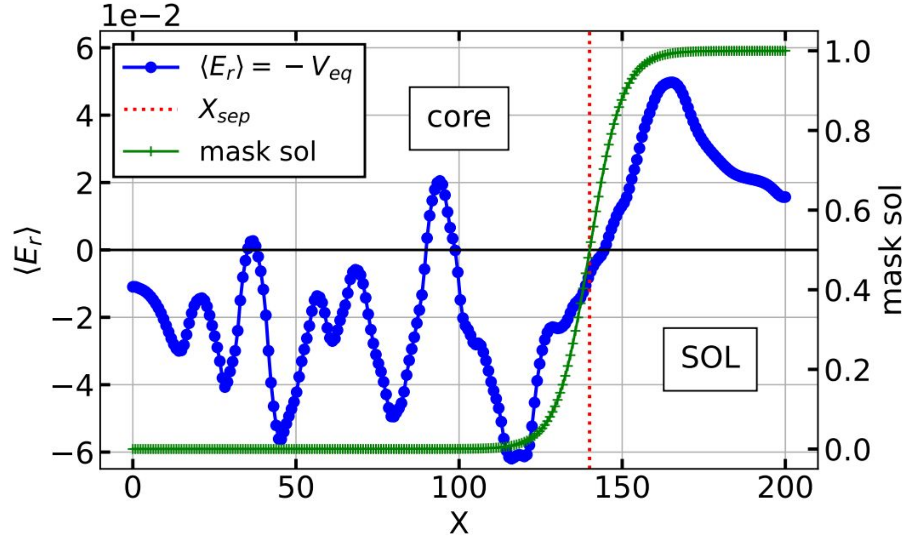
- Core: Force balance → $E_r < 0$
- SOL: sheath condition → $E_r \propto \frac{-\nabla_r T_e}{e} > 0$

But isothermal condition → we impose *artificial* $\nabla_r T_e$ in SOL

$$\begin{aligned}
\partial_t N_{eq} &= -\partial_x \Gamma_{turb} - \mathscr{M}_{sol} C_{sol} |1 + \Lambda - \phi_{eq}| + D_0 \partial_x^2 N_{eq} + S_N \\
\partial_t V_{eq} &= -\partial_x \Pi_{RS} + \nu_0 \partial_x^2 V_{eq} - \mathscr{M}_{sol} C_{sol} \left[\int_{x_{sep}}^{x_{max}} |\Lambda - \phi_{eq}| dx' + \tau (V_{eq} - \partial_x \Lambda) \right] \\
&\quad - (1 - \mathscr{M}_{sol}) \mu (V_{eq} - V_{eq}^{FB}) \\
\partial_t N_k &= + i k_y (\phi_k \partial_x N_{eq} - V_{eq} N_k) + i g k_y (\phi_k - N_k) + \mathscr{M}_{sol} C_{sol} \phi_k \\
&\quad + (1 - \mathscr{M}_{sol}) C (\phi_k - N_k) + D_1 \nabla_\perp^2 N_k - D_{NL} N_k^2 N_k^* \\
\partial_t \Omega_k &= - i k_y g (1 + \tau) N_k - i k_y V_{eq} \Omega_k + i k_y \partial_x [\phi_k \partial_x (V_{eq} + \tau \partial_x N_{eq})] \\
&\quad - i k_y \partial_x V_{eq} \partial_x (\phi_k + \tau N_k) + \mathscr{M}_{sol} C_{sol} \phi_k \\
&\quad + (1 - \mathscr{M}_{sol}) C (\phi_k - N_k) + \nu_1 (\partial_x^2 - k_y^2) \Omega_k
\end{aligned}$$

$$\Lambda = \Delta\phi_{sheath} \propto \frac{T_e}{e}$$





Tokam1D – Electromagnetic

Solving generalized Ohm's law:
parallel vector potential $\Psi = -A_\parallel$

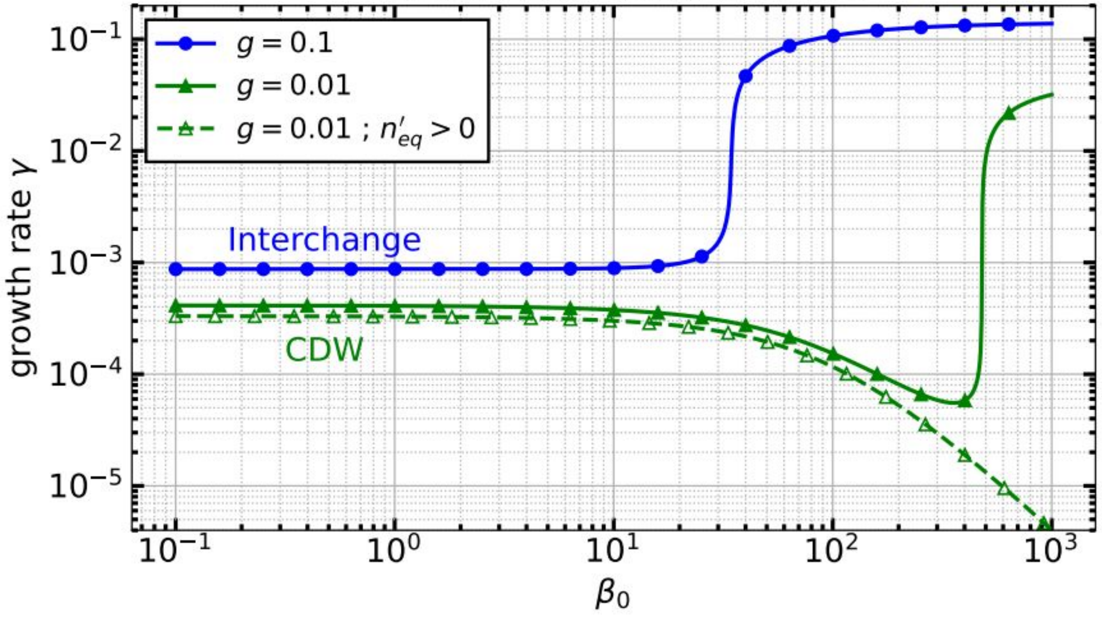
- Magnetic flutter: slows down electron parallel dynamics
- Electron inertia
- Magnetic induction: $E_\parallel = -\nabla_\parallel \phi + \partial_t \Psi$

Linear analysis:

- β_0 stabilizes CDW instability
- β_0 destabilizes interchange
- Ideal EM-interchange instability at large β_0

3D model of equations

$$\begin{aligned}
&\partial_t n + \{\phi, n\} = gn\partial_y(\phi - \ln n) + \left(\nabla_{\parallel 0} + \beta_0\{\psi,\ \cdot\ \}\right)\nabla_\perp^2 \psi + S_n \\
&\partial_t \Omega + \nabla_{\perp i}\{\phi, \nabla_{\perp i}(\phi + \tau \ln n)\} = -(1+\tau) g \partial_y \ln n \\
&\qquad\qquad\qquad\qquad\qquad\qquad + \frac{1}{n}\left(\nabla_{\parallel 0} + \beta_0\{\psi,\ \cdot\ \}\right)\nabla_\perp^2 \psi \\
&\left(\partial_t + \{\phi - \ln n,\ \cdot\ \}\right)\left(\beta_0 \psi - \frac{\mu}{n}\nabla_\perp^2 \psi\right) = \nabla_{\parallel 0}(\phi - \ln n) + \eta_0 \nabla_\perp^2 \psi
\end{aligned}$$



Growth rate Tokam1D-EM

Energetics

Multiplication of the model equations by $(1+\tau)N$ and $\phi+\tau N$ [Scott 97]

Total energy conservation

$$\frac{d\mathscr{E}_{tot}}{dt} = P_{\mathscr{E}} - D_{\mathscr{E}}$$

$$\mathscr{E}_{tot} = \int E_{tot}\, d\mathscr{V} = \int \frac{1}{2}\left\{(1+\tau)N^2 + [\nabla_\perp(\phi+\tau N)]^2\right\} d\mathscr{V}$$

$$P_{\mathscr{E}} = (1+\tau)\int N S_N\, d\mathscr{V}$$

$$D_{\mathscr{E}} = \int \frac{j_\parallel^2}{\sigma_0} d\mathscr{V} + D(1+\tau)\int (\nabla_\perp N)^2 d\mathscr{V} + \nu \int \left[\nabla_\perp^2(\phi+\tau N)\right]^2 d\mathscr{V}$$

Energy channels

$$\begin{aligned}
E_{Neq} &= (1+\tau)N_{eq}^2 + \left(\tau\partial_x N_{eq}\right)^2 \\
E_{Veq} &= V_{eq}^2 \\
E_{turb} &= 2(1+\tau)|N_k|^2 + 2|\partial_x\phi_k|^2 + 2|\tau\partial_x N_k|^2 + 4\tau\Re(\partial_x\phi_k\partial_x N_k^*) \\
&\quad + 2k_y^2\left[|\phi_k|^2 + |\tau N_k|^2 + 2\tau\Re(\phi_k N_k^*)\right] \\
&\quad - 2k_y\Im\left[(\phi_k\partial_x\phi_k^*) + \tau N_k\partial_x\phi_k^* + \tau\phi_k\partial_x N_k^* + \tau^2 N_k\partial_x N_k^*\right] \\
E_{Neq-Veq} &= 2\tau V_{eq}N_{eq}
\end{aligned}$$

- Compressibility terms necessary to achieve total energy conservation
- Predator-prey behaviour between flows & turbulence