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# Indirect evidence of avalanche-like transport in TCV plasmas backed by 1D nonlinear simulations



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P.225



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## 1. Motivation: avalanche-like transport

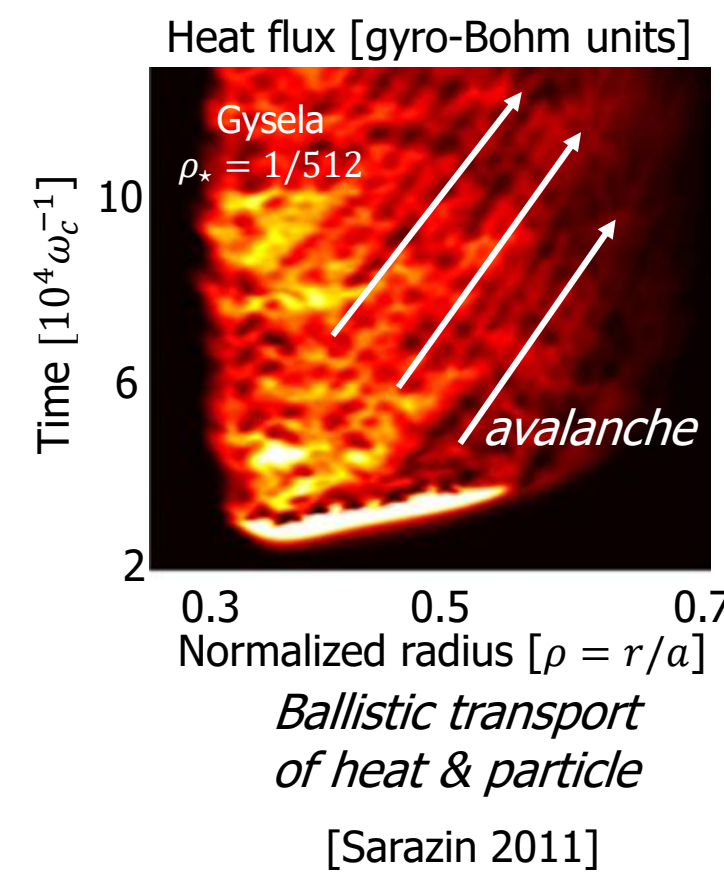
- ❖ Tokamak confinement largely governed by **turbulence**
- ❖ Simulations shows that turbulence organises at mesoscale into **avalanches, zonal flows & staircases**

[Hahn 1995] [Lin 1998] [Dif-Pradalier 2010]  
[Idomura 2014] [Diamond 2005] [Kosuga 2014]

- ❖ But difficult experimental observations [Politzer 00]

Which **turbulent regimes** favour turbulence self-organisation?  
Can we identify experimental signatures of avalanche & staircases using reduced modelling?

- Objectives:**
- ✓ Develop nonlinear flux-driven model:
    - Self-consistent generation of avalanches & flows
    - Various turbulence regimes
  - ✓ Find signatures for experiments in different turb. regimes
  - ✓ Explore link with zonal flows & staircases



## 2. Tokam1D: reduced flux-driven model [Panico 2024 (sub.)]

- ❖ 2 competing instabilities:

[Hasegawa-Wakatani 1983] ; [Sarazin 1998] ; [Bian 2003]

**Interchange (RBM / ITG -like)**

**B-field inhomogeneity:**  $g = 2\rho_* a/R$

**Collisional Drift Waves (CDW)**

**Parallel conductivity:**  $\sigma = \omega_{ce}/\nu_{ei}$

**Electron density continuity equation**

$$\partial_t N + \{\phi, N\} - g \partial_y (\phi - N) = \sigma \nabla_{\parallel}^2 (N - \phi) + D \nabla_{\perp}^2 N + S_N$$

$$N = \ln N$$

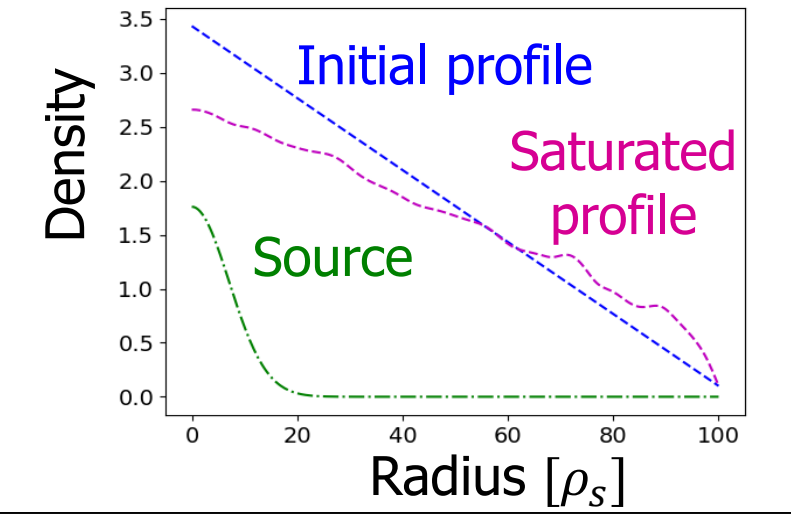
$$\phi = e\phi/T_e$$

$$\tau = T_i/T_e$$

**Charge balance equation (generalized vorticity  $\Omega = \nabla_{\perp}^2 (\phi + \tau N)$ )**

$$\partial_t \Omega + (1 + \tau) g \partial_y N + \nabla_{\perp,i} \{\phi, \nabla_{\perp,i} (\phi + \tau N)\} = \sigma \nabla_{\parallel}^2 (N - \phi) + \nu \nabla_{\perp}^2 \Omega$$

- ❖ **Flux-driven:** source of particle  $S_N$
- ❖ Reduced to 1d-radial: single mode retained for the fluctuations ( $k_{\parallel}, k_{\theta}$ )  
⇒ **Adiabatic parameter:**  $C = k_{\parallel}^2 \sigma$



## 3. Simulations: avalanche transport at large magnetic curvature

Scan of  $g = 2\rho_* a/R$  at fixed  $C = 10^{-3}$

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

Source

$\Gamma_{turb} = \langle n v_{Ex} \rangle$ : average turbulent flux of particles

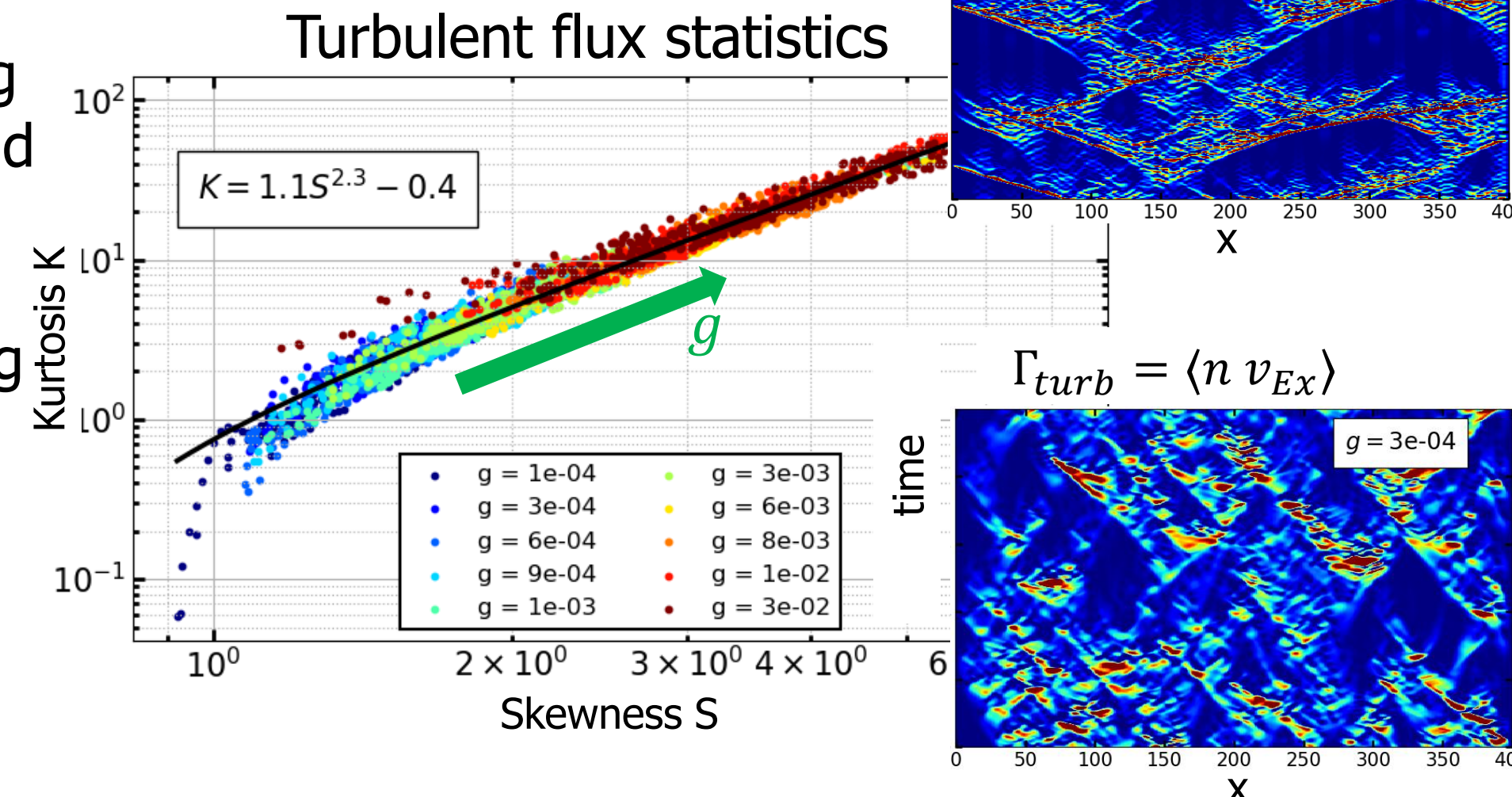
Parameter dependencies  
 $g \propto \frac{T_e^{1/2}}{RB}$  ;  $C \propto k_{\parallel}^2 \frac{T_e^{5/2}}{nB}$

Transition to avalanche-like transport at large  $g$

- ❖ skewness & kurtosis  $\nearrow$  with  $g$   
⇒ avalanches intensity and width  $\nearrow$

- ❖ Polynomial dependance of kurtosis on skewness for all  $g$   
[Labit 2007]

- ❖ Avalanches propagate both in & outwards but turbulent flux always positive

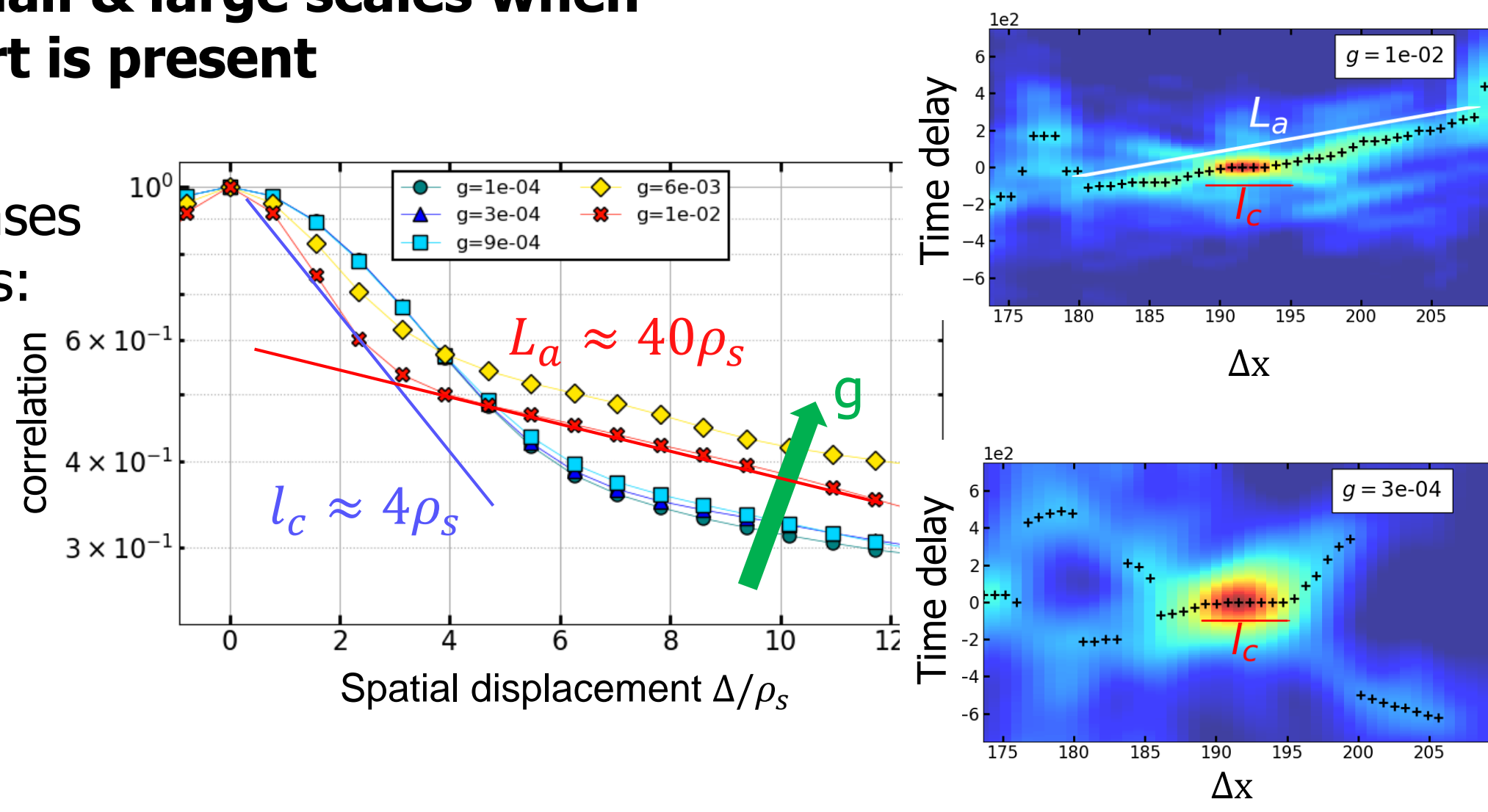


Correlation found at small & large scales when avalanche-like transport is present

- ❖ 2 correlation slopes in cases dominated by avalanches:

- $l_c$ : eddy size  $\approx 4 - 7 \rho_s$
- $L_a$ : avalanche size  $\approx 30 - 50 \rho_s$

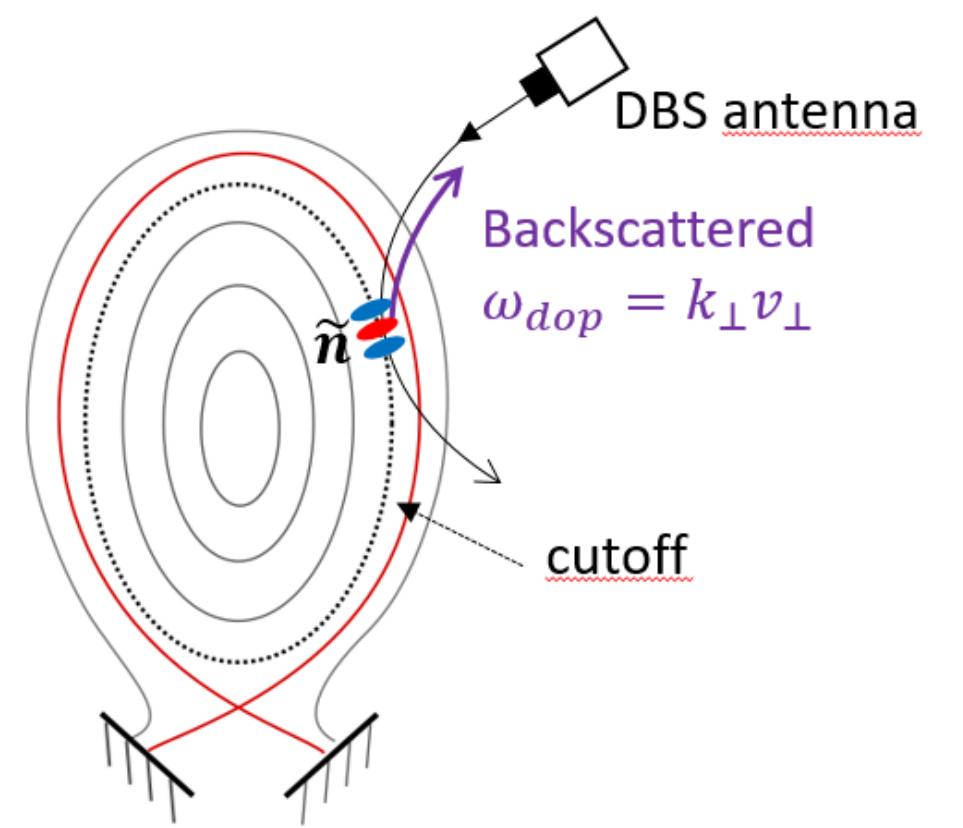
- ❖ Structure size  $\searrow$  with  $g$



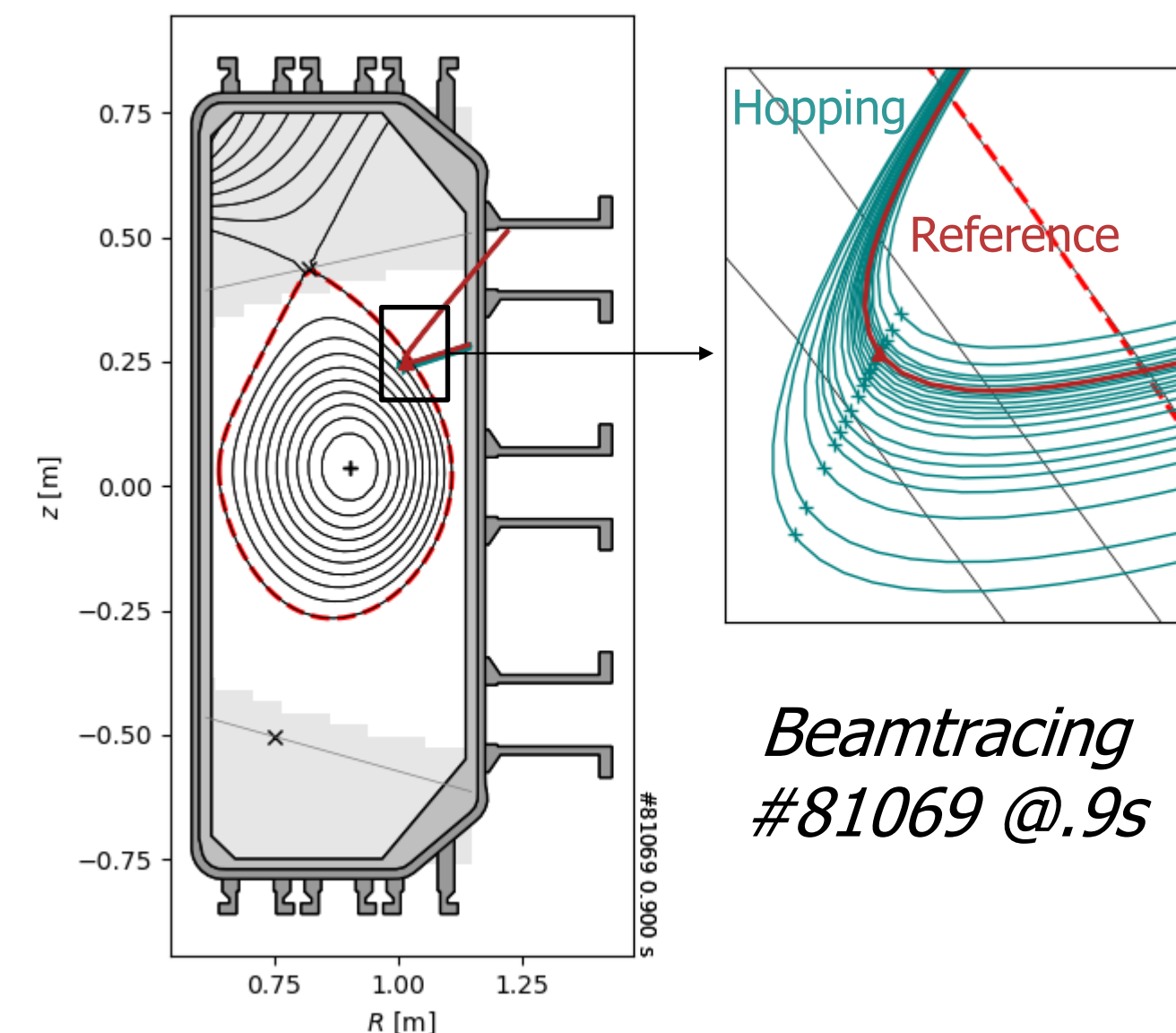
## 4. Experiments: Hints of avalanches in TCV using Doppler reflectometry

Correlation Doppler backscattering (CDBS)

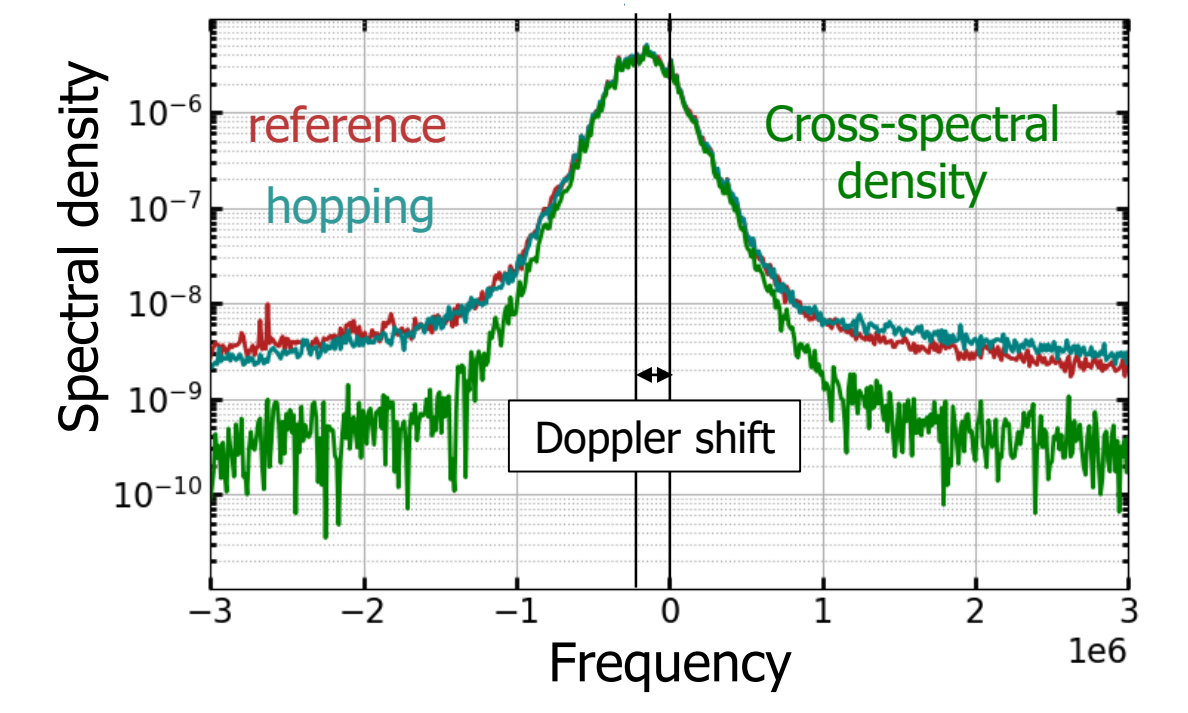
- ❖ Dual V-band system in X-mode:  $k_{\perp} \in [4, 10] \text{ cm}^{-1}$
- ❖ Signal scattered off density fluctuations  $\tilde{n}$  at radial cutoff
- ❖ 2 channels ⇒ allows for spatial correlation measurements at  $k_{\perp}$



Method



- ❖ Reference channel at fixed position & hopping channel scanned radially
- ❖ Doppler shift ⇒  $v_{\perp} \approx E_r/B$
- ❖ Cross-spectrum ⇒ correlation & delay



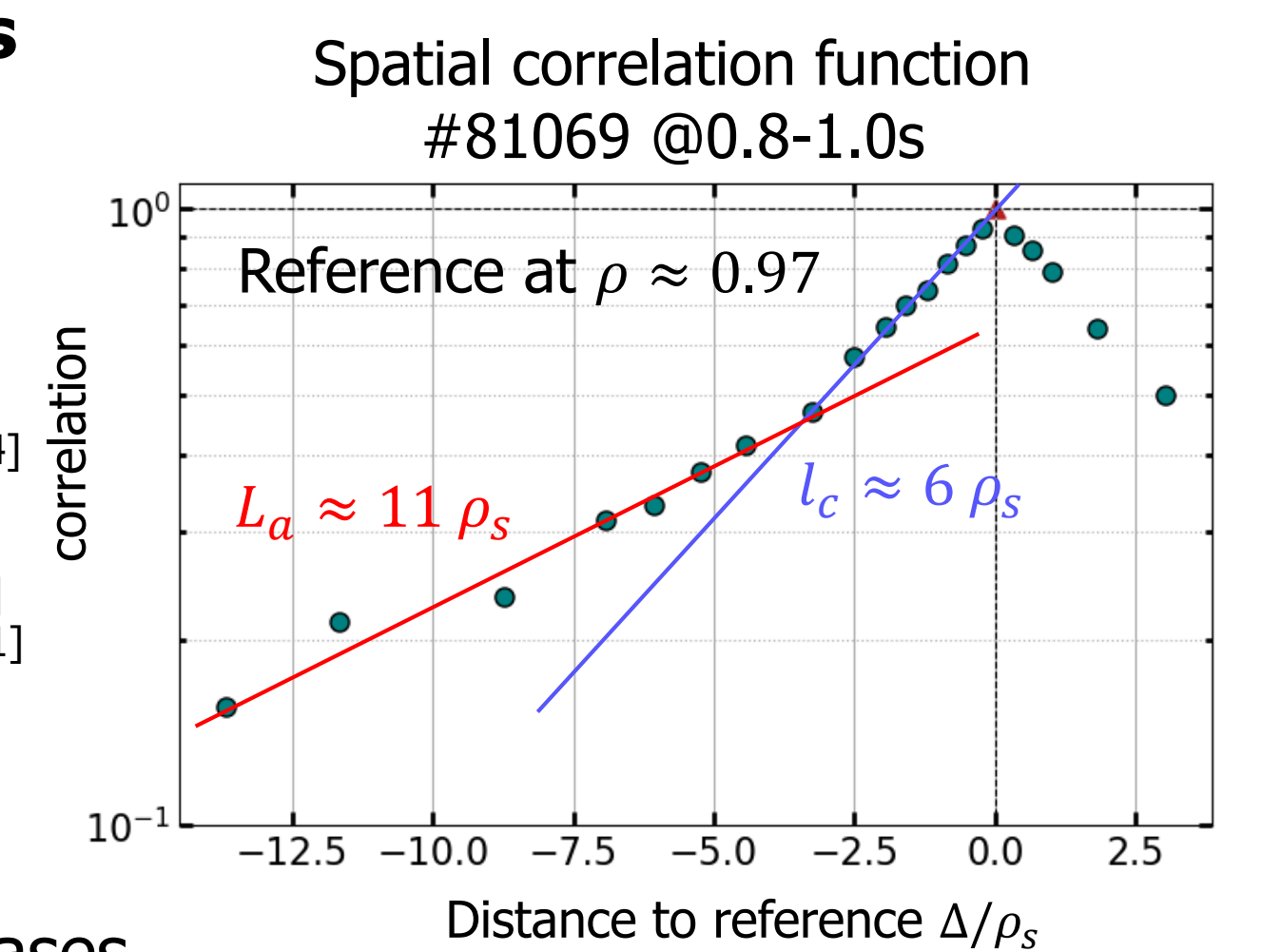
Correlation found at small & large scales

- ⚠ 2-slope correlation function similar to simulations only on **amplitude** signal

- ❖ 2 correlation slopes:
  - Eddy size:  $l_c \approx 4 - 6 \rho_s$
  - Avalanche size:  $L_a \sim 10 - 20 \rho_s$

[McKee 2001]  
[Hennequin 2004]  
[Schirmer 2007]  
[Hornung 2017]  
[Schneider 2021]

- ❖ [work in progress]
  - measurement at different  $\rho_s$  and heating conditions
  - Explore experimental signatures of staircases



## 5. Avalanches reinforce staircases at large $g$

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

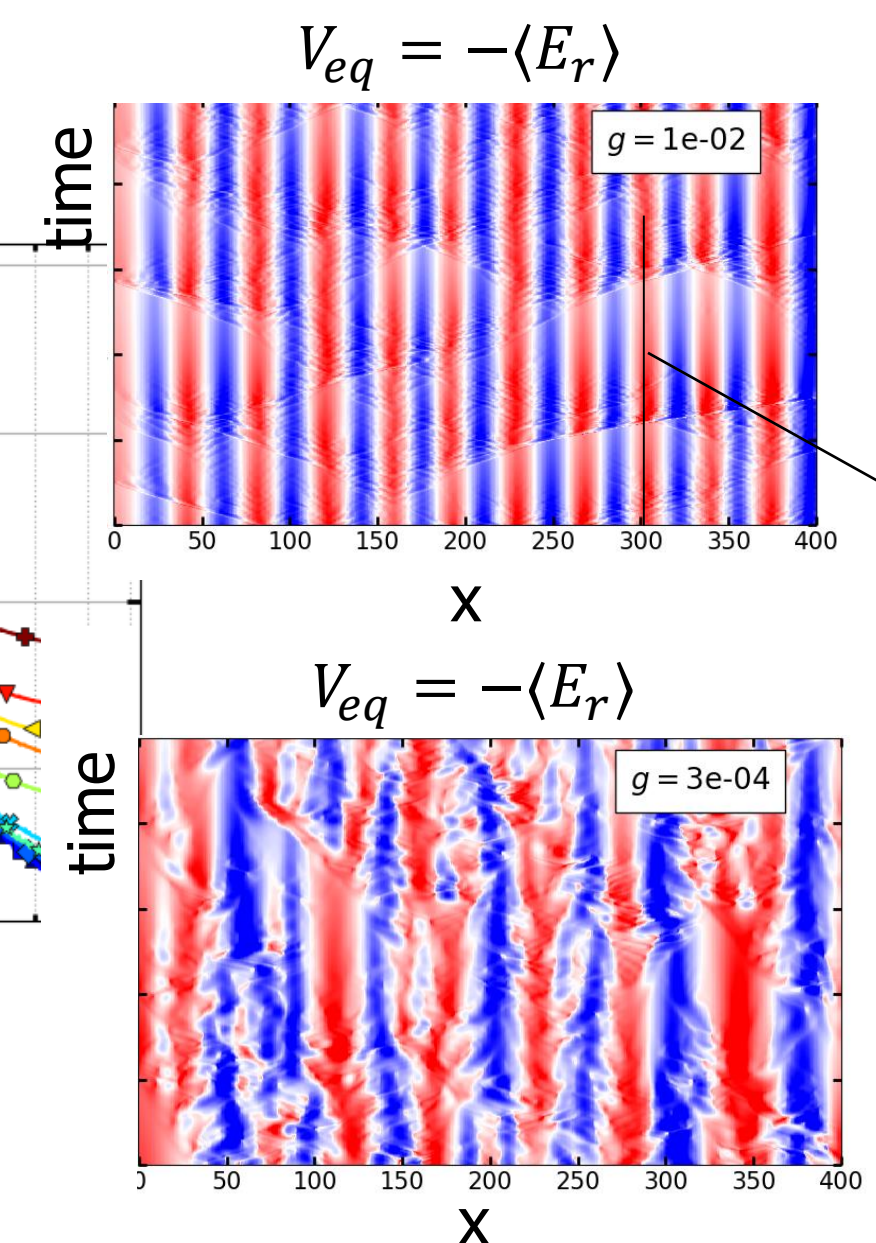
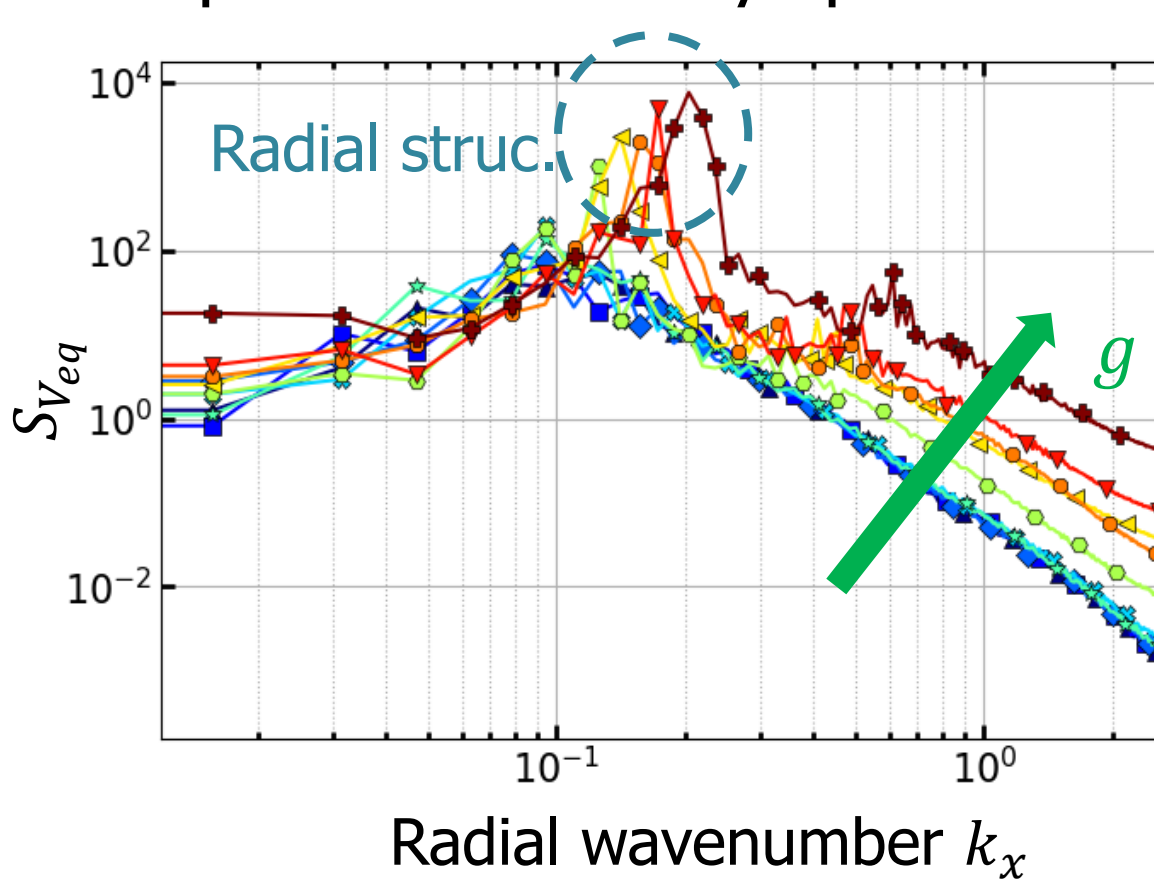
Turbulent drive: Reynolds stresses **Viscous & friction damping**

Electric:  $\Pi_E = \langle \tilde{v}_{Er} \tilde{v}_{E\theta} \rangle = -2k_y \Im(\phi_k^* \partial_x \phi_k)$

Diamagnetic:  $\Pi_* = \langle \tilde{v}_* \tilde{v}_{E\theta} \rangle = -2k_y \Im(\tau N_k^* \partial_x \phi_k)$

[Smolyakov 2000] ; [Sarazin 2021]

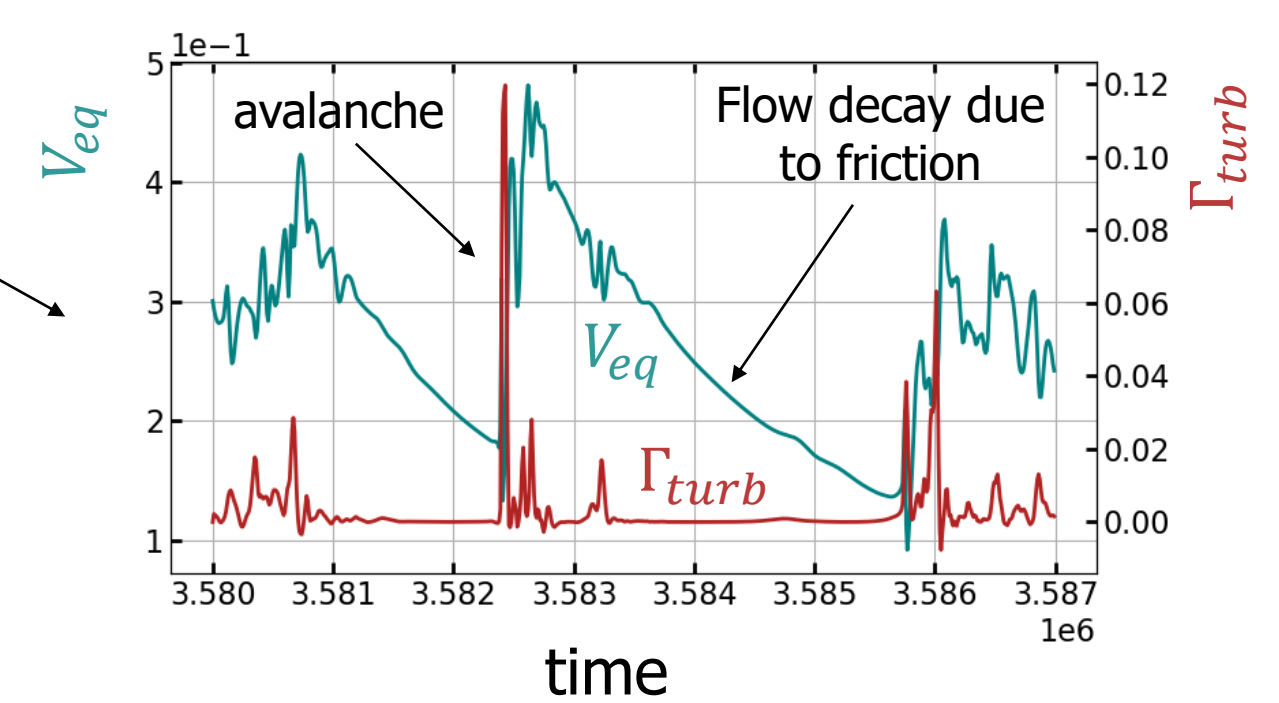
Equilibrium velocity spectrum



- ❖ Staircases expected to limit radial extension of avalanches [Dif-Pradalier 2017]

- ❖ Current simulations show that avalanches reinforce staircases instead (at large  $g$ )

- ❖ High  $g$ : Flows structured in staircases 'reactivated' by passing avalanches



- ❖ Low  $g$ : Meandering / splitting & merging events observed at steady-state

## 6. Conclusion

**Simulations**

- ❖ Reduced model for avalanche, flow & turbulence interaction
- ❖ Transition to avalanche & staircase in interchange dominated plasmas (large magnetic curvature):
  - Eddy & avalanche size similar to experiments
- ❖ Staircases appear together with avalanches
- ❖ Staircases strengthened by passing avalanches

**Experiments**

- ❖ Correlation measurements using two DBS channels
- ❖ Robust scenario & diagnostic method
- ❖ Two correlation lengths obtained close to the  $E_r$  well

**Future prospects**

- ❖ Simulations:
  - On-going additions: equilibrium flows, SOL and electromagnetic effects
- ❖ Experiments:
  - Varying  $\rho_s$  through gas scan from D to H (isotope effect) & heating scheme ⇒ explore different turbulent regimes
  - Explore experimental signatures of staircases in  $E_r$  measurements



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