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## Persistence of linear ITG mode properties in flux-driven turbulent non-linear simulations

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## Summary

**Objective:** Find a reduced description for turbulence in tokamak plasmas

**Method:** Analysis of GYSELA simulation 3D output

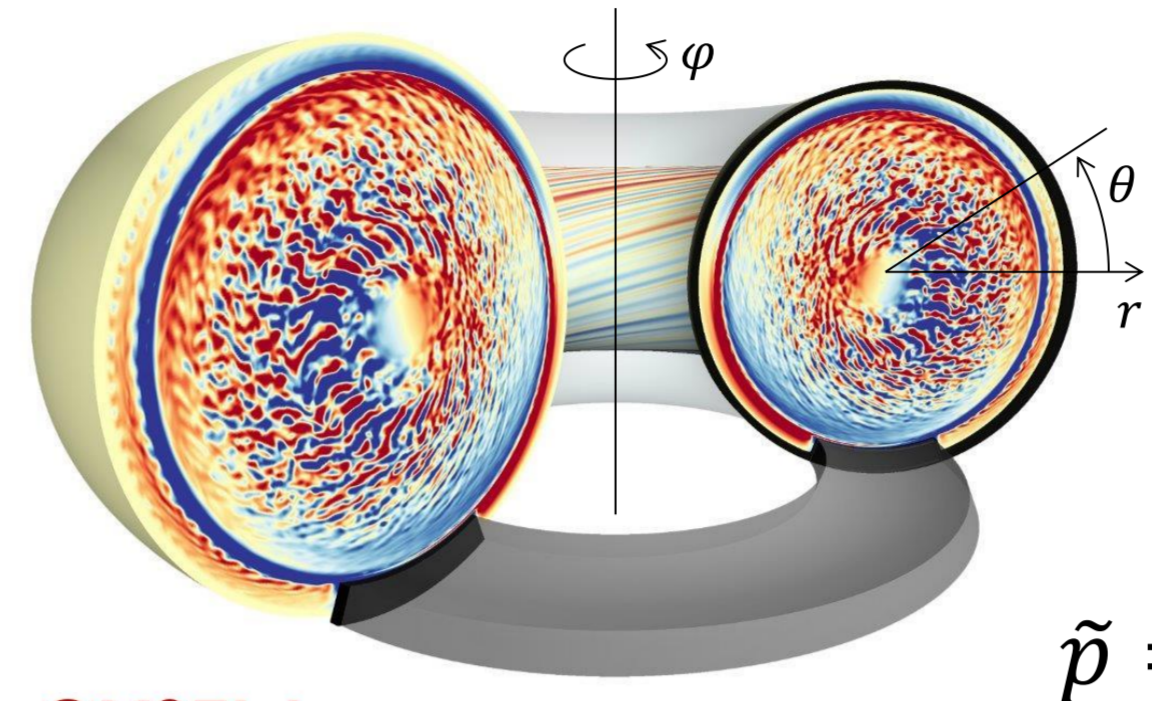
→ What are turbulent vortices' dynamics? → How to reduce the description?

**Results:**

- Zonal flows act as toroidal motion, and zonal shear acts as radial motion
- Zonal shear yields stationary tilt of turbulent eddies
- Pressure-potential phase shift distribution is narrow, around quasi-linear value
- QuaLiKiz linear prediction in qualitative agreement with GYSELA simulation

## GYSELA [Grandgirard 2016]

- GK Vlasov (5D) + Q.N
- GLOBAL = full torus, full-f
- $S_{heat} \rightarrow$  **Self-organized profiles, flows**



$$\tilde{p} = \int \left( \frac{m}{2} v_{\parallel}^2 + \mu B \right) \left( 1 - \frac{\omega - n v_{*}}{\omega - k_{\parallel} v_{\parallel} - n \omega_D} \right) F_{eq} \frac{e \tilde{\phi}}{T_{eq}}$$

## QuaLiKiz [Citrin 2017]

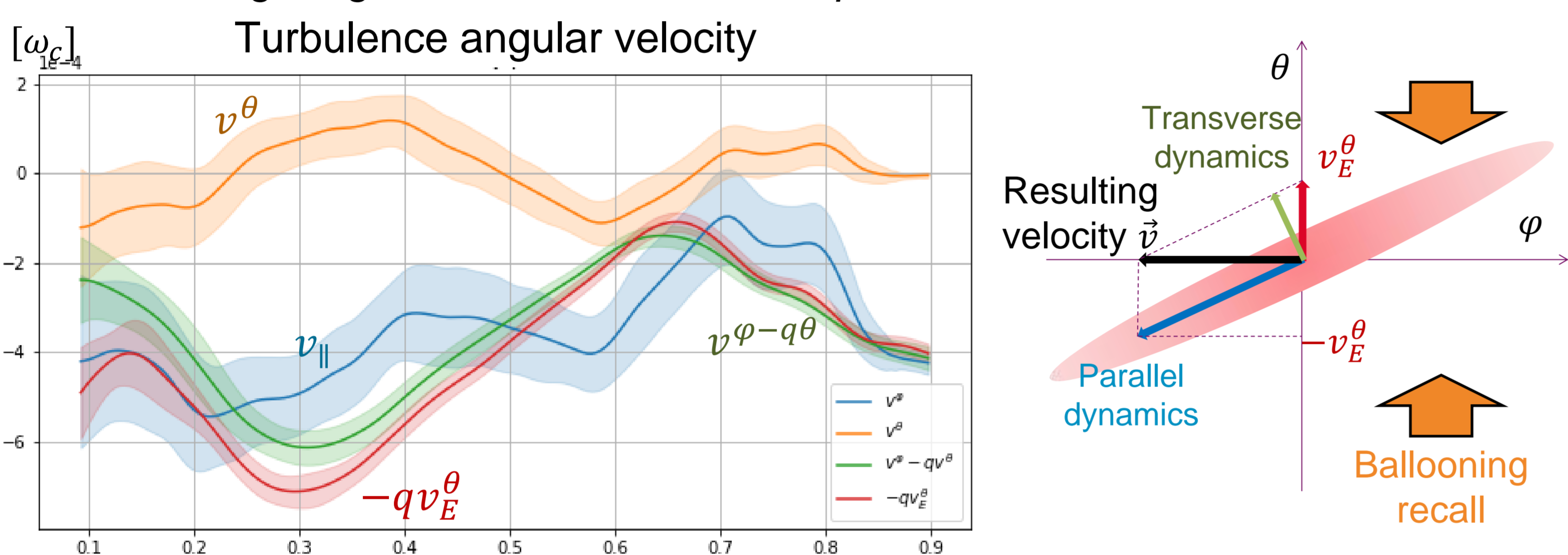
- GK quasi-linear solver
- LOCAL = flux-surface, linear
- Profile-driven
- Ad-hoc saturation rule
- **Baseline for linear effects**

## Turbulent motion due to zonal flows is toroidal

**Question:** How does turbulence move?

$$\text{Minimize } \int |\phi(t + \Delta t, \vec{x}) - \phi(t, \vec{x} + \vec{v}(t, r) \Delta t)|^2 R d\theta d\varphi \rightarrow \vec{v}(t, r) \approx \left\langle \frac{\partial \omega}{\partial \vec{k}} \right\rangle_{FS}$$

This is image registration on 3D turbulent potential data



## Zonal flow shear leads to no visible strain of turbulence

**Question:** How is turbulence shaped?

$$\text{Minimize } \int |\phi(r + \Delta r, \vec{x}) - \phi(r, \vec{x} + \vec{s}(t, r) \Delta r)|^2 R d\theta d\varphi \rightarrow s^{\theta, \varphi}(t, r) \approx \left\langle \frac{\partial k_r}{\partial k_{\theta, \varphi}} \right\rangle_{FS}$$

**Expectation**  $\frac{dk_r}{dt} = \gamma_E k_{\theta}$

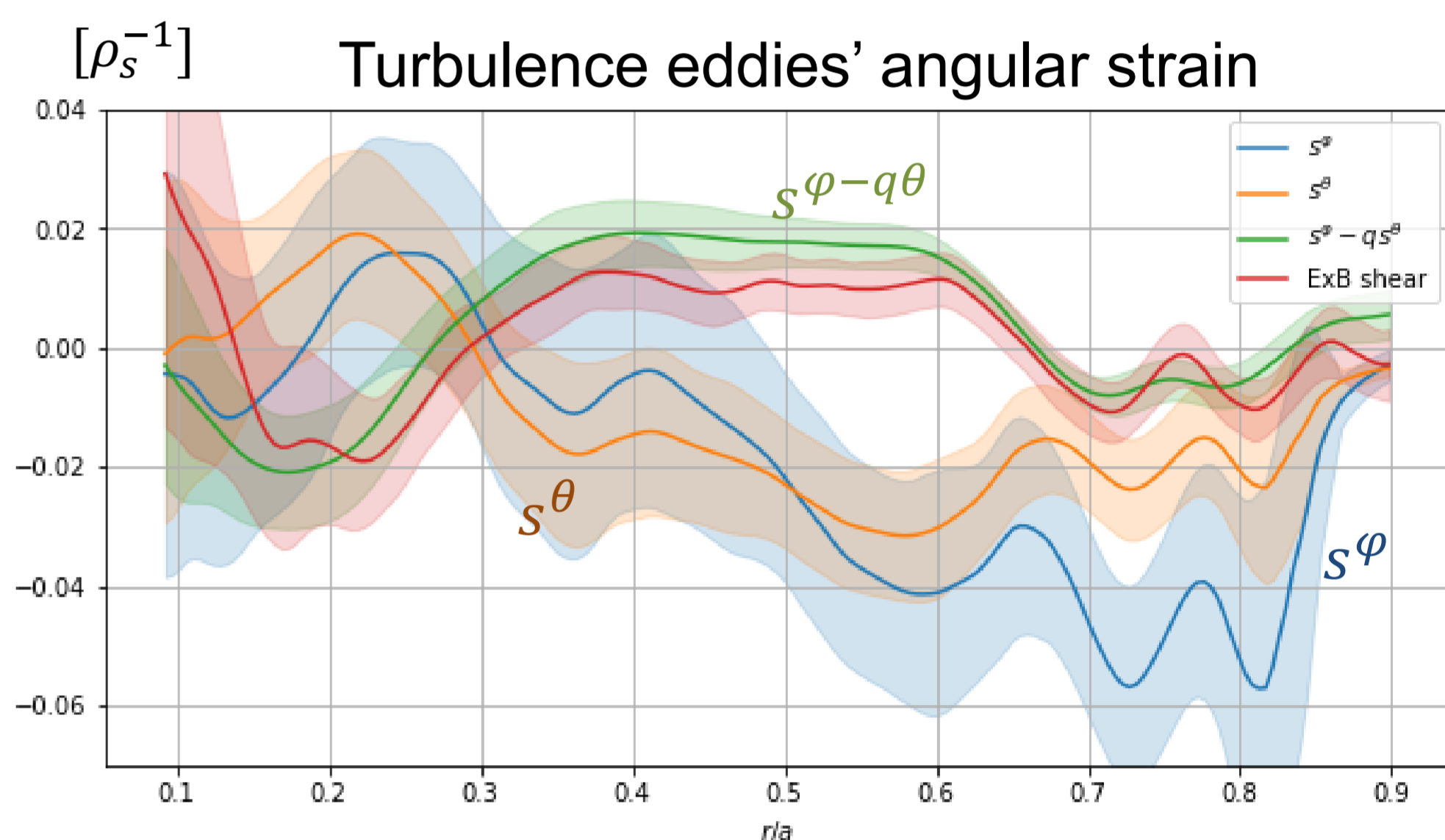
$$\rightarrow \frac{D\vec{s}}{Dt} = \partial_r \vec{v} + \dots$$

**Observation**  $s^{\varphi - q\theta} \approx -q \gamma_E$

**Linear recall does not help**

Tested as least-squares fit

$$\partial_t \vec{s} \neq \alpha(r) \partial_r \vec{v} + \beta(r) \vec{s} + \gamma(r) v^r \partial_r \vec{s} + \delta^{\vec{s}}(r)$$



## Flow maxima act as turbulence traps

ExB shear regulates turbulence [Diamond 2005]

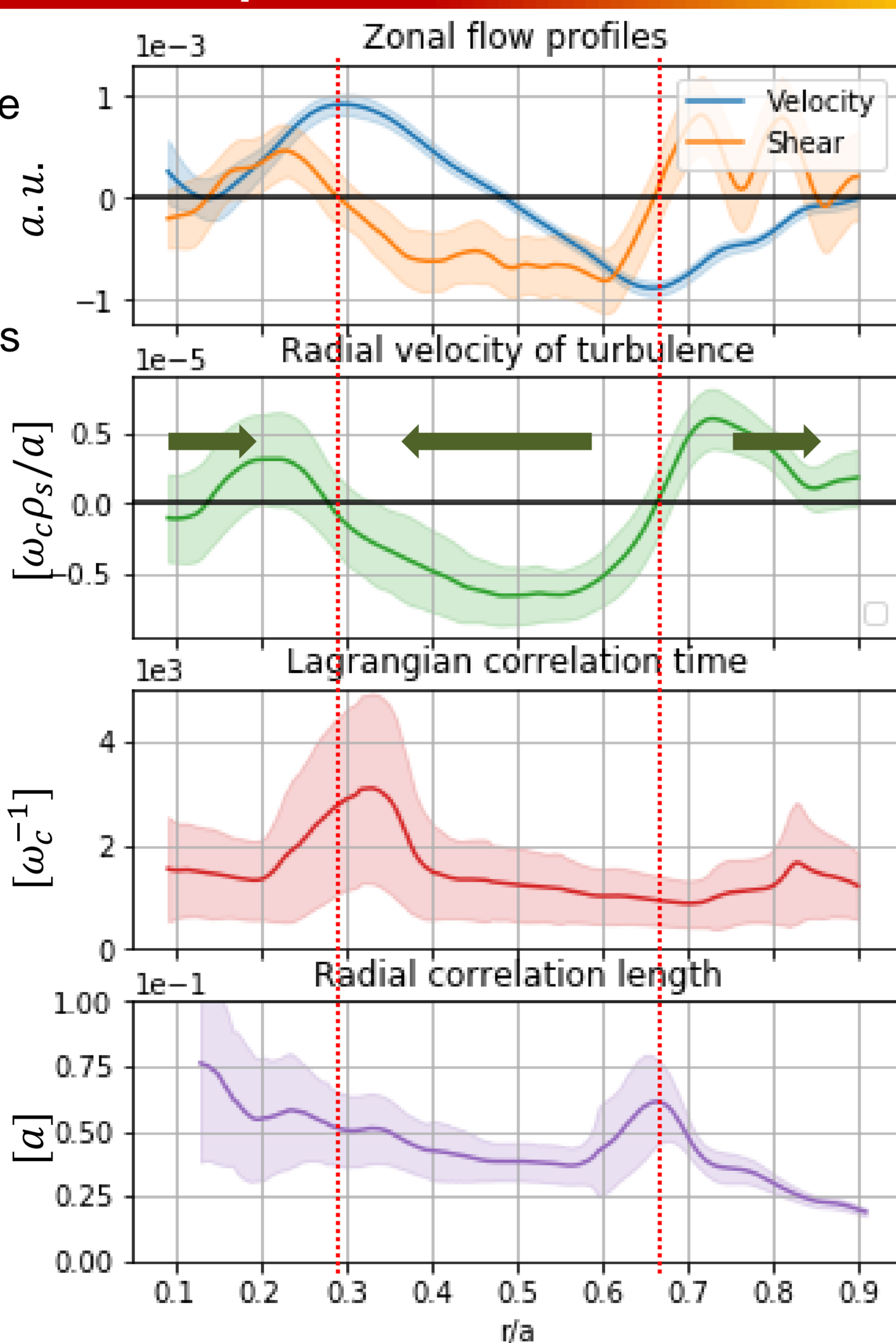
Radial turbulence velocity is governed by ExB shear [McMillan 2009, Idomura 2009]

- Zonal flow maximum → Converging radial velocity → **turbulence is trapped**
- Zonal flow minimum → Diverging radial velocity → **turbulence is stretched**

Shear sign affects turbulence

$$D \neq D_0 / (1 + \alpha \gamma_E^2)$$

[Hinton 1990]

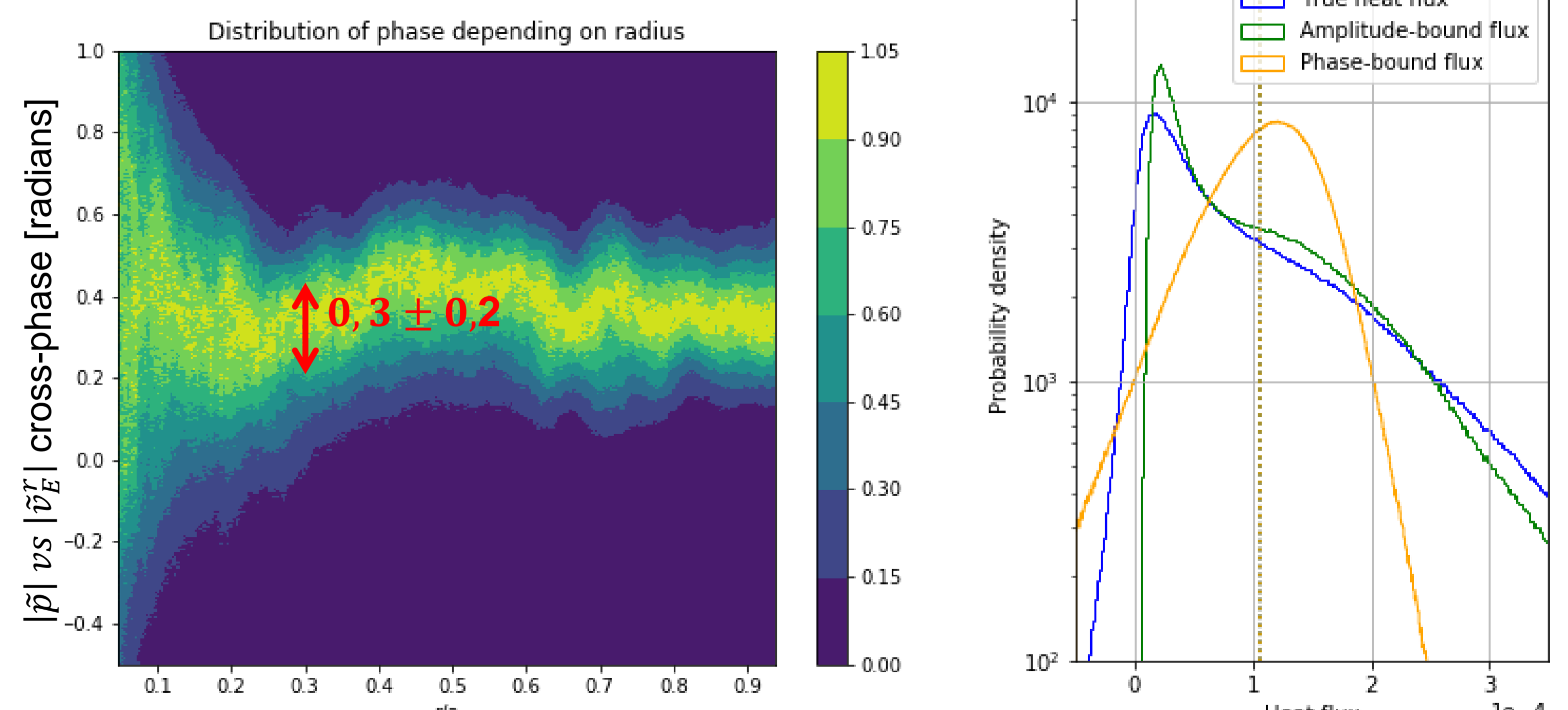


## Phase fluctuations do not carry heat flux

Turbulent heat flux decomposition

$$Q = \langle \tilde{v}_E \tilde{p} \rangle_{\varphi} = \sqrt{\langle \tilde{v}_E^2 \rangle_{\varphi} \langle \tilde{p}^2 \rangle_{\varphi}} \sin \alpha = A \sin \alpha$$

Phase histogram: low deviation → **non-critical for flux prediction**



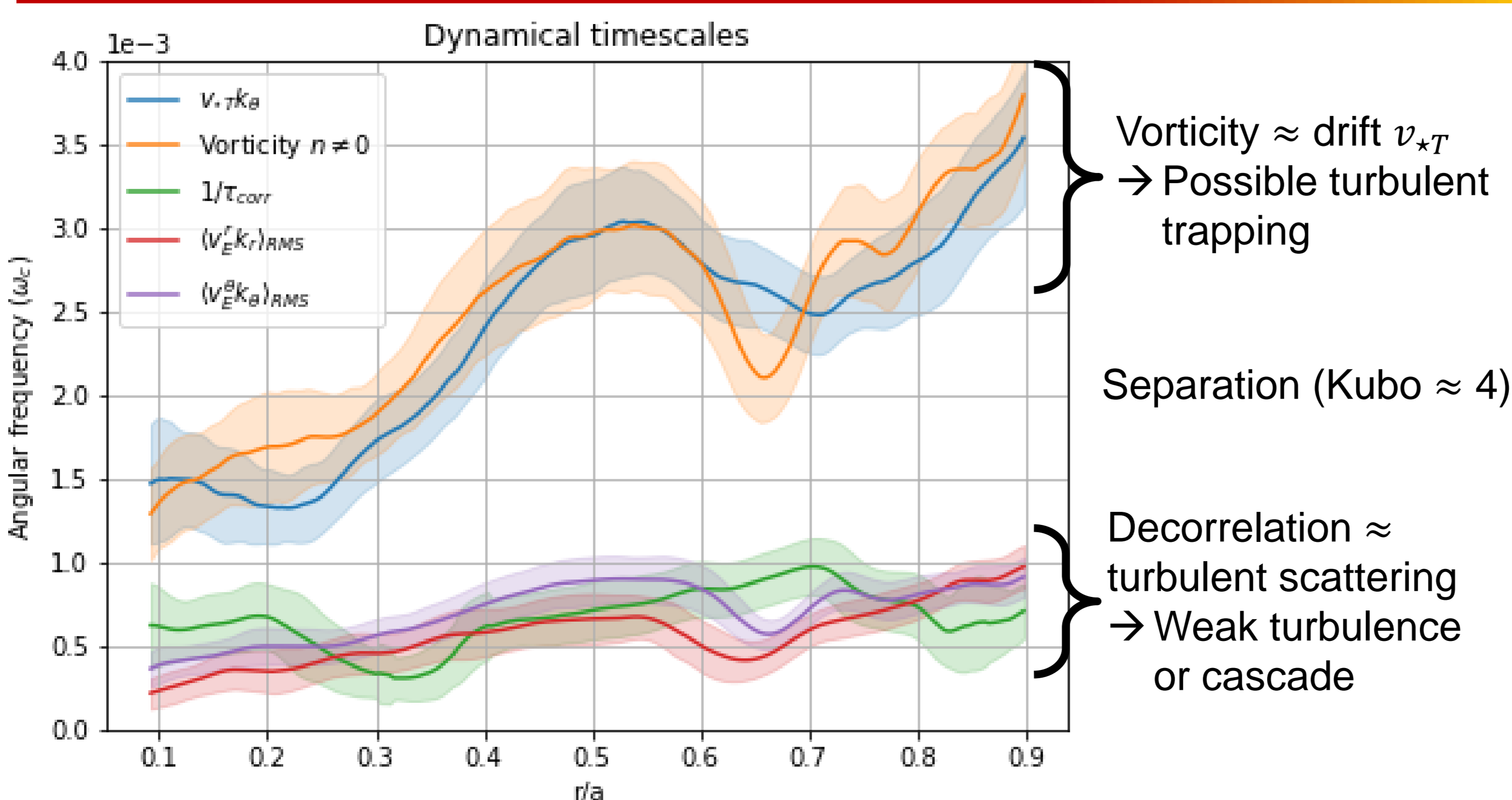
## QuaLiKiz linear response is valid in the most active region

QuaLiKiz run with GYSELA time-averaged profile  $\pm 1 \times \text{stddev}(R/L_T)$

→ QuaLiKiz predicts region  $r/a < 0.4$  as quiescent (stable or  $\gamma < 10^{-4} \omega_c$ ),

**BUT** Same region is turbulent in GYSELA

## Flow time-scales suggest coherent non-linear dynamics



## QuaLiKiz phase agrees with GYSELA dynamics [Casati 2009]

