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Key role of phase dynamics & diamagnetic drive on Reynolds stress in fusion plasma turbulence

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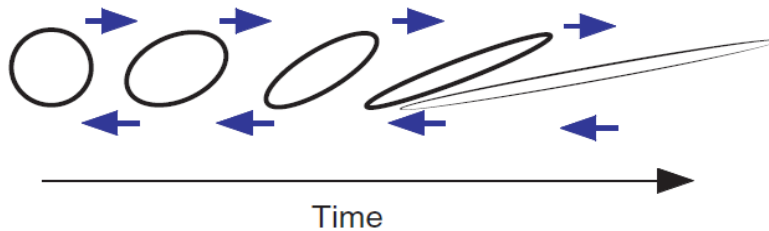
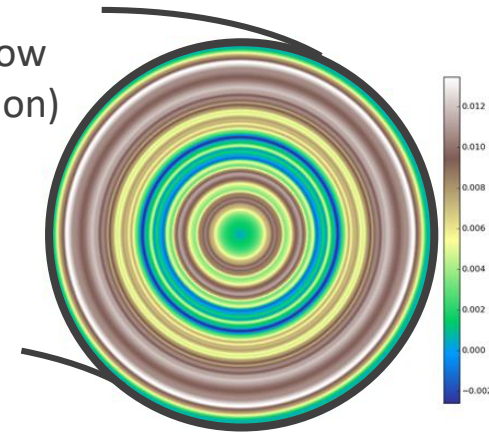
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Ack: N. Fedorczak, Ö. Gürcan, P. Hennequin, C. Passeron
Festival de Théorie 2019, Chengdu Theory Festival 2018

AAPPS-DPP, 2021/09/29

- ▶ Turbulence rotates poloidally:
mean flow velocity $V_E \sim -E_r$
- ▶ Radial shear of V_E (i.e. E_r') $\Rightarrow$ turbulent vortex decorrelation
 - $\rightarrow$ Dominant mechanism for turbulence control
 - $\rightarrow$ Transport barriers, optimized confinement

Mean poloidal flow
(GYSELA simulation)



[Biglari-Diamond-Terry 1990;
Itoh-Itoh 1996; Terry 2000]

- ▶ **Turbulence** generates **zonal & mean flows** via **Reynolds stress**
- ▶ **Issue** addressed in this talk:
What dominant mechanisms govern Reynolds stress dynamics ?

- Start from **GK equation**, focusing on **E×B advection**:

$$\partial_t \bar{f} + \{J \cdot \phi, \bar{f}\} = RHS \quad \text{with gyro-average operator } J \approx 1 + \frac{\mu}{2} \nabla_{\perp}^2$$

Poisson brackets (account for E×B advection: $\mathbf{v}_E \cdot \nabla \bar{f}$)

- Account for **quasi-neutrality** (adiabatic electrons):

$$n_0 \Omega = \langle J \cdot \bar{f} \rangle_v \approx \langle \bar{f} \rangle_v + \frac{1}{2} \nabla_{\perp}^2 p_{\perp} \quad \text{Potential vorticity } \Omega = \phi - \langle \phi \rangle - \nabla_{\perp}^2 \phi$$

- Where it comes: **transport of potential vorticity**

$$\partial_t \Omega - \nabla_{\perp, i} \{ \phi + p_{\perp}, \nabla_{\perp, i} \phi \} = \langle J \cdot RHS \rangle_v$$

[Parra-Catto PPCF 2009;
Abiteboul PoP 2011;
Ajay JPP 2020]

- Integrate & flux-surface average → equation on $\langle u_{E\theta} \rangle = \partial_r \langle \phi \rangle$

$$\frac{\partial \langle u_{E\theta} \rangle}{\partial t} + \frac{1}{r^2} \frac{\partial}{\partial r} \left[r^2 (\pi + \pi^*) \right] = rhs$$

[Diamond-Kim PoP 1991;
Smolyakov PoP 2000;
McDevitt PRL 2010]

Reynolds' stress

$$\pi = \langle \tilde{u}_{Er} \tilde{u}_{E\theta} \rangle$$

Diamagnetic Reynolds' stress

$$\pi^* = \langle \tilde{u}_r^* \tilde{u}_{E\theta} \rangle$$

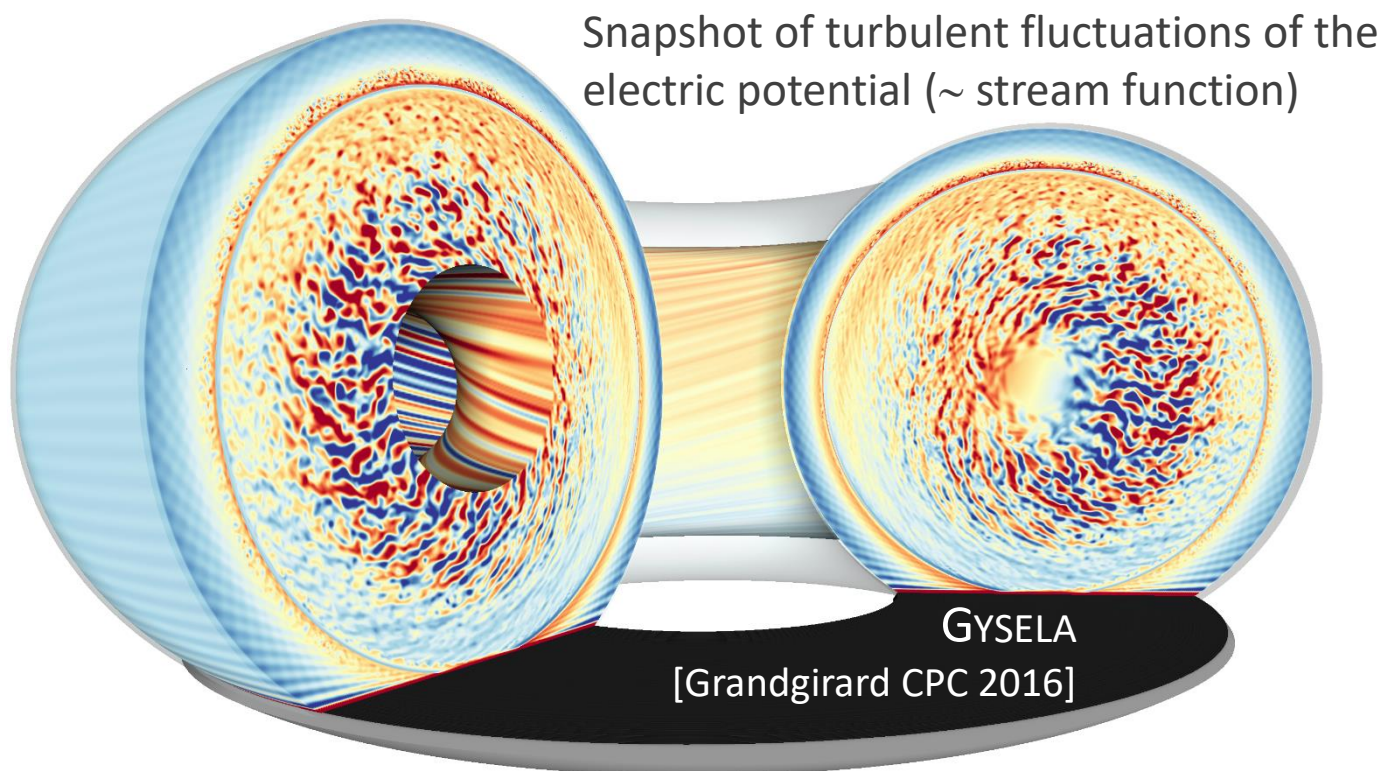
with $\begin{cases} \tilde{u}_{Er} = -\frac{1}{r} \partial_{\theta} \tilde{\phi} \\ \tilde{u}_r^* = -\frac{1}{r} \partial_{\theta} \tilde{p}_{\perp} \end{cases}$

[Sarazin, Dif-Pradalier, Garbet et al., PPCF 63 (2021) 064007]

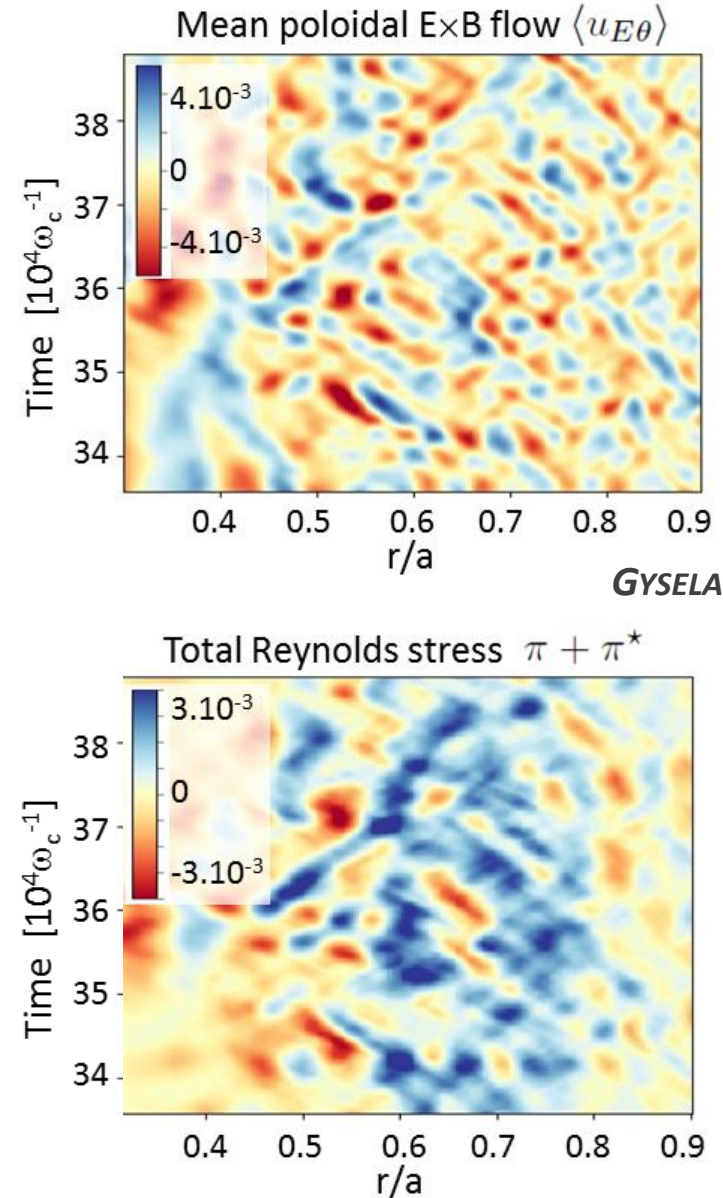
- ▶ Comparative weight & properties of
Reynolds stress $\pi = \langle \tilde{u}_{Er} \tilde{u}_{E\theta} \rangle$ *vs.*
diamagnetic Reynolds stress $\pi^* = \langle \tilde{u}_r^* \tilde{u}_{E\theta} \rangle$
 - ▶ Dynamics of the **Reynolds stress**: specific role of the **phase**
- Means:** 1st principle gyrokinetic simulations (GYSELA)
reduced nonlinear model

► Flux-driven 5D GyroKinetics

- Kinetic description $\rightarrow$ gyro-centers distribution function (Boltzmann eq.)
- Self-consistency = Quasi-Neutrality (Poisson eq.)
- Adiabatic electrons in cases under study



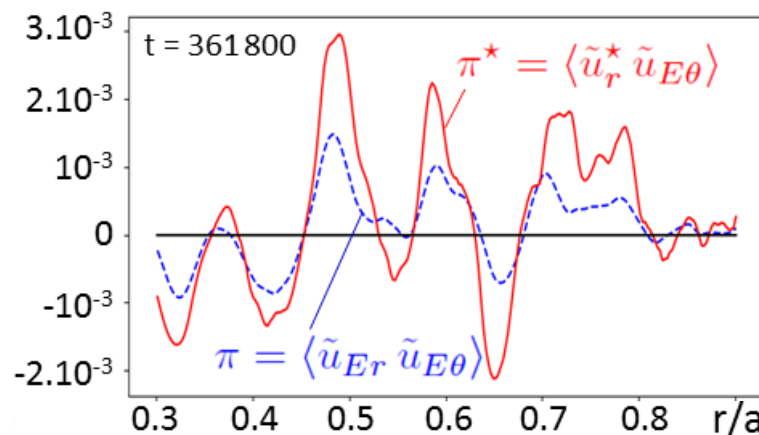
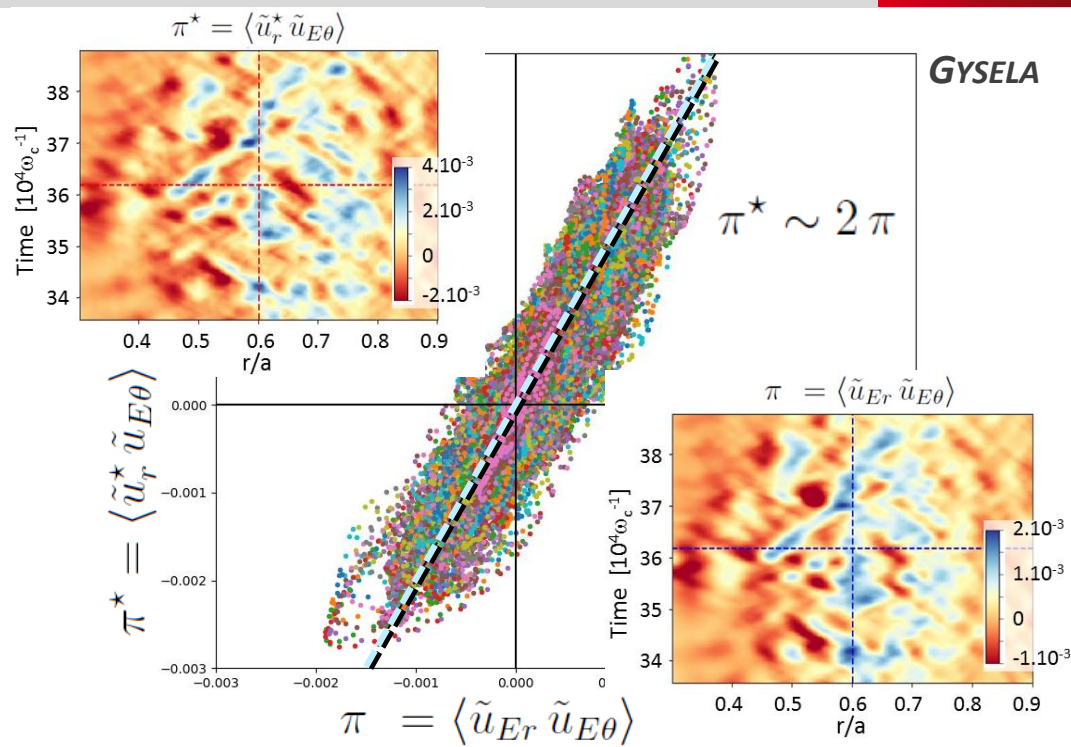
- Analysis of a statistically saturated turbulent regime
- $E \times B$ turbulent flux exhibits bursts and avalanches
- Imprint of **avalanche-like patterns** on $E \times B$ mean flow
- Similar pattern on the total Reynolds' stress $\pi + \pi^*$



► Diamagnetic Reynolds stress about 2 times larger than $E \times B$ contribution

► Diamagnetic $\pi^* = \langle \tilde{u}_r^* \tilde{u}_{E\theta} \rangle$ and $E \times B$ $\pi = \langle \tilde{u}_{Er} \tilde{u}_{E\theta} \rangle$ contributions are **in phase** (minima & maxima coincide)

► Consequence:
Pressure is NOT simply advected by $E \times B$ flow $\neq$ passive scalar
 $\Rightarrow$ possible impact on analysis of exp. data Cf. e.g. [Vermare PoP 2018]



► Let's assume $\partial_t p_{\perp} + \mathbf{u}_E \cdot \nabla p_{\perp} = 0$

Then $\hat{p}_{\perp k, \omega} = -\frac{\omega_p^*}{\omega} \hat{\phi}_{k, \omega}$

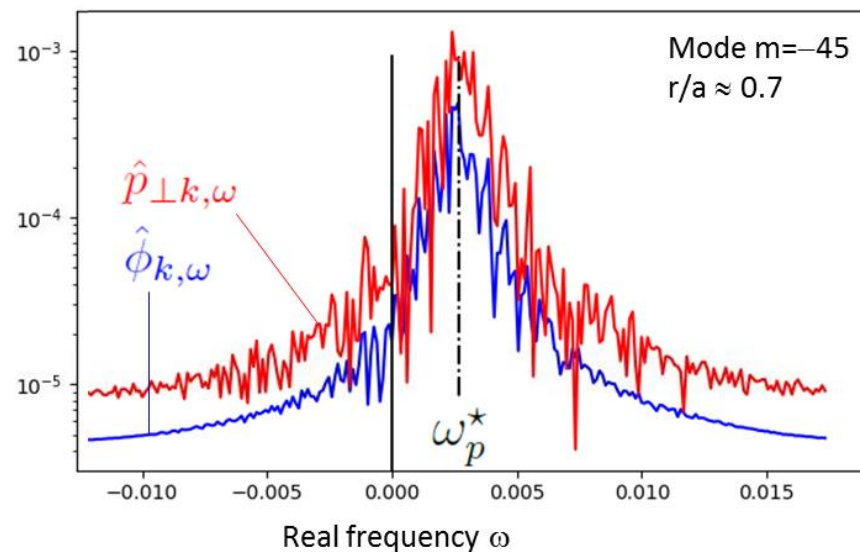
($\omega_p^* = k_{\theta} \partial_r \langle p_{\perp} \rangle$ ion diamagn. freq.)

So that $\pi^* = -\sum_{\omega, k} k_r k_{\theta} \frac{\omega_p^*}{\omega} |\hat{\phi}_{k, \omega}|^2$

Opposite to $\pi = \sum_{\omega, k} k_r k_{\theta} |\hat{\phi}_{k, \omega}|^2$

► GYSELA simulations (ITG turbulence):

- $\omega \approx \omega_p^*$



- Let's assume $\partial_t p_{\perp} + \mathbf{u}_E \cdot \nabla p_{\perp} = 0$

Then $\hat{p}_{\perp k, \omega} = -\frac{\omega_p^*}{\omega} \hat{\phi}_{k, \omega}$

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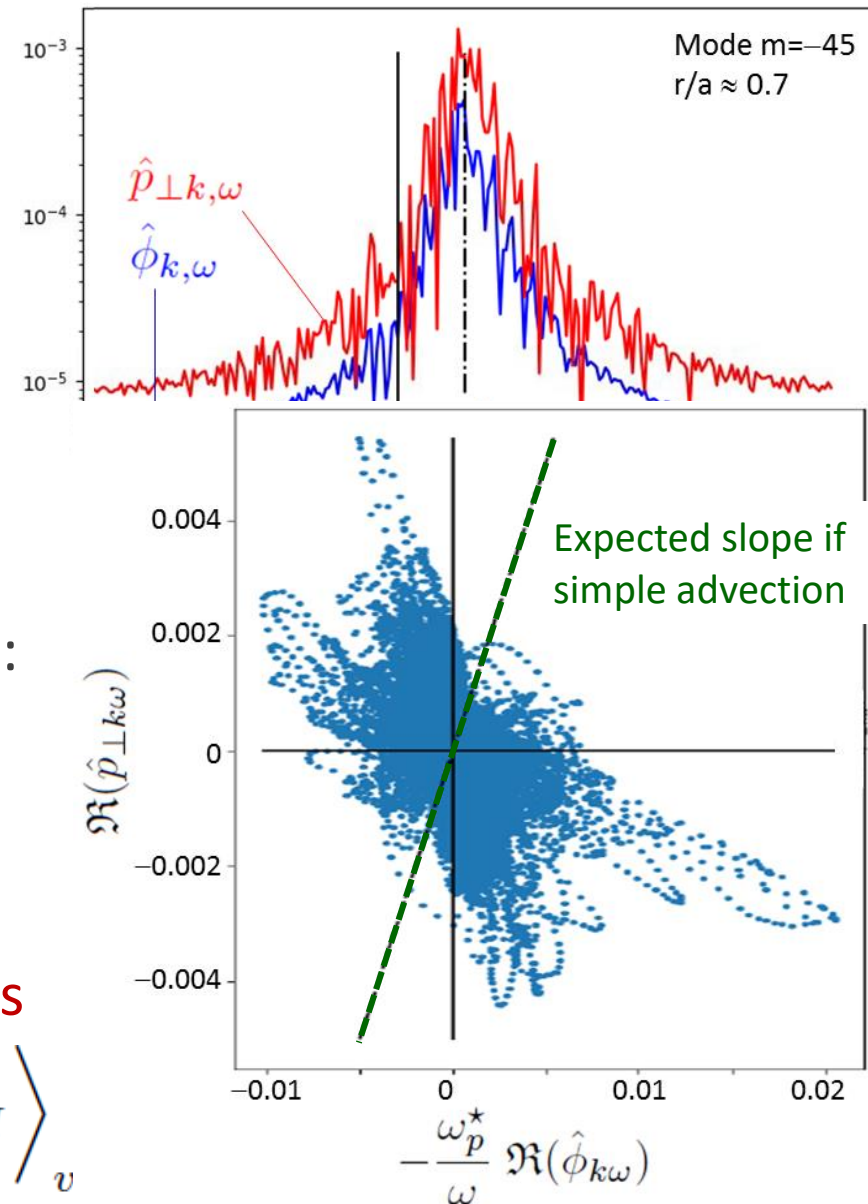
Opposite to $\pi = \sum_{\omega, k} k_r k_{\theta} |\hat{\phi}_{k, \omega}|^2$

- GYSELA simulations (ITG turbulence):

- $\omega \approx \omega_p^*$
- No clear relationship between $\hat{p}_{\perp k, \omega}$ and $\hat{\phi}_{k, \omega}$

- Linear GK relationship: resonances

$$\hat{p}_{\perp k, \omega} = - \left\langle \frac{\omega^* - \omega_d - k_{\parallel} v_{\parallel}}{\omega - \omega_d - k_{\parallel} v_{\parallel}} \mu B F_M \right\rangle_v$$



[Sarazin, Dif-Pradalier, Garbet et al., PPCF 63 (2021) 064007]

- ▶ Comparative weight & properties of
Reynolds stress $\pi = \langle \tilde{u}_{Er} \tilde{u}_{E\theta} \rangle$ vs.
diamagnetic Reynolds stress $\pi^* = \langle \tilde{u}_r^* \tilde{u}_{E\theta} \rangle$
- ▶ Dynamics of the Reynolds stress: specific role of the phase

Means: 1st principle gyrokinetic simulations (GYSELA)
reduced nonlinear model

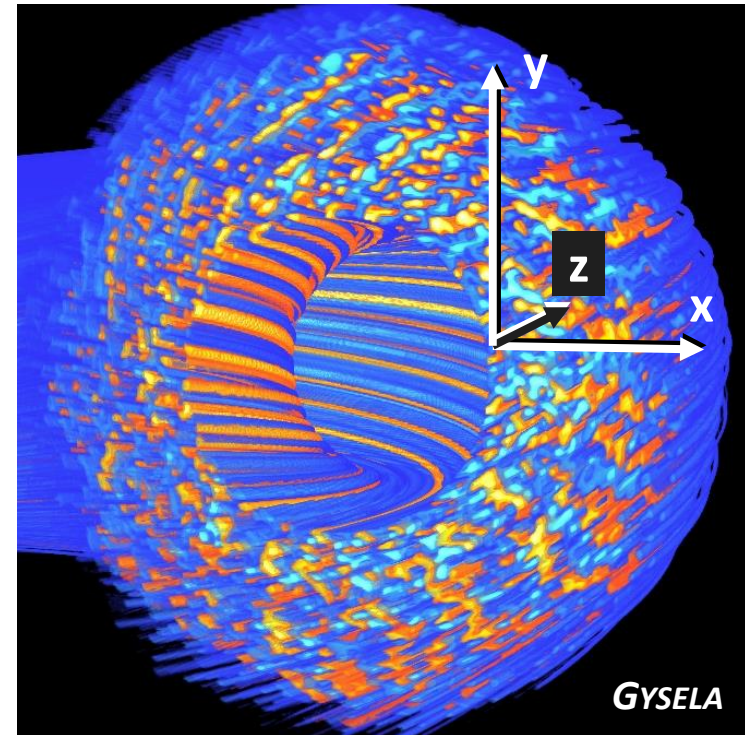
► Magnetized plasma $\mathbf{B} \neq \text{Cst}$

Isotherm, cold ions, only resonant modes $k_{\parallel}=0$

$$\begin{cases} \partial_t n + \mathbf{v}_E \cdot \nabla n = S & \text{Density} \\ \partial_t \Omega + \mathbf{v}_E \cdot \nabla \Omega + g \partial_y n = 0 & \text{Vorticity} \end{cases}$$

$$\mathbf{v}_E = \mathbf{z} \times \nabla \phi$$

$\sim 2(\rho_s/R)$ effective gravity
(only retained compressibility term
→ governs interchange instability)



► **Scale separation:** mean $\langle \dots \rangle(x,t)$
& fluctuations $\tilde{\dots}(x,y,t)$

Mean poloidal flow $V_E = \partial_x \langle \phi \rangle$

$$\begin{aligned} n(x, y, t) &= N(x, t) + \tilde{n}(x, y, t) \\ \Omega(x, y, t) &= V_E'(x, t) + \nabla_{\perp}^2 \tilde{\phi}(x, y, t) \end{aligned}$$

► Retaining **single wave vector** k_y

$$\begin{aligned} \tilde{n}(x, y, t) &= n_k e^{ik_y y} + cc \\ \tilde{\phi}(x, y, t) &= \phi_k e^{ik_y y} + cc \end{aligned}$$

[Sarazin PoP 2000;
Bian PoP 2003;
McMillan PoP 2009]

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► 1D nonlinear system (+ Dissipation)

- **Mean fields** ($\in \mathbb{R}$)
$$\begin{cases} \partial_t N &= -\partial_x \Gamma + S \\ \partial_t V_E &= -\partial_x \Pi \end{cases}$$

Turbulent Flux $\Gamma = \langle \tilde{v}_{Ex} \tilde{n} \rangle = -\Im(2k_y n_k \phi_k^*)$

Reynolds stress $\Pi = \langle \tilde{v}_{Ex} \tilde{v}_{Ey} \rangle = -\Im(2k_y \phi_k^* \partial_x \phi_k)$

- **Fluctuations** ($\in \mathbb{C}$)
$$\begin{cases} \partial_t n_k &= -ik_y (V_E n_k + v_\star \phi_k) \\ \partial_t \Omega_k &= -ik_y (V_E \Omega_k + g n_k - V_E'' \phi_k) \end{cases}$$

Potential vorticity

$$\Omega_k = (\partial_x^2 - k_y^2) \phi_k$$

Diamagnetic drift

$$v_\star = -\partial_x N$$

► **Linear instability** = "interchange" ~ Rayleigh-Bénard

$$\partial_t n_k = -ik_y (V_E n_k + v_\star \phi_k)$$

$$\partial_t \Omega_k = -ik_y (V_E \Omega_k + g n_k - V_E'' \phi_k)$$

Diamagnetic drift $v_\star = -\partial_x N$

Potential vorticity $\Omega_k = (\partial_x^2 - k_y^2) \phi_k$

► **Dispersion relation**

$$\omega_\pm - k_y V_E = \frac{k_y V_E''}{2k_\perp^2} \pm \frac{k_y}{k_\perp} \left(\frac{V_E''^2}{4k_\perp^2} - g v_\star \right)^{1/2}$$

Doppler shift

Stabilization
⇒ Instability Threshold

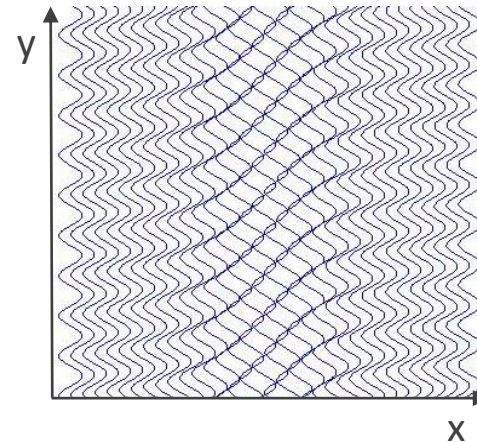
Instability drive = curvature
 × mean gradient
 → **Linear growth rate γ**

$$V_E = Cst \Rightarrow \gamma = \frac{k_y}{k_\perp} \sqrt{g v_\star}$$

- Discriminate **phase** and **amplitude** of fluctuations

$$\begin{cases} n_k = |n_k| e^{i\varphi_n} \\ \phi_k = |\phi_k| e^{i\varphi_\phi} \end{cases} \Rightarrow \begin{cases} \Gamma = -2k_y |n_k| |\phi_k| \sin \Delta\varphi_{n\phi} \\ \Pi = -2k_y |\phi_k|^2 \partial_x \varphi_\phi \end{cases}$$

Phase gradient $\partial_x \varphi_\phi$
 $\equiv$ Phase shift of k_y waves

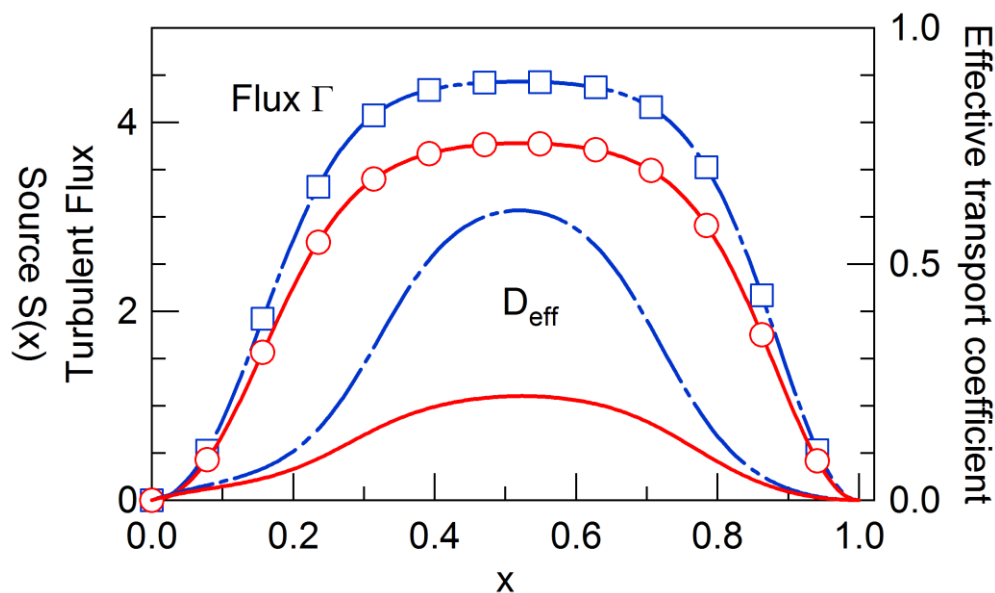
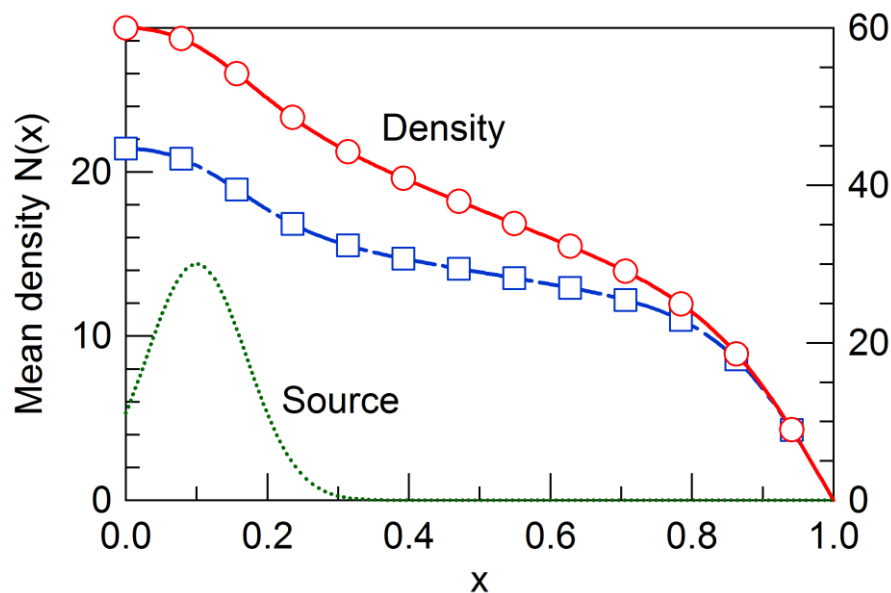
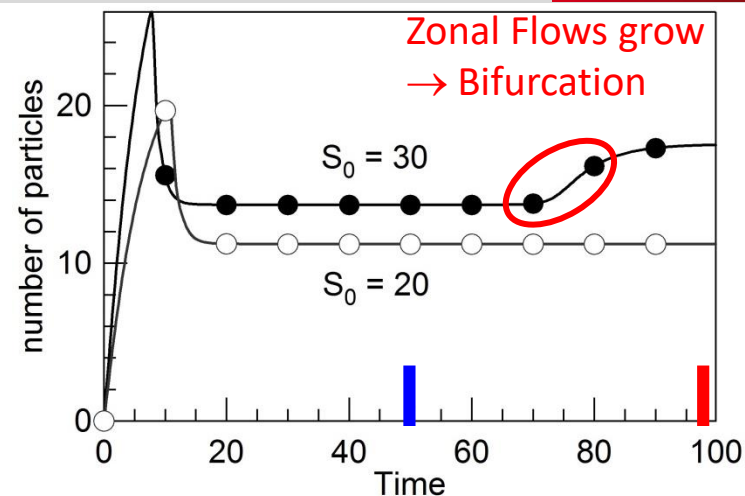


- Reynolds' stress Π can grow due to
- Amplitude $|\phi_k|^2$
 - Phase gradient $\partial_x \varphi_\phi \sim k_x$

Note: phase curvature already identified as a possible key player
*"phase patterning can generate ZF w/o
 turbulence inhomogeneity"*: $\partial_x \Pi \sim |\phi_k|^2 \partial_x^2 \varphi_\phi$

[Z. Guo, P. Diamond PRL 2016;
 Xu NF 2020]

- **Zonal Flows** are excited above a threshold in source magnitude S_0
- Turbulence magnitude & effective transport are reduced at their onset



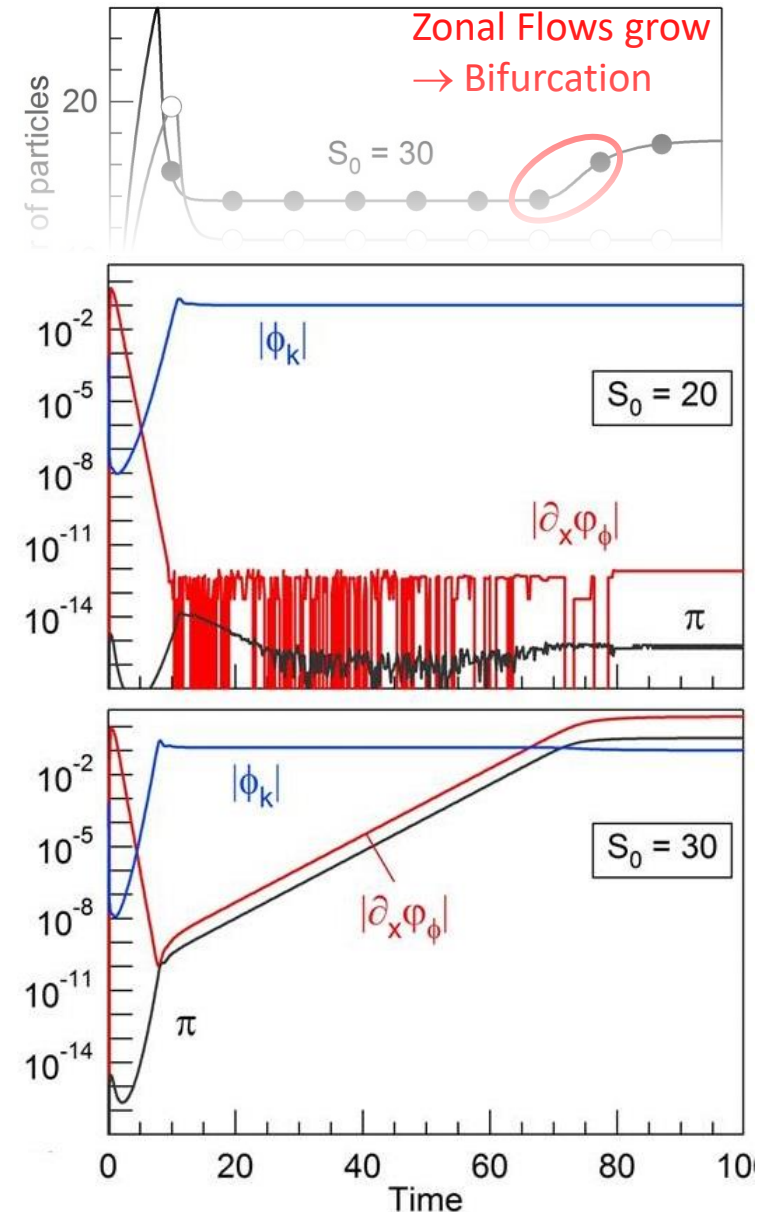
- **Zonal Flows** are excited above a threshold in source magnitude S_0
- Turbulence magnitude & effective transport are reduced at their onset
- **ZF are driven by an instability of the phase gradient** (reminiscent of the tilting instability)

[Drake PFB 1992; Guzdar PFB 1993;
Rosenbluth PoP 1994; Fedorczak PPCF 2013]
- Estimate of phase instability growth rate

$$\begin{cases} \frac{\partial(\partial_x \varphi_\phi)}{\partial t} = -k_y \frac{\partial V_E}{\partial x} & \Leftrightarrow \frac{dk_r}{dt} = -k_\theta V_E' \\ \frac{\partial V_E}{\partial t} = 2k_y \frac{\partial}{\partial x} (|\phi_k|^2 \partial_x \varphi_\phi) \end{cases}$$

$$\Rightarrow \frac{\partial^2(\partial_x \varphi_\phi)}{\partial t^2} \approx \boxed{-2k_y^2 \frac{\partial^2 |\phi_k|^2}{\partial x^2}} \partial_x \varphi_\phi$$

$\sim (\text{phase instability growth rate})^2$

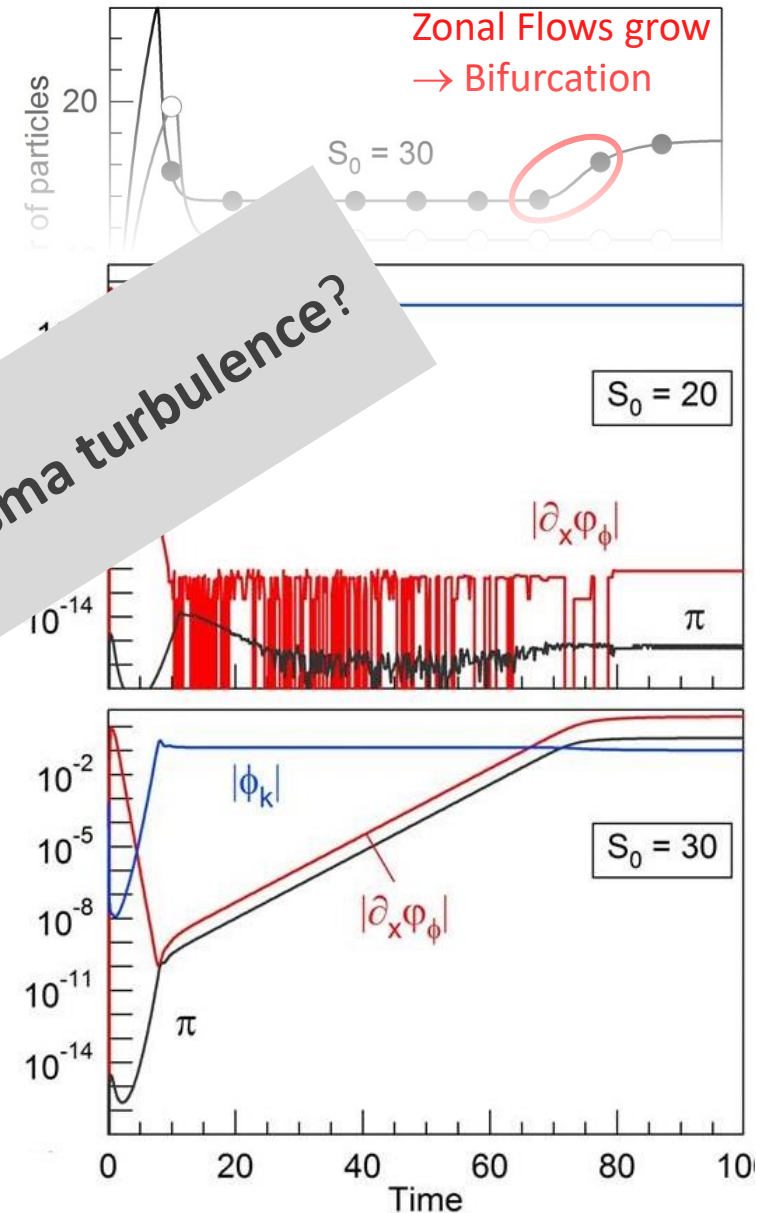


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[Drake PFB 1992]
Rosenbluth PoP 1994

- Estimate of phase instability growth rate

$$\begin{aligned} \frac{\partial(\partial_x \varphi_\phi)}{\partial t} &= -k_\theta V_E' \\ \frac{\partial V_E}{\partial t} &= 2k_y \frac{\partial}{\partial x} (\partial_x \varphi_\phi) \Rightarrow \frac{\partial^2(\partial_x \varphi_\phi)}{\partial t^2} \approx \boxed{-2k_y^2 \frac{\partial^2 |\phi_k|^2}{\partial x^2}} \partial_x \varphi_\phi \\ &\sim (\text{phase instability growth rate})^2 \end{aligned}$$



- Similar decomposition with **3D output GYSELA data** (ion turbulence)

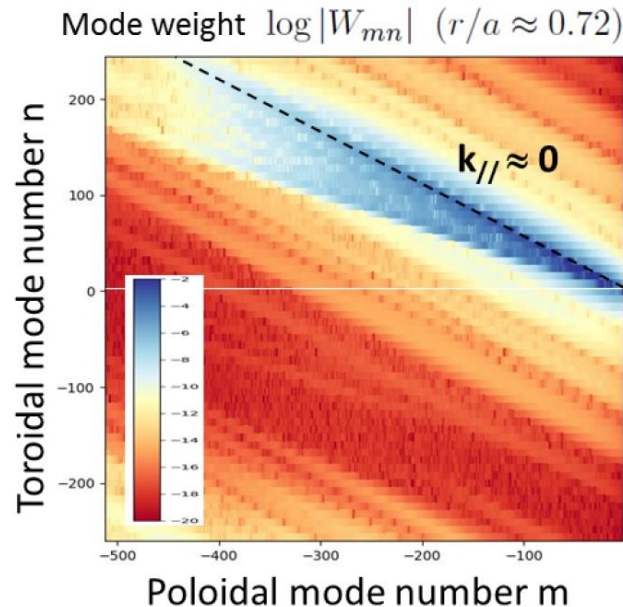
$$\Pi = - \sum_{m>0,n} \frac{2m}{r} |\hat{\phi}_{mn}|^2 \partial_r \varphi_{mn}^\phi = \sum_{m>0,n} \Pi_{mn} \quad \begin{array}{l} \text{2D Fourier decomposition} \\ (m,n) = (\text{poloidal, toroidal}) \\ \text{mode numbers} \end{array}$$

$$= \mathcal{I}(r,t) \varphi'(r,t) \Delta(r,t)$$

Turbulence intensity

$$\sum_{m>0,n} \frac{2m}{r} |\hat{\phi}_{mn}|^2$$

$$\text{Phase gradient: } \varphi'(r,t) = - \sum_{m>0,n} W_{mn} \partial_r \varphi_{mn}^\phi$$



$$W_{mn}(r) = \frac{\langle |\Pi_{mn}| \rangle_t}{\langle \Pi \rangle_t}$$

- Similar decomposition with **3D output GYSELA data** (ion turbulence)

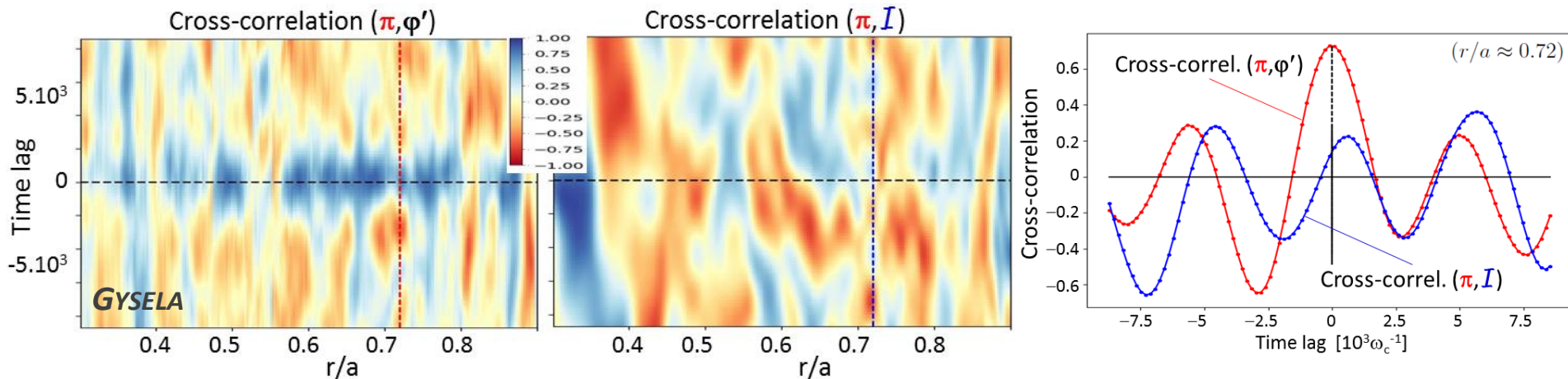
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$$= \mathcal{I}(r,t) \varphi'(r,t) \Delta(r,t)$$

Turbulence intensity

Phase gradient: $\varphi'(r,t) = - \sum_{m>0,n} W_{mn} \partial_r \varphi_{mn}^\phi$

- Reynolds stress Π well correlated with φ' , not with $\mathcal{I}$
 $\Rightarrow$ phase dynamics is critical



► **Zonal & mean flows** excited by turbulence

- Reynolds stress $\pi = \langle \tilde{u}_{Er} \tilde{u}_{E\theta} \rangle \approx -\frac{1}{B^2 r} \langle \partial_\theta \tilde{\phi} \partial_r \tilde{\phi} \rangle$
- Diamagnetic Reynolds stress $\pi^* = \langle \tilde{u}_r^* \tilde{u}_{E\theta} \rangle \approx -\frac{1}{enB^2 r} \langle \partial_\theta \tilde{p}_\perp \partial_r \tilde{\phi} \rangle$

► **Diamagnetic Reynolds stress in phase with & larger than E×B RS**

- Pressure does not behave as a passive scalar
- Numerical evidence of its **critical role in the build up of large scale flows at the plasma boundary** → cf. talk **Dif-Pradalier** (this conf.)
- Experimental evidence? Role in triggering transport barriers?

► **Reynolds stress dynamics governed by the phase gradient**

- Growing evidence that phase is a key ingredient to RS drive
- **Robustness** w.r.t. turbulence properties (e.g. electron turbulence)?
- Role of phase instab. in triggering **staircases / transport barriers?**
- What mechanism governs the **transport of phase, if any ?**

Back up slides

► Drift velocities $\mathbf{u}_{\perp}^{(1)} = \mathbf{u}_E + \mathbf{u}_i^* = \frac{\mathbf{B} \times \nabla \phi}{B^2} + \frac{\mathbf{B} \times \nabla p_{\perp}}{enB^2}$

$$\mathbf{u}_{\perp}^{(2)} = \mathbf{u}_{pol} \approx -\frac{m_i}{eB^2} [\partial_t + (\mathbf{u}_E + \mathbf{u}_i^*) \cdot \nabla] \nabla_{\perp} \phi$$

► Charge conservation $\nabla \cdot \mathbf{j} = 0$

$$\begin{aligned} \nabla \cdot \mathbf{j}_{pol} &\approx -\frac{nm_i}{B^2} (\partial_t + \mathbf{u}_E \cdot \nabla) \nabla_{\perp}^2 \phi - \frac{m_i}{eB^3} \nabla \cdot \left[\left(\frac{\mathbf{B} \times \nabla p_{\perp}}{B} \cdot \nabla \right) \nabla_{\perp} \phi \right] \\ &\approx -\frac{nm_i}{B^2} \left(\partial_t \nabla_{\perp}^2 \phi + \frac{1}{B} \{ \phi, \nabla_{\perp}^2 \phi \} \right) \\ &\quad - \frac{m_i}{eB^3} \{ \nabla_{\perp, i} p_{\perp}, \nabla_{\perp, i} \phi \} + \{ p_{\perp}, \nabla_{\perp}^2 \phi \} \end{aligned}$$

~ divergence of $\pi^* = \langle \tilde{u}_r^* \tilde{u}_{E\theta} \rangle$

~ divergence of $\pi = \langle \tilde{u}_{Er} \tilde{u}_{E\theta} \rangle$