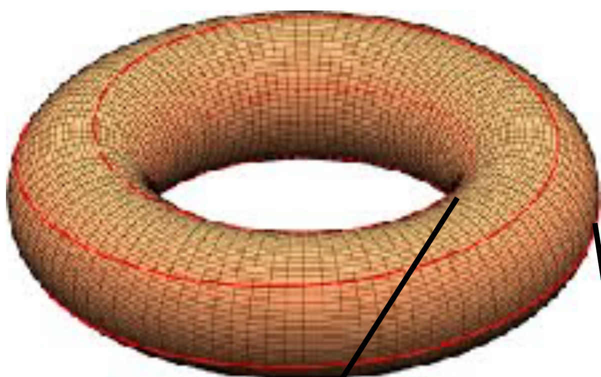
EASW8 (Daejeon, Korea) July 30 (2018)

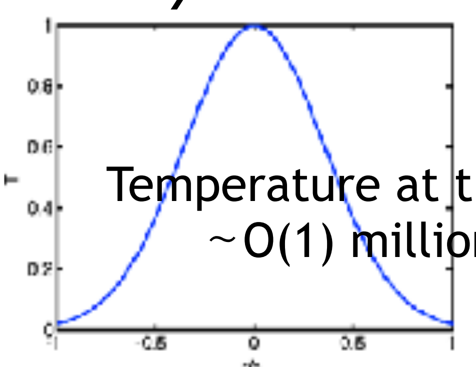
Spatio-temporal dynamics of turbulence coupling with zonal flows

**M. Sasaki[1,2] , T. Kobayashi[3] , K. Itoh[2,3,4] ,
N. Kasuya[1,2] , Y. Kosuga[1,2] , A. Fujisawa[1,2] ,
S. Inagaki[1,2] , S.-I. Itoh[1,2,5]**

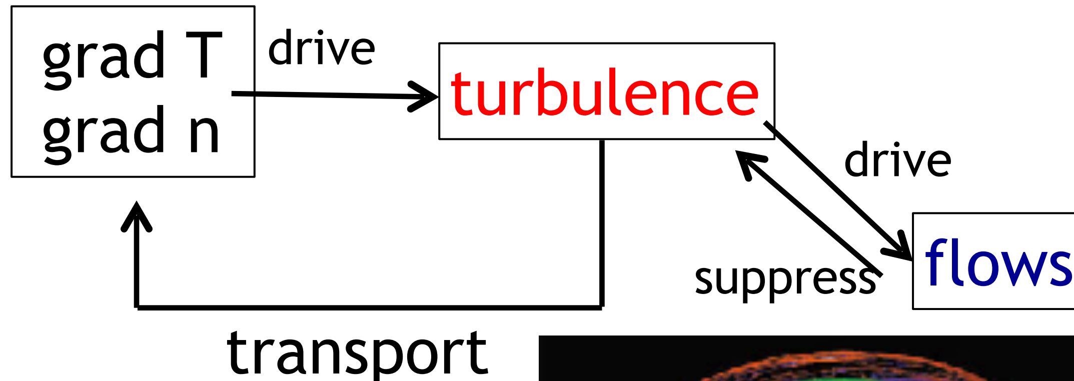
(1) Research Institute for Applied Mechanics, Kyushu Univ.
(2) Research Center for Plasma Turbulence, Kyushu Univ.
(3) National Institute for Fusion
(4) Institute of Science and Technology Research, Chubu Univ.

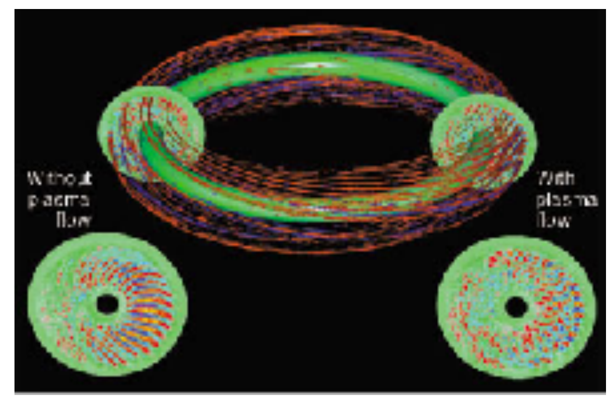
Plasma profile and turbulence





Temperature at the core
~O(1) million degree



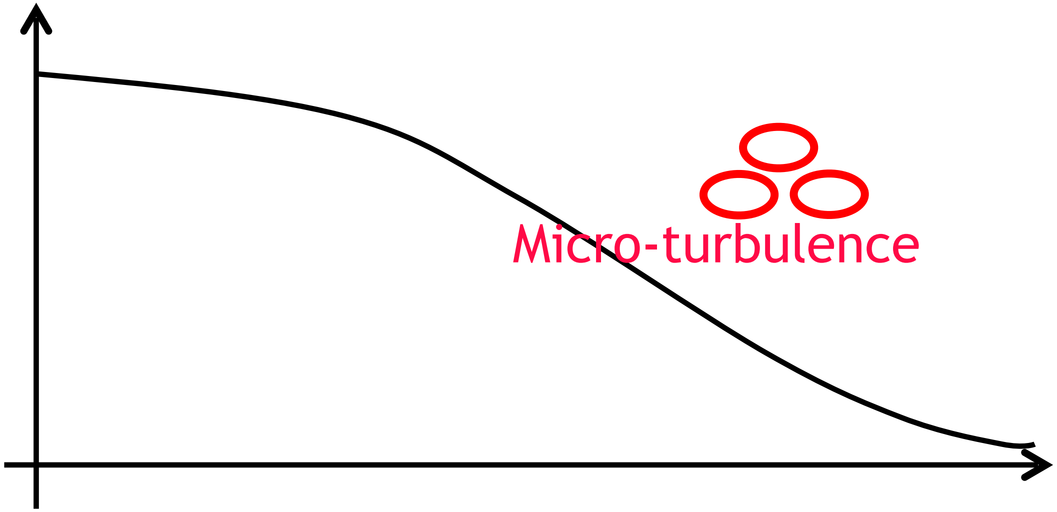


Transport is dominated by turbulence

In order to control the plasma profiles,
we have to understand
how the turbulence profile is determined.

How is the turbulence profile is determined?

interaction with sheared flows & turbulence propagation

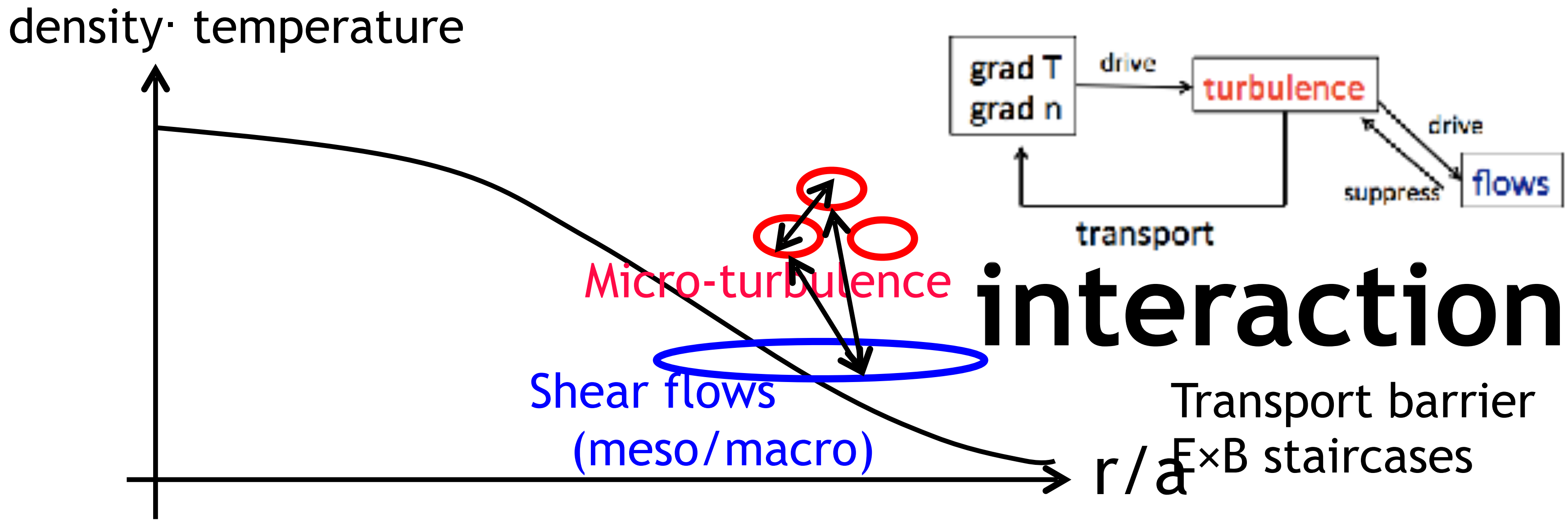


·How does the turbulence interact with sheared flows

·How does the turbulence propagate?

How is the turbulence profile is determined?

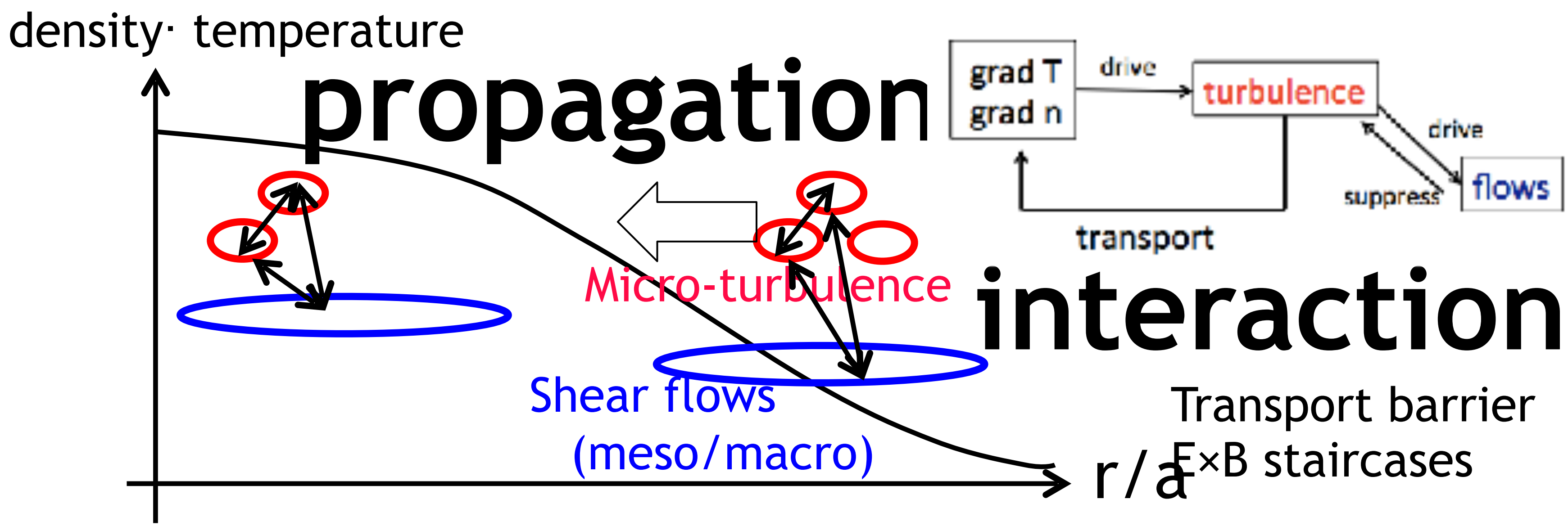
interaction with sheared flows & turbulence propagation



·How does the turbulence interact with sheared flows
·How does the turbulence propagate?

How is the turbulence profile is determined?

turbulence propagation & interaction with sheared flows

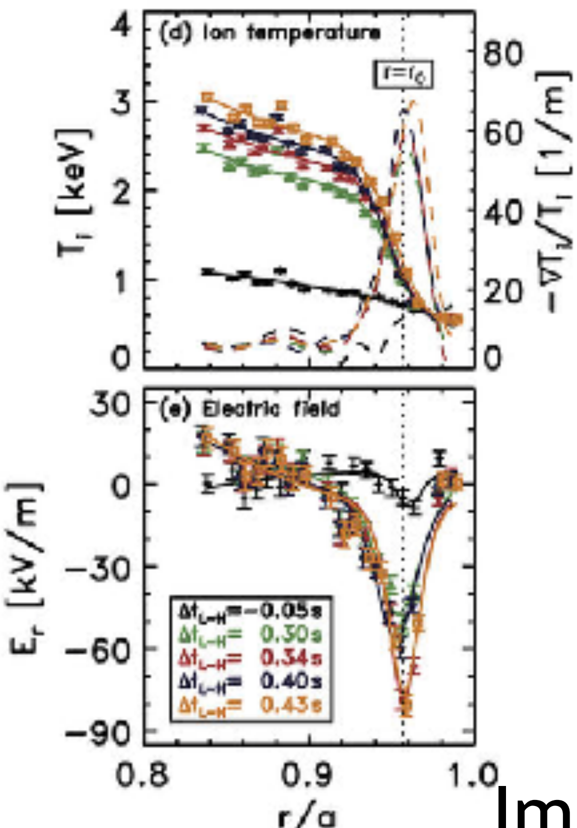


·How does the turbulence interact with sheared flows

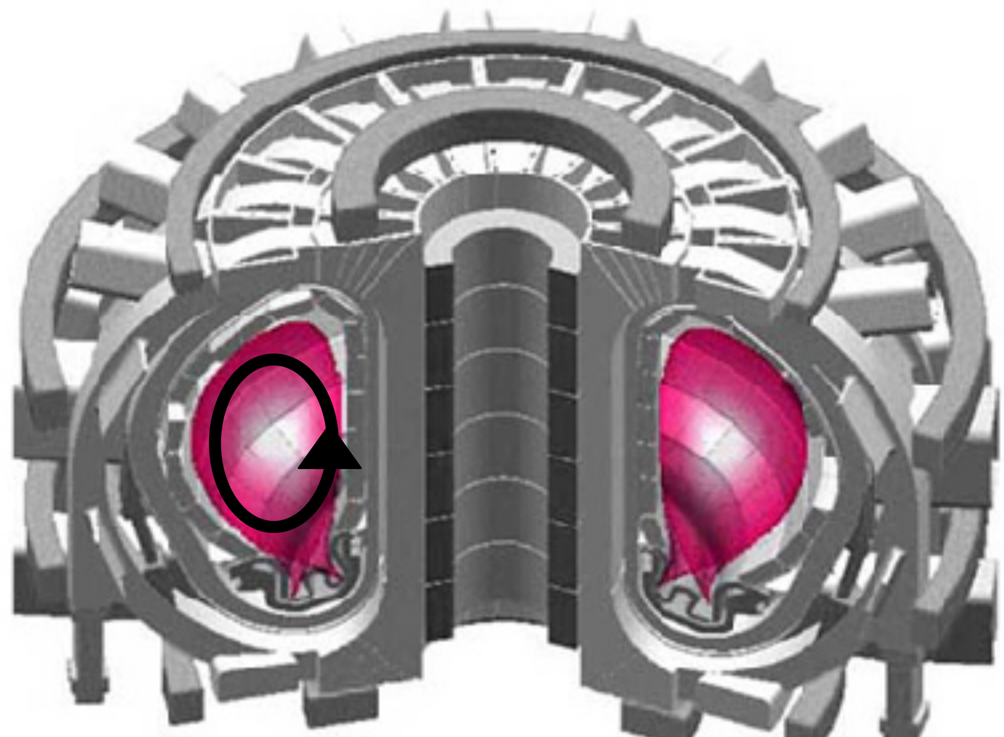
·How does the turbulence propagate?

How the turbulence interacts with sheared flows

Where in the shear flows is the turbulence suppresse



Kamiya, Scie. Rep ‘16

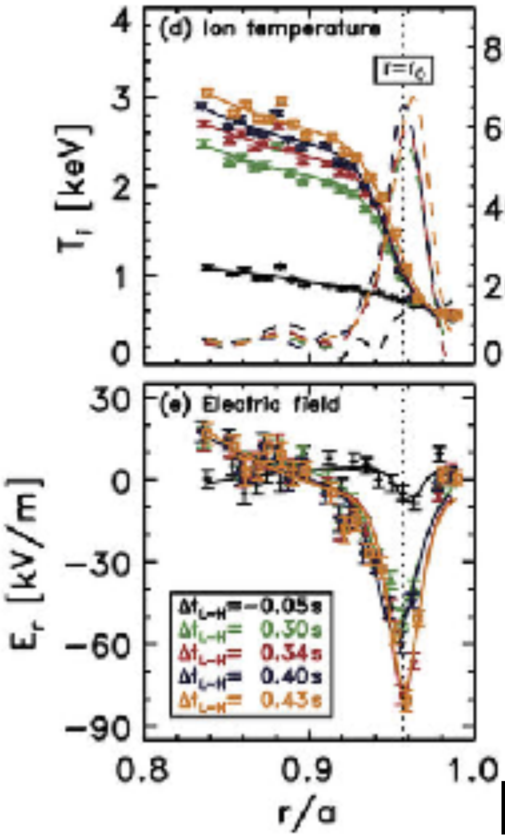


Importance of the flow shear and curvatu
has been pointed out experimentally.

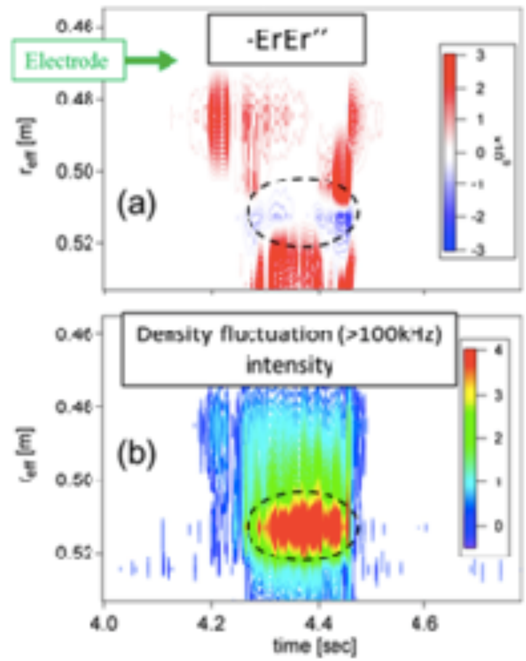
→Theory??

How the turbulence interacts with sheared flows

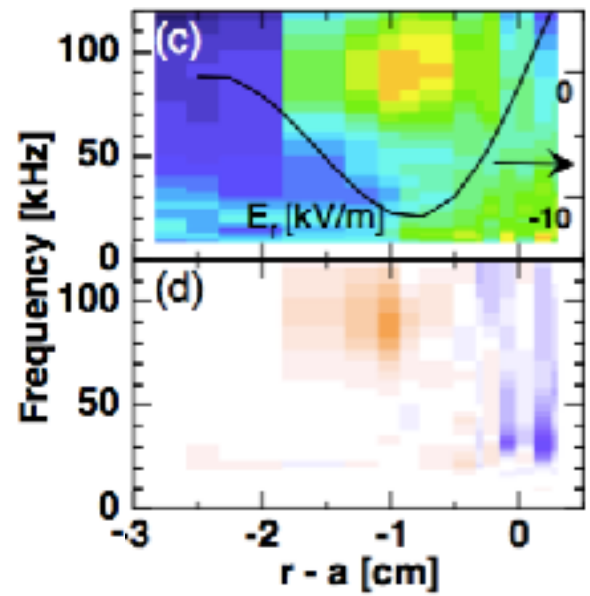
Where in the shear flows is the turbulence suppressed



Kamiya, Scie. Rep '16



Tokuzawa, PoP'14



Kobayashi, Sci. Rep. '17

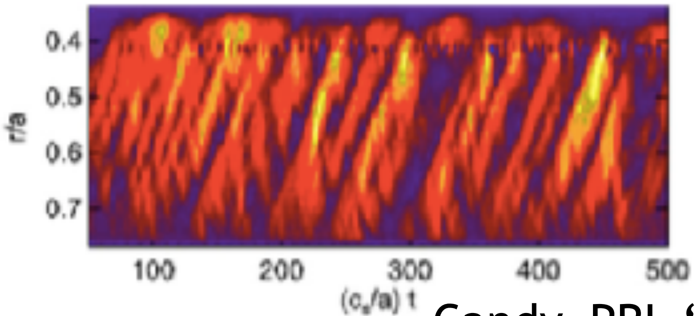
Importance of the flow shear and curvatu
has been pointed out experimentally.

→Theory??

How the turbulence propagates

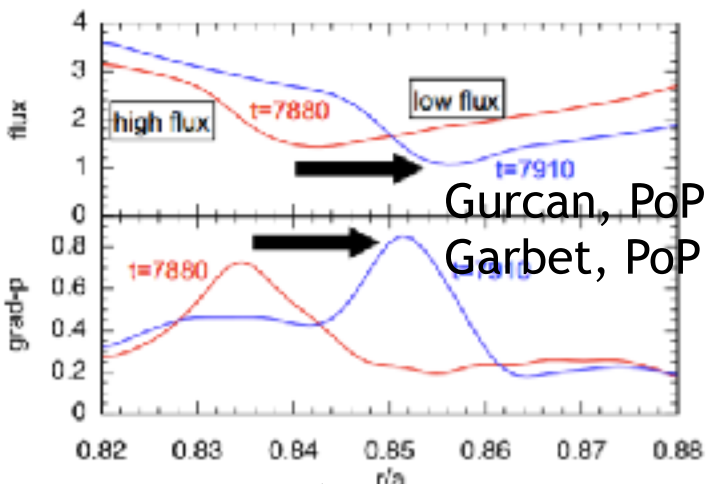
Avalanche

Diamond, PoP ‘02



Candy, PRL ‘03

Turbulence spreading

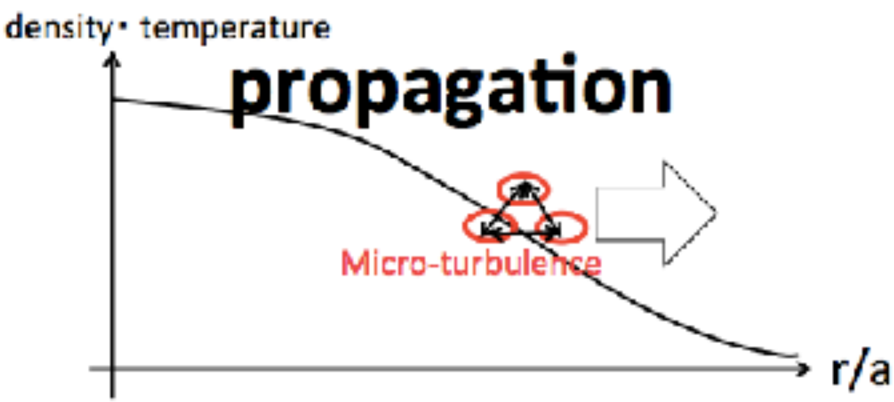


Gurcan, PoP ‘05
Garbet, PoP ‘07

Sugita, PPCF ‘12

Ballistic propagation of grad & turb

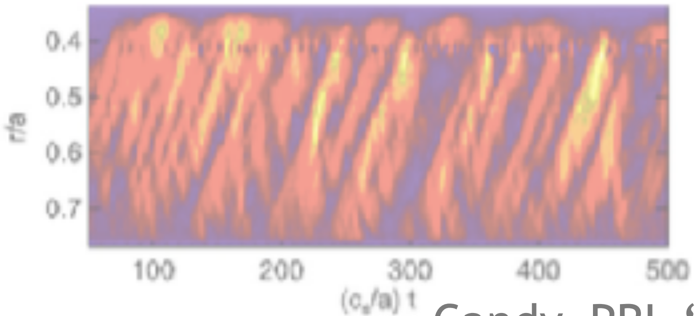
Turbulence propagation due to self-coupling



How the turbulence propagates

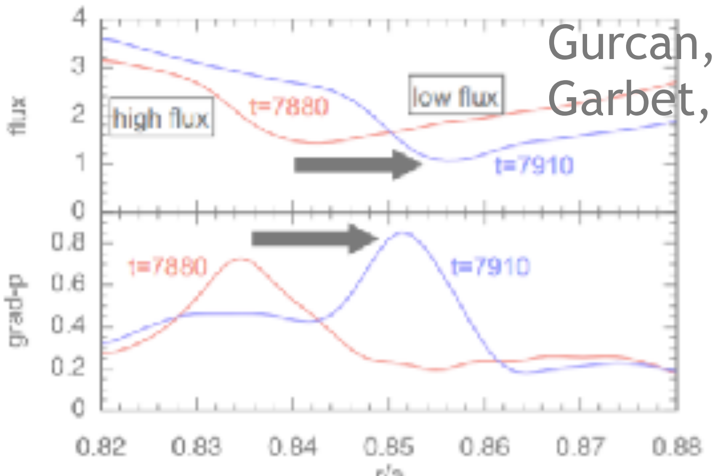
Avalanche

Diamond, PoP '02



Candy, PRL '03

Turbulence spreading

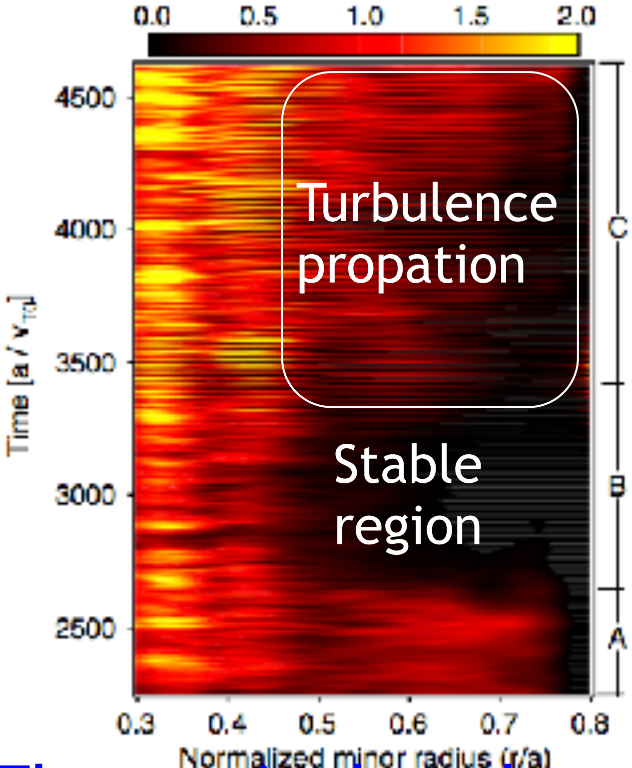


Gurcan, PoP '05
Garbet, PoP '07

Sugita, PPCF '12 Ballistic propagation of grad & turb

Turbulence propagation associated with shear flow

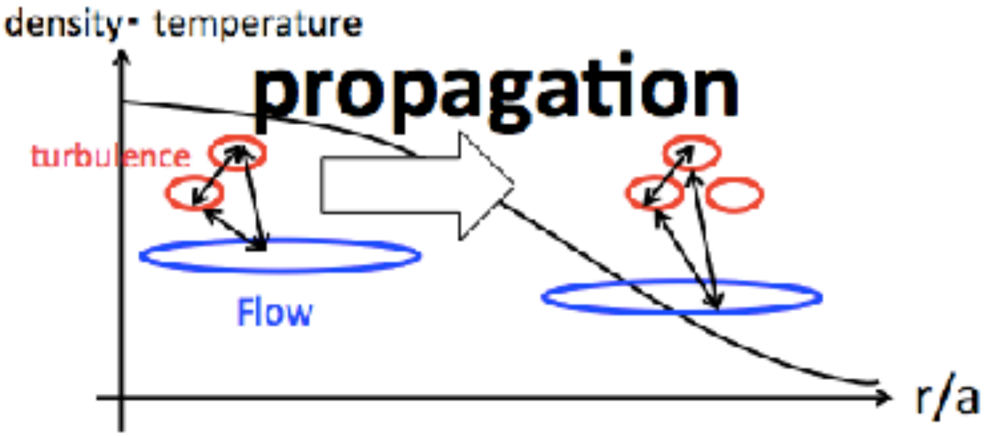
Zarzoao, PRL '13

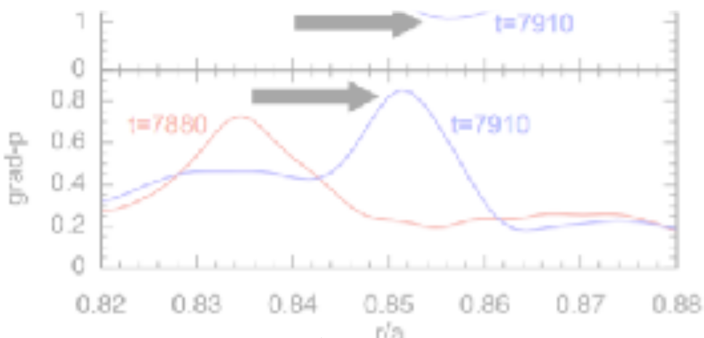


Theoretical understanding is necessary

How the turbulence propagates

Avalanche Diamond, PoP '02





Sugita, PPCF '12 Ballistic propagation of grad & turb

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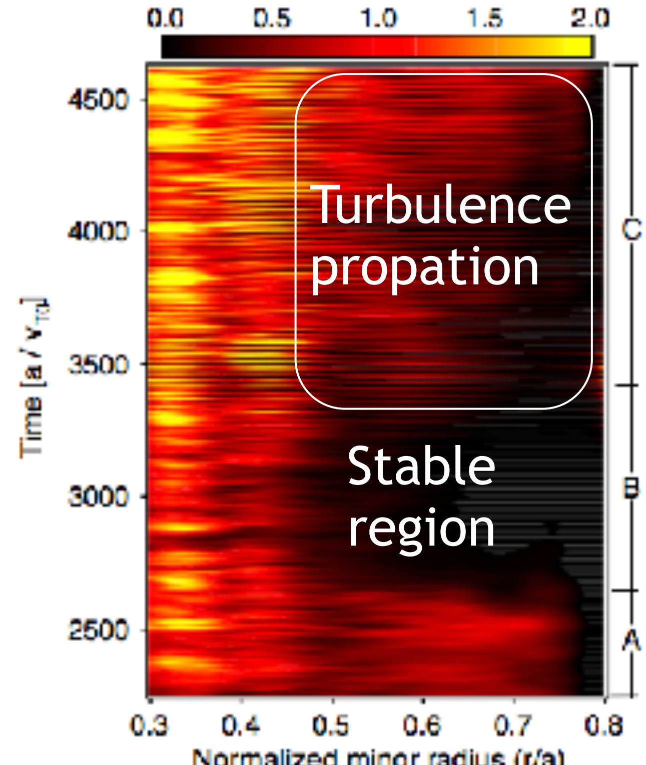
Zarzoao, PRL '13



Theoretical understanding is necessary

Previous model is NOT enough to explain the observations

Evolution of turb energy

Propagation

$$\partial_t I = \gamma_L I - \Delta\omega_0 \left(1 + \alpha V'^2 + \beta V V''\right) I + D\partial_x \left(I \partial_x I\right)$$

Biglari, PoF'89

Itoh, PPCF '15

Gurcan, PoP '05

$$I = \int I_k \, dk$$

Suppression (interaction with flow)

Although the 2nd order effects of the flow are considered,

1st order effect (turbulence trapping) is NOT included

Key mechanism: Turbulence trapping

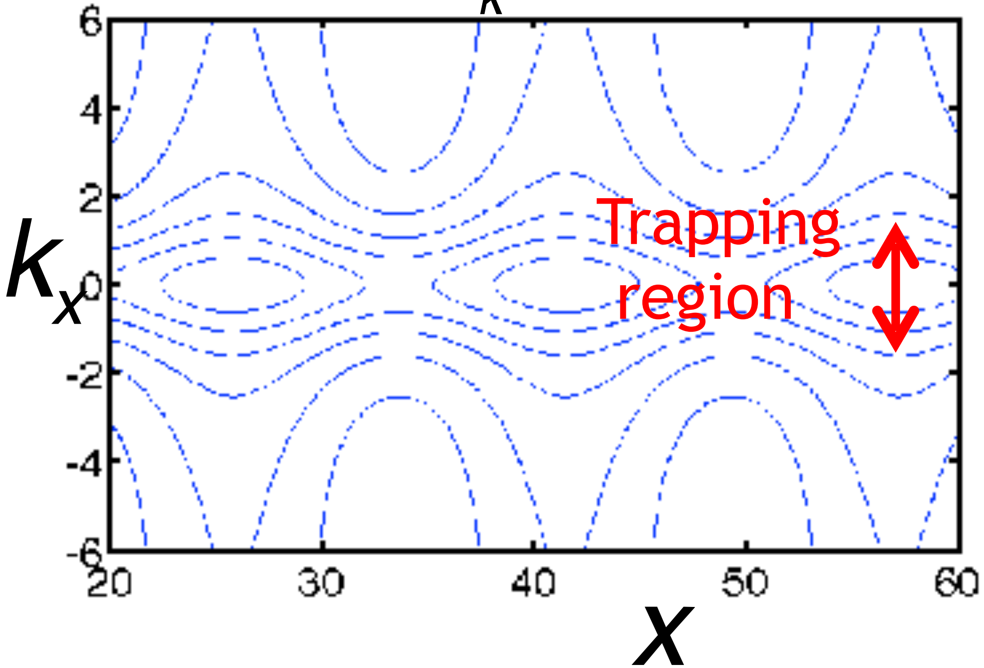
$$\partial_t N_k + \{\omega_k, N_k\} = 0$$

N_k: wave action

$\gamma_L, \Delta\omega << 1$

ω_k constant of the motion ⇒ Turbulence moves along the contour of ω_k

Contour of ω_k (w/o MF)



$$\omega_k = \frac{k_y}{1 + k_x^2 + k_y^2} + k_y V_y(x, t)$$

Island width : $k_{r,acp} = \sqrt{\frac{V_G (1 + k_\theta^2)^2}{1 - V_G (1 + k_\theta^2)}}$.

$$\omega_b = \sqrt{\frac{2 k_\theta^2 q_r^2 V_G}{(1 + k_\theta^2)^2}},$$

Kaw, PPCF '02

Phase space dynamics → turb trappin

Purpose of this study

We investigate

the interaction of the turbulence and zonal flow,

focusing on **the turbulence trapping effect**.

(typical example of the sheared flow

⇒ ·spatial distribution of suppression

·new mechanism of turb propagation

Before going to the contents of the research,

I will show you a branch of zonal flow we focus on.

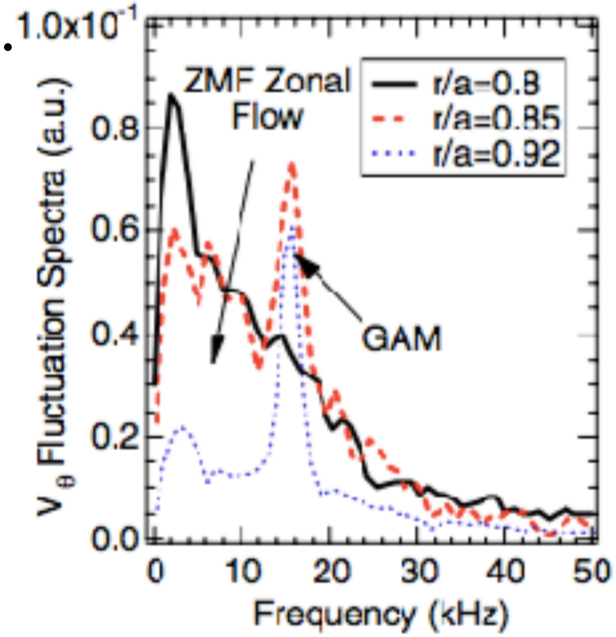
Zonal flows in tokamak

There are two kinds of zonal flows in tokamak.

$$\mathbf{V}_E = \frac{E_r}{B_0(1+\varepsilon\cos\theta)}\mathbf{e}_\theta$$

Inhomogeneity in poloidal direction

$$\nabla_\perp \cdot \mathbf{V}_E \neq 0$$



Gupta, PRL'06

$$\partial_t n + \boxed{n\nabla_\perp \cdot \mathbf{V}_E} + n\nabla_\parallel V_\parallel = 0$$

Finite in tokamak

Zonal flows in tokamak

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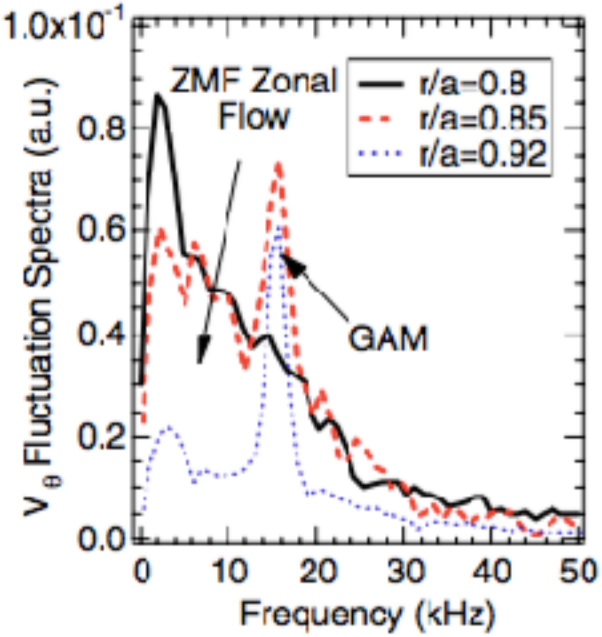

Gupta, PRL’06

$$\partial_t n + \boxed{n\nabla_\perp \cdot \mathbf{V}_E + n\nabla_\parallel V_\parallel} = 0$$

$$\approx 0$$

: incompressible flow

→ stationary zonal flow

Zonal flows in tokamak

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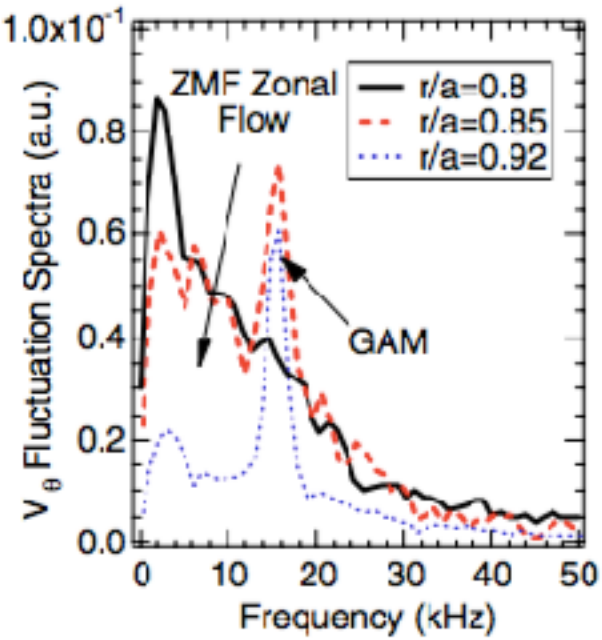

Gupta, PRL'06

≈ 0

: compressible flow

→ geodesic acoustic mode (GAM)

: incompressible flow

→ stationary zonal flow

Zonal flows in tokamak

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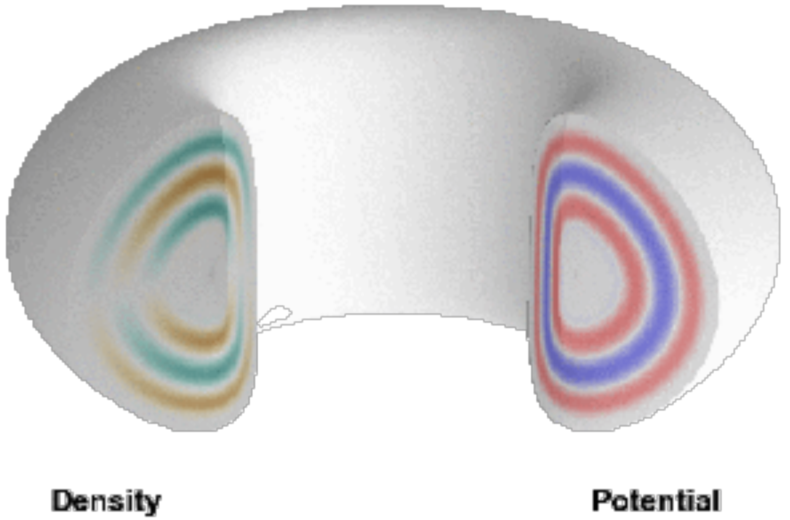
$$\mathbf{V}_E = \frac{E_r}{B_0\left(1+\varepsilon\cos\theta\right)}\mathbf{e}_\theta$$

Inhomogeneity in poloidal direction

⇩

$$\nabla_\perp \cdot \mathbf{V}_E \neq 0$$

Spatial structure of GAM



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≈ 0

: incompressible flow

→ stationary zonal flow

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Zonal flows in tokamak

Spatial structure of GAM

We investigate

the **interaction of the turbulence and GAM**,

focusing on **the turbulence trapping effect**.

$$\partial_t n + n\nabla_\perp \cdot \mathbf{V}_E + n\nabla_\parallel V_\parallel = 0$$

≈ 0

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Zonal flows in tokamak

Spatial structure of GAM

We investigate
the interaction of the turbulence and GAM,
focusing on **the turbulence trapping effect**.

·spatial distribution of suppression
·new mechanism of turb propagation

Model in this study

Evolution of the wavenumber spectrum of turb

$$N_k(x,\mathbf{k}) = I_k/\omega_k$$

$$\partial_t N_k + \frac{\partial \omega_k}{\partial \mathbf{k}} \cdot \nabla N_k - \nabla \omega_k \cdot \frac{\partial N_k}{\partial \mathbf{k}} = \gamma_L N_k - \Delta\omega N_k^2$$

↑ propagation

↑ Shear flow effect →

$$\omega_k = \frac{k_y}{1 + k_x^2 + k_y^2} + k_y V_y(x,t)$$

Drift wave

Evolution of the sheared flow (GAM)

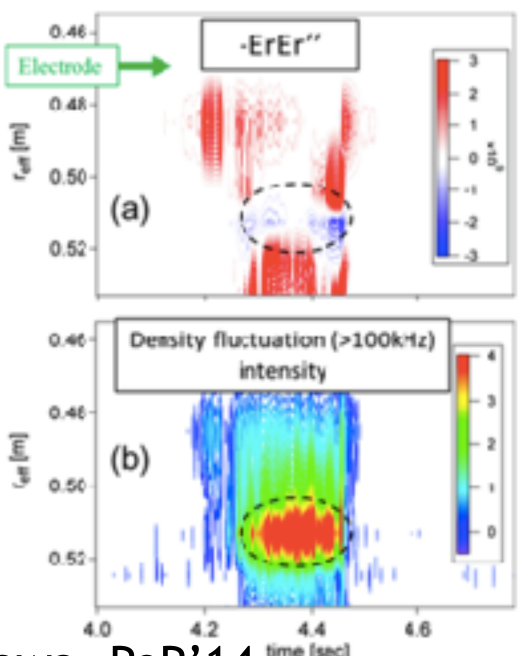
$$\partial_t V_y + \varepsilon \left\langle \tilde{n} \sin\theta \right\rangle = -\partial_x \Pi_{xy} + \mu \partial_x^2 V_y$$

↑ Reynolds stress

$$\Pi_{xy} = -\int \frac{k_x k_y}{\left(1 + k_x^2 + k_y\right)^2} N_k dk^2$$

Spatially homogeneous turb

Spatial distribution of the turb suppression



Tokuzawa, PoP'14

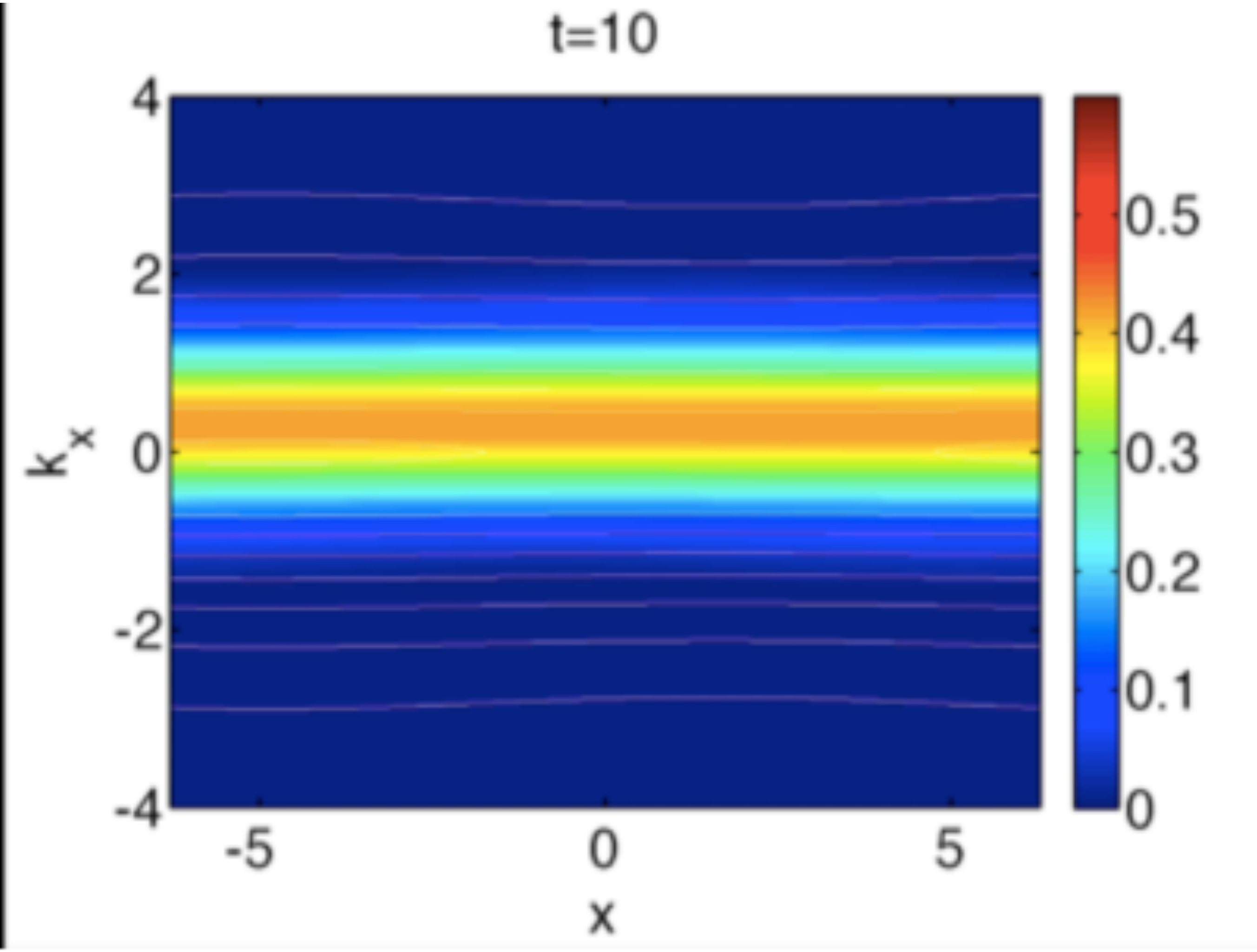
M. Sasaki, PoP (2018)

Editor's Pick

Role of the flow shear and curvature on the turbulence profile is focused on.

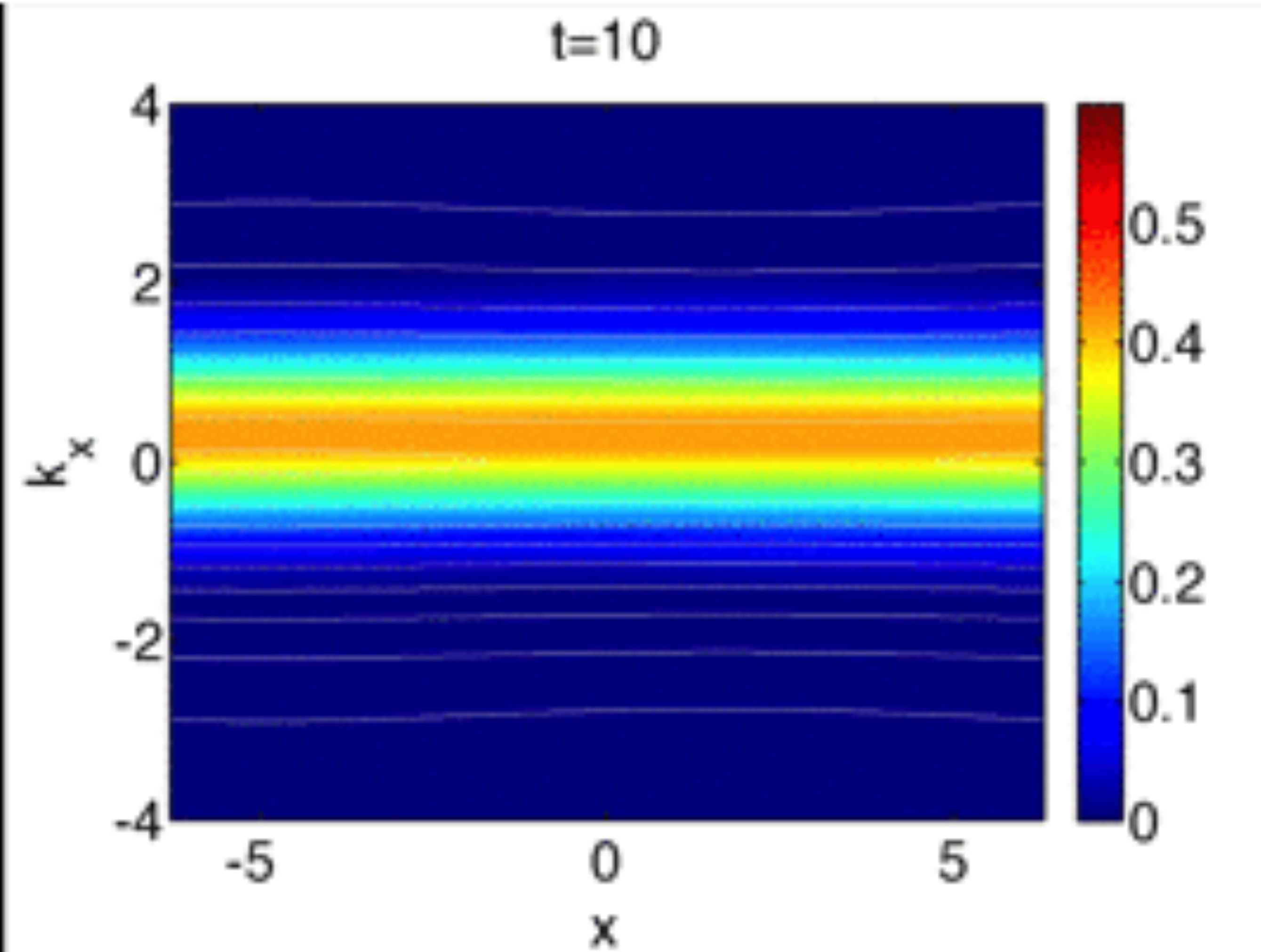
Evolution of turb

White line: ω_k

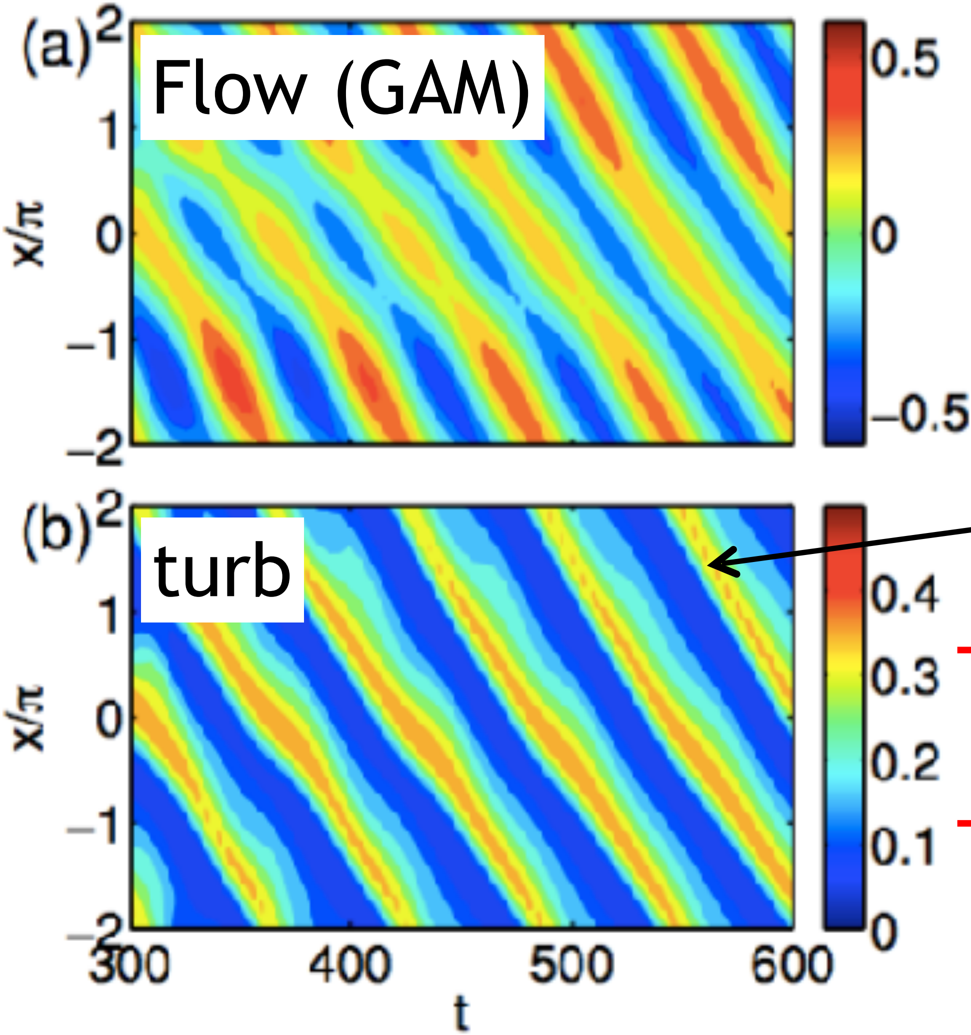


Evolution of turb

White line: ω_k



Spatiotemporal evolution of flow & turb



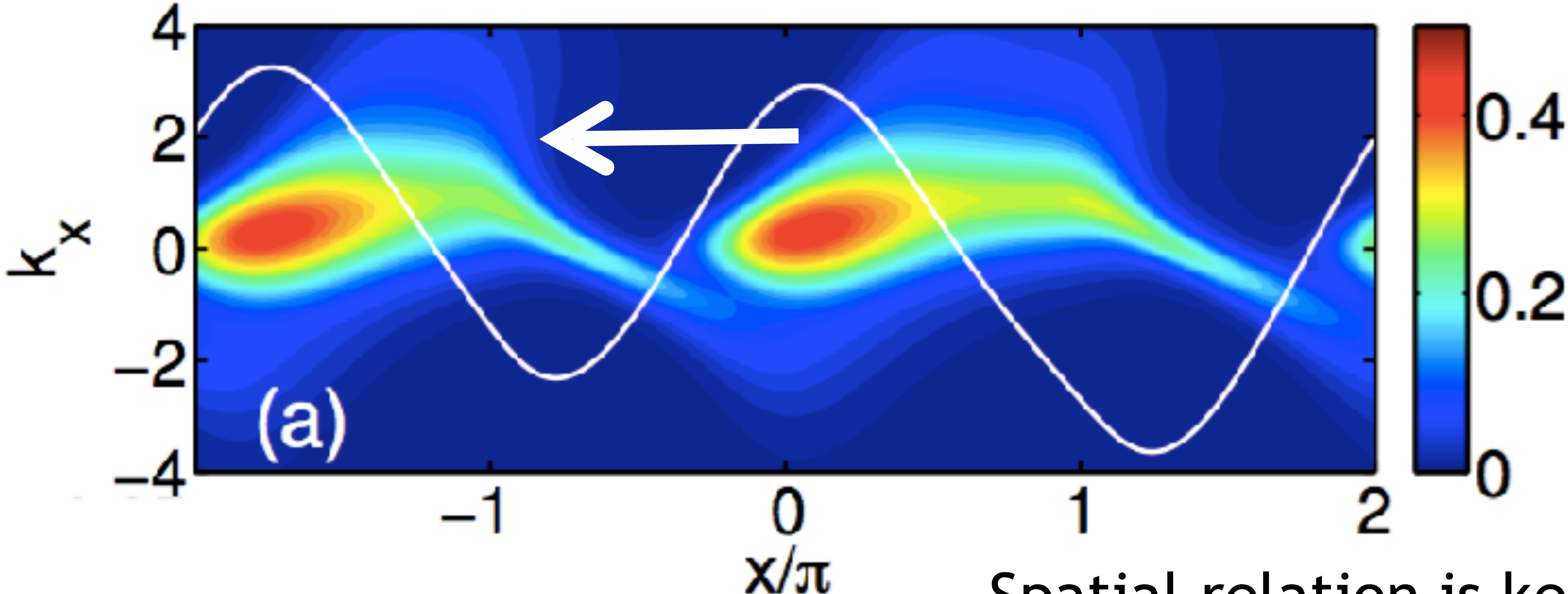
$$I(x,t) = \int I_k \, dk$$

Turb is trapped by the flow

↓

Turb propagates with the phase velocity of the flow

Spatial relation between flow & turb



Spatial relation is kep
in the wave-frame.

V’’>0 : turb exclusion

V’’<0 : turb trapping

Spatial distributions of the energies of flow & turb

turb

$$\partial_t I + \partial_x \left(\hat{v}_g I \right) = -2\Pi_{xy}\partial_x V_y + \hat{\gamma}_L I - \Delta\hat{\omega} I^2$$

propagation (turb trapping) — **suppression**

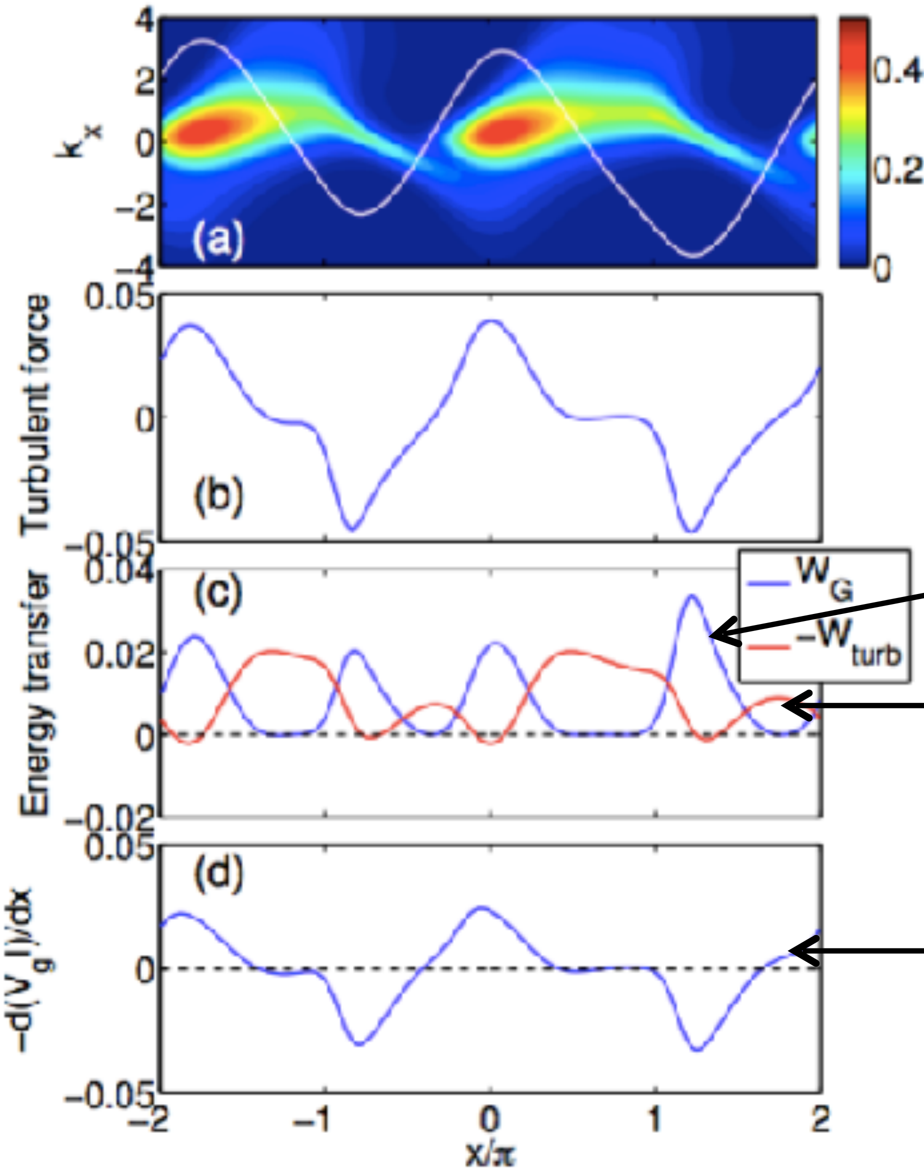
flow

$$\partial_t V_y^2 = -2 V_y \partial_x \Pi_{xy} + 2\mu V_y \partial_x^2 V_y$$

Driving force by turb (Reynolds work)

By the spatial integration,
Predator-Prey model (Diamond, PPCF '05) can be deduced.

Spatial profile of each effect



$$\partial_t I + \partial_x\left(\hat{v}_g I\right) = -2\Pi_{xy}\partial_x V_y + \hat{\gamma}_L I - \Delta\hat{\omega} I^2$$

$$\partial_t V_y^2 = -2V_y\partial_x\Pi_{xy} + 2\mu V_y\partial_x^2 V_y$$

Driving force of flow

: VV''

Turb suppression effect

: V'2

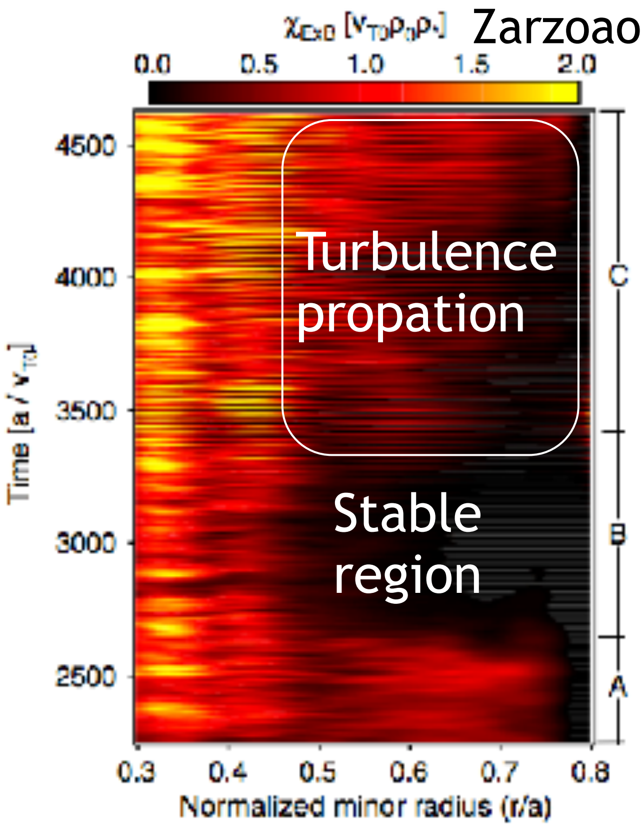
Energy conservation

Turb propagation

: V'' (trapping effect)

Spatially inhomogeneous turb

Nonlocal turb propagation by sheared flow



Zarzoao, PRL '13

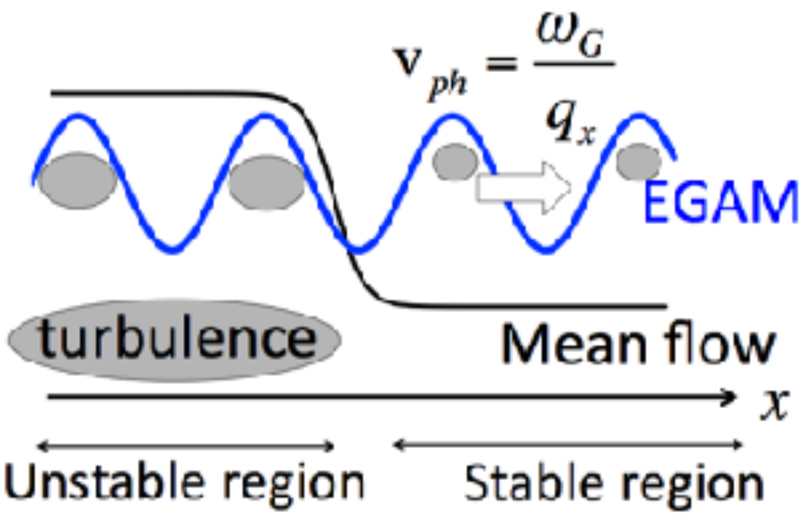
M. Sasaki, Sci. Rep. (2017)

It is studied
why turbulence can propagate in the stable region.

Situation we consider

Interaction of
energetic particle driven GAM(EGAM) with turb

Zarzoso, PRL ‘13

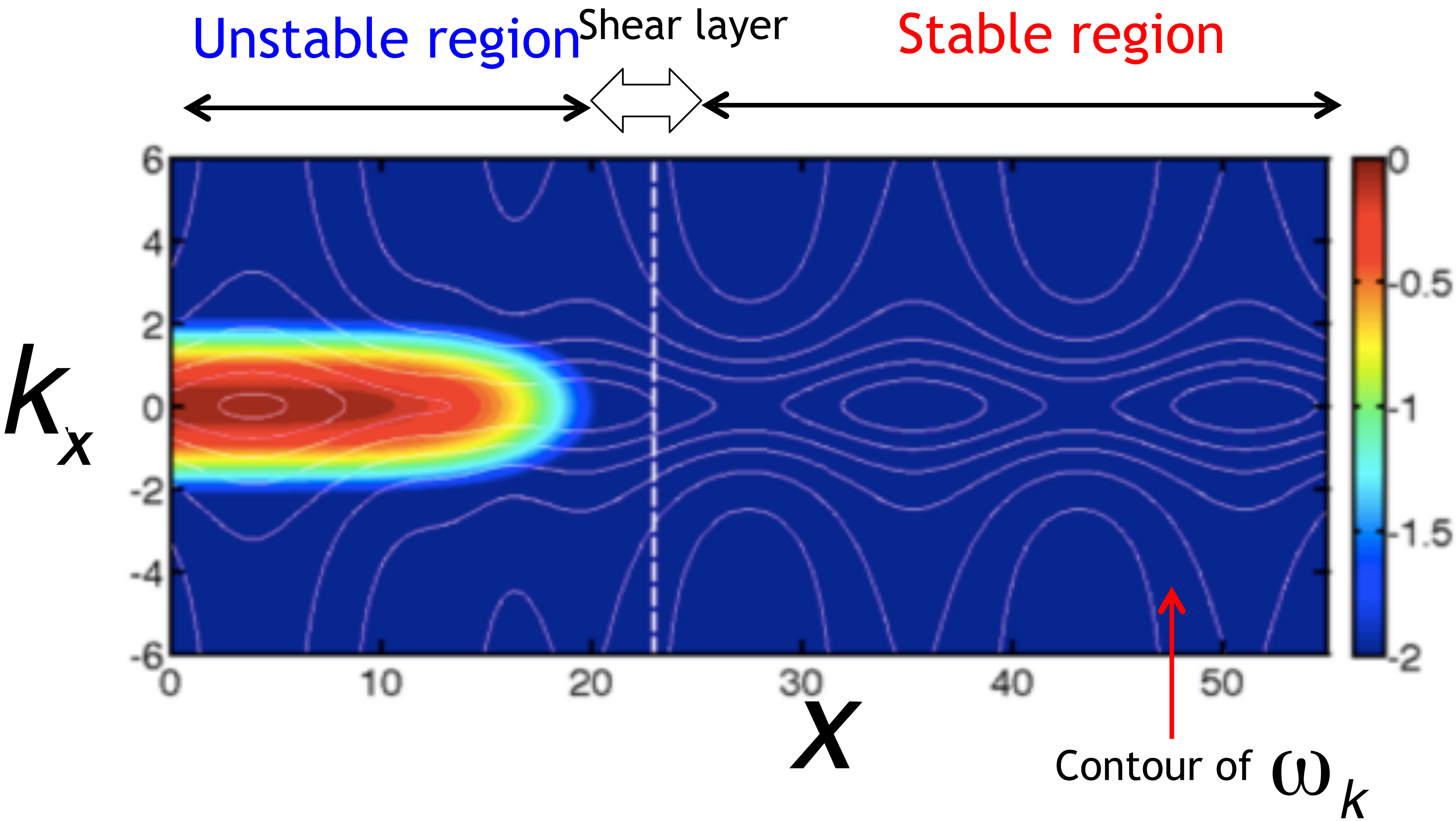


EGAM can propagate
in the turb stable region

→amplitude of EGAM is given
constant in space.
Only turb is solved.

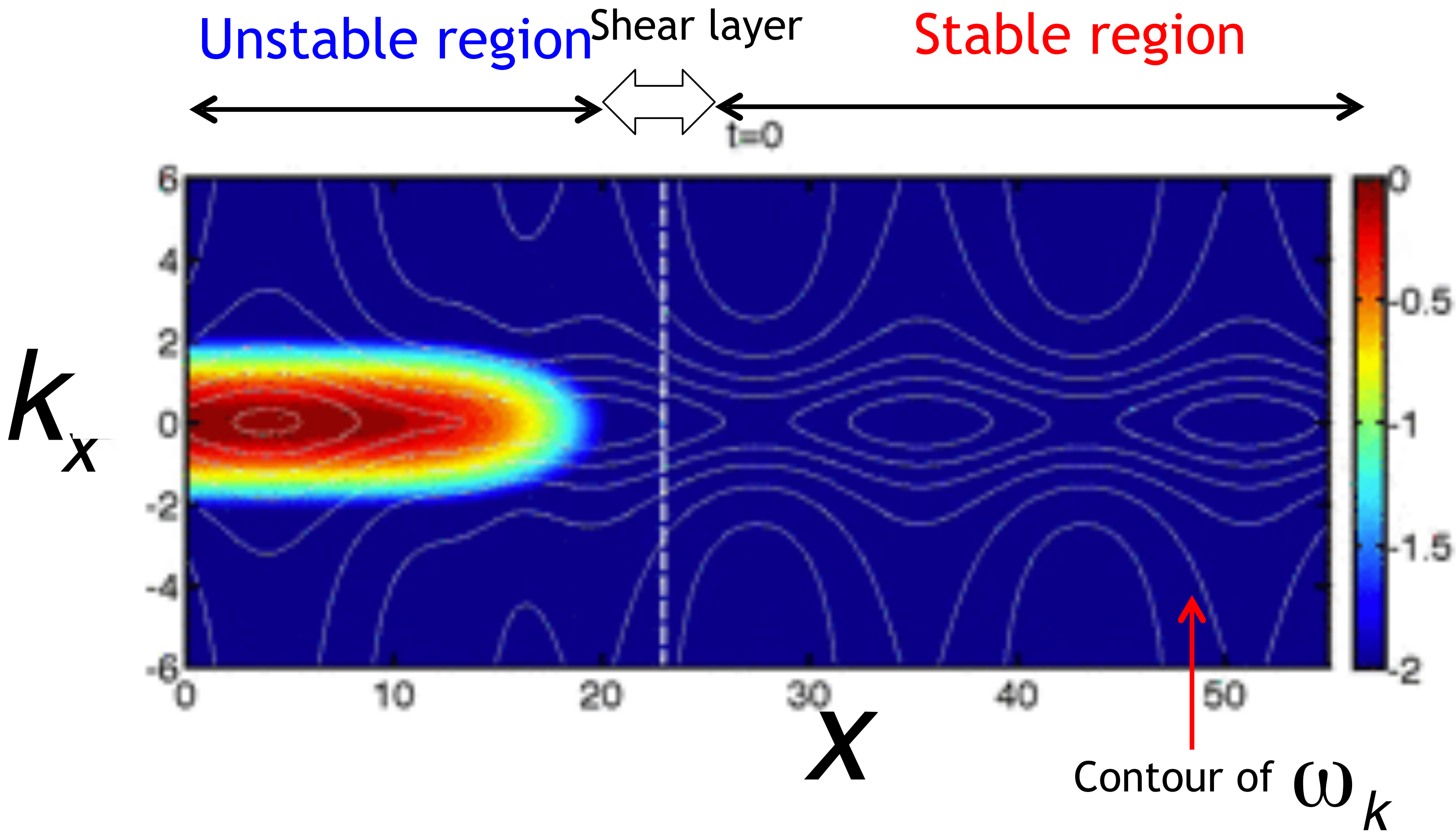
Can EGAM carries turb into stable region ?

Evolution of turb spectrum



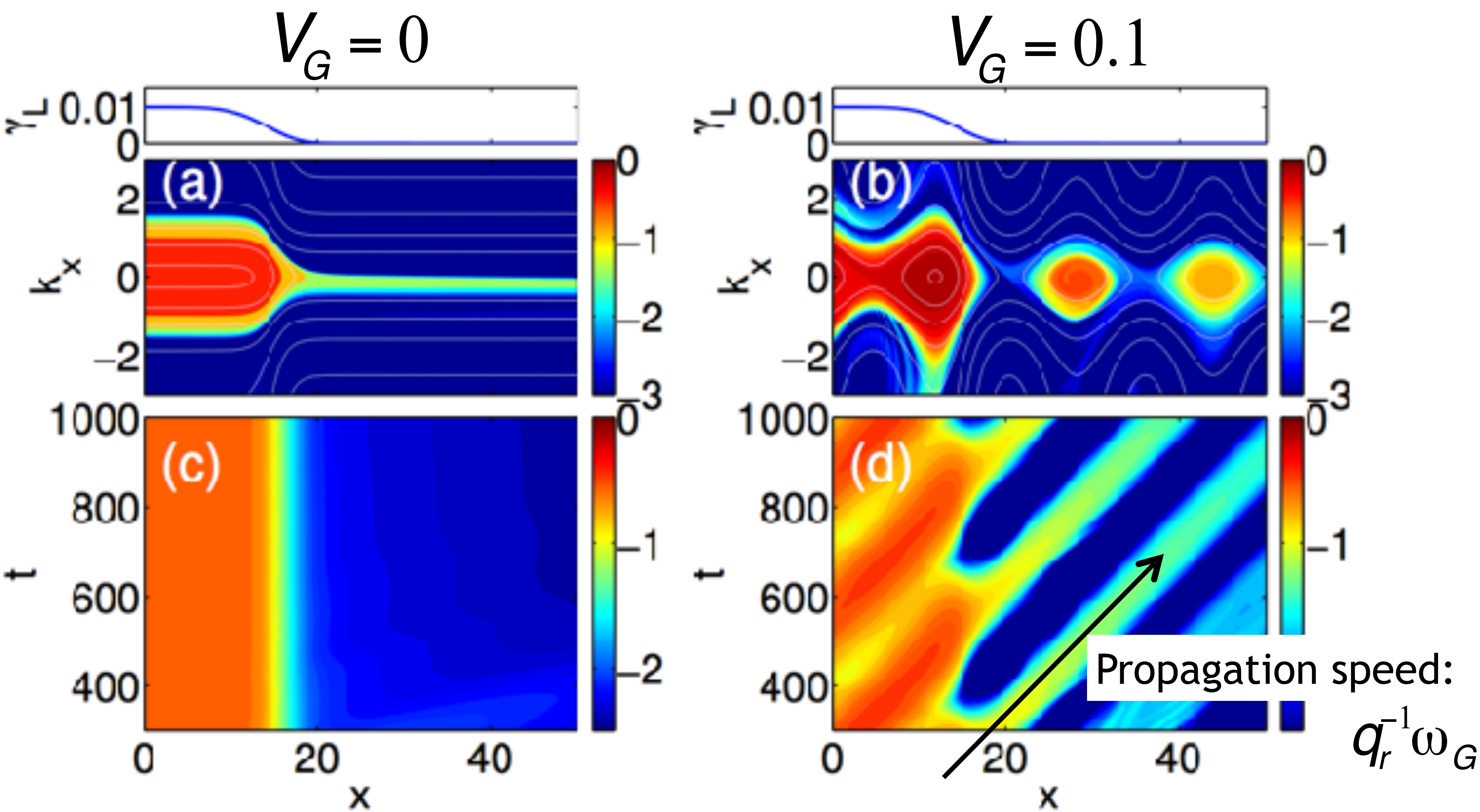
EGAM can carry clumps of turb into stable regior

Evolution of turb spectrum



EGAM can carry clumps of turb into stable regior

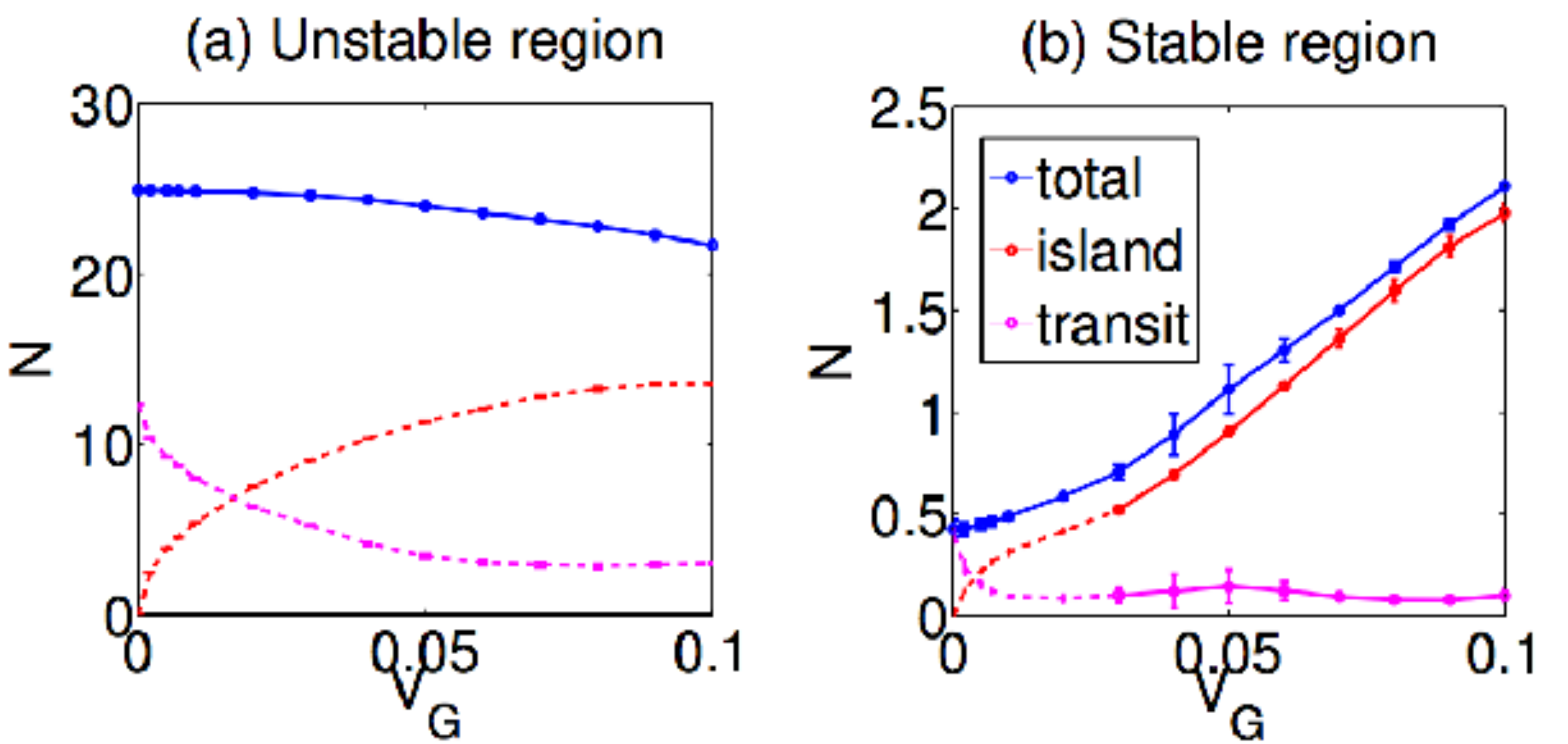
Turb propagation



Turbulence leaks into stable region by EGAM.

The propagation speed is the phase velocity of EGA

Suppression & Enhancement of turb by EGAM



Unstable region: turb suppression

Stable region: turb enhancement ←turb trapping

Comparison with other mechanisms

	propagation speed	turbulence intensity	propagation distance
avalanche	$\sim V_d$	$< \lvert\tilde{\phi}\rvert^2$	$\sim a$
turbulence spreading	$\sim V_d$	$\lvert\tilde{\phi}\rvert^2$	$\sim 10\rho_i$
EGAM	$q_x^{-1}\omega_G$	$I_{trap}(V_G)$	$q_x^{-1}\Delta\omega^{-1}\omega_G$

Sci. Rep (2017)

Turb flux by EGAM: $\Gamma_{\mathrm{EGAM}} = \dfrac{\omega_G}{q_r} I_{\mathrm{trap}}$

Turb flux by turbulence spreading: $\Gamma_{\mathrm{spread}} \sim V_d \left|\tilde{\phi}\right|^2$

$$\frac{\Gamma_{\mathrm{EGAM}}}{\Gamma_{\mathrm{spread}}} \sim O(1)$$

Turb propagation by EGAM can be comparable with that by turbulence spreading

Summary

Novel mechanisms for
spatial distribution of turb suppression &
propagation

1. Turb trapping & exclusion appears due to flow curvature.

1. V’’>0: turb exclusion → turb suppression

   this mechanism is the 1st order:
   important for the formation of the transport barrier
   (the Reynolds stress 2nd order)

3. V’’<0: turb trapping → turb propagation

   nonlocal propagation of turb is expected.

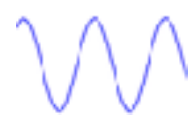
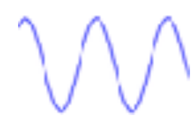
4. In future, self-consistent treatment of
   the flow, flow shear, flow curvature will be discussed.

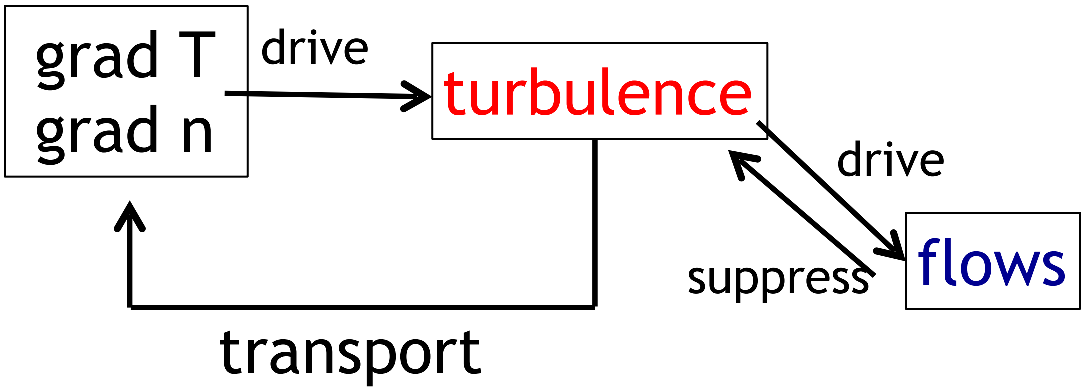
backup

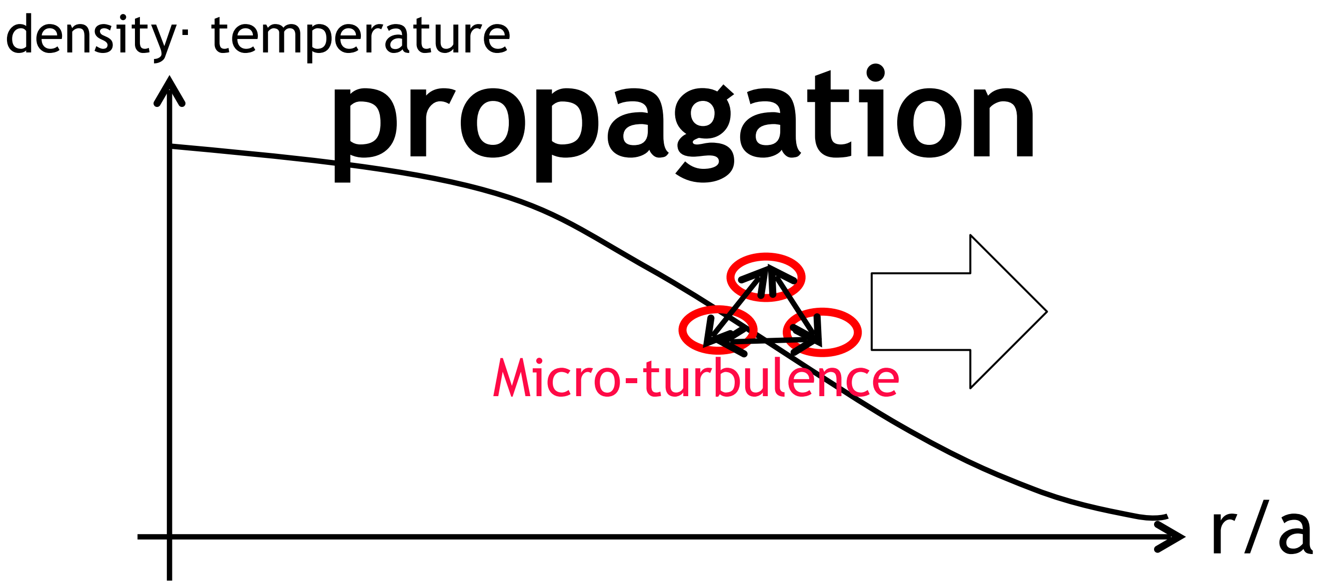
Turbulence trapping by GAM is studied

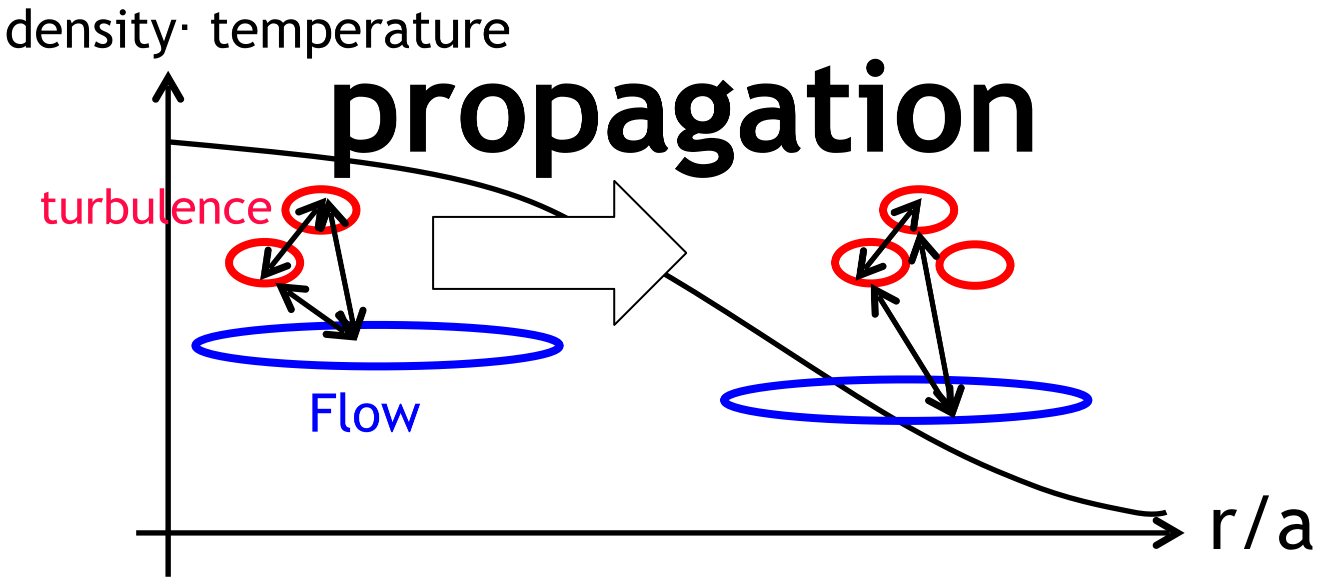
We investigate
the interaction of the turbulence and zonal flow,
focusing on **the turbulence trapping effect.**

→ ·spatial distribution of suppression
(typical example of the sheared flow
·new mechanism of turb propagation

	Driving force	freq	Spatial structure
Mean Poloidal flow	Pressure grad, Turbulence	0	 Shear & curvature
Stationary ZF	turbulence	~0	
GAM	Turbulence EPs	C_s/R	


grad T
grad n
drive
turbulence
drive
flows
suppress
transport


density· temperature
propagation
Micro-turbulence
r/a


density· temperature
propagation
turbulence
Flow
r/a