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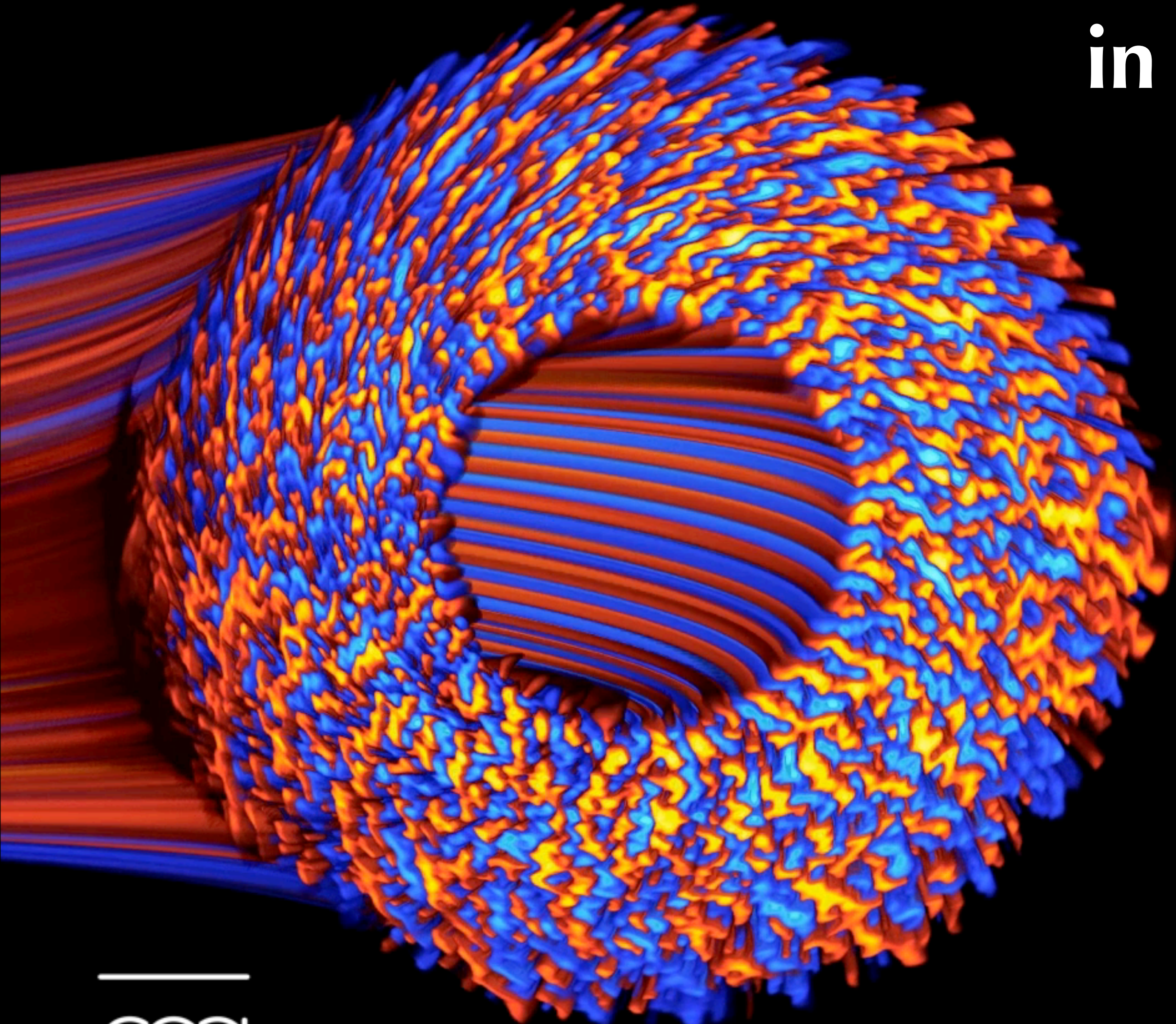

Antoine Strugarek

Wave — Mean-Flows
Interactions in Fluids
KITP, UCSB

With Y. Sarazin, A. S. Brun, and the GYSELA team
Special thanks: Festival of theory

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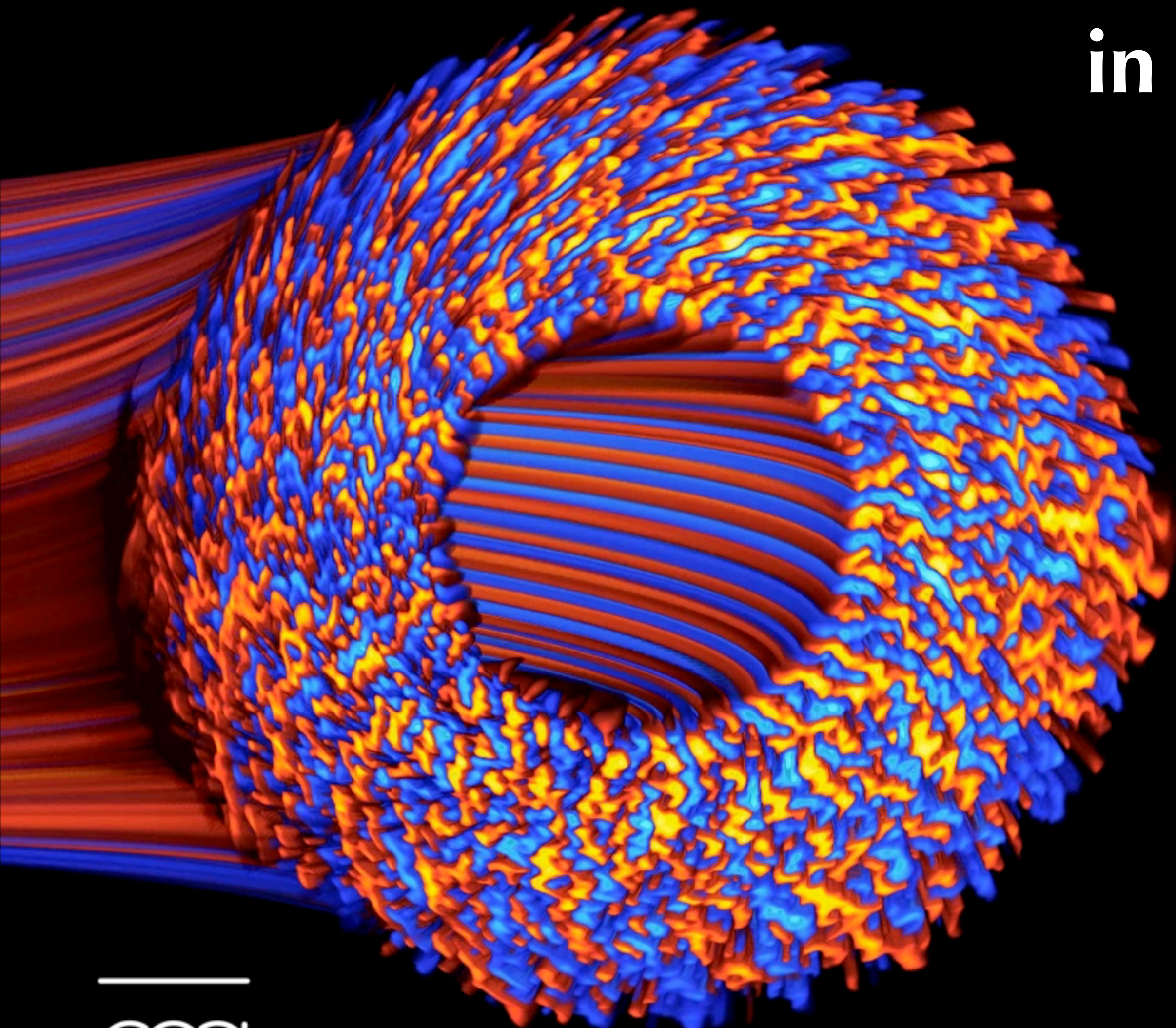

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Outline

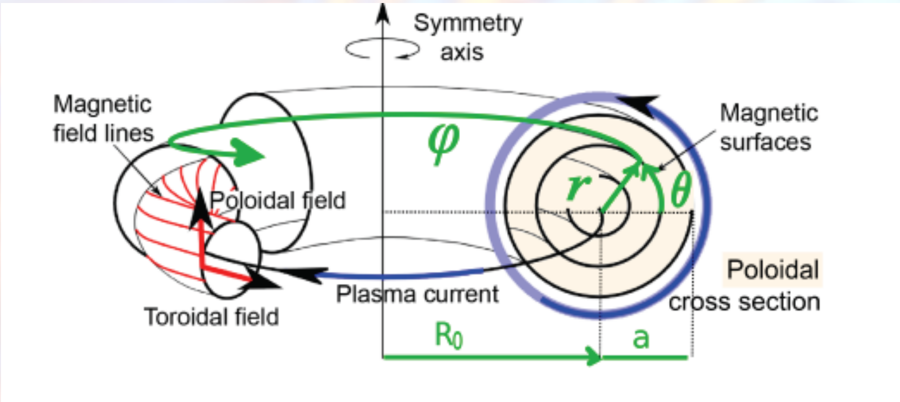
» Why study transport barriers?

» Gyrokinetic (GK) formalism for turbulent transport and mean flows in tokamak plasma

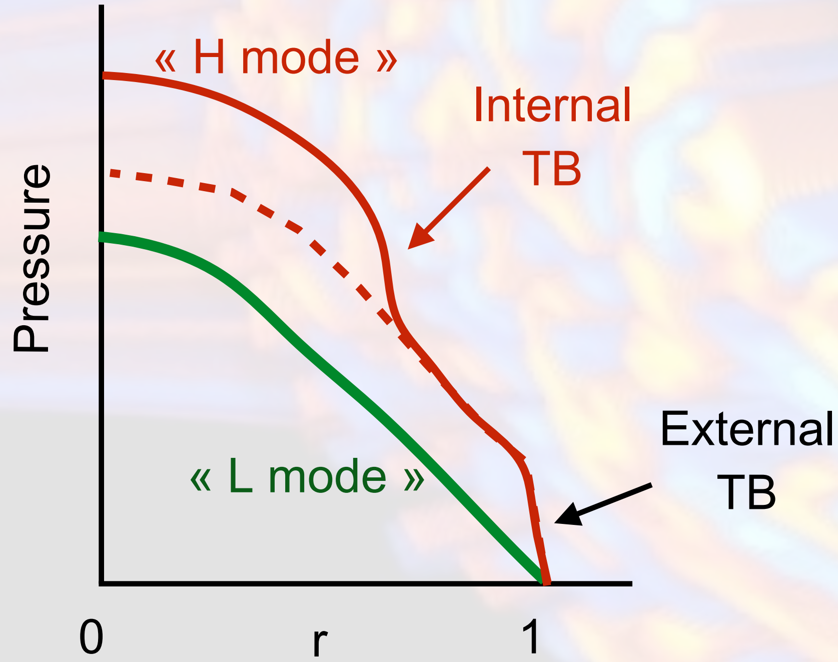
» How to impose sheared flows in a self-consistent GK simulation

» Transport barrier and sheared flows: creation, sustainment and stability

Transport barriers (TB) in a tokamak plasma



Tokamak geometry with circular cross-section



» Goal: confine energy in the center

» Use self-organization capability of the plasma to create TBs (ITER main scenarii)

» Any external control on the TBs position, stability or strength is extremely beneficial in the path of building a fusion device

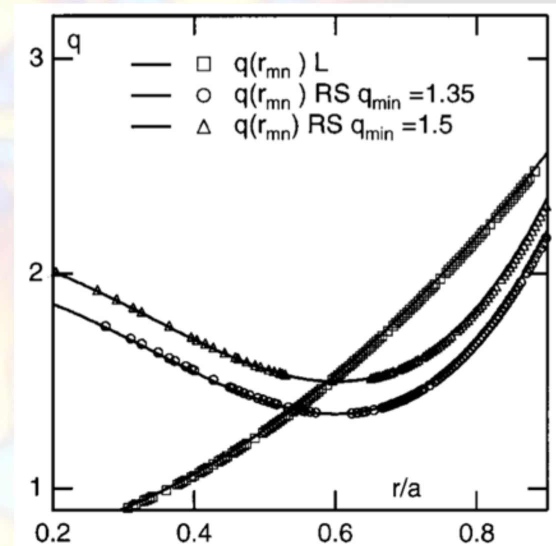
How to generate transport barriers in a tokamak plasma

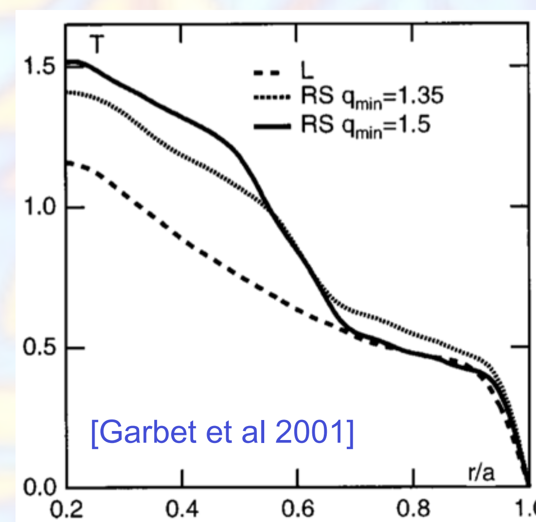
Two possible mechanisms

➔ Magnetic topology (magnetic shear)

- Magnetic shear ⟶ linear stabilisation
- « Inversed » profile ⟶ role of non-resonant modes?

[Joffrin et al 2003, Candy et al 2004, Sarazin, Strugarek et al 2010]





[Garbet et al 2001]

How to generate transport barriers in a tokamak plasma

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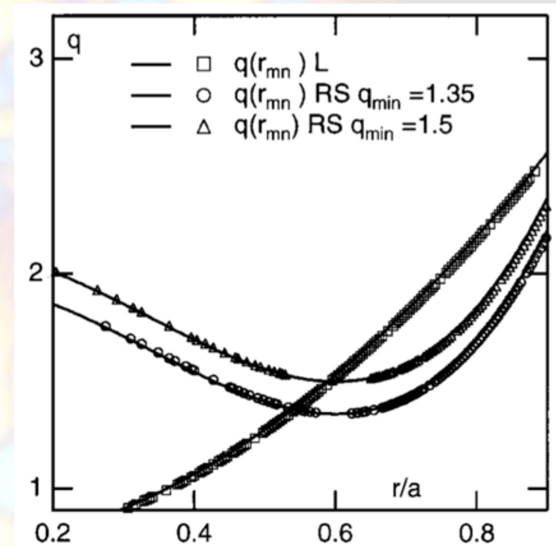
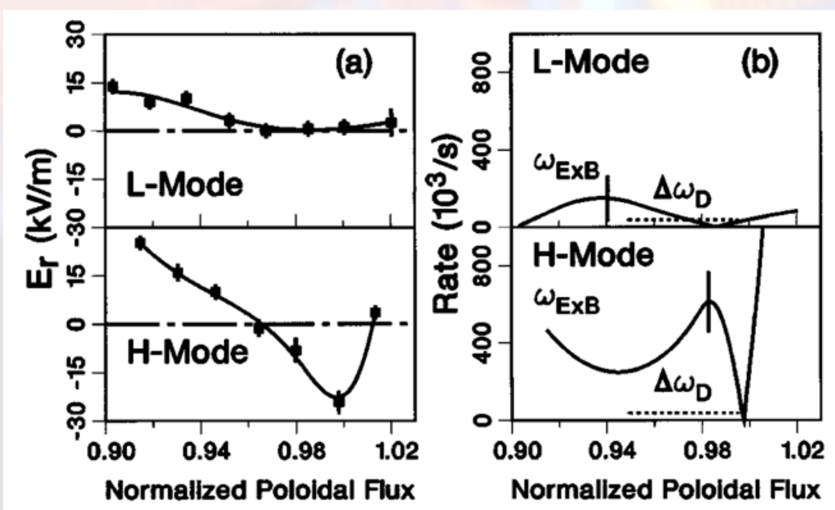
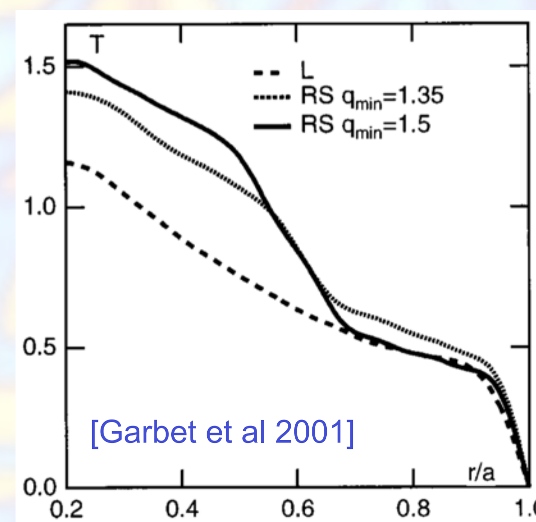


➔ Velocity shear
- Toroidal ⟶ transfer || momentum
- Poloidal ⟶ polarize the plasma

[Terry 2000, Wolf 2003, Connor 2004, …]

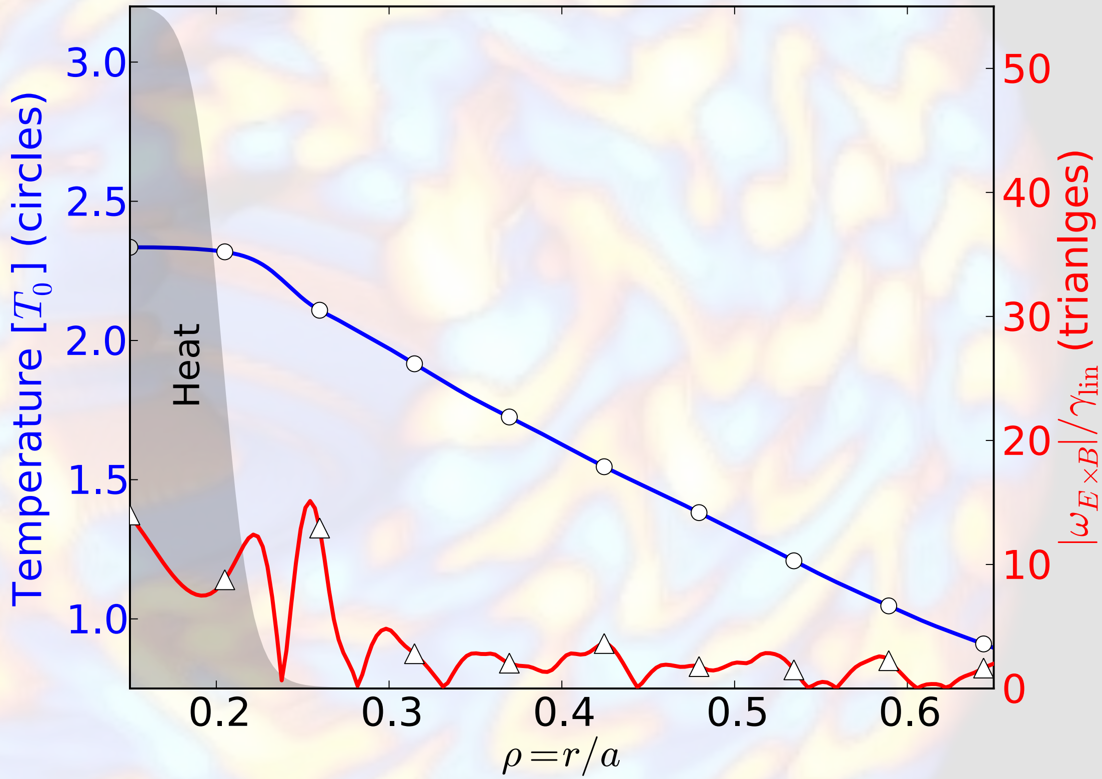


[Burrell 1997]
(DIII-D)



Turbulent transport, sheared flows and transport barriers

Heating power ➔ turbulent transport ➔ mean profiles



Turbulent transport, sheared flows and transport barriers

Heating power ➔ turbulent transport ➔ mean profiles

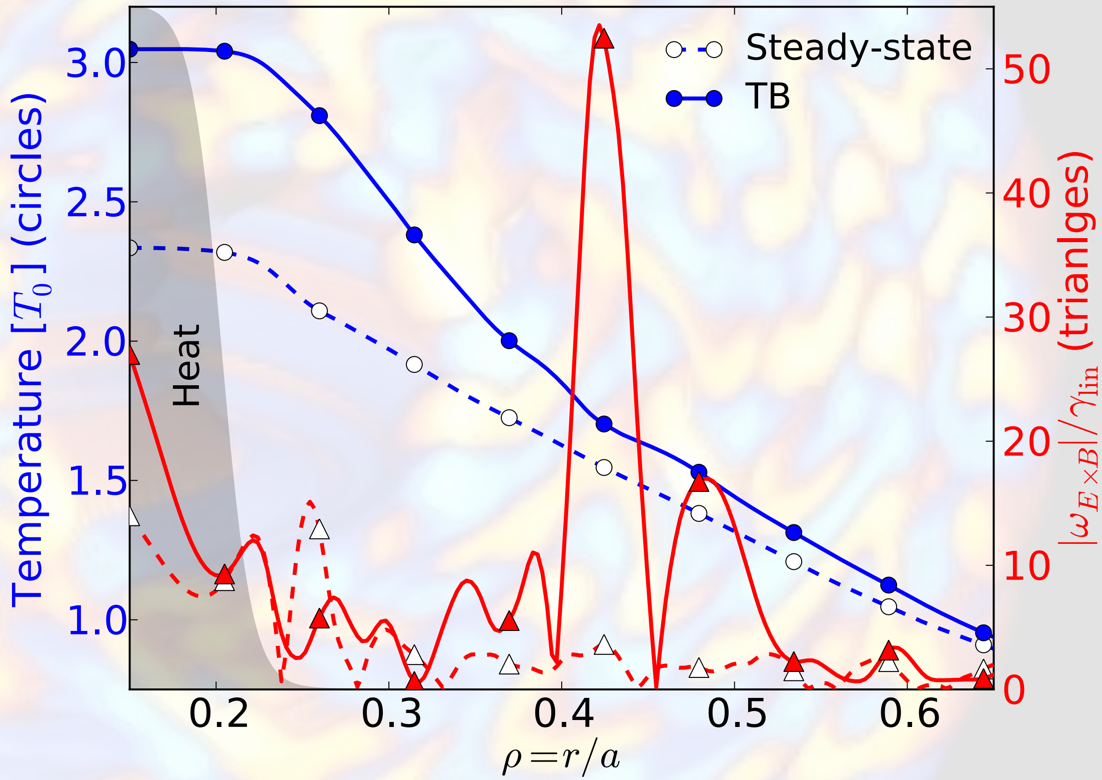
Transport barrier triggered

- with an externally imposed shear

  [Ono et al 1988, Craddock et al 1991, Leblanc et al 95, 99]

- spontaneously thanks to intrinsic sheared flow developing the heat input increases

  [Biglari et al 1990, Waltz et al 1994]



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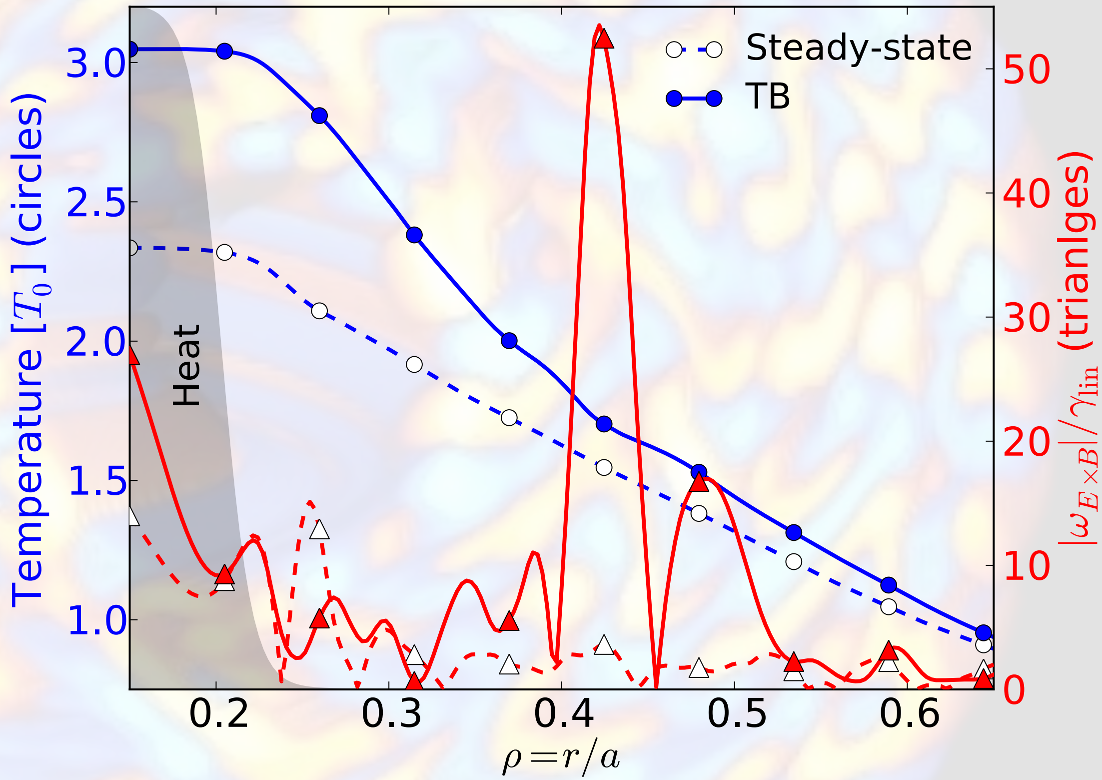


How those sheared flows interact with turbulence to allow TBs creation?

ITG turbulence with the GYSELA code

"Vlasov"

$$\partial_t f + \boldsymbol{\nabla} \cdot \left(\dot{\mathbf{Z}} f\right) = \mathcal{C}(f,f)$$

Quasi-neutrality

$$-\underbrace{\sum_{\text{ions}} \nabla \cdot \left(\frac{n_s m_s}{B^2} \nabla_\perp \phi\right)}_{\leftrightarrow \text{ Vorticity}} = \sum_{\text{species}} q_s \int \mathrm{d}v\, \mathcal{J} \cdot \bar{f}$$

+ adiabatic electrons

» Global code (≠ ‘flux-tube’)

➔ large scale transport events
➔ boundary conditions

» Full-f and flux-driven code (≠ ‘δf’, gradient-driven)

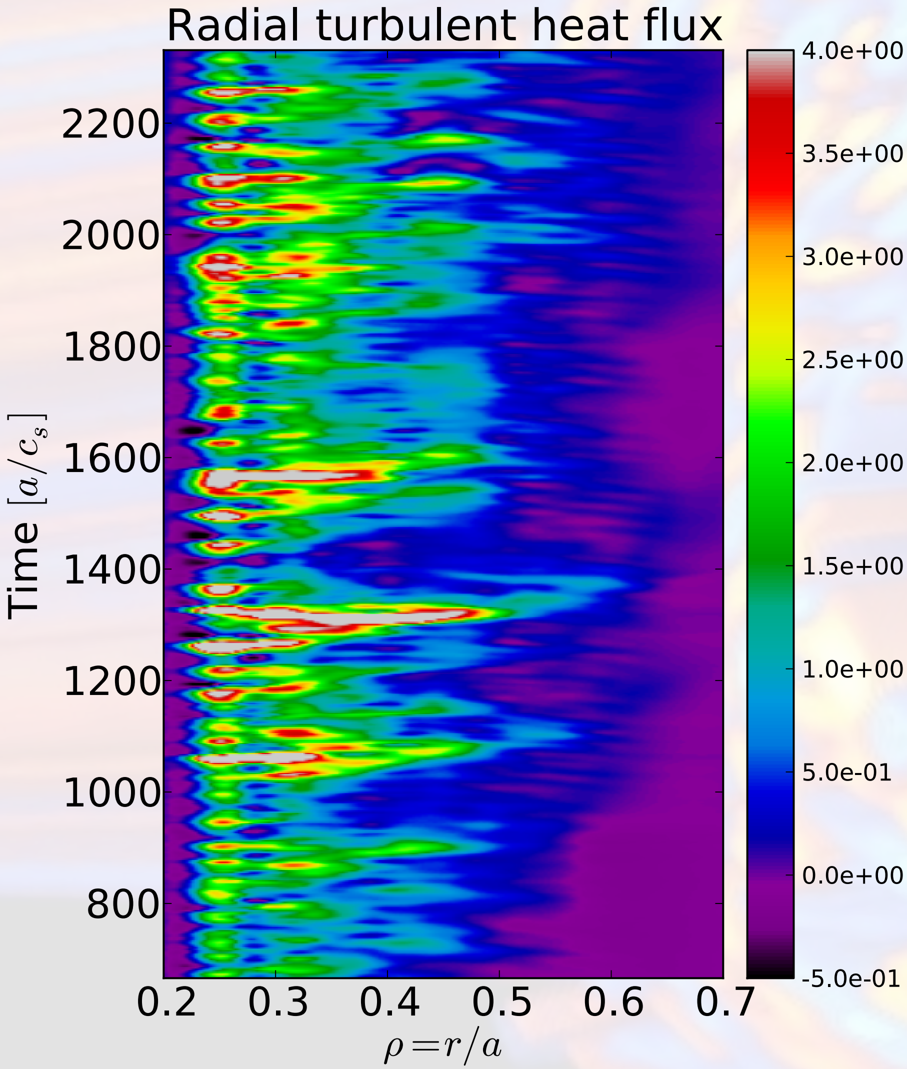
➔ Equilibrium & flucutations: no scale separation
➔ Profile relaxation: statistical steady-state
➔ Prescribed driving flux

Parameters

$$\rho_\star = 1/150$$
$$\nu_\star = 0.1$$

[Grandgirard et al 2007,2008]

Intrinsic shear in ITG turbulence: no transport barrier



» Intrinsic sheared flows observed in two regimes

– Highly correlated to the turbulent heat flux structure

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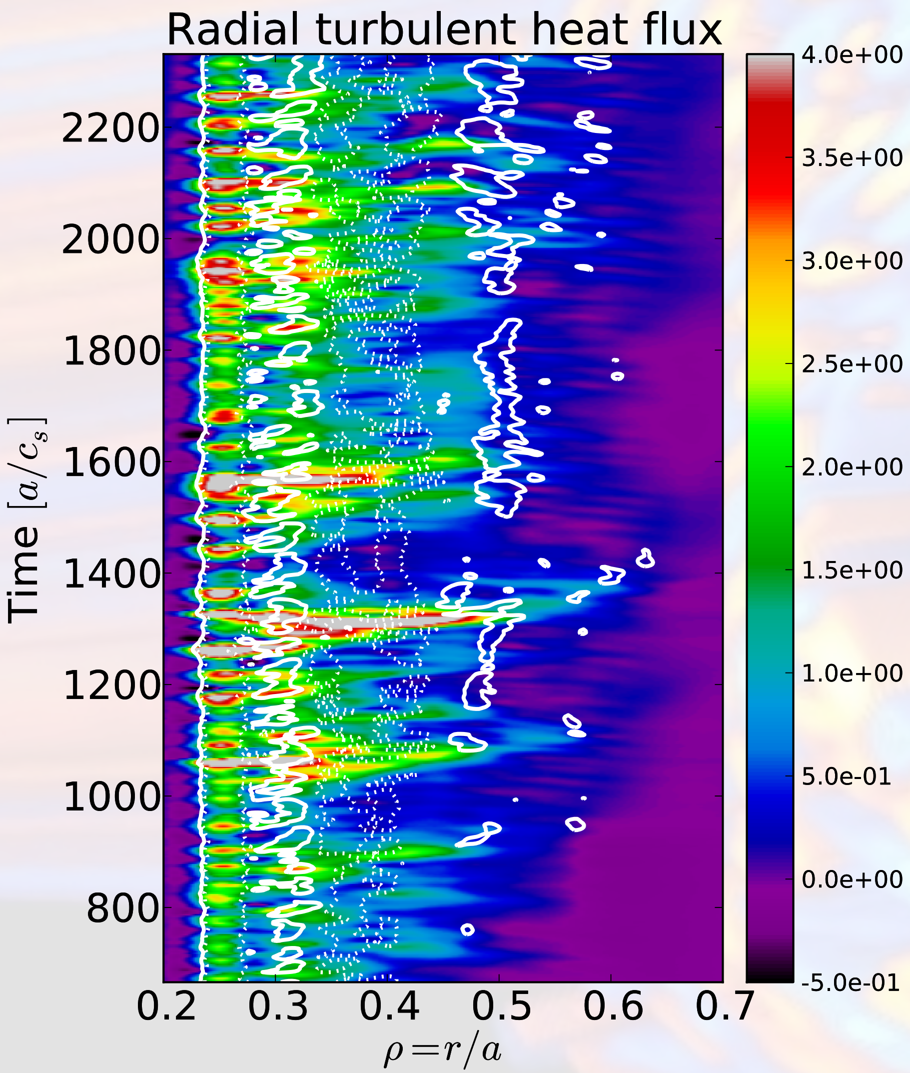

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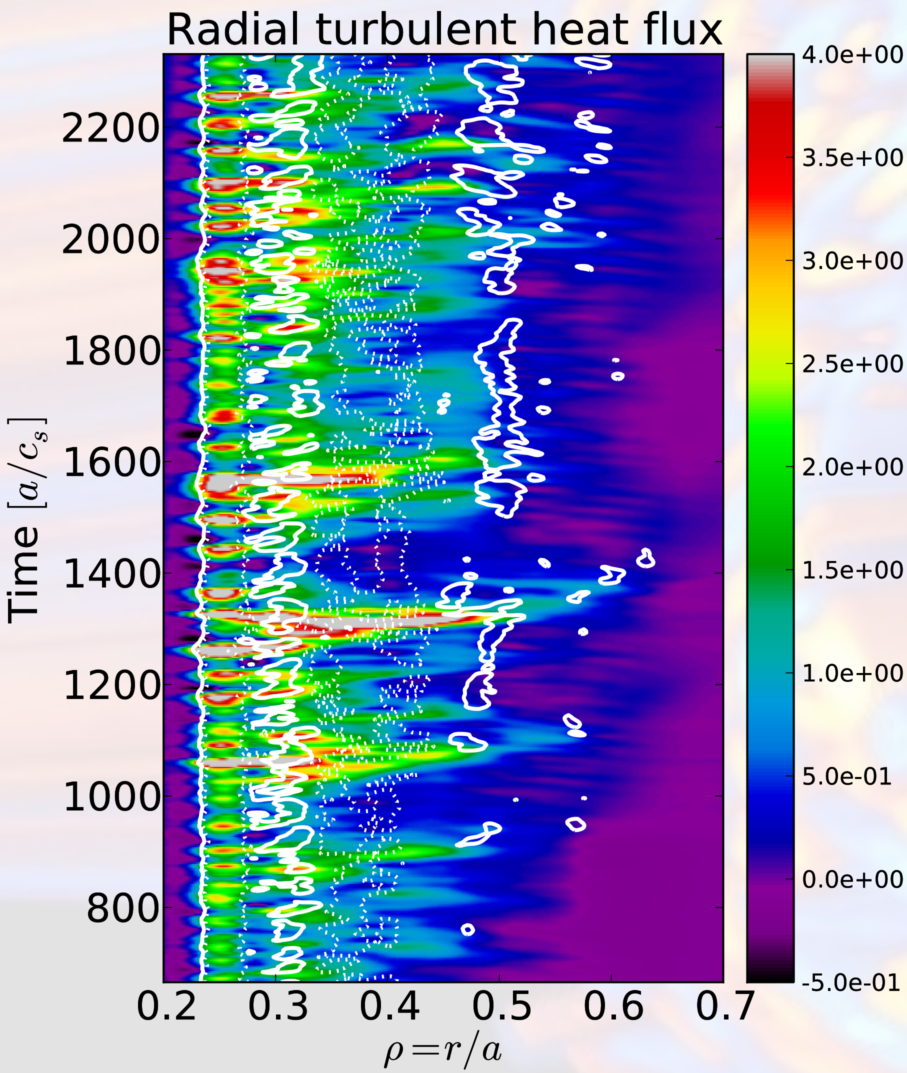

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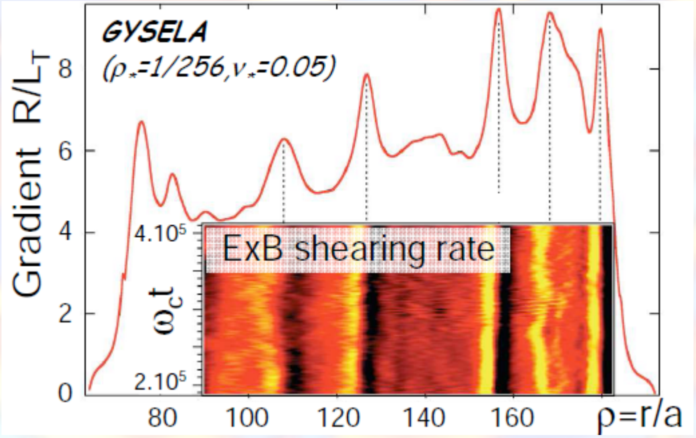

Close to threshold

[Dif-Pradalier et al, PRE 2010]

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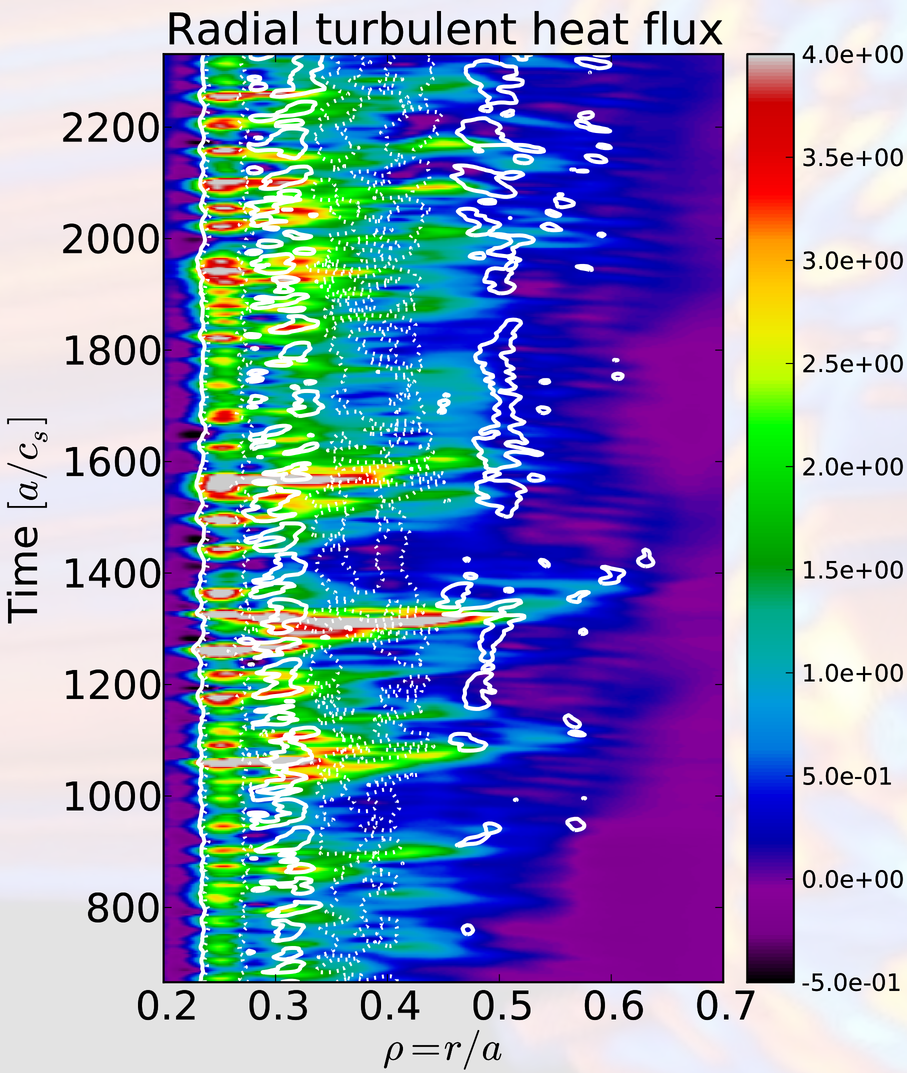

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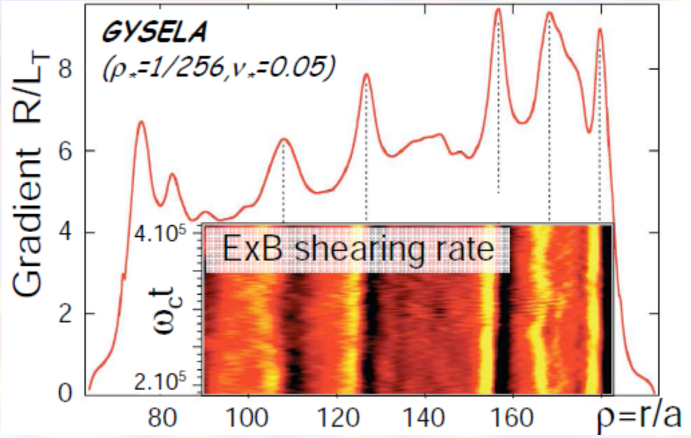


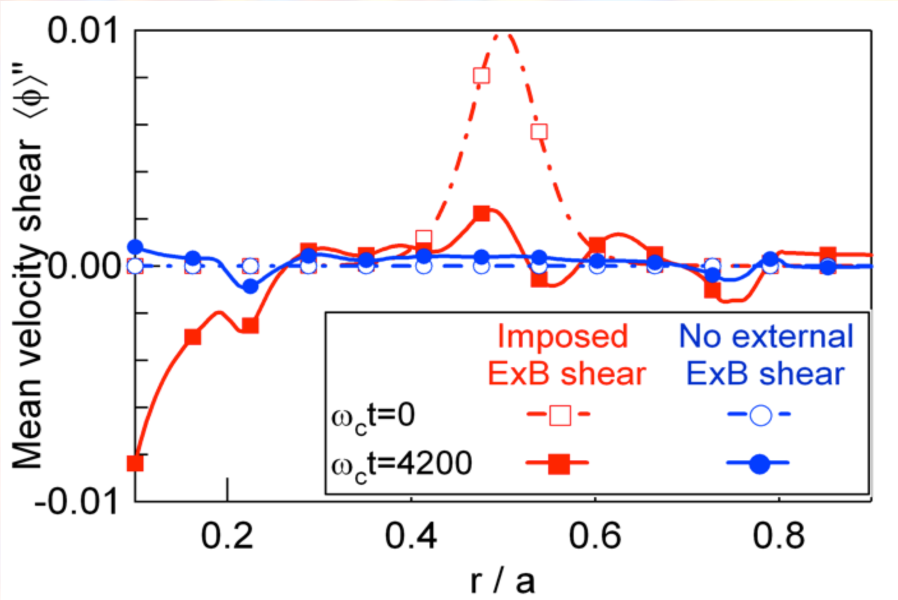
Close to threshold

[Dif-Pradalier et al, PRE 2010]

No strong transport barrier is driven → Externally impose a shear

How to polarize the plasma in the GK formalism?

Adding a prescribed poloidal v_{E0} component to GK equation



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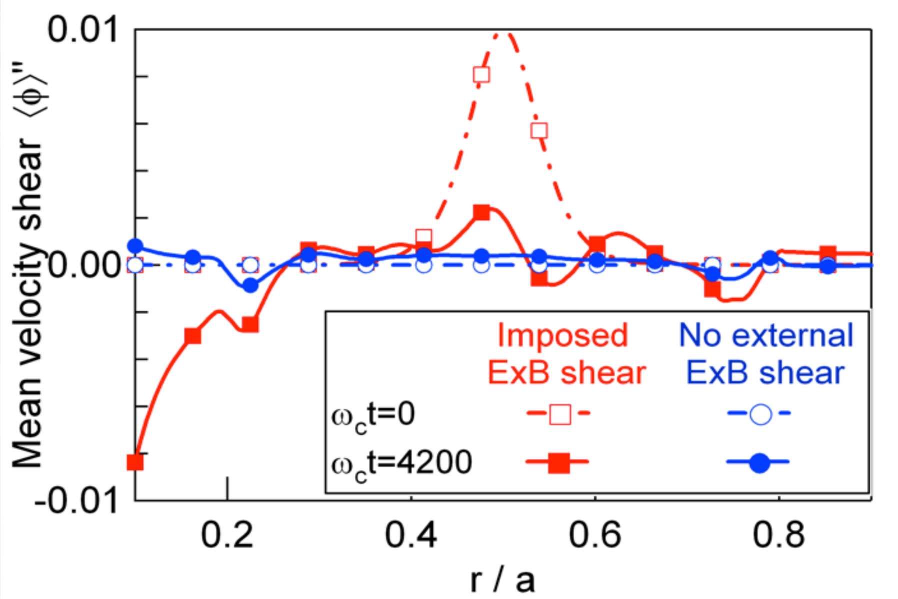

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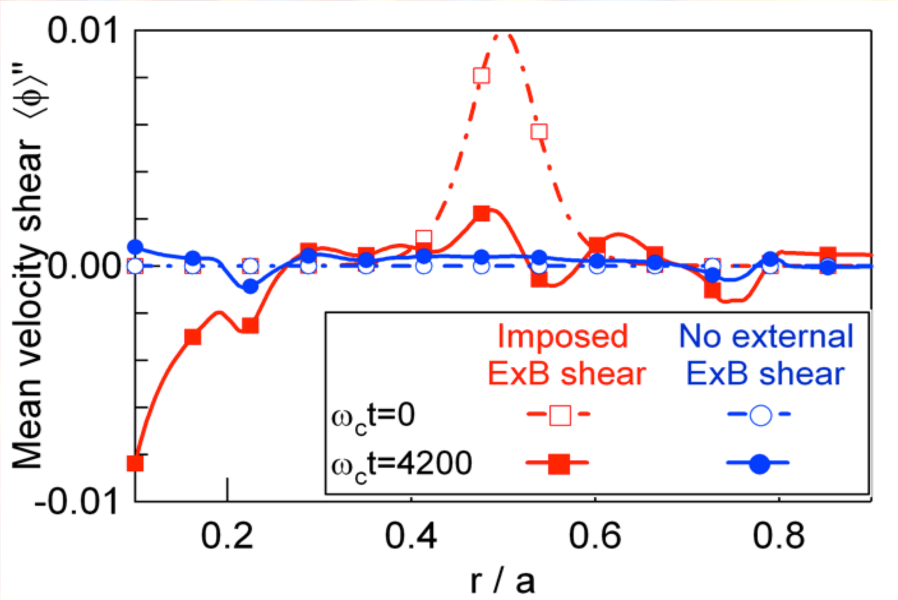

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Include a sheared flow in the equilibrium distribution function (δf codes)

[McMillan et al 2011]

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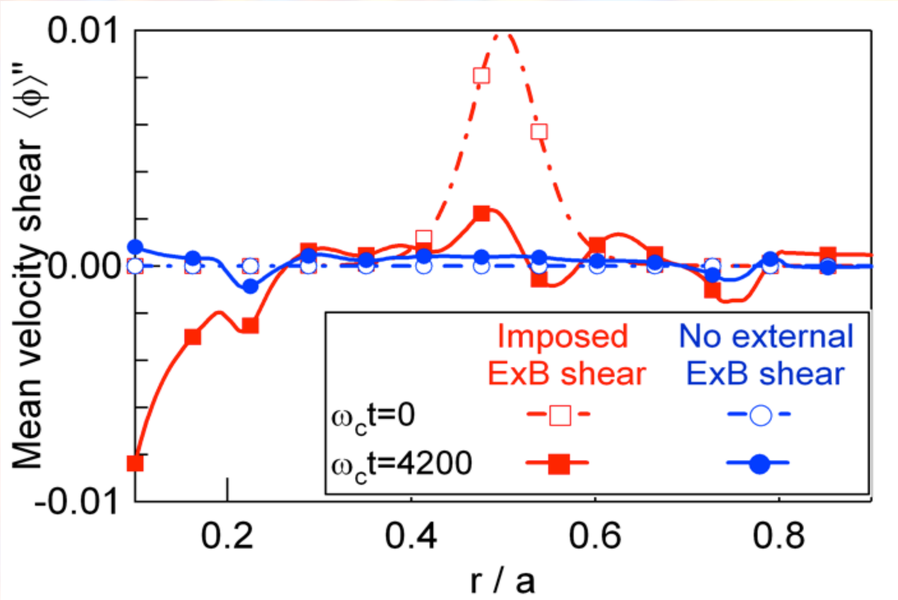

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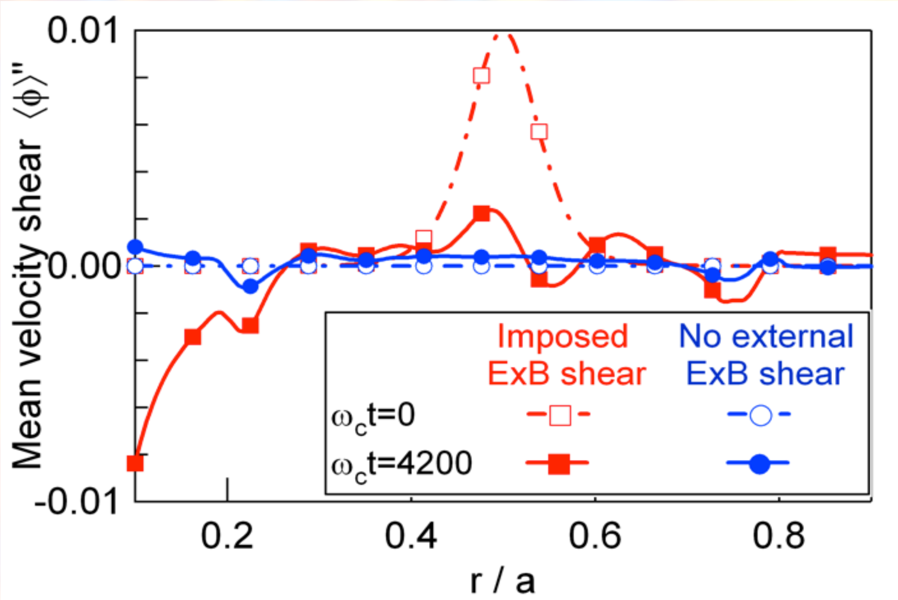

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Add a source term (in the GK eq.) mimicking experimental setup

$$\partial_t f + \nabla \cdot \left(\dot{\mathbf{Z}} f \right) = \mathcal{C}(f,f) + S_W$$

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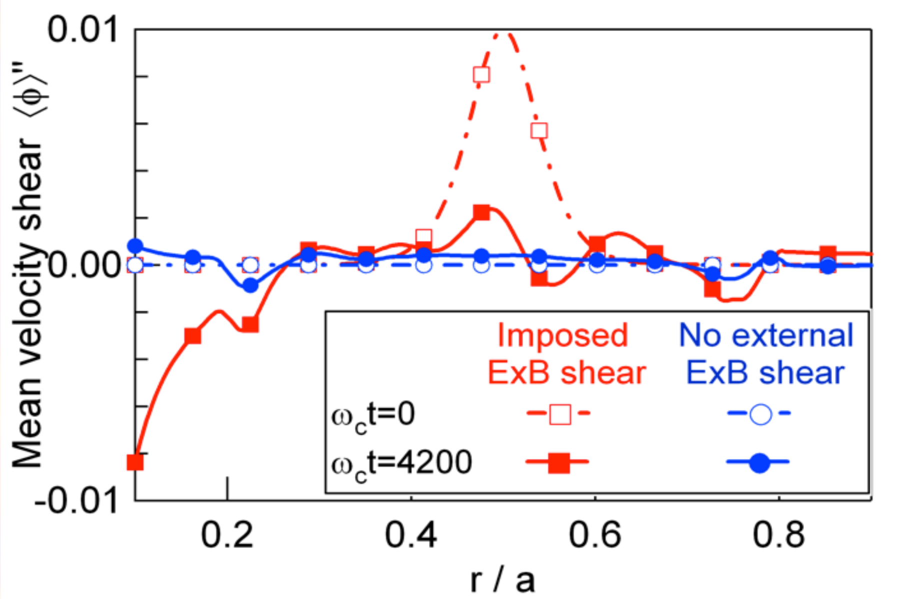

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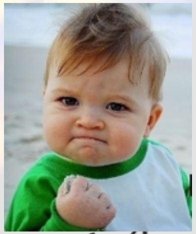

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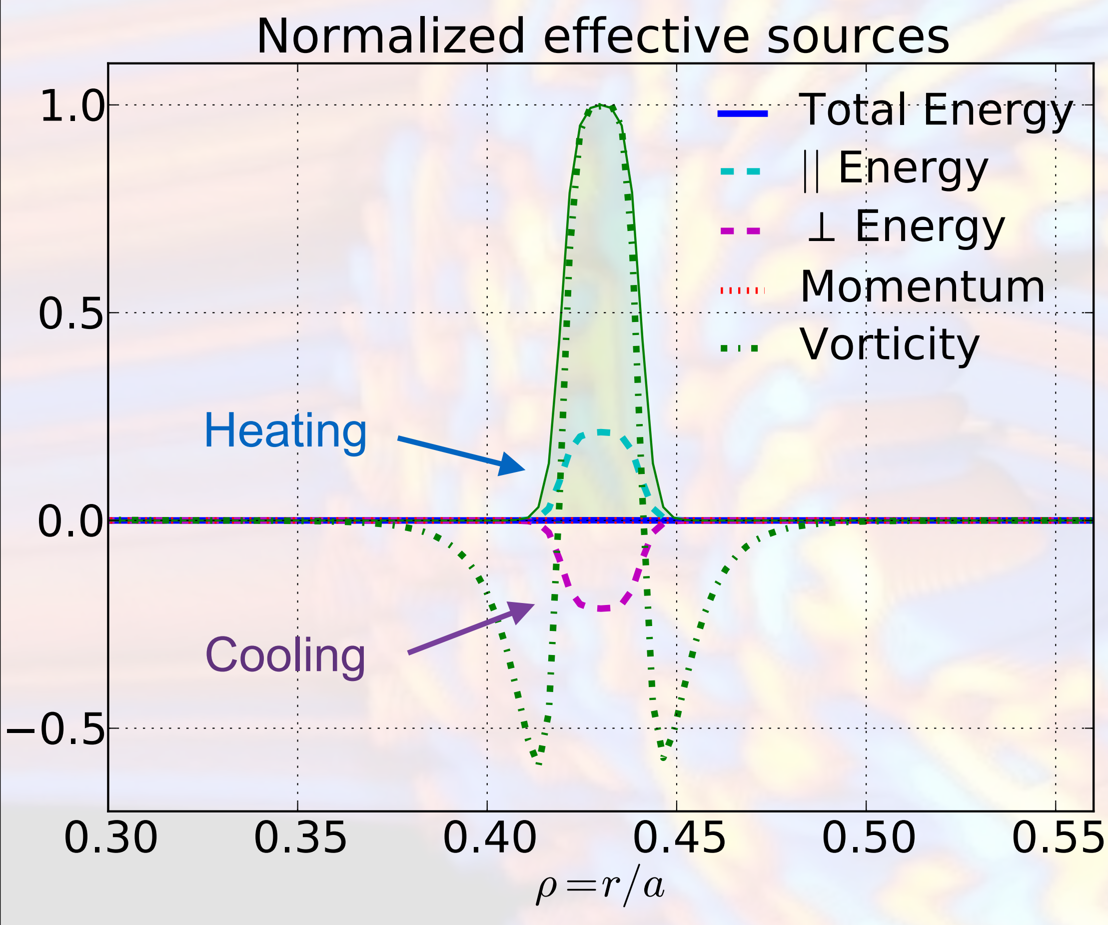
Design of vorticity source(s) in the GK formalism



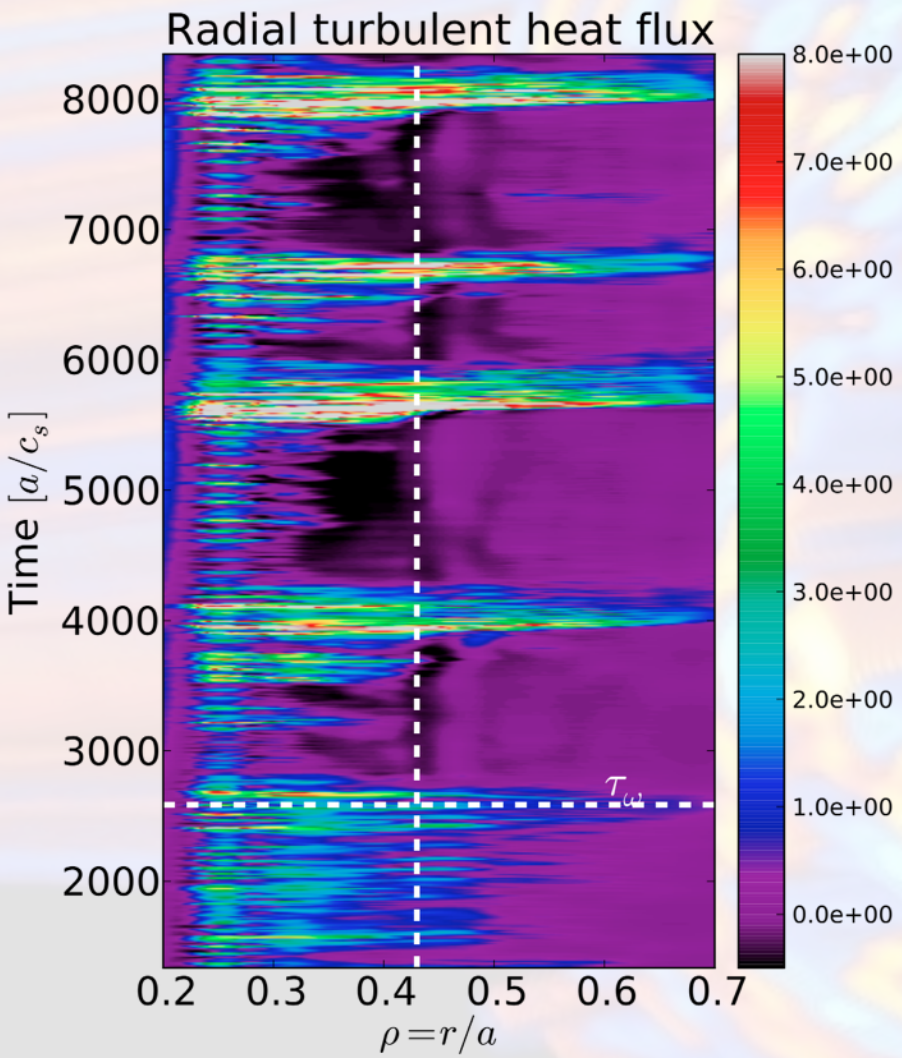
$$\partial_t f + \nabla \cdot \left(\dot{\mathbf{Z}} f \right) = \mathcal{C}(f, f) + S_W$$

- S_W acts mainly on velocity space over a certain radial domain
- S_W generally acts on the density, momentum and energy locally
- Pure vorticity source:

$$S_W \propto \left(v_{||}^2 - \mu \right) e^{(-v_{||}^2/2 - \mu)}$$

[Strugarek et al, 2013, PPCF+PRL]

Quasi-periodic trigger/relaxation of transport barriers



» The turbulent transport is suppressed (flux/10) and the temperature profile steepens

» Large heat bursts occur ➔ barrier relaxation

» The barrier slowly rebuilds and relaxes quasi-periodically

» The ExB shear is also destroyed quasi-periodically

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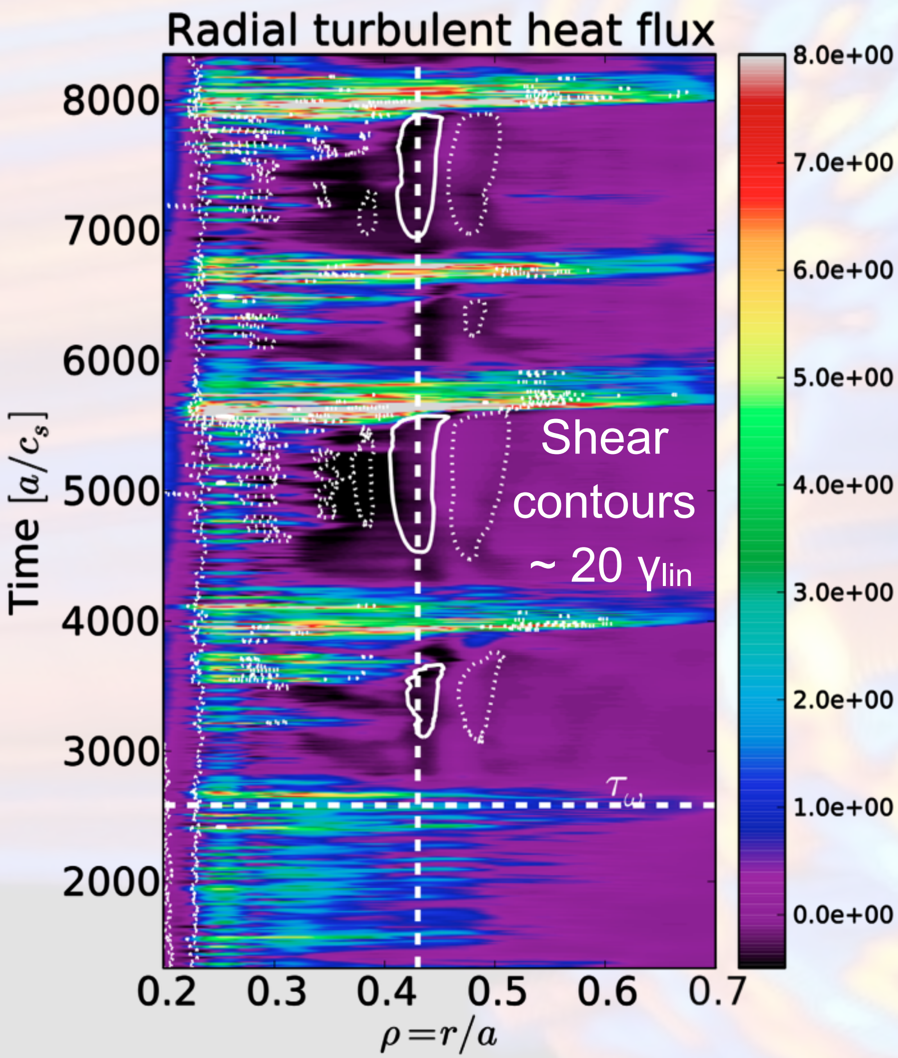

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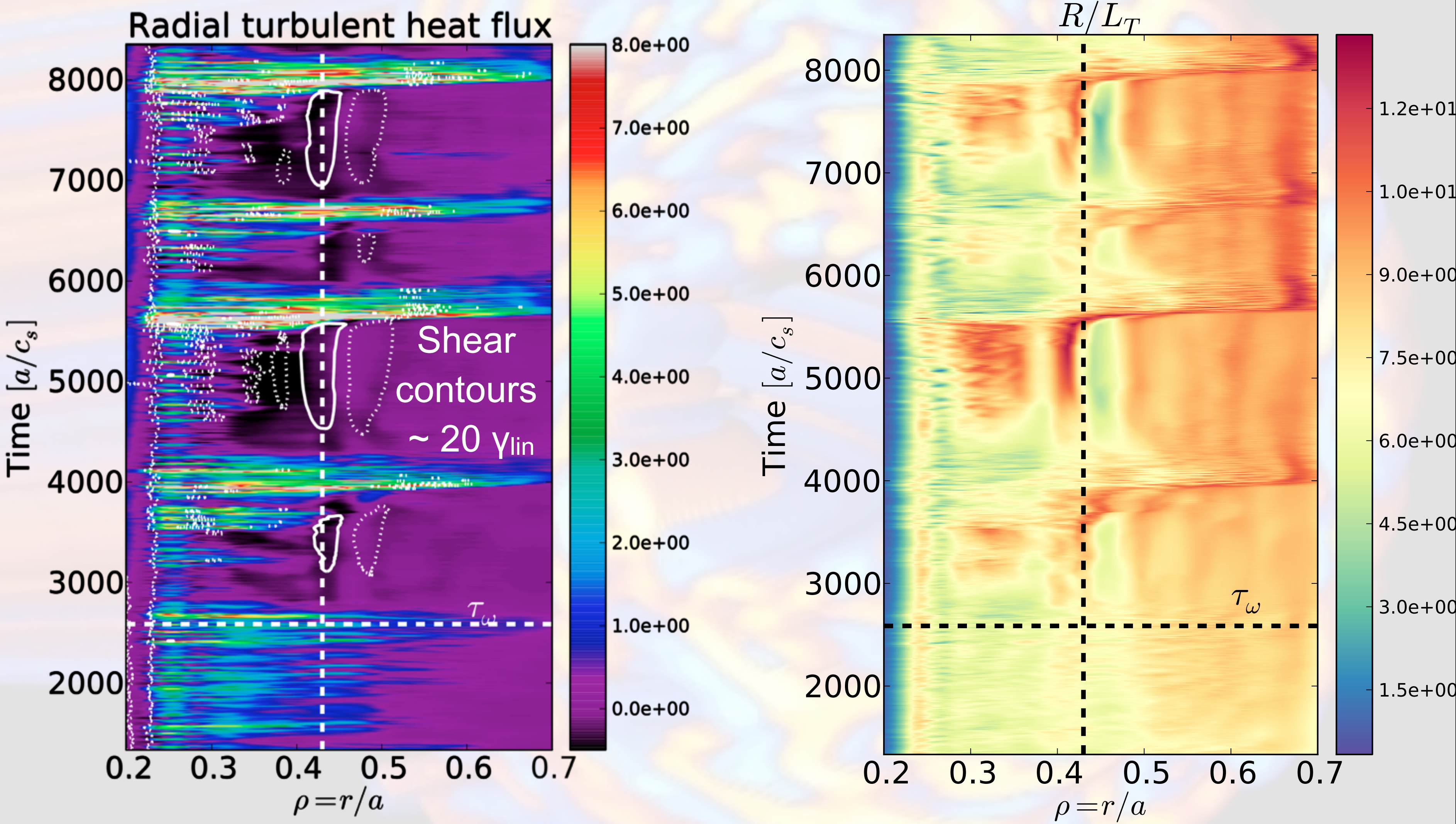

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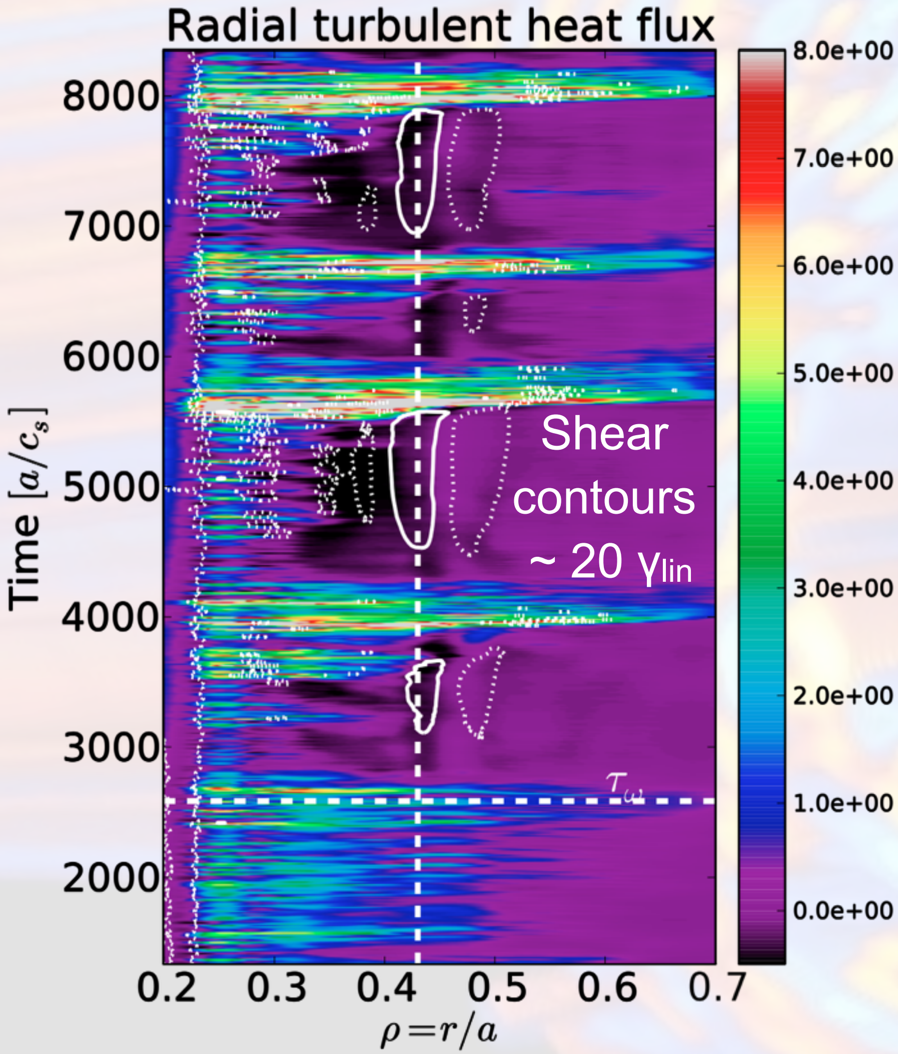
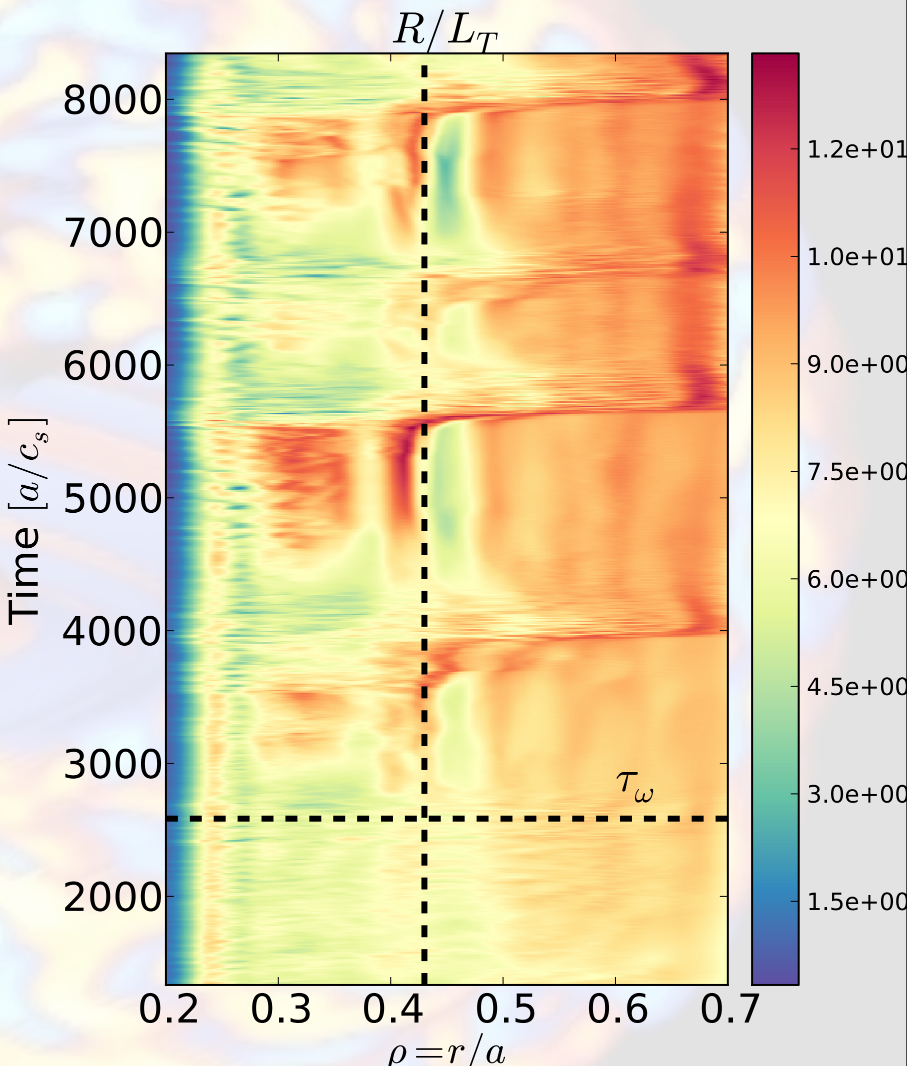
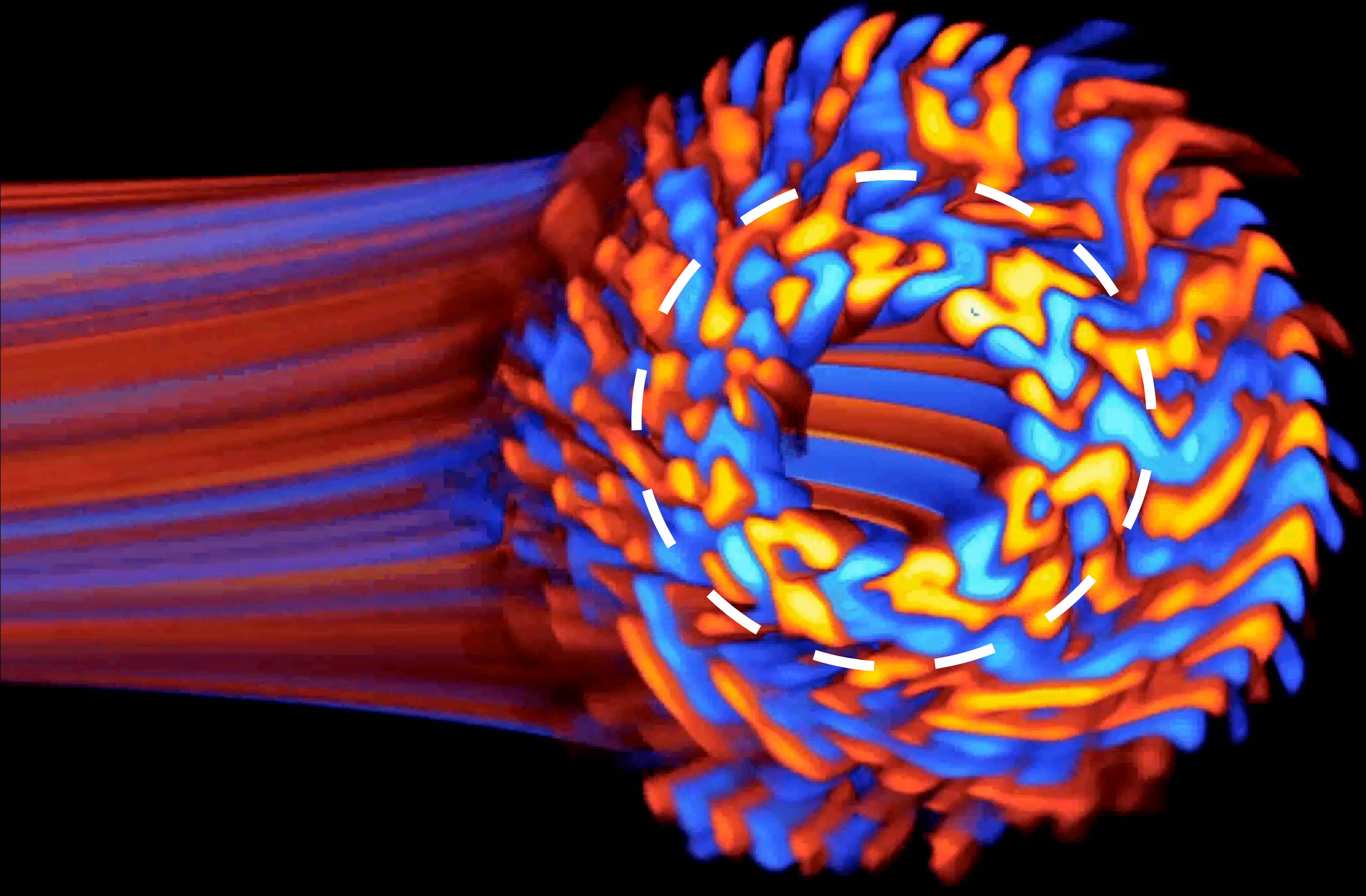
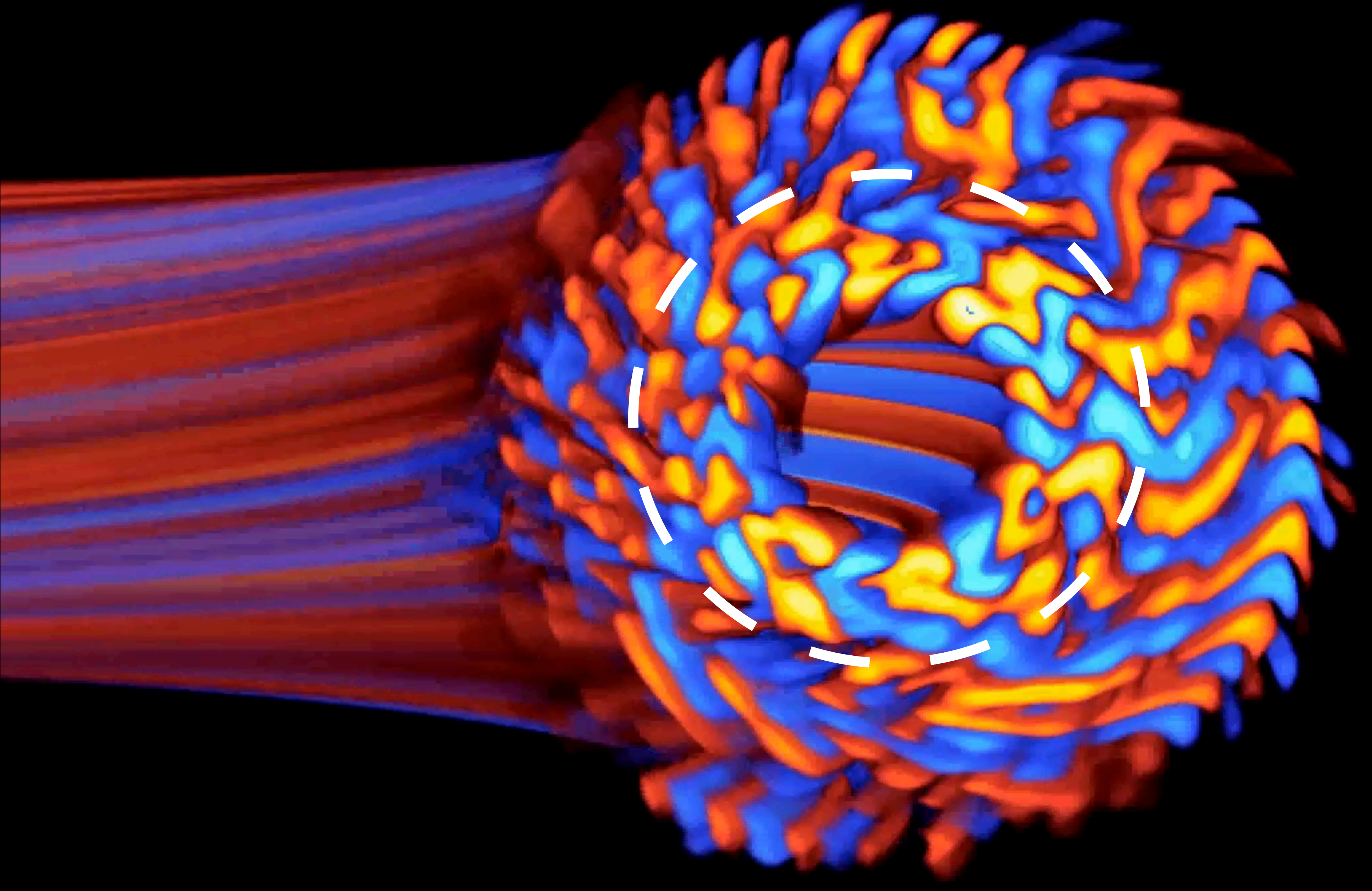


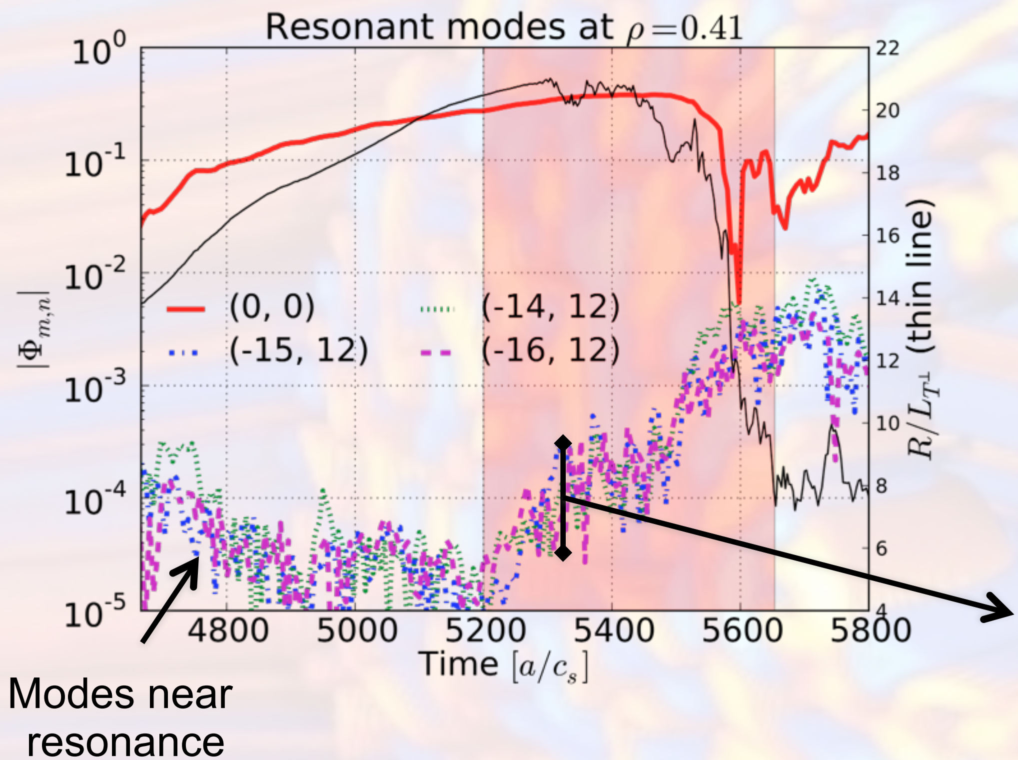


Why both the barrier and the shear are destroyed?

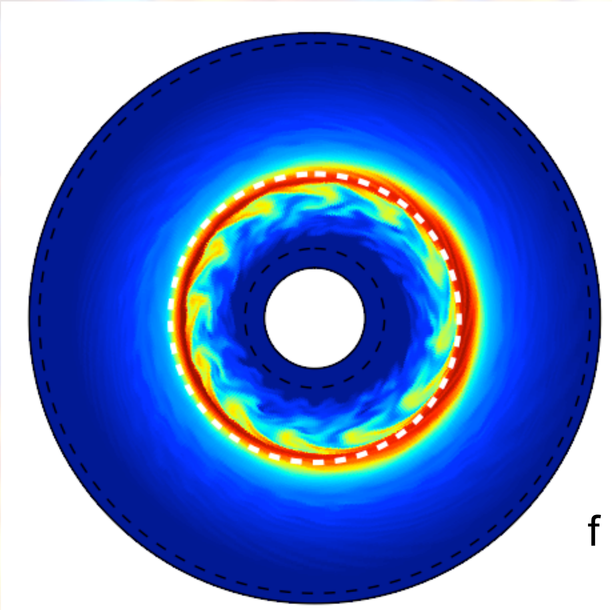




ITG modes grow inside the barrier and suppress it



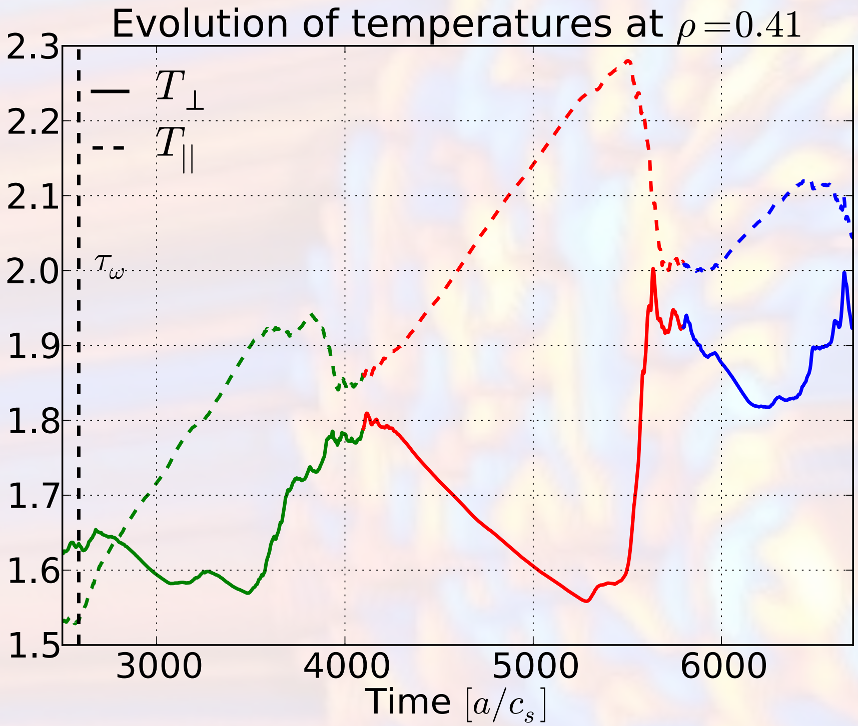
» ITG resonant modes grow exponentially on the inner side of the barrier (linearly unstable??)



» The barrier (and shear) are destroyed at very different values of ω_E
➔ *a priori* not a shear instability

Heat transport ➔ T gradient eroded ➔ Barrier suppressed

The anisotropic temperature lowers the threshold



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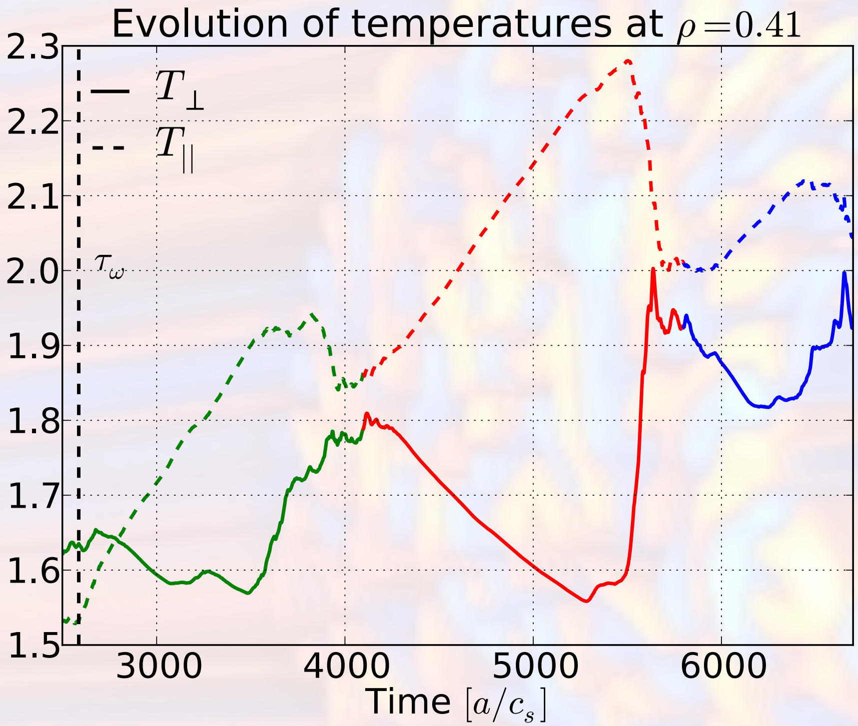
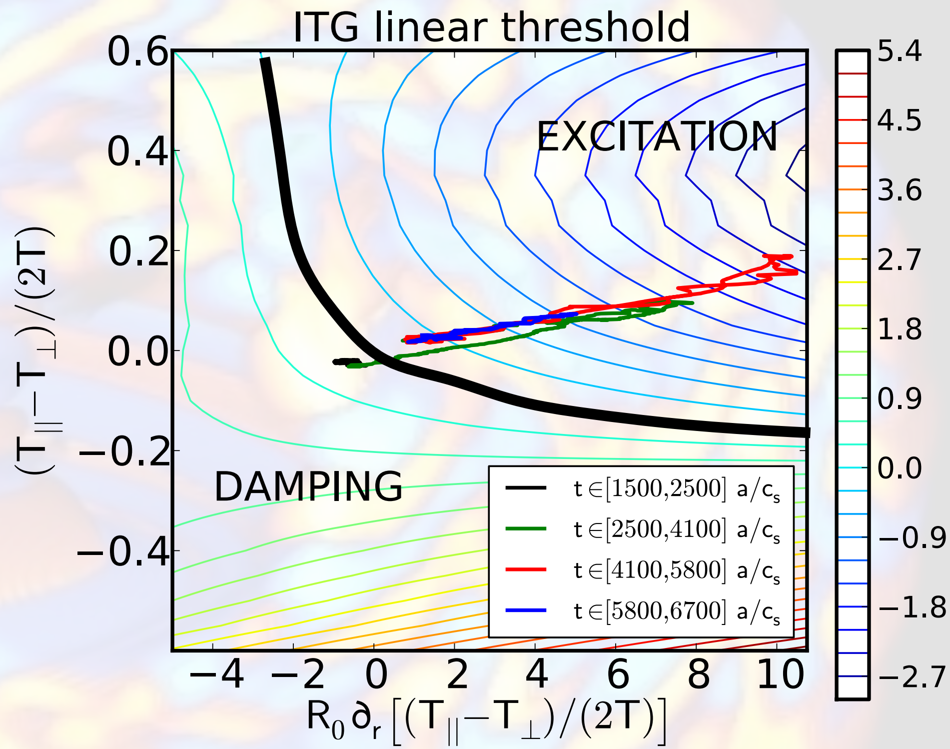
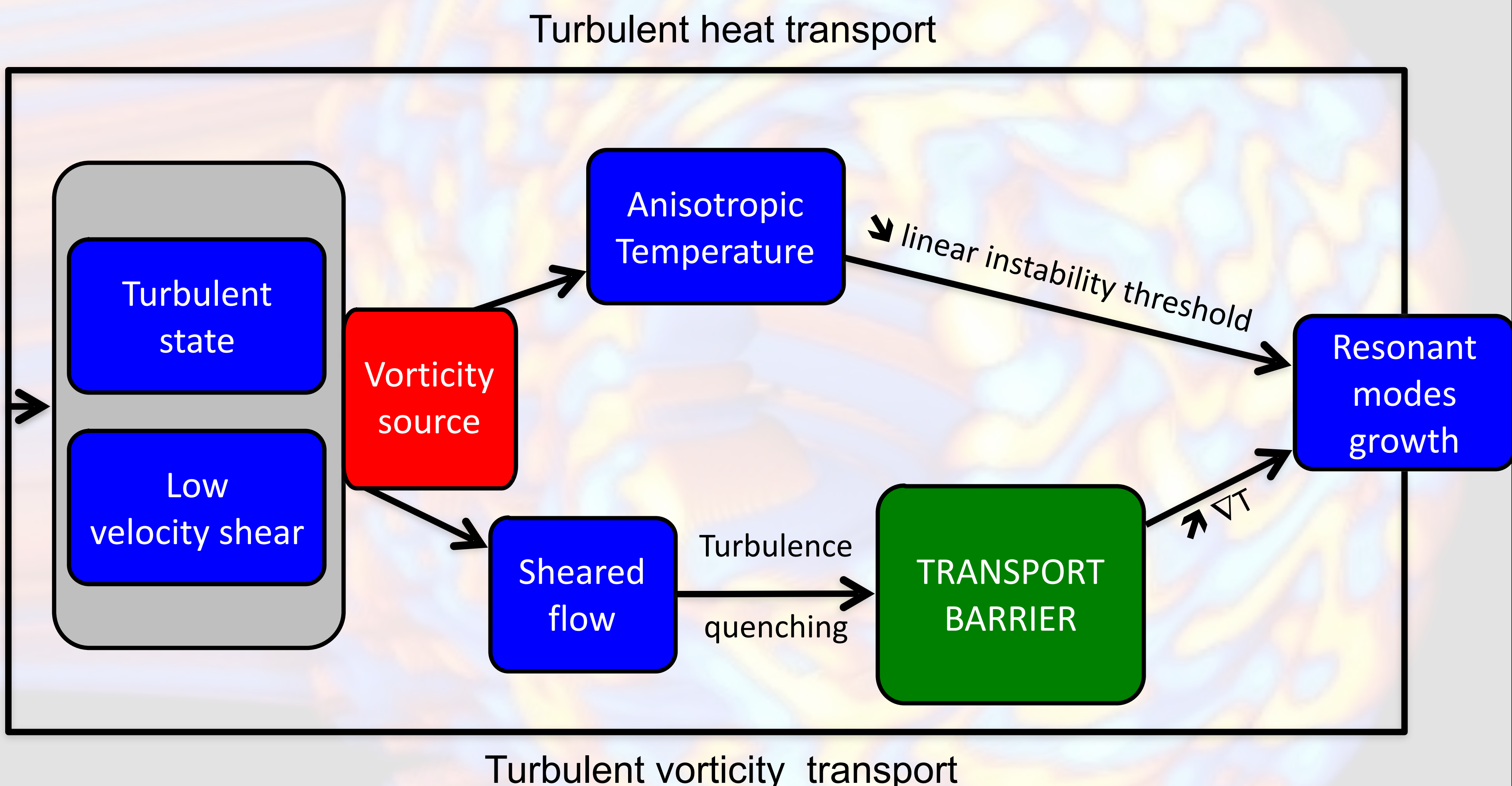




The ITG excitation threshold significantly lowers with the T anisotropy

A new process for transport barrier relaxation



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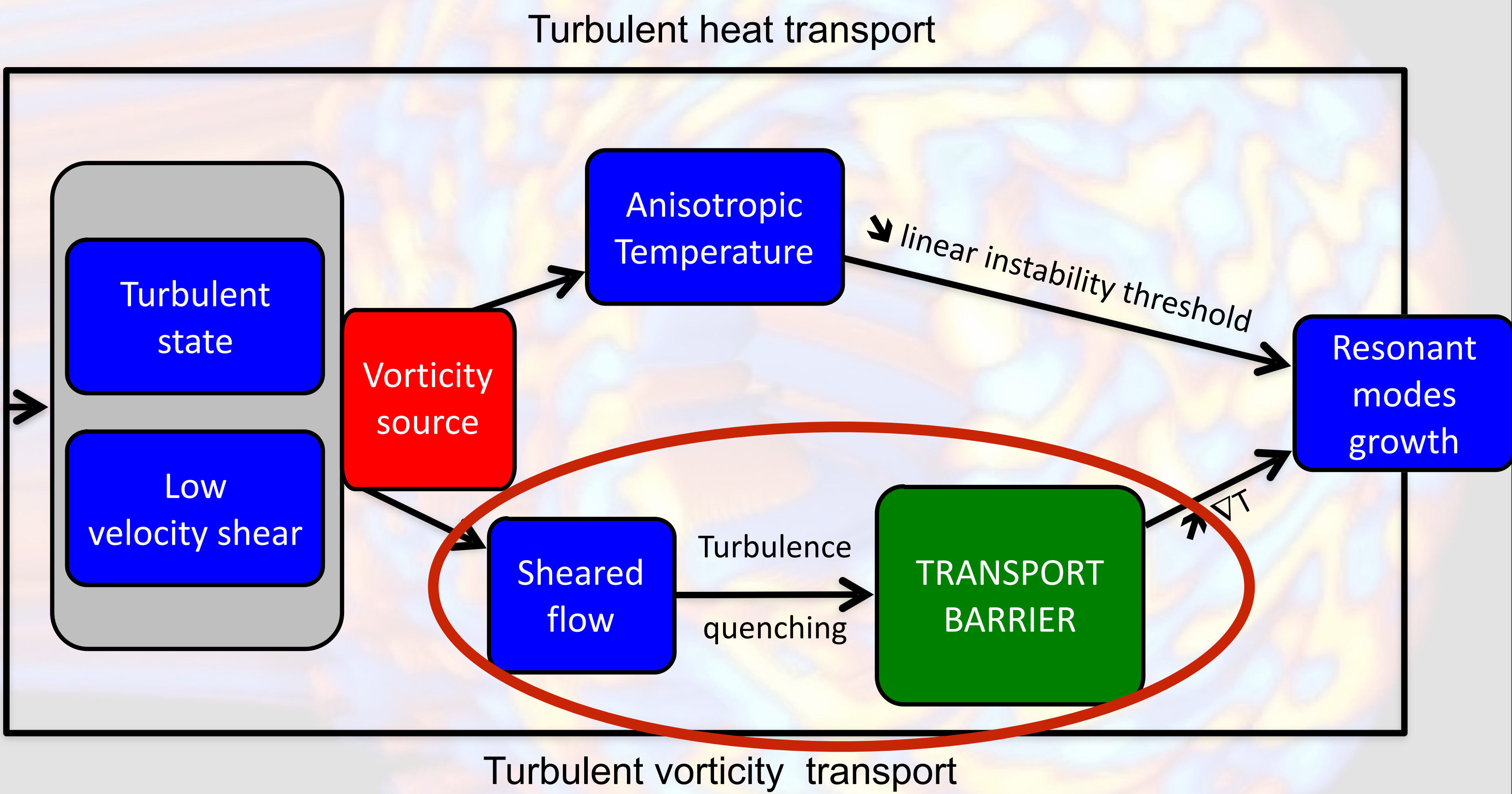
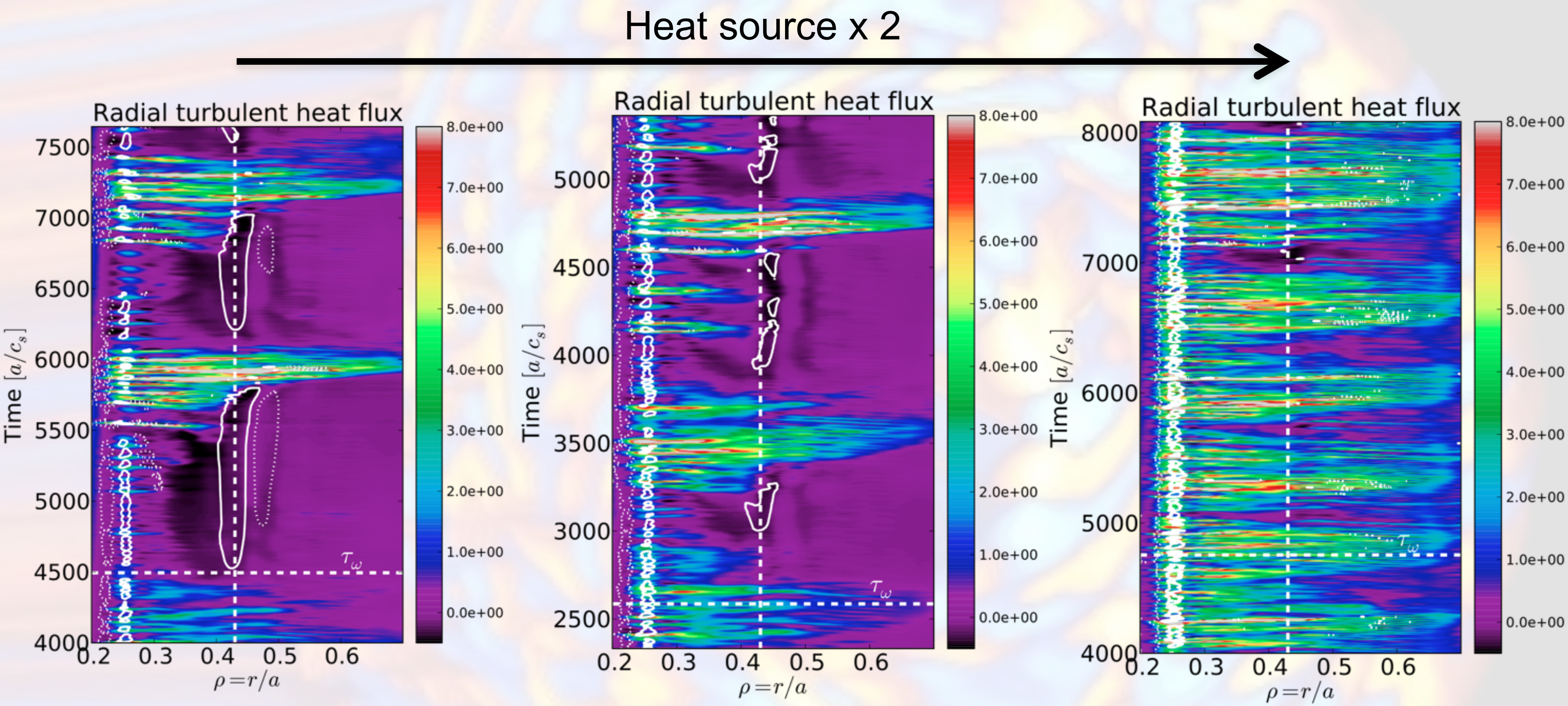


Vorticity source *vs* turbulent transport



Competition:

- Vorticity source amplitude
- Reynolds stress amplitude

$$\partial_t W = \underbrace{-\partial_r \mathcal{J}}_{\text{Turbulence}} + \underbrace{\mathcal{S}}_{\text{Source}}$$

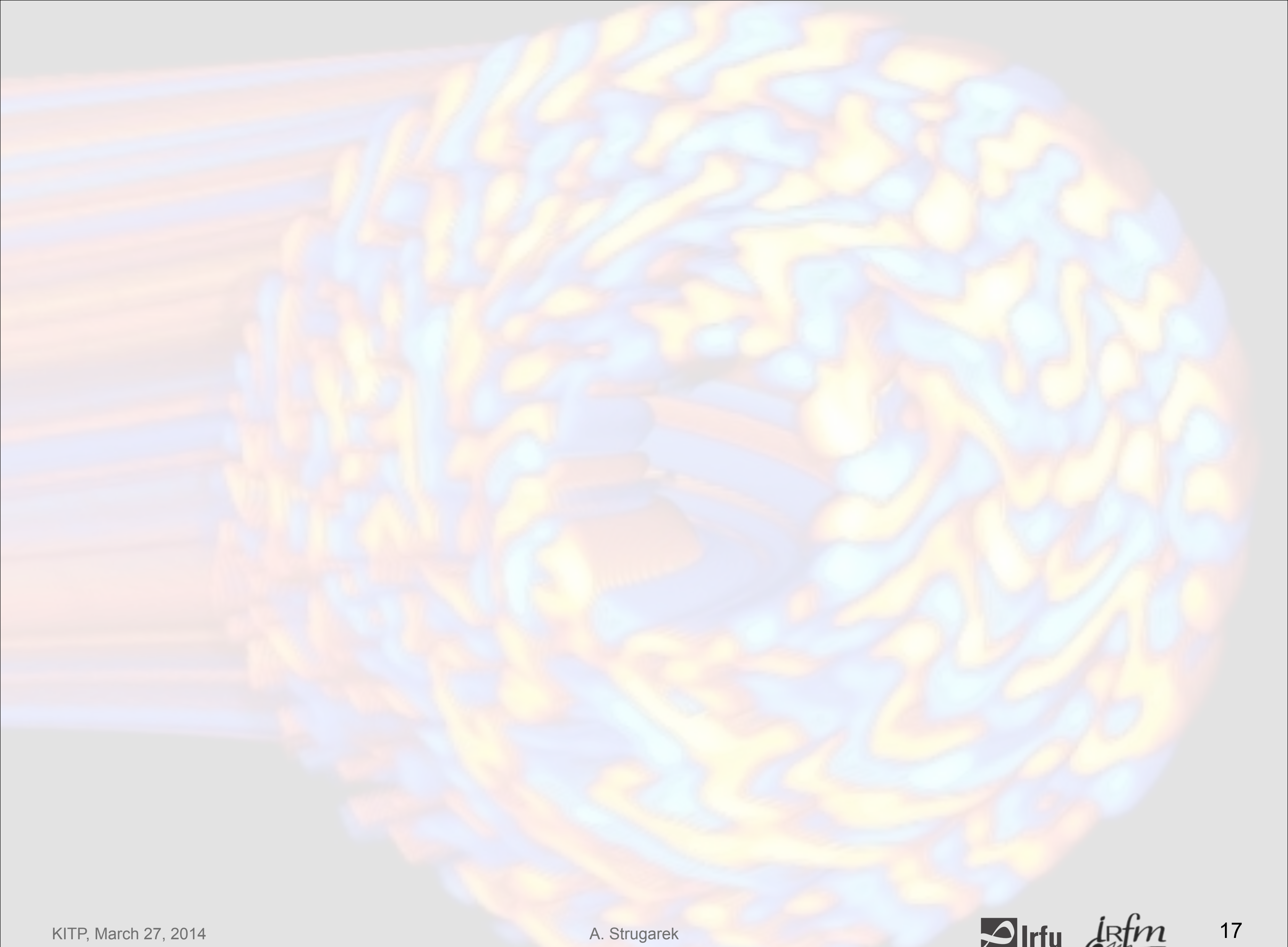
[cf Beyer et al 2007]

Conclusions and Perspectives

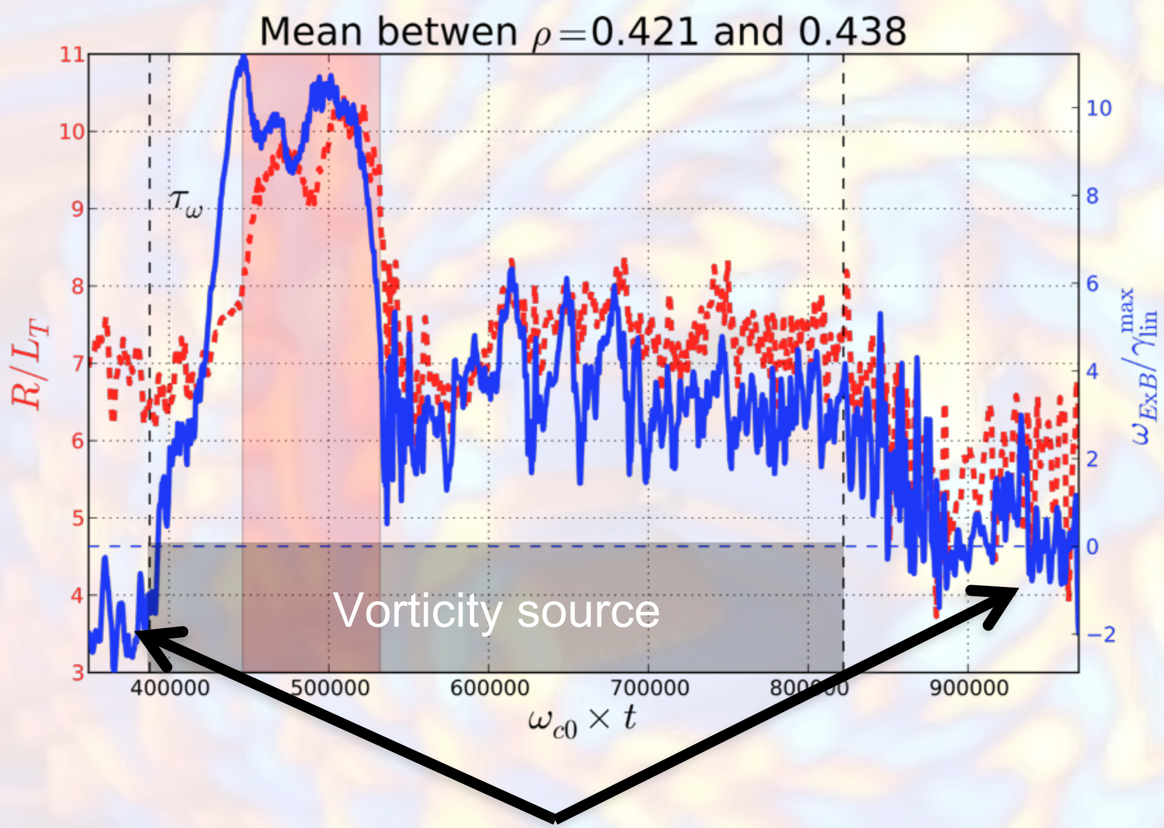
- A transport barrier related to an externally induced sheared flow is observed in gyrokinetic simulations
- A new mechanism based on a (physical) strong temperature anisotropy is found to be at the origin of the destabilization of such barrier
- Our results promote a renewed interest in experimental setup where the plasma is externally polarized, e.g. with Ion Bernstein Waves
- A better experimental determination of the temperature anisotropy would also be highly valuable in the context of transport barrier stability

» The vorticity source could be altered to locally allow a heating/cooling of the plasma, this reducing the T anisotropy

» Stable barriers could also be simulated with an ad-hoc on/off switch on the vorticity source, with interesting experimental implications

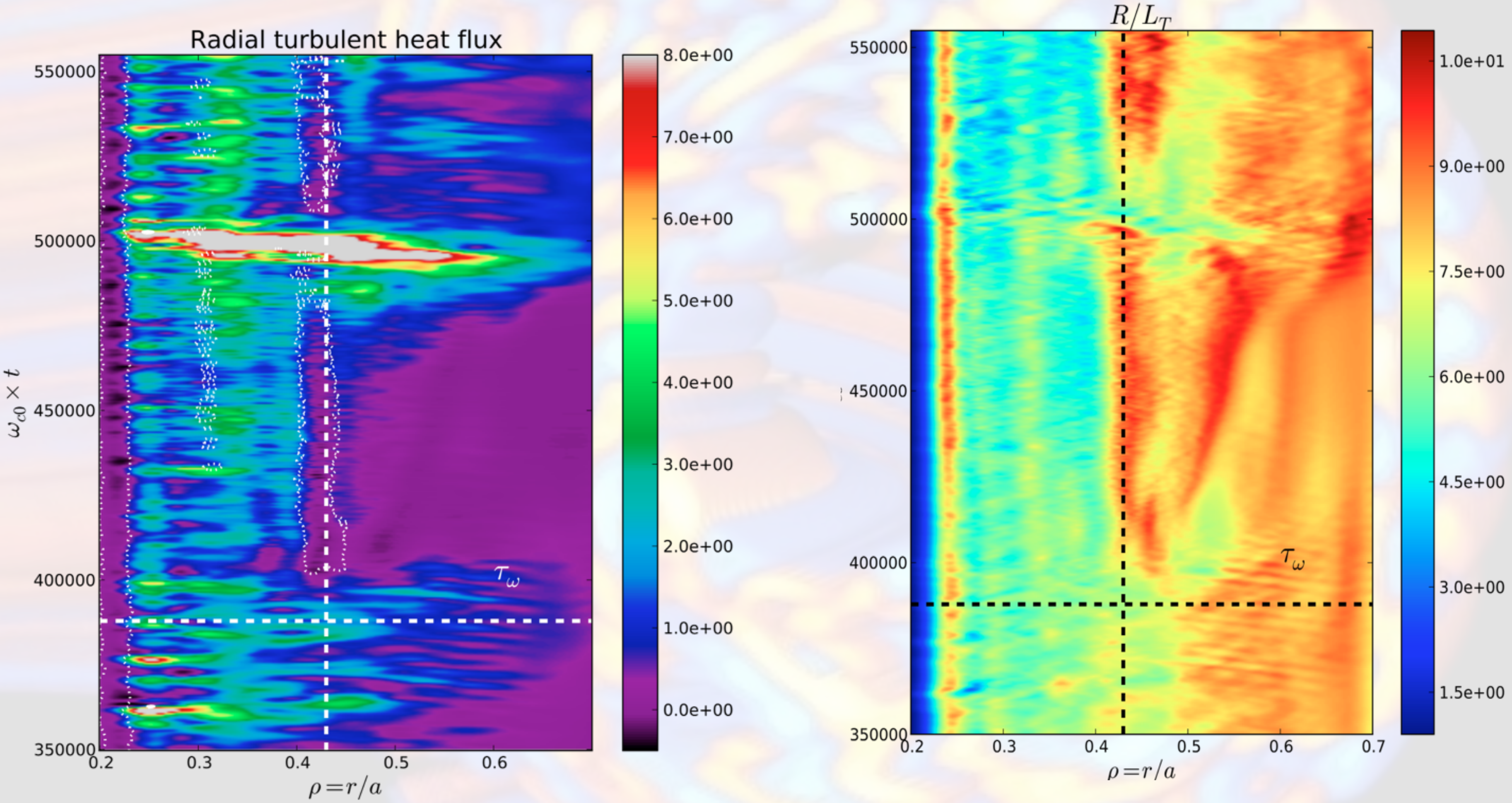


No hysteresis



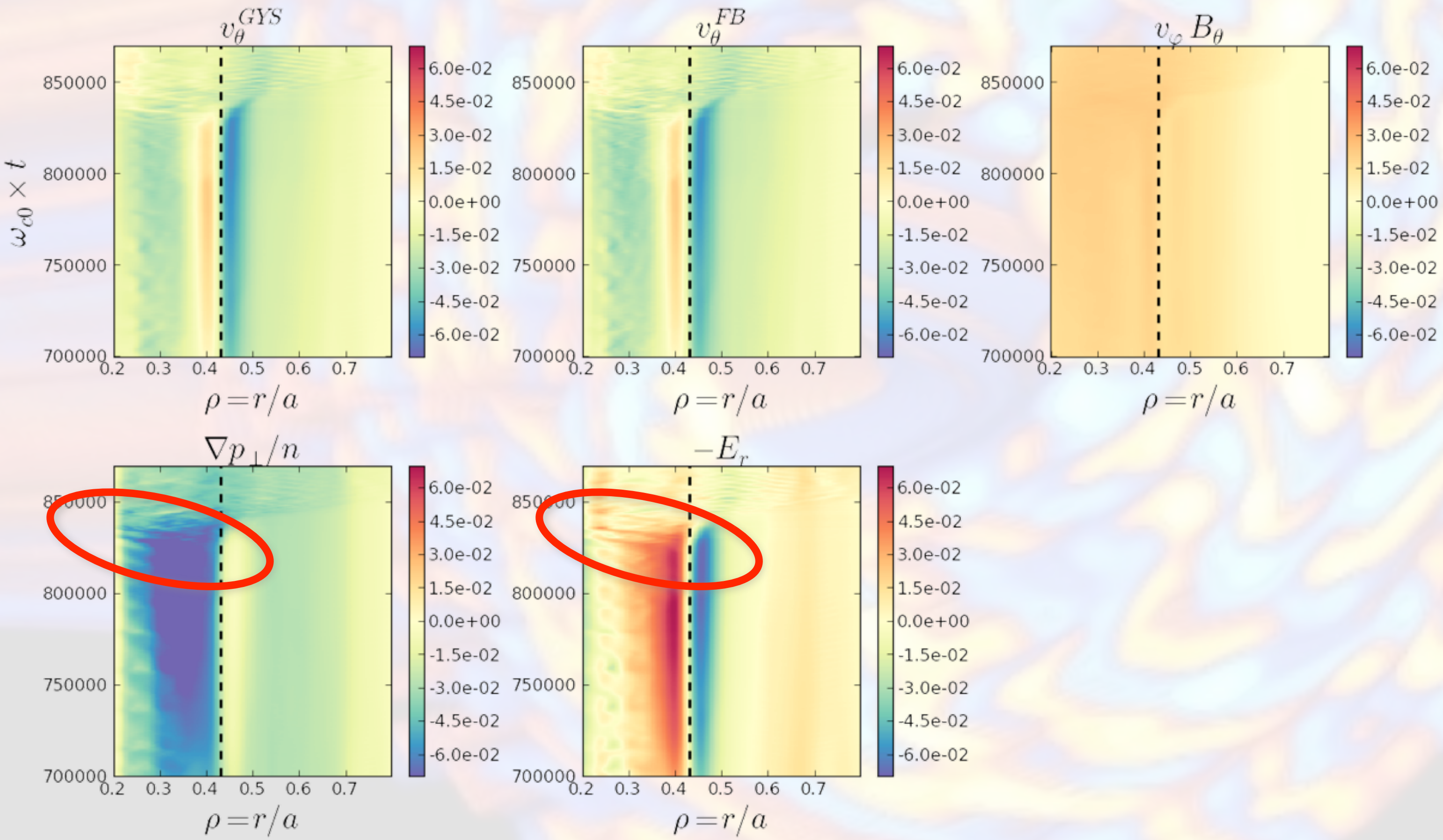
The system relaxes towards its initial state

Effect of the sign of the vorticity source



Force balance

$$B_\varphi v_\theta = -E_r + \frac{\partial_r p_\perp}{en} + B_\theta v_\varphi$$



Vorticity source effect