

Turbulent transport in magnetised plasmas

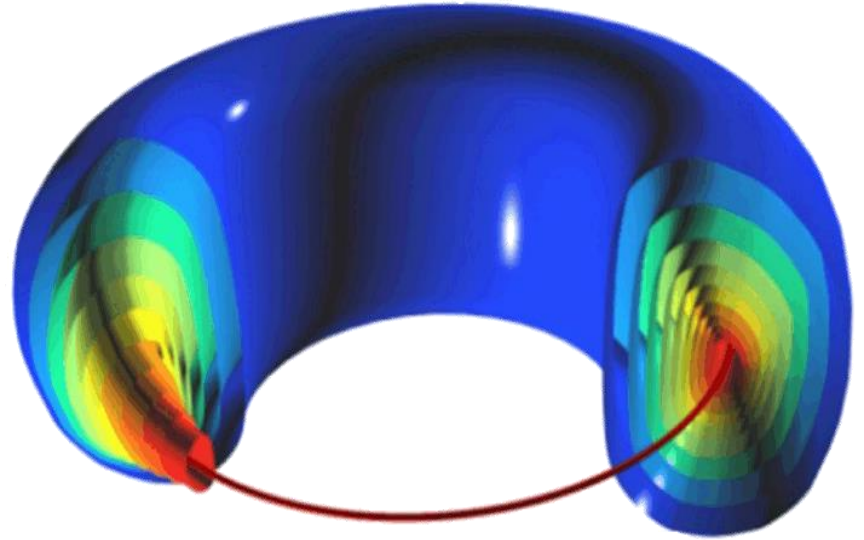
Xavier Garbet

IRFM

CEA Cadarache

Turbulent transport: why?

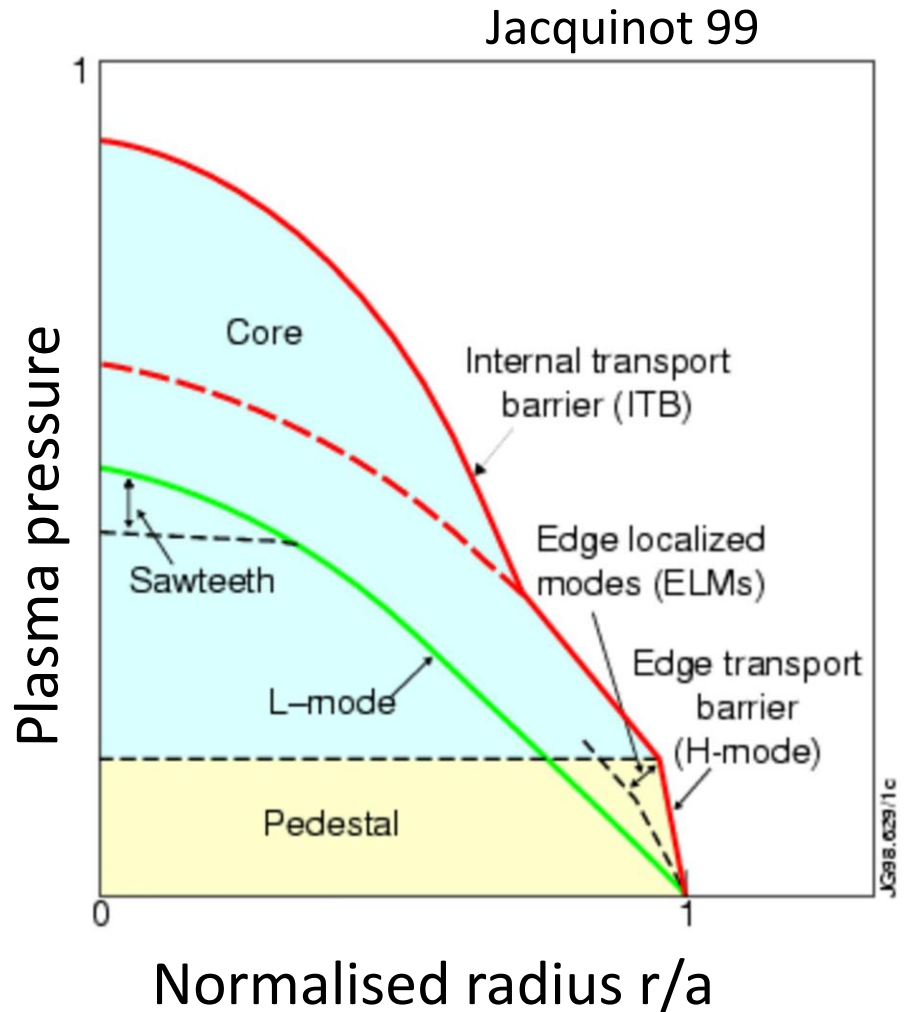
- Turbulent transport degrades confinement in magnetic fusion devices
- Would like to improve confinement → transport barriers
- Plays an important role in astrophysics and geophysics



Nested magnetic surfaces

Turbulent transport: why?

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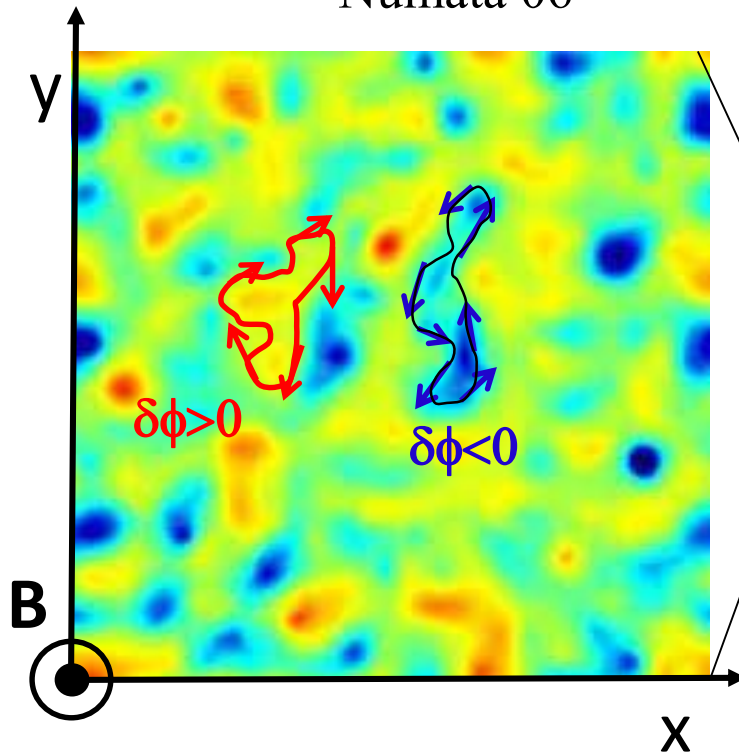


Outline

- Turbulent transport : an introduction
- Fluxes vs gradients and thermodynamics
- Building transport barriers
- Turbulence self-regulation : when instability threshold matters

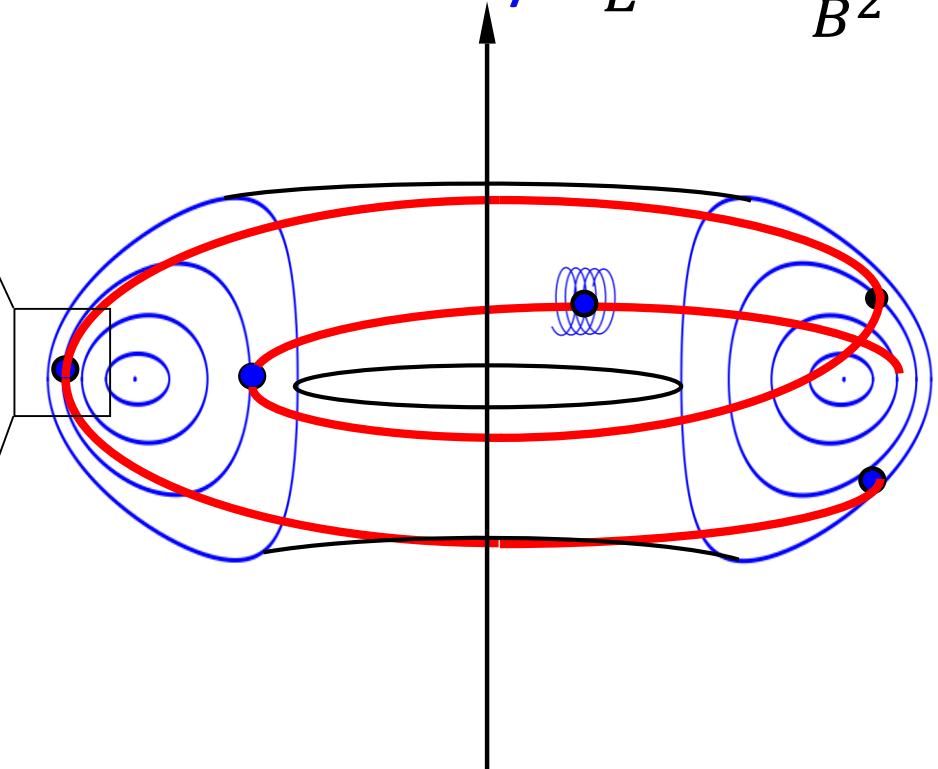
Turbulent transport rules confinement in tokamaks

Numata 06



Iso-lines electric
potential ϕ

$E \times B$ drift velocity $\mathbf{v}_E = \frac{\mathbf{B} \times \nabla \phi}{B^2}$

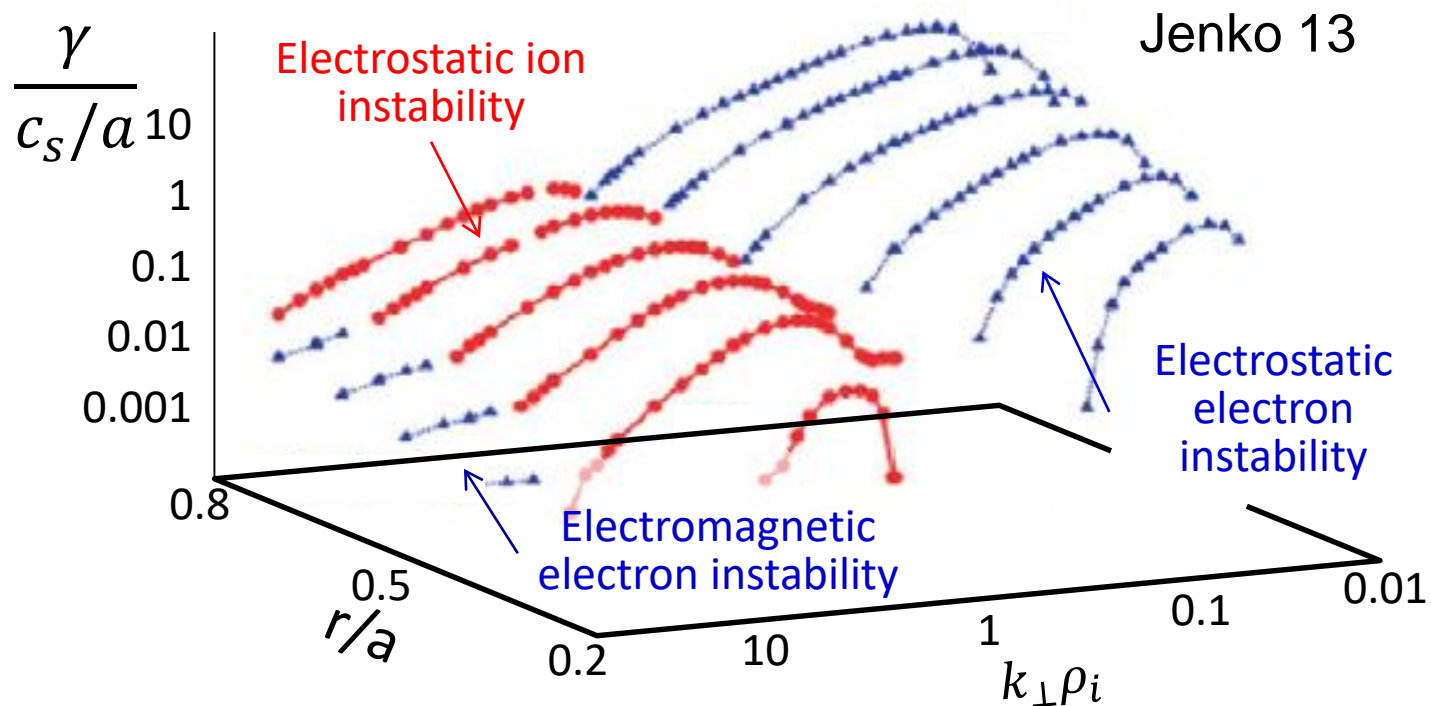


Diffusion $D \sim |\mathbf{v}_E|^2 \tau_c$

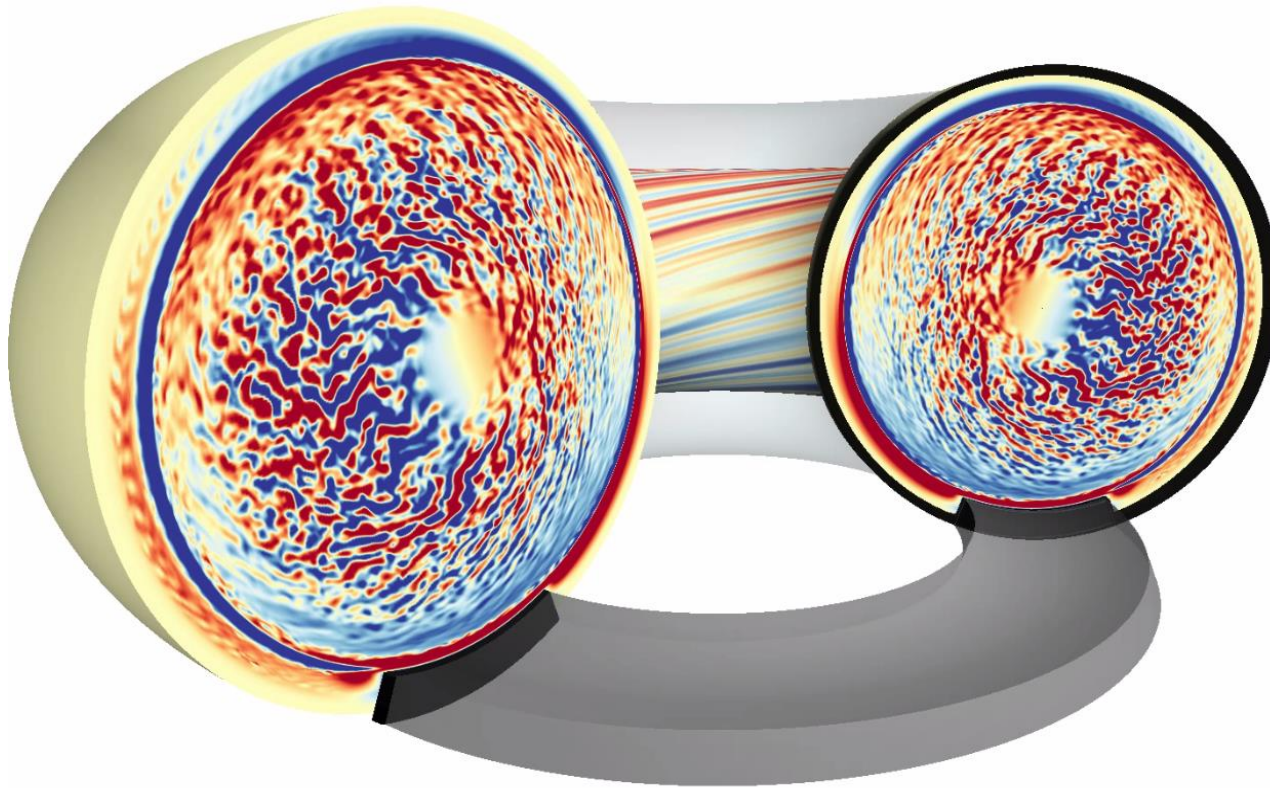
Confinement time $\tau_E \sim \frac{a^2}{D}$

Turbulence is driven by micro-instabilities

- Driven by gradients → **instability threshold** Kadomtsev 66, Coppi 67, Horton 81, Rewoldt 87, Romanelli 89
- Family of **drift-waves** - interchange $\nabla P \cdot \nabla B > 0$ usually prevails.



What does it look like?



Grandgirard
GYSELA-X
2020

Building a transport model

- Power law decay , frequency spectra are broad Hennequin 04,09, Mazzucato 08,09

- Amplitude \sim mixing-length theory Prandtl 1905

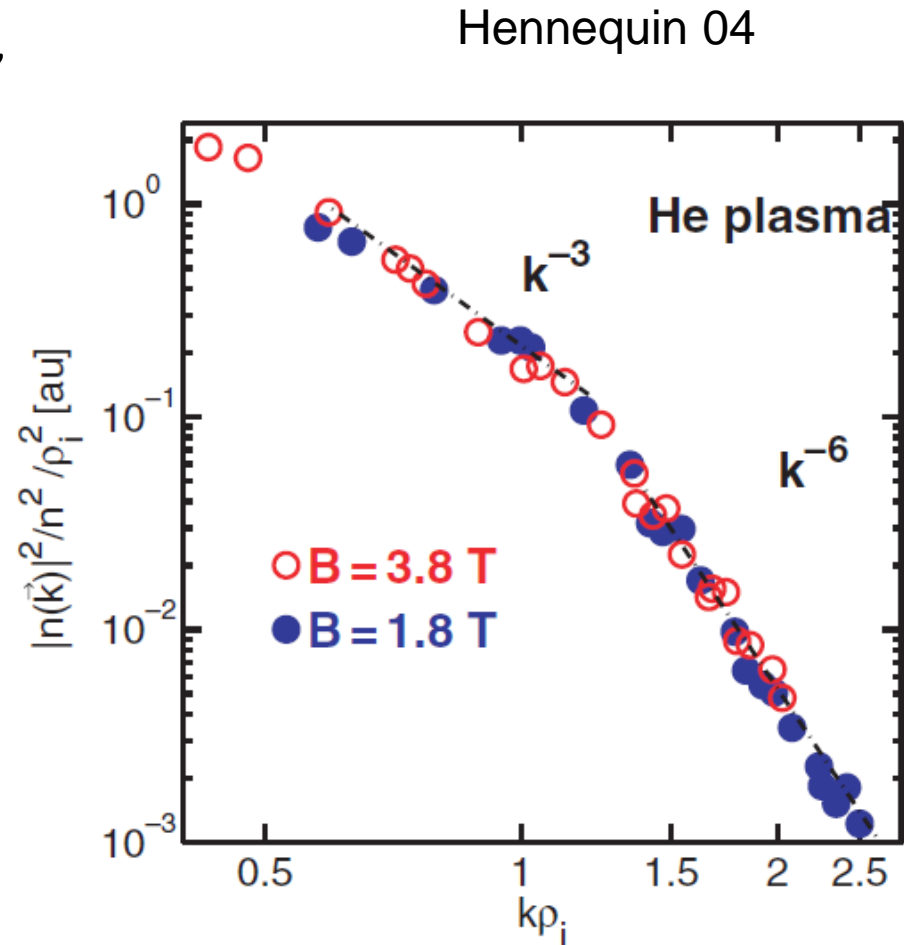
$$\frac{\delta n}{n} \sim \frac{\ell_c}{L_n}$$

→ yields diffusion vs gradients

$$D \sim \frac{\ell_c^2}{\tau_c}$$

→ reduced transport models

Staebler 07, Bourdelle 16



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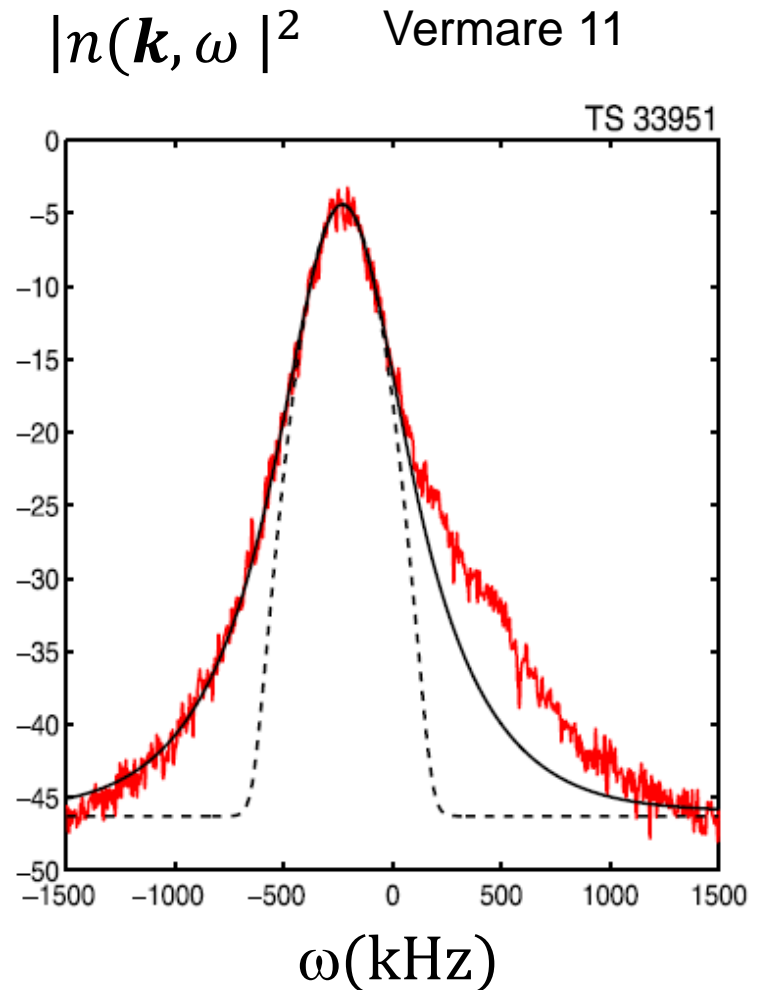
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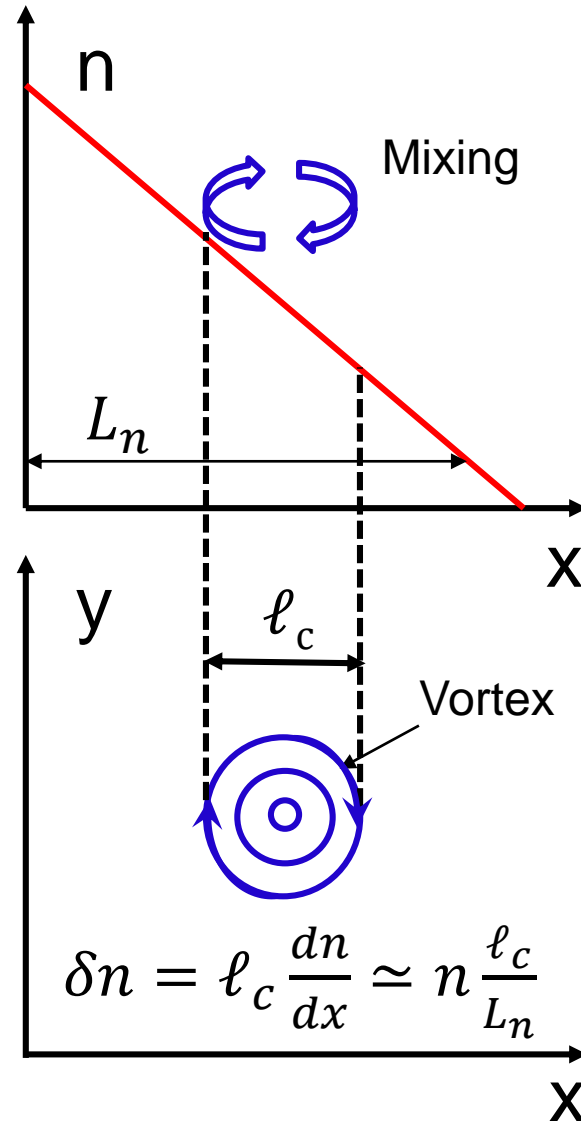
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Issues

- Up-gradient transport is ubiquitous – consistency with second principle?
- Can turbulent transport be controlled?
- Scale separation may not hold: interaction between small and large scales mediated by mesoscale turbulent structures.

Outline

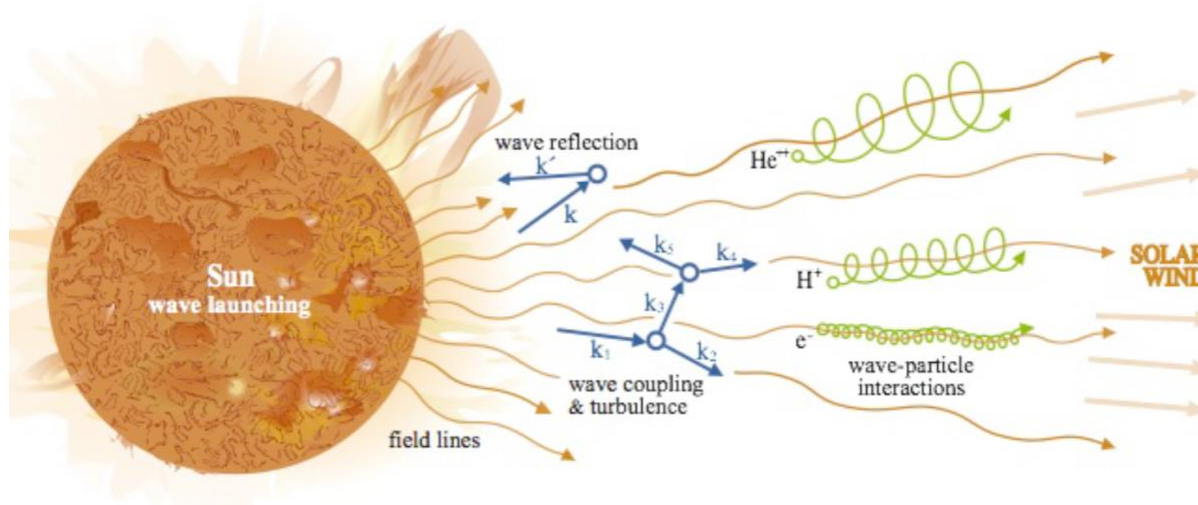
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Transport equations bear a puzzling shape

- Evolution of density, velocity, temperature $\mathbf{A} = (N, V, T)$

$$\frac{\partial \mathbf{A}}{\partial t} + \nabla \cdot \mathbf{\Gamma} = \mathbf{\Sigma} \quad \mathbf{\Gamma} = \bar{\bar{\mathbf{L}}} \cdot \mathbf{A}' + \mathbf{\Gamma}_{\text{res}}$$

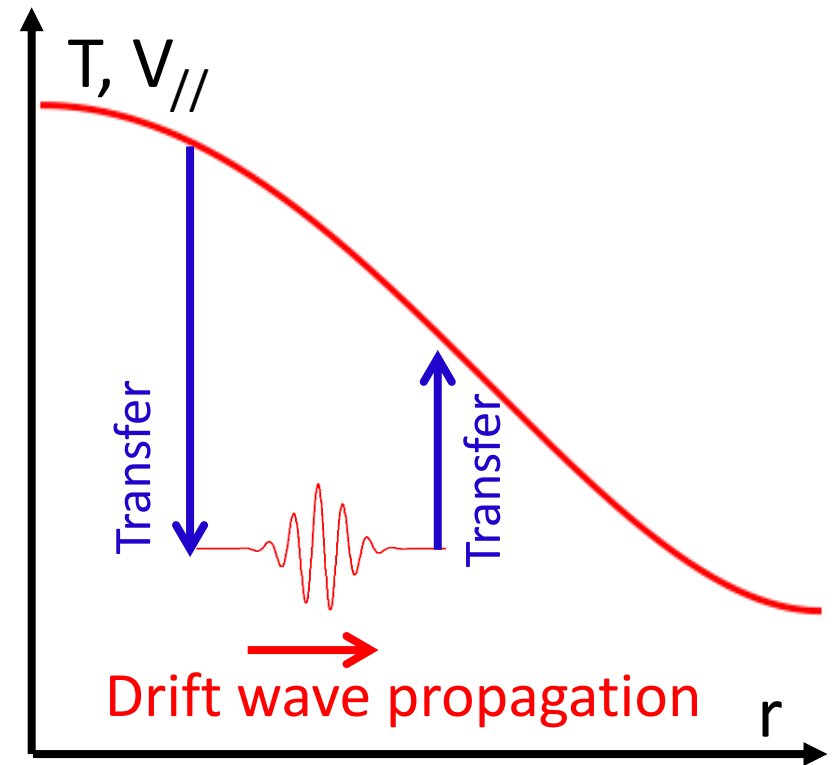
- Transport matrix $\bar{\bar{\mathbf{L}}}$ is symmetric Onsager 1931. Unexpected:
 - “residual” stress and heat flux $\mathbf{\Gamma}_{\text{res}}$
 - turbulent heating and acceleration $\mathbf{\Sigma}$ Rudakov 71, Ott 72



Bale 2012

Wave transport is responsible for residual fluxes

- Total field + particle momentum/energy is conserved → **extended thermodynamics** Boozer 92, Krommes 93, Sugama 96, Watanabe 06, XG 13
- Residual = fluxes of momentum/ energy carried by waves.
- Requires **symmetry breaking** Peeters 07, Gürcan 07, Diamond 08, Camenen 09 **e.g. mean shear flow**



Turbulence produces momentum and heat sources

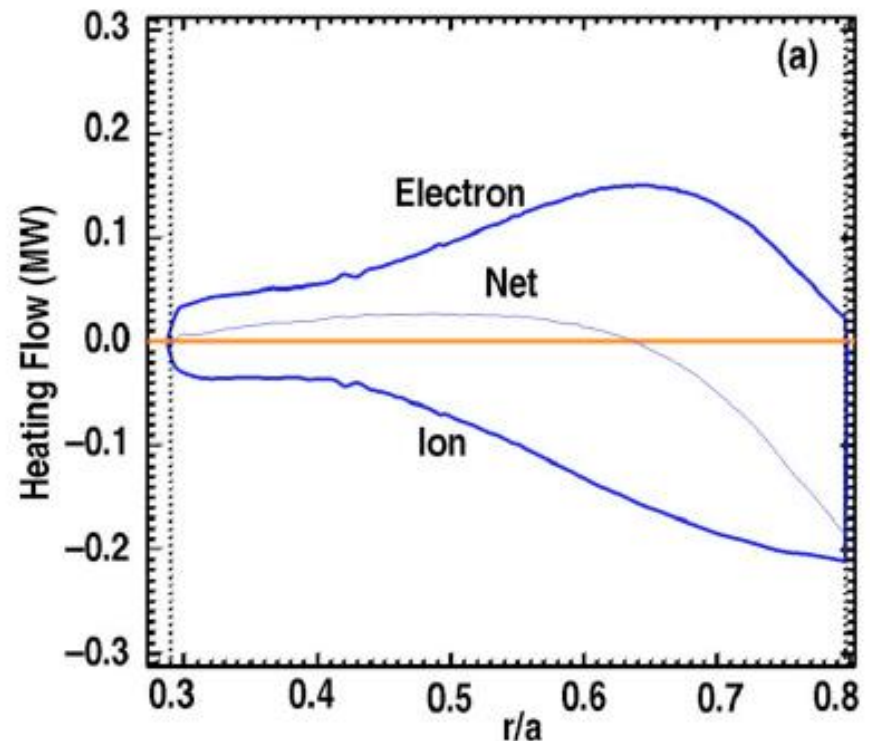
- **Source terms** Itoh 88, Hinton 06, Barnes 12, Lu Wang 13, XG 13, Seiferling 18, Wang 18

$$\Sigma_{V_{\parallel}} = \langle neE_{\parallel} \rangle$$

$$\Sigma_T = \langle \mathbf{J} \cdot \mathbf{E} \rangle$$

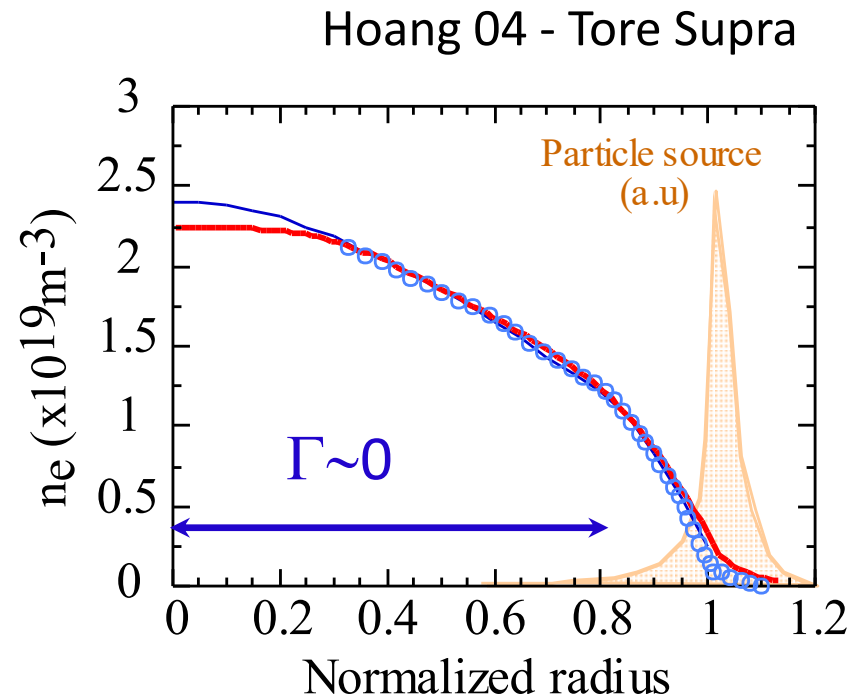
- Correlation requires **symmetry breaking**
- Charge conservation \rightarrow transfer Waltz 11 . Wave energy transport \rightarrow net effect Zhao 12

Waltz 08



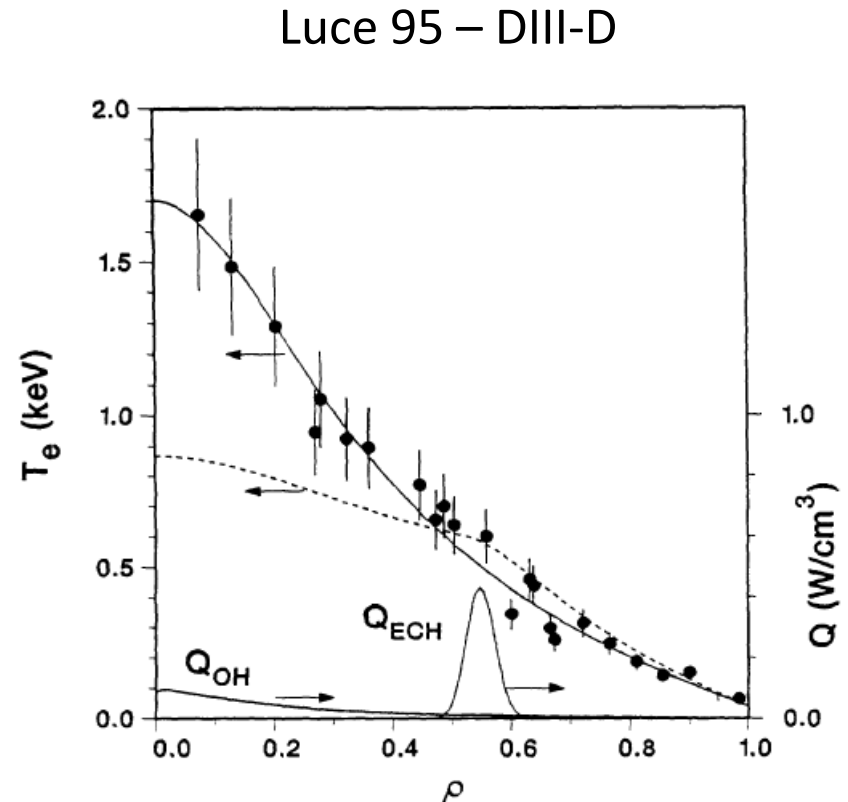
Turbulent pinch theory successfully tested in tokamaks

- Particle flux $\Gamma = -D \frac{dn}{dr} + \mathcal{V}n$
- “Pinch velocity” \mathcal{V} due to temperature and velocity gradients, and compressibility
Angioni 03 & 06, XG 04, Camenen 09
- Entropy production rate > 0
XG05.
- Onsager symmetry \rightarrow thermal pinch Dominguez 89, Luce 92, Itoh 96, Mantica 05, Lu Wang 11



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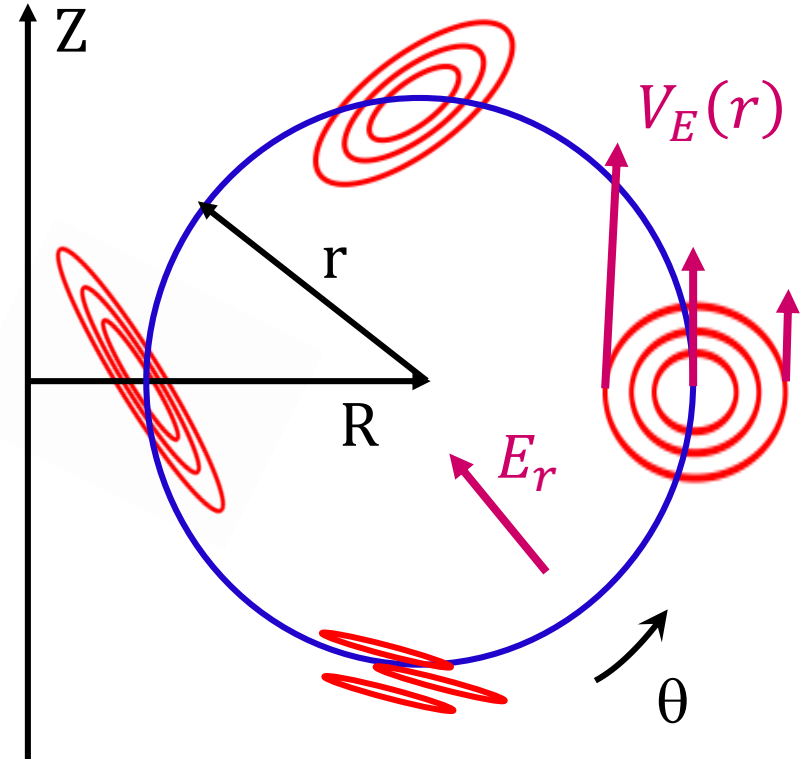
Mean shear flow reduces turbulent transport

- Mean shear flow → vortex distortion, size reduction.
Shear flow rate

$$\omega_E = \frac{dV_E}{dr}$$

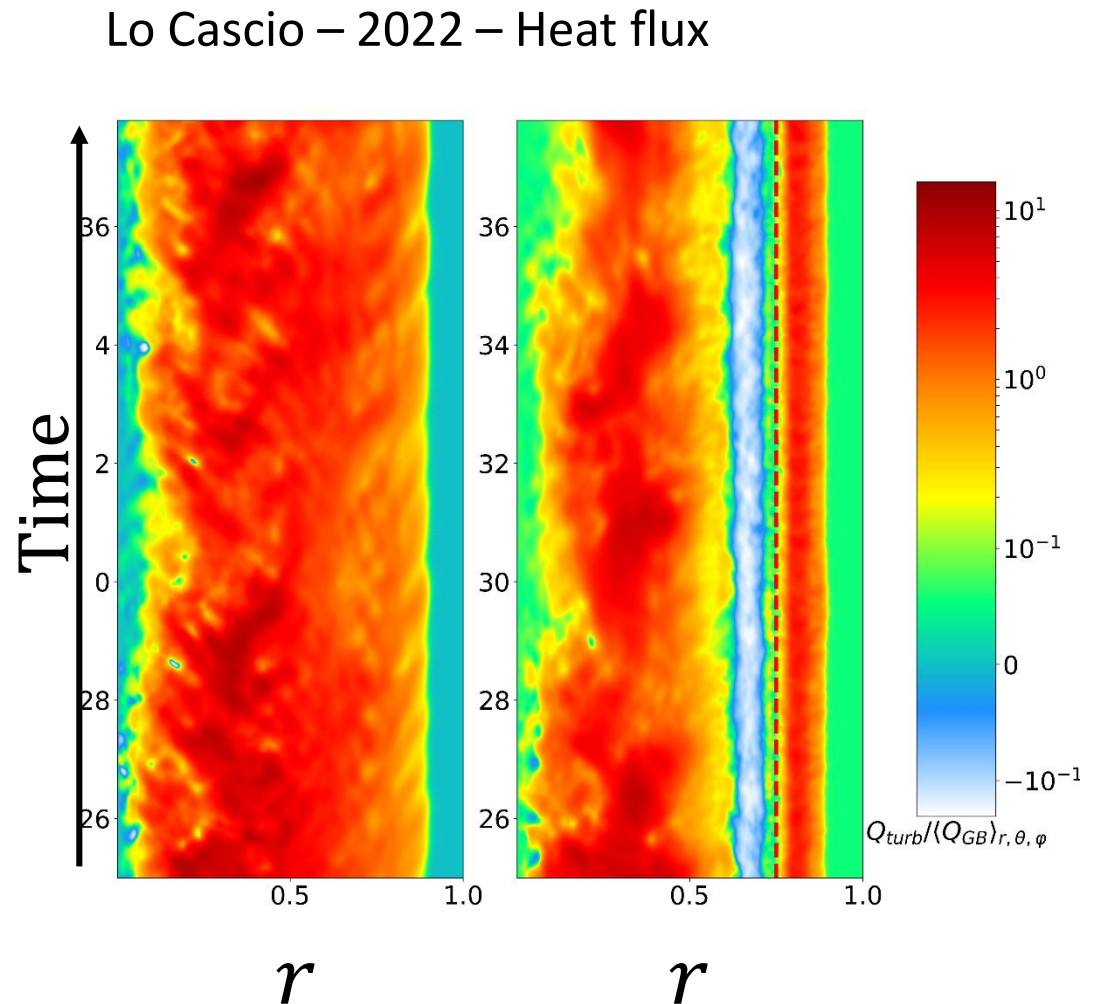
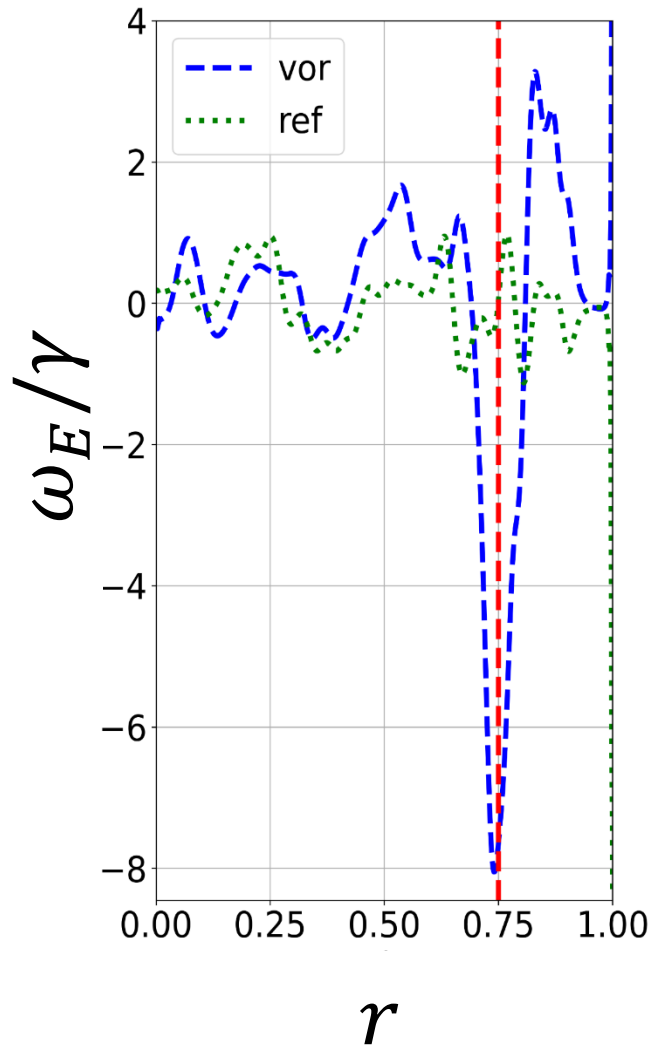
- Reduction of correlation length → diffusivity is reduced
- Turbulence quench Biglari 90, Waltz 95, Hahm 95

$$\omega_E > \gamma_{max}$$



$$V_E(r) = -\frac{E_r}{B}$$

Evidence of shear flow driven transport barriers



Controlling shear flows

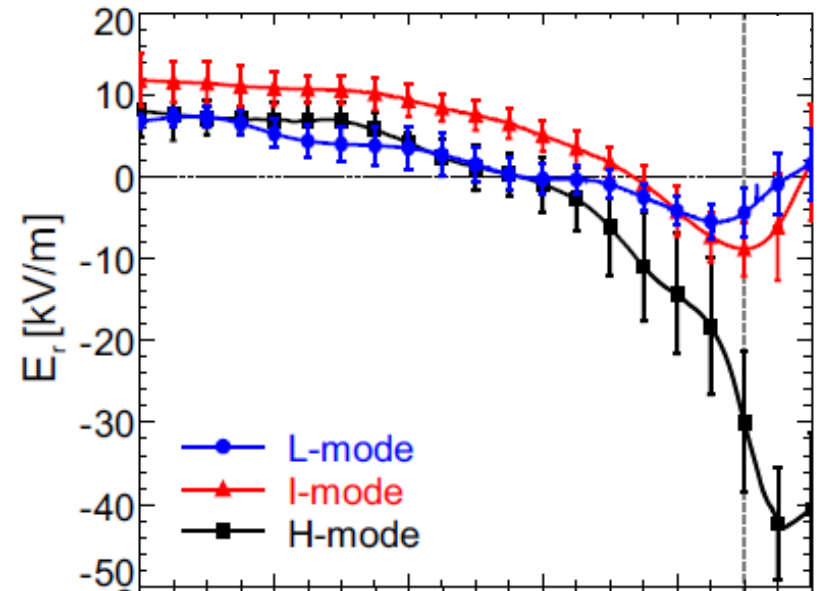
- Radial electric field controlled by radial currents

Itoh 88, Kobayashi 20

$$\epsilon_{pol} \frac{\partial E_r}{\partial t} = - \sum J_r$$

- Many contributions: viscous damping, Reynolds stress, orbit losses, wave momentum transport, neutrals → power threshold
- Mean shear flow only? Burrell 99, Gohil 11, Ryter 13, Viezzer 13, Schmitz 12, Tynan 13

Viezzer 13, AUG



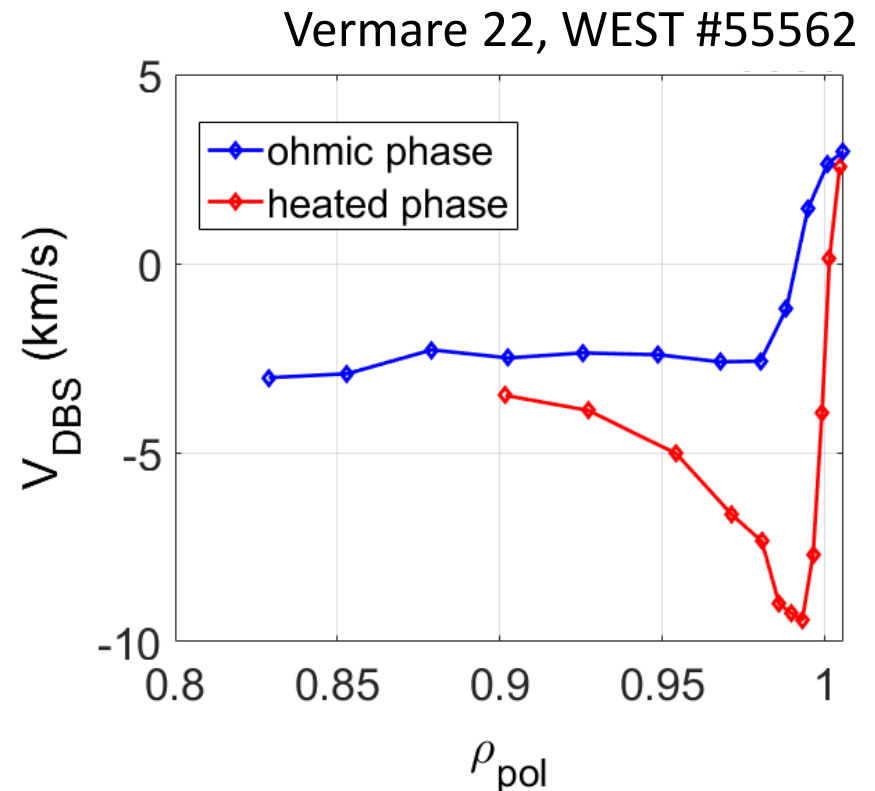
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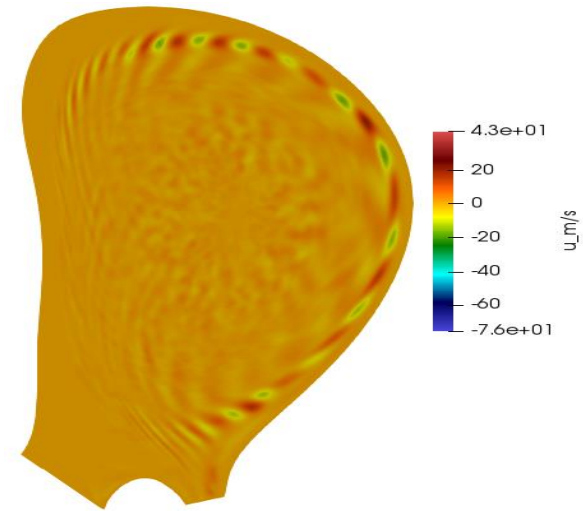


Magnetic perturbations is one way to control mean flows

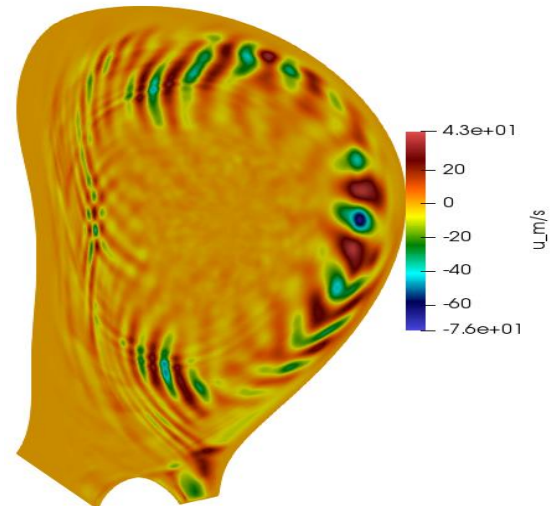
- Ergodic field lines degrade confinement: E_r shear weaker Schmitz 19, Becoulet 22, + less zonal flow generation Chen 20
- Non resonant 3D field perturbations enhance E_r Varennes 22 + effect on stability Huang 22 . Can be optimised Park 21

Becoulet 22

w/o RMP

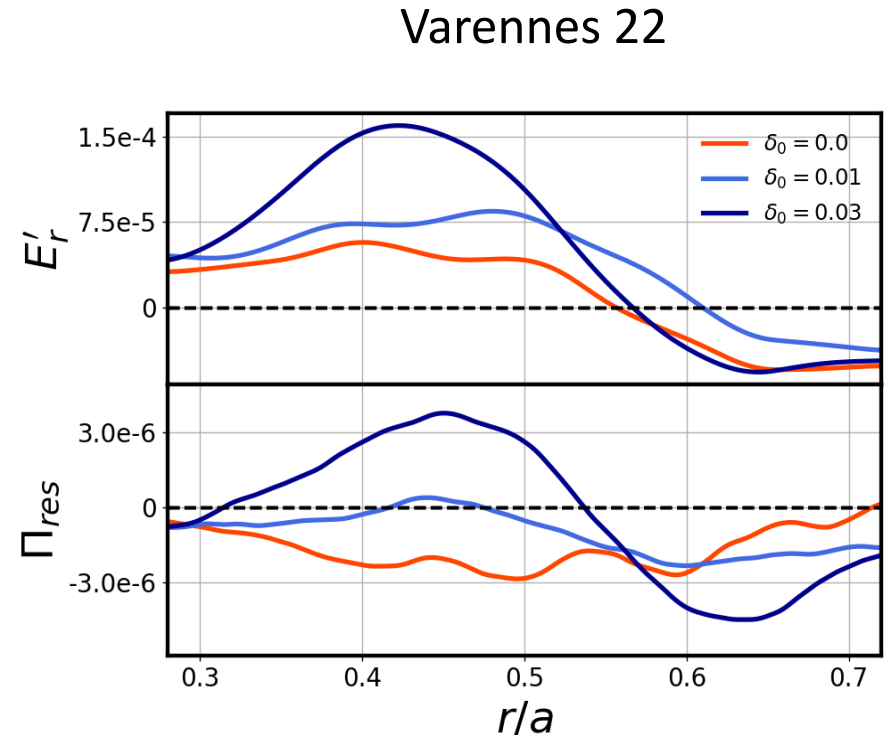


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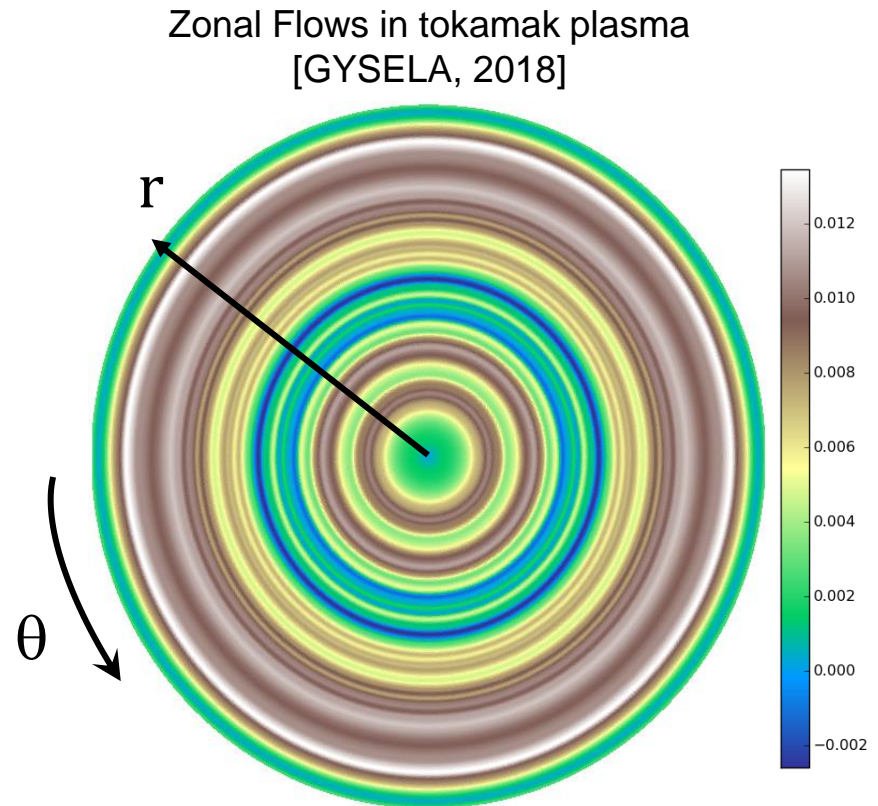


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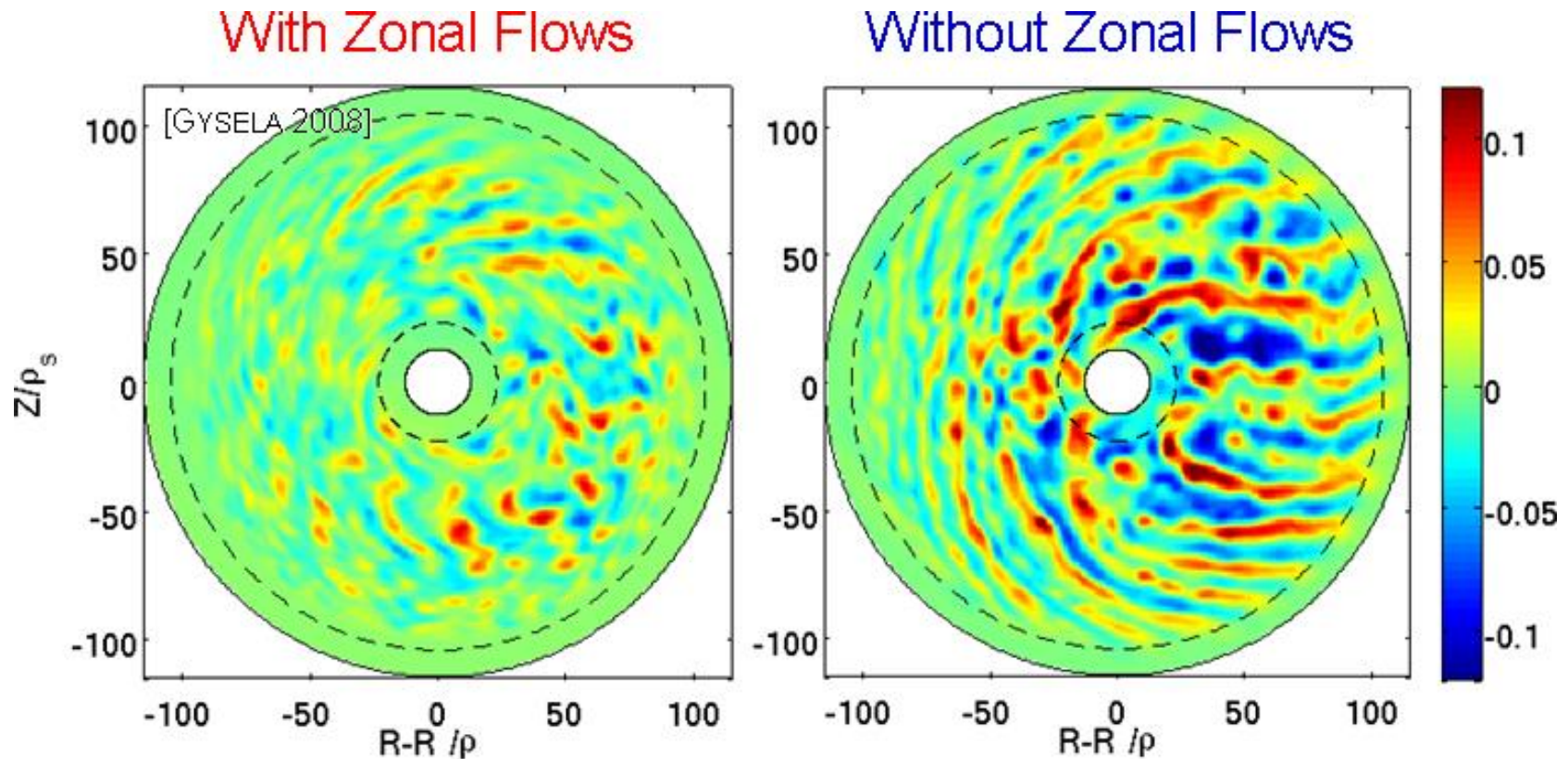
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Turbulence drives zonal flows

- **Zonal Flows** generated by **turbulence** Sagdeev 78, Hasegawa 79, Lin 98, Diamond 05
- **Similar to jet streams in rotating fluids** Roberts 68, Busse 70



Zonal flows back react on turbulence via wave scattering from large to small scales



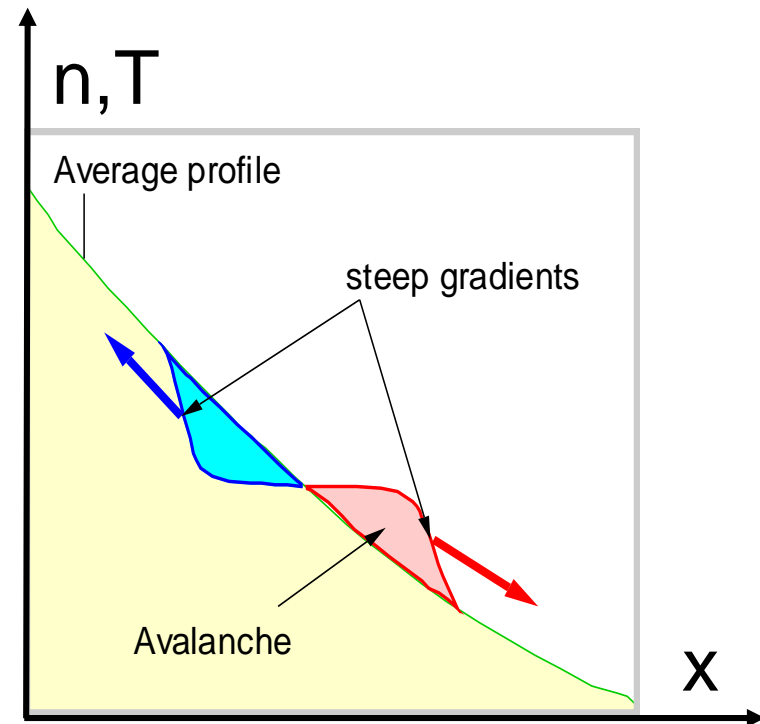
Avalanches enhance transport

- **Avalanches:** large scale transport events

Diamond 95, Carreras 96, Sarazin 98, XG 98, Beyer 02, Sanchez 15

- **Propagating fronts**

Hahm 04, Gurcan 05, XG07, Idomura 09, McMillan 09, Villard 19



Avalanches enhance transport

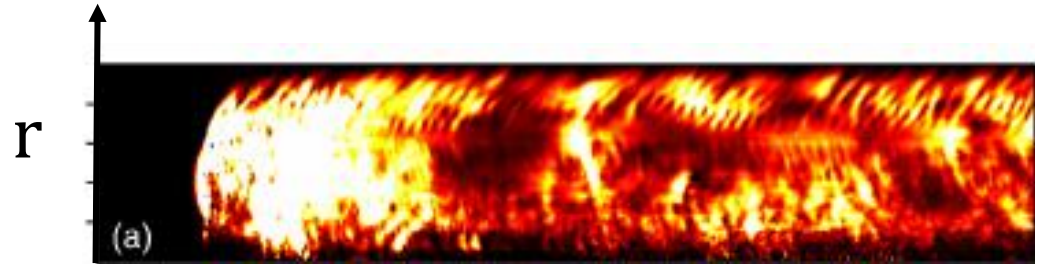
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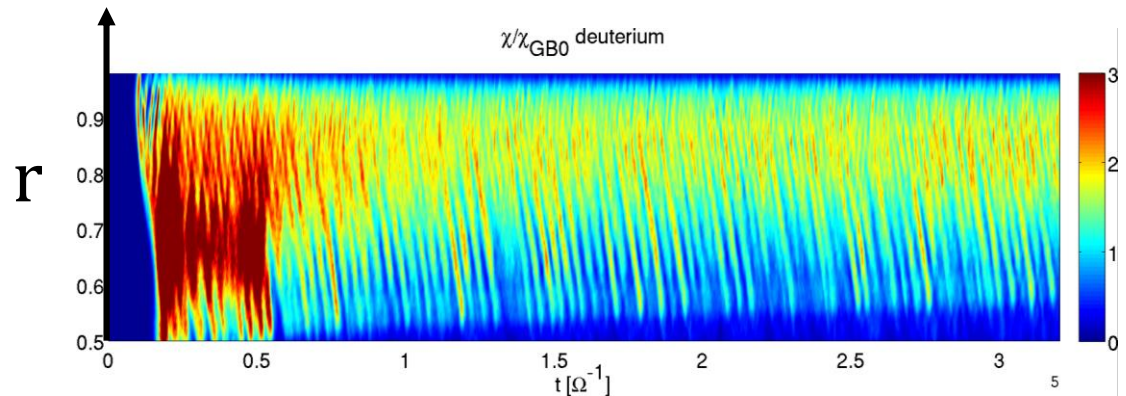
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Heat diffusivity vs radius and time



Idomura 09 GT5D



Villard 16 ORB5

time

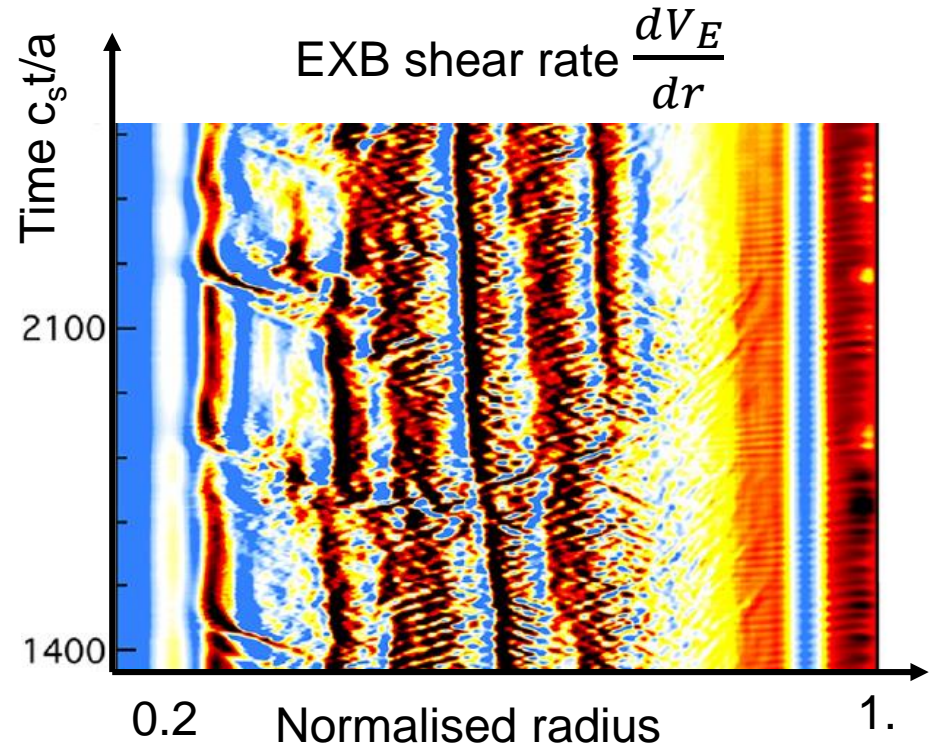
Turbulence self-organises near threshold

Dif-Pradalier 17

- Staircase patterns observed in turbulence simulations Dif-Pradalier

15&17, Rath 16, Weigl 18, Wang 18, Qi 19, Ivanov 20.

- Consistent with observations Hornung 16, Choi 20, Qi 21.



- Staircase : avalanching areas bounded by zonal shear layers Kosuga 14, Ashourvan 16, 17, Wang 18, Guo 19, XG21

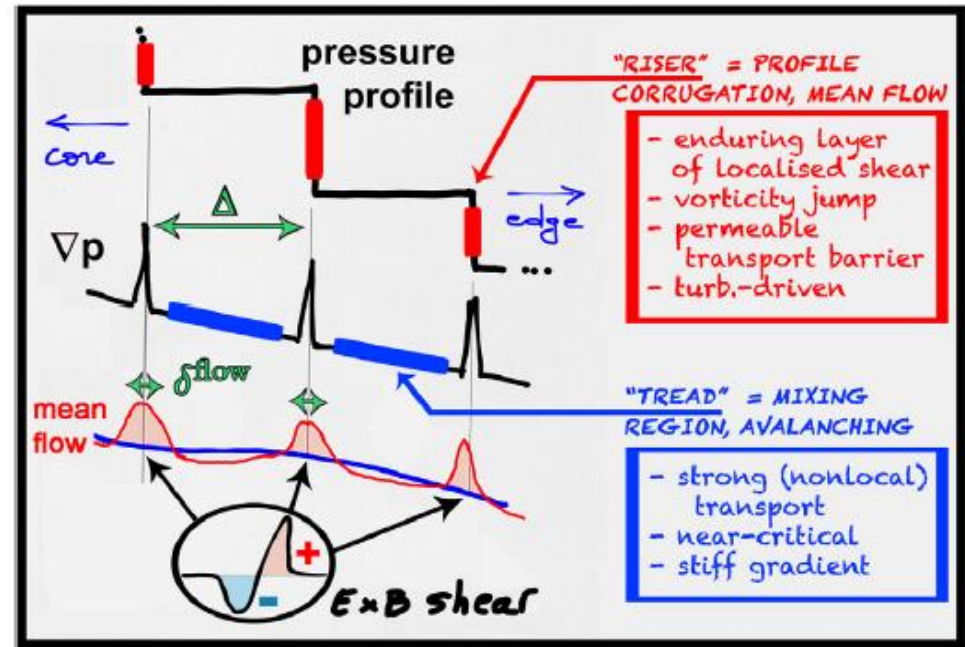
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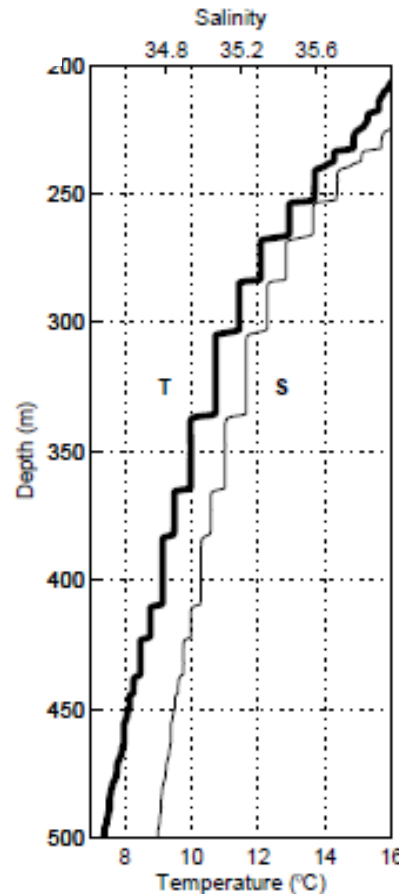
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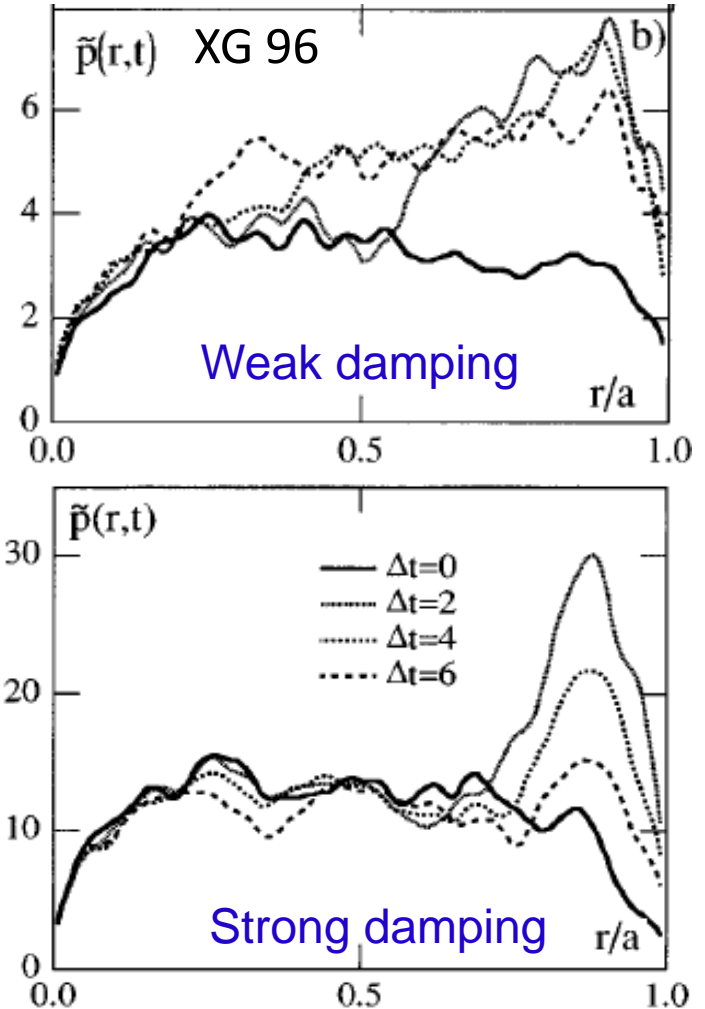
Salt fingers in thermocline of the tropical atlantic Schmitt Science 05

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Turbulence spreads

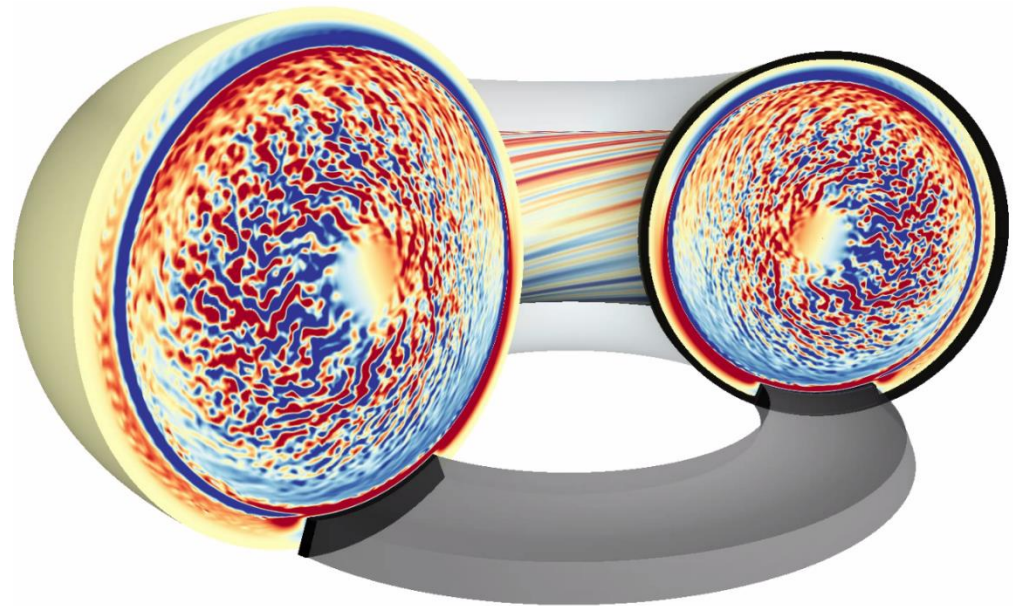
- 2 mechanisms XG 94,96:
 - wave group velocity Kishimoto 96,99
 - front propagation Diamond-Hahm 95, Gürcan 05, Zonca 05, XG07
- Range of spreading depends on damping. Related to avalanches Idomura 09, McMillan 09



Interplay of edge with core turbulence

- Immersive boundary conditions → limiter
 - Produces turbulence, propagates inward
 - Back-reacts on far edge turbulence.
- turbulence fills-in linearly stable edge region

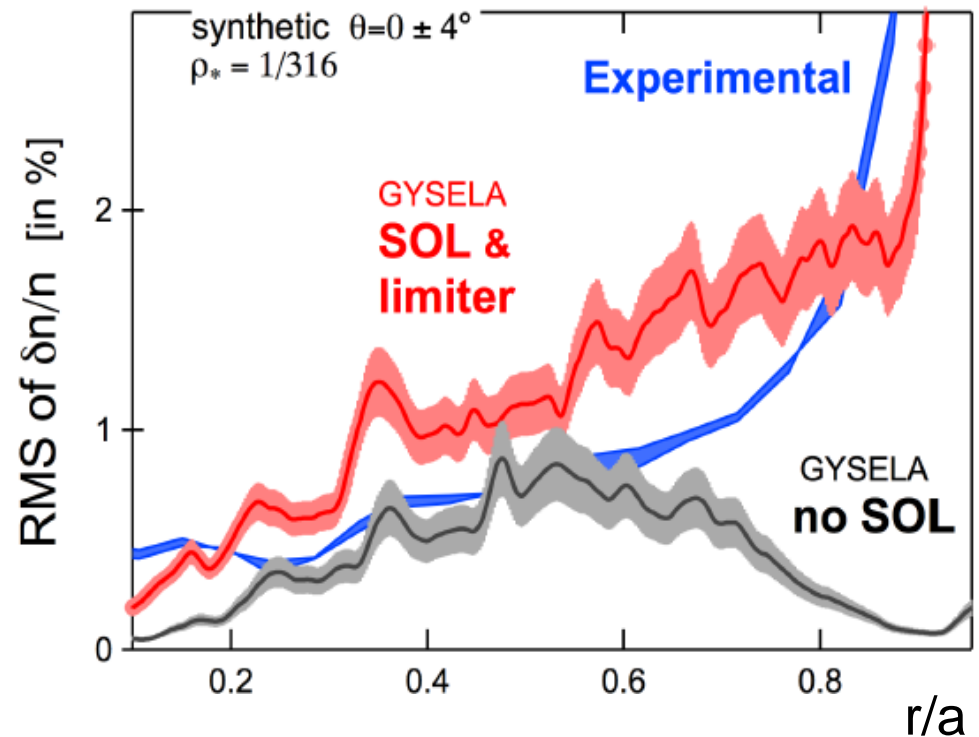
GYSELA
2020



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Dif-Pradalier 2022



Conclusion

- A lot has been understood – key is self-organisation via flows
- Some outstanding issues:
 - interplay edge/core turbulence (see plenary S. Krasheninnikov)
 - electromagnetic effects (see plenary J. Garcia), link with MHD
 - interplay with collisional transport, 3D magnetic perturbations