

Turbulent transport in magnetised plasmas

Xavier Garbet

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Xavier Garbet. Turbulent transport in magnetised plasmas. 48th conference on plasma physics, Jun 2022, On line conference, France. cea-03736714

HAL Id: cea-03736714
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Submitted on 22 Jul 2022

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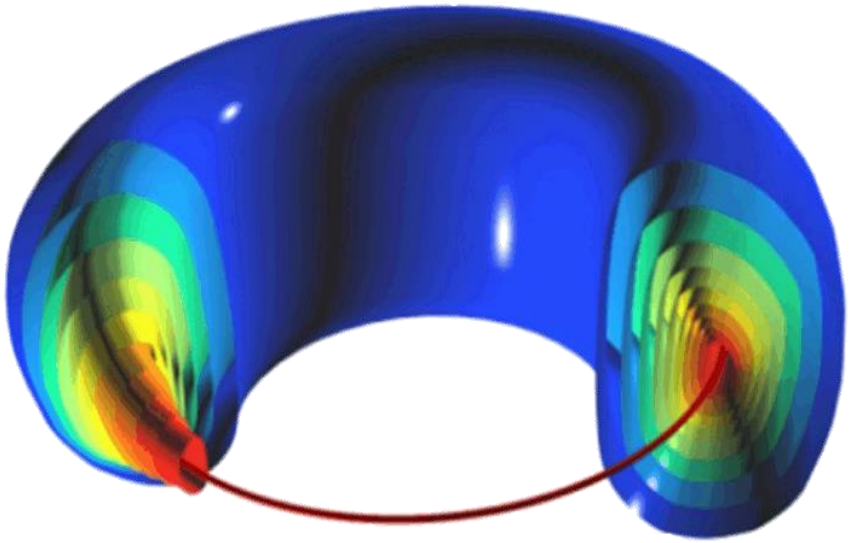
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Turbulent transport in magnetised plasmas

Xavier Garbet
IRFM
CEA Cadarache

Turbulent transport: why?

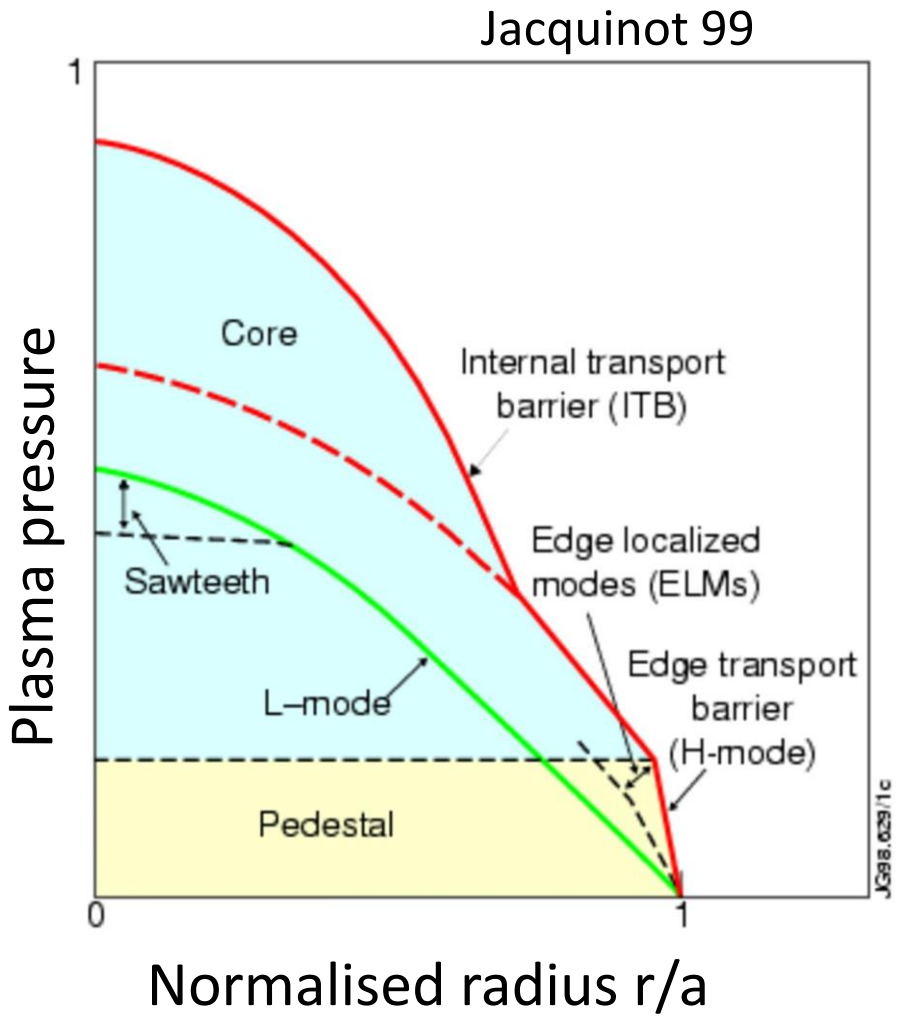
- Turbulent transport degrades confinement in magnetic fusion devices
- Would like to improve confinement $\rightarrow$ transport barriers
- Plays an important role in astrophysics and geophysics



Nested magnetic surfaces

Turbulent transport: why?

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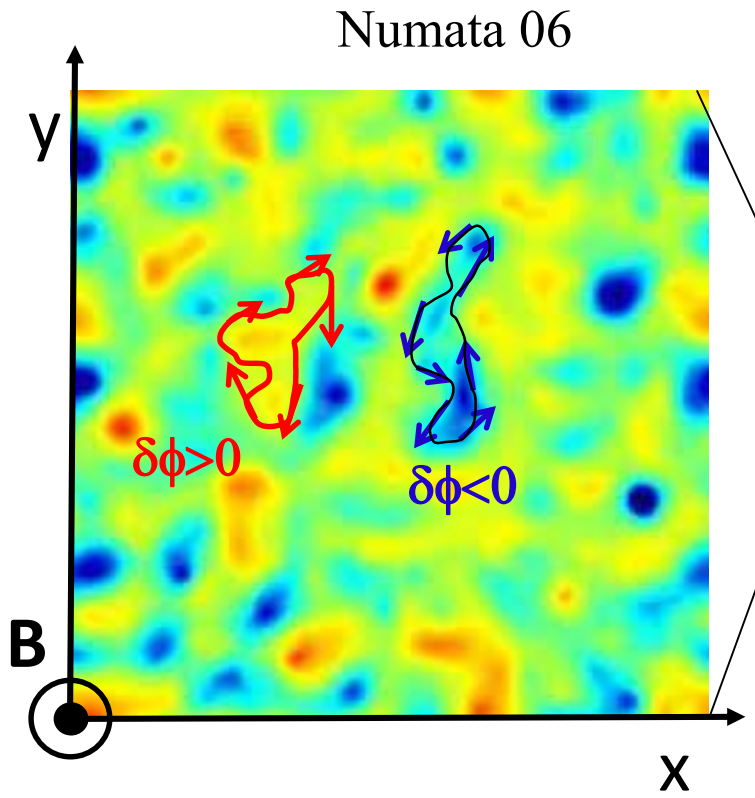


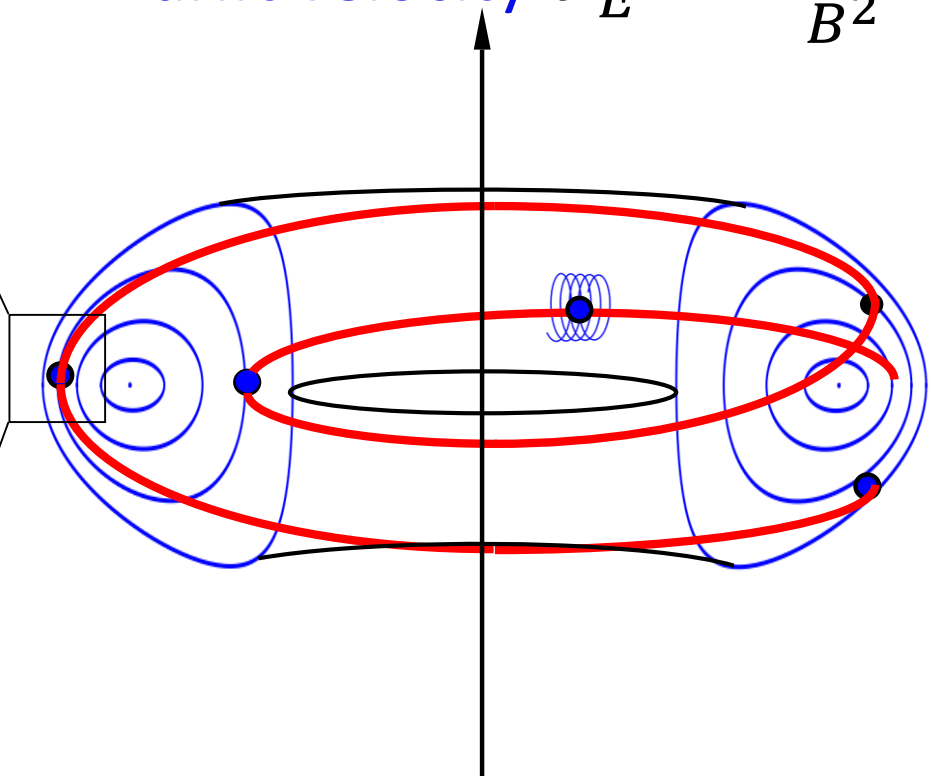
Outline

- Turbulent transport : an introduction
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- Turbulence self-regulation : when instability threshold matters

Turbulent transport rules confinement in tokamaks

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





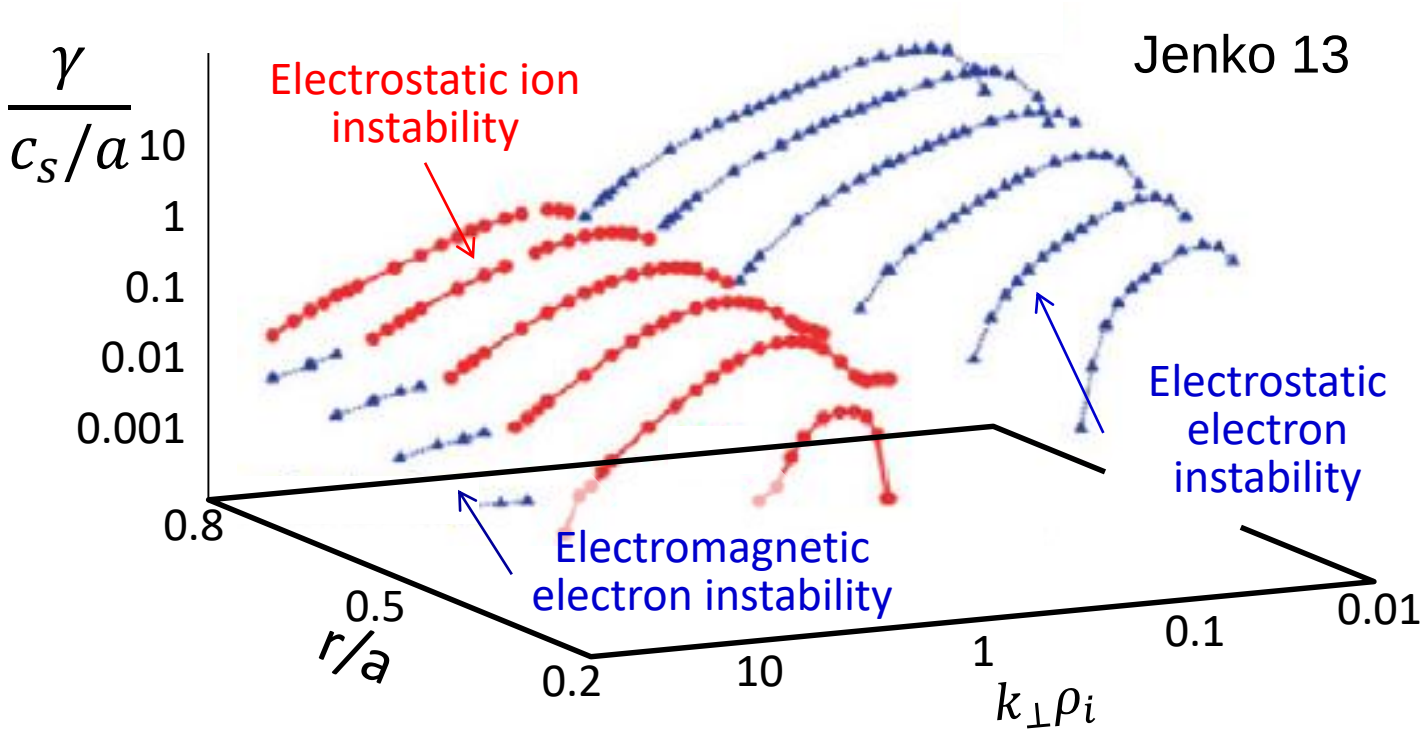
Iso-lines electric potential ϕ

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

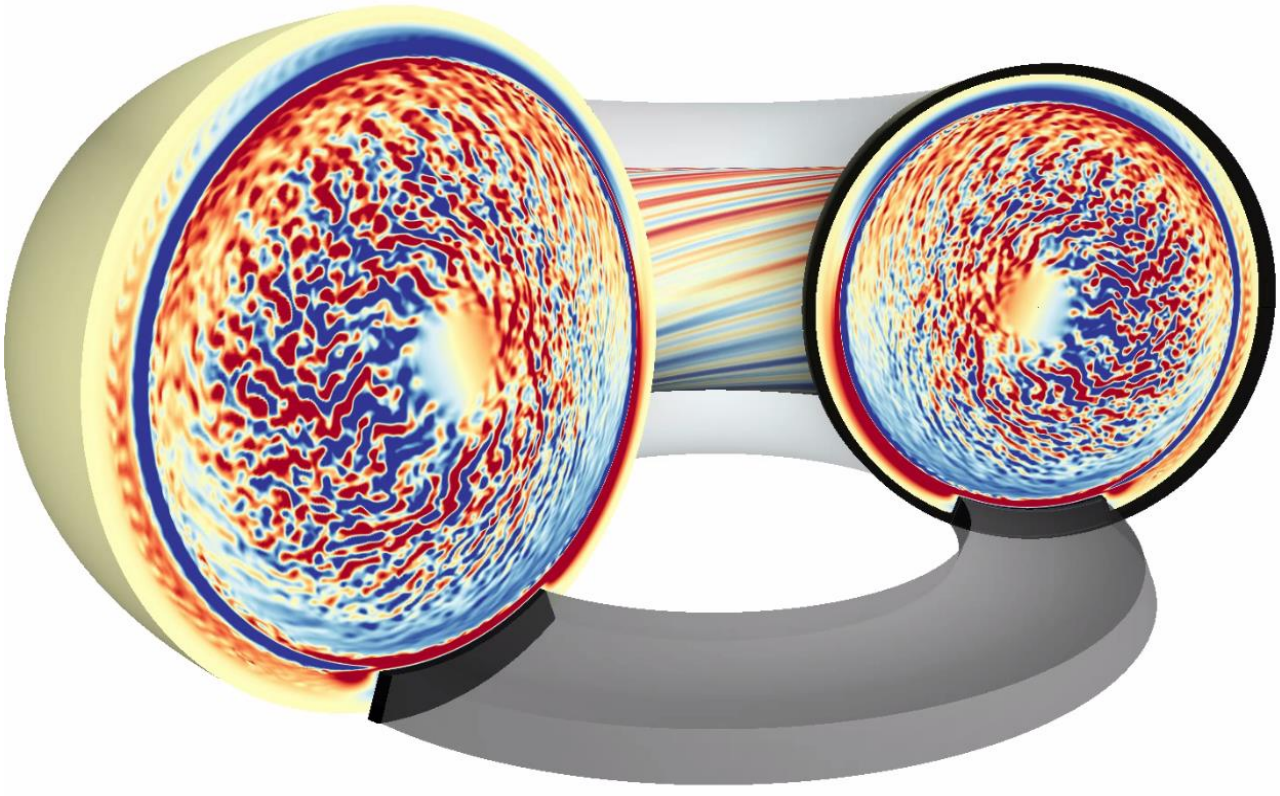
Confinement time $\tau_E \sim \frac{a^2}{D}$

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 $\nabla P \cdot \nabla \mathrm{B} > 0$ 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 ~mixing-length theory Prandtl 1905

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

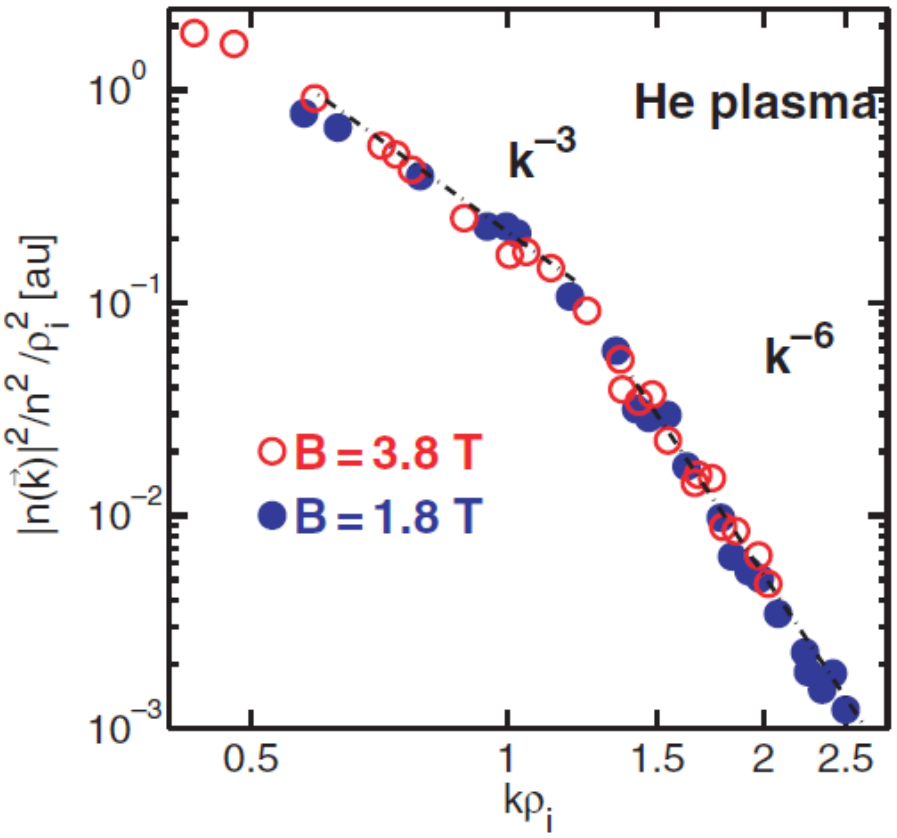
→ yields diffusion vs gradients

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

→ reduced transport models

Staebler 07, Bourdelle 16

Hennequin 04



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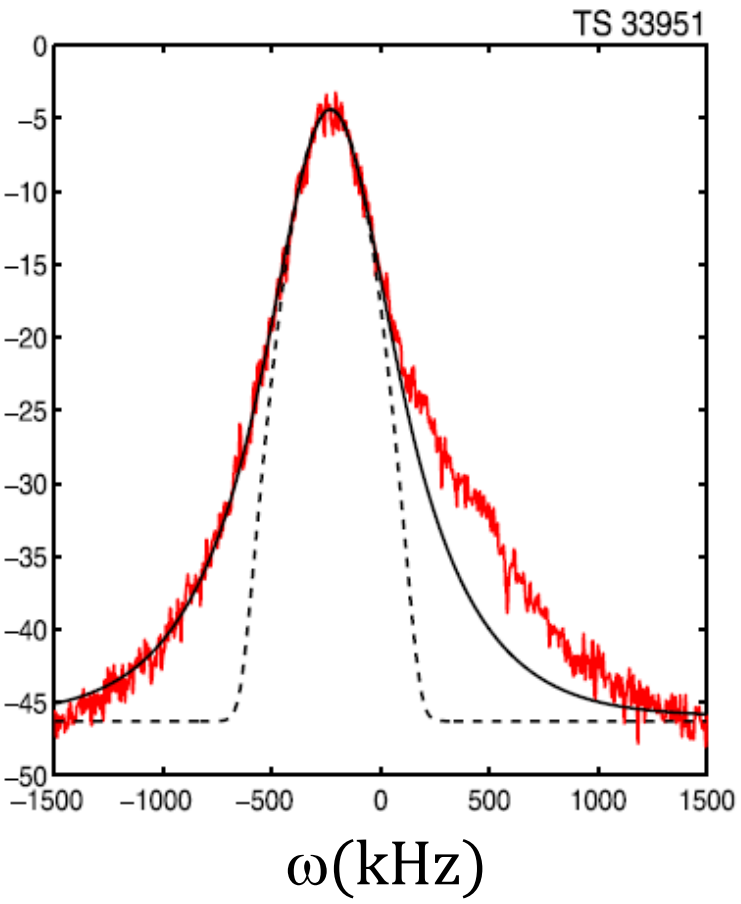
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$|n(\boldsymbol{k}, \omega)|^2$ Vermare 11



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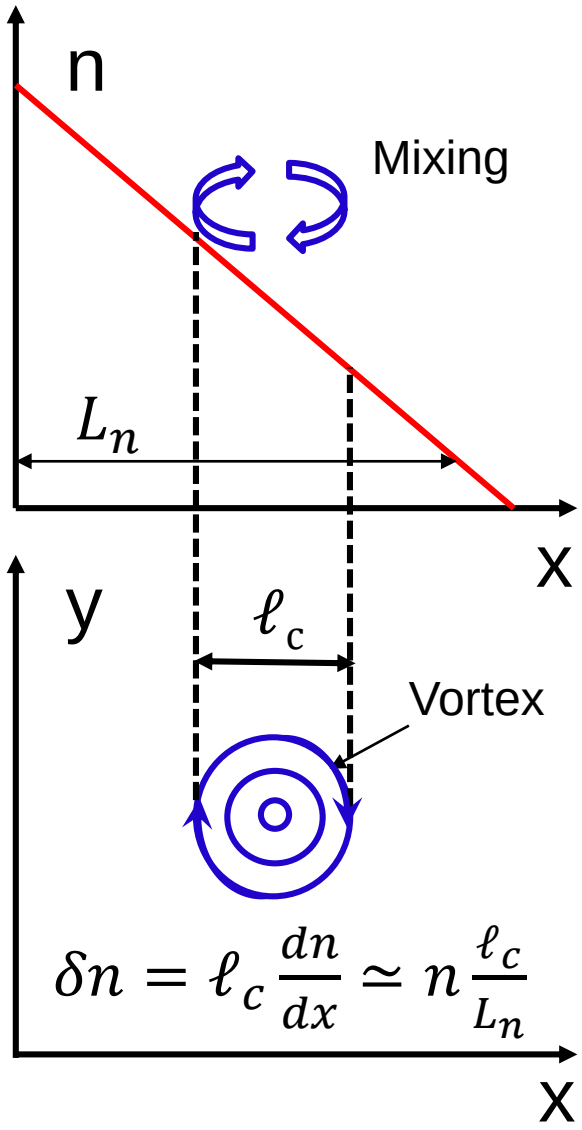
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→ yields diffusion vs gradients

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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.

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Transport equations bear a puzzling shape

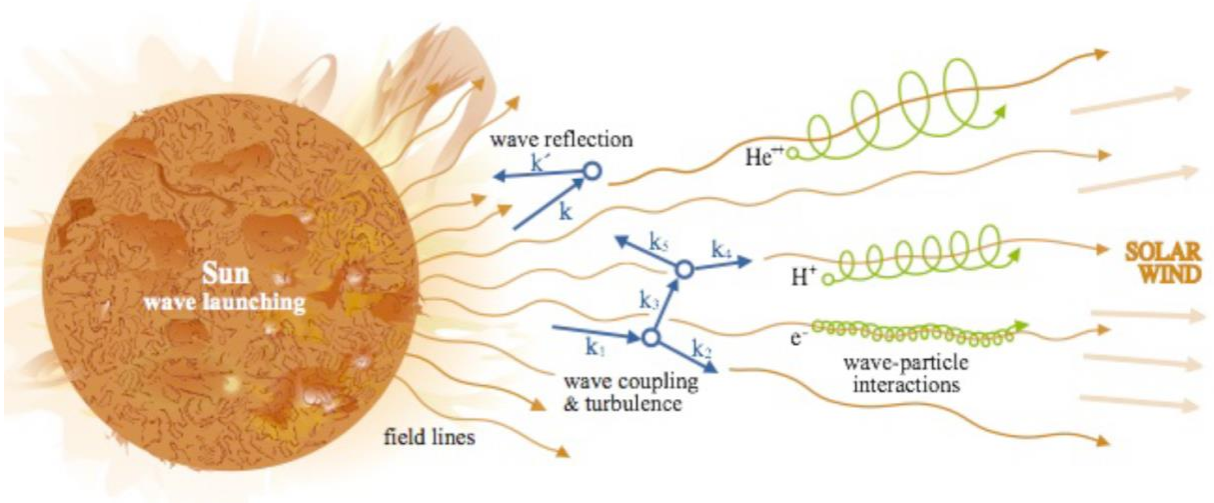
- Evolution of density, velocity, temperature **A** = (N,$V_{//}$,T)

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

- Transport matrix $\bar{\bar{L}}$ is symmetric Onsager 1931. Unexpected:

- "residual" stress and heat flux $\boldsymbol{\Gamma}_{\mathbf{res}}$

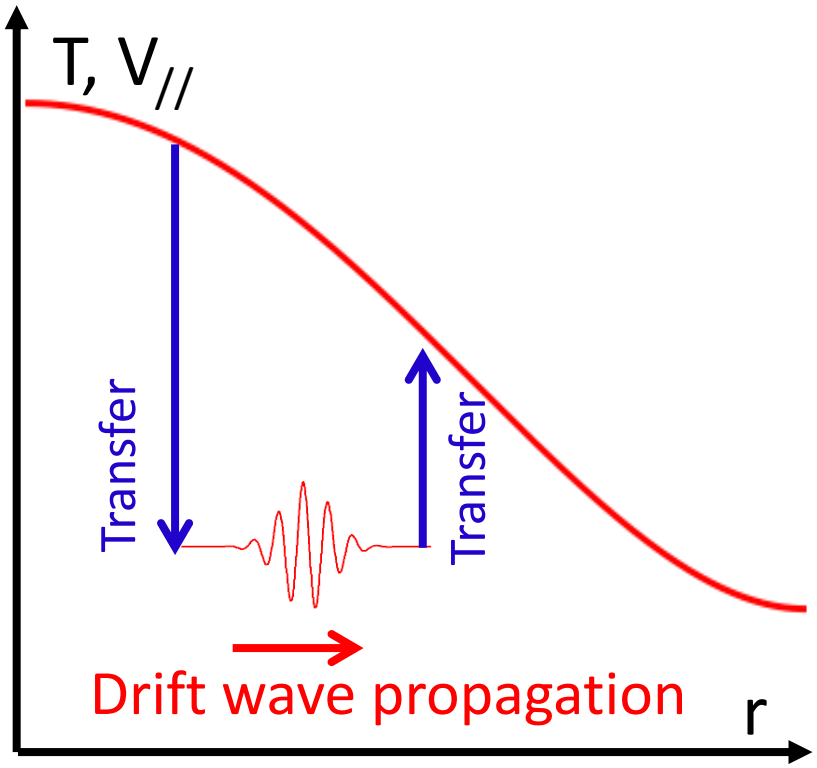
- turbulent heating and acceleration $\boldsymbol{\Sigma}$ Rudakov 71, Ott 72



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

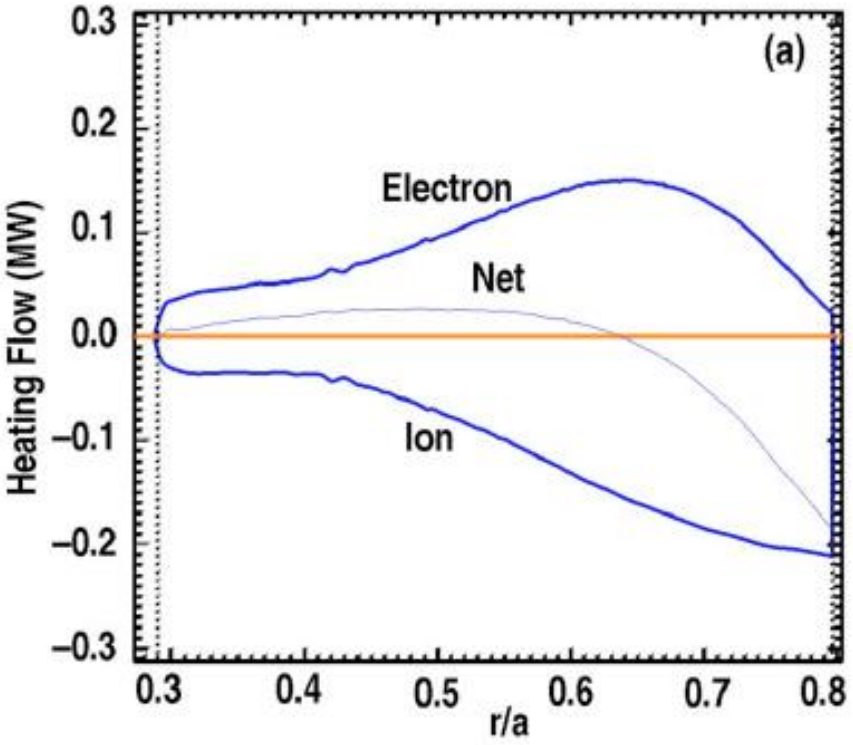
- Source terms Itoh 88, Hinton 06, Barnes 12, Lu Wang 13, XG 13, Seiferling 18, Wang 18

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

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

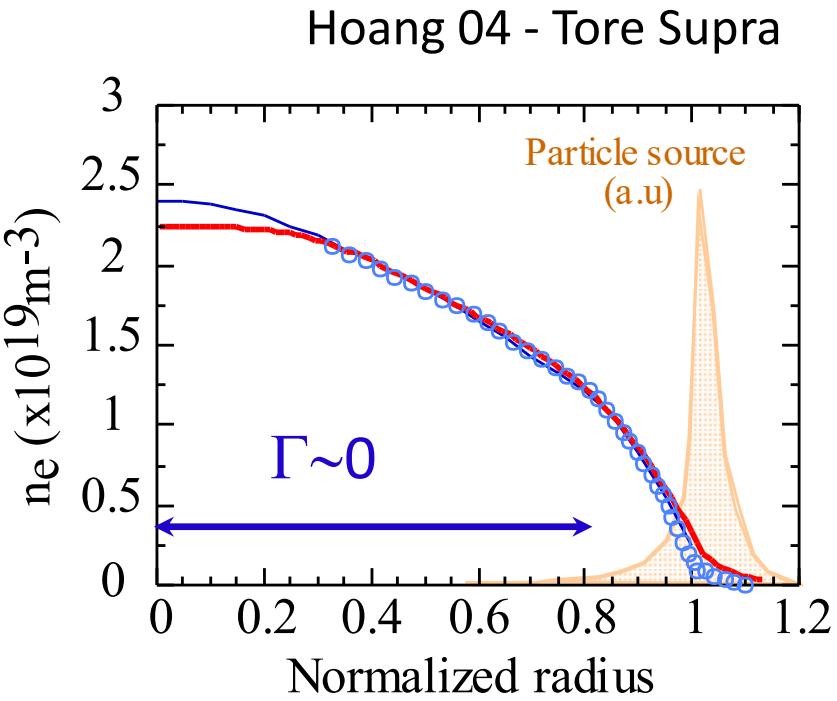
- Correlation requires symmetry breaking
- Charge conservation → transfer Waltz 11 . Wave energy transport → net effect Zhao 12

Waltz 08



Turbulent pinch theory successfully tested in tokamaks

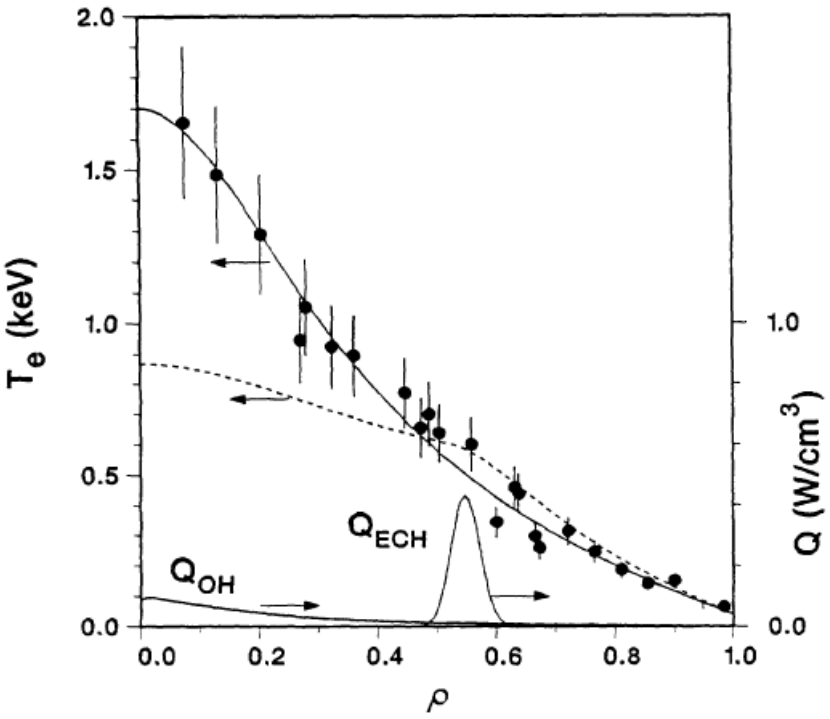
- Particle flux $\Gamma = -D\frac{dn}{dr} + \mathcal{V}n$
- "Pinch velocity" $\mathcal{V}$ due to temperature and velocity gradients, and compressibility
  Angioni 03 & 06, XG 04, Camenen 09
- Entropy production rate > 0
  XG05.
- Onsager symmetry → thermal pinch Dominguez 89, Luce 92, Itoh 96, Mantica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



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Luce 95 – DIII-D



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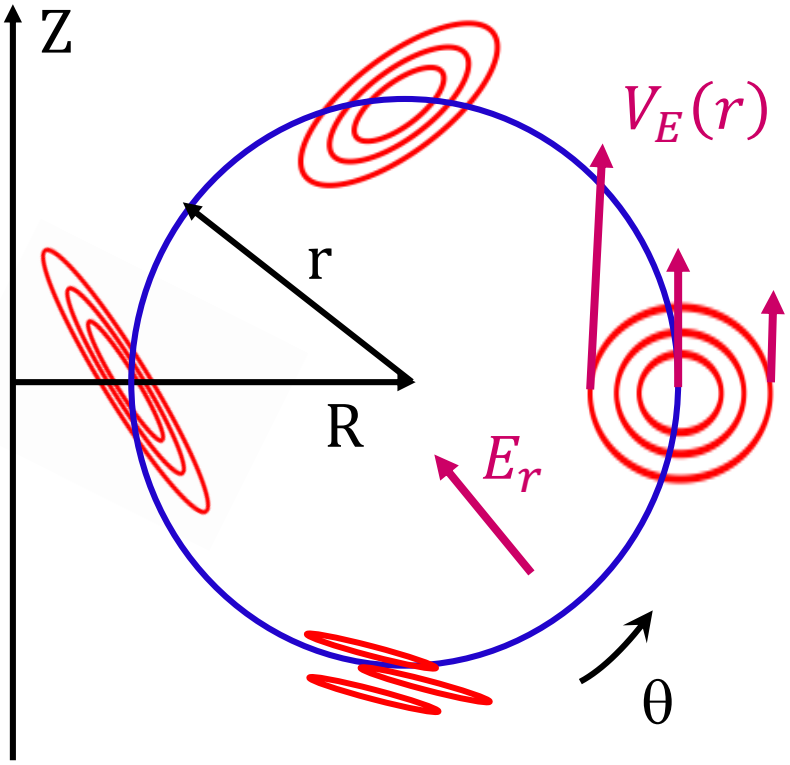
Mean shear flow reduces turbulent transport

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

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

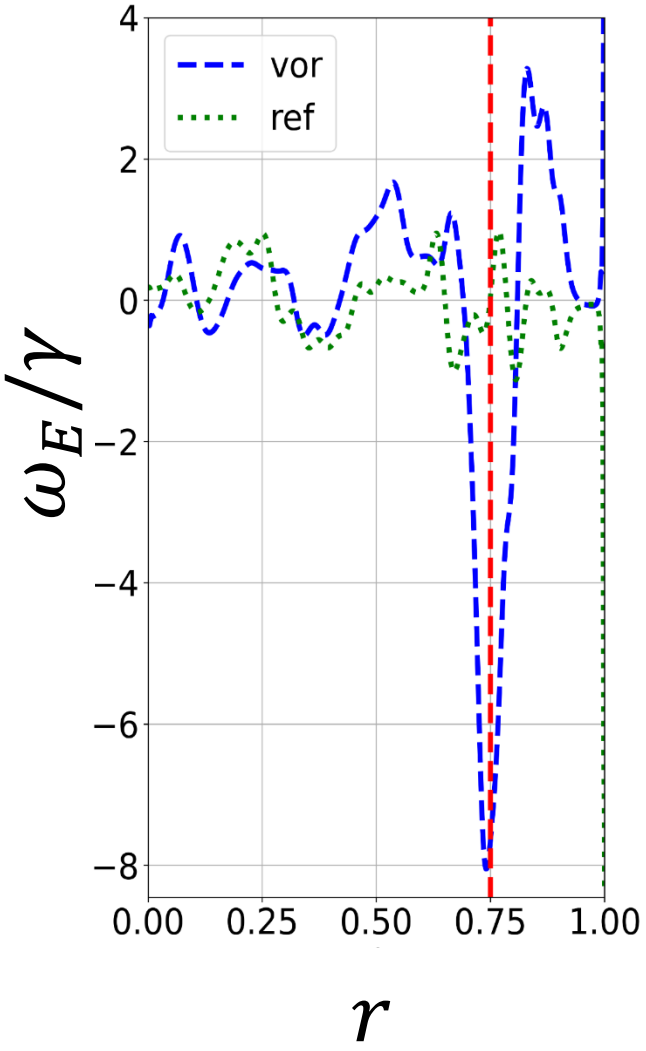
- Reduction of correlation length → diffusivity is reduced
- Turbulence quench Biglari 90, Waltz 95, Hahm 95

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

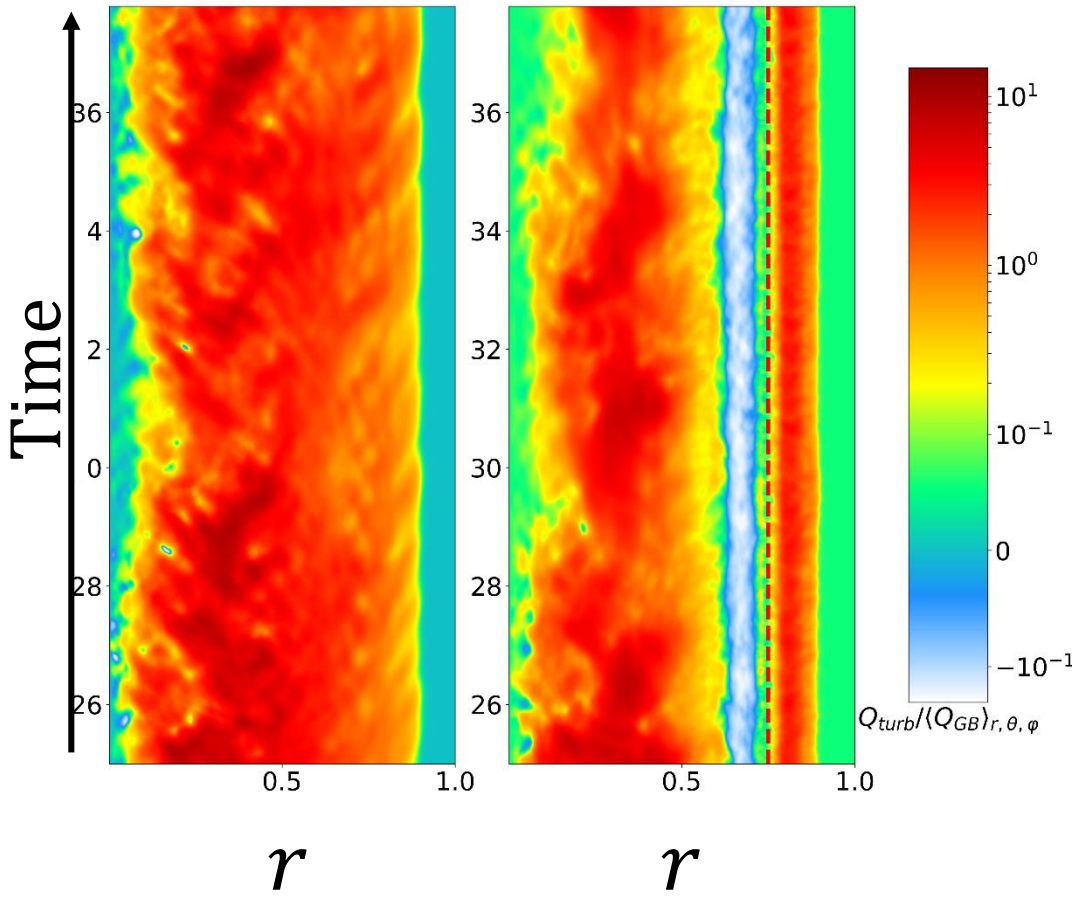


$$V_E(r) = -\frac{E_r}{B}$$

Evidence of shear flow driven transport barriers



Lo Cascio – 2022 – Heat flux



Controlling shear flows

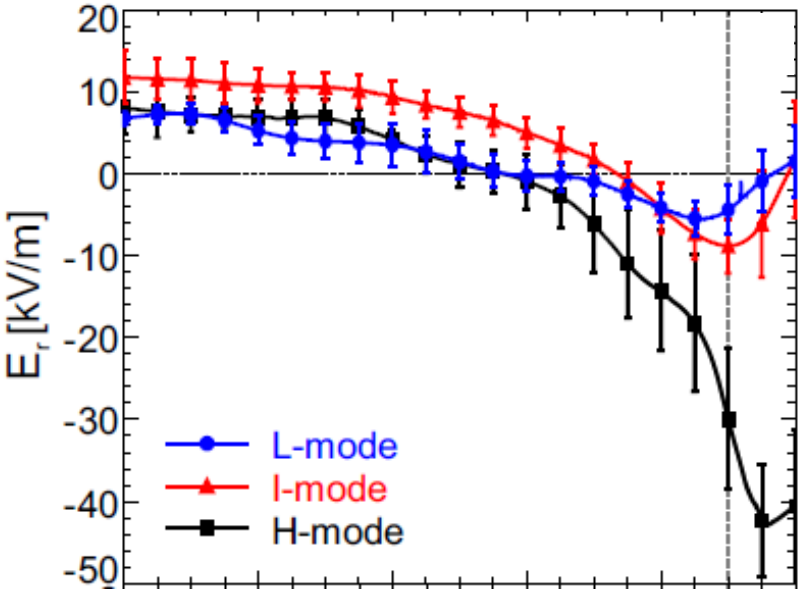
- Radial electric field controlled by radial currents

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 $\rightarrow$ power threshold
- Mean shear flow only? Burrell 99, Gohil 11, Ryter 13, Viezzer 13, Schmitz 12, Tynan 13

Viezzer 13, AUG



Controlling shear flows

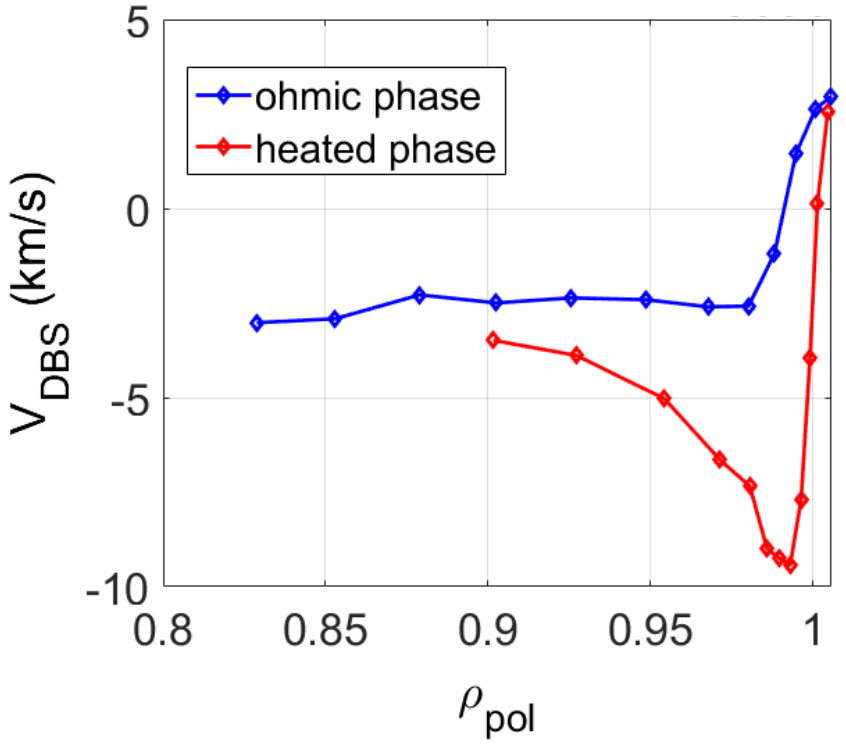
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Vermare 22, WEST #55562

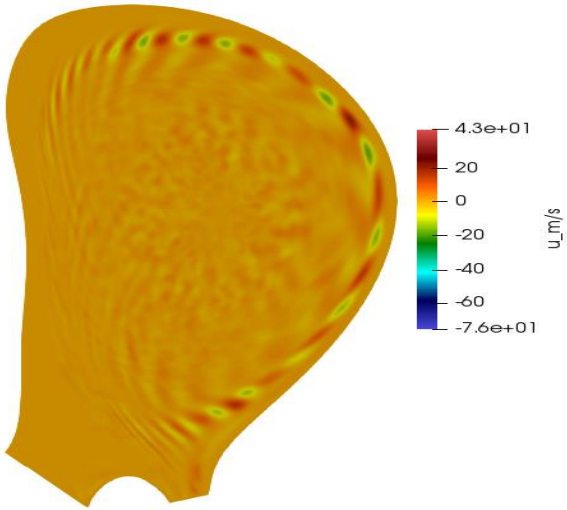


Magnetic perturbations is one way to control mean flows

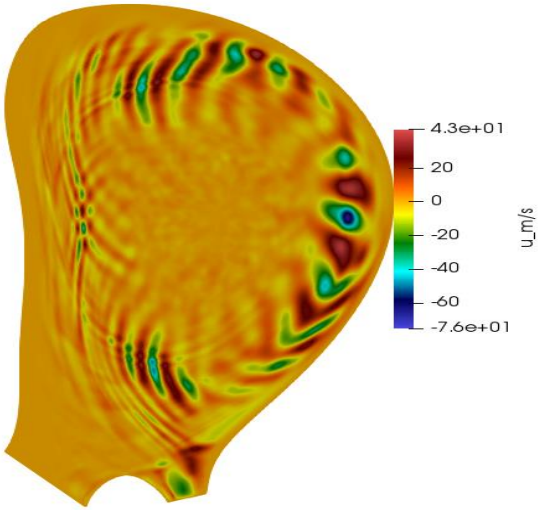
- Ergodic field lines degrade confinement: E_r shear weaker Schmitz 19, Becoulet 22, + less zonal flow generation Chen 20
- Non resonant 3D field perturbations enhance E_r Varennes 22 + effect on stability Huang 22 . Can be optimised Park 21

Becoulet 22

w/o RMP



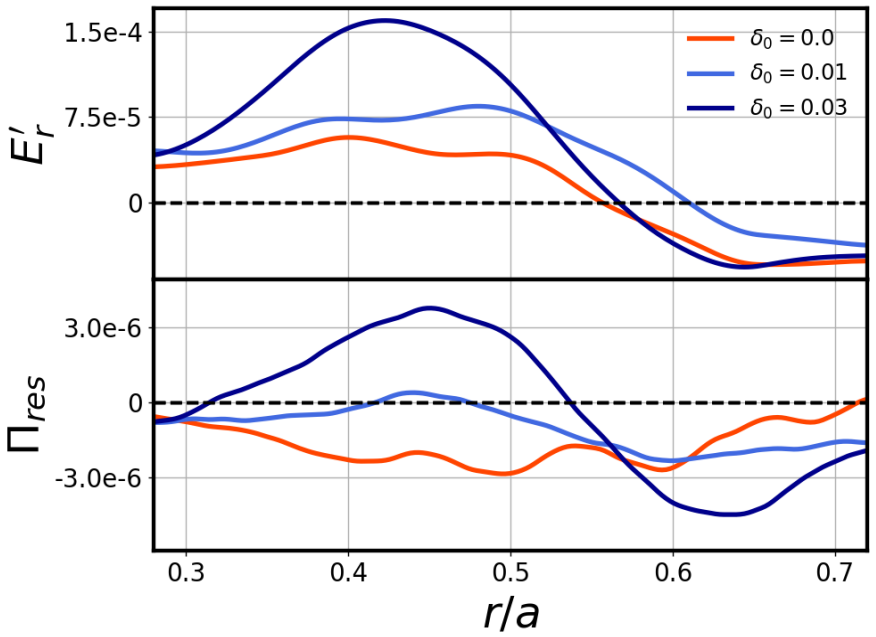
with RMP



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Varennes 22



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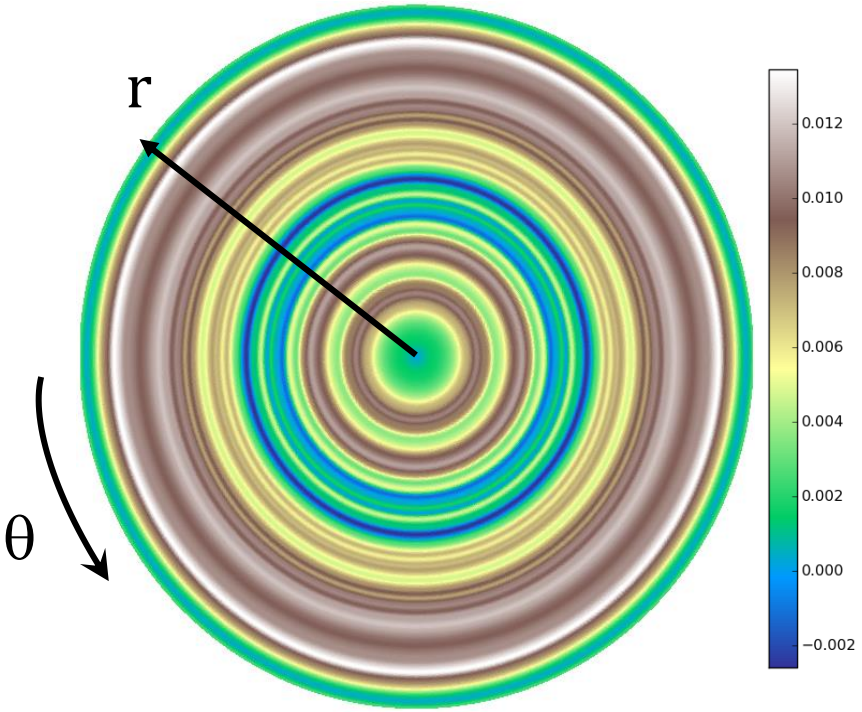
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Turbulence drives zonal flows

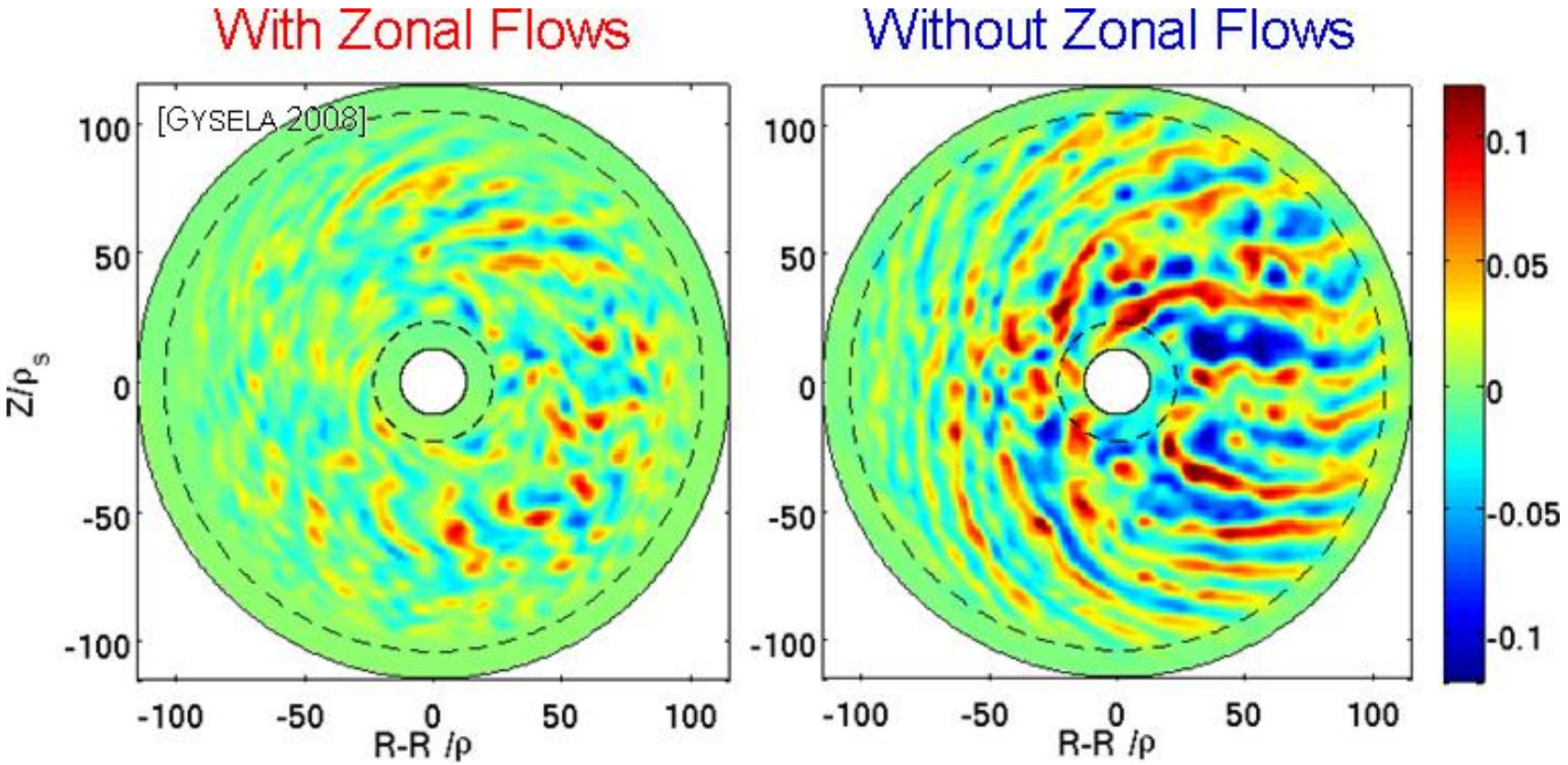
- Zonal Flows generated by turbulence Sagdeev 78, Hasegawa 79, Lin 98, Diamond 05

- Similar to jet streams in rotating fluids Roberts 68, Busse 70

Zonal Flows in tokamak plasma
[GYSELA, 2018]



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



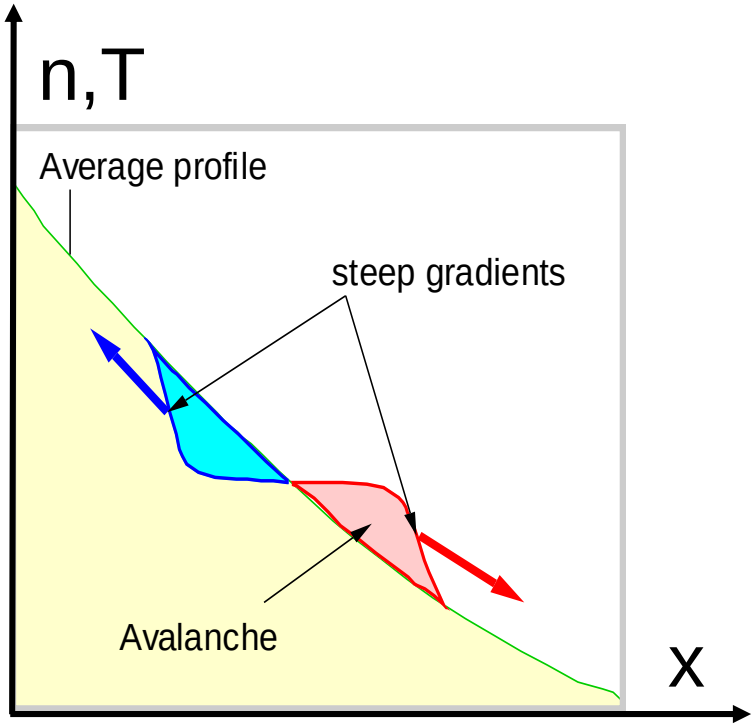
Avalanches enhance transport

- 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



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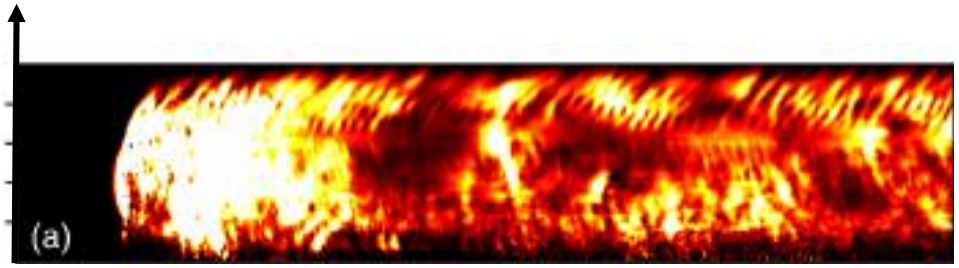
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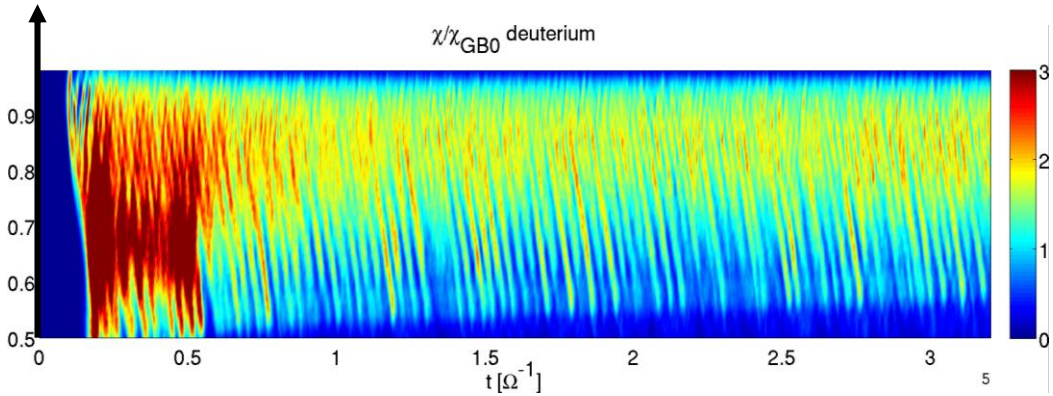
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Heat diffusivity vs radius and time



Idomura 09 GT5D



Villard 16 ORB5

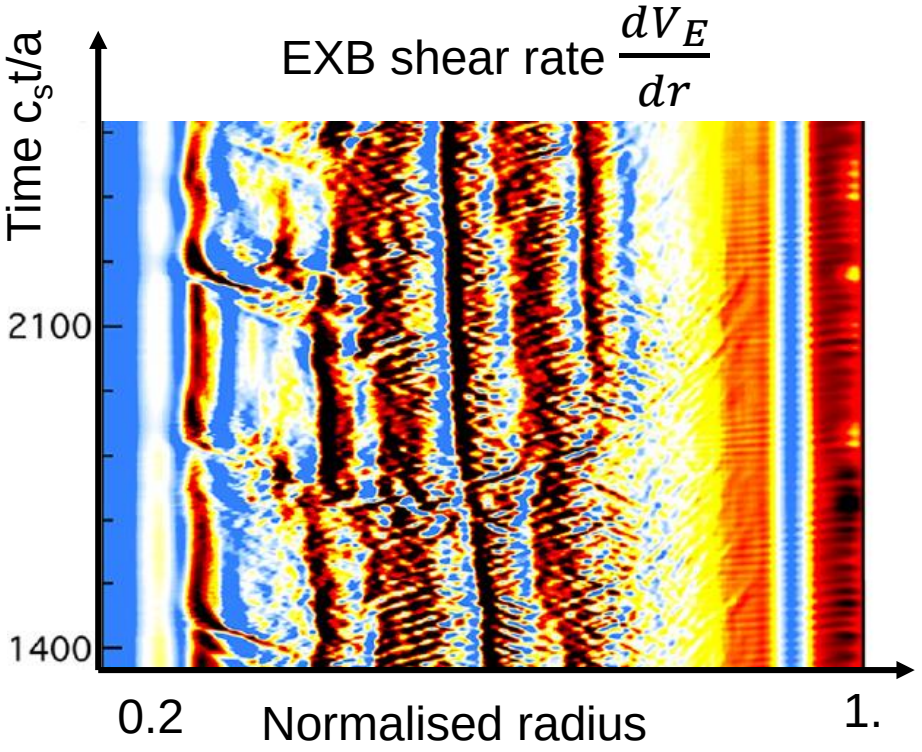
time

Turbulence self-organises near threshold

Dif-Pradalier 17

- Staircase patterns observed in turbulence simulations Dif-Pradalier 15&17, Rath 16, Weikl 18, Wang 18, Qi 19, Ivanov 20.

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



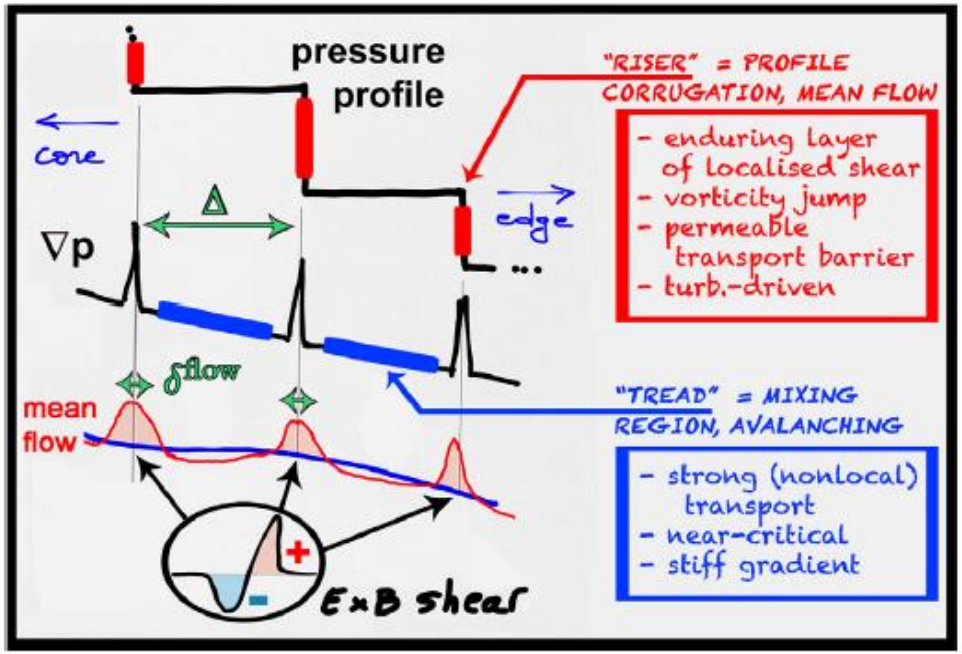
- Staircase : avalanching areas bounded by zonal shear layers Kosuga 14, Ashourvan 16, 17, Wang 18, Guo 19, XG21

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Dif-Pradalier 15

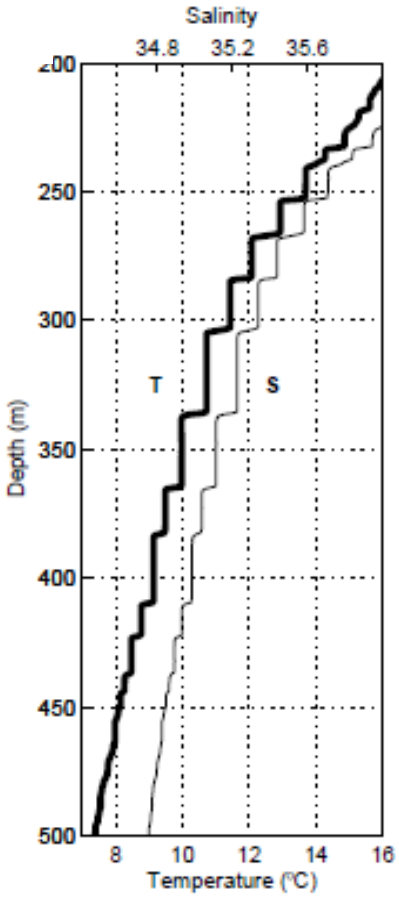


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Salt fingers in thermocline of the tropical atlantic Schmitt Science 05

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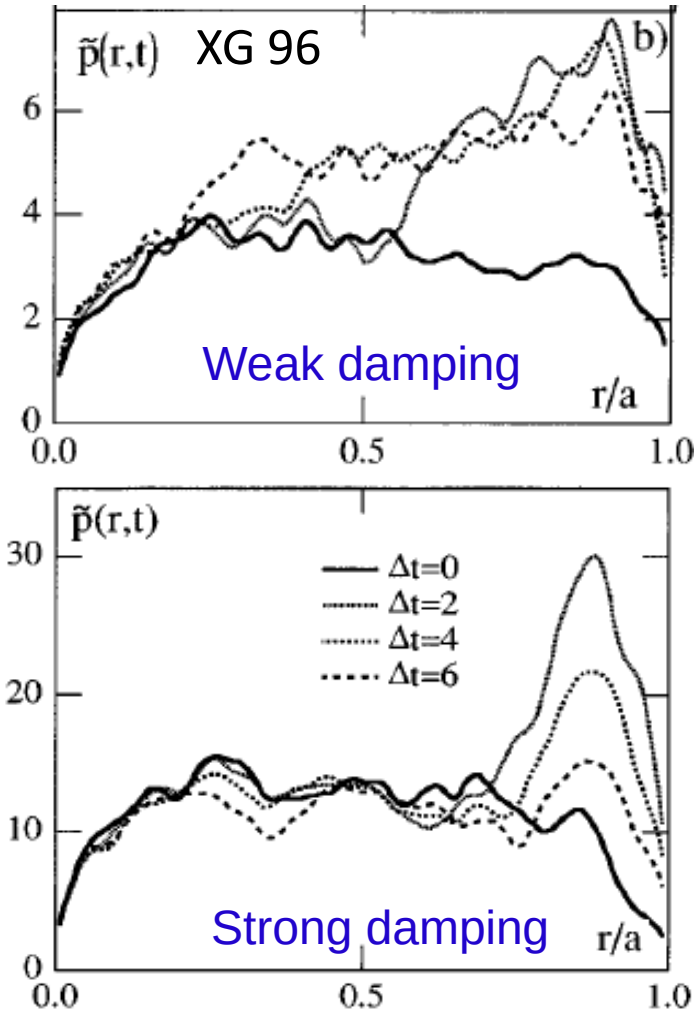
Turbulence spreads

- 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

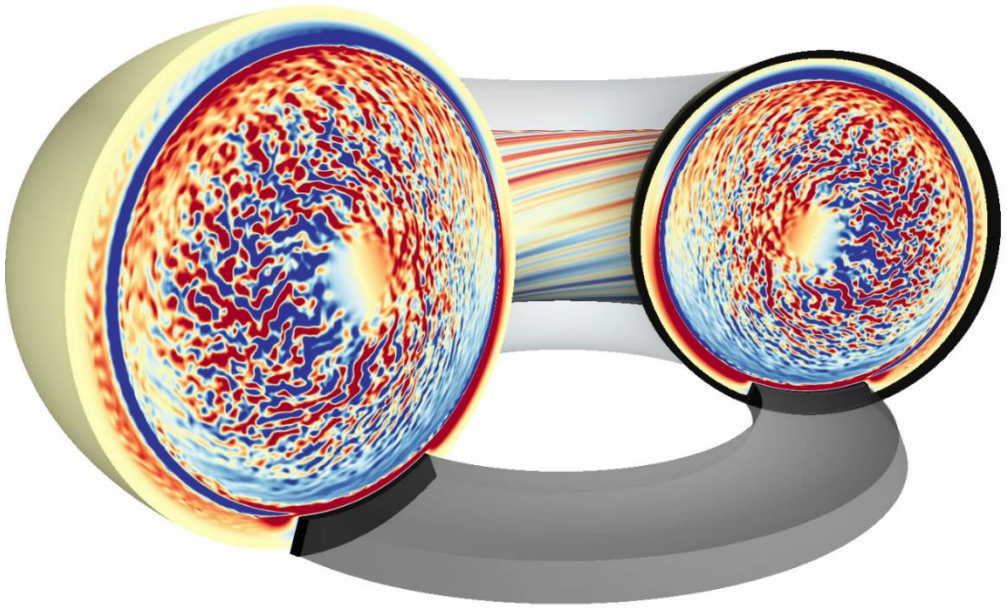


Interplay of edge with core turbulence

- Immersive boundary conditions → limiter
- Produces turbulence, propagates inward
- Back-reacts on far edge turbulence.

→ turbulence fills-in linearly stable edge region

GYSELA 2020

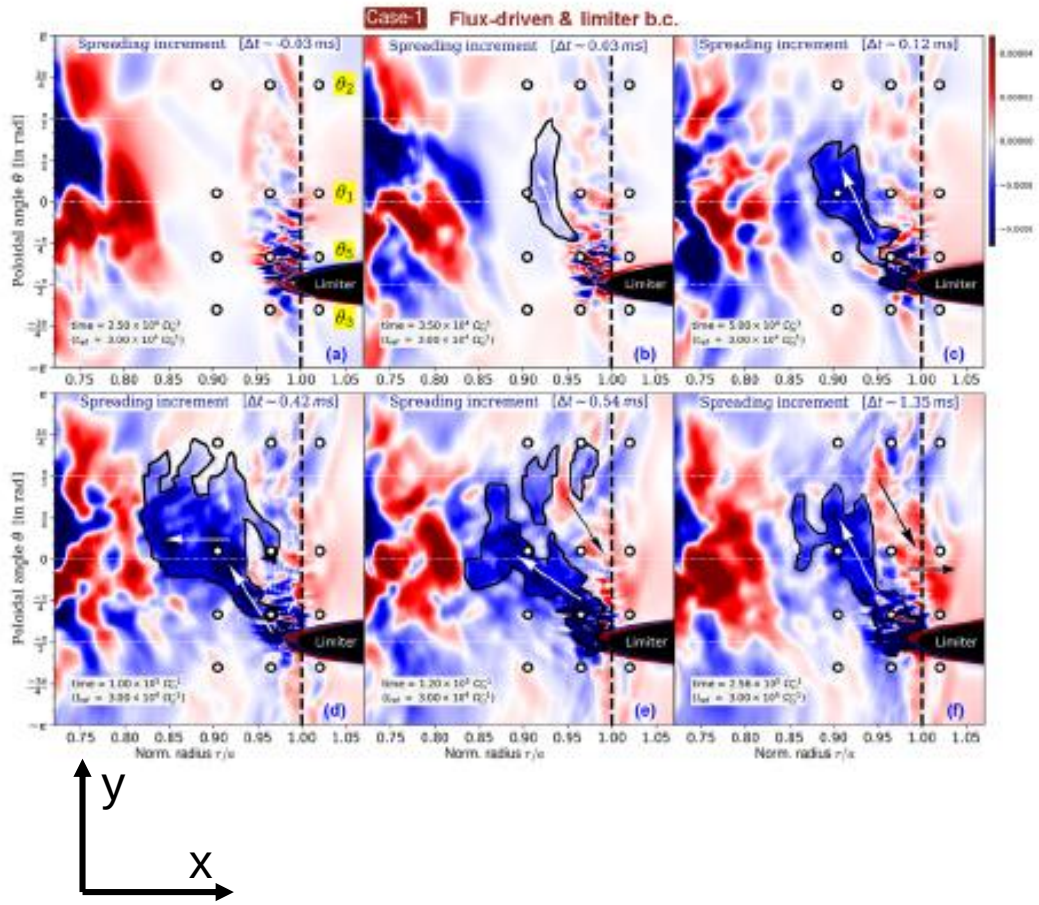


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Dif-Pradalier 2022

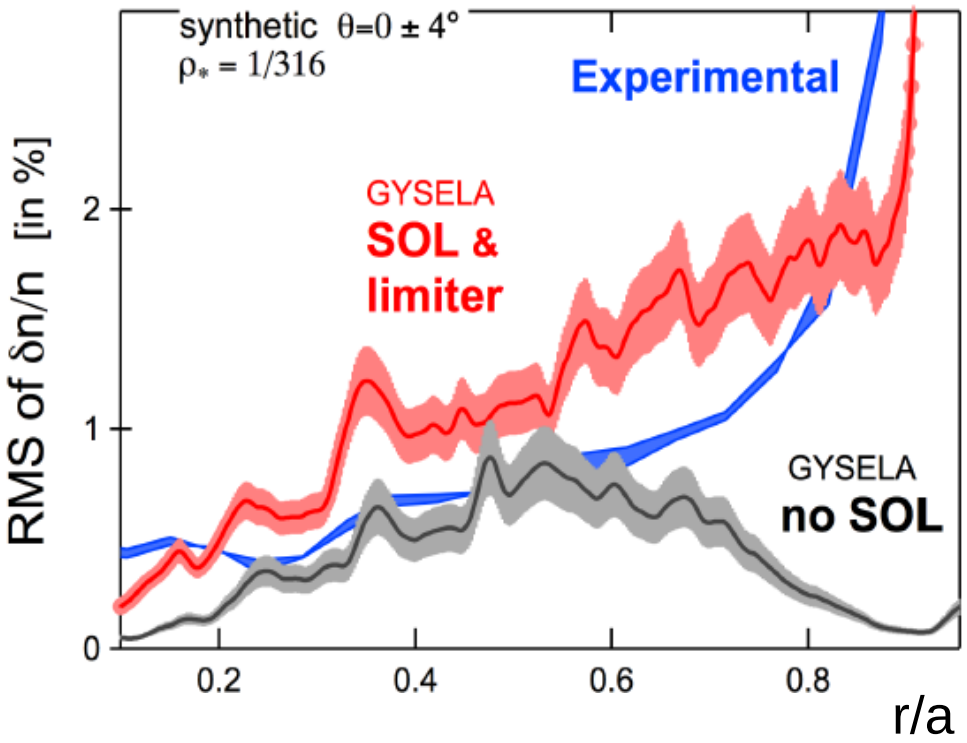


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Dif-Pradalier 2022



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