Simulation of edge plasma turbulence

Paolo Ricci

A. Fasoli, I. Furno, F. Halpern, S. Jolliet, J. Loizu,

A. Mosetto, B. Rogers[1], C. Theiler

Centre de Recherches en Physique des Plasmas

École Polytechnique Fédérale de Lausanne, Switzerland

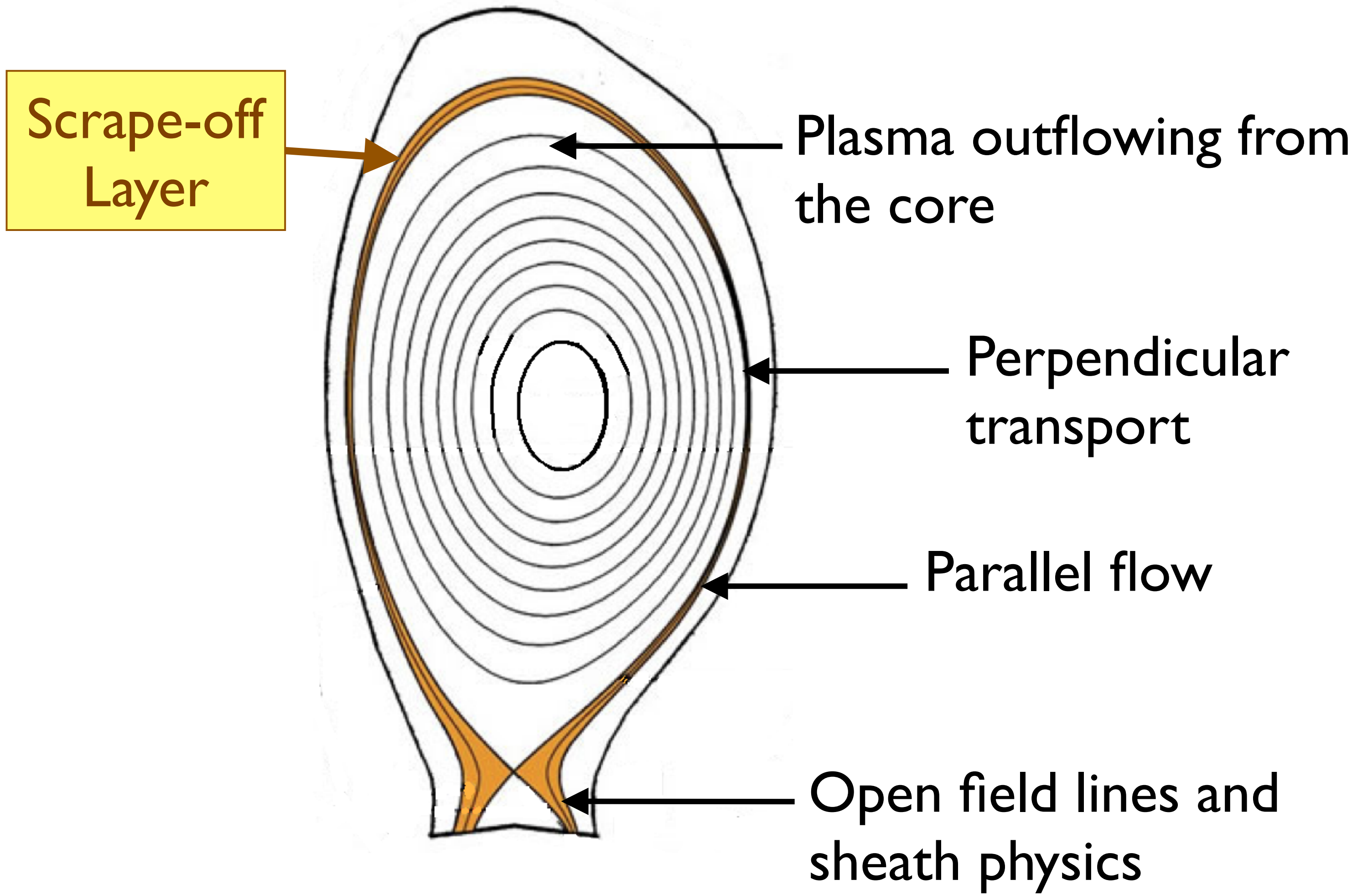
1) Dartmouth College, Hanover NH

How can we simulate edge plasma turbulence?

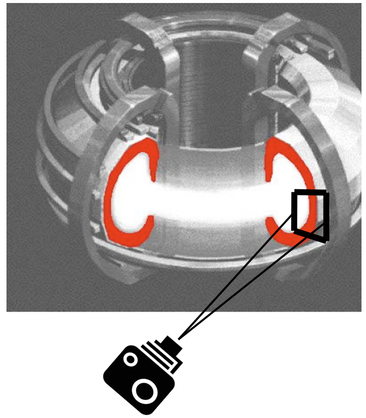
How can we gradually approach its complexity by using basic plasma physics devices? What are we learning on their dynamics?

In the tokamak SOL, what is the mechanism setting turbulence amplitude? The transport level? The pressure scale length?

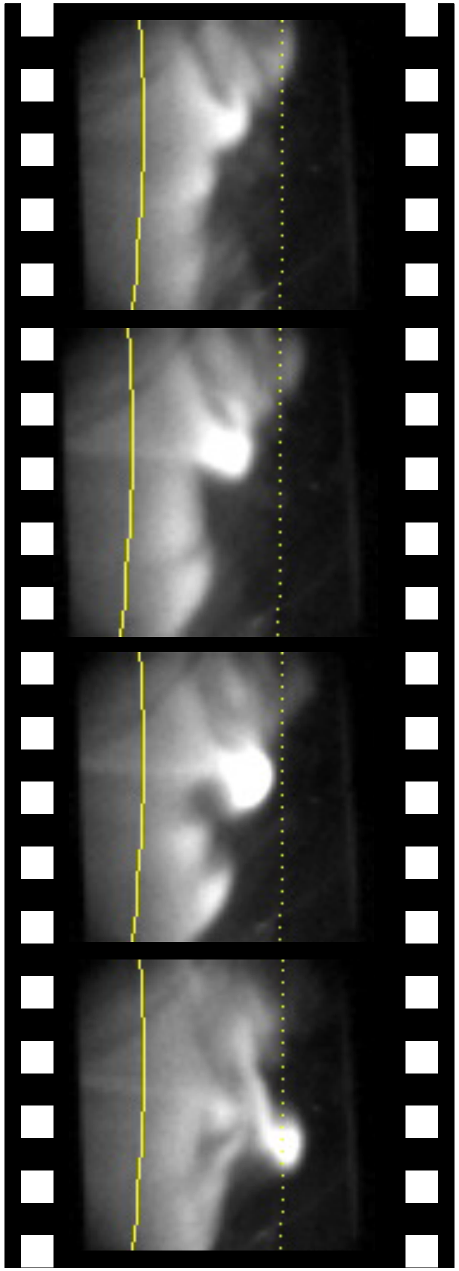
SOL channels particles and heat to the wall



Properties of SOL turbulence



$$L_{fluc} \sim L_{eq}$$
$$n_{fluc} \sim n_{eq}$$



Courtesy of R. Maqueda

Collisional
magnetized plasma

The GBS code, a tool to simulate SOL turbulence

Collisional Plasma → Braginskii model → $\rho_i \ll L,\ \omega \ll \Omega_{ci}$ → Drift-reduced Braginskii equations

Convection | Magnetic curvature | Parallel dynamics | Source

$$\frac{\partial n}{\partial t} + [\phi, n] = \hat{C}(nT_e) - n\hat{C}(\phi) - \nabla_\parallel (n V_{\parallel e}) + S$$

T_e, Ω (vorticity) → similar equations ($T_i \ll T_e$)

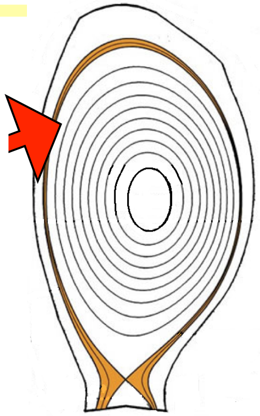
$V_{\parallel e}$, $V_{\parallel i}$ → parallel momentum balance

$$\nabla_\perp^2 \phi = \Omega$$

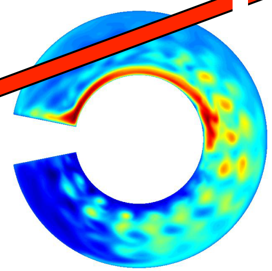
Solved in 3d geometry, taking into account plasma sources, turbulent transport, and losses at the vessel

GBS analysis of configurations of increasing complexity

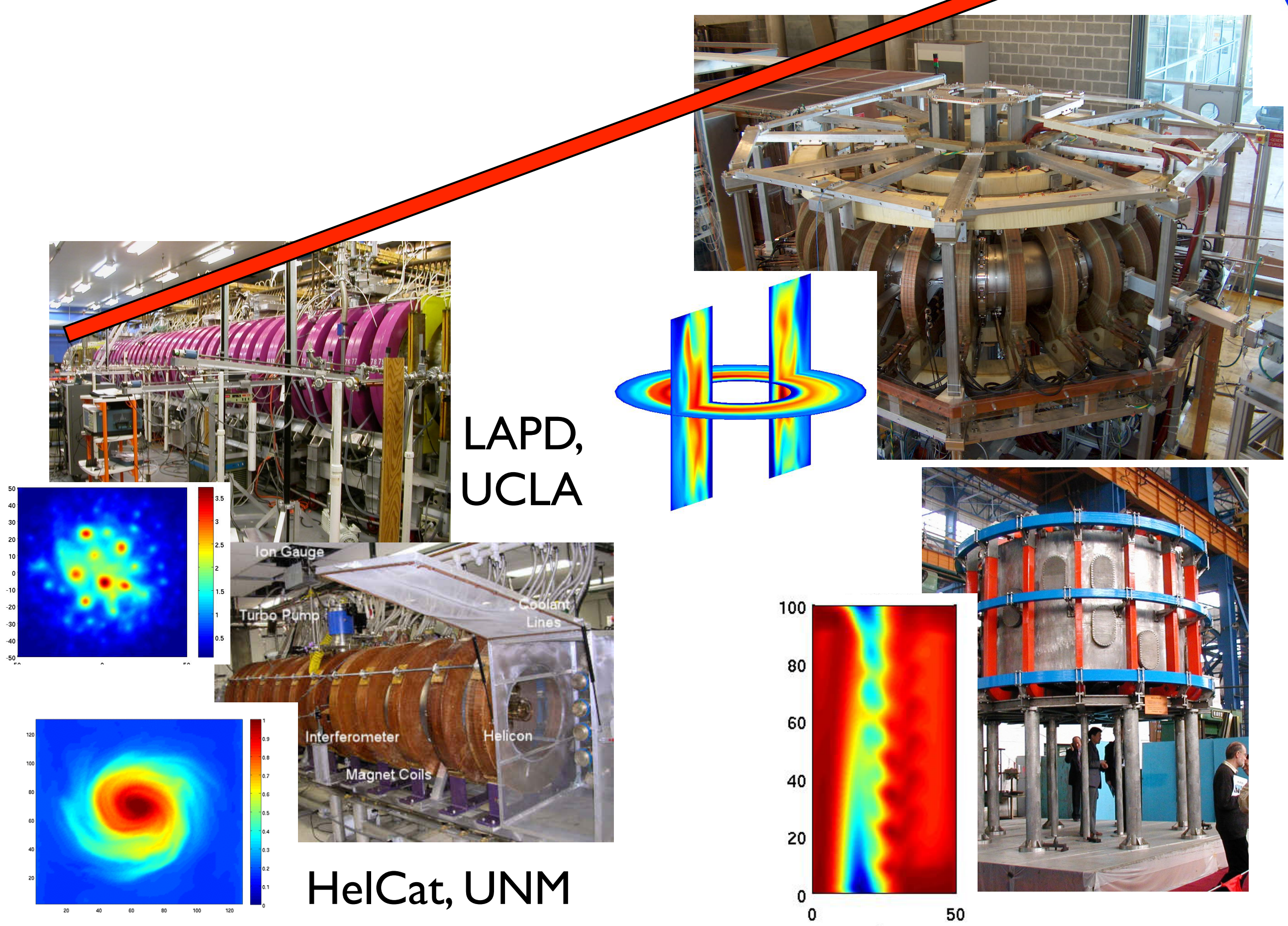
From linear devices, to Simple Magnetized Tori (SMT), and to SOL



ITER-like SOL



Limited SOL

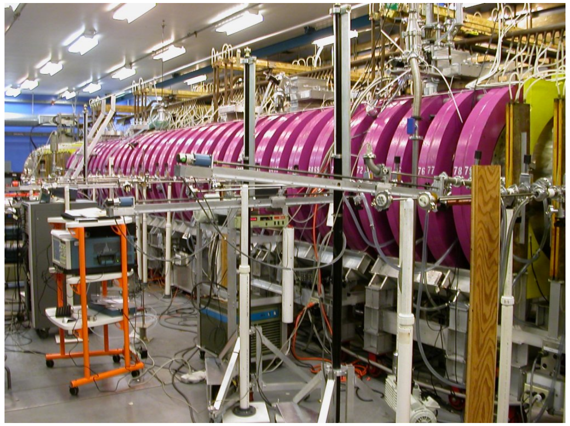


LAPD, UCLA

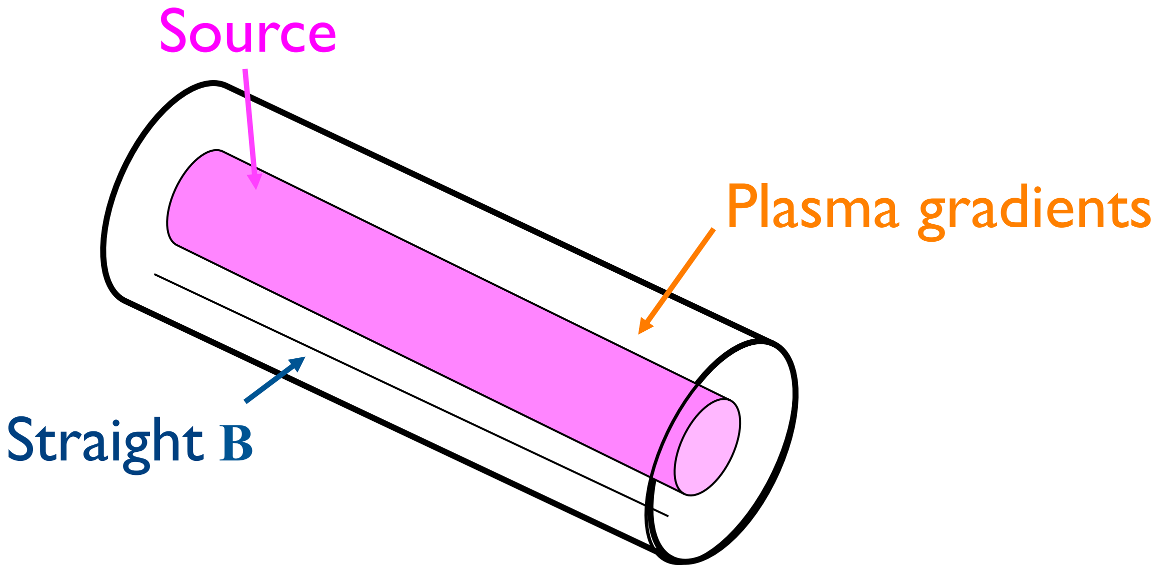
TORPEX, CRPP

HelCat, UNM

Helimak, UTexas

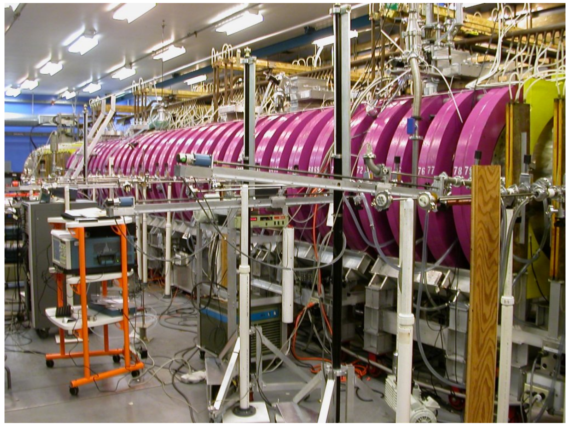


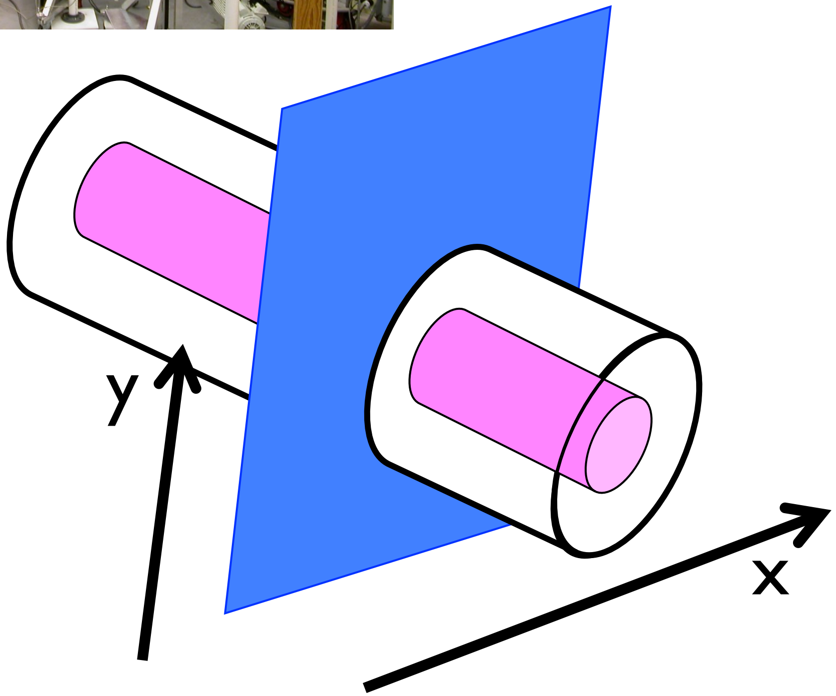
GBS simulation of a linear device: LAPD

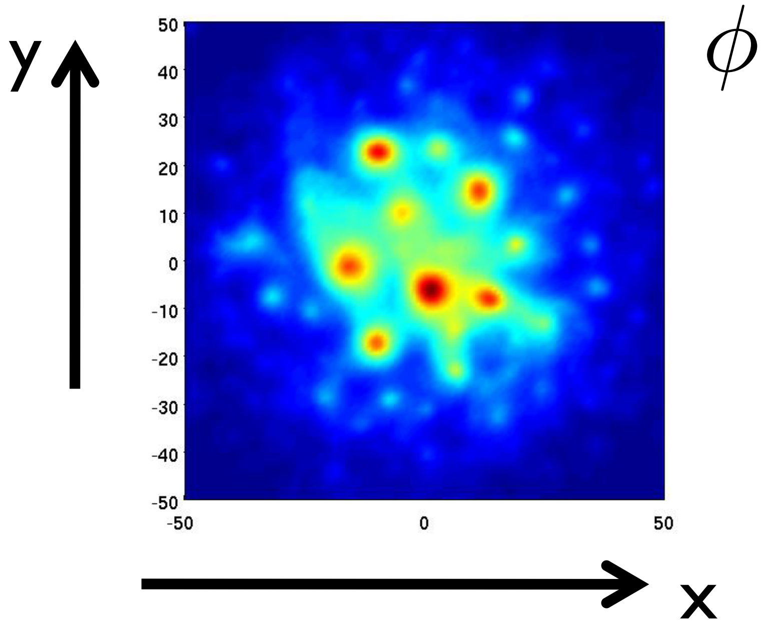


$$\overbrace{\frac{\partial n}{\partial t} + [\phi, n]}^{\text{Convection}} = \cancel{\overbrace{\hat{C}(nT_e) + n\hat{C}(\phi)}^{\text{Magnetic curvature}}} - \overbrace{\nabla_{\parallel}(nV_{\parallel e})}^{\text{Parallel dynamics}} + \overbrace{S}^{\text{Source}}$$

GBS simulation of a linear device: LAPD



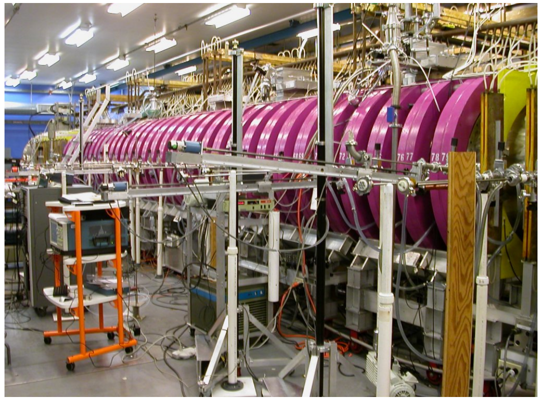




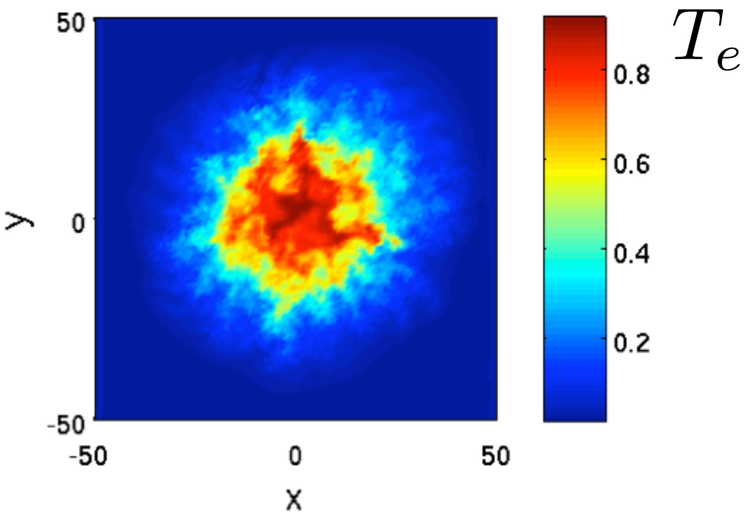
Convection; Magnetic curvature; Parallel dynamics; Source

$$\underbrace{\frac{\partial n}{\partial t} + [\phi, n]}_{\text{Convection}} = \underbrace{\cancel{\hat{C}(nT_e) - n\hat{C}(\phi)}}_{\text{Magnetic curvature}} - \underbrace{\nabla_\parallel (nV_{\parallel e})}_{\text{Parallel dynamics}} + \underbrace{S}_{\text{Source}}$$

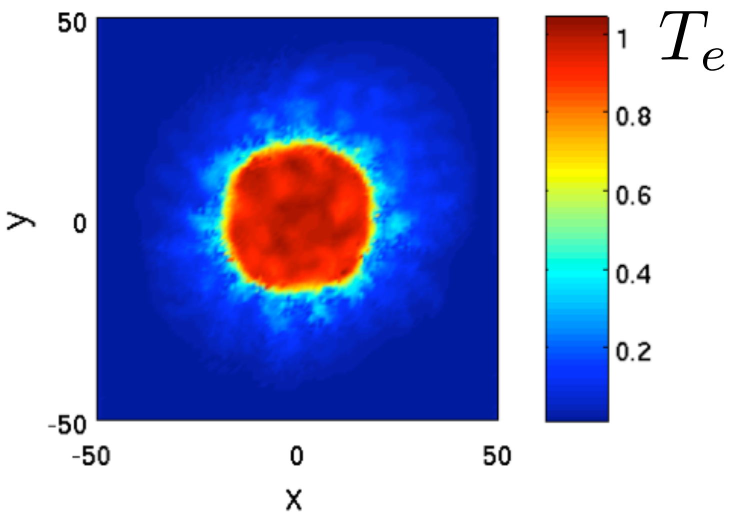
Kelvin-Helmholtz instability is the turbulence drive



Plasma gradients → Drift waves / Kelvin-Helmholtz / Sheath mode

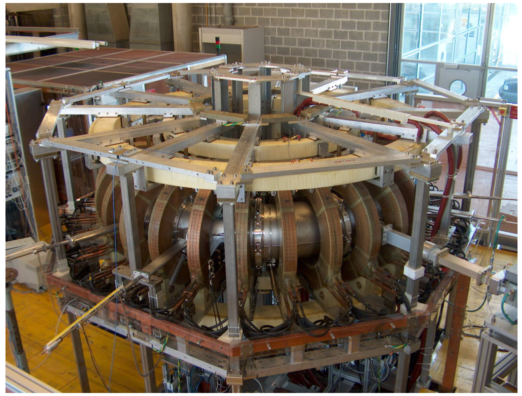


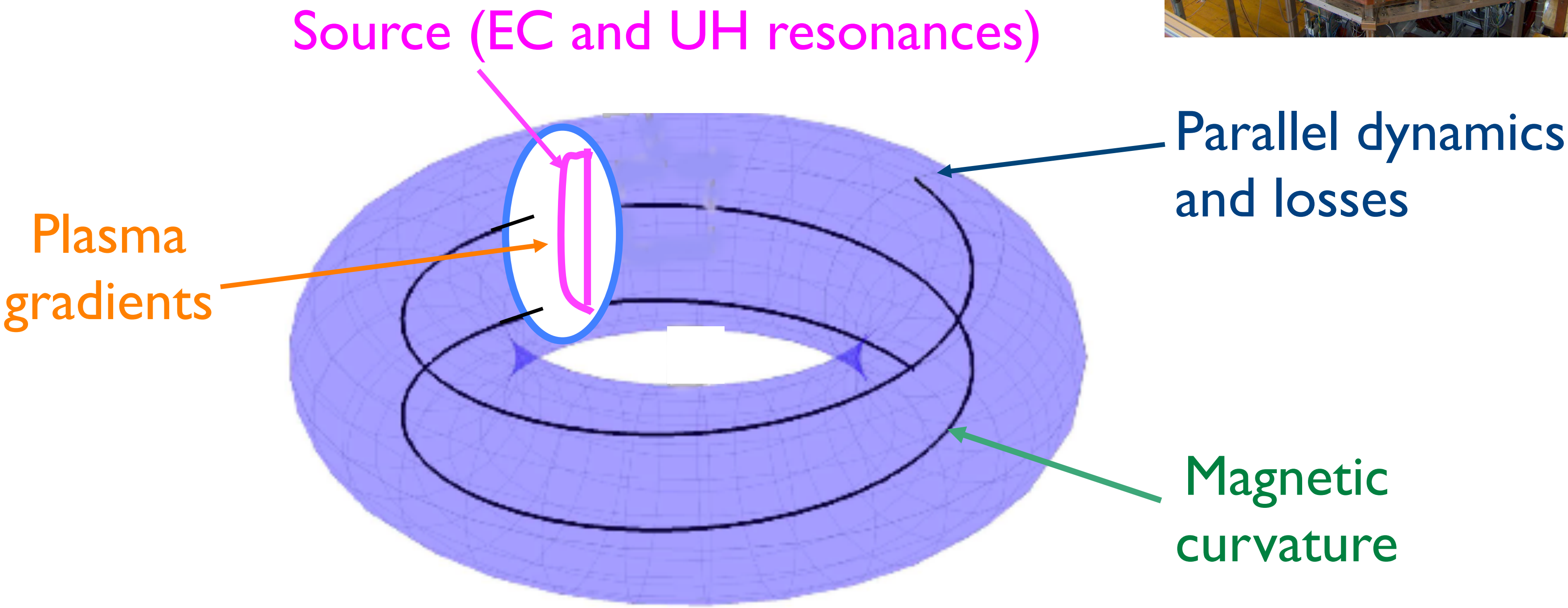
With K-H drive



Without K-H drive

The Simple Magnetized Plasma (SMT) TORPEX

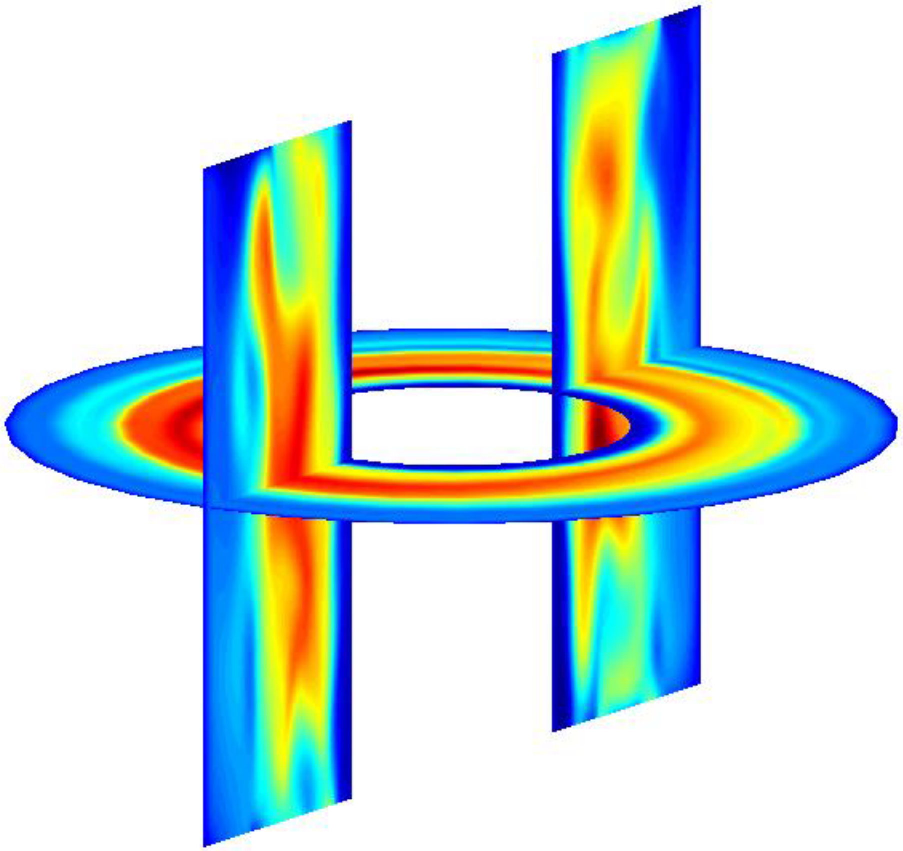




Simple magnetic curvature

$$\boxed{\frac{\partial n}{\partial t} + [\phi, n]} = \boxed{\frac{2}{R}\frac{\partial (nT_e)}{\partial y} - \frac{2n}{R}\frac{\partial \phi}{\partial y}} - \boxed{\nabla_{\|}(nV_{\|e})} + \boxed{S}$$

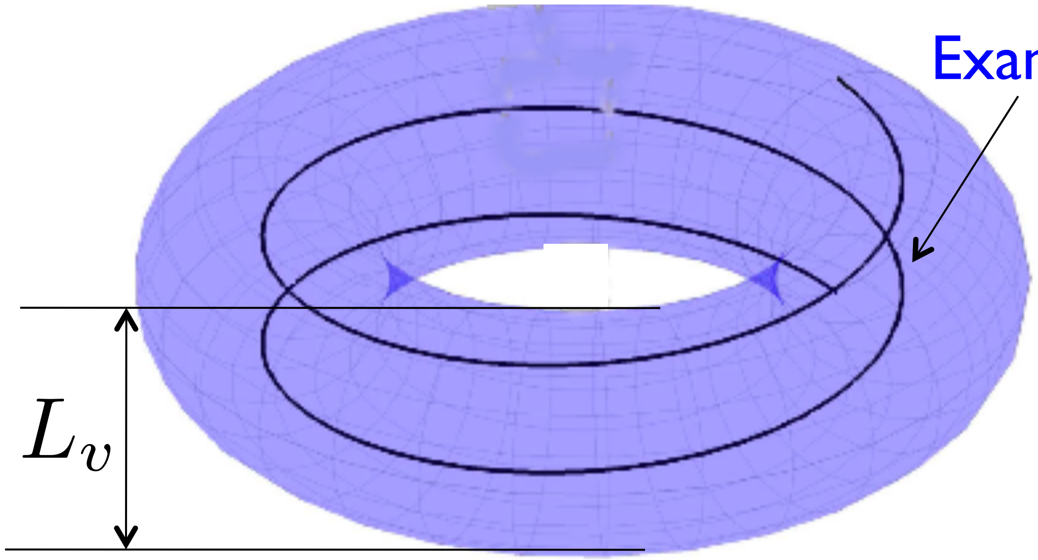
GBS simulations of TORPEX



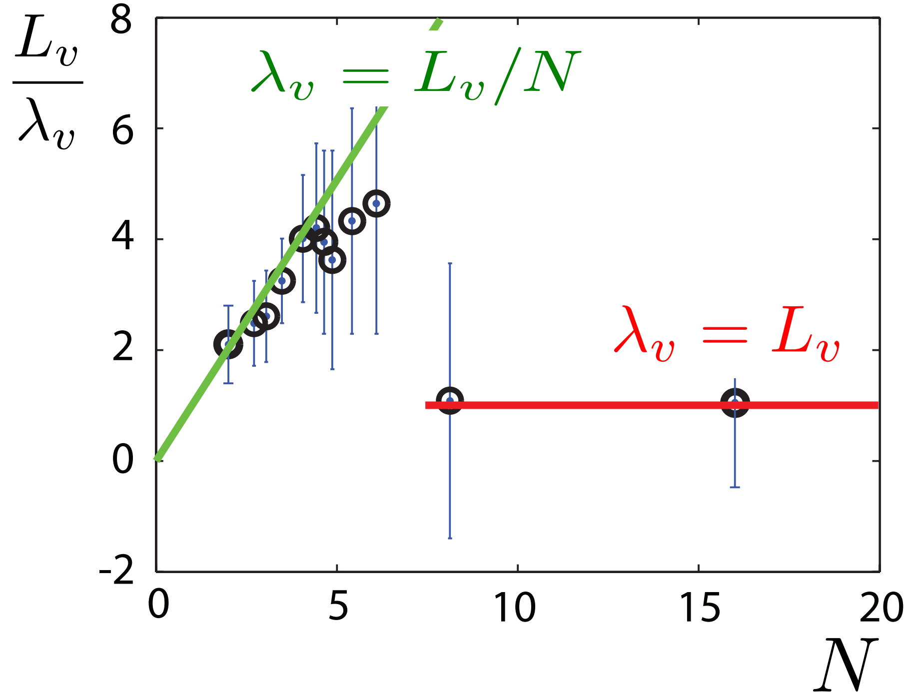
Two poloidal and
one toroidal cuts for ϕ

Global evolution of both equilibrium and fluctuations

Experimental features of TORPEX turbulence



Depends on N, the number of B turns



λ_v : experimental vertical wavelength

Ideal interchange mode

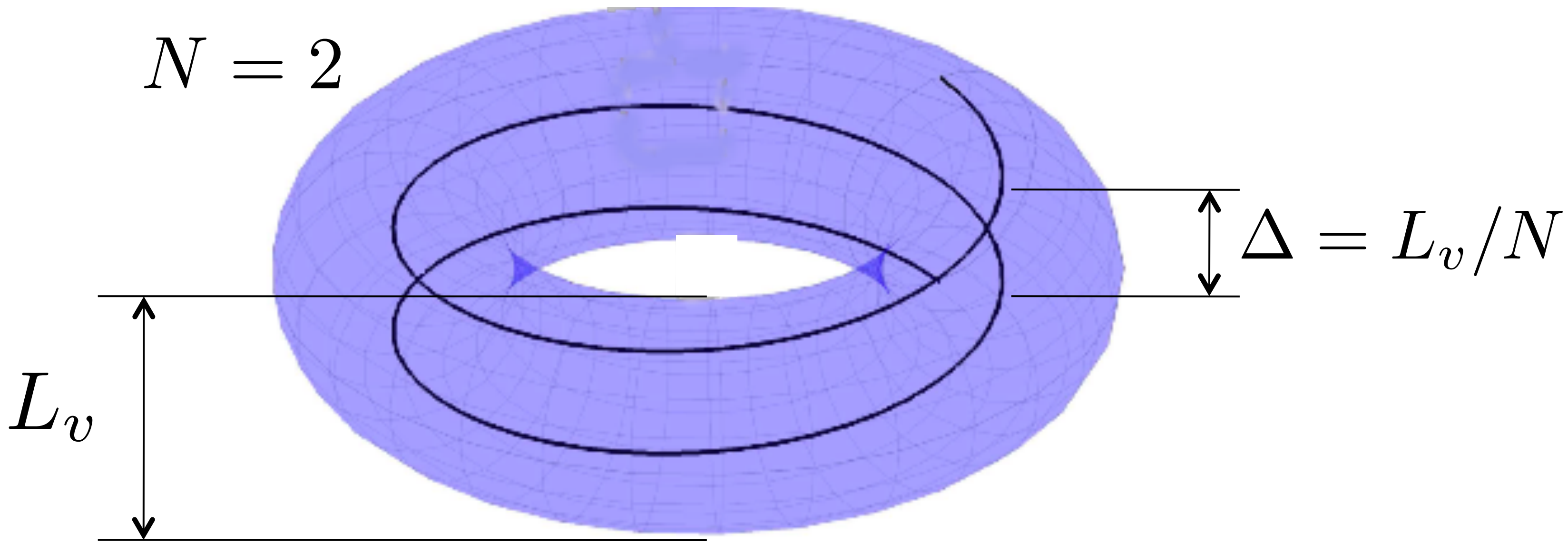
$k_{\|} = 0$ ➡

n + T_e eqs. $\longrightarrow$ $$\frac{\partial p_e}{\partial t} = [p_e, \phi]$$

Vorticity eq. $\longrightarrow$ $$\frac{\partial \nabla_\perp^2 \phi}{\partial t} = \frac{2}{R}\frac{\partial p_e}{\partial y}$$

➡ $$\gamma = \gamma_I \qquad \gamma_I = c_s\sqrt{\frac{2}{L_p R}}$$

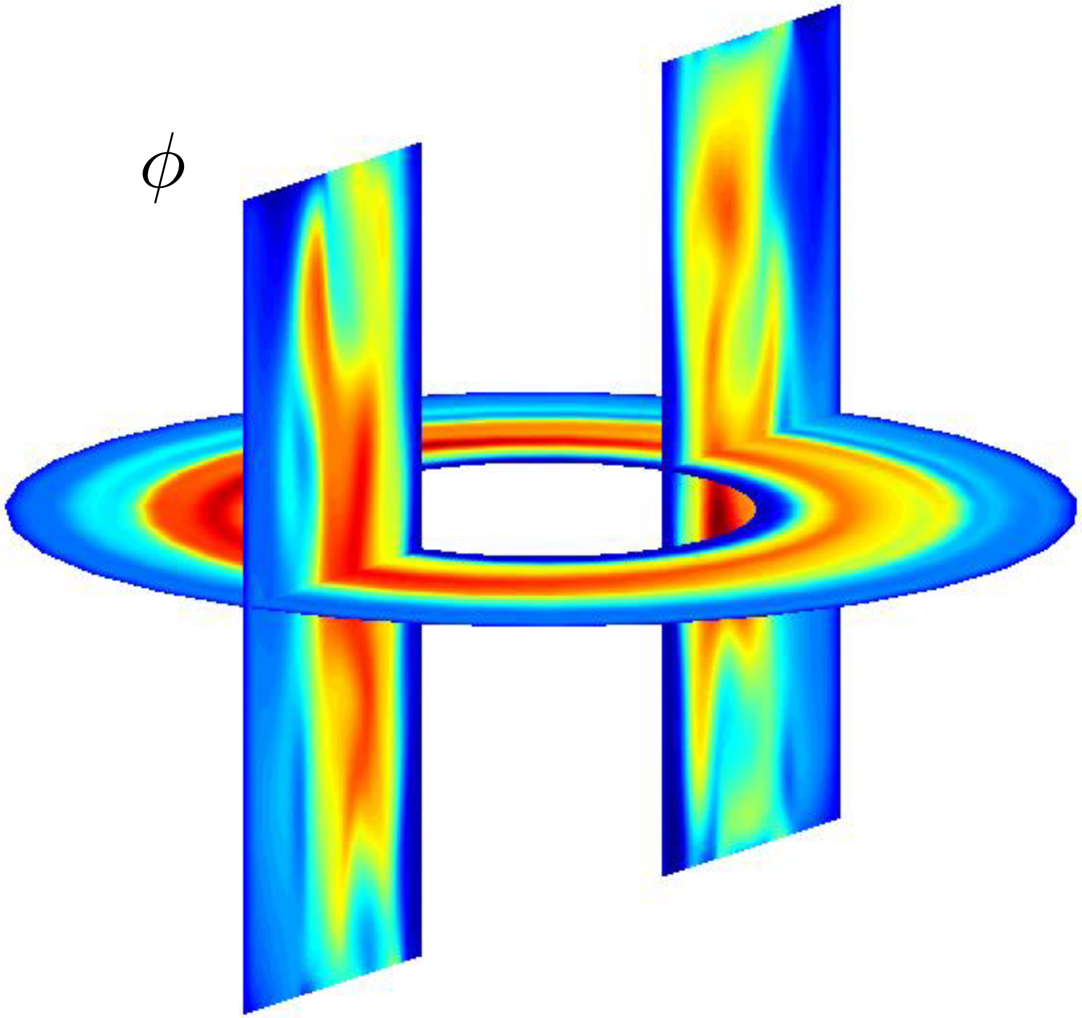
Anatomy of a $k_{\|} = 0$ perturbation



λ_v : longest possible vertical wavelength of a perturbation

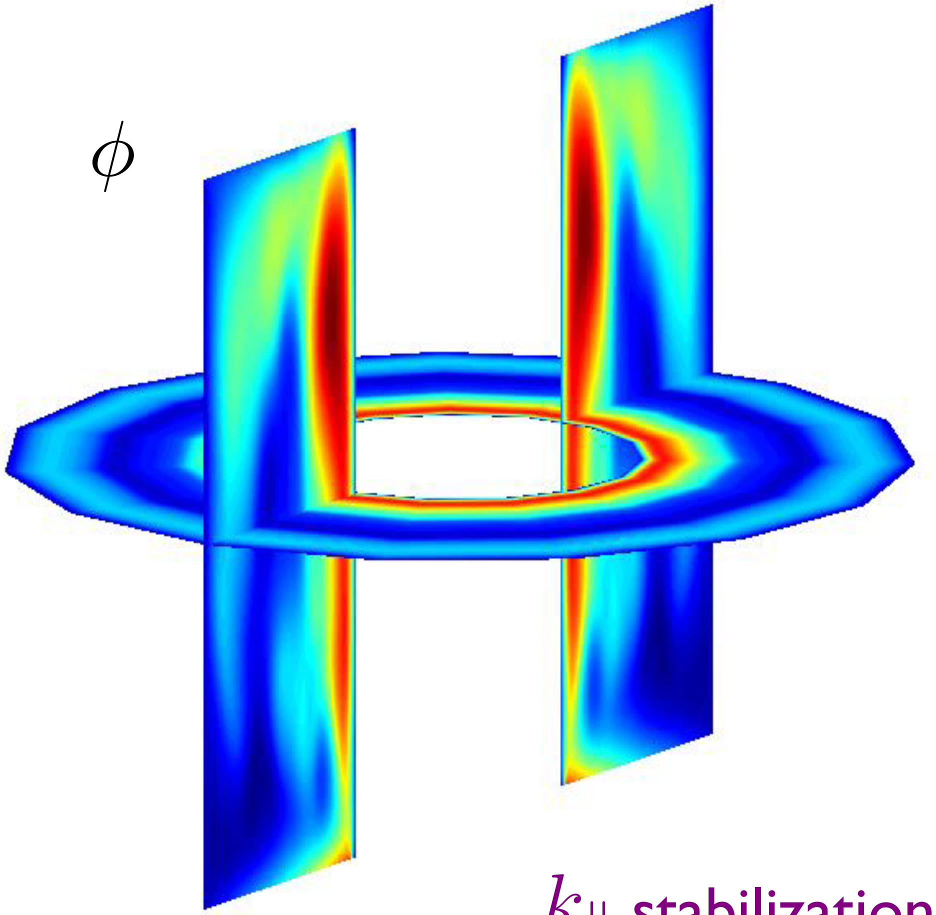
$$\boxed{\text{If } k_{\|} = 0 \text{ then } \lambda_v = \Delta = \frac{L_v}{N}}$$

For N~1-6, ideal $k_{\|} = 0$ interchange modes dominant



N=2

At high N>7, Resistive Interchange Mode turbulence



Toroidally symmetric

$\lambda_v \sim L_v$

$k_{\|}$ stabilization, requires high N and $\eta_{\|} \neq 0$

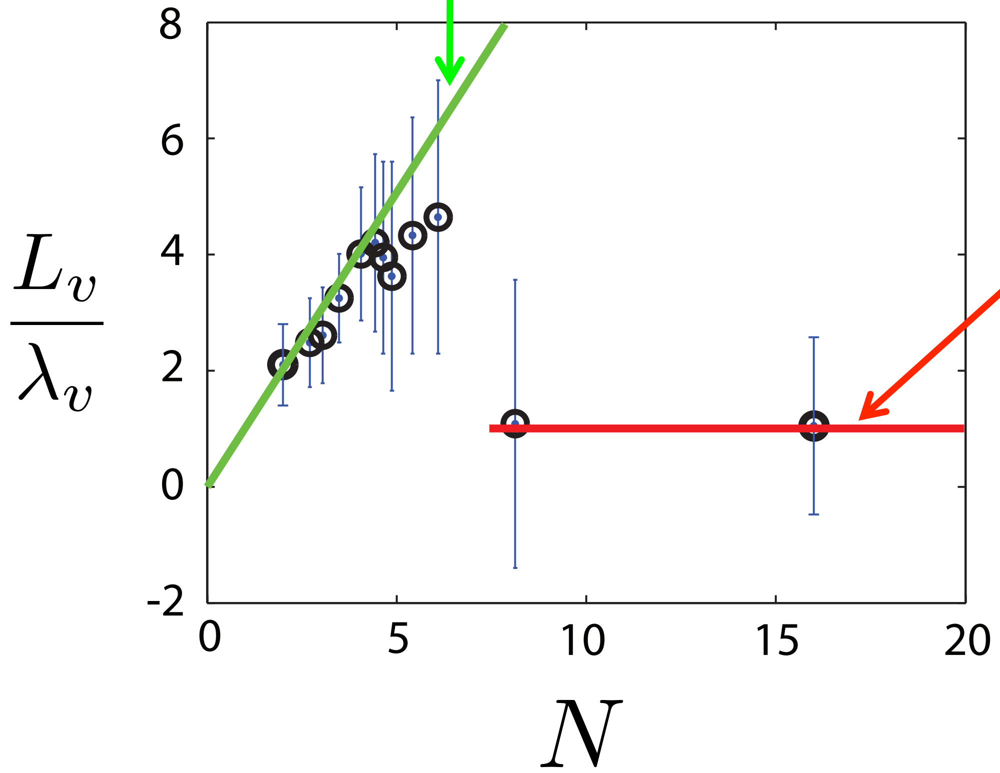
Introducing $k_{\|} \neq 0$ modes

$$\gamma^2 = \gamma_I^2 - \gamma \frac{4\pi V_A^2 k_{\|}^2}{\eta_{\|} c^2 k_y^2}, \quad \gamma_I = c_s \sqrt{\frac{2}{R L_p}}$$

TORPEX turbulent regimes

$$k_{\parallel} = 0 \quad (\lambda_v = L_v/N)$$

Ideal interchange regime

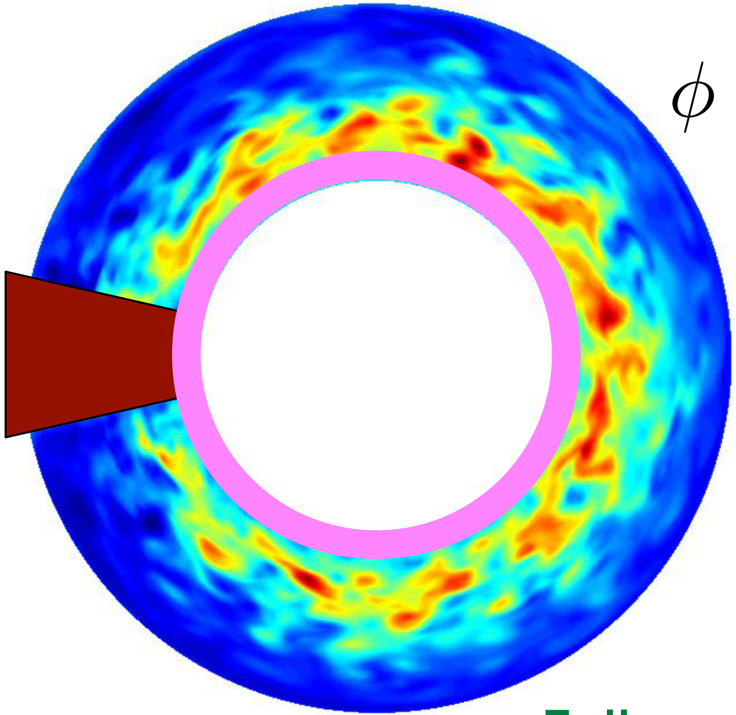


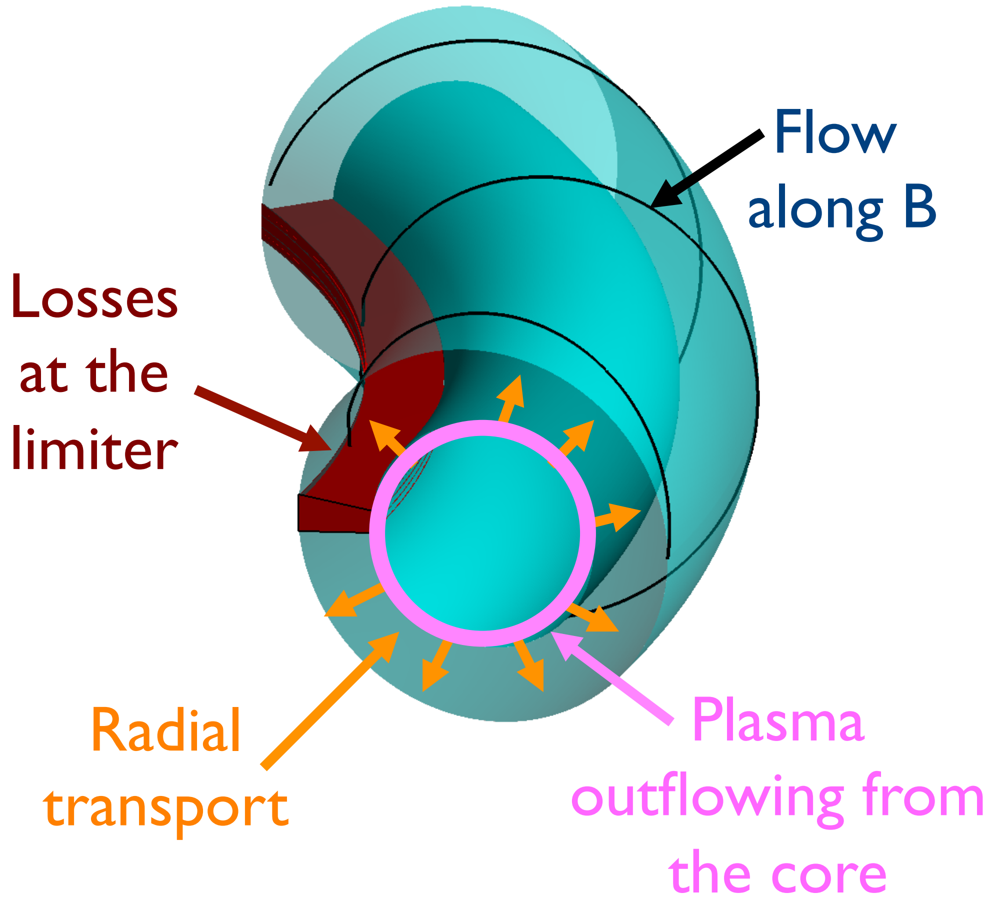
$$k_{\parallel} \neq 0 \;\; (\lambda_v = L_v)$$

Resistive interchange regime

Linear theory, nonlinear simulations, experiments in agreement

Tokamak SOL simulations





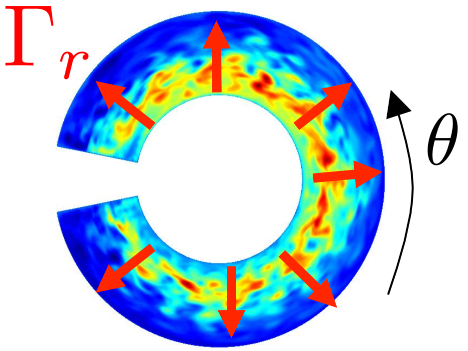
Full curvature operator

$$\frac{\partial n}{\partial t} + [\phi, n] = \hat{C}(nT_e) - n\hat{C}(\phi) - \nabla_{\|}(nV_{\|e}) + S$$

What is the mechanism setting the turbulence amplitude?
Radial transport? L_p in the SOL?

Turbulent transport with gradient removal (GR) saturation

Turbulence saturates when it removes its drive $\rightarrow \dfrac{\partial p_{e1}}{\partial r} \sim \dfrac{\partial p_{e0}}{\partial r} \rightarrow k_r p_{e1} \sim p_{e0}/L_p$



$$\frac{\partial p_e}{\partial t} \simeq [p_e, \phi]$$

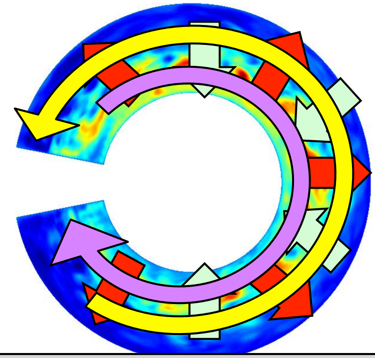
$$\Gamma_r = \left\langle p_{e1} \frac{\partial \phi_1}{\partial \theta} \right\rangle \sim \frac{\gamma p_{e0}}{L_p k_r^2} \sim \frac{\gamma p_{e0}}{k_\theta}$$

GR hypothesis

Nonlocal linear theory, $k_r \sim \sqrt{k_\theta / L_p}$

$$\rightarrow \boxed{D_{GR} = \frac{\Gamma_r}{p_{e0}/L_p} \sim \frac{\gamma L_p}{k_\theta}}$$

Turbulence saturation due to Kelvin-Helmholtz instability (KH)



Primary instability grows until it causes KH unstable shear flow $\rightarrow$ $\dfrac{\partial \omega}{\partial t} \sim [\phi, \omega] \rightarrow \phi_1 \sim \dfrac{\gamma}{k_\theta^2}$

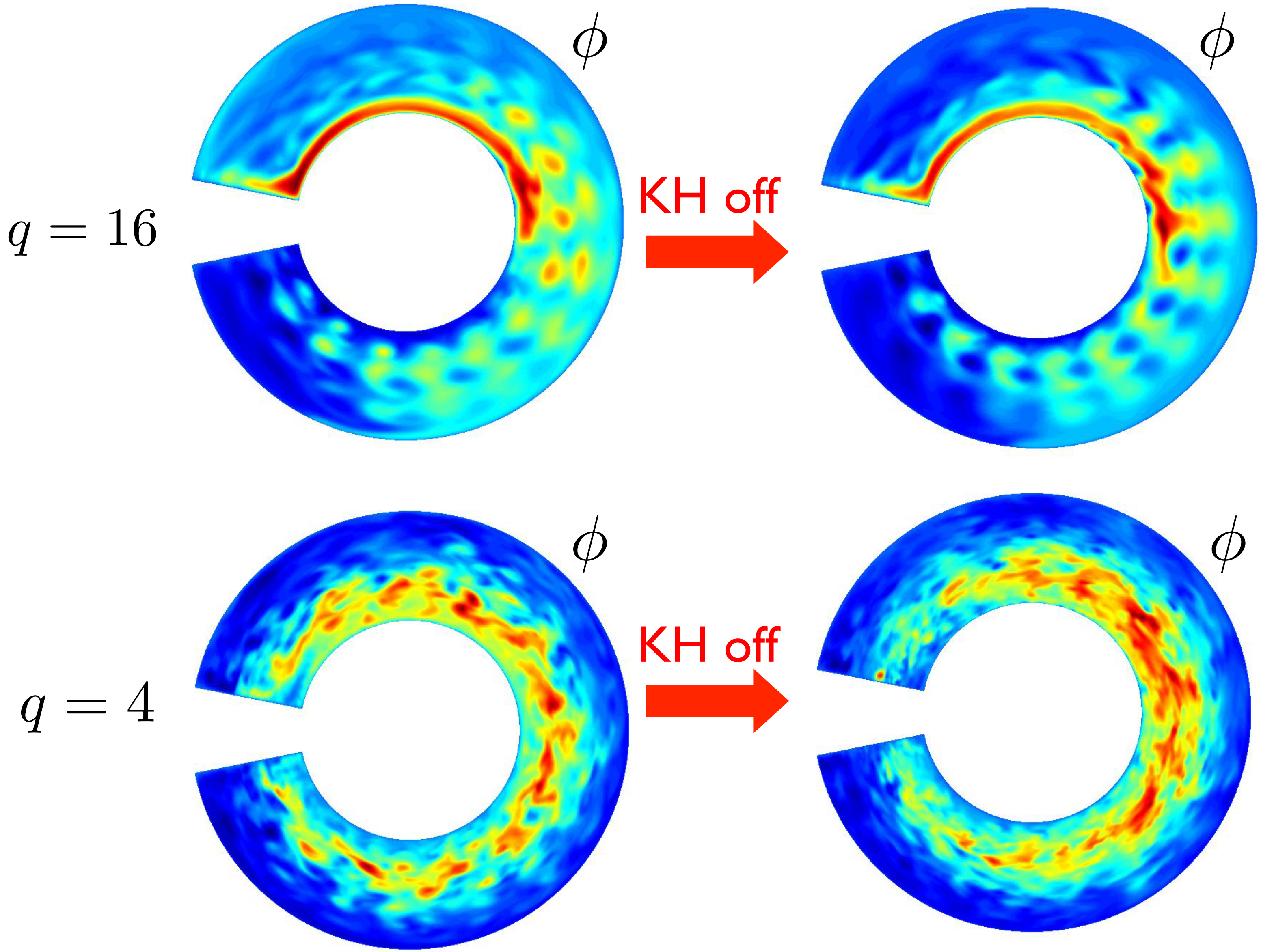
$$\Gamma_r = \left\langle p_{e1} \frac{\partial \phi_1}{\partial \theta} \right\rangle \sim \frac{\gamma p_{e0}}{L_p k_\theta^2} \quad \Rightarrow \quad \boxed{D_{KH} \sim \frac{\gamma}{k_\theta^2}}$$

KH vs GR mechanism:

$$\frac{D_{KH}}{D_{GR}} \sim \frac{1}{k_\theta L_p} < 1$$

We expect KH to limit the transport, provided that KH is unstable!

Is KH really setting transport?

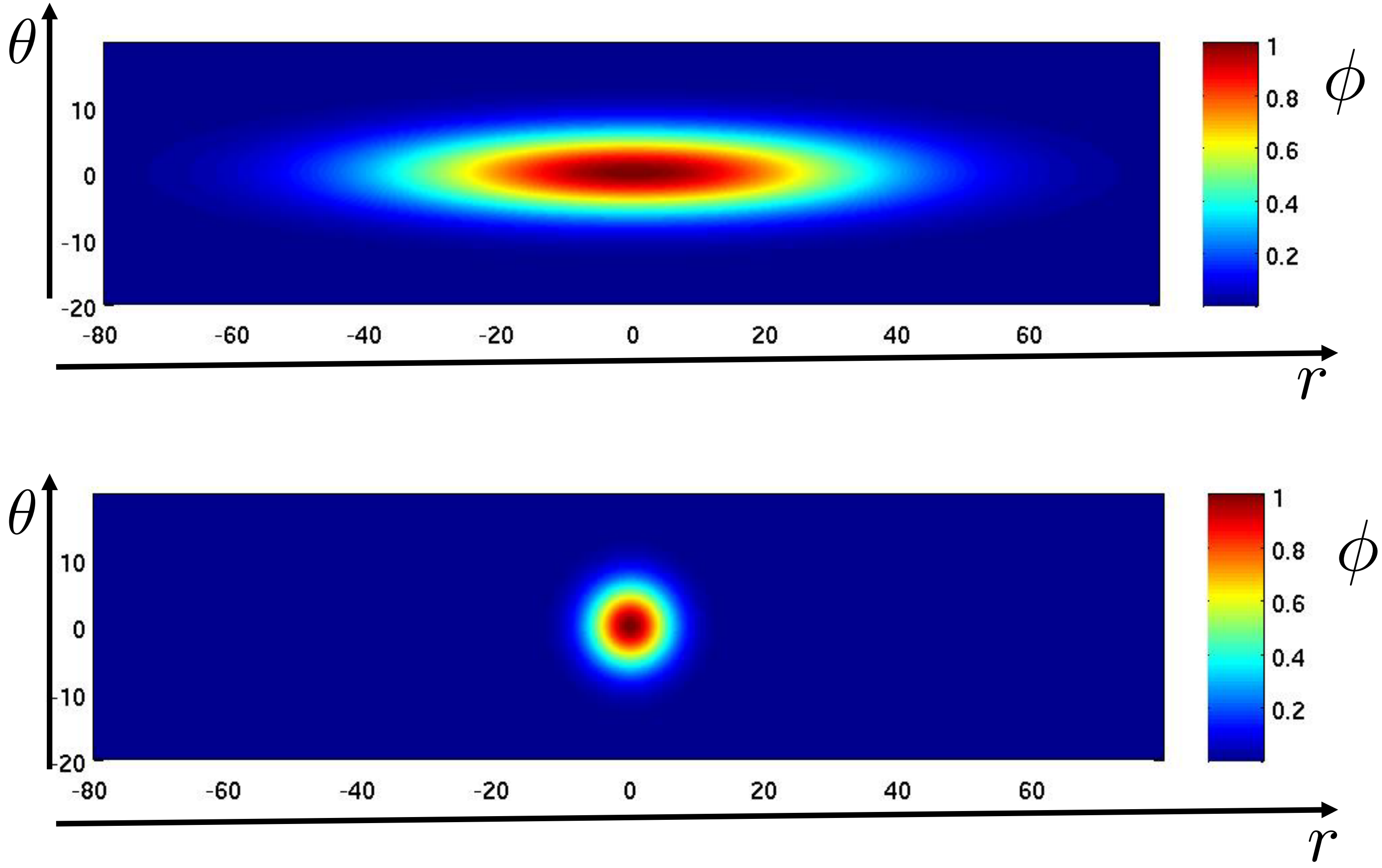


KH saturates turbulence

KH plays a minor role: GR!

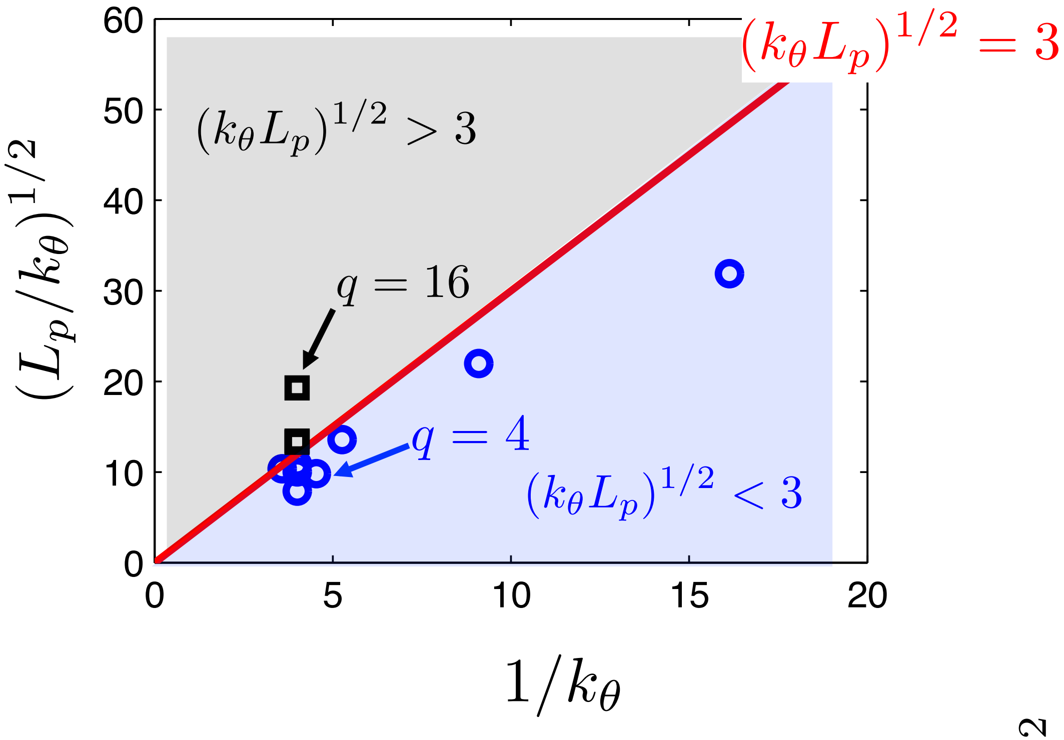
Why is KH stable at low q but not higher q?

Only elongated eddies are KH unstable



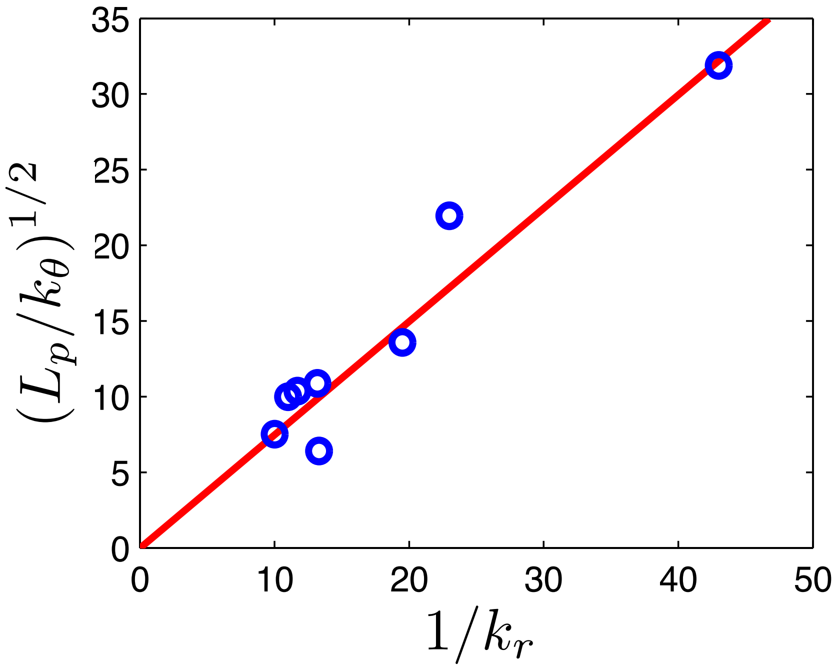
By comparing eddy turn over time and KH growth rate, KH unstable if: $\sqrt{k_\theta L_p} > 3$

Why is KH stable at low q but not higher q?



q=4 simulations are in the KH stable region

The eddies show the GR scaling properties



Transport and profile scaling for KH stable cases

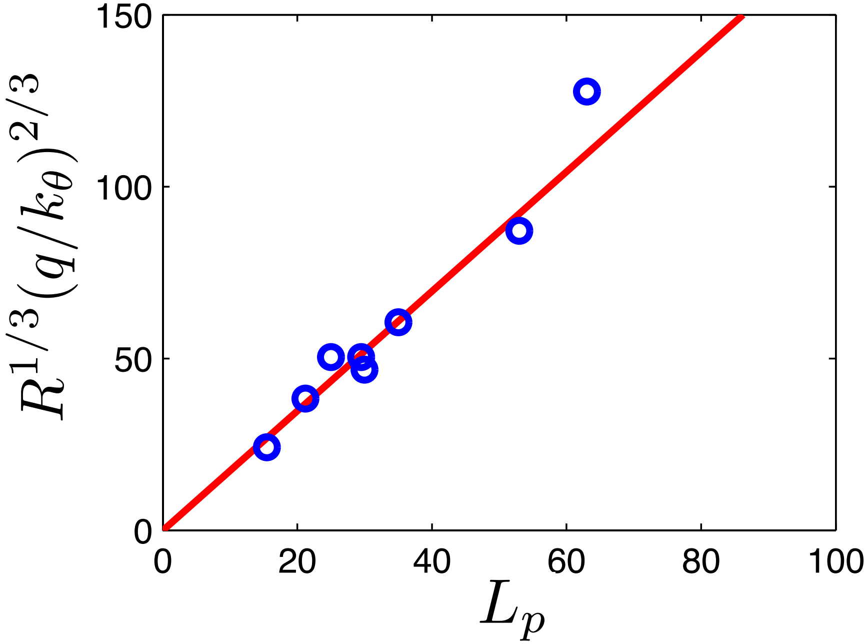
Balance of perpendicular transport and parallel losses

$$\frac{d\Gamma_r}{dr} \sim L_\parallel \sim \frac{n_0 c_s}{qR}$$

Bohm's

$$\boxed{L_p \sim R^{1/3}(q/k_\theta)^{2/3}}$$

Simulations show expected scaling

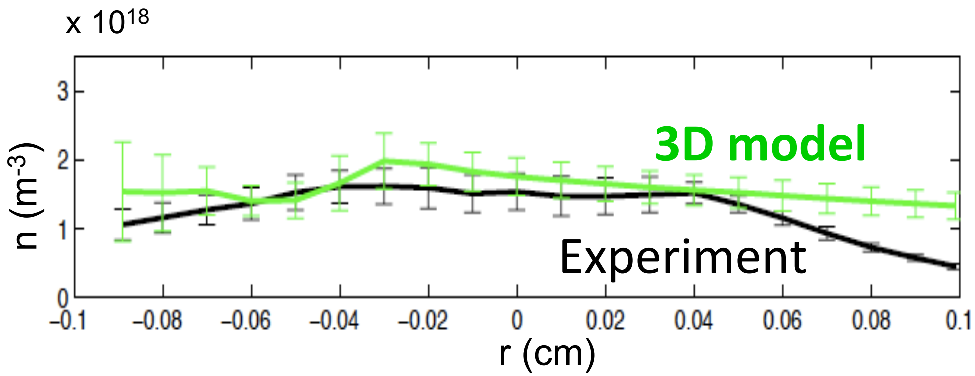


What are we learning from GBS simulations?

- The use of a progressive approach to investigate turbulence in complex configurations
- Basic plasma physics device turbulence properties:
  - Linear device (LAPD): Kelvin-Helmholtz is the main drive
  - Simple Magnetized Torus (TORPEX): competition between ideal interchange and resistive interchange
- SOL turbulence:
  - Saturation mechanism given by gradient removal or Kelvin-Helmholtz instability
  - Scaling of radial transport and pressure scale length
- How to perform comparisons between experiments and simulations (not shown)

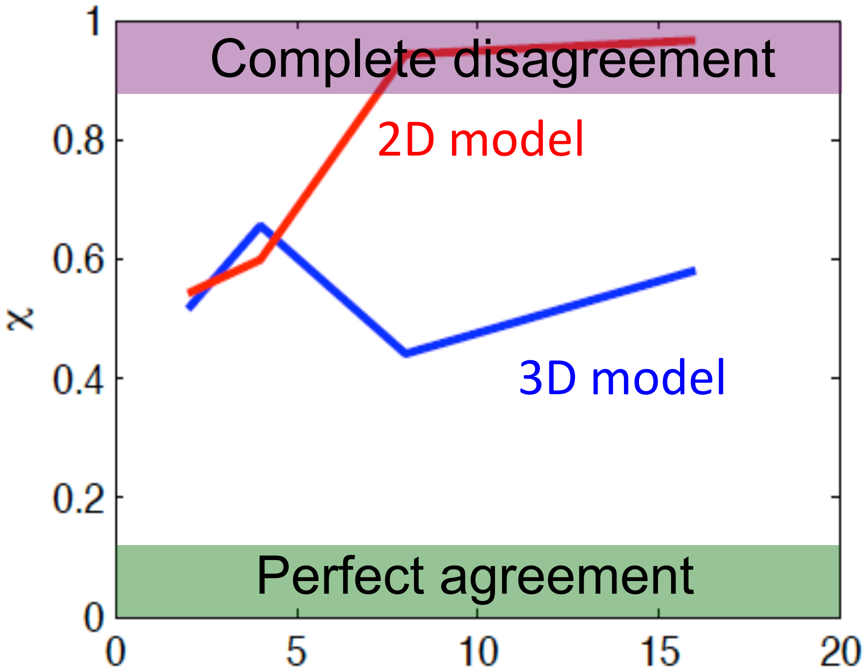
Code validation methodology and application on TORPEX

- Comparison performed using a number of observables



- A composite metric that takes into account the "hierarchy level" of each observable is introduced.

- The "quality" of the comparison is defined.

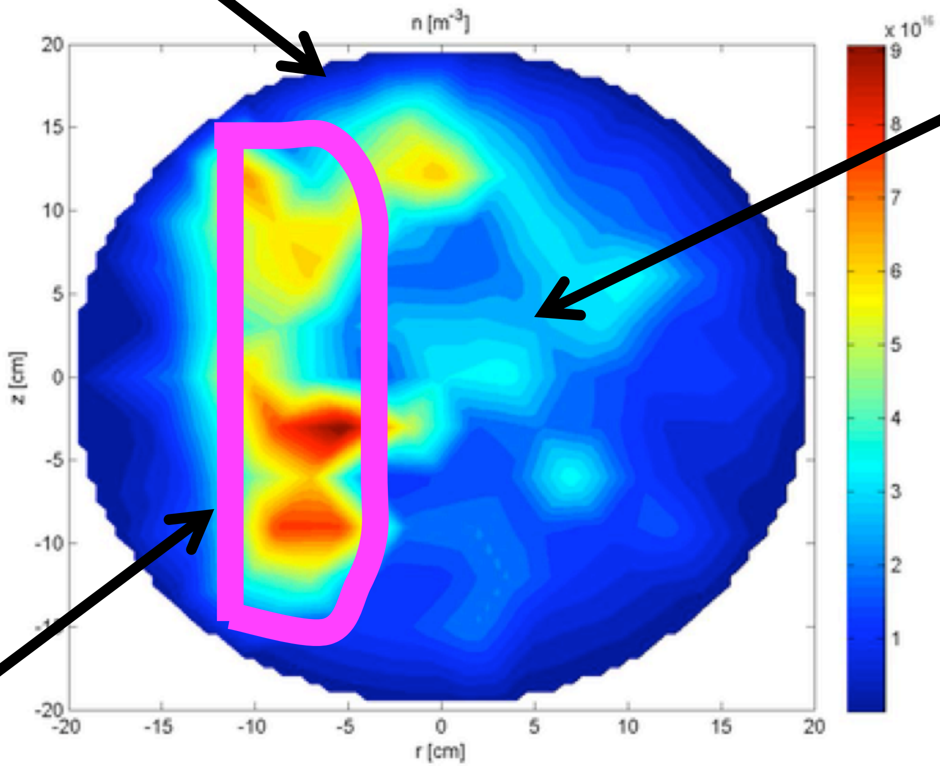


- The methodology has been applied to TORPEX

What needs to be done…

Better boundary conditions

Physics of neutrals



Better source modeling