Global simulation of plasma turbulence in laboratory plasmas

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A paradigm of laboratory plasma turbulence, TORPEX

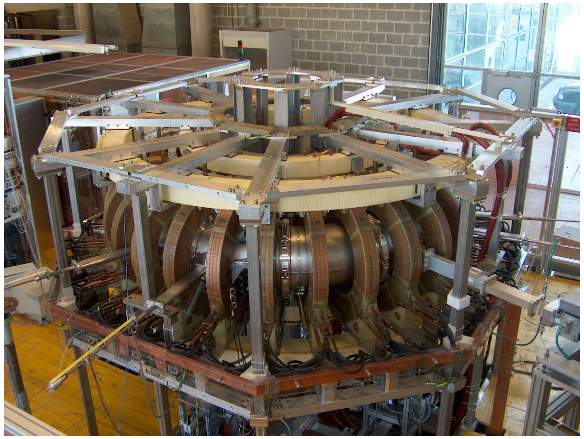
How its dynamics can be approached?

What can we learn from TORPEX simulations?

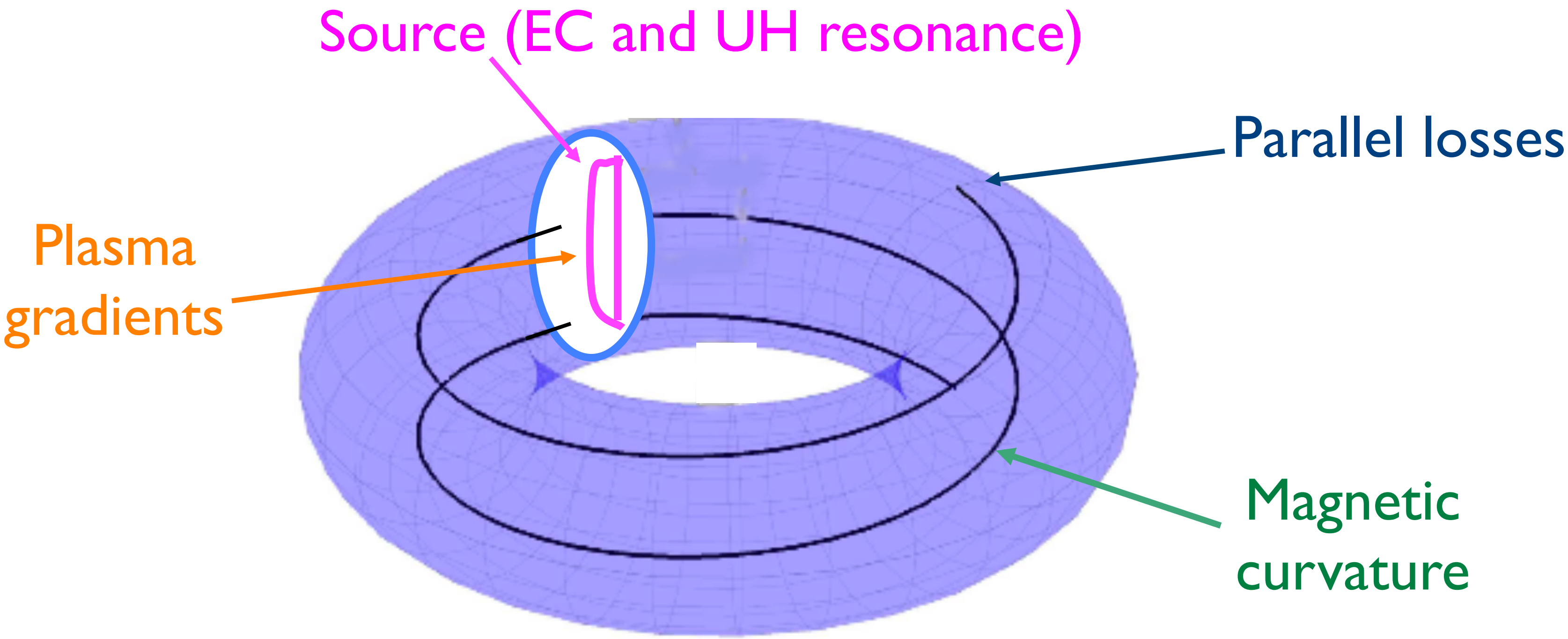
Some examples: turbulent regimes, transport,

non-thermal particle dynamics, simulations/experiments comparison

The TORPEX experiment, paradigm of plasma turbulence

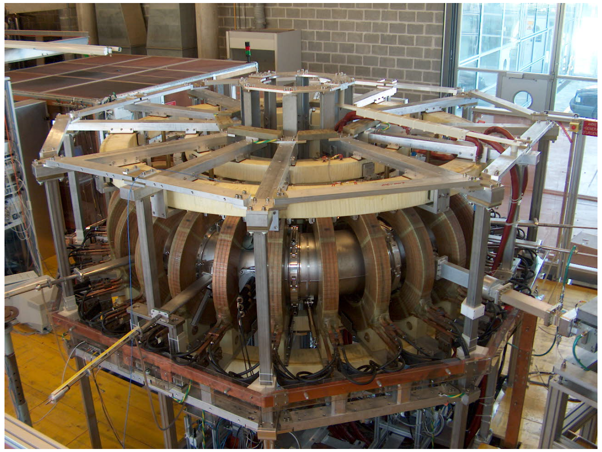


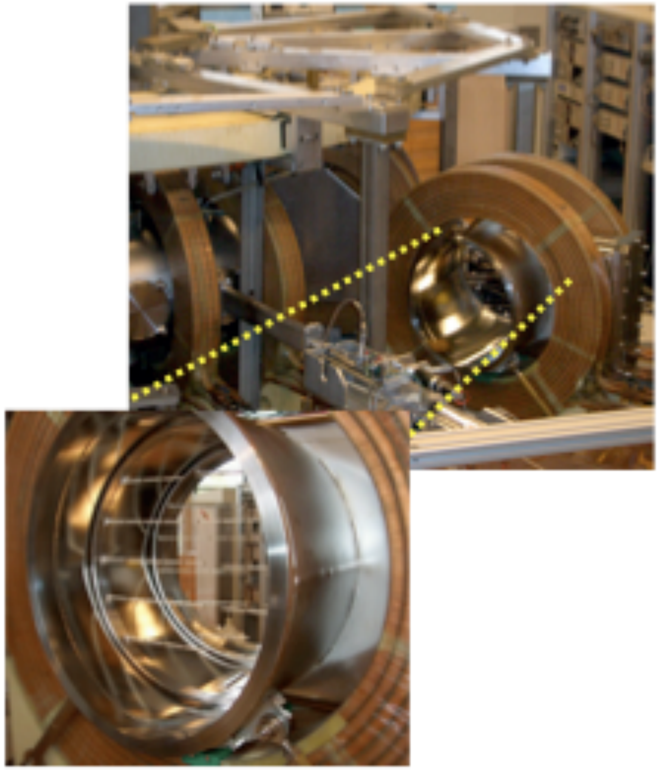
crpp.epfl.ch/basplasmas/

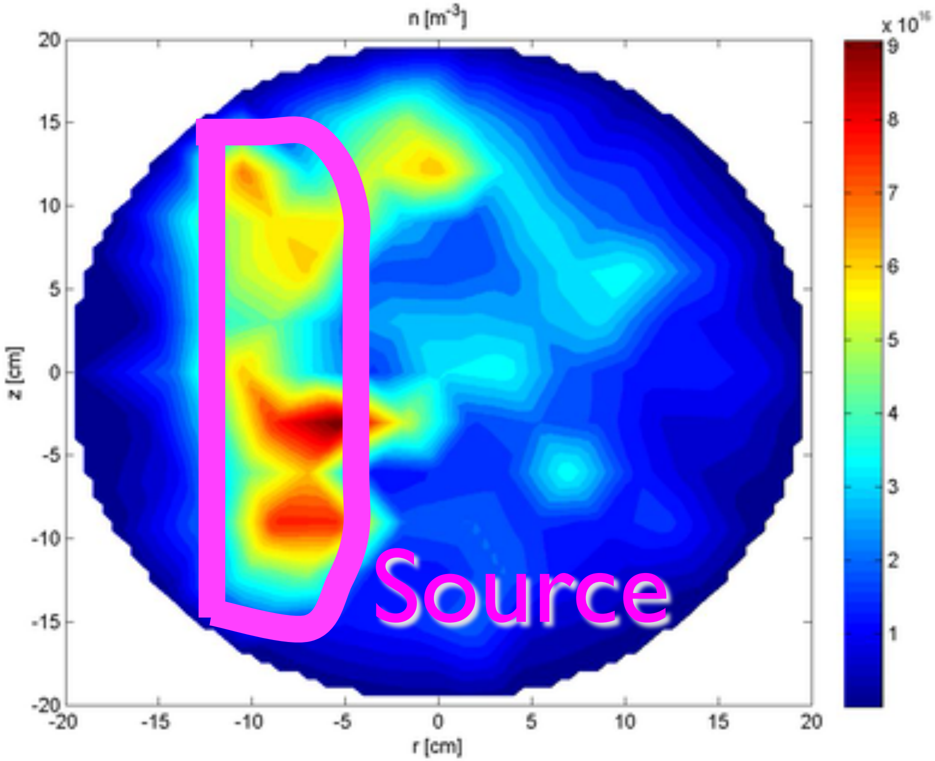


Fasoli *et al.*, PoP 2006, PPCF 2010

High resolution diagnostics with full coverage



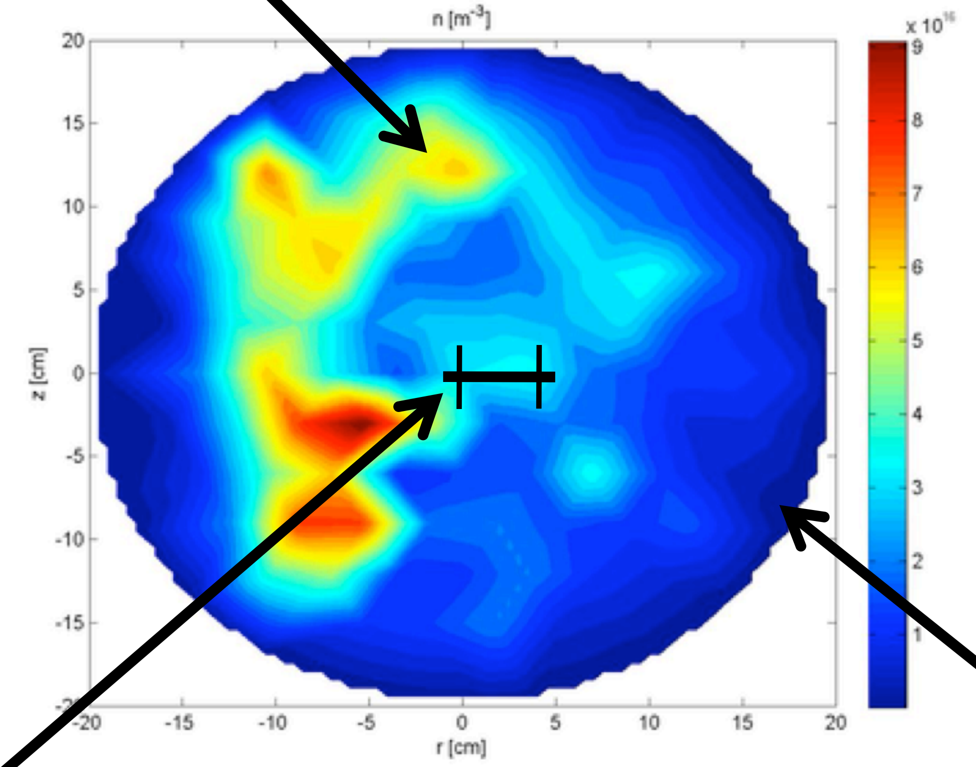




➡ Measurements of all relevant plasma and field parameters

Properties of TORPEX turbulence

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



$T_i << T_e$

$\beta << 1$

$\omega << \Omega_{ci}$

$L_{\parallel} >> L_{\perp}$

Collisional

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

$L >> \rho_i$

Fluid model

Collisional Plasma → **Braginskii model** → $\rho_i \ll L,\ \beta \ll 1,\ \omega \ll \Omega_{ci}$ → **Electrostatic Drift-reduced Bragiskii equations**

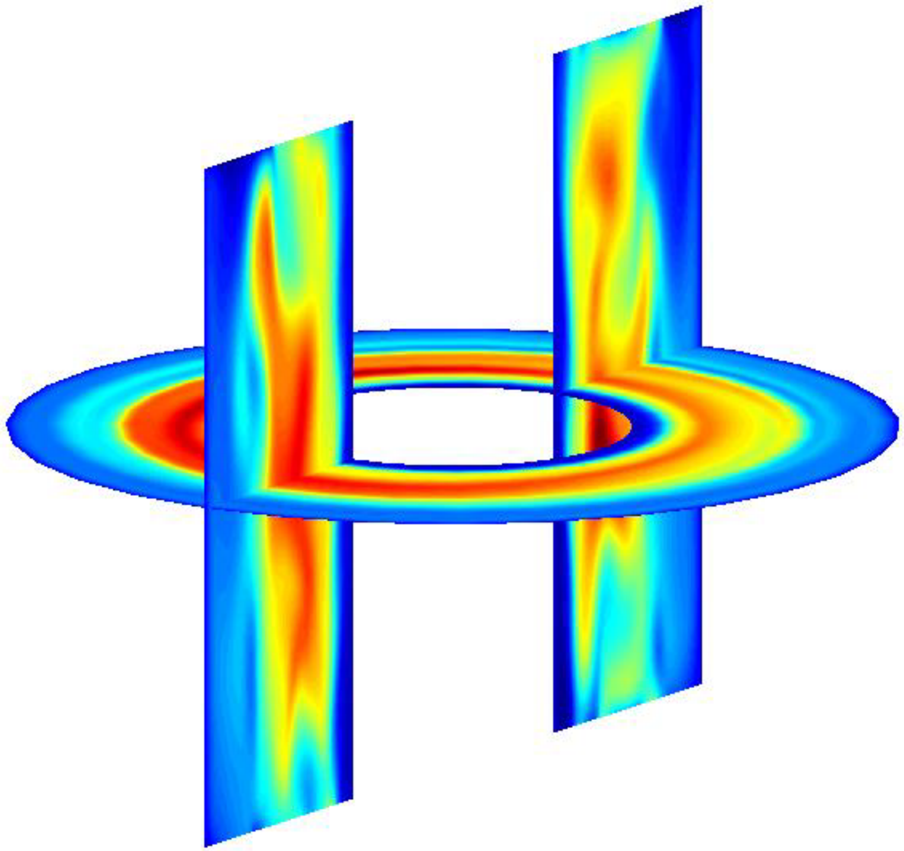
$$\overbrace{\frac{\partial n}{\partial t} + [\phi, n]}^{\text{Convection}} = \overbrace{D_n \nabla^2 n}^{\text{Diffusion}} + \overbrace{\frac{2}{R}\left(n \frac{\partial T_e}{\partial y} + T_e \frac{\partial n}{\partial y} - n \frac{\partial \phi}{\partial y} \right)}^{\text{Magnetic curvature}} - \overbrace{\nabla_{\parallel}(n V_{\parallel e})}^{\text{Parallel dynamics}} + \overbrace{S}^{\text{Source}}$$

T_e, Ω (vorticity) → similar equations

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

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

Global simulations



Evolve both equilibrium and fluctuations

Anatomy of TORPEX turbulence

- Turbulent regimes?
- Particle transport? Saturation mechanism?
  Macroscopic structure dynamics?
- Non-thermal particle dynamics?
- How experiments and simulations compare?

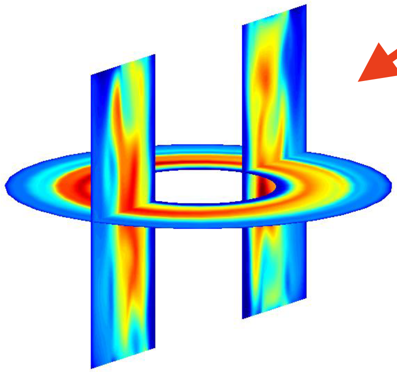
The turbulent regimes

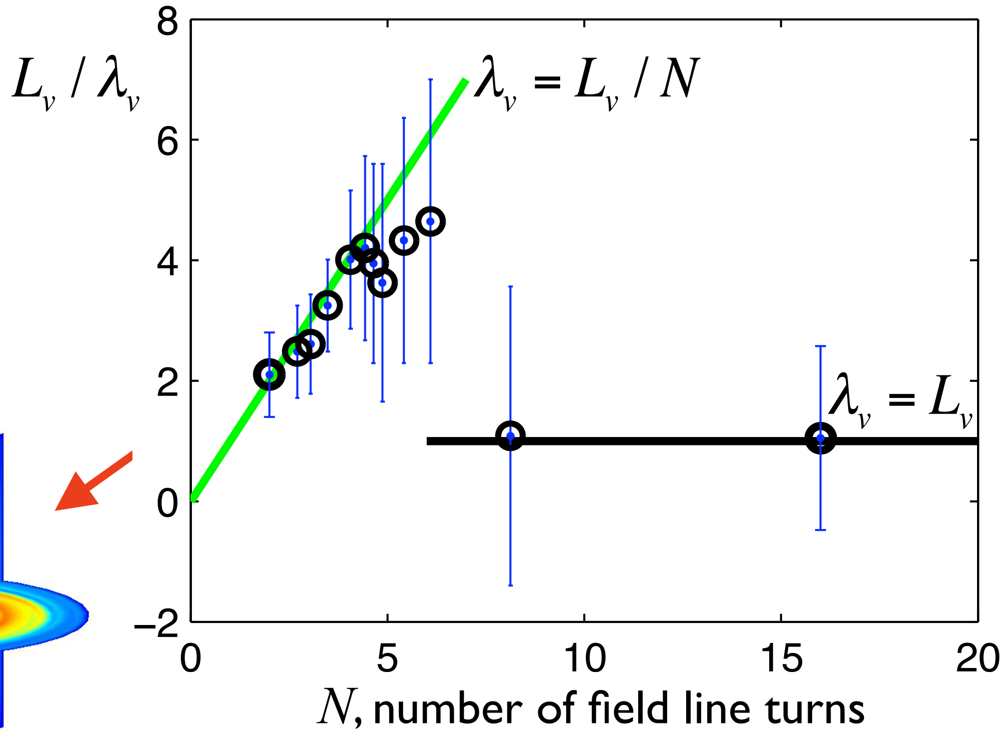
Plasma gradients
+
Magnetic curvature

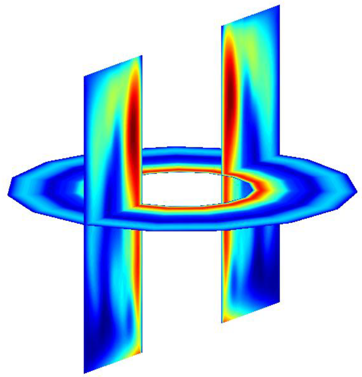
Ideal interchange $k_{\parallel} = 0,\ \lambda_v = L_v / N$

Resistive interchange $\nu \neq 0,\ k_{\parallel} \neq 0,\ \lambda_v = L_v$

Drift waves $k_{\parallel} \neq 0,\ \rho_s / \lambda_v = 0.1$

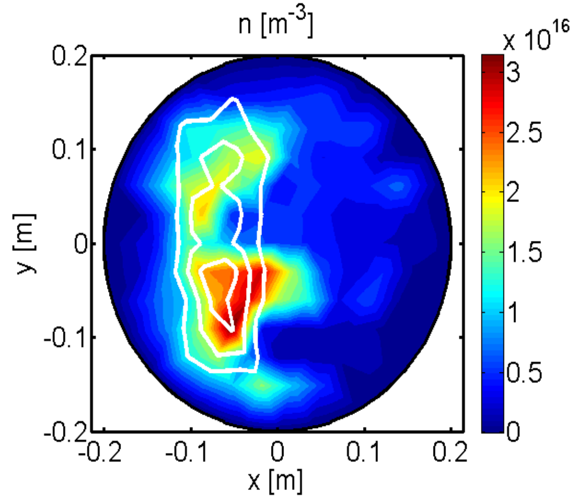






P. Ricci et al., PRL (2010)

Transport: saturation mechanism and macroscopic structures (blobs)

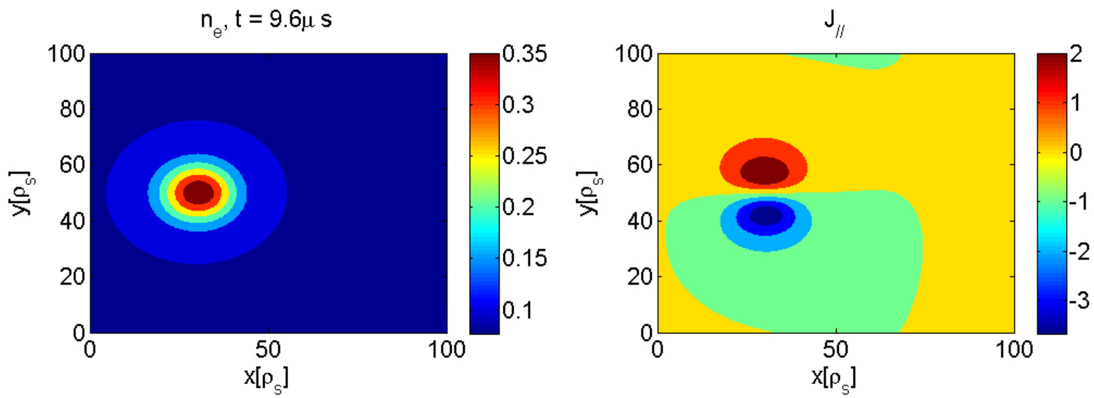


- Non-local linear modes grow and saturate when they remove the turbulence drive:

$$\Longrightarrow \Gamma = \Gamma(n_0, T_0, L_p, B_z)$$

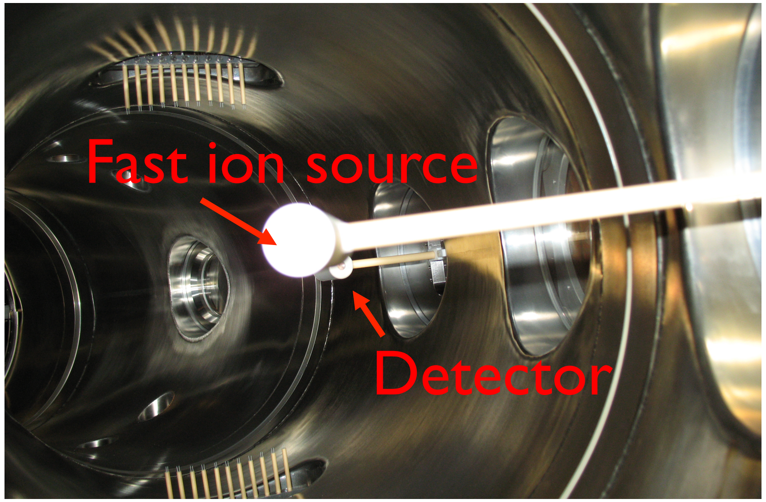
P. Ricci et al., PRL (2008)

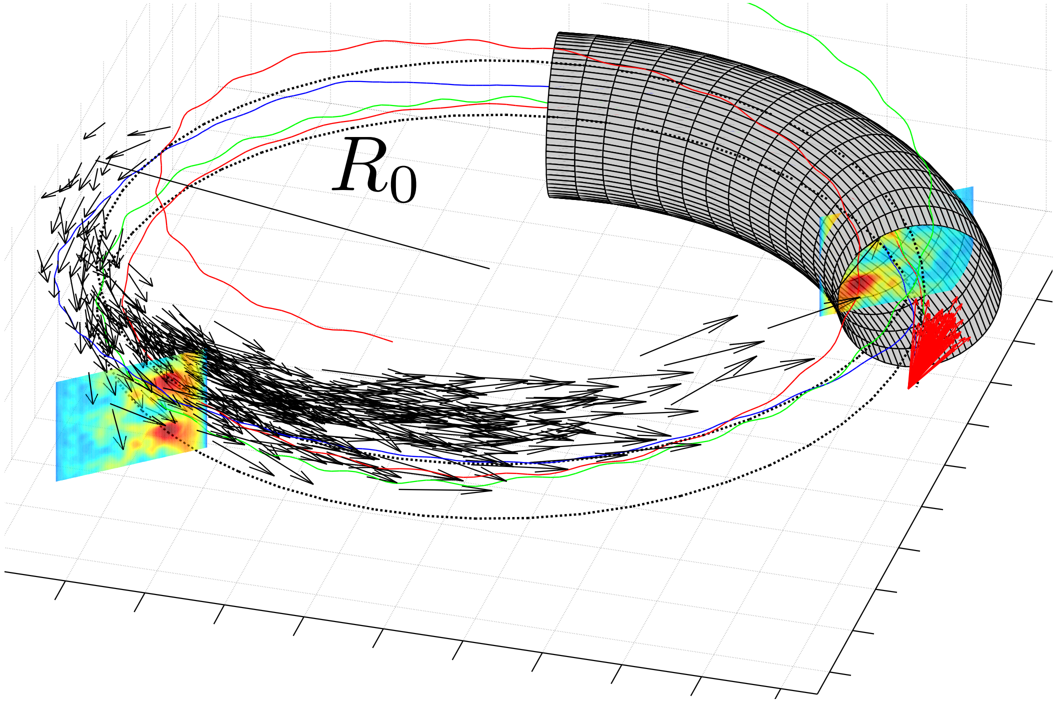
- Blob dynamics has been analyzed separately in the details:



I. Furno et al., PPPCF (2011)

Suprathermal particle dynamics





Suprathermal particle dynamics displays subdiffusive, diffusive, and superdiffusive dispersion

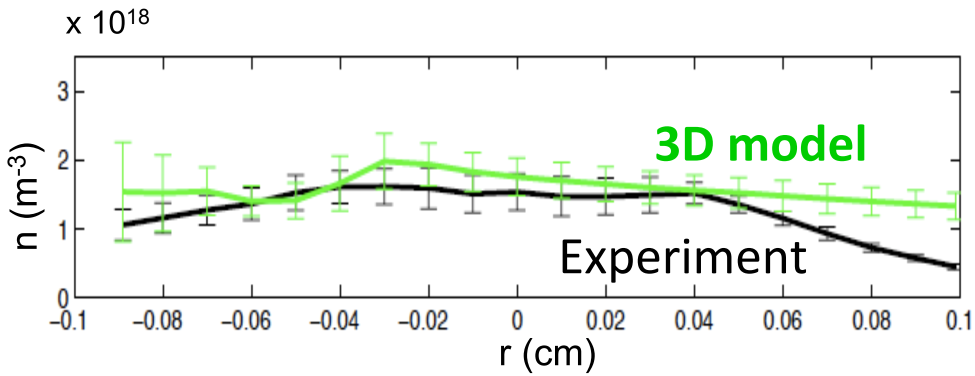
Gustafson et al., PRL 2012

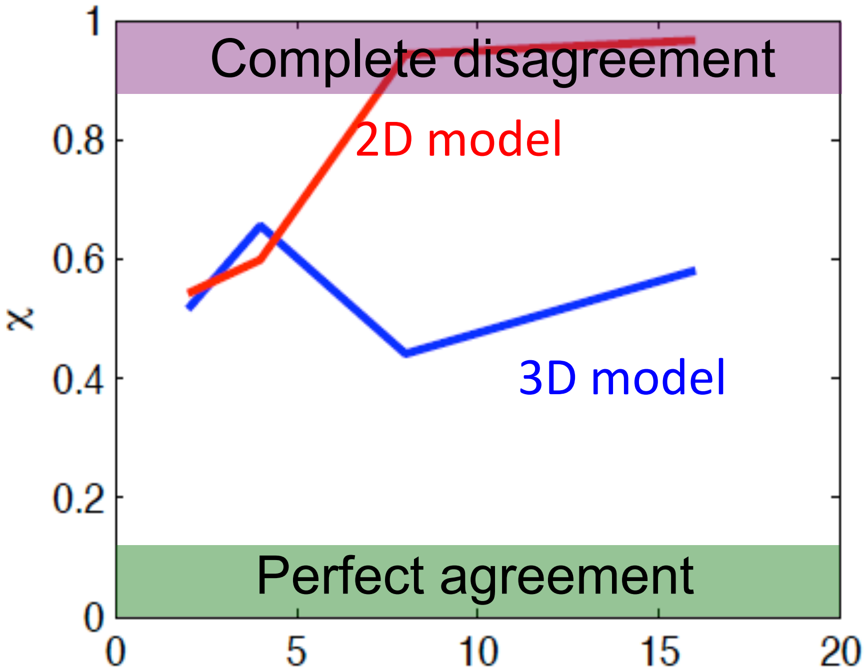
Quantitative experiment/simulation comparison

- 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 has to be defined.

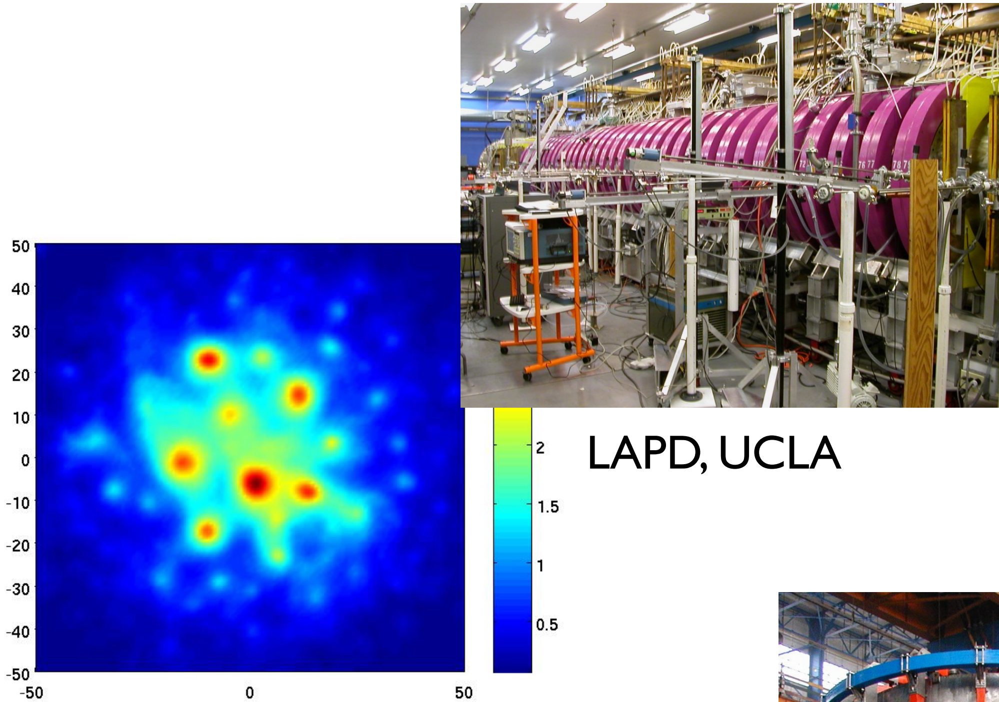




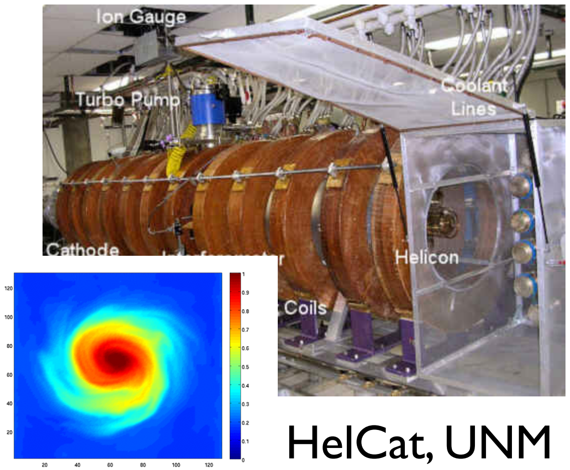
Ricci *et al.*, PoP 2009, PoP 2011

Analysis of other configurations

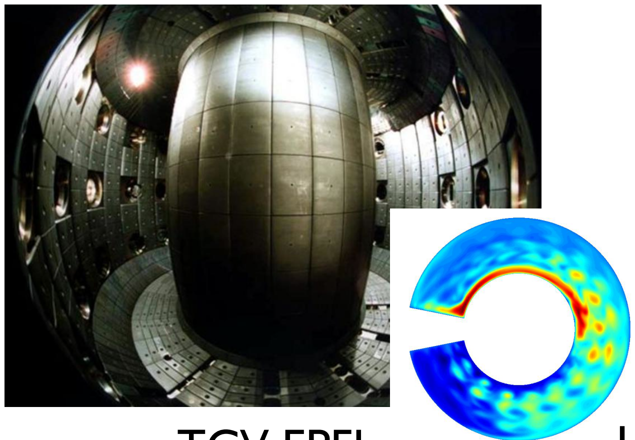
Similar simulation approach used in a number of other devices



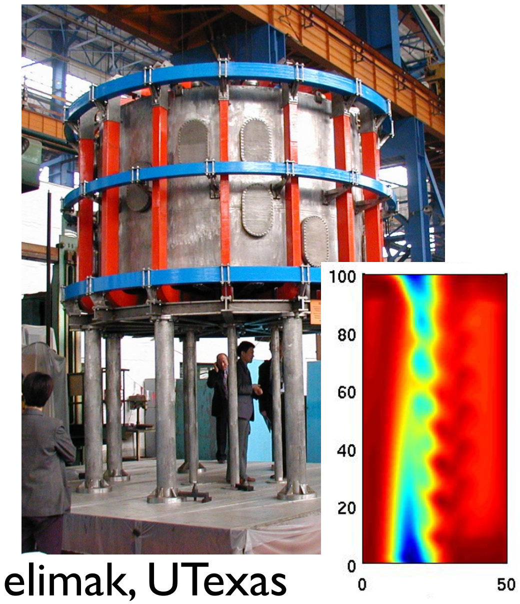
LAPD, UCLA



HelCat, UNM



TCV, EPFL



Helimak, UTexas

Concluding remarks

What are we learning from TORPEX modeling?

- By using global simulations and evolving both plasma equilibrium and fluctuations, it is possible to interpret the experimental results.
- The turbulence is subject to a number of driving mechanisms, as a competition between ideal interchange, drift waves, and resistive interchange.
- The properties of plasma turbulence reflect the different linear drives and saturates by removing its drive
- Even in a simple configuration, suprathermal particle dynamics surprisingly shows sub-, super-, and diffusive behavior
- Similar analysis can be carried out in other basic plasma devices.
- TORPEX is providing an ideal test-bed for a close comparison between experiments and simulations.