Turbulent transport of fast ions in the simple magnetized torus

Kyle Gustafson

Alexandre Bovet

Ambrogio Fasoli

Ivo Furno

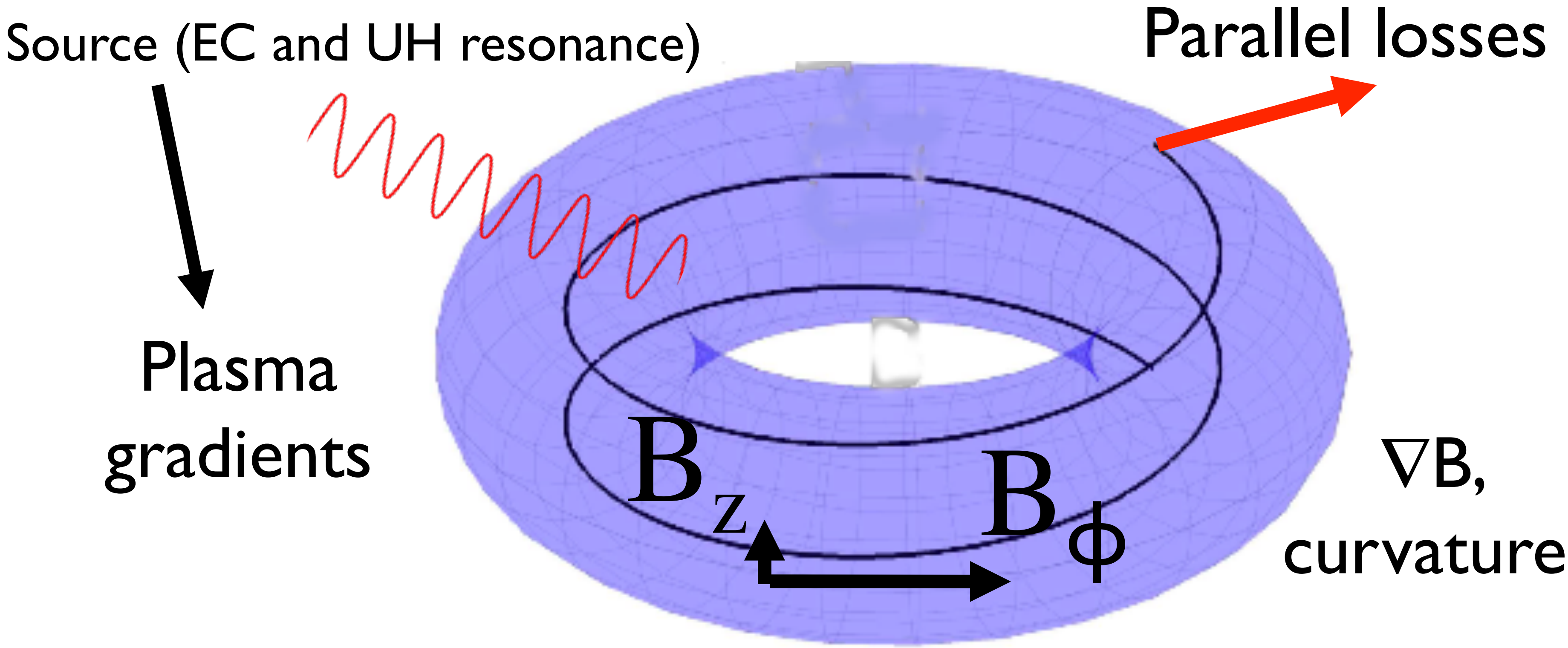
Paolo Ricci

Centre de Recherches en Physique des Plasmas (CRPP)

École Polytechnique Fédérale de Lausanne

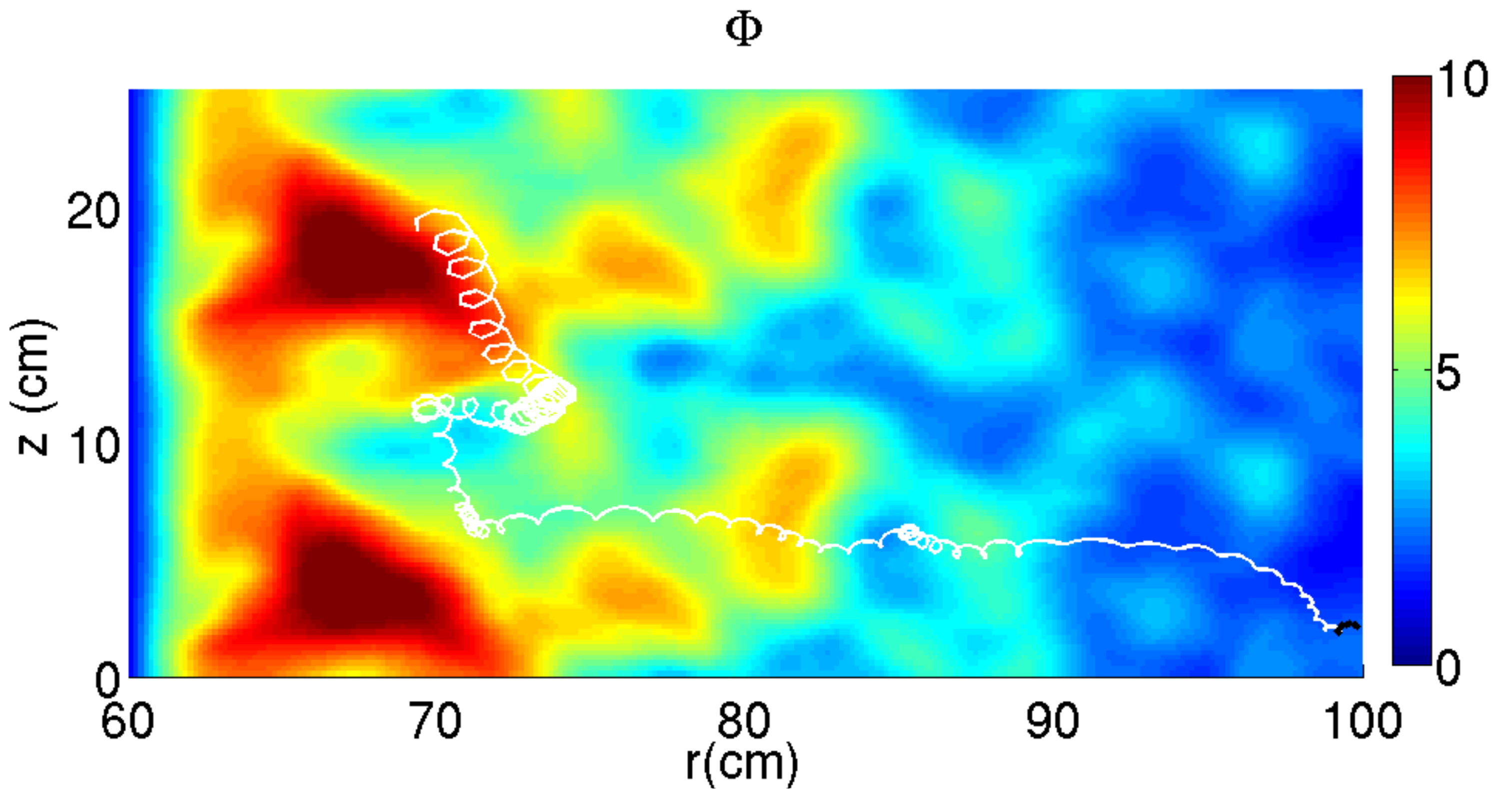
Switzerland

Simple magnetized torus (SMT)



- Our inspiration is the TORPEX SMT at CRPP TORPEX turbulence in drift-wave, ideal-interchange and resistive-interchange modes

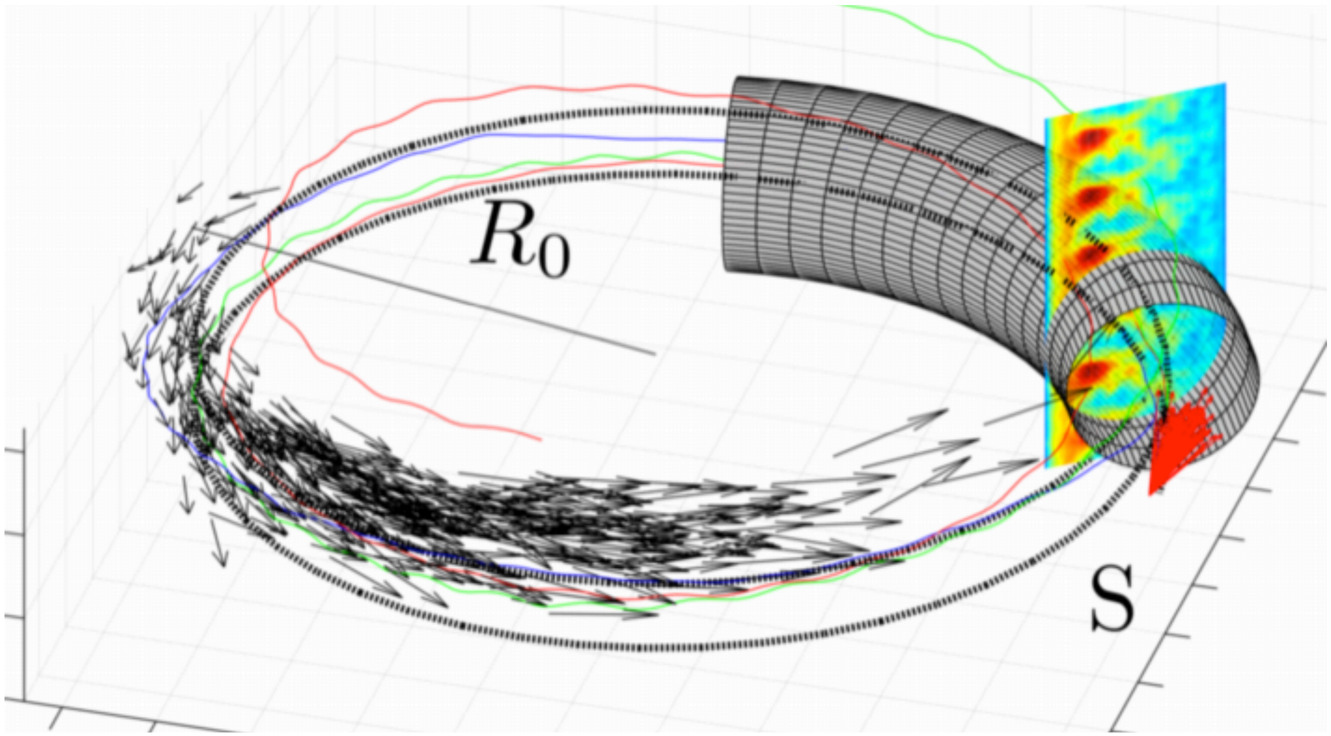
Ideal interchange mode in SMT: $k_{\parallel} \equiv 0$



- Mode (coherent) and blob (intermittent) regions
- Injection of fast ions in center of the box
- Using full Lorentz force: no drift approximation
  - Amplitude of fluctuations $\xi : \Phi = \Phi_0 + \xi\tilde{\Phi}$

Fast ions in SMT turbulence

TORPEX is equipped with a Li^{+6} source at $\mathcal{E}$ = 100 – 1000 eV



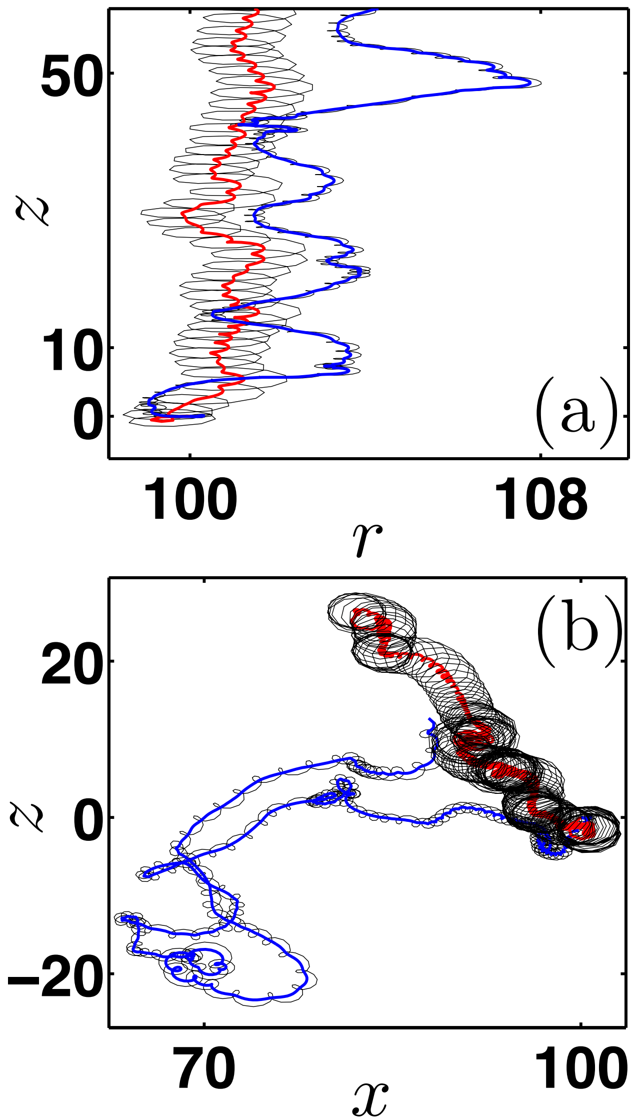
Our goal is to establish a comprehensive theoretical framework for understanding dispersion of the fast ions in SMT ideal-interchange mode turbulence, including TORPEX.

SMT (a) versus slab (b) fast ions

Colored curve is gyrocenter position

Black is ion position

$\mathcal{E}_2 > \mathcal{E}_1$



Drift approximation

- Curvature and ∇B drift

$$\mathbf{v}_{SMT} = \frac{1}{r}\left(\frac{v_\perp^2}{2} + v_\parallel^2\right)\frac{\hat{z}}{\Omega_L}$$

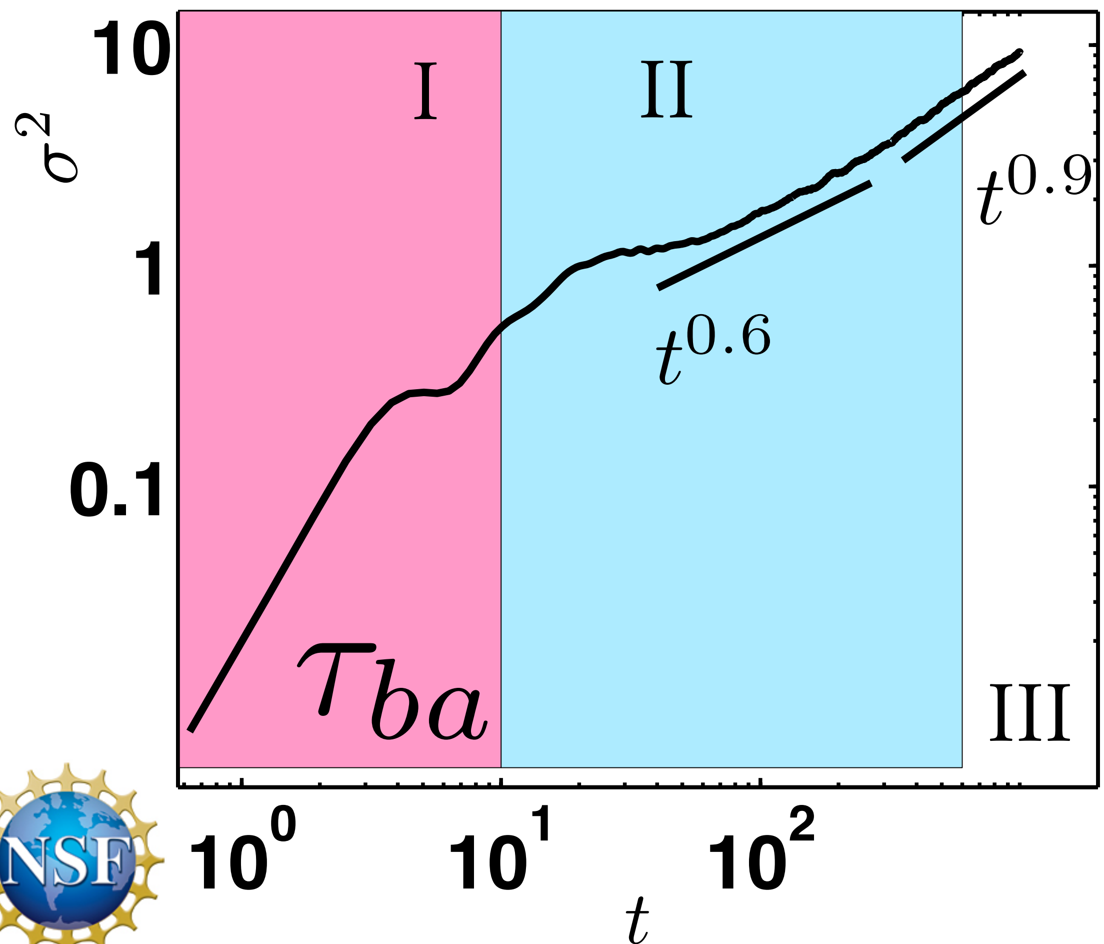
- Larmor motion defining a gyrocenter

$$\mathbf{v}_{E\times B} = \frac{\mathbf{E}\times\mathbf{B}}{B^2} = \frac{E_r}{B}\hat{z} - \frac{E_z}{B}\hat{r}$$

$$\langle \mathbf{v}_{E\times B}\rangle_R = \frac{1}{2\pi}\oint \mathbf{v}_{E\times B}(R-\rho)d\theta$$

Phases of dispersion for SMT

$$\sigma^2 \equiv \left\langle (\delta x - \langle \delta x \rangle)^2 \right\rangle \propto t^\gamma \qquad \delta x \equiv x - x_0$$



I. Short ballistic phase

$$\gamma \sim 2$$

II. Intermediate phase:

$\gamma > 1$ if $\mathcal{E} < 50$

$\gamma < 1$ if $\mathcal{E} > 50$

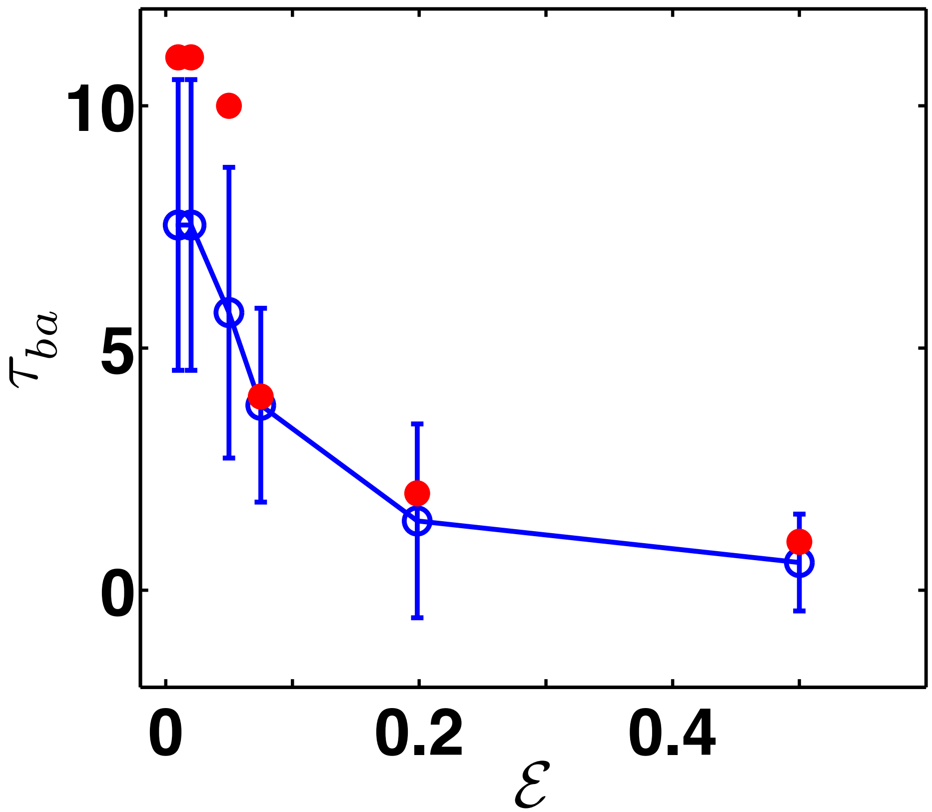
III. Slow transition to asymptotic phase:

$$\gamma \sim 1$$

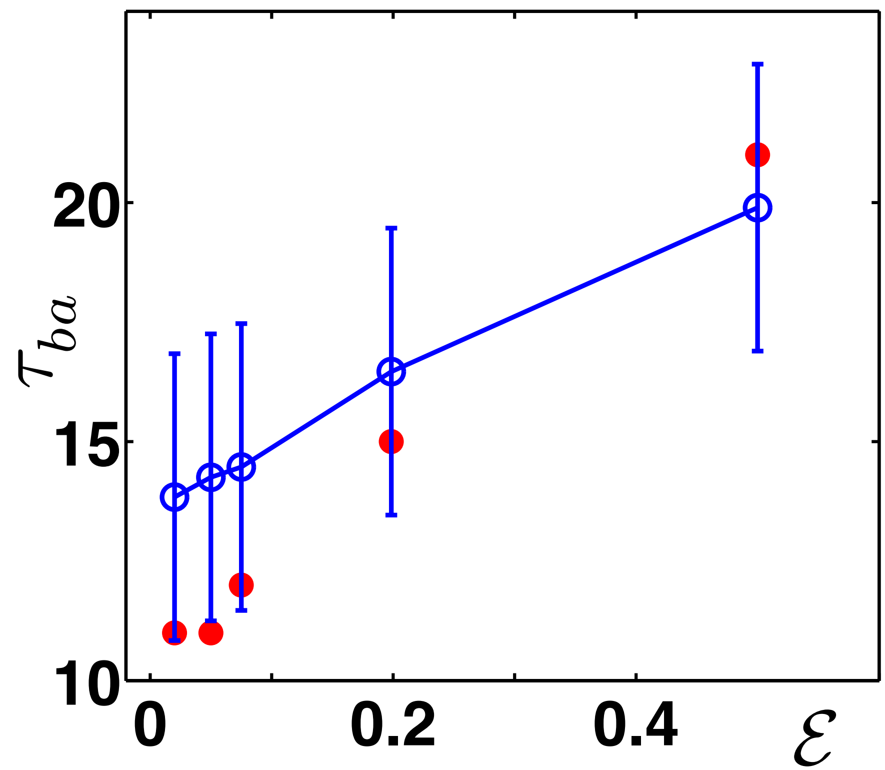
Ballistic phase for gyrocenters

$$\frac{|\mathbf{v}_{0,\perp}|}{|\Delta \mathbf{v}_\perp|} \sim 1 \qquad \Delta \mathbf{v}_\perp \equiv \mathbf{v}_\perp(\tau_{ba}) - \mathbf{v}_{0,\perp}$$

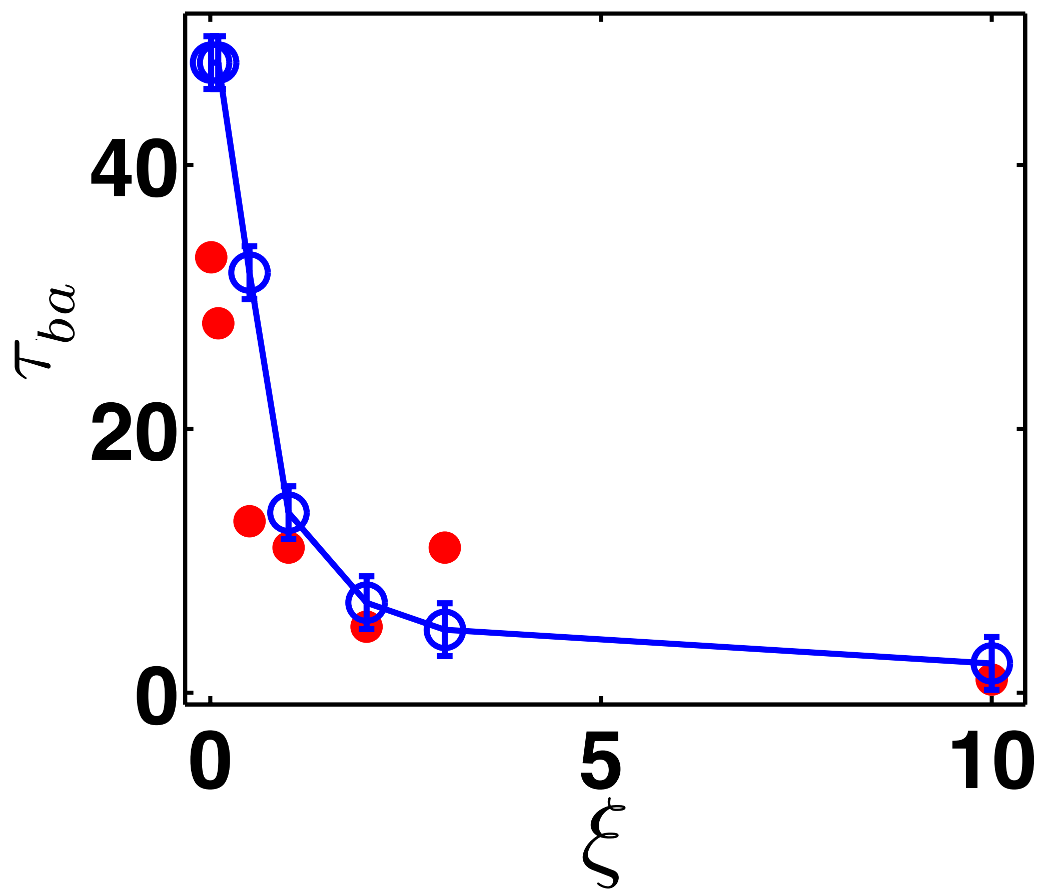
$$\tau_{ba} \sim \frac{\lambda_c}{2\pi v_{SMT}}$$



$$\tau_{ba} \sim \frac{\lambda_c}{2\pi \langle v_{E\times B}\rangle_R}$$

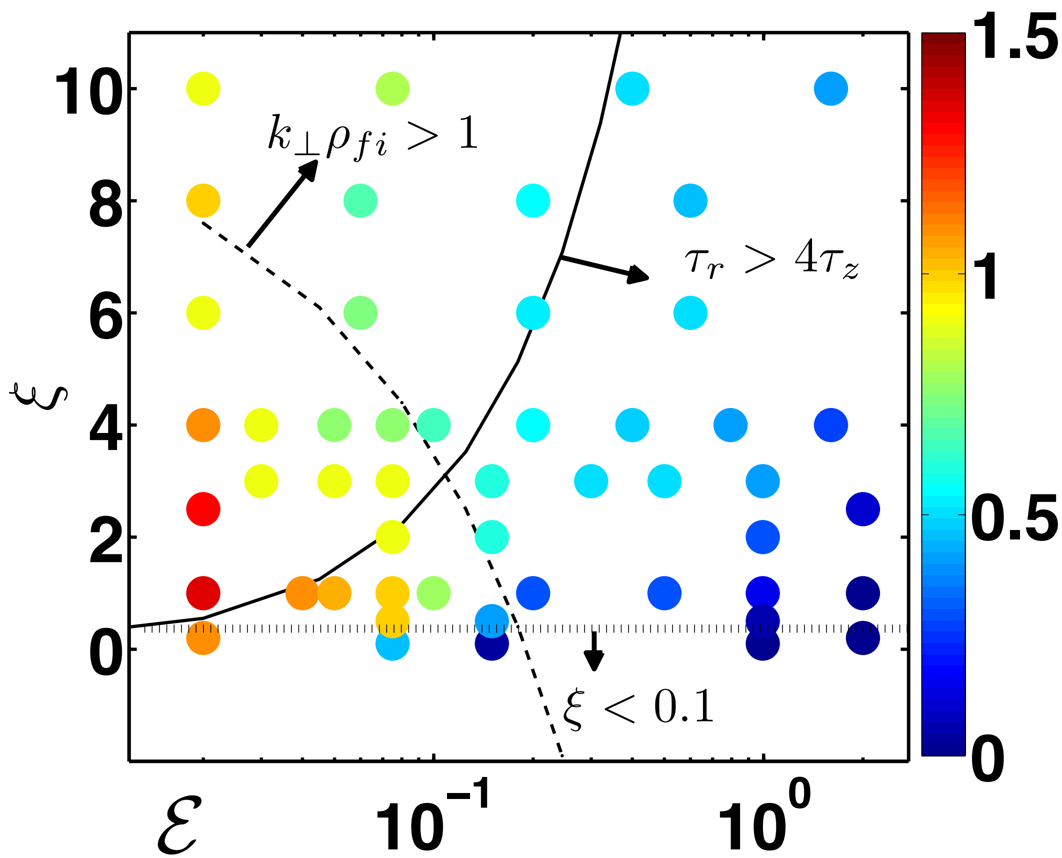


Ballistic phase for gyrocenters



As the turbulence amplitude, ξ, is increased *post hoc*, the estimate for τ_{ba} is bounded from above at small ξ by the Eulerian correlation time: $\tau_{ba} \sim \tau_c$

γ scan in ξ and $\mathcal{E}$ for SMT



Colors: value of γ for scan in injection energy $\mathcal{E}$ and turbulent amplitude ξ.

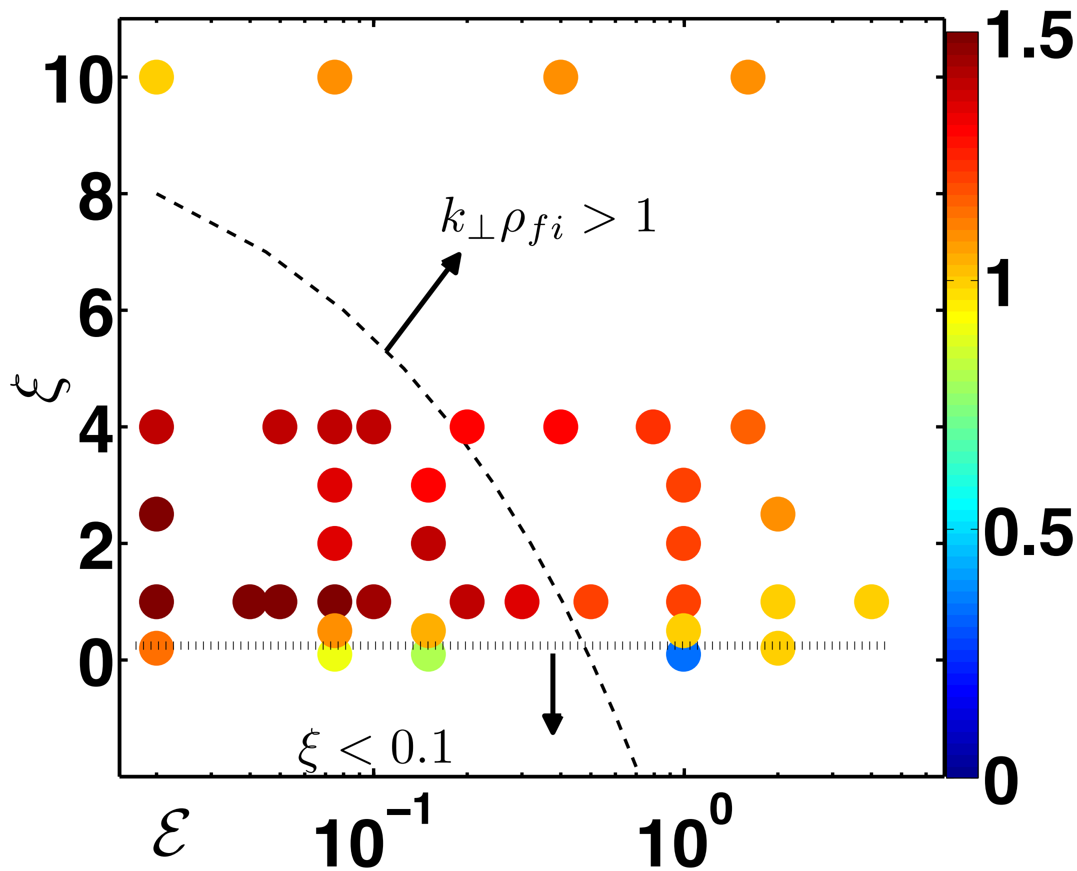
Superdiffusion at low $\mathcal{E}$ due to large step sizes in the coherent mode region

Subdiffusion at large injection energy in SMT due to curvature drift, which causes radial trapping at the $t_r > 4t_z$ boundary

Larmor averaging causes diffusion for large ξ

Small ξ results in slow radial transport due to disconnected topology

γ scan in ξ and $\mathcal{E}$ for slab



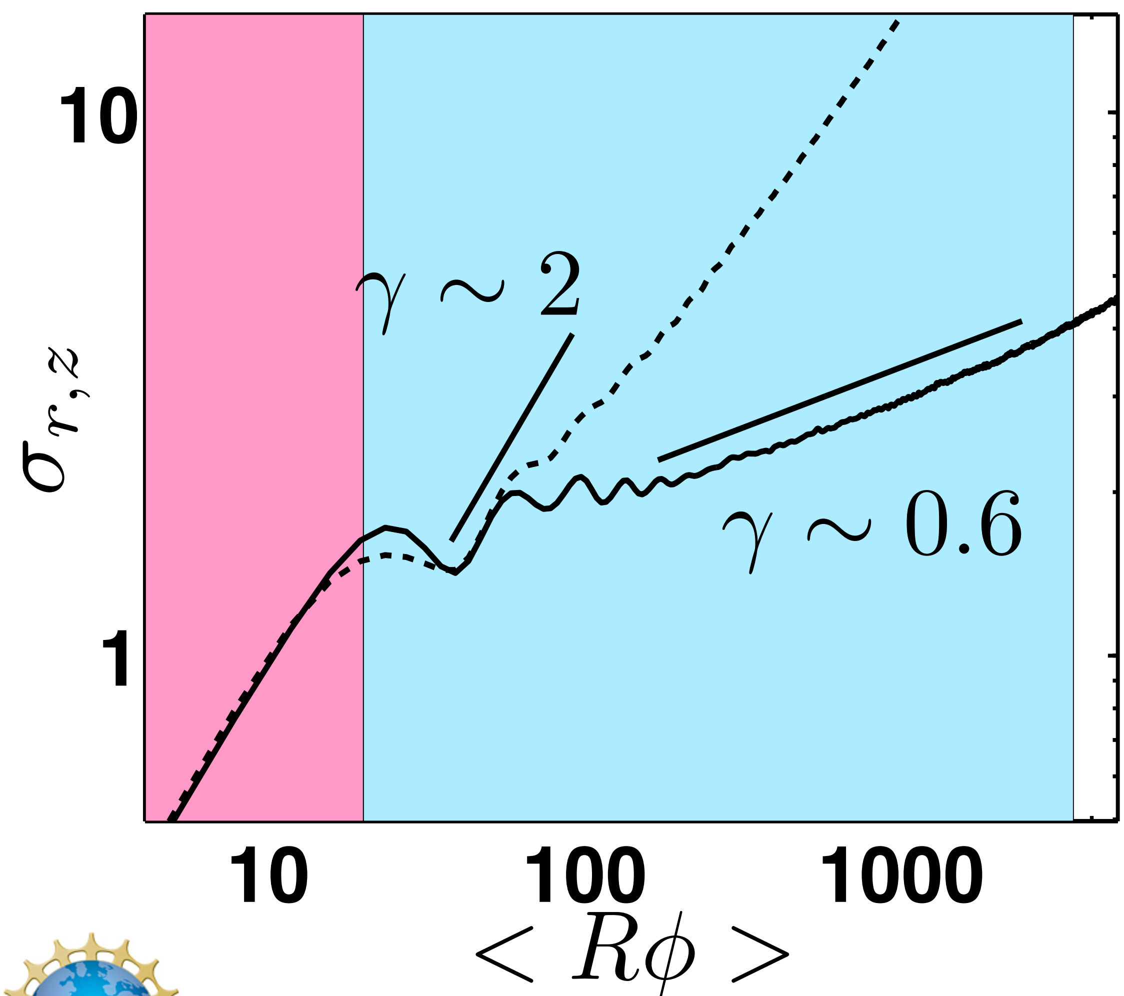
Colors: value of γ for scan in injection energy $\mathcal{E}$ and turbulent amplitude ξ.

Superdiffusion for low $\mathcal{E}$

Increased Larmor averaging causes diffusion, but never subdiffusion

Small ξ results show slow radial transport due to disconnected topology

Prediction for TORPEX



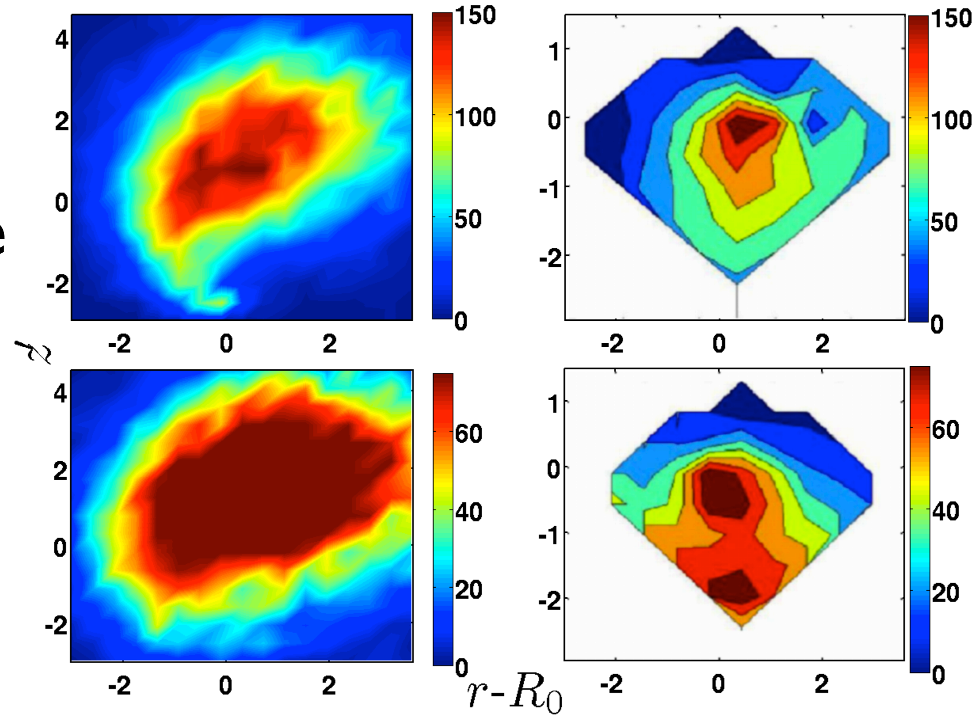
- Measurement limited by:
  - toroidal resolution of detector
  - boundaries of TORPEX
- Requires an injection energy large enough for a significant curvature drift, but not so large that the population is lost to the boundaries.

First measurements: single time point

Radial spreading due to plasma is consistent with simulations.

Measurement of γ in ballistic and subdiffusive phases will be accessible with new toroidal sliding rail.

Theory Experiment



B field, no plasma

B field + plasma

Conclusions

- We have established a framework for interpreting fast ion data in simple magnetized torii and related experiments.
- We showed the interplay of some fundamental influences on transport:
  - Turbulent ExB drifts with gyroaveraging
  - Curvature and ∇B drifts perpendicular to pressure gradient
- Experimental comparisons are encouraging and will advance soon.