Dispersion of fast ions in models of anisotropic plasma turbulence

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(results contained here were obtained at U Maryland)

with Professor William Dorland, U Maryland
and Ingmar Brömstrup

Generalized dispersion of particles

i.e. Metzler/Klafter Phys Rep 339 (2000) 1-77; Balescu book and articles

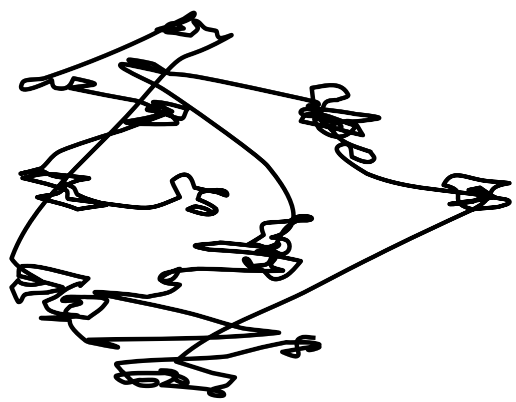
$$\delta x = x(t) - x(0)$$

$$\sigma^2 = \overline{(\delta x - \overline{\delta x})^2}$$

$$\sigma^2(t) \sim t^\gamma$$

- $\gamma < 1$ subdiffusive
- $\gamma = 1$ diffusive
- $\gamma > 1$ superdiffusive
- $\gamma = 2$ ballistic

Brownian walk $\subset$ continuous time random walks

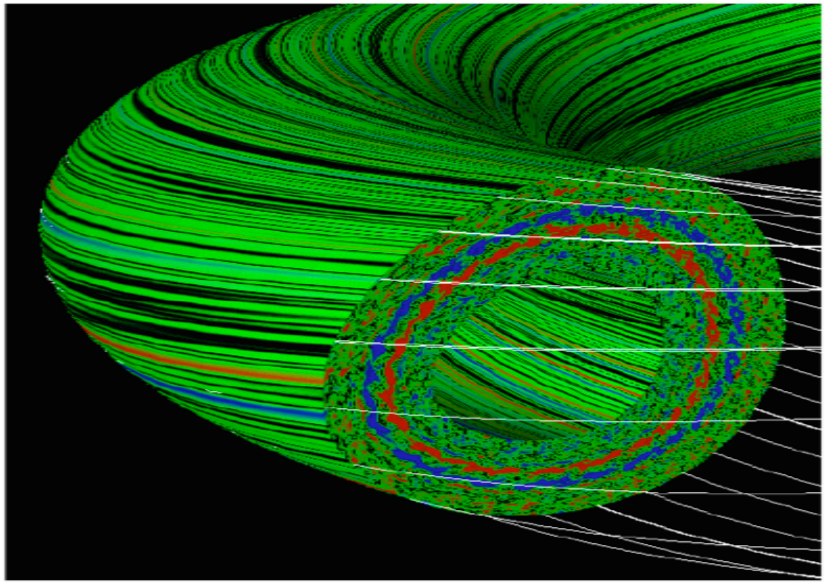
$\gamma = 1$  $\gamma > 1$  $\gamma < 1$ 

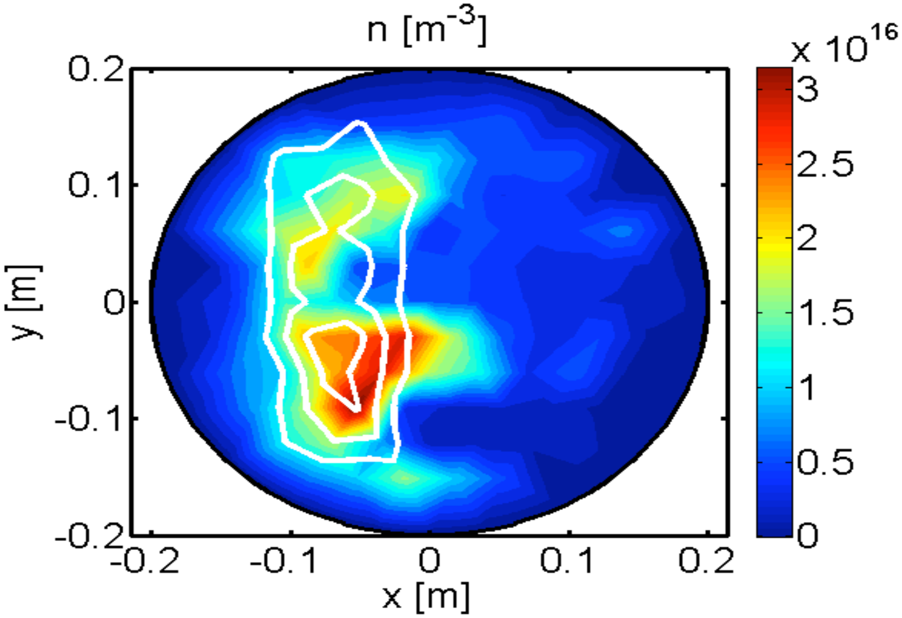
Δt_1 = Δt_2 = Δt_3

Random walks in turbulence

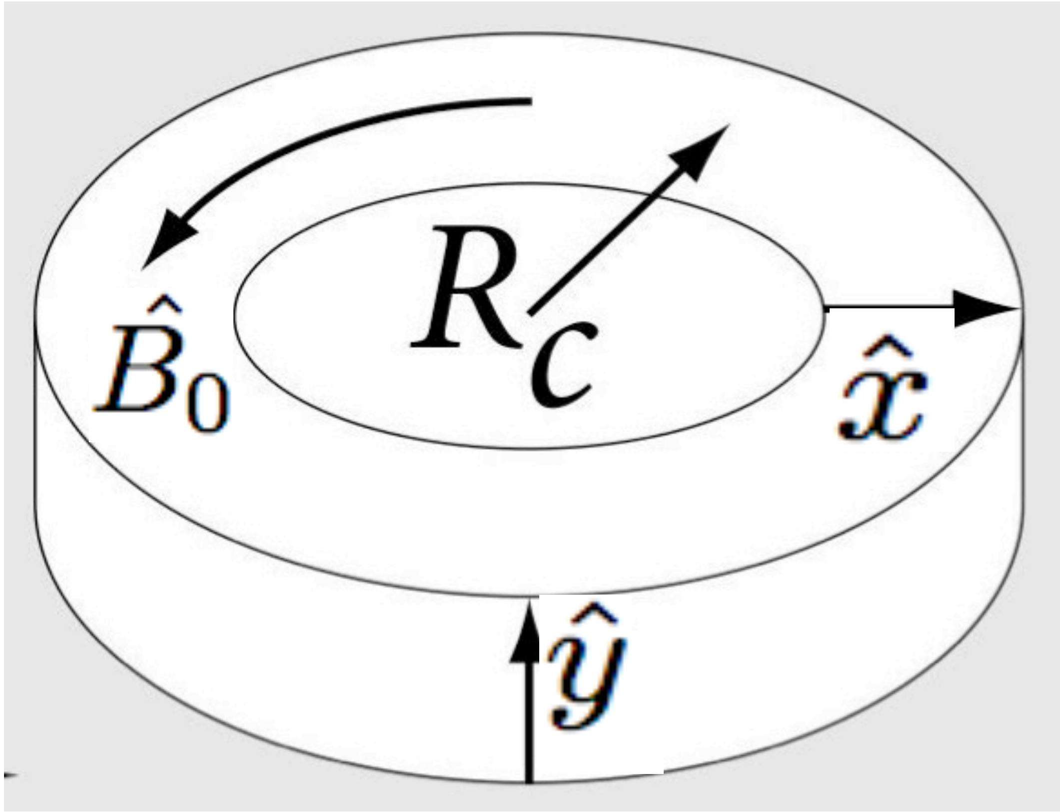
1) Microscale core turbulence with zonal flows (thesis work, in preparation for publication)

2) Macroscale edge turbulence with blobs (new project)





Z pinch geometry



- Magnetic field only toroidal, B ~ 1/r to edge.
- Gyroaveraged ExB drift produces radial (x) and axial (y) turbulent dispersion.
- Axial B drift $\mathbf{v}_B$ is constant for each particle.

$$\Omega_s = \frac{q_s B}{m_s c} \qquad \mathbf{v}_B = \frac{v_\parallel^2 + \frac{1}{2} v_\perp^2}{\Omega_s R_c} \hat{y}$$

Pressure-gradient-driven instability in a gyrokinetic Z-pinch

Brömstrup PhD, U Maryland 2008; Ricci *et al* PRL 97 245001 (2006)

Our new gyrokinetic, local ($1/L_n = -\nabla n/n$), δf, particle-in-cell code (GSP), provides markers as Lagrangian tracer probes.

We extract a subset of these tracers and compare the absolute dispersion in the nonlinear phase of the turbulence.

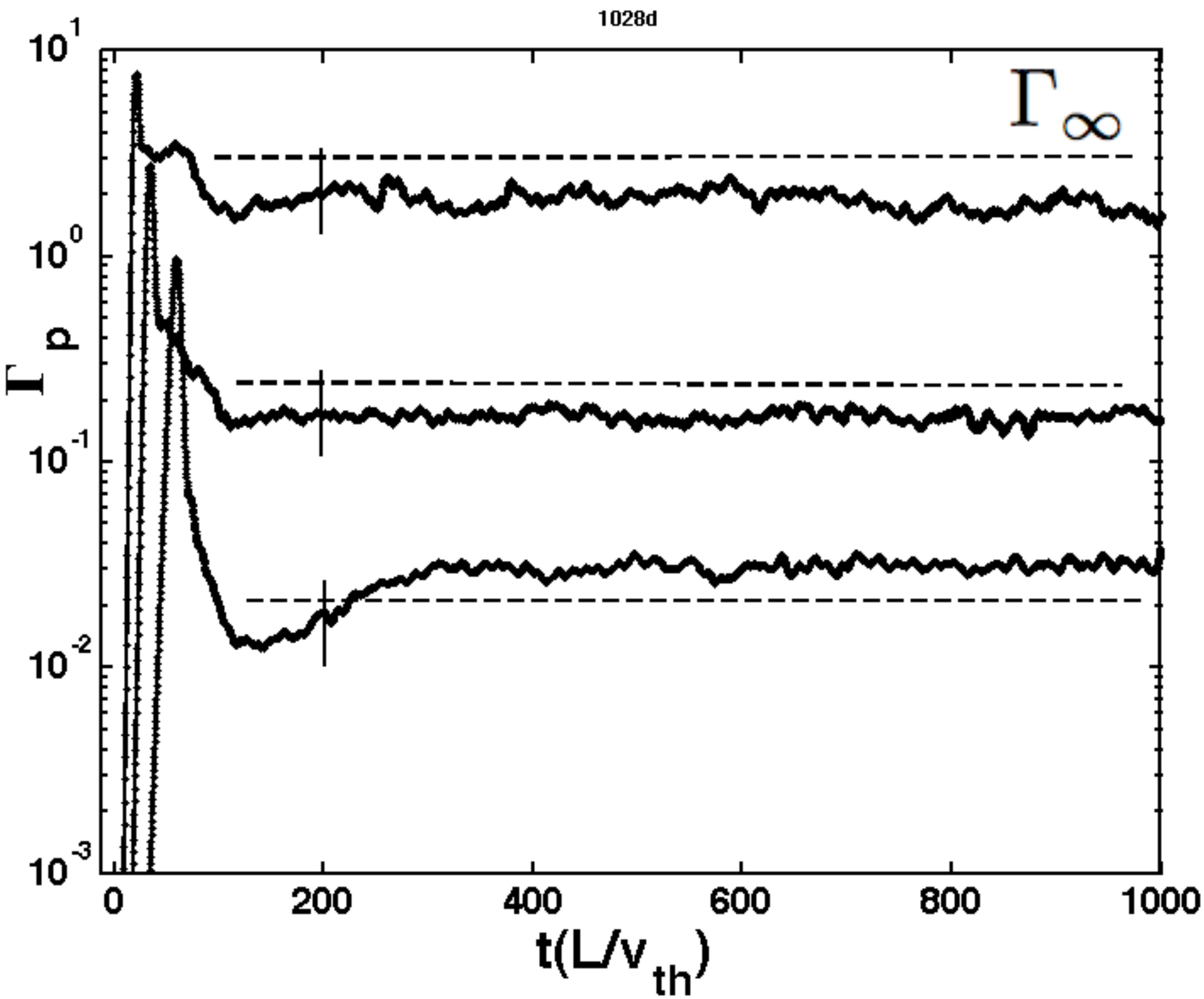
Turbulence driven by density gradient ($1/L_T = 0$) and curvature, unstable for $2/7 < L_n/R < \pi/2$

Results from nonlinear gyrokinetic simulations

- Benchmarked fluxes with GS2
- Axially: superdiffusive to ballistic
- Radially: diffusive for several density gradients
- Comparing diffusion coefficients from test-particles and flux/gradient relation
- Dependence of test-particle diffusion coefficient on gyroradius

Particle flux compared with GS2

Ricci *et al* PRL 97 245001 (2006) for GS2 data



$$\Gamma_p = \sum_i^{N_{part}} \delta f_1 \langle v_x \rangle_R$$

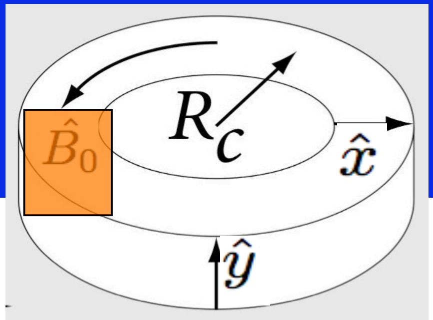
Top to bottom: strong to weak gradient;

Dashed lines:
published GS2 values

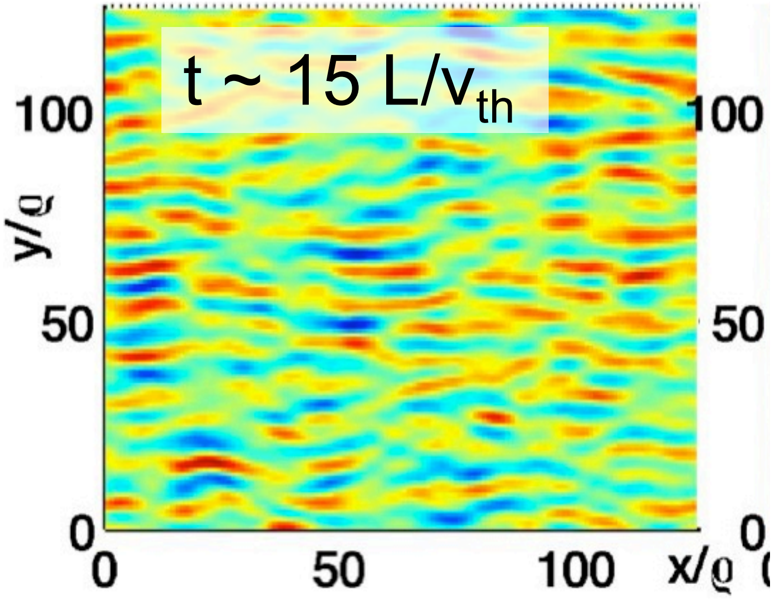
Units for Γ_p :

$(\rho_i/R)^2 n_0 v_{th_i}$

Gyrokinetic turbulence

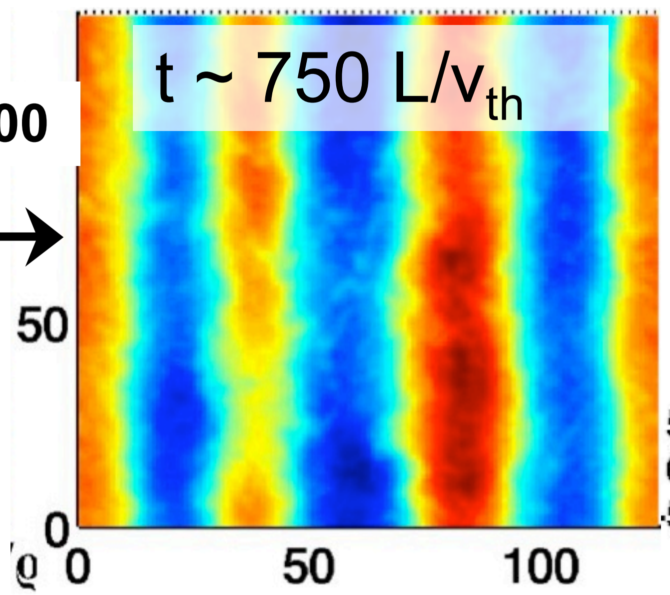


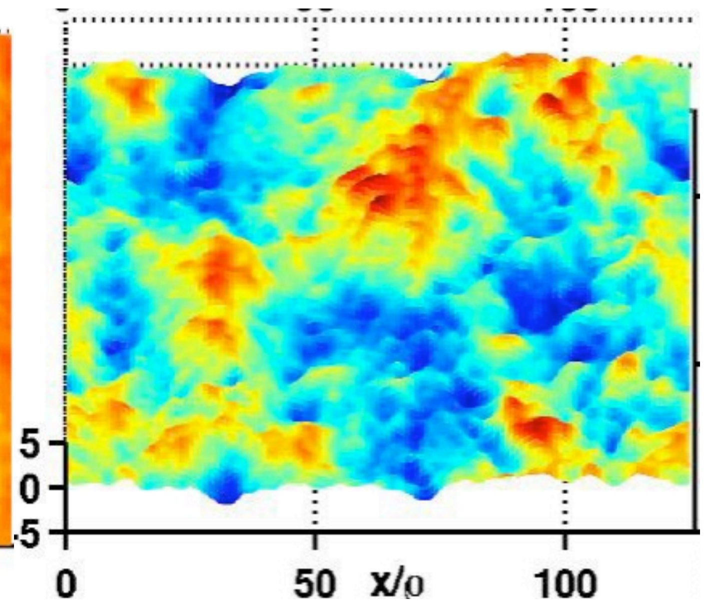
Linear phase - growing k_y modes



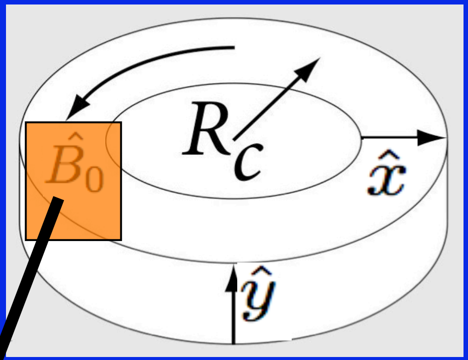
Surface plots of electrostatic potential, $\Phi(x,y)$

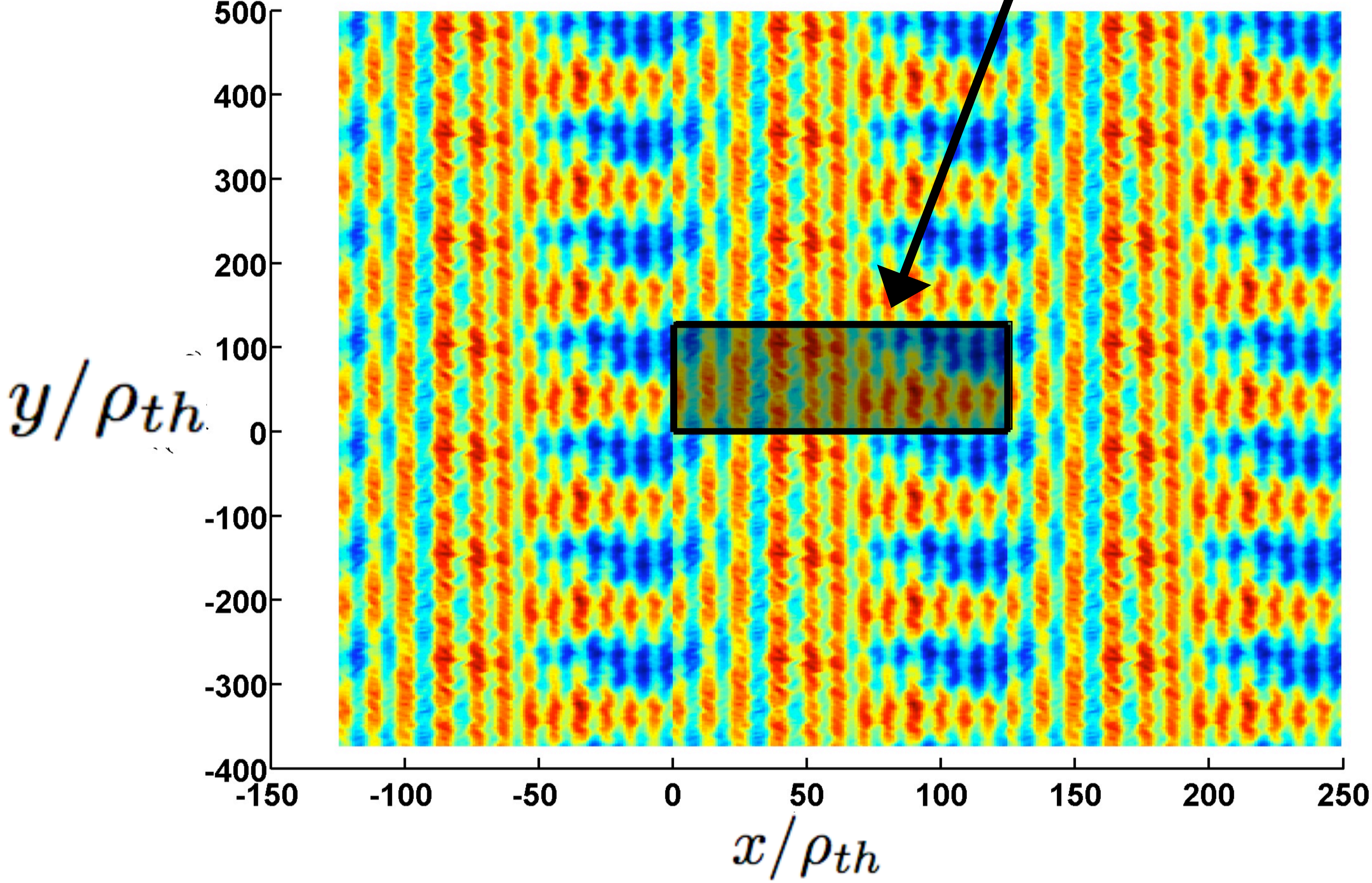
Nonlinear phase - steady zonal flow with background turbulence





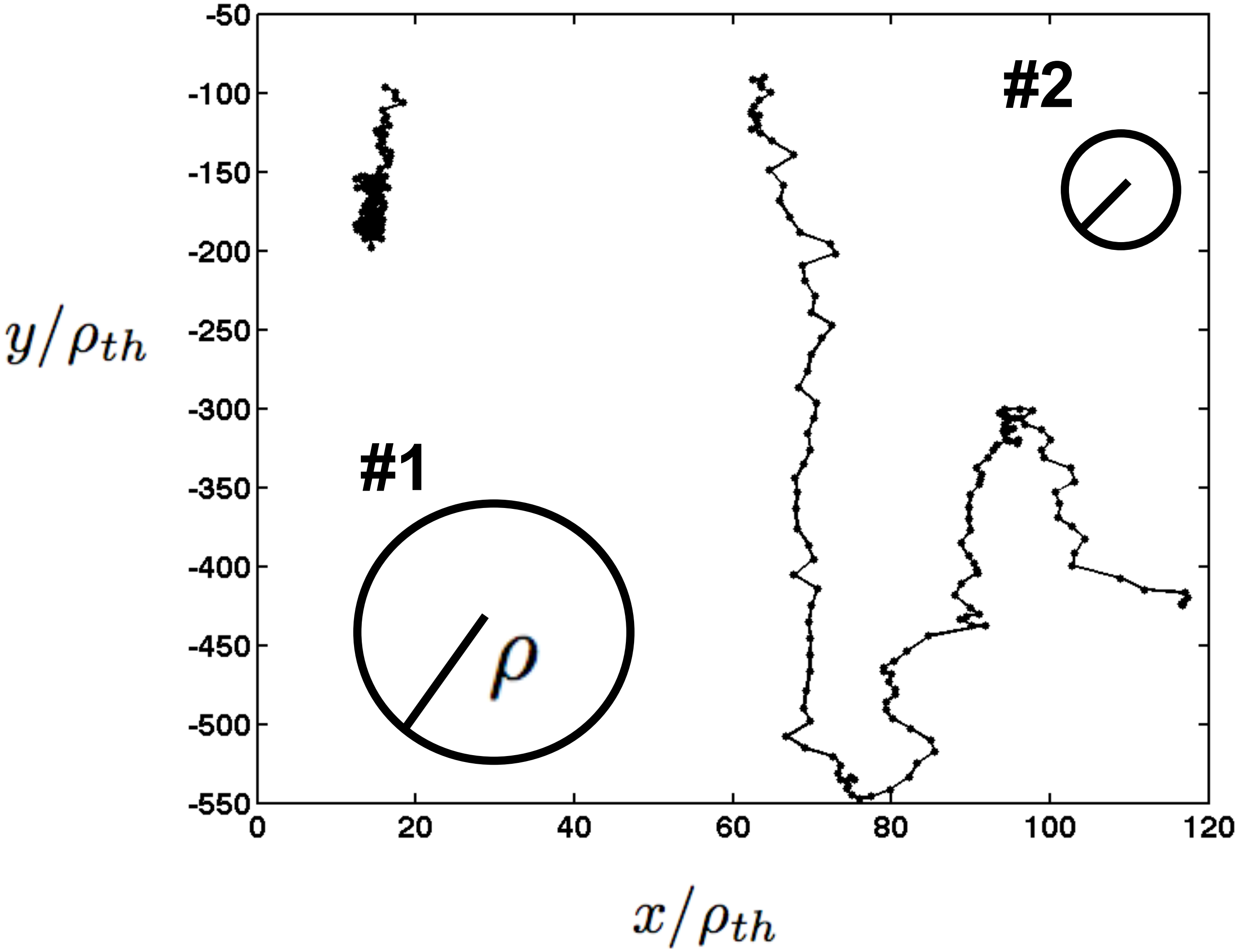
Periodic copies for tracers to follow





Sample gyrocenter trajectories

Marker particles distributed on $v_\perp$ grid

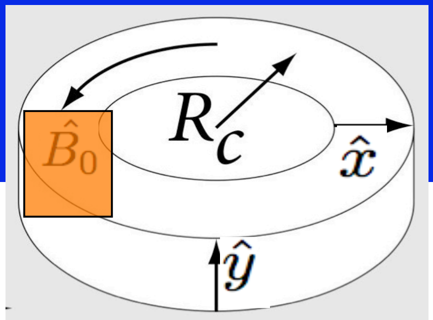


$\Delta x_1 \sim 5\ \rho_{th}$

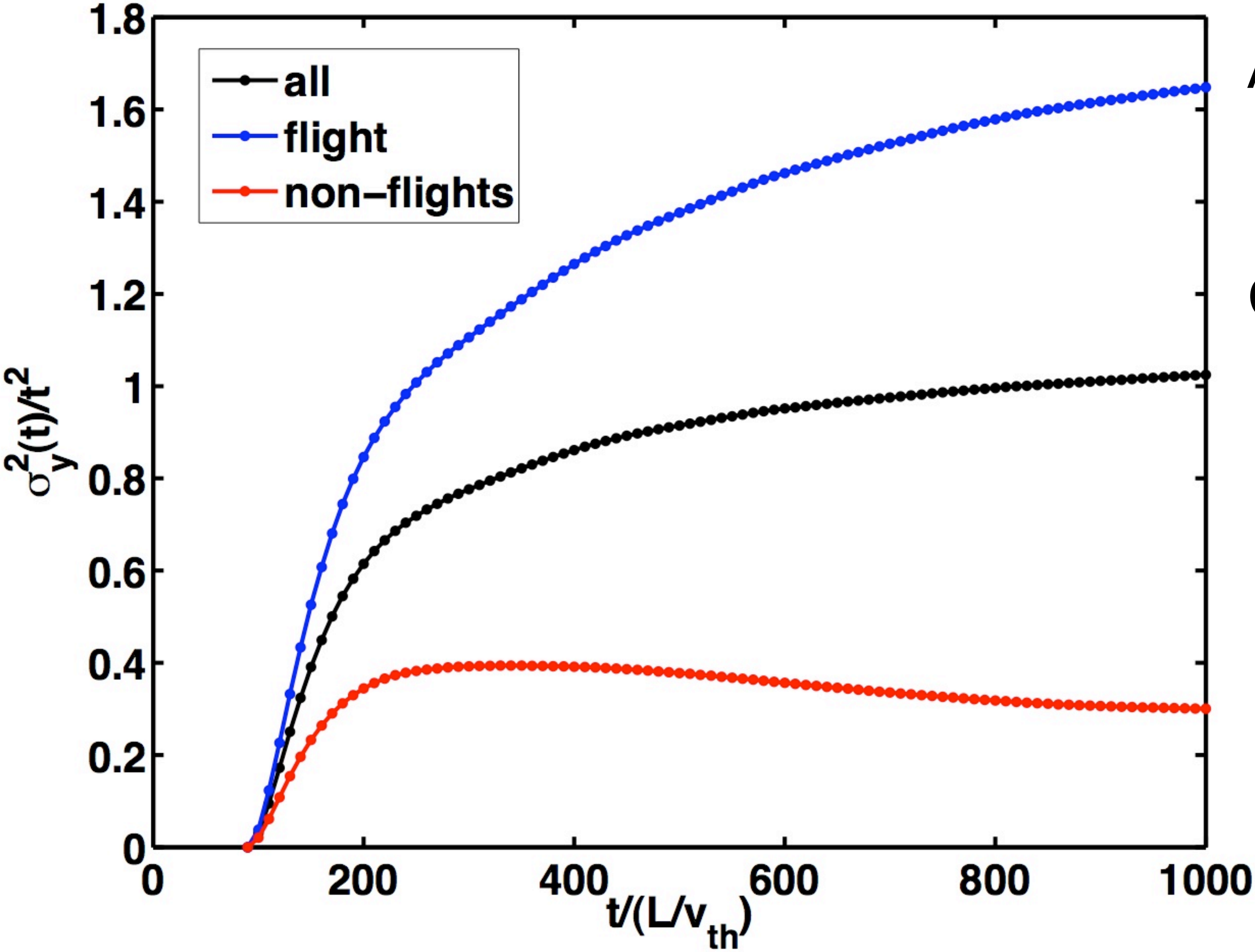
$\Delta x_2 \sim 60\ \rho_{th}$

Larger $v_\perp$ implies more trapping in E x B vortices (for a given turbulence scale)

Axial displacements



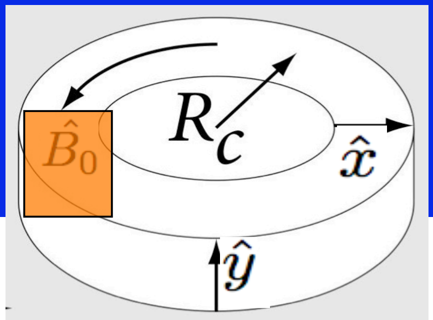
Gustafson, del Castillo Negrete, Dorland, PoP 102309 (2008)



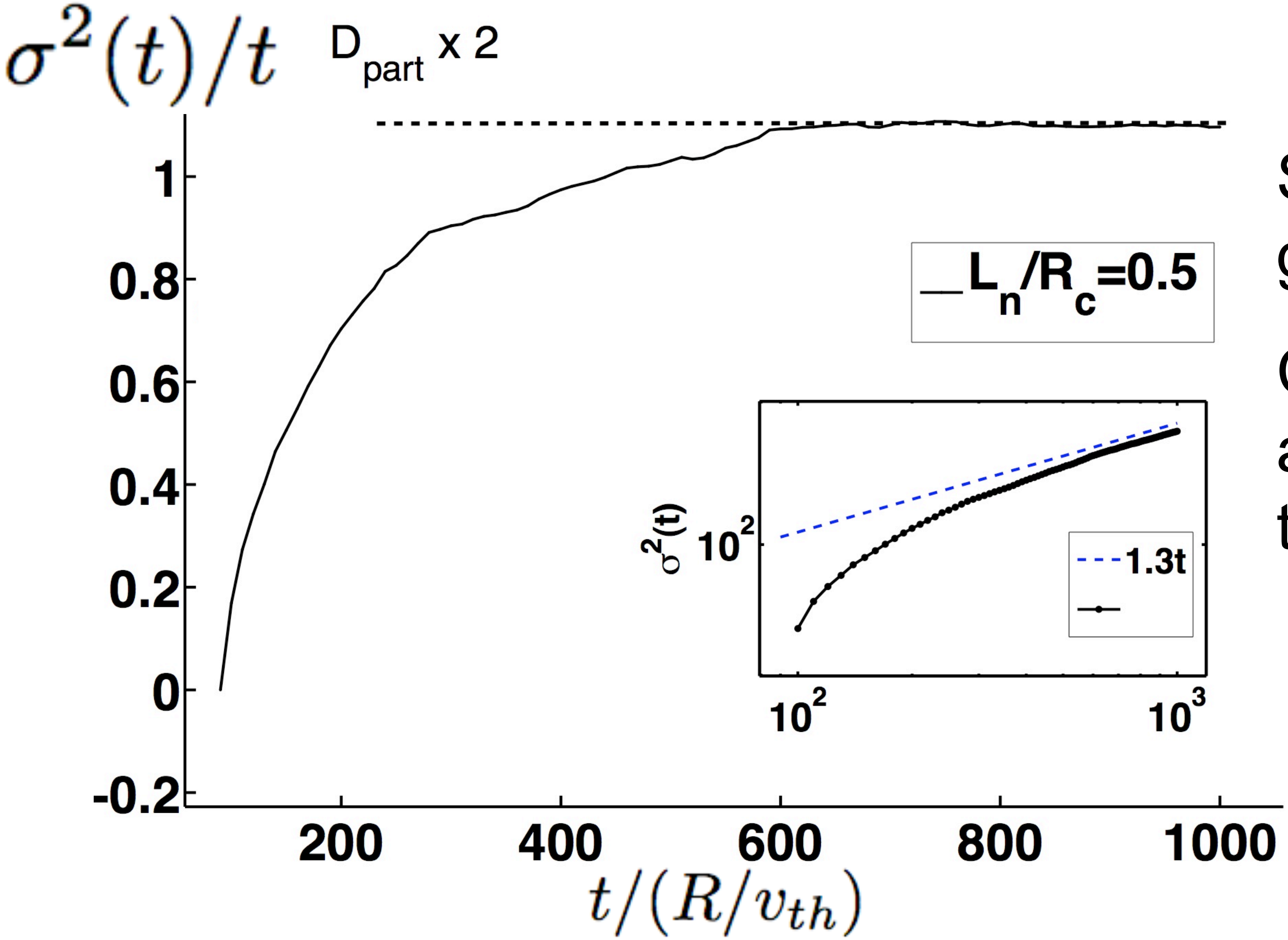
Approaching ballistic (γ~2)

Consistent with our study of a prescribed vortex chain in shear flow (see ref.)

Radial displacements



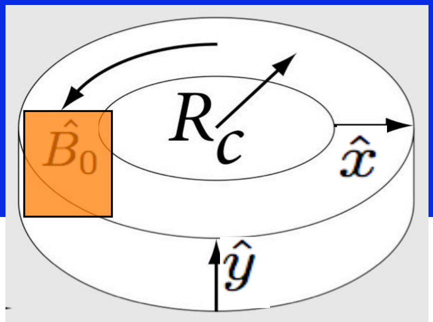
c.f. Manfredi & Dendy PRL 1996; Zhang *et al* PRL 2008; Sanchez et al PRL 2008; Hauff *et al* PRL 2009

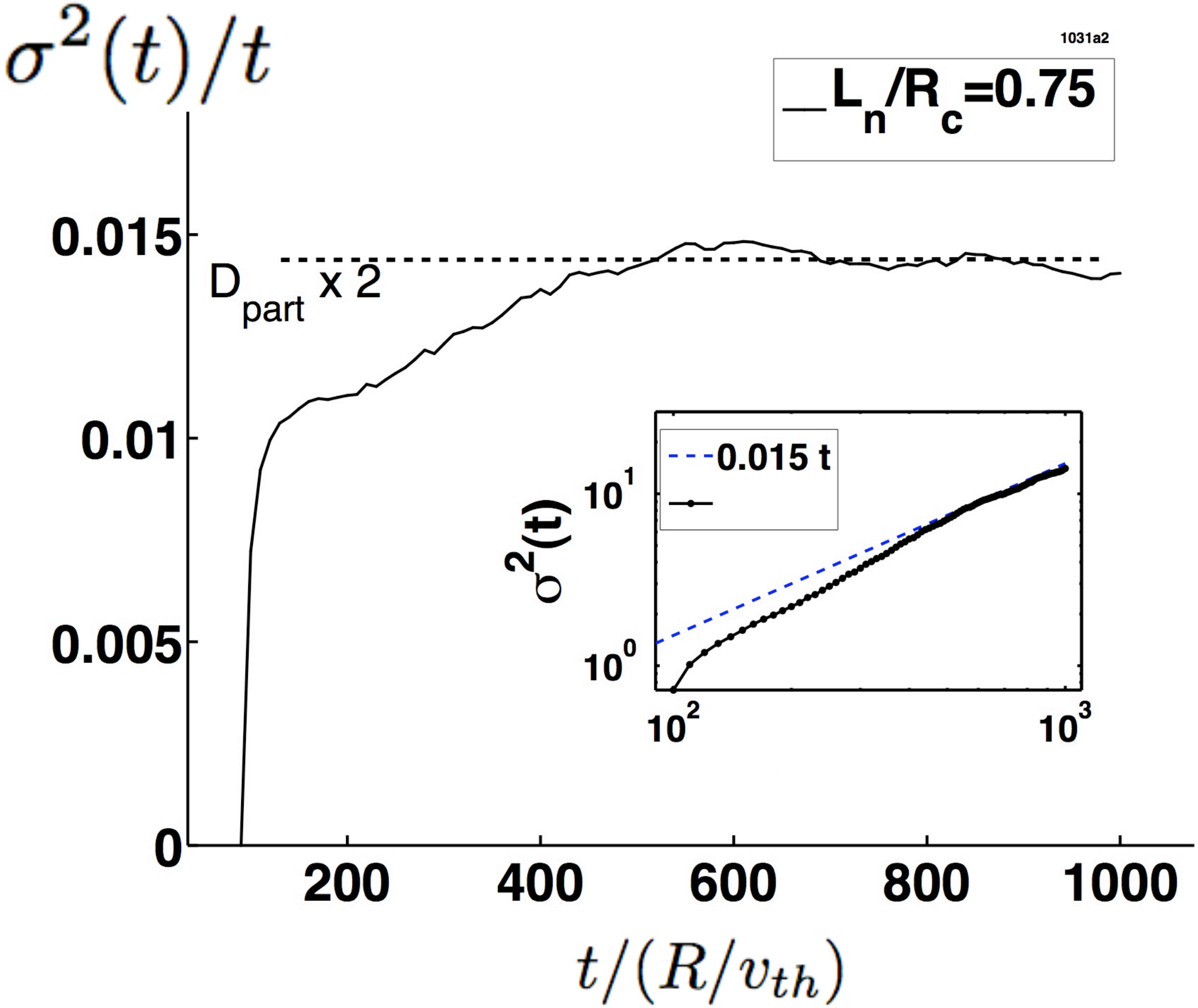


Strongest gradient tested

Clearly diffusive after
t = 600 R/v_{th}.

Radial displacements





Medium gradient (L_n)

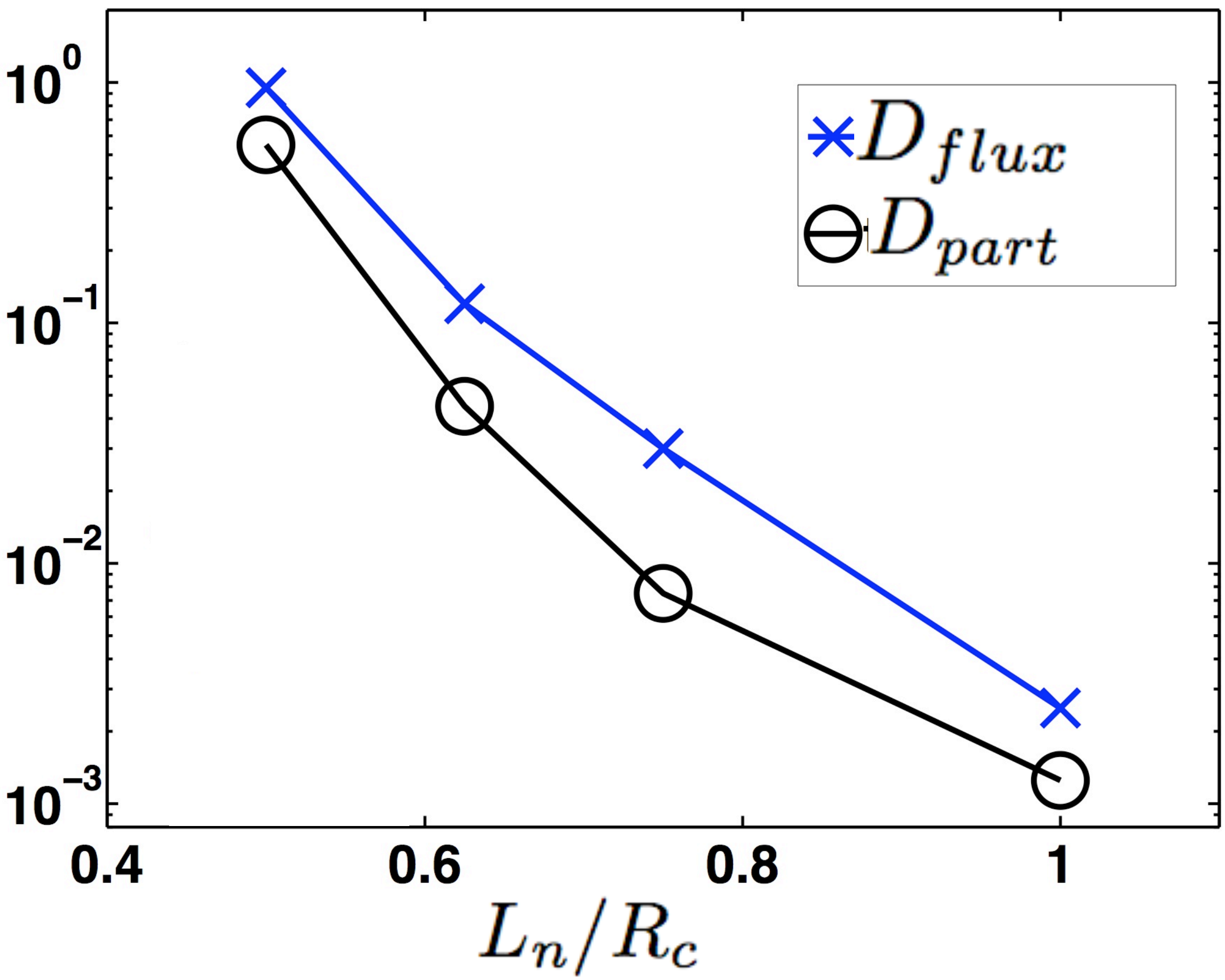
Clearly diffusive after t = 600 R/v_{th}.

Smaller diffusivity consistent with observed change in flux

Diffusivity two ways

Basu *et al* Phys Plasmas, 10 2003

$$D_{part} = \frac{\sigma_x^2(t)}{2t} \overset{?}{=} D_{flux} = \Gamma_\infty L_n$$



Conservation of potential vorticity,

$$\Pi = \nabla^2\phi - n + x\ ,$$

in the inviscid local L_n limit implies these should be equal.

Disagreement : artificial dissipation and Krook collision operator, or new version of potential vorticity is needed.

Diffusivity depends on gyroradius

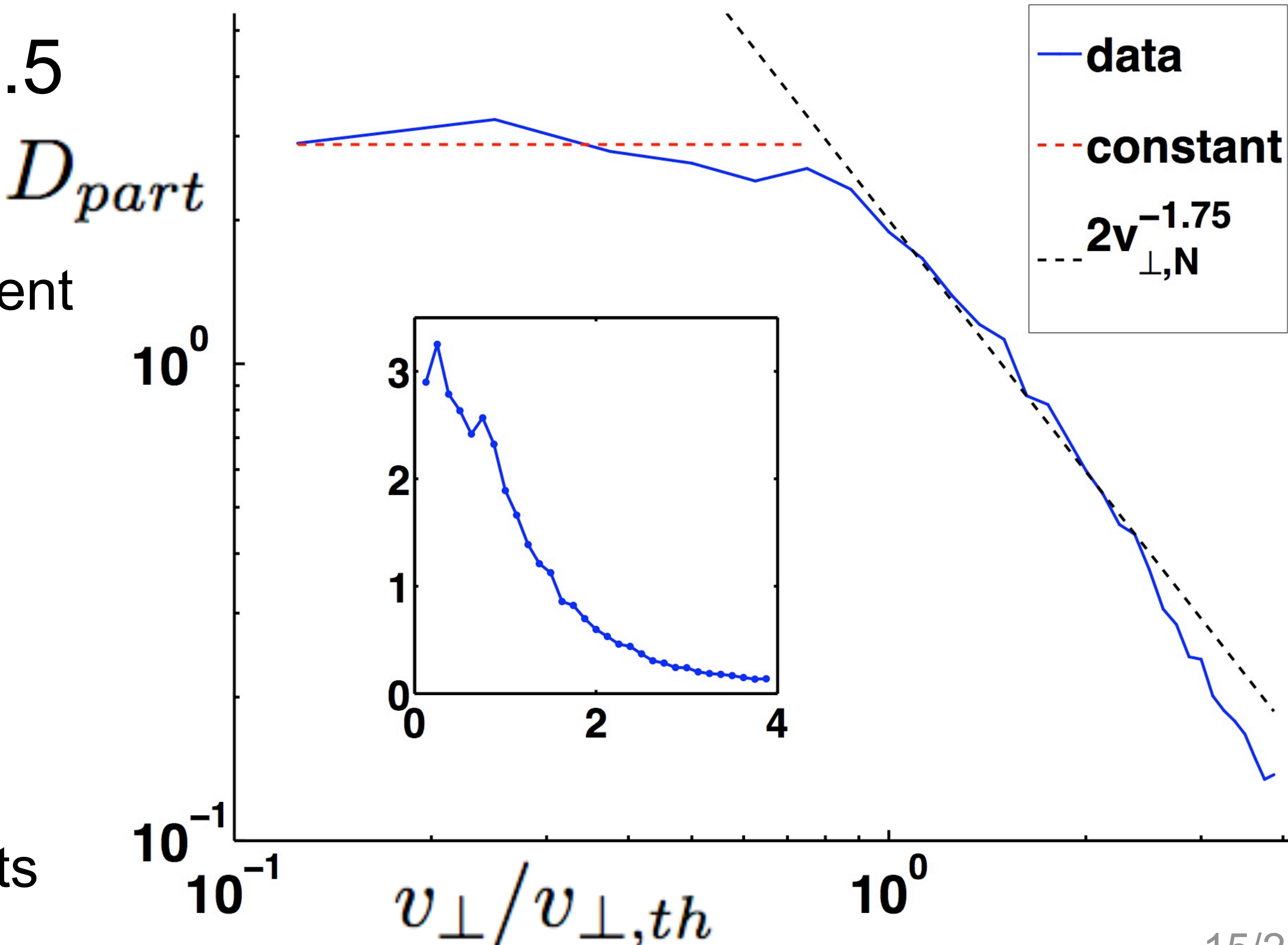
see Hauff & Jenko PoP 102309 (2006) and references therein

$L_n/R_c = 0.5$

Strong gradient
→
turbulent scales comparable to ρ_{th}

→

decay of diffusivity sets in later

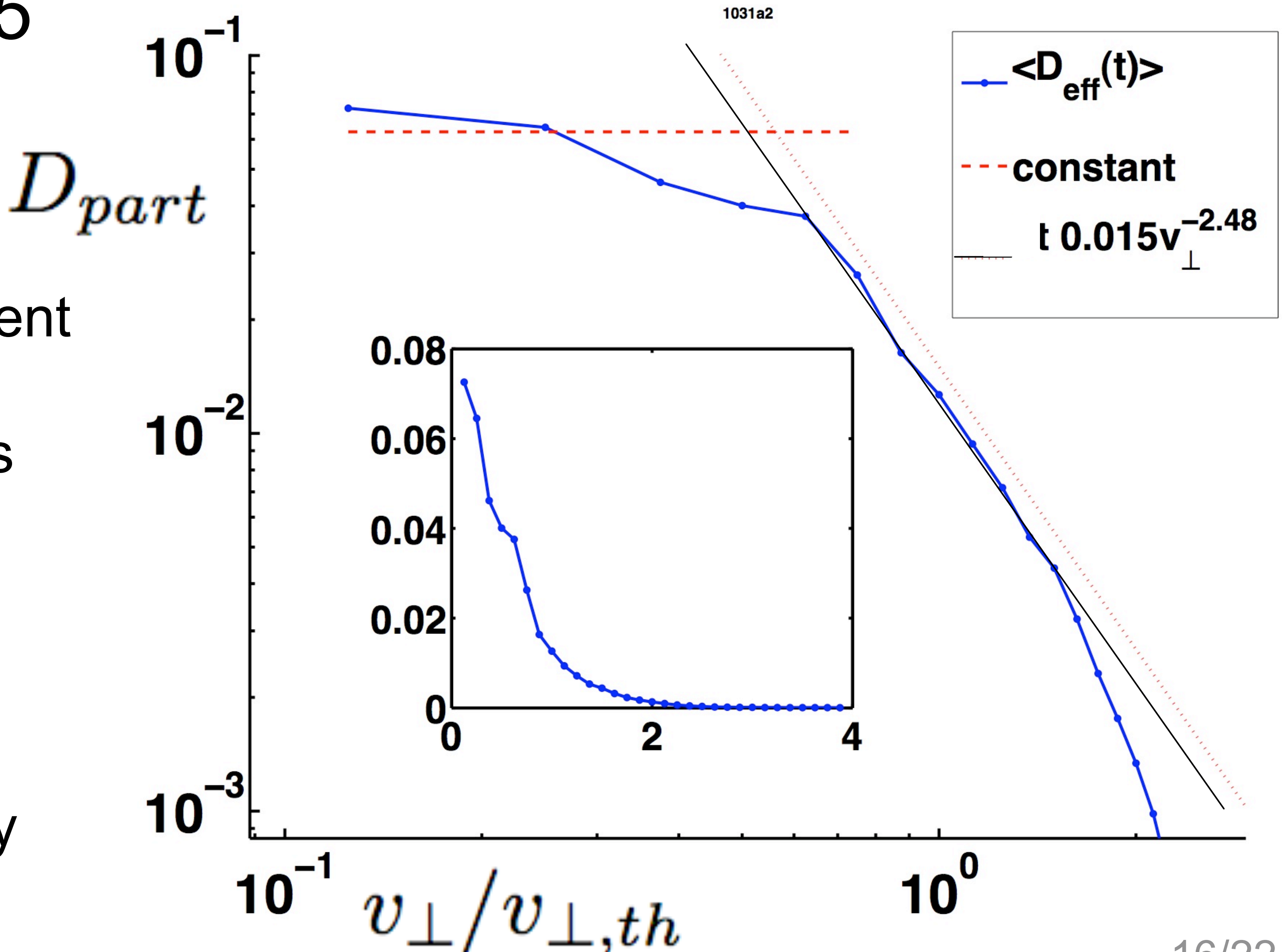


Diffusivity depends on gyroradius

$L_n/R_c = 0.75$

Weaker gradient
$\longrightarrow$
smaller scales of turbulence

$\longrightarrow$
turbulent trapping smooths away at smaller ρ_{th}

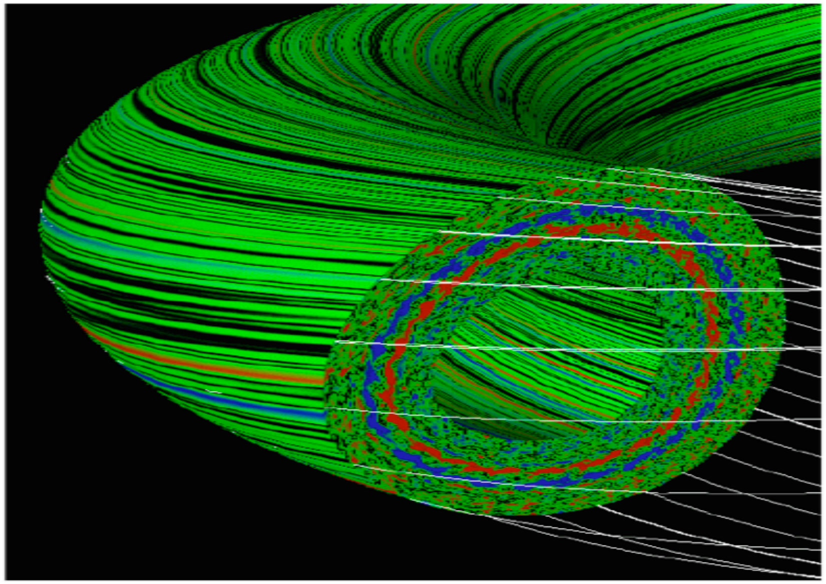


Summary of these results

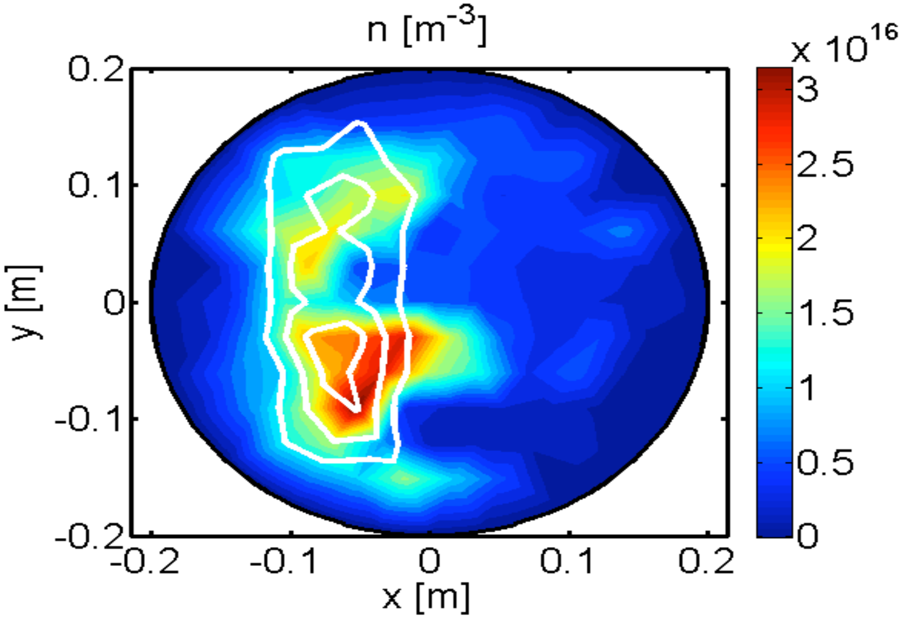
- New gyrokinetic PIC code, valid at large $k_\perp\rho$, is benchmarked with GS2 and convenient for studying particle dispersion
- Zonal flows in a local gyrokinetic simulation give diffusive radial test-particle transport at the ion Larmor radius scale.
- Test-particle diffusivity, D_{part}, is related to Fick's law diffusivity, D_{flux}.
- Energy dependence of diffusivity shows clear trends for several values of the density gradient.

Random walks in turbulence

1) Microscale turbulence with zonal flows



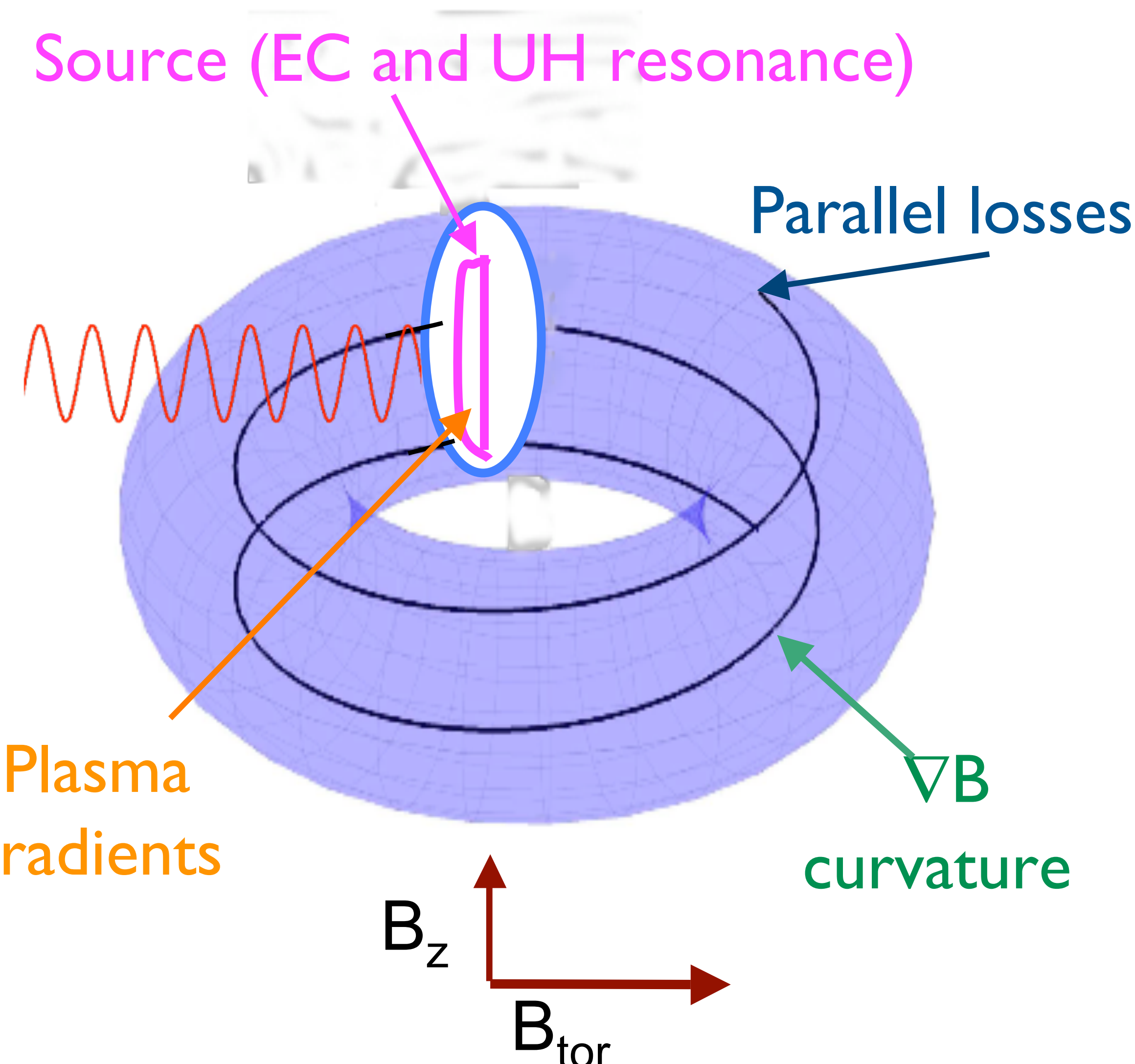
2) Macroscale turbulence with blobs



New project: fast ions in TORPEX

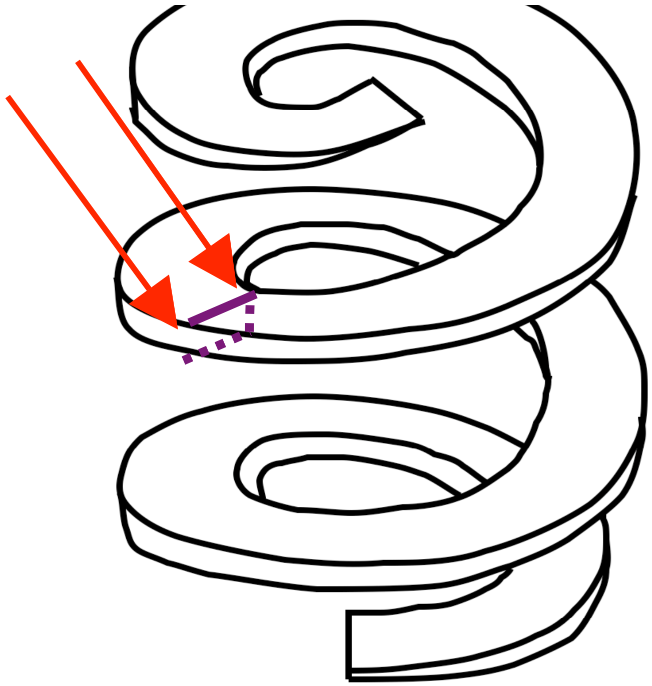
A. Fasoli, *et al*, Phys. Plasmas 13, 055902 2006

- Experimental model of scrape-off-layer - simple magnetized torus.
- Well-characterized blobs could drive nondiffusive transport

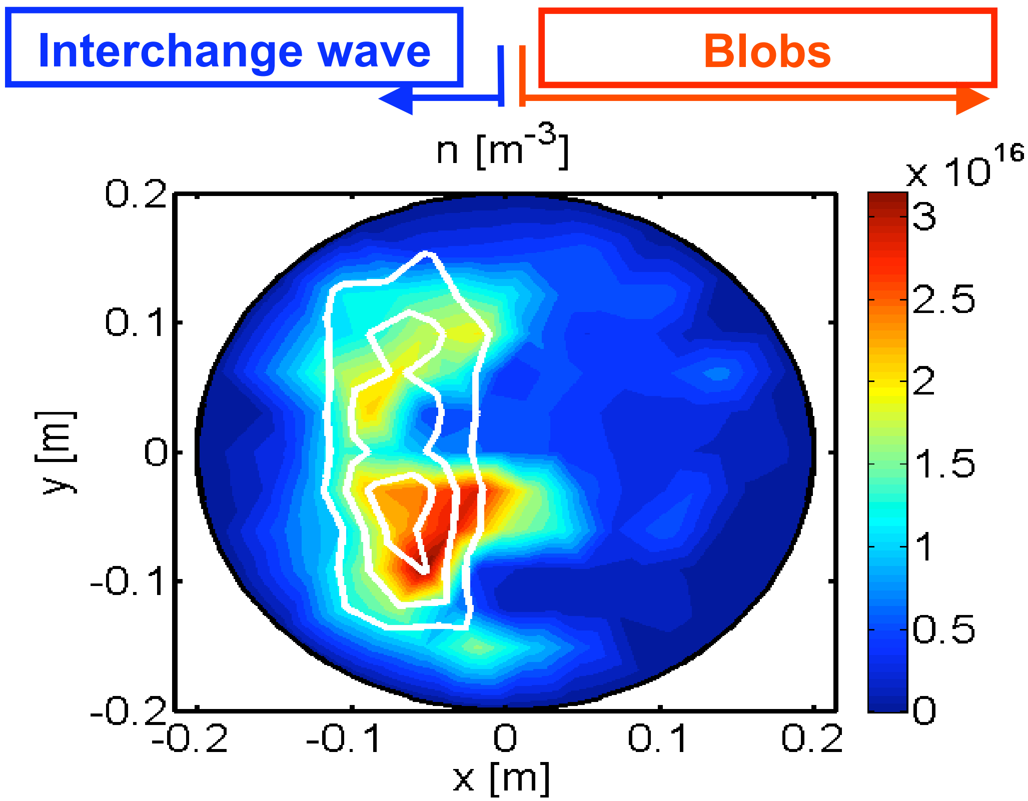


Simulated fast ions in turbulent E-field: drift-reduced Braginskii equations

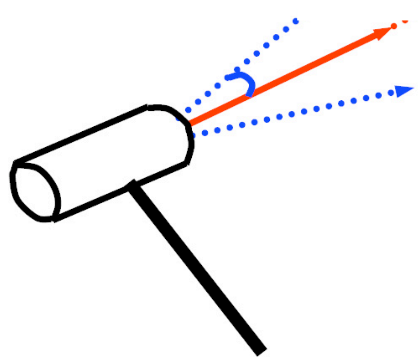
Periodic boundary conditions



$k_{||}$=0
2D simulation



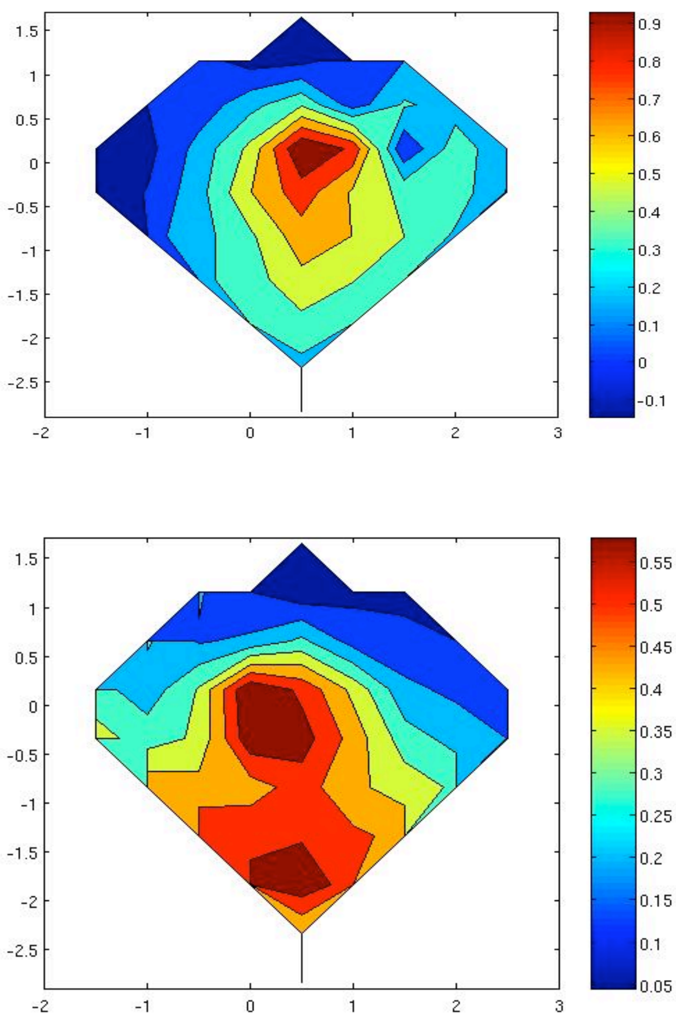
r [m]



Tracer particle source with realistic spread in energies (10%) and in angular distribution (0.2rad)

Fast ions: early results

Data



Synthetic diagnostic

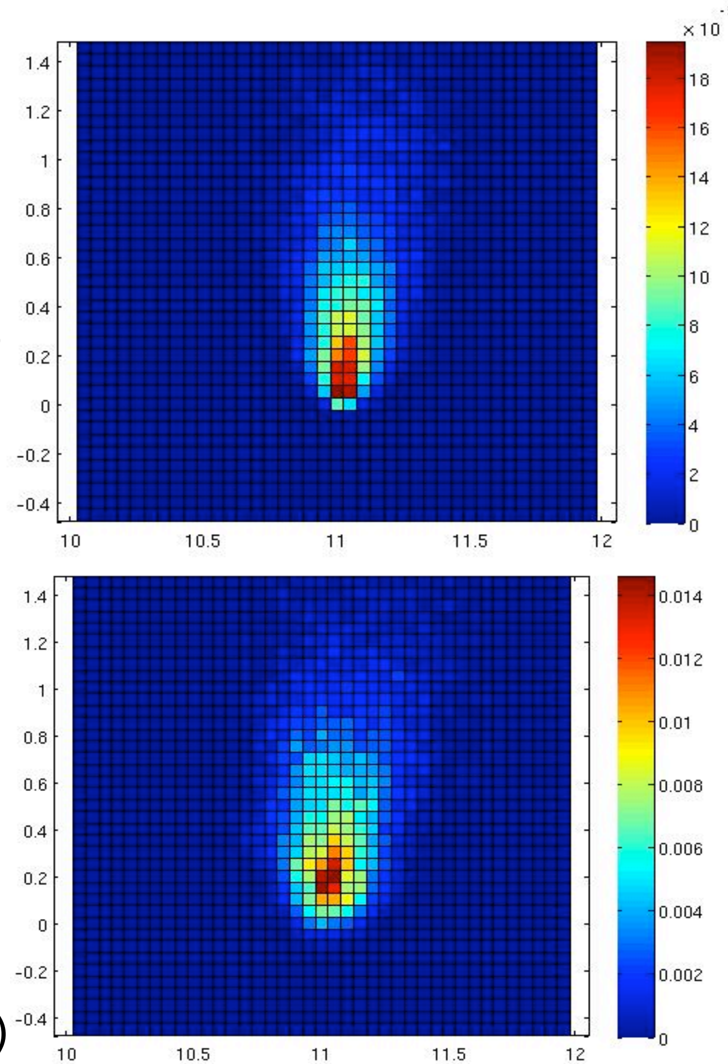
Without plasma

E_{fast}= 300eV

With plasma

z (cm)

z (cm)



r (cm)

Plyushchev, PhD EPFL 2010

Bürckel, Diploma EPFL 2009

Asymptotic modeling for high and low energy ions

- To be characterized in terms of the variance and a separable continuous time random walk: trapping time and flight length distributions
- Radial trapping increases with particle energy because averaging effects make radial streaming ineffective