Particle tracking in the entropy mode of a Z pinch with δf gyrokinetic simulations

Kyle Gustafson, Ph.D. candidate
Prof. William Dorland
(University of Maryland Physics Dept.)
Dr. Diego del Castillo Negrete
(Oak Ridge Lab, Fusion Energy Division)
Ingmar Broemstrup
Michael Barnes
(University of Maryland Physics Dept.)

Vienna workshop Sept 15-19 2008

Project goals

- Create a gyrokinetic turbulent velocity field for the entropy mode in a Z pinch using a δf PIC simulation
- Follow trajectories of self-consistent δf markers at all values of $v_\perp$
- Analyze displacements of the ensemble of markers
- Look for the presence or absence of non-diffusive transport

Standard description of transport

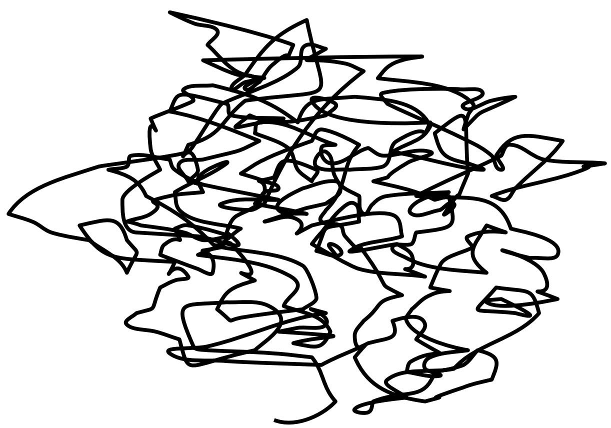
- Assumption of asymptotic diffusion
  - Markovian - local in time
  - Fickian - local in space

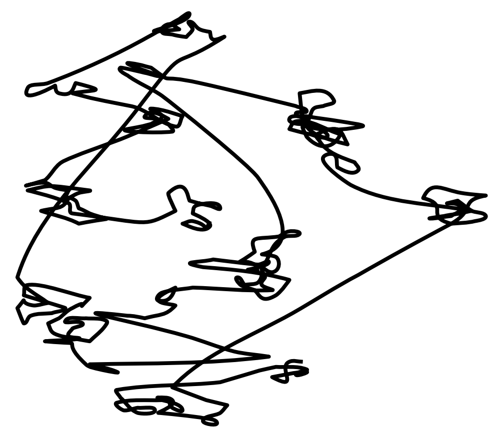
$$\Gamma_{particles} = \langle nv \rangle = -D\frac{\partial n}{\partial r}$$

- Individual displacements of particles are drawn from Gaussian white noise without waiting time between kicks
- Underlies the interpretation of transport processes in many cases - is this justified?

Generalized description of transport: continuous time random walks

Brownian motion vs. Lèvy flights





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

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

ordinary diffusion

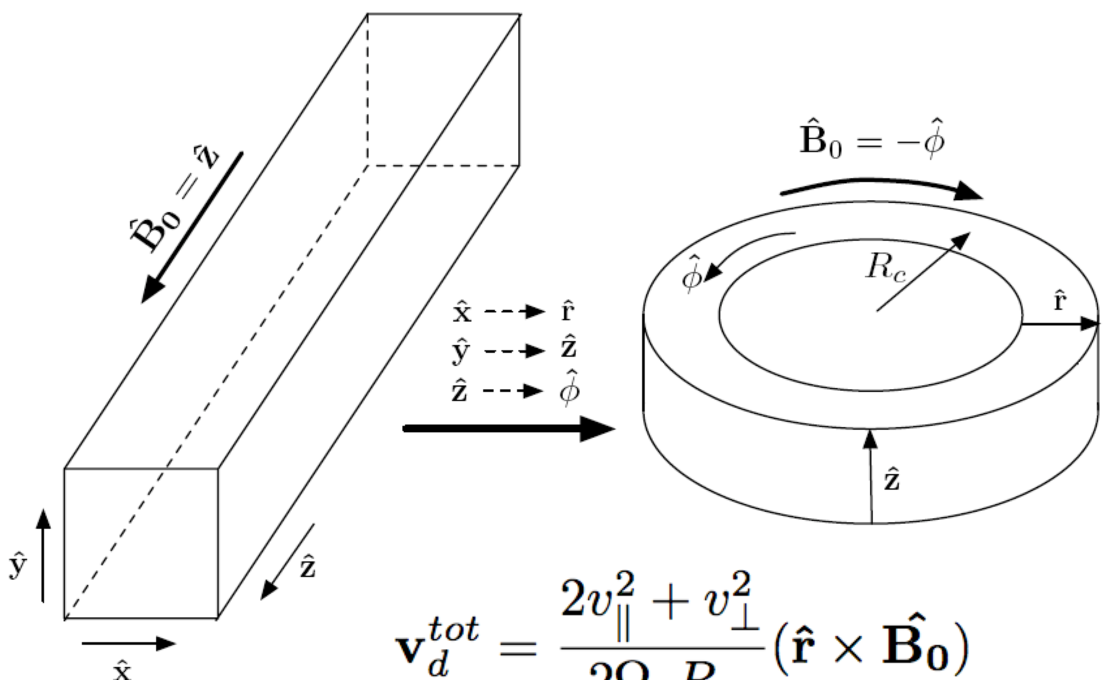
$$\sigma^2(t) \sim t^\gamma$$

- $\gamma < 1$ subdiffusive
- $\gamma = 1$ diffusive (normal)
- $\gamma > 1$ superdiffusive

non-diffusive transport

Z pinch geometry and relevance

i. Code coordinates ii. Plasma coordinates



$$\mathbf{v}_d^{tot} = \frac{2v_\parallel^2 + v_\perp^2}{2\Omega_s R_c}(\hat{\mathbf{r}} \times \hat{\mathbf{B_0}})$$

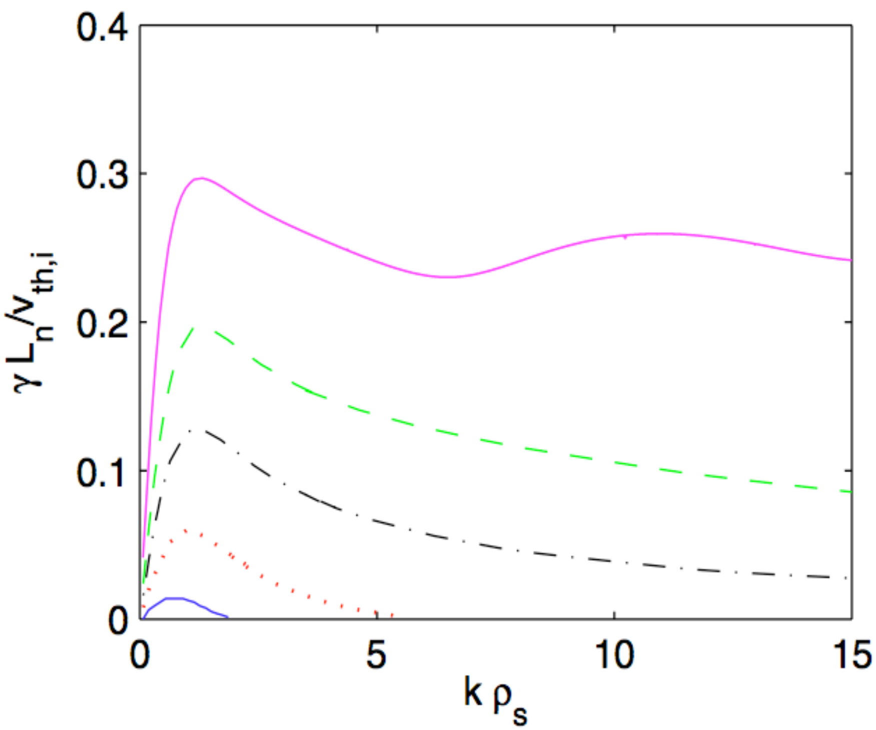
$$\Omega_s = \frac{q_s B}{m_s}$$

Broemstrup Thesis, Maryland, 2008

- Magnetic field only toroidal, 1/r to edge
- ExB drift radial transport
- Total vertical drift $\mathbf{v}_d^{tot}$ comes from curvature and $\nabla \mathbf{B}$
- Zonal flows similar to toroidal dynamics

Entropy mode

a.k.a. drift-temperature-gradient mode



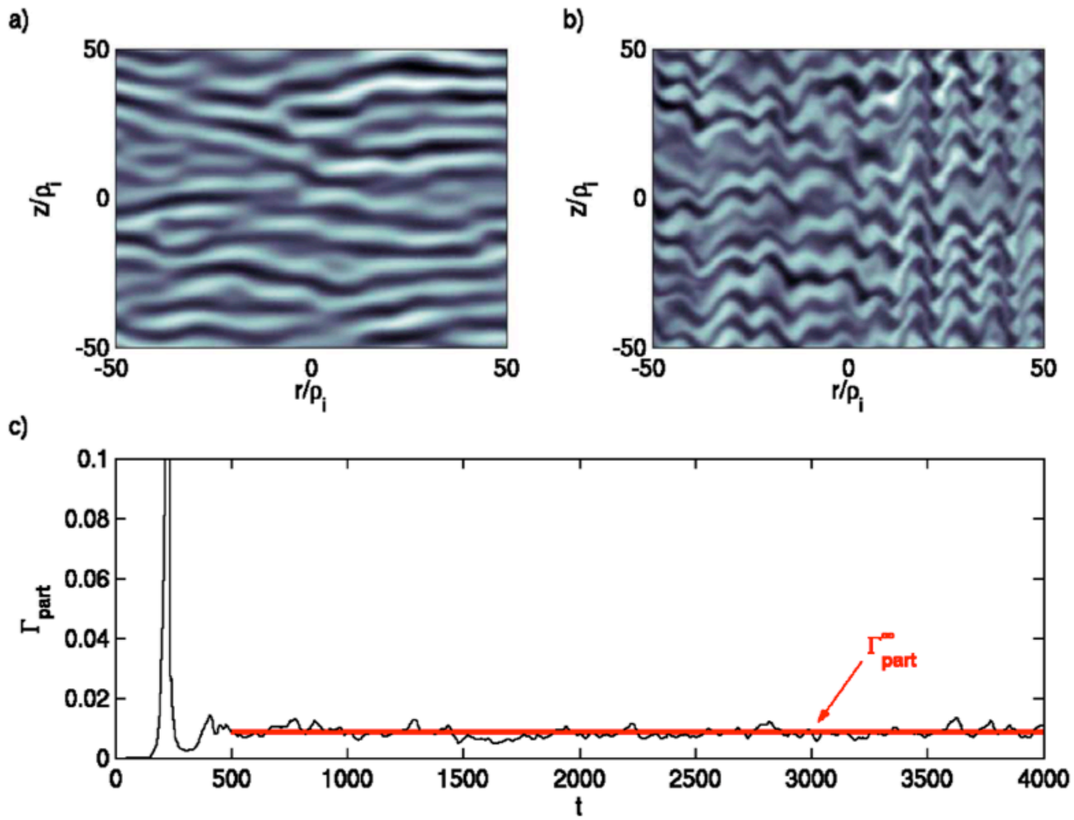
$T_e=T_i$, $\nu=0$, $T'=0$ linear gyrokinetic growth rates for L_n/R_c = {1.25, 1, 0.8, 0.67, 0.5}, from top

Ricci et al, PoP 062102 (2006)

- Z pinch plasma with $\beta << 1$, $k_{||} = 0$, $k\rho_i \sim 1$
- Linear instability boundary $2/7 < L_n/R_c < \pi/2$, where L_n is the scale length of the temperature gradient
- Growth rates and box-averaged fluxes have been obtained in published work
- Growth rate is similar to the ideal interchange mode at $k\rho_i \sim 1$

Entropy mode

a.k.a. drift-temperature-gradient mode



ϕ at earlier and later times as vertical shear flows develop - averaged particle flux stabilizes

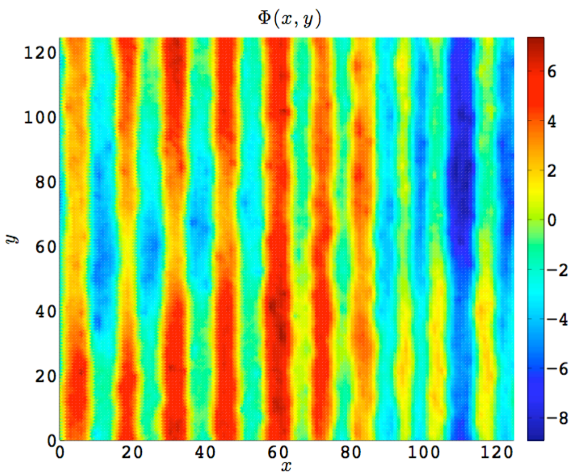
- Z pinch plasma with $\beta << 1$, $k_{||} = 0$, $k\rho_i \sim 1$
- Transition from radial streamers to Kelvin-Helmholtz instability
- Zonal flows reduce particle flux

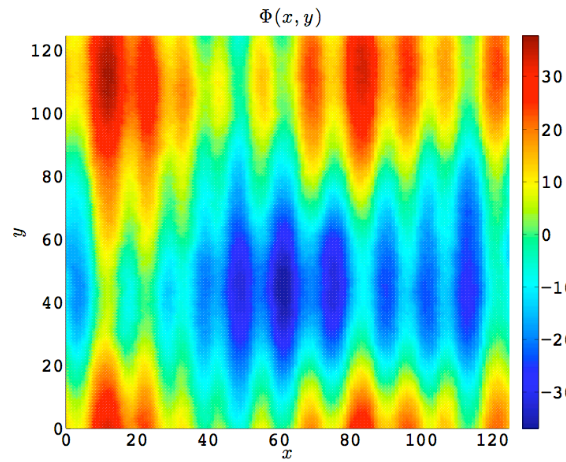
Ricci, Rogers, Dorland, PRL 97 245001 (2006)

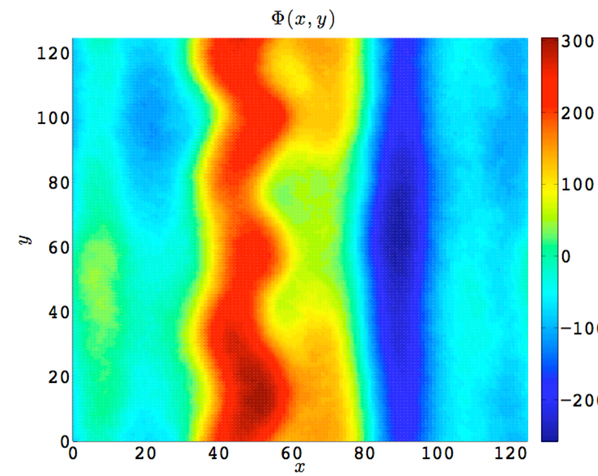
Code specifications

- δf particle-in-cell method for gyrokinetics
- Solve m.o.c. for weights $w_i \equiv \frac{< \delta f >_R}{F_0}|_{R_i, v_{\perp i}, v_{\parallel i}}$
- Evolution of electrons and ions
- Local approximation for gradients
- $J_0(k_\perp v_\perp / \Omega_s) < \delta f >_R$ with FFTs, not 4-pt avg
- Periodic boundaries, but can track particles outside of the box
- Collision operator has been implemented but is not studied in this contribution

Scale of density gradient: 128x128x1

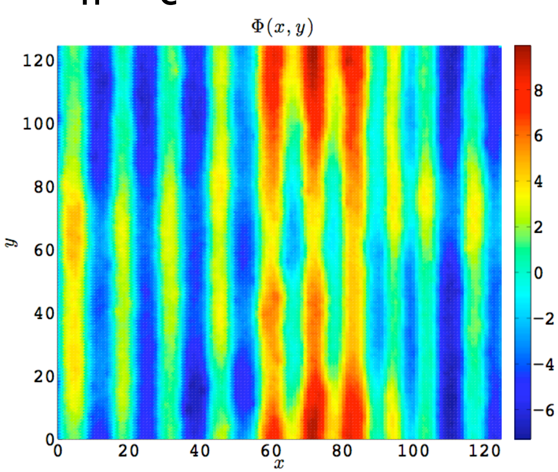


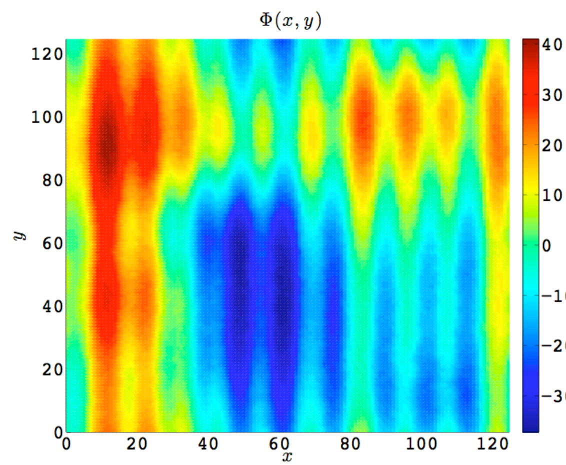


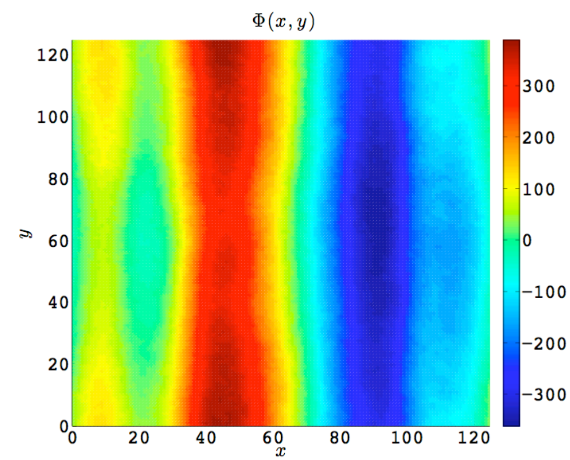


$L_{n/}R_c$=1, t=150 | L_n/R_c=0.75, t=150 | L_n/R_c=0.5,t=150

L_n/R_c=1, t=250 | L_n/R_c=0.75, t=250 | L_n/R_c=0.5,t=250

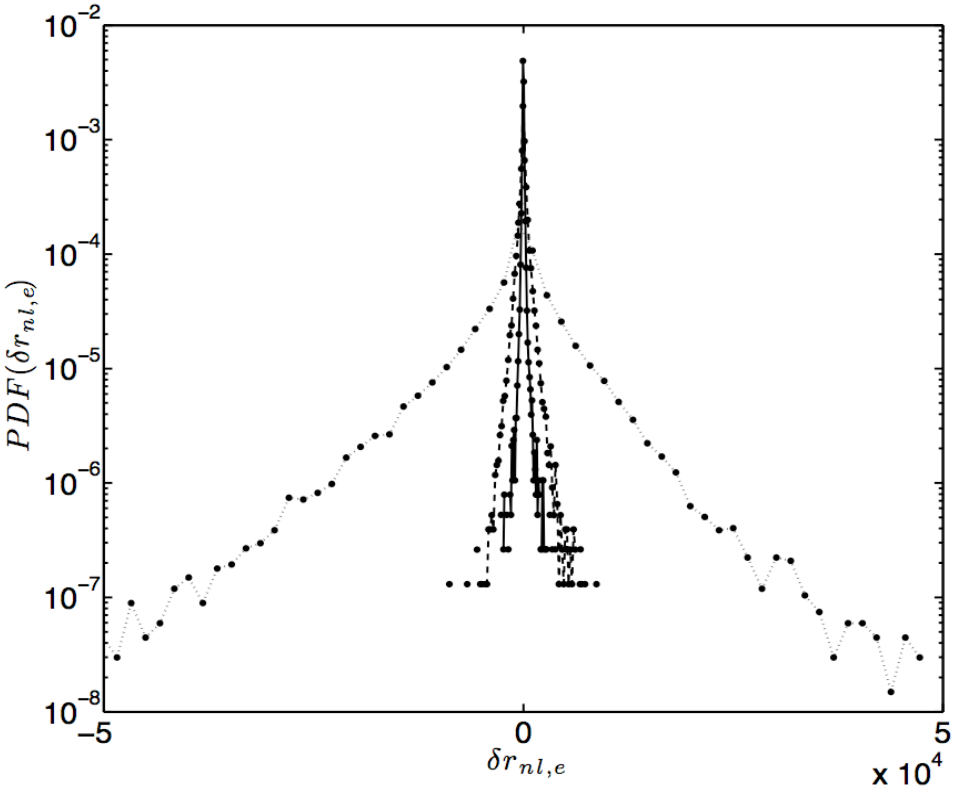


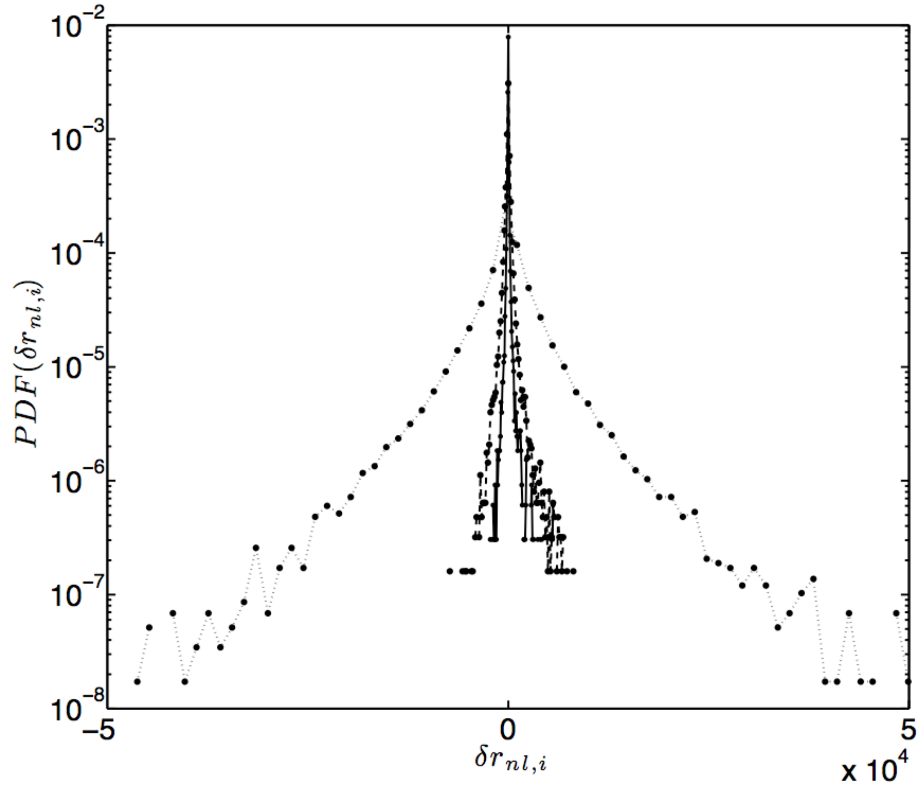




Dominant wavenumber decreases as gradient strengthens →

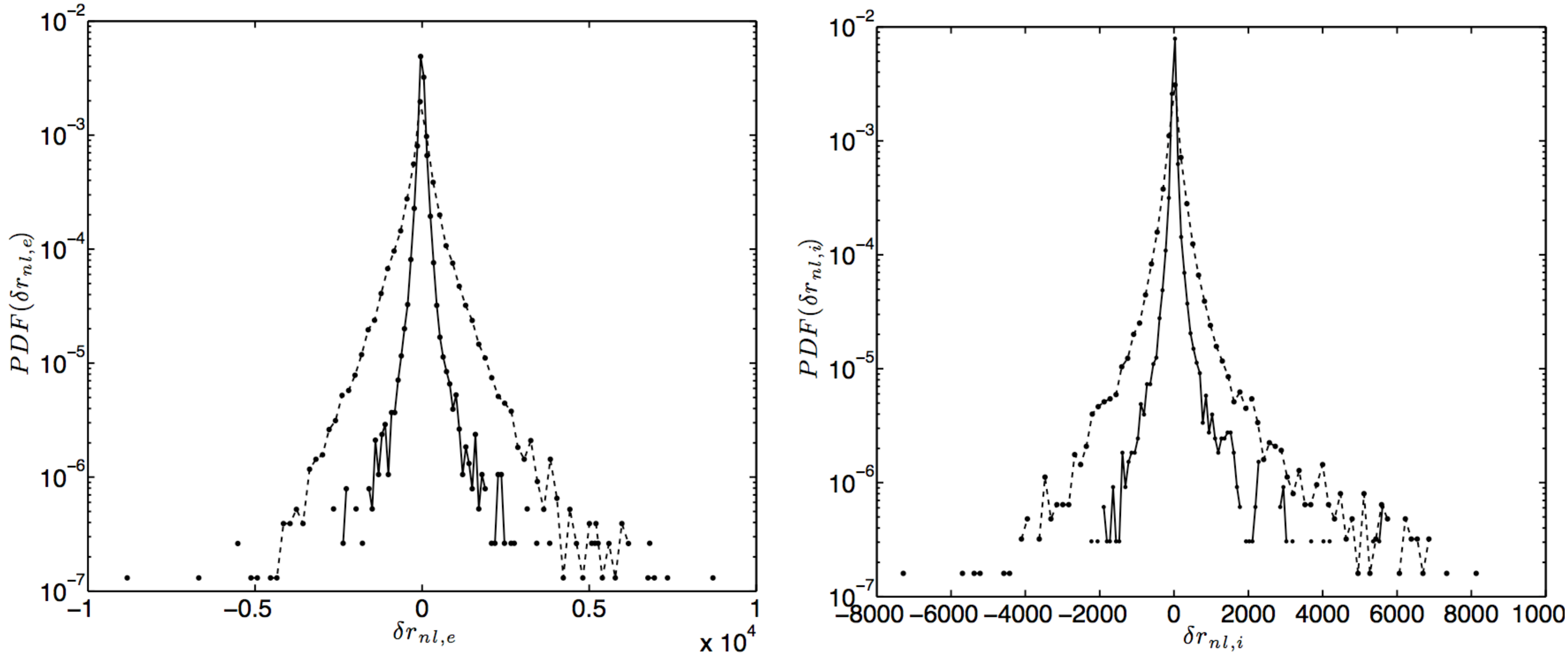
Probability distribution of displacements for ions and electrons





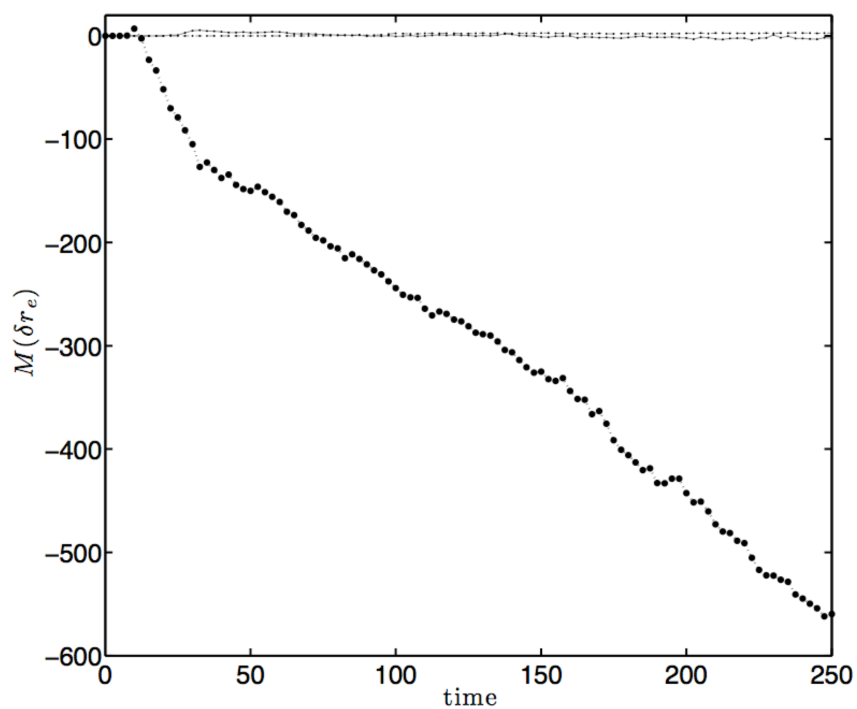
- Stronger gradients cause more radial spreading, mostly from the linear phase

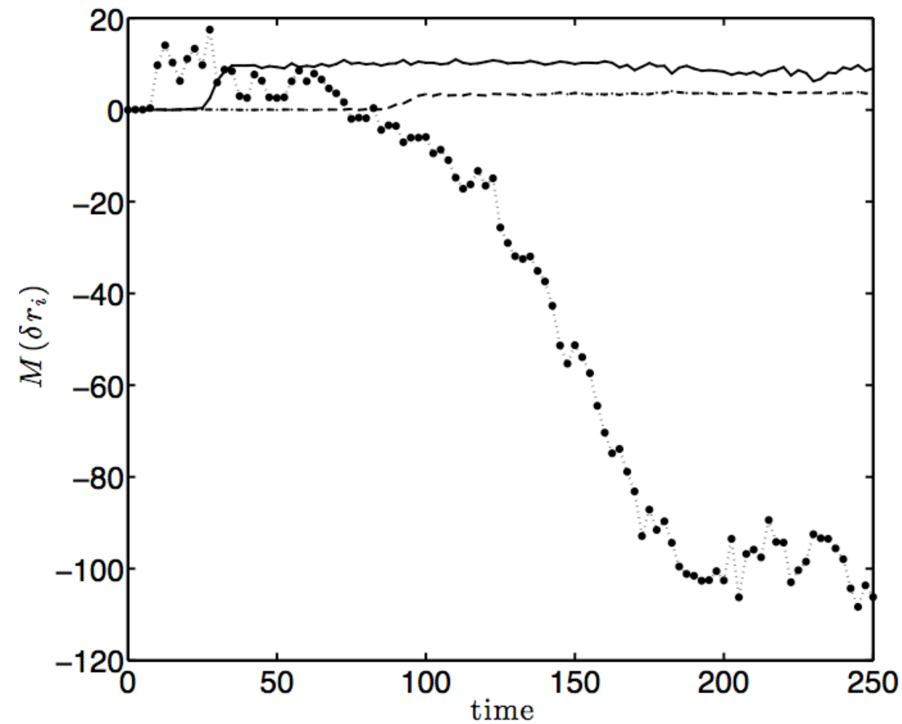
Probability distribution of displacements for ions and electrons



- Stronger gradients cause more radial spreading, skewed in the positive radial direction

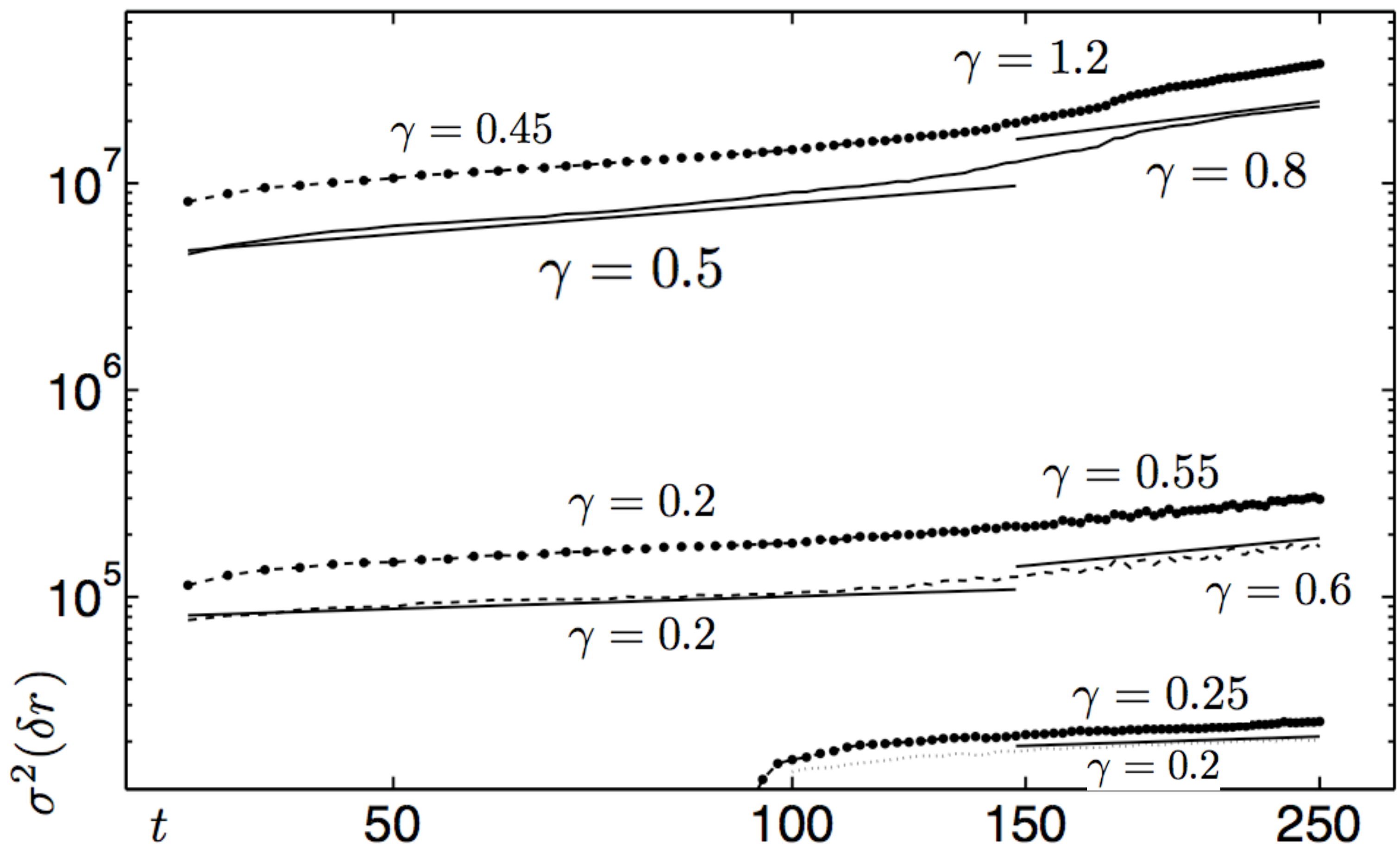
Mean in radial direction





- Movement of the mean is much more pronounced for stronger gradients

Variance in radial direction

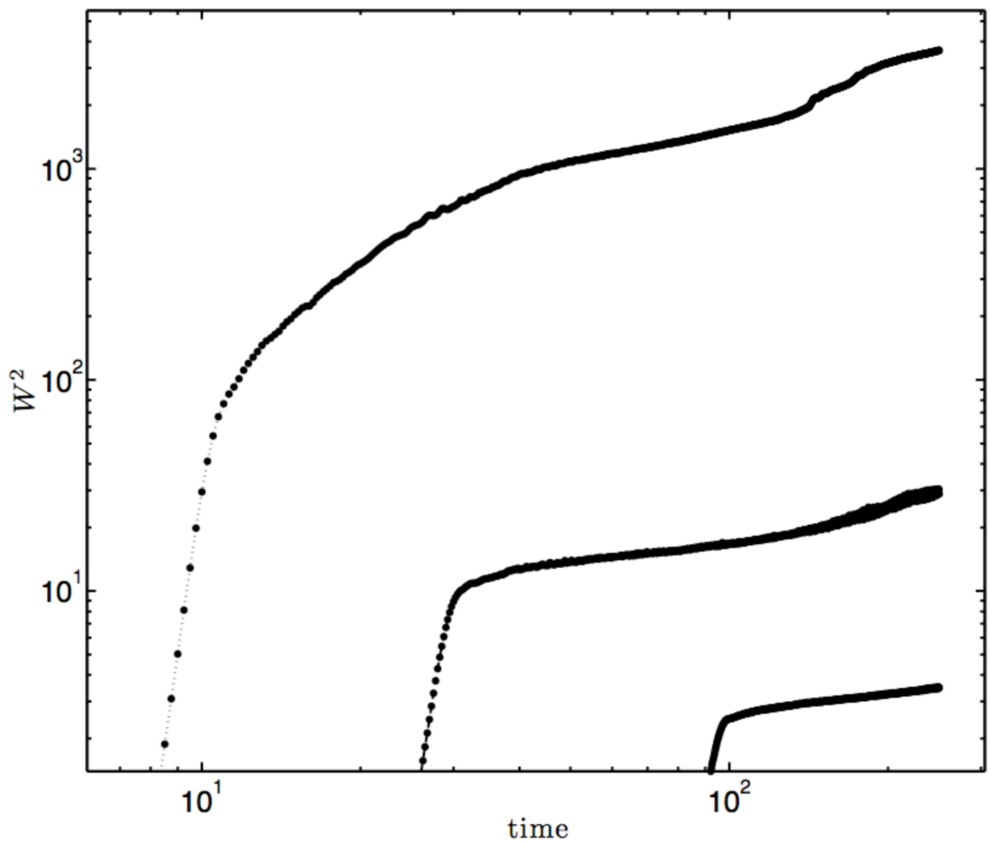


- Electrons (markers) and ions, L_n/R_c = {1.,0.75,0.5} increasing gradient upward

Variance in radial direction

- Transition from one subdiffusive regime to another, except for electrons in strongest gradient
- Larger offset for stronger gradients because of fast linear growth phase

Weights' growth



- Two regimes in time, just like the variance - is it particle noise? Work-in-progress…

Conclusions

- Mean grows much more quickly for strong forcing
- Variance grows quickly during linear phase, then grows much more slowly - linear phase is longer for less forcing - does weight growth dominate?
- More work is needed to decide whether non-diffusive transport is relevant in the entropy mode - need to look at collisionality
- see Hauff & Jenko Phys. Plasmas 102316, (2007) for non-diffusive behavior in continuum gyrokinetic simulations

Acknowledgements

The work is supported by the Fannie and John Hertz Foundation, the Department of Energy through the Center for Multiscale Plasma Dynamics and Oak Ridge National Laboratory.