Collisions in Strongly-Coupled and Strongly-Magnetized Plasmas

Dan Dubin UCSD

Challenges:

Describe and measure collisional relaxation for strongly-coupled plasmas

Describe and measure collisional relaxation for plasmas in strong magnetic fields

Strongly-coupled plasma: $k_B T < \frac{Z^2 e^2}{a}$ Þ $T < 2.3\,\text{eV}\; Z^2 \left(\frac{n}{10^{21}\,\text{cm}^{-3}}\right)^{1/3}$

kinetic energy per charge < Coulomb interaction for nearest neighbors

ICF plasma; white dwarf star; giant planet interior; cryogenic nonneutral plasma

magnetized plasma: $r_c < l_D$ Þ $B > 0.32\ \text{Tesla}\sqrt{n/10^{12}\,cm^{-3}}$ (electrons)

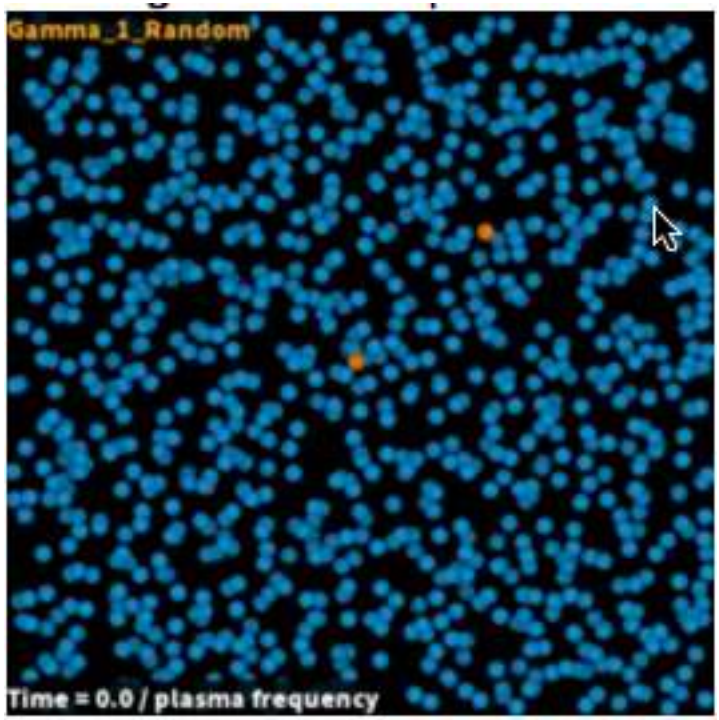
cyclotron radius < Debye length

Tokamak edge plasma; sunspot; nonneutral plasma

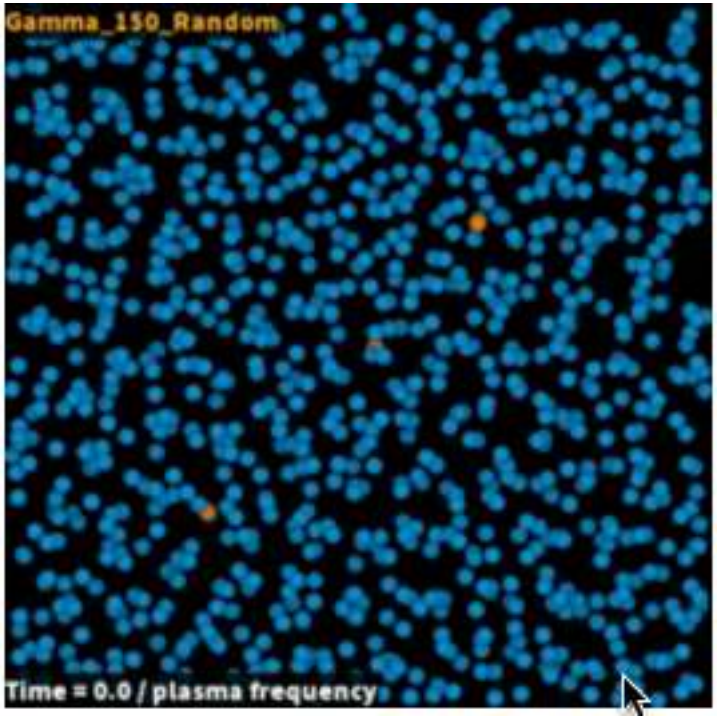
Transport Coefficients in Strongly-Coupled Plasma

Large –Scale simulations essential eg. PPPM MD

Higher temperature: gas-like
Large mean-free path



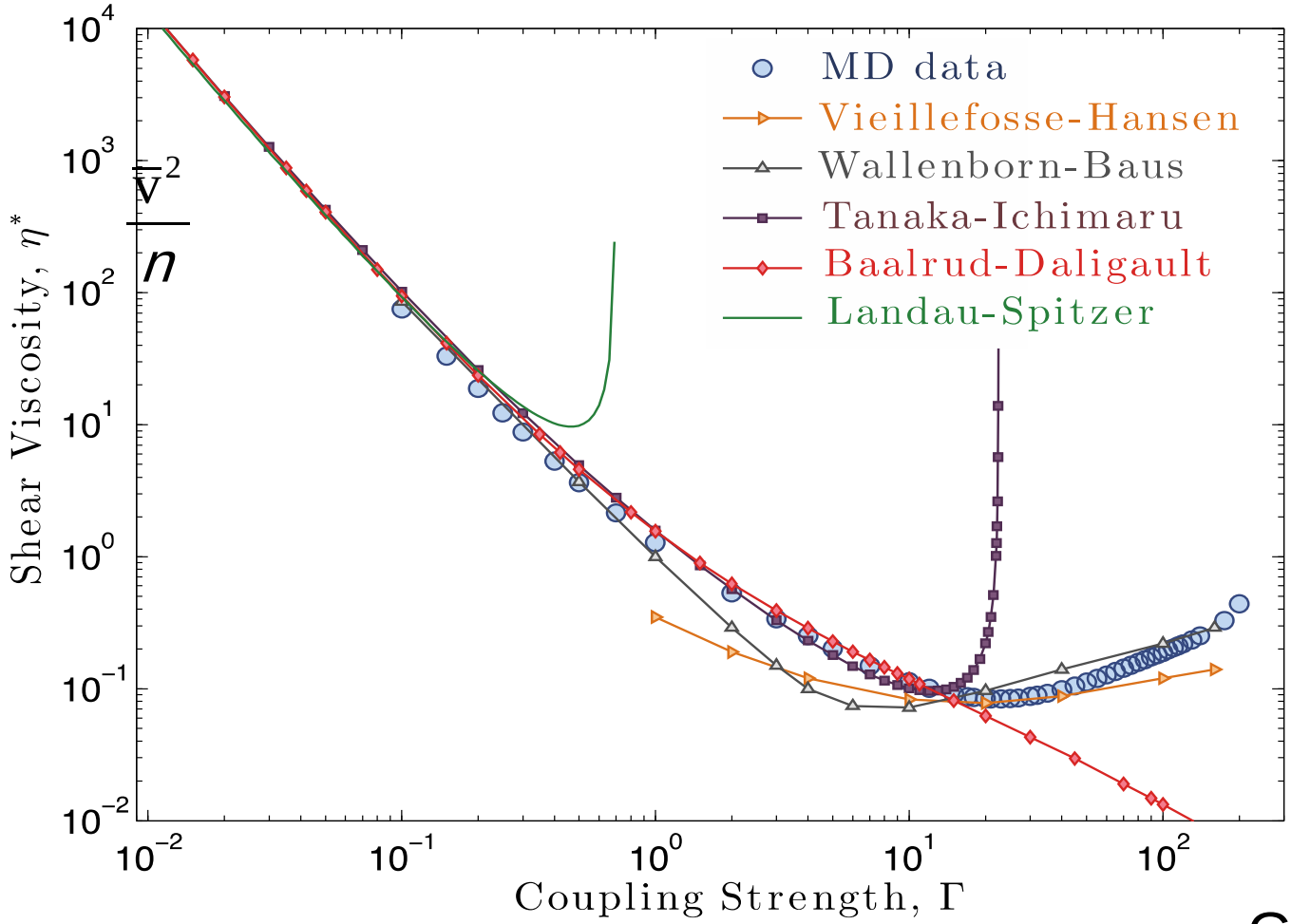
Lower temperature: fluid-like
caging apparent



Simulations have provided intuition for new effective potential theory of collisional transport in strongly-coupled plasmas

LANL Dense Plasma Theory Group

Shear viscosity in a strongly-coupled single-component plasma

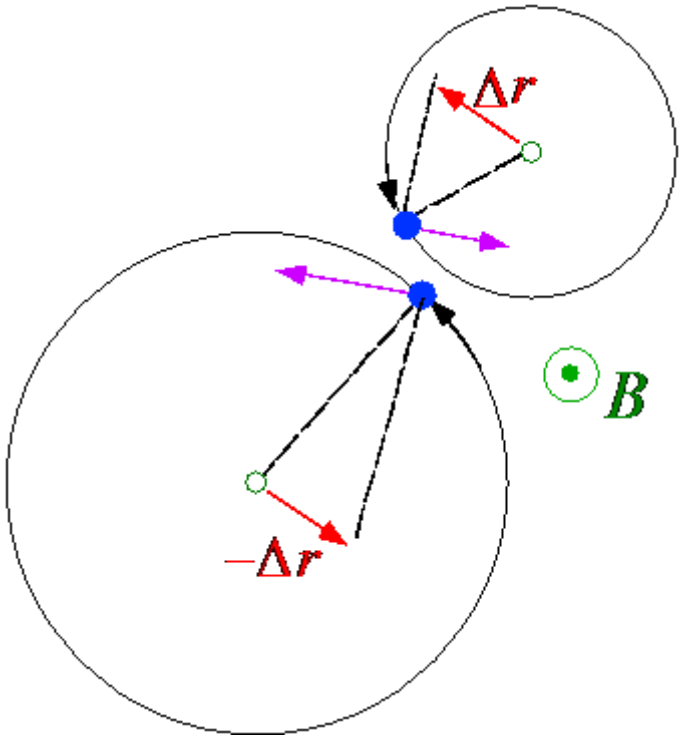


G= $e^2 / ak_B T$

Other transport coefficients? Effect of magnetic field?
Long-range interactions?

Daligault, Rasmussen and Baalrud, Phys. Plasmas 2014

Classical collision theory does not work for magnetized plasma with $r_c < l_D$



Cross-field particle diffusion: random steps from collisions

Step size $\Delta r \sim r_c$

Frequency of steps $\Delta t^{-1} \sim$ collision frequency ν_c

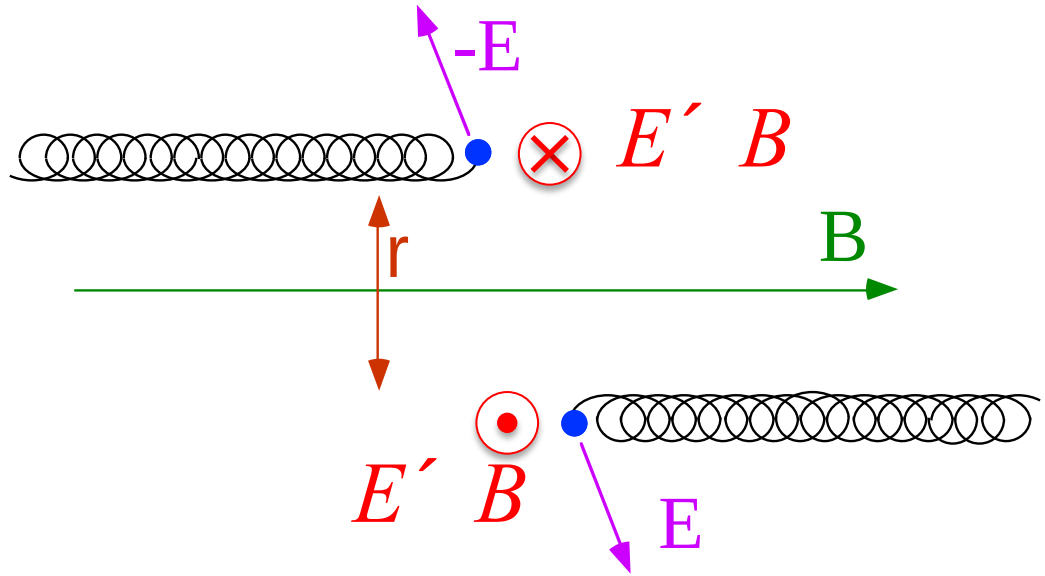
$$D \sim \frac{\langle \Delta r^2 \rangle}{\Delta t} \sim n_c r_c^2$$

Spitzer 1955
Longmire and Rosenbluth 1956
Simon 1956
Rosenbluth and Kaufmann 1958
Braginskii 1958

Heat conduction $\chi = \frac{k}{n} \sim D \sim n_c r_c^2 \mu 1/B^2$

When $r_c < l_D$

- Most collisions are long-range: $r_c \lesssim r \lesssim l_D$



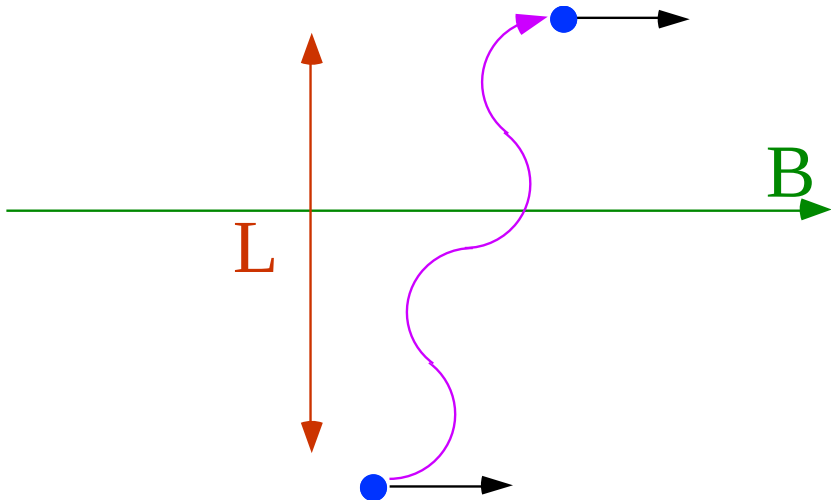
Heat conduction of parallel energy:

$$k/n \sim n_c < r^2 > \quad \boxed{\Rightarrow k \sim n n_c l_D^2 >> k^{class}}$$

Particle Diffusion from ExB drifts:

$$\boxed{D \sim 10' D^{class}}$$ (for current experiments at UCSD)

Emission and adsorption of lightly-damped plasma waves (predicted to) enhance transport



$\rho \sim$ plasma width L (but $\nu < \nu_c$)

if L $\gtrsim 10^2\ \lambda_D$ Waves enhance transport: $k \sim 0.01\, n n_c l_D L$

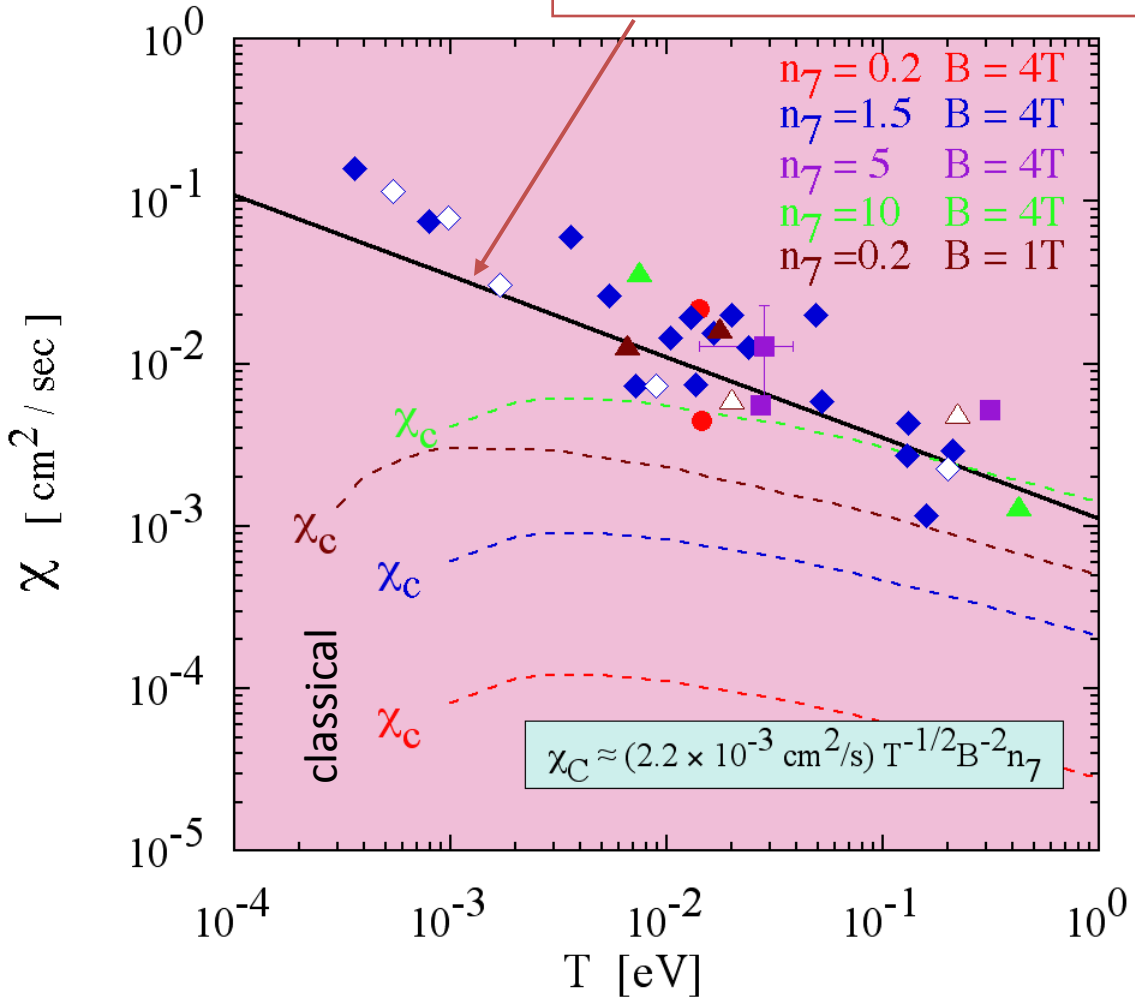
if L $< 10^2\ \lambda_D$ Waves unimportant: $k = 1.2\, n n_c l_D^2$

Rosenbluth and Liu '76
Dubin and O'Neil '97

Thermal Conduction: theory and experiment

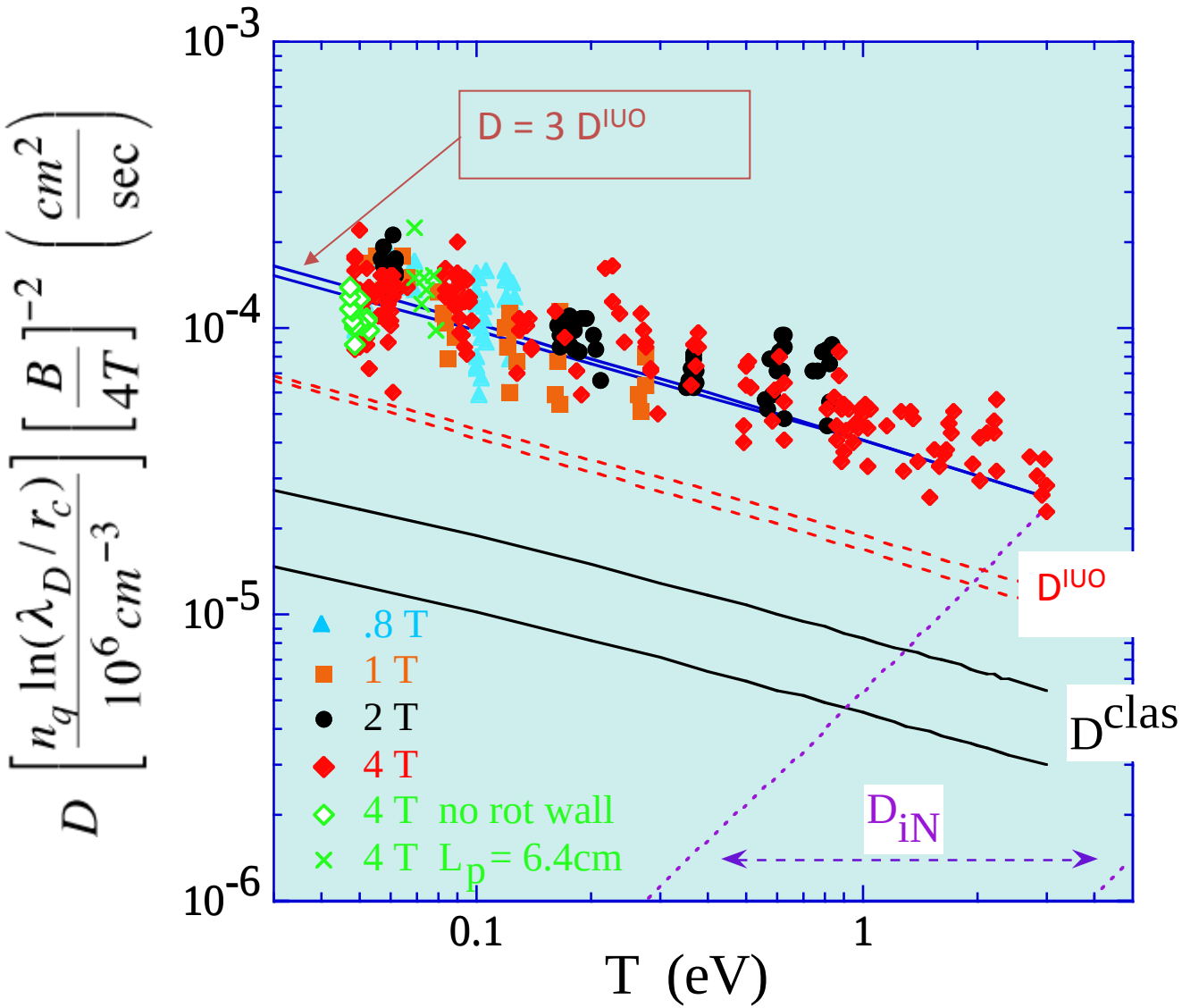
κ is up to 300x classical

$$k / n = 1.2\, n_c l_D^2 = 0.097 \frac{e^2}{m\bar{v}}$$



Hollmann , Anderegg and Driscoll, PRL

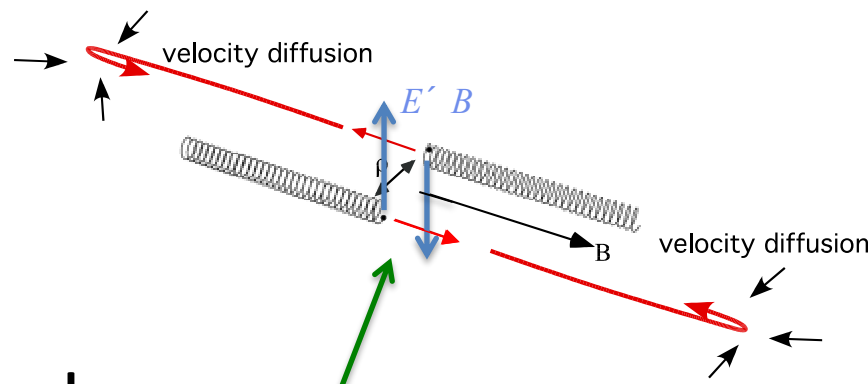
Theory of long range ExB drift collisions that includes effect of collisional caging agrees with experiments!



Collisional caging enhances some relaxation processes from long range collisions

- Guiding centers can collide more than once *while remaining correlated*
- Multiple correlated

collisions increase cross-field particle diffusion and collisional drag force



ExB drifts are in the same direction for each collision of this pair

D. Dubin, Phys. Plas. 21, 052108 (2014)

Summary

- There has been recent progress in our understanding of collisional processes in strong magnetic fields and in strongly-coupled plasmas
- More remains to be done:
- experimental tests; transport theory for magnetized and strongly coupled plasma; transport from plasma waves/phonons…