Spin Drag in a Bose Gas

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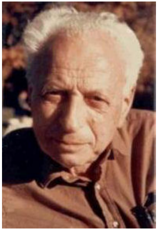
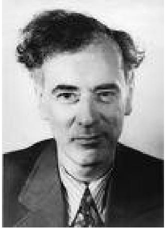
Tisza-Landau two-fluid hydrodynamics (1938-1941)



Tisza

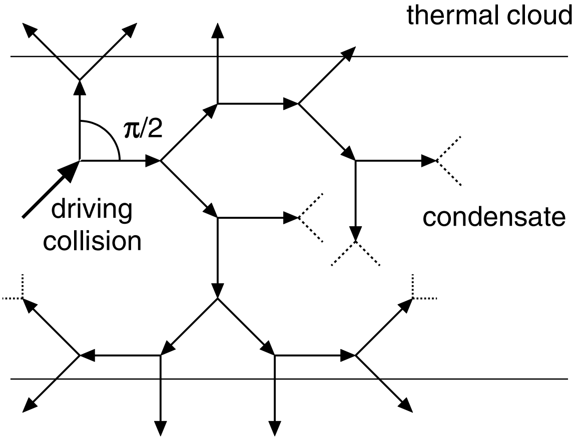


Landau

Superfluid: component of liquid which is associated with macroscopic occupation (BEC) of one single-particle state. Carries zero entropy, flows without dissipation with an irrotational velocity.

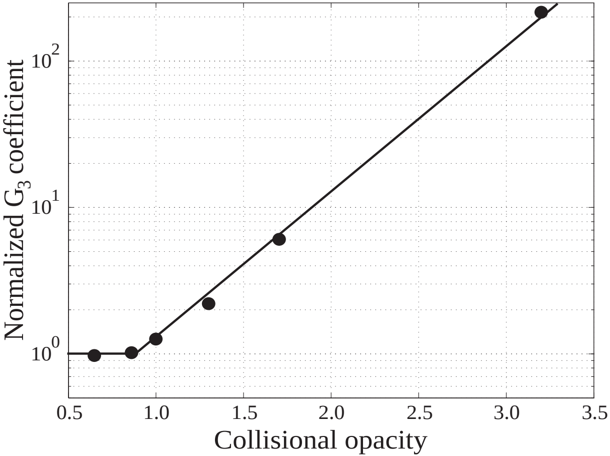
Normal fluid: comprised of incoherent thermal excitations, behaves like any fluid at finite temperatures in local thermodynamic equilibrium. This requires strong collisions.

Avalanches



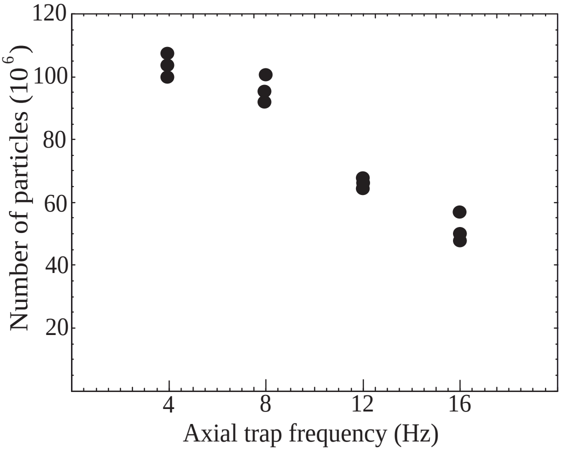
Limits the density in a ultra-cold atomic cloud

Enhanced 3-body decay due to avalanches



Collision opacity = sample size/mean free path

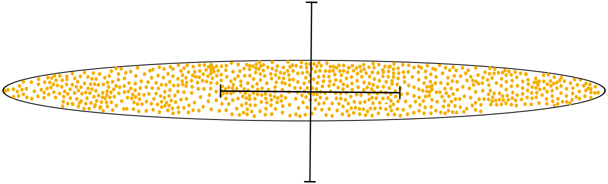
Number of particles



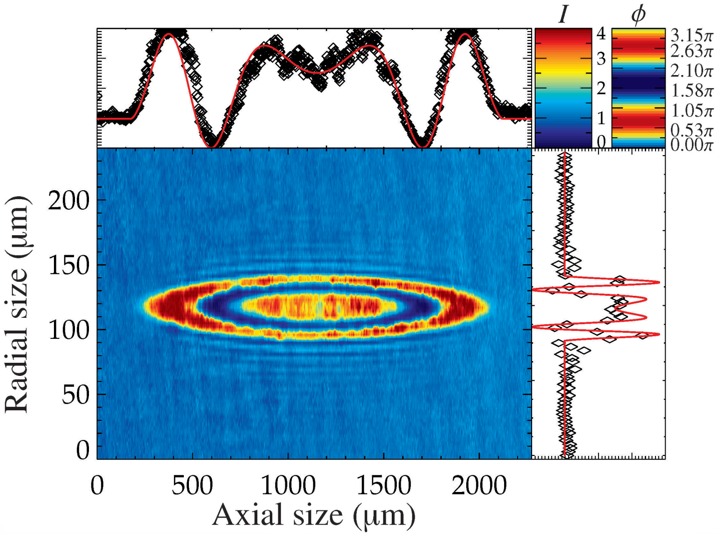
Solution: Prepare atoms in a cigar-shape trap

Hydrodynamic, cold thermal cloud

- Radial trap size $<$ mean free path $<$ axial size
- Collision rate $\approx$ 100–200 Hz,
  radial/axial trap frequencies $\approx$ 100 Hz/1 Hz
- Large atom number due to suppression of avalanches after three-body collisions



Phase contrast imaging – Images



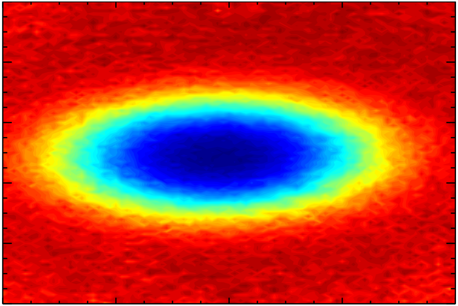
Heat conduction

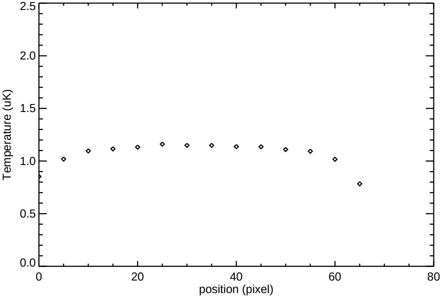
"Conduction of heat through a cold, trapped sample of atoms"

Heat conduction (Experiment)

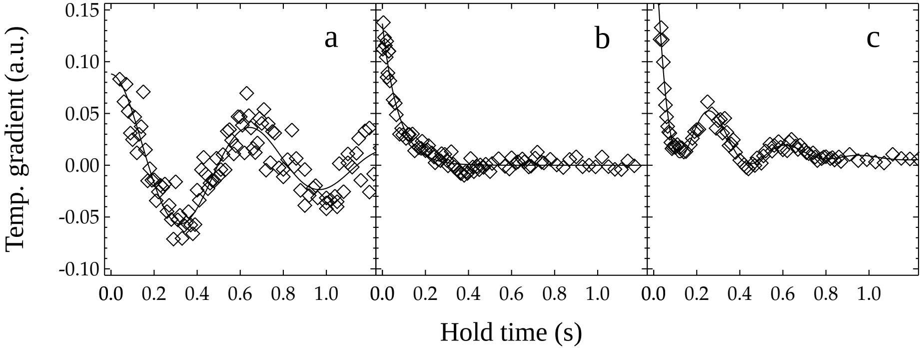
Thermal excitation

- Starting point: cold atomic cloud, $N \approx 4 \times 10^8$ atoms and $T \approx 1\ \mu$K.
- Apply Bragg pulse: introduce heat locally.
- Wait for rethermalisation.



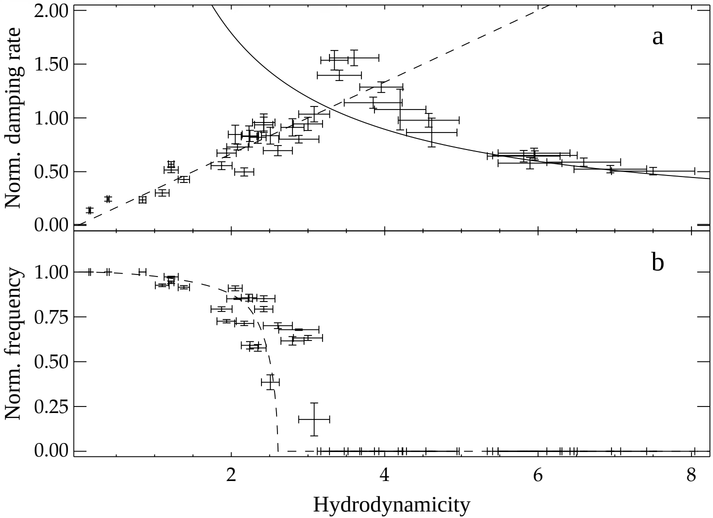


Heat gradient for different hydrodynamicity



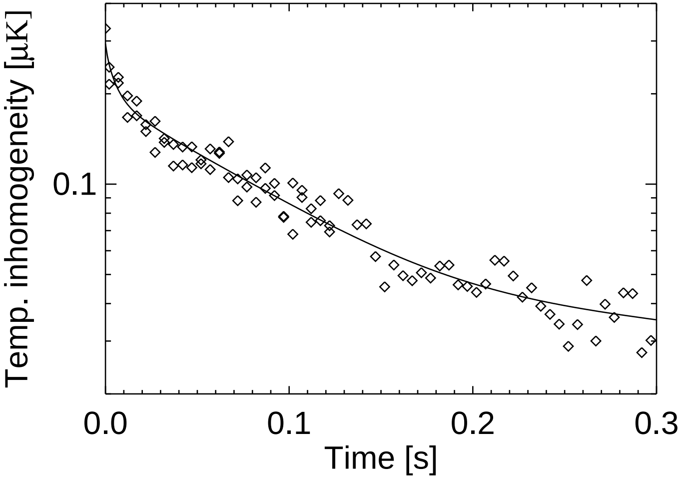
R. Meppelink *et al.*, *Enhanced Heat Flow in the Hydrodynamic Collisionless Regime*, Phys. Rev. Lett. **103**, 095301 (2009).

Thermal dipole mode



R. Meppelink *et al.*, *Enhanced Heat Flow in the Hydrodynamic Collisionless Regime*, Phys. Rev. Lett. **103**, 095301 (2009).

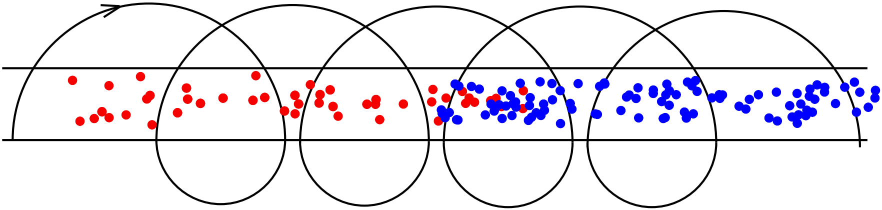
Thermal relaxation



Experimental: $\kappa = 6.4 \pm 0.3$

Results linear confinement

- Large heat conduction in radial collisionless regime!
- Caused by atoms spiraling around the beam (high angular momentum.)
- Large effective mean free path ⇒ heat conduction large!



Spin drag

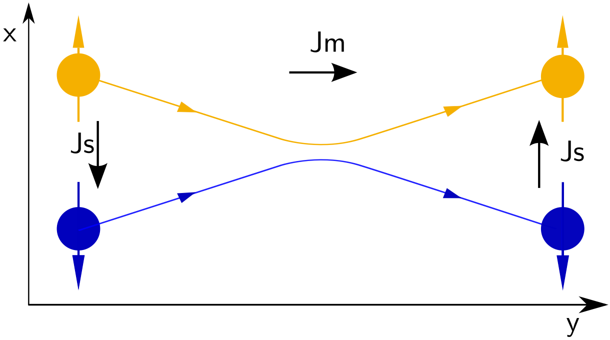
"Damping of spin motion in a thermal cloud"

Motivation

- Transport phenomena in solid state
  - Ohm's Law
  - Hall effect
  - Peltier effect
  - Seebeck effect
  - Drag
- Transport of electron charge
- Electrons have spin - spintronics
- Atoms have only spin and mass
- Clean measurement of spin drag!

For fermions: Sommer *et al.*, Nature **472**, 201 (2011)

Spin drag

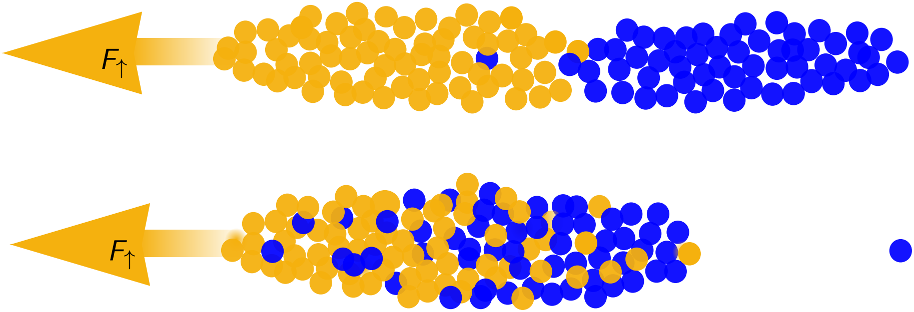


- Charge or mass current conserved
- Spin current switched direction
- Strong damping

Condensed matter *vs.* cold atoms

Condensed matter	Cold atoms
electrons	atoms
charge	mass
electric field	magnetic field gradient
electron spin	pseudo-spin $^1/_2$
e-e interactions	atom-atom interactions
e-photon interactions	-
e-impurities interactions	-
current	absorption imaging

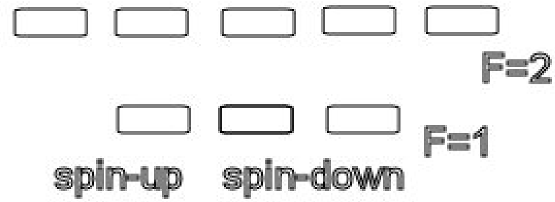
Spin drag



Drag - constant velocity difference

Realization

- Cool atoms in magnetic trap in spin *up* ($|F = 1, m = -1\rangle$)
- Atoms trapped in an optical dipole trap (spin independent trapping)
- Apply RF sweep $\rightarrow$ equal mixture spin *up* and spin *down* ($|F = 1, m = -1\rangle$, $|F = 1, m = 0\rangle$)

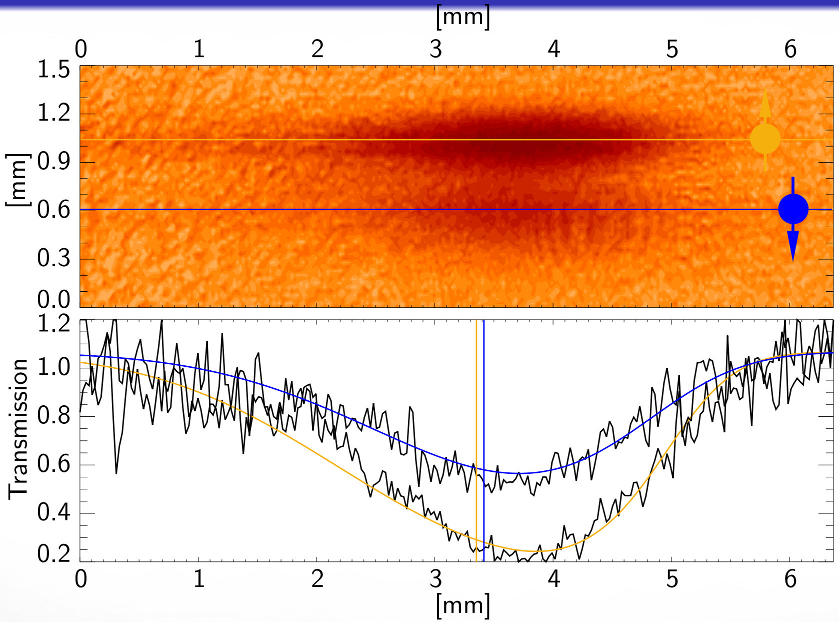


- Apply magnetic gradient in axial direction on spin *up*
- Apply Stern-Gerlach in radial direction for separation
- Apply absorption imaging for temperature and particle number detection

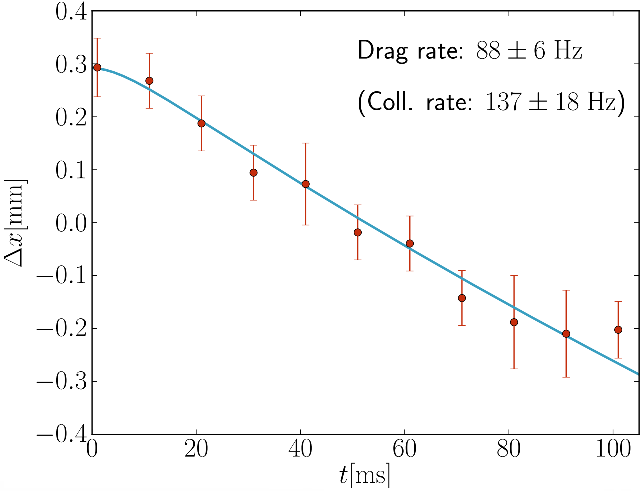
Experiment – Some general notes

- Optical dipole trap: confinement 3.5 Hz/835 Hz
- Na atoms in the trap: 4.5×10^8
- Temperature 1–10 μK
- Total collision rates $\gamma_{\text{coll}} \approx 1.4$ kHz
- Deep in hydrodynamic regime $\gamma_{\text{coll}}/\omega_{\text{ax}} > 60$
- Much larger than other experiments - essential in the experiment presented

Measurement – Constant force



Drag rate – Constant force



Spin drag

The differential equations describing the system

$$\begin{aligned} m\ddot{x}_\uparrow - m\gamma\Delta\dot{x} + \frac{\mathrm{d}V(x_\uparrow)}{\mathrm{d}x_\uparrow} &= F_\uparrow \\ m\ddot{x}_\downarrow + m\gamma\Delta\dot{x} + \frac{\mathrm{d}V(x_\downarrow)}{\mathrm{d}x_\downarrow} &= 0 \end{aligned}$$

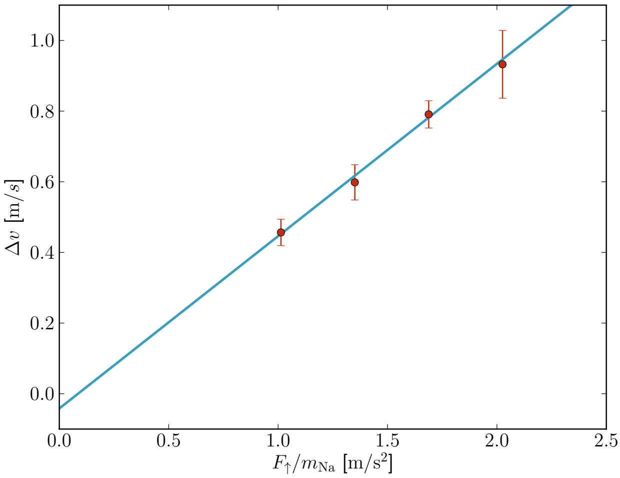
Steady state (neglect potential)

$$\gamma \approx \frac{F_\uparrow}{2m\dot{x}_{\uparrow\downarrow}}$$

Drag rate

$$\gamma \equiv \frac{\Gamma(\Delta\dot{x})}{f_\uparrow f_\downarrow\, m\, n_{\mathrm{tot}}\, \Delta\dot{x}_{\uparrow\downarrow}}$$

Linear regime – Constant force

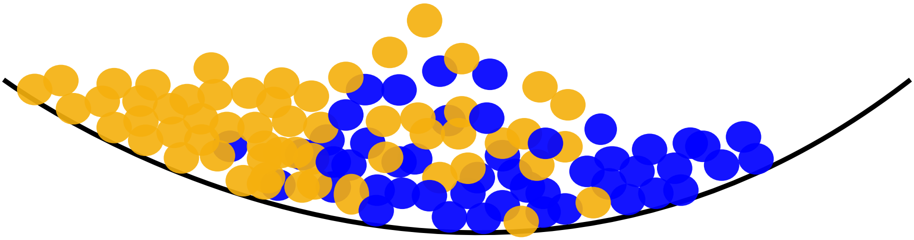


Spin Drag - Little Boson Collider

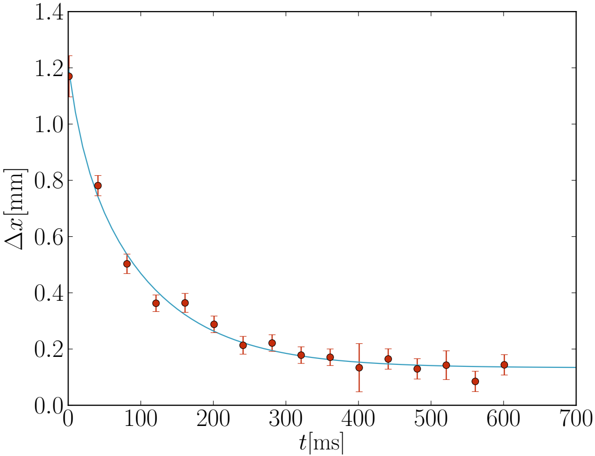
Problem: Low drag rate γ, clouds separate

Solution

- Separate the spin species in a trap
- Let system evolve

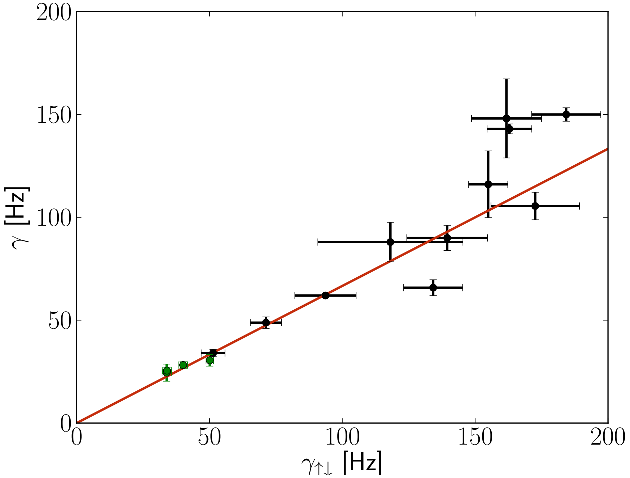


Spin Drag - Little Boson Collider



Drag rate deduced from damping constant: $\gamma = 2\omega_{\mathrm{ax}}^2/\beta$

Drag rate *vs.* Collision rate (Classical)



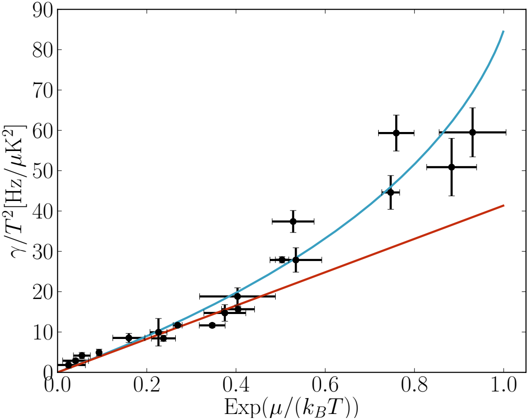
Ratio $\gamma/\gamma_{\uparrow\downarrow} = 2/3$ independent of temperature

L. Vichi, S. Stringari, Phys. Rev. A **60**, 4734 (1999)

Wait! There is more ...(degeneracy)

- Electrons are fermions
- Sodium atoms are bosons
- Collision rate is no longer a good measure
- Fugacity - a measure of phase-space density: $\mathrm{Exp}(\mu/k_{\mathrm{B}}T)$
- Drag rate scaled with $T^2 \Rightarrow$ temperature independent curve

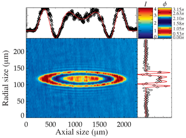
Drag rate *vs.* Fugacity (Quantum regime)



- Bose enhancement $\rightarrow$ precursor of the phase transition
- Predicted by ab initio theory - no fitted parameters

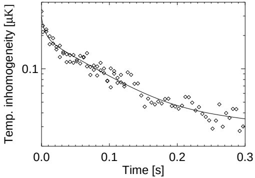
H.J. van Driel, R.A. Duine, & H.T.C. Stoof, Phys. Rev. Lett. **105**, 155301 (2010)

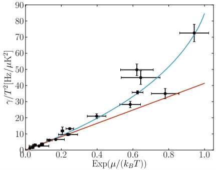
Take-away message



Phase contrast imaging:
hydrodynamic clouds!

Heat conduction:
transition from collisionless to hydrodynamic

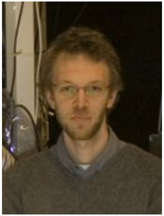


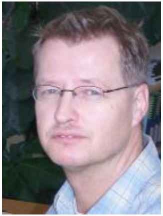


Bose enhancement of spin drag:
Agreement between theory and experiment

The Crew

Experiment



Silvio Koller – Alexander Groot – Pieter Bons – PvdS

Theory


Rembert Duine – Henk Stoof

It's gotta be tough to be a Texan