Universal Spin Transport in Strongly Interacting Fermi Gases

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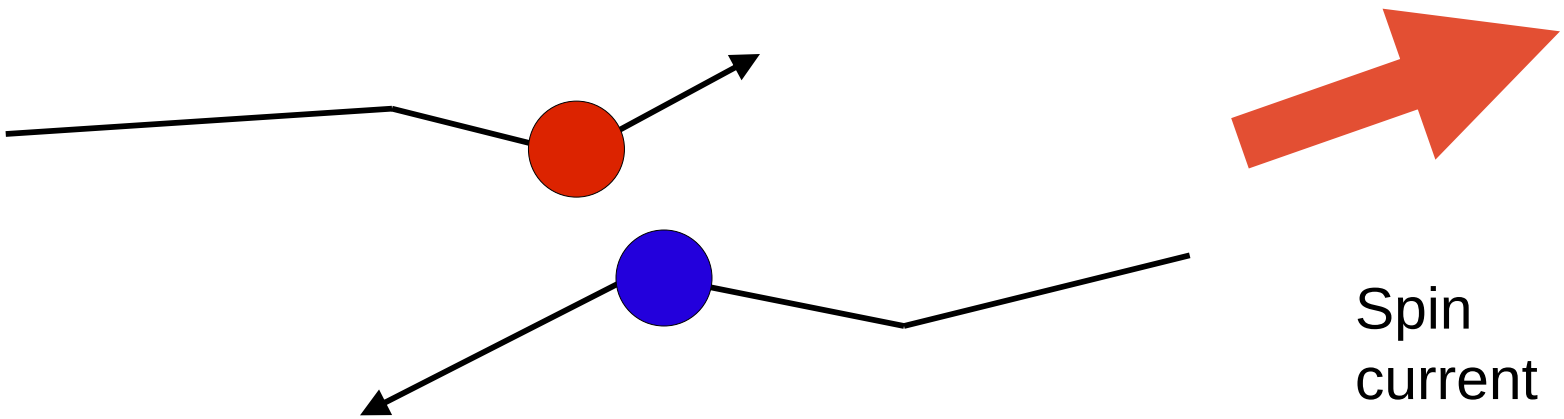
Spin Transport

- Net relative motion of atoms with different spin



- Damped due to collisions

Earlier experiments:
DeMarco & Jin, PRL **88**, 040405 (2002)
Du *et al,* PRL **101**, 150401 (2008)

Some theory:
D'Amico & Vignale. PRB **62**, 4853 (2000)
Parish & Huse. PRA **80**, 063605 (2009)
Bruun. NJP **13**, 035005 (2011)

Unitary Fermi Gas

- Ultracold (~100nK) fermionic atoms
- Interactions tunable by an applied magnetic field (Feshbach resonance)
  - Strongest interactions at s-wave resonance (unitarity)
- Superfluid transition
  - Vortices: Zwierlein *et al*. *Nature* **435**, 1047-1051 (2005)
- Nearly zero (quantum-scale) viscosity
  - Cao *et al*. *Science* **331**, 58-61 (2010)

Connection to Other Systems

- Spintronics
  - Magnetic data storage, information processing

- Quark-gluon plasma
  - Strongly interacting Fermions
  - Nearly zero viscosity:

    Elliptic flow in heavy ion collisions at RHIC[1] and ALICE at LHC[2]

    1. e.g. Adams *et al* (STAR). Nuc. Phys. A **757**, 102-183 (2005)

    2. Aamodt *et al* (ALICE). PRL **105**, 252302 (2010)

Spin transport parameters

- Spin drag coefficient Γ_{sd}

$$F_{\mathrm{sd}} = \frac{1}{2} M \Gamma_{\mathrm{sd}} v_{\mathrm{rel}}$$

  - D'Amico & Vignale. PRB **62**, 4853 (2000)
- Spin diffusivity D_s

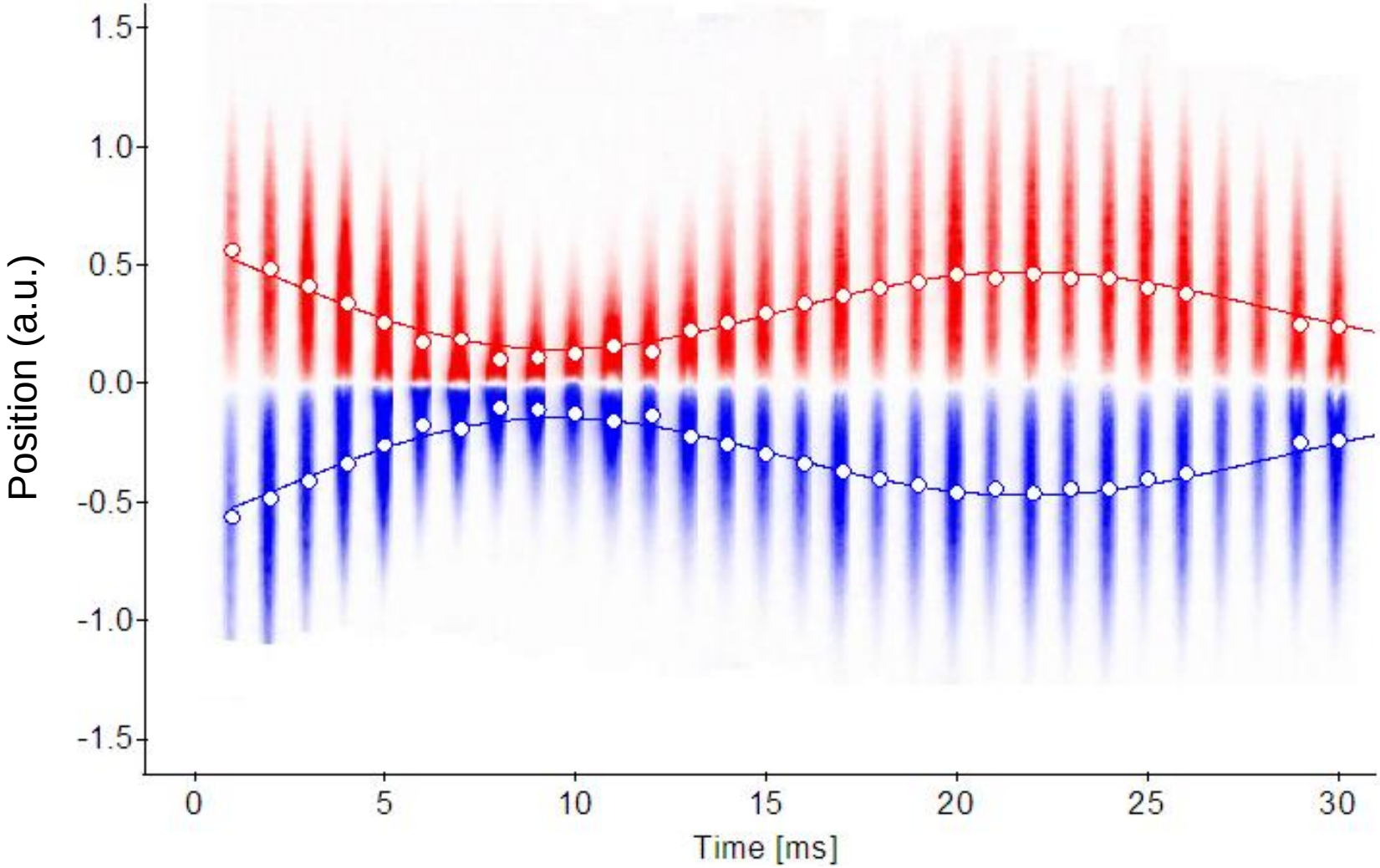
$$J_s = -D_{\mathrm{s}} \frac{\partial (n_\uparrow - n_\downarrow)}{\partial z}$$

  - Parish & Huse. PRA **80**, 063605 (2009)
  - Bruun. NJP **13**, 035005 (2011)

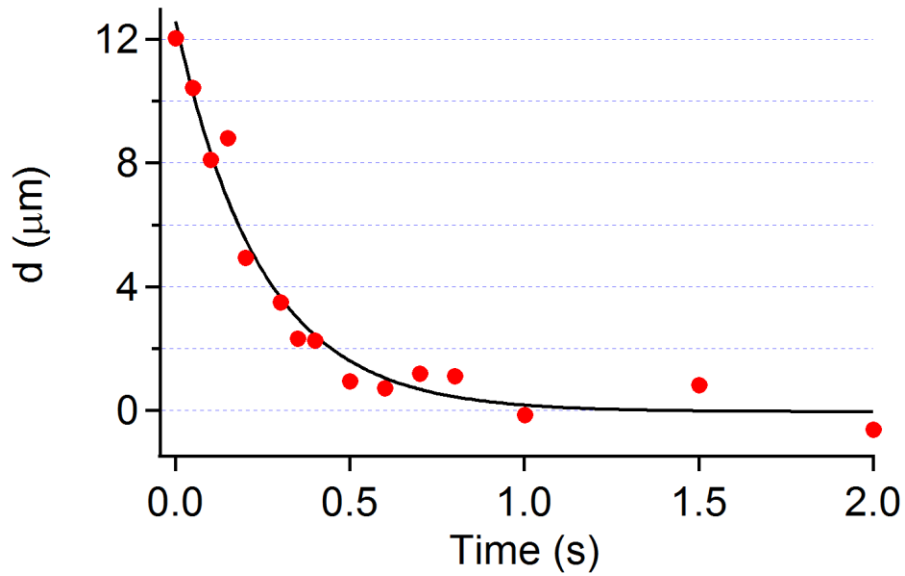
Experiment

- ^{6}Li trapped in a magnetic / optical dipole trap
- 50/50 mixture of two spin states
- Separate the spin states via magnetic gradient pulses
- Rapidly set the magnetic field to the Feshbach resonance
- Apply cooling or heating
- Observe the evolution

Collision of Two Fermi Gases



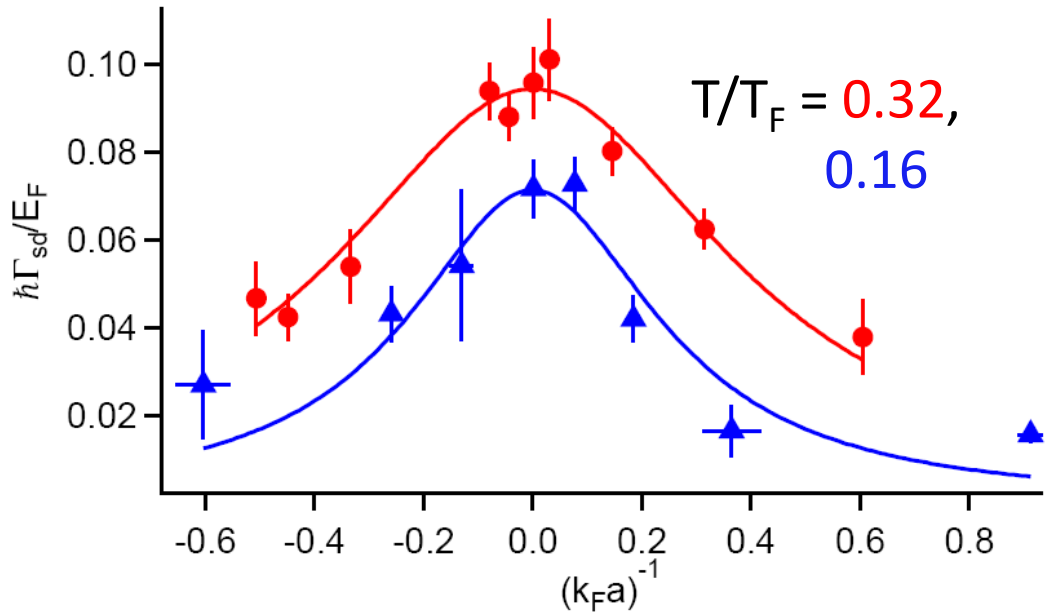
Measuring Spin Drag



$$\ddot{d} + \Gamma_{sd}\dot{d} + \omega^2 d = 0$$

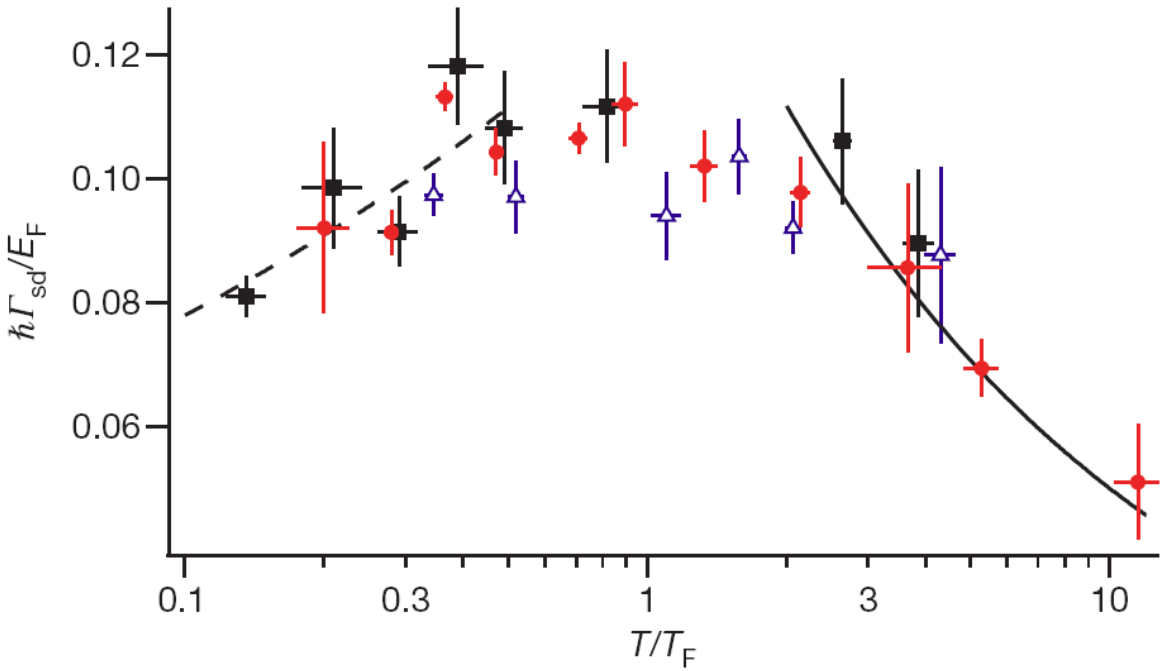
Overdamped, use an exponential fit to get Γ_{sd}

Spin Drag vs Interaction Strength



- Maximum drag on resonance

Results for Spin Drag: Unitarity



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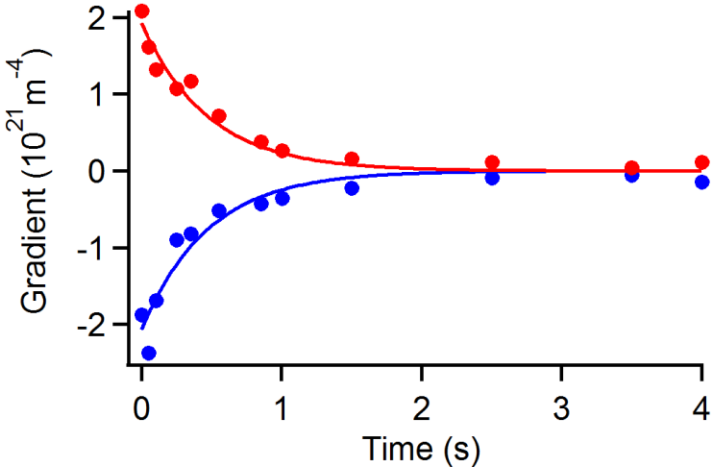
- Maximum drag near T_F

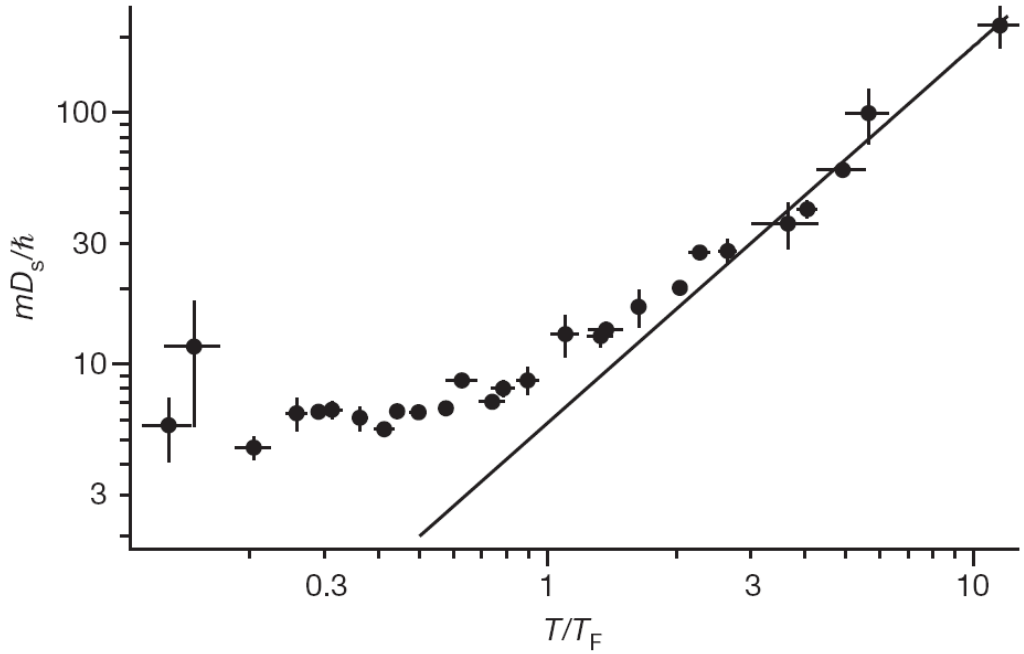
Measuring Spin Diffusivity

- D_s from spin density gradient and equilibration time



Gradient decays at the same rate as *d*

Spin Diffusion at Unitarity

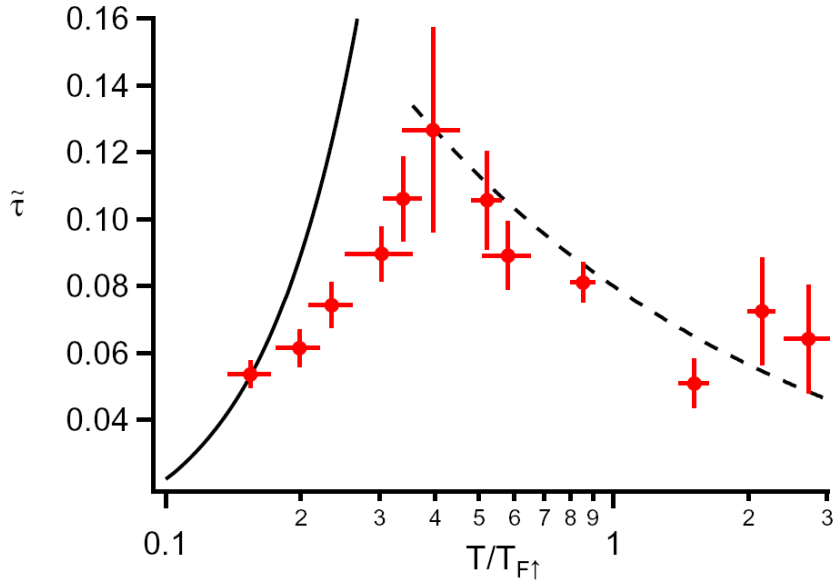


Nature **472**, 201 (2011)

- Minimum D_s = 6.3(3) $\hbar/m$ for $T < 0.5\ T_F$
- $T^{3/2}$ scaling for $T > 2\ T_F$
  - unconstrained fit: $T^{1.4(1)}$

Highly Polarized Gas

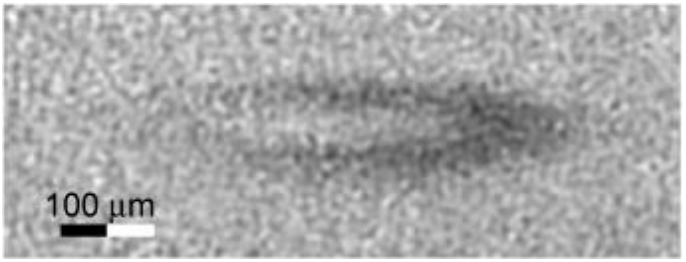
- Same procedure, but with a 90/10 mixture
- More Pauli blocking than in 50/50 case

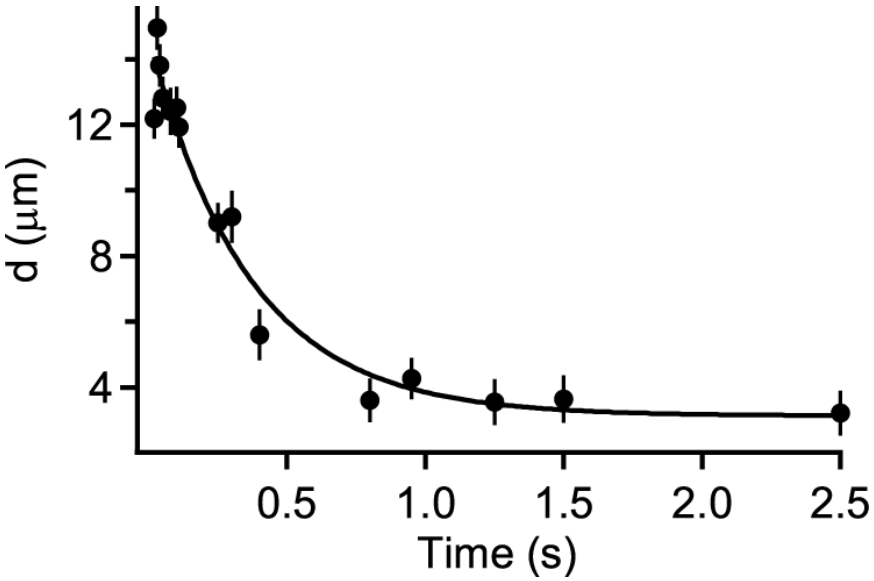


A. Sommer et al New J. Phys **13**, 055009 (2011)
Solid line: Bruun et al., PRL **100**, 240406 (2008)

Spin Transport in SF

- 60/40 mixture
- Below T_C: superfluid core





- Still overdamped.
- Collisions at SF-Normal interface or inside the SF?

Conclusions

- Spin drag is strong at unitarity
- Measured spin drag and spin diffusivity vs temperature
- Maximum spin drag near T_F
- Minimum spin diffusion below T_F
- Stronger Pauli blocking in highly-polarized gas
- Sping drag also observed in a superfluid

Acknowledgements

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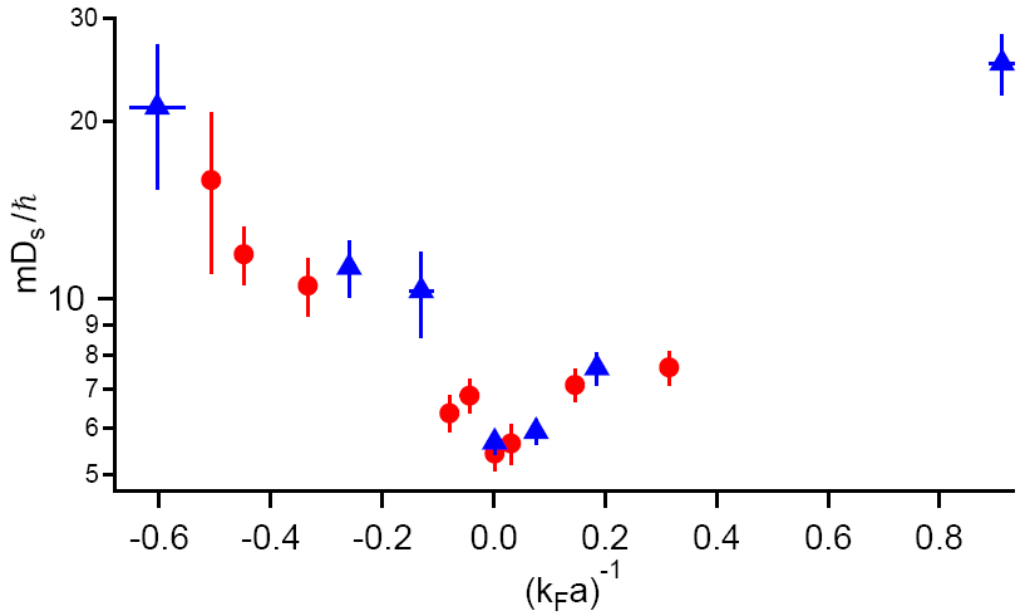
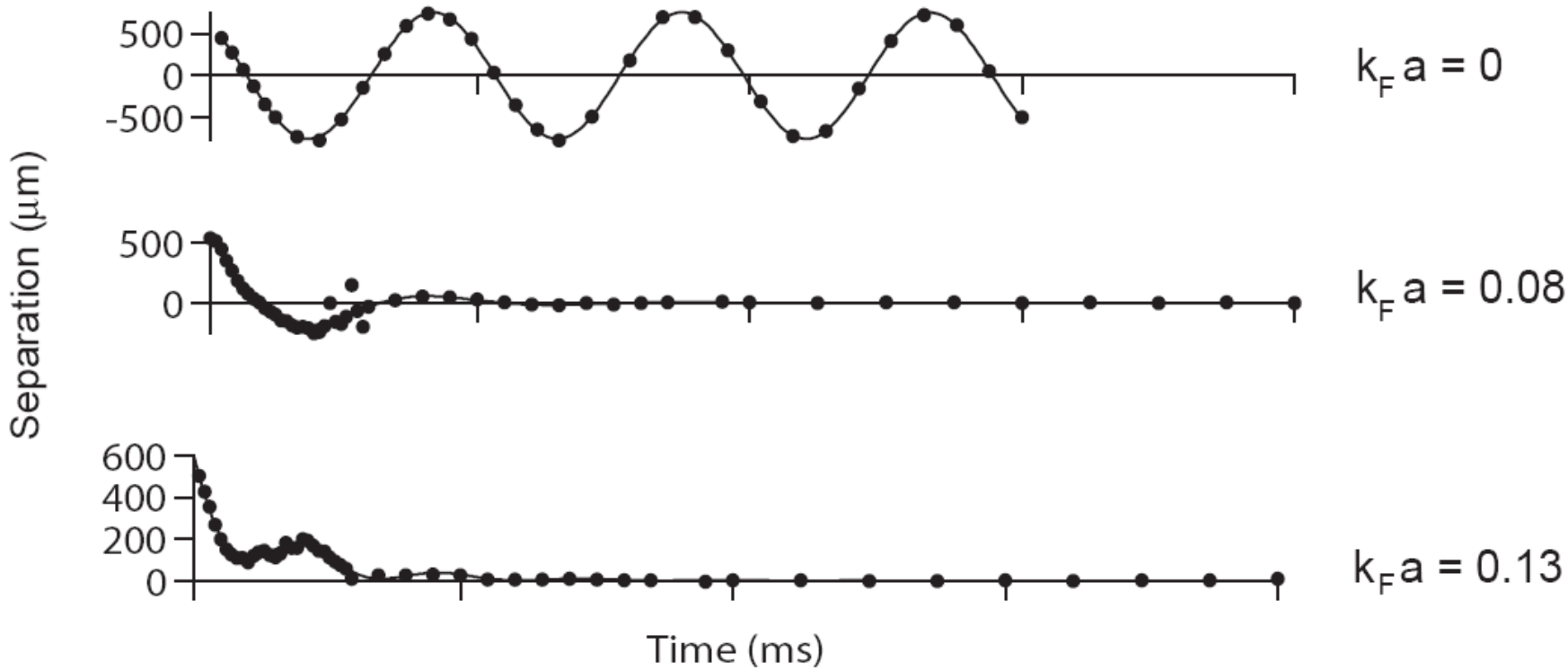
Spin Diffusion vs Interaction Strength



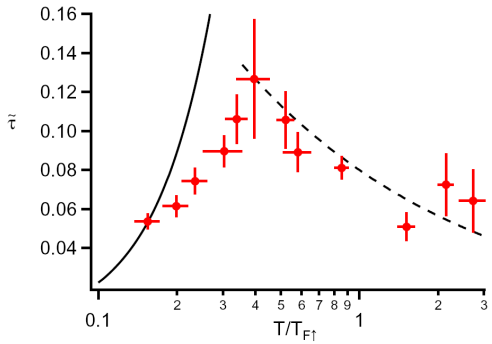
- Minimum diffusivity on resonance

Varying Interactions

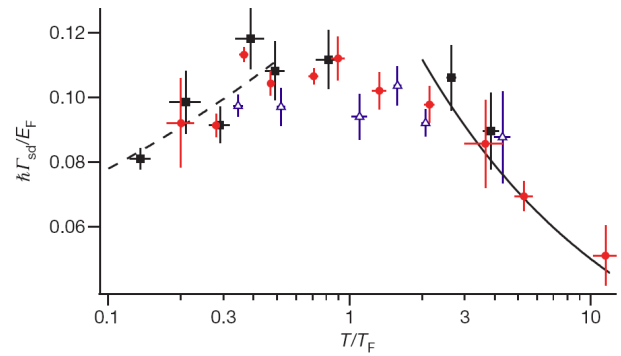


- More Pauli blocking in the polaron case

Polaron damping



50/50 Spin drag



Drag reduction from peak down to 0.15 T_F:

Polaron :
51(6)% reduction

Balanced Gas:
26(4) % reduction

Spin Susceptibility

- Spin conductivity: $\sigma_{\mathrm{s}} = n/(m\Gamma_{\mathrm{sd}})$

- Einstein relation: $\chi_{\mathrm{s}} = \sigma_s/D_{\mathrm{s}}$

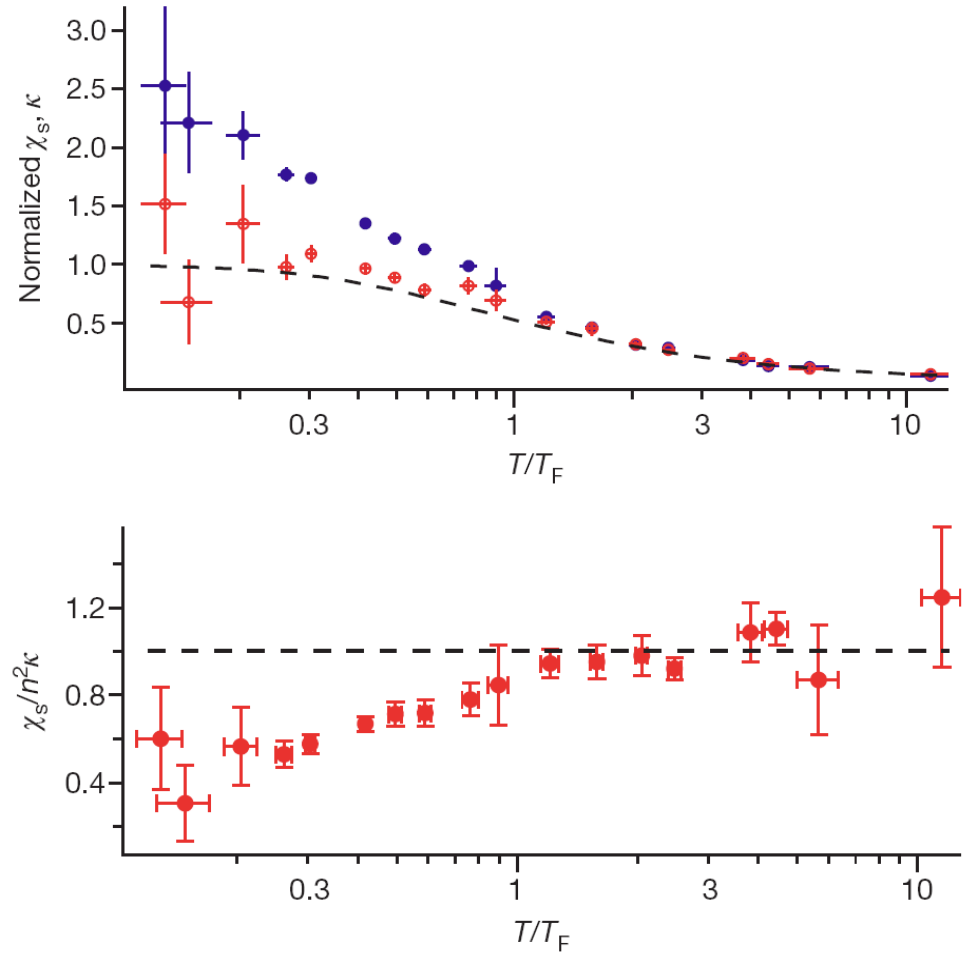
- Derivation – Magnetization in a spin-dependent potential:

spin-diffusion $\leftrightarrow$ *spin-conduction*

$$0 = -D_s\nabla(n_1 - n_2) + \sigma_s\nabla(\mu_1 - \mu_2)$$

Spin Susceptibility

Susceptibility < Compressibility for $T < T_F$



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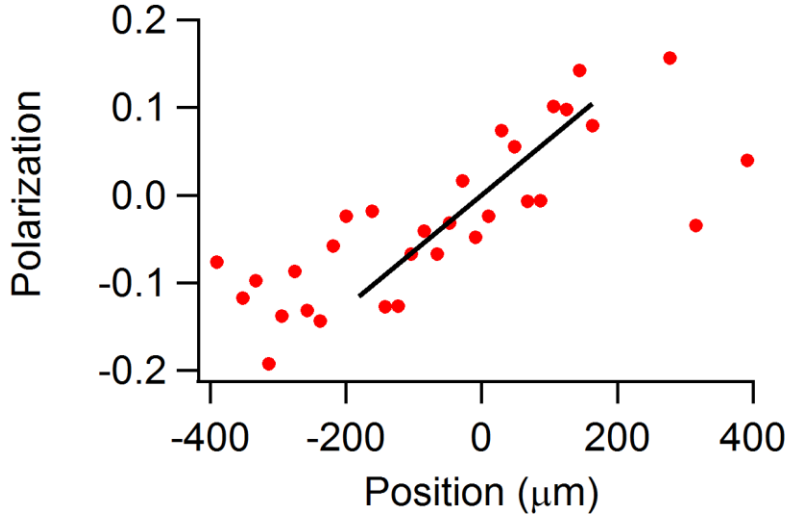
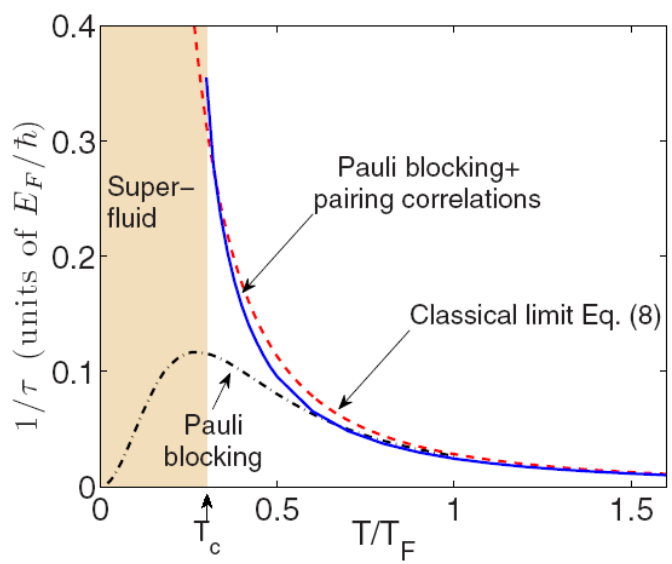
Getting the gradient



Expectations

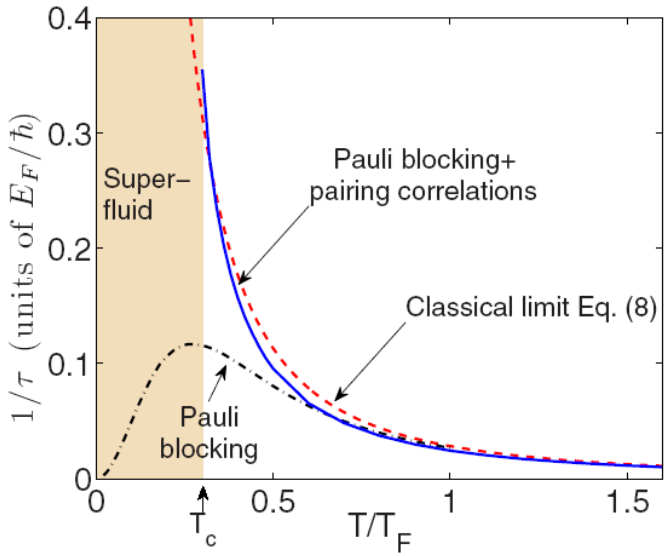
- Known power laws at high temperature
- For $T \approx T_F$, expect $D_s \approx \hbar/m$
- For $T \ll T_F$, correlations may influence transport

See:
Riedl et al., PRA **78**, 053609 (2008)
Bruun and Smith PRA **72** 043605 (2005)

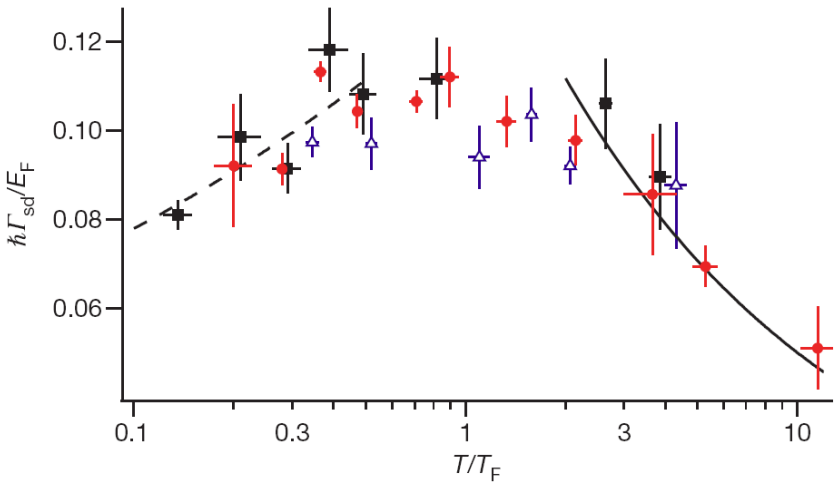


Comparison

- No enhanced spin drag at low T



Riedl et al., PRA **78**, 053609 (2008)



Sommer et al, Nature **472**, 201 (2011)

Relation to Homogeneous Values

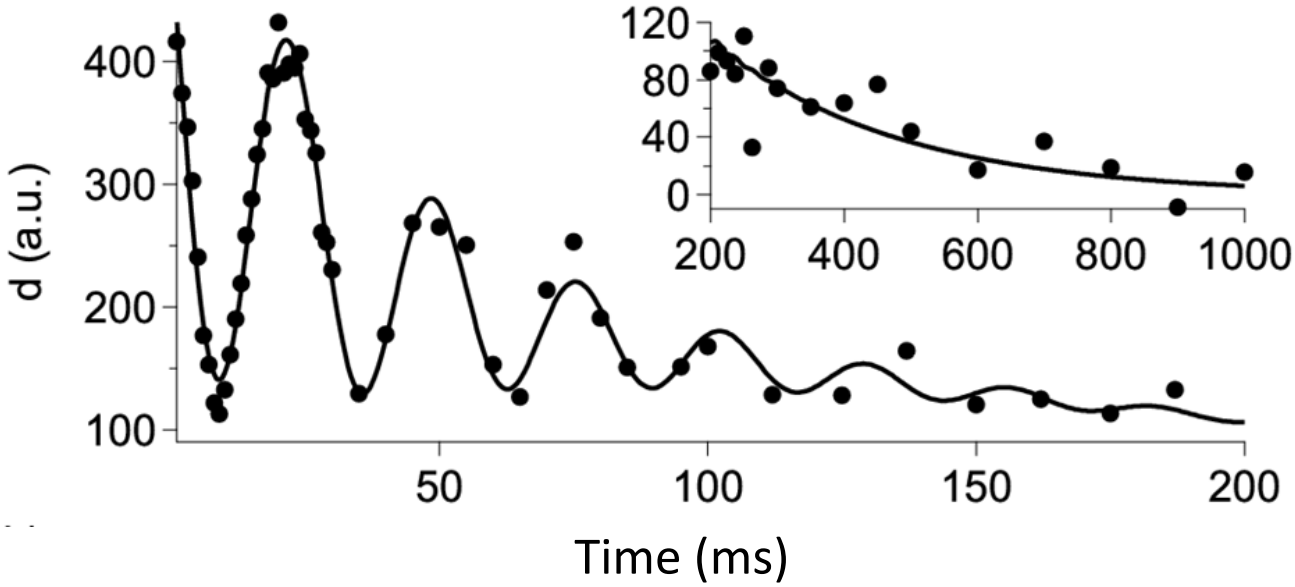
- Non-uniform density and average velocity
- Trap average: $\langle G \rangle = \frac{1}{N} \int \mathrm{d}^3 r \, G(\vec{r}) \, n(\vec{r})$
- Measured values:

$$\Gamma_{\mathrm{sd}} = \frac{\langle \tilde{\Gamma}_{\mathrm{sd}} u_{z,\mathrm{rel}} \rangle}{\langle u_{z,\mathrm{rel}} \rangle}$$

$$D_{\mathrm{s}} = \tilde{D}_{\mathrm{s}}(0) \frac{\langle u_{z,\mathrm{rel}} \rangle}{u_{z,\mathrm{rel}}(0)}$$

$$\chi_{\mathrm{s}} = \frac{\tilde{\Gamma}_{\mathrm{sd}}(0) u_{z,\mathrm{rel}}(0)}{\omega_z^2 d} \tilde{\chi}_{\mathrm{s}}(0)$$

Center of Mass Difference



- Bouncing at early times
- Exponential relaxation at late times