SPIN DRAG IN A PERFECT FLUID

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Group Meeting
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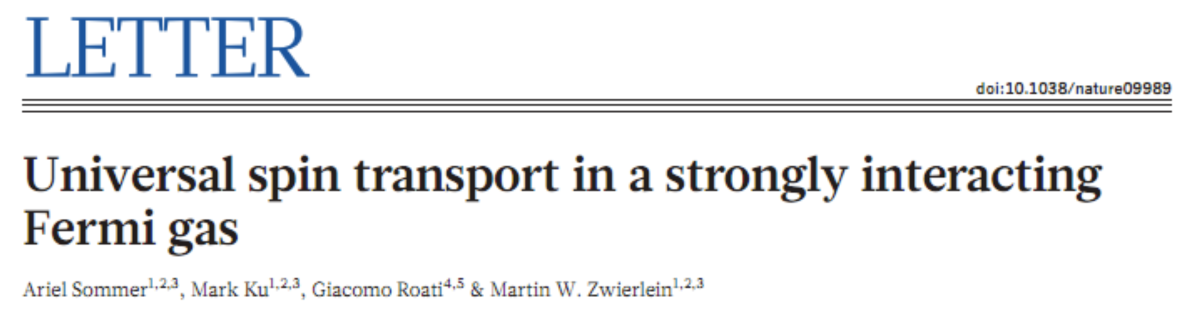

LETTER

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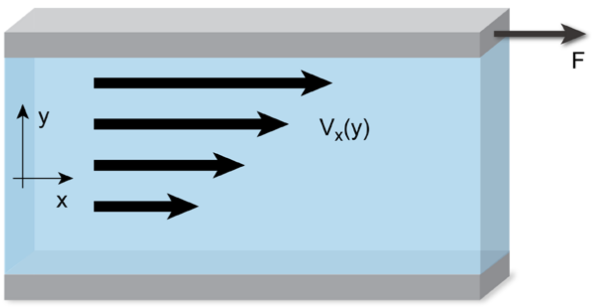
Universal spin transport in a strongly interacting Fermi gas

Ariel Sommer[1,2,3], Mark Ku[1,2,3], Giacomo Roati[4,5] & Martin W. Zwierlein[1,2,3]

MOTIVATION

- Understanding of transport of mass + spin in strongly interacting quantum fluids important for superconductivity to nuclear physics
  - Also “spintronics” uses spin currents, so this research is useful
- Mass flow has been observed to have extremely low viscosity, what about spin flow?

COLLISIONS + VISCOSITY



- Imagine: move the top plate to the right
- If the fluid is viscous, the bottom plate will feel a force to the right
- How does this happen?
- Top plate causes nearby atoms to acquire an average velocity to the right
- Atoms can move downwards to transmit force to the right through neighbouring sheets of atoms
- If the atoms can move easily without colliding with each other (large mean free path), a large force is transmitted to the bottom plate. The viscosity is high.
- Short mean free path => low viscosity

COLLISIONS + VISCOSITY

- low viscosity = small mean free path = high collision rate
- Strongly interacting implies high collision rate/low viscosity
- Cool atoms down, collision rates between two spins (fermions) are reduced due to Pauli blocking
  - Viscosity should increase @ low T for fermions
- But viscosity (of mass flow) is observed to decrease @ low T…
  - Pairs of up + down spins form bosons, which collide @ enhanced rate

- What if we remove pairing? Viscosity of individual spins in a strongly interacting system?

THE EXPERIMENT

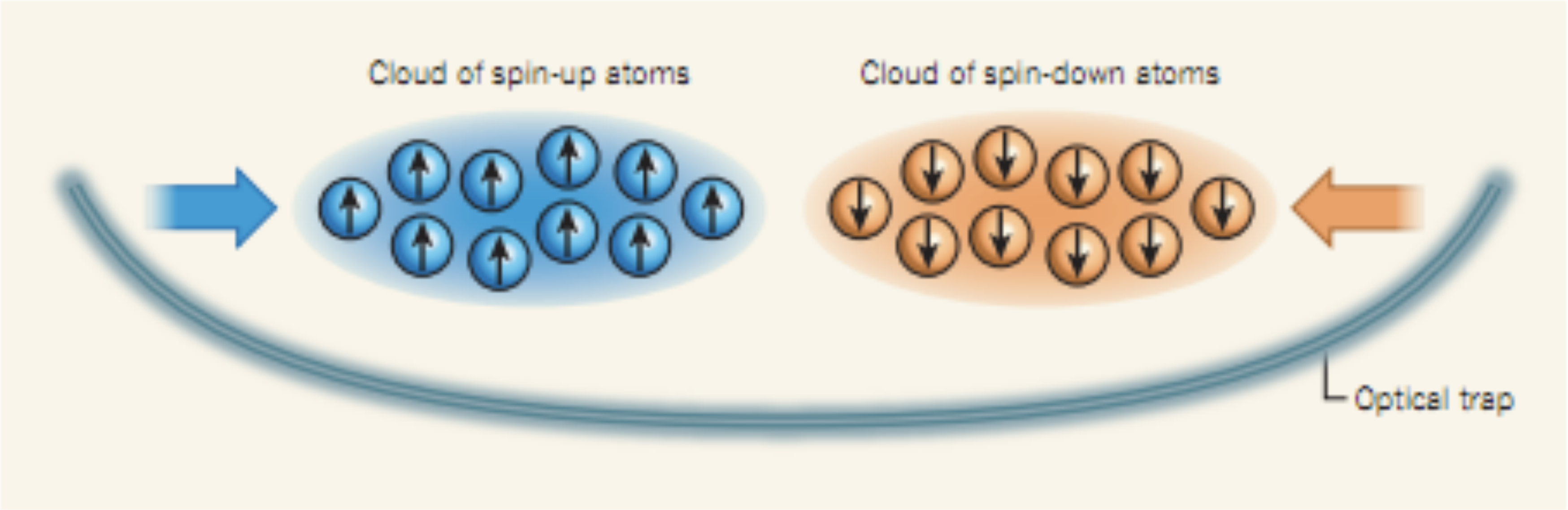


Figure 1 | Bouncing atomic clouds in an optical trap. Sommer *et al.*[2] used a magnetic-field gradient to separate clouds of spin-up and spin-down fermionic atoms in an optical trap. When the clouds were released, by turning off the magnetic-field gradient, they were pushed towards each other by the optical trap, which acts like a bowl. The strongly interacting clouds bounce off each other several times and then penetrate each other slowly, on a timescale of a second, demonstrating extremely high resistance to spin flow.

THE EXPERIMENT

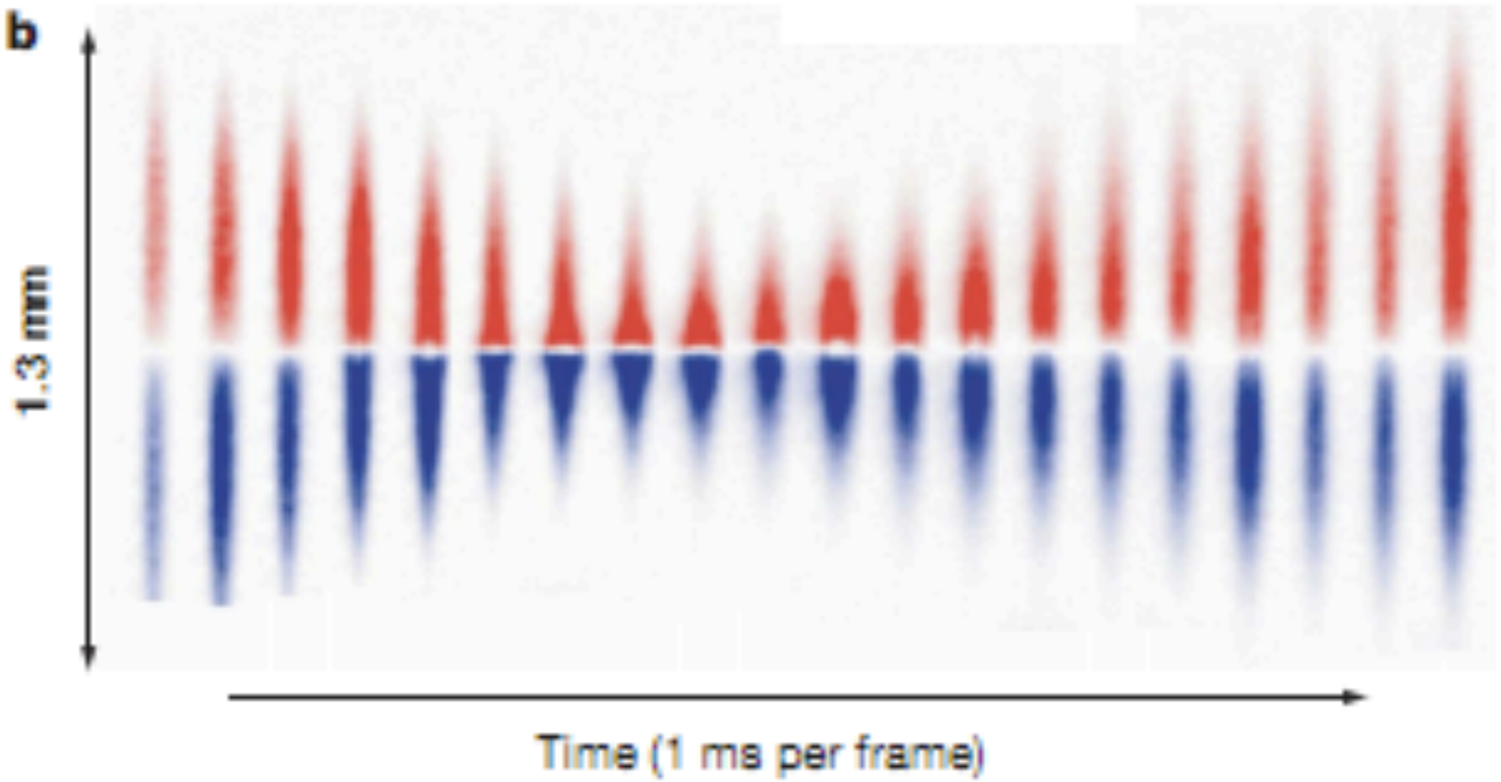
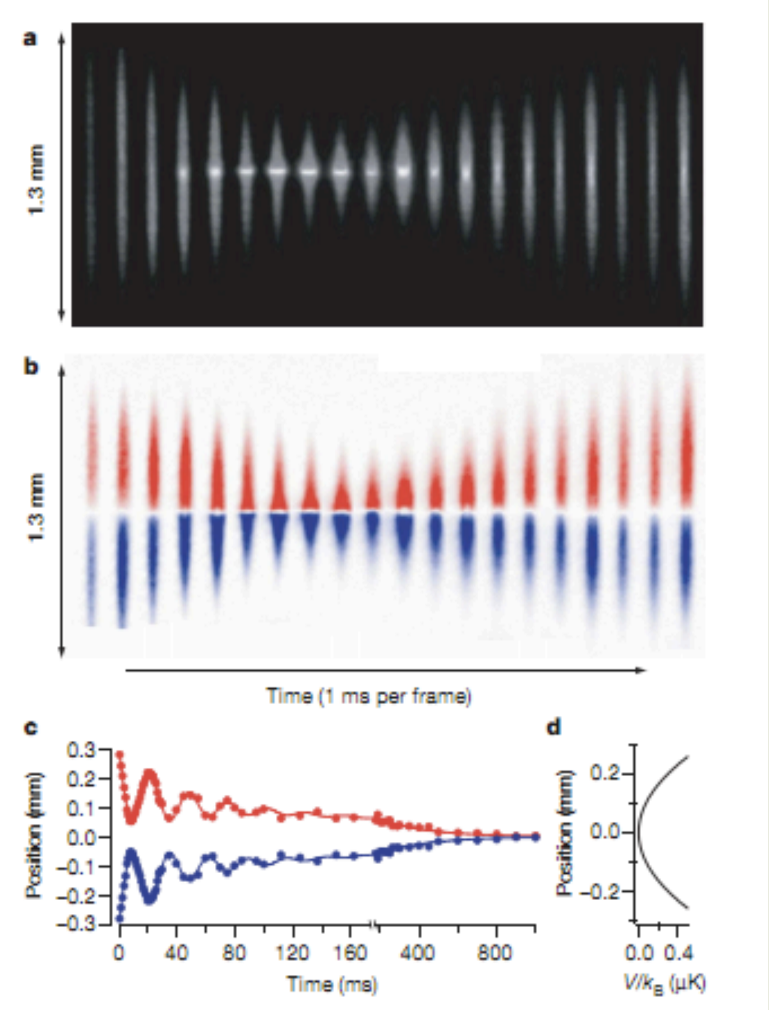


FIGURE 1



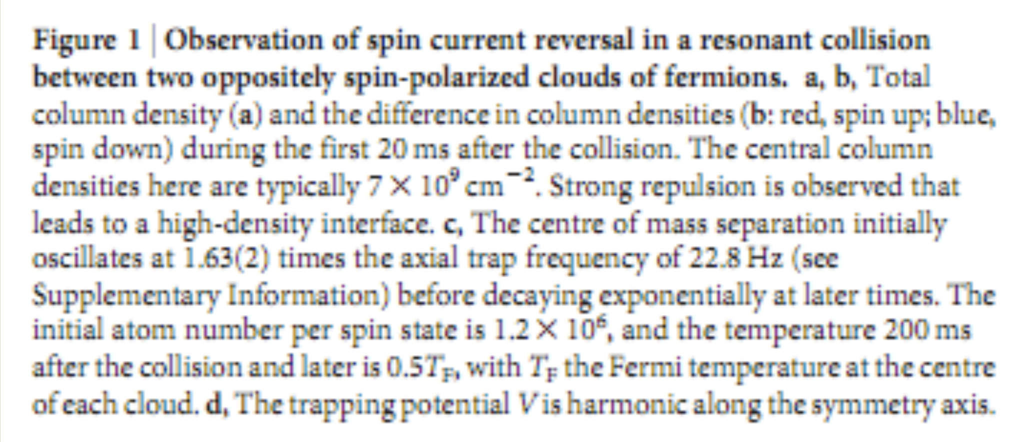
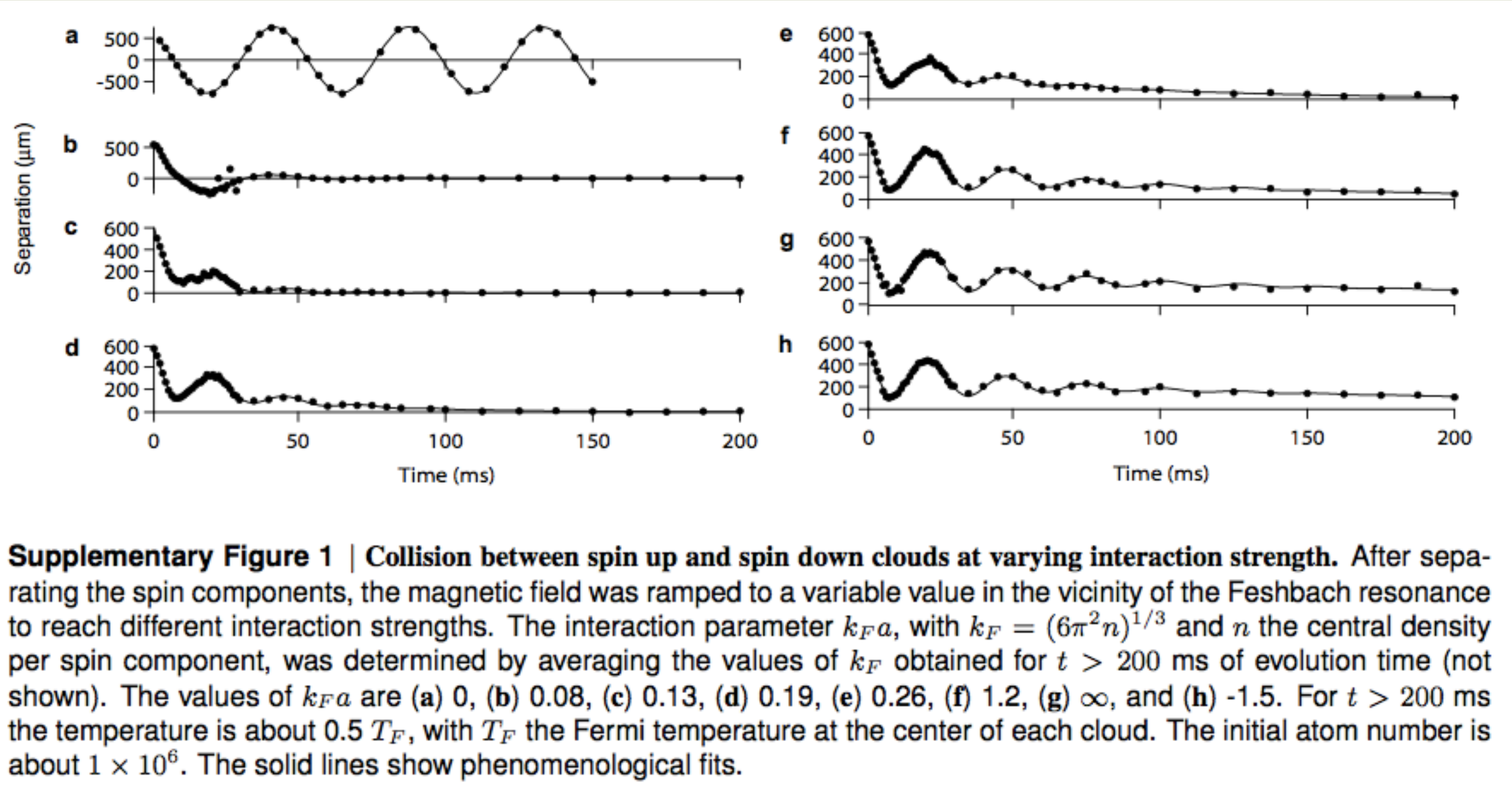


Figure 1 | Observation of spin current reversal in a resonant collision between two oppositely spin-polarized clouds of fermions. **a, b,** Total column density (**a**) and the difference in column densities (**b**: red, spin up; blue, spin down) during the first 20 ms after the collision. The central column densities here are typically 7×10^9 cm^{-2}. Strong repulsion is observed that leads to a high-density interface. **c,** The centre of mass separation initially oscillates at 1.63(2) times the axial trap frequency of 22.8 Hz (see Supplementary Information) before decaying exponentially at later times. The initial atom number per spin state is 1.2×10^6, and the temperature 200 ms after the collision and later is $0.5T_F$, with T_F the Fermi temperature at the centre of each cloud. **d,** The trapping potential V is harmonic along the symmetry axis.

SUPPLEMENTARY FIGURE 1

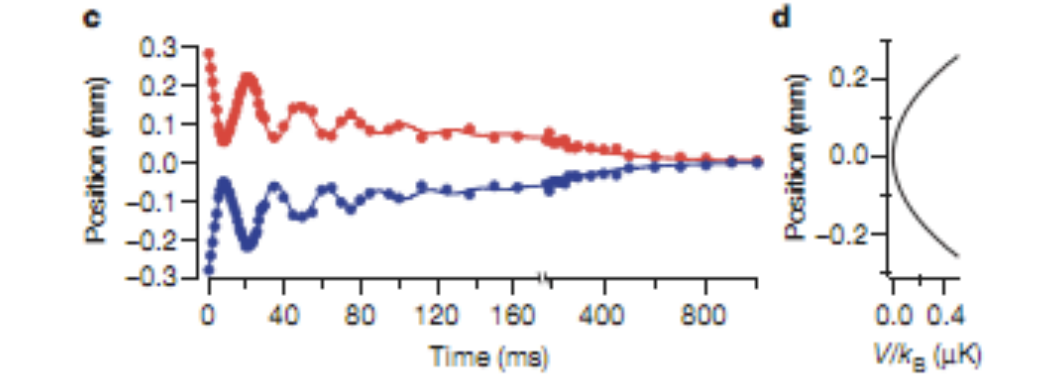


Supplementary Figure 1 | **Collision between spin up and spin down clouds at varying interaction strength.** After separating the spin components, the magnetic field was ramped to a variable value in the vicinity of the Feshbach resonance to reach different interaction strengths. The interaction parameter $k_F a$, with $k_F = (6\pi^2 n)^{1/3}$ and n the central density per spin component, was determined by averaging the values of k_F obtained for $t > 200$ ms of evolution time (not shown). The values of $k_F a$ are (**a**) 0, (**b**) 0.08, (**c**) 0.13, (**d**) 0.19, (**e**) 0.26, (**f**) 1.2, (**g**) ∞, and (**h**) -1.5. For $t > 200$ ms the temperature is about 0.5 T_F, with T_F the Fermi temperature at the center of each cloud. The initial atom number is about 1×10^6. The solid lines show phenomenological fits.

SPIN DRAG COEFFICIENT

- Spin drag coefficient, Γ_{sd}
  - Rate of momentum transfer between opposite spin atoms
    - (obviously related to collision rate)
  - Classically (for high T),

$$\Gamma_{\mathrm{sd}} \propto n\sigma v \propto \frac{E_F}{\hbar}\left(T/T_F\right)^{-1/2}$$



  - To extract G from data
    - Fit exponential

$$\Gamma_{\mathrm{sd}}\dot{d} + \omega_z^2 d = 0$$

$$\Gamma_{\mathrm{sd}} = \omega_z^2 \tau.$$

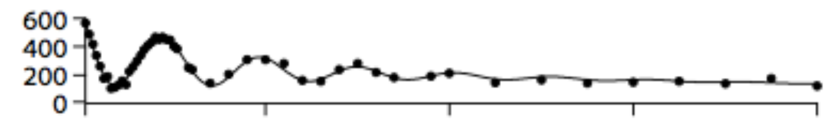
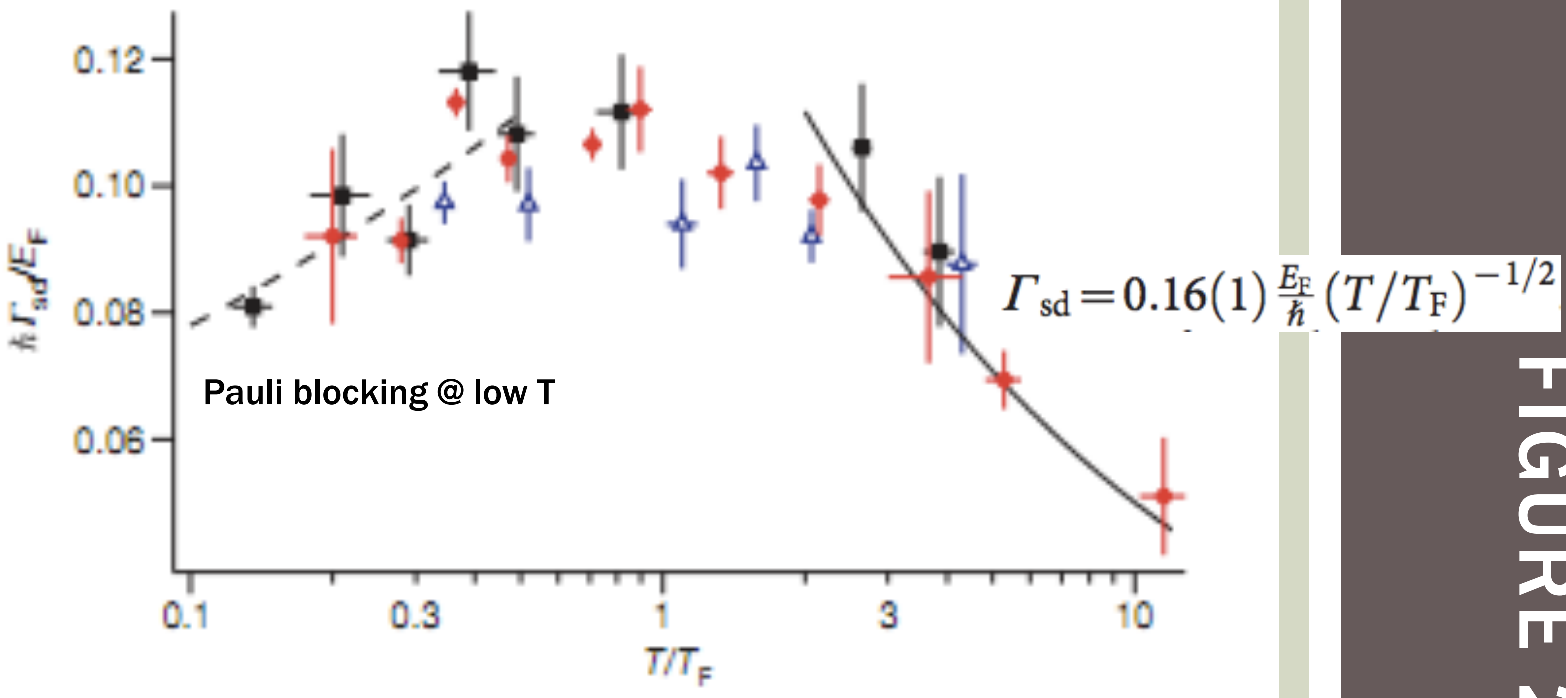


FIGURE 2



Pauli blocking @ low T

$$\Gamma_{sd} = 0.16(1)\,\frac{E_F}{\hbar}\,(T/T_F)^{-1/2}$$

Figure 2 | Spin drag coefficient of a trapped Fermi gas with resonant interactions. The spin drag coefficient Γ_{sd} is normalized by the Fermi rate $E_F/\hbar$ at the trap centre, whereas the temperature is normalized by $T_F = E_F/k_B$. We find agreement between measurements taken at three different axial trapping frequencies, 22.8 Hz (red circles), 37.5 Hz (blue triangles) and 11.2 Hz (black squares). The data for $T/T_F > 2$ fit to a $T^{-1/2}$ law (solid line). Dashed line, a power law fit for $T/T_F < 0.5$ to show the trend. Each point is a mean from typically three determinations of Γ_{sd}, each obtained from a time series of about 30 experimental runs and weighted according to the standard deviation from fitting error and shot to shot fluctuations. Error bars, ±1s.e.

SPIN DIFFUSIVITY

Spin diffusivity

$$J_s = -D_s \frac{\partial(n_\uparrow - n_\downarrow)}{\partial_z}$$

Gradient of spin density

Spin current

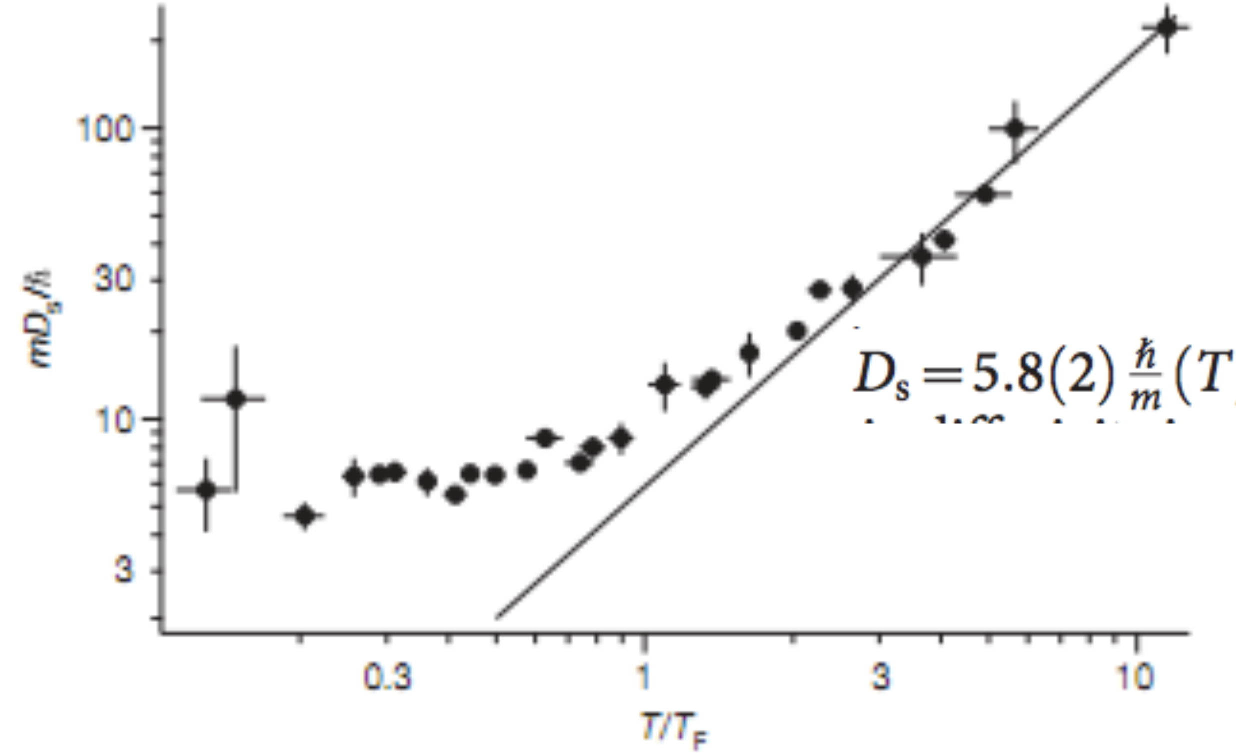
$$J_s = \tfrac{1}{2}(n_\uparrow + n_\downarrow)\dot{d}$$

Trap averaged velocity

@ high T, on resonance

$$D_s \propto v/n\sigma \propto T^{3/2}$$

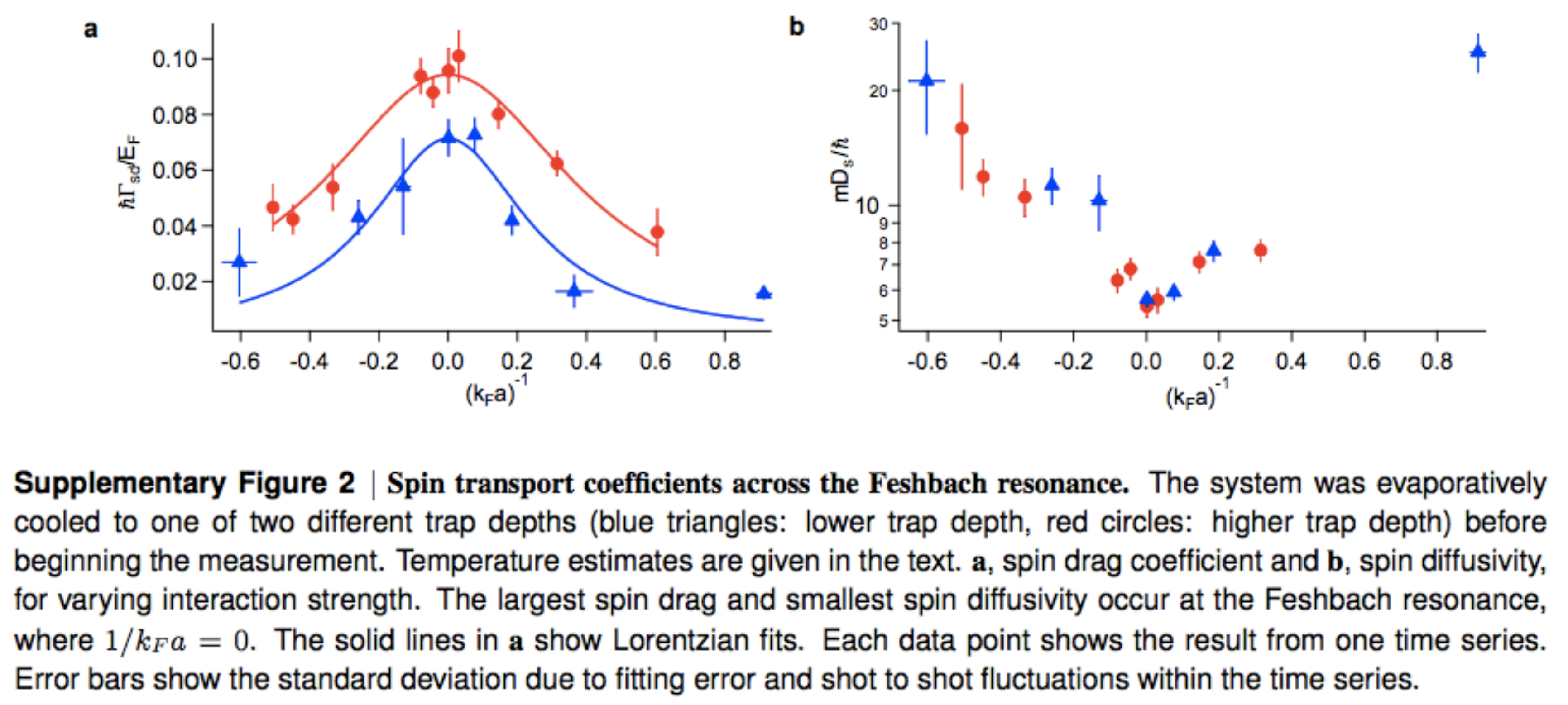
FIGURE 3



$$D_s = 5.8(2)\,\frac{\hbar}{m}\,(T/T_F)^{3/2}$$

Figure 3 | Spin diffusivity of a trapped Fermi gas. Shown is the spin diffusivity on resonance (D_s, normalized by $\hbar/m$; filled circles) as a function of the dimensionless temperature T/T_F. At high temperatures, D_s obeys the universal $T^{3/2}$ behaviour (solid line). At low temperatures, D_s approaches a constant value of $6.3(3)\hbar/m$ for temperatures below about $0.5T_F$, establishing the quantum limit of spin diffusion for strongly interacting Fermi gases. Error bars, ±1s.e.

SUPPLEMENTARY FIGURE 2



Supplementary Figure 2 | **Spin transport coefficients across the Feshbach resonance.** The system was evaporatively cooled to one of two different trap depths (blue triangles: lower trap depth, red circles: higher trap depth) before beginning the measurement. Temperature estimates are given in the text. **a**, spin drag coefficient and **b**, spin diffusivity, for varying interaction strength. The largest spin drag and smallest spin diffusivity occur at the Feshbach resonance, where $1/k_Fa = 0$. The solid lines in **a** show Lorentzian fits. Each data point shows the result from one time series. Error bars show the standard deviation due to fitting error and shot to shot fluctuations within the time series.

They claim that the observation of an increase in diffusivity and decrease in drag for positive scattering length means that there is no ferromagnetic state in repulsive Fermi gases (apparently, diffusion should stop entirely).

SPIN SUSCEPTIBILITY

- Spin susceptibility describes the spin response to an infinitesimal magnetic field or chemical potential difference between spins
  - CMP people care because this quantity can discriminate between different states of matter

$$\chi_s = \frac{\partial\left(n_\uparrow - n_\downarrow\right)}{\partial\left(\mu_\uparrow - \mu_\downarrow\right)}$$

SPIN SUSCEPTIBILITY

- In a magnetic field gradient, particles with opposite spin are forced apart at a rate determined my the spin conductivity
  - Assume standard relation:

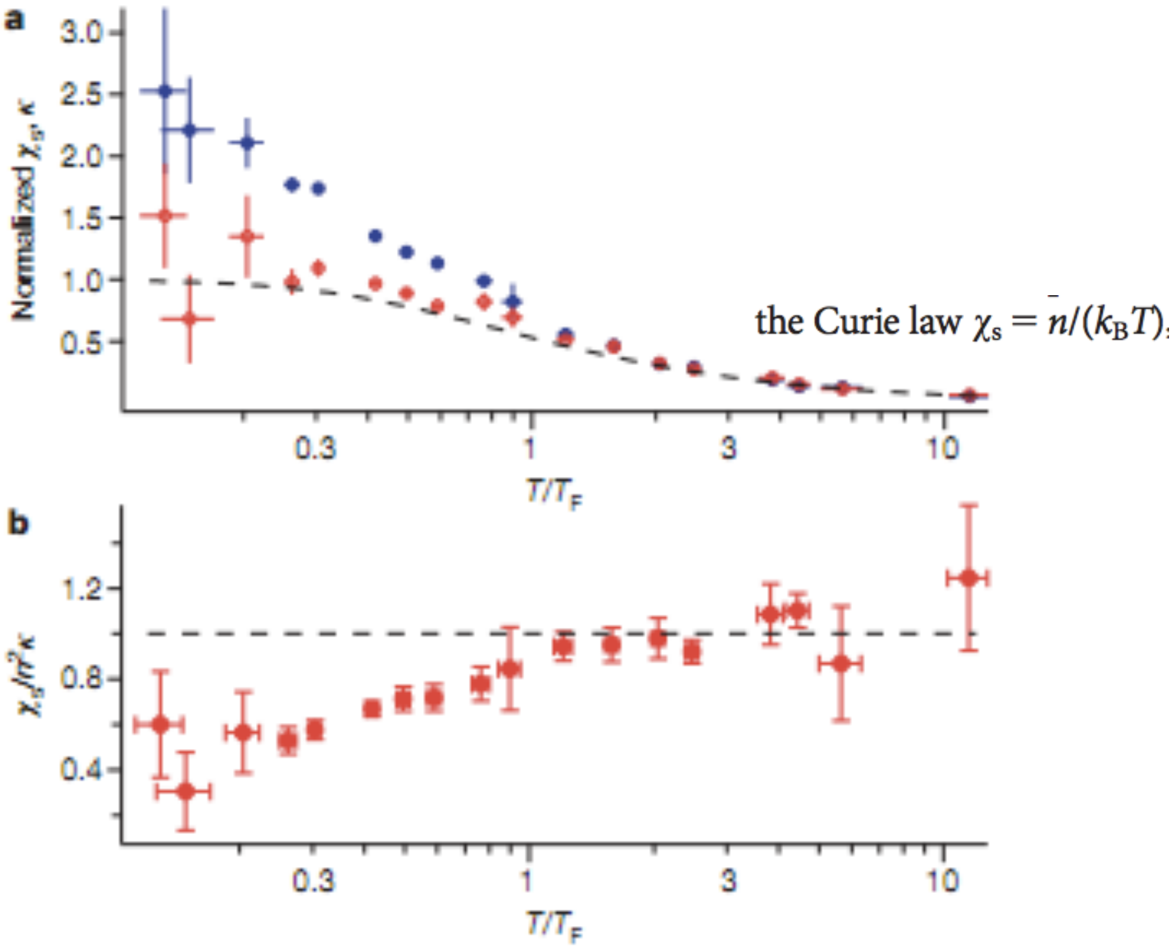
$$\sigma_s = n/(m\Gamma_{sd}),$$

- Diffusion acts to recombine spins

$$\chi_s = \sigma_s/D_s.$$

- Combining it all together:

$$\chi_s = \frac{1}{md\omega_z^2}\frac{\partial\left(n_\uparrow - n_\downarrow\right)}{\partial z}$$



the Curie law $\chi_s = \bar{n}/(k_B T)$

Figure 4 | Spin susceptibility on resonance. a, Spin susceptibility (χ_s, open red circles) and isothermal compressibility (κ, filled blue circles), normalized by the values for an ideal Fermi gas at zero temperature. For temperatures below T_F, χ_s becomes suppressed relative to κ, owing to interactions between opposite-spin atoms. Dashed line, χ_s of a non-interacting Fermi gas for comparison. **b,** Red circles, χ_s divided by the value of $n^2\kappa$ obtained from the same clouds. At temperatures above T_F, the ratio of χ_s to $n^2\kappa$ approaches unity (dashed line). Error bars, ±1s.e.

FIGURE 4

In classical regime of uncorrelated spins, susceptibility equals (normalized) compressibility

If pairs were formed @ low T, there would be a sharp decrease in X_S – no evidence of a gap down to $0.2T_F$

CONCLUSION

- Two dilute (but strongly interacting) gases bounce off each other
- Studied spin transport in strongly interacting Fermi gases
  - Measured the spin drag coefficient, spin diffusivity, and spin susceptibility
- Spin diffusivity approached a limiting value, “establishing the quantum limit of diffusion for strongly interacting Fermi gases”
  - Claimed as evidence against ferromagnetism