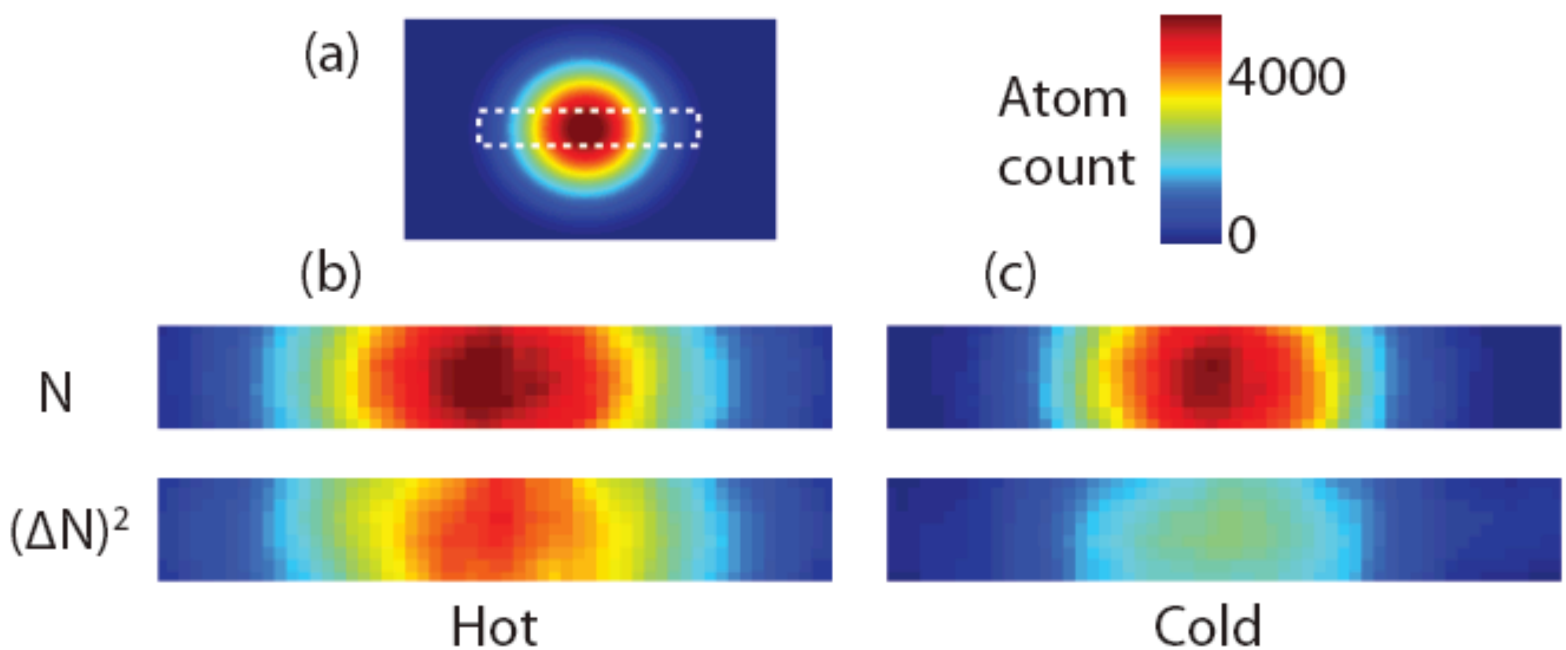
Suppression of Density Fluctuations in a Quantum Degenerate Fermi Gas

Christian Sanner, Edward J. Su, Aviv Keshet, Ralf Gommers, Yong-il Shin, Wujie Huang, and Wolfgang Ketterle
MIT-Harvard Center for Ultracold Atoms, Research Laboratory of Electronics,
and Department of Physics, Massachusetts Institute of Technology, Cambridge MA 02139

We study density profiles of an ideal Fermi gas and observe Pauli suppression of density fluctuations (atom shot noise) for cold clouds deep in the quantum degenerate regime. Strong suppression is observed for probe volumes containing more than 10,000 atoms. Measuring the level of suppression provides sensitive thermometry at low temperatures. After this method of sensitive noise measurements has been validated with an ideal Fermi gas, it can now be applied to characterize phase transitions in strongly correlated many-body systems.



DAMOP Highlight

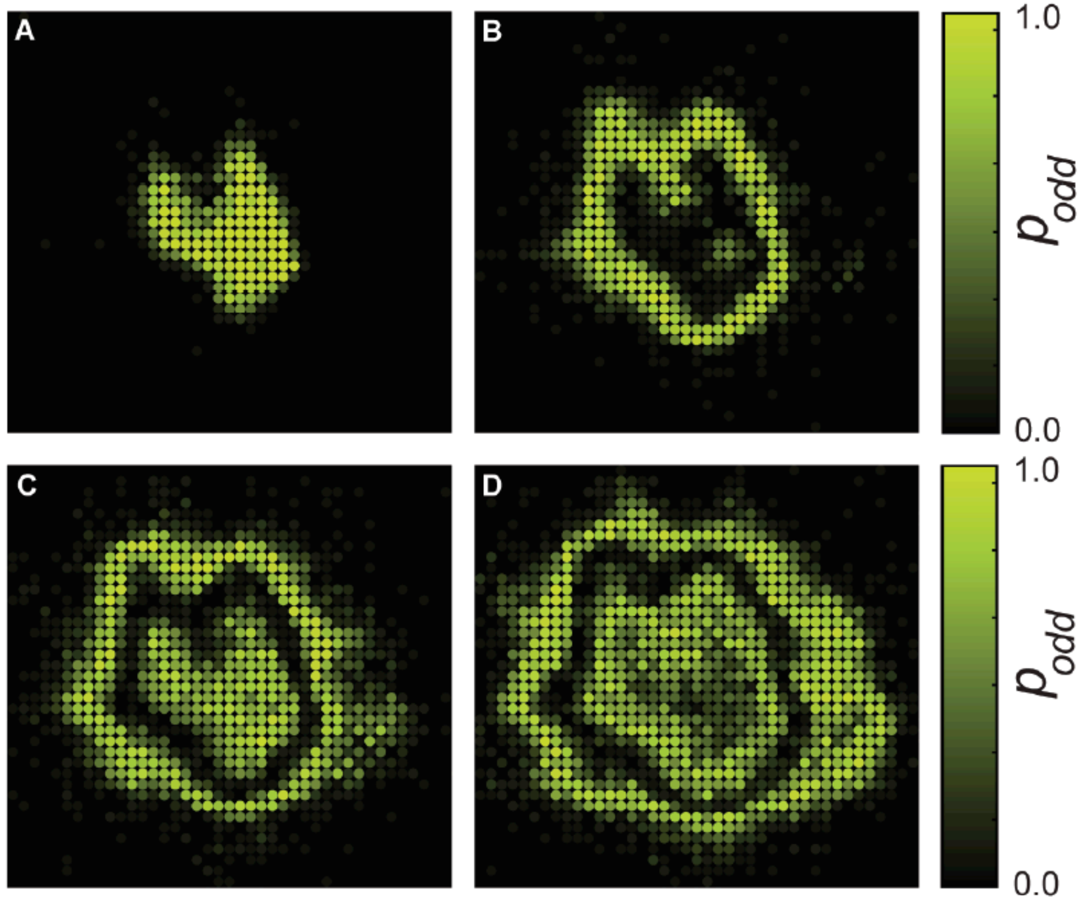


Fig. 2. Single-site imaging of shell structure in the Mott insulator. The images show p_{odd} on each site determined by averaging 20 images. The lattice is ramped to $22E_r$ and the final transverse confinement is 45Hz. As the atom number is varied, the number of shells in the insulator increases from one to four. The value of p_{odd} for odd (even) numbered shells is close to one (zero). The atom numbers, determined by in-situ imaging of clouds expanded in the plane, are **A**, 120 ± 10, **B**, 460 ± 20, **C**, 870 ± 40 and **D**, 1350 ± 70.

Fermi statistics

Two fermions can’t be in the same state

- …because they are anti-symmetric under exchange
- …because they obey anti-commutation relations
- …because this is a way to make the energy bounded from below

Pauli exclusion: *before*

- Suppression of elastic collisions

$$k_B T < \frac{\hbar^2 l\,(l+1)}{2mb^2} - \frac{C_6}{b^6}$$

$$b^2 = \sqrt{\frac{6C_6 m}{\hbar^2 l\,(l+1)}}$$

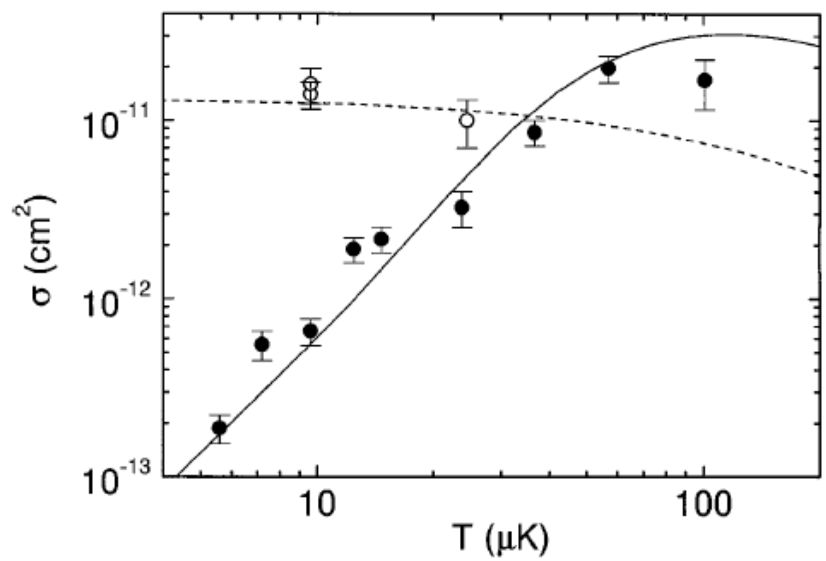
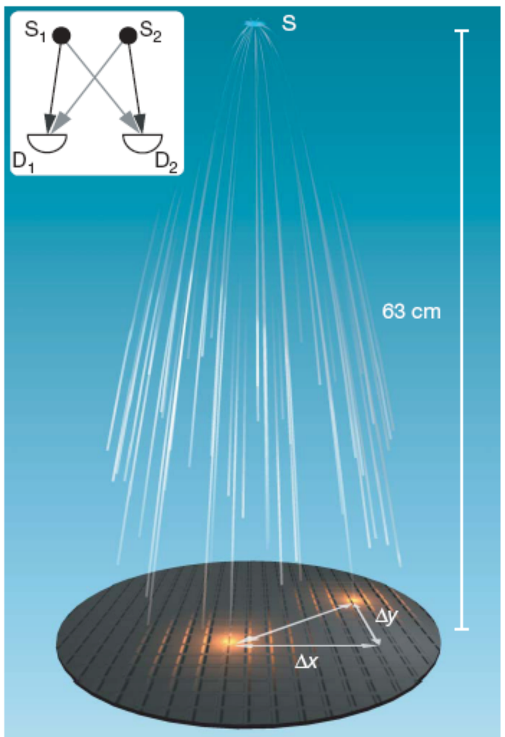


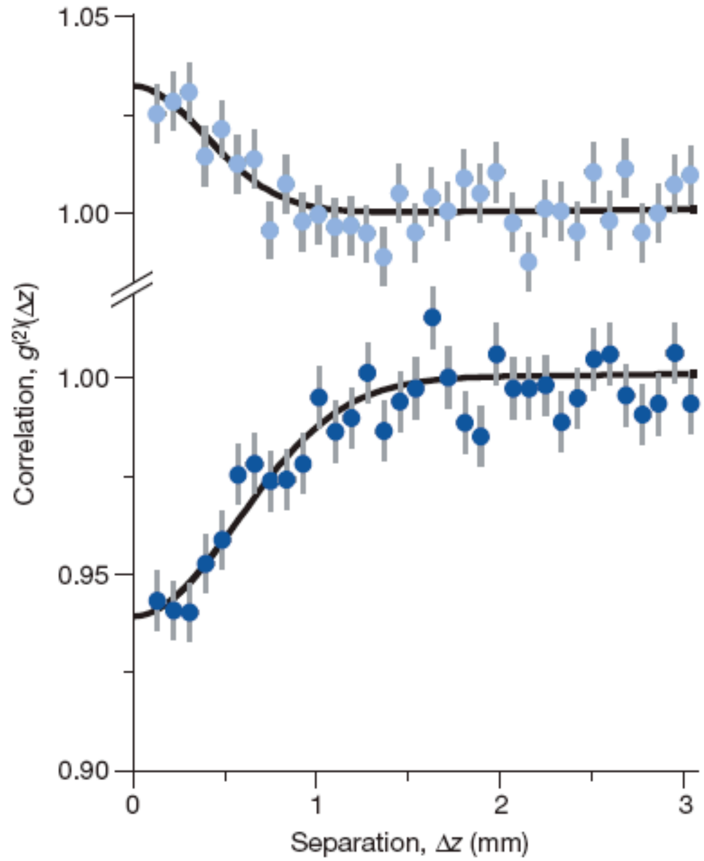
FIG. 2. Elastic cross sections vs temperature. The s-wave cross section (○), measured using a mixture of spin states, shows little temperature dependence. However, the p-wave cross section (●), measured using spin-polarized atoms, exhibits the expected threshold behavior and is seen to vary by over 2 orders of magnitude. The lines are a fit to the data, as described in the text, yielding $a_t = (157 \pm 20)a_0$.

DeMarco, …, 1999

Pauli exclusion: *before*

- Anti-bunching

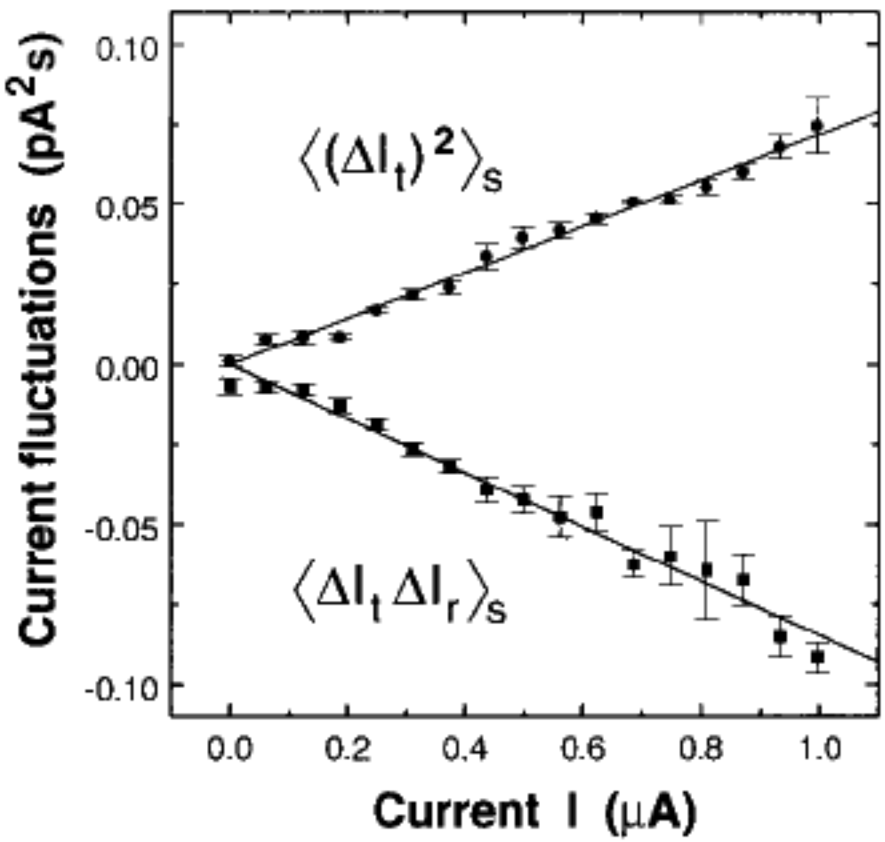




T. Jeldt, …, 2007

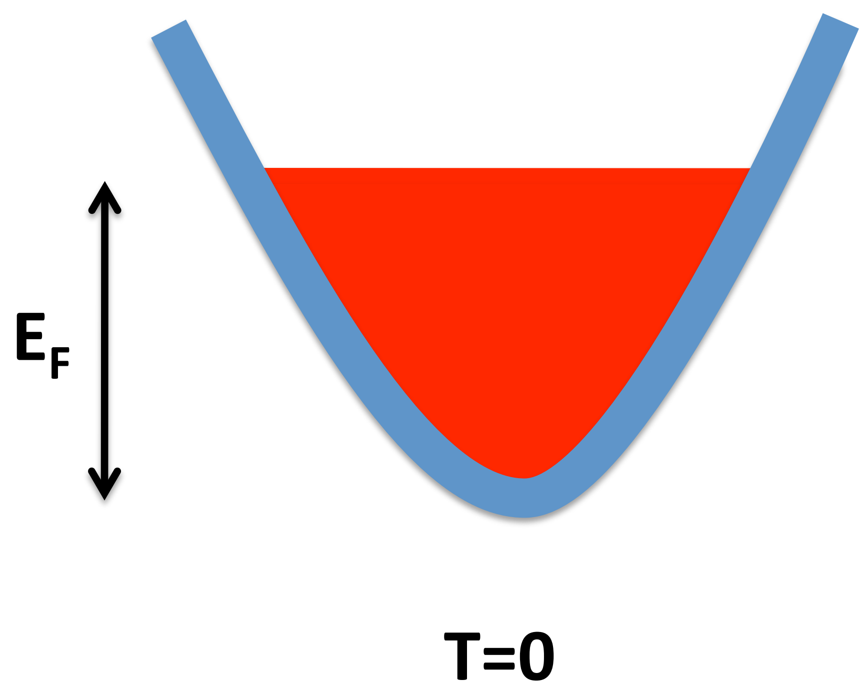
Pauli exclusion: *before*

- HBT with e^-

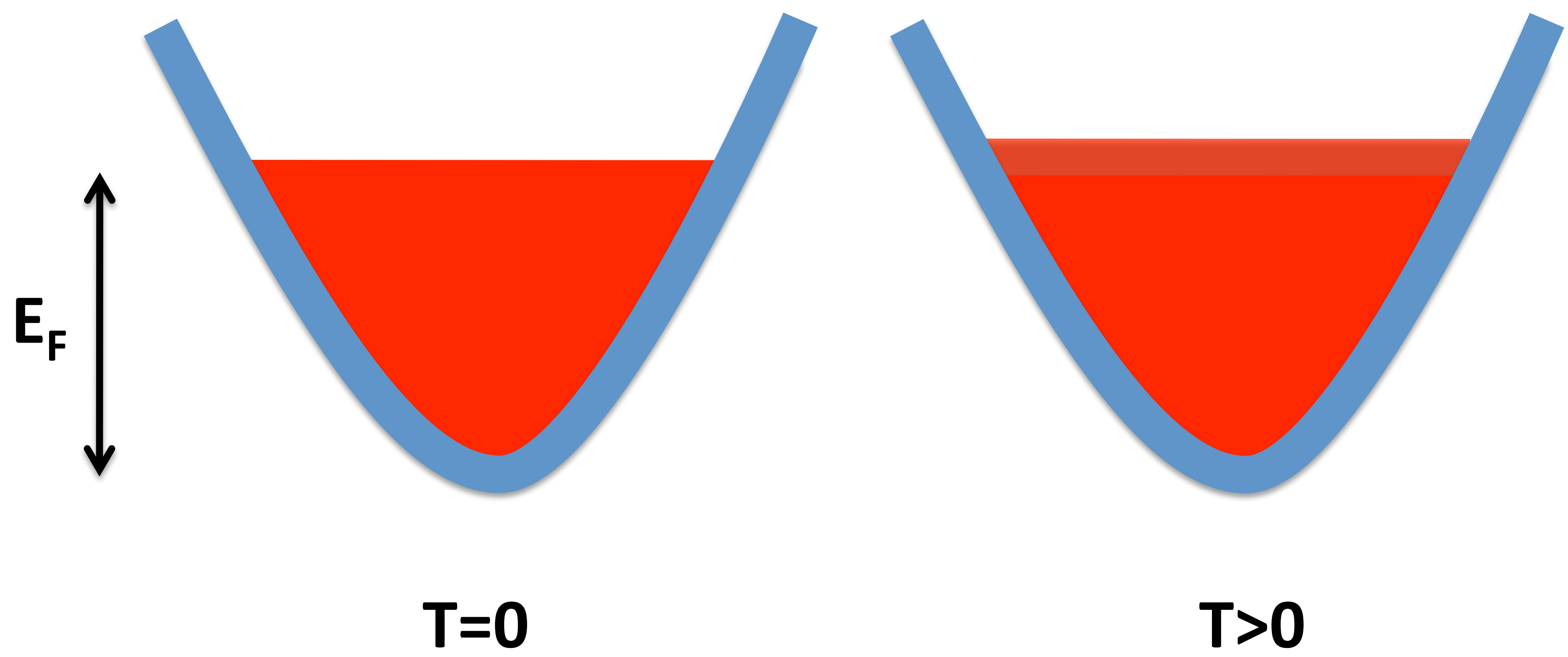


Henny, …, 1999

This paper's Idea: *in-trap density*



This paper's Idea: *in-trap density*



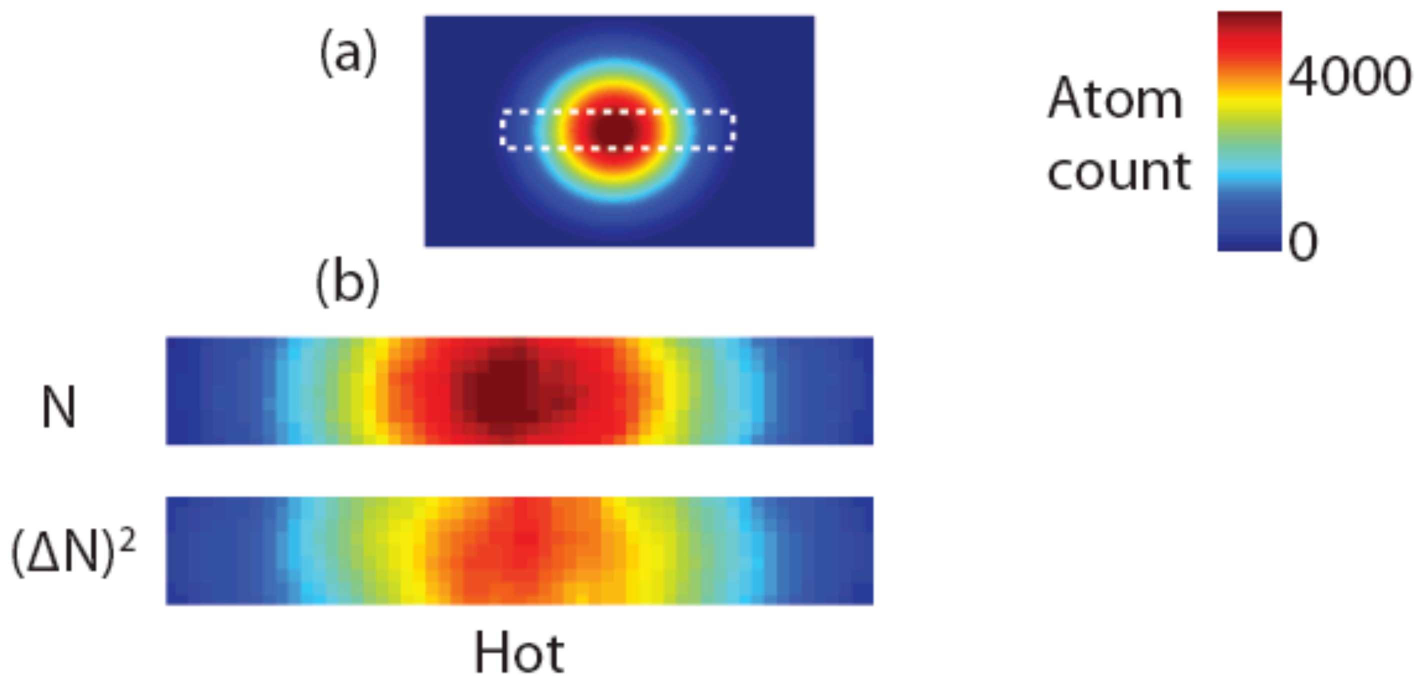
This paper's Idea

- Look at suppression of fluctuations in trap density
- Use this to determine temperature via fluctuation dissipation theorem:

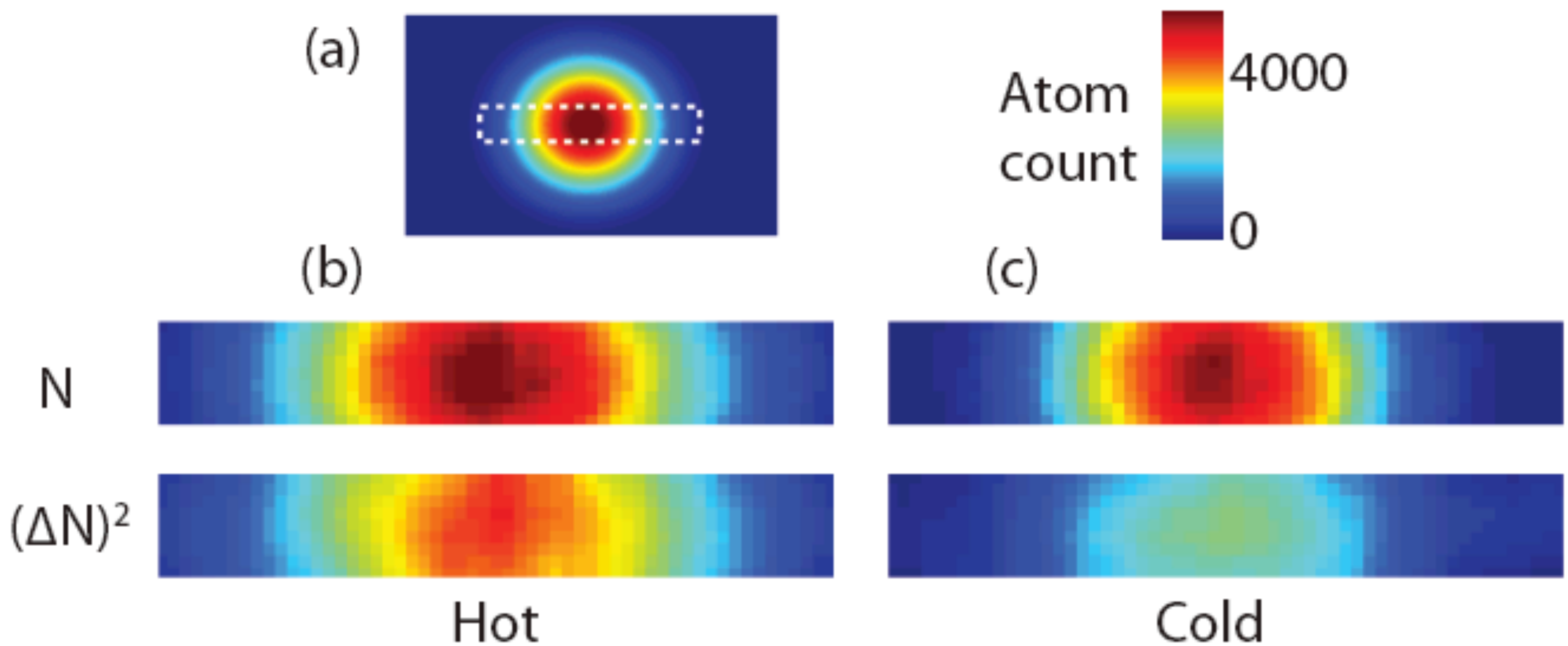
$$\frac{\Delta N^2}{< N >} = n k_B T \kappa_T$$

- "noise thermometry"

Results 1: ΔN^2 *vs* T



Results 1: ΔN^2 *vs T*



Results 1: ΔN^2 *vs T*

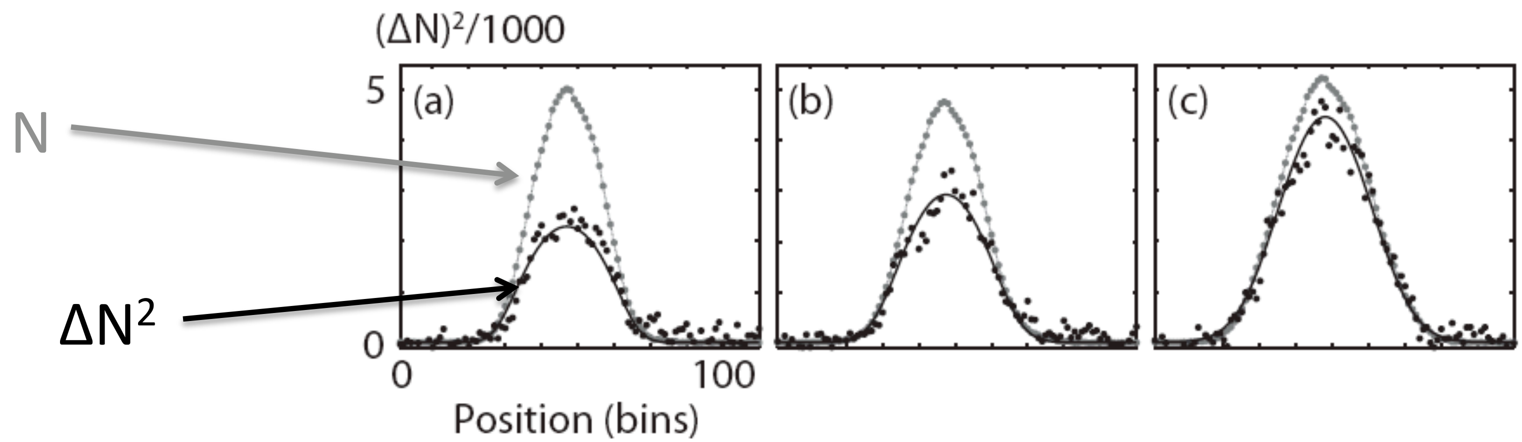


FIG. 3: Comparison of observed variances (black dots) with a theoretical model (black line) and the observed atom number (gray), at three different temperatures (a, b, and c), showing 50, 40, and 15% suppression. Noise thermometry is implemented by fitting the observed fluctuations, resulting in temperatures T/T_F of $0.23\pm.01$, $0.33\pm.02$, and $0.60\pm.02$. This is in good agreement with temperatures $0.21\pm.01$, $0.31\pm.01$, and $0.6\pm.1$ obtained by fitting the shape of the expanded cloud [29]. The quoted uncertainties correspond to one standard deviation and are purely statistical.

Results 2: ΔN^2 vs T

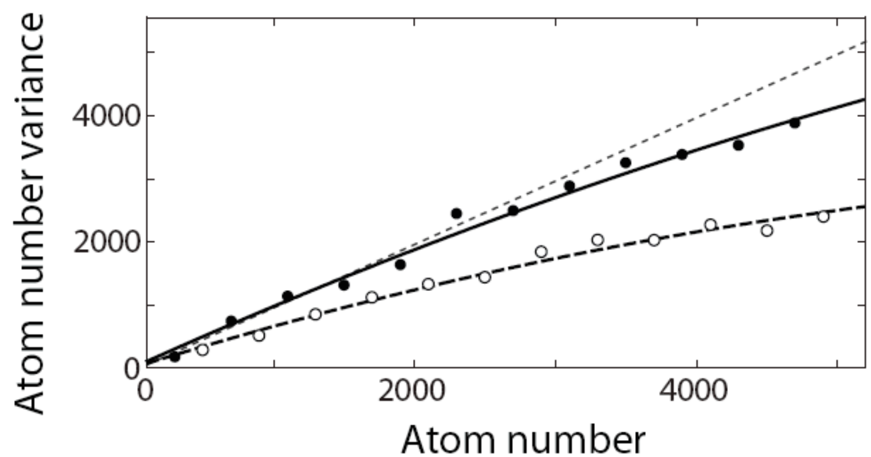


FIG. 4: Atom number variance vs. average atom number. For each spatial position, the average atom number per bin and its variance were determined using 85 images. The filled and open circles in the figure are averages of different spatial bin positions with similar average atom number. For a hot cloud at T/T_F=0.6 (filled circles), the atom number variance is equal to the average atom number (dotted line, full Poissonian noise) in the spatial wings where the atom number is low. The deviation from the linear slope for a cold cloud at T/T_F=0.21 (open circles) is due to Pauli suppression of density fluctuations. There is also some suppression at the center of the hot cloud, where the atom number is high. The solid and dashed lines are quadratic fits for the hot and cold clouds to guide the eye.

How they did the experiment:

- 2.5E6 ^{6}Li
- ODT: $\omega_r=2\pi*160$Hz, $\omega_z=2\pi*230$Hz
- B=520G (near zero crossing)
- 4us exposure @ 12% I_{sat}
- 7ms TOF

How they did the experiment:

- Imaged after TOF
  - PSD is conserved after expansion (…next page)
  - Increases the # of fully resolved bins
  - Allows adjustment of the OD
  - Avoids imaging artifacts caused by high magnification

How they did the experiment:

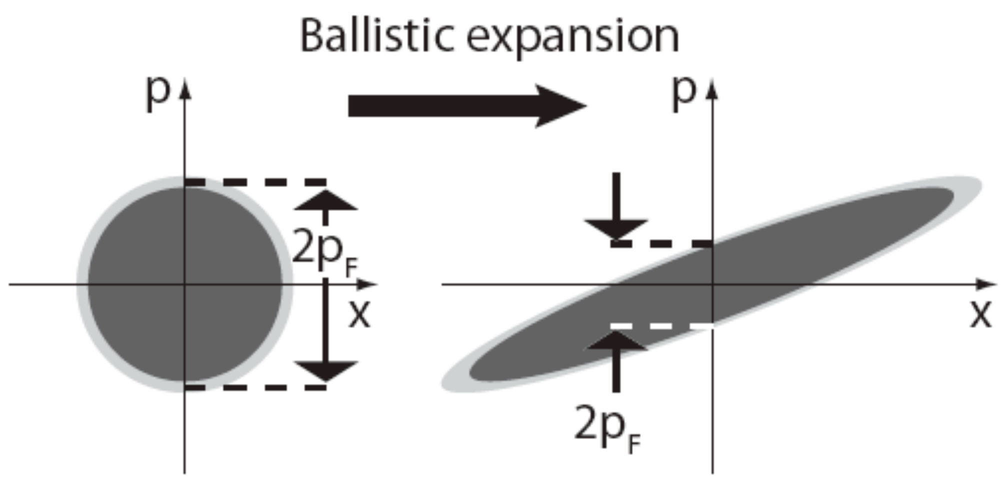


FIG. 1: Phase space diagram of ballistic expansion of a harmonically trapped Fermi gas. Ballistic expansion conserves phase space density and shears the initially occupied spherical area into an ellipse. In the center of the cloud, the local Fermi momentum and the sharpness of the Fermi distribution are scaled by the same factor, keeping the ratio of local temperature to Fermi energy constant. The same is true for all points in the expanded cloud relative to their corresponding unscaled in-trap points.

How they did the experiment:

- This ballistic expansion technique only works for a harmonic potential
  - All lattice thermometry must be done in-situ
- Can only scatter 6 photons/atom before ^{6}Li atoms are doppler shifted 20% out of resonance
- This ballistic expansion technique only works for a harmonic potential
  - All lattice thermometry must be done in-situ

How they did the experiment:

- Subtract off photon shot noise
  - In thermal cloud, assuming Poissonian statistics?

$$\frac{\Delta N^2}{< N >^2} = \frac{2g}{< N >} + \frac{\Delta t^2}{< t >^2}$$

where

$$t = e^{-\frac{\sigma N}{A}}$$

and

$$\frac{\Delta t^2}{< t >^2} = \frac{\sigma^2}{A^2} \Delta N^2$$

Noise Thermometry

$$\frac{\Delta N^2}{N} = n k_B T \kappa_T$$

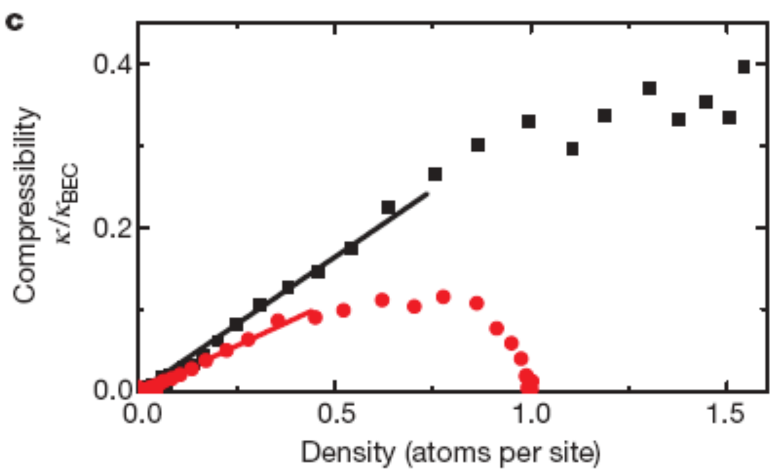
- Ideal gas

$$\kappa_T = \frac{1}{n k_B T} \quad \rightarrow \quad \frac{\Delta N^2}{N} = 1$$

- Fermi gas

$$\kappa_T = \frac{3}{2 n E_F} \quad \rightarrow \quad \frac{\Delta N^2}{N} = \frac{3}{2} \frac{k_B T}{E_F}$$

Noise Thermometry: *elsewhere*



Gemelke, …, 2009

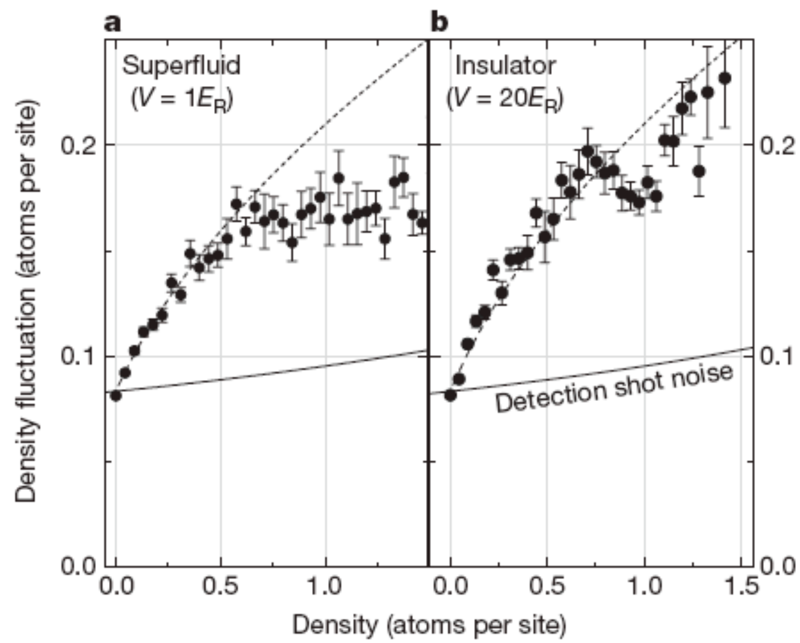


Figure 4 | The fluctuation of local density extracted from a set of eleven absorption images in the weak and deep lattice regimes. The insulator and superfluid show a pronounced difference at one atom per site, where the insulator's fluctuation is suppressed by incompressibility. In the superfluid, constant compressibility initiates a flattening. At low densities, in both the weak (**a**) and the deep (**b**) lattice regimes, the fluctuation shows a characteristic $\sqrt{n}$ dependence, where the gas is presumed to be normal; the dashed line shows the best-fitted $\sqrt{n}$ dependence. The total number of atoms was $N = 8{,}300$ (superfluid) and $N = 9{,}600$ (Mott insulator) with $a = 310a_B$ for both sets. Error bars indicate standard error in the mean.

Noise Thermometry: *elsewhere*

Local observation of antibunching in a trapped Fermi gas

Torben Müller,[1] Bruno Zimmermann,[1] Jakob Meineke,[1]
Jean-Philippe Brantut,[1] Tilman Esslinger,[1,*] and Henning Moritz[1,2]

[1]*Institute for Quantum Electronics, ETH Zurich, 8093 Zurich, Switzerland*
[2]*Institut für Laser-Physik, Universität Hamburg, 22761 Hamburg, Germany*
(Dated: 20100507004100)

Local density fluctuations and density profiles of a Fermi gas are measured in-situ and analyzed. In the quantum degenerate regime, the weakly interacting ^{6}Li gas shows a suppression of the density fluctuations compared to the non-degenerate case, where atomic shot noise is observed. This manifestation of antibunching is a direct result of the Pauli principle and constitutes a local probe of quantum degeneracy. We analyze our data using the predictions of the fluctuation-dissipation theorem and the local density approximation, demonstrating a fluctuation-based temperature measurement.

PACS numbers: 03.75.Ss, 05.30.Fk, 67.85.Lm,

Noise Thermometry: *elsewhere*

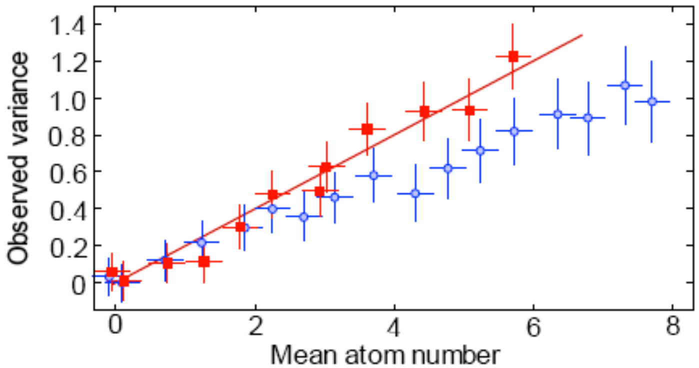
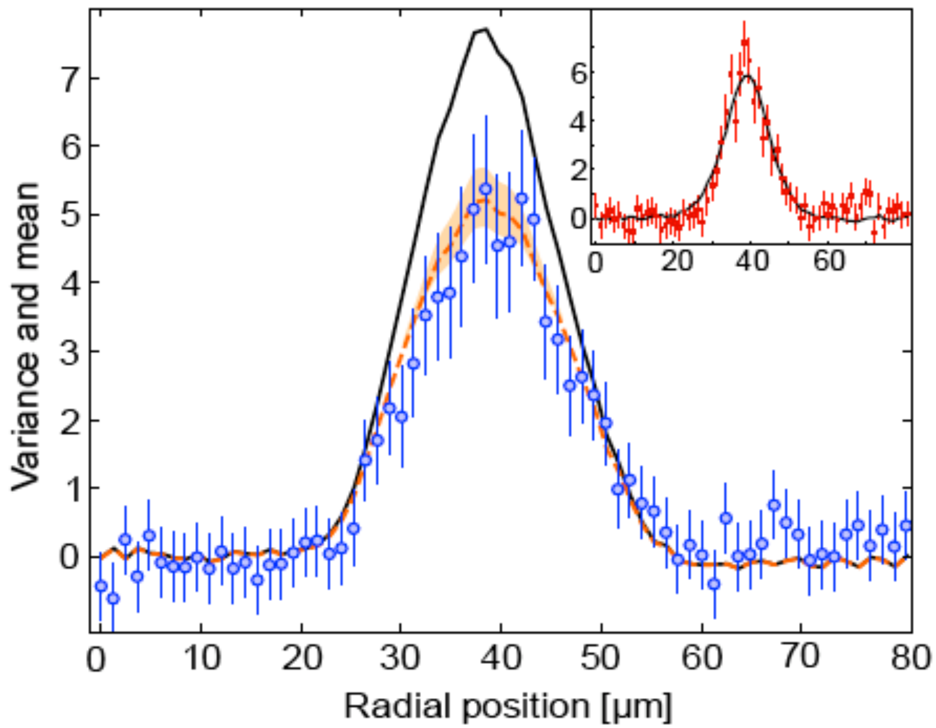


FIG. 2: Observed variance versus mean of the atom number detected on a pixel. Red squares show the data for a non-degenerate and blue circles for a quantum degenerate gas. The solid red line is a linear fit to the non-degenerate gas, yielding a slope of 0.20 ± 0.02. For the data shown, 80 experiments were performed, 60 for the degenerate case and 20 for the non-degenerate case. The error bars shown are estimated from the subtraction of photon shot noise which is the dominant contribution.



Noise Thermometry: *elsewhere*

$$\Delta N^2 = k_B T \frac{d < N >}{d\mu}$$

Vary $U_0 \frac{d < N >}{d\mu}$

Measure ΔN^2

Infer $\frac{k_B T}{U_0} = 0.27 \pm 0.04$

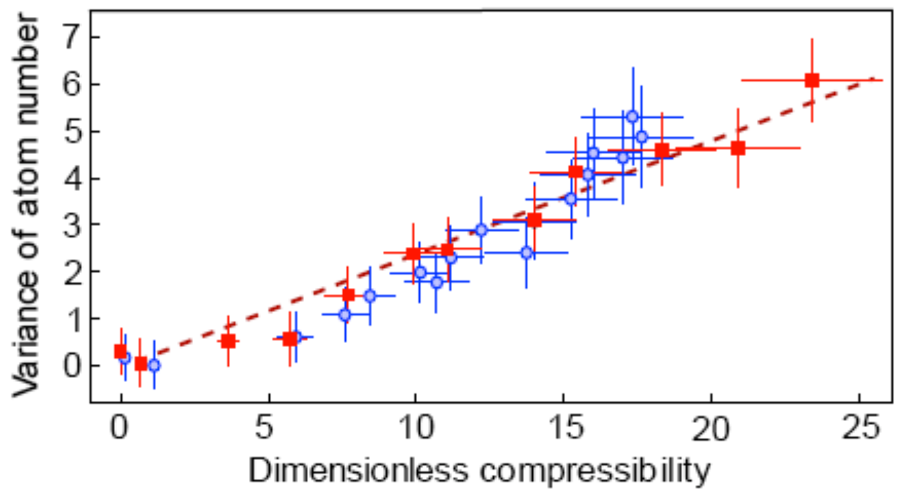


FIG. 4: Fluctuation-based temperature measurement. Variance of atom number detected on an effective pixel versus dimensionless compressibility. The blue circles and red squares show the data for the quantum degenerate and the non-degenerate case, respectively. The slope gives a measure of the temperature in units of the trap depth, according to (4). The dashed red line is fitted to the red squares.

Noise Thermometry: *elsewhere*

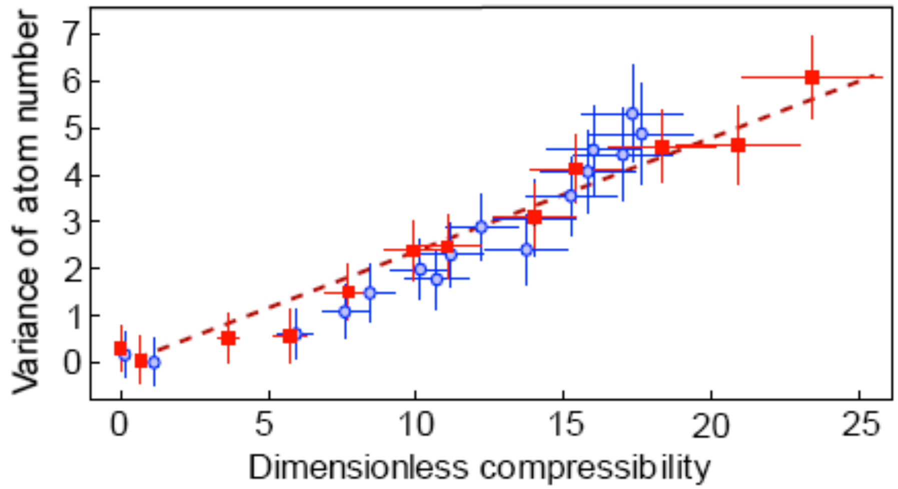
RESULTS

Fermi Gas:

$$T = 145 \pm 31 nK$$

Thermal Gas:

$$T = 1.10 \pm 0.06 \mu K$$



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Conclusions

- Suppression of density fluctuations in Fermi gas
- If you know the compressibility, can use this as a noise thermometer