Novel Probes for Fermionic Gases

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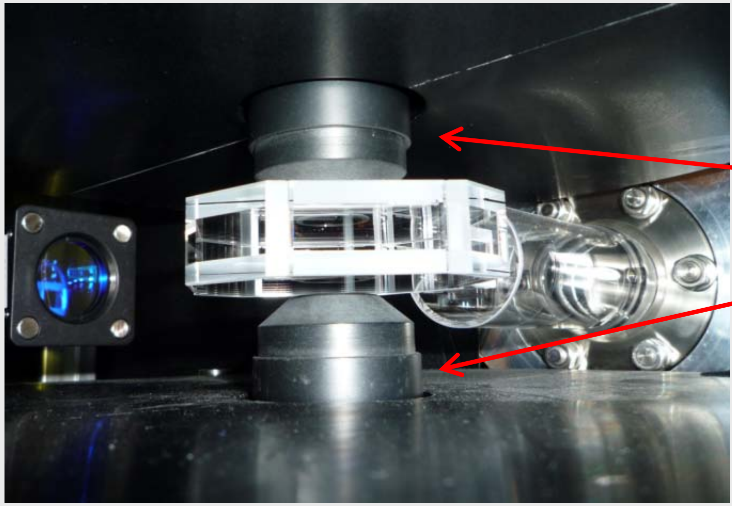
J.-P. Brantut, H. Moritz, T. Esslinger
ETH Zürich

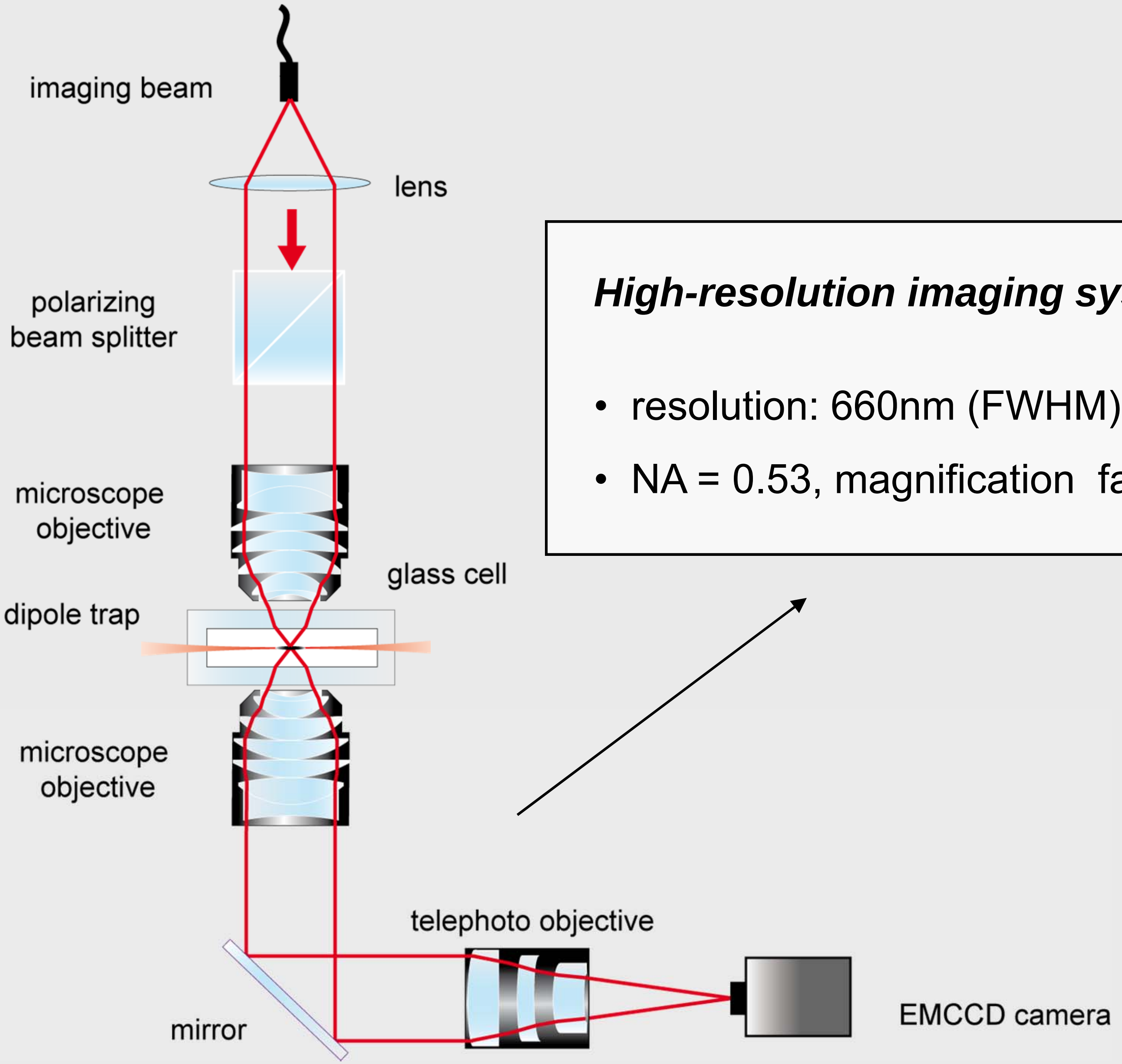
Experimental setup



^{6}Li atoms

Microscope objectives

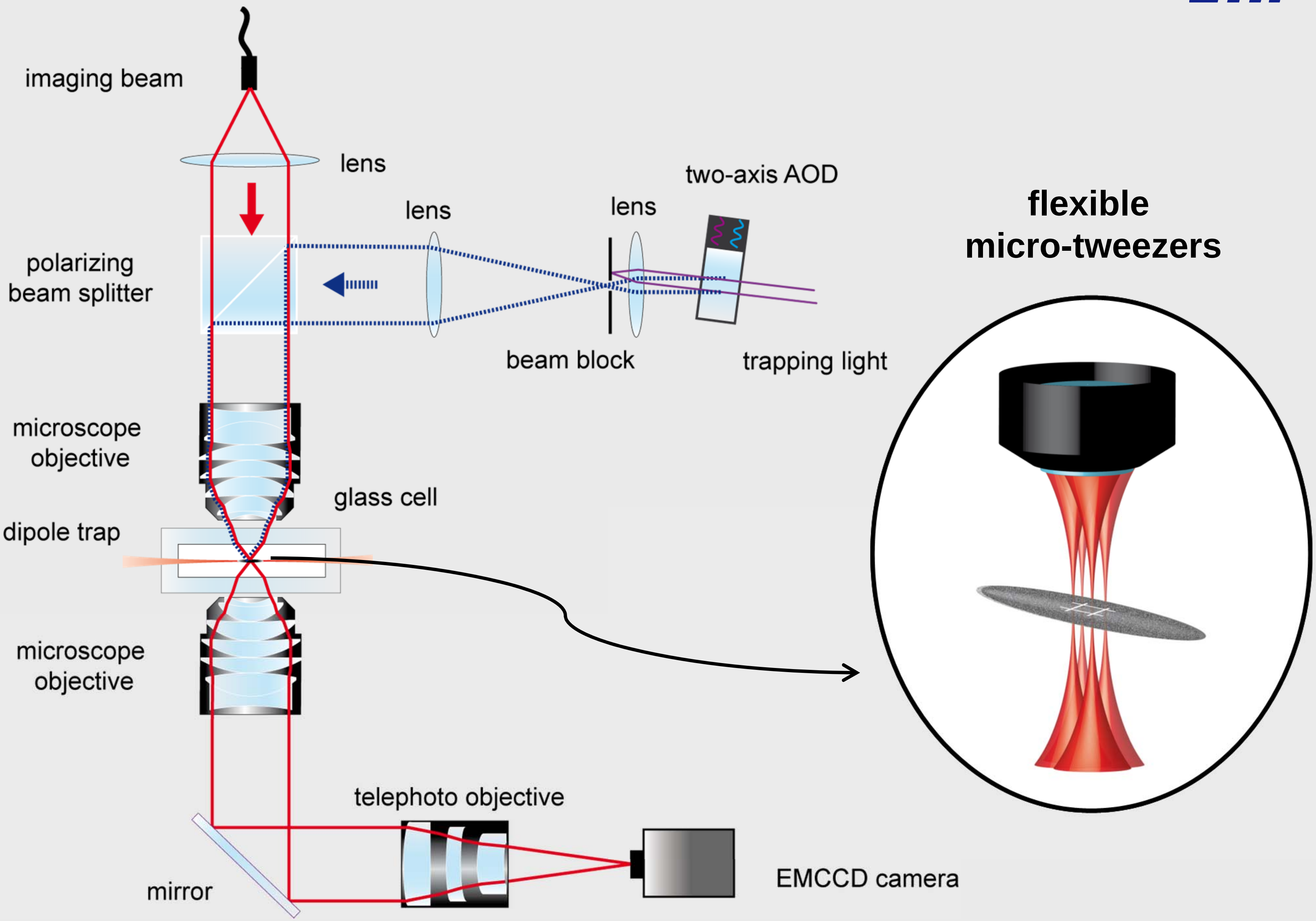
Microscope setup



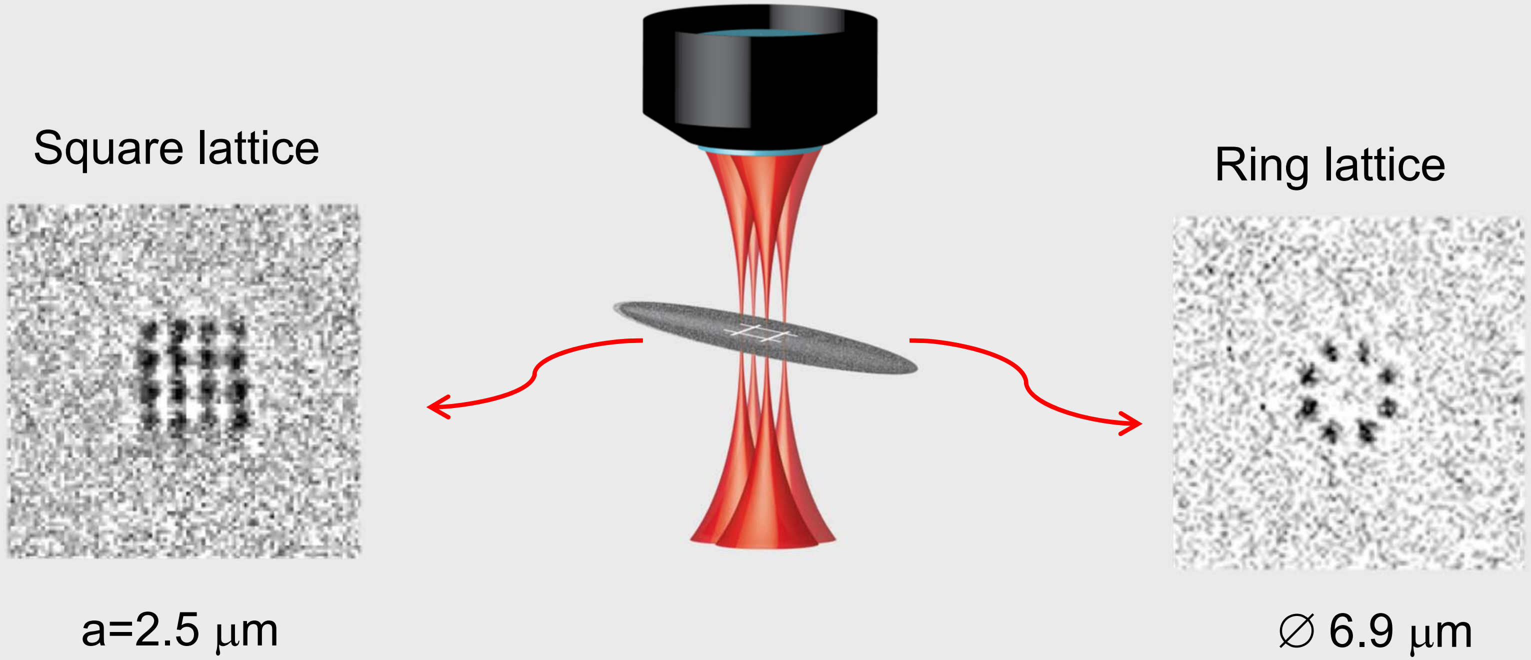
High-resolution imaging system:

- resolution: 660nm (FWHM) for λ=671nm
- NA = 0.53, magnification factor: 54

Microscopic manipulation



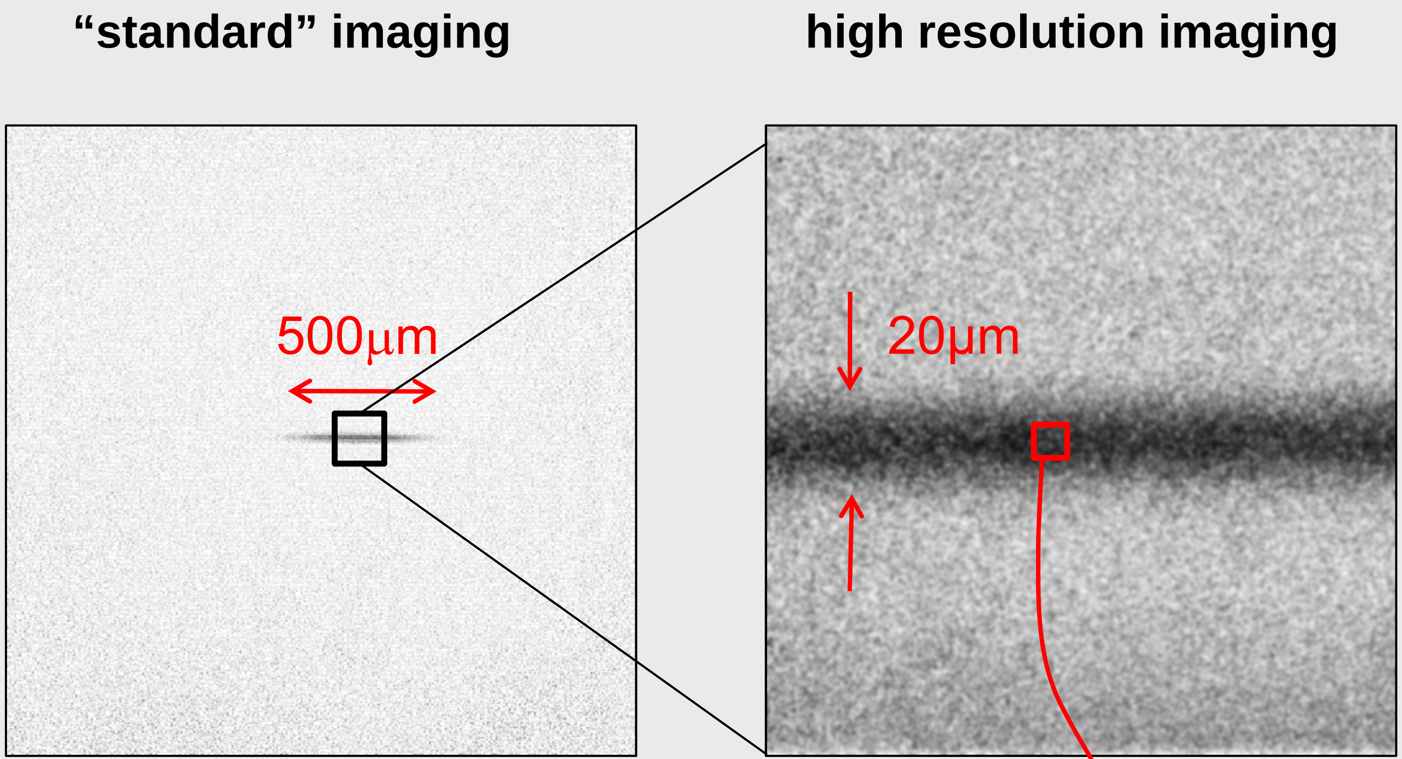
Atoms in micro-traps



B. Zimmermann, T. Müller, J. Meineke, T. Esslinger, H. Moritz, New Journal of Physics 13, 043007 (2011)

Imaging through the microscope

ETH



Information on
- **correlations, quantum statistics?**
- **temperature, susceptibilities?**
- **entanglement?**

Microscopic probing …

… of in-situ density fluctuations

Quantum statistics and fluctuations

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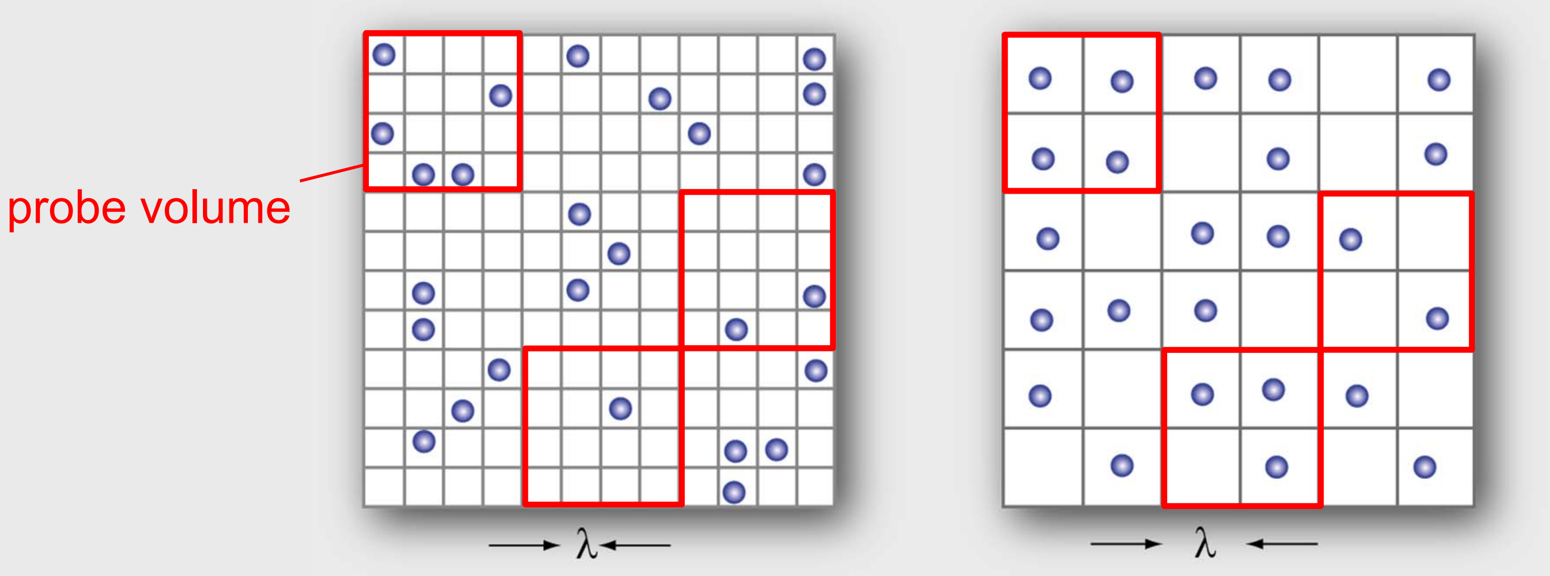
thermal | **quantum degenerate**

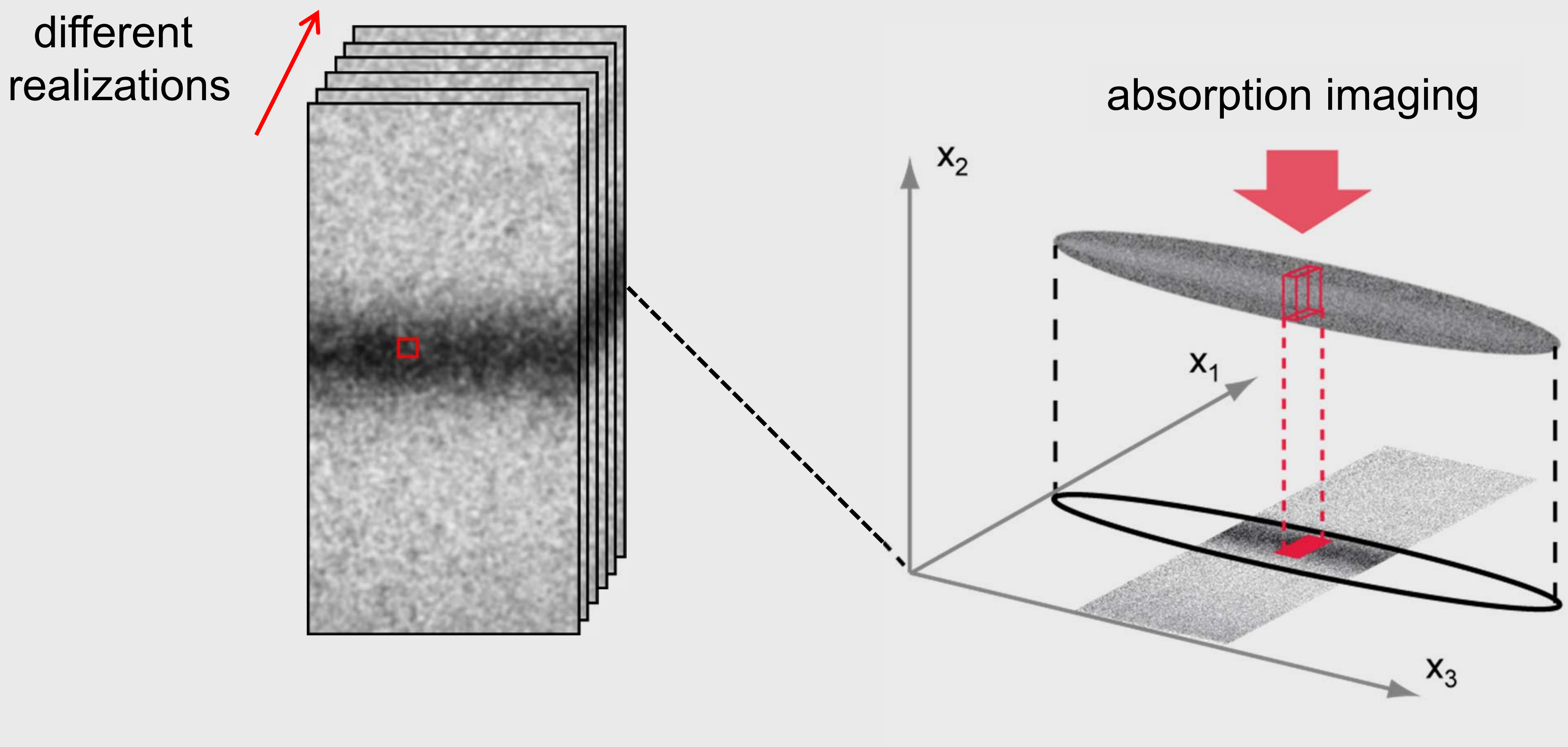


Suppressed density fluctuations in a degenerate Fermi gas due to Pauli principle!

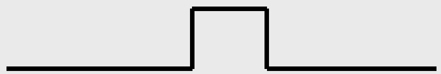
$$\partial N^2 = \underbrace{\langle N \rangle}_{\text{thermal}} \cdot \left(1 \underbrace{- \frac{1}{2^{3/2}} \frac{\langle N \rangle \lambda^3}{V} + \dots}_{\text{higher order quantum correction}} \right)$$

For 1D Bose gases: J. Esteve et al., PRL 96,130403 (2006) & J. Armijo et al., PRL 105, 230402 (2010)
For 2D Bose gases: C.-L. Hung, X. Zhang, Na. Gemelke, C. Chin, Nature 470, 236 (2011)

Measurement of density fluctuations

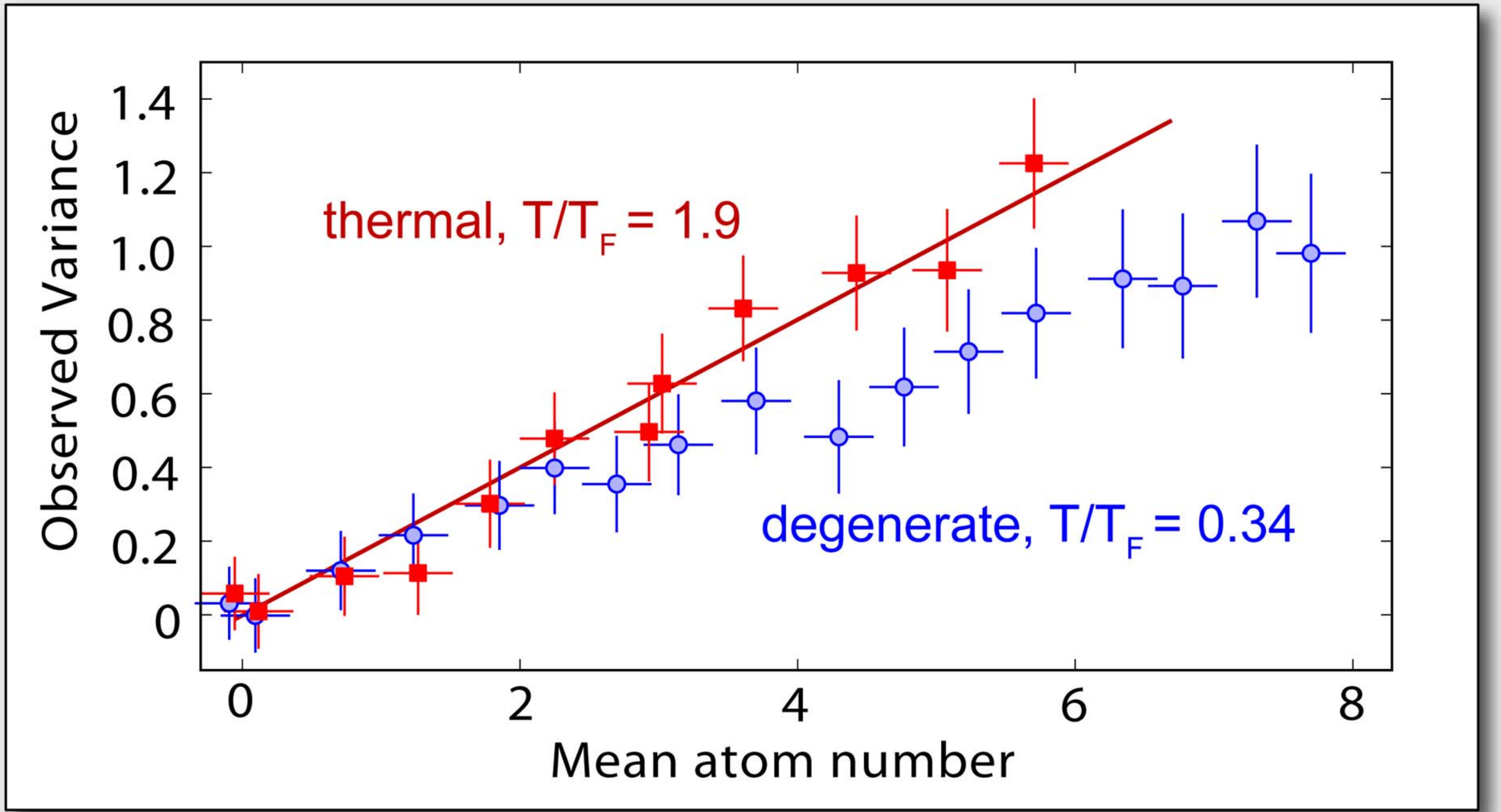


- Calculate **mean** and **variance** over many realizations
- Account for **photon shot noise** and **imaging** effects

Fluctuation in gas on a pixel 

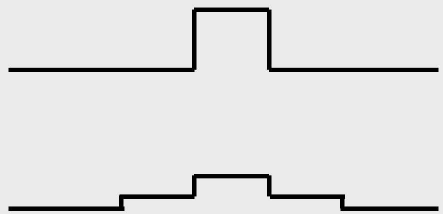
Effect of imaging resolution 

Data



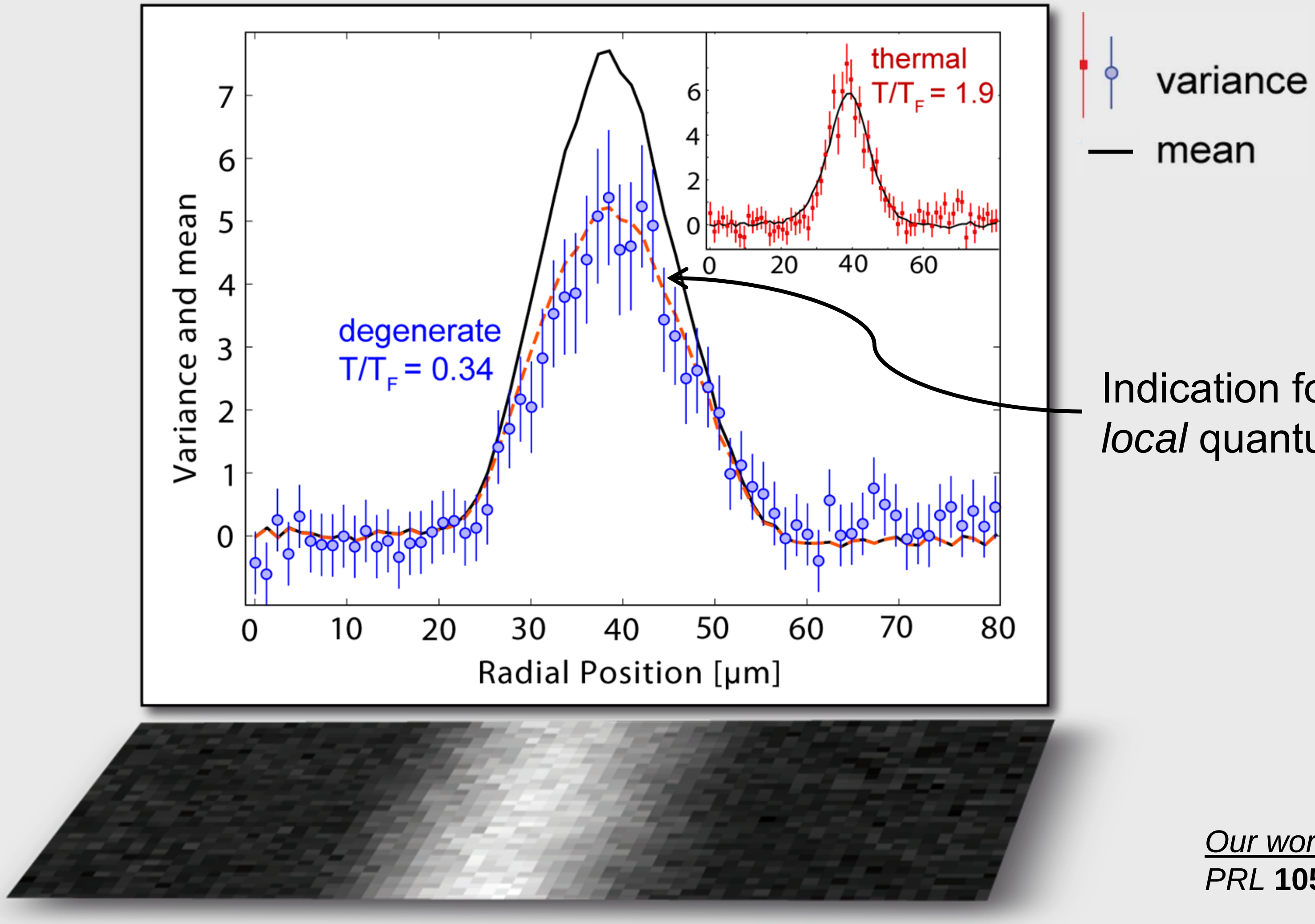
Why slope < 1? Fluctuation in gas on a pixel

Effect of imaging resolution



T. Müller, B. Zimmermann, J. Meineke, J.-P. Brantut, T. Esslinger. H. M., PRL 105,040401 (2010)

Manifestation of antibunching

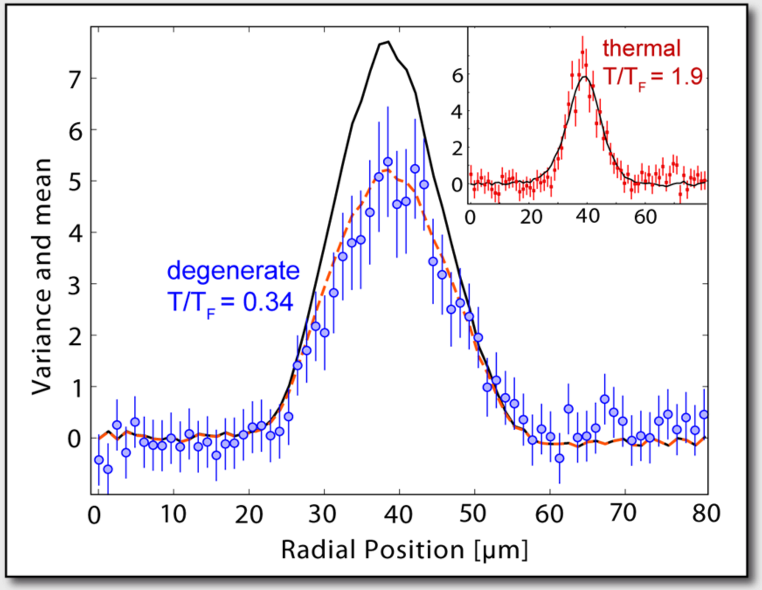


Indication for the level of *local* quantum degeneracy

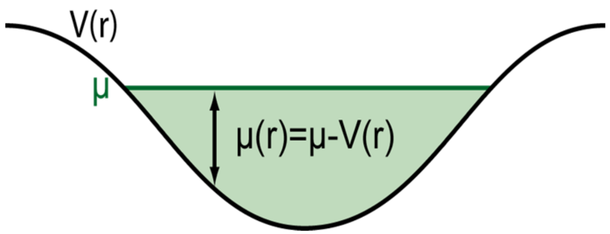
Our work at ETH Zürich:
PRL ***105****, 040401 (2010)*

Similar work at MIT in TOF:
PRL ***105****, 040402 (2010)*

Thermodynamic properties



local density approximation



Compressibility $\frac{\partial\langle N\rangle}{\partial\mu} = \frac{\partial\langle N(r)\rangle}{\partial r}\cdot\left(\frac{\partial\mu}{\partial r}\right)^{-1}$

Fluctuation-dissipation theorem: $\left(\frac{k_B T}{U_0}\right)\left(\frac{\partial\langle N\rangle}{\partial\mu}\right) = \partial N^2$

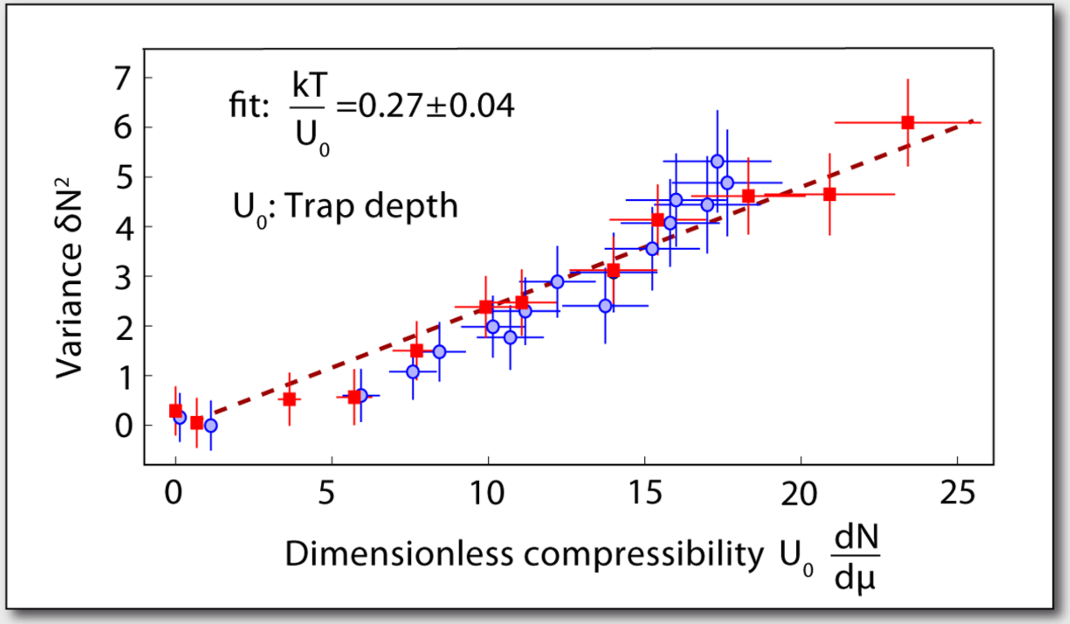
density fluctuations

U_0: Trap depth

model independent measurement of *temperature*

Q. Zhou and T. L. Ho, Phys. Rev. Lett. 106, 225301 (2011);
κ in SF-MI: N. Gemelke, X. Zhang, C.-L. Hung, C. Chin, Nature 460, 995 (2009).

Fluctuation-based thermometry

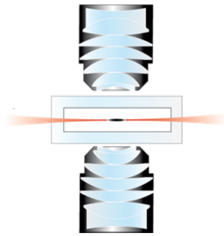


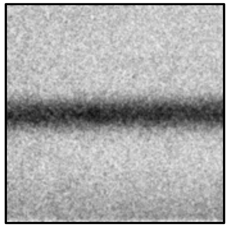
$$\partial N^2 = \frac{k_B T}{U_0} \cdot \left(U_0 \cdot \frac{\partial \langle N \rangle}{\partial \mu} \right)$$

Temperature:	Conventional	Fluctuation-based
degenerate	205±30 nK	145±31 nK
thermal	1,6 ±0.2 μK	1,1 ±0.06 μK

T. Müller , B. Zimmermann, J. Meineke, J.-P. Brantut, T. Esslinger, H. Moritz,
Phys. Rev. Lett. **105**, 040401 (2010)

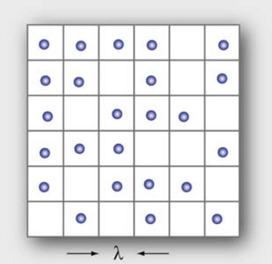
Microscopic access

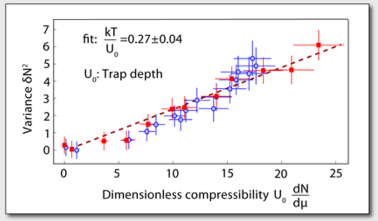




fluctuations
correlations

thermodynamic
properties





Here: Anti-bunching

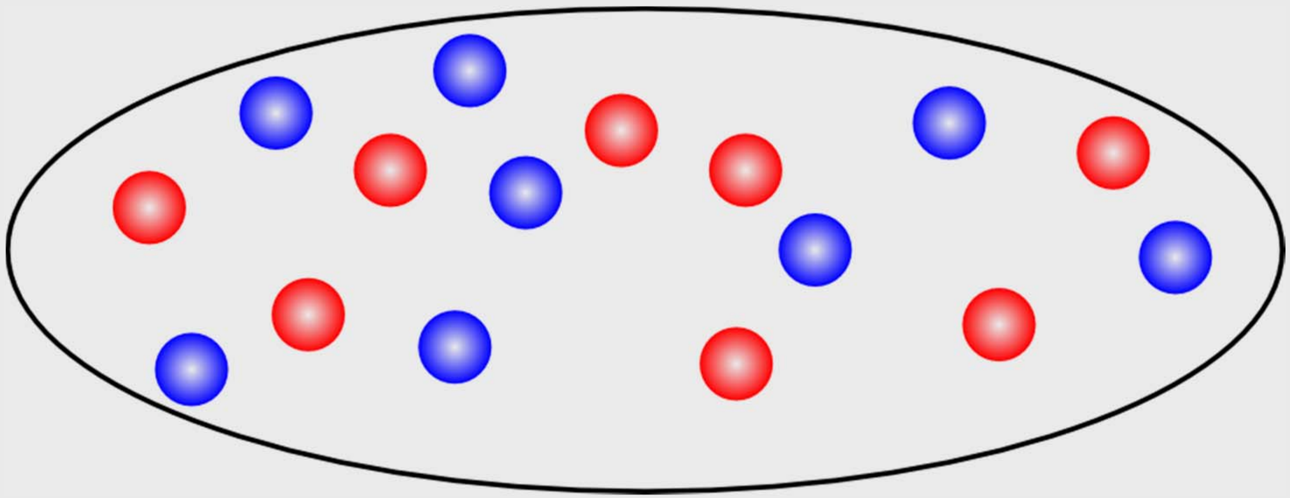
Also: Structure factor
see Chin/Greiner/Bloch groups

Temperature
Suszeptibilities, e.g. compressiblity

Microscopic probing …

… of in-situ <u>spin</u> fluctuations

Local Spin-Fluctuations



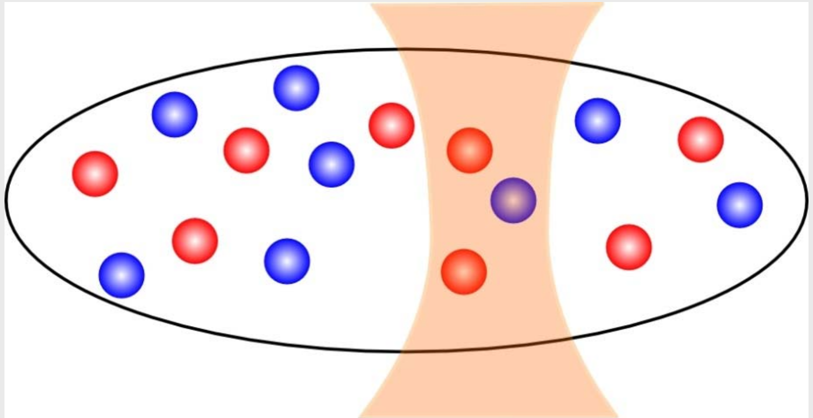
Two-component quantum gas

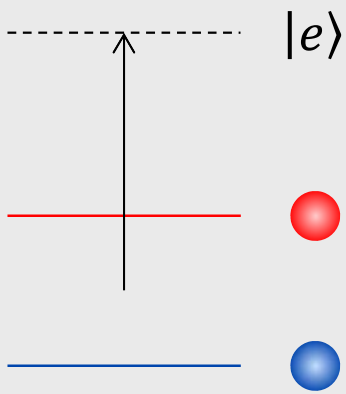
$$\langle m^2 \rangle = \langle (n_\uparrow - n_\downarrow)^2 \rangle = \langle n_\uparrow^2 \rangle + \langle n_\downarrow^2 \rangle - 2\langle n_\uparrow n_\downarrow \rangle$$

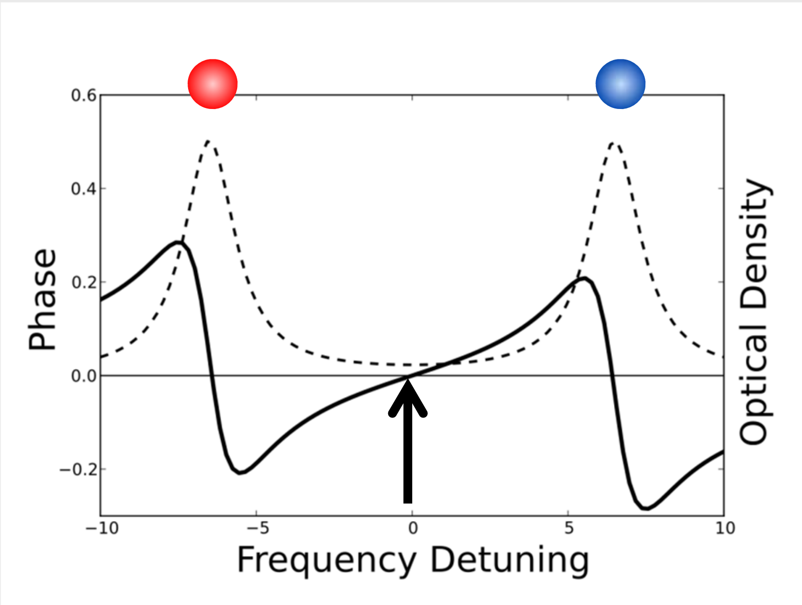
$$\langle n_\uparrow n_\downarrow \rangle = \langle \Psi_\uparrow^\dagger \Psi_\uparrow \Psi_\downarrow^\dagger \Psi_\downarrow \rangle$$

G. M. Bruun et al., PRL 102, 030401 (2009)

Measuring Spin-Polarization







Phase-shift ∝ spin-polarisation

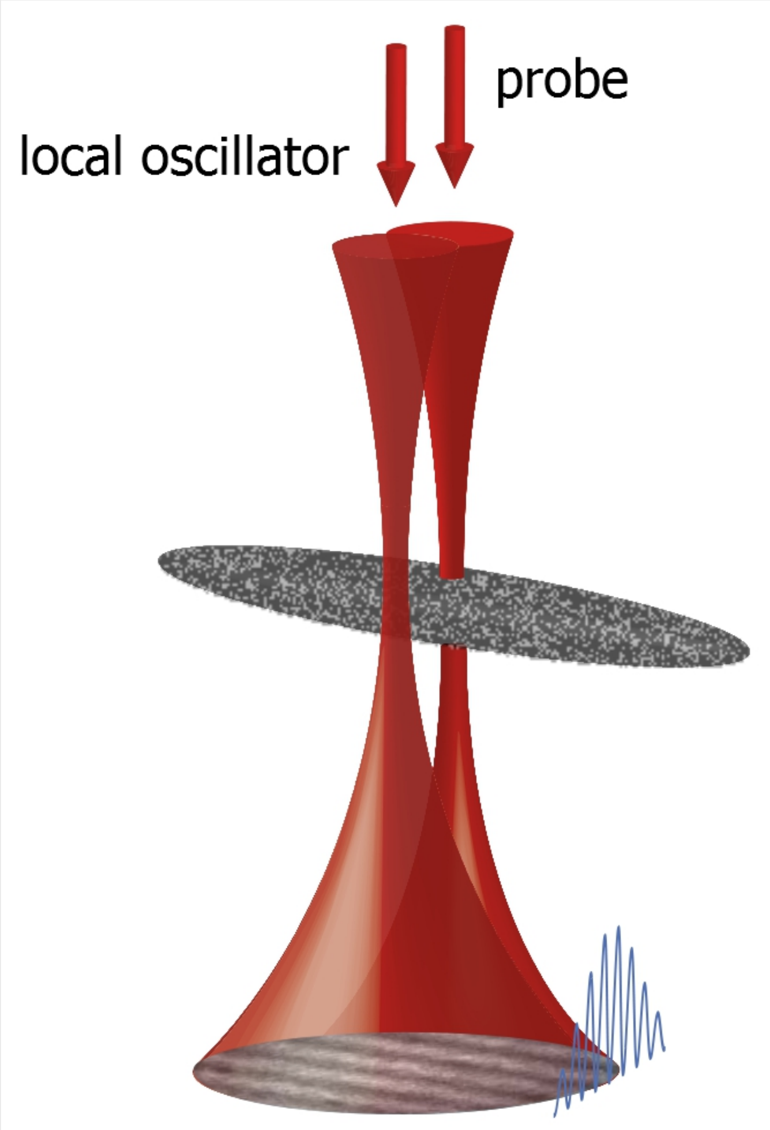
$$\phi \propto \underbrace{(n_\uparrow - n_\downarrow)}_{m}$$

$$\delta\phi^2 \propto \langle n_\uparrow^2 \rangle + \langle n_\downarrow^2 \rangle - 2\langle n_\uparrow n_\downarrow \rangle$$

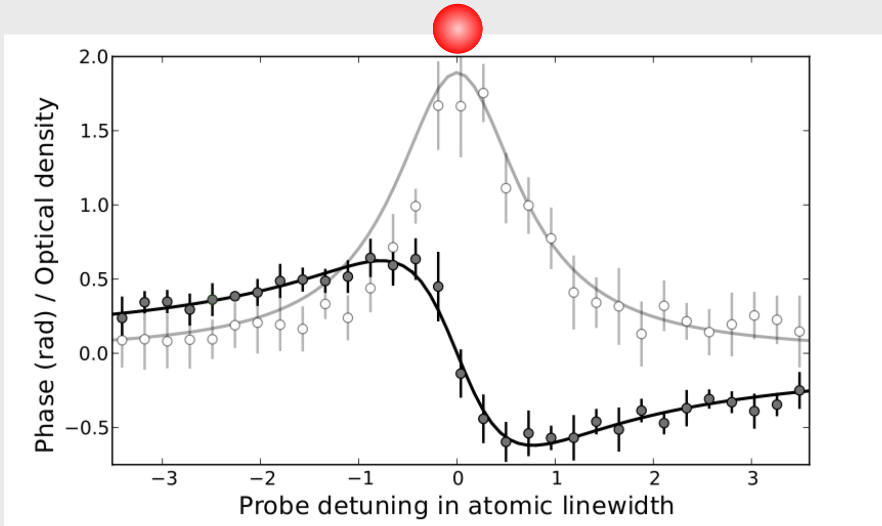
Spin-spin correlator

Speckle: Sanner et al., PRL 106, 010402 (2011)

The Interferometer



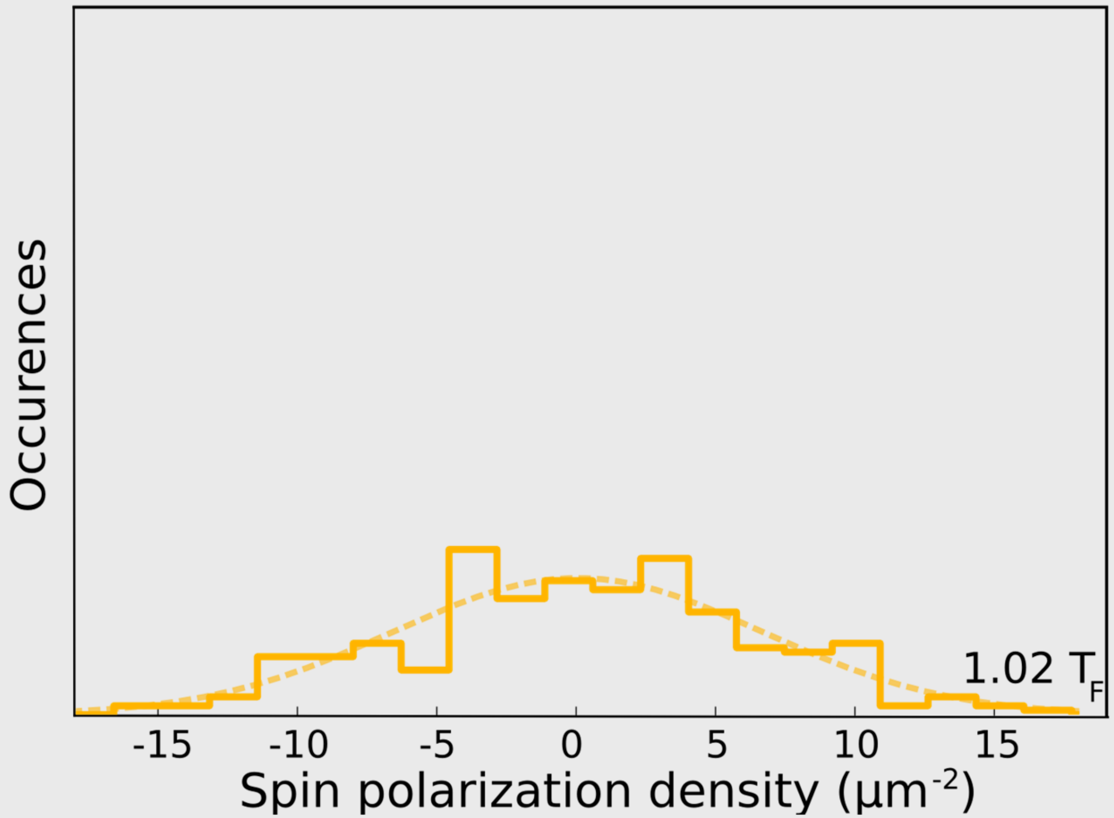
Spin polarised sample, close to resonance



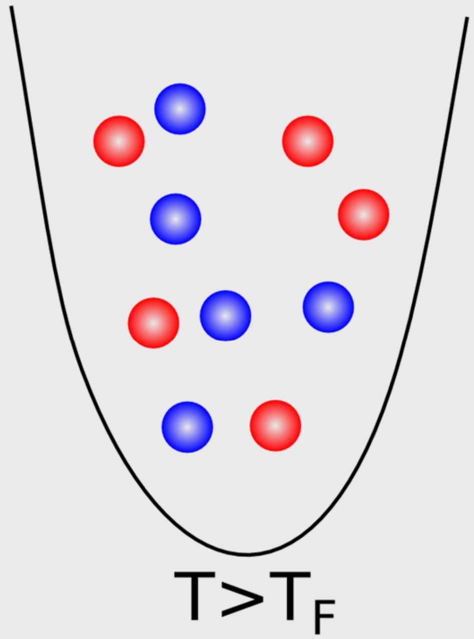
Single component

J. Meineke, J.-P. Brantut, D. Stadler, T. Müller, H. Moritz, T. Esslinger, Nature Phys. DOI: 10.1038 (2012)

Distribution of Spin-Polarization



Size of technical fluctuations



Weakly interacting gas

J. Meineke, J.-P. Brantut, D. Stadler, T. Müller, H. Moritz, T. Esslinger, Nature Phys. DOI: 10.1038 (2012)

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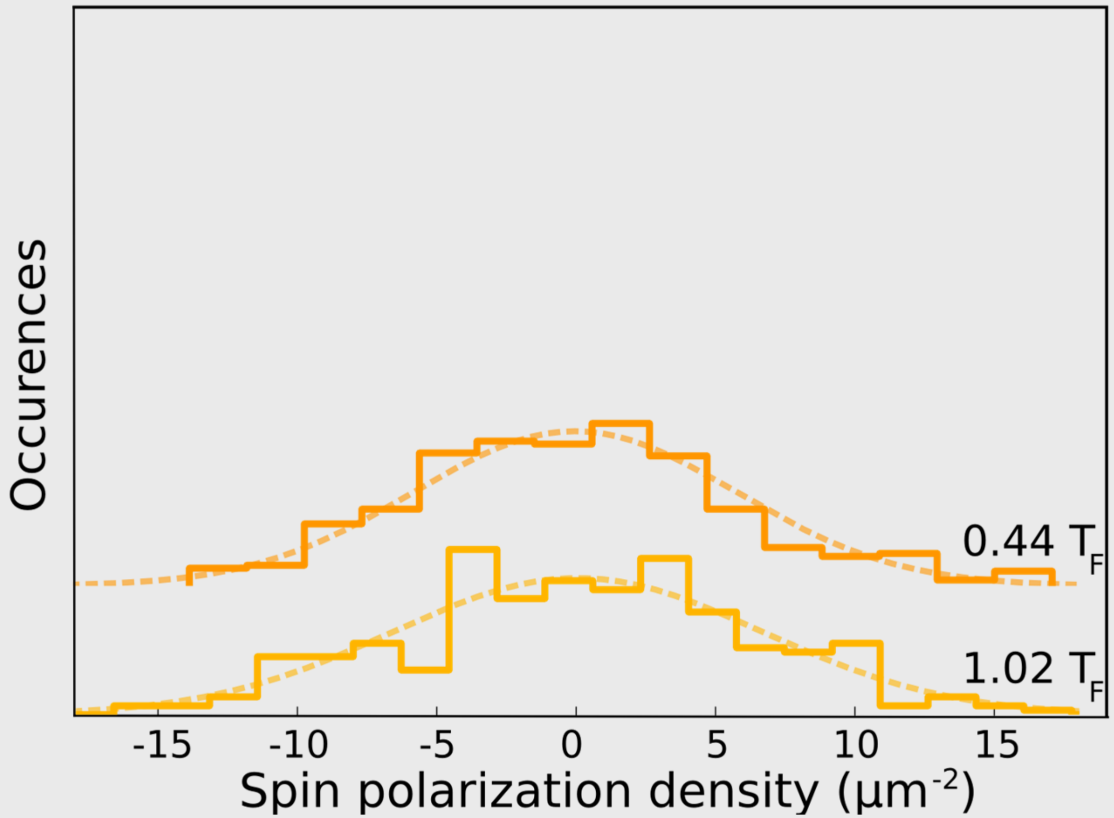

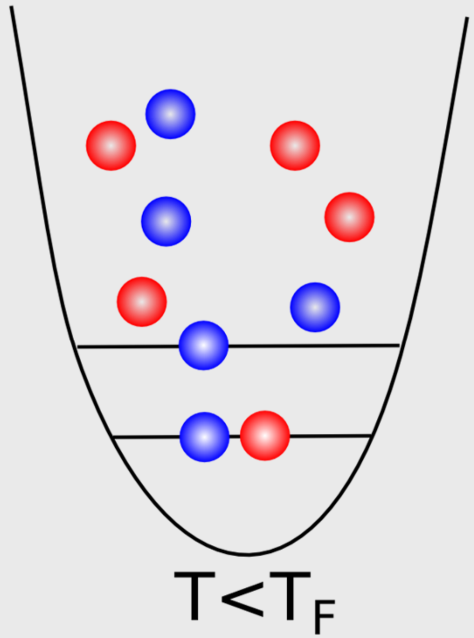

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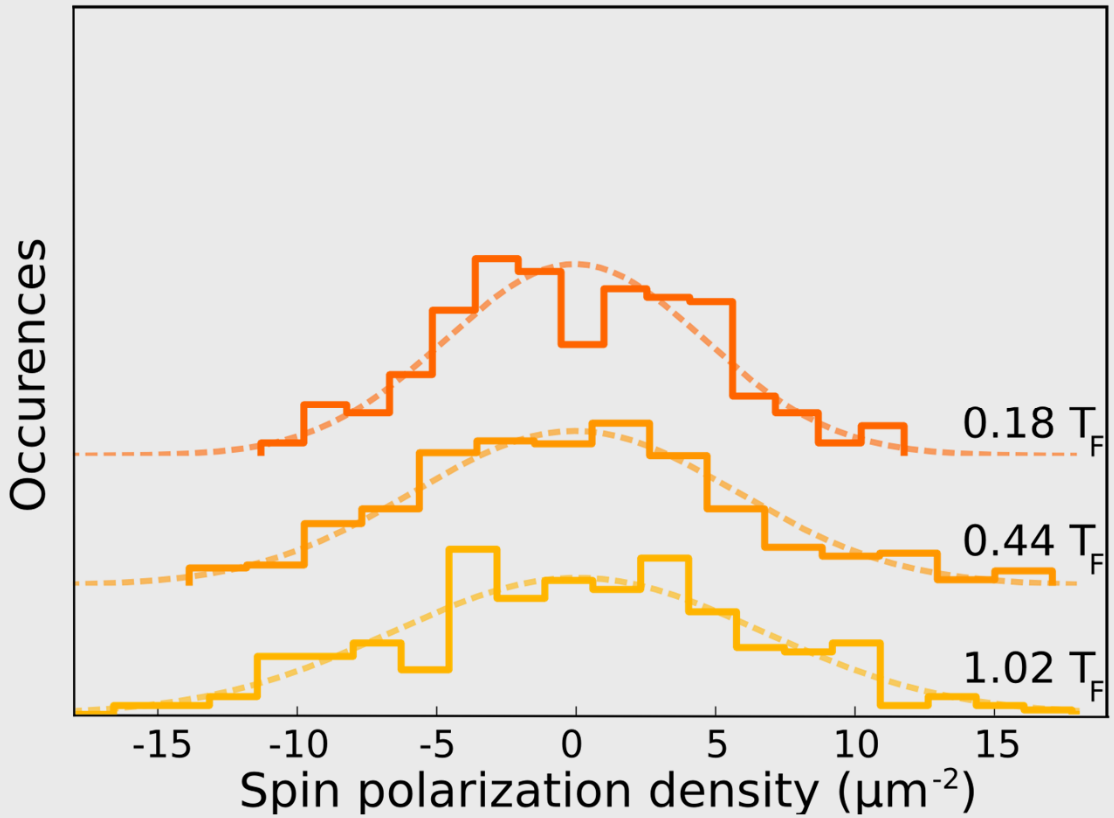
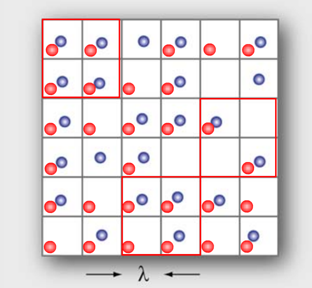
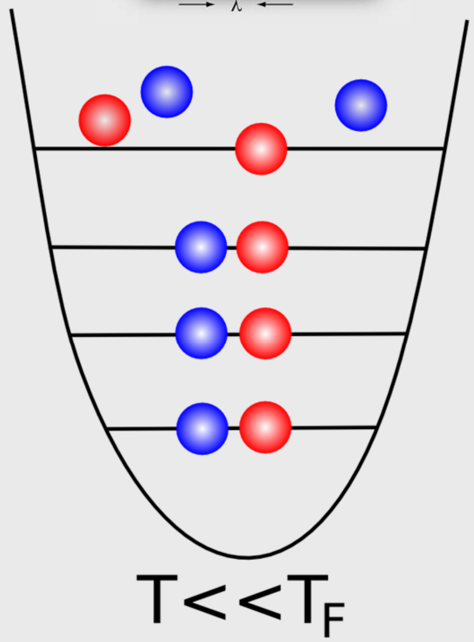


Size of technical fluctuations

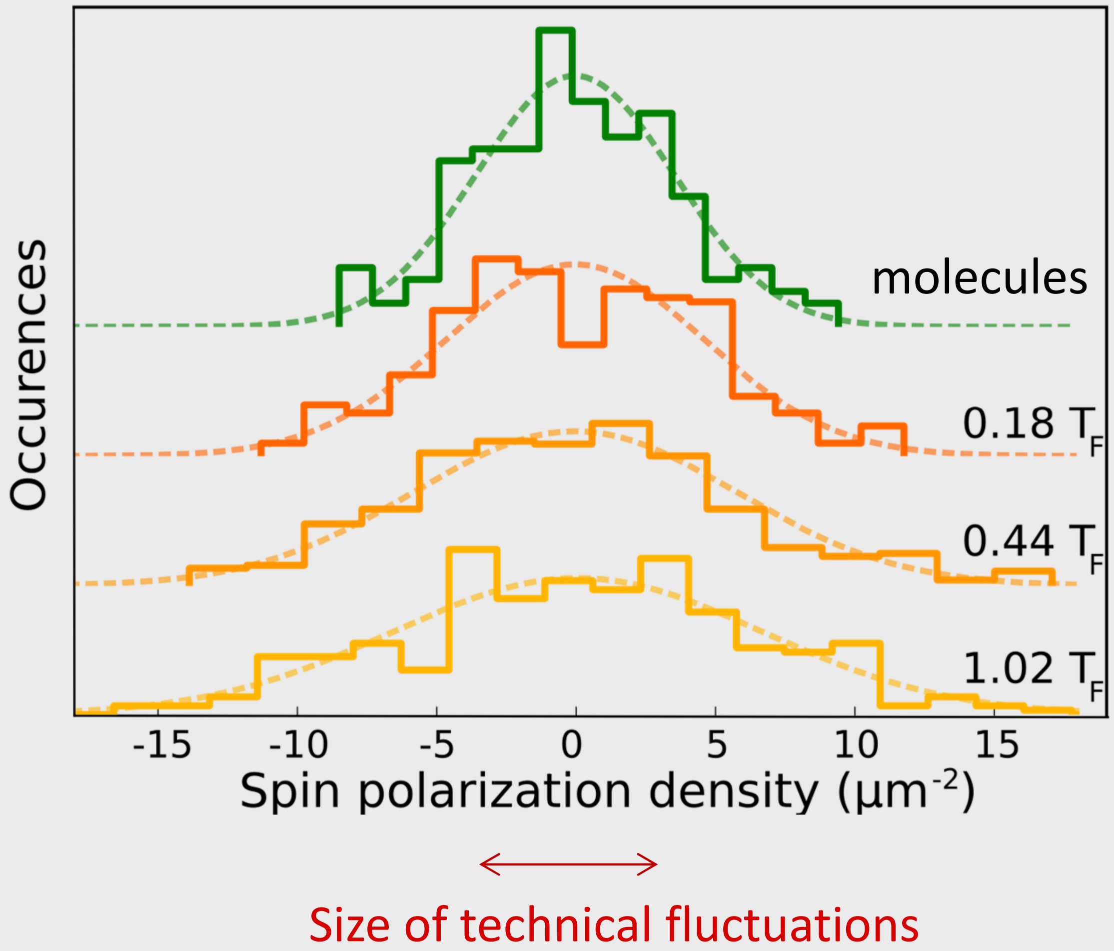


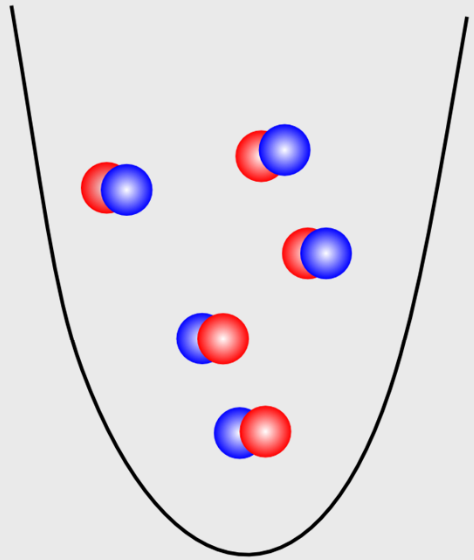


Weakly interacting gas

J. Meineke, J.-P. Brantut, D. Stadler, T. Müller, H. Moritz, T. Esslinger, Nature Phys. DOI: 10.1038 (2012)

Suppression of Spin-Fluctuations

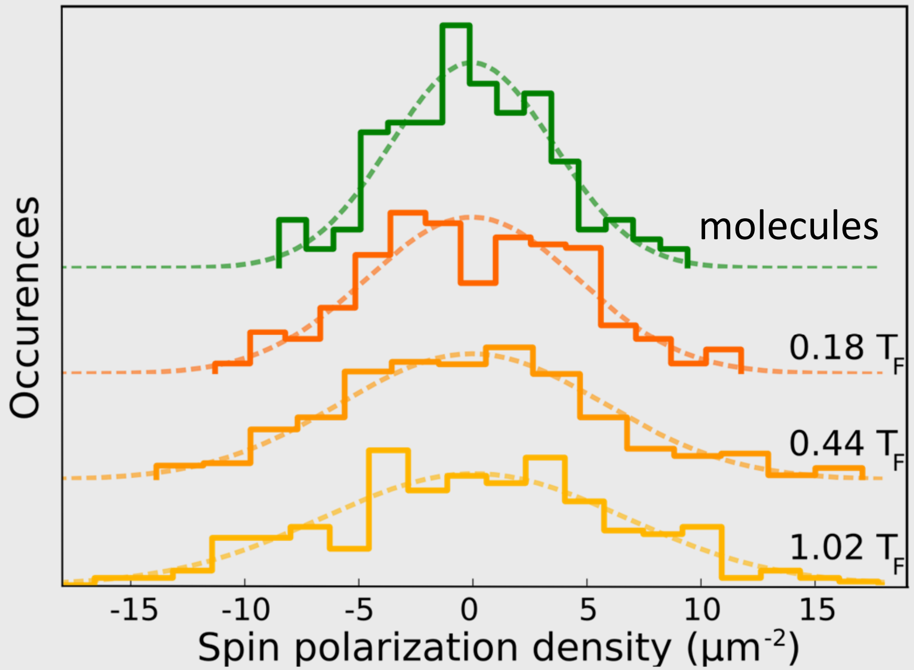


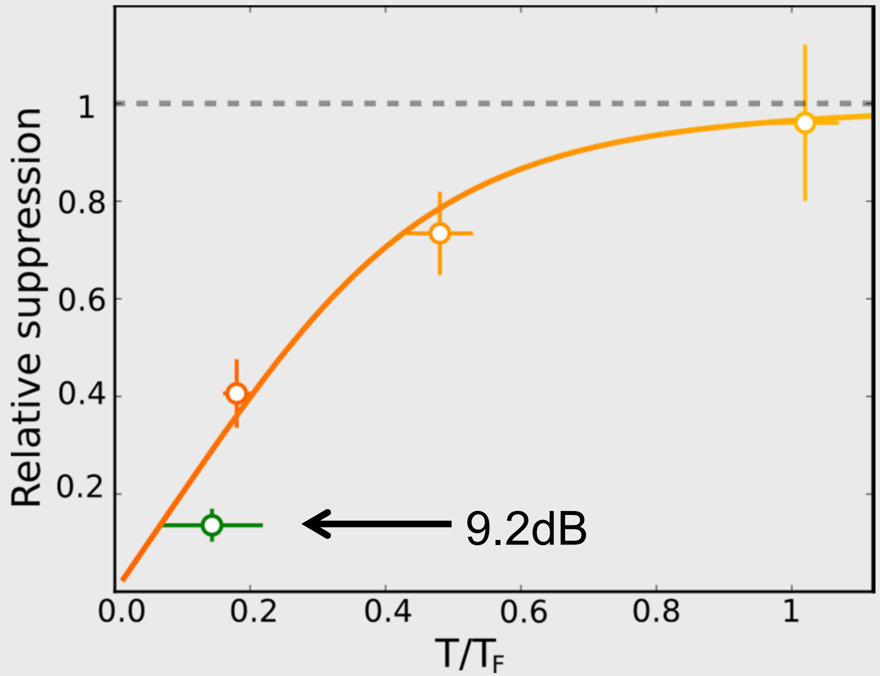


Strong repulsive interactions

J. Meineke, J.-P. Brantut, D. Stadler, T. Müller, H. Moritz, T. Esslinger, Nature Phys. DOI: 10.1038 (2012)

Distribution of Spin-Polarization

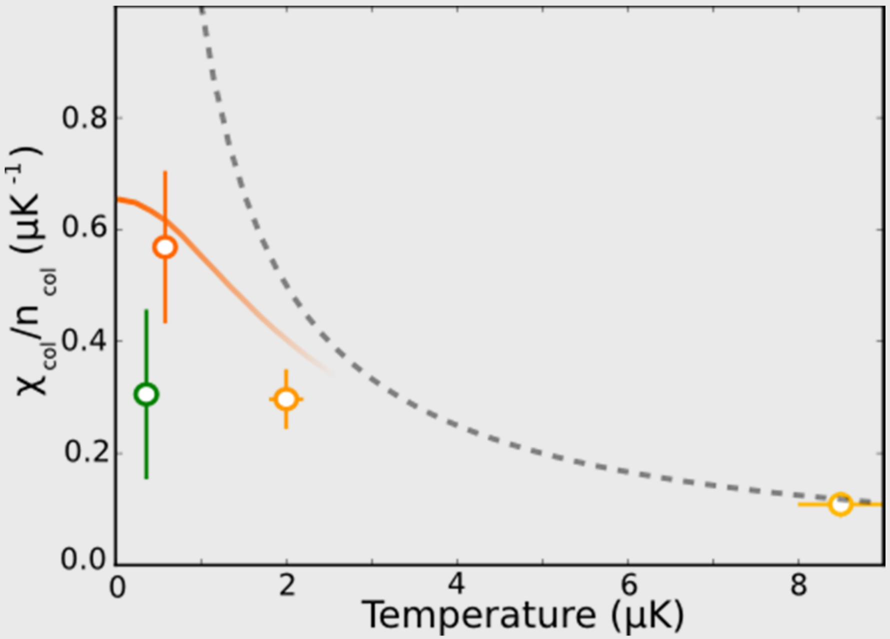




Size of technical fluctuations

J. Meineke, J.-P. Brantut, D. Stadler, T. Müller, H. Moritz, T. Esslinger, Nature Phys. DOI: 10.1038 (2012)

Spin-Susceptibility



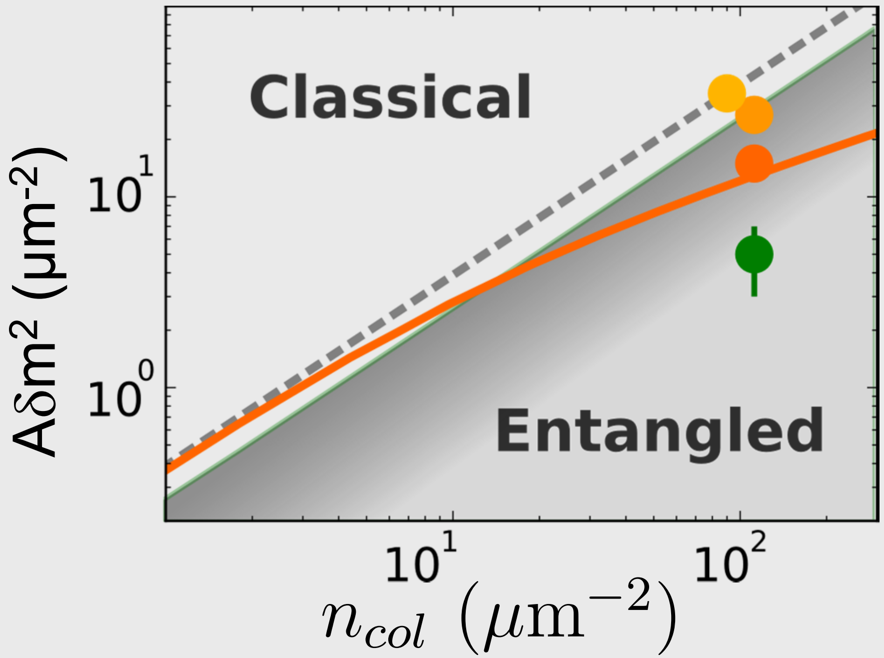
Fluctuation-Dissipation Theorem

- δm^2 and $T \Rightarrow$ spin-susceptibility $\quad \chi = \frac{\partial(n_\uparrow - n_\downarrow)}{\partial(\mu_\uparrow - \mu_\downarrow)}$

$$k_B T \, \chi = \delta m^2$$

Other measurements of spin-susceptibility: Salomon, Zwierlein, Ketterle groups

Entanglement



Inequality for Collective Spin Observable

- Collection of 2-Level Systems: $\vec{J} = \sum \vec{\sigma_i}$
- For separable states and symmetry under spin rotations:

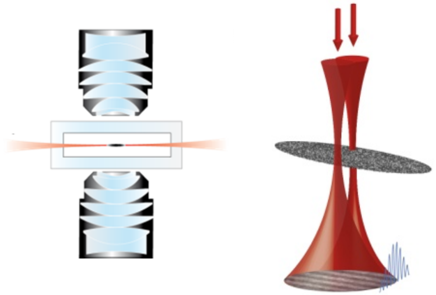
$$\frac{\Delta J_z^2}{\langle N \rangle} \geq \frac{2}{3} \quad \Rightarrow \quad \frac{A\delta m^2}{n_{col}} \geq \frac{2}{3}$$

Wiesniak et al., NJP 7, 258 (2005); Toth et al., PRA 79, 042334 (2009)

Novel Probes

ETH

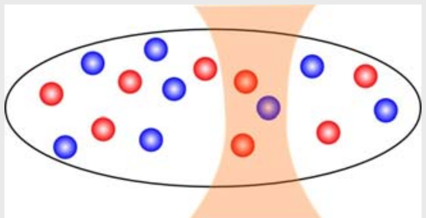
Microscopic access



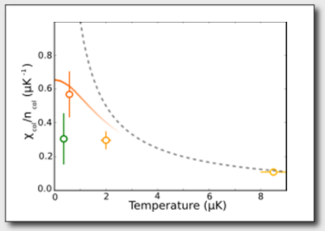
fluctuations
correlations

thermodynamic
properties

mesoscopic
systems

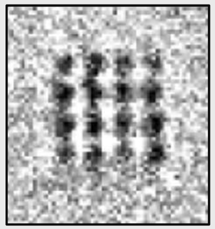


Measure spin-fluctuations



Extract spin-susceptibility

Witness entanglement



Zürich – Team

Jakob Meineke — David Stadler — Torben Müller — Sebastian Krinner — Jean-Philippe Brantut

Henning Moritz

Tilman Esslinger