Towards a Quantum Gas Microscope for Fermions

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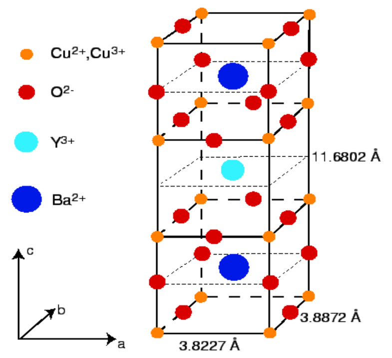
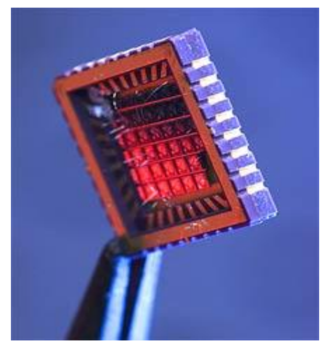
Ultracold Fermi Gases: a Model System

Strongly-correlated electronic systems
Technologically important, poorly understood

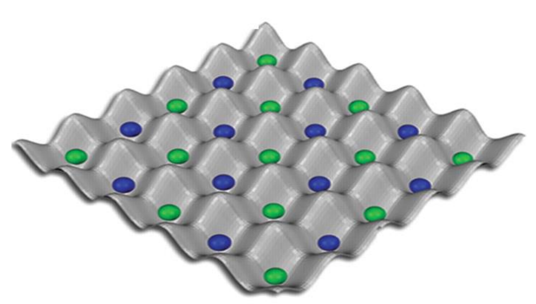


High-T_c Superconductors

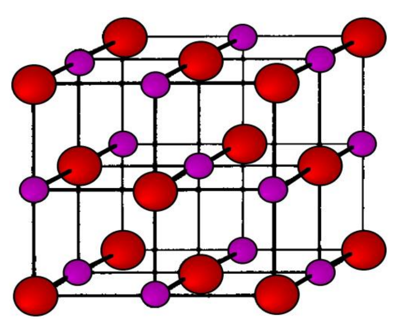


Spintronic devices

Ultracold atomic gases can **simulate** strongly correlated electronic physics in a controllable manner.



Atoms in Optical Lattices



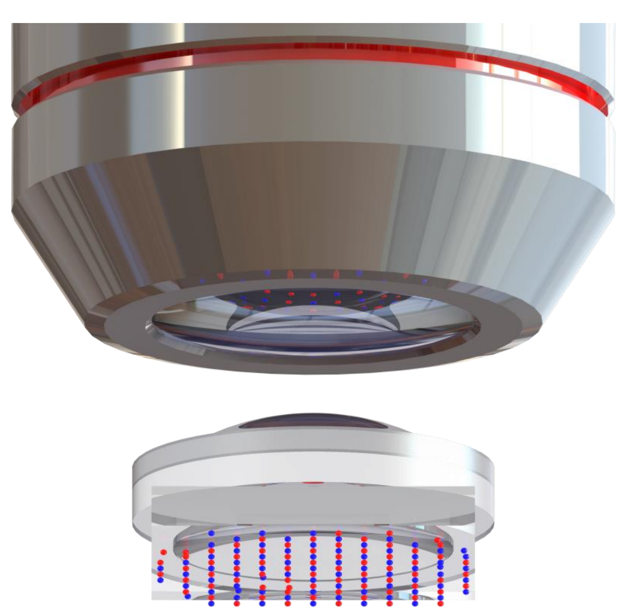
Condensed Matter Systems

Goal: Single-site Imaging of Fermions in a Optical Lattice

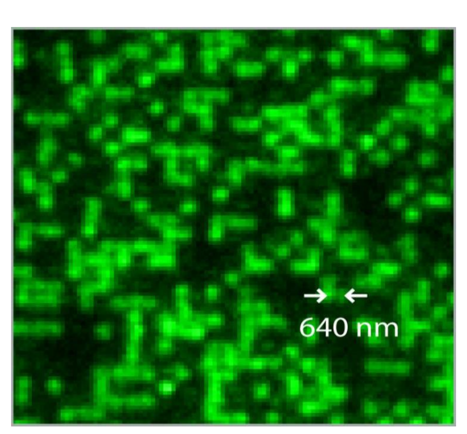
A high-resolution imaging system allows detection of fermionic atoms on individual lattice sites.

Single-site Resolution

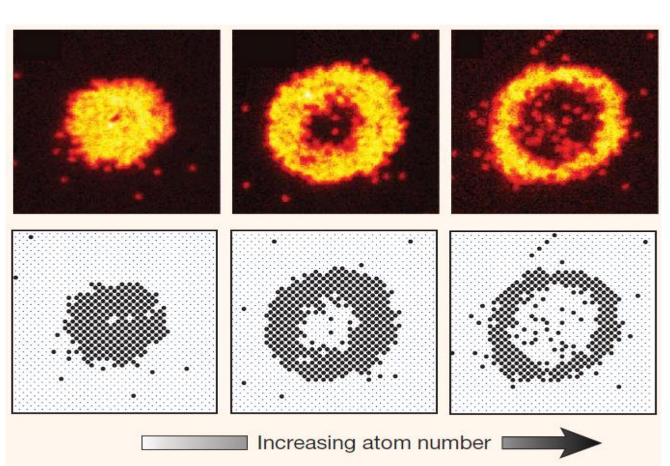
- Direct imaging of fluctuations and correlation functions
- Engineering arbitrary lattice geometries
- Single-site addressing
- New, "algorithmic" cooling schemes



Previous work at Harvard and Munich has achieved single-site detection for bosonic atoms.



Bakr *et al.*, Nature 462, 74-77 (2009)

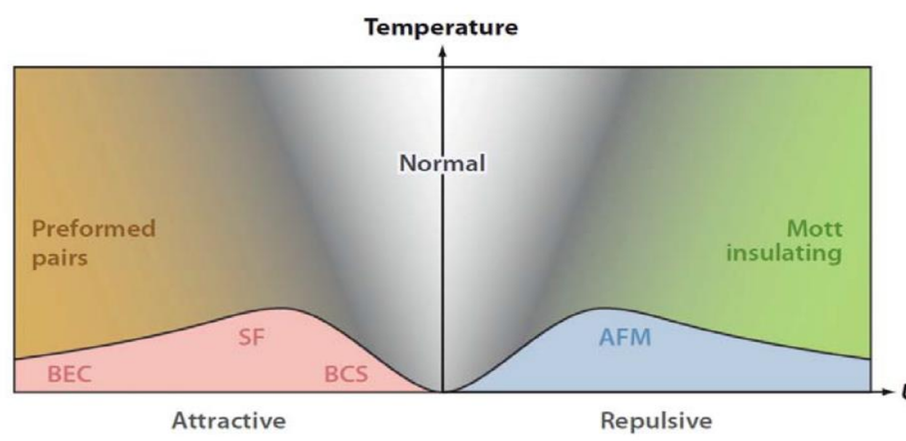


Sherson *et al.*, Nature 467, 68-71 (2010)

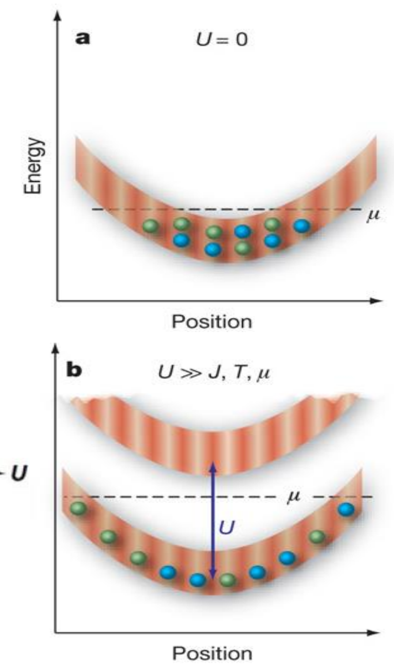
Matter is made of fermions → a fermion microscope!

Fermi-Hubbard Physics

$$\hat{H} = -J\sum_{\langle ij\rangle,\sigma}\left(\hat{c}^{\dagger}_{j\sigma}\hat{c}_{i\sigma} + \text{h.c.}\right) + U\sum_{i}\hat{n}_{i\uparrow}\hat{n}_{i\downarrow} + \sum_{i}\varepsilon_i \hat{n}_i$$



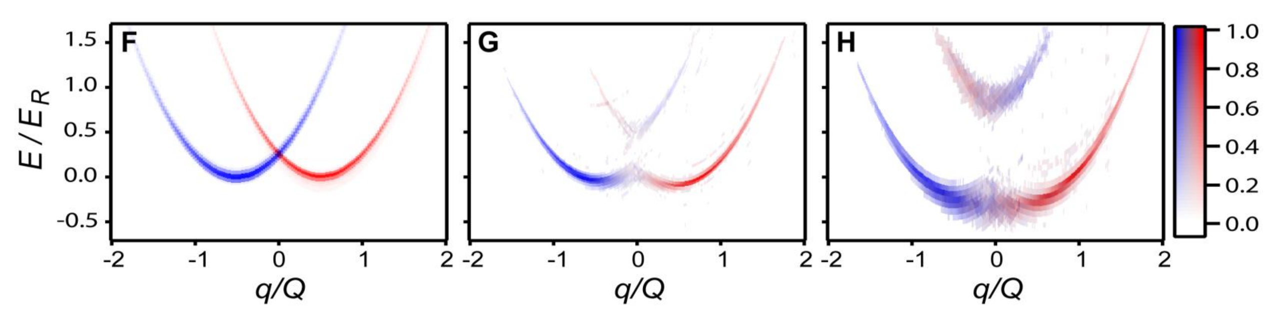
Esslinger, Ann. Rev. of Cond. Matt. Phys. 1, 129-152 (2010)



Joerdens *et al.*, Nature 455, 204-207 (2008)

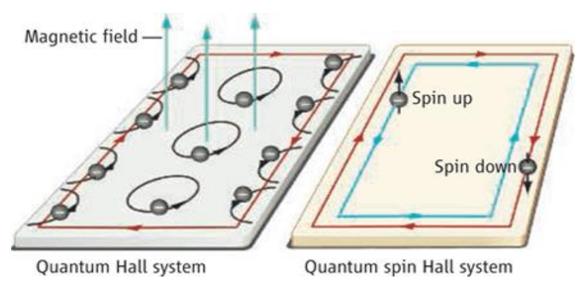
Direct imaging of the Mott insulating and the antiferromagnetic phases in the Fermi Hubbard model might be possible.
BIG QUESTION: Does Fermi-Hubbard predict High-Tc Superconductivity?

Synthetic Gauge Fields



Cheuk *et al.*, arXiv:1205:3483 (2012)
Previous work: Wang *et al.*, arXiv: 1204:1887 (2012)

Raman coupling can be used to engineer synthetic magnetic fields and spin-orbit coupling in system of fermionic atoms.

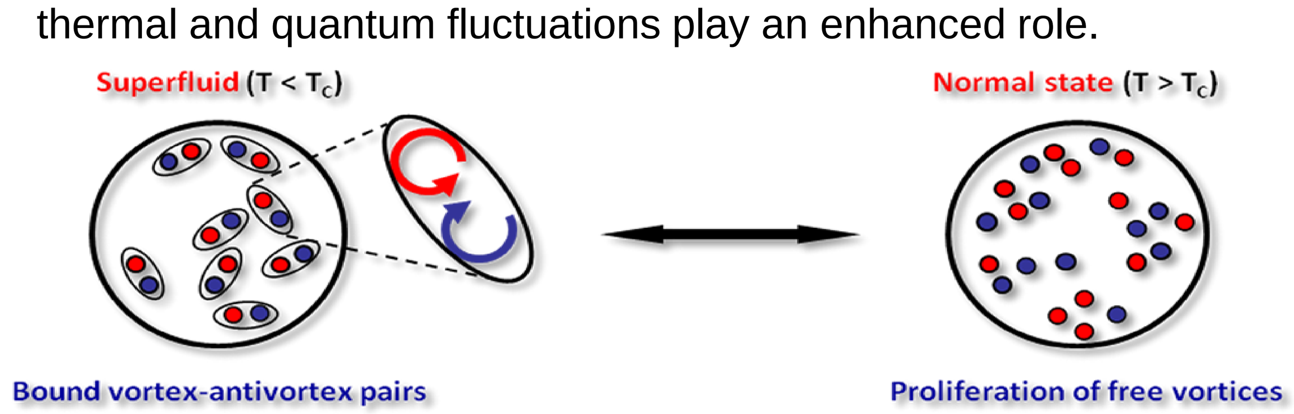


Nagaosa, Science 318, 758-759 (2007)

Possible goals: Explore quantum hall physics and topological insulators with a fermi gas microscope.

Reduced Dimensionality

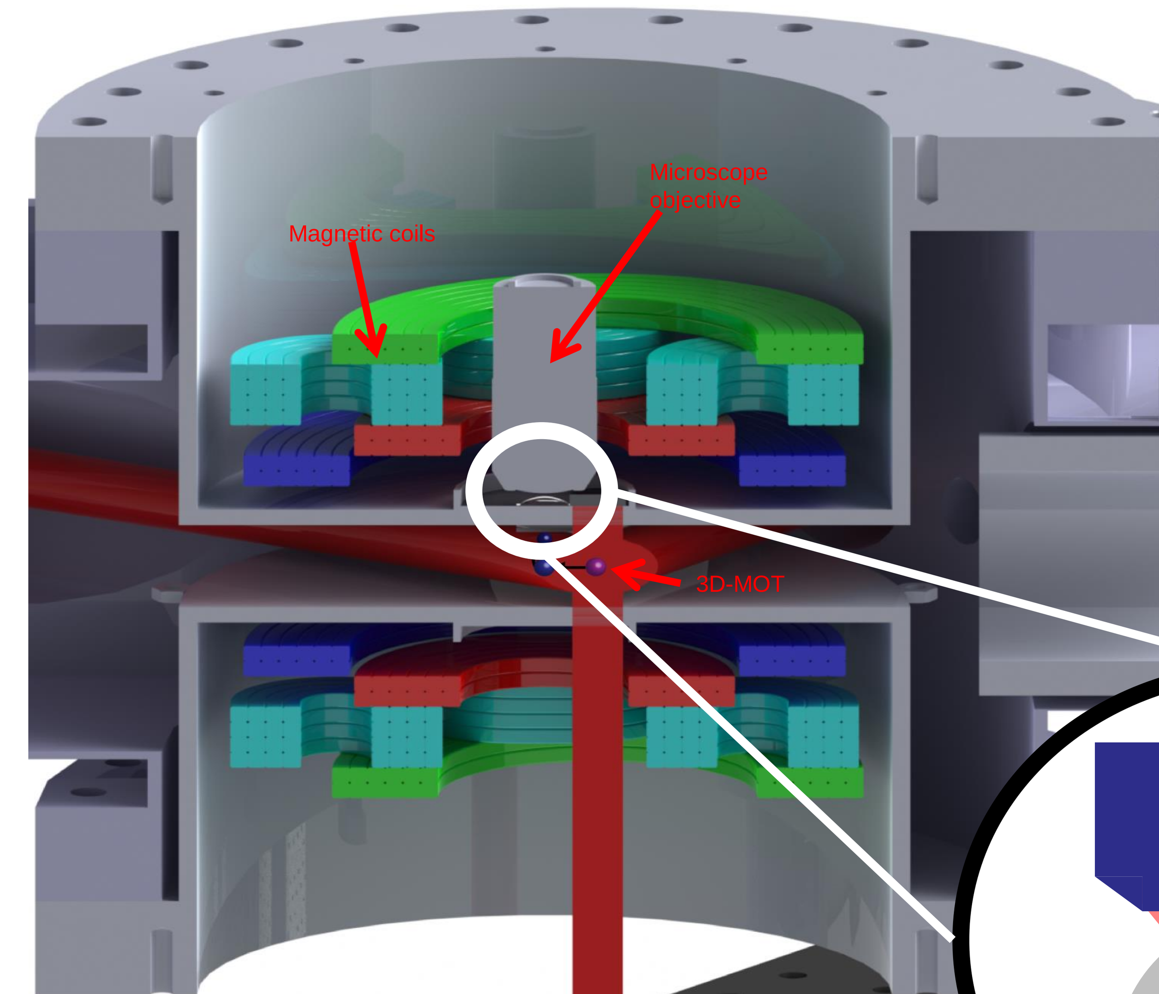
A quantum gas microscope provides the natural playground for studying strongly interacting fermions in a single 2D plane – thermal and quantum fluctuations play an enhanced role.

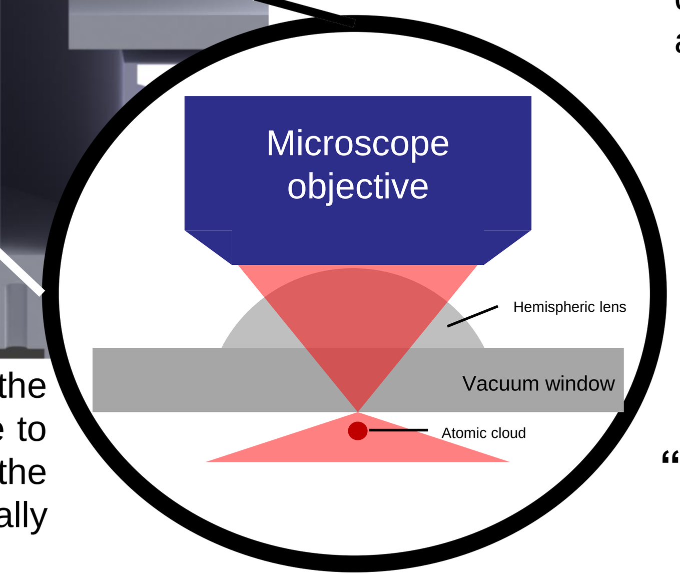


Hadzibabic *et al.*, Nature 441, 1118 (2006)

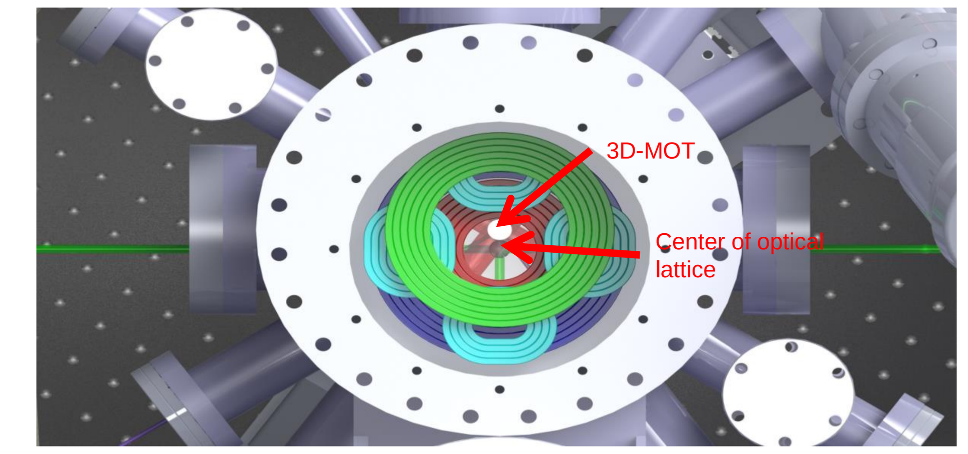
The microscope may allow in-situ observation of BKT phase transition: dissociation of vortex pairs above the transition temperature.

Novel Features of our Experiment Design





Side View: Bucket window viewports allow to position the microscope objective and the magnetic coils very close to the imaging axis. The 3D MOT is created 12 mm apart from the optical imaging axis, atoms are transported magnetically in front of the imaging system.



Top View: The 3D MOT laser beams (red) and a quadrupole magnetic trap (green) are centered around the 3D-MOT position. The center of the three-dimensional optical lattice is in the center of the imaging axis.

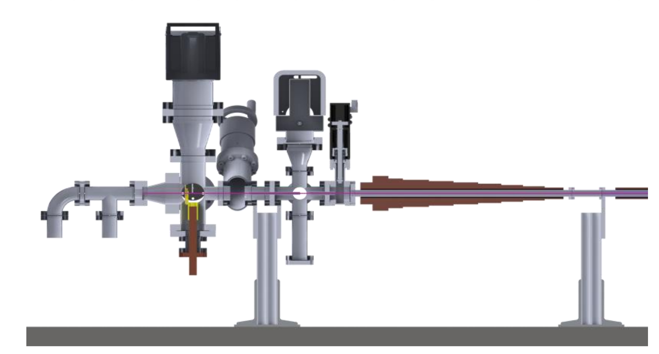
Rayleigh criterion for optical resolution

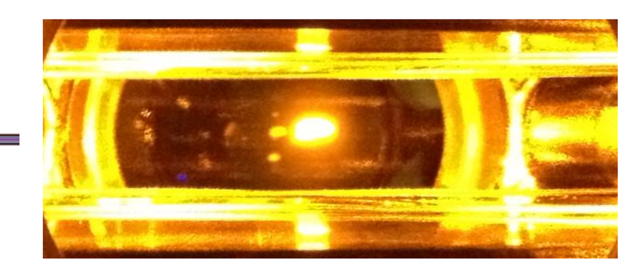
$$r = \frac{1.22\,\lambda}{2\,n\sin(\theta)} = \frac{0.61\,\lambda}{NA}$$

"Solid Immersion" effect enhances NA by a factor of 1.54

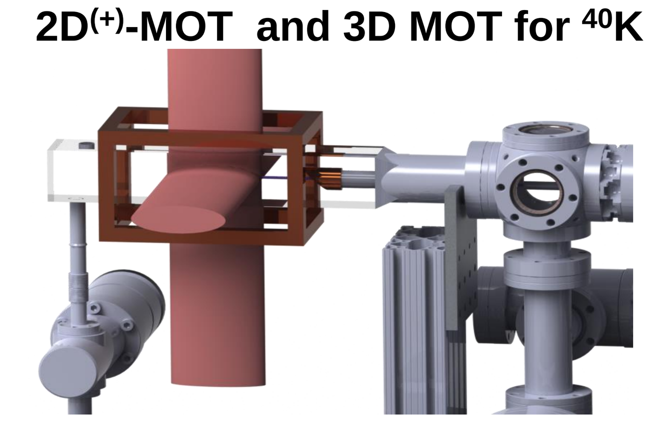
Experiment Status

Zeeman Slower and 3D MOT for ^{23}Na

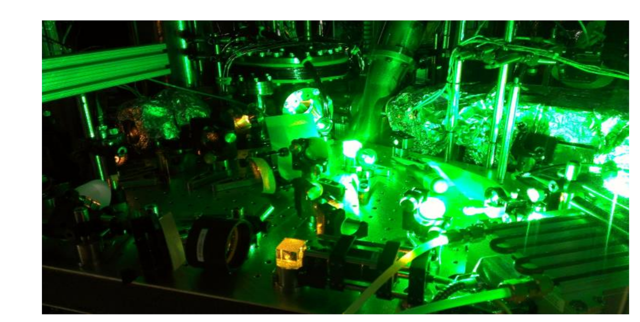




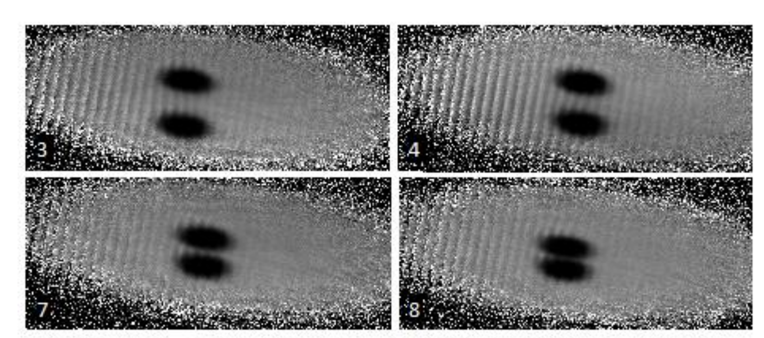
2D$^{(+)}$-MOT and 3D MOT for ^{40}K



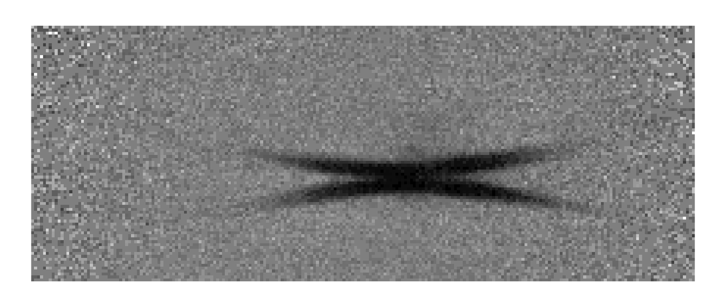
Plugged Quadrupole Trap



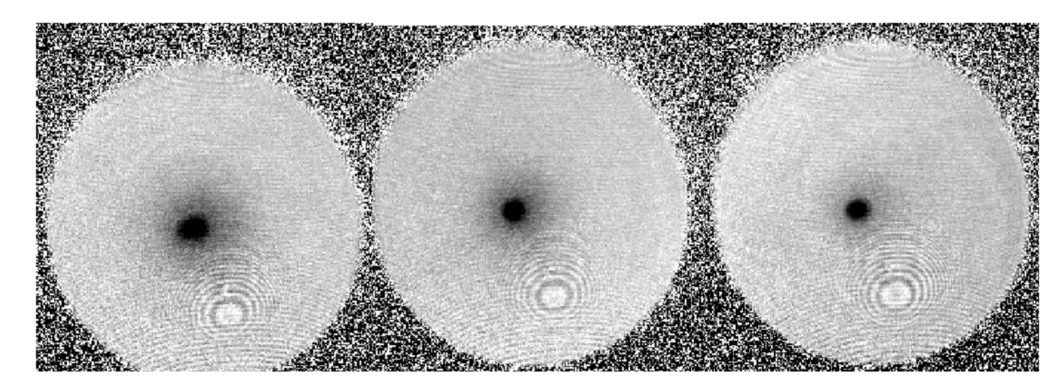
Atoms being transported under the microscope (seen from the side)



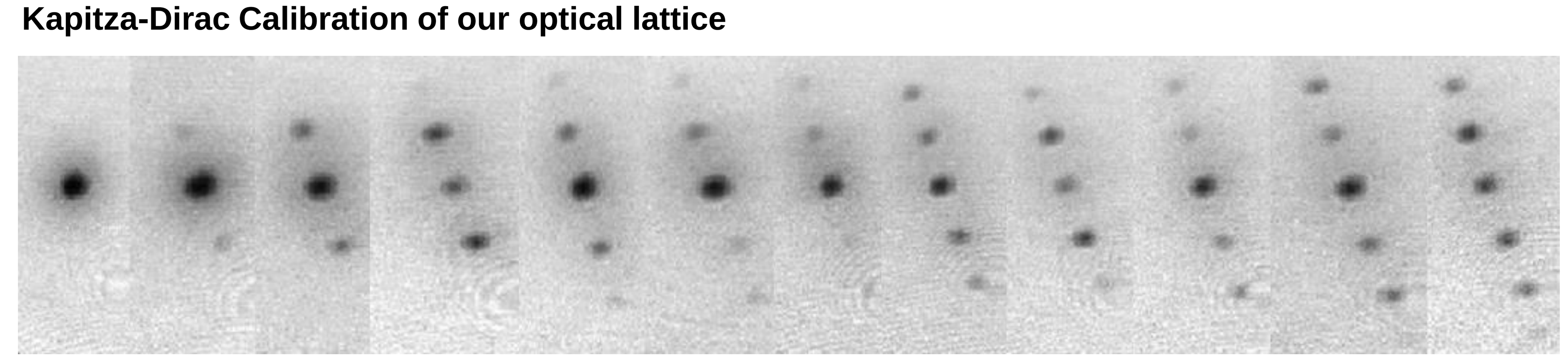
Hybrid trap under the microscope



Sodium BEC created under the microscope via evaporation in our hybrid trap (seen from the top)



Kapitza-Dirac Calibration of our optical lattice



Coming up…
- **Load fermions into the optical lattice**
- **Single-site Imaging!**