A Quantum Gas Microscope for Detecting Single Atoms in a Hubbard-regime Optical Lattice

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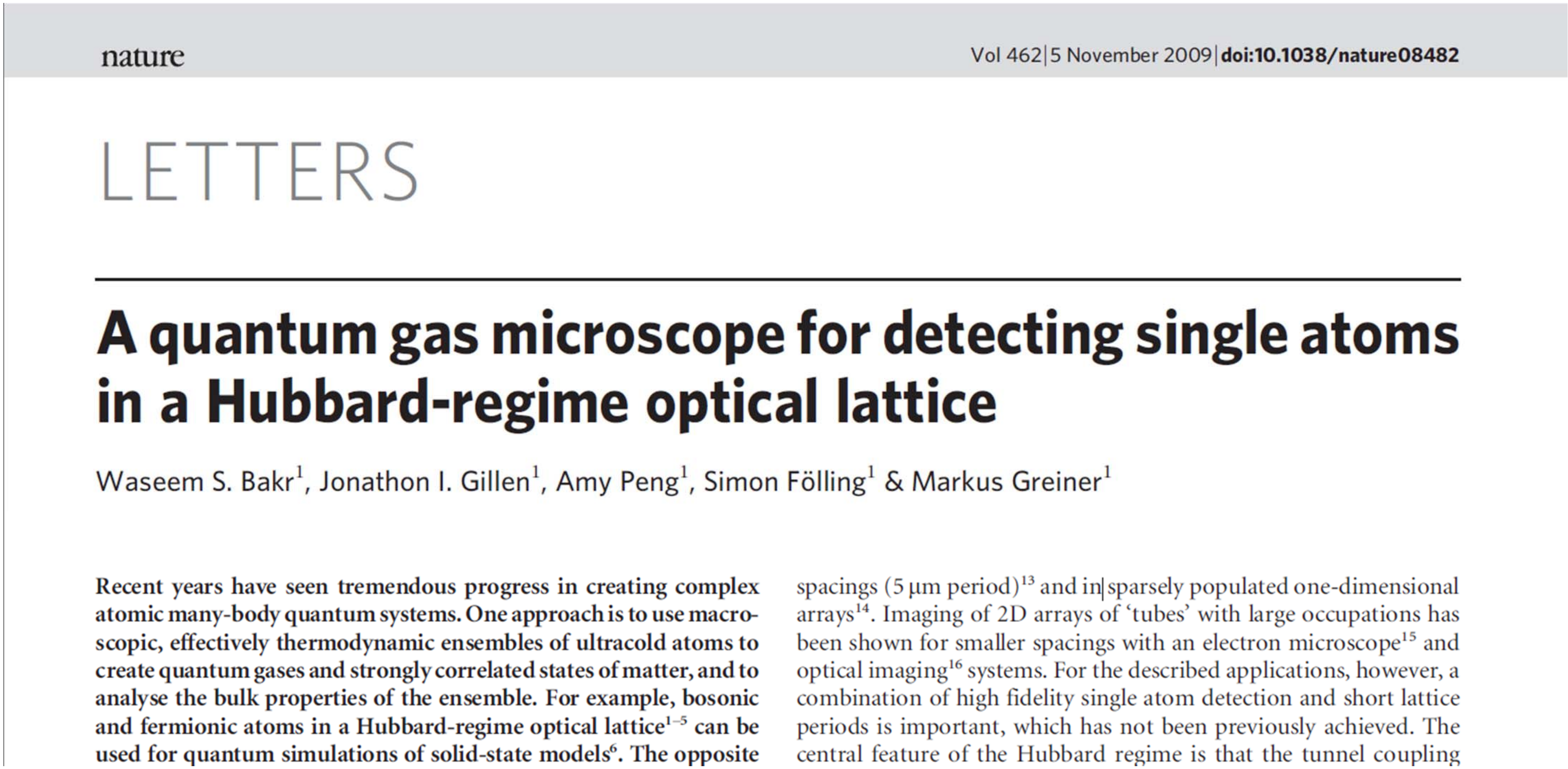
Outline

- *Background and Theory*
- Apparatus and Experiment
- Results and Data
- Citations and Relevance



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LETTERS

A quantum gas microscope for detecting single atoms in a Hubbard-regime optical lattice

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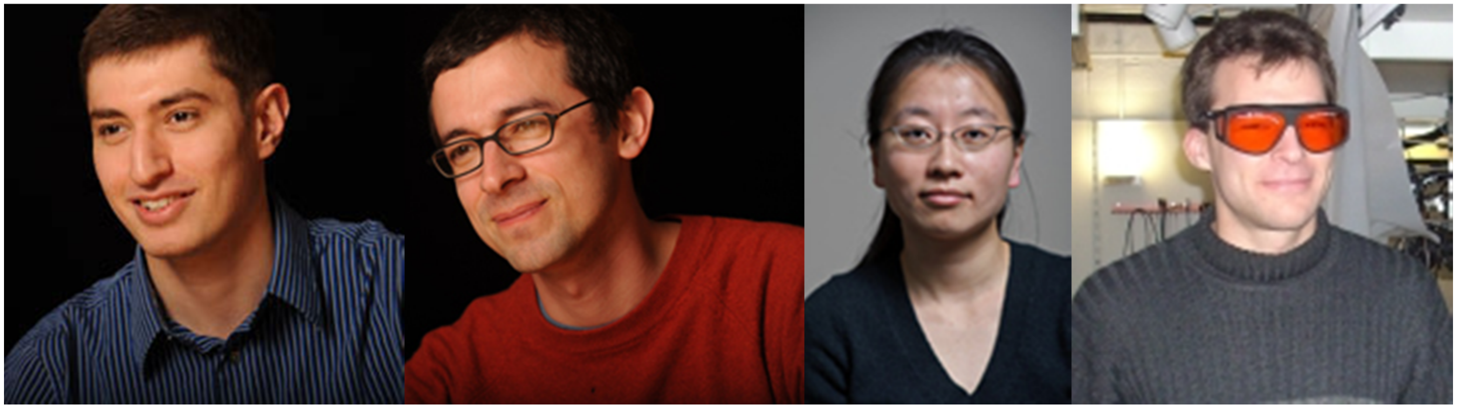
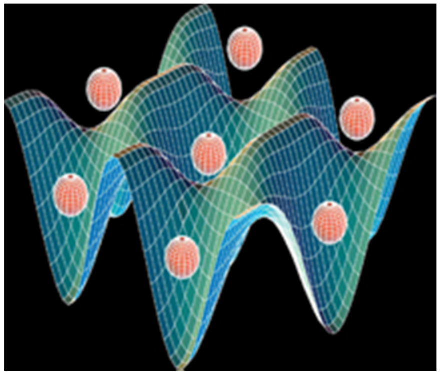
Recent years have seen tremendous progress in creating complex atomic many-body quantum systems. One approach is to use macroscopic, effectively thermodynamic ensembles of ultracold atoms to create quantum gases and strongly correlated states of matter, and to analyse the bulk properties of the ensemble. For example, bosonic and fermionic atoms in a Hubbard-regime optical lattice[1–5] can be used for quantum simulations of solid-state models[6]. The opposite

spacings (5 μm period)[13] and in sparsely populated one-dimensional arrays[14]. Imaging of 2D arrays of 'tubes' with large occupations has been shown for smaller spacings with an electron microscope[15] and optical imaging[16] systems. For the described applications, however, a combination of high fidelity single atom detection and short lattice periods is important, which has not been previously achieved. The central feature of the Hubbard regime is that the tunnel coupling



What is a *Hubbard-regime optical lattice*?

- In solid-state physics, we study crystals.
  - A lot of physics arise because of the periodic potential
  - But the potential is limited by the kind of crystals available
- Optical lattice
  - Periodic potential formed by interfering laser beams
- Load ultracold atoms onto optical lattices
  - Atoms can tunnel and interact with each other
  - Can obtain various phases: superconductivity, superfluidity, Mott insulator
- Mott insulator
  - Caused by interactions, not band structures
  - Can be explained by the Hubbard model



Researchers have tried both microscopic and macroscopic approaches

- Microscopic
  - Build quantum system atom by atom
  - Complete control over all degrees of freedom
- Macroscopic
  - Thermodynamic ensemble of ultracold atoms
  - Can only analyze bulk properties

- These two approaches are not good enough

A quantum gas microscope bridges the macroscopic and microscopic

- Allows one to detect, and study the properties of every single atom of a macroscopic quantum system
- Doing so is difficult in the Hubbard regime
  - Small lattice spacings ~ 500 nm
- Previous attempts by other groups only managed large spacings ~ 5μm

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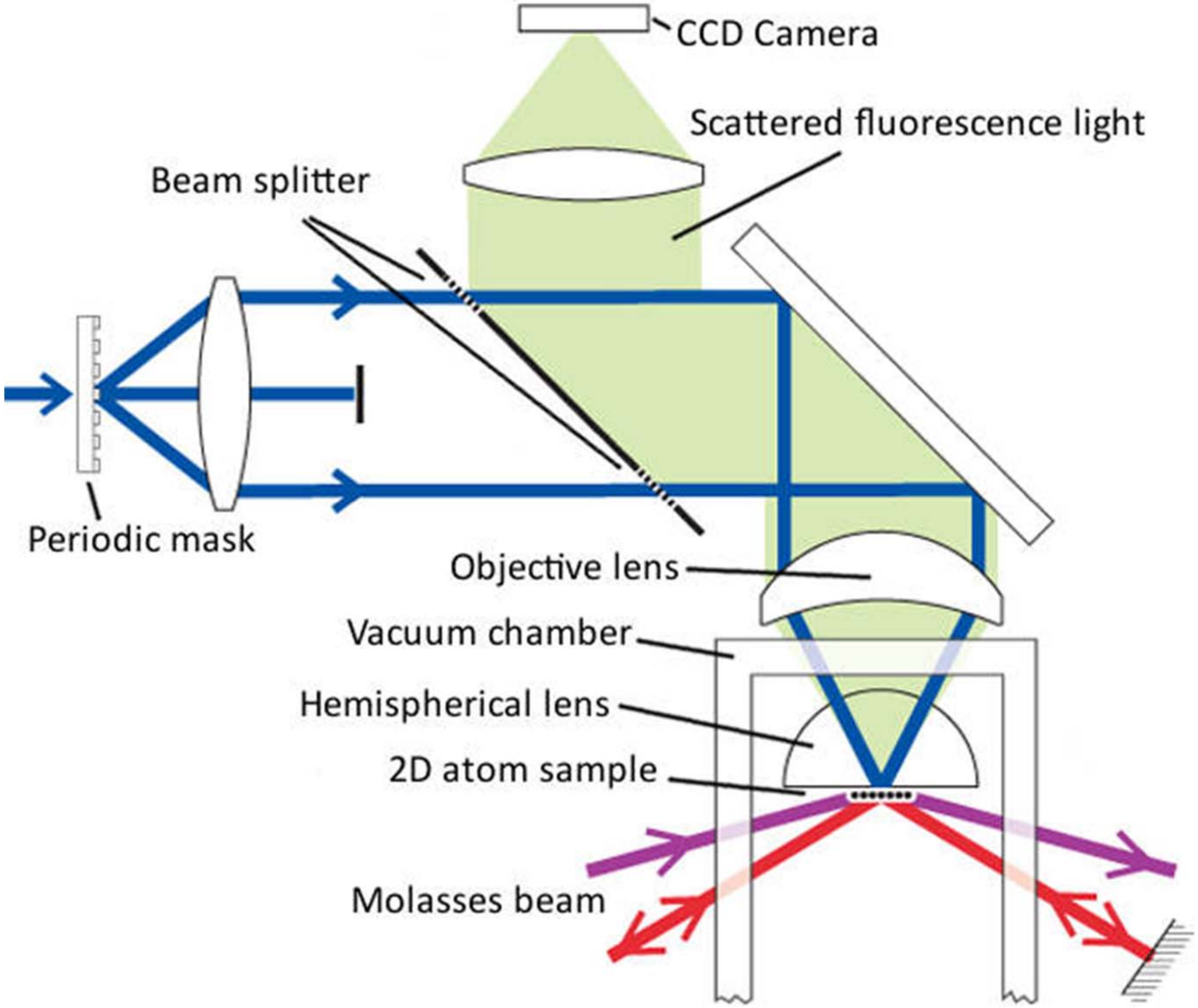
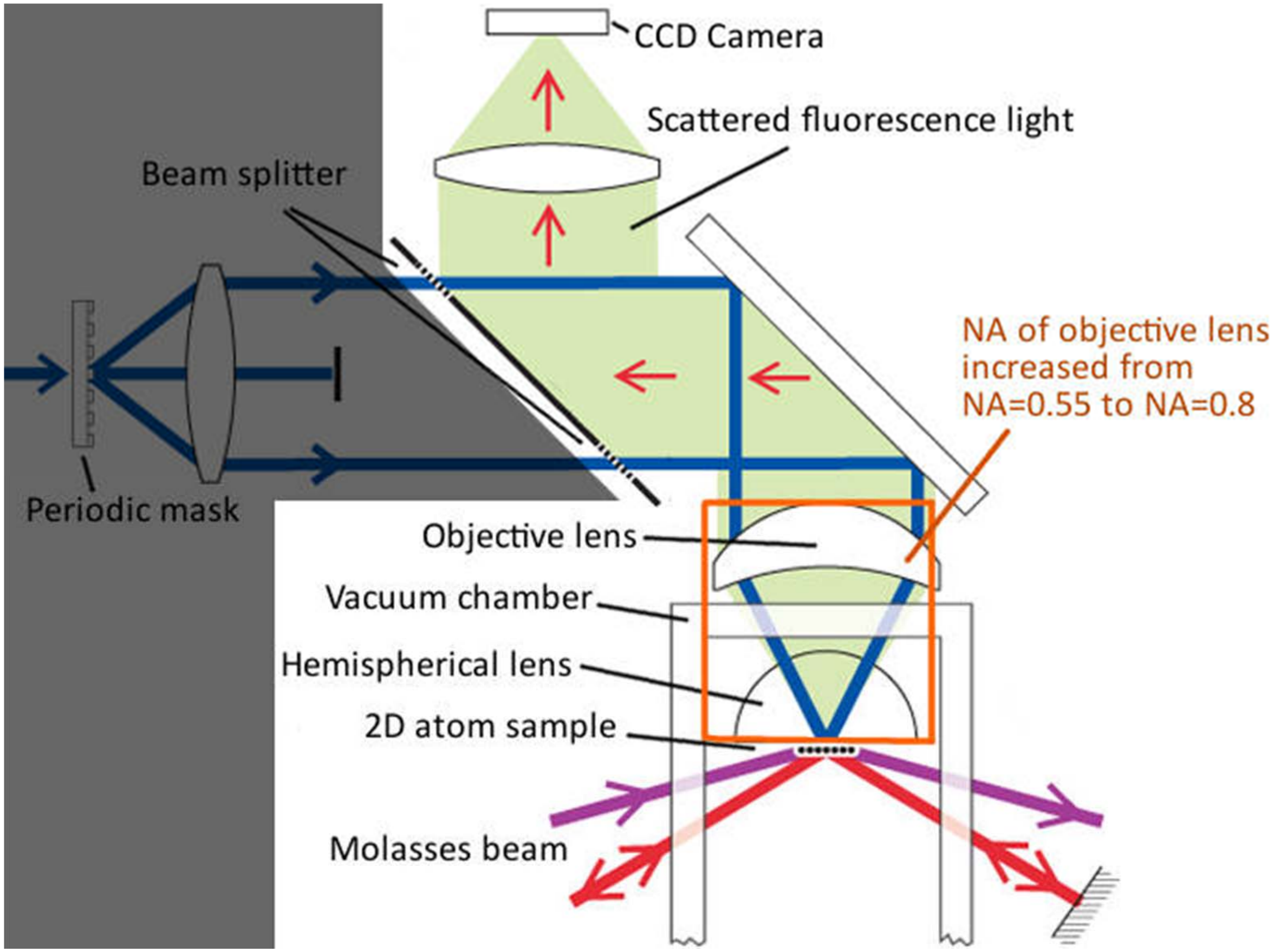
Diagram of quantum gas microscope



(image modified from W.S. Bakr et al. 2009)

Optical imaging path



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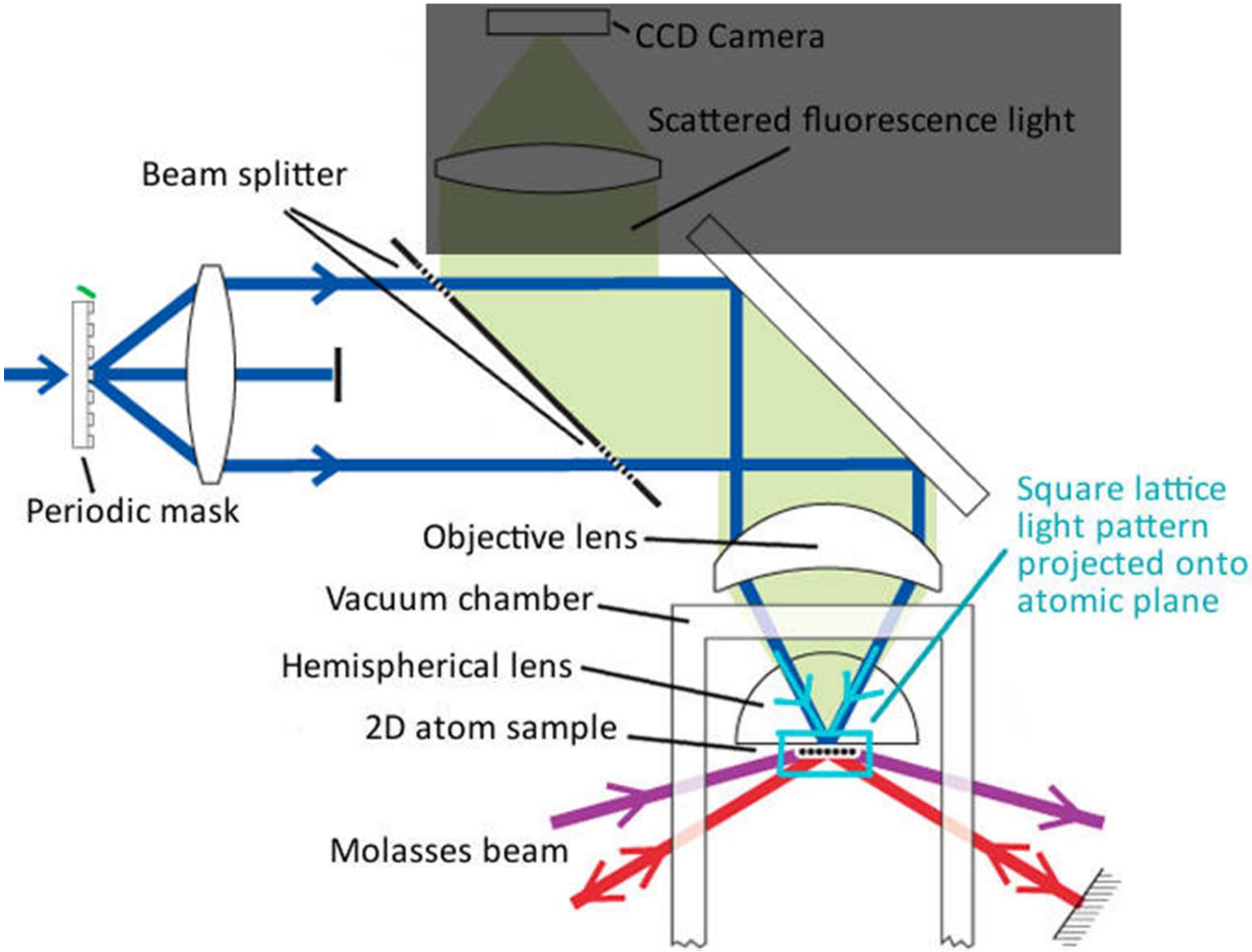
Optical lattice creation



(image modified from W.S. Bakr et al. 2009)

Specifics of the experiment

- 2D Bose-Einstein condensate of ^{87}Rb used for atomic plane
- Square optical lattice generated with periodicity of a = 640nm
- Lattice potential well depth of 5500 * E_{rec}
  - – $E_{rec} = h^2/8ma^2$ is the recoil energy of the effective lattice wavelength and m is the mass of ^{87}Rb

The 2D optical lattice sites are expected to be either empty or singly occupied

- High lattice depth implies that initially many atoms will occupy the same sites
- Pairs of atoms undergo light-assisted collisions and escape (timescale ~100μs)
- Single-atom loss from trap expected primarily from collisions with background gas (half-life >10s)
- Need intermediate exposure time for images (actual exposure time: 0.2-1s)

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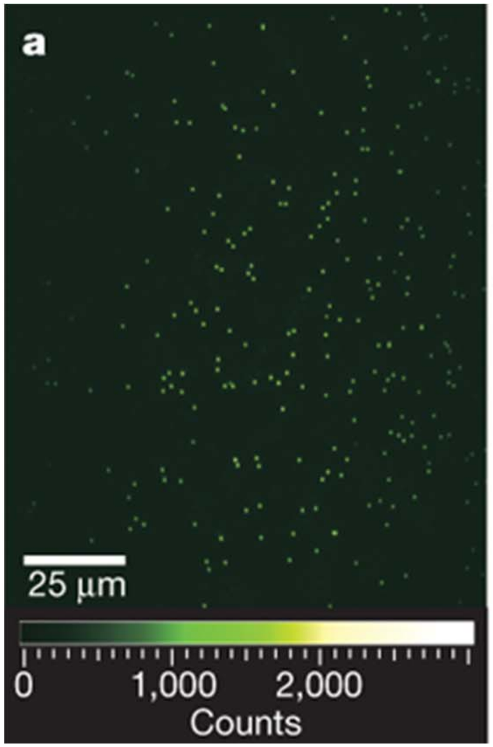
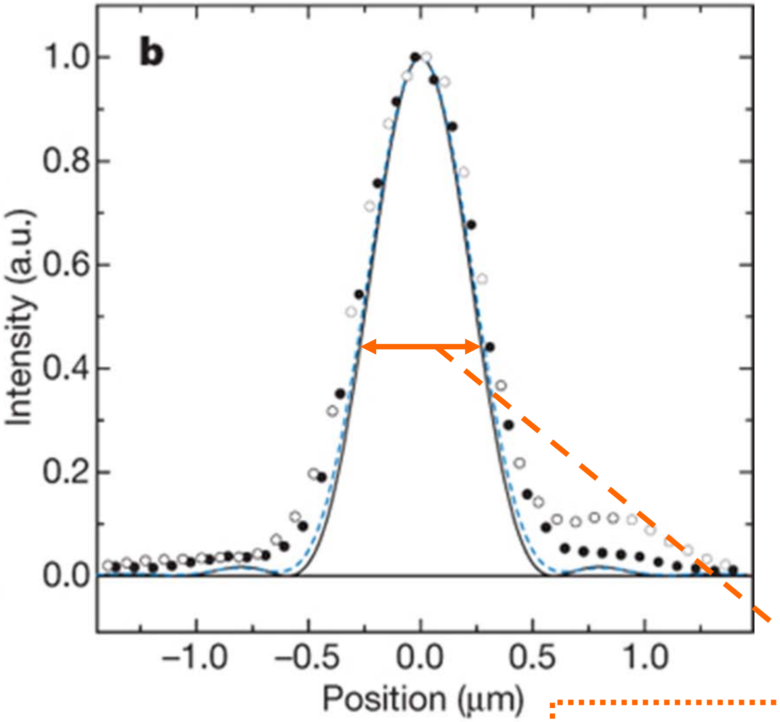
Individual lattice sites were detected

Field of view with sparse site occupation



Response of a single atom



●: horizontal profile

○: vertical profile

—: the expected Airy function (ideal)

---: the expected profile from a single atom (realistic)

FWHM (full width at half maximum) size
x-dir: 570 nm
y-dir: 630 nm

(Theoretical minimum: ~520 nm)

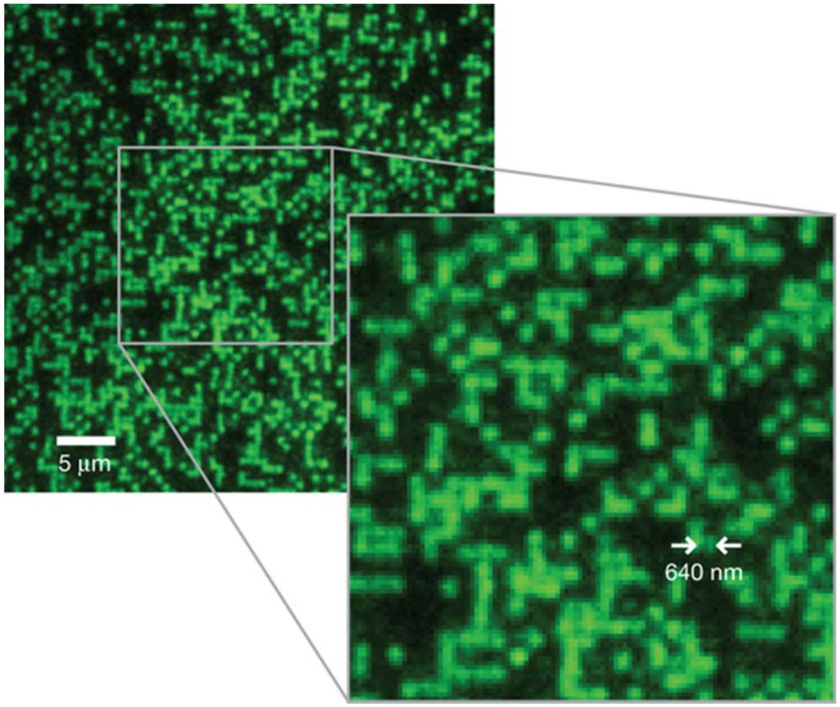
Lattice sites exhibit high stability

The same high-resolution optics are used to generate both the lattice and the image

Planar drift < 10% of lattice spacing in an hour

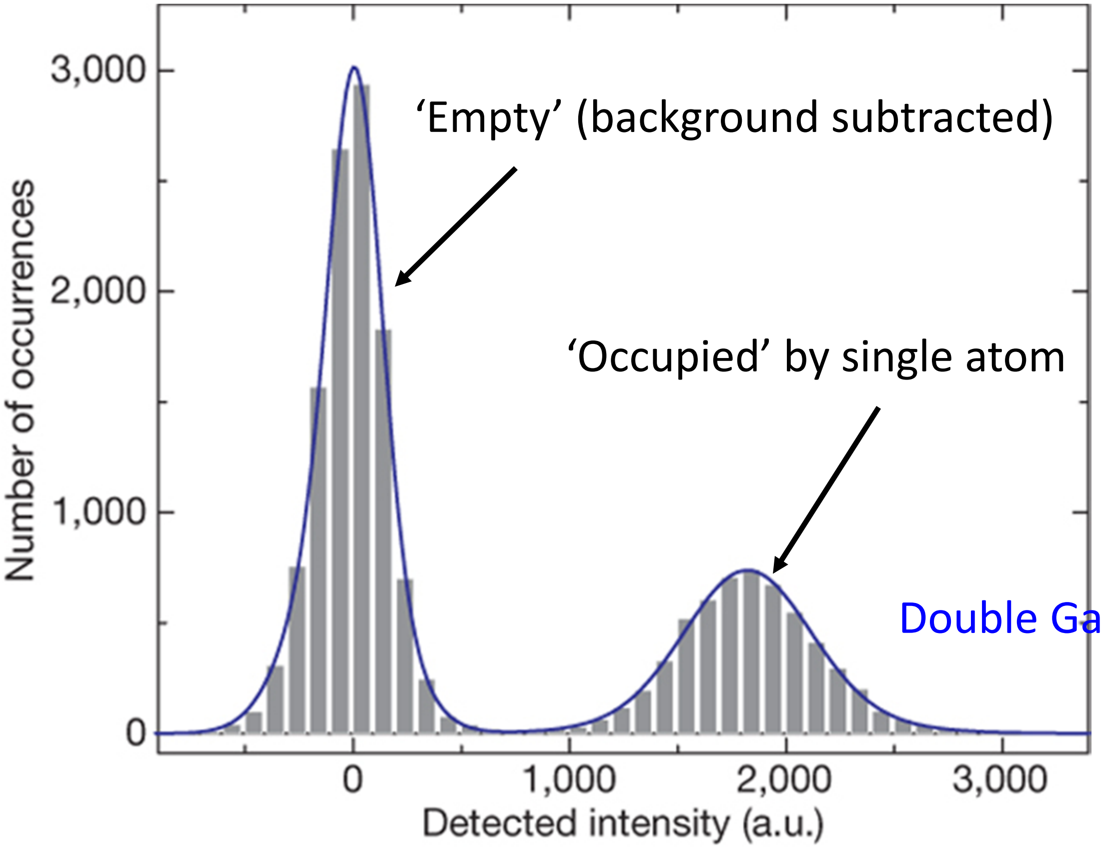
Shot noise < 15% r.m.s in an hour

Single atoms on a 640-nm-period optical lattice



Lattice sites exhibit high fidelity

Brightness distribution histogram of lattice sites for an exposure time of 1 s.



‘Empty’ (background subtracted)

‘Occupied’ by single atom

Double Gaussian fitted

Benefits of the quantum gas microscope

Able to image **~1,000** individual atoms on the sites of an optical lattice with **640nm** site spacing with **98%** fidelity

Gives full control over the lattice geometry on a single-site level.

Opens many new possibilities for quantum simulations and quantum information applications

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Citation Analysis

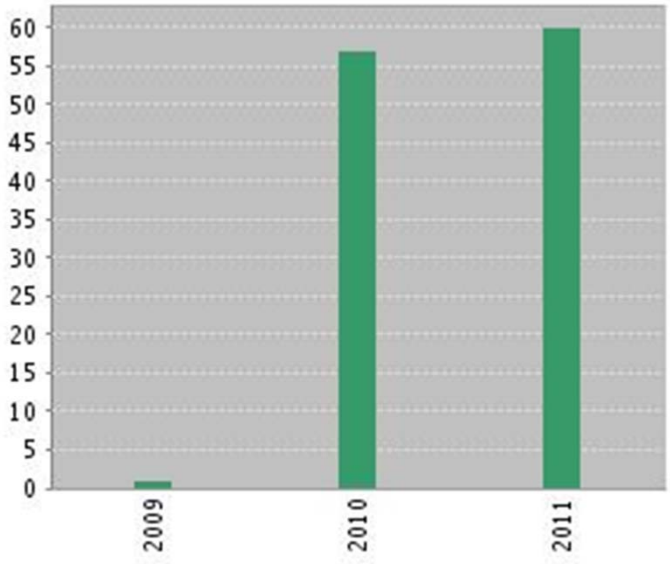
- 118 citations
- 107 in physics, 64 in optics, 1 in chemistry

- Citations per year:

2009 – 1

2010 – 57

2011 – 60



Citation Analysis

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- B. Capogrosso-Sansone et al. Quantum Phases of Cold Polar Molecules in 2D Optical Lattices.
Phys. Rev. Lett. 104, 112 (2010). Times Cited: 23

Thank you
for your attention!