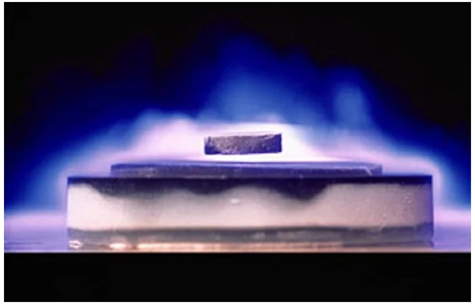
QUANTUM GAS MICROSCOPY

Julian Léonard
TU Wien/Harvard University
Innsbruck, 11th July 2023

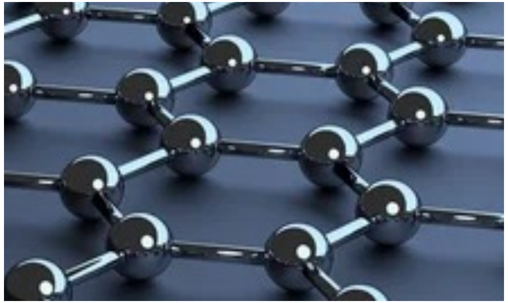
THE CHALLENGE OF MANY-BODY QUANTUM SYSTEMS

Understand and design quantum materials
One of the biggest challenges
of 21st century quantum physics



Technological relevance

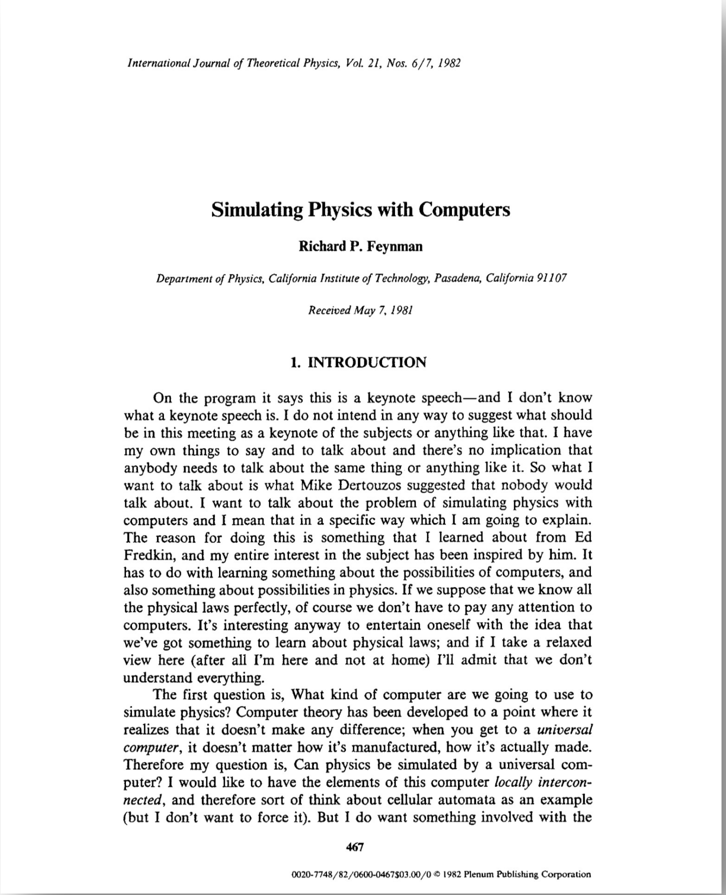
- High-Tc superconductivity
- Magnetism
- Novel quantum sensors
- Quantum technologies



Fundamental interest

- Parameter changes
- Benchmark theories
- Often even "simple" models not solvable
- Discern different effects

THE CHALLENGE OF MANY-BODY QUANTUM SYSTEMS



International Journal of Theoretical Physics, Vol. 21, Nos. 6/7, 1982

Simulating Physics with Computers

Richard P. Feynman

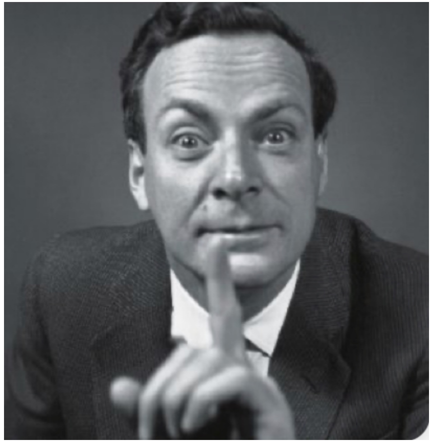
Department of Physics, California Institute of Technology, Pasadena, California 91107

Received May 7, 1981

1. INTRODUCTION

On the program it says this is a keynote speech—and I don't know what a keynote speech is. I do not intend in any way to suggest what should be in this meeting as a keynote of the subjects or anything like that. I have my own things to say and to talk about and there's no implication that anybody needs to talk about the same thing or anything like it. So what I want to talk about is what Mike Dertouzos suggested that nobody would talk about. I want to talk about the problem of simulating physics with computers and I mean that in a specific way which I am going to explain. The reason for doing this is something that I learned about from Ed Fredkin, and my entire interest in the subject has been inspired by him. It has to do with learning something about the possibilities of computers, and also something about possibilities in physics. If we suppose that we know all the physical laws perfectly, of course we don't have to pay any attention to computers. It's interesting anyway to entertain oneself with the idea that we've got something to learn about physical laws; and if I take a relaxed view here (after all I'm here and not at home) I'll admit that we don't understand everything.

The first question is, What kind of computer are we going to use to simulate physics? Computer theory has been developed to a point where it realizes that it doesn't make any difference; when you get to a *universal computer*, it doesn't matter how it's manufactured, how it's actually made. Therefore my question is, Can physics be simulated by a universal computer? I would like to have the elements of this computer *locally interconnected*, and therefore sort of think about cellular automata as an example (but I don't want to force it). But I do want something involved with the

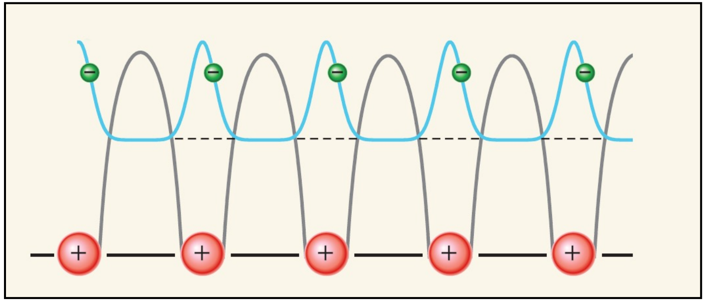


R. P. Feynman's vision

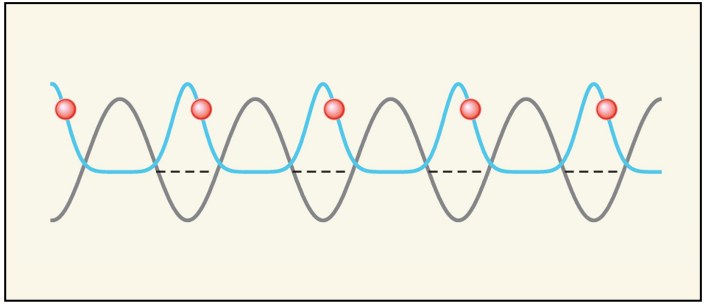
A quantum simulator to study the properties of an another quantum system

QUANTUM SIMULATION

Real materials



Ultracold quantum matter



Lattice constant: ~Å

Densities: ~10^{25}/cm^3

Temperatures: ~K

Same quantum regime:
λ/d >1

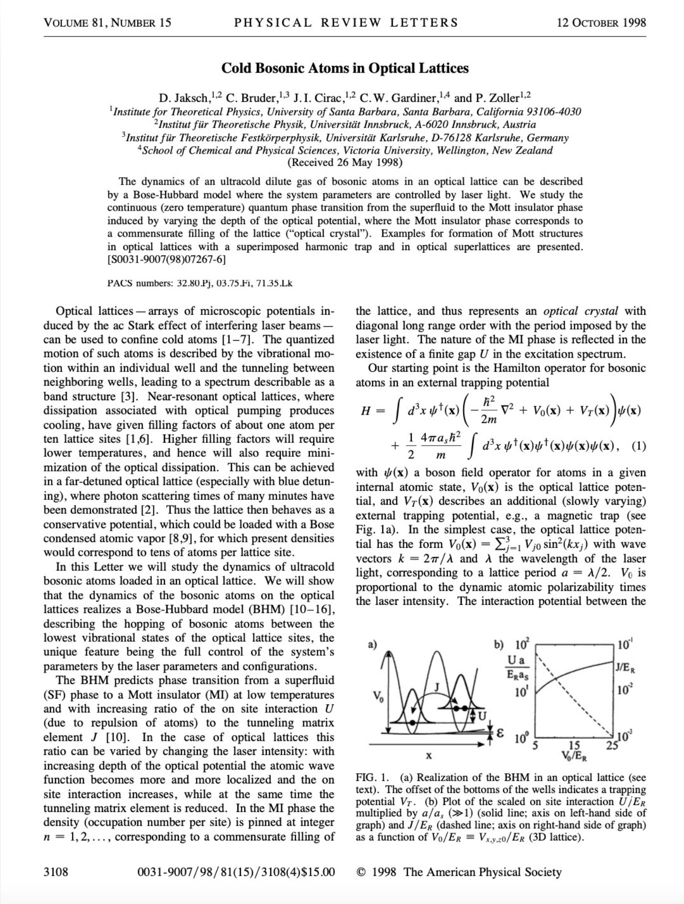
Universality of quantum mechanics!

Lattice constant: ~μm

Densities: ~10^{14}/cm^3

Temperatures: ~nK

OPTICAL LATTICES



VOLUME 81, NUMBER 15 PHYSICAL REVIEW LETTERS 12 OCTOBER 1998

Cold Bosonic Atoms in Optical Lattices

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[2] *Institut für Theoretische Physik, Universität Innsbruck, A-6020 Innsbruck, Austria*
[3] *Institut für Theoretische Festkörperphysik, Universität Karlsruhe, D-76128 Karlsruhe, Germany*
[4] *School of Chemical and Physical Sciences, Victoria University, Wellington, New Zealand*
(Received 26 May 1998)

The dynamics of an ultracold dilute gas of bosonic atoms in an optical lattice can be described by a Bose-Hubbard model where the system parameters are controlled by laser light. We study the continuous (zero temperature) quantum phase transition from the superfluid to the Mott insulator phase induced by varying the depth of the optical potential, where the Mott insulator phase corresponds to a commensurate filling of the lattice ("optical crystal"). Examples for formation of Mott structures in optical lattices with a superimposed harmonic trap and in optical superlattices are presented. [S0031-9007(98)07267-6]

PACS numbers: 32.80.Pj, 03.75.Fi, 71.35.Lk

Optical lattices — arrays of microscopic potentials induced by the ac Stark effect of interfering laser beams — can be used to confine cold atoms [1–7]. The quantized motion of such atoms is described by the vibrational motion within an individual well and the tunneling between neighboring wells, leading to a spectrum describable as a band structure [3]. Near-resonant optical lattices, where dissipation associated with optical pumping produces cooling, have given filling factors of about one atom per ten lattice sites [1,6]. Higher filling factors will require lower temperatures, and hence will also require minimization of the optical dissipation. This can be achieved in a far-detuned optical lattice (especially with blue detuning), where photon scattering times of many minutes have been demonstrated [2]. Thus the lattice then behaves as a conservative potential, which could be loaded with a Bose condensed atomic vapor [8,9], for which present densities would correspond to tens of atoms per lattice site.

In this Letter we will study the dynamics of ultracold bosonic atoms loaded in an optical lattice. We will show that the dynamics of the bosonic atoms on the optical lattices realizes a Bose-Hubbard model (BHM) [10–16], describing the hopping of bosonic atoms between the lowest vibrational states of the optical lattice sites, the unique feature being the full control of the system's parameters by the laser parameters and configurations.

The BHM predicts phase transition from a superfluid (SF) phase to a Mott insulator (MI) at low temperatures and with increasing ratio of the on site interaction U (due to repulsion of atoms) to the tunneling matrix element J [10]. In the case of optical lattices this ratio can be varied by changing the laser intensity: with increasing depth of the optical potential the atomic wave function becomes more and more localized and the on site interaction increases, while at the same time the tunneling matrix element is reduced. In the MI phase the density (occupation number per site) is pinned at integer $n = 1, 2, \dots,$ corresponding to a commensurate filling of the lattice, and thus represents an *optical crystal* with diagonal long range order with the period imposed by the laser light. The nature of the MI phase is reflected in the existence of a finite gap U in the excitation spectrum.

Our starting point is the Hamilton operator for bosonic atoms in an external trapping potential

$$H = \int d^3x\, \psi^\dagger(\mathbf{x}) \left(-\frac{\hbar^2}{2m} \nabla^2 + V_0(\mathbf{x}) + V_T(\mathbf{x}) \right) \psi(\mathbf{x}) + \frac{1}{2} \frac{4\pi a_s \hbar^2}{m} \int d^3x\, \psi^\dagger(\mathbf{x}) \psi^\dagger(\mathbf{x}) \psi(\mathbf{x}) \psi(\mathbf{x}), \quad (1)$$

with $\psi(\mathbf{x})$ a boson field operator for atoms in a given internal atomic state, $V_0(\mathbf{x})$ is the optical lattice potential, and $V_T(\mathbf{x})$ describes an additional (slowly varying) external trapping potential, e.g., a magnetic trap (see Fig. 1a). In the simplest case, the optical lattice potential has the form $V_0(\mathbf{x}) = \sum_{j=1}^{3} V_{j0} \sin^2(kx_j)$ with wave vectors $k = 2\pi/\lambda$ and λ the wavelength of the laser light, corresponding to a lattice period $a = \lambda/2$. V_0 is proportional to the dynamic atomic polarizability times the laser intensity. The interaction potential between the

FIG. 1. (a) Realization of the BHM in an optical lattice (see text). The offset of the bottoms of the wells indicates a trapping potential V_T. (b) Plot of the scaled on site interaction U/E_R multiplied by a/a_s ($\gg 1$) (solid line; axis on left-hand side of graph) and J/E_R (dashed line; axis on right-hand side of graph) as a function of $V_0/E_R \equiv V_{x,y,z0}/E_R$ (3D lattice).

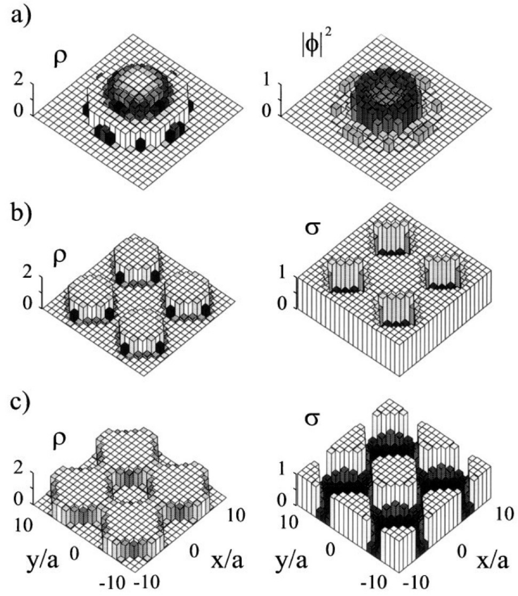
 0031-9007/98/81(15)/3108(4)$15.00

Optical lattices realize Bose-Hubbard Hamiltonian:

$$H = -J \sum_{\langle i,j \rangle} b_i^\dagger b_j + \sum_i \epsilon_i \hat{n}_i + \frac{1}{2} U \sum_i \hat{n}_i (\hat{n}_i - 1)$$

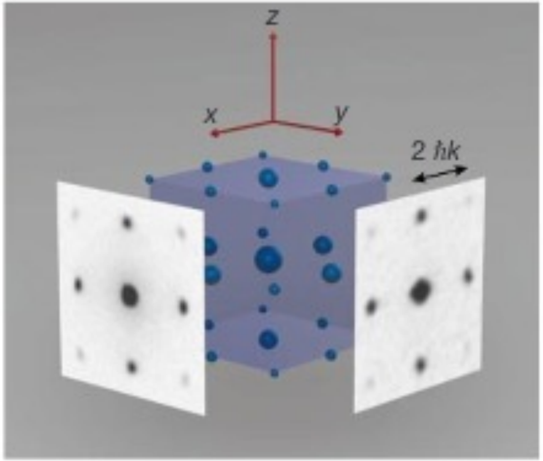
Full parameter control:

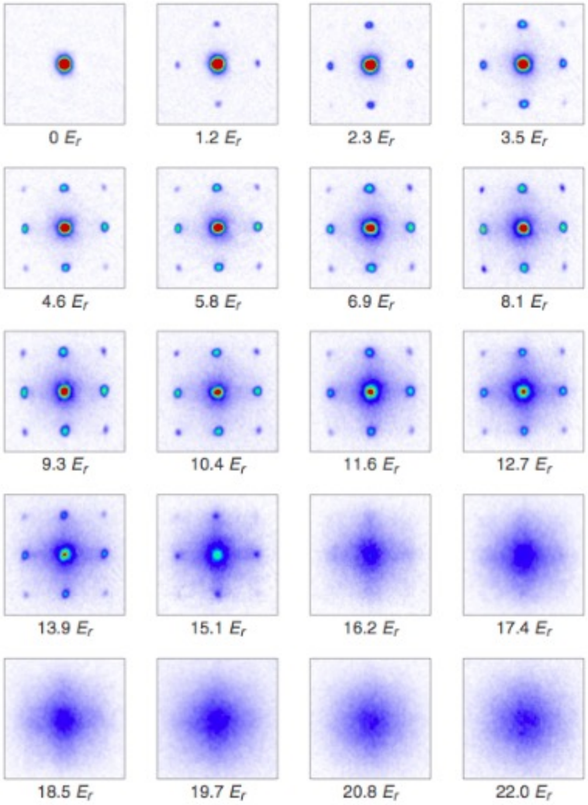
- Tunneling
- Interactions
- Density
- Temperature



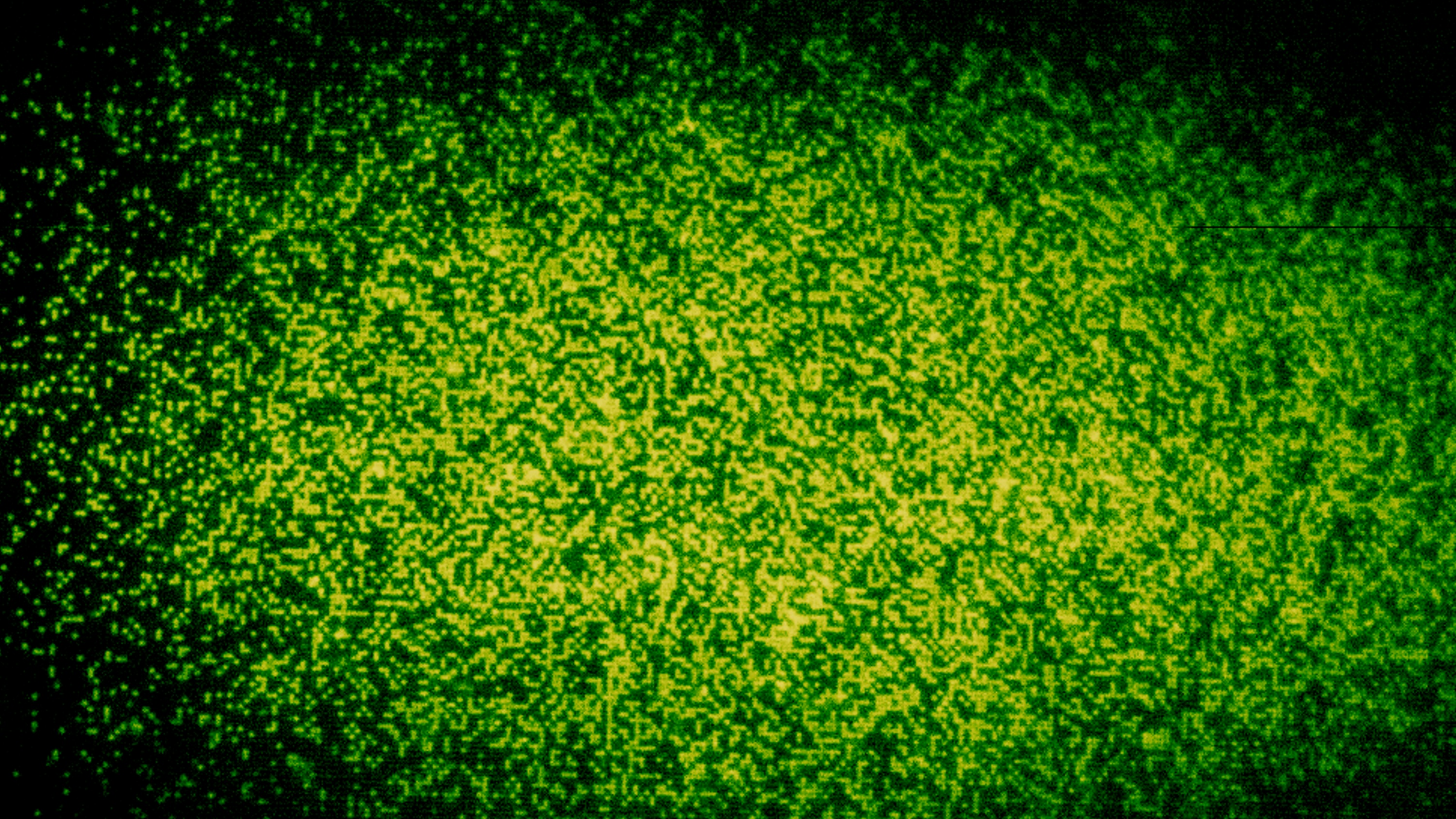
Prediction:
Superfluid–Mott insulator transition should be reachable

SUPERFLUID–MOTT INSULATOR TRANSITION





Hensch group (MPQ Munich)
M. Greiner et al., Nature 415, 39 (2002)



OUTLINE

1 Tools

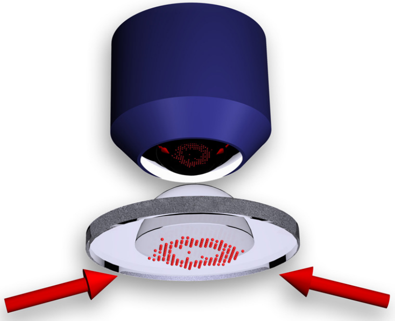
2 Bosonic quantum matter

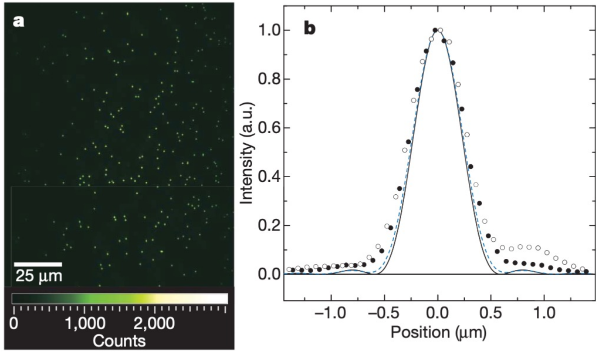
3 Fermionic quantum matter

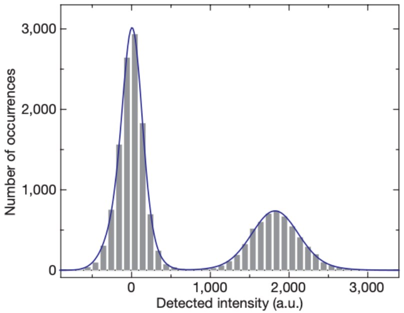
4 Long-range interacting systems

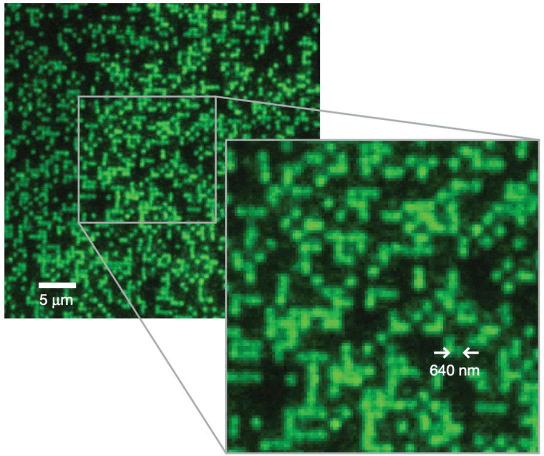
5 Recent trends

SITE-RESOLVED READOUT







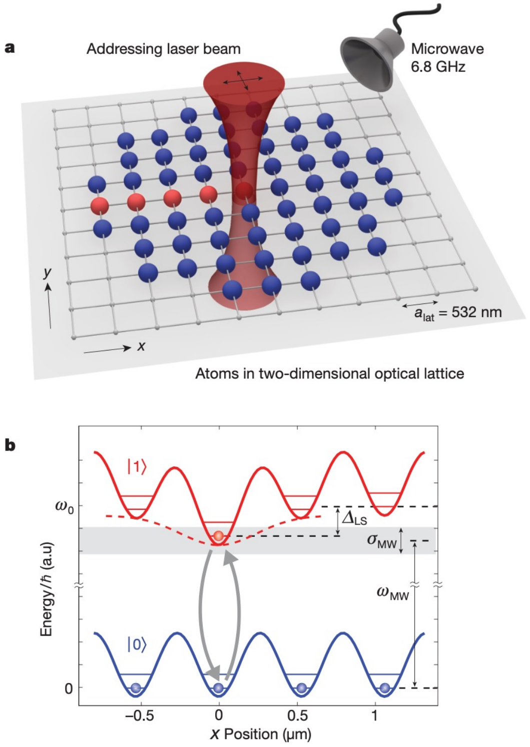


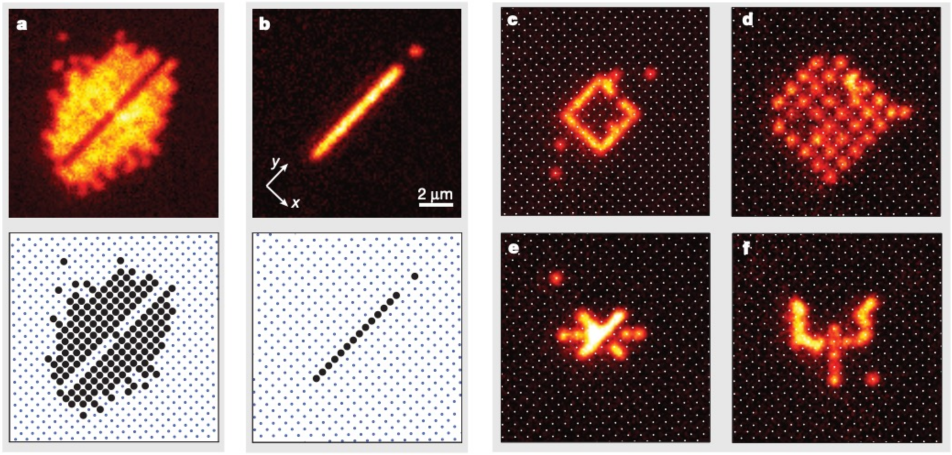
Very precise:

>99% readout fidelity

Earlier work in groups:
D. Meschede (Bonn)
D. Weiss (Penn state)
H. Ott (Kaiserslautern)

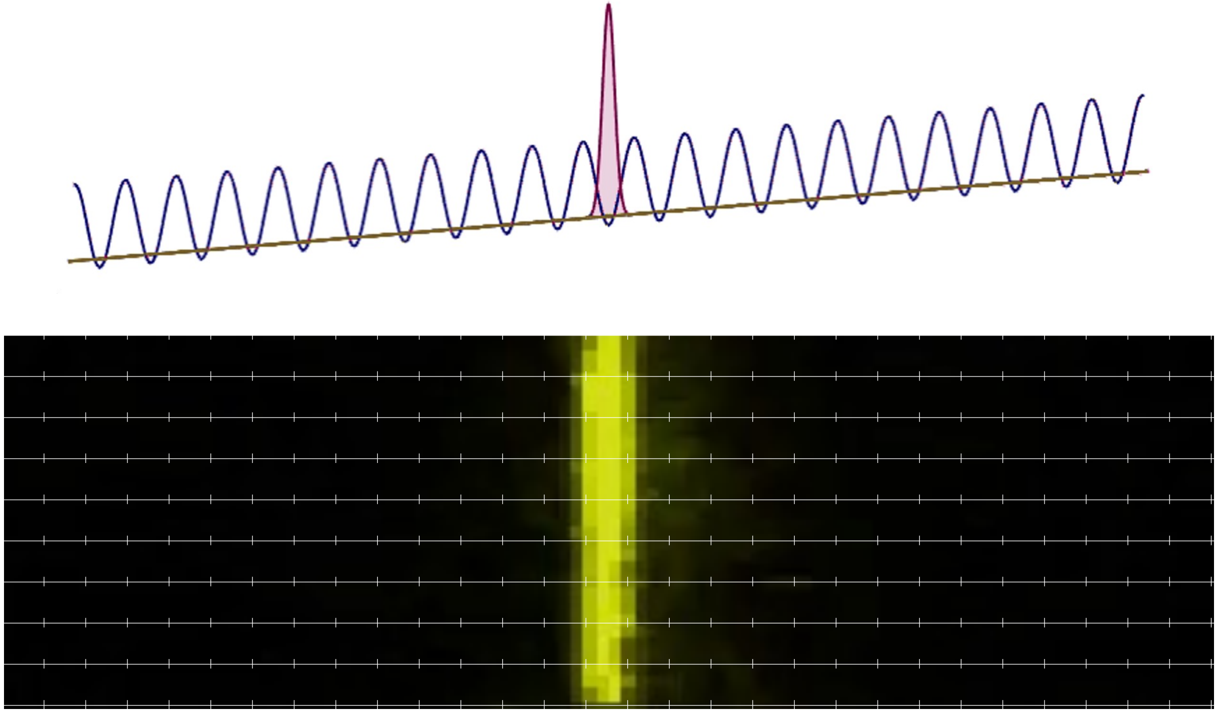
SITE-RESOLVED ADRESSING



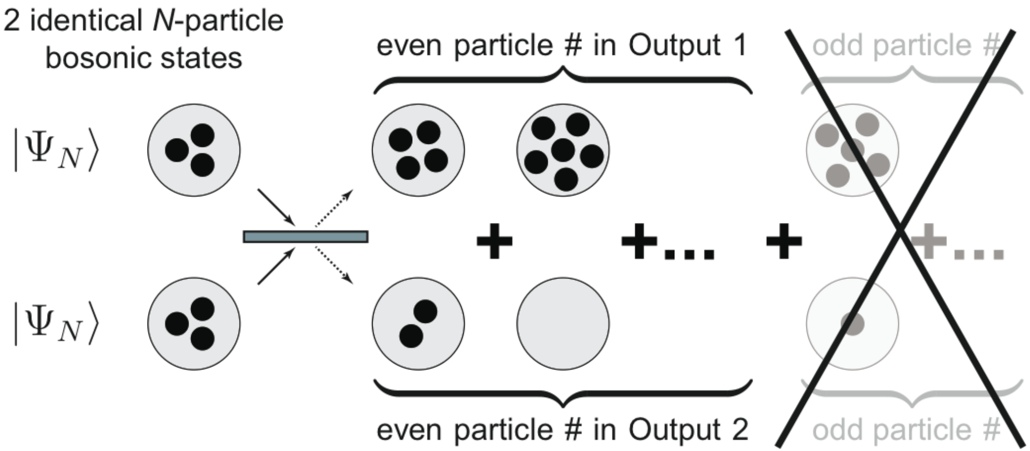


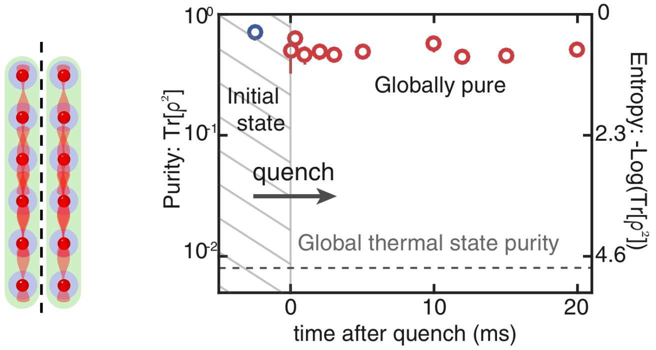
Bloch group (MPQ Munich)
C. Weitenberg et al., Nature 471, 322 (2011)

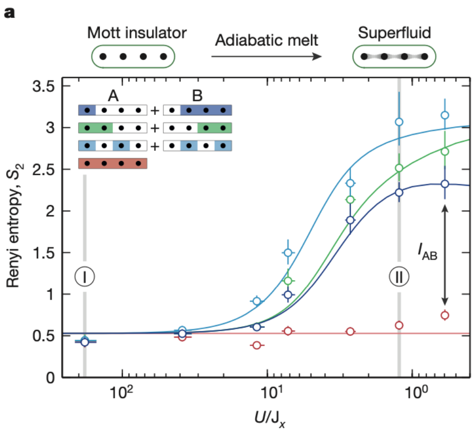
SITE-RESOLVED ADRESSING



ENTANGLEMENT AND STATE PURITY





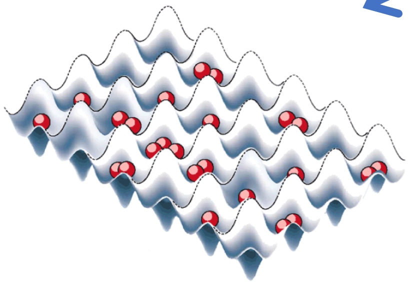


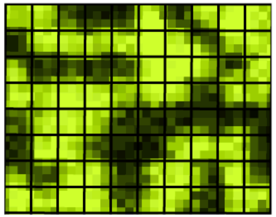
OUTLINE

BOSONIC MOTT INSULATORS

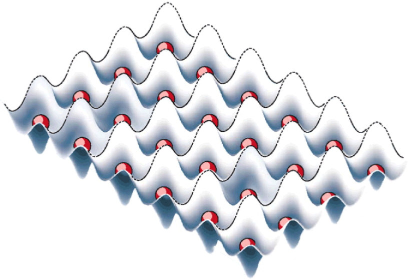
quantum phase
transition

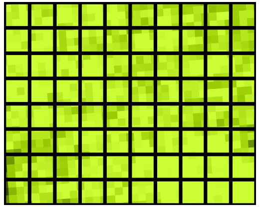
Superfluid



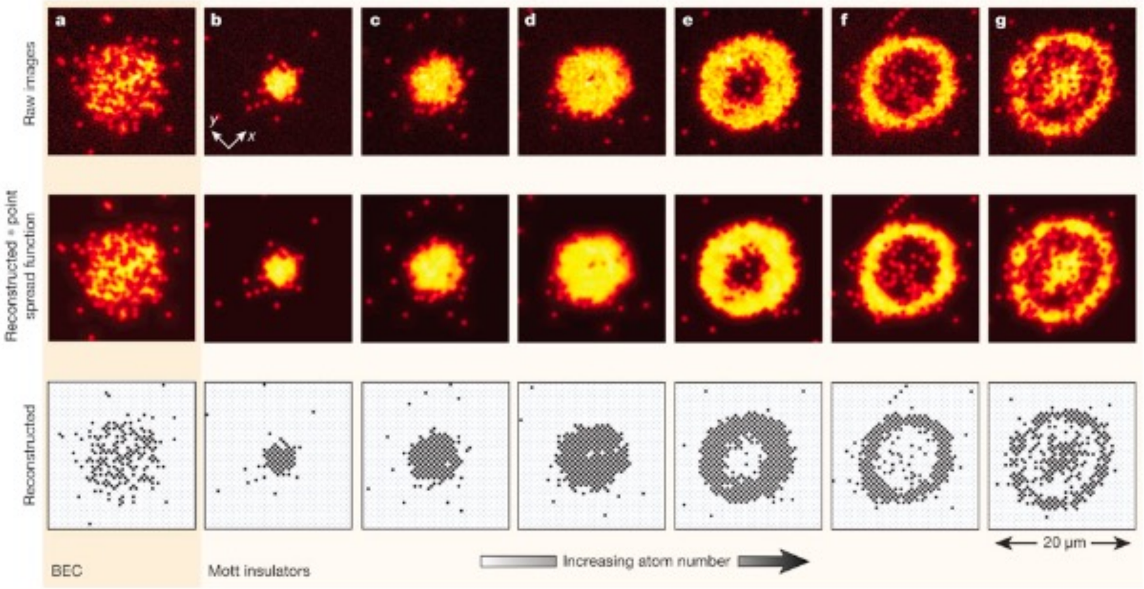


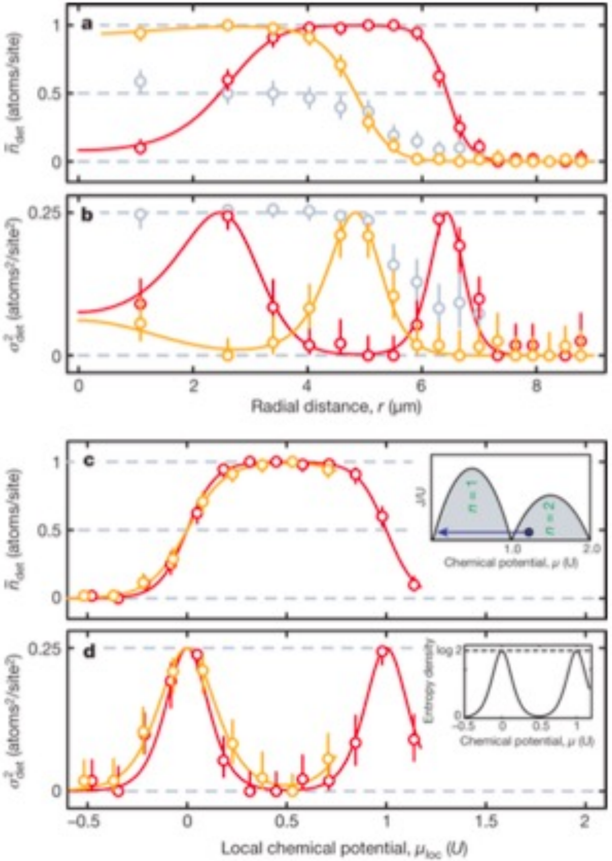
Mott insulator





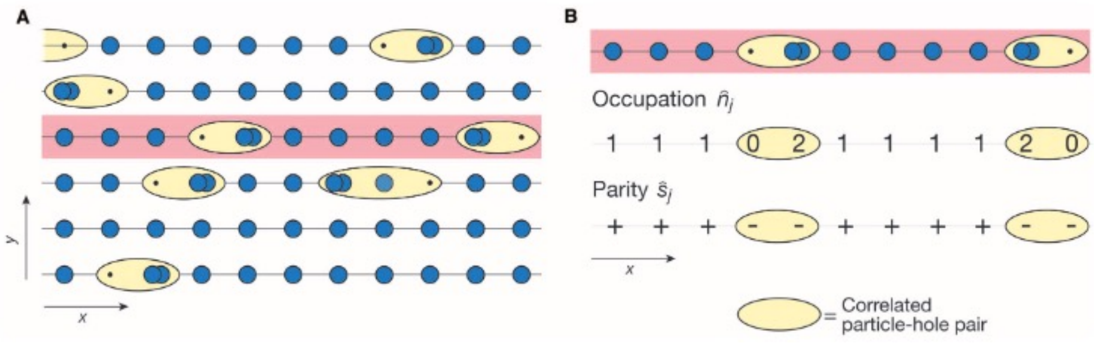
BOSONIC MOTT INSULATORS

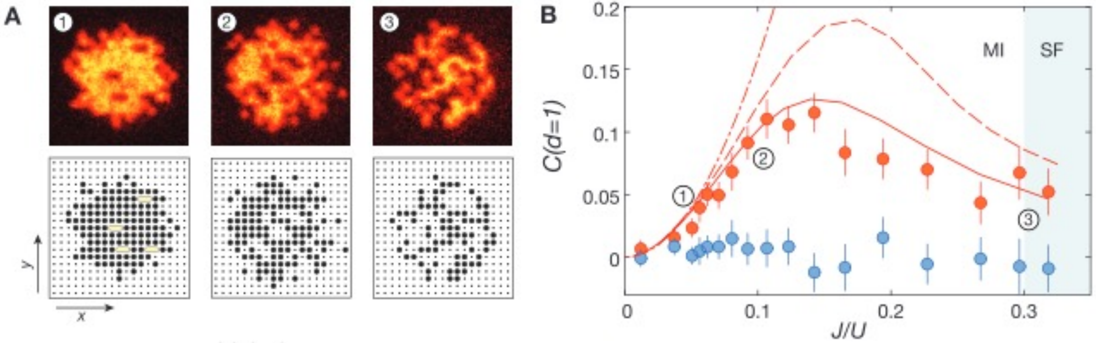




Bloch group (MPQ Munich)
J. Sherson et al., Nature 467, 68 (2010)

PARTICLE-HOLE PAIRS





Bloch group (MPQ Munich)
M. Endres et al., Science 334, 200 (2011)

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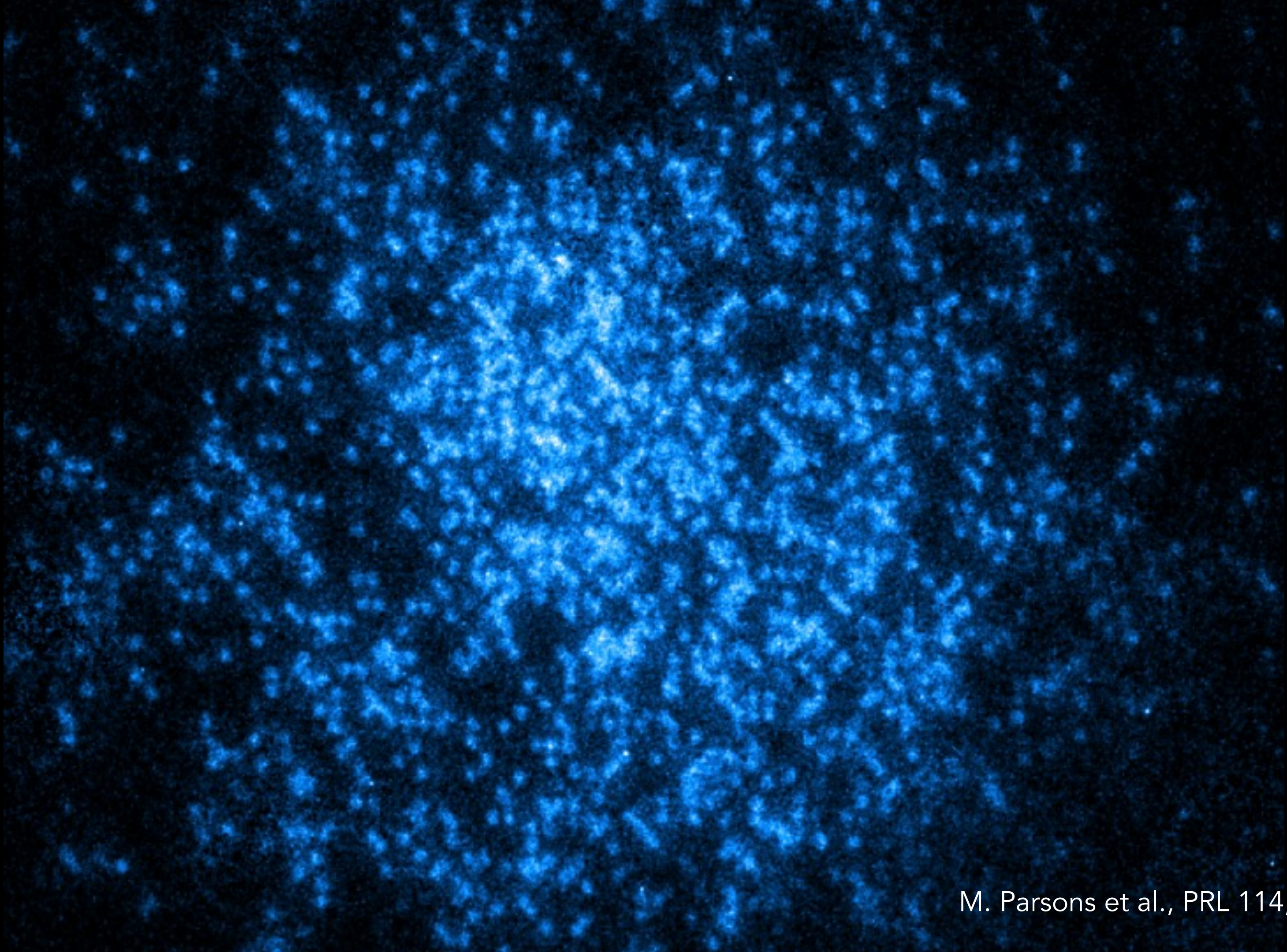
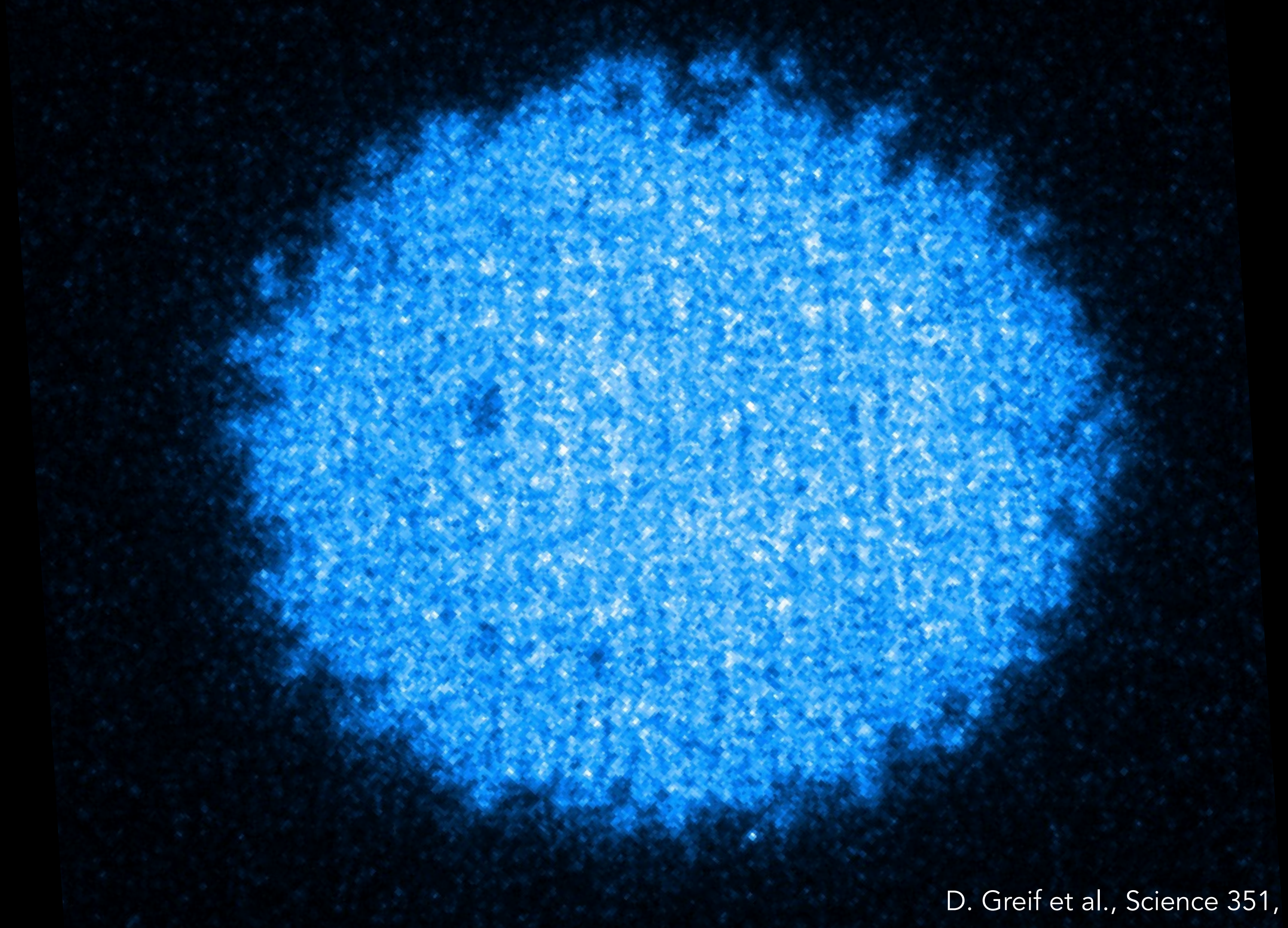
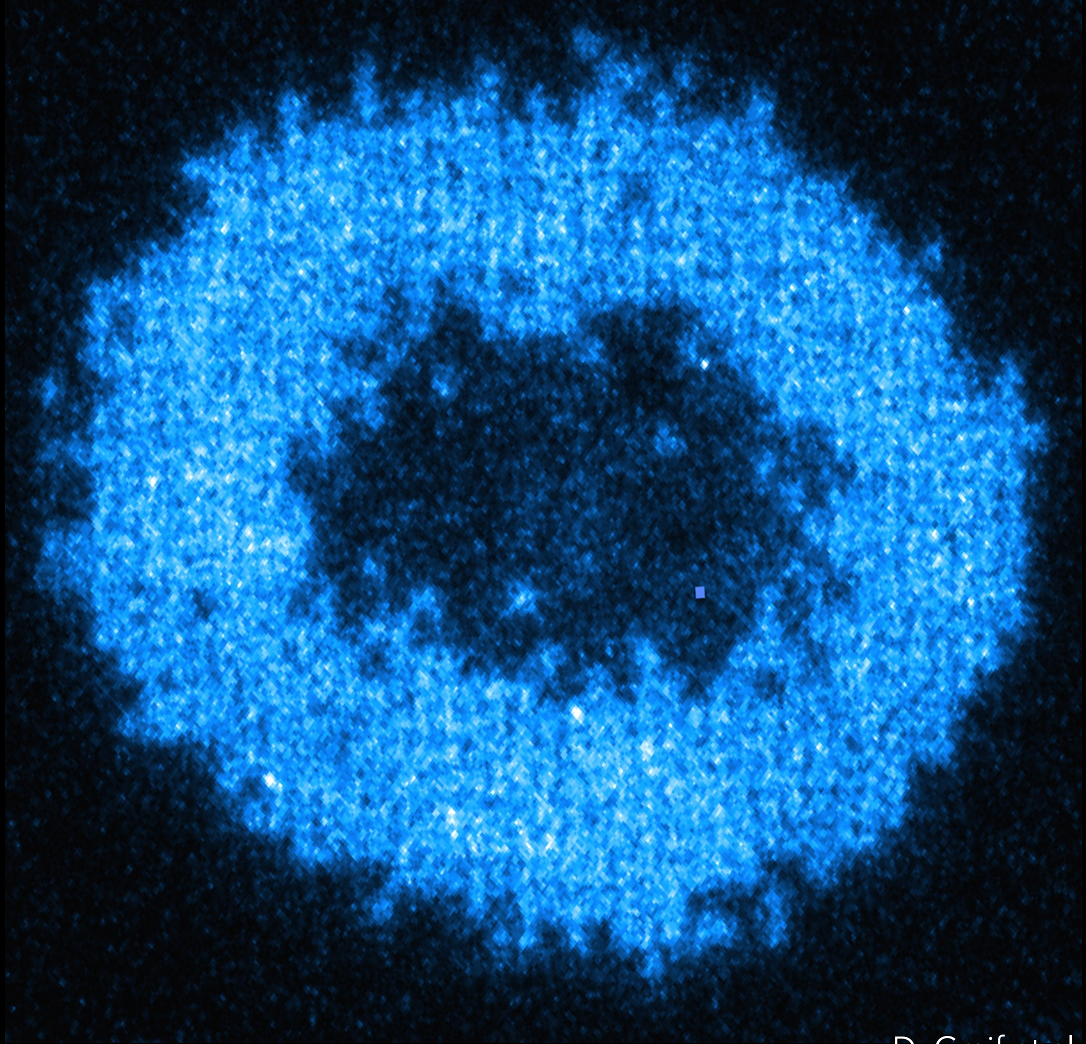


M. Parsons et al., PRL 114, 213002 (2015)

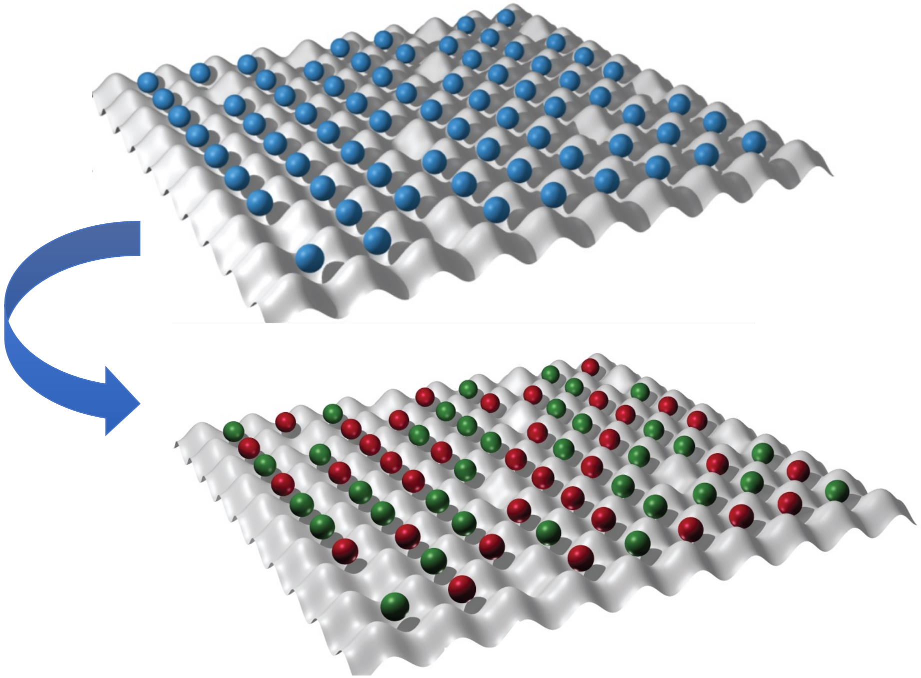


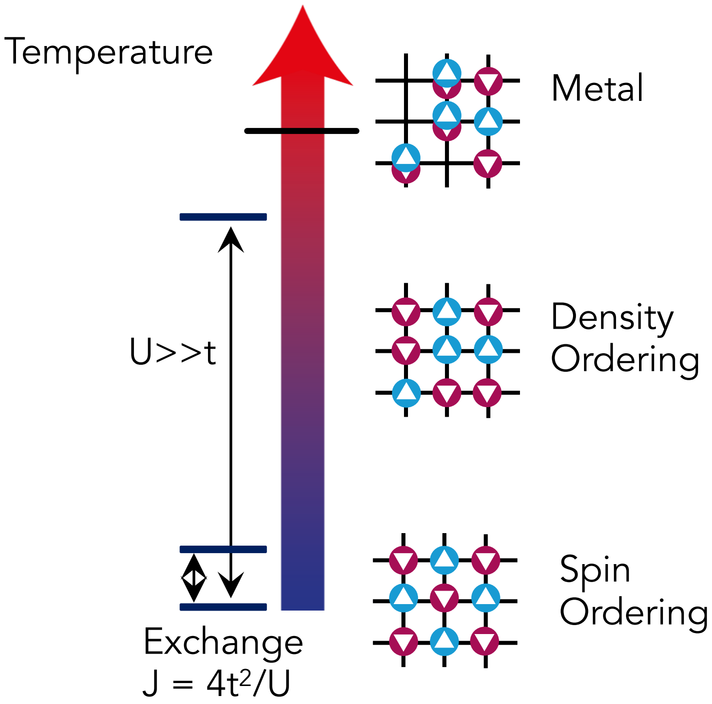
D. Greif et al., Science 351, 953 (2016)



D. Greif et al., Science 351, 953 (2016)

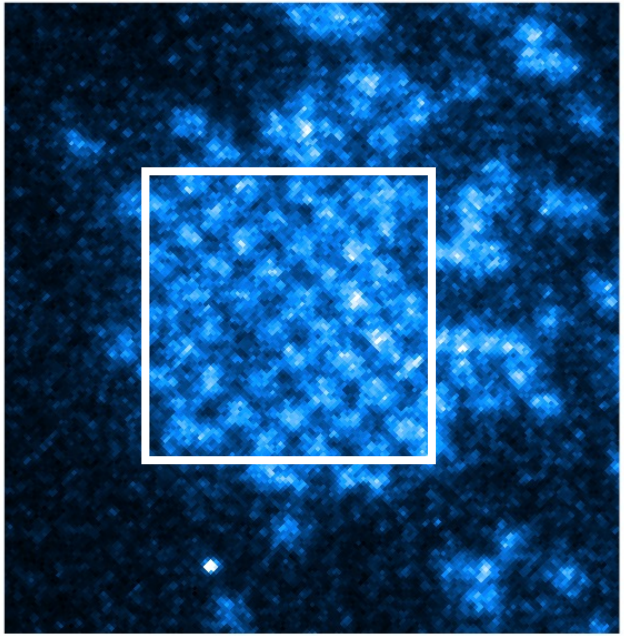
QUANTUM MAGNETISM



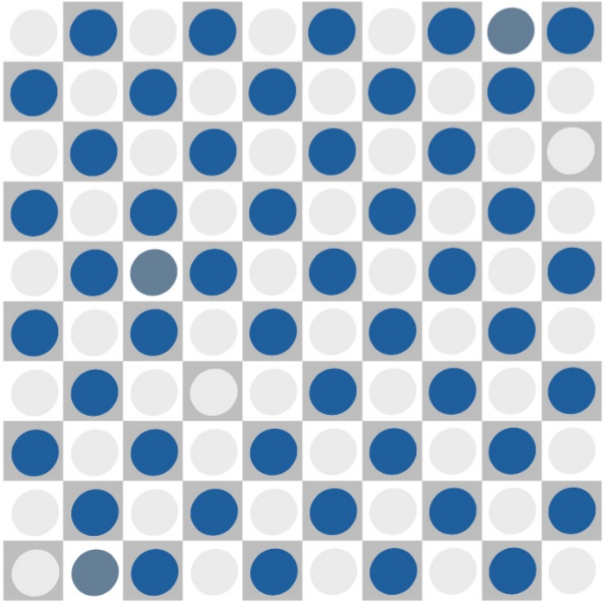


$$\hat{H} = -t \underbrace{\sum_{\langle i,j\rangle,\sigma} \left(c^\dagger_{i,\sigma} c_{j,\sigma} + \text{H.c.}\right)}_{\text{tunneling}} + \underbrace{U \sum_i \hat{n}_{i\uparrow}\hat{n}_{i\downarrow}}_{\text{On-site interaction}}$$

ANTIFERROMAGNETIC ORDER



$|\uparrow\rangle$ only

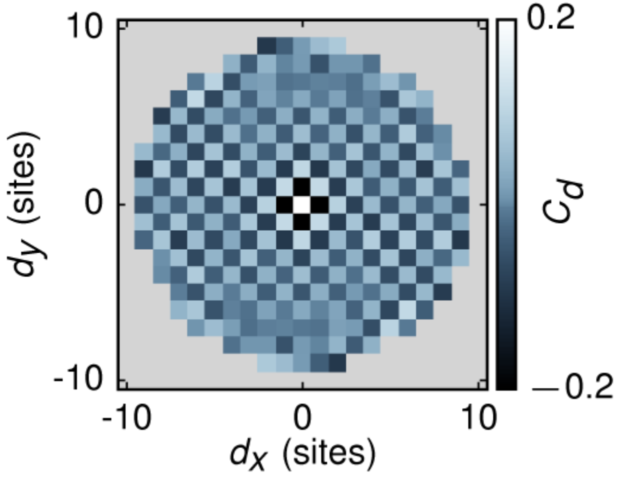


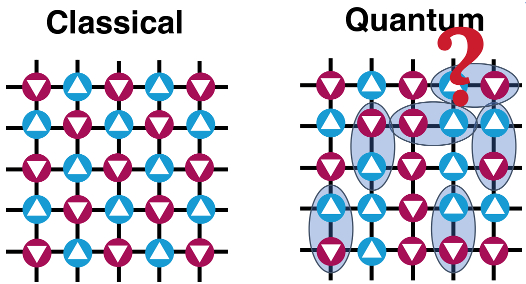
Temperature: $T/t = 0.25$

$T/J = 0.5$

A. Mazurenko et al., Nature 545, 462 (2017)

ANTIFERROMAGNETIC ORDER

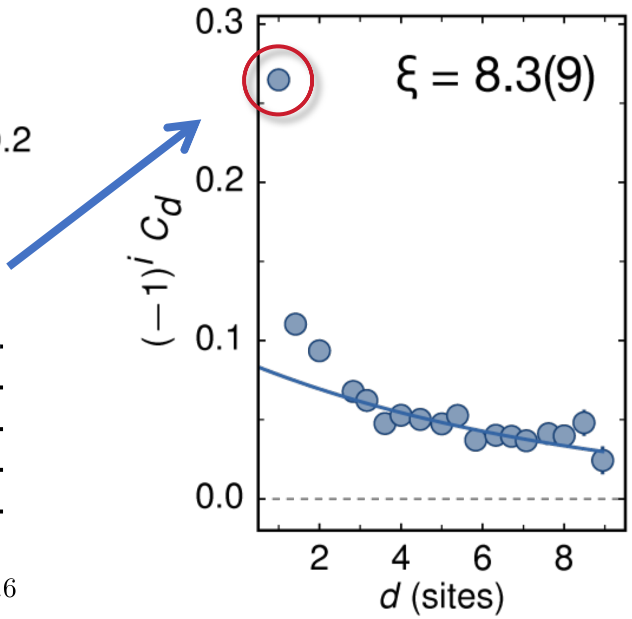




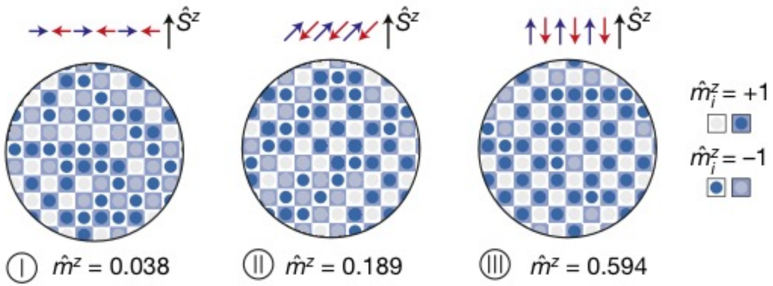
$M_{\text{clas}}(T \to 0) = 1$ $M_{\text{qm}}(T \to 0) = 0.6$

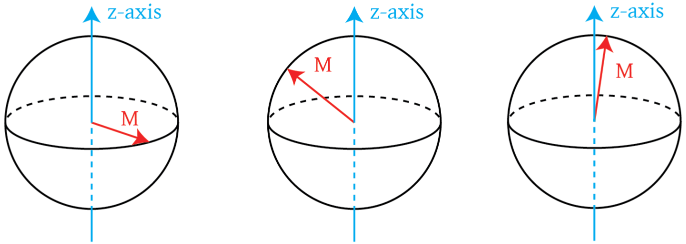
2D: exponential decay of correlations expected

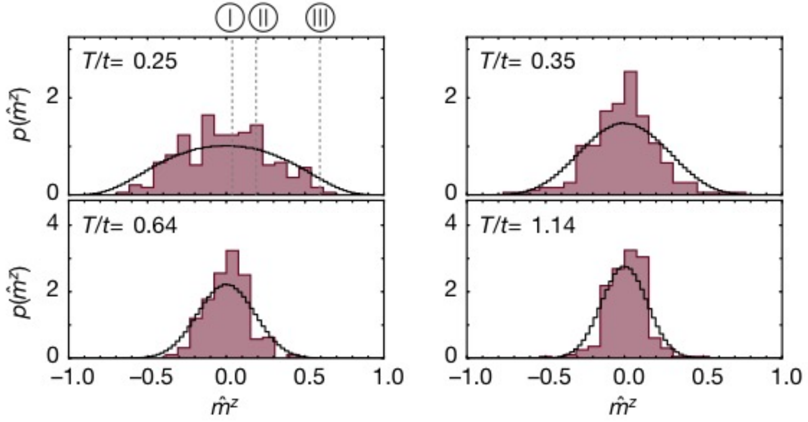
$$\langle S_i^z S_{i+d}^z \rangle \propto \exp\left(-d/\xi\right)$$



QUANTUM ANTIFERROMAGNET

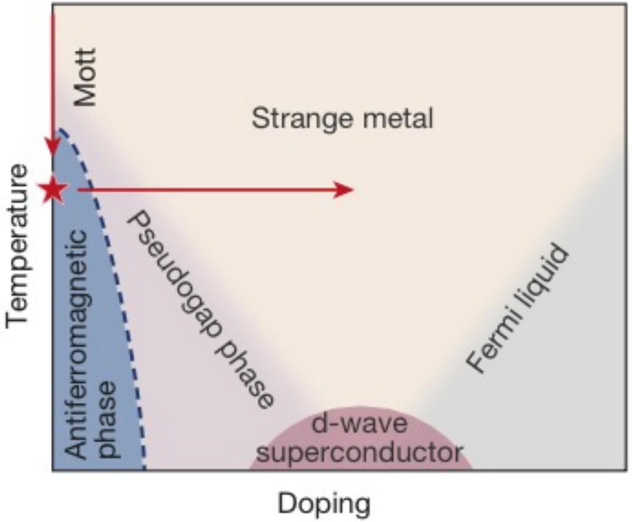


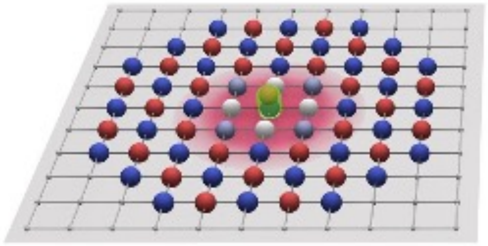


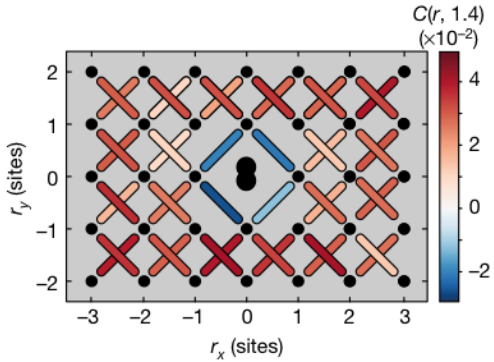


Greiner group (Harvard)
A. Mazurenko et al., Nature 545, 462 (2017)

DOPING AN ANTIFERROMAGNET







No numerics possible:
Many open questions about the phase diagram

Controlled doping

➔ Gain microscopic understanding of high-Tc superconductivity

Bloch group (MPQ Munich)
J. Koepsell et al., Nature 572, 358 (2019)

OUTLINE

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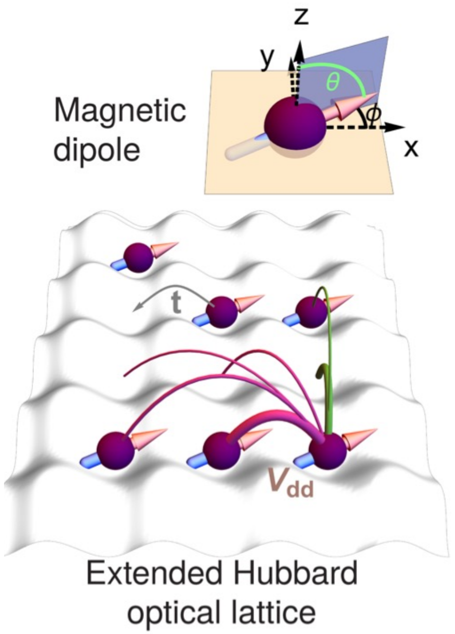
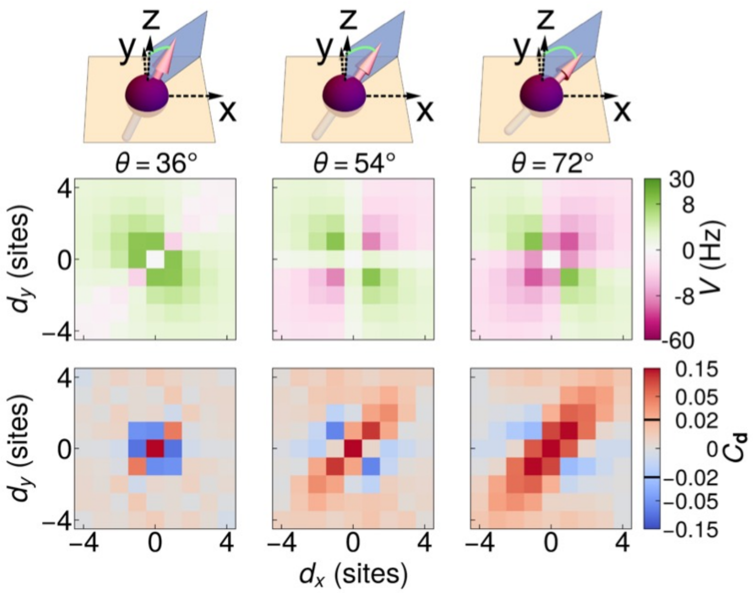
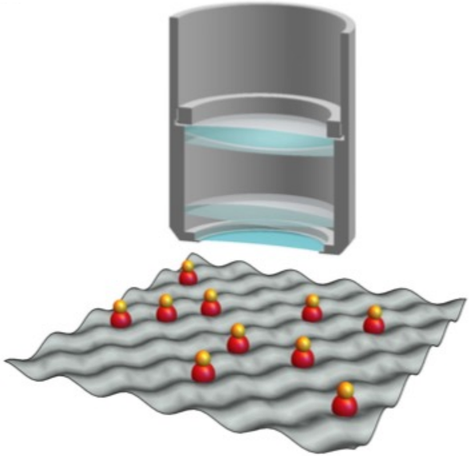
DIPOLAR ATOMS

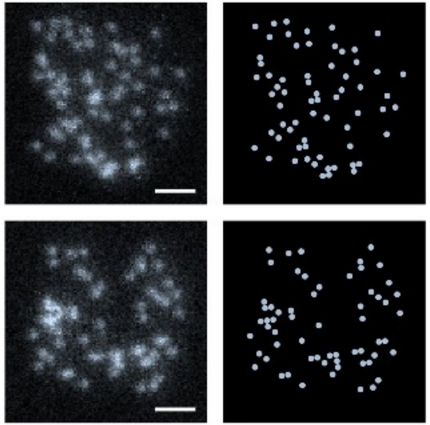


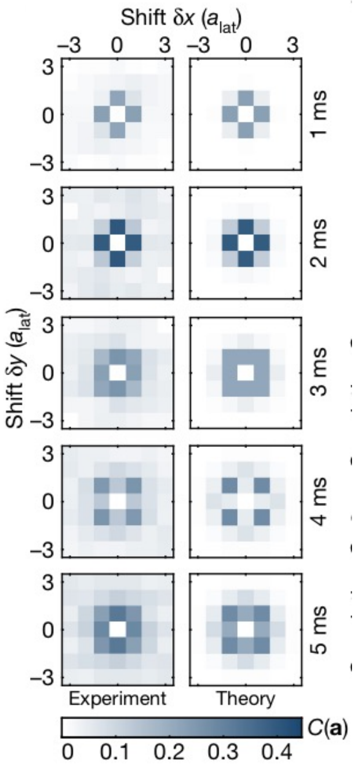


Permanent magnetic dipole moment
➔ <30Hz interactions over neighboring sites

DIPOLAR MOLECULES

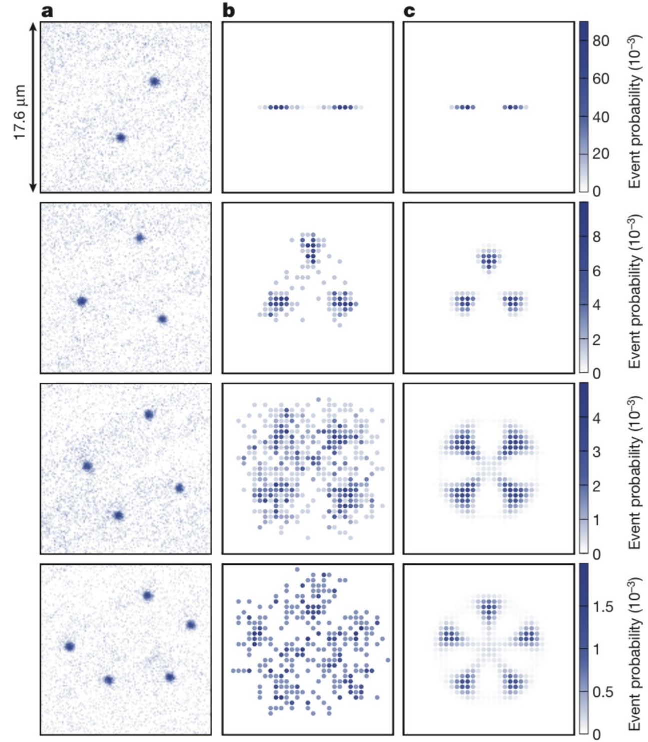


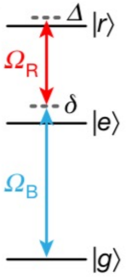




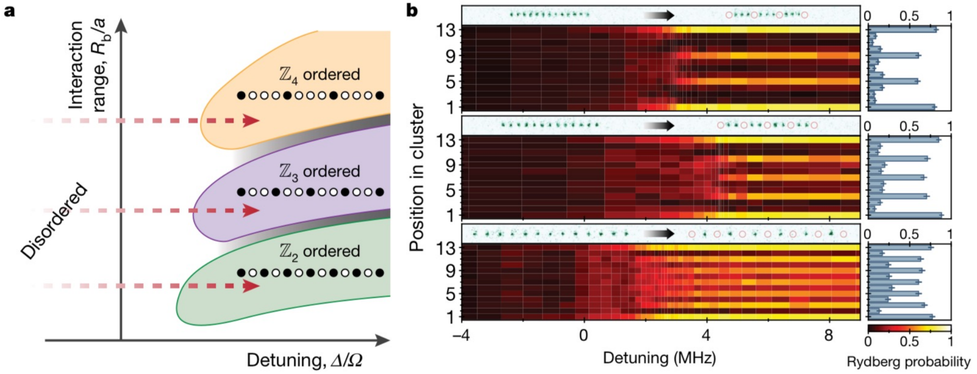
Permanent electric dipole moment
➔ kHz interactions over neighboring sites

RYDBERG INTERACTIONS





Extremely large dipole moments
➔ MHz interactions over several um



Bloch group (MPQ Munich)
T. Fukuhara et al., Nature Phys. 9, 235 (2013)

Lukin group (Harvard)
H. Bernien et al., Nature 551, 581 (2017)

OUTLINE

1 Tools

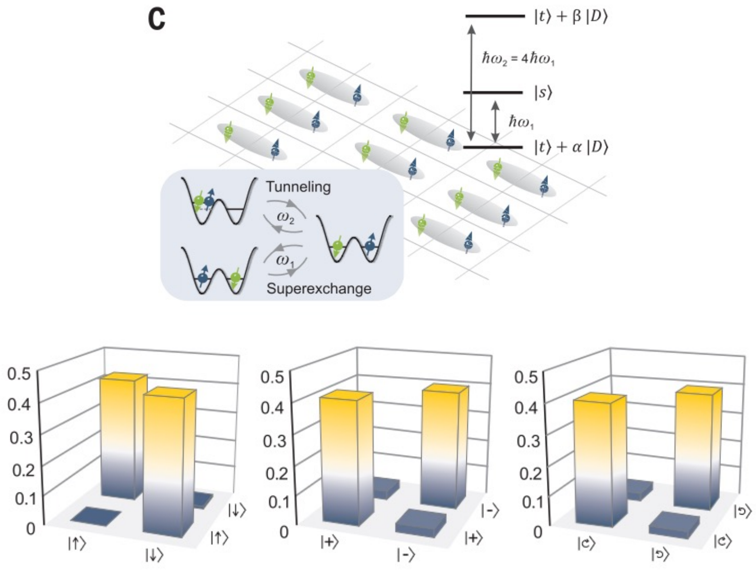
2 Bosonic quantum matter

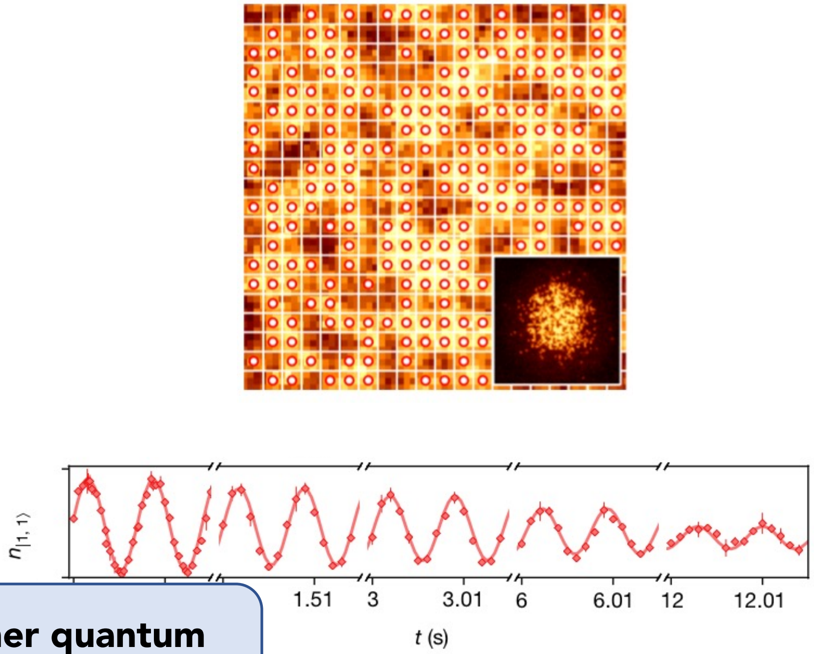
3 Fermionic quantum matter

4 Long-range interacting systems

5 Recent trends

QUANTUM INFORMATION



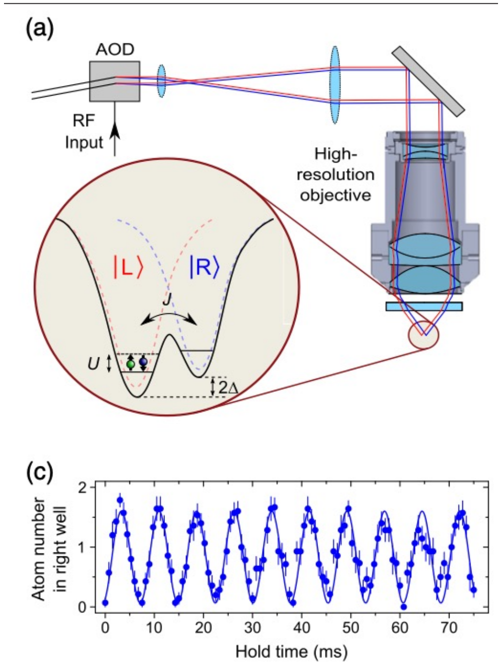


Competitive with other quantum computing platforms!

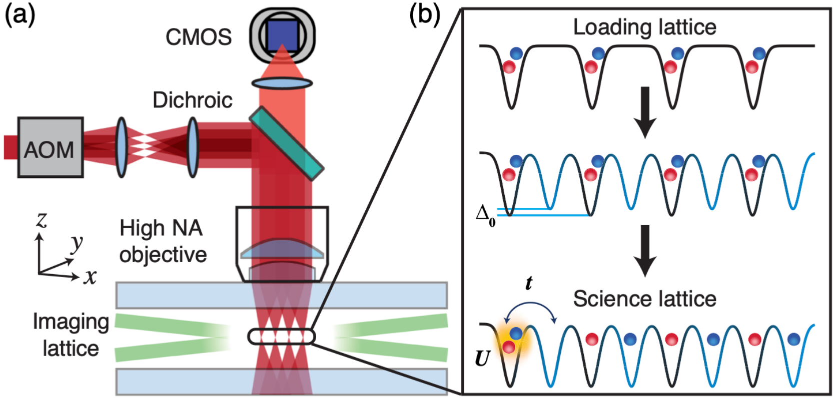
Jian-Wei Pan group (Heidelberg
B. Yang et al., Science 369, 550 (

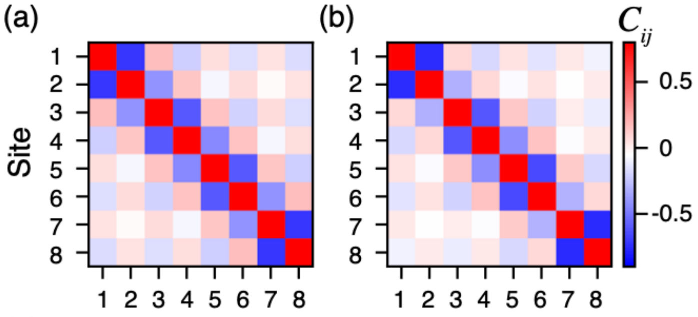
lein group (MIT)
artke et al., Nature 601, 537(2022)

HUBBARD TWEEZERS



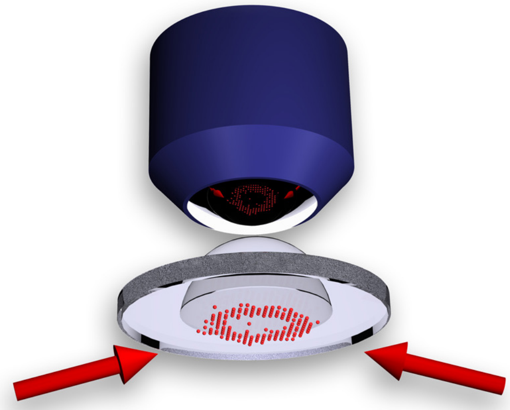
Jochim group (Heidelberg)

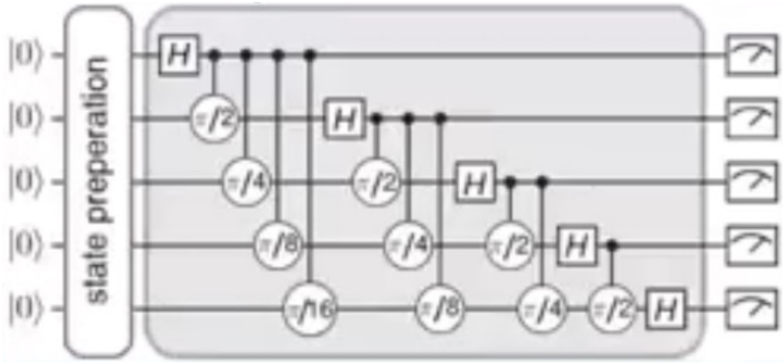




Bakr group (Princeton)

SUMMARY





Study strongly correlated systems

Tunable parameters AND microscopic control

Poor electron-qubit mapping in quantum computers

Need for controlled fermionic systems

THANK YOU