Quantum simulation of antiferromagnetic spin chains in an optical lattice

Simon, J. *Nature* **472**, 307-312. (2011)

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Overview

- Quantum Simulation
- Motivation and Theory
- Methodology
- Results
- Conclusion :)

Introduction to Quantum Simulation

Why choosing quantum simulation?

Difficulty of physical experiment: find system that exhibits characteristic Hamiltonian

1. hindered by complex structure and interactions in magnetic condensed matter systems
2. difficult to control varying system parameters.

Simulation by computers:

Will take too much time because of extreme complexity quantum entanglement.

Advantages of quantum simulation: Fast and Easy to control.

Optical Lattices

- Interference patterns used to create potentials: $V_{dip} = -\mathbf{d}\cdot\mathbf{E}$. d: dipole moment; E: external electric field
- Creation of homomorphic systems: simulation in a controlled and almost pure environment
- Intensity ⇨ depth
- Angle of beams ⇨ spacing

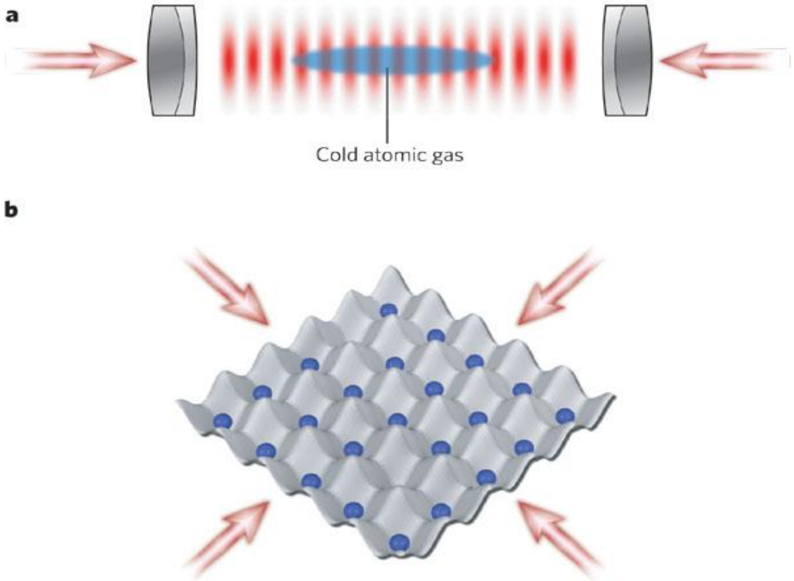

FIGURE 1. Formation of optical lattices.**a**, An optical standing wave is generated by superimposing two laser beams. The antinodes (or nodes) of the standing wave act as a perfectly periodic array of microscopic laser traps for the atoms. The crystal of light in which the cold atoms can move and are stored is called an optical lattice. **b**, If several standing waves are overlapped, higher-dimensional lattice structures can be formed, such as the two-dimensional optical lattice shown here.

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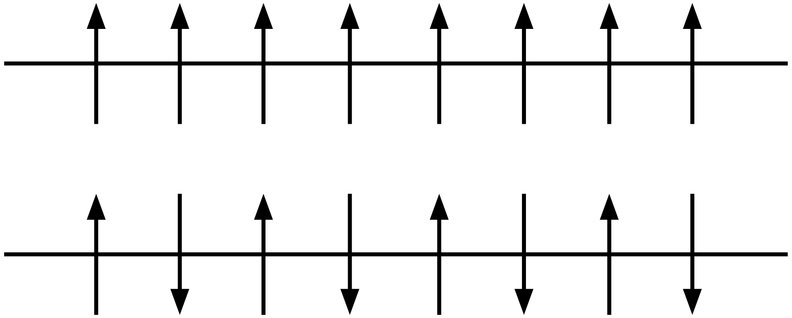
Motivation

“Simulate a one-dimensional chain of interacting Ising spins by using a Mott insulator of spinless bosons in a tilted optical lattice.”

The Ising Model

- Basic spin magnet model
- Phases and phase transition
- Difficulty in computation at phase transition

$$H=\Sigma \boxed{Js_i s_{i+1}} - \boxed{b_i s_i}$$



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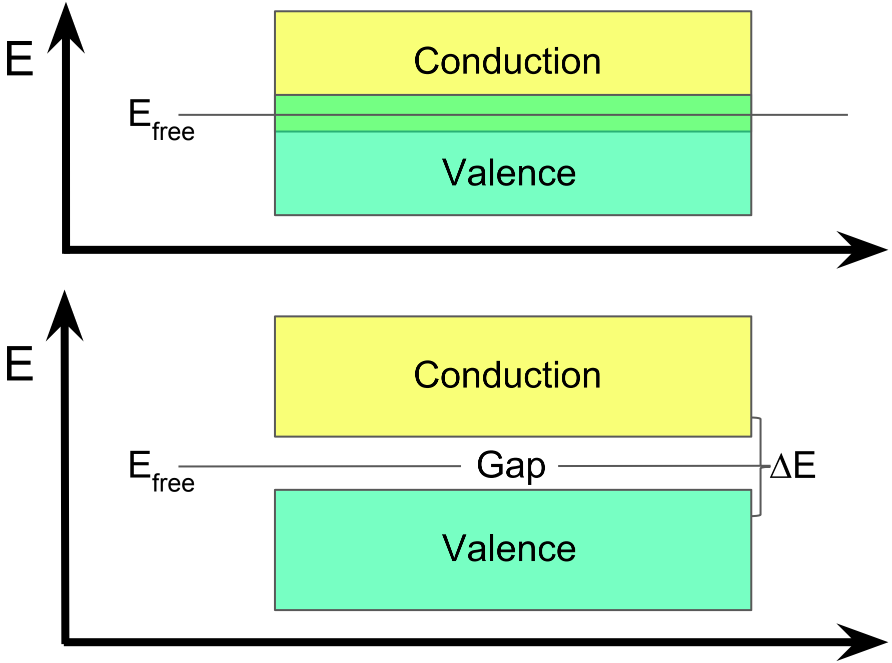
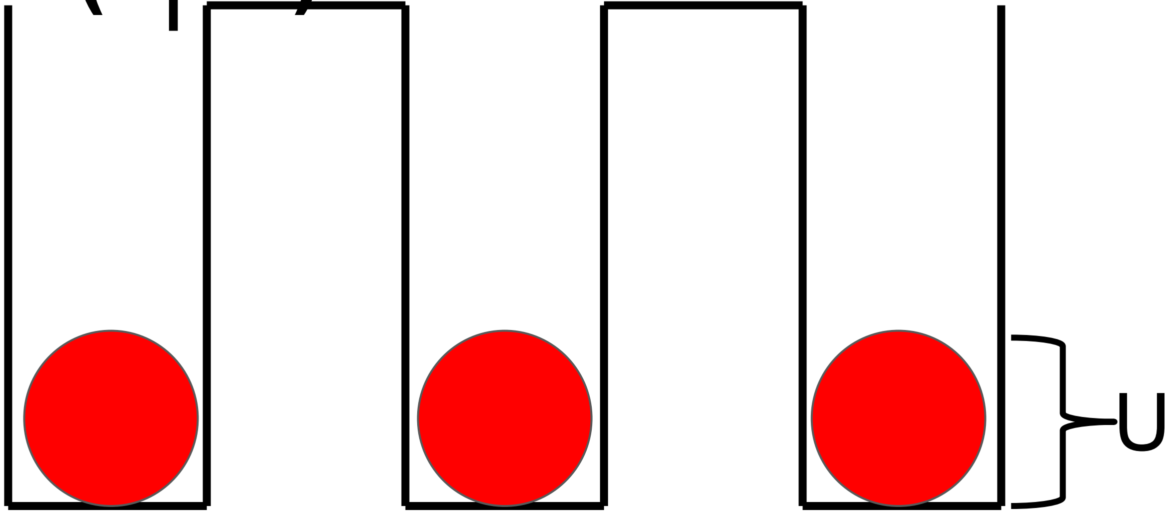
Mott Insulators

- Insulator with band structure of conductor
- Caused by electron interactions raising conduction band
- Can control conduction by changing interaction energy



The Hubbard model

$$H=\Sigma\, t(a_i a^\dagger_{i+1} + a^\dagger_i a_{i+1})+U\frac{1}{2}\, n_i (n_i+1)$$



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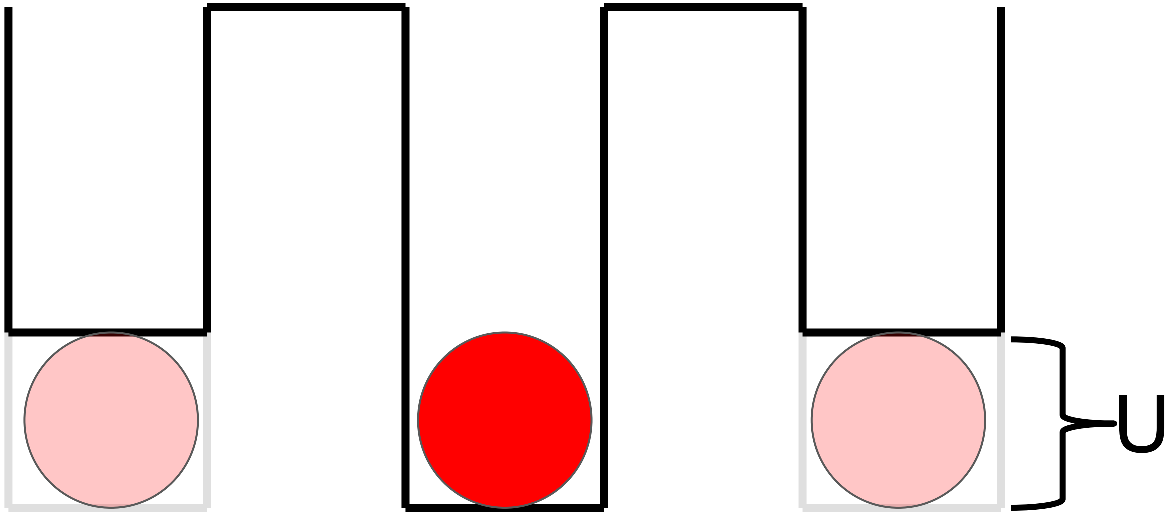
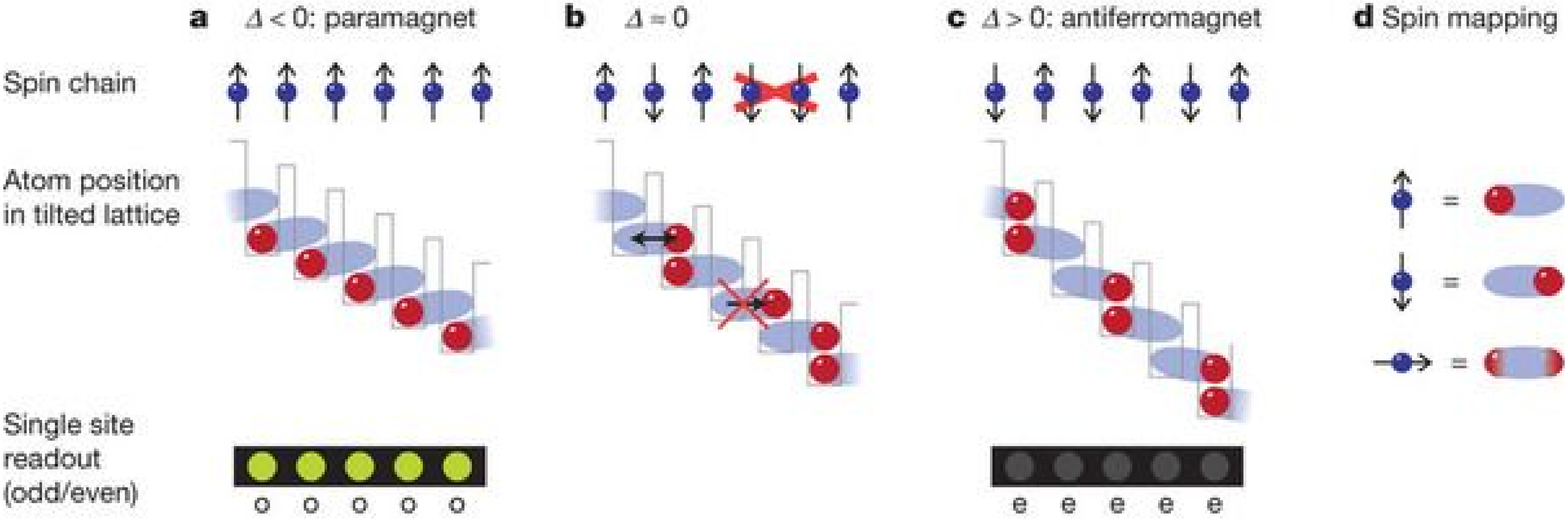


Tilted lattices

- Create a Mott insulator
- Tilt to control tunneling
- Homomorphic to spin change


a $\Delta < 0$: paramagnet
b $\Delta = 0$
c $\Delta > 0$: antiferromagnet
d Spin mapping
Spin chain
Atom position in tilted lattice
Single site readout (odd/even)
o o o o o
e e e e e
=
=
=

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Methodology: Experimental Details

- Mott insulator of ^{87}Rb in a two dimensional Optical Lattice
  - Spacing: a = 680 nm
  - Depth: 35 E_r

    Lattice Recoil Energy, $E_r = h^2/ma^2$

- By varying a B-field: drive a phase transition from paramagnetic into antiferromagnetic phase

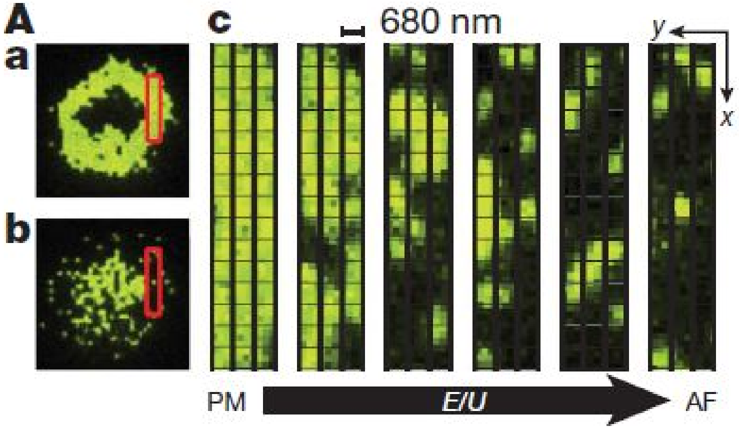
- Magnetic Domain Formation: Observed through both
  - in situ site-resolved imaging
  - noise correlation measurements

- In the focal plane of a high resolution imaging system

Imaging System

Quantum Gas Microscope:

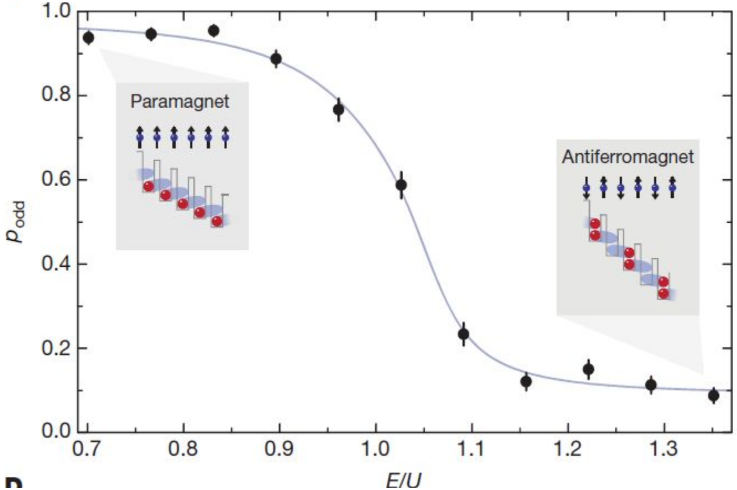
- Use fluorescence imaging after pinning the atoms in a deep lattice.
- Detects single atoms on individual lattice sites

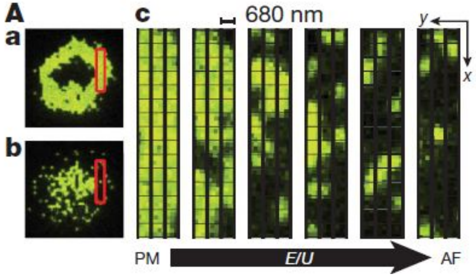


- Sensitive only to the parity of site occupation number
    - Paramagnetic Domains (one atom per lattice site): Bright
    - Antiferromagnetic Domain (0-2-0-2 occupation): Dark

In situ Imaging: Procedure

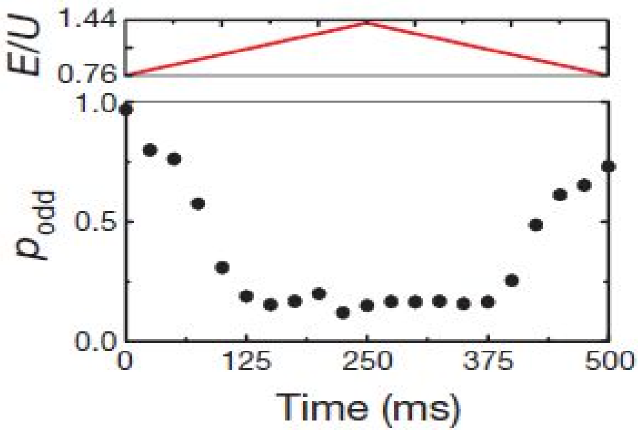
- Generate h_z: tilt the lattice by E per lattice site, by applying a B-field gradient in the longitudinal plane
- Ramp/Increase the tilt: stopping at various times to observe spin ordering
    - Initial Mott state has good overlap with the paramagnetic ground state
    - Initiate the gradient ramp on the paramagnetic side of the phase transition (typically at E/U = 0.7)





Reversibility

- A crucial characteristic of an adiabatic transition is that it is reversible



Ramp from a paramagnetic phase (E/U = 0.7) to an antiferromagnetic phase (E/U = 1.2) and back in 500 ms

- Recovery of the singly occupied states:
  - Reversibility of the process
  - Forward ramp is an antiferromagnet

Quantum Noise Correlation Measurement

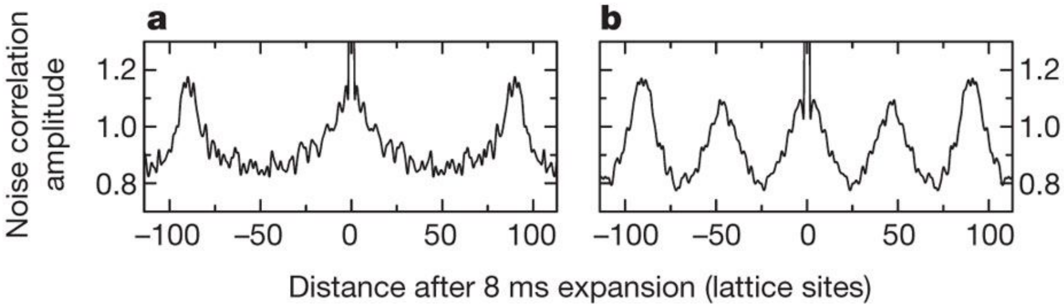
- In situ site measurement: locally identify magnetic domains and estimate their size

- But:
    - is not a direct measurement of antiferromagnetic order
    - does not reflect the broken symmetry in the antiferromagnetic phase

- Employ Second Method: 1-dimensional Quantum Noise Interferometry

Quantum Noise Correlation Measurement

- One Dimensional Spatial Autocorrelation: at beginning and end of the ramp (from paramagnetic phase to antiferromagnetic phase)



- Expect the spectrum to exhibit:
  - For paramagnetic phase: peaks at momentum difference P = h/a, characteristic of a Mott insulator
  - For Antiferromagnetic phase: peaks at P = h/2a, indicating spatial ordering with twice the wavelength

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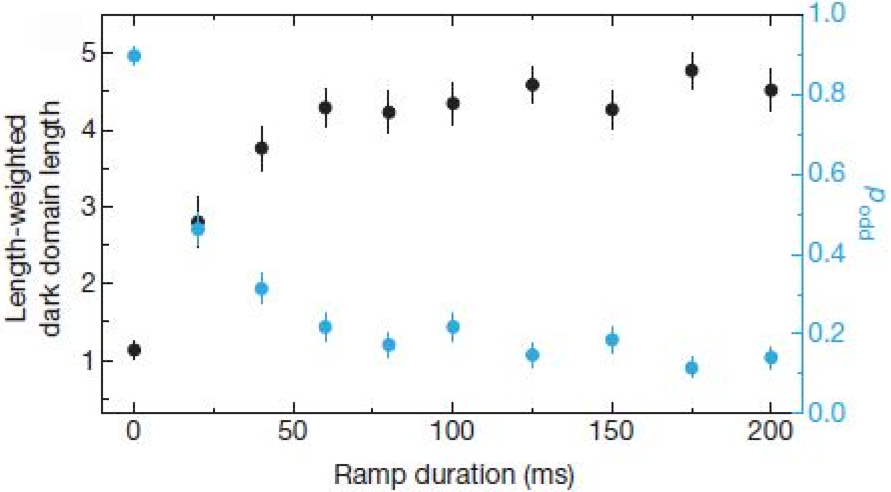
Timescale for Domain Formation

from a single six-site chain

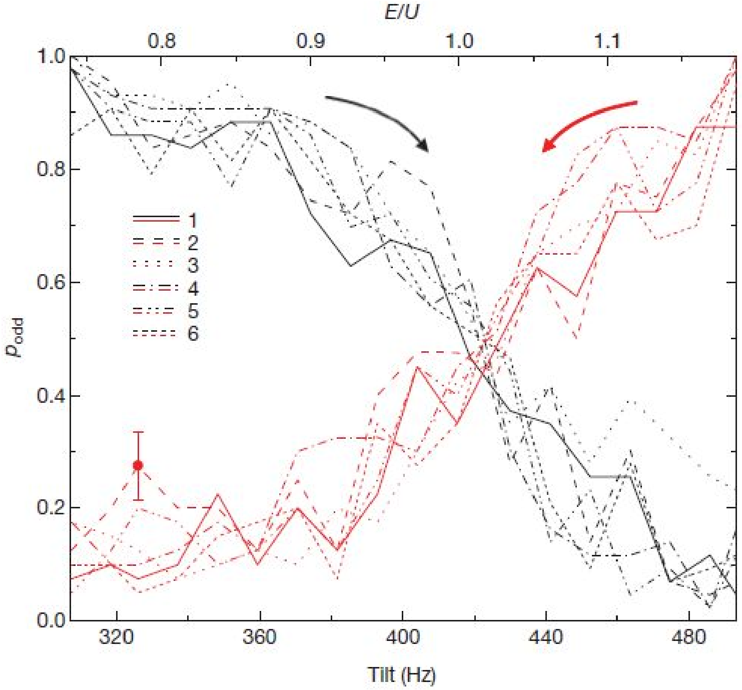


Ramping from paramagnetic phase to antiferromagnetic phase, E/U = 0.7 to 1.2

Timescale for domain formation is ~50ms, consistent with tunneling-driven transition

Producing domains of highest-energy state

six individual lattice sites

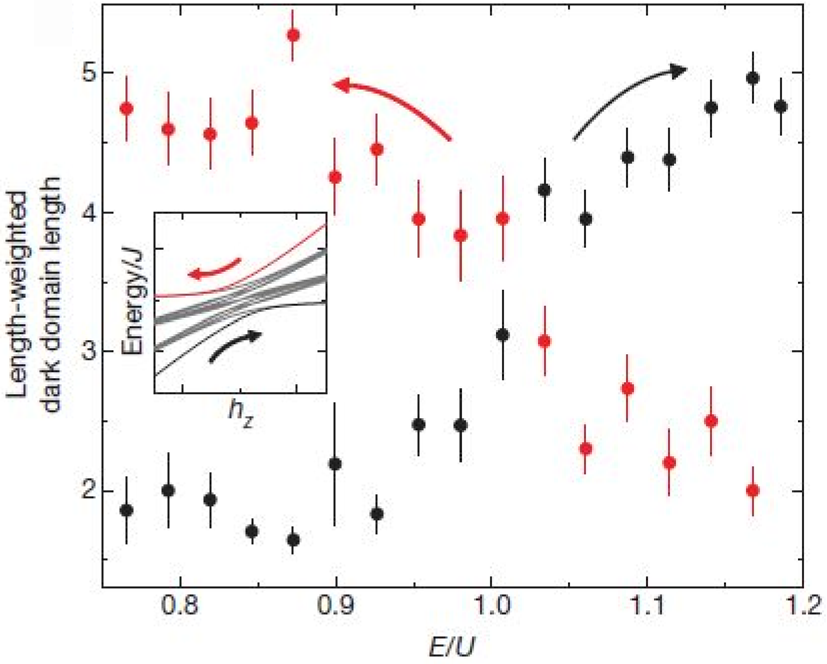


To prepare:

1. Inhibit tunneling
2. Rapidly ramp up the field gradient (8ms)
3. Slowly ramp down with tunneling uninhibited

We get a paramagnet on the antiferromagnetic side of the transition ->

converted adiabatically into an antiferromagnet on the paramagnetic side single six-site chain



The authors verified formation of spin domains

A quantum simulation of an Ising chain is experimentally realized

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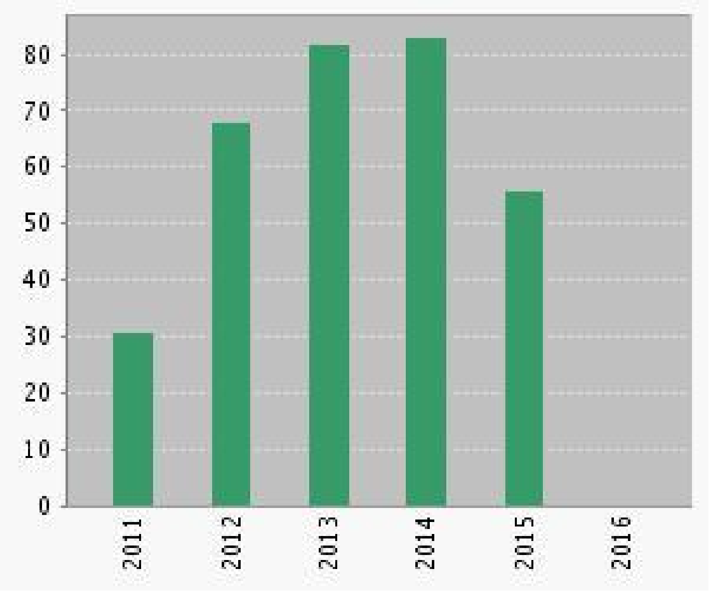
Conclusion

- Citation Review
- Critique
- Summary

Citation Review



Web of Science

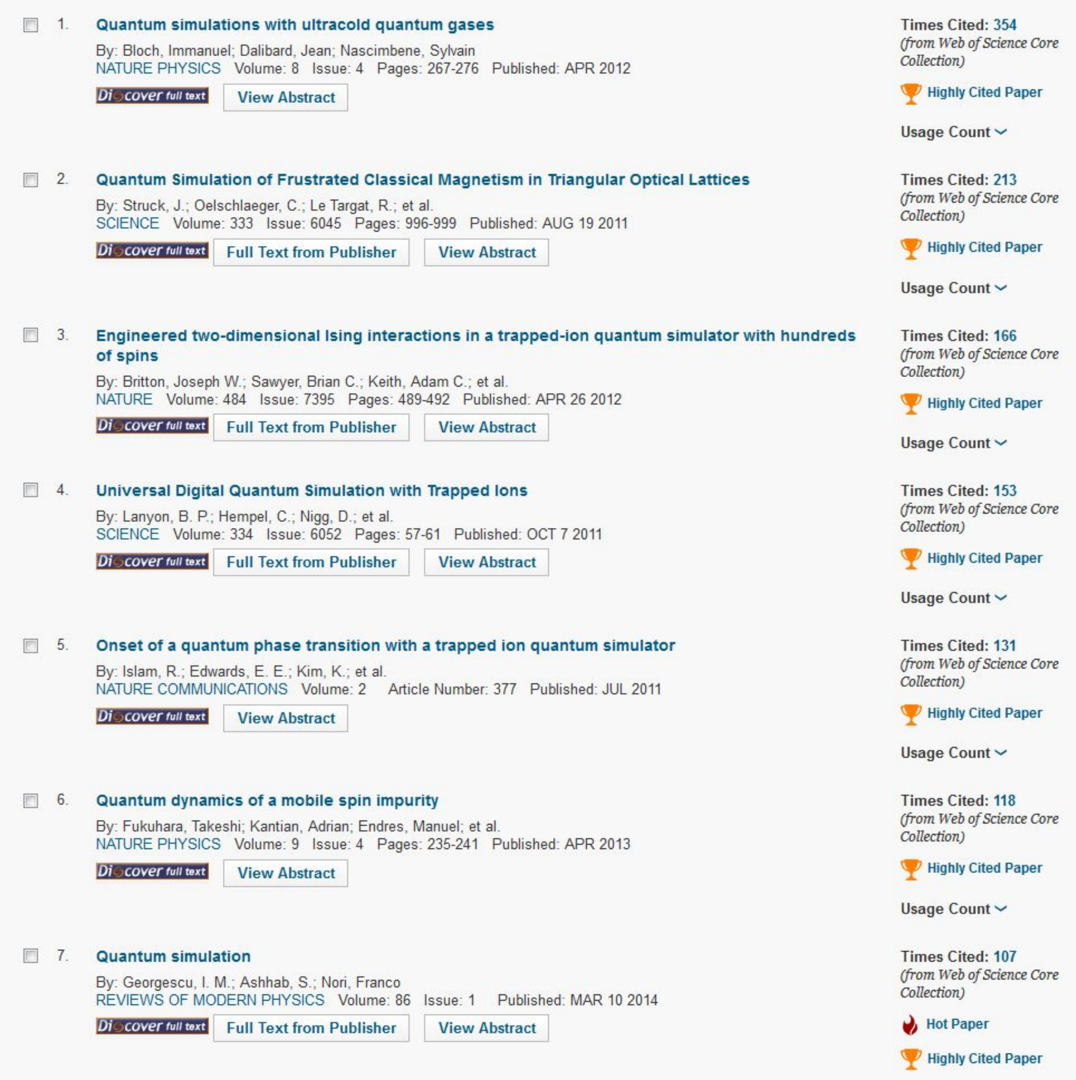
The paper quickly gained attention

Google Scholar

494 citations

Web of Science

320 citations



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By: Bloch, Immanuel; Dalibard, Jean; Nascimbene, Sylvain
NATURE PHYSICS Volume: 8 Issue: 4 Pages: 267-276 Published: APR 2012

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By: Georgescu, I. M.; Ashhab, S.; Nori, Franco
REVIEWS OF MODERN PHYSICS Volume: 86 Issue: 1 Published: MAR 10 2014

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The field of quantum simulation is quickly growing

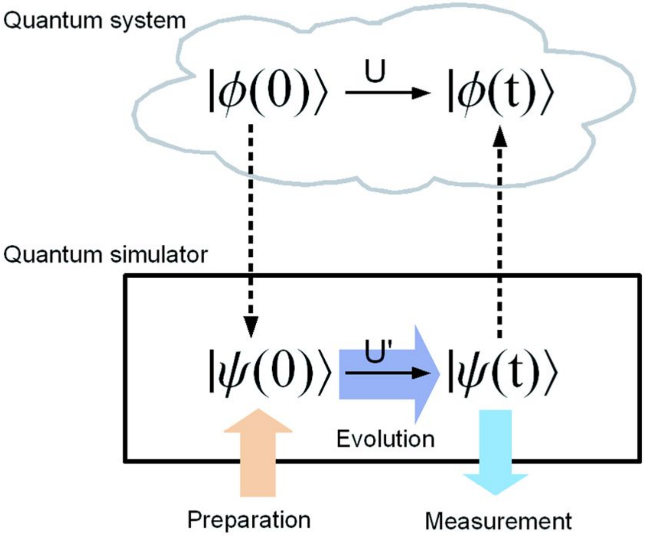
Quantum simulator systems:

- Ultracold quantum gases
- Trapped ions
- Photons
- Superconducting circuits
- Neutral atoms
- Polar molecules
- Electrons in semiconductors
- Nuclear spins (NMR)

Most of these have been experimentally demonstrated

Quantum simulators can be used to study:

- Condensed matter physics
  - Quantum phase transitions
  - High Tc superconductors
- High energy physics
  - Lattice gauge theories
  - Dirac particles
- Cosmology
  - Universe expansion
  - Hawking radiation
- And much more! (nuclear physics, chemistry, biology)



Georgescu, I.M., Ashhab, S. and Nori, F., 2014. Quantum simulation. *Reviews of Modern Physics*, *86*(1), p.153.

Critique

Difficult to understand, does not seem accessible to general audience

“In this work, we simulate a one-dimensional chain of interacting Ising spins by using a Mott insulator[10,29,30] of spinless bosons in a tilted optical lattice[31].”

Summary

- Quantum simulation: using one system to study another that is more difficult to access
- The authors of this paper experimentally realize a quantum simulation of an Ising chain
- Quantum simulation is a growing field with many applications
- Very influential
- Hard to understand

Acknowledgements

Pictures:

Figure 1:Formation of optical lattice

Quantum coherence and entanglement with ultracold atoms in optical lattices Immanuel Bloch *Nature* **453**, 1016-1022(19 June 2008) doi:10.1038/nature07126

Georgescu, I.M., Ashhab, S. and Nori, F., 2014. Quantum simulation. *Reviews of Modern Physics*, *86*(1), p.153.

Thanks for listening!