It’s a Boson! No wait, it’s two Bosons!

Quantum Walks in Optical Lattices

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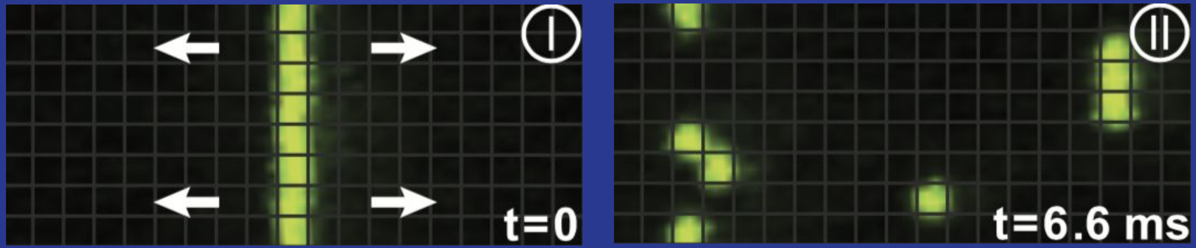

The Paper

Strongly correlated quantum walks in optical lattices

Philipp M. Preiss[1], Ruichao Ma[1], M. Eric Tai[1], Alexander Lukin[1], Matthew Rispoli[1], Philip Zupancic[1,*], Yoav Lahini[2], Rajibul Islam[1], Markus Greiner[1,†]

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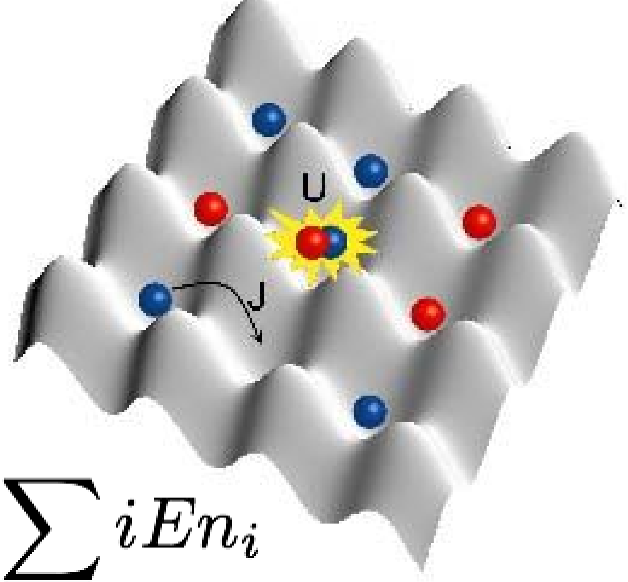
Note: uncited images are from Preiss, et al.

Introduction

- Cold atoms experiments realize toy model Hamiltonians
  - Strong collaborations between theorists and experimentalists
  - Ability to observe weakly interacting many-body systems to strongly correlated dynamics
  - *Bose-Hubbard Model* - simple theoretical model of interacting bosons on optical lattice

- Can probe interesting physics
  - Many-body localization and dynamics of interacting quantum disordered systems
  - Universal and efficient quantum computation
  - Quantum effects when more than one particle participates in the quantum walk simultaneously - Hanbury Brown and Twiss (HBT) effect

Hamiltonian for interacting bosons on a lattice.



$$H_{BH} = \sum_{\langle i,j \rangle} J a_i^\dagger a_j + \sum_i \frac{U}{2} n_i (n_i - 1) + \sum_i i E n_i$$

Image: https://terpconnect.umd.edu/~pauls/research.html

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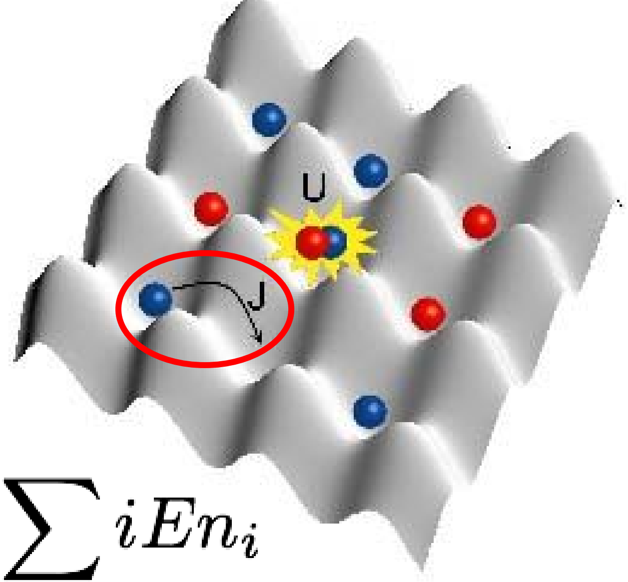
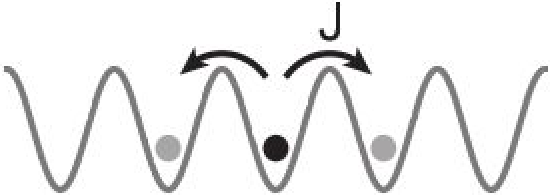


$$H_{BH} = \boxed{\sum_{\langle i,j \rangle} J a_i^\dagger a_j} + \sum_i \frac{U}{2} n_i(n_i - 1) + \sum_i iEn_i$$

J-tunneling amplitude between lattice sites



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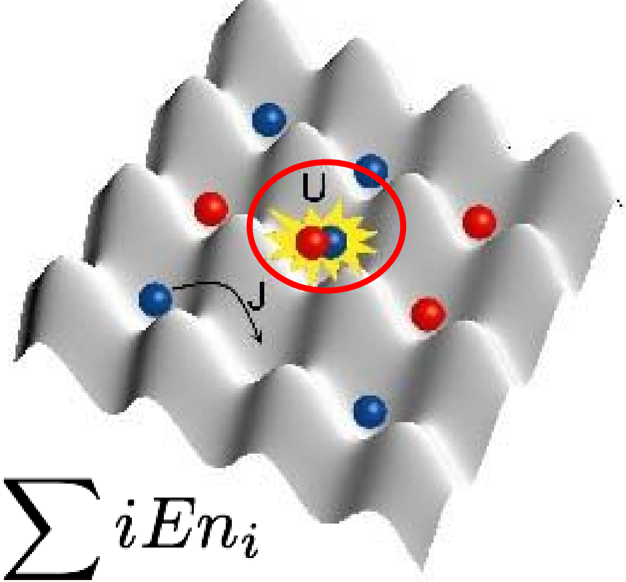
Hamiltonian for interacting bosons on a lattice.



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U-repulsive on site interaction

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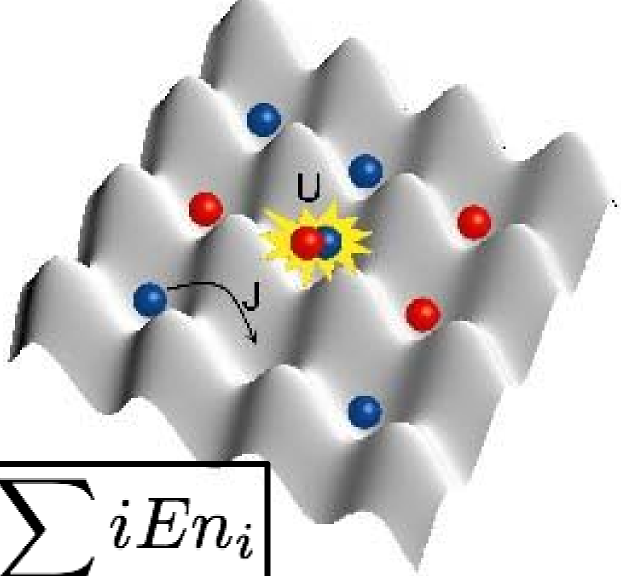
Hamiltonian for interacting bosons on a lattice.



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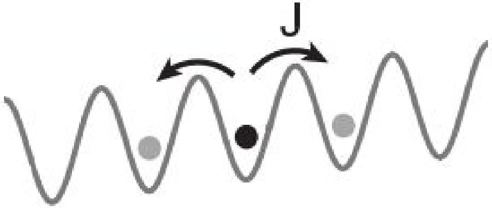
E-energy shift per lattice site



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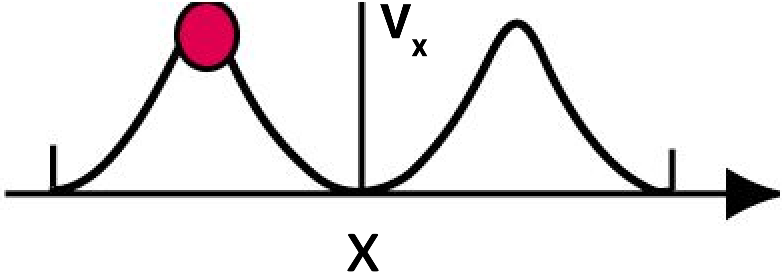
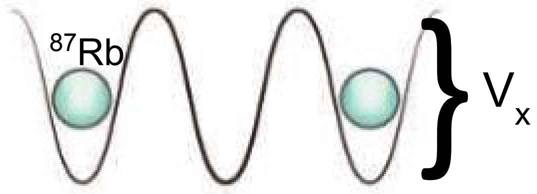
Potential Gradient Induces Bloch Oscillations



- Oscillations of a quantum particle within a small length scale in position space when exposed to external force
- Dispersion of probability distribution in position space
- Refocuses to initial position after one oscillation period

Image: Nikita Butakov

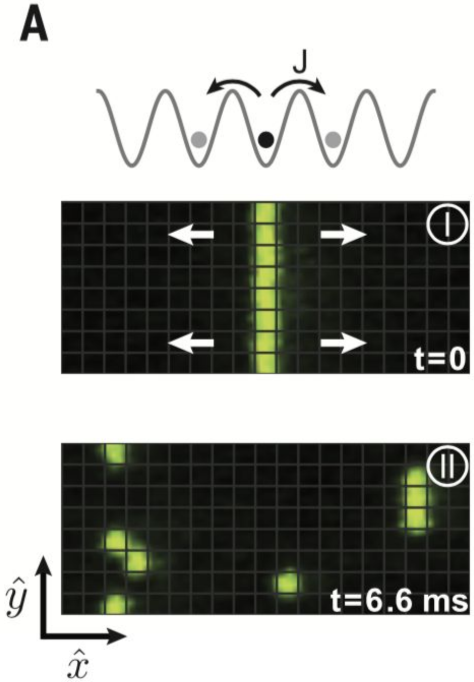
Experimental Setup



- Ultracold Bosonic ^{87}Rb atoms in an optical lattice
- Atoms initially prepared in 2D Mott Insulator (1-2 atoms per site)
- Potential is flattened in one direction to allow quantum walk (performed at reduced lattice depth V_x)
- Fluorescence imaging in deep optical lattice
- Pairs separated by magnetic field along direction of quantum walk prior to imaging

Single Particle Quantum Walk

- A: Without potential
  - Particles spread linearly
  - Interference leads to coherent wavefront rather than Gaussian like classical walk



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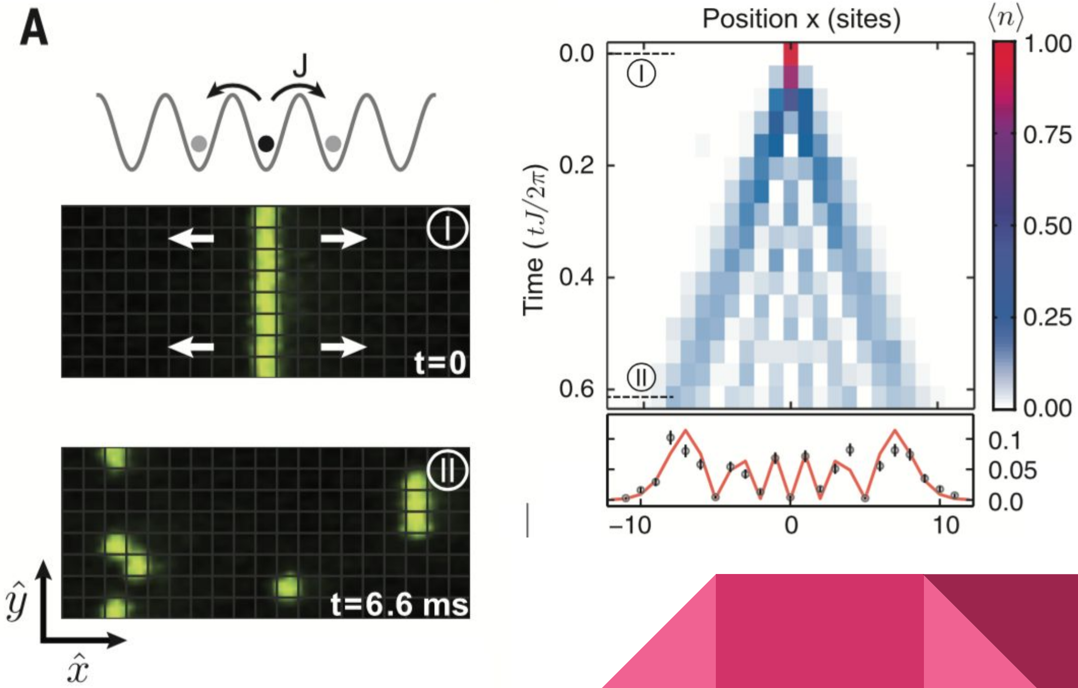
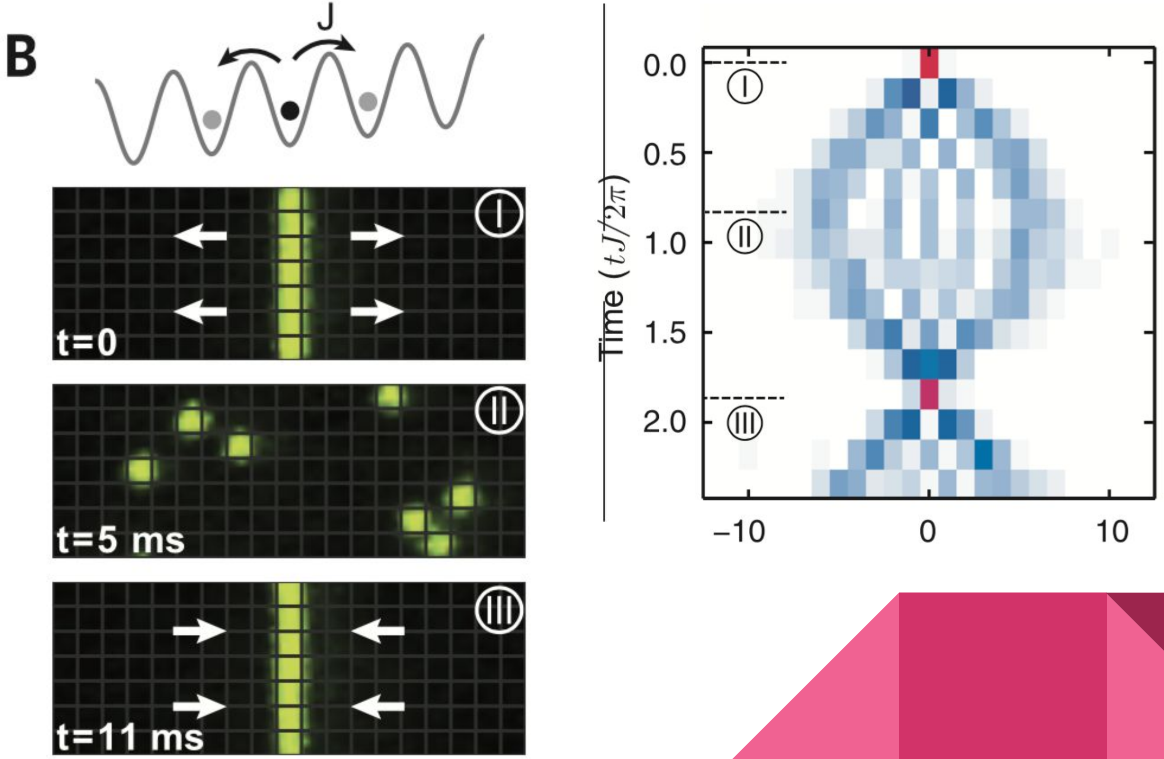


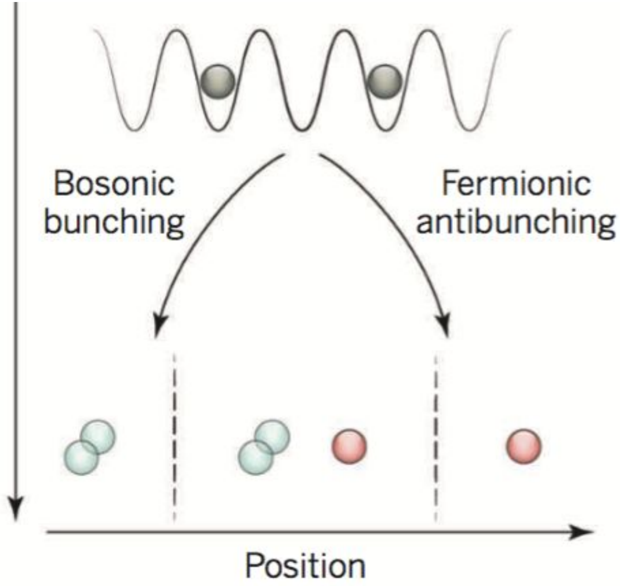
Single Particle Quantum Walk

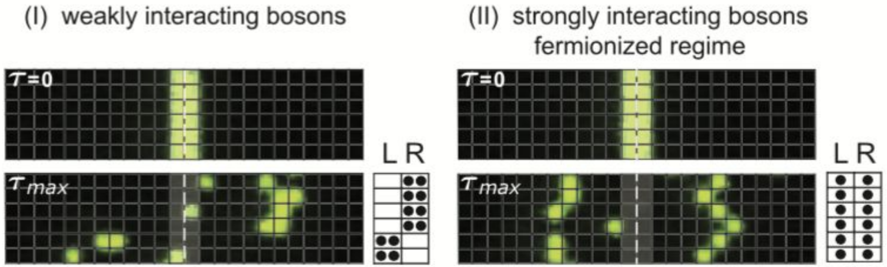
- B: With potential
  - Particles undergo Bloch oscillation
  - Particles localized to small volume



Two-Particle Quantum Walk

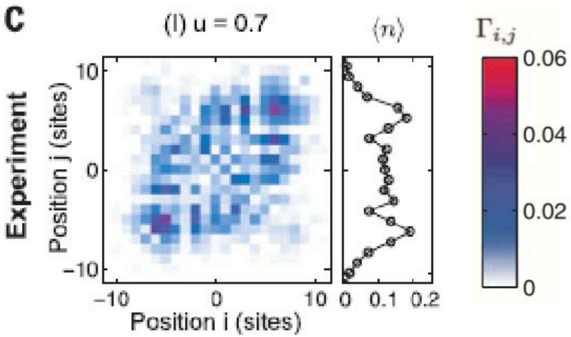
- Particles undergo Hanbury Brown and Twiss interference
- Bosons add constructively in close proximity
  - Leads to bunching
- Fermions add destructively
  - Leads to antibunching
- With strong repulsive interactions, bosonic particle pairs undergo “fermionization”





Two-Particle Fermionization

- Two particles starting in adjacent sites $a_0^\dagger a_1^\dagger |0\rangle$
- As interaction strength increases, repulsive interactions compete with and overcome HBT interference



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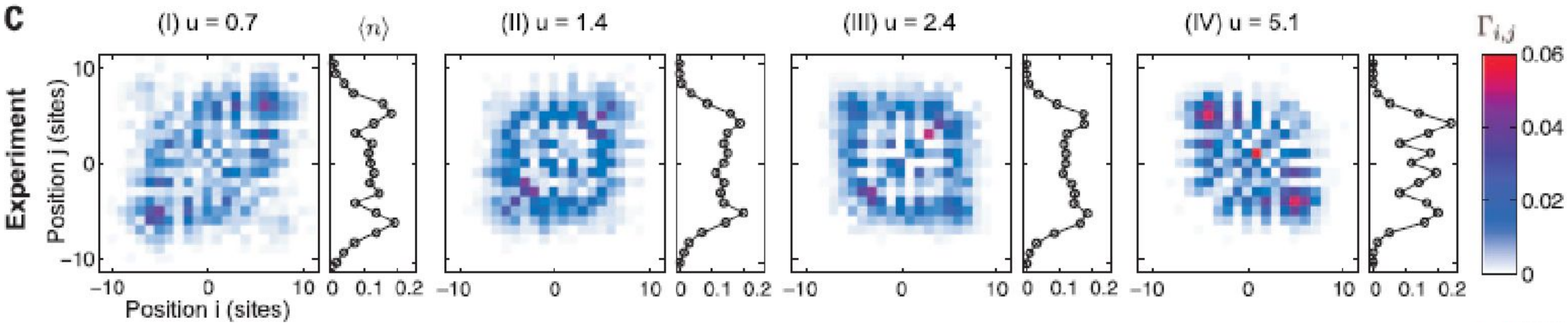

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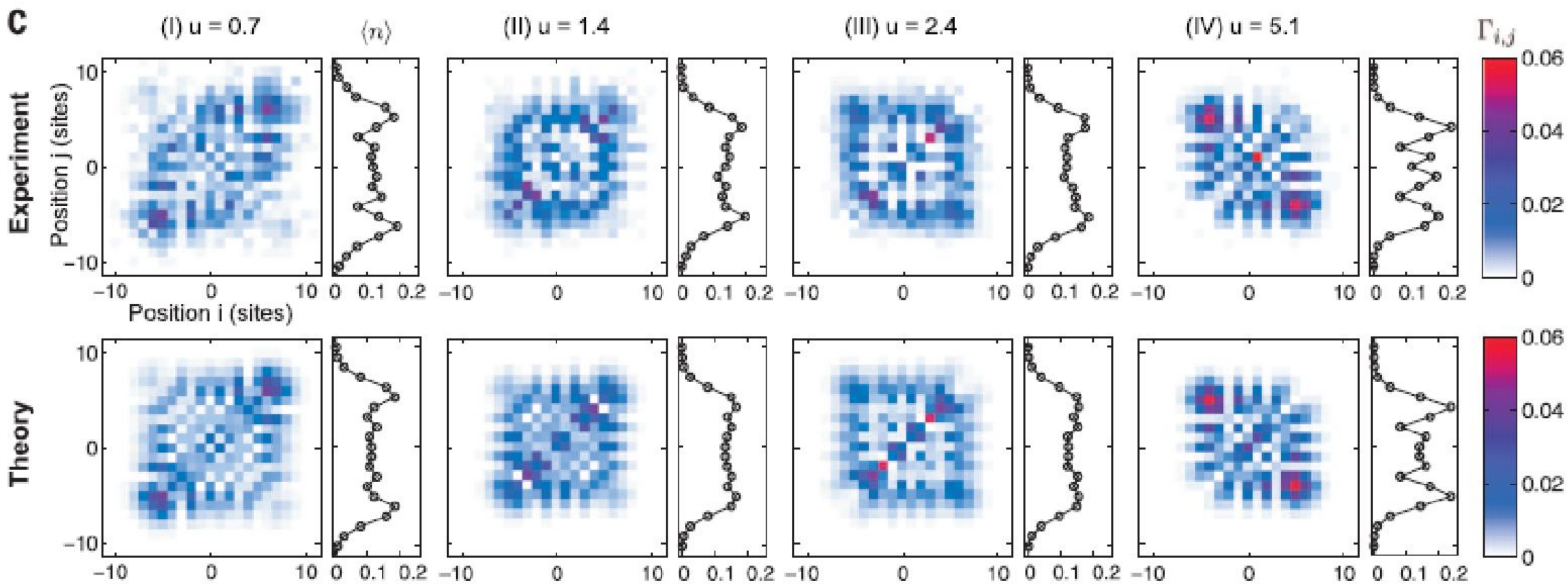
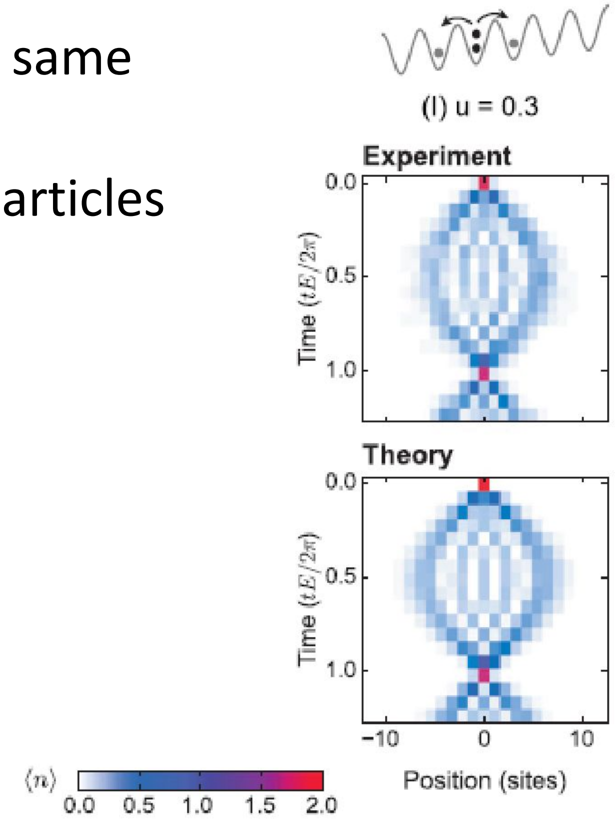


Strong Interactions: Repulsively Bound Pairs

- Two particles starting in same state $(1/\sqrt{2})a_0^\dagger a_0^\dagger|0\rangle$
- For weak interactions, particles act independently



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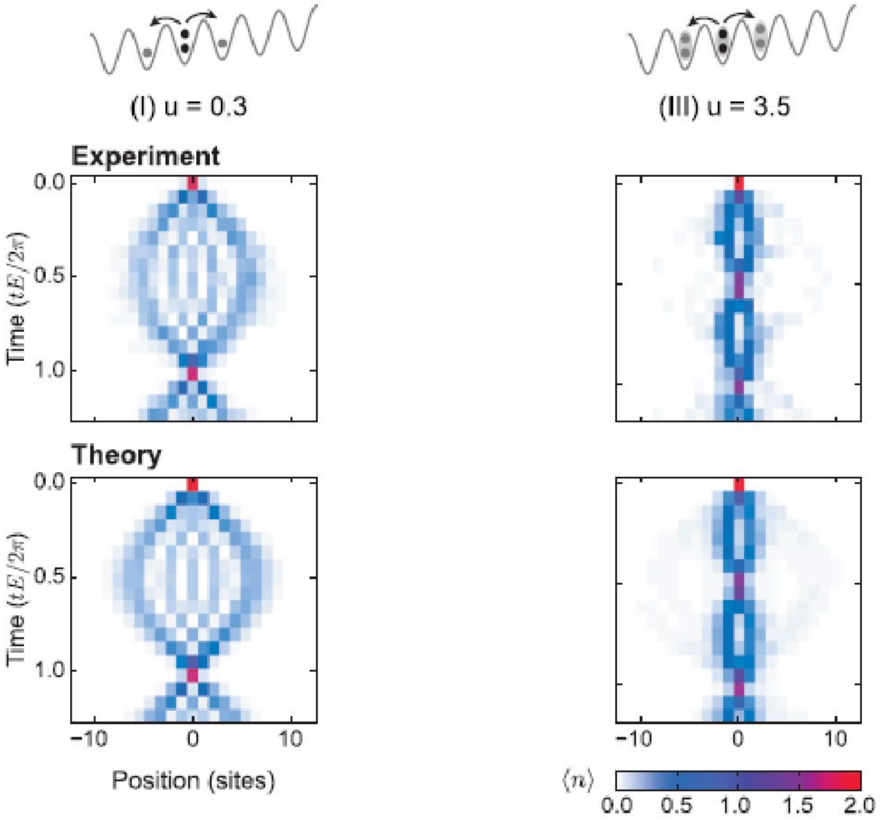

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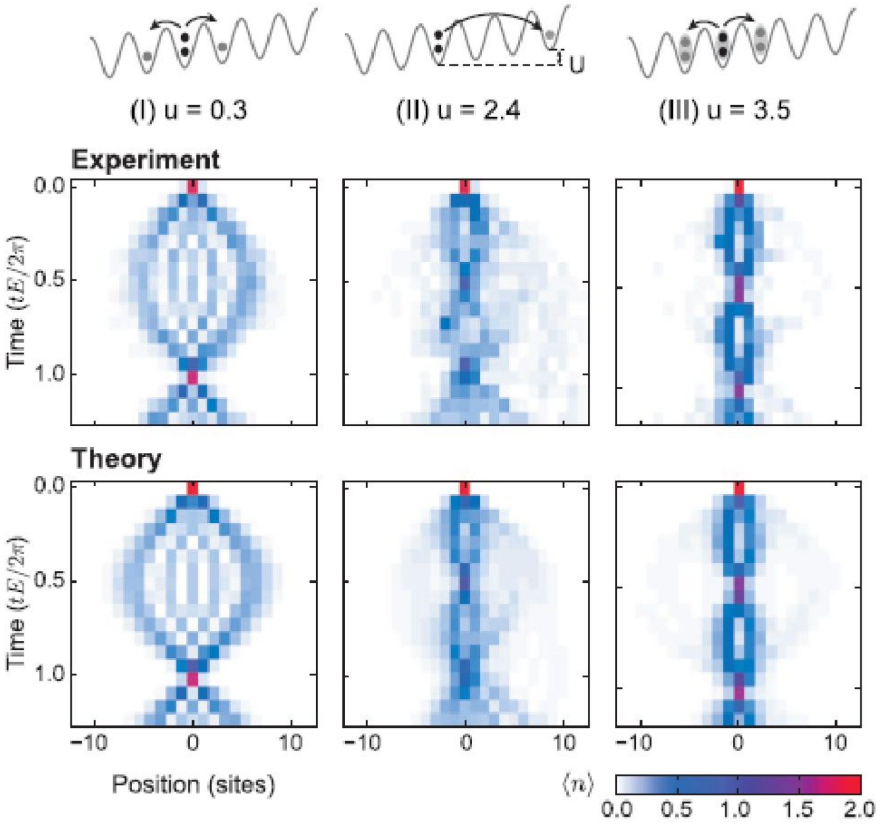
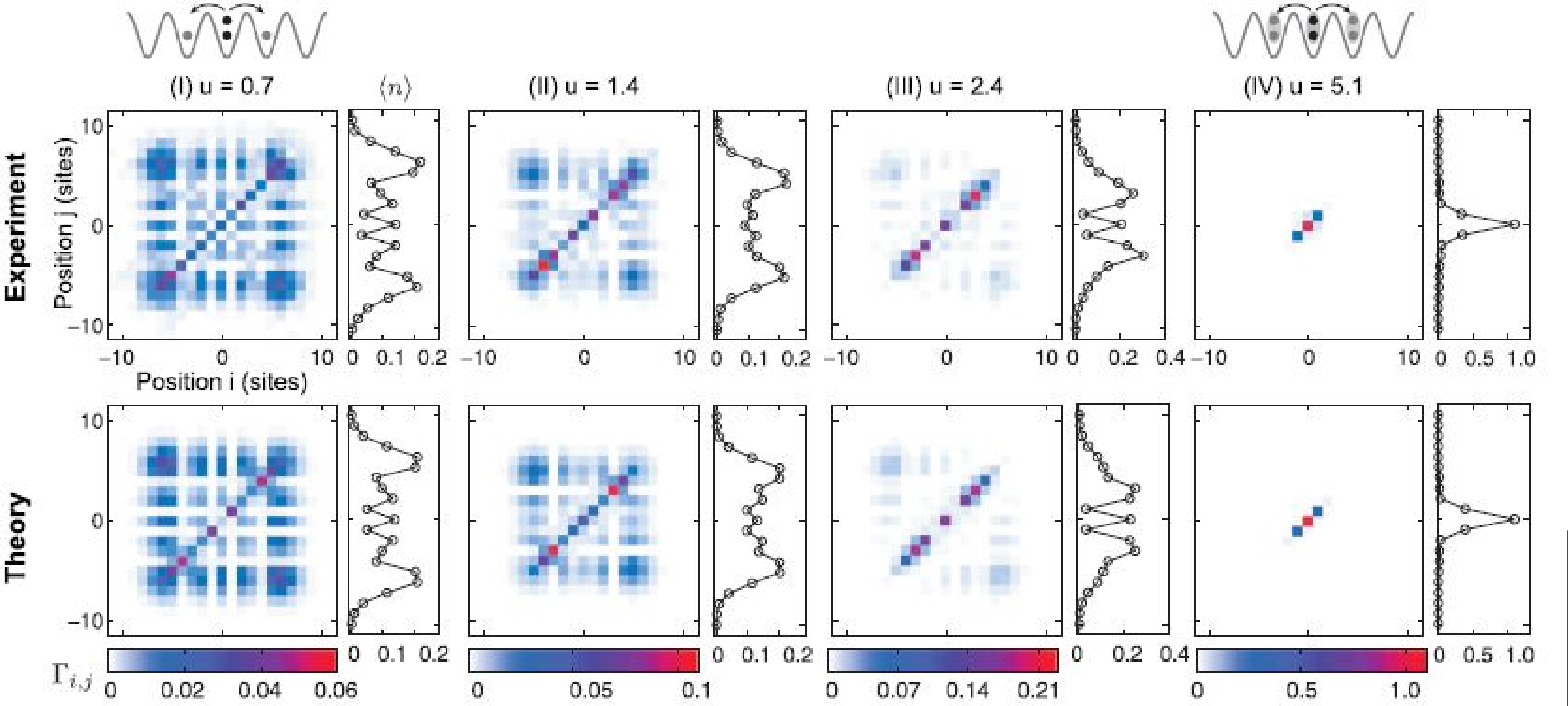
- Two particles starting in same state $(1/\sqrt{2})a_0^\dagger a_0^\dagger|0\rangle$
- For weak interactions, particles act independently
- For strong interactions, particles move together as a repulsively bound pair
- Complicated dynamics in intermediate regime



Repulsively Bound Pairs (cont.)



Citation Analysis

- Paper Birthday: March 2015 (~1 year 9 months)
- 59 citations
  - ~50% experimental, ~50% theoretical
  - 3 papers specifically proposed new methods of studying similar systems
  - 4 papers from the same group
  - Many papers that provided more complex conditions:
    - cylindrical environments
    - fermionic atoms (Ytterbium atoms!)
    - polarized atoms

Citation Analysis - Notable Papers

- Most cited citing paper:
  - Site-Resolved Imaging of Fermionic ^{6}Li in an Optical Lattice

    Maxwell F. Parsons, Florian Huber, Anton Mazurenko, Christie S. Chiu, Widagdo Setiawan, Katherine Wooley-Brown, Sebastian Blatt, and Markus Greiner
    Phys. Rev. Lett. **114**, 213002 – Published 28 May 2015
  - 34 citations and same corresponding author
  - Many more Lithium papers among citing (common cold atom)
- Extra interesting paper:

Quantum coherent oscillations in the early universe

Igor Pikovski and Abraham Loeb
Phys. Rev. D **93**, 101302(R) – Published 25 May 2016

Paper Critique

- Good:
  - Really great data!
  - Well polished paper
  - Publicly accessible abstract included
- Bad:
  - Lots of acronyms with little help for those outside the field
  - Does not describe methods in great detail (nor citations)

Conclusion

- Preiss, *et al.*, developed a system to create *2-particle* bosonic random walks in an optical lattice
- This system matched theoretical predictions and principal effects both non-interacting and a strongly correlated system
  - Observed Bloch oscillations and HBT effects
- This technique provides access to the exploration of fundamental condensed matter systems
  - Ex: Microscopics of complicated systems, such as ones with disorder and rapid changes (quench)