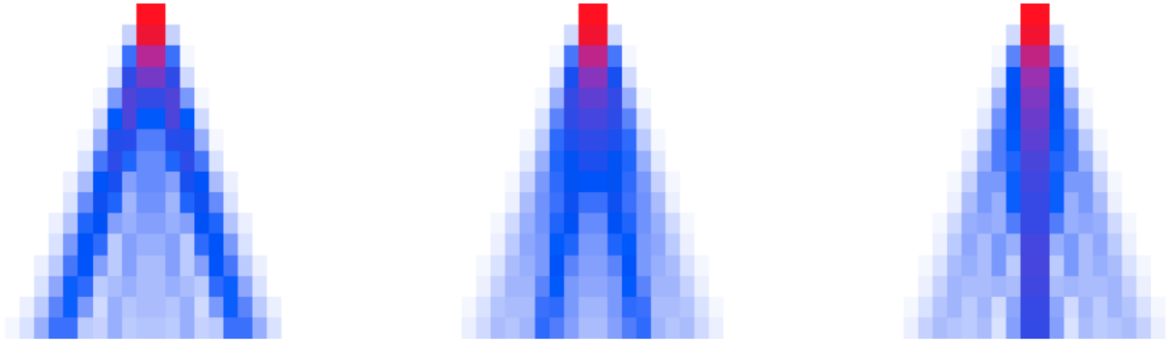


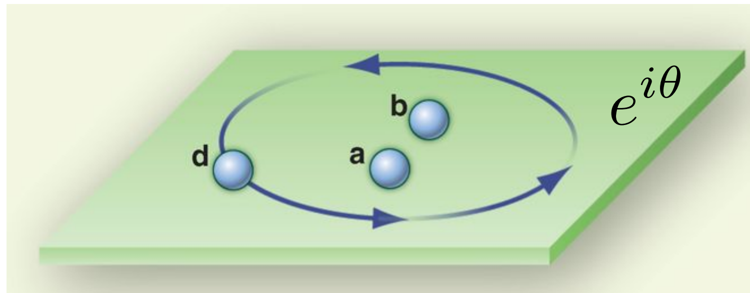
Simulating Anyonic Statistics in Few-Body Dynamics

Philipp Preiß
Physikalisches Institut
Universität Heidelberg

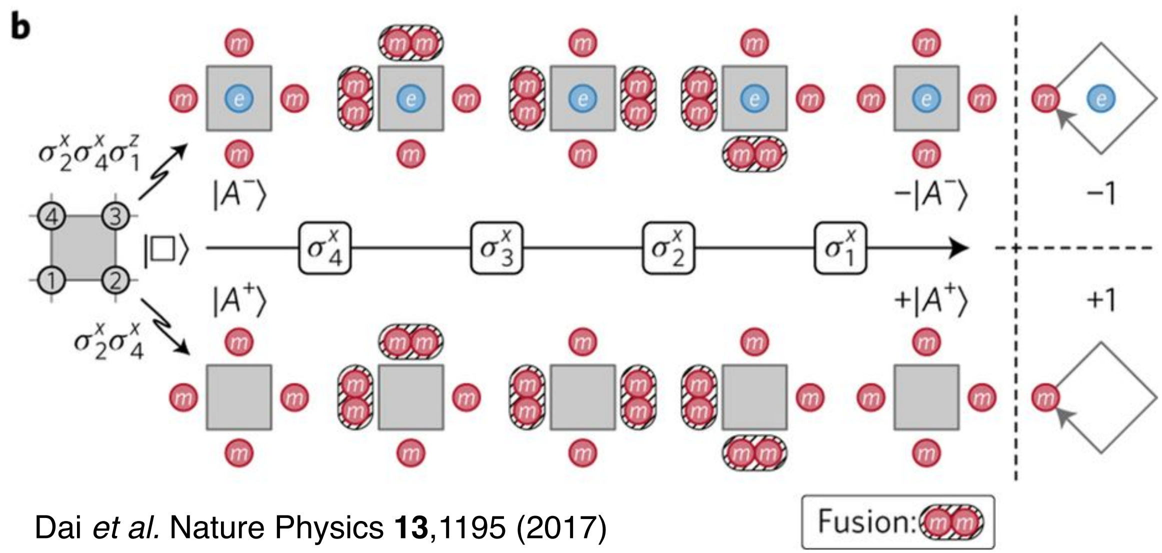
Anyon Physics of Ultracold Atomic Gases
14.12.2018

Anyonic quasiparticles with ultracold atoms

Fractional Statistics



2D topologically ordered systems



Dai *et al.* Nature Physics **13**,1195 (2017)

See also the next talk by Christof Weitenberg

One-dimensional anyon models

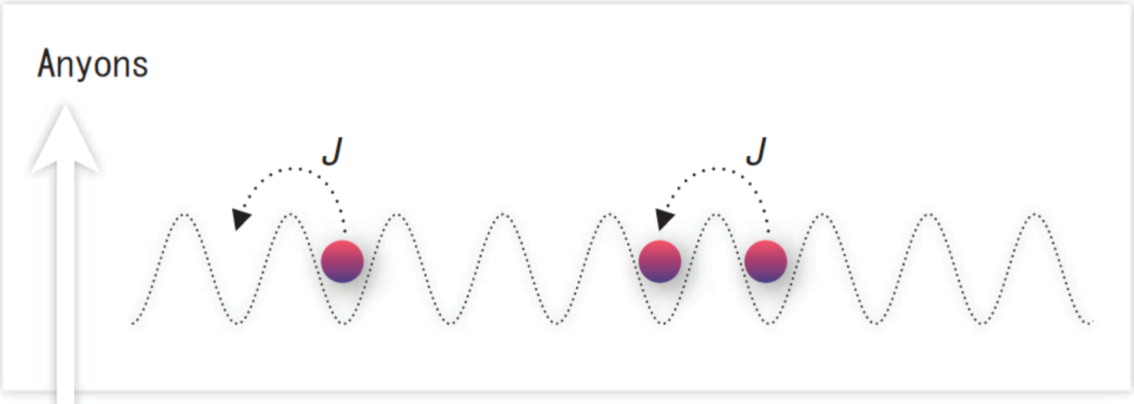
Fractional statistics

$$a_j a_k^\dagger - e^{-i\theta \mathrm{sgn}(j-k)} a_k^\dagger a_j = \delta_{jk}$$

$$a_j a_k = e^{i\theta \mathrm{sgn}(j-k)} a_k a_j$$

$\theta = 0$ bosons

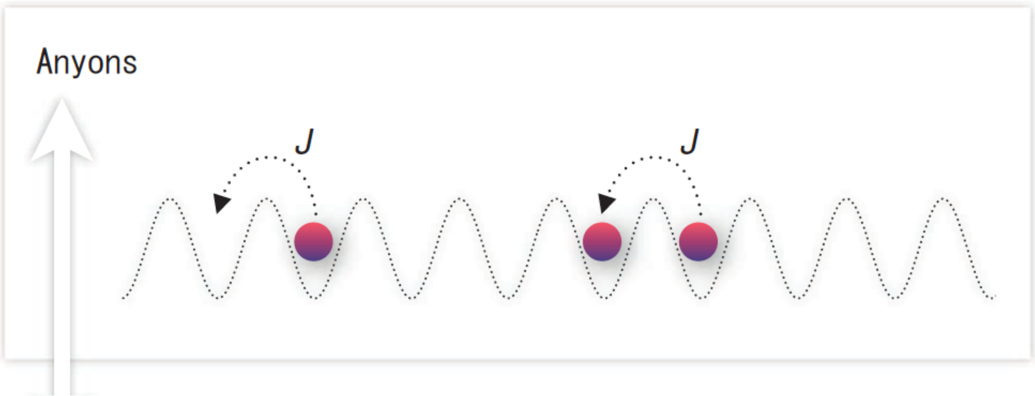
$\theta = \pi$ pseudo-fermions

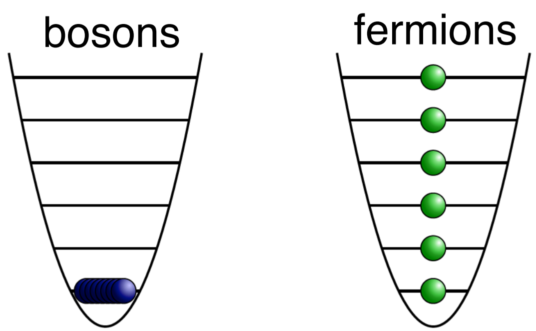


Keilmann *et al.*, Nature Communications **2**, 361(2011)

What are the phases and dynamics of anyonic particles in one dimension?

Engineering anyonic statistics





???

Engineering of effective anyonic statistics:

- Raman-assisted tunneling
- Lattice shaking
- Lattice depth modulation

Sebastian Greschner, Luis Santos, Thassilo Keilmann, Marco Roncaglia, Axel Pelster, André Eckardt, Yunbo Zhang, and many others …

Keilmann *et al.,* Nature Communications **2**, 361(2011)

Outline

Simulation of Anyons with one-dimensional Bosons

I. Engineering occupation-dependent tunneling

Lattice modulation in Mott insulators

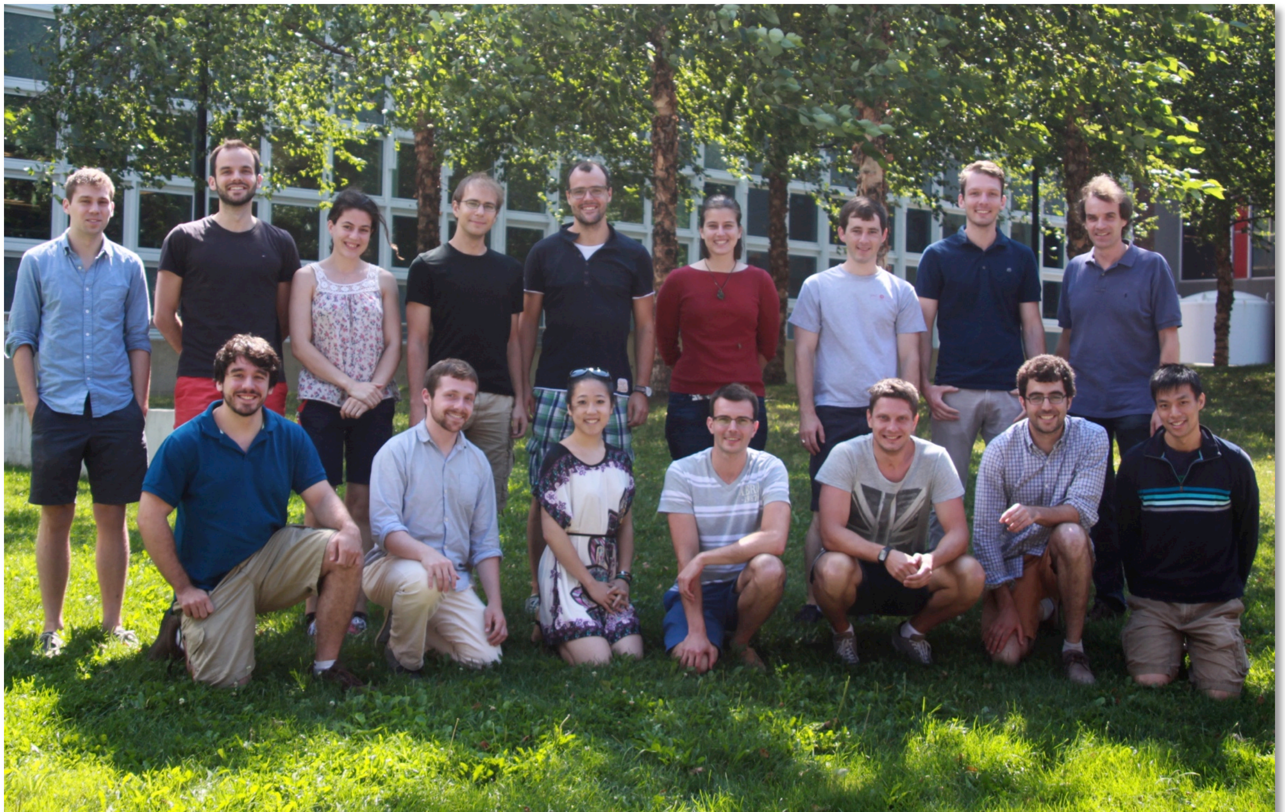
II. Identify a suitable experimental setting

Quantum walks of two bosons

Ask anything any time!

The team

Greiner group Harvard University



Markus Greiner
Ruichao Ma
Eric Tai
Matthew Rispoli
Jon Simon
Rajibul Islam

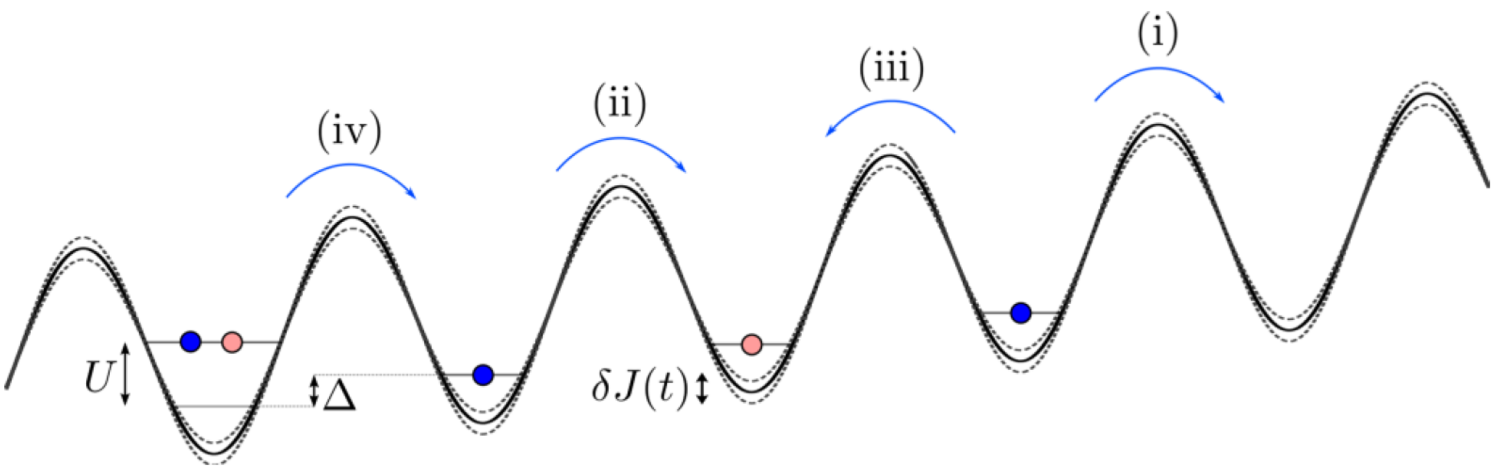
R. Ma *et al.*: Photon-Assisted Tunneling in a Biased Strongly Correlated Bose Gas PRL 107, **095301** (2011)
P. M. Preiss *et al.:* Strongly Correlated Quantum Walks in Optical Lattices Science **347** 1229 (2015)

Anyon-Boson Mapping

single particle: no phase shifts

two particles: occupation-dependent phase

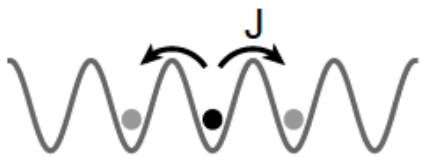
Lattice amplitude modulation



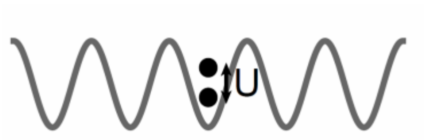
L. Cardarelli *et al.,* PRA **94**, 023615 (2016)
C. Sträter *et al.,* PRL **117**, 205303 (2016)

Bose-Hubbard Model

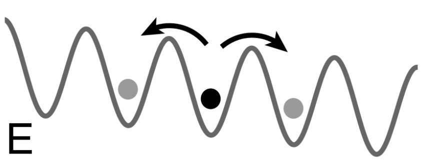
$$H_{\mathrm{BH}} = -\sum_i J(t)(a_i^\dagger a_{i+1} + \mathrm{h.c.}) + \sum_i iEn_i + \sum_i \frac{U}{2} n_i(n_i - 1)$$



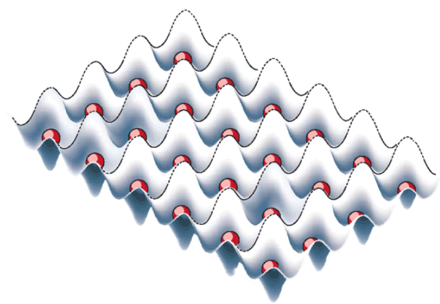
tunneling J



interaction U



bias E

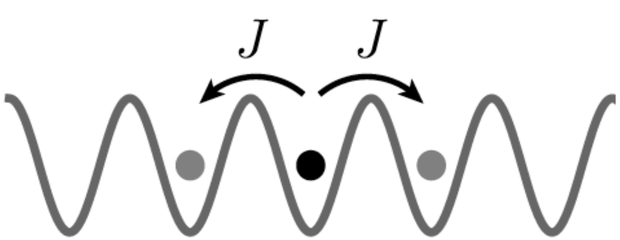


$J \ll U$

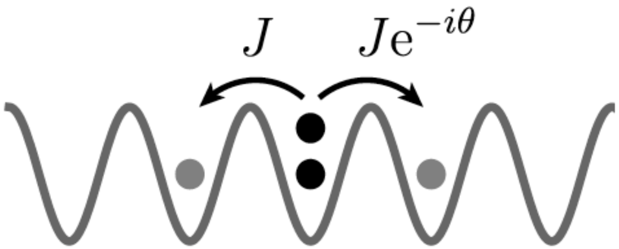
Mott insulator

Initialize one particle per site

Anyon-Boson Mapping

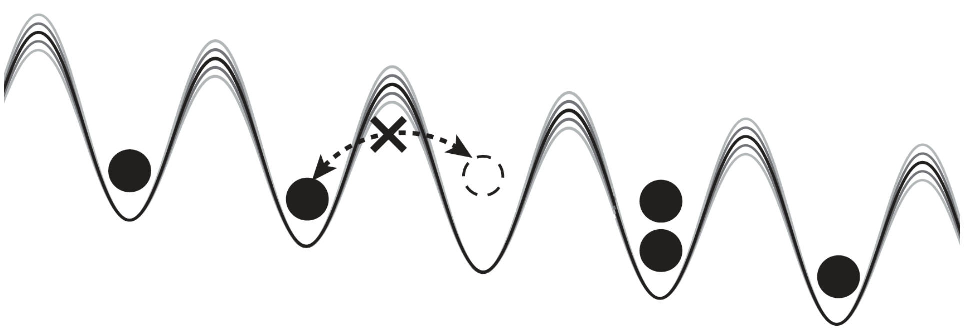


single particle: no phase shifts



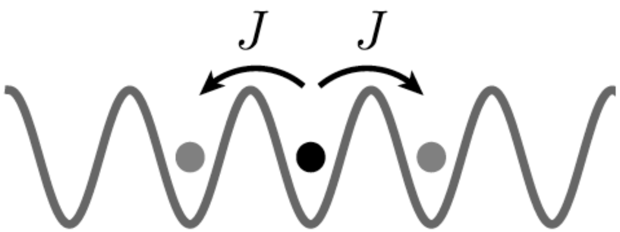
two particles: occupation-dependent phase

Strong tilt: suppress direct tunneling

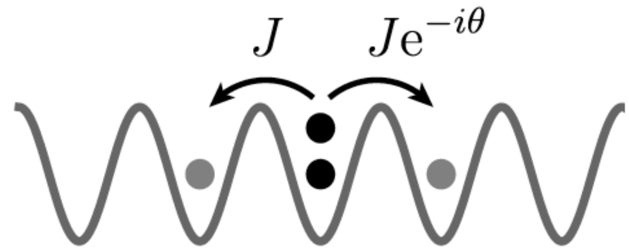


L. Cardarelli *et al.,* PRA **94**, 023615 (2016)
C. Sträter *et al.,* PRL **117**, 205303 (2016)

Anyon-Boson Mapping



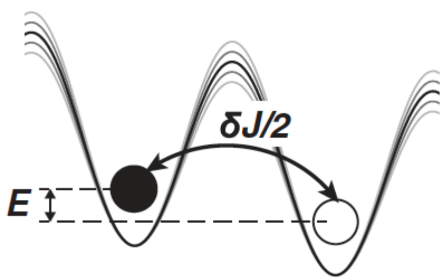
single particle: no phase shifts



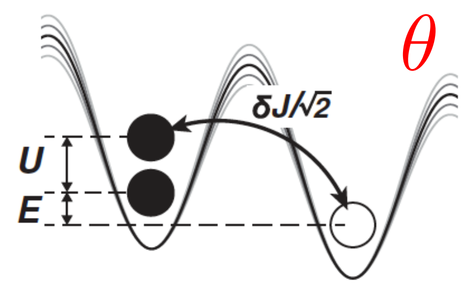
two particles: occupation-dependent phase

Restore individual processes

$$J(t) = J + \delta J \cos(\omega_{\mathrm{mod}} t + \phi)$$



$$\hbar\omega_{\mathrm{mod}} = E$$



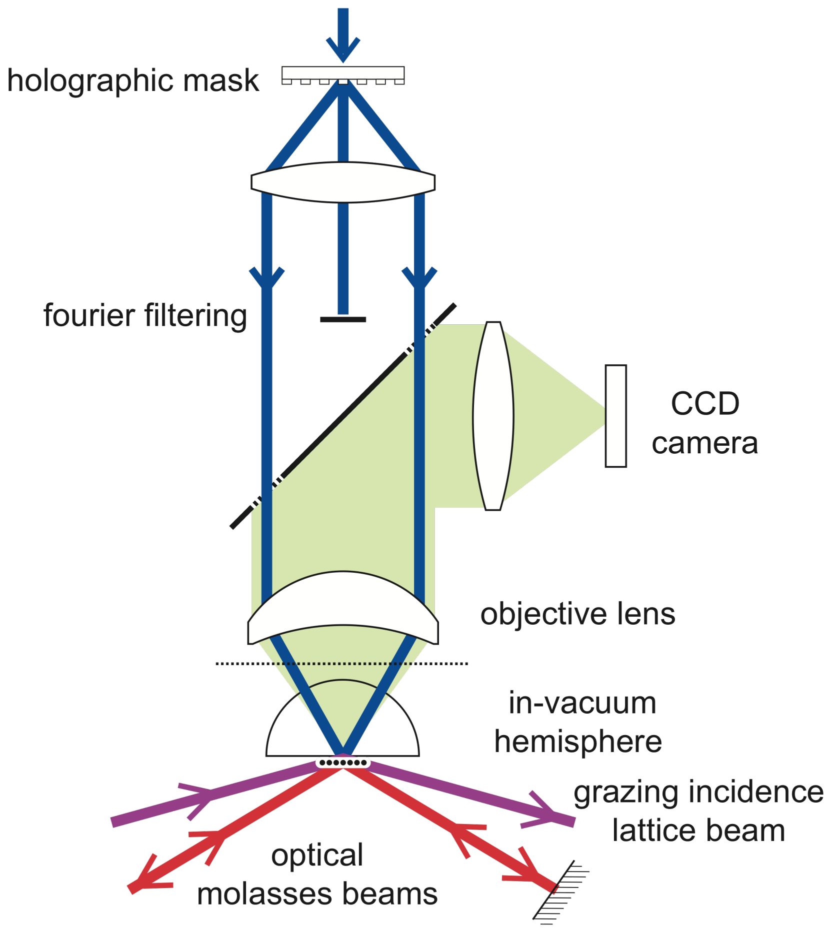
$$\hbar\omega_{\mathrm{mod}} = U + E$$

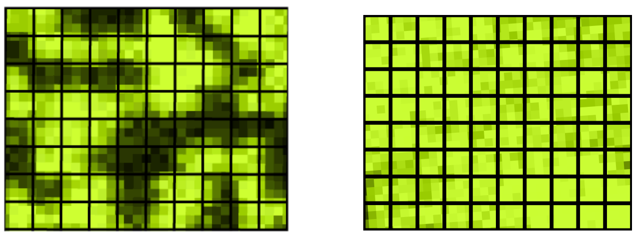
$$\hbar\omega_{\mathrm{mod}} = U - E$$

L. Cardarelli *et al.,* PRA **94**, 023615 (2016)
C. Sträter *et al.,* PRL **117**, 205303 (2016)

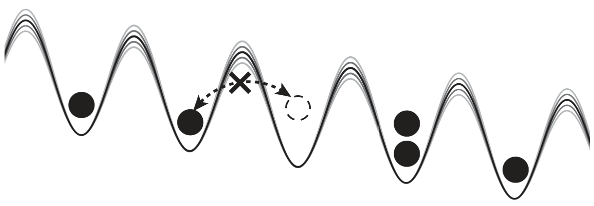
Experiment

Bosonic quantum gas microscope

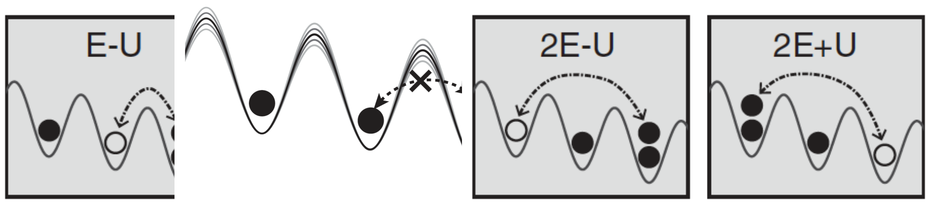


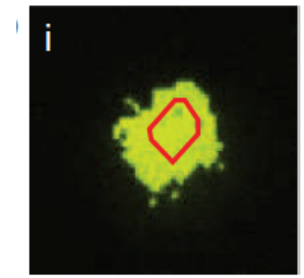


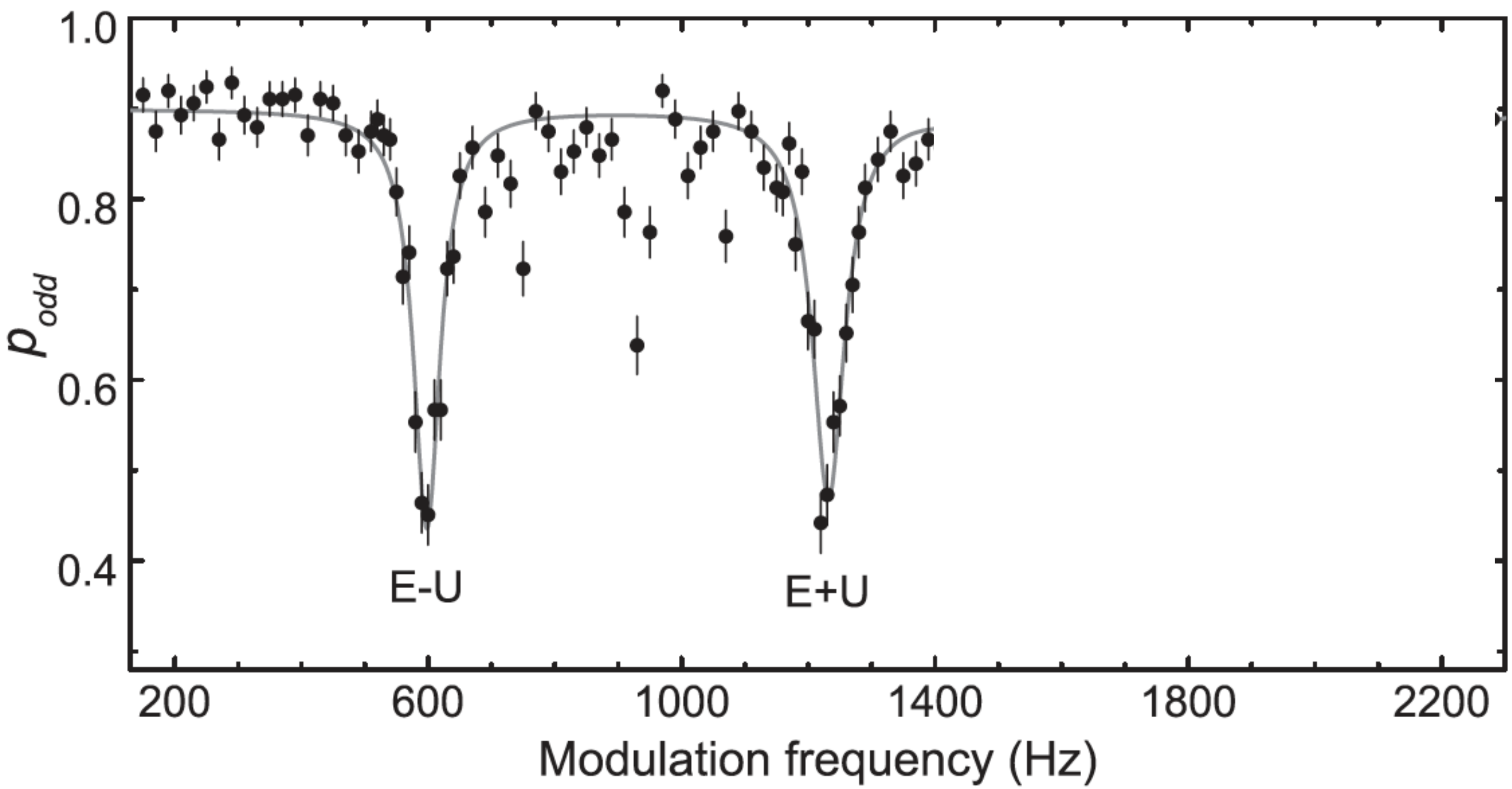
- Rubidium 87 in 2D square lattice
- Site-resolved imaging
- Initialize one particle per site



Photon-assisted tunneling

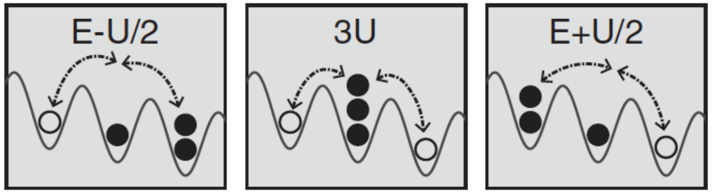


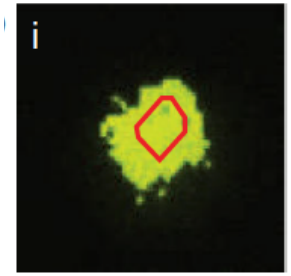


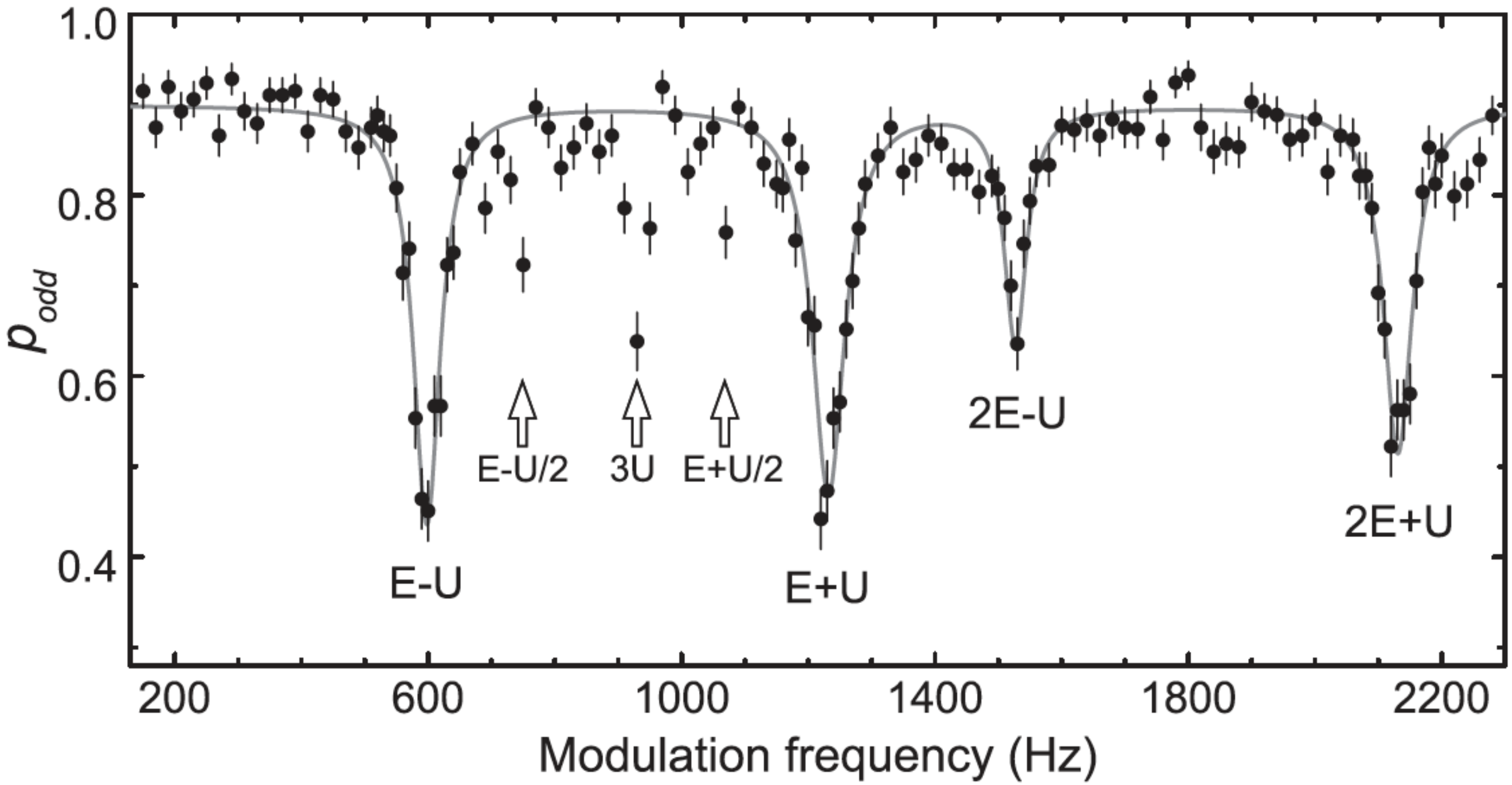


R. Ma *et al.* PRL 107, **095301** (2011)

Photon-assisted Tunneling

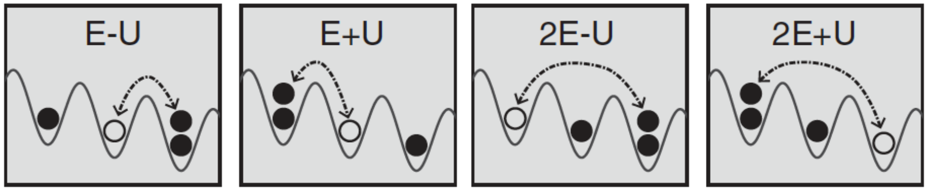


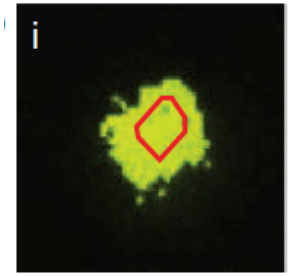


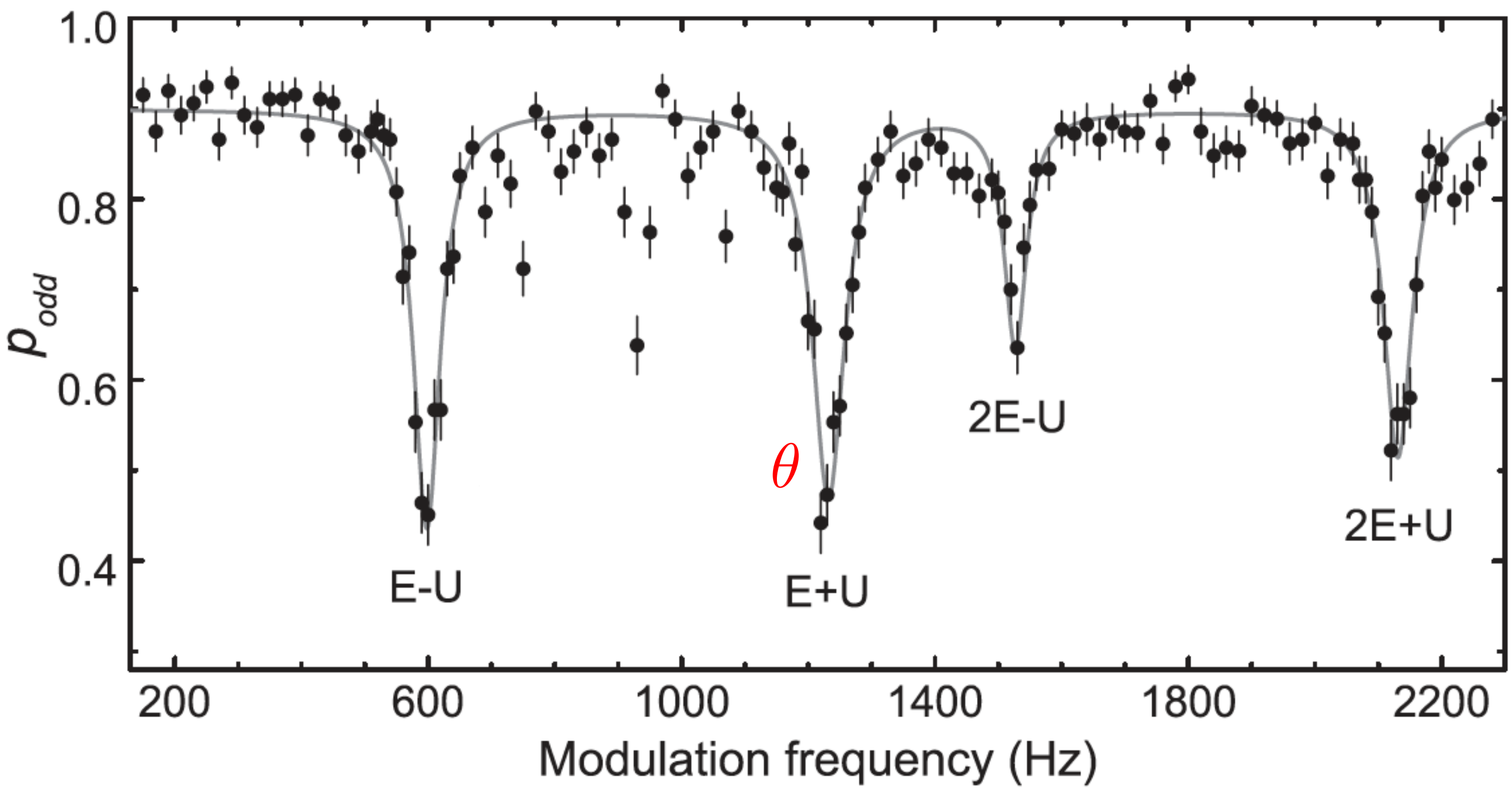


R. Ma *et al.* PRL 107, **095301** (2011)

Photon-assisted tunneling





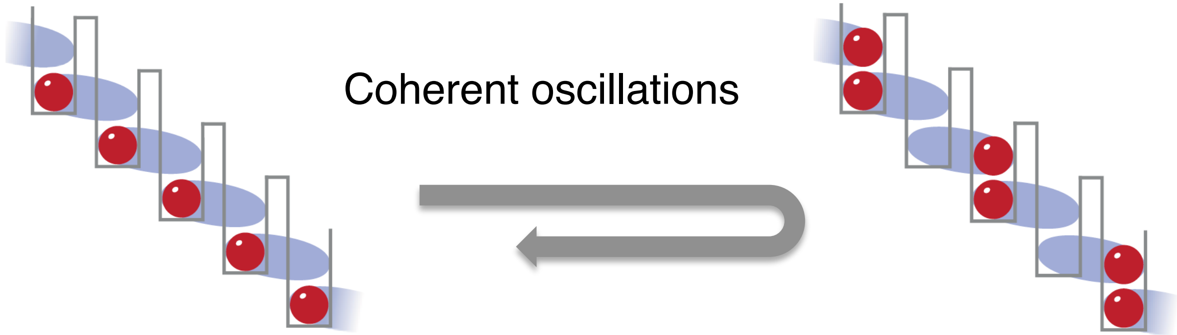


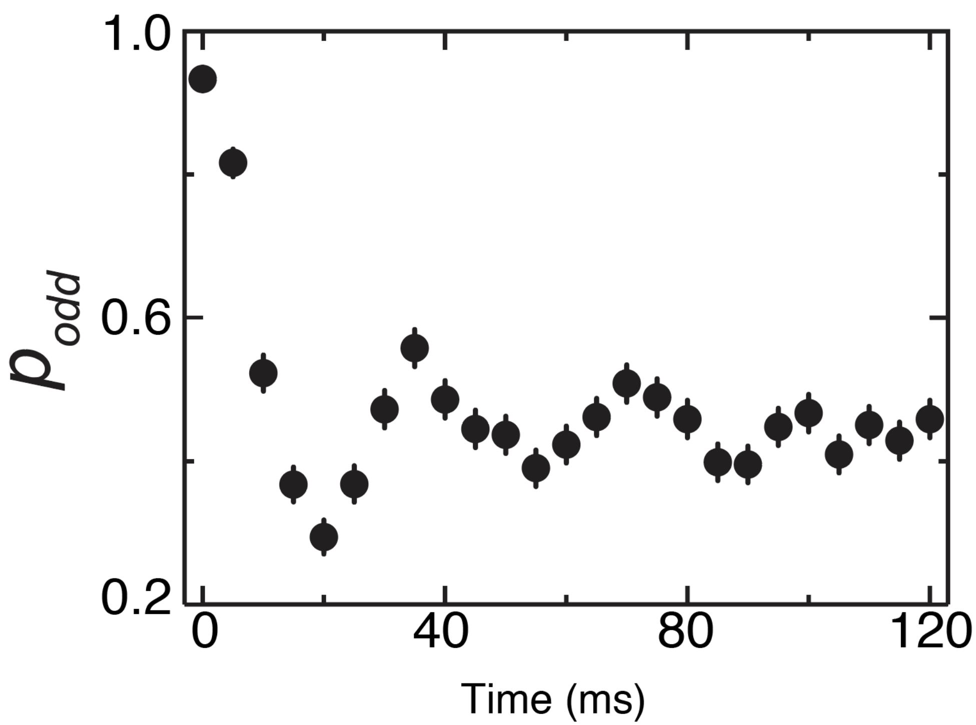
R. Ma *et al.* PRL 107, **095301** (2011)

Photon-assisted many-body dynamics

Prepare
$E > U$

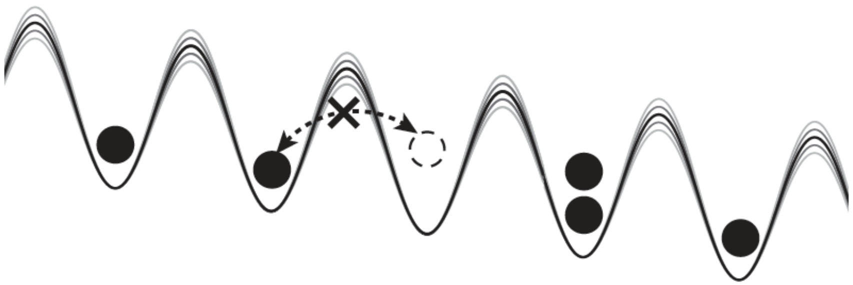
Drive
$\hbar\omega_{\mathrm{mod}} = E - U$

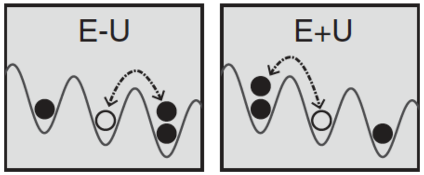


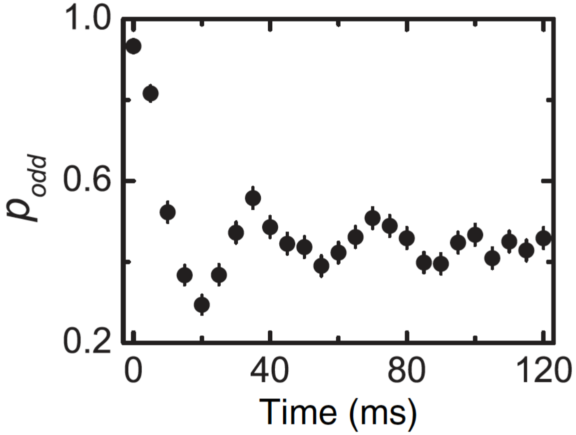


Photon-assisted tunneling

Summary







- Suppression of free tunneling
- Selective assisted tunneling
- Coherent many-body dynamics
- Combine for multi-chromatic drive

All ingredients demonstrated

Outline

Simulation of Anyons with one-dimensional Bosons

I. Engineering occupation-dependent tunneling

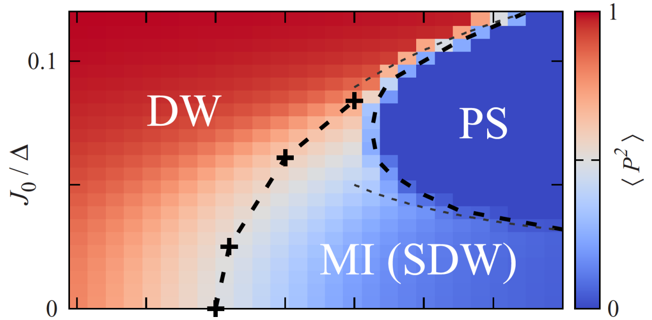
Lattice modulation in Mott insulators

II. Identify a suitable experimental setting

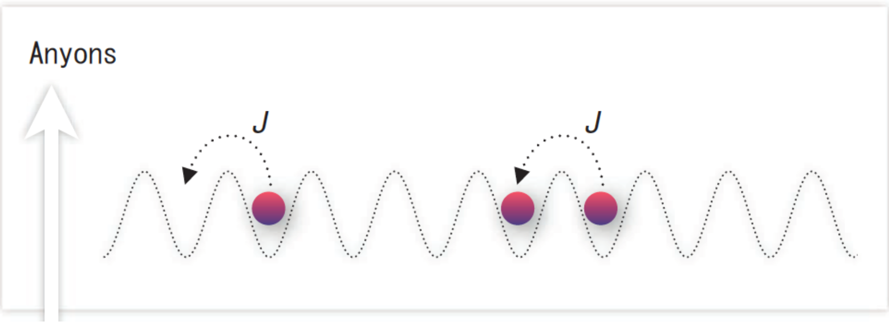
Quantum walks of two bosons

Experimental settings

Picking the right scenario

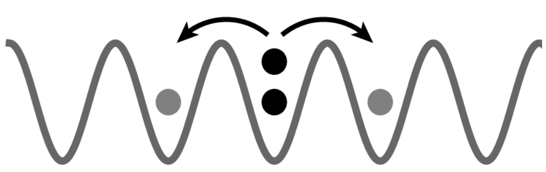


L. Cardarelli *et al.*, PRA **94**, 023615 (2016)



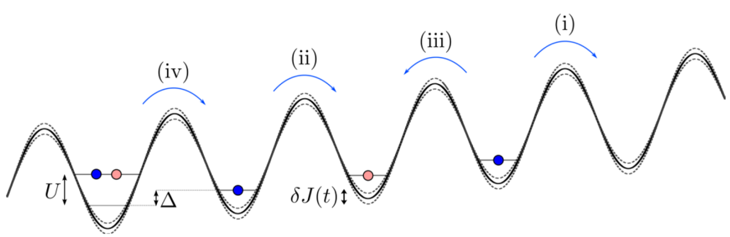
Keilmann *et al.*, Nature Communications **2**, 361(2011)

Focus on few-body dynamics



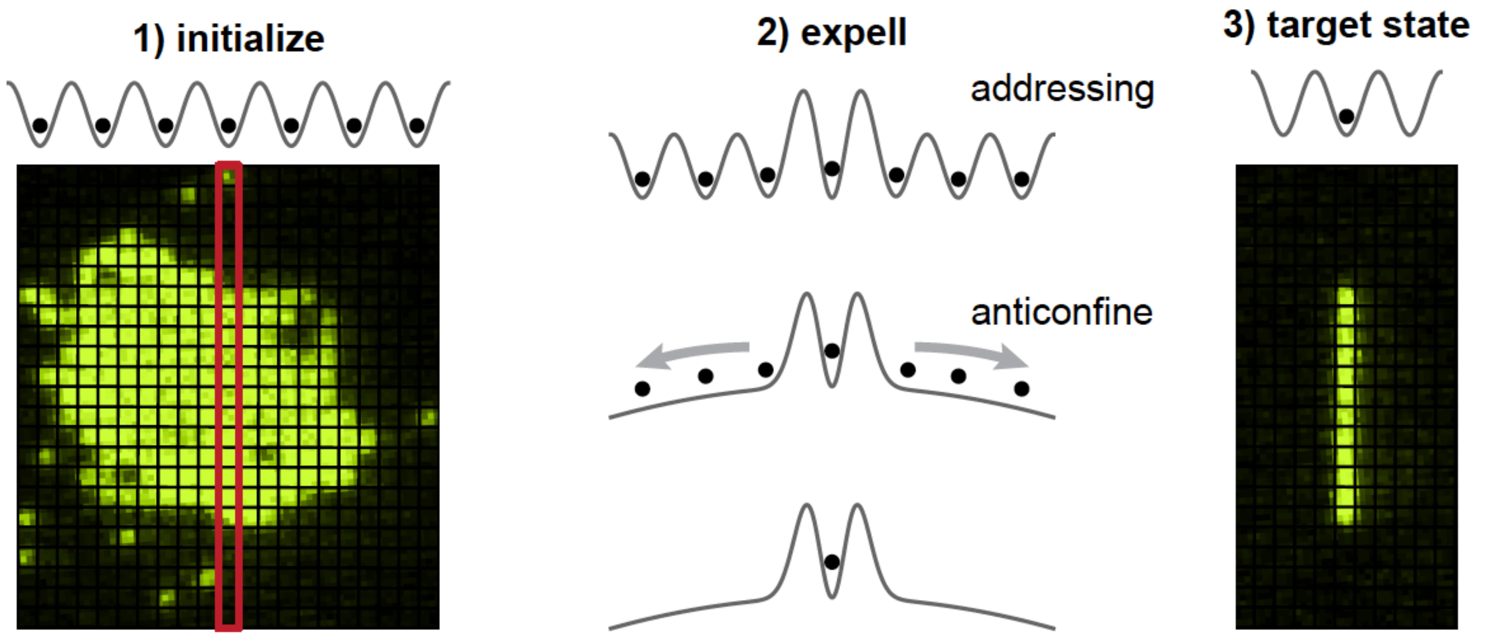
Experiment

+



Numerics

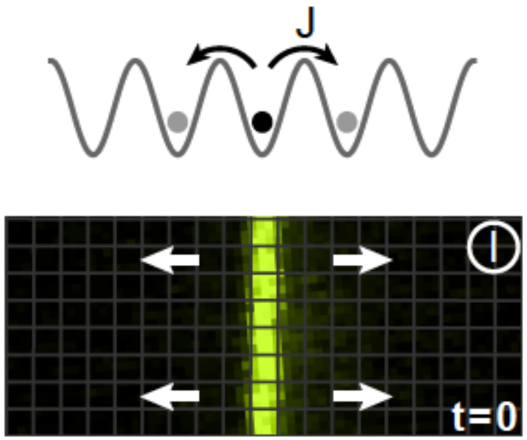
Control over individual Bosons



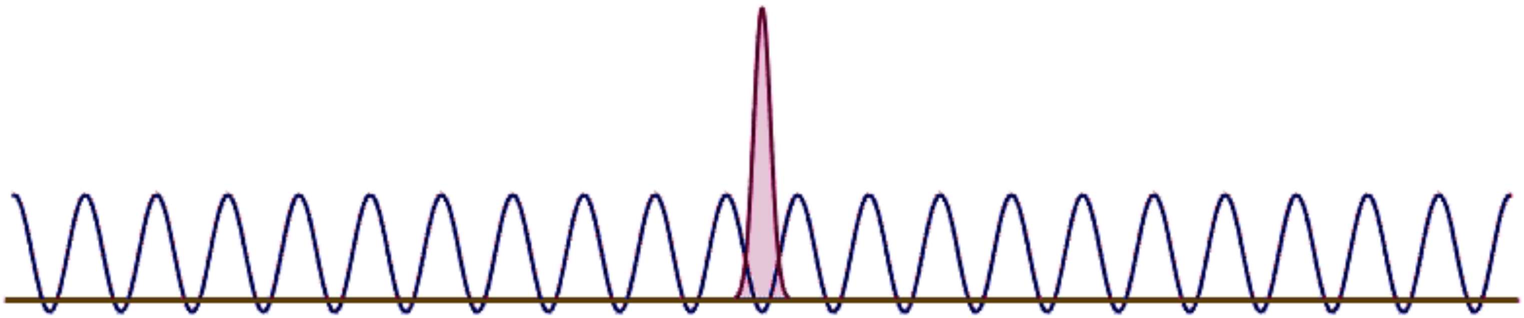
Single-Particle Quantum Walk

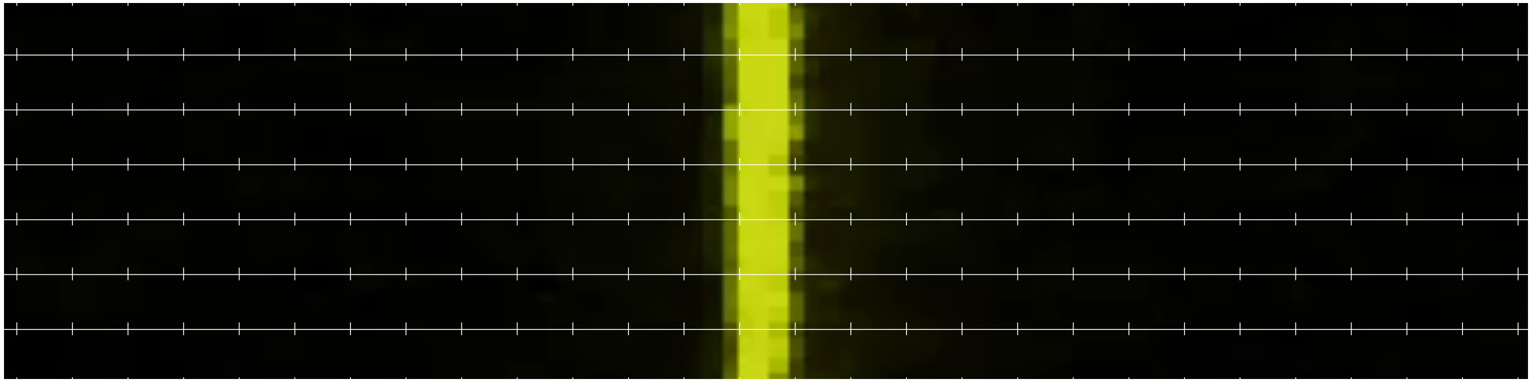
Free quantum walks of individual particles

Single realization



Single-Particle Quantum Walk

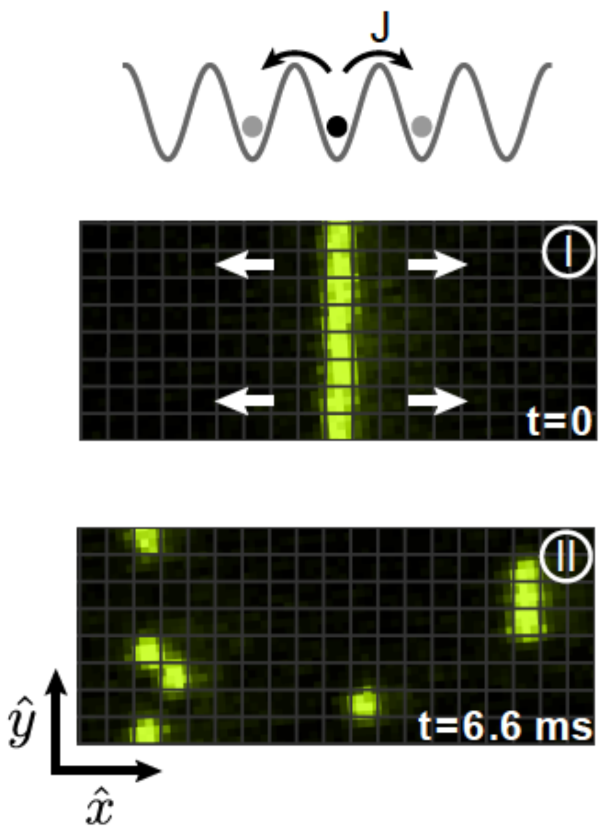




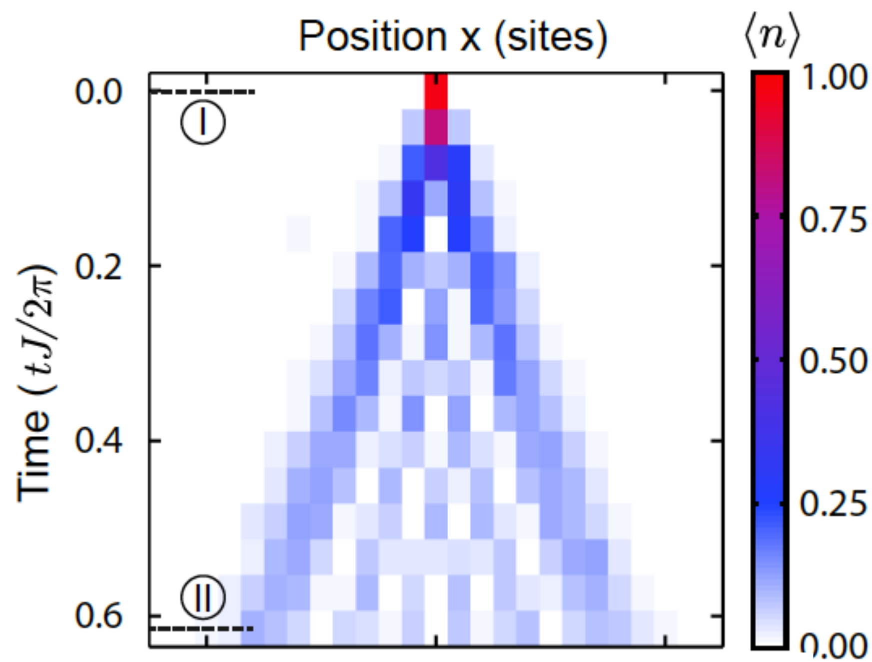
Single-Particle Quantum Walk

Free quantum walks of individual particles

Single realization

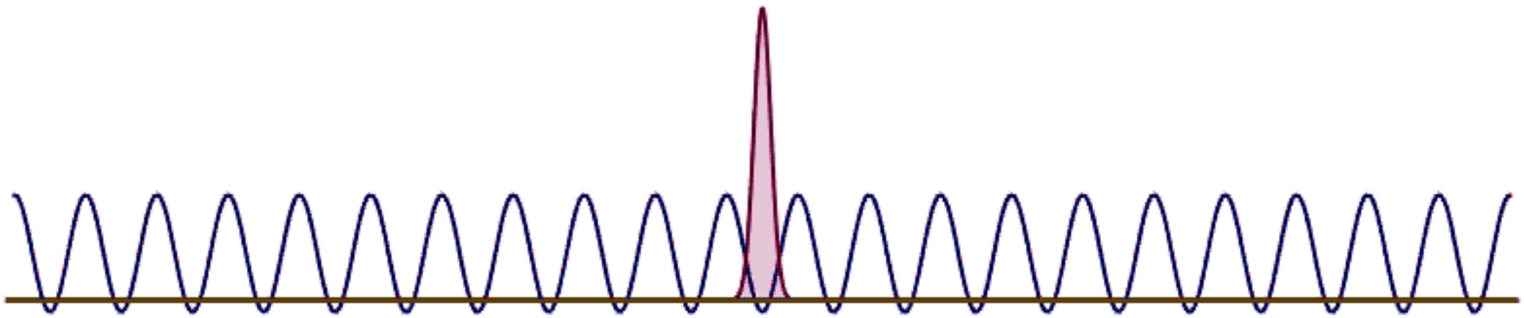


Average density evolution

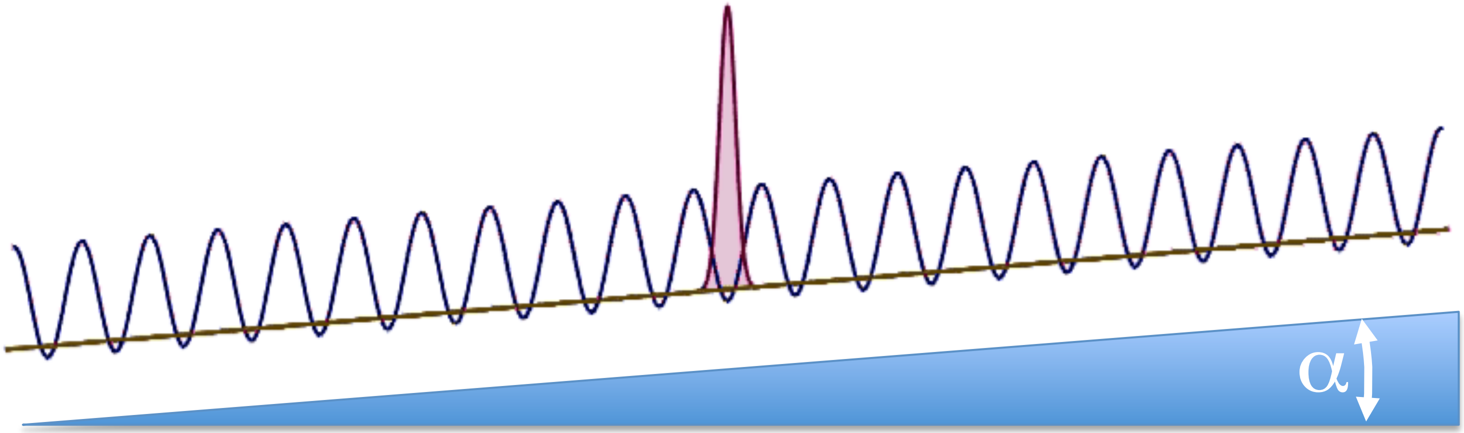


P. M. Preiss *et al.*, Science **347** 1229 (2015)

How do we know it is really quantum motion?

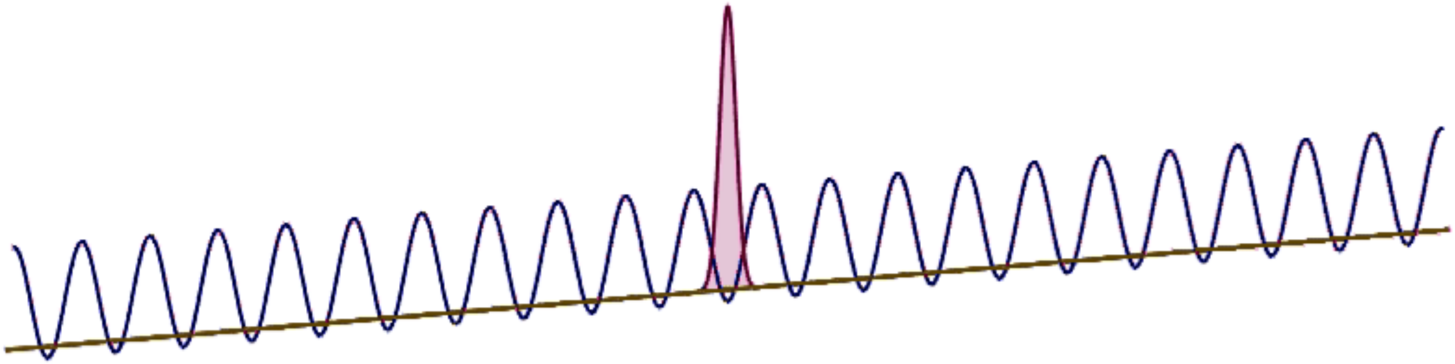


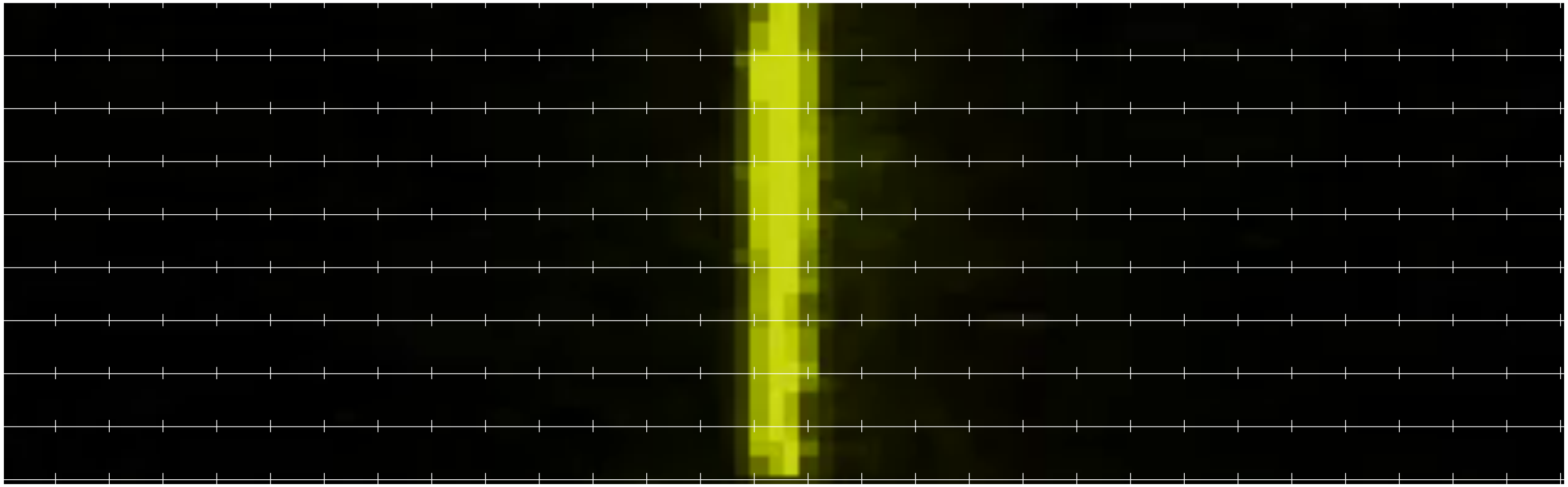
Tilt: Bloch Oscillations



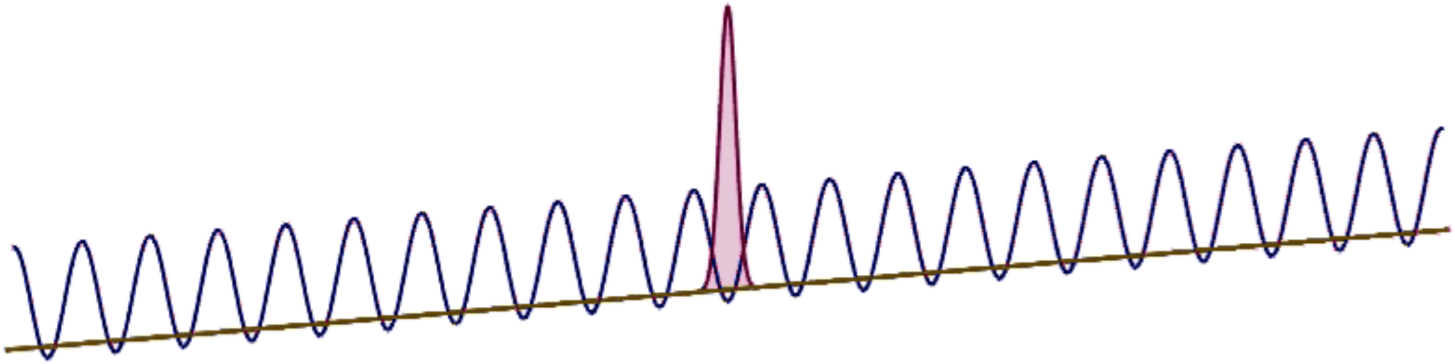
Refocusing of matter wave:
absolutely impossible for classical motion

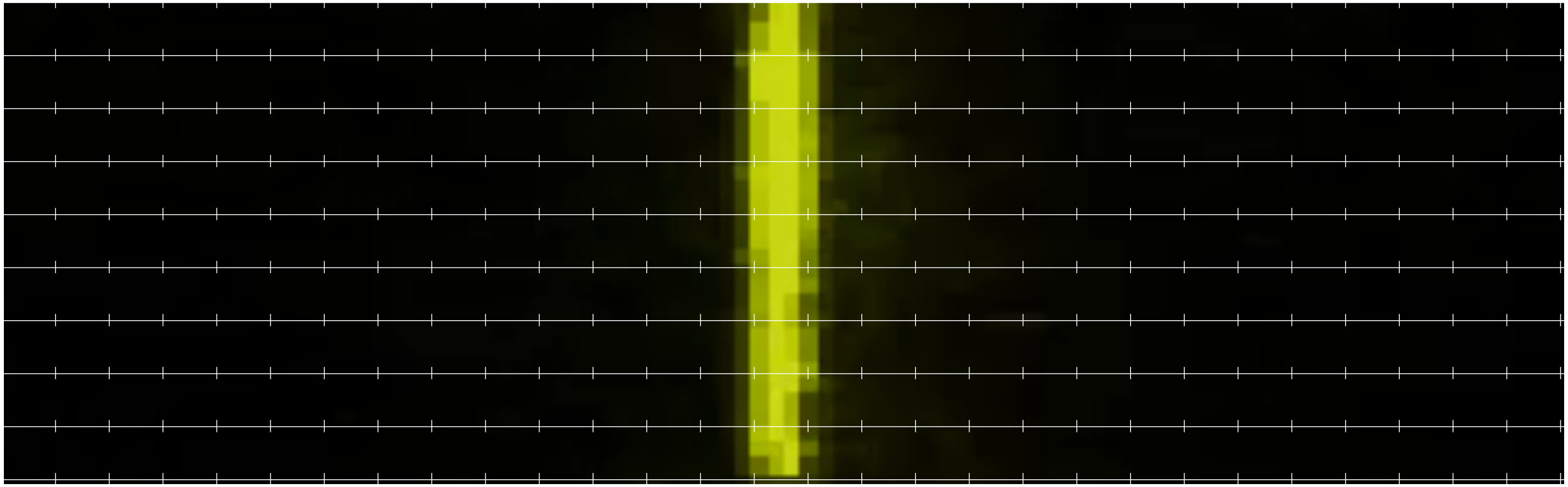
Single-Particle Bloch Oscillations



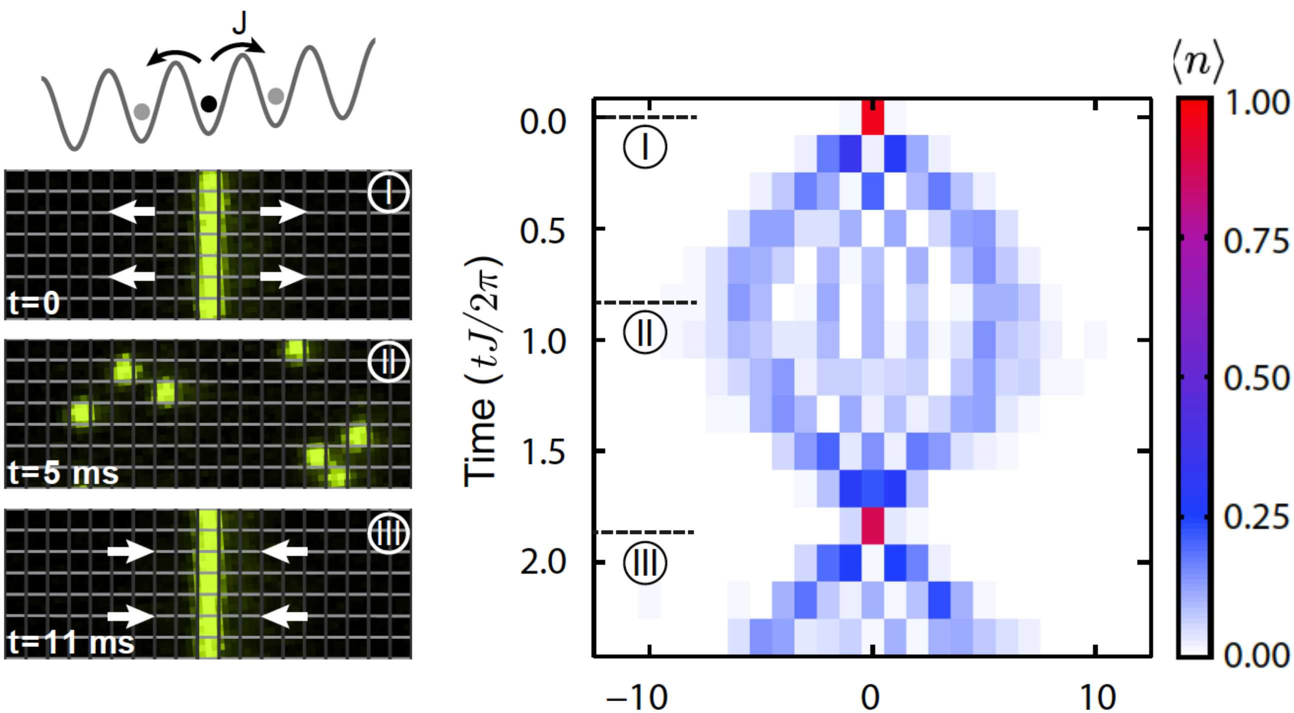


Single-Particle Bloch Oscillations





Single-Particle Bloch Oscillations



- Temporal period $T_B = \frac{2\pi}{F}$, spatial width $L_B = \frac{4J}{F}$
- Delocalized over ~14 sites = 10µm.
- Revival probability 96(3)%

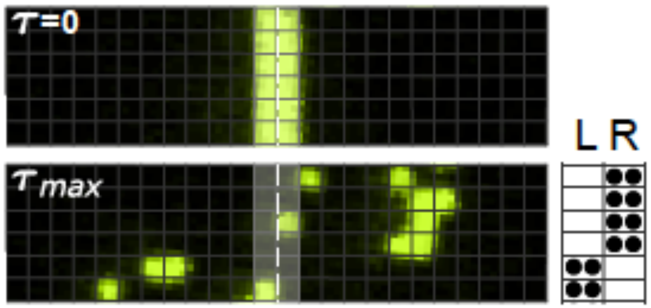
See also: E. Haller *et al.*, PRL**104**, 200403 (2010)
M. Genske *et al.*, PRL **110**, 190601 (2013)

Hanbury Brown-Twiss Interference

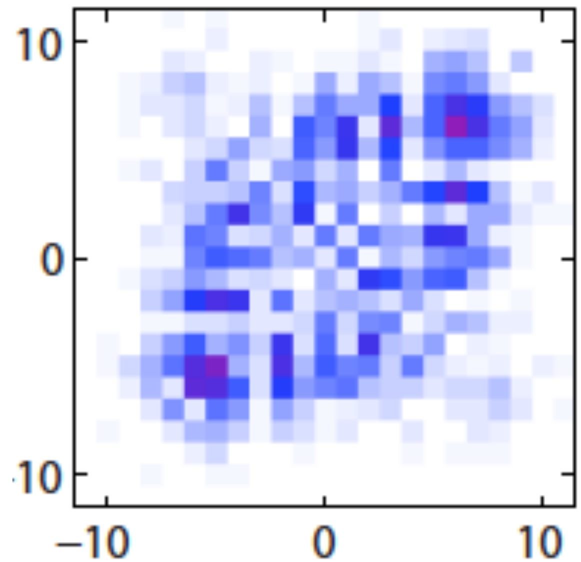
Bunching of non-interacting bosons

$$U \ll J$$

Single realization



Histogram of many runs



$$\Gamma_{i,j} = \langle a_i^\dagger a_j^\dagger a_j a_i \rangle$$

Very strong signature of bosonic statistics

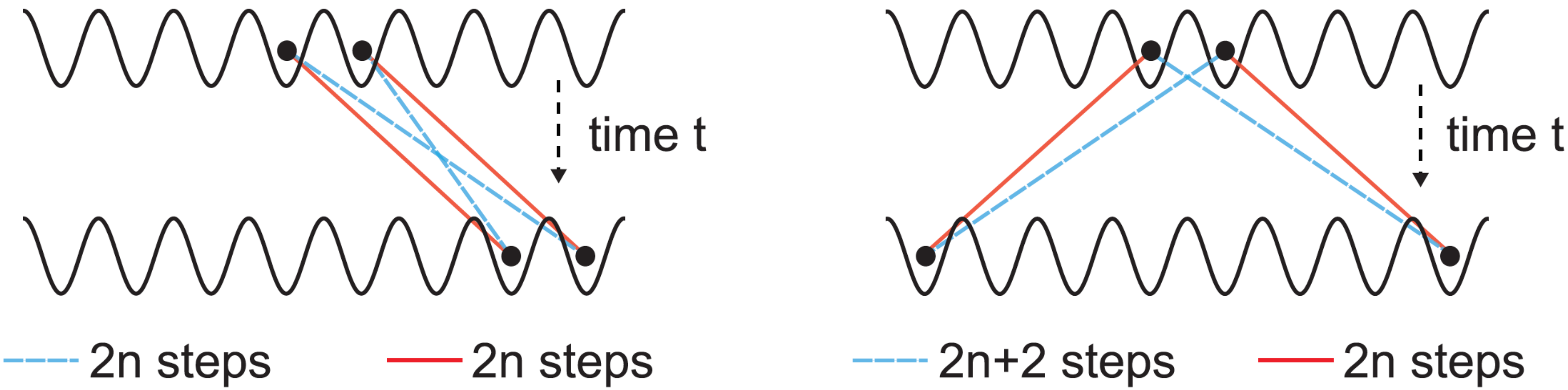
Sensitivity to quantum statistics

Time evolution of two free bosons

$$H_{free} = -J \sum_{\langle i,j \rangle} (a_i^\dagger a_j + \text{h.c.})$$

$$|\Psi(t)\rangle = e^{-\frac{it}{\hbar}H}|\Psi(0)\rangle = 1 + (-\frac{it}{\hbar}H) + \frac{1}{2}(-\frac{it}{\hbar}H)^2 + \dots$$

Each tunneling step = phase i

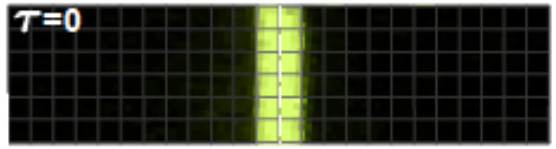


Correlation properties from microscopic tunneling phases

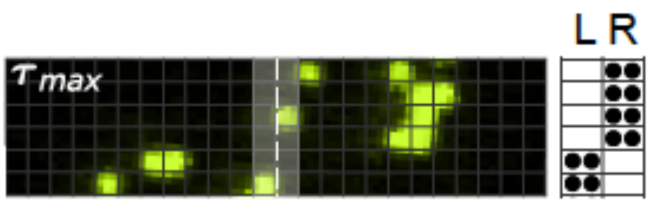
Fermionization of Bosons

Bosons with strong repulsive interactions

Weak interactions u<1



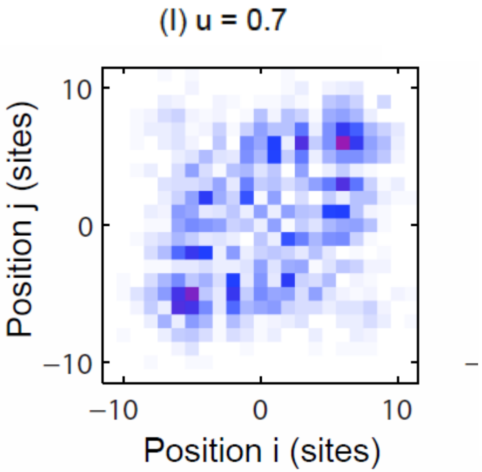
Strong interactions u>>1

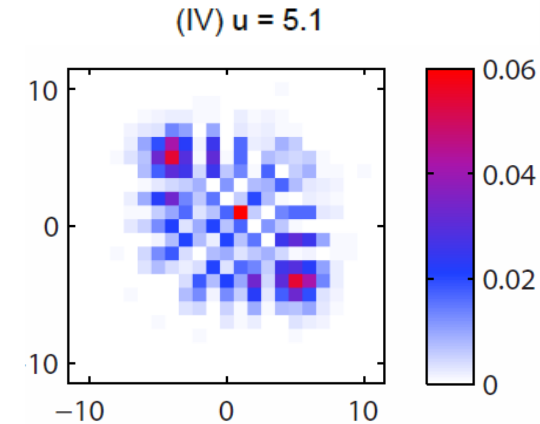


In 1D, hard-core bosons ⟺ free spinless fermions

Experiments on Tonks-Girardeau gas: Weiss group, Bloch group

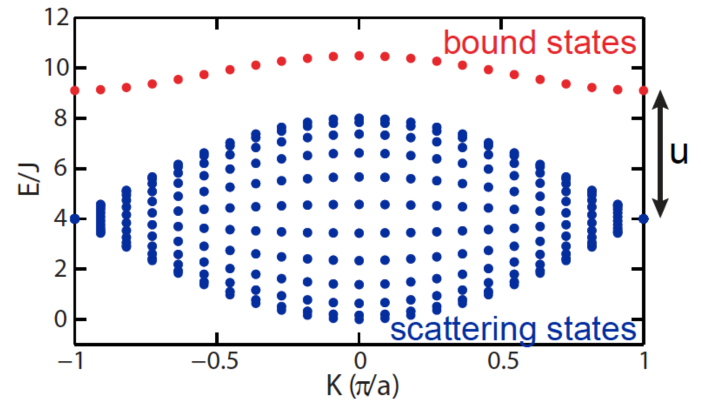
T. Kinoshita *et al.*, Science **305** (2004), B. Paredes *et al.*, Nature **429** (2004)

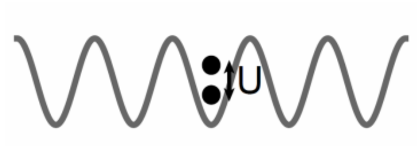




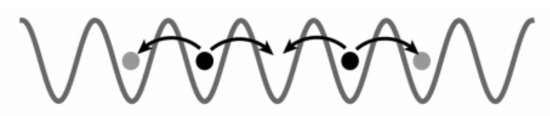
Proposal: Y. Lahini *et al.*, PRA **86** 011603 (2012)

Repulsively Bound Pairs



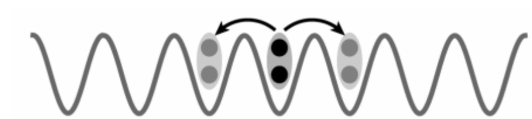


Weak interaction

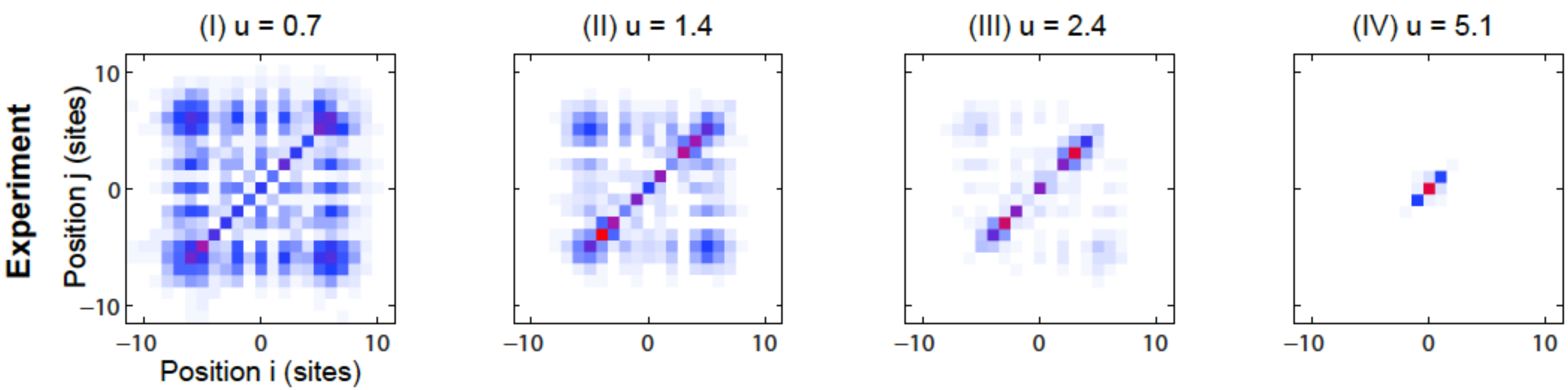


- No HBT interference terms
- Independent quantum walk

Strong interaction

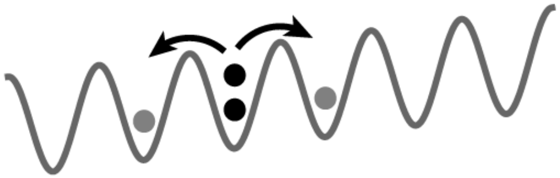


- Pairs bound by repulsive interaction
- Quantum walk of the pair $J_{eff} = \frac{2J^2}{U}$

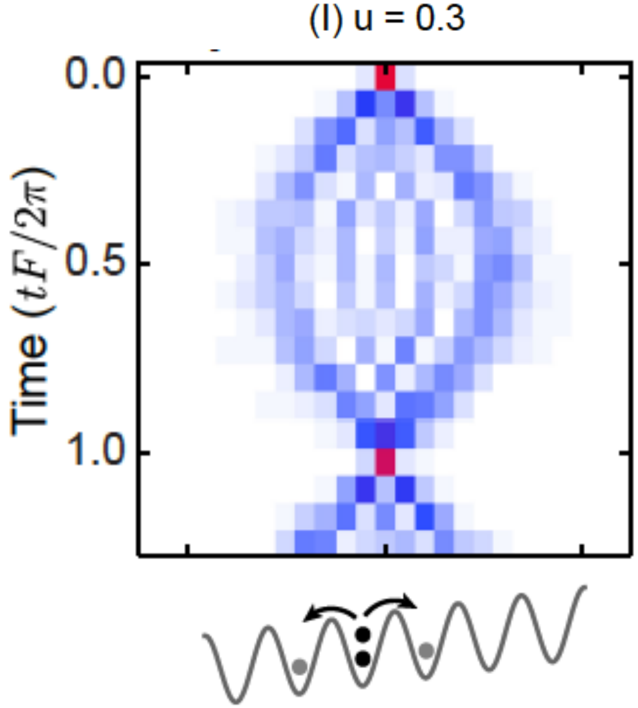


See also: K.Winkler *et al*., Nature **441** 853 (2006)
A. Ahlbrecht *et al*., New J. Phys. **14**, 073050 (2012)

Bloch Oscillations of Two Bosons



Weak interaction



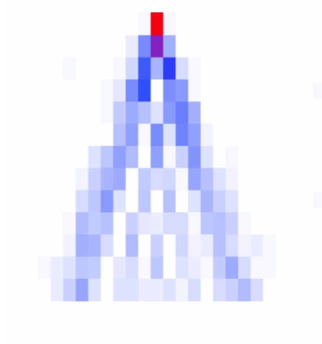
- Independent oscillations
- Clean revival

See also: R. Khomeriki *et al.*, PRA **81** 065601 (2010), G. Corrielli *et al*., Nature Comm. **4**1556 (2013)

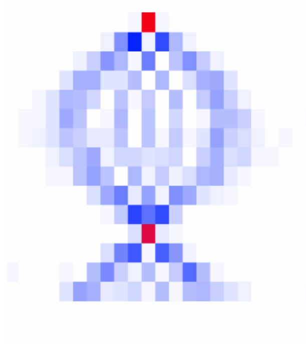
Summary

Quantum Walks

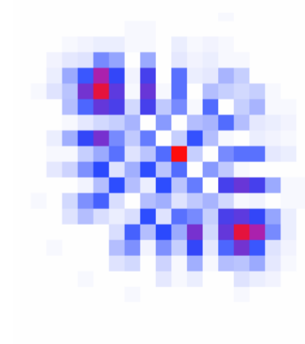
Quantum Walk



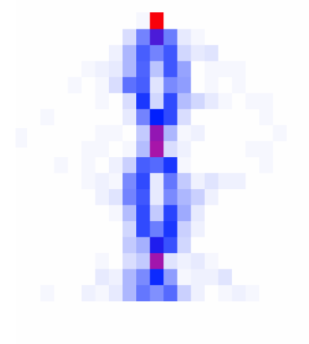
Bloch Oscillation



Fermionization

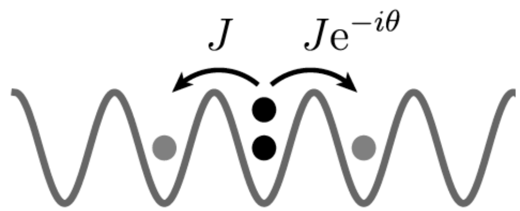


Bound Pairs



Coherent dynamics **Sensitivity to statistics** **Formation of bound state**

Numerical calculations



Strong overlap with other proposals:

L.Wang *et al.,* PRA 90, **063618** (2014)

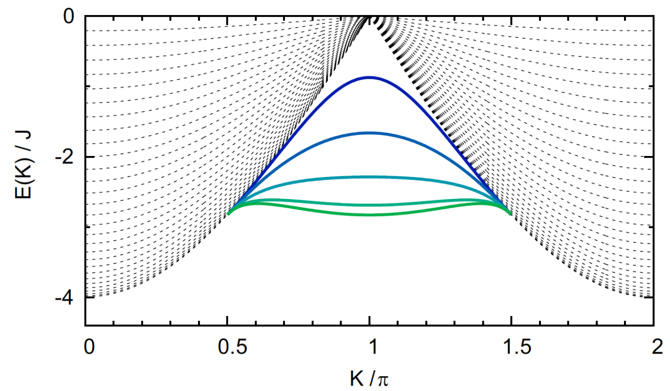
S. Greschner *et al.,* PRA 97, **053605** (2018)

L. Cardarelli *et al.,* PRA **94**, 023615 (2016)

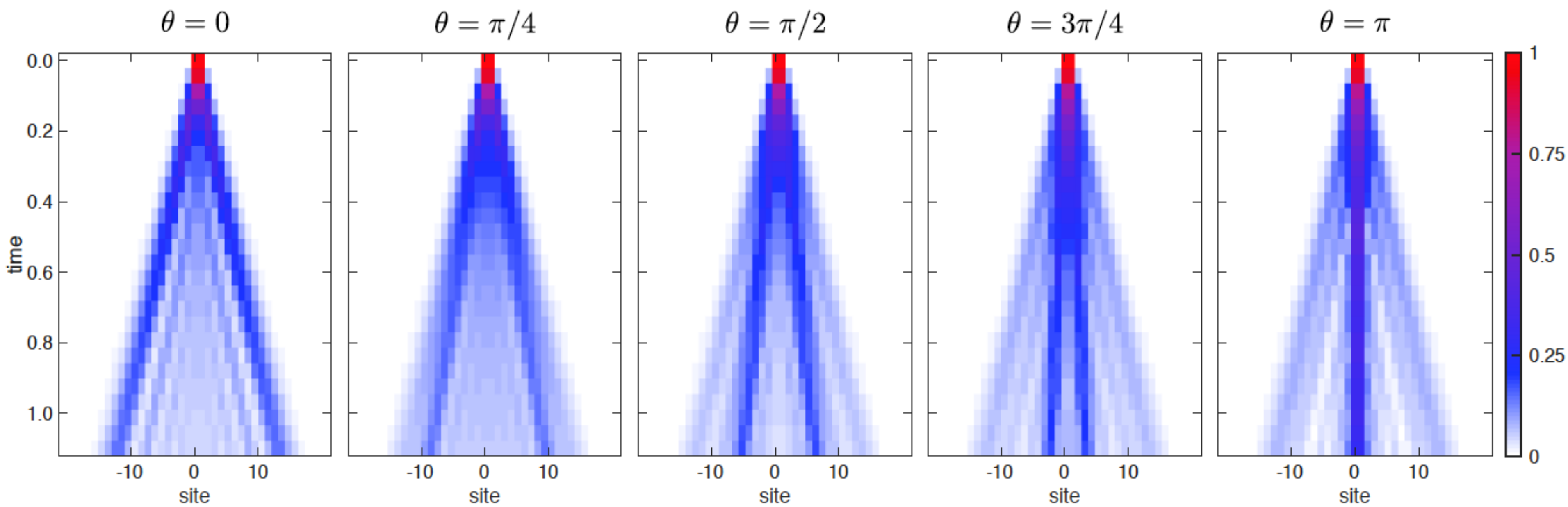
Bound state formation

Partially paired phase

S. Greschner *et al.*, PRA 97, **053605** (2018)



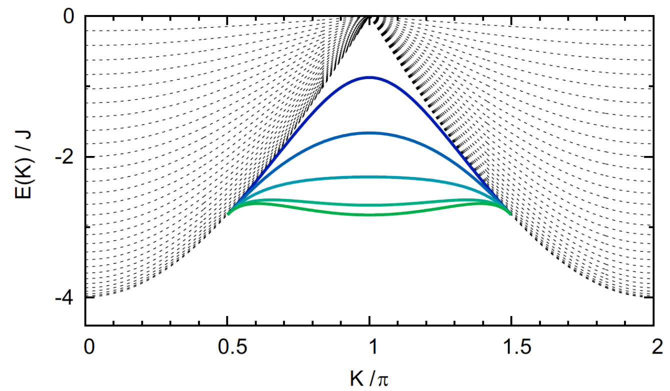
Bosons with photon-assisted tunneling U' = 0; E'=0



See also: Wang *et al.*, PRA 90, **063618** (2014)

Bound state formation

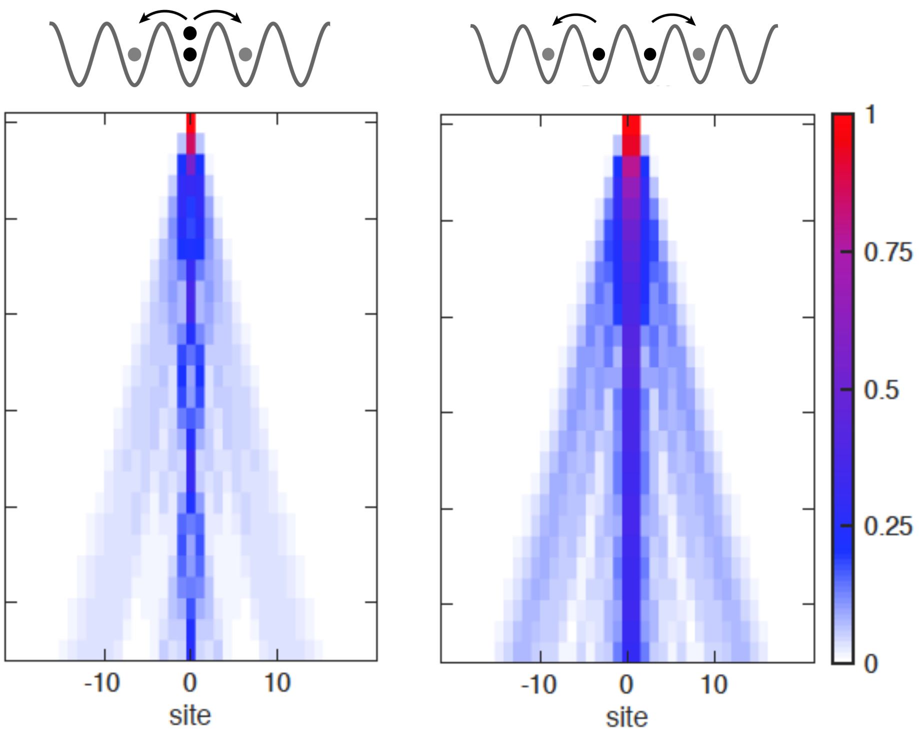
S. Greschner *et al.*, PRA 97, **053605** (2018)



Partially paired phase

Bosons with photon-assisted tunneling U' = 0; E'=0

$$\theta = \pi$$

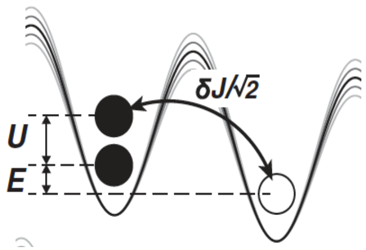


Mapping out the bound state with different initial placements

Quantum walk asymmety

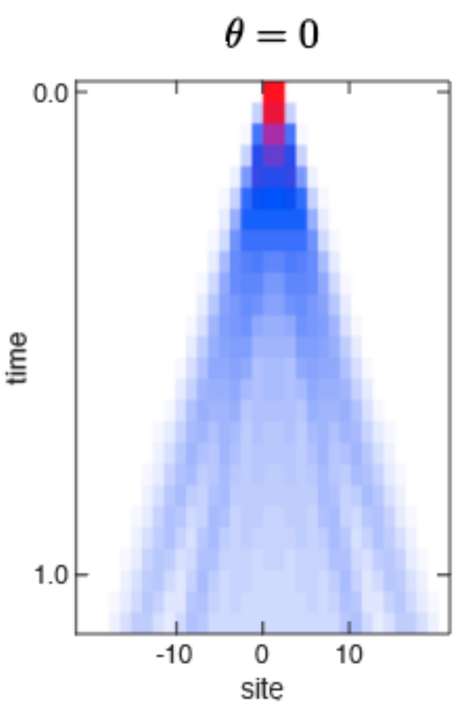
Re-introduce interactions

U’ = 2; δ=0



$$\hbar\omega_{\mathrm{mod}} = E + U + \tilde{u}$$

$$\hbar\omega_{\mathrm{mod}} = E - U - \tilde{u}$$

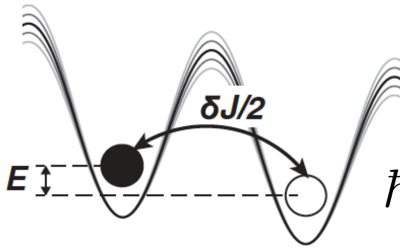


Interaction- and statistics-induced asymmetry

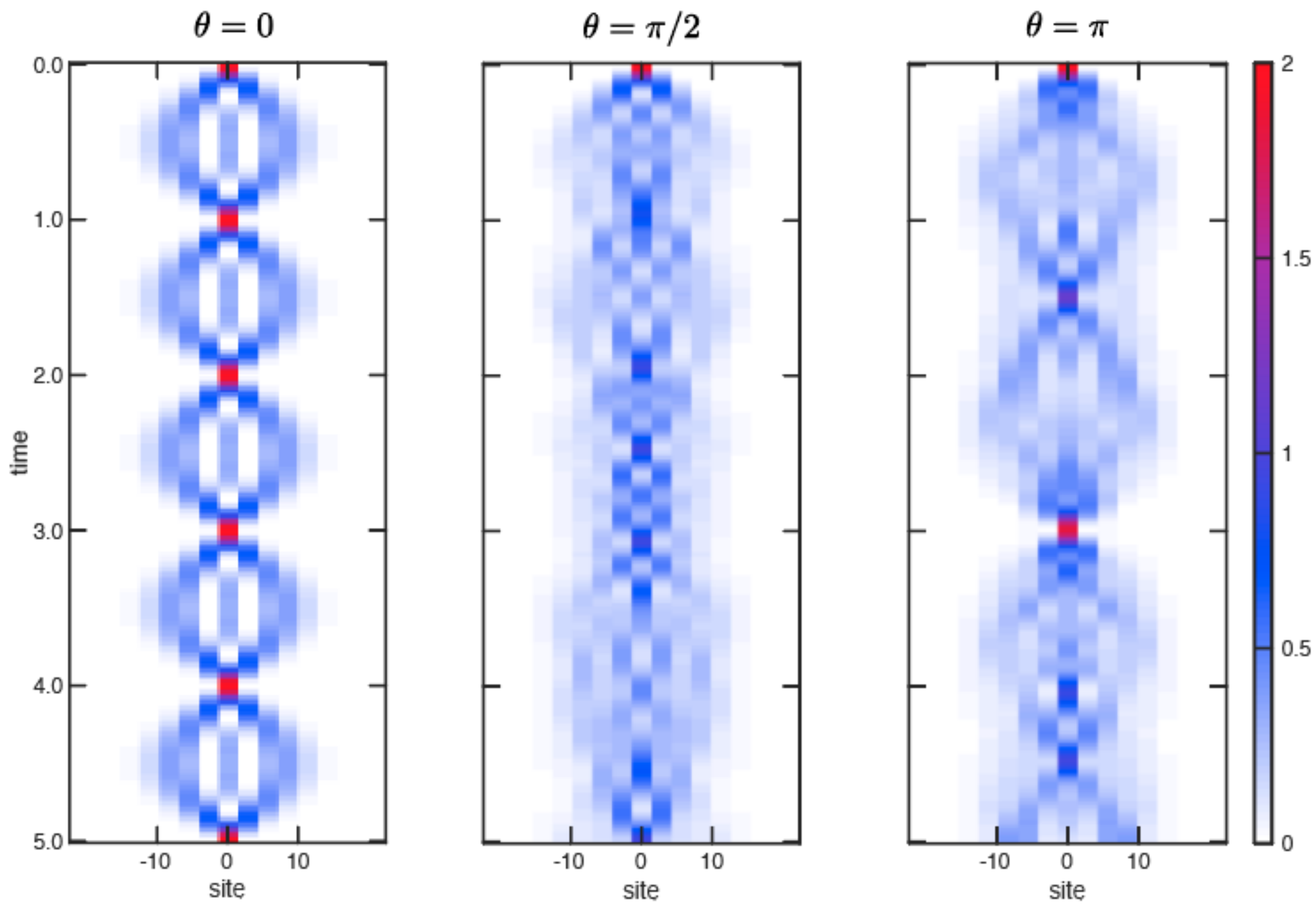
Bloch oscillations

Non-interacting walkers with gradient

U' = 0; δ=1



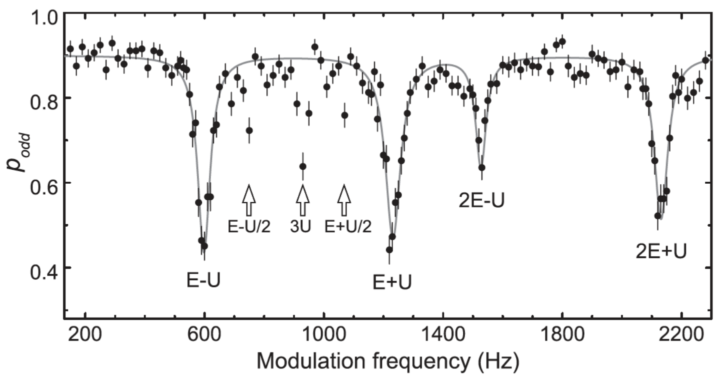
$$\hbar\omega_{\mathrm{mod}} = E - \delta$$

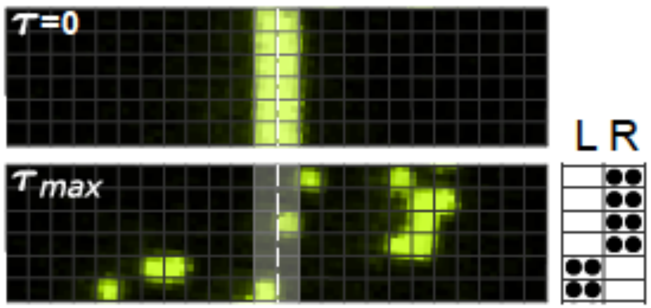


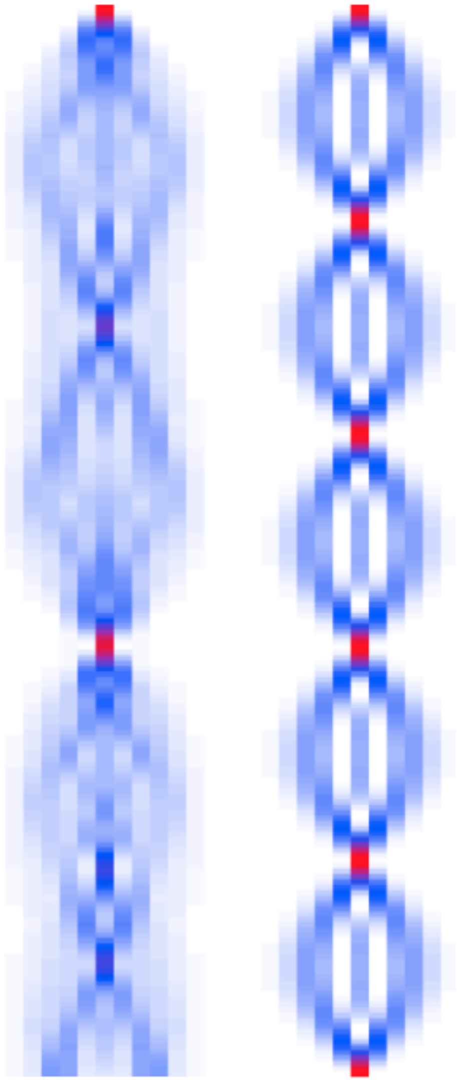
Destruction and frequency tripling of Bloch oscillations

Summary

Boson dynamics and engineered tunneling





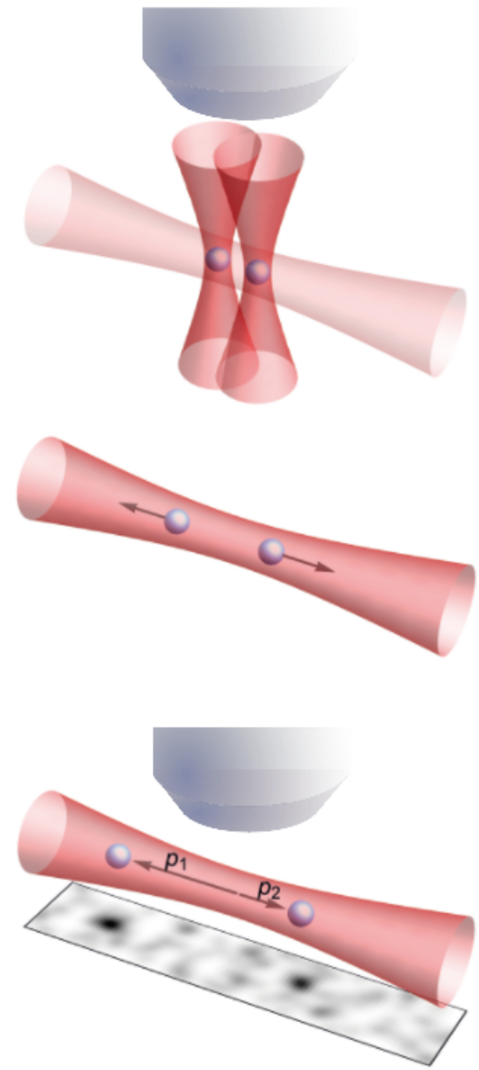


- Occupation-dependent tunneling demonstrated
- Fully controlled two-particle dynamics
- Signatures with available systems sizes & scales

Acknowledgements

Few-fermion systems in optical tweezers

Group of Selim Jochim @ Heidelberg University



Thank you for your attention!

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Center for Quantum Dynamics

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MARIE CURIE ACTIONS

Daimler und Benz Stiftung