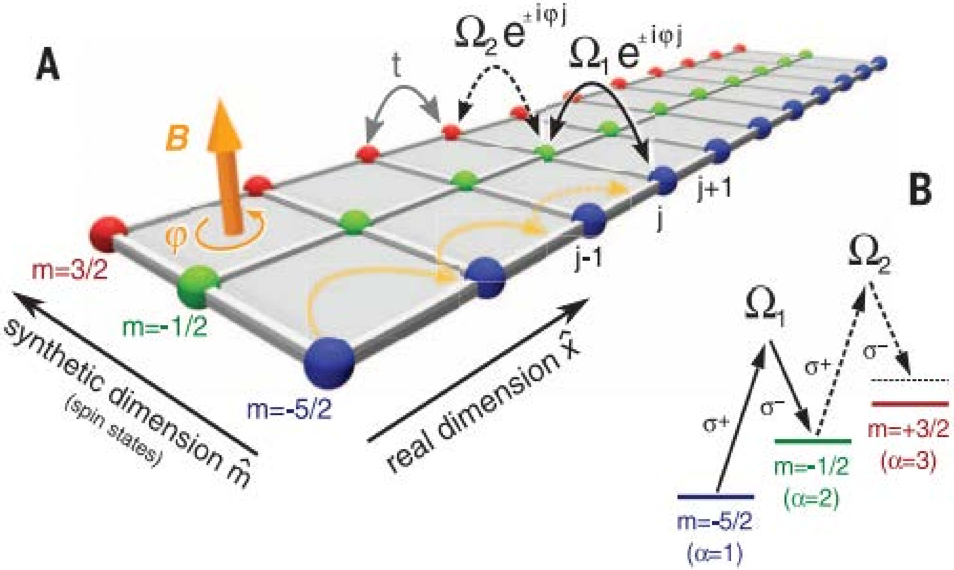
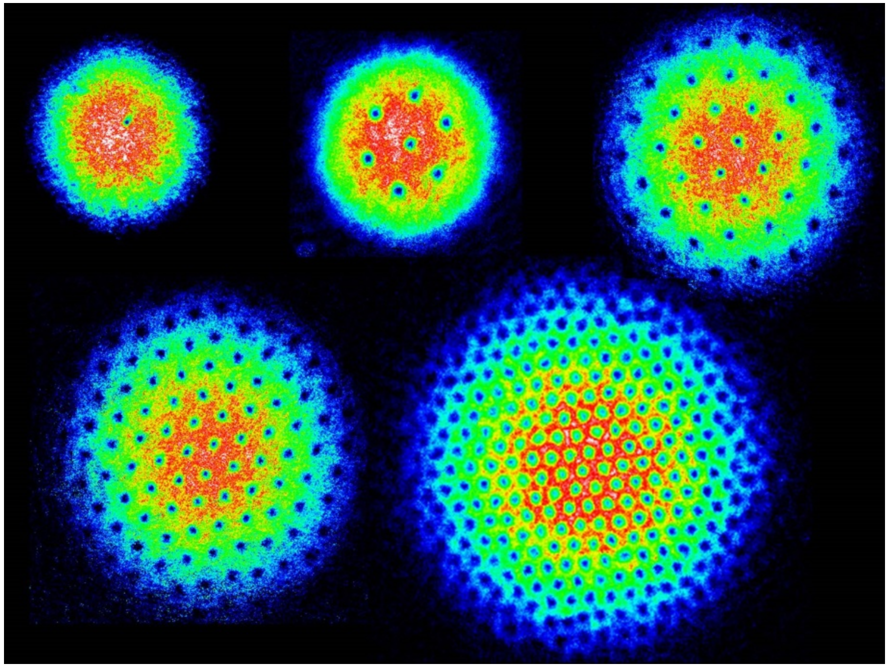
Artificial gauge fields for ultracold atoms

- Rotating gases
- Raman-induced gauge fields
- Laser-assisted tunneling / shaking
- Synthetic lattices
- …

Fallani group, LENS



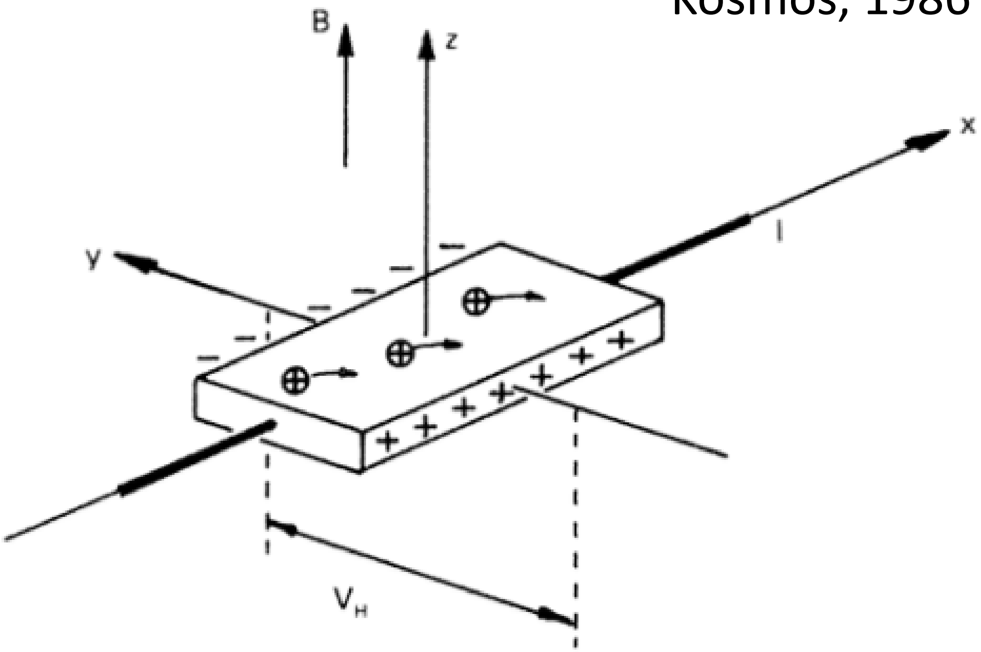


Cornell group, JILA

Artificial gauge fields for ultracold atoms

Some really interesting physics associated with charged particles coupled to electromagnetic gauge potentials

Kosmos, 1986



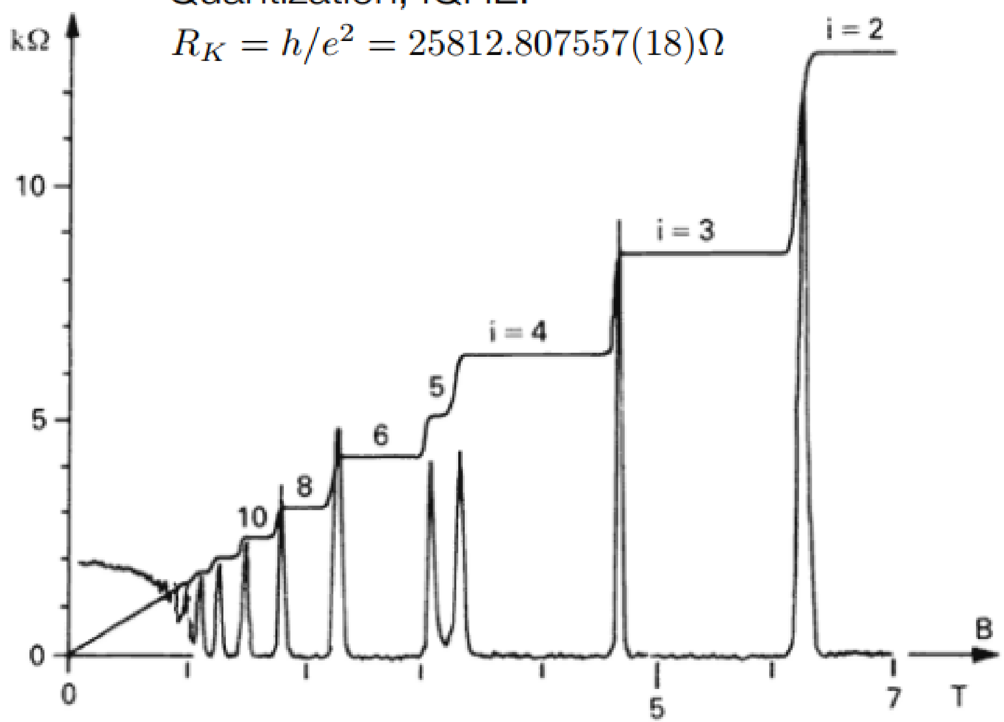
$$\vec{F} = q\left(\vec{E} + \vec{v} \times \vec{B}\right)$$

Artificial gauge fields for ultracold atoms

Some really interesting physics associated with charged particles coupled to electromagnetic gauge potentials

Quantization, IQHE:

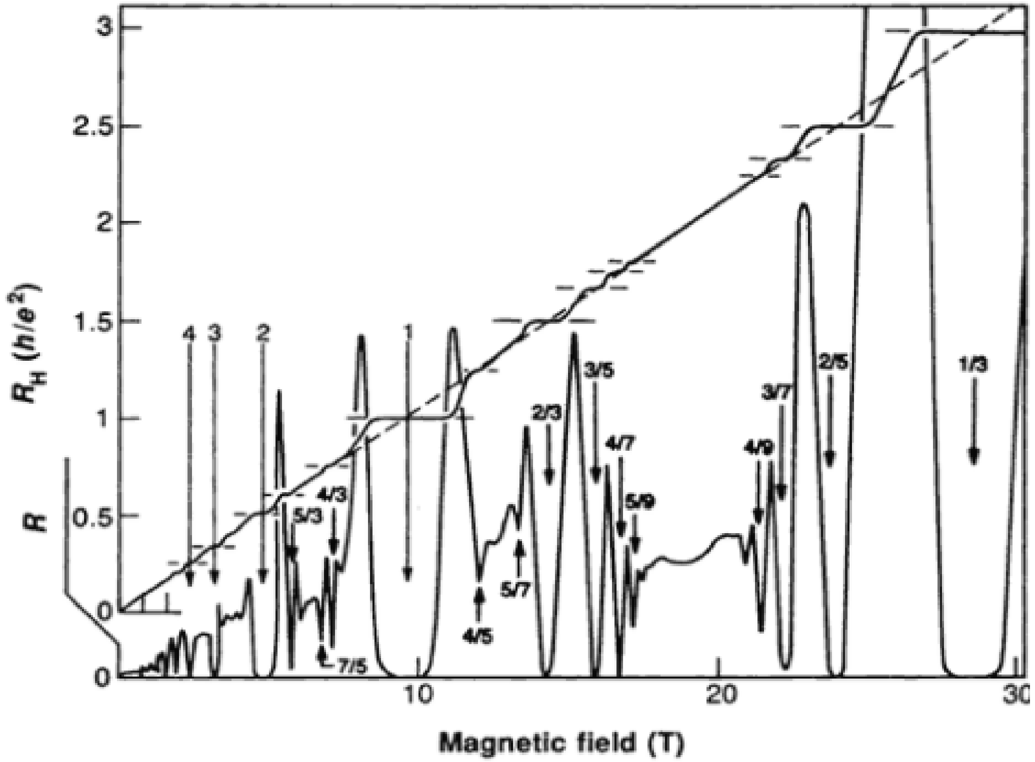
$R_K = h/e^2 = 25812.807557(18)\Omega$



von Klitzing

Artificial gauge fields for ultracold atoms

Some really interesting physics associated with charged particles coupled to electromagnetic gauge potentials



Tsui, Störmer, et al.

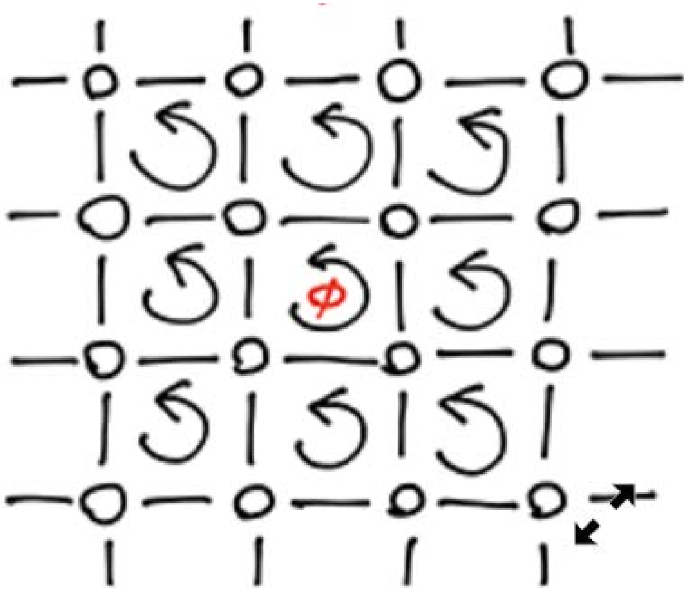
Emergent Topological Order

Frustration + Interactions = ???

Landau levels = high degeneracy

Goldman, Juzeliūnas, Öhberg, Spielman (2014)

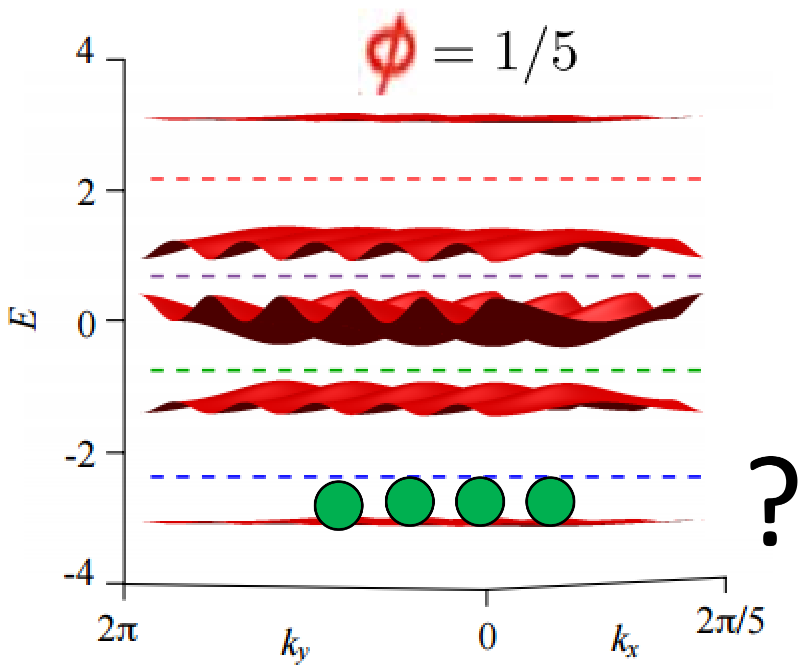
Flat energy bands in lattices



APS/Cheng Chin and Erich Mueller

Hofstadter model – charged particle in magnetic field

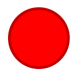
Energy spectrum



How do interacting particles arrange themselves?

Artificial gauge fields for ultracold atoms

Neutral atoms are neutral → no natural Lorentz force



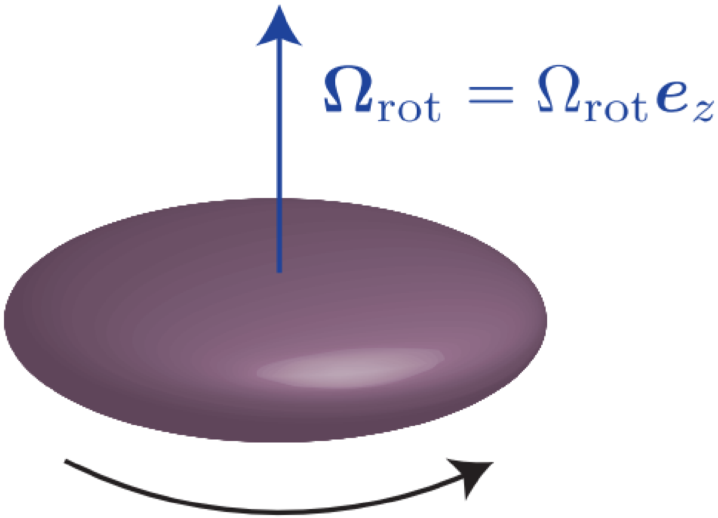
$q = 0$

$$\vec{F} = q\left(\vec{E} + \vec{v} \times \vec{B}\right) = 0$$

Need some tricks to engineer “effective” gauge fields

Rotating atomic gases

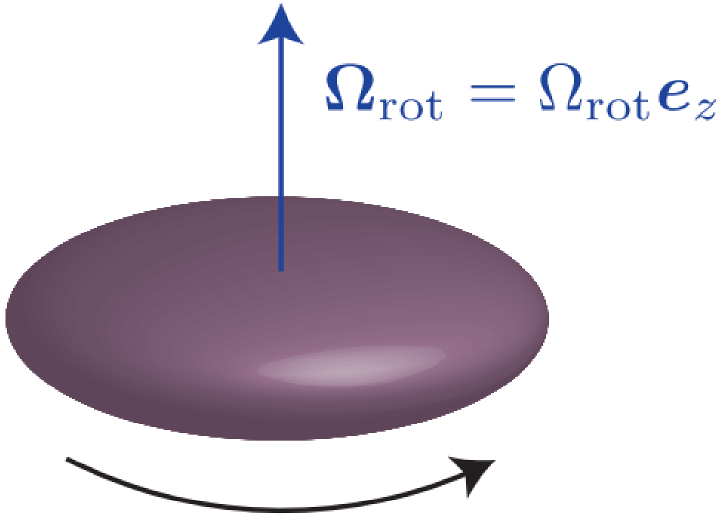
Uniform rotation can mimic a *B*-field



Goldman, Juzeliūnas, Öhberg, Spielman (2014)

Rotating atomic gases

Uniform rotation can mimic a *B*-field



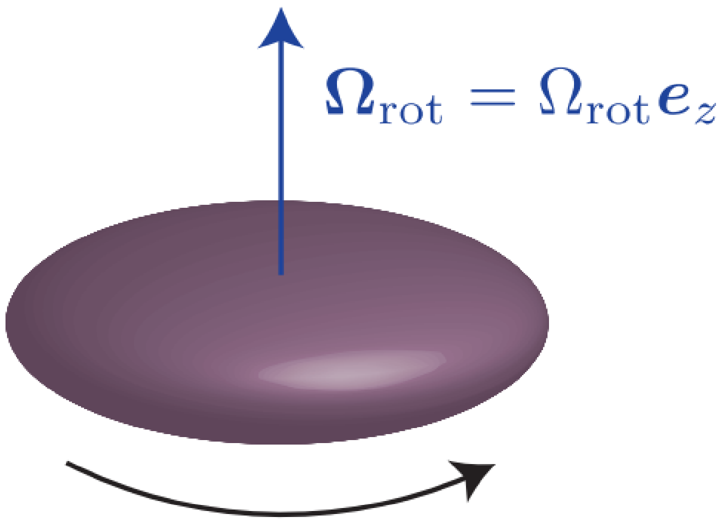
Goldman, Juzeliūnas, Öhberg, Spielman (2014)

$$\boldsymbol{\mathcal{A}} = m\boldsymbol{\Omega}_{\rm rot} \times \mathbf{r}$$

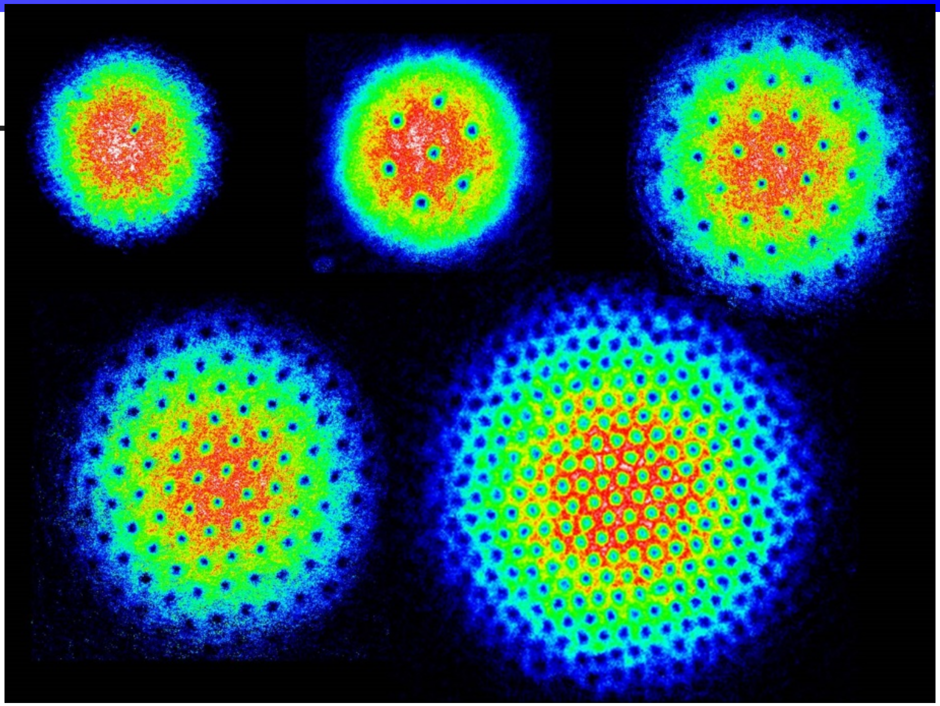
$$\boldsymbol{\mathcal{B}} = \boldsymbol{\nabla} \times \boldsymbol{\mathcal{A}} = 2m\Omega_{\rm rot}\mathbf{e}_z$$

Rotating atomic gases

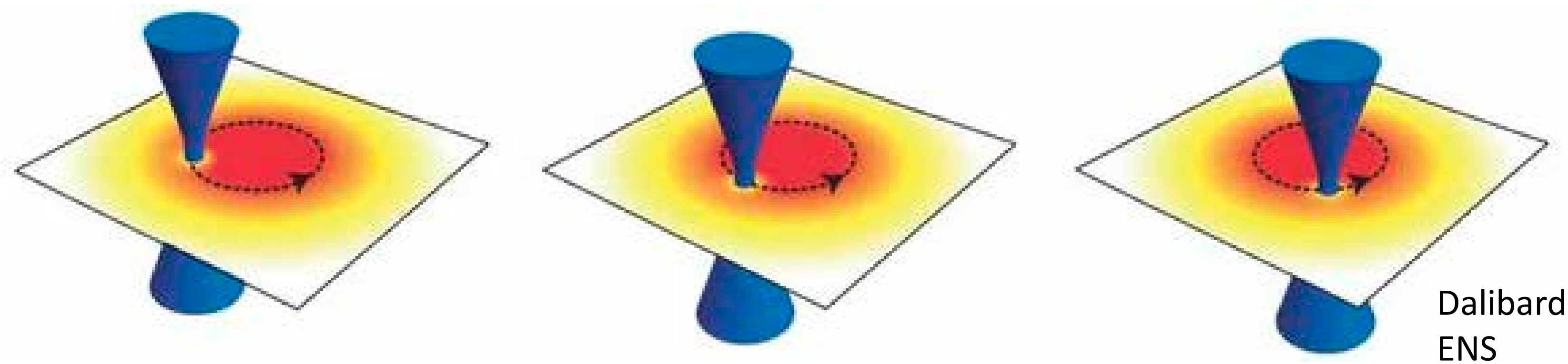
Uniform rotation can mimic



Goldman, Juzeliūnas, Öhberg, Spielman (2014)



Cornell group, JILA (also, Ketterle group, MIT & Dalibard group, ENS)



Dalibard group, ENS

Rotating atomic gases

THE DIRECT OBSERVATION OF INDIVIDUAL FLUX LINES IN TYPE II SUPERCONDUCTORS

U. ESSMANN and H. TRÄUBLE
Institut für Physik am Max-Planck-Institut für Metallforschung, Stuttgart and Institut für theoretische und angewandte Physik der Technischen Hochschule Stuttgart

Received 4 April 1967

Triangular flux line lattices have been observed by electron microscopy on Pb-4at% In and niobium specimens in the remanent state. These lattices contain various kinds of defects.

The Abrikosov solution [1] of the Ginsburg-Landau equations [2] for the mixed state of type II superconductors predicts a periodic arrangement of flux lines (flux line lattice) penetrating the specimen parallel to the applied field. Neutron diffraction studies [3,4] on niobium and nuclear magnetic resonance studies on vanadium [5] give evidence for the existence of a close packed arrangement of flux lines.

In this paper we present results on the flux line arrangement obtained by sirect observation of individual flux lines. As was shown in previous papers [6-8], the magnetic structures on the surfaces of ferromagnets and superconductors can be revealed with a resolution of about 500 Å or better by depositing small ferromagnetic particles on the specimen and observing the resulting patterns in the electron microscope by means of a replica technique.

We report here the magnetic structures of Pb-4at%In (κ = 1.35 at 1.1°K [8]) and niobium in the remanent state at 1.1°K based on observations on the end surfaces of well-annealed mono- or polycrystalline rods (4 mm diameter, 50 mm length) that had been magnetized parallel to the rod axis in a field of 3000 Oe. Parts of the surfaces exhibited a quite well defined triangular lattice of "points of exit" of the magnetic flux (fig. 1). In polycrystalline Pb-4at%In the lattice parameter (nearest neighbour separation) is a = 3500 Å. If each of the indivudual spots is as-

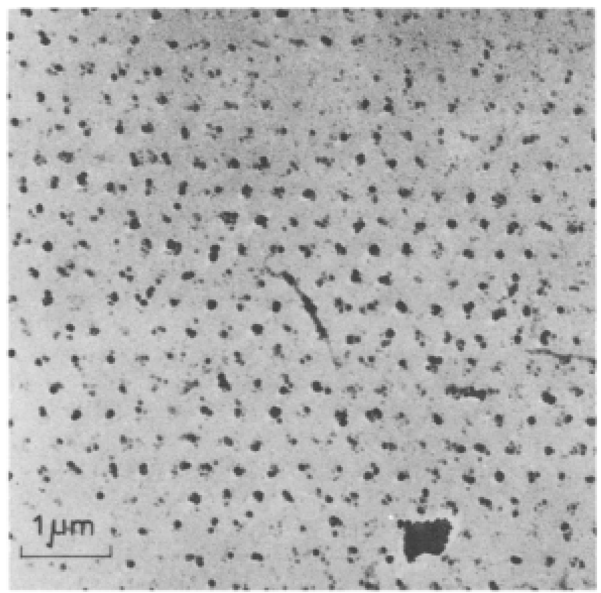
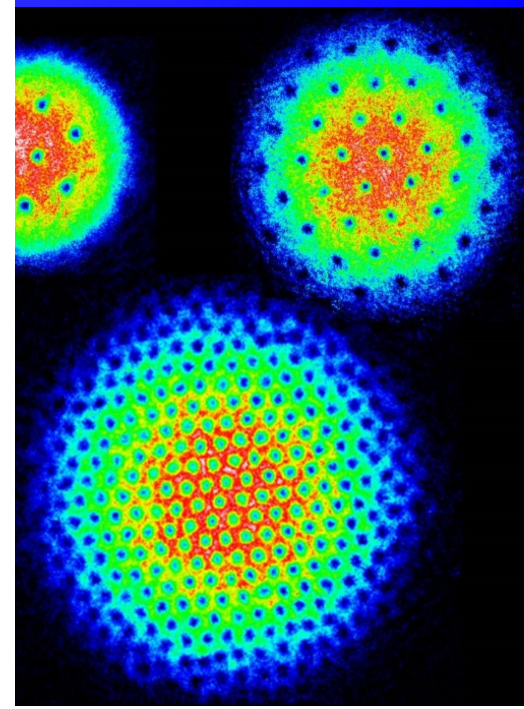
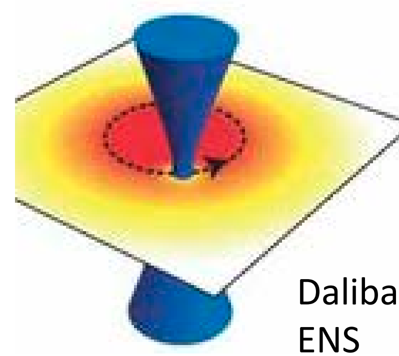


Fig. 1. "Perfect" triangular lattice of flux lines on the surface of a lead-4at%indium rod at 1.1°K. The black dots consist of small cobalt particles which have been stripped from the surface with a carbon replica.

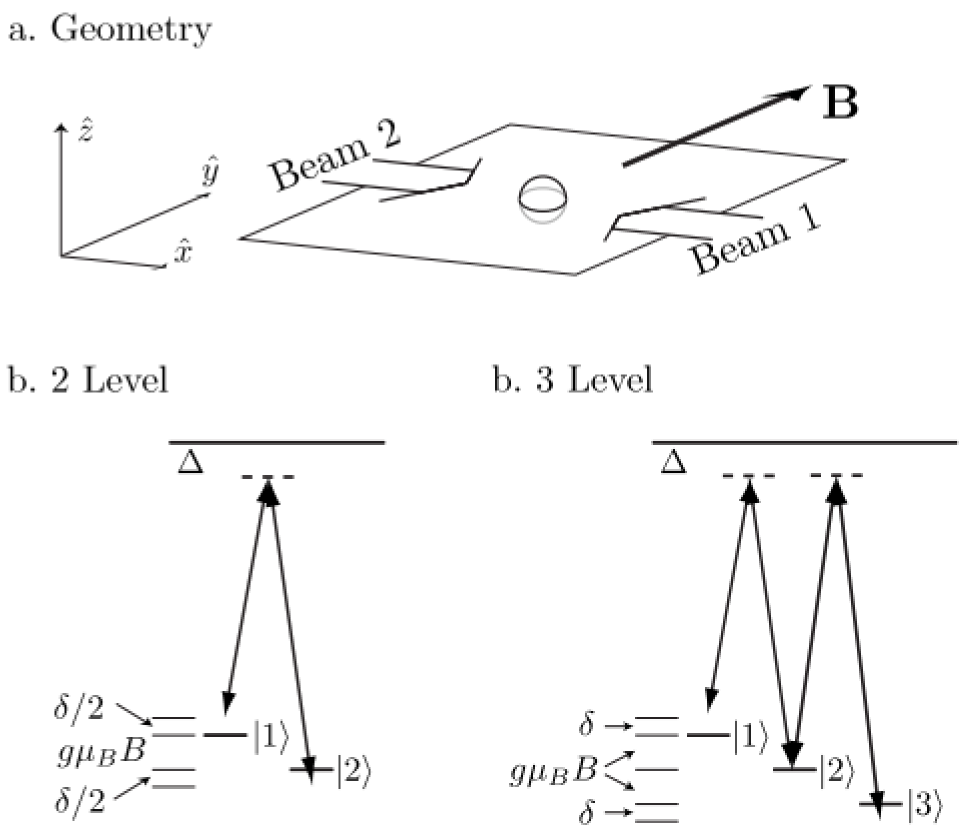


A (also, Ketterle group, MIT & Dalibard group, ENS)



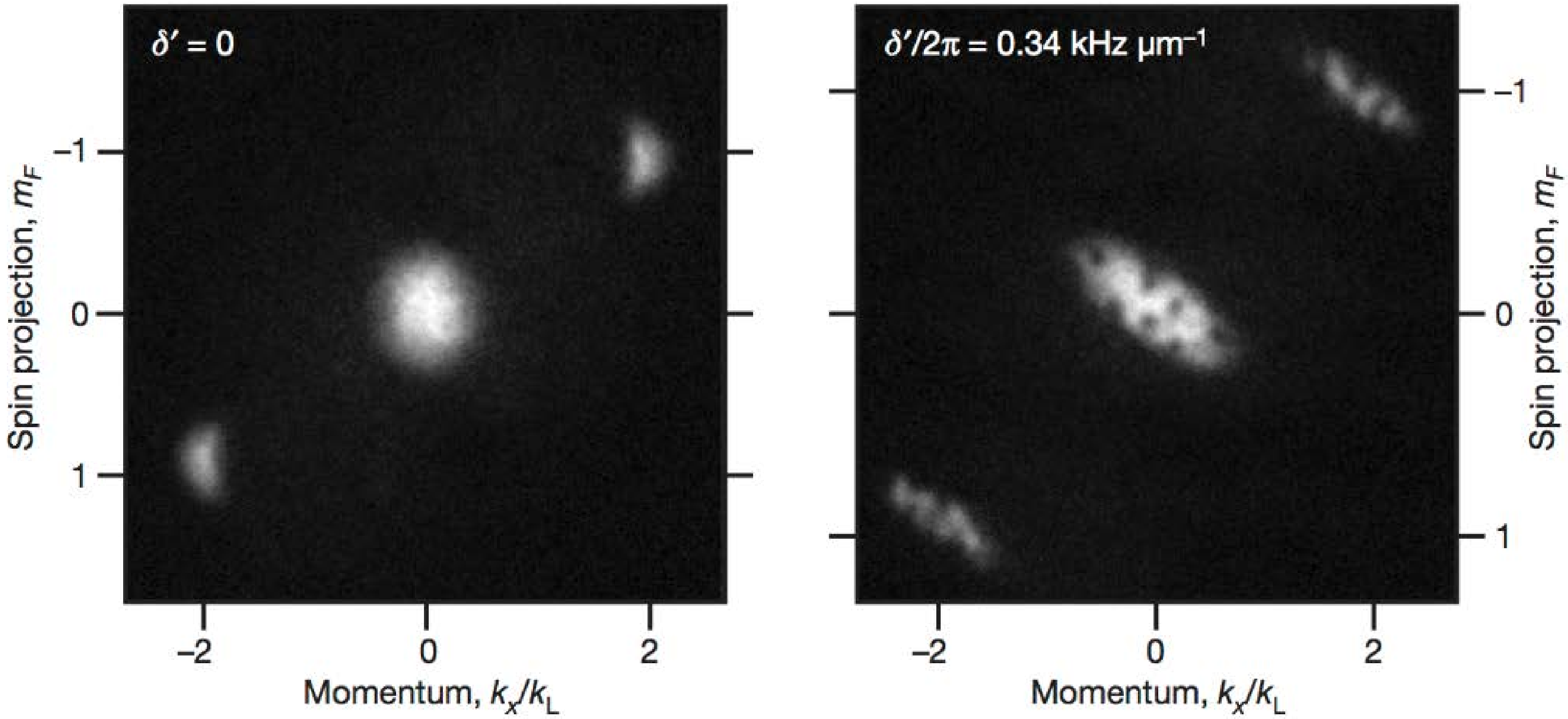
Dalibard group, ENS

Raman-induced artificial gauge fields



Spielman, JQI

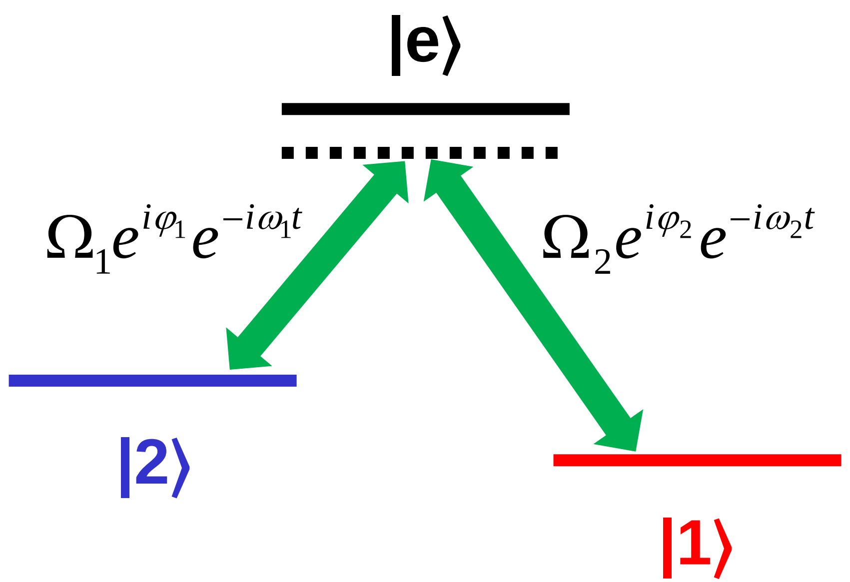
Raman-induced artificial gauge fields



Spielman, JQI

Raman-induced artificial gauge fields

Geometric phases from internal degrees of freedom



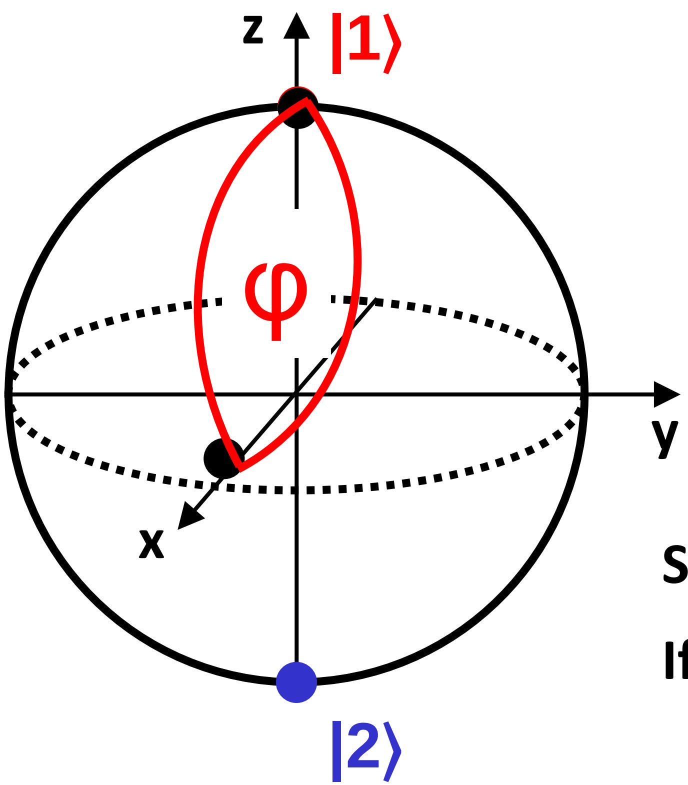
"dressed" eigenstates can be superpositions of |1⟩ and |2⟩

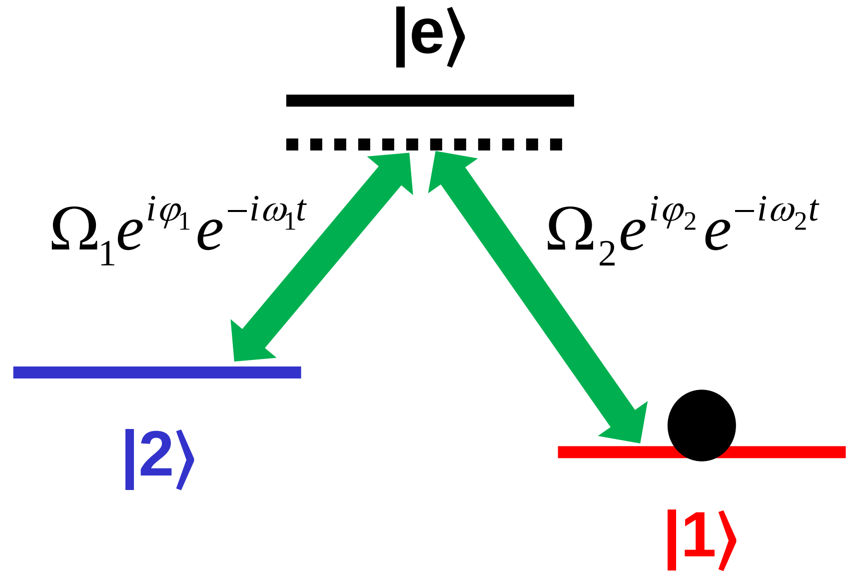
$$\left| g \right\rangle = \sin\theta \left| 1 \right\rangle + e^{i\phi} \cos\theta \left| 2 \right\rangle$$

Dum & Olshanii, PRL (1994)
Higbie & Stamper-Kurn, PRA (2002)
Spielman, PRA (2009)

Raman-induced artificial gauge fields

Geometric phases from internal degrees of freedom





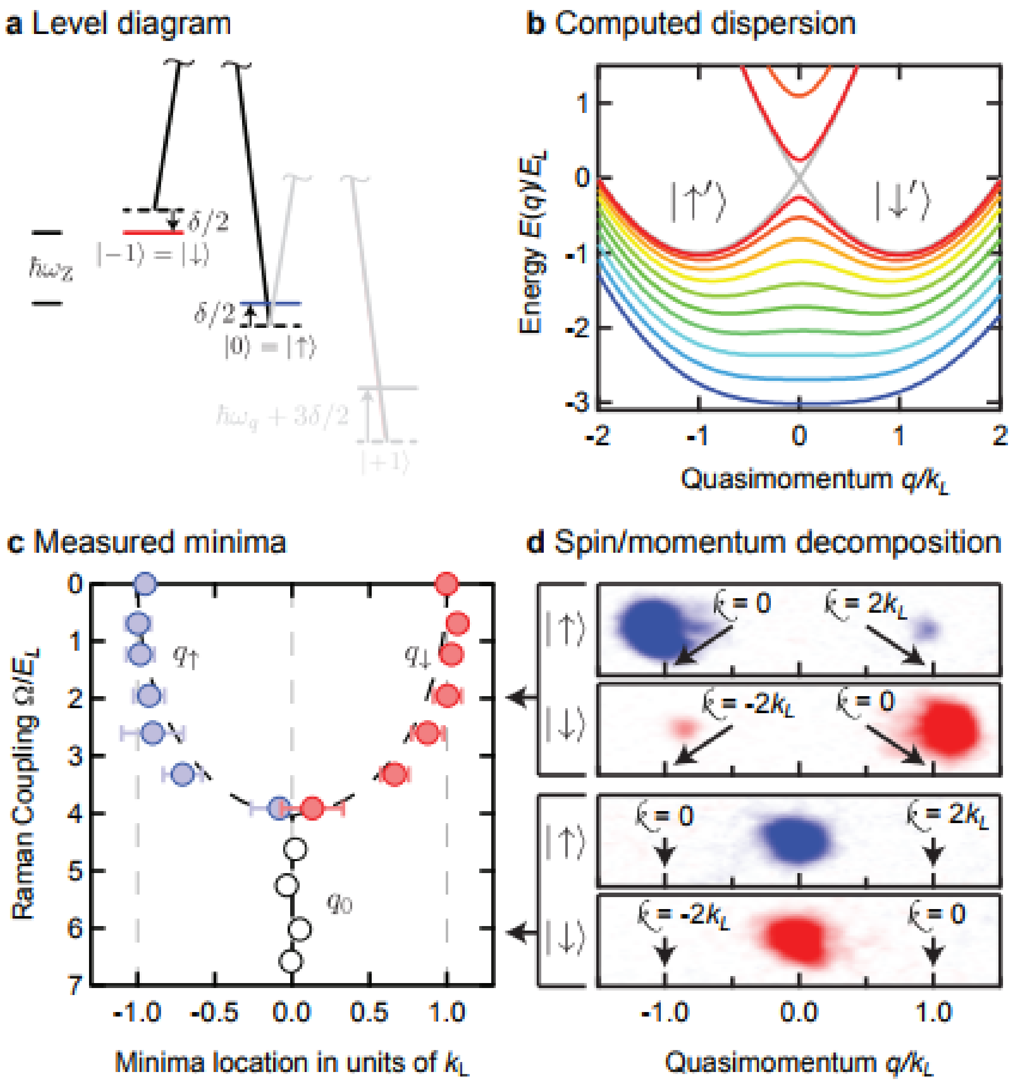
Suppose θ or ϕ depend on position.

If our particle follows a closed path in space…

Dum & Olshanii, PRL (1994)
Higbie & Stamper-Kurn, PRA (2002)
Spielman, PRA (2009)

$$|g\rangle = \sin\theta|1\rangle + e^{i\phi}\cos\theta|2\rangle$$

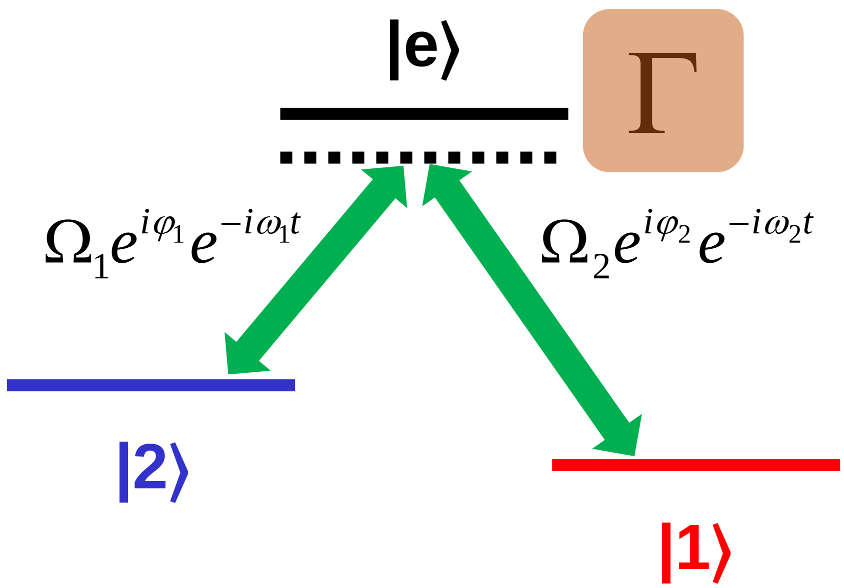
Raman spin-orbit coupling



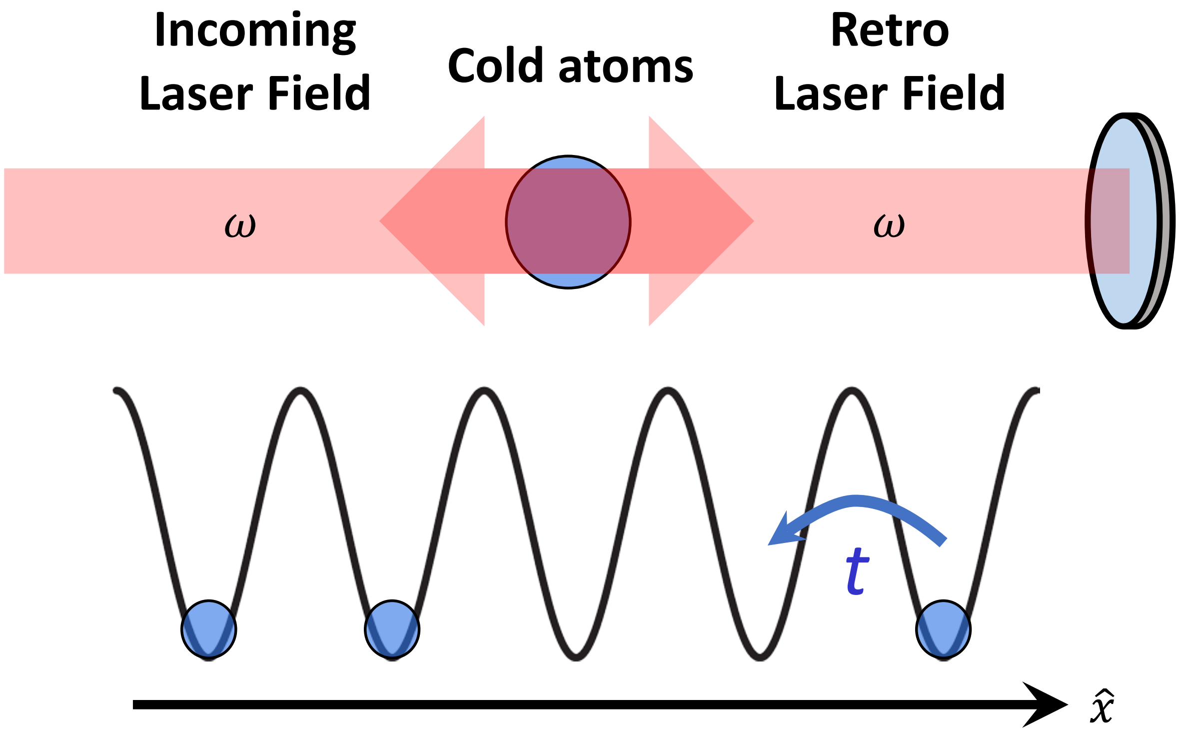
Lin, et al. Nature 2011

Raman-induced artificial gauge fields

Ultimately also limited to weak effective fields due to heating (off-resonant Rayleigh scattering)



Laser-assisted tunneling



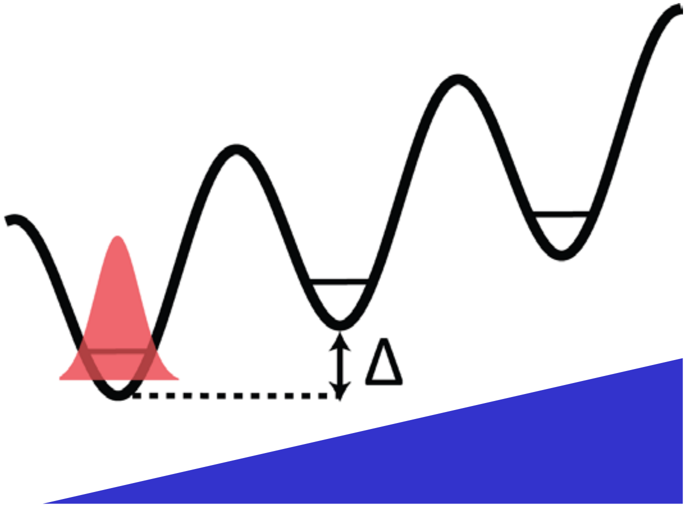
$$H_{tight-binding} = -t\sum_n \left(c_n^\dagger c_{n+1} + \text{h.c.}\right)$$

Laser-assisted tunneling

Turn off (off-resonant) tunneling with linear gradient

Raman transition
“turns it back on”

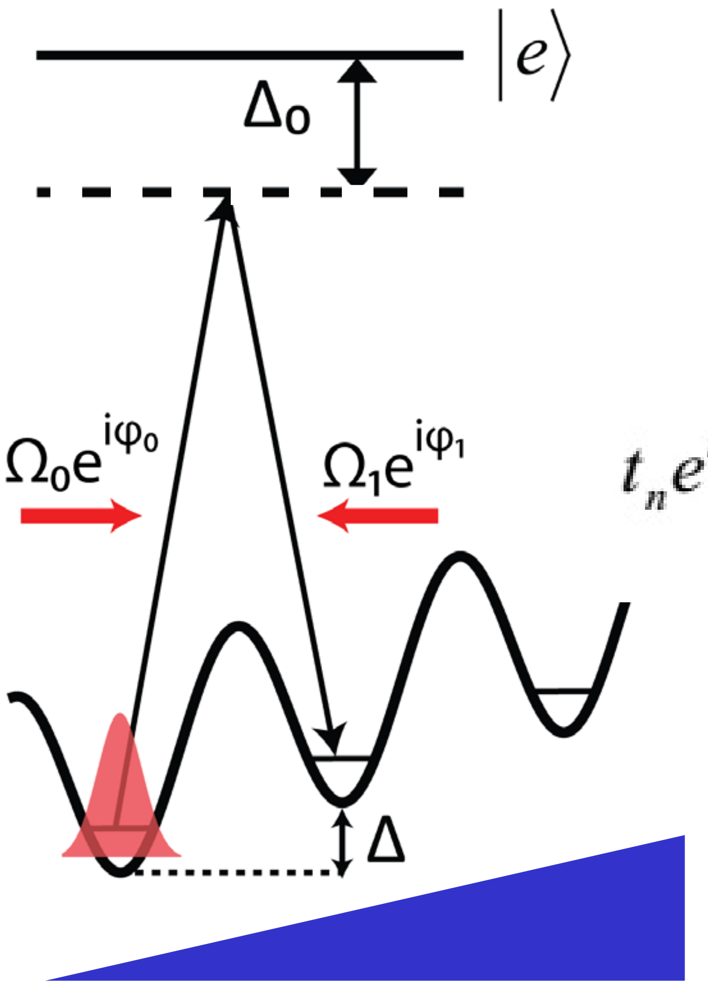
+ tunneling phase!



Jaksch & Zoller, NJP (2003)
Aidelsburger, *et al.*, PRL (2013)
Miyake, *et al.*, PRL (2013)

Laser-assisted tunneling

Turn off (off-resonant) tunneling with linear gradient



Raman transition
"turns it back on"

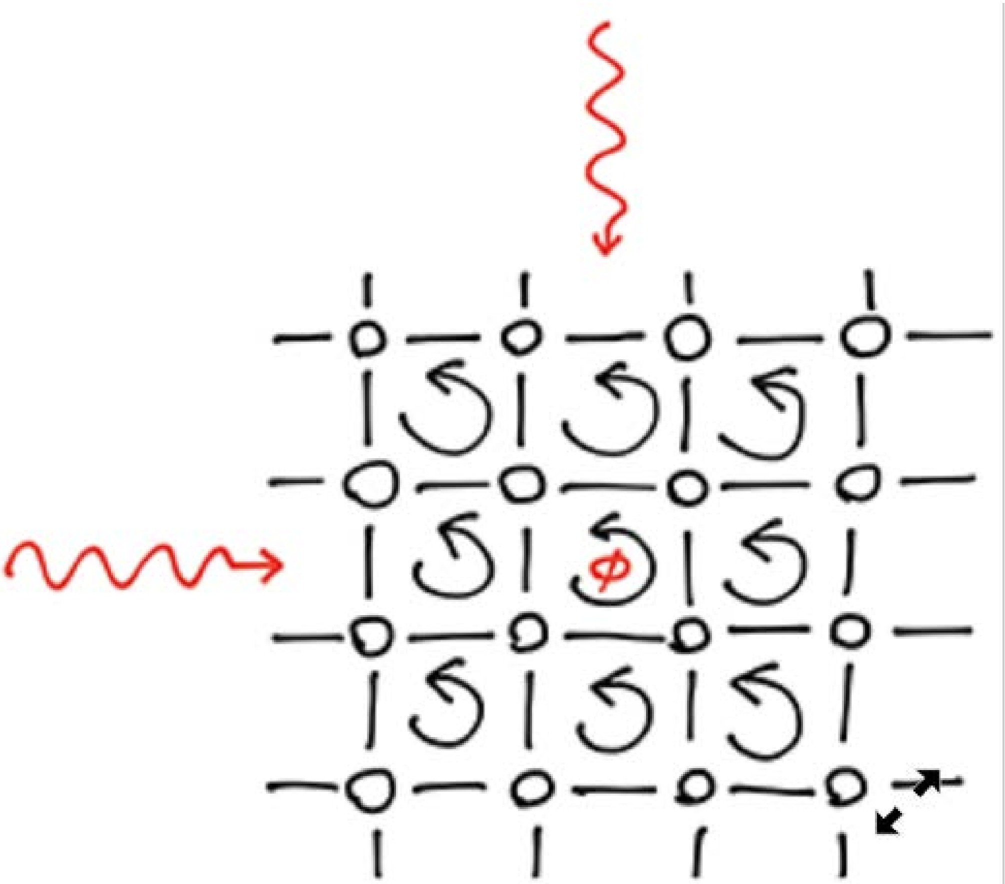
+ tunneling phase!

$$t_n e^{i\phi_n} = \frac{1}{2}\int dx\, w^*(x-x_n)\left[\frac{\Omega_0\Omega_1}{2\Delta_0}e^{i2kx}e^{i(\varphi_0-\varphi_1)}\right]w(x-x_{n+1})$$

Jaksch & Zoller, NJP (2003)
Aidelsburger, *et al.*, PRL (2013)
Miyake, *et al.*, PRL (2013)

Laser-assisted tunneling

In 2D, with well chosen $\vec{q}$

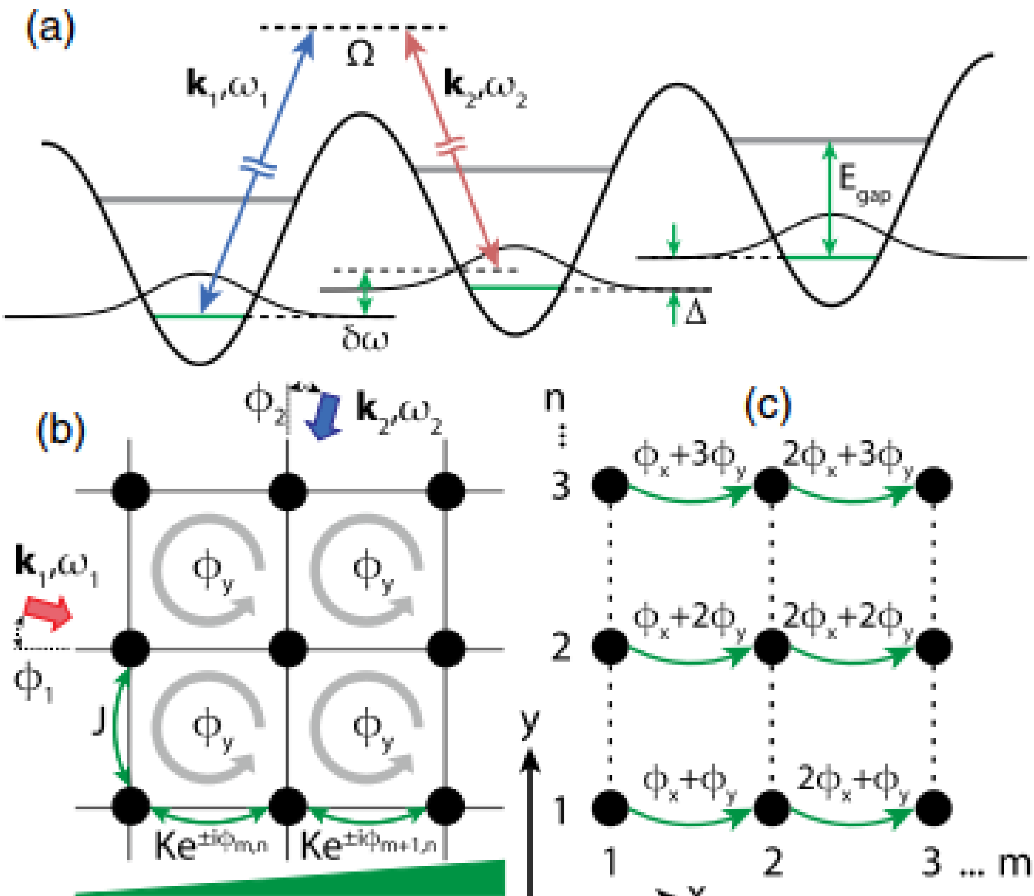


APS/Cheng Chin and Erich Mueller

Some control over the flux by choice of laser beam alignment

Laser-assisted tunneling

In 2D, with well chosen $\vec{q}$



APS/Cheng Chin and Erich Mueller

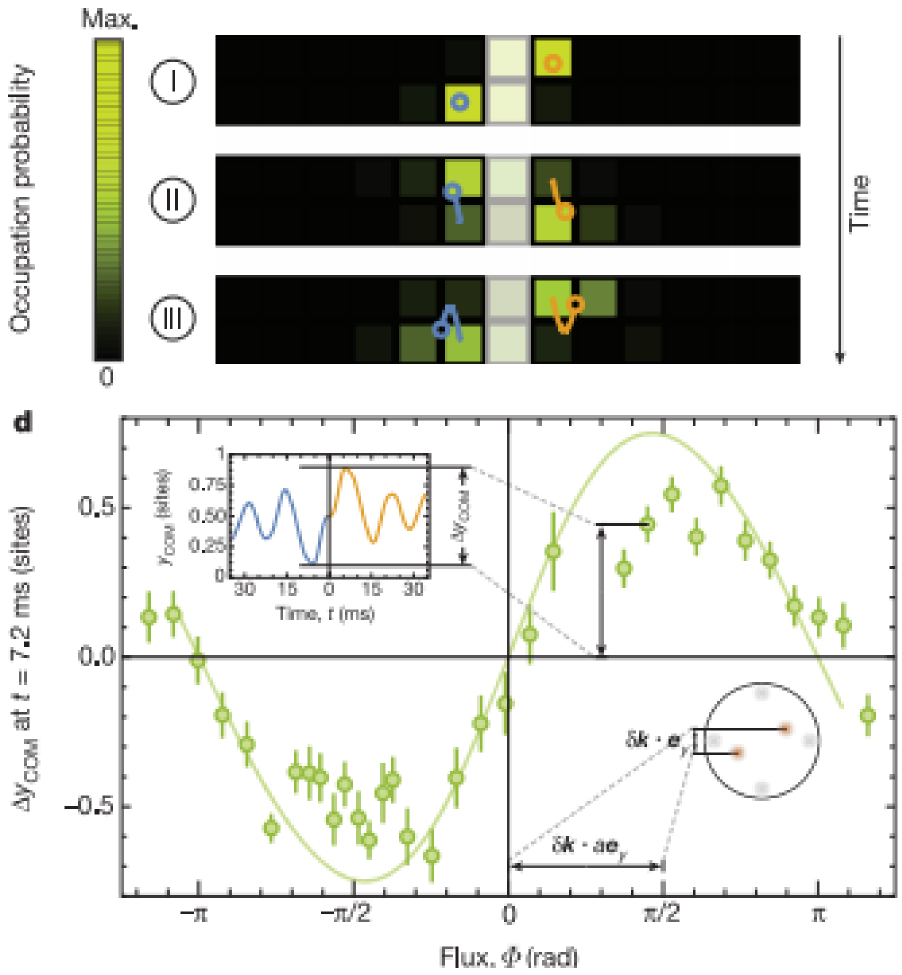
Some control over the flux by choice of laser beam alignment

Significant effects of heating remain – outstanding challenge to the field of how to stabilize against heating with interactions present

Aidelsburger, *et al.*, PRL (2013)
Miyake, *et al.*, PRL (2013)

Laser-assisted tunneling

Recently combined with quantum gas microscopes!

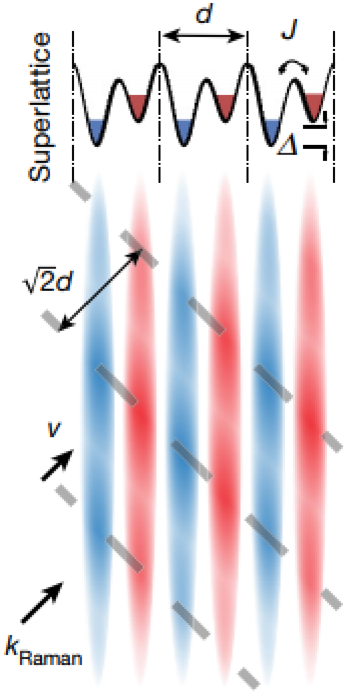


Greiner group
Nature, 2017

Laser-assisted tunneling

A stripe phase with supersolid properties in spin–orbit-coupled Bose–Einstein condensates

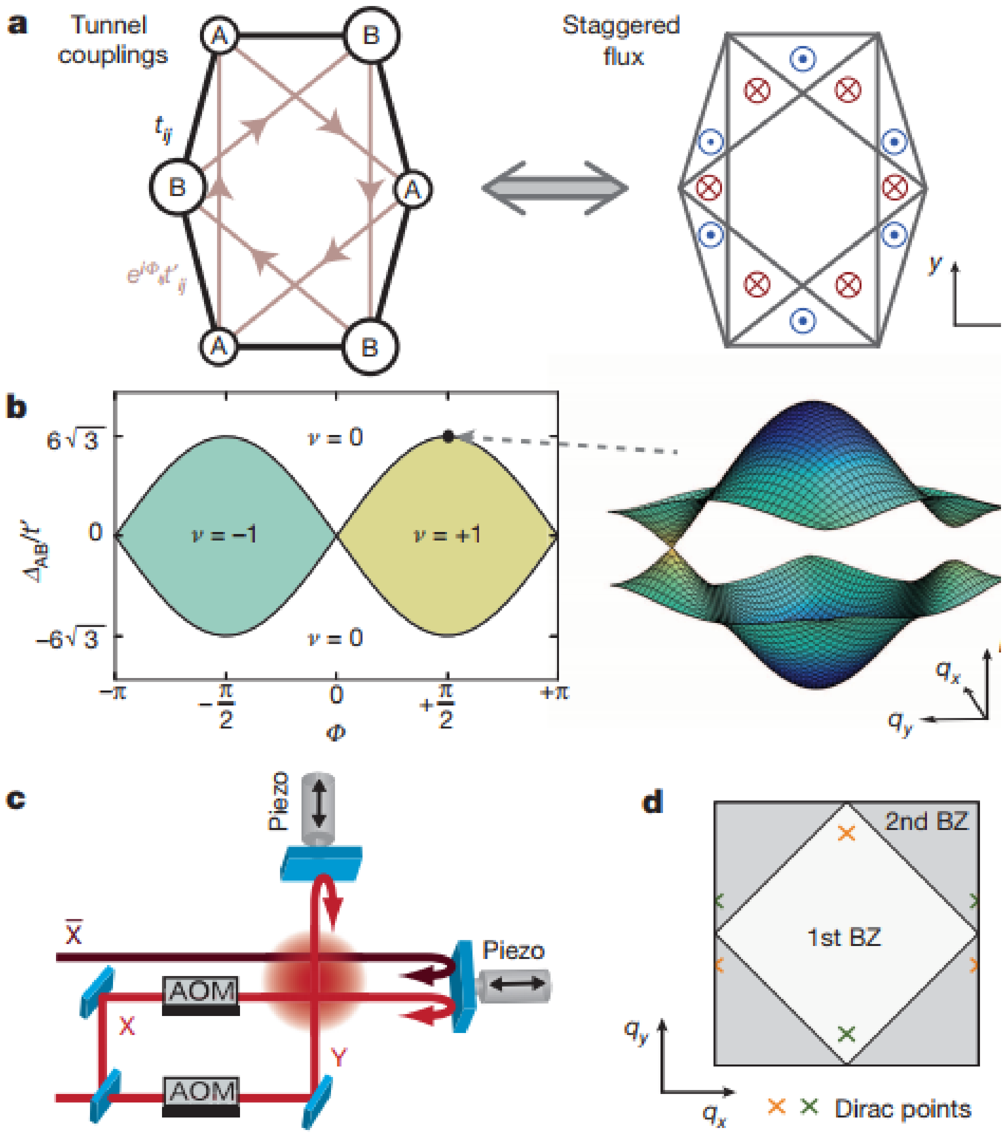
Jun-Ru Li[1]*, Jeongwon Lee[1]*, Wujie Huang[1], Sean Burchesky[1], Boris Shteynas[1], Furkan Çağrı Top[1], Alan O. Jamison[1] & Wolfgang Ketterle[1]



Moving density modulation from Raman potential

Floquet Hamiltonians

topological Haldane model



related "shaking" techniques

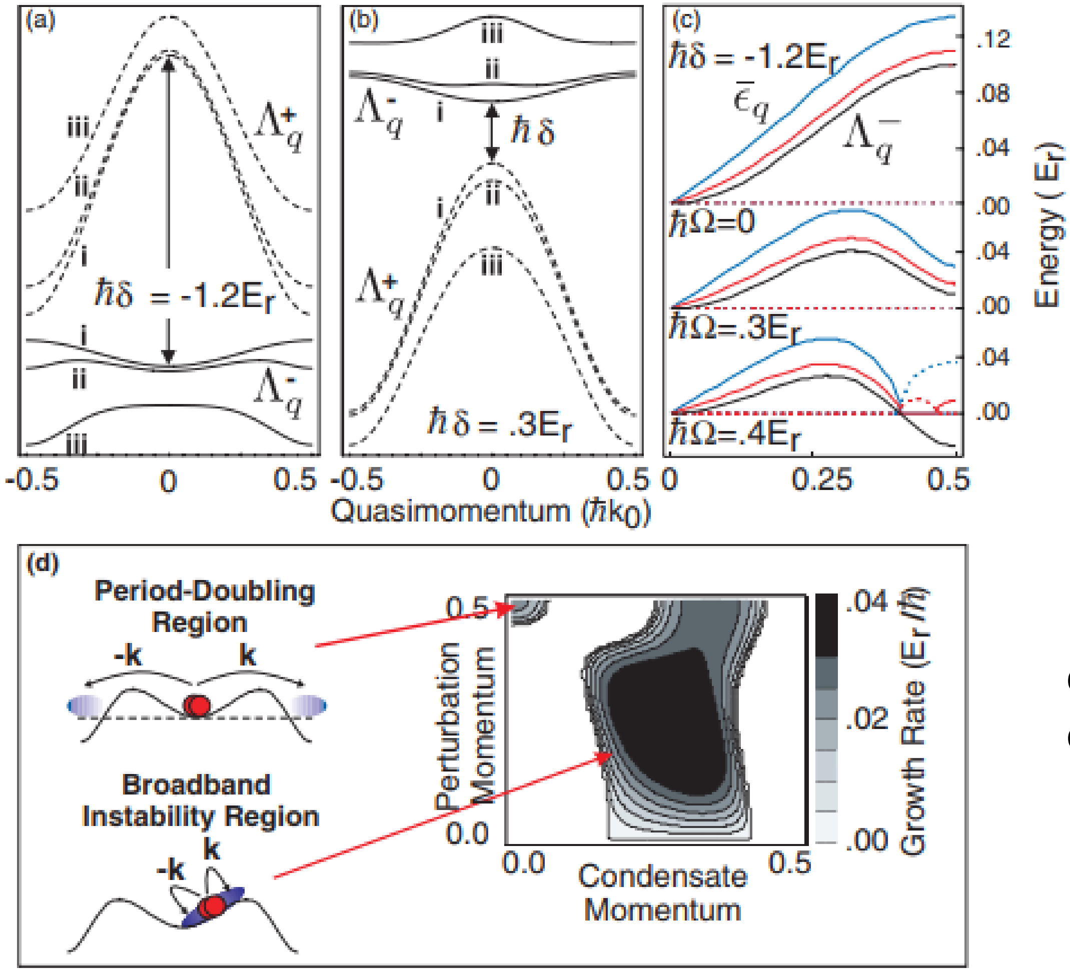
Sengstock group, Hamburg

Esslinger group, ETH Zürich

others…

Floquet driven lattices

Gemelke, et al. PRL 2005



Periodic modulation leads to coupling of bands / modification of the band structure

Alternative schemes / synthetic lattices

For some problems, one has to go to heroic efforts to engineer certain effects in real space lattices – often at a price

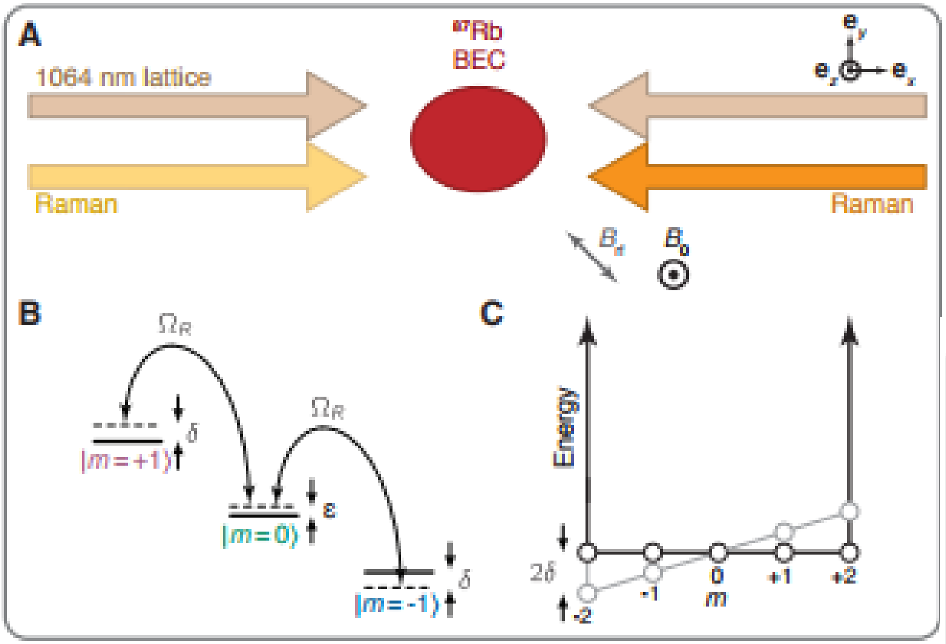
Examples:

- Mimicking the coupling of electrons to electromagnetic gauge fields
- Realizing hard-wall boundary conditions / periodic boundary conditions
- Realizing generic types/forms of disorder
- Realizing higher-dimensional ($d \geq 4$) physics

Some of these problems become much easier (even trivial) if one of the "dimensions" to a system is represented by discrete quantum states, such as internal states

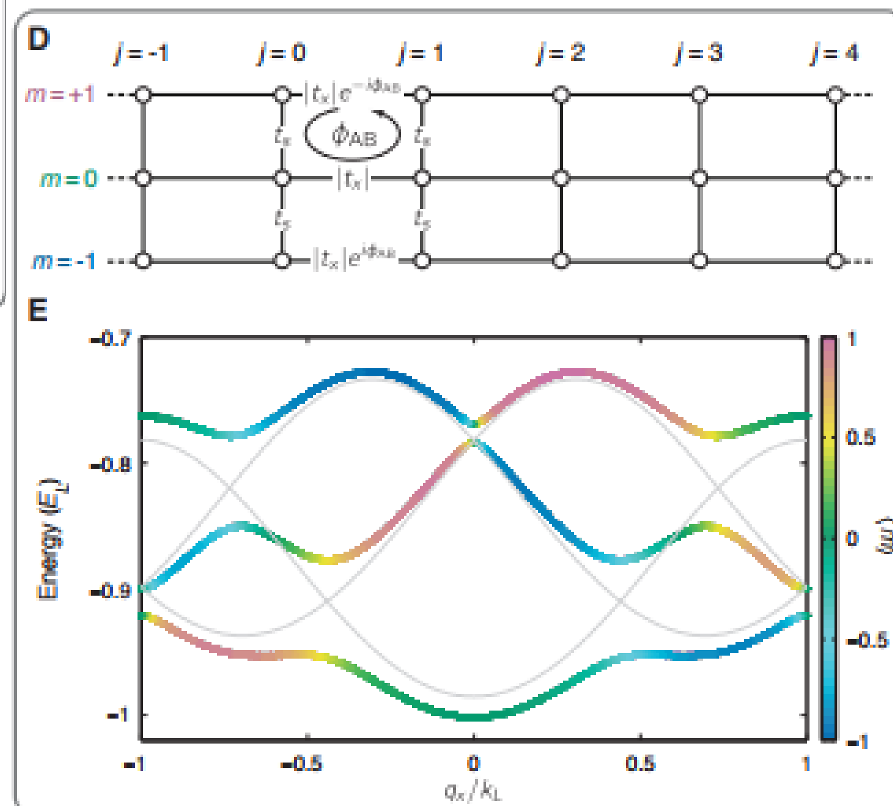
Boada, *et al*. PRL (2012)
Celi, *et al*. PRL (2013)
and now many more

Partially synthetic chiral ladders



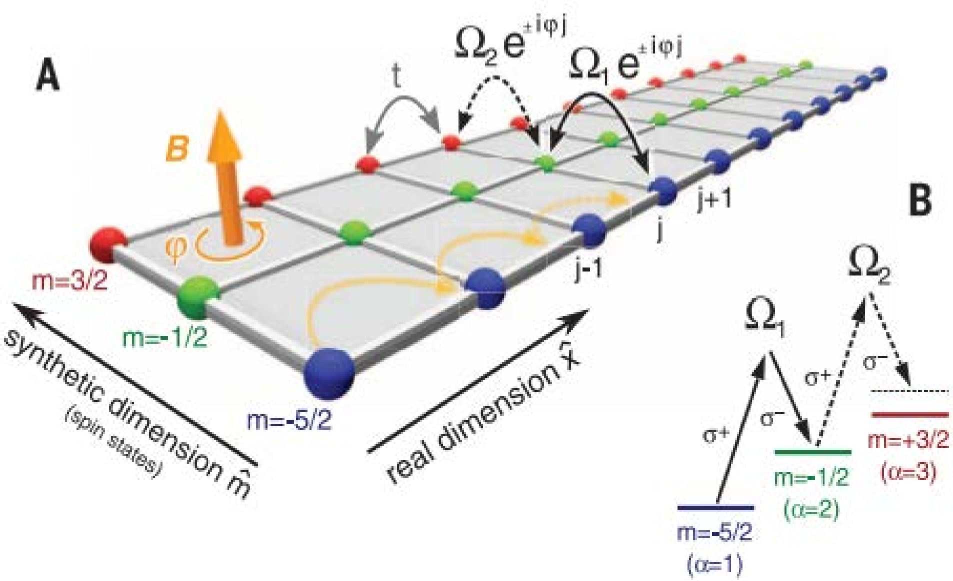
Fallani group /
Spielman group (2015)

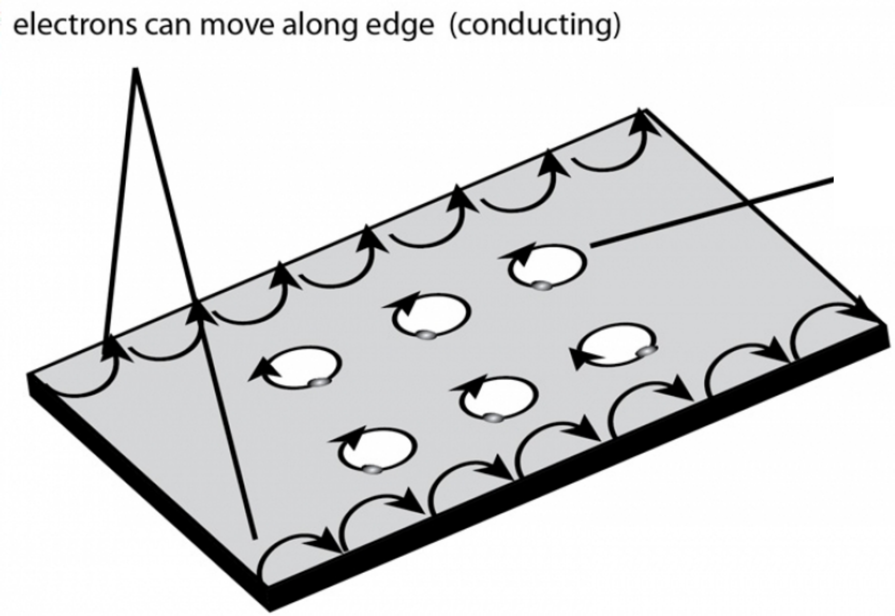
Celi, *et al*. PRL (2013)



Partially synthetic chiral ladders

Celi, *et al*. PRL (2013)

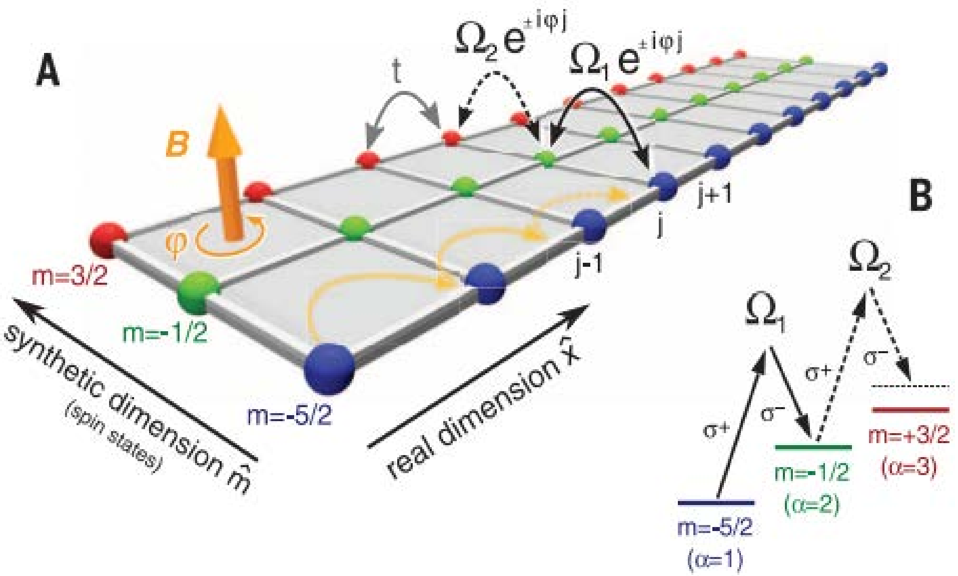


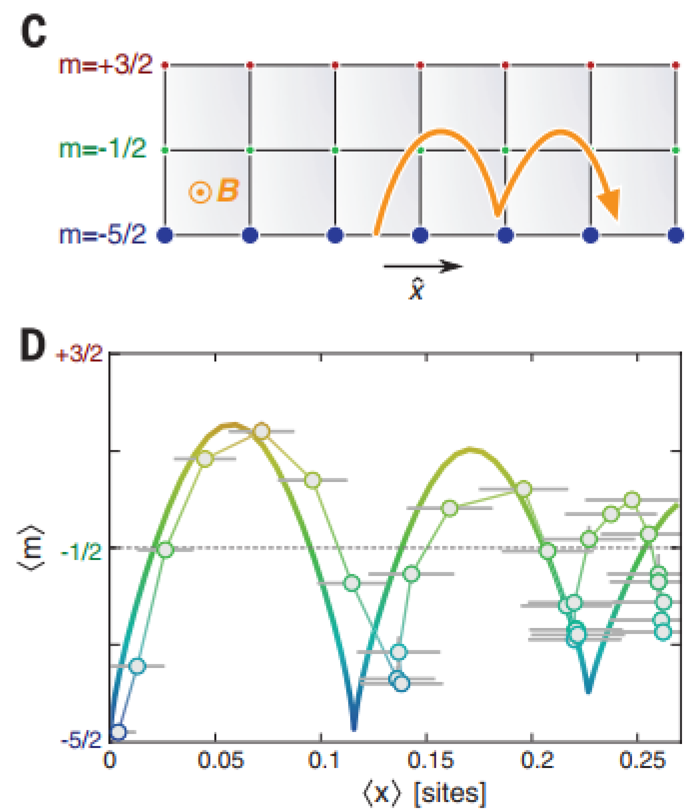


Fallani group /
Spielman group (2015)

Partially synthetic chiral ladders

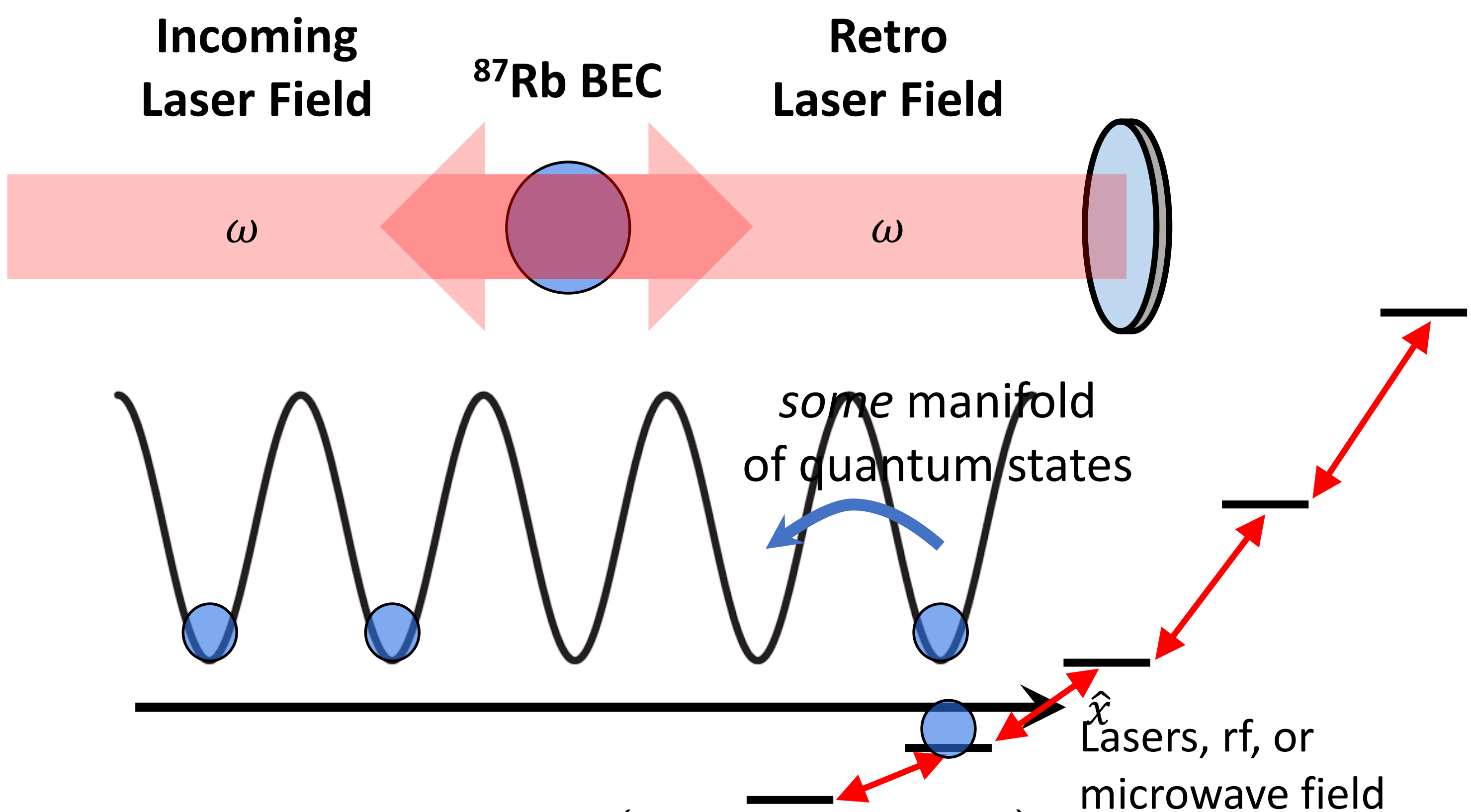
Celi, *et al*. PRL (2013)





Fallani group /
Spielman group (2015)

Fully synthetic lattices



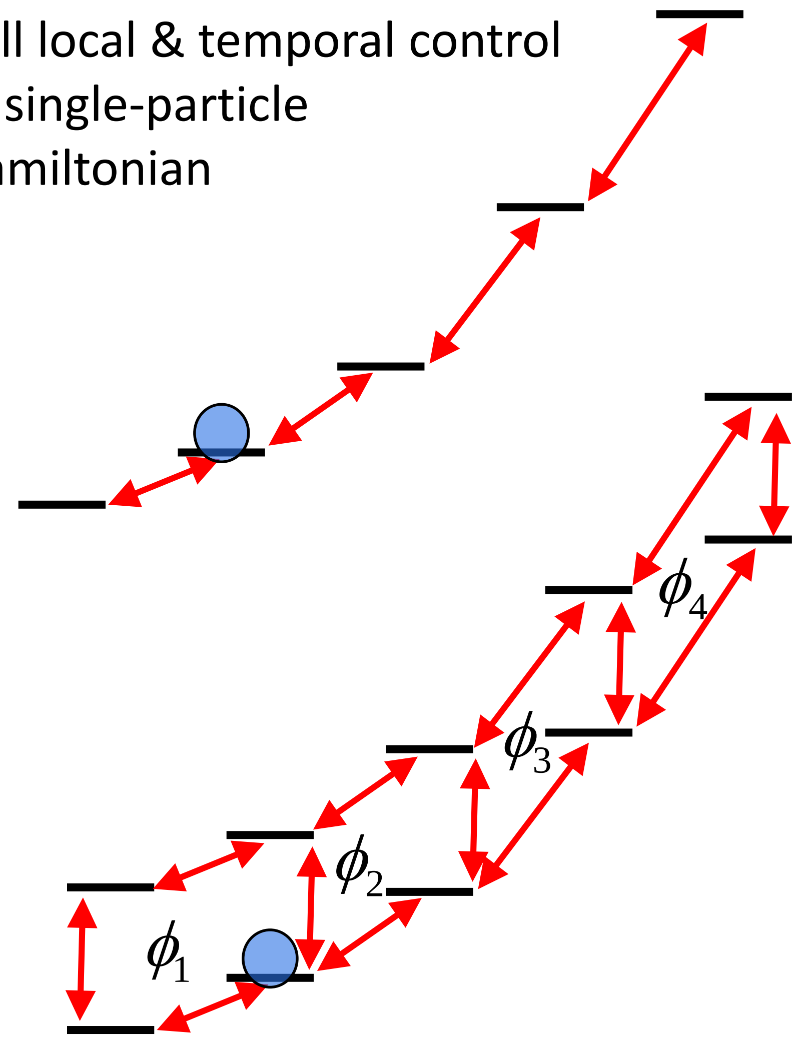
$$H_{s.p.} = -t\sum_{n}\left(c_n^{\dagger}c_{n+1} + \text{h.c.}\right)$$

Field-driven transitions between states – form a "synthetic lattice"

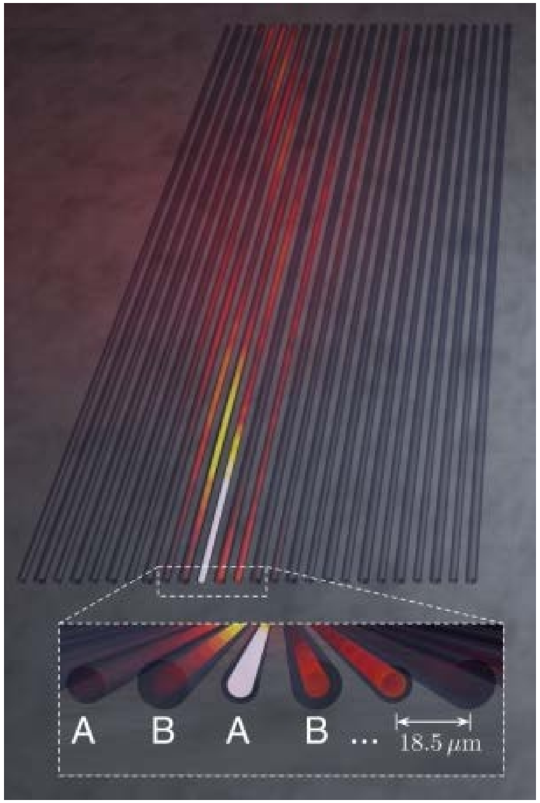
- Real-valued tunneling
- Limited by finite temperature

Synthetic lattice engineering

Full local & temporal control of single-particle Hamiltonian

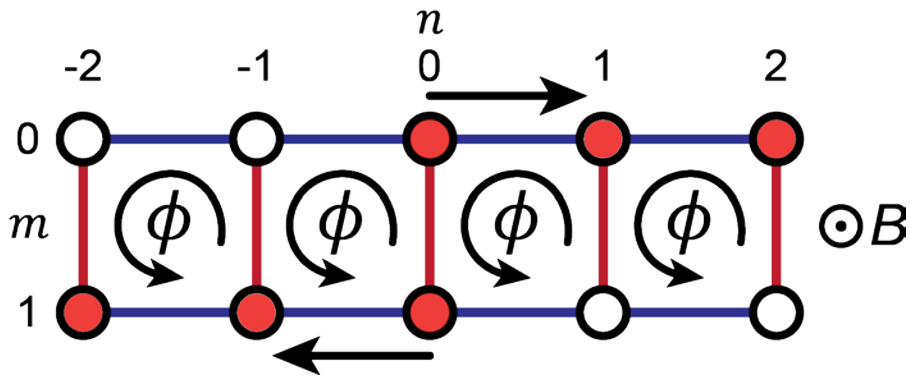


analogous to **photonic simulators** (**Szameit**, Hafezi, Silberhorn, Segev, etc.)

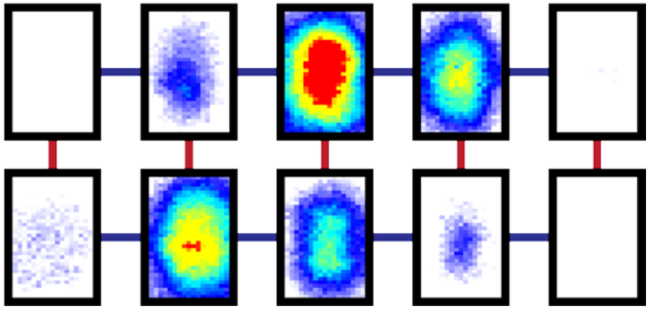


Chiral currents on 2D flux ladders

"shearing" ≡ $\langle n \rangle_{m=0} - \langle n \rangle_{m=1}$

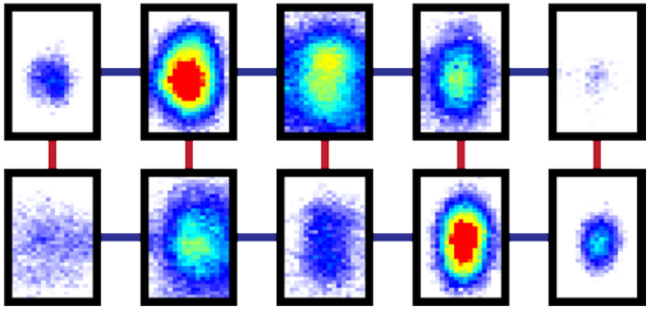


$\phi = +\pi/2$



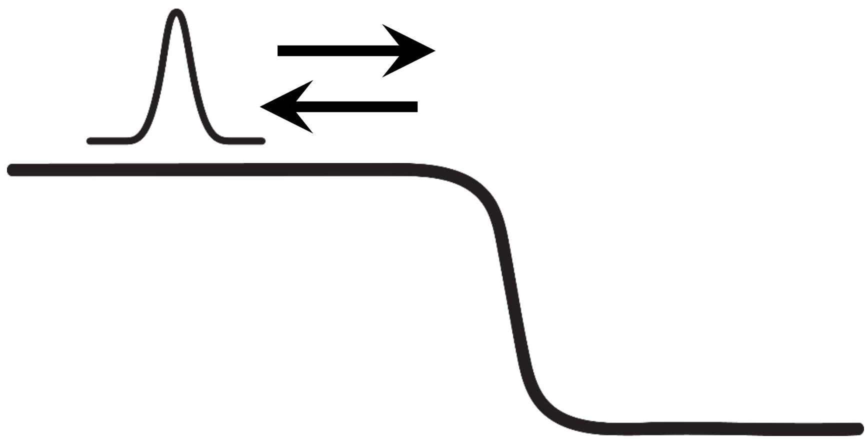
Images taken at 500 μs (1.05 h/t)

$\phi = -\pi/2$

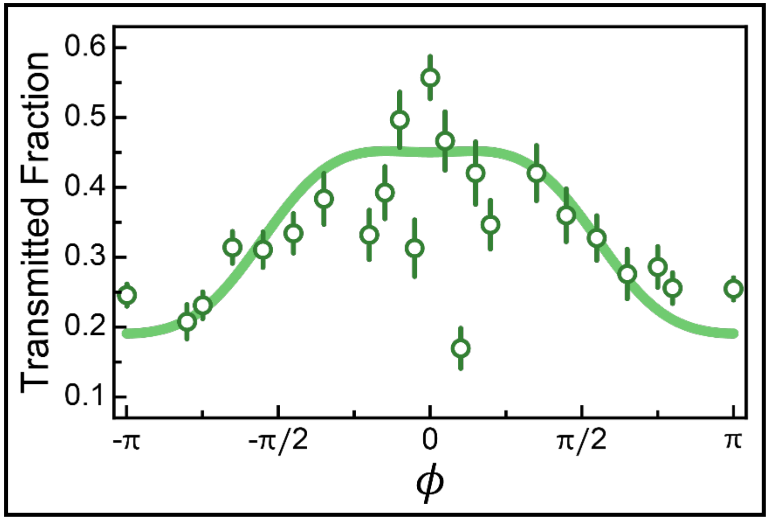


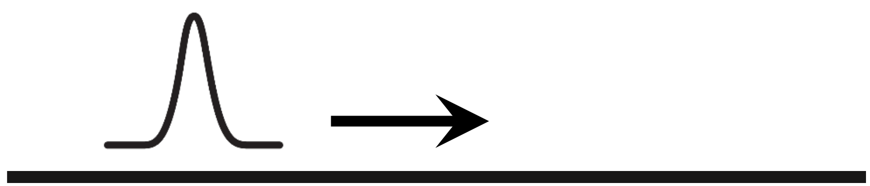
F. A. An, E. J. Meier, and BG. (Science Advances)

Inhomogeneous flux - topological reflection



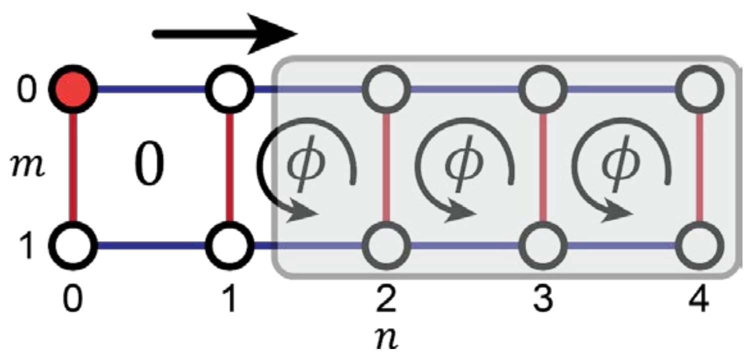
Quantum reflection from a potential dip





The site-potentials are completely flat in our case

But still a boundary condition to match



F. A. An, E. J. Meier, and BG. (Science Advances)