Topological quantum matter – a new frontier for ultracold atoms (and molecules)

Wolfgang Ketterle
Massachusetts Institute of Technology
MIT-Harvard Center for Ultracold Atoms

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Workshop on the Grand Challenges in Quantum Fluids and Solids
Buffalo, NY

Massachusetts Institute of Technology

Some (of the many) goals of ultracold atom science:

- Simulate known phenomena in many-body physics
- Quantitative many-body physics
- Demonstrate new materials/new phenomena

Two new materials:

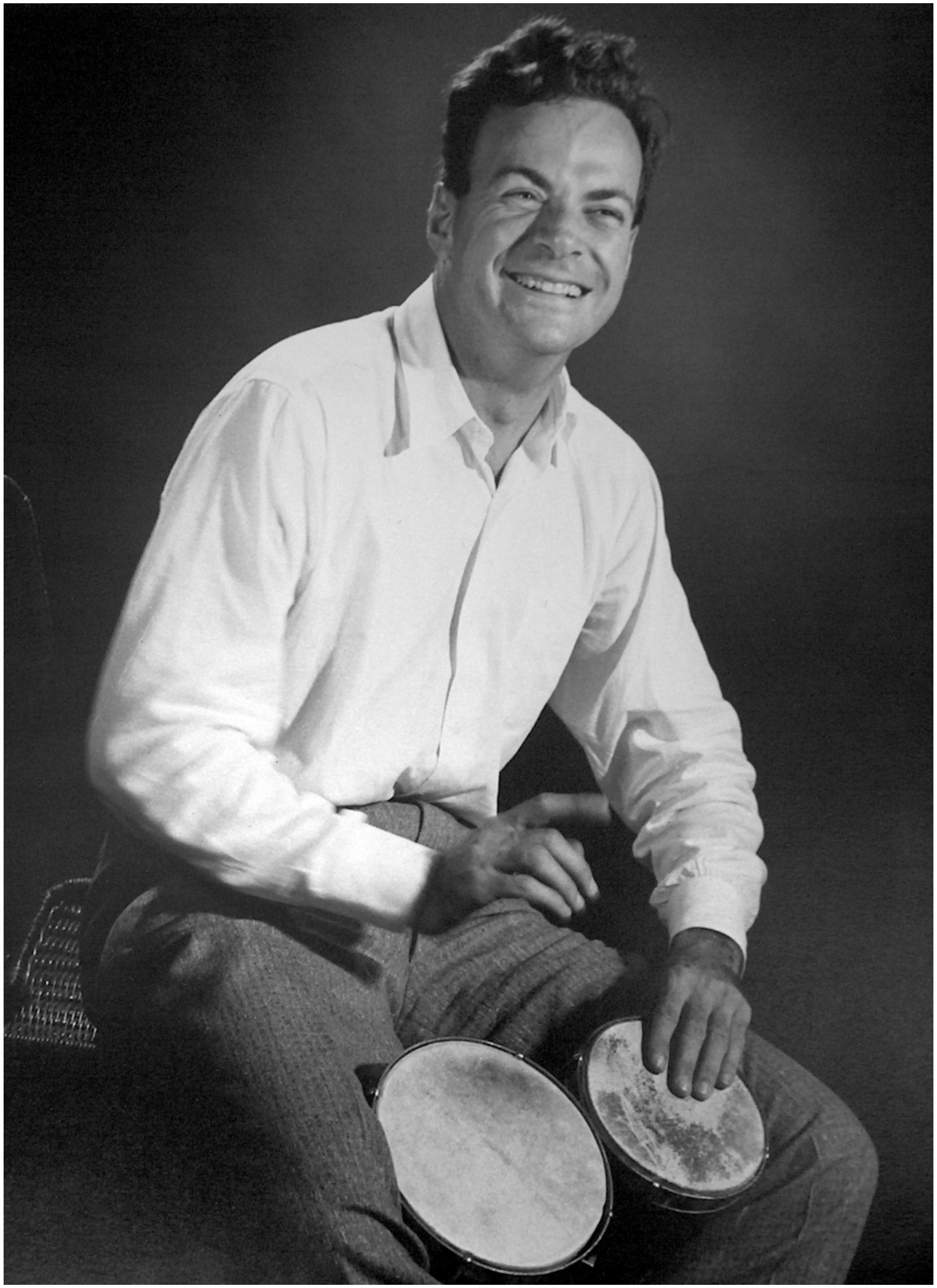
The Bose-Einstein condensate –
the simplest superfluid (model for ^4He)

Paired fermions – the simplest model for a superconductor

Two ways of going beyond realizing “natural” materials:

- Add extra bells and whistles

- Digital quantum simulation (time evolution approximated by quantum logic operations)



Richard Feynman 1981

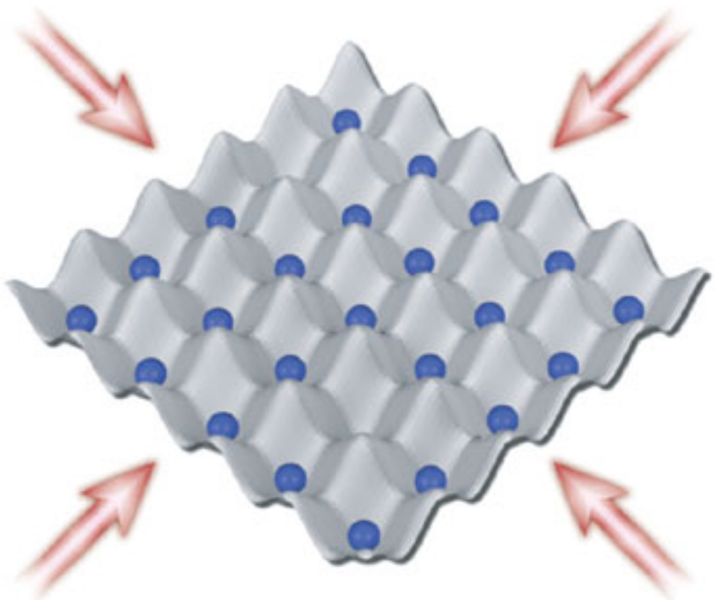
envisioned a quantum simulator ....

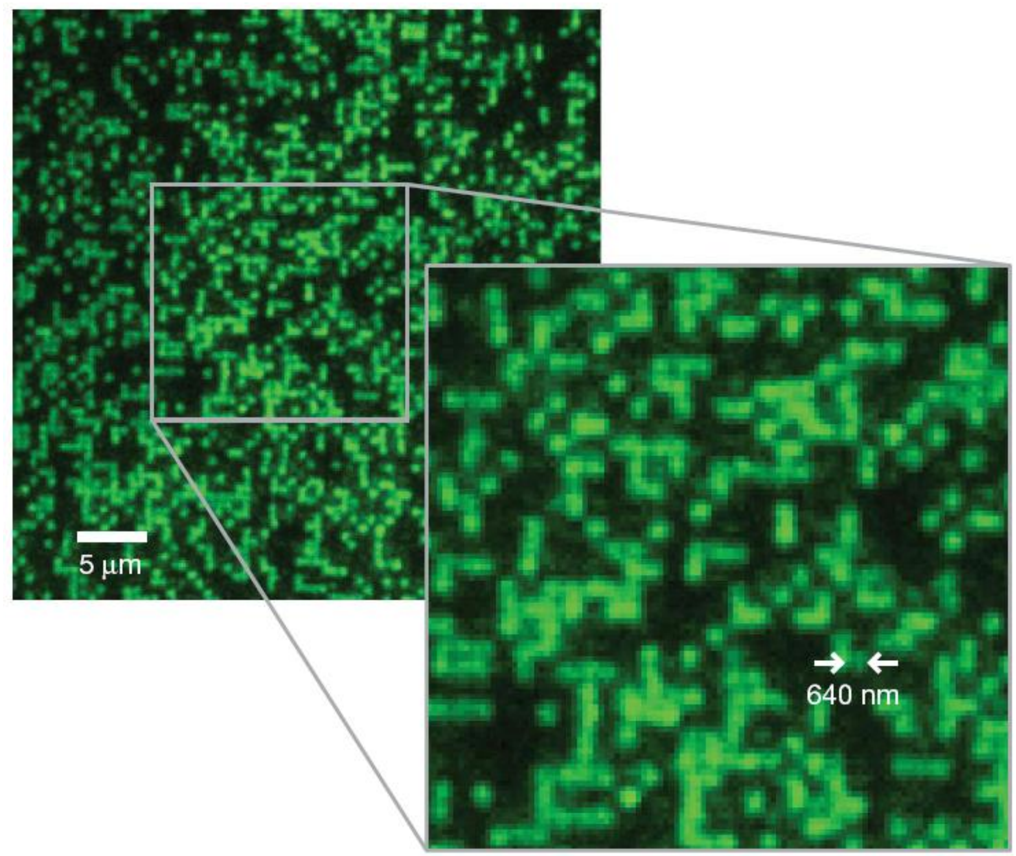
Our approach:

Atomic legos

Freeze atoms close to absolute zero: nanokelvin, make them stand still

Assemble them to behave like important materials



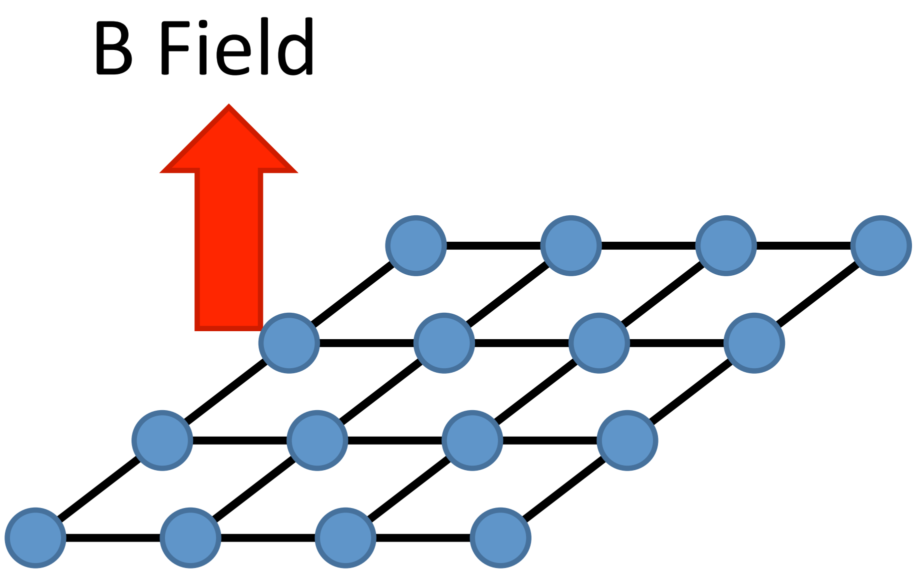


Greiner labs, Harvard

One of the most important "materials" in physics:

Electrons in a magnetic field

- Landau levels
- Hall effect
- Quantum Hall effect
- Fractional Hall effect



High field

- one flux quantum per unit cell
- Cyclotron orbit comparable to atomic distance

requires 10,000 Tesla

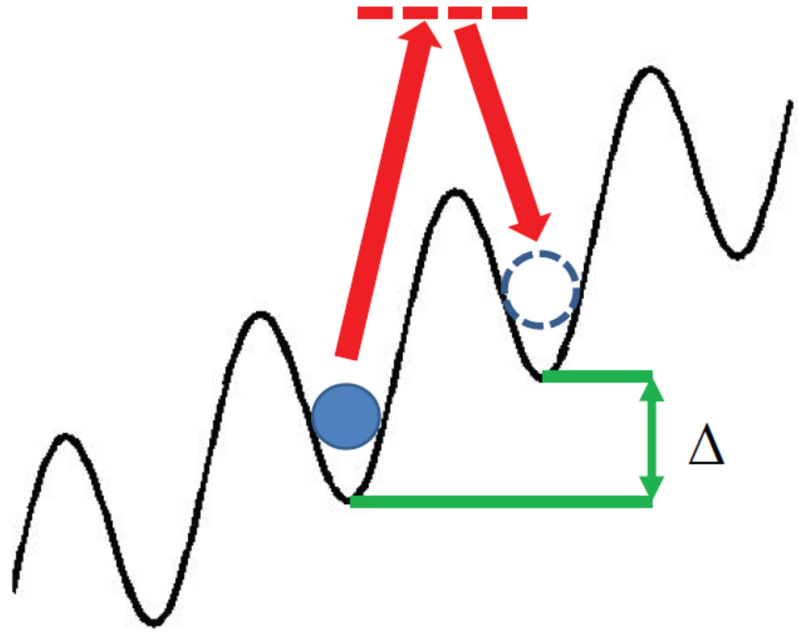
Synthetic magnetic field:

Imprint the same phase into the wavefunction of a moving neutral particle as a magnetic field (or vector potential) for a charged particle

How to engineer these phases in a lattice?

Concept:

Create a situation where motion (tunneling) is only possible with the help of laser beams



How to engineer these phases?

Concept:

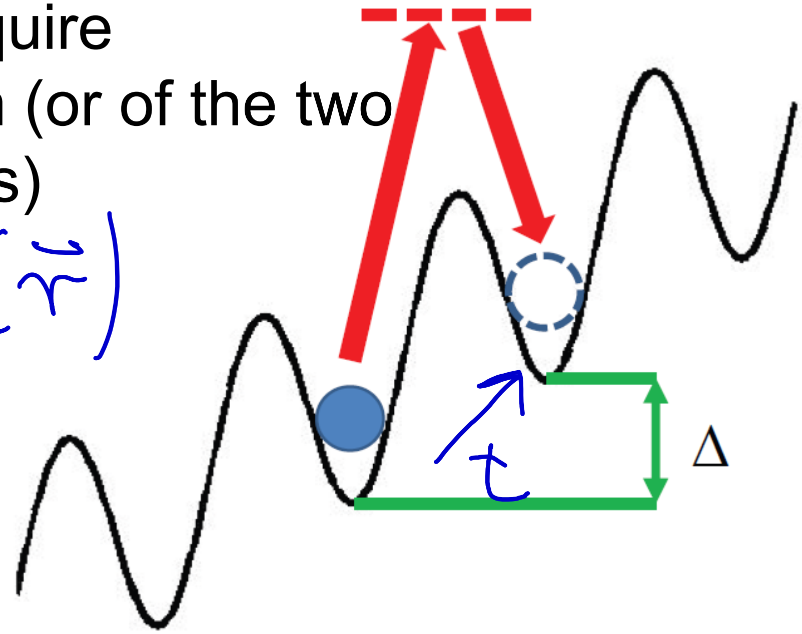
Create a situation where motion (tunneling) is only possible with the help of laser beams

Result:

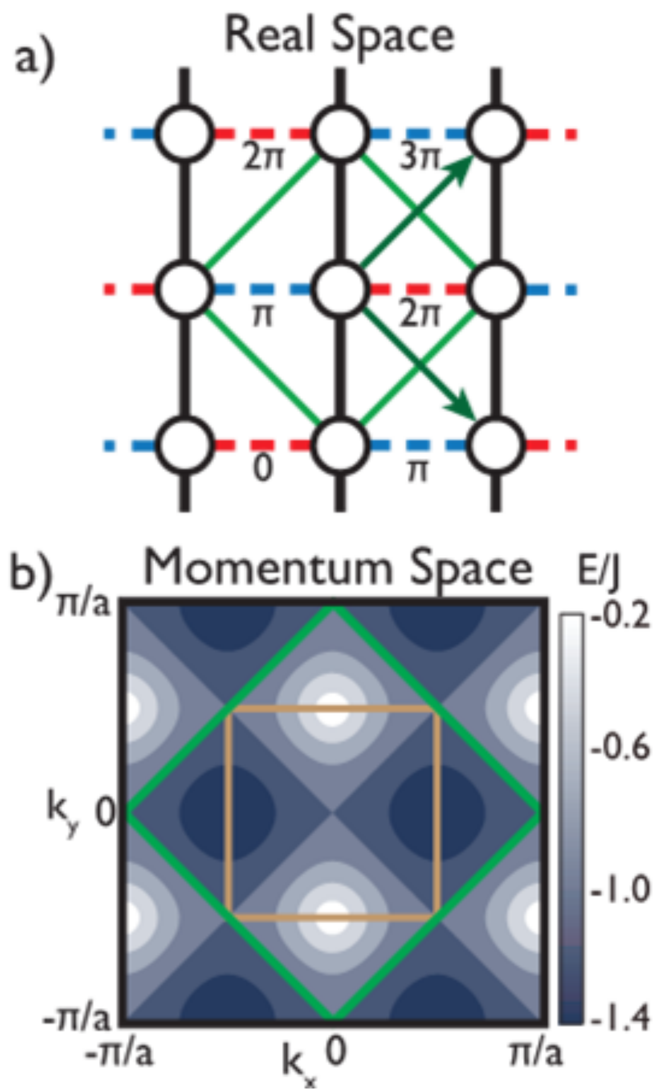
Tunneling matrix element will acquire the local phase of the laser beam (or of the two photon field for Raman processes)

$$t \rightarrow t\, e^{i\varphi_{Laser}(\vec{r})}$$

$$\varphi_{Laser} = \Delta\vec{k}\,\vec{r}$$



Realized: 2013 (MIT, Ketterle group; Munich, Bloch group)



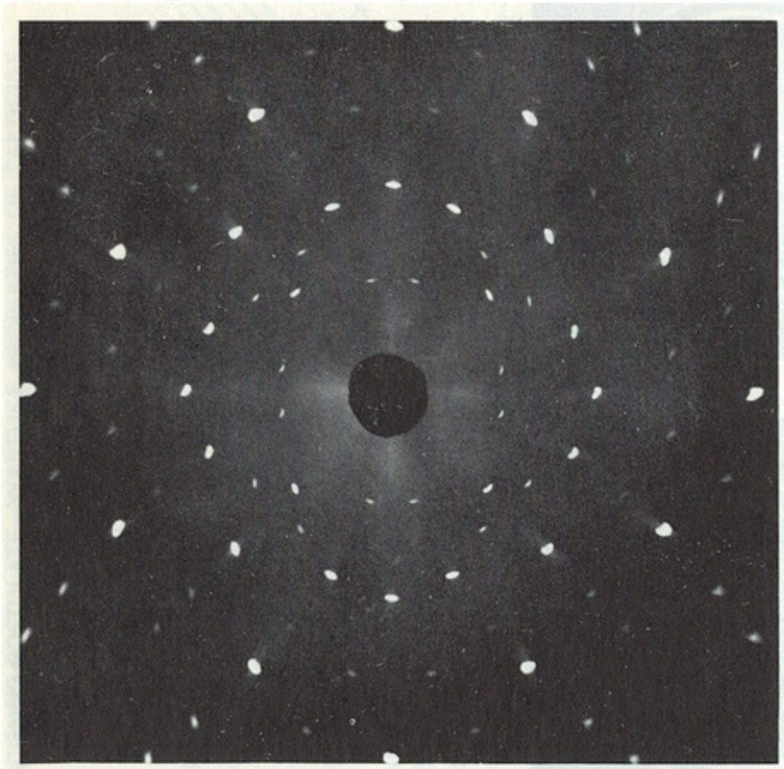
Super-strong magnetic field

One half flux quantum per unit cell

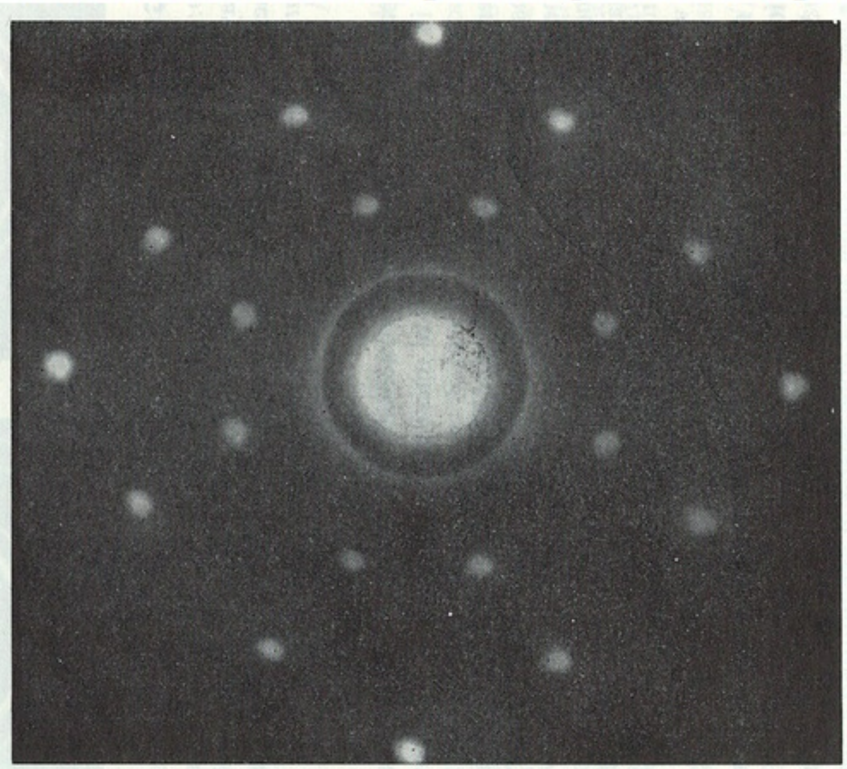
Unit cell with vector potential has doubled in size!

Comparison of X-ray and Neutron Diffraction for Sodium Chloride (NaCl)

Laue pattern of x-ray diffraction by a single NaCl crystal.

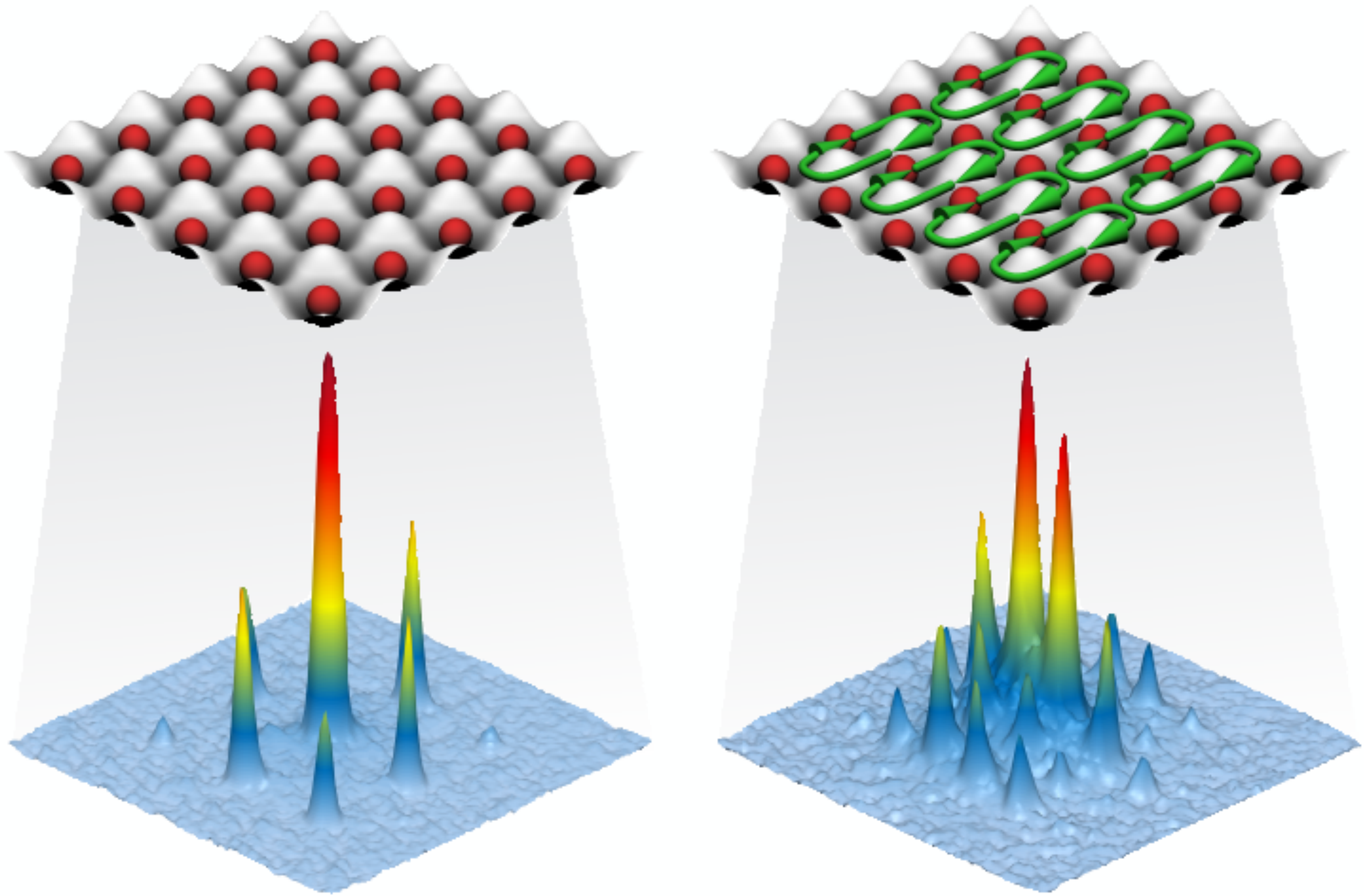


Laue pattern of diffraction of neutrons from a nuclear reactor by a single NaCl crystal.



http://www.public.asu.edu/~gbadams/spr13/diffcomp.html

C.J. Kennedy, W.C. Burton, W.C. Chung, and W. Ketterle, *Observation of Bose-Einstein Condensation in a Strong Synthetic Magnetic Field*, Nature Physics, in print; preprint, arXiv:1503.08243 (2015).



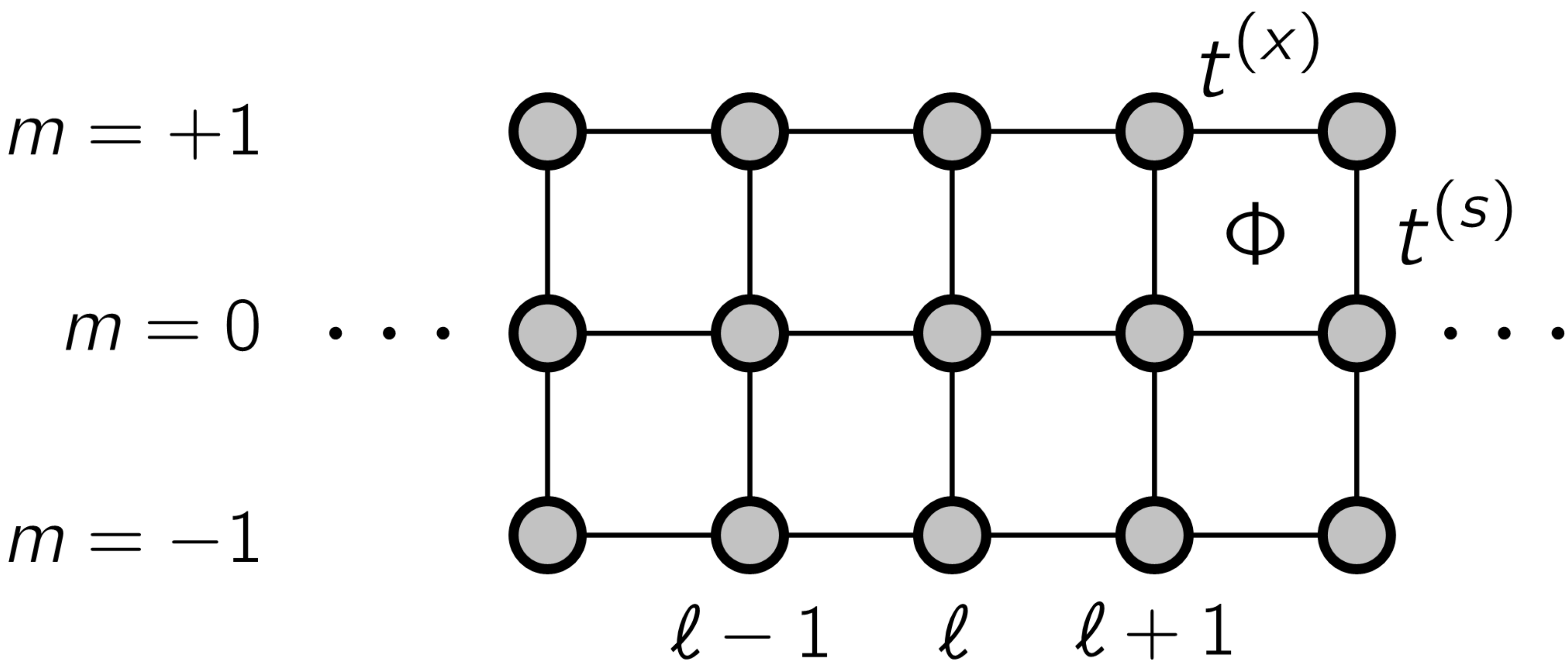
Three extensions:

- Synthetic dimensions
- Spin degree of freedom
- Third dimension – Weyl points

Synthetic magnetic fields with synthetic dimensions (Spielman group, Maryland)

Use internal Zeeman states as extra dimension

Tight binding model



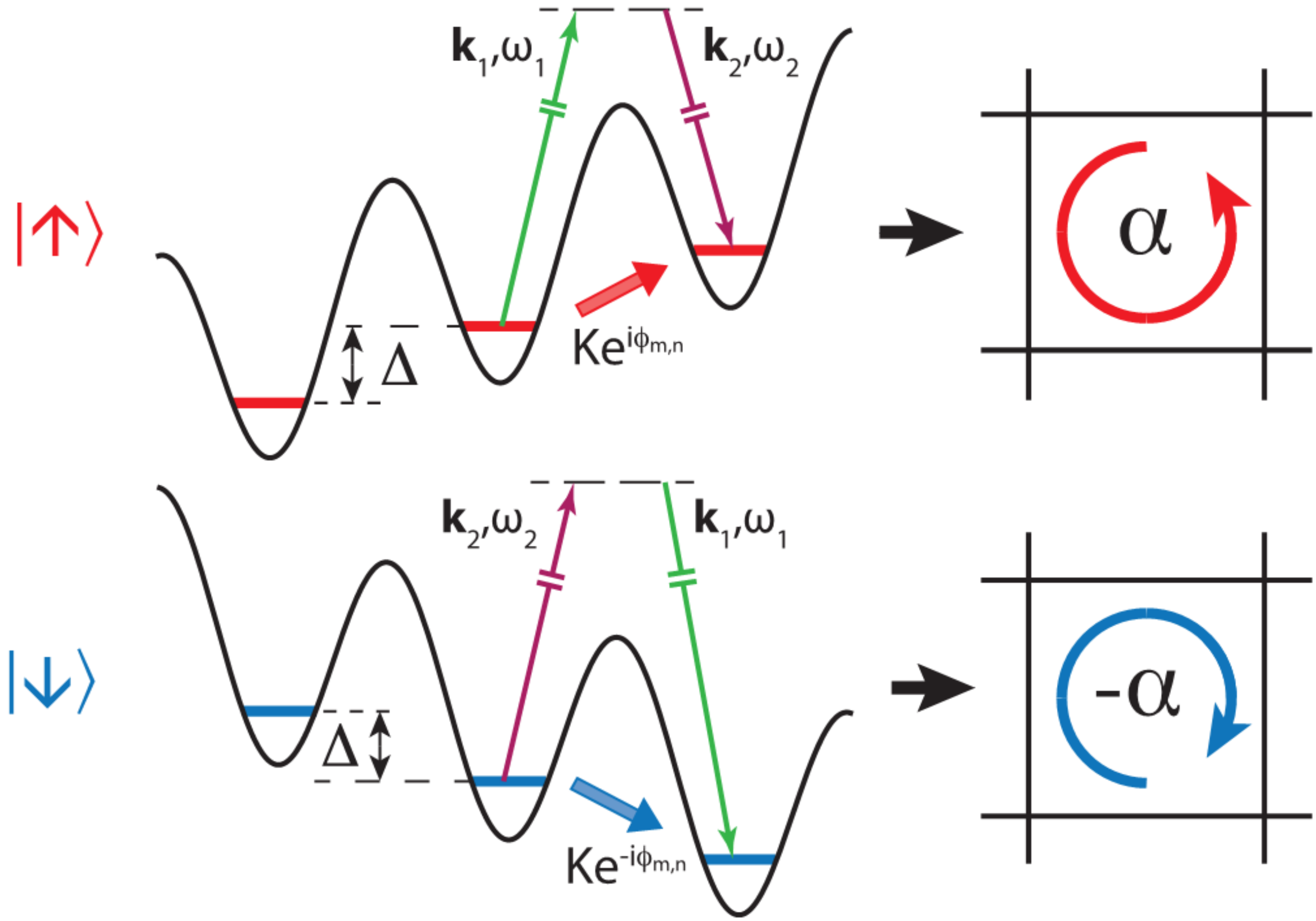
Now: Spin degree of freedom

How to engineer spin-orbit coupling for neutral atoms?

Kennedy C J, Siviloglou G A, Miyake H, Burton W C and Ketterle W, Phys. Rev. Lett. **111**, 225301 (2013). Spin-orbit coupling and spin Hall effect for neutral atoms without spin-flips

In our scheme:

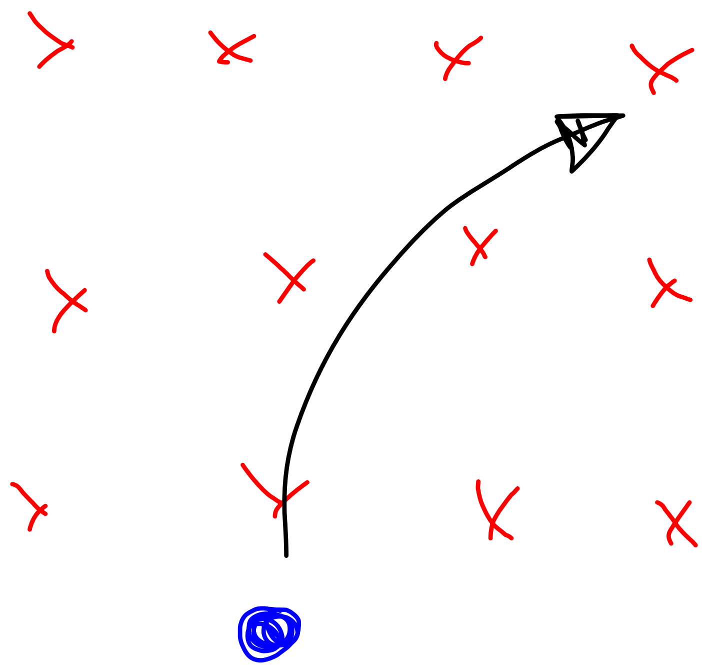
signs of B, A, phase of tunneling matrix elements reflect the momentum transfer by Raman beams



$$\phi_{m,n} = (mk_x a + nk_y a)\,\sigma_z \quad \mathbf{A} = \frac{\hbar}{a}(k_x x + k_y y)\,\hat{\mathbf{x}}\,\sigma_z$$

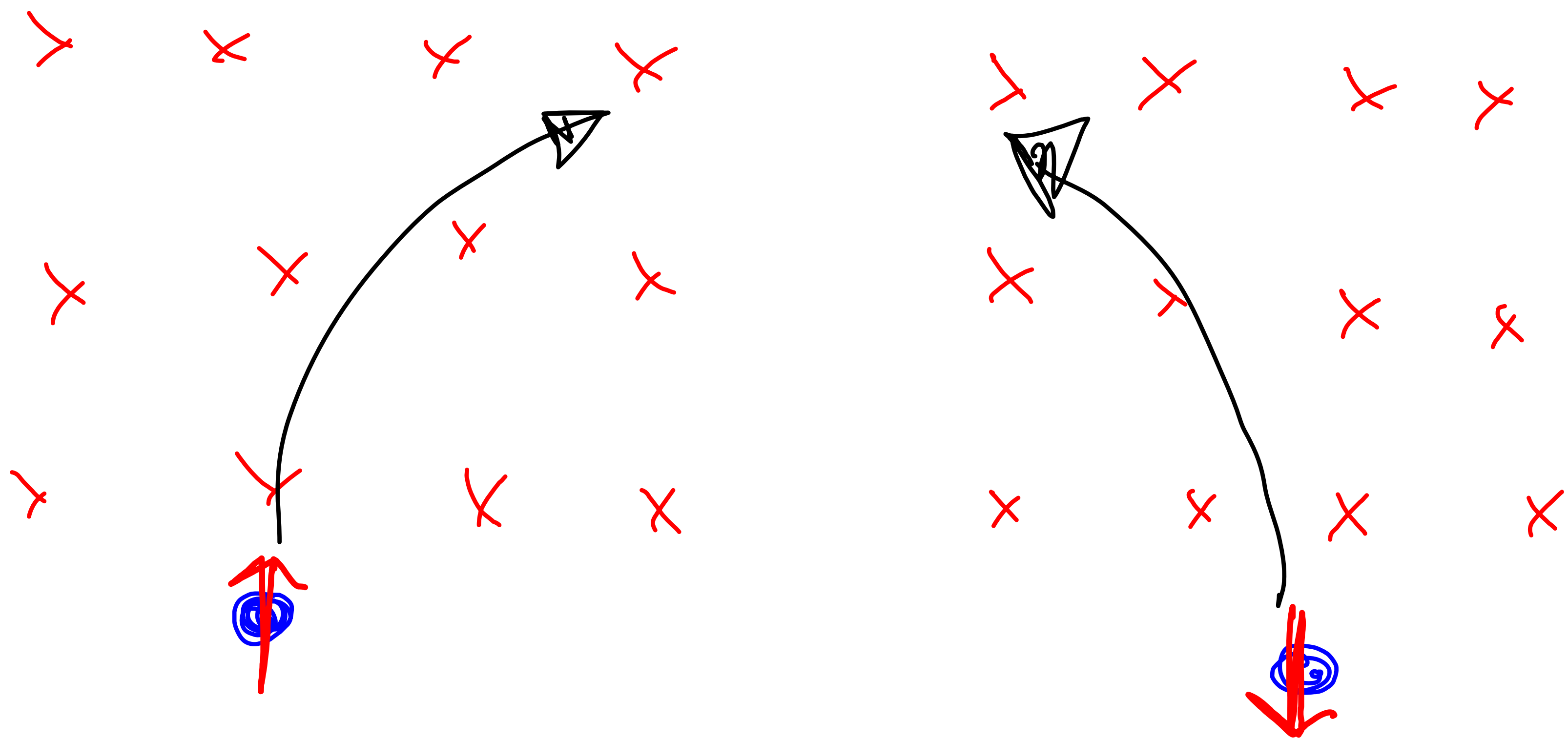
Hall effect

B field separates charge



Spin Hall effect

B field separates spin



Means that effective B field is different for two spins

Time reversal symmetry

- Quantized spin Hall effect (two opposite quantum Hall phases)
- Z topological index (due to conservation of σ_z)
- Topological insulator

PRL **96,** 106802 (2006) PHYSICAL REVIEW LETTERS week ending 17 MARCH 2006

Quantum Spin Hall Effect

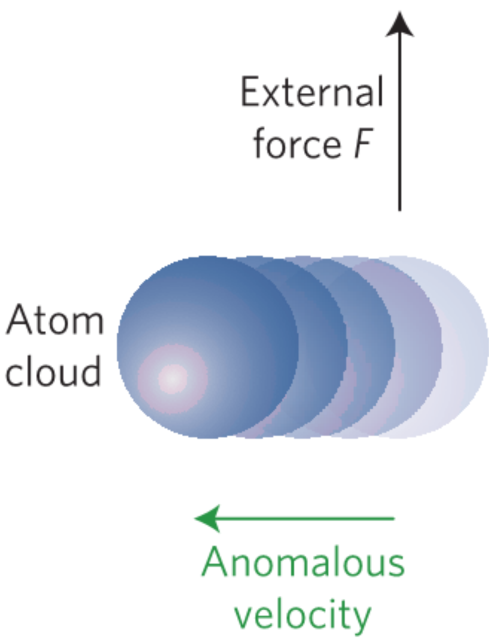
B. Andrei Bernevig and Shou-Cheng Zhang
Department of Physics, Stanford University, Stanford, California 94305, USA

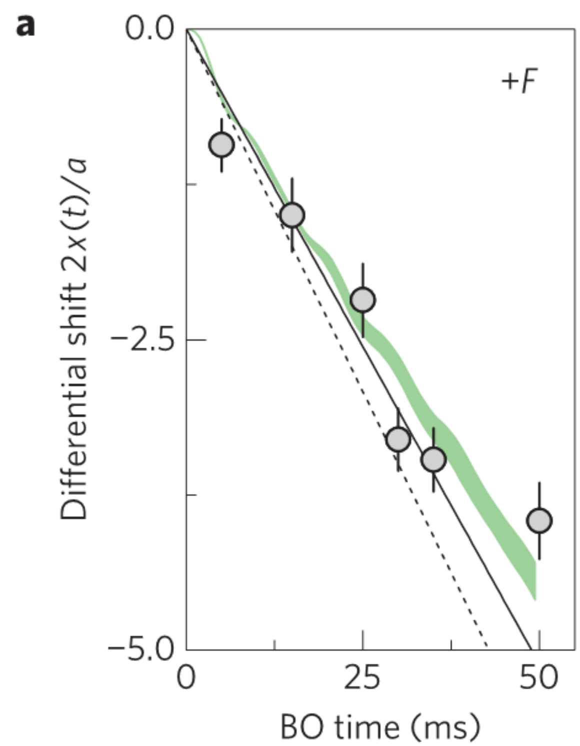
Exact realization of this idealized proposal

LETTERS
PUBLISHED ONLINE: 8 DECEMBER 2014 | DOI: 10.1038/NPHYS3171
nature physics

Measuring the Chern number of Hofstadter bands with ultracold bosonic atoms

M. Aidelsburger[1,2*], M. Lohse[1,2], C. Schweizer[1,2], M. Atala[1,2], J. T. Barreiro[1,2†], S. Nascimbène[3], N. R. Cooper[4], I. Bloch[1,2] and N. Goldman[3,5]





Slope implies C=1

New discoveries in single particle physics

Topological phases

- Berry phase
- TKNN invariant, quantized Hall effect
- Chern number

Hamiltonians with topological phases

Lots of theoretical work (Jaksch, Zoller, Lewenstein, ……..)

New experimental frontier (Maryland, Hamburg, Munich, Zurich, MIT …)

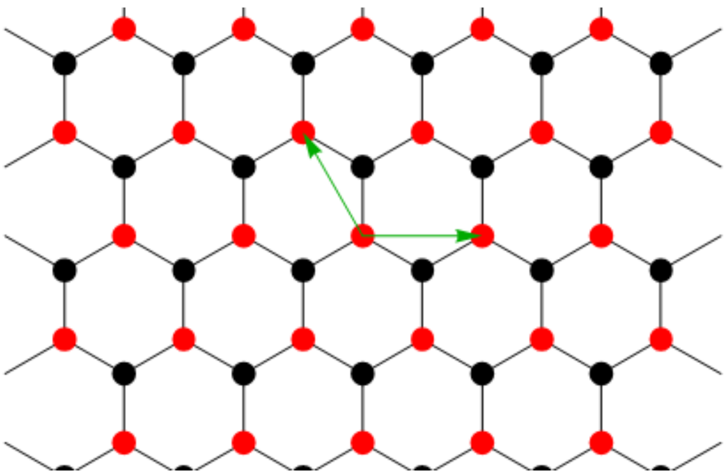
Various techniques: Berry phase by coupling two internal states, laser assisted tunneling, lattice modulation

LETTER

doi:10.1038/nature13915

Experimental realization of the topological Haldane model with ultracold fermions

Gregor Jotzu[1], Michael Messer[1], Rémi Desbuquois[1], Martin Lebrat[1], Thomas Uehlinger[1], Daniel Greif[1] & Tilman Esslinger[1]



Graphene lattice
+ breaking inversion symmetry
+ breaking time reversal symmetry

Complex next nearest neighbor hopping
Energy offset

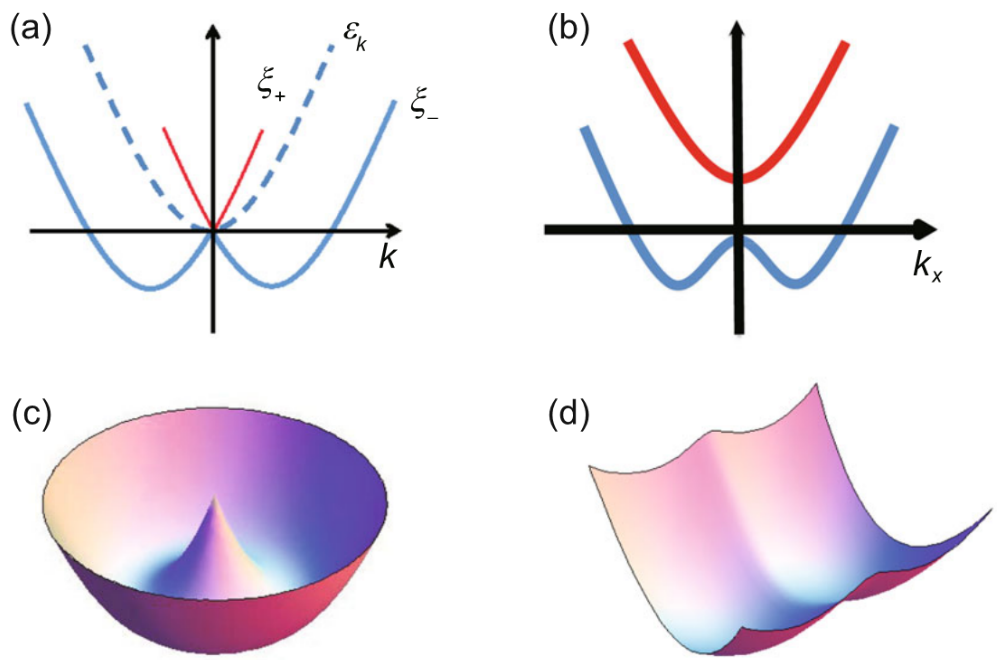
The model of Haldane is the first example of a topological insulator beyond quantum Hall effect

Spin orbit coupling

Using laser beams to couple the spin degree of freedom to the motional state

$k_x \sigma_y$

(using Doppler sensitive (k_x) two-photon Raman spinflips between atomic hyperfine states



chiral $p_x + ip_y$-wave superfluid

p wave Feshbach resonance
polar molecules, dressed by microwaves
coupling to orbital degrees of freedoms

ARTICLE

Received 12 Apr 2014 | Accepted 25 Aug 2014 | Published 30 Sep 2014
DOI: 10.1038/ncomms6064

Chiral superfluidity with *p*-wave symmetry from an interacting *s*-wave atomic Fermi gas

Bo Liu[1], Xiaopeng Li[1,2], Biao Wu[3,4] & W. Vincent Liu[1,5]

ARTICLE

Received 7 Mar 2014 | Accepted 25 Jun 2014 | Published 25 Jul 2014
DOI: 10.1038/ncomms5504

Majorana modes and *p*-wave superfluids for fermionic atoms in optical lattices

A. Bühler[1], N. Lang[1], C.V. Kraus[2,3], G. Möller[4], S.D. Huber[5] & H.P. Büchler[1]

Outlook

Engineering the tunneling phase in optical lattices

New tools

Laser assisted tunneling

Superlattices

Lattice modulation

New elements

Dirac points

Weyl points

Spin-orbit coupling

Bands with Chern number

New science

Quantum Hall physics

Topological insulators

Majorana fermions?

New quantum phases of matter

New frontiers:

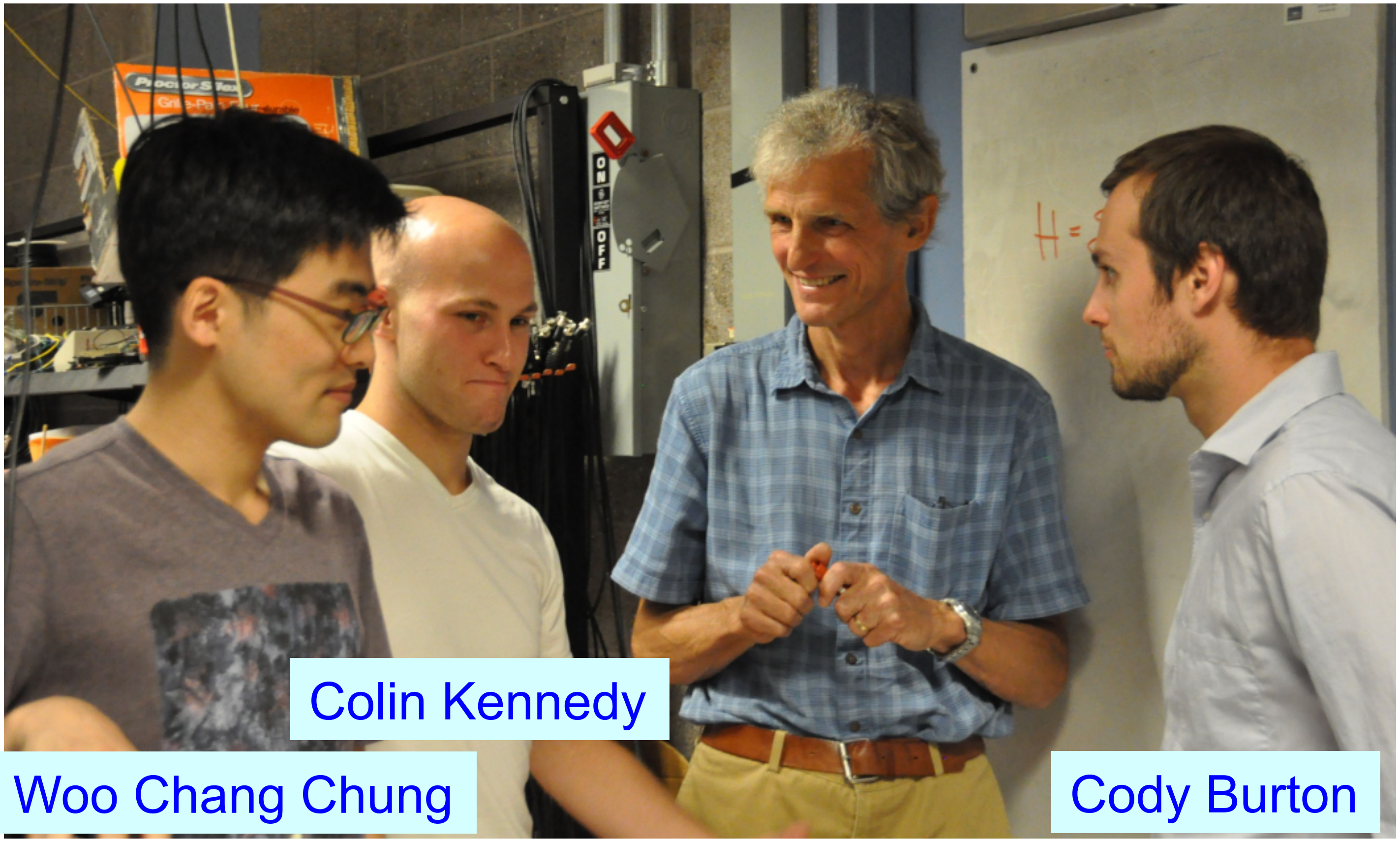
Precision many body physics
Interactions at the unitarity limit
Synthetic gauge field
Rapidly rotating gases
Quantum Hall effect
Spin-orbit coupling
Disorder – Anderson localization
Few-body correlations, Effimov states
Quantum magnetism (spin Hamiltonians, frustration)
Orbital magnetism (flat bands)
SU(N) magnetism
Matter with dipolar interactions (Rydberg, polar molecules,
high μ atoms)

Credits:

BEC 4

Rb BEC in optical lattices

former members:
Hiro Miyake
Georgios Siviloglou



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