Tilted lattices, Bloch oscillations, laser assisted tunneling and synthetic gauge fields

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July 9, 2014
Quantum matter at Ultralow Temperatures
Varenna, Italy

Massachusetts
Institute of
Technology

Varenna Summer School 1991 on Laser Cooling

Varenna Summer School 1998 on Bose-Einstein Condensation

Varenna Summer School 2006 on Fermi gases

The quest for new materials

Our approach: Atomic legos

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

Assemble them to behave
like the simplest realization of important materials

Tradition in physics:
Look for simple realizations of interesting phenomena

We like paradigmatic models!
Hydrogen atom, two-level system, harmonic oscillator

Hubbard models, ideal Fermi gas, phonon-free band structure, single-band approximation, independent electrons ….

Use the tools and precision of atomic physics to realize important Hamiltonians of many-body physics

Bosons

- Weakly interacting Bose gas (BEC)
- Bose-Hubbard model (Mott insulator)
- Spinor condensates

Fermions

- BEC-BCS crossover
- Fermions with “infinite” interaction strength
- Imbalanced Fermi superfluids
- Fermi-Hubbard model

Two ways of going beyond realizing “natural” materials:

- Add extra bells and whistles
- Digital quantum simulation (time evolution approximated by quantum logic operations)

One of the most important “materials” in physics:

Electrons in a magnetic field

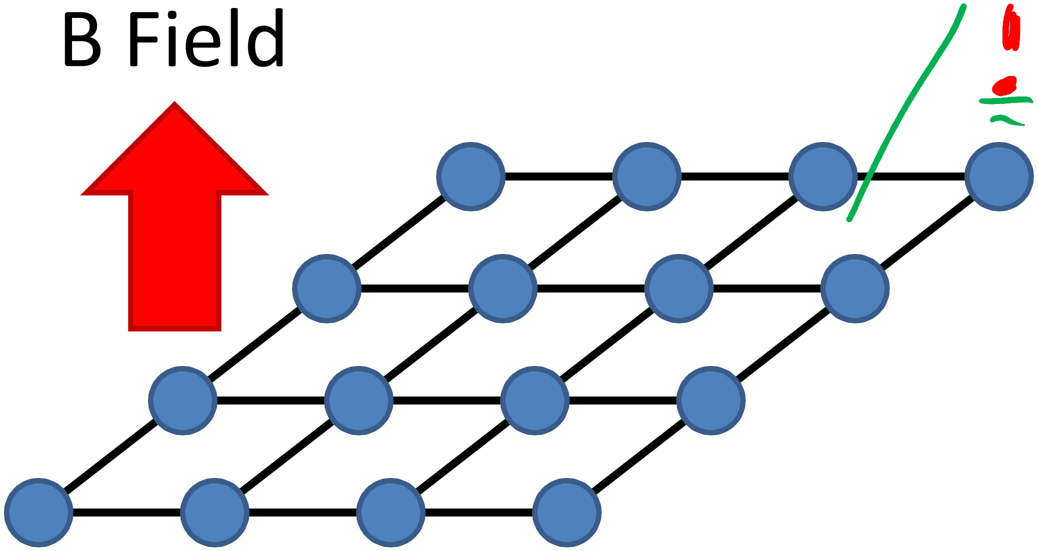
- Landau levels
- Hall effect
- Quantum Hall effect
- Fractional Hall effect

Extend to:

- other particles
  - more spin states
  - bosons

- High field
  - one flux quantum per unit cell
  - requires 10,000 Tesla

$$\Phi = \int B \, dA \overset{!}{=} \Phi_0 = \frac{h}{q}$$



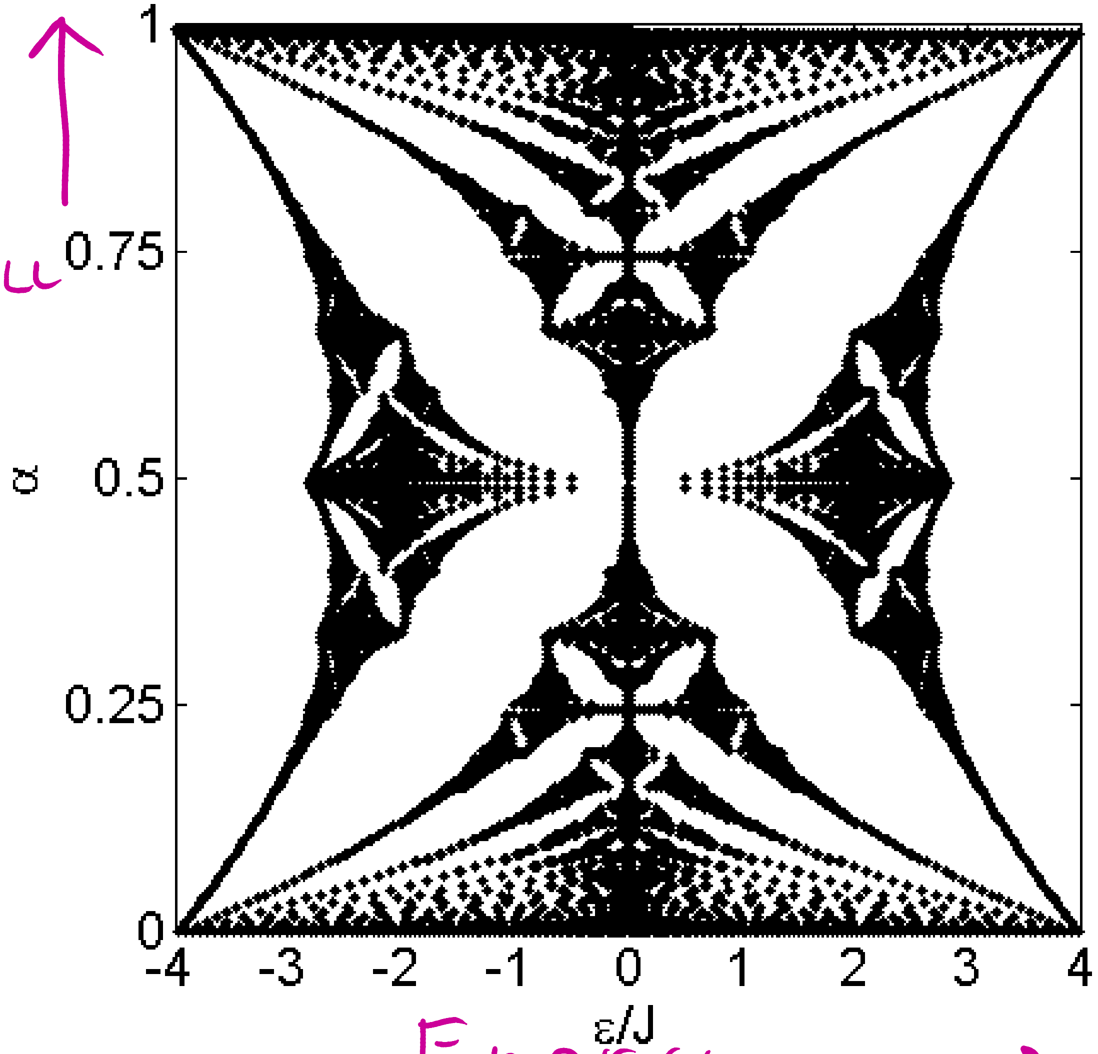
PHYSICAL REVIEW B VOLUME 14, NUMBER 6 15 SEPTEMBER 1976

Energy levels and wave functions of Bloch electrons in rational and irrational magnetic fields*

Douglas R. Hofstadter†
Physics Department, University of Oregon, Eugene, Oregon 97403

$$\frac{\Phi_{\text{UNIT CELL}}}{\Phi_0}$$

$$\Phi_0 = \frac{h}{q}$$



Energy →

Hofstadter Butterfly

Fractal structure of energy levels

So far only observed in superlattices

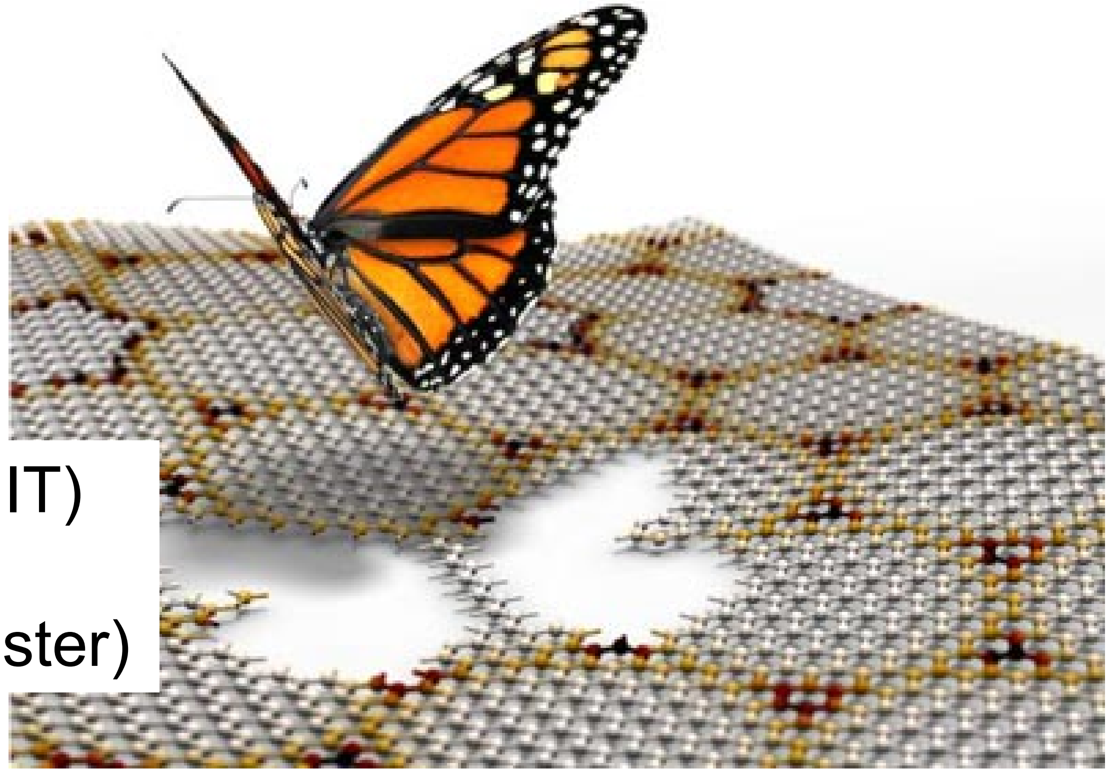
Albrecht, von Klitzing, et al. 2001, some evidence

Graphene 2013:
3 groups

Hofstadter's butterfly spotted in graphene

May 15, 2013 1 comment

Physics World
May 2013



Butterfly spotted in 2D superlattice

Ashoori, Jarillo-Herrero (MIT)
Kim (Columbia)
Novoselov, Geim (Manchester)

How to study this with neutral atoms?

$$E = -\vec{\mu}\,\vec{B}$$

spin
effect

How to study this with neutral atoms?

~~$E = -\vec{\mu}\vec{B}$~~ ~~spin effect~~

$$\vec{F} = q\vec{v}\times\vec{B}$$

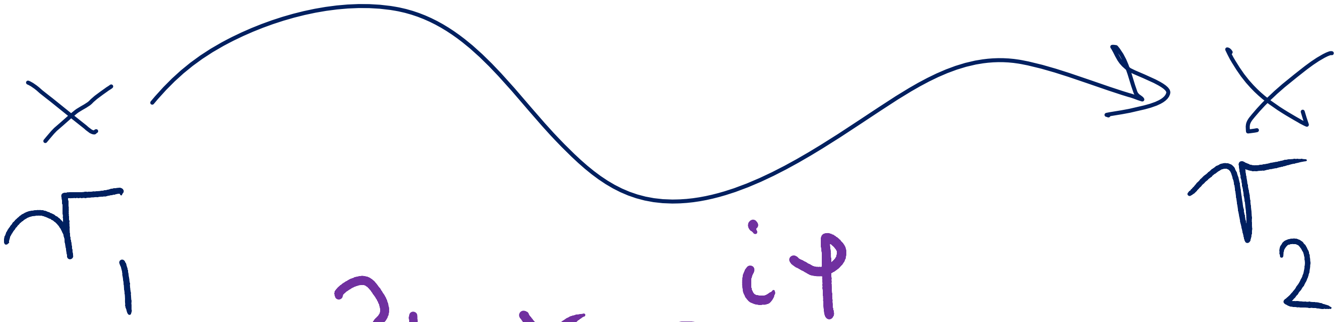
Lorentz Force

orbital effect

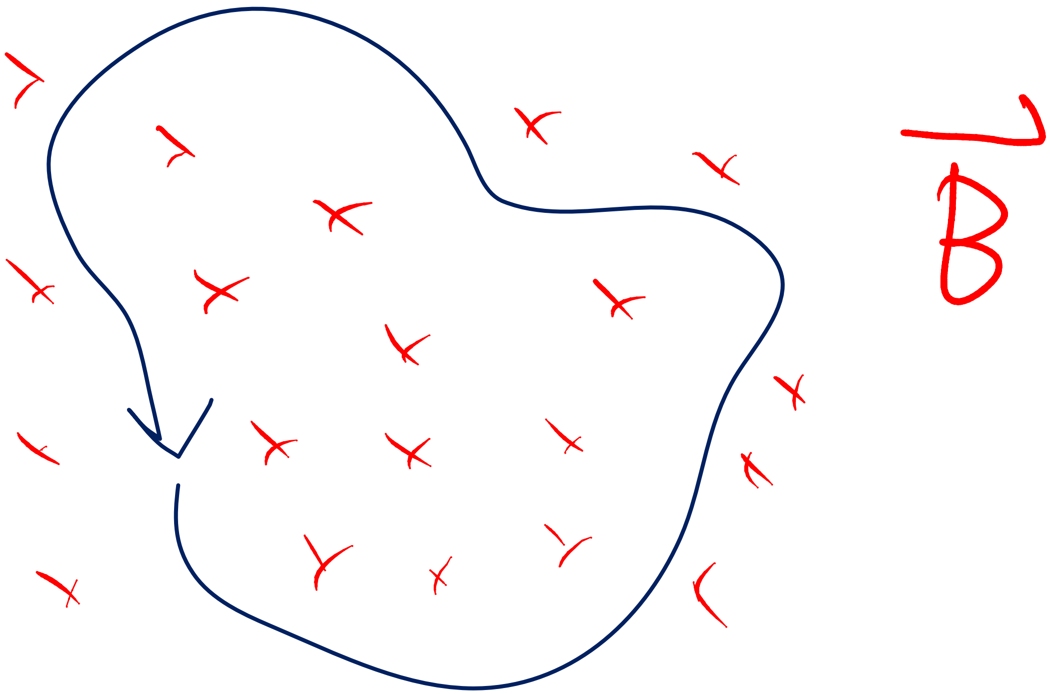
$$\vec{B} = \vec{\nabla} \times \vec{A}$$

$$\vec{B} = \vec{\nabla} \times \vec{A}$$

$$\varphi = \frac{q}{\hbar} \int_{r_1}^{r_2} \vec{A} \, d\vec{s}$$



$$\psi \times e^{i\varphi}$$



$$\varphi_{\text{enclosed}} = \frac{q}{\hbar}\int \vec{A}\, d\vec{s} = \frac{q}{\hbar}\int \underbrace{\underbrace{(\vec{\nabla}\times\vec{A})}_{B}\, d^2r}_{\Phi} = 2\pi\frac{\Phi}{\Phi_0}$$

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?

Concept:

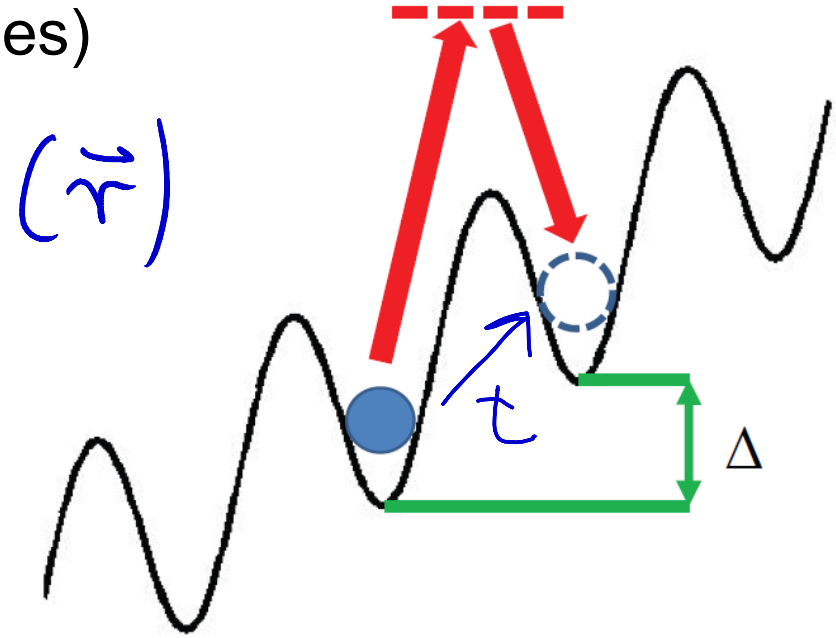
Create a situation where tunneling is only possible with the help of laser beams

Result:

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

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

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

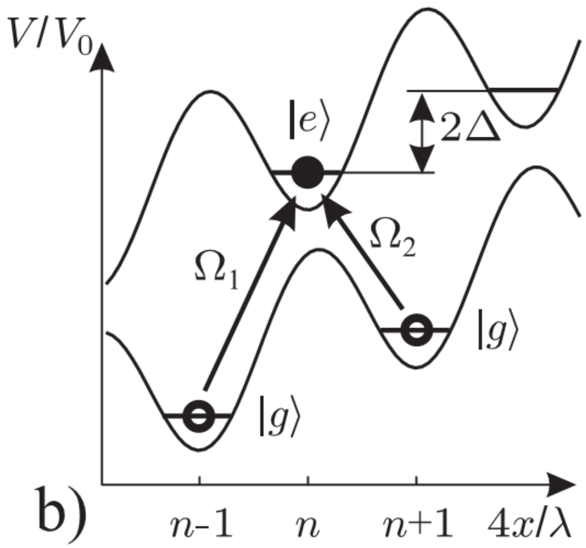


Crucial element
Laser assisted tunneling

Refs.
theory: Lots of suggestions
exp.:
Arimondo group, Pisa (2008)
Dos Santos group, Paris, PRL 106, 213002 (2011)
Bloch group, Munich (2011)

Note: frequency modulated or shaken lattices (Arimondo, Tino, Greiner, Sengstock) do not provide spatial phase (unless complex lattices and modulation schemes are used - Lewenstein, Sengstock, Esslinger)

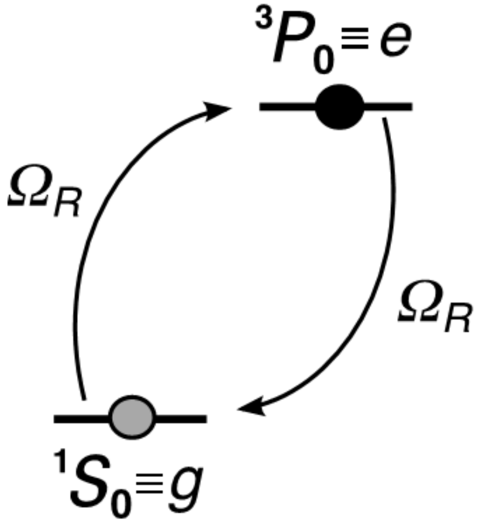
Jaksch, Zoller 2003



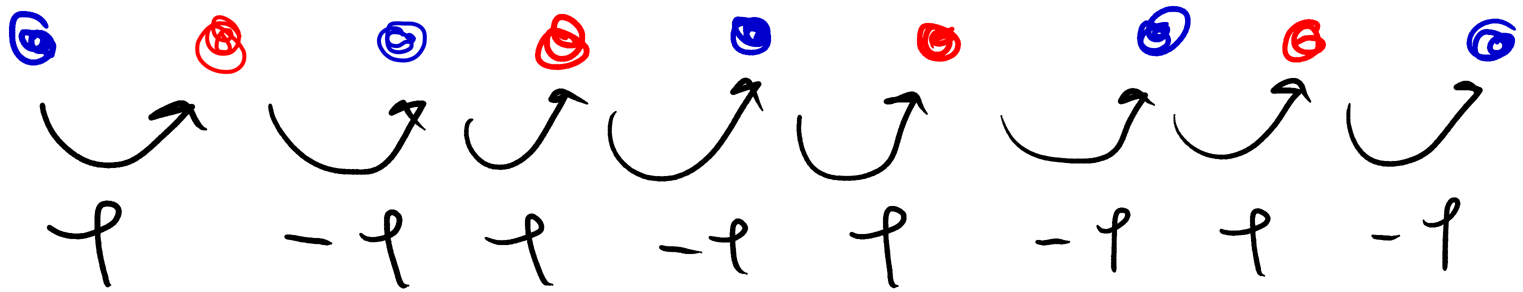
Raman process between two different hyperfine states, trapped in spin-dependent lattice

Dalibard, Gerbier 2010

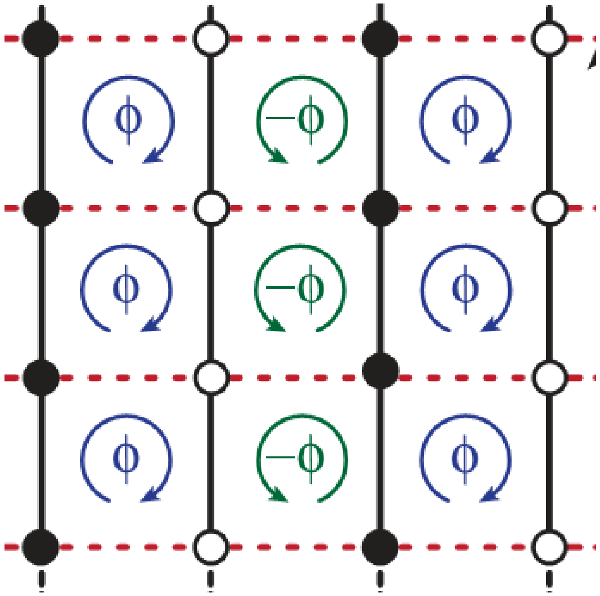
Optical transition in atoms with a long-lived metastable excited state, such as alkaline-earth atoms or ytterbium



These schemes, in their easiest implementation, lead to staggered flux



(those authors suggested rectification using additional laser beams and tilt or superlattices)

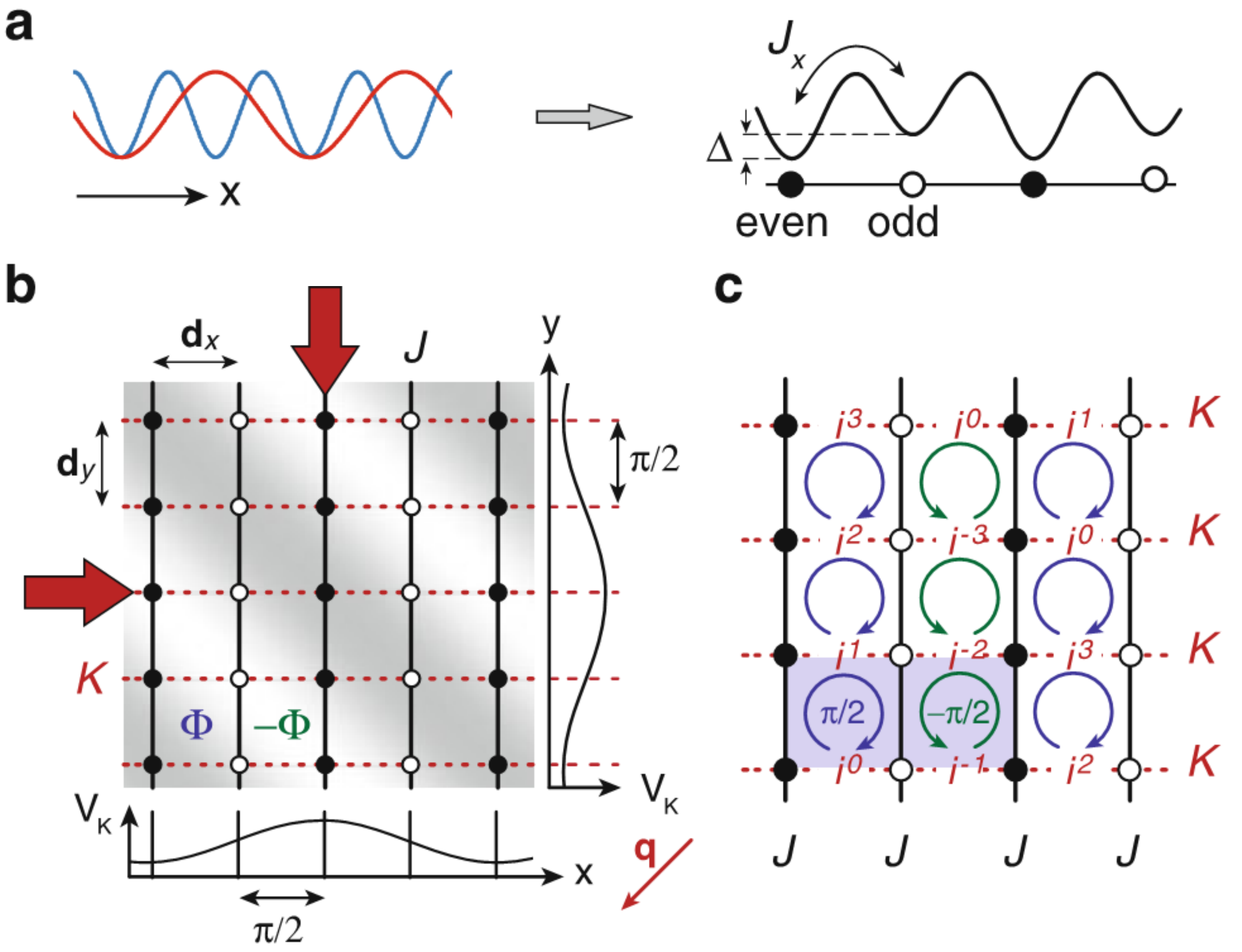


Experimental realization of staggered magnetic field in superlattices

Selected for a Viewpoint in *Physics*
PRL **107,** 255301 (2011) PHYSICAL REVIEW LETTERS week ending 16 DECEMBER 2011

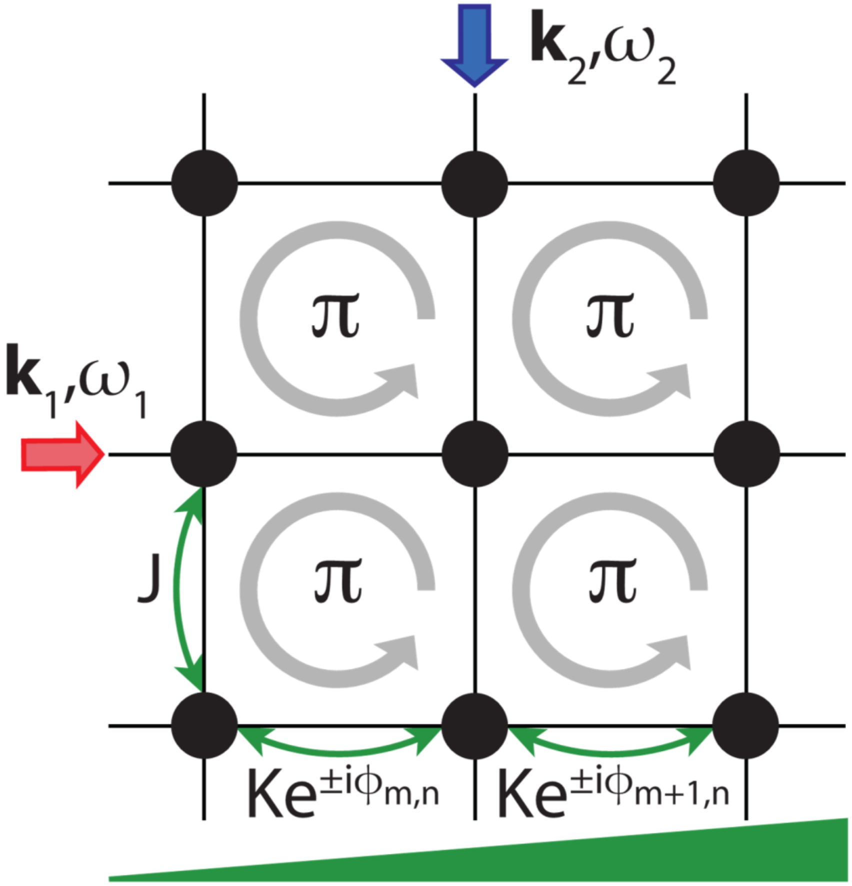
Experimental Realization of Strong Effective Magnetic Fields in an Optical Lattice

M. Aidelsburger,[1,2] M. Atala,[1,2] S. Nascimbène,[1,2,3] S. Trotzky,[1,2] Y.-A. Chen,[1,2,*] and I. Bloch[1,2,†]



Scheme for Creating Synthetic Magnetic Fields

Experimental Setup

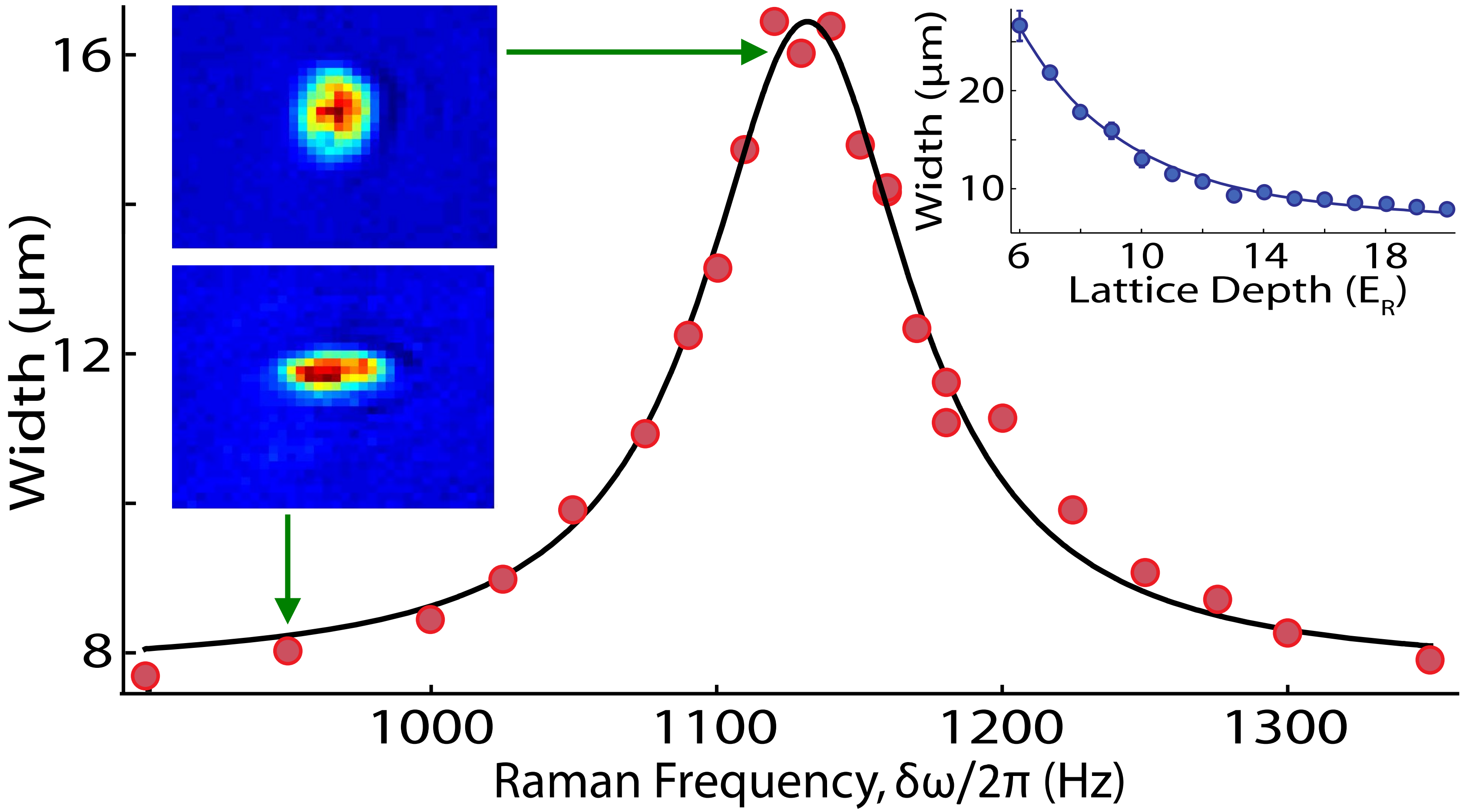


- **Features**
  - 2D or 3D lattice with a tilt
  - Works in cubic lattice
  - Use 2-photon Raman transition
  - Works for spinless system (one internal state)
  - Far-off resonant beams
  - Only need 2 laser beams to create uniform flux
  - Flexibility in realizing any enclosed flux through angle of Raman beams

Observing Raman Assisted Tunneling

$\alpha = 1/2$

In situ width versus Raman detuning



Compared to realization with Raman spin flips (Spielman, NIST):

No internal states (or A, B sites) needed in optical lattices
Near resonant lasers not necessary ⇒ no heating due to spontaneous emission (however, heating possible due to modulation)

Miyake H, Siviloglou G A, Kennedy C J, Burton W C and Ketterle W, . Rev. Lett. 111, 185302 (2013).
Realizing the Harper Hamiltonian with Laser-Assisted Tunneling in Optical Lattices

Extension/modification of theoretical proposals by Jaksch/Zoller, Gerbier/Dalibard, Kolovsky

Related work: Munich (I. Bloch): Appl. Phys. B (2013) ,
Phys. Rev. Lett. 111, 185301 (2013).

How to engineer these phases?

Concept:

Create a situation where tunneling is only possible
with th

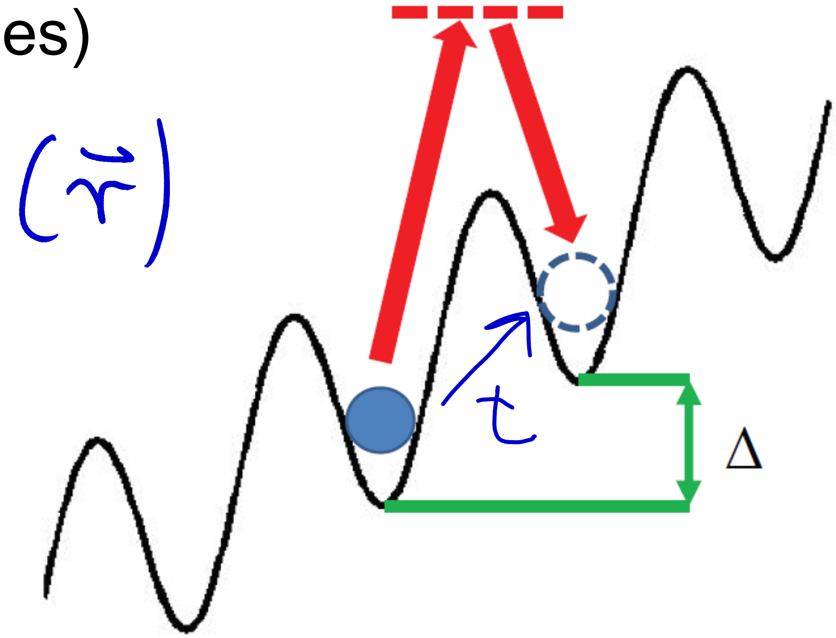
Result

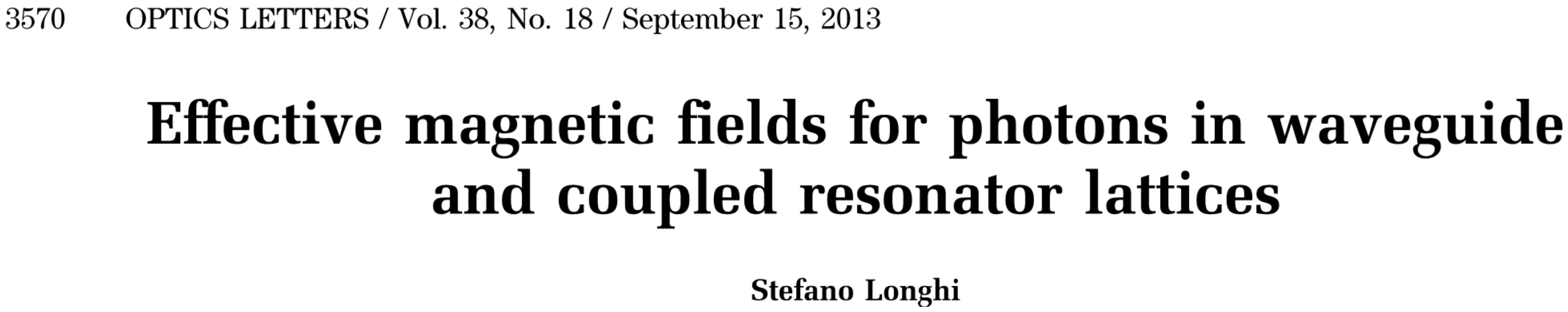
Tunne
the local phase of the laser beam (or of the two
photon field for Raman processes)

We would probably not be interested in this systems if it were not for its analogy with electrons in magnetic fields

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

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



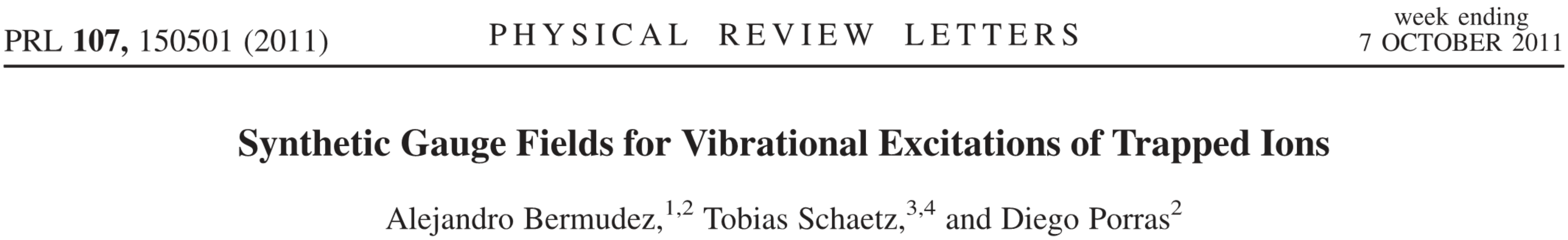


3570 OPTICS LETTERS / Vol. 38, No. 18 / September 15, 2013

Effective magnetic fields for photons in waveguide and coupled resonator lattices

Stefano Longhi

using a square lattice of optical waveguide resonators



PRL **107,** 150501 (2011) PHYSICAL REVIEW LETTERS week ending 7 OCTOBER 2011

Synthetic Gauge Fields for Vibrational Excitations of Trapped Ions

Alejandro Bermudez,[1,2] Tobias Schaetz,[3,4] and Diego Porras[2]

photon assisted tunneling of phonons in an array of micro traps

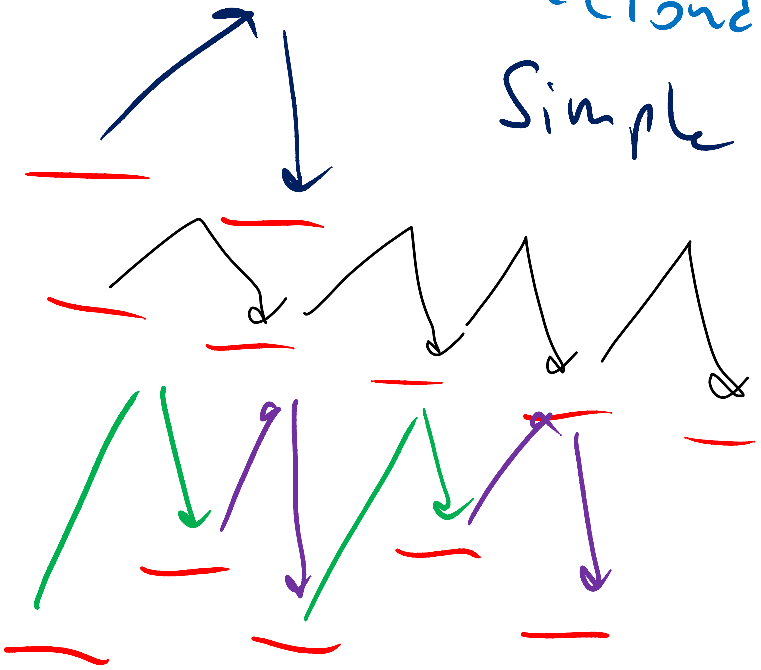
Large momentum transfers are needed:

$$P_{mech} = P_{can} - A$$

$n\hbar k$ momentum transfer ⇒

P_{can}^{max}, $A_{max} \simeq n\hbar k$

$$B_{max} \simeq \frac{n\hbar k}{d_{cloud}}$$



Simple Raman $n=2$

tilt: $n = \frac{d_{cloud}}{\lambda}$

double Raman $n = \frac{d_{cloud}}{\lambda}$

Now: Spin degree of freedom

How to engineer spin-orbit coupling for neutral atoms?

Raman spinflip scheme

Flip the spin in a momentum-dependent way (using the Doppler shift)

Our new scheme

Diagonal in σ_z
Abelian SU(2) gauge field

Affect the motion of spin up and WITHOUT flipping the spin (using Zeeman shifts to address spin up and down differently)

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

Origin of spin-orbit coupling:

Motion of charged particles in electric field

$$(\mathbf{p} \times \mathbf{E}) \cdot \boldsymbol{\sigma}$$

$\vec{E} = E\,\hat{e}_z$ $\Rightarrow$ Rashba coupling:

$$(\boldsymbol{\sigma} \times \mathbf{p})_z = \sigma_x p_y - \sigma_y p_x$$

E field in x-y plane $\Rightarrow$ Spin-orbit coupling term diagonal in σ_z

Radial field $\mathbf{E} \sim E(x, y, 0)$ $\Rightarrow$ $\boxed{E\sigma_z(xp_y - yp_x)}$

Corresponds to spin-dependent magnetic field $\sigma_z B\,\hat{e}_z$

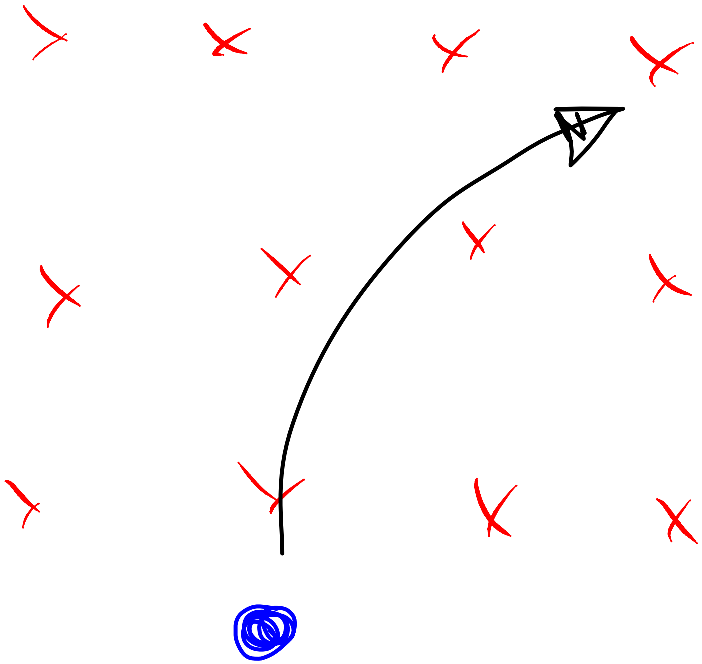
Symmetric gauge $\mathbf{A} = \frac{\sigma_z B}{2}(y, -x, 0)$

$\vec{A}\cdot\vec{p}$ term: $\boxed{\sigma_z B(xp_y - yp_x)}$

(Bernevig and Zhang, PRL 2006)

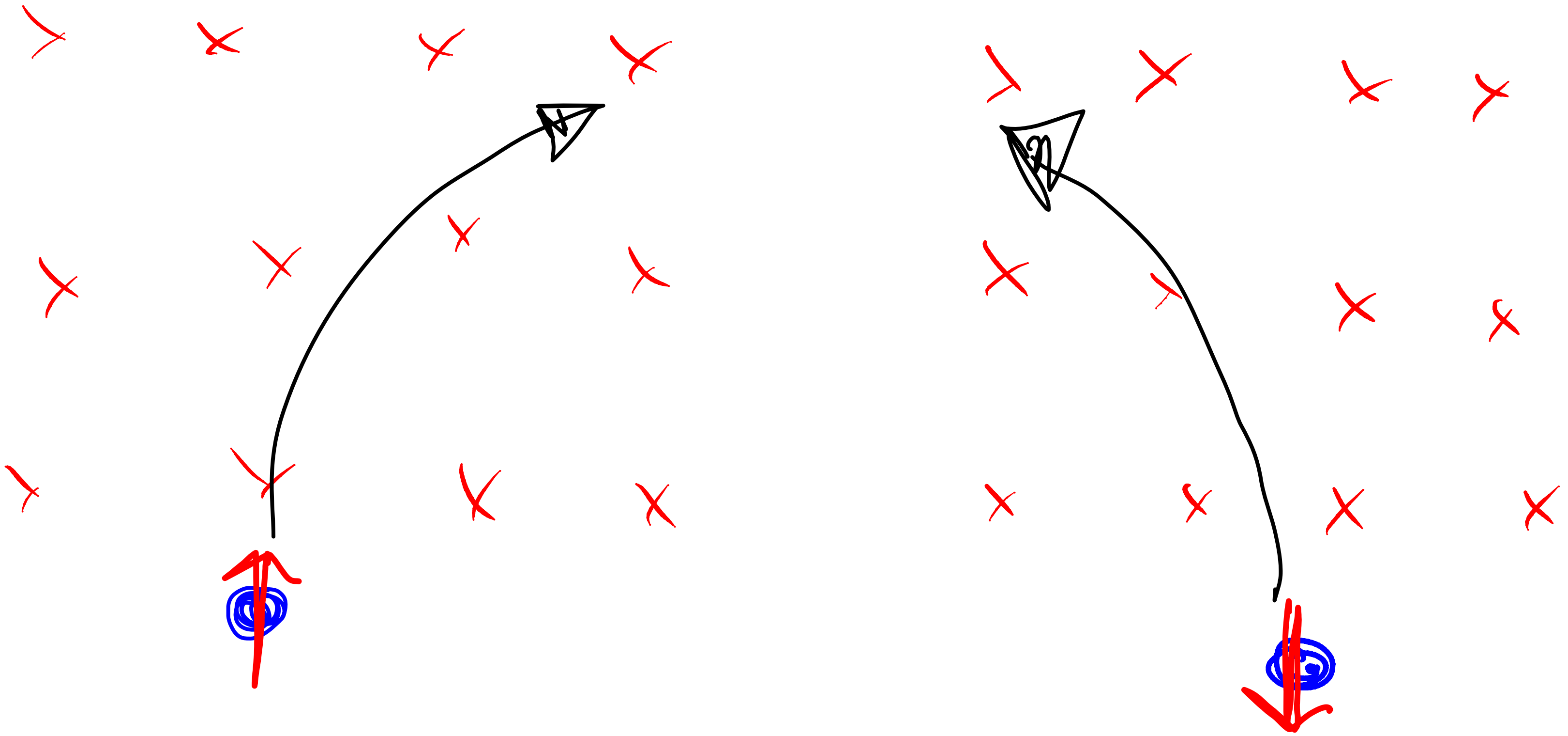
Hall effect

B field separates charge



Spin Hall effect

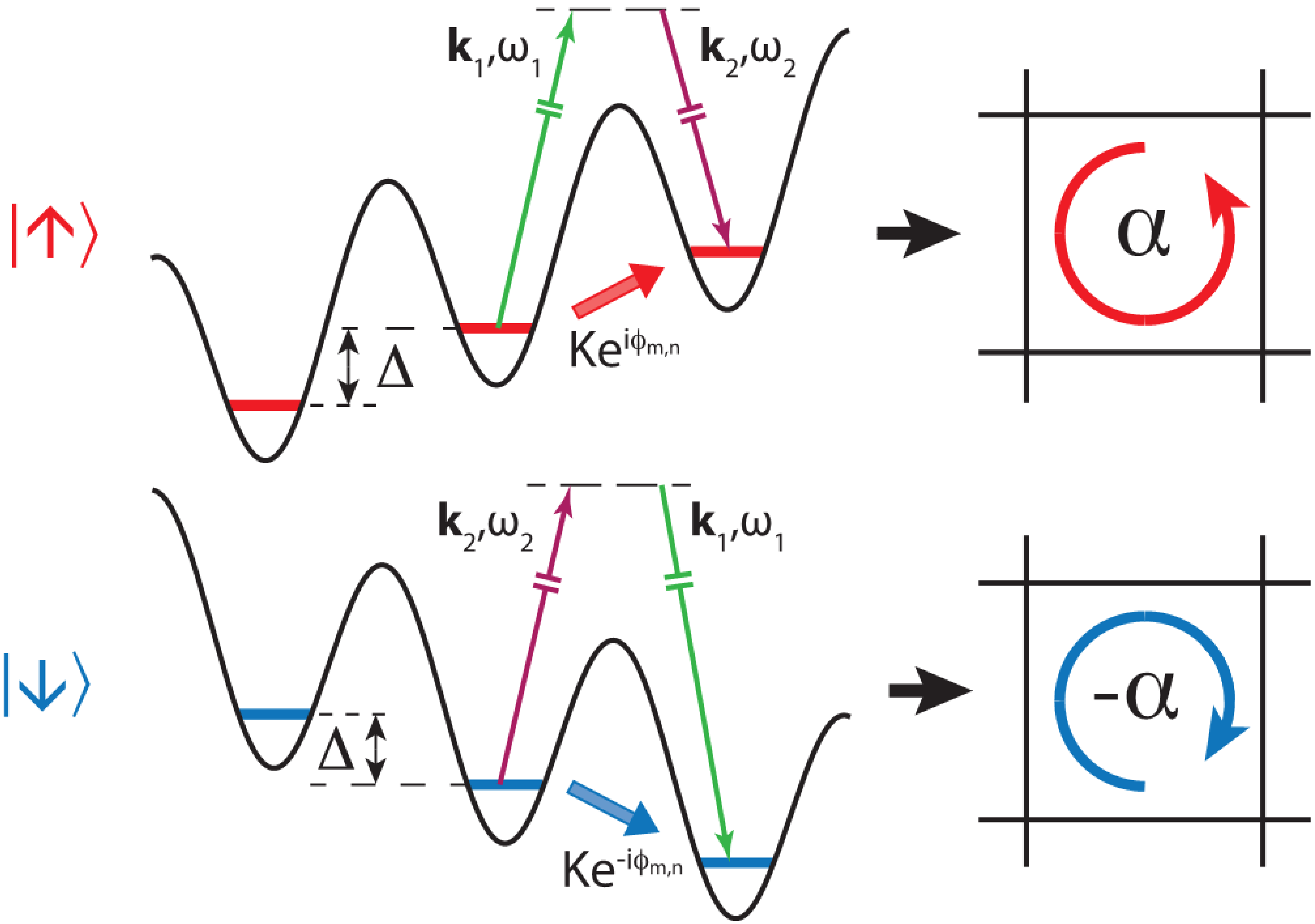
B field separates spin



Means that effective B field is different for two spins

In our scheme:

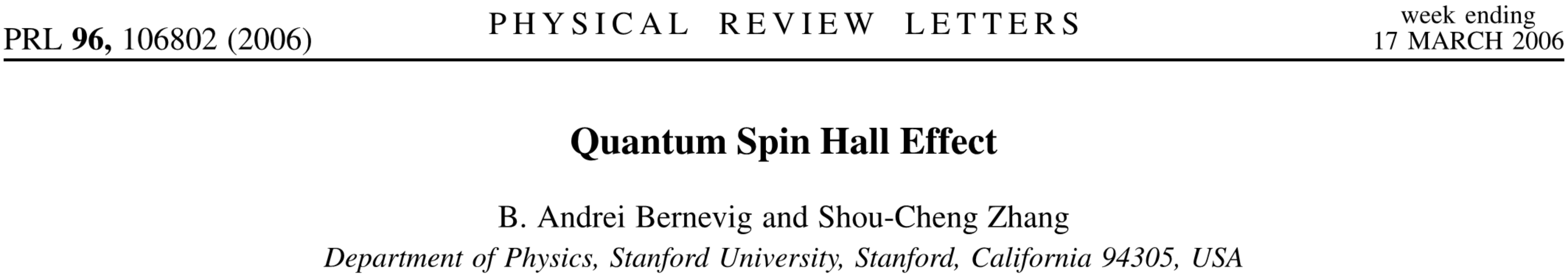
signs of B, A, phase of tunneling matrix elements reflect the momentum transfer by Raman beams



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

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

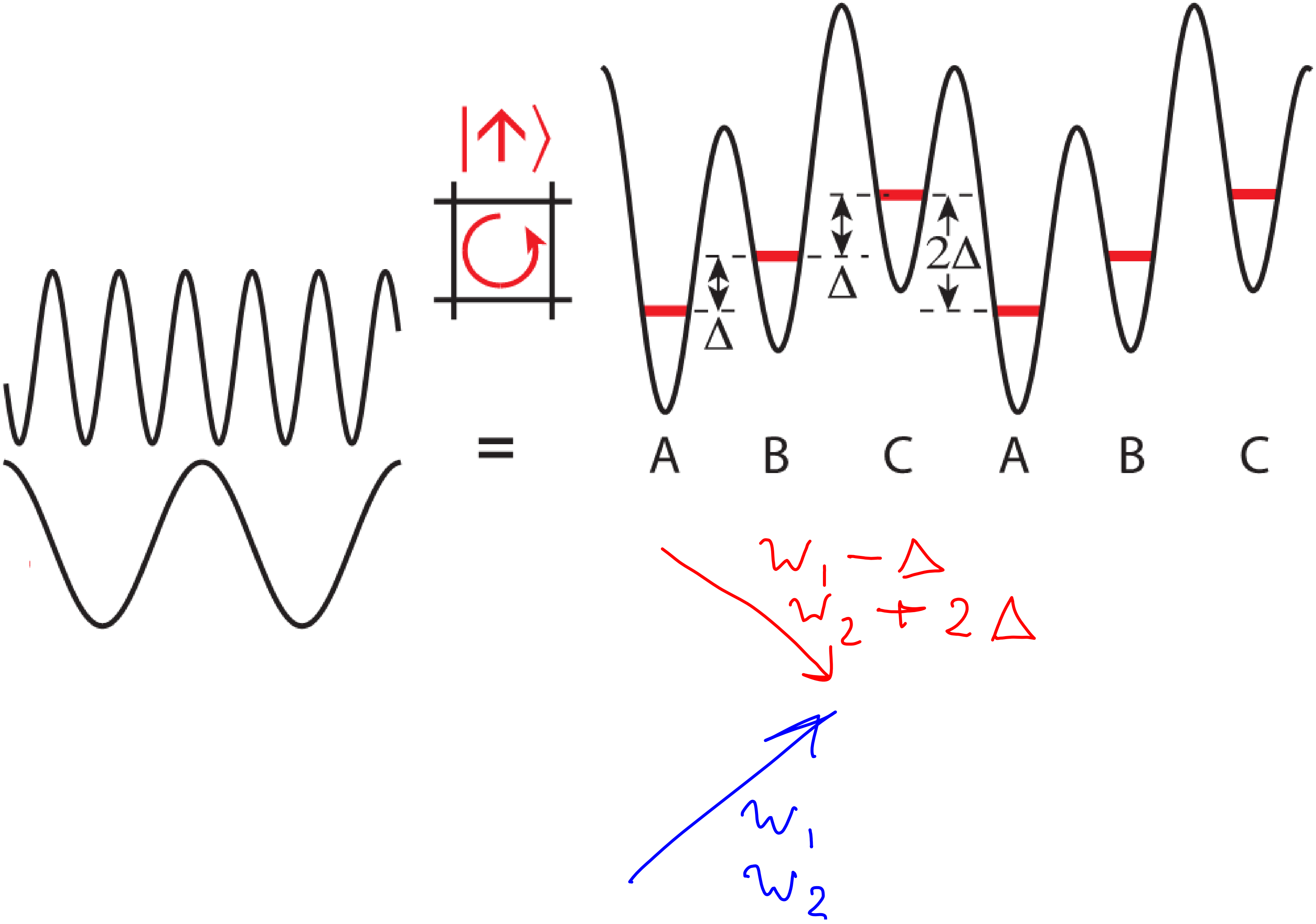
B. Andrei Bernevig and Shou-Cheng Zhang

Department of Physics, Stanford University, Stanford, California 94305, USA

Exact realization of this idealized proposal

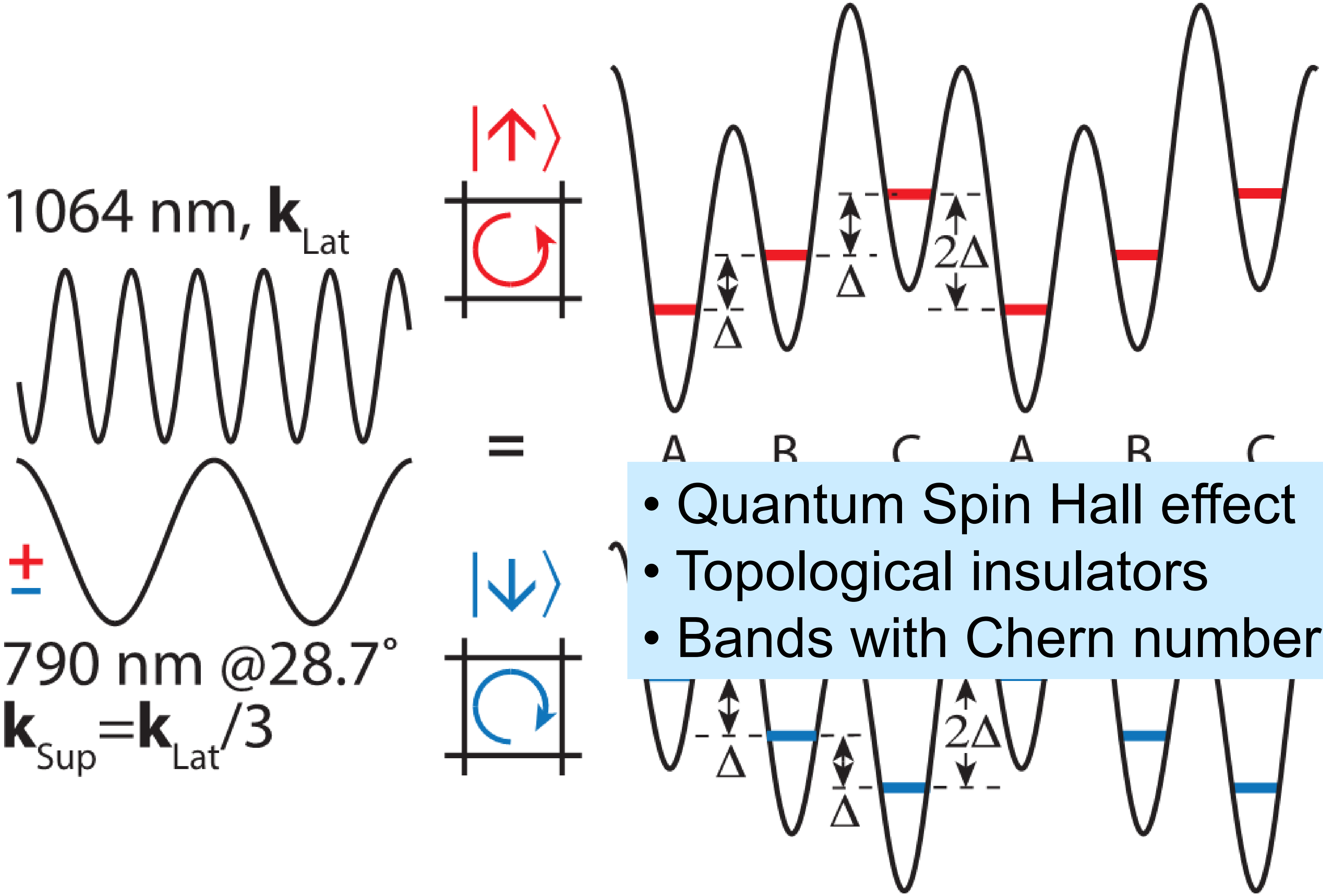
New way to rectify flux:

Single internal state, triple superlattice



Spin-dependent superlattice

Magic wavelength with vector AC Stark effect (fictitious B field)



- Quantum Spin Hall effect
- Topological insulators
- Bands with Chern numbers

Conclusion:

New schemes prove that arbitrary high B fields and spin Hall effect can (at least in principle) be implemented by adding only

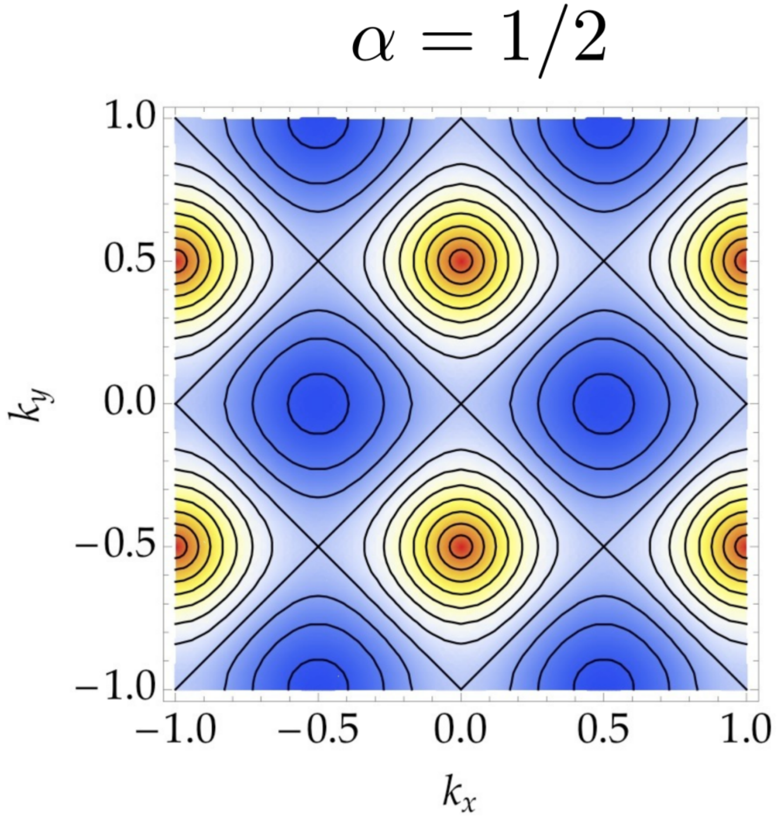
- two far off-resonant laser beams to a
- simple cubic lattice
- plus tilt (or triple superlattice)

- Spinflips are NOT necessary for certain forms of spin-orbit coupling and quantum spin Hall effect (diagonal in σ_z)
- Spinflips necessary only for other forms of spin-orbit coupling and non-Abelian gauge fields

Micromotion and heating issues (or realizing the ground state of modulated lattices)

Next step:

Realize the ground state of the Harper-Hofstadter Hamiltonian, observe 2x2 structure of Brioullin zone by momentum analysis (TOF)



$$H = \frac{\mathbf{p}^2}{2m} + V_{\mathrm{latt}}(\mathbf{r}) - \frac{\Delta}{a}\mathbf{x} + \Omega \sin\left(\delta\mathbf{k}\cdot\mathbf{r} - \frac{k_x a}{2} - \omega t\right)$$

In Wannier/Wannier-Stark basis:

$$H = \sum_{m,n}\Big(- m\Delta|m,n\rangle\langle m,n| - J_y|m,n+1\rangle\langle m,n| + h.c.$$

$$+ \sum_{m',n'} \Omega|m',n'\rangle\langle m',n'|\sin\left(\delta\mathbf{k}\cdot\mathbf{r} - \frac{k_x a}{2} - \omega t\right)|m,n\rangle\langle m,n|\Big)$$

Now: eliminate spatial dependence (tilt) and time dependence of diagonal terms by unitary transformation

Tunneling matrix element K (in tilt direction) and J (perpendicular) are time-dependent:

$$K(t) = \Omega\Phi_{y0}\big(\Phi_{x1}\cos(\omega t - \phi_{m,n}) - \Phi'_{x1}\sin(\omega t - \phi_{m,n})\big)e^{-i\omega t}$$

$$\sum_r J_r(\Gamma_x)e^{ir(\omega t - \phi_{m,n})}$$

$$J(t) = -J_y\sum_r J_r(\Gamma_x)e^{ir(\omega t + (k_x - k_y)a/2 - \phi_{m,n})}$$

Time averaging over one period of the laser modulation (rotating wave approximation):

$$K_{\text{eff}} = \frac{\Omega\Phi_{y0}}{2}e^{-i\phi_{m,n}}\left[\Phi_{x1}\Big(J_0(\Gamma_x) + J_2(\Gamma_x)\Big) + i\Phi'_{x1}\Big(J_0(\Gamma_x) - J_2(\Gamma_x)\Big)\right]$$

$$J_{\text{eff}} = -J_yJ_0(\Gamma_y) = J$$

Tuning the tunneling rates

Formal treatment of the Wannier-Stark to Harper mapping gives

$$K = \Omega\Phi_{y0}\left[\Phi_{x1}\frac{J_1(\Gamma_x)}{\Gamma_x} + i\Phi'_{x1}\frac{dJ_1(\Gamma_x)}{d\Gamma_x}\right]$$

$$J = J_y J_0(\Gamma_y))$$

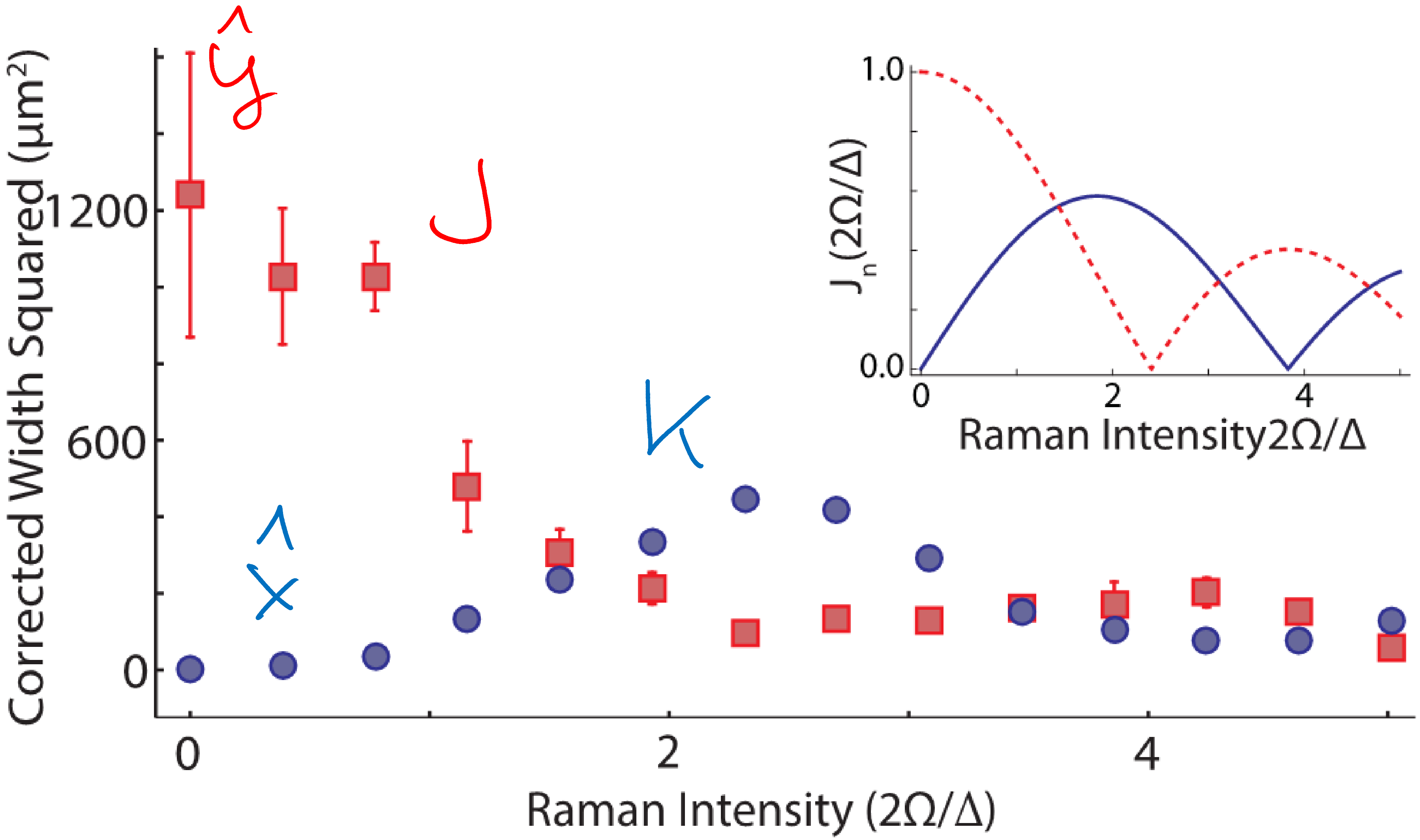
$$\Gamma_i = \frac{2\Omega\Phi_{y0}\Phi_{x0}}{\Delta}\sin\left(\frac{k_i a}{2}\right)$$

In the tight-binding limit:

$$K = J_x J_1\left(\frac{2\Omega}{\Delta}\right)$$

$$J = J_y J_0\left(\frac{2\Omega}{\Delta}\right)$$

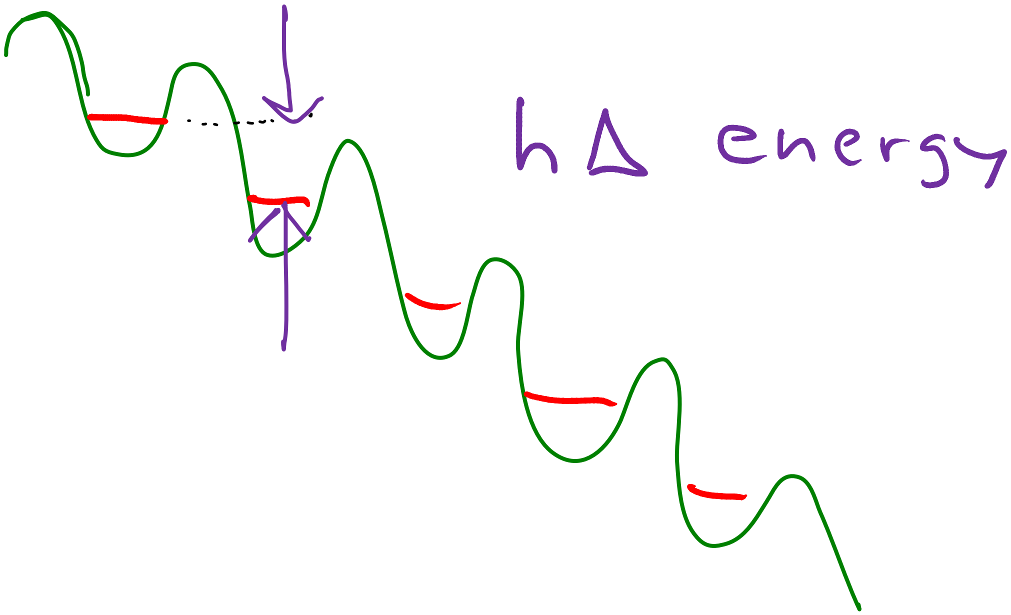
Tunneling rates include Bessel functions depending on intensity of Raman beams


ŷ
J
x̂
K
Corrected Width Squared (μm²)
1200
600
0
0
2
4
Raman Intensity (2Ω/Δ)
1.0
0.0
J_n(2Ω/Δ)
0
2
4
Raman Intensity2Ω/Δ

Back to heating:
Hamiltonian has terms neglected in the RWA oscillating at $n\Delta$ (Δ is tilt frequency or Bloch oscillation frequency)

$\Rightarrow$ Wave function has extra frequencies (energies) of $n\Delta$
= micromotion (analog to Paul trap)

Motion is coherent unless we have interactions (collisions)



Important question: Understand how micromotion and interactions lead to heating

Micromotion in a tilted lattice:
Bloch oscillations

Unitary transformation to derive the effective lattice Hamiltonian creates a “rotating” frame where the Bloch oscillations have disappeared.

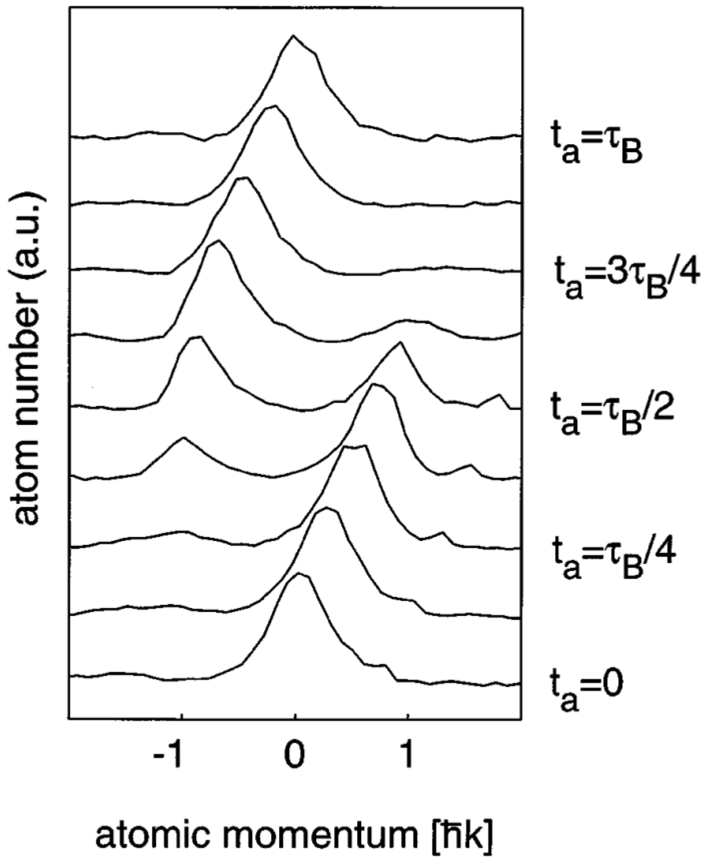
Lab frame: Bloch oscillations are present

VOLUME 76, NUMBER 24 PHYSICAL REVIEW LETTERS 10 JUNE 1996

Bloch Oscillations of Atoms in an Optical Potential

Maxime Ben Dahan, Ekkehard Peik, Jakob Reichel, Yvan Castin, and Christophe Salomon
Laboratoire Kastler Brossel, Departement de Physique, Ecole Normale Supérieure, 24 rue Lhomond,
75231 Paris Cedex 05, France

(Received 19 January 1996)



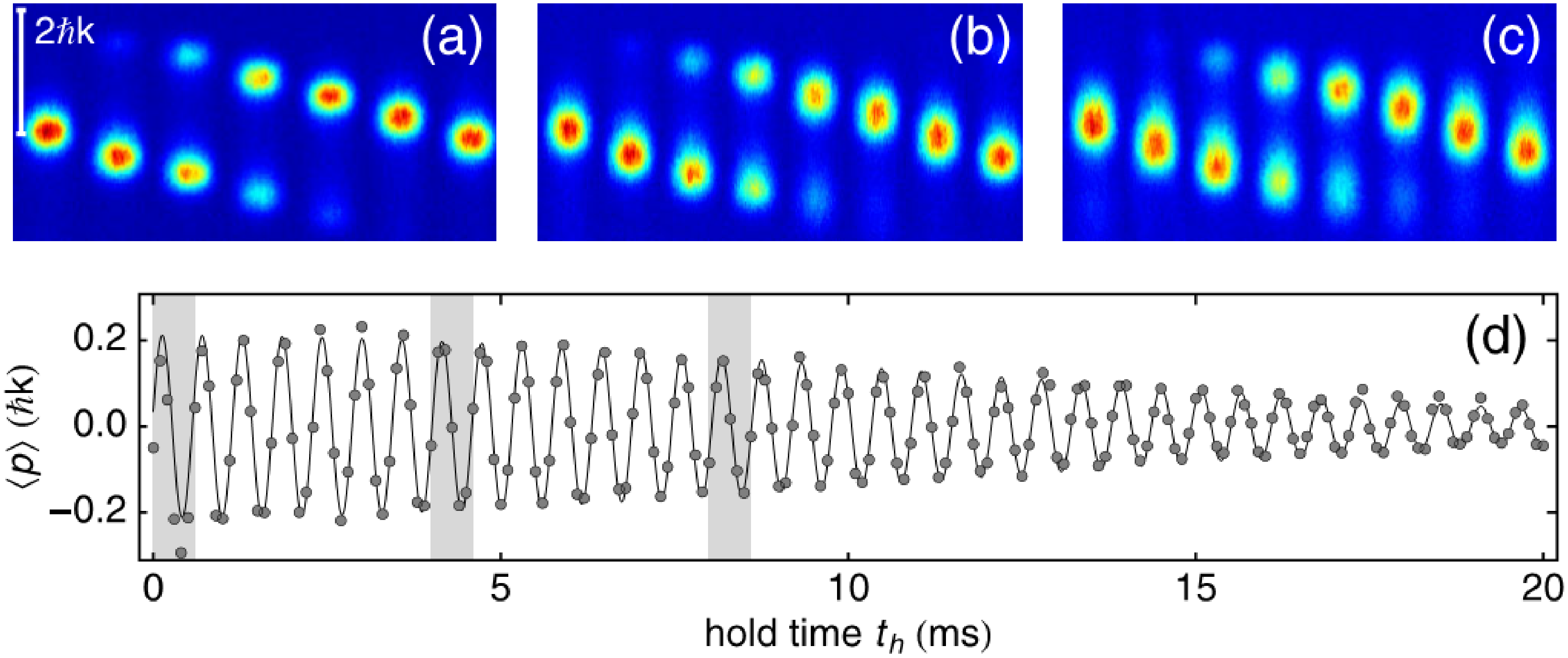
$\frac{d}{dt}$(quasimomentum) = Force

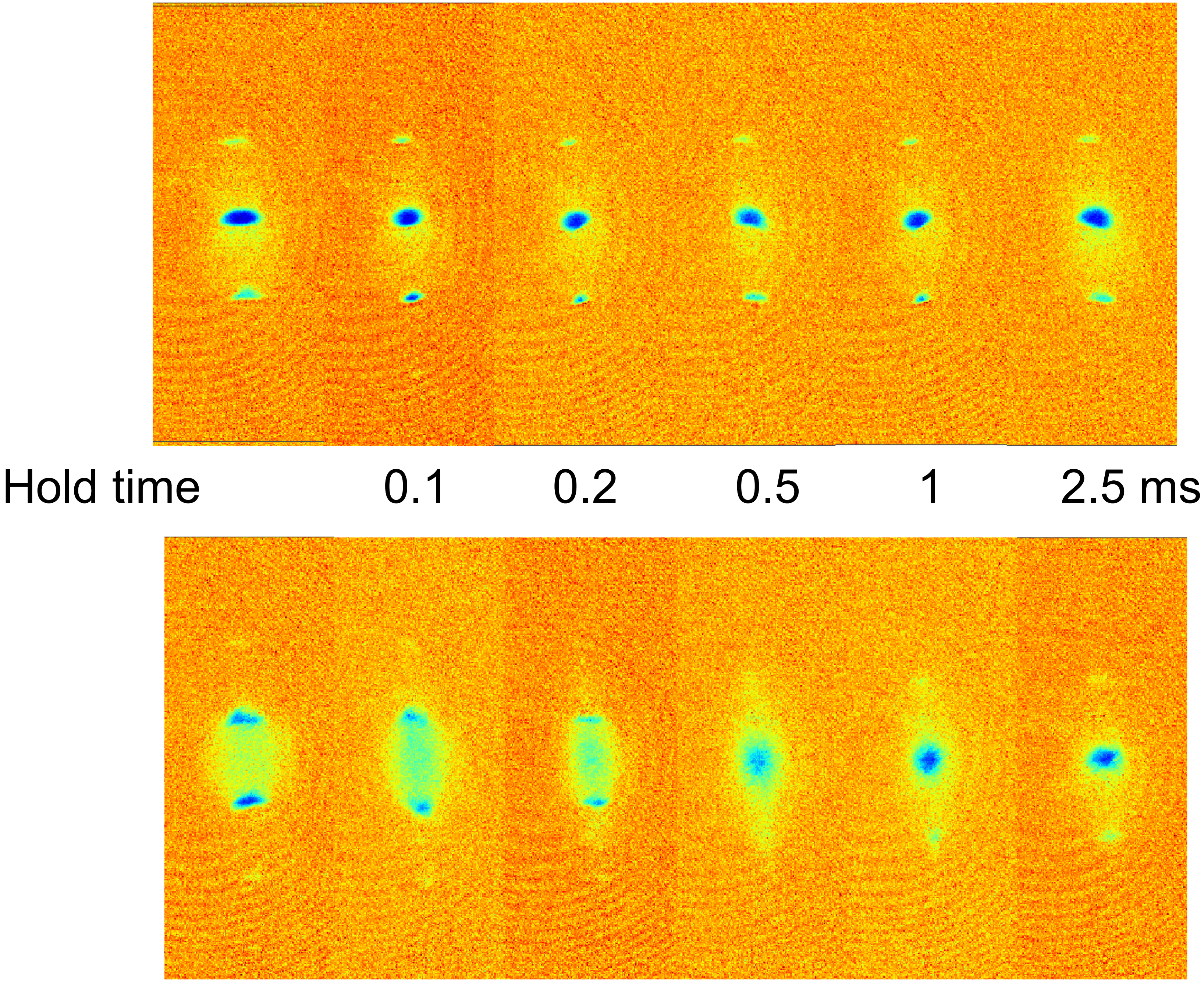
PRL **112,** 193003 (2014) PHYSICAL REVIEW LETTERS week ending
16 MAY 2014

Interaction-Induced Quantum Phase Revivals and Evidence for the Transition to the Quantum Chaotic Regime in 1D Atomic Bloch Oscillations

F. Meinert,[1] M. J. Mark,[1] E. Kirilov,[1] K. Lauber,[1] P. Weinmann,[1] M. Gröbner,[1] and H.-C. Nägerl[1]
[1]*Institut für Experimentalphysik und Zentrum für Quantenphysik, Universität Innsbruck, 6020 Innsbruck, Austria*

(Received 16 September 2013; published 15 May 2014)



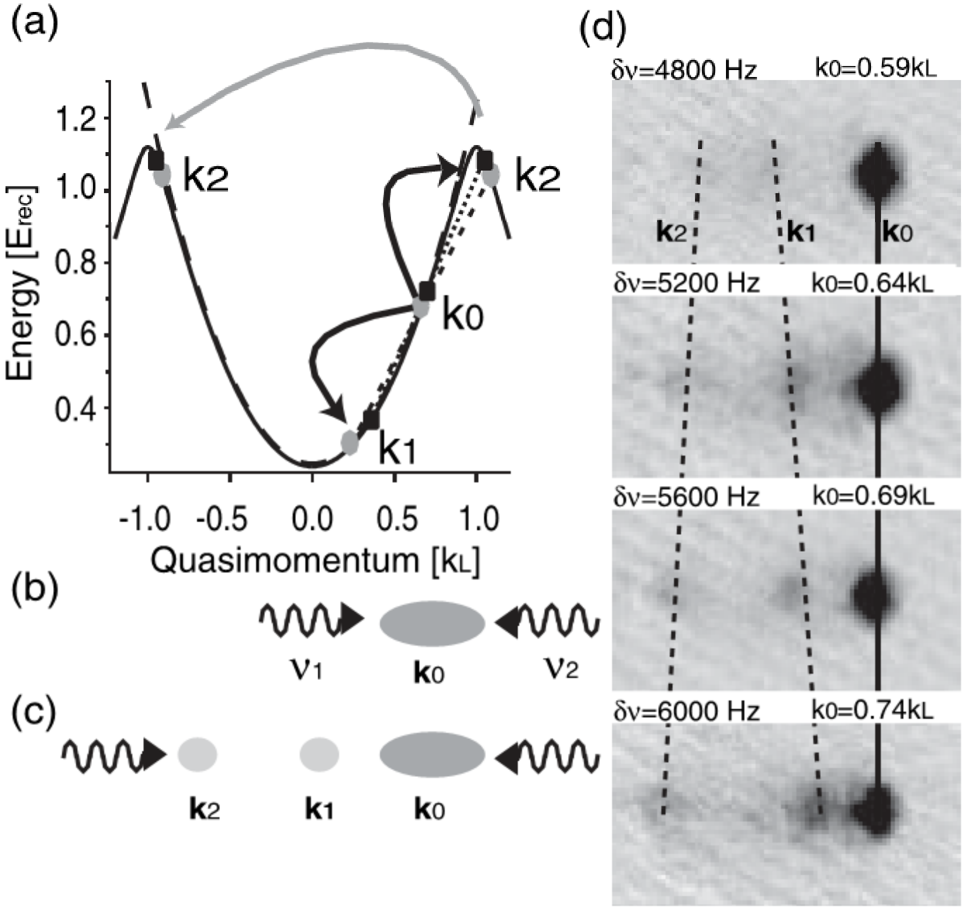


Rapid decay of states near the edge of the Brioullin zone

PRL **96,** 020406 (2006) PHYSICAL REVIEW LETTERS week ending 20 JANUARY 2006

Parametric Amplification of Scattered Atom Pairs

Gretchen K. Campbell, Jongchul Mun, Micah Boyd, Erik W. Streed, Wolfgang Ketterle, and David E. Pritchard*
MIT-Harvard Center for Ultracold Atoms, Research Laboratory of Electronics and Department of Physics,
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
(Received 12 September 2005; published 19 January 2006)



Related work:
Florence
Stanford

However, these studies looked at decay of fixed quasimomentum states --- not in a tilted lattice

More relevant: Decay of Bloch oscillations

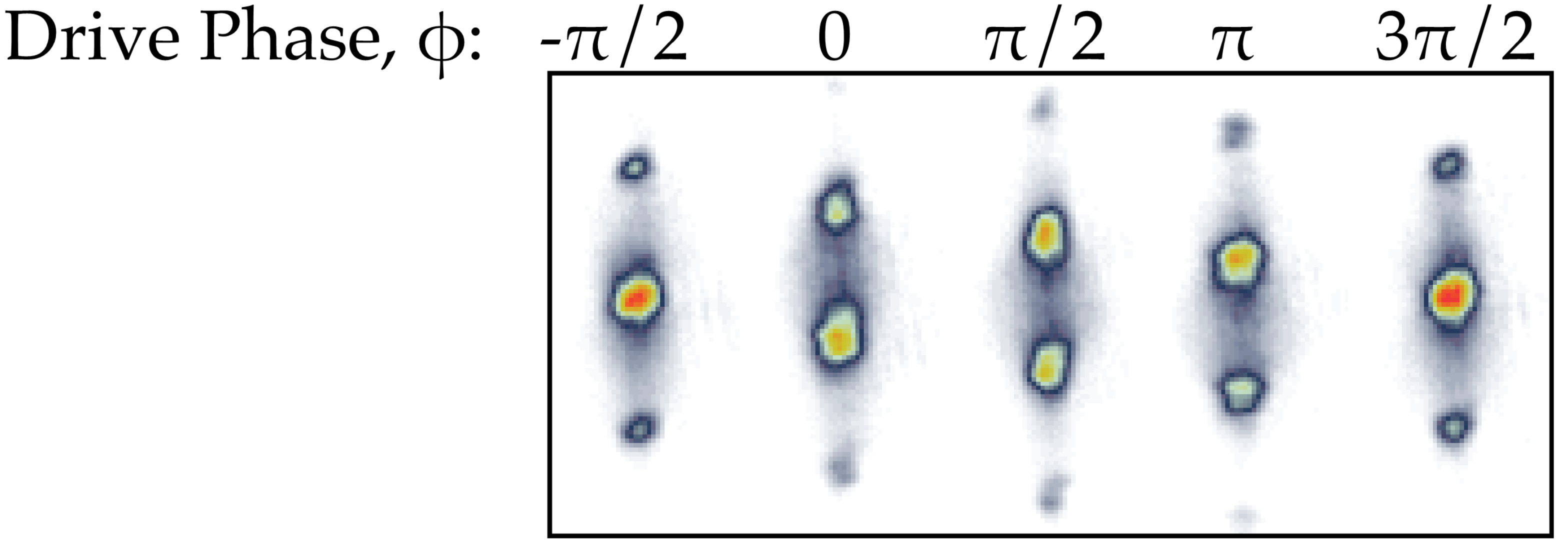
However, Bloch oscillations usually decay by dephasing

whereas the micromotion is driven Bloch oscillations

Study the simplest Hamiltonian with tilt:

Dilute gas, 1 D lattice with tilt, driven by amplitude modulation (effective Hamiltonian is the plain vanilla lattice)

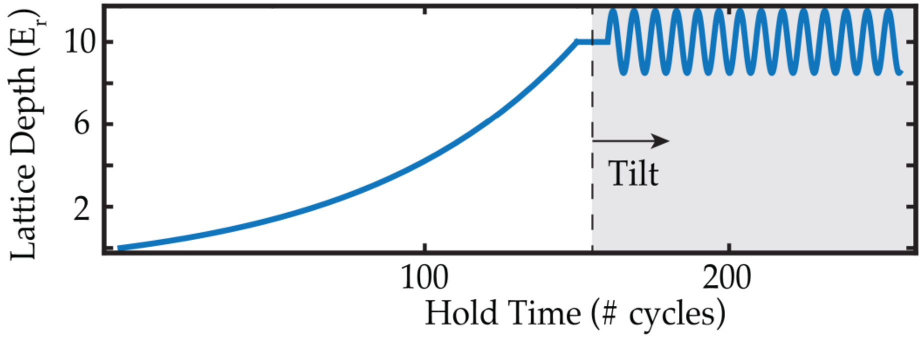
We observe long-lived superfluids

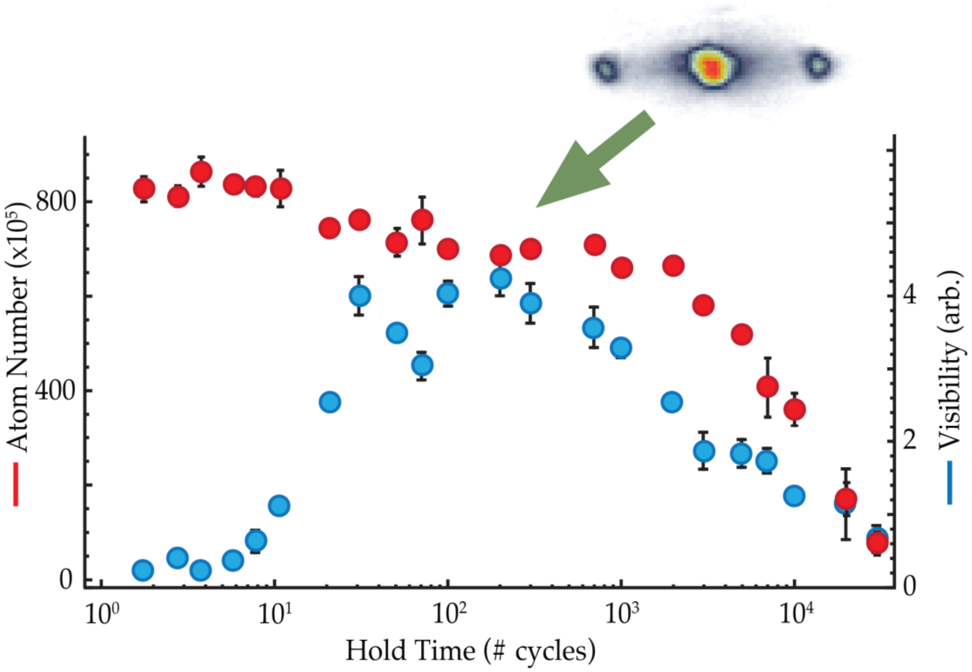


Experimental Sequence

Go to low filling! <n>~1

- Levitated dipole trap
- Reduce chemical potential: ~300 Hz
- Trap frequencies: 9, 10, 20 Hz
- Fast, accurate gradient turn-on via RF spin flip from |1,-1> to |2,-2> states
- SF peaks robust over broad parameter ranges



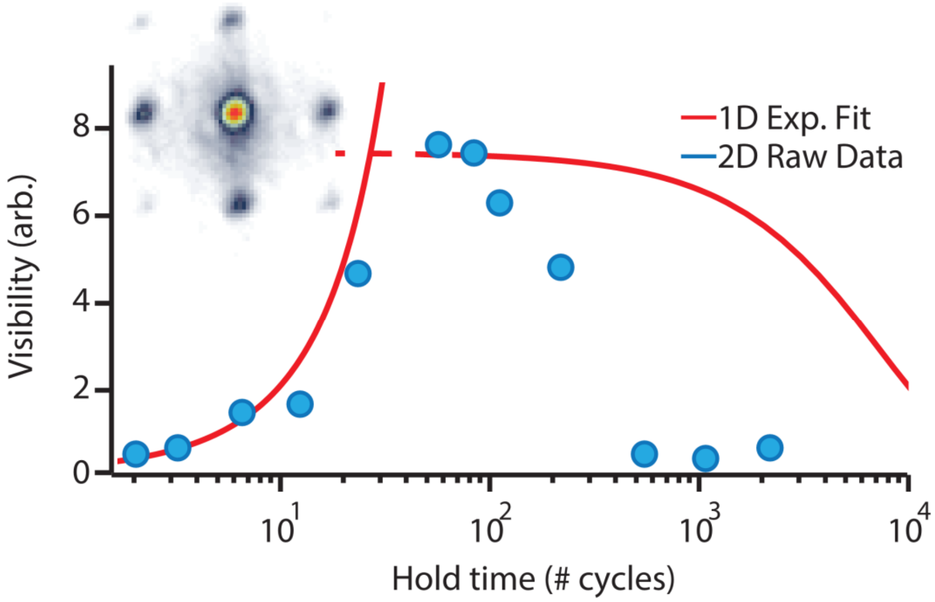


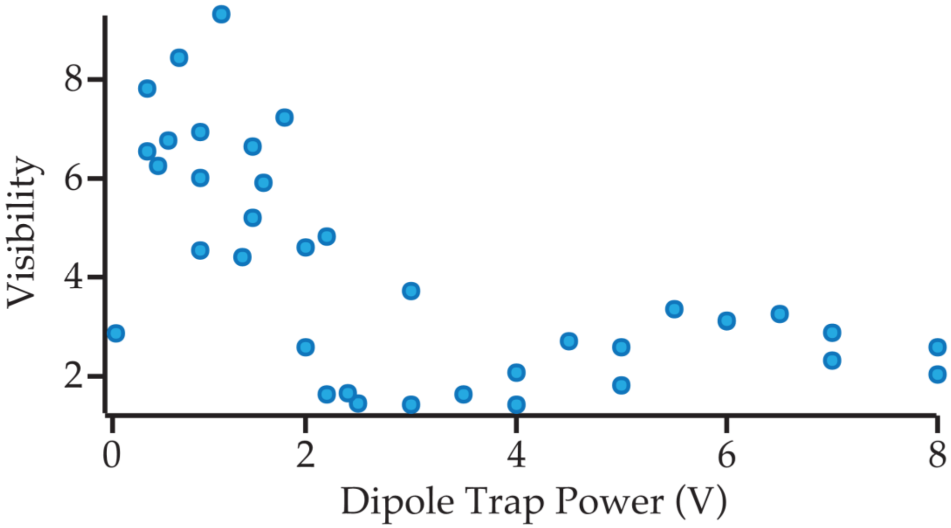
Modulation in 2D

We observe long lived superfluid peaks in 2D as well!

Coherence can be controllably destroyed by increasing density via dipole traps

Coherence observed in the regime applicable for Harper Hamiltonian!!





First time (?) that ground state (superfluid state) has been observed in tilted lattices with modulation

Ground state of an effective Hamiltonian which shows the micromotion

Next:
study the role of interactions, develop quantitative understanding (analysis in collaboration with Erich Mueller and Sayan Choudhury)

Improve lifetime by identifying technical noise, controlling density, improving state preparation, changing the spectrum (lattice) in the orthogonal directions

Outlook

Engineering the tunneling phase in optical lattices

Spin-orbit coupling
Topological insulators
Spin Hall physics
Majorana fermions
Topological phase transitions

Credits:

BEC 4

Rb BEC in optical lattices

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