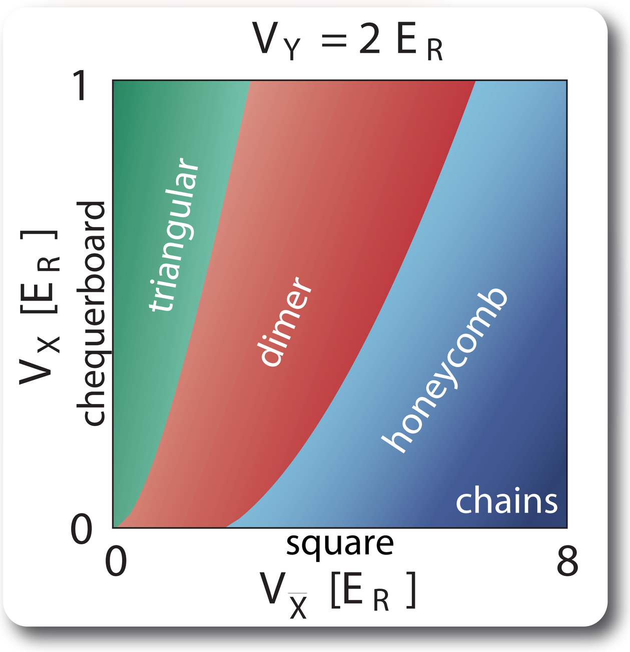
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Engineering Dirac points with ultracold fermions in a tunable optical lattice

Daniel Greif, Leticia Tarruell, Thomas Uehlinger, Gregor Jotzu and Tilman Esslinger
Institute for Quantum Electronics, ETH Zurich, Switzerland, http://www.quantumoptics.ethz.ch

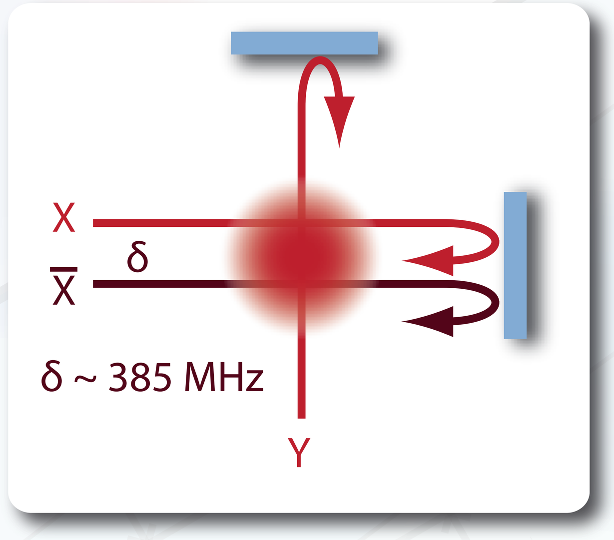
Tunable Lattice



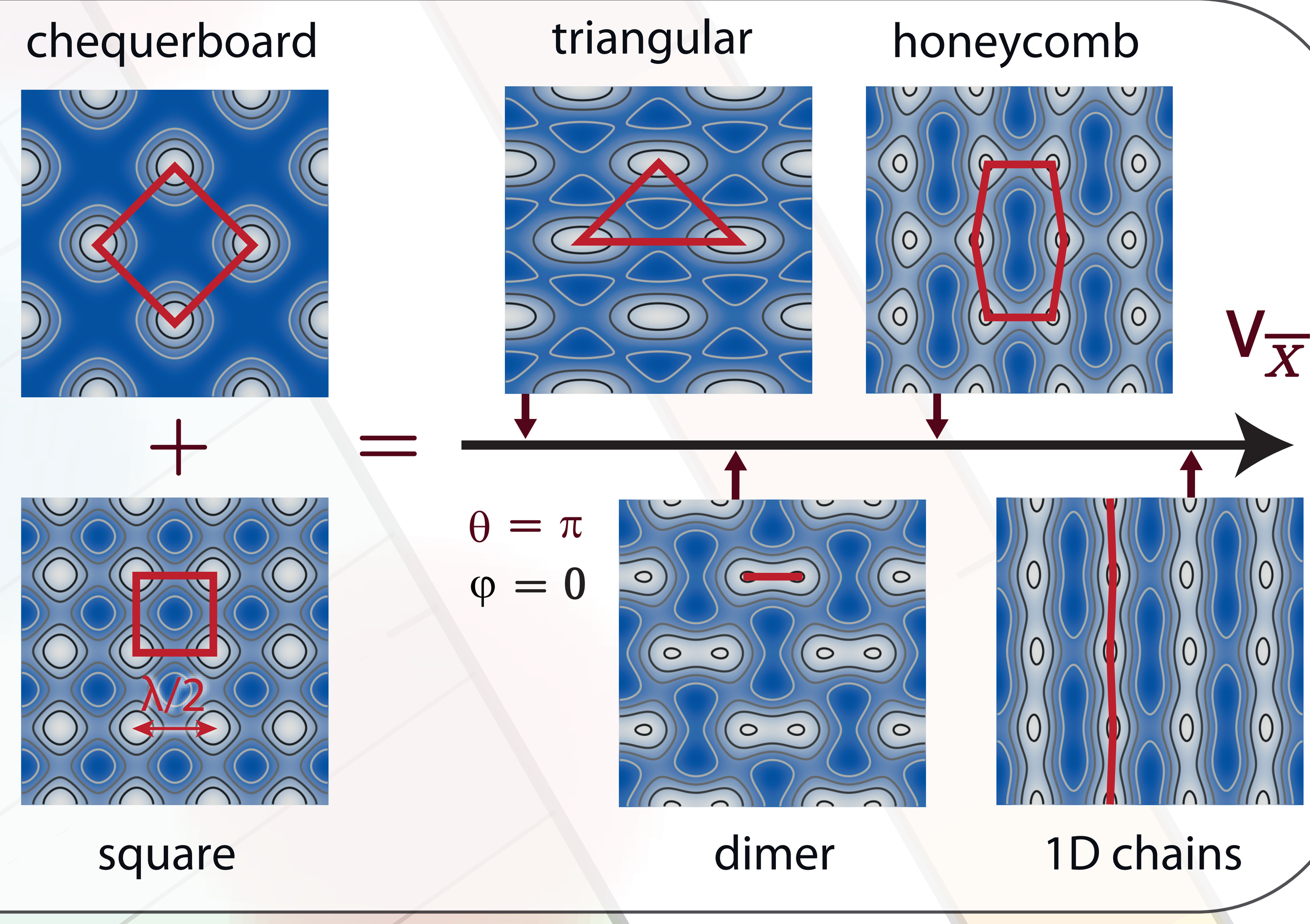
The properties of solid-state materials are critically influenced by the topological properties of their band structure. A prime example is the honeycomb lattice of graphene, where the presence of Dirac points leads to massless electrons causing a drastic increase in carrier mobility.
Compared to realisations in solid state materials, the approach with cold atoms offers a very flexible approach and new access to this type of systems.

In our experiment we subject the atoms to an optical lattice of tunable geometry created by interfering laser beams. It allows us to continously and dynamically tune between different lattice geometries including chequerboard, triangular, dimer, honeycomb and coupled 1D chain configurations.

Lattice with tunable geometry

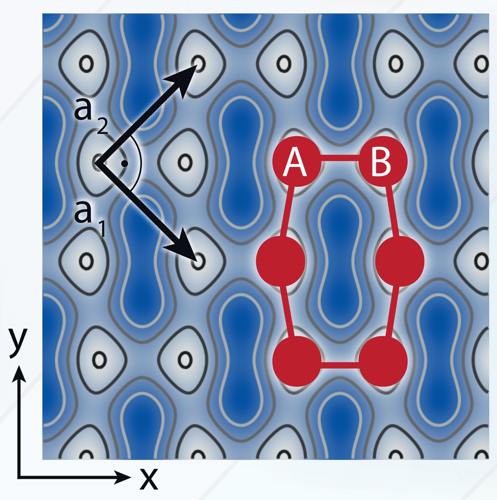


$$V(x,y) = -V_{\bar{X}}\cos^2(kx+\theta/2) - V_X\cos^2(kx) - V_Y\cos^2(ky) - 2\alpha\sqrt{V_X V_Y}\cos(kx)\cos(ky)\cos(\varphi)$$



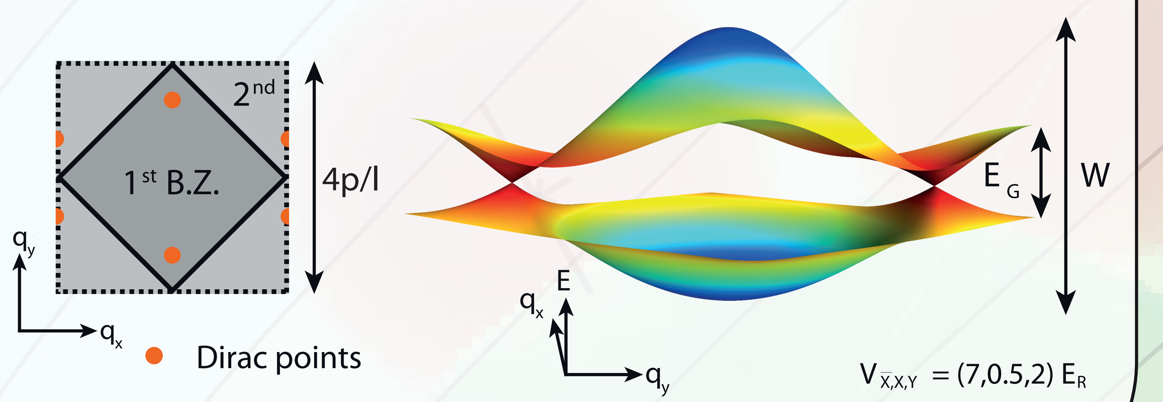
Honeycomb Lattice

Real space potential



- two-site unit cell
- square shaped Brillouin zone
- two Dirac points located inside the Brillouin zone
- control over sublattice energy offset (inversion symmetry)
- existence of Dirac points resilient upon variation of lattice parameters

Reciprocal space



Probing Dirac Points

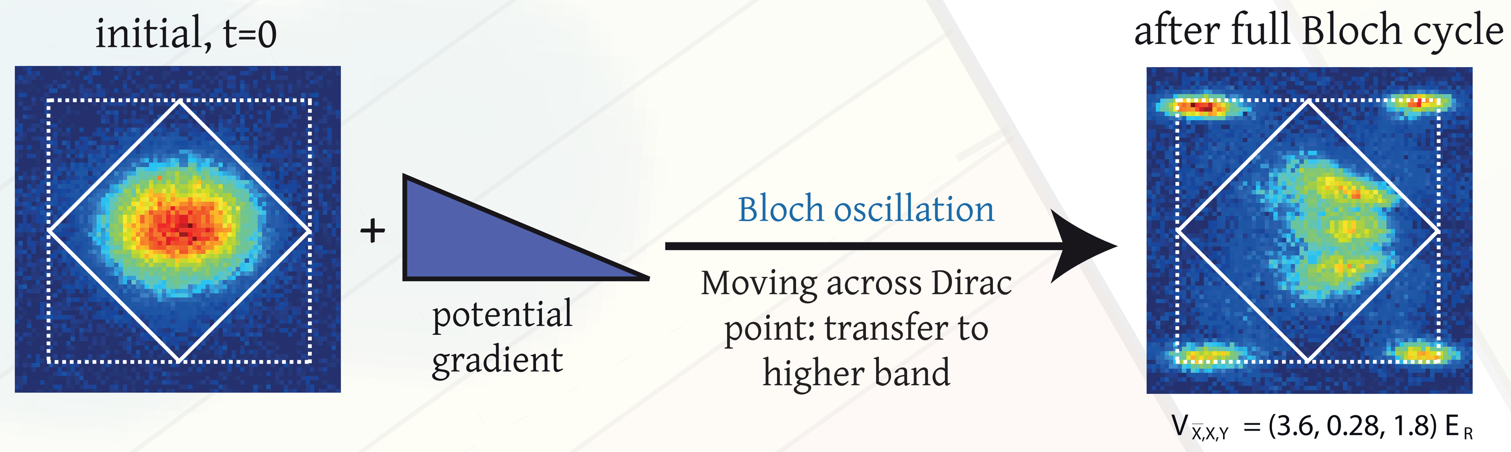
Experimental procedure

Spin polarized Fermi gas of about 60.000 ^{40}K atoms in $|F=9/2, m_F=-9/2\rangle$

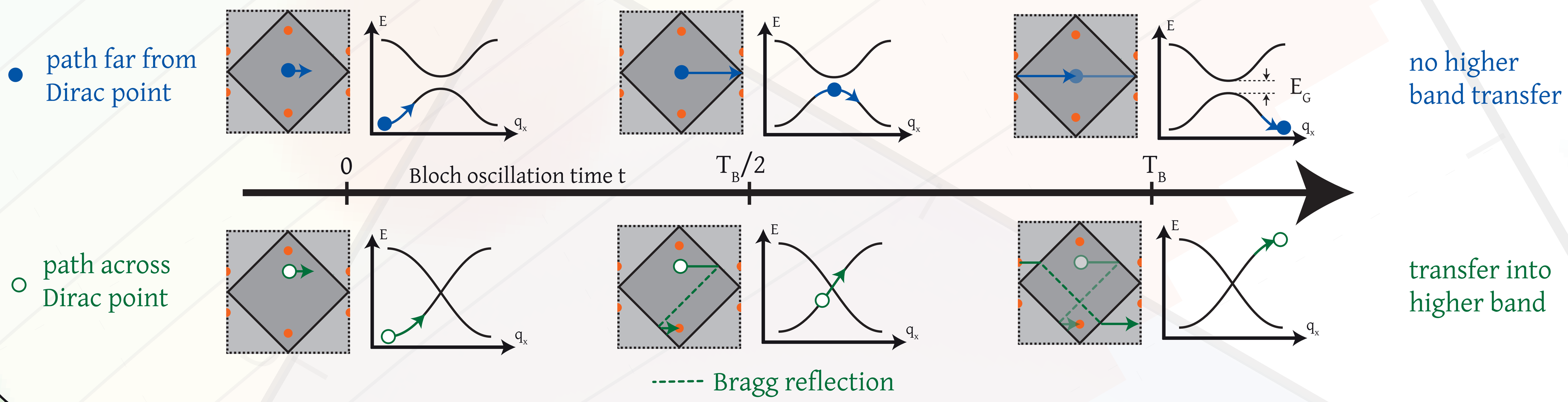
Atoms loaded into tunable optical lattice of variable depths $V_{\bar{X}}$, V_X and V_Y

Initial distribution centered around q=0

Application of potential gradient and detection of quasimomentum distribution after one Bloch period

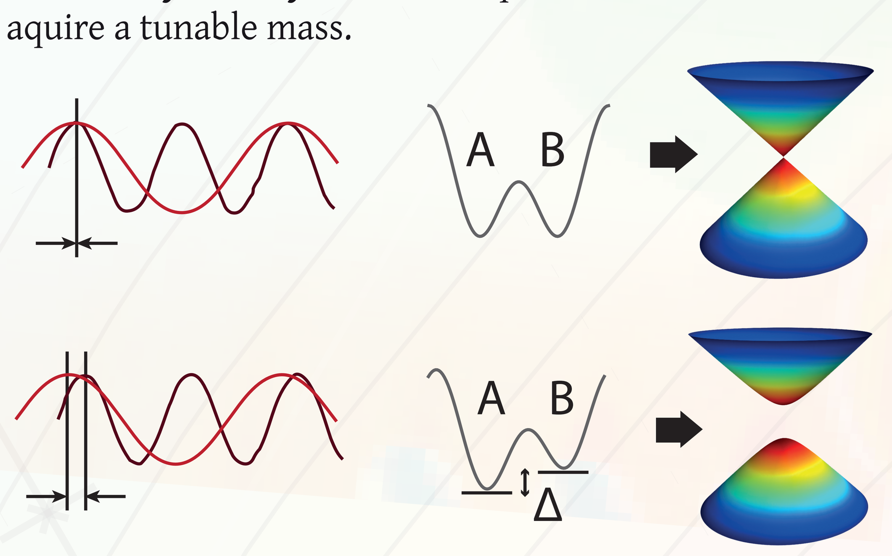


Bloch oscillations and interband transfers

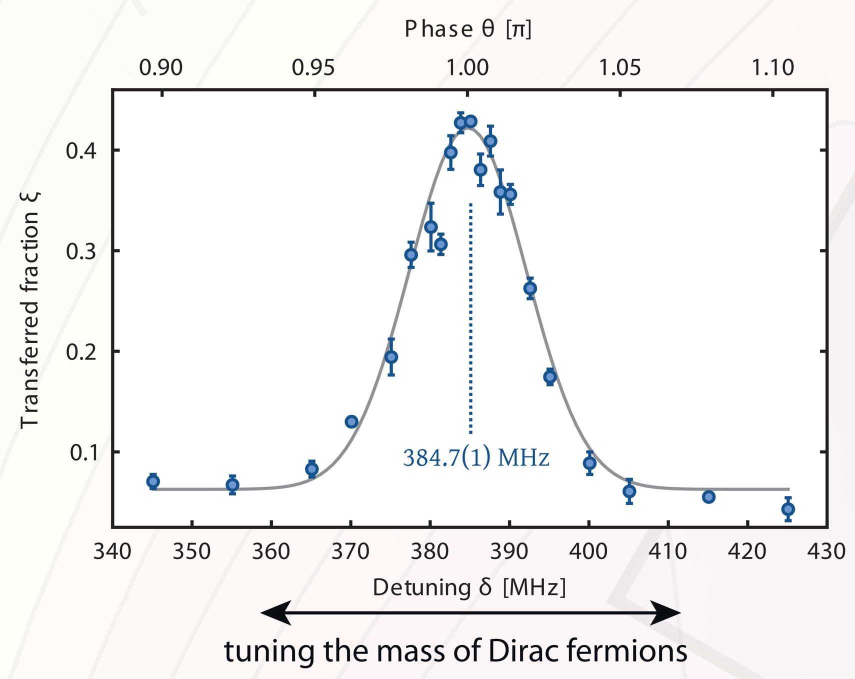


Inversion Symmetry

Varying the frequency detuning δ between the X and X̄ lattice beam changes the relative positioning of the chequerboard and square lattice potentials. This changes the energy offset Δ between the A and B sublattices and hence breaks inversion symmetry. As a consequence, the Dirac fermions aquire a tunable mass.



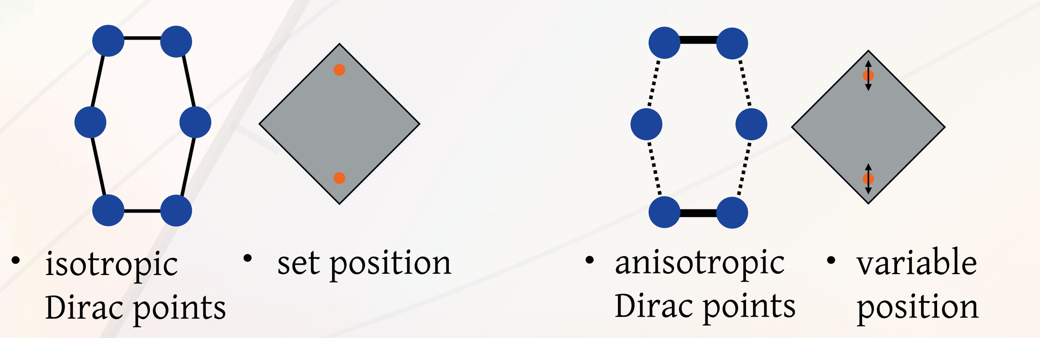
After one full Bloch cycle we measure the total fraction ξ of atoms in the 2nd Brillouin zone after adiabatic ramp down of the lattice and 15 ms time of flight.



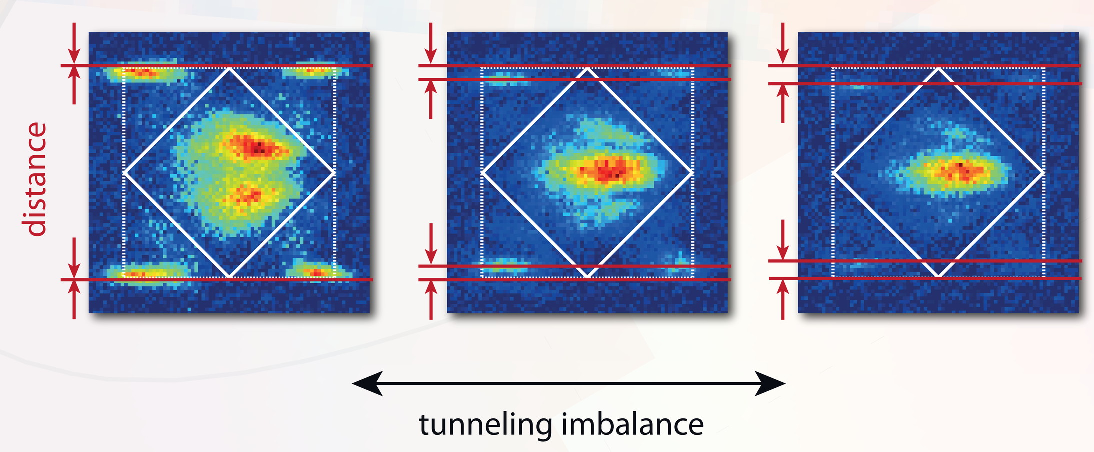
We identify the peak position with the situation of a vanishing site offset. We find good agreement with an independent calibration (Raman-Nath diffraction on ^{87}Rb: 388(4) MHz).

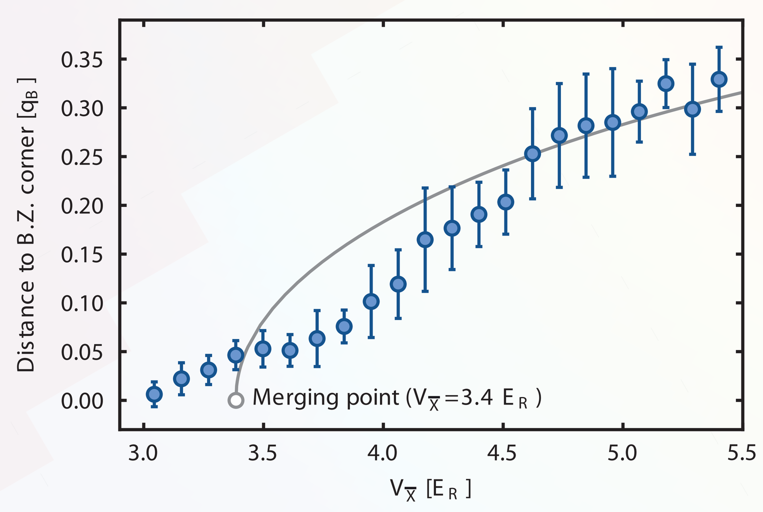
Moving Dirac Points

A variation of the lattice intensities leads to an imbalance of the tunneling links. This moves the Dirac points in the Brillouin zone.



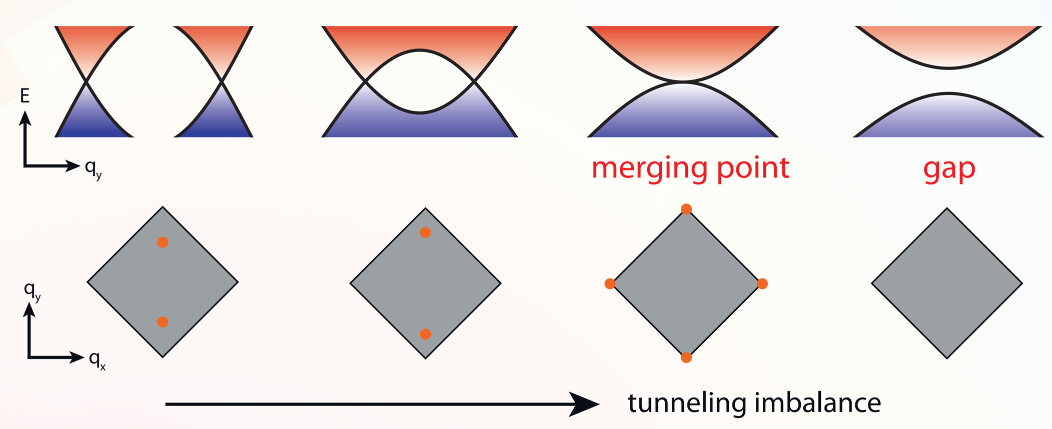
Due to the finite momentum width of the cloud, Bloch oscillations along the q_x-axis allow us to also resolve this displacement of the Dirac points when tuning the tunneling imbalance.





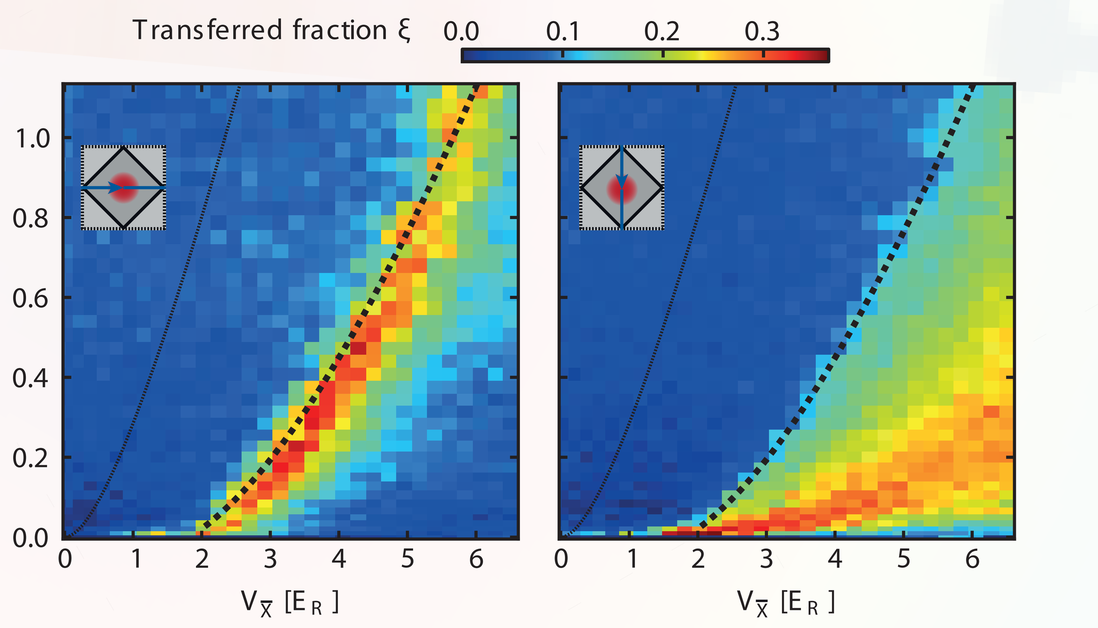
Topological Transition

Approaching a critical lattice anisotropy the Dirac points move to the corner of the Brillouin zone, where they merge and a gap opens. At this point the dispersion relation is quadratic along the q_y-axis and linear along q_x. For half-filled 2D-systems this corresponds to a Lifshitz transition from a semi-metal to a band insulating state.

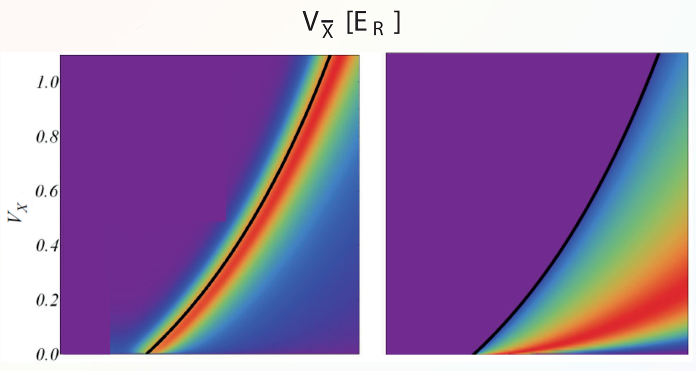


By scanning the potentials $V_{\bar{X}}$ and V_X we map out the topological transition to the honeycomb lattice, in excellent agreement with *ab initio* calculations.

Applying a potential gradient in the perpendicular direction also allows to detect the Dirac points far in the honeycomb regime.



Transferred fraction agrees with theory based on universal Hamiltonian:
L.K. Lim, J.N.Fuchs and G. Montambaux, Phys. Rev. Lett. 108, 175303 (2012)



Outlook

- Combination of various lattice geometries with interactions
- Interferometric detection of Berry phase
- Topologically ordered states

Paper: L. Tarruell, D. Greif, T. Uehlinger, G. Jotzu and T.Esslinger, Nature 483, 302–305 (2012)