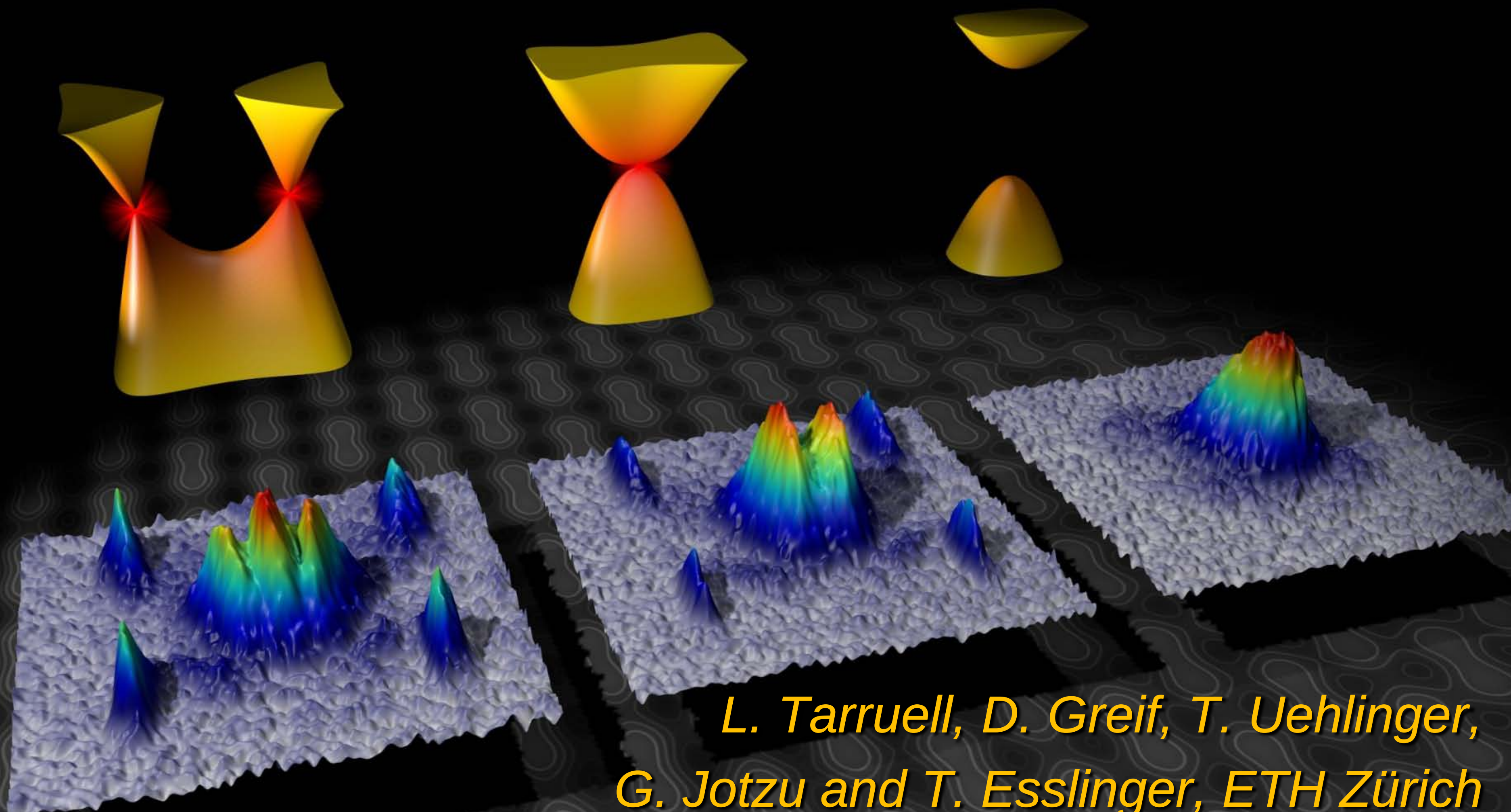
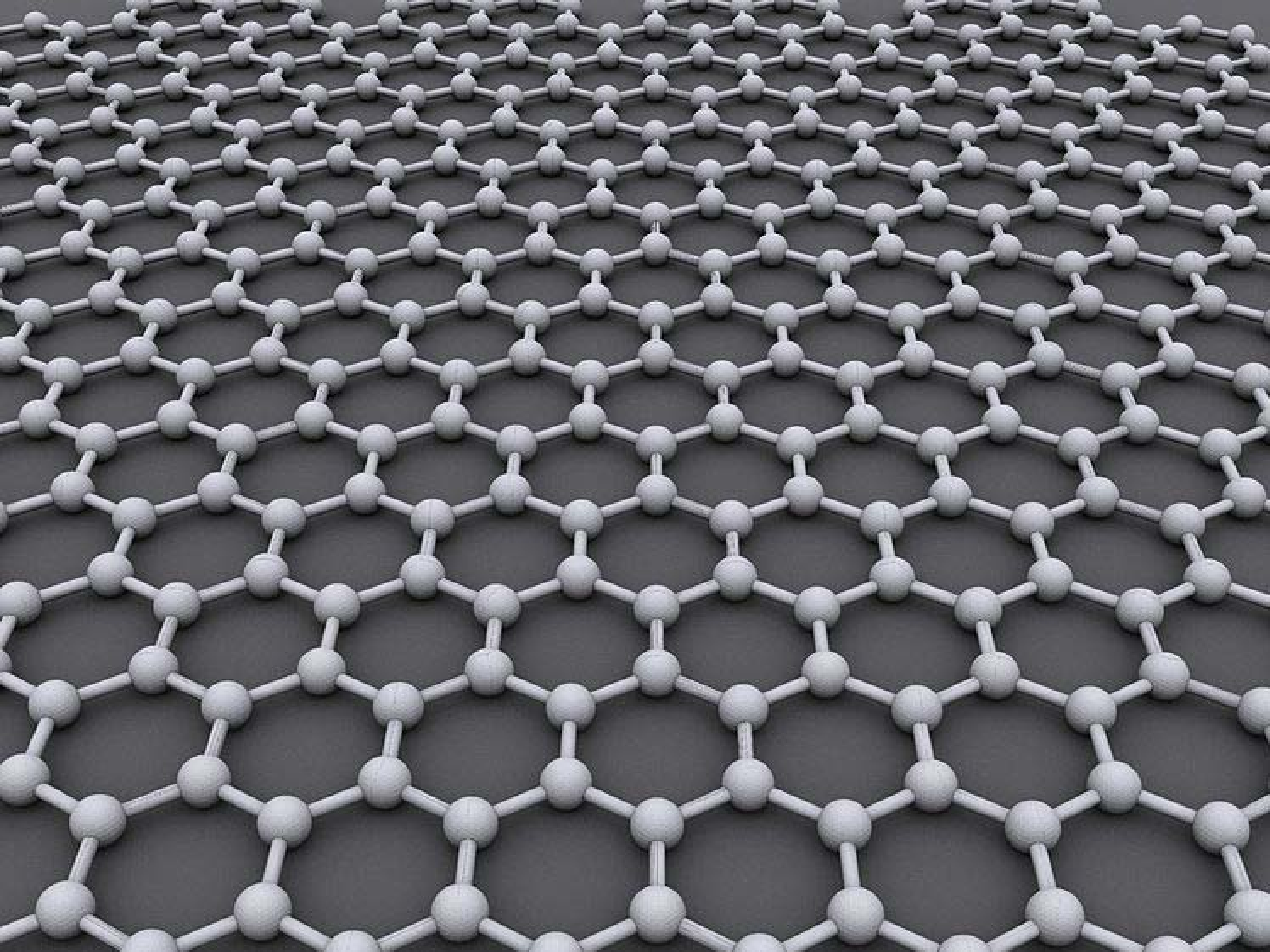
Engineering Dirac points with ultracold fermions in optical lattices

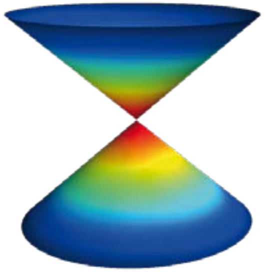


L. Tarruell, D. Greif, T. Uehlinger, G. Jotzu and T. Esslinger, ETH Zürich

KITP – 30/10/2012



Band structures with topological defects



Topological defects: Dirac points

Quantum gases in lattices with topological defects

Excited bands:

- 1D « Dirac point » (Weitz group, Bonn)
- Quadratic avoided band crossing (Hemmerich group, Hamburg)

Honeycomb lattice: Dirac points in the lowest band !

- BEC in a honeycomb lattice (Sengstock group, Hamburg, Stamper-Kurn group, Berkeley)

Outline

ETH

An optical lattice of tunable geometry

Probing Dirac points by interband transitions

Adjusting, moving and merging Dirac points

Double transfer through Dirac points

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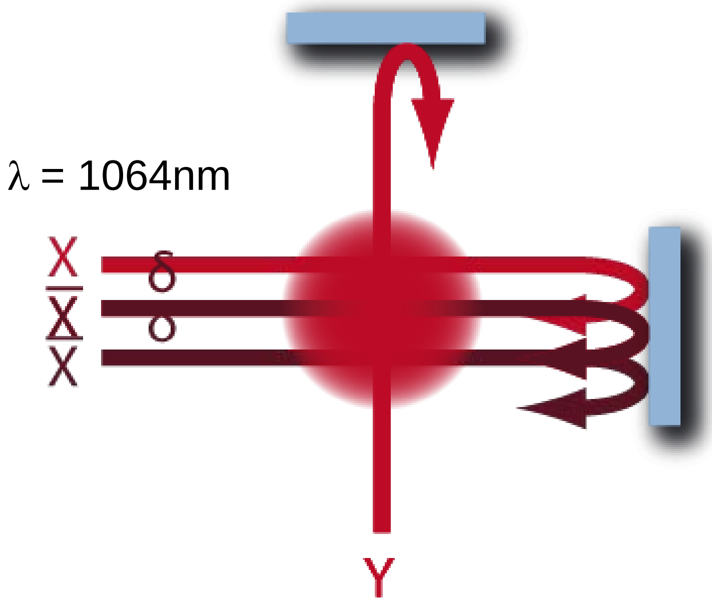
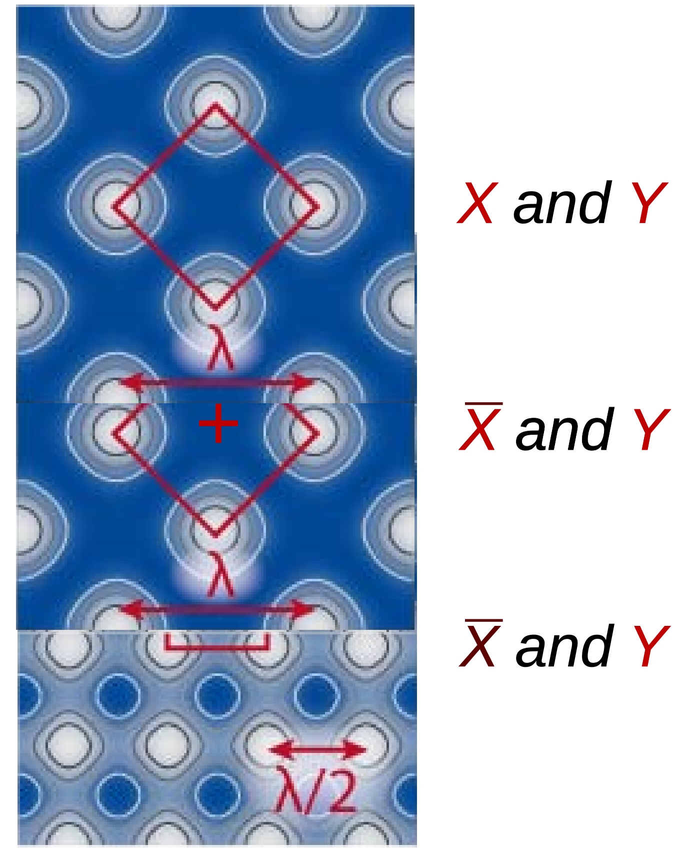
Setup



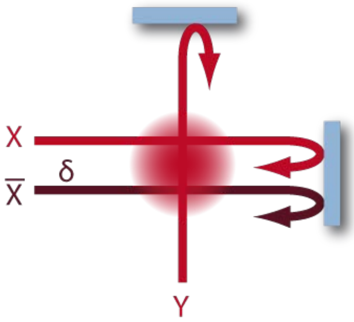
Optical potential

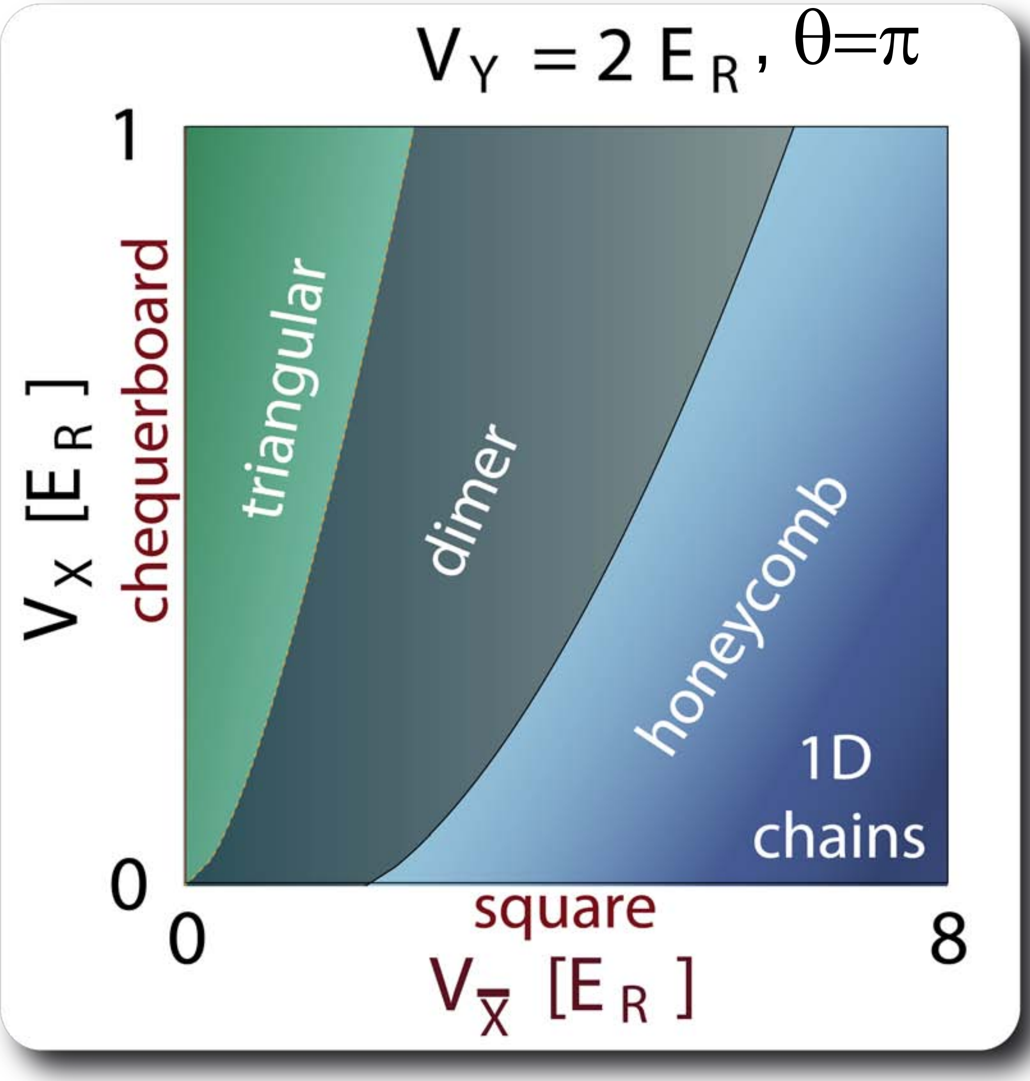


$$V(x,y) = \boxed{V_{\bar{X}} \cos^2(kx + \theta/2)} + \boxed{V_X \cos^2(kx) + V_Y \cos^2(ky) + 2\alpha\sqrt{V_X V_Y}\cos(kx)\cos(ky)}$$

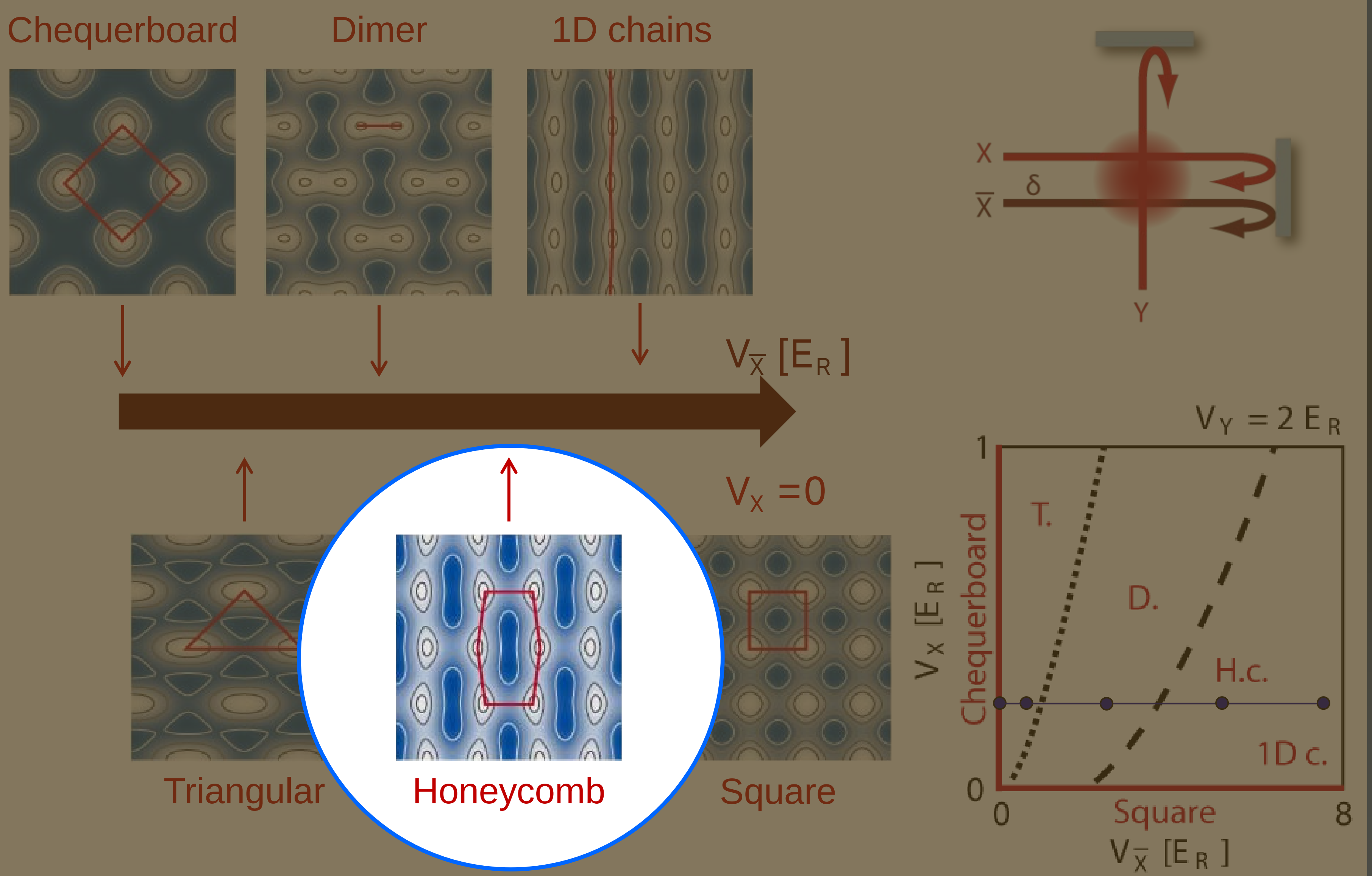
An optical lattice of tunable geometry

ETH





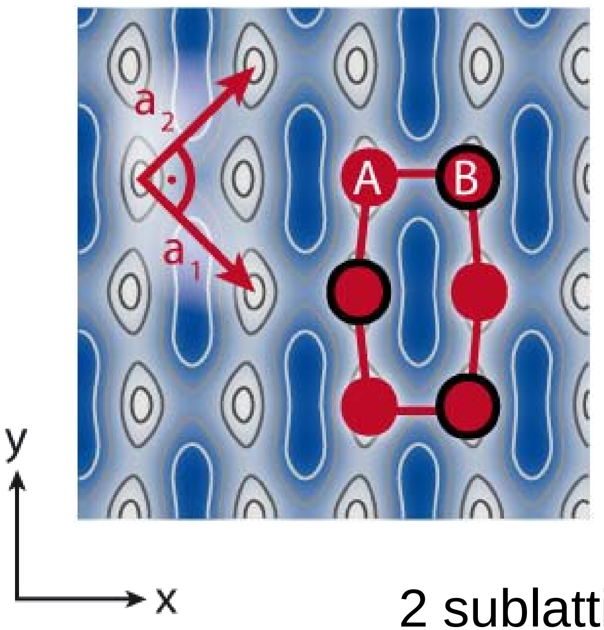
An optical lattice of tunable geometry

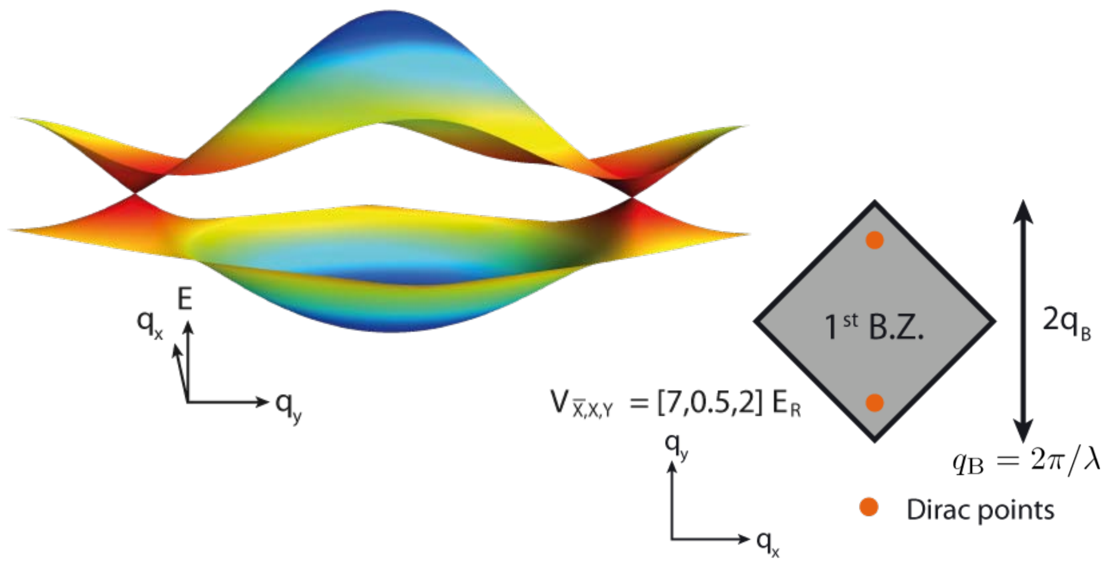


Honeycomb lattice

Real space

Reciprocal space





2 sublattices → 2 sub-bands

2 Dirac points inside the Brillouin zone:

- Conical energy spectrum
- Spinor wavefunctions
- Dirac fermions

Topologically equivalent to regular hexagonal lattice

Outline

ETH

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Probing Dirac points by interband transitions

Adjusting, moving and merging Dirac points

Double transfer through Dirac points

Probing the Dirac points

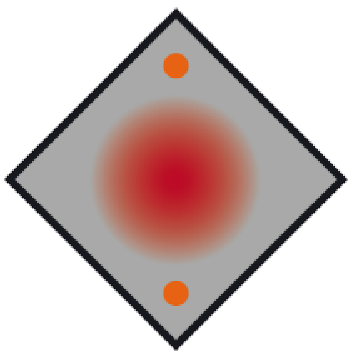
ETH

Challenges: vanishing density of states
small energy scales

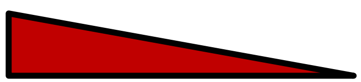
Probe energy splitting of
the bands **dynamically**

T. Salger *et al.*, Phys. Rev. Lett. **99**, 190405 (2007)

Bloch oscillations + interband transitions

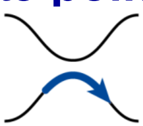


+



Pot. Gradient ≙ Force

Passing away from Dirac point:
stay in lowest band

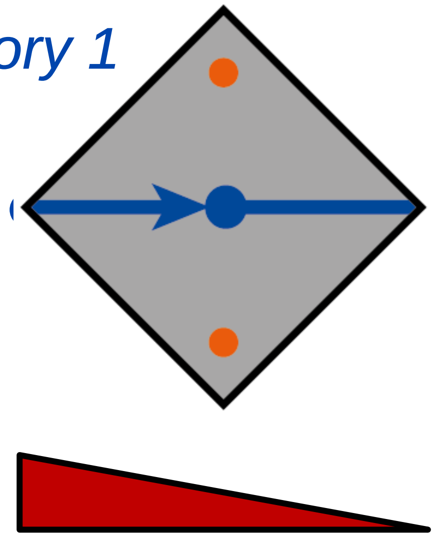


Passing through Dirac point:
transfer to 2nd band

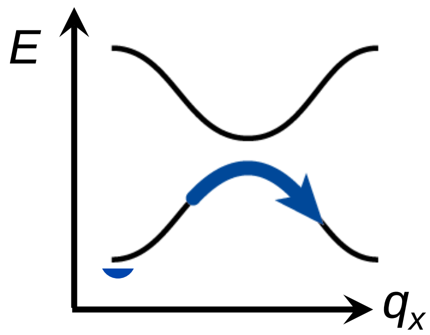
Observable: quasi-momentum distribution

Interband transitions

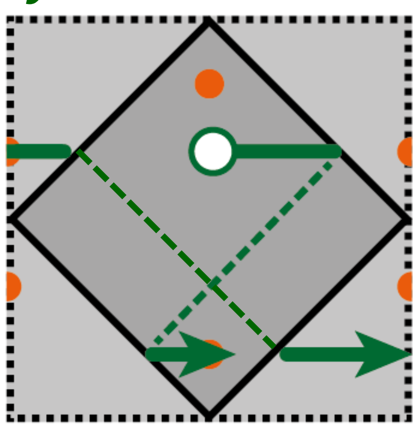
● *trajectory 1*



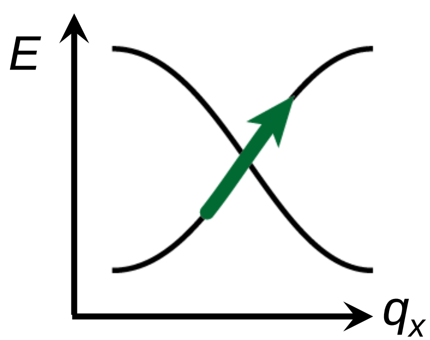
Stay in lowest band



○ *trajectory 2*



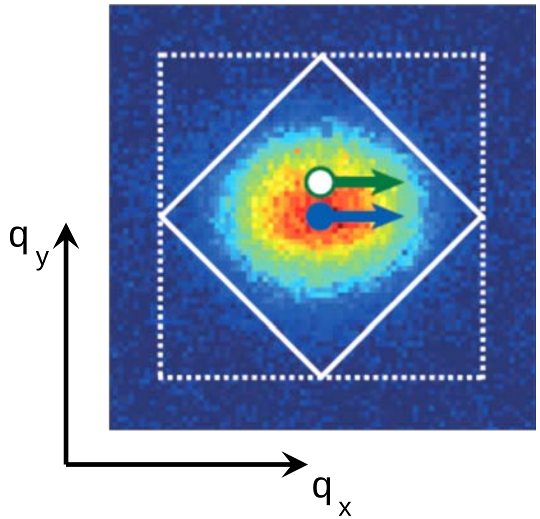
Transfer to 2nd band

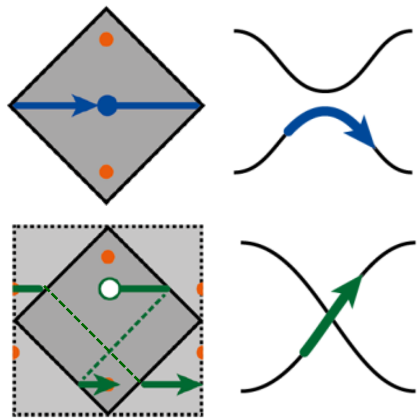


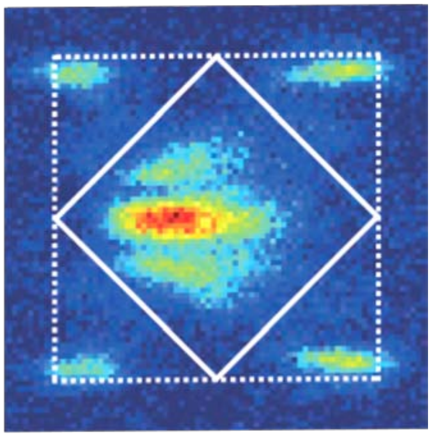
Interband transitions: experiment

Starting point: $t=0$

After a Bloch cycle: $t=T_B$







~60.000 spin-polarized ^{40}K atoms

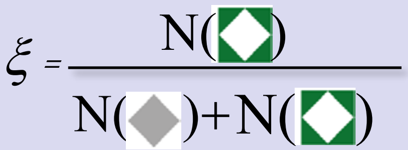
Non-interacting gas

Lowest band of a honeycomb lattice

Transfer to 2nd band at the position of the Dirac points

Quantitative measurements

Higher band fraction



Outline

An optical lattice of tunable geometry

Probing Dirac points by interband transitions

Adjusting, moving and merging Dirac points

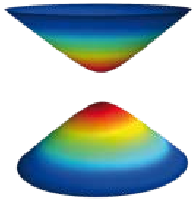
Double transfer through Dirac points

Tuning the Dirac points

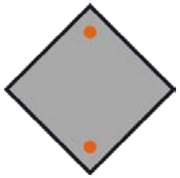
Dirac points with ultracold atoms

Tunability

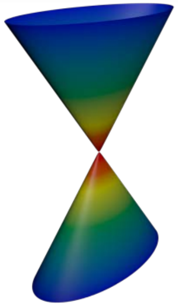
Gap/effective mass



Dirac point position



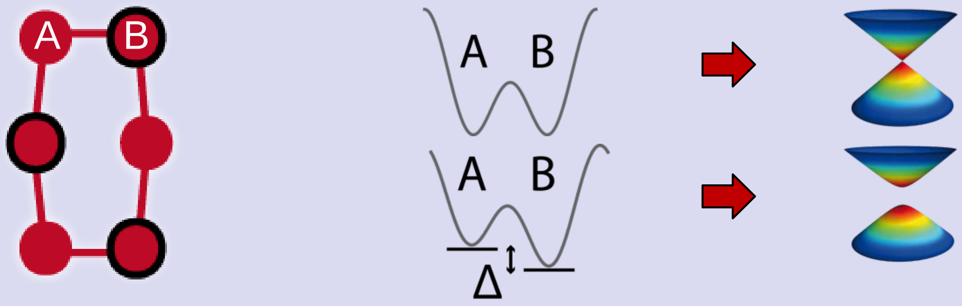
Cone asymmetry



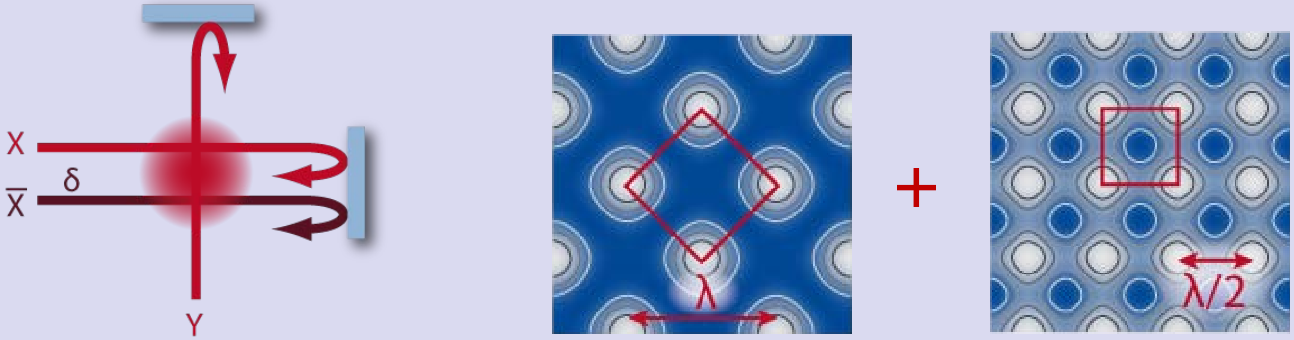
S.-L. Zhu, B. Wang, and L.-M. Duan, *Phys. Rev. Lett.* **98**, 260402 (2007).
B. Wunsch, F. Guinea, and F. Sols, *New J. Phys.* **10**, 103027 (2008).
K. L. Lee *et al.*, *Phys. Rev. A* **80**, 043411 (2009).
G. Montambaux *et al.*, *Phys. Rev. B* **80**, 153412 (2009).

Breaking inversion symmetry

Control of sublattice energy offset

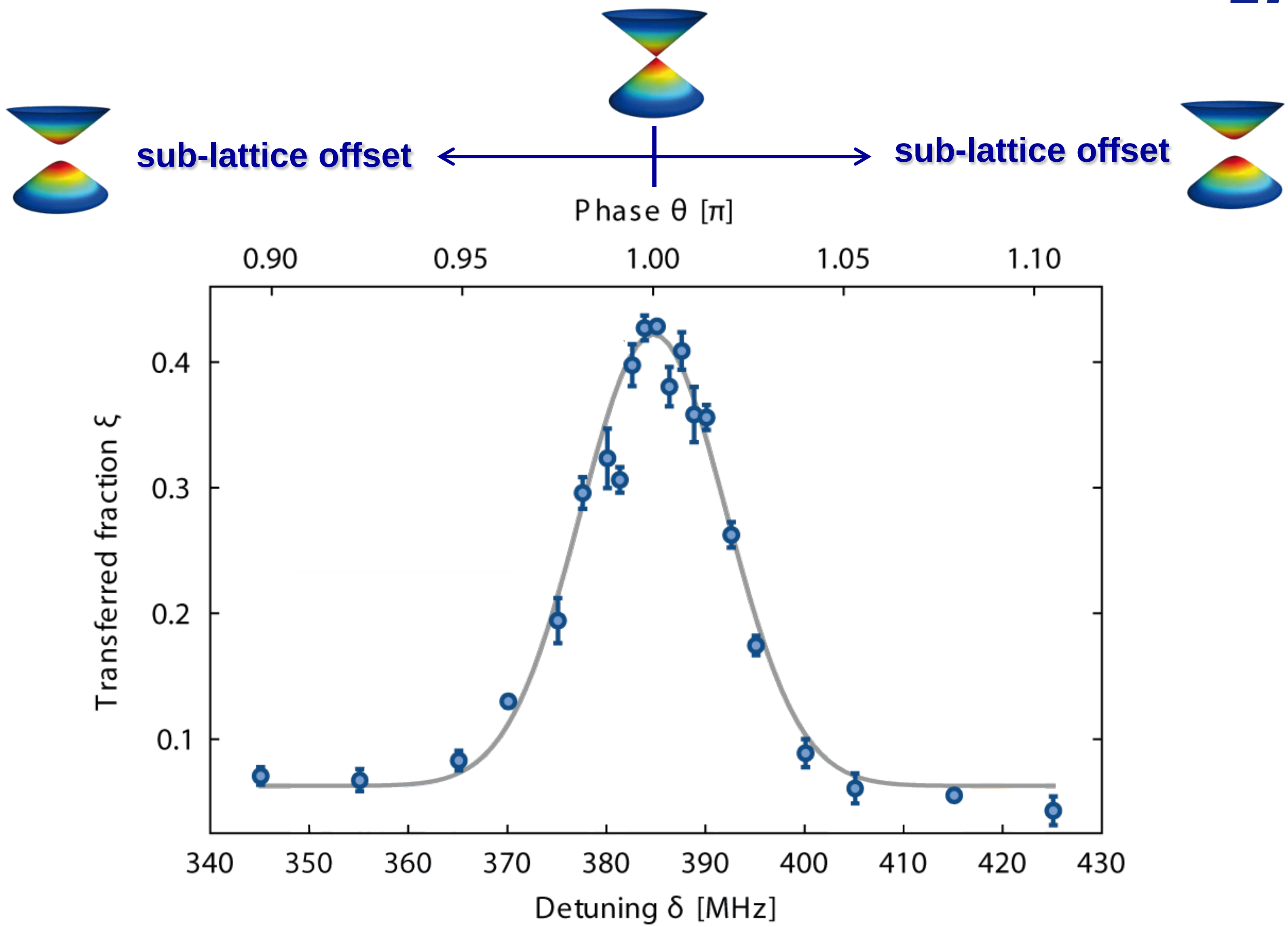


Experiment



Relative positioning θ of X and X̄ (detuning δ)

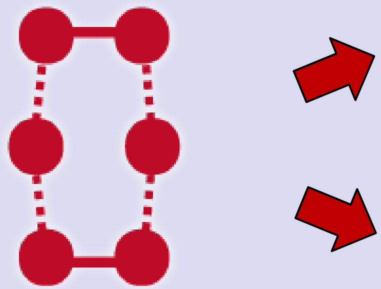
Breaking inversion symmetry

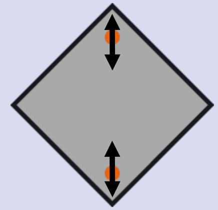


Position and anisotropy of Dirac cones

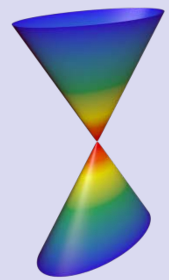
ETH

Anisotropic tunneling



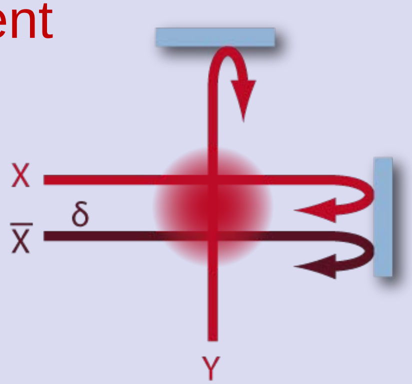


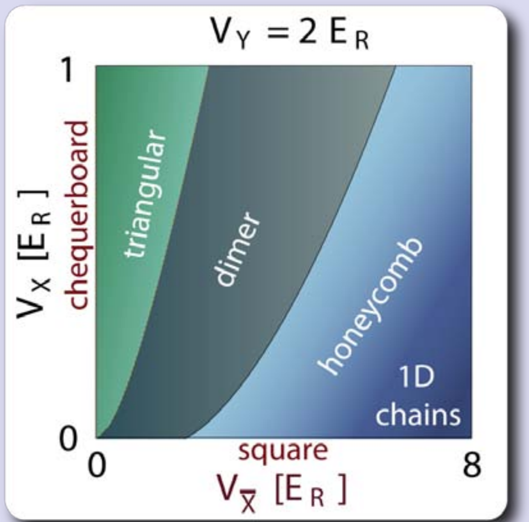
Dirac point position



Cone asymmetry

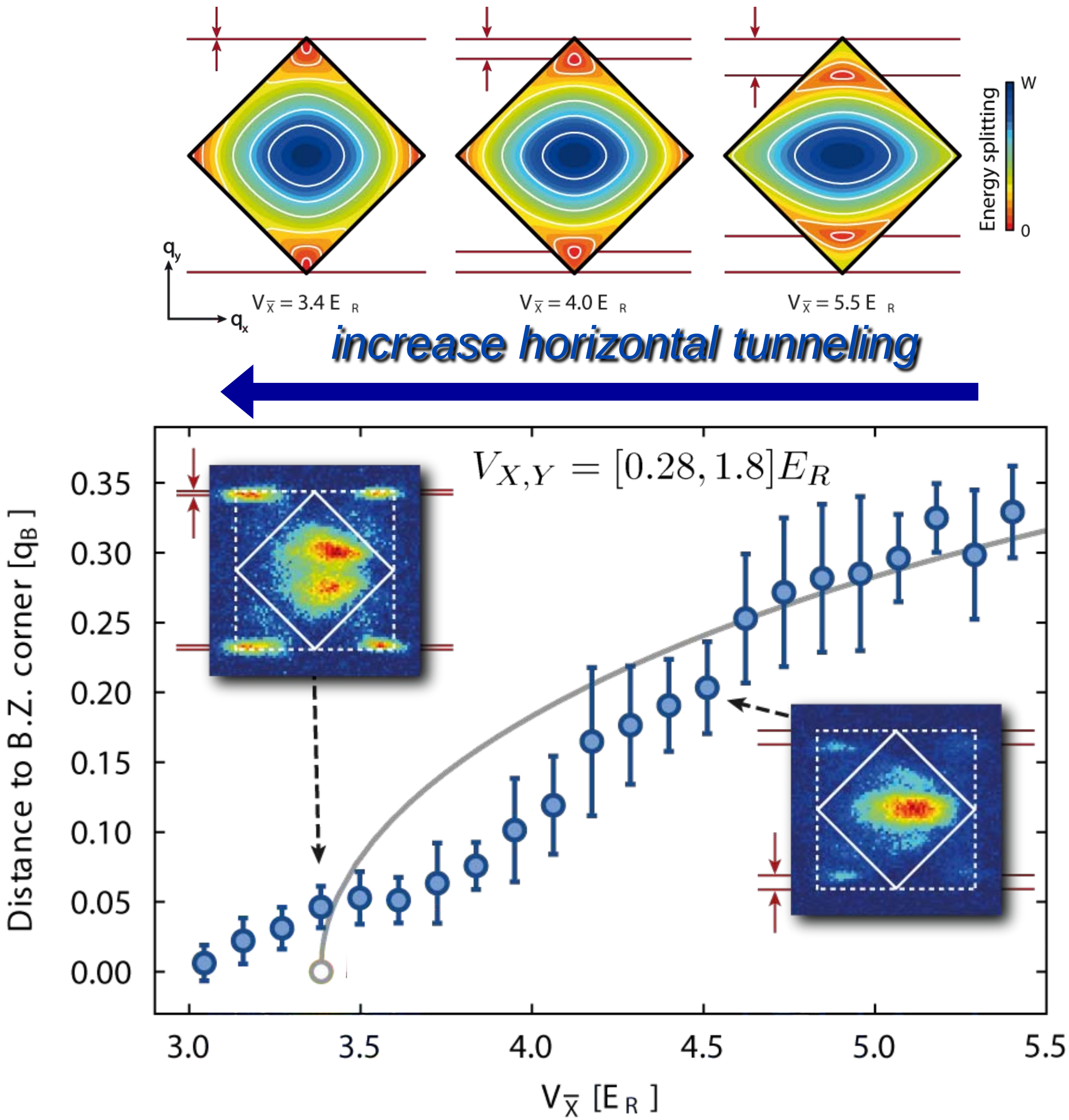
Experiment

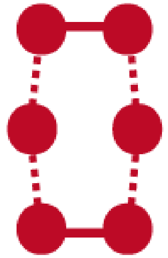




Adjusting the laser intensities X and $\overline{X}$

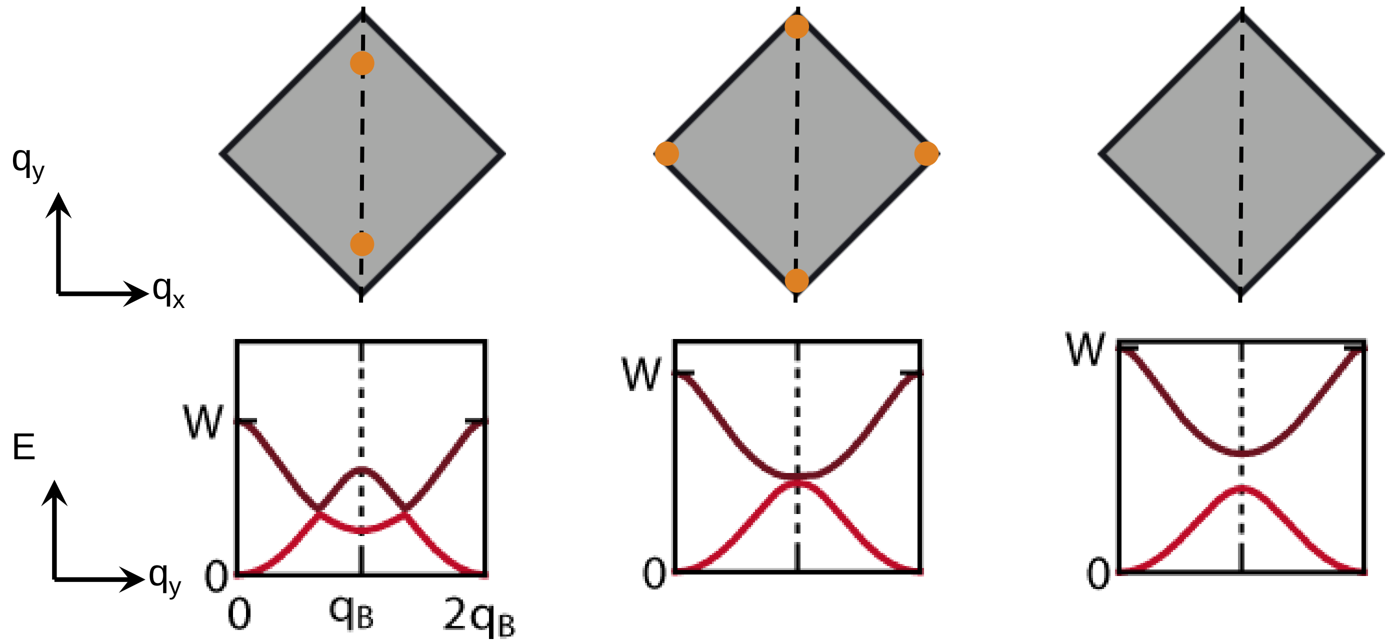
Moving Dirac points



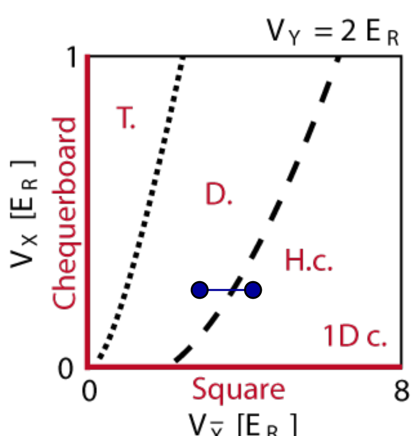


Merging Dirac points

ETH



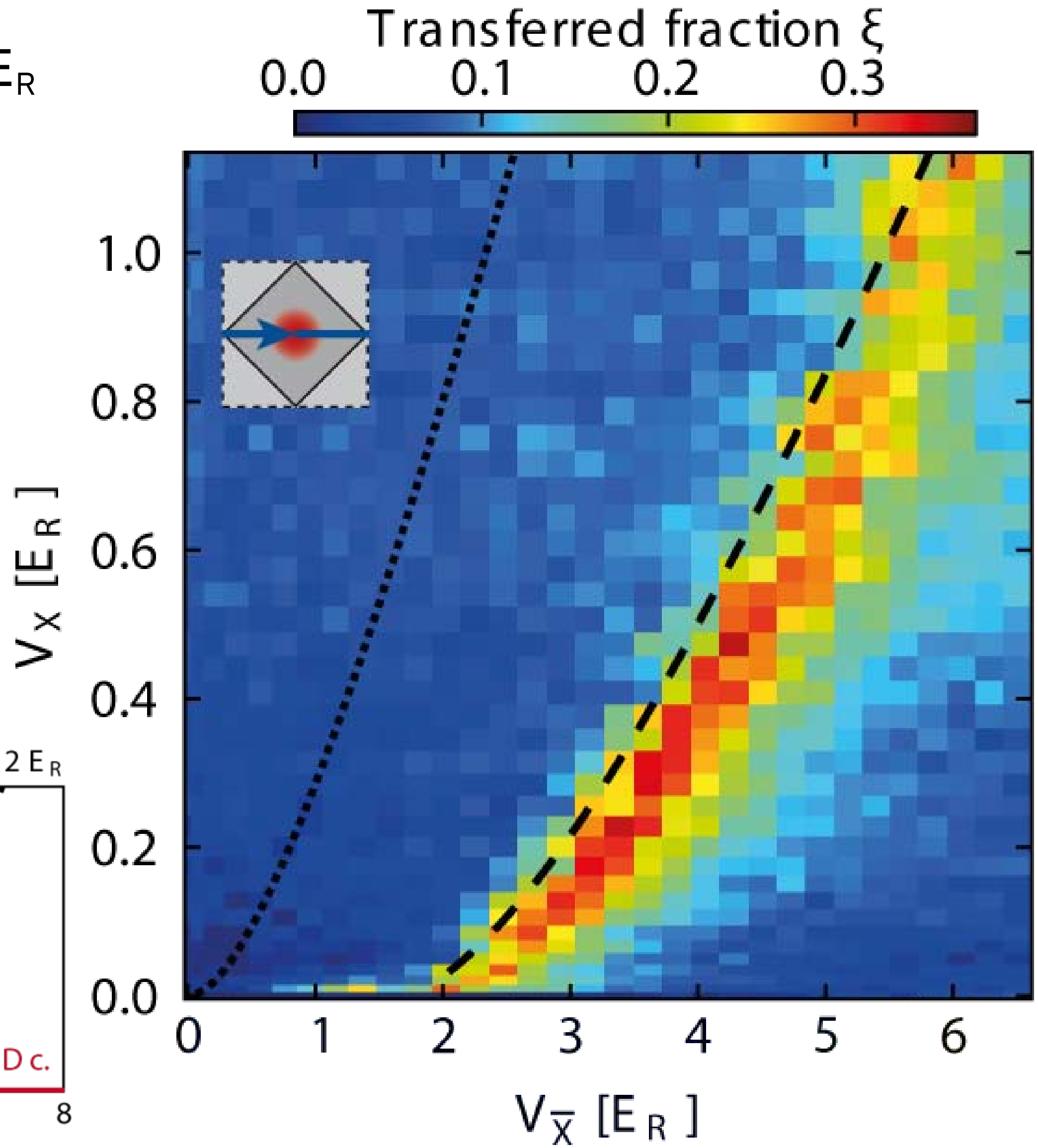
Dirac points → *Topological Transition* → *No Dirac points*



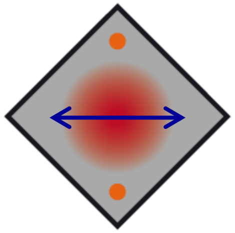
Lifshitz transition, Sov. Phys. JETP **11**, 1130 (1960)

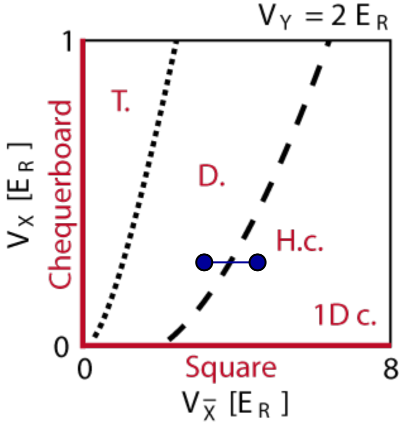
The topological transition

$V_Y = 1.8\ E_R$



Force along x





The topological transition

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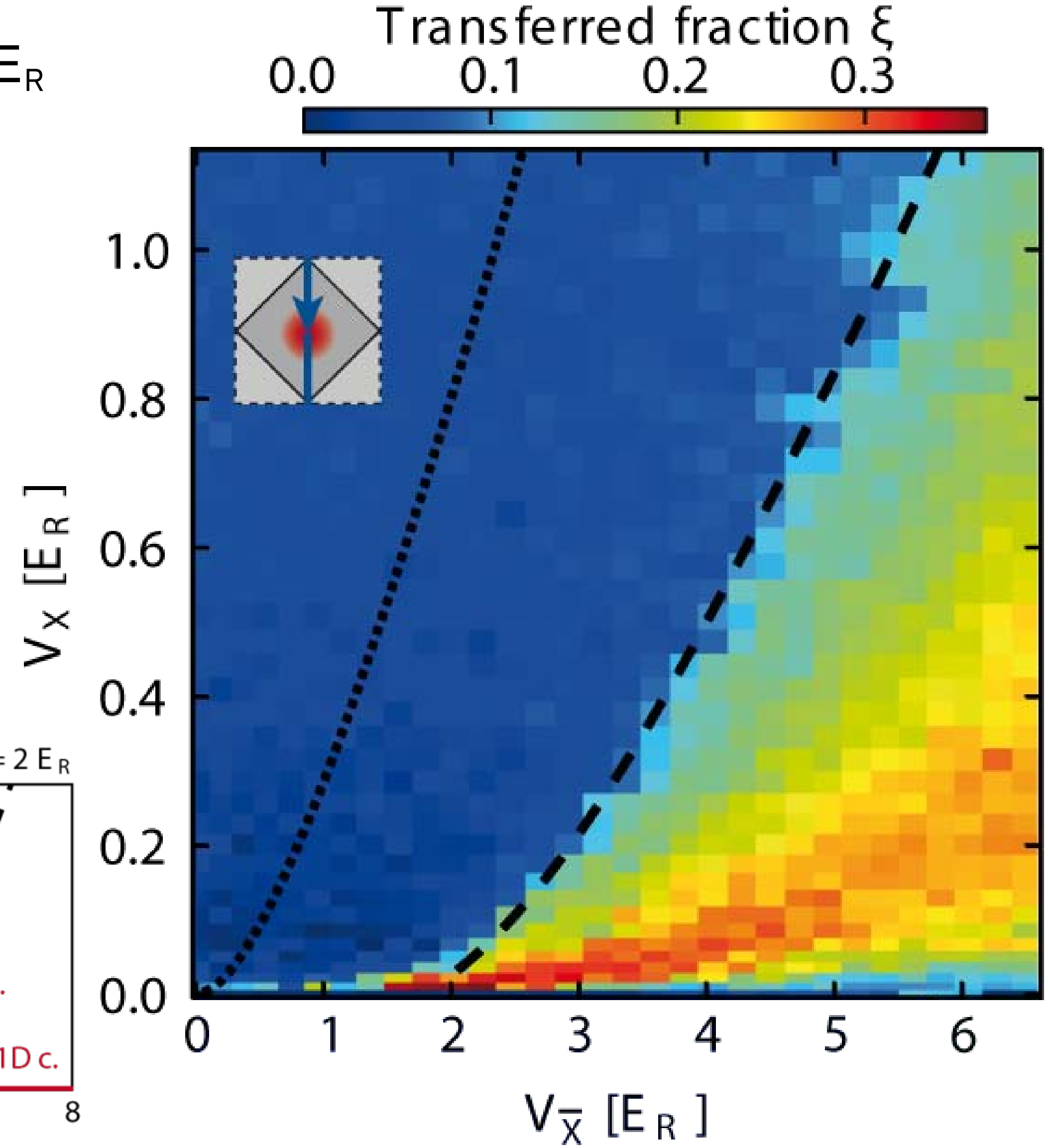
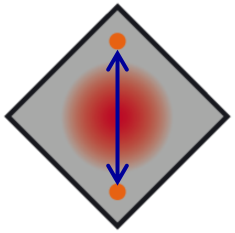
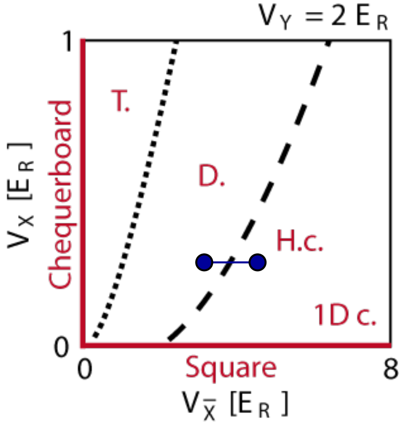
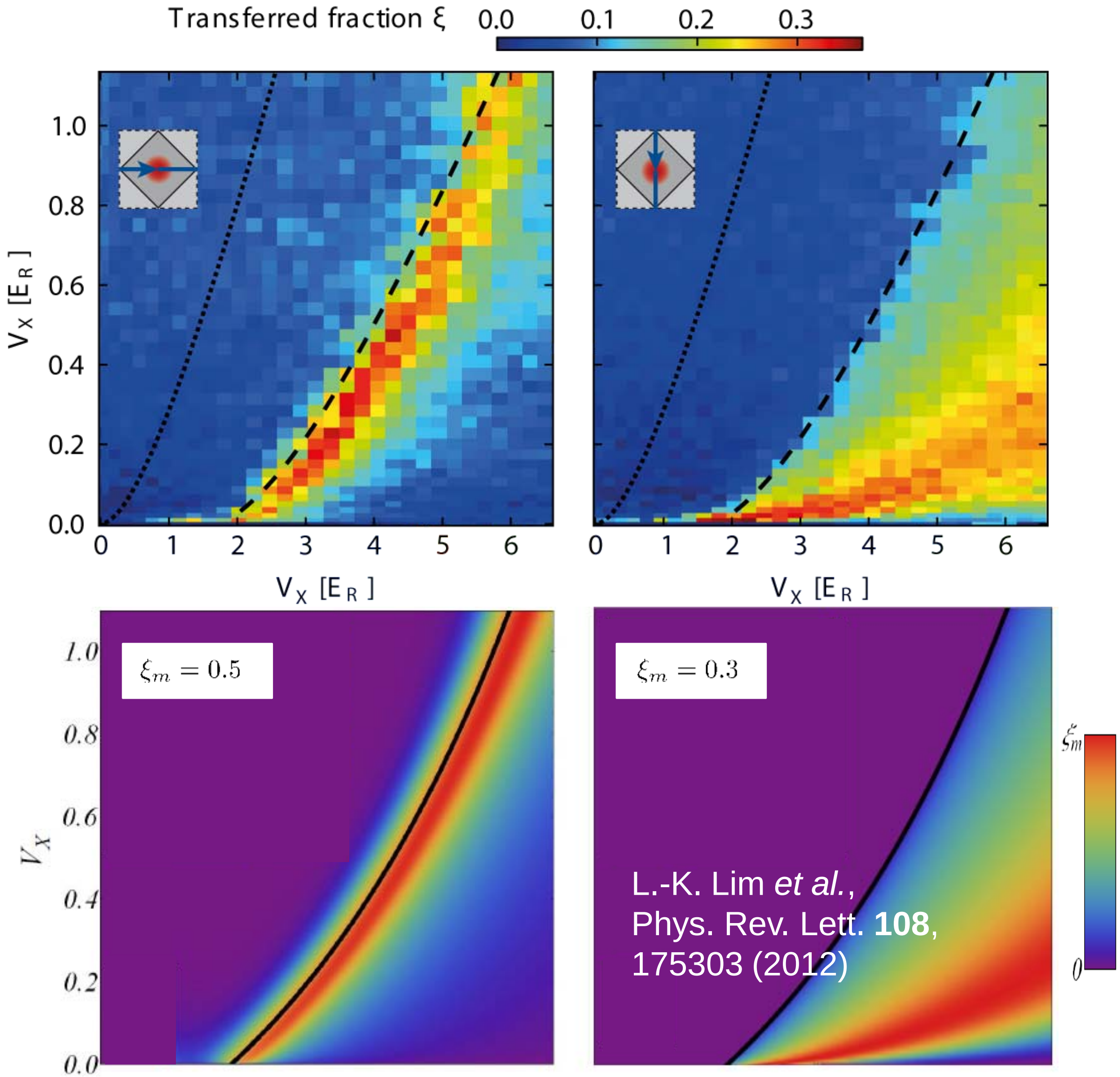


Force along y





The topological transition



L.-K. Lim *et al.*, Phys. Rev. Lett. **108**, 175303 (2012)

Outline

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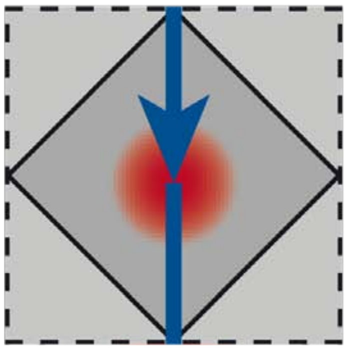
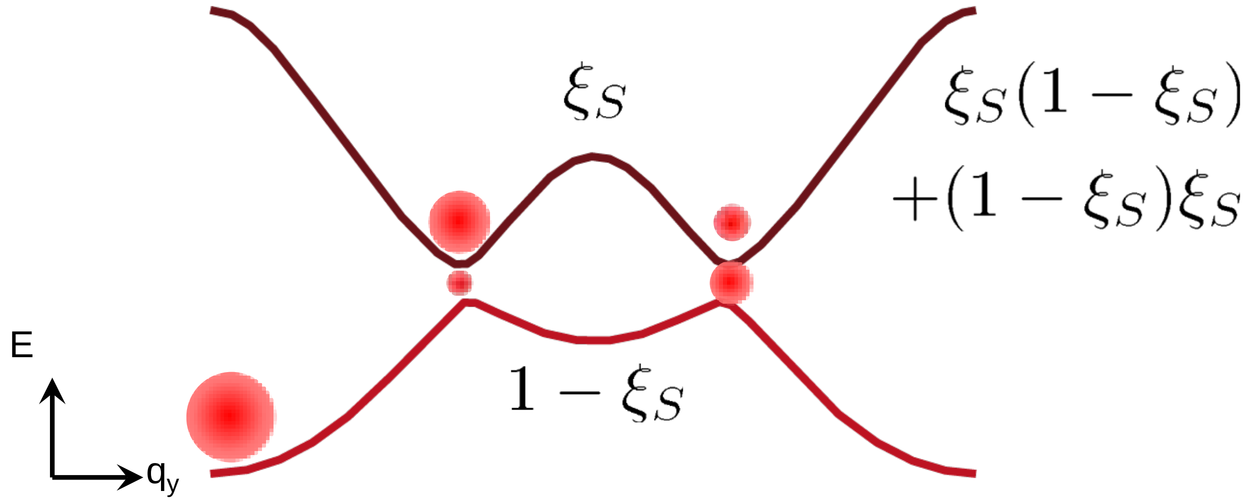
Double transfer through Dirac points

Double transfer through Dirac points



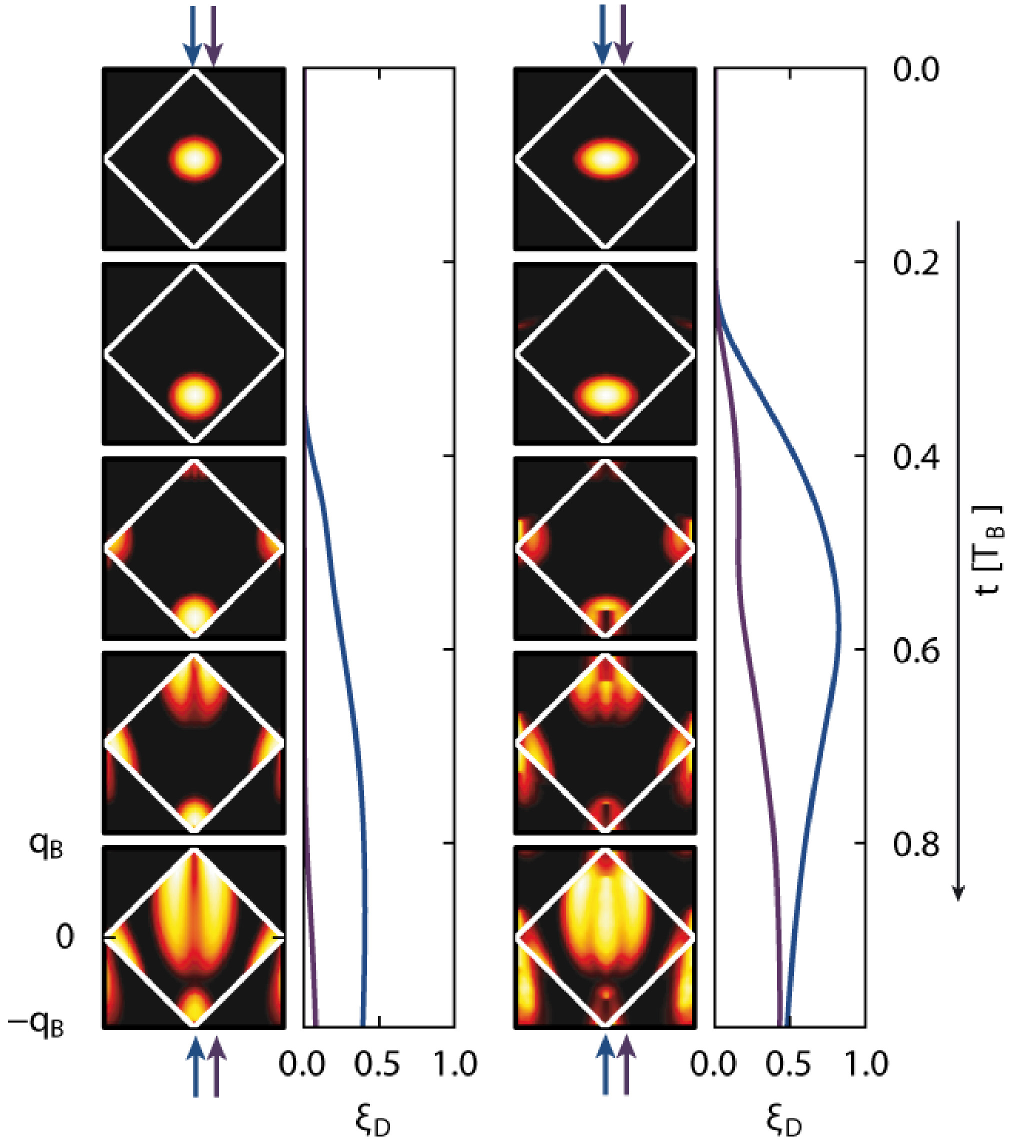


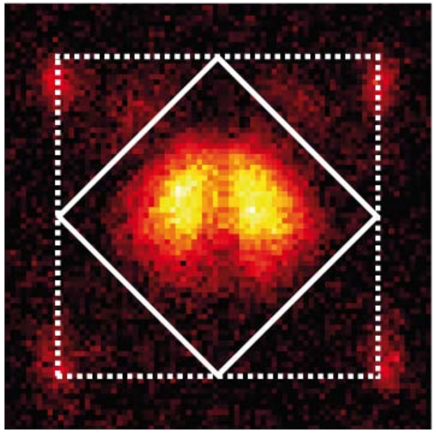
Dirac points as atomic beam-splitters

After a Bloch cycle: $\xi_D = 2\xi_S(1-\xi_S)$

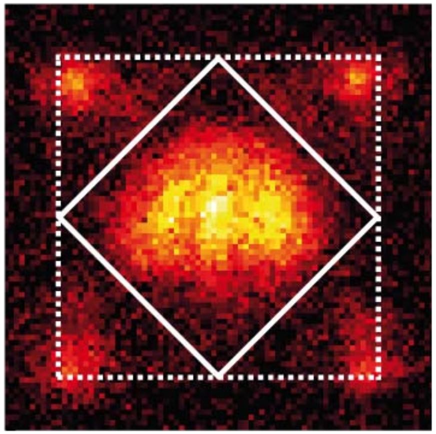
Transferred fraction ξ_D maximum for $\xi_S = 1/2$

Quasi-momentum resolved transitions



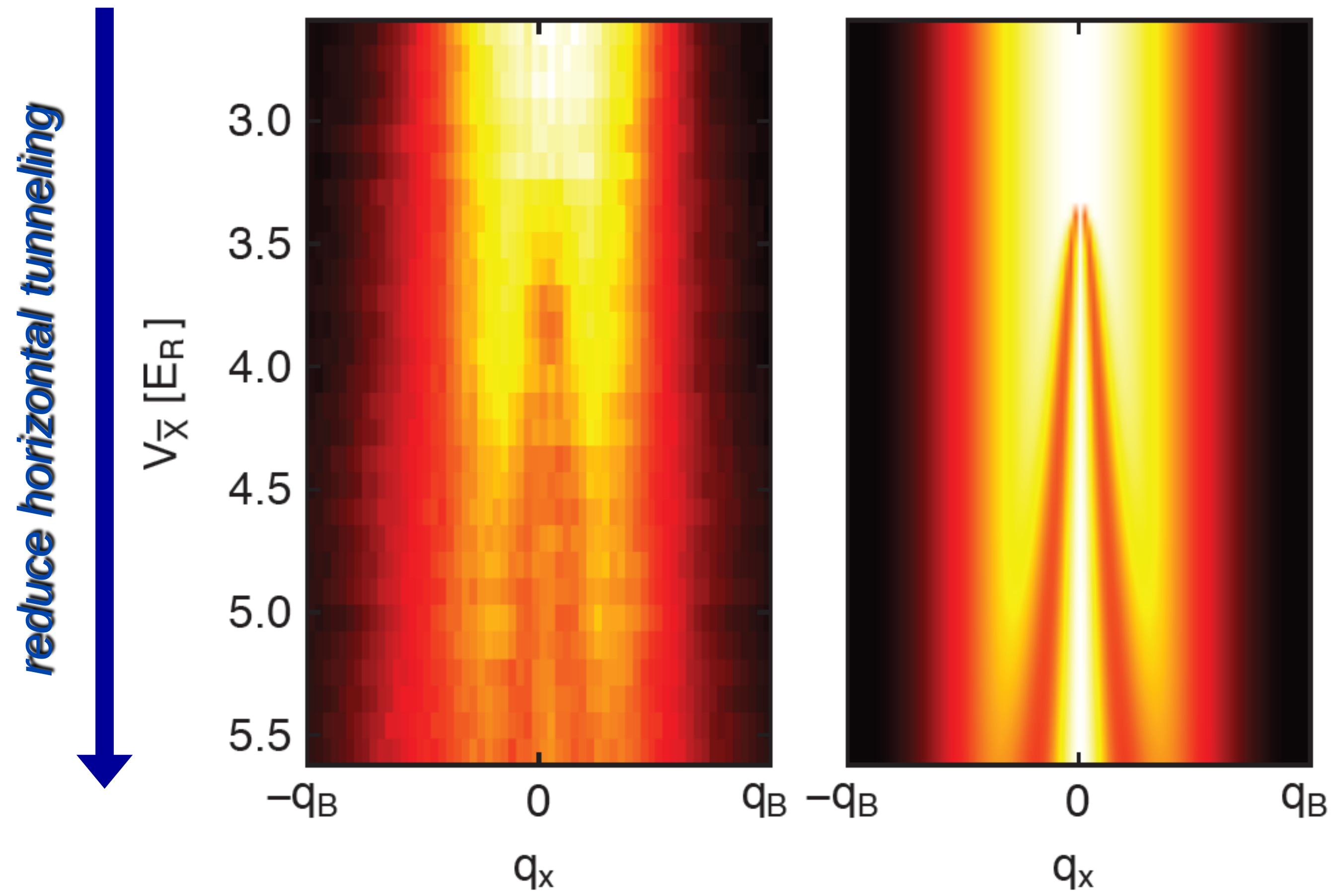


$V_{\bar{X},X,Y} = [2.7(2), 0.13(1), 1.8(1)]\ E_R$
$\theta = 1.013(1)\pi$



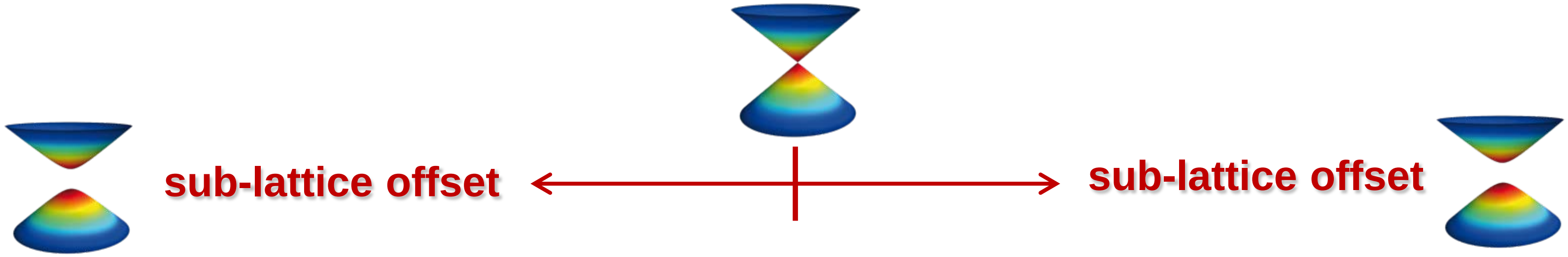
$V_{\bar{X},X,Y} = [4.3(3), 0.13(1), 1.8(1)]\ E_R$
$\theta = 1.013(1)\pi$

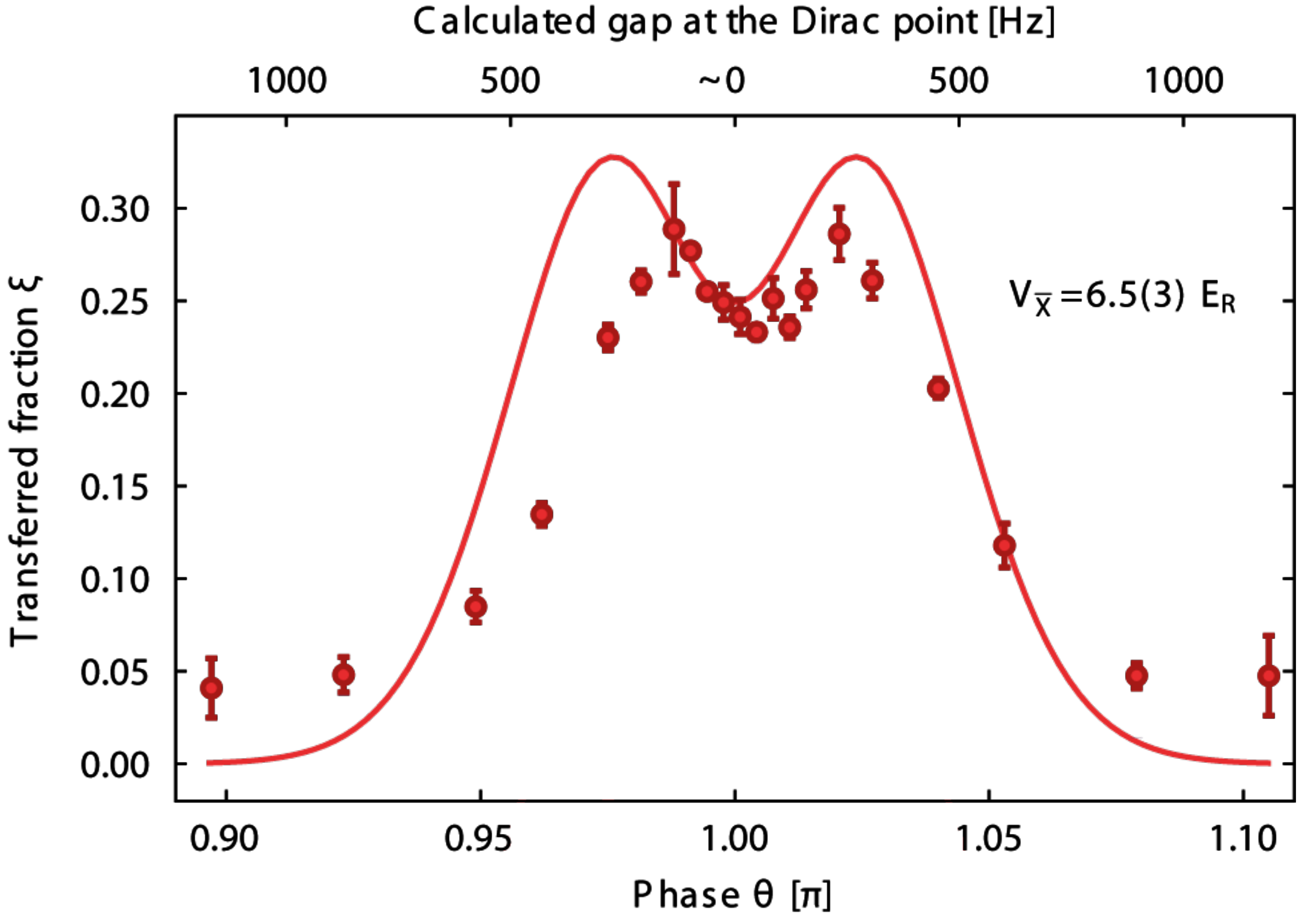
Quasi-momentum resolved transitions



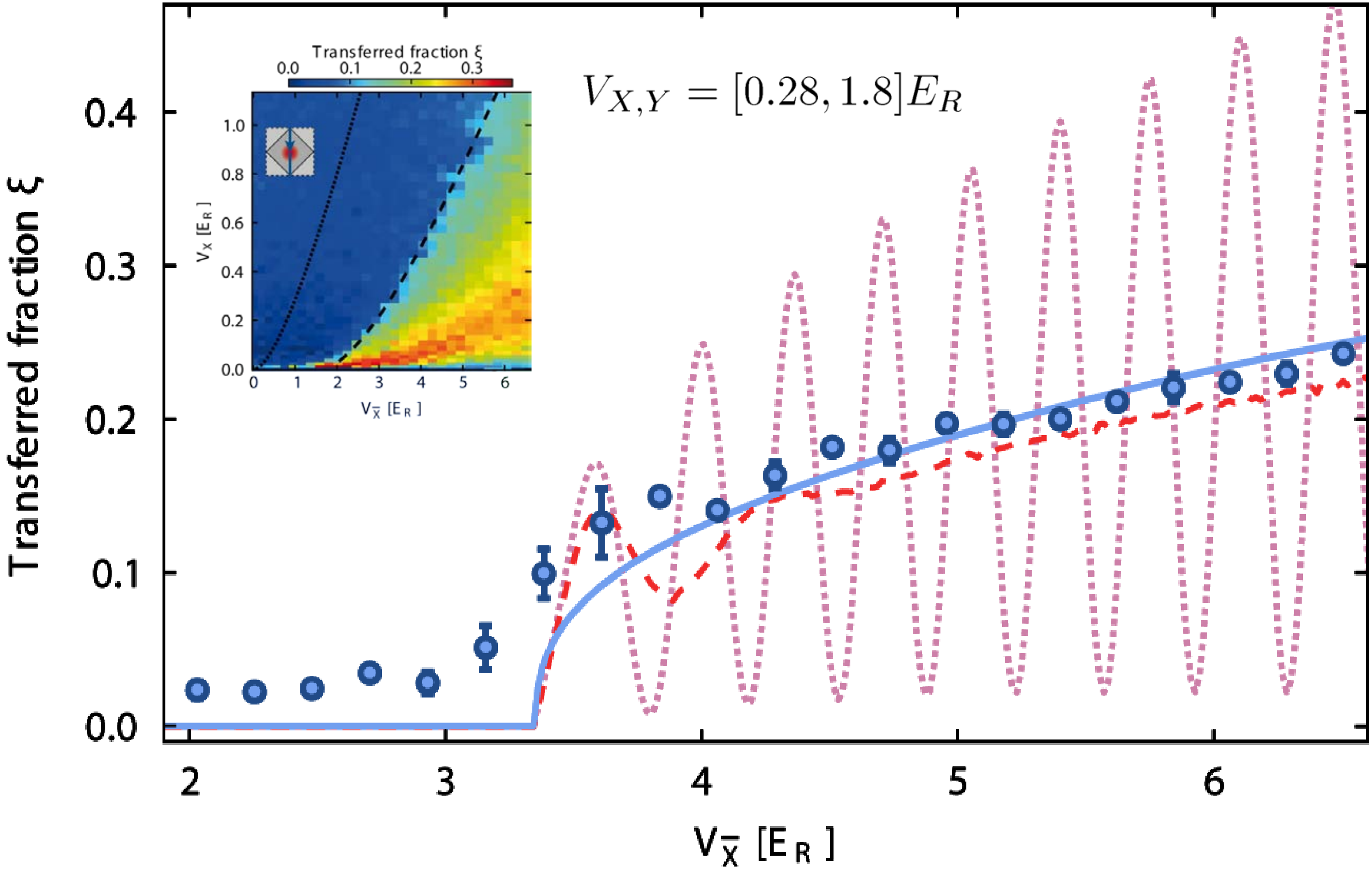
Breaking inversion symmetry

ETH





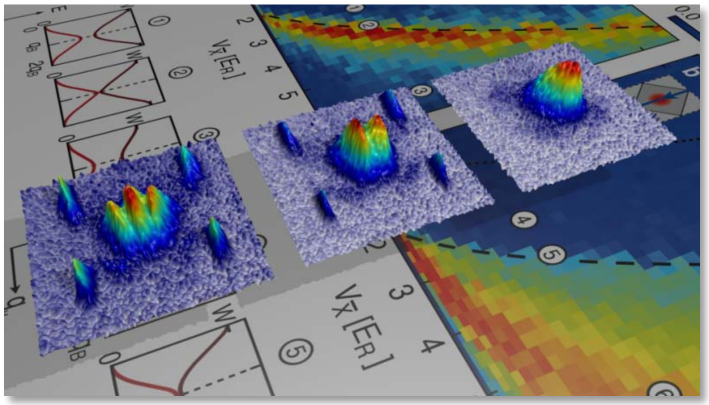
Stueckelberg interferences



Conclusion

ETH

Summary



Optical lattice of tunable geometry

Probing Dirac points *via* interband transitions

Adjusting, moving and merging Dirac points

Mapping out the topological transition

Double transfer through Dirac points

L. Tarruell, D. Greif, T. Uehlinger, G. Jotzu, and T. Esslinger, Nature **483**, 302 (2012)

T. Uehlinger, D. Greif, G. Jotzu, L. Tarruell, T. Esslinger, L. Wang, and M. Troyer, arXiv:1210.0904

Outlook

Detection of Berry phase/curvature

Topologically ordered states

Combination of honeycomb lattice structure with interactions

Study other accessible geometries: dimer, triangular, zig-zag chains…

The ETH lattice team

ETH

Thank you for your attention !