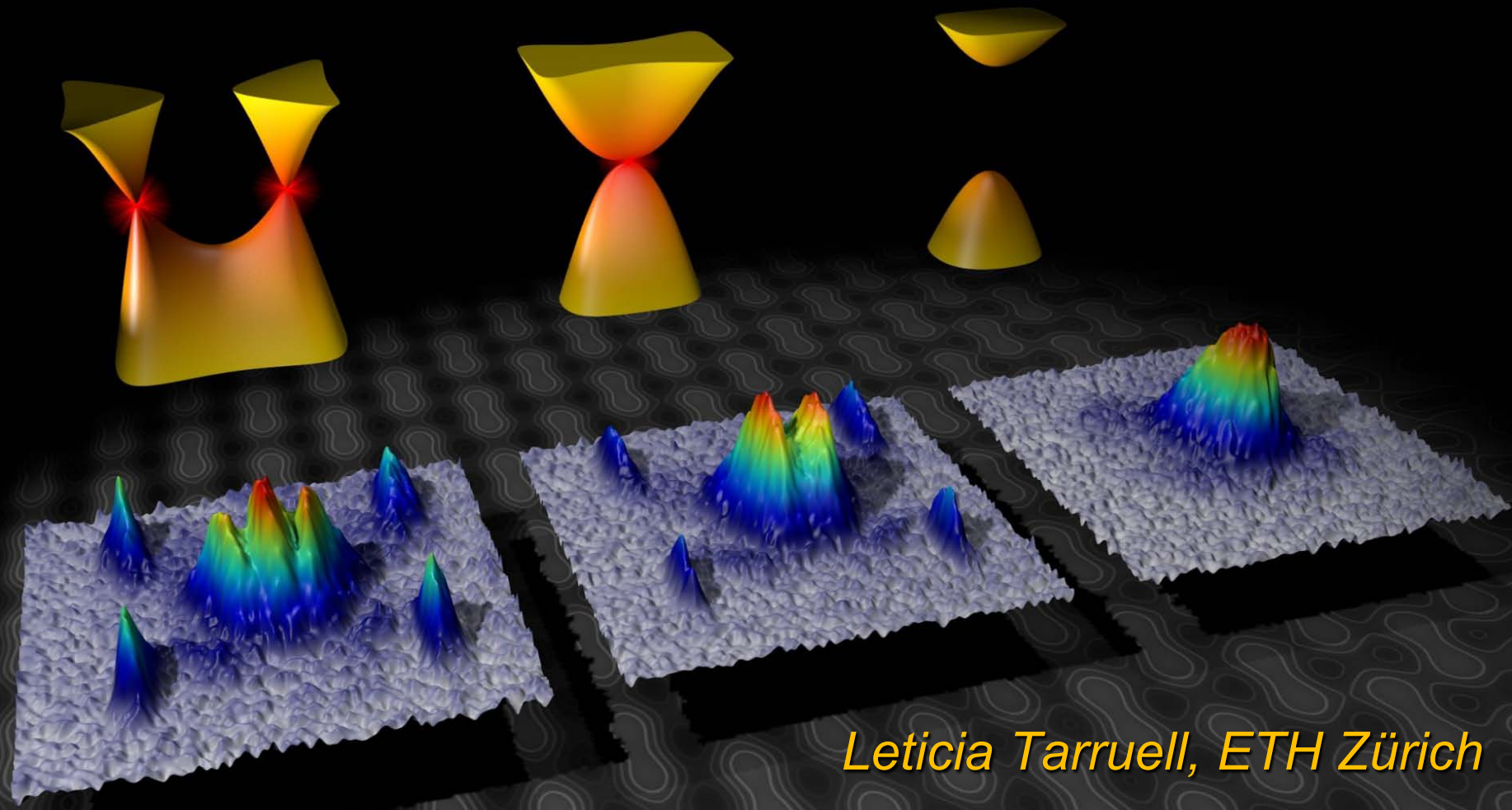
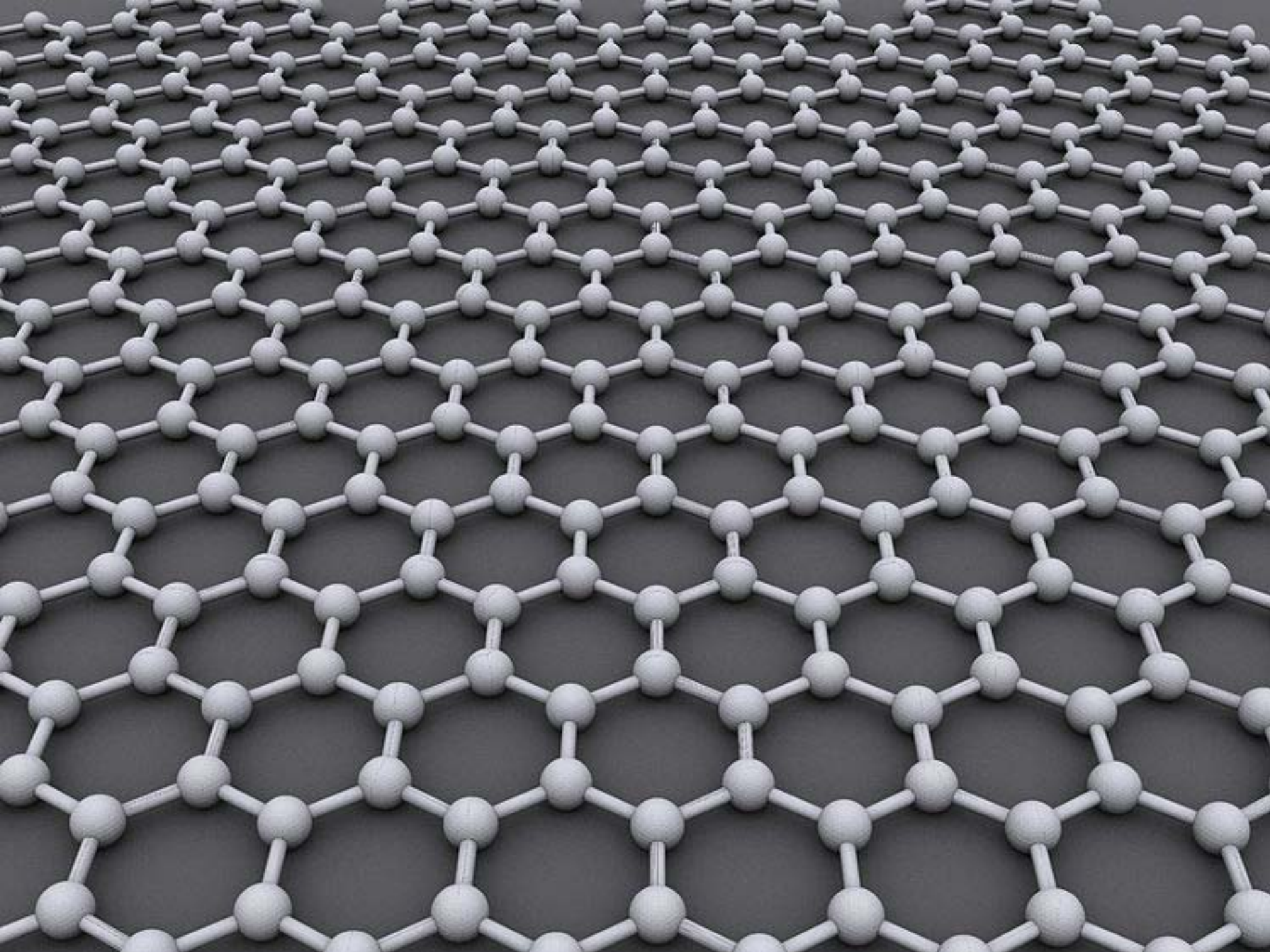
Engineering Dirac points with ultracold fermions in optical lattices



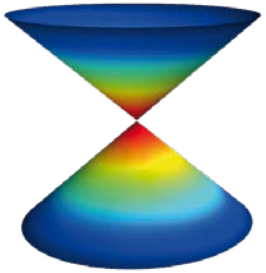
Leticia Tarruell, ETH Zürich

Lyon – 08/06/2012



Band structures with topological defects

ETH



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

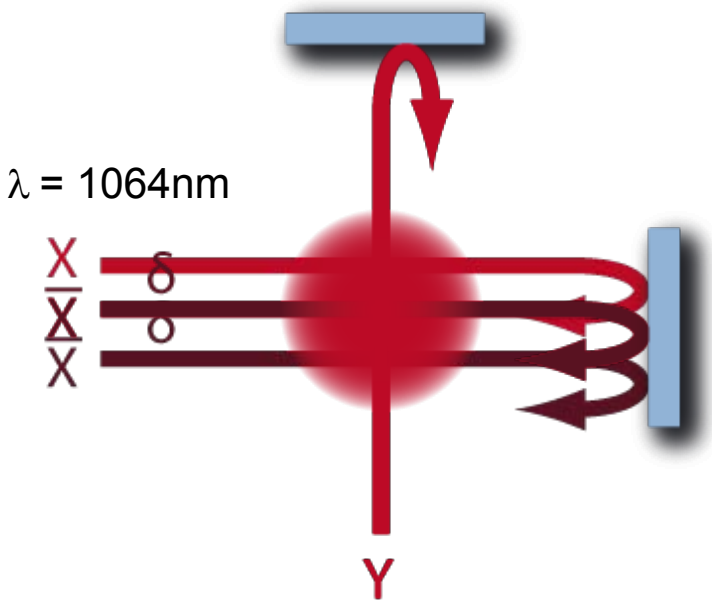
Probing Dirac points by interband transitions

Adjusting, moving and merging Dirac points

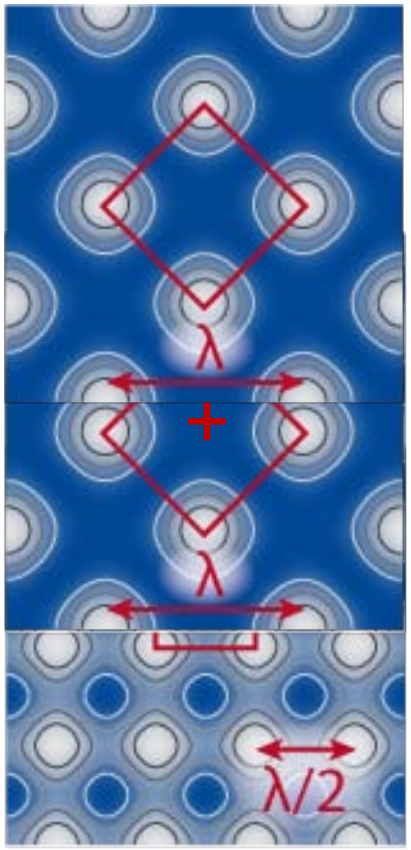
An optical lattice of tunable geometry

ETH

Setup



Optical potential



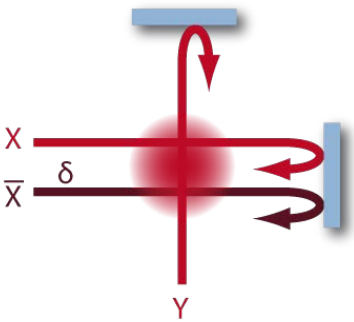
X and *Y*

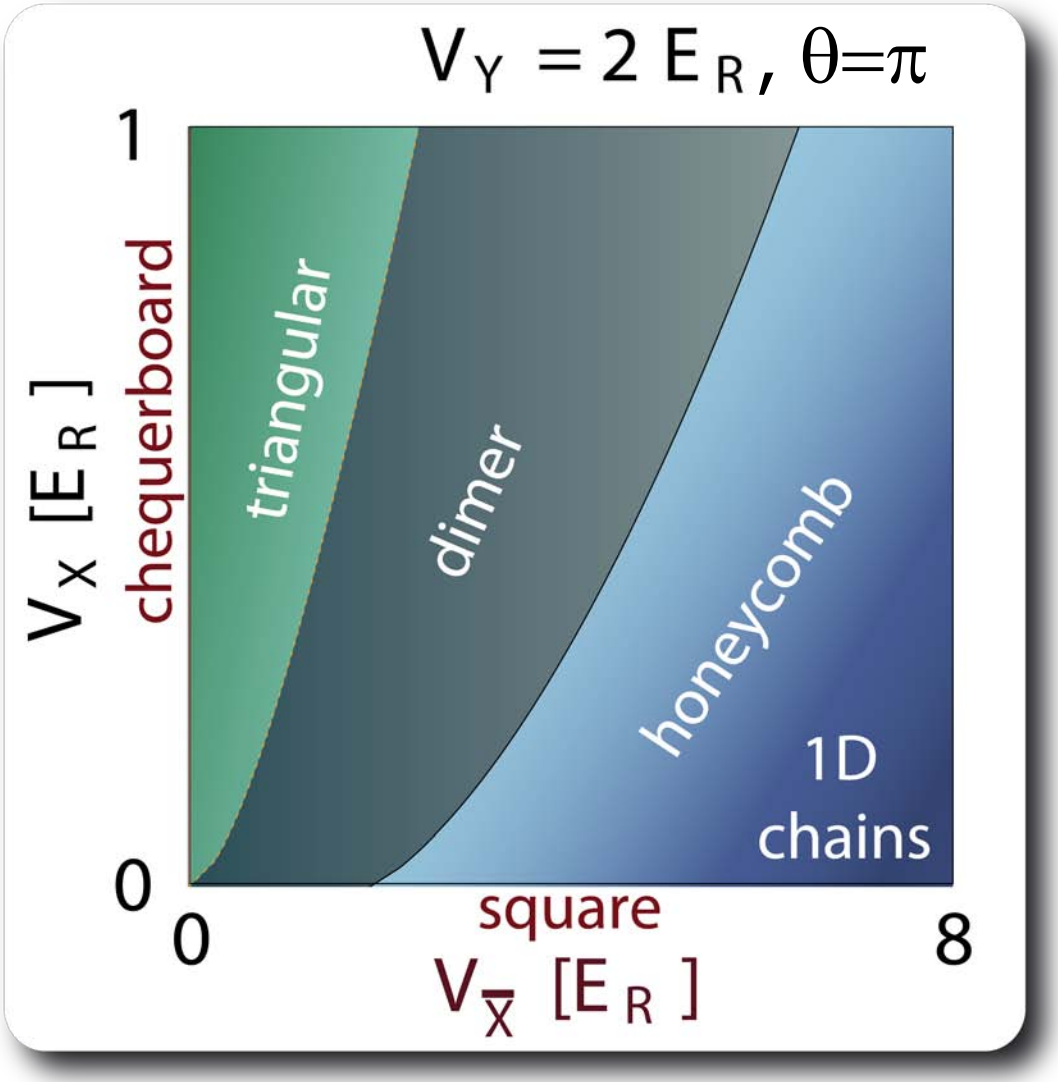
X̄ and *Y*

X̄ and *Y*

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

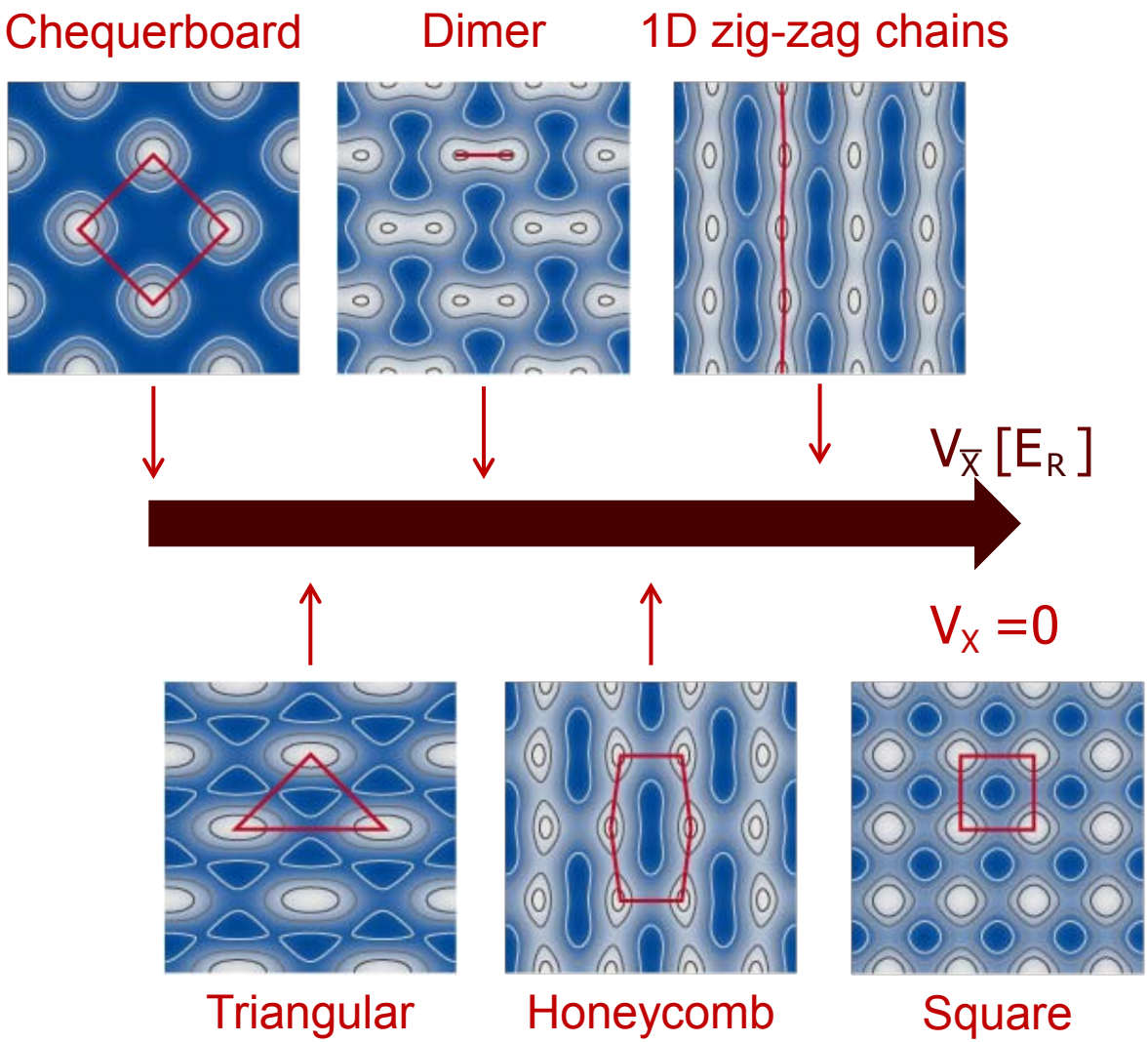
An optical lattice of tunable geometry

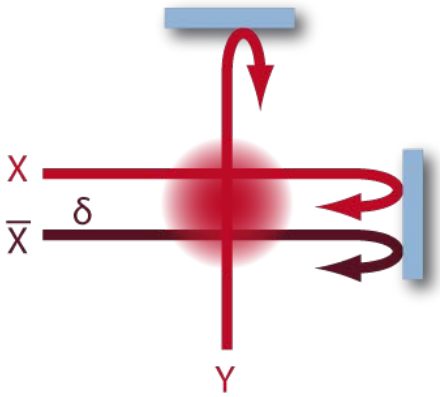


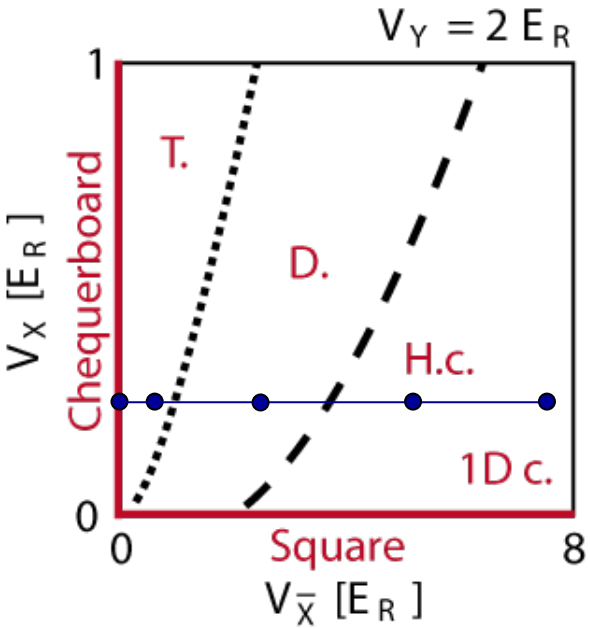


An optical lattice of tunable geometry

ETH

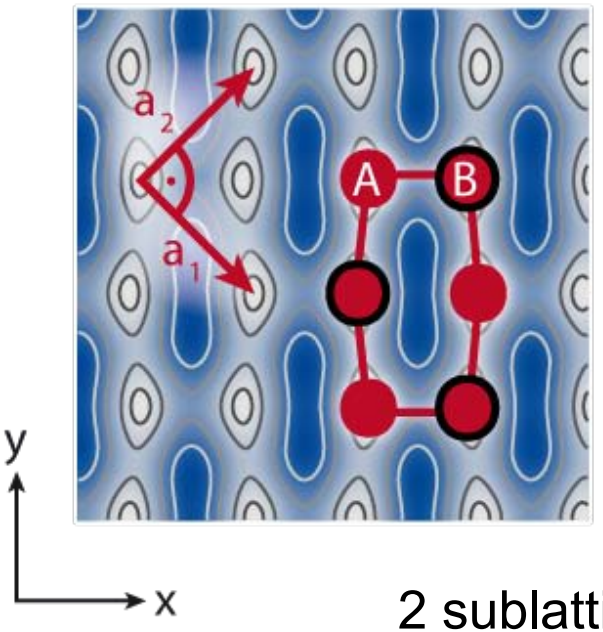




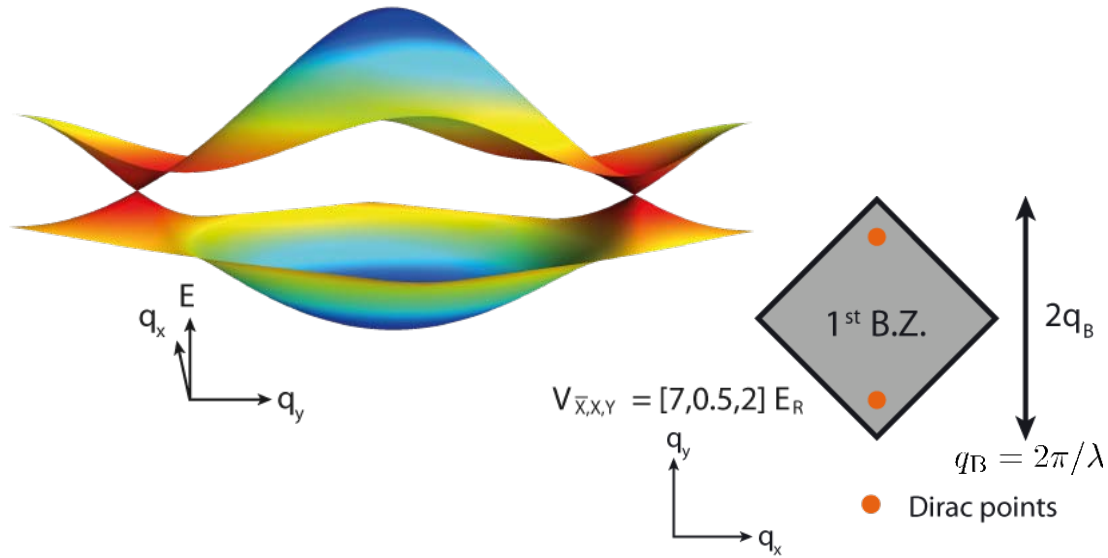


Honeycomb lattice

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

Probing the Dirac points

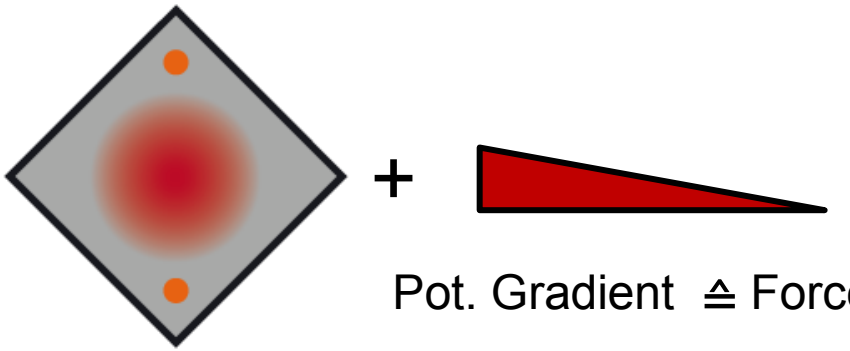
ETH

Challenges: vanishing density of states
small energy scales

Probe energy splitting of
the bands **dynamically**

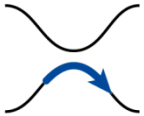
T. Salger *et al.*, Phys. Rev. Lett. **99**, 190405 (2007)

Bloch oscillations + interband transitions

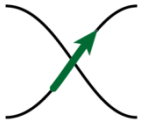


Pot. Gradient ≙ Force

Passing away from Dirac point:
stay in lowest band



Passing through Dirac point:
transfer to 2nd band

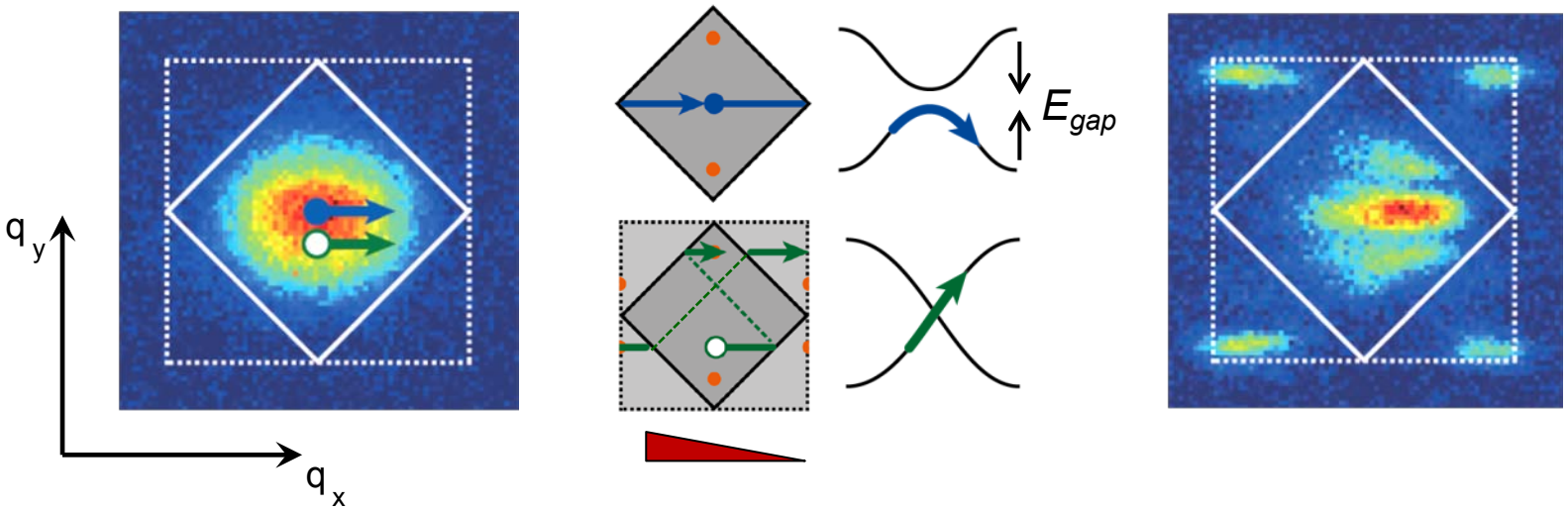


Observable: quasi-momentum distribution

Interband transitions: 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

$$V_{\bar{X},X,Y} = (4.1, 0.28, 1.8)E_R$$

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

Energy resolution:

$$E_{\mathrm{res}}/h \sim 88\,\mathrm{Hz}$$
$$E_{\mathrm{gap}}/h \sim 500\,\mathrm{Hz}$$

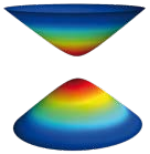
Tuning the Dirac points

ETH

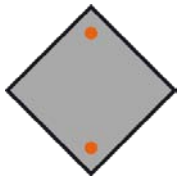
Dirac points with ultracold atoms

Tunability

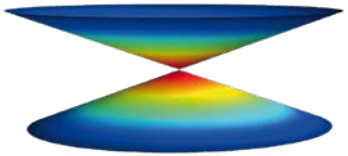
Mass



Dirac point position



Cone asymmetry

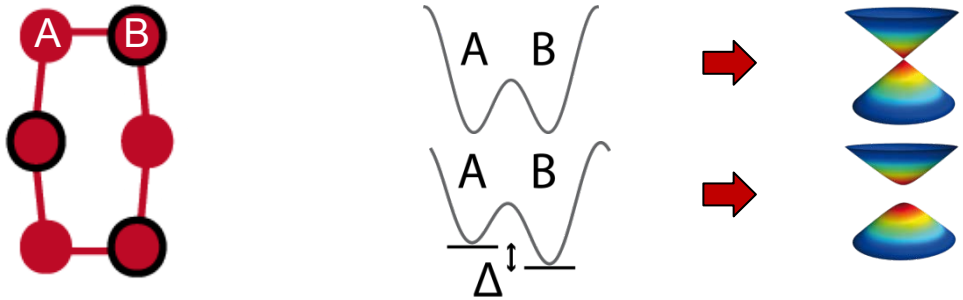


S.-L. Zhu, B. Wang, and L.-M. Duan, *Phys. Rev. Lett.* **98**, 260402 (2007).
B. Wunsch, F. Guinea, and F. Sols, *New J. Phys.* **10**, 103027 (2008).
G. Montambaux *et al.*, *Phys. Rev. B* **80**, 153412 (2009).
K. L. Lee *et al.*, *Phys. Rev. A* **80**, 043411 (2009).

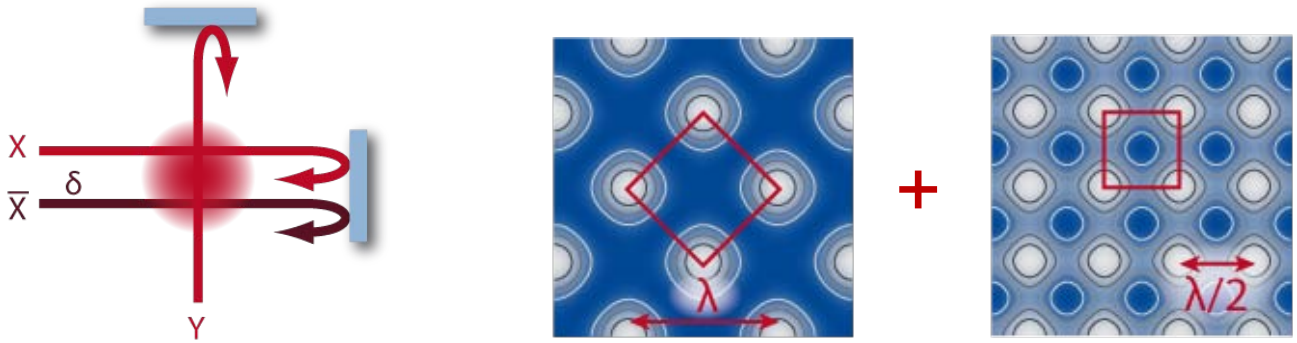
Breaking inversion symmetry

ETH

Control of sublattice energy offset



Experiment

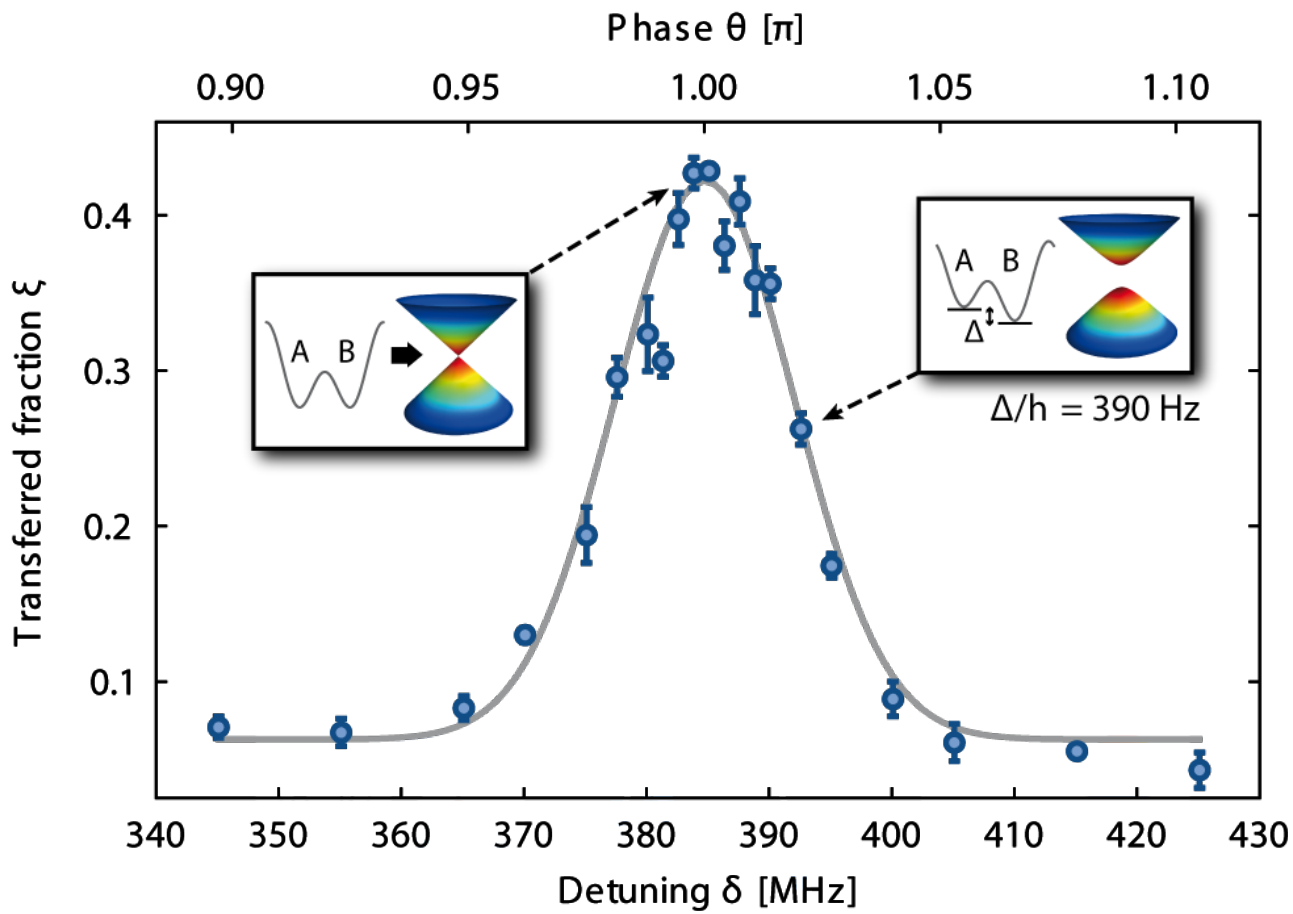


Relative positioning θ of X and $\bar{X}$ (detuning δ)

Breaking inversion symmetry

Higher band fraction

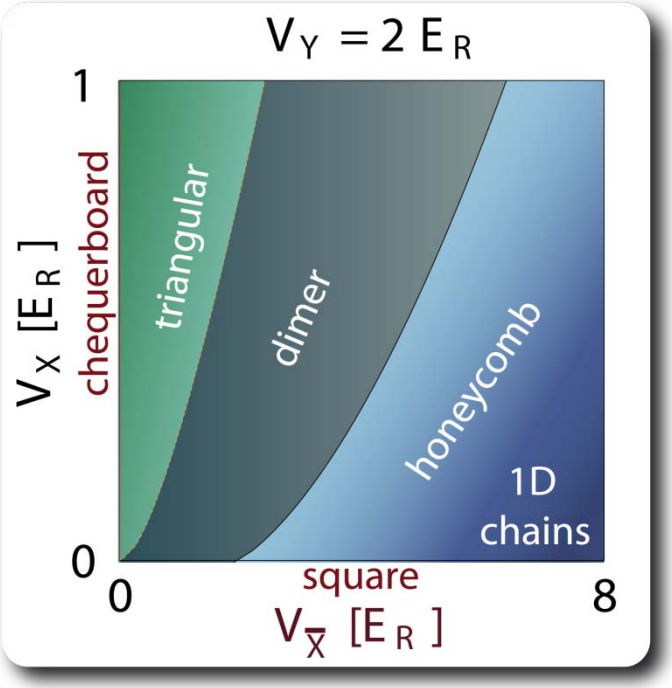
$$\xi = \frac{N(\blacklozenge)}{N(\diamond)+N(\blacklozenge)}$$

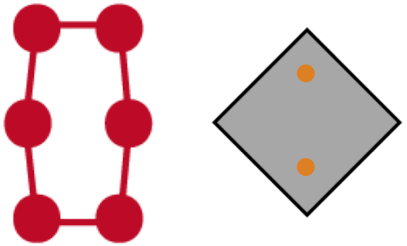


Tuning the mass of Dirac fermions

Position and anisotropy of Dirac cones

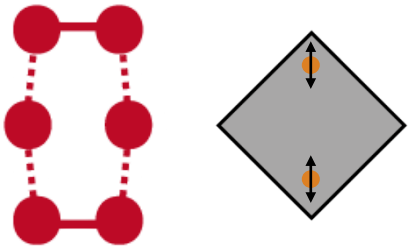
Adjusting the laser intensities $(V_X, V_{\bar{X}})$



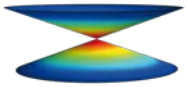


- isotropic Dirac points

- fixed position



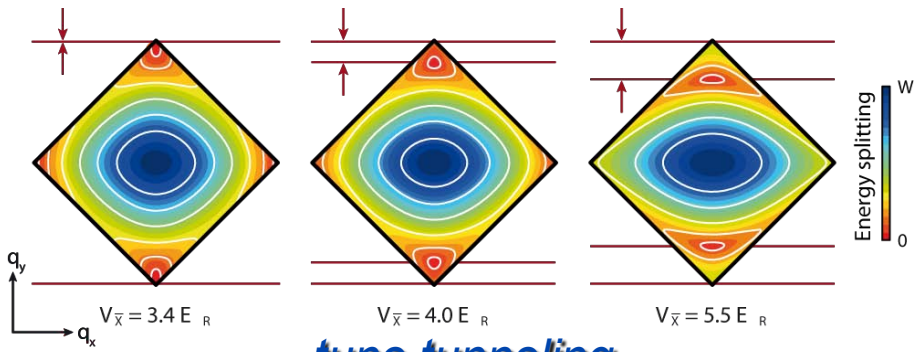
- anisotropic Dirac points



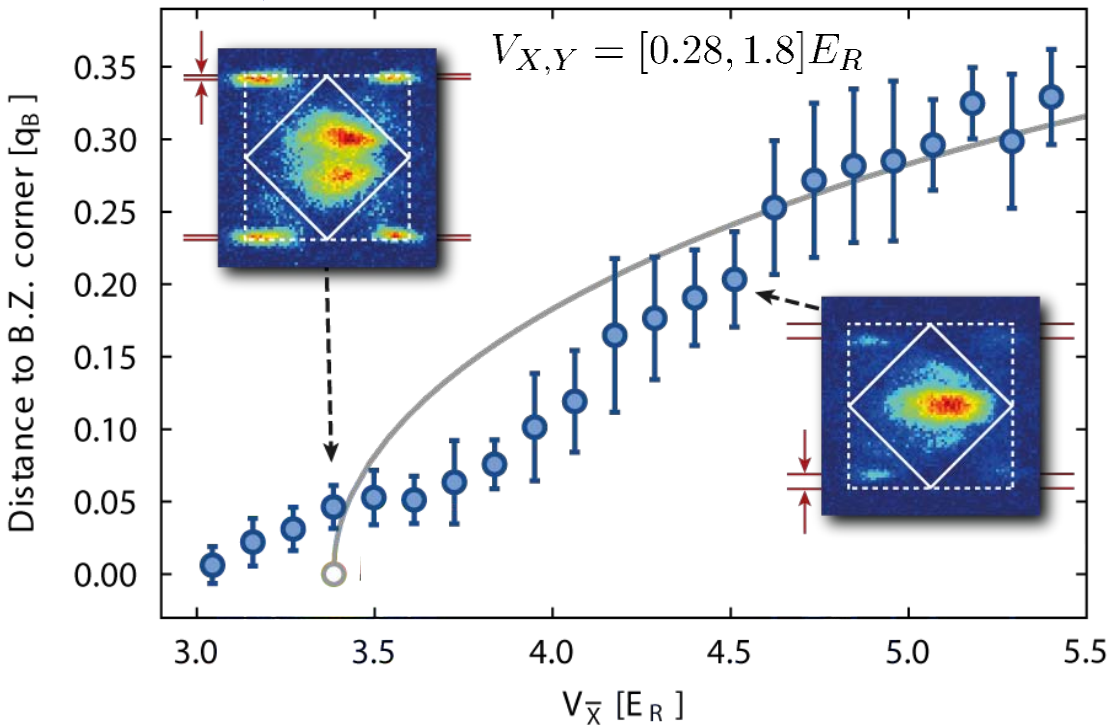
- different positions

G. Montambaux *et al.*, *Phys. Rev. B* **80**, 153412 (2009)

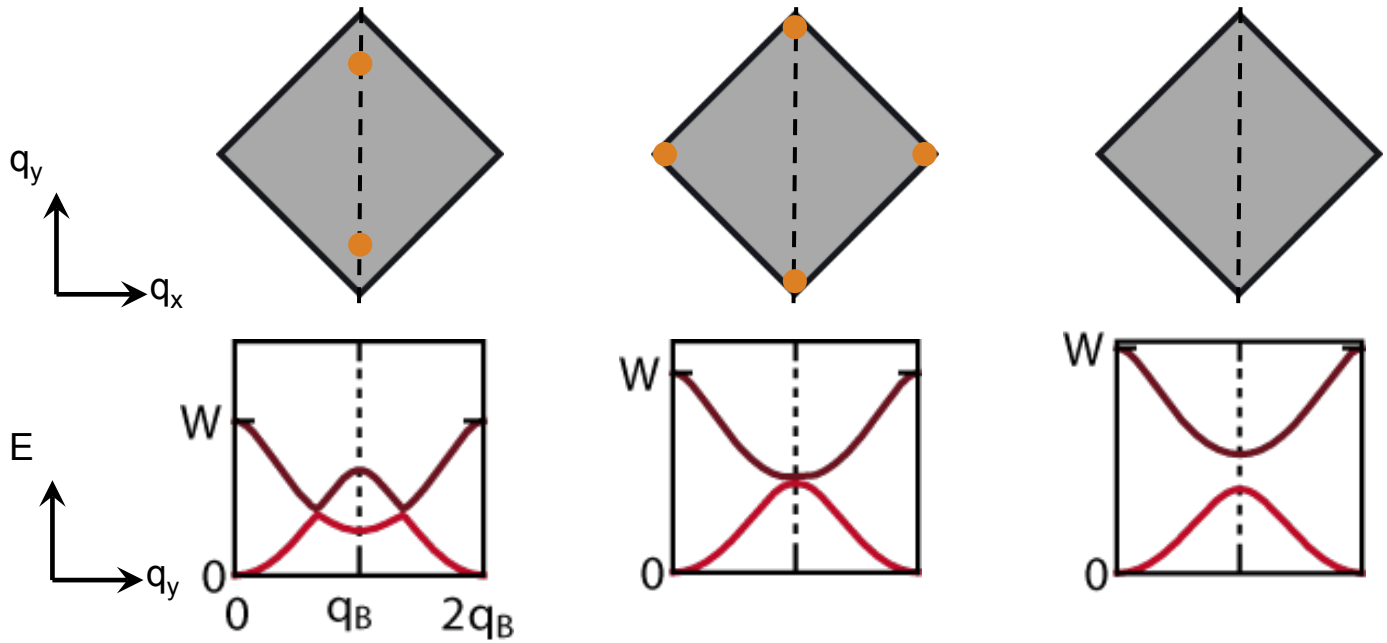
Moving Dirac points



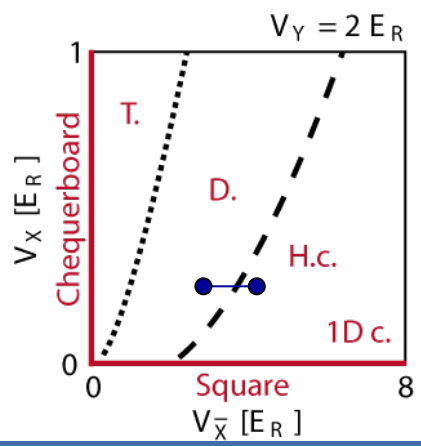
tune tunneling



Merging Dirac points



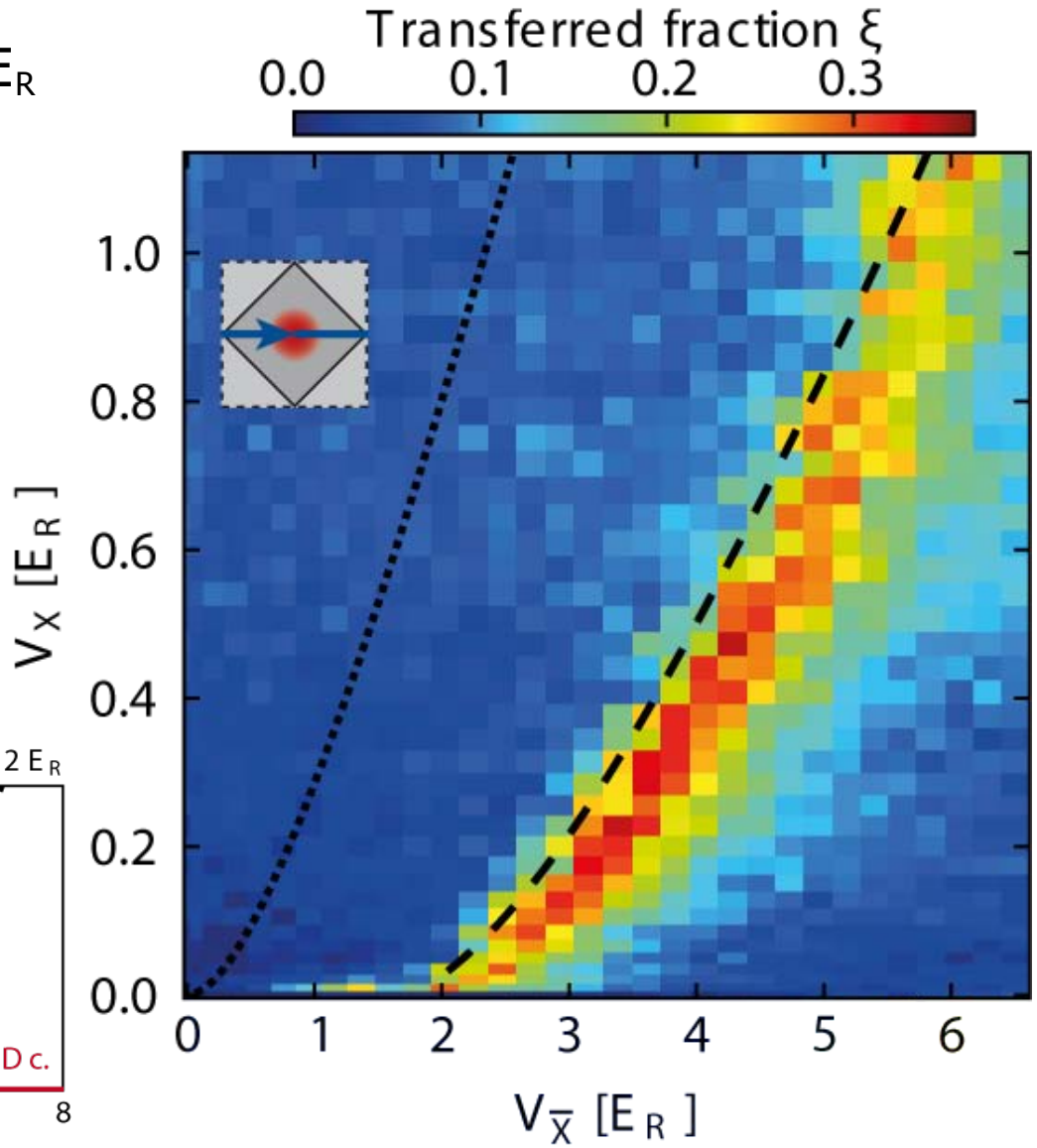
Dirac points → *Topological Transition* → *No Dirac points*

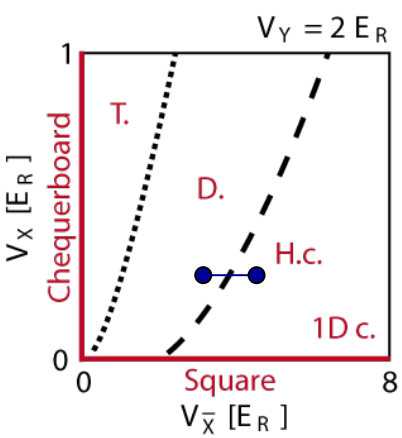


Lifshitz transition, Sov. Phys. JETP **11**, 1130 (1960)

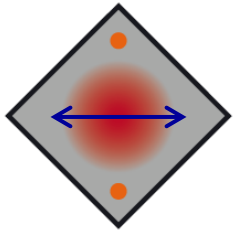
The topological transition

$V_Y = 1.8\ E_R$



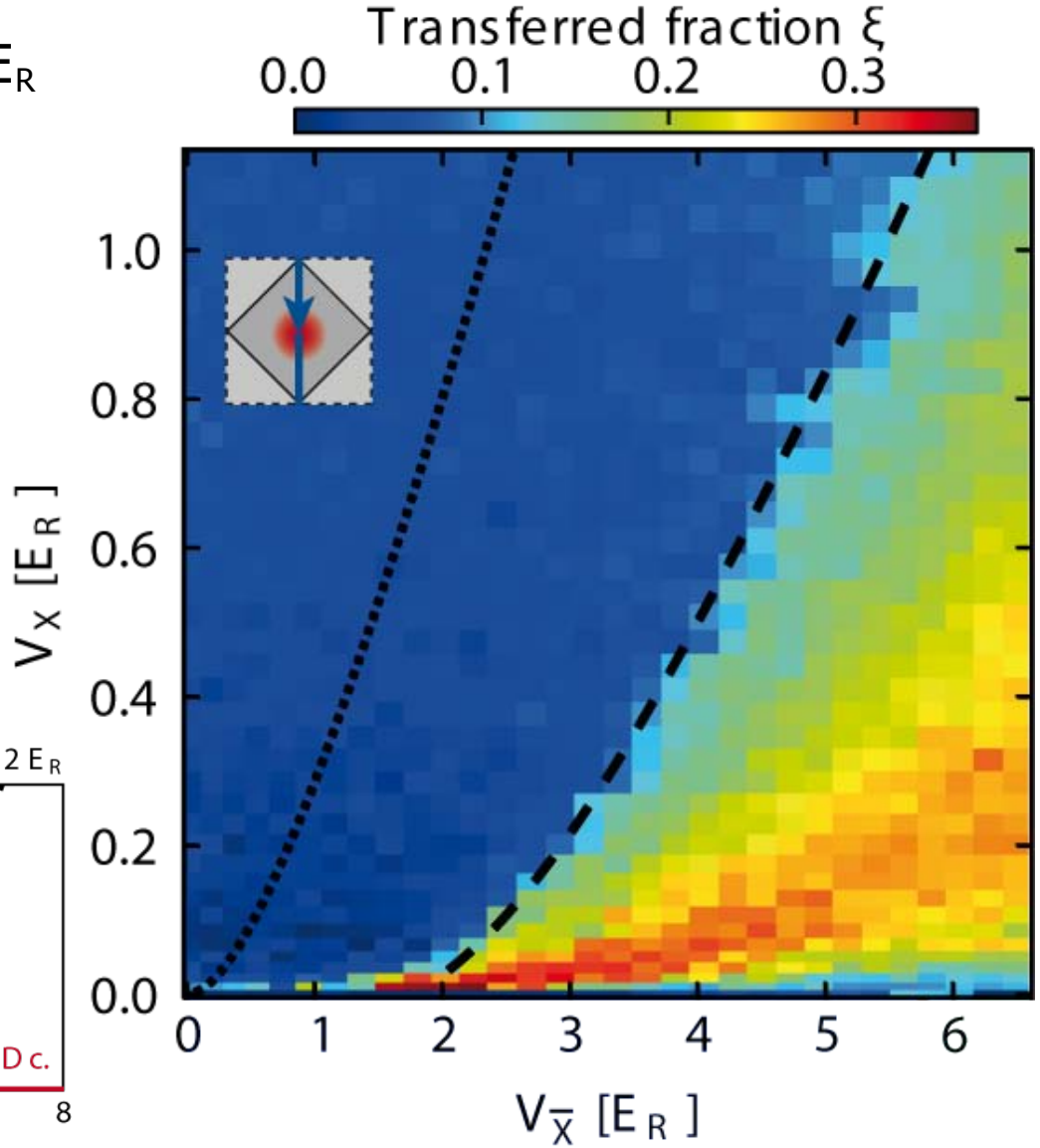


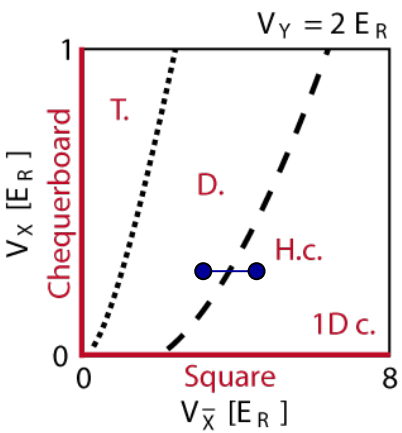
Force along x



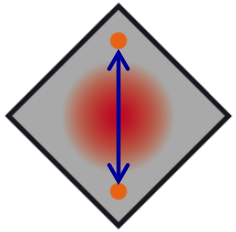
The topological transition

$V_Y = 1.8\ E_R$

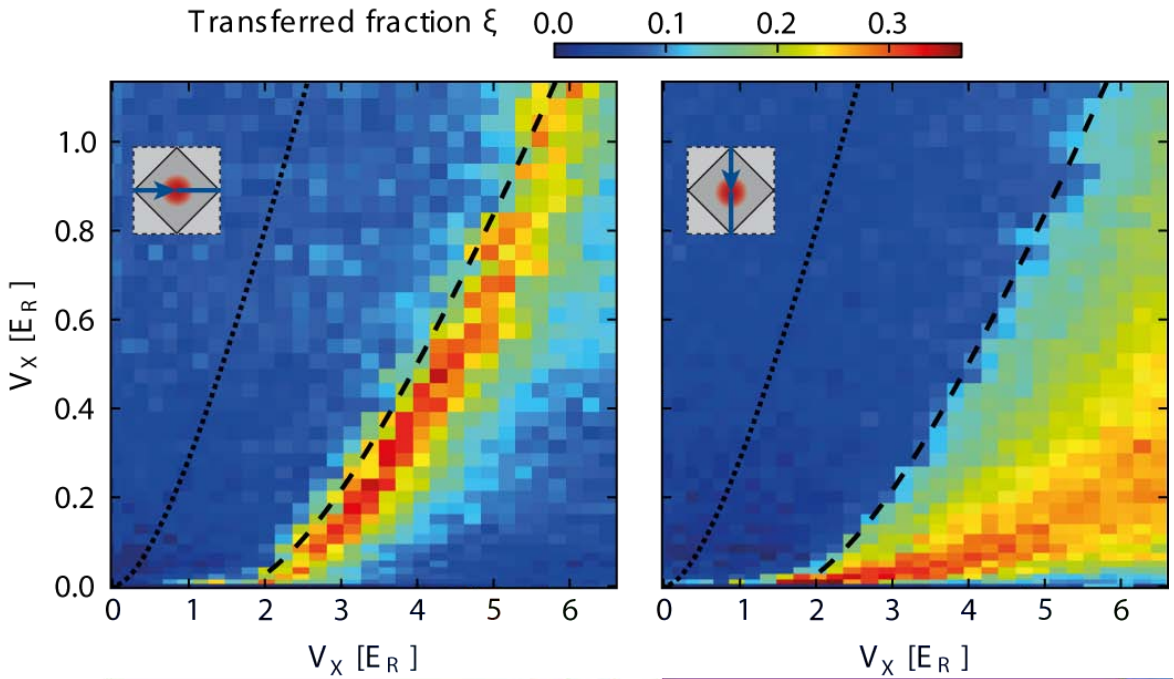


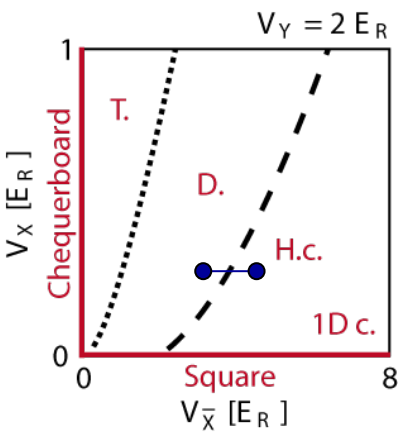


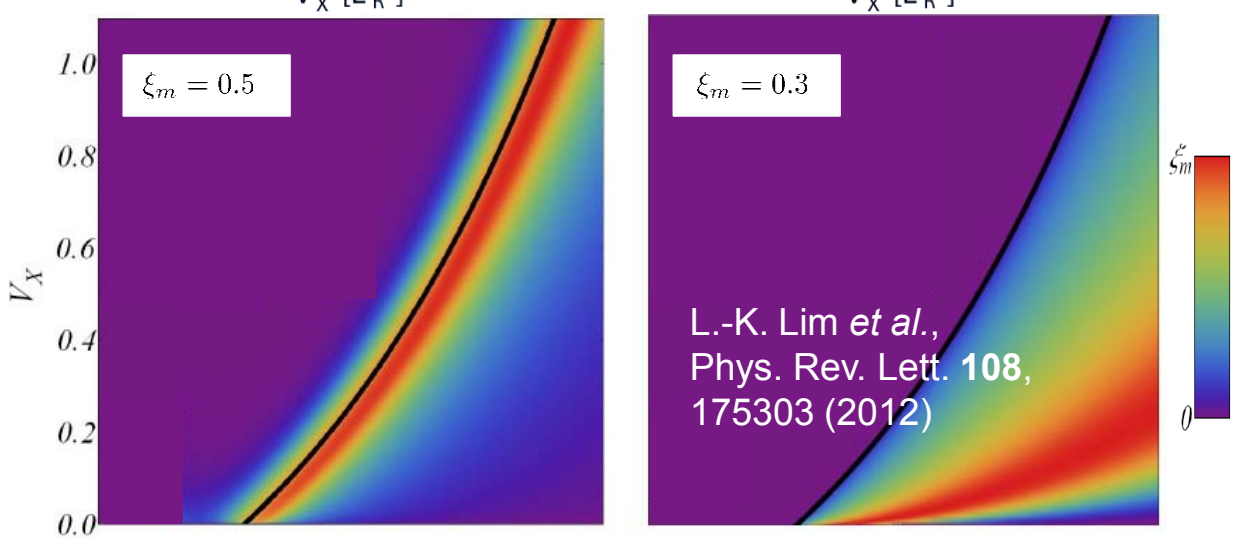
Force along y



The topological transition



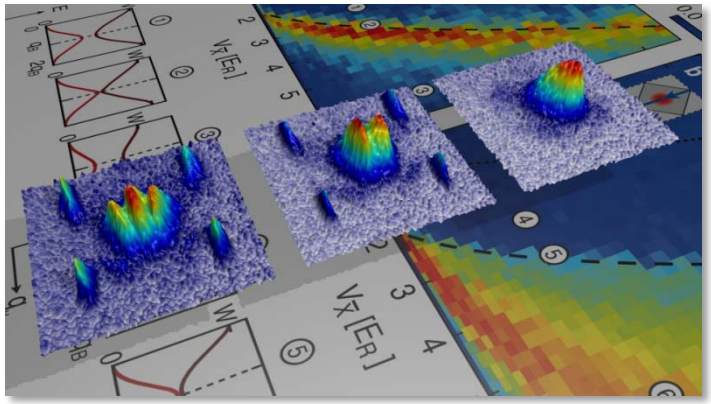




L.-K. Lim *et al.*, Phys. Rev. Lett. **108**, 175303 (2012)

Conclusion

Summary



Optical lattice of tunable geometry

Probing Dirac points *via* interband transitions

Adjusting, moving and merging Dirac points

Mapping out the topological transition

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

Outlook

Detection of the Berry phase

Topologically ordered states

Combination of complex lattice geometries with interactions

The group


L. T.
Gregor Jotzu
Thomas Uehlinger
Daniel Greif
Tilman Esslinger

Cold atoms in Bordeaux

with Philippe Bouyer, Giorgio Santarelli, Baptiste Battelier

http://www.lp2n.institutoptique.fr/

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