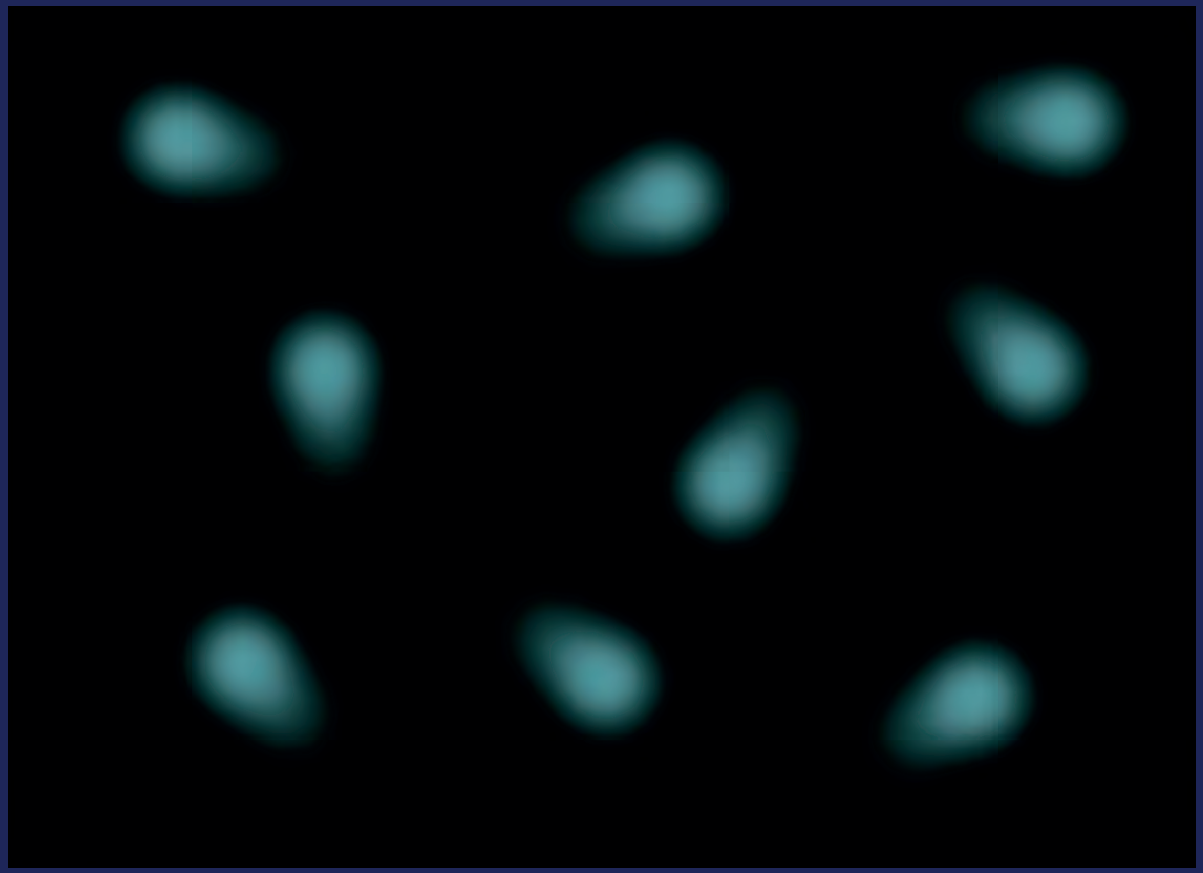
Building quantum systems from scratch

Tilman Esslinger ETH Zürich

Funding: ETH, EU (ERCadv TransQ, SIQS, TherMiQ, QUIC, ColOpt), NCCR QSIT, SNF

www.quantumoptics.ethz.ch



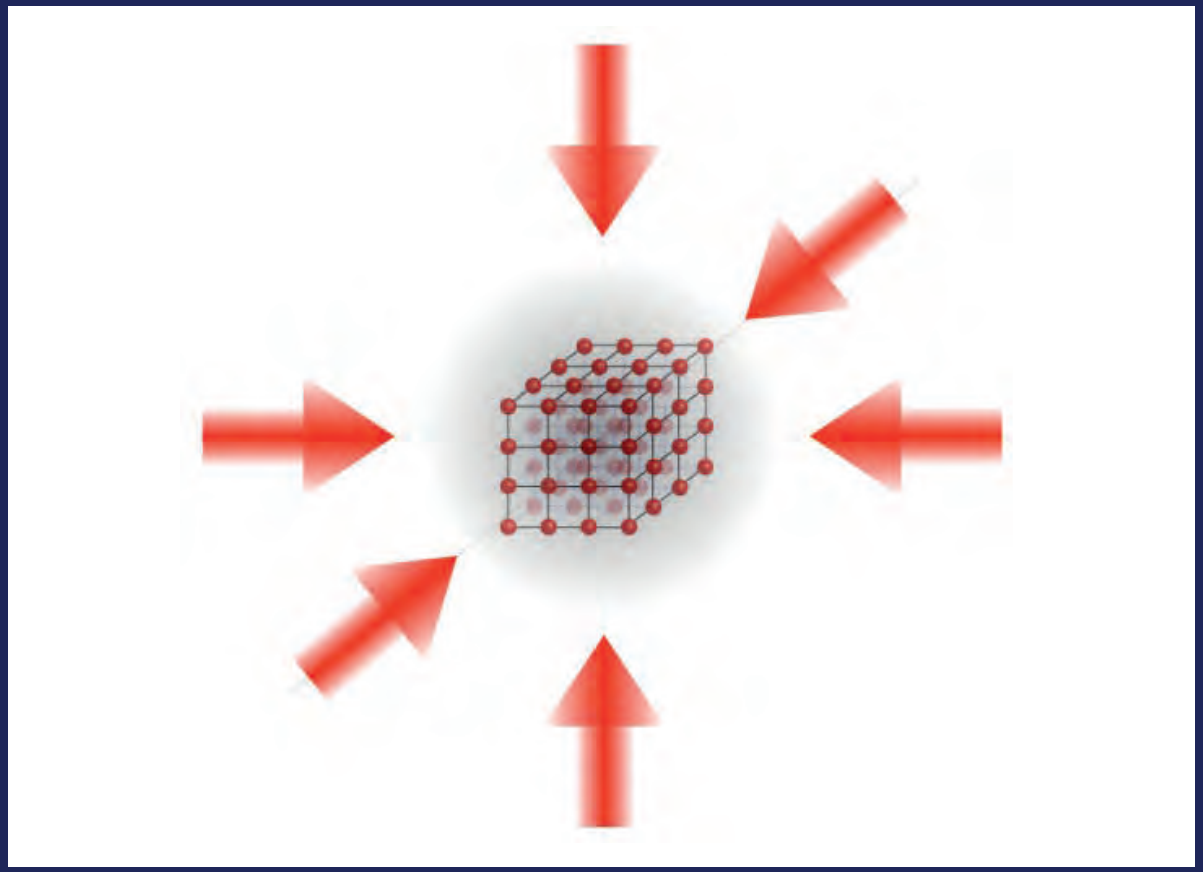


FIGURE 1. *Classification topologique obtenue en comptant le nombre de "poignées" d'un objet. Cette classification est robuste, puisqu'un objet ne change pas de classe quand on le déforme légèrement, et elle ne dépend pas d'éventuelles symétries spatiales géométriques de l'objet.*

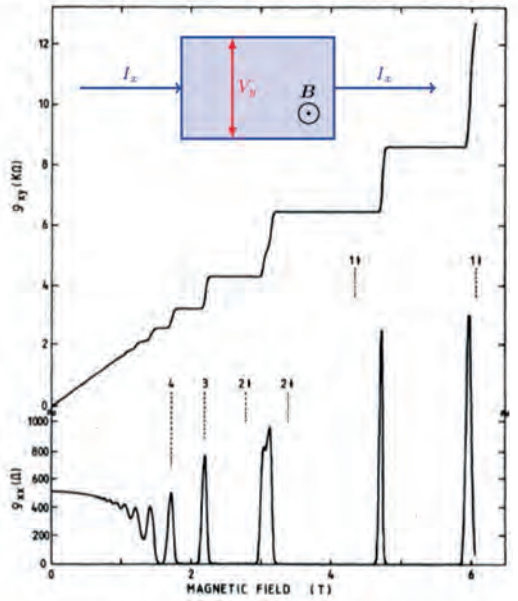
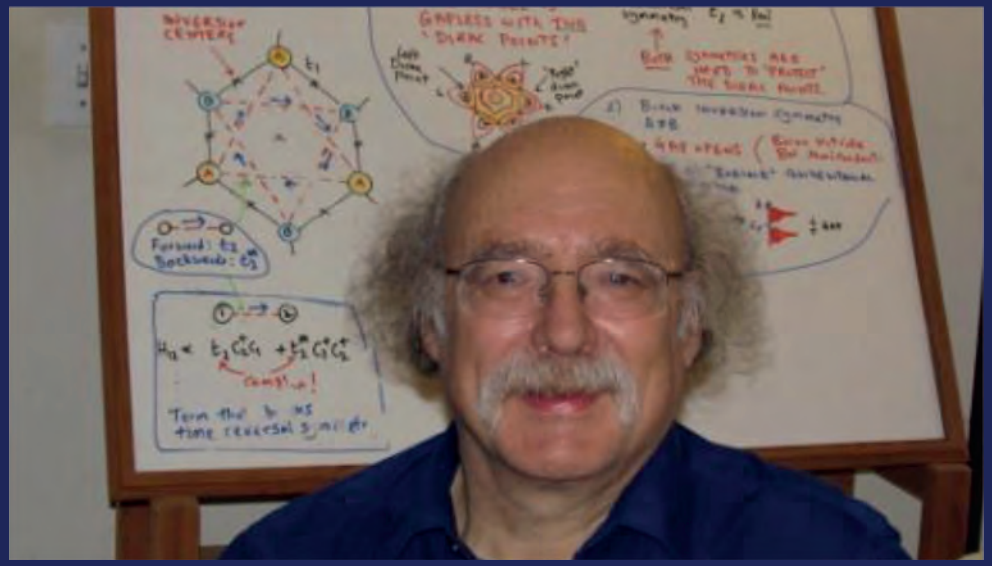
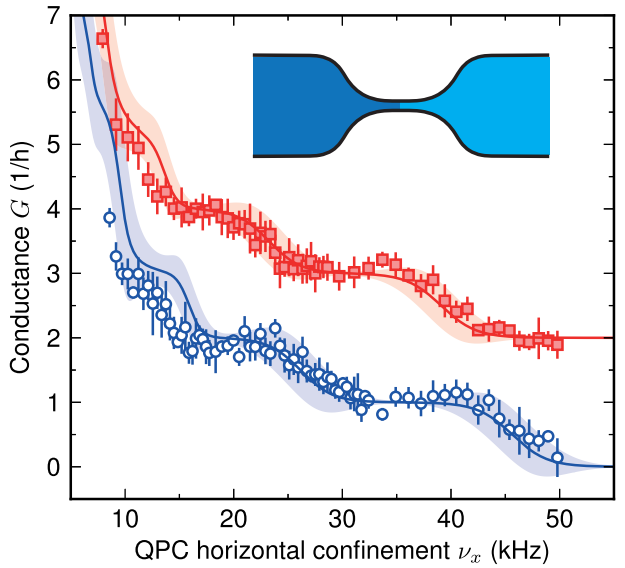


FIGURE 2. *Exemple de manifestation d'un ordre topologique dans un gez 2D d'électrons plongé dans un grand champ magnétique : la résistivité de Hall ρ_{xy} mesurée dans une expérience d'effet Hall quantique présente des plateaux quantifiés quand on varie le champ magnétique ; dans cette mesure, un courant I_x circule dans un échantillon rectangulaire $L_x \times L_y$ et on mesure une tension V_y aux bornes de l'échantillon. Cette quantification est robuste : elle subsiste en présence d'un désordre (modéré) dans l'échantillon. Figure extraite de* VON KLITZING *(1986).*

Haldane model



Quantized conductance



Where is the physics?

$$H = T + U + V_{trap}$$

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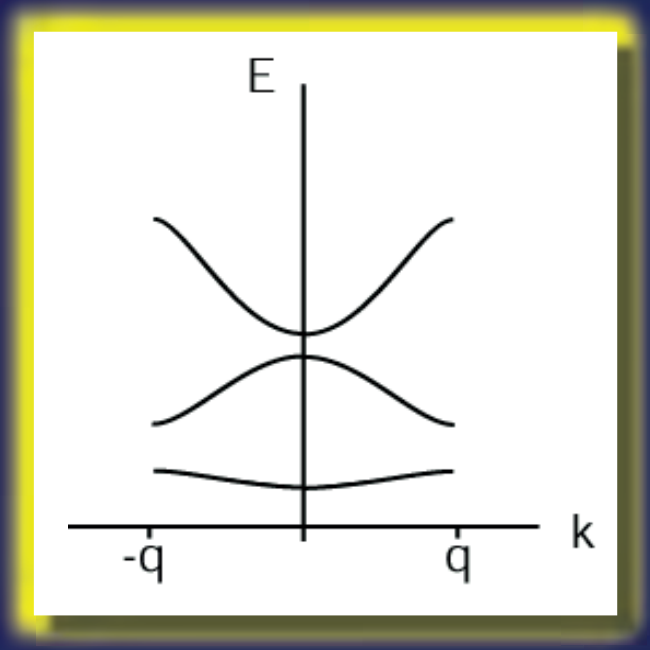

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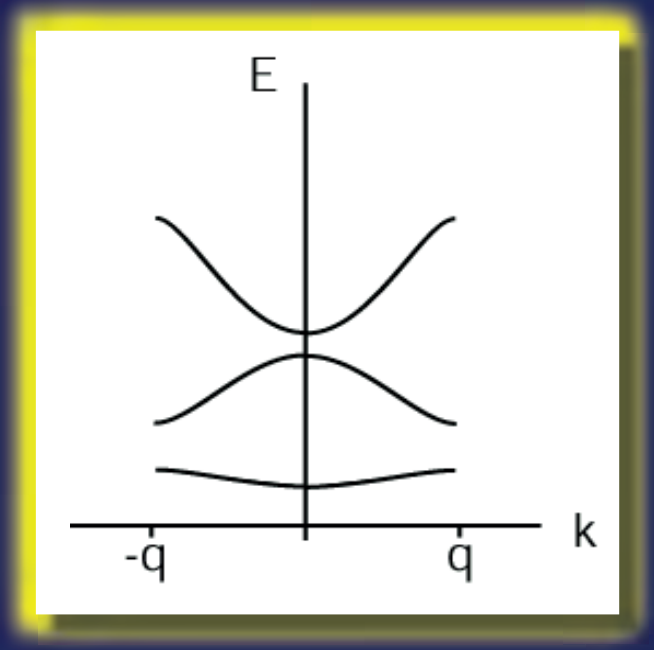

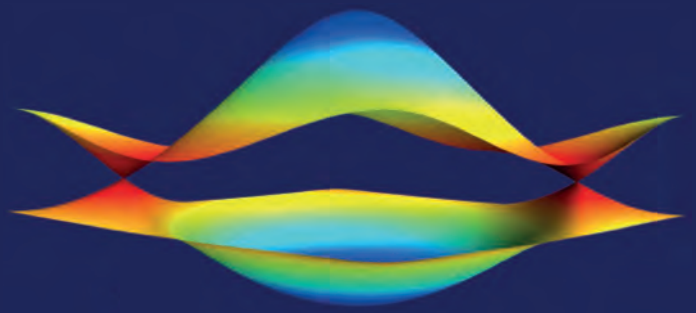

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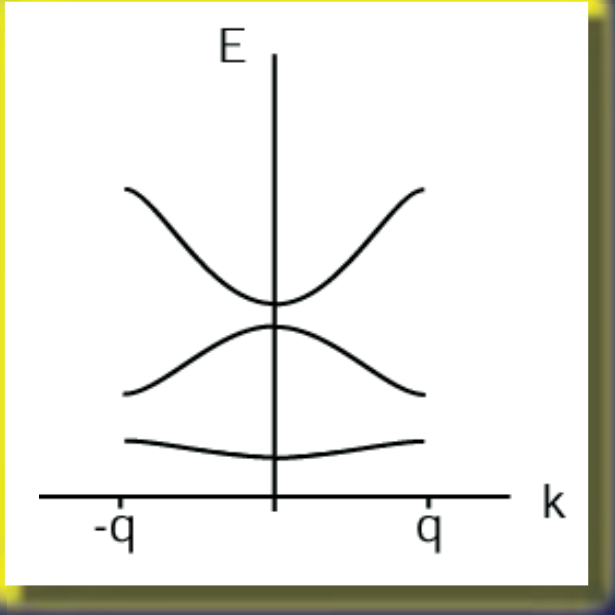

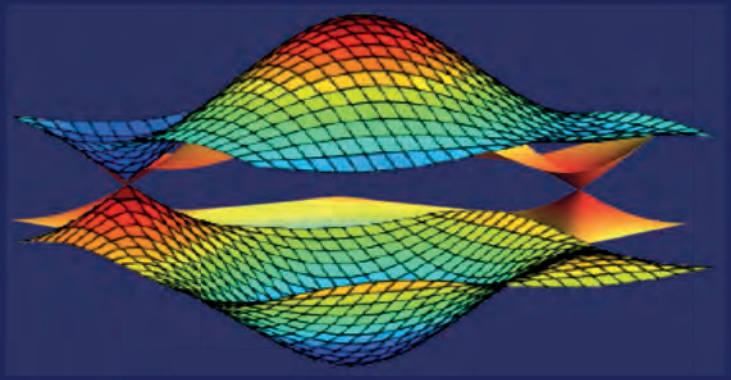

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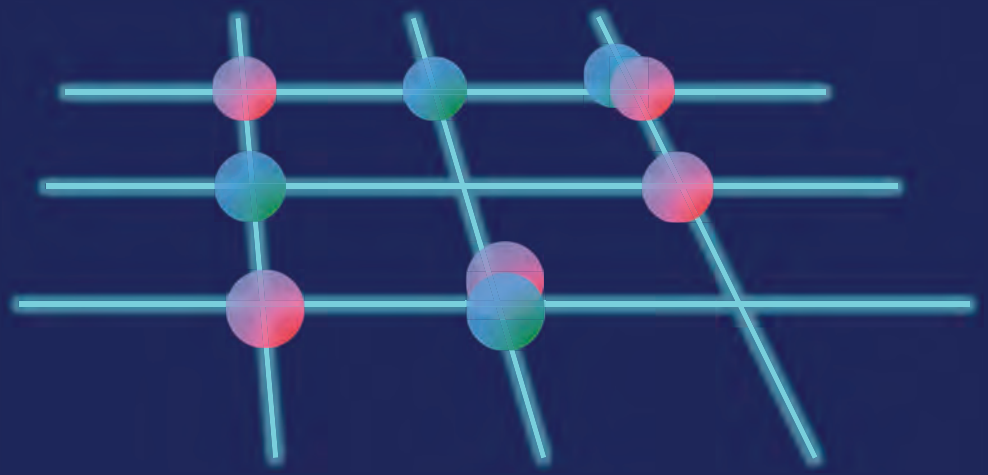

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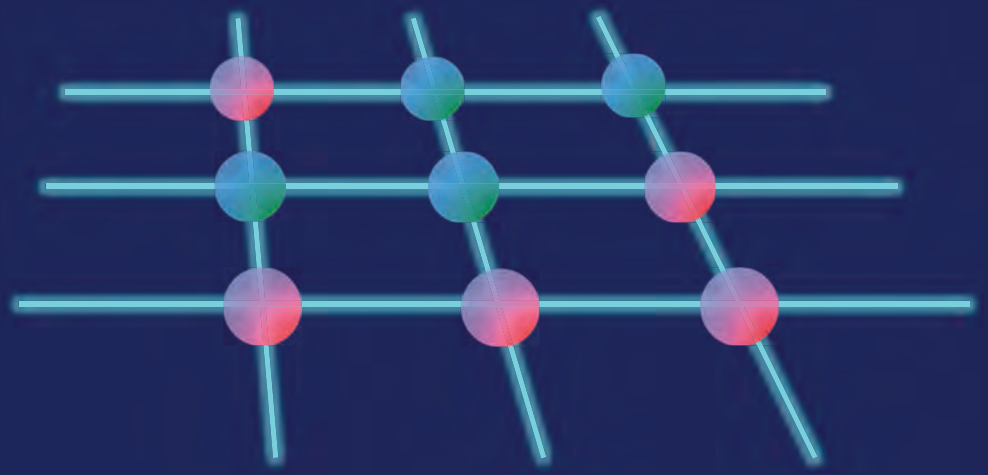
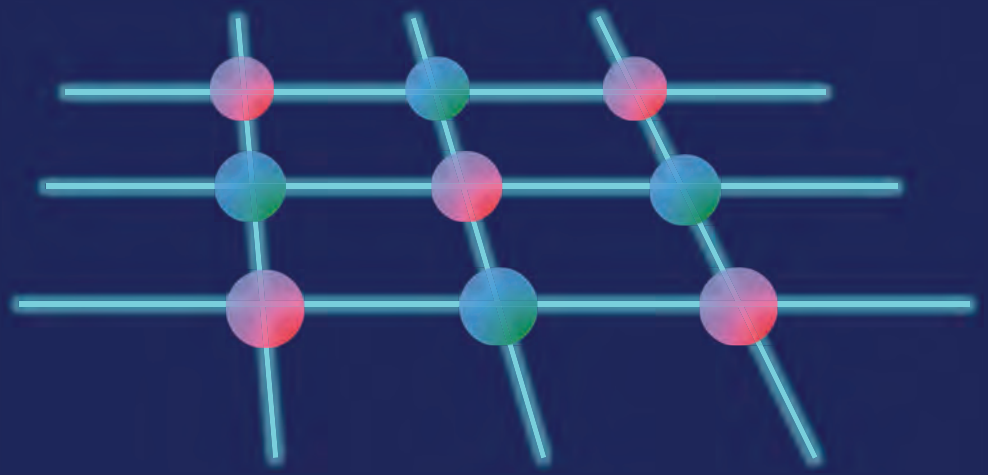


$$H = T + U + V_{trap}$$



$$H = T + U + V_{trap}$$

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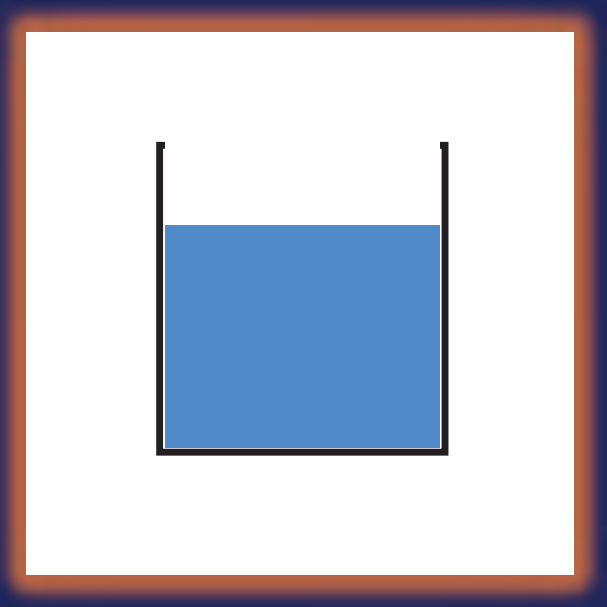
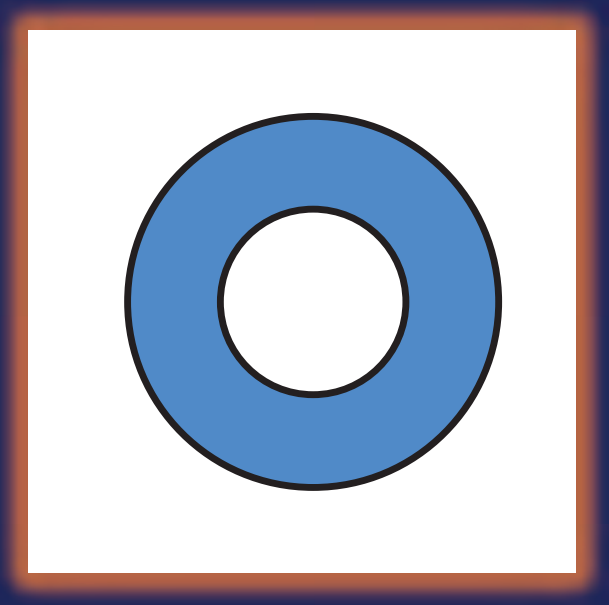


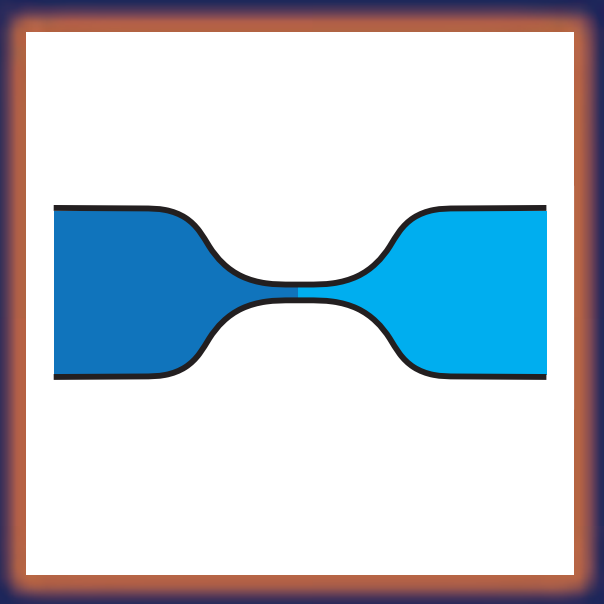
e.g. Cambridge, ENS

$$H = T + U + V_{trap}$$



e.g. NIST (Campbell), ENS

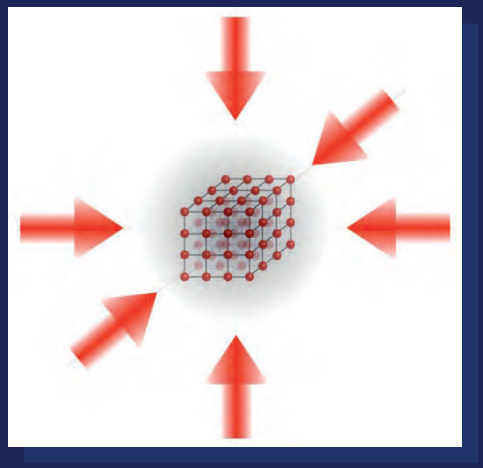
$$H = T + U + V_{trap}$$



Transport: ETH, JILA,

Josephson: Heidelberg, Firenze,…

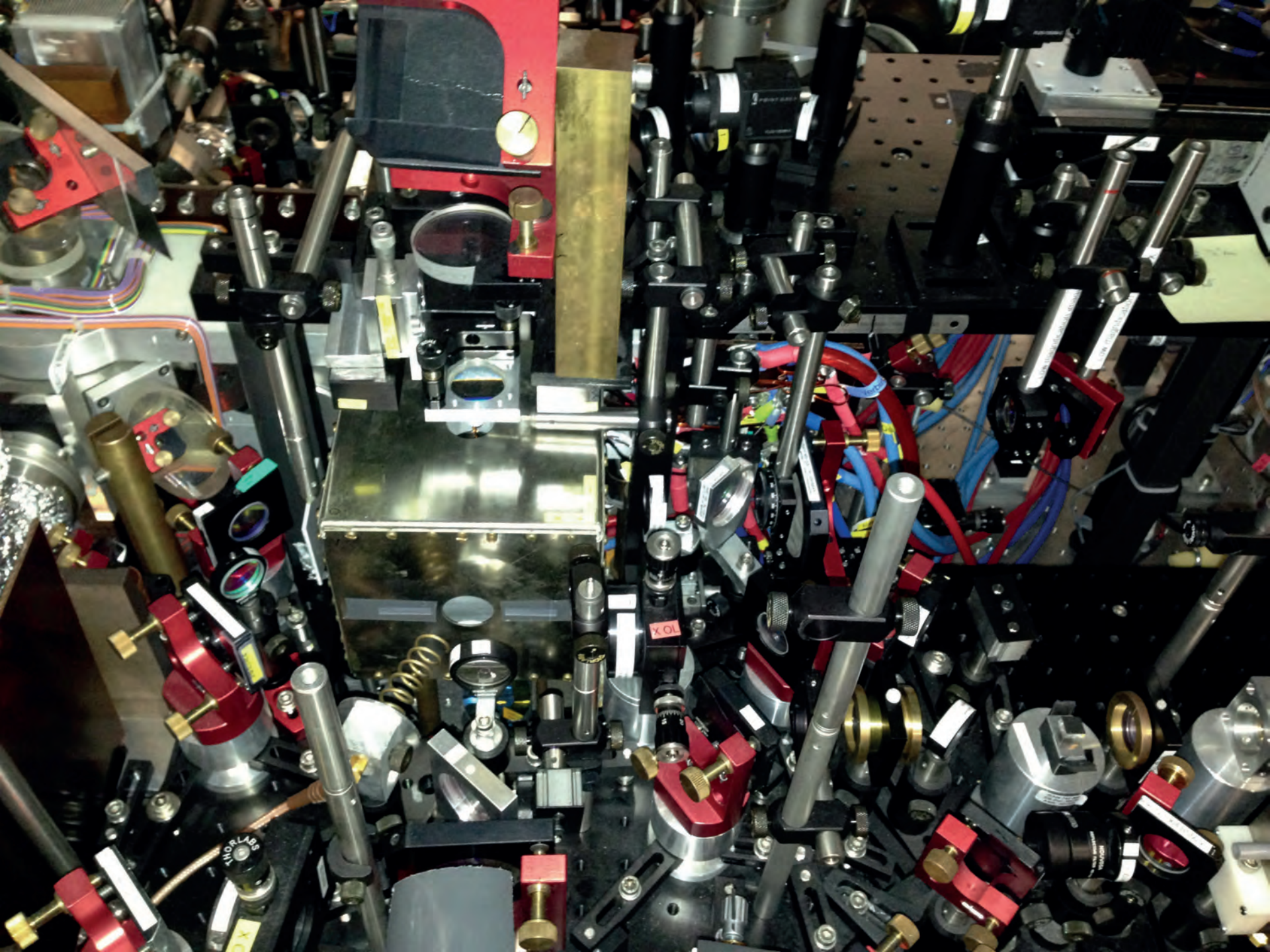
Building the Hamiltonian



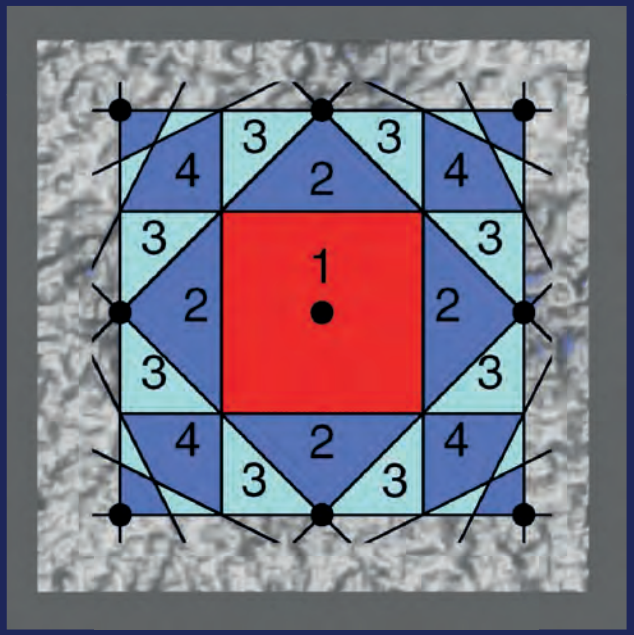
Quantum Gases (^{40}K)

Optical Lattices

See also: Mainz/Munich, Hamburg, MIT, Illinois, Rice,…


THORLABS

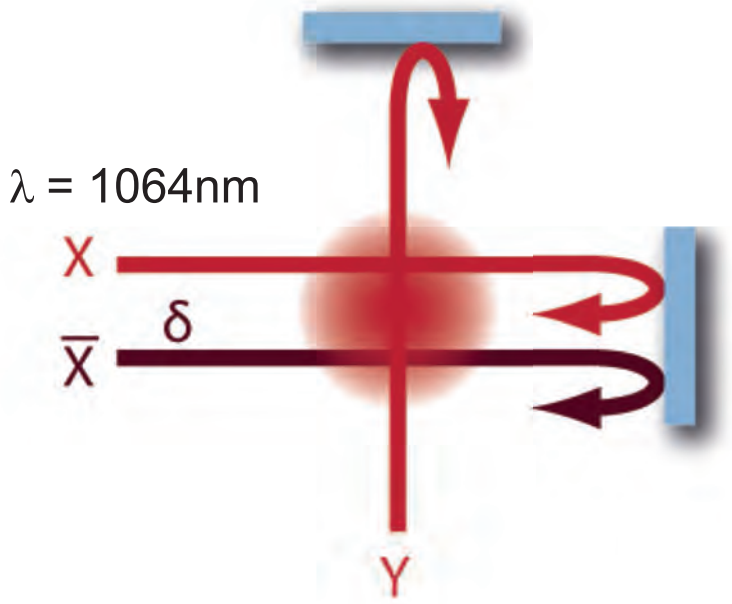
Simple Measurement...



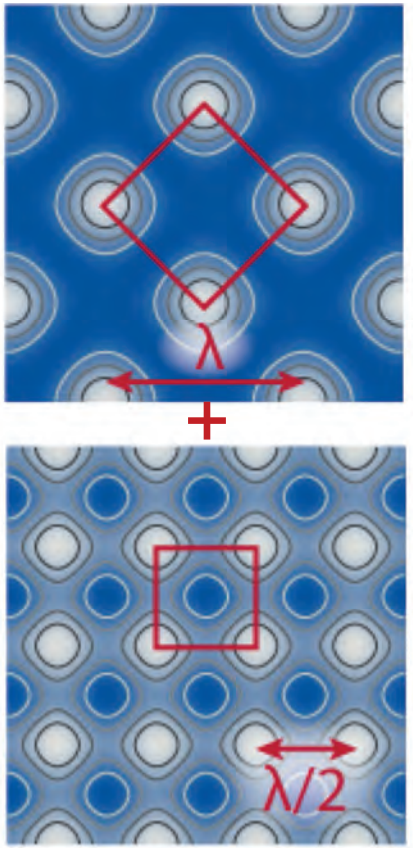
Simple structure...

Tunable Geometry Optical Lattice

Setup

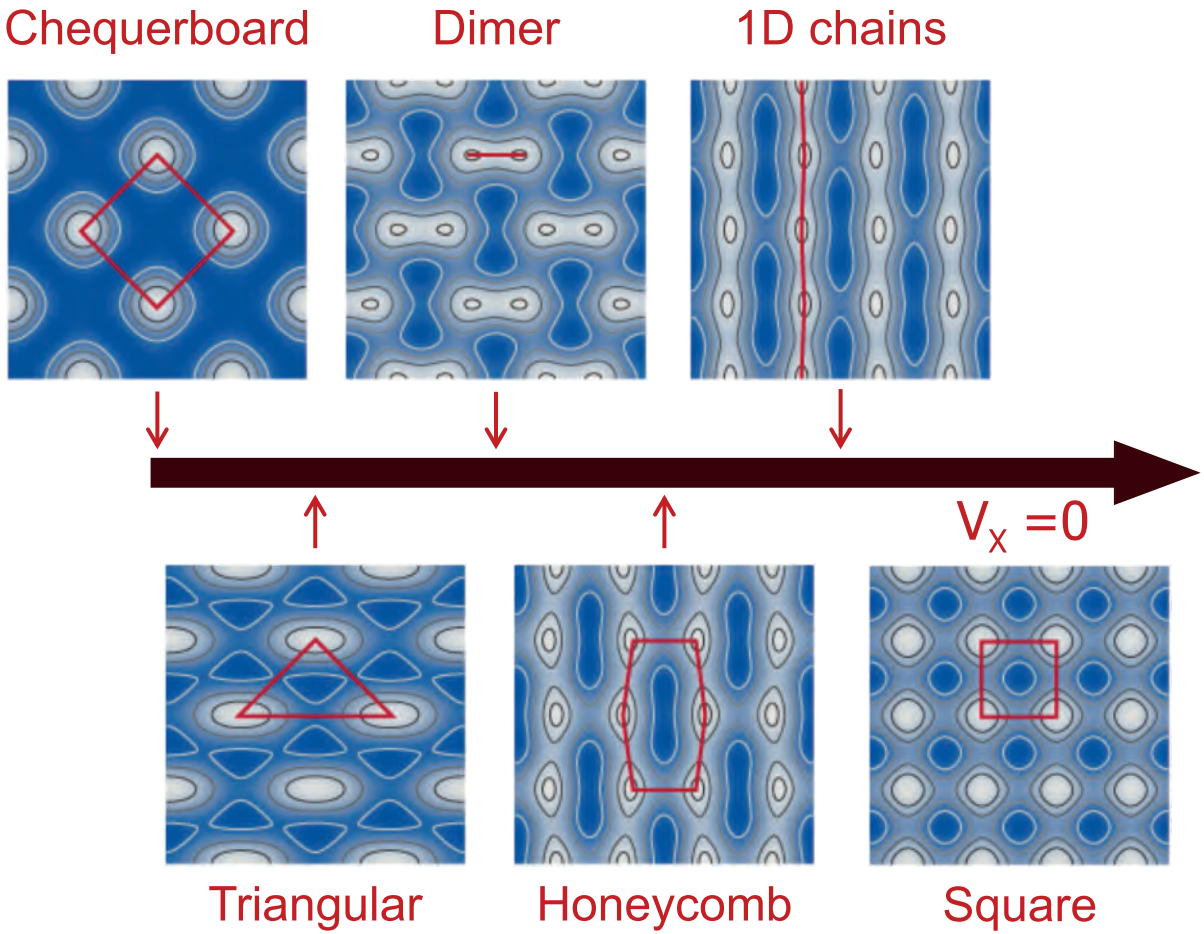


Optical potential

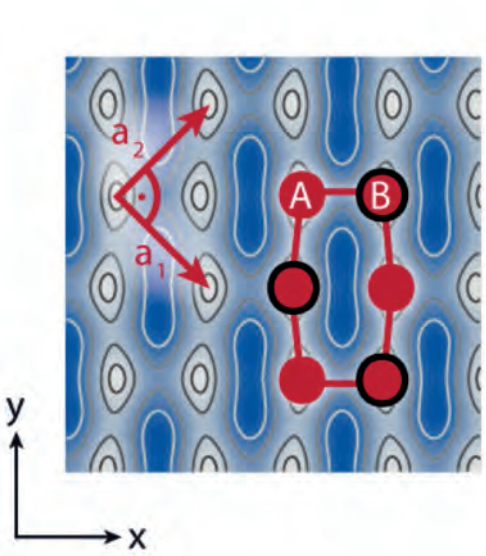


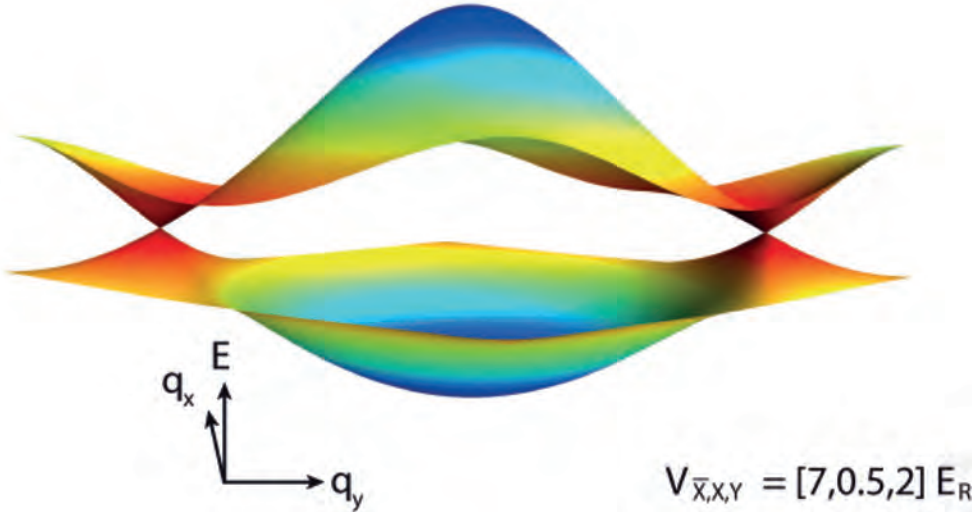
Other complex lattices: NIST, Munich, Hamburg, Berkeley, …

Tunable Geometry Optical Lattice



Honeycomb Lattice





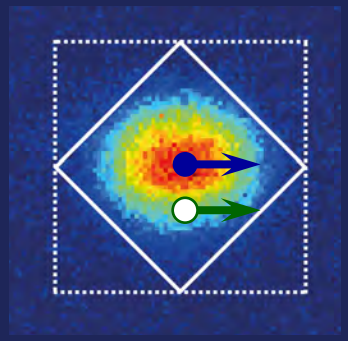
Probing the Dirac points

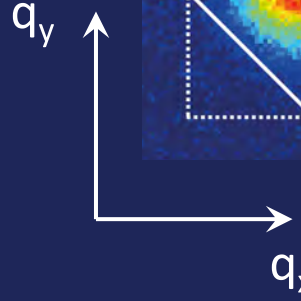
vanishing density of states

small energy scales

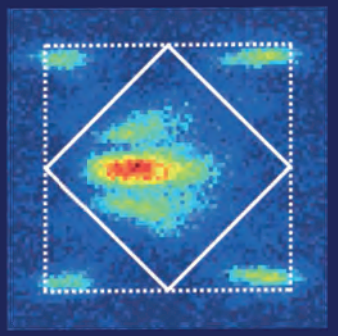
Bloch oscillation and interband transitions

Starting point

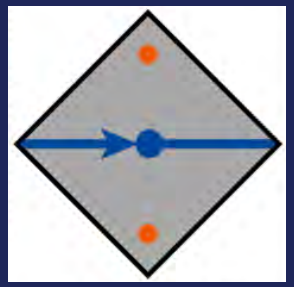


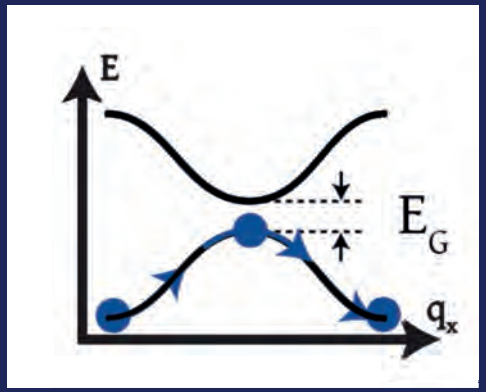


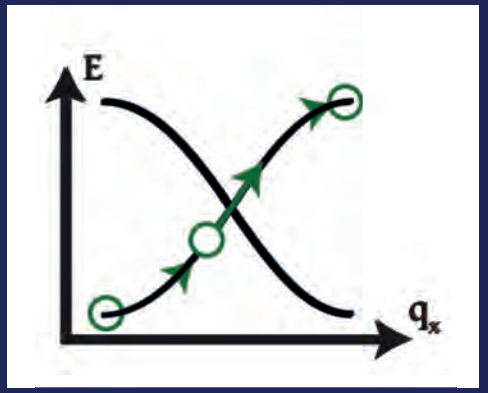
\+ magnetic gradient



Transfer to 2nd band

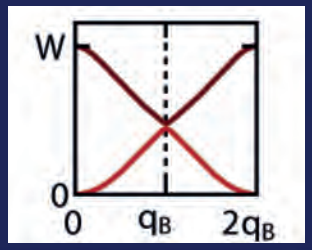


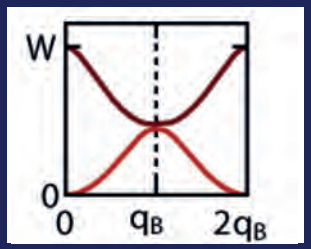


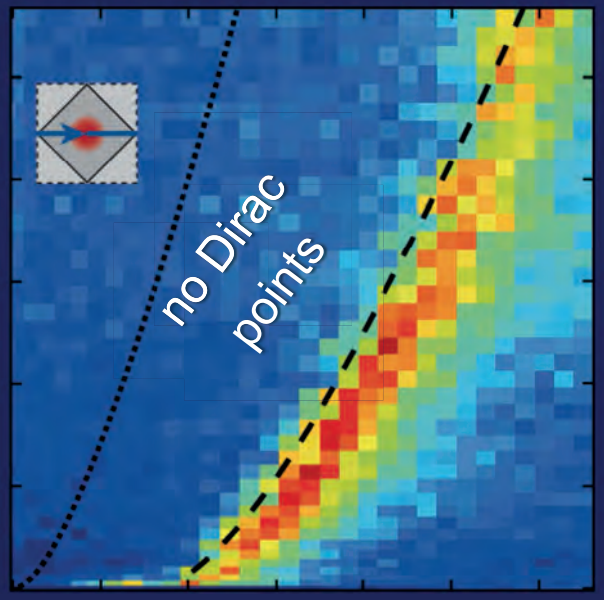


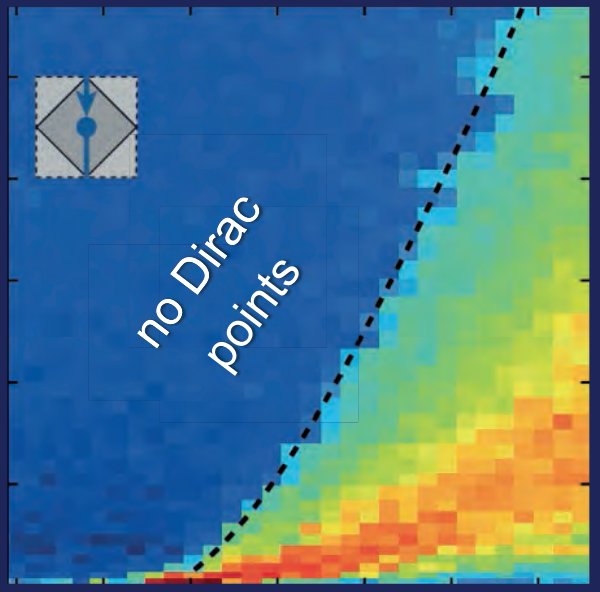
M. Dahan, E. Peik, J. Reichel, Y. Castin, and C. Salomon, PRL 76, 4509 (1996)

Touching Dirac points







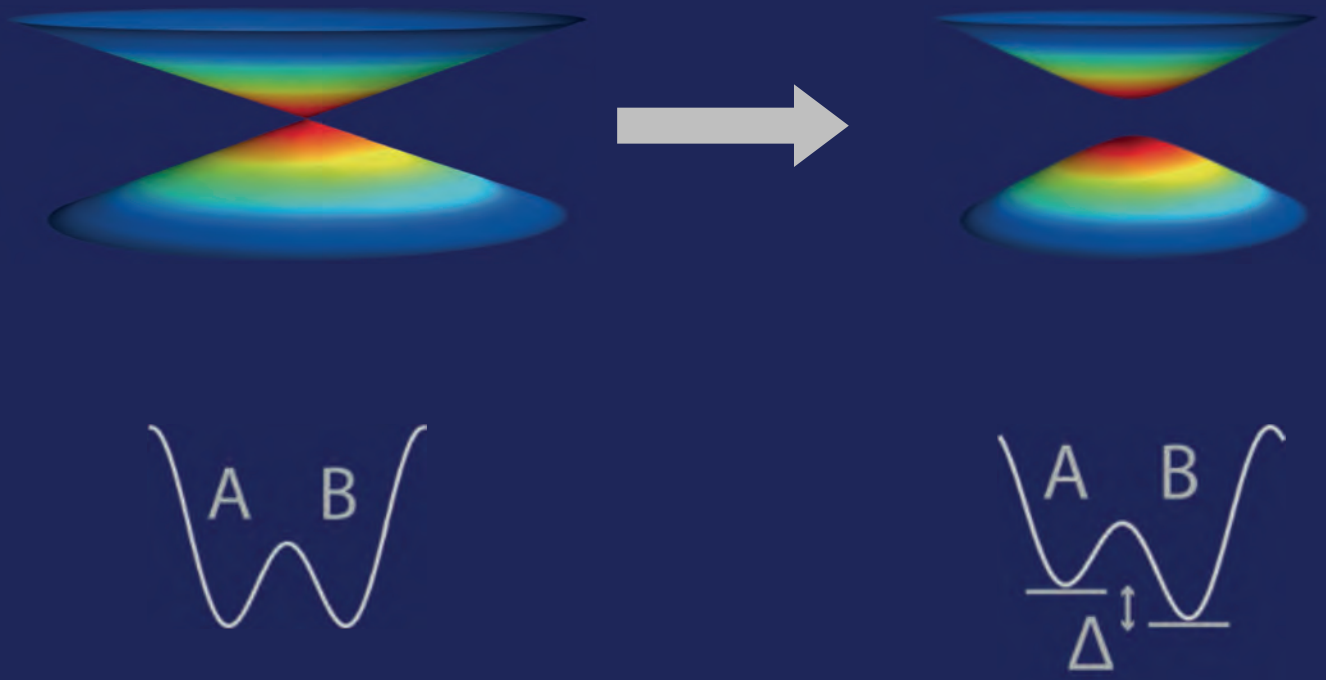


L. Tarruell, D. Greif, T. Uehlinger, G. Jotzu, and T. Esslinger, Nature 483, 302–305 (2012).

Theory, see also: L.-K. Lim, J.-N. Fuchs, G. Montambaux, PRL 108, 175303 (2012)

Breaking Inversion Symmetry

Berry curvature

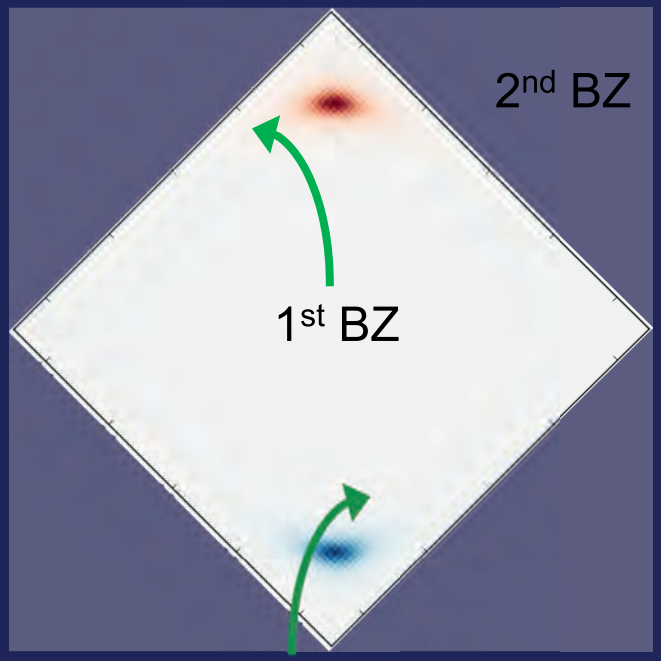


See also: L. Duca, Science 347, 288 (2015)

Review: N. Goldman, G. Juzeliunas, P. Ohberg, I. Spielman, Rep. Prog. Phys. 77, 126401, (2014)

Goldman, N., Cooper, N., & Dalibard, J. (2017). Preparing and Probing Chern Bands with Cold Atoms. doi:10.1017/9781316084366.016

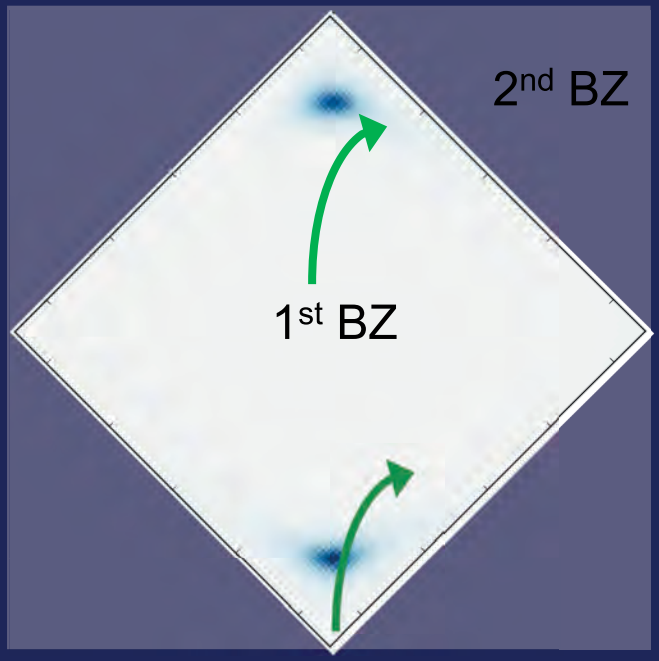
Berry Curvature and Transverse Drift



$$\dot{\boldsymbol{r}} = \frac{1}{\hbar}\partial_{\boldsymbol{k}}\epsilon(\boldsymbol{k}) - \dot{\boldsymbol{k}} \times \boldsymbol{\Omega}(\boldsymbol{k})$$
$$\hbar\dot{\boldsymbol{k}} = \boldsymbol{F}(\boldsymbol{r})$$

Chang and Niu, PRL 75, 1348 (1995)
Price and Cooper, PRA 85, 033620 (2012)

Berry Curvature and Transverse Drift



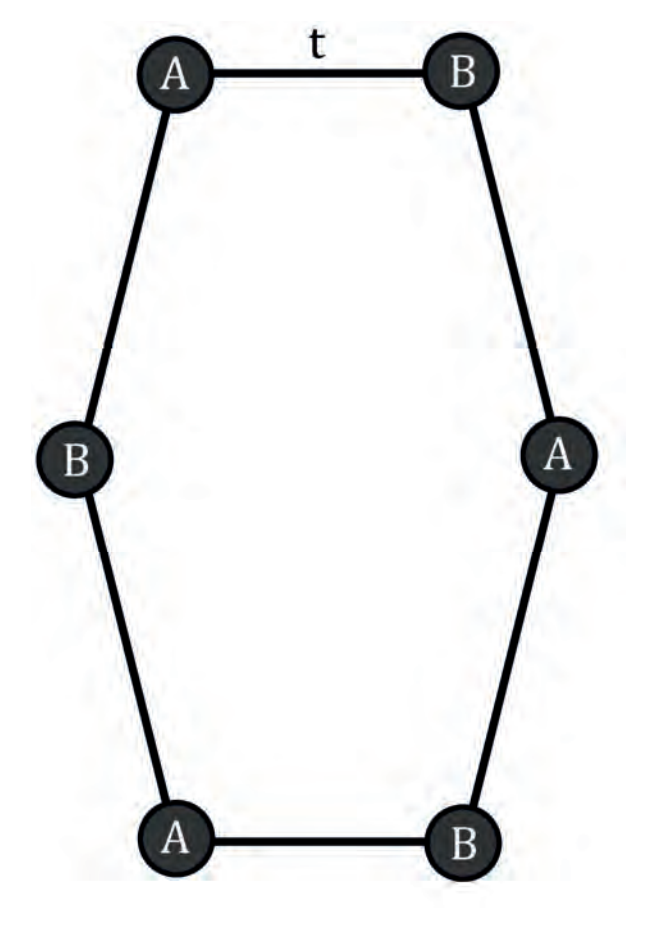
Like a Hall current

Topological Haldane model

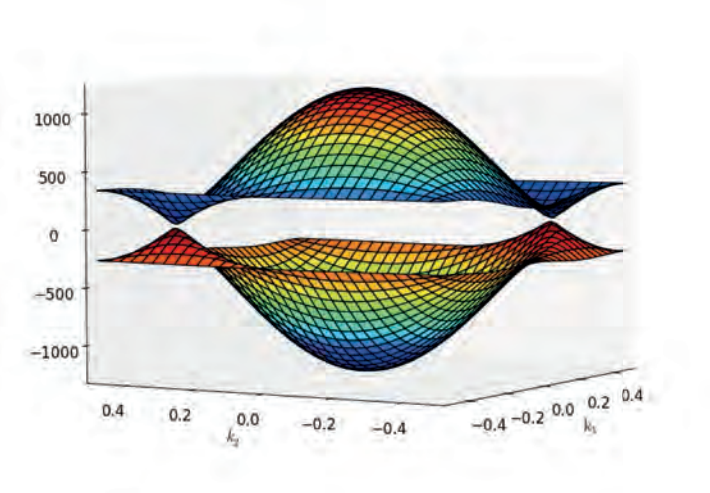
Proposal for Quantum Hall Effect *without* magnetic field!

Haldane, PRL **61**,2015-2018 (1988)

Topological Haldane model



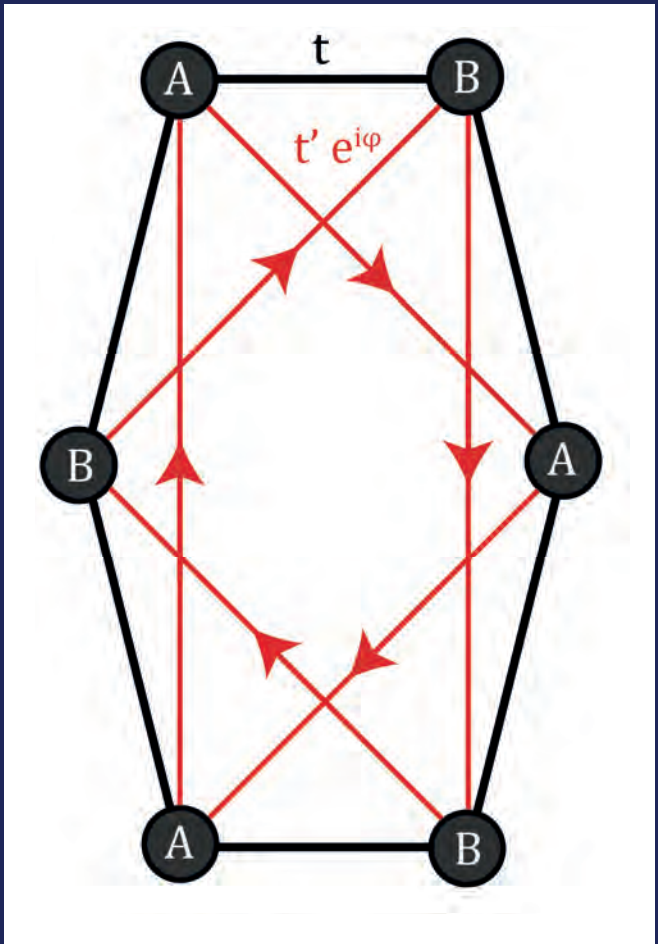
Start from a honeycomb lattice



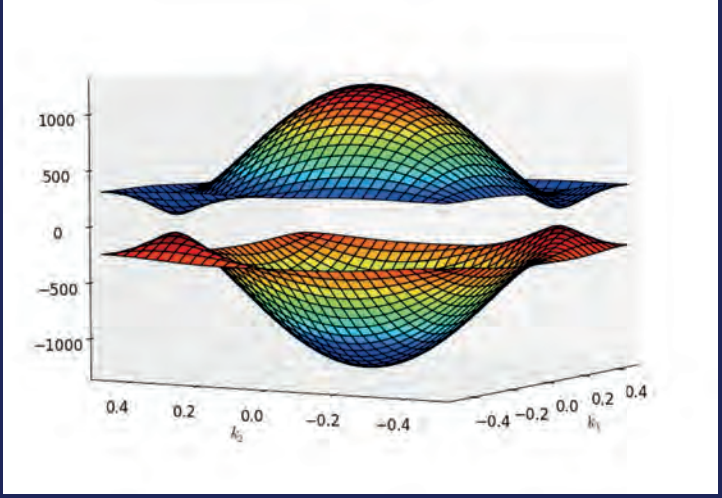
inversion and time-reversal symmertry


Topological Haldane model
break time-reversal symmetry

Topological Haldane model



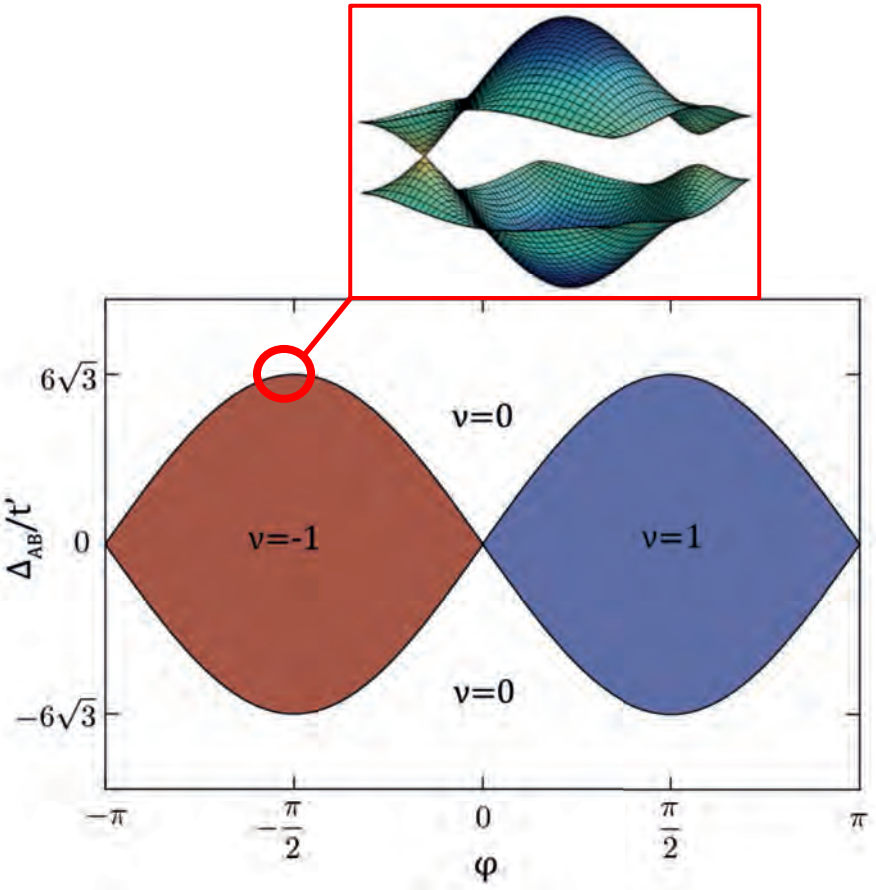
break time-reversal symmetry with complex next-nearest neighbour tunnellings



➔ Topological Chern insulator, with non-zero Hall conductance

Topological Haldane model

Inversion symmetry



Time-reversal symmetry

Haldane, PRL **61**,2015-2018 (1988)

How?

geometrical constant of order unity, and g is the Landé g factor for the electrons.

While the particular model presented here is unlikely to be directly physically realizable, it indicates that, at least in principle, the QHE can be placed in the wider context of phenomena associated with broken time-reversal invariance, and does not necessarily require external magnetic fields, but could occur as a consequence of magnetic ordering in a quasi-two-dimensional system.

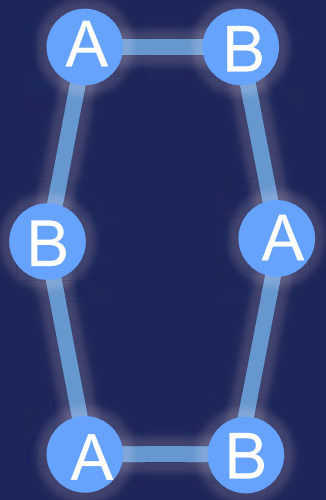
Haldane, PRL **61**,2015-2018 (1988)

Breaking time-reversal symmetry

Proposal for Photovoltaic Hall effect in graphene

T. Oka und H. Aoki, PRL **79**, 081406 (2009)

Breaking time-reversal symmetry

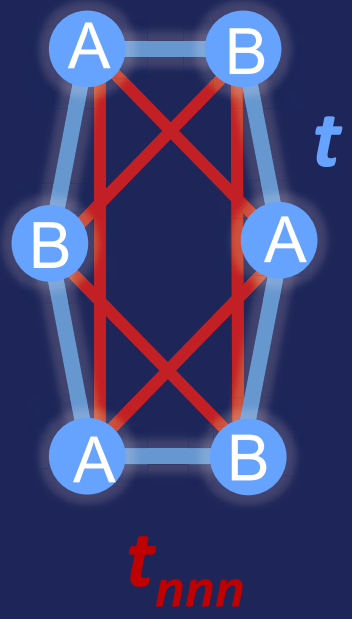


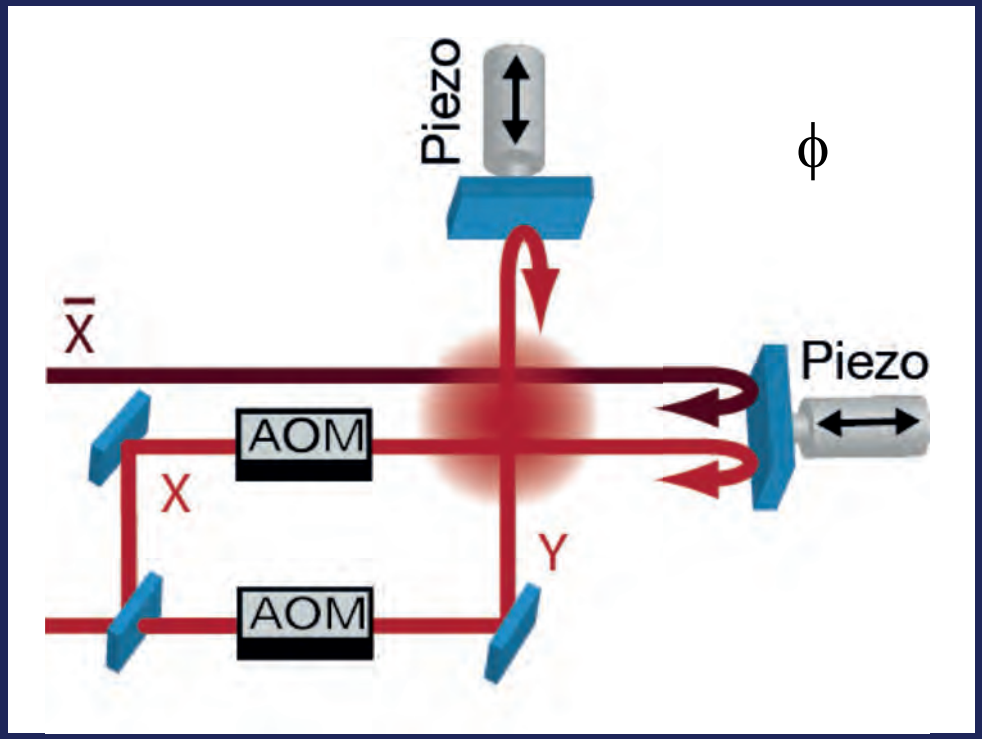
Other proposals to realize topological Hamiltonains:
T. Kitagawa et al., Phys. Rev. B 82, 235114 (2010)
P. Hauke et al., Phys. Rev. Lett 109, 145301 (2012)

Realisation in photonic system: Rechtsman et. al Nature 496, 196–200 (2013)

Breaking time-reversal symmetry

Lattice Shaking

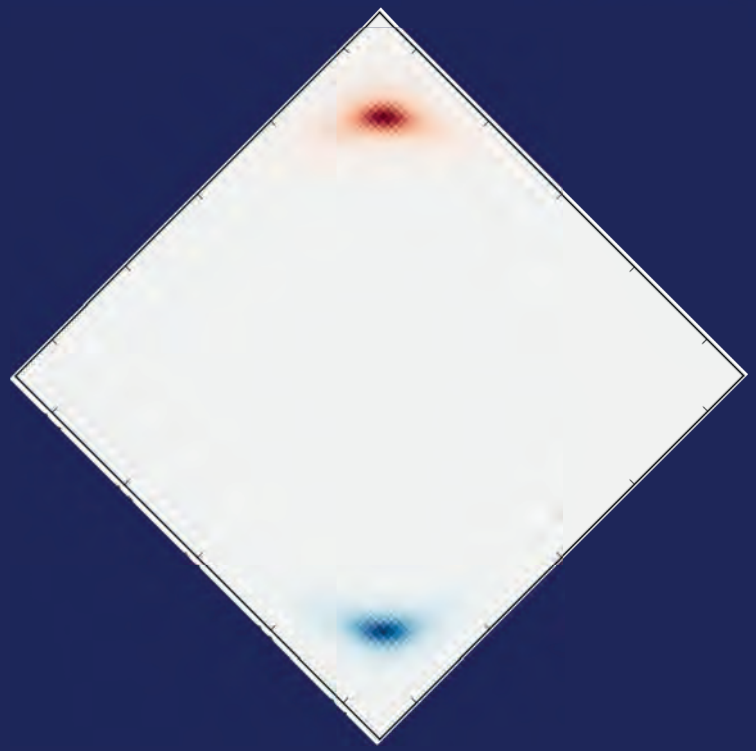




Lattice shaking: Pisa — Lignier, PRL **99**, 220403 (2007)
Hamburg/Barcelona — Struck, Science **333**, 996-9 (2011), PRL 108, 225304 (2012)
Chicago — Parker, Nat. Phys. **9**, 769-774 (2013)

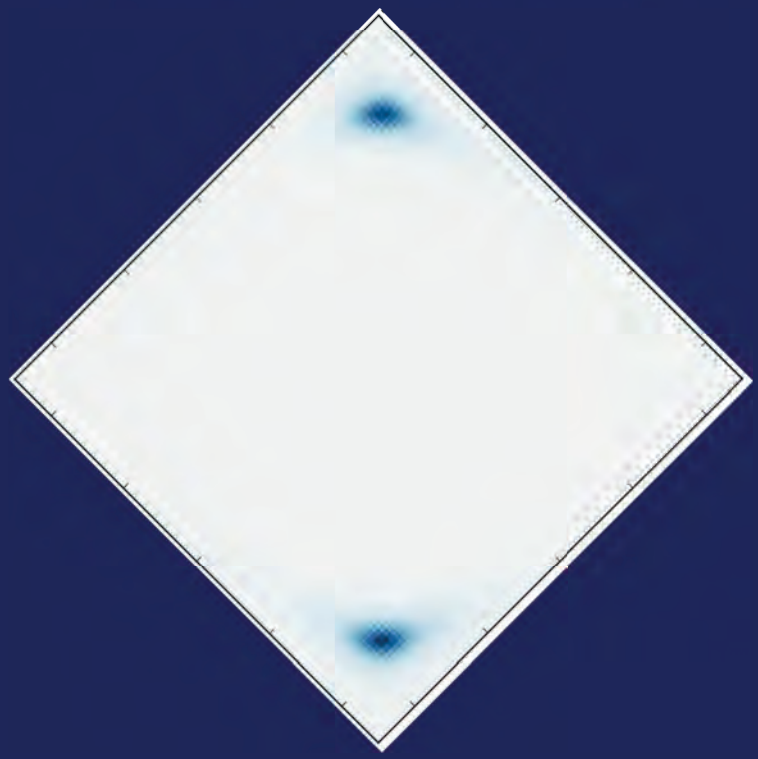
Berry Curvature

Trivial band insulator



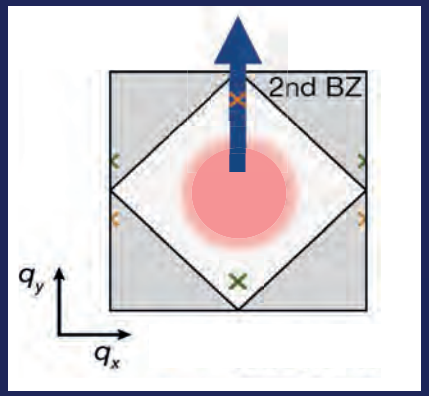
Chern number 0

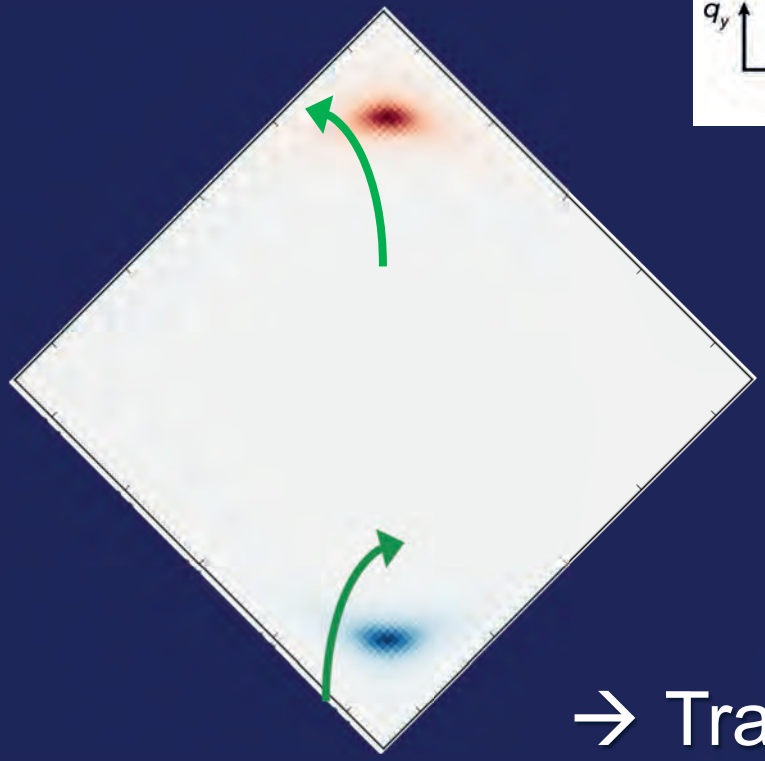
Chern insulator

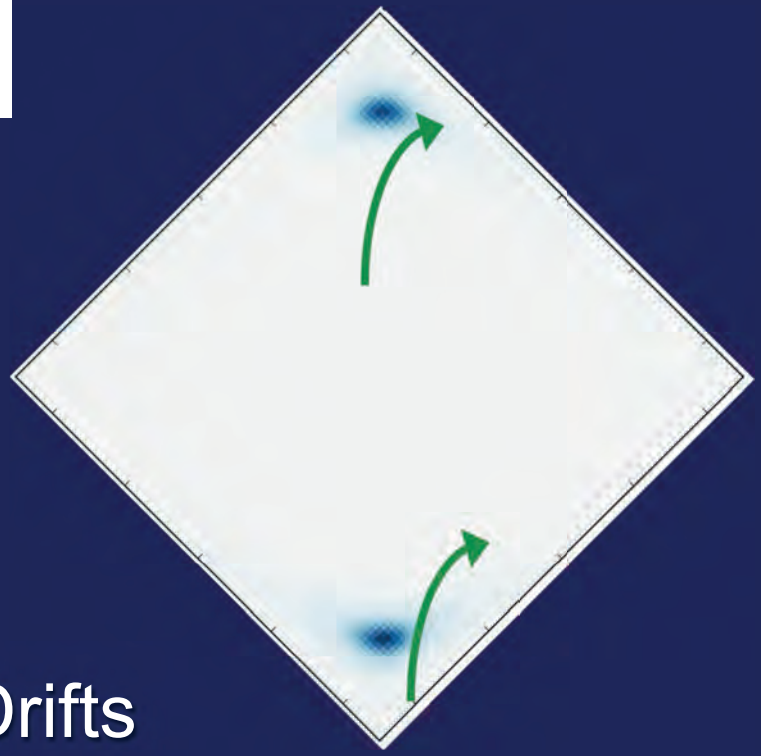


Chern number -1

Berry Curvature - Measurement



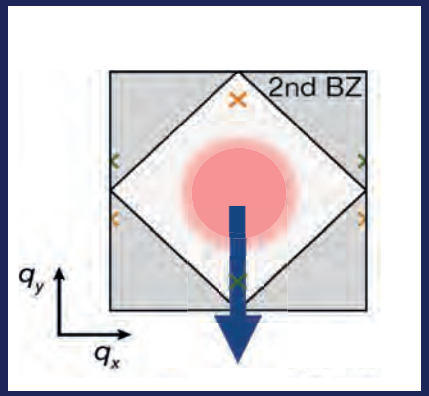


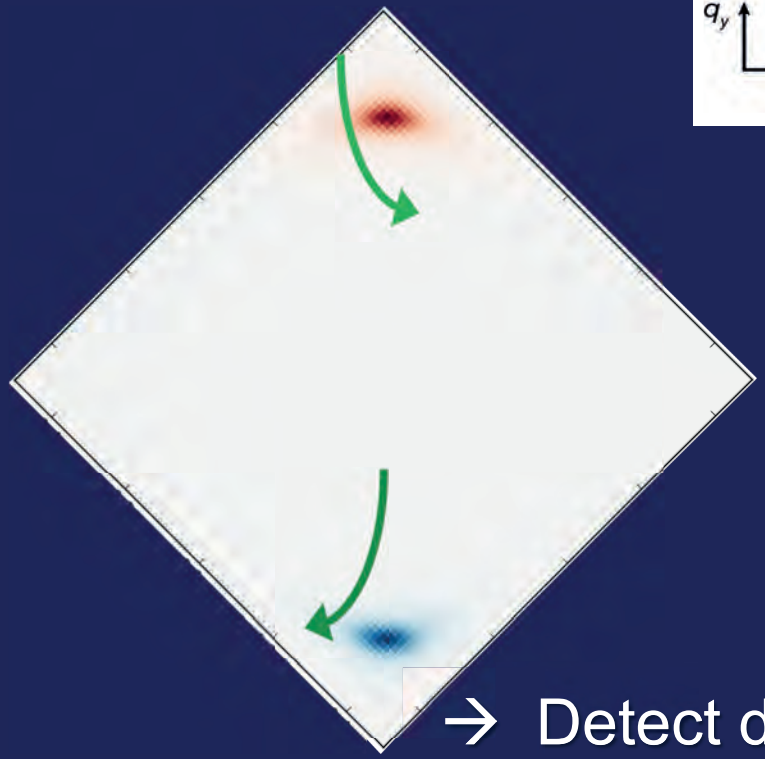


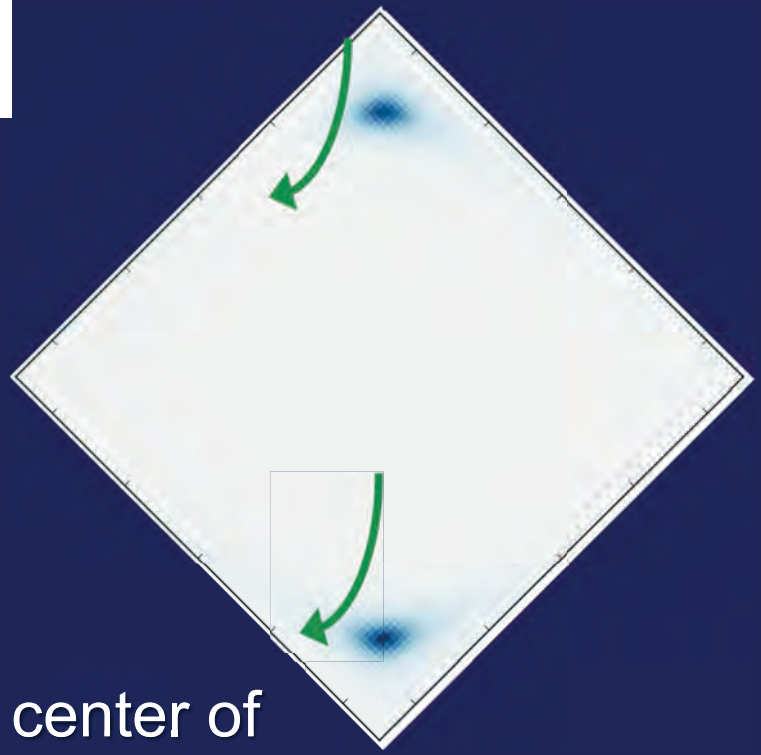
→ Transverse Drifts

See also: M. Aidelsburger et al., Nature Physics 11, 162 (2015)

Berry Curvature - Measurement







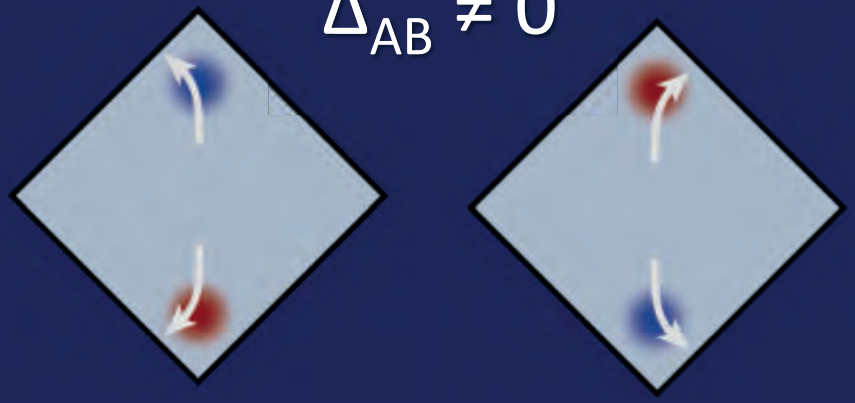
→ Detect difference in center of mass position after full Bloch cycle

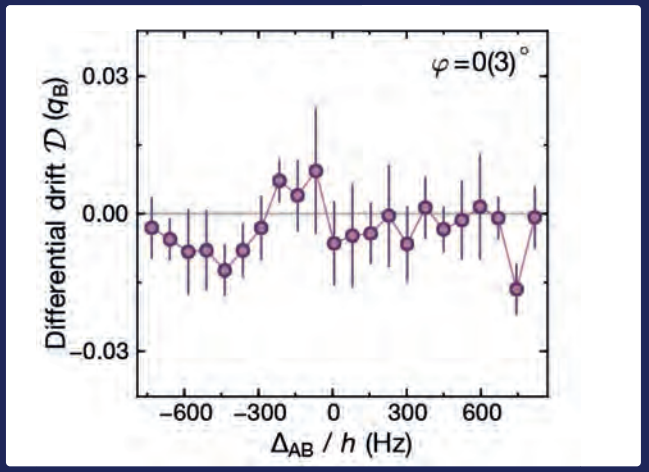
See also: M. Aidelsburger, Nature Physics 11, 162 (2015)

Topological features of the system

topologically trivial

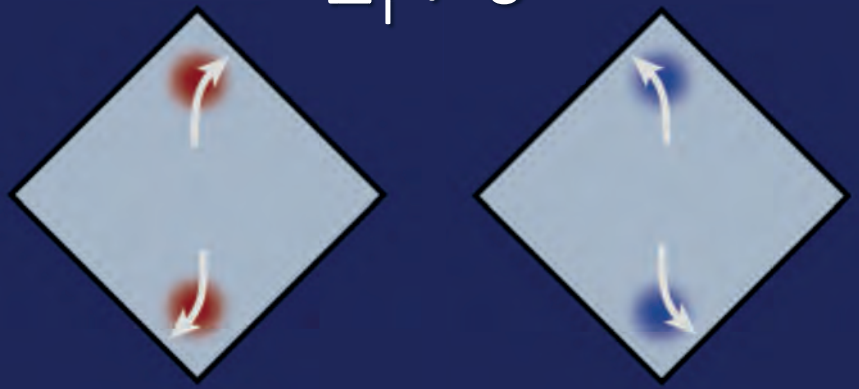
$\Delta_{AB} \neq 0$

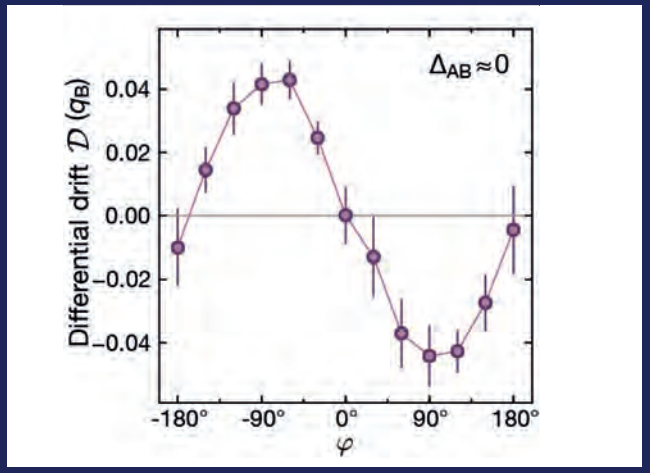




nonzero Chern number

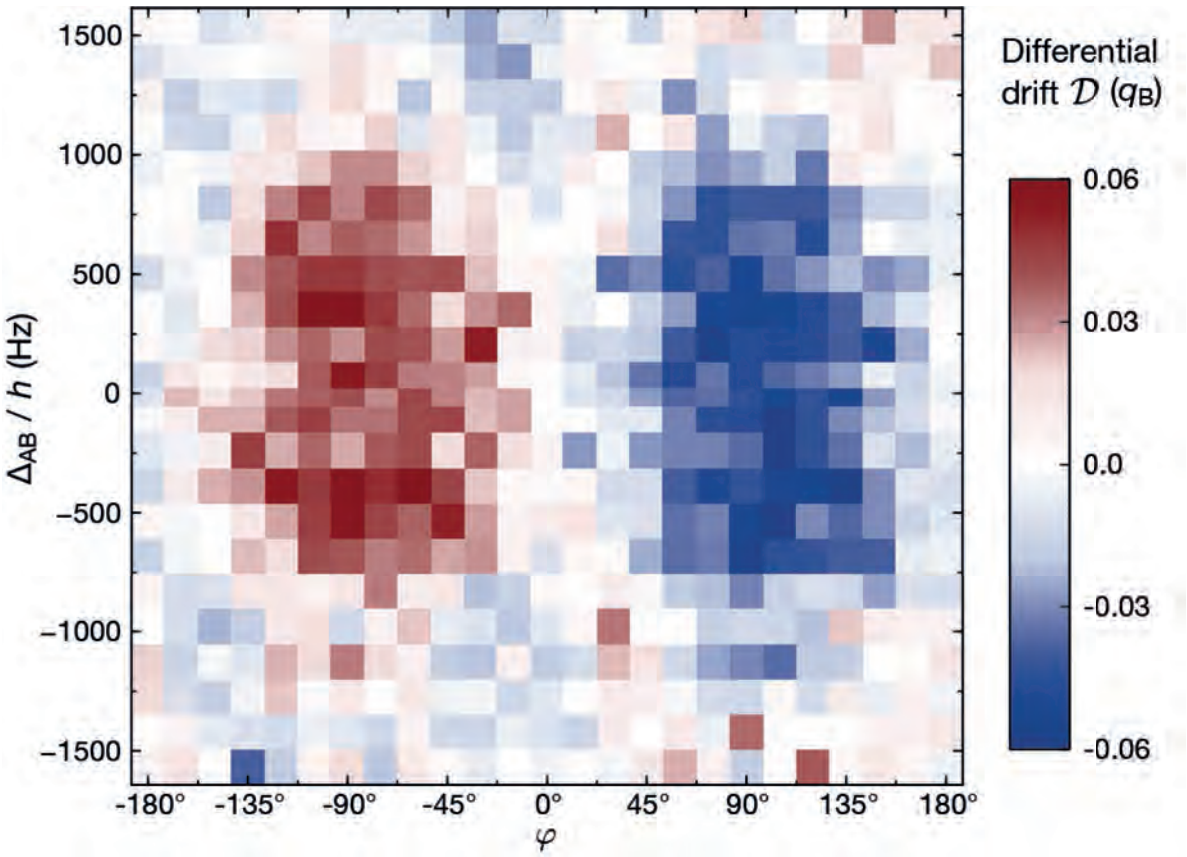
$\Delta_T \neq 0$





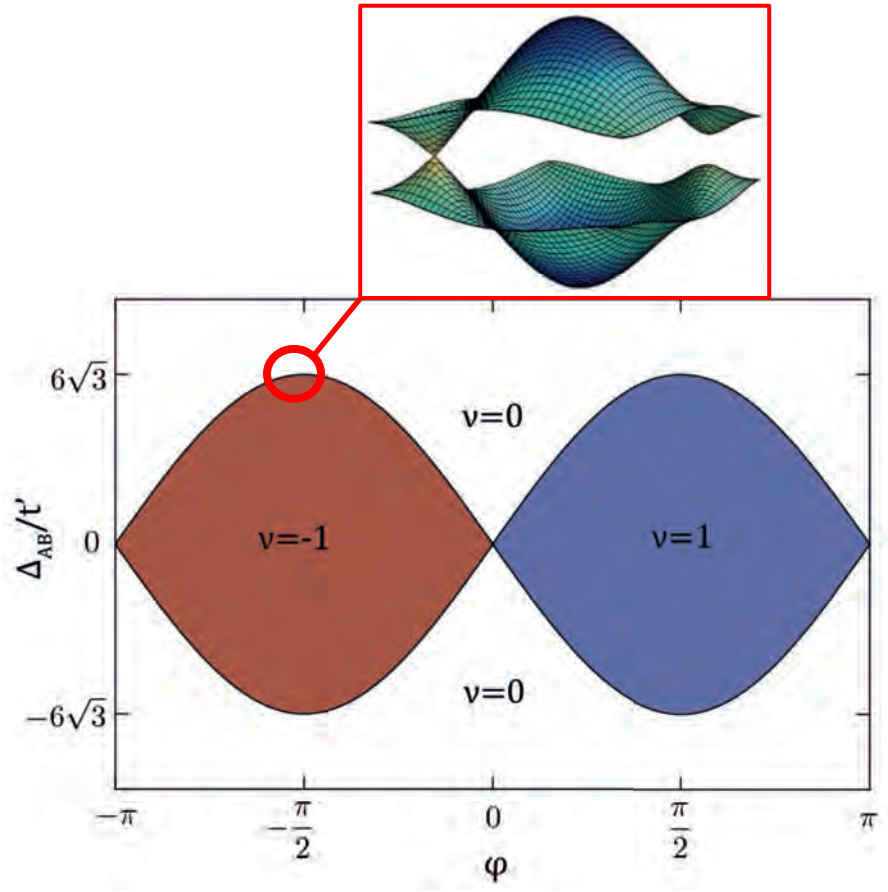
G. Jotzu, M. Messer, R. Desbuquois, M. Lebrat, T. Uehlinger, D. Greif, T. E., Nature 515, 237 (2014)

Observing Transverse Drifts

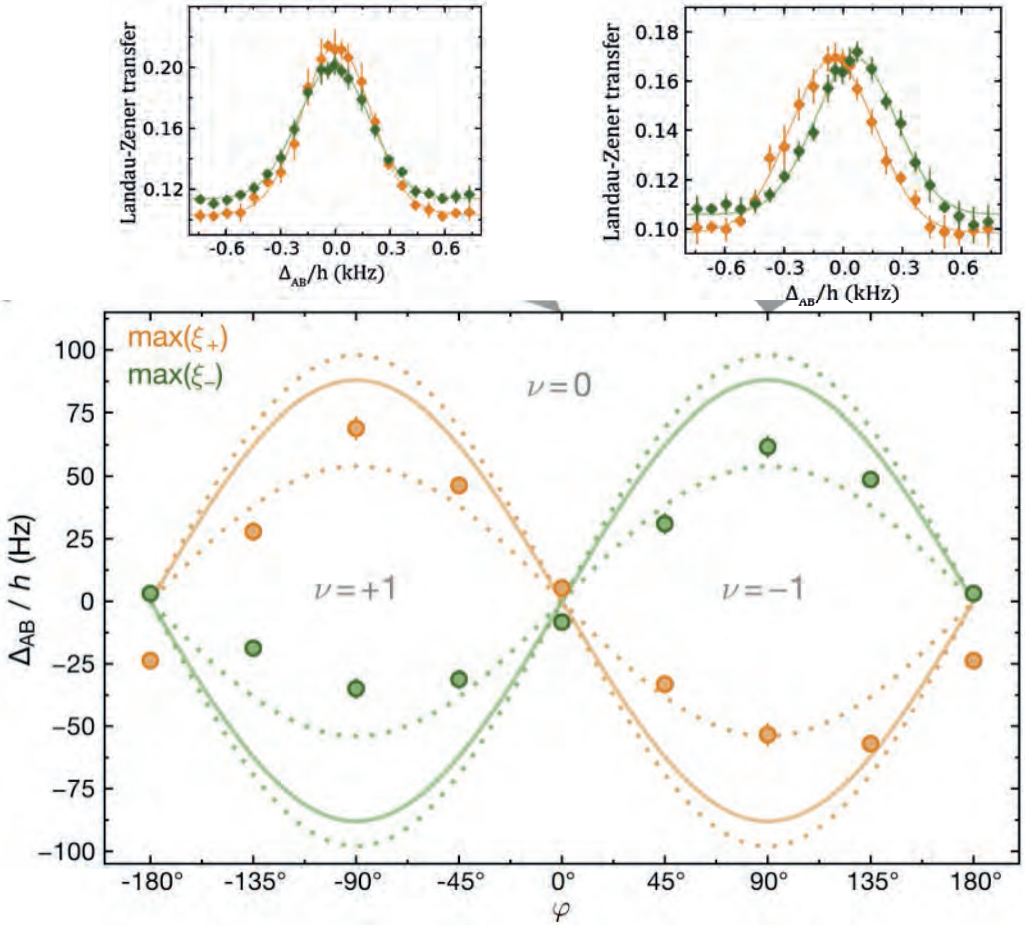


G. Jotzu, M. Messer, R. Desbuquois, M. Lebrat, T. Uehlinger, D. Greif, T. E., Nature 515, 237 (2014)

Mapping out the transition line



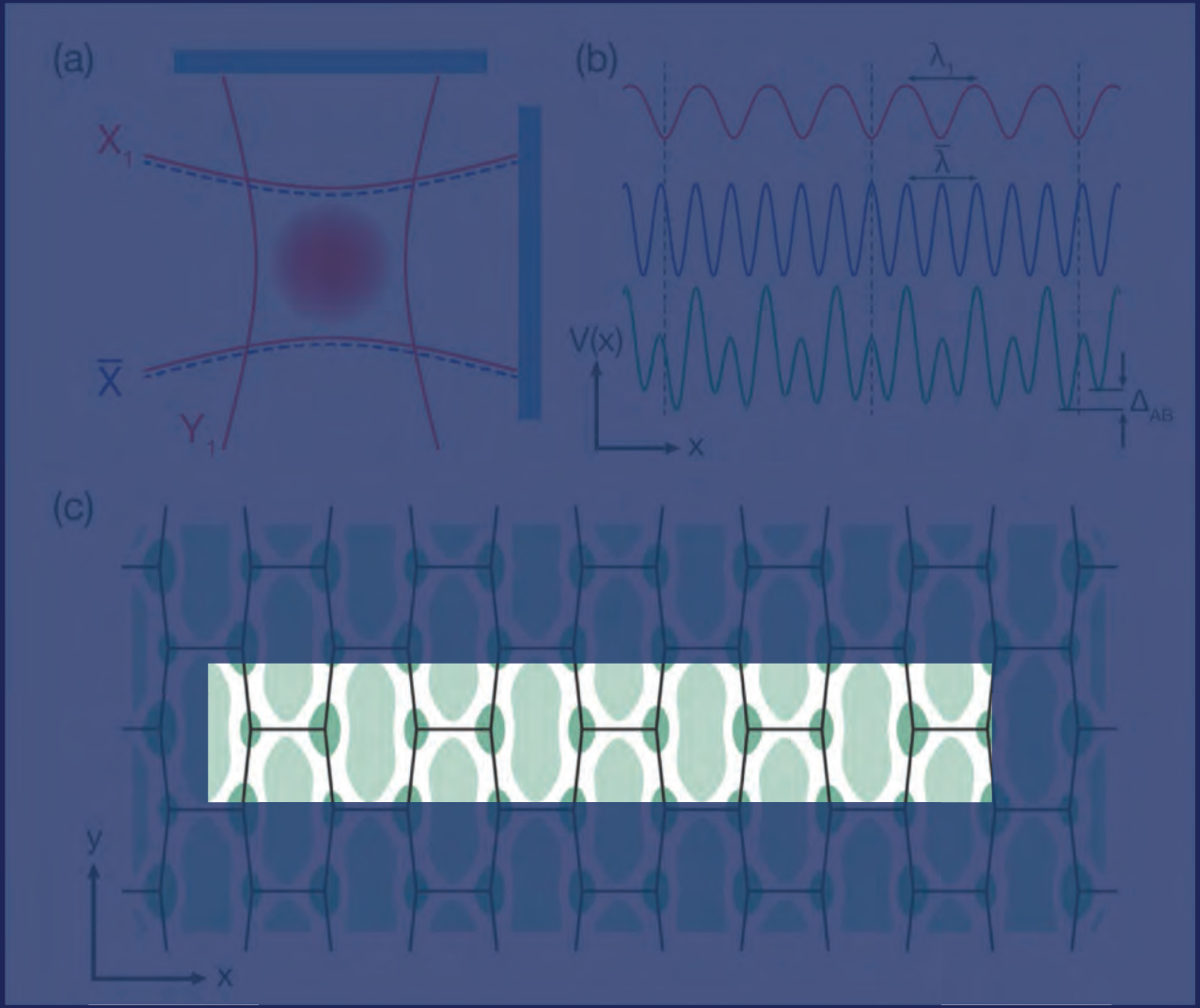
Mapping out the transition line



G. Jotzu, M. Messer, R. Desbuquois, M. Lebrat, T. Uehlinger, D. Greif, T. E., Nature 515, 237 (2014)

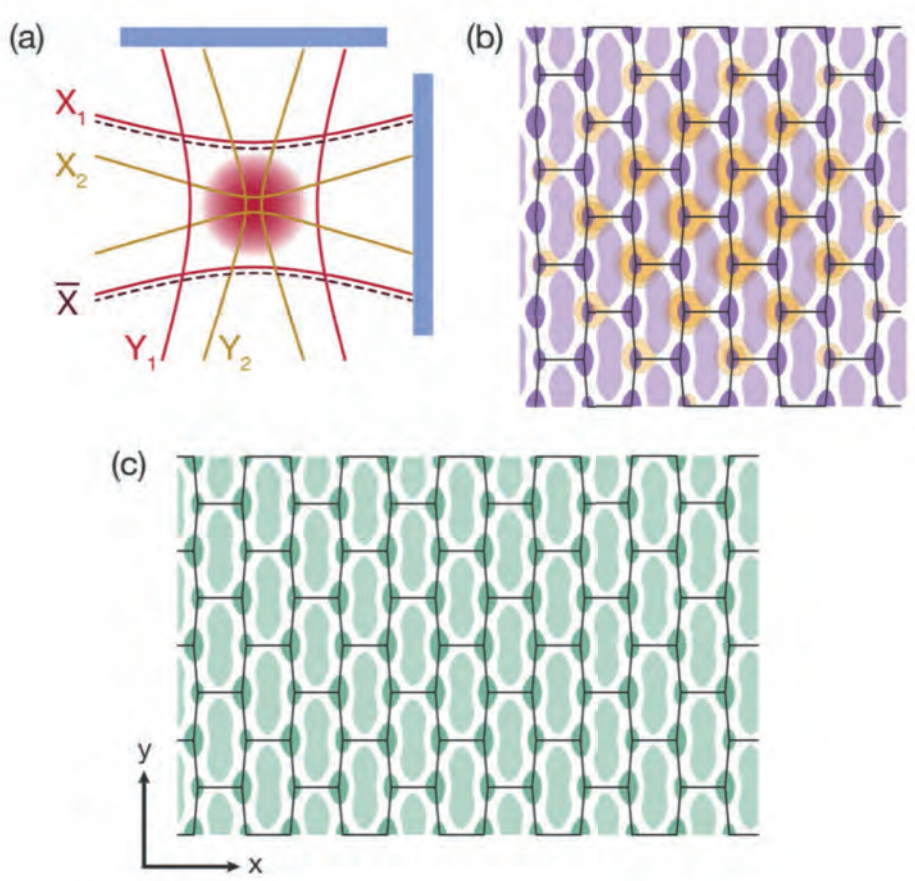
Edge states

Edge states



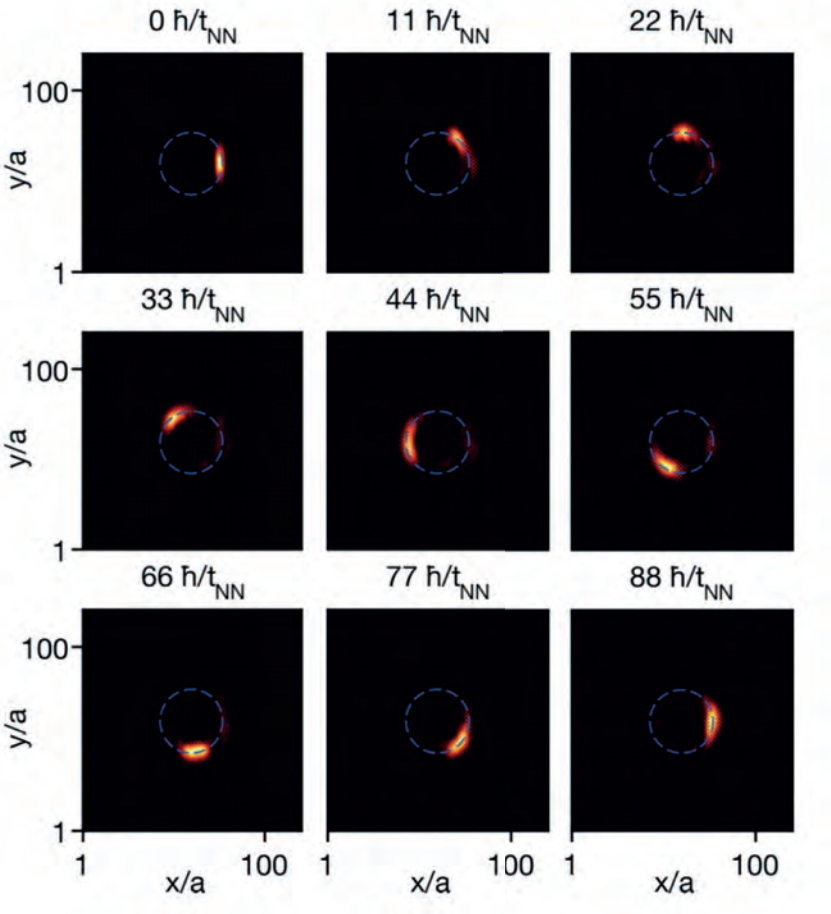
N. Goldman, G. Jotzu, M. Messer, R. Desbuquois, T. E., PRA 94, 043611 (2016)

Edge states



N. Goldman, G. Jotzu, M. Messer, R. Desbuquois, T. E., PRA 94, 043611 (2016)

Edge states

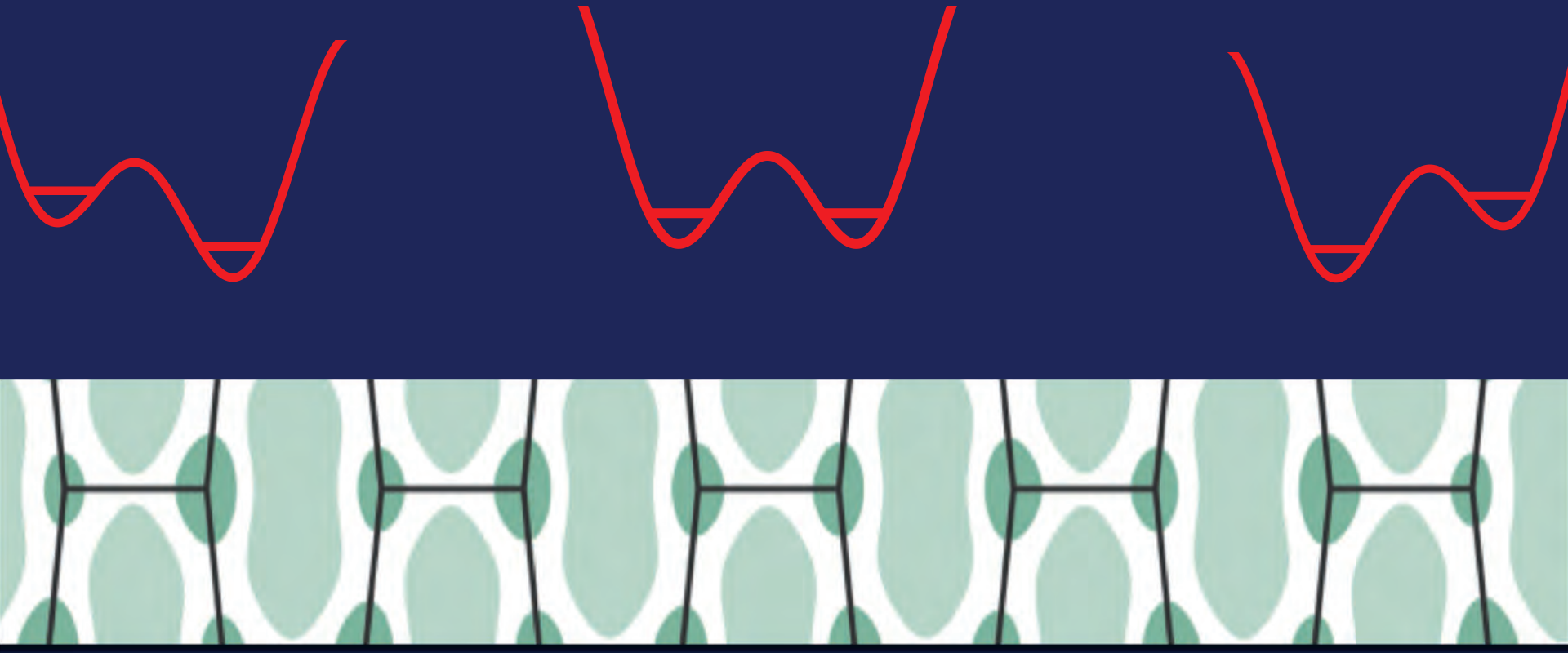


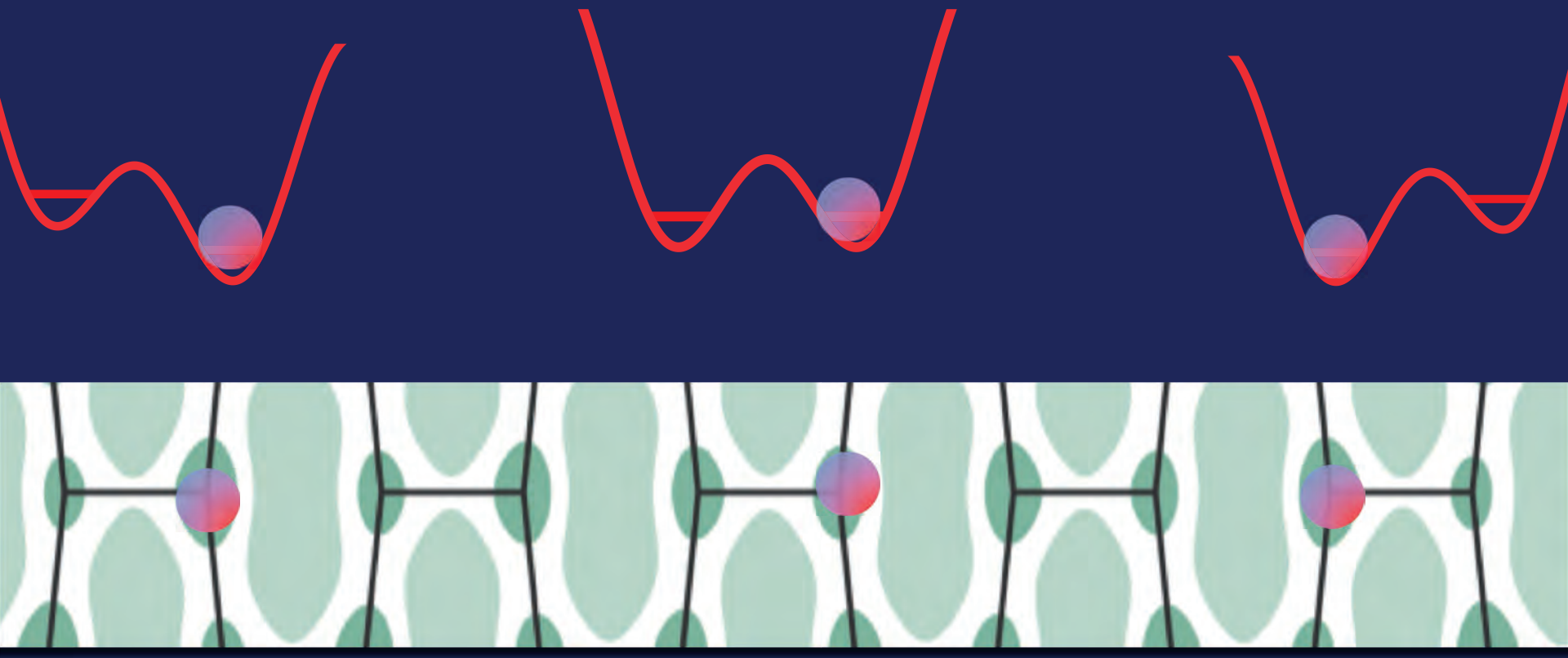
N. Goldman, G. Jotzu, M. Messer, R. Desbuquois, T. E., PRA 94, 043611 (2016)

Interactions?

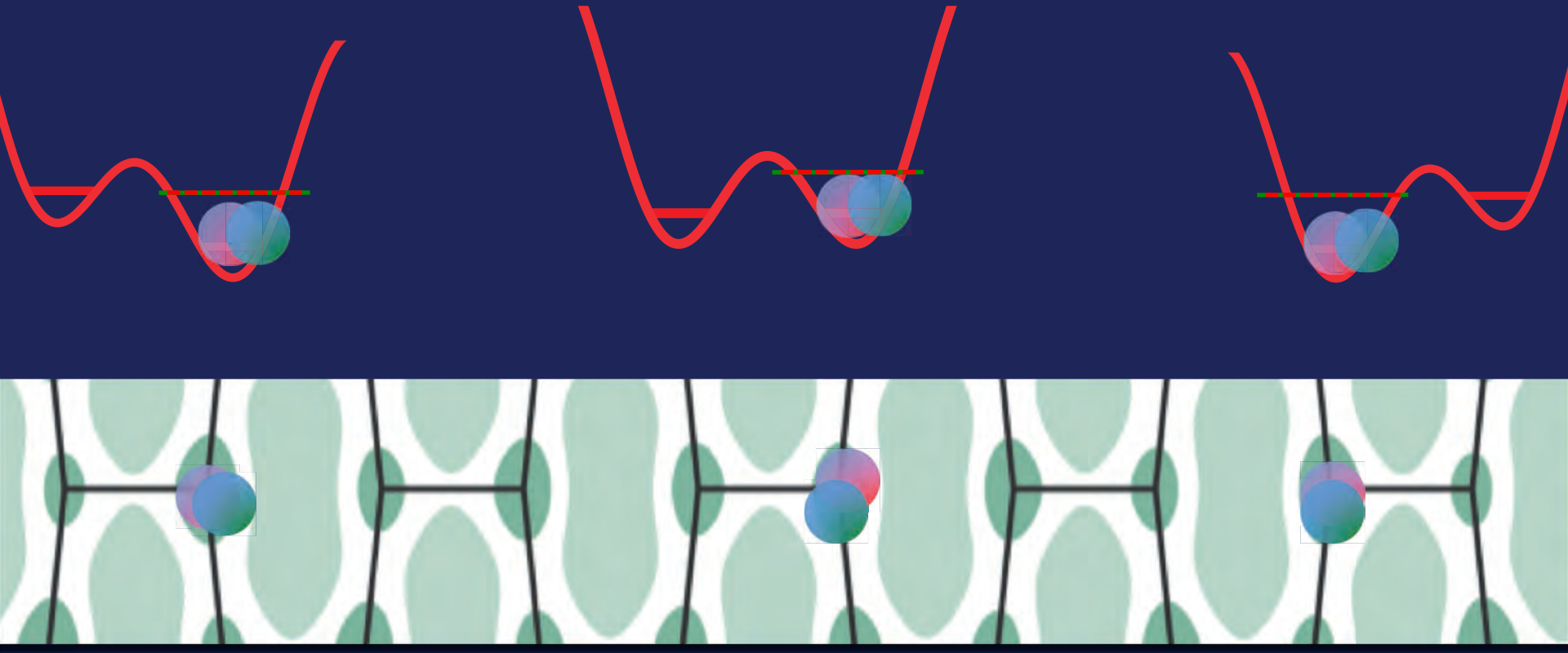
Theoretical challenge

Experimental challenge

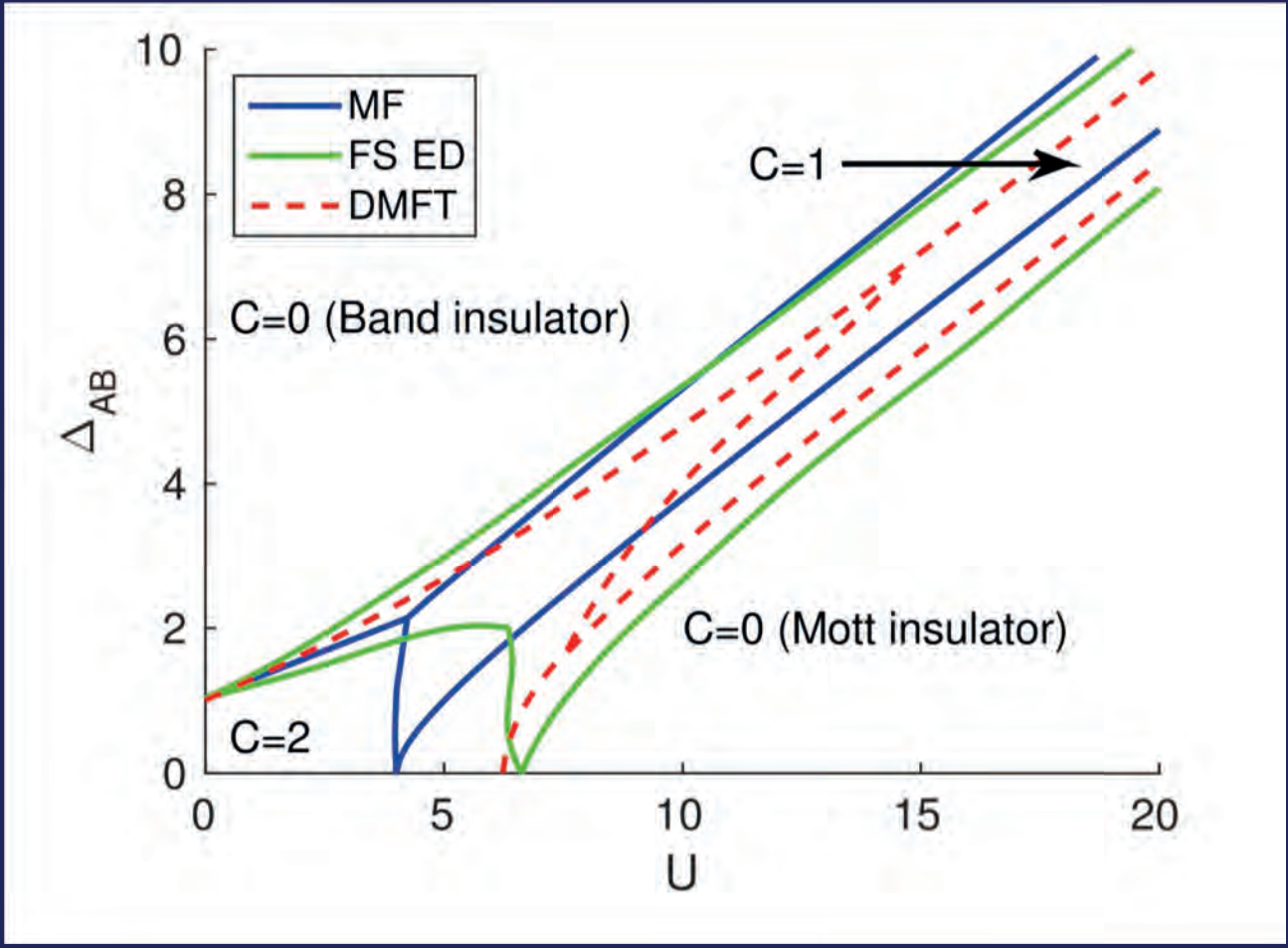




Interactions

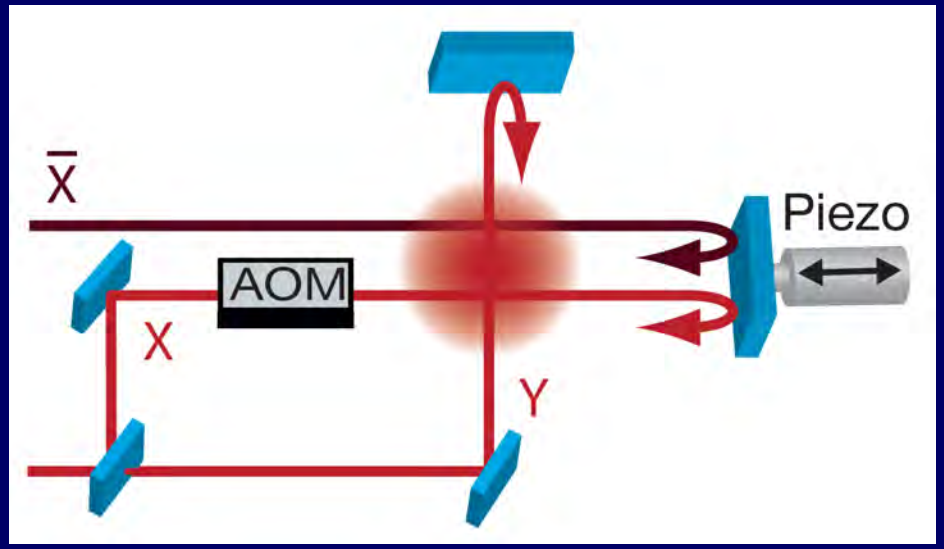


Interactions

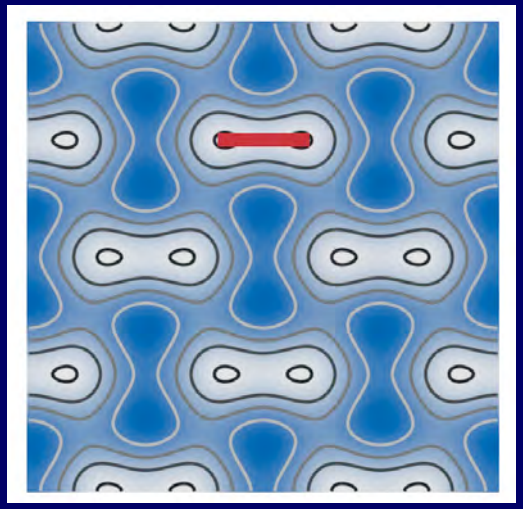


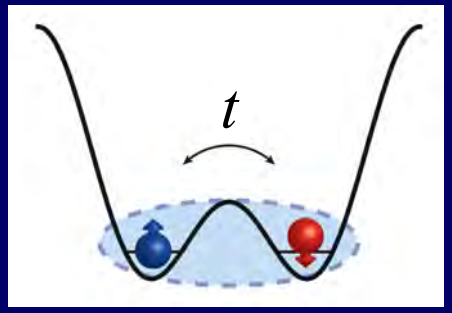
Topological Phase Transitions in the Repulsively Interacting Haldane-Hubbard Model
T. I. Vanhala, T. Siro, L. Liang, M. Troyer, A. Harju, and Päivi Törmä, PRL 116, 225305 (2016)

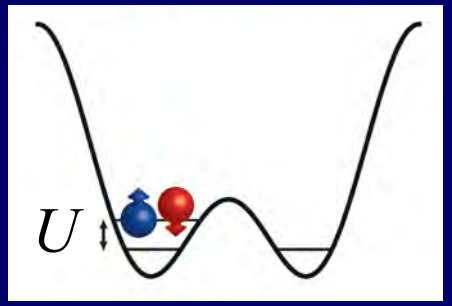
Shaking and interactions



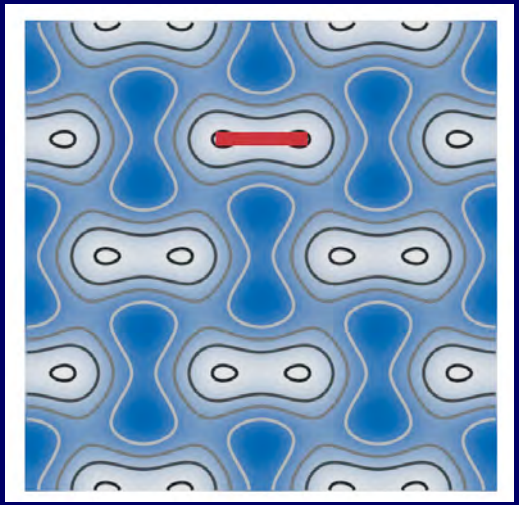
Double well



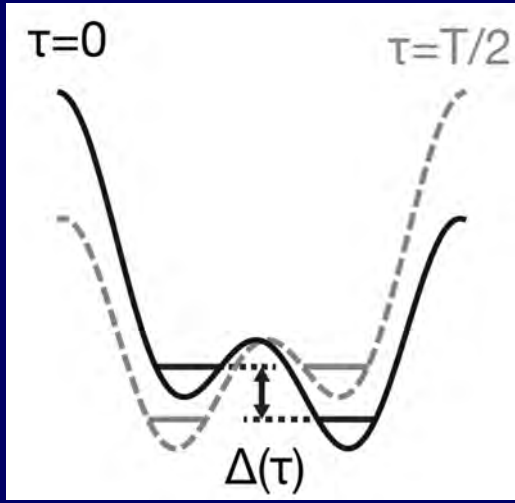




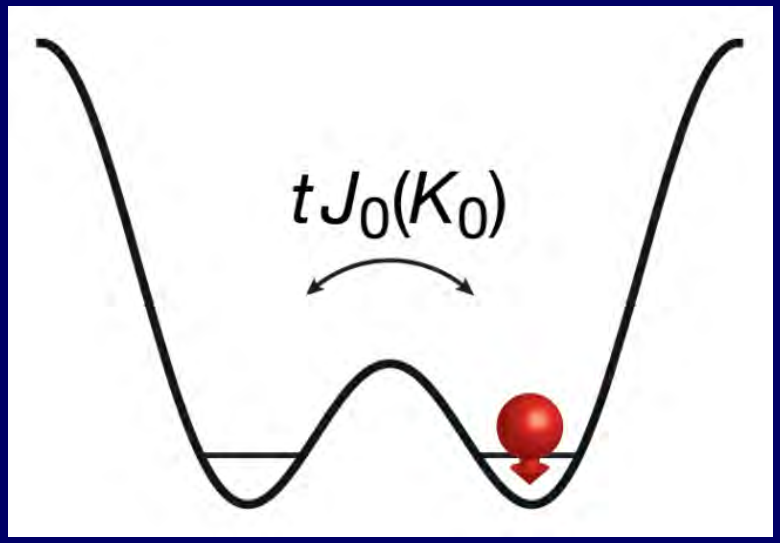
Driven double well



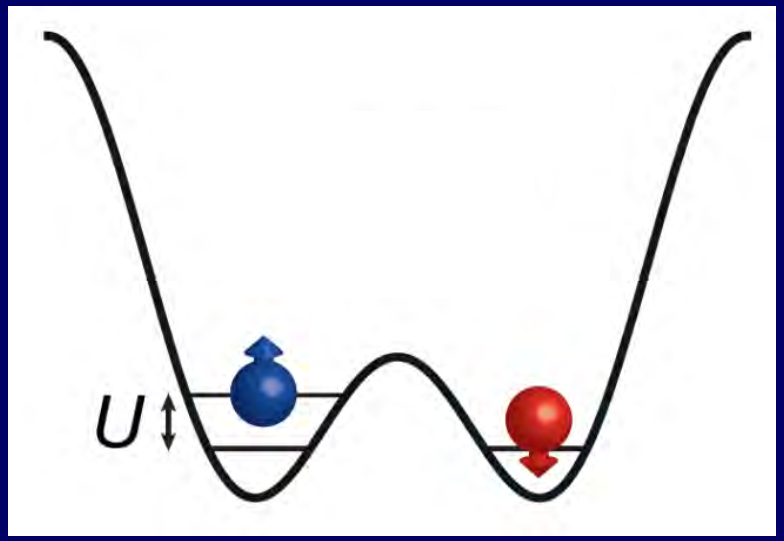
$$t \to t J_0(K_0)$$



Driven double well

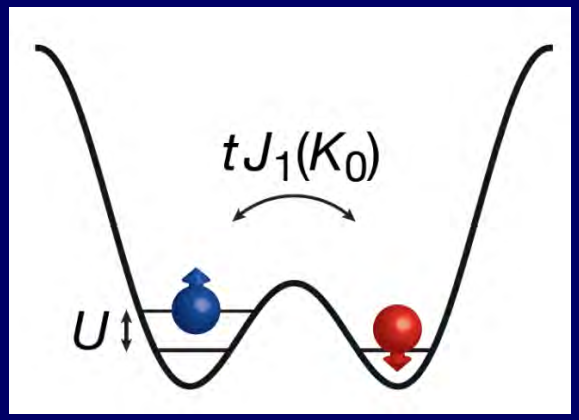


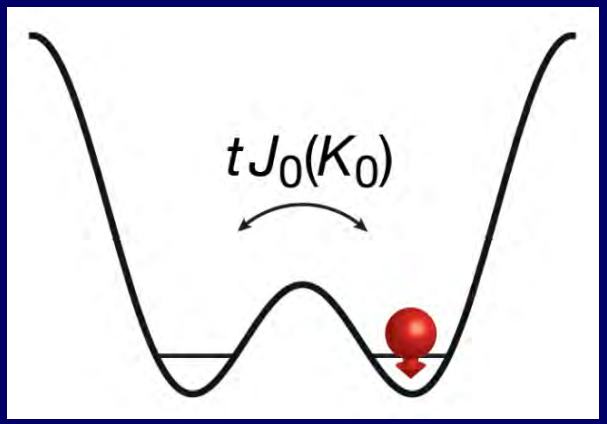
Driven double well



$U \approx \omega$

Driven double well



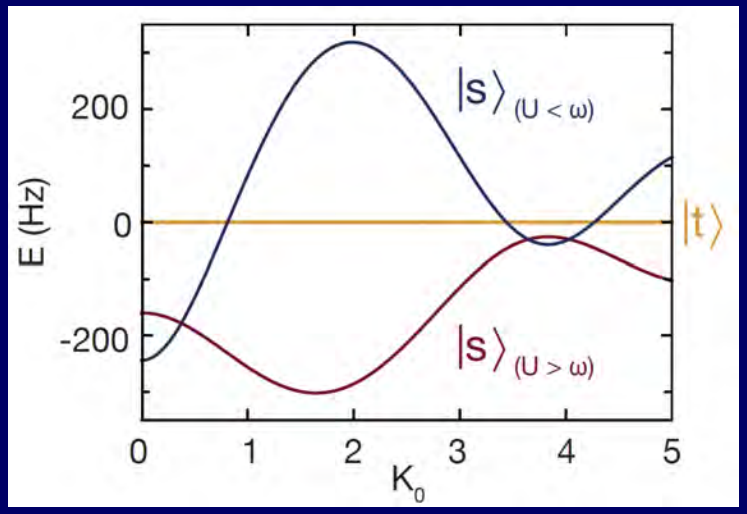


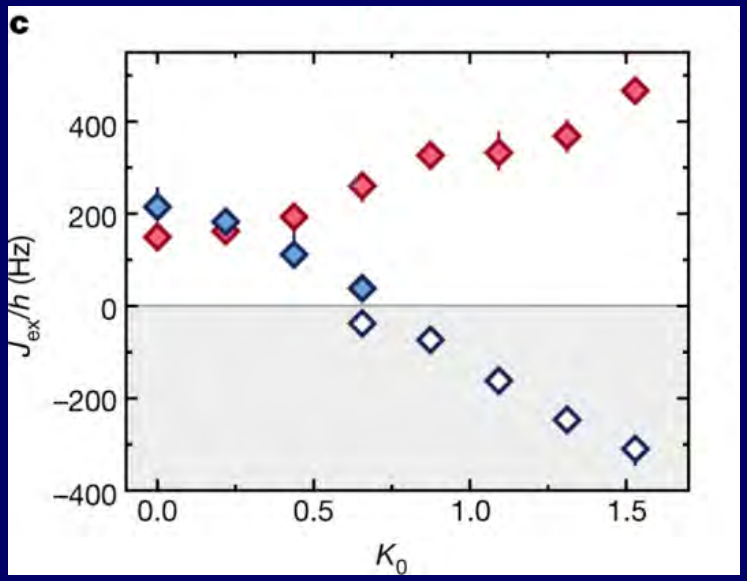
Exchange

$$\hbar\omega >> (\hbar\omega - U) > t$$

$$J_{\text{ex}} = -\frac{4t^2 J_0^2(K_0)}{U} - \frac{4t^2 J_1^2(K_0)}{U - \hbar\omega}$$

Driven double well



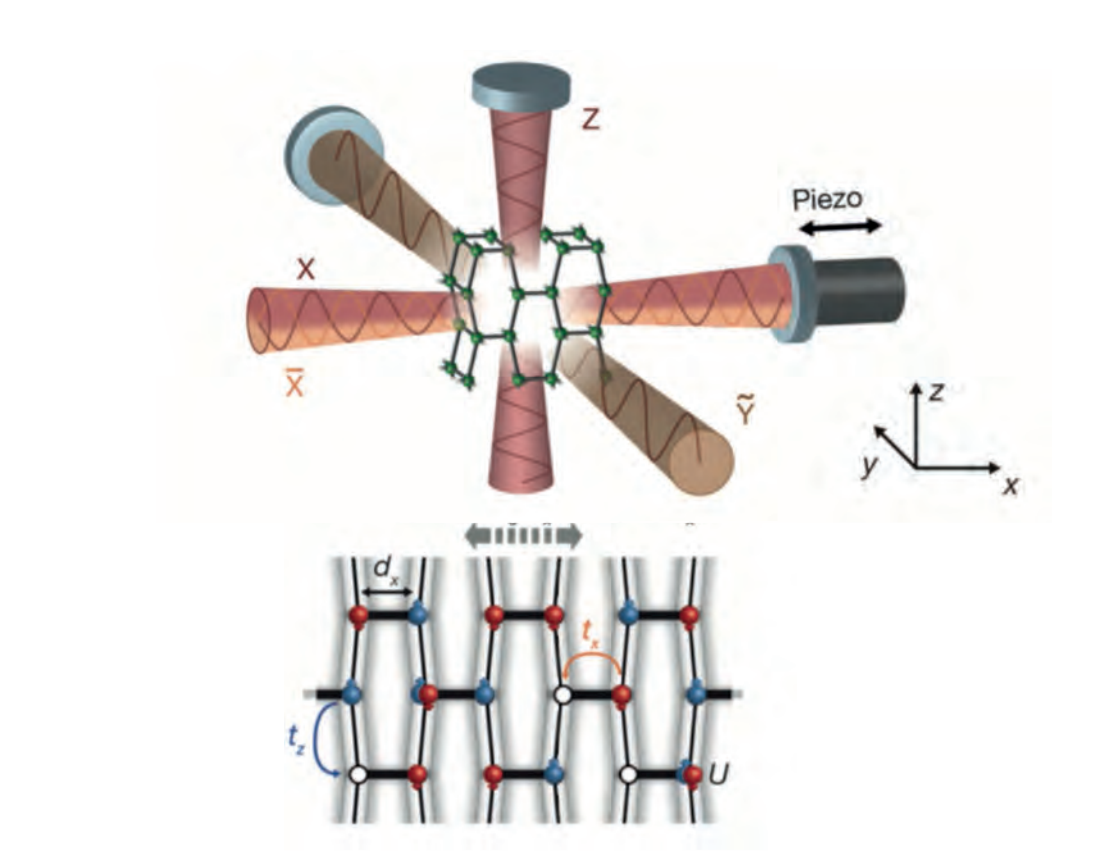


U=9.1 kHz > ω

U=6.5 kHz < ω

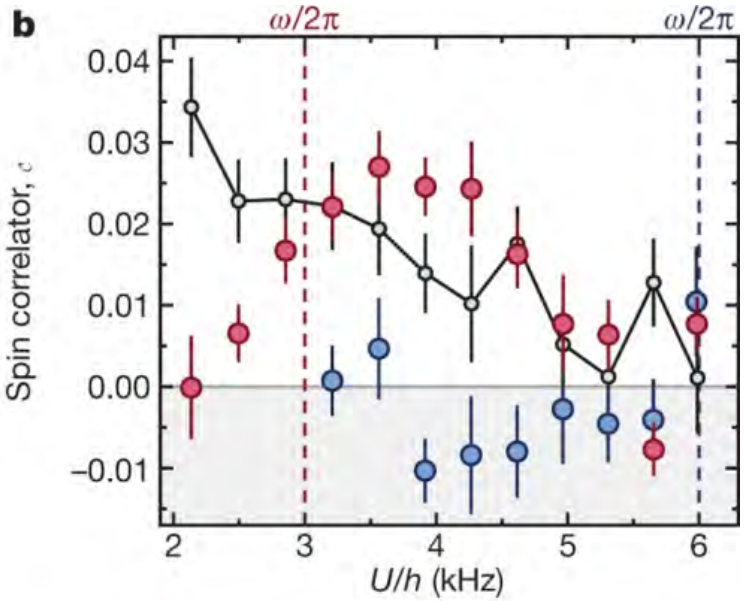
R. Desbuquois M. Messer, F. Görg, K. Sandholzer, G. Jotzu, and T. E., PRA **96**, 053602 (2017)

Magnetic correlations in driven lattice



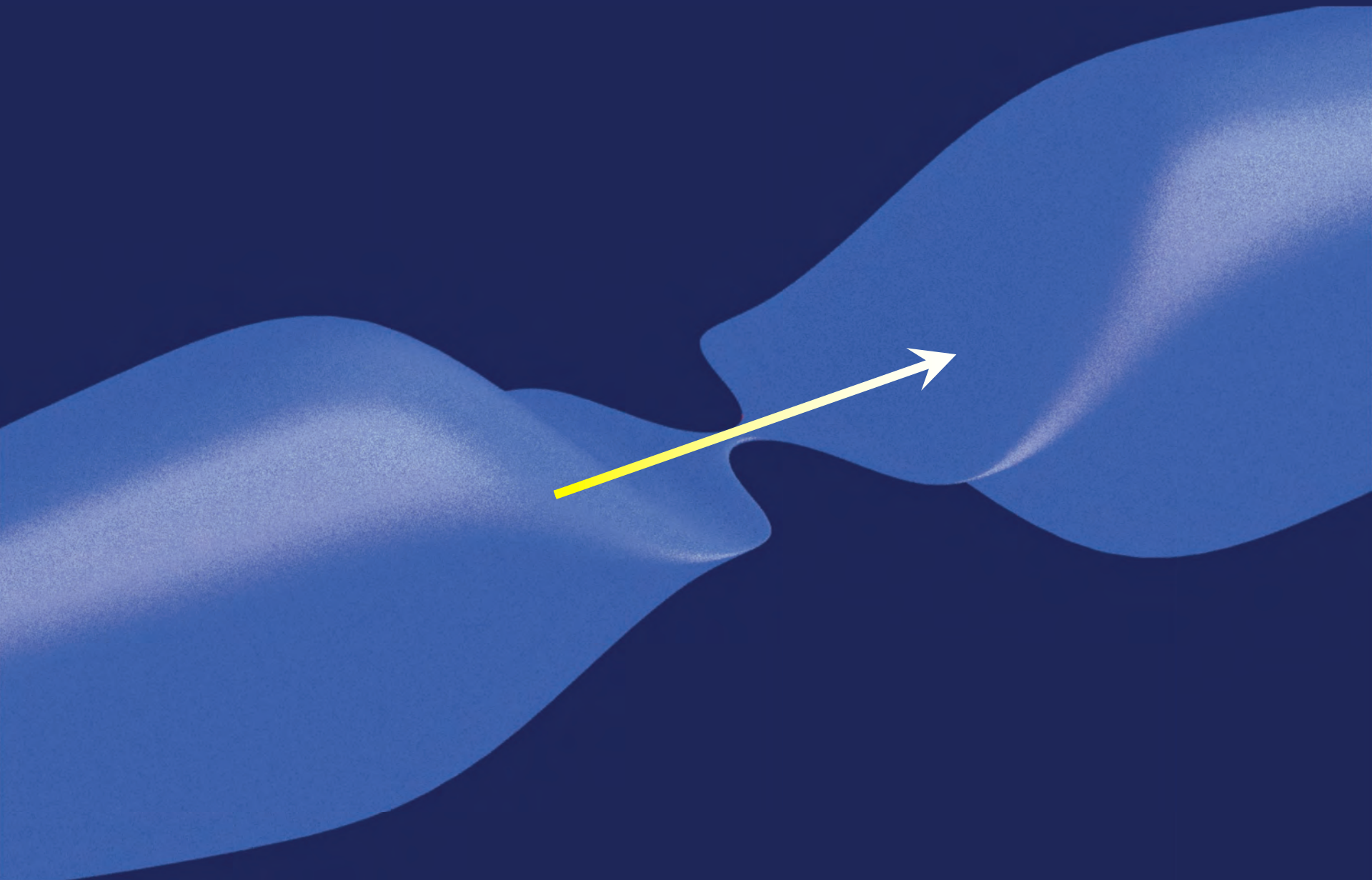
F. Görg, M. Messer, K. Sandholzer, G. Jotzu, R.Desbuquois, T.E., Nature 553, 481-485 (2018)
Also: J. Coulthard, S. R. Clark, S. Al-Assam, A. Cavalleri, D. Jaksch, Phys. Rev. B 96, 085104 (2017)

Enhancement of magnetic corrlations in driven lattice

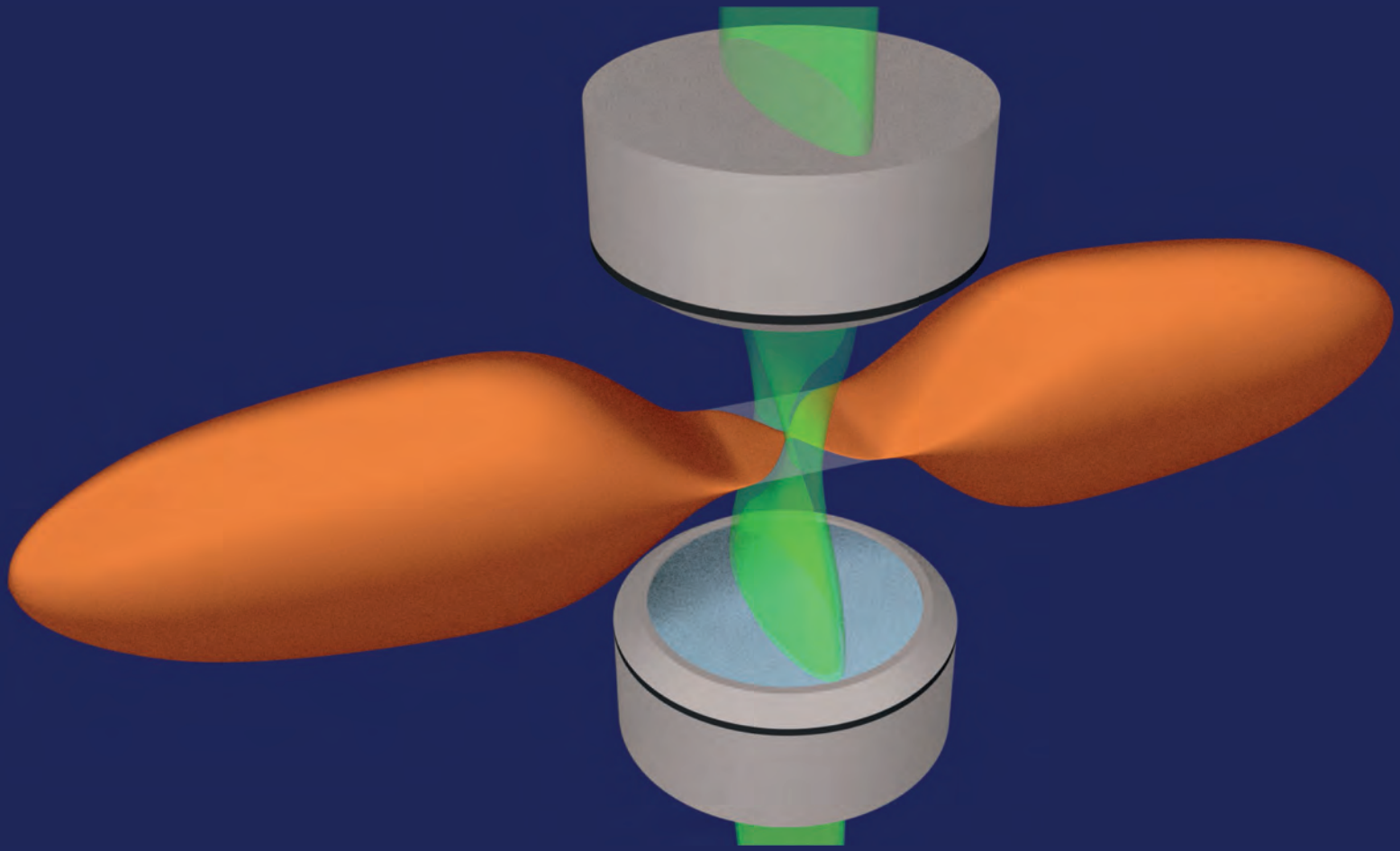


F. Görg, M. Messer, K. Sandholzer, G. Jotzu, R.Desbuquois, T.E., Nature 553, 481-485 (2018)
Also: J. Coulthard, S. R. Clark, S. Al-Assam, A. Cavalleri, D. Jaksch, Phys. Rev. B 96, 085104 (2017)

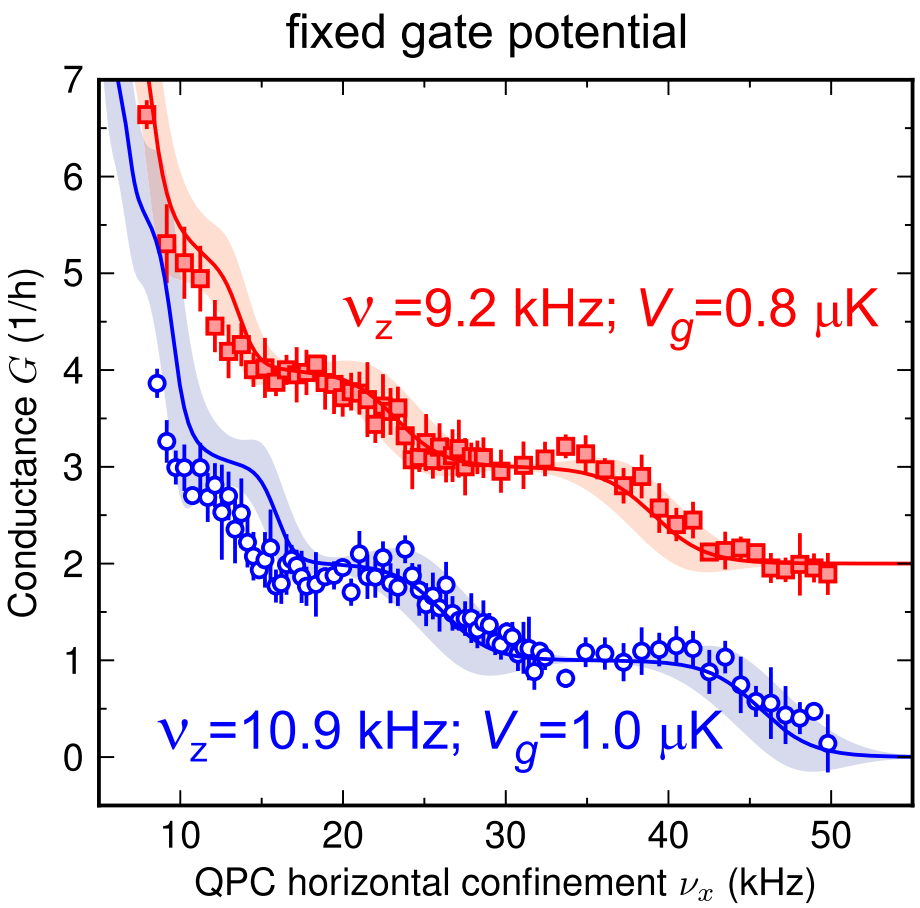
Quantum Point Contact for Fermions



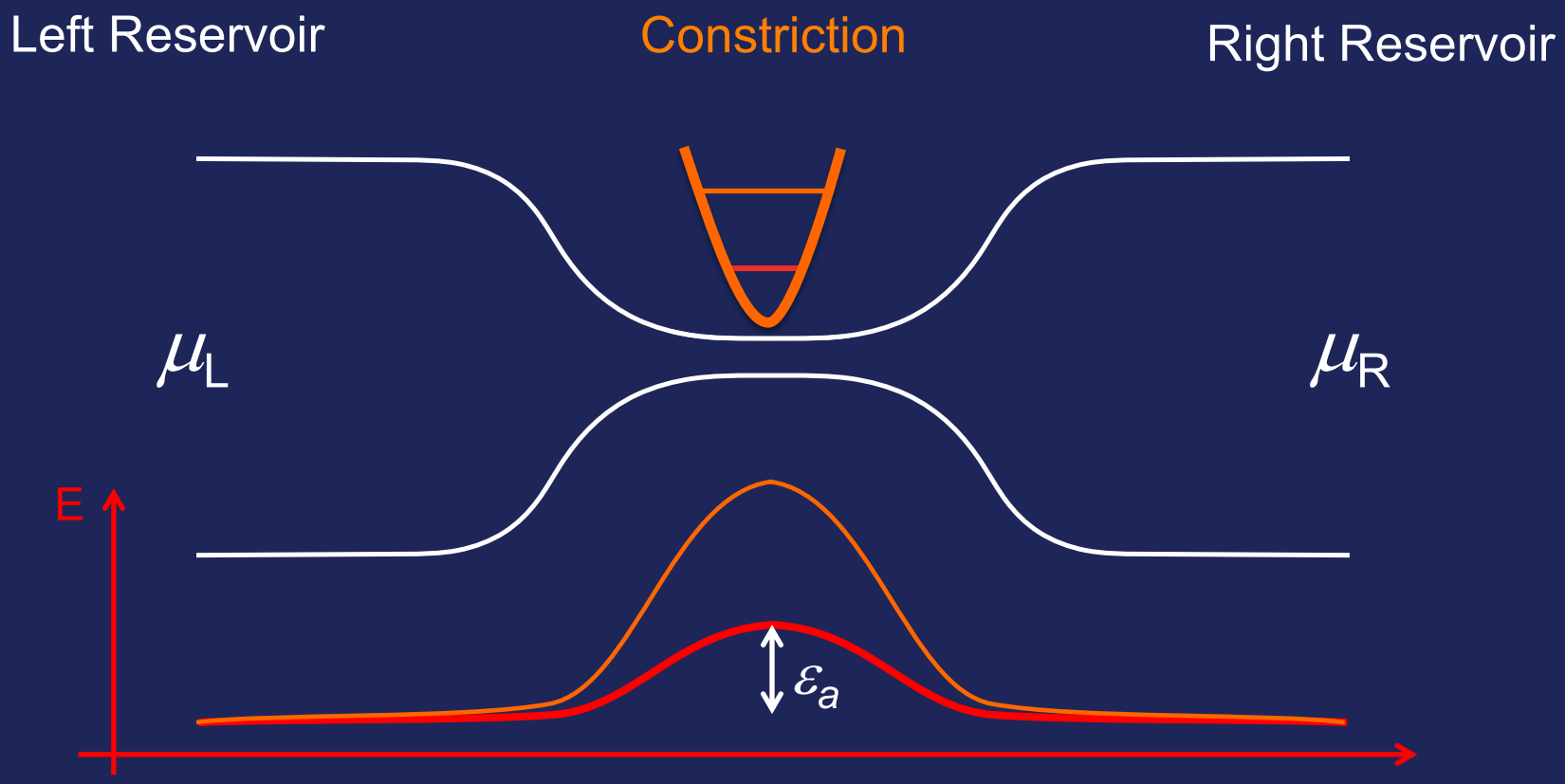
Quantum Point Contact for Fermions

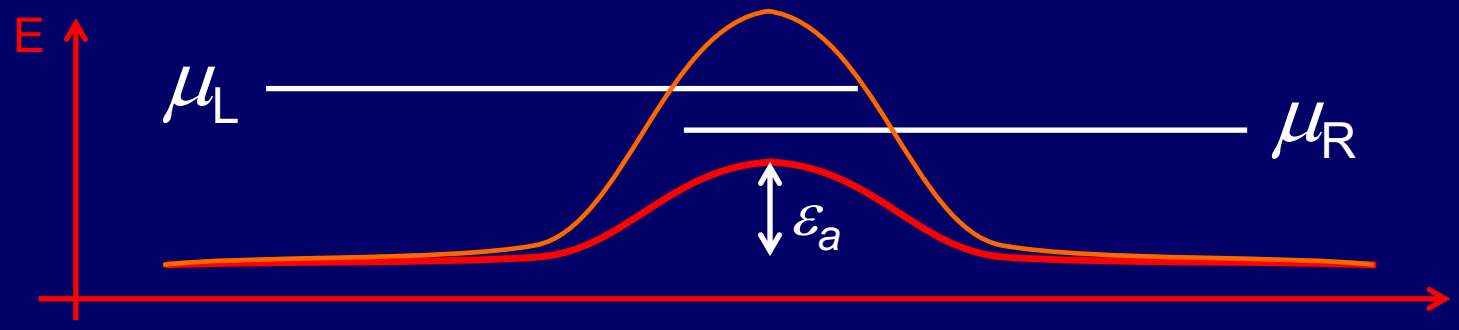


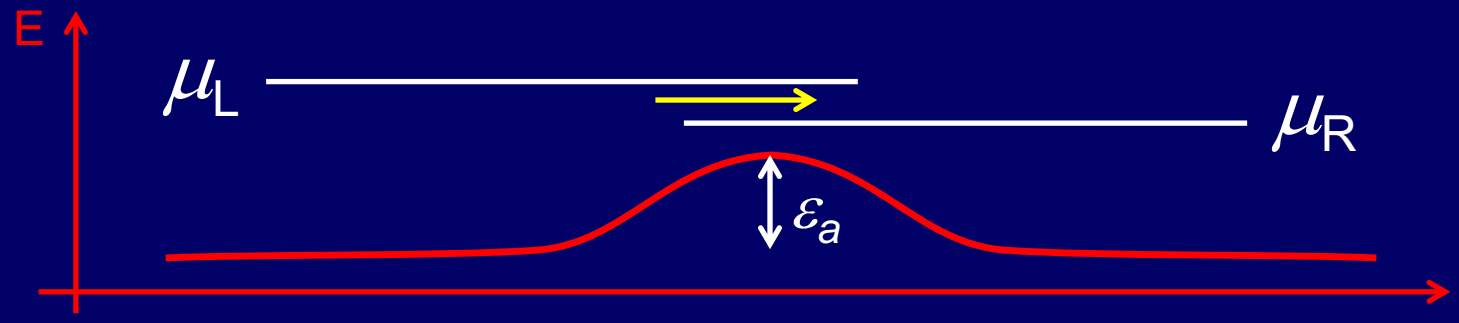
Quantum Point Contact



S. Krinner, D. Stadler, D. Husmann, J.P. Brantut and T. Esslinger, Nature 517, 64 (2015)

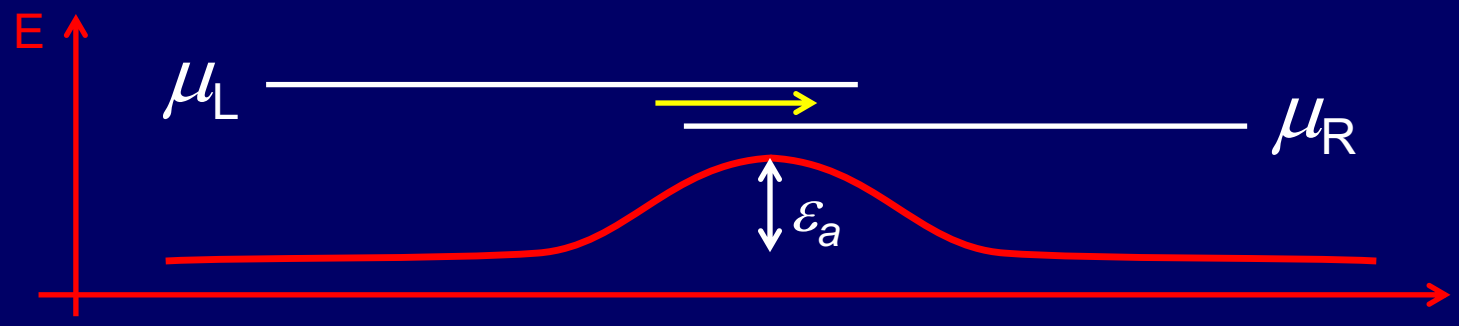

Left Reservoir
Constriction
Right Reservoir
μ_L
μ_R
E
ε_a


E
μ_L
μ_R
ε_a


E
μ_L
μ_R
ε_a

Current for T=0, T_a=1:

$$I_a = \int_{\varepsilon_F}^{\varepsilon_F+\Delta} d\varepsilon \; g_a(\varepsilon)\, v_a(\varepsilon)\; T_a(\varepsilon)$$



Current for T=0, T_a=1:

$$I_a = \int_{\varepsilon_F}^{\varepsilon_F+\Delta} d\varepsilon \; g_a(\varepsilon) \; v_a(\varepsilon) \; T_a(\varepsilon)$$

Current for T=0, T_a=1:

$$I_a = \int_{\varepsilon_F}^{\varepsilon_F+\Delta} d\varepsilon \; g_a(\varepsilon)\, v_a(\varepsilon)\; T_a(\varepsilon) = \frac{\Delta}{h}$$

velocity:

$$v_a(\varepsilon) = \frac{\hbar k_a}{m} = \sqrt{2(\varepsilon - \varepsilon_a)/m}$$

density of states:
(right movers)

$$g_a(\varepsilon) = \frac{1}{2\pi}\frac{dk_a}{d\varepsilon} = \frac{1}{2\pi\hbar v_a(\varepsilon)}$$

Landauer, Büttiker, Imry

Current for T=0, T_a=1:

$$I_a = \int_{\varepsilon_F}^{\varepsilon_F+\Delta} d\varepsilon \; g_a(\varepsilon)\, v_a(\varepsilon)\; T_a(\varepsilon) = \frac{\Delta}{h}$$

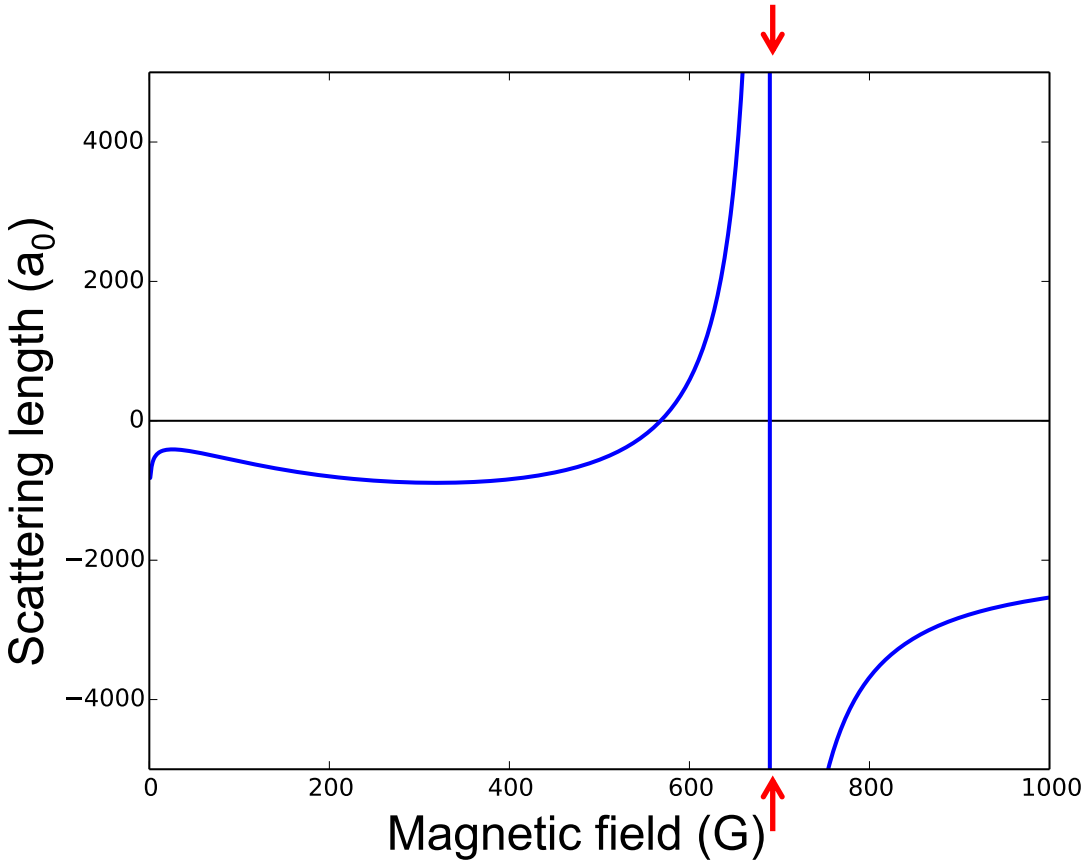
Conductance $\qquad G = \dfrac{1}{h}$

Consequence of Heisenberg + Pauli's principle

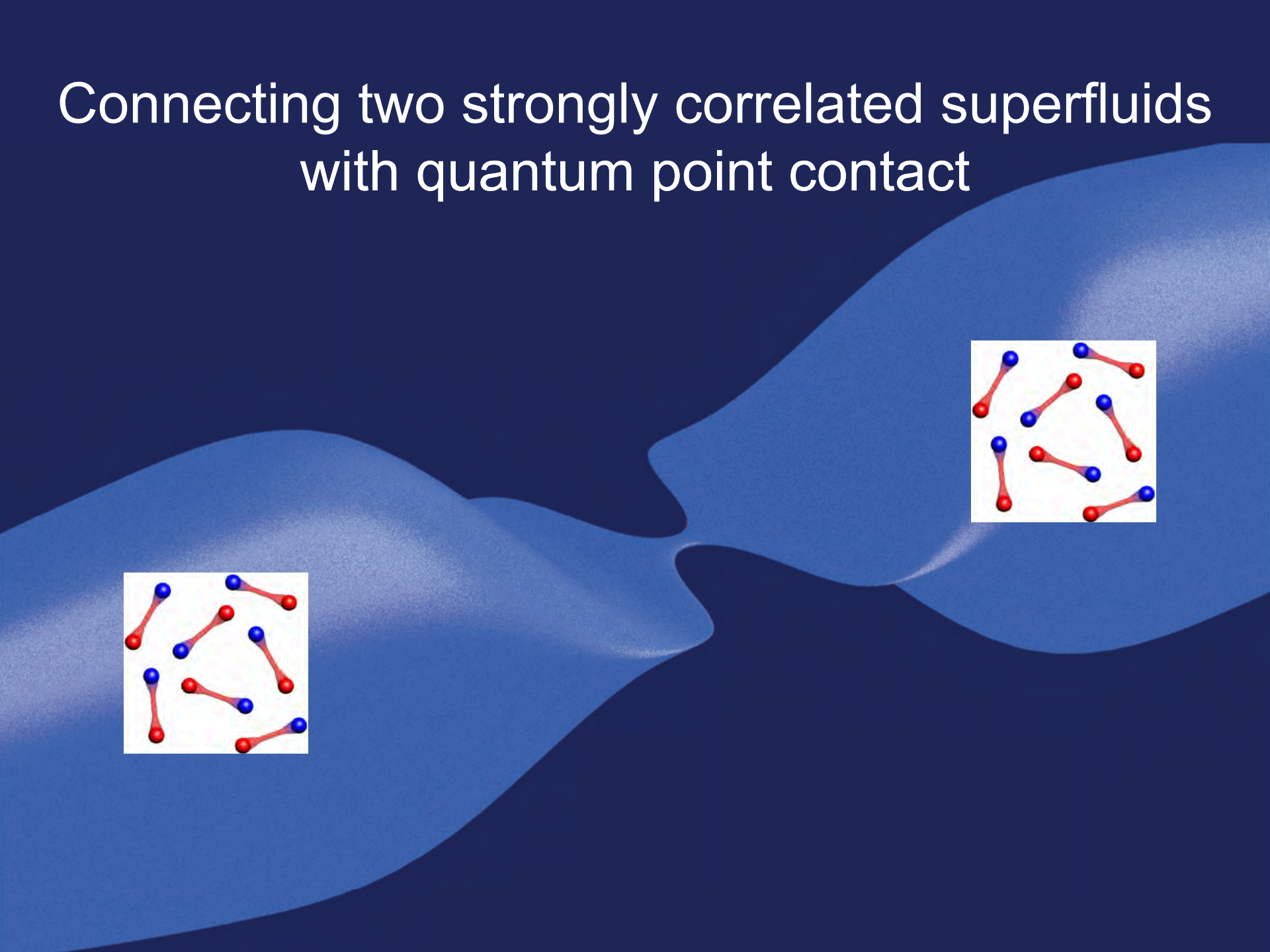
Landauer, Büttiker, Imry

Connecting two strongly correlated superfluids with quantum point contact

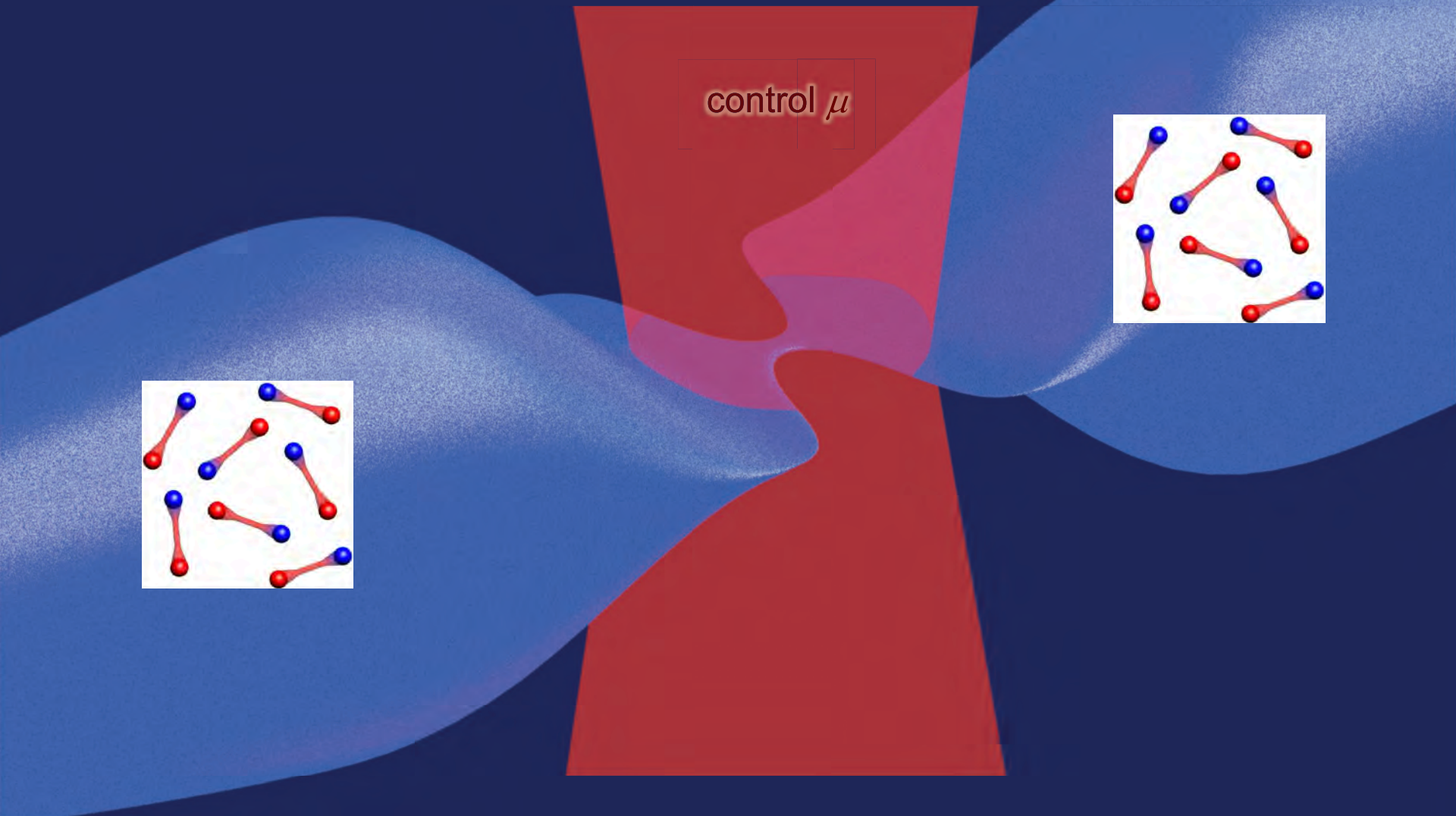
Connecting two strongly correlated superfluids with quantum point contact



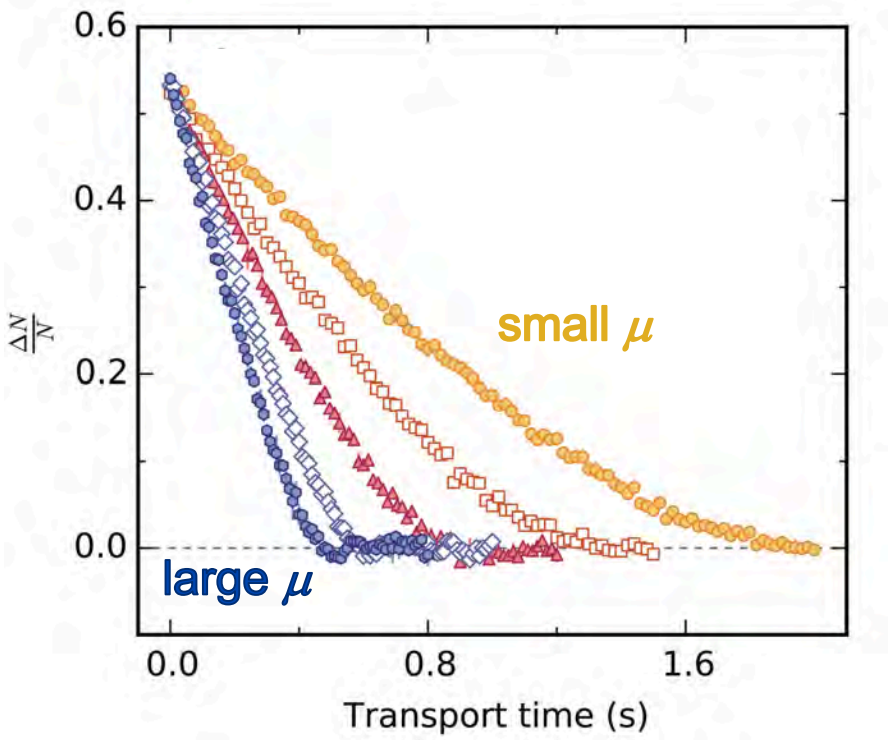
Connecting two strongly correlated superfluids with quantum point contact



Connecting two strongly correlated superfluids with quantum point contact

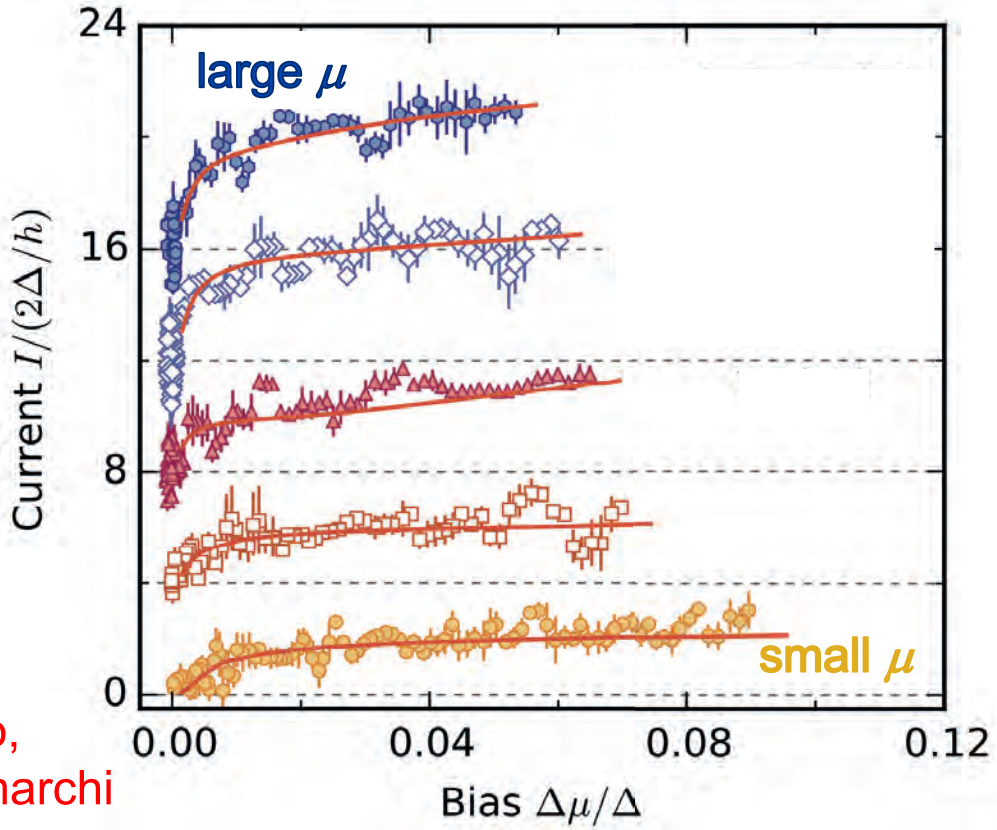


Connecting two strongly correlated superfluids with quantum point contact



Connecting two strongly correlated superfluids with quantum point contact

Theory:
Shun Uchino,
Thierry Giamarchi



Dominik Husmann, Shun Uchino, Sebastian Krinner, Martin Lebrat, Thierry Giamarchi, Tilman Esslinger, Jean-Philippe Brantut, Science 350, 1498-1501 (2015)

Connecting two strongly correlated superfluids with quantum point contact

Theory:
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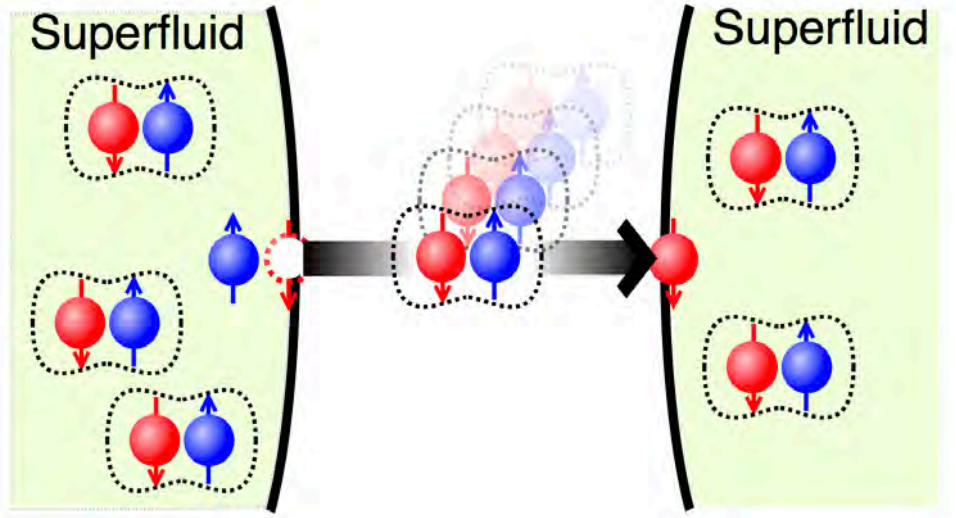
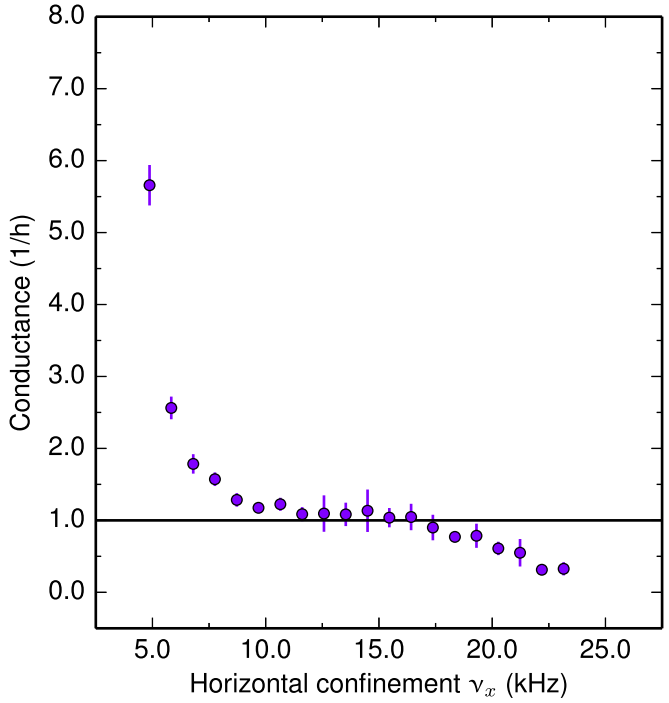
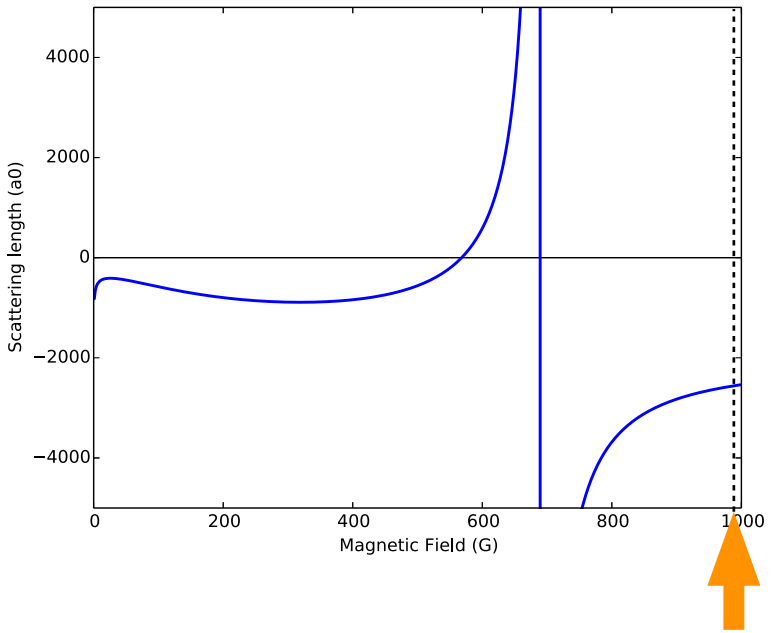


Gap for single particle transfer bridged by coherent transfer of n pairs
(multiple Andreev reflection)

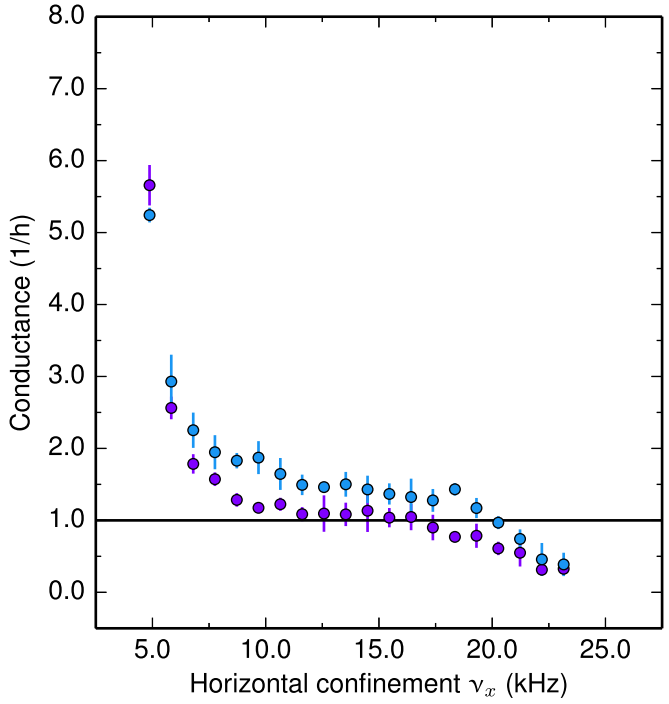
Dominik Husmann, Shun Uchino, Sebastian Krinner, Martin Lebrat, Thierry Giamarchi, Tilman Esslinger, Jean-Philippe Brantut, Science 350, 1498-1501 (2015)
Josephson Effect: G. Valtolina, , A. Burchianti, A. Amico, E. Neri, K. Xhani, J. A. Seman, A. Trombettoni, A. Smerzi, M. Zaccanti, M. Inguscio, G. Roati, Science 3501505-1508 (2015).

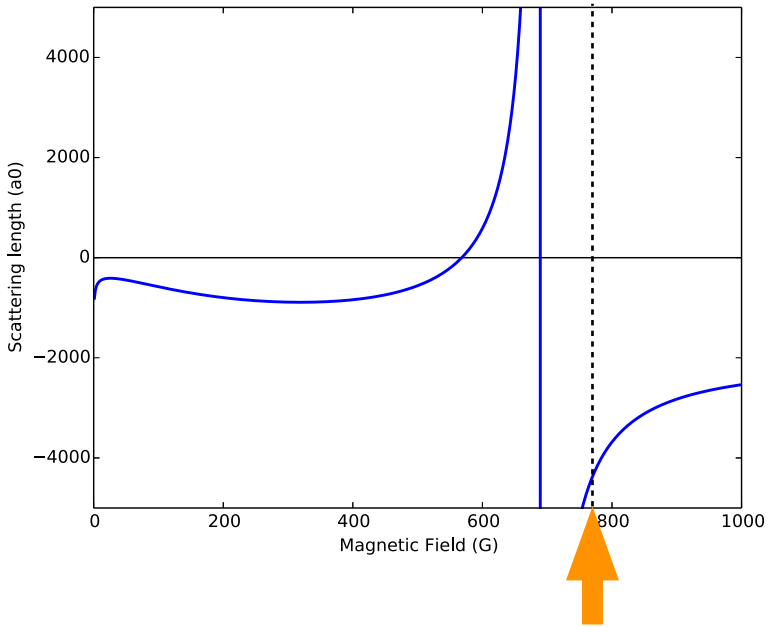
Changing Interactions



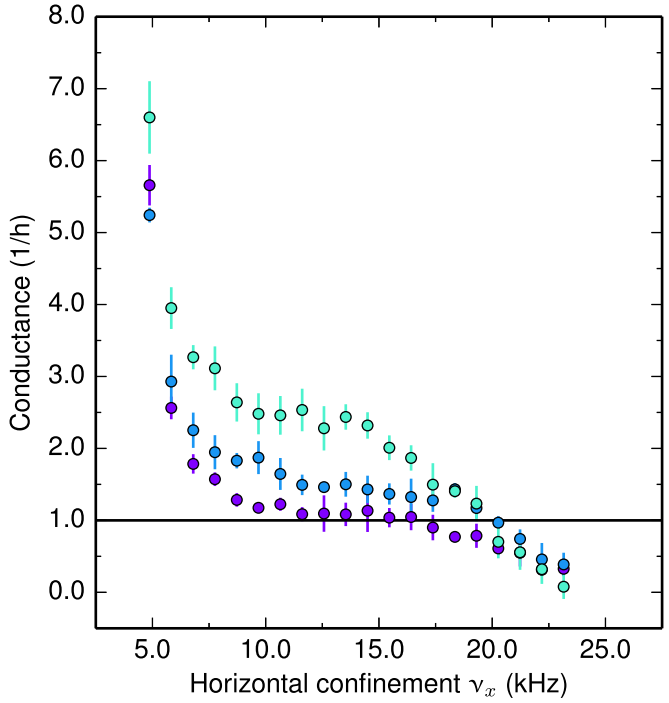


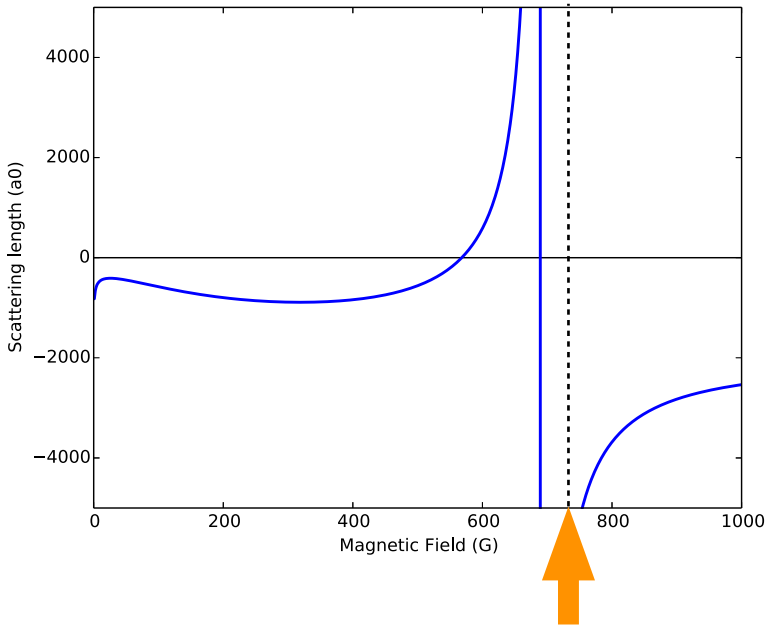
Changing Interactions



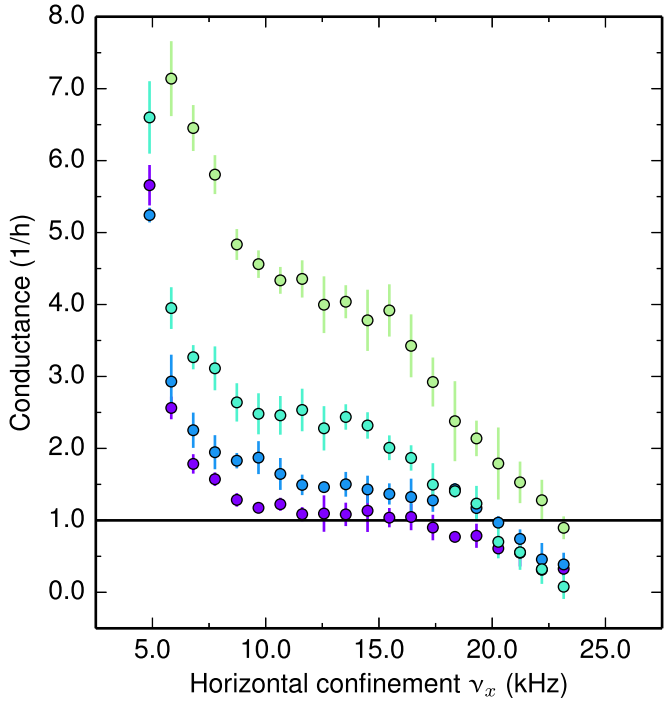


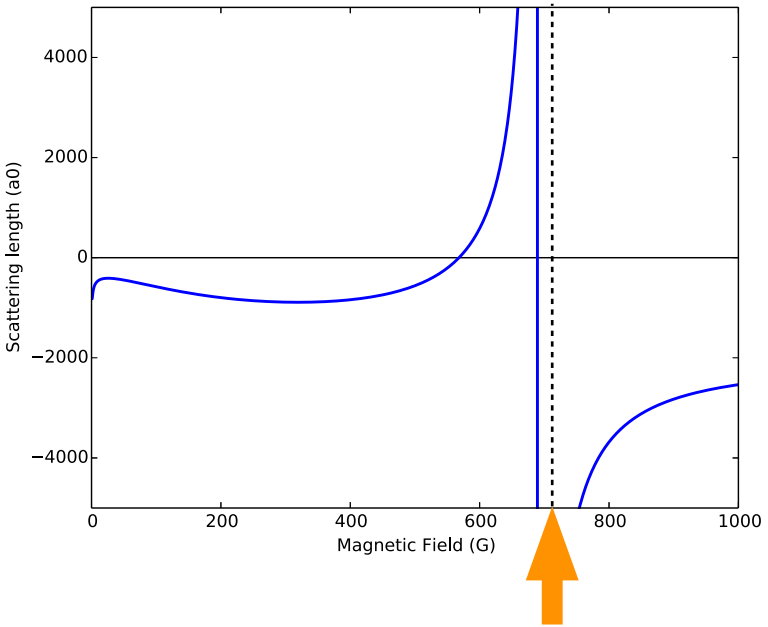
Changing Interactions



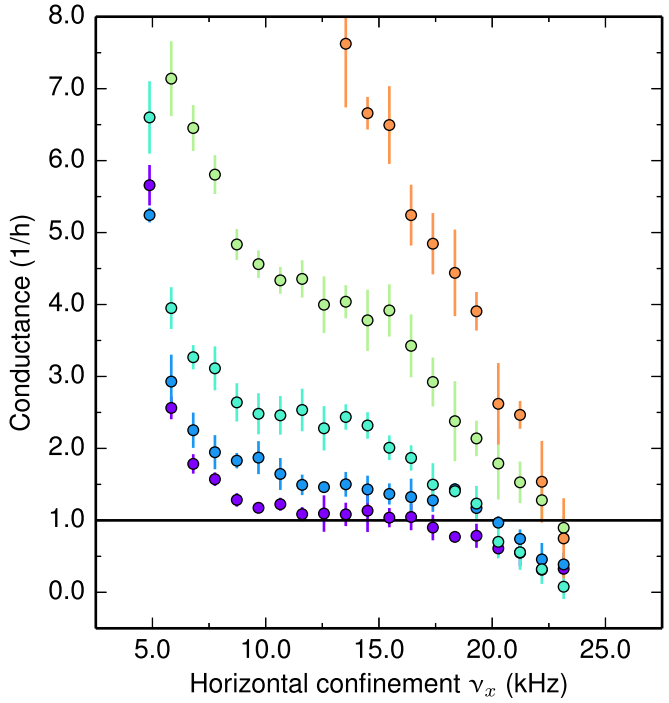


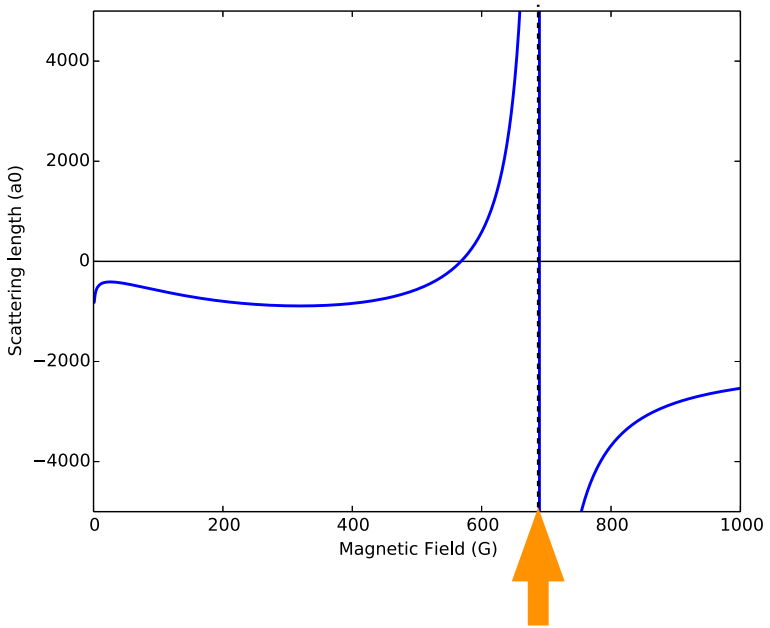
Changing Interactions





Changing Interactions





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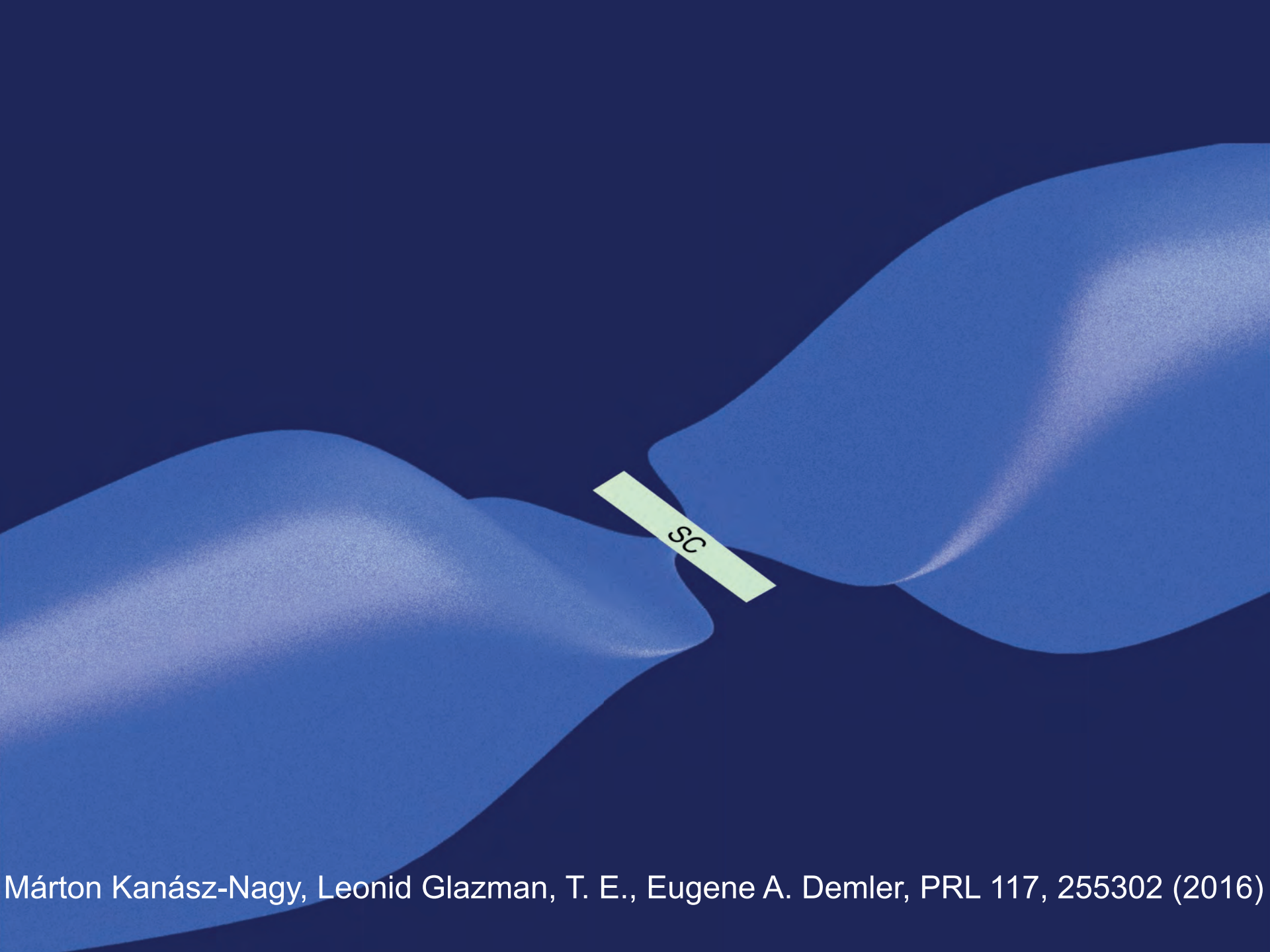
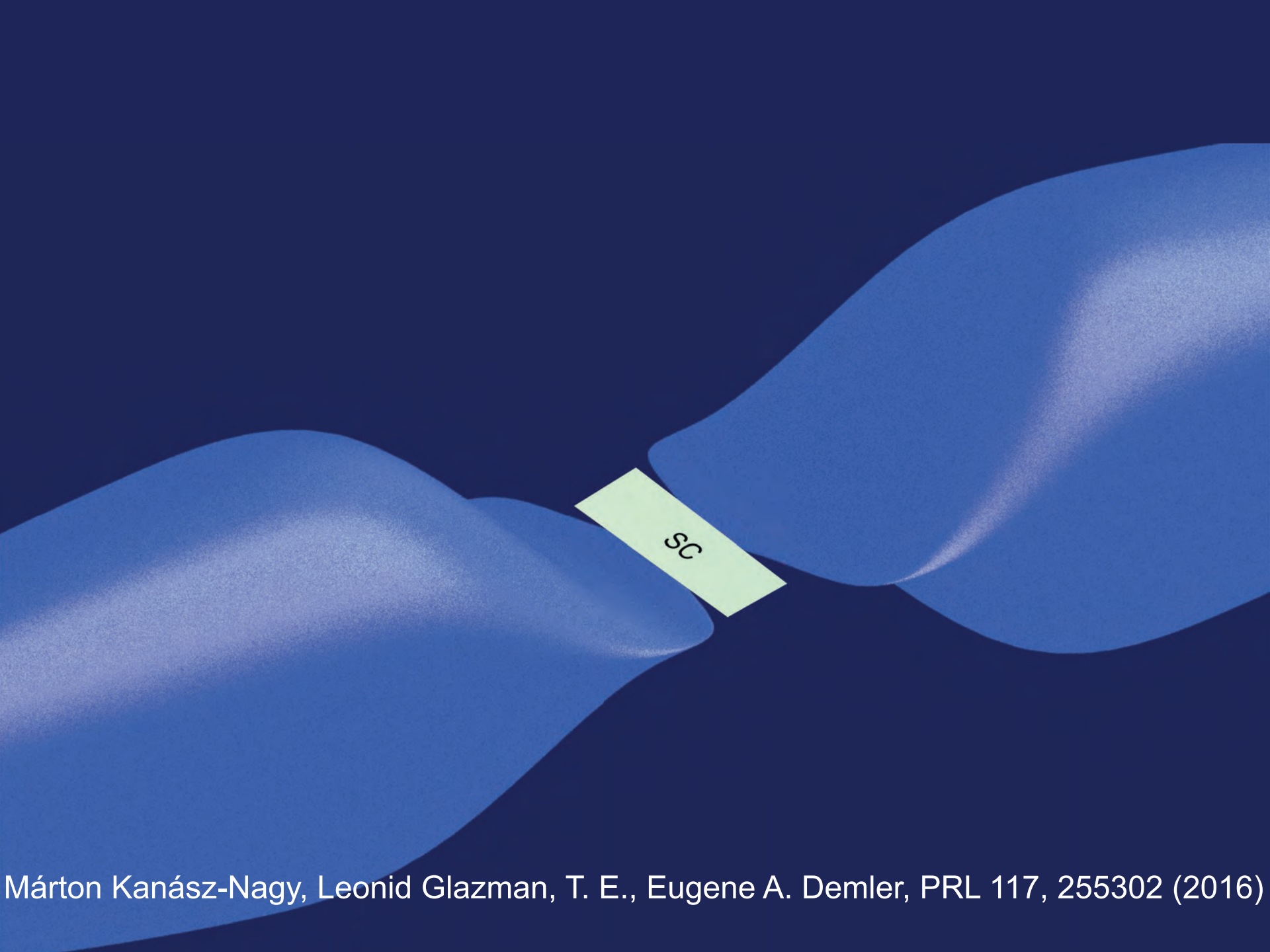
Márton Kanász-Nagy, Leonid Glazman, T. E., Eugene A. Demler, PRL 117, 255302 (2016)



Márton Kanász-Nagy, Leonid Glazman, T. E., Eugene A. Demler, PRL 117, 255302 (2016)



Márton Kanász-Nagy, Leonid Glazman, T. E., Eugene A. Demler, PRL 117, 255302 (2016)

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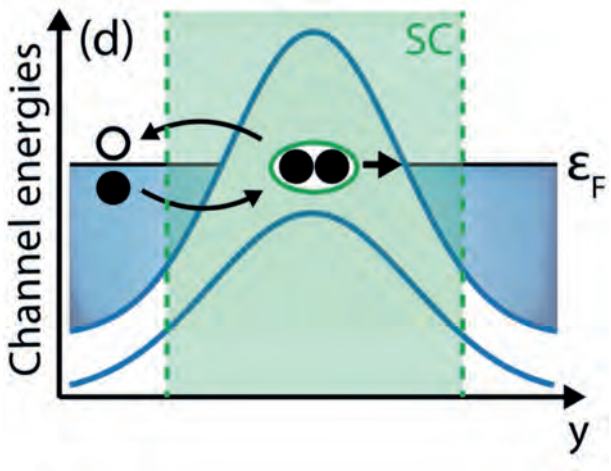
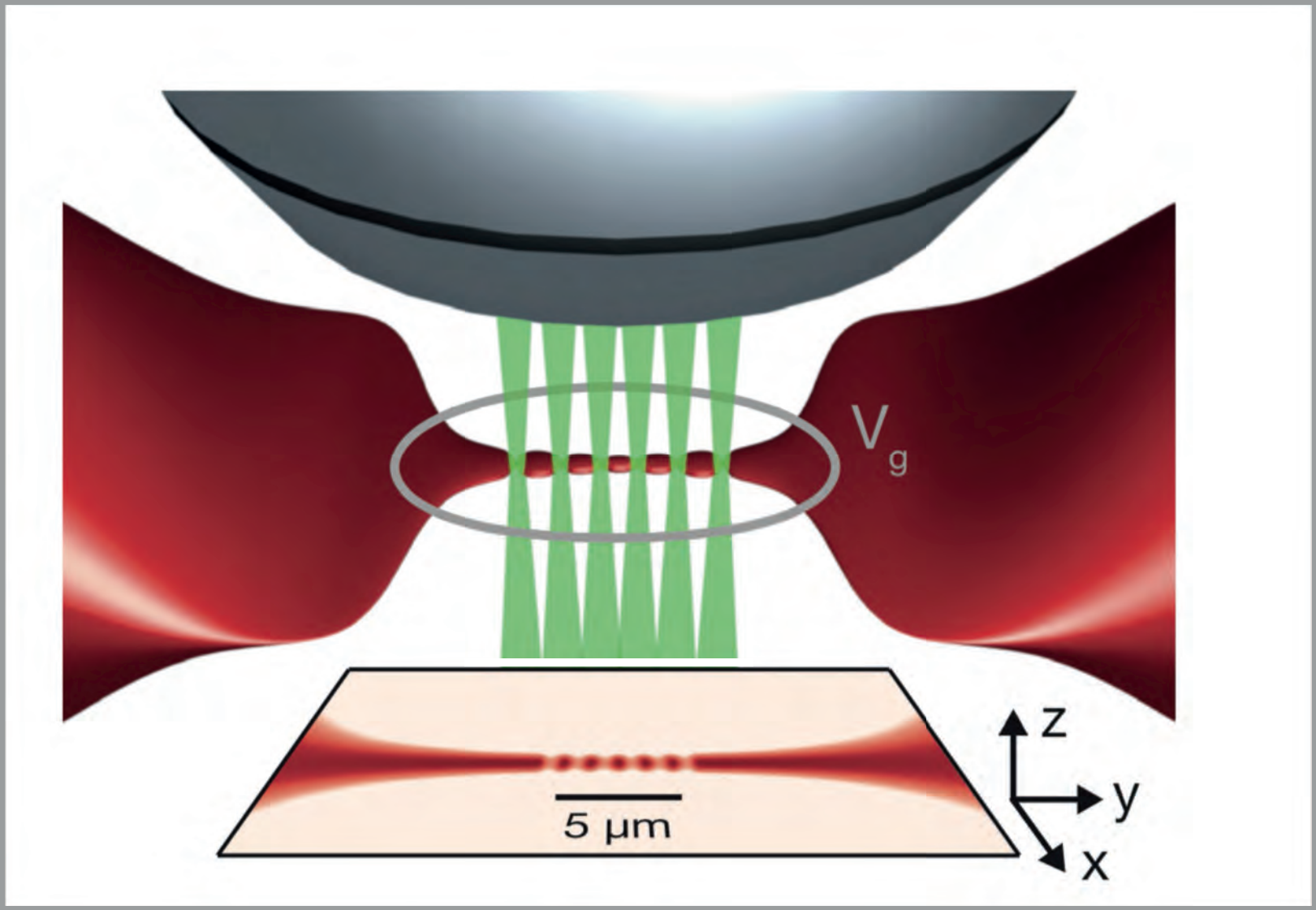


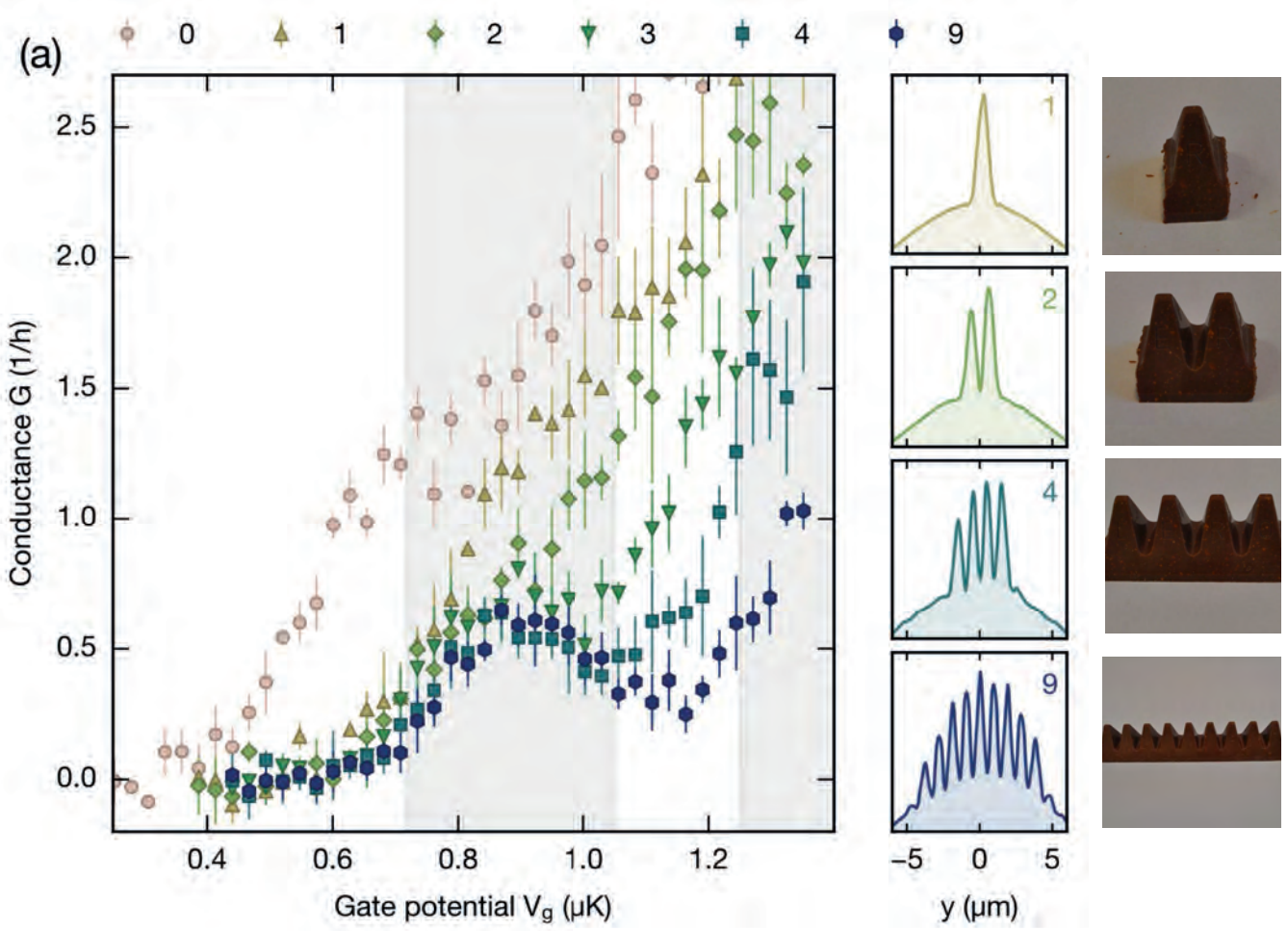
Enhanced pairing in channel

Márton Kanász-Nagy, Leonid Glazman, T. E., Eugene A. Demler, PRL 117, 255302 (2016)

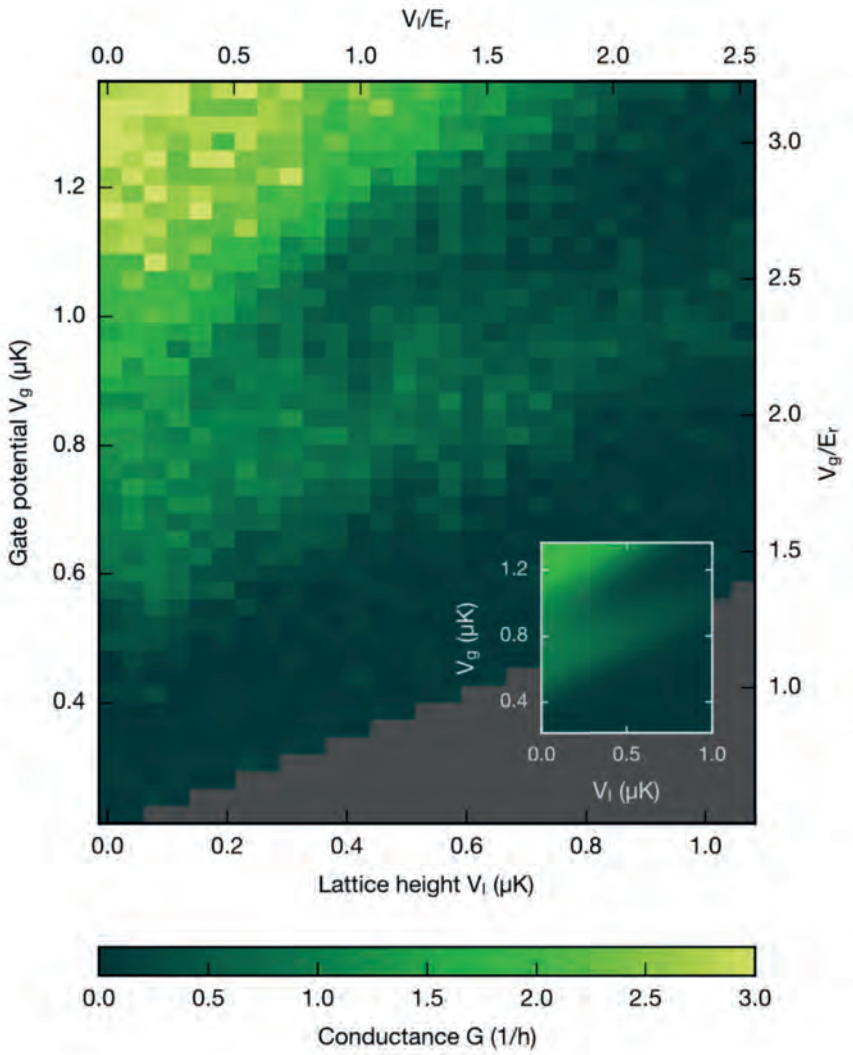
Transport



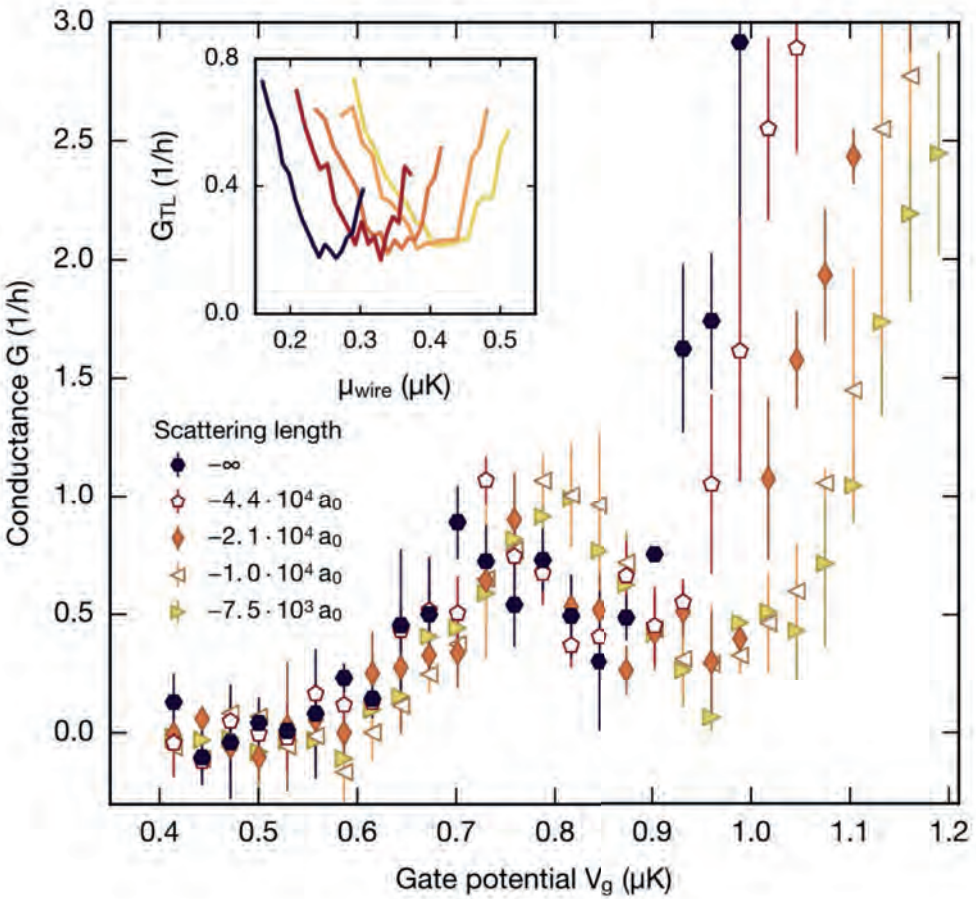
Site by site


(a)
0
1
2
3
4
9
Conductance G (1/h)
2.5
2.0
1.5
1.0
0.5
0.0
0.4
0.6
0.8
1.0
1.2
Gate potential V_g (μK)
1
2
4
9
−5
0
5
y (μm)

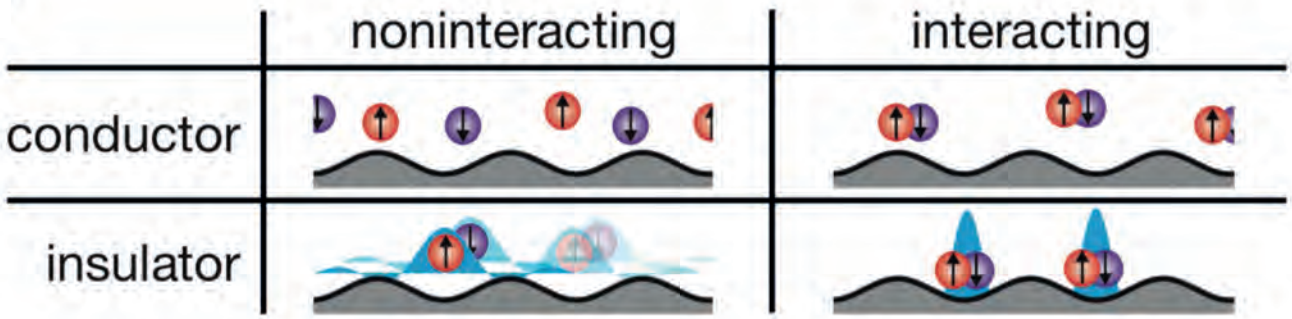
Increase lattice



Interactions

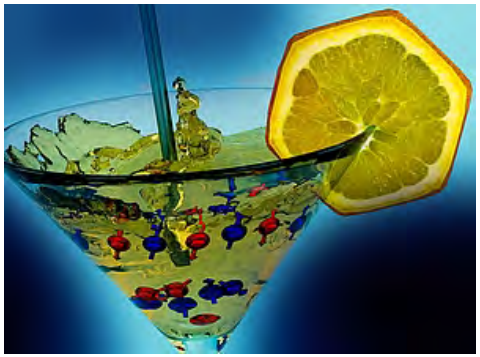


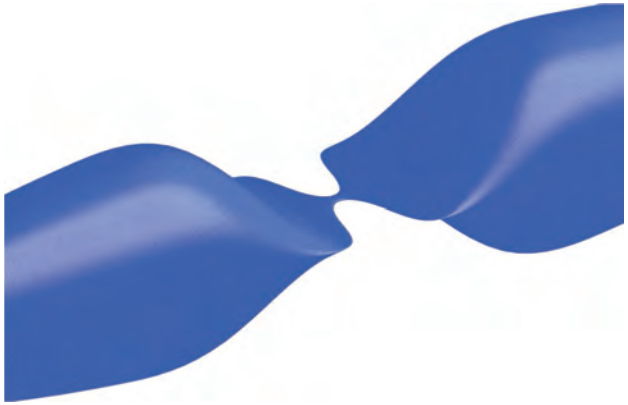
Luther-Emry liquid

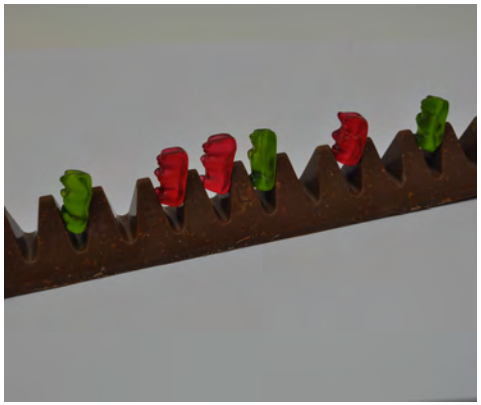


Martin Lebrat, Pjotrs Grišins, Dominik Husmann, Samuel Häusler, Laura Corman, Thierry Giamarchi, Jean-Philippe Brantut, T. E., arXiv:1708.01250, PRX 8, 011053 (2018)

Conclusions







Thanks!

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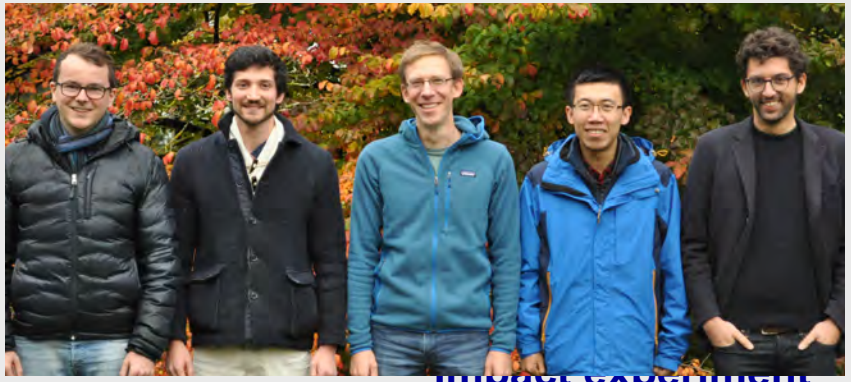

Quantum Gases in Optical Lattices

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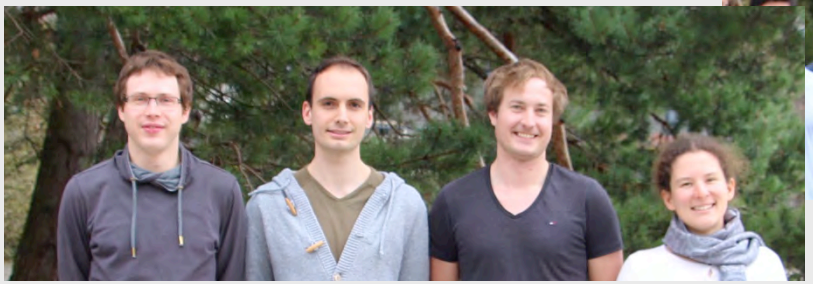

Wilhelm Zwerger

Lithium Microscope

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Dominik Husmann
Martin Lebrat
Samuel Häusler
Philipp Fabritius
Jean-Philippe Brantut (now EPFL)

+ Thierry Giamarchi
Pjotrs Grisins

BEC and Cavity

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Tobias Donner
Nishant Dogra
Katrin Kröger