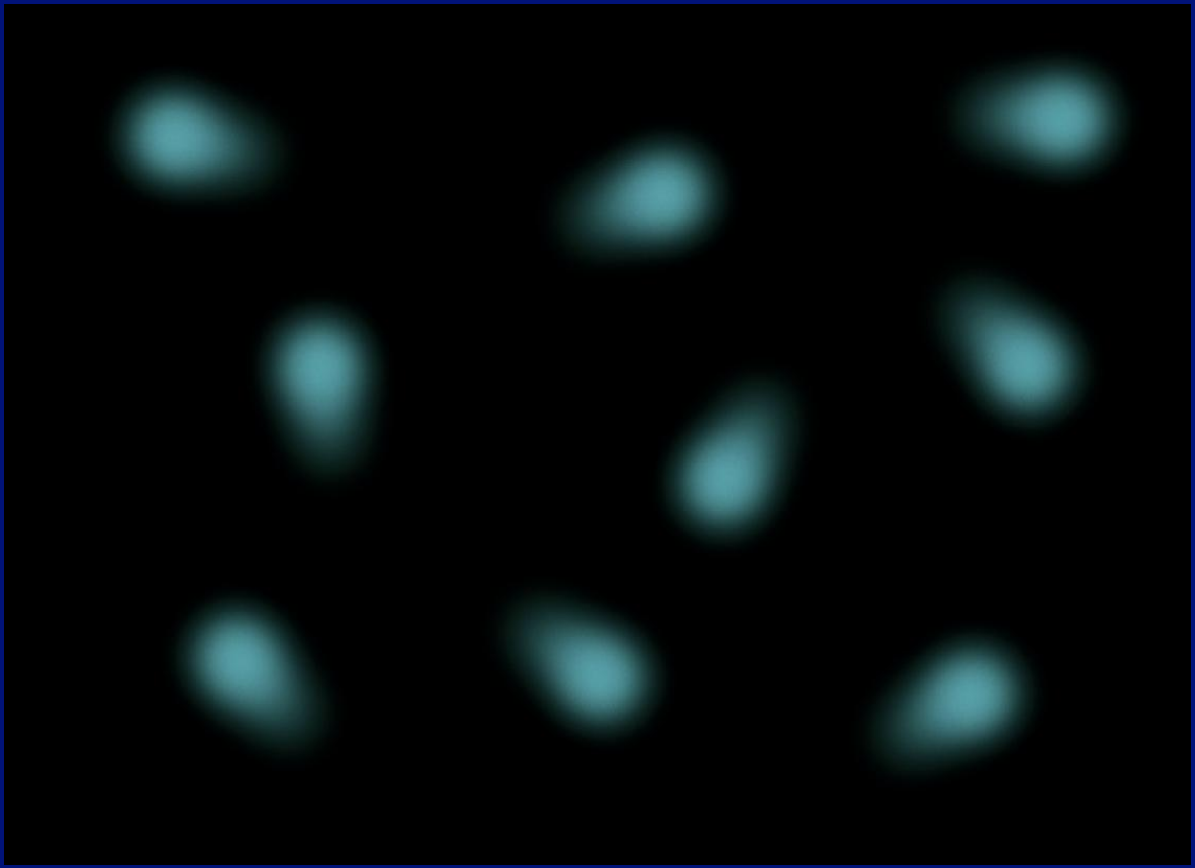
The topological Haldane model

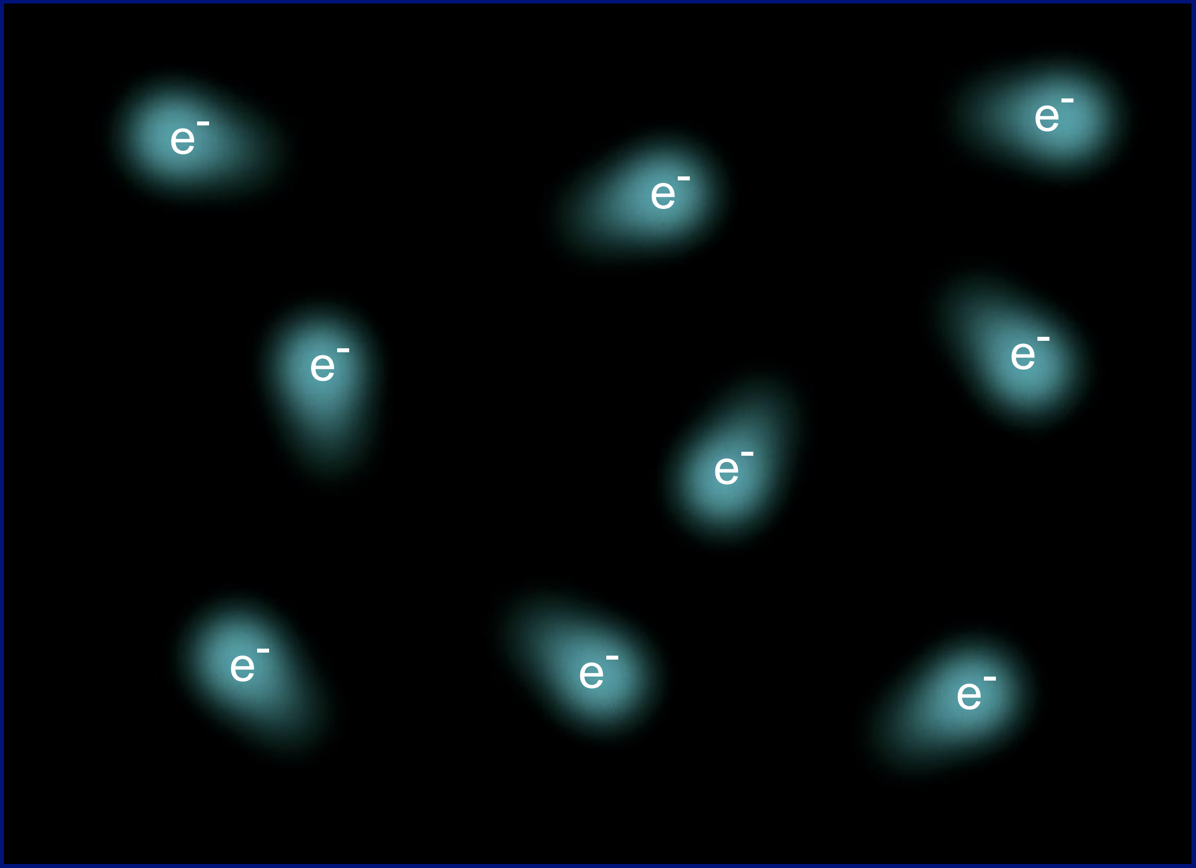
Tilman Esslinger   ETH Zürich

- Haldane model
- Update on anti-ferromagnetic correlations
- Quantized conductance

Funding: ETH, EU (ERCadv SQMS, SIQS, TherMiQ), NCCR QSIT, SNF

www.quantumoptics.ethz.ch

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Metals Insulators

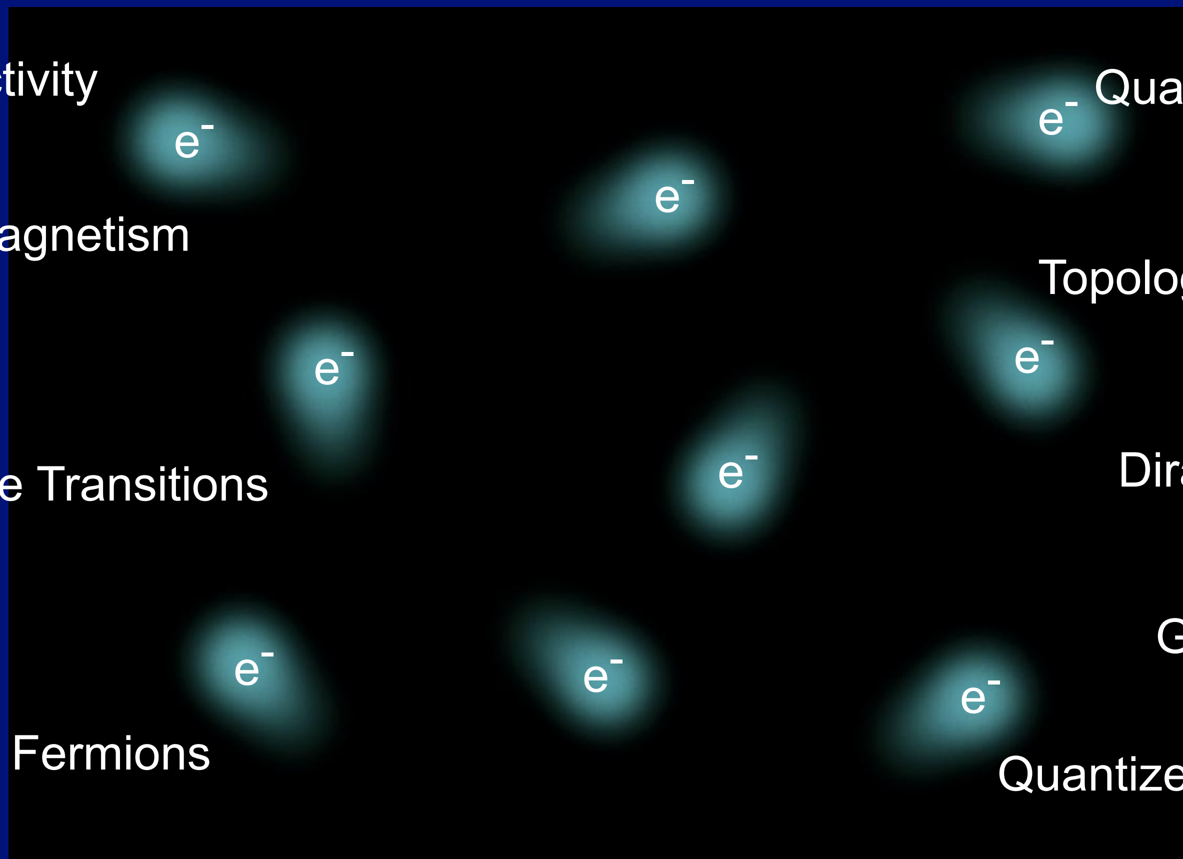
Superconductivity

Quantum Magnetism

Quantum Phase Transitions

Majorana Fermions

High Tc



Quantum Hall Effect

Topological Insulators

Dirac Fermions

Graphene

Quantized Conductance

Photovoltaic Quantum Hall effect

Why cold atoms?

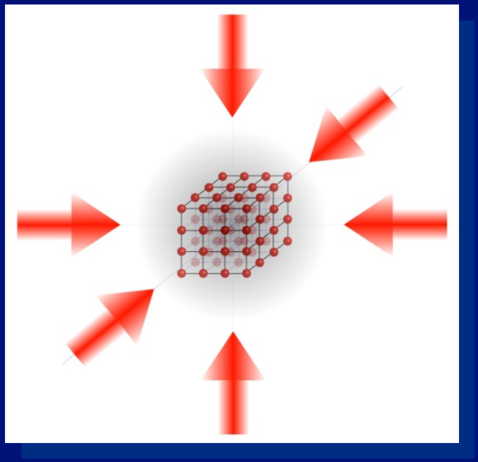
- Different approach
- New regimes
- Surprises

What can we do?

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

Building the Hamiltonian

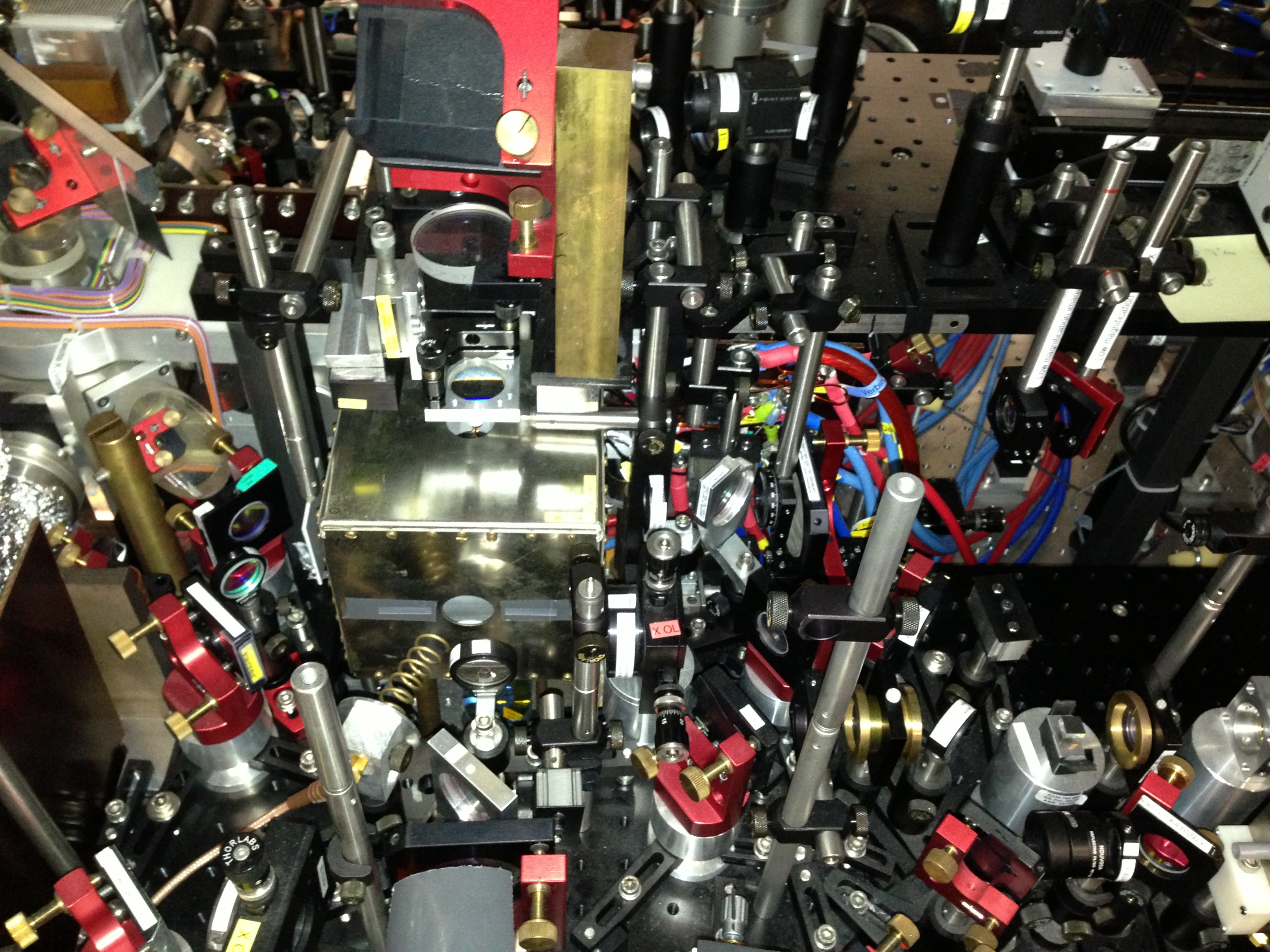
+



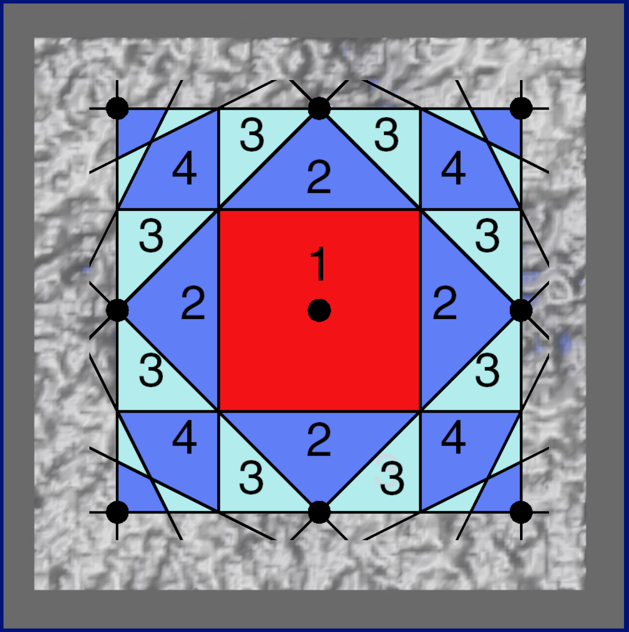
Quantum Gases (^{40}K)

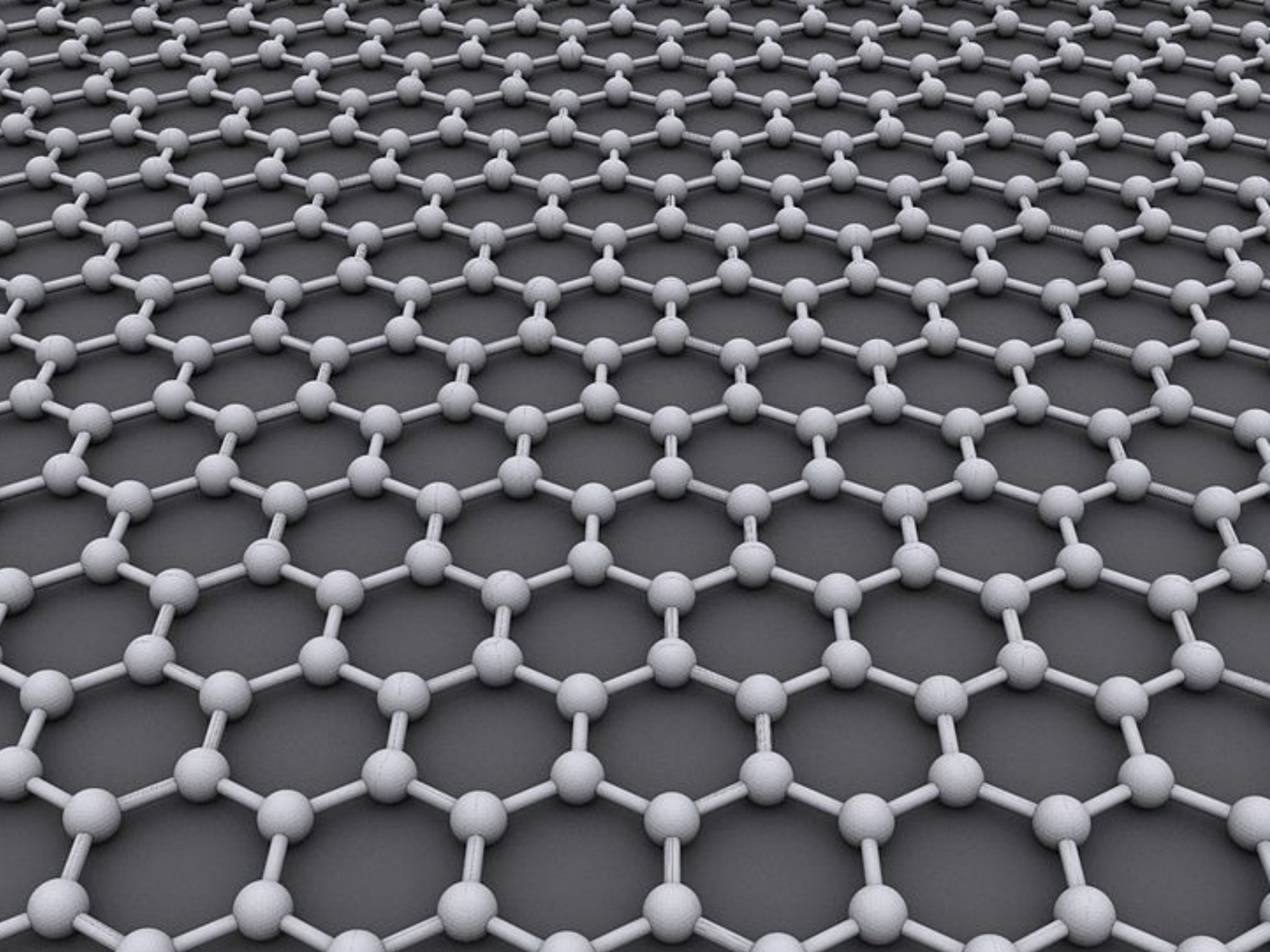
Optical Lattices

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


X OL
THORLABS

Measuring

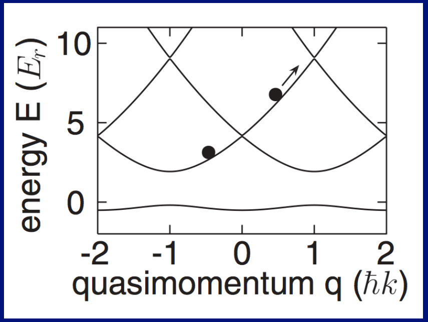




Bose gases in lattices with topological defects

BEC in Excited bands:

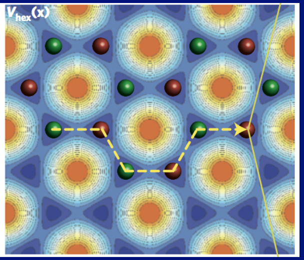
- 1D « Dirac point » (Weitz group, Bonn)
  S. Kling *et al.*, Phys. Rev. Lett. 105, 215301 (2010)
  T. Salger *et al.*, Phys. Rev. Lett. 107, 240401 (2011)



- Quadratic avoided band crossing (Hemmerich group, Hamburg)
  M. Ölschläger *et al.*, Phys. Rev. Lett. 108, 075302 (2012)

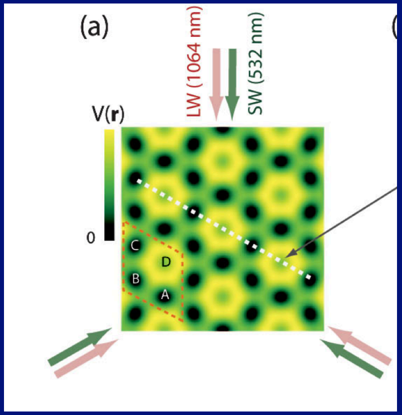
BEC in a Honeycomb lattice:

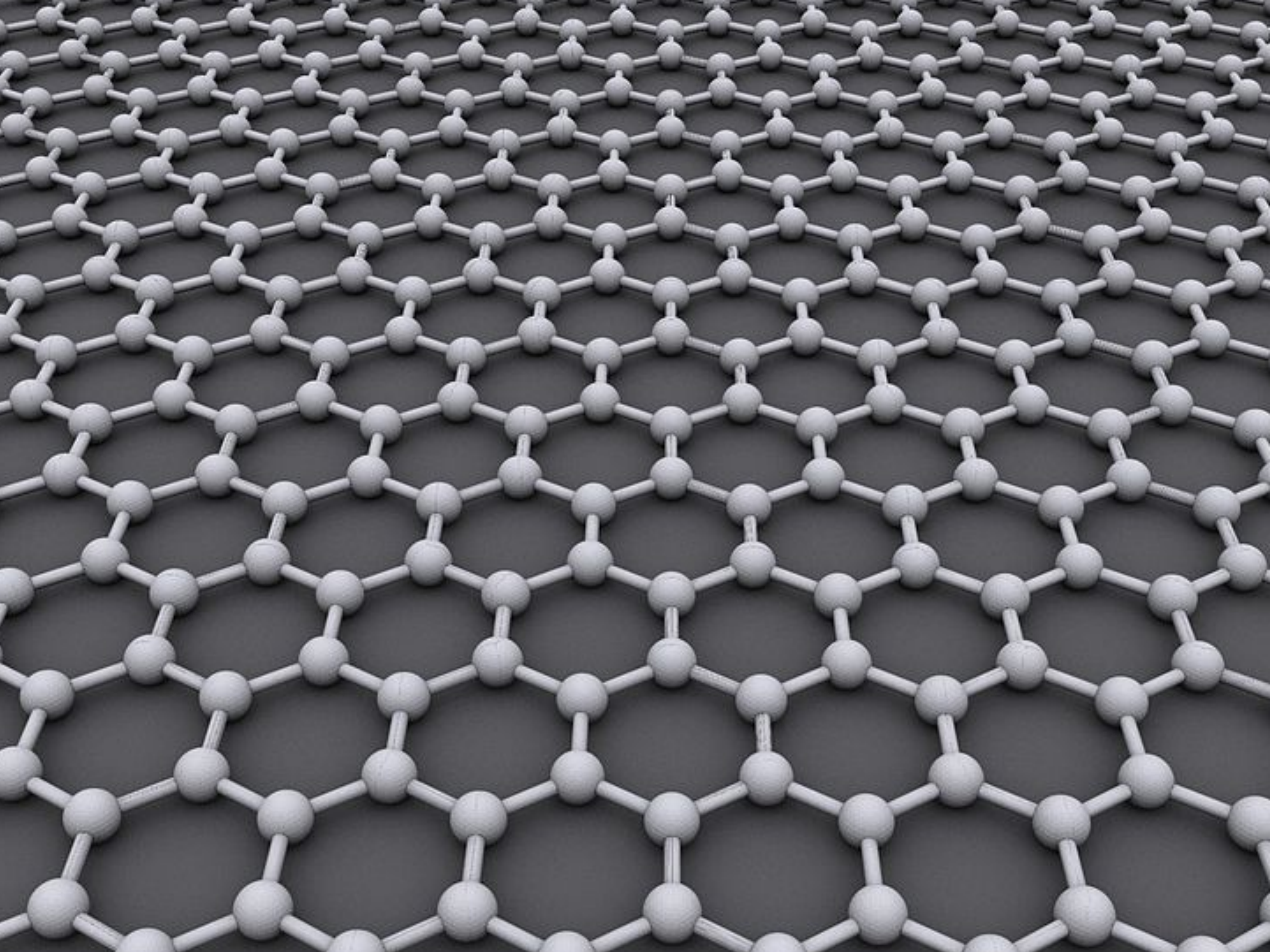
(Sengstock group, Hamburg)
P. Soltan-Panahi *et al.,* Nature Phys. 7, 434 (2011)
P. Soltan-Panahi *et al.*, Nature Phys. 8, 71 (2012)



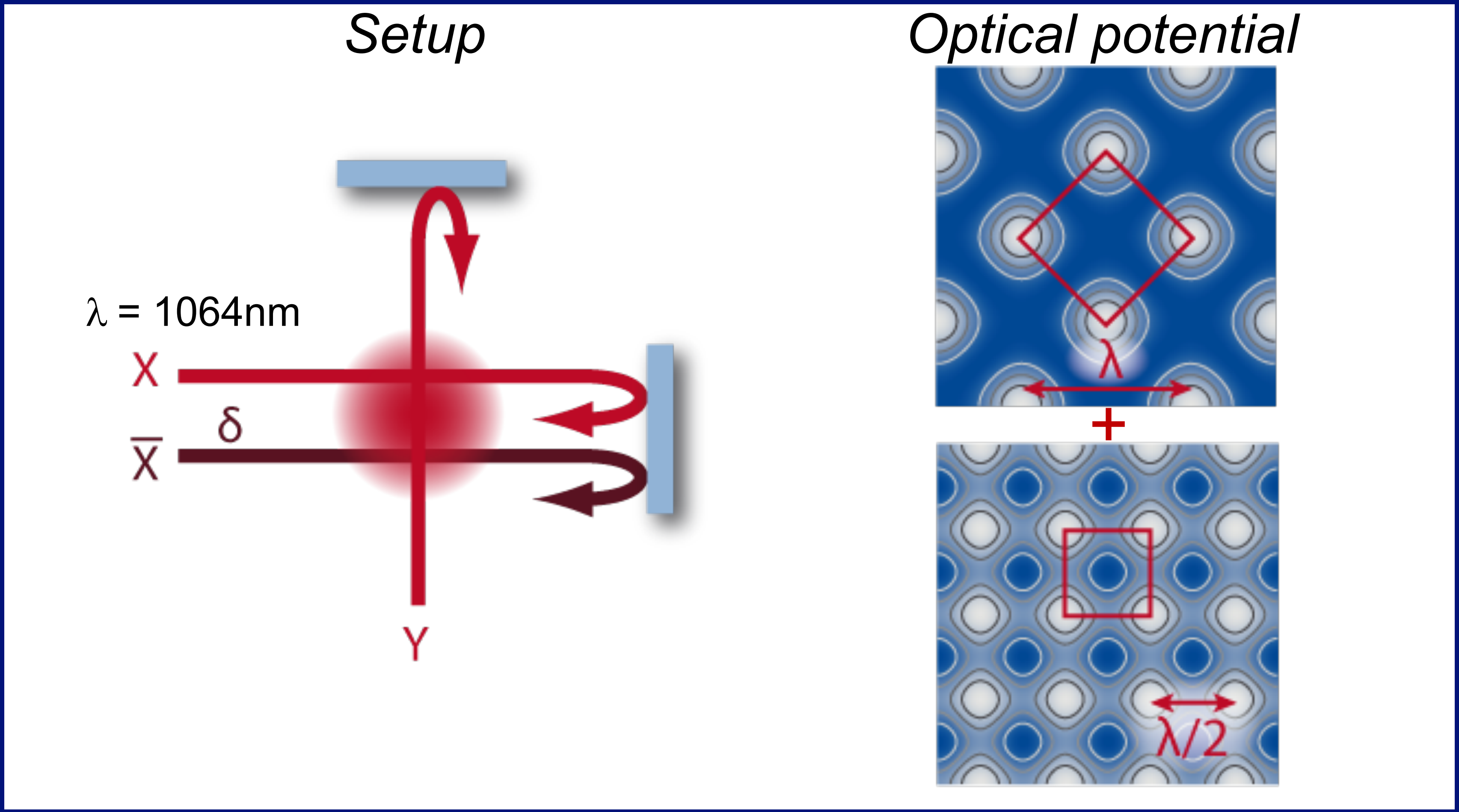
BEC in Kagome:

(Dan Stamper-Kurn, Berkeley)
G.B. Jo et al. Phys. Rev. Lett. 108, 045305 (2012)



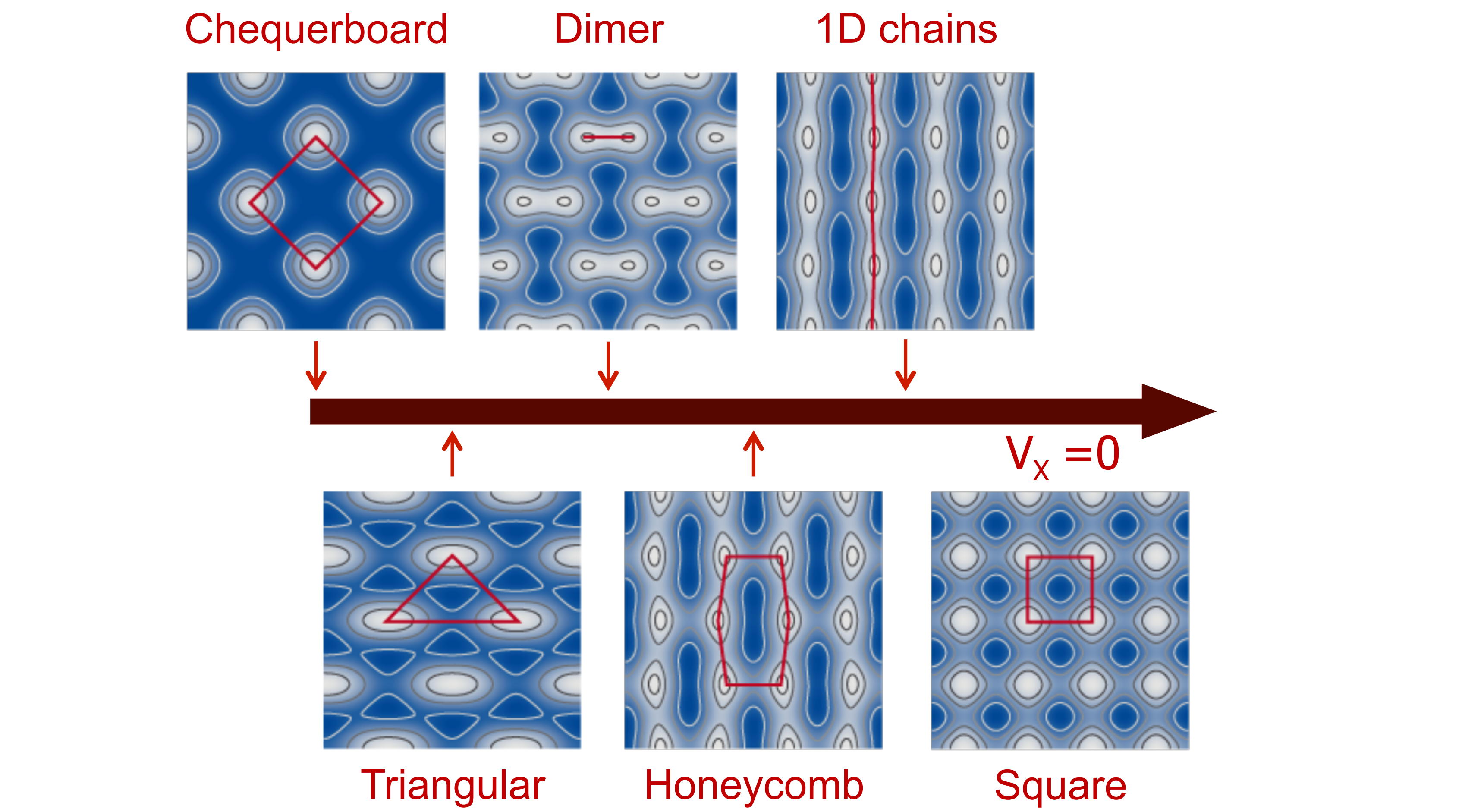


Tunable Geometry Optical Lattice

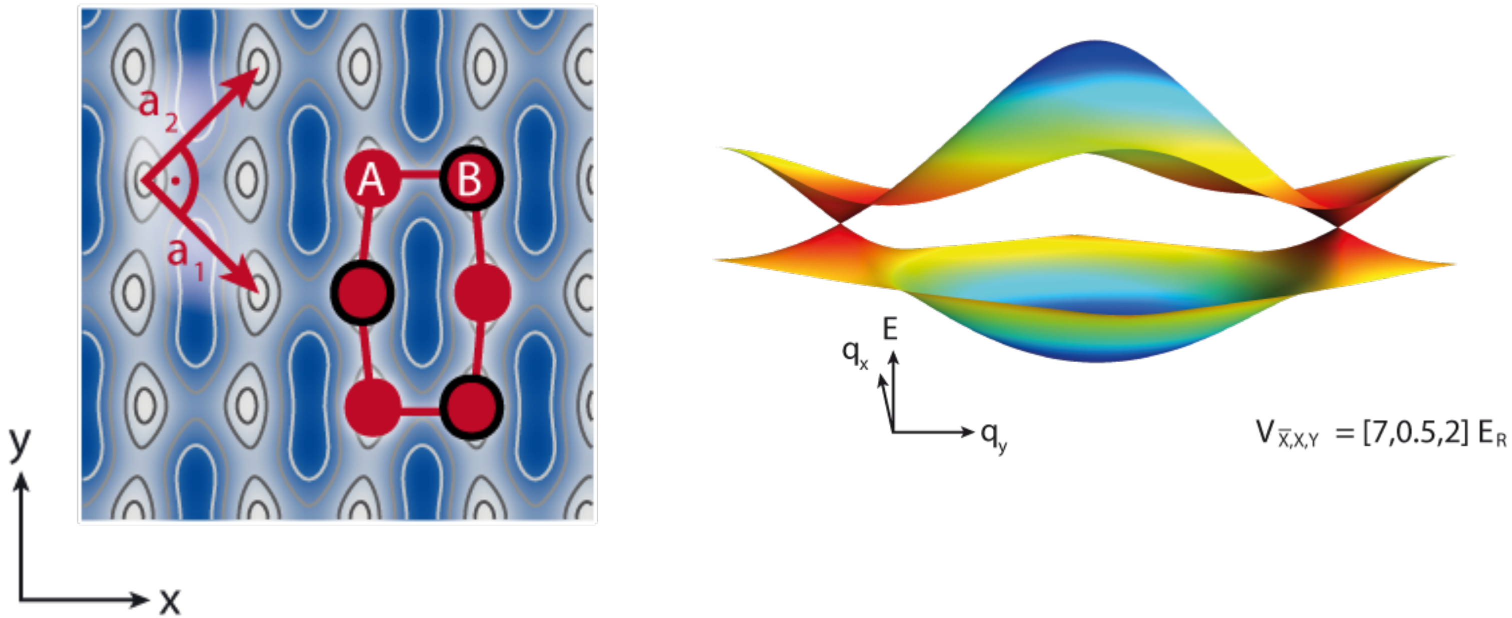


Other complex lattices: NIST, Munich, Hamburg, Berkeley

Tunable Geometry Optical Lattice



Honeycomb Lattice



Thanks to Dario Poletti

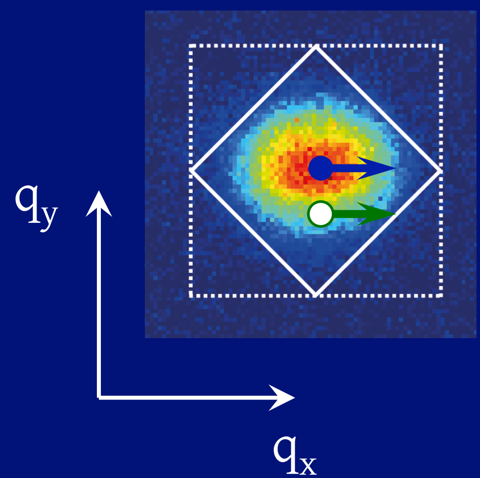
Probing the Dirac points

vanishing density of states

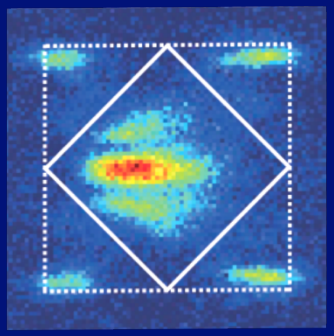
small energy scales

Bloch oscillation and interband transitions

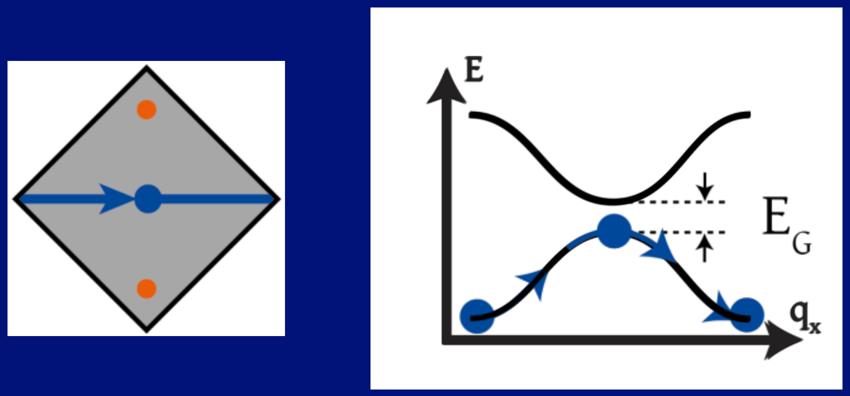
Starting point

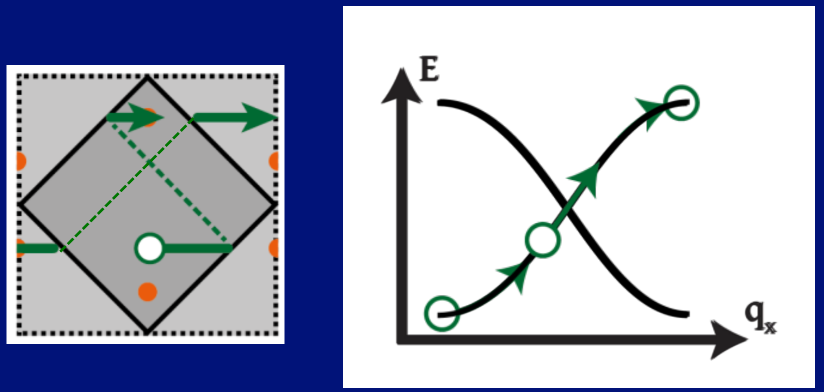


+ magnetic gradient



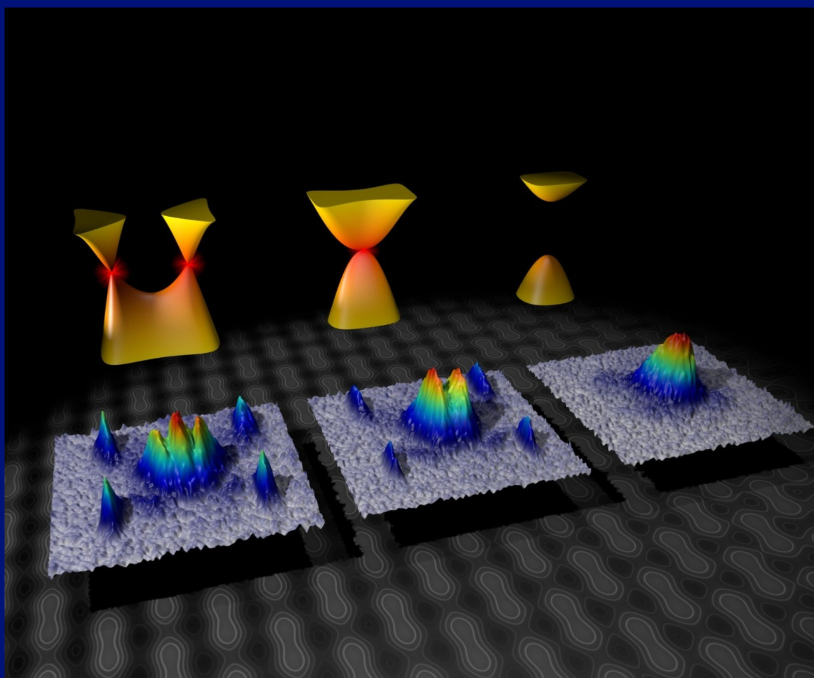
Transfer to 2nd band

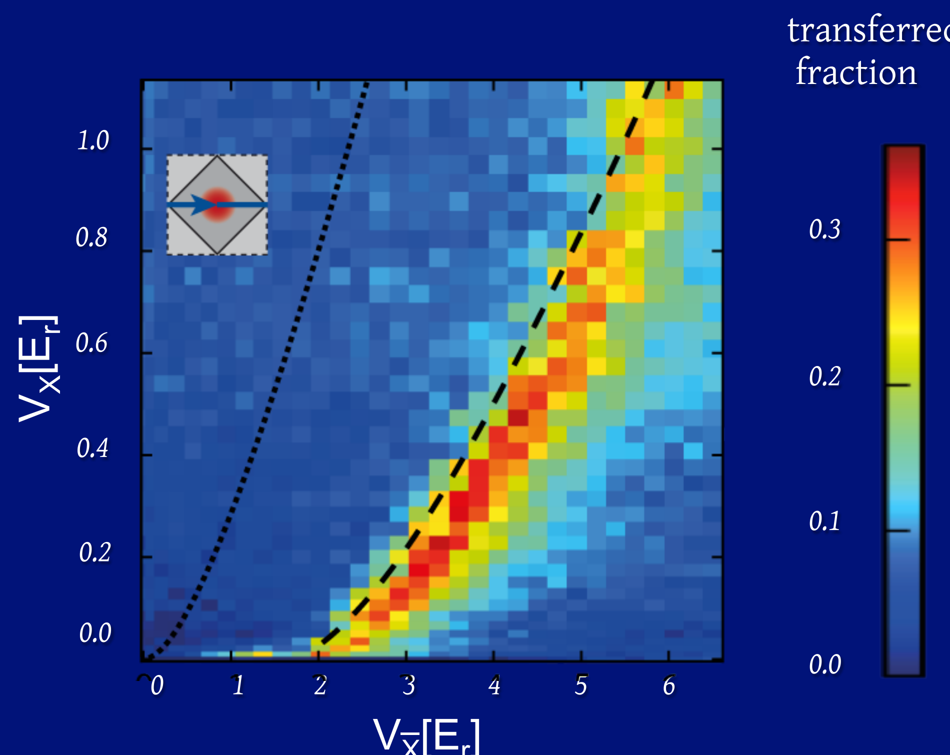


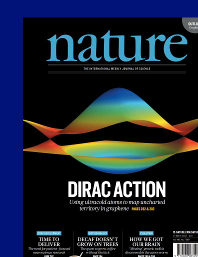


Method in 1D: T. Salger et. al, Phys. Rev. Lett. 99, 190405 (2007)

Merging and annihilating Dirac points

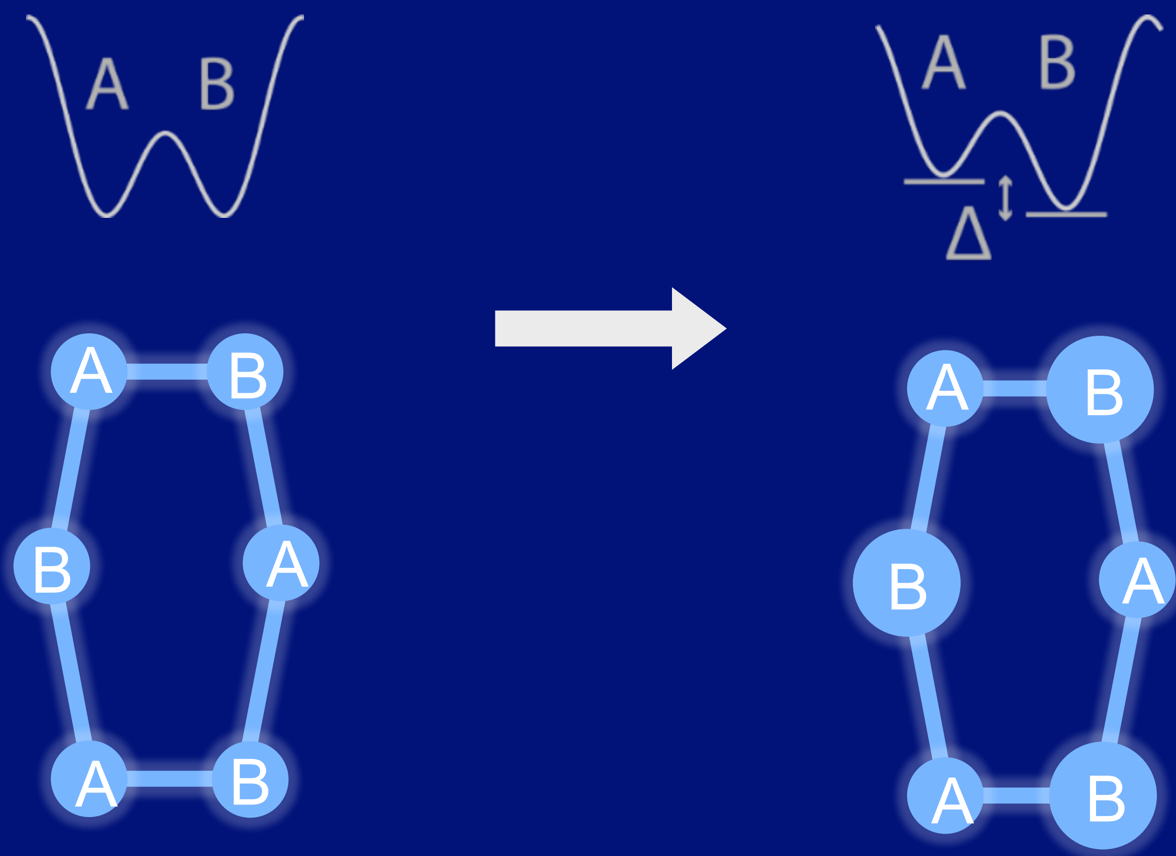




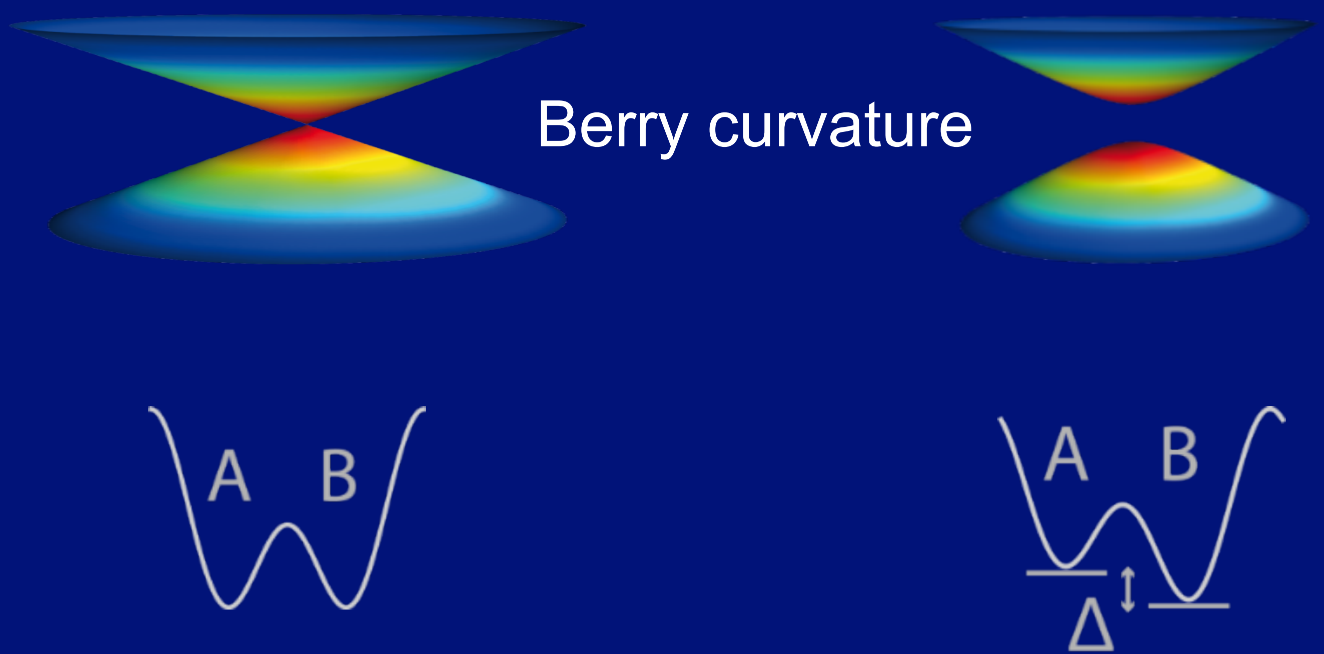


L. Tarruell, D. Greif, T. Uehlinger, G. Jotzu, and T. Esslinger, Nature 483, 302–305 (2012).
K. K. Gomes, W. Mar, W. Ko, F. Guinea & H. C. Manoharan, Nature 483, 306–310 (2012).
See also: L.-K. Lim, J.-N. Fuchs, G. Montambaux, PRL 108, 175303 (2012)

Breaking Inversion Symmertry

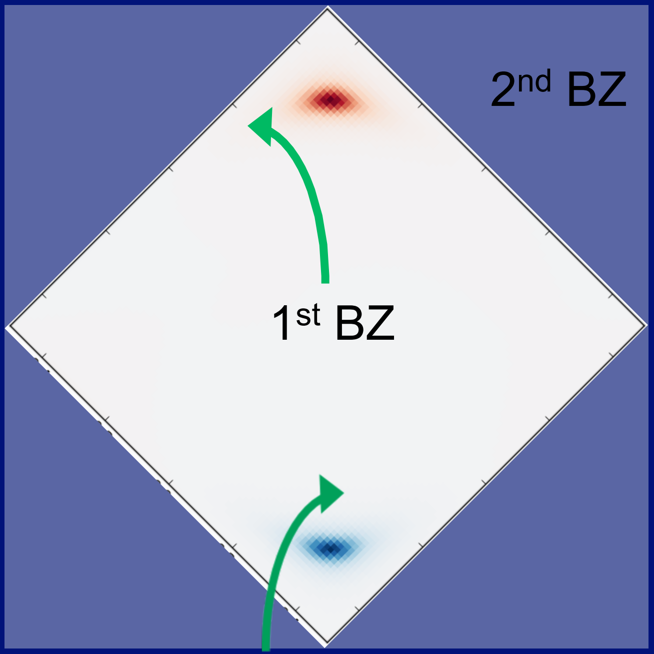


Breaking Inversion Symmertry



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

Berry Curvature and Transverse Drift

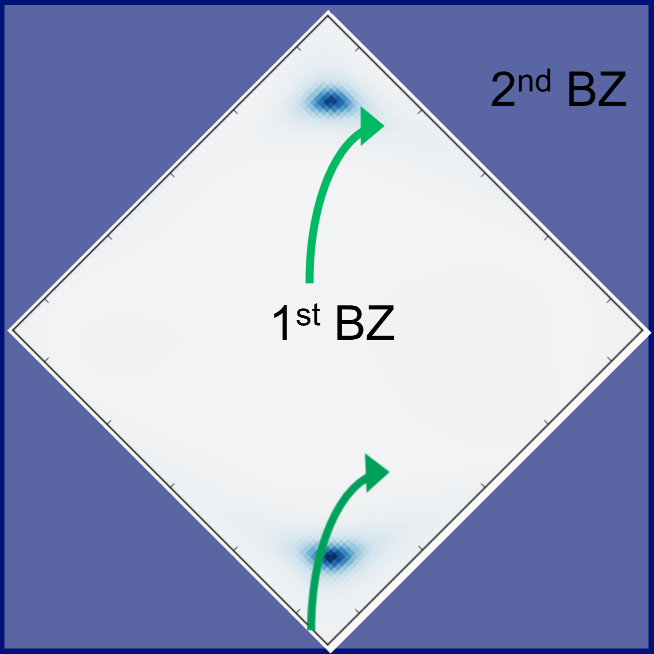


$$\dot{\boldsymbol{r}} = \frac{1}{\hbar}\partial_{\boldsymbol{k}}\epsilon(\boldsymbol{k}) - \dot{\boldsymbol{k}} \times \boldsymbol{\Omega}(\boldsymbol{k})$$

$$\hbar\dot{\boldsymbol{k}} = \boldsymbol{F}(\boldsymbol{r})$$

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

Berry Curvature and Transverse Drift



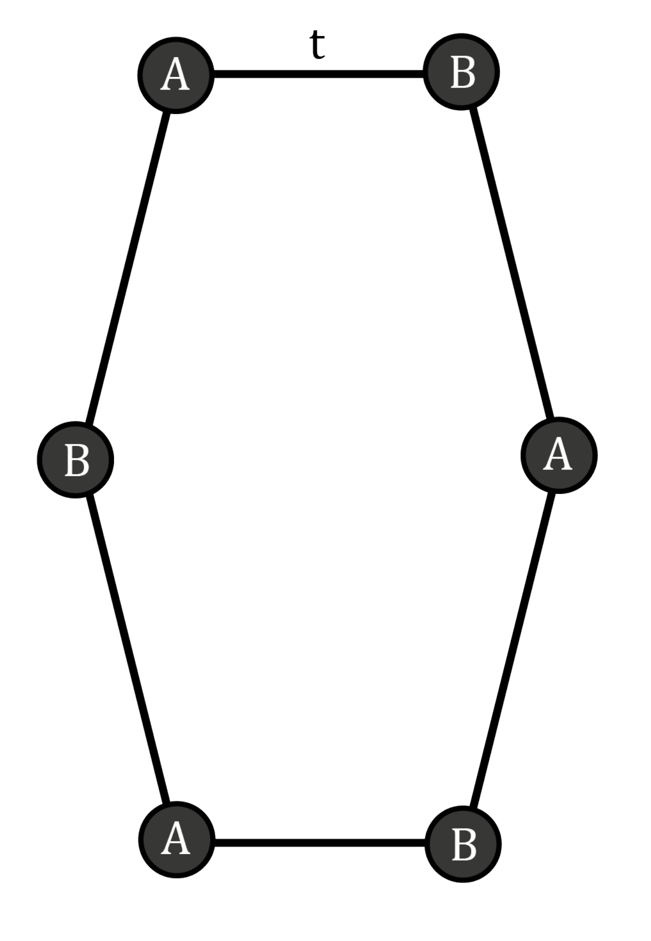
Like a Hall current

Topological Haldane model

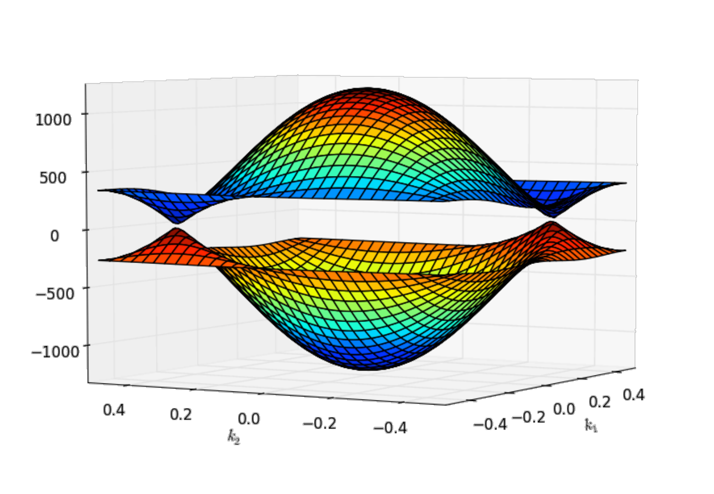
Proposal for Quantum Hall Effect *without* magnetic field!

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

Topological Haldane model

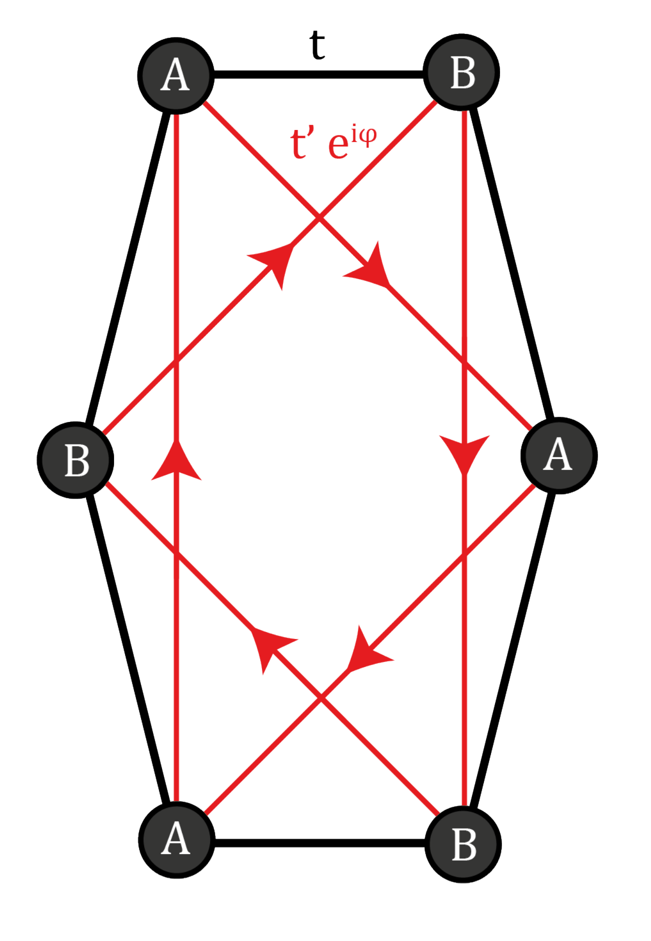


Start from a honeycomb lattice

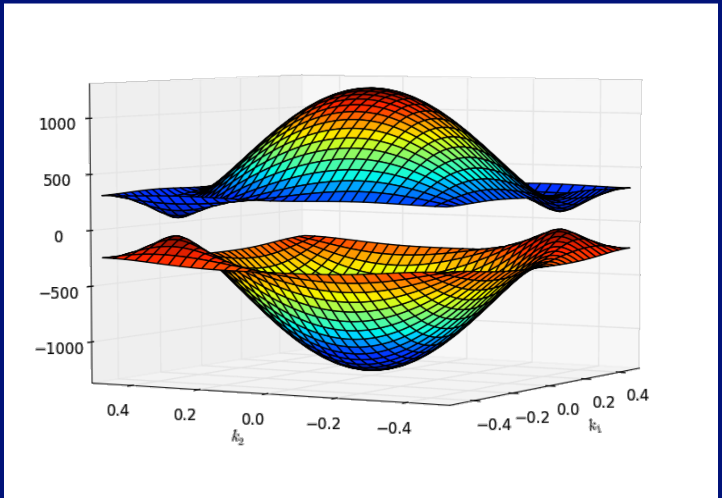


inversion and time-reversal symmertry

Topological Haldane model

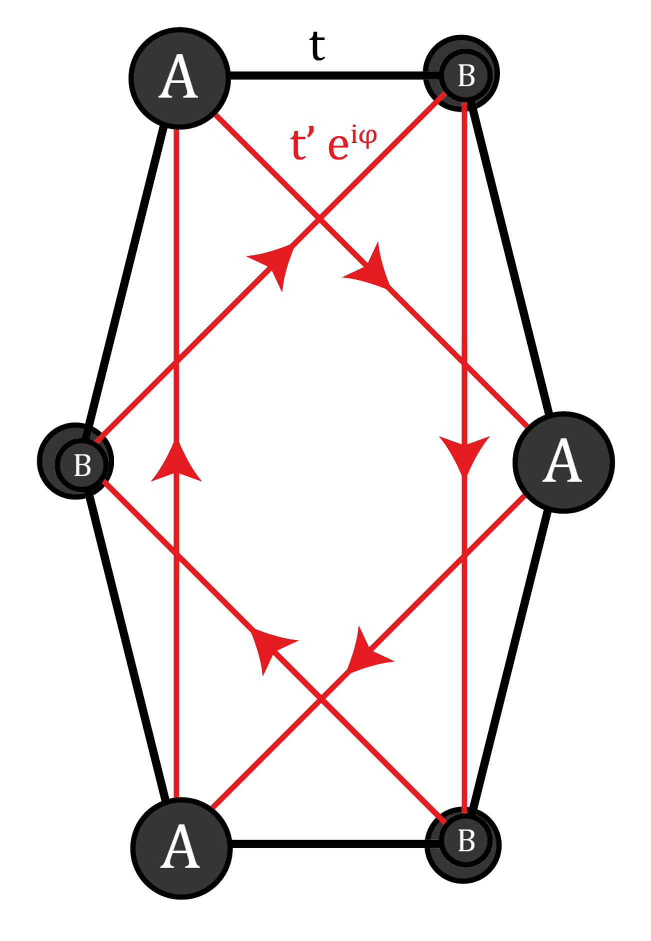


break time-reversal symmetry with complex next-nearest neighbour tunnellings

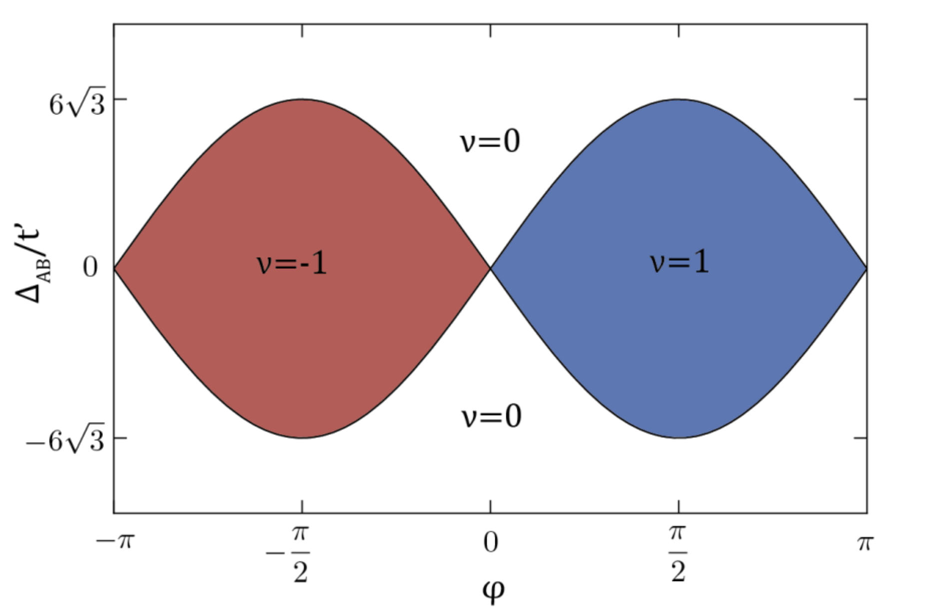


➔ Topological Chern insulator, with non-zero Hall conductance

Topological Haldane model

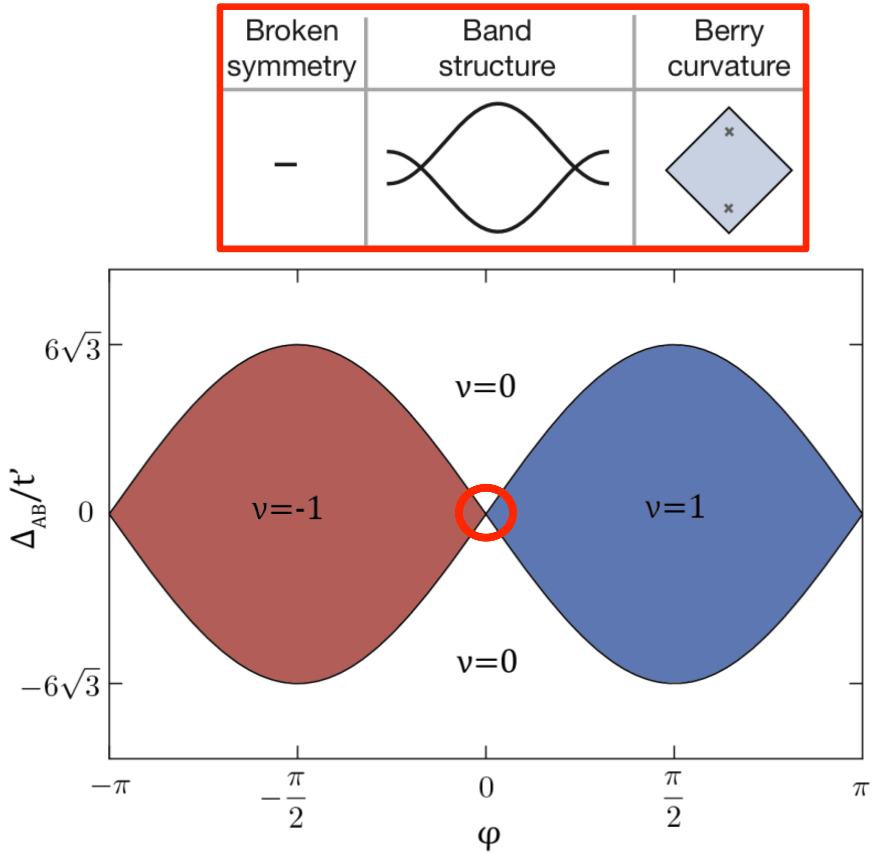


Additionally break time-reversal symmetry with energy offset



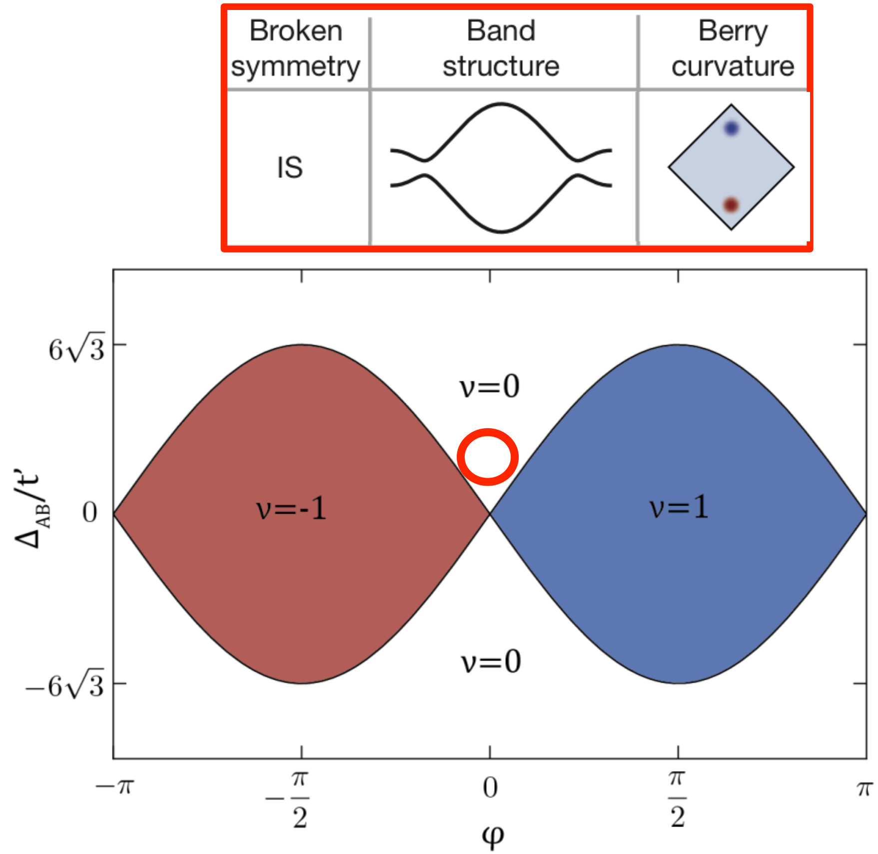
➔ Distinct topological phases

Topological Haldane model



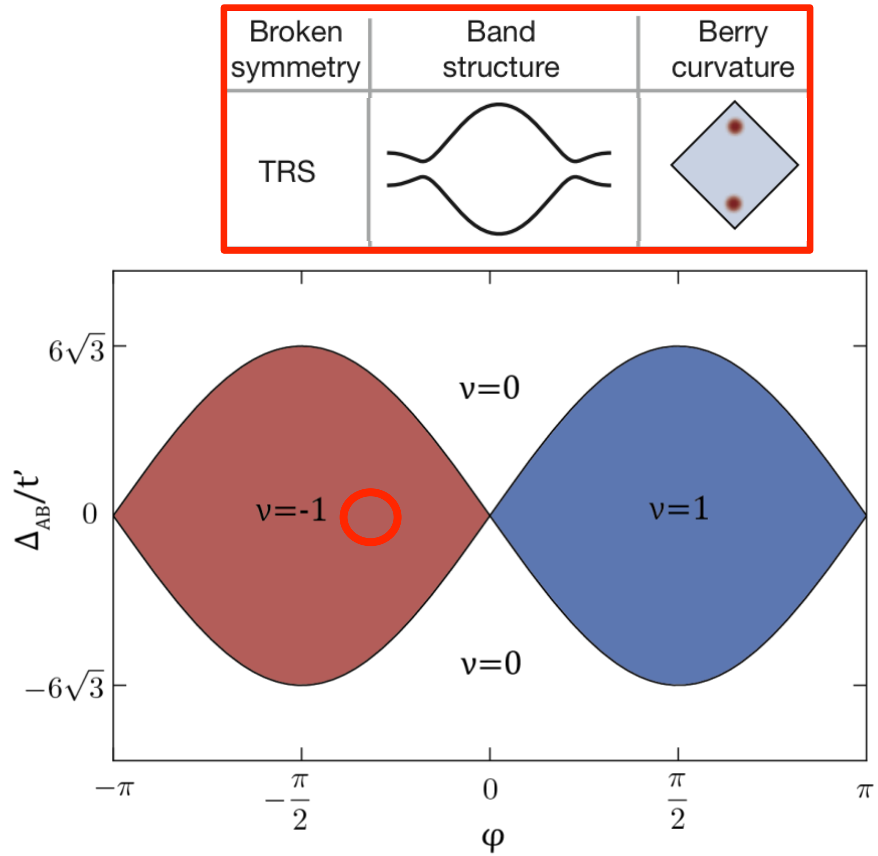
Haldane, PRL **61**,2015-2018 (1988)

Topological Haldane model



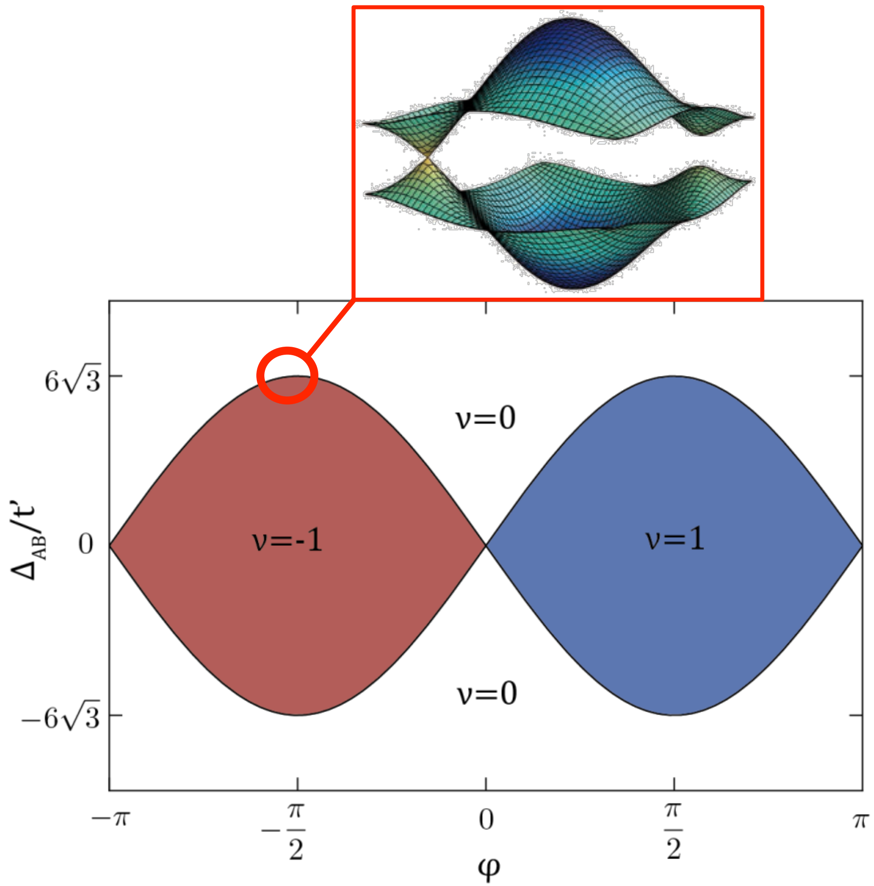
Haldane, PRL **61**,2015-2018 (1988)

Topological Haldane model



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

Topological Haldane model



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.

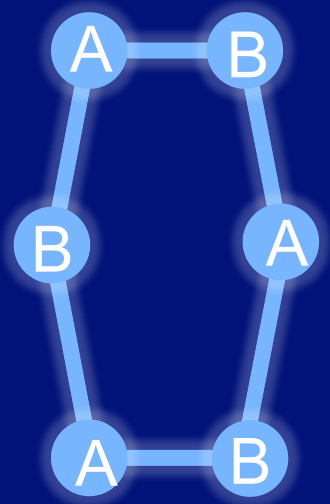
Haldane, PRL **61**,2015-2018 (1988)

Breaking time-reversal symmetry

Proposal for Photovoltaic Hall effect in graphene

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

Breaking time-reversal symmetry

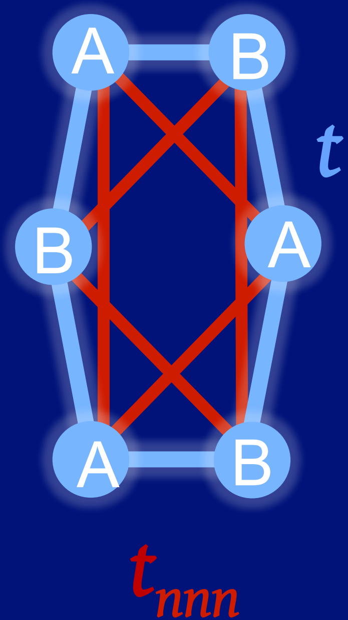


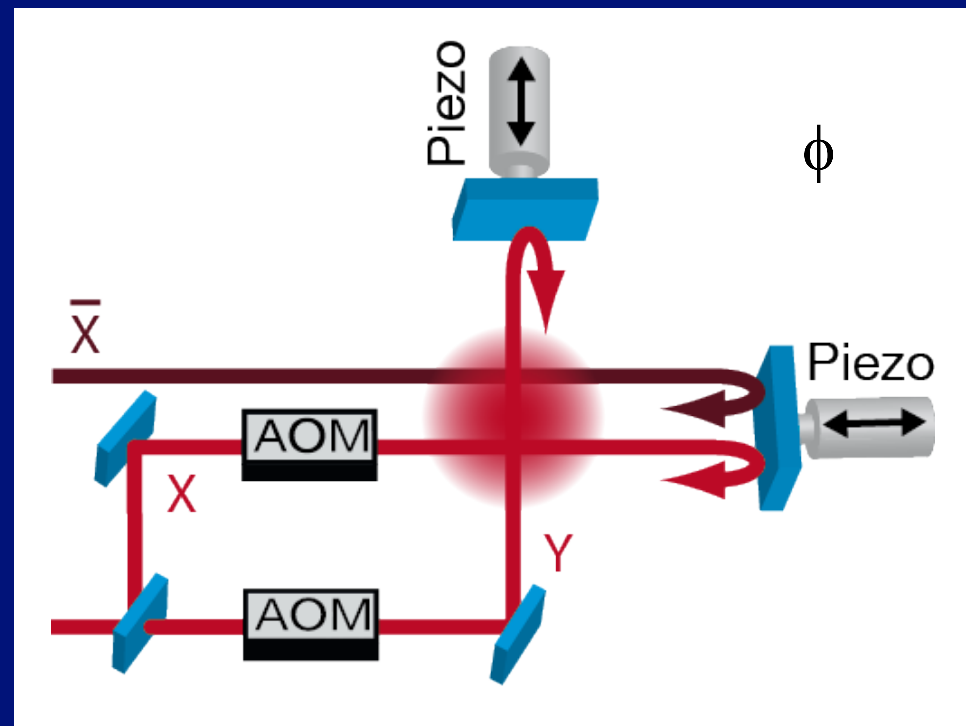
Other proposals to realize topological Hamiltonains:
T. Kitagawa et al., Phys. Rev. B 82, 235114 (2010)
P. Hauke et al., Phys. Rev. Lett 109, 145301 (2012)

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

Breaking time-reversal symmetry

Lattice Shaking

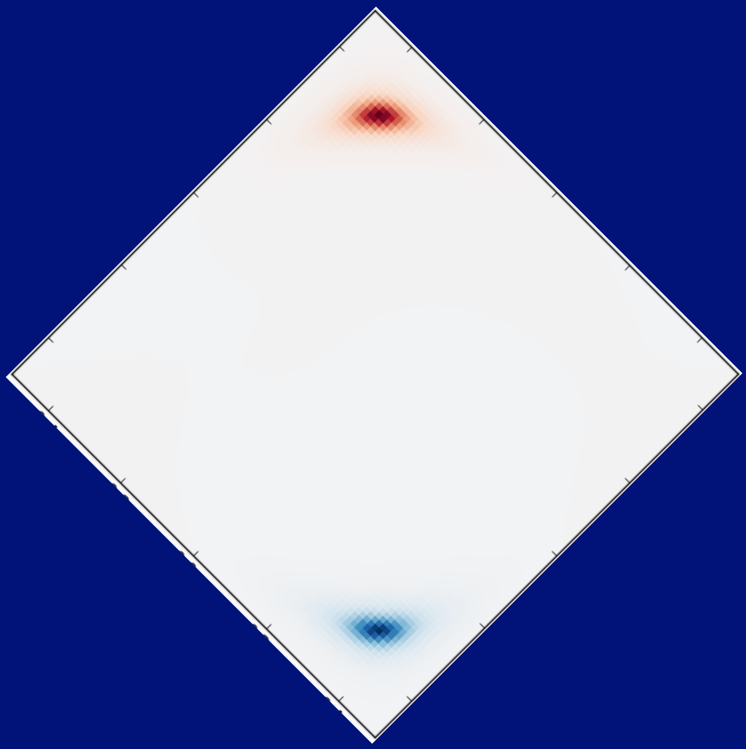




Lattice shaking: Pisa — Lignier, PRL **99**, 220403 (2007)
Hamburg/Barcelona — Struck, Science **333**, 996-9 (2011), PRL 108, 225304 (2012)
Chicago — Parker, Nat. Phys. **9**, 769-774 (2013)

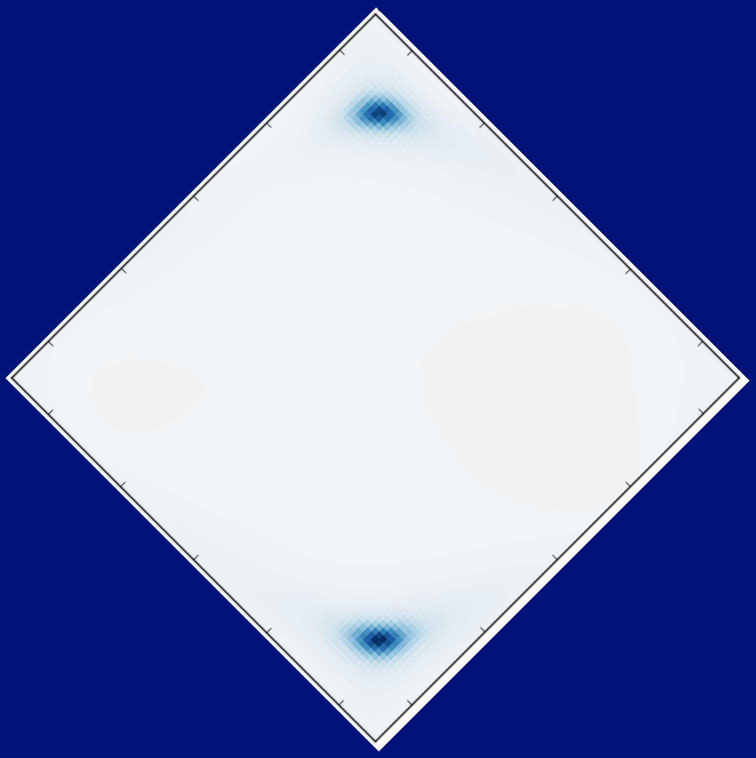
Berry Curvature

Trivial band insulator



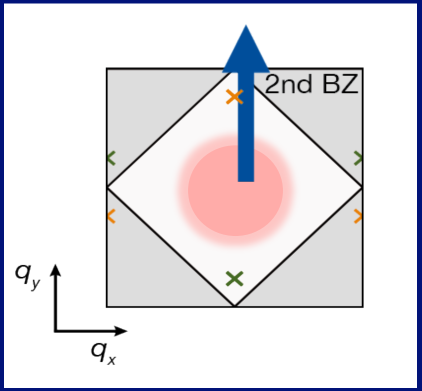
Chern number 0

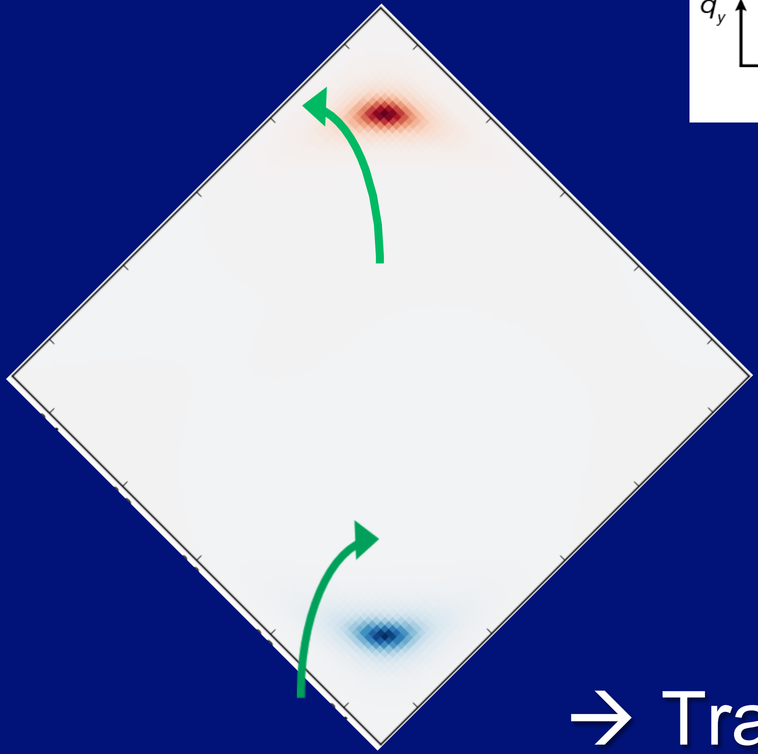
Chern insulator

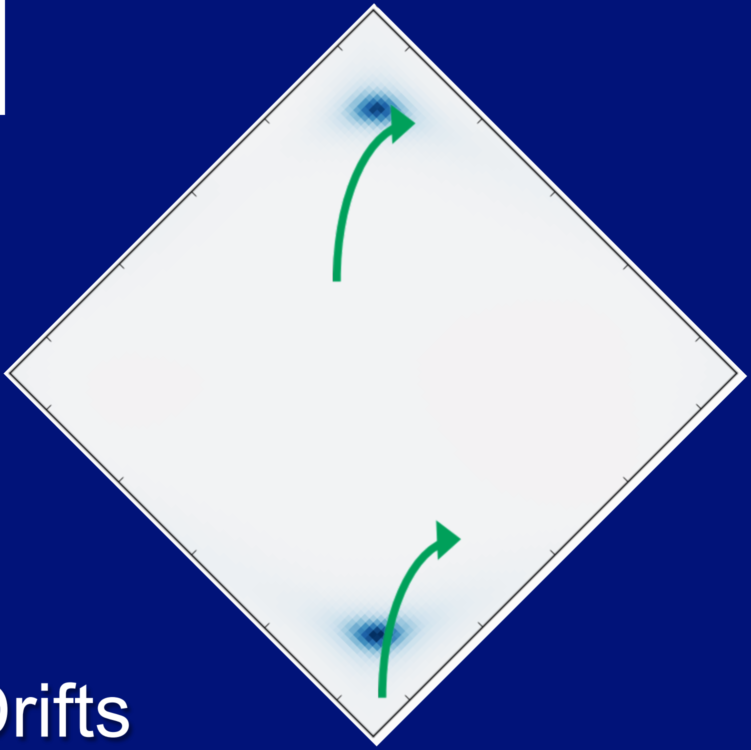


Chern number -1

Berry Curvature - Measurement

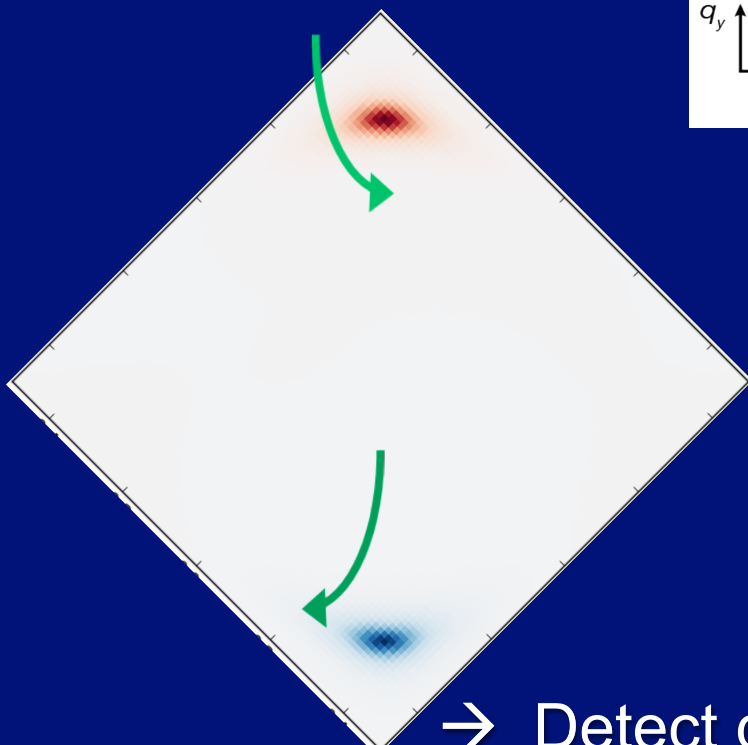


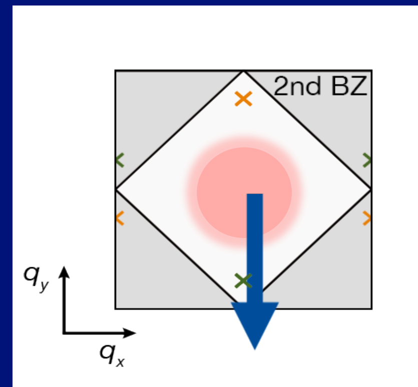


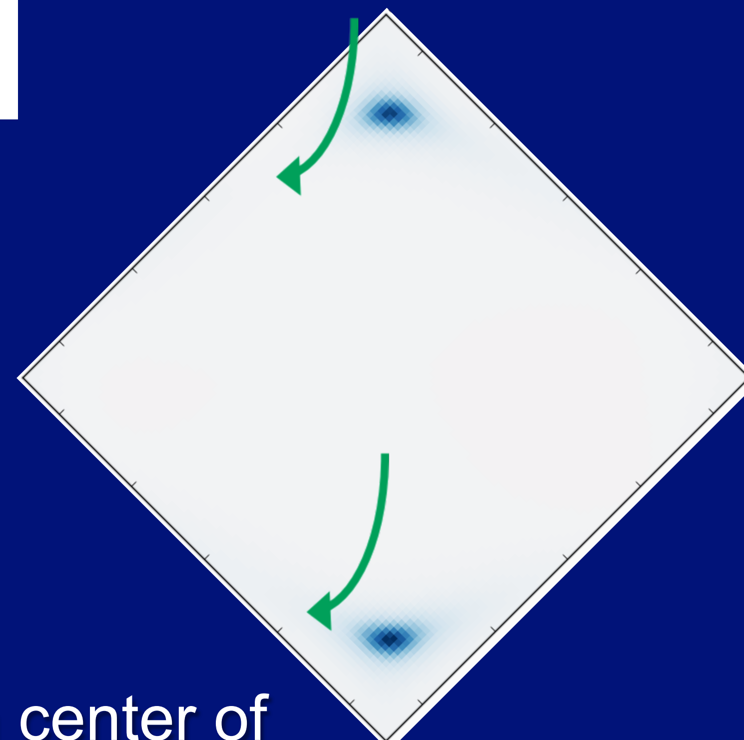


→ Transverse Drifts

Berry Curvature - Measurement



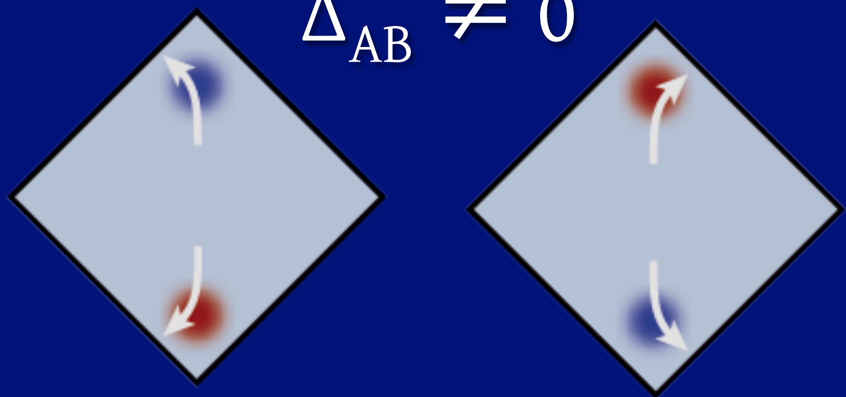




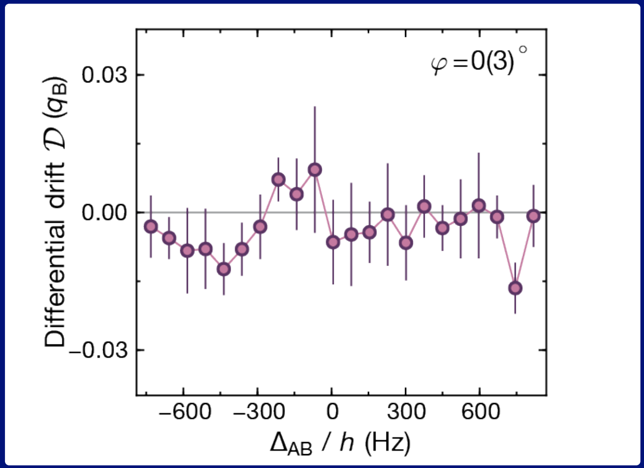
→ Detect difference in center of mass position after full Bloch cycle

Topological features of the system

$\Delta_{AB} \neq 0$

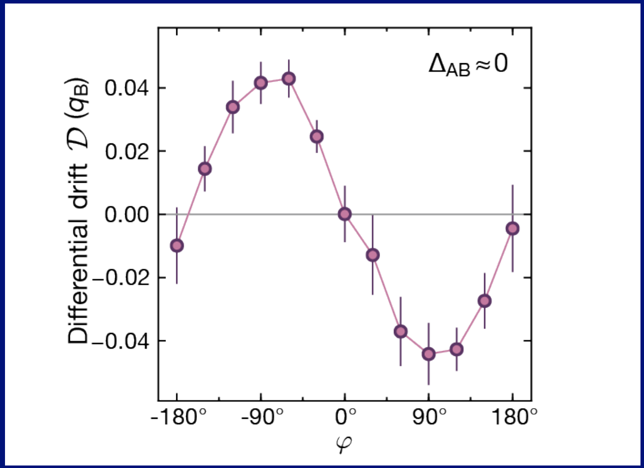


topologically trivial



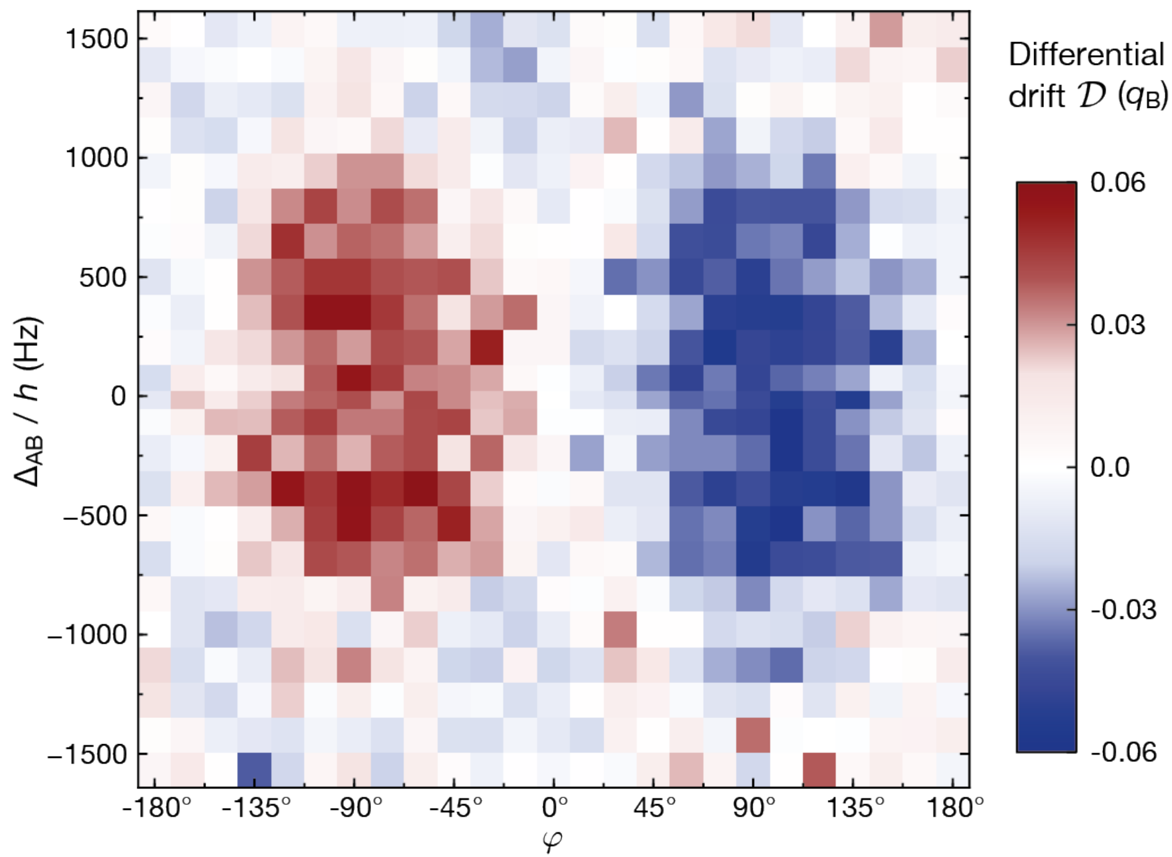
$\Delta_T \neq 0$

nonzero Chern number



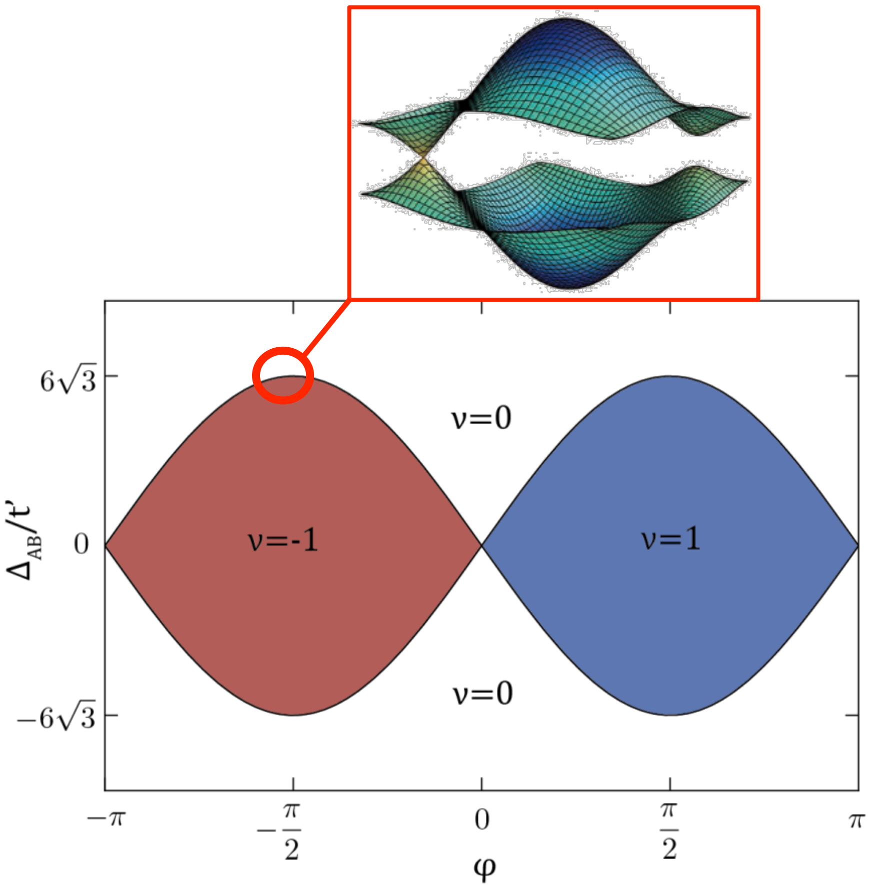
G. Jotzu, M. Messer, R. Desbuquois, M. Lebrat, T. Uehlinger, D. Greif, T. E., Nature 515, 237 (2014)

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



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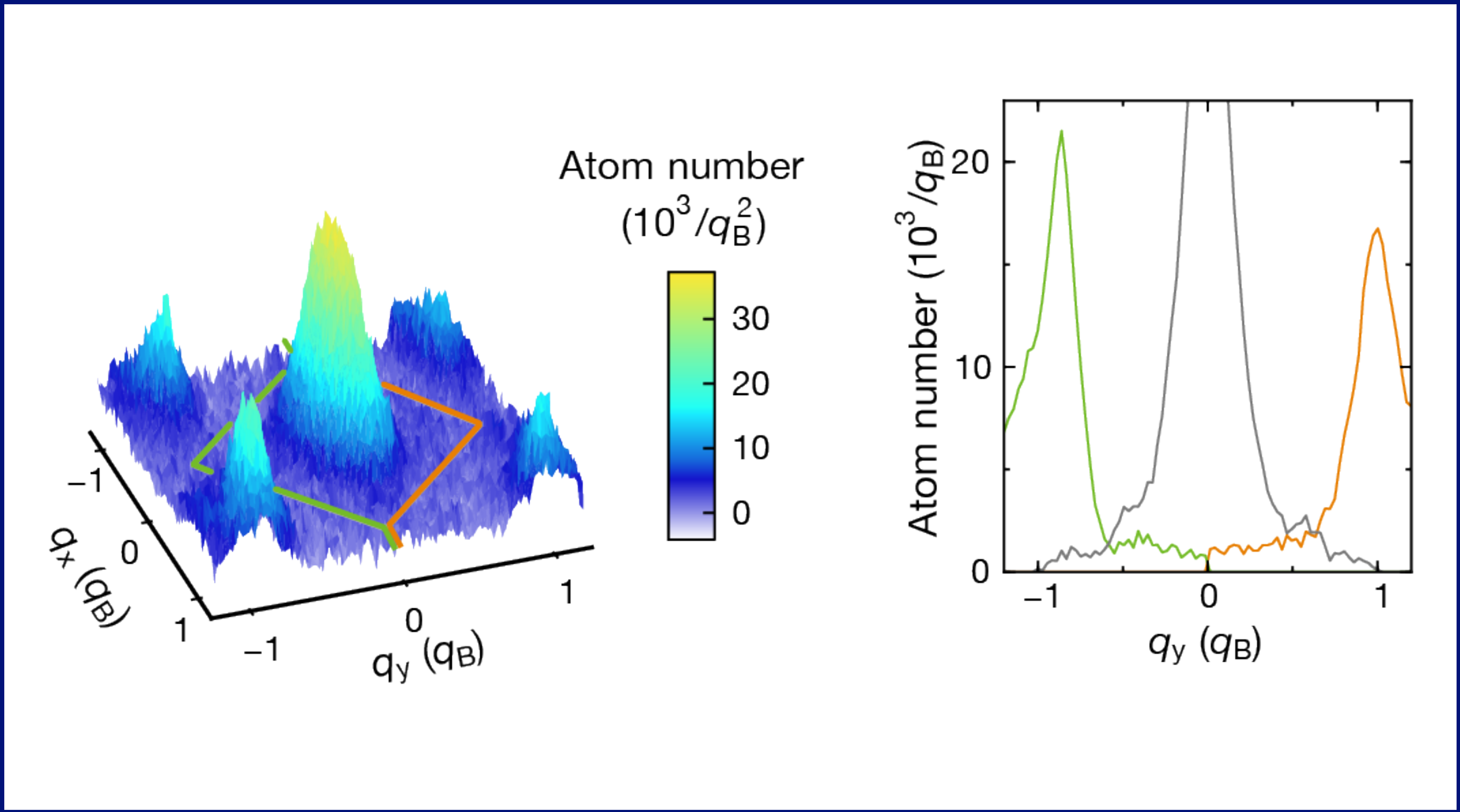

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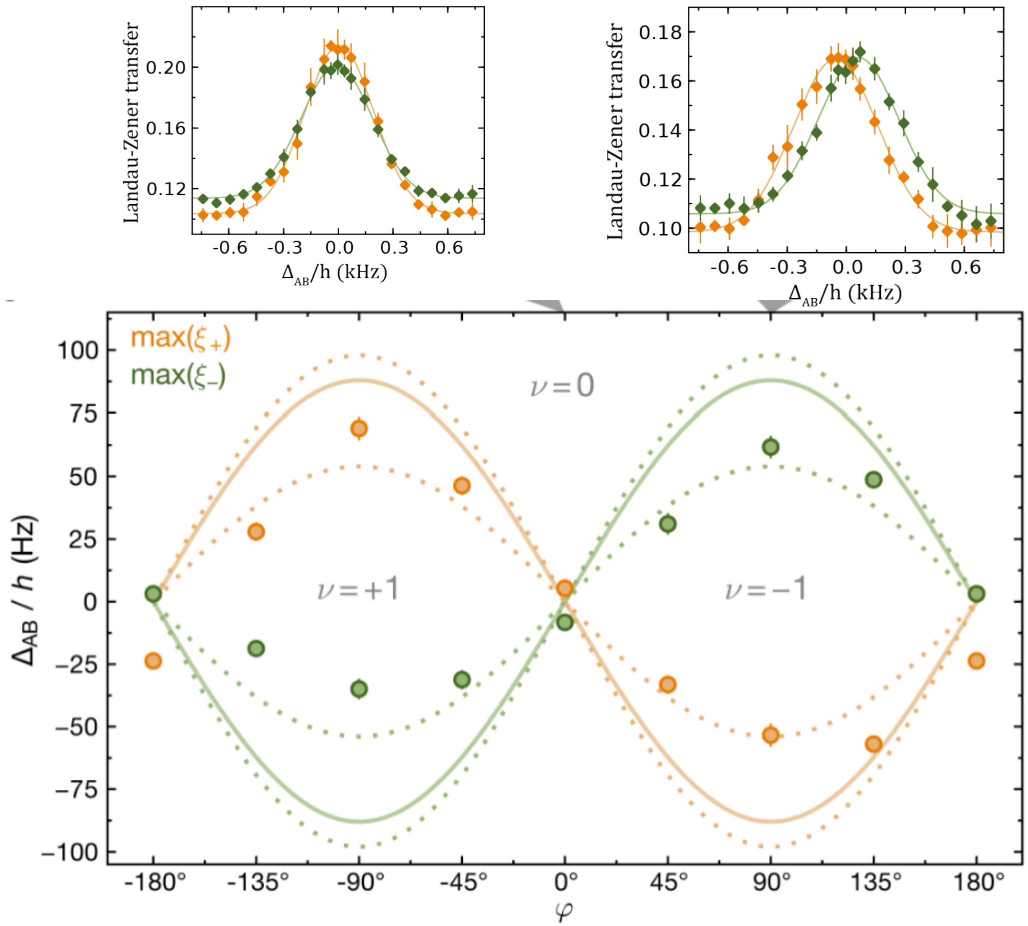


G. Jotzu, M. Messer, R. Desbuquois, M. Lebrat, T. Uehlinger, D. Greif, T. E., Nature 515, 237 (2014)

What about interactions?

Little is known

What about interactions?

Loaded interacting gas into
coupled layers of Haldene models

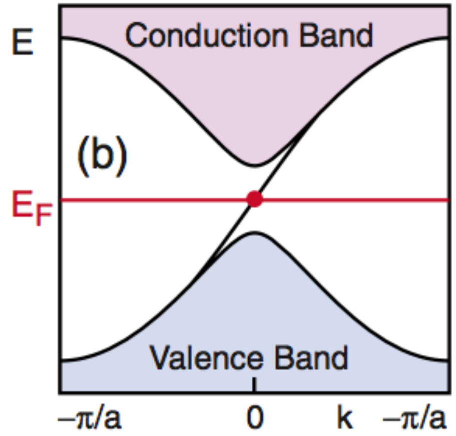
➔ Observed no significant heating

What about spin dependence?

What about spin dependence?

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

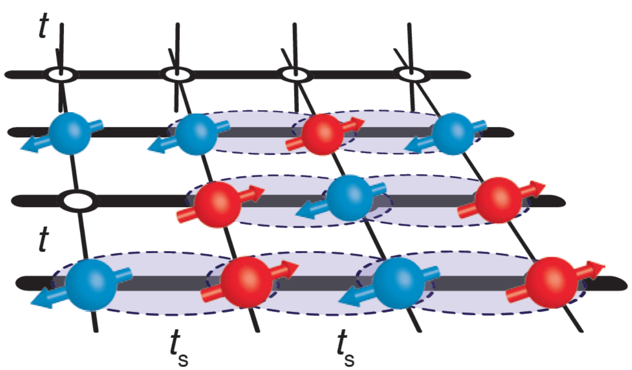
What about quantized edge currents?

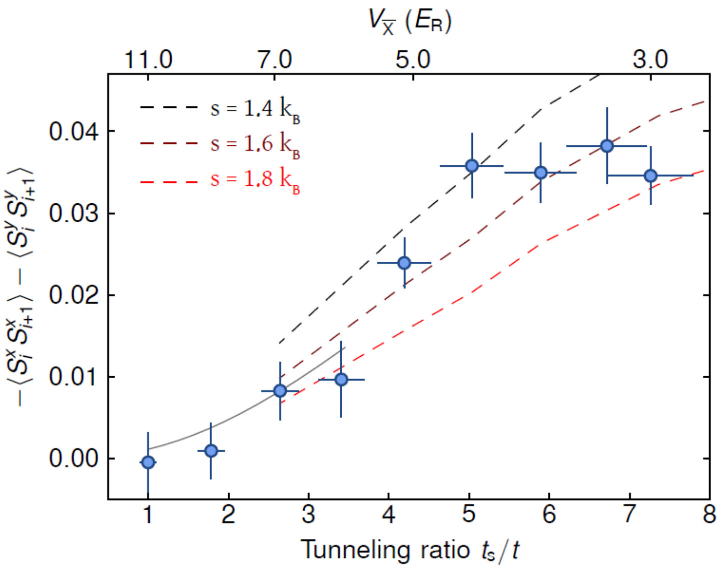


Hasan, Kane RMP 82, 3045 (2010)

Update on anti-ferromagnetic correlations

Antiferromagnetic correlations in the anisotropic Hubbard model

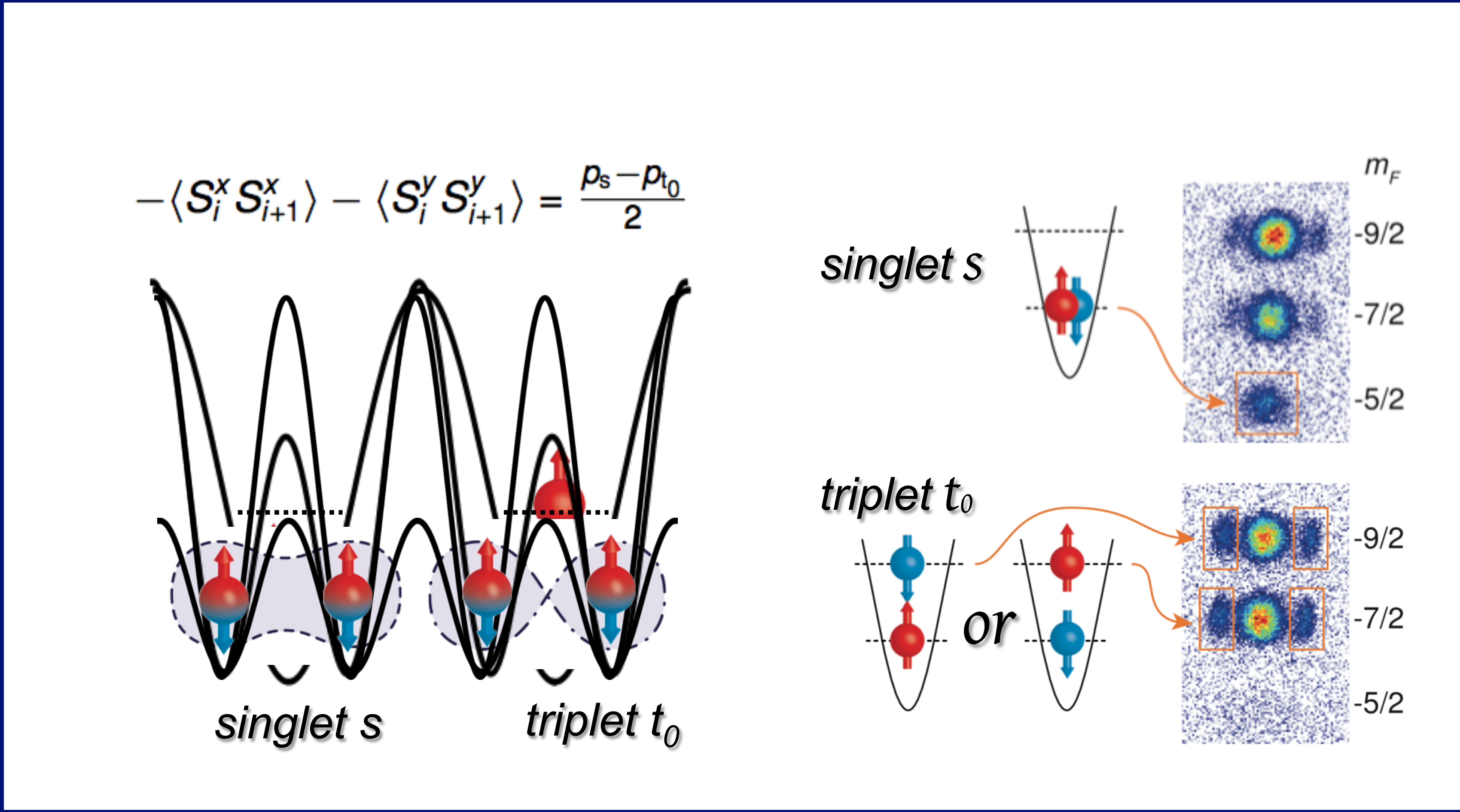




D. Greif , T. Uehlinger, G. Jotzu, L. Tarruell, T. Esslinger , Science 340, 6138 (2013)

J. Imriska et al., PRL 112, 115301 (2014), also: Hulet group, Nature (2015)

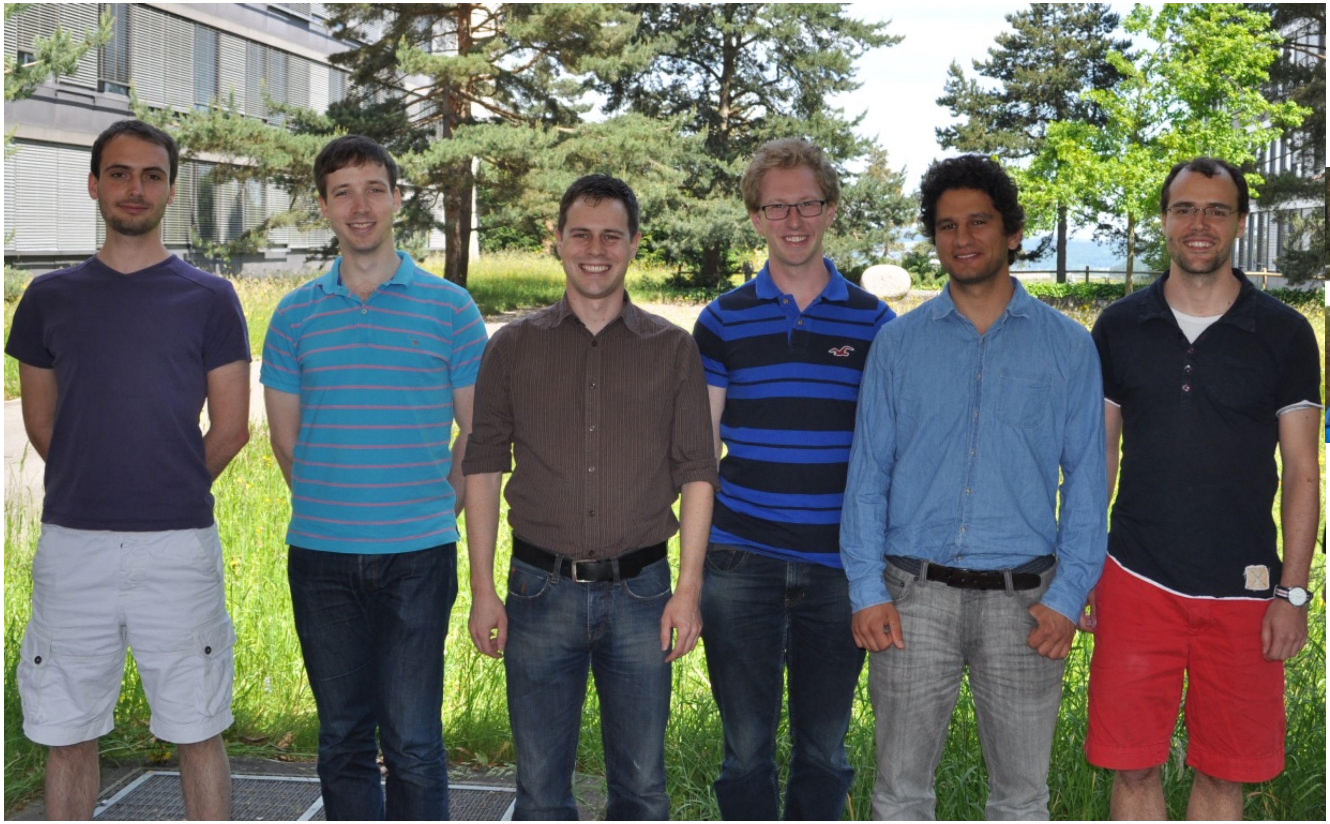
Detection protocol



D. Greif , T. Uehlinger, G. Jotzu, L. Tarruell, T. Esslinger , Science 340, 6138 (2013)

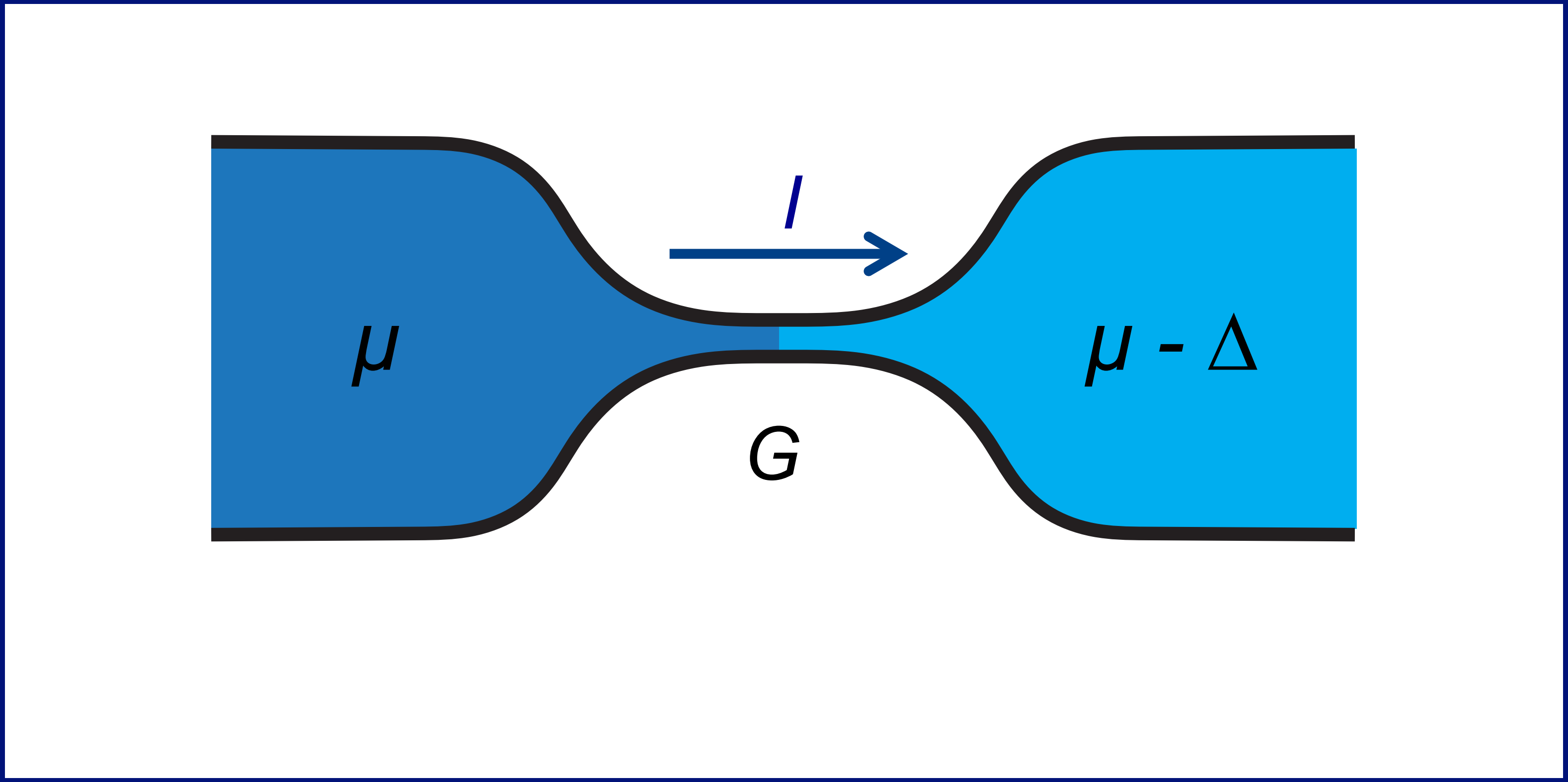
The Lattice team

+ Leticia Tarruell: now @ ICFO, Barcelona

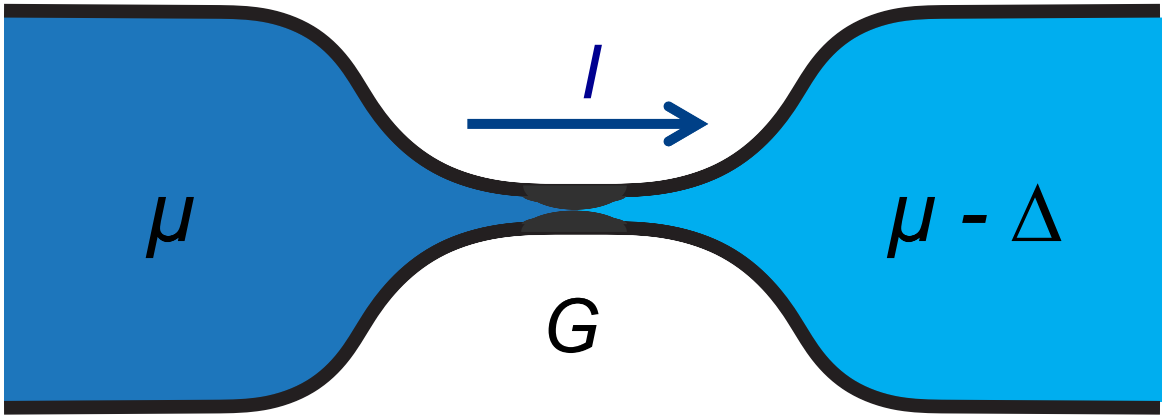


Martin Lebrat | Rémi Desbuqouis | Thomas Uehlinger | Michael Messer | Gregor Jotzu | Daniel Greif | Frederic Görg

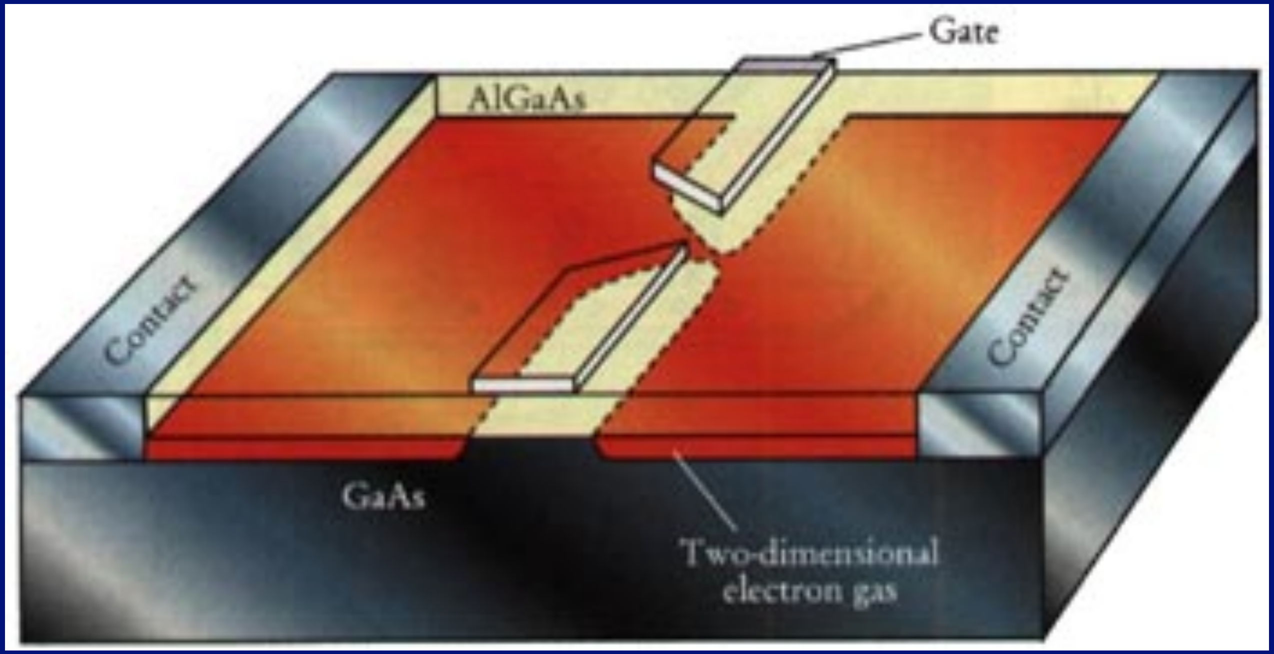
Transport between two Terminals



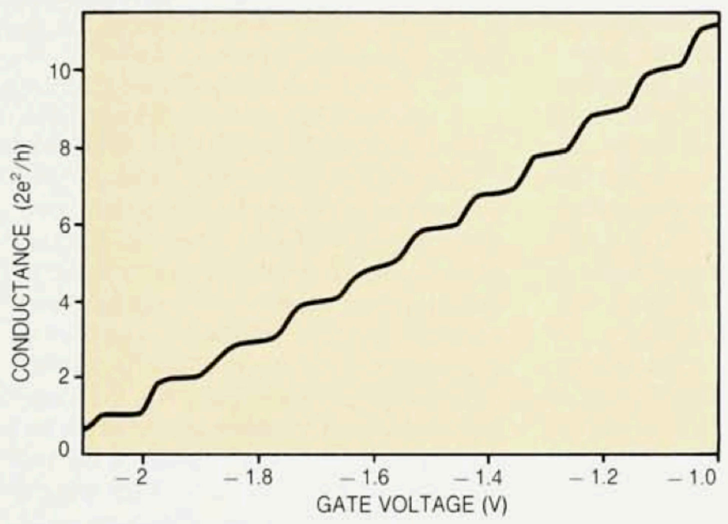
Transport between two Terminals



Quantum Point Contacts



Quantized Conductance



Conductance of a narrow channel connecting two two-dimensional reservoirs of electrons increases in steps of $2e^2/h$ when the width of the channel increases. The more negative the gate voltage is, the narrower the channel is. (Adapted from reference 1.)

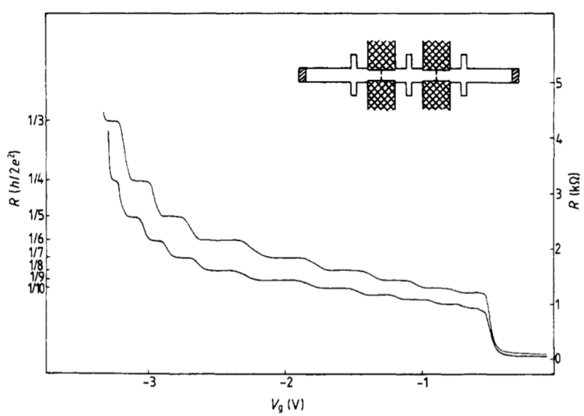
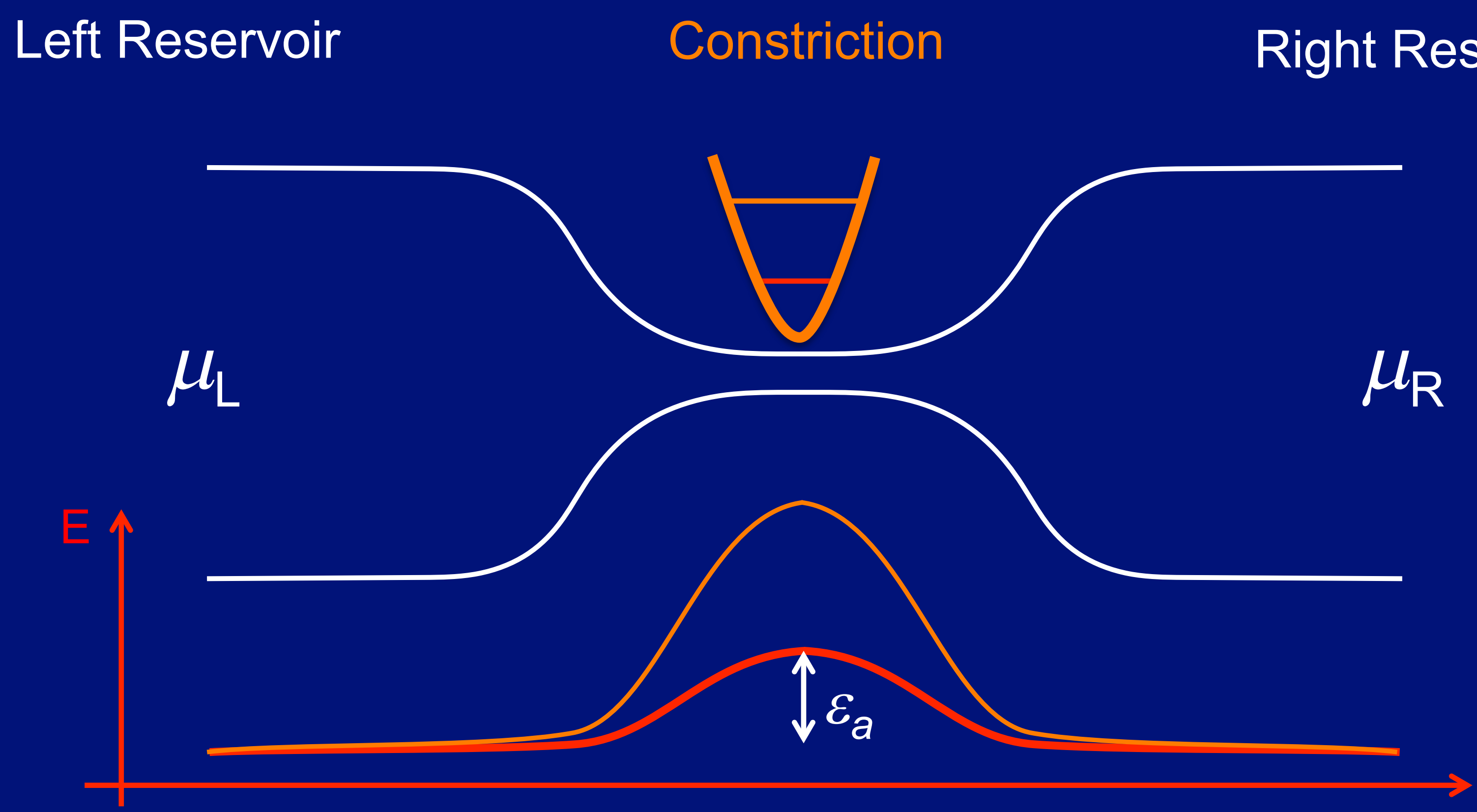


Figure 1. The channel resistance at $T \sim 0.1$ K is plotted as a function of gate voltage for two different carrier concentrations induced by illumination. The existence of a resistance quantised in units of $h/2ie^2$, where i is the number of occupied sub-bands, is illustrated. The inset shows a schematic diagram of the device used in this work. The split gate itself is 0.5 μm wide and 0.4 μm long. Two split gates are illustrated, one of which is selected for the experiment.

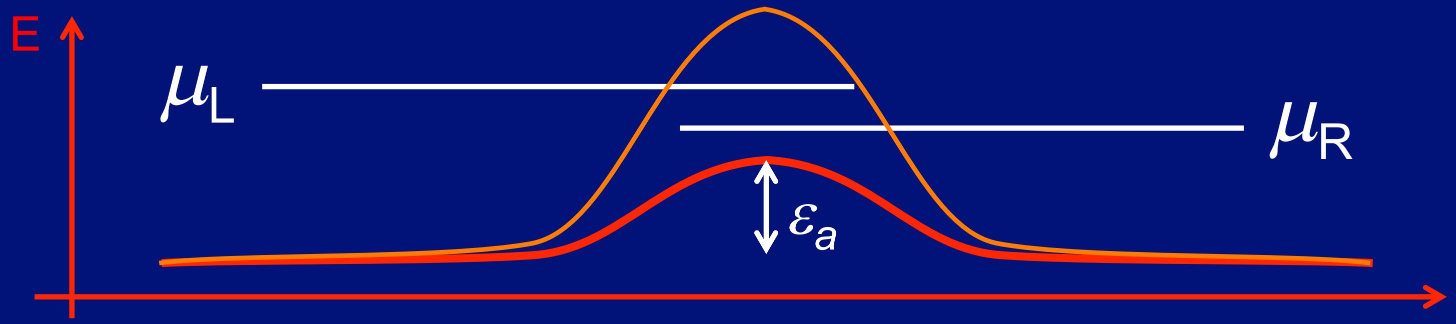
B. J. van Wees, H. van Houten, C. W. J. Beenakker, J. G. Williamson, L. P. Kouwenhoven, D. van der Marel, C. T. Foxon, Phys. Rev. Lett. 60, 848 (1988);

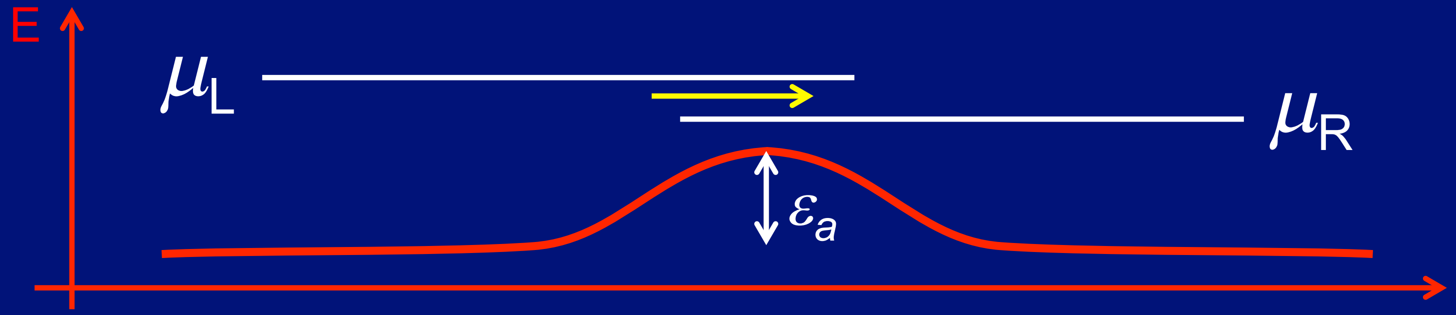
D A Wharam, T J Thornton, R Newbury, M Pepper, H Ahmed, J E F Frost, D G Hasko, D C Peacock, D A Ritchie and G A C Jones, J. Phys. C: Solid State Phys. 21 L209

Why?



Left Reservoir
Constriction
Right Reservoir
μ_L
μ_R
E
ε_a

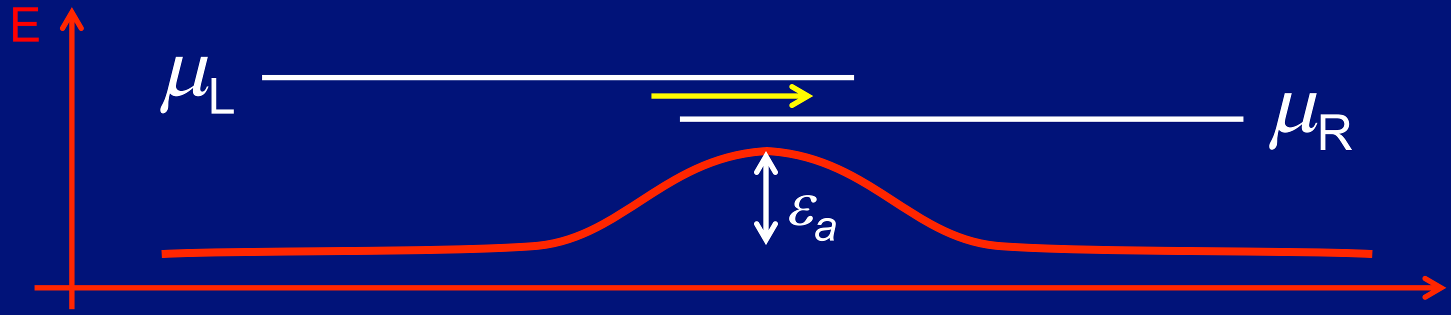

E
μ_L
μ_R
ε_a



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 $$G = \frac{1}{h}$$

Landauer, Büttiker, Imry

Multimode Conductance

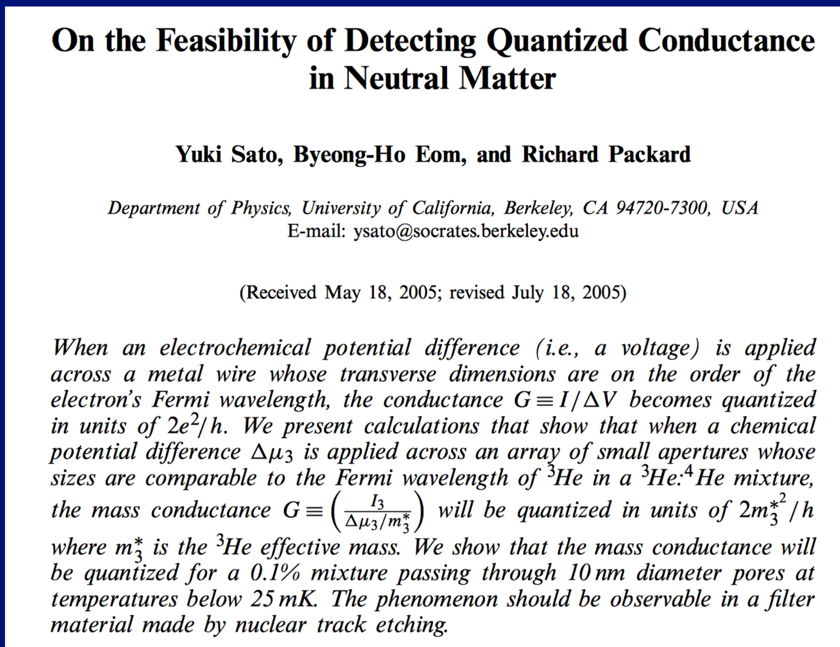
$$G = \frac{1}{h}\sum_n \frac{1}{\Delta\mu}\int_{E_n}^{\infty} dE\left[f_L(E) - f_R(E)\right]$$

Landauer, Büttiker, Imry

Quantized Conductance in Neutral Matter?

Cold atoms proposal: Thywissen, J. H., Westervelt, R. M. & Prentiss, M. Quantum point contacts for neutral atoms. Phys. Rev. Lett. 83, 3762–3765 (1999).

Quantized Conductance in Neutral Matter?



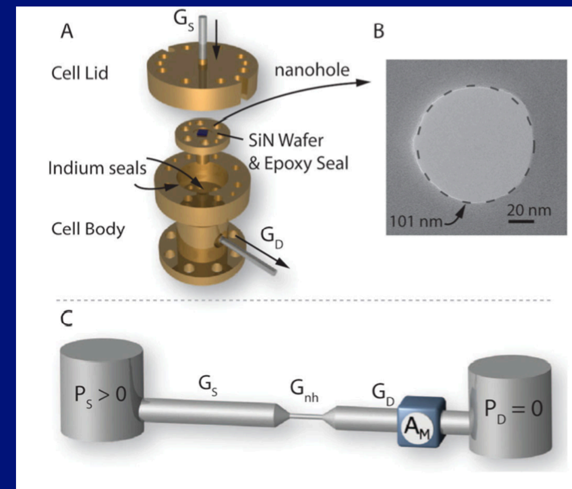
On the Feasibility of Detecting Quantized Conductance in Neutral Matter

Yuki Sato, Byeong-Ho Eom, and Richard Packard

Department of Physics, University of California, Berkeley, CA 94720-7300, USA
E-mail: ysato@socrates.berkeley.edu

(Received May 18, 2005; revised July 18, 2005)

When an electrochemical potential difference (i.e., a voltage) is applied across a metal wire whose transverse dimensions are on the order of the electron's Fermi wavelength, the conductance $G \equiv I/\Delta V$ becomes quantized in units of $2e^2/h$. We present calculations that show that when a chemical potential difference $\Delta\mu_3$ is applied across an array of small apertures whose sizes are comparable to the Fermi wavelength of ^3He in a ^3He:^4He mixture, the mass conductance $G \equiv \left(\frac{I_3}{\Delta\mu_3/m_3^*}\right)$ will be quantized in units of $2m_3^{*2}/h$ where m_3^* is the ^3He effective mass. We show that the mass conductance will be quantized for a 0.1% mixture passing through 10 nm diameter pores at temperatures below 25 mK. The phenomenon should be observable in a filter material made by nuclear track etching.

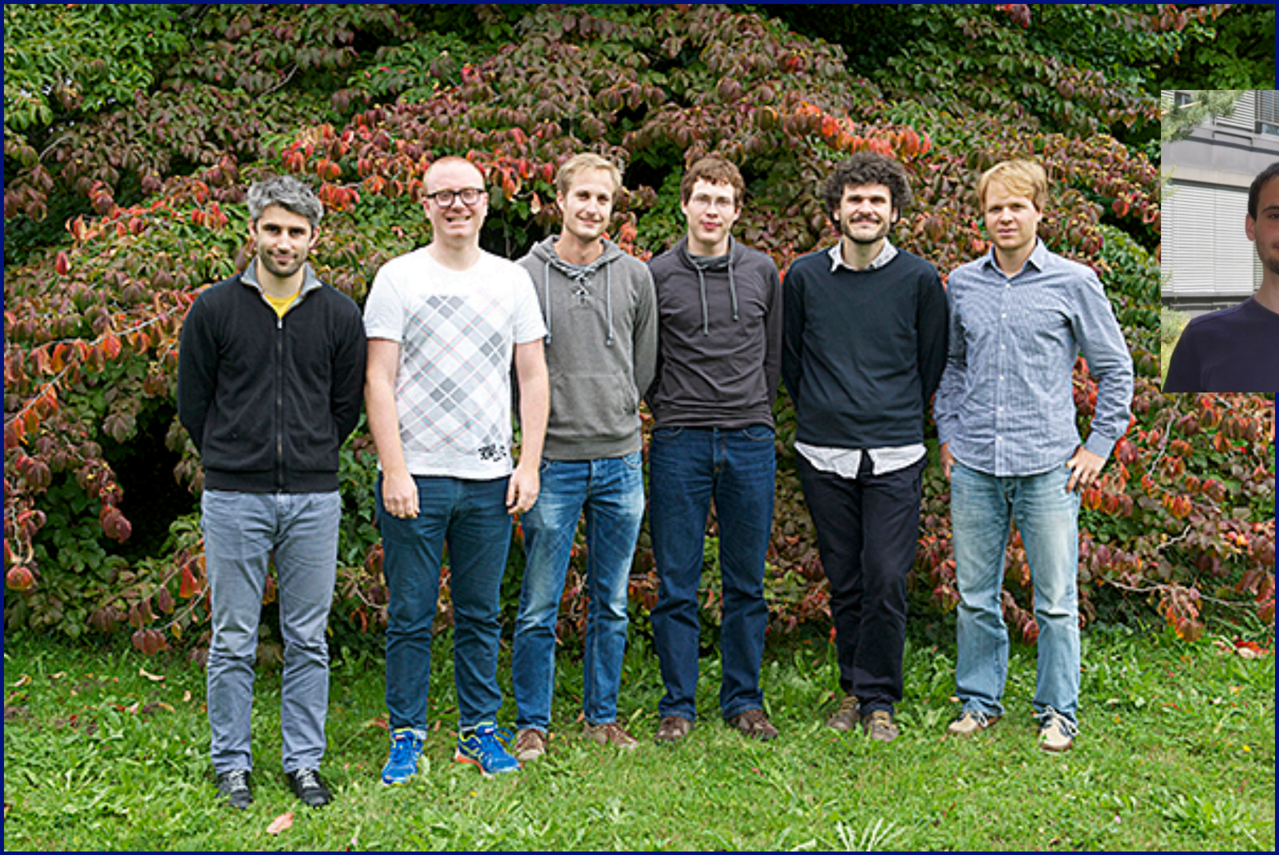


M. Savard, C. Tremblay-Darveau, and G. Gervais, PRL 103, 104502 (2009)

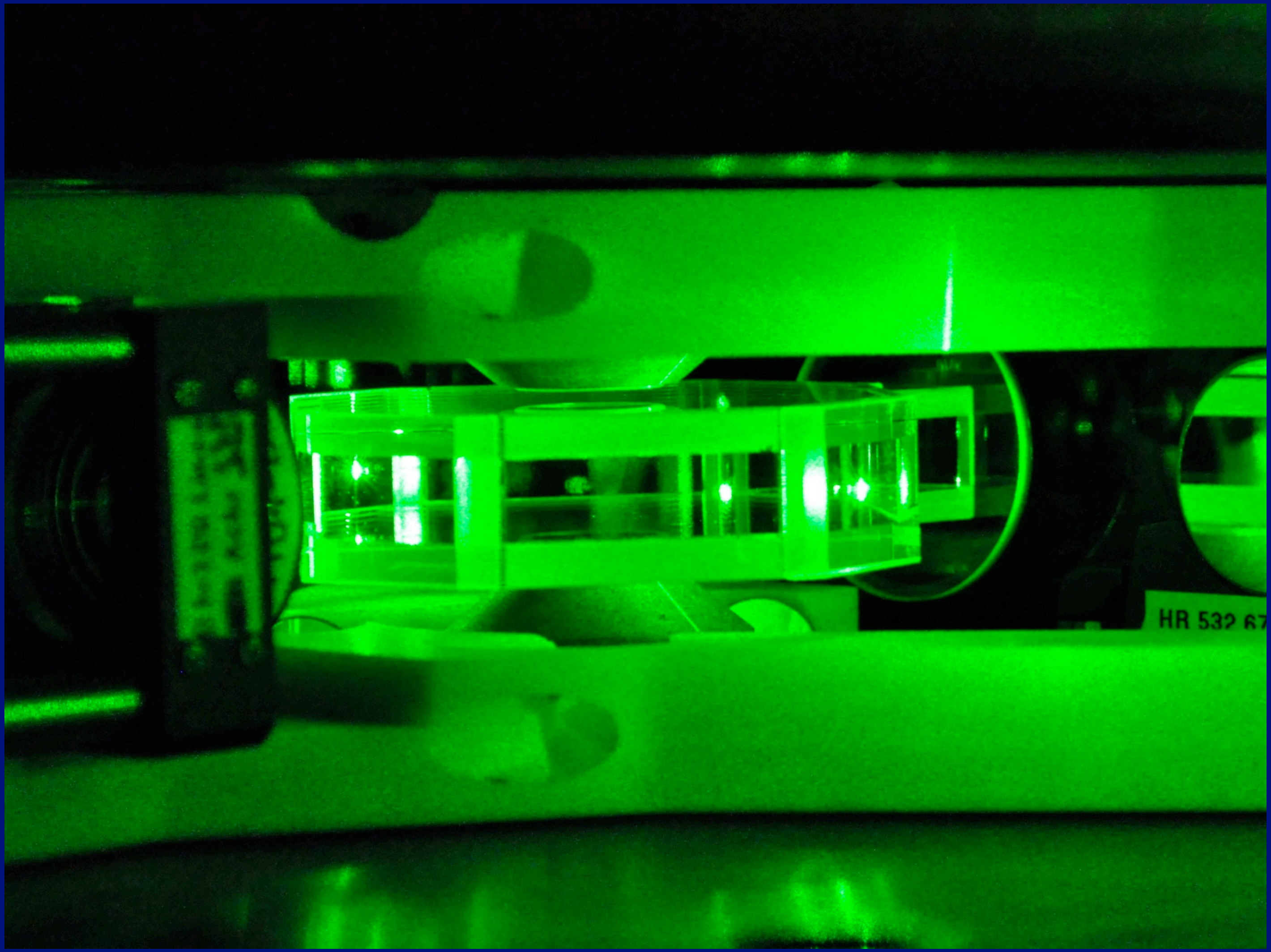
See also: G. Lambert, G. Gervais, and W.J. Mullin, Low Temp. Phys. 34, 249 (2008).

Quantized Conductance in Neutral Matter?

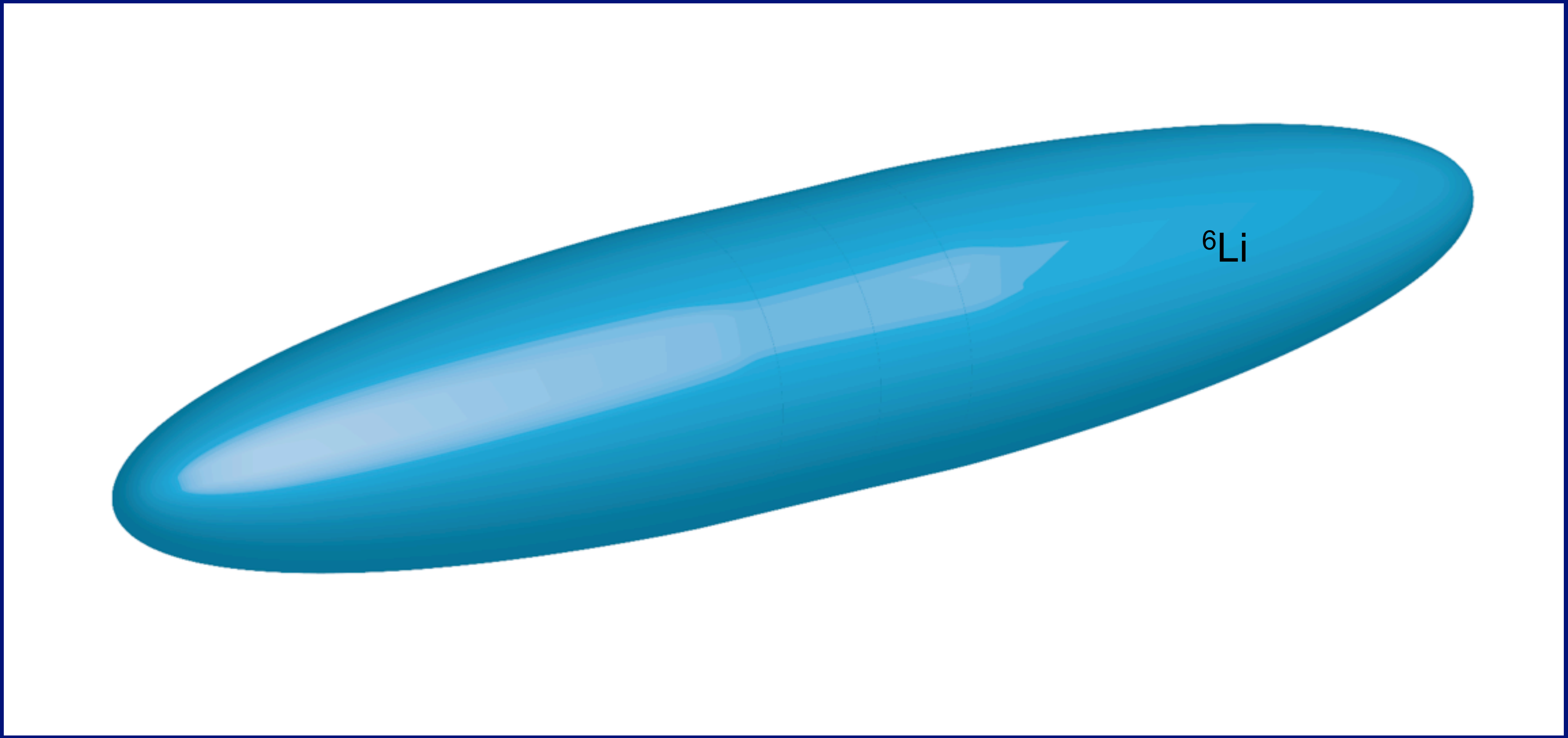
- Method to measure conductance
- Ballistic channel
- Quantum degenerate Fermi gas
- Resolve individual conduction channels
- Adiabatic regime
- Applicability of Landauer theory
(mean free path > trap)



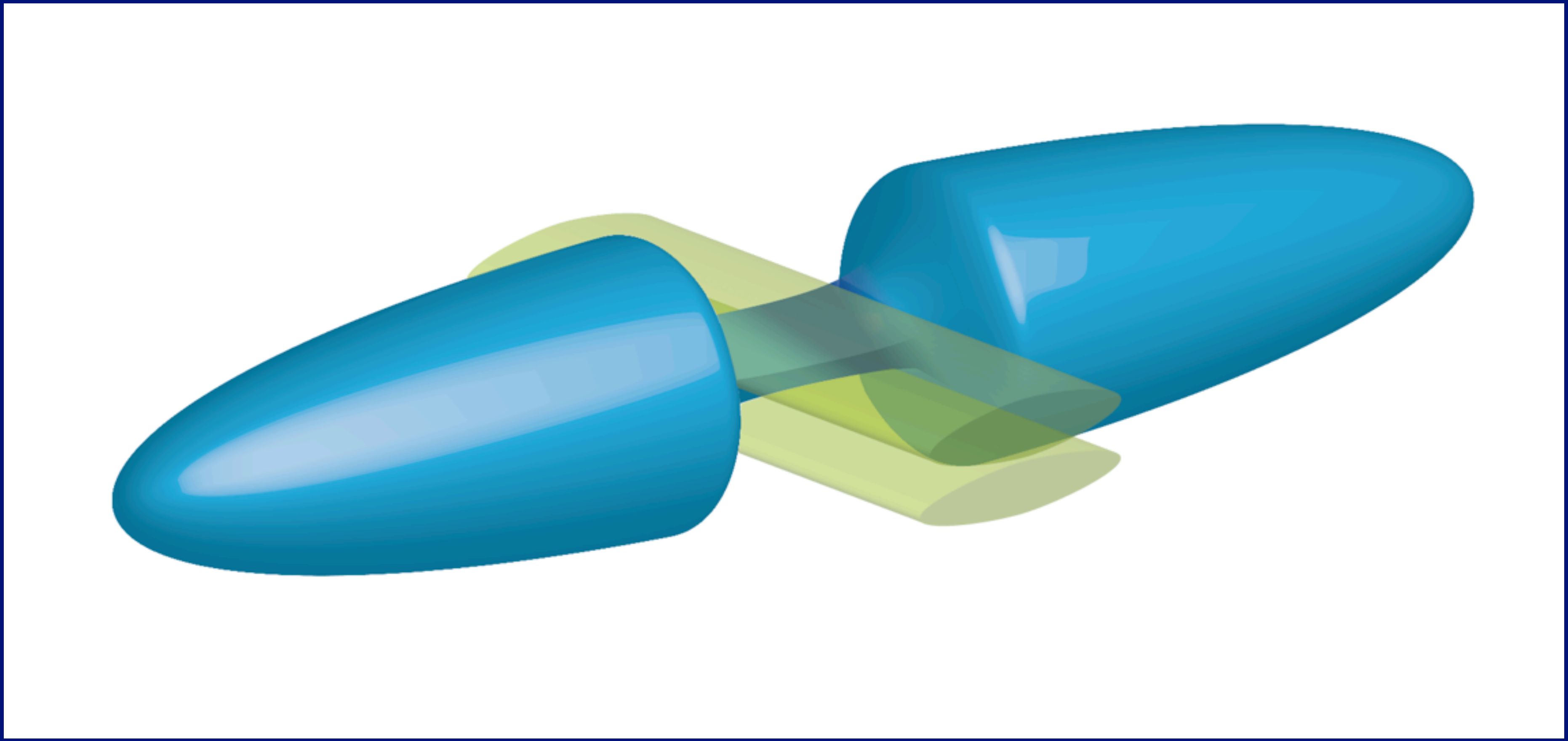

Jean-Philippe Brantut, David Stadler, Dominik Husmann, Samuel Häusler, Charles Grenier, Sebastian Krinner
Martin Lebrat



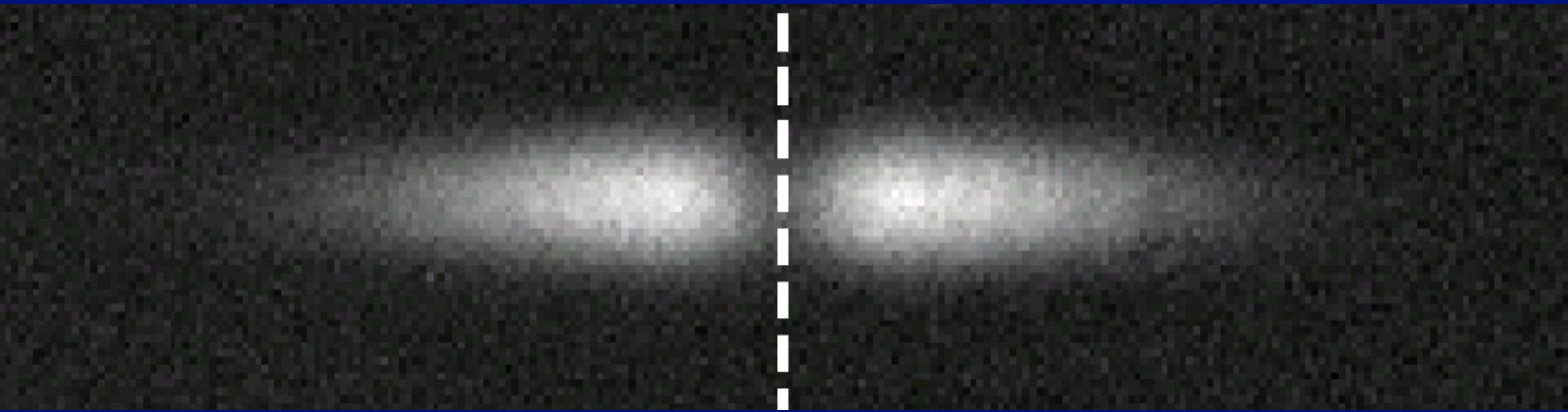
Thanks to Henning Moritz now @ Hamburg



^{6}Li



Fermi battery

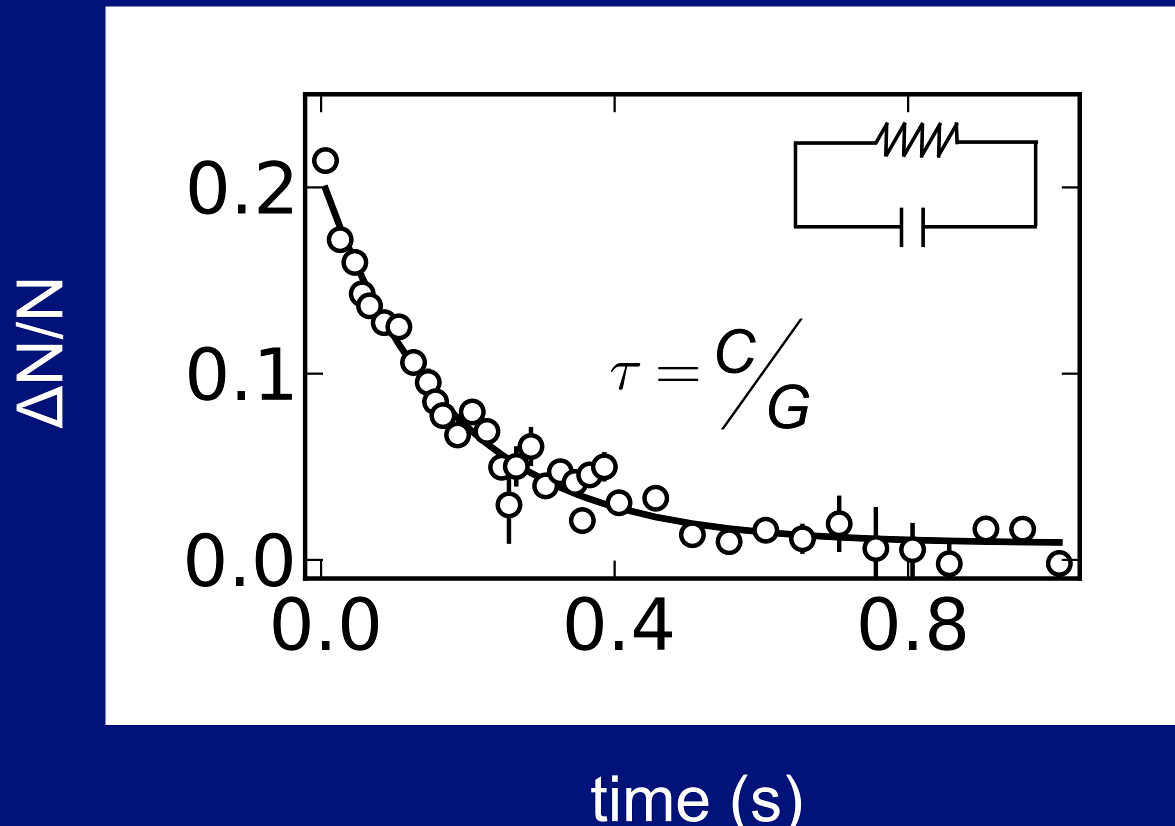


reservoir   channel   reservoir

N_L N_R

J.-P. Brantut, J. Meineke, D. Stadler, S. Krinner, T. Esslinger, Science 337, 1069 (2012)

Battery discharge

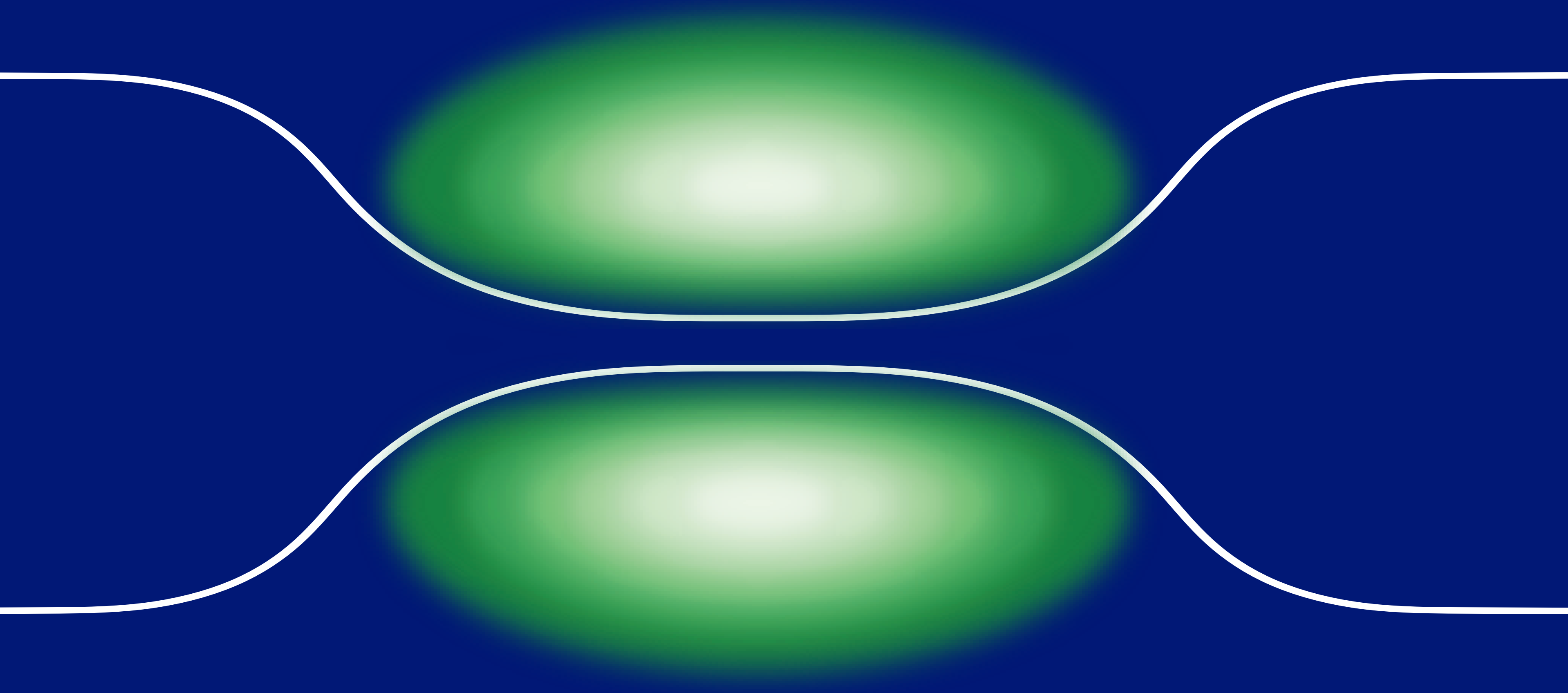


$$\frac{d}{dt}\Delta N = -\frac{G}{C}\Delta N$$

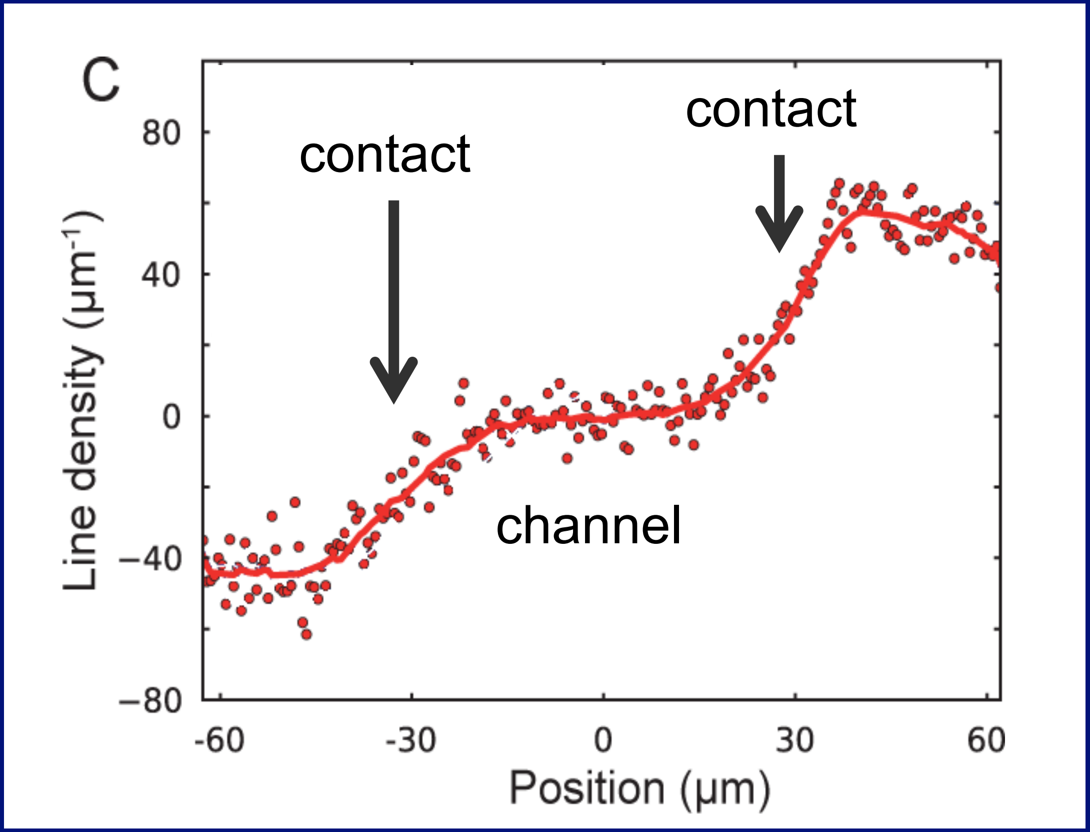
G: conductance

C: compressibility $\partial N/\partial \mu$

Resistance?

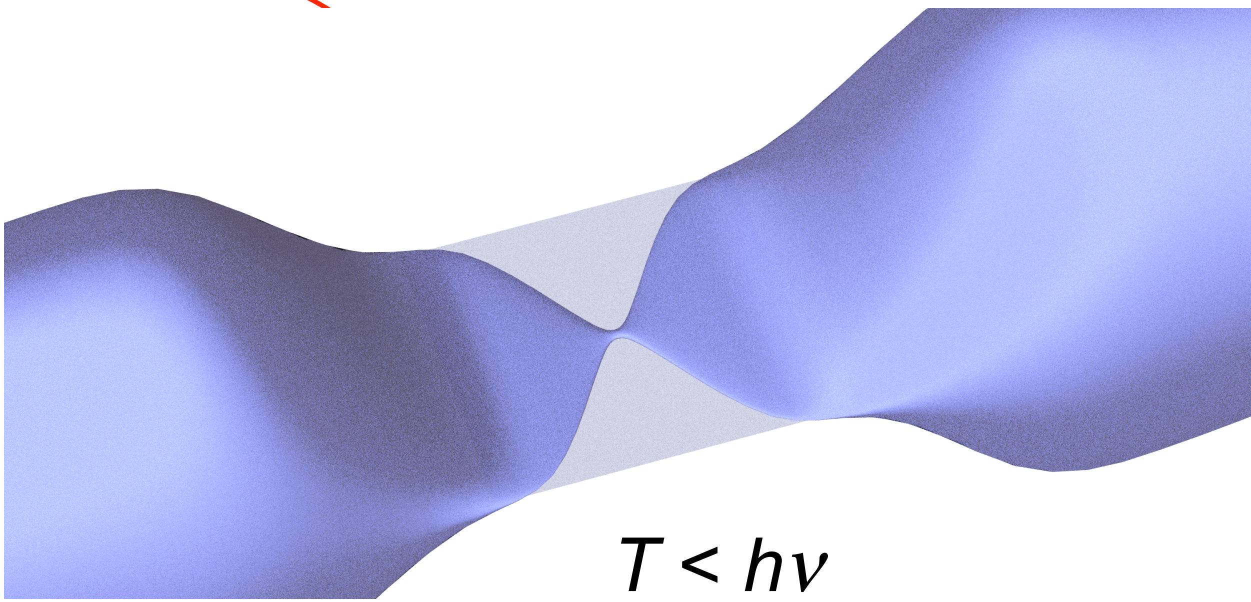


Ballistic Multimode Channel



J.-P. Brantut, J. Meineke, D. Stadler, S. Krinner, T. Esslinger, Science 337, 1069 (2012)

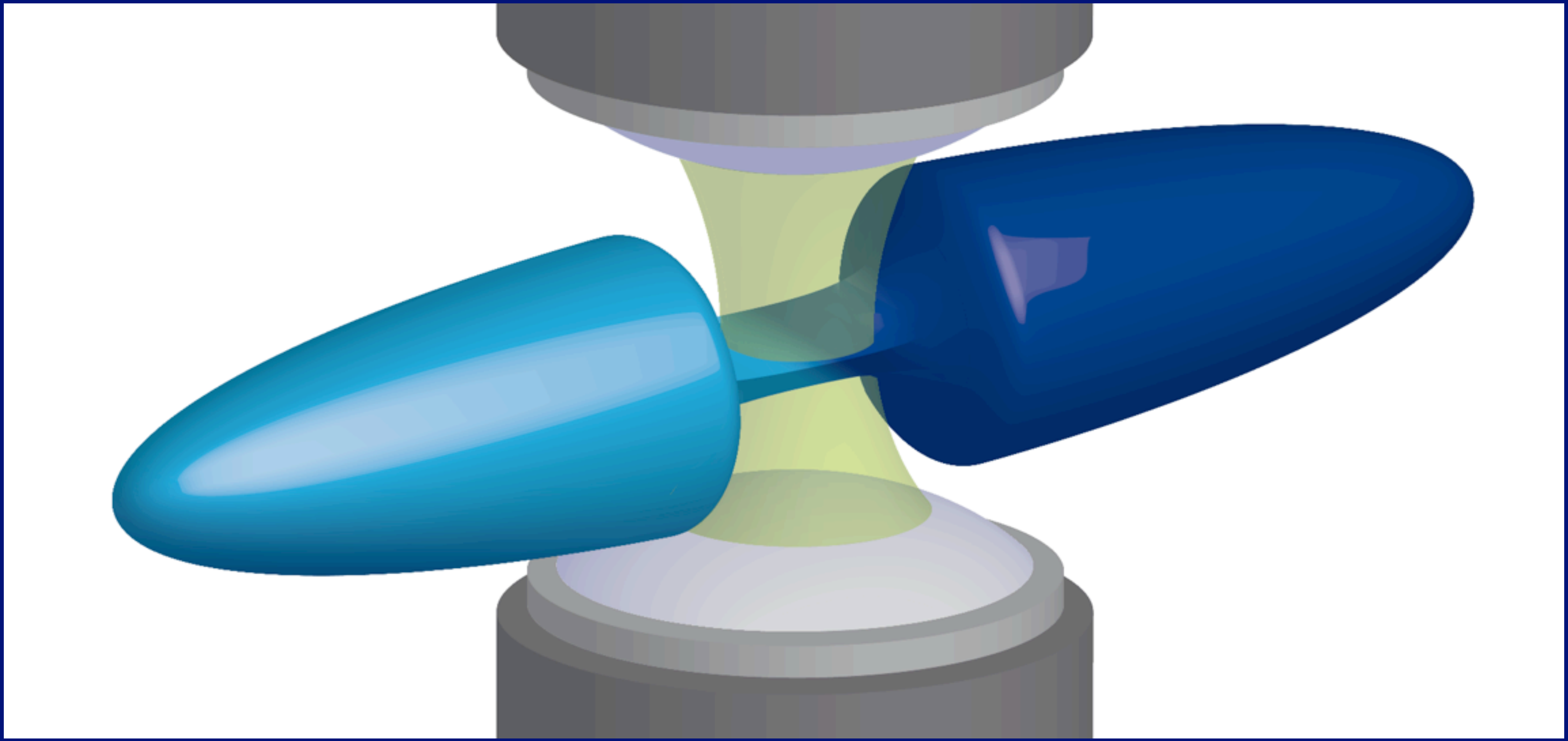
Dreams and worries

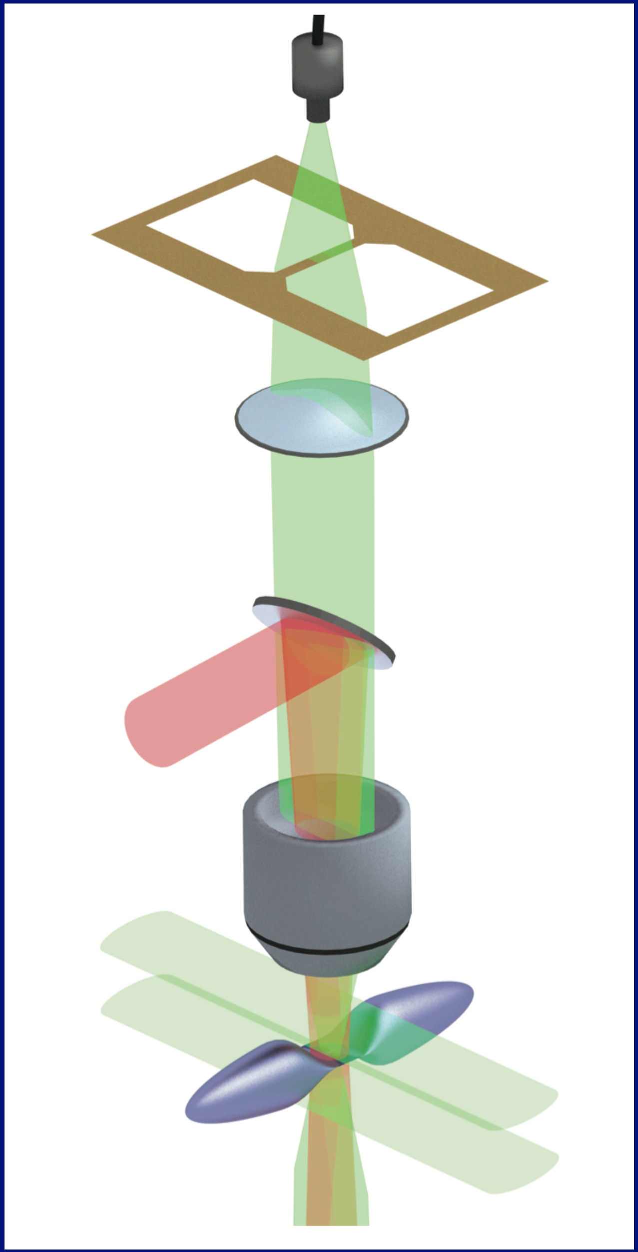


$T < h\nu$

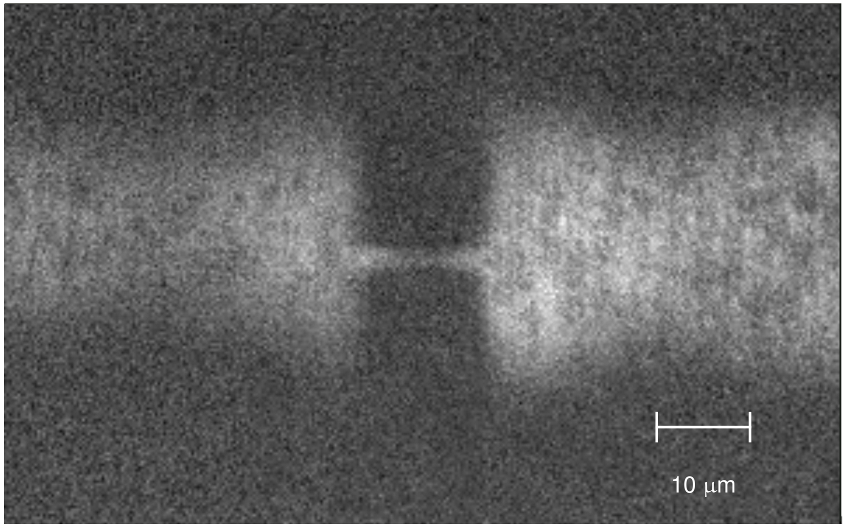
10 atoms in channel

Single Mode Channel?



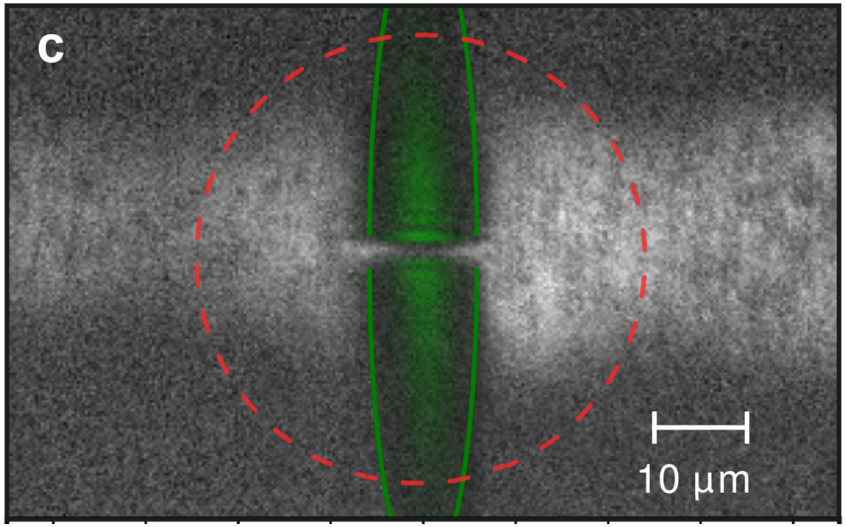


Quantum Point Contact

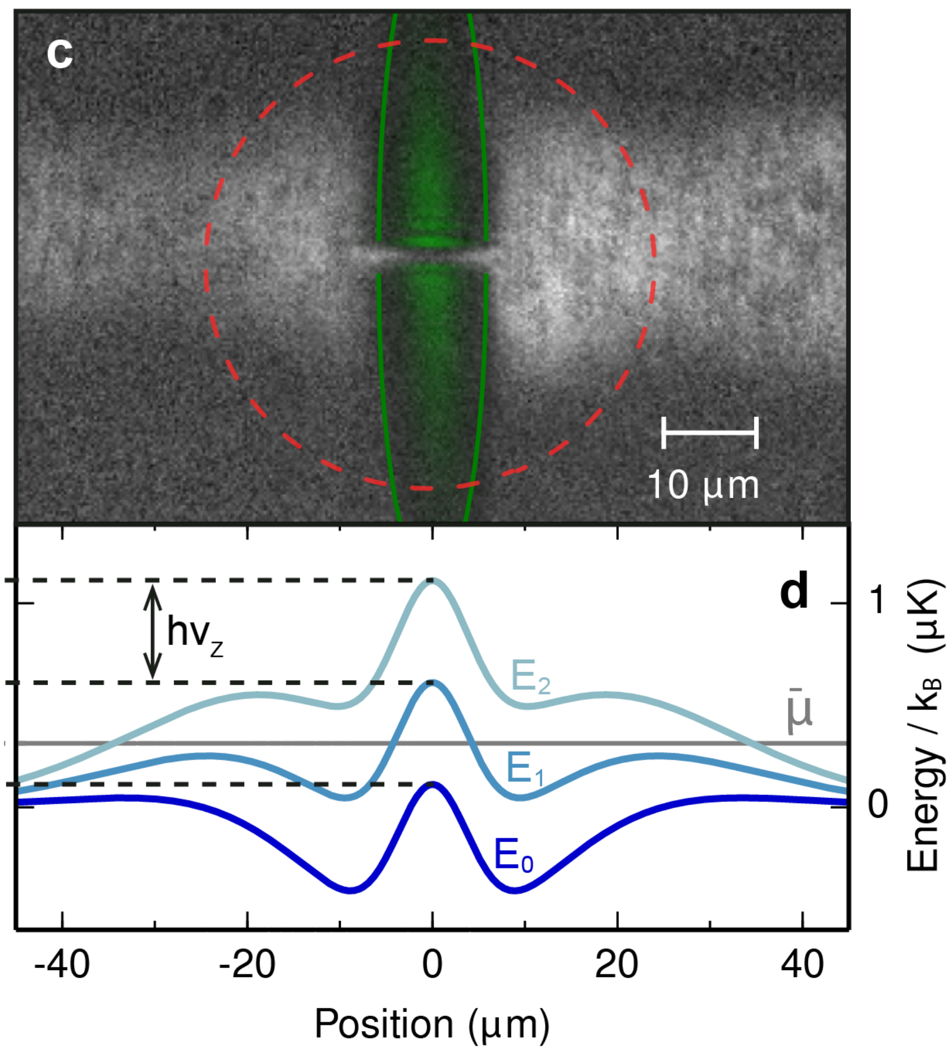


Fermi wavelength of 2.2 μm

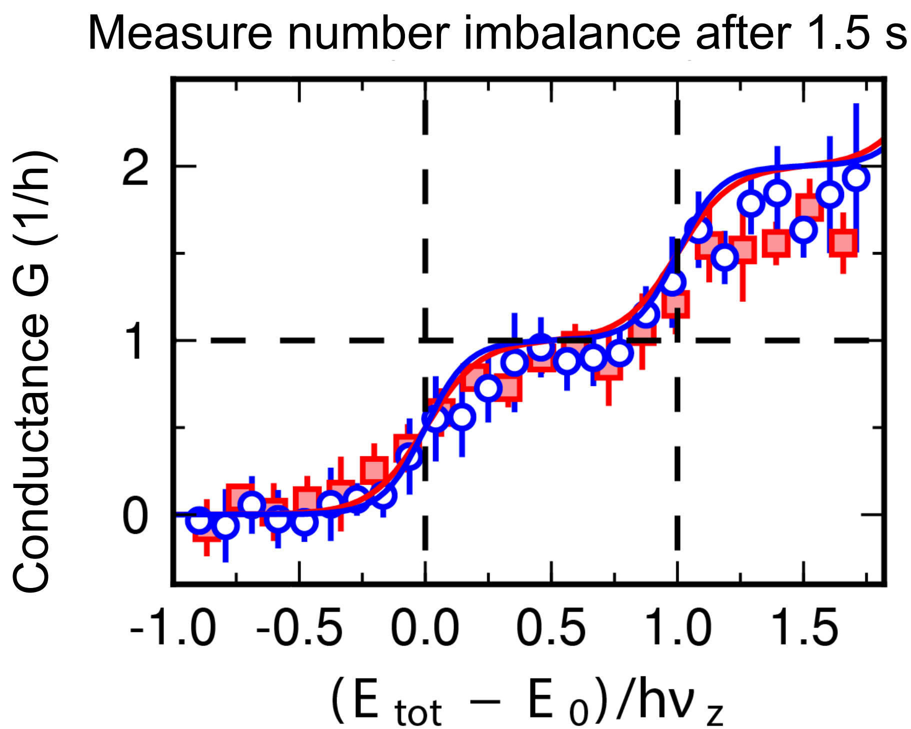
Quantum Point Contact



Quantum Point Contact



Quantum Point Contact



ν_x=31.8 kHz

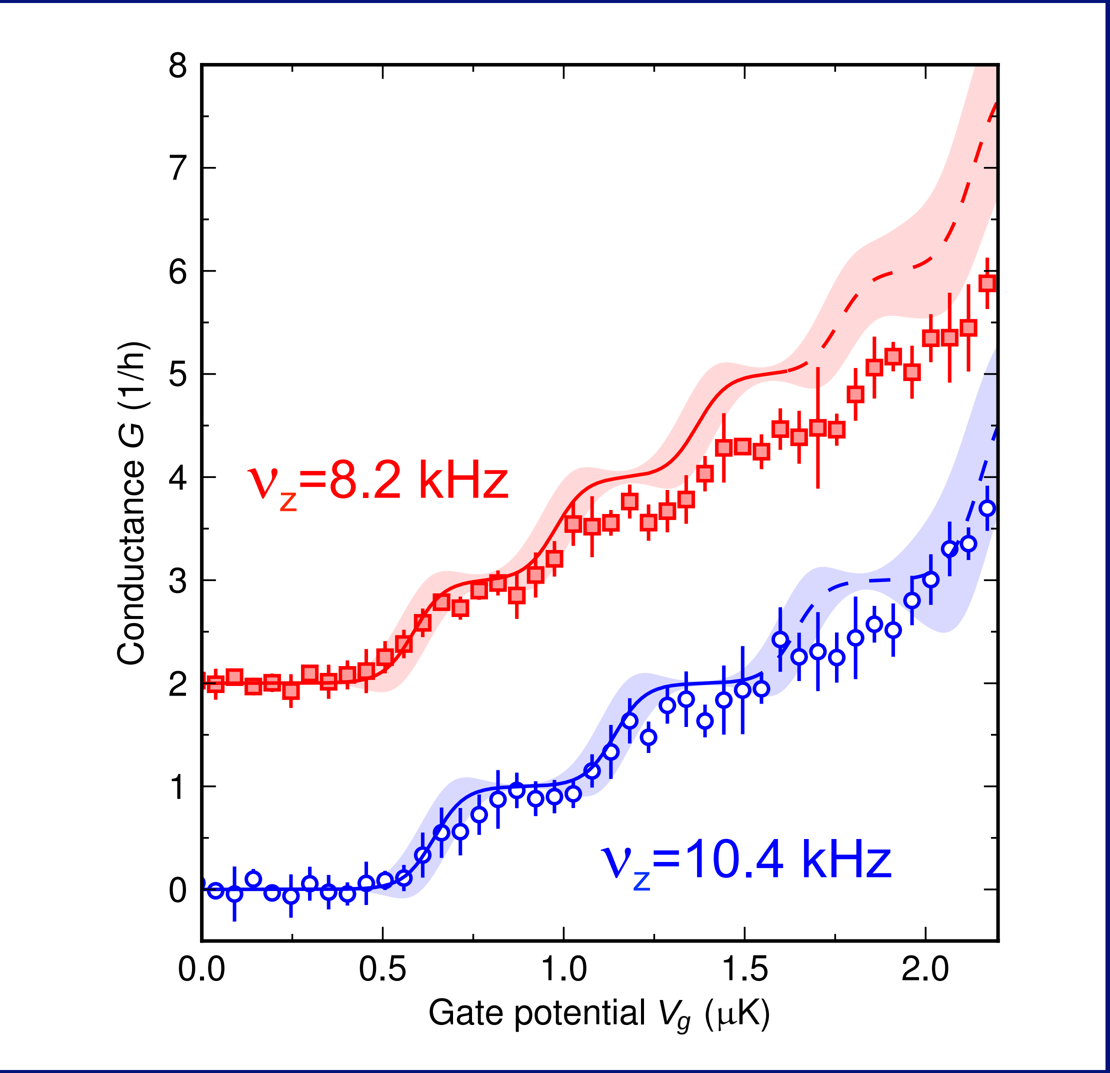
ν_z=10.4 kHz

ν_z=8.2 kHz

T= 35 nK (=0.1 T_F) < $h\nu_z \approx$ 500 nK

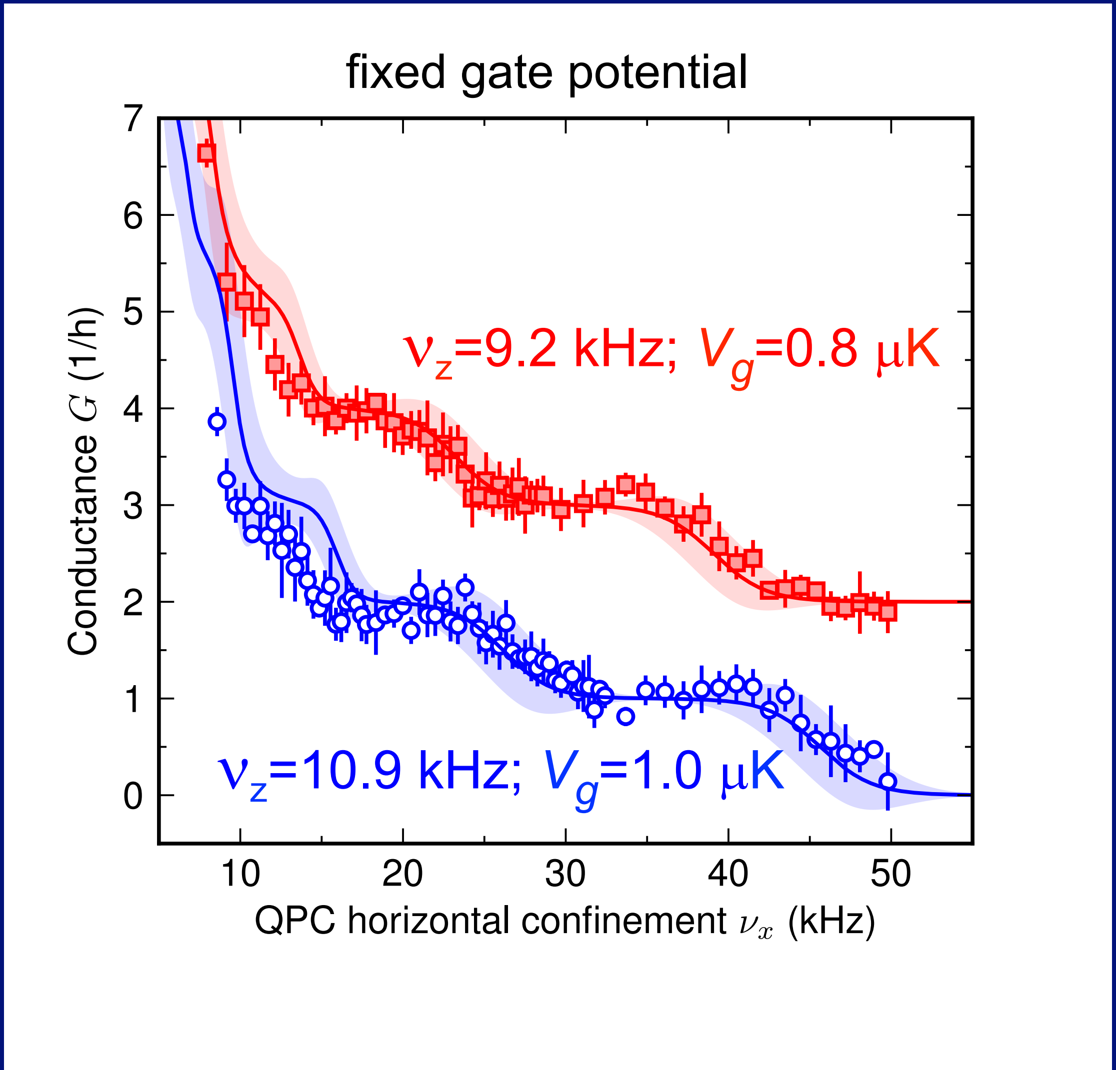
S. Krinner, D. Stadler, D. Husmann, J.P. Brantut and T. Esslinger, Nature 517, 64 (2015)

Quantum Point Contact



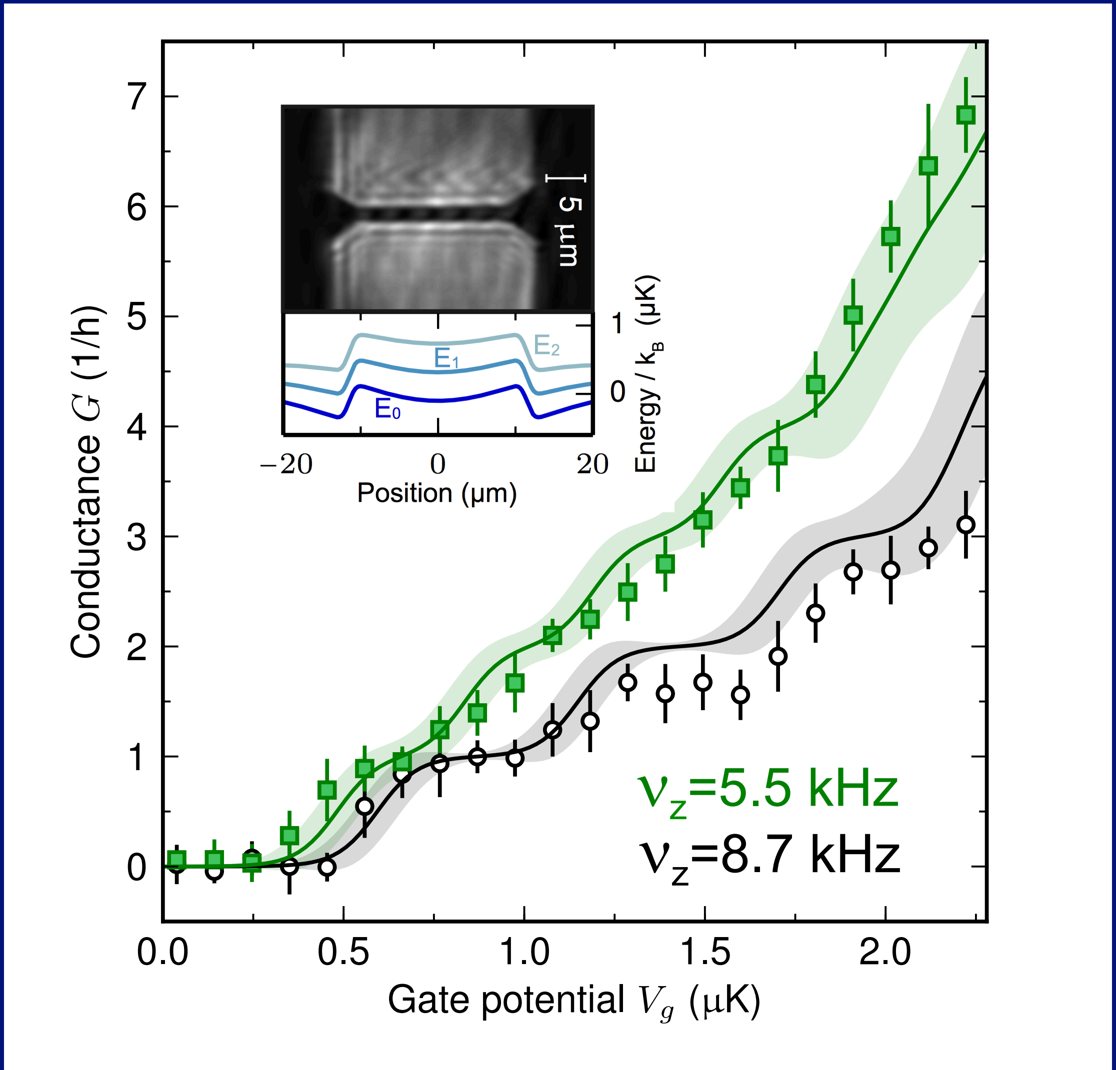
S. Krinner, D. Stadler, D. Husmann, J.P. Brantut and T. Esslinger, Nature 517, 64 (2015)

Quantum Point Contact



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

Quantum Wire

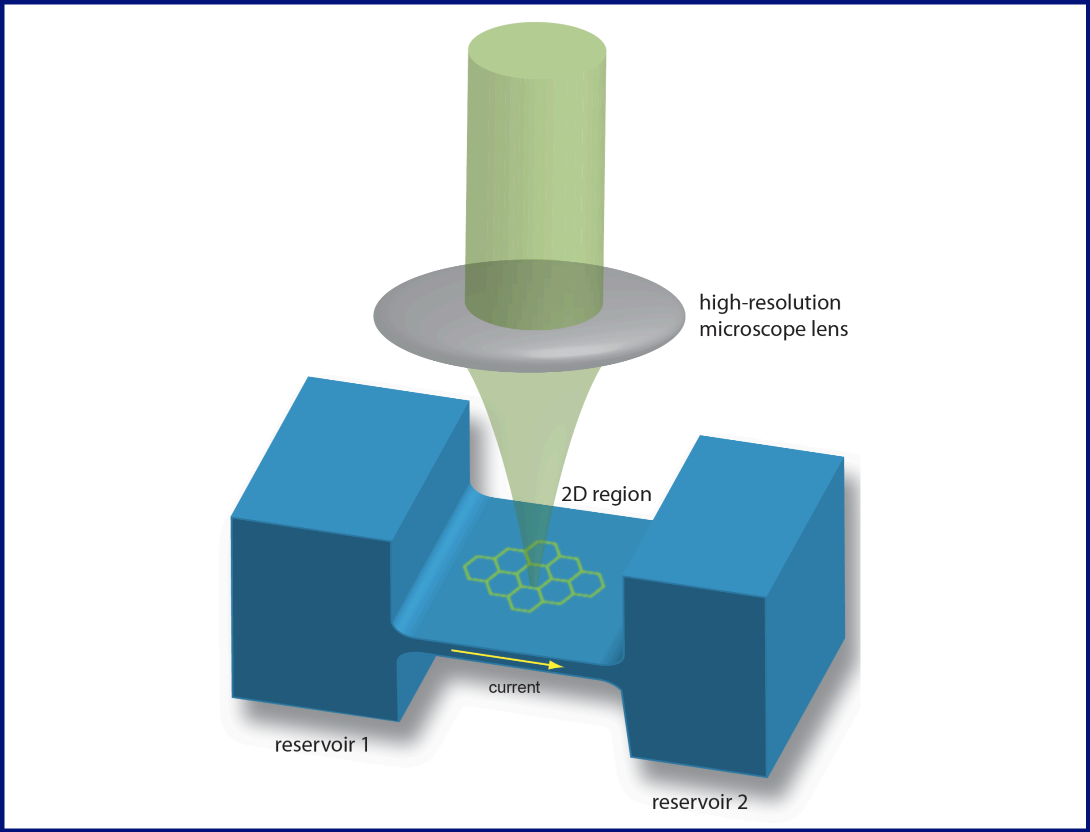


S. Krinner, D. Stadler, D. Husmann, J.P. Brantut and T. Esslinger, Nature 517, 64 (2015)

Conclusions

- Ballistic and adiabatic channels can be produced
- Isolated system
- Ultraballistic regime, mean free path >> system
- Tunable Interactions
- Spin transport
- Precision measurement of h???

Outlook: Quantum Simulation of Devices



Thanks !

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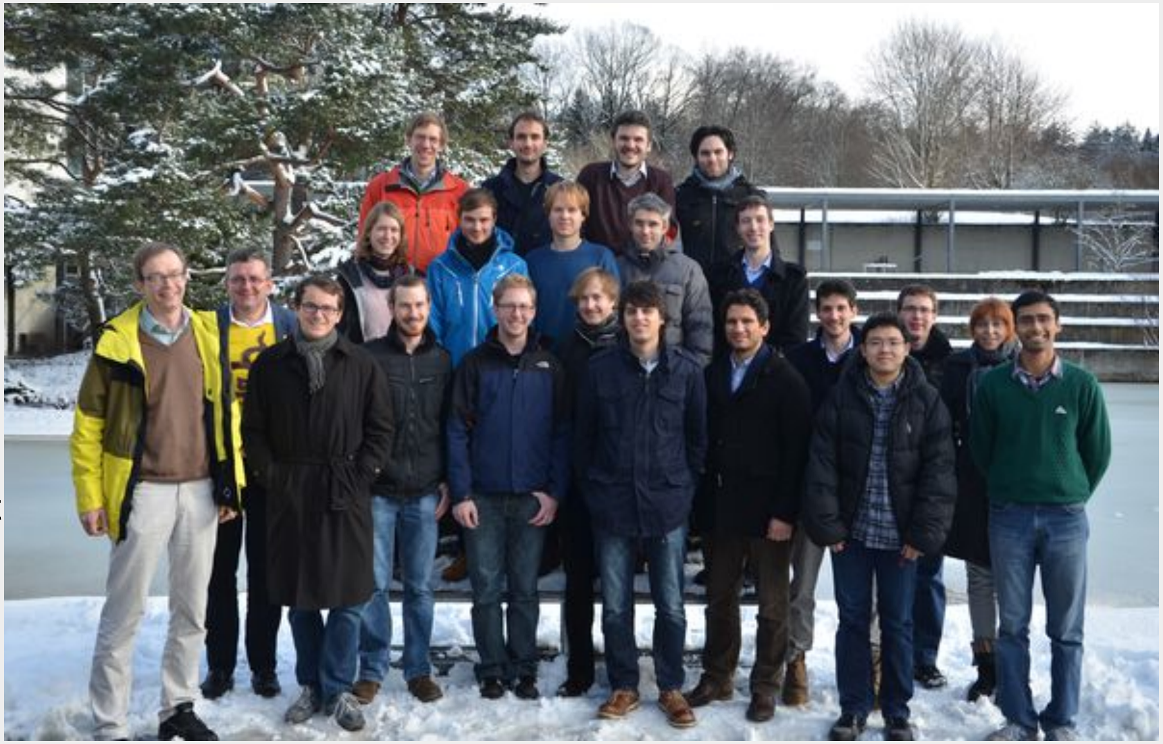
Quantum Gases in Optical Lattices
Daniel Greif
Thomas Uehlinger
Gregor Jotzu
Michael Messer
Rémi Desbuquois
Frederic Görg
(Leticia Tarruell)

Lithium Microscope
Jean-Philippe Brantut
Sebastian Krinner
Dominik Husmann
Martin Lebrat
Samuel Häusler
Shuta Nakajima
(David Stadler)



BEC and Cavity
Ferdinand Brennecke
(Rafael Mottl)
Tobias Donner
Renate Landig
Lorenz Hruby
Andrea Morales
Manuele Landini

Impact experiment
Tobias Donner
Julian Leonard
Moonjoo Lee
Andrea Morales
Philip Zupancic

Electronics
Alexander Frank

Administration: Stephanie Schorlemer, Eik Szee Goh Aschauer

Former Members: Rafael Mottl, David Stadler, Ferdinand Brennecke, Jakob Meineke, Laura Corman (ENS), Leticia Tarruell (ICFO), Torben Müller, Kristian Baumann (Stanford), Silvan Leinss, Robert Jördens (NIST), Bruno Zimmermann, Henning Moritz (Hamburg), Christine Guerlin (Thales), Niels Strohmaier (Hamburg),Thomas Bourdel (Palaiseou), Kenneth Günter, Michael Köhl (Cambrigde), Anton Öttl, Stephan Ritter (MPQ), Thilo Stöferle (IBM), Yosuke Takasu (U Kyoto)
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