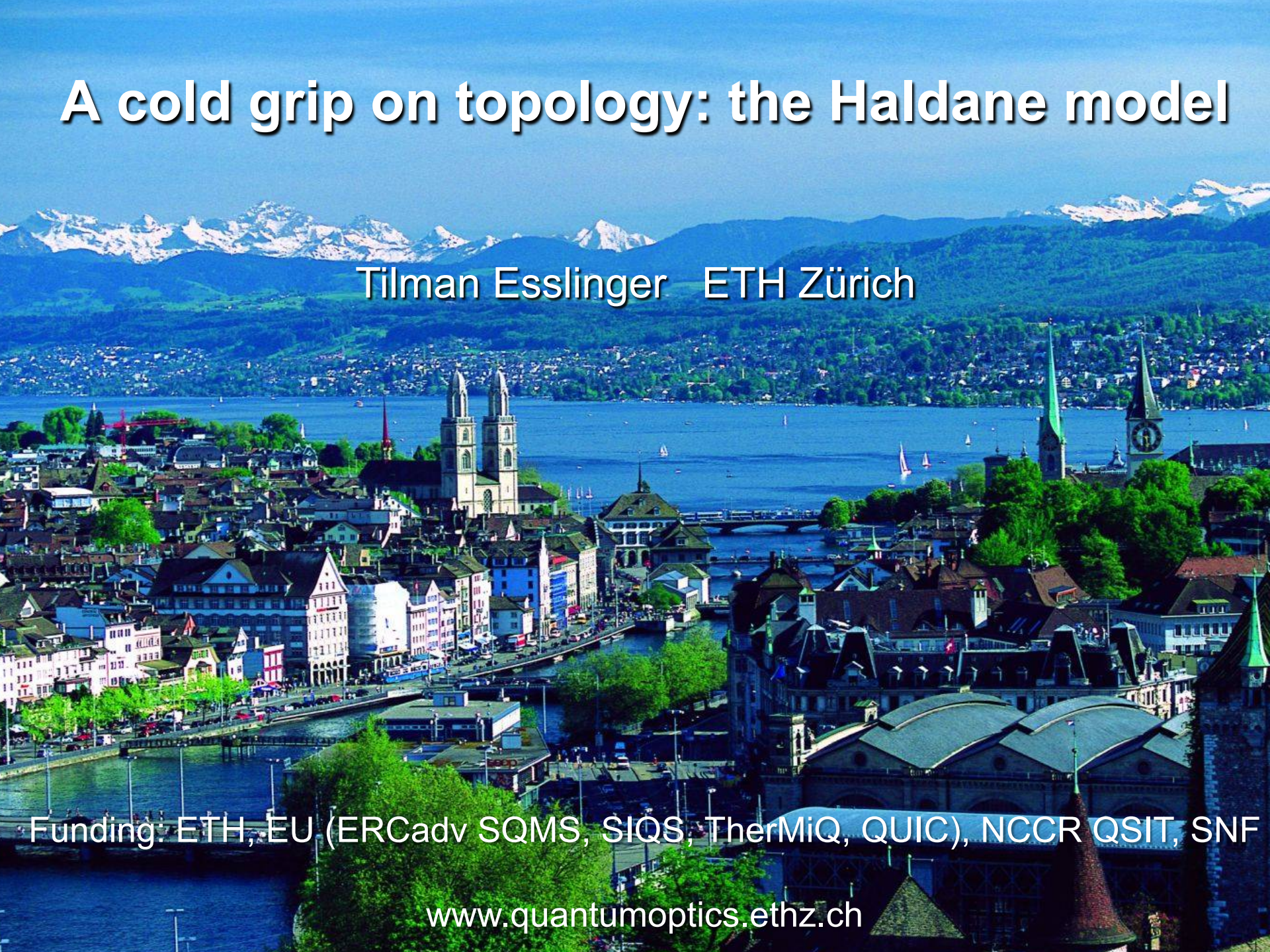
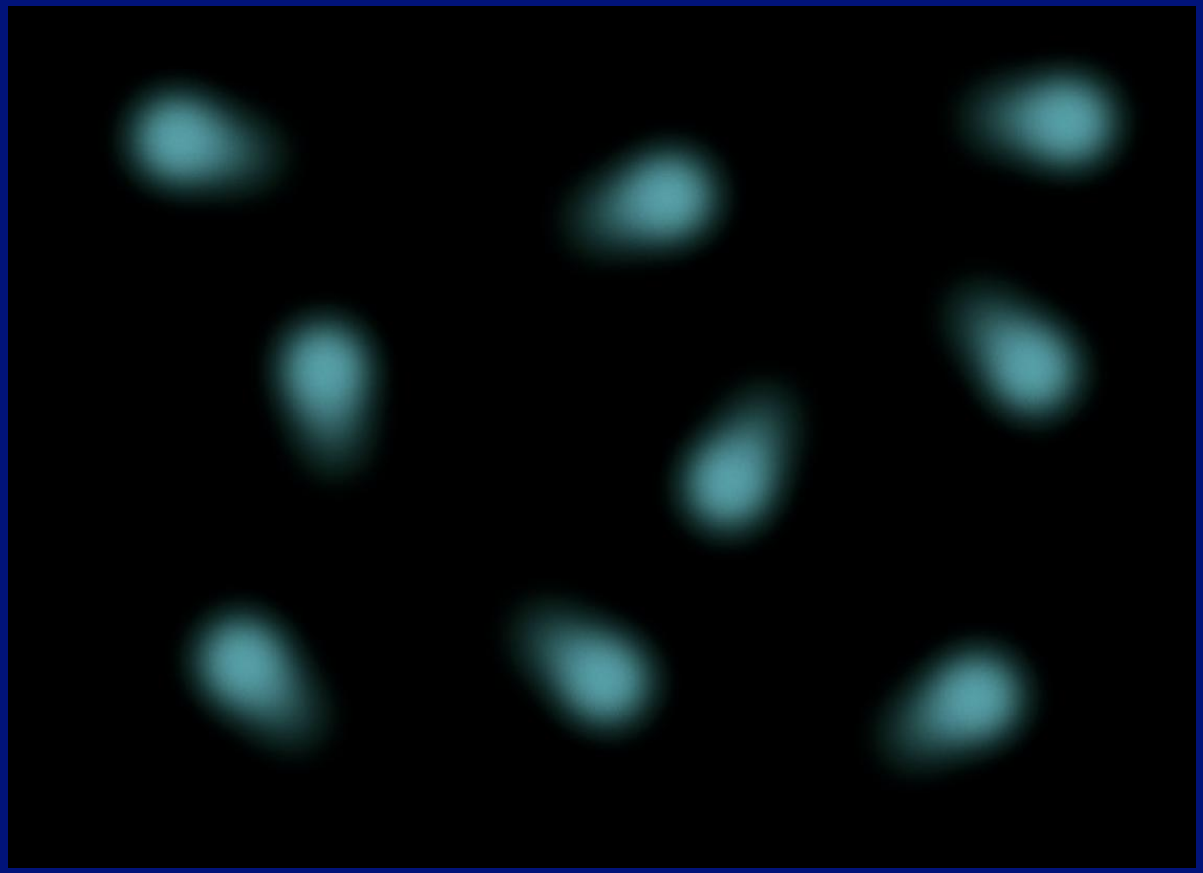
A cold grip on topology: the Haldane model

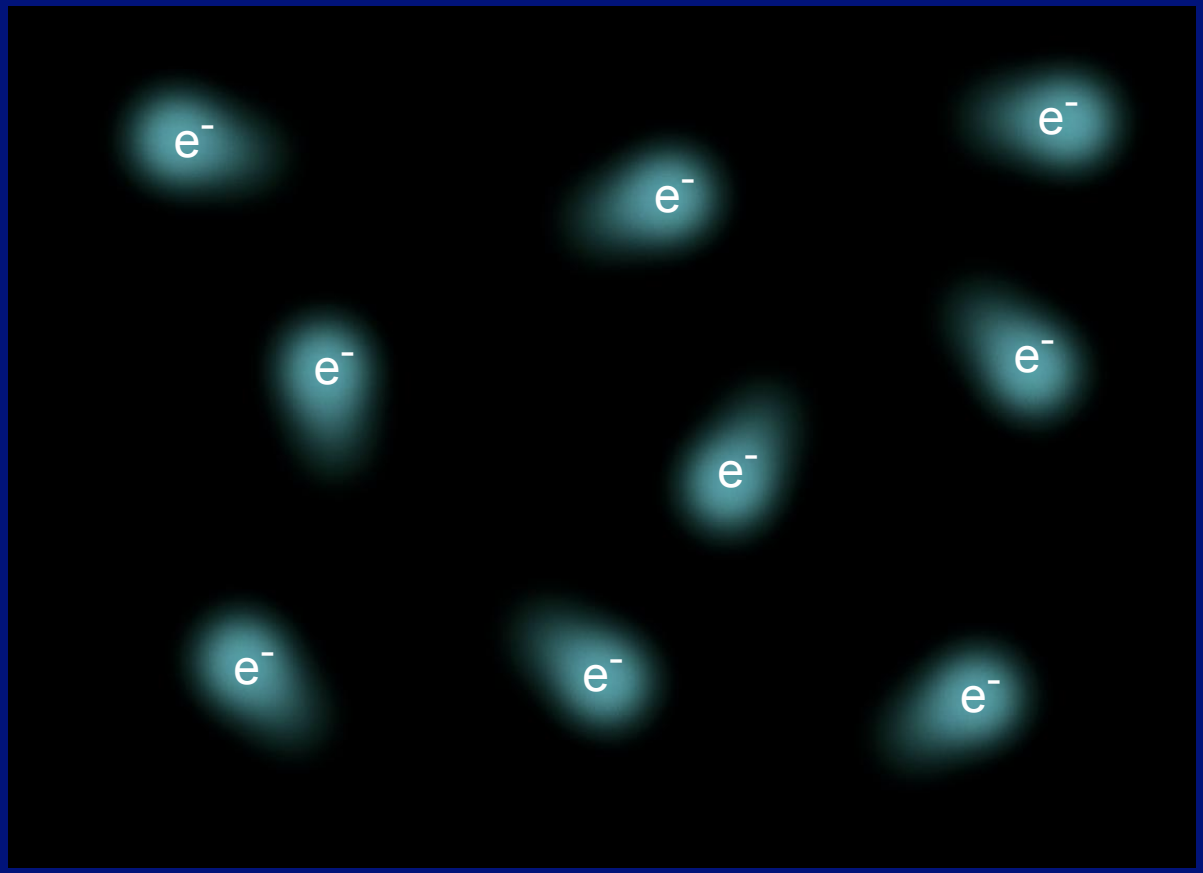
Tilman Esslinger ETH Zürich

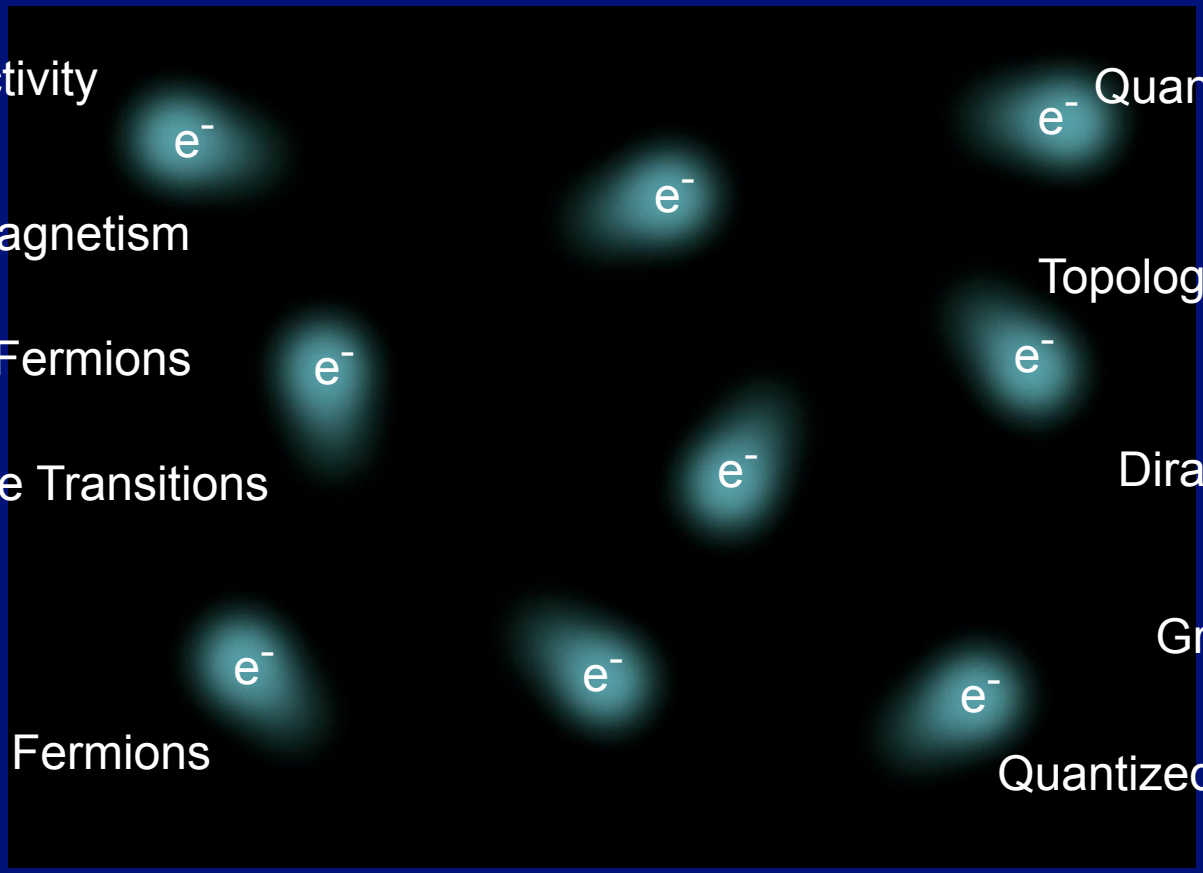


Funding: ETH, EU (ERCadv SQMS, SIQS, TherMiQ, QUIC), NCCR QSIT, SNF

www.quantumoptics.ethz.ch




e-
e-
e-
e-
e-
e-
e-
e-
e-

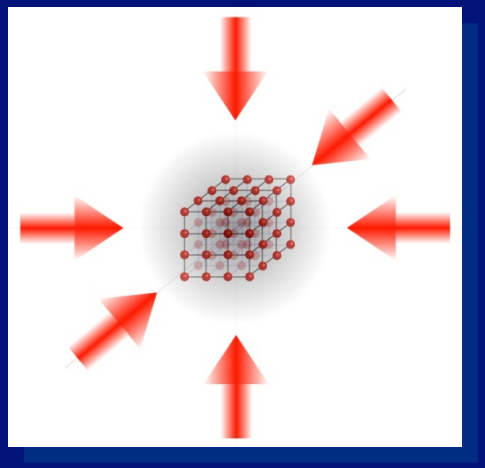

Metals
Insulators
Superconductivity
Quantum Hall Effect
Quantum Magnetism
Topological Insulators
Weyl Fermions
Quantum Phase Transitions
Dirac Fermions
Graphene
Majorana Fermions
Quantized Conductance
High Tc
Photovoltaic Quantum Hall effect

Why cold atoms?

- Different approach
- New systems
- New regimes
- New questions
- Surprises

Building the Hamiltonian

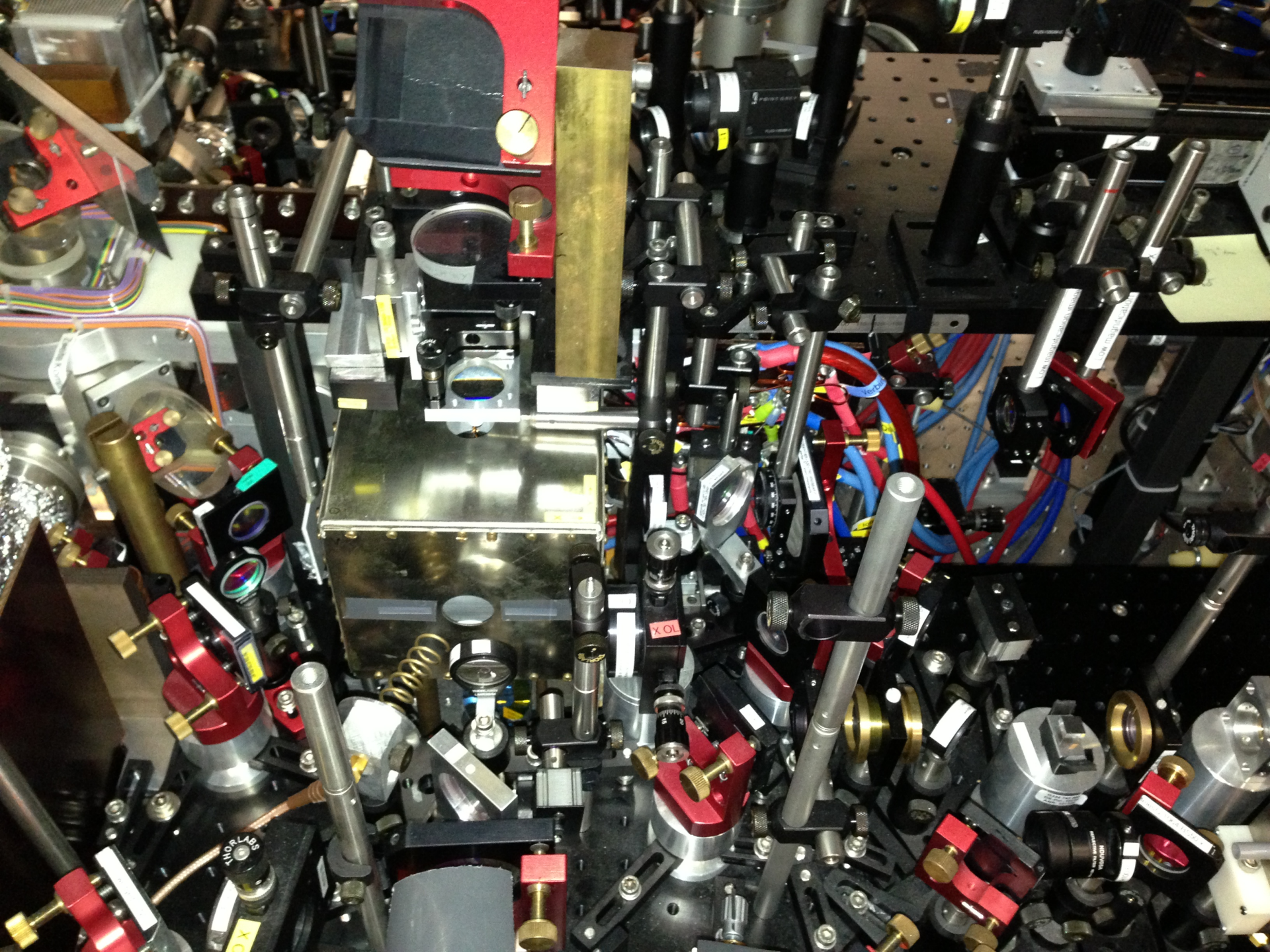
+



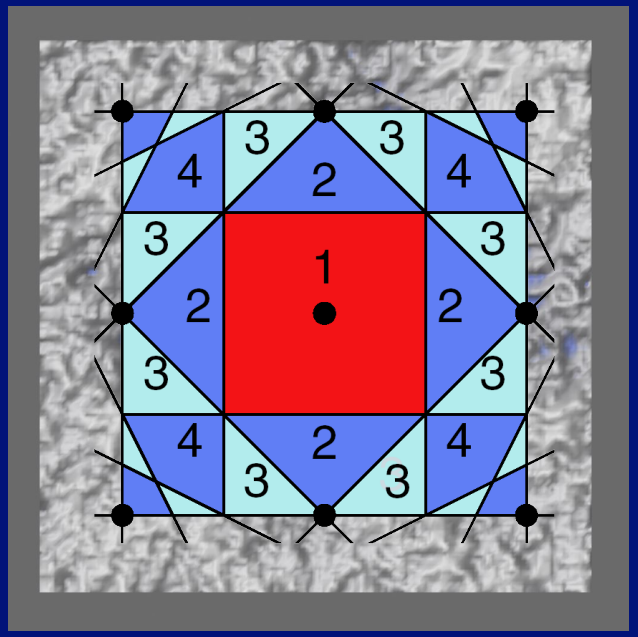
Quantum Gases (^{40}K)

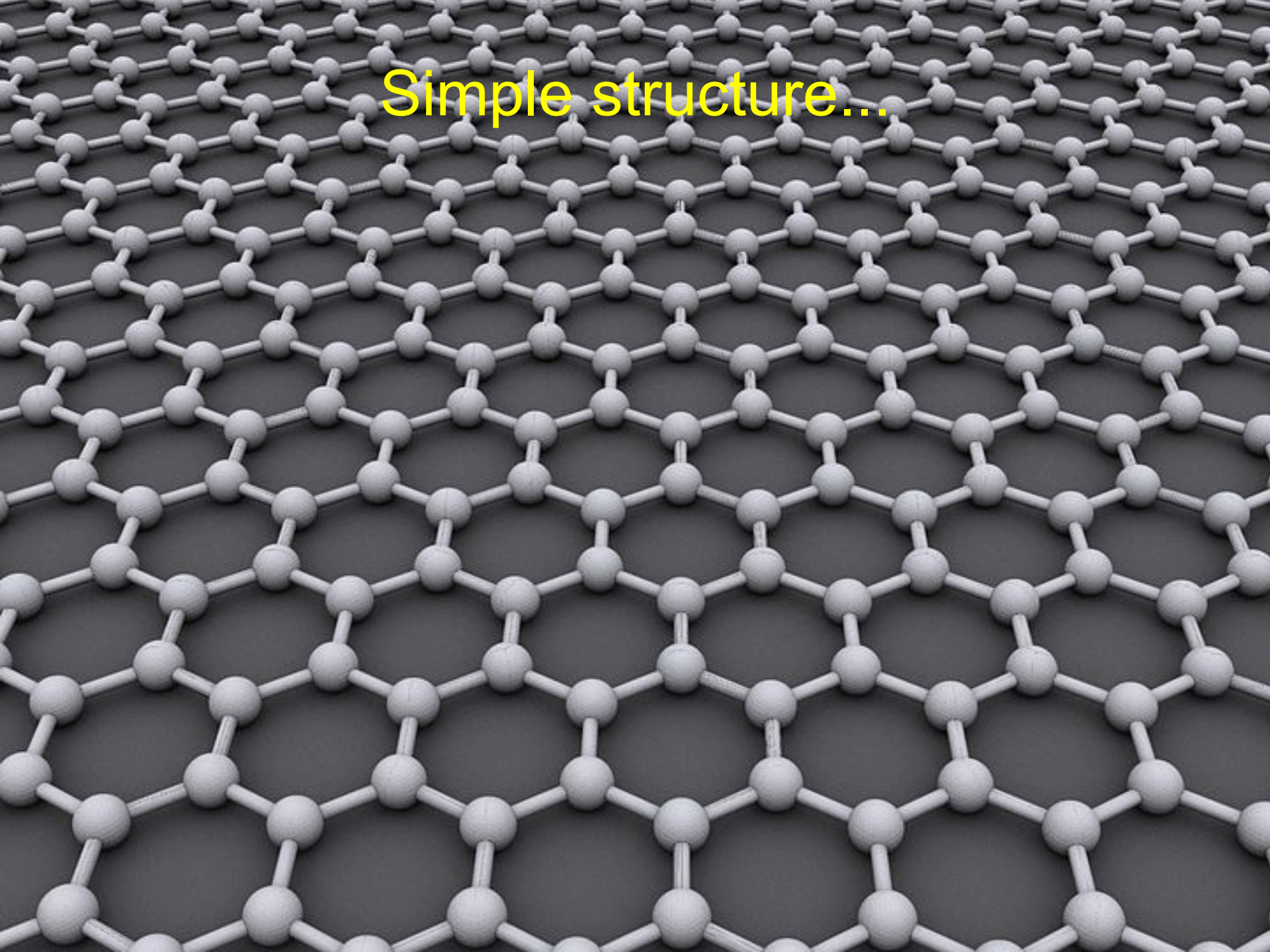
Optical Lattices

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

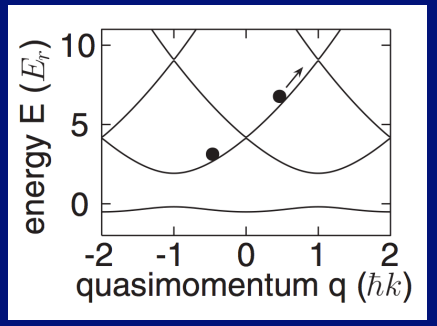

X OL
THORLABS

Simple Measurement...



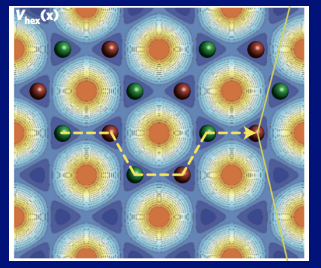

Simple structure...

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)

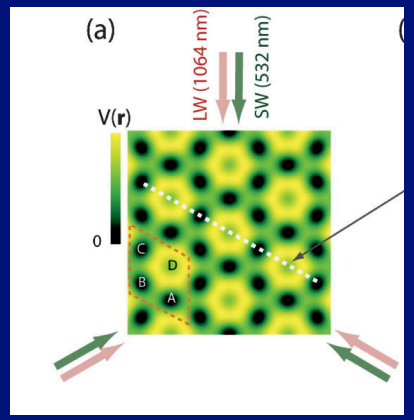


BEC in a Honeycomb lattice:

(Sengstock group, Hamburg)

P. Soltan-Panahi *et al.,* Nature Phys. 7, 434 (2011)

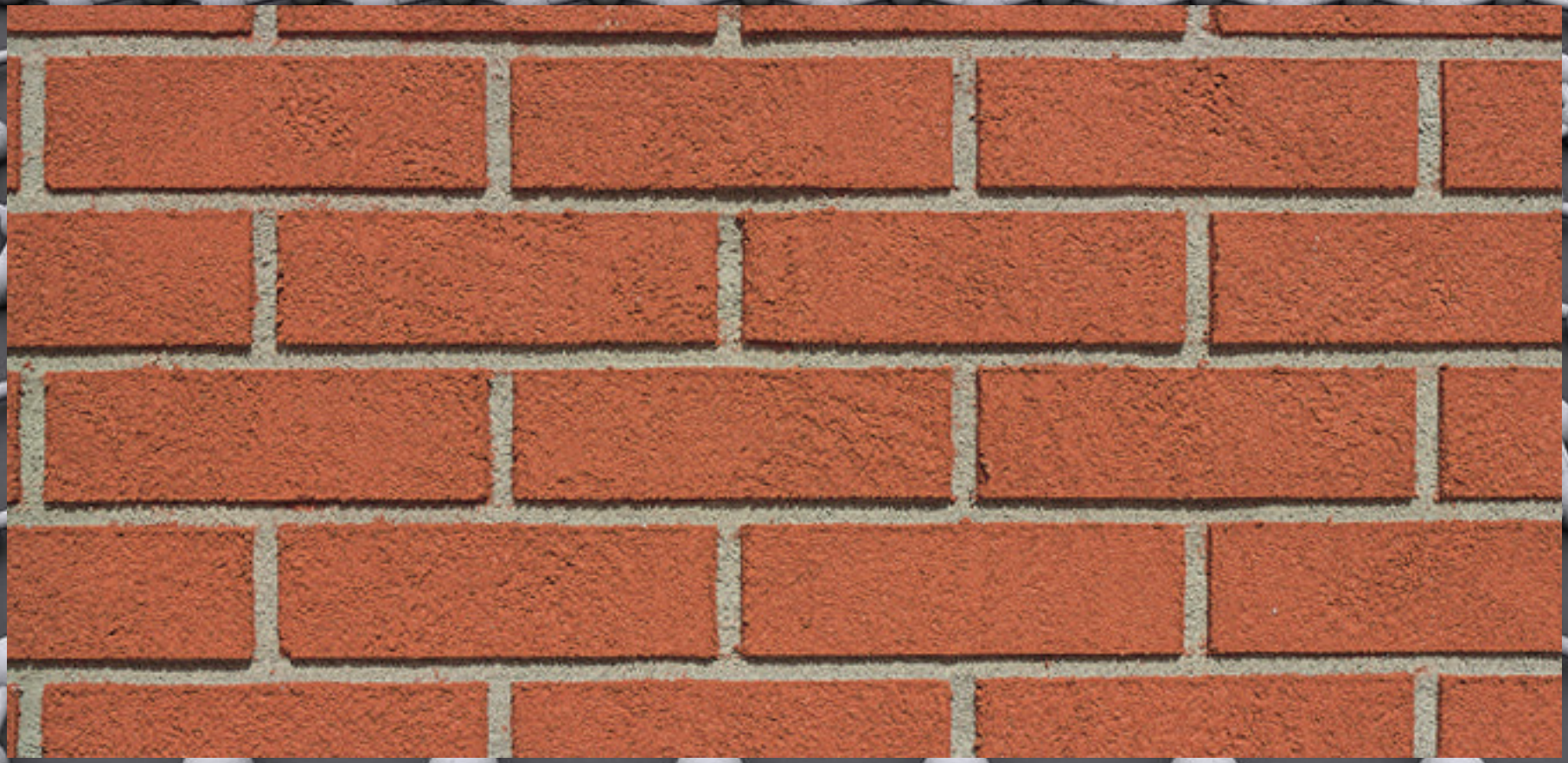
P. Soltan-Panahi *et al.*, Nature Phys. 8, 71 (2012)



BEC in Kagome:

(Dan Stamper-Kurn, Berkeley)

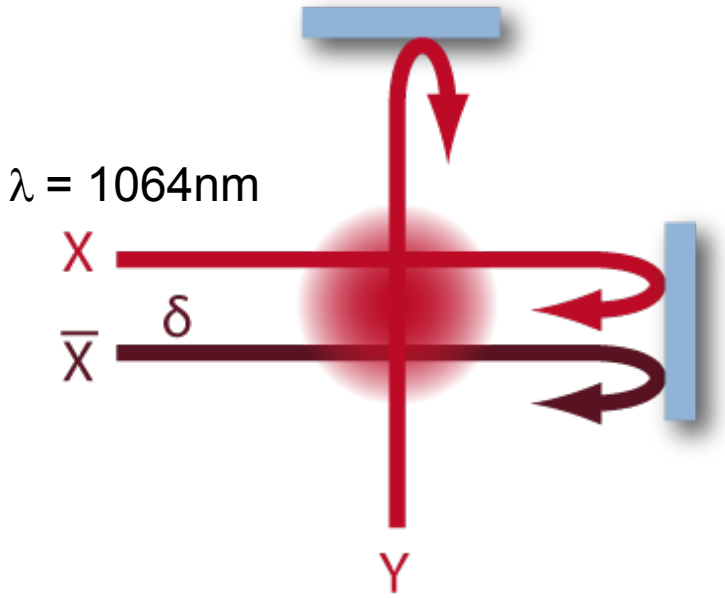
G.B. Jo et al. Phys. Rev. Lett. 108, 045305 (2012)



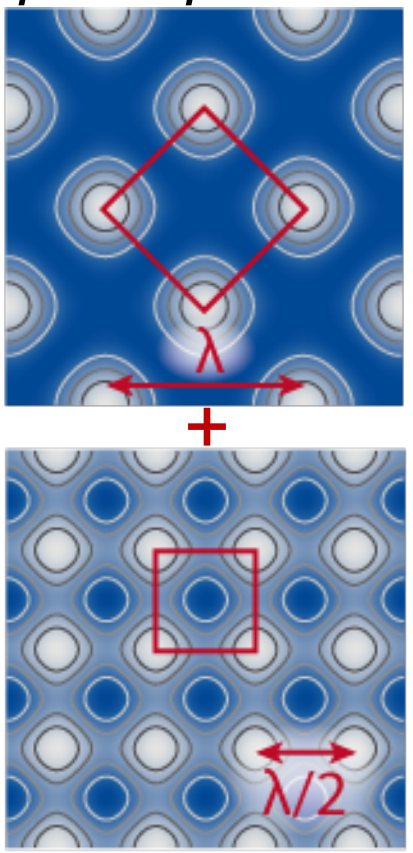
Thanks to Dario Poletti and Corinna Kollath

Tunable Geometry Optical Lattice

Setup

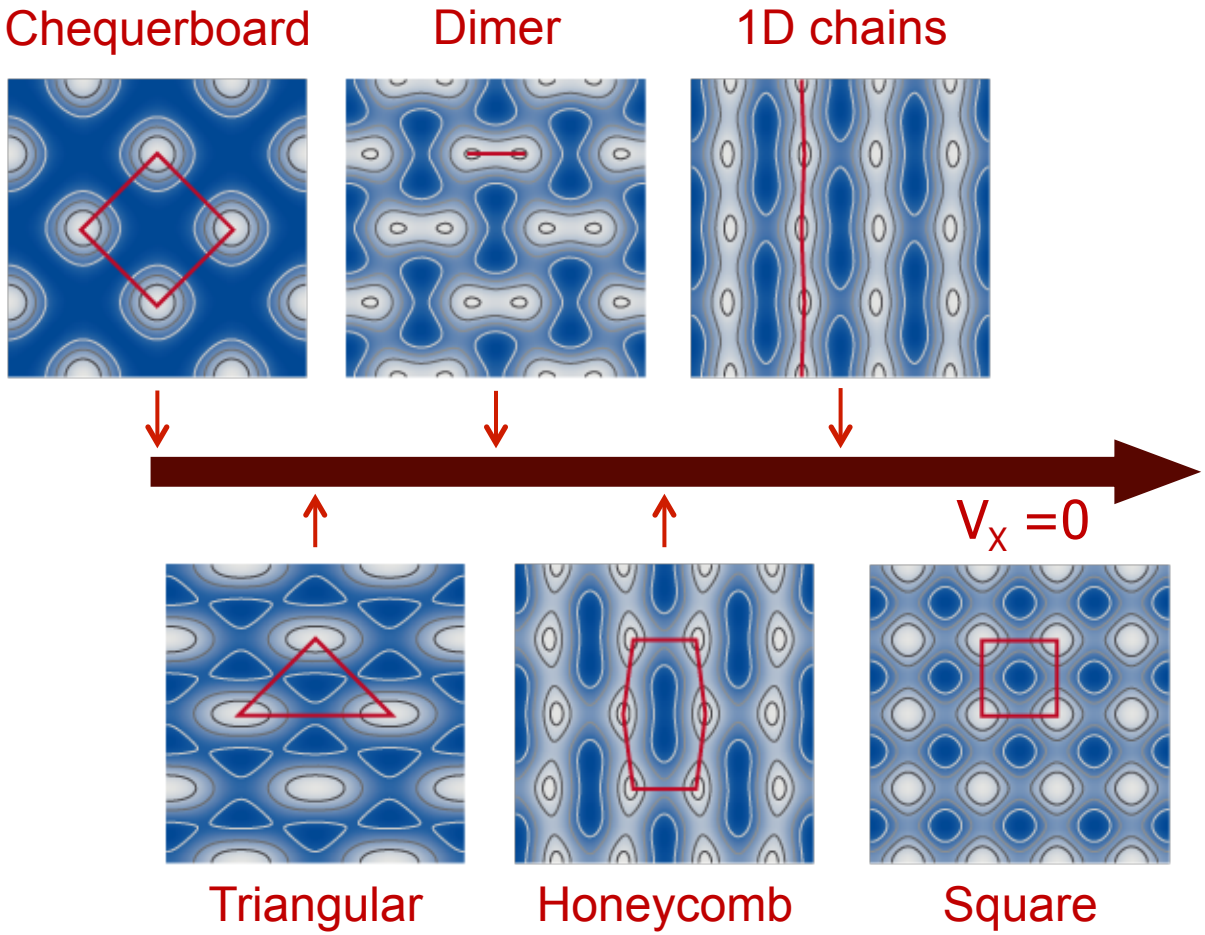


Optical potential

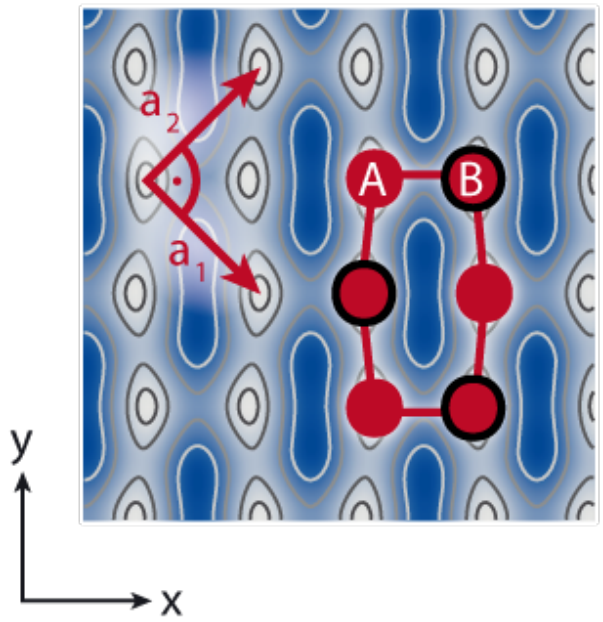


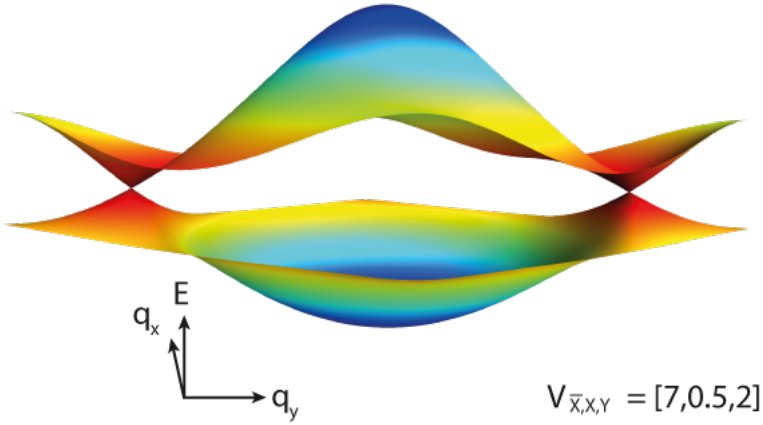
Other complex lattices: NIST, Munich, Hamburg, Berkeley

Tunable Geometry Optical Lattice



Honeycomb Lattice





$V_{\bar{X},X,Y} = [7,0.5,2]\ E_R$

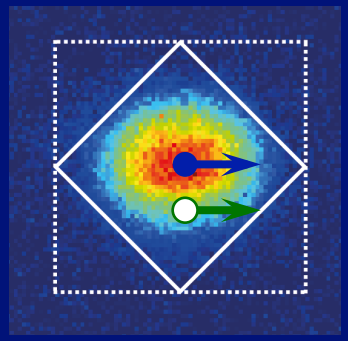
Probing the Dirac points

vanishing density of states

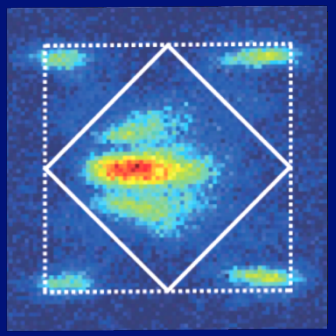
small energy scales

Bloch oscillation and interband transitions

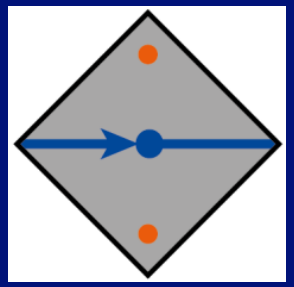
Starting point

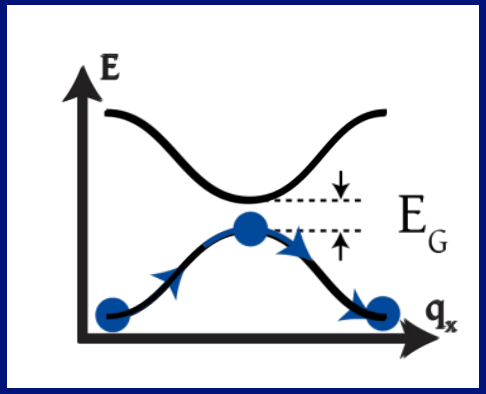


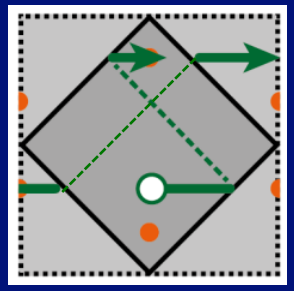
+ magnetic gradient

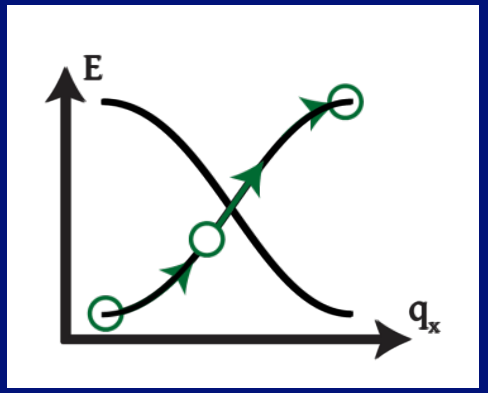


Transfer to 2nd band



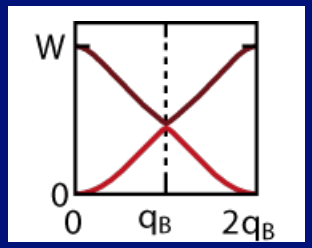


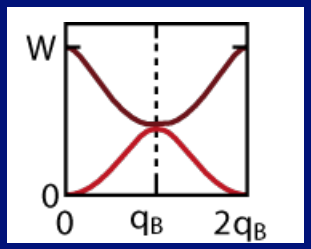


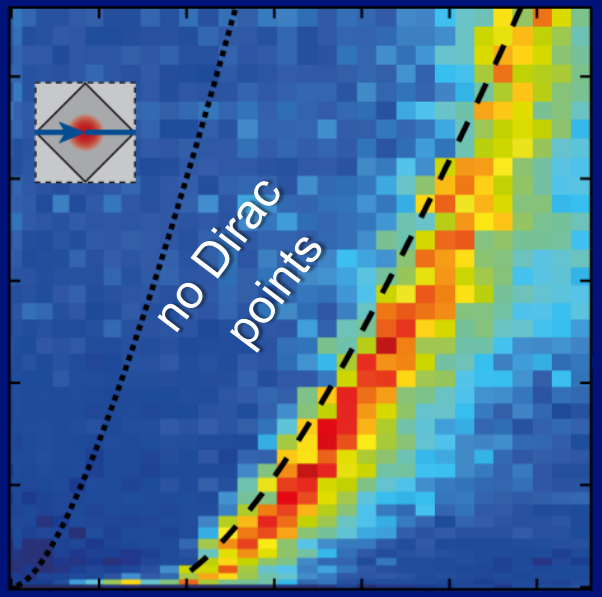


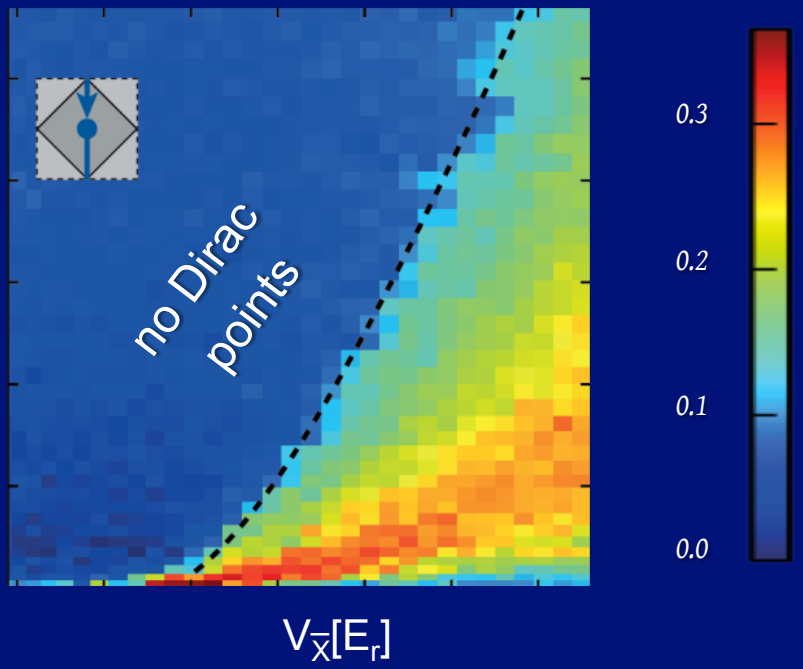
Method in 1D: T. Salger et. al, Phys. Rev. Lett. 99, 190405 (2007)

Touching Dirac points







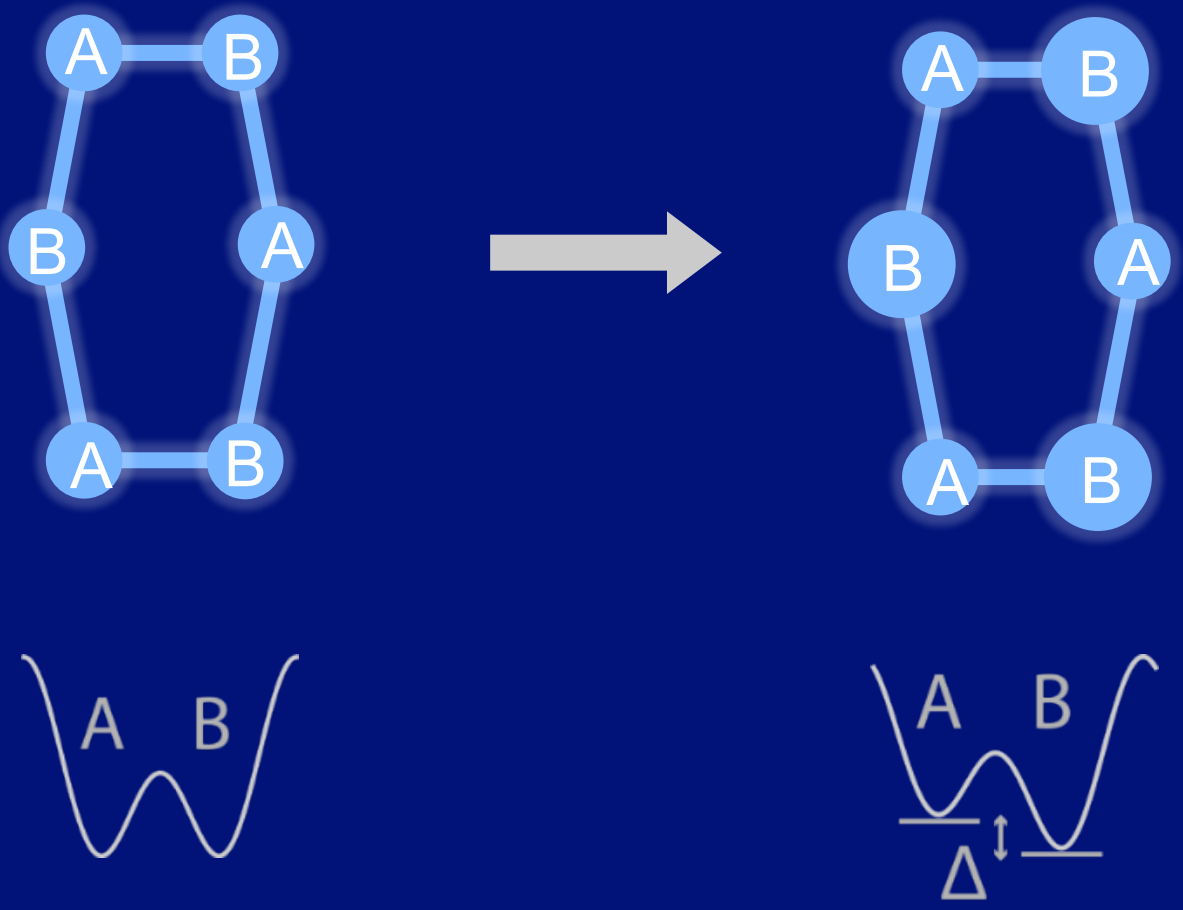


L. Tarruell, D. Greif, T. Uehlinger, G. Jotzu, and T. Esslinger, Nature 483, 302–305 (2012).

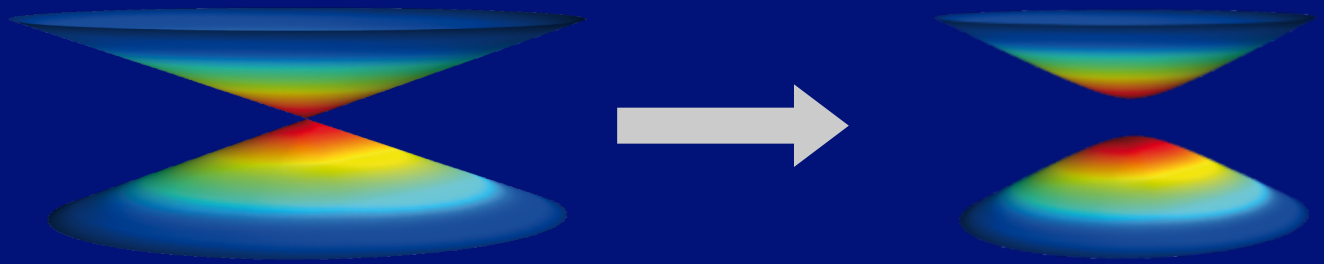
Theory, see also: L.-K. Lim, J.-N. Fuchs, G. Montambaux, PRL 108, 175303 (2012)

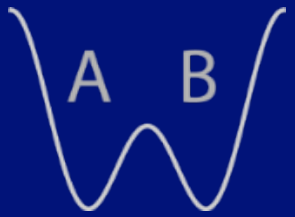
Breaking Inversion Symmetry

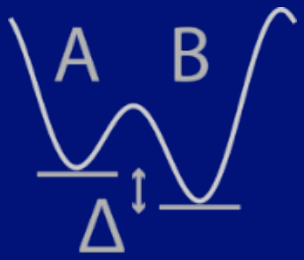
Breaking Inversion Symmetry



Berry curvature

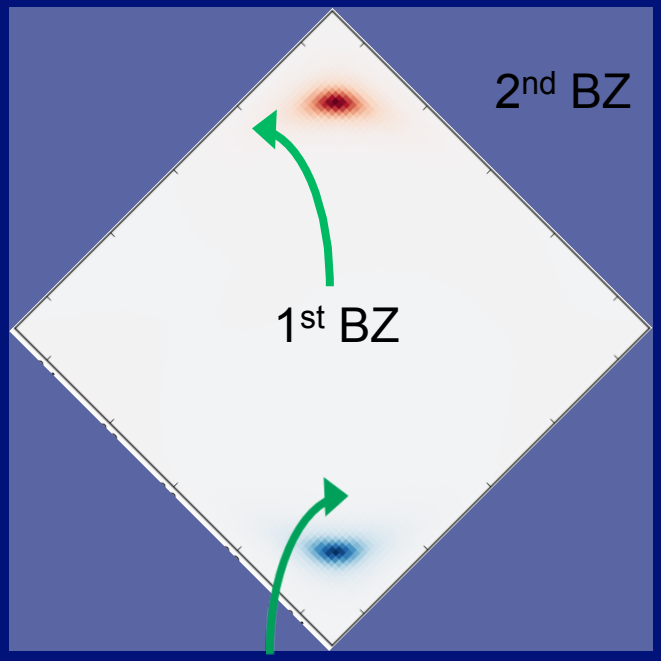






See also: L. Duca, Science 347, 288 (2015)

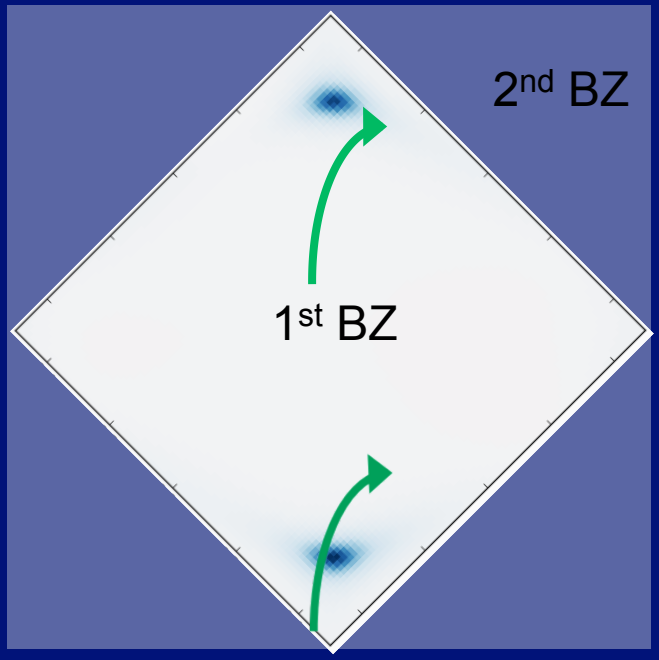
Berry Curvature and Transverse Drift



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

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

Berry Curvature and Transverse Drift



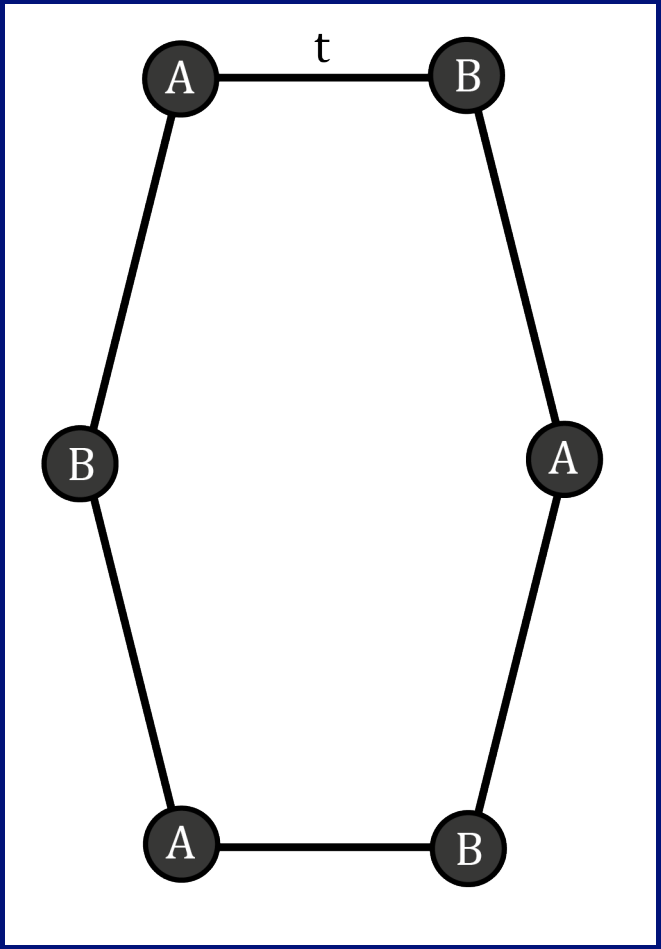
Like a Hall current

Topological Haldane model

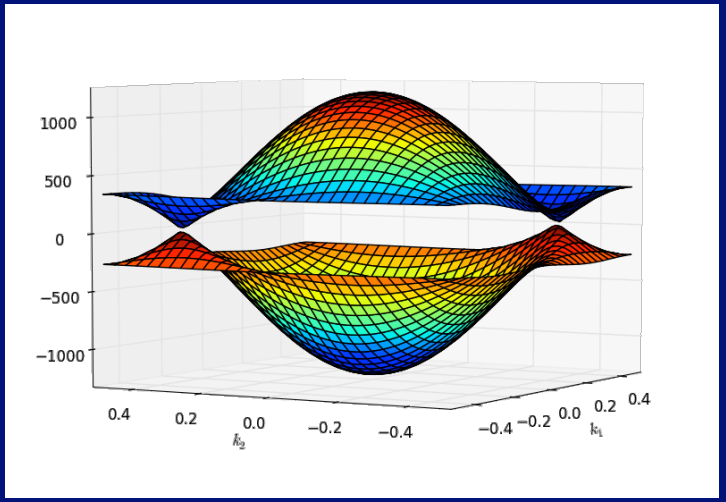
Proposal for Quantum Hall Effect *without* magnetic field!

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

Topological Haldane model



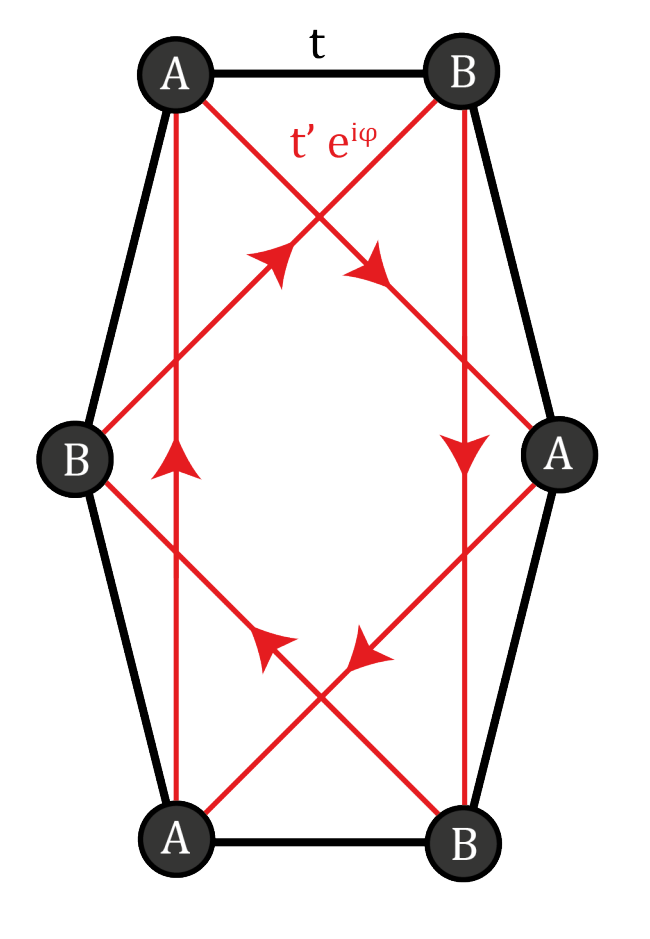
Start from a honeycomb lattice



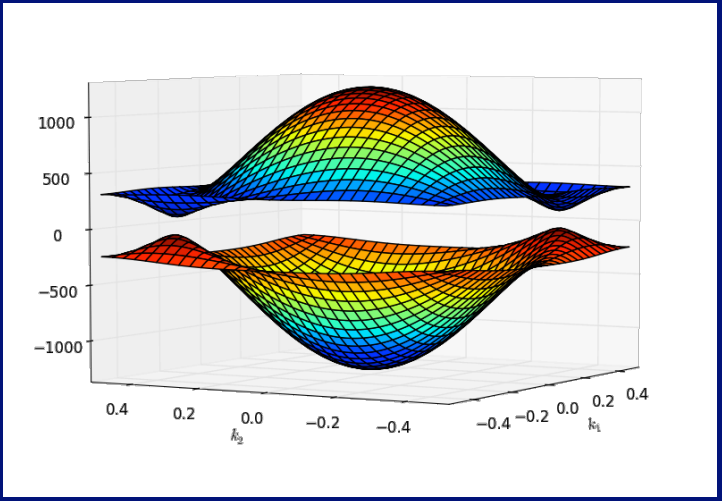
inversion and time-reversal symmertry


Topological Haldane model
break time-reversal symmetry

Topological Haldane model

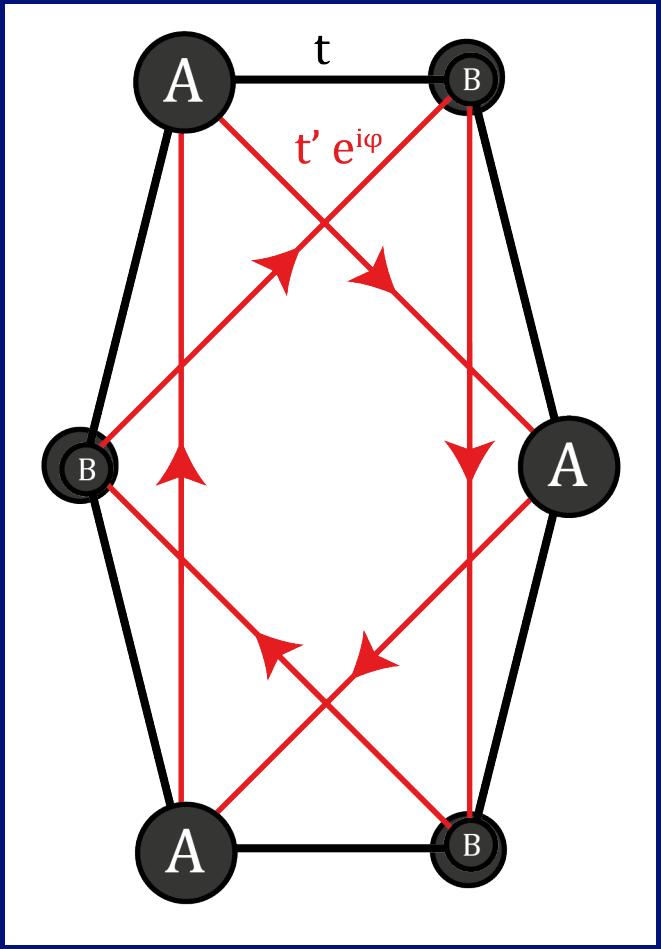


break time-reversal symmetry with complex next-nearest neighbour tunnellings

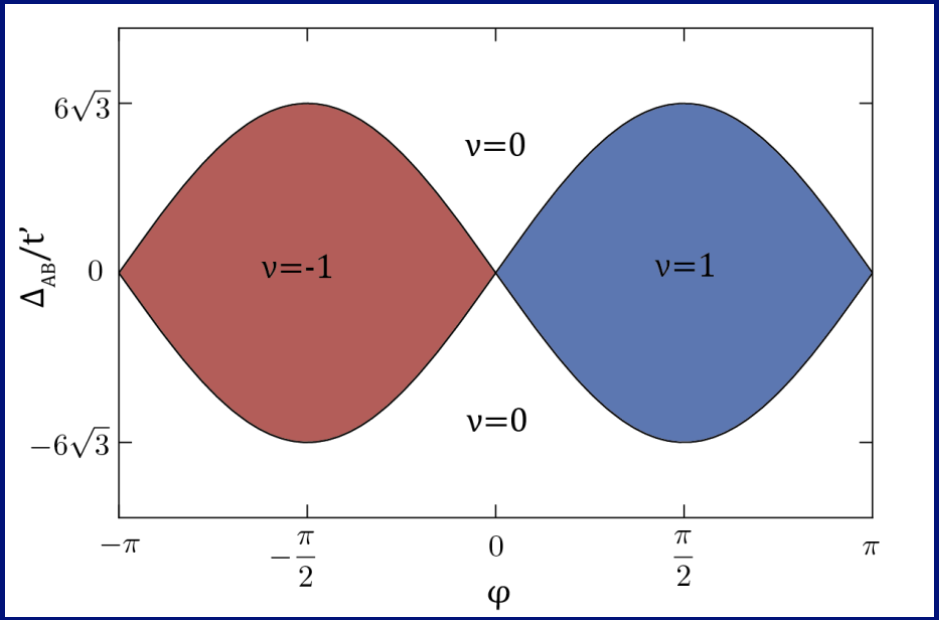


➔ Topological Chern insulator, with non-zero Hall conductance

Topological Haldane model

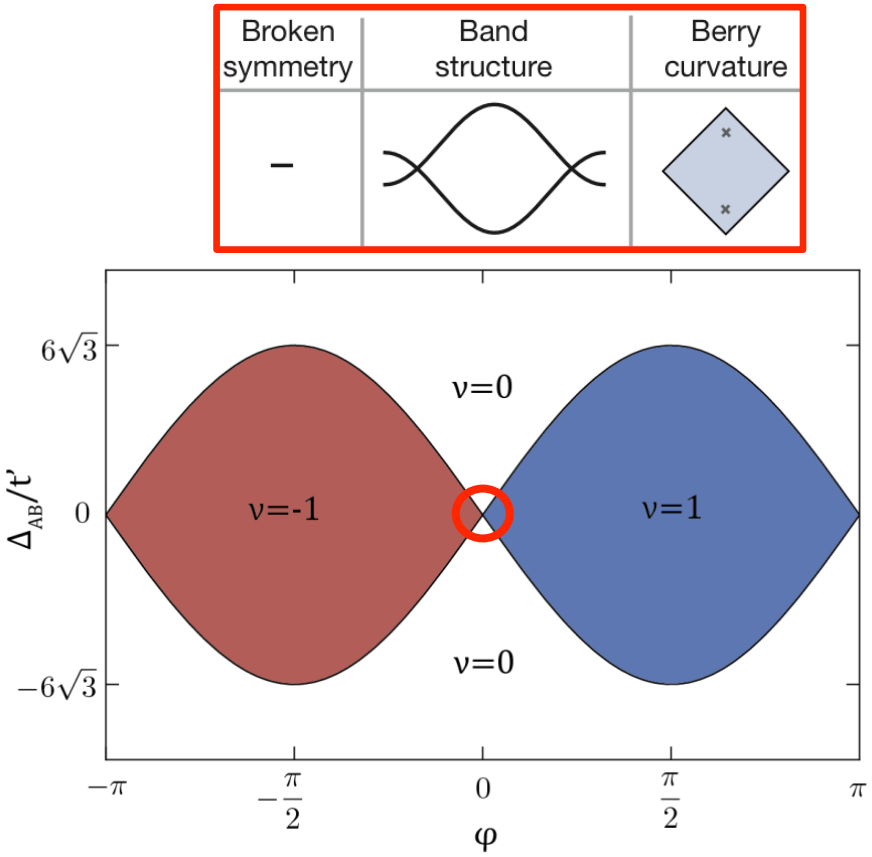


Additionally break time-reversal symmetry with energy offset



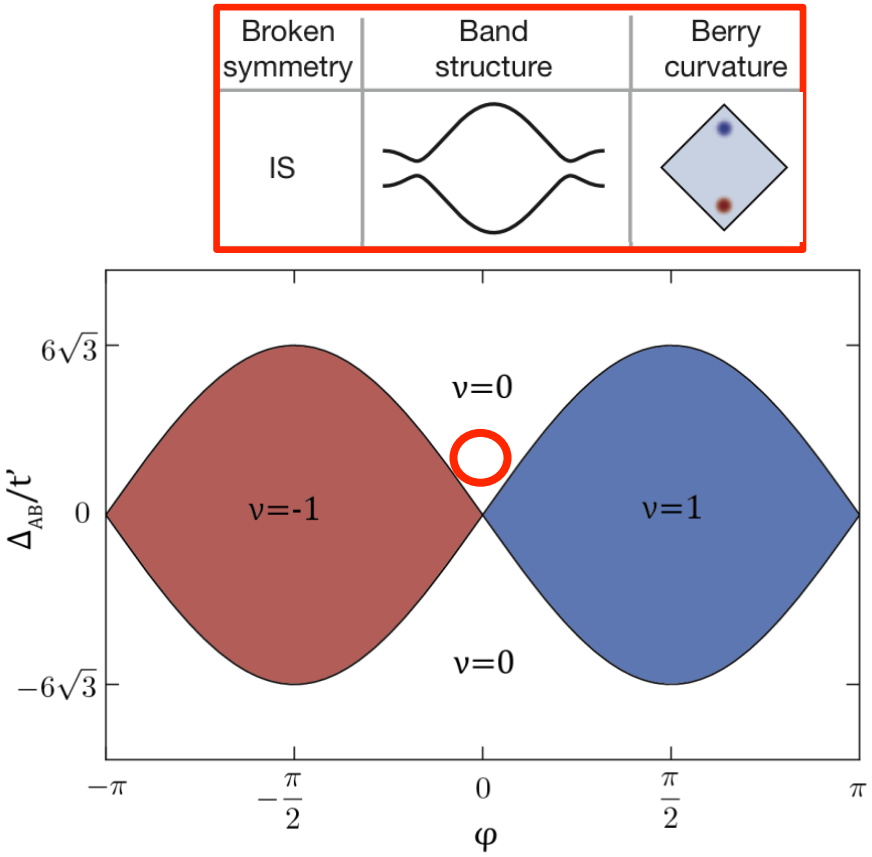
➔ Distinct topological phases

Topological Haldane model



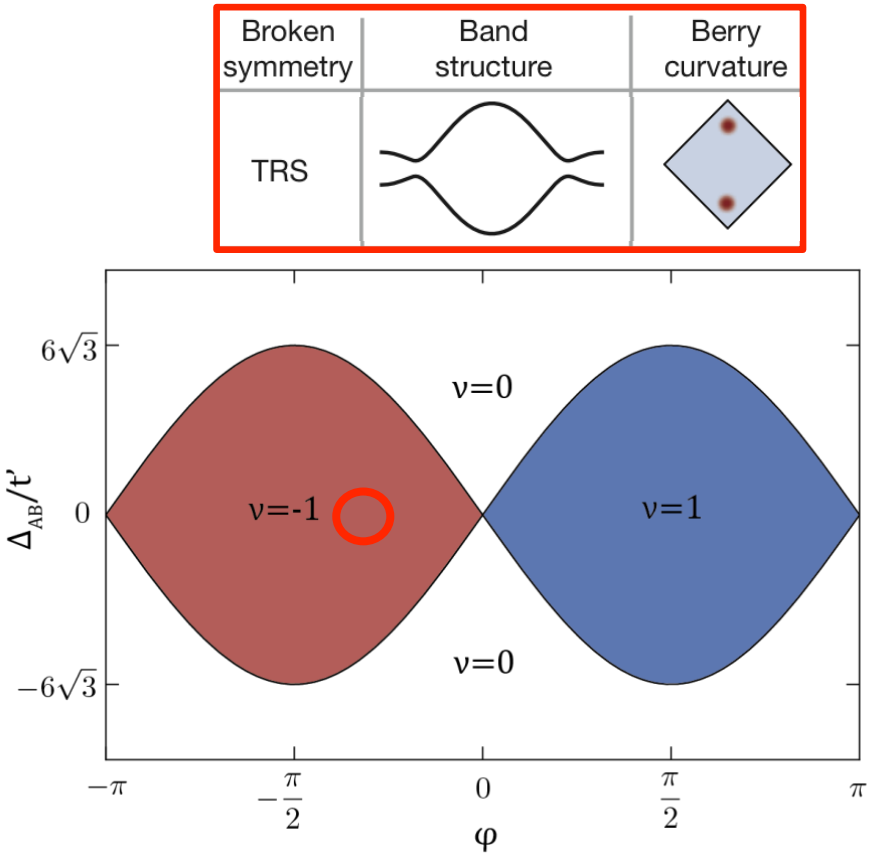
Haldane, PRL **61**,2015-2018 (1988)

Topological Haldane model



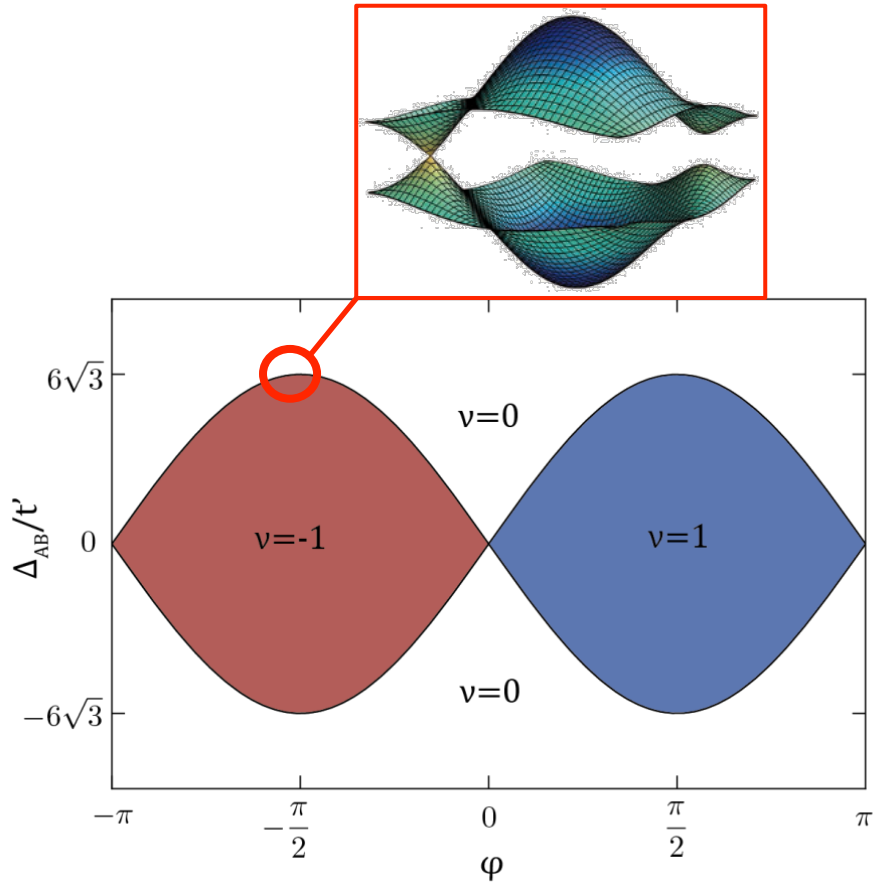
Haldane, PRL **61**,2015-2018 (1988)

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.

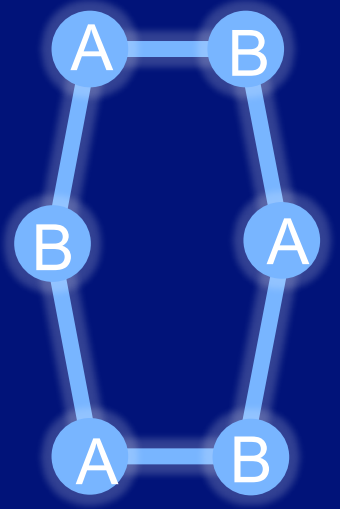
Haldane, PRL **61**,2015-2018 (1988)

Breaking time-reversal symmetry

Proposal for Photovoltaic Hall effect in graphene

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

Breaking time-reversal symmetry

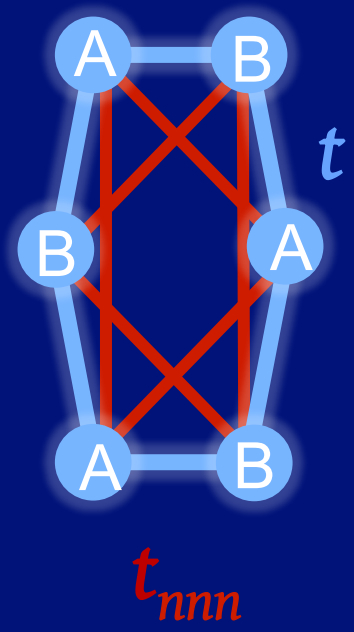


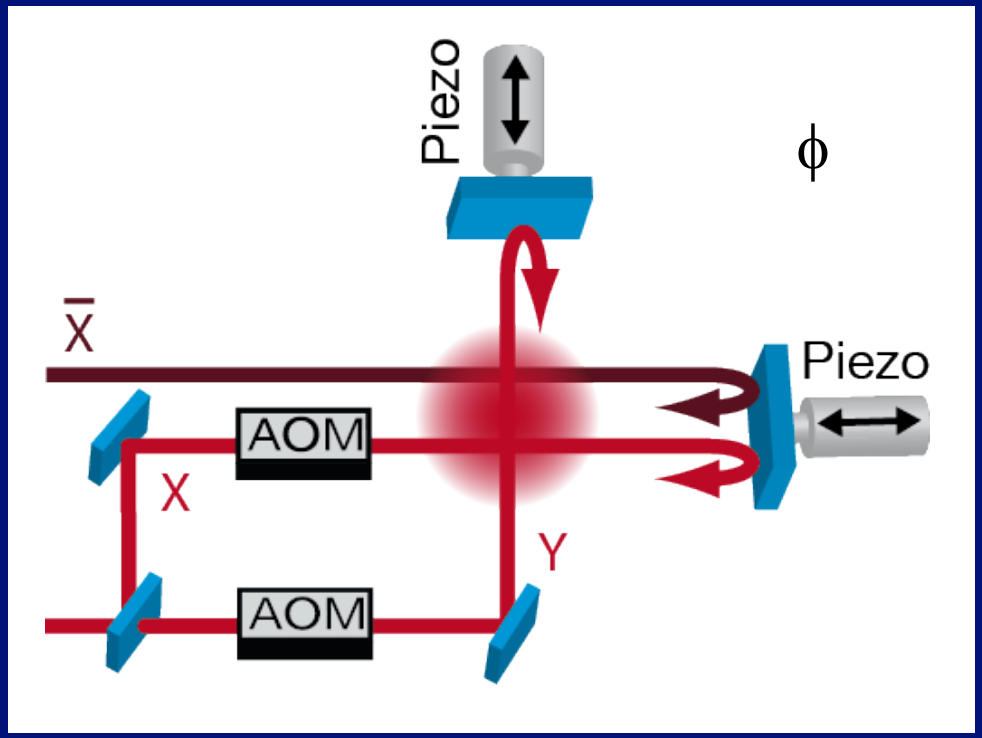
Other proposals to realize topological Hamiltonains:
T. Kitagawa et al., Phys. Rev. B 82, 235114 (2010)
P. Hauke et al., Phys. Rev. Lett 109, 145301 (2012)

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

Breaking time-reversal symmetry

Lattice Shaking

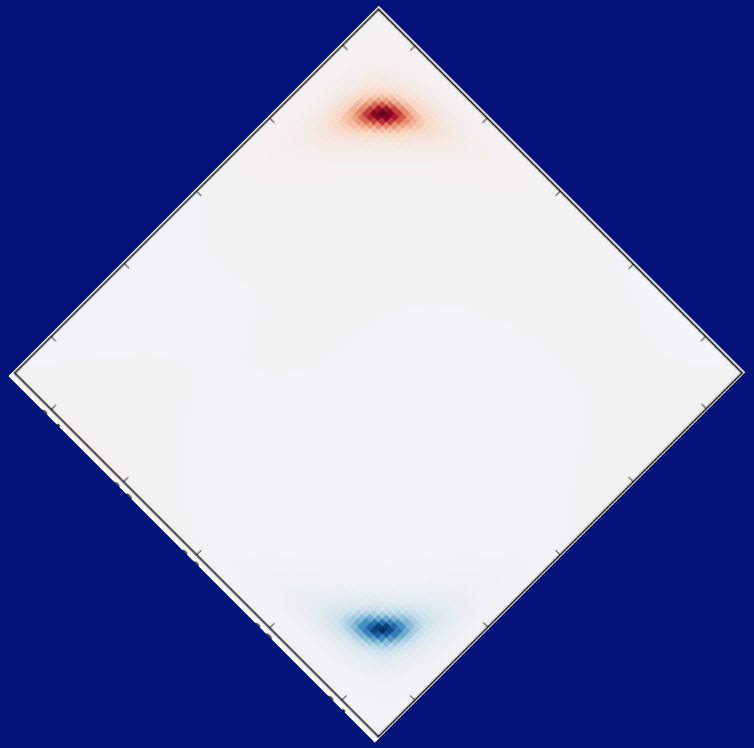




Lattice shaking: Pisa — Lignier, PRL **99**, 220403 (2007)
Hamburg/Barcelona — Struck, Science **333**, 996-9 (2011), PRL 108, 225304 (2012)
Chicago — Parker, Nat. Phys. **9**, 769-774 (2013)

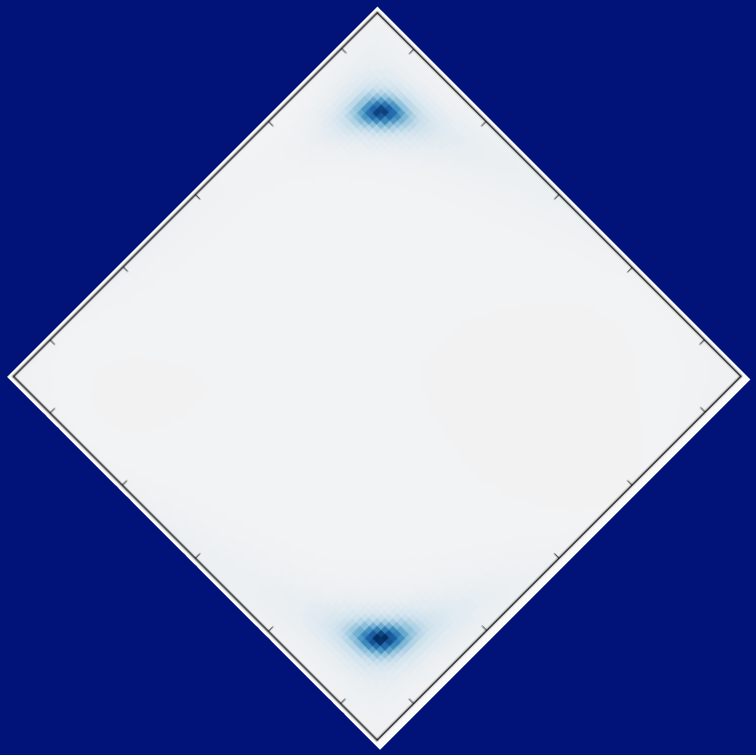
Berry Curvature

Trivial band insulator



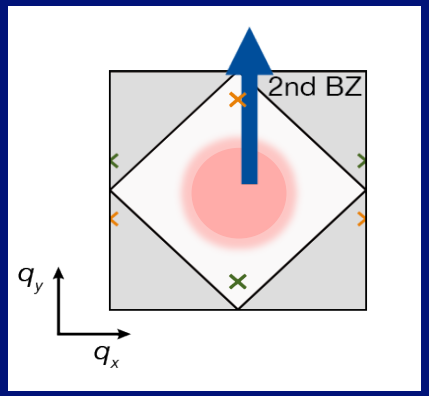
Chern number 0

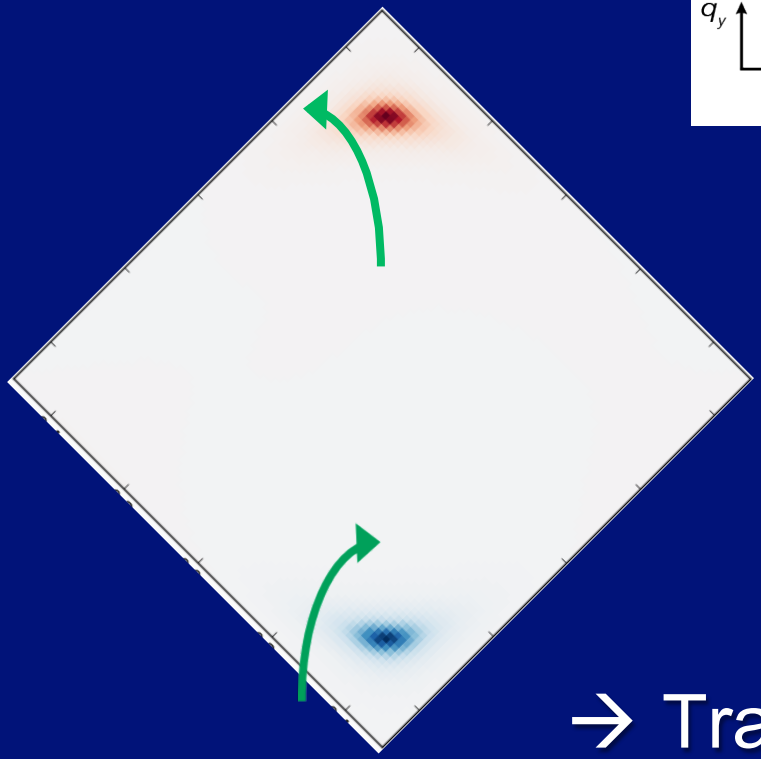
Chern insulator

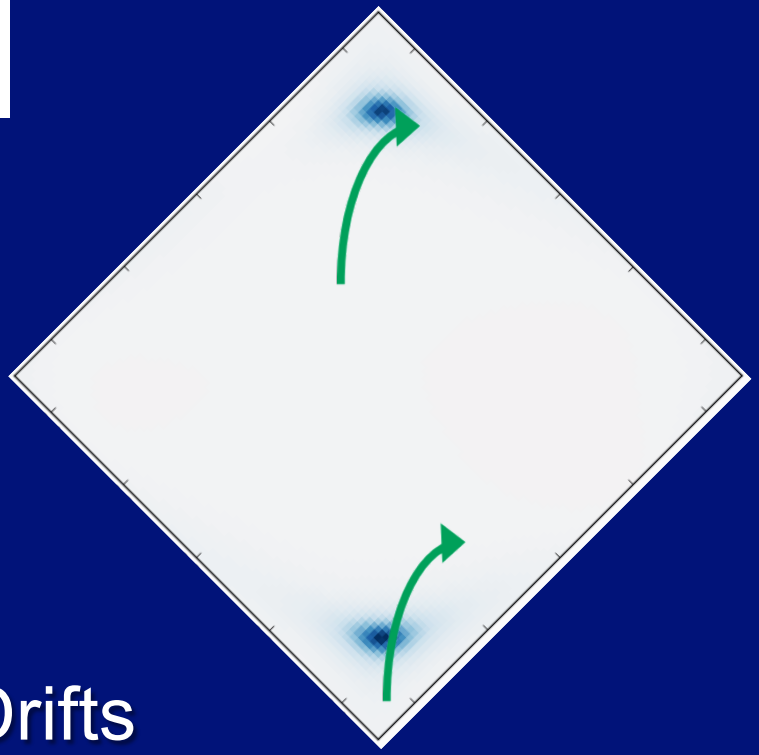


Chern number -1

Berry Curvature - Measurement



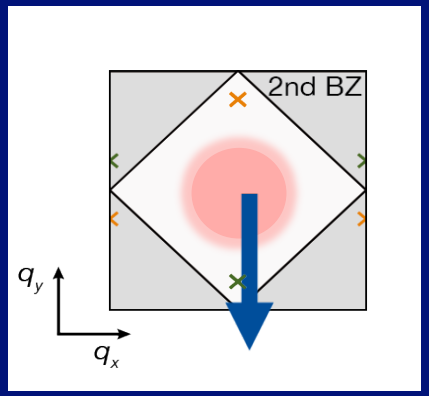


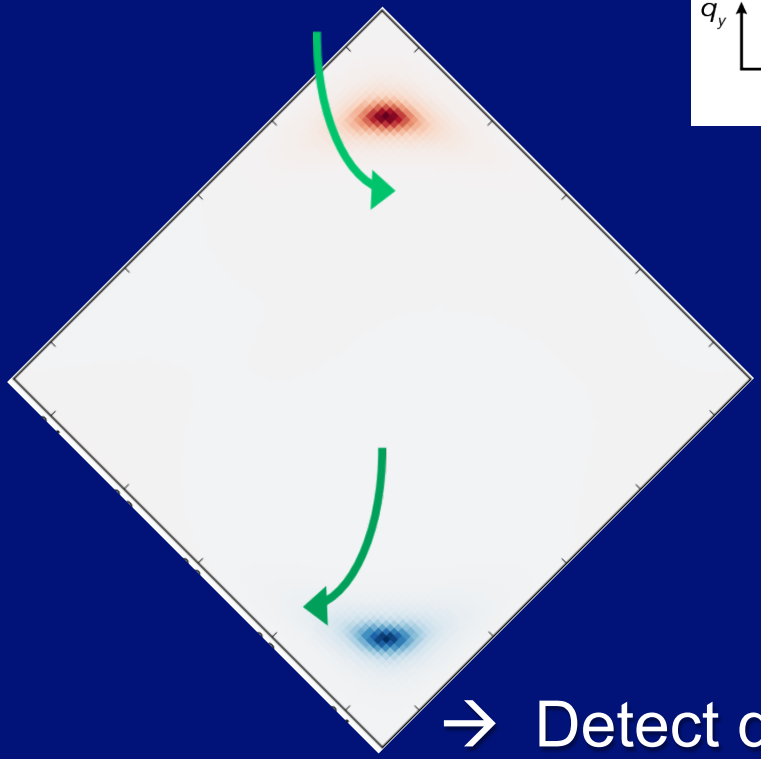


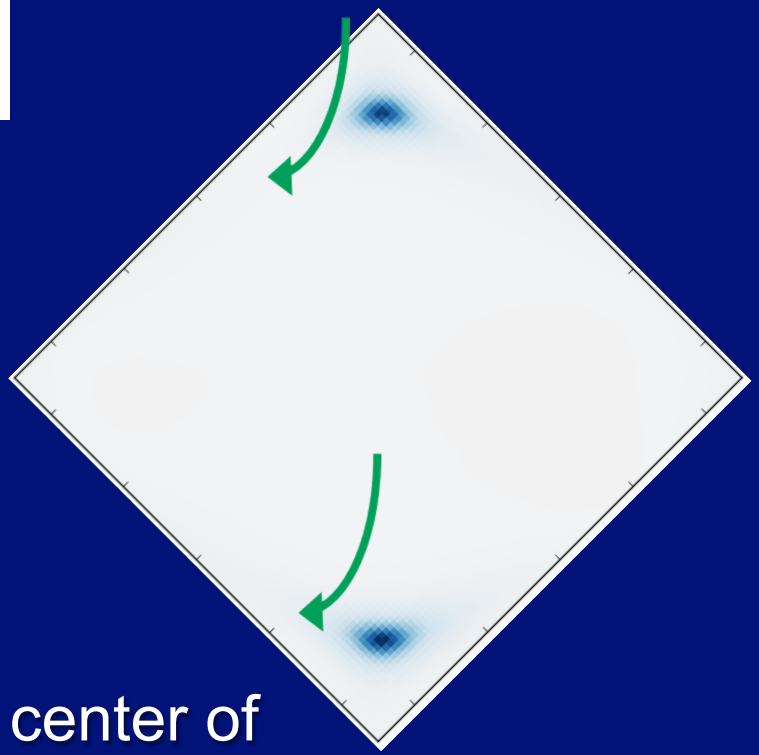
→ Transverse Drifts

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

Berry Curvature - Measurement







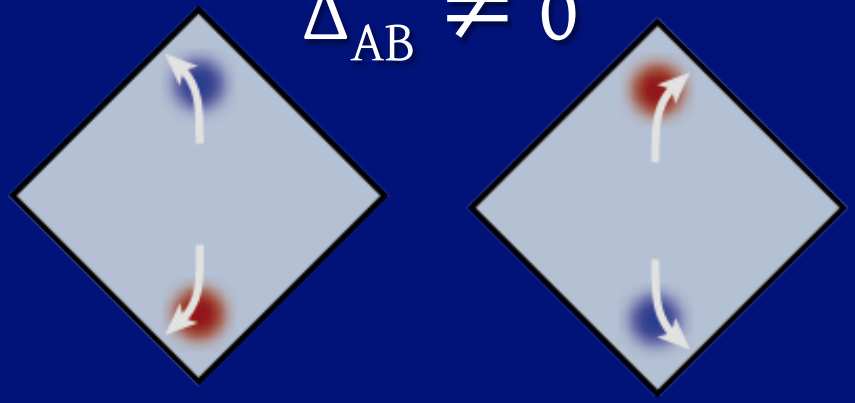
→ Detect difference in center of mass position after full Bloch cycle

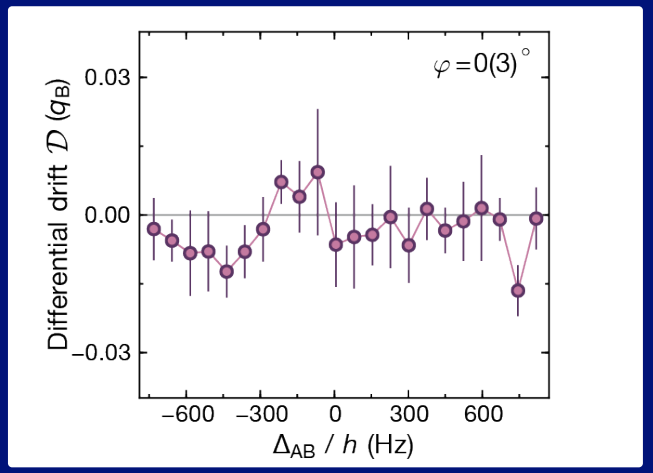
See also: M. Aidelsburger, Nature Physics 11, 162 (2015)

Topological features of the system

topologically trivial

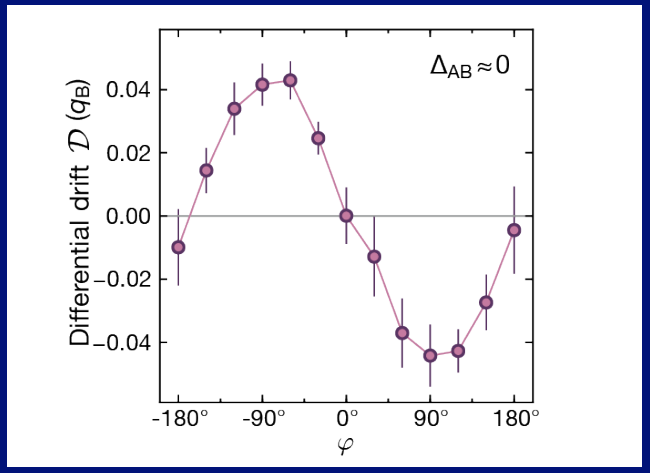
$\Delta_{AB} \neq 0$





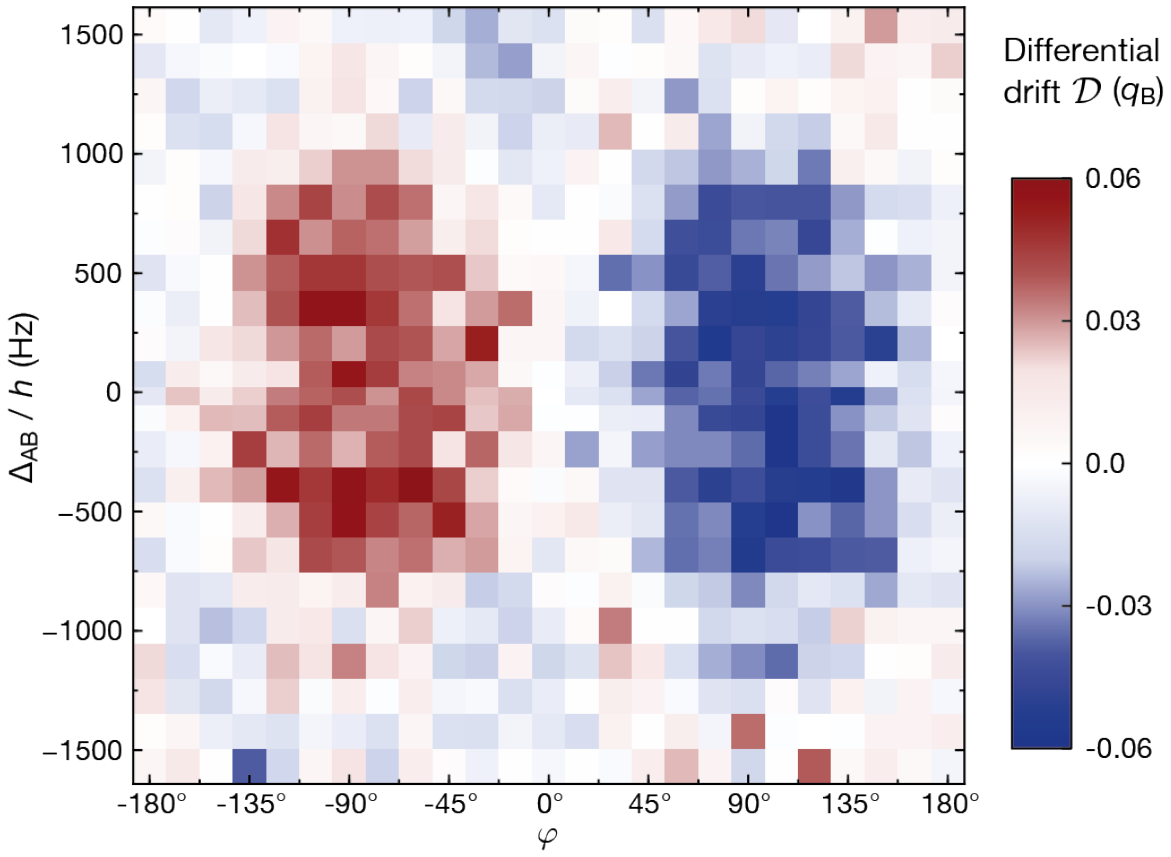
nonzero Chern number

$\Delta_T \neq 0$



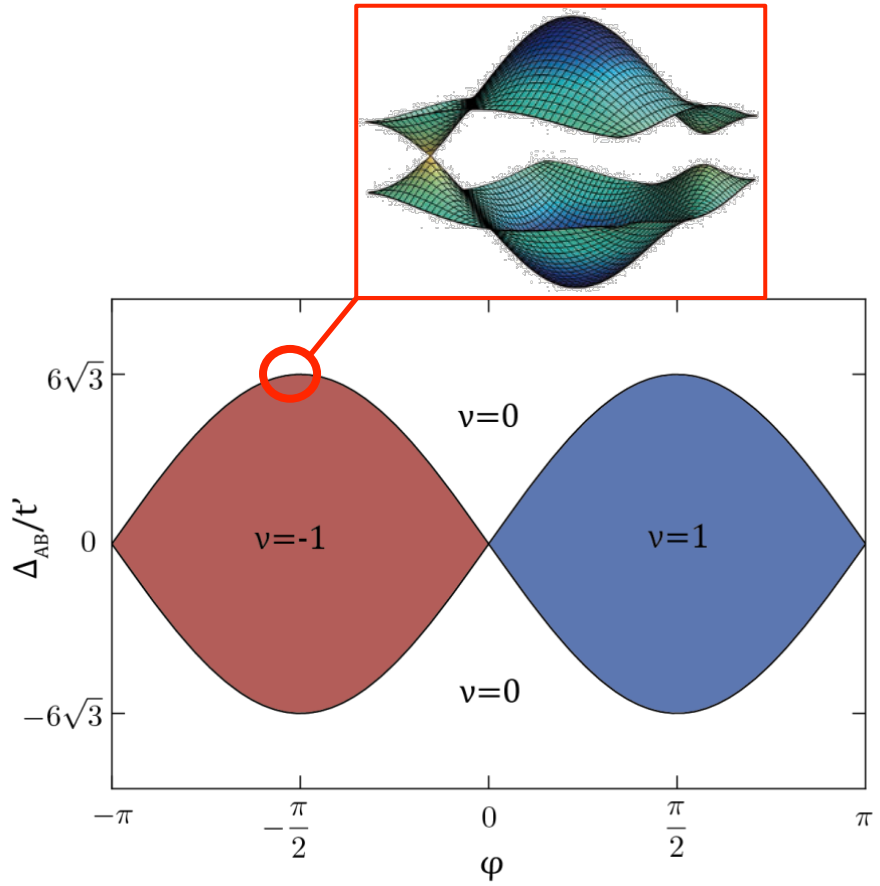
G. Jotzu, M. Messer, R. Desbuquois, M. Lebrat, T. Uehlinger, D. Greif, T. E., Nature 515, 237 (2014)

Observing Transverse Drifts

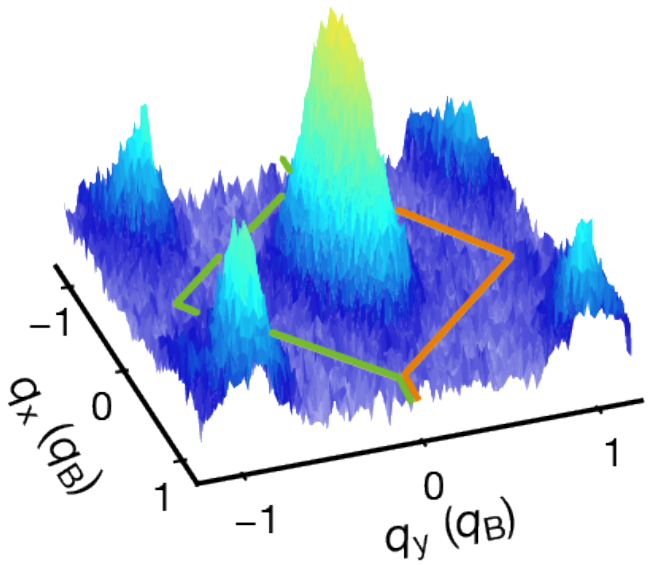


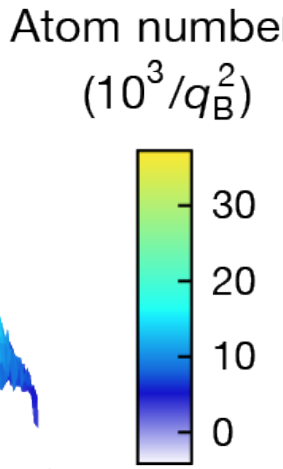
G. Jotzu, M. Messer, R. Desbuquois, M. Lebrat, T. Uehlinger, D. Greif, T. E., Nature 515, 237 (2014)

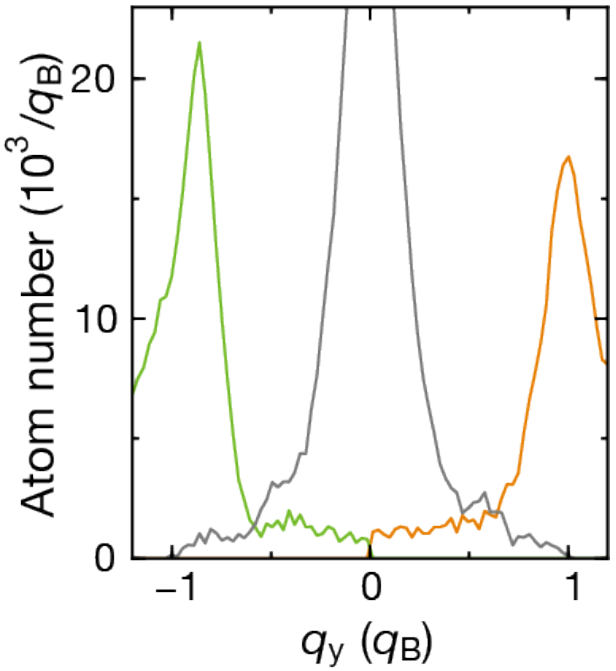
Mapping out the transition line



Mapping out the transition line

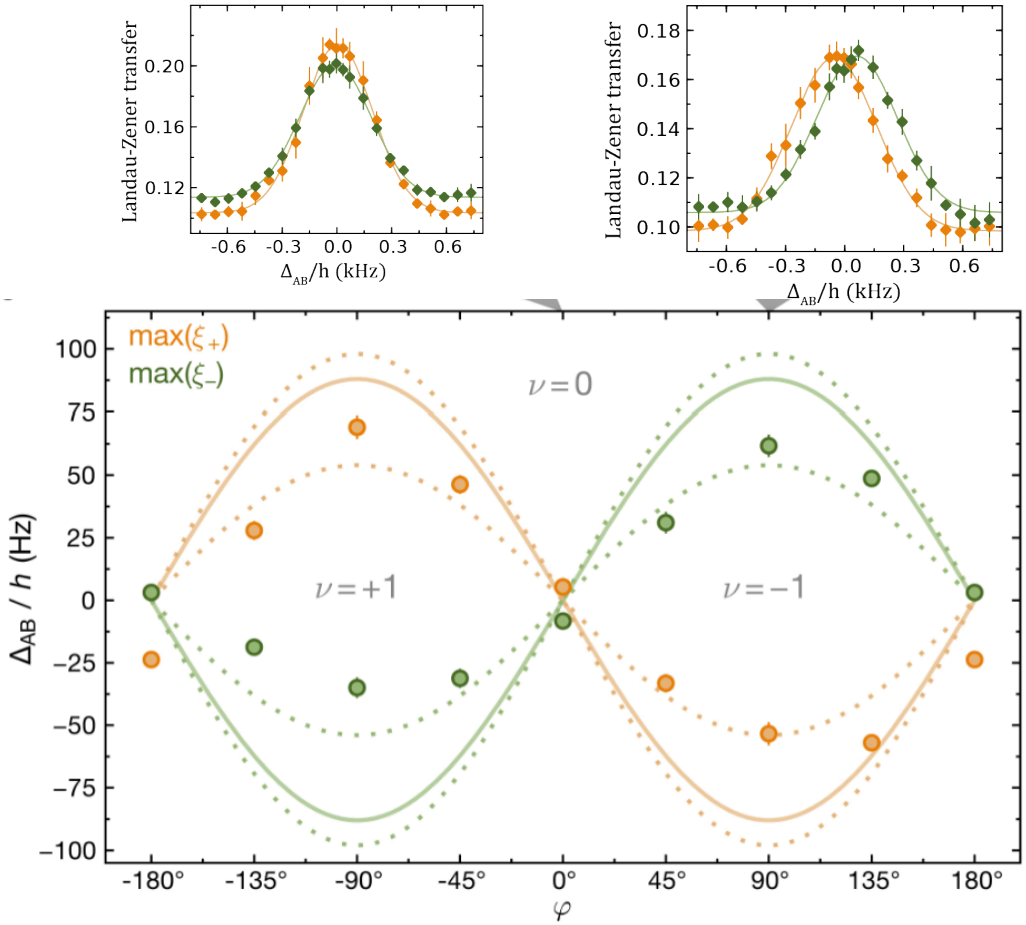






G. Jotzu, M. Messer, R. Desbuquois, M. Lebrat, T. Uehlinger, D. Greif, T. E., Nature 515, 237 (2014)

Mapping out the transition line



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

What about interactions?

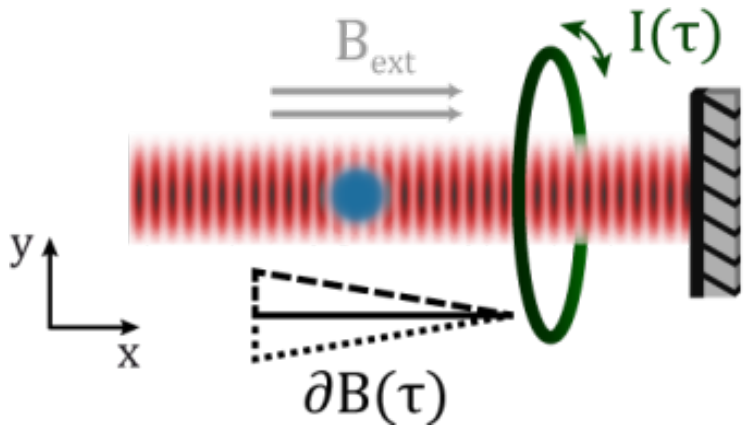
Little is known

What about interactions?

Loaded interacting gas into
coupled layers of Haldene models

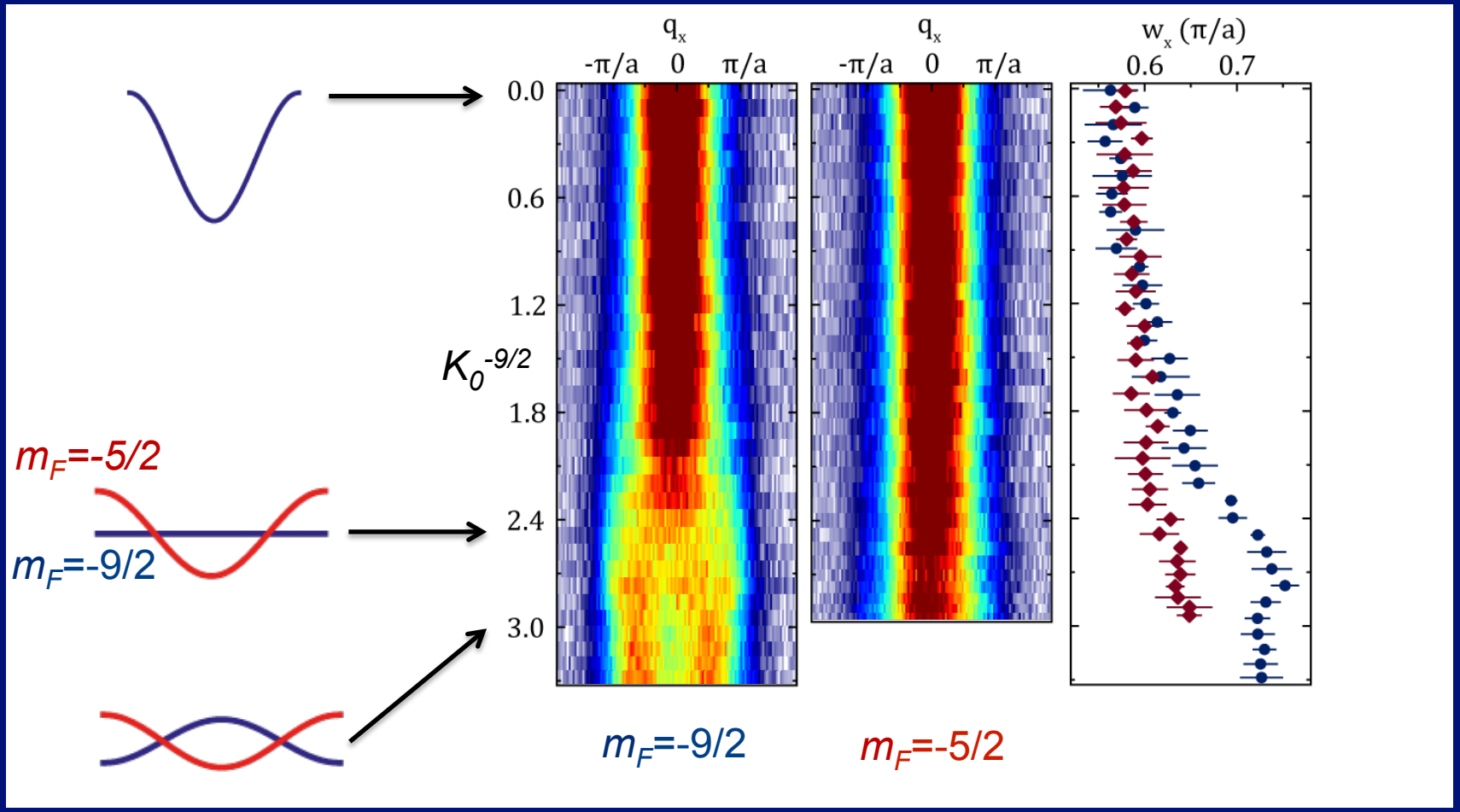
➔ Observed no significant heating

What about spin dependency?



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

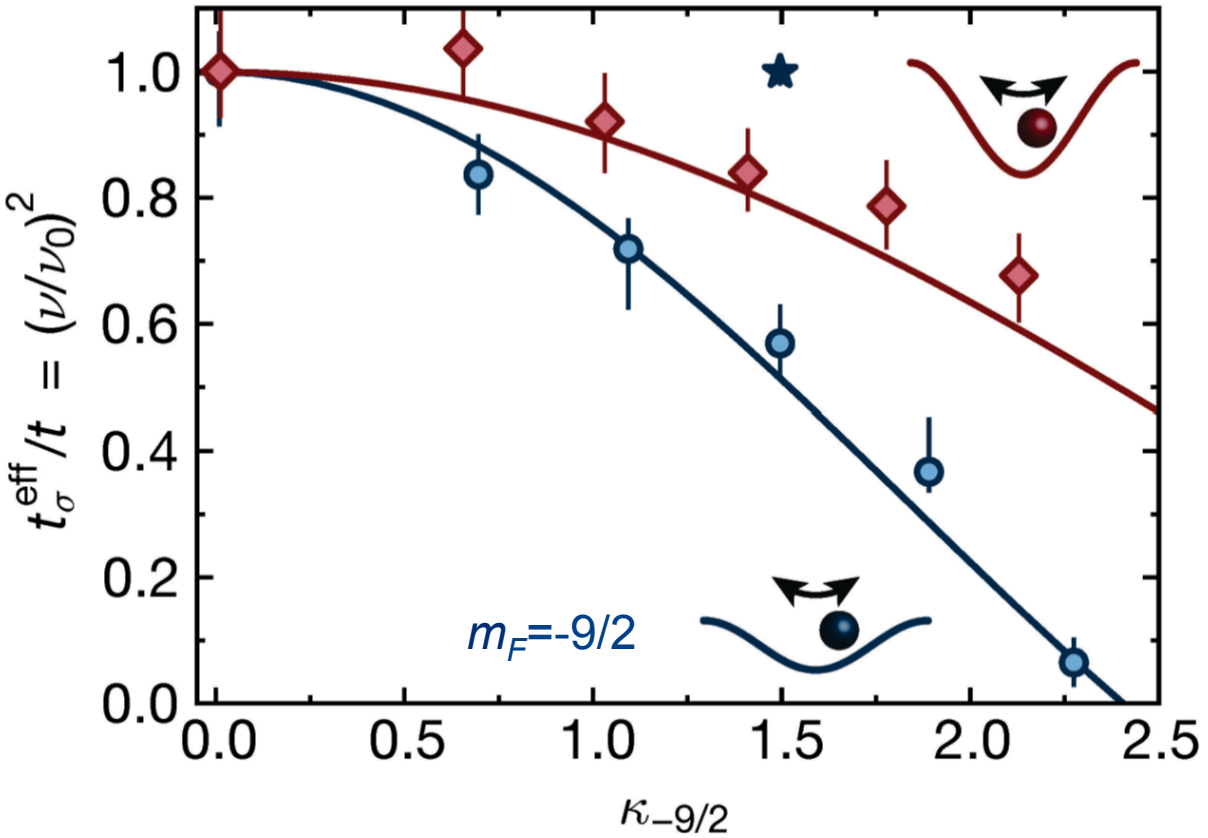
What about spin dependence?



The band structure is different for each internal state

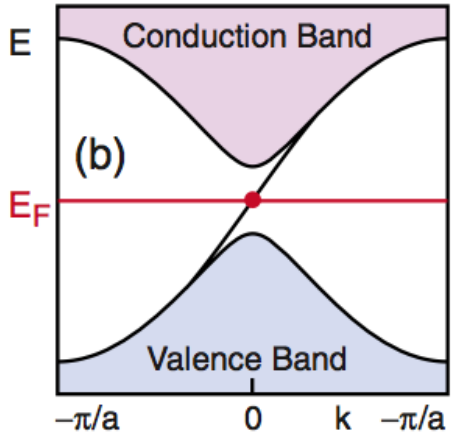
G. Jotzu, M. Messer, F. Görg, D. Greif, R. Desbuquois, and T.E. PRL 115, 073002 (2015)

What about spin dependence?



G. Jotzu, M. Messer, F. Görg, D. Greif, R. Desbuquois, and T.E. PRL 115, 073002 (2015)

What about quantized edge currents?

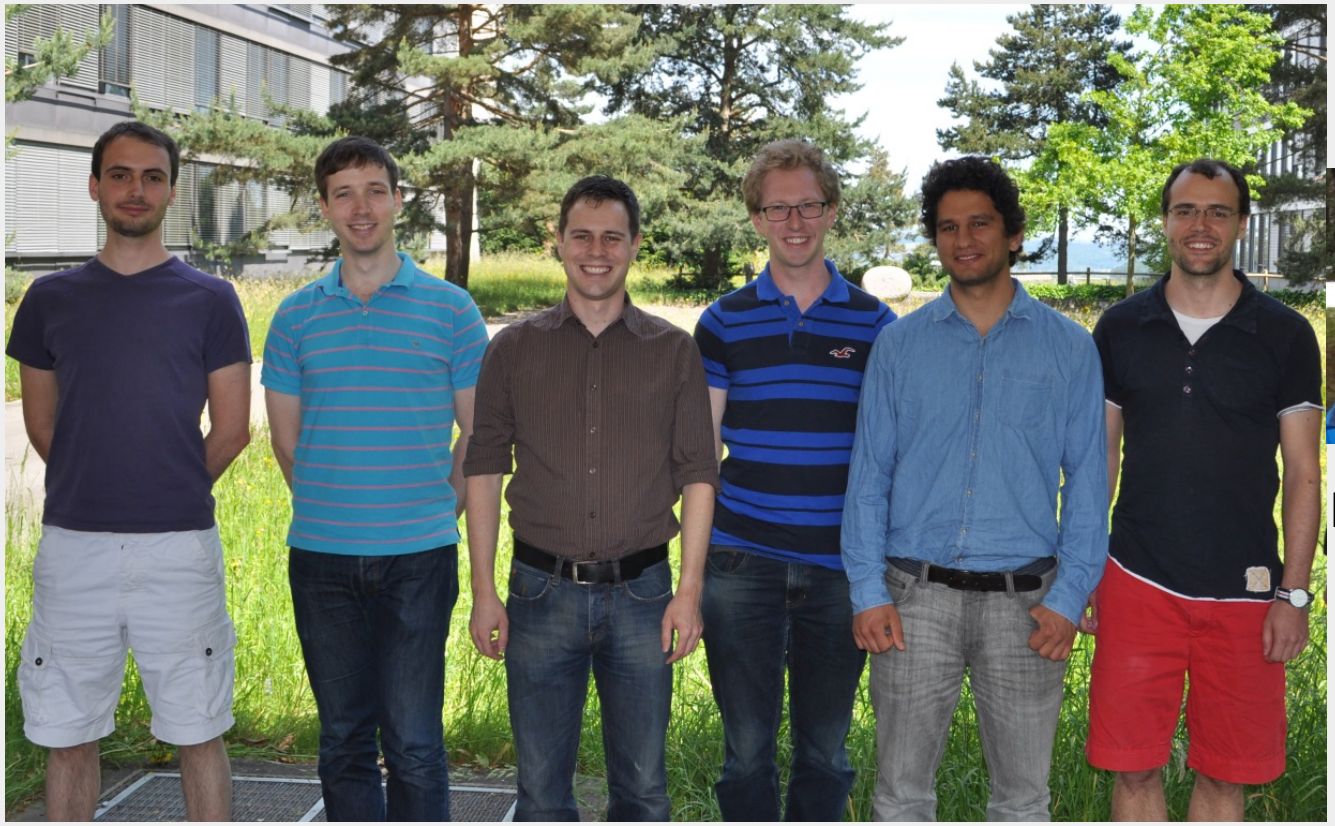


Hasan, Kane RMP 82, 3045 (2010)

See: M. Mancini et al. Science 349, 1510 (2015)
B. K. Stuhl et al. Science 349, 1514 (2015)

The Lattice team

+ Leticia Tarruell: now @ ICFO, Barcelona



Frederic Görg

Martin Lebrat now@Lithium

Rémi Desbuqouis

Thomas Uehlinger now@Sensirion

Michael Messer

Gregor Jotzu

Daniel Greif now@Harvard

Supersolidity?

Supersolidity?

Coexistence of:

- non-trivial diagonal long-range order
- off-diagonal long-range order

A. J. Leggett, Phys. Rev. Lett. 25, 1543 (1970)

A possible Hamiltonian

$$H = J \sum_{\langle i,j \rangle} b_i^\dagger b_j + \frac{1}{2} U_0 \sum_i n_i (n_i - 1)$$

$$+ \frac{1}{2} U_{\sigma_1} \sum_{\langle i,j \rangle} n_i n_j + \frac{1}{2} U_{\sigma_2} \sum_{\langle\langle i,j \rangle\rangle} n_i n_j + \cdots$$

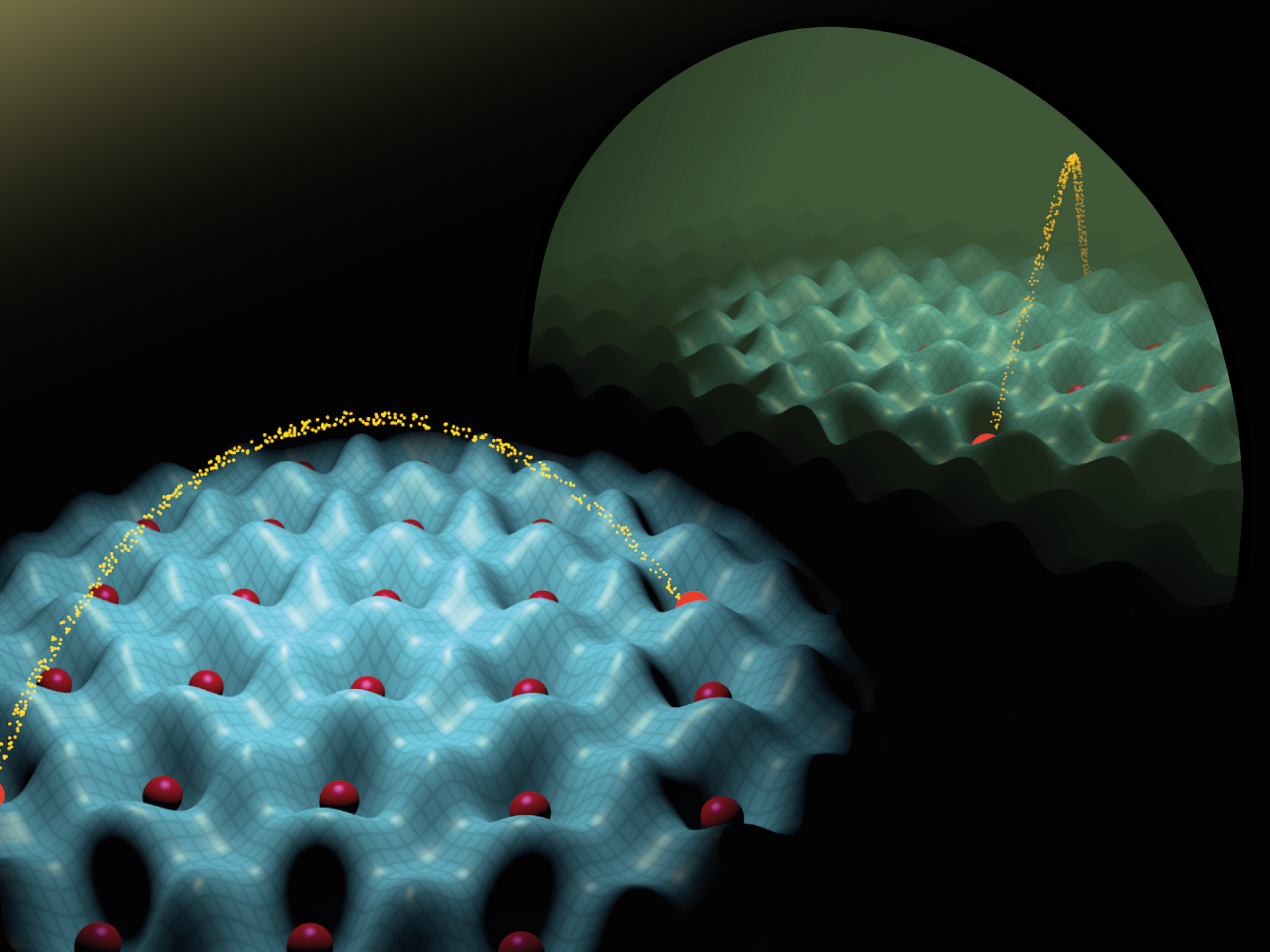
K. Goral, L. Santos, and M. Lewenstein, PRL 88, 170406 (2002)
Scarola, V. W. & Sarma, S. D.. Phys. Rev. Lett. 95, 033003 (2005)

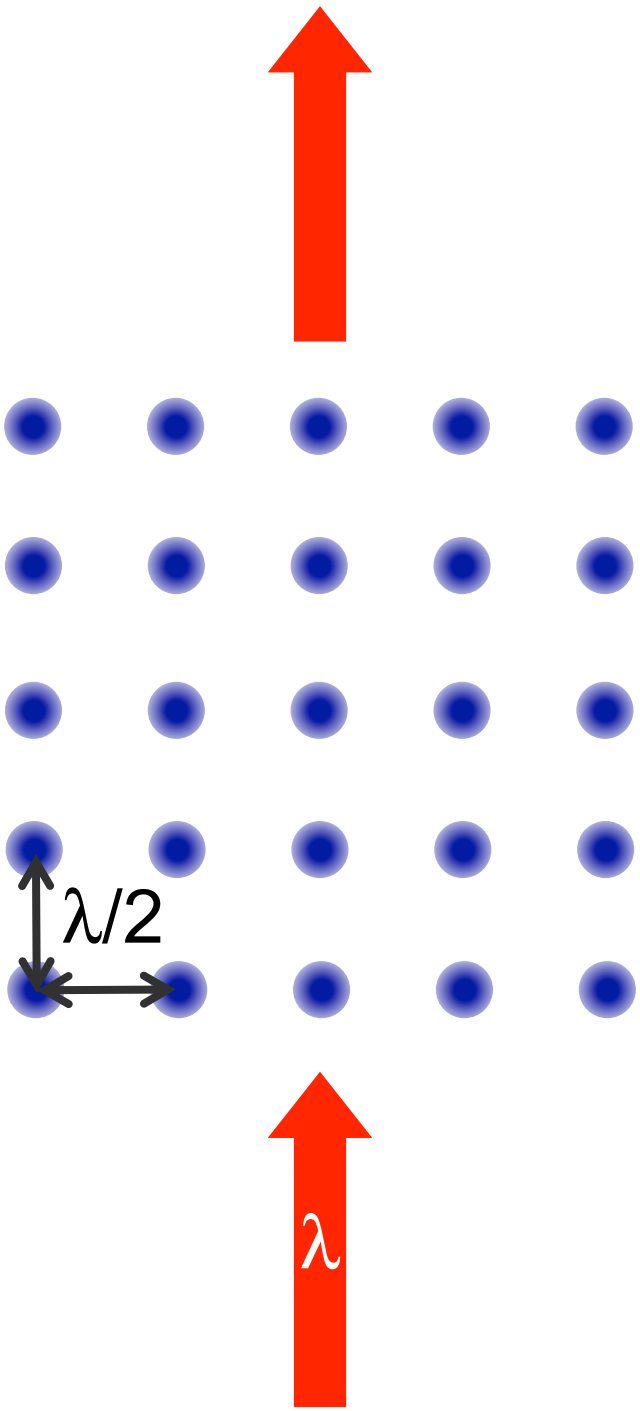
Long-range interactions

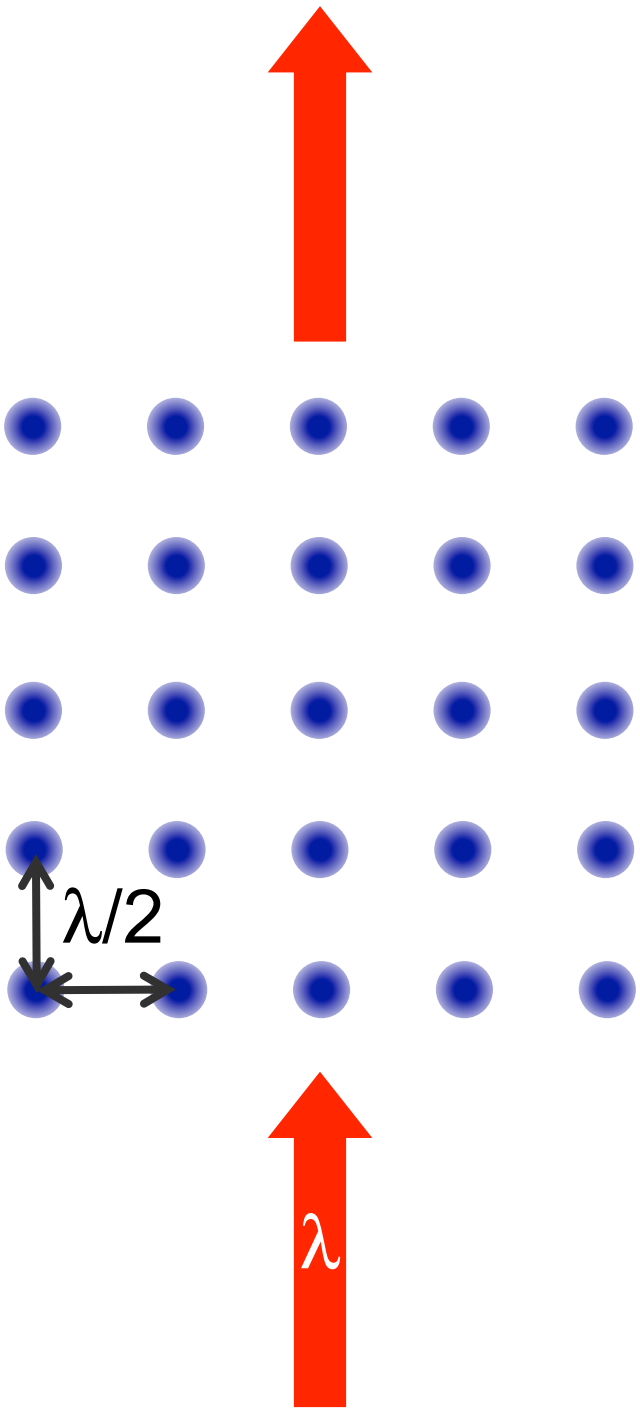
Dipolar molecules/atoms

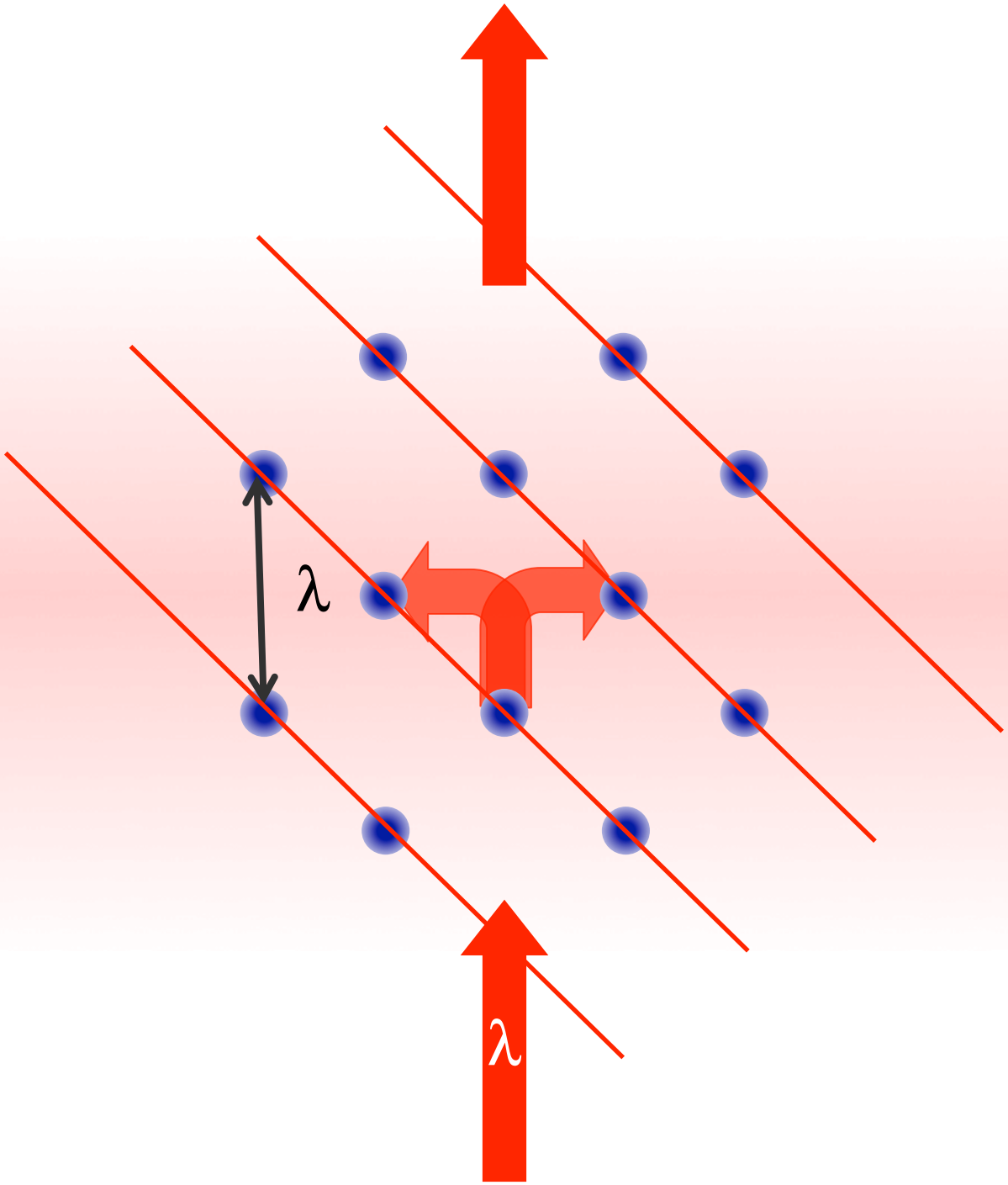
Rydberg atoms

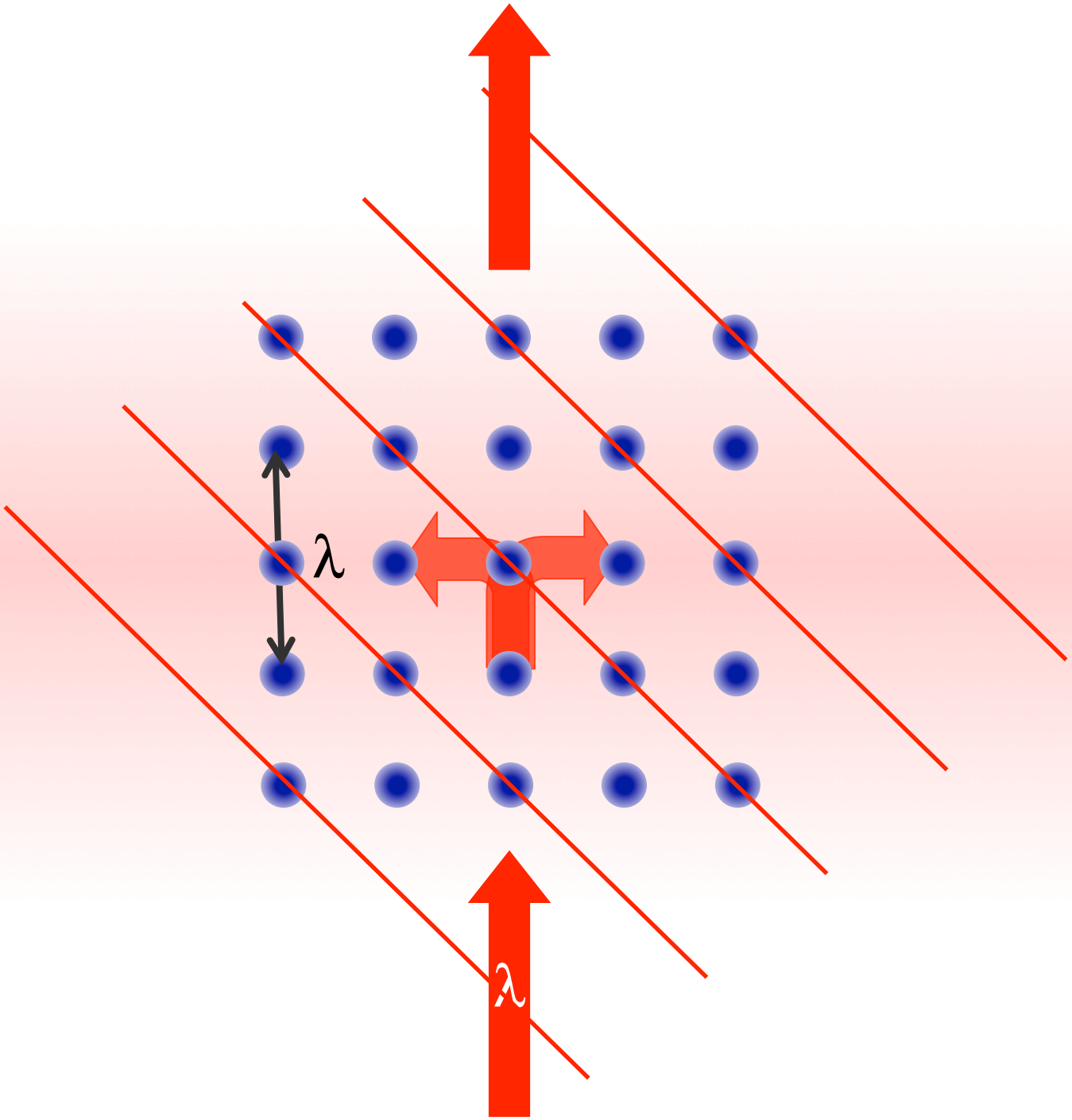
Cavity mediated interactions

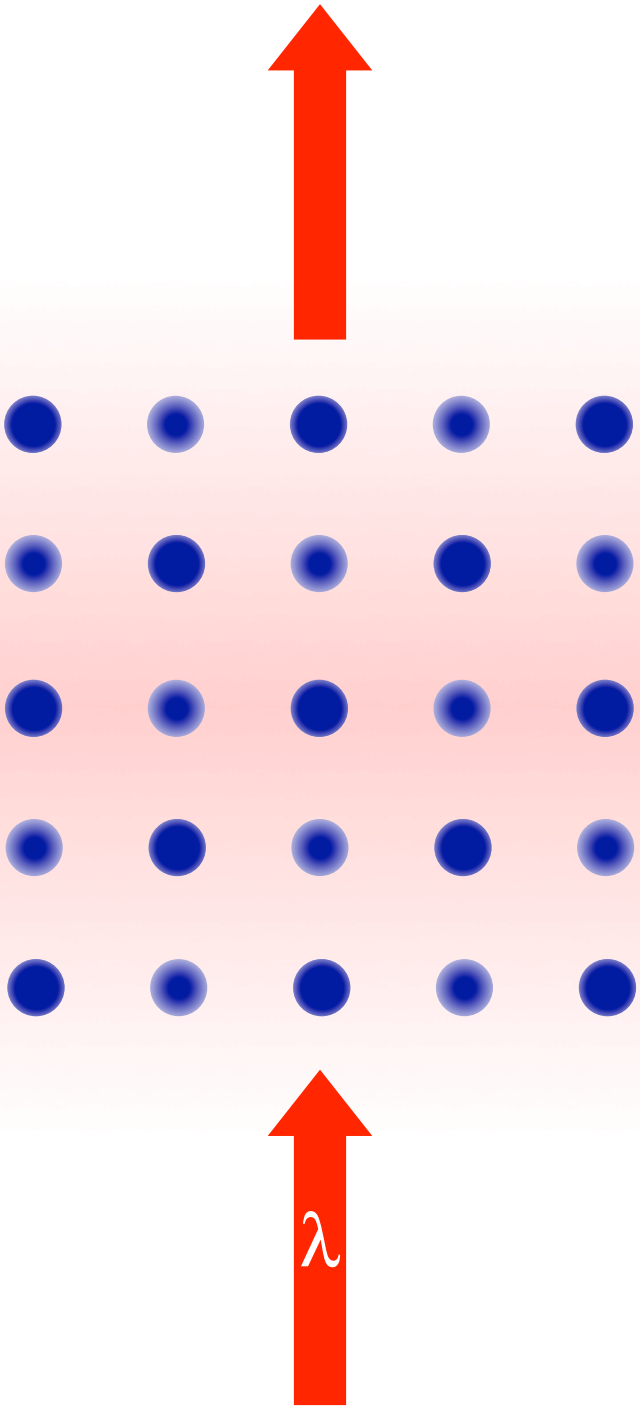


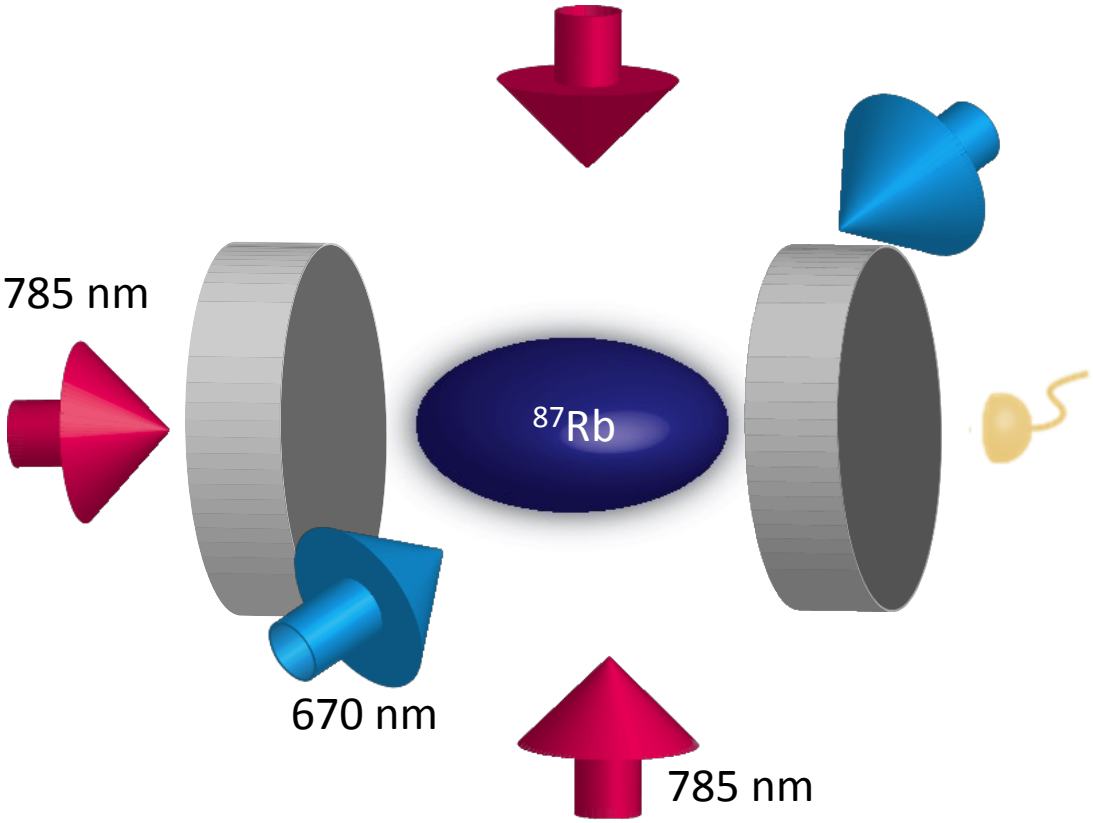

λ/2
λ


λ/2
λ


λ
λ


λ
λ

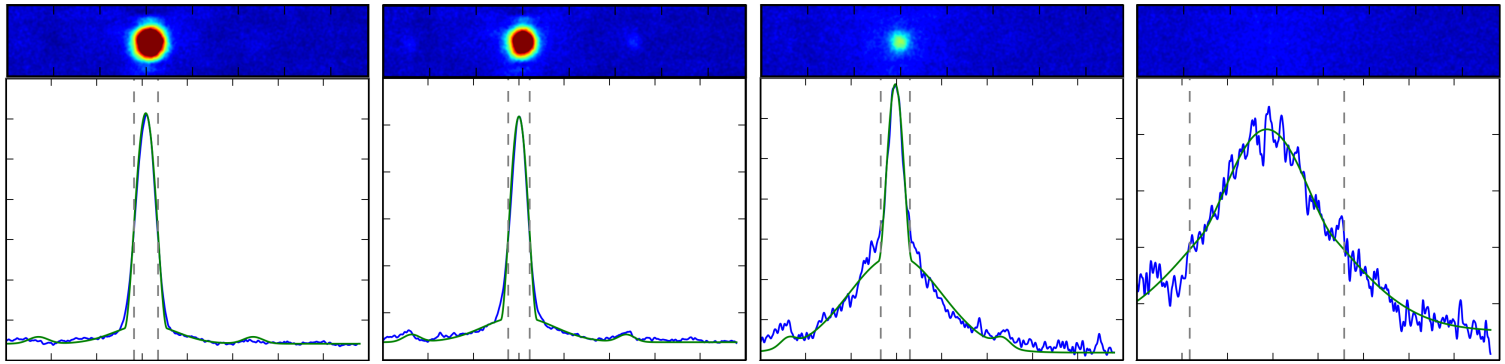

λ



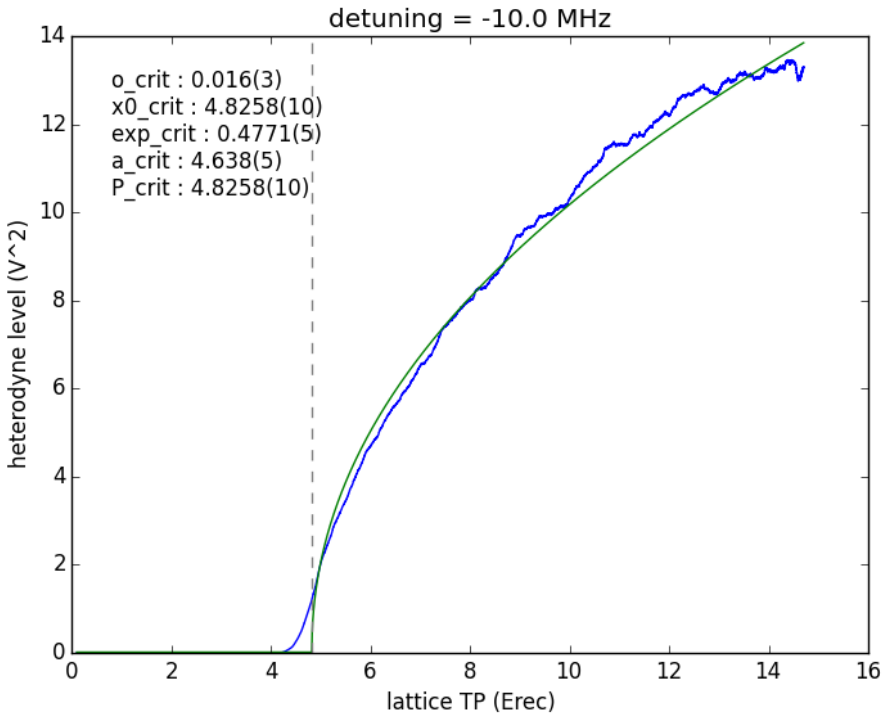
$$U_{short} \propto P_{785}$$

$$U_{long} \propto \frac{P_{785}}{\Delta_c}$$

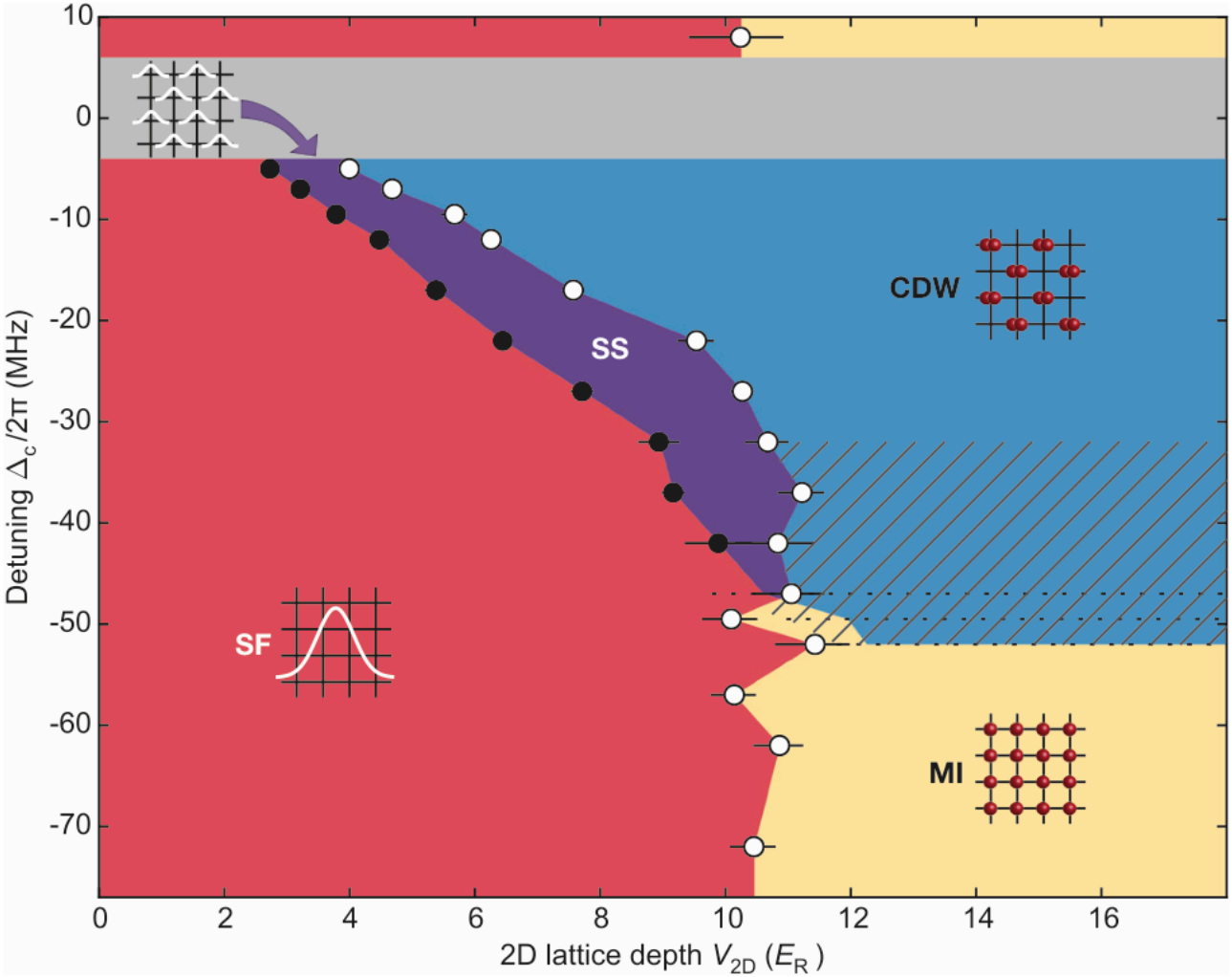
Coherence: Measure of superfluid order parameter



Cavity output: measure of checkerboard order parameter



Phase diagram

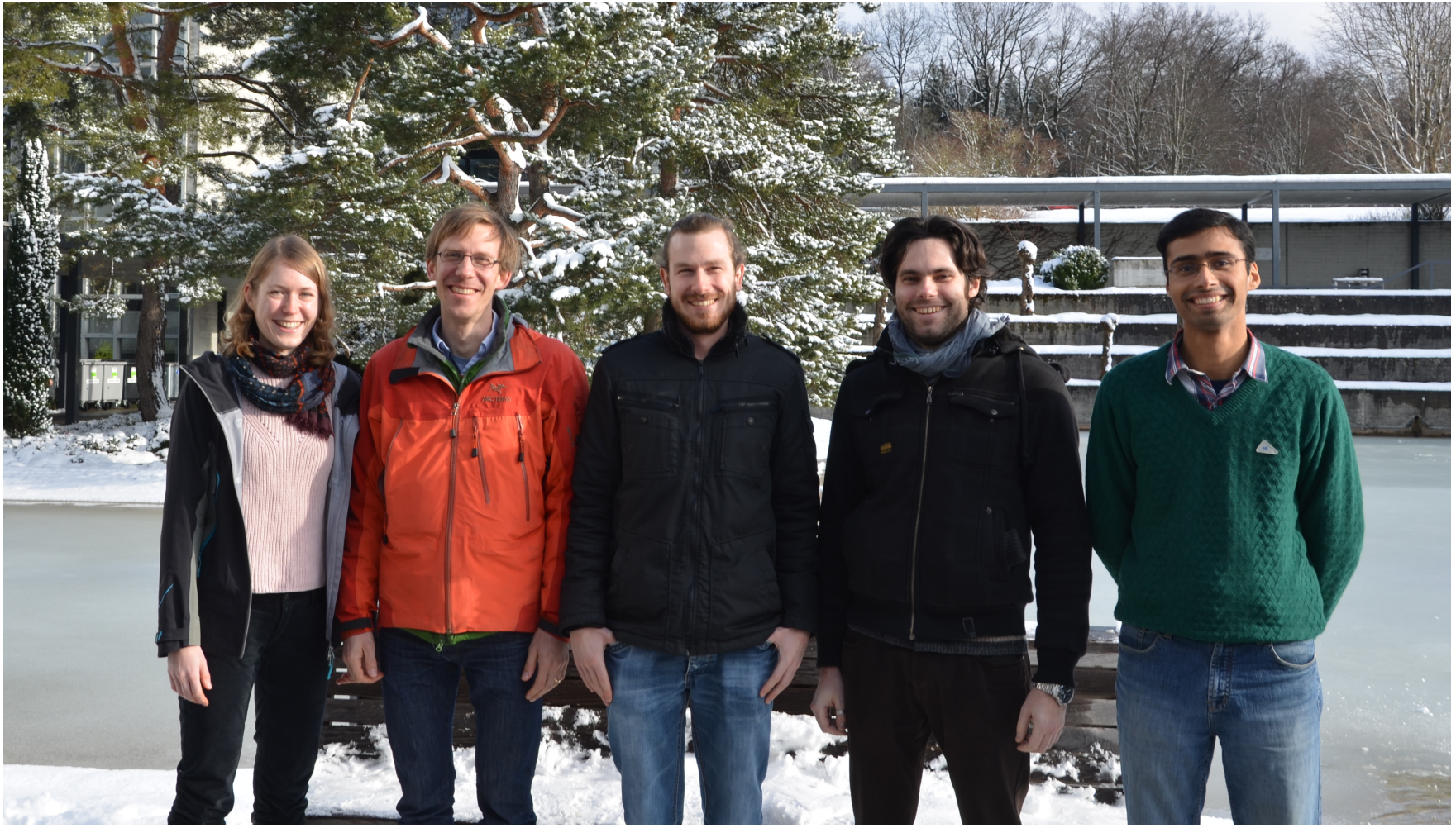


Renate Landig, Lorenz Hruby, Nishant Dogra, Manuele Landini, Rafael Mottl, Tobias Donner, TE, Nature 532, 476 (2016), arXiv:1511.00007

Related work: J. Klinder, H. Keßler, M. Reza Bakhtiari, M. Thorwart, and A. Hemmerich, Phys. Rev. Lett. 115, 230403 (2015), arXiv:1511.00850

Ferdinand Brennecke now@University Bonn

Rafael Mottl now@Mettler-Toledo



Renate Landig

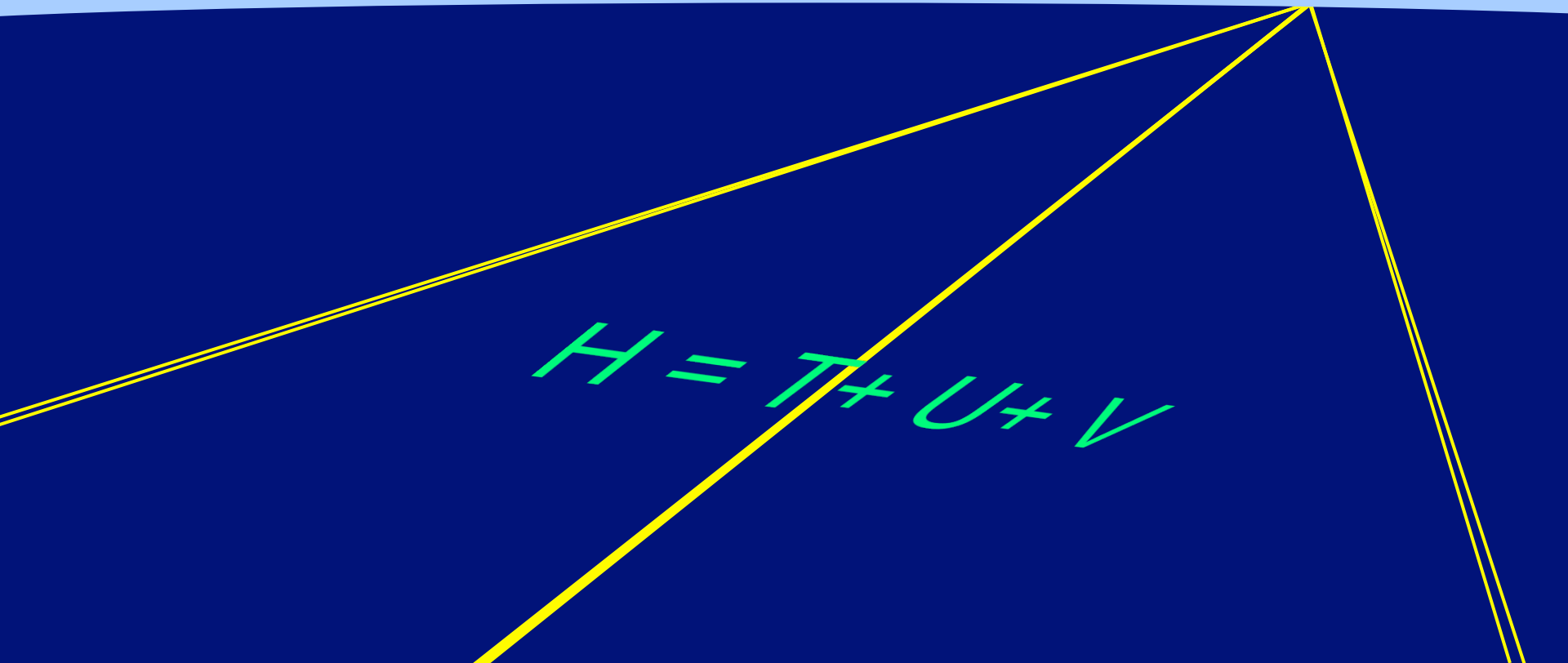
Tobias Donner

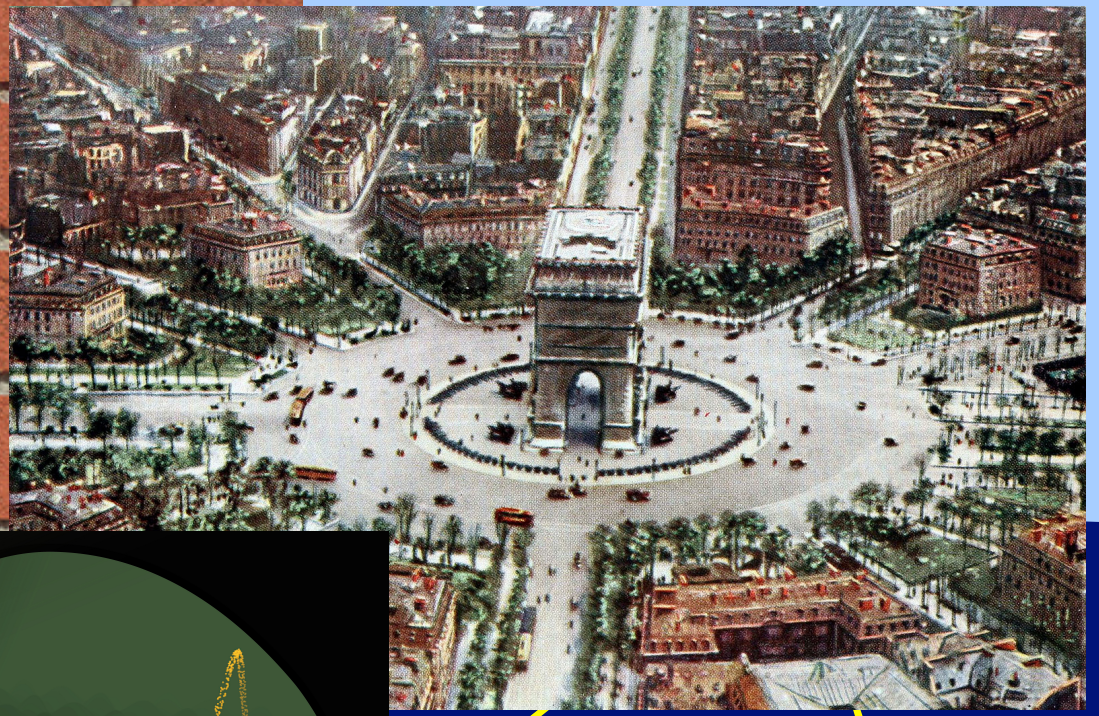
Lorenz Hruby

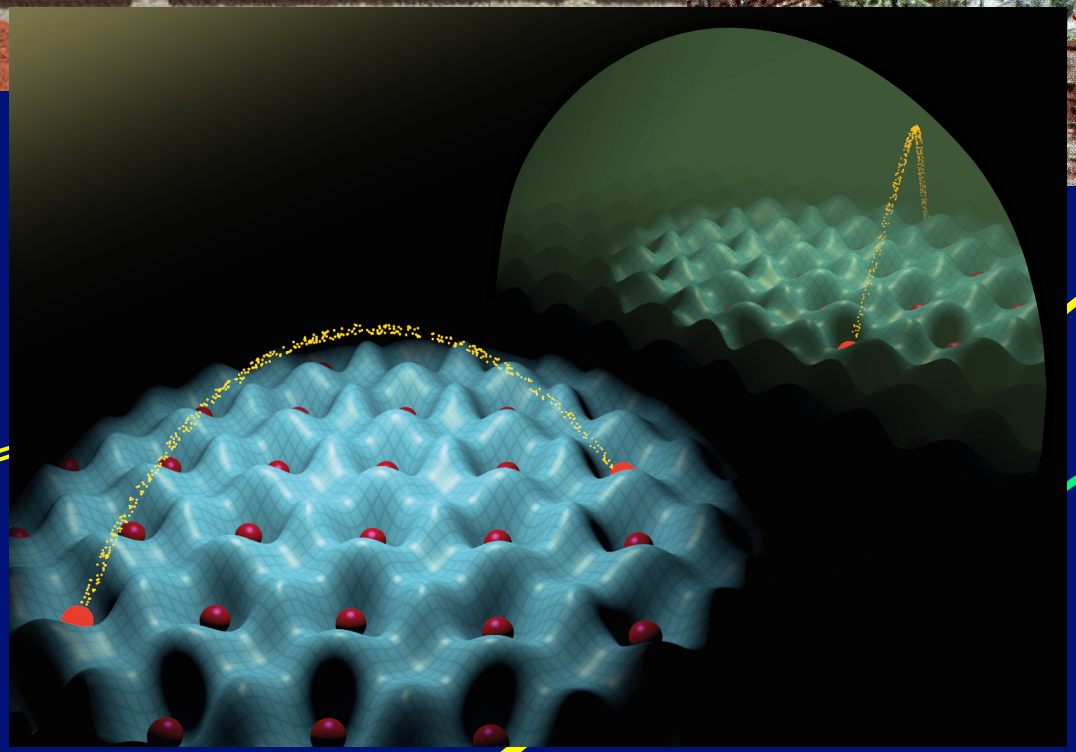
Manuele Landini

Nishant Dogra

Deeper understanding of many-body quantum physics







Thanks !

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

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
Tobias Donner
Renate Landig
Lorenz Hruby
Nishant Dogra
Manuele Landini
(Rafael Mottl)
(Ferdinand Brennecke)

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

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)

Theory discussions: Ehud Altmann, Gianni Blatter, Georg Bruun, Nigel Cooper, Eugene Demler, Antoine Georges, Thierry Giamarchi, Gian Michele Graf, Sebastian Huber, Corinna Kollath, Dario Poletti, Christian Rüegg, Manfred Sigrist, Wilhelm Zwerger, …