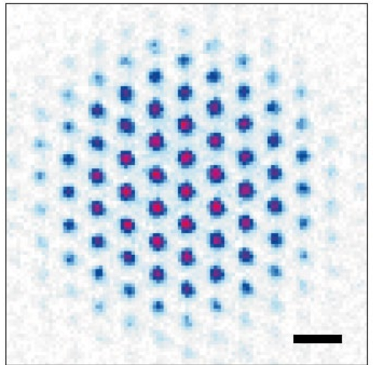
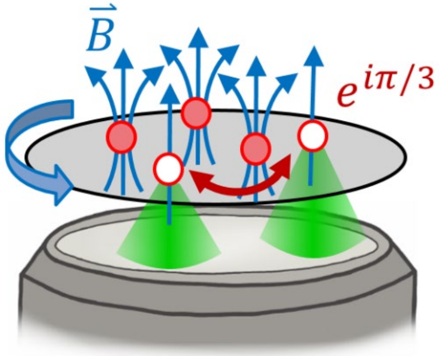
Experimental Floquet techniques for realizing topological models with ultracold atoms





Christof Weitenberg, University of Hamburg

KITP Workshop TOPOLOGY21

June 3rd 2021

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG
ILP INSTITUT FÜR LASERPHYSIK
CUI THE HAMBURG CENTRE FOR ULTRAFAST IMAGING
FOR 2414
SFB
SFB 925: Light induced dynamics and control of strongly correlated quantum systems
erc European Research Council

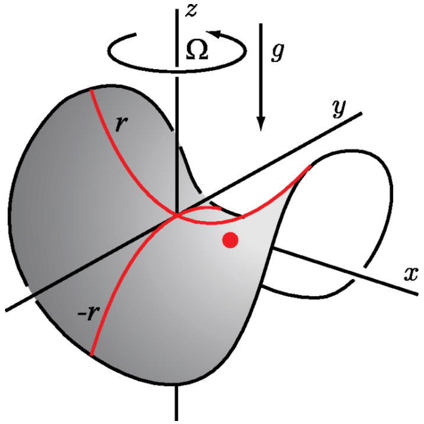
Outline

1. Floquet systems, how to engineer topology? (general introduction)
2. How to probe topology? (focus on experiments in Hamburg)
3. Interacting topological matter under the microscope (Outlook)

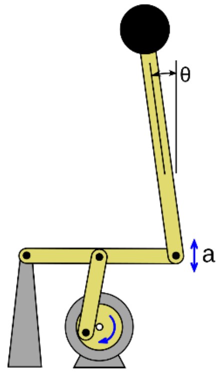
Floquet Engineering – tailoring a system by a periodic drive

Floquet theory
Periodically driven system = effective Hamiltonian + micromotion

Oscillating saddle point potential (e.g. ion traps):
stable trapping



Kapitza's pendulum (fast drive of pivot point):
upright state as new stable equilibrium position

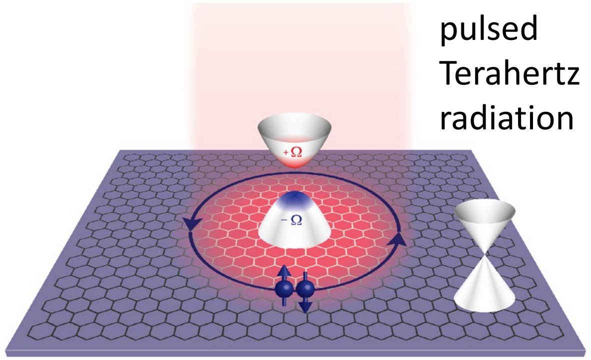


Motivation: effective system has new properties

1) otherwise not accessible in the specific system (trapping with saddle point, artificial gauge fields)
2) fundamentally impossible in a static system (upright pendulum, anomalous phases).

Why ultracold atoms?

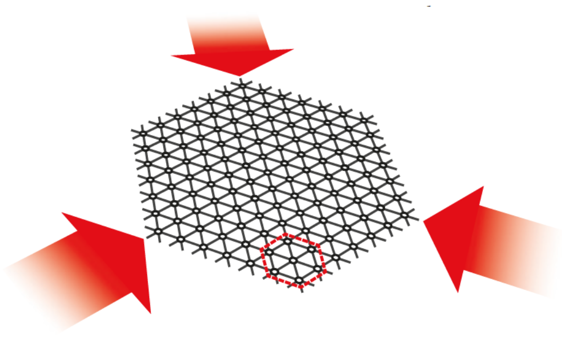
Solid state crystal



Complicated environment
- Terahertz radiation,
- pulsed lasers for high intensity,
- ultrafast measurement schemes

McIver et al., Nat. Phys. 16, 38 (2020).

Cold atoms in optical lattices



Quantum simulation platform
- high control (versatile driving schemes)
- easily accessible time scales (kHz driving).
- Large driving amplitudes possible
- AND: Floquet required for topology

Toolbox of techniques: lattice shaking, amplitude modulation, additional Raman beams, modulation of the interaction strength, modulation of external field gradients, combination of the above,…
Toolbox of concepts: tunnel renormalization, band hybridization, laser-assisted tunneling,…

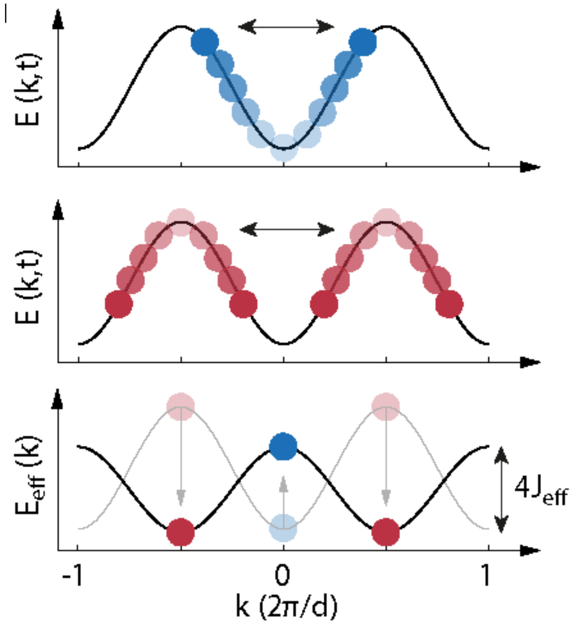
Oka & Kitamura, Annual Rev. Cond. Mat. Phys. 10, 387 (2019).
Rudner & Lindner, Nat. Rev. Phys. 2, 229 (2020).
Photonics: Ozawa et al., Rev. Mod. Phys. 91, 015006 (2019).

Bukov, D'Alessio, & Polkovnikov, Adv. Phys. 64, 139 (2015).
Eckardt, Rev. Mod. Phys. 89, 011004 (2017).
Goldman & Dalibard, Phys. Rev. X 4, 031027 (2014).
Weitenberg & Simonet, arXiv:2102.07009 (2021).

Tunnel renormalization in driven lattices

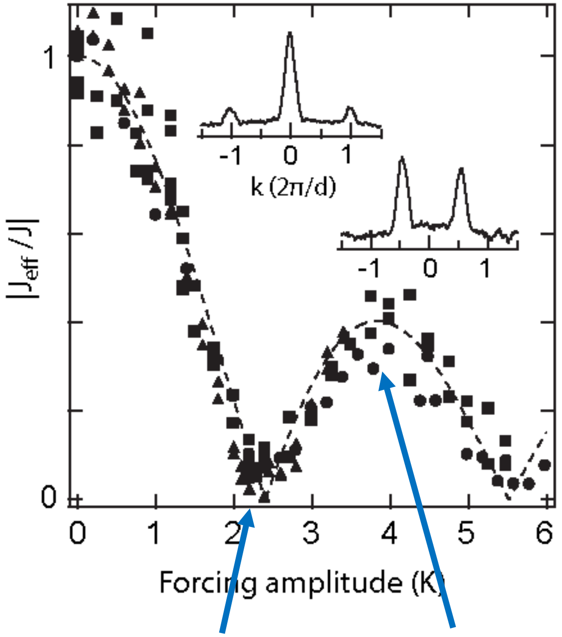
Simple driven 1d lattice

Lignier et al., PRL 99, 220403 (2007).



Tight binding dispersion $E(k) = -2J\cos(kd)$
Oscillating intertial force $F(t) = F_0\cos(\Omega t)$
with driving strength $K_0 = dF_0/\hbar\Omega$

Lowest order of $1/\Omega$ expansion: $\widehat{H}_{\text{eff}} = \langle \widehat{H}(t) \rangle_T$
Renormalized dispersion with $J_{\text{eff}} = J\,\mathcal{J}_0(K_0)$
(Bessel function of the first kind of order zero)



Dynamical localization

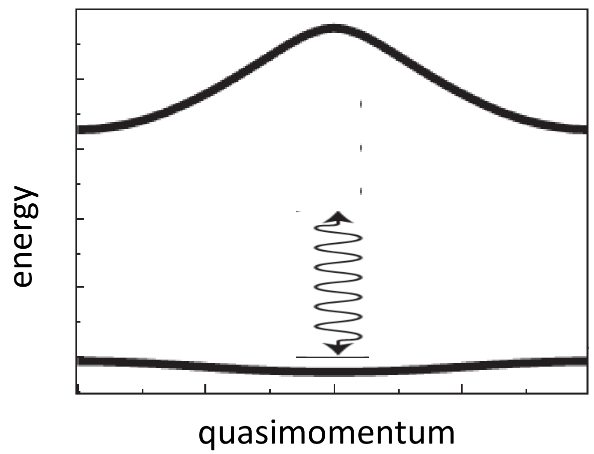
Band inversion
$\mathcal{J}_0(K_0) < 0$
BEC at $k = \pi/d$

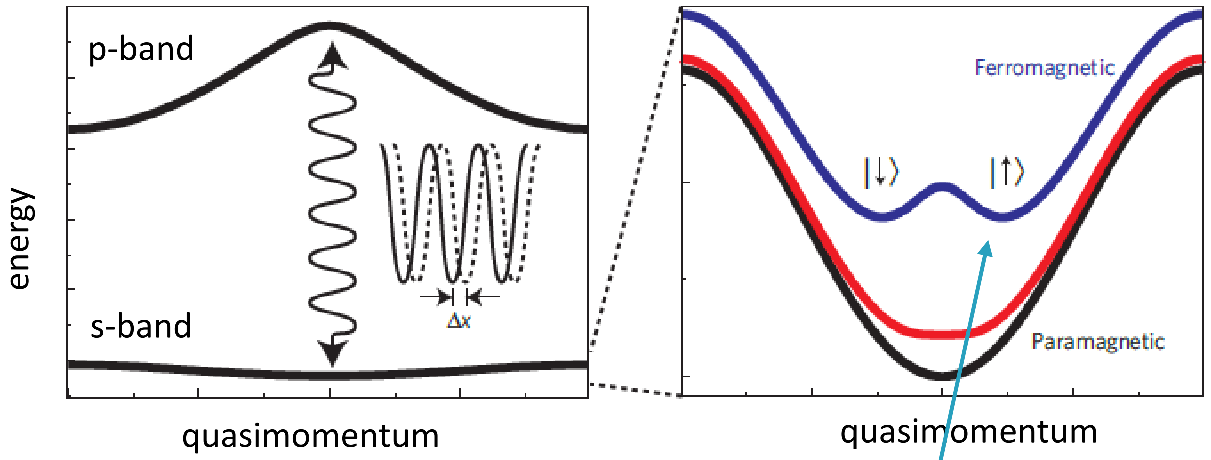
Remark 1: In driven triangular lattice, $J < 0$ leads to frustration and intriguing magnetic phases of the classical XY model
Struck, et al., Science 333, 996 (2011). Struck, et al., Nat. Phys. 9, 738 (2013).

Remark 2: Same physics in static lattice with external force (e.g. oscillating magnetic field gradient)
Jotzu et al., PRL 115, 073002 (2015).

Remark 3: In Hubbard model, renormalize spin exchange interactions
Coulthard/Jaksch et al., PRB 96, 085104 (2017). Görg/Esslinger et al., Nature 553, 481 (2018).

Hybridization of bands





Off-resonant drive: tunnel renormalization (single band picture)

Resonant drive: hybridization of bands, dressing of Bloch states (compare dresssing of atomic states by light)

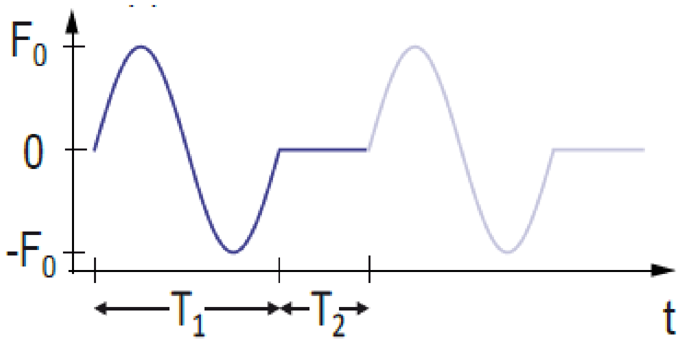
Drastially modified dispersion (beyond the cosine-shape of an s-band) e.g. double-well dispersion (map to spin model)
Parker, Ha & Chin, Nat. Phys. 9, 769 (2013).
Clark, Feng & Chin, Science 354, 606 (2016).
Fujiwara et al., PRL 122, 10402 (2019).

Remark 1: Change of perspective: Spectroscopy versus Floquet states, adiabatic preparation of Floquet states

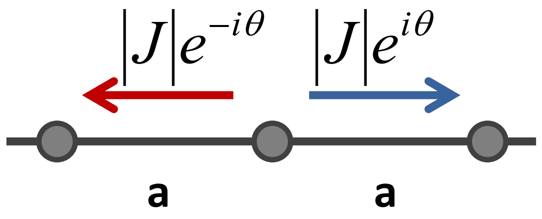
Remark 2: Resonant coupling also between two s-bands in a non-Bravais lattice with sublattice offset (see later)
Fläschner et al., Science 352, 1091 (2016).

Tunable Peierls phase via lattice shaking

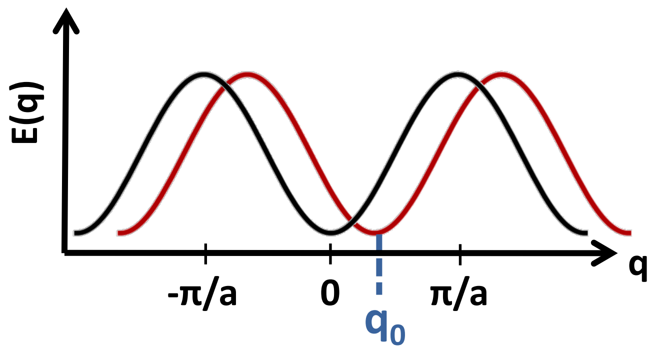
Explicitly break time-reversal symmetry (TRS) in the shaking protocol



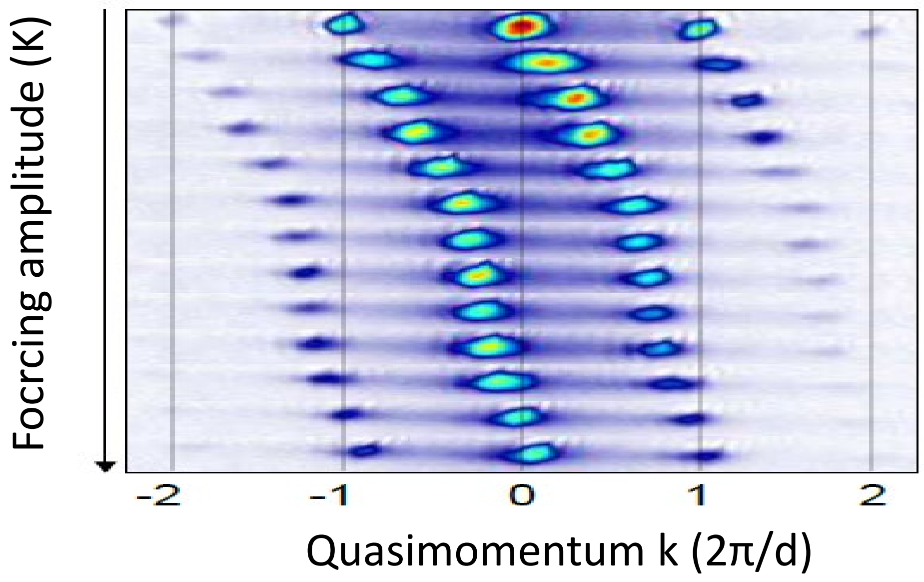
Obtain Peierls phase θ on the tunneling element



Corresponds to shifted dispersion with minimum at $q_0 = \theta/a$



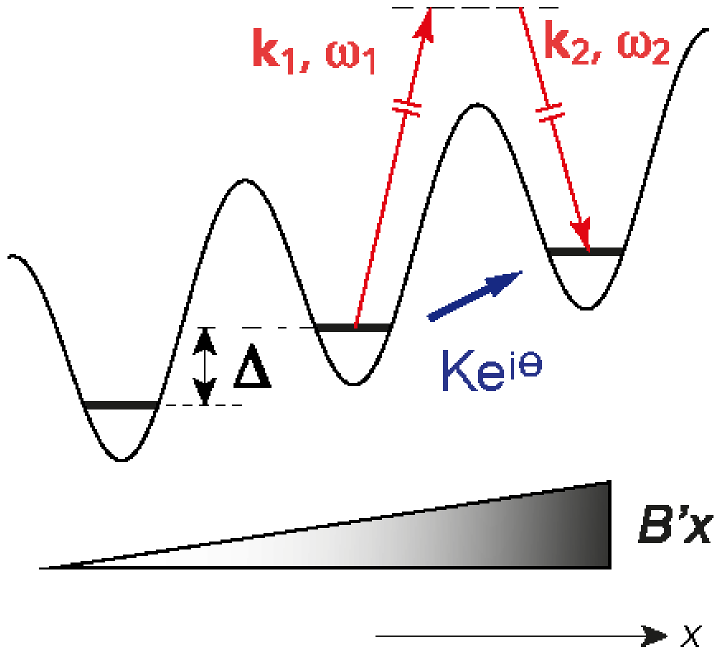
Directly reveal via BEC at dispersion minimum

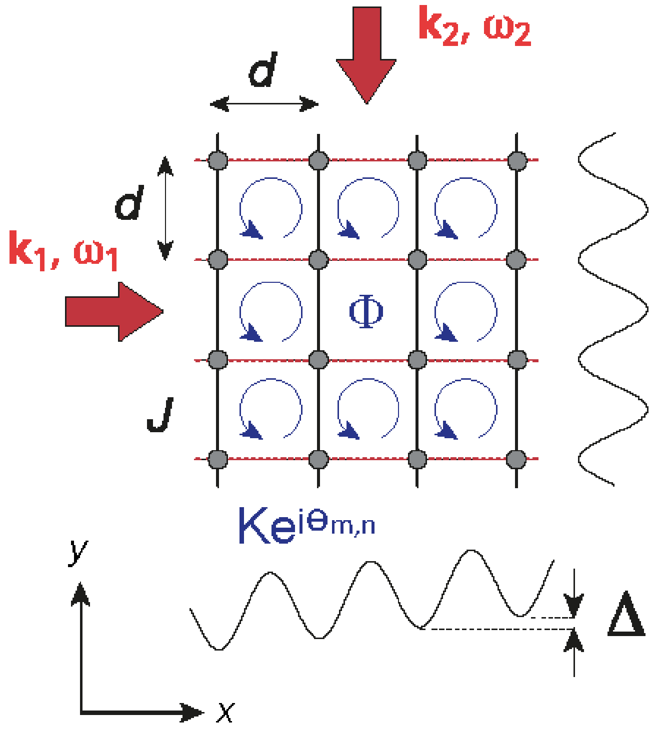


Struck et al., PRL 108, 225304 (2012).

More generally: break TRS via relative phase of two modulations (e.g. shaking along x and y in 2d system)

Laser-assisted tunneling





- Suppress and restore tunneling via two-photon coupling
- Restored tunneling $K_{\text{pert}} = K\, e^{-i\, \delta\boldsymbol{k}\cdot\boldsymbol{R}_{m,n}}$ (acquire local laser phase)
- Compare to homogeneous phase for lattice shaking

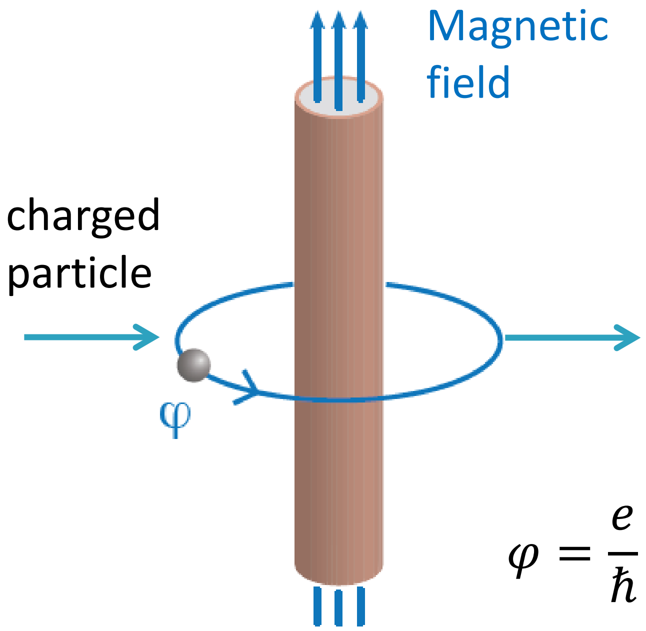
- Secondary moving lattice with $\delta\boldsymbol{k} = \boldsymbol{k}_1 - \boldsymbol{k}_2$,
- Amplitude modulation with locally varying phase

Remark: with Hubbard U, make resonant tunneling occupation dependent

Proposal: Jaksch & Zoller, New J. Phys. 5, 56 (2003). Gerbier & Dalibard, New J. Phys. 12, 033007 (2010)
Miyake , Ketterle et al. PRL 111, 185302 (2013). Aidelsburger, Bloch et al. PRL 111, 1185301 (2013).

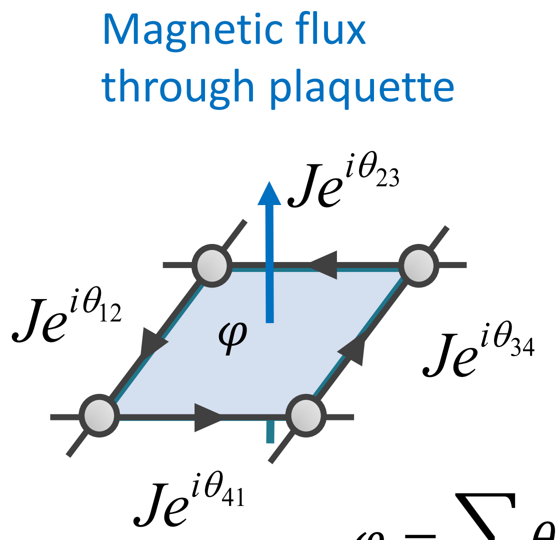
Artificial gauge fields

Aharonov Bohm phase



$$\varphi = \frac{e}{\hbar}\phi_B$$

Peierls substituion



particle in lattice

$$\varphi = \sum \theta_{ij}$$

Artificial gauge field:

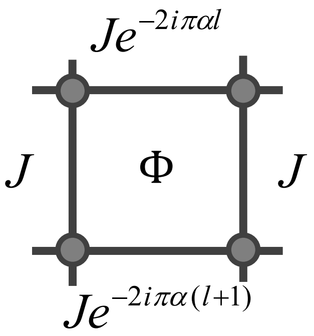
- Implement Peierls phases directly (via Floquet)
- Very large effective magnetic fields accessible

Remark 1: One implements a specific gauge by choosing the Peierls phases (therefore the name)
Remark 2: Gauge choice can make subtle differences, e.g. in adiabatic preparation, Wang et al., arXiv:2009.00560 (2020).

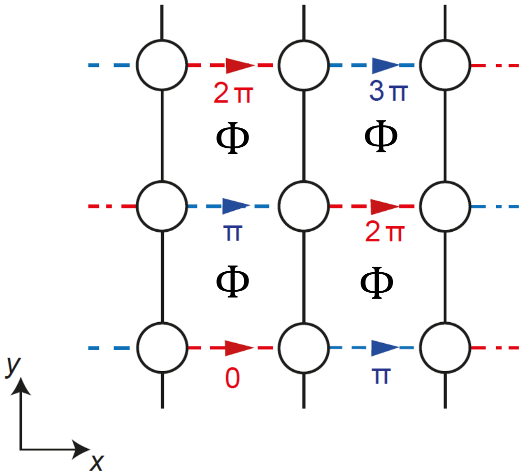
Reviews: Dalibard et al., Rev. Mod. Phys. 83, 1523 (2011). Goldman & Dalibard, PRX 4, 031027 (2014). Zhang et al., Adv. Phys. 67, 253 (2018). Cooper et al., Rev. Mod. Phys. 91, 015005 (2019). Weitenberg & Simonet, arXiv:2102.07009 (2021).

Floquet realization of the Harper-Hofstadter model

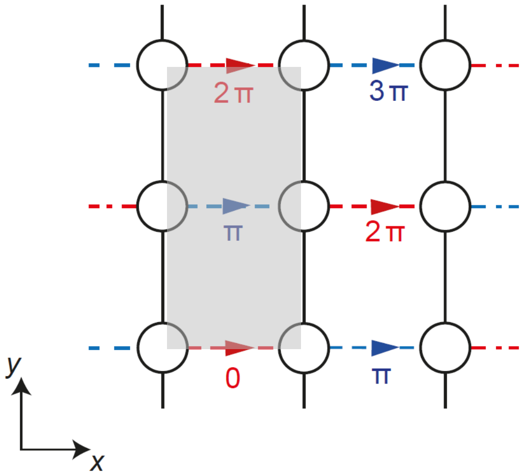
General flux α



Flux $\alpha = 1/2$, $\Phi = \pi$



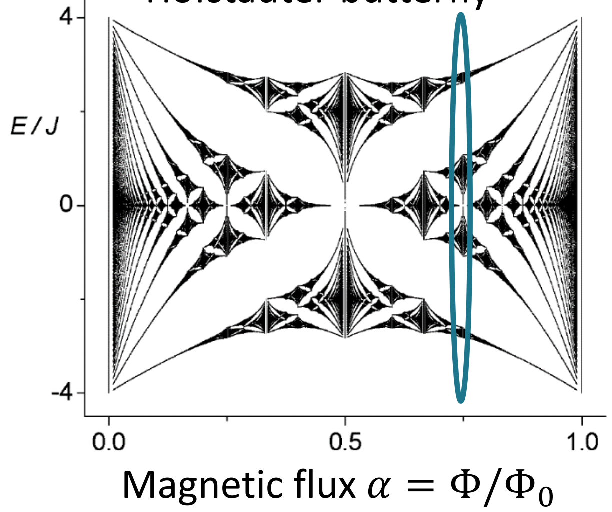
Magnetic unit cell

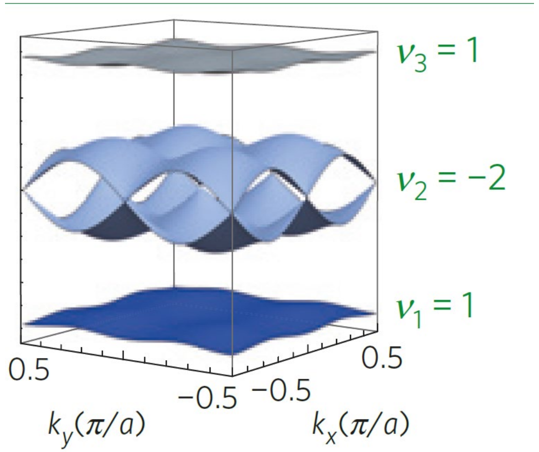


Harper-Hofstadter model

- Square lattice with homogeneous magnetic flux Φ per plaquette (lattice version of quantum Hall effect).
- Rational values of $\alpha = \Phi/\Phi_0 = q/p$: splitting into p subbands (Hofstadter butterfly)
- Increased spatial period pa: magnetic unit cell, smallest unit cell with an integer number of flux quanta.
- Realize via laser-assisted tunneling (e.g. in the Landau gauge $\boldsymbol{A} = -By\, \boldsymbol{e}_x$)

Hofstadter butterfly





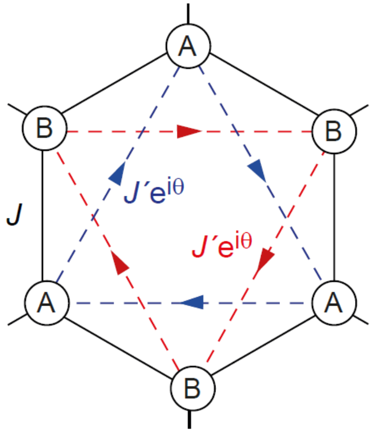
Proposal: Jaksch & Zoller, New J. Phys. 5, 56 (2003). Gerbier & Dalibard, New J. Phys. 12, 033007 (2010)
Miyake , Ketterle et al. PRL 111, 185302 (2013). Aidelsburger, Bloch et al. PRL 111, 1185301 (2013).

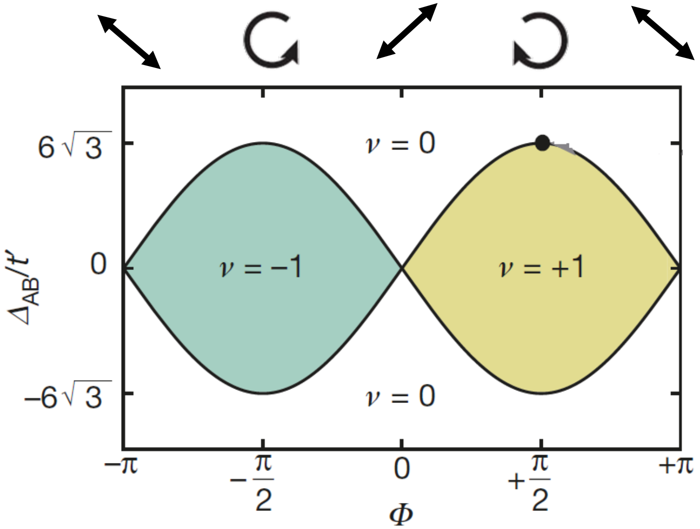
Floquet realization of the Haldane model

Haldane model

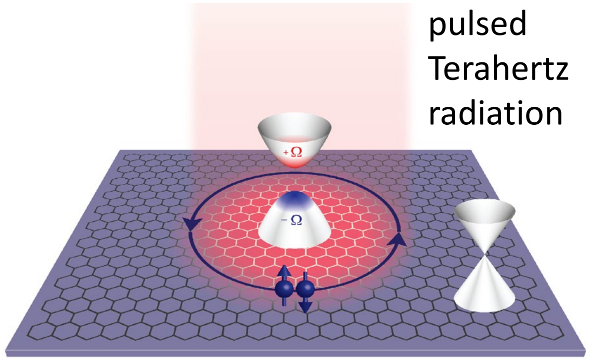
- Honeycomb lattice with Peierls phases θ on the NNN tunneling
- Staggered flux in subplaquettes, no net magnetic flux (shaking sufficient)
- Realize by elliptical shaking with phase ϕ, which maps onto the Peierls phase θ.

Haldane, PRL 61, 2015 (1988)





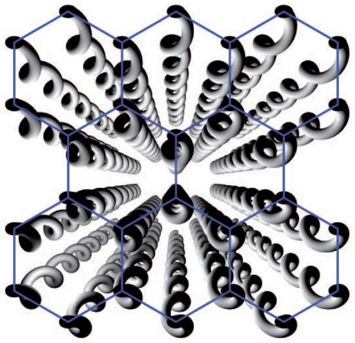
Floquet engineering of the Haldane model



pulsed Terahertz radiation

Terahertz-driven graphene

Oka & Aoki, PRB 79, 081406(R) (2009)
McIver et al. Nat. Phys. 16, 38 (2020)

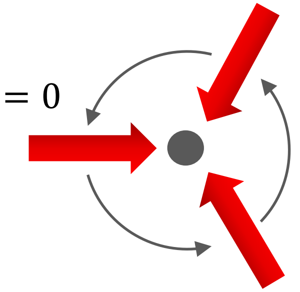


Photonic wave guides

Rechtsman et al.
Nature 496, 196 (2013)

$\delta\nu = 2\Delta\nu\left[\cos(\omega t) + \sqrt{3}\sin(\omega t)\right]$

$\delta\nu = 0$



$\delta\nu = 2\Delta\nu\left[-\cos(\omega t) + \sqrt{3}\sin(\omega t)\right]$

Lattice shaking

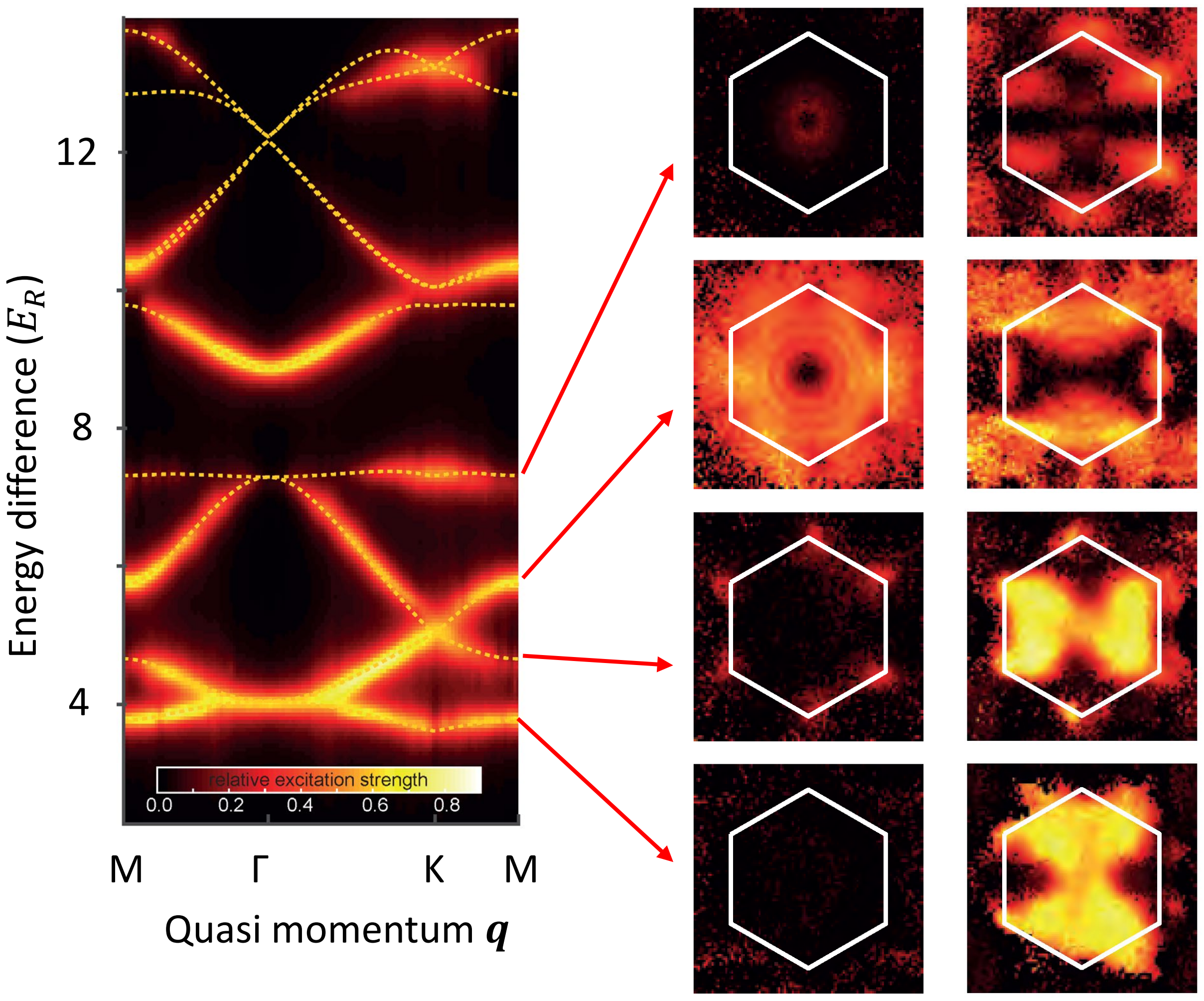
Jotzu et al. Nature 515, 237 (2014)
Fläschner et al.,
Science 352, 1091 (2016)

Outline

1. Floquet systems, how to engineer topology? (general introduction)
2. How to probe topology? (focus on experiments in Hamburg)
3. Interacting topological matter under the microscope (Outlook)

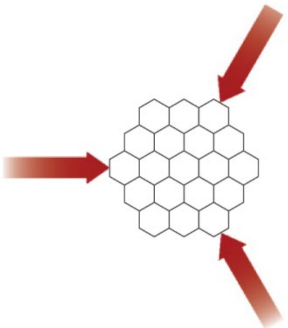
Multiband Spectroscopy of the Honeycomb Lattice

Band structure | Excitation strength $P(\boldsymbol{q})$



symmetric | asymmetric

Amplitude modulation



- Excitation strength depends on the perturbation opertator
- Access information on the eigenstates

Can one also obtain the topology from the excitation strength?

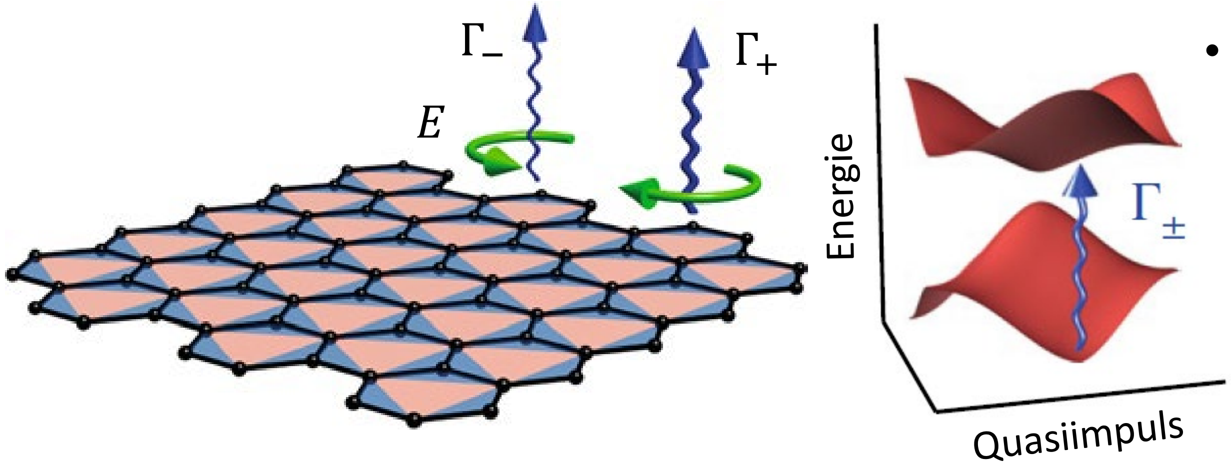
N. Fläschner et al., PRA 97, 051601(R) (2018).

Quantized circular Dichroism

Topology from spectroscopy

- Choose suitable perturbation: $\hat{H}_{\pm}(t) = \hat{H}_0 + 2E\{\cos(\omega t)\,\hat{x} \pm \sin(\omega t)\,\hat{y}\}$
- Excitation rates $\Gamma_{+}(\omega) \neq \Gamma_{-}(\omega)$
- Differential integrated rate: $\Delta\Gamma_{\pm}^{\text{int}} \equiv \int d\omega[\Gamma_{+}(\omega) - \Gamma_{-}(\omega)]/2$

Quantized response: $\Delta\Gamma_{\pm}^{\text{int}}/A_{\text{cell}} = (1/\hbar^2)C \cdot E^2$



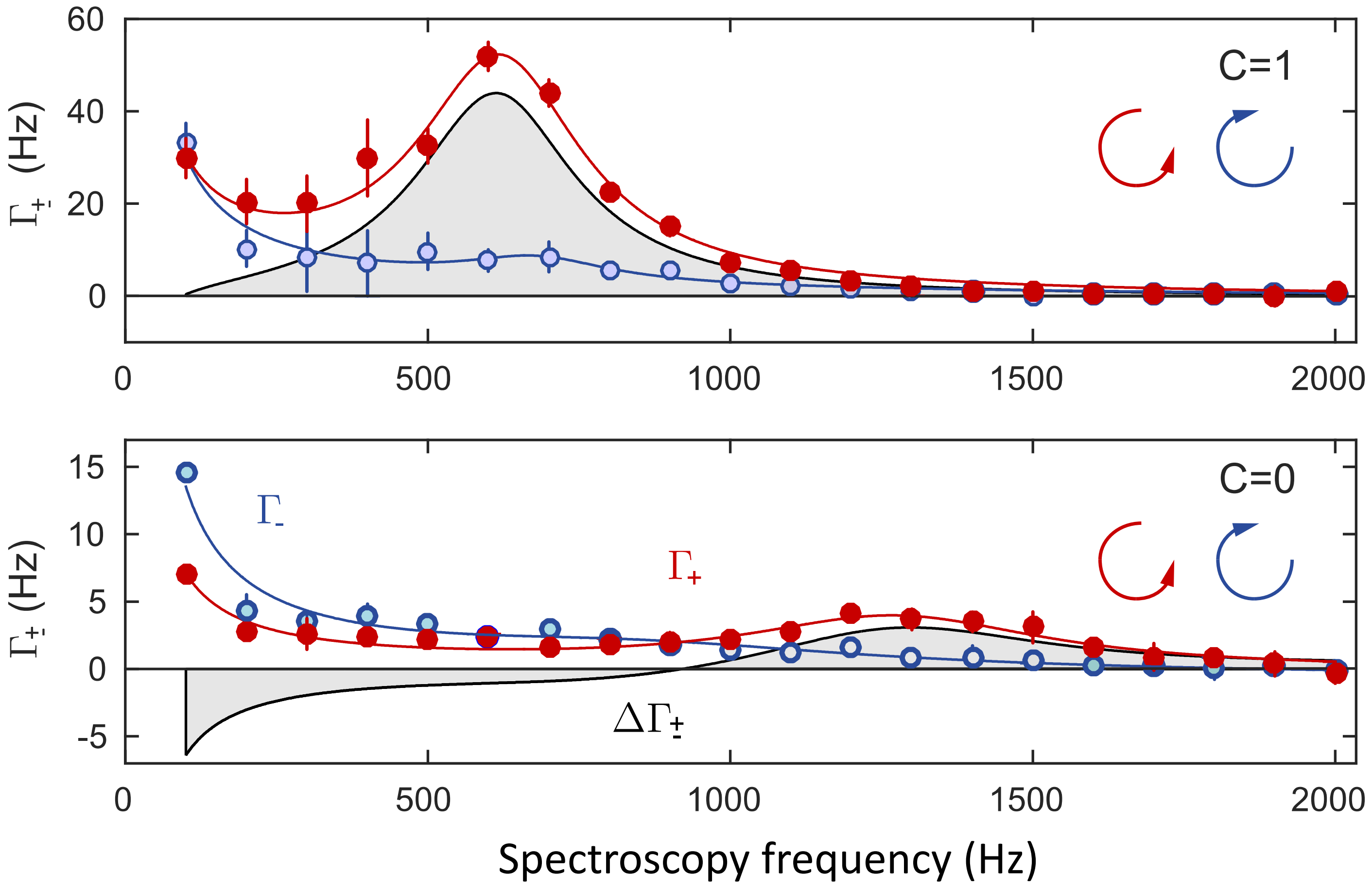
- Dissipative counterpart to the Hall conductivity
- Measurement without Transport

Separation of time scales

- In our case, the system $\hat{H}_0$ is already shaken ($\omega_{\text{Fl}}/2\pi \sim$ 6 kHz)
- Spectroscopy is an additional shaking with smaller frequency ($\omega/2\pi \sim$ 1 kHz)

Proposal: D. T. Tran/Goldman et al., Science Adv. 3, e1701207 (2017).
Hall drift measurement: M. Aidelsburger et al., Nature Phys. 11, 162 (2015)

Chiral Spectra



$C_{\exp} = 0.92(12)$

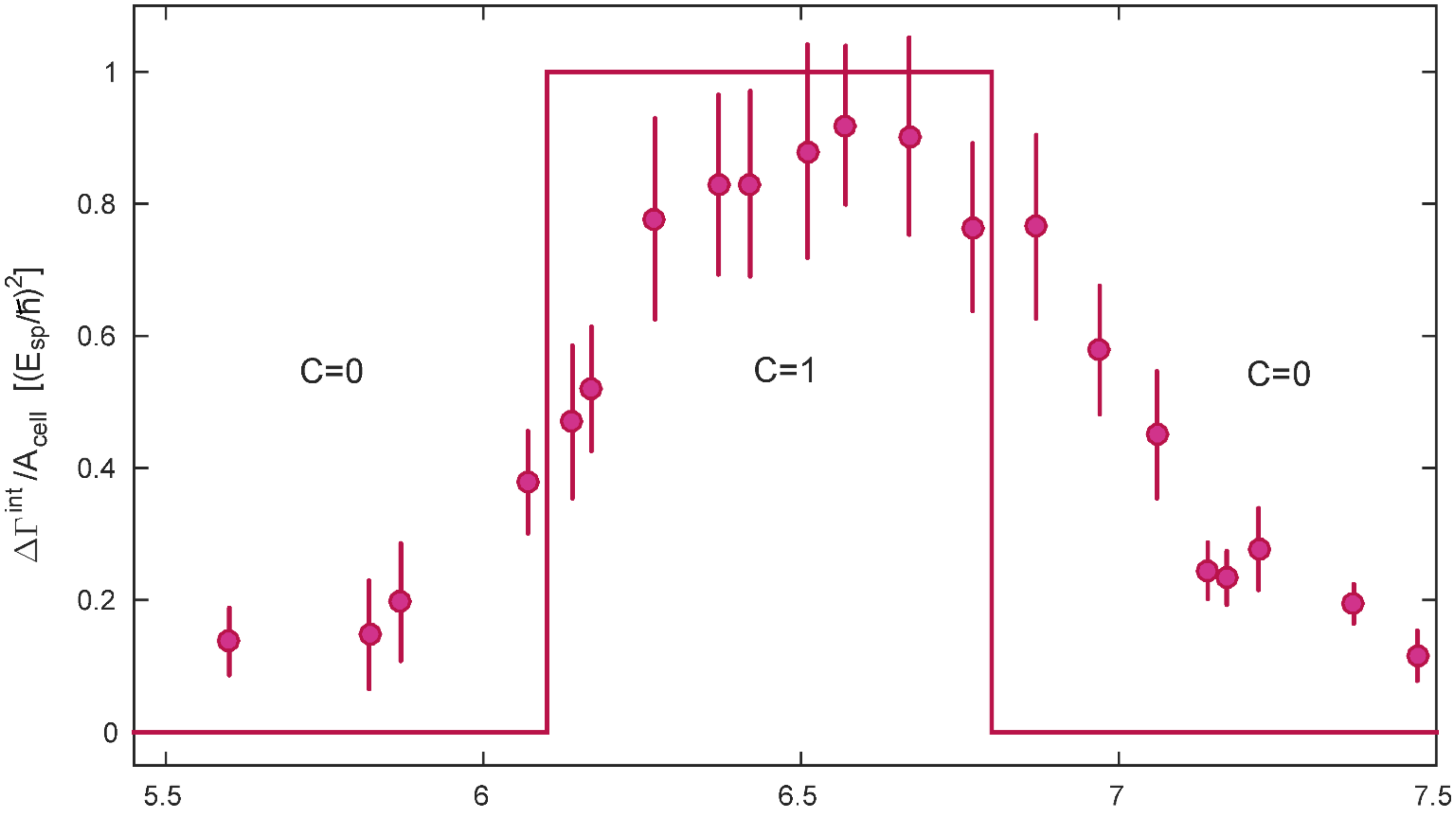
$C_{\exp} = 0.12(4)$

Gray area $\Delta\Gamma_\pm^{\text{int}} = \int d\omega[\Gamma_+(\omega) - \Gamma_-(\omega)]/2$

$$\Delta\Gamma_\pm^{\text{int}}/A_{\text{cell}} = C_{\exp}\,(E_{\text{sp}}/\hbar)^2$$

L. Asteria et al., Nature Physics 15, 449 (2019).

Dichroims Signal over the topological Phase Transition

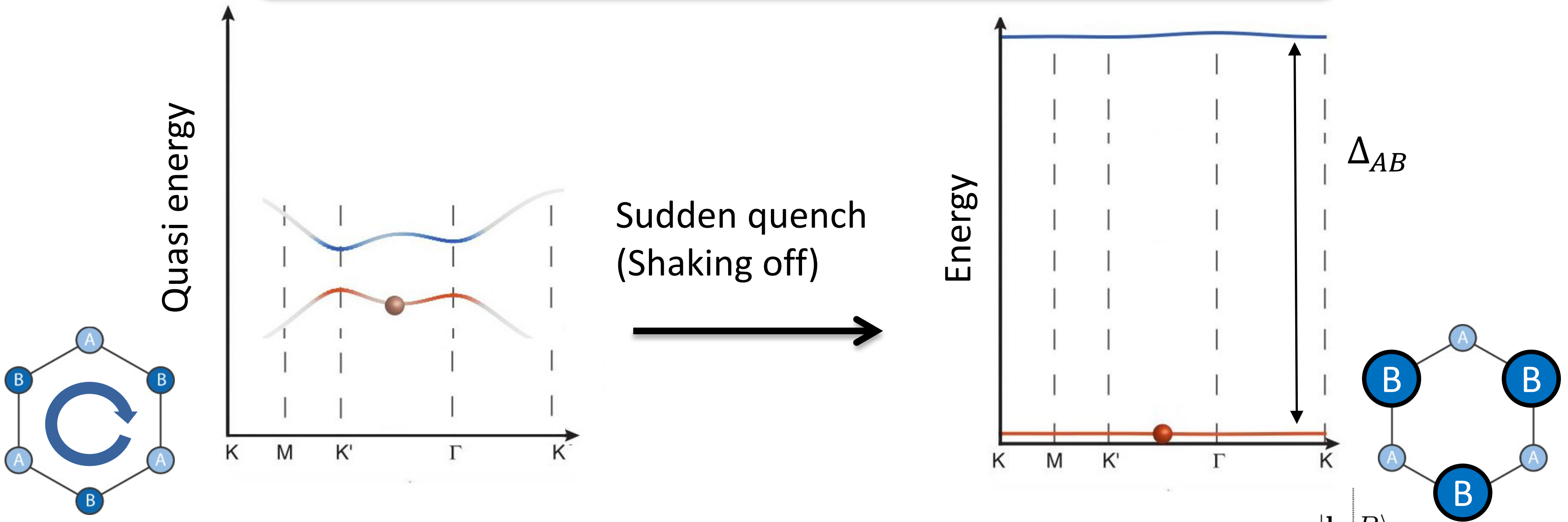


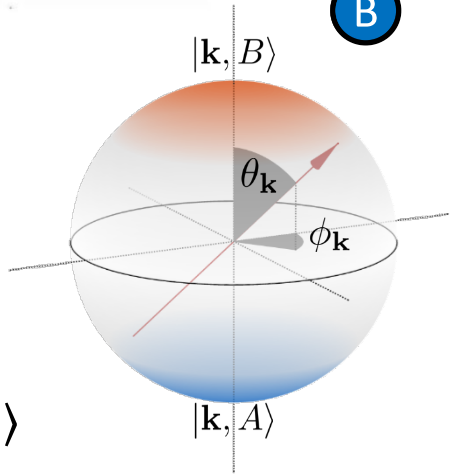
- Experimental demonstration of a new topological effect
- Promising approach to detect fractional quantum Hall states
  Repellin & Goldman, PRL 122, 166801 (2019).

L. Asteria et al., Nature Physics 15, 449 (2019).

Bloch State Tomography of Floquet Systems

Can one detect the geometry of the eigenstates directly?





- Initial eigenstates of the Floquet system:

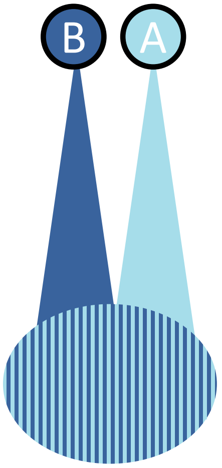
$$|k\rangle = -\sin\left(\frac{\theta_k}{2}\right)\exp(-i\phi_k)\,|k, A\rangle + \cos\left(\frac{\theta_k}{2}\right)|k, B\rangle$$

- Time evolution after the quench (projection onto Basis states):

$$|k\rangle = -\sin\left(\frac{\theta_k}{2}\right)\exp(-i\phi_k)\,|k, A\rangle + \underline{e^{i\frac{\Delta_{AB} t}{\hbar}}}\cos\left(\frac{\theta_k}{2}\right)|k, B\rangle$$

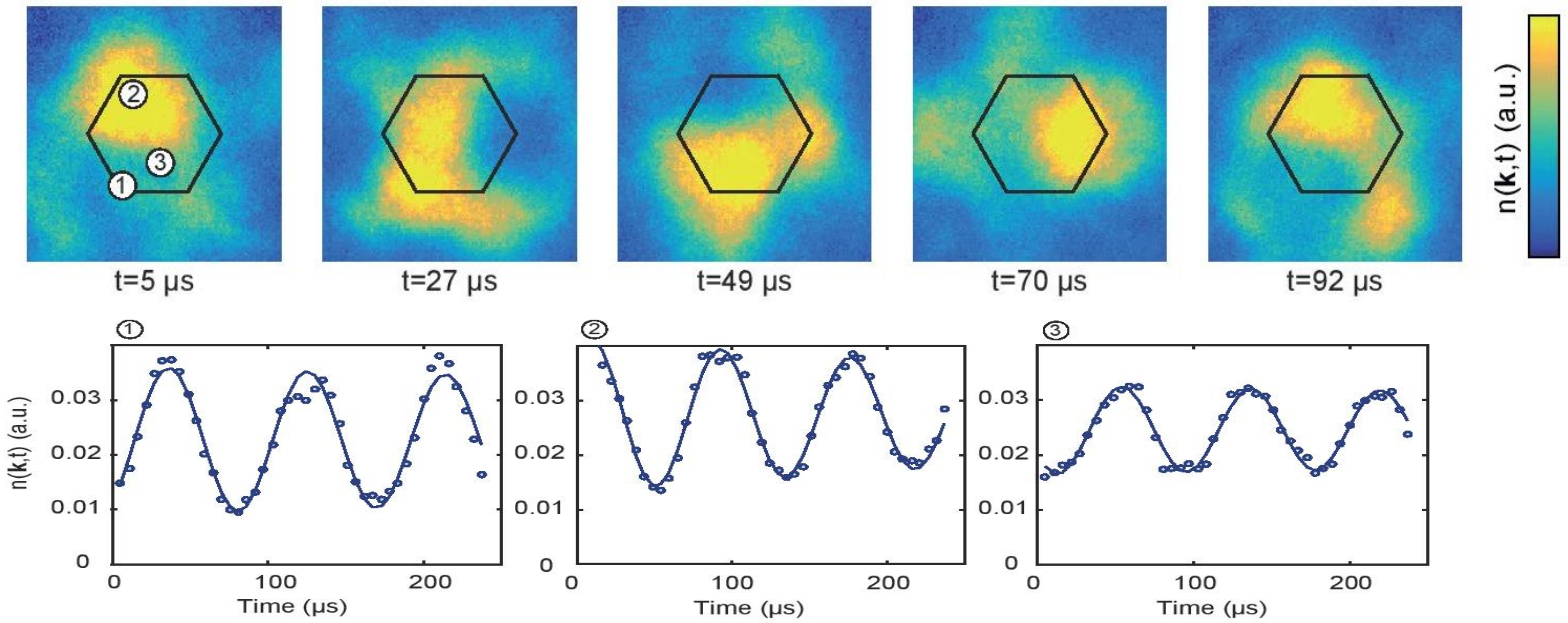
Proposal: P. Hauke, M. Lewenstein, A. Eckardt, PRL 113, 045303 (2014).

Bloch State Tomography of Floquet Systems



$$|k\rangle = -\sin\left(\frac{\theta_k}{2}\right)\exp(-i\phi_k)\,|k,A\rangle + e^{i\frac{\Delta_{AB}t}{\hbar}}\cos\left(\frac{\theta_k}{2}\right)|k,B\rangle$$

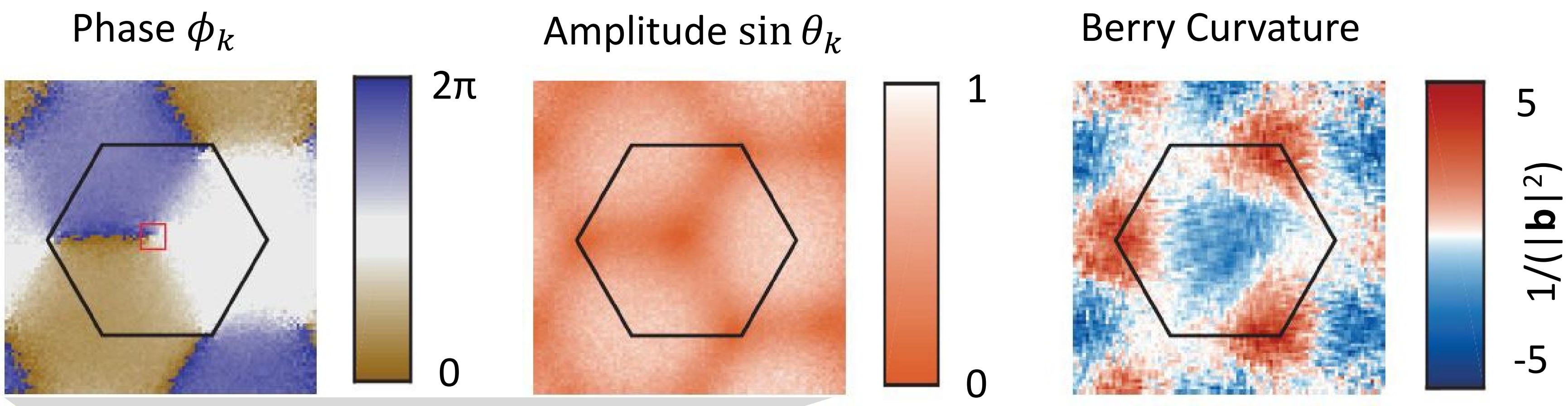
$$n(k,t) = |c|^2\left(1 - \sin\theta_k \cos(t\,\Delta_{\mathrm{AB}}/\hbar + \phi_k)\right)$$

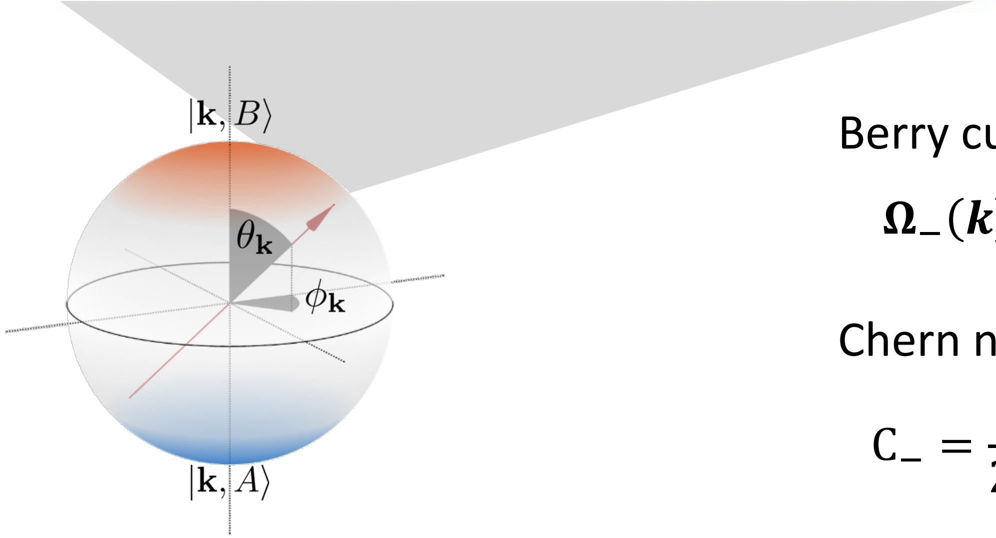


Pixelwise evaluation of the oscillation

Proposal: P. Hauke, M. Lewenstein, A. Eckardt, PRL 113, 045303 (2014).
Experiment: N. Fläschner et al., Science 352, 1091 (2016).

Measurement of the Berry Curvature





Sublattice pseudo-spin

Berry curvature from derivatives of the data:

$$\boldsymbol{\Omega}_-(\boldsymbol{k}) = \boldsymbol{\nabla}_\mathbf{k} \times i\hbar \left\langle u_k^- \right| \frac{\partial}{\partial \boldsymbol{k}} \left| u_k^- \right\rangle = -\frac{1}{2}\sin\theta(\partial_{k_x}\theta\partial_{k_y}\phi - \partial_{k_y}\theta\partial_{k_x}\phi)\,\hat{e}_z$$

Chern number from integration:

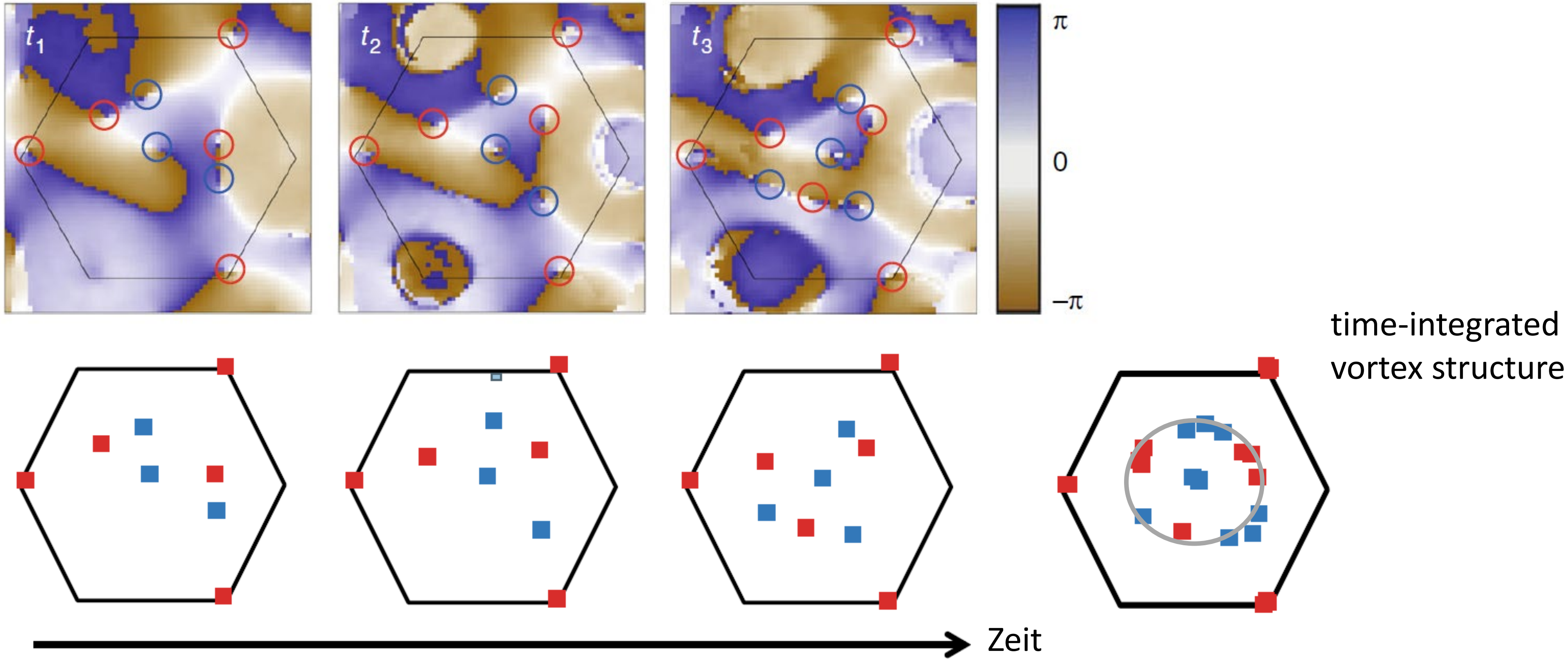
$$\mathrm{C}_- = \frac{1}{2\pi}\iint_{\mathrm{BZ}} \boldsymbol{\Omega}_-(\boldsymbol{k}) \cdot d\boldsymbol{k} = 0.005 \pm 0.003$$ (integer, but trivial)

How can we study non-trivial bands despite the heating?
Tomography of the dynamics after quench into Floquet system

N. Fläschner et al., Science 352, 1091 (2016).
Proposal: P. Hauke, M. Lewenstein, A. Eckardt, PRL 113, 045303 (2014).

Appearance of dynamical vortices

Quench into the Floquet system: Phase profiles for different evolution times

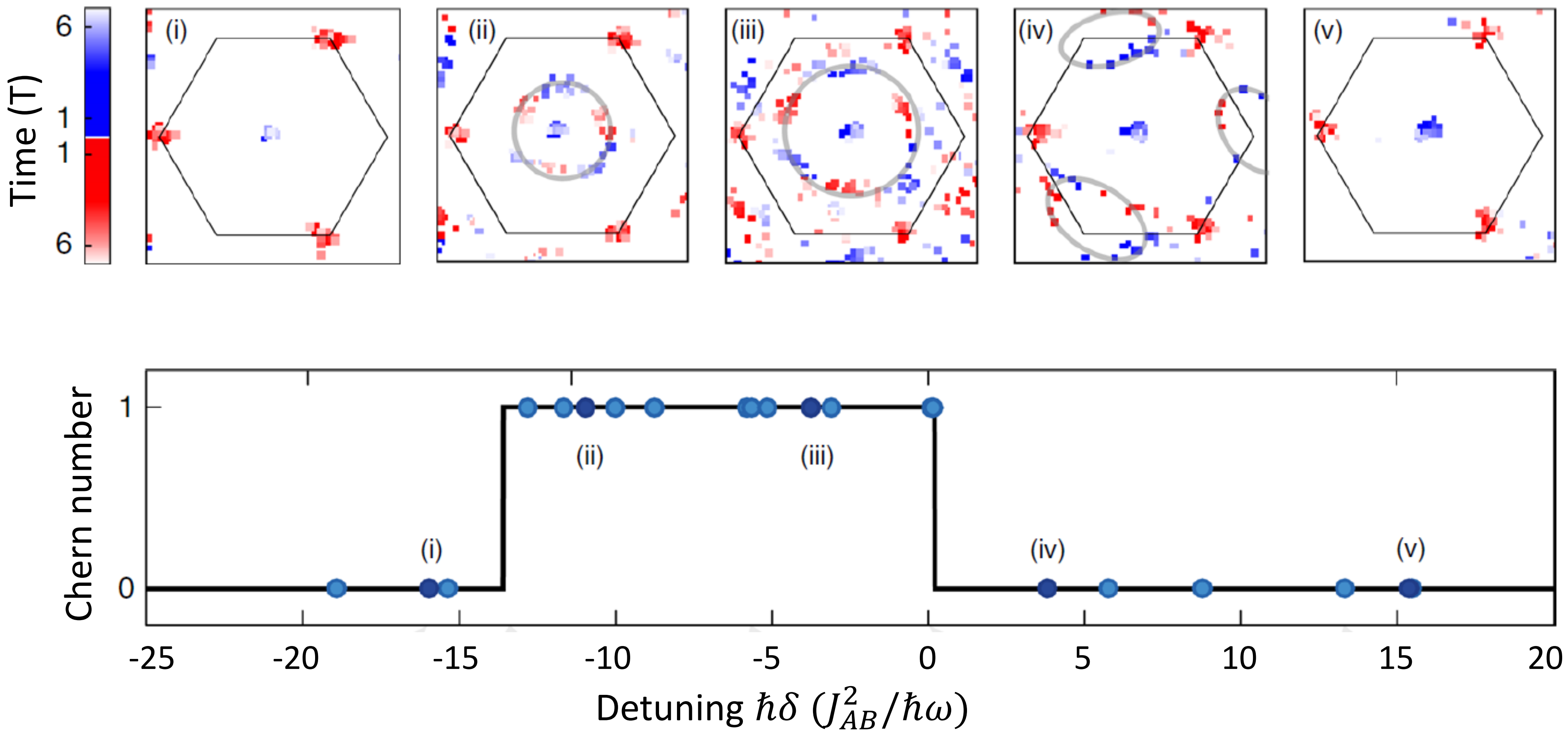


blue = vortex
red = anti-vortex

Linking number (dynamics)
= Chern number of final system (static)

N. Fläschner et al., Nature Phys. 14, 265 (2018). M. Tarnowski et al., Nature Commun. 10, 1728 (2019).
Compare: Wang, PRL 118, 185701 (2017). Yu, PRA 96, 023601 (2017). Ünal, PRR 1, 022003(R) (2019).

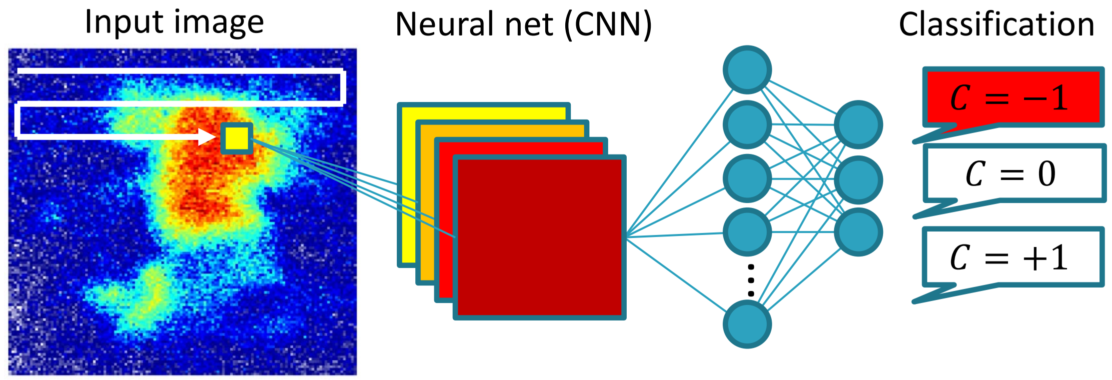
Linking number: Topology from dynamics



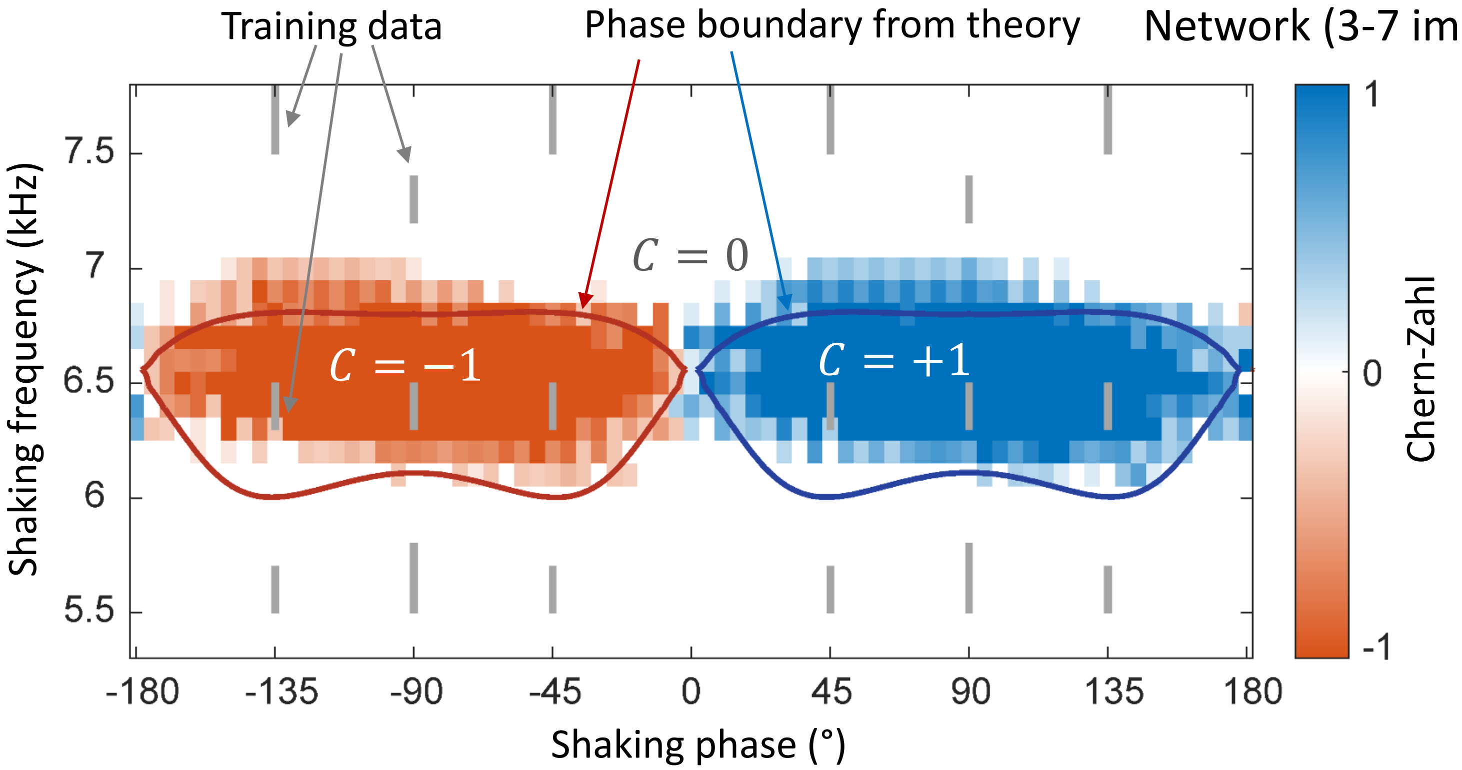
Connect topology and dynamics

M. Tarnowski, F. N. Ünal, N. Fläschner, B. S. Rem, A. Eckardt, K. Sengstock, C. Weitenberg, Nature Commun. 10, 1728 (2019).

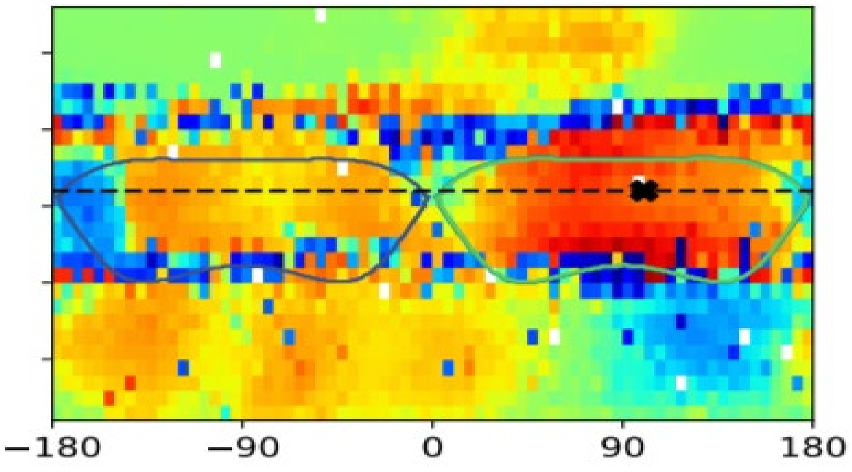
Topological phase diagram via machine learning



Classification via the trained Network (3-7 images per parameter)



Unsupervised machine learning (Influence Function)



Rem et al., Nature Phys. 15, 917 (2019).

Käming et al., arXiv:2101.05712 (2021)

Outline

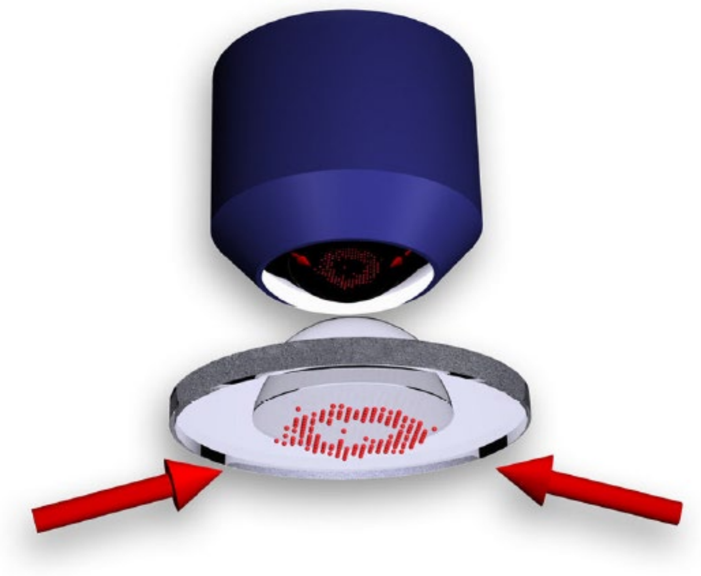
1. Floquet systems, how to engineer topology? (general introduction)
2. How to probe topology? (focus on experiments in Hamburg)
3. Interacting topological matter under the microscope (Outlook)

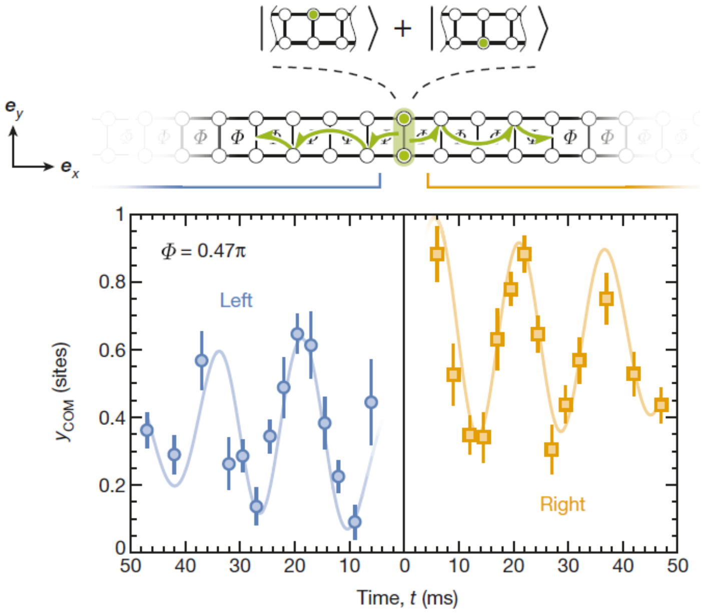
Towards interacting topological matter

Ultracold topological matter under the microscop

- Real-space approach, tailored potentials
- Prepare and detect low filling factor

Two bosons in a flux ladder

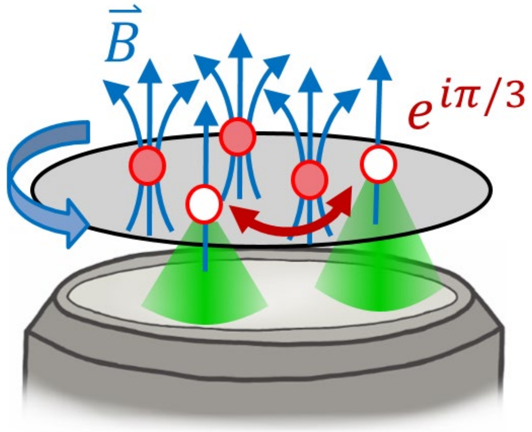




Tai, Greiner et al. Nature 546, 519 (2017)

Quantum Hall droplets

Rotating microtraps, bulk systems

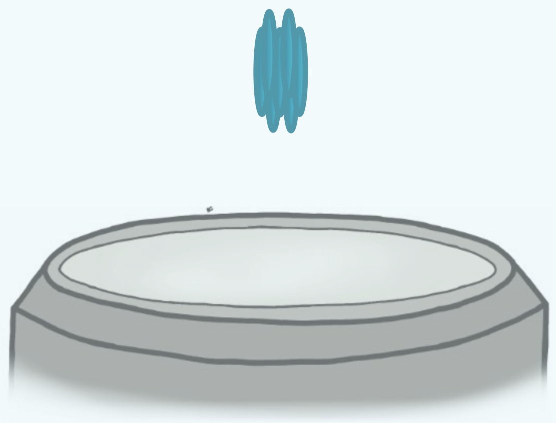


Optimized adiabatic preparation

Andrade et al., arXiv:2009.08943 (2020)

New approach: Quantum gas magnifier

High resolution imaging

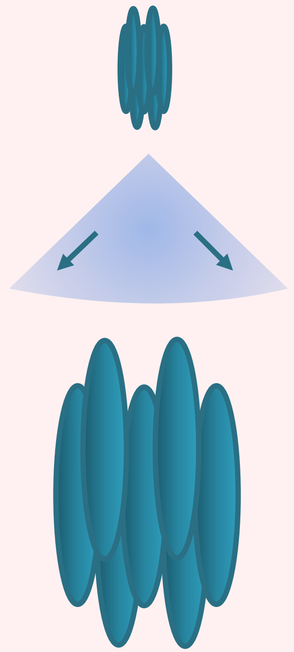


Optical lens

Getting closer to the quantum system....

...or bring it closer to us!

Quantum Gas Magnifier



Matter wave lens

single-shot, sub-lattice resolved images of the 3D system!

Asteria et al., arXiv:2104.10089 (2021)

Working principle of the Quantum Gas Magnifier

Array of „tubes“, triangular lattice, $\sim10^5$ ^{87}Rb atoms

<u>Initial position x_0</u>

Harmonic trap ω for $T/4$

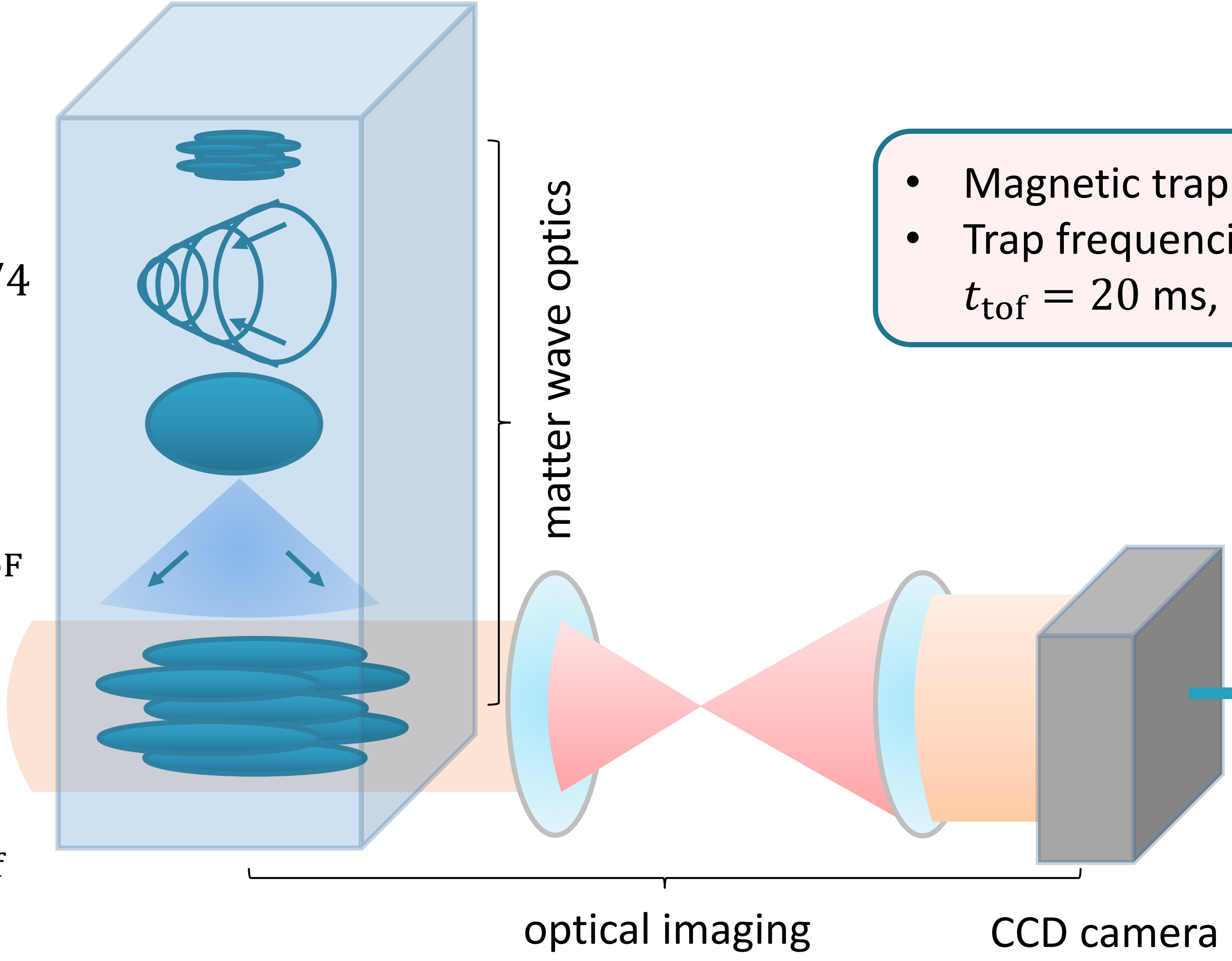
<u>Momentum $p = m\omega x_0$</u>

Free expansion for t_{ToF}

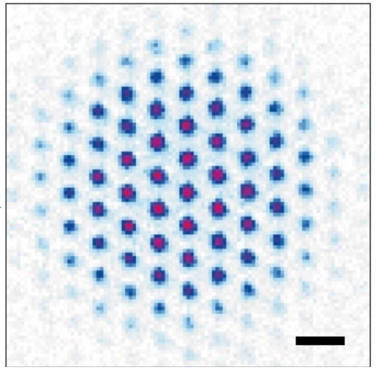
<u>Final position</u>

$x = p/m\, t_{\mathrm{tof}} = \omega t_{\mathrm{tof}} x_0$

Magnification $M = \omega t_{\mathrm{tof}}$



- Magnetic trap is smooth and isotropic
- Trap frequencies up to $\omega/2\pi$ =700 Hz, $t_{\mathrm{tof}} = 20$ ms, up to 93-fold magnification



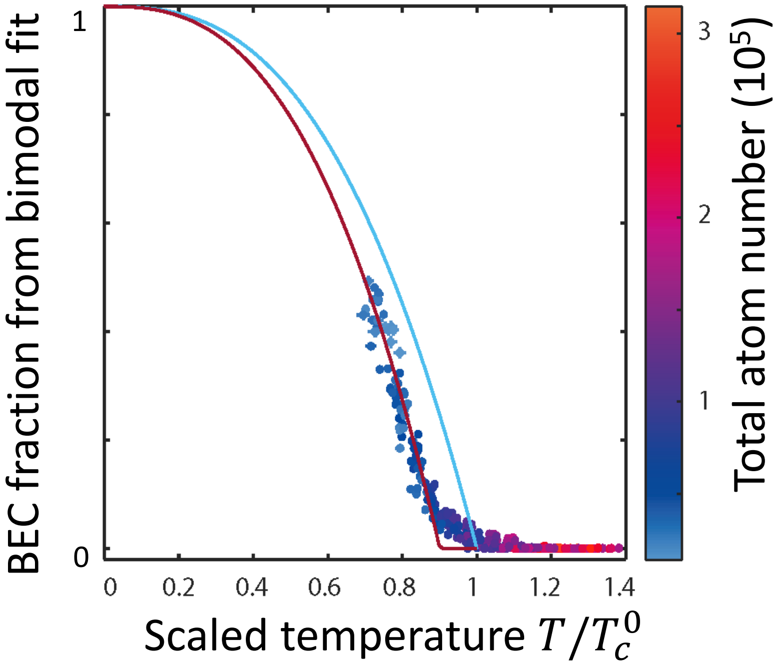
- Optical imaging ($a_{\mathrm{lat}} \triangleq 60$ µm)

<u>Excellent resolution, single-shot image!</u>

Asteria et al., arXiv:2104.10089 (2021)

Precision measurements with the quantum gas magnifier

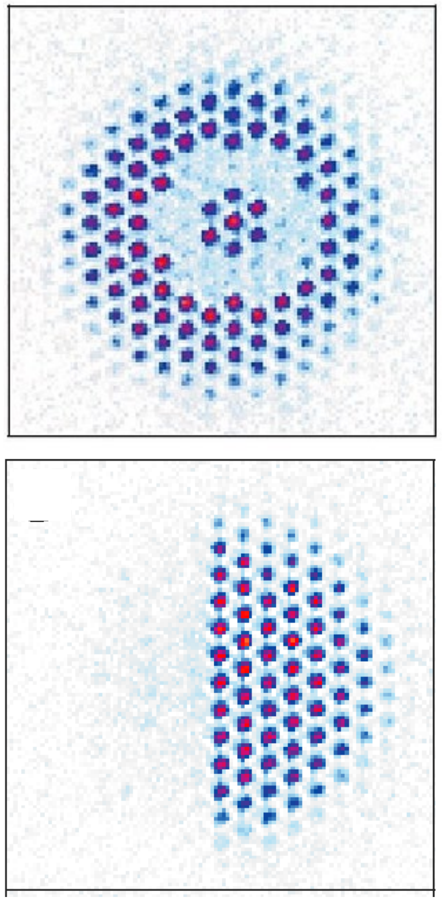
Precision thermodynamics



- Cross over regime with power law $\alpha = 2.69(1)$
- Strong interaction shift $T_c = 0.89(1)\, T_c^0$

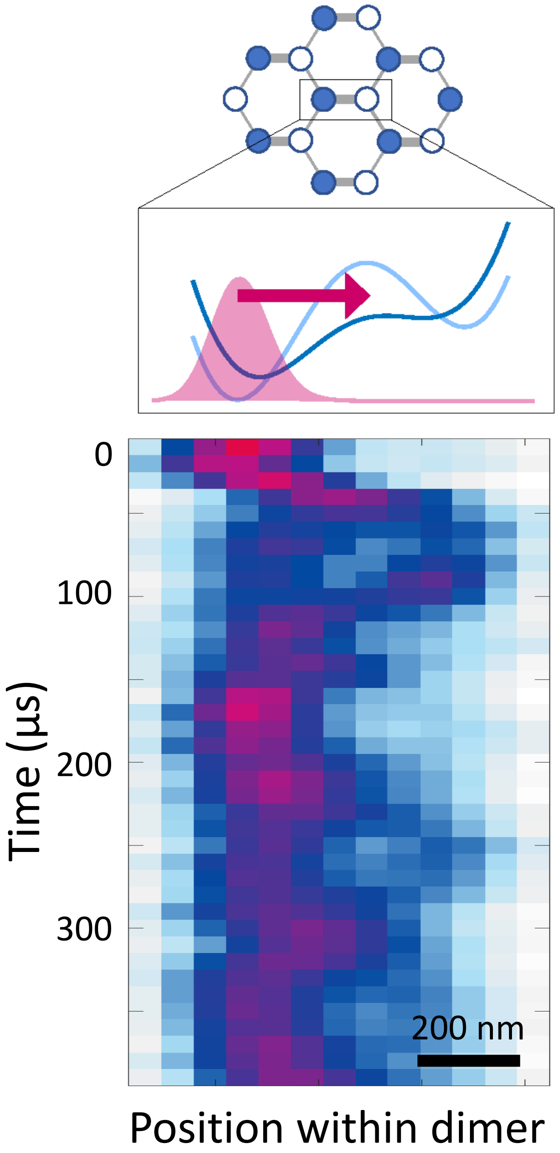
Theory?

Local RF addressing



- Prepare arbitrary density patterns
- Full functionality of a quantum gas microscope

Resolving nanoscale dynamics

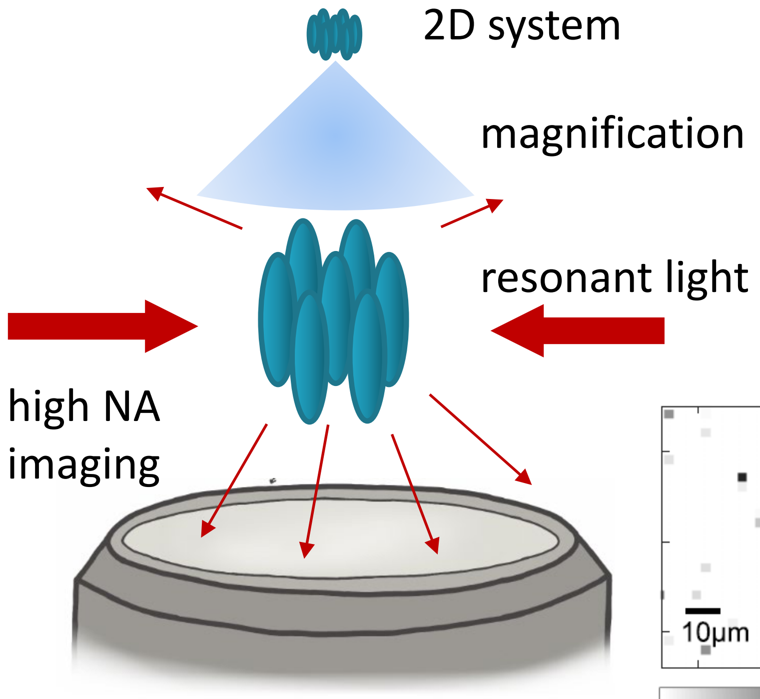


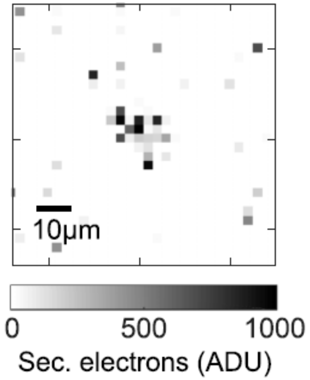
Luca Asteria et al., arXiv:2104.10089 (2021)

Towards the single-atom resolved regime

Quantum gas microscope 2.0

- Single-atom regime via free-space fluorescence imaging
- Magnified lattice spacing is larger than diffusive expansion

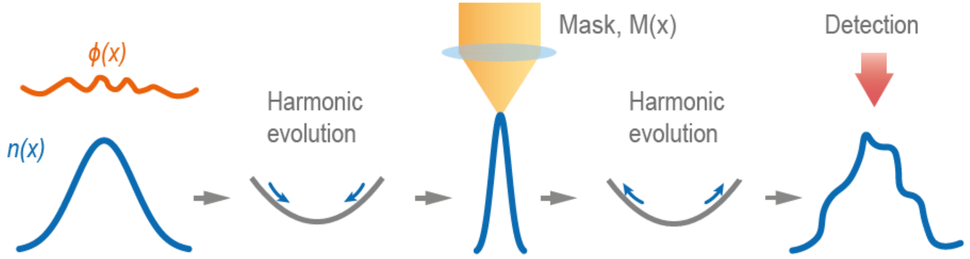




Bergschneider/Jochim et al., PRA 97, 063613 (2018).
Bücker/Schmiedmayer, New J. Phys. 11, 103039 (2009).

Access coherence properties with high spatial resolution

- Manipulation in Fourier space
- Image Talbot revivals

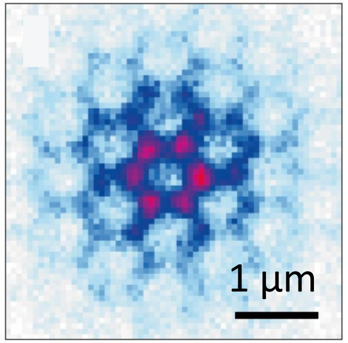


Murthy & Jochim, arXiv:1911.10824 (2019).
Santra/Ott et al., Nature Commun. 8, 15601 (2017).

New possibilities

- Applicable to species, where laser cooling or deep optical lattices are not available
- Extend microscopes to exotic atoms
- Also new regimes, lattice geometries
- No parity projection

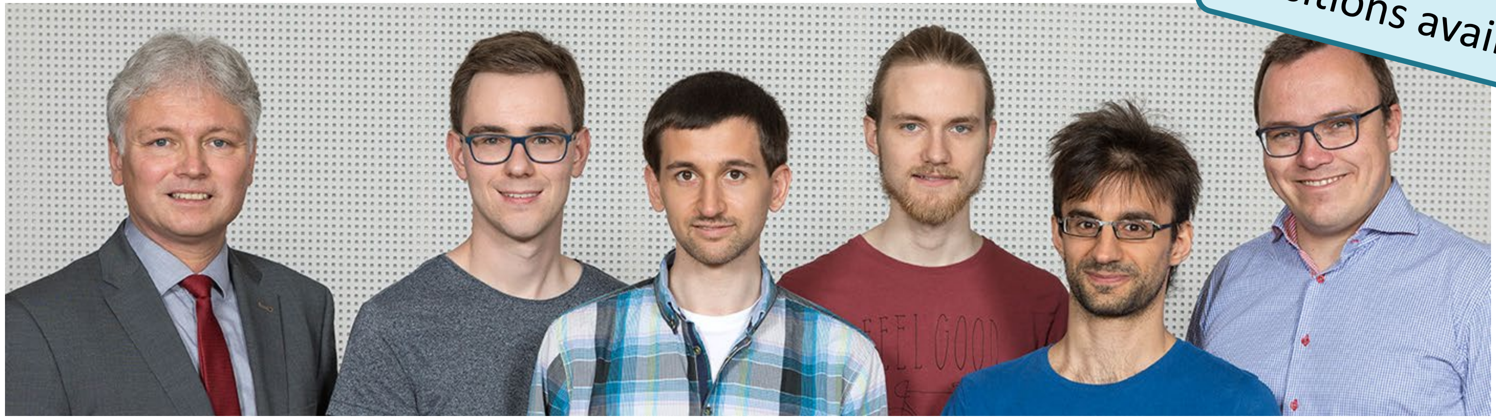
New real-space access to quantum many-body systems



Acknowledgements

Hamburg experimental team

Positions available!



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CUI THE HAMBURG CENTRE FOR ULTRAFAST IMAGING

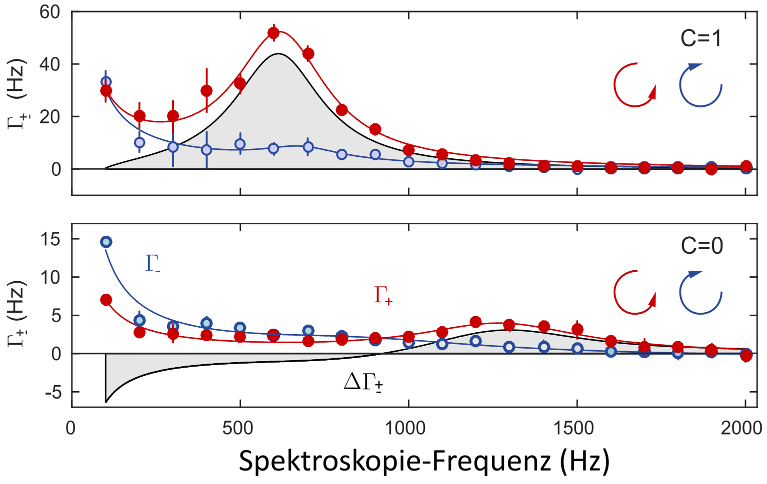
FOR 2414

SFB
SFB 925: Light induced dynamics and control of strongly correlated quantum systems

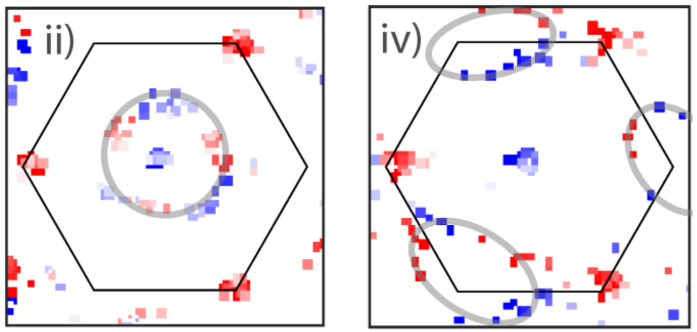
erc European Research Council

Summary

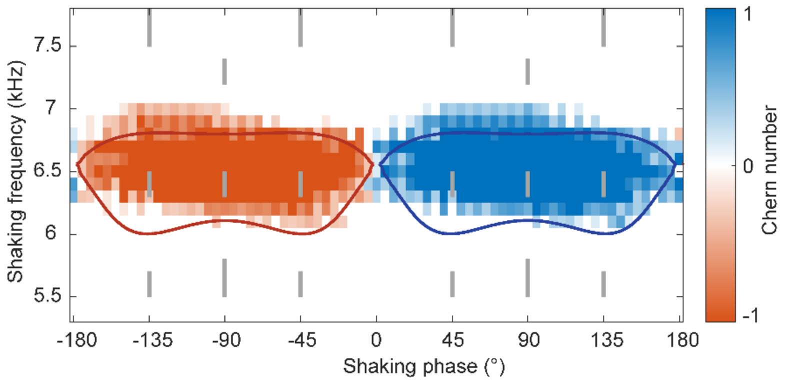
Quantized circular dichroism



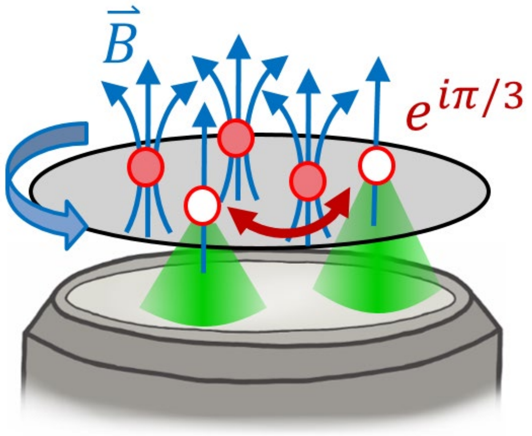
State tomography and linking number



Machine learning of topol. phases



Quantum Hall droplets



Quantum gas magnifier