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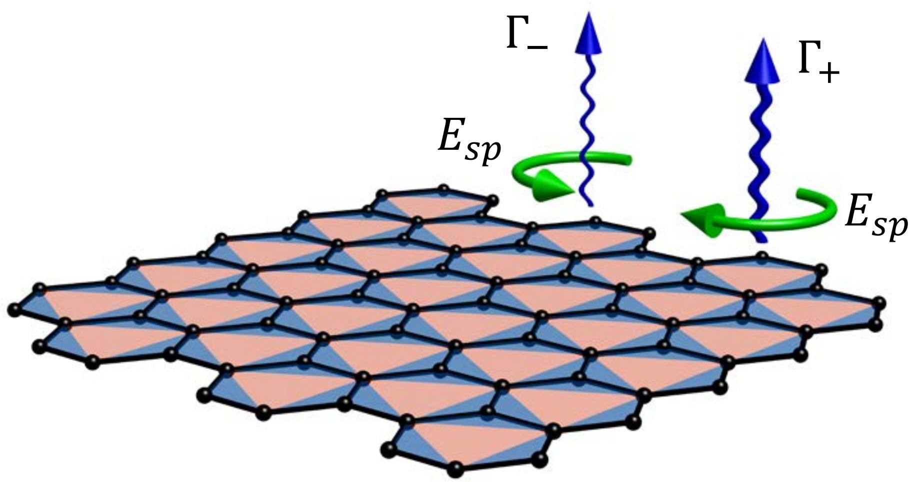
Quantized circular dichroism in ultracold topological matter



Christof Weitenberg

Vilnius, 30.07.2018

The Team

The Hamburg Team

Luca Asteria

Matthias Tarnowski

Nick Fläschner

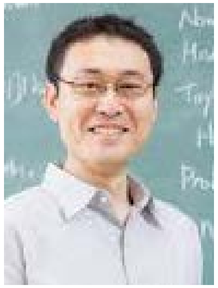
Benno Rem

Christof Weitenberg

Klaus Sengstock

The Brussels Theory Team (Dichroism)

Duc-Thanh Tran



Tomoki Ozawa

Nathan Goldman

The Dresden Theory Team (Linking number)

Nur Ünal

André Eckardt

References

Asteria et al., arXiv:1805.11077 (2018)

Tarnowski et al., arXiv:1709.01046 (2017)

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

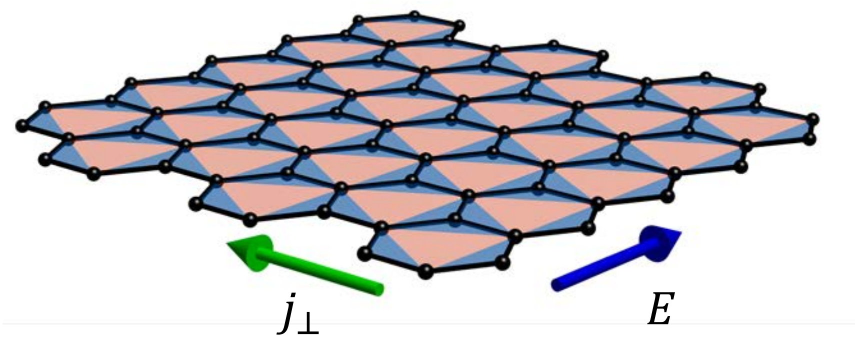
Funding

CUI THE HAMBURG CENTRE FOR ULTRAFAST IMAGING

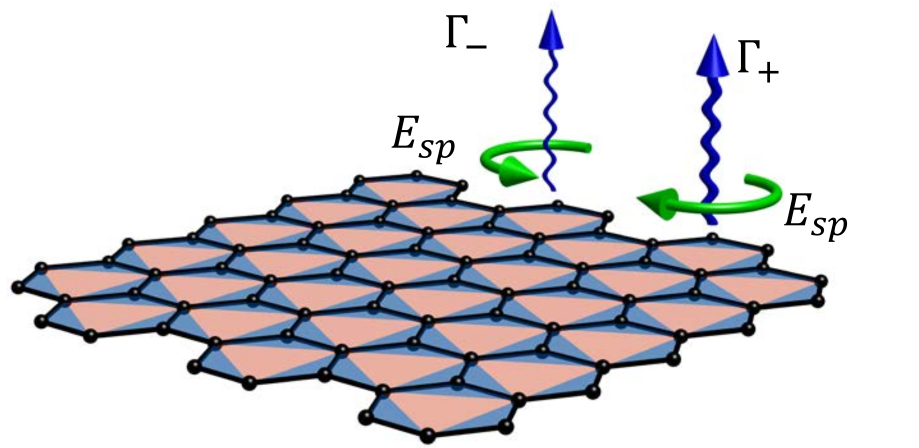
FOR 2414

Topological phenomena

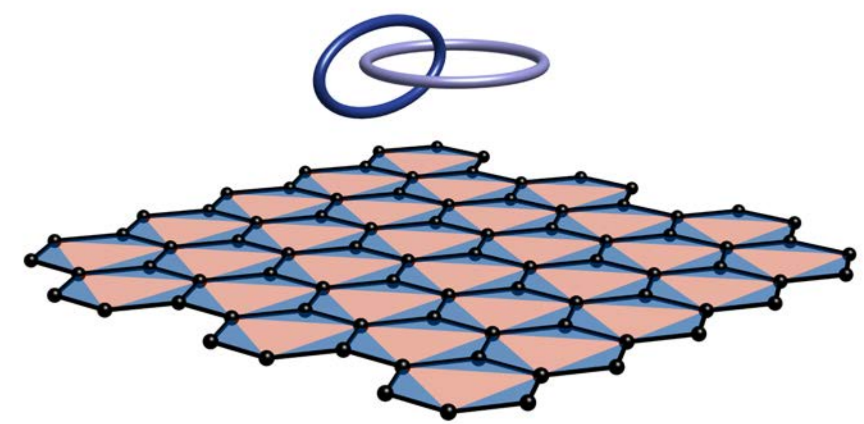
Quantized transport $j_\perp = (e^2/\hbar) C \cdot E$

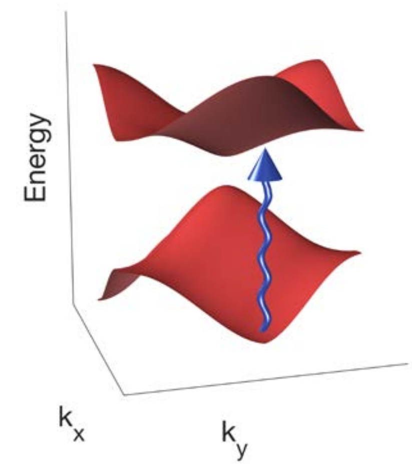


Quantized depletion $\Delta\Gamma_{\pm}^{int}/A_{cell} = \left(\frac{1}{\hbar^2}\right) C \cdot E_{sp}^2$

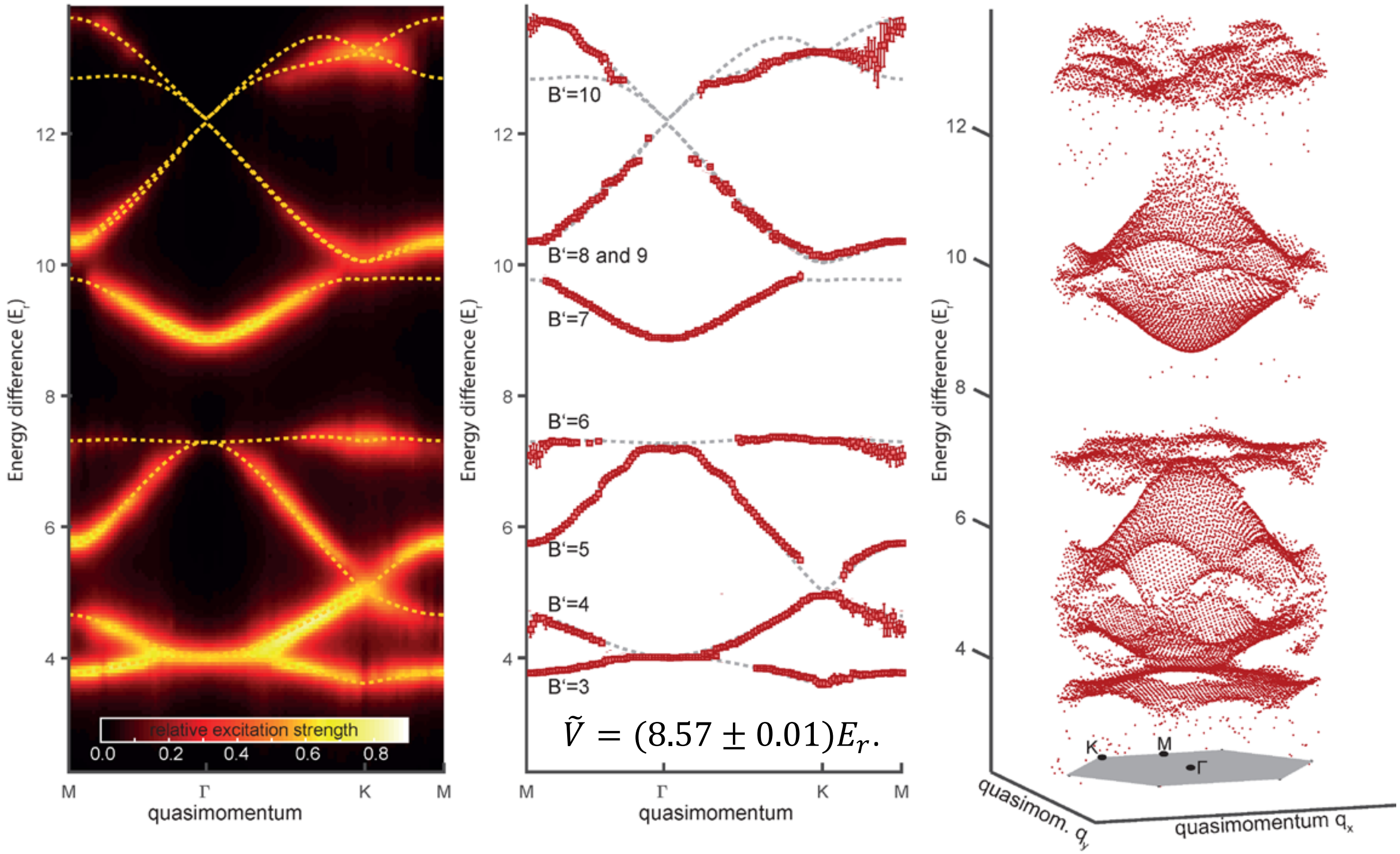


Topological signatures in dynamics far from equilibrium





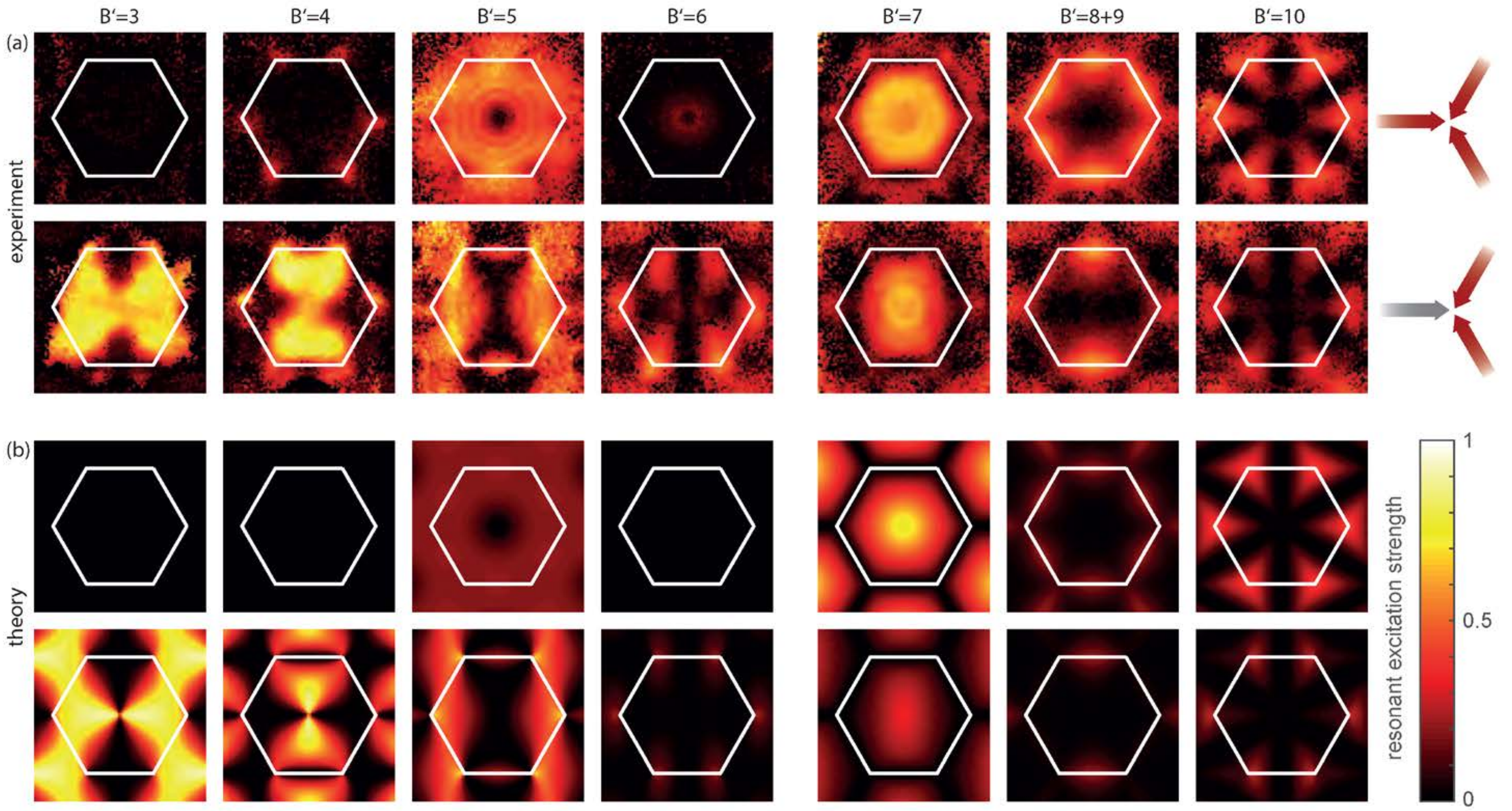
Excursion: Multiband spectroscopy of the honeycomb lattice



- Measure band structure via spectroscopy (here: amplitude modulation)
- determine lattice depth with error of $1.2 \cdot 10^{-3}$

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

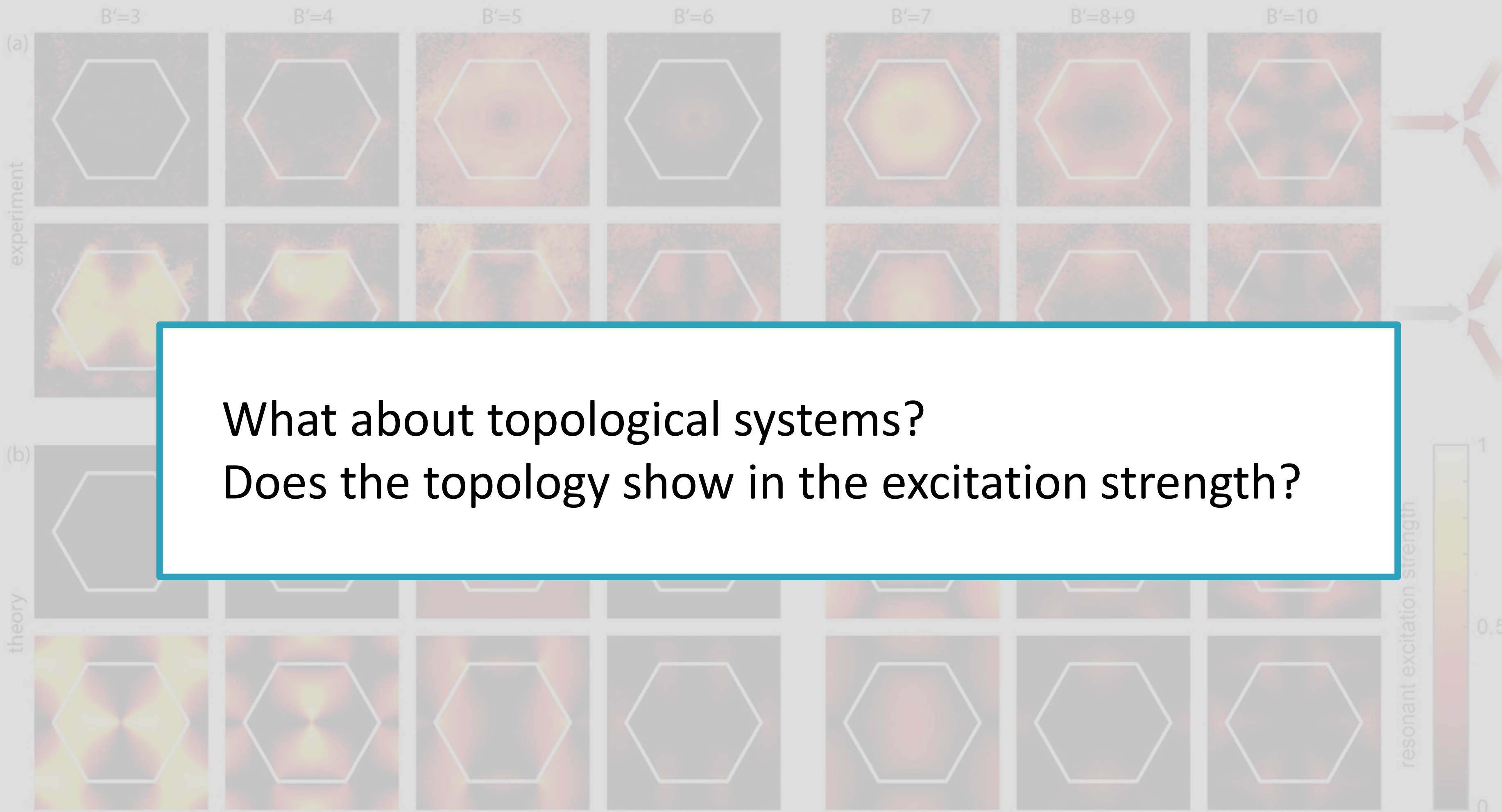
Resonant excitation strengths



- Also consider the excitation strengths: learn about the eigenstates
- Here: accessibility of bands depends on symmetry of perturbation

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

Resonant excitation strengths



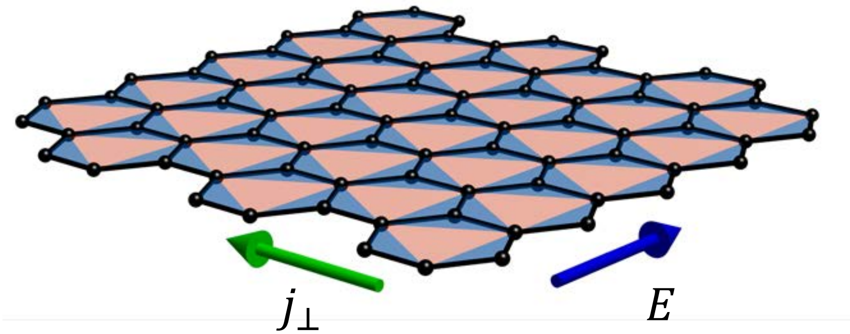
What about topological systems?
Does the topology show in the excitation strength?

- Also consider the excitation strengths: learn about the eigenstates
- Here: accessibility of bands depends on symmetry of perturbation

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

Topological phenomena

Quantized transport $j_{\perp} = (e^2/\hbar) C \cdot E$



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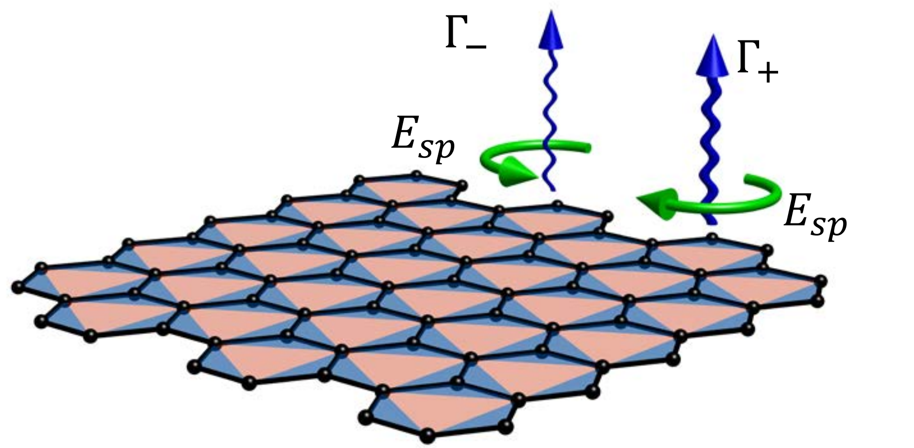

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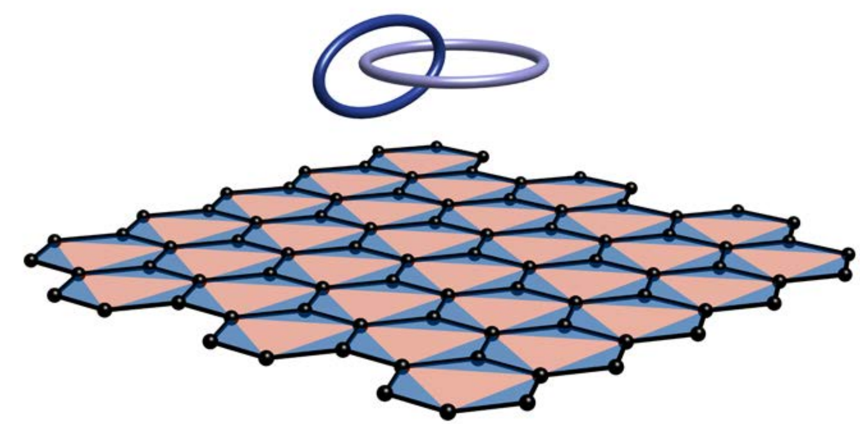

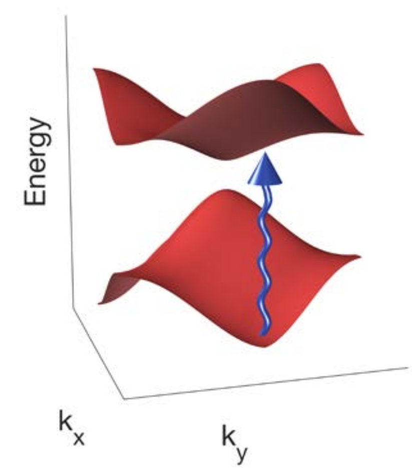

Quantized circular dichroism in Chern insulators

$$\hat{H}_{\pm}(t) = \hat{H}_0 + 2E\{\cos(\omega t)\,\hat{x} \pm \sin(\omega t)\,\hat{y}\}$$

Topological Hamiltonian
(e.g. Haldane model)

Chiral spectroscopy

- Transformation into the accelerated frame… $H'_{\pm} = R^{-1}\, H_{\pm}\, R$
- Leads to $H'_{\pm}(t) \approx \hat{H}_0 + \frac{2E}{\hbar\omega}\left\{\sin\omega t\,\frac{\partial \hat{H}_0}{\partial k_x} \mp \cos\omega t\,\frac{\partial \hat{H}_0}{\partial k_y}\right\}$
- Fermi's golden rule: $\Gamma_{\pm}(\omega) = \frac{2\pi}{\hbar}\left(\frac{E}{\hbar\omega}\right)^2 \sum_{n>0} \left|\left\langle n \left| \frac{1}{i}\frac{\partial \hat{H}_0}{\partial k_x} \mp \frac{\partial \hat{H}_0}{\partial k_y} \right| 0 \right\rangle\right|^2 \delta(\varepsilon_n(k) - \varepsilon_0(k) - \omega)$
- **Differential integrated rate:**

$$\Delta\Gamma_{\pm}^{int} \equiv \int \frac{d\omega[\Gamma_+(\omega) - \Gamma_-(\omega)]}{2} = \left(\frac{E}{\hbar}\right)^2 \underbrace{4\pi\,\mathrm{Im} \sum_{n>0}\sum_{k} \left\langle 0 \left| \frac{\partial H_0}{\partial k_x} \right| n \right\rangle \left\langle n \left| \frac{\partial H_0}{\partial k_y} \right| 0 \right\rangle / (\varepsilon_0 - \varepsilon_n)^2}_{= C \cdot A_{\mathrm{cell}}}$$

Chern number

$$\boxed{\Delta\Gamma_{\pm}^{int}/A_{cell} = (1/\hbar^2)\,C \cdot E^2}$$

D. T. Tran, et. al, Science Advances 3, e1701207 (2017)

Quantized circular dichroism in Chern insulators

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- Leads…
- Fermi… $\ldots k) - \omega)$
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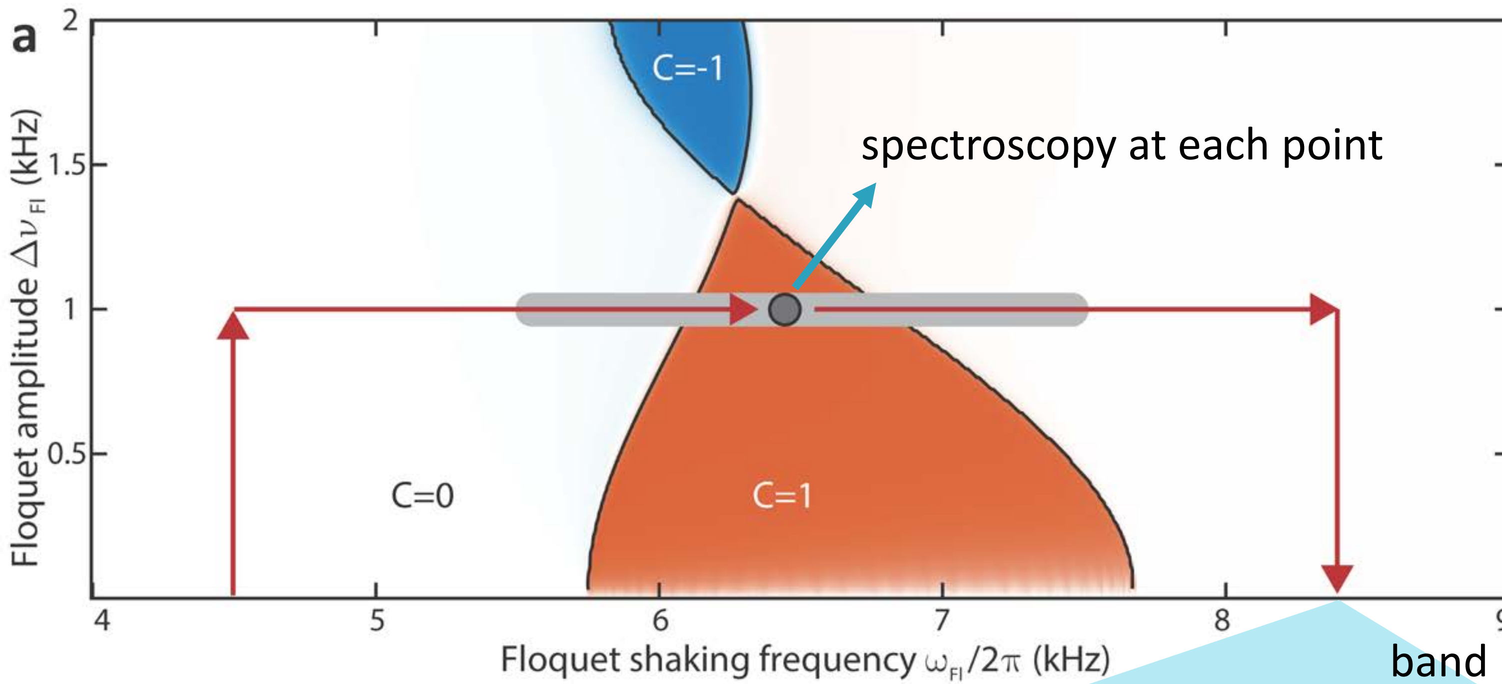
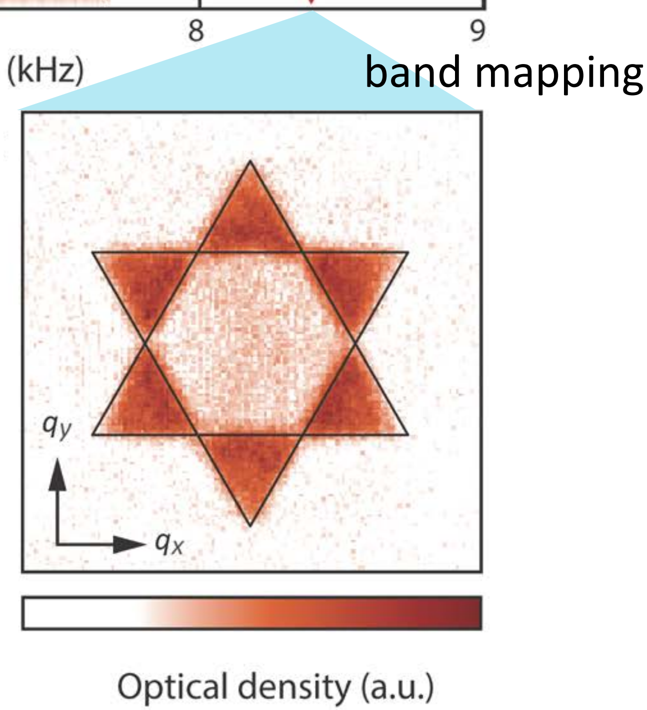
Chern number

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

D. T. Tran, et. al, Science Advances 3, e1701207 (2017)

Floquet engineering of a Chern insulator





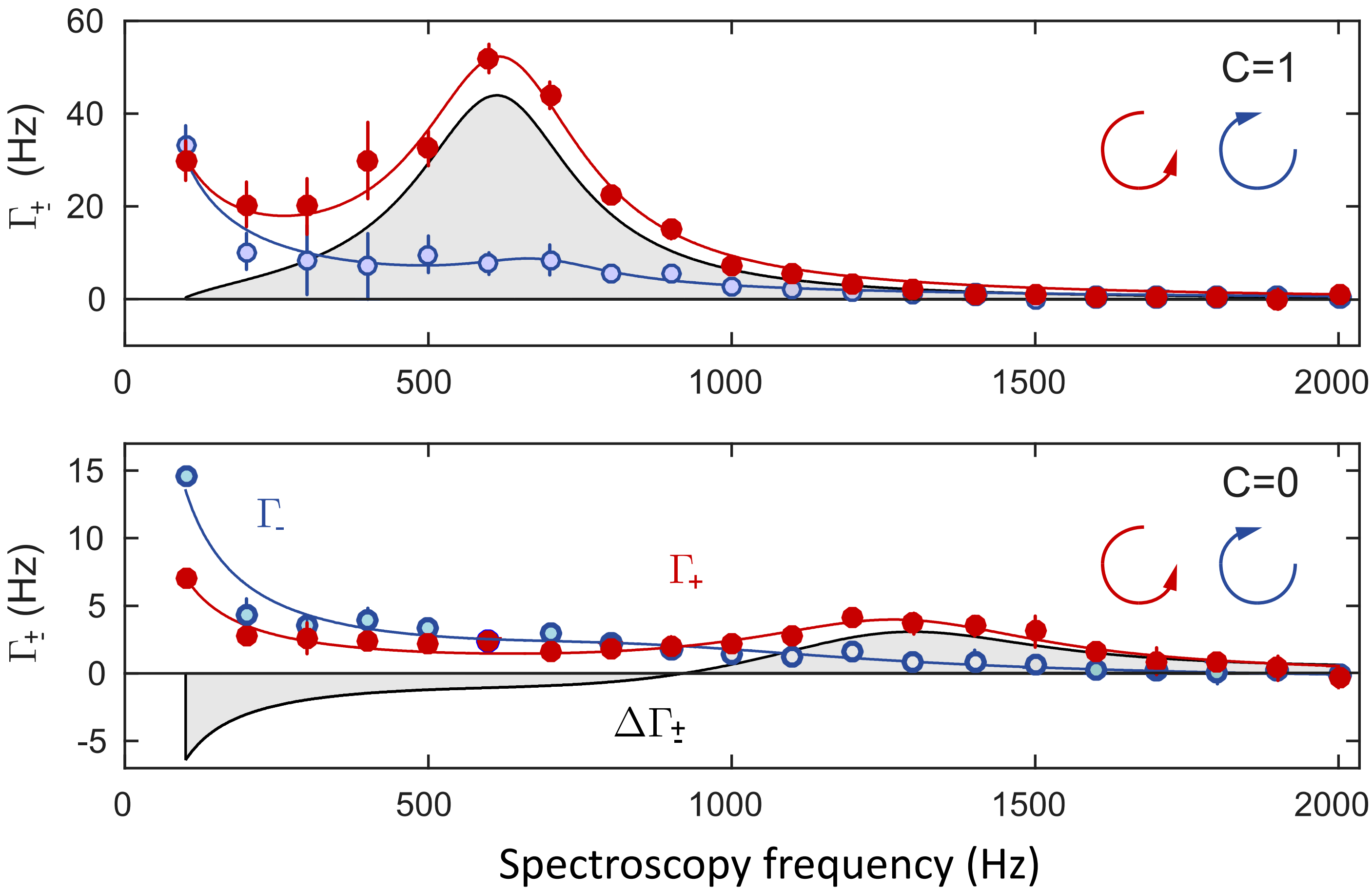
measurement procedure

Spectroscopy via circular lattice shaking

(at much smaller frequencies than
Floquet engineering frequencies)

Asteria et al., arXiv:1805.11077 (2018)

Chiral spectra



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

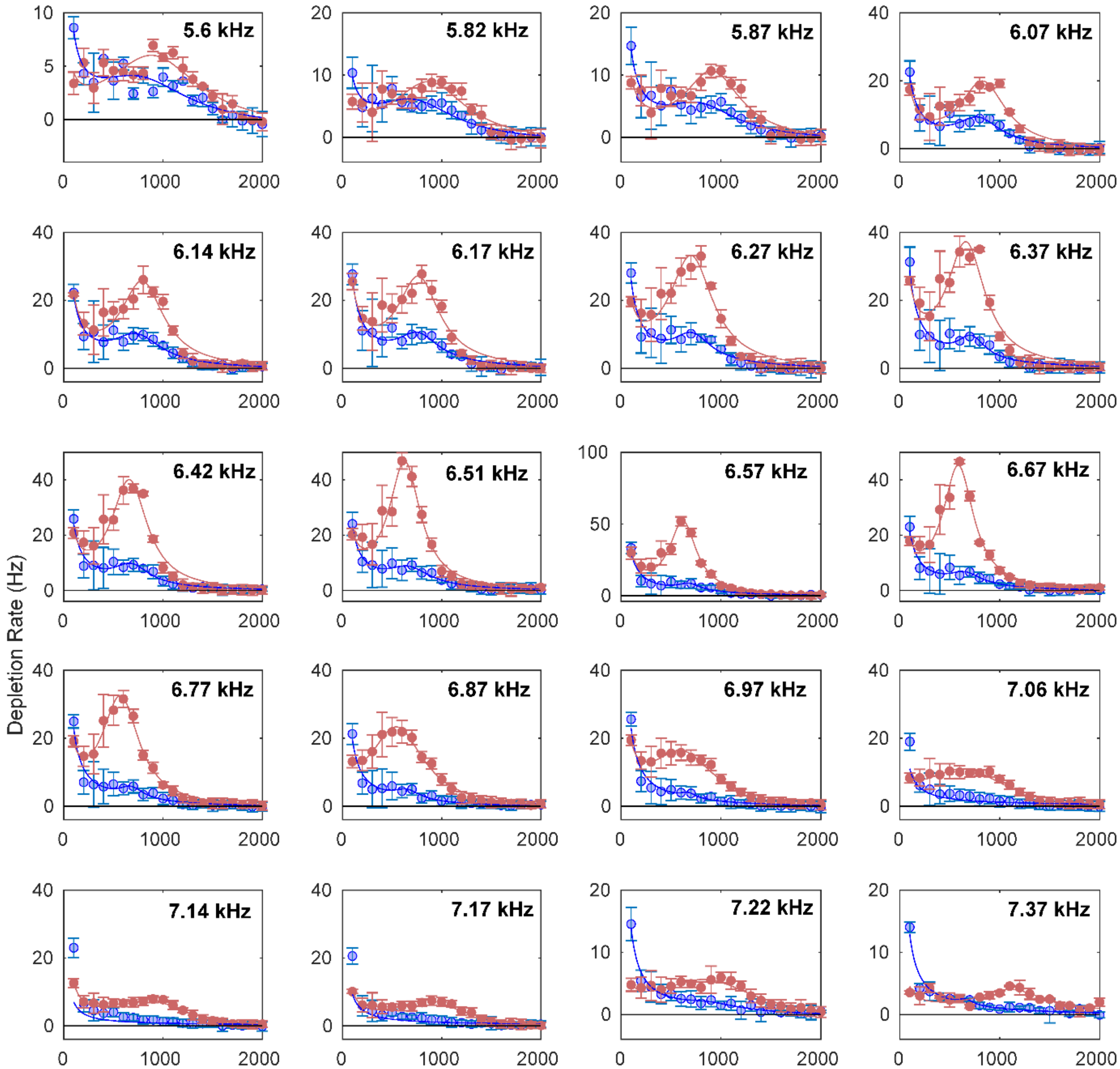
$C_{\mathrm{exp}} = 0.12(4)$

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

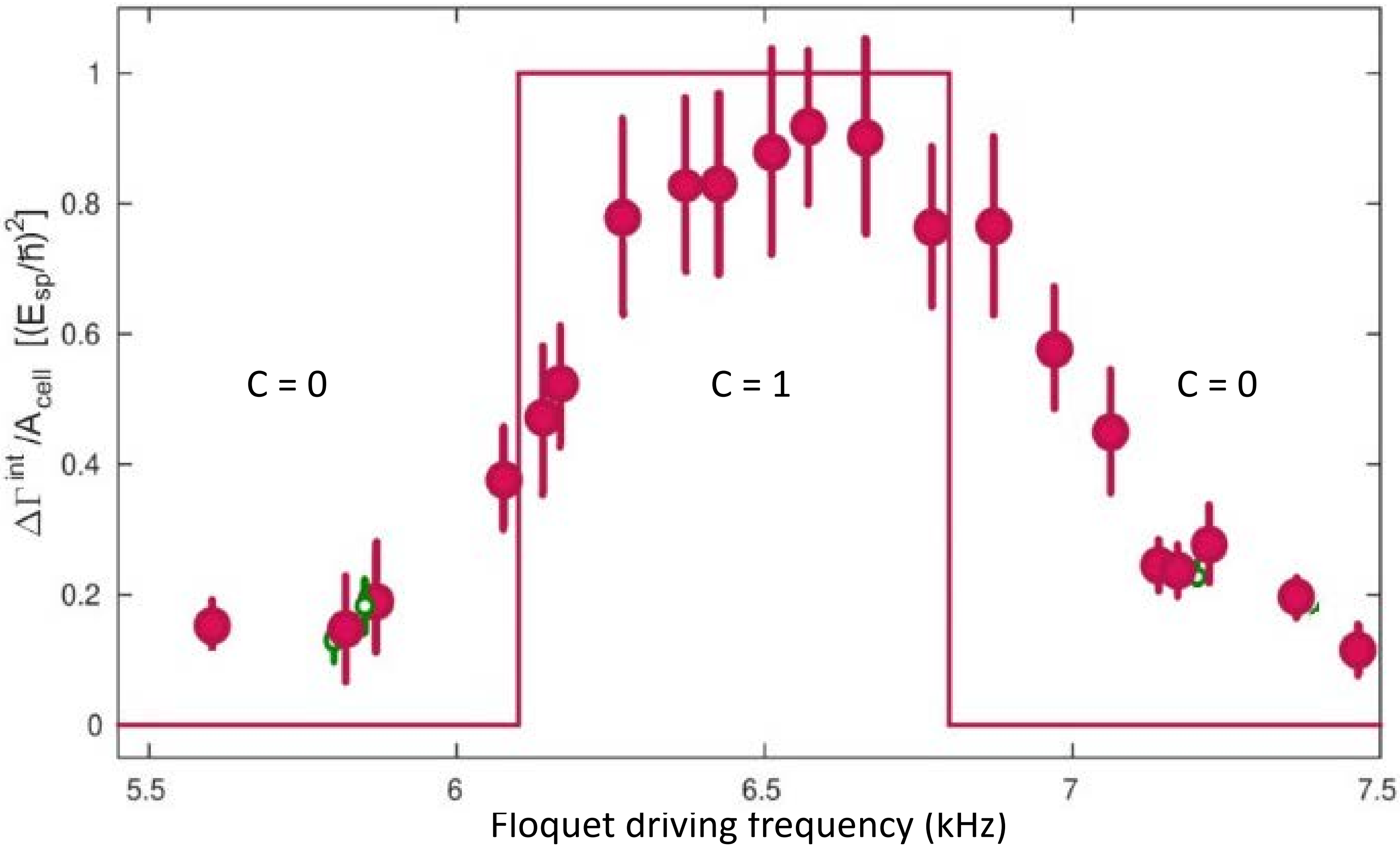
Dichroic signal $C_{\mathrm{exp}} = \Delta\Gamma^{\mathrm{int}}/A_{\mathrm{cell}} \cdot (\hbar/E_{\mathrm{sp}})^2$

Experimental confirmation of quantized circular dichroism

Chiral spectra across phase transition

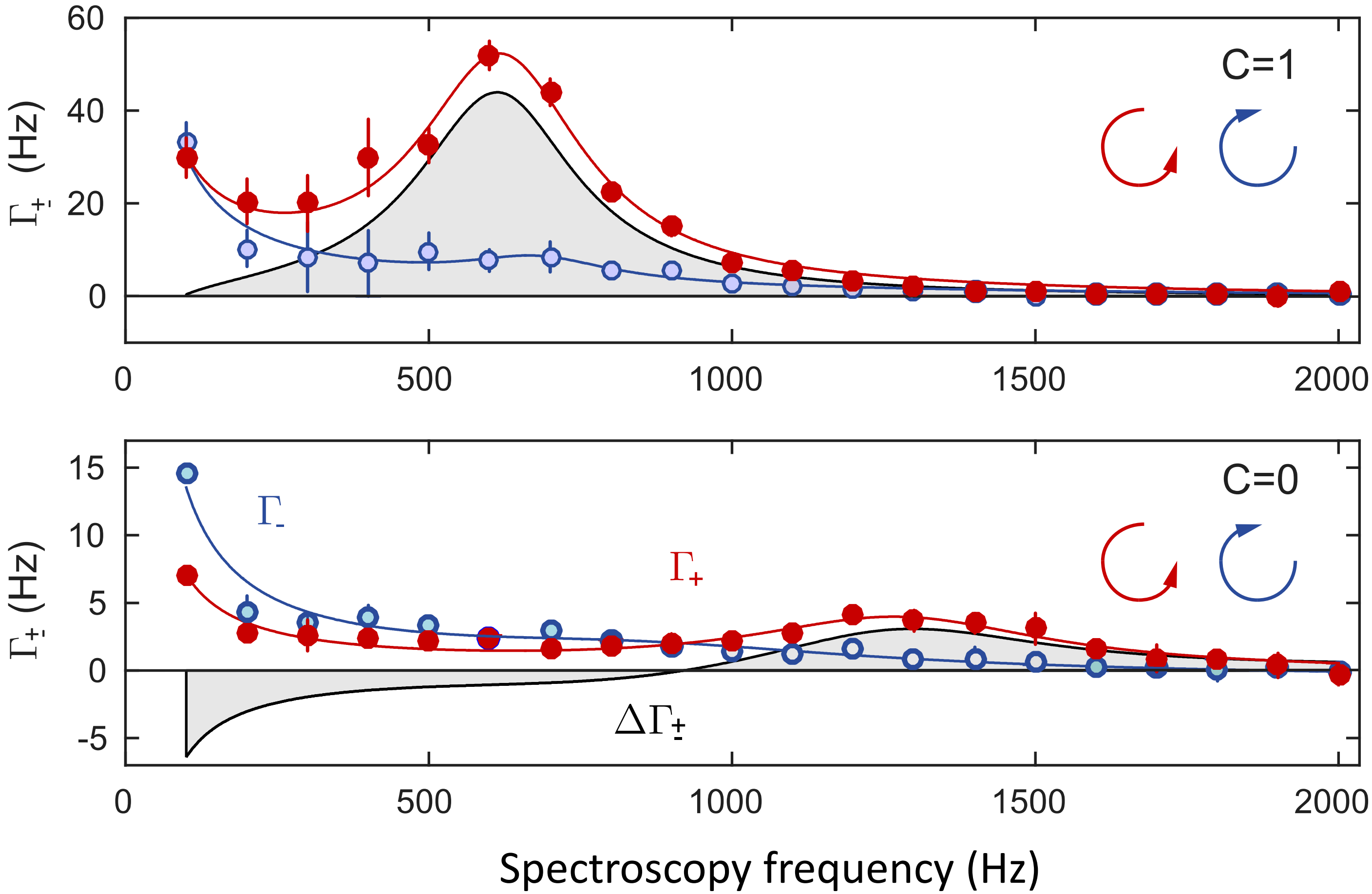


Dichroic signal across topological phase transition

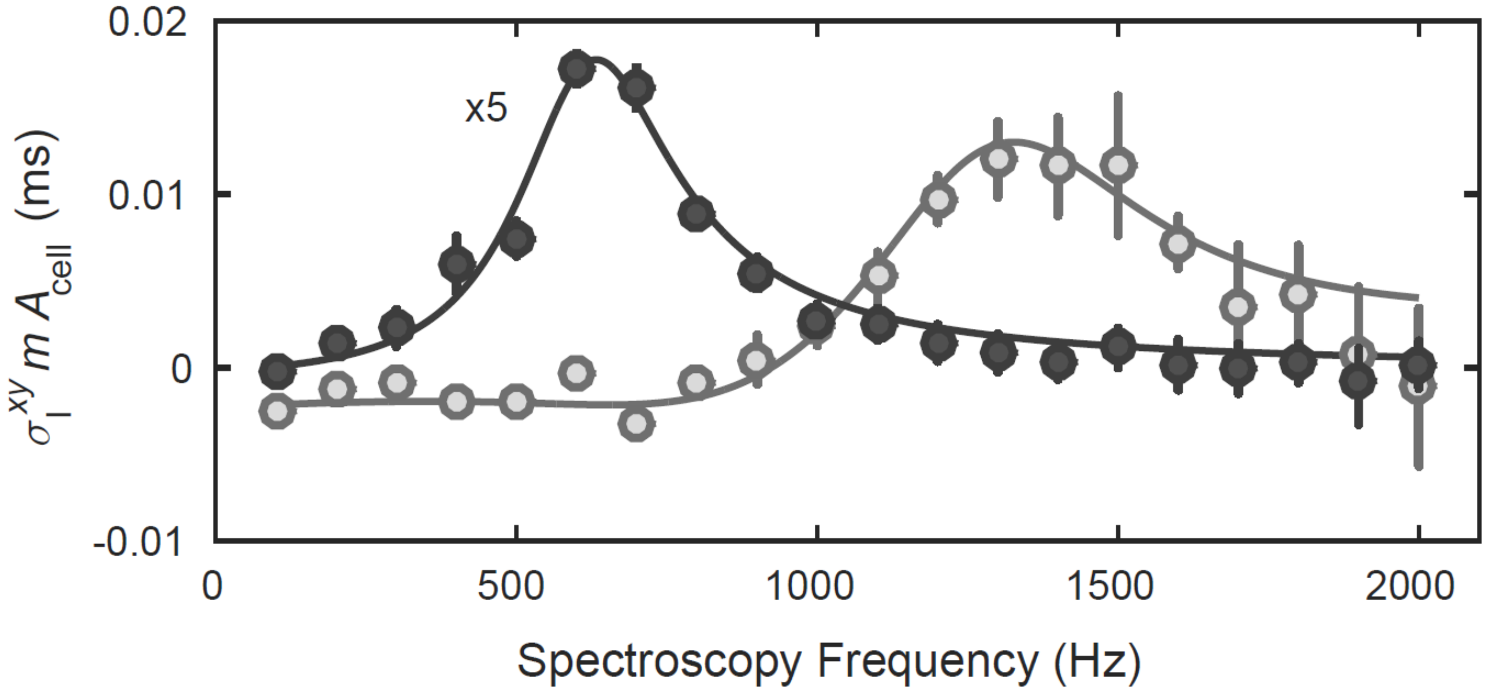


Smooth drop of signal in the transition region
General: Finite size, inhomogeneous systems, finite temperature
Spectroscopic: Fourier broadening, breakdown of RWA, contribution of edge states

Chiral spectra



Optical conductivity

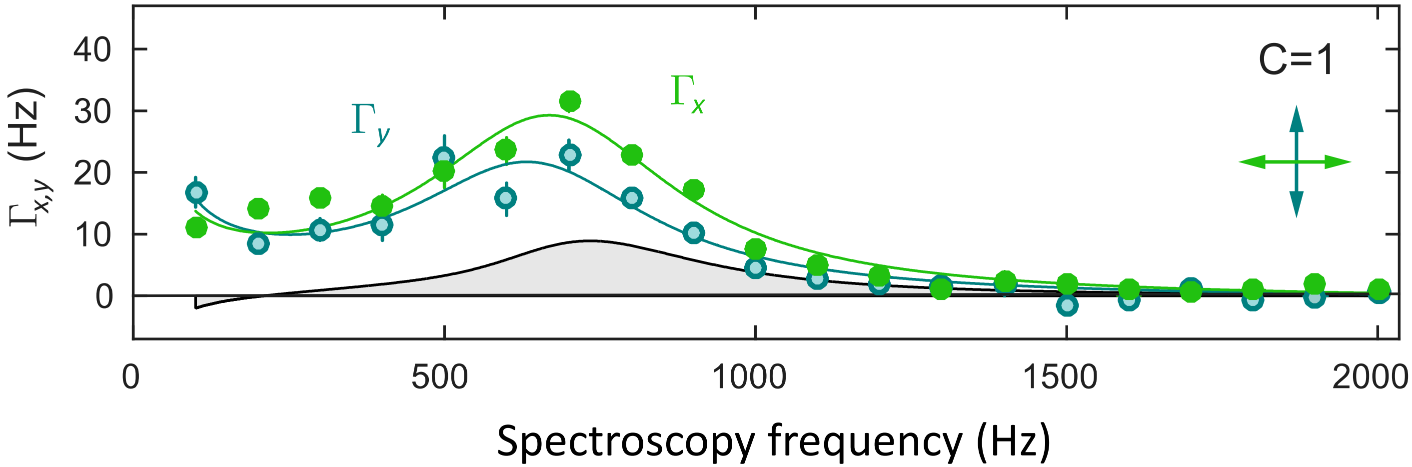


Measurement of the imaginary part of the optical conductivity
$\sigma_I^{xy}(\omega) = \hbar\omega \cdot \Delta\Gamma_{\pm}\,(\omega)/4\pi A_{cell}E^2$

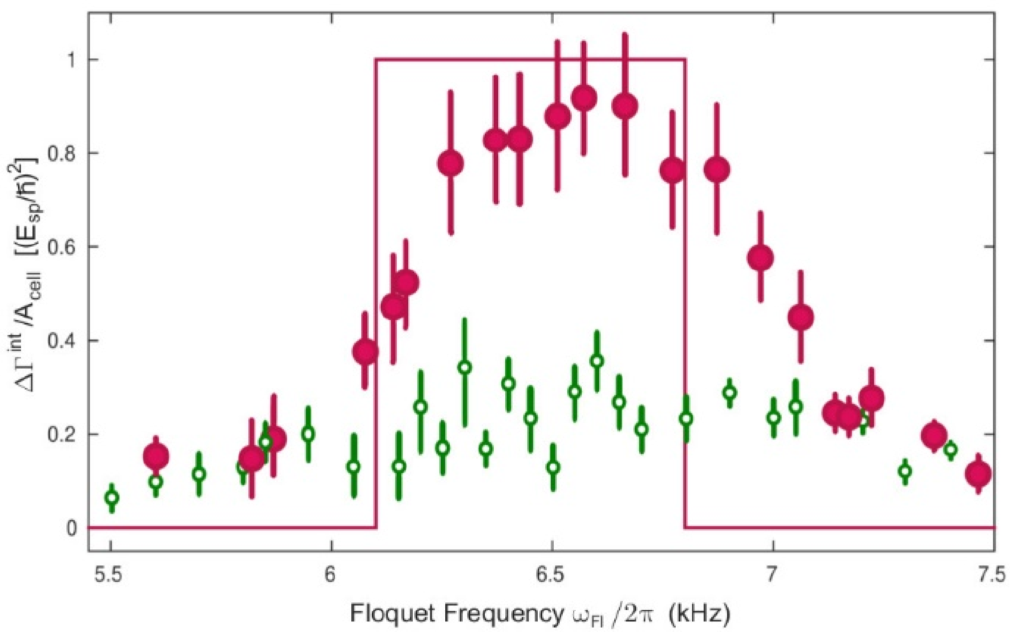
Access to the optical conductivity in topological matter

Compare: Andersen,…, Thywissen, arXiv:1712.09965 (2017)

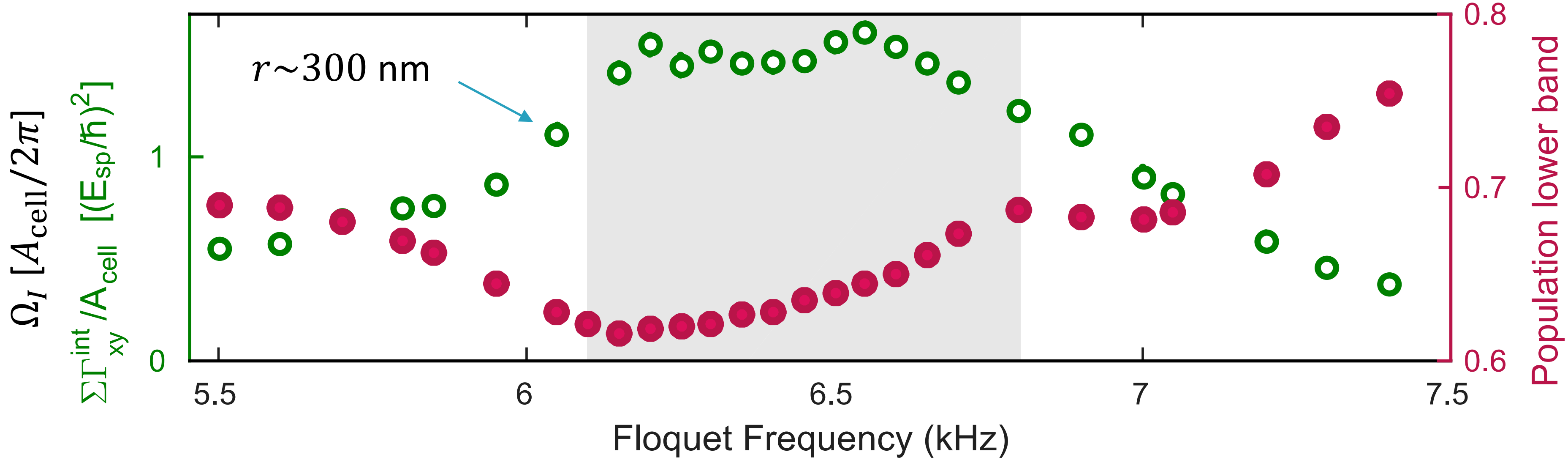
Linear dichroism



- Linear dichroism is negligible across the phase transition
- Supports the chiral nature of the bands



Wannier spread functional



- Linear shaking gives access to the quantum metric tensor $g_{\mu\nu}(\boldsymbol{k})$
- Sum of rates $\Sigma\Gamma_{xy}^{int} = \int d\omega\big[\Gamma_x(\omega) + \Gamma_y(\omega)\big]/2$
- Integrated signal $\left(\frac{\hbar}{E_{sp}}\right)^2 \left(\frac{1}{2\pi}\right) \Sigma\Gamma_{xy}^{int} = \overline{\mathrm{Tr}[g_{\mu\nu}(\boldsymbol{k})]} \equiv \Omega_I$ Gives access to the Wannier spread Ω_I
- Wannier spread sets lower bound on the quadratic spread of the Wannier function (in C=0 regime)

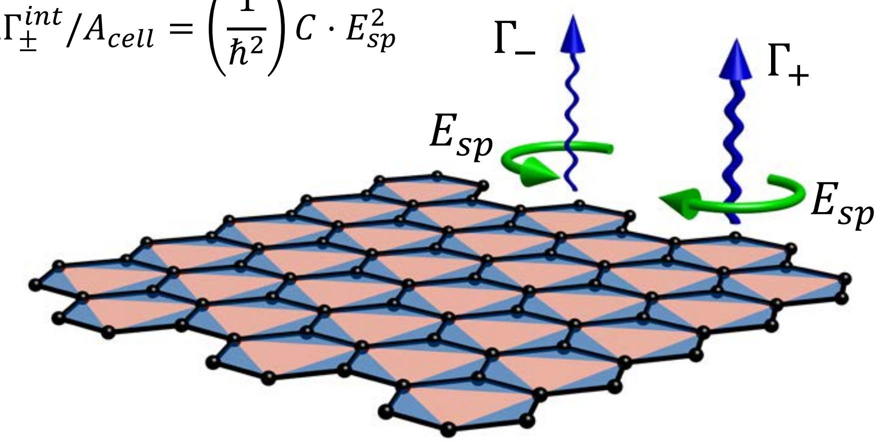
First experimental estimation of the Wannier-spread functional!

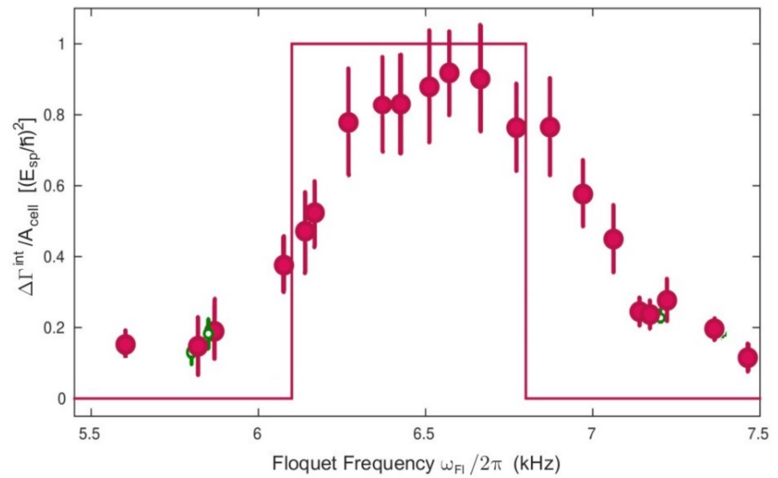
Ozawa & Goldman, arXiv:1803.05818 (2018)

Summary

- Experimental confirmation of a new topological effect
- Depletion rate measurements as new method to access topology
- Also access optical conductivity and Wannier spread functional
- Relevant method in solid state systems
- Promising approach to study interacting system

$$\Delta\Gamma_{\pm}^{int}/A_{cell} = \left(\frac{1}{\hbar^2}\right) C \cdot E_{sp}^2$$





Asteria et al., arXiv:1805.11077 (2018)

Topological phenomena

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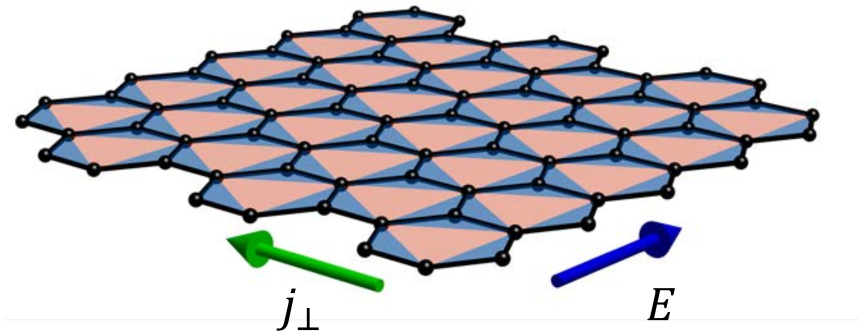

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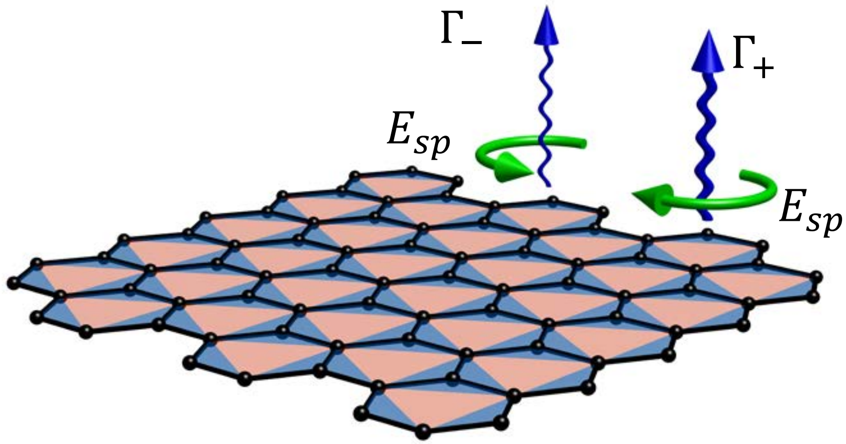

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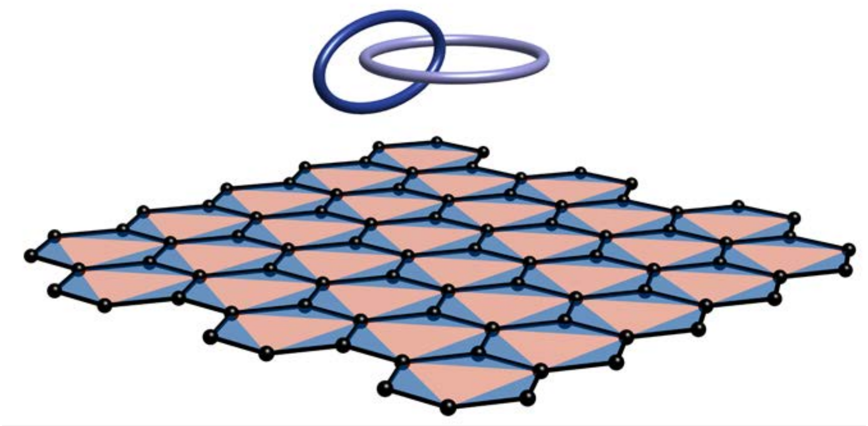
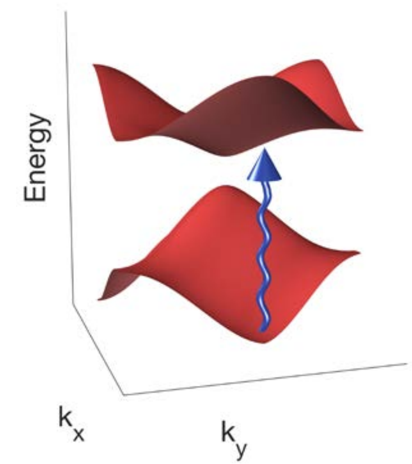
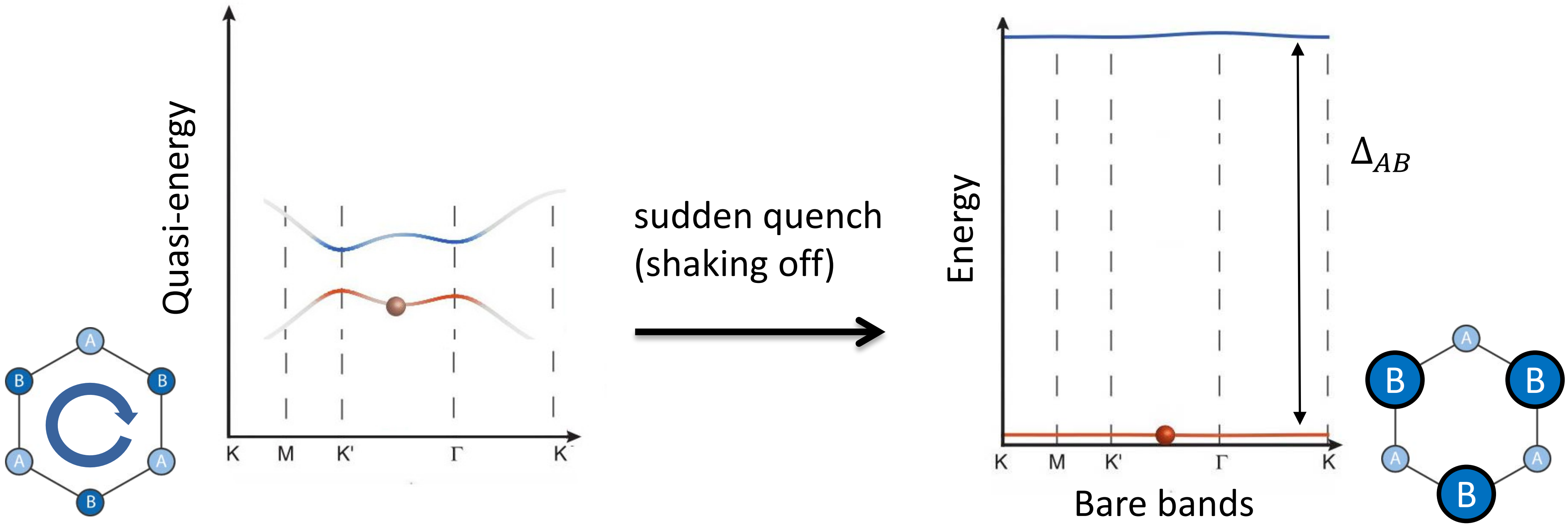




State tomography of Floquet system



- Initial Floquet system eigenstates:

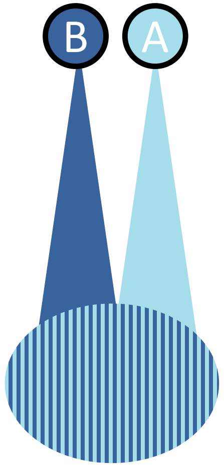
$$|k\rangle = -\sin\left(\frac{\theta_k}{2}\right)\exp(-i\phi_k)\,|k,A\rangle + \cos\left(\frac{\theta_k}{2}\right)|k,B\rangle$$

- Time evolution after quench (project onto basis states):

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

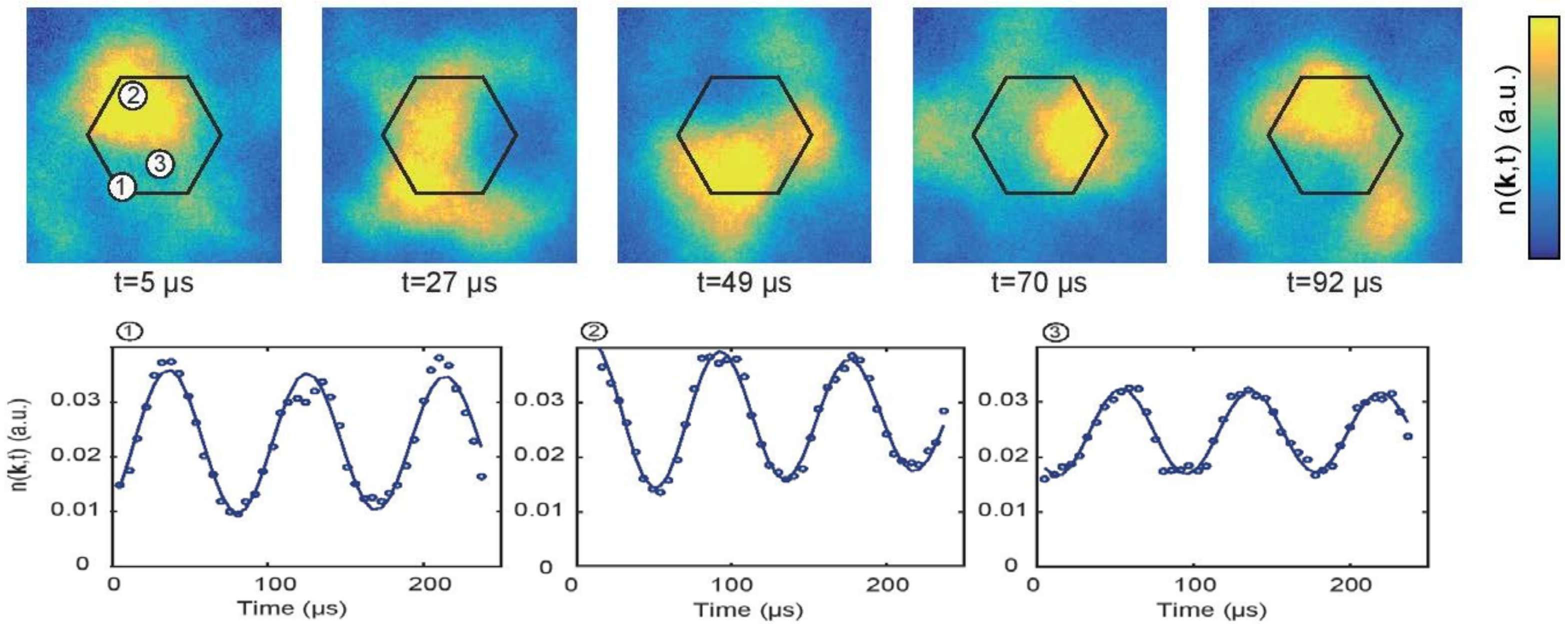
Fläschner et al., *Science* **352,** 1091 (2016) inspired by: Hauke et al. PRL 113, 045303 (2014).

State tomography of Floquet system



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

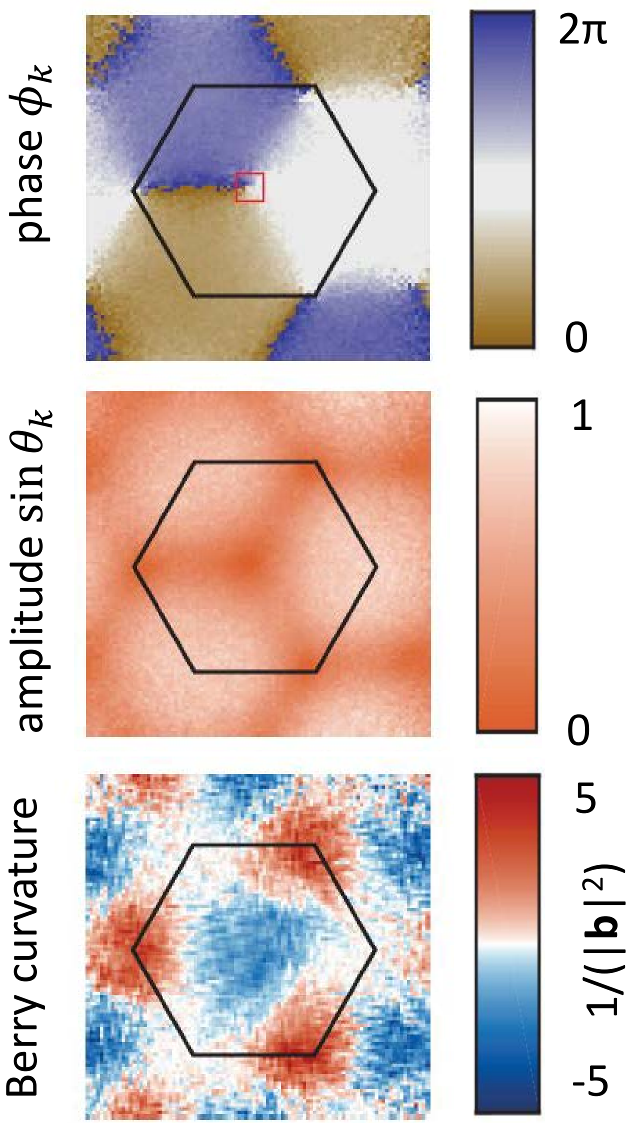
$$\boxed{n(k,t) = |c|^2\left(1 - \sin\theta_k \cos(t\,\Delta_{\mathrm{AB}}/\hbar + \phi_k)\right)}$$



Pixelwise evaluation of oscillation

Fläschner et al., *Science* **352,** 1091 (2016) inspired by: Hauke et al. PRL 113, 045303 (2014).

Berry Curvature

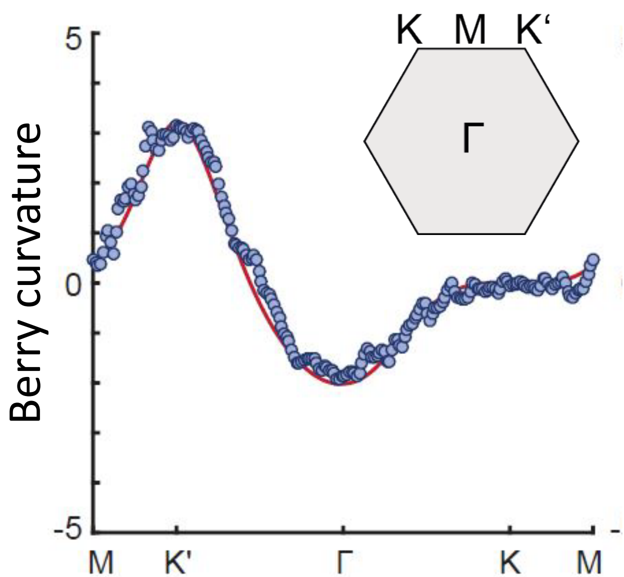


Obtain Berry curvature from derivatives of the data:

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

Obtain Chern number from integration:

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



Fläschner et al., *Science* **352,** 1091 (2016)

Preservation of dynamical Chern number

Unpublished data

C=-0.001 C=-0.008 C=-0.013 C=-0.016 C=-0.015

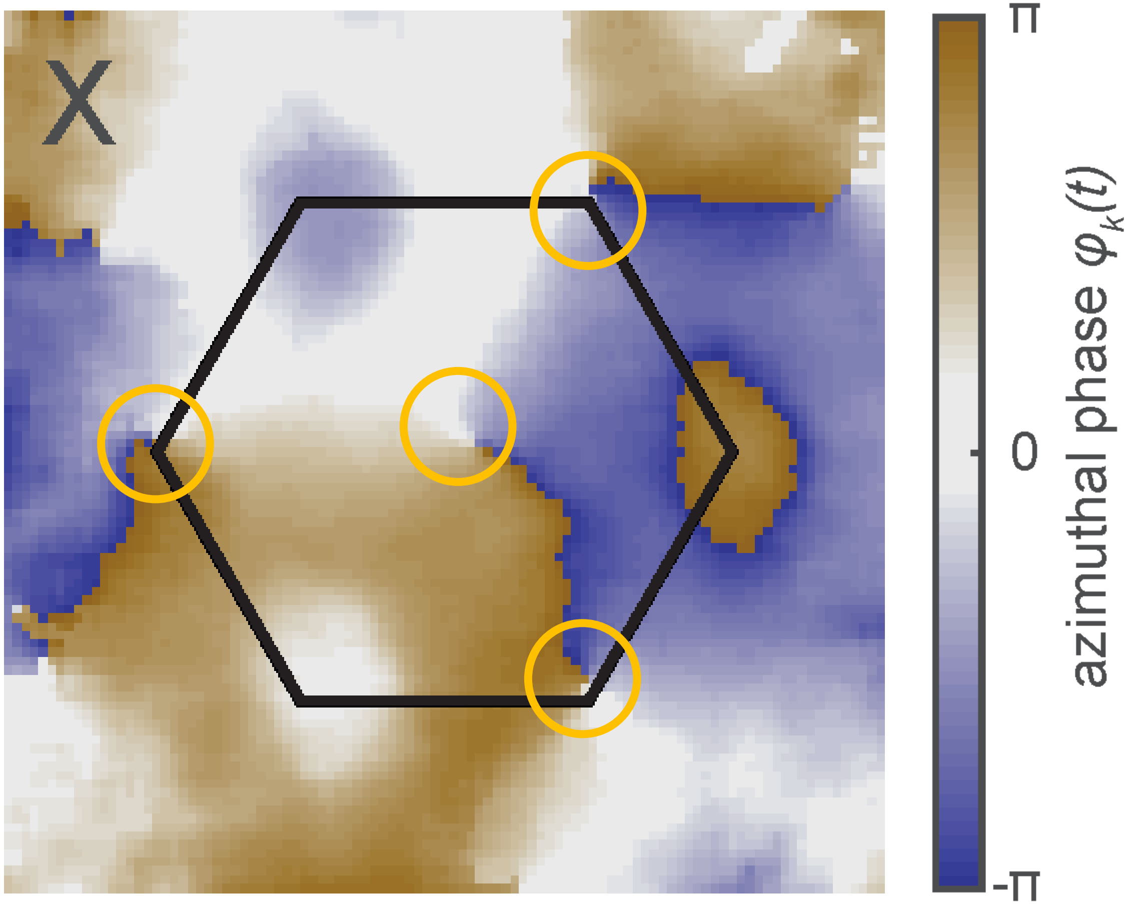
Time after quench (μs)

156 273 390 507 663

Appearance of dynamical vortices

Phase profiles for different evolution times after the quench

Static vortices
(at the Dirac points of
the final Hamiltonian)



Fläschner et al., Nature Phys. **14**, 265 (2018)

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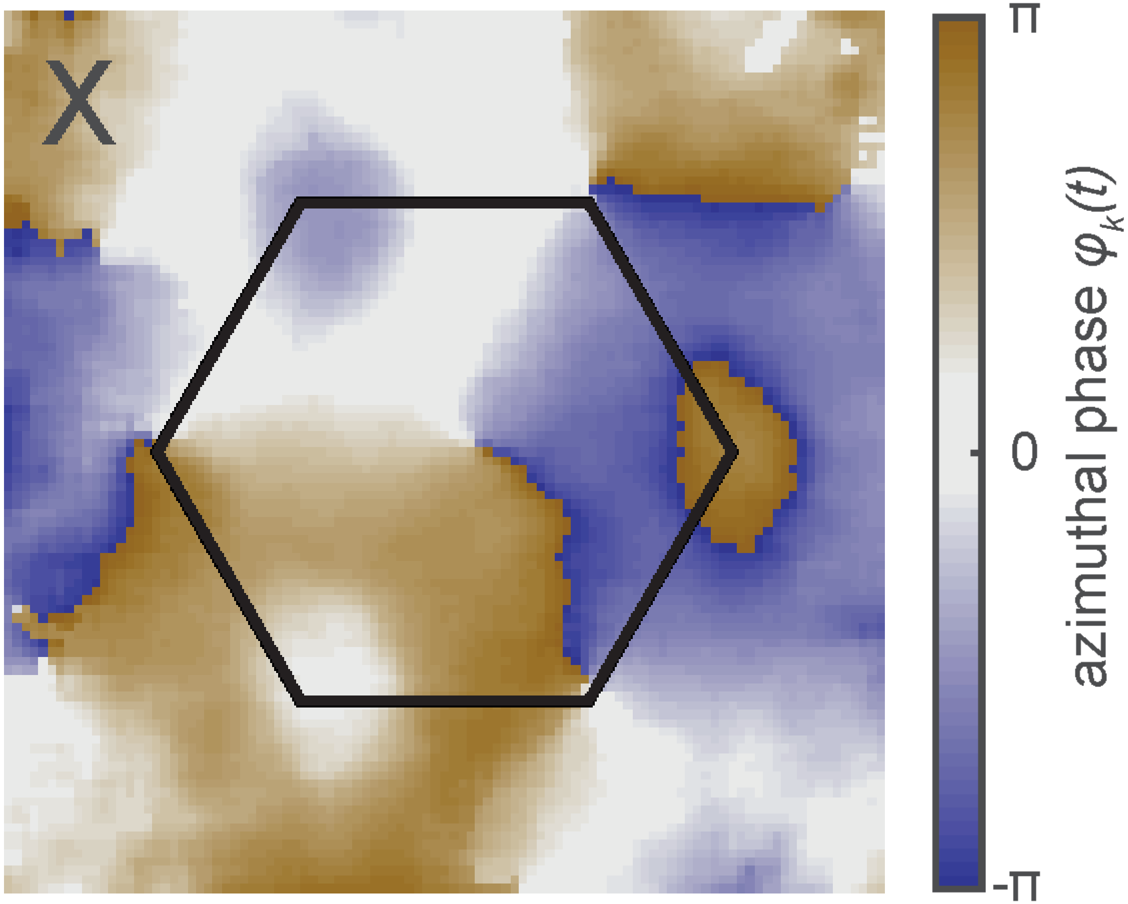
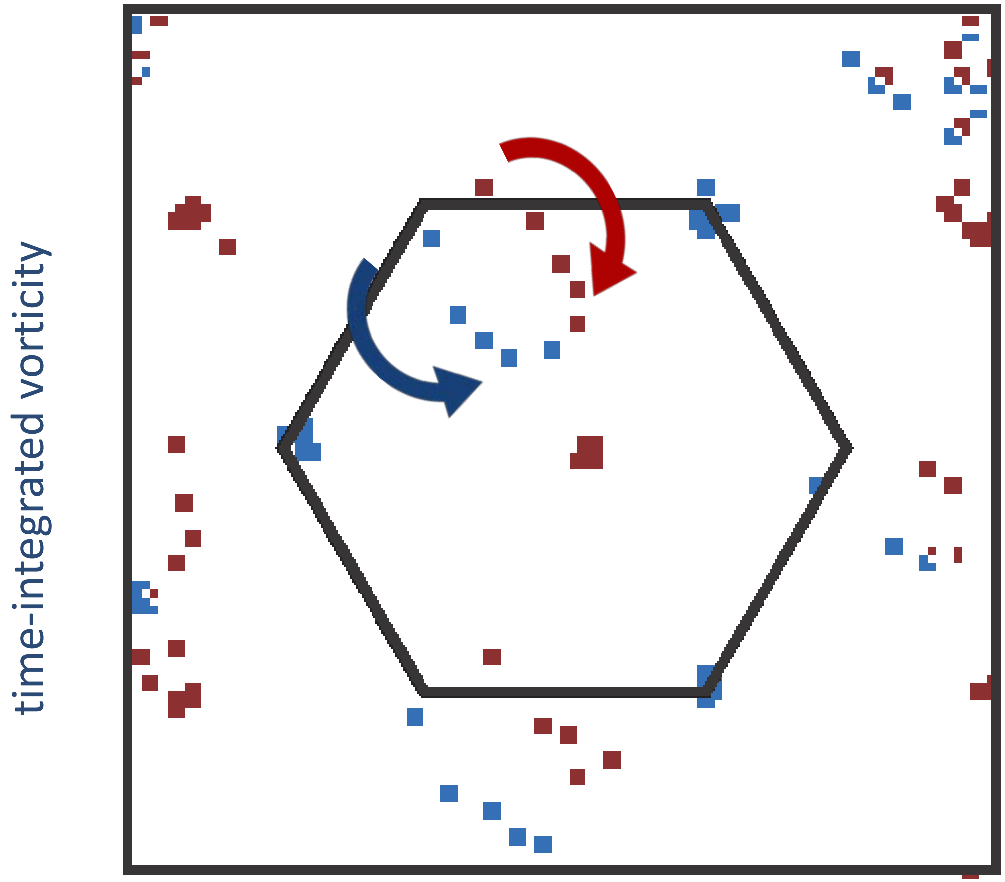


Related to concept of dynamical phase transition
Heyl et al. PRL 110, 135704 (2013),
Blatt group PRL (2017), Monroe group (2017)

Fläschner et al., Nature Phys. **14**, 265 (2018)

Vortex contours



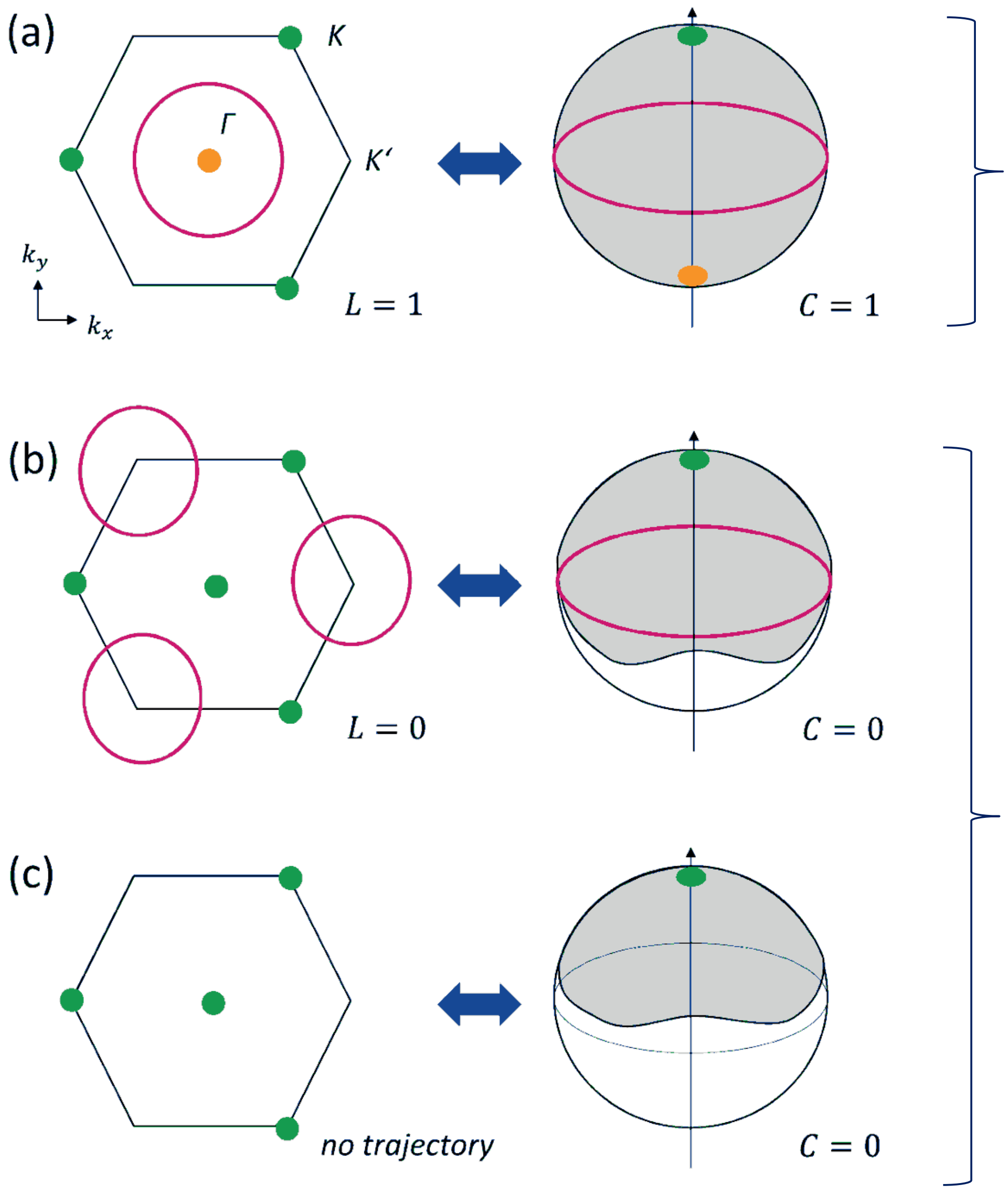
Red = vortex
Blue = antivortex

The dynamical vortices trace out a closed contour

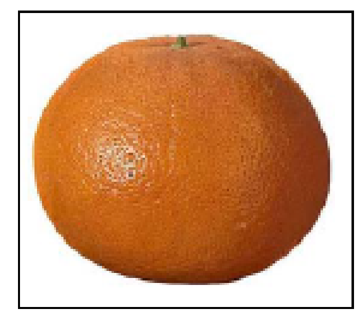
What can we learn from this trajectory?

Mapping between Chern number and „linking number“

Dynamical vortex contour encloses one of the static vortices



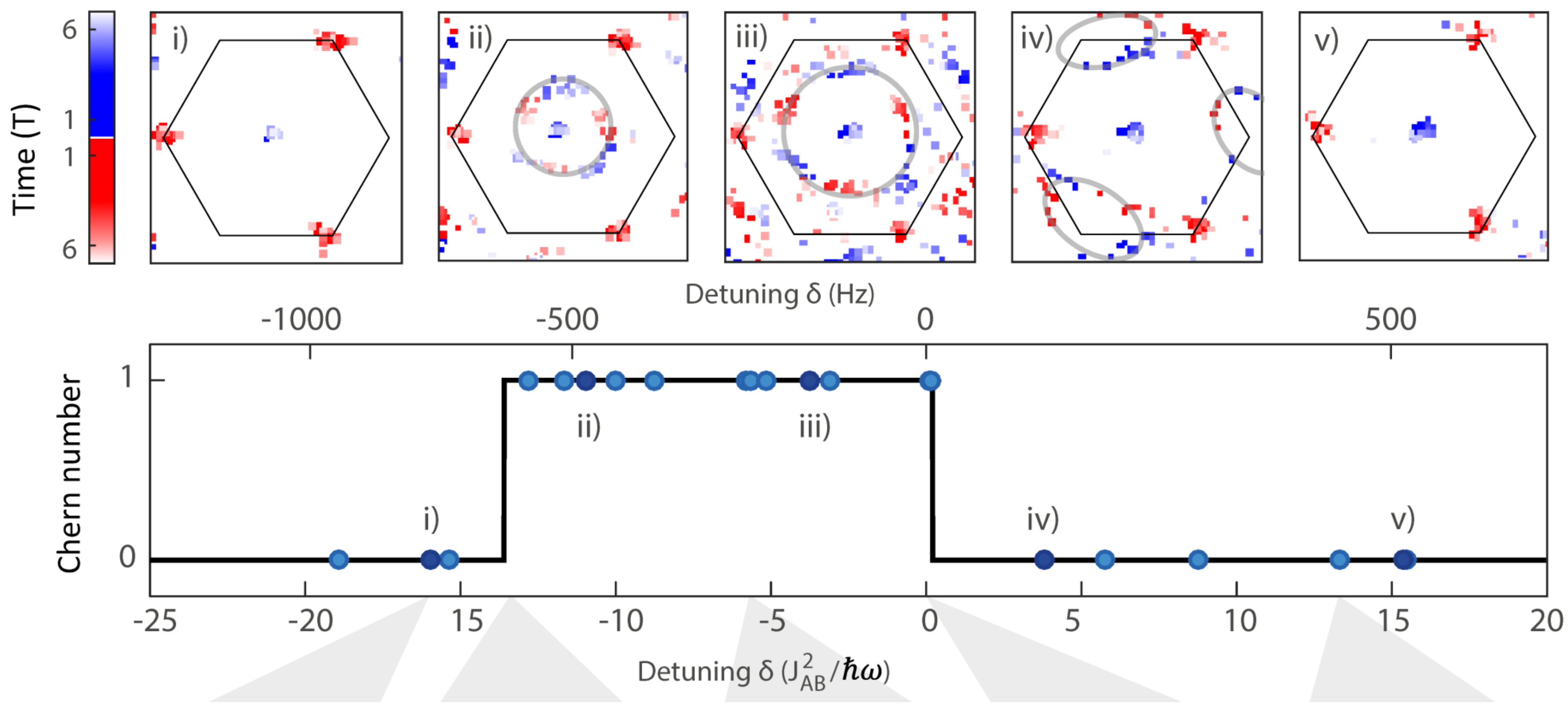
non-trivial



trivial

Proposal: Wang/Zhai et al. PRL 118, 185701 (2017). Yu PRA 96, 023601 (2017).

Linking number: topology from dynamics after quench

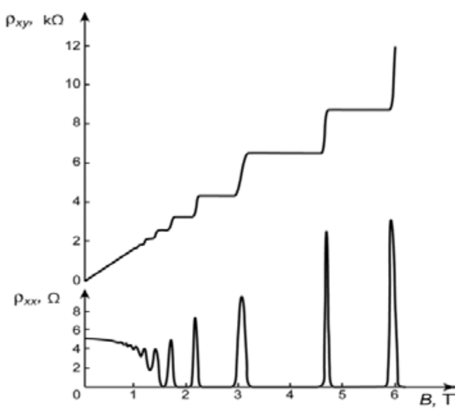


Tarnowski et al., arXiv:1709.01046 (2017). Collaboration with André Eckardt and Nur Ünal

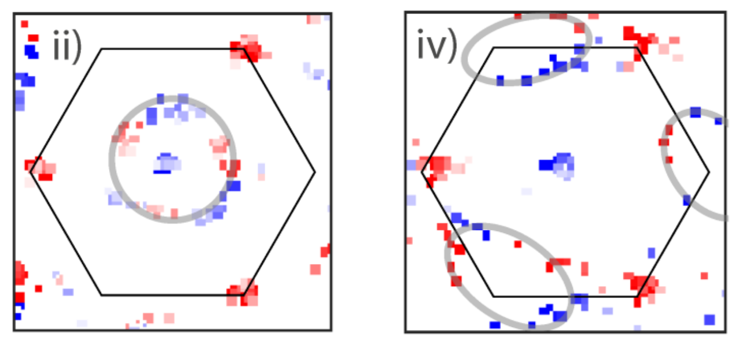
Detecting Topology „with the naked eye“

Topology of Bloch eigenstates of a lattice

Quantized Hall conductance



Dynamical vortices after a quench



Linking of vortex contours

Infer Topology from Quantization

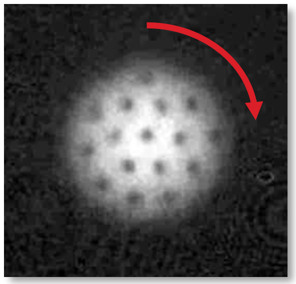
Directly see Topology „with the naked eye“

Also with cold atoms:
Jotzu/Esslinger et al. Nature 515, 237-240 (2014).
Aidelsburger/Bloch et al. Nat. Phys. 11, 162–166 (2015).

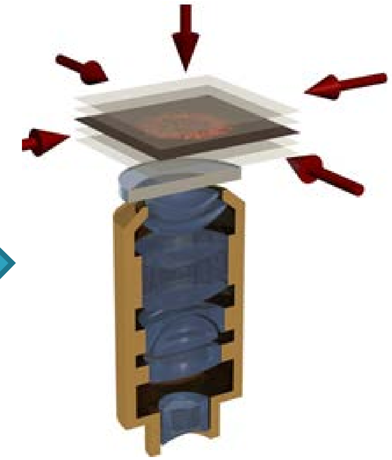
Proposal: Wang/Zhai et al. PRL 118, 185701 (2017).
Experiment: Tarnowski/Sengstock et al., arXiv:1709.01046

Advertisement: new project

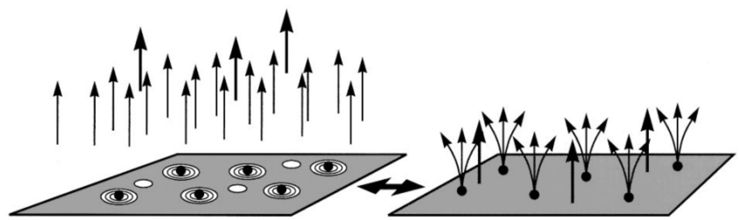
Artificial gauge fields



Quantum gas microscope



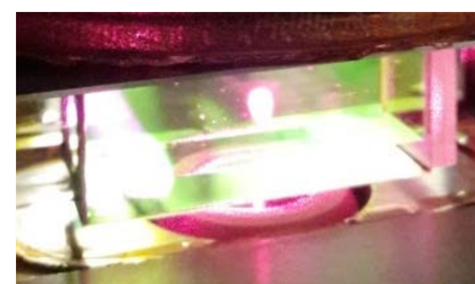
Realization of fractional quantum Hall effect



Quasiparticle excitations are anyons

ANYθN: Engineering and exploring anyonic quantum gases

- funded as ERC Starting Grant 2018
- Positions available…



New setup: lithium quantum gas microscope

Thank you

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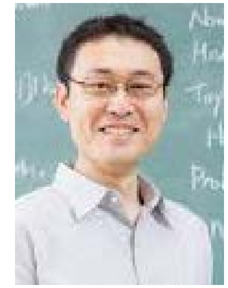

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