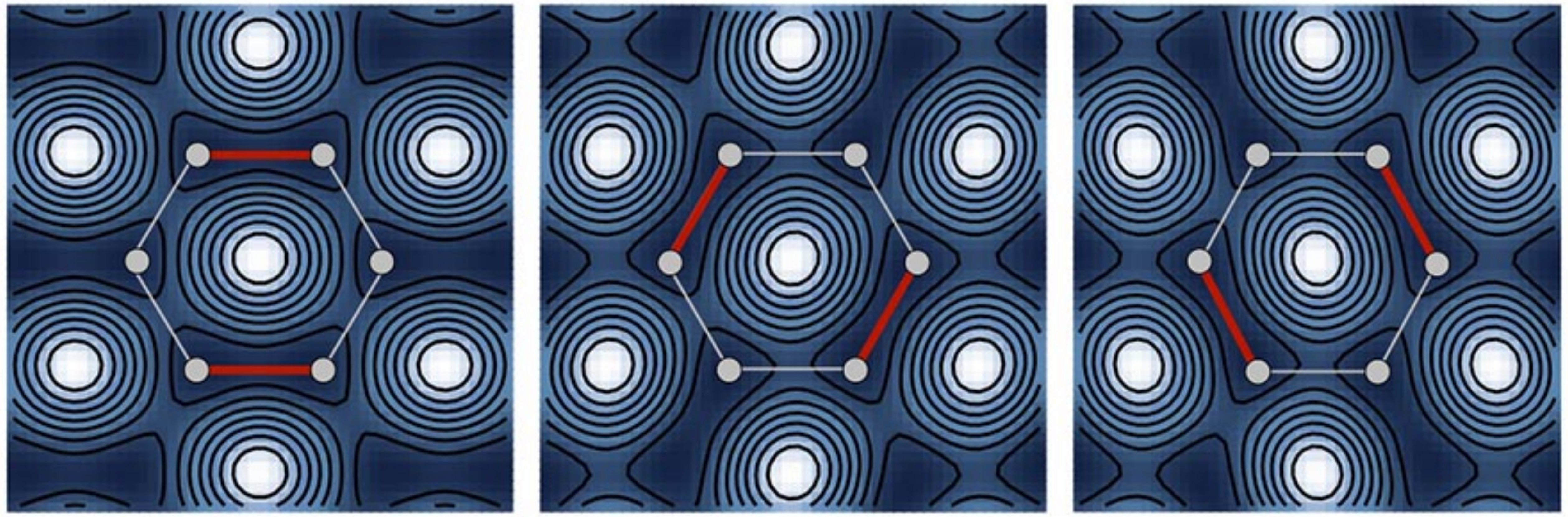
Anomalous Floquet topological systems with ultracold atoms



Monika Aidelsburger
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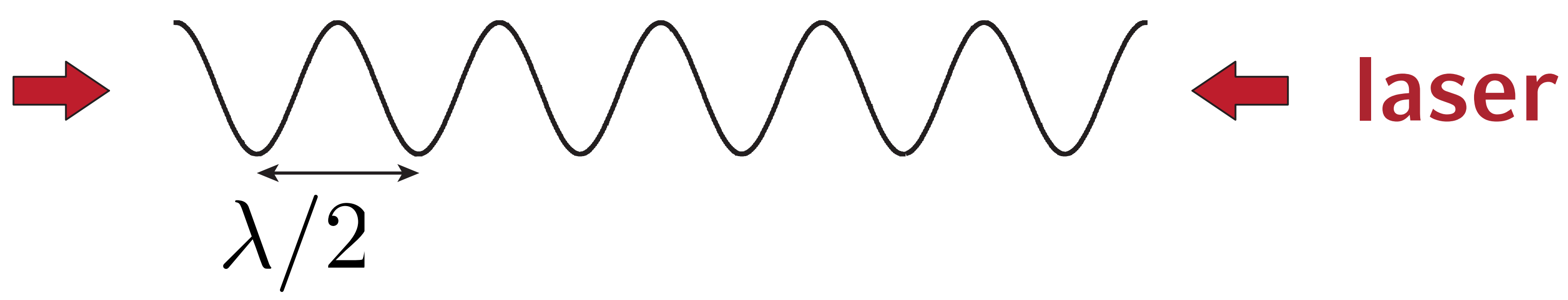
Munich Center for Quantum Science & Technology

GEFÖRDERT VOM Bundesministerium für Bildung und Forschung
Deutsche Forschungsgemeinschaft
European Research Council

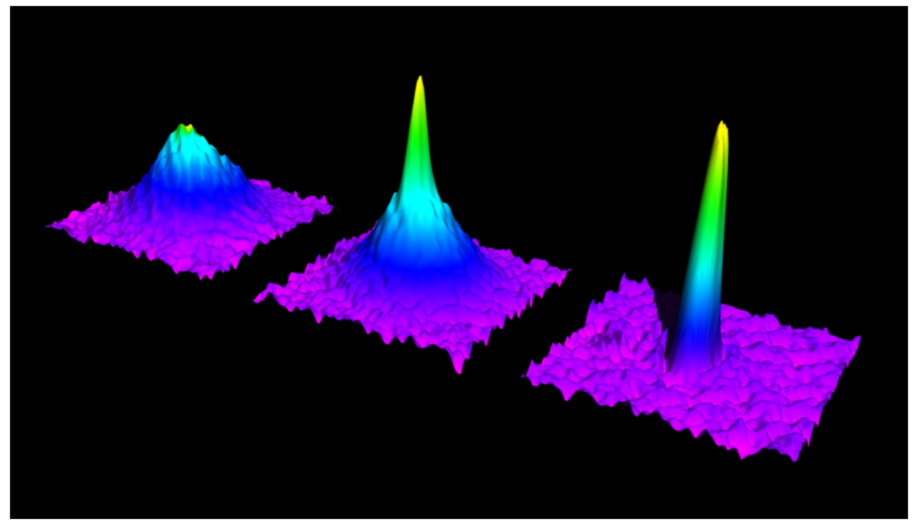
Ultracold atoms in optical lattices

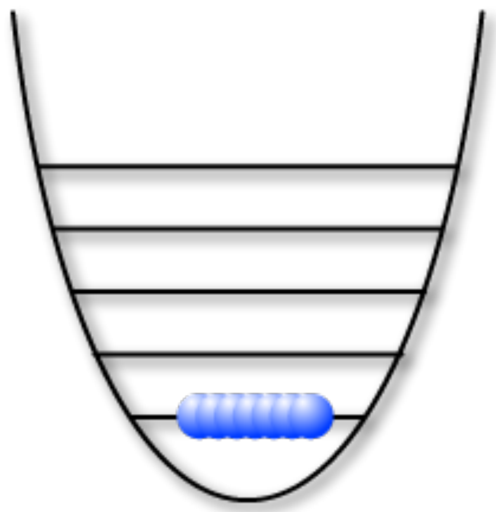
Quantum simulation with ultracold atoms in optical lattices:

- Atoms confined in periodic potentials



Bose-Einstein Condensate:





I. Bloch et al. Rev. Mod. Phys. 80, 885 (2008); C. Gross and I. Bloch, Science 357 (2017)

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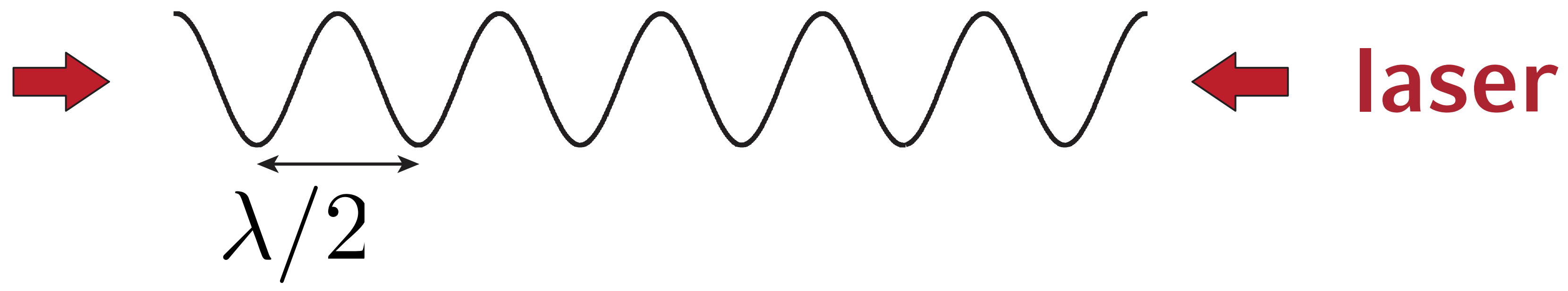
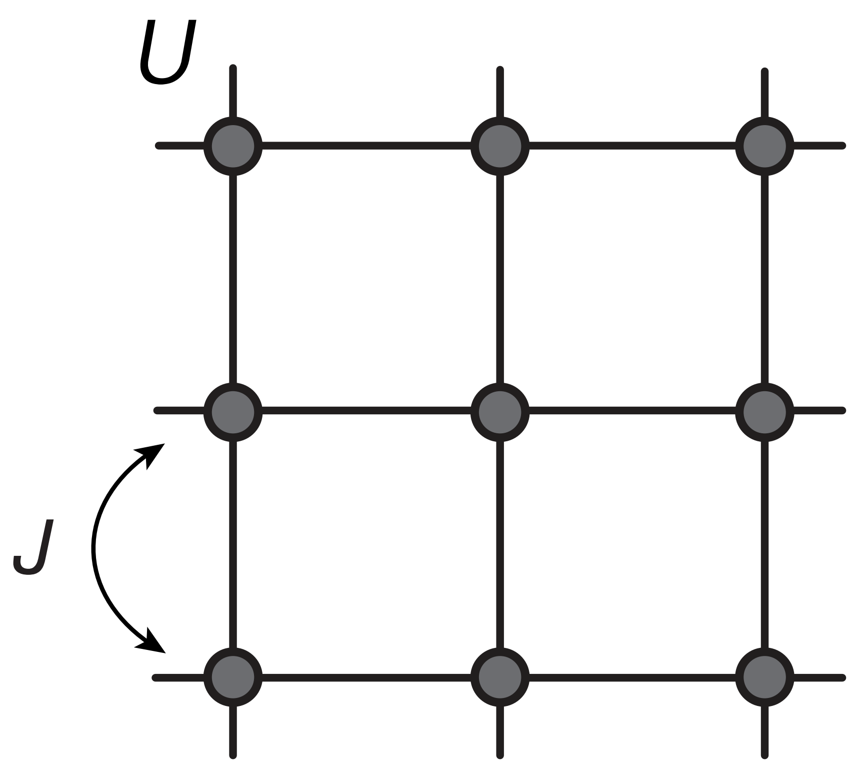
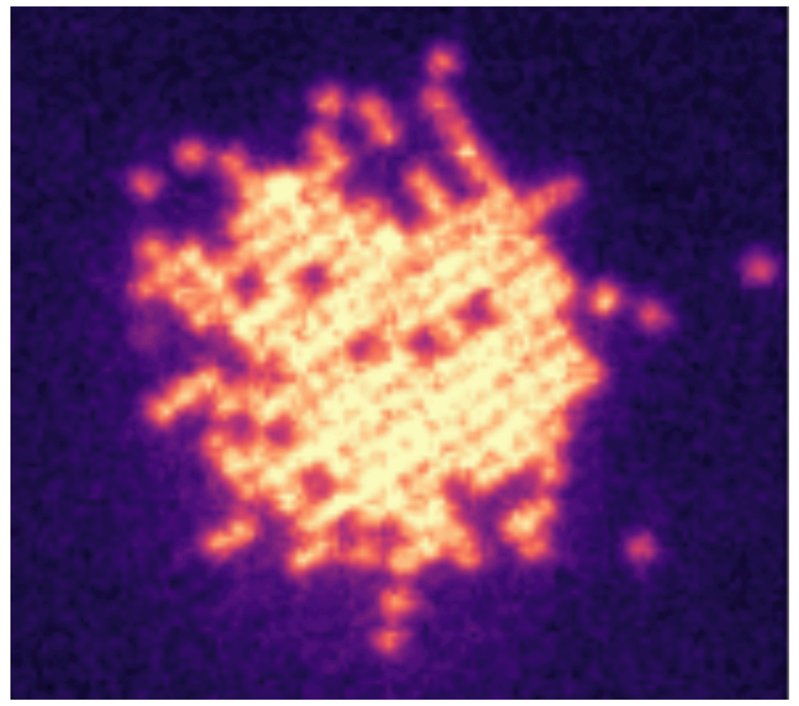


- Quantum simulation of Hubbard models





Cs atoms

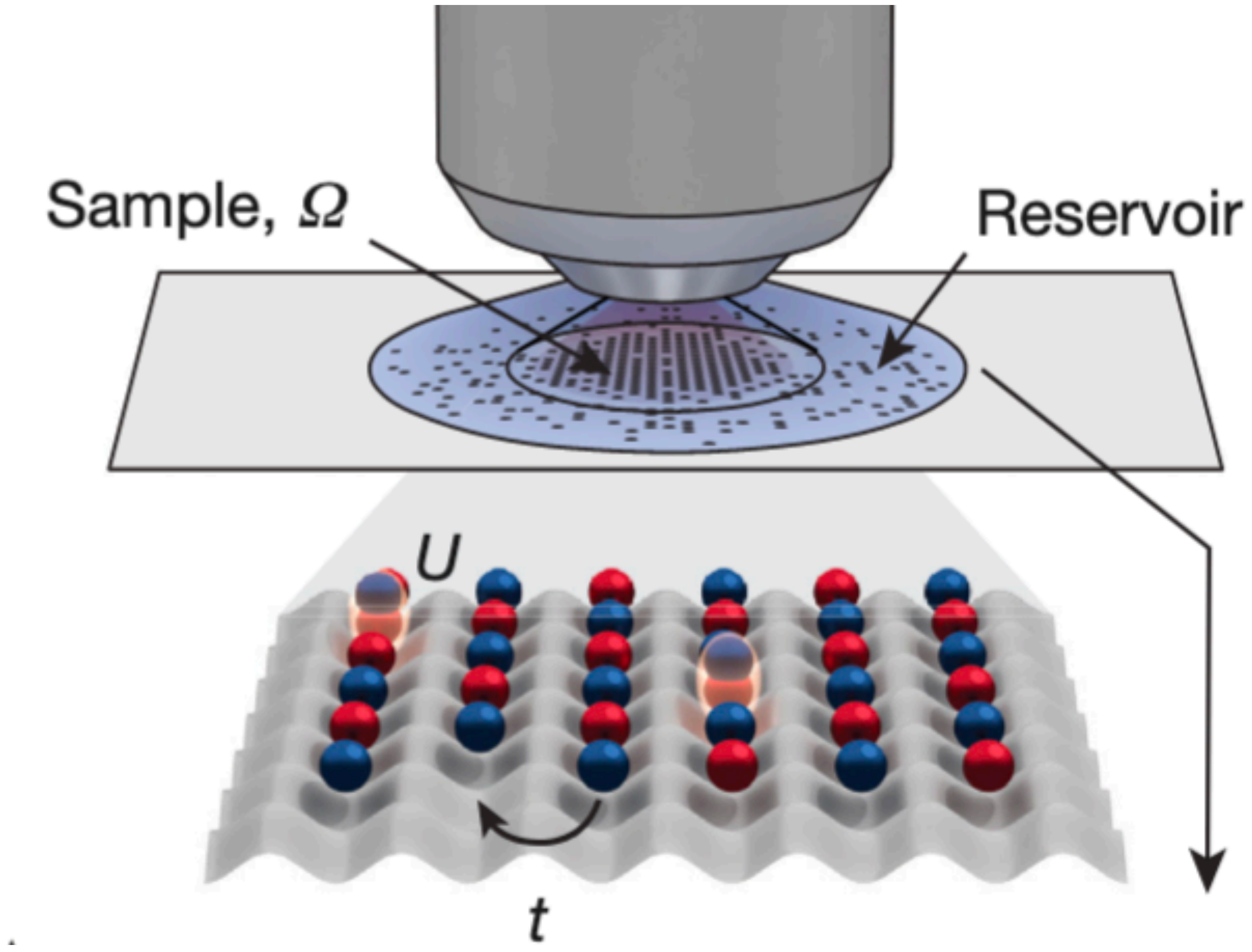
- Access to local observables using quantum gas microscopes

$$\hat{H} = -J \sum_{\langle i,j \rangle} \hat{a}_i^\dagger \hat{a}_j + \frac{U}{2} \sum_i \hat{n}_i(\hat{n}_i - 1)$$

I. Bloch et al. Rev. Mod. Phys. 80, 885 (2008); C. Gross and I. Bloch, Science 357 (2017)

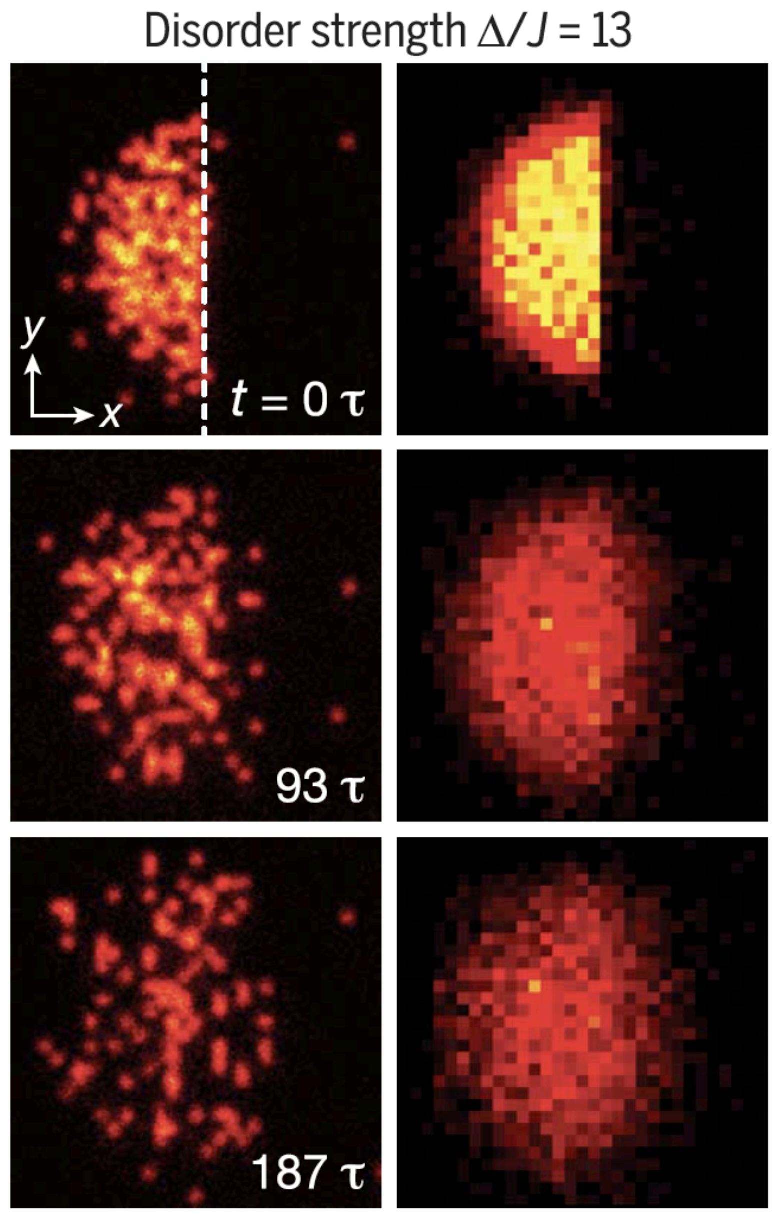
Ultracold atoms in optical lattices

Anti-ferromagnetic correlations in the Fermi-Hubbard model:



A. Maruzenko, ... M. Greiner, Nature (2017)

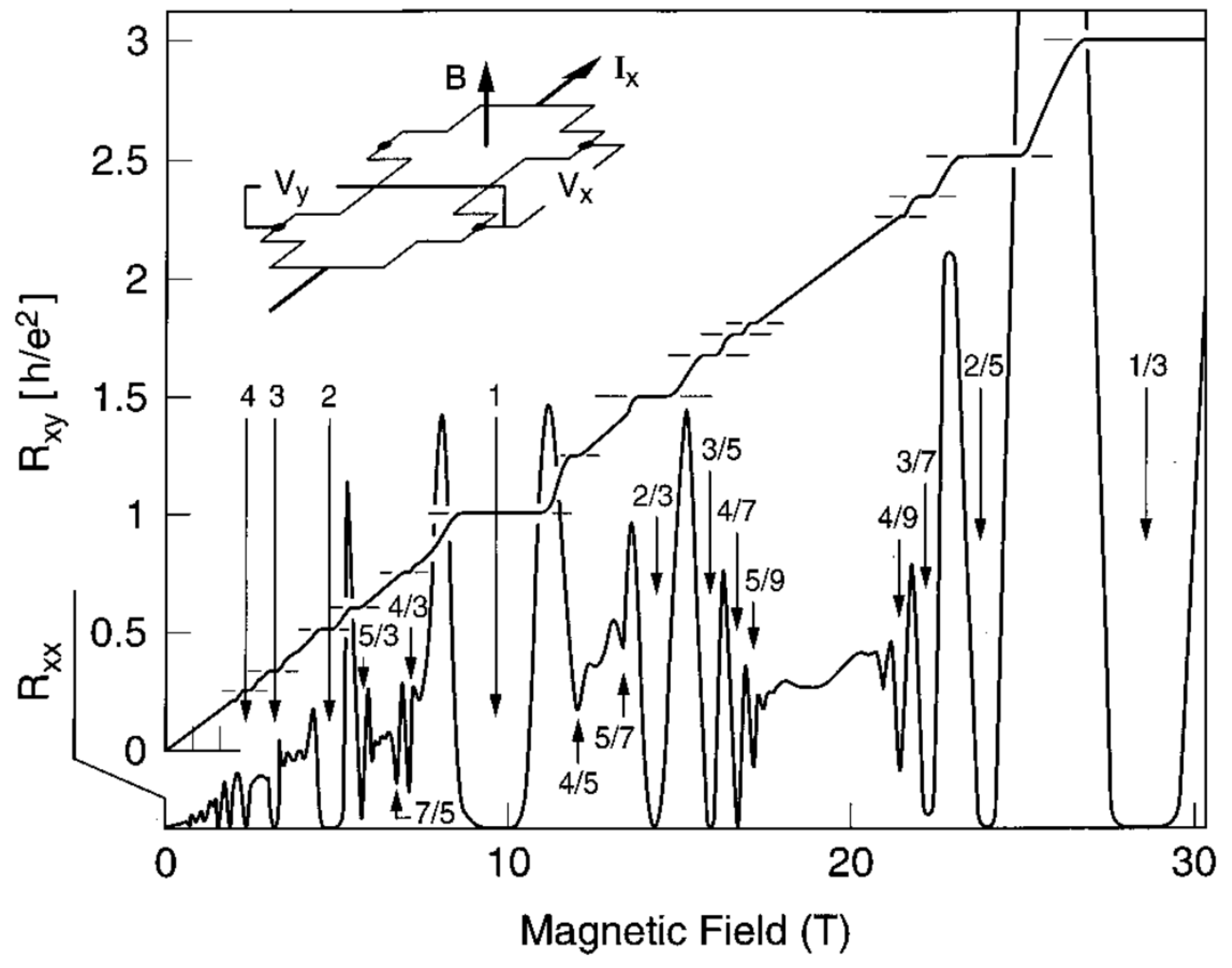
Thermalization of isolated quantum-many body systems:



J. Y. Choi, ..., I. Bloch, Science **352**, 1547 (2016)

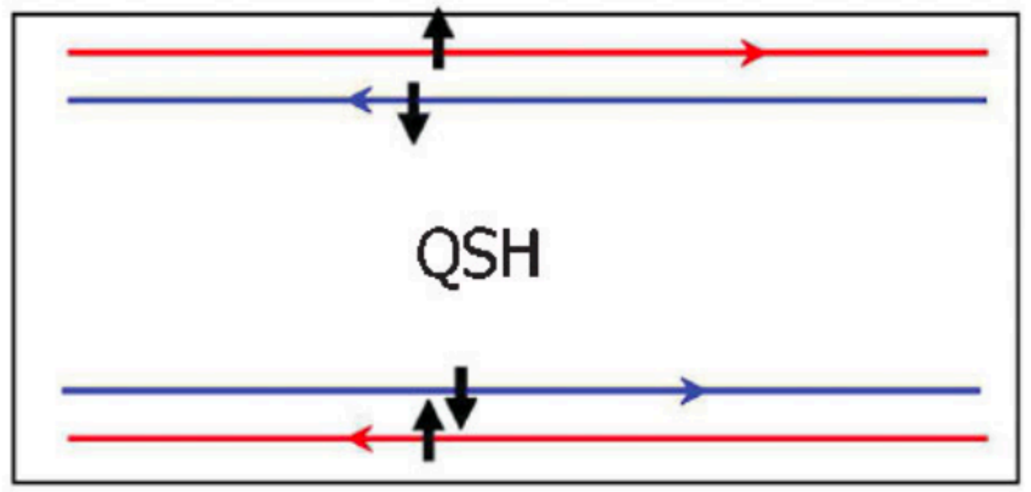
Topological phases of matter

Integer & fractional quantum Hall insulators



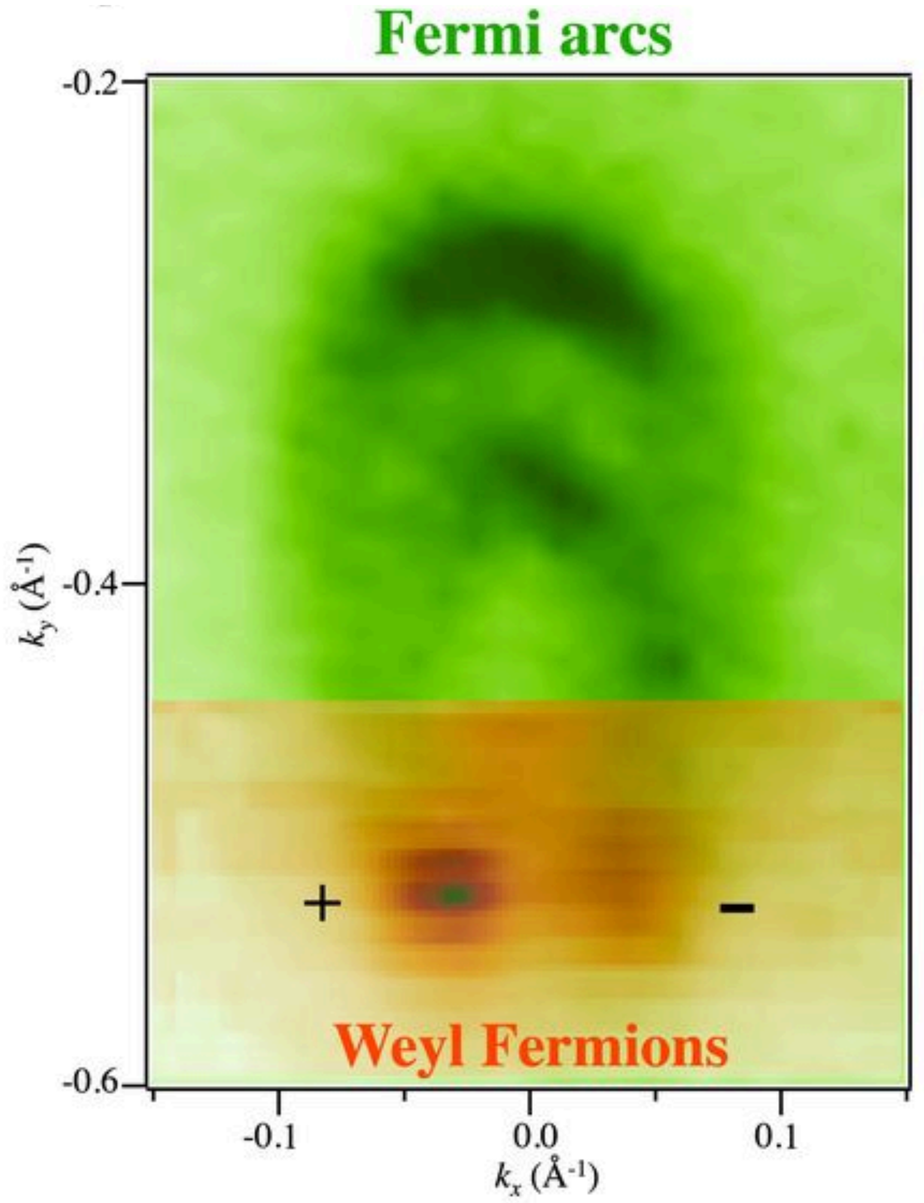
K. Klitzing, Rev. Mod. Phys. (1986)
Stormer et al., Rev. Mod. Phys. (1999)

Topological insulators in 2D & 3D



M. König et al., Science (2007)
A. Roth et al., Science (2009)

Weyl semimetals



L. Lu et al., Science (2015)
S.-Y. Xu et al., Science (2015)

...

Review: X.-L. Qi & S.-C. Zhang, Rev. Mod. Phys. (2011)

How to engineer
topological phases?

Floquet engineering

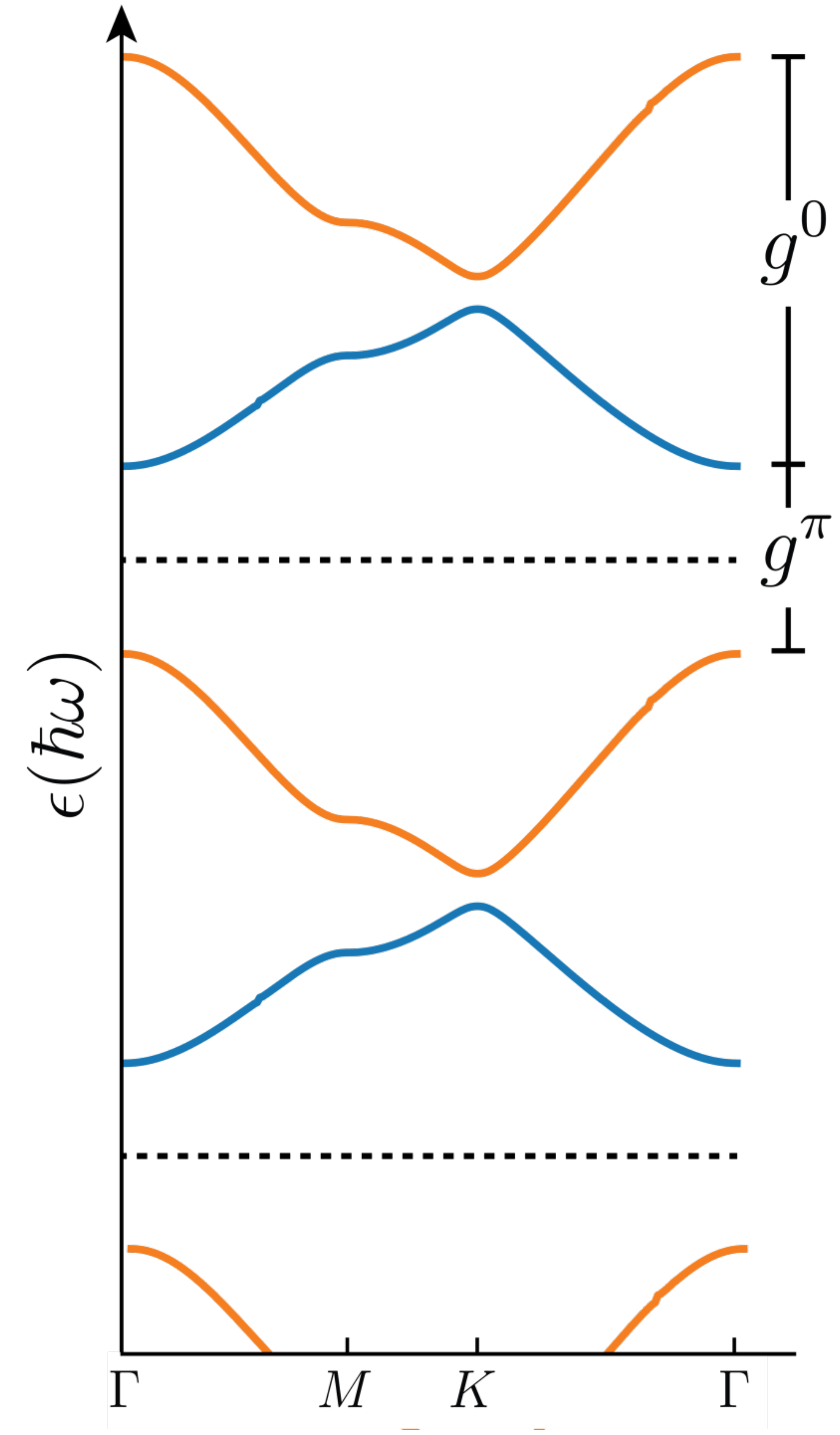
- Time-periodic driven Hamiltonian

$$\hat{H}(t) = \hat{H}(t+T)$$

- Stroboscopic time evolution governed by effective Floquet Hamiltonian $\hat{H}^F$

$$\hat{U}(T,0) = \exp\left(-\frac{i}{\hbar}T\hat{H}^F\right)$$

Engineer $\hat{H}_F$ with topological properties!

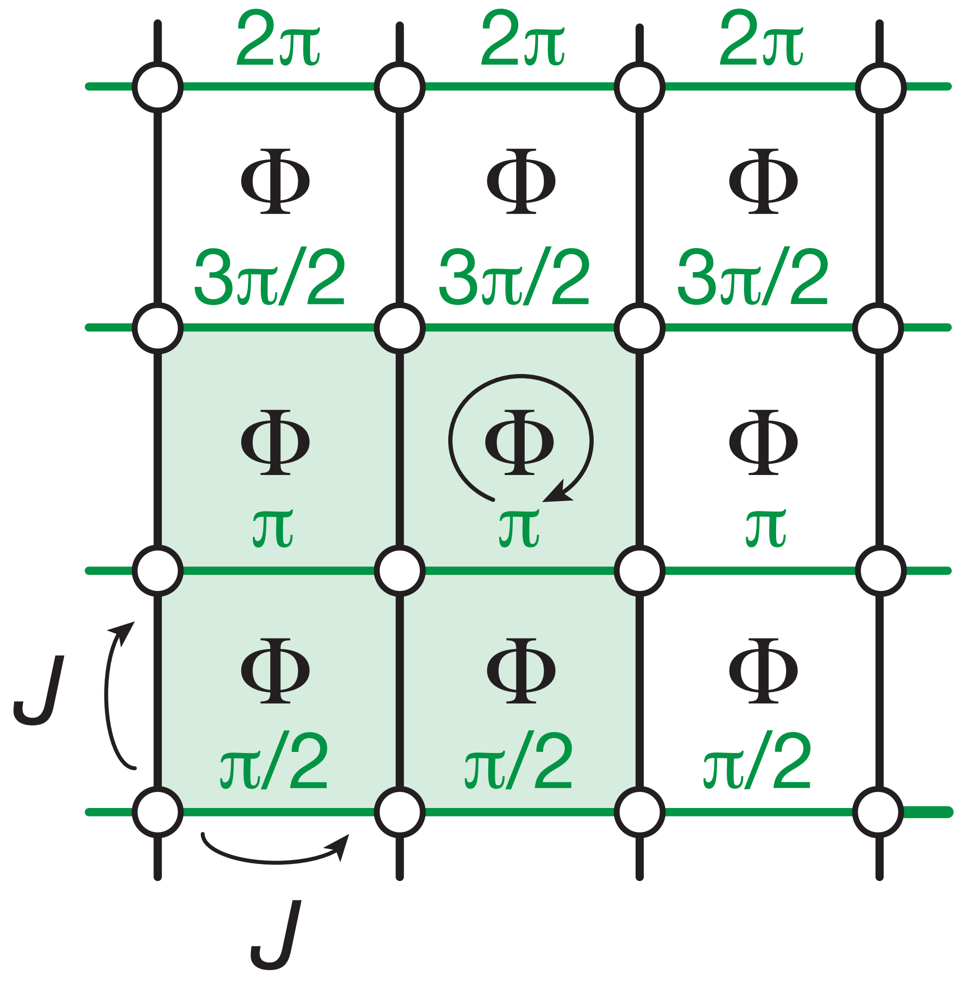


N. Goldman et al. PRX (2014); M. Bukov et al. Adv. in Phys. (2015); A. Eckardt, Rev. Mod. Phys. (2017)

Topological lattice models

Hofstadter model

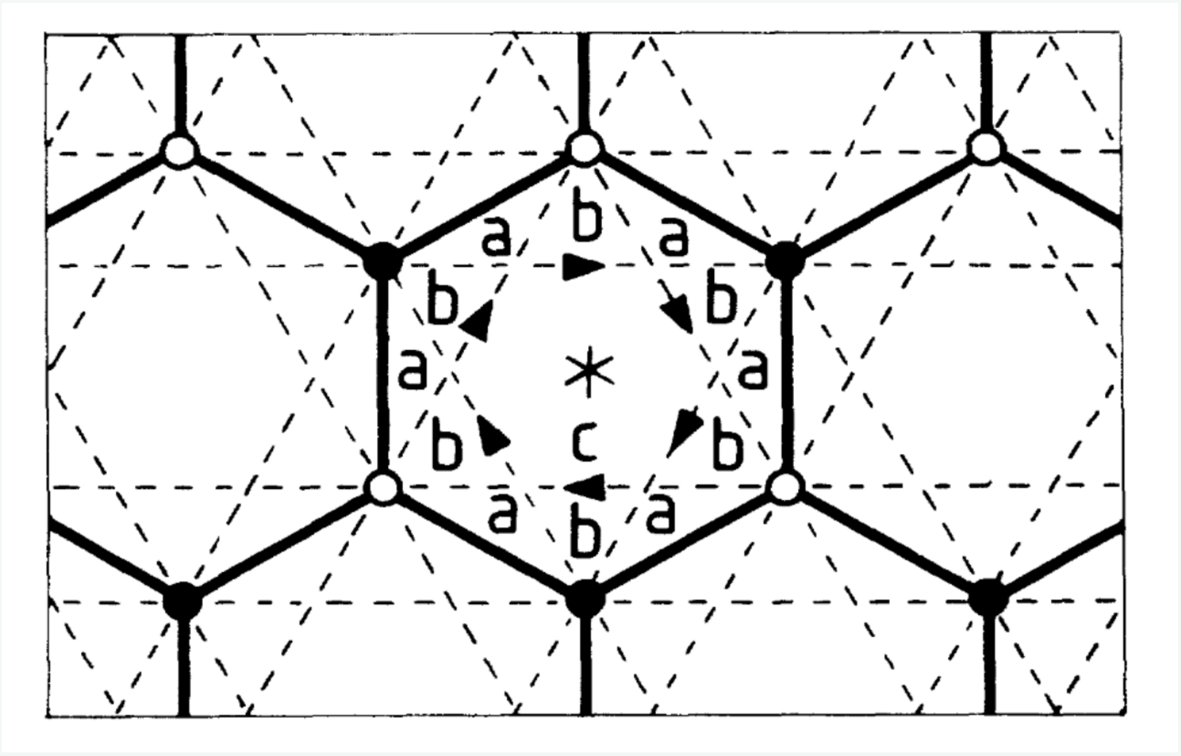
Harper, Proc. Phys. Soc., Sect.A **68**, 874 (1955)
Azbel, Zh. Eksp. Teor. Fiz. **46**, 929 (1964)
Hofstadter, PRB **14**, 2239 (1976)



$$\hat{H} = -J \sum_{m,n} \left(\mathrm{e}^{in\Phi} \hat{a}^{\dagger}_{m+1,n} \hat{a}_{m,n} + \hat{a}^{\dagger}_{m,n+1} \hat{a}_{m,n} + \mathrm{h.c.} \right)$$

Haldane model

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



$$\hat{H} = \sum_{\langle ij \rangle} t_{ij} \hat{c}^{\dagger}_i \hat{c}_j + \sum_{\langle\langle ij \rangle\rangle} \mathrm{e}^{i\Phi_{ij}} t'_{ij} \hat{c}^{\dagger}_i \hat{c}_j + \Delta_{AB} \sum_{i \in A} \hat{c}^{\dagger}_i \hat{c}_i$$

Ma et al., PRL (2013); H. Miyake et al., PRL (2013)
E. M. Tai et al., Nature (2017)
G. Jotzu et al., Nature (2014) ;Tarnowski et al., Nat. Comm. (2019)

Review: N. Cooper et al. Rev. Mod. Phys. **91**, 015005 (2019)

Topological invariants

Chern number:

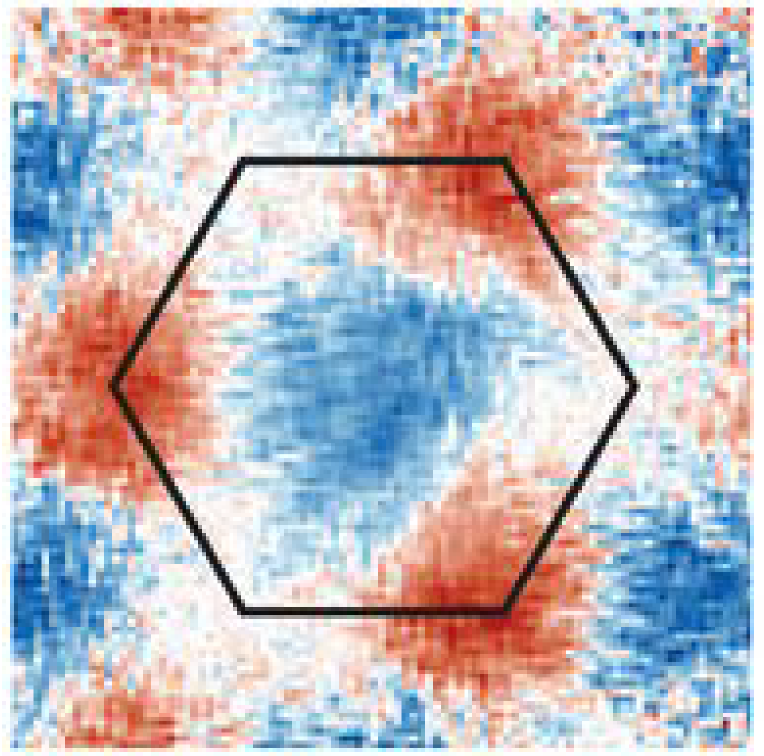
$$\mathcal{C}^{\mu} = \frac{1}{2\pi}\int_{\mathrm{BZ}} \Omega^{\mu}\mathrm{d}^2 q$$

$|u_{\mu}(\mathbf{q})\rangle$: periodic Bloch function

μ: band index

Berry curvature:

$$\Omega_{\mu} = i\left(\langle \partial_{q_x} u_{\mu} | \partial_{q_y} u_{\mu}\rangle - \langle \partial_{q_y} u_{\mu} | \partial_{q_x} u_{\mu}\rangle\right)$$



Weitenberg/Sengstock

M. Atala, et al., Nat. Phys. (2013); L. Duca et al., Science (2015)
G. Jotzu et al., Nature (2014); M. A. et al., Nature Phys. (2015)
N. Fläschner, Science (2016); T. Li, Science (2016)
Tarnowski et al., Nat. Comm. (2019);
L. Asteria et al., Nat. Phys. (2019);
B. Rem et al., Nat. Phys. (2019); .....

Transport measurements

Semiclassical dynamics

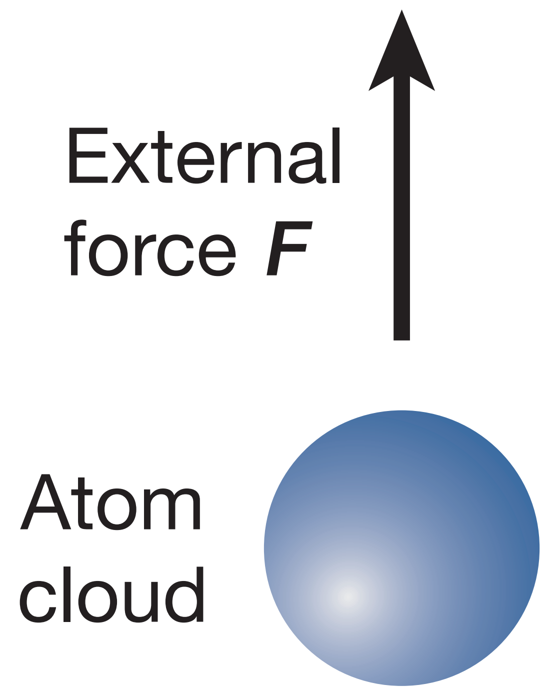
- *Bloch oscillations* captured by *band velocity*

$$\mathbf{v}_\mu^{\mathrm{band}} = \frac{1}{\hbar}\partial_{\mathbf{q}} E_\mu$$

μ: band index

- *Anomalous transverse velocity* proportional to *Berry curv.* Ω_μ

$$\mathbf{v}_\mu^x(\mathbf{q}) = -\frac{F}{\hbar}\Omega_\mu(\mathbf{q})$$



Karplus & Luttinger, Phys. Rev. (1954); D. Xiao et al., Rev. Mod. Phys. (2010)
A. Dauphin & N. Goldman, PRL (2013); H. Price & N. Cooper, PRA (2012)

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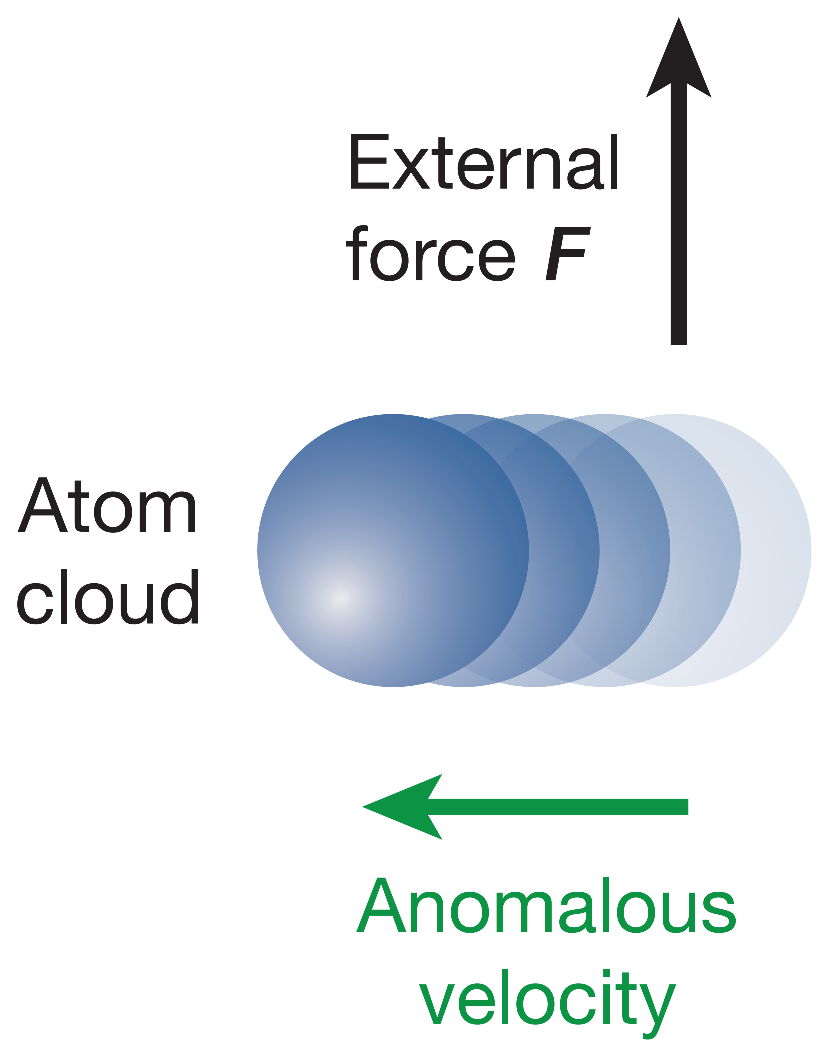
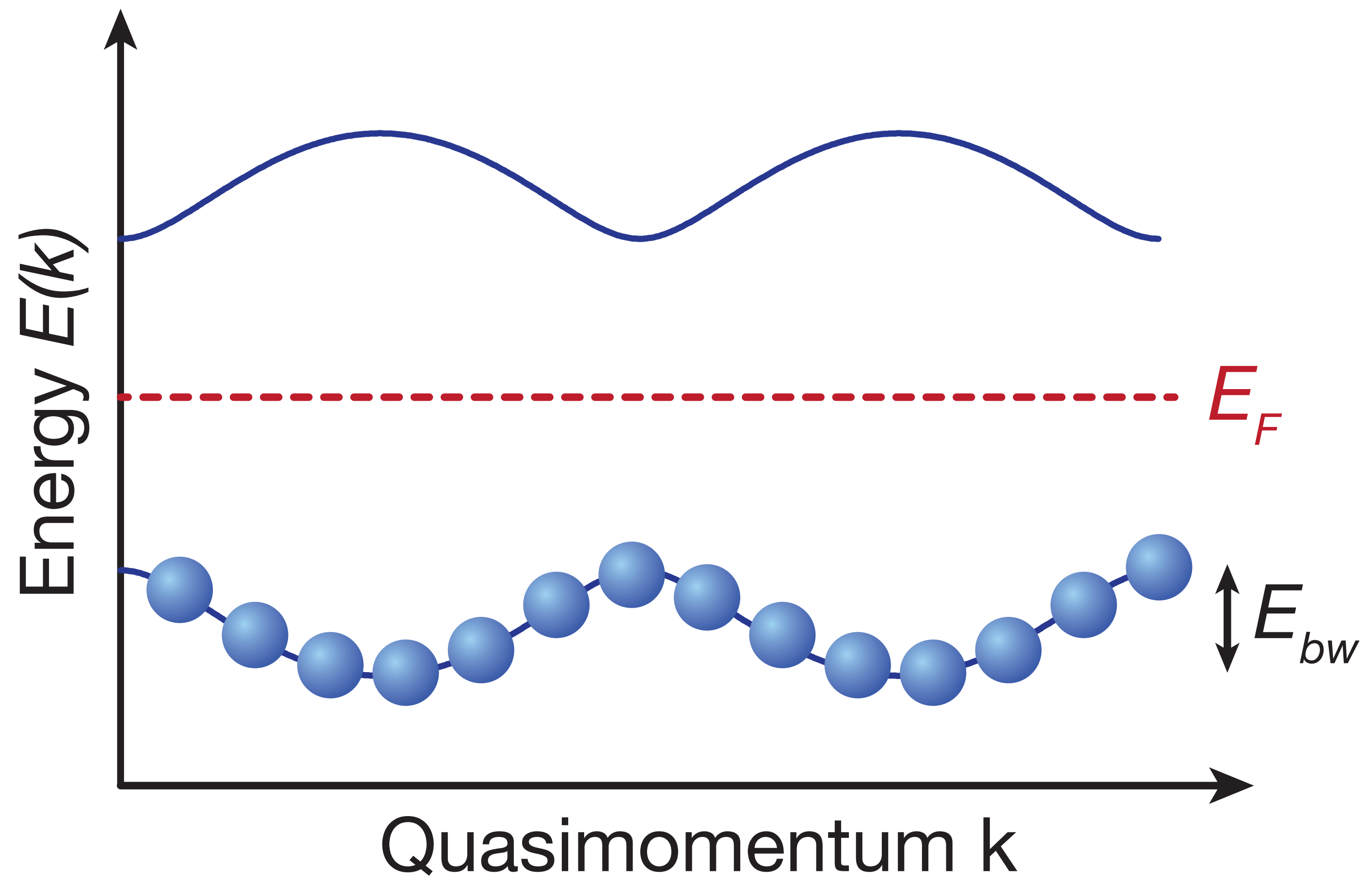


Prepare condensate at momentum ***q*** and *probe Berry curvature locally!*

Karplus & Luttinger, Phys. Rev. (1954); D. Xiao et al., Rev. Mod. Phys. (2010)
A. Dauphin & N. Goldman, PRL (2013); H. Price & N. Cooper, PRA (2012)

Hall deflection



Contribution from band velocity vanishes

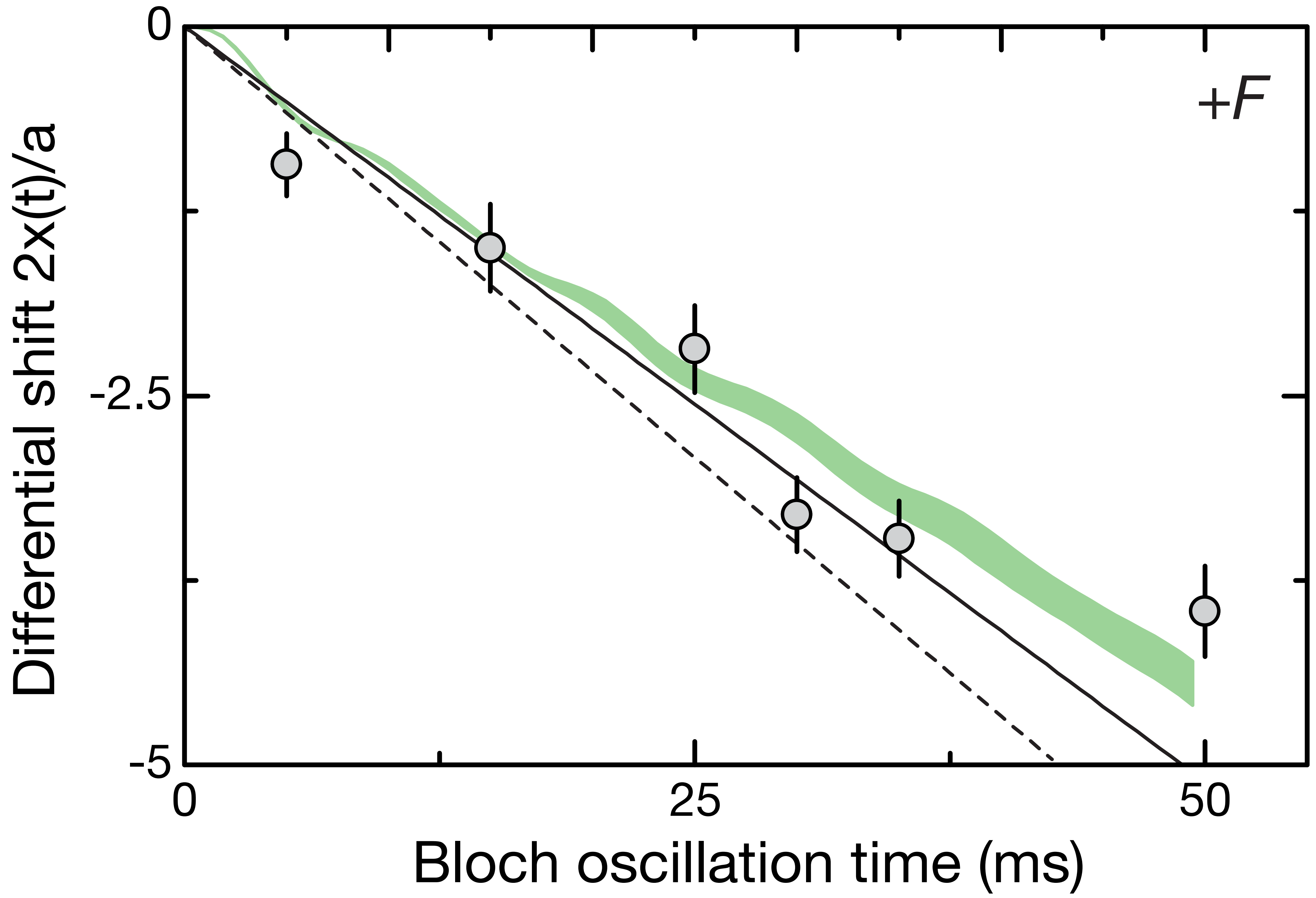
$$\int \partial E_\mu / \partial k_{x,y} \mathrm{d}^2\mathrm{k} = 0$$

Transverse center-of-mass motion (μth band):

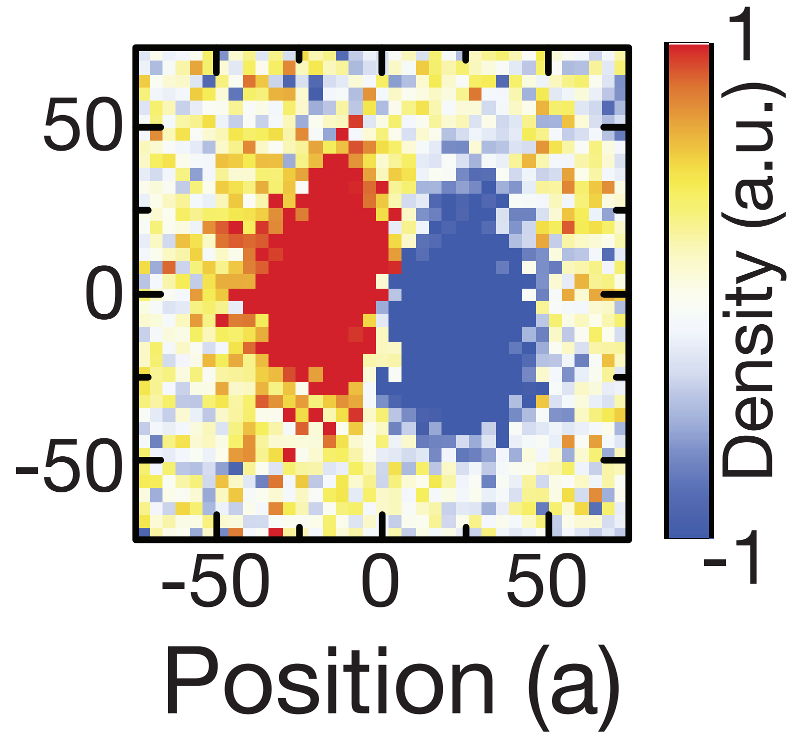
$$x_\mu(t) = -\frac{4a^2 F}{h} \nu_\mu \, t$$

M. A. et al., Nature Phys. (2015)
See also: G. Jotzu et al., Nature (2014)

Hall deflection



Difference image for $\pm\Phi$



$$\nu_{\mathrm{exp}} = 0.99(5)$$

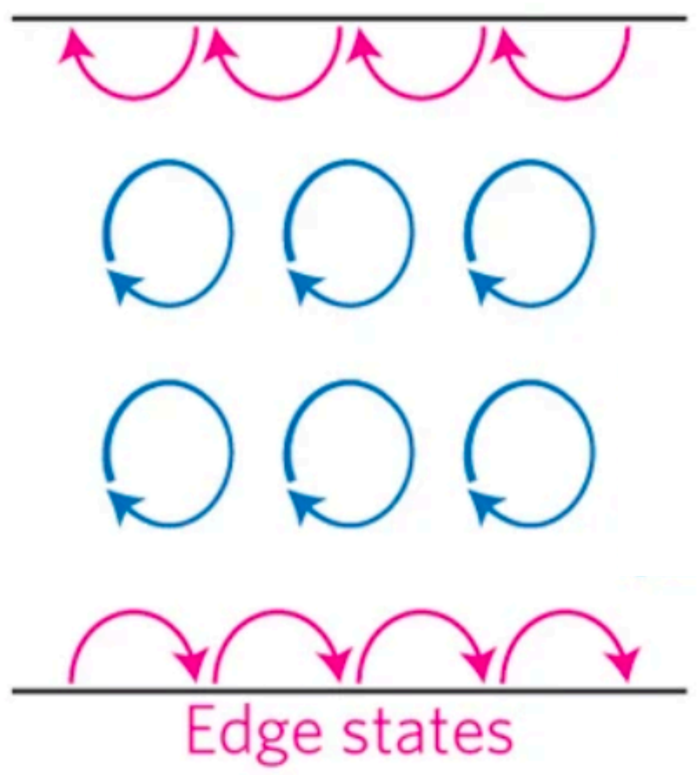
M. A. et al., Nature Phys. (2015)
See also: G. Jotzu et al., Nature (2014)

Can we go beyond emulating
static topological systems?

Anomalous Floquet phases

Floquet engineering:

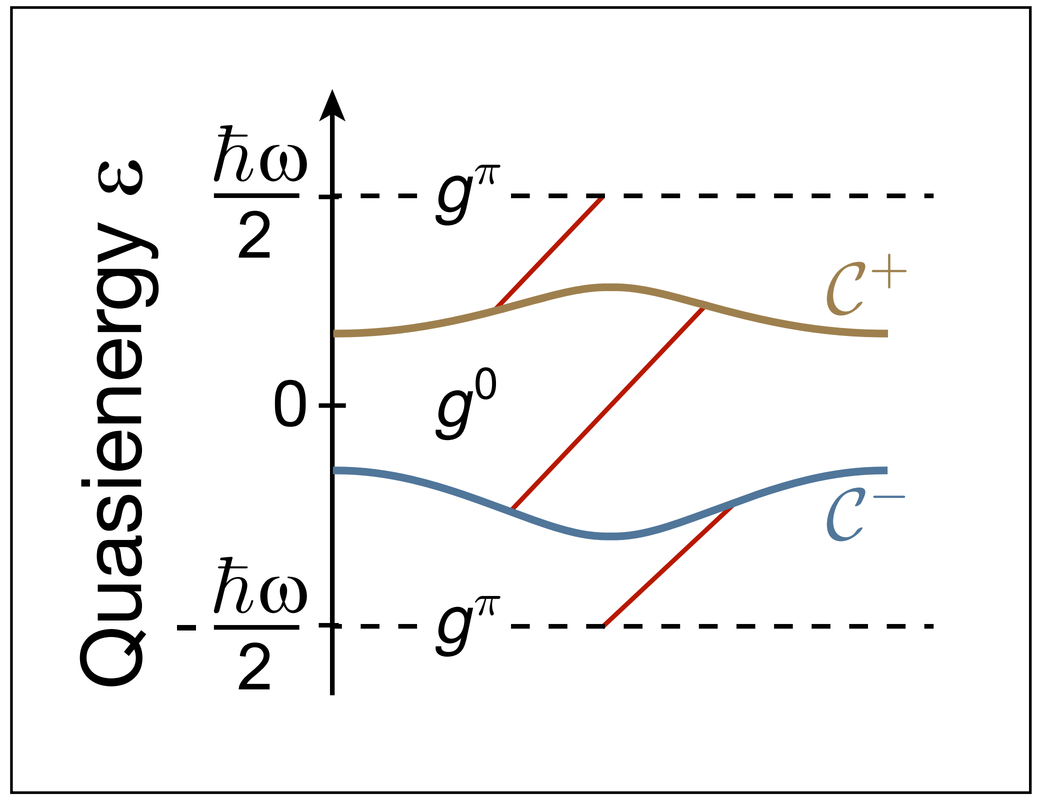
- High-frequency limit:
  $\rightarrow$ known **bulk-edge correspondence**
- Chern number uniquely determines
  # net edge modes in the gap



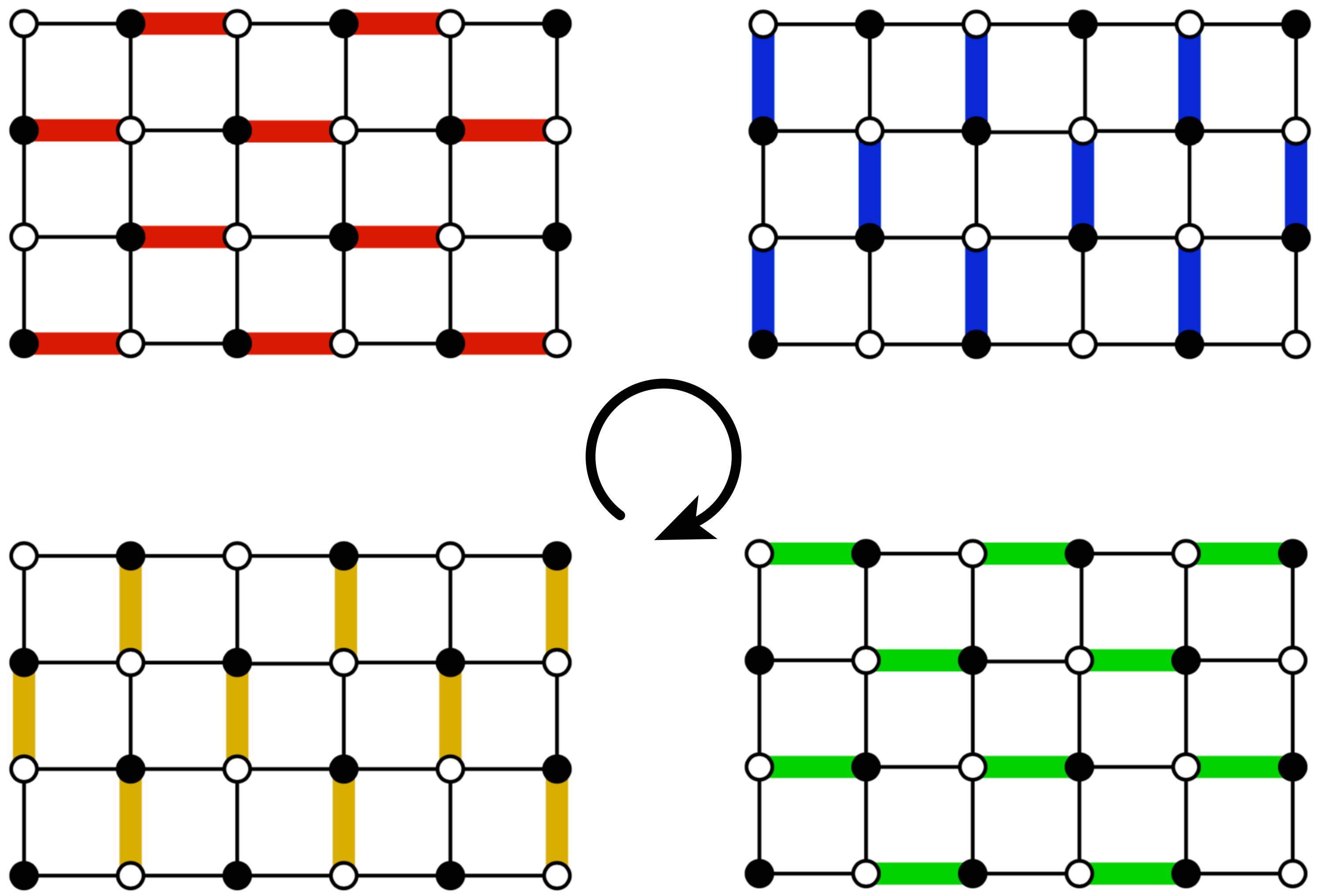
Beyond high-frequency limit:

T. Kitagawa et al., PRB **82**, 235114 (2010)
M. Rudner et al., PRX **3**, 031005 (2013)

- Edge modes, but **zero** Chern numbers!
- Robust edge transport $\longleftrightarrow$ localized bulk!

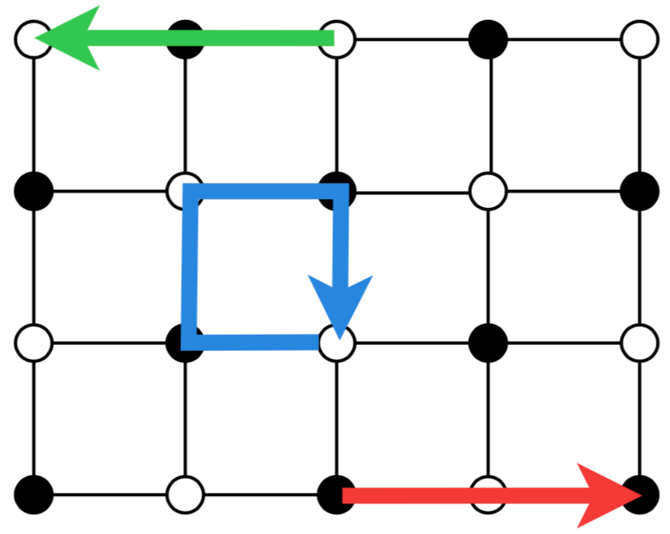


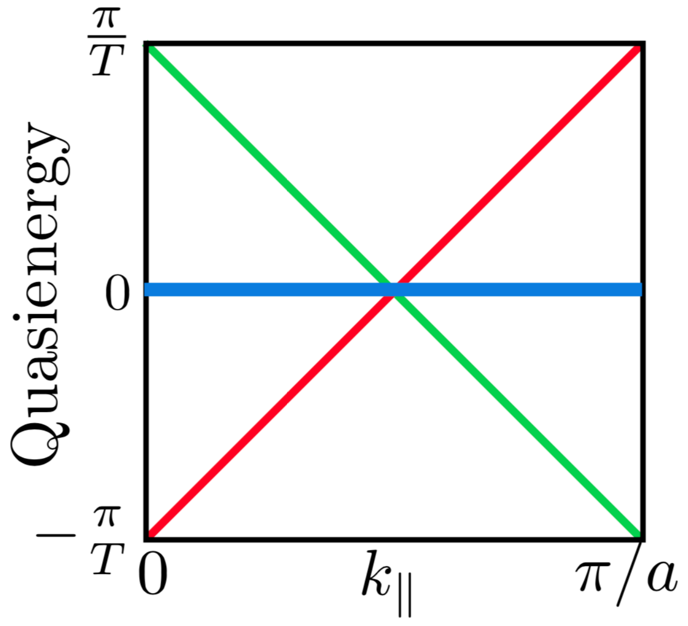
Stepwise modulated square lattice



- Topology not determined by properties of $\hat{H}_{\mathrm{eff}}$!
- Full time-dependence is important
- Non-trivial winding of quasi-energy spectrum

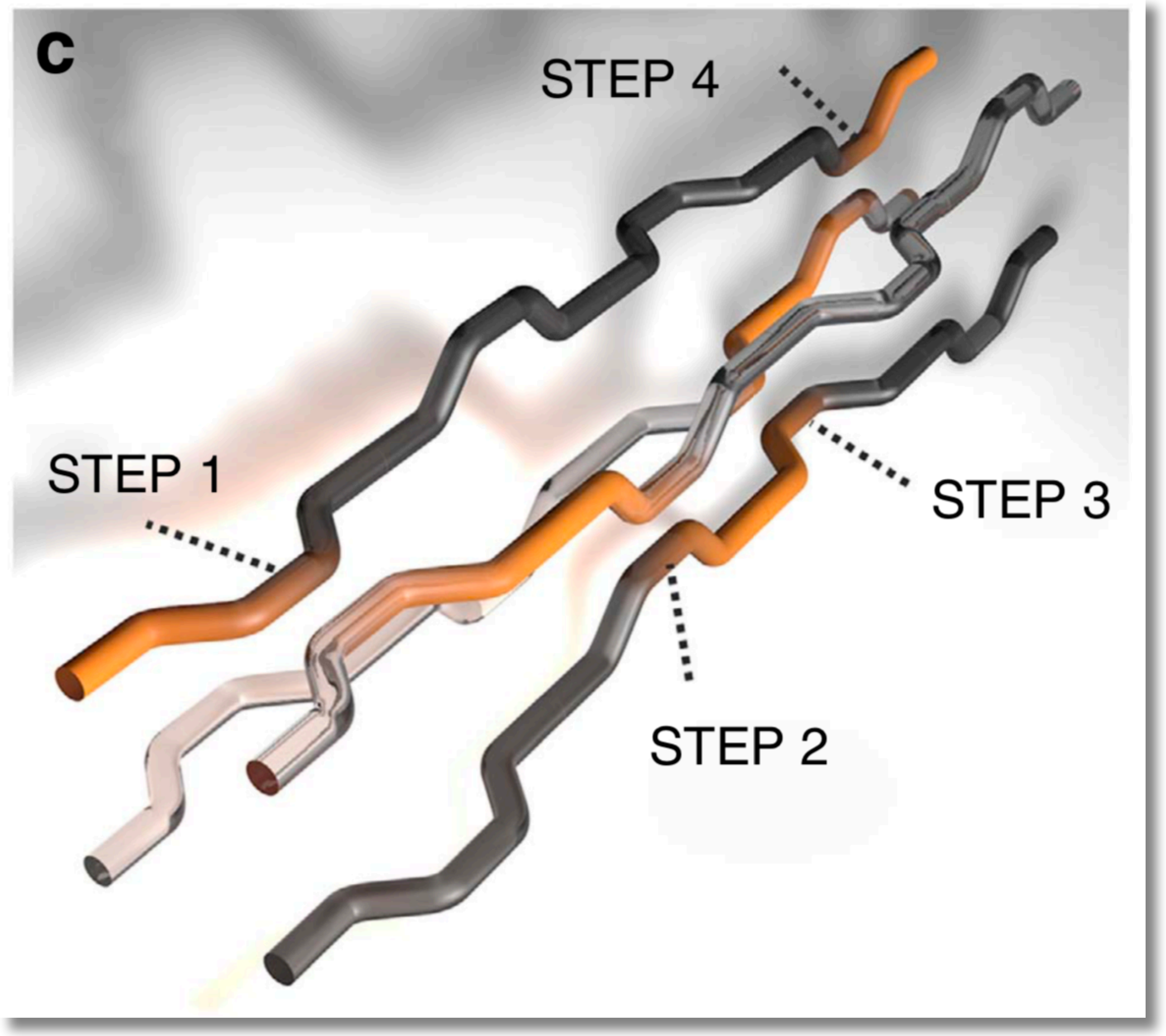
→ two degenerate flat bands at ε=0, with *trivial topology!*

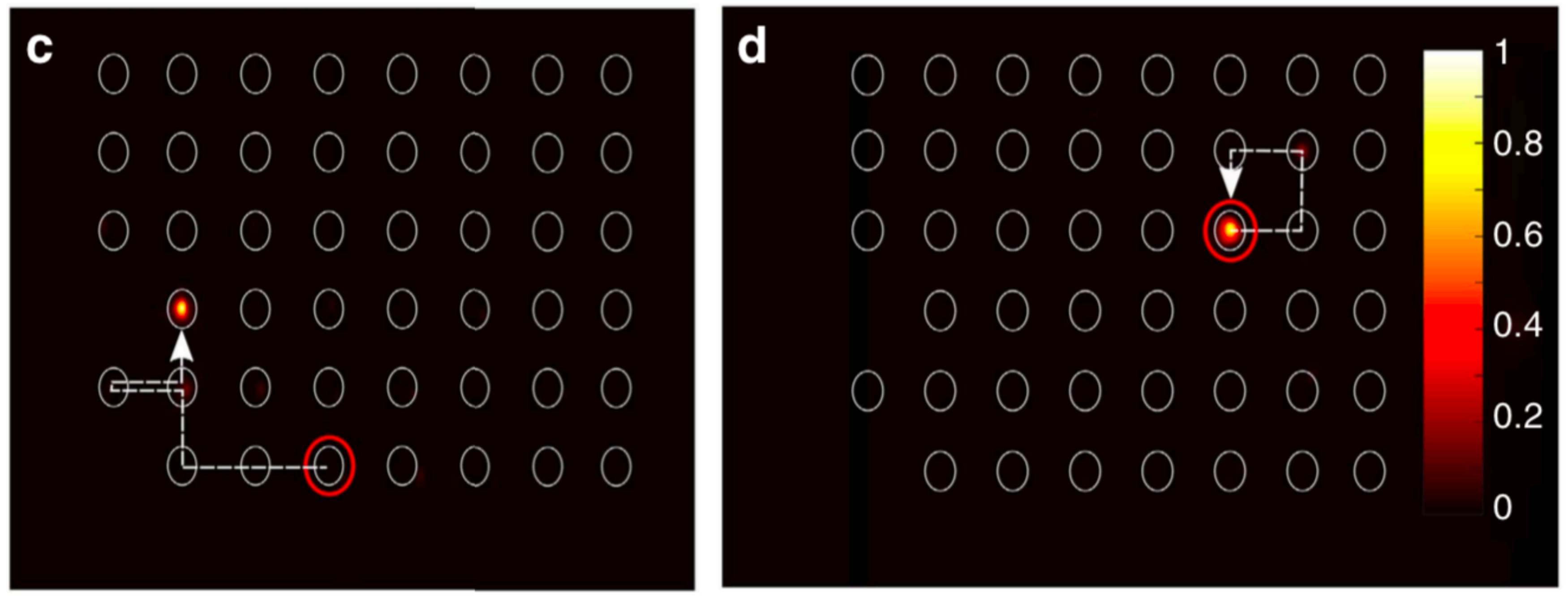




T. Kitagawa et al., Phys. Rev. B **82**, 235114 (2010), M. Rudner et al., PRX **3**, 031005 (2013)

Coupled waveguide arrays





→ Robust edge transport

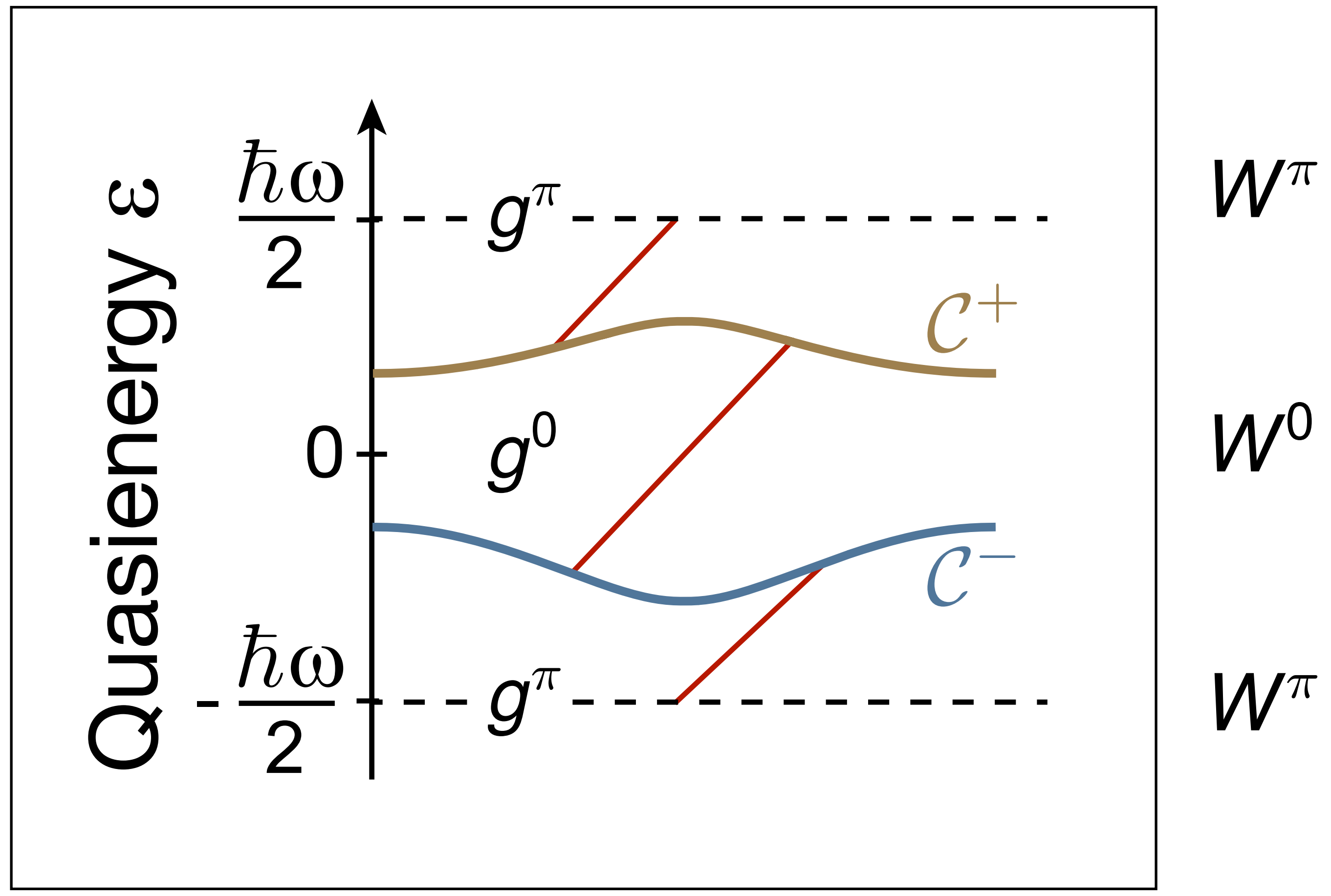
Cold atoms:

- Reveal *bulk and edge-state physics*
- Study *many-body phases*

S. Mukherjee et al., Nat. Commun. **8**, 13918 (2017), L. J. Maczewsky et al., Nat. Commun. **8**, 13756 (2017)

Topological Floquet phases

How to characterize the topological properties?



Winding number counts
 # edge modes in gap!

$$\mathcal{C}^{\pm} = \mp(W^0 - W^\pi)$$

$$W[U] = \frac{1}{8\pi^2}\int \mathrm{d}t\mathrm{d}q_x\mathrm{d}q_y \times \mathrm{Tr}(U^{-1}\partial_t U[U^{-1}\partial_{q_x}U, U^{-1}\partial_{q_y}U])$$

T. Kitagawa et al., Phys. Rev. B **82**, 235114 (2010); M. Rudner et al., PRX **3**, 031005 (2013); N. Ünal et al., PRL 122, 253601 (2019)

Topological Floquet phases

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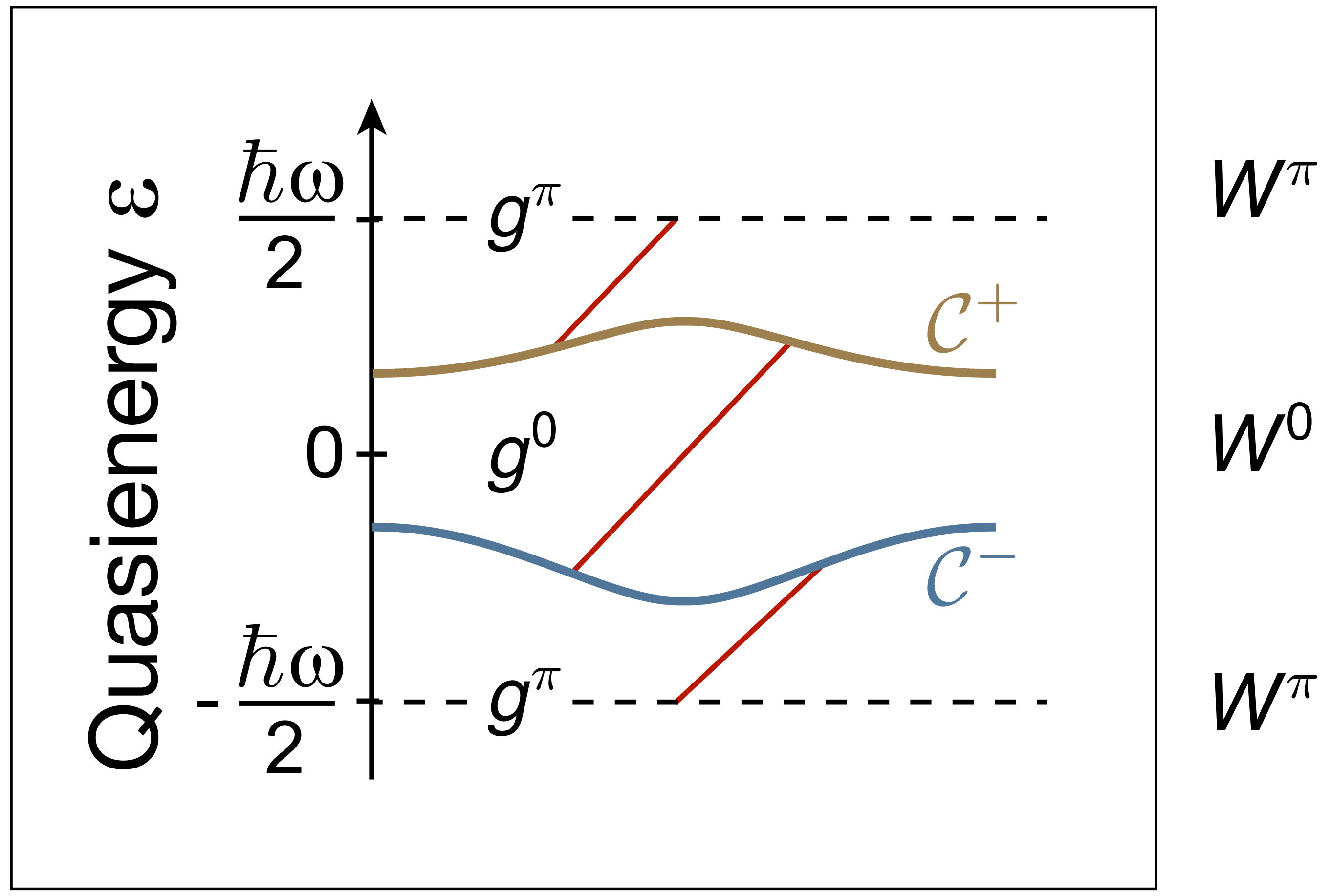


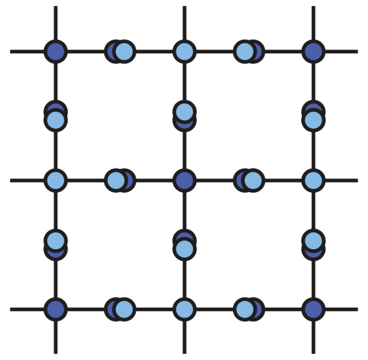
Winding number counts # edge modes in gap!

$$\mathcal{C}^{\pm} = \mp(W^0 - W^\pi)$$

Complete set of invariants given by winding numbers!

T. Kitagawa et al., Phys. Rev. B **82**, 235114 (2010); M. Rudner et al., PRX **3**, 031005 (2013); N. Ünal et al., PRL 122, 253601 (2019)

Experimental realization

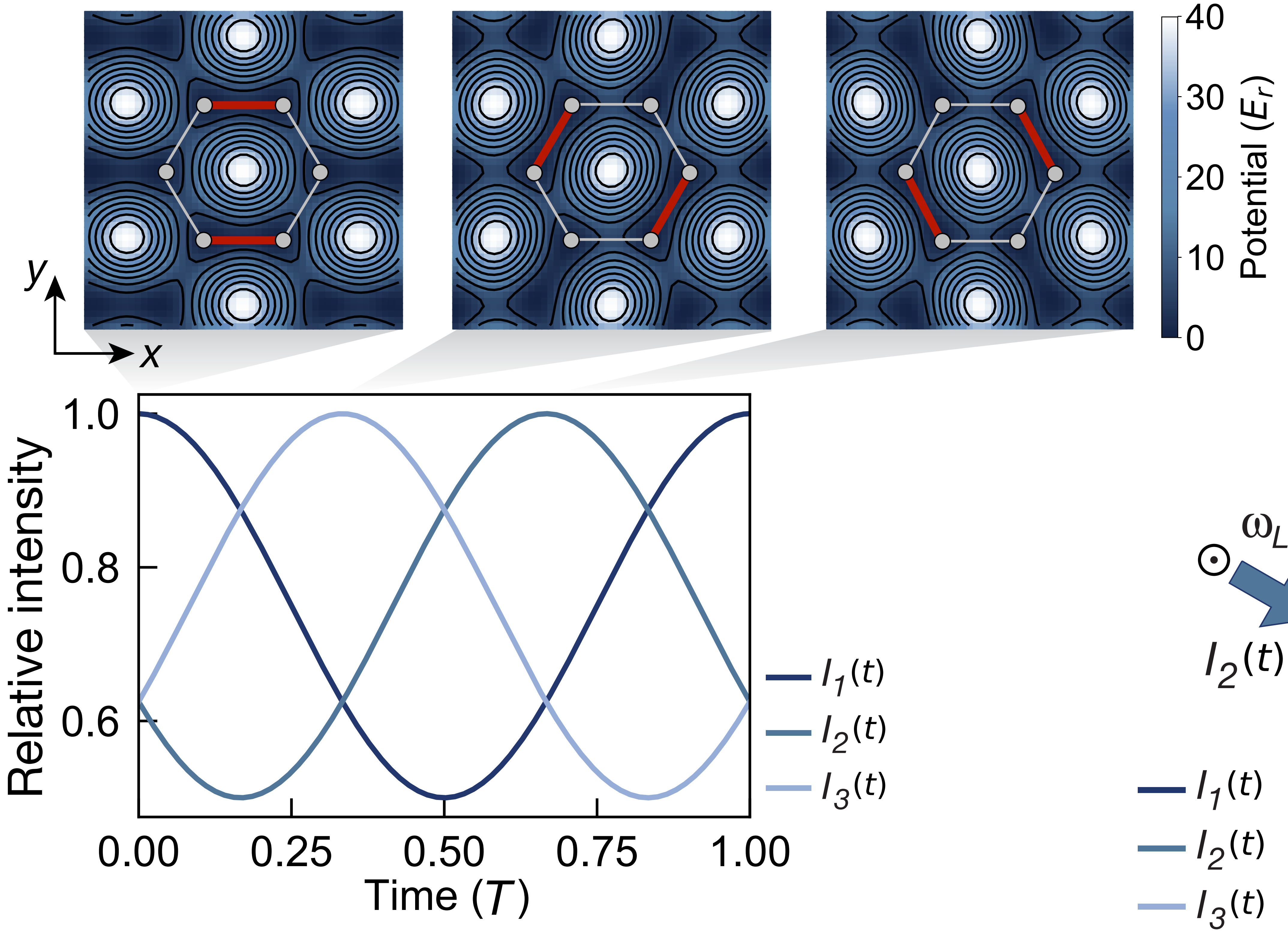


Periodically-modulated hexagonal lattice

Modulate NN tunnelings between λJ and J

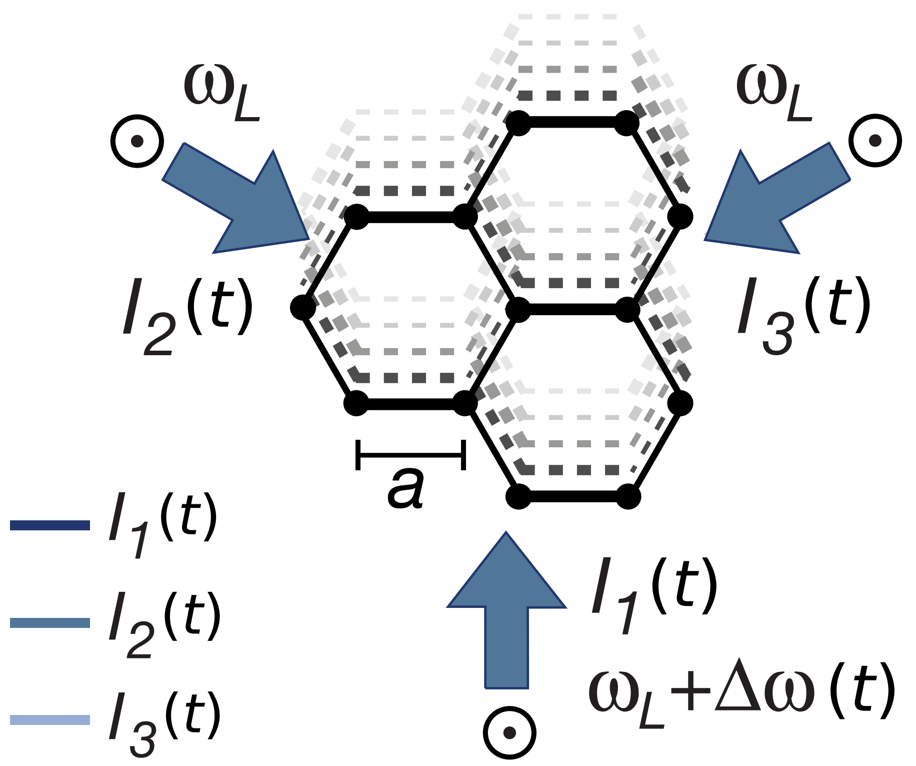
T. KITAGAWA ET AL., PRB **82**, 235114 (2010)

Continuous modulation scheme:



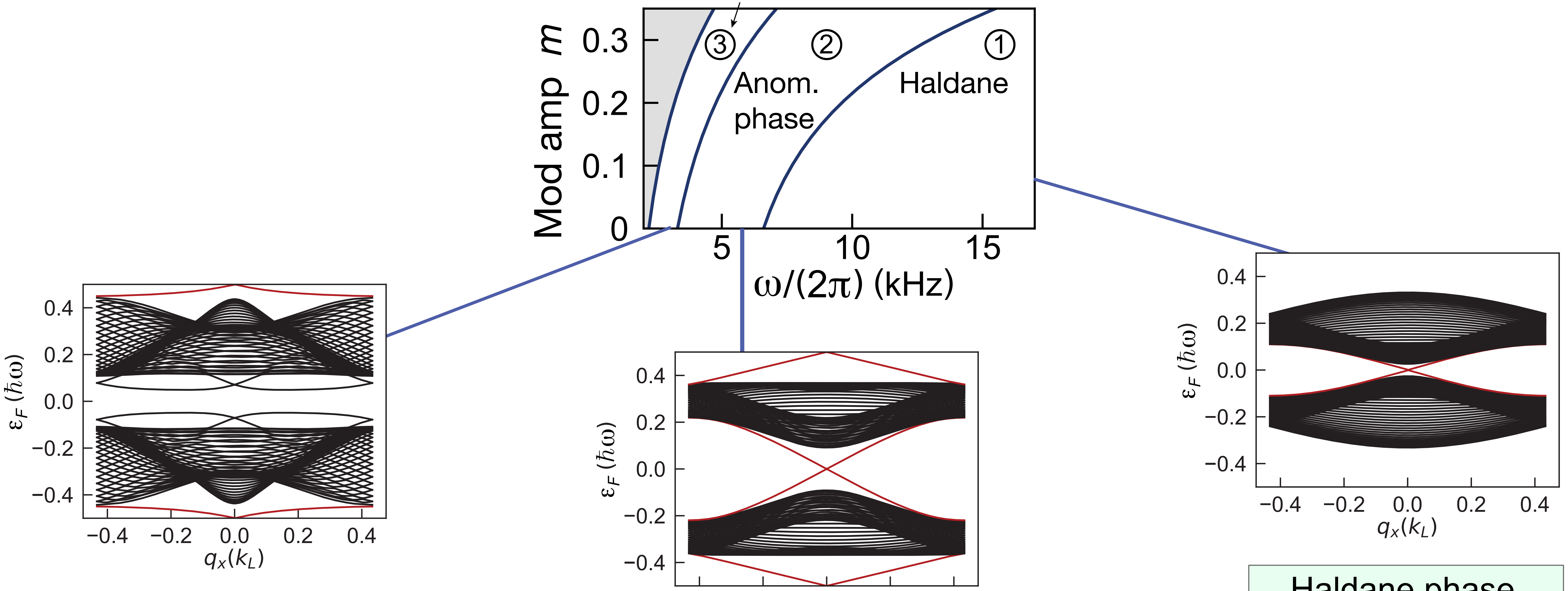
Here: Bosonic ^{39}K

$\lambda = 737\mathrm{nm}, \quad a = 284\mathrm{nm}$



K. WINTERSPERGER, ..., M.A., NATURE PHYS. **16**, 1058-1063 (2020); SEE ALSO: A. QUELLE ET AL., NEW J PHYS. **19**, 113010 (2017)

Phase diagram



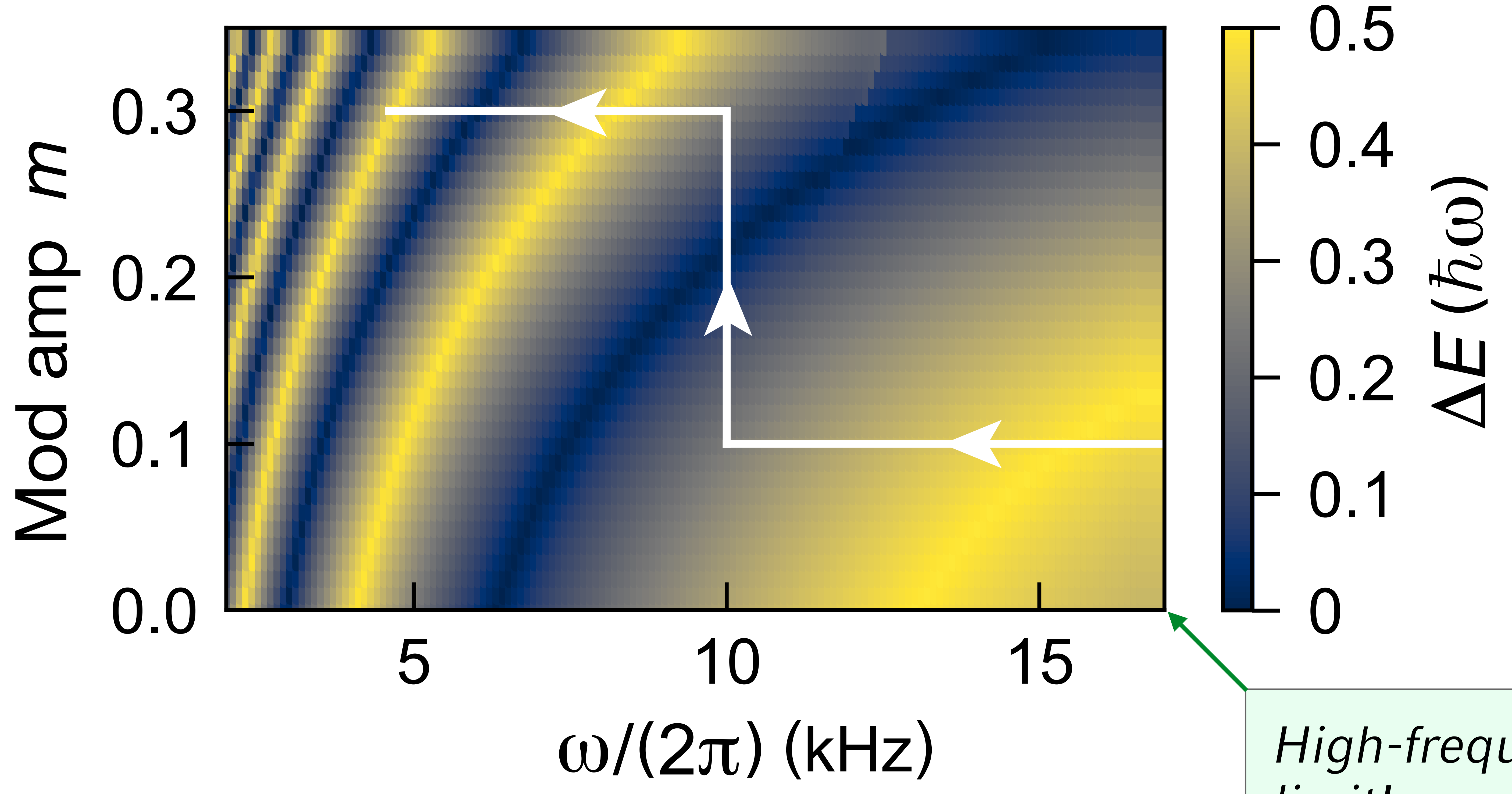
Haldane-like phase
$\mathcal{C}^{\pm} = \pm 1$

Anomalous phase
$\mathcal{C}^{\pm} = 0$

Haldane phase
$\mathcal{C}^{\pm} = \mp 1$

K. Wintersperger, ..., M.A., Nature Phys. **16**, 1058-1063 (2020)

Probing the phase diagram

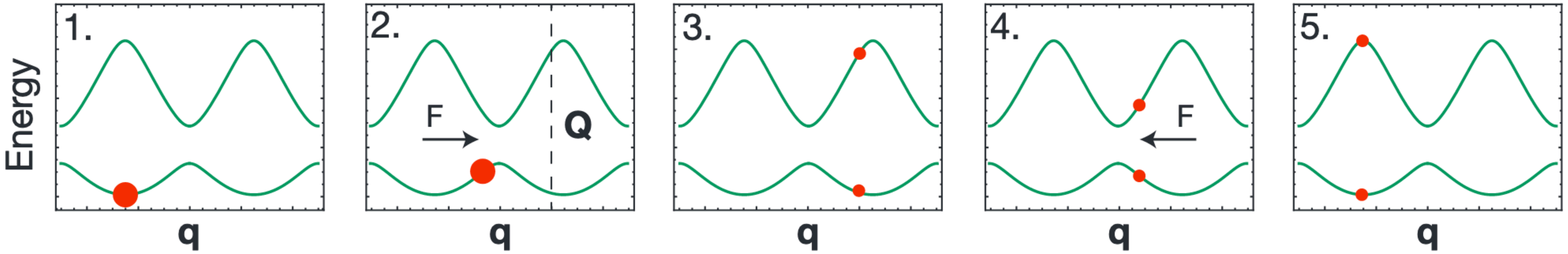


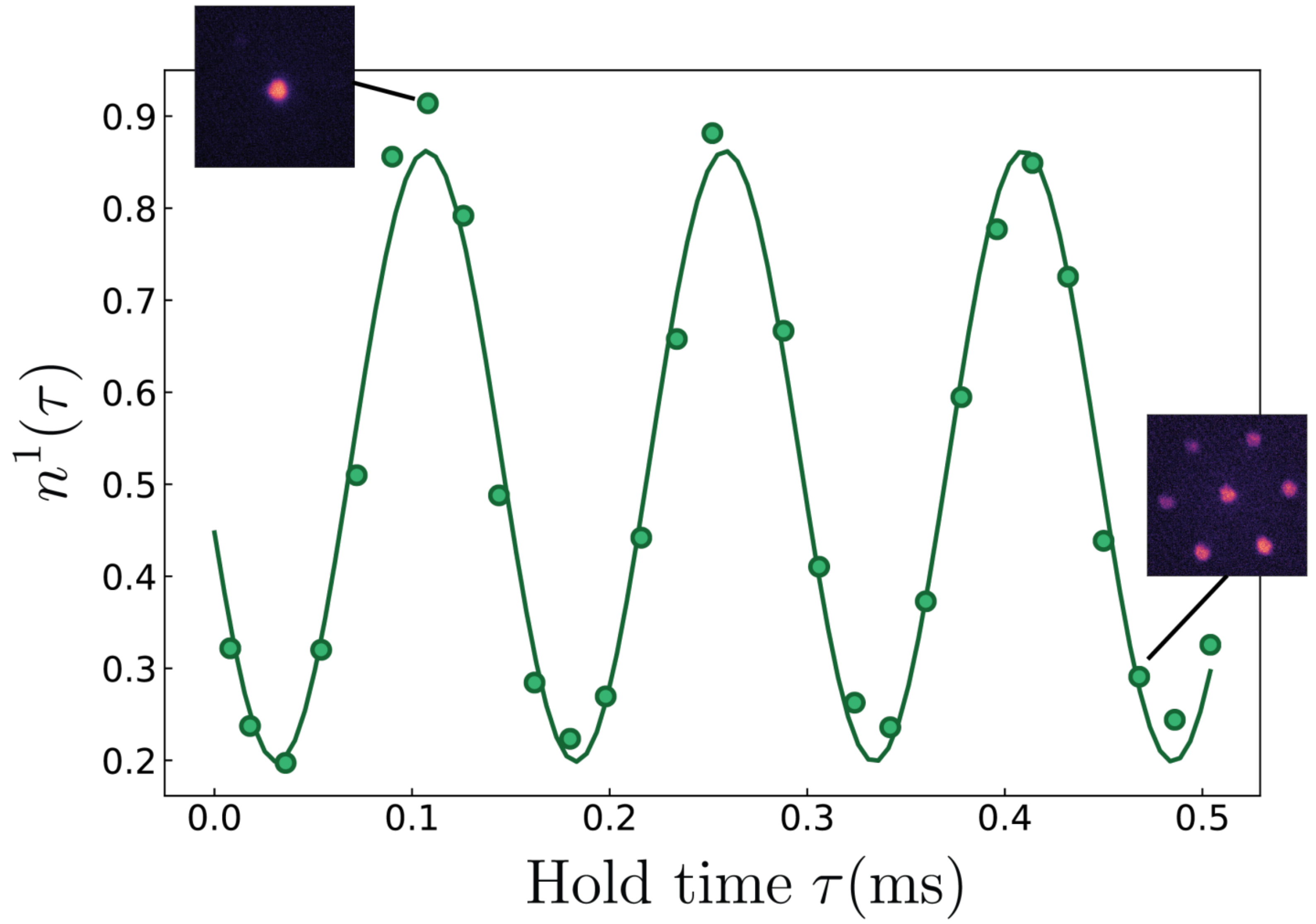
High-frequency limit!

K. Wintersperger, ..., M.A., Nature Phys. **16**, 1058-1063 (2020)

Stückelberg oscillations

Hold time



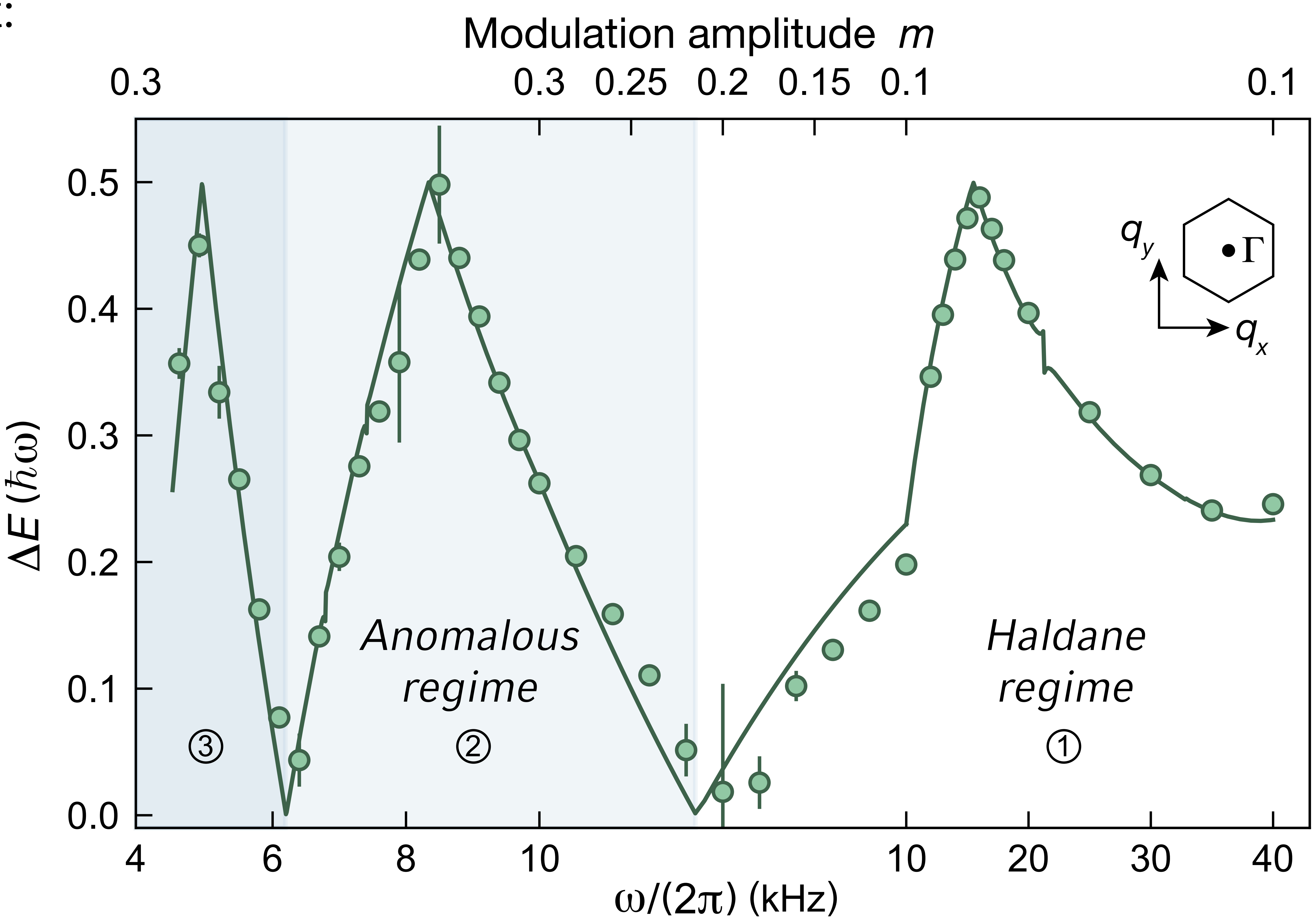


$$n^1(\tau) \propto \cos\left(\frac{E_Q^2 - E_Q^1}{\hbar}\tau\right)$$

Stückelberg, Helv. Phys. Acta 5, 369 (1932)
Shevchenko et al., Phys. Rep. 492, 1 (2010)
Zanesini et al., PRA 82, 065601, (2010), Weitz PRL 105, 215301 (2010)

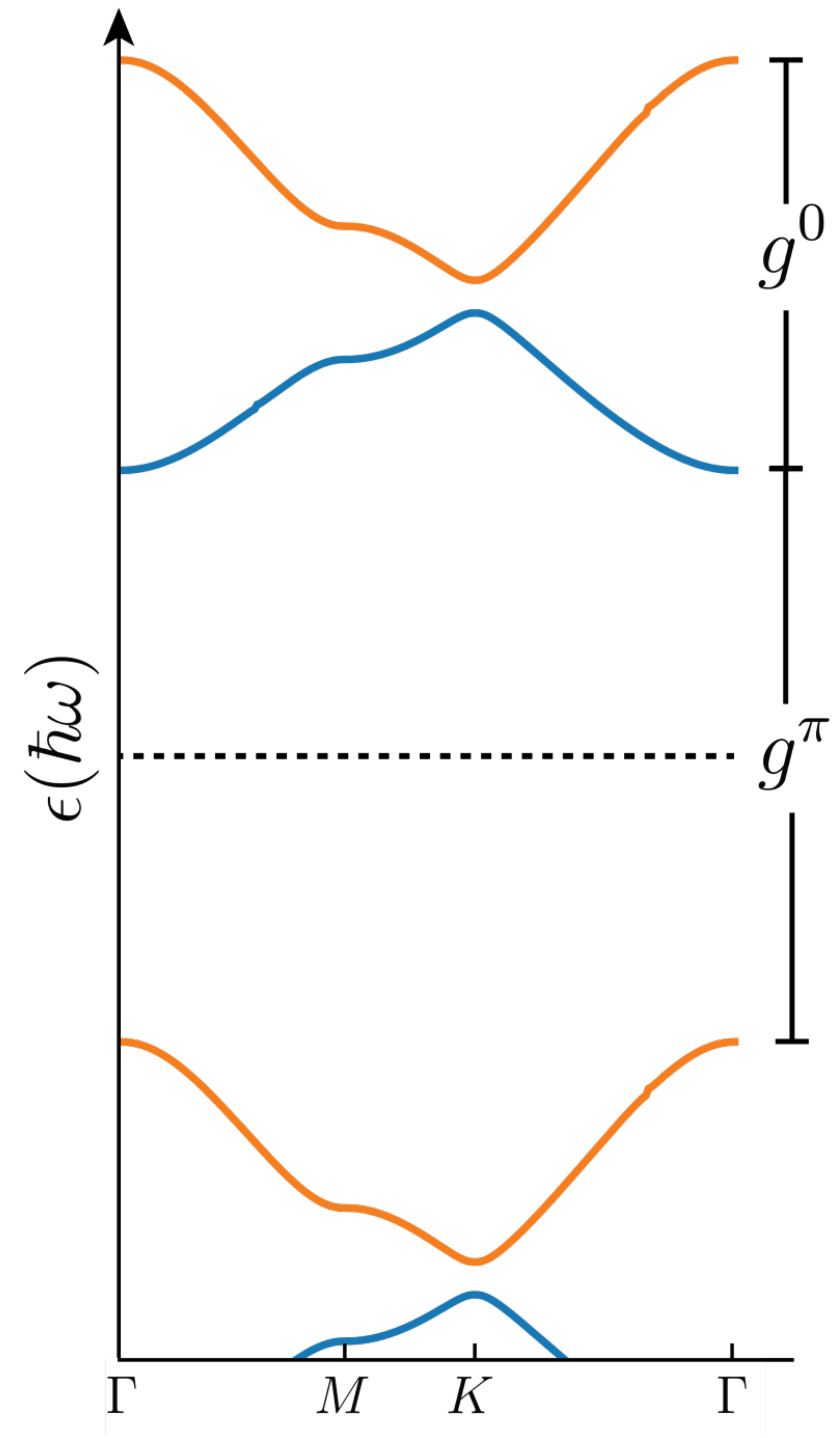
Identify phase transition via gap closing

Γ-point:



K. Wintersperger, ..., M.A., Nature Phys. **16**, 1058-1063 (2020)

Identify which gap closes

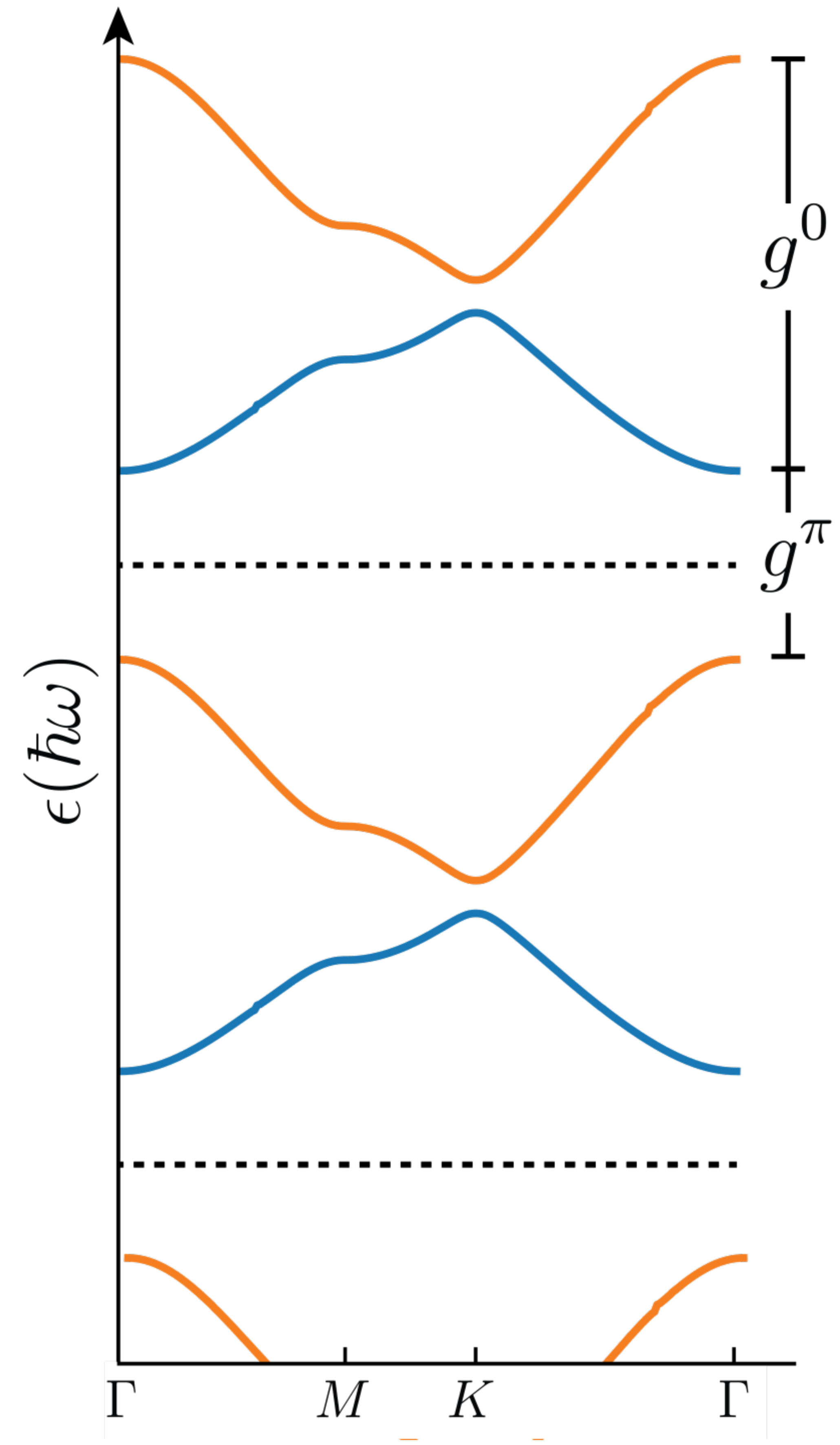


- We always measure the *smaller energy gap:* $\min(g^0, g^\pi)$
- In the *high-frequency limit* we probe g^0

K. Wintersperger, …., M.A., Nature Phys. **16**, 1058-1063 (2020)

N. Ünal et al., PRL 122, 253601 (2019)

Identify which gap closes

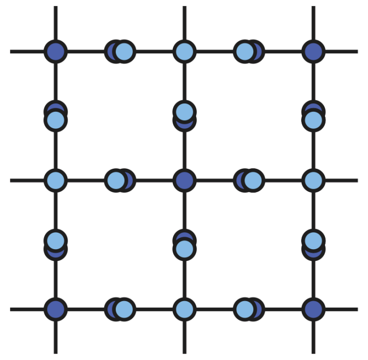


- We always measure the *smaller energy gap:* $\min(g^0, g^\pi)$
- In the *high-frequency limit* we probe g^0
- Transition, when

  $g^0 = g^\pi = \hbar\omega/2$

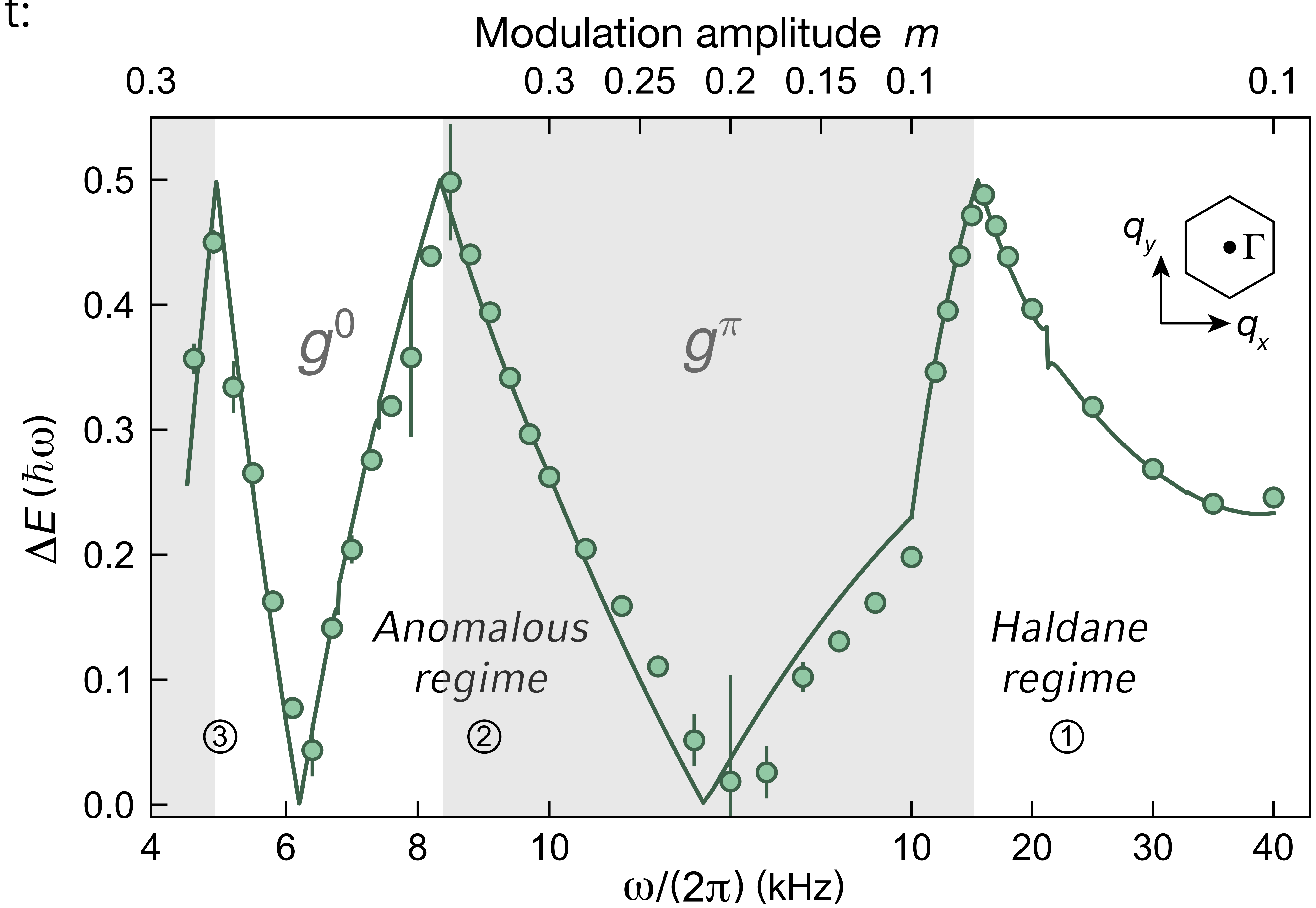
K. Wintersperger, ..., M.A., Nature Phys. **16**, 1058-1063 (2020)

N. Ünal et al., PRL 122, 253601 (2019)



Identify which gap closes

Γ-point:

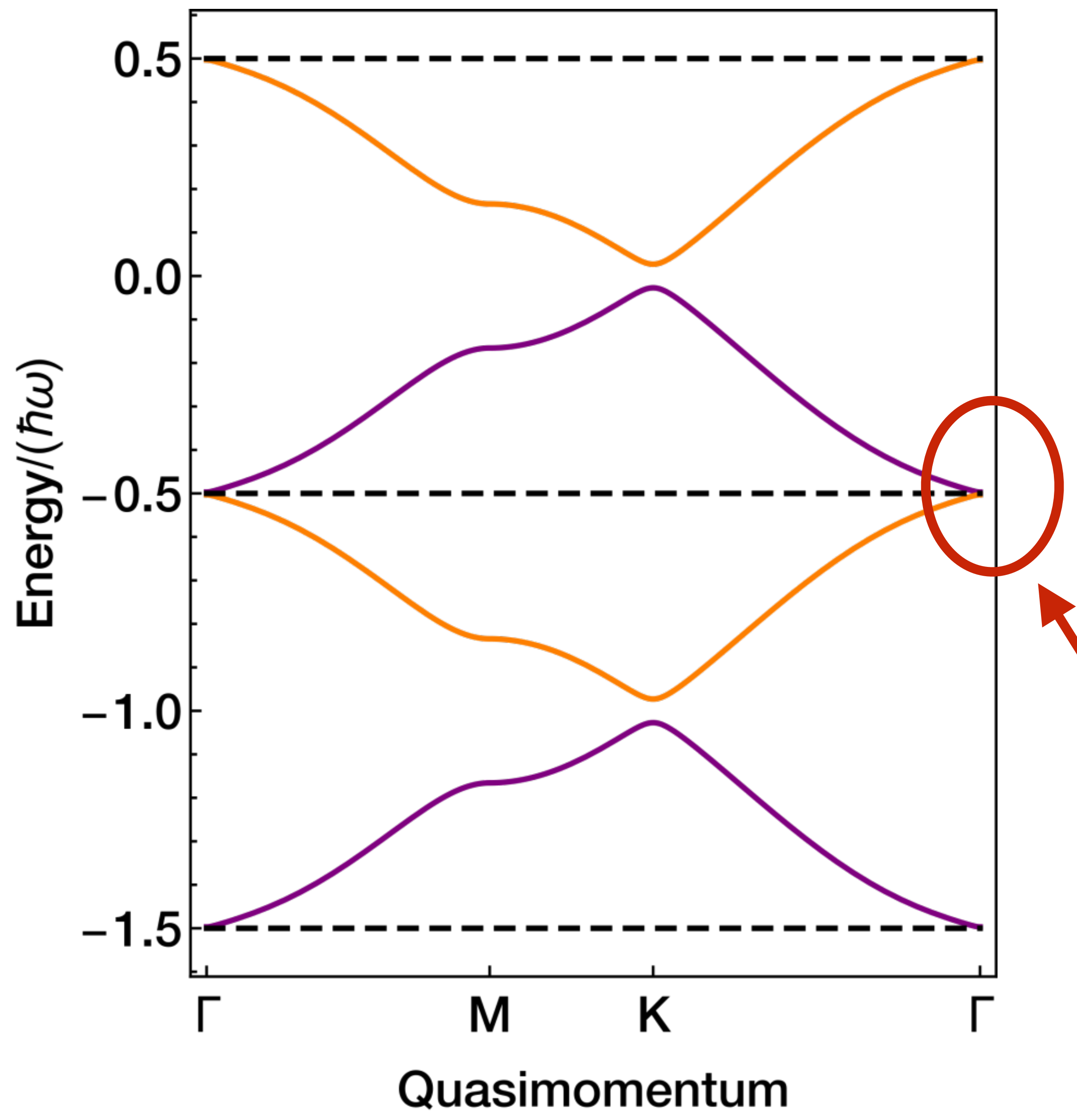


K. Wintersperger, ..., M.A., Nature Phys. **16**, 1058-1063 (2020)

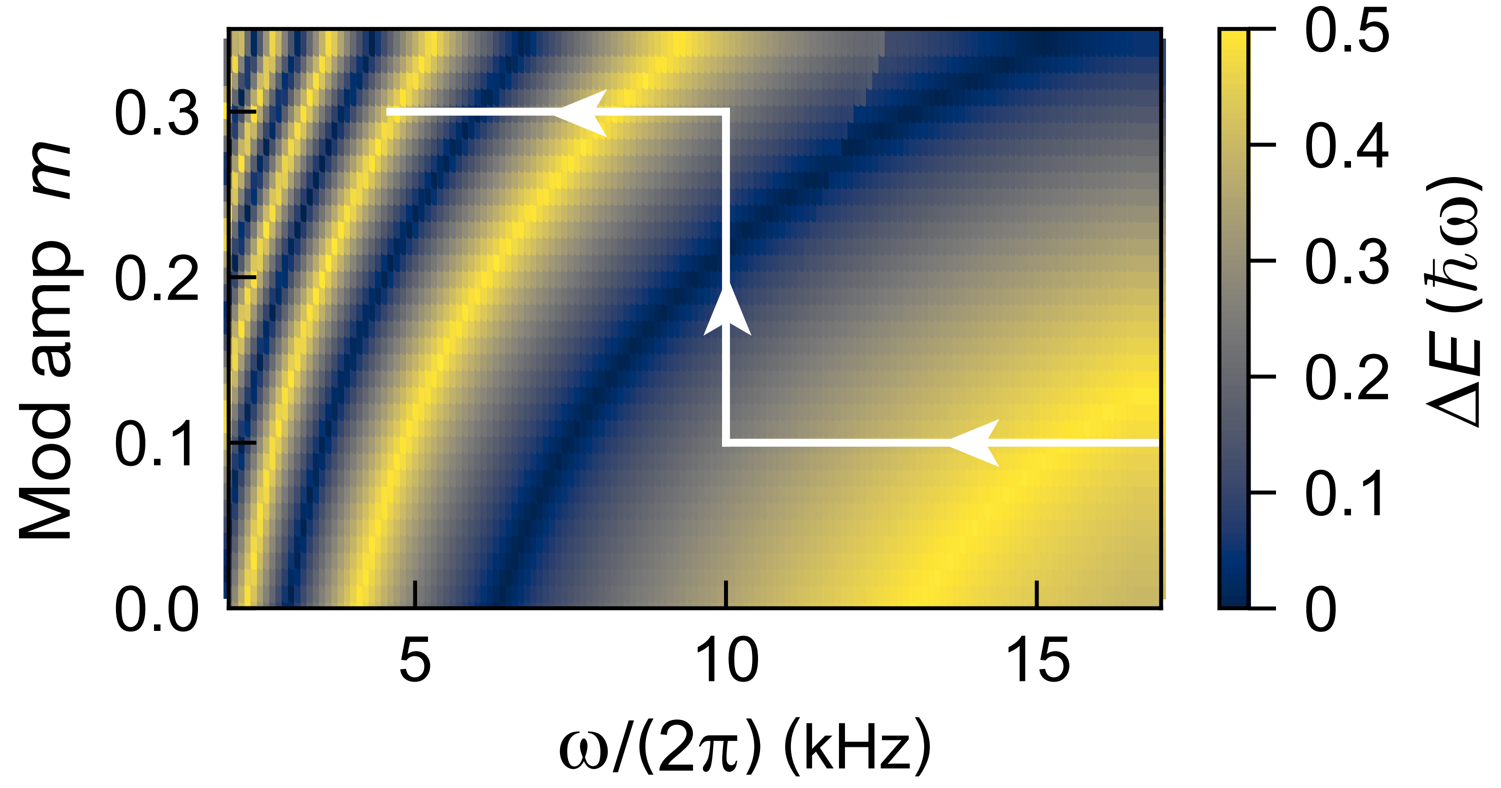
Determine bulk geometric properties

Topology of gap-closing point

Band-touching singularities



- Consider 3D-parameter space: (q_x, q_y, λ)

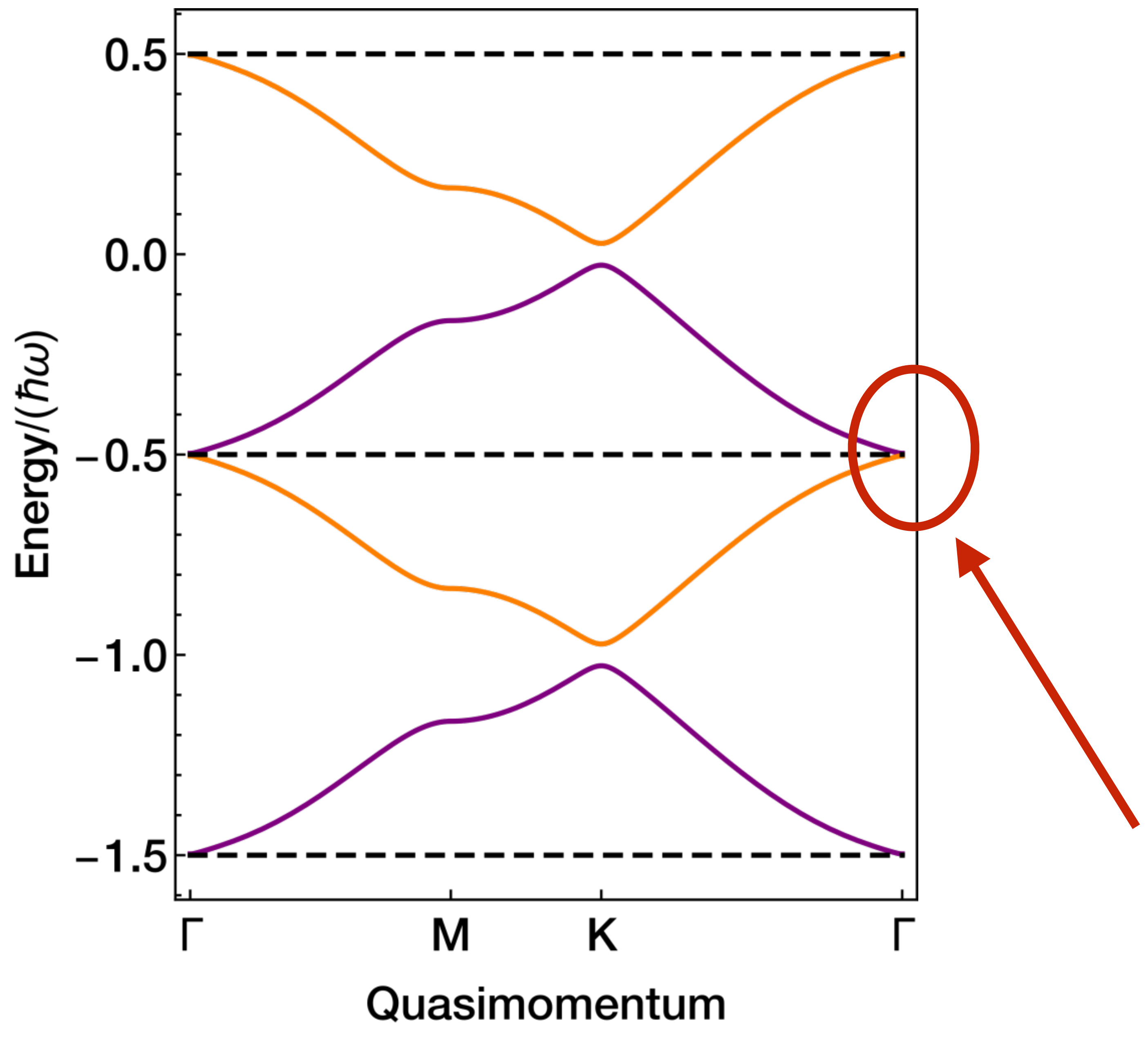


Topological charge $Q_s = \pm 1$

F. Nathan et al, New J. Phys. 17, 125014 (2015); N. Ünal et al., PRL 122, 253601 (2019)

Topology of gap-closing point

Band-touching singularities



- Consider 3D-parameter space: (q_x, q_y, λ)
- Topological charge describes change in Winding number

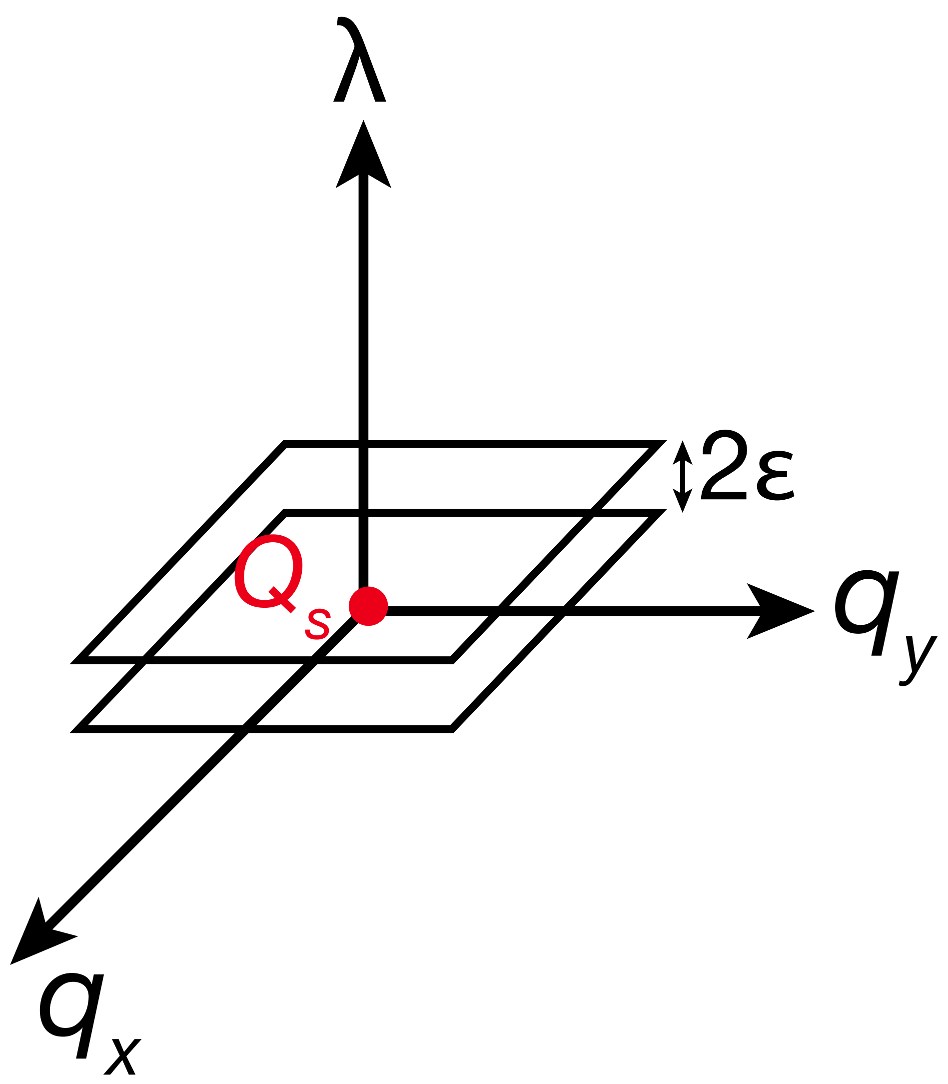
$$W^j_{\lambda_s+\varepsilon} = W^j_{\lambda_s-\varepsilon} + Q^j_s$$

Topological charge $Q_s = \pm 1$

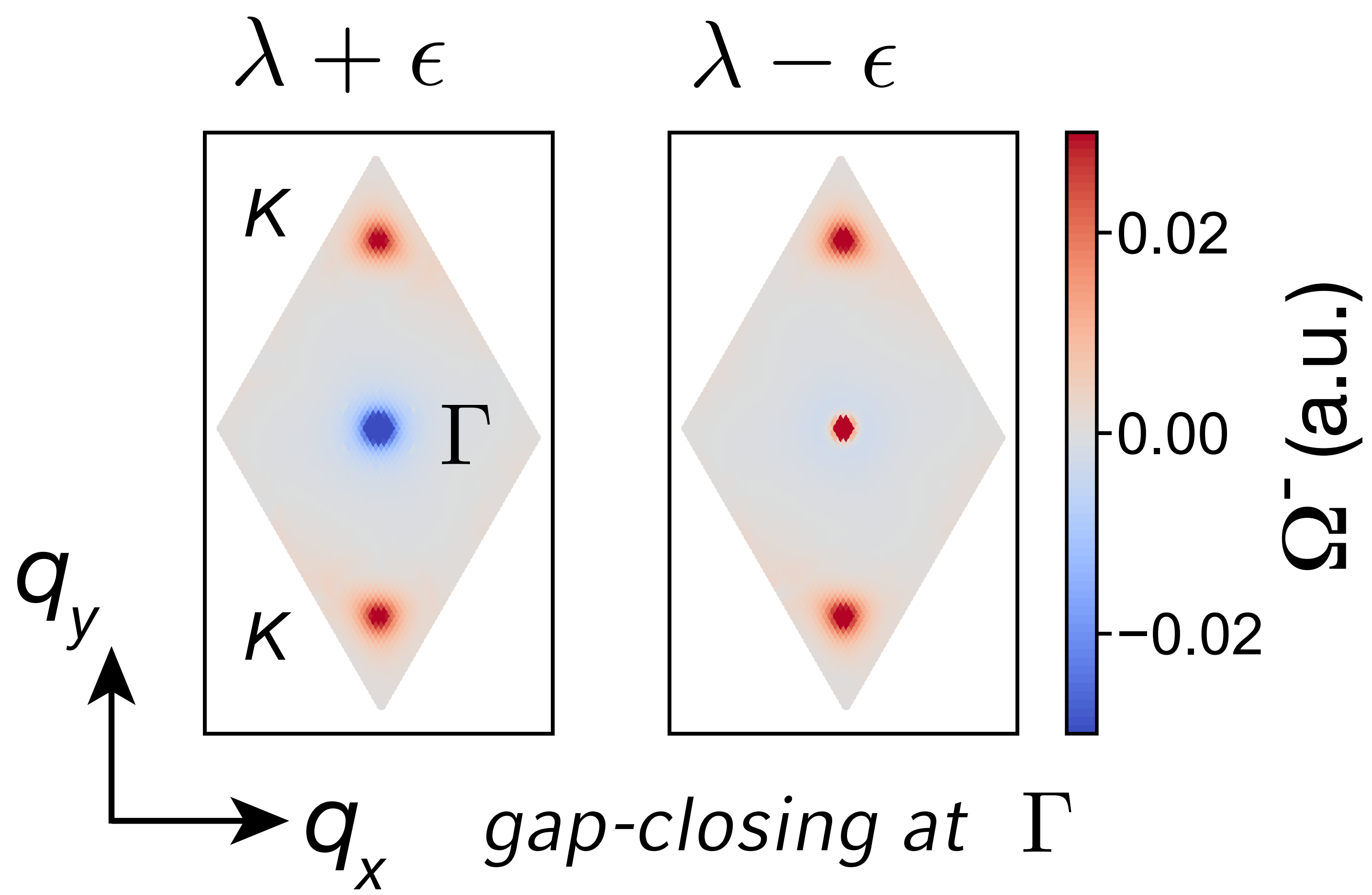
F. Nathan et al, New J. Phys. 17, 125014 (2015); N. Ünal et al., PRL 122, 253601 (2019)

Determine topological charge

Measure Berry flux associated with Q_s



Measure *Berry-flux locally shortly before and after* the gap-closing point!

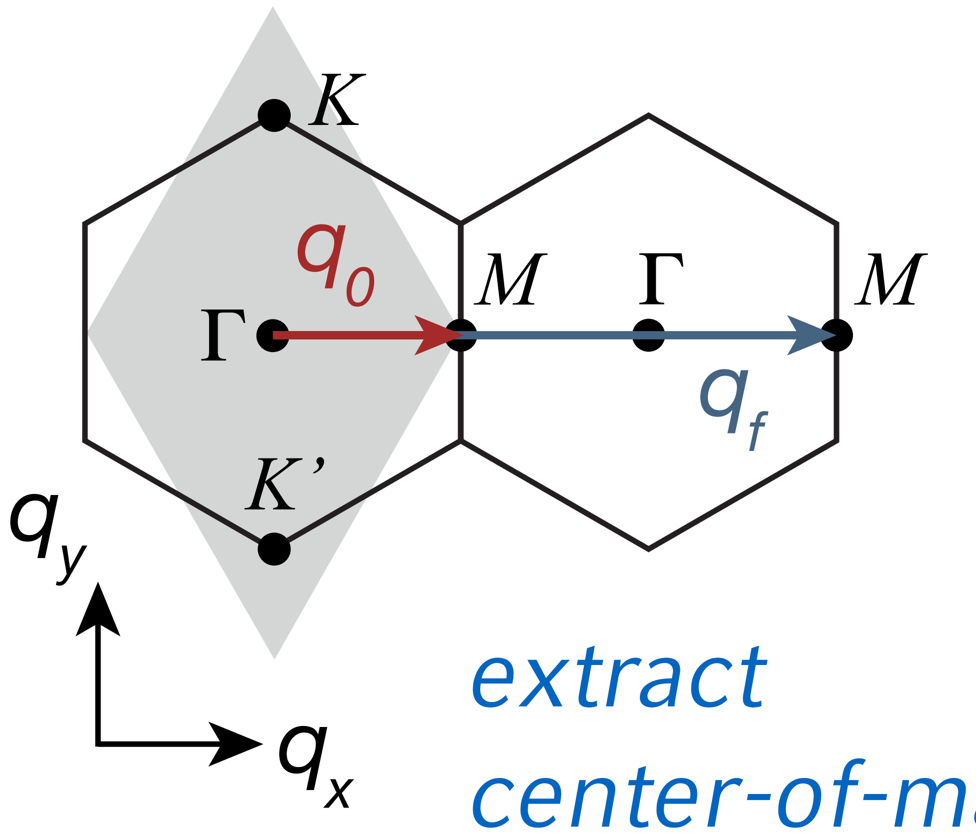


F. Nathan et al, New J. Phys. 17, 125014 (2015); N. Ünal et al., PRL 122, 253601 (2019)

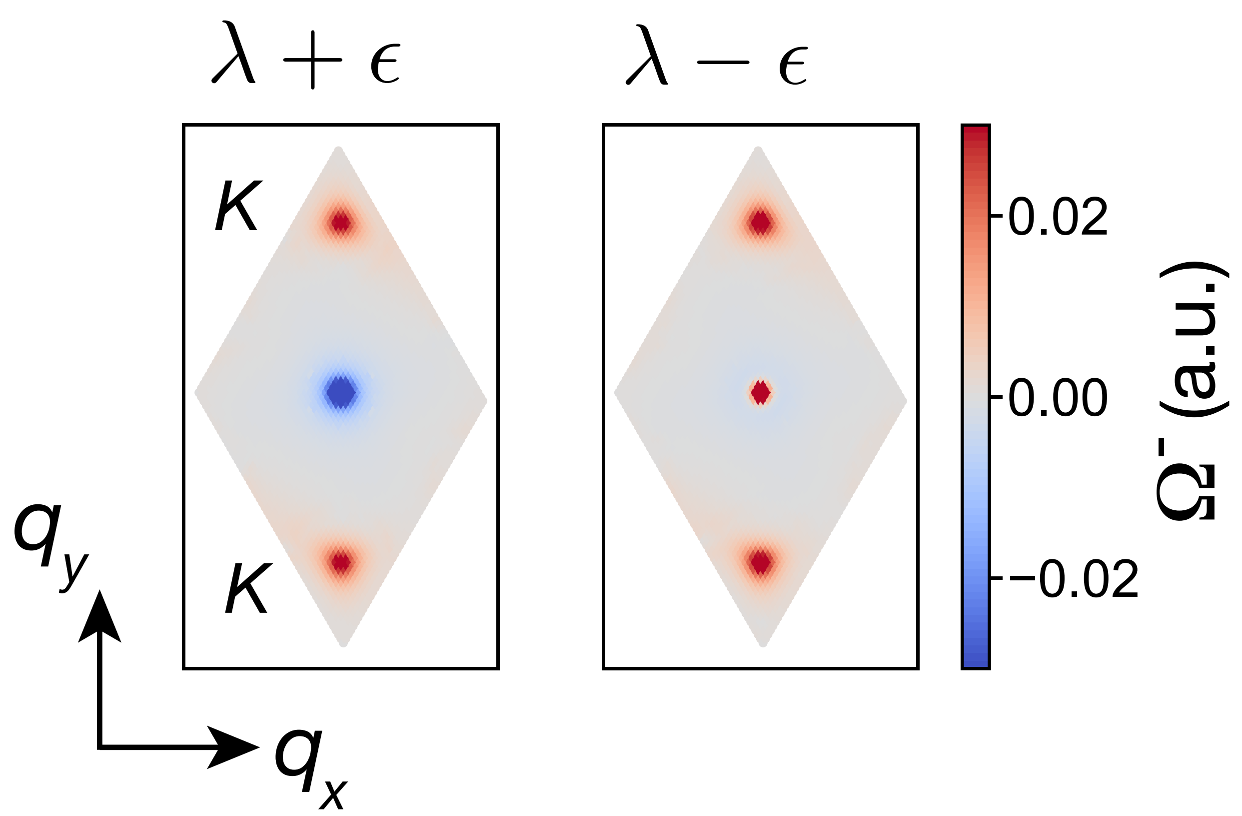
Local Hall deflection

Anomalous transverse velocity proportional to *Berry curv.* Ω_μ

$$\mathbf{v}^x_\mu(\mathbf{q}) = -\frac{F}{\hbar}\Omega_\mu(\mathbf{q})$$



extract center-of-mass

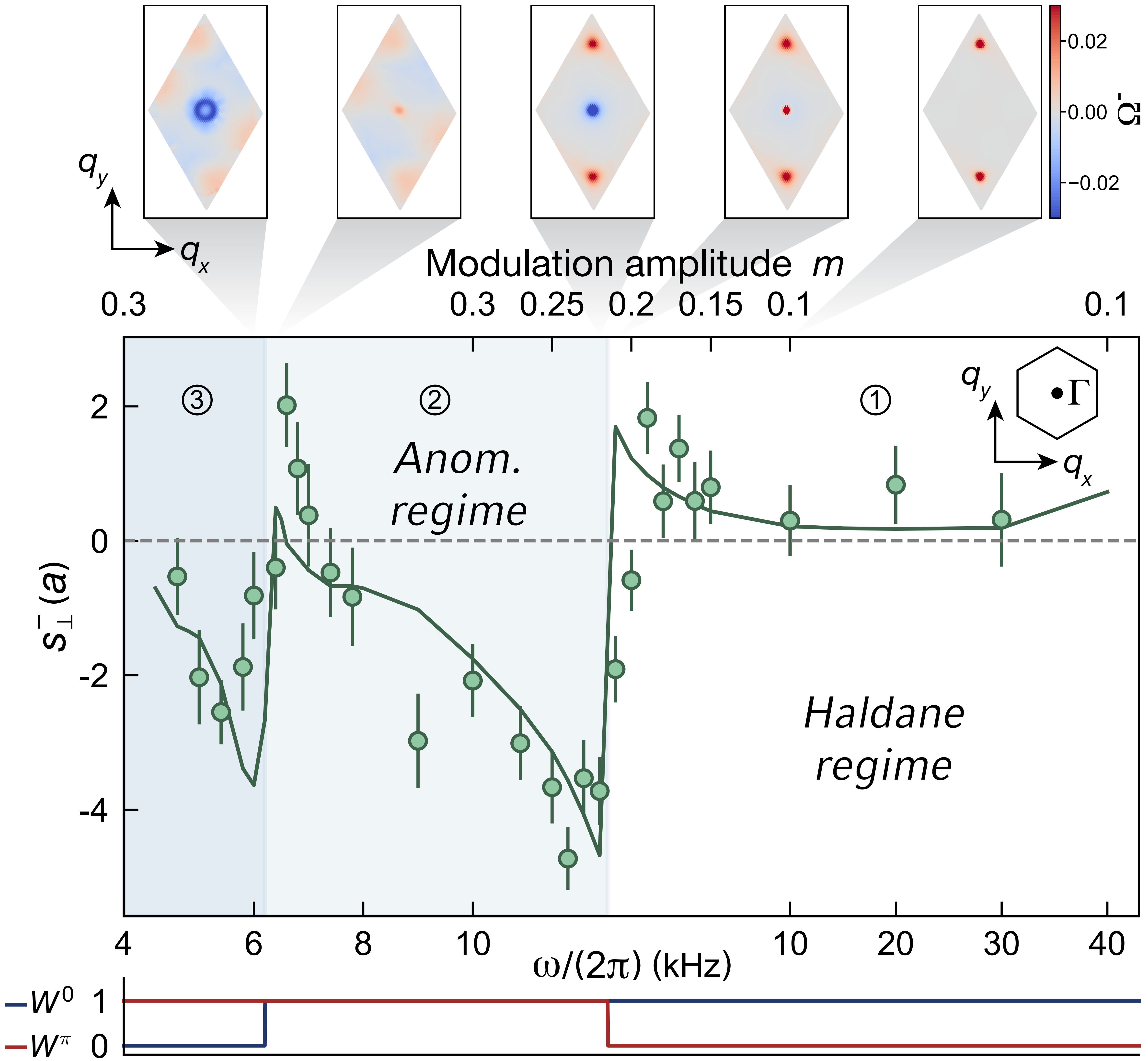


$$Q^0_s = \mathrm{sgn}\left(\Delta s^-_\perp(\mathbf{q}_s)\right)$$

F. Nathan et al, New J. Phys. 17, 125014 (2015); N. Ünal et al., PRL 122, 253601 (2019)

Berry curvature from local Hall deflection

$\mathbf{\Gamma}$-point:

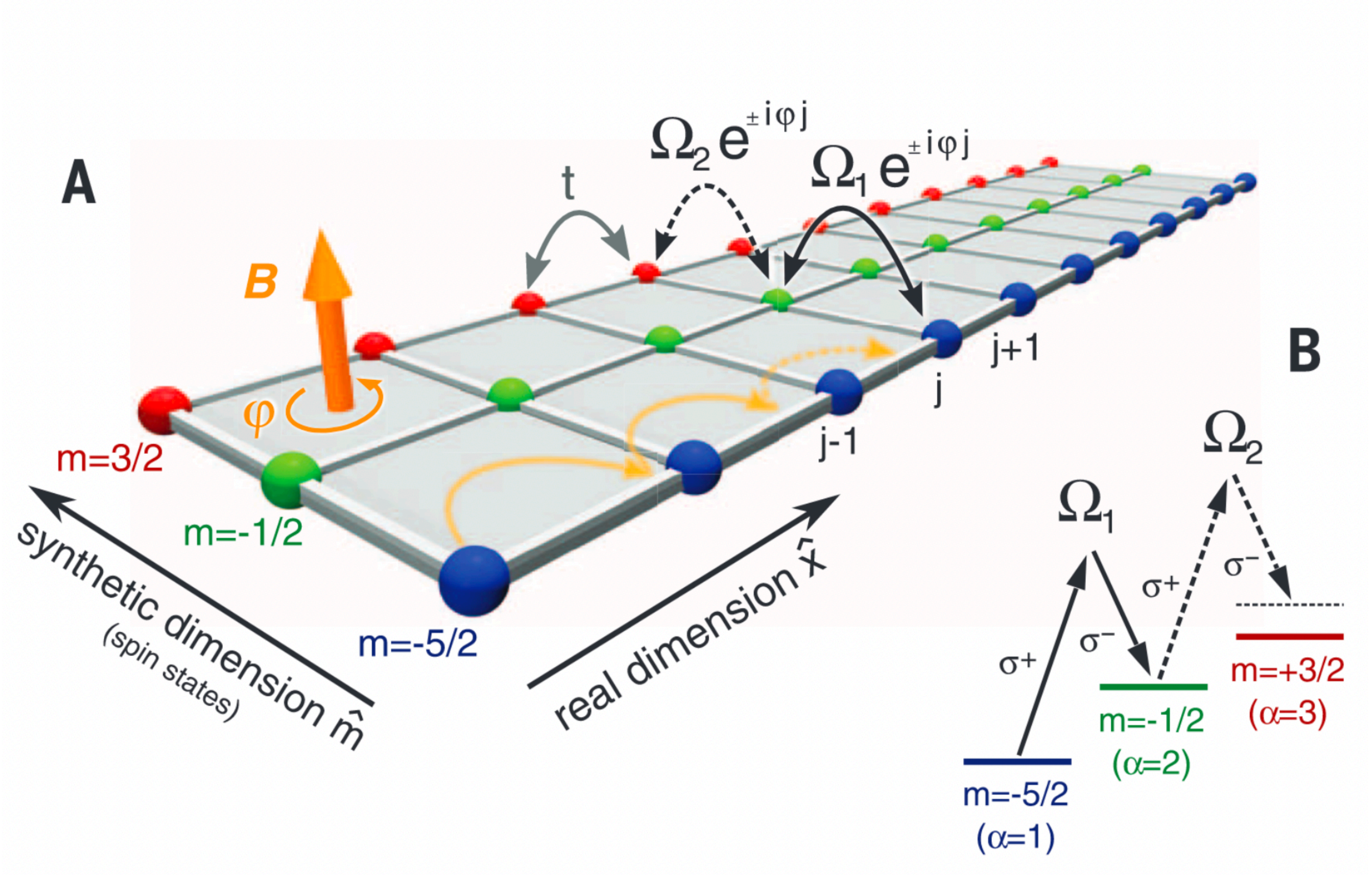


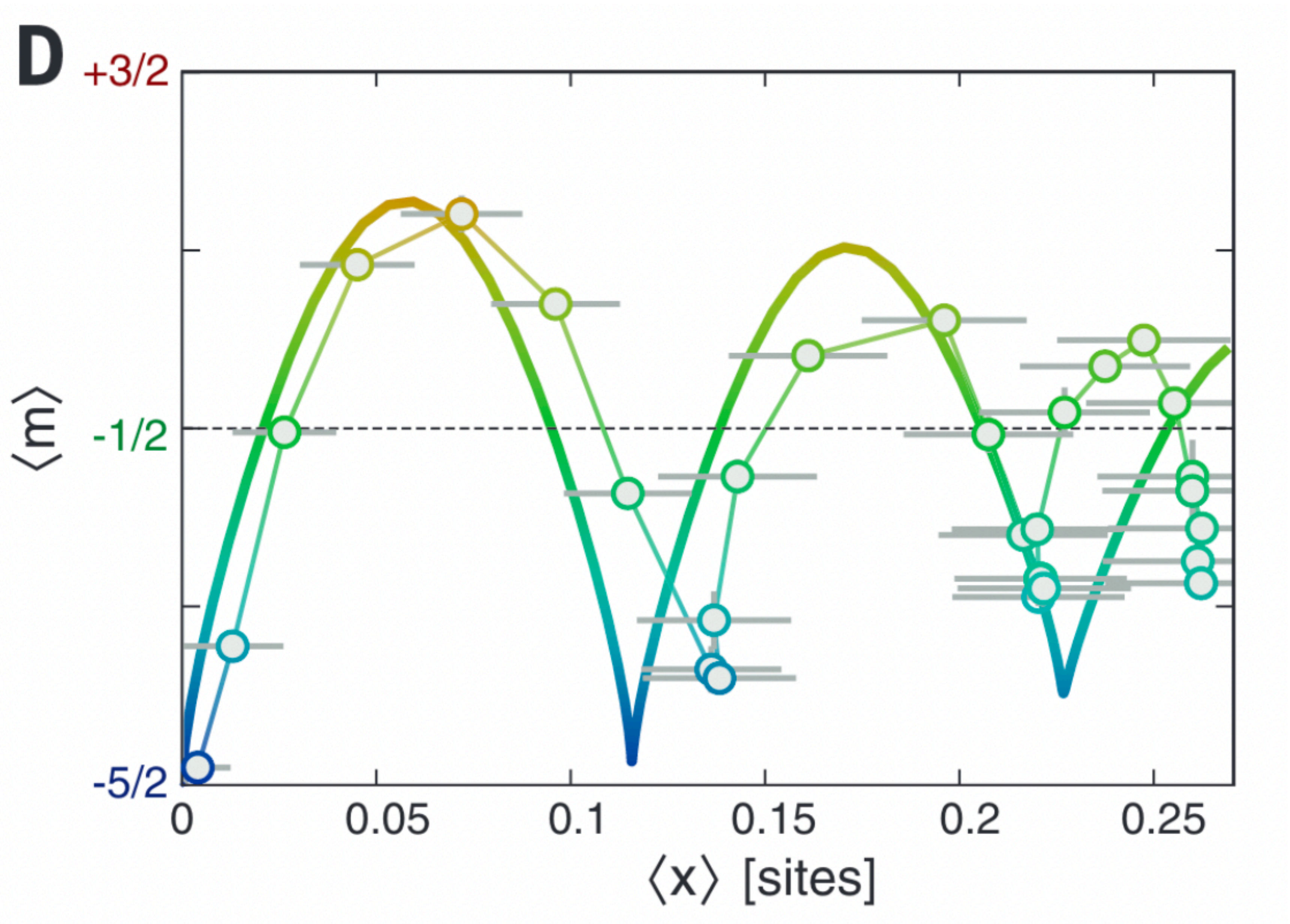
Complete set of topological invariants!

K. Wintersperger, …., M.A.,
Nature Phys. **16**, 1058 (2020)

Can we observe topological edge modes?

Synthetic dimensions





Mancini, ..., Fallani, Science **349** (2015)
Stuhl, ..., Spielman, Science **349** (2015)

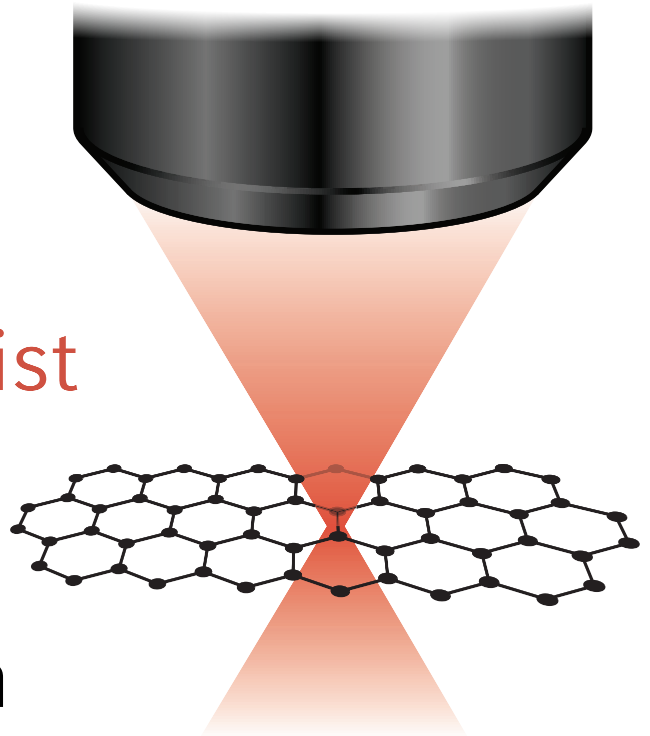
See also: Chalopin, ..., Nascimbène, Nature Physics (2020)

Edge dynamics

Realizing a sharp edge:

NA=0.5

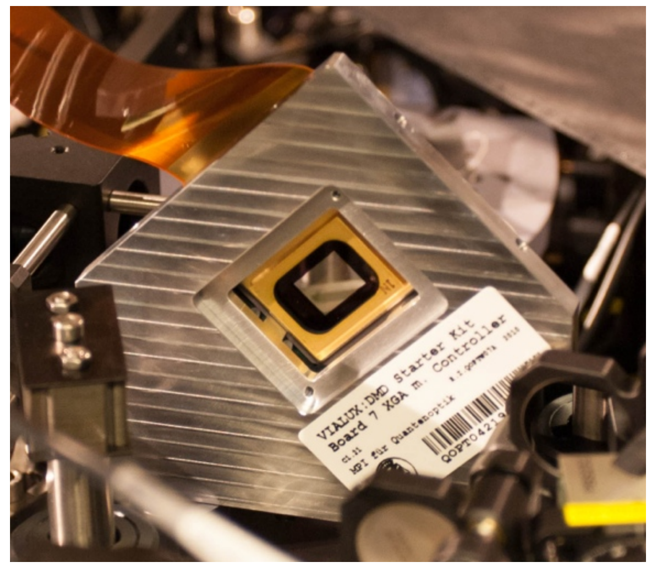
1064nm
~1.1μm waist



a=287nm

+

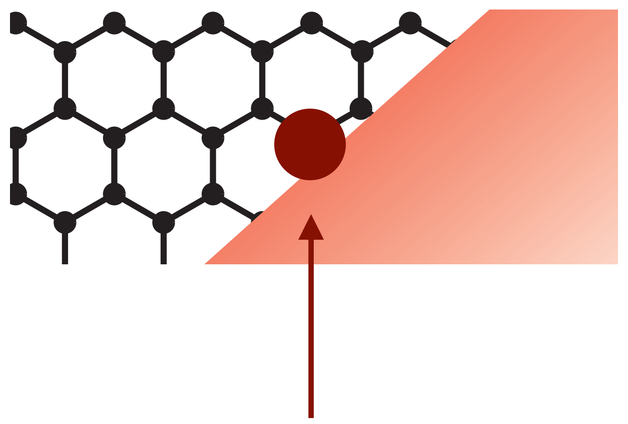
DMD



638nm light (repulsive)

=

edge



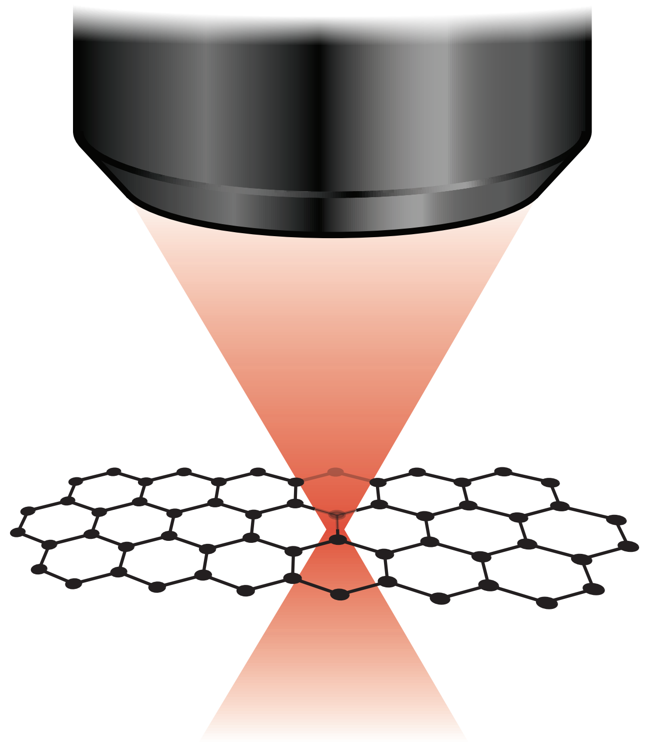
loc. wavepacket

Width of the edge: 2-3 lattice sites!

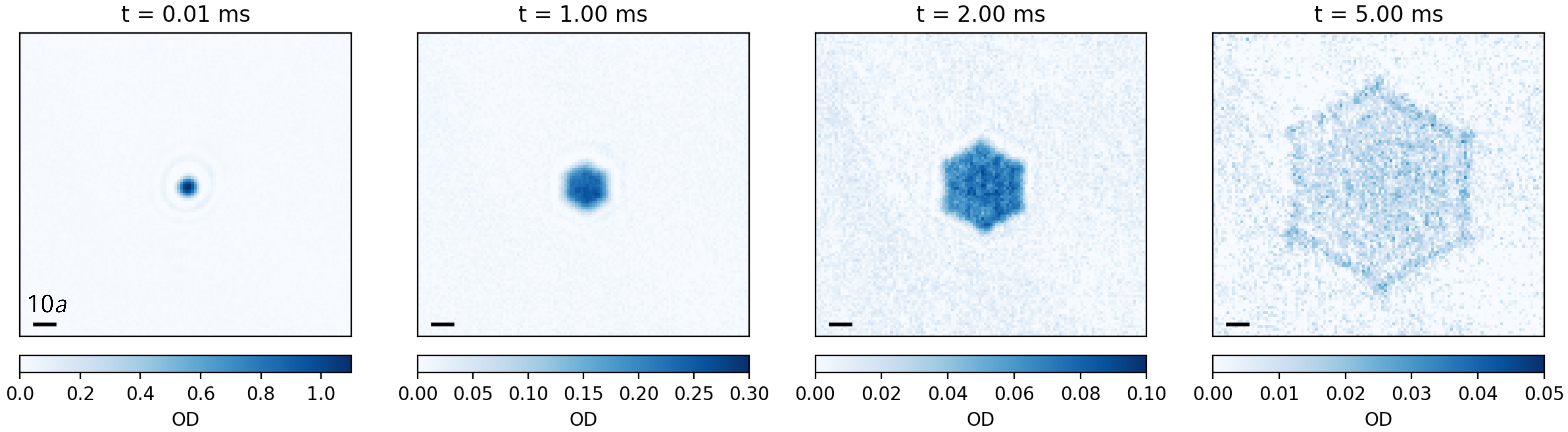
Preliminary!

Bulk expansion

Lattice depth: 6Er; λ=745nm;
$\omega_r = 2\pi \times 17\text{Hz}$; $\omega_z = 2\pi \times 250\text{Hz}$



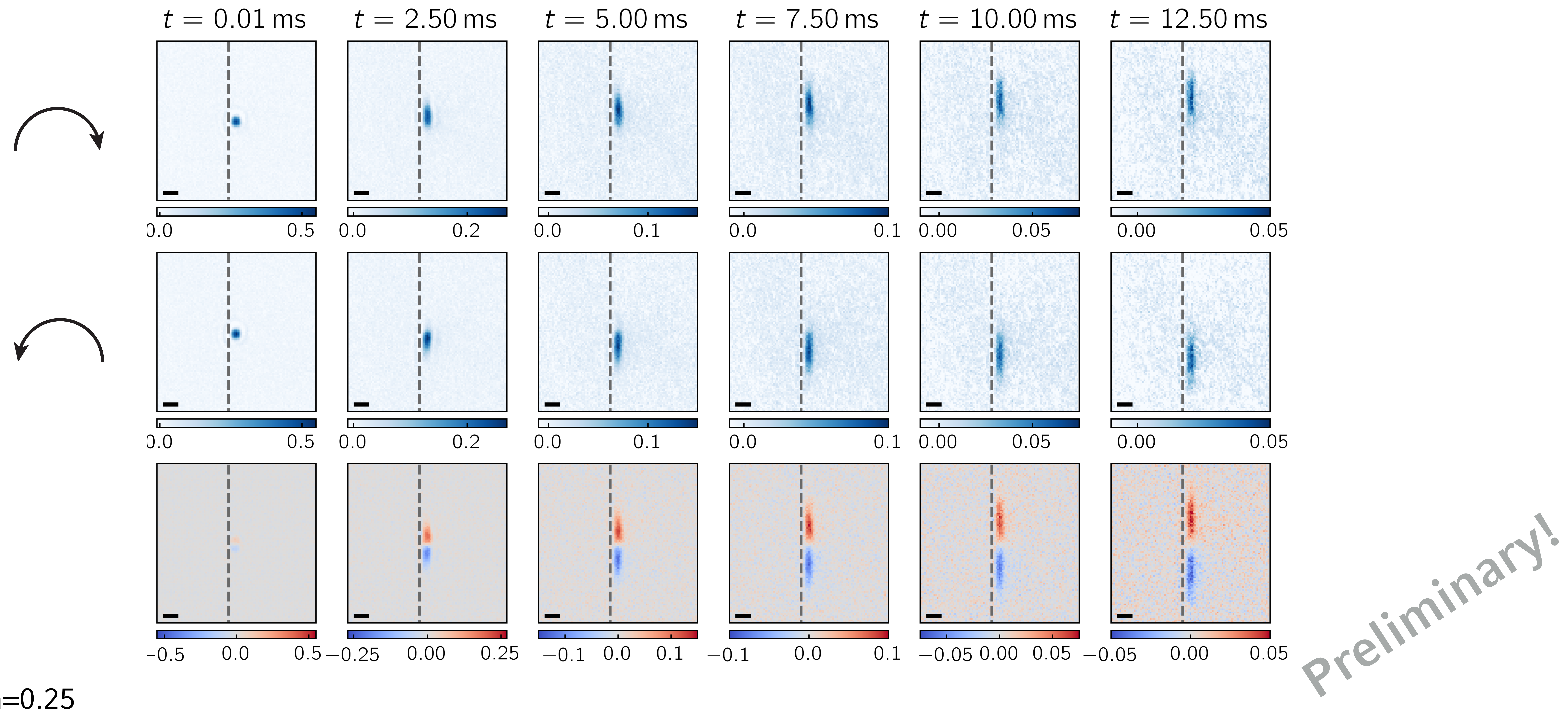
$$\mathbf{v}_\mu^{\text{band}} = \frac{1}{\hbar}\partial_{\mathbf{q}} E_\mu$$



U. Schneider et al., Nature Phys. **8**, 213 - 218 (2012); J. P. Ronzheimer et al., Phys. Rev. Lett. **110**, 205301 (2013)

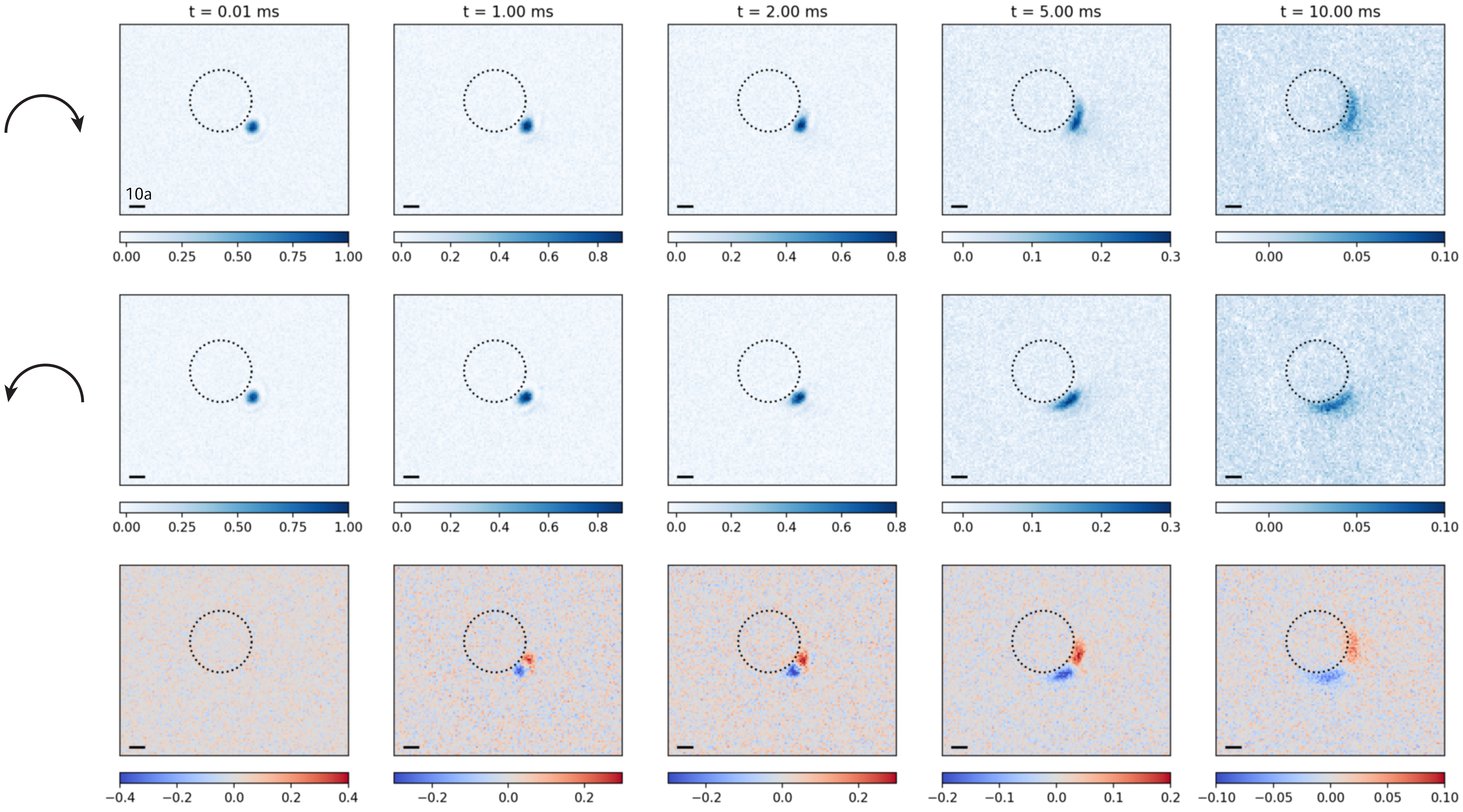
Preliminary!

Edge dynamics in anomalous regime



f=7kHz, m=0.25

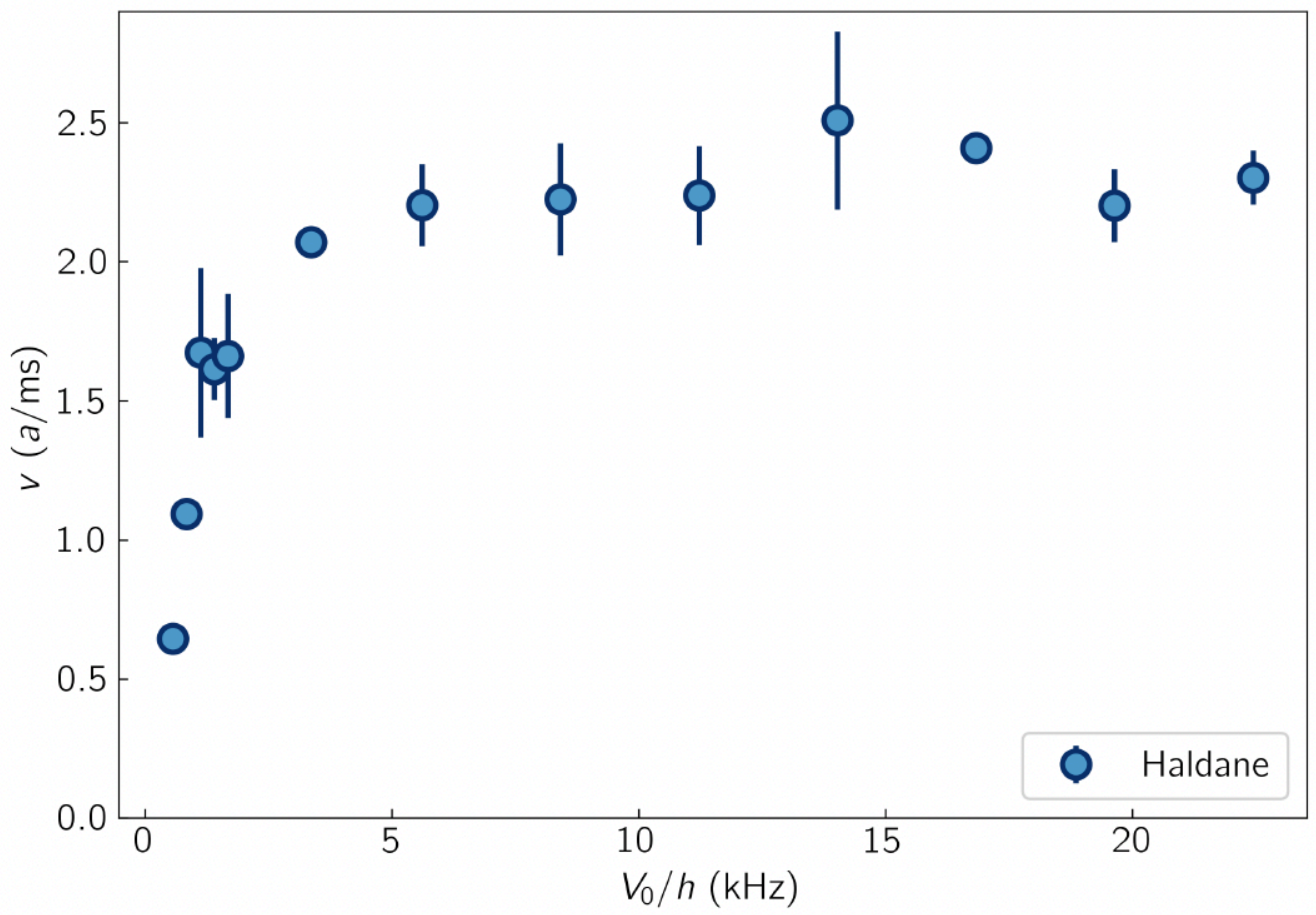
Edge dynamics in anomalous regime



f=7kHz, m=0.25

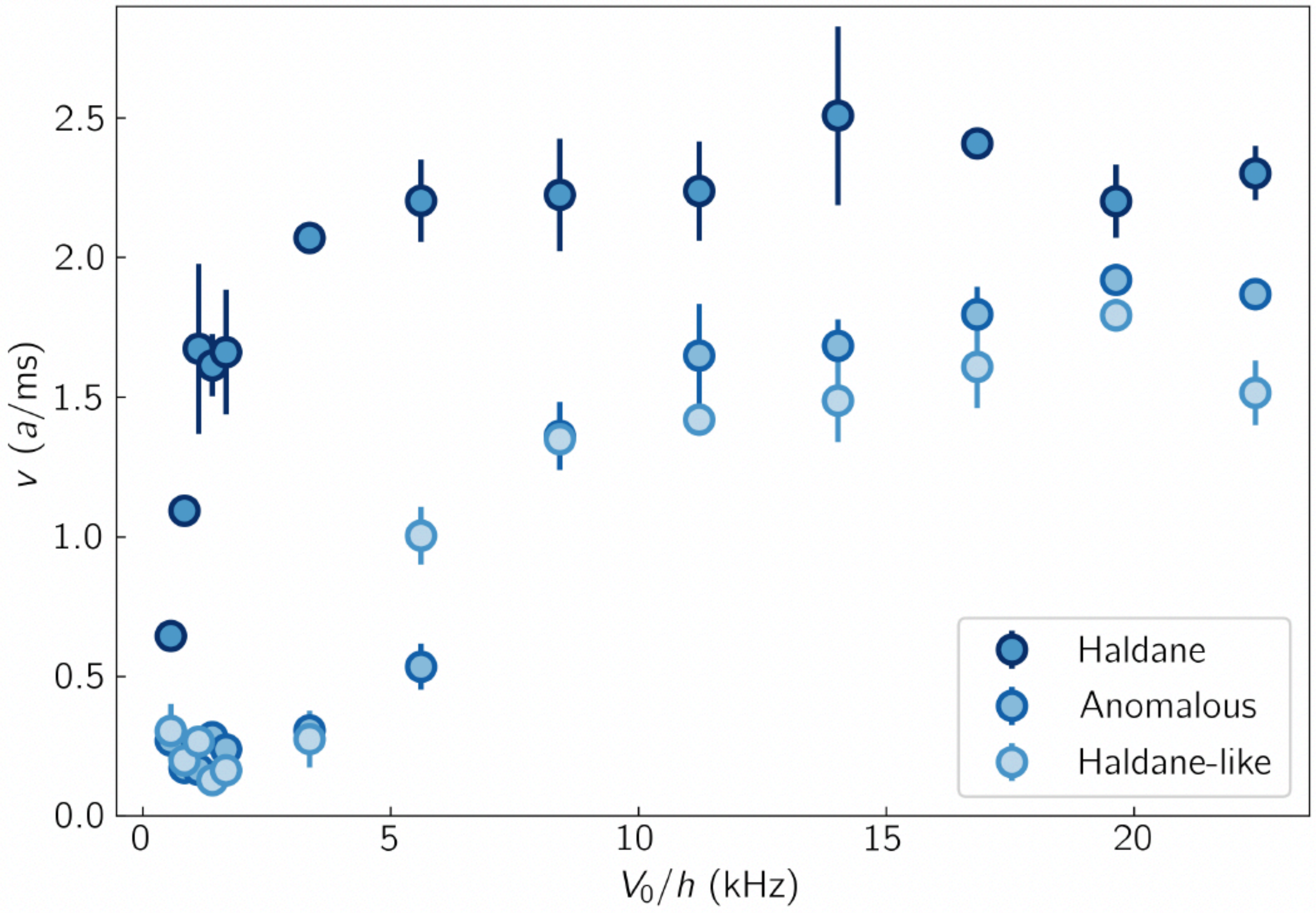
Preliminary!

Generating a topological interface



Preliminary!

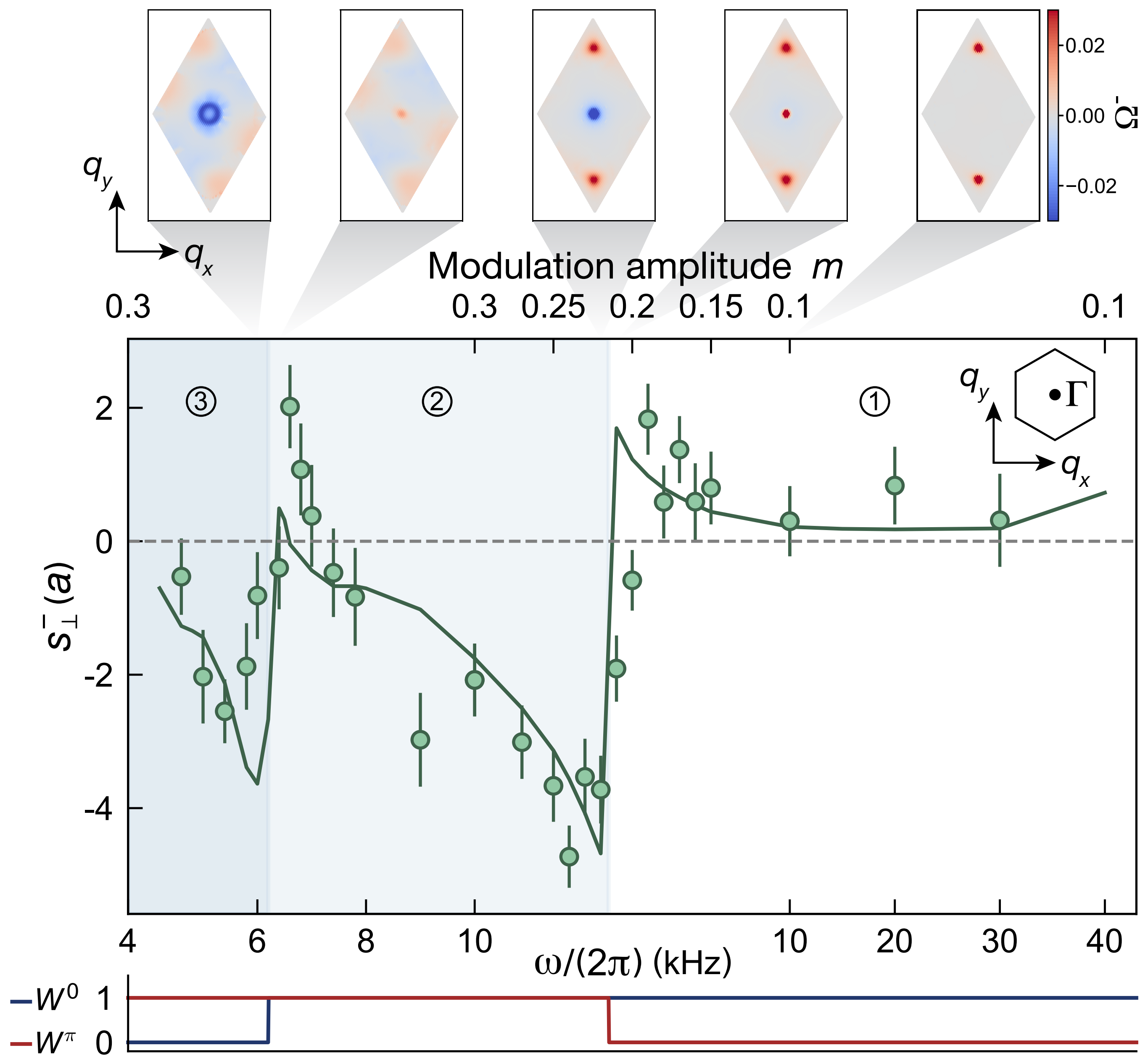
Generating a topological interface



Preliminary!

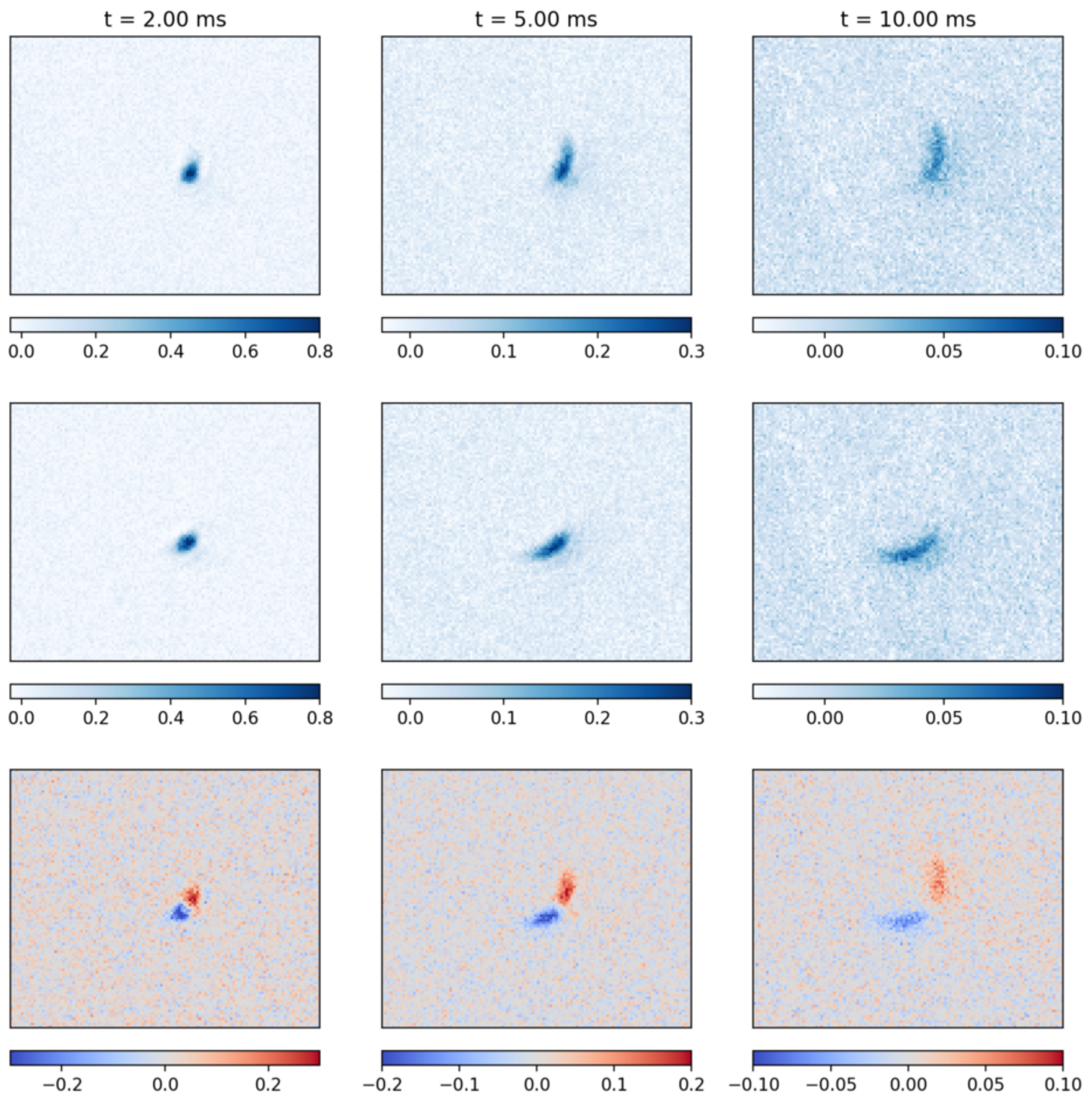
Summary

Bulk



K. Wintersperger, ..., MA,
Nature Phys. **16**, 1058-1063 (2020)

Edge

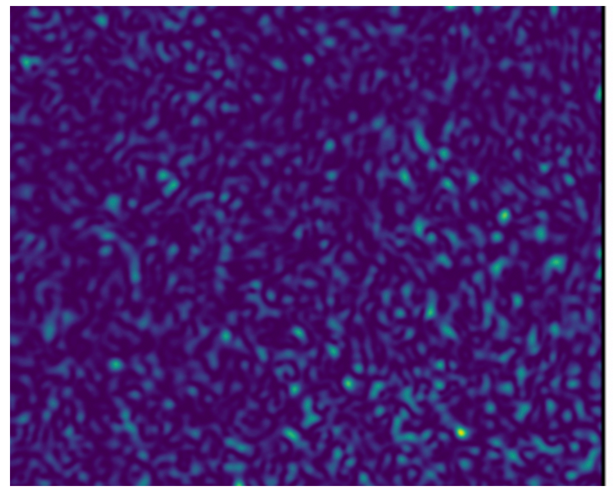


Preliminary!

Outlook

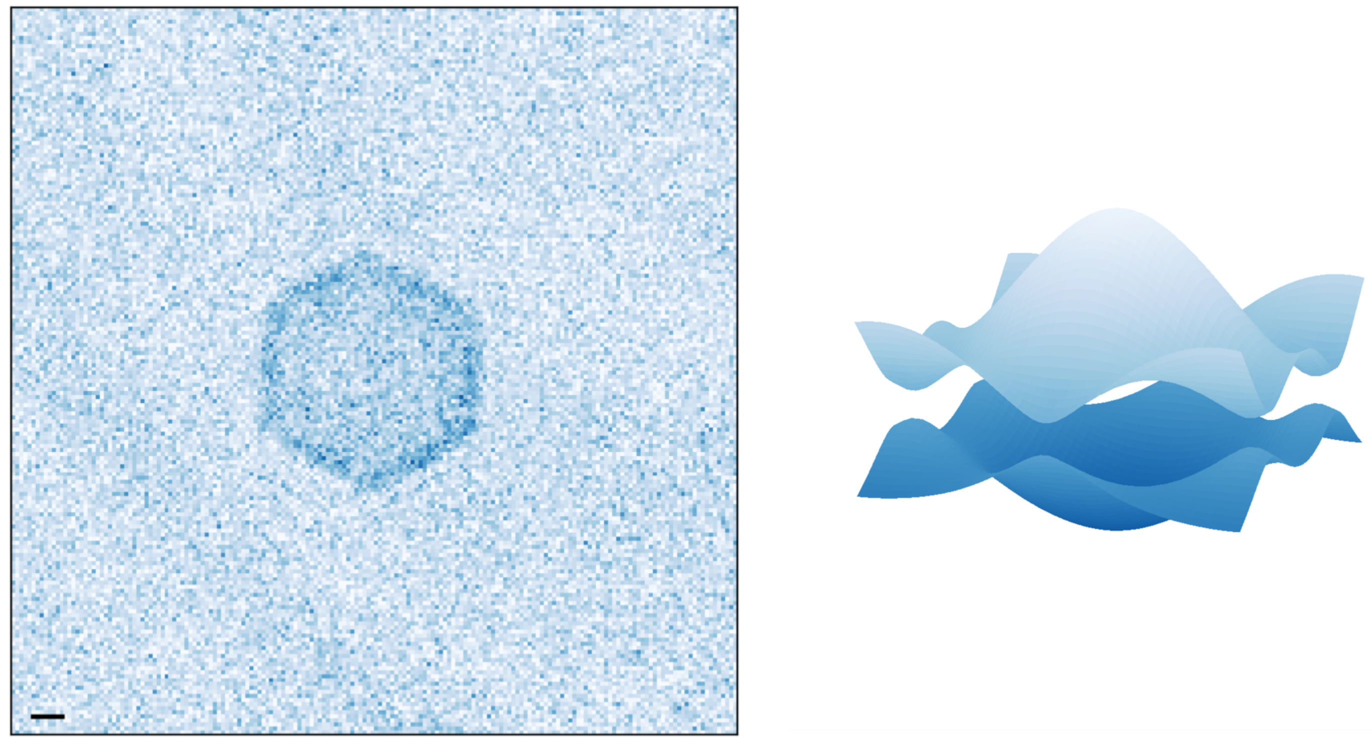
Outlook:

- Interplay of topology & disorder
- Realization of many-body top. phases

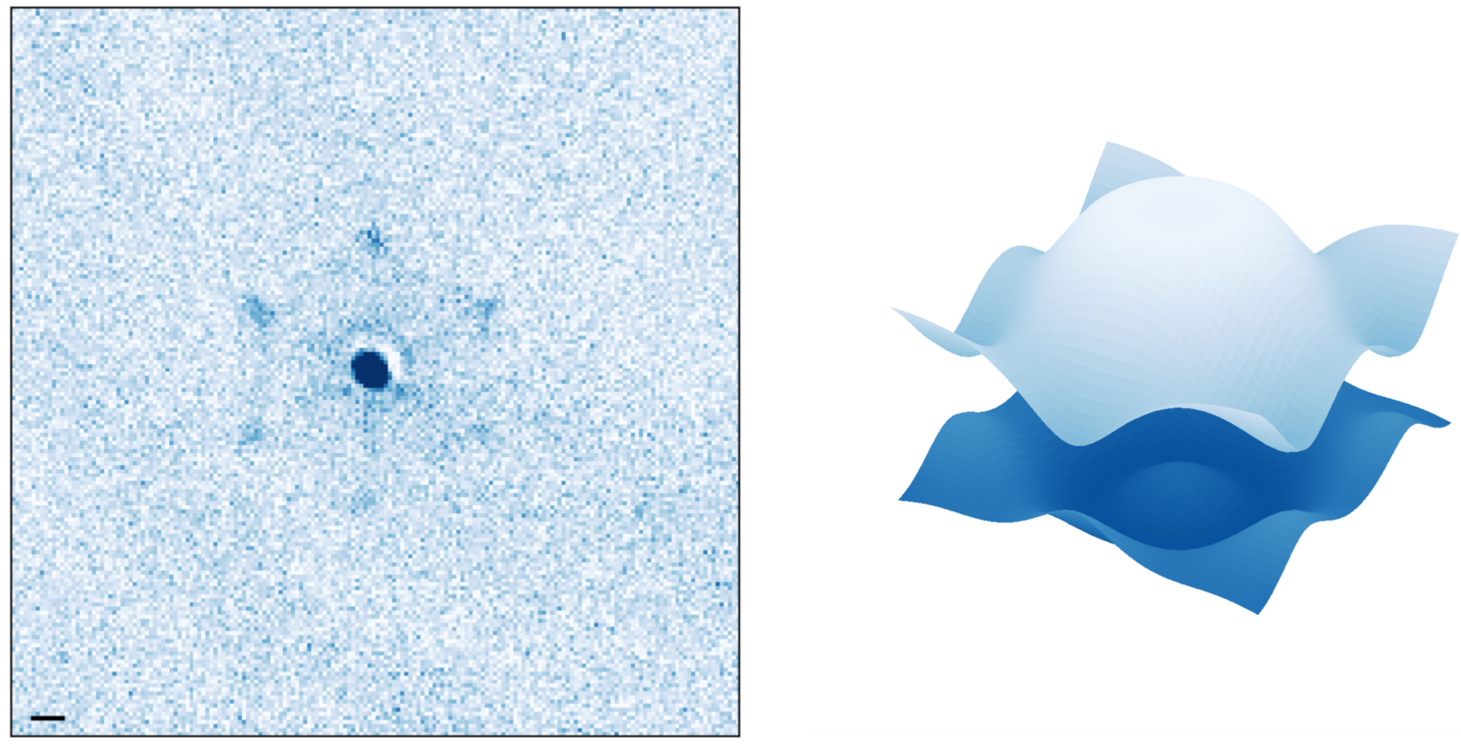


Bulk expansion in the modulated lattice: $\mathbf{v}_\mu^{\text{band}} = \frac{1}{\hbar}\partial_{\mathbf{q}} E_\mu$

Haldane:



Anomalous:



C. A. Bracamontes et al.
Phys. Rev. Lett. **128** (2022)

Preliminary!

The team

Experiment

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Karen Wintersperger,
Alexander Hesse
Raphaël Saint-Jalm
Immanuel Bloch

Theory anomalous Floquet top. systems

- Nur Ünal (Cambridge, UK)
- André Eckardt (TU Berlin)
- Nathan Goldman (ULB Brussels)
- Marco Di Liberto (U of Padova)

K. Wintersperger, …., M.A., Nature Phys. **16**, 1058-1063 (2020); Ch. Braun et al. (in preparation)