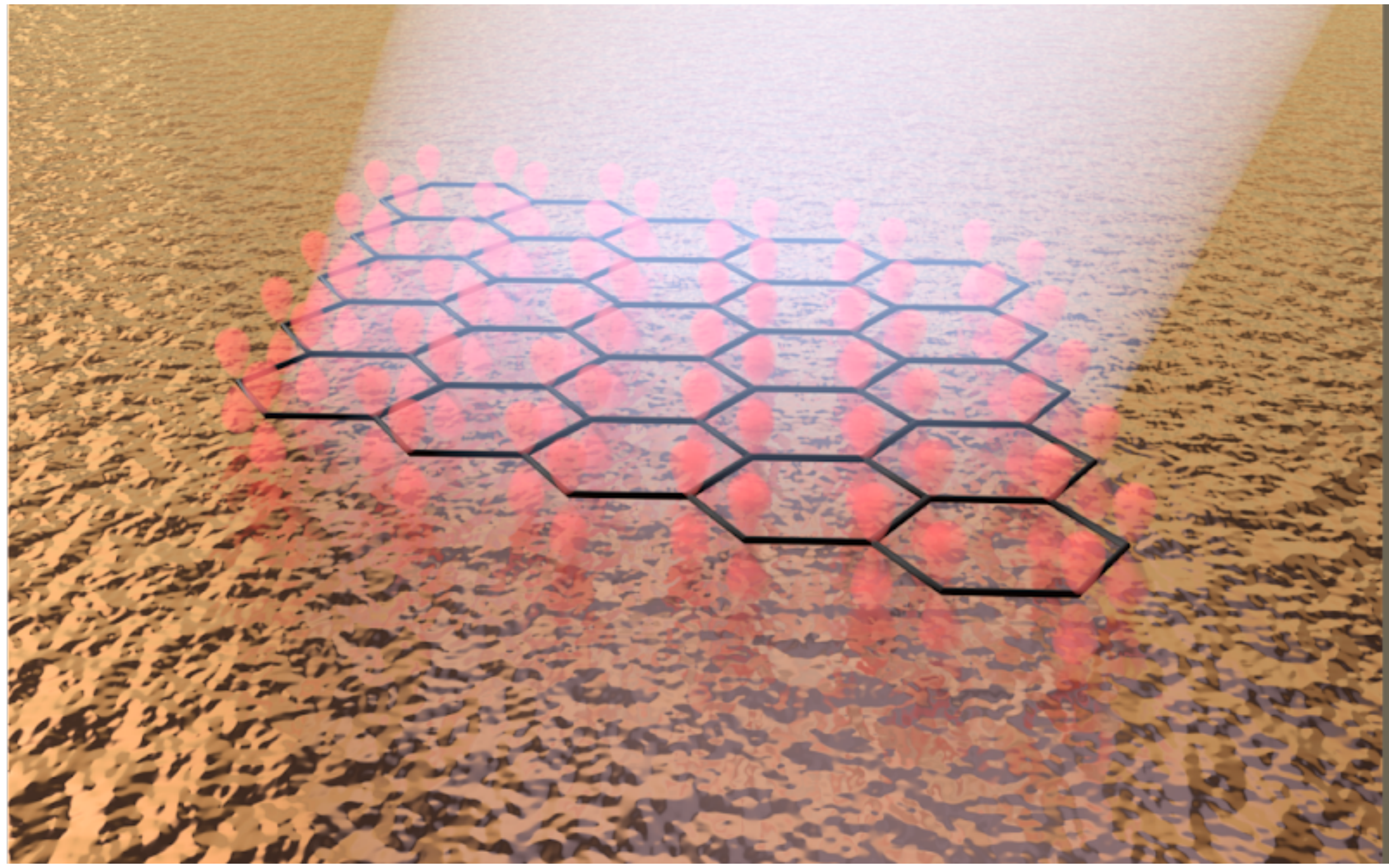
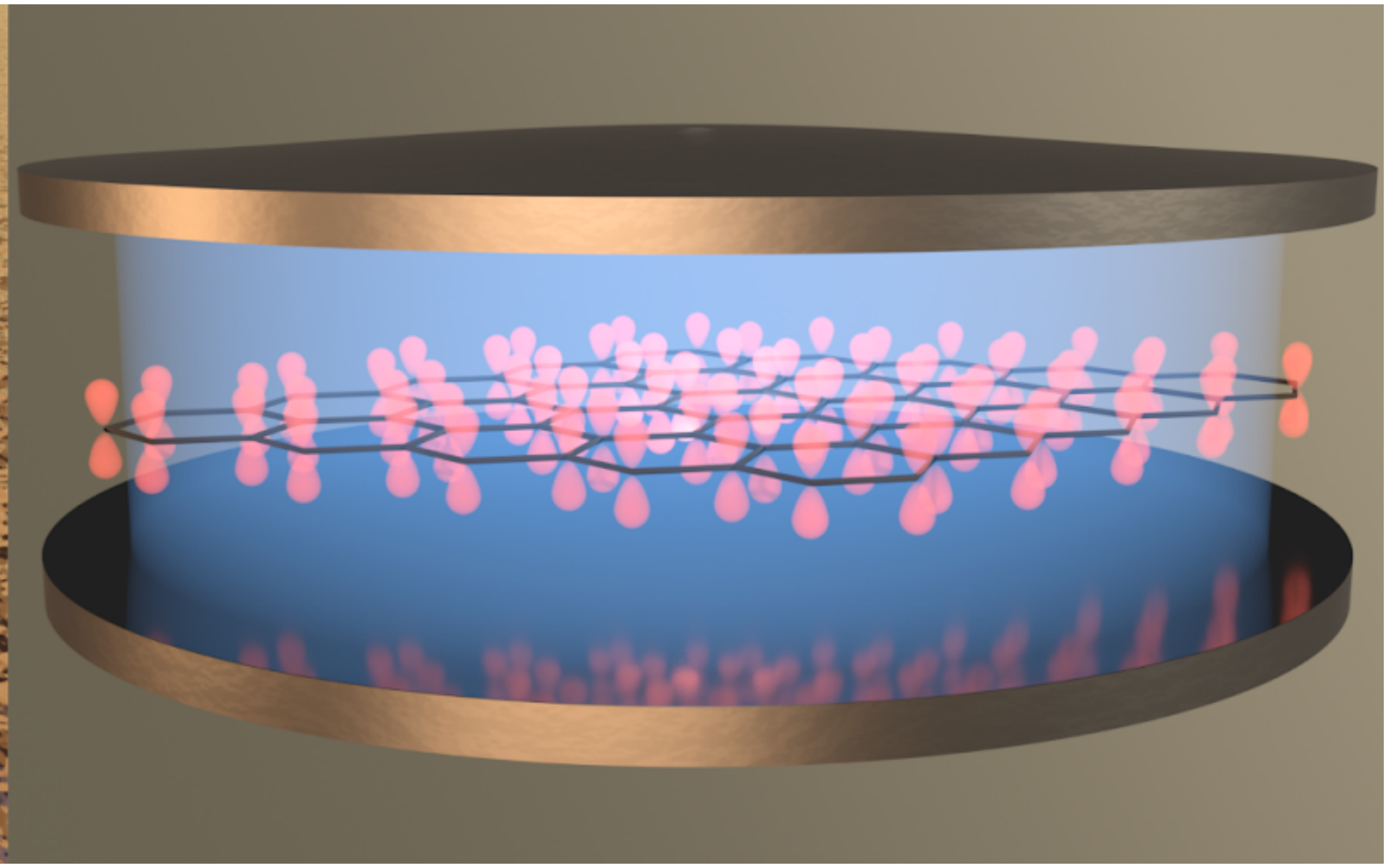
Light-matter engineering of topology in quantum materials





Colloquium: Nonthermal pathways to ultrafast control in quantum materials,
A. de la Torre, D. M. Kennes, M. Claassen, S. Gerber, J. McIver, MAS,
Rev. Mod. Phys. 93, 041002 (2021)

Cavity Quantum Materials,
F. Schlawin, D. M. Kennes, MAS,
Applied Physics Reviews 9, 011312 (2022)

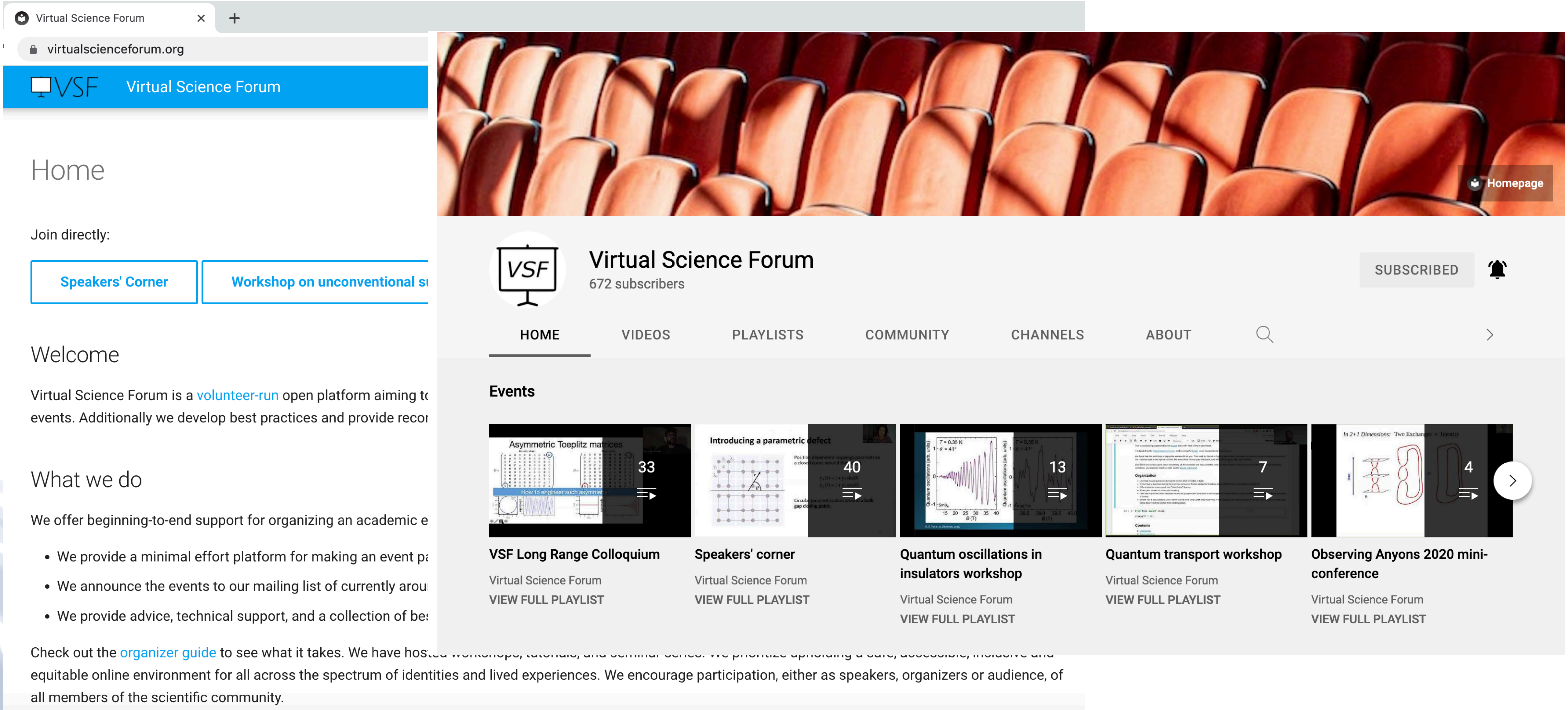
Michael A. Sentef

QDev Summer School
Copenhagen, July 7-8 , 2022

Emmy Noether-Programm
Deutsche Forschungsgemeinschaft DFG
DFG
Funded through DFG Emmy Noether programme (SE 2558/2)

Notes for these lectures: cf. https://lab.sentef.org/teaching/

Before I start …



Outline of lectures

1 - Intro

Pump-probe spectroscopy
Floquet theory in a nutshell
Dirac fermion with circularly polarized laser
Floquet topology across platforms
Floquet sidebands in time-resolved photoemission
Light-induced anomalous Hall effect

Exercise 1— Gap opening in circularly driven Dirac fermions I: Discrete time evolution

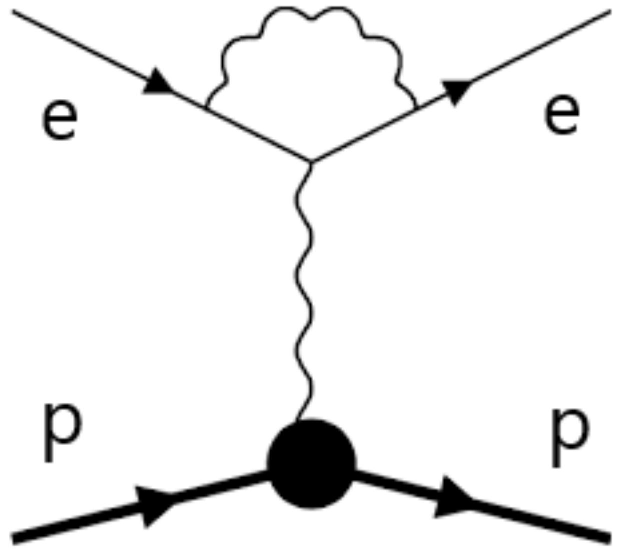
2 - Floquet concepts

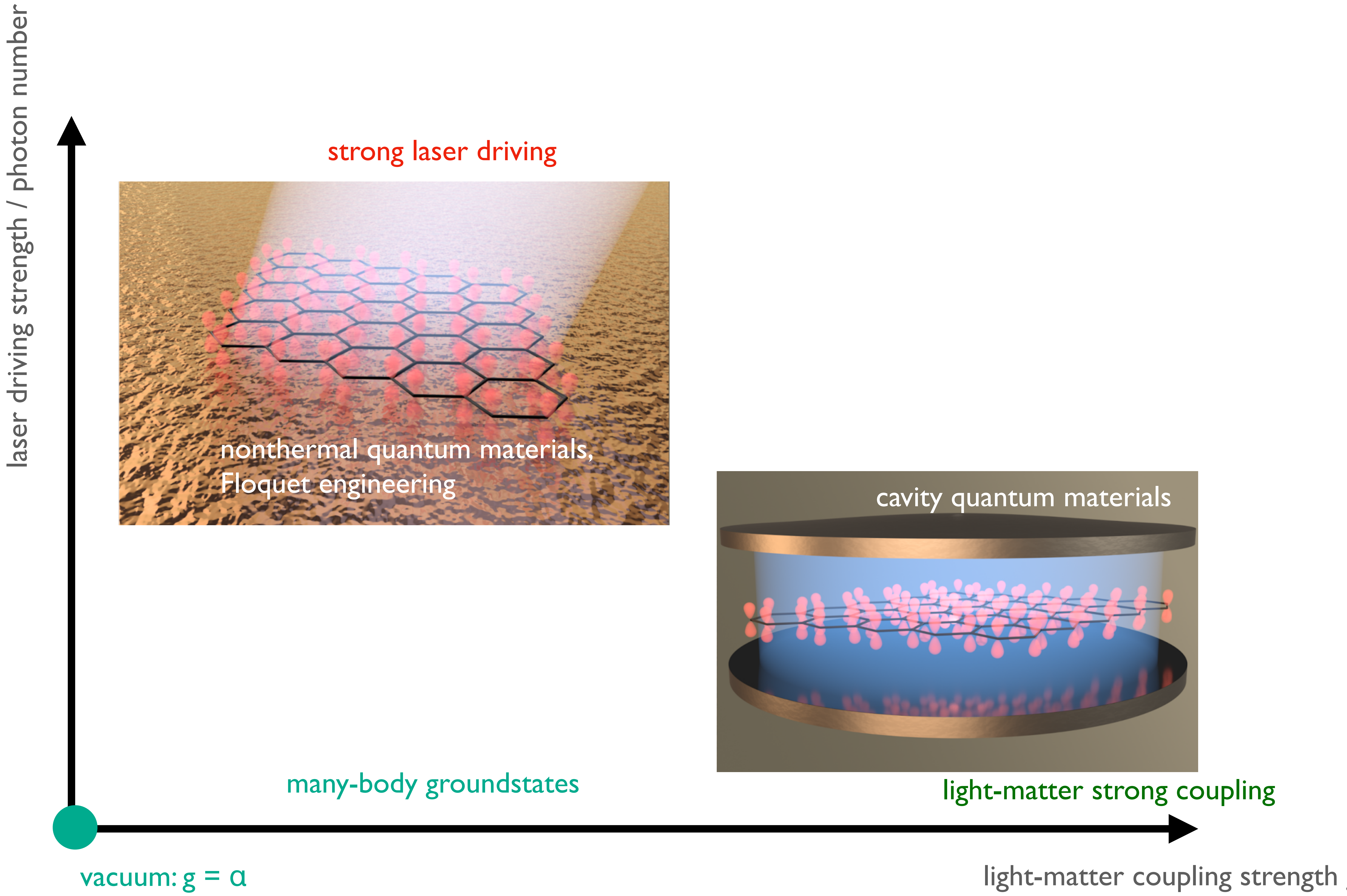
Exercise 2— Gap opening in circularly driven Dirac fermions II: Floquet

3 - From Floquet to cavity

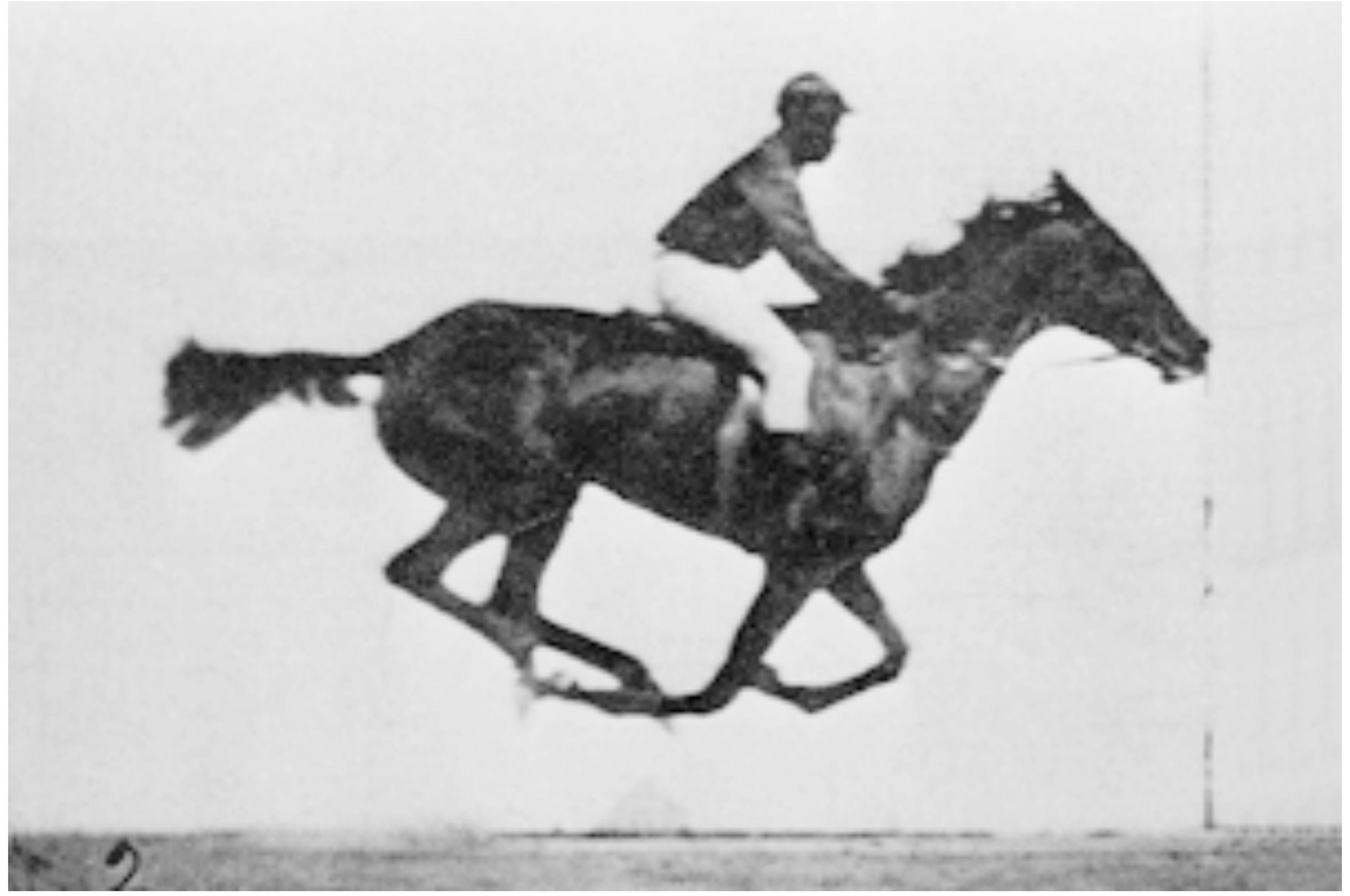
Can we employ light-matter interactions to change materials properties?

$$\alpha = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{\hbar c} = \frac{\mu_0}{4\pi}\frac{e^2 c}{\hbar} = \frac{k_e e^2}{\hbar c} = \frac{e^2}{2\varepsilon_0 ch} = \frac{c\mu_0}{2R_K} = \frac{e^2 Z_0}{2h} = \frac{e^2 Z_0}{4\pi\hbar}$$

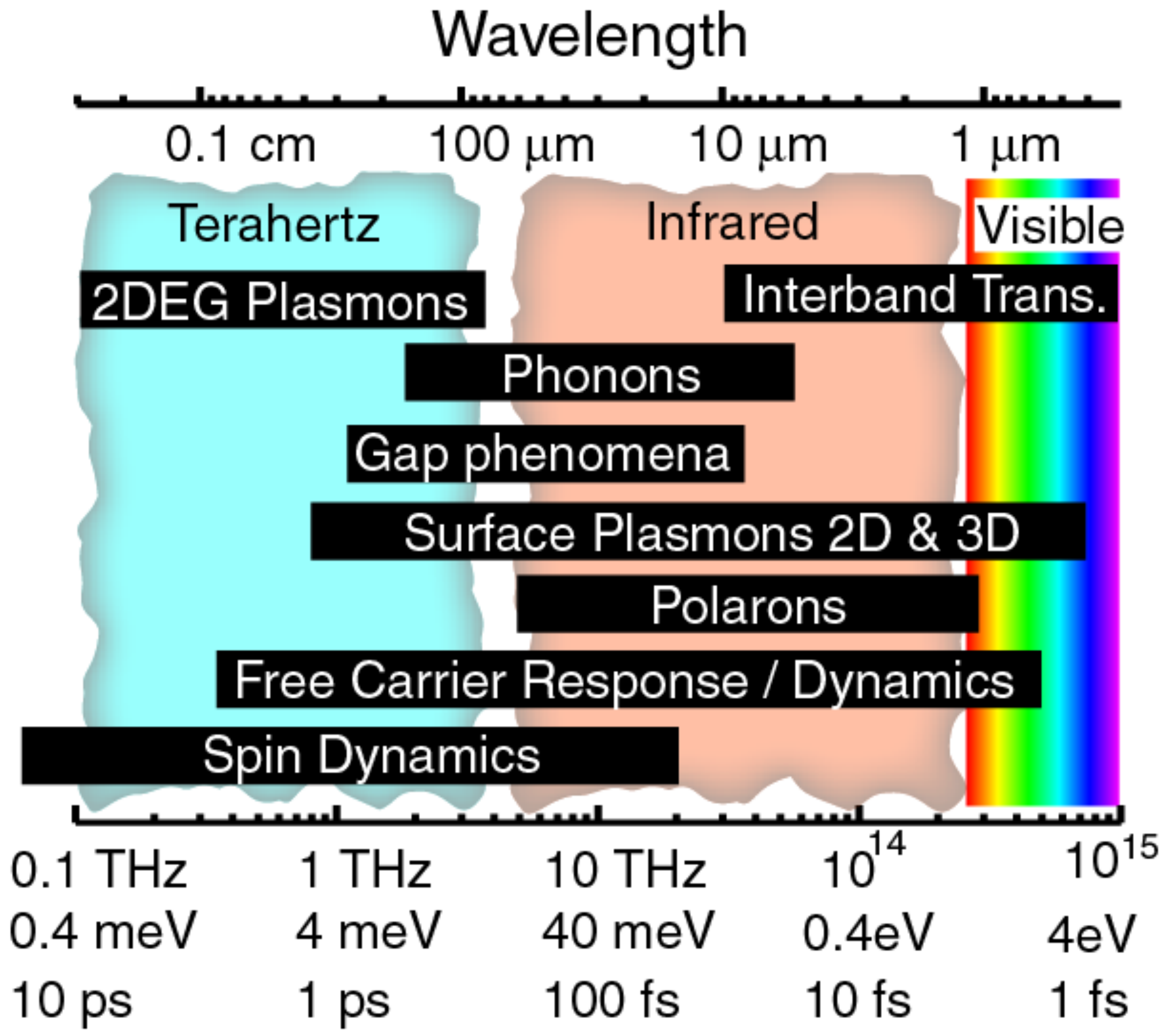




Stroboscopic investigations of dynamic phenomena



Muybridge 1887



employ time-resolved pump-probe spectroscopy to investigate dynamic phenomena on their intrinsic time and energy scales

Stroboscopic investigations of dynamic phenomena

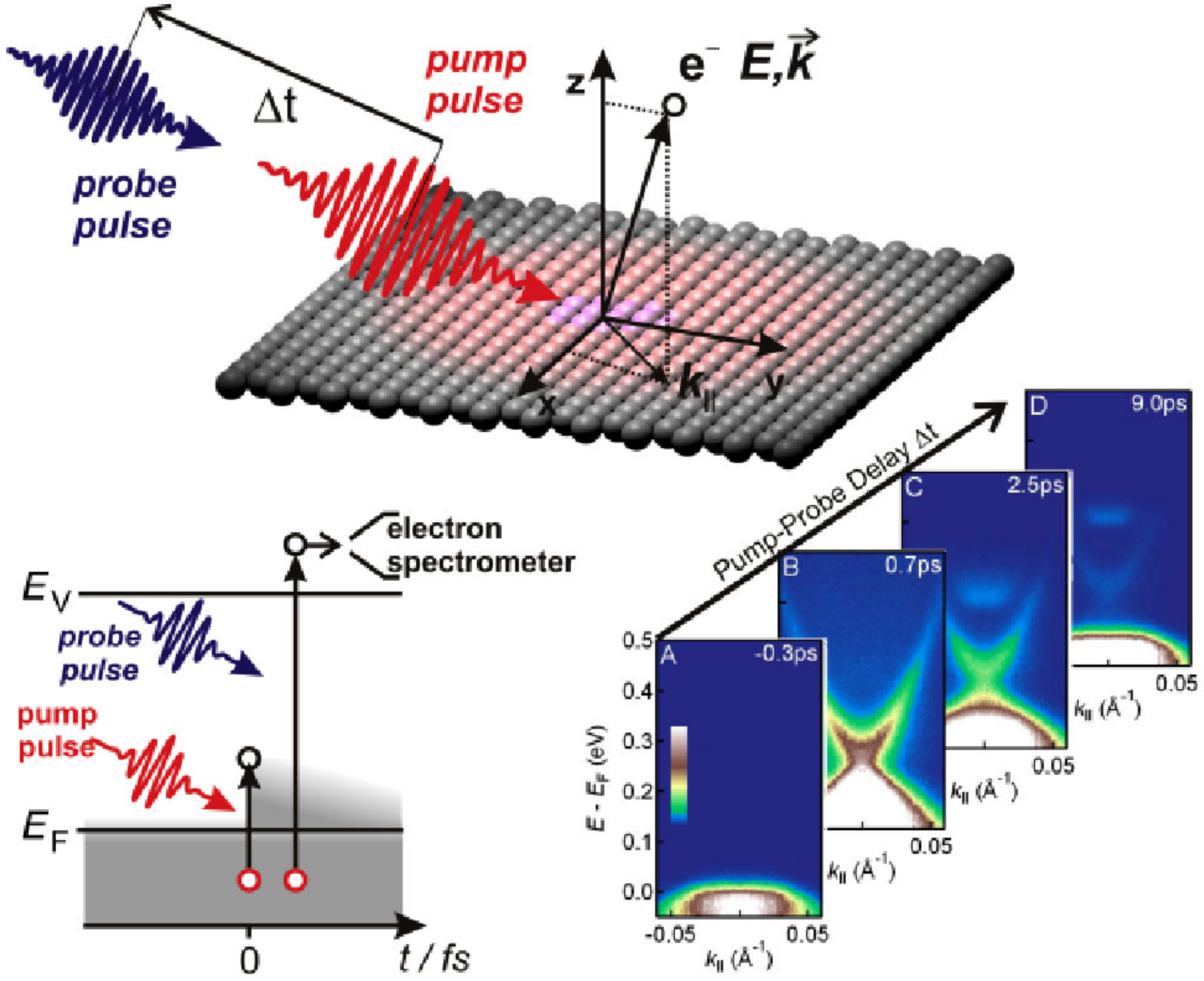
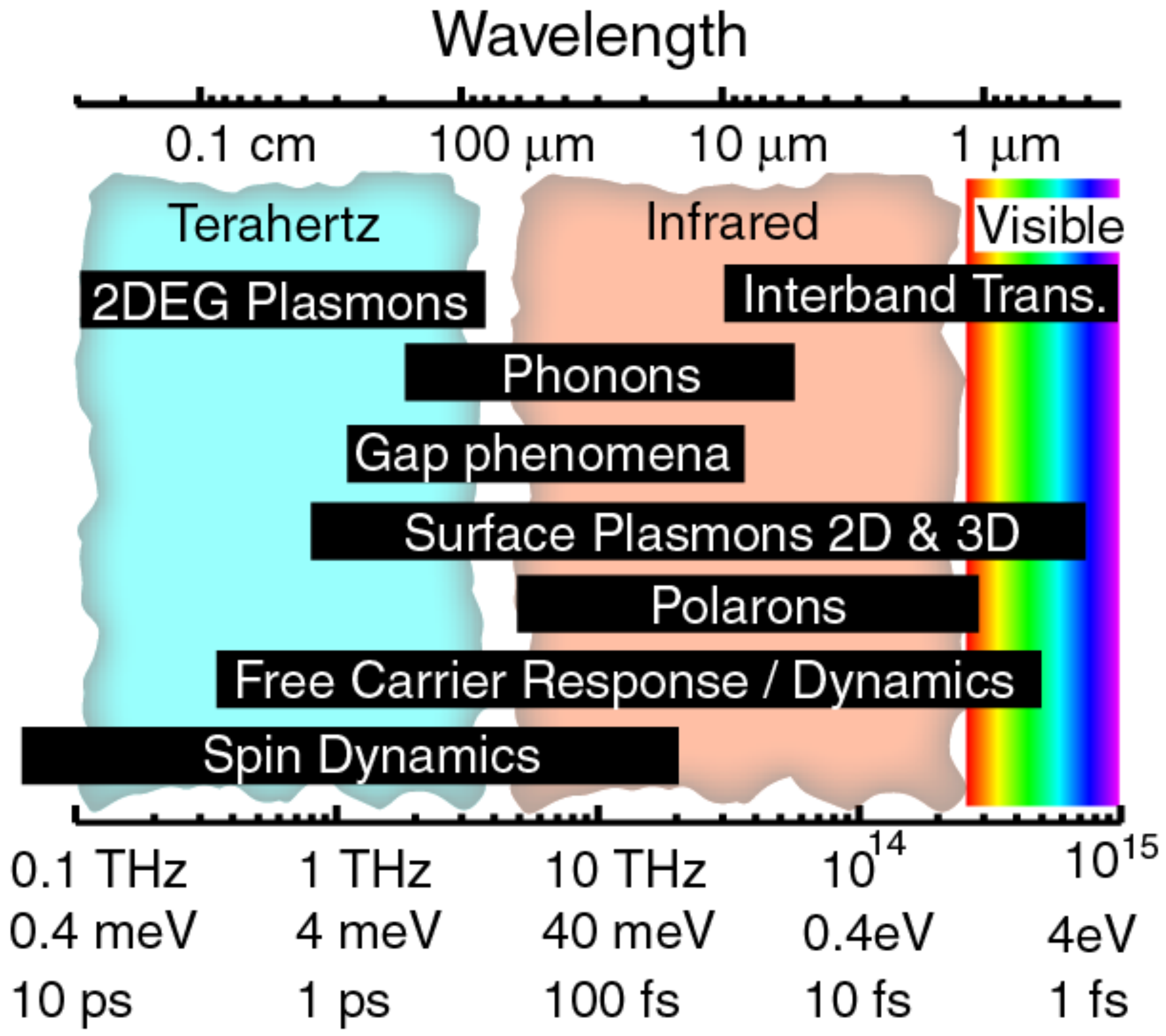


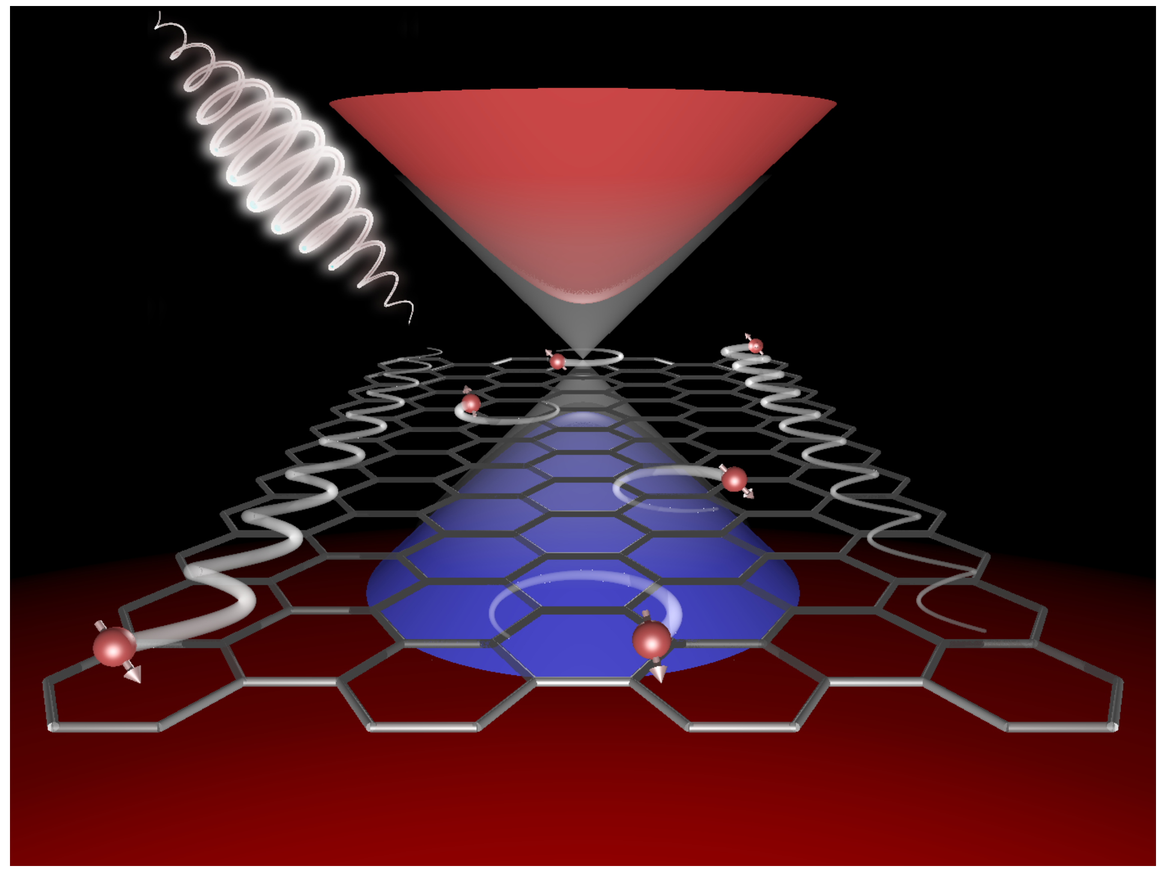
Image source: FHI Berlin



employ time-resolved pump-probe spectroscopy to investigate dynamic phenomena on their intrinsic time and energy scales

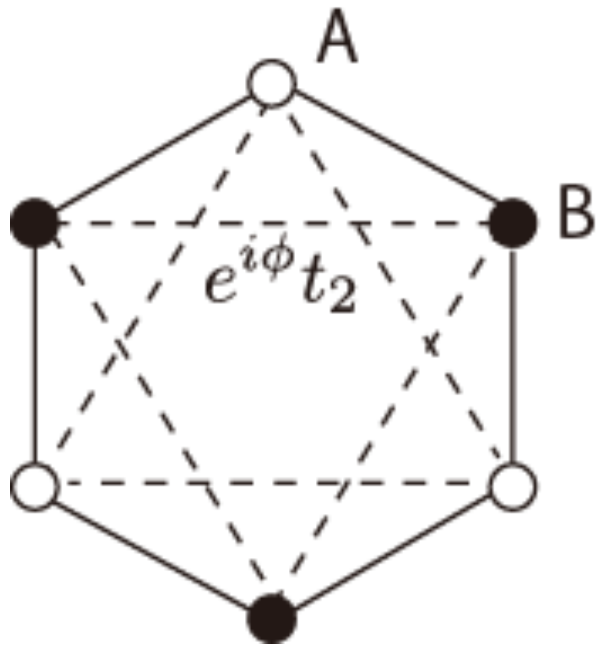
Can one engineer the Haldane model dynamically?

Graphene + circularly polarized light (breaks trs)



?

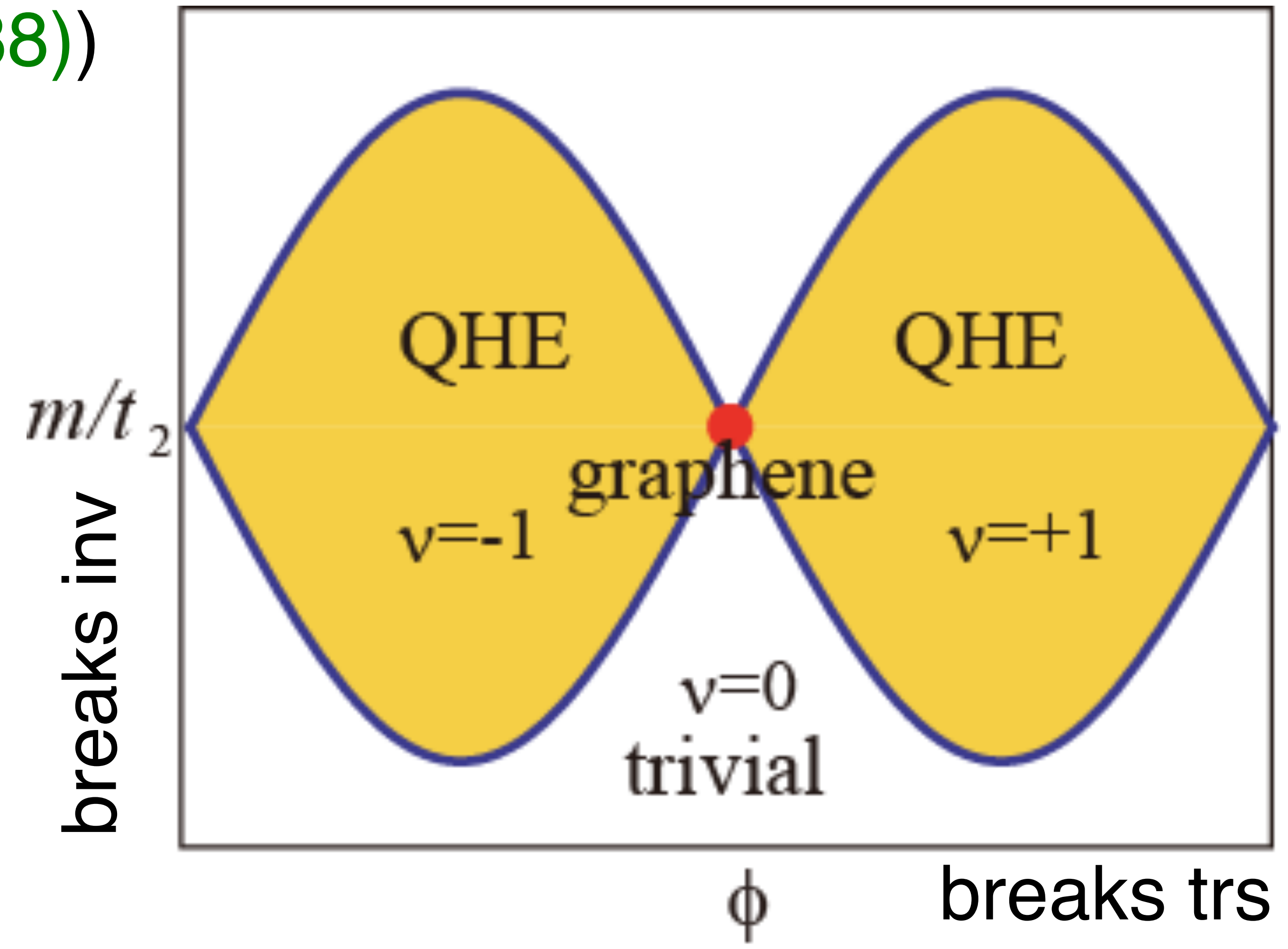
Haldane model (PRL 61, 2015 (1988))

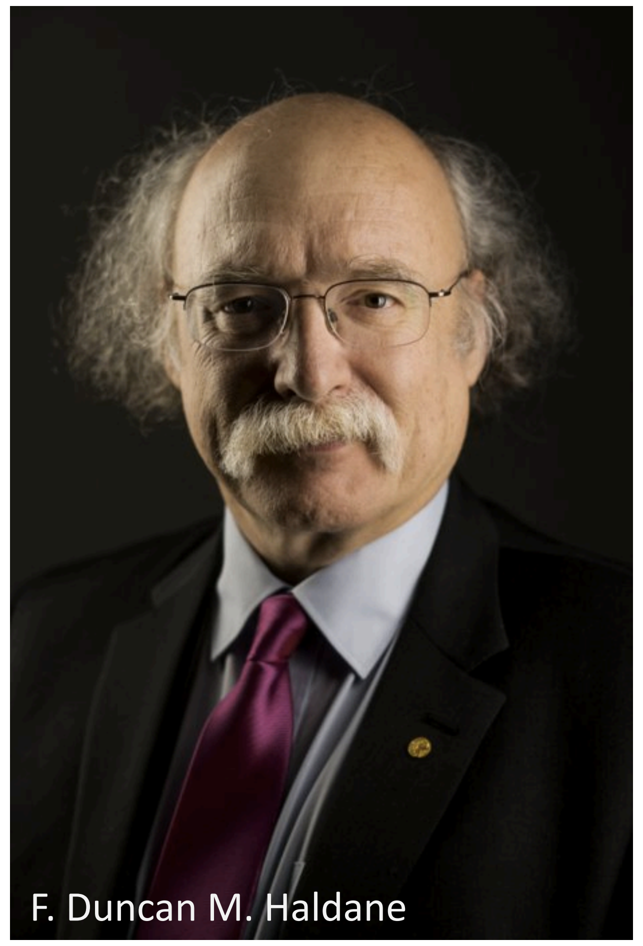


Local flux ϕ

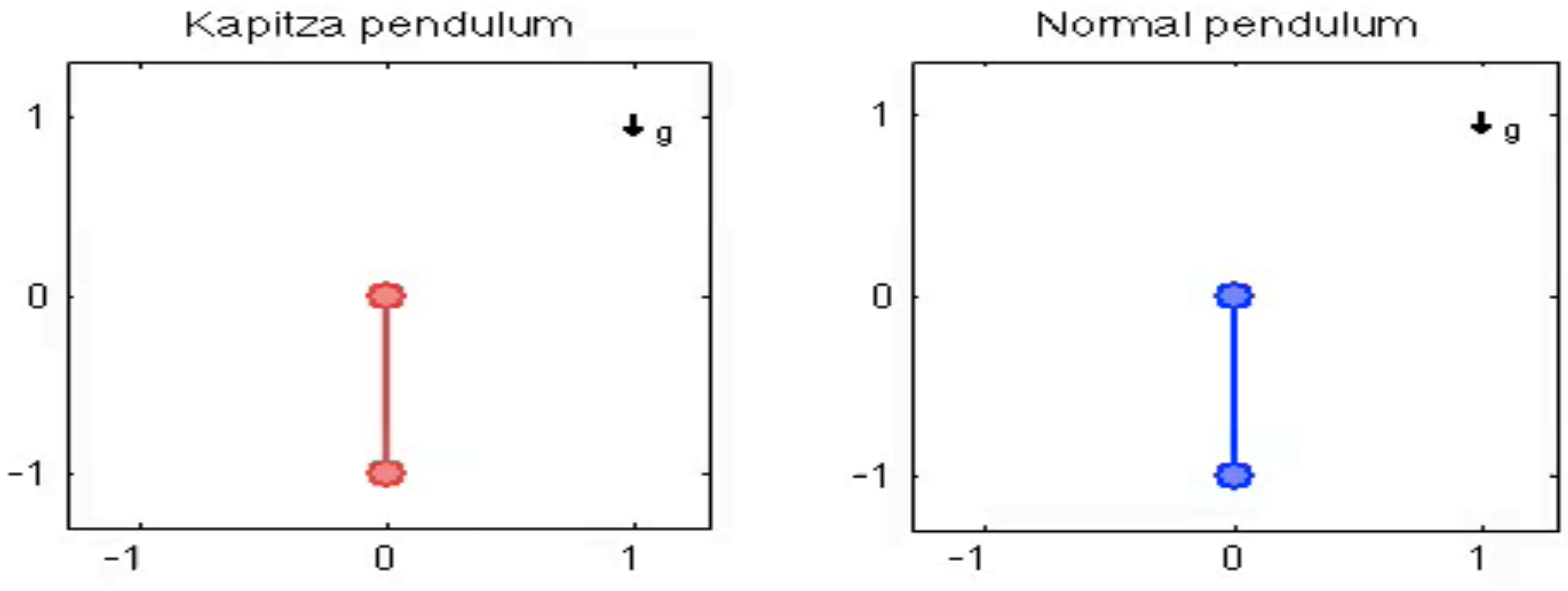
Staggered field *m*

Fictitious fields!





Kapitza pendulum: dynamical stabilization of metastable state



Floquet theory in a nutshell (more details later)

time periodic system

$$i\partial_t \psi = H(t)\psi \qquad H(t) = H(t+T) \qquad \Omega = 2\pi/T$$

=discrete Fourier trans. $\Big\downarrow$

$$\Psi(t) = e^{-i\varepsilon t} \sum_m \phi^m e^{-im\Omega t}$$

Floquet Hamiltonian (static eigenvalue problem)

$$\sum_{m=-\infty}^{\infty} \mathcal{H}^{mn} \phi_\alpha^m = \varepsilon_\alpha \phi_\alpha^n$$

ε: Floquet quasi-energy

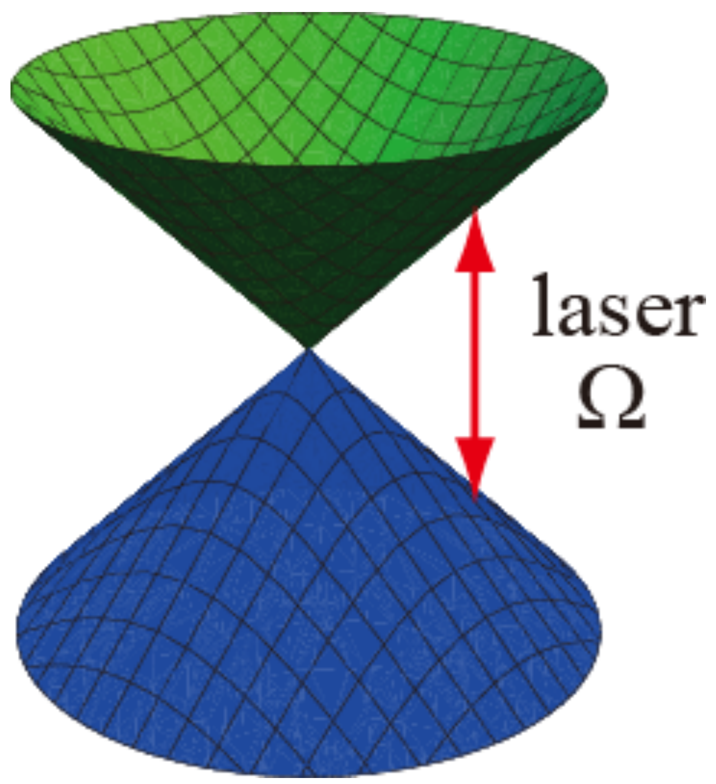
$$(\mathcal{H})^{mn} = \frac{1}{T}\int_0^T dt H(t) e^{i(m-n)\Omega t} \boxed{+ m\delta_{mn}\Omega I}$$

comes from the $i\partial_t$ term

$$H_m = \mathcal{H}^{m0}$$

~ absorption of m “photons”

Dirac fermion with circularly polarized laser



coupling to AC field

$$\boldsymbol{k} \longrightarrow \boldsymbol{k} + \boldsymbol{A}(t)$$

$$k = k_x + ik_y$$
$$\boldsymbol{A}(t) = (F/\Omega \cos \Omega t,\, F/\Omega \sin \Omega t)$$
$$A = F/\Omega$$

time dependent Schrödinger equation

$$i\partial_t \psi_k = \begin{pmatrix} 0 & k + Ae^{i\Omega t} \\ \bar{k} + Ae^{-i\Omega t} & 0 \end{pmatrix} \psi_k$$

Floquet theory

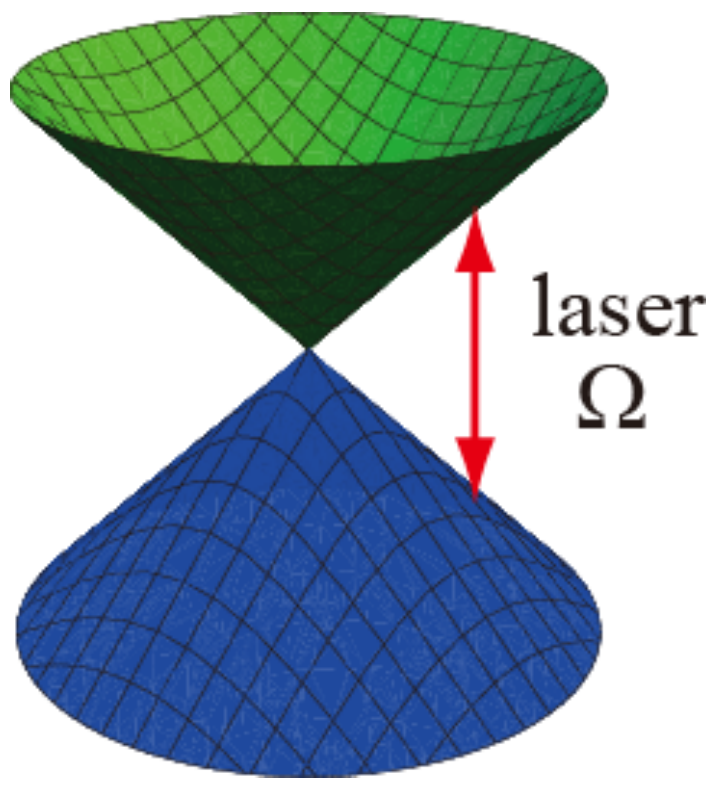
$$(\mathcal{H})^{mn} = \frac{1}{T}\int_0^T dt H(t) e^{i(m-n)\Omega t} + m\delta_{mn}\Omega I$$

$$H^{\mathrm{Floquet}} = \begin{pmatrix} \Omega & k & 0 & A & 0 & 0 \\ \bar{k} & \Omega & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & k & 0 & A \\ A & 0 & \bar{k} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -\Omega & k \\ 0 & 0 & A & 0 & \bar{k} & -\Omega \end{pmatrix}$$

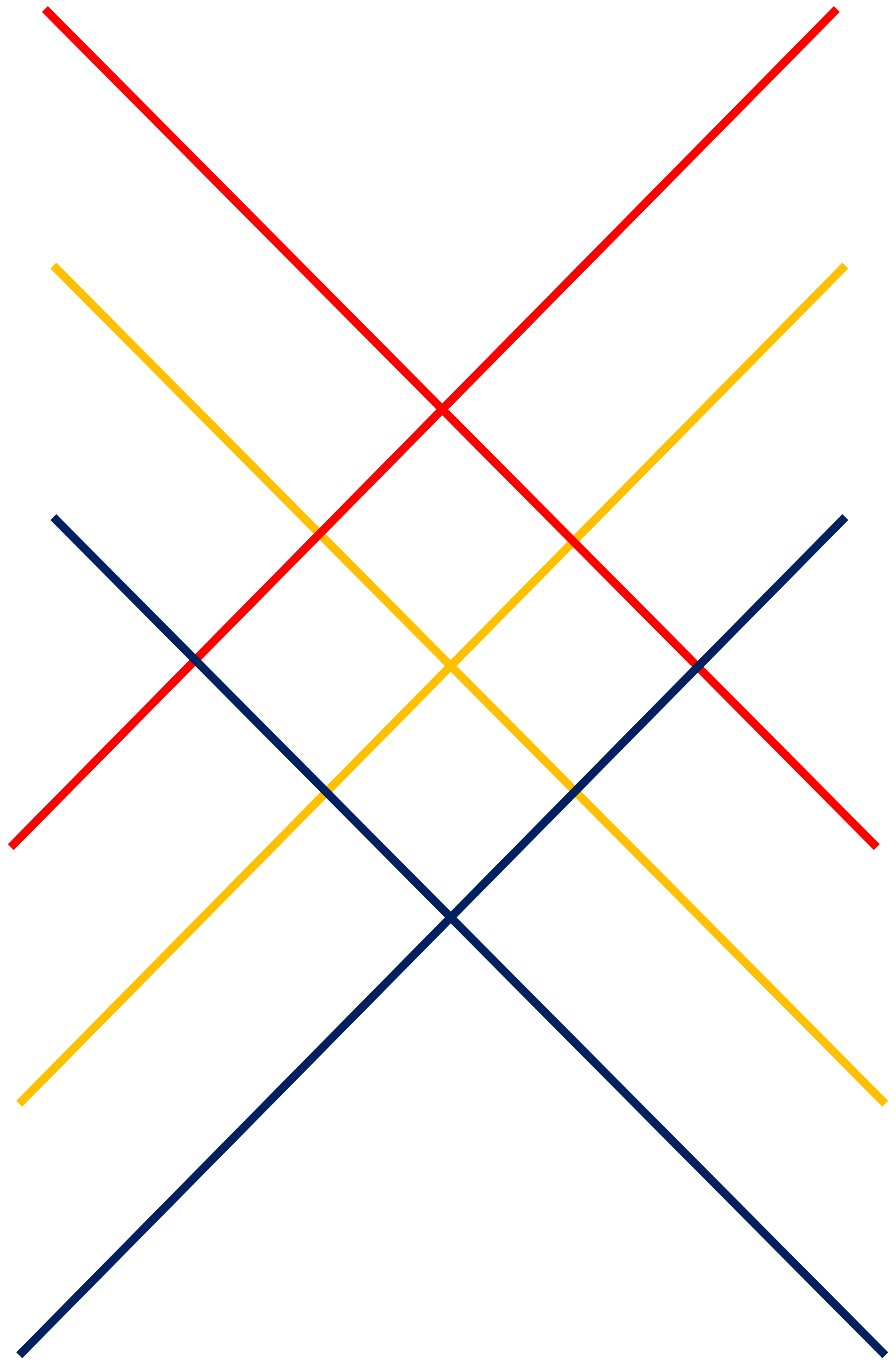
truncated at m=0,+1, -1 for display

Oka & Aoki, Phys. Rev. B 79, 081406(R) (2009)
Kitagawa et al., Phys. Rev. B 82, 235114 (2010)

Dirac fermion with circularly polarized laser



$$H^{\text{Floquet}} = \begin{pmatrix} \Omega & k & 0 & A & 0 & 0 \\ \bar{k} & \Omega & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & k & 0 & A \\ A & 0 & \bar{k} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -\Omega & k \\ 0 & 0 & A & 0 & \bar{k} & -\Omega \end{pmatrix}$$



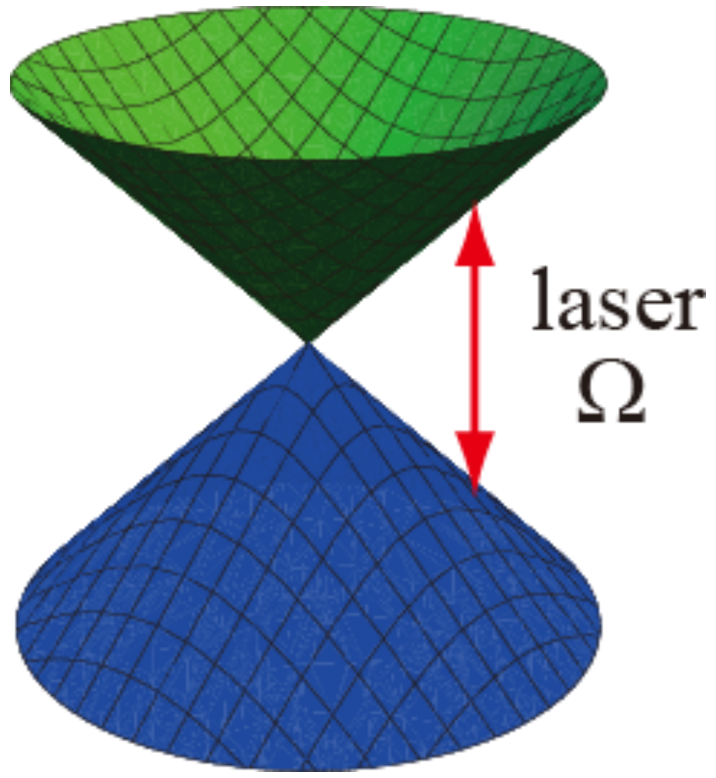
1-photon absorbed state

0-photon absorbed state

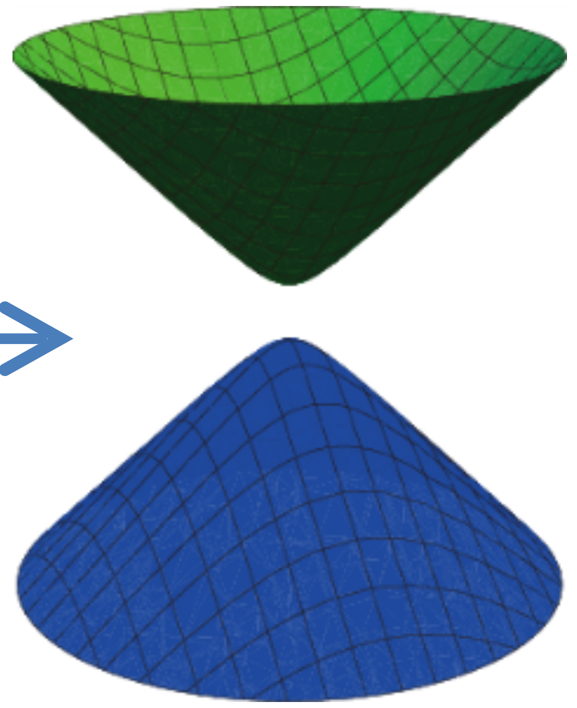
-1-photon absorbed state

Oka & Aoki, Phys. Rev. B 79, 081406(R) (2009)
Kitagawa et al., Phys. Rev. B 82, 235114 (2010)

Dirac fermion with circularly polarized laser



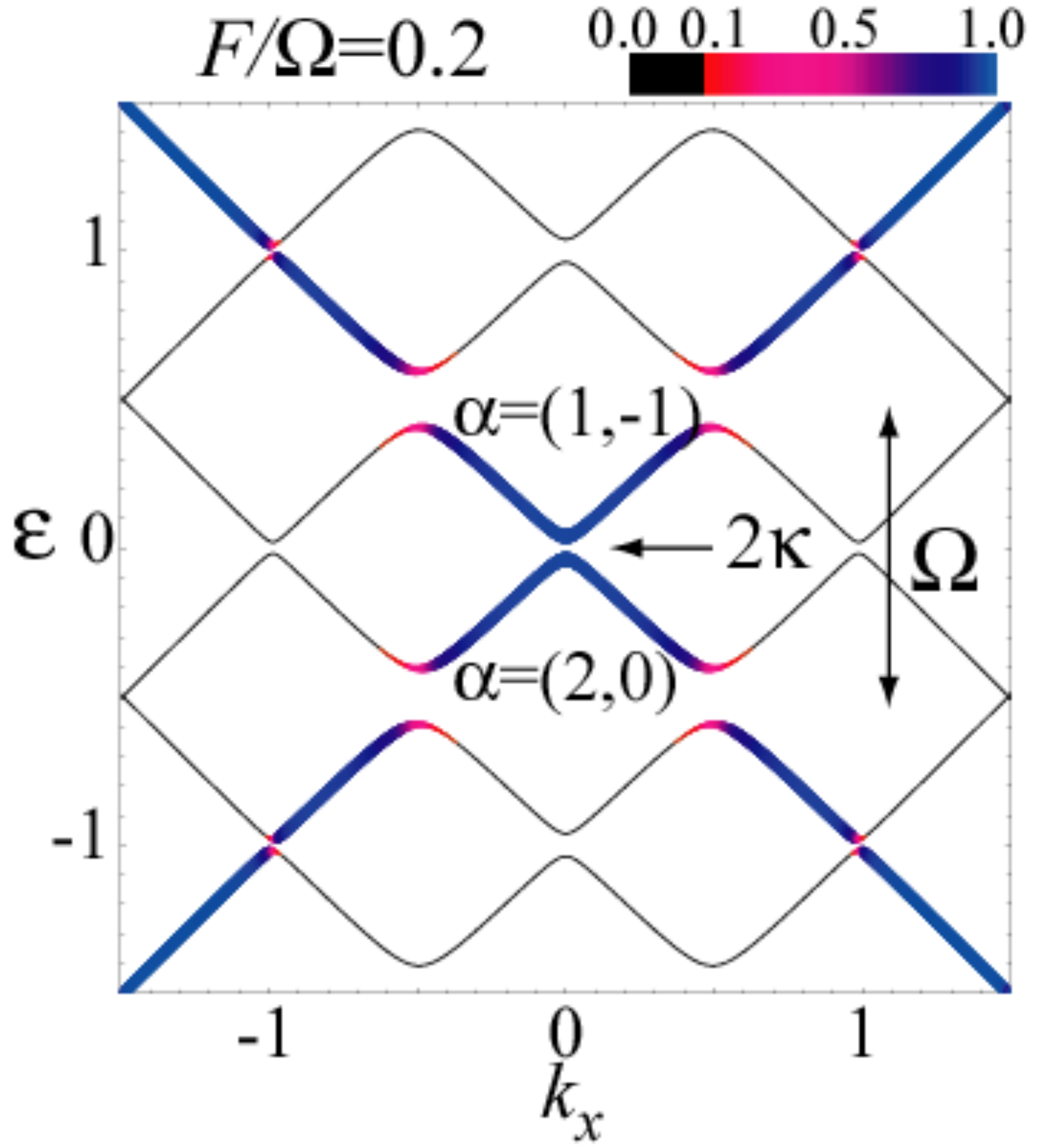
$$\kappa = \frac{\sqrt{4A^2+\Omega^2}-\Omega}{2} \sim A^2/\Omega$$



Mass term =
synthetic field stemming from a
real time-dependent field A(t)

sign of mass term determined
by chirality of light

$$H^{\mathrm{Floquet}} = \begin{pmatrix} \Omega & k & 0 & A & 0 & 0 \\ \bar{k} & \Omega & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & k & 0 & A \\ A & 0 & \bar{k} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -\Omega & k \\ 0 & 0 & A & 0 & \bar{k} & -\Omega \end{pmatrix}$$



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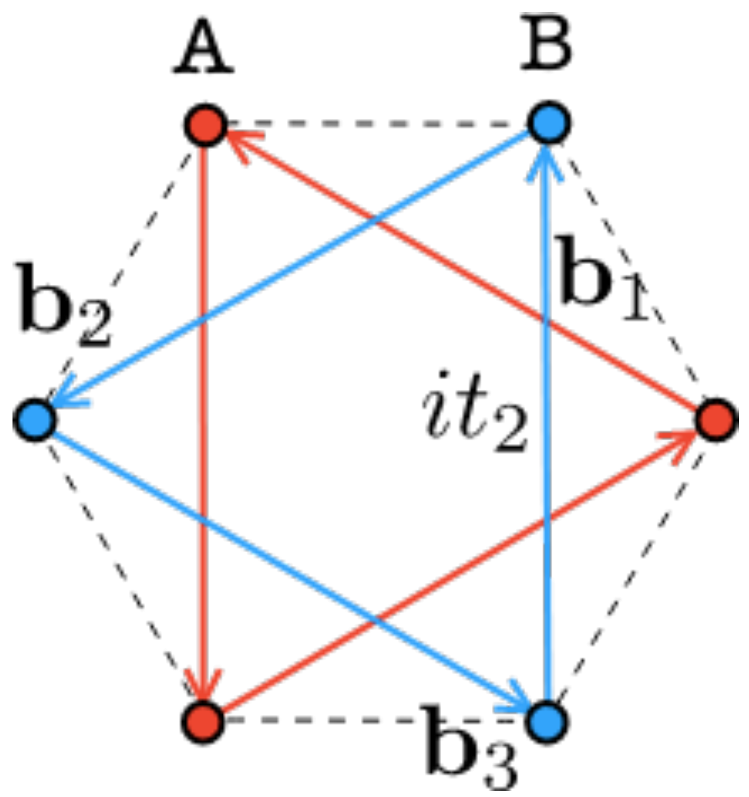
Haldane, PRL 61, 2015 (1988)

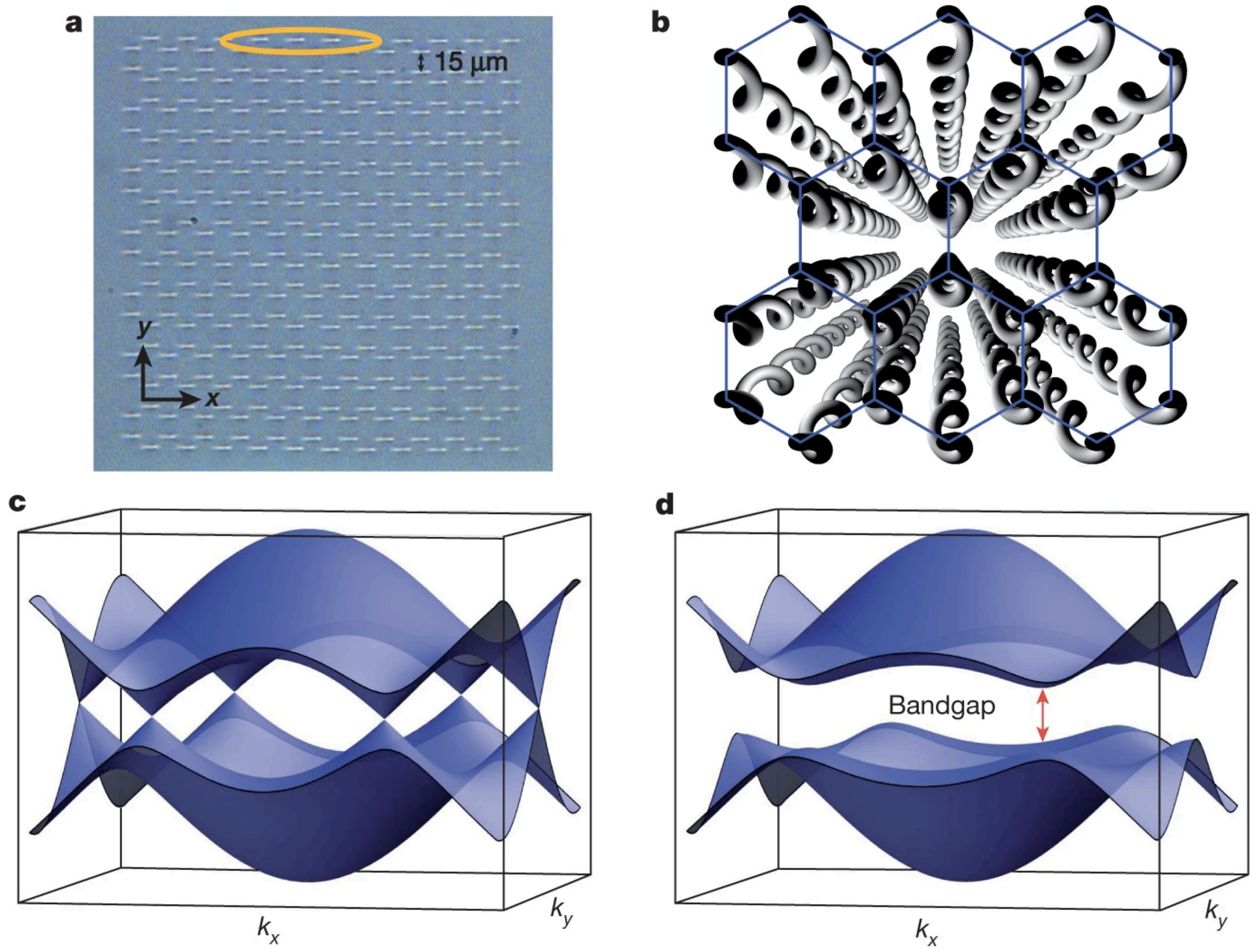


Oka and Aoki, PRB 79, 081406 (2009)

Floquet topology across platforms

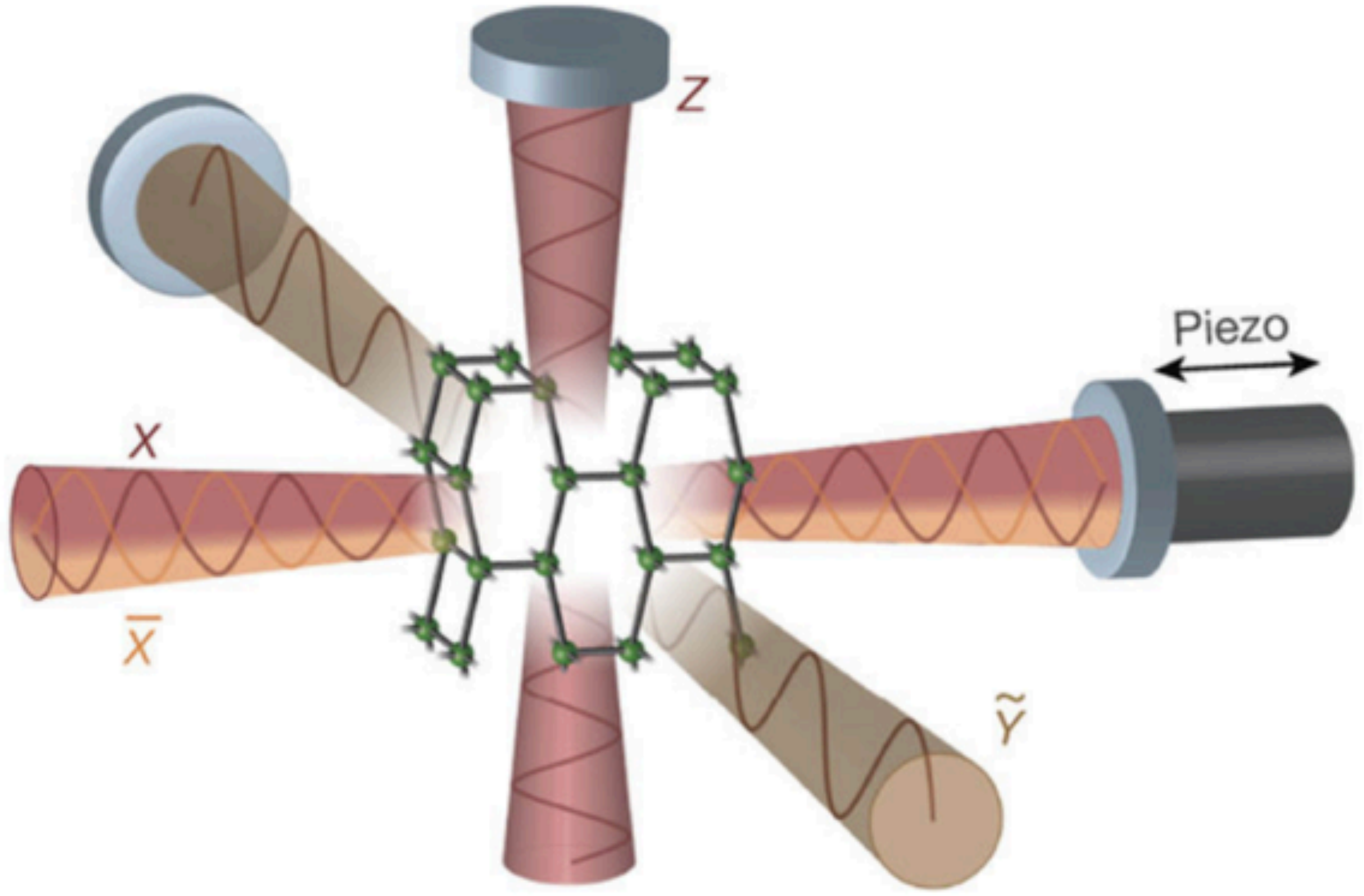
Photonic Floquet topological insulators

M. Rechtsman et al., Nature 496, 196 (2013)



Haldane model with ultracold fermions

G. Jotzu et al., Nature 515, 237 (2014)



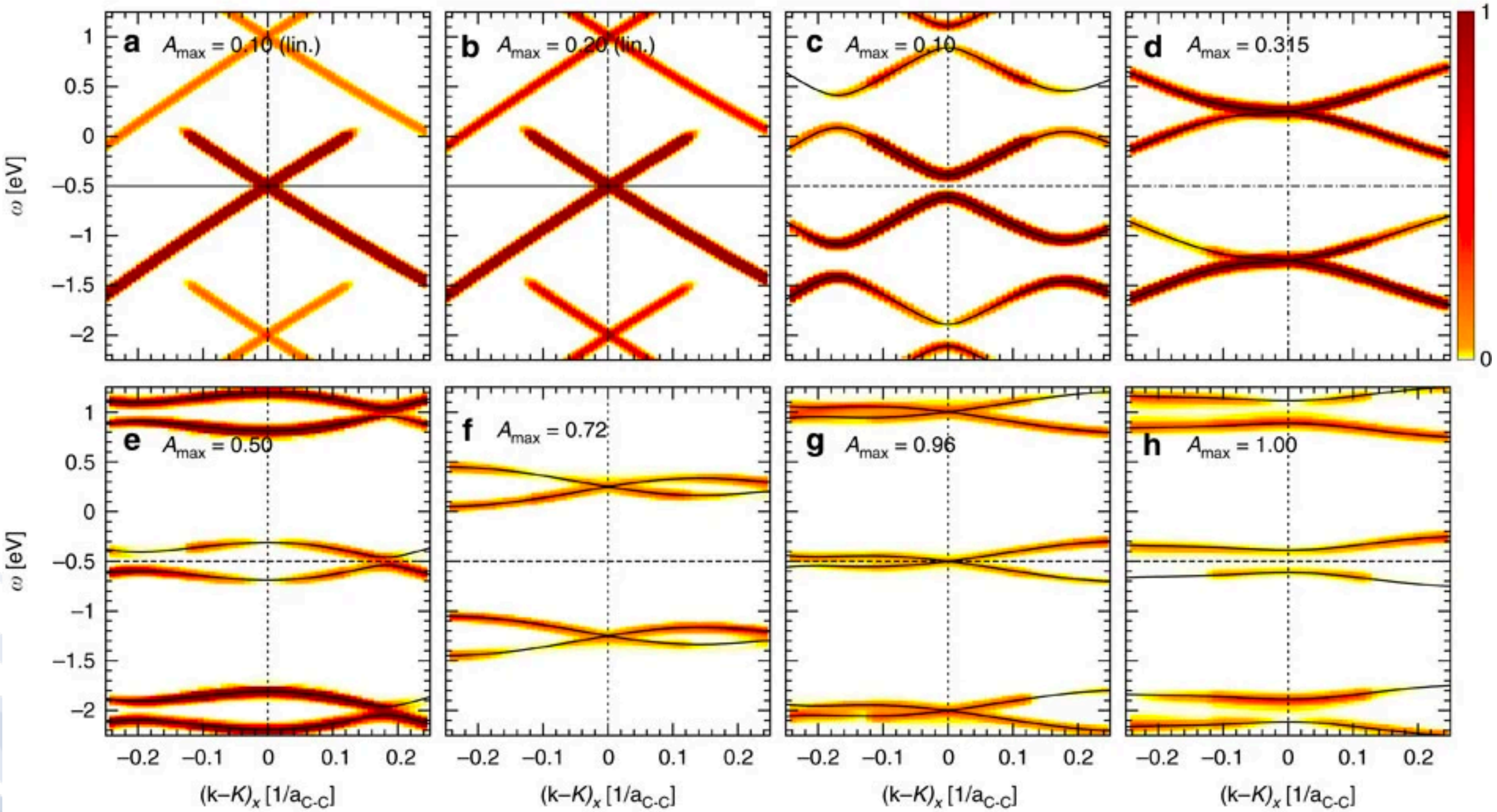
review:

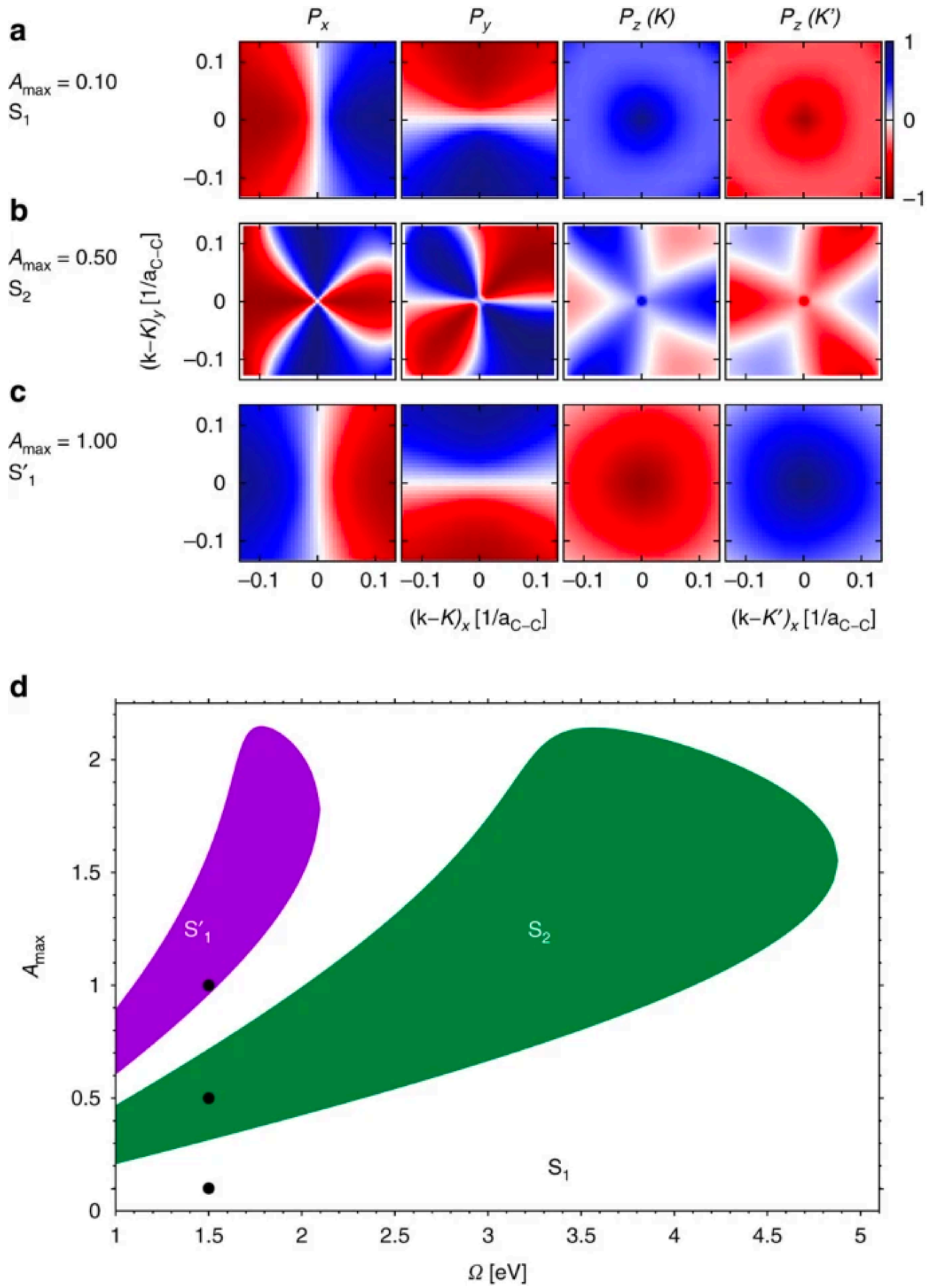
M. Rudner and N. Lindner, Nat. Rev. Phys. 2, 229 (2020)

MAS et al., Nature Communications 6, 7047 (2015)

Floquet sidebands in materials

Prediction for graphene …

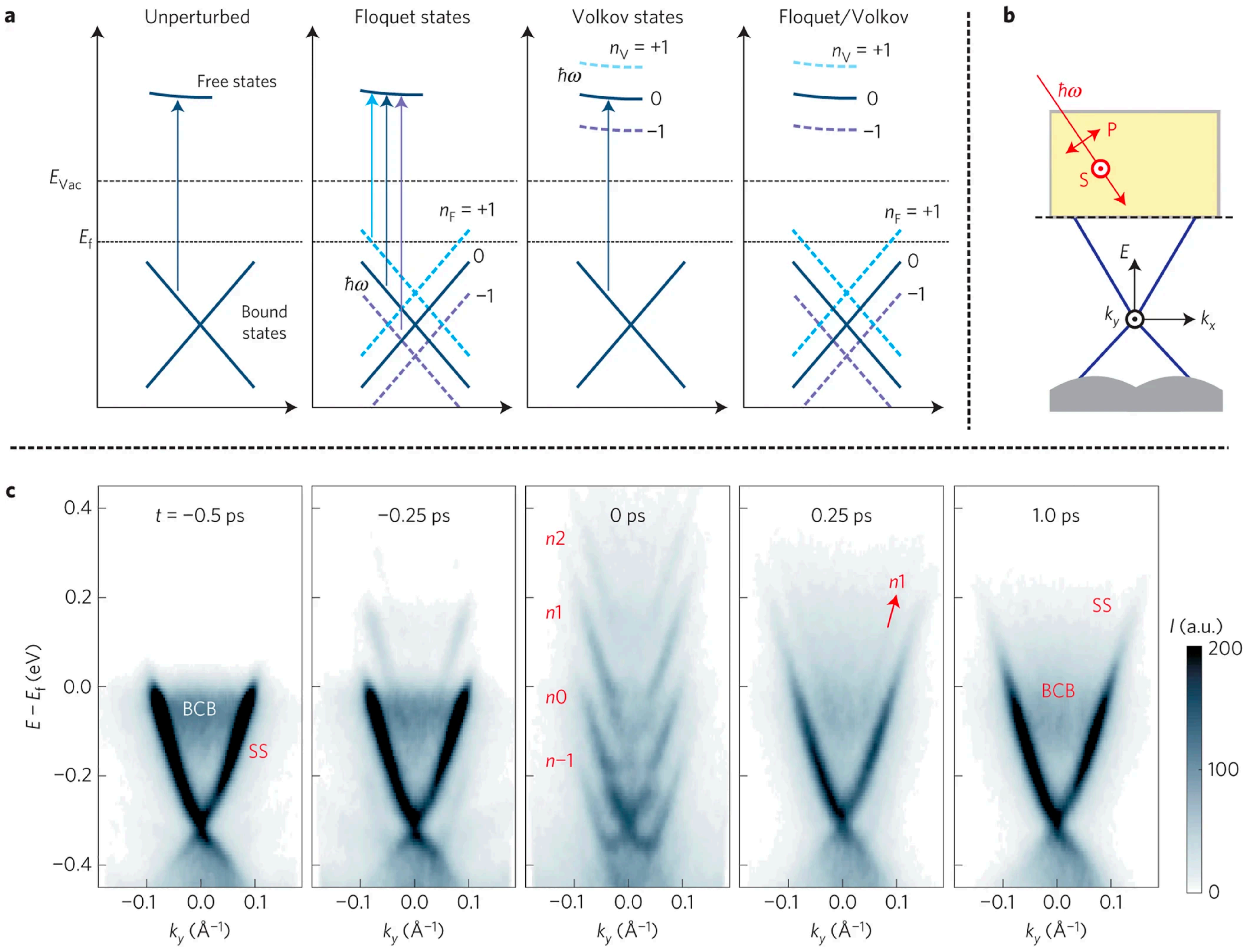




Y. H. Wang et al., Science 342, 453 (2013)
F. Mahmood et al., Nature Physics 12, 306-310 (2016)
[Nuh Gedik group at MIT]

Floquet sidebands in materials

… observation in 3D topological insulator surface 2D Dirac fermions

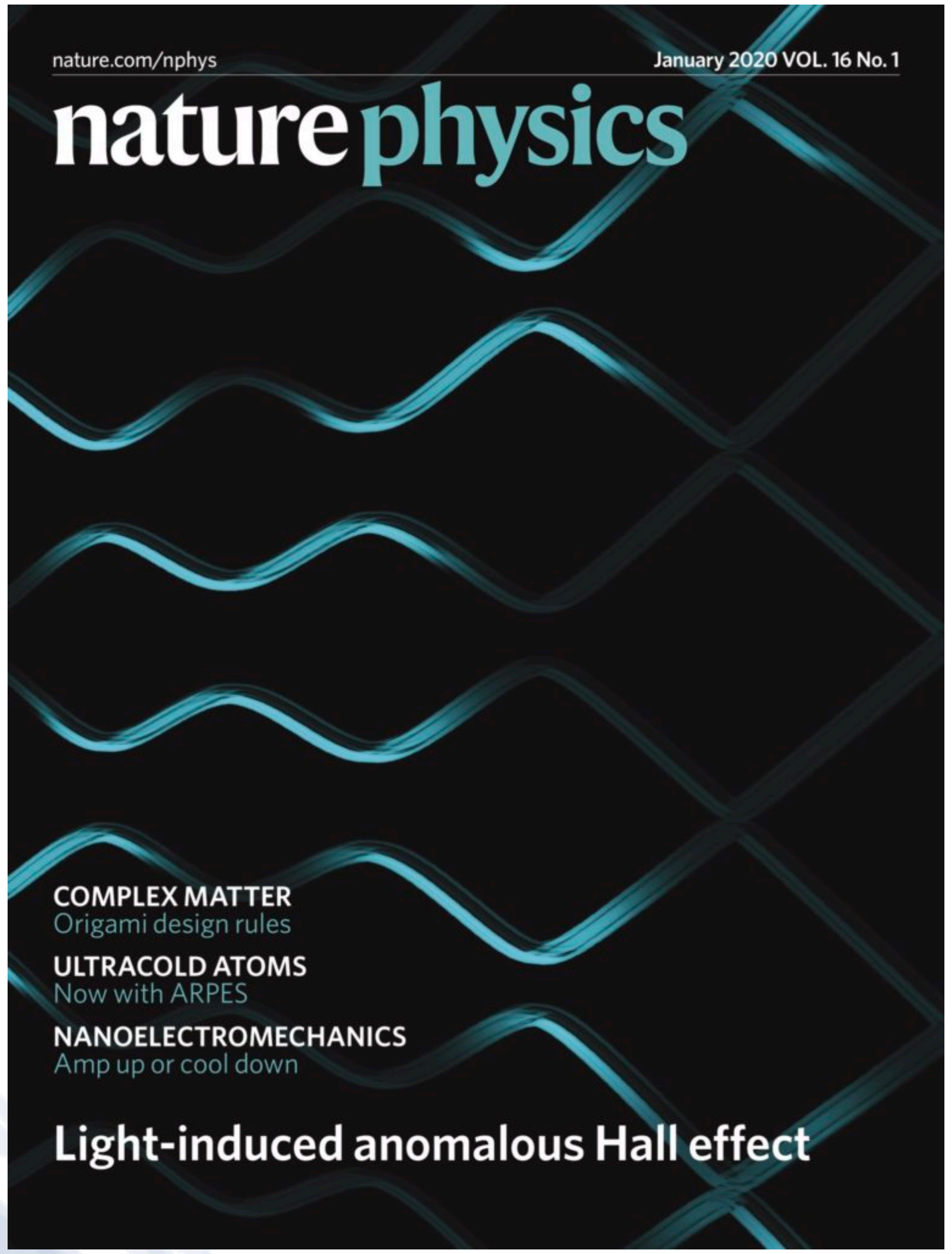


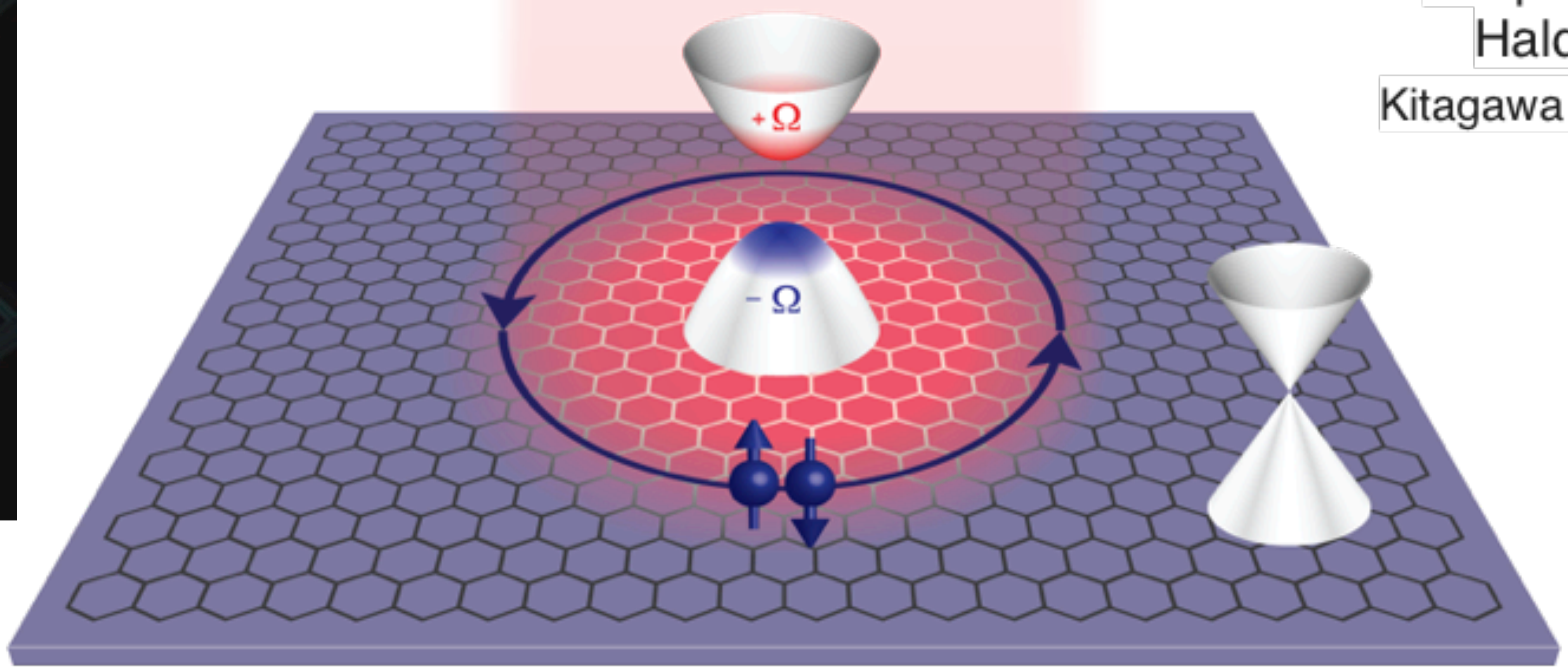
What about observing Floquet states in time-resolved photoemission of graphene?

Ongoing challenge to overcome decoherence and dissipation

e.g., Aeschlimann et al., Nano Lett. 21, 5028 (2021)

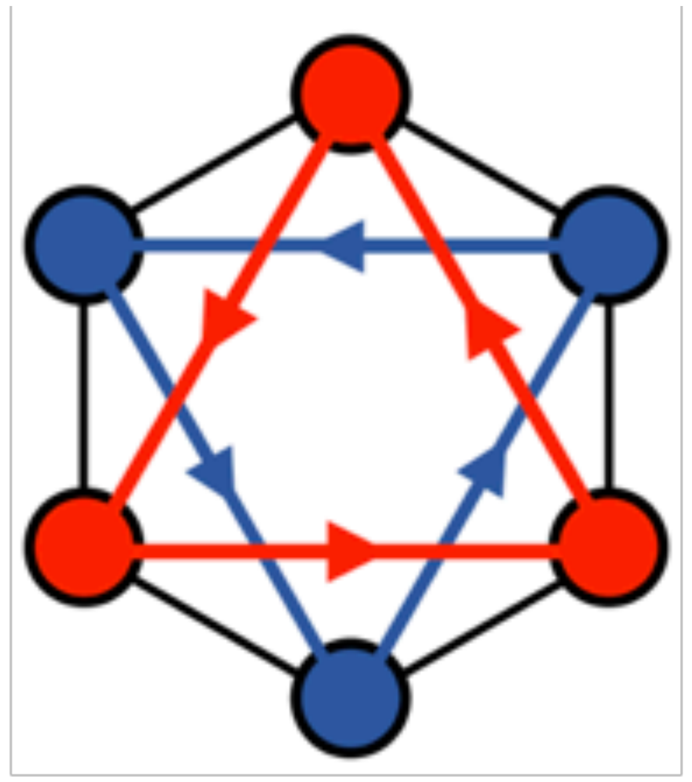
Light-induced anomalous Hall effect





Graphene

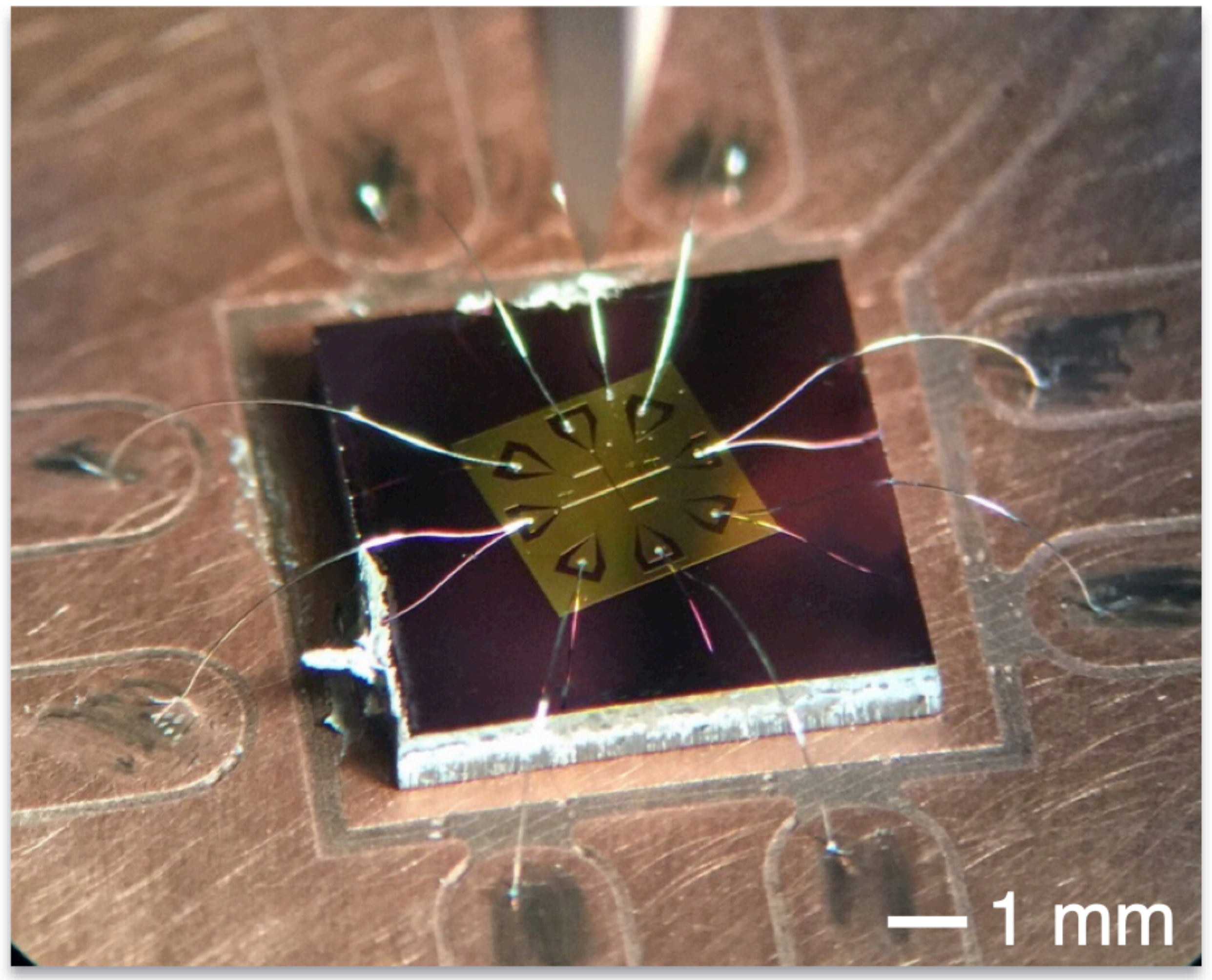
T. Oka & H. Aoki, PRB (2009)

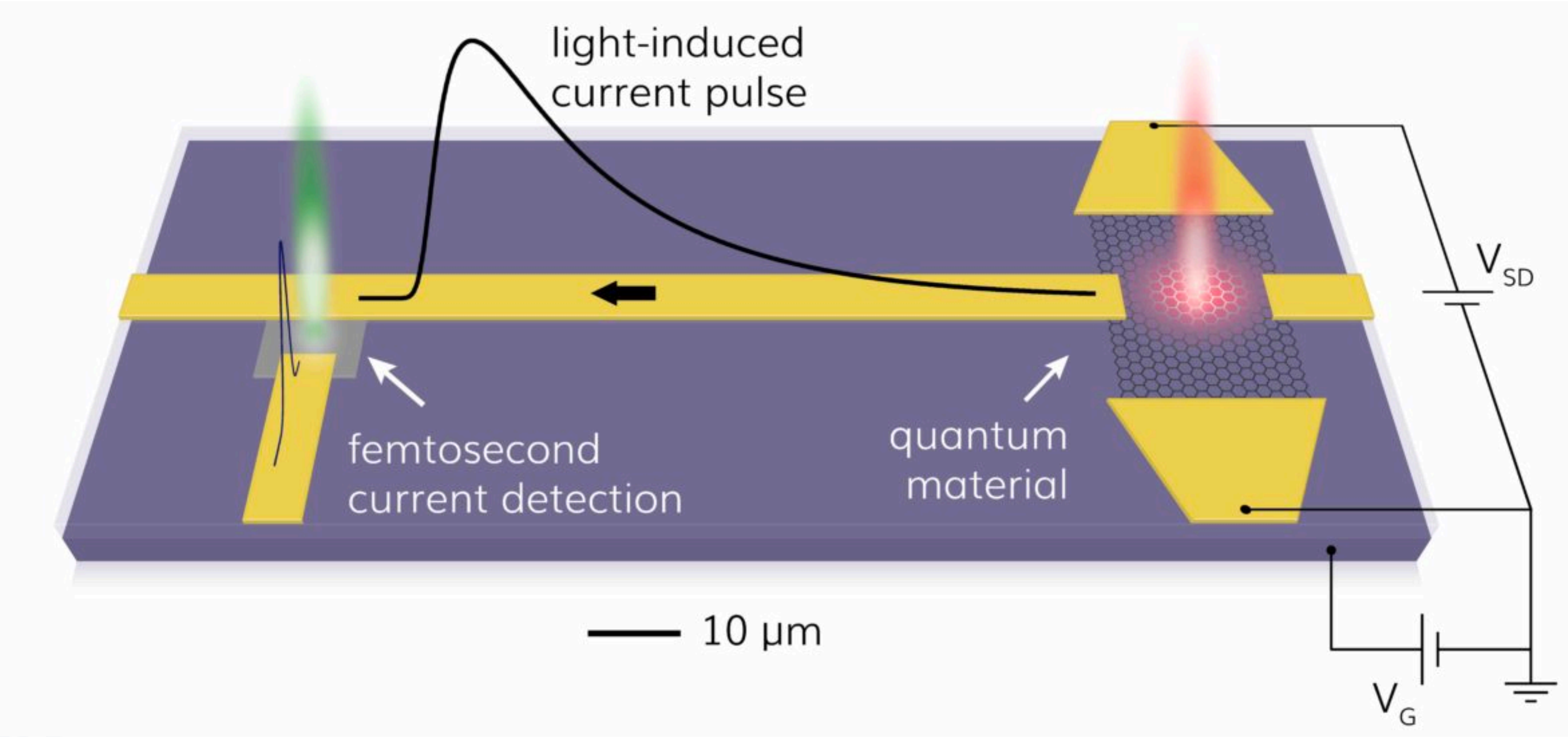


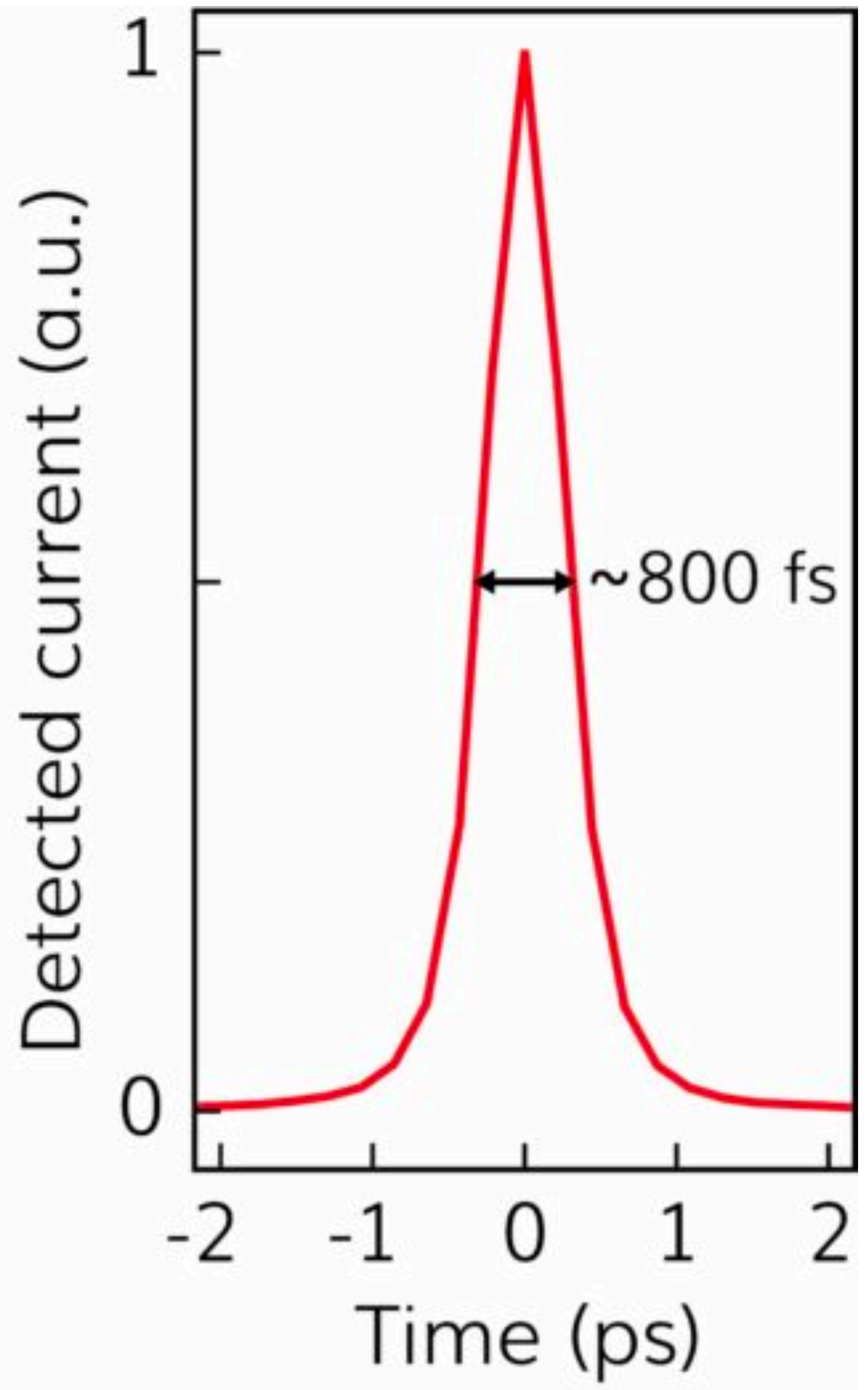
Floquet-engineered Haldane Model

Kitagawa *et al.* PRB (2011)

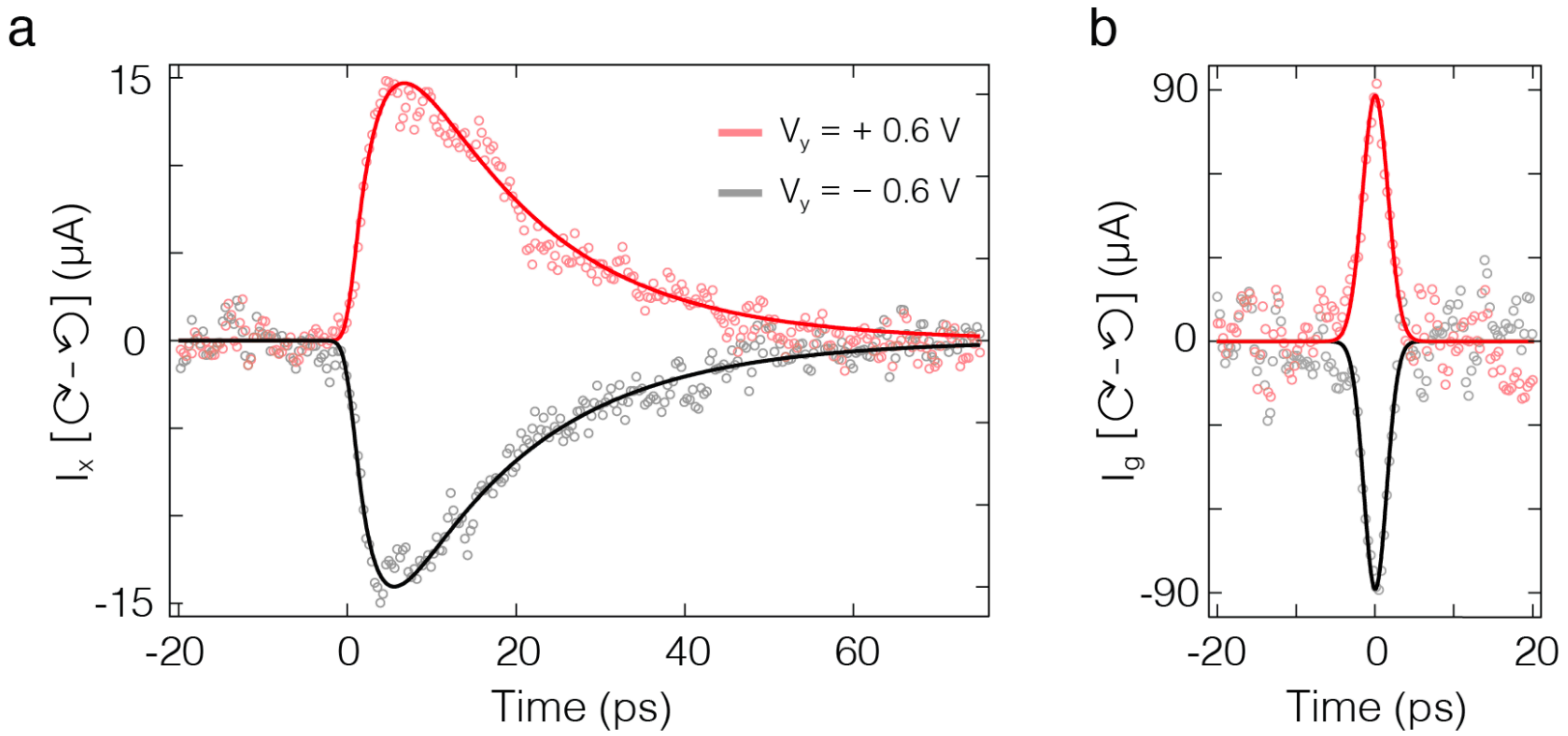
Femtosecond science on-chip



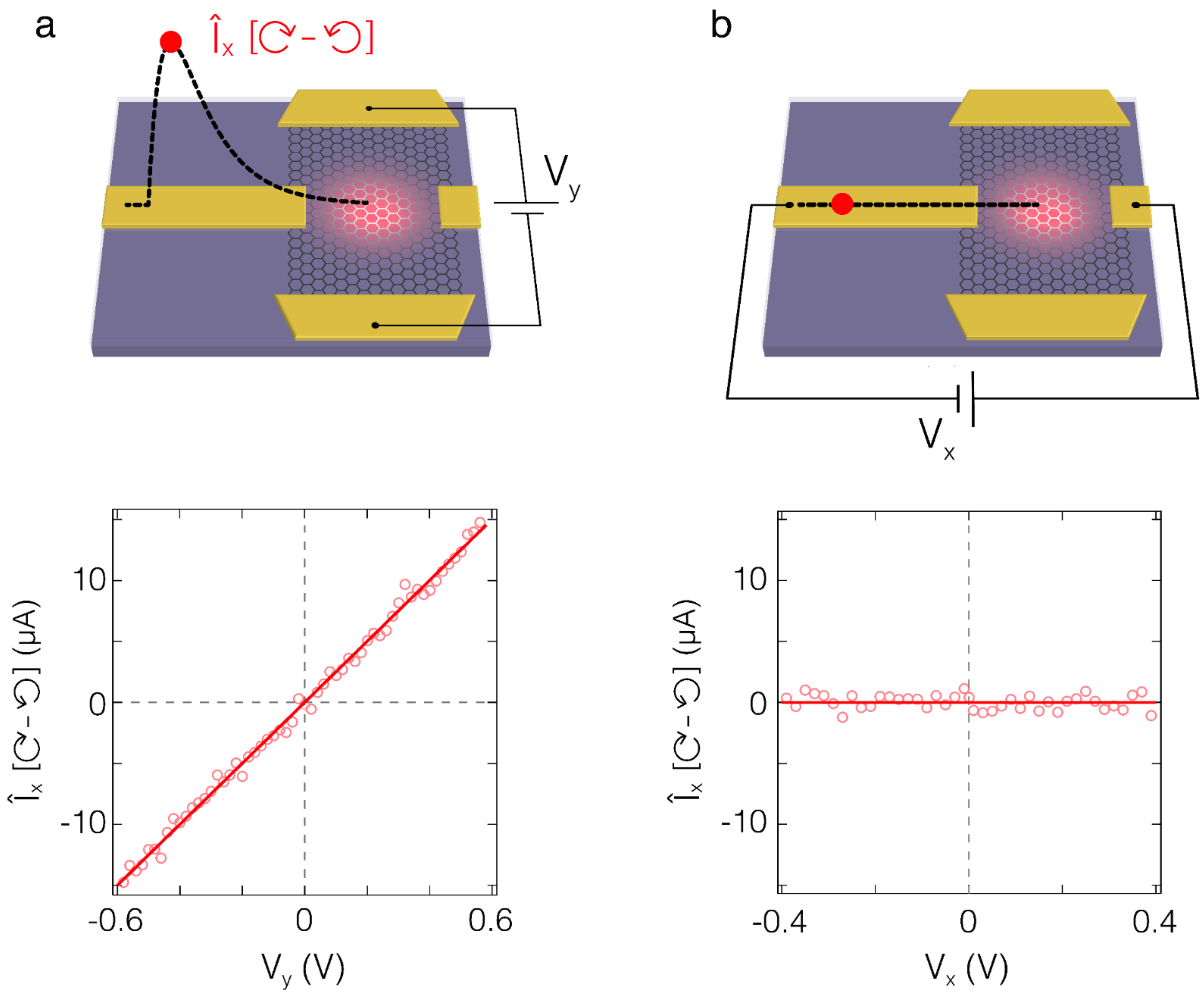




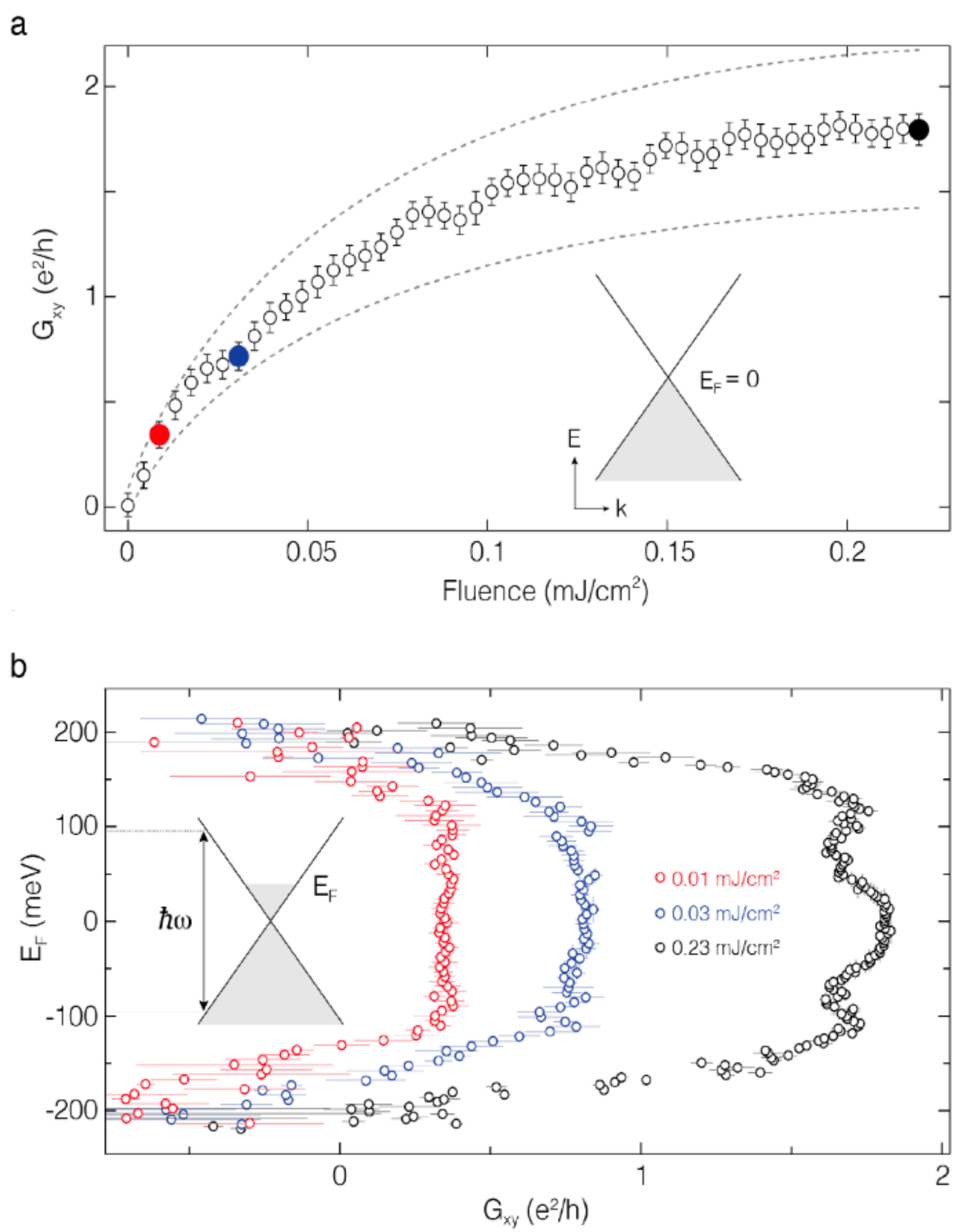
Light-induced anomalous Hall effect

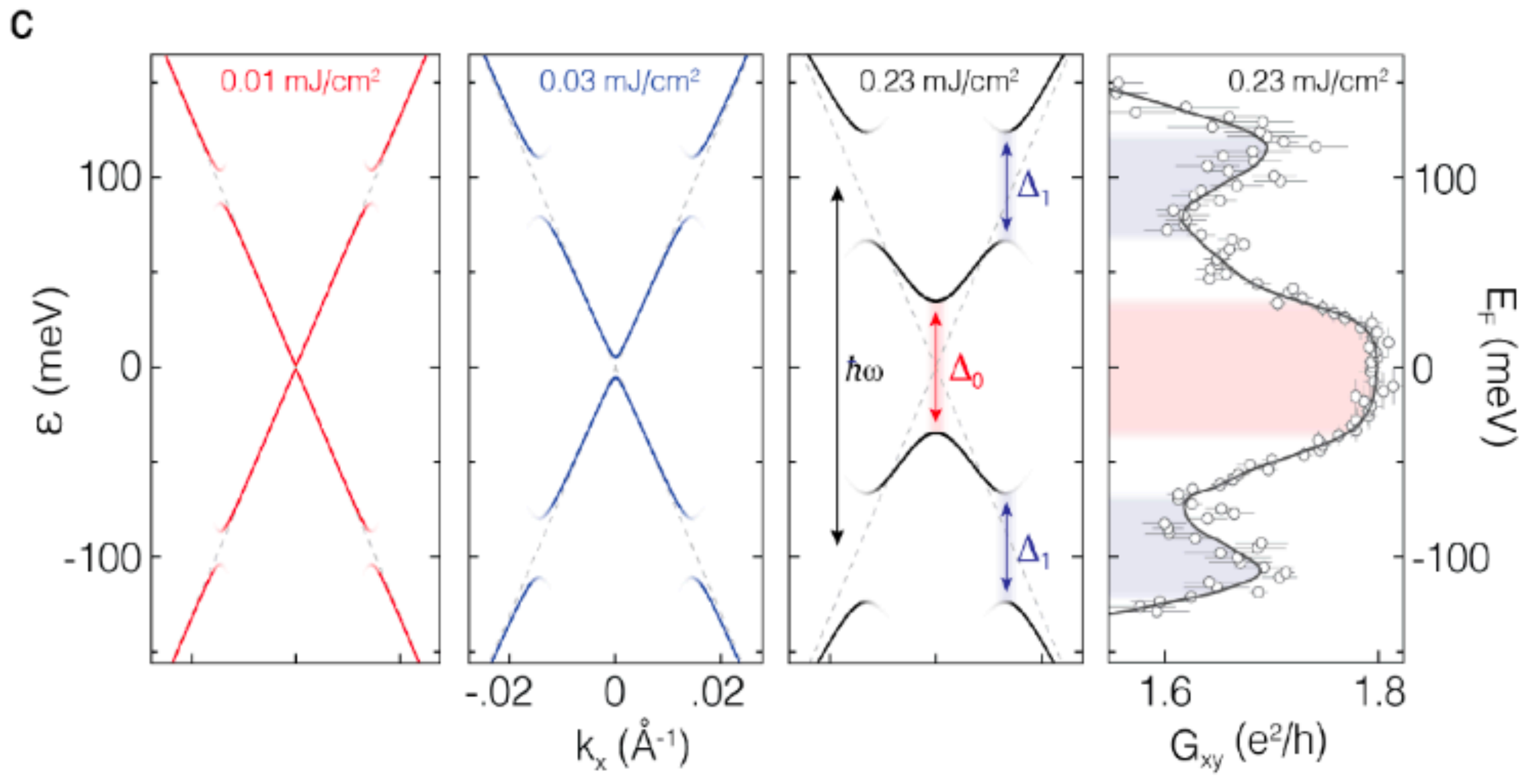


Light-induced anomalous Hall effect



Light-induced anomalous Hall effect

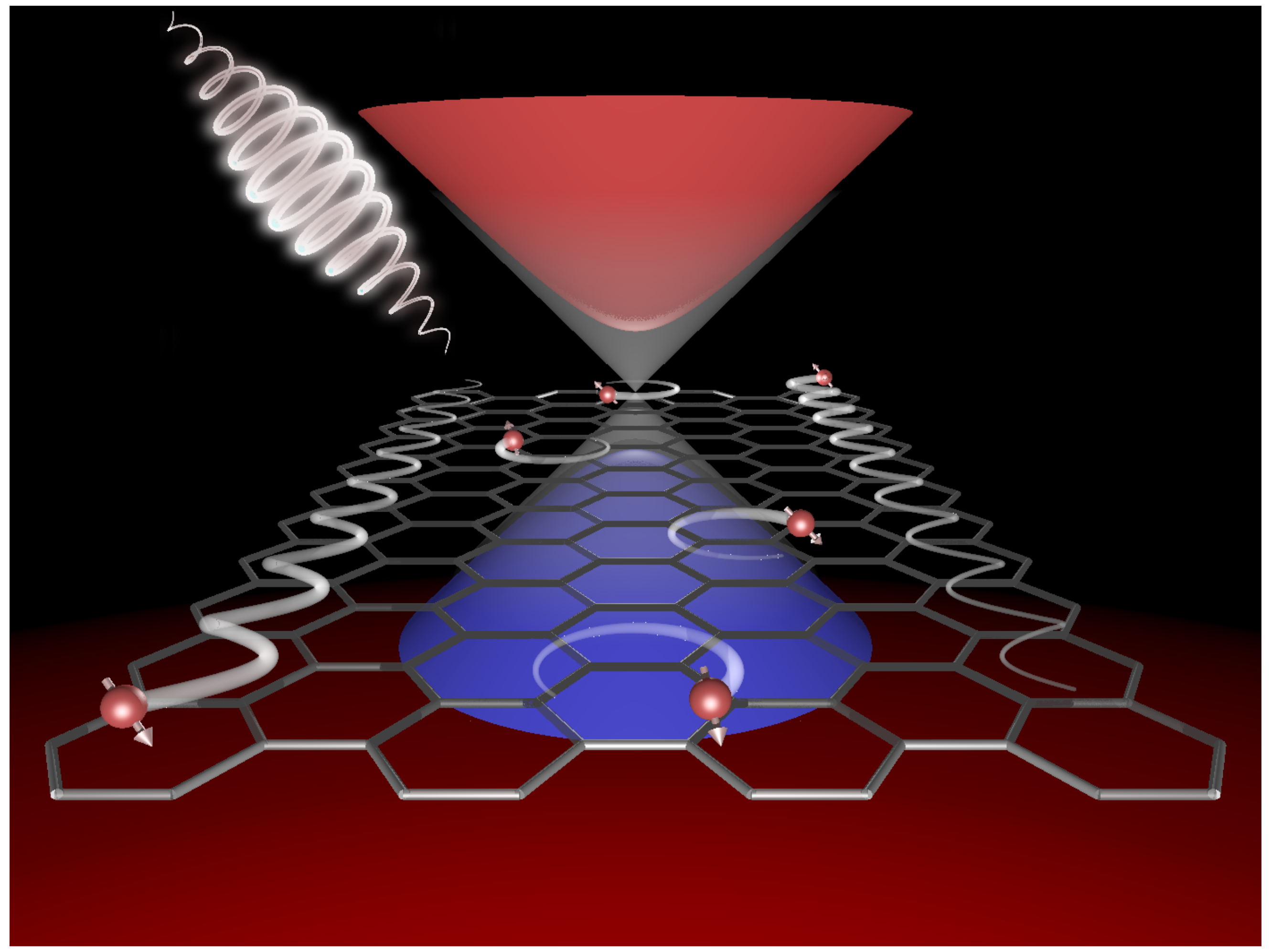


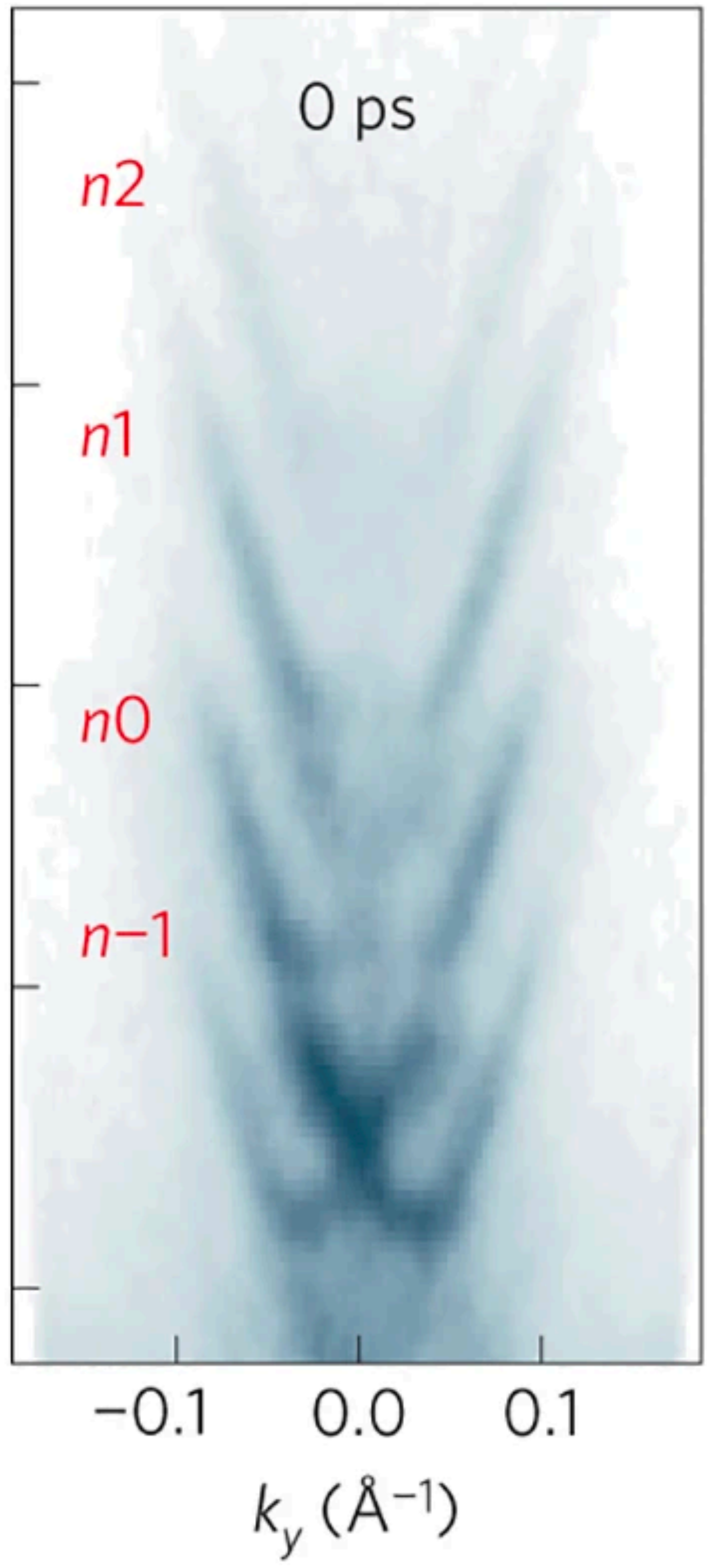


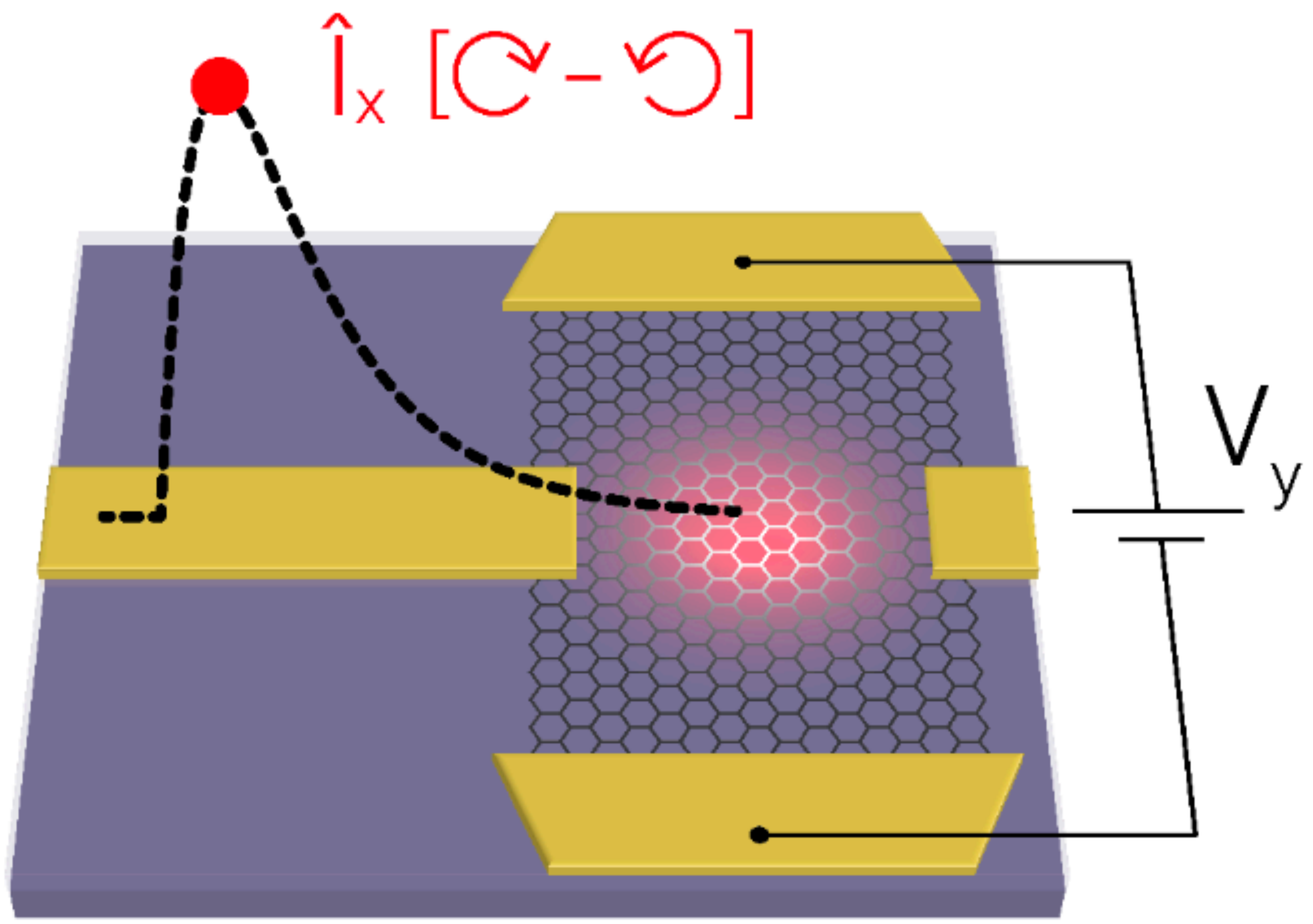
observations:
- a light-induced Hall effect without applying magnetic field
- has the right symmetries (changing from right-handed to left-handed light changes the sign)
- Hall conductance at strong laser fluence approaches a value consistent with 2e^2/h
- shows peaks and dips reminiscent of Floquet-induced gaps as a function of chemical potential
- … are these really Floquet topology effects?

Theory: yes but there are also population imbalance contributions
(S.A. Sato et al., Phys. Rev. B 99, 214302 (2019))

Summary part I





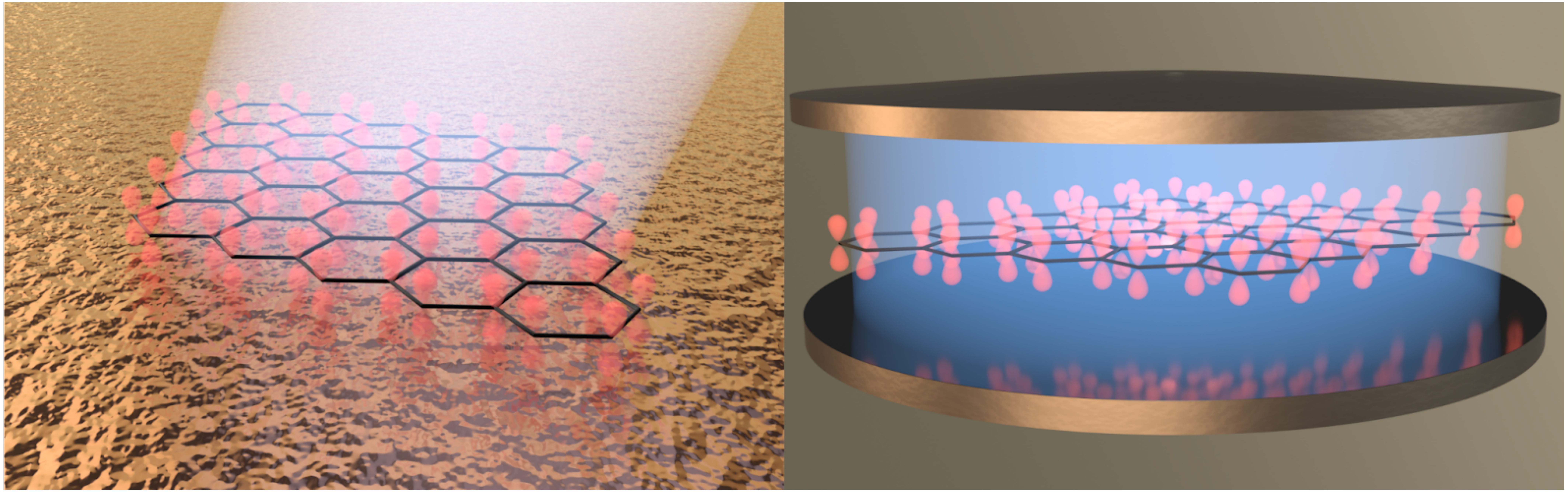


- Floquet theory as a basis to understand dynamics in periodically driven systems
- Floquet topological insulator: induce the nontrivial Haldane mass term with circularly polarized light
- Time-resolved photoemission spectroscopy and ultrafast (femtosecond) transport as efficient experimental probes of light-induced states of matter

II Floquet concepts

[whiteboard]

III From Floquet to cavity



[whiteboard]