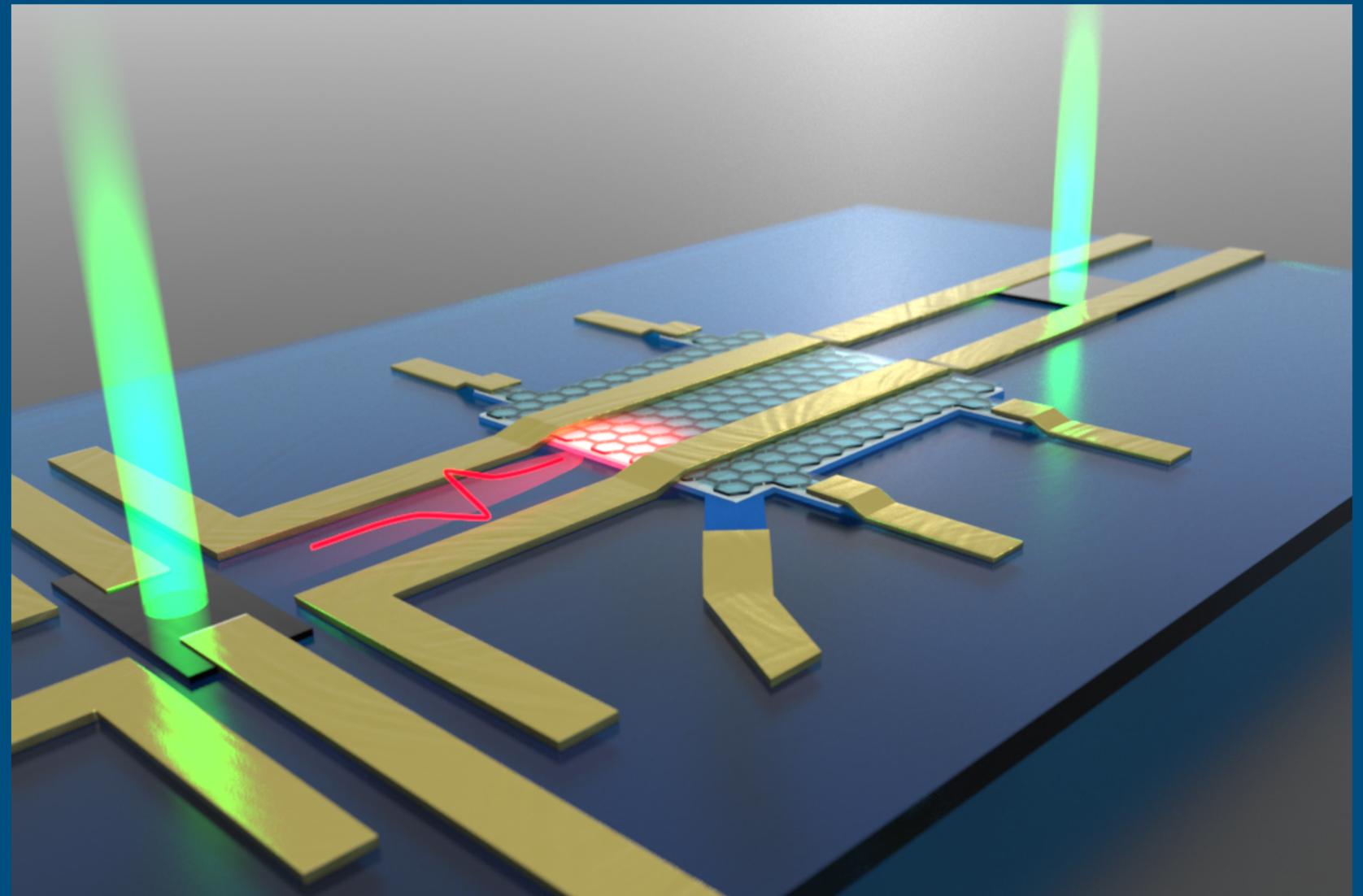


# Ultrafast optoelectronic probes of quantum materials

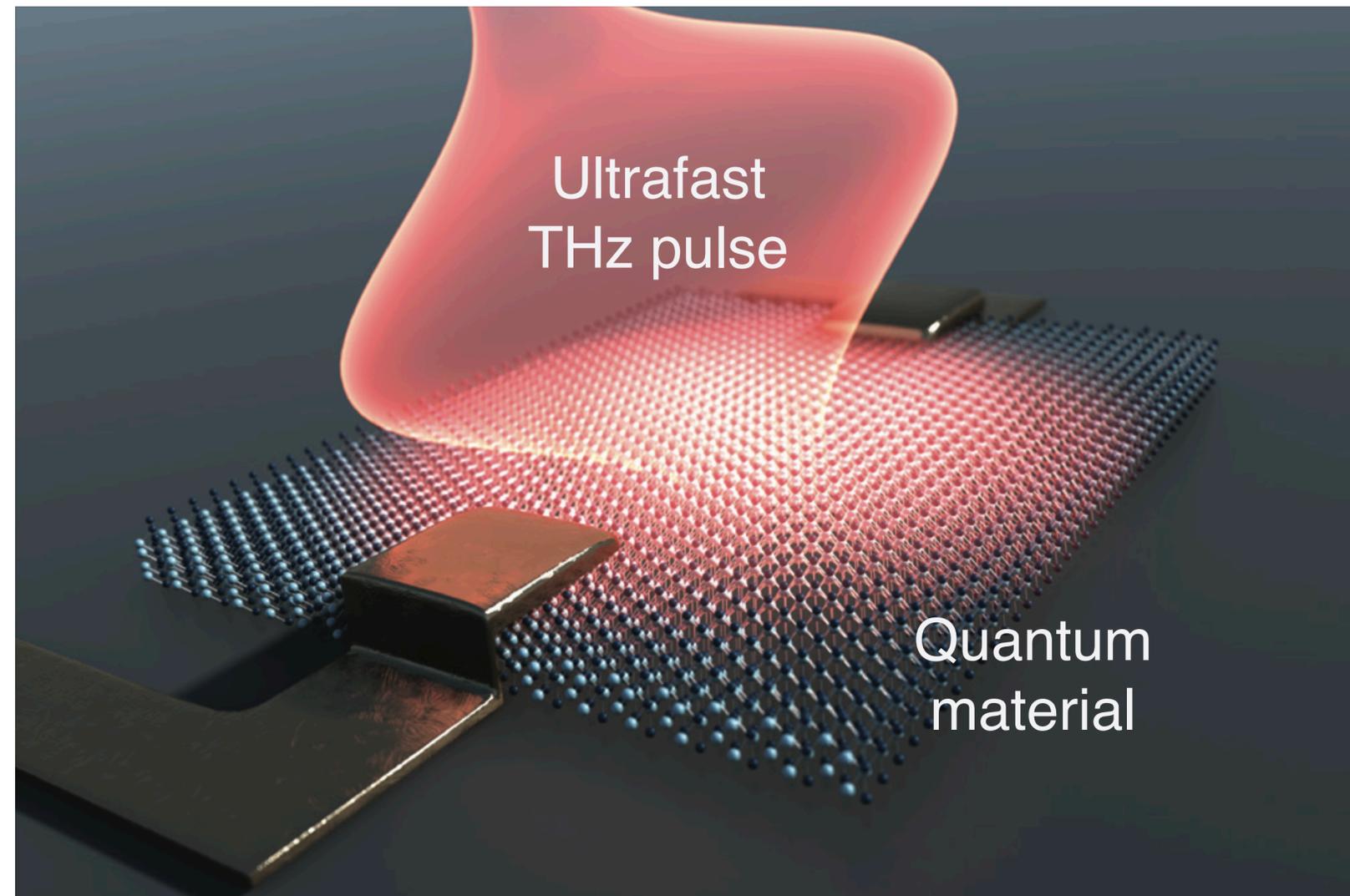
**James McIver**

Max Planck Hamburg (MPSD)  
Columbia University



SPICE seminar  
October 26, 2022

# Ultrafast control of quantum materials



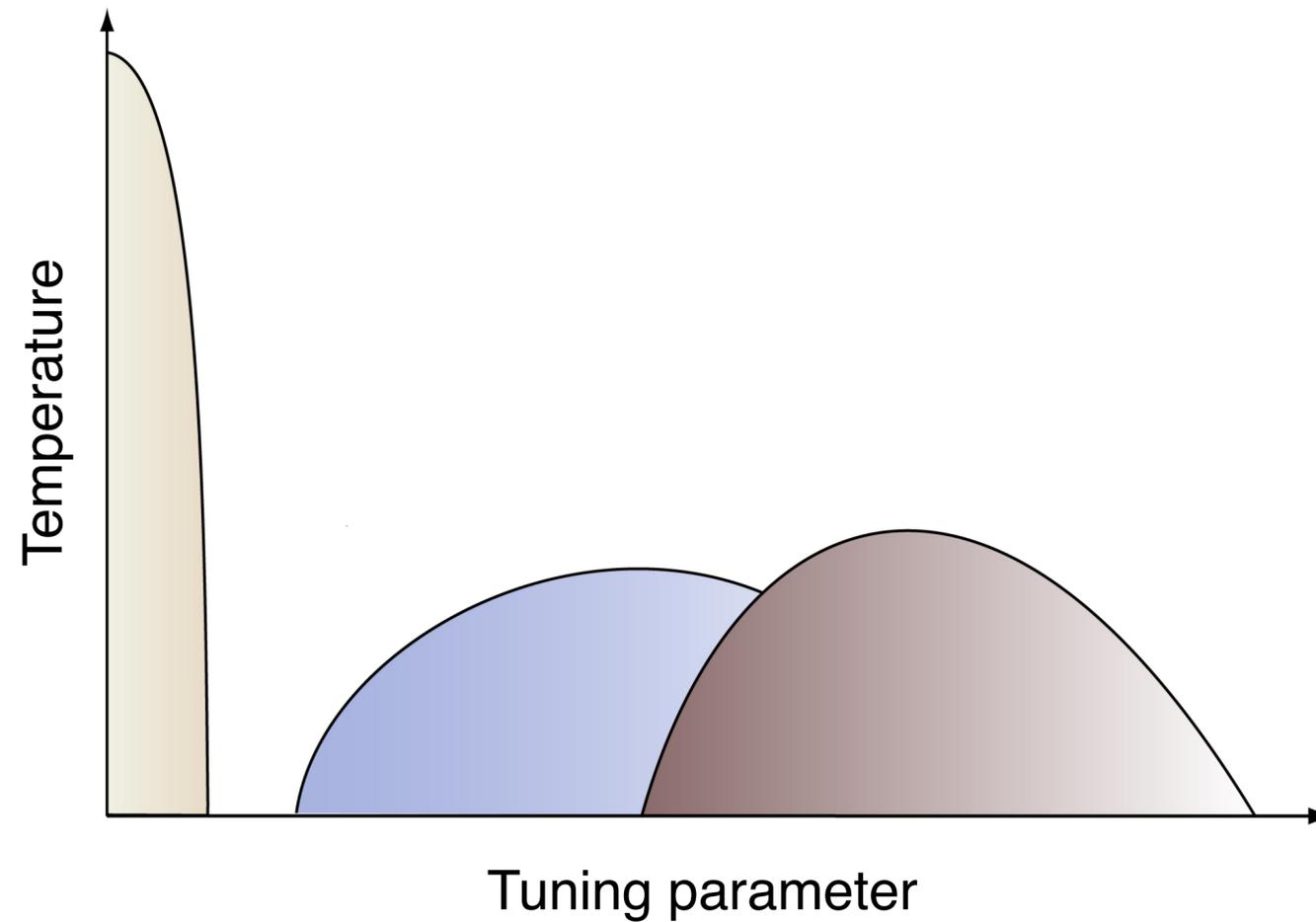
**New states of matter, new functionalities**

# Periodically driven systems



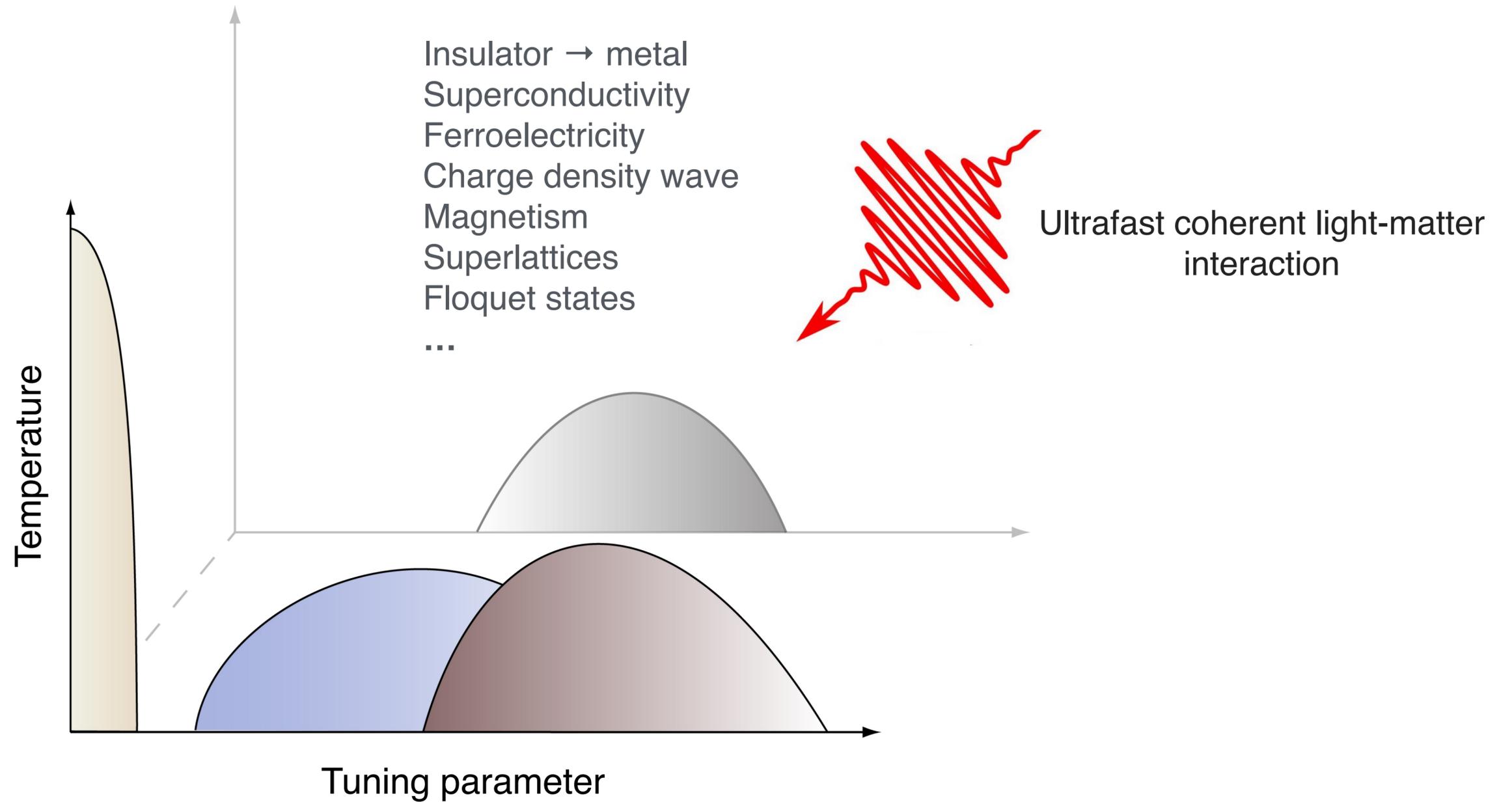
**Driven systems exhibit new regions of stability**

# Ultrafast control of quantum materials

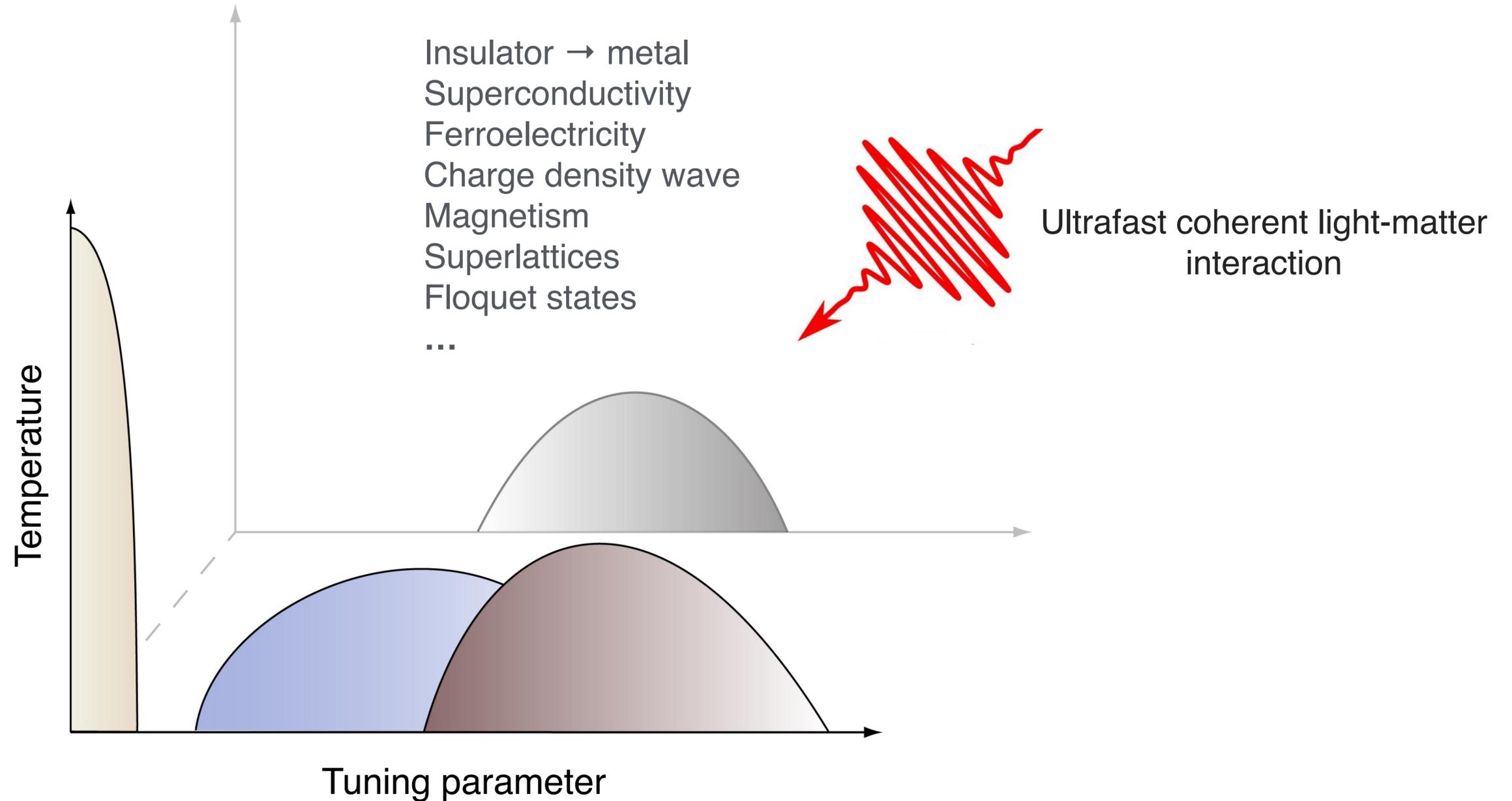


e.g. chemical doping, electrostatic gating,  
pressure, strain, magnetic field etc.

# Ultrafast control of quantum materials



# Ultrafast control of quantum materials



## Review articles:

Gianetti *et al.*, *Advances in Physics* **65**, 58 (2016)

Basov, Averitt & Hsieh, *Nature Materials* **16**, 1077 (2017)

Oka & Kitamura, *Ann. Rev. Cond. Matt. Phys.* **10**, 387 (2019)

Rudner & Lindner, *Nature Reviews Physics* **2**, 229 (2020)

Mitrano & Wang, *Communications Physics* **3**, 184 (2020)

Disa, Nova & Cavalleri, *Nature Physics* **17**, 1087 (2021)

# Ultrafast control of quantum materials

Insulator → metal  
Superconductivity  
Ferroelectricity  
Charge density wave  
Magnetism  
Superlattices  
Floquet states

Ultrafast coherent light-matter interaction

## REVIEWS OF MODERN PHYSICS

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### Colloquium: Nonthermal pathways to ultrafast control in quantum materials

Alberto de la Torre, Dante M. Kennes, Martin Claassen, Simon Gerber, James W. McIver, and Michael A. Sentef  
Rev. Mod. Phys. **93**, 041002 – Published 14 October 2021



## Review articles:

Gianetti *et al.*, *Advances in Physics* **65**, 58 (2016)

Basov, Averitt & Hsieh, *Nature Materials* **16**, 1077 (2017)

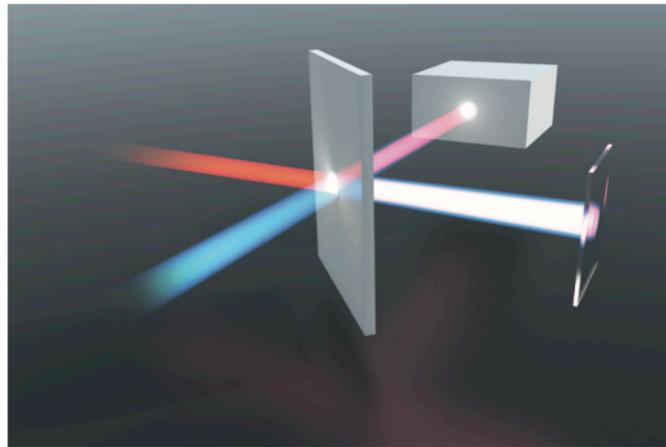
Oka & Kitamura, *Ann. Rev. Cond. Matt. Phys.* **10**, 387 (2019)

Rudner & Lindner, *Nature Reviews Physics* **2**, 229 (2020)

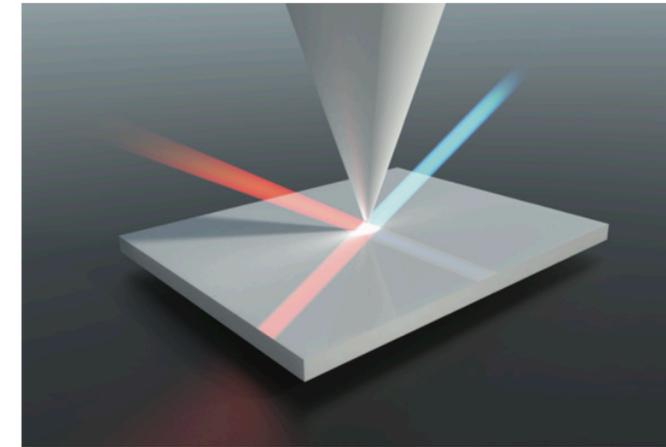
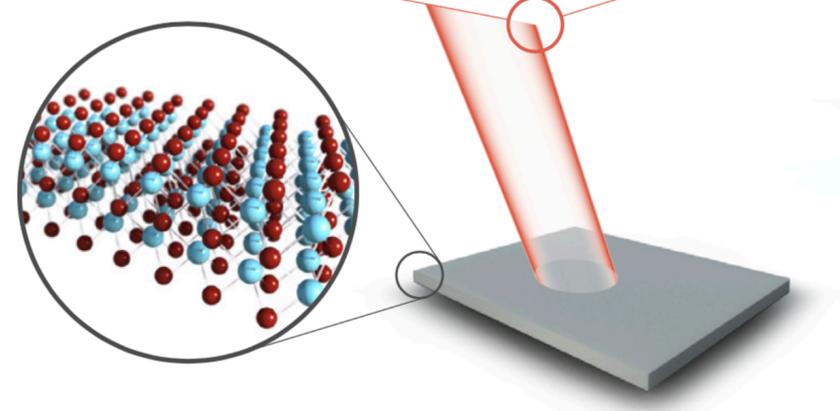
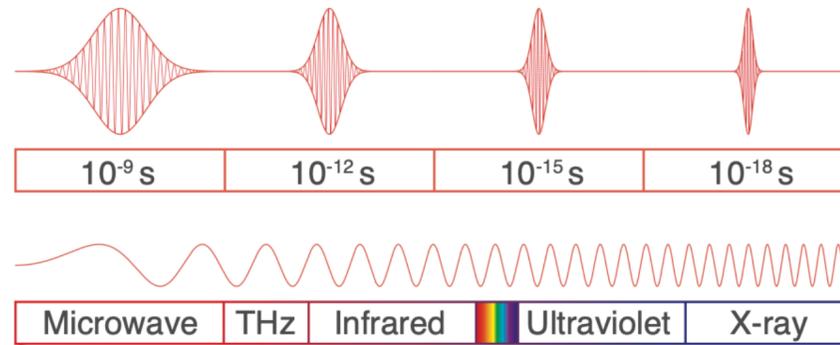
Mitrano & Wang, *Communications Physics* **3**, 184 (2020)

Disa, Nova & Cavalleri, *Nature Physics* **17**, 1087 (2021)

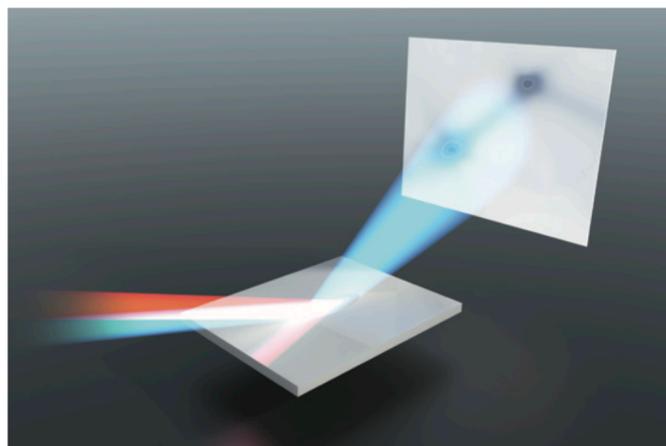
# Probes of ultrafast phenomena



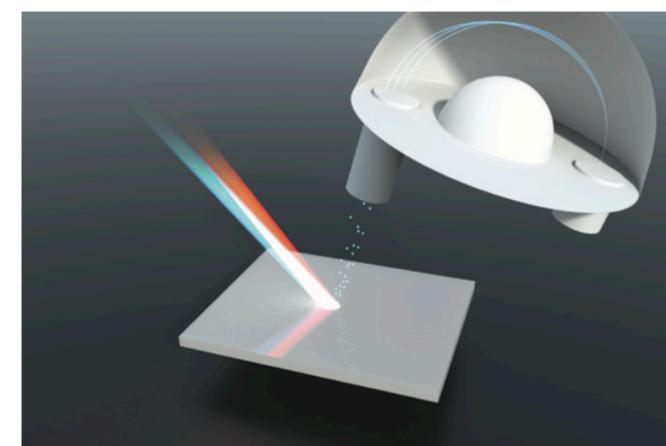
Optical probes



Scanning probes

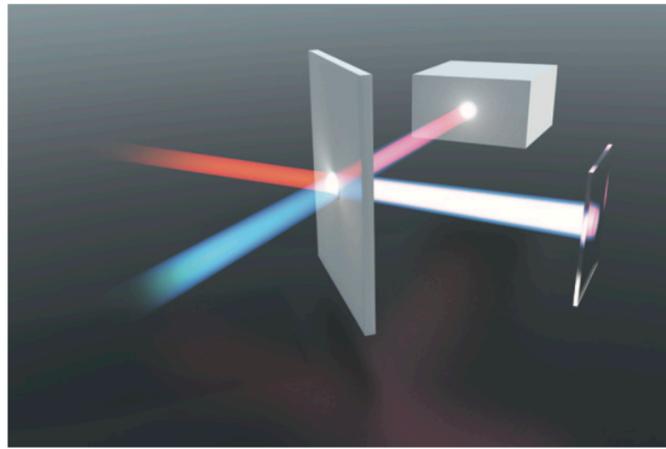


Scattering probes

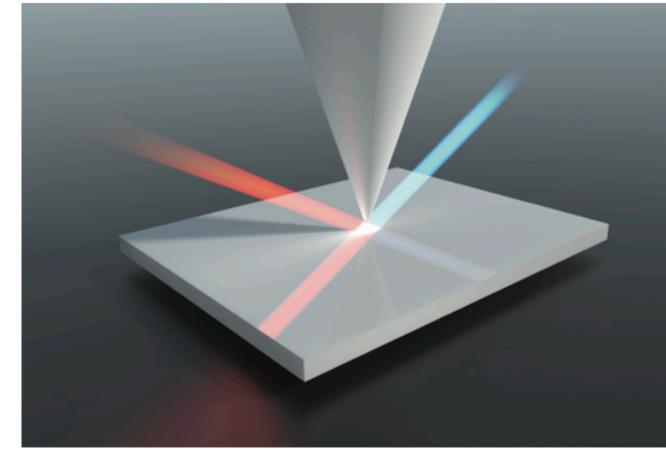
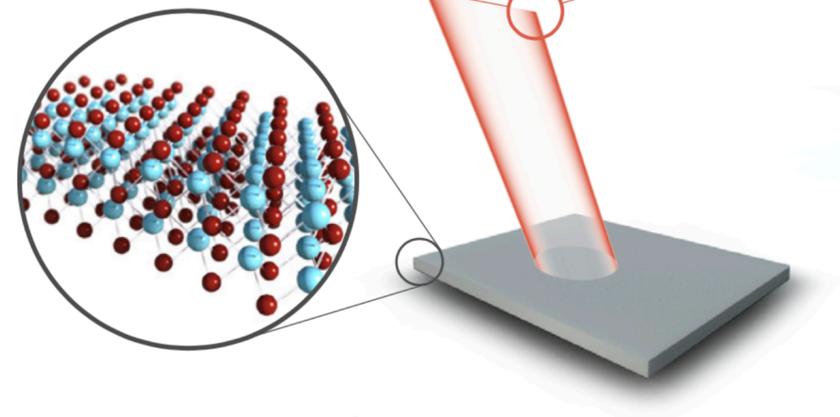
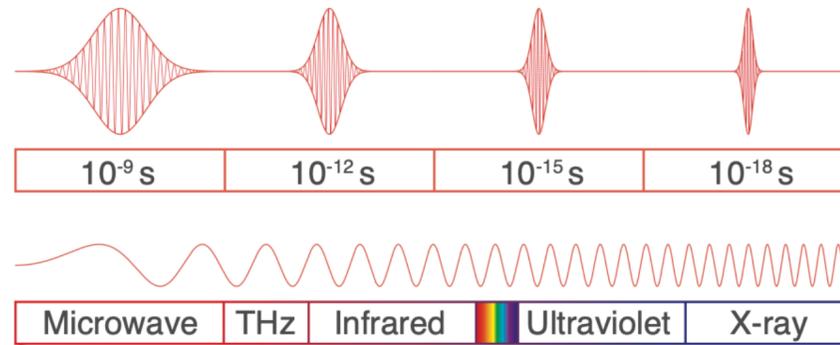


ARPES

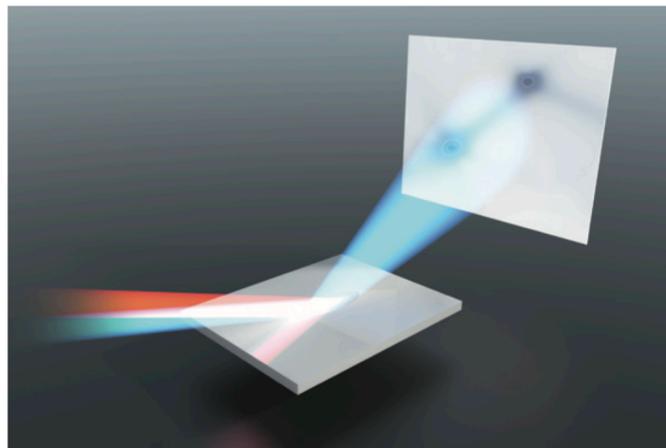
# Probes of ultrafast phenomena



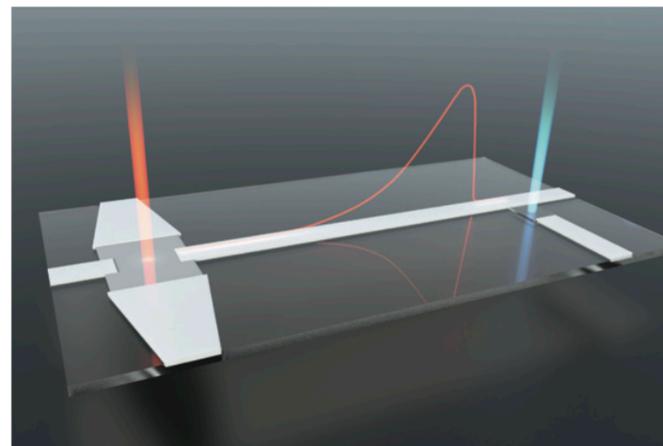
Optical probes



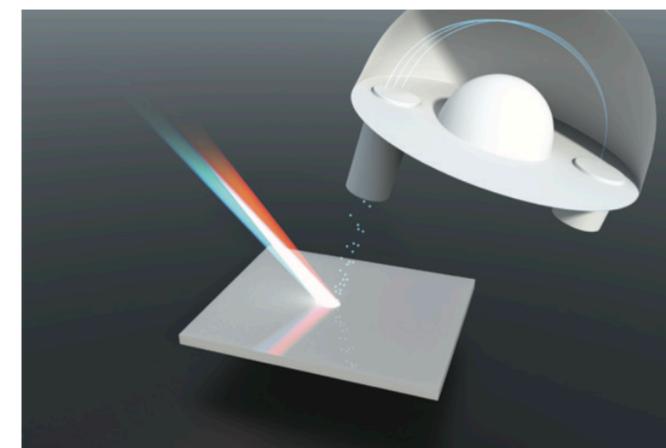
Scanning probes



Scattering probes



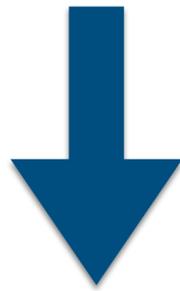
Transport



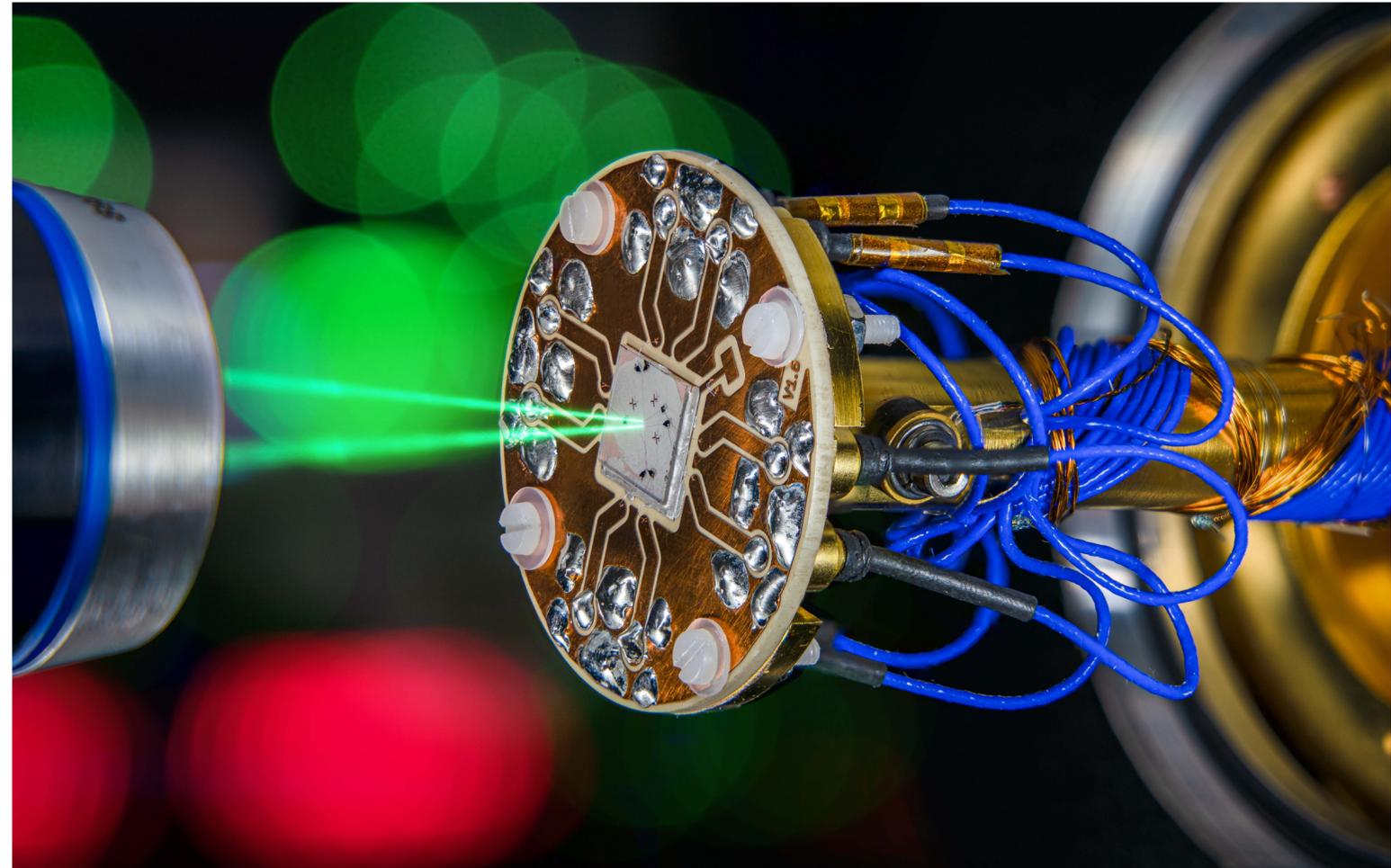
ARPES

# Femtosecond science on-chip

Ultrafast control  
of quantum materials



On-chip optoelectronic  
devices



Functionalizing non-  
equilibrium phenomena

Enhanced control via  
device engineering

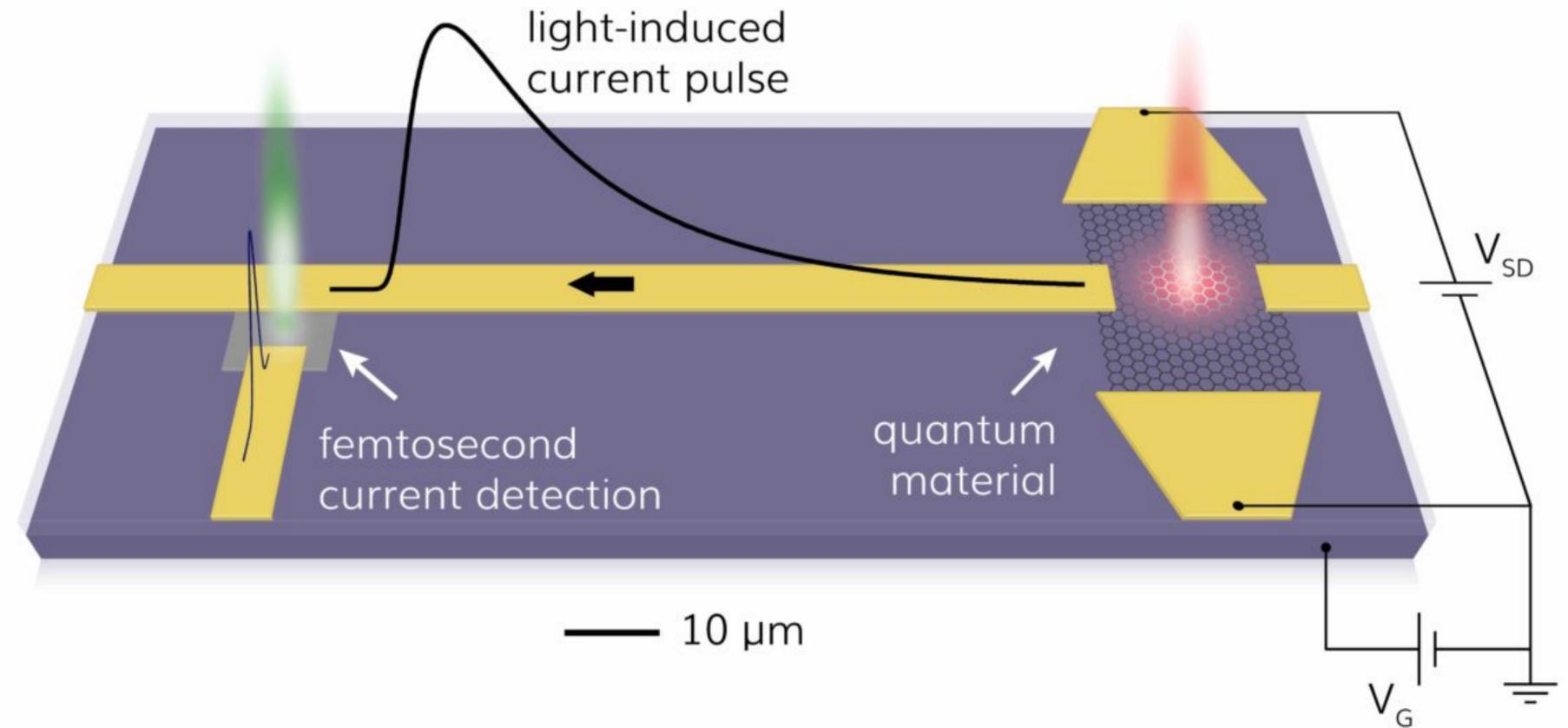
Unveil new phenomena  
via ultrafast currents

# Femtosecond science on-chip

**Ultrafast control  
of quantum materials**



**On-chip optoelectronic  
devices**



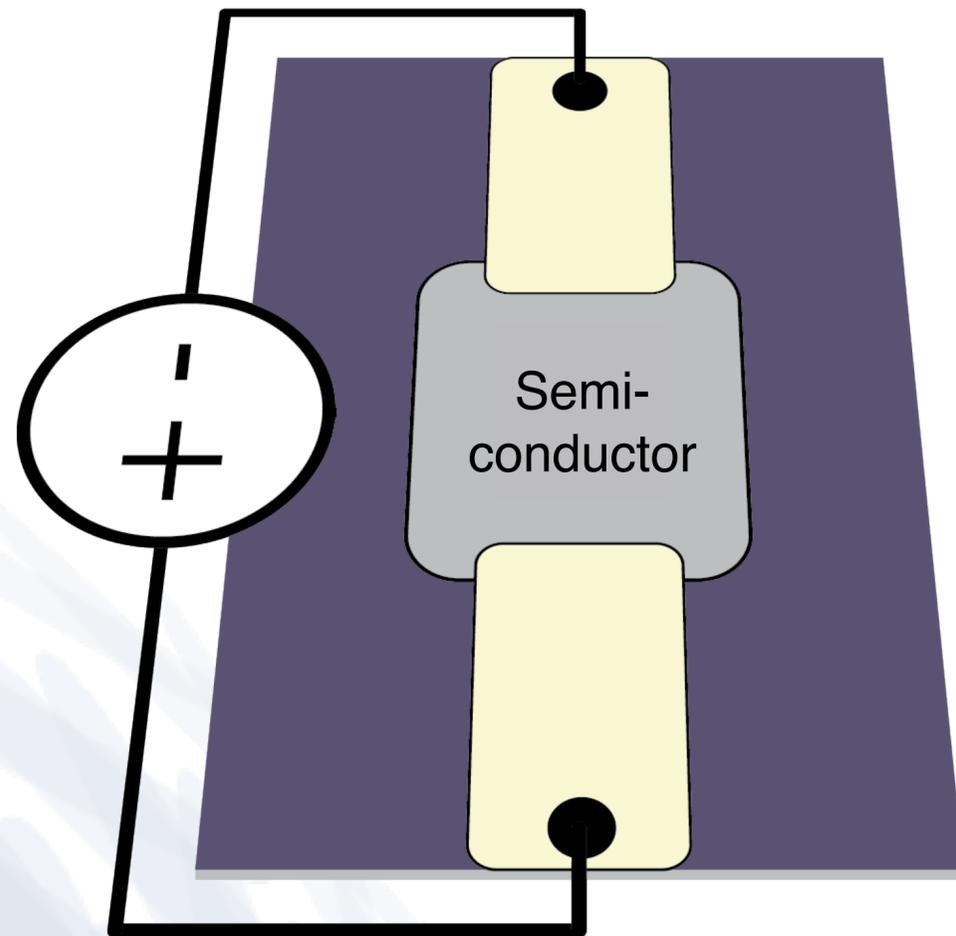
Functionalizing non-  
equilibrium phenomena

Enhanced control via  
device engineering

Unveil new phenomena  
via ultrafast currents

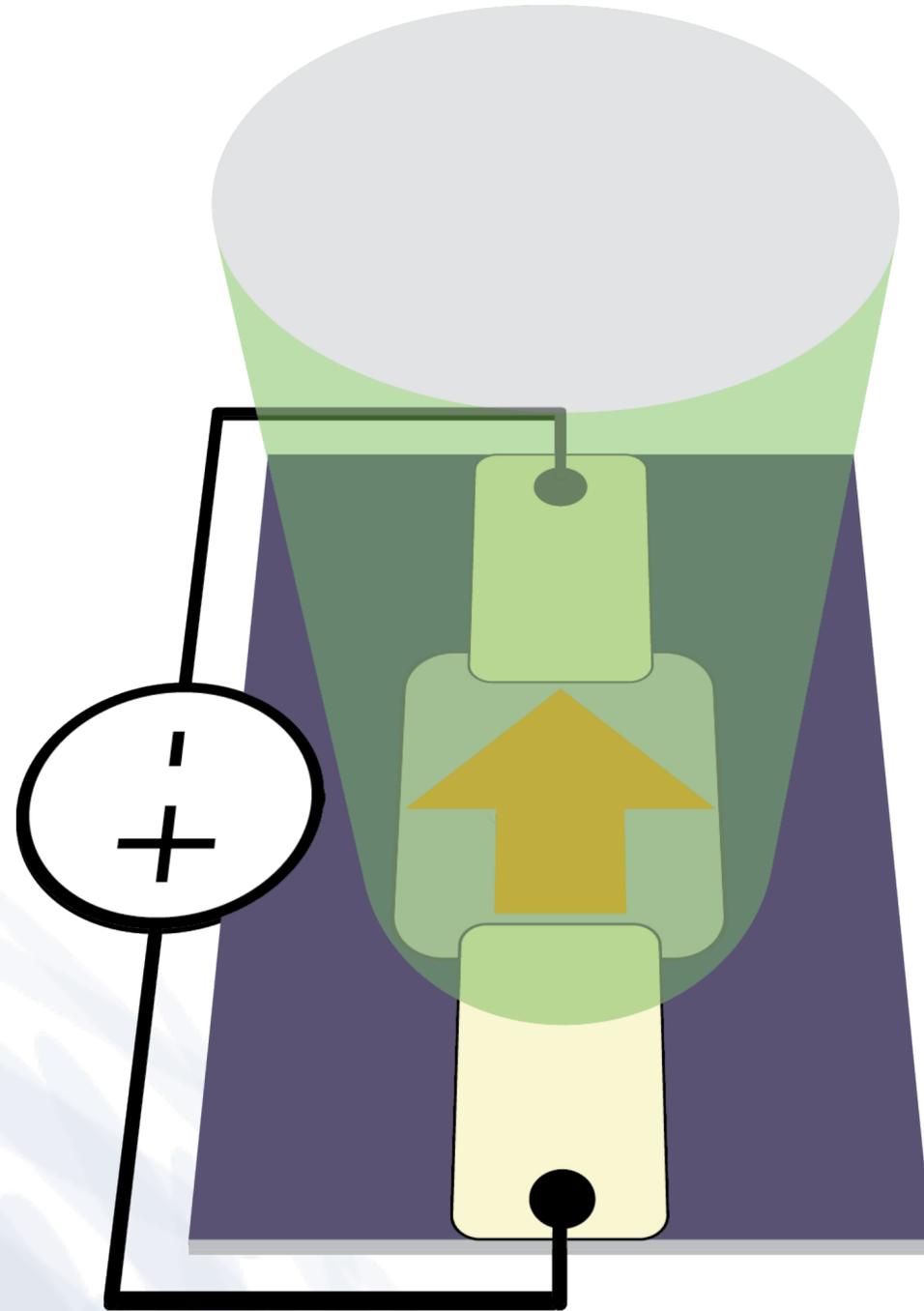
# Femtosecond science on-chip

**LASER OFF:** Electrically insulating  
No current flow



Photoconductive switch

# Femtosecond science on-chip



Photoconductive switch

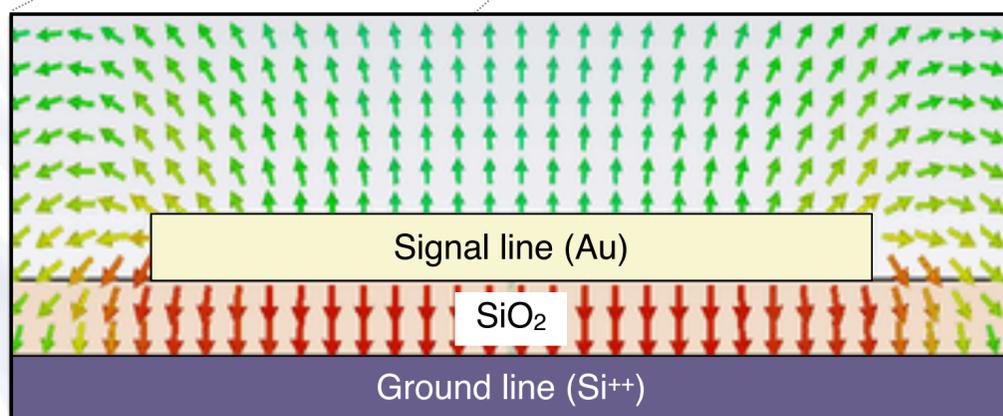
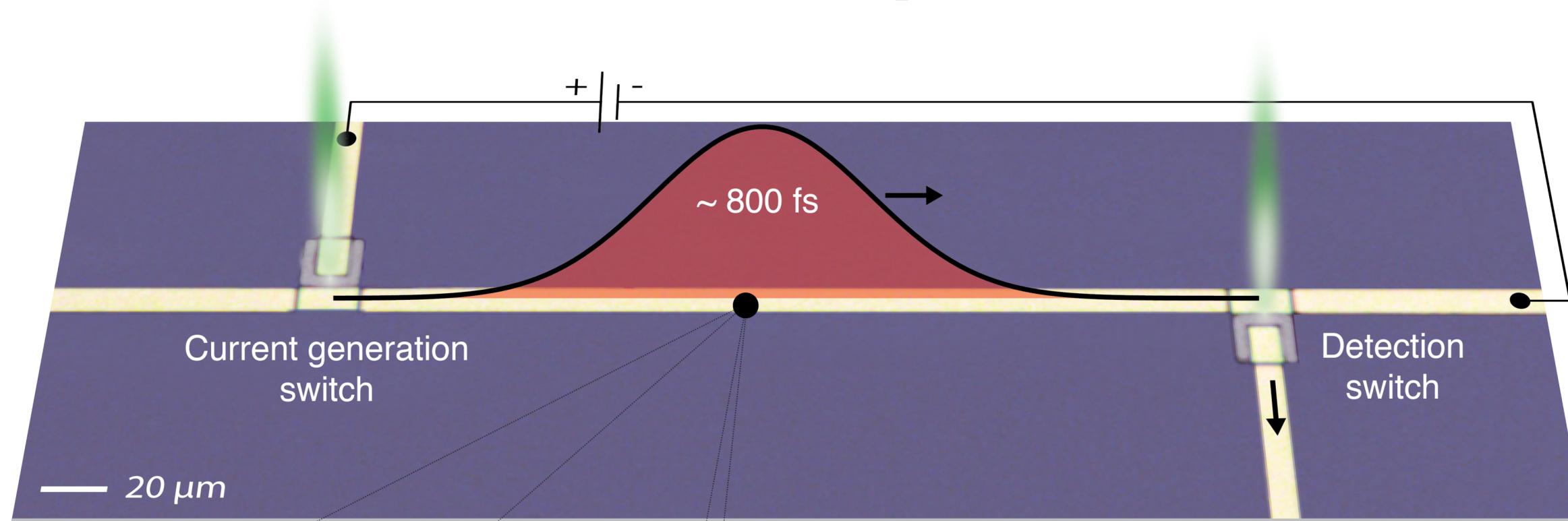
**LASER OFF:** Electrically insulating  
No current flow

**LASER ON:** Electrically conducting  
Current flow

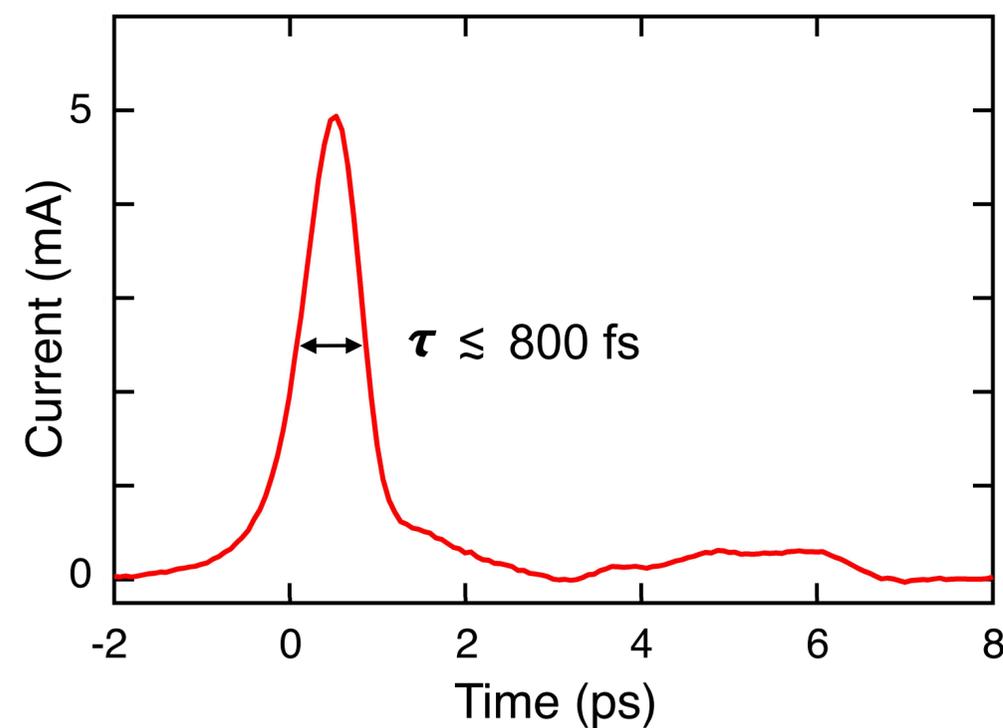
Operate at high speeds  
using ultrafast laser pulses

$$\tau \lesssim 1 \text{ ps}$$

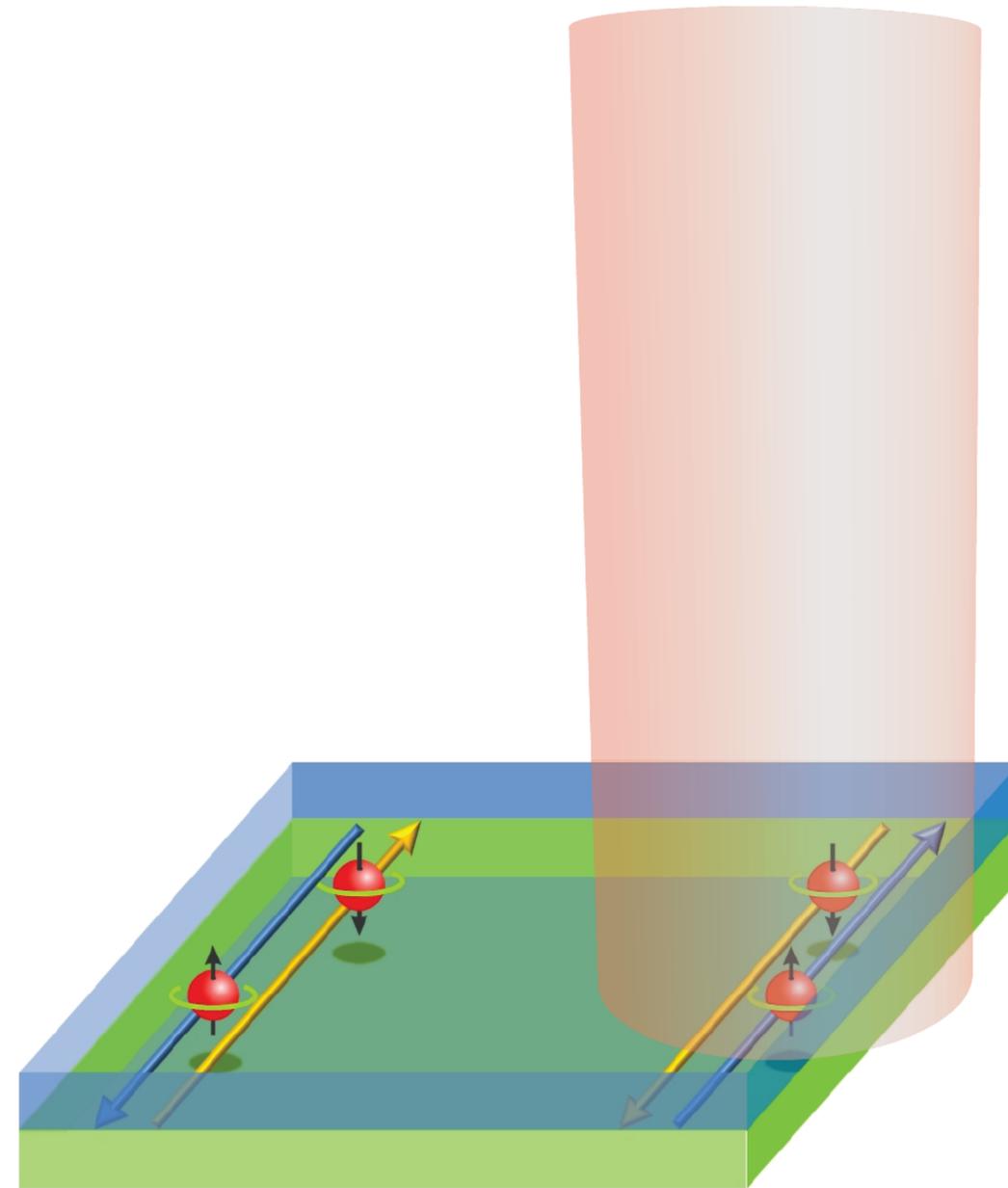
# Femtosecond science on-chip



Microstrip transmission line

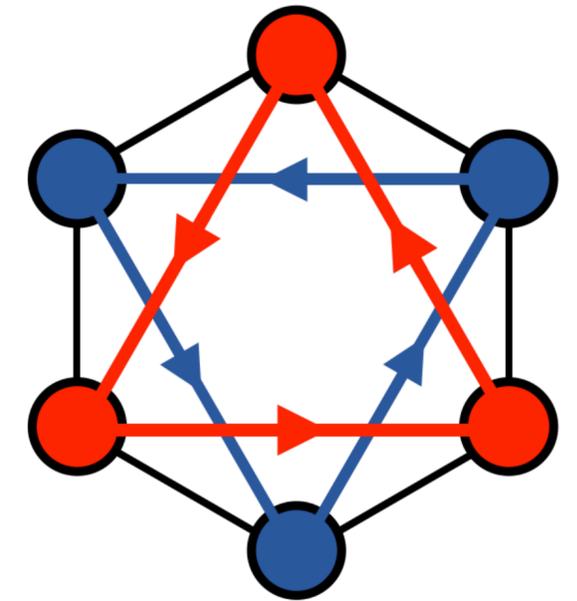
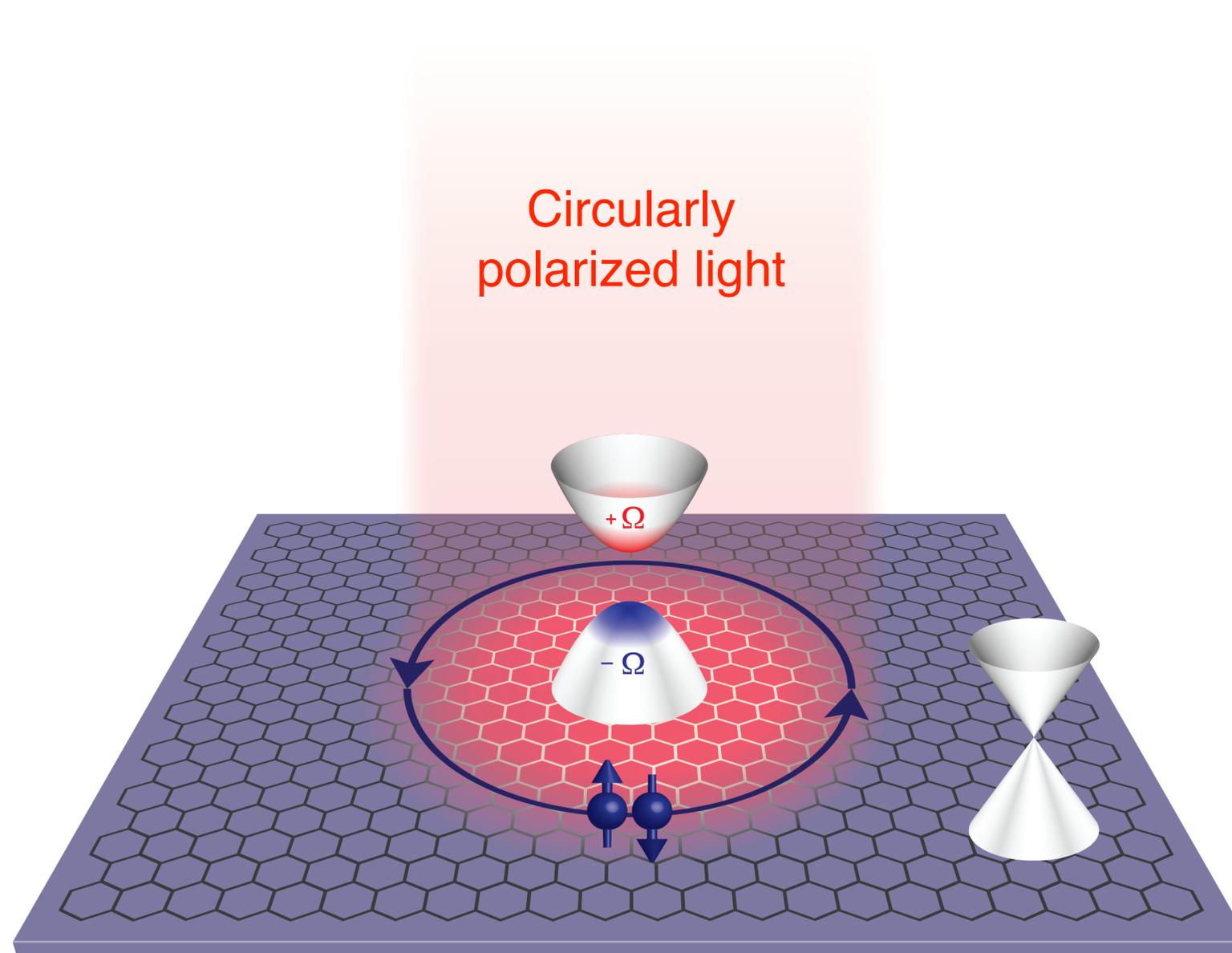


# Light-induced topological transport



**Manipulate the topology of materials with light**

# Floquet topological insulator in graphene

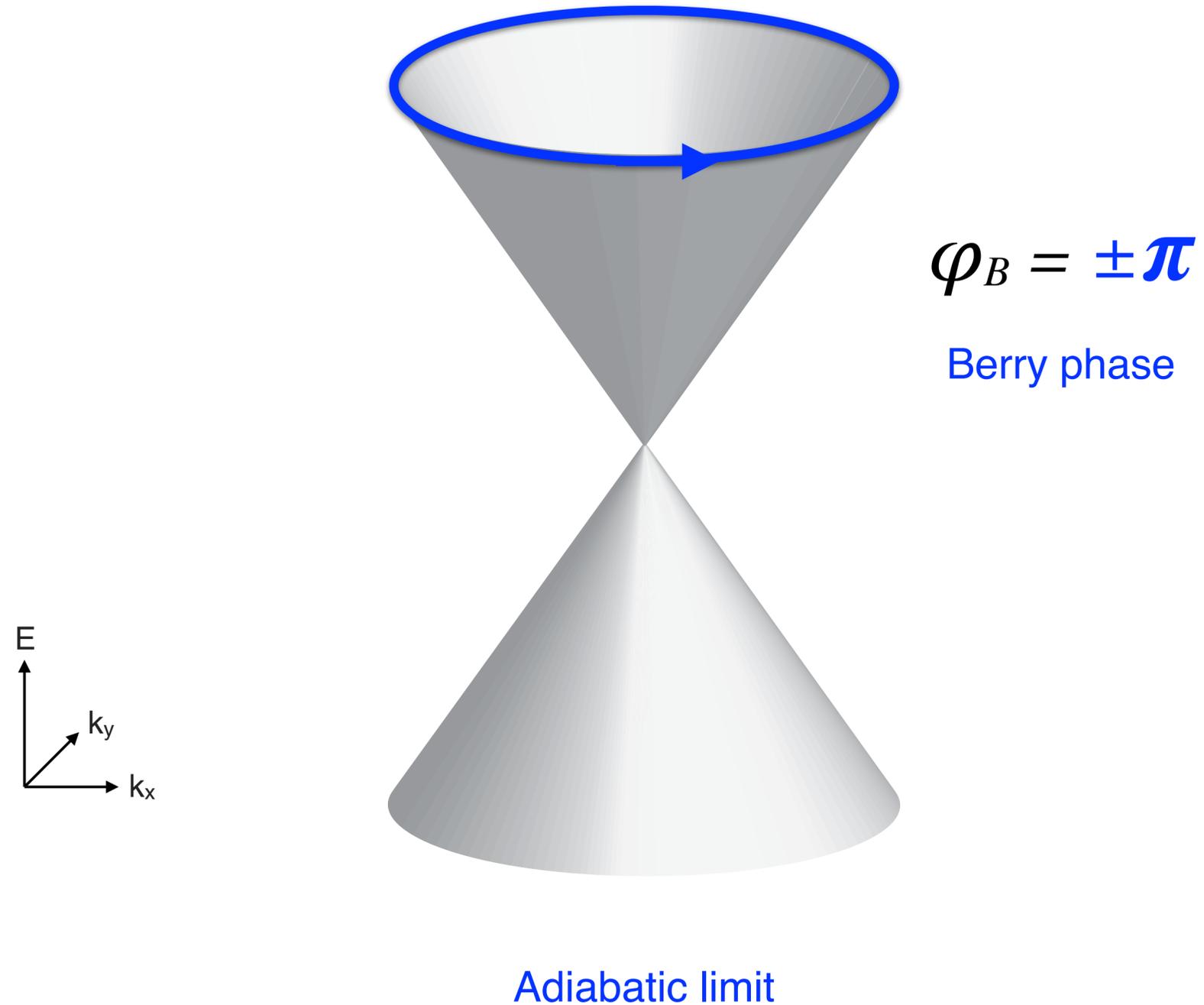


Floquet-engineered  
Haldane Model

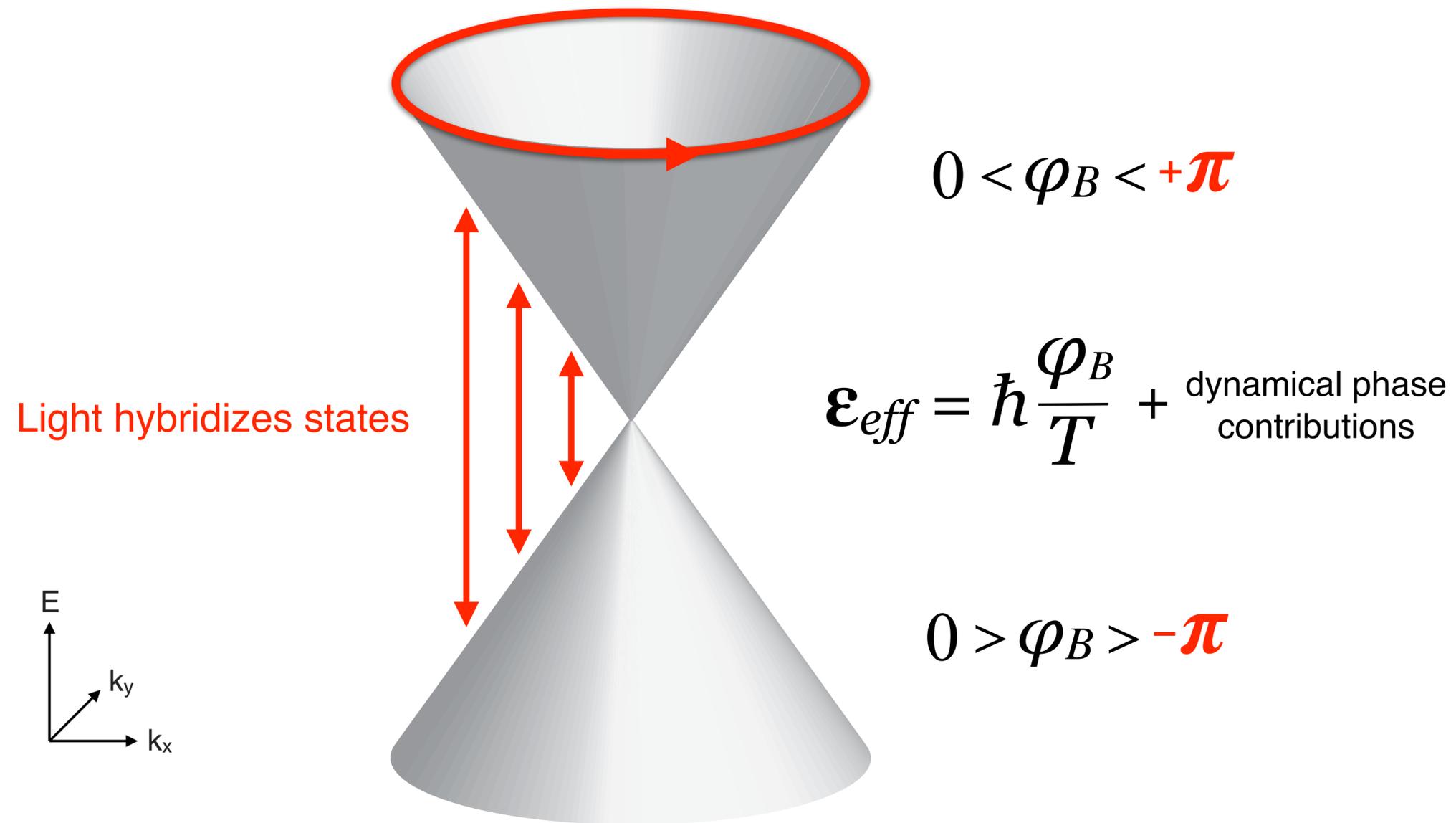
Kitagawa *et al.* *Phys. Rev. B*  
84, 235108 (2011)

Oka & Aoki, *Phys. Rev. B* **79**, 081406 (2009)

# Floquet topological insulator in graphene



# Floquet topological insulator in graphene



Light hybridizes states

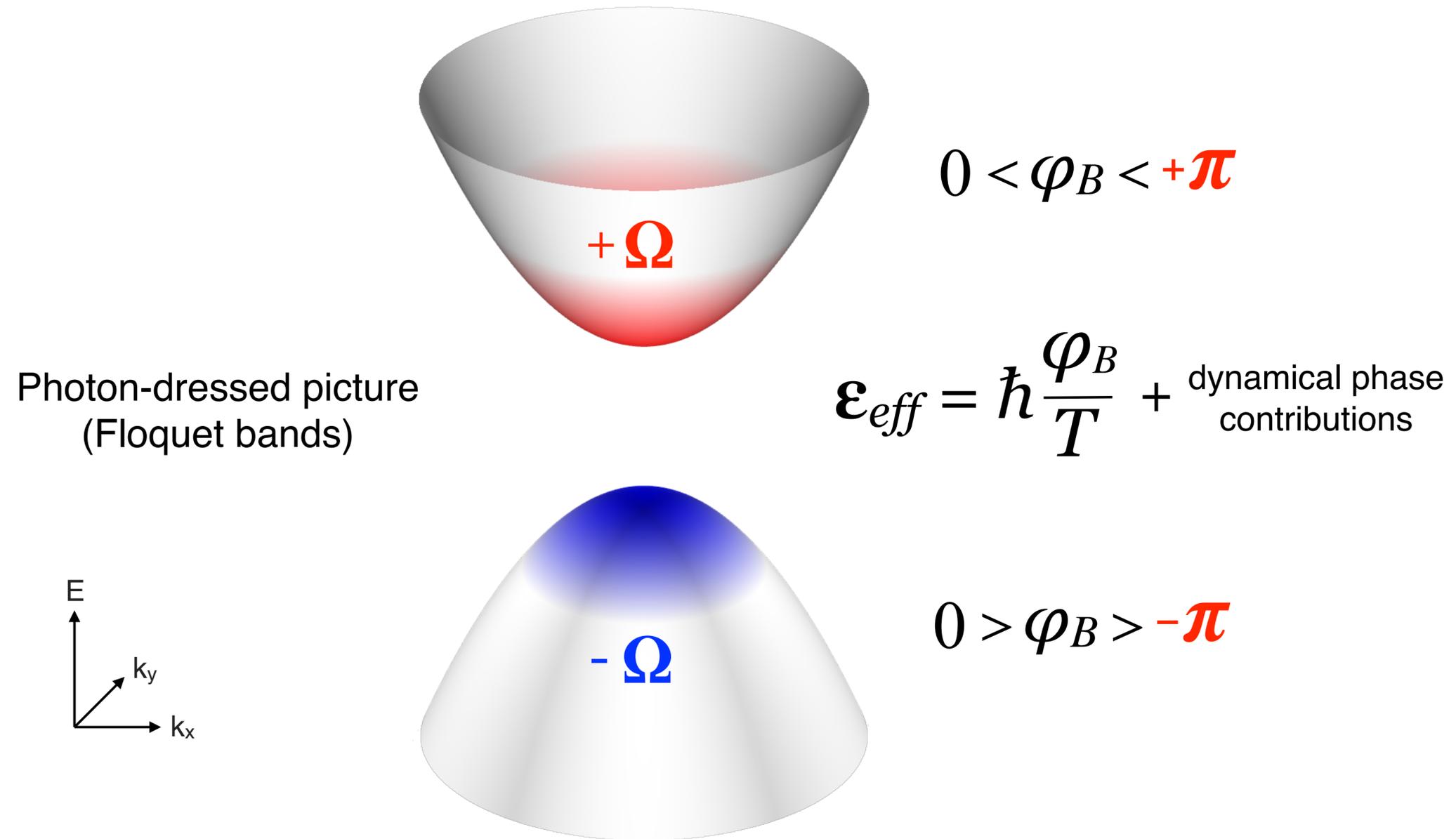
$$0 < \varphi_B < +\pi$$

$$\epsilon_{eff} = \hbar \frac{\varphi_B}{T} + \text{dynamical phase contributions}$$

$$0 > \varphi_B > -\pi$$

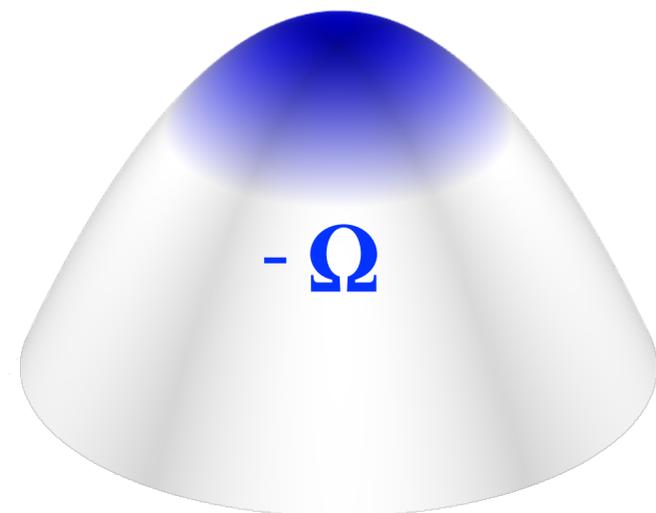
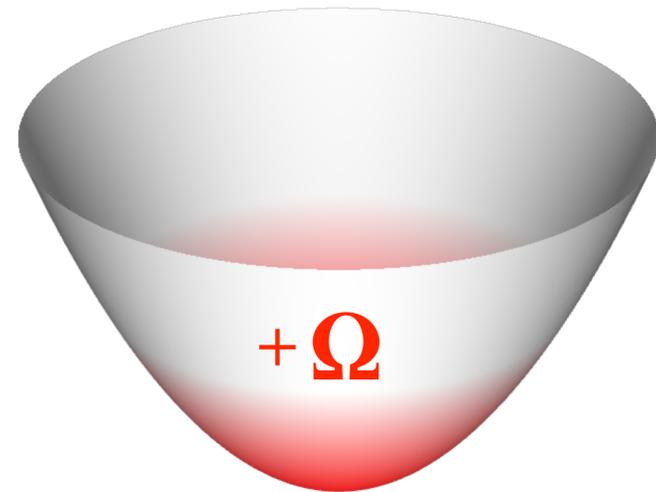
Non-adiabatic limit  
(driven w/ circularly polarized light)

# Floquet topological insulator in graphene



$\Omega$ : Berry curvature

# Floquet topological insulator in graphene



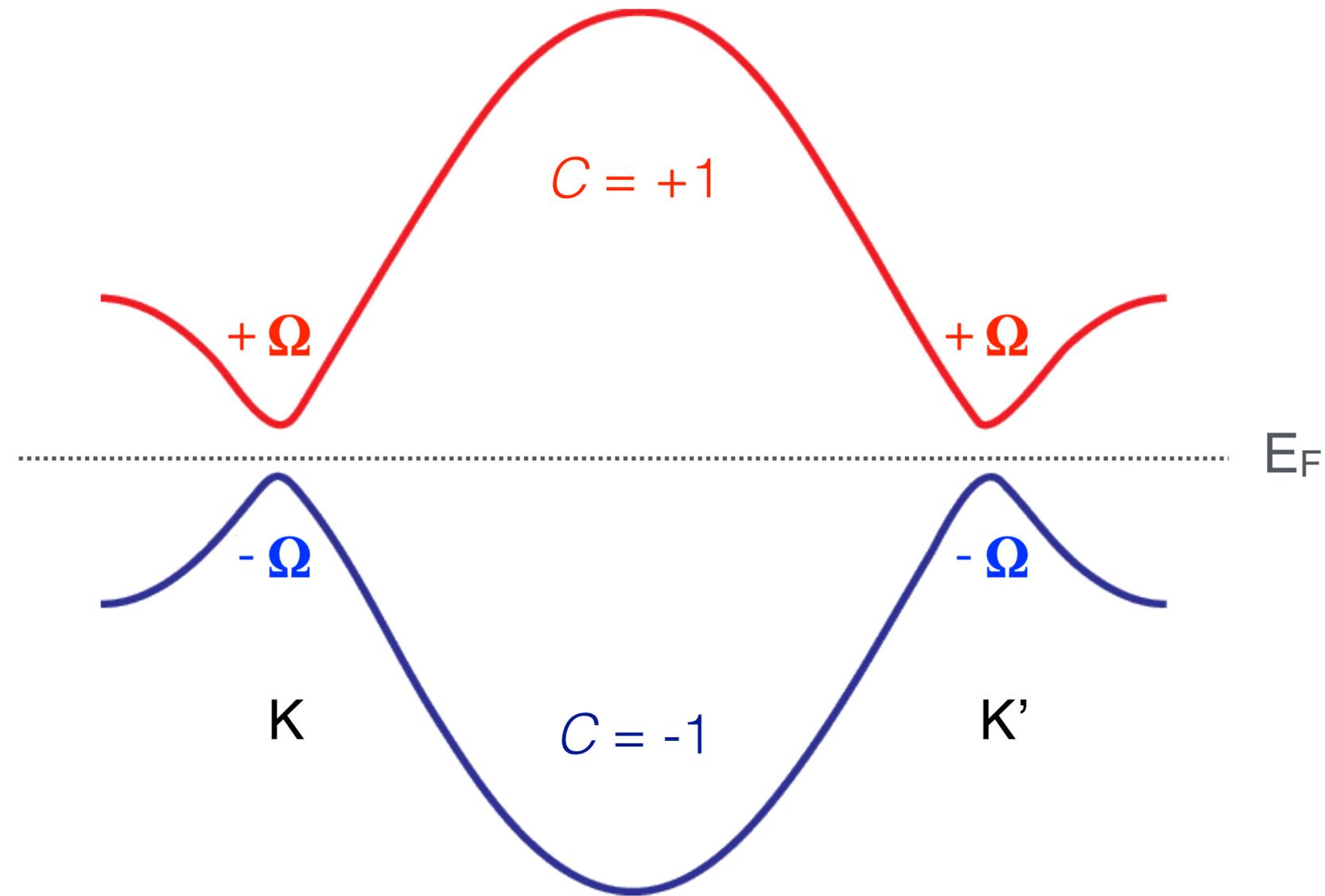
$\Omega$ : Berry curvature

Anomalous velocity:

$$\mathbf{v}_n(\mathbf{k}) = \frac{\partial \varepsilon_n(\mathbf{k})}{\hbar \partial \mathbf{k}} - \underbrace{\frac{e}{\hbar} \mathbf{E} \times \boldsymbol{\Omega}_n(\mathbf{k})}_{\sigma_{xy}}$$

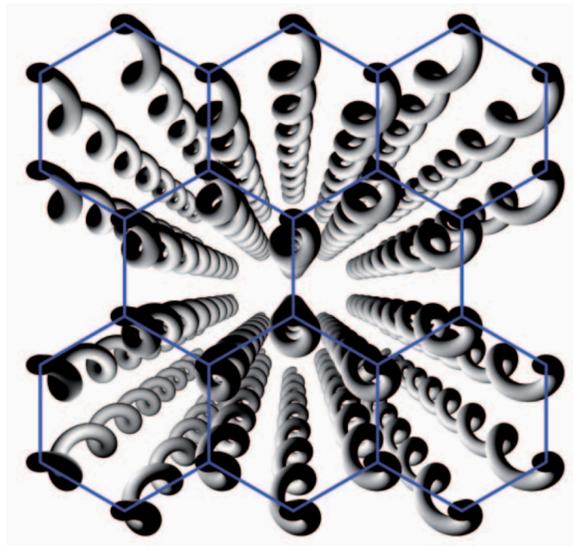
# Floquet topological insulator in graphene

$\Omega$ : Berry curvature



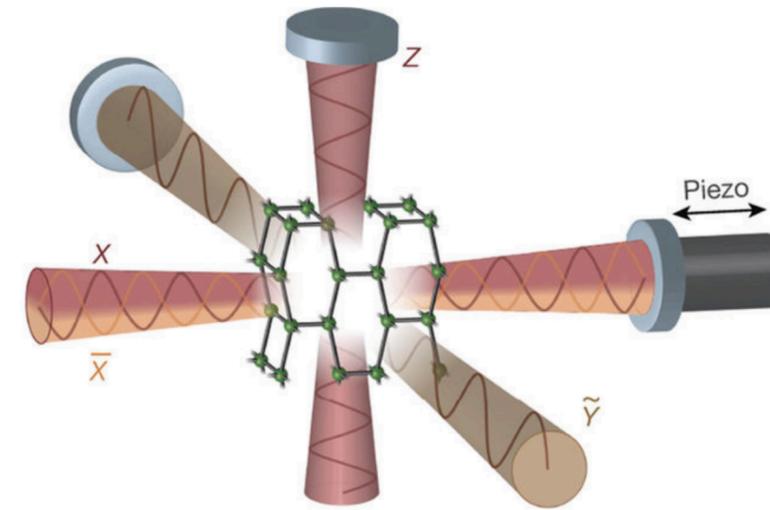
Topological Chern Insulator  $\rightarrow$  Quantum anomalous Hall effect

# Floquet topological insulator in graphene



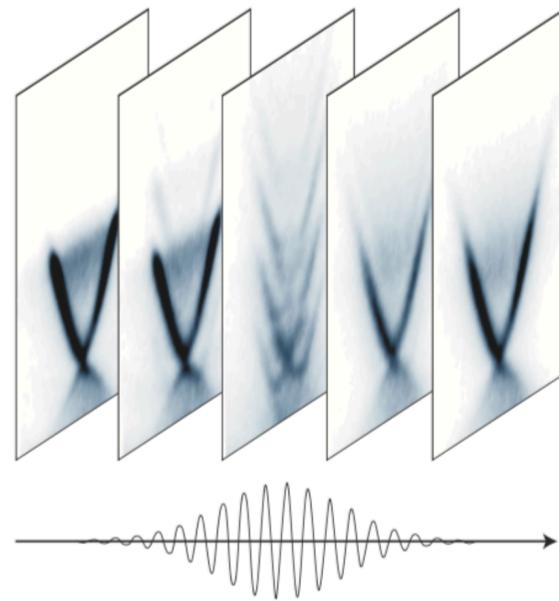
**Photonic waveguides**

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



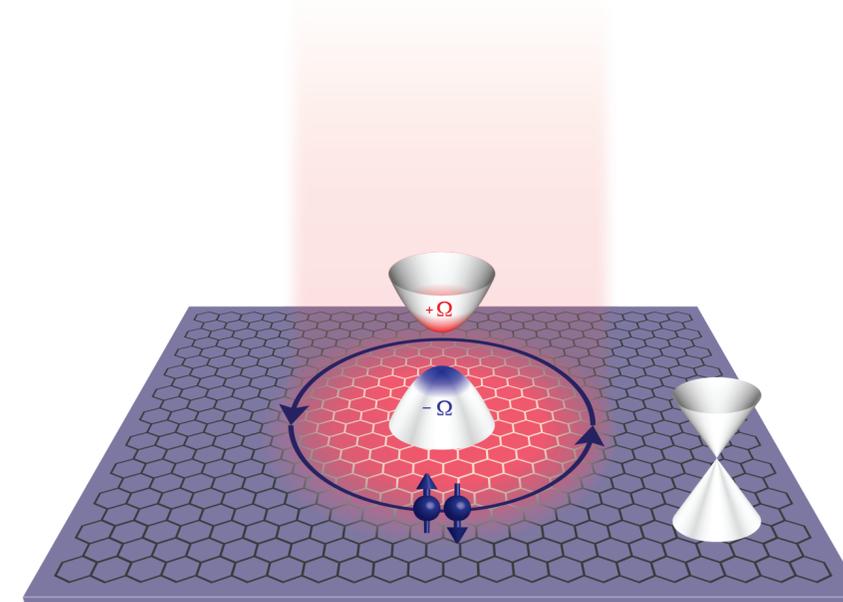
**Optical lattices**

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



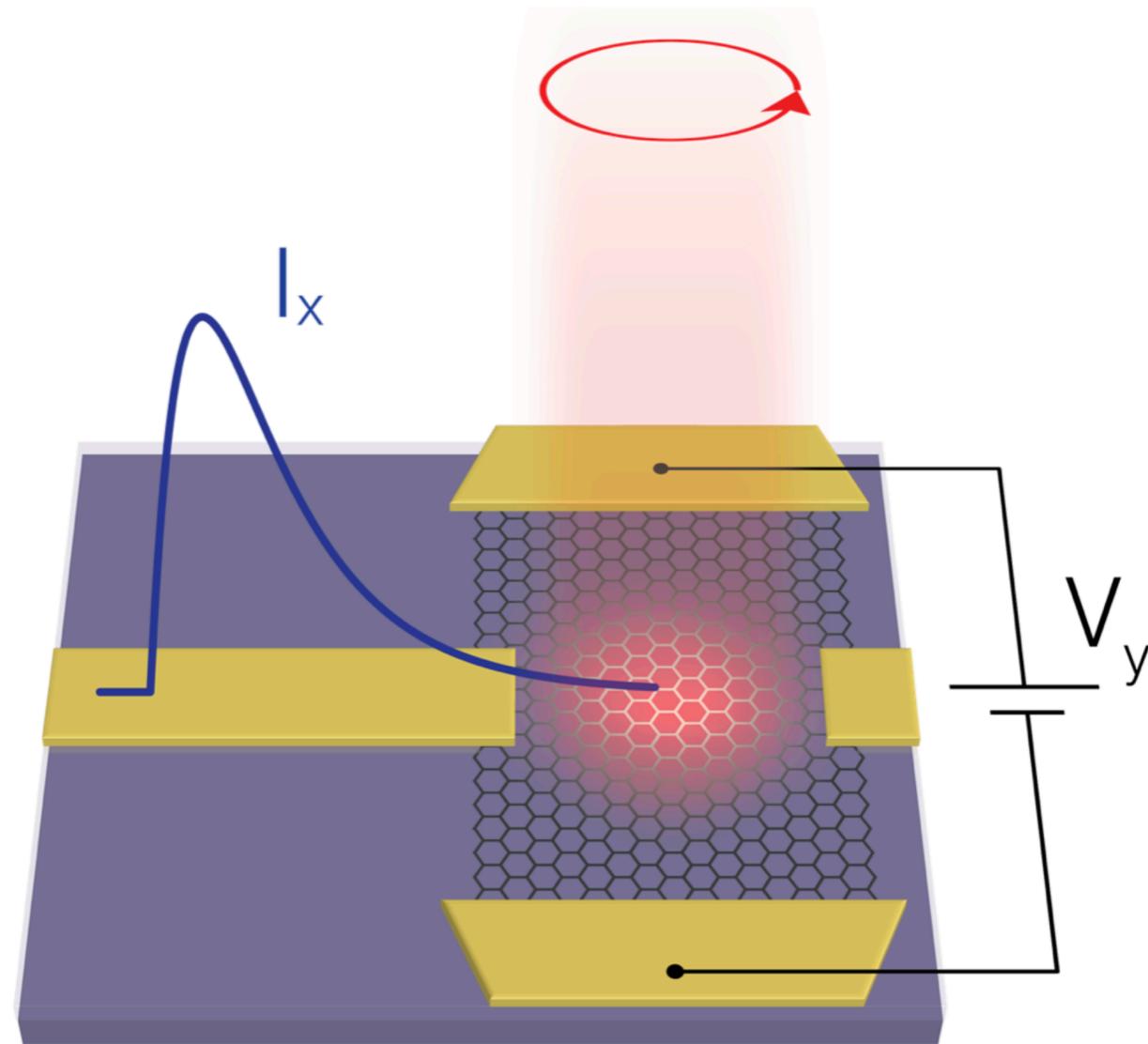
**ARPES Bi<sub>2</sub>Se<sub>3</sub>**

Wang *et. al*, *Science* 342, 453 (2013)



**Light-induced topological transport in graphene?**

# Light-induced anomalous Hall effect in graphene



$$E_g \sim E^2 / \omega^3$$

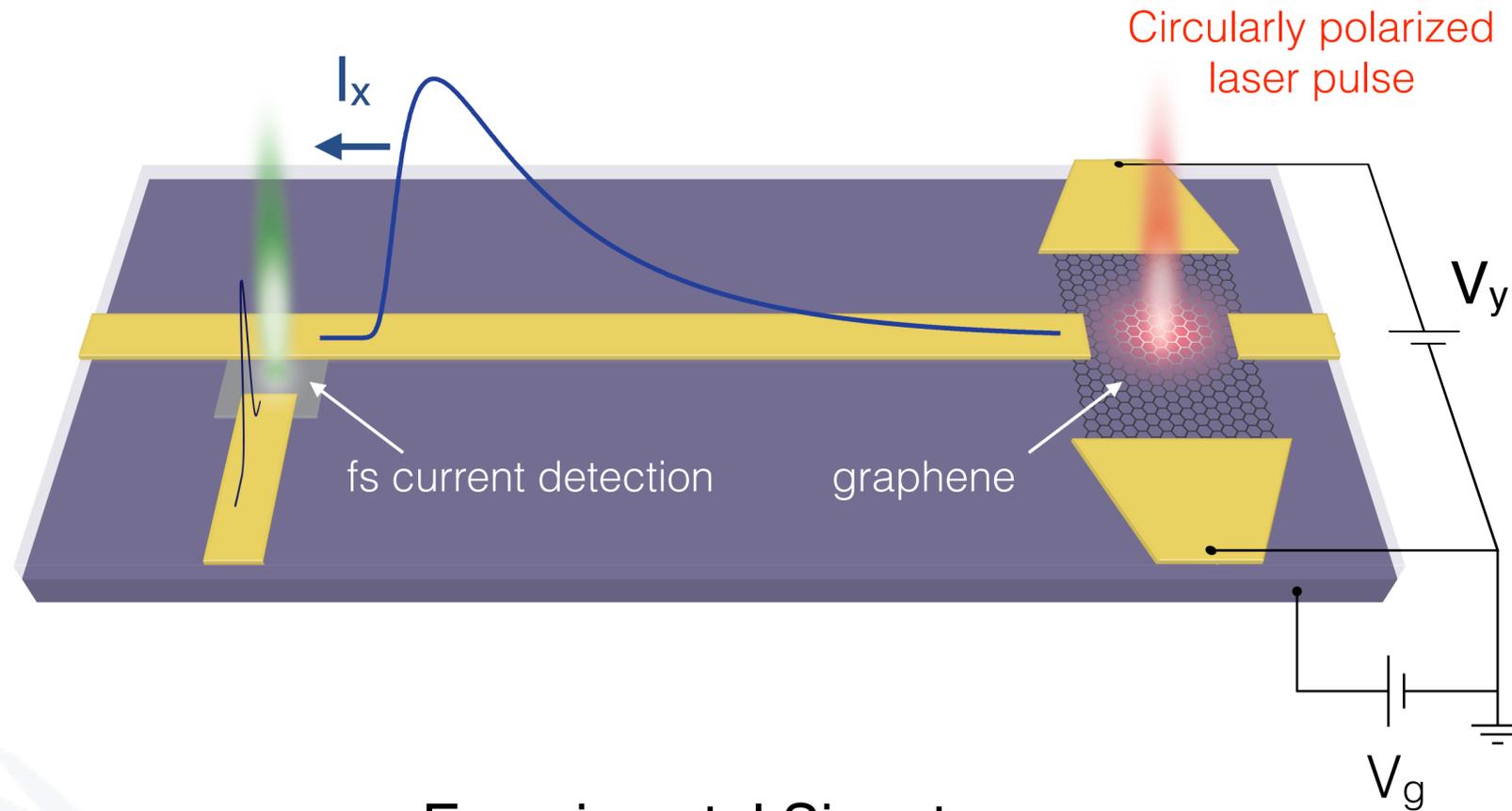
Required laser field strength  
 $\sim 10^7 - 10^{10}$  V/m

Ultrafast mid-infrared  
laser pulse

Ultrafast current pulses

Requires ultrafast  
transport techniques

# Light-induced anomalous Hall effect in graphene



## Experimental Signatures:

*For a fixed light helicity:*

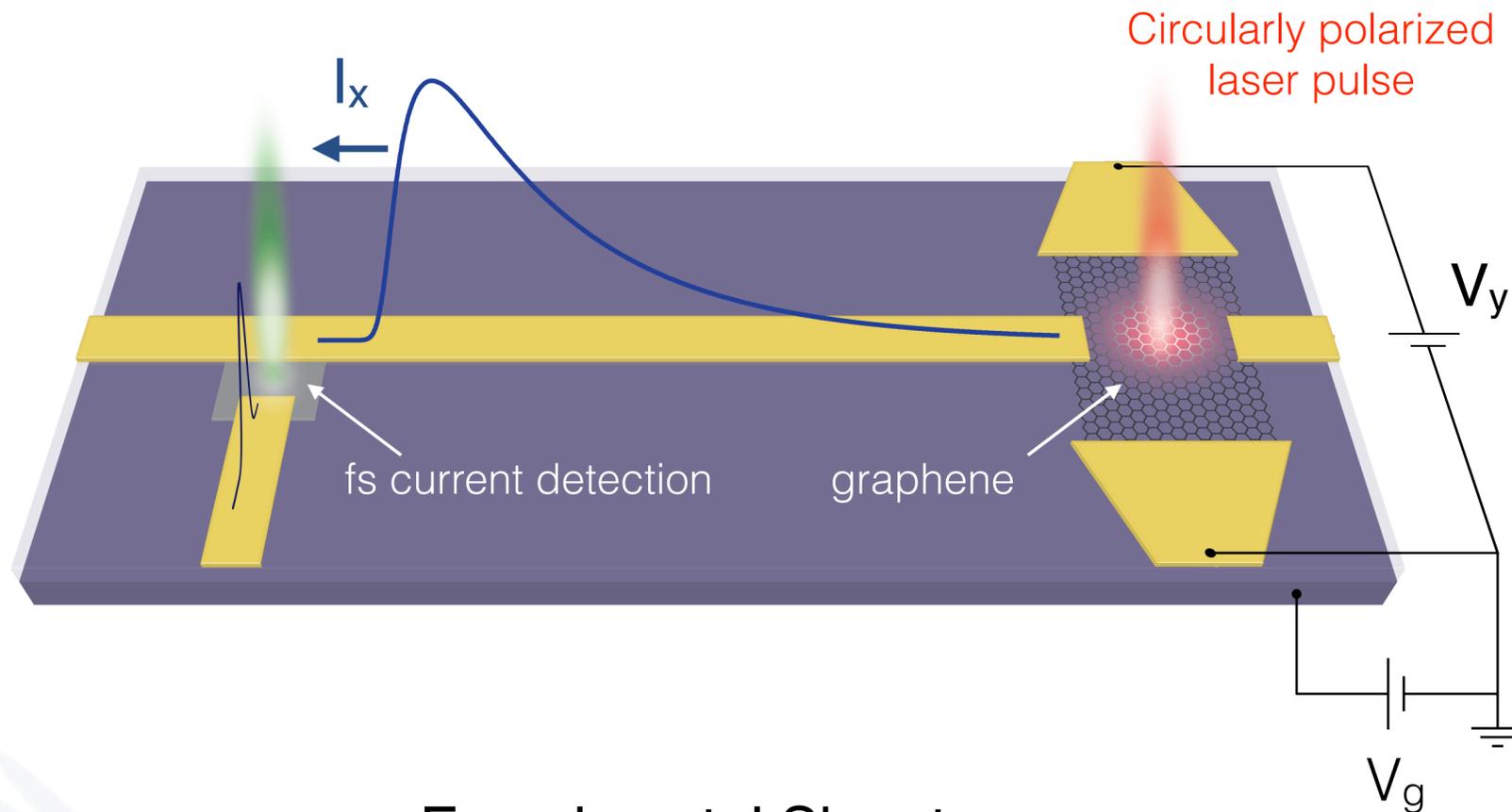
$I_x$  scales linearly with  $V_y$

*For a fixed  $V_y$ :*

$I_x$  reverses with light helicity

→ we measure  $I_x$  [↺ - ↻]

# Light-induced anomalous Hall effect in graphene



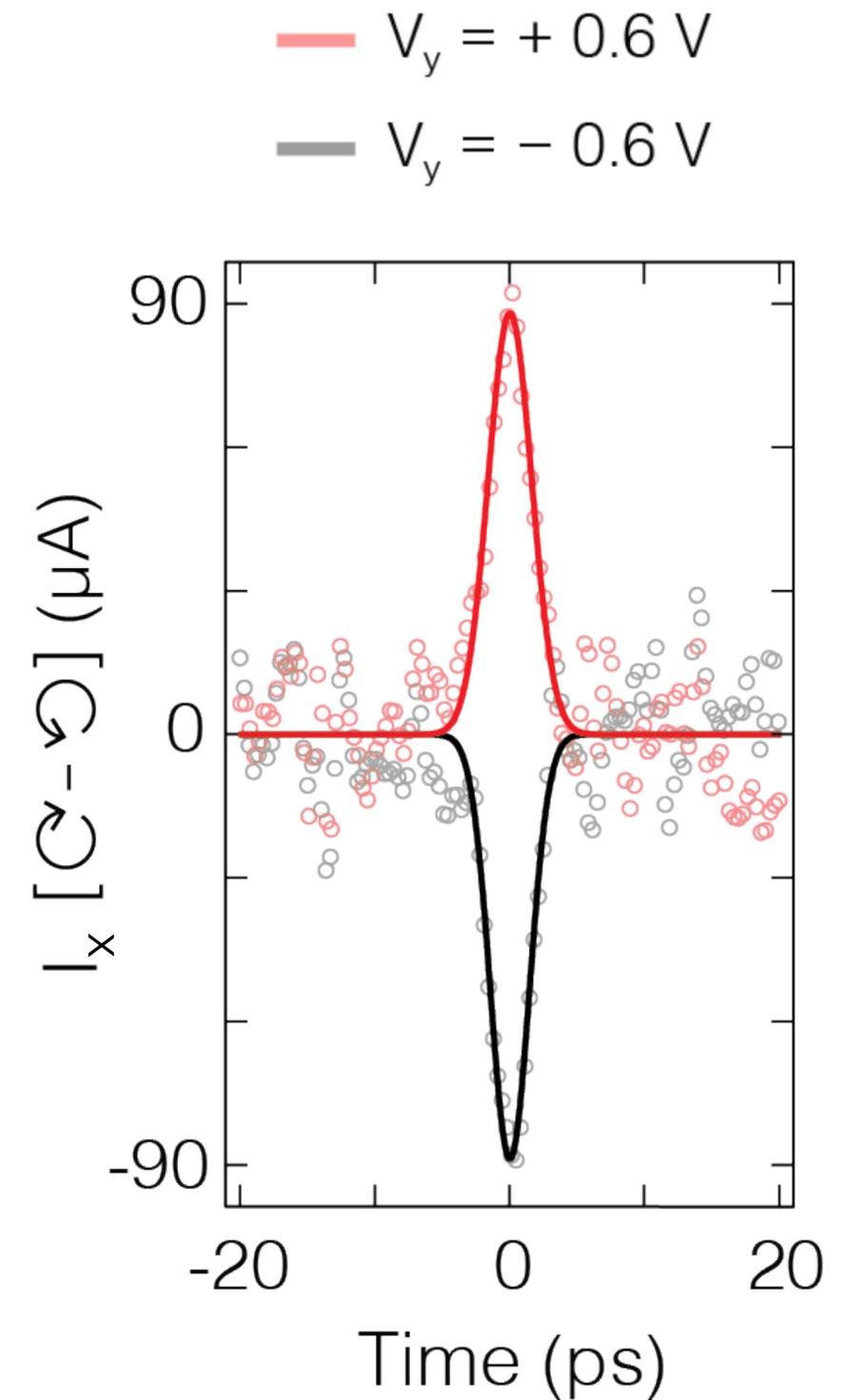
## Experimental Signatures:

*For a fixed light helicity:*

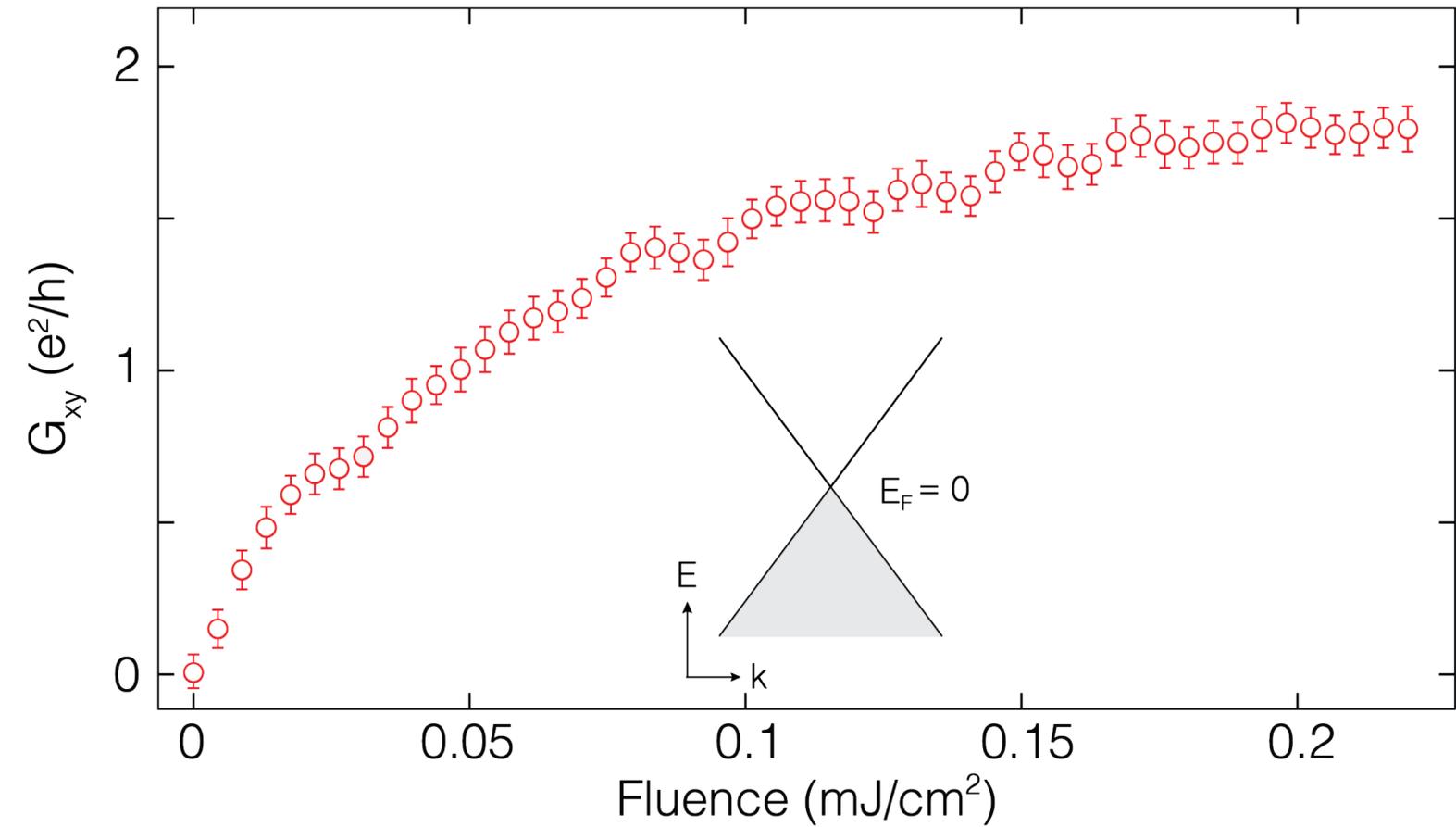
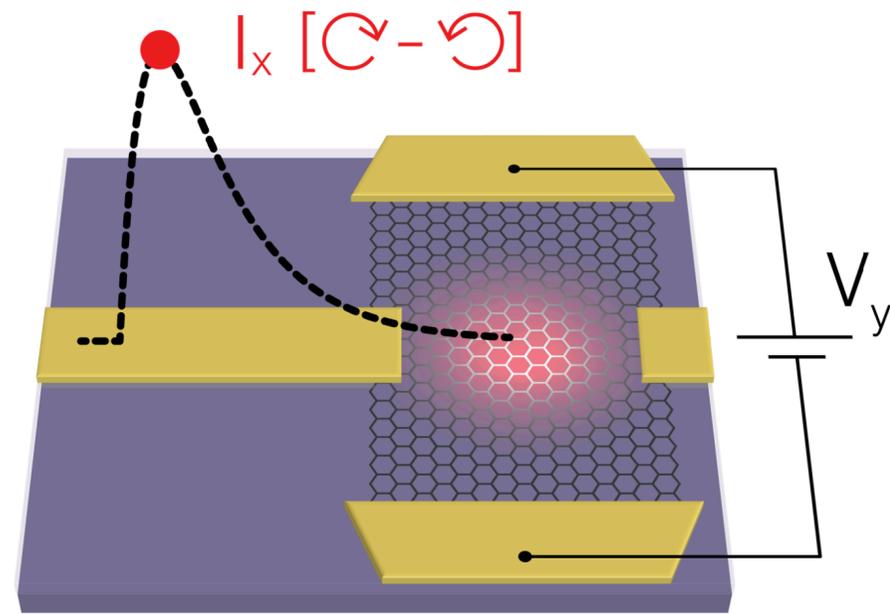
$I_x$  scales linearly with  $V_y$

*For a fixed  $V_y$ :*

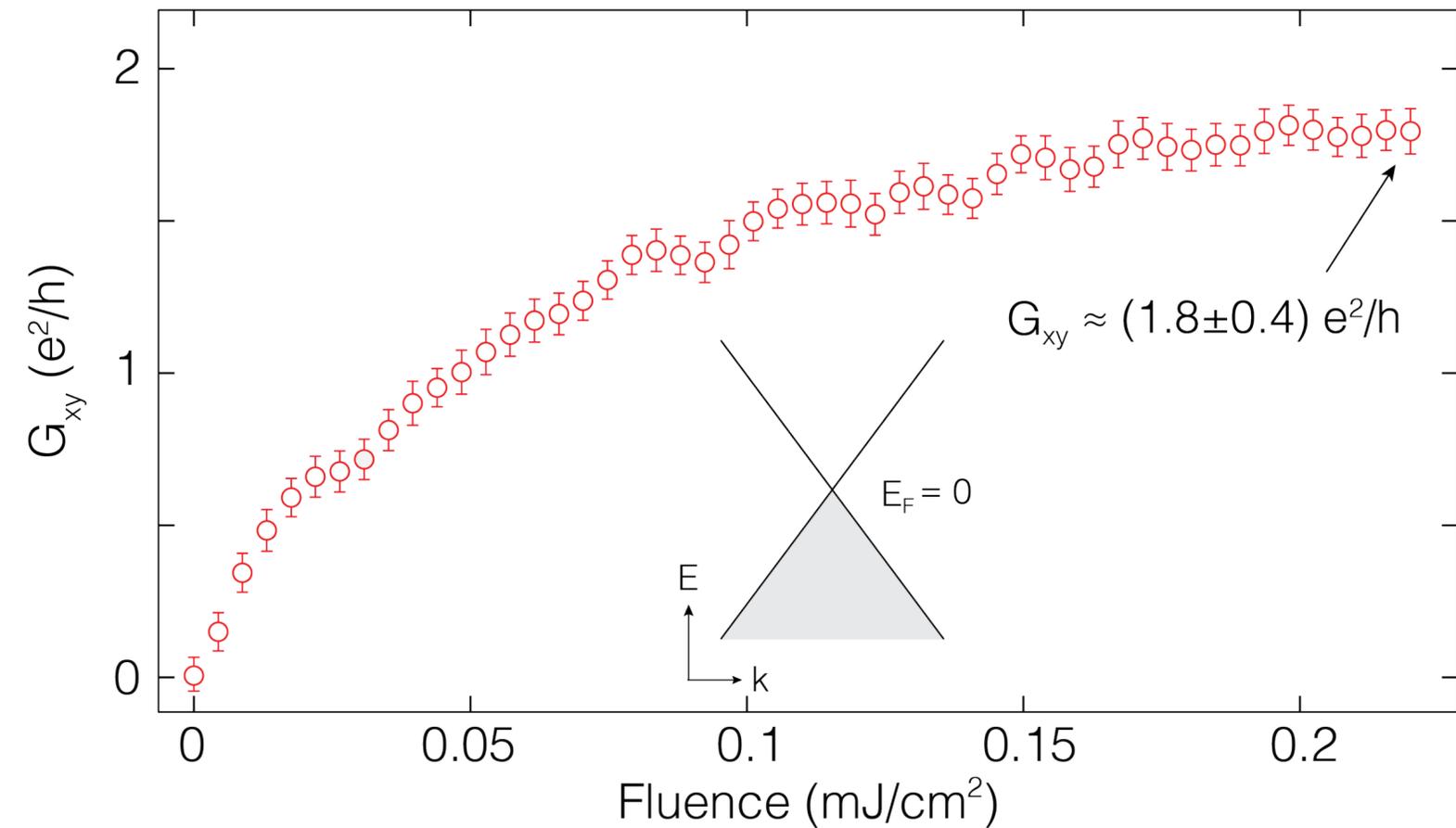
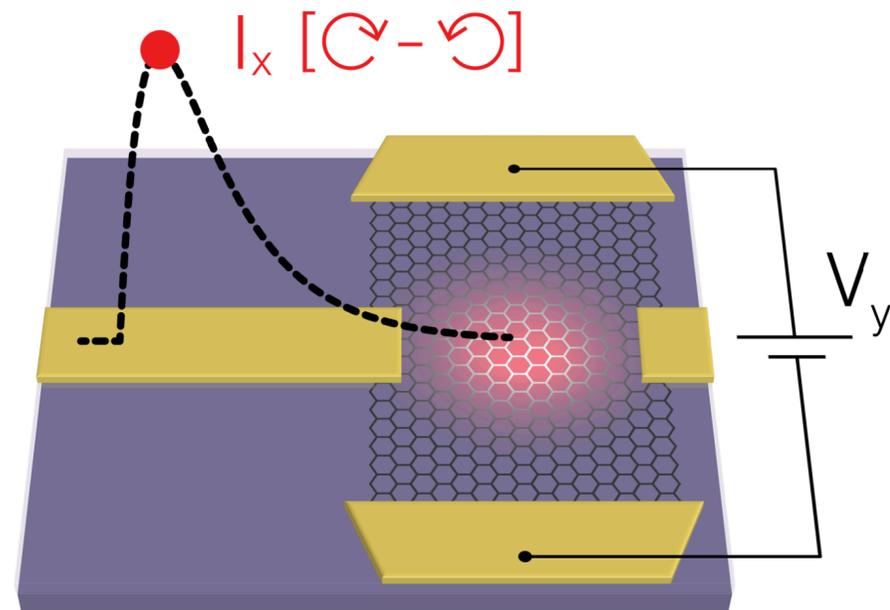
$I_x$  reverses with light helicity



# Light-induced anomalous Hall effect in graphene



# Light-induced anomalous Hall effect in graphene



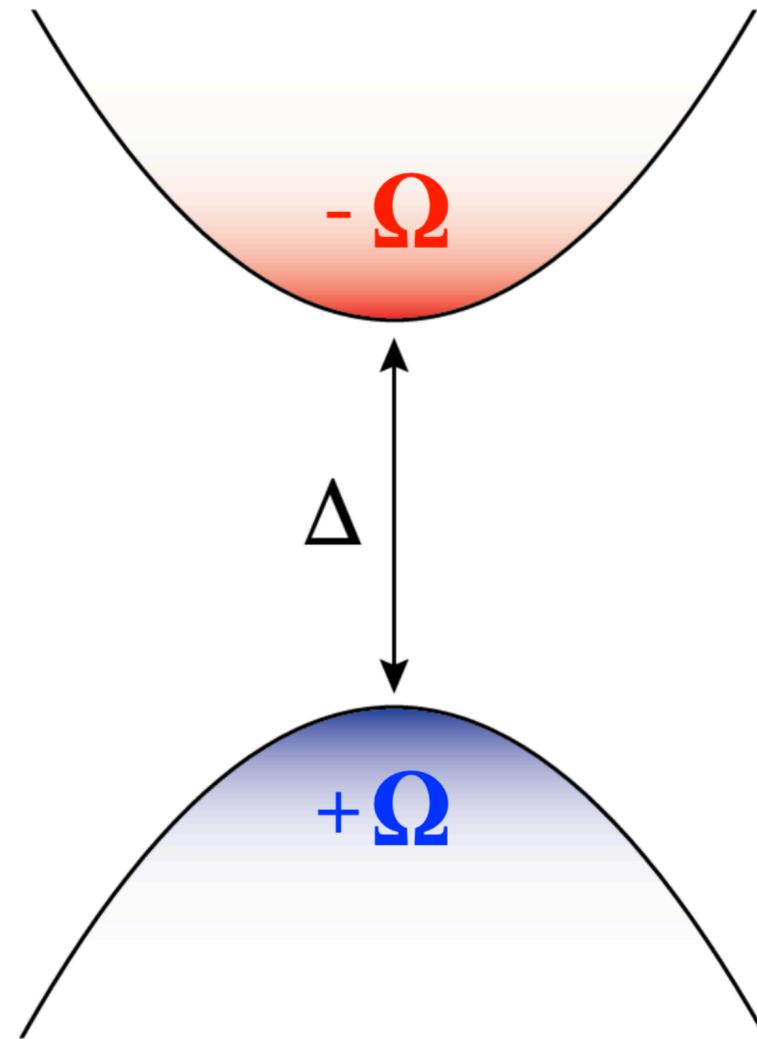
*Theoretical predictions for mid-IR light:*

Foa Torres *et al.*, *Phys. Rev. Lett.* 113, 266801 (2014)

Mikami *et al.*, *Phys. Rev. B* 93, 144307 (2016)

Mclver *et al.* *Nature Physics* 16, 38-41 (2020)

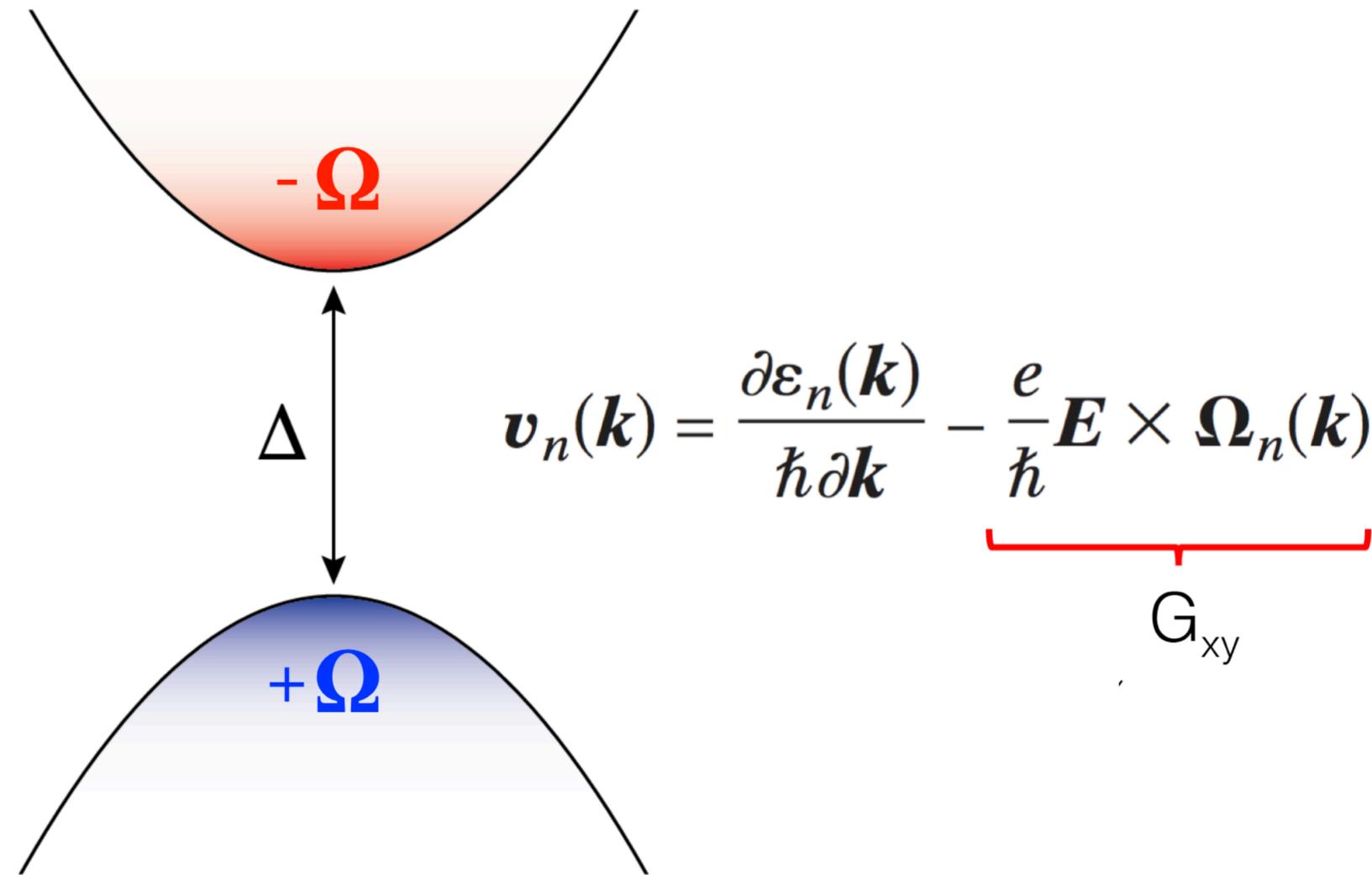
# Topological Floquet bands



Hall current  $\propto$  total occupied  $\Omega$

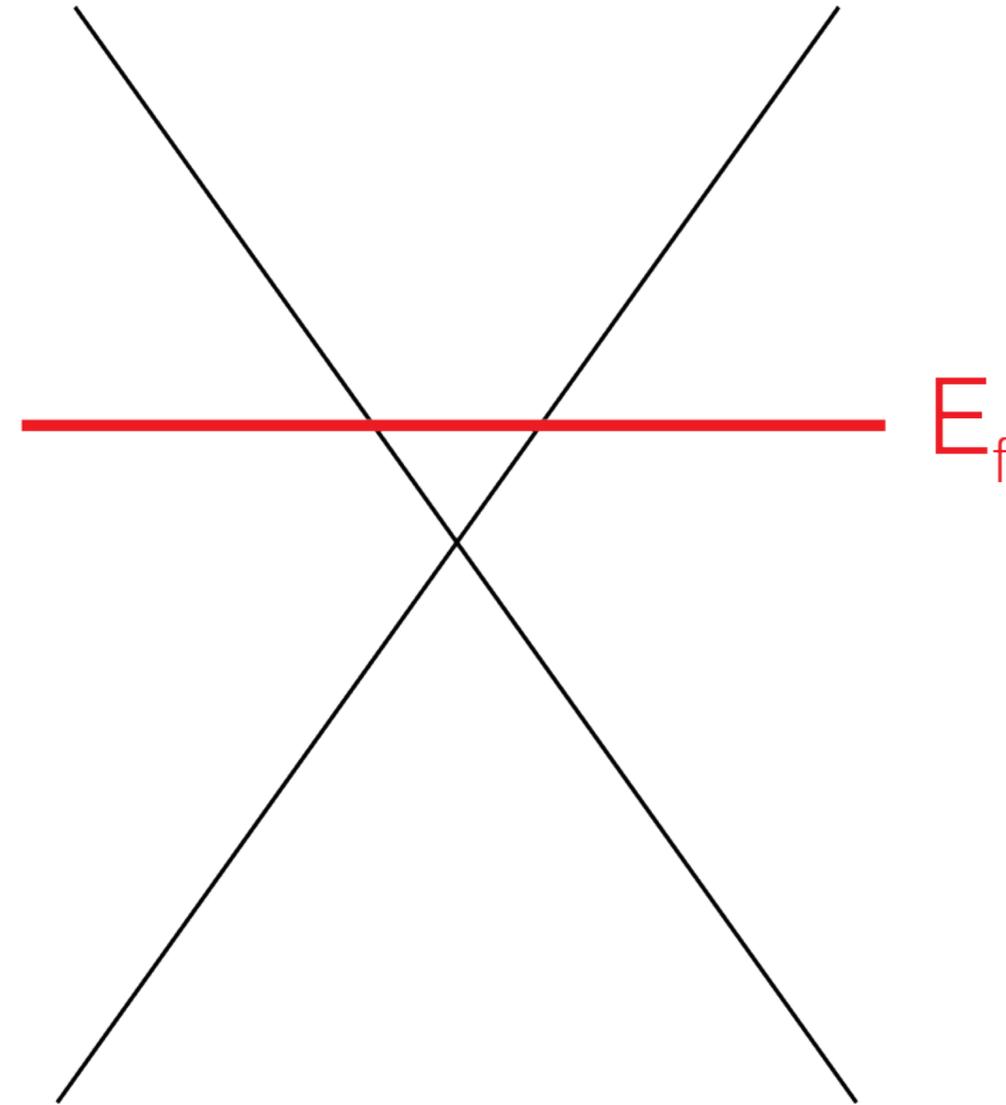
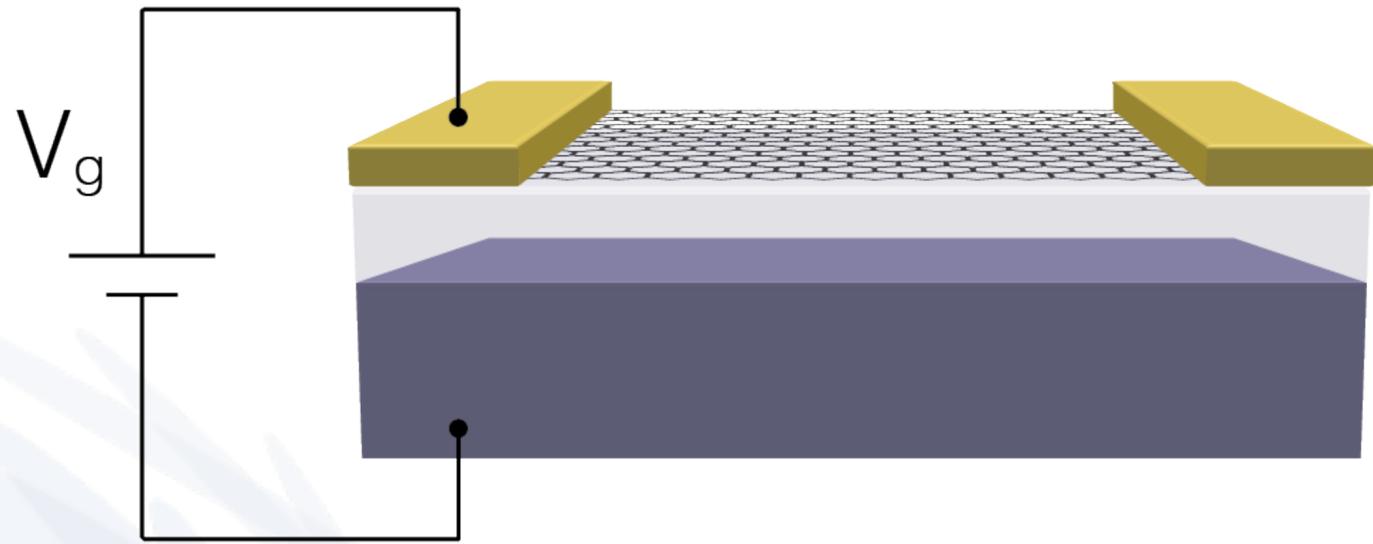
$\Omega$ : Berry curvature

# Topological Floquet bands

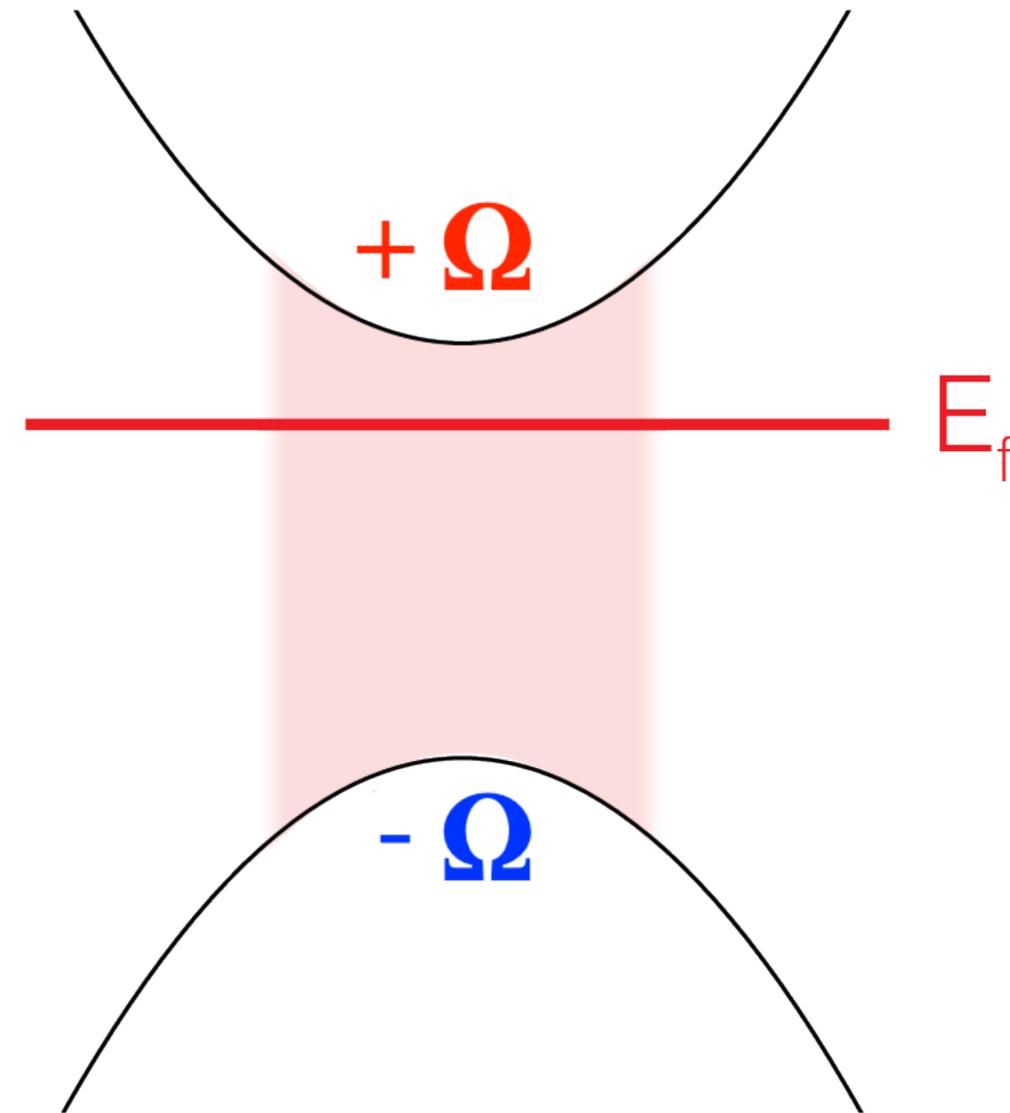
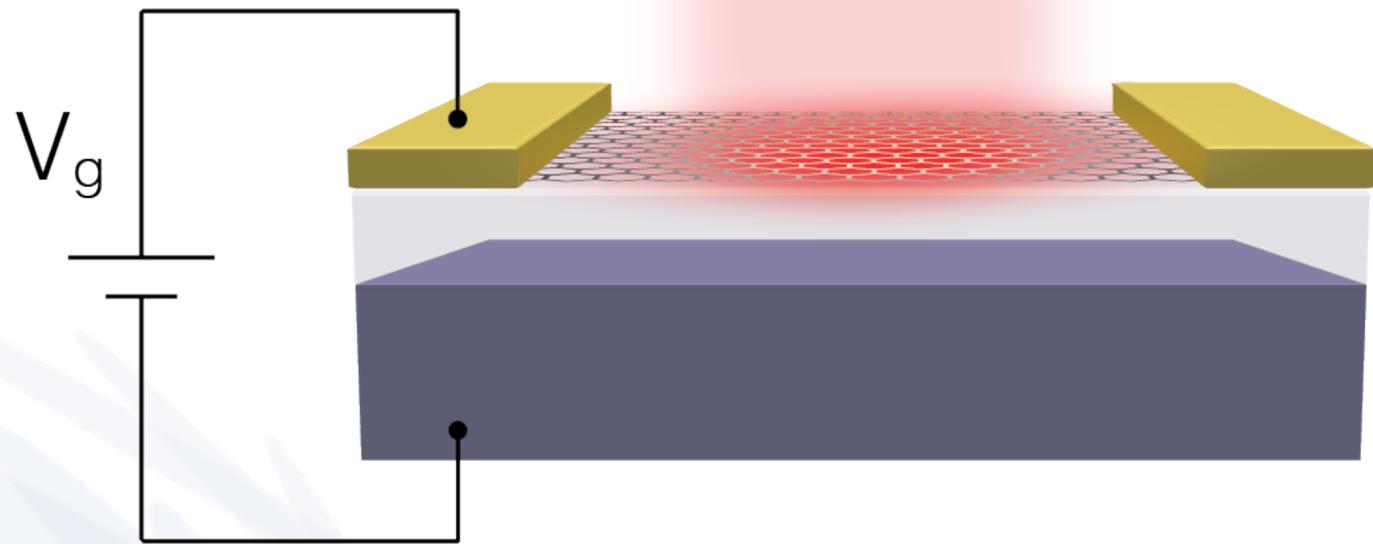


Hall current  $\propto$  total occupied  $\Omega$

# Topological Floquet bands

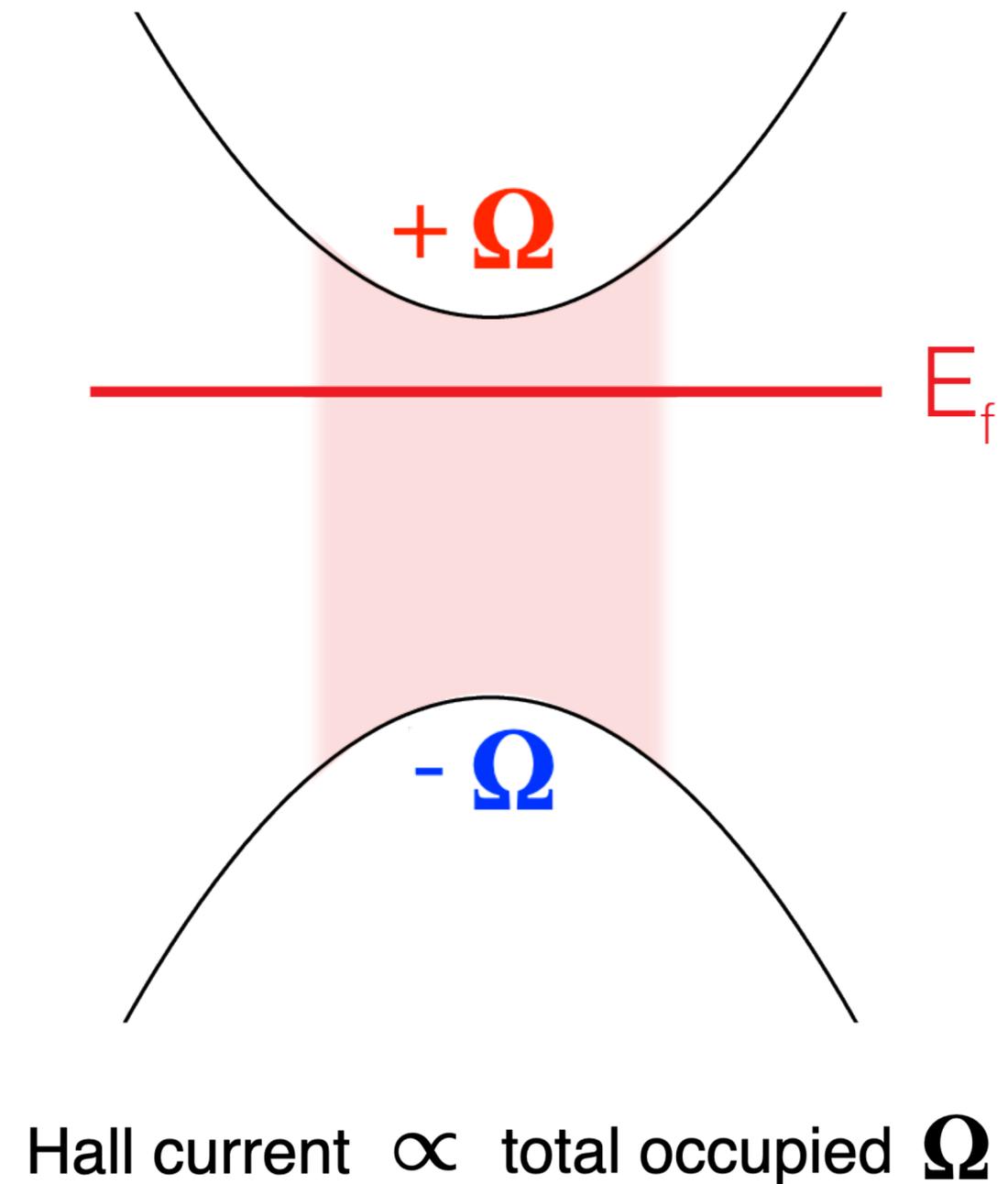
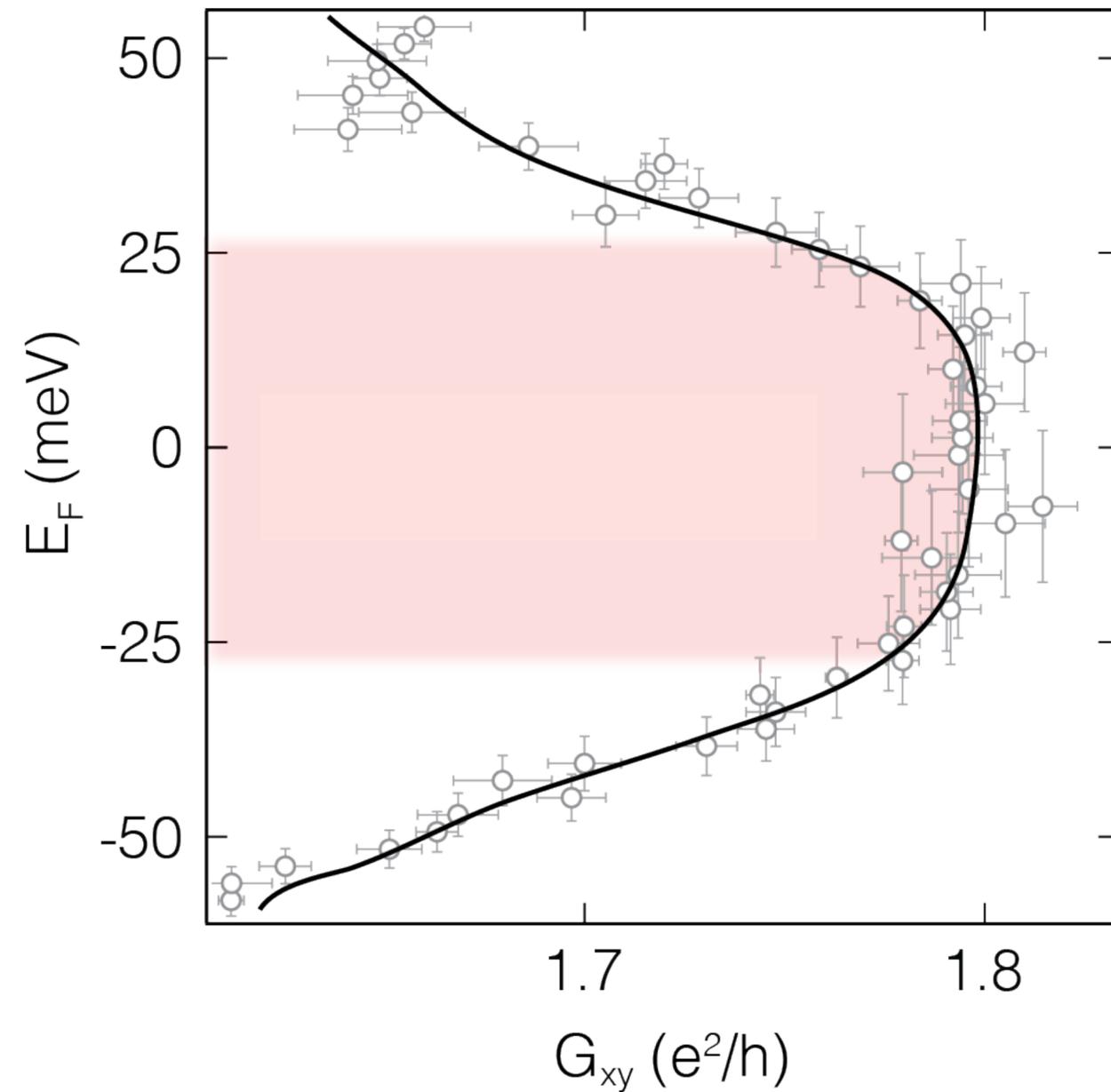


# Topological Floquet bands

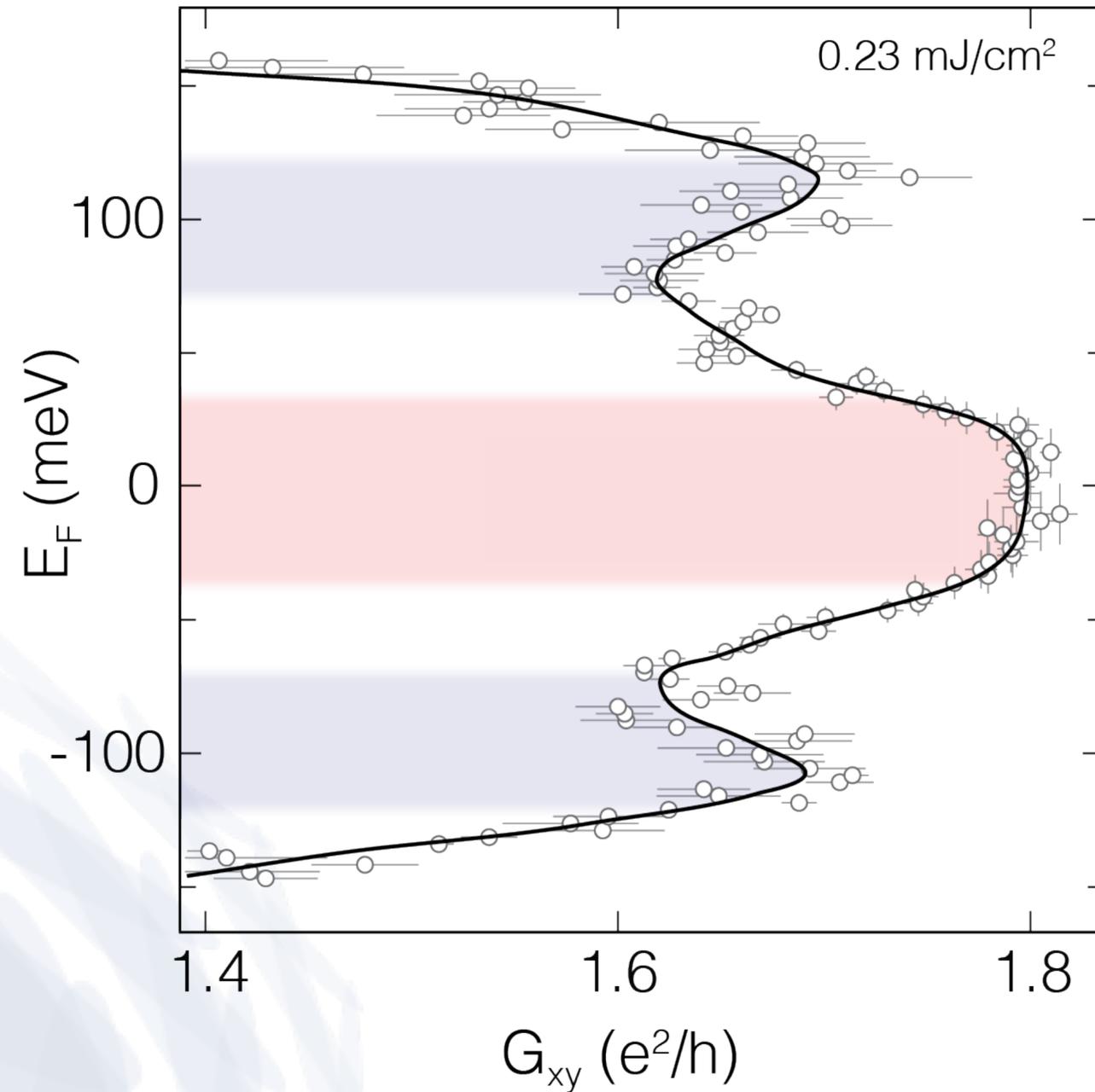


Hall current  $\propto$  total occupied  $\Omega$

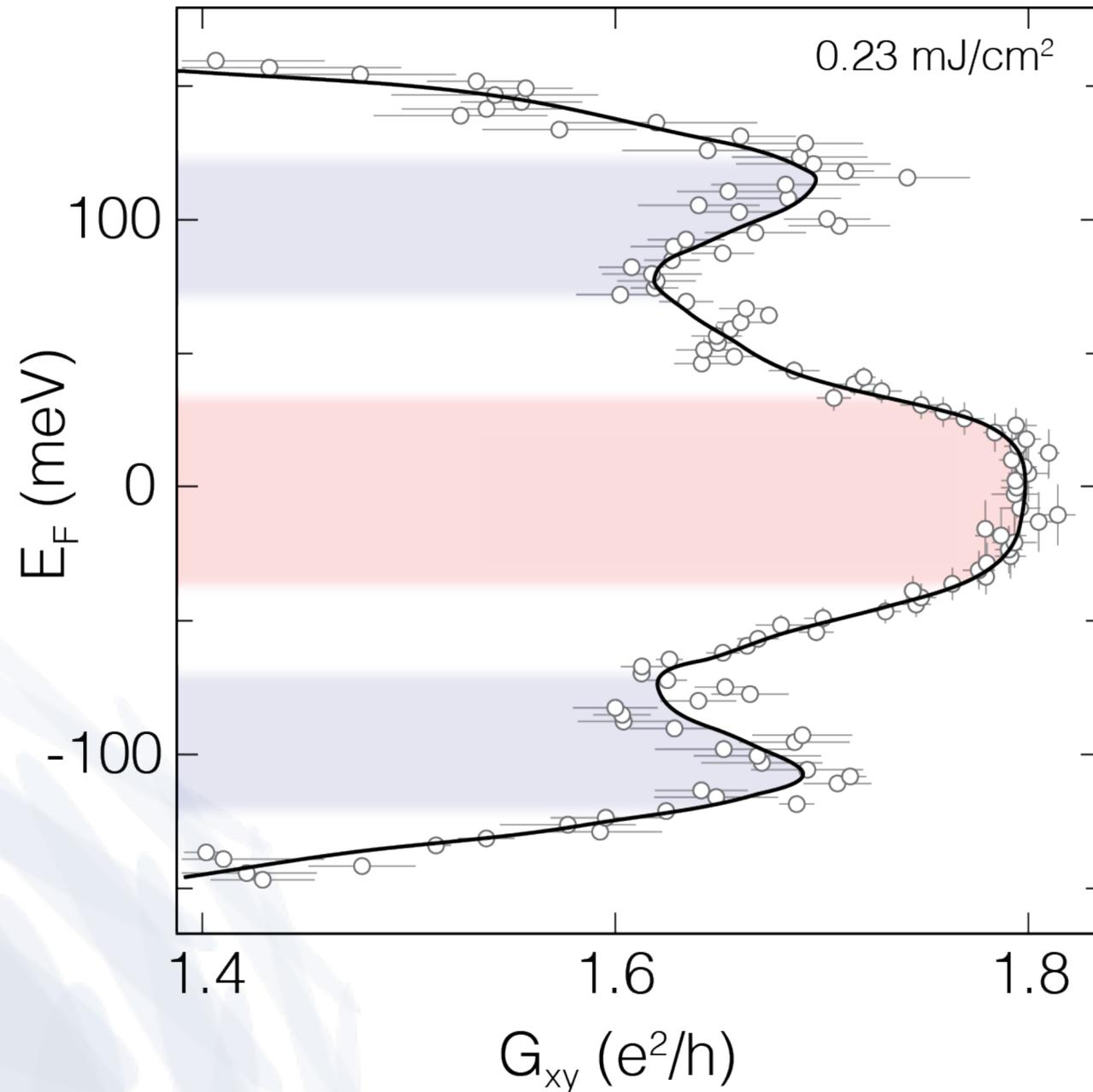
# Topological Floquet bands



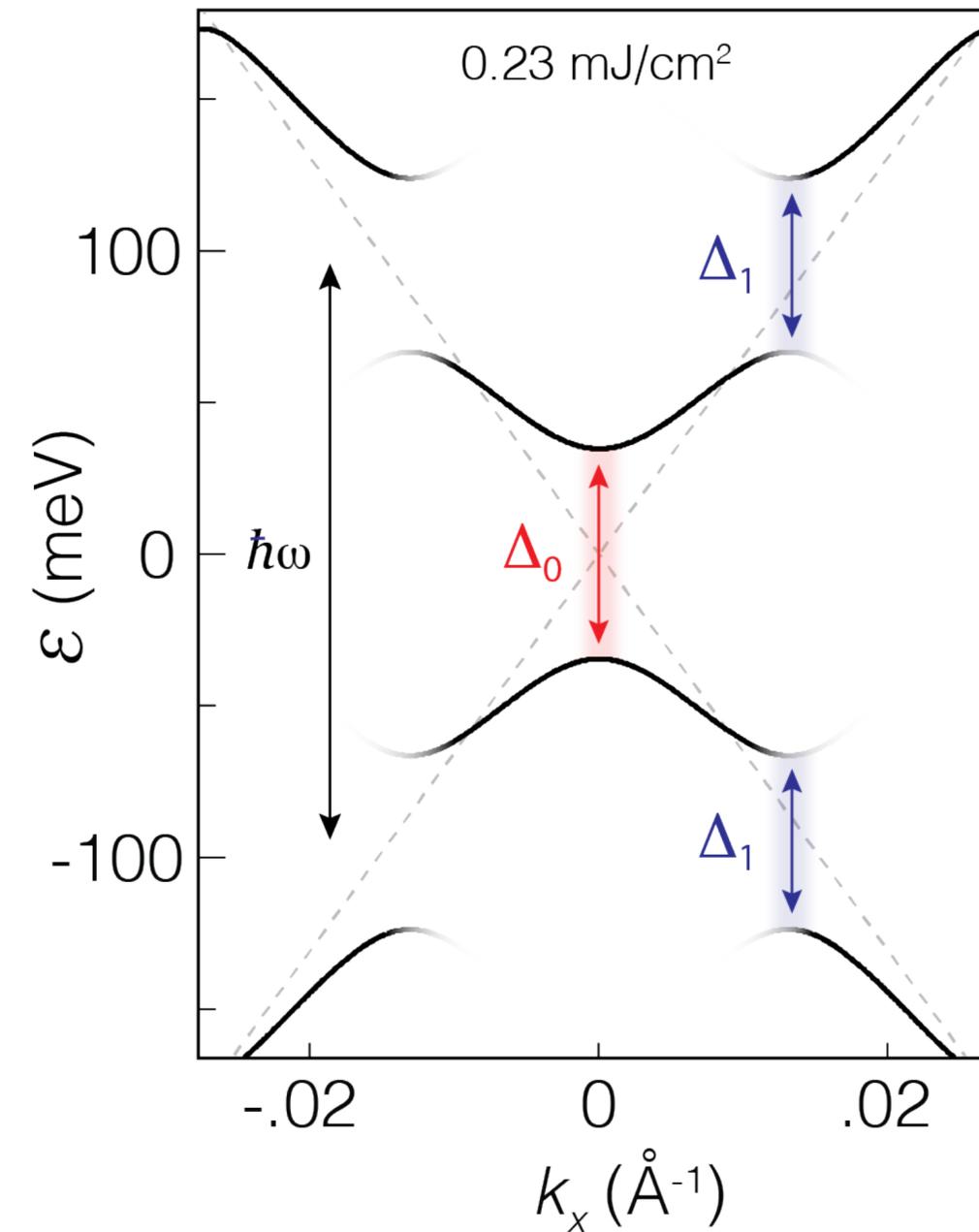
# Light-induced anomalous Hall effect in graphene



# Light-induced anomalous Hall effect in graphene



Floquet calculations:



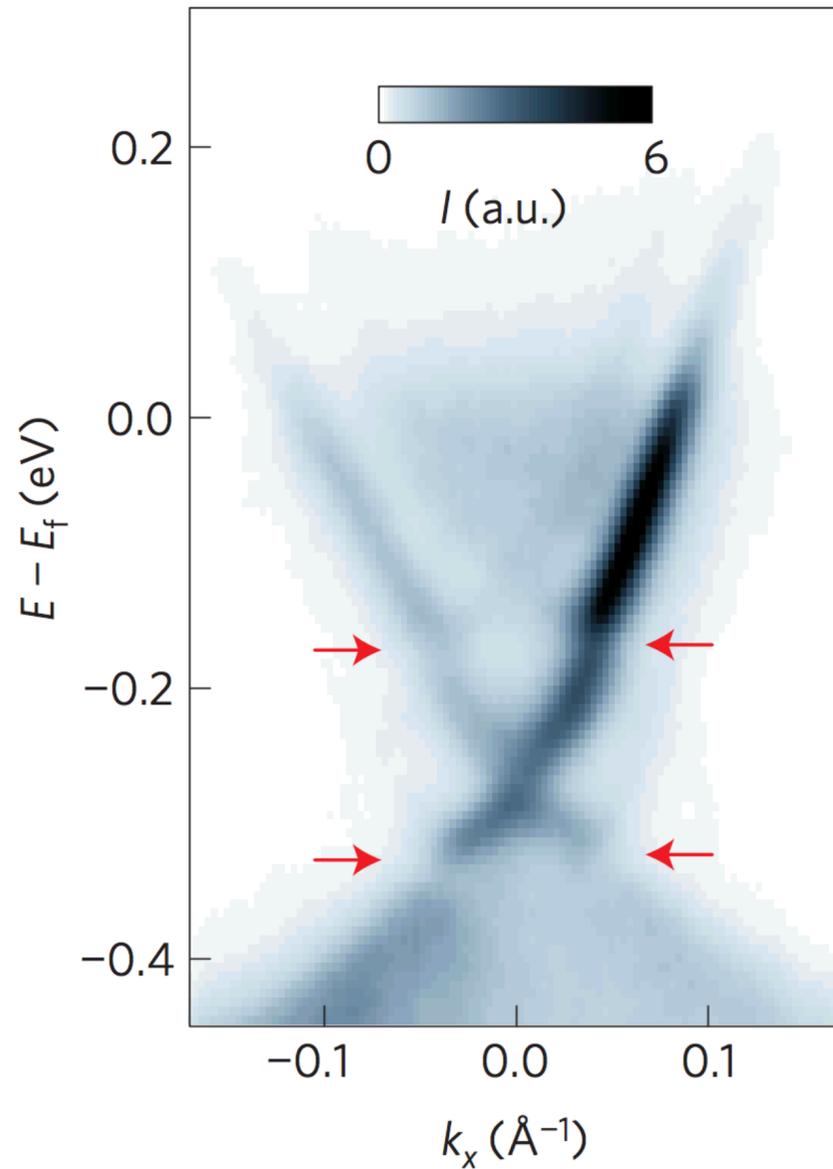
Gaps  $\Delta_0, \Delta_1$

Wang *et al.* *Science* 342, 453 (2013)

Mahmood *et al.* *Nature Phys.* 12, 306 (2016)

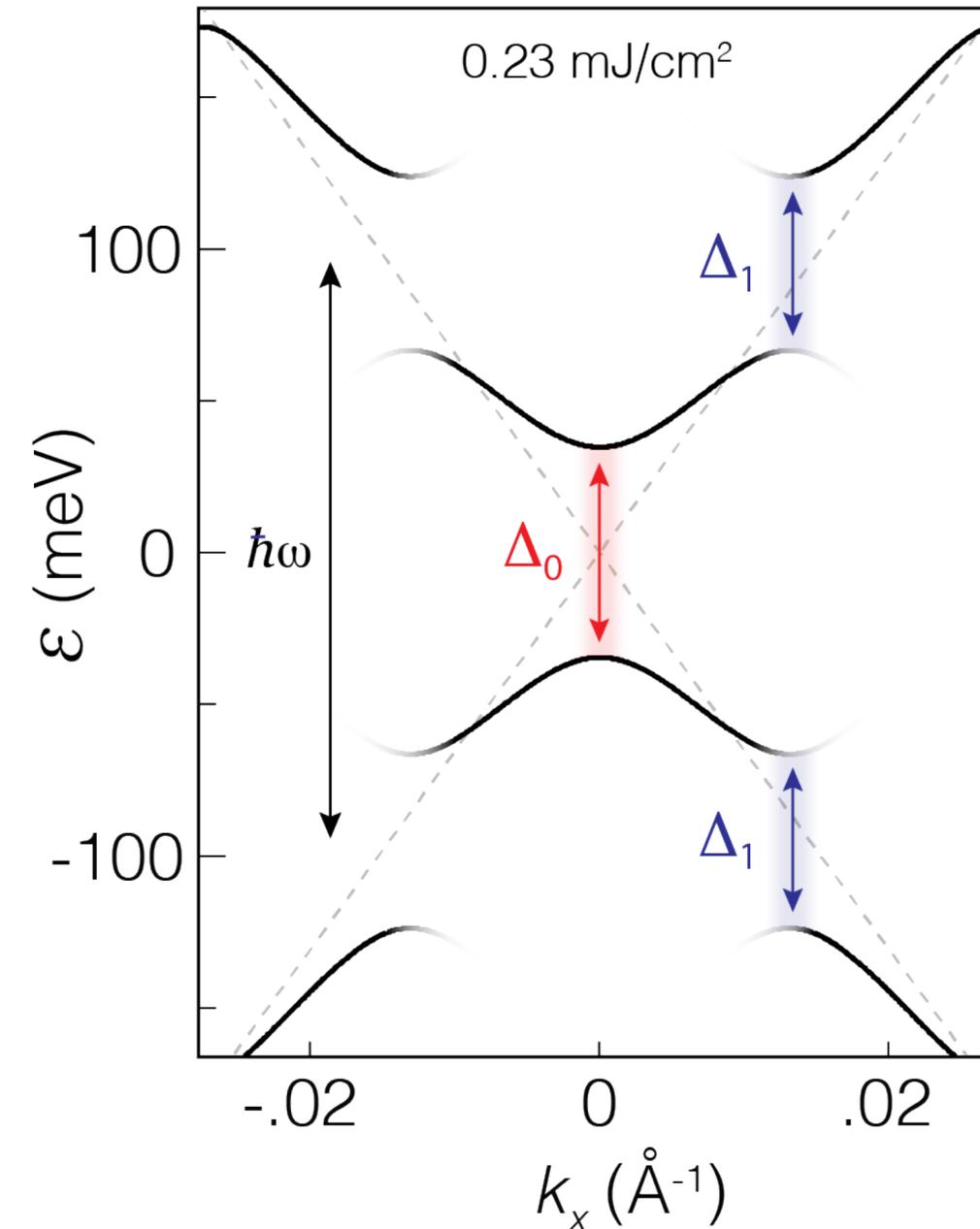
# Light-induced anomalous Hall effect in graphene

tr-ARPES measurements



$\text{Bi}_2\text{Se}_3$  surface Floquet states

Floquet calculations:



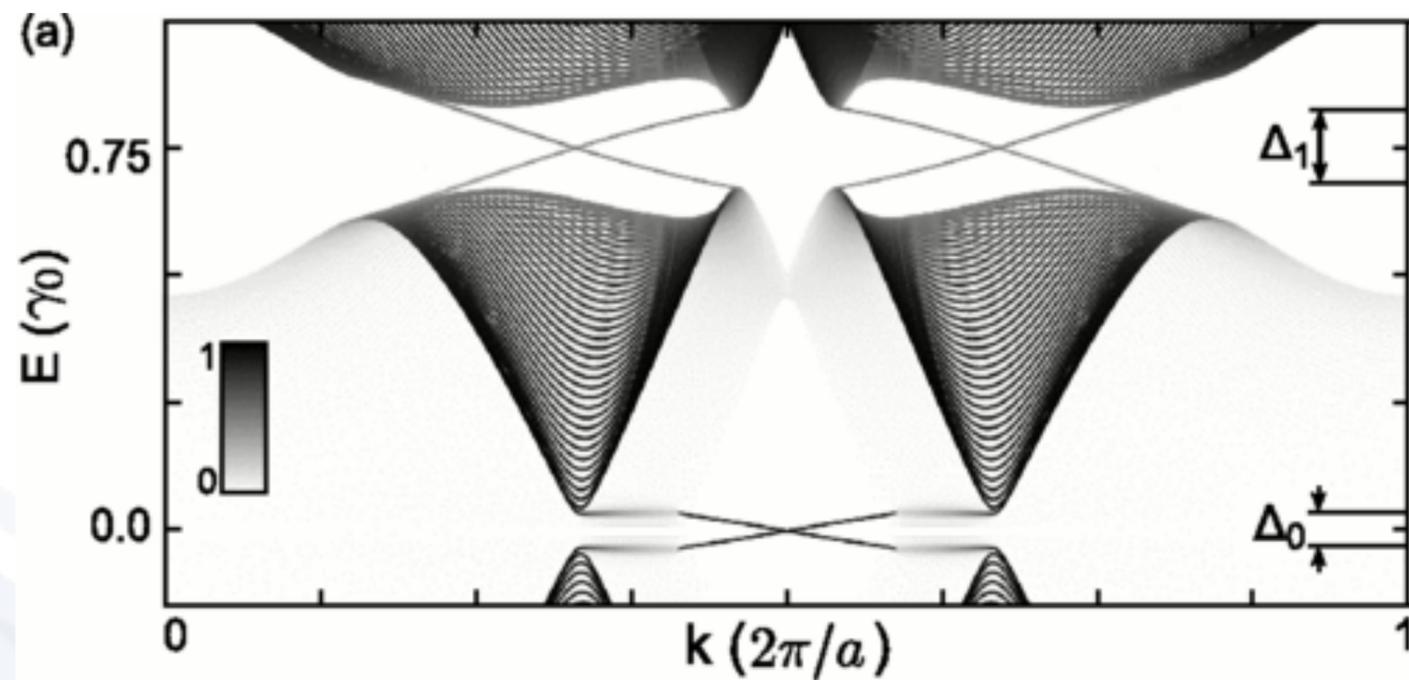
Gaps  $\Delta_0, \Delta_1$

Wang *et al.* *Science* 342, 453 (2013)

Mahmood *et al.* *Nature Phys.* 12, 306 (2016)

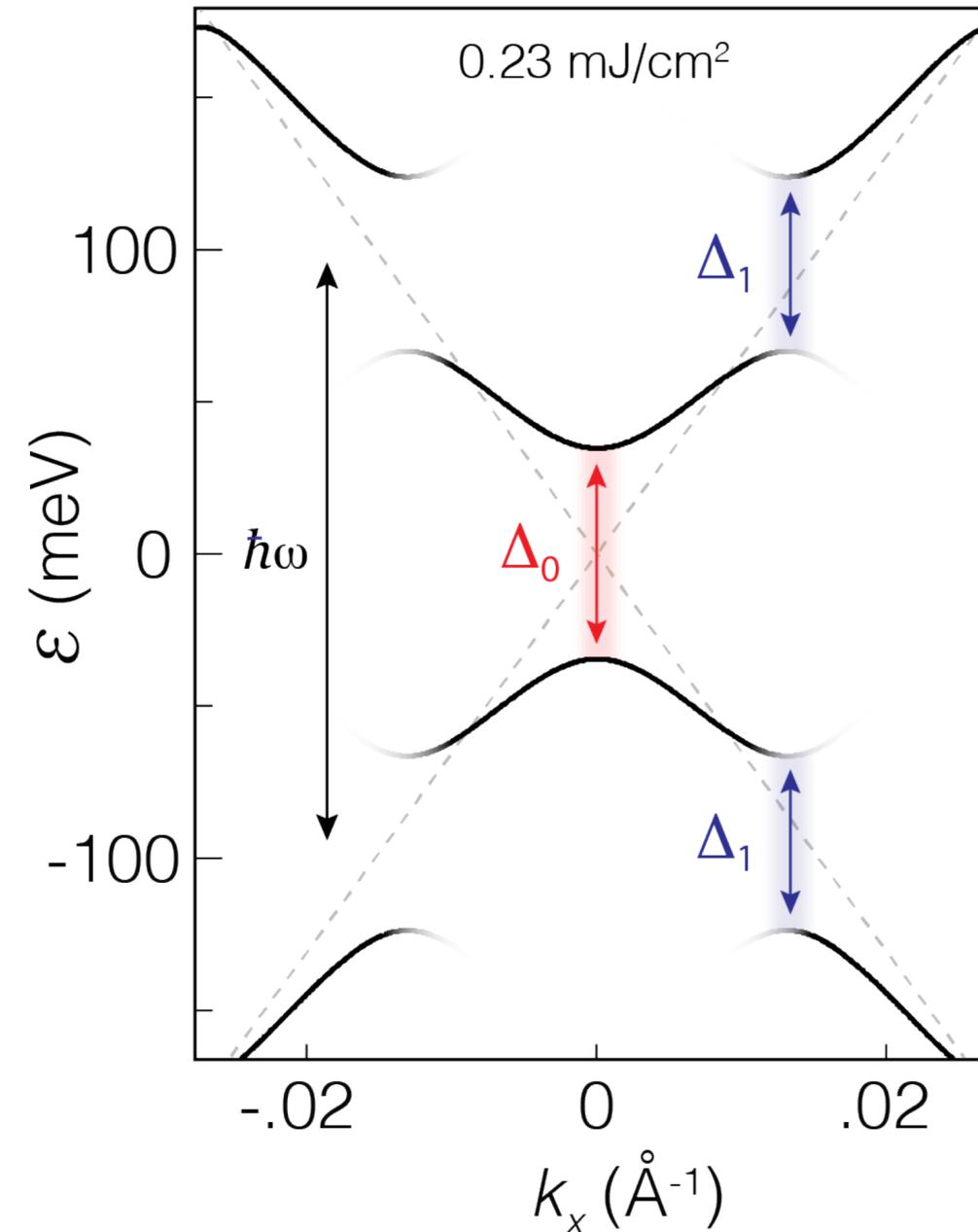
# Light-induced anomalous Hall effect in graphene

Predicted edge state spectra



Foa Torres *et al.*, *Phys. Rev. Lett.* 113, 266801 (2014)

Floquet calculations:

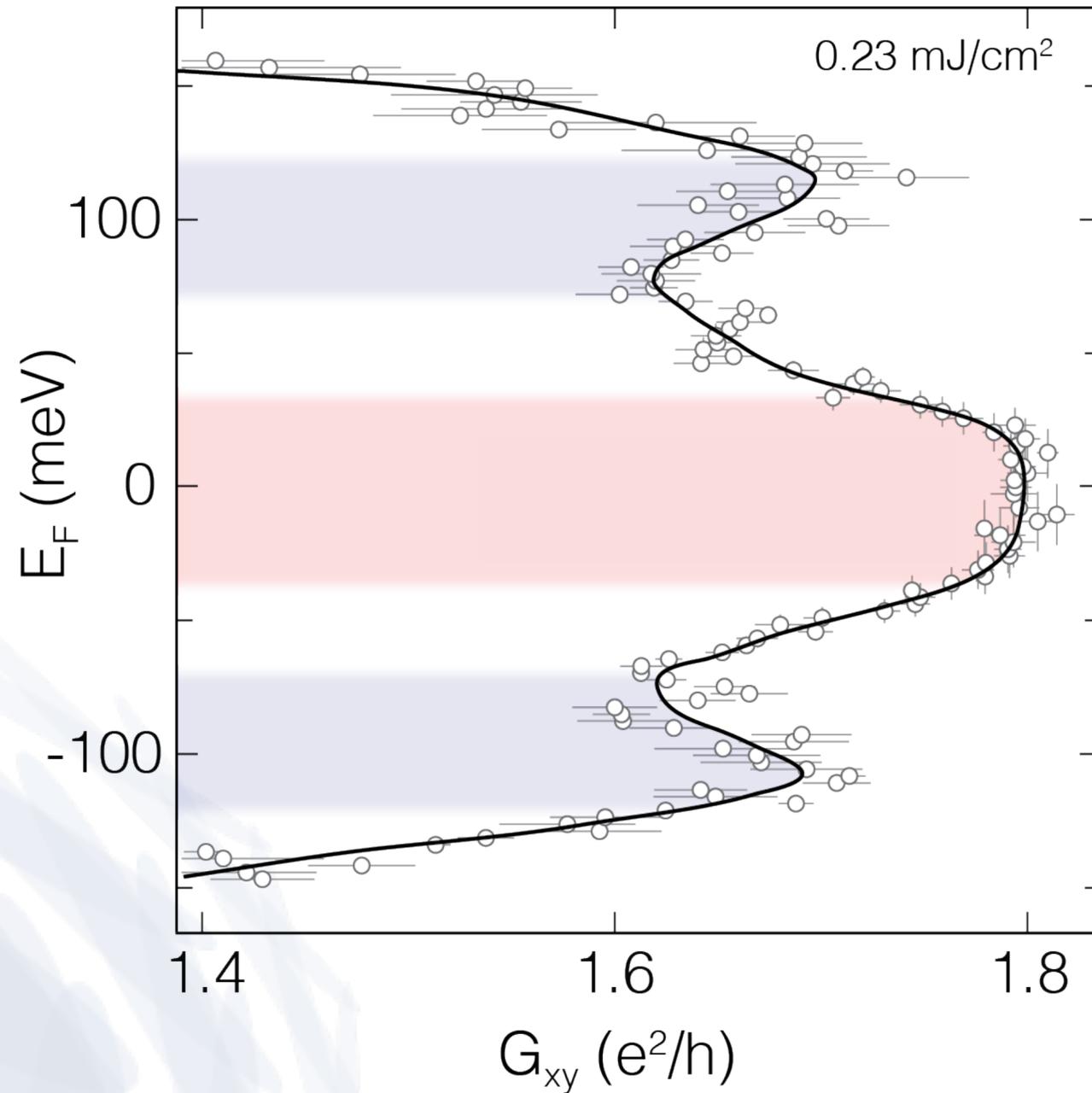


Gaps  $\Delta_0, \Delta_1$

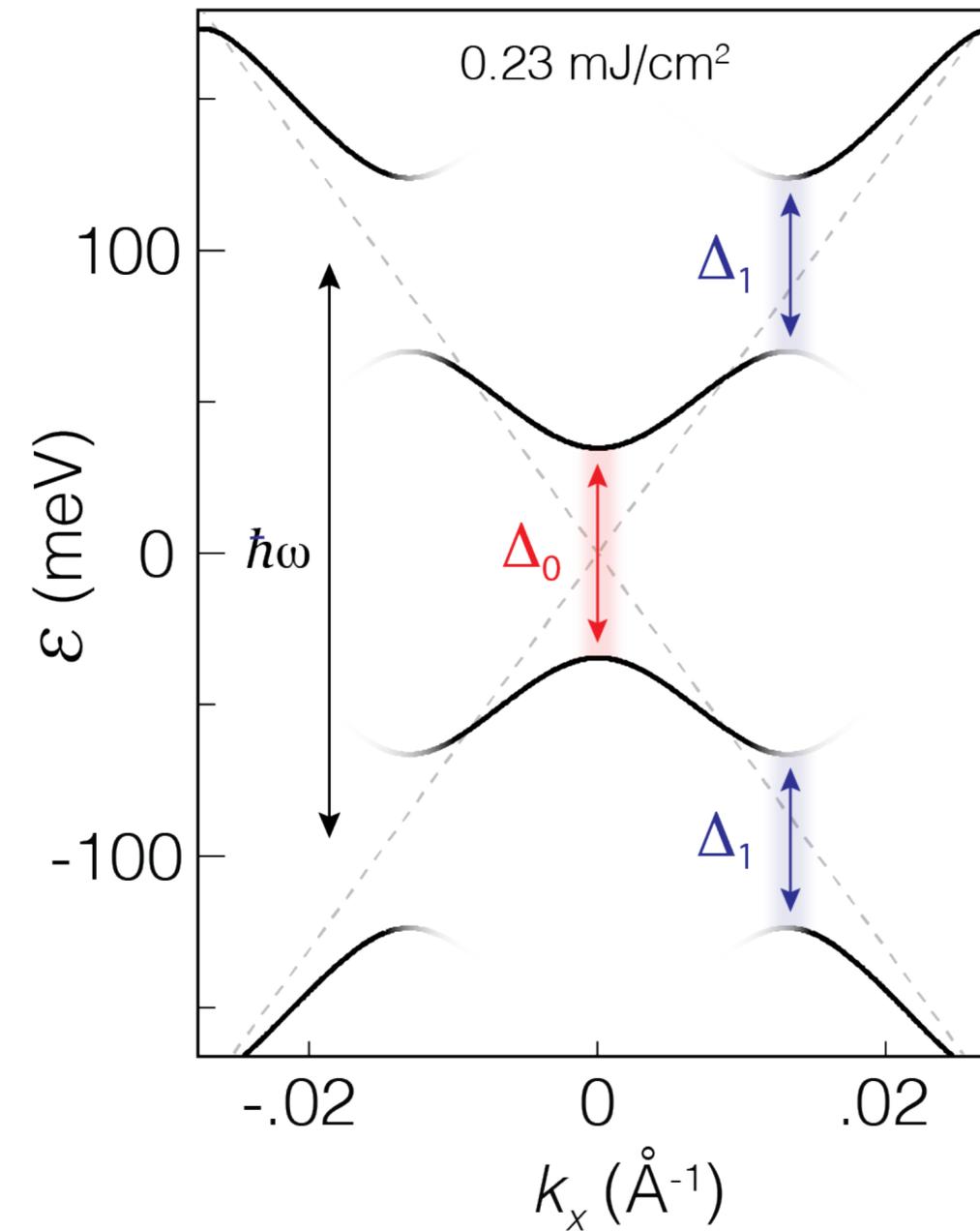
Wang *et al.* *Science* 342, 453 (2013)

Mahmood *et al.* *Nature Phys.* 12, 306 (2016)

# Light-induced anomalous Hall effect in graphene

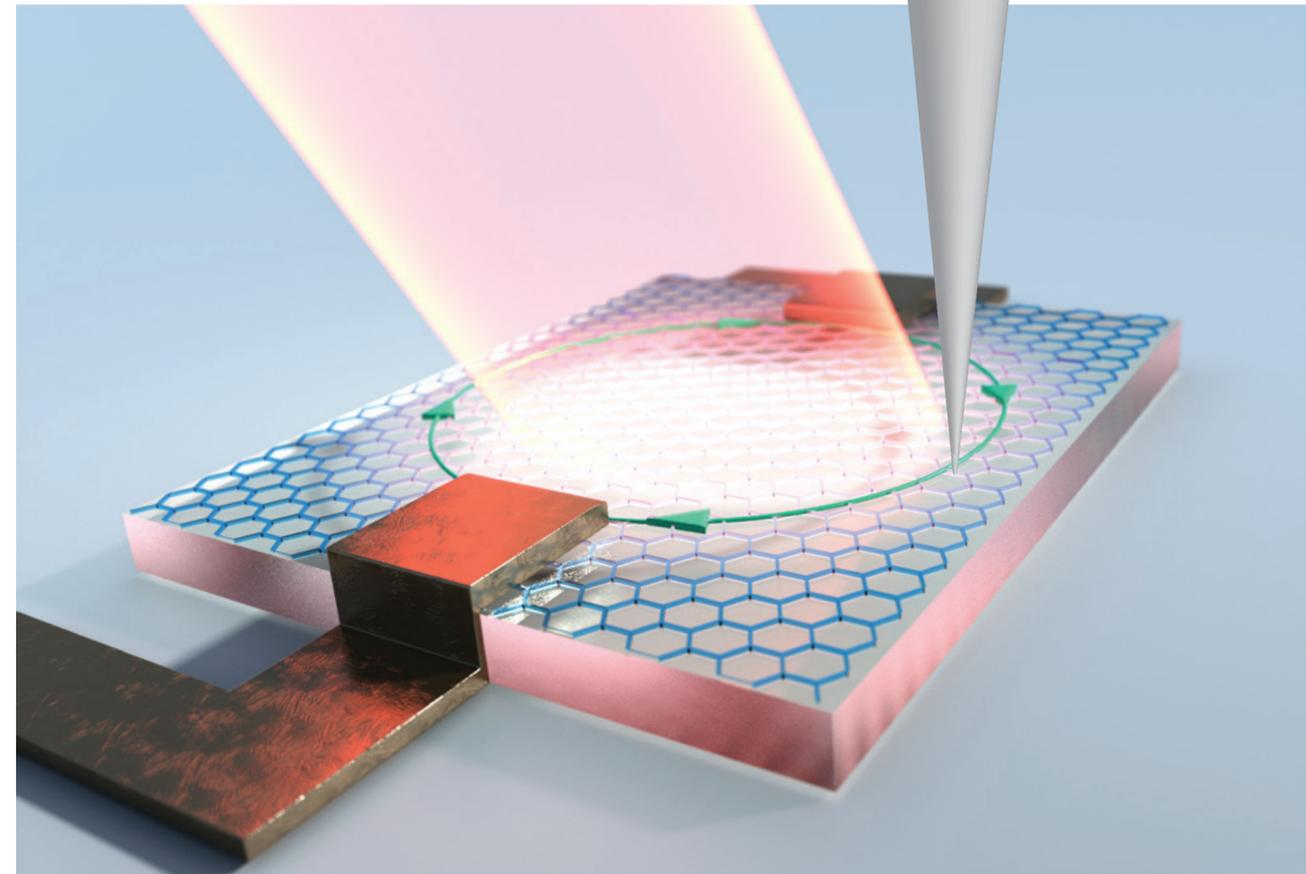


Floquet calculations:



# Light-induced topological edge states

Ultrafast scanning probes  
(stay tuned)



**Big picture: Light-induced edge states**

# Postdoc positions available



**@MPSD in Hamburg**



**@Columbia in NYC**

**[mciverlab.com](http://mciverlab.com)**

# Acknowledgements



**The group**

## **MPSD/UHH**

Andrea Cavalleri  
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Angel Rubio  
Shunsuke Sato  
Michael Sentef  
Dante Kennes  
Ludwig Mathey

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# Ultrafast optoelectronic probes of quantum materials

Thank you!

