# Nonequilibrium Materials Engineering

Michael A. Sentef
*lab.sentef.org*
Max-Planck Institute for the Structure and Dynamics of Matter, Hamburg

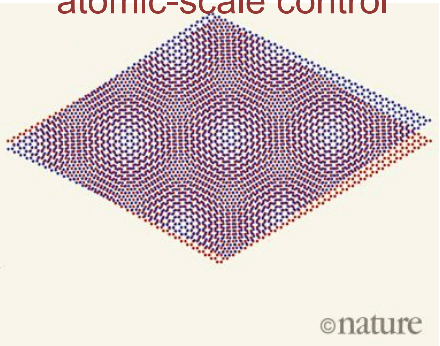
Paris Edge, September 26, 2019

Funded through Deutsche Forschungsgemeinschaft
Emmy Noether Programme (SE 2558/2-1)

Max Planck Institute for the Structure and Dynamics of Matter

# Engineering materials with light

**condensed matter**
quantum materials
atomic-scale control




Y. Cao et al., Nature 556, 43 (2018)

**ultrafast spectroscopy**
revealing elementary couplings
light-induced new states of matter

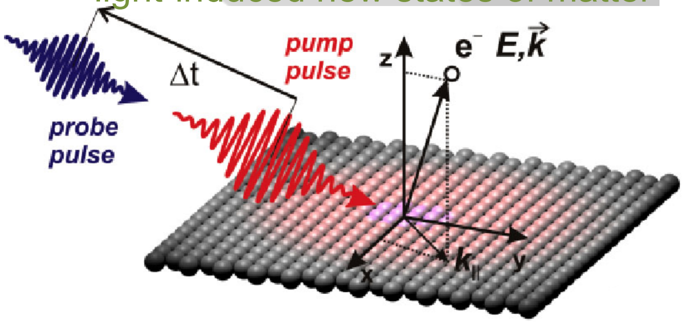
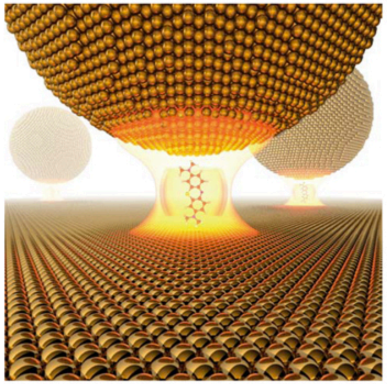



Image courtesy: J. Sobota

**pump-probe: strong classical fields**

**nonequilibrium materials engineering**



R. Chikkaraddy et al., Nature 535, 127 (2016)

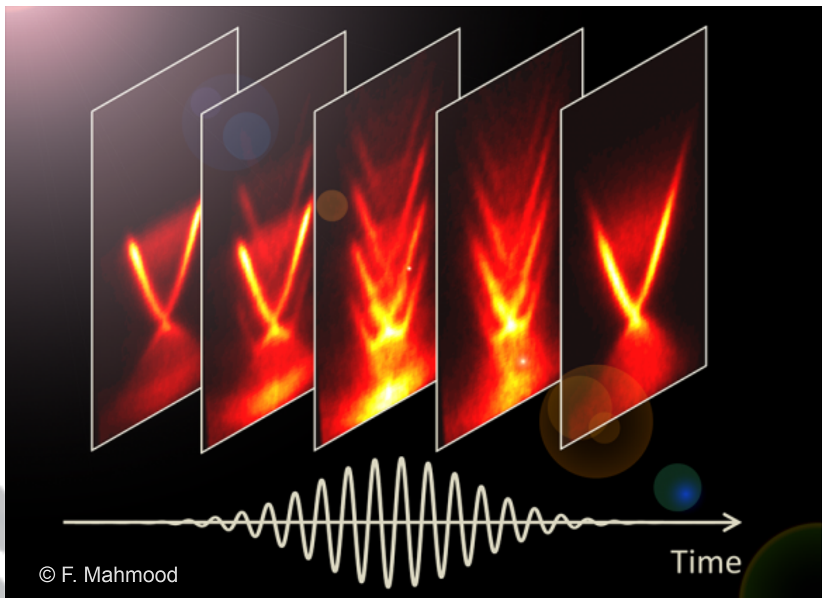
**quantum optics**
nanoplasmonics
polaritonic chemistry

**QED: vacuum fluctuations**

# Engineering materials with light

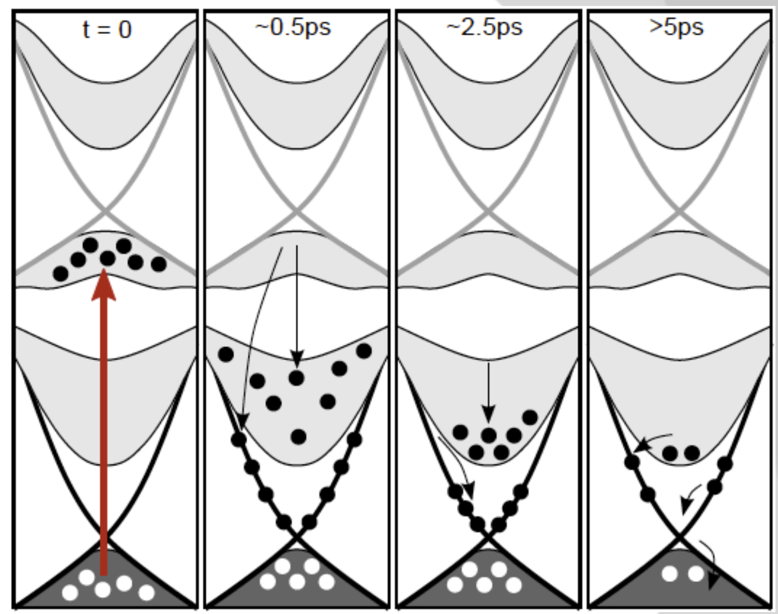
mpsd

### Hamiltonian engineering
e.g., Floquet-Bloch bands




F. Mahmood et al., Nature Physics 12, 306 (2016)

### Distributional engineering




J. Sobota et al., JESRP 195, 249 (2014)

**many ingredients, hard to disentangle**

**this talk**: (I) tailored symmetry breaking, (II) vacuum fluctuations

# Some recent key results

## How to engineer materials with light?

Part I: Optical control of chiral superconductors

Short laser pulses allow for switching of Majorana modes

*M. Claassen et al., Nat. Phys. 15, 766 (2019)*

Part II: From classical to quantized photon fields

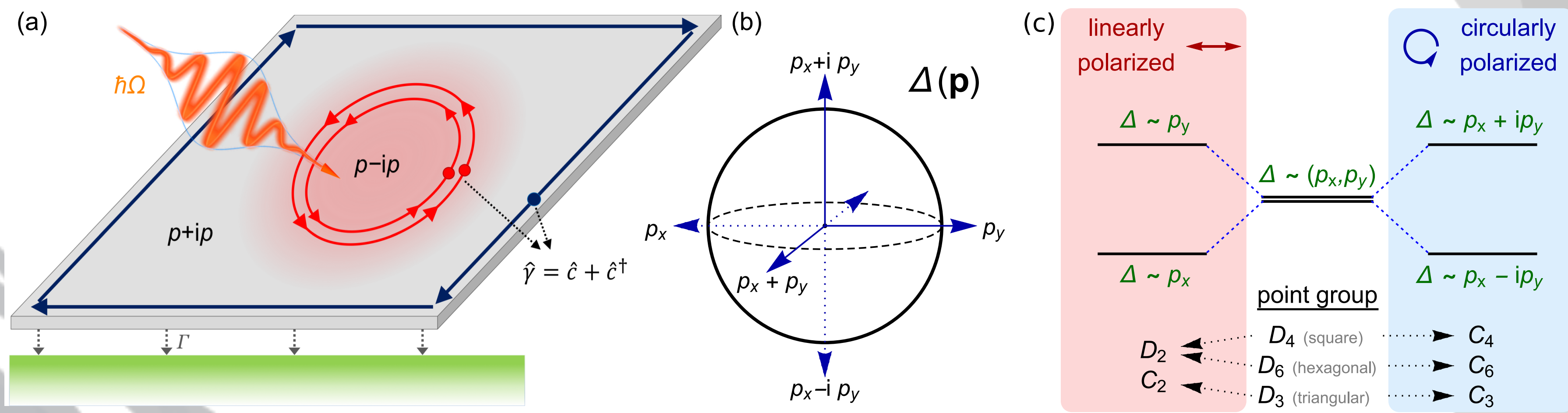
Materials engineering in an optical cavity using vacuum fluctuations

*M. A. Sentef et al., Science Advances 4, eaau6969 (2018)*

# I Optical control of Majoranas

- can one switch the chirality of a 2D topological superconductor?

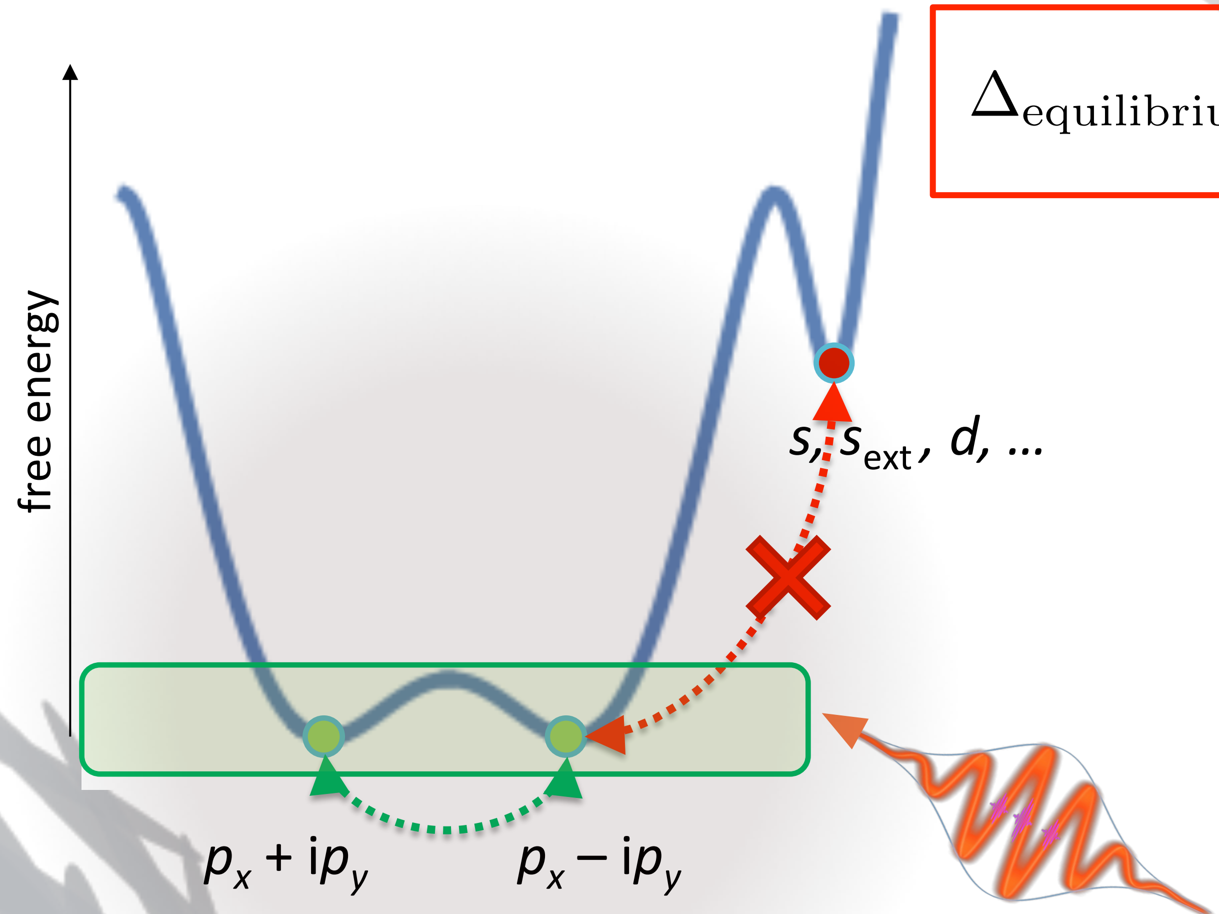
$Sr_2RuO_4$(?), highly doped graphene, twisted bilayer graphene, ...?




key idea: use two-pulse sequence with linearly and circularly polarized light

# Nonequilibrium pathway to switching

$$\Delta_{\text{equilibrium}} \sim \begin{cases} p_x + ip_y \\ p_x - ip_y \end{cases}$$




$$\Delta_{\text{non-eq}}(t) \sim \cos(\theta)\ \text{“}p_x + ip_y\text{”} \ +\ \sin(\theta)e^{i\phi}\ \text{“}p_x - ip_y\text{”}$$

# Model and Method

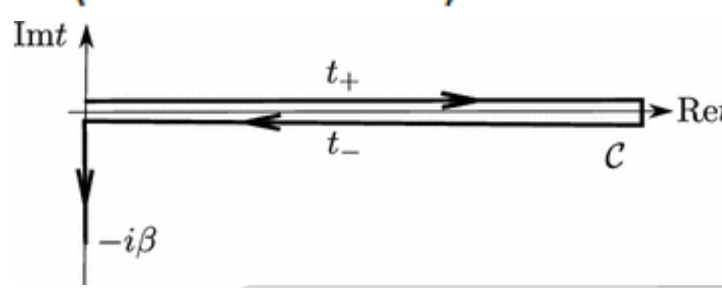


multiband Bogoliubov-de-Gennes Hamiltonians for doped graphene (d+id) and Sr2RuO4 (p+ip)
coupling to fermionic reservoir to dissipate energy
laser driving via Peierls substitution

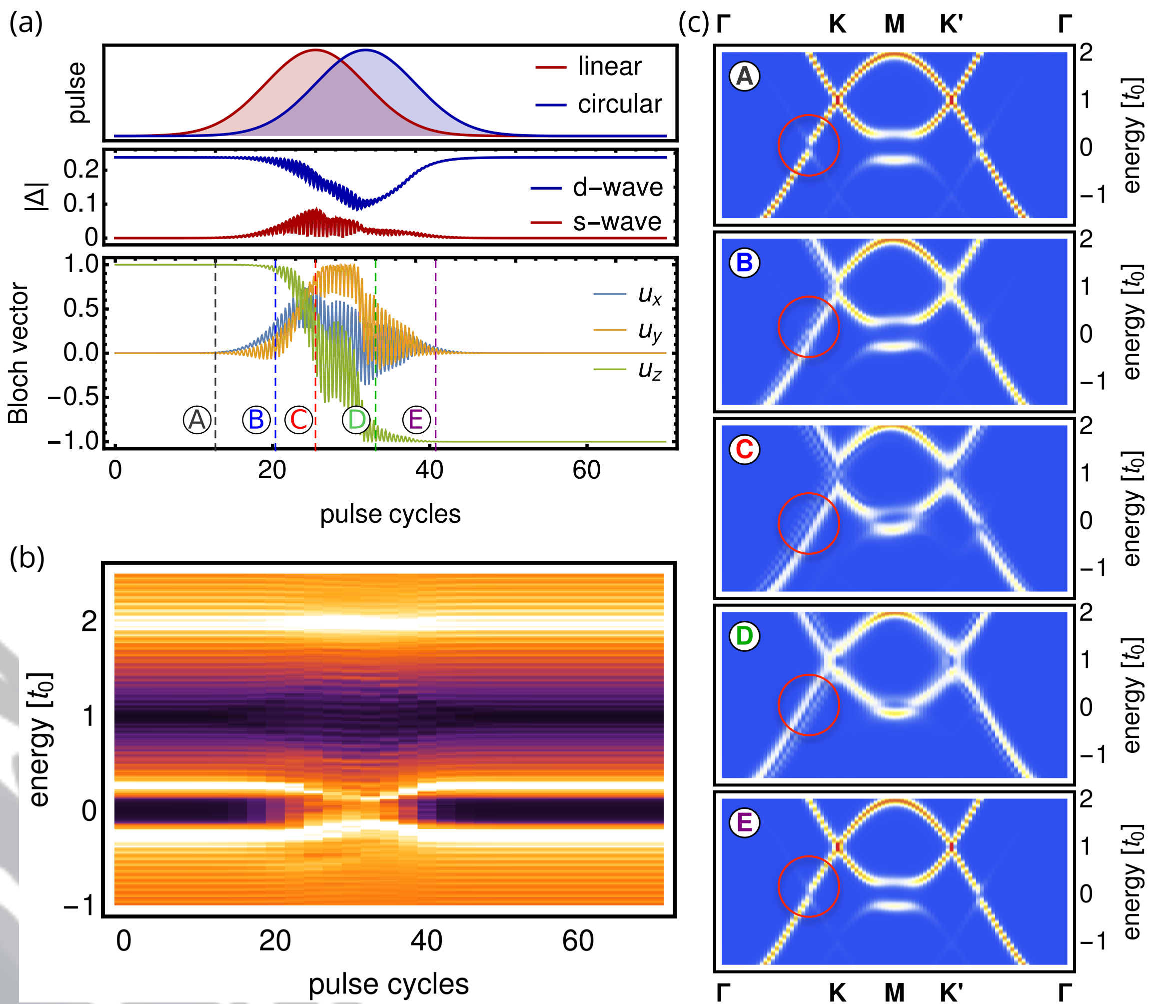
self-consistent Keldysh equations of motion for Nambu Green's functions:

$$i\partial_t \mathcal{G}_{\mathbf{k}}(t,t') = \mathcal{H}_{\mathbf{k}}(t, \boxed{\mathbf{\Delta}_{\mathbf{k}}(t)})\, \mathcal{G}_{\mathbf{k}}(t,t') + \int d\tau\, \boxed{\hat{\Sigma}_{\mathbf{k}}(t,\tau)}\, \mathcal{G}_{\mathbf{k}}(\tau,t')$$

$$\mathbf{\Delta}_{\mathbf{k}}(t) = \frac{1}{L} \sum_j v^{(j)} \hat{\eta}^{(j)}_{\mathbf{k}} \sum_{\substack{\mathbf{k}' \\ \alpha\beta}} \hat{\eta}^{(j)}_{\mathbf{k}'\alpha\beta} \left\langle \hat{c}_{-\mathbf{k}',\beta\downarrow} \hat{c}_{\mathbf{k}',\alpha\uparrow} \right\rangle$$



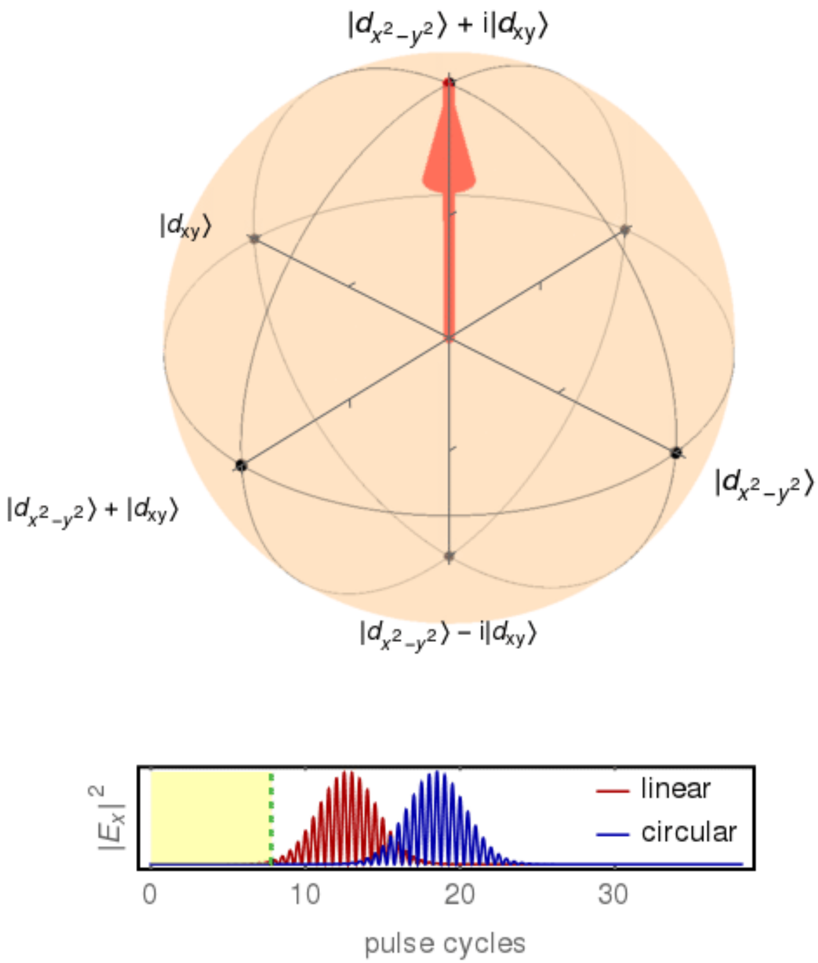
# Optical control of Majoranas




two-pulse sequence reverses d+id state in graphene

time-resolved spectroscopy tracks chirality reversal

# Bloch vector rotation



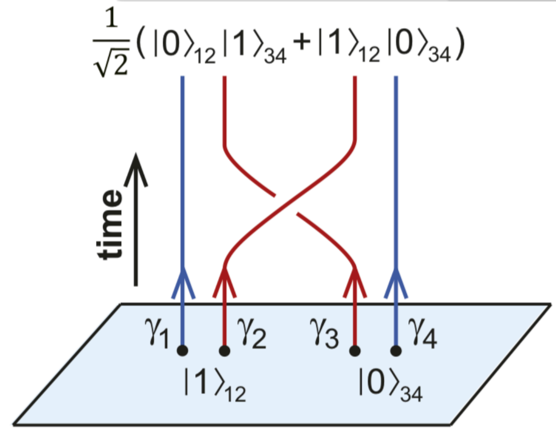
# A „programmable“ topological quantum computer?

mpsd

**non-Abelian statistics of Majorana fermions:**

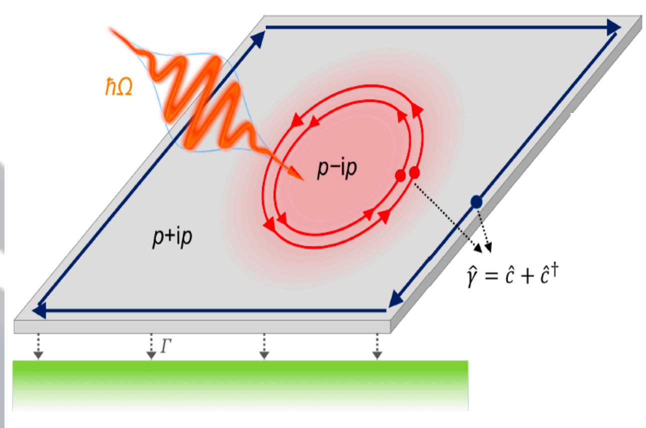
- half-quantum vortices of chiral superconductors host single Majorana fermions
- Two Majoranas represent one electron: **½ + ½ = 1**

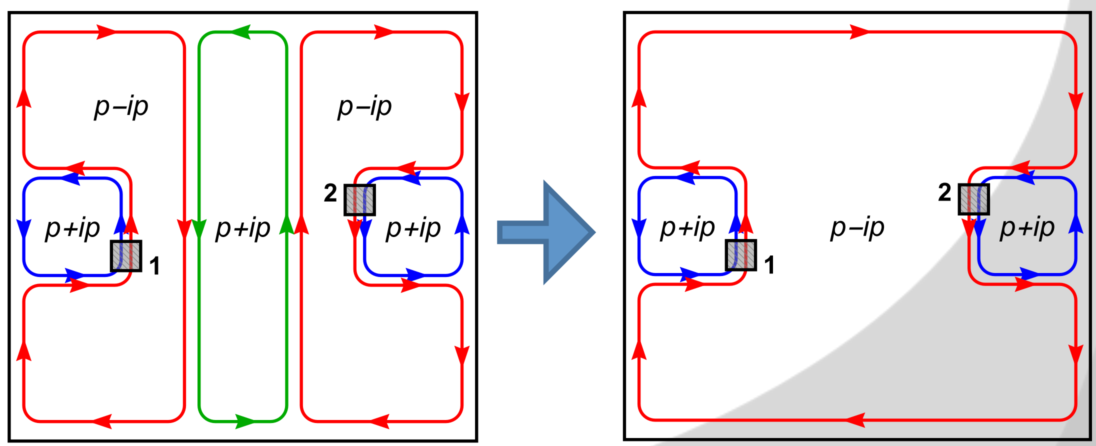
  → Braiding between Majoranas is a non-Abelian operation in electron (charge) basis!




*Ivanov, PRL 86, 268 (2001)*
*B. Lian et al., PNAS 115, 10938 (2018)*

simplest operation: a **switchable Hadamard gate**



# Summary I

- All-optical control of chiral Majorana modes
- towards arbitrarily programmable quantum computer?

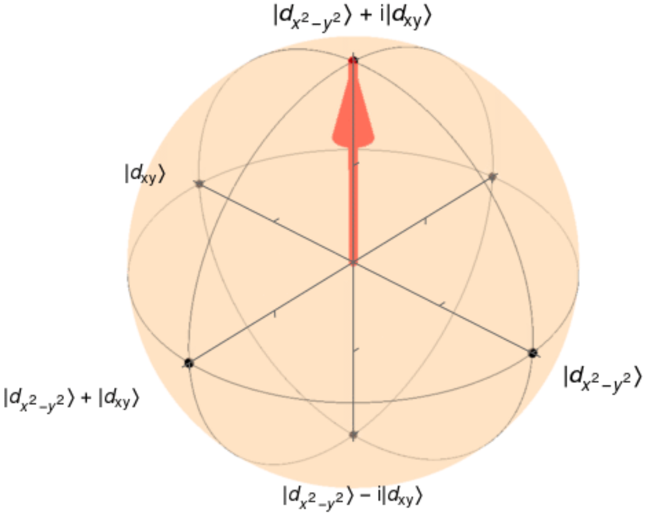
„program the gate optically, read it out electrically“

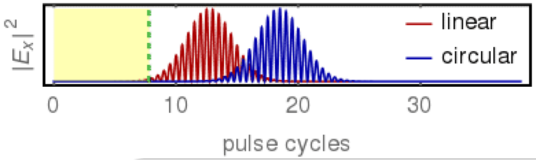
*M. Claassen et al.,*
*Nat. Phys. 15, 766 (2019)*

M. Claassen

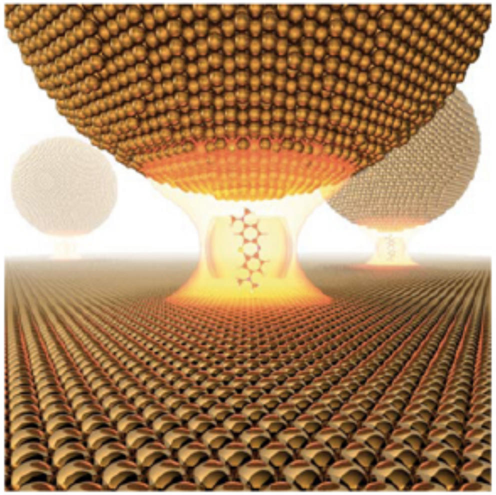
D. Kennes

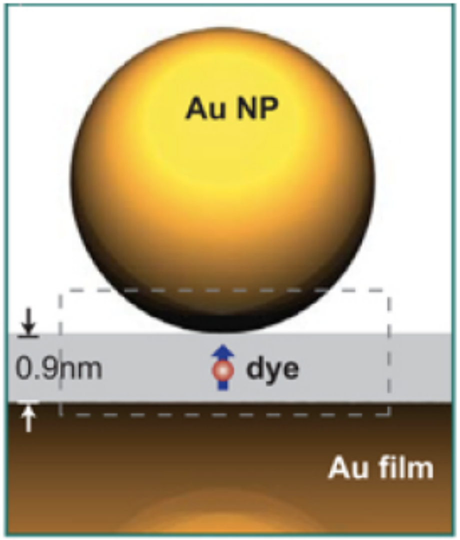
M. Zingl



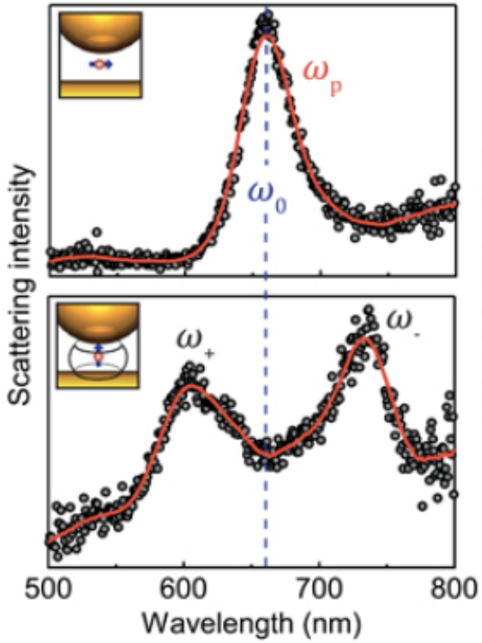



# From classical to quantum light





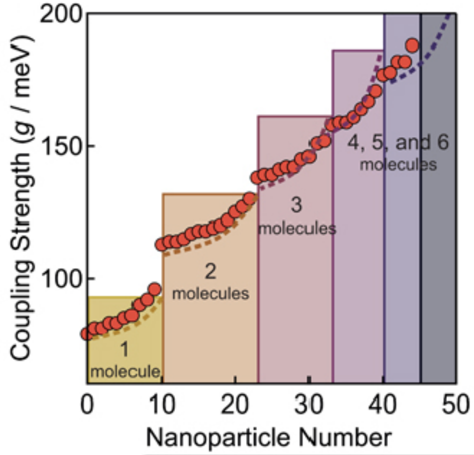

R. Chikkaraddy et al., Nature 535, 127 (2016)




Rabi splitting

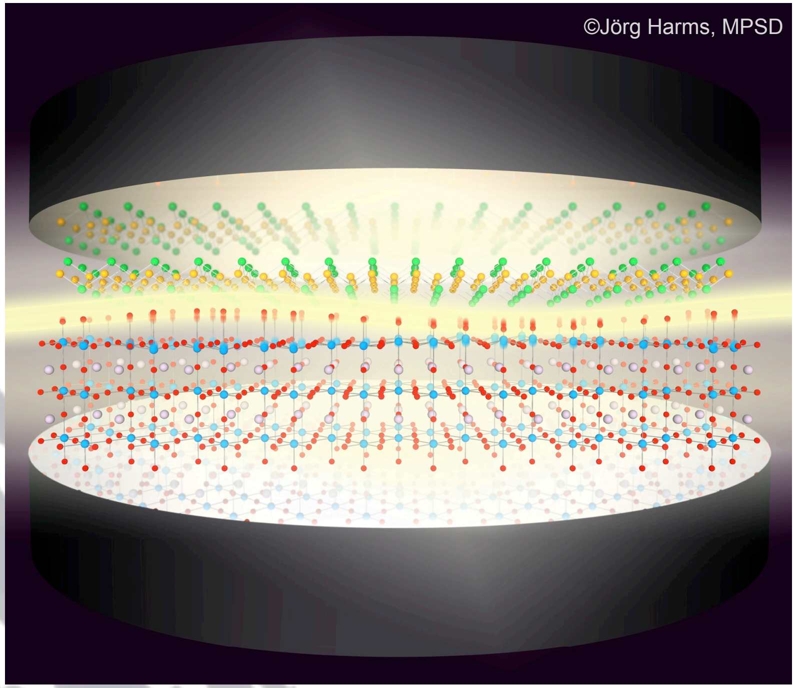
**collective strong light-matter coupling**

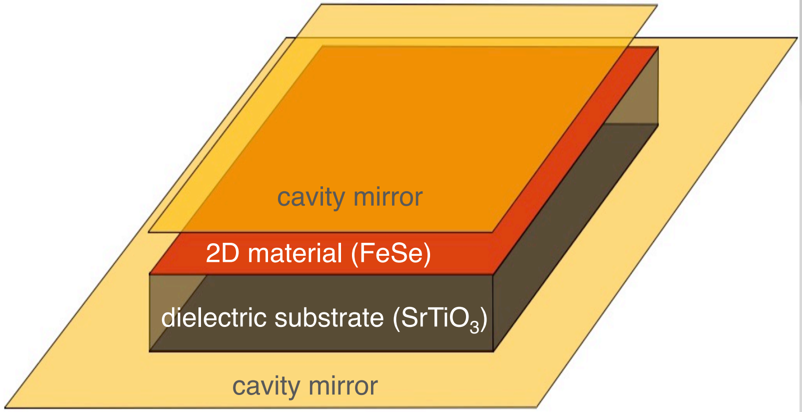
**what about cavity materials?**



# II Cavity materials

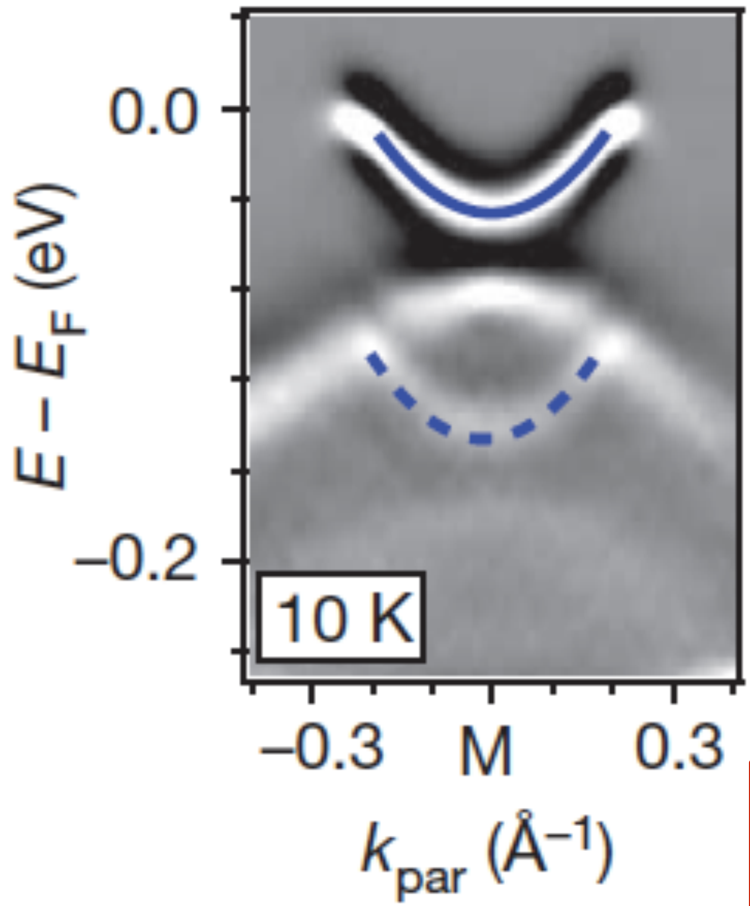
- can one use enhanced vacuum fluctuations to change materials properties?



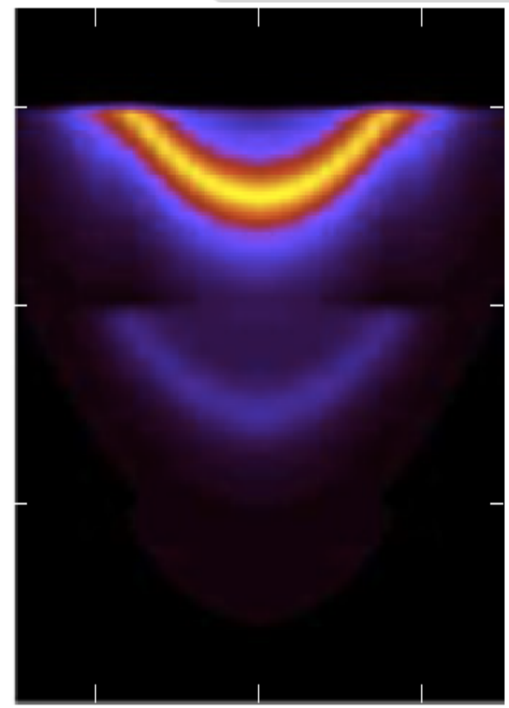



# monolayer FeSe/STO: ARPES

experiment




theory



replica bands: forward (small-q) electron-phonon scattering

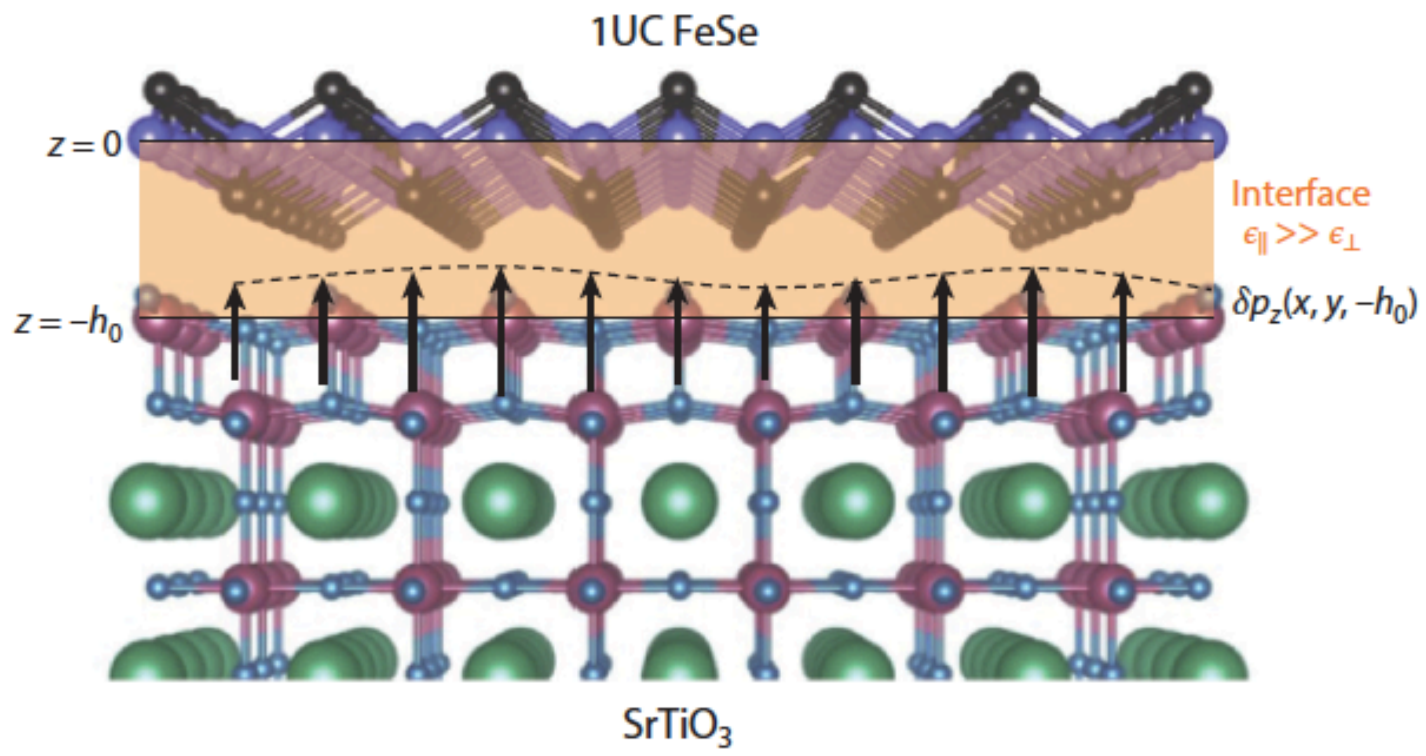
*Lee et al., Nature 515, 245 (2014)*

*Rademaker et al., New J. Phys. 18, 022001 (2016)*

# monolayer FeSe/STO: interfacial phonon

bare el-phonon vertex $g(\vec{q}) = g_0 \exp(-|\vec{q}|/q_0)$ *Lee et al., Nature 515, 245 (2014)*

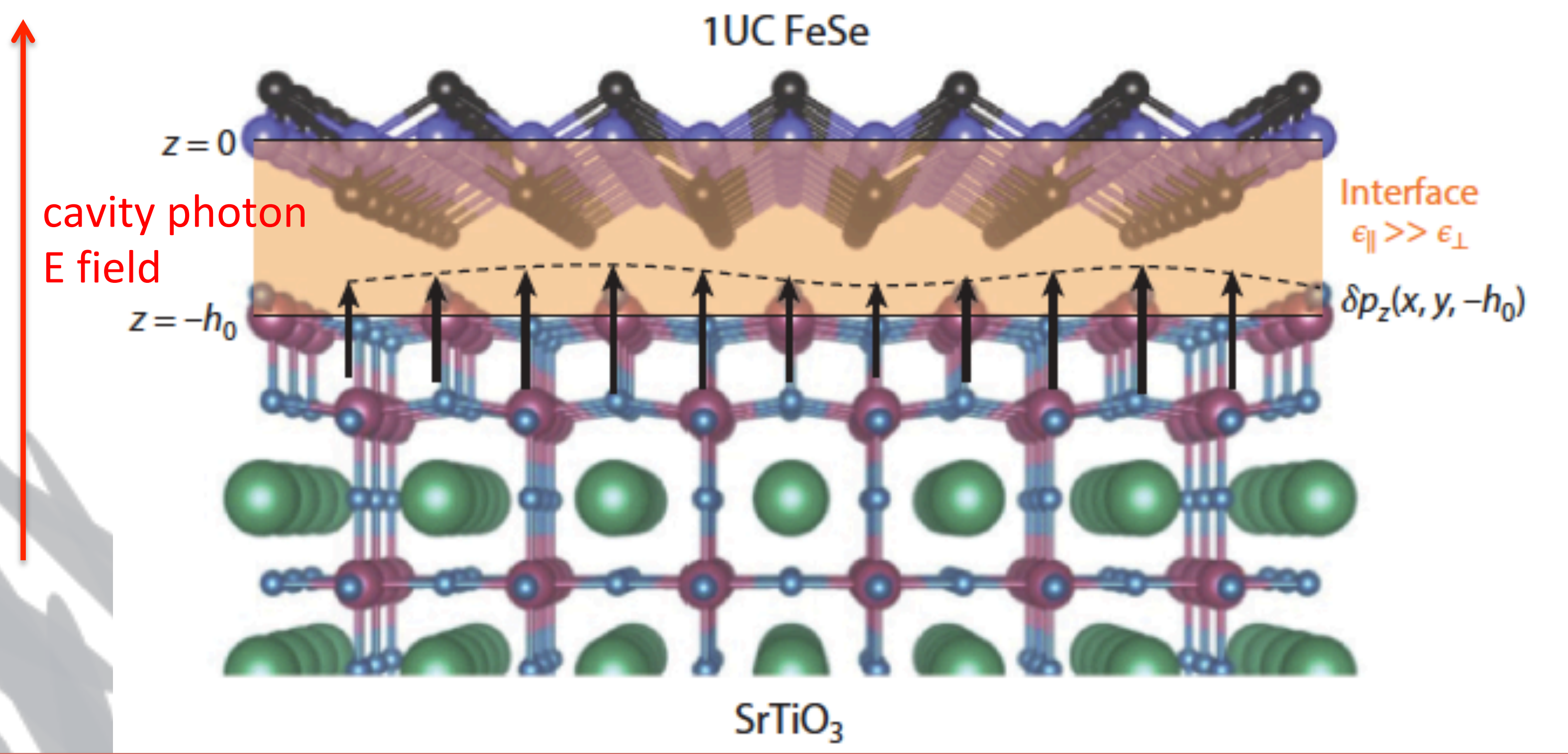
$$q_0^{-1} = h_0\sqrt{\epsilon_{\|}/\epsilon_{\perp}} \quad \epsilon_{\|}/\epsilon_{\perp} \approx 100$$




*Huang and Hoffman, Annu. Rev. CMP 8, 311 (2017)*

# Cavity engineering

- idea: use phonon polaritons to enhance electron-phonon coupling




*Huang and Hoffman, Annu. Rev. CMP 8, 311 (2017)*

# Model and Method

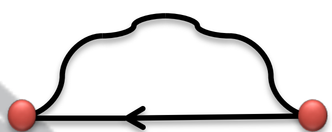
electrons — el-polariton coupling — polaritons

$$H = \sum_{\vec{k},\sigma} \epsilon_{\vec{k}} c^\dagger_{\vec{k},\sigma} c_{\vec{k},\sigma} + \frac{1}{\sqrt{N}} \sum_{\vec{k},\vec{q},\sigma,\lambda=\pm} c^\dagger_{\vec{k}+\vec{q},\sigma} c_{\vec{k},\sigma} \left(g^*_\lambda(\vec{q})\alpha^\dagger_{-\vec{q},\lambda} + g_\lambda(\vec{q})\alpha_{\vec{q},\lambda}\right) + \sum_{\vec{q},\lambda=\pm} \omega_\lambda(\vec{q})\alpha^\dagger_{\vec{q},\lambda}\alpha_{\vec{q},\lambda}$$

bare el-phonon vertex $g(\vec{q}) = g_0 \exp(-|\vec{q}|/q_0) \qquad q_0^{-1} = h_0\sqrt{\epsilon_\parallel/\epsilon_\perp}$

G-self-consistent Migdal-Eliashberg theory

$$\hat{\Sigma}(\vec{k}, i\omega_n) = \frac{-1}{N\beta} \sum_{\vec{q},m,\lambda=\pm} |g_\lambda(\vec{q})|^2 D^{(0)}_\lambda(\vec{q}, i\omega_n - i\omega_m)\hat{\tau}_3 \hat{G}(\vec{k}+\vec{q}, i\omega_m)\hat{\tau}_3$$

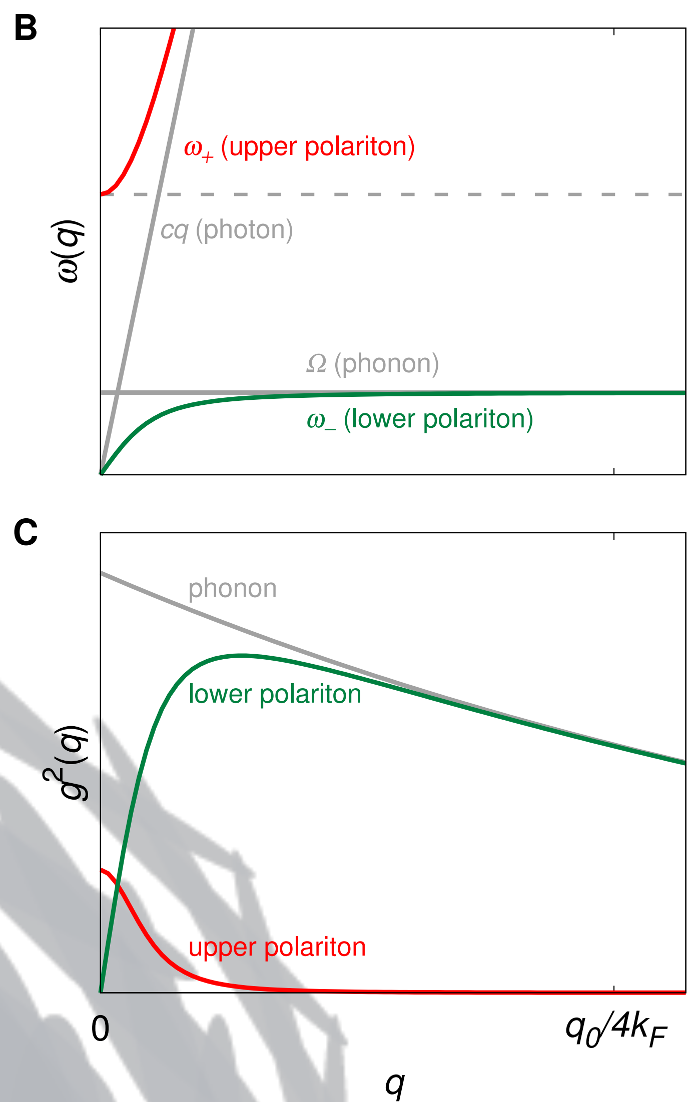


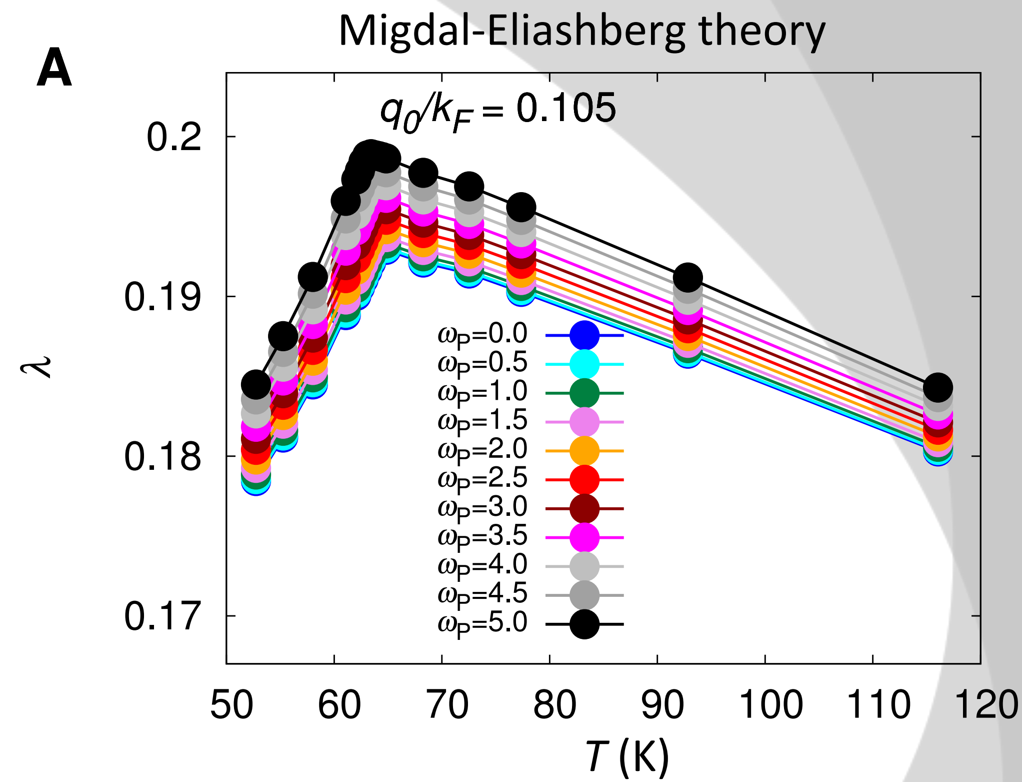
$$\hat{\Sigma}(\vec{k}, i\omega_n) = i\omega_n[1 - Z(\vec{k}, i\omega_n)]\hat{\tau}_0 + \chi(\vec{k}, i\omega_n)\hat{\tau}_3 + \phi(\vec{k}, i\omega_n)\hat{\tau}_1$$

$$\lambda \equiv Z(\vec{k}_F, i\pi/\beta) - 1$$

Mass enhancement: $m^*/m = 1 + \lambda$

# Cavity materials: Phonon polaritons



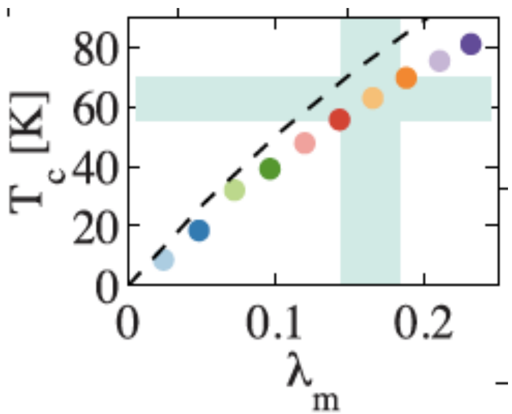



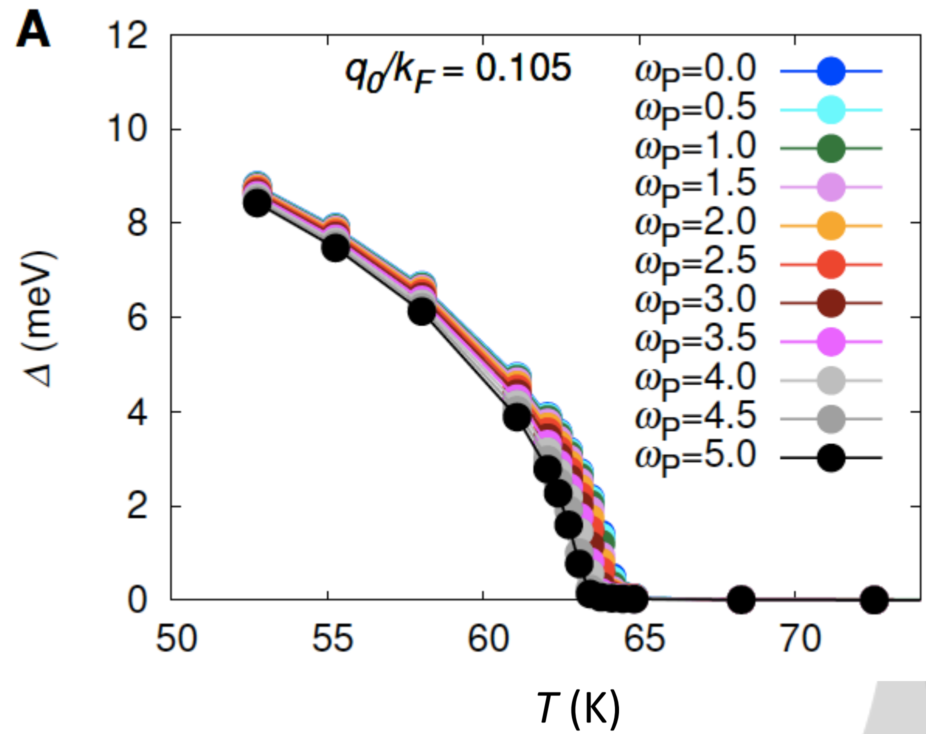

enhanced electron-phonon coupling, controlled by cavity volume ($\omega_p$ ~ 1/sqrt(volume))

# Superconductivity



Rademaker et al., New J. Phys. 18, 022001 (2016)




in cavity: $\lambda$ enhanced, but $\Omega$ suppressed

**suppressed superconductivity despite enhanced el-ph coupling**

forward scattering

$$T_C \approx \frac{\lambda\Omega}{2+3\lambda}$$

vs.

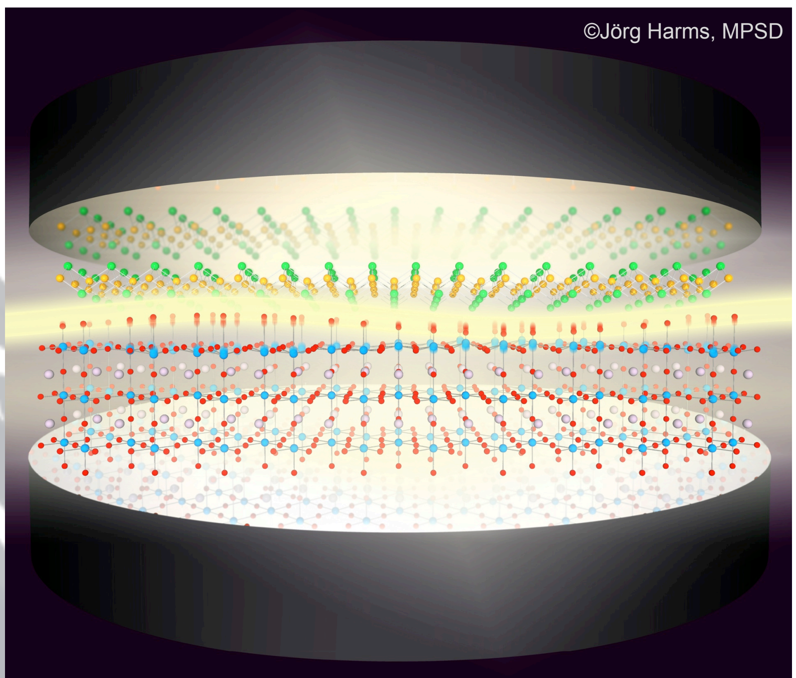
$$T_{C,\mathrm{BCS}} \approx 1.13\Omega\exp(-\frac{1}{\lambda})$$

q-independent scattering

# Summary II

- cavity leads to enhanced electron-phonon coupling
- can one also enhance superconductivity?

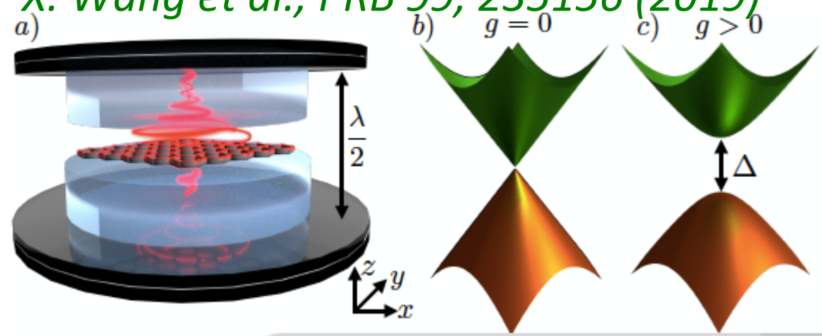
*M. A. Sentef, M. Ruggenthaler, A. Rubio, Science Advances 4, eaau6969 (2018)*




M. Ruggenthaler A. Rubio

Cavity-induced quantum-anomalous Hall effect in graphene

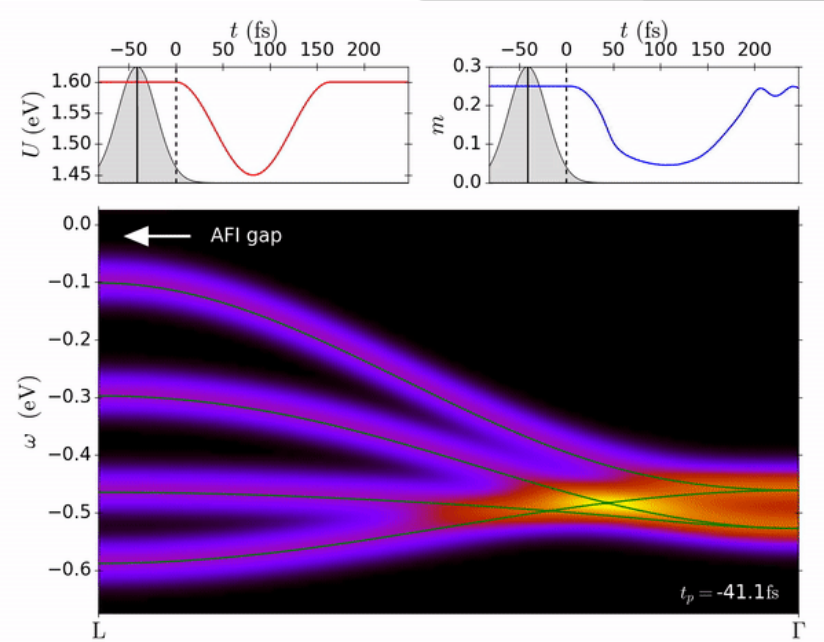
*X. Wang et al., PRB 99, 235156 (2019)*



# Outlook

## manipulation of correlations and topology with light

predicting light-induced
Weyl semimetal in
pyrochlore iridates




*N. Tancogne-Dejean et al., PRL 121, 097402 (2018)*
*G. E. Topp et al., Nature Comm. 9, 4452 (2018)*
*N. Tancogne-Dejean et al., arXiv:1906.11316*


PERSPECTIVE | TOPOLOGICAL MATTER

“Weyl”ing away time-reversal symmetry

Eduardo H. da Silva Neto

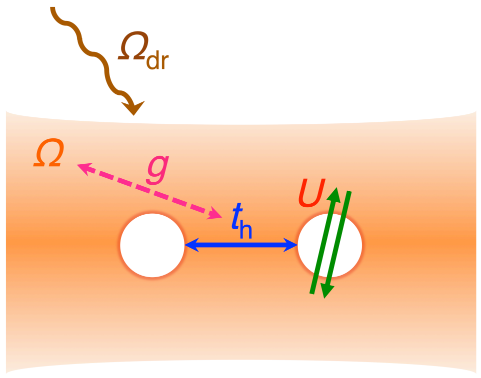
+ See all authors and affiliations

*Science* 20 Sep 2019:
Vol. 365, Issue 6459, pp. 1248-1249
DOI: 10.1126/science.aax6190

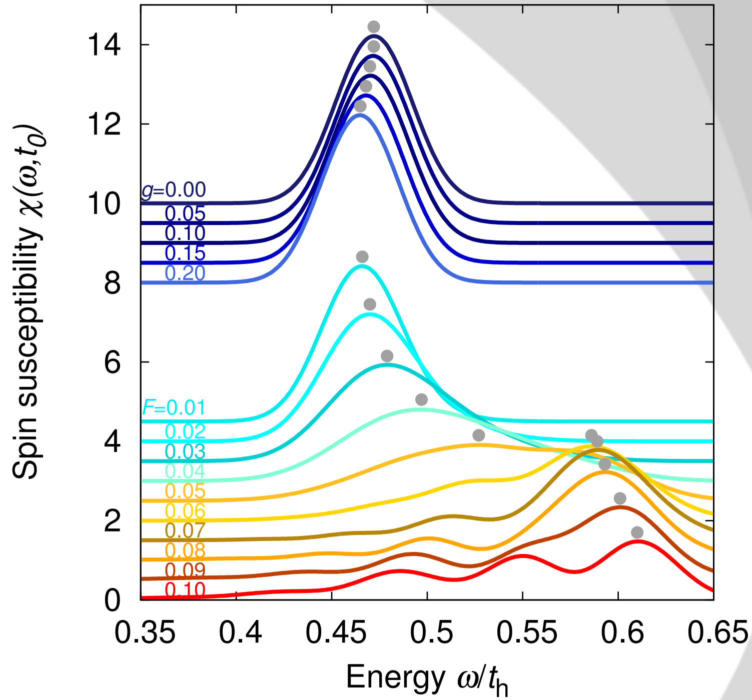
Nicolas Tancogne-Dejean    Gabriel Topp    also cf. Gabriel‘s talk

# Outlook

## cavity-Floquet crossover (w/ M. Eckstein's group)




cavity only: cf. Kiffner et al., PRB 2019 (Jacksch group)




manipulate correlations (kinetic exchange coupling) with virtual and real photons!