Nonequilibrium Materials Engineering

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and Ultrafast Bandgap Photonics UBP

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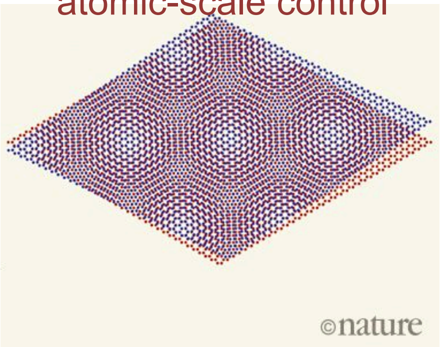
Max Planck Institute for the Structure and Dynamics of Matter

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

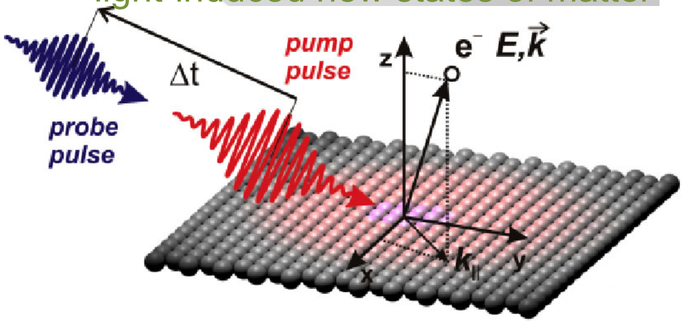
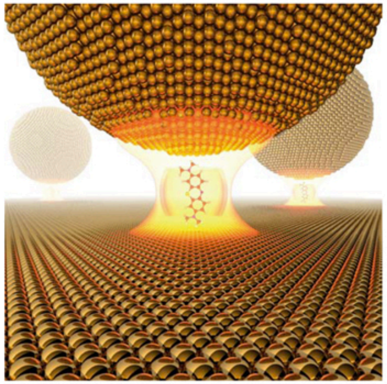


Image courtesy: J. Sobota

pump-probe: strong classical fields

nonequilibrium materials engineering



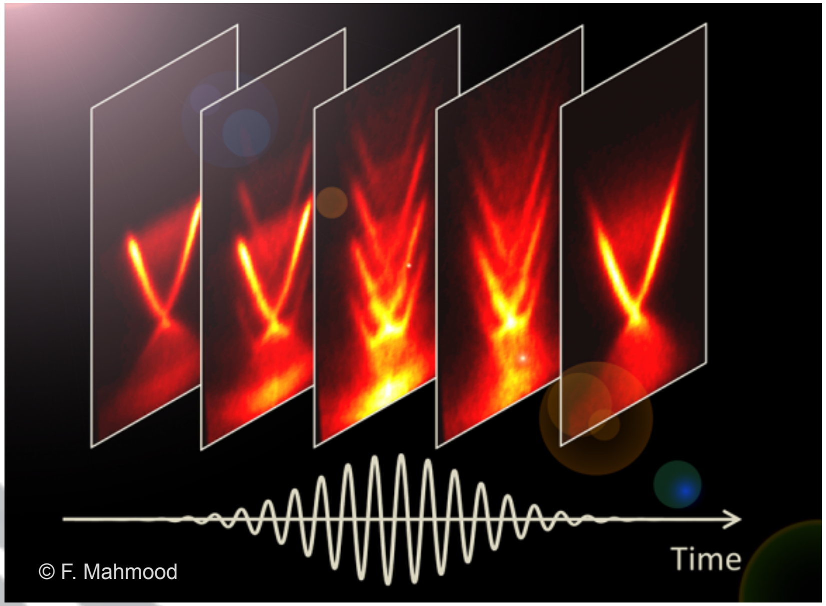
R. Chikkaraddy et al., Nature 535, 127 (2016)

quantum optics
nanoplasmonics
polaritonic chemistry

QED: vacuum fluctuations

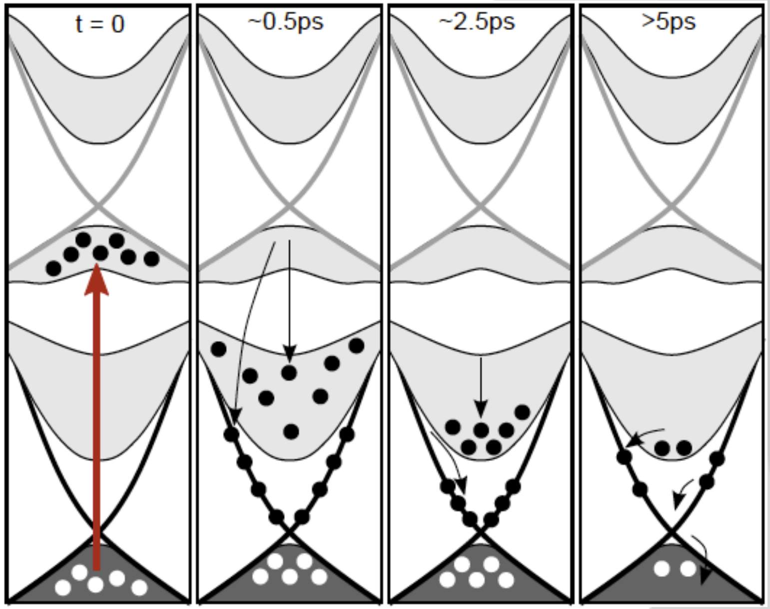
Engineering materials with light

Hamiltonian engineering
e.g., Floquet-Bloch bands



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

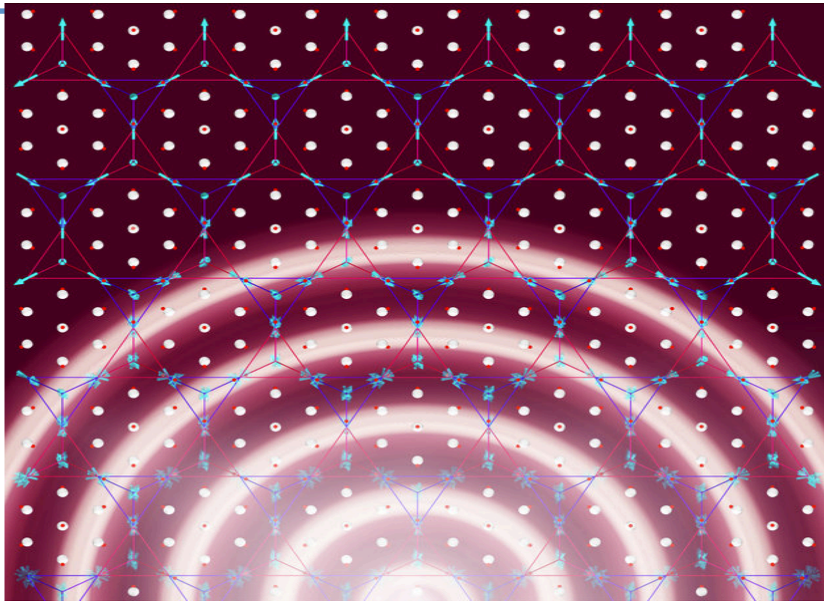
Distributional engineering

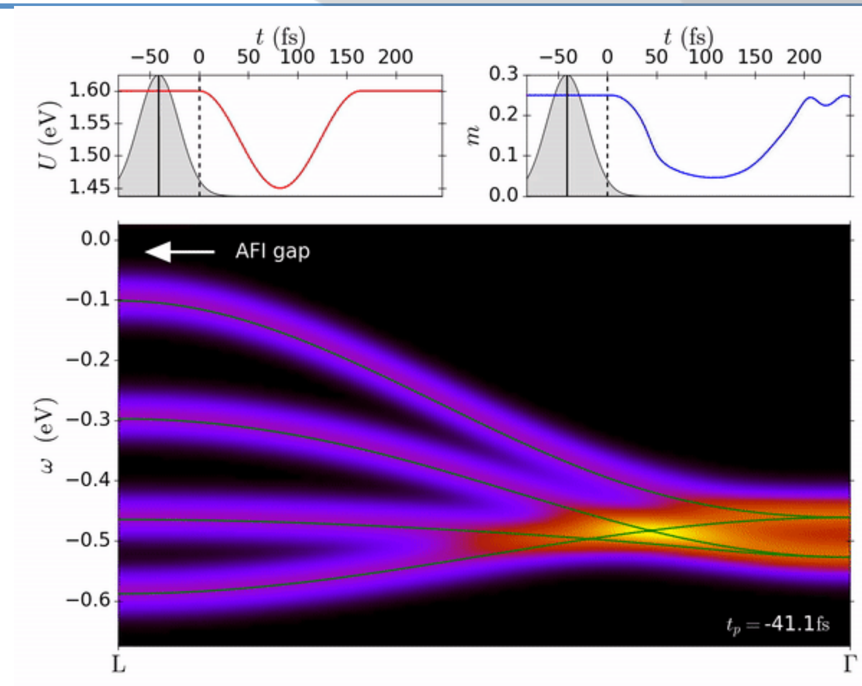


J. Sobota et al., JESRP 195, 249 (2014)

many ingredients, hard to disentangle

Engineering topology with light





G. E. Topp et al., Nature Comm. 9, 4452 (2018)
N. Tancogne-Dejean, MAS, A. Rubio, PRL 121, 097402 (2018)

Coupling engineering

Dynamical ab initio Hubbard U

Light-induced Weyl fermions in pyrochlore iridates

Time-resolved photoemission

nonthermal effects

bands + distributions important

Gabriel Topp

Nicolas Tancogne-Dejean

How to „engineer" materials with light at long time scales?

(I) Switch between (meta)stable states optically

Optical control of chiral superconductors

Short laser pulses allow for switching of Majorana modes

M. Claassen et al., arXiv:1810.06536, to appear in Nature Physics

(II) Use quantum instead of classical light

Cavity QED materials engineering

Materials engineering in an optical cavity using vacuum fluctuations

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

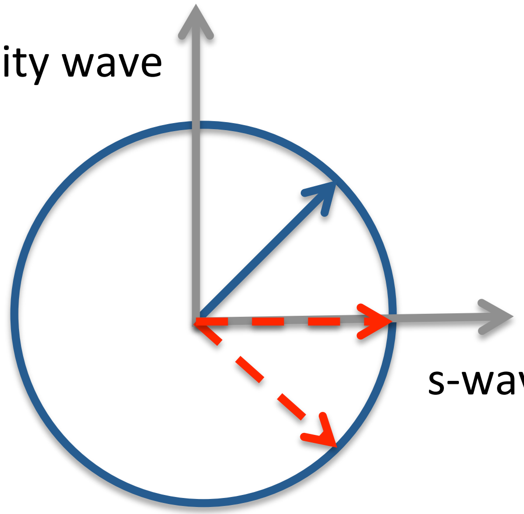
I Optical control of Majoranas

- prior work: optical control of competing orders

Theory of Laser-Controlled Competing Superconducting and Charge Orders

M. A. Sentef, A. Tokuno, A. Georges, and C. Kollath
Phys. Rev. Lett. **118**, 087002 – Published 21 February 2017

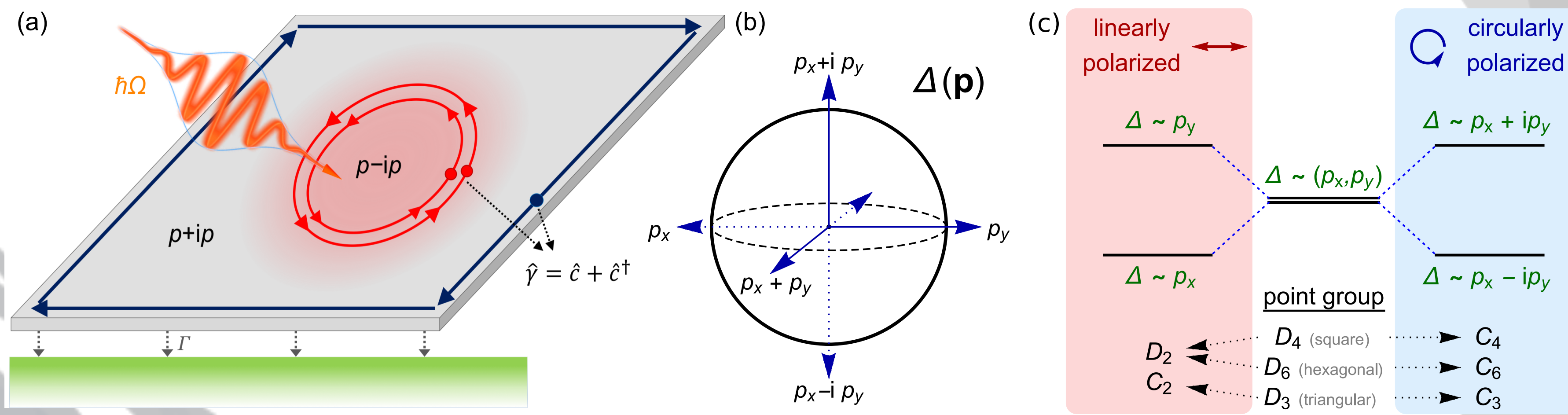
  – near-resonant laser driving switches between phases



I Optical control of Majoranas

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

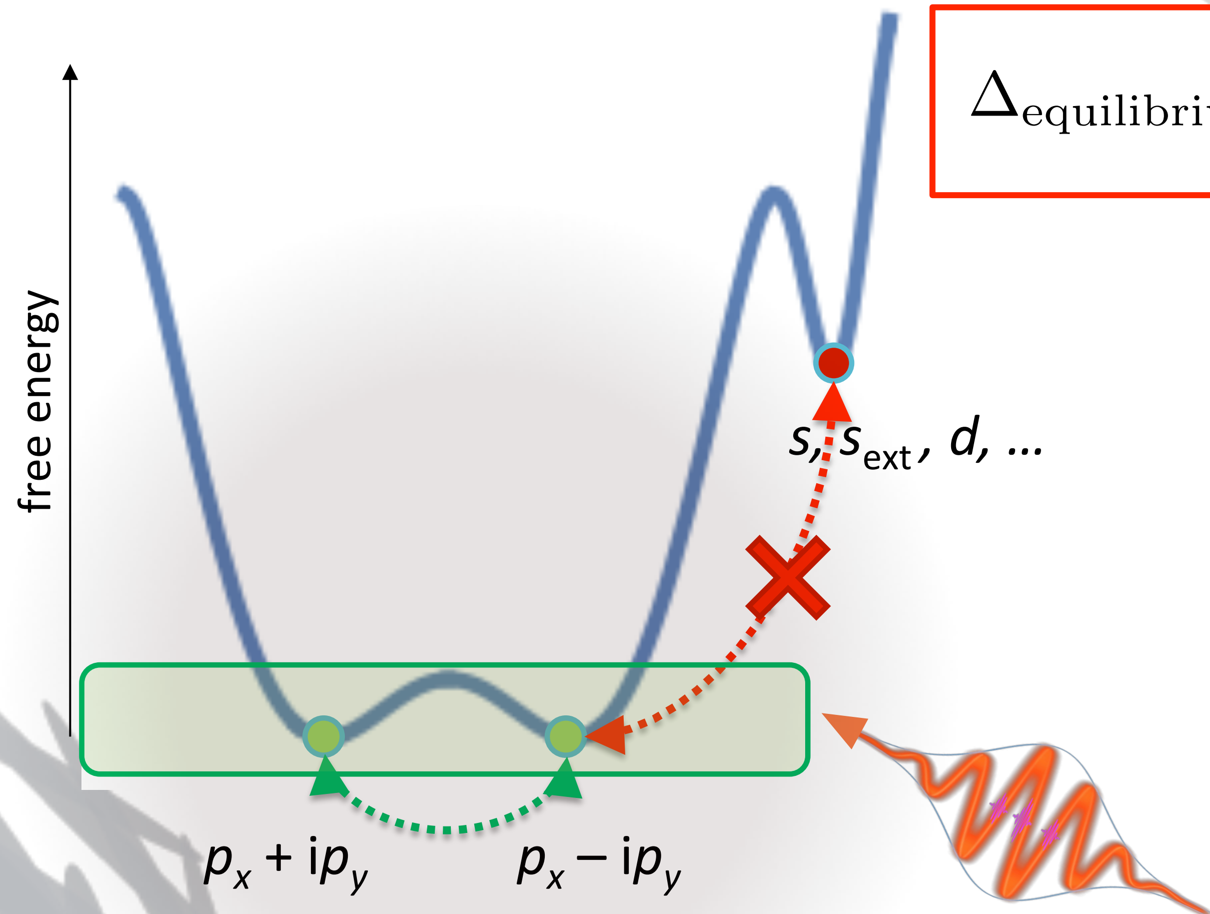
Sr_2RuO_4, highly doped graphene, twisted bilayer graphene, ...?



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

Nonequilibrium pathway to switching

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



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

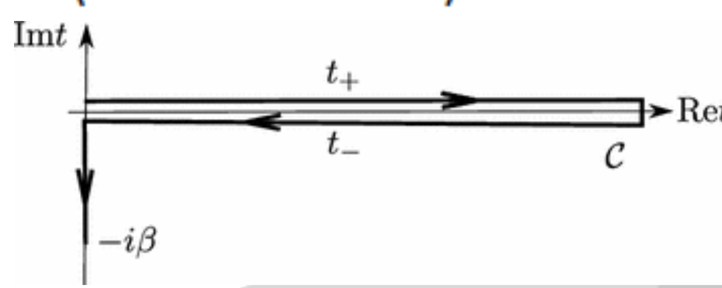
Model and Method

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

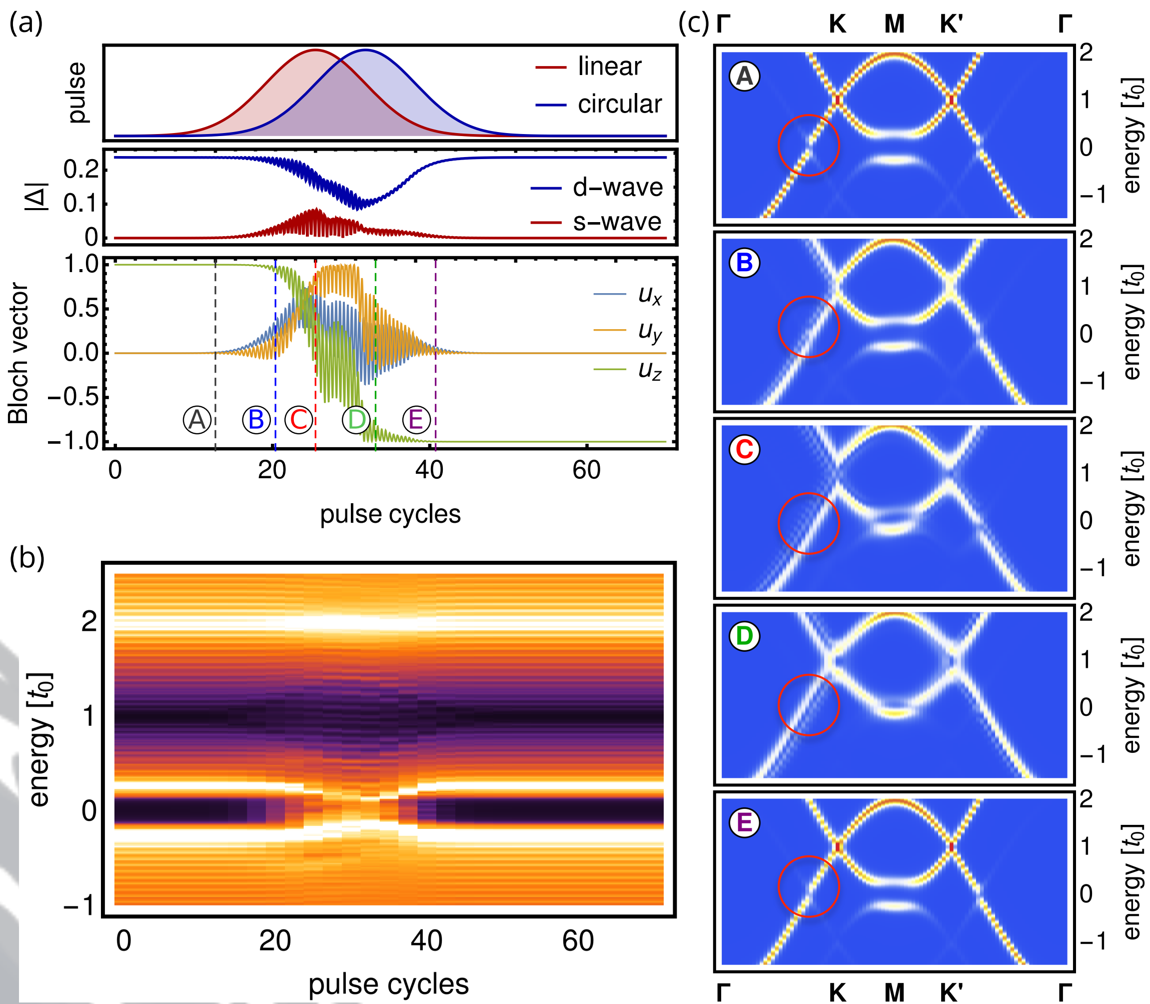
self-consistent Keldysh equations of motion for Nambu Green's functions:

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

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



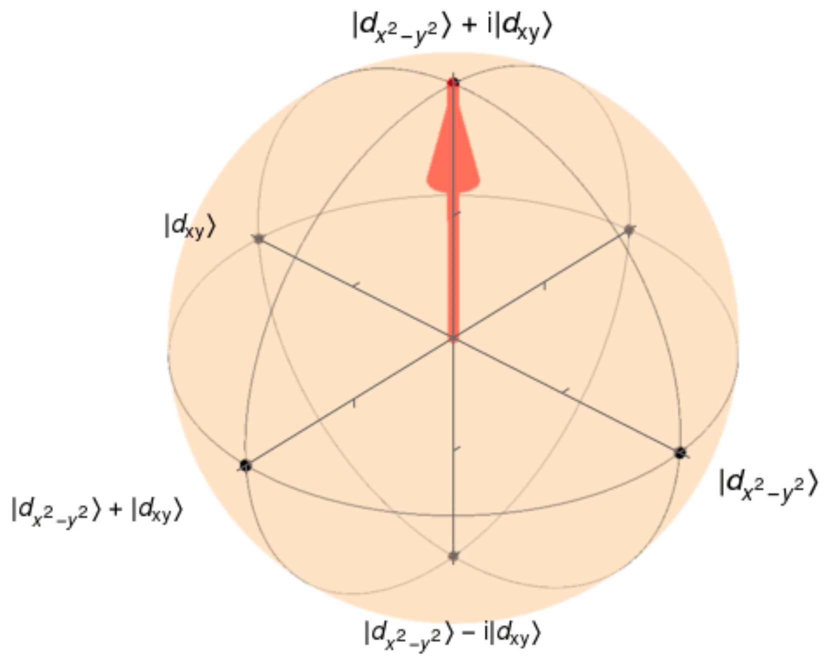
Optical control of Majoranas

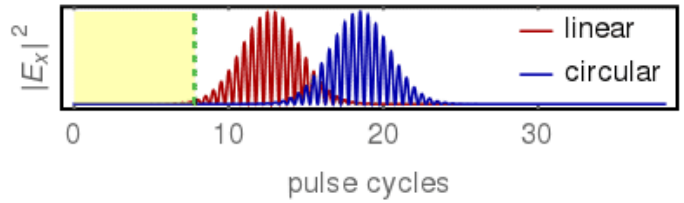


two-pulse sequence reverses d+id state in graphene

time-resolved spectroscopy tracks chirality reversal

Bloch vector rotation



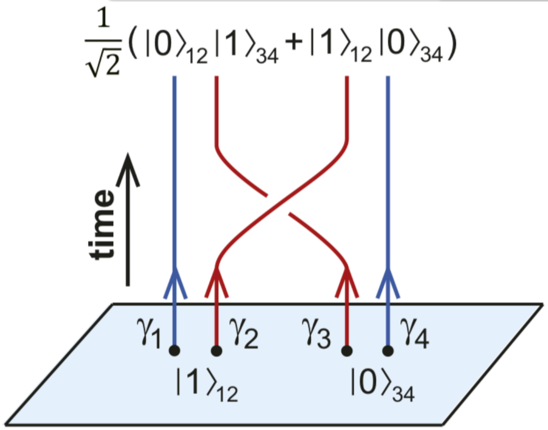


A „programmable“ topological quantum computer?

non-Abelian statistics of Majorana fermions:

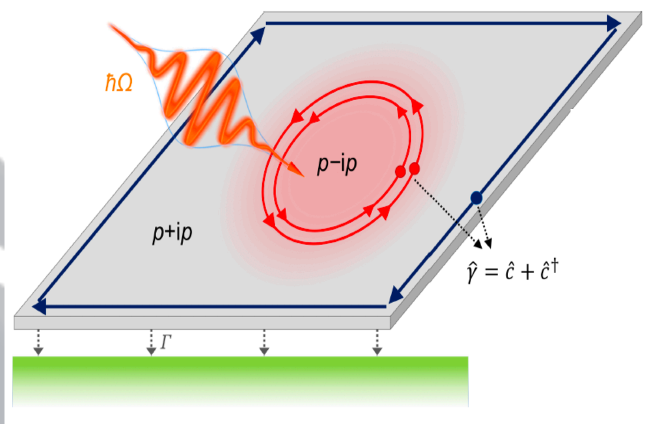
- half-quantum vortices of chiral superconductors host single Majorana fermions
- Two Majoranas represent one electron: **½ + ½ = 1**

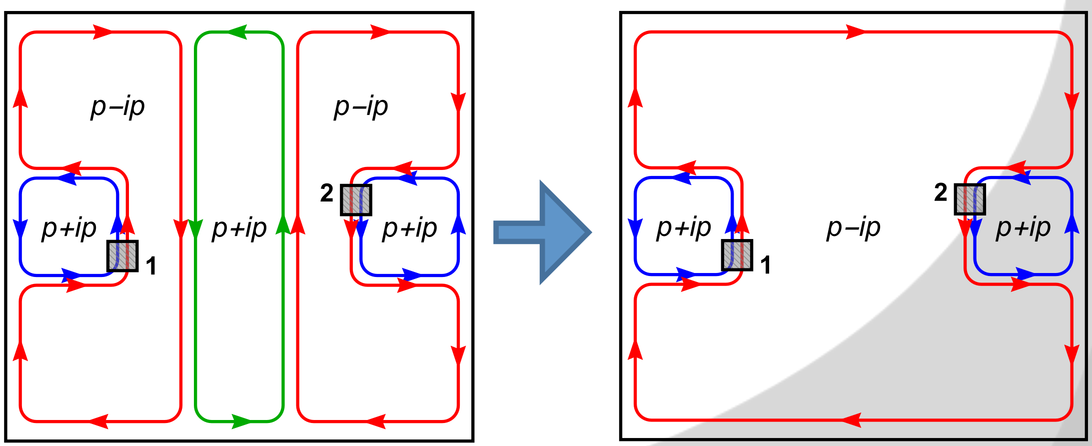
  → Braiding between Majoranas is a non-Abelian operation in electron (charge) basis!



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

simplest operation: a **switchable Hadamard gate**





Summary I

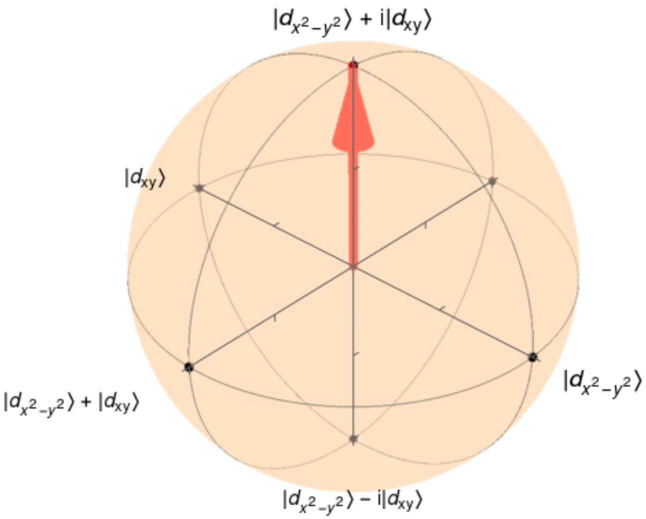
- All-optical control of chiral Majorana modes
- towards arbitrarily programmable quantum computer?

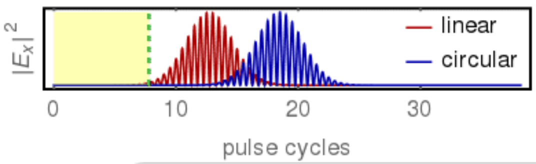
„program the gate optically, read it out electrically“

M. Claassen et al., arXiv:1810.06536, to appear in Nat. Phys.

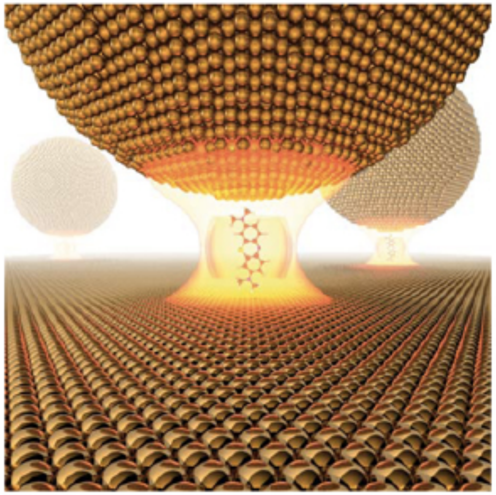
M. Claassen

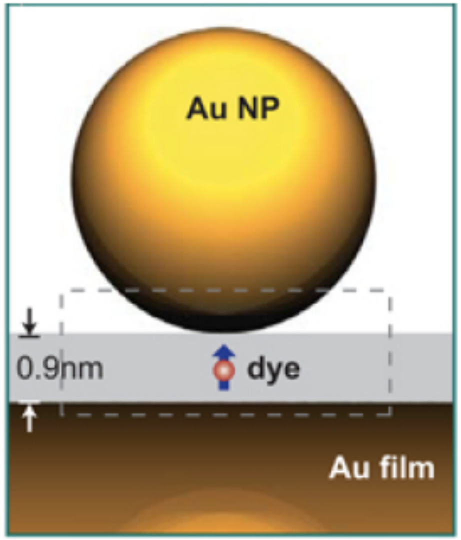
D. Kennes



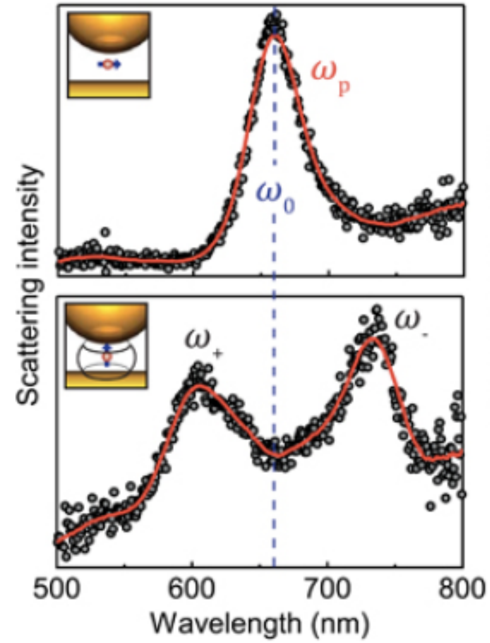


From classical to quantum light





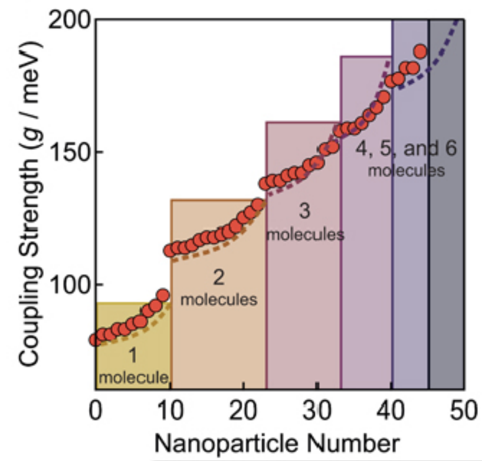
R. Chikkaraddy et al., Nature 535, 127 (2016)



Rabi splitting

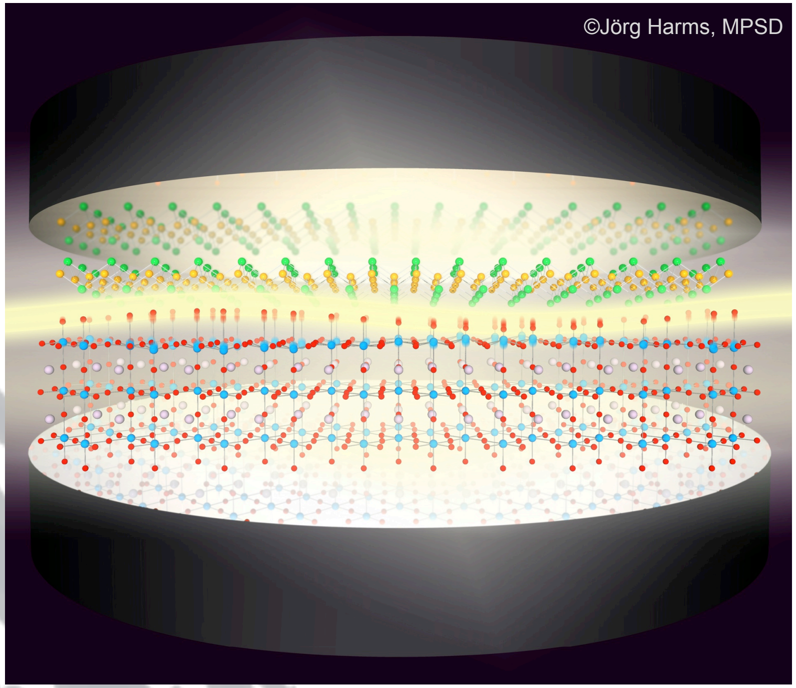
collective strong light-matter coupling

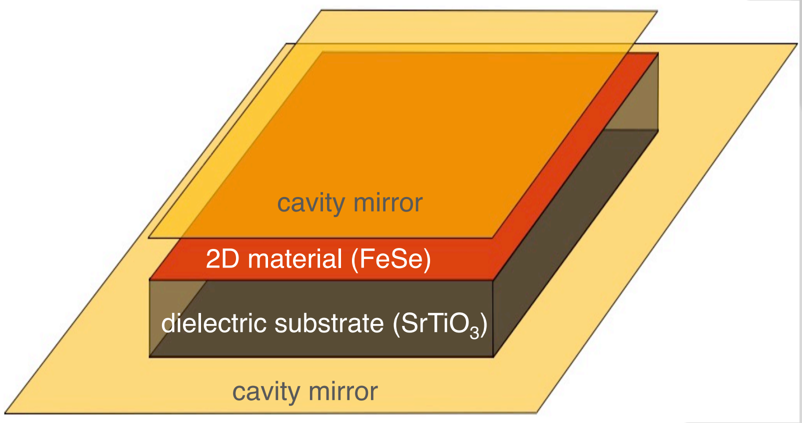
what about cavity materials?



II Cavity materials

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





Cavity materials

BCS superconductors: phonon-mediated superconductivity
Ginzburg, Phys. Lett. 13, 101 (1964): exciton-mediated superconductivity?
Ruvalds, Phys. Rev. B 35, 8869(R) (1987): plasmon-mediated superconductivity?

PRL 104, 106402 (2010) PHYSICAL REVIEW LETTERS week ending 12 MARCH 2010

Exciton-Polariton Mediated Superconductivity

Fabrice P. Laussy,[1] Alexey V. Kavokin,[1,2] and Ivan A. Shelykh[3,4]

PHYSICAL REVIEW B 93, 054510 (2016)

Superconductivity and other collective phenomena in a hybrid Bose-Fermi mixture formed by a polariton condensate and an electron system in two dimensions

Ovidiu Cotleţ,[1,*] Sina Zeytinoğlu,[1,2] Manfred Sigrist,[2] Eugene Demler,[3] and Ataç Imamoğlu[1]

Cavity-assisted mesoscopic transport of fermions: Coherent and dissipative dynamics.

Hagenmüller et al., 1801.09876

Cavity quantum-electrodynamical polaritonically enhanced electron-phonon coupling and its influence on superconductivity

M. A. Sentef,[1,*] M. Ruggenthaler,[1] and A. Rubio[1,2,3]

1802.09437

Cavity-mediated electron-photon superconductivity

Frank Schlawin[1], Andrea Cavalleri[1,2] and Dieter Jaksch[1]

1804.07142

Superradiant Quantum Materials

Giacomo Mazza[1,2,*] and Antoine Georges[2,3,1,4]

1804.08534

Cavity Quantum Eliashberg Enhancement of Superconductivity

Jonathan B. Curtis,[1,2,*] Zachary M. Raines,[1,2] Andrew A. Allocca,[1,2] Mohammad Hafezi,[1] and Victor M. Galitski[1,2]

1805.01482

Manipulating quantum materials with quantum light

Martin Kiffner[1,2], Jonathan Coulthard[2], Frank Schlawin[2], Arzhang Ardavan[2], and Dieter Jaksch[2,1]

1806.06752

Cavity superconductor-polaritons

Andrew A. Allocca,* Zachary M. Raines, Jonathan B. Curtis, and Victor M. Galitski

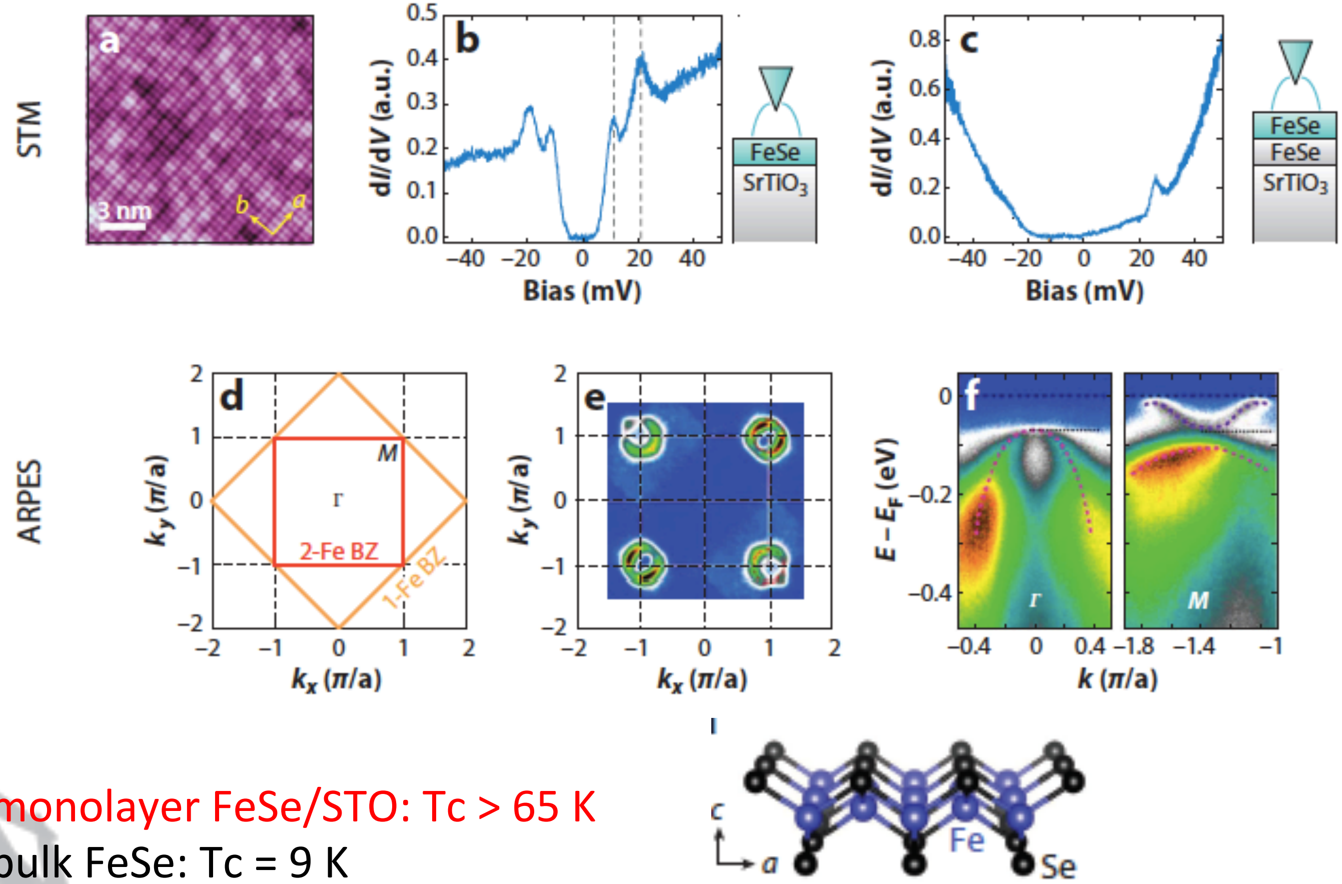
1807.06601

Ab-initio Exciton-polaritons: Cavity control of Dark Excitons in two dimensional Materials

Simone Latini,[1,*] Enrico Ronca,[1,†] Umberto De Giovannini,[1,2,‡] Hannes Hübener,[1,§] and Angel Rubio[1,3,¶]

1810.02672

monolayer FeSe/STO

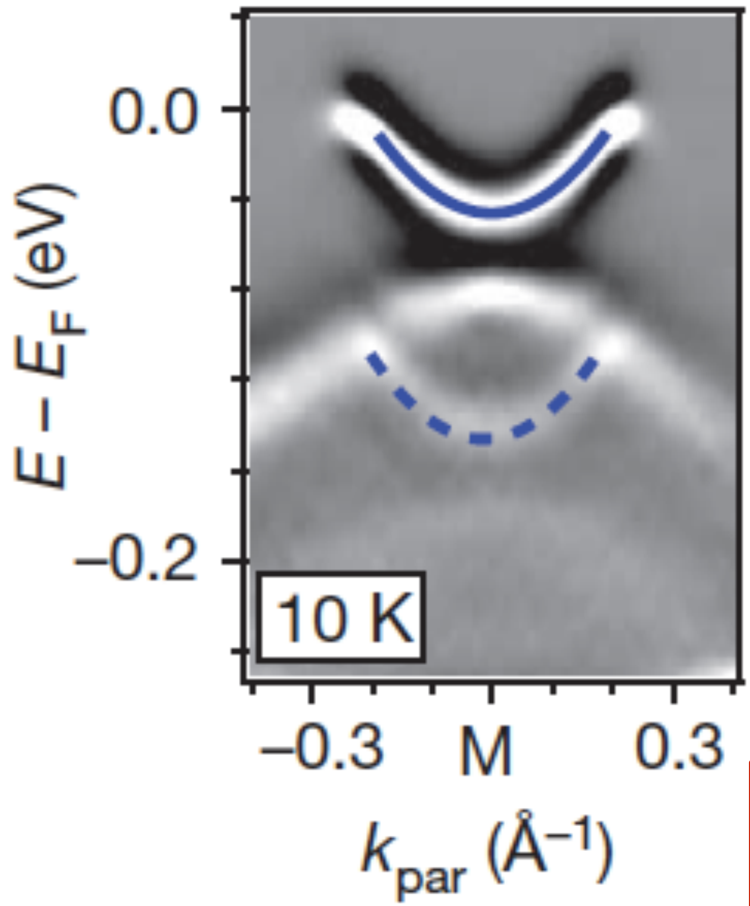


monolayer FeSe/STO: Tc > 65 K
bulk FeSe: Tc = 9 K

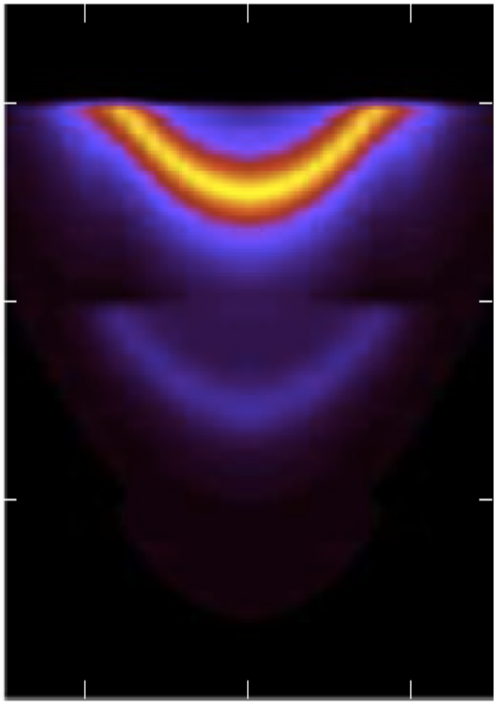
Wang QY, Li Z, Zhang WH, Zhang ZC, Zhang JS, et al. 2012. *Chin. Phys. Lett.* 29:037402
Liu D, Zhang W, Mou D, He J, Ou YB, et al. 2012. *Nat. Commun.* 3:931
Huang and Hoffman, Annu. Rev. CMP 8, 311 (2017)

monolayer FeSe/STO: ARPES

experiment



theory



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

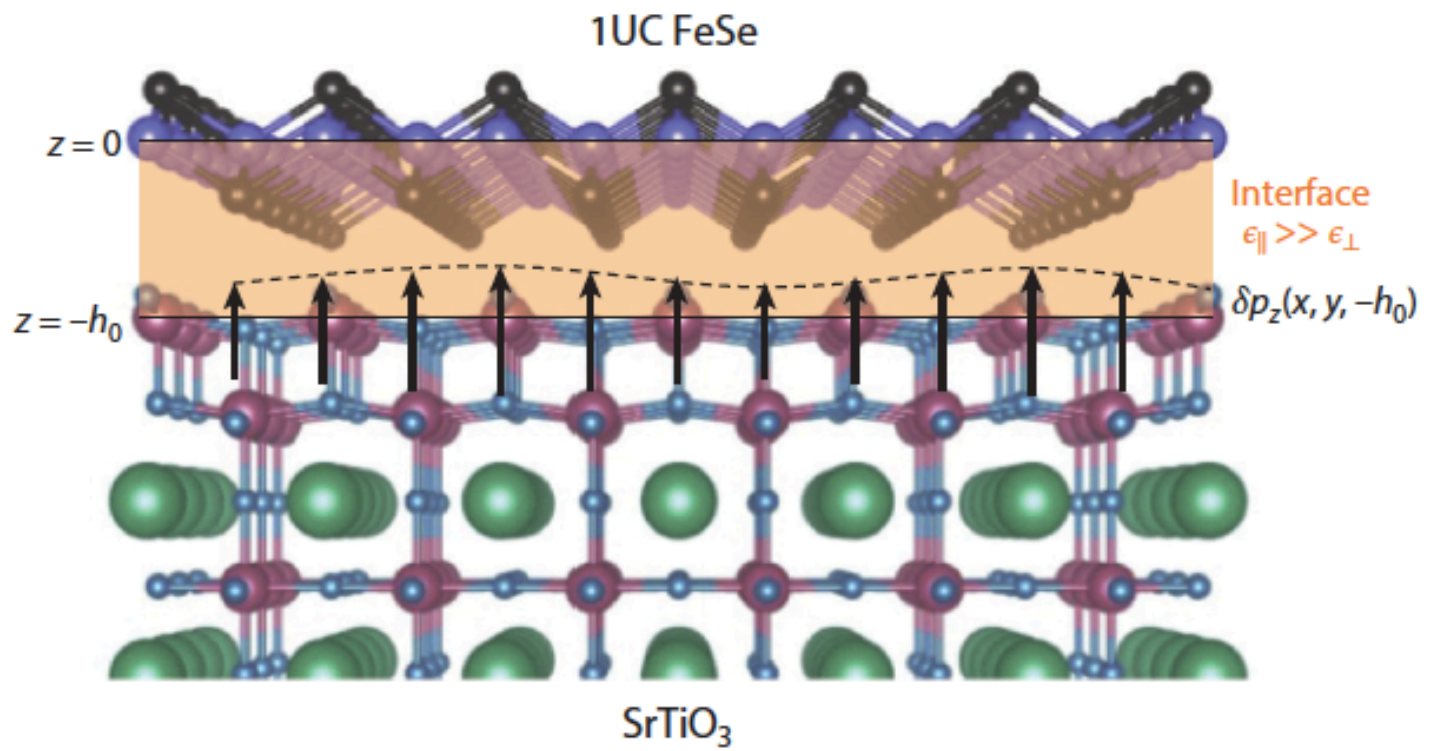
Lee et al., Nature 515, 245 (2014)

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)*

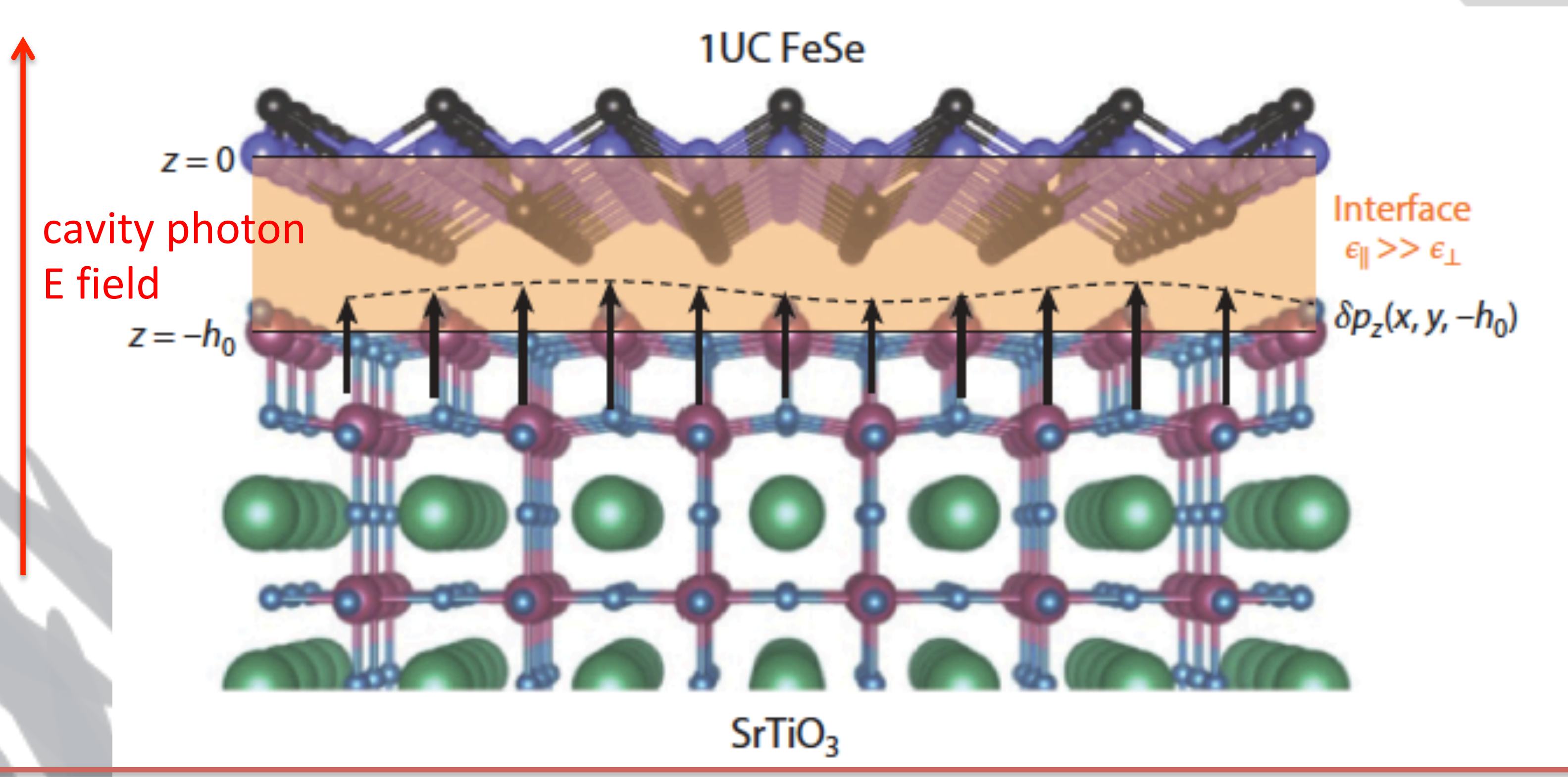
$$q_0^{-1} = h_0 \sqrt{\epsilon_{\|}/\epsilon_{\perp}} \quad \epsilon_{\|}/\epsilon_{\perp} \approx 100$$



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

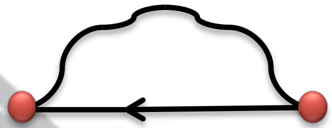
electrons   el-polariton coupling   polaritons

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

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

G-self-consistent Migdal-Eliashberg diagram

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

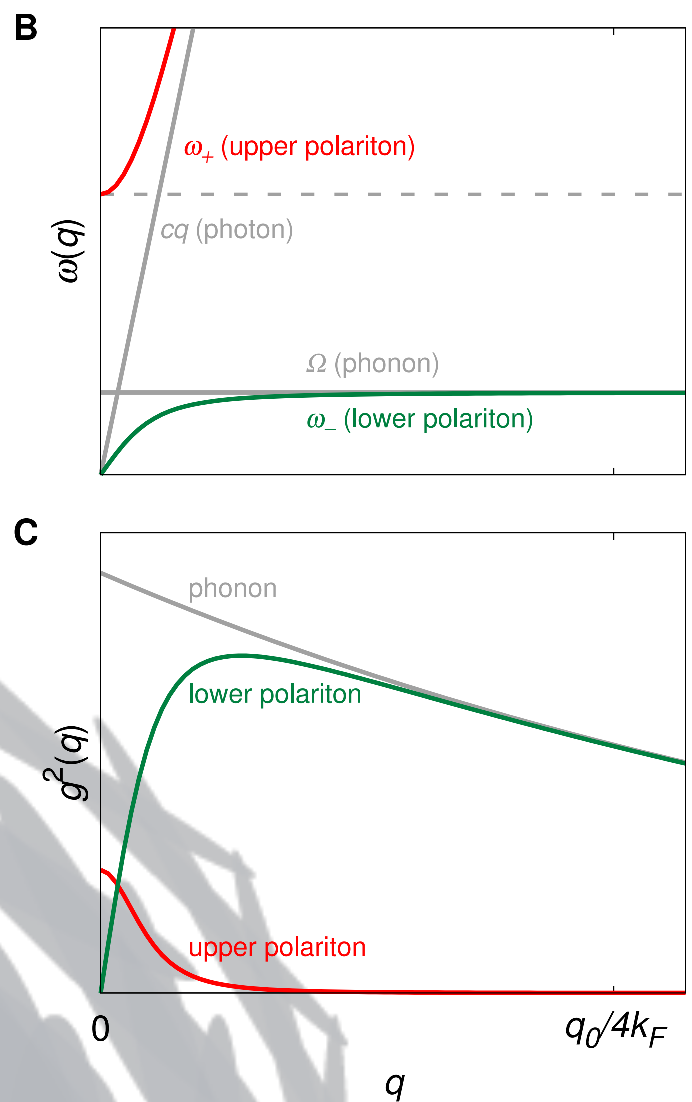


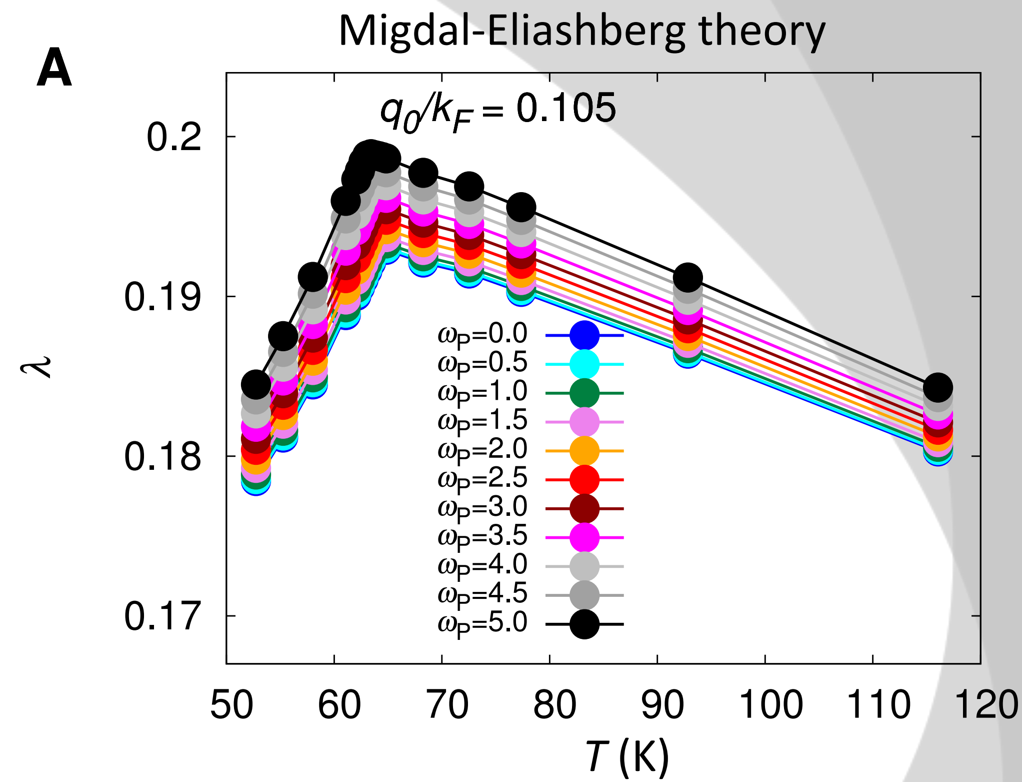
$$\hat{\Sigma}(\vec{k}, i\omega_n) = i\omega_n [1 - Z(\vec{k}, i\omega_n)] \hat{\tau}_0 + \chi(\vec{k}, i\omega_n) \hat{\tau}_3 + \phi(\vec{k}, i\omega_n) \hat{\tau}_1$$

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

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

Cavity materials: Phonon polaritons

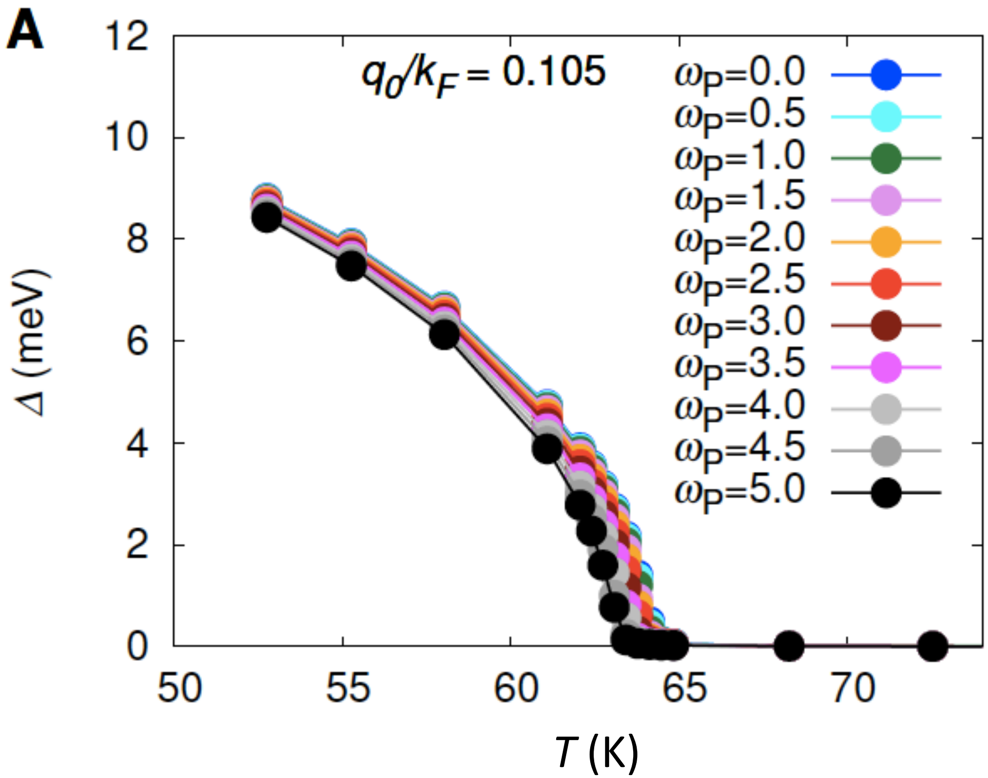




enhanced electron-phonon coupling, controlled by cavity volume

Superconductivity

mpsd



suppressed superconductivity despite enhanced el-ph coupling

forward scattering

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

vs.

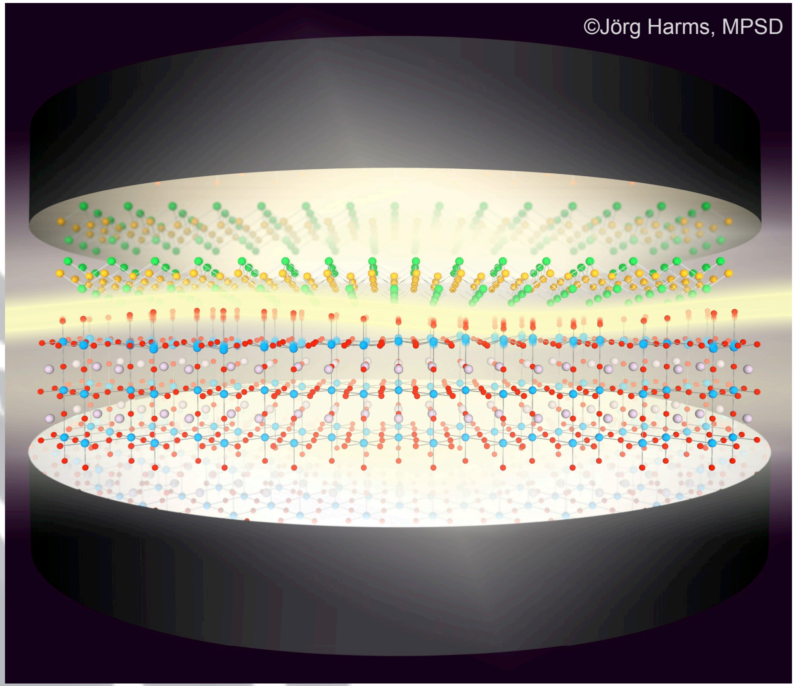
$$T_{C,\mathrm{BCS}} \approx 1.13\Omega \exp(-\tfrac{1}{\lambda})$$

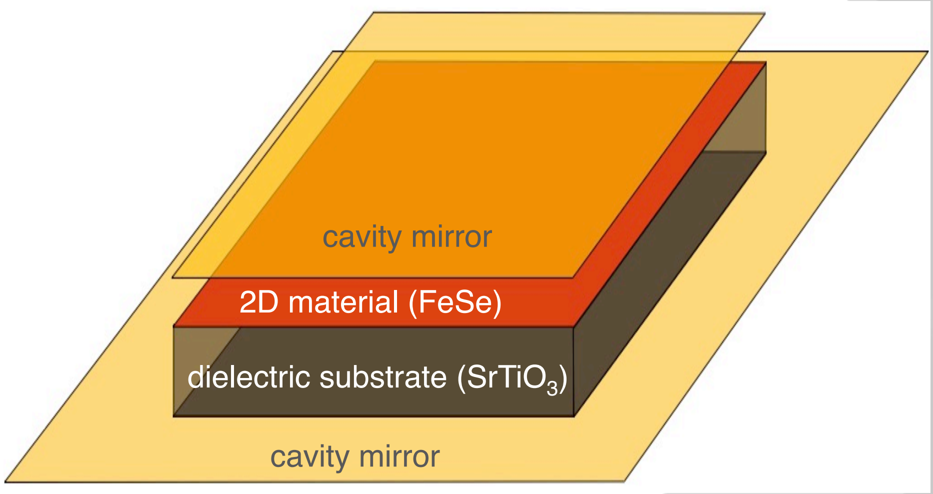
q-independent scattering

Summary II

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

M. A. Sentef, M. Ruggenthaler, A. Rubio, arXiv:1802.09437
Science Advances 4, eaau6969 (2018)





Team and collaborators

mpsd

thank you for your attention!

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