Nonequilibrium Materials Engineering

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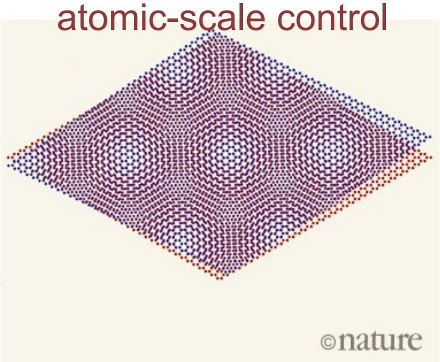
Engineering materials with light

condensed matter
quantum materials
atomic-scale control



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

nonequilibrium materials engineering

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

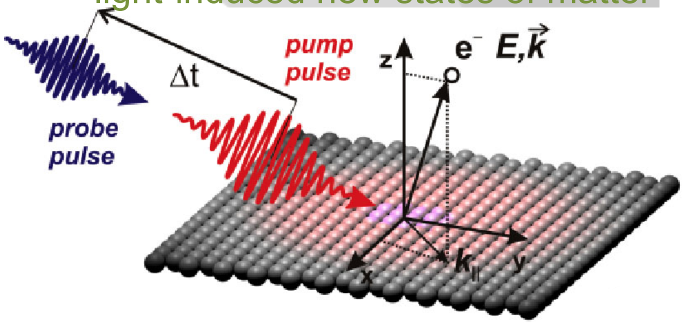
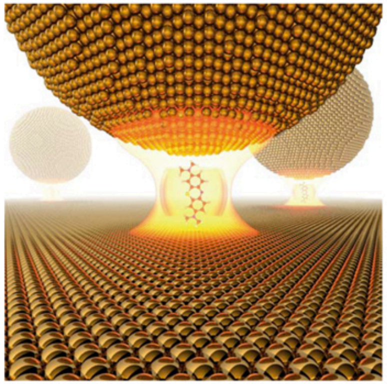


Image courtesy: J. Sobota

pump-probe: strong classical fields



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

quantum optics
nanoplasmonics
polaritonic chemistry

QED: vacuum fluctuations

Engineering materials with light

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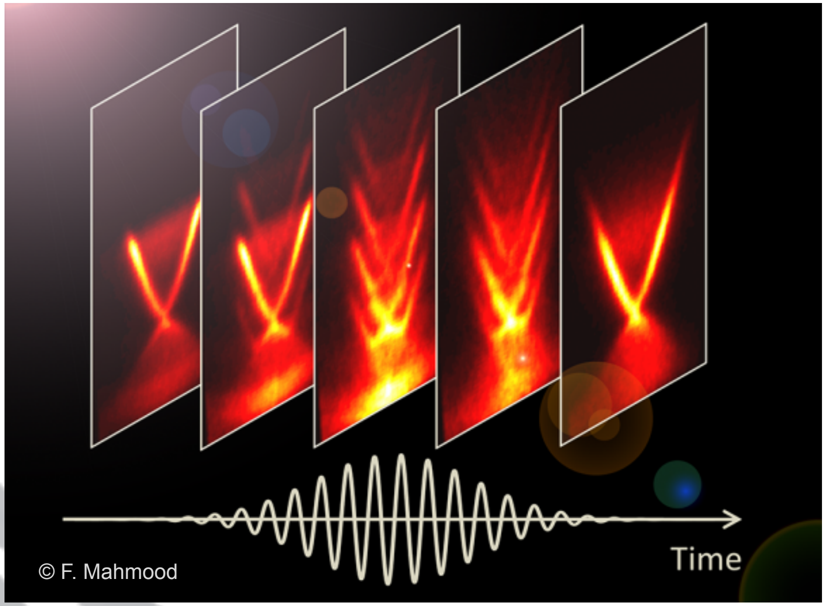
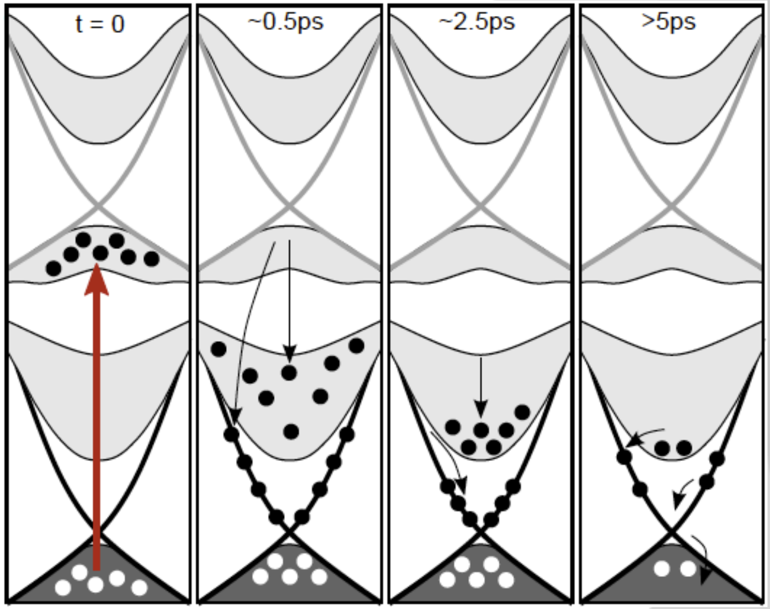
Hamiltonian engineering

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

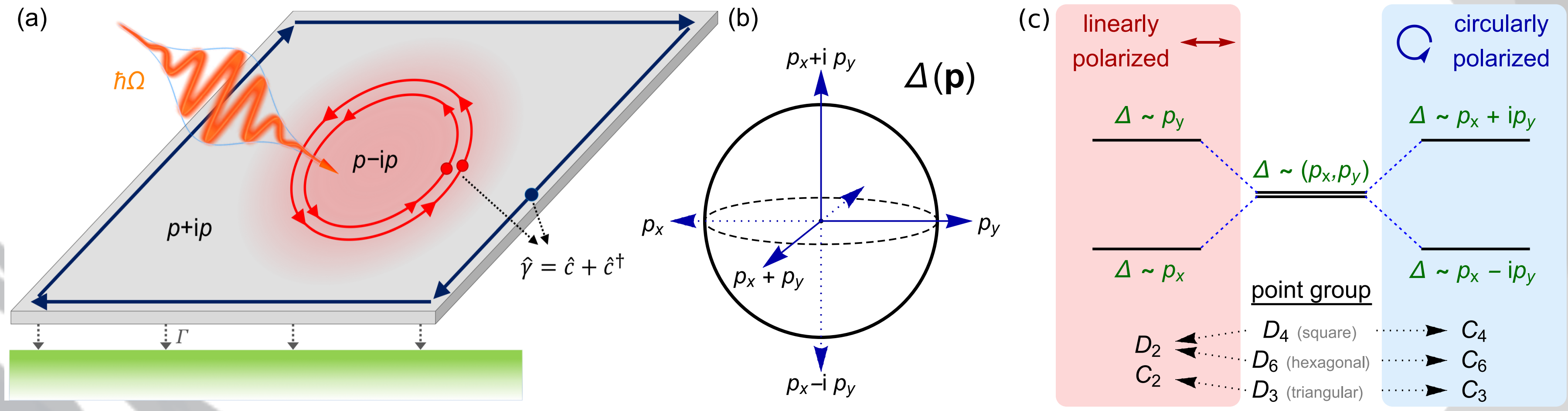
Materials engineering in an optical cavity using vacuum fluctuations

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

I Optical control of Majoranas

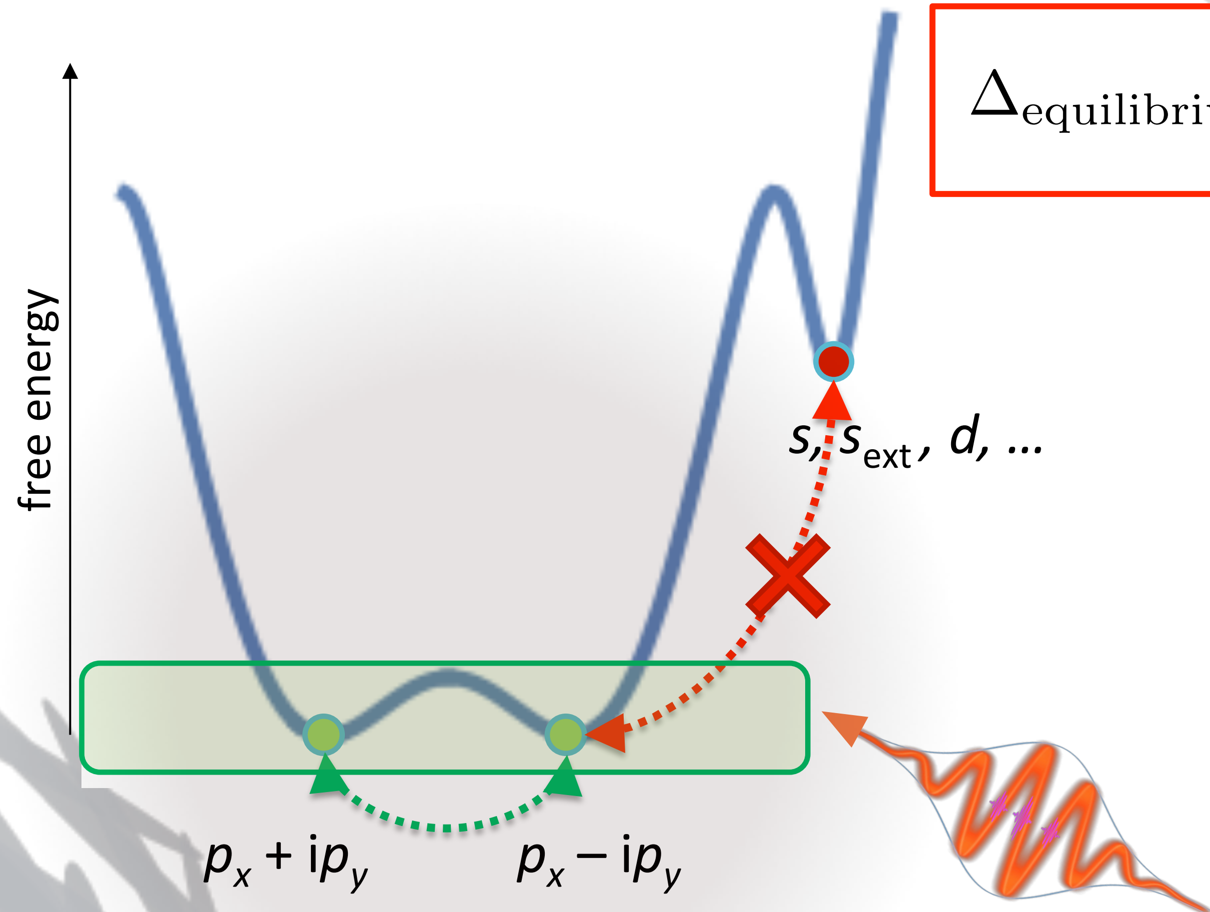
- can one switch the chirality of a 2D topological superconductor?

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

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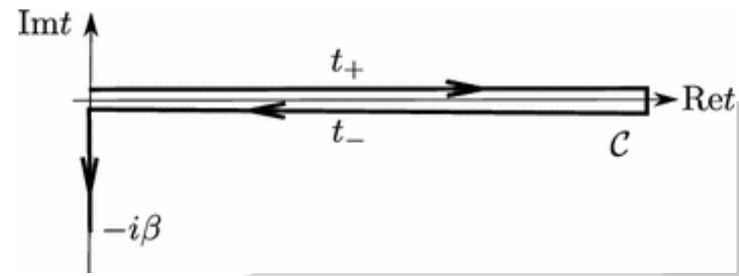
multiband Bogoliubov-de-Gennes Hamiltonians for doped graphene (d+id) and Sr2RuO4 (p+ip)
coupling to fermionic reservoir to dissipate energy
laser driving via Peierls substitution

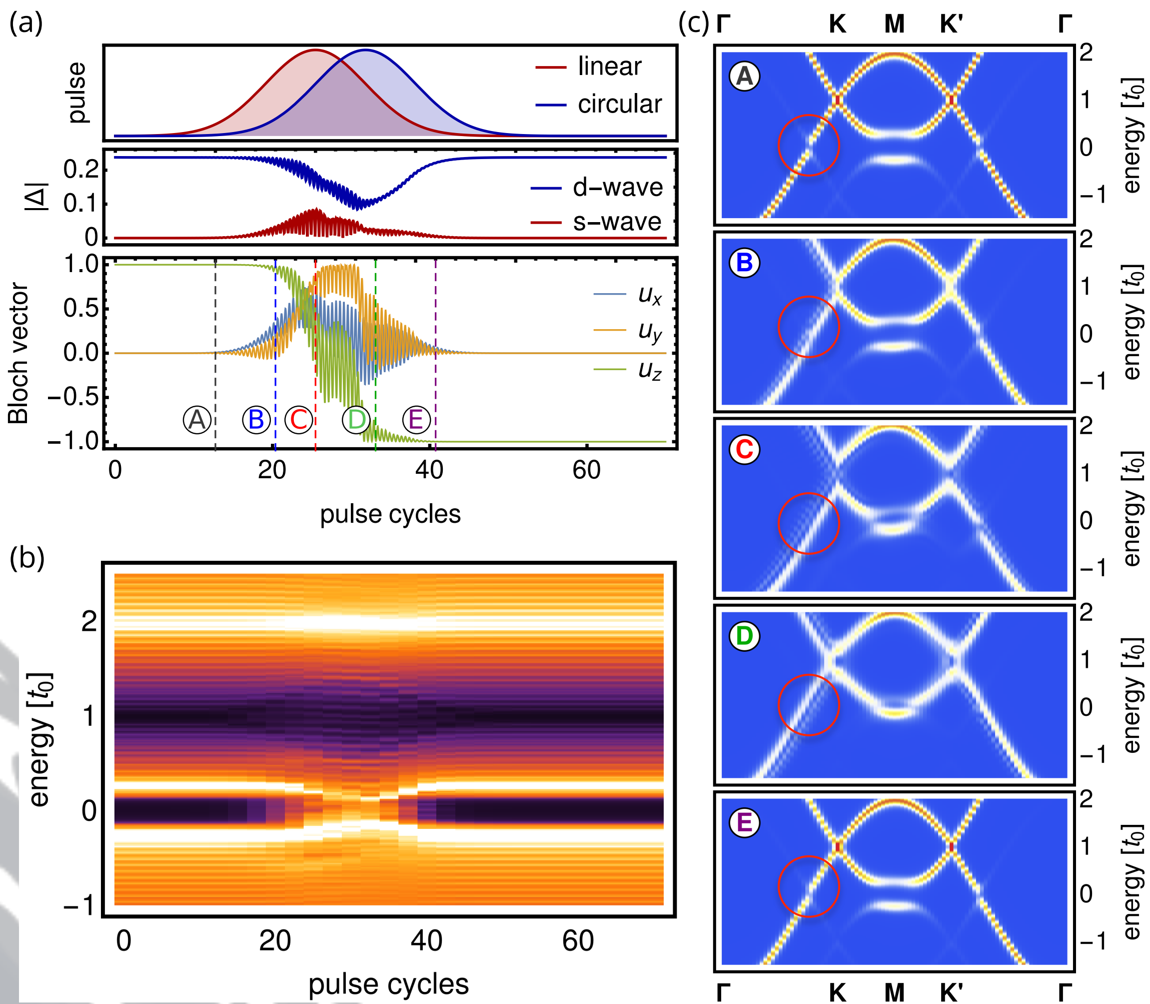
self-consistent Keldysh equations of motion for Nambu Green's functions:

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

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



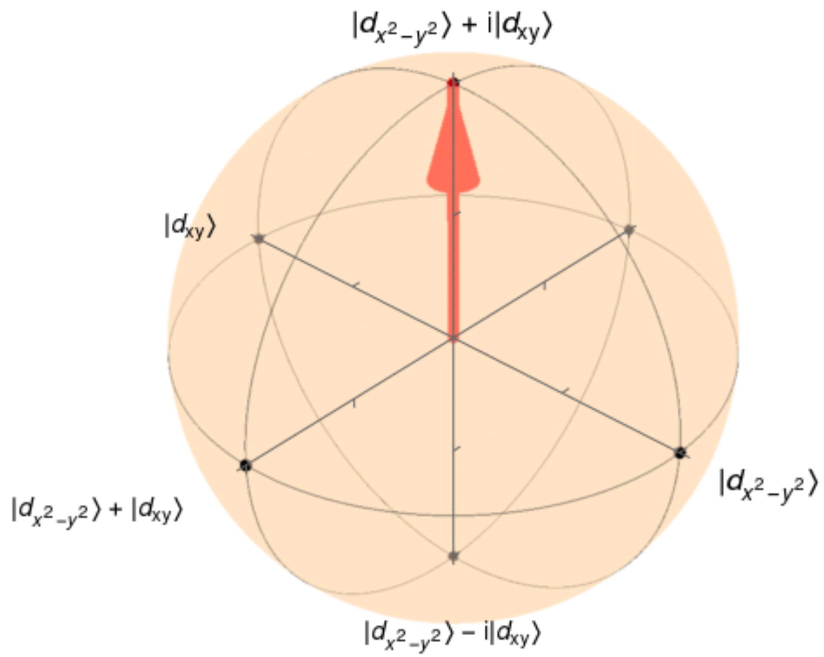
Optical control of Majoranas

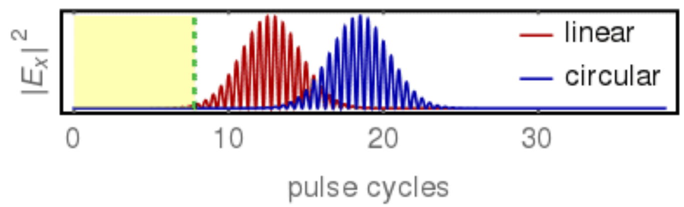


two-pulse sequence reverses d+id state in graphene

time-resolved spectroscopy tracks chirality reversal

Bloch vector rotation





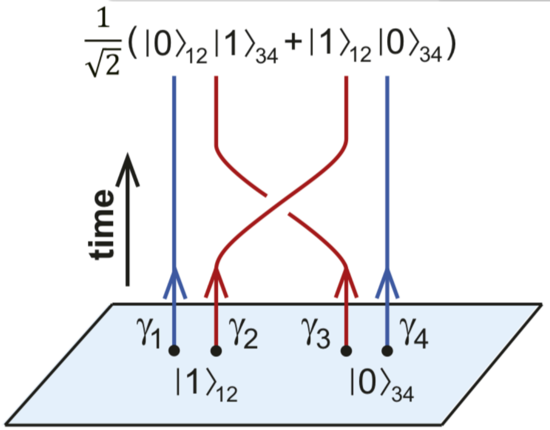
A „programmable“ topological quantum computer?

non-Abelian statistics of Majorana fermions:

- half-quantum vortices of chiral superconductors host single Majorana fermions

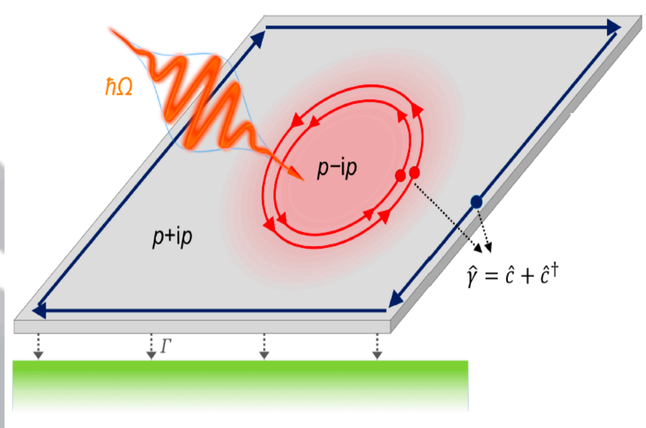
- Two Majoranas represent one electron: **½ + ½ = 1**

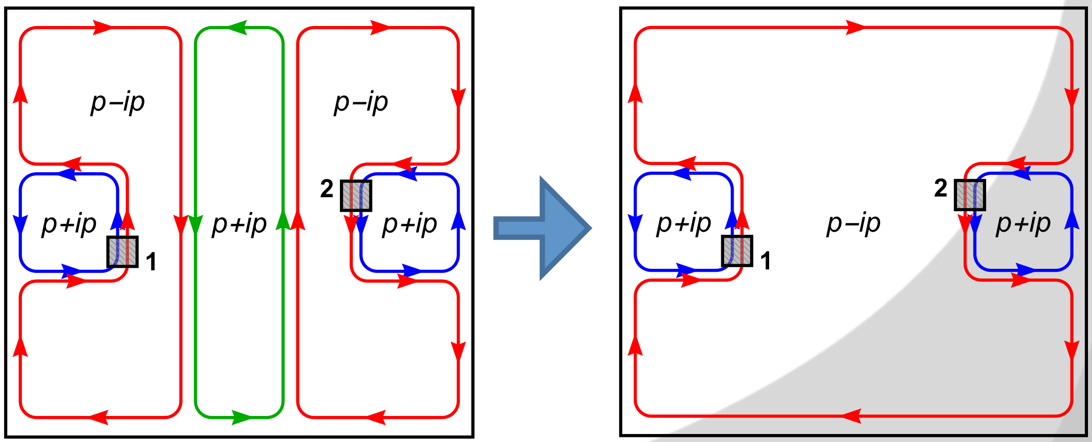
  → Braiding between Majoranas is a non-Abelian operation in electron (charge) basis!



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?

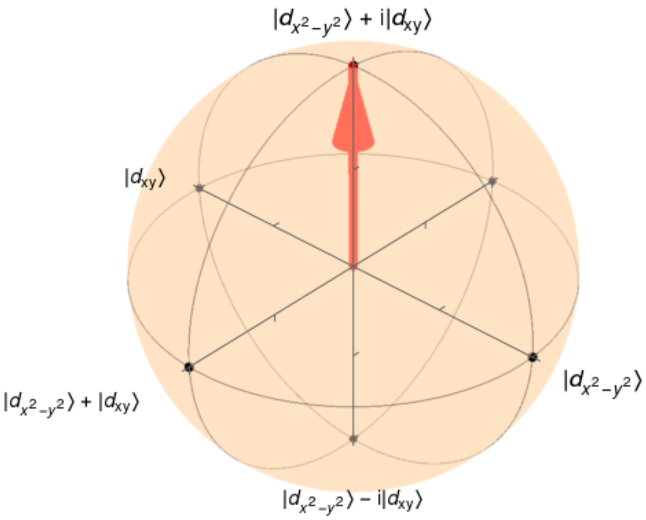
„program the gate optically, read it out electrically“

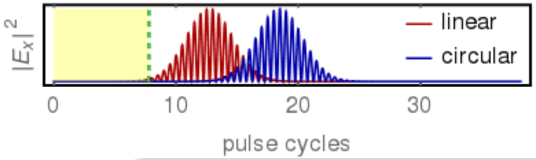
M. Claassen et al.,
Nat. Phys. 15, 766 (2019)

M. Claassen

D. Kennes

M. Zingl





Cavity QED matter coupling

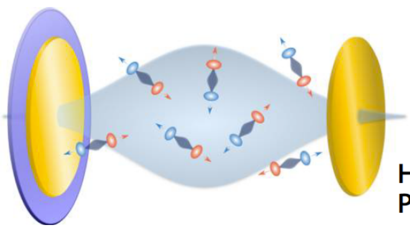
CAVITY QUANTUM ELECTRODYNAMICS

A new generation of experiments shows that spontaneous radiation from excited atoms can be greatly suppressed or enhanced by placing the atoms between mirrors or in cavities.

Serge Haroche and Daniel Kleppner Physics Today 1989

changing the vacuum changes the matter!

Recent years: Placing atoms and molecules in cavities shown to sometimes dramatically change their properties and chemical reactions. Scientists talk about „light-matter (collective) strong coupling“.

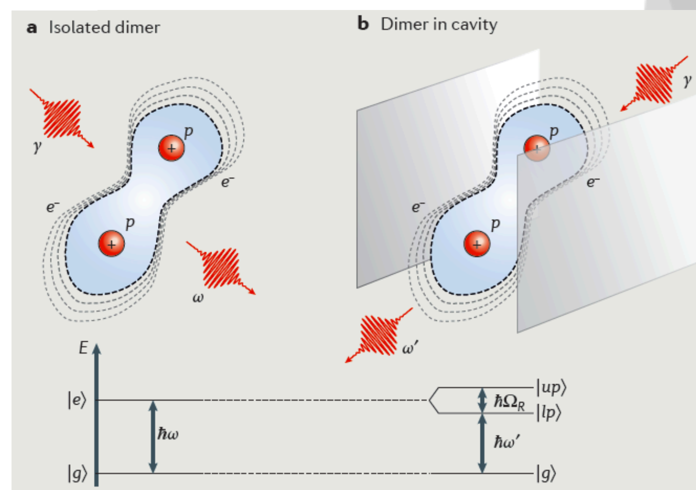


Hybrid Light–Matter States in a Molecular and Material Science Perspective

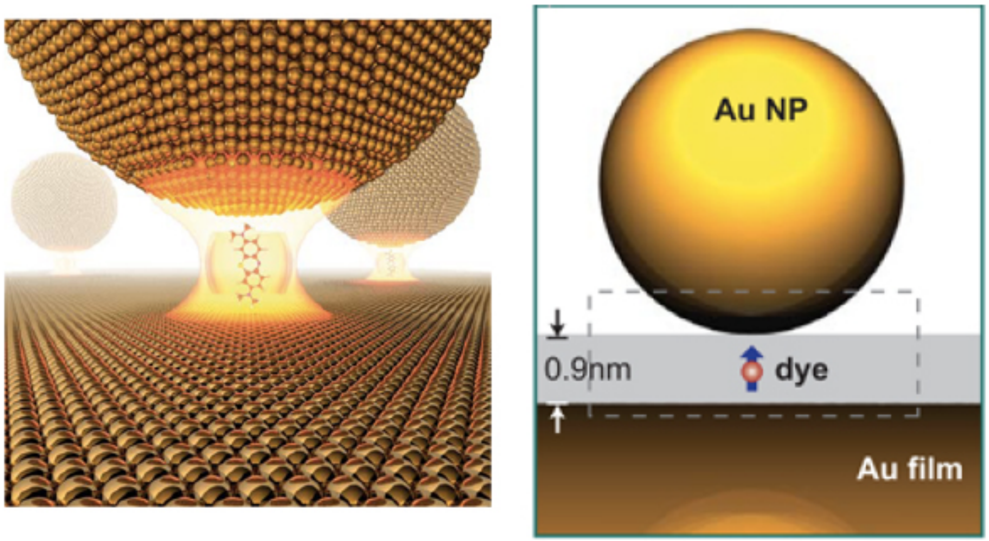
T. Ebbesen, Acc. Chem. Res. 49, 2403 (2016)

higher enhancements. Another direction is to check physical phenomena that are sensitive to phonon energy. Metal–insulating and superconducting transitions for instance might be significantly modified under strong coupling.

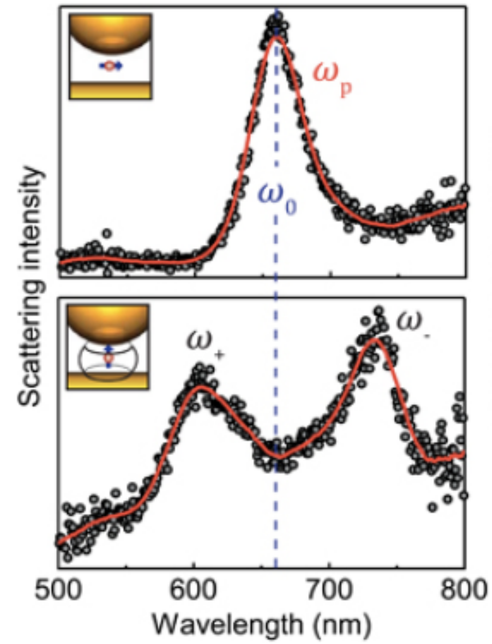
M. Ruggenthaler et al., Nat. Rev. Chem. 2, 0118 (2018)
J. Feist et al., ACS Photonics 5, 205 (2017)
R. F. Ribeiro et al., Chem. Sci. 9, 6325 (2018)
J. Flick et al., Nanophotonics 7, 1479 (2018)
A. F. Kockum et al., Nat. Rev. Phys. 1, 19 (2019)



From classical to quantum light



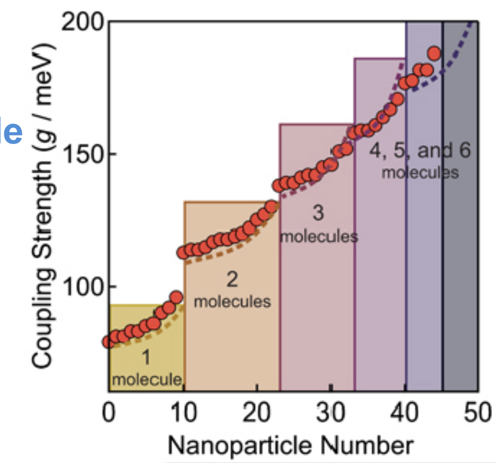
R. Chikkaraddy et al., Nature 535, 127 (2016)



Rabi splitting

collective **strong light-matter coupling**
when many atoms interact with the same cavity photon mode

cavity materials: many atoms interact with the same modes



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

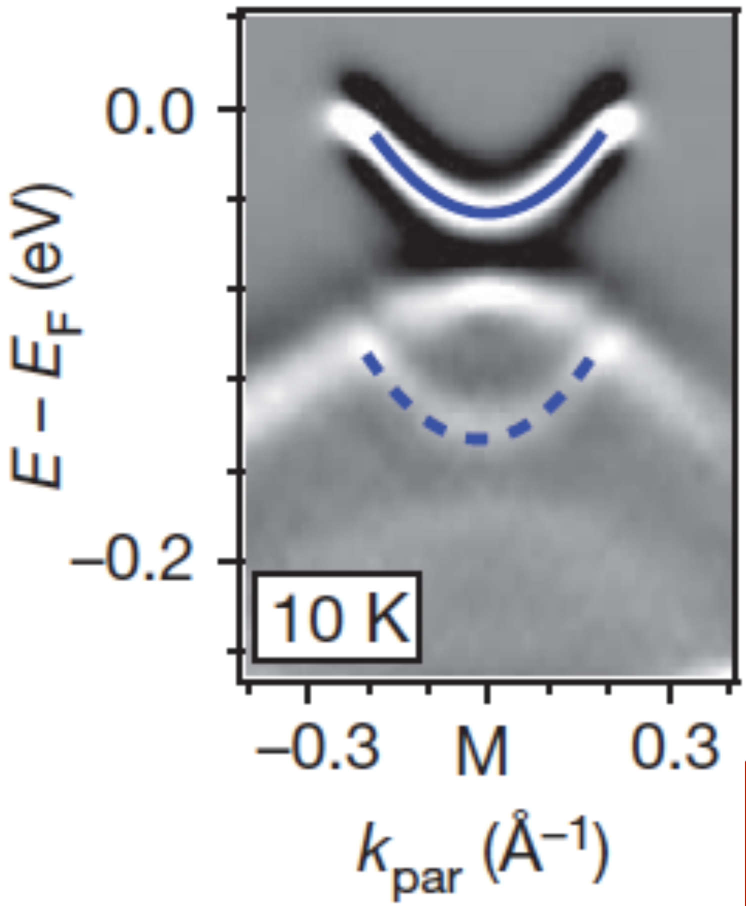
Ab-initio Exciton-polaritons: Cavity control of Dark Excitons in two dimensional Materials

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

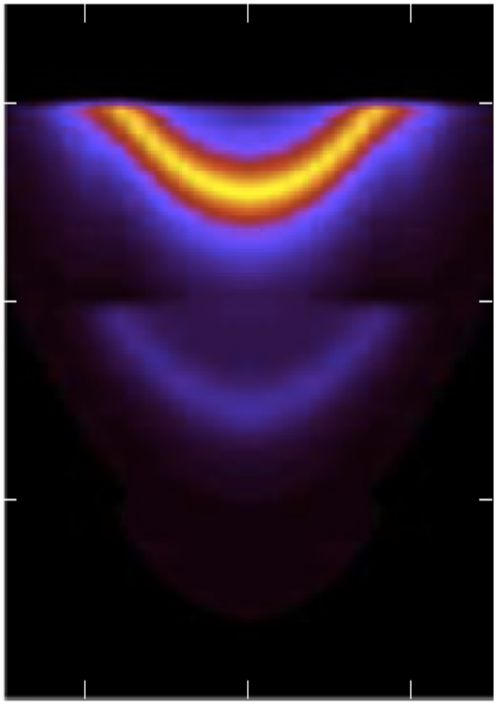
1810.02672

monolayer FeSe/STO: ARPES

experiment



theory



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

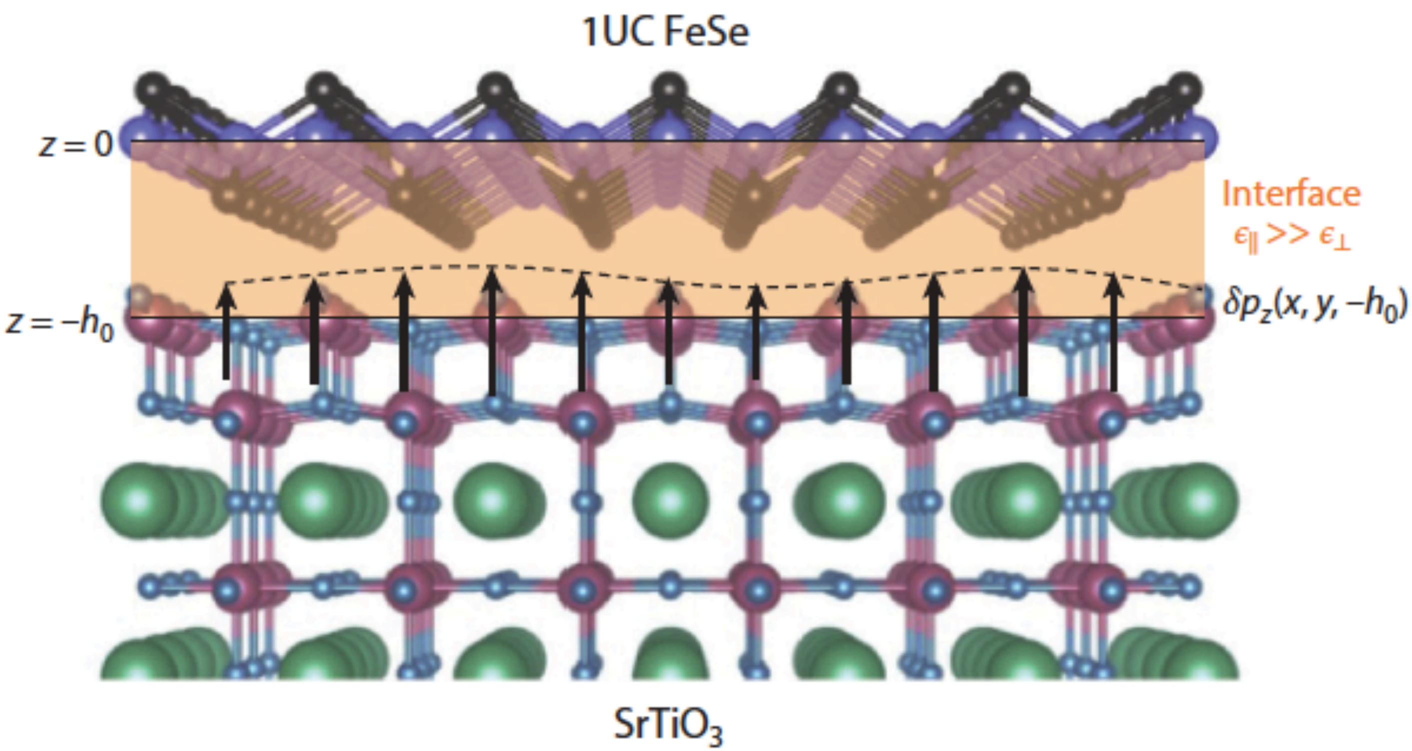
Lee et al., Nature 515, 245 (2014)

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)*

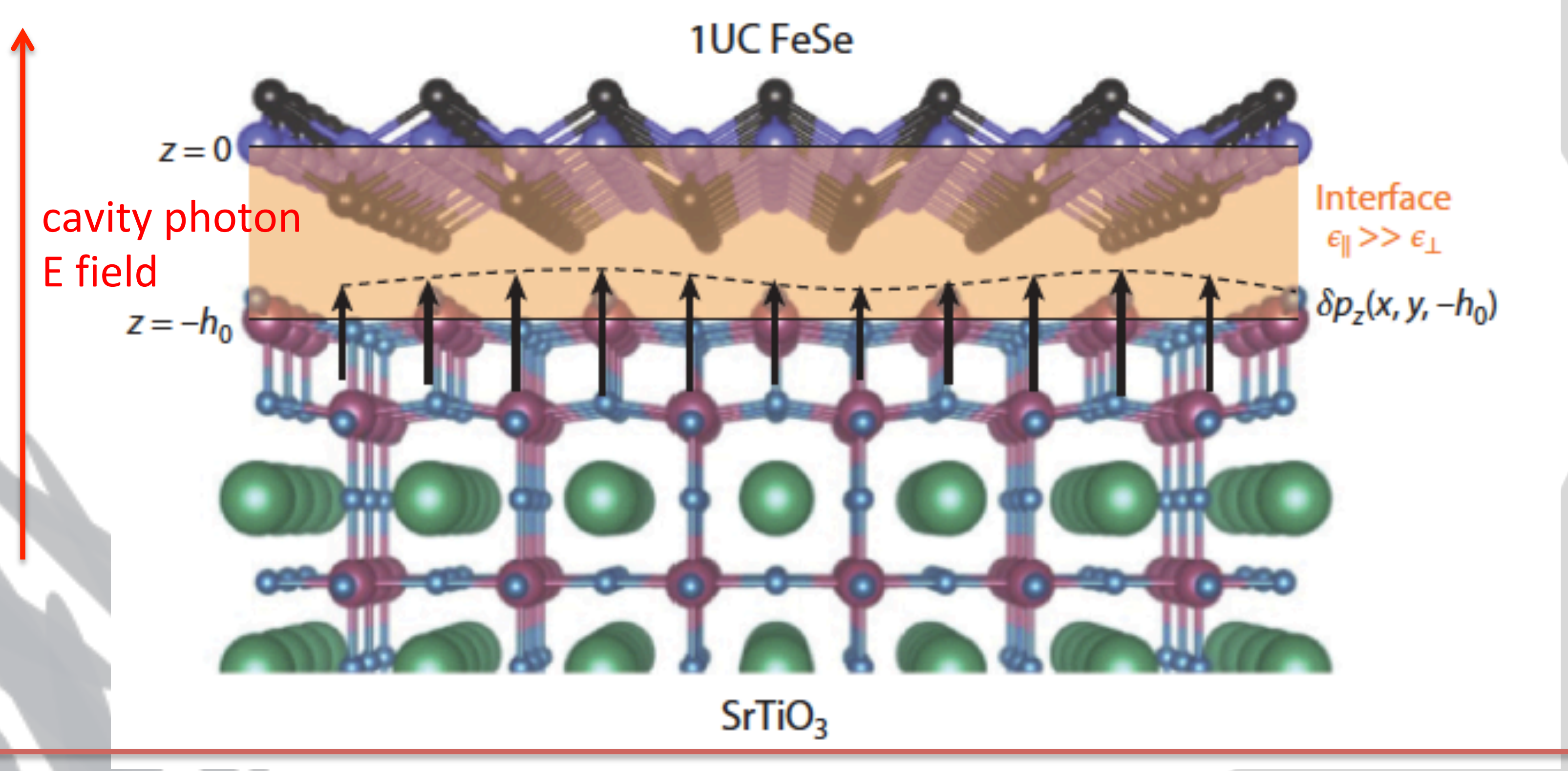
$$q_0^{-1} = h_0\sqrt{\epsilon_{\|}/\epsilon_{\perp}} \quad \epsilon_{\|}/\epsilon_{\perp} \approx 100$$



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

Cavity engineering

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



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

Model and Method

mpsd

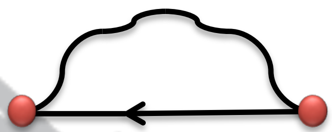
electrons | el-polariton coupling | polaritons

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

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

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

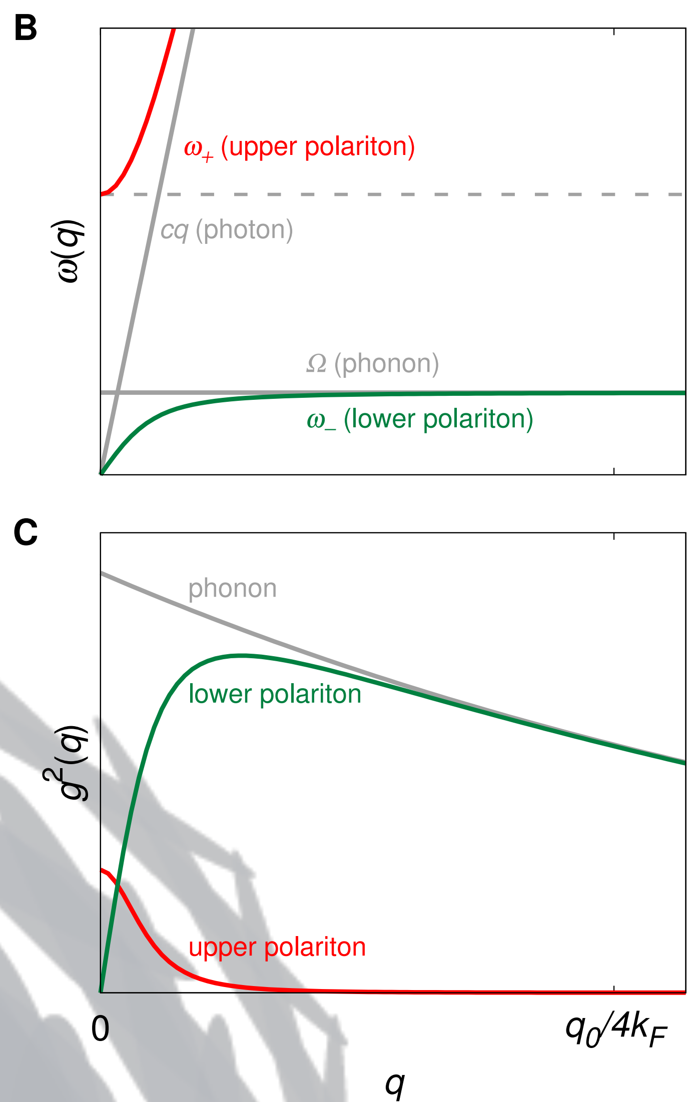


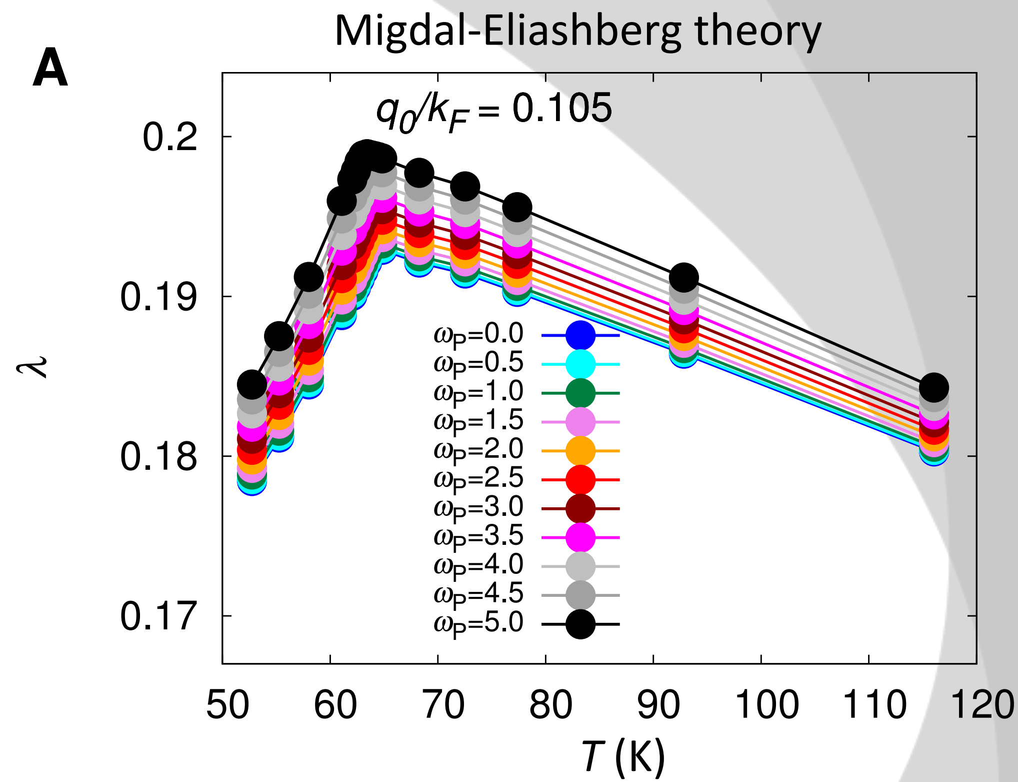
$$\hat{\Sigma}(\vec{k}, i\omega_n) = i\omega_n[1 - Z(\vec{k}, i\omega_n)]\hat{\tau}_0 + \chi(\vec{k}, i\omega_n)\hat{\tau}_3 + \phi(\vec{k}, i\omega_n)\hat{\tau}_1$$

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

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

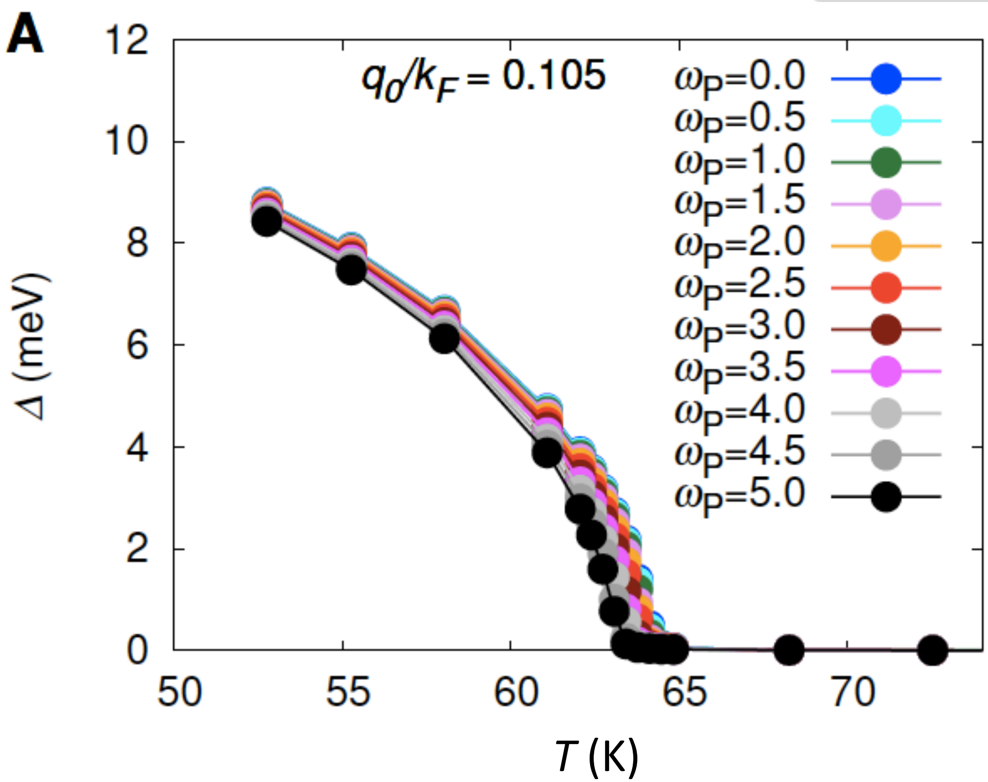
Cavity materials: Phonon polaritons





enhanced electron-phonon coupling, controlled by cavity volume

Cavity superconductivity?



suppressed superconductivity despite enhanced el-ph coupling

reason for suppression: forward scattering

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

vs.

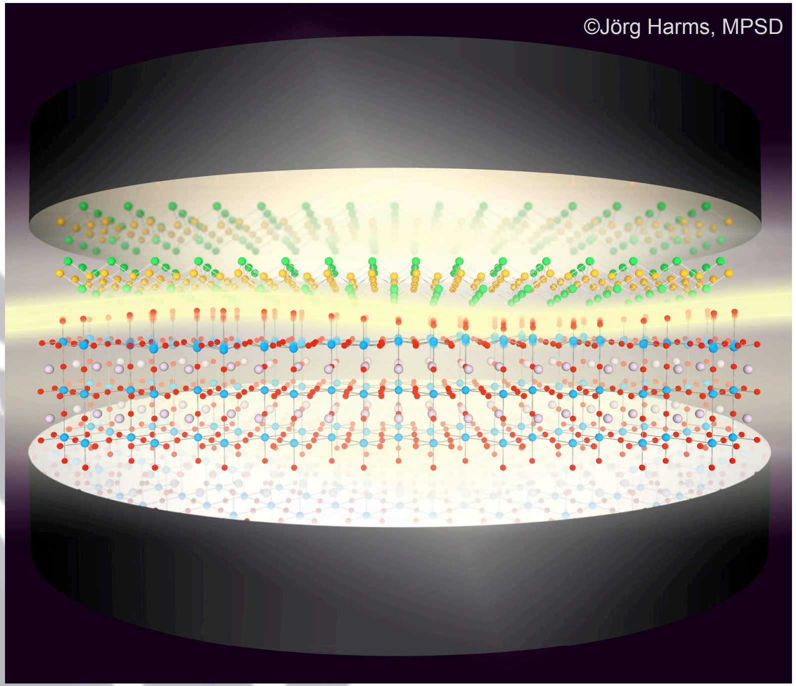
$$T_{C,\mathrm{BCS}} \approx 1.13\Omega \exp(-\tfrac{1}{\lambda})$$

q-independent scattering

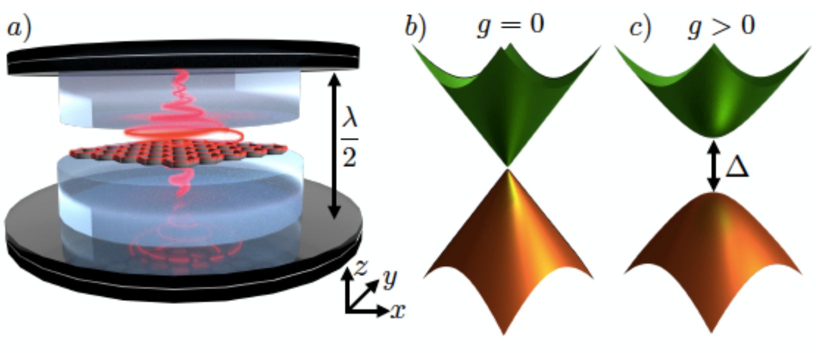
Status as of October 2019 ...

- cavity leads to enhanced electron-phonon coupling
- FeSe/STO: works in conjunction with other pairing mechanisms
- can one also enhance superconductivity?

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



Cavity-induced quantum-anomalous Hall effect in graphene:
Xiao Wang, E. Ronca, M. A. Sentef
arXiv:1903.00339, PRB 2019



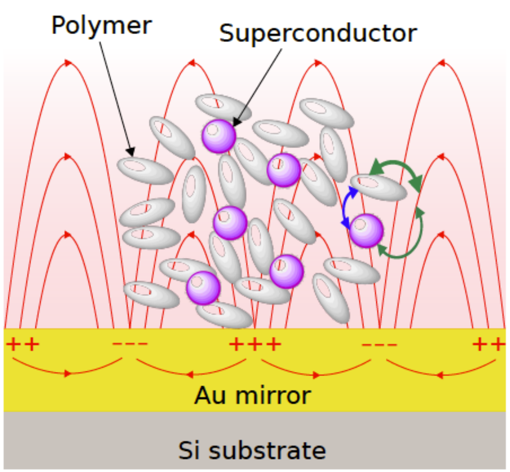
... recent news

arXiv:1911.01459

mpsd

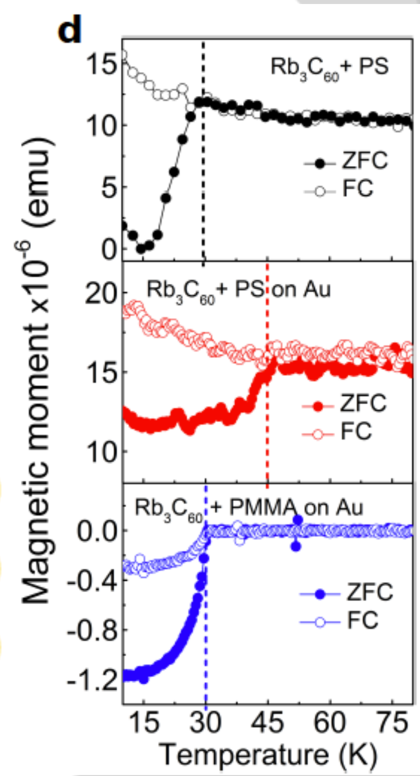
Exploring Superconductivity under Strong Coupling with the Vacuum Electromagnetic Field

A. Thomas[1], E. Devaux[1], K. Nagarajan[1], T. Chervy[1], M. Seidel[1], D. Hagenmüller[1], S. Schütz[1], J. Schachenmayer[1], C. Genet[1], G. Pupillo[1*] & T. W. Ebbesen[1*]



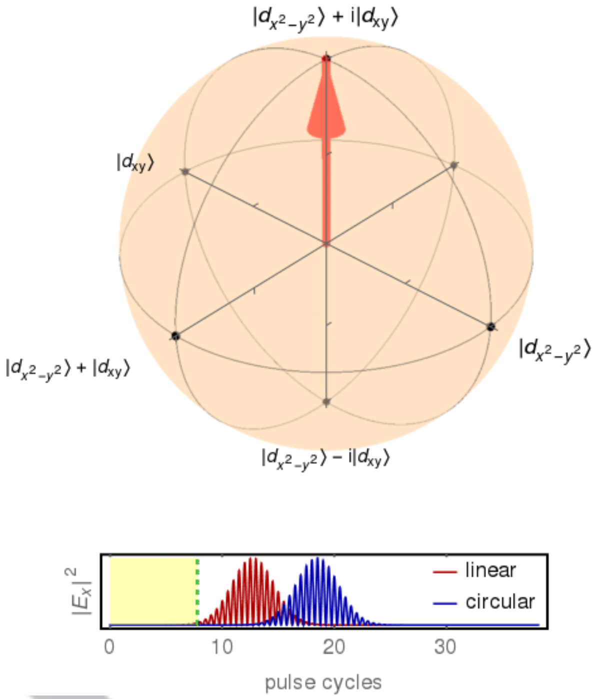
... consistent with enhanced electron-phonon coupling due to polariton formation and mode softening

By placing the superconductor-surface plasmon system in a SQUID magnetometer, we find that the superconducting transition temperatures (T_c) for both compounds are modified in the absence of any external laser field. For YBCO, T_c decreases from 92 K to 86 K while for Rb_3C_{60}, it increases from 30 K to 45 K at normal pressures.

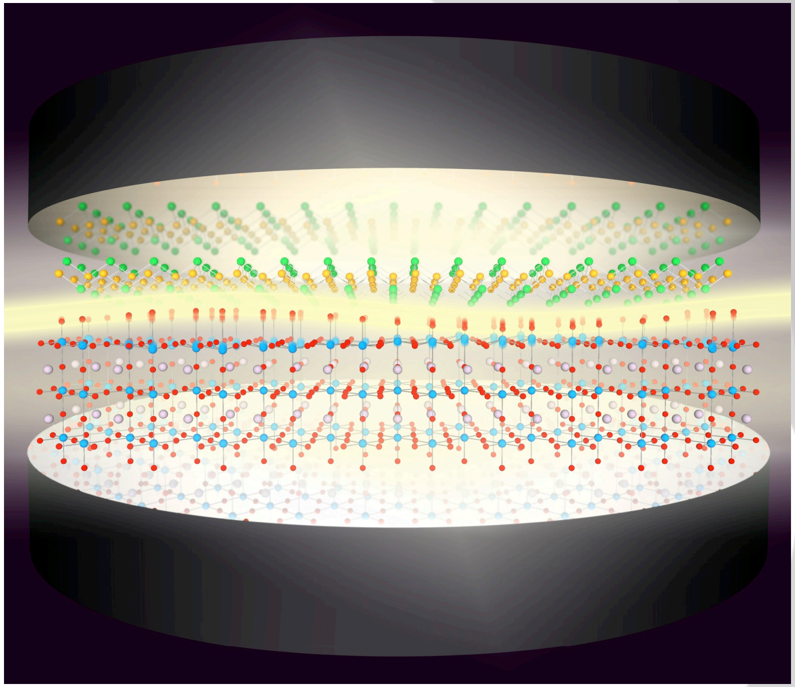


Summary

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



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



Many opportunities for light-matter materials control!

Thank you for your attention!