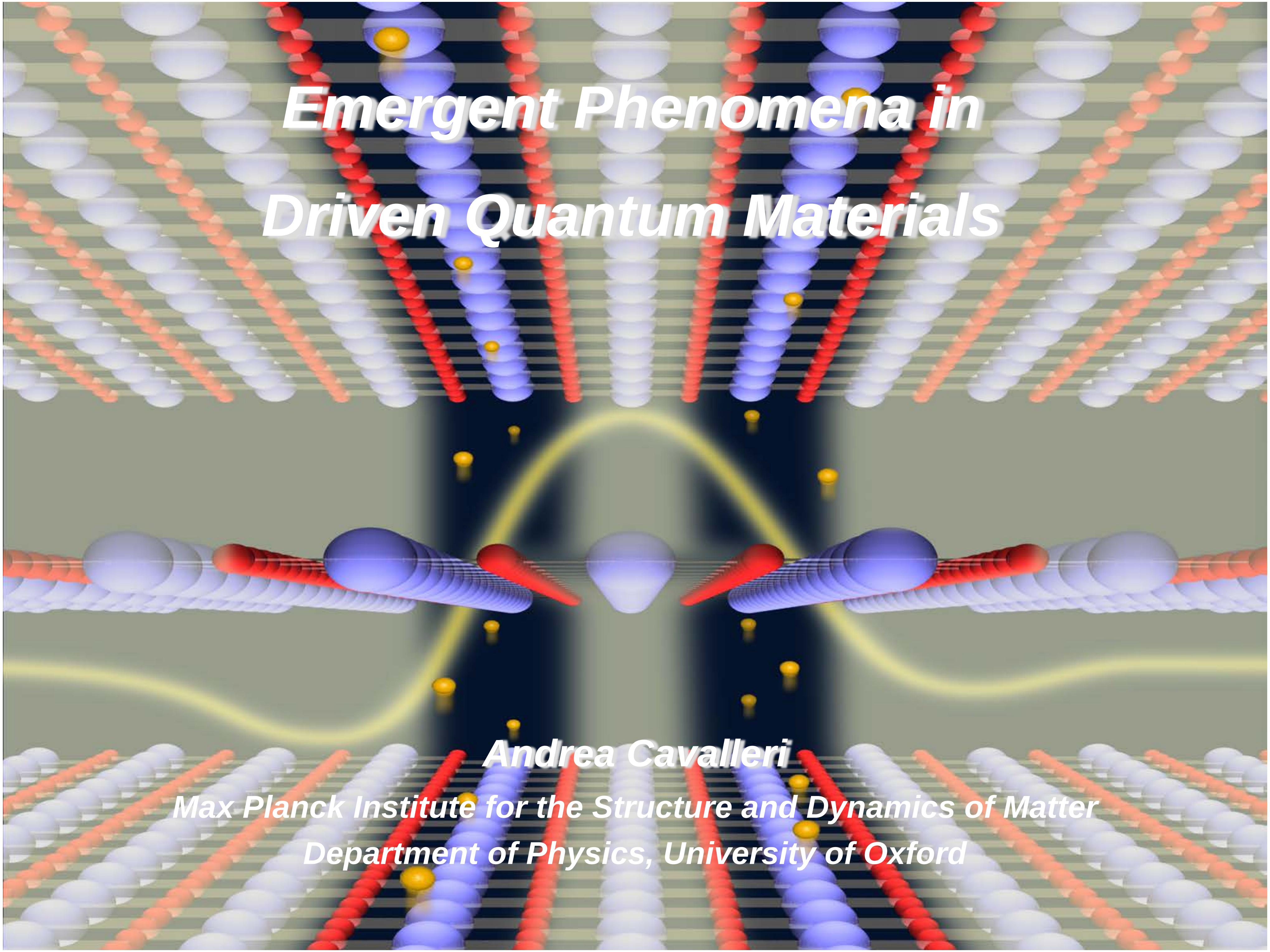


Emergent Phenomena in Driven Quantum Materials

Andrea Cavalleri

Max Planck Institute for the Structure and Dynamics of Matter

Department of Physics, University of Oxford

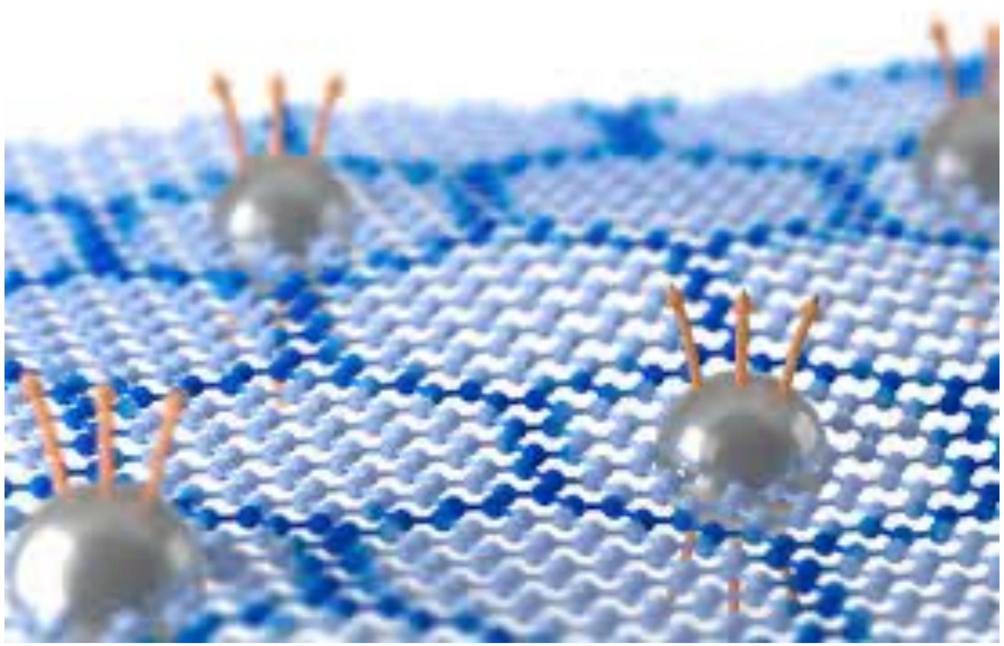
Quantum Materials do “big things”

Macroscopic properties determined by quantum mechanics

Exhibit large response functions and extreme sensitivity

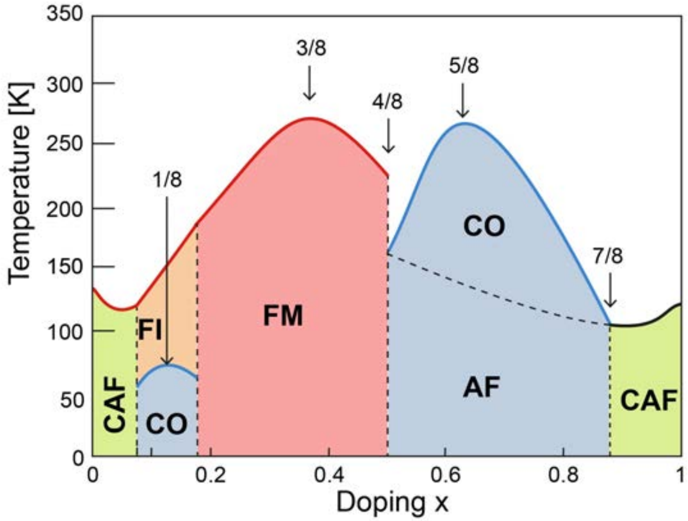
High T_c Superconductivity

Topologically Protected Transport

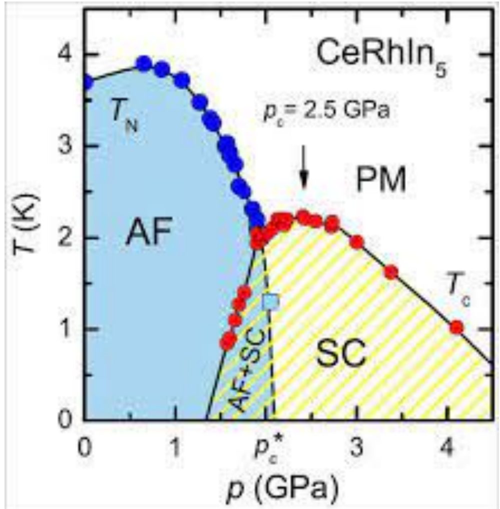


Quantum Materials – difficult to optimize

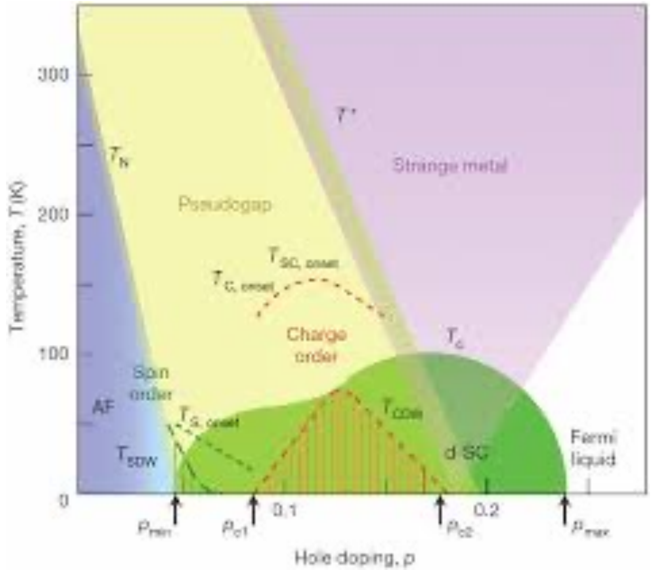
Magnetoresistive Manganites



Heavy Fermions

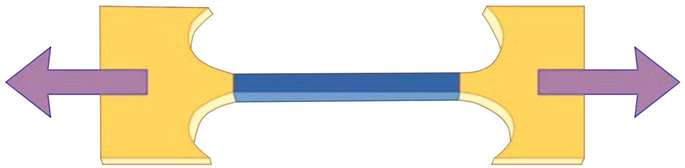


High Tc Superconductors

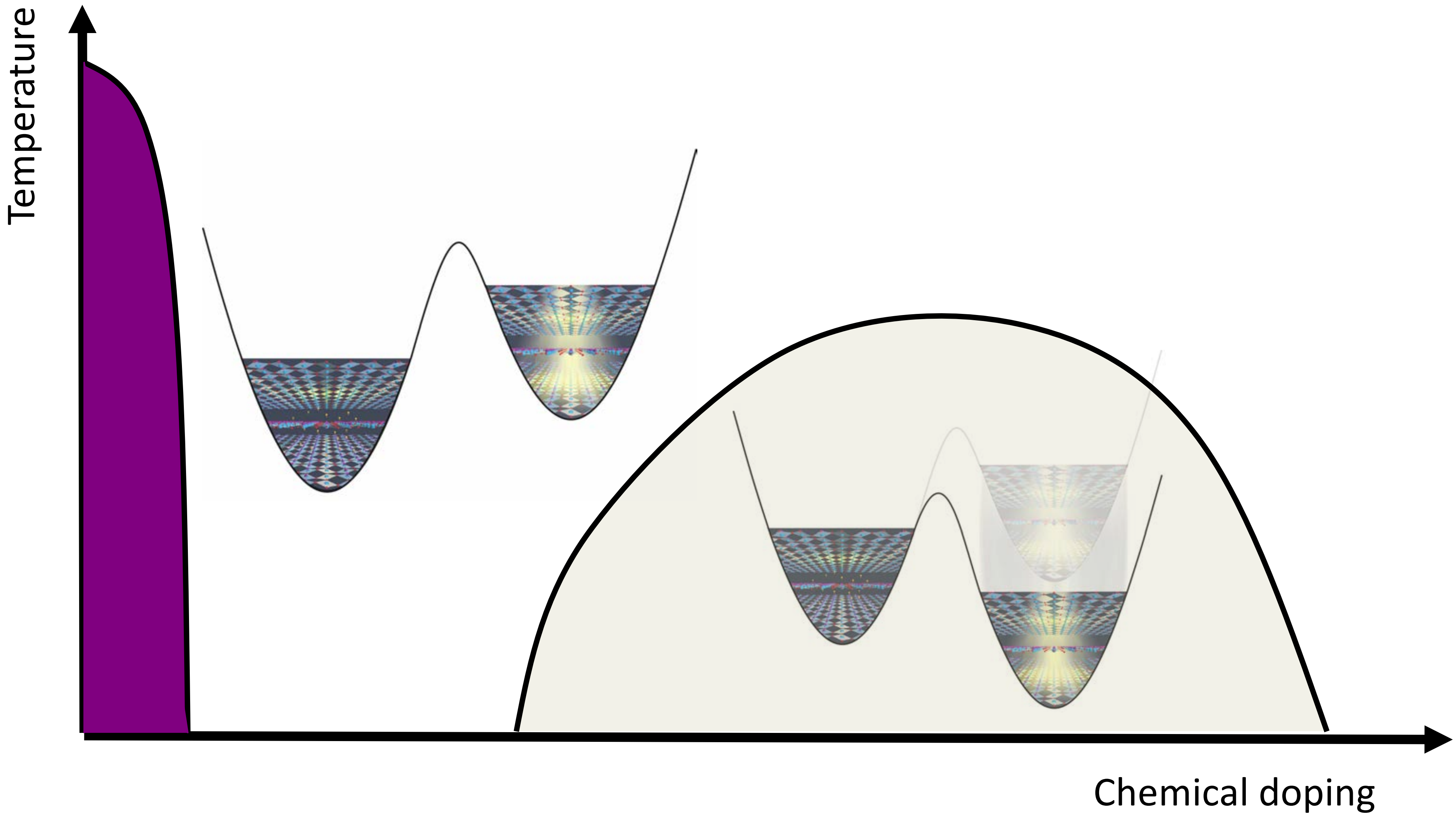


Materials Growth

Strain

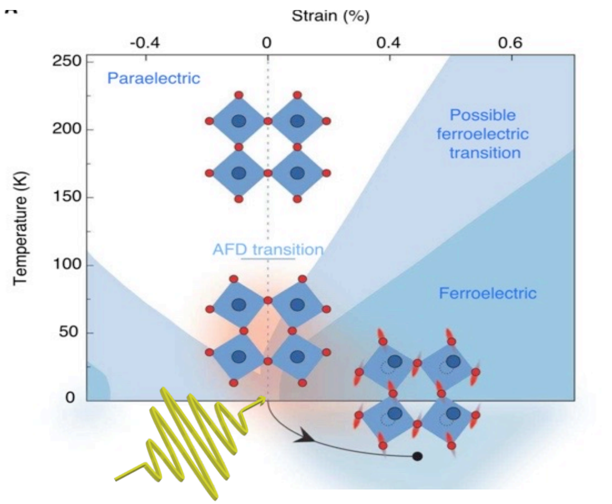


Phase competition on similar energy scales

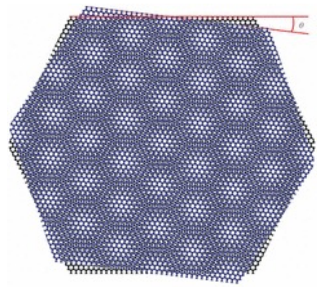


Control of quantum materials by non-standard means

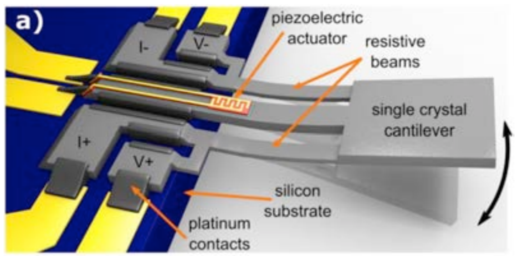
Important scientific advances and new physical phenomena are expected in settings in which quantum materials are exposed to unconventional fields



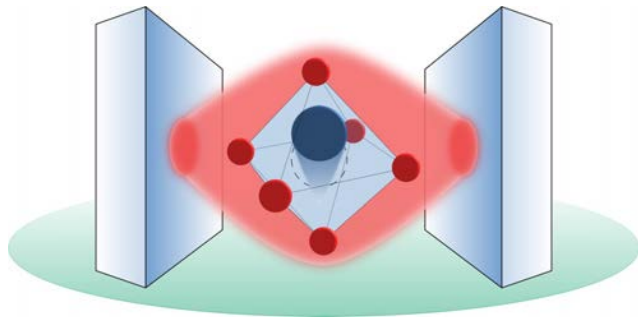
Dynamically Driven Matter



Synthetic Quantum Materials



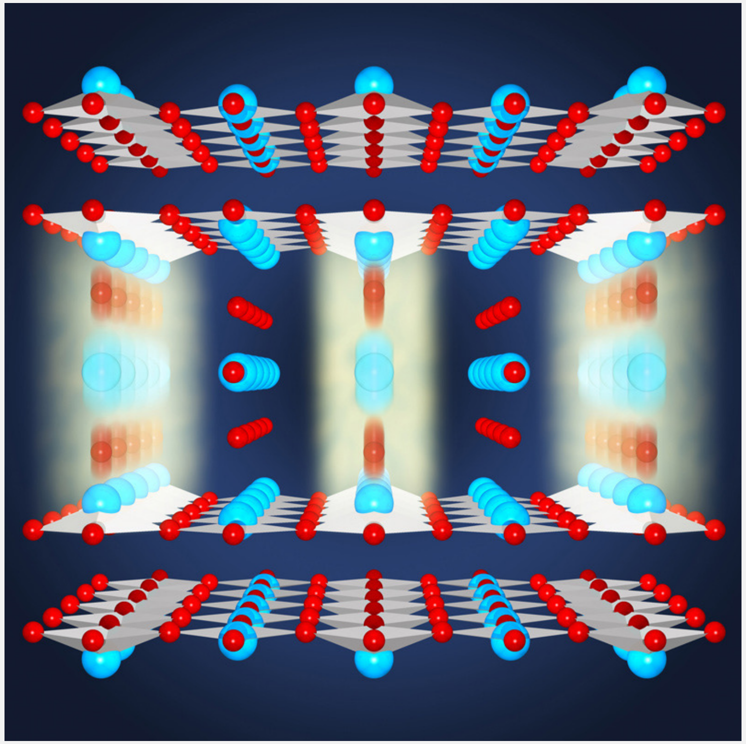
Extreme strain



Quantum Materials in Quantum Cavities

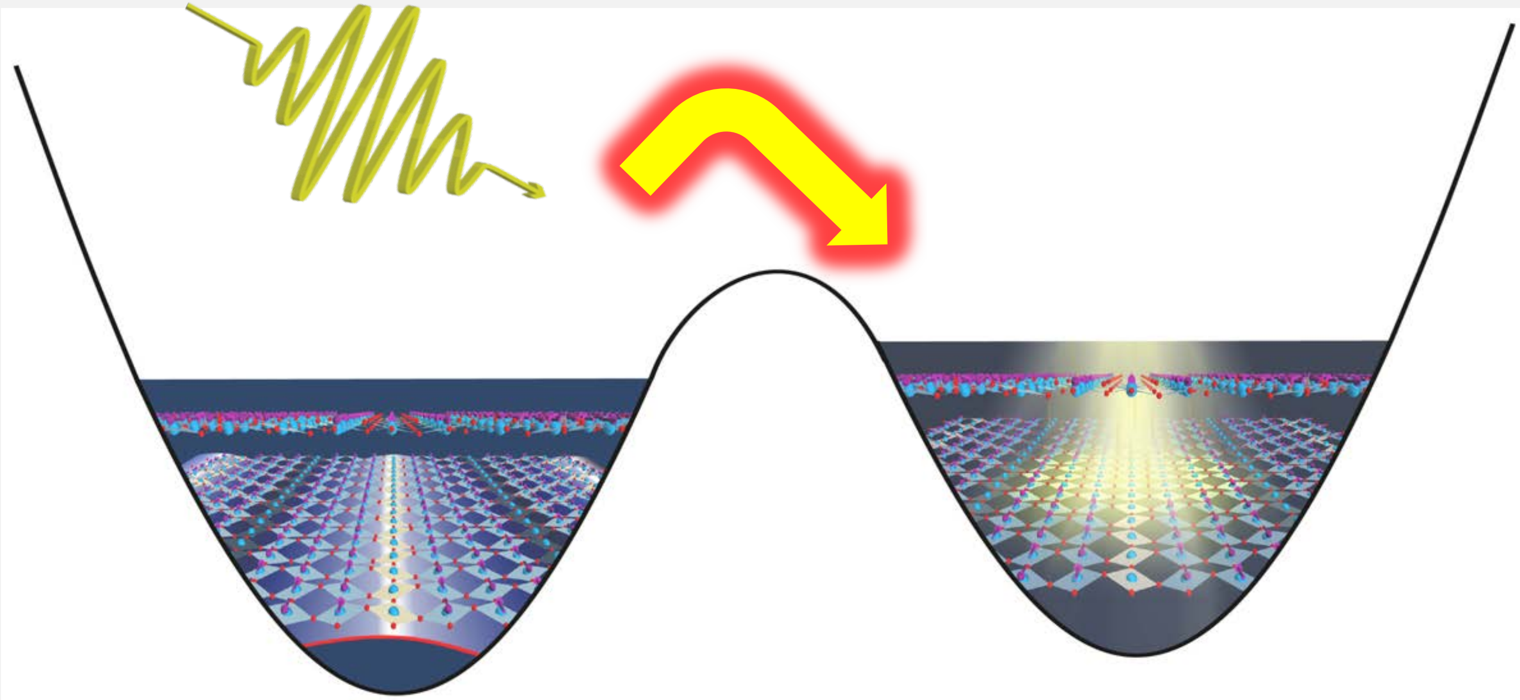
We look for new physics in driven quantum materials

Dynamical modulation can manipulate the functional properties of a solid



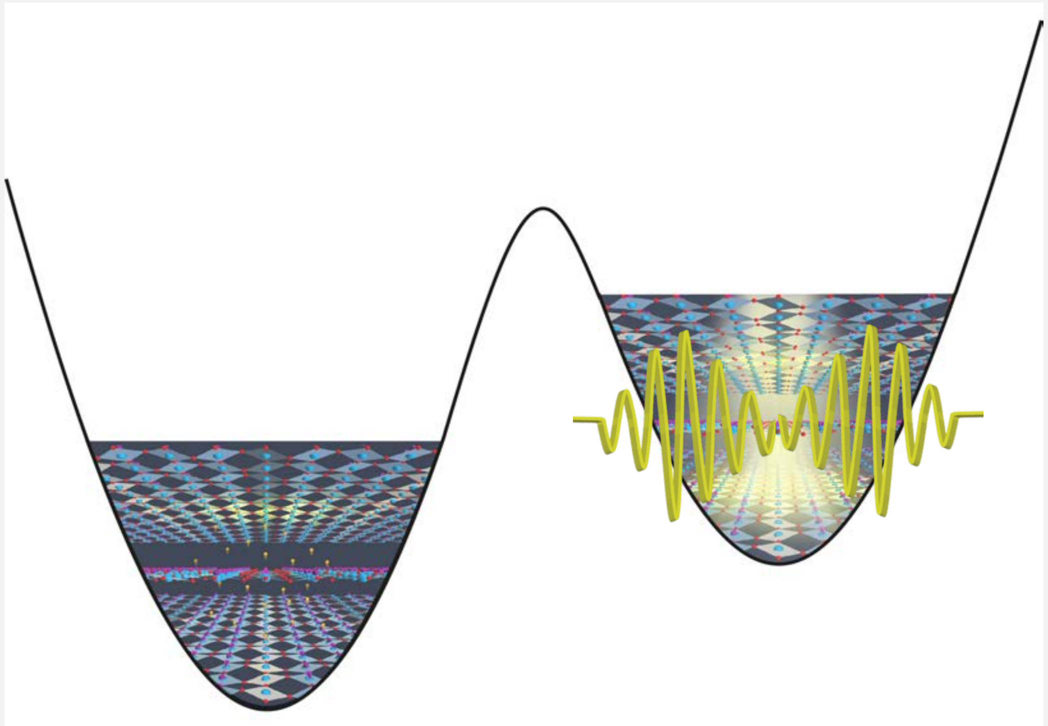
Generating hidden phases

Dynamical modulation can create switch between metastable states



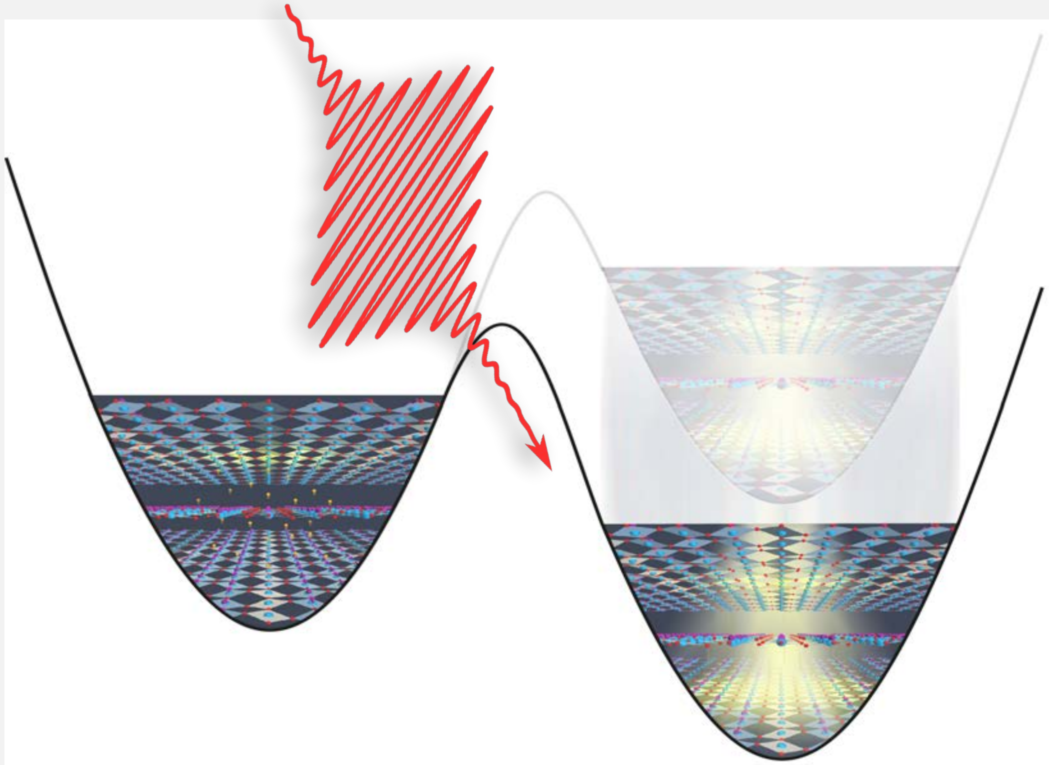
Cooling fluctuations

Dynamical modulation can create cool fluctuations that destroy coherence

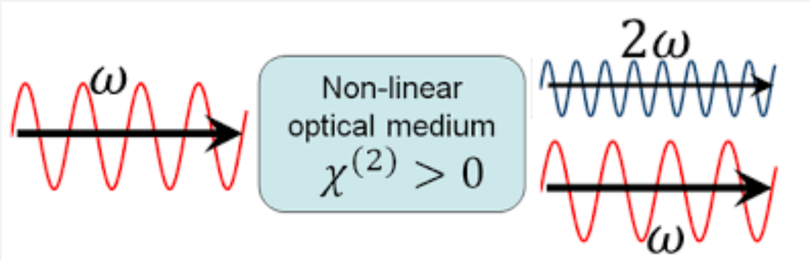


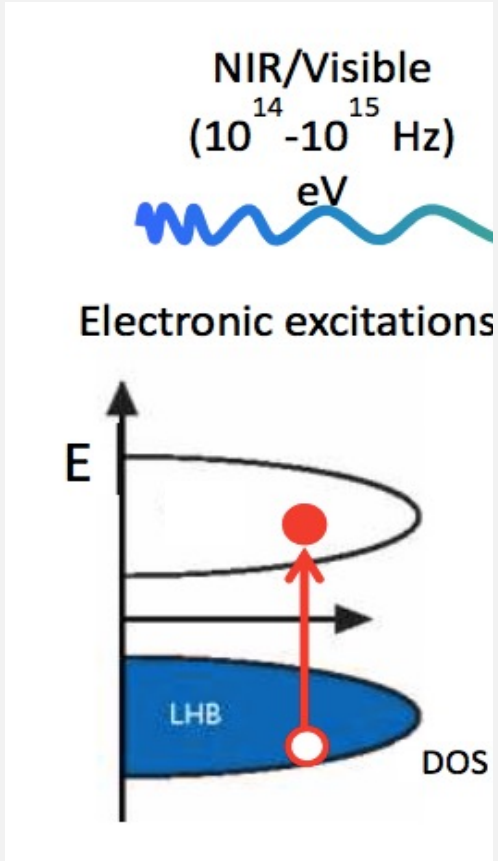
Renormalizing the energy landscape

Dynamical modulation can create reshape the energy landscape

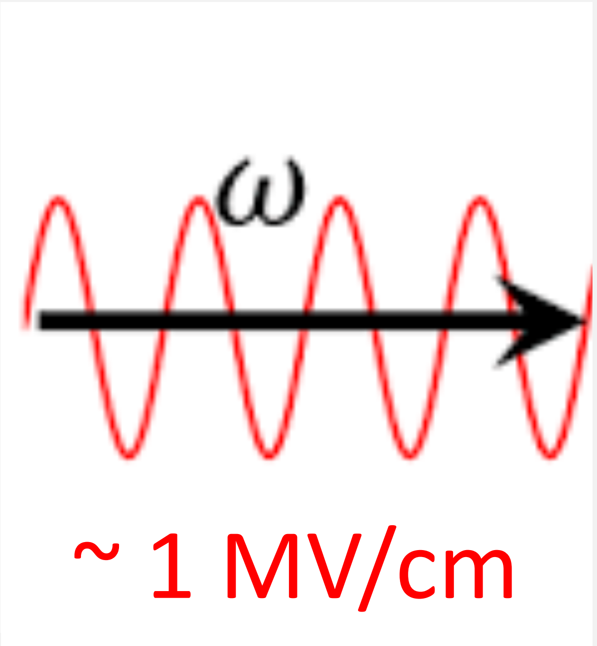


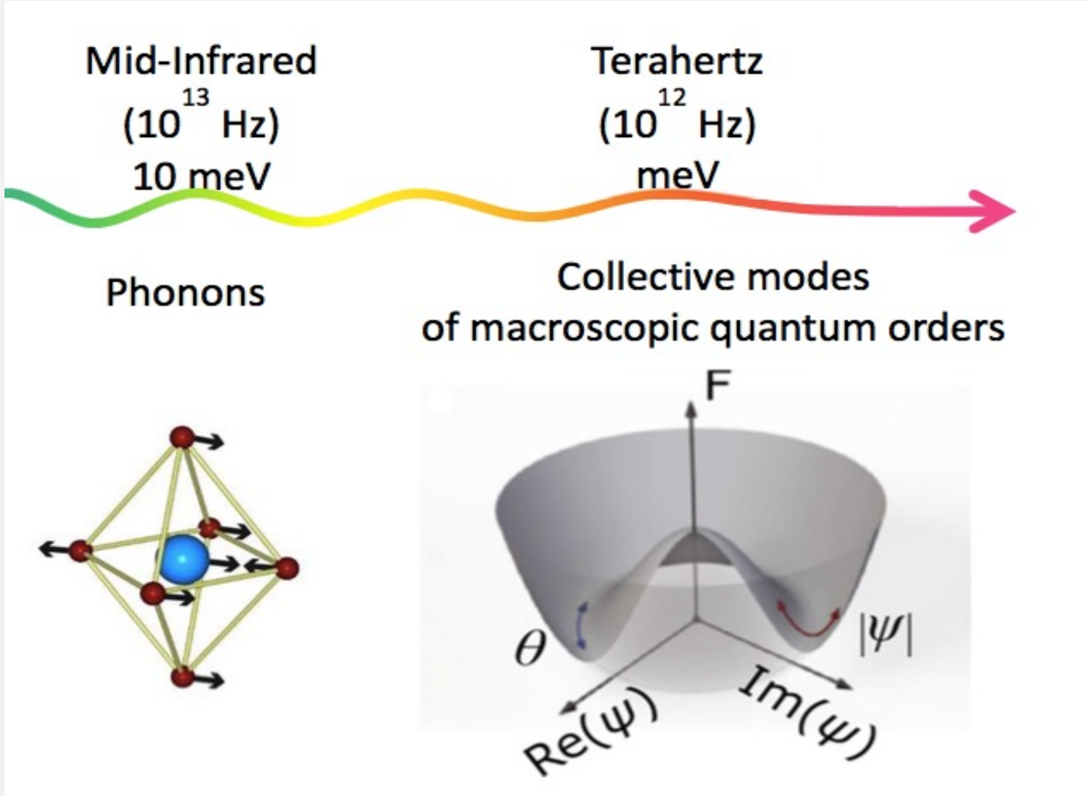
60 years of Nonlinear Optics in the visible





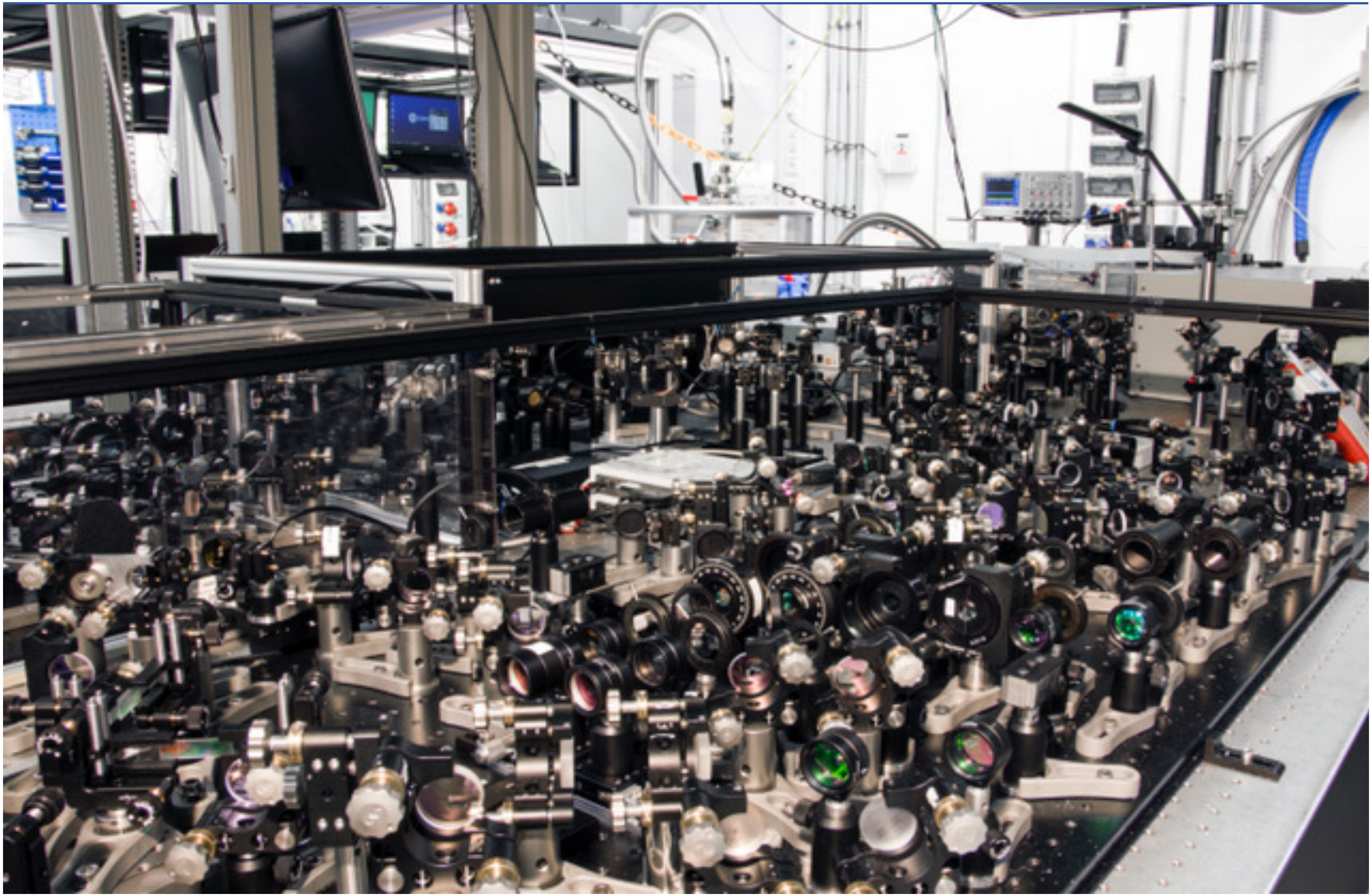
Nonlinear Optics for quantum Materials – low frequencies



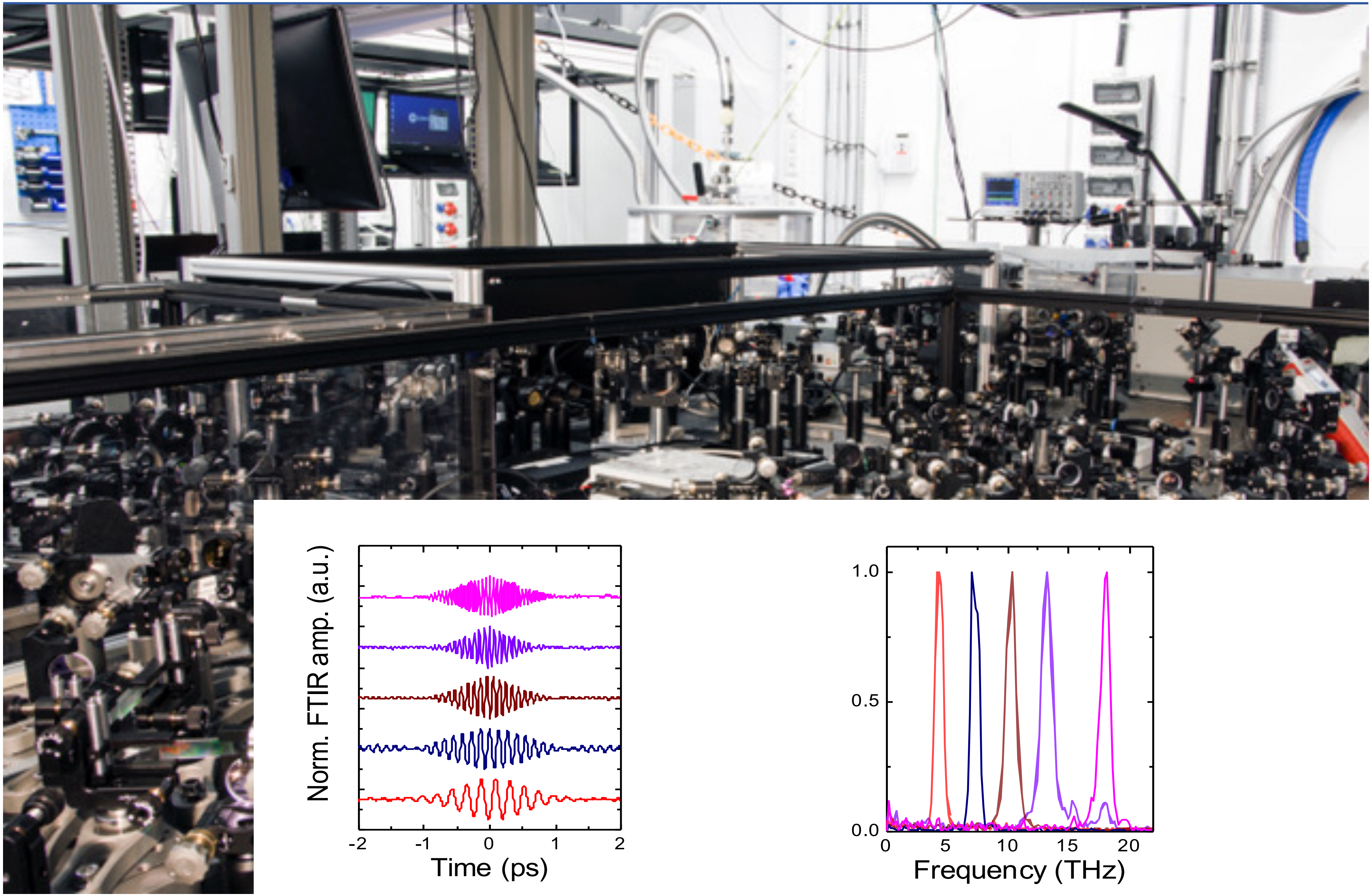


Until recently only FELs could provide strong far IR

Modern Tabletop Optical Sources: strong fields across the spectrum



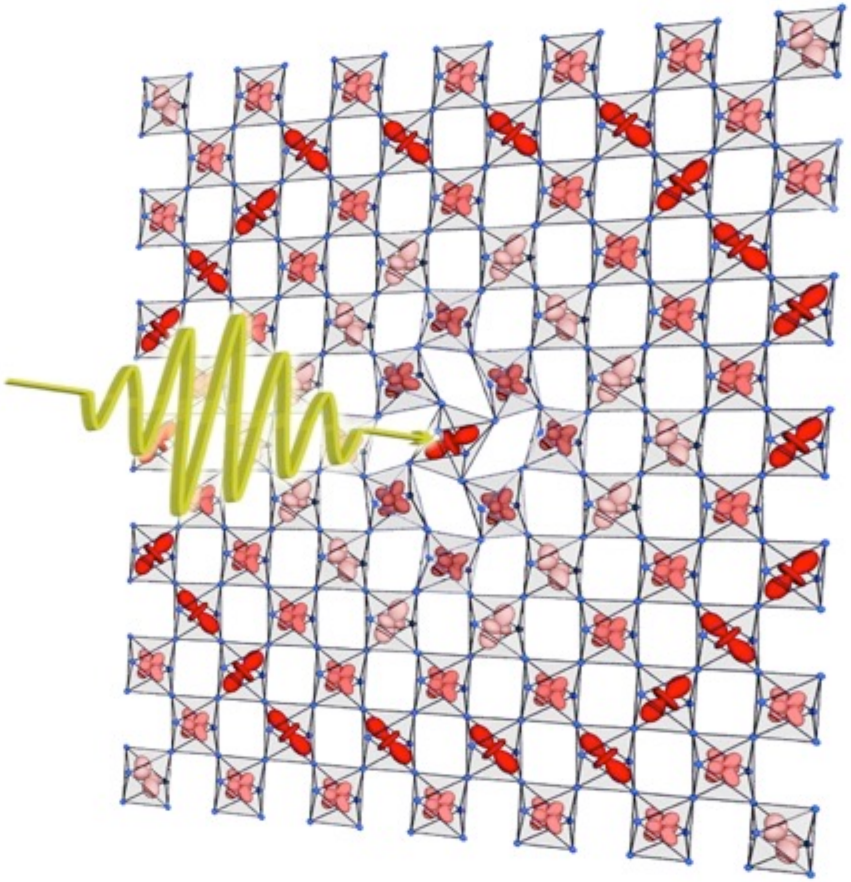
Modern Tabletop Optical Sources: strong fields across the spectrum



Periodically driven lattices

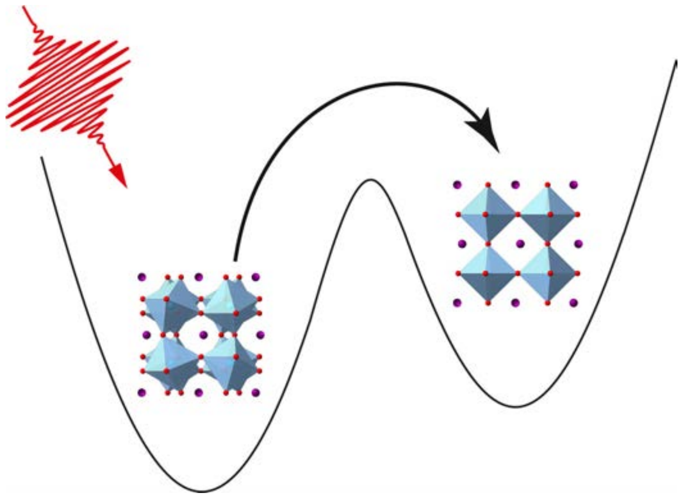
E ~ MV/cm

Displacements ~ %



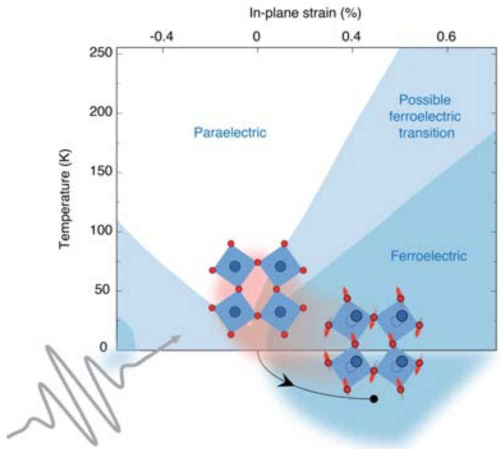
Inducing new Crystal Structures with Light

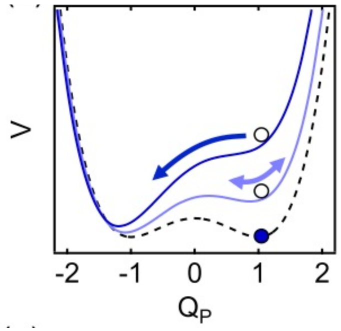
Hidden Phases



M. Rini et al., *Nature* 449, 72 (2007)

Switching ferroelectricity





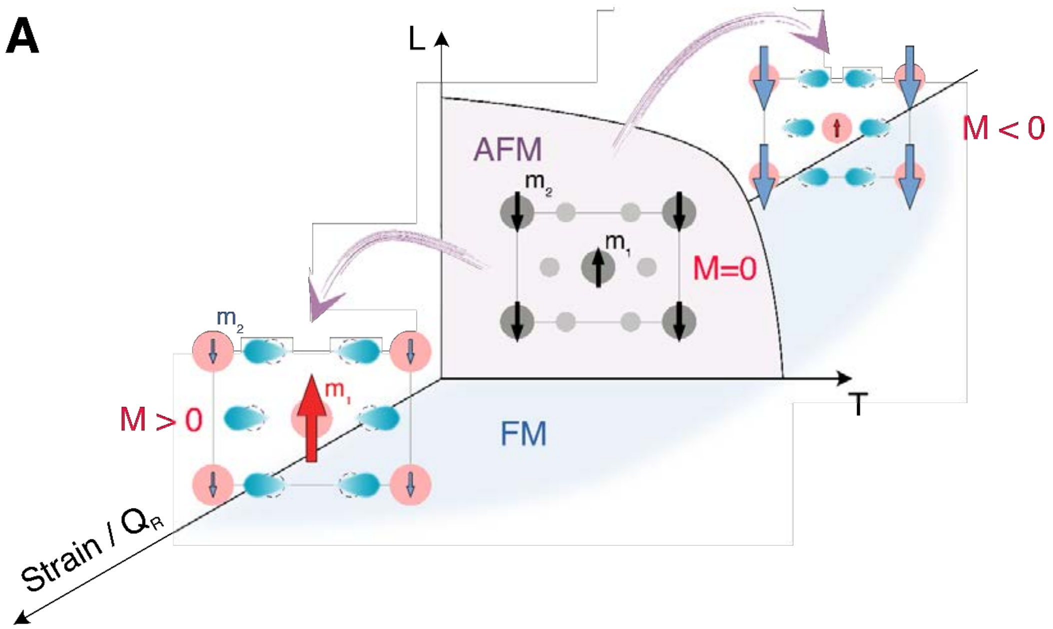
A. von Högen et al. *Nature* 555, 79 (2018)

T.F. Nova et al. *Science* 364, 1075 (2019)

M. Henstridge et al. *Nature Physics* (2022)

Controlling Magnetism and Topology

Induced ferromagnetism

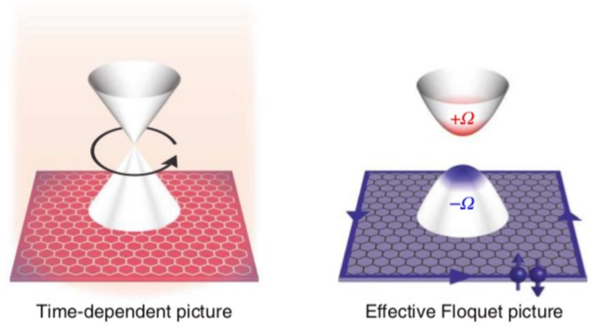


T. F. Nova et al., *Nature Physics* 13, 132 *(2017)*

A. Disa et al., *Nature Physics 16, 937 (2020)*

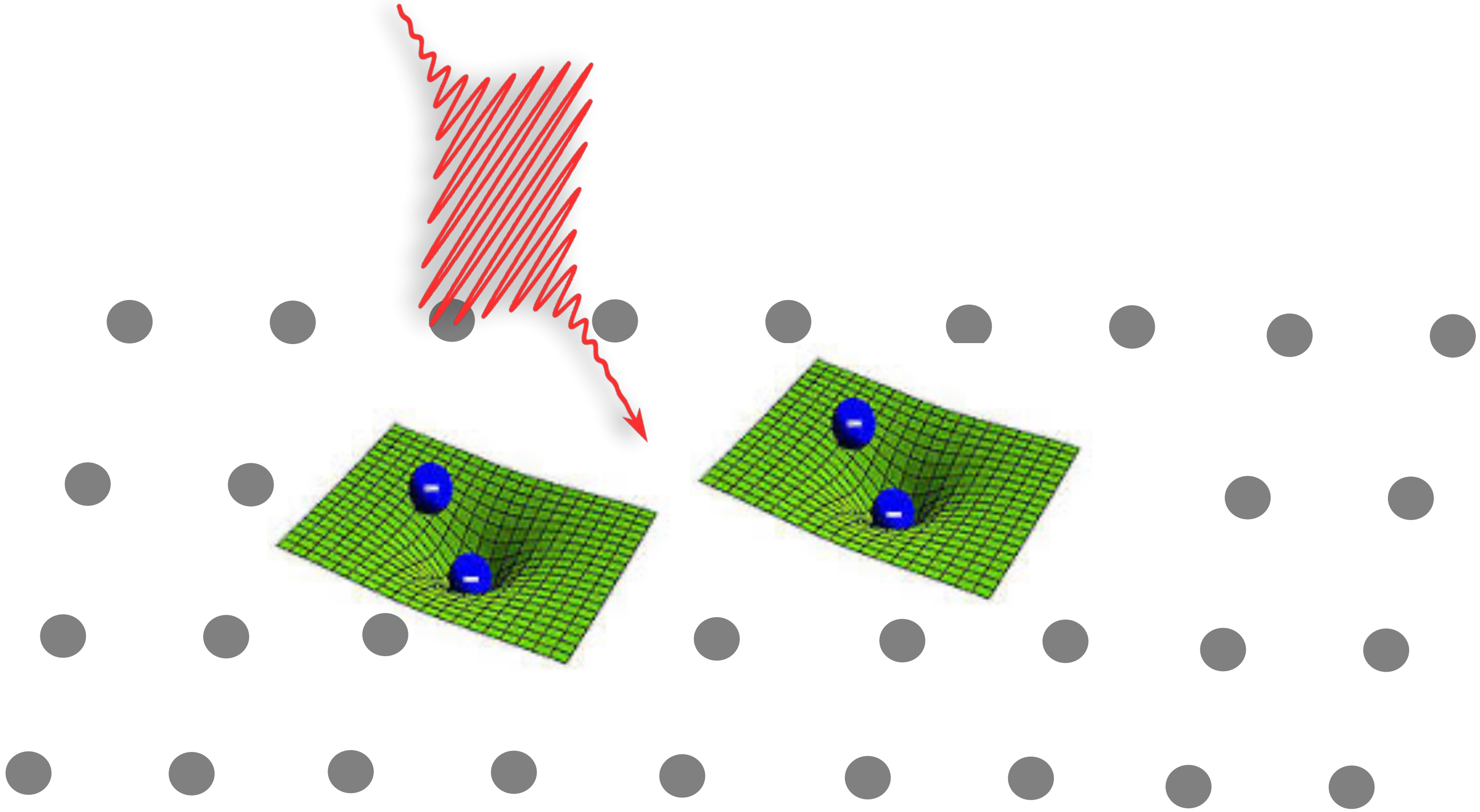
A. Disa et al., *Nature 617, 73 (2023)*

Induced Topology



J. Mciver et al., *Nature Physics* 16, 38 *(2020)*

Today's talk: Controlling Superconductivity



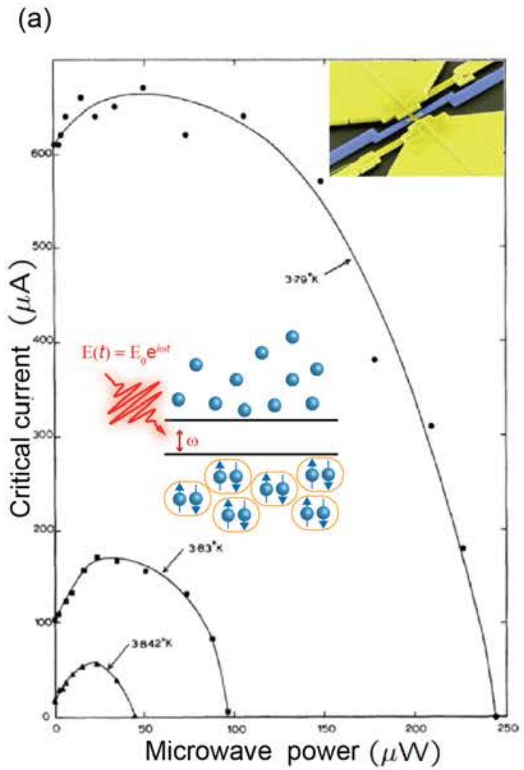
(1) Control pairing fields

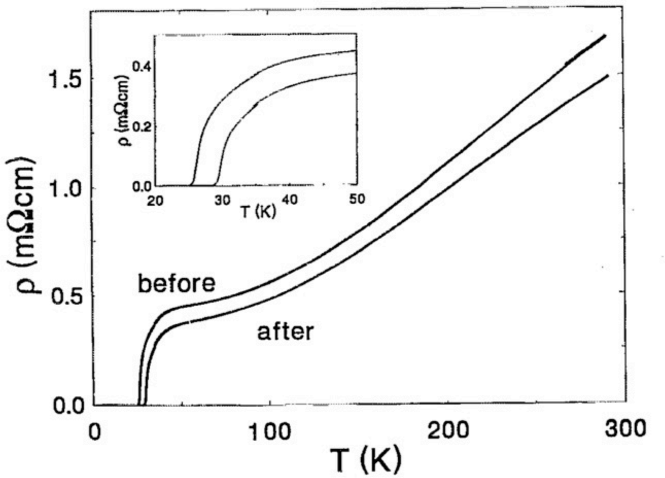
(2) Control "phase" coherence

Enhancing Superconductivity with radiation: history

Microwave irradiation

UV irradiation





Nieva, G. *et al. Applied Physics Letters* 60, 2159-2161, (1992).

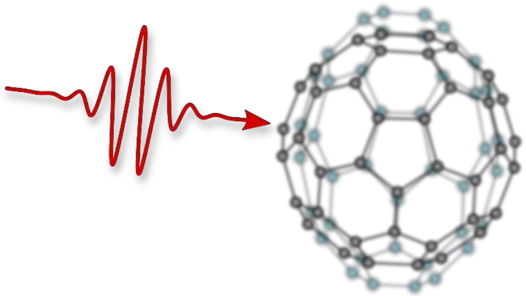
Yu, G. *et al. Physical Review B* 45, 4964-4977, (1992).

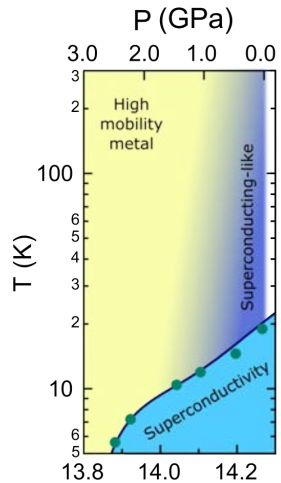
Wyatt, A. F. G., *Physical Review Letters* 16, 1166-1169, (1966).

G. Eliashberg., M. *JETP Letters* 11, 114, (1970).

Control of Superconductivity in Organics

K_3C_{60}





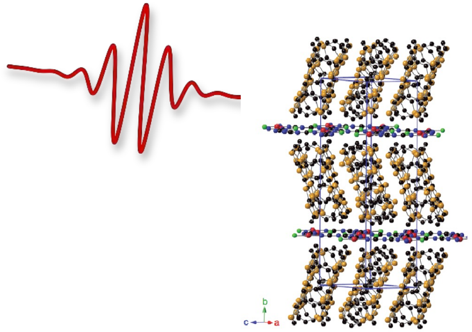
M. Mitrano et al., Nature 530, 461-464 (2016)

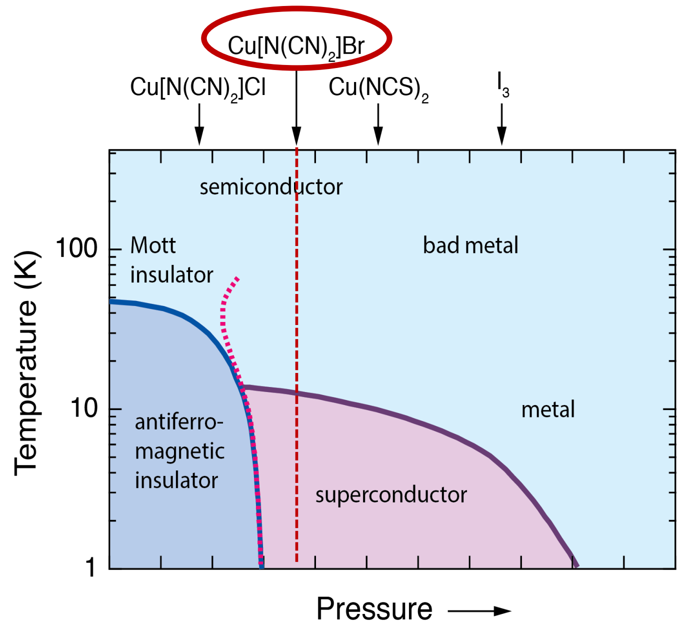
A. Cantaluppi et al., Nature Physics 14, 837 (2018)

M. Budden et al., Nature Physics 17 611 (2021)

E. Rowe et al., Nature Physics (2023)

k-ET_2Br





M. Buzzi et al, *Phys. Rev. X* 10, 031028 (2020)

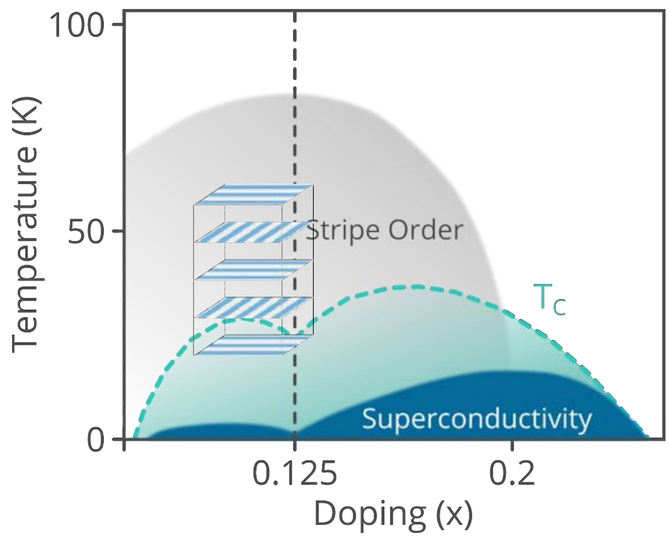
M. Buzzi et al, *Phys. Rev. Lett* 127, 197002 (2021)

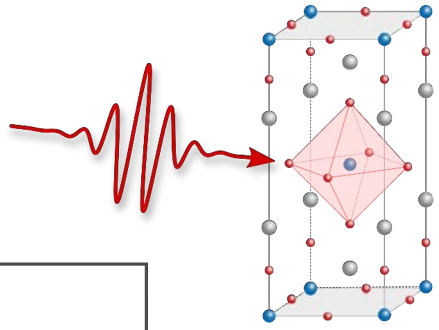
Control of Superconductivity in Cuprates

$La_{1.8-x}Eu_{0.2}Sr_xCuO_4$

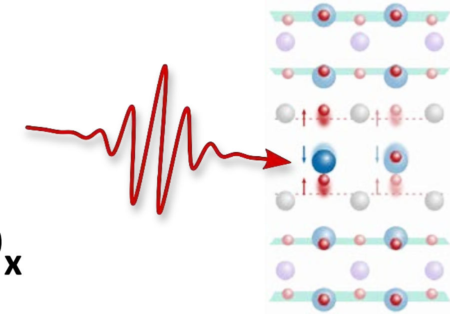
$La_{2-x}Ba_xCuO_4$

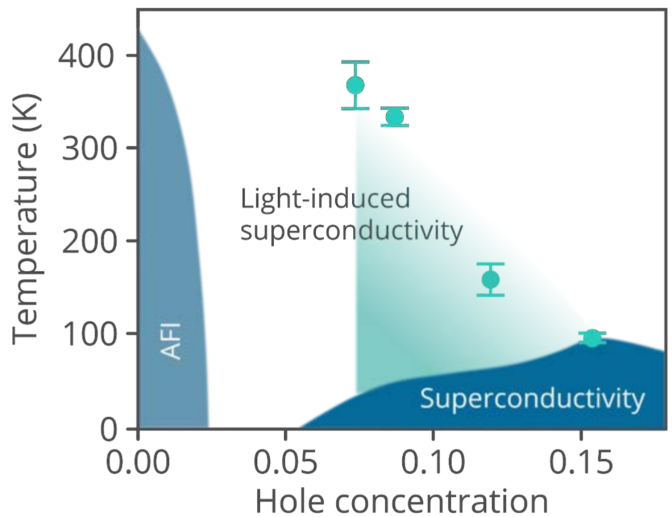
$La_{1.6-x}Nd_{0.4}Sr_xCuO_4$





$YBa_2Cu_3O_x$





D. Fausti et al, *Science* 331, 6014 (2011)

D. Nicoletti et al, *Phys Rev B* 90, 100503 (2014)

K. Cremin et al. PNAS 40, 19875 (2019)

M. Nishida et al. ArXiv2303.01961 (2023)

W. Hu et al, *Nature Materials* 13, 705 (2014)

B. Liu et al, *Phys. Rev. X* 10, 011053 (2020)

A. Von Hoegen et al. *Phys. Rev. X 12, 031008 (2022)*

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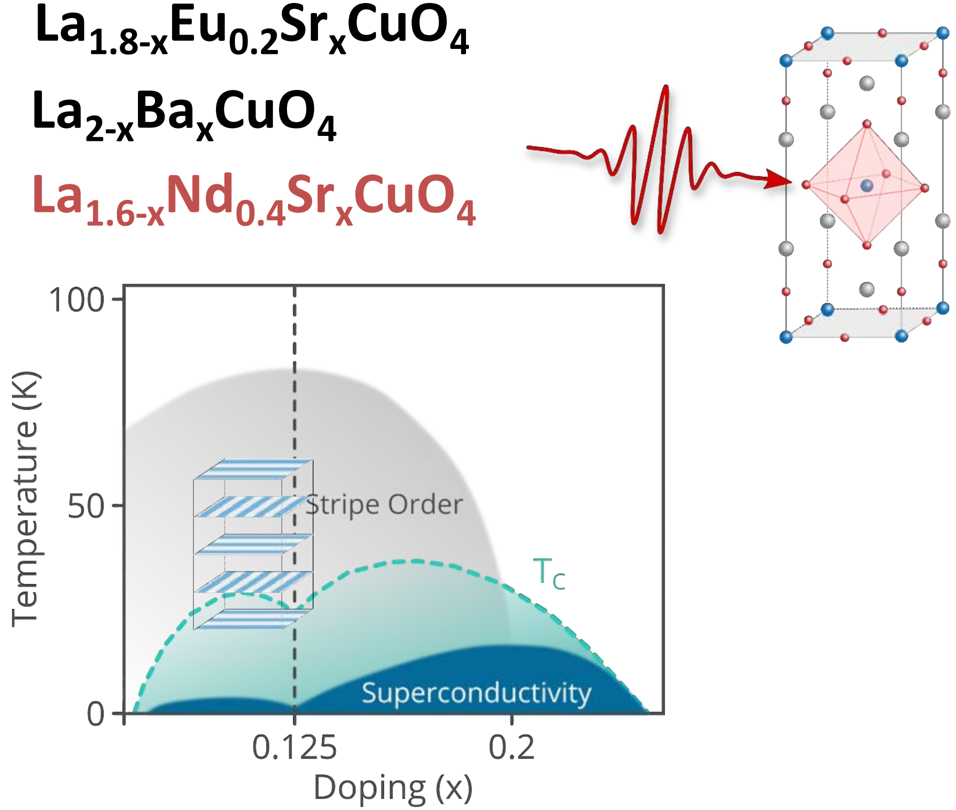

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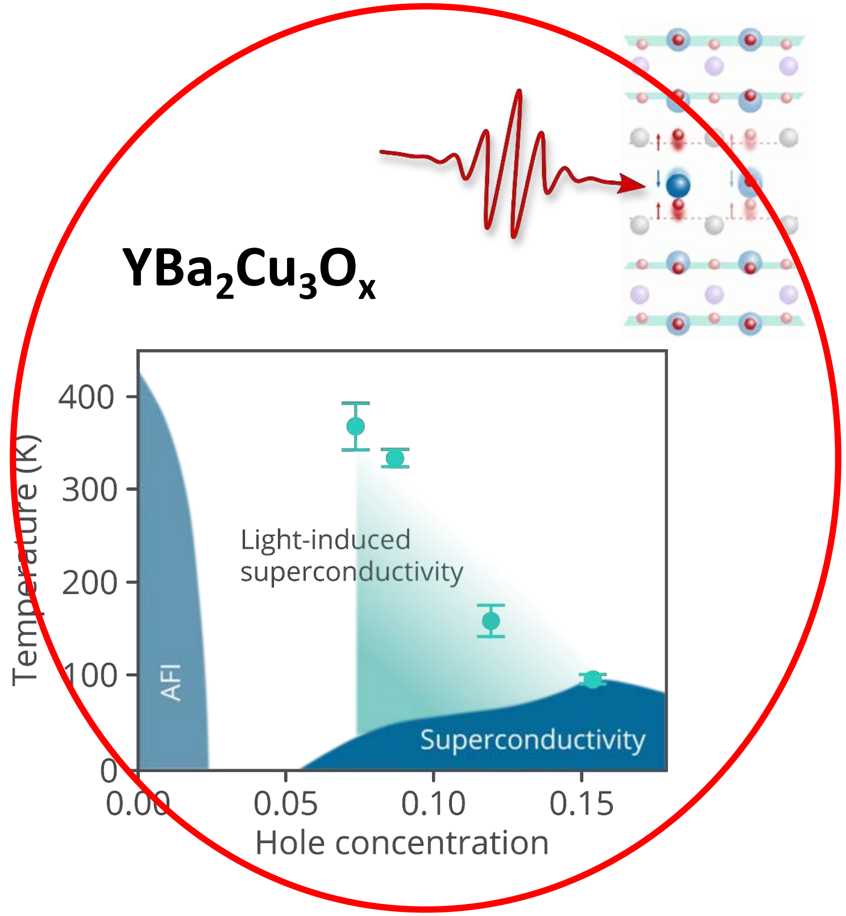

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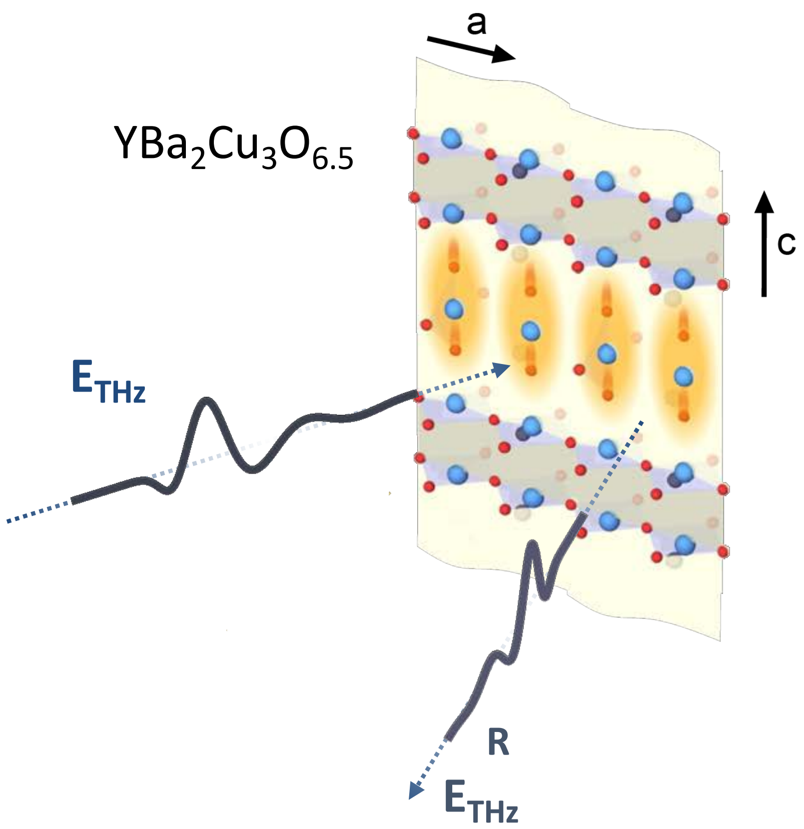
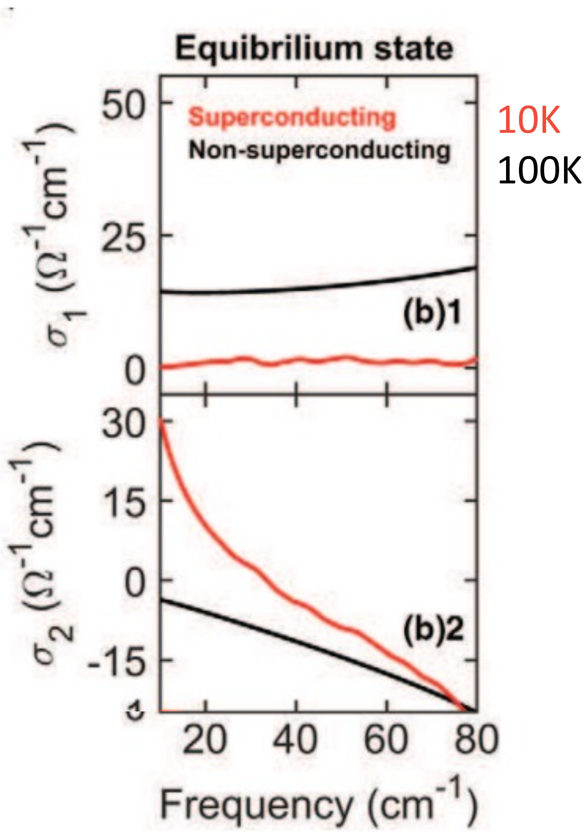
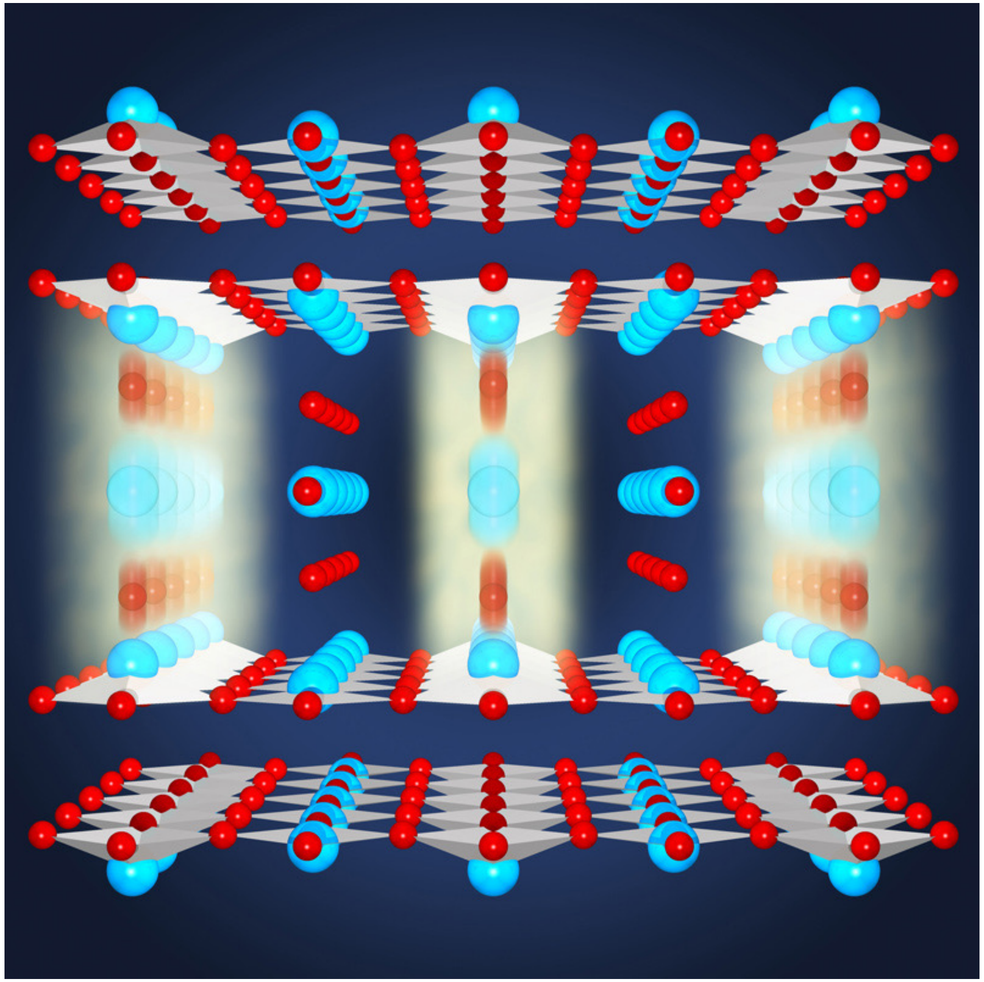
$YBa_2Cu_3O_x$: signatures of equilibrium superconductivity



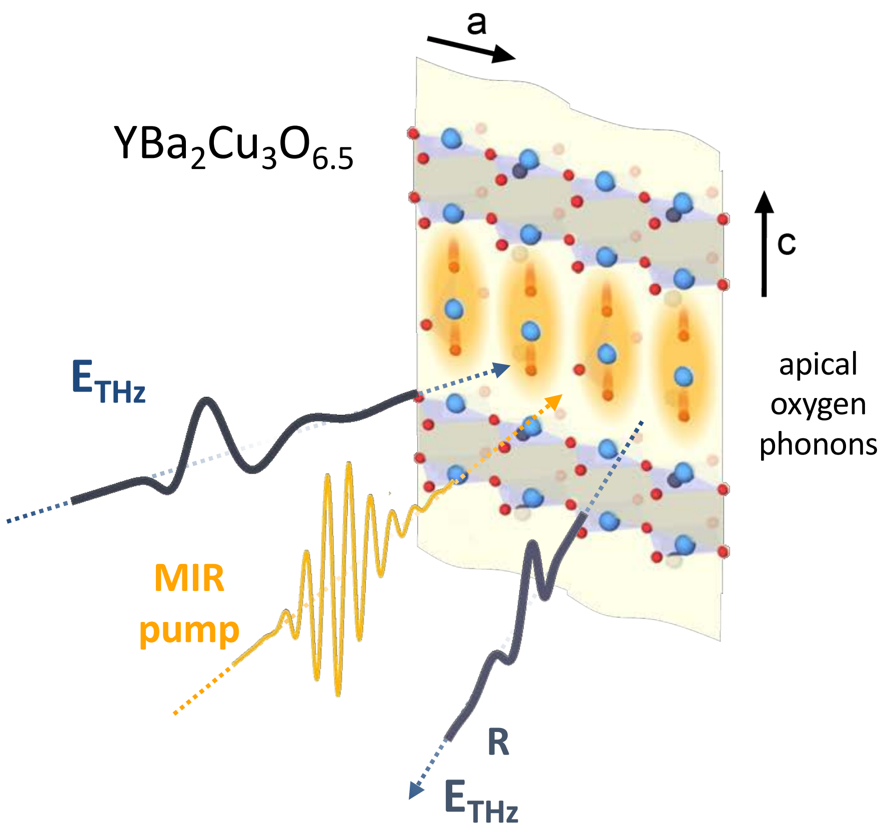
B. LIU et al. PHYS. REV. X 10, 011053 (2020)



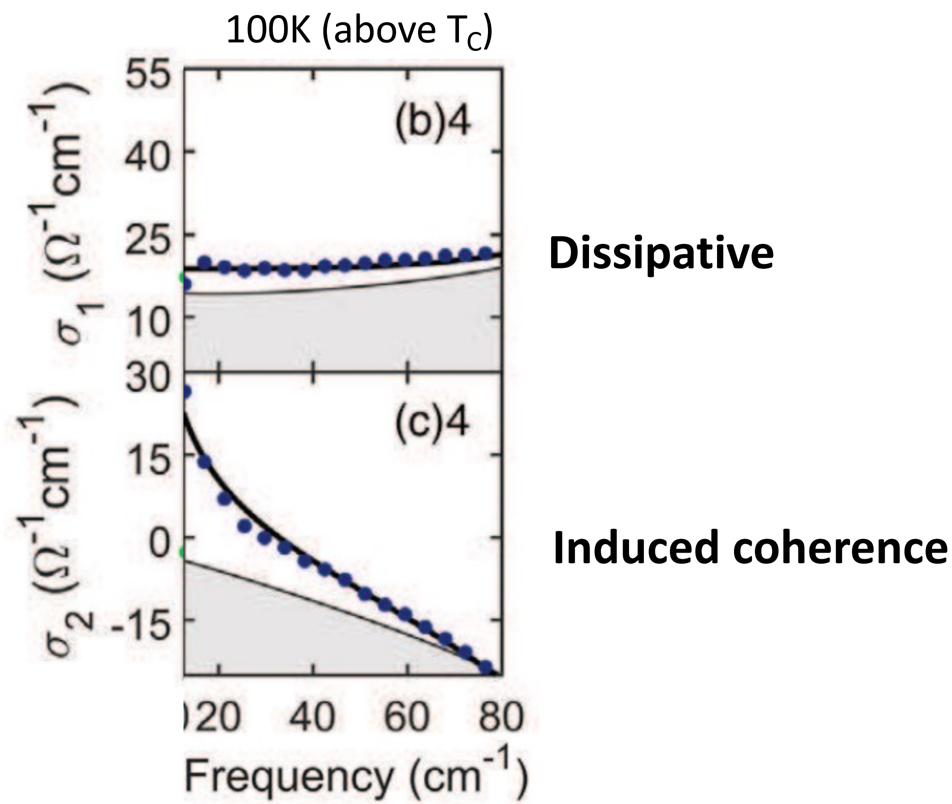
Driven $YBa_2Cu_3O_x$



$YBa_2Cu_3O_x$: signatures of induced coherent transport



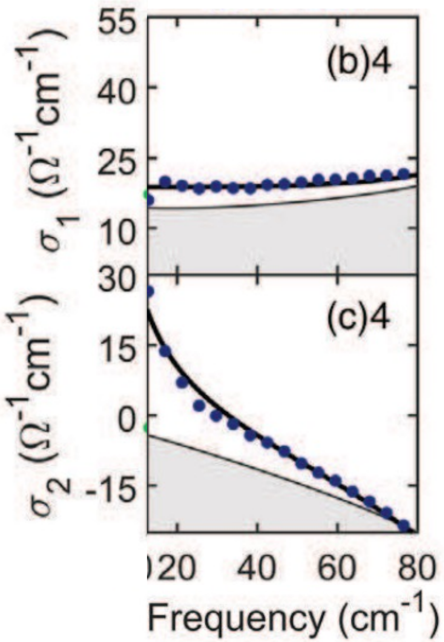
B. LIU et al. PHYS. REV. X 10, 011053 (2020)



$YBa_2Cu_3O_x$: signatures of induced coherent transport

$$\sigma_1(\omega) + i\sigma_2(\omega) = \frac{\sigma_0}{1 - i\omega\tau}$$

Figure of merit – Extrapolated DC resistivity



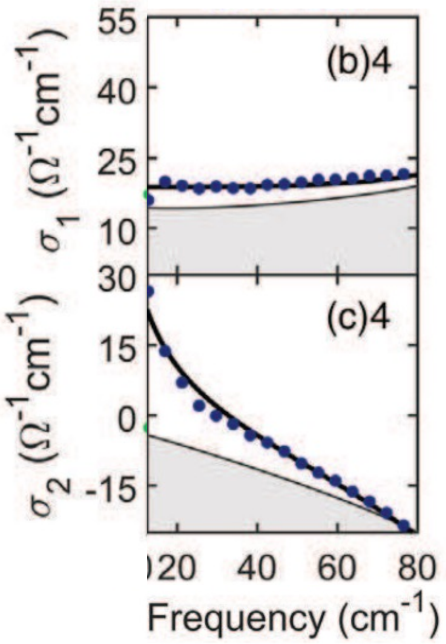
Dissipative

Induced coherence

$$\frac{1}{\rho_0} = \lim_{\omega \to 0} \sigma_1(\omega)$$

$YBa_2Cu_3O_x$: signatures of induced coherent transport

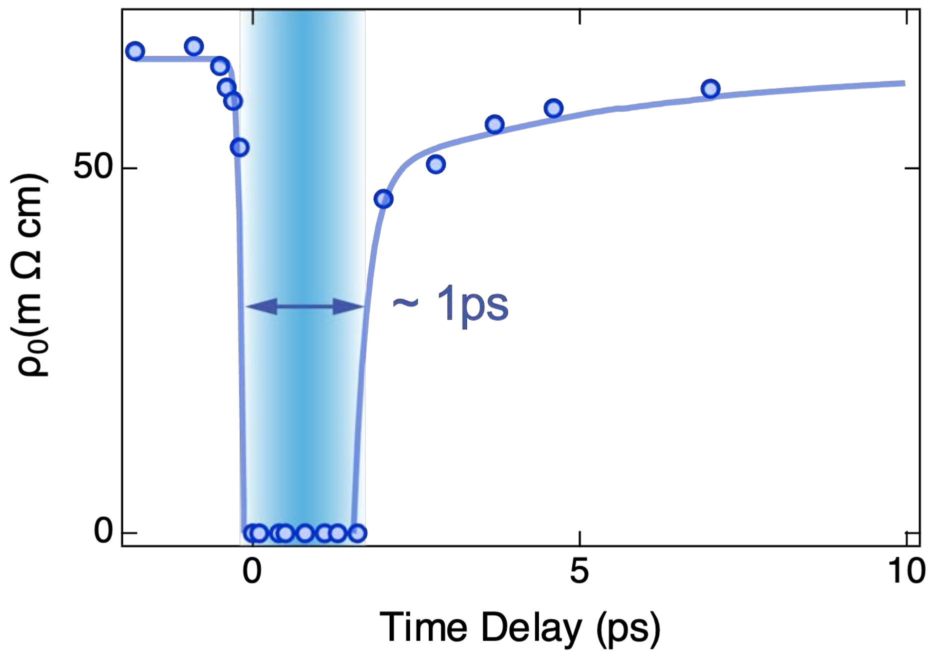
$$\sigma_1(\omega) + i\sigma_2(\omega) = \frac{\sigma_0}{1 - i\omega\tau} \qquad \frac{1}{\rho_0} = \lim_{\omega\to 0} \sigma_1(\omega)$$



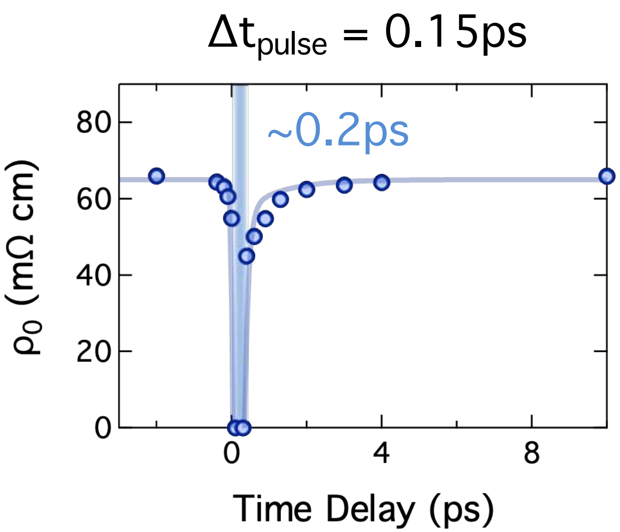
Dissipative

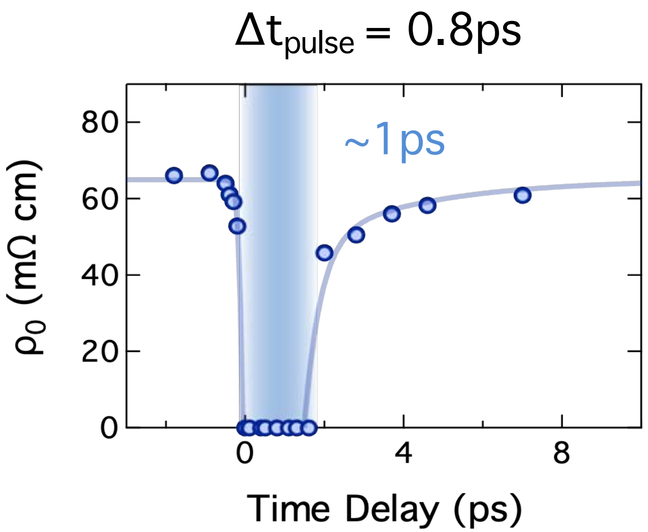
Induced coherence

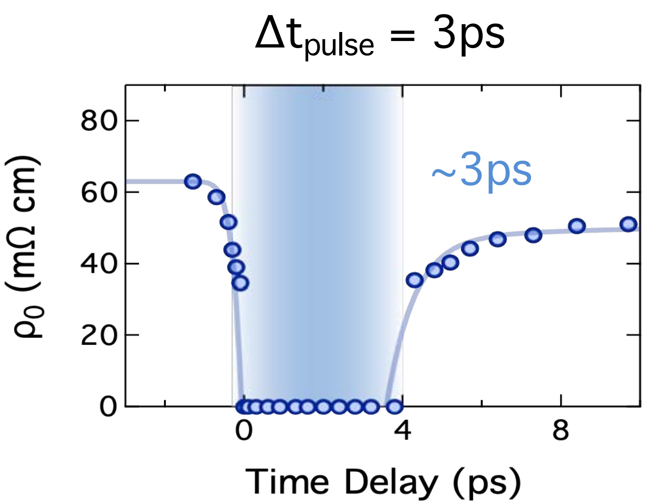
Extrapolated DC resistivity

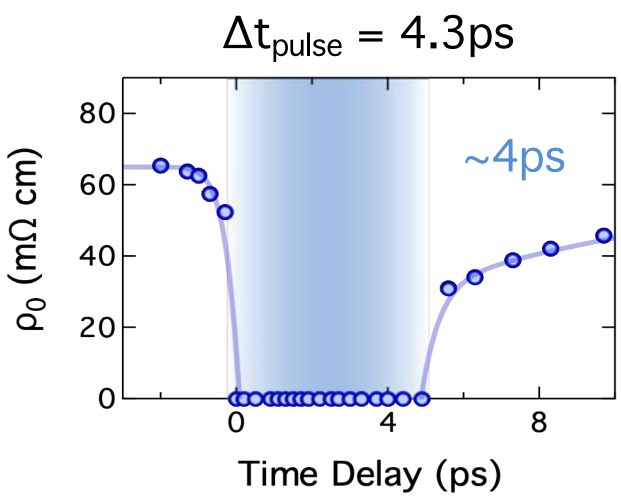


ρ_0 vs. time for four different pulse durations



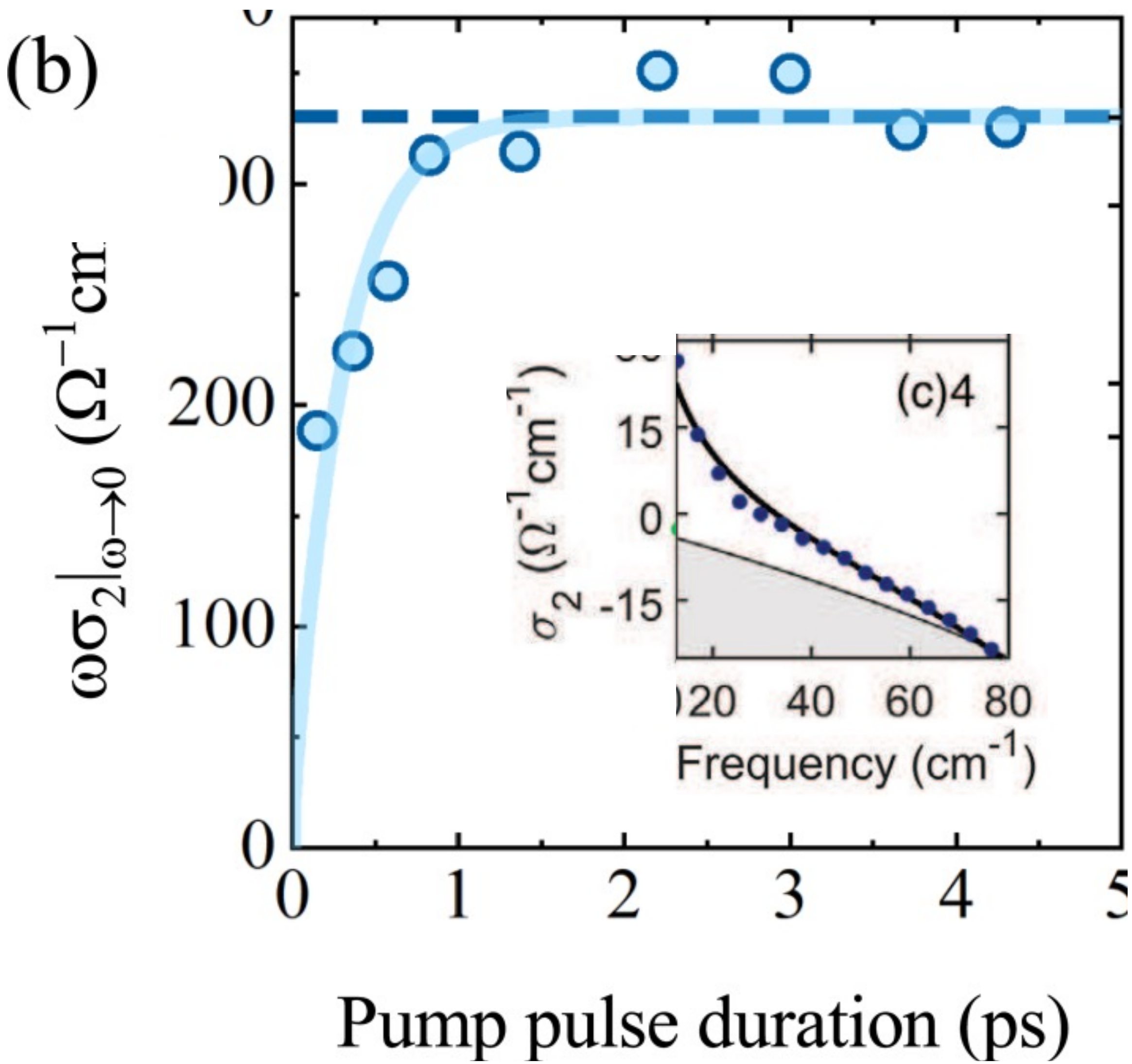






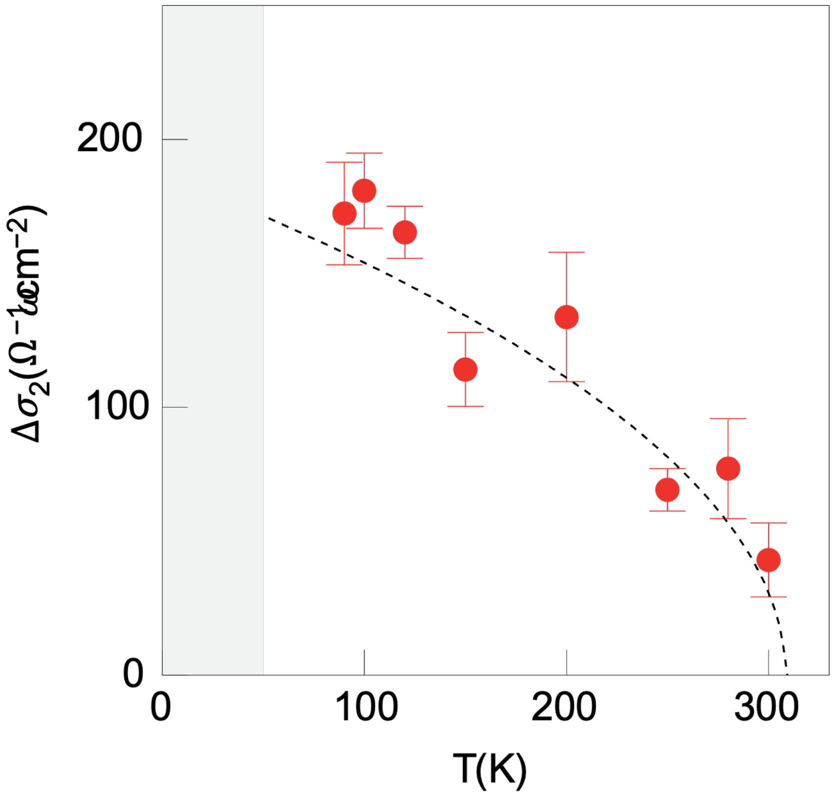
A. Ribak et al. ***Phys. Rev. B 107, 104508 (2023)***

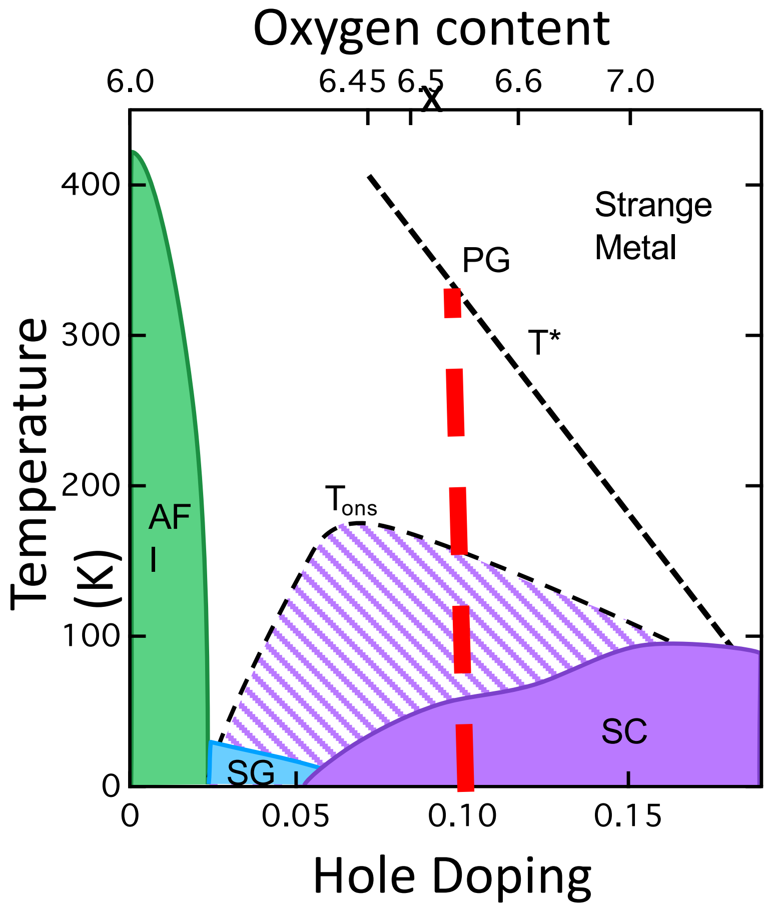
$YBa_2Cu_3O_x$: density of Cooper pairs



Zero temperature superfluid density

Up to very high temperatures: pseudogap scale



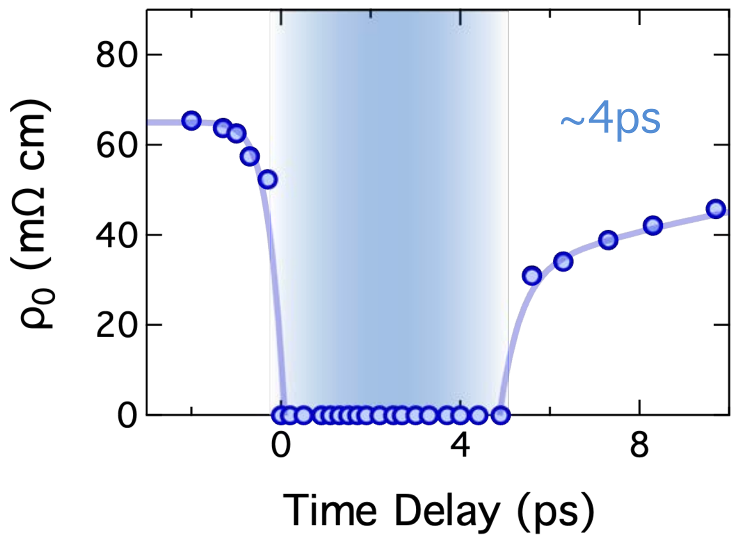


W. Hu et al., Nat. Mater. 13, 705 (2014)

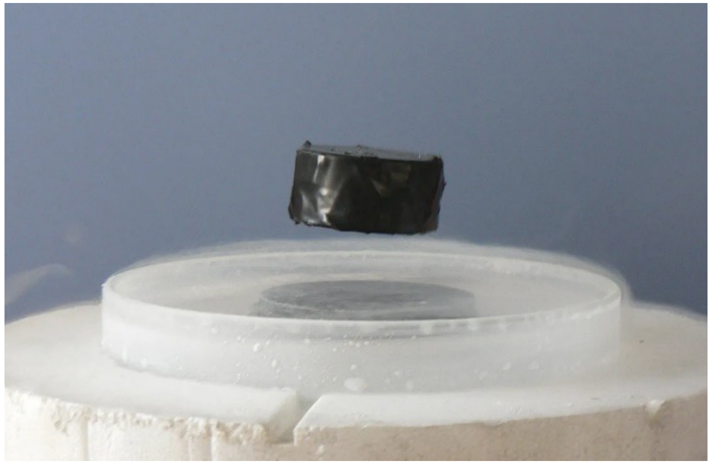
S. Kaiser *et al.*, Phys. Rev. B 89, 184516 (2014)

Does this state also expel a magnetic field ?

Dissipation-less transport



Meissner effect ?



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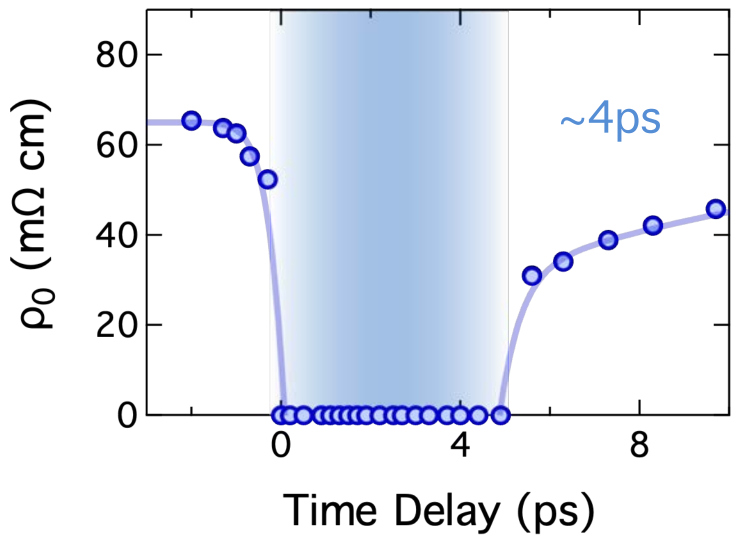
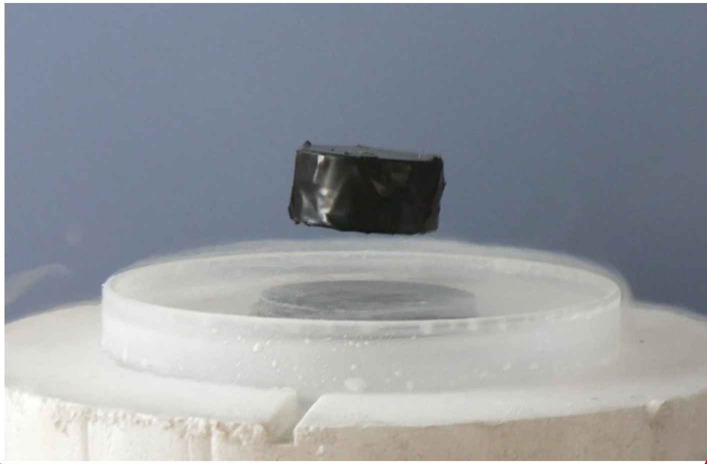
Dissipation-less transport



Meissner effect ?



People

Giovanni De Vecchi

Sebastian Fava

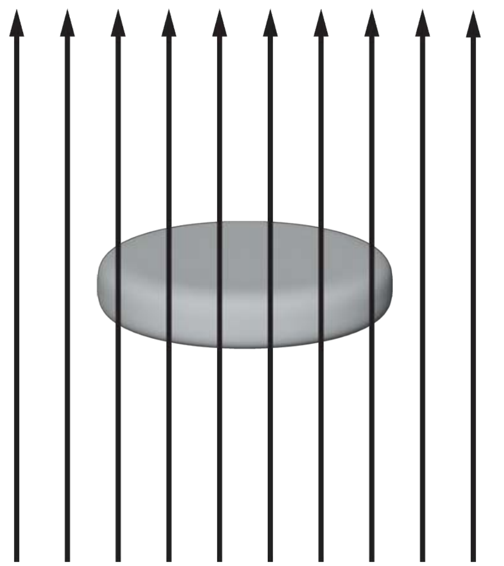
YBCO samples:
Bernhard Keimer & group

Michele Buzzi

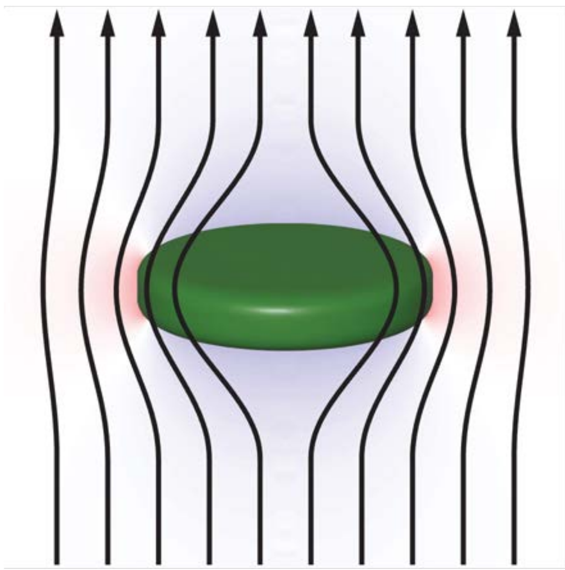
Gregor Jotzu

Meissner Effect

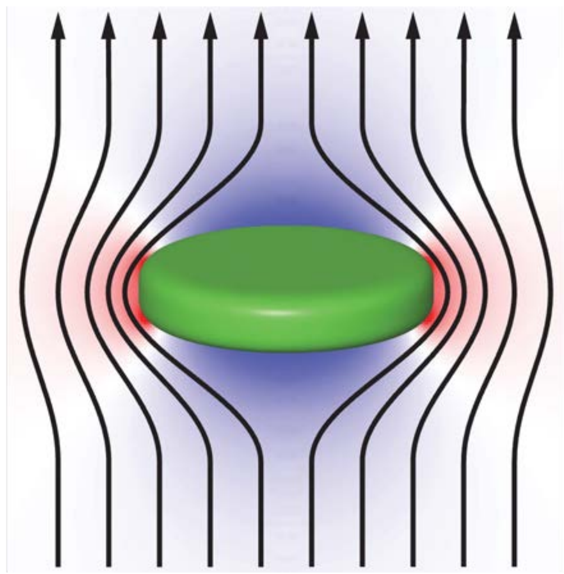
Initial Metallic State



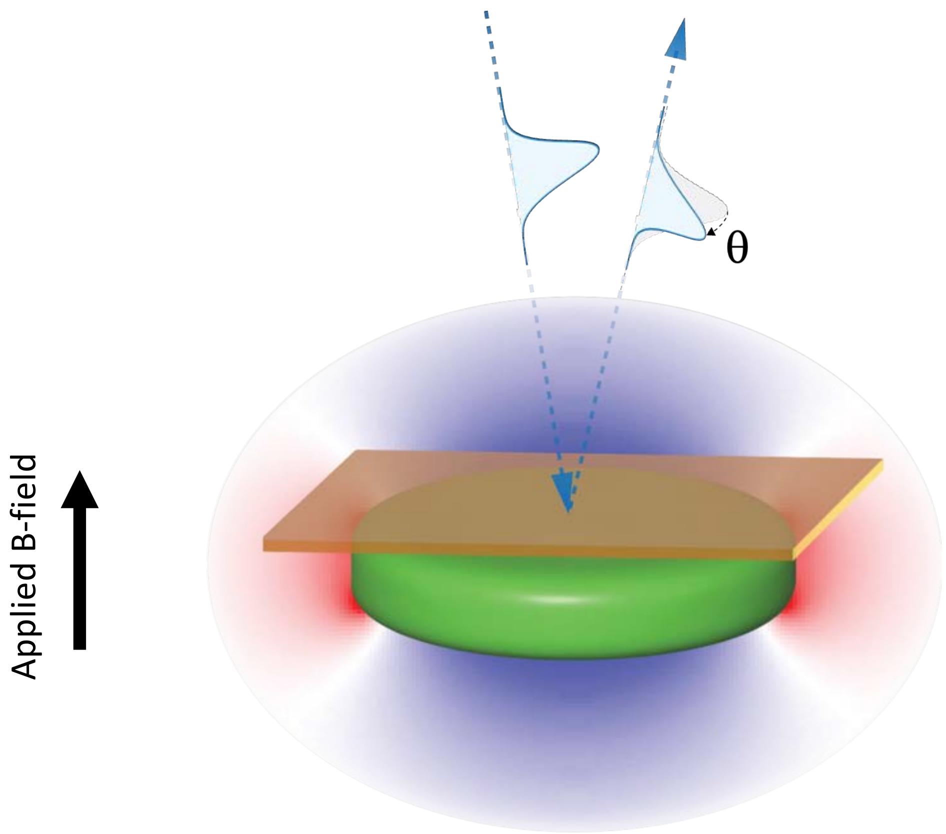
Transient State



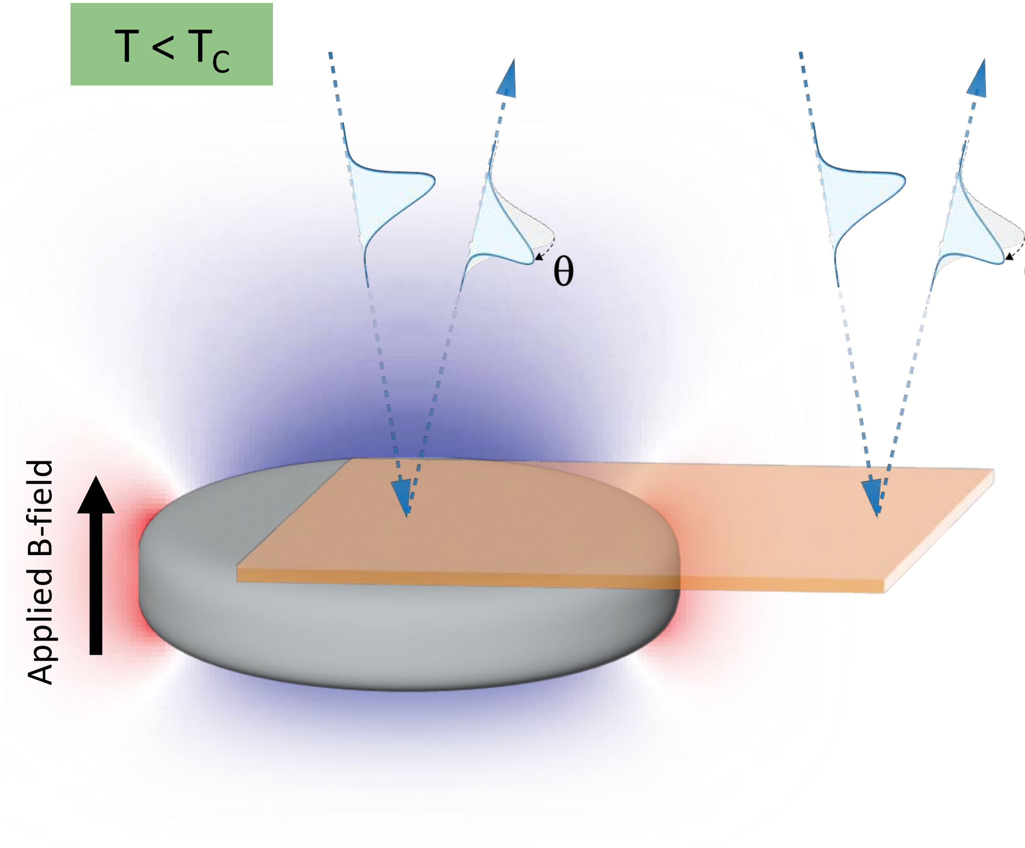
Superconducting State

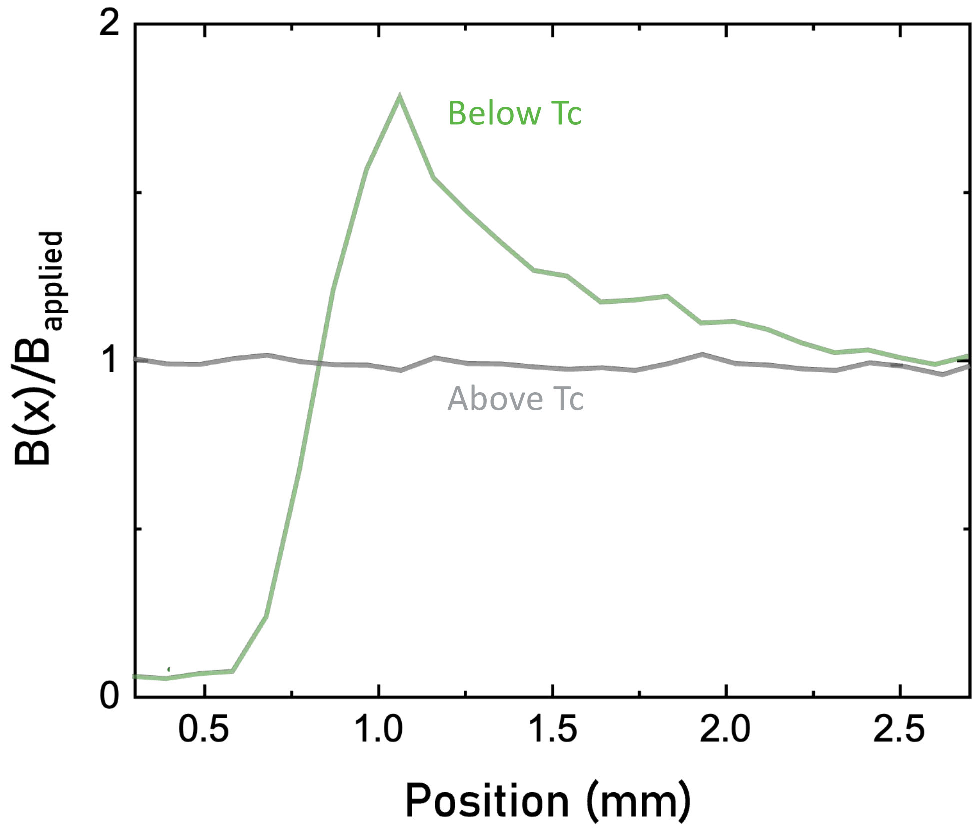


Ultrafast Faraday Magnetometry

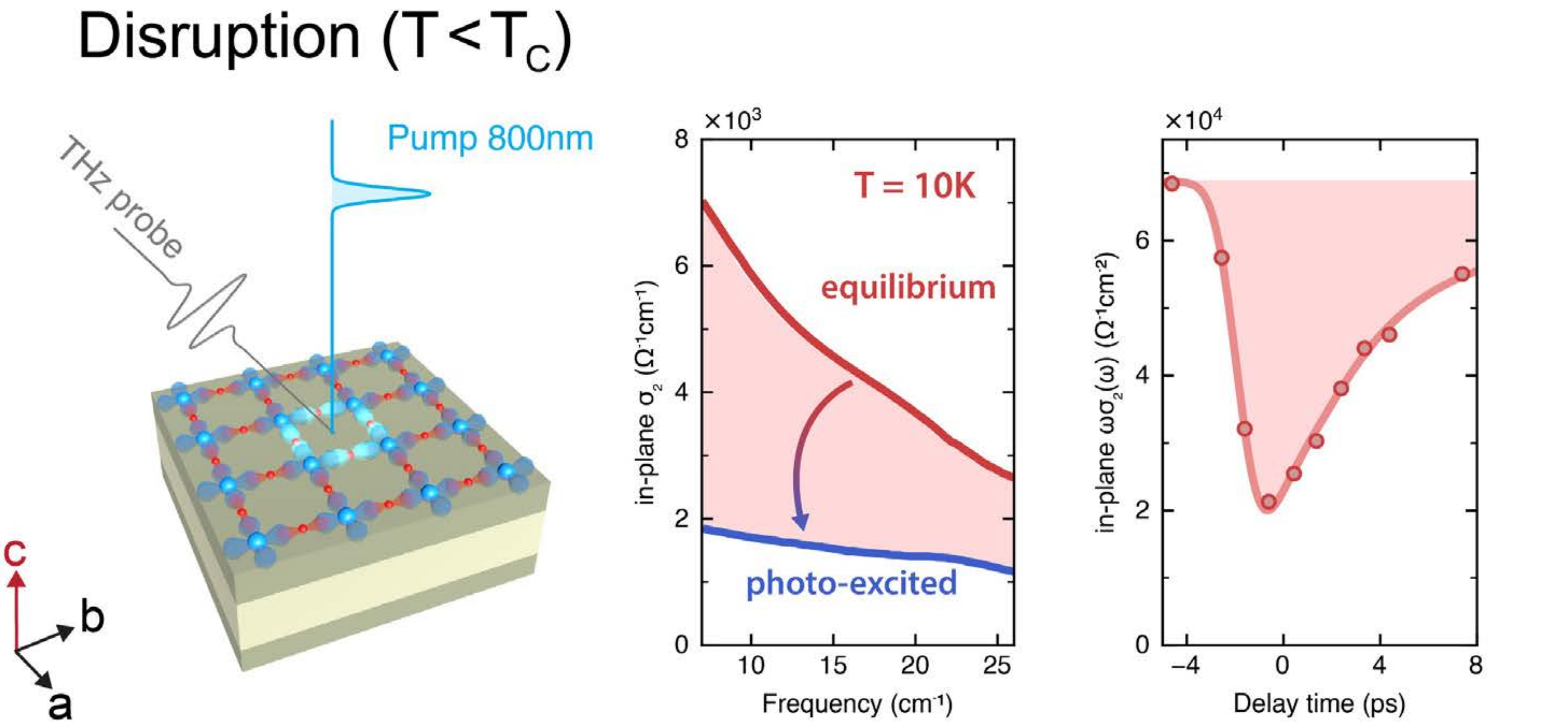


Calibration 1: Static B-Field Expulsion





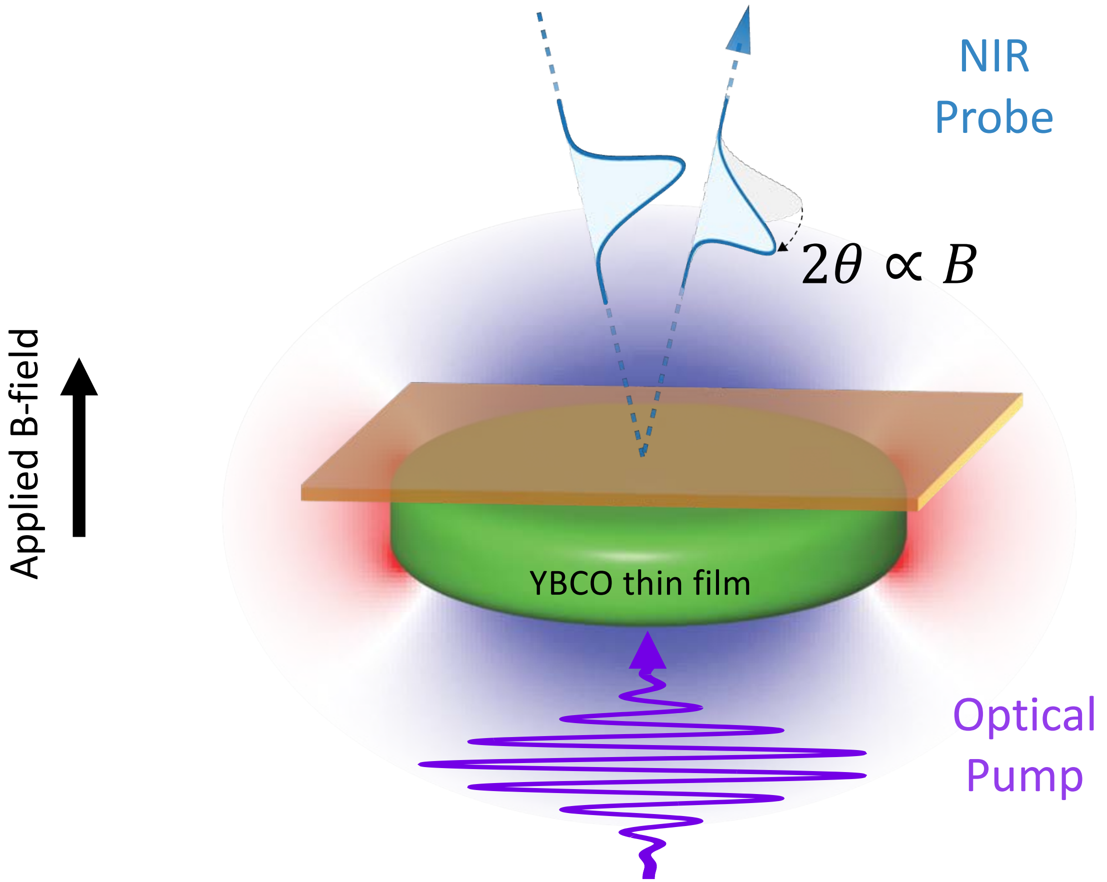
Calibration 2: Disruption



Averitt et al. PRB 2001

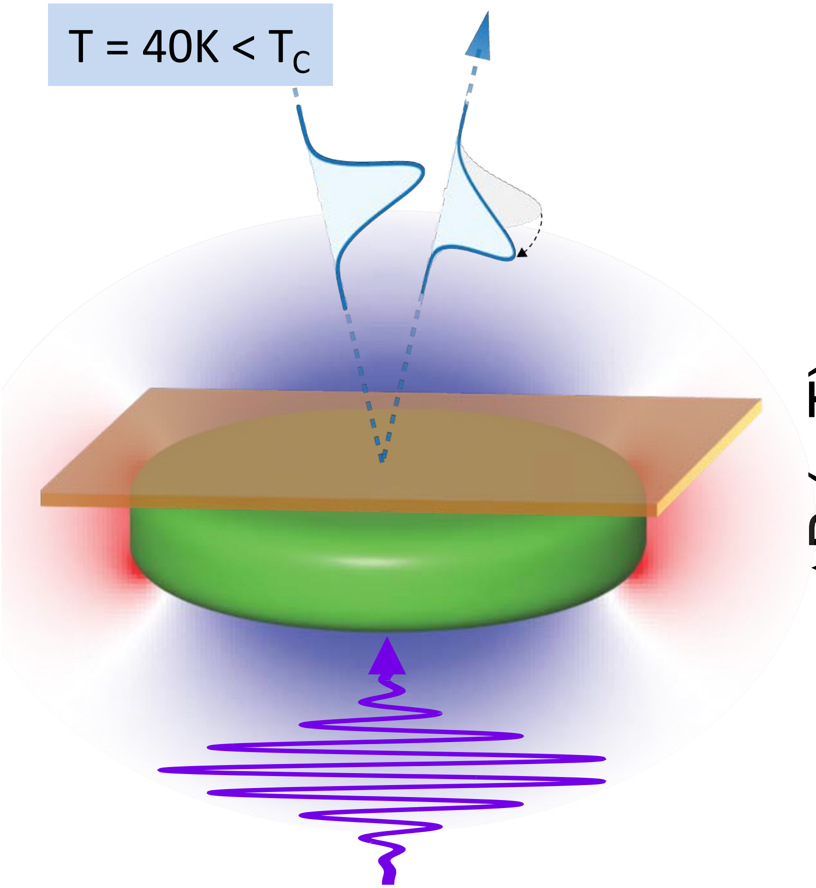
Calibration 2: disruption of Superconductivity

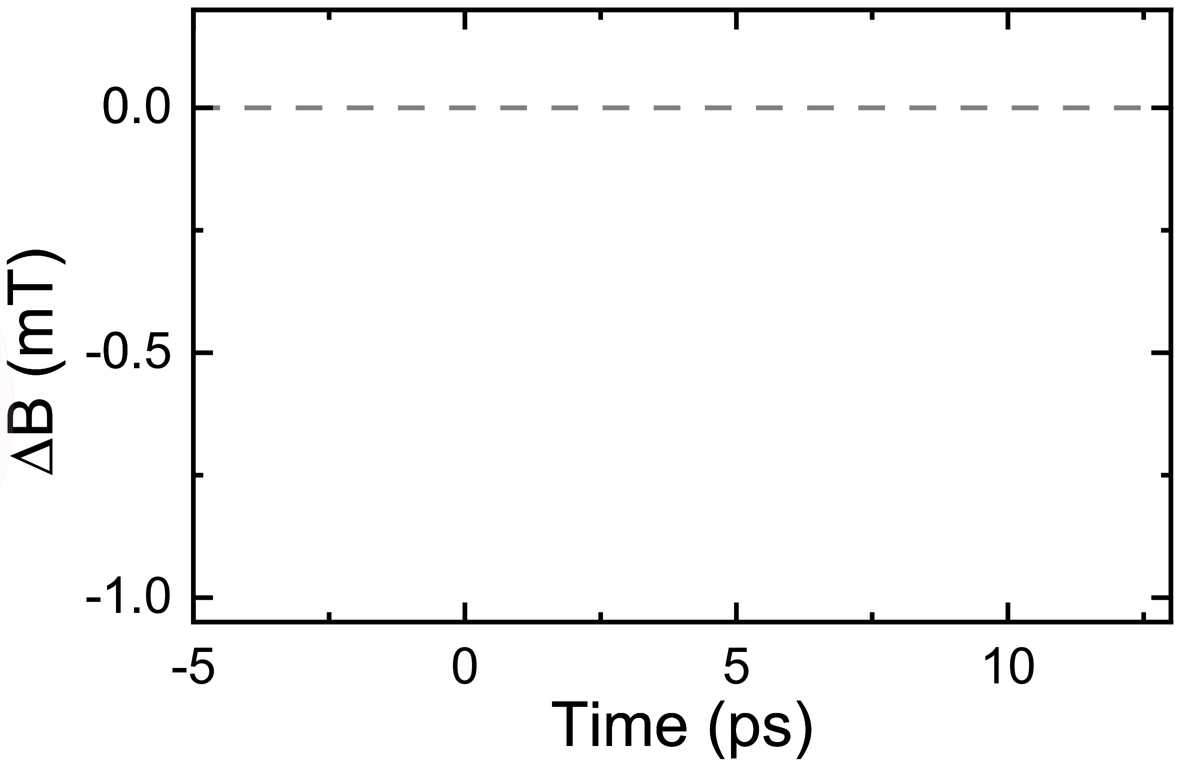
$T = 40K < T_C$



Giovanni De Vecchi

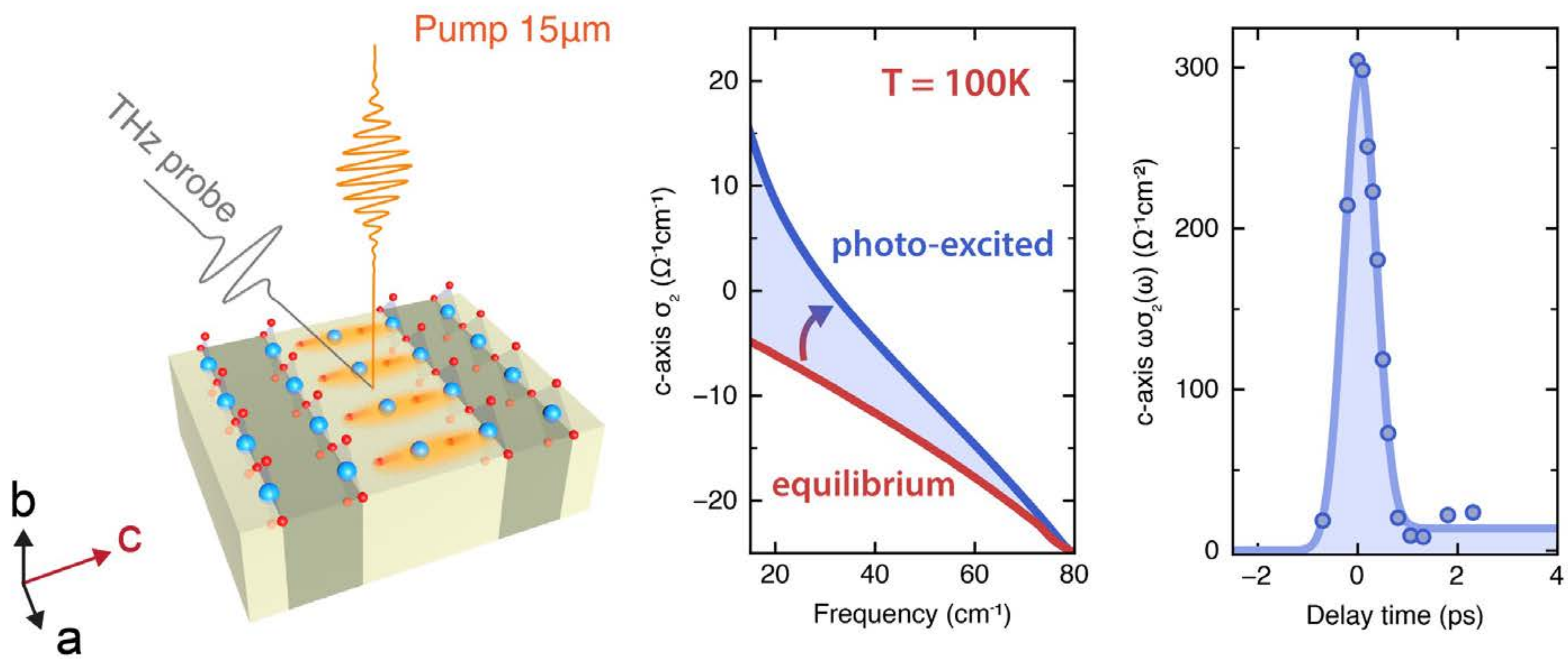
Dynamics: Superconductor to Metal



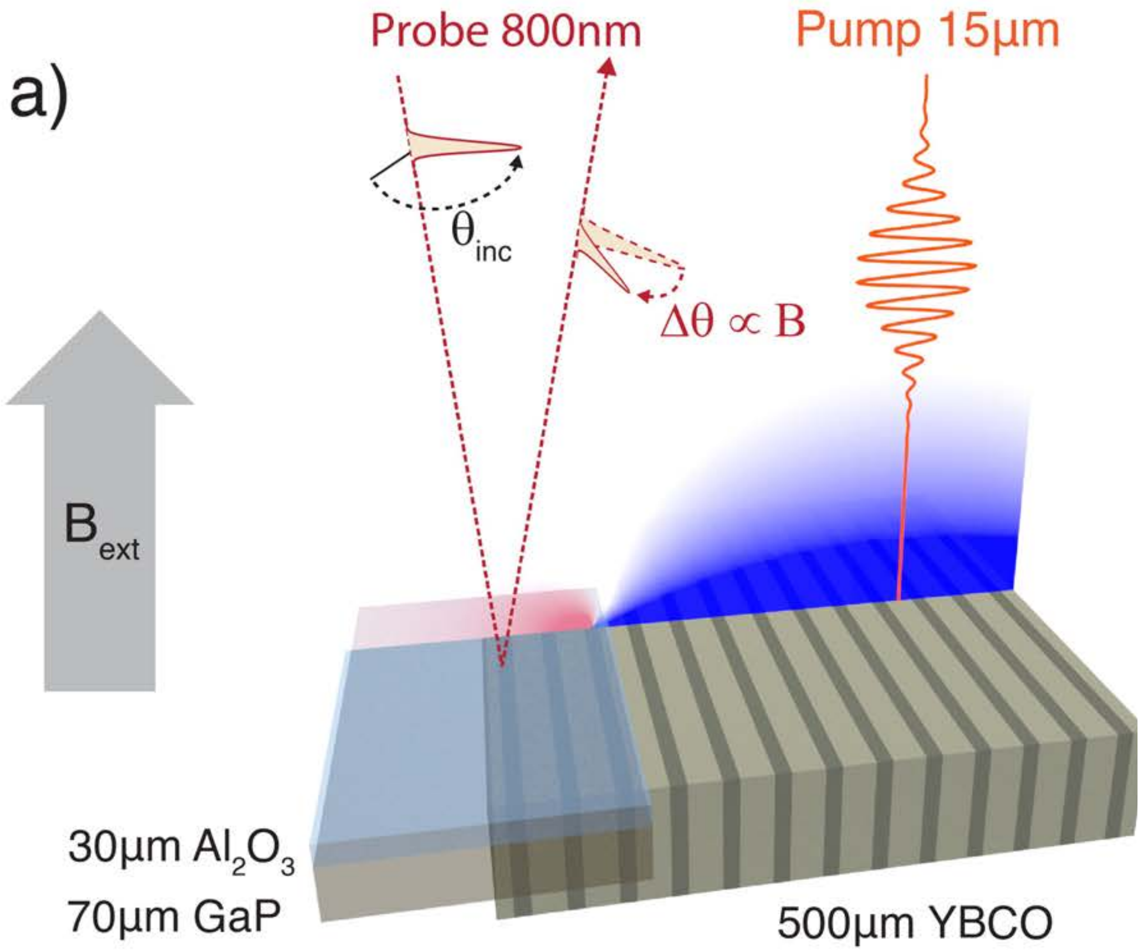


Enhancement of Superconductivity $YBCO_{6.48}$

Enhancement ($T > T_C$)

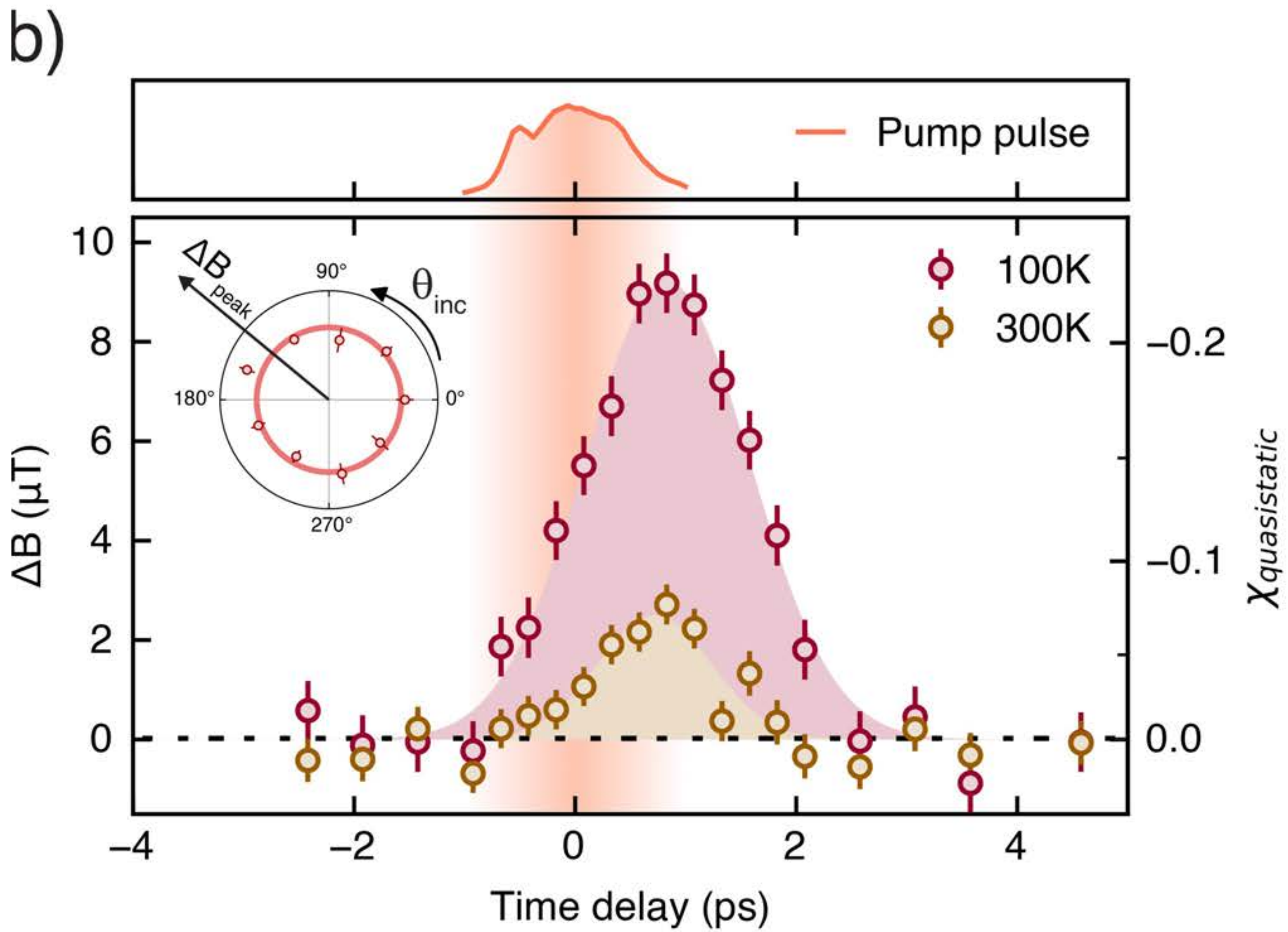


Ultrafast Meissner Effect



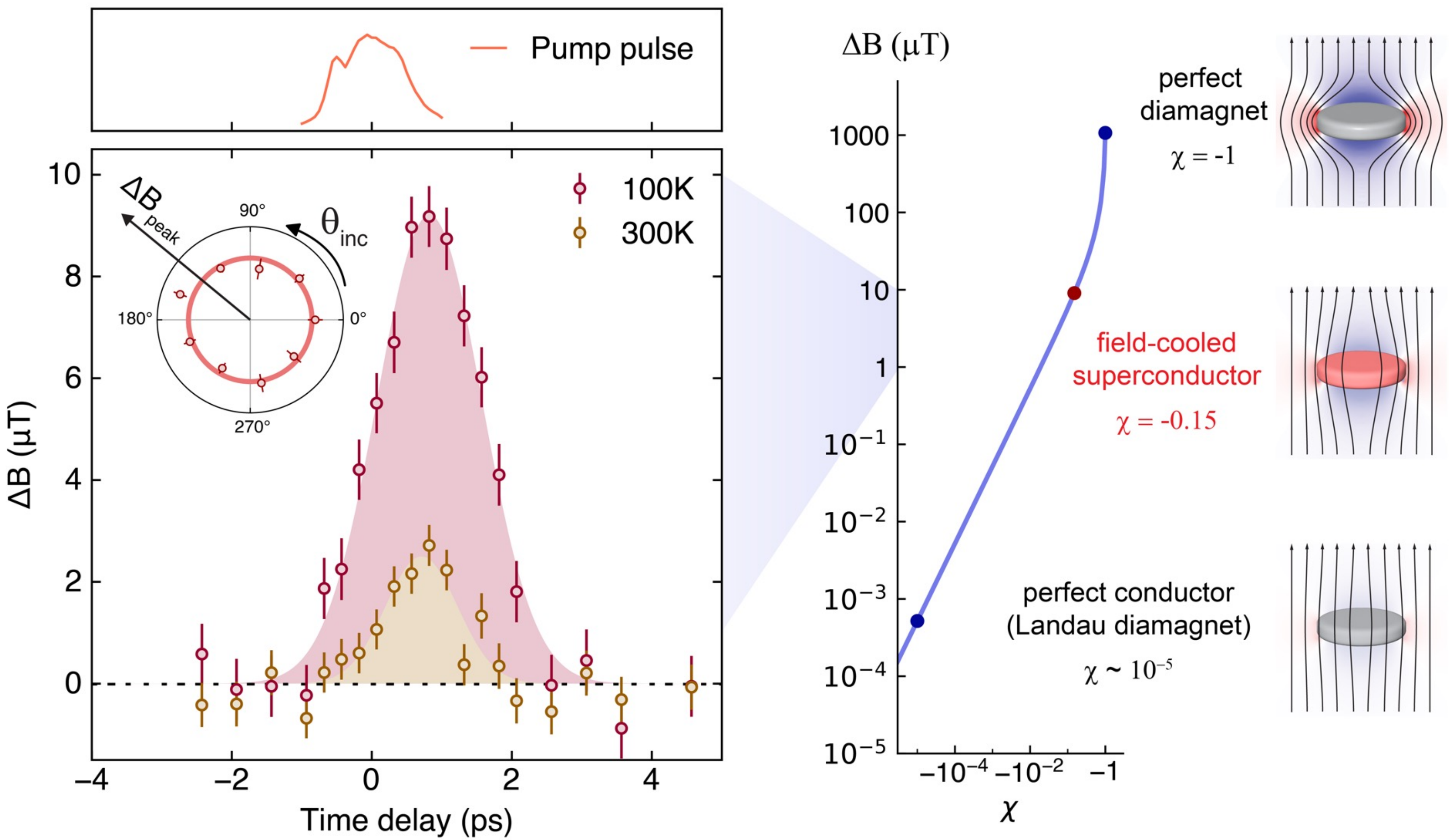
Sebastian Fava

Ultrafast Meissner Effect



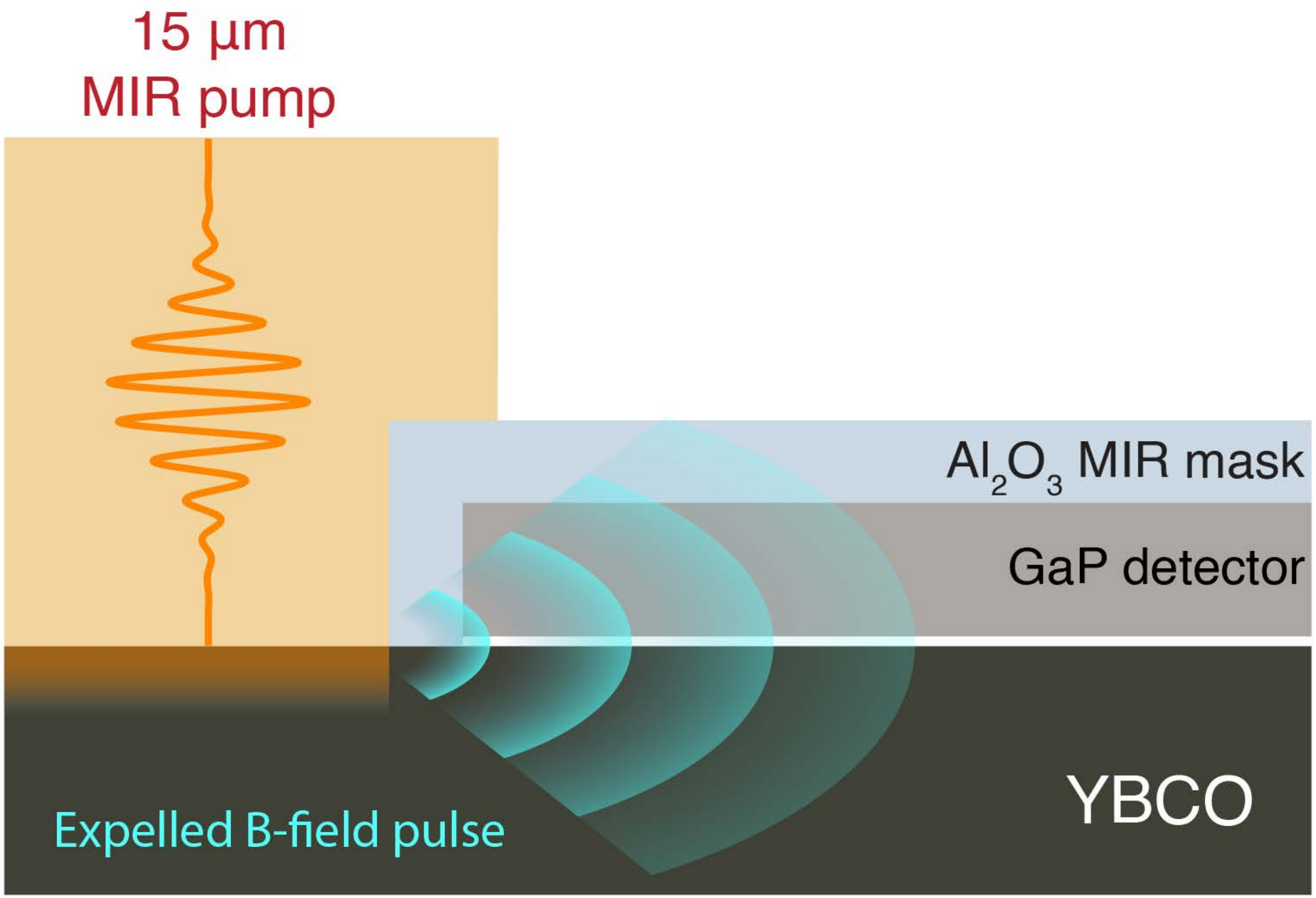
S. Fava, G. DeVecchi, G. Jotzu, M. Buzzi et al. forthcoming

A colossal diamagnetic response

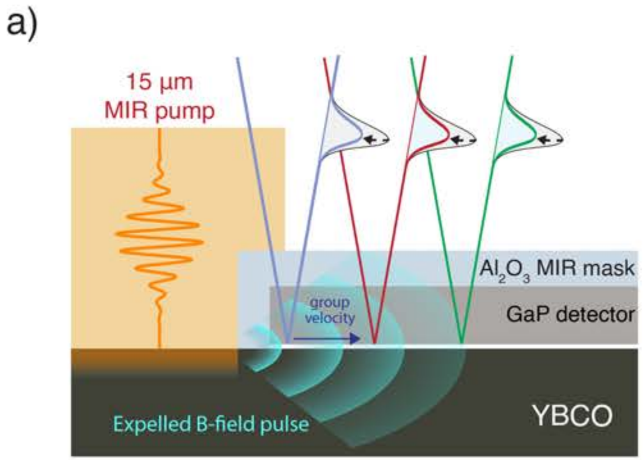


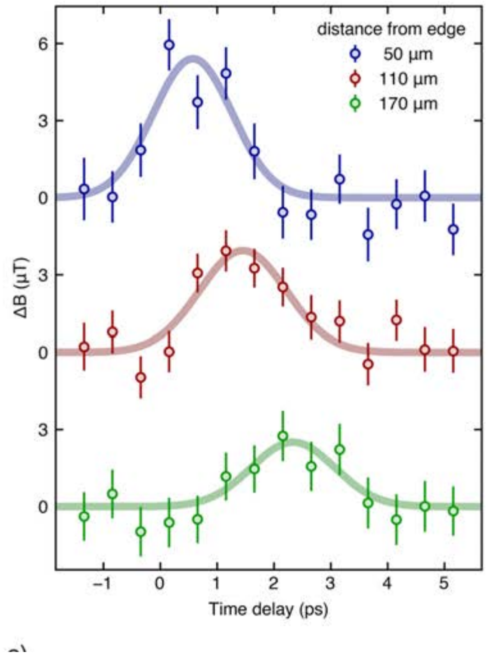
S. Fava, G. DeVecchi, G. Jotzu, M. Buzzi et al. forthcoming

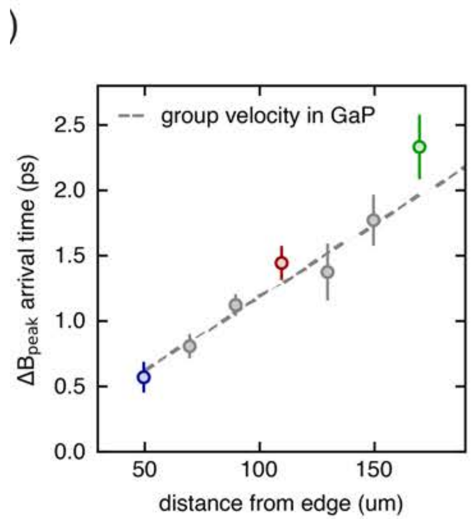
The Ultrafast Meissner effect: electrodynamics



The Ultrafast Meissner effect: electrodynamics

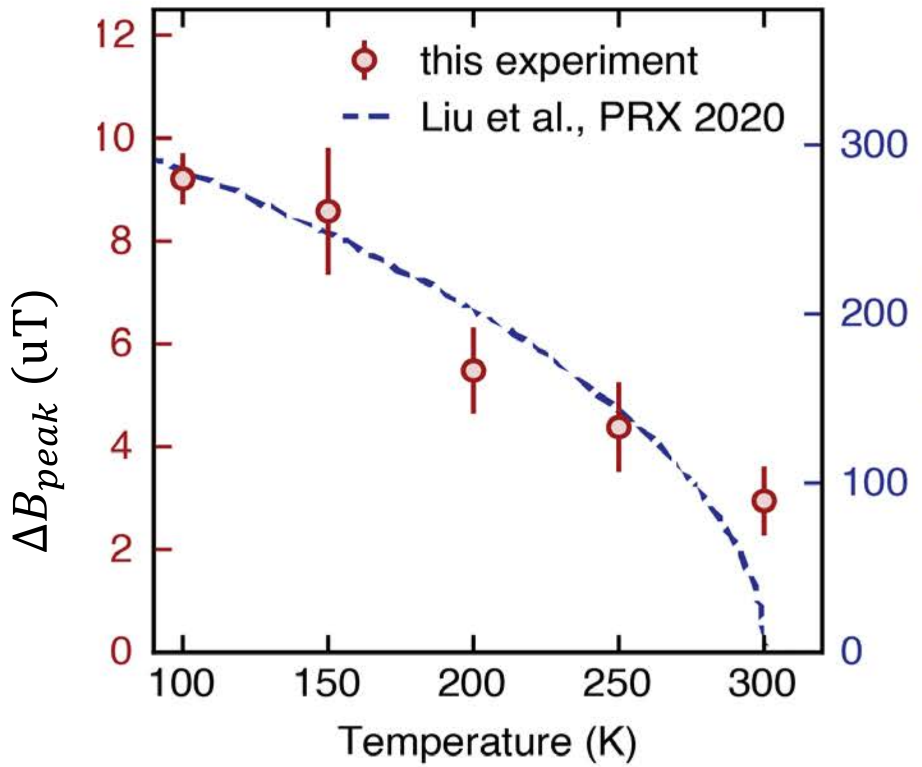




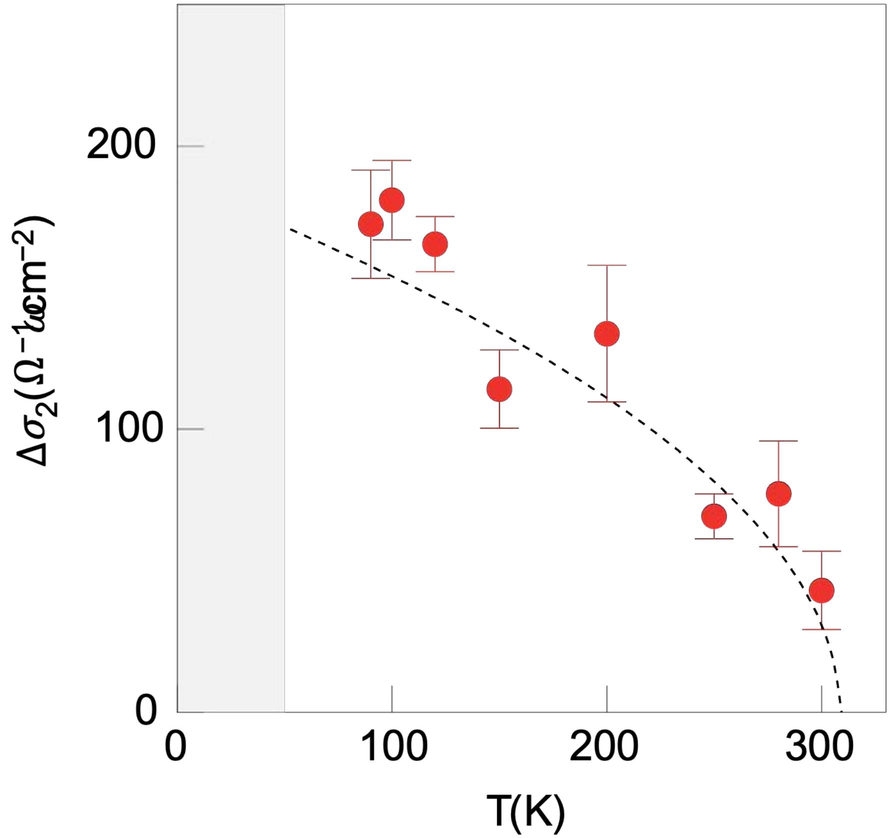


Temperature Dependence

Magnetic

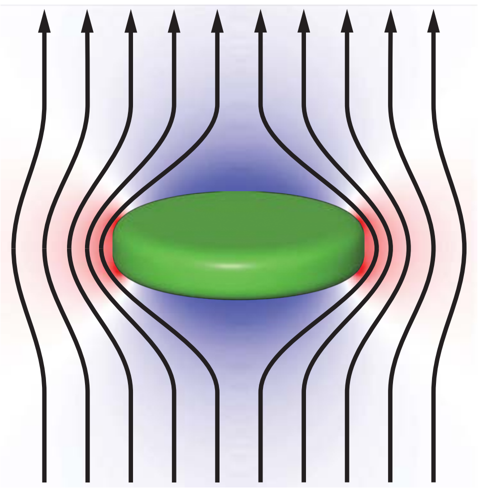


Optical

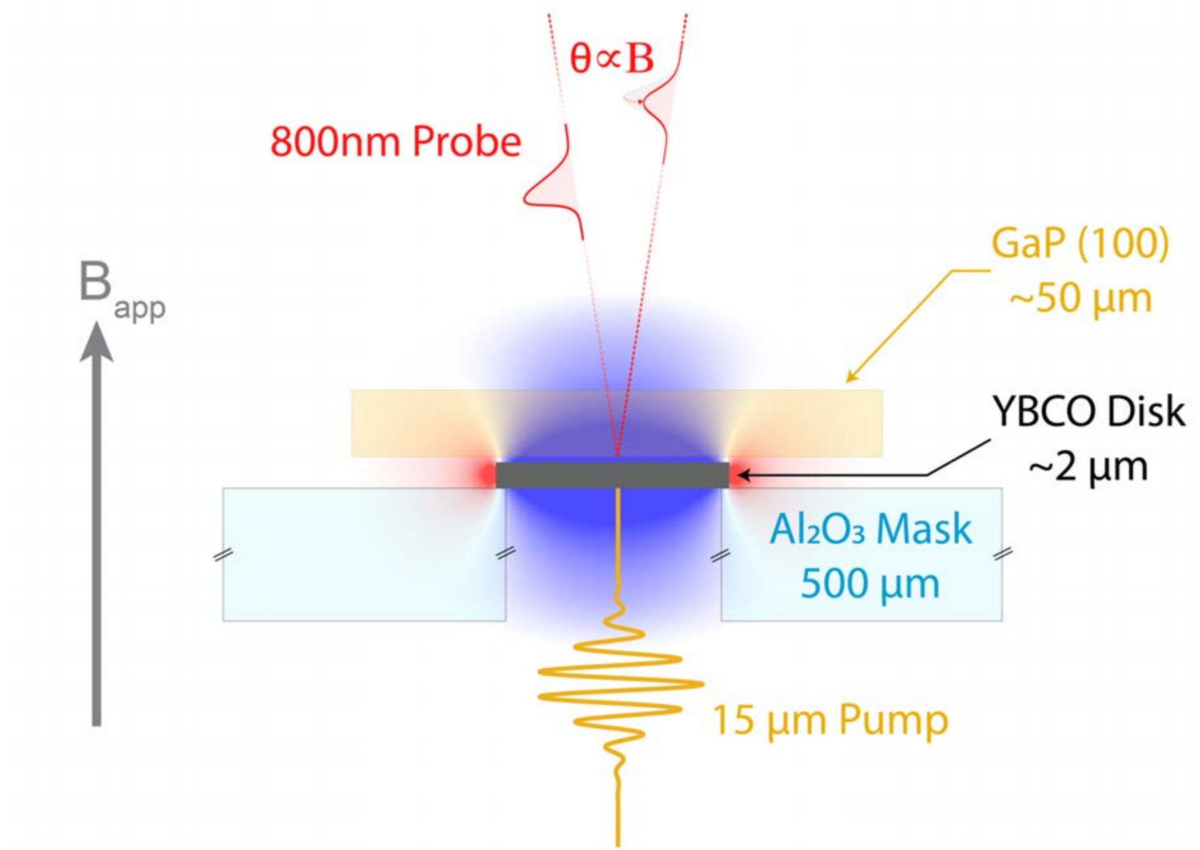


S. Fava, G. DeVecchi, G. Jotzu, M. Buzzi et al. forthcoming

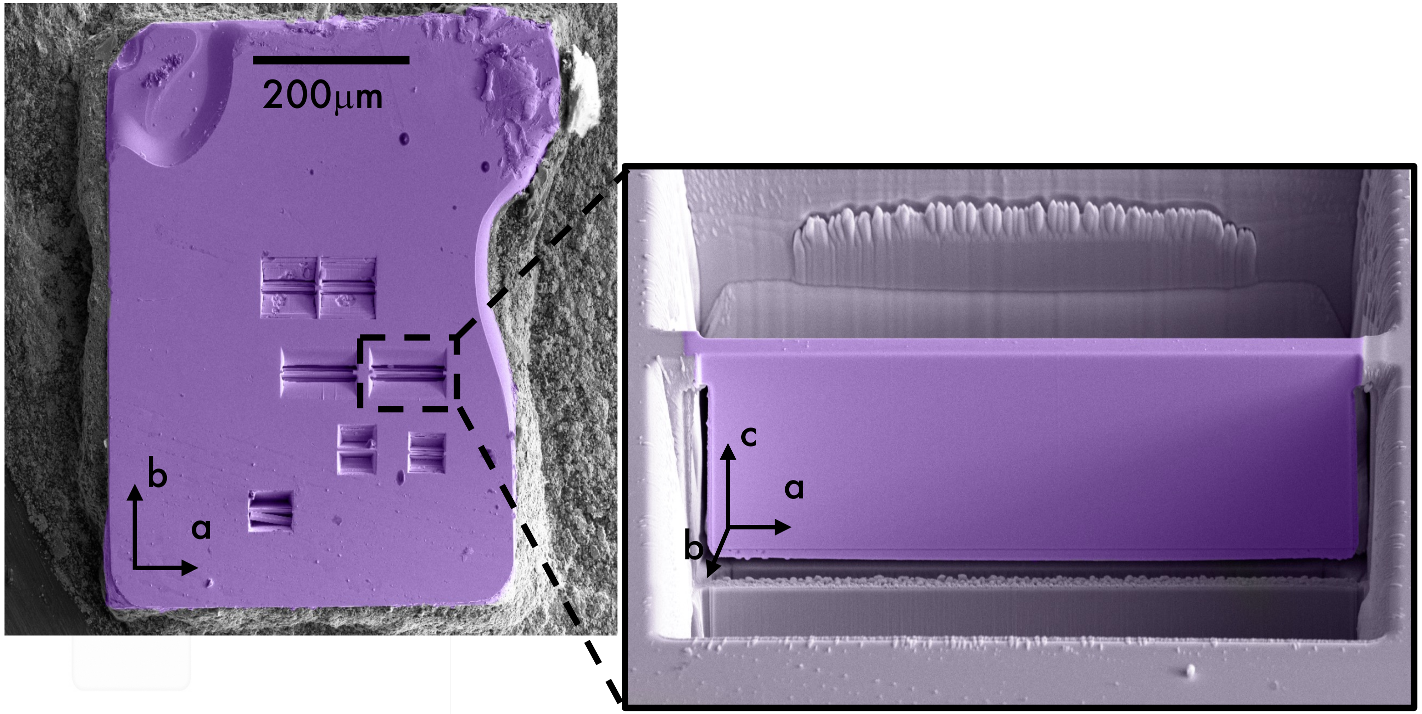
Outlook: $YBa_2Cu_3O_x$ disk-shaped lamellas



150 µm diameter
2 µm thick YBCO disk



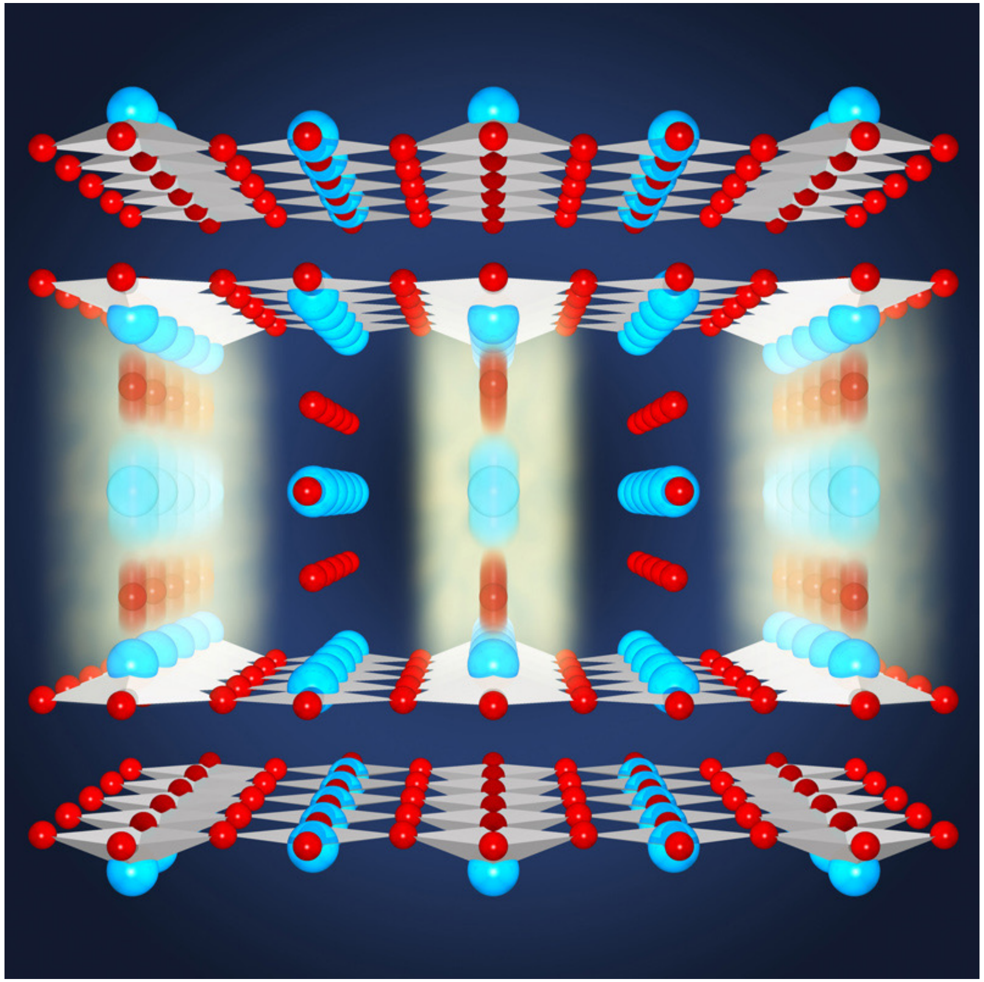
Lamellas through microstructuring



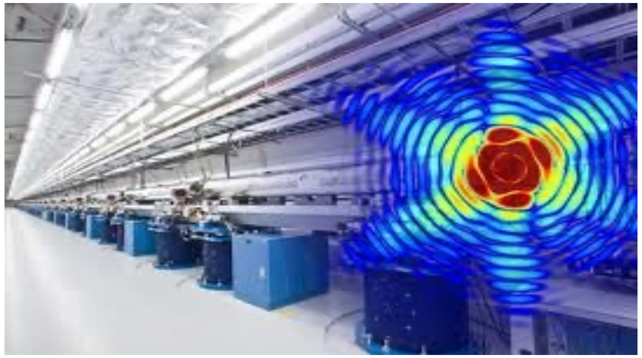
Phillip Moll

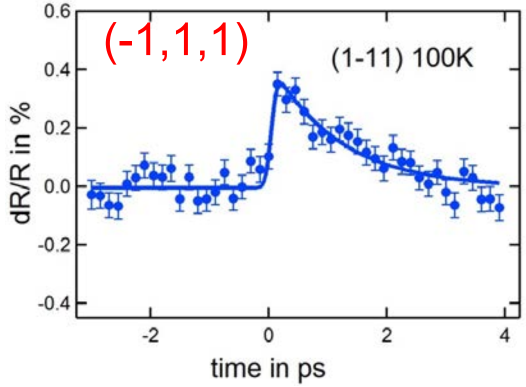
Carsten Putzke

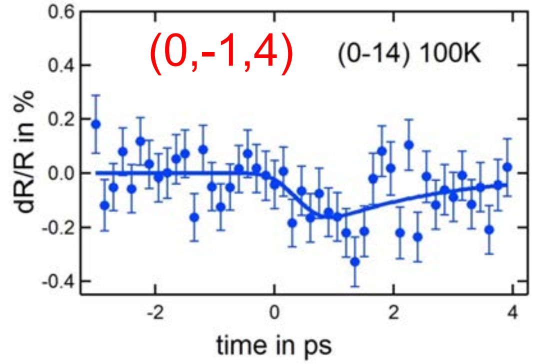
What is the physics of nonlinear phonons ?

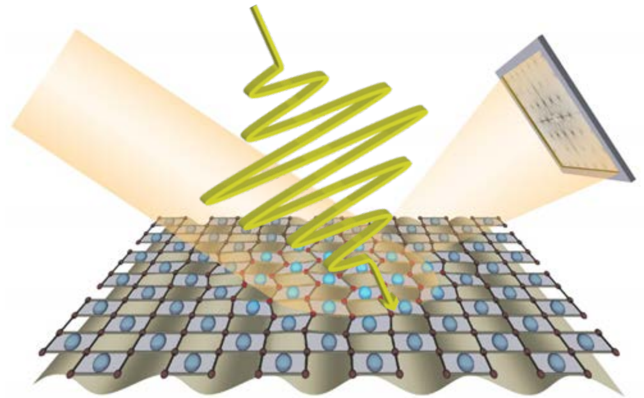


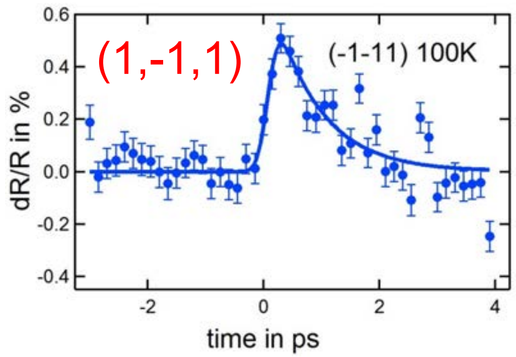
Femtosecond X-ray Scattering: New Crystal Structure

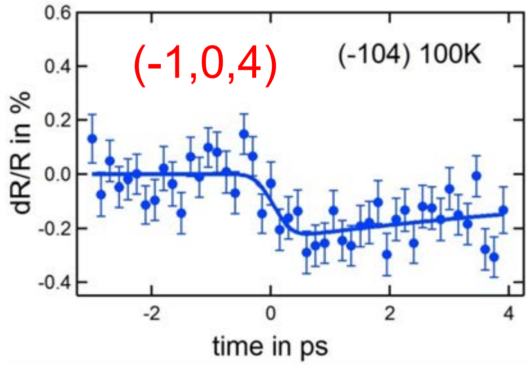








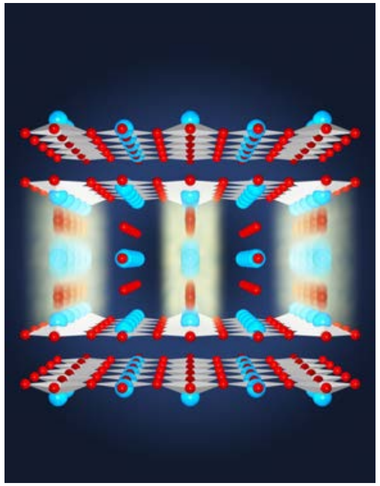


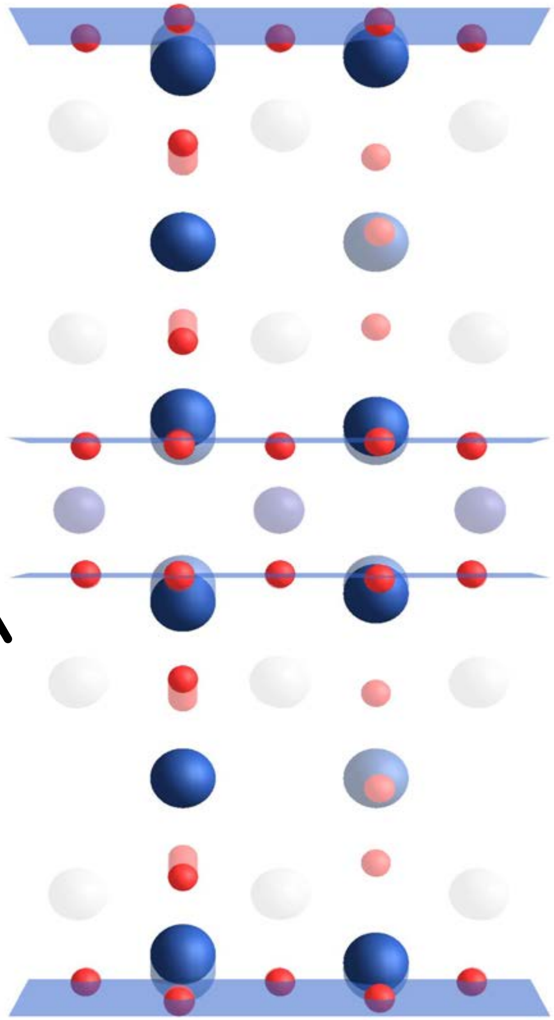


with A. Subedi, A. Georges

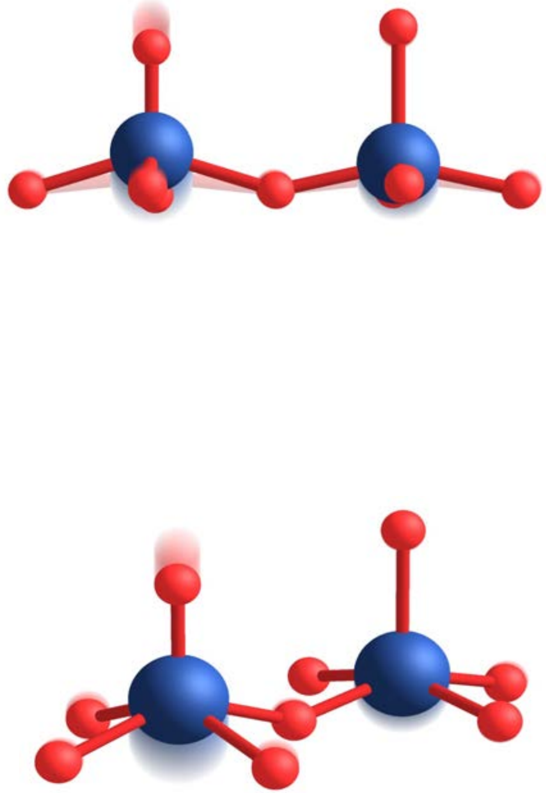
R. Mankowsky et al. *Nature 516,71 (2014)*

New crystal structure in $YB_2Cu_3O_{6+x}$



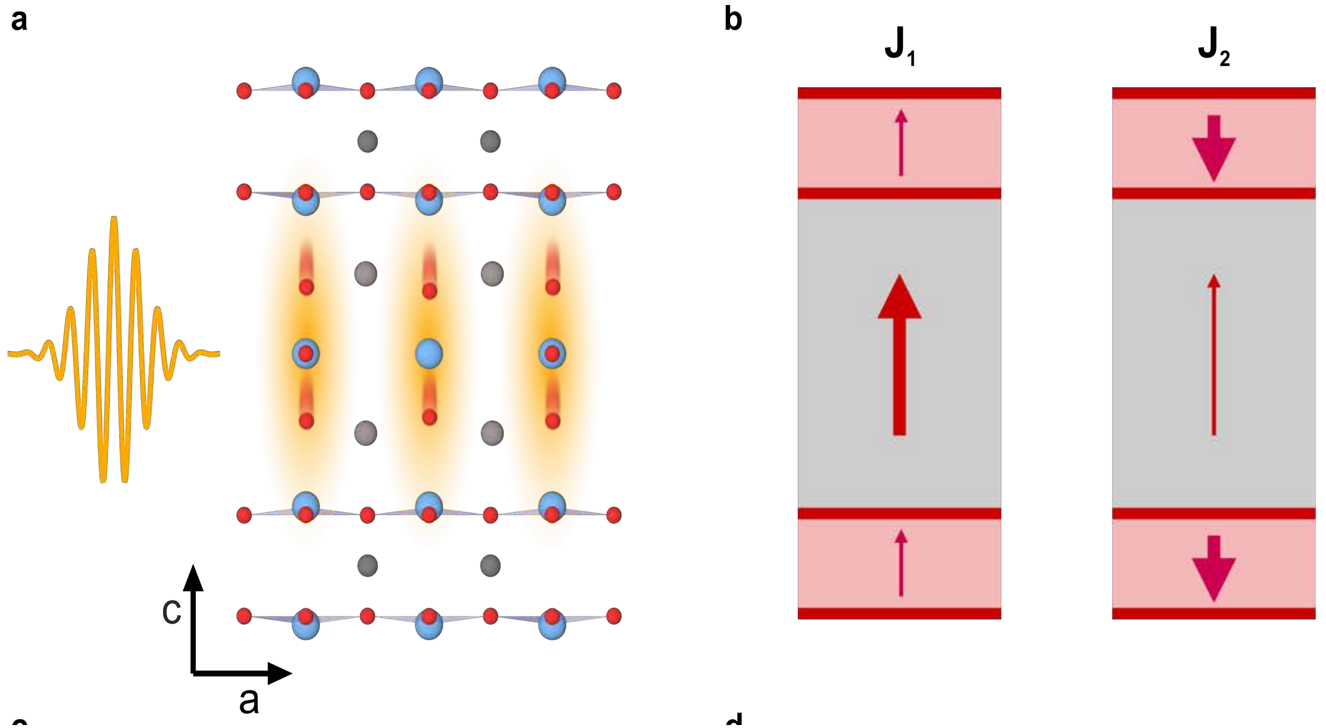


d ~ 3 %



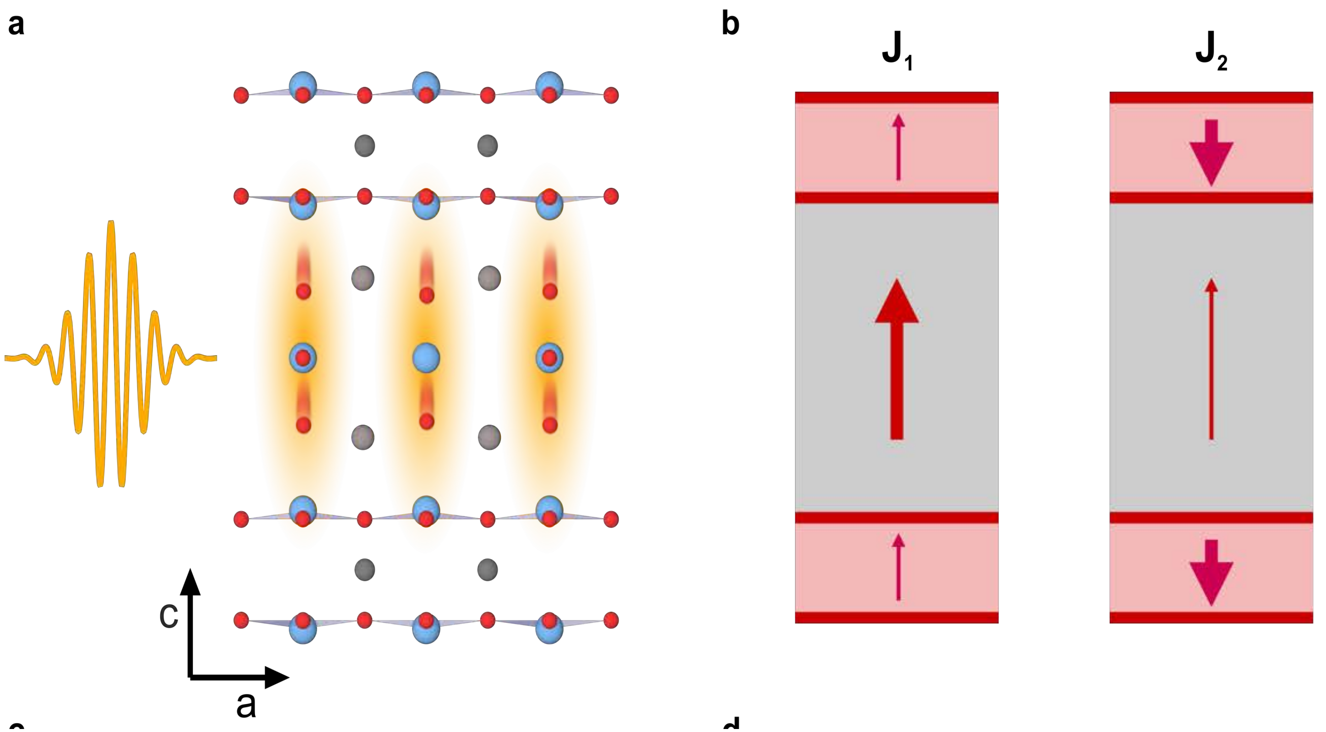
R. Mankowsky et al. *Nature* 516, 71 (2014)

How does the driven mode couple to interlayer tunneling



Tri-linear coupling: one phonon and two plasmons

$$U_{non-linear} = \frac{1}{2}\omega_{IR}^2\, Q_{IR}^2 + \frac{1}{2}\omega_{J_1}^2(q)\, J_1^2 + \frac{1}{2}\omega_{J_2}^2(q)\, J_2^2 + \boldsymbol{A}\, q^2 Q_{IR} J_1 J_2$$



M. Michael *et al.*, Phys. Rev B 102, 174505 (2020)

M. Michael *et al.*, Phys. Rev B 105, 17301 (2022)

with Marios Michael, Eugene Demler

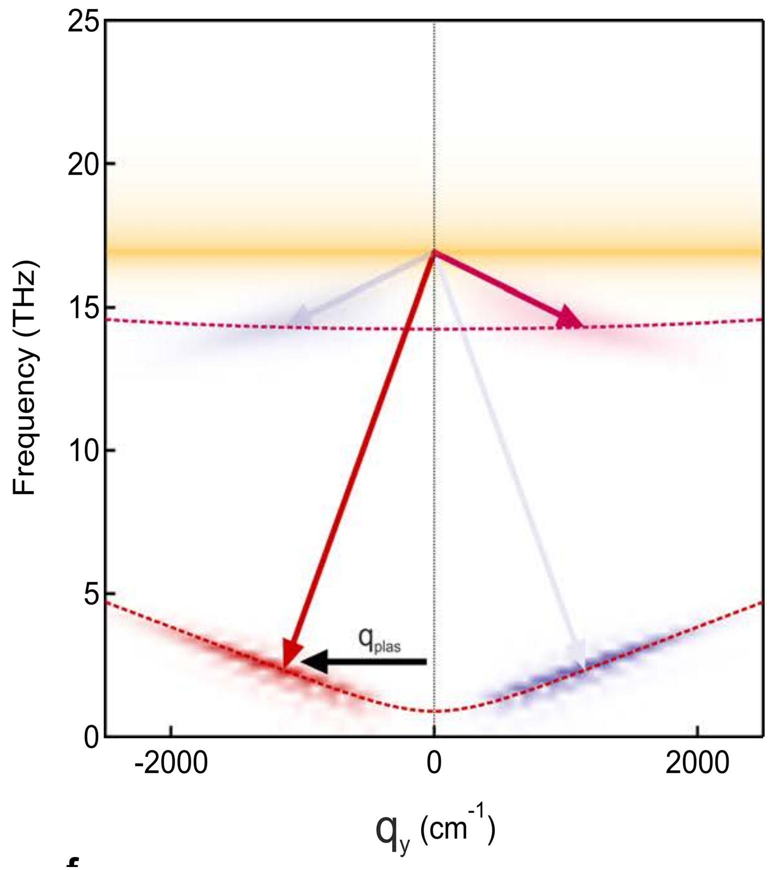
Three mode mixing – one phonon and two plasmons

$$\ddot{Q}_{IR} + 2\gamma_{IR}\dot{Q}_{IR} + \omega_{IR}^2 Q_{IR} = Z^* E(t)$$

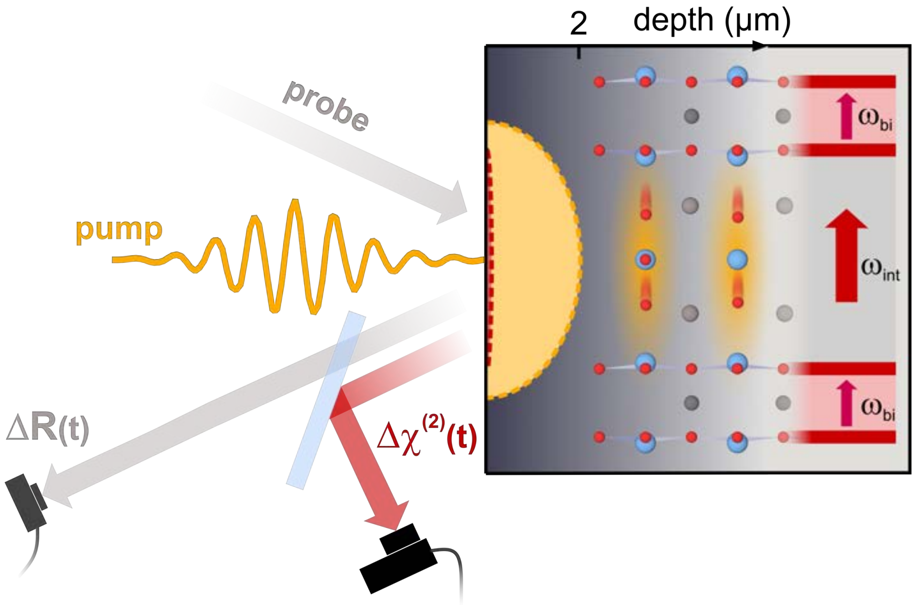
$$\ddot{J}_1 + 2\gamma_{J_1}\dot{J}_1 + \omega_{J_1}^2(q)J_1 = -aq^2 Q_{IR} J_2$$

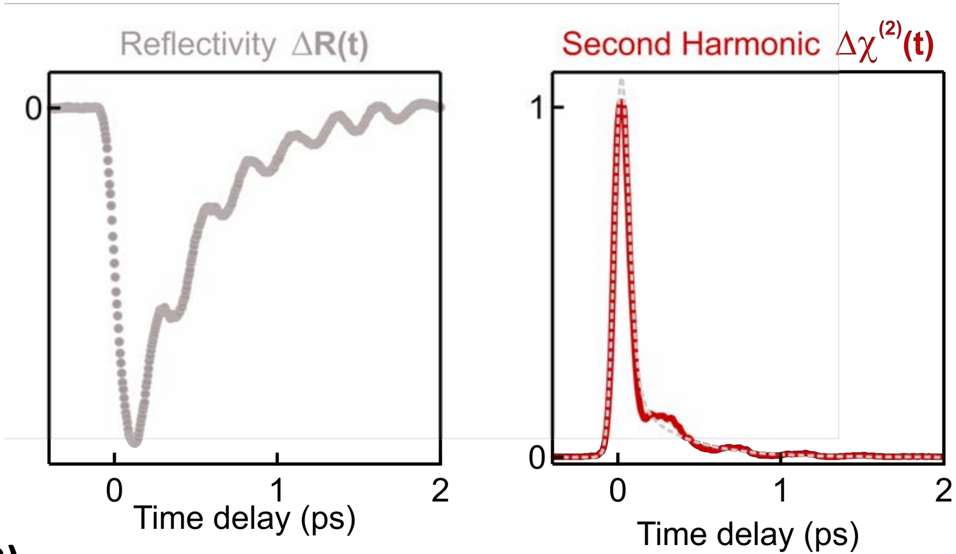
$$\ddot{J}_2 + 2\gamma_{J_2}\dot{J}_2 + \omega_{J_2}^2(q)J_2 = -aq^2 Q_{IR} J_1$$

Resonant if $\omega_{IR}=\omega_{IP1}+\omega_{IP2}$



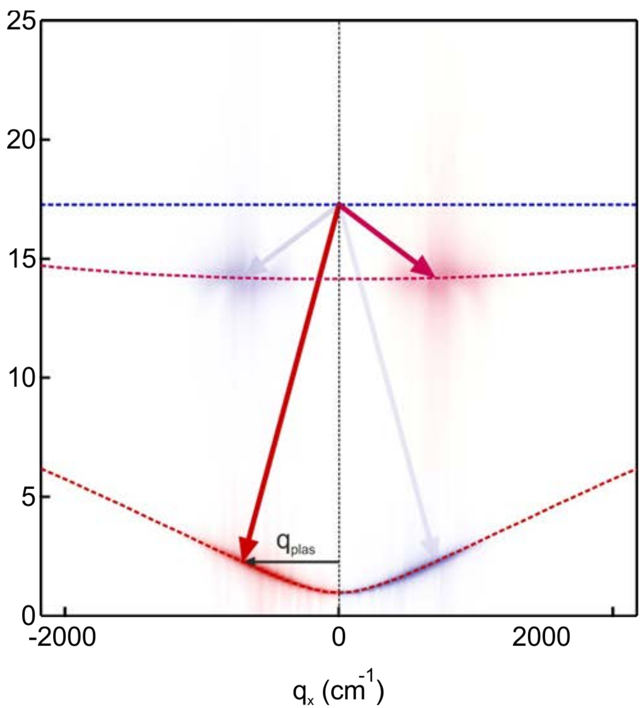
Measuring coherent dynamics: time resolved SHG

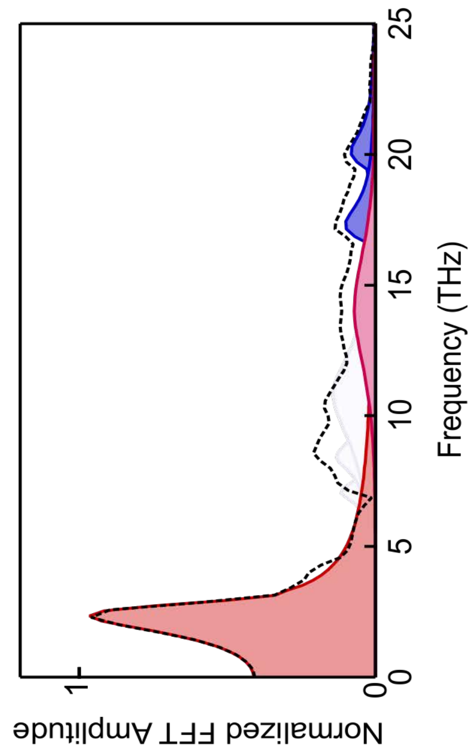




A. Von Hoegen et al. Phys. Rev. X 12, 031008 (2022)

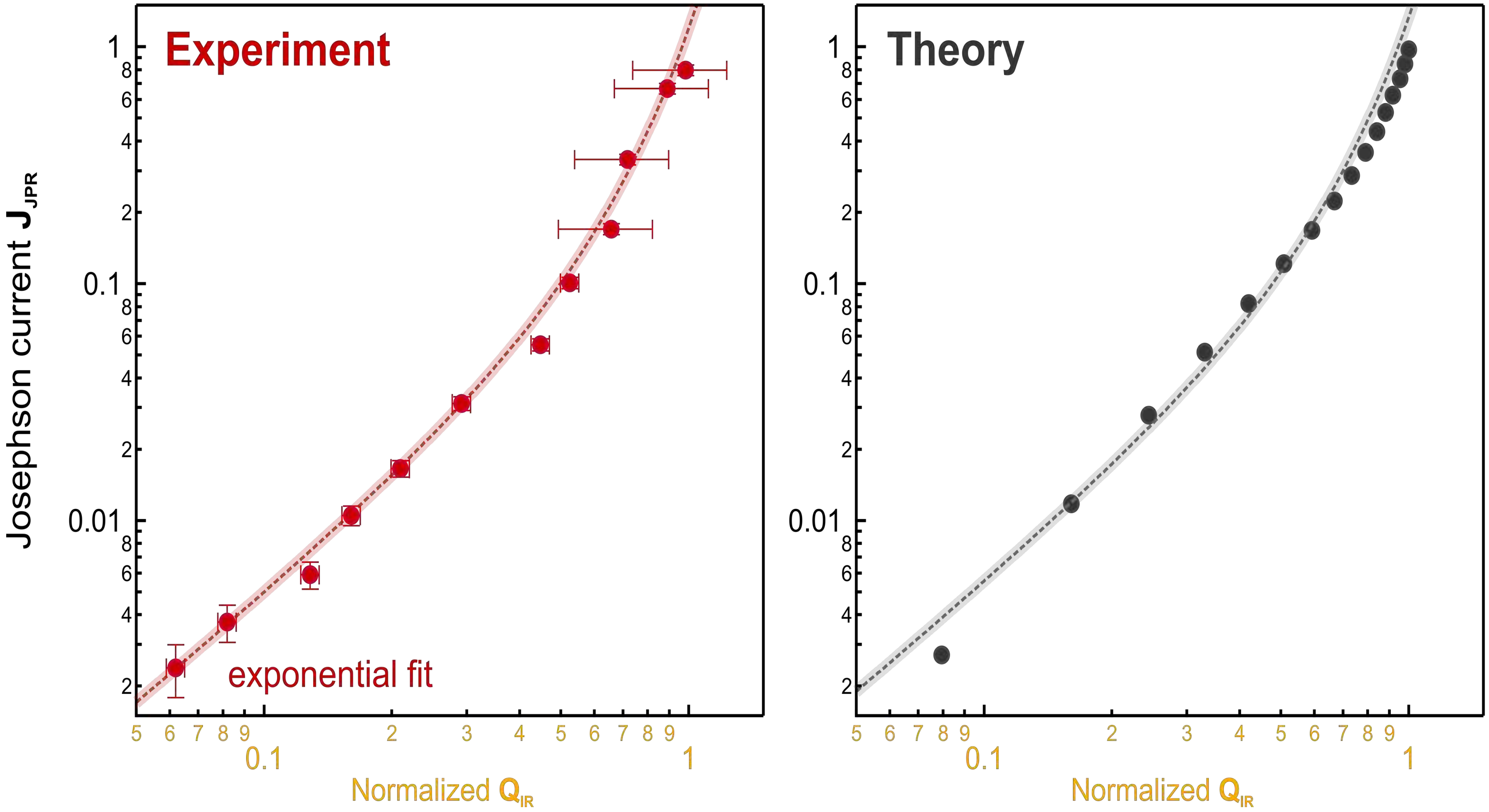
1) Frequency resonant three mode mixing





M. Michael *et al.*, Phys. Rev B 102, 174505 (2020) **A. Von Högen et al. Phys Rev X 12, 031008 (2022)**

2) Exponential amplification of the plasma mode



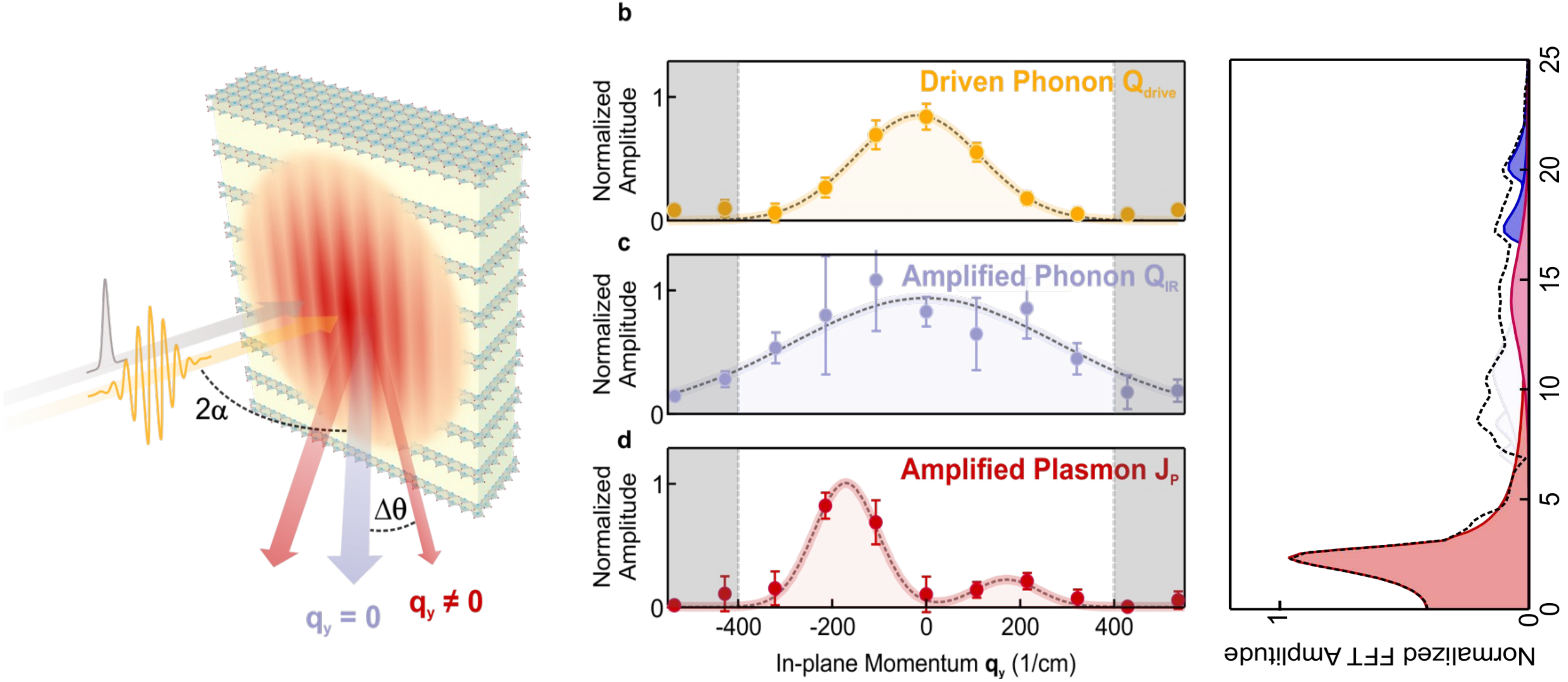
A. Von Högen et al. Phys Rev X 12, 031008 (2022)

M. Michael *et al.*, Phys. Rev B 102, 174505 (2020)

3) Amplification at finite momentum

Momentum Resolved Nonlinear Scattering

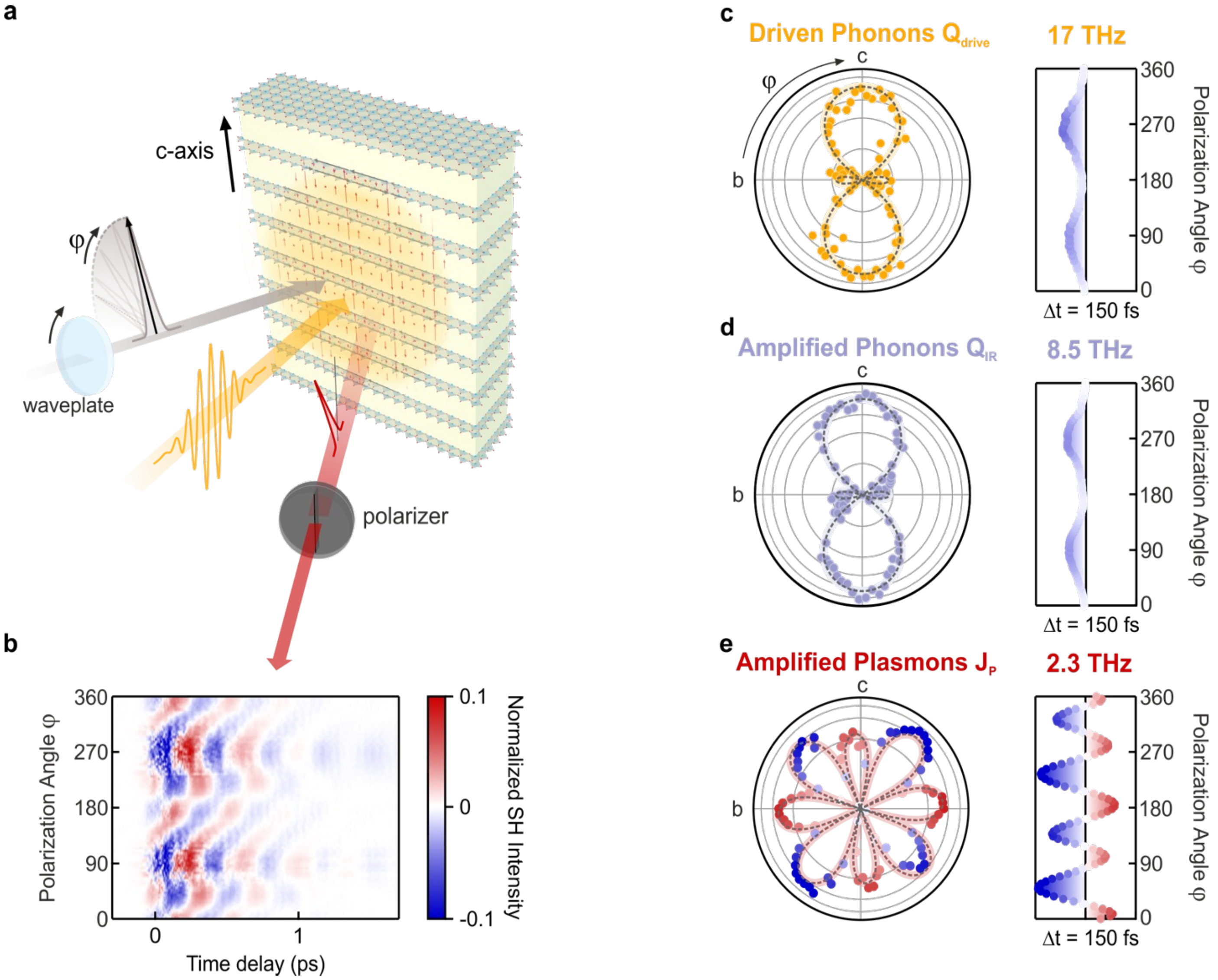
$H_I \sim A\, q^2 Q_{IR} J_1 J_2$

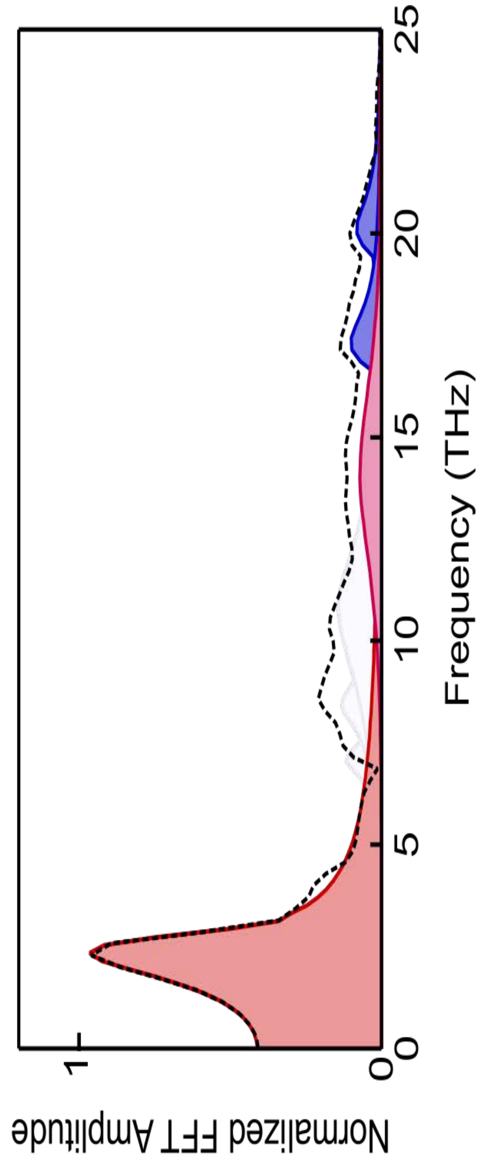


A. Von Högen et al. Phys Rev X 12, 031008 (2022)

M. Michael *et al.*, Phys. Rev B 102, 174505 (2020)

4) Complex Mode symmetry – not a phonon

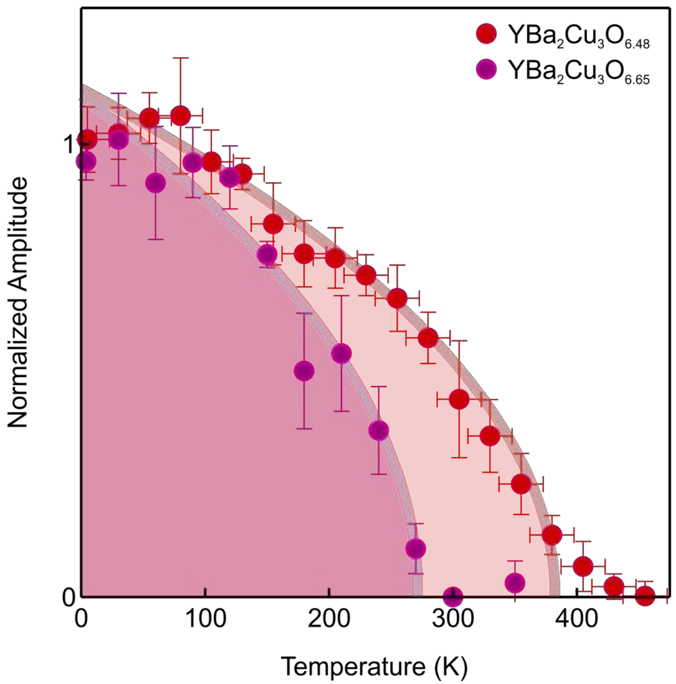


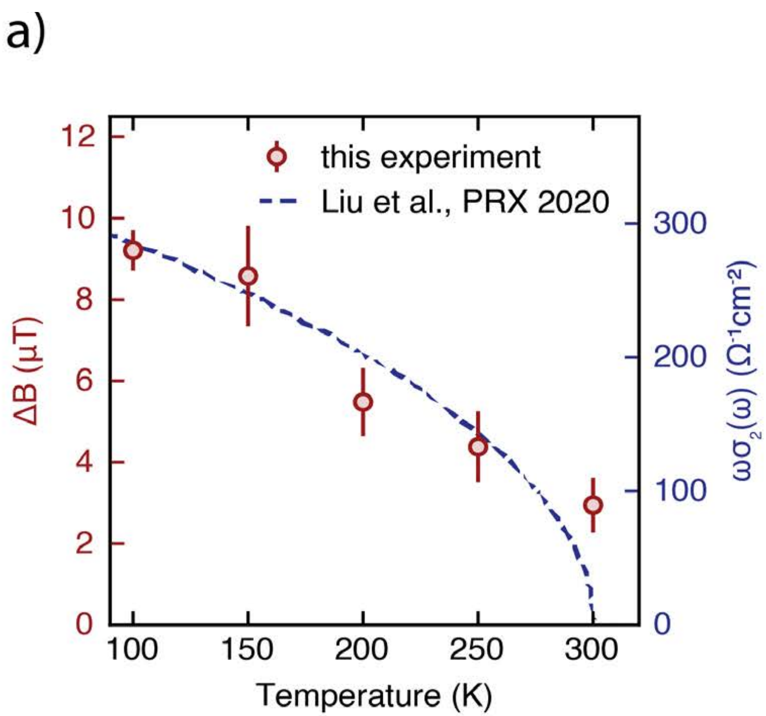


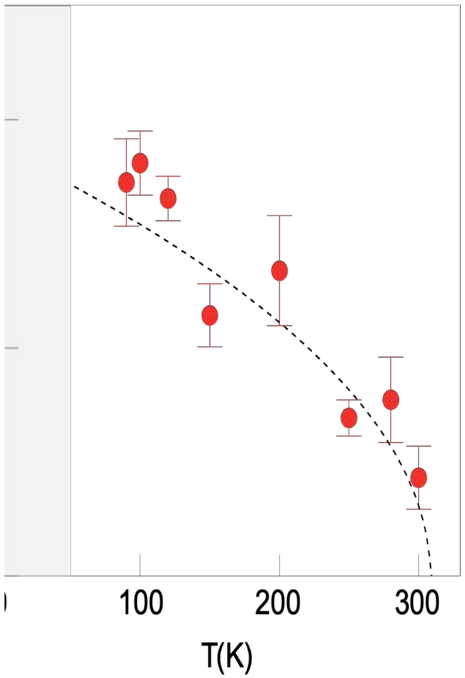
A. Von Högen et al. Phys Rev X 12, 031008 (2022)

5) Anomalous temperature dependence (up to T*)

Coherent Plasmons **Meissner** **Optical**

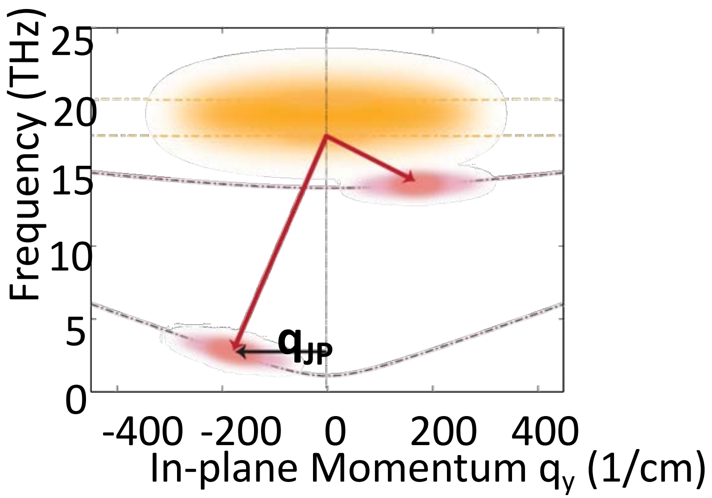


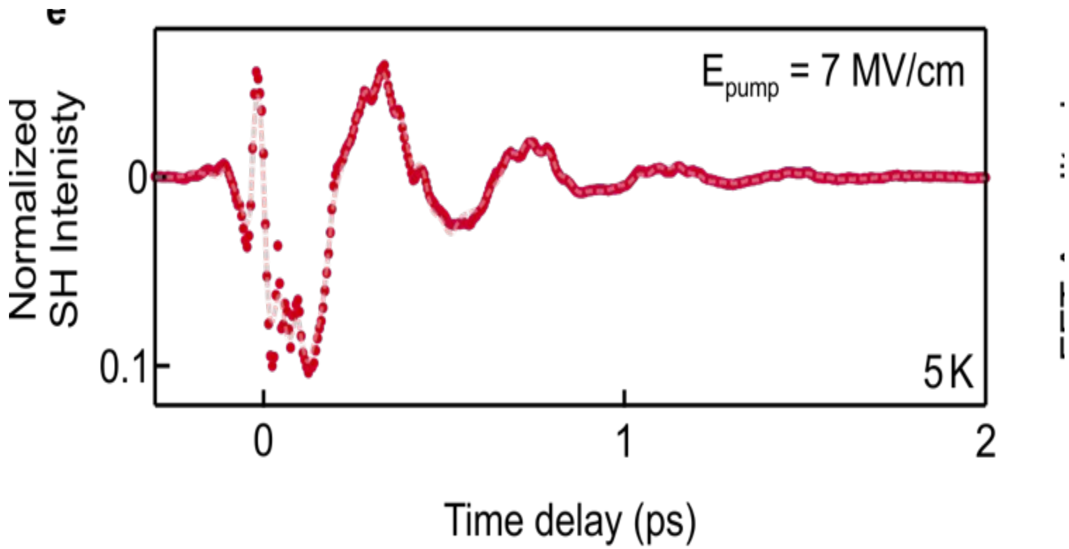


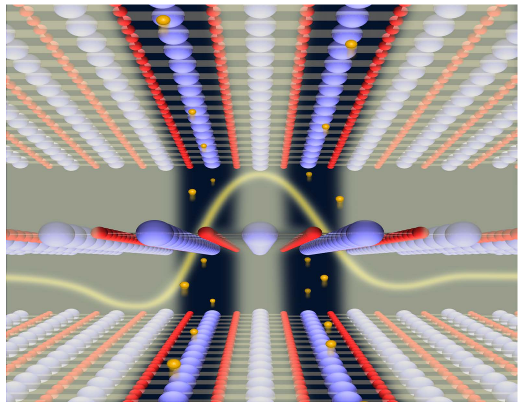


A. Von Högen et al. Phys Rev X 12, 031008 (2022)

Similarities with polariton condensates, time crystals……

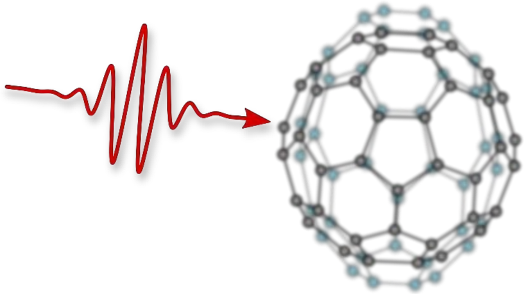


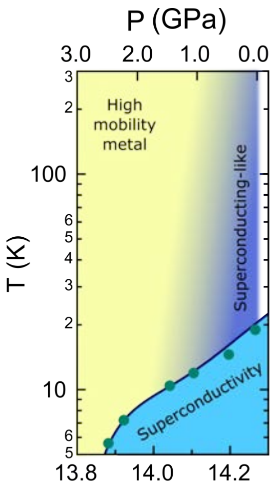


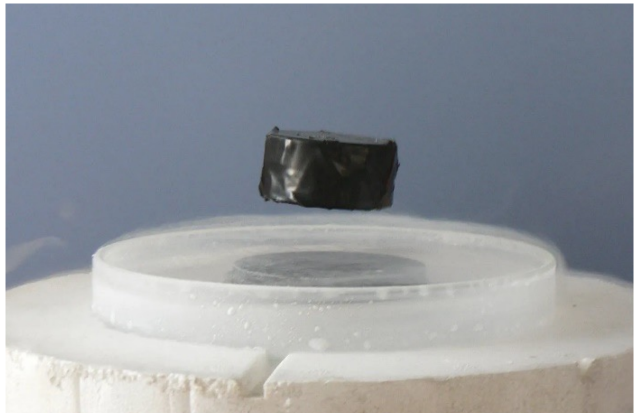


A. Von Högen et al. Phys Rev X 12, 031008 (2022)

Do these explain the optical and magnetic properties?

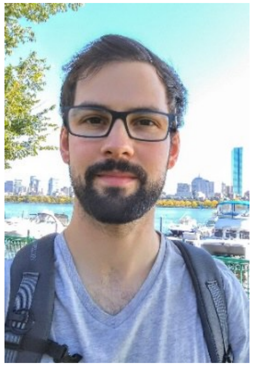






Acknowledgements


N. Taherian


Alexander von Hoegen


Michael Först


Albert Liu


Michael Fechner


Bernhard Keimer


Sebastian Fava


Giovanni De Vecchi

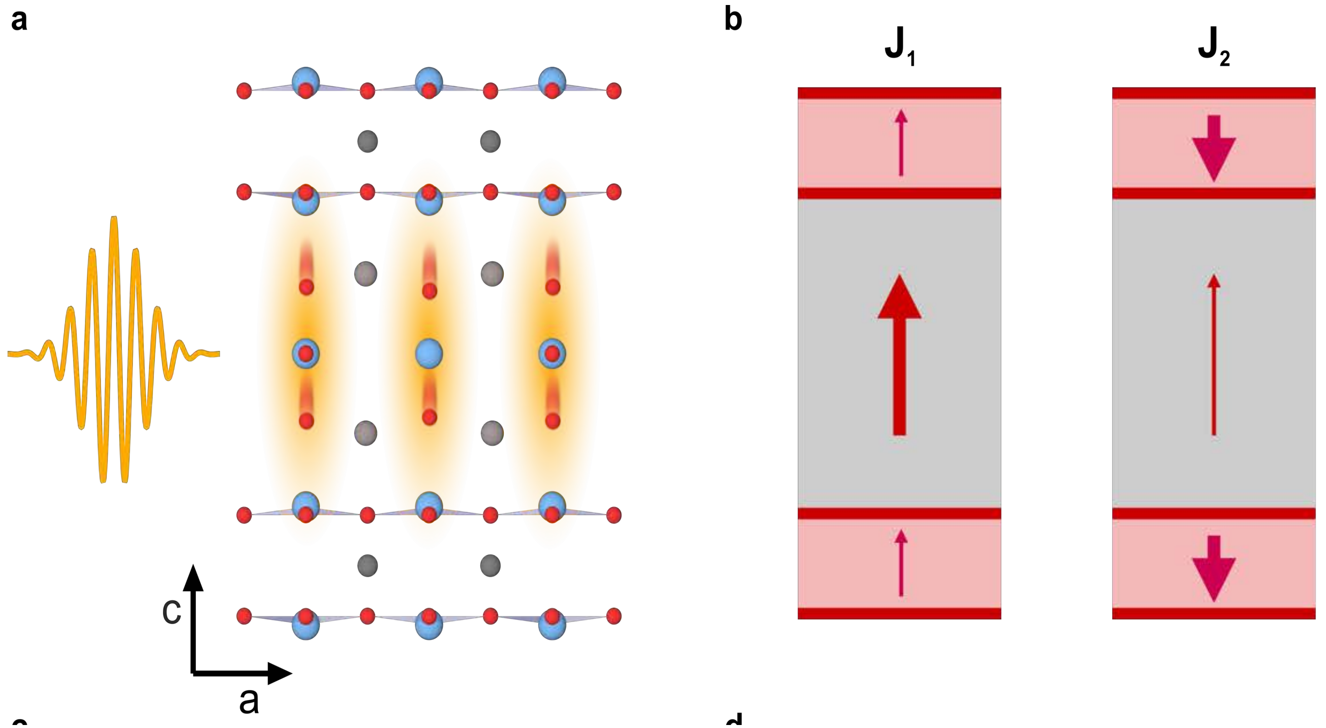

Michele Buzzi


Gregor Jotzu


Marios H. Michael


Eugene Demler

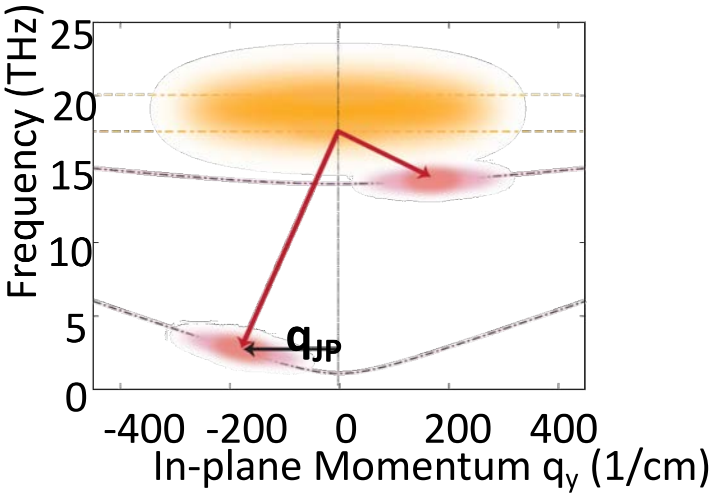
Is this model unique?



With two phonons – I have TWO possible resonances

THREE MODE MIXING

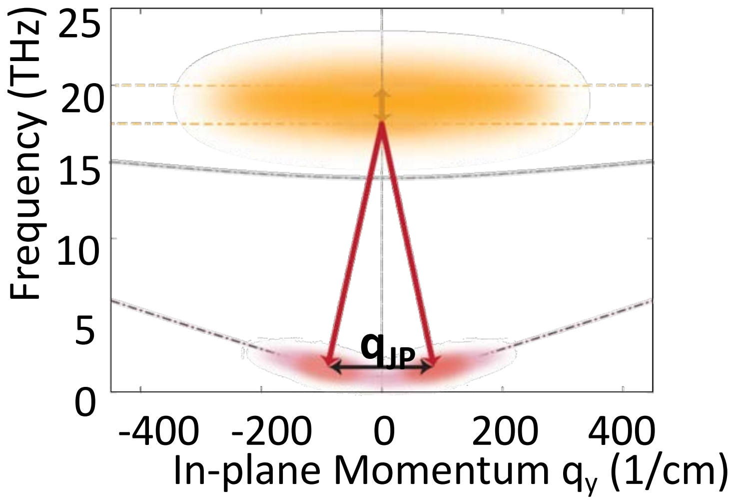
$$gq^2(Q_{1,IR} + Q_{2,IR})J_1\,J_2$$

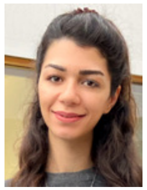


FOUR MODE MIXING

$$g(Q_{1,IR} + Q_{2,IR})^2 J_1^2$$

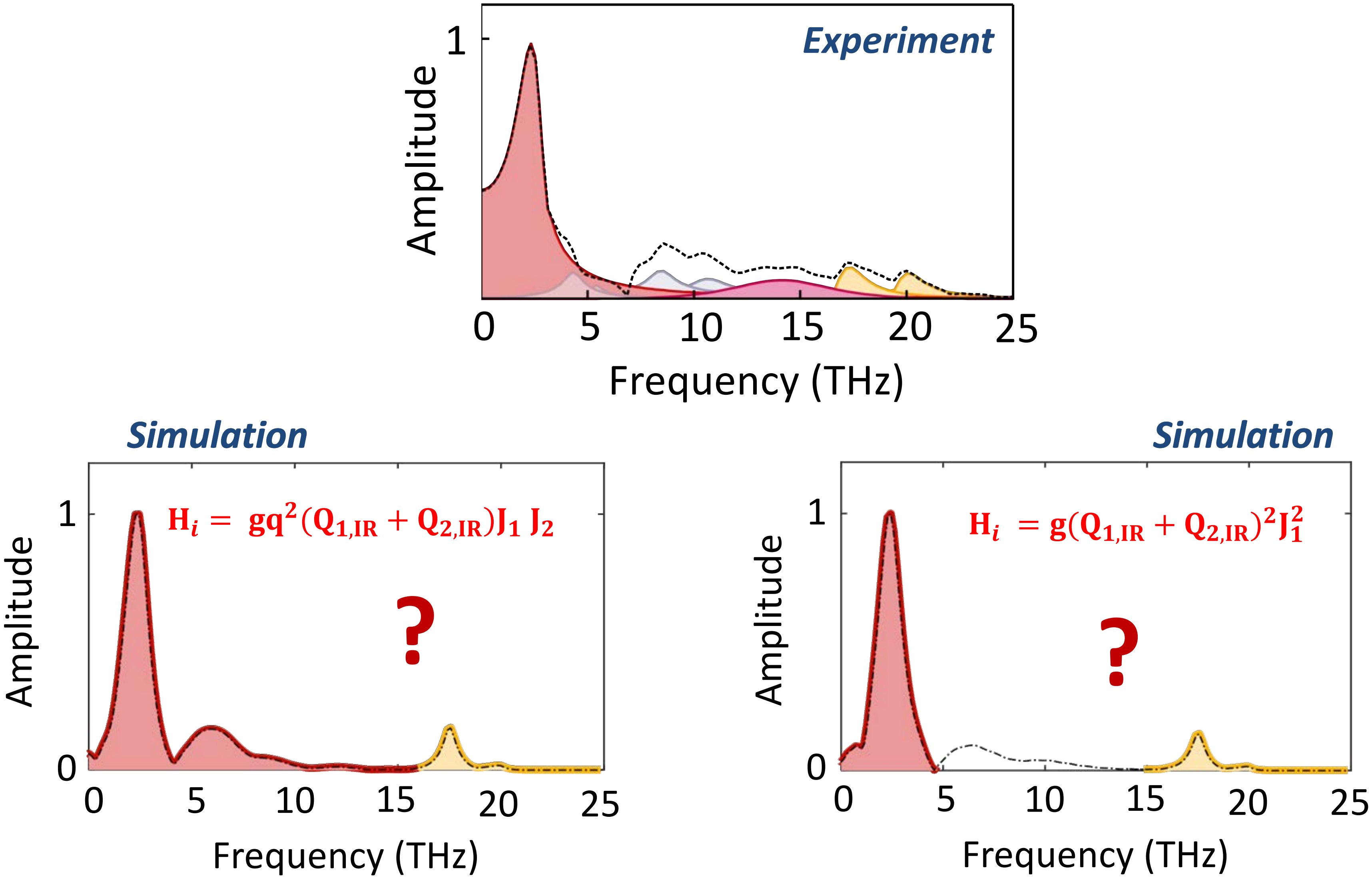
$$gQ_{1,IR}{}^2 J_1^2 + Q_{2,IR}{}^2 J_1^2 + Q_{1,IR}\,Q_{2,IR}\,J_1^2$$



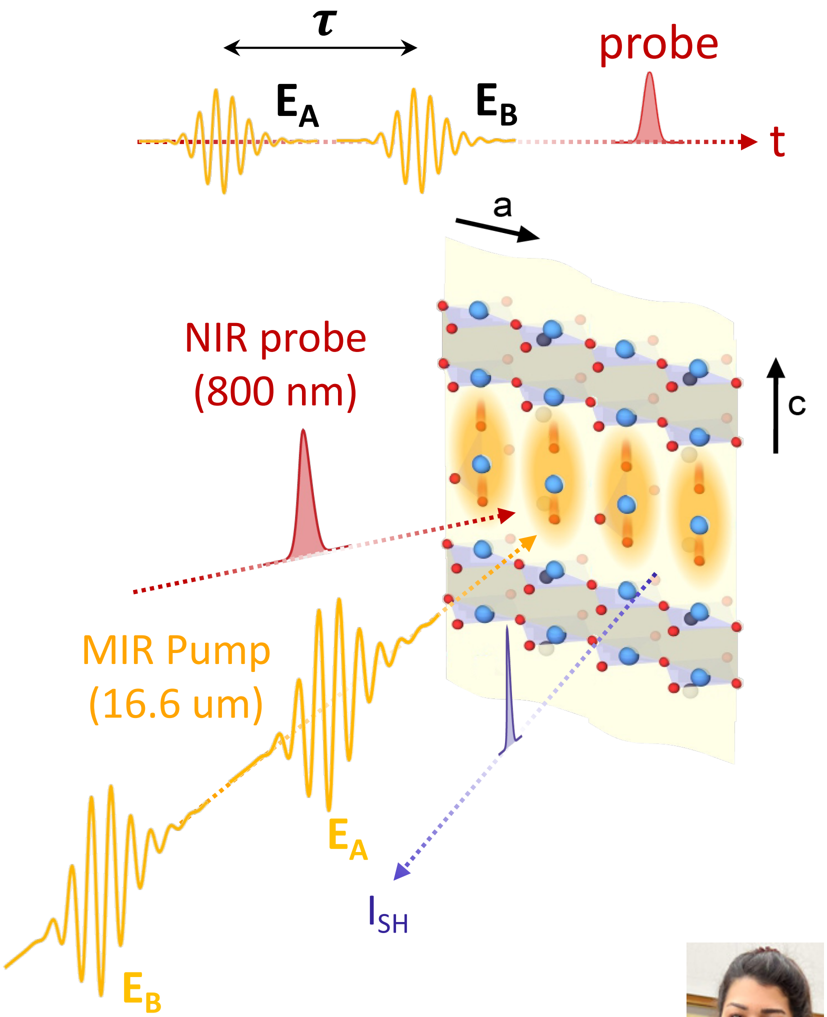


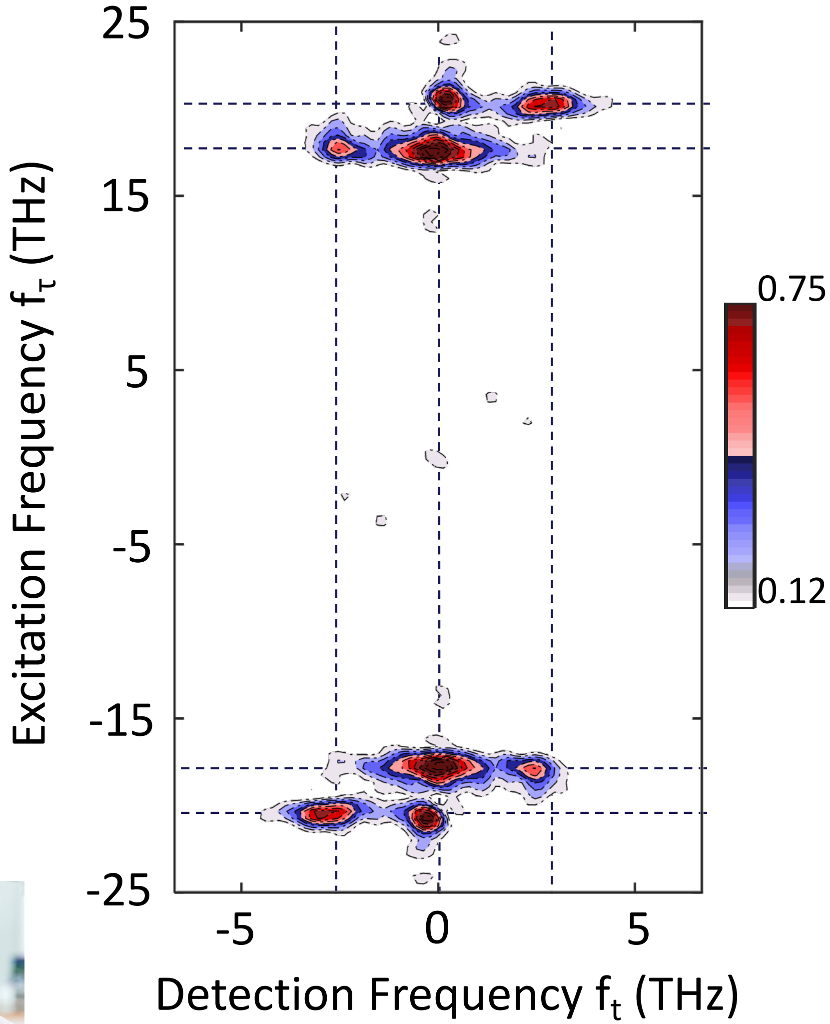
N. Taherian

One-dimensional pump probe: ambiguous assignment



Two dimensional spectroscopy to resolve ambiguity





N. Taherian

Albert Liu

N.Taherian, et al. (in preparation).

Experiment vs theory: four waves and not three waves

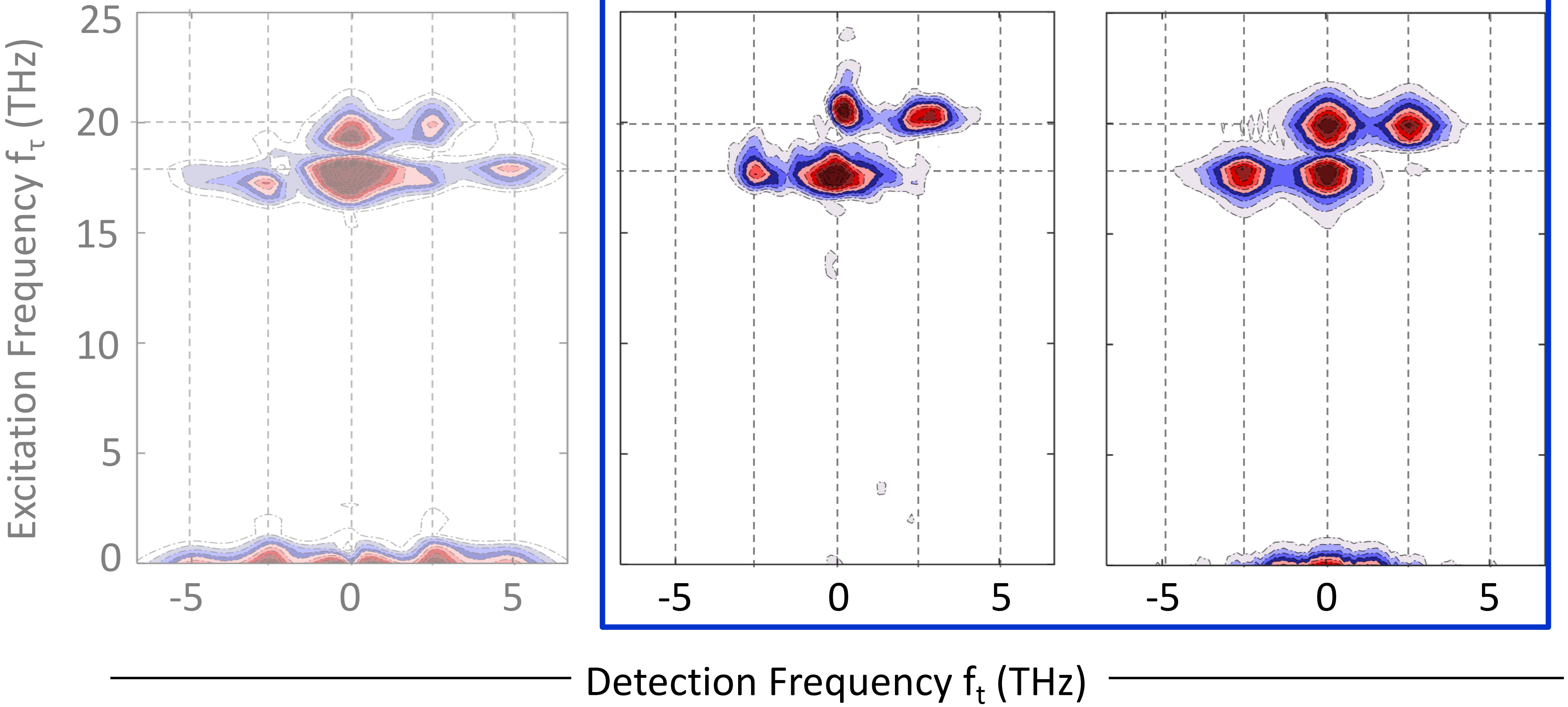
2D Simulation: three waves

2D Experiment

2D Simulation four waves

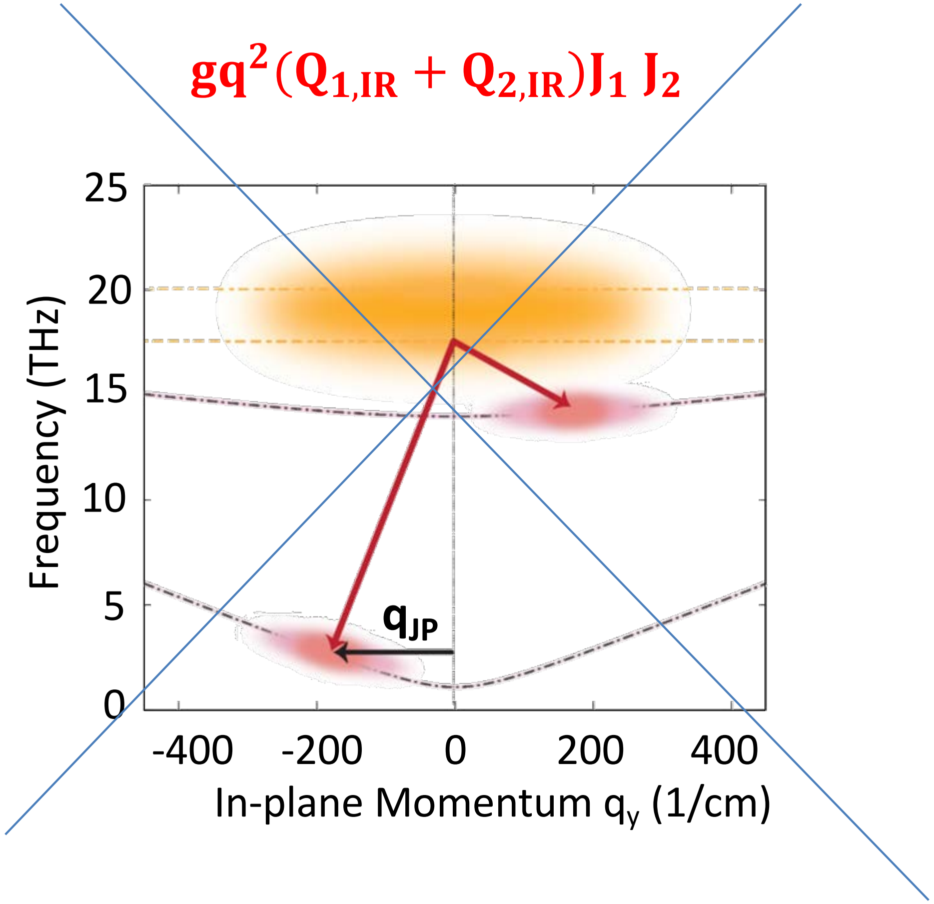
$$H_i = gq^2(Q_{1,IR} + Q_{2,IR})J_1\, J_2$$

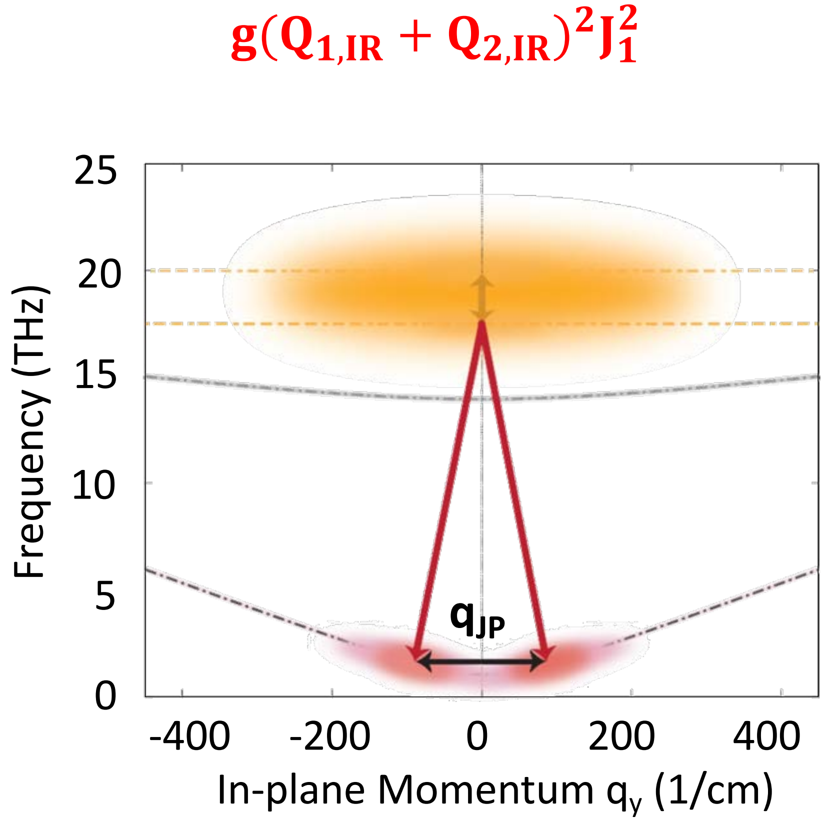
$$H_i = g(Q_{1,IR} + Q_{2,IR})^2 J_1^2$$



N.Taherian, et al. (in preparation).

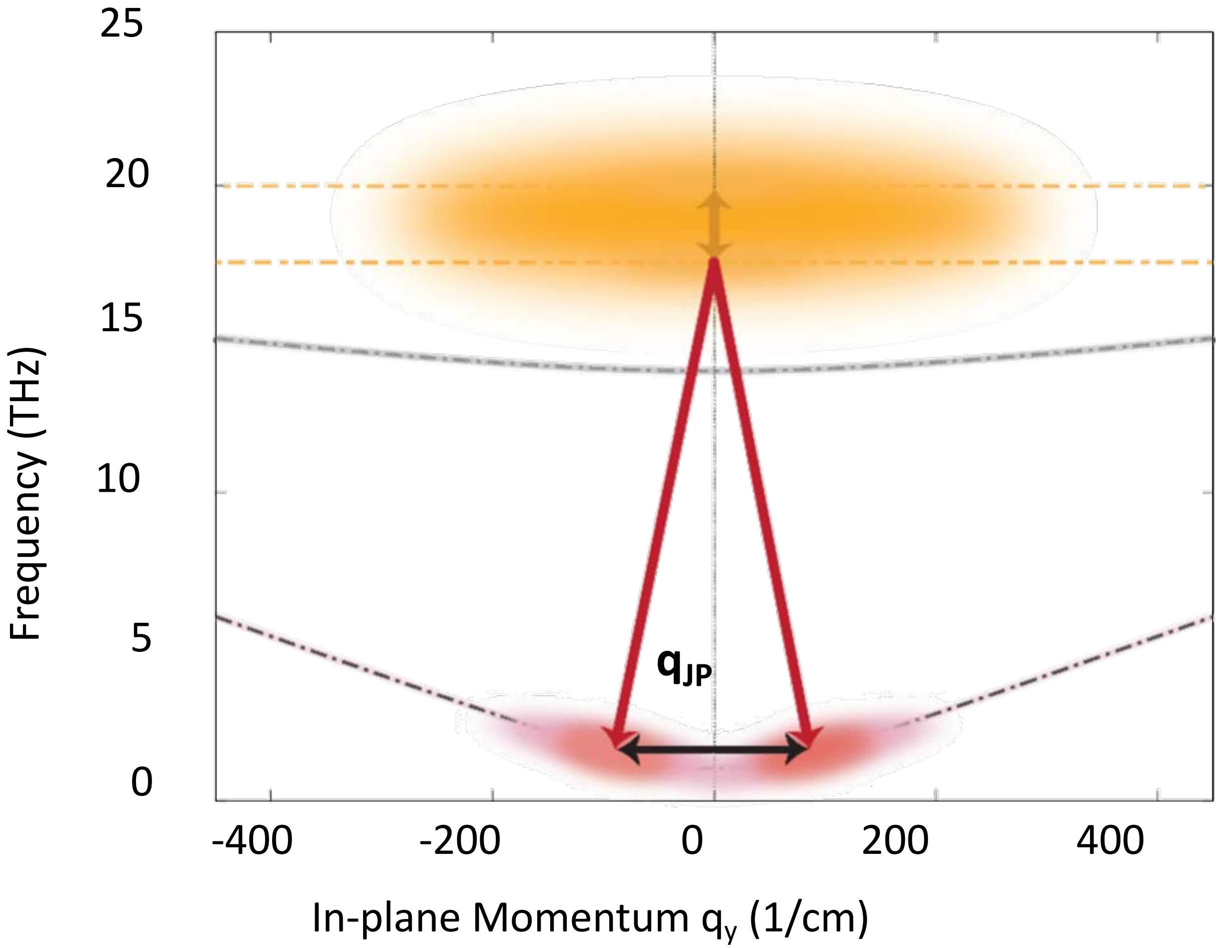
Four mode parametric coupling



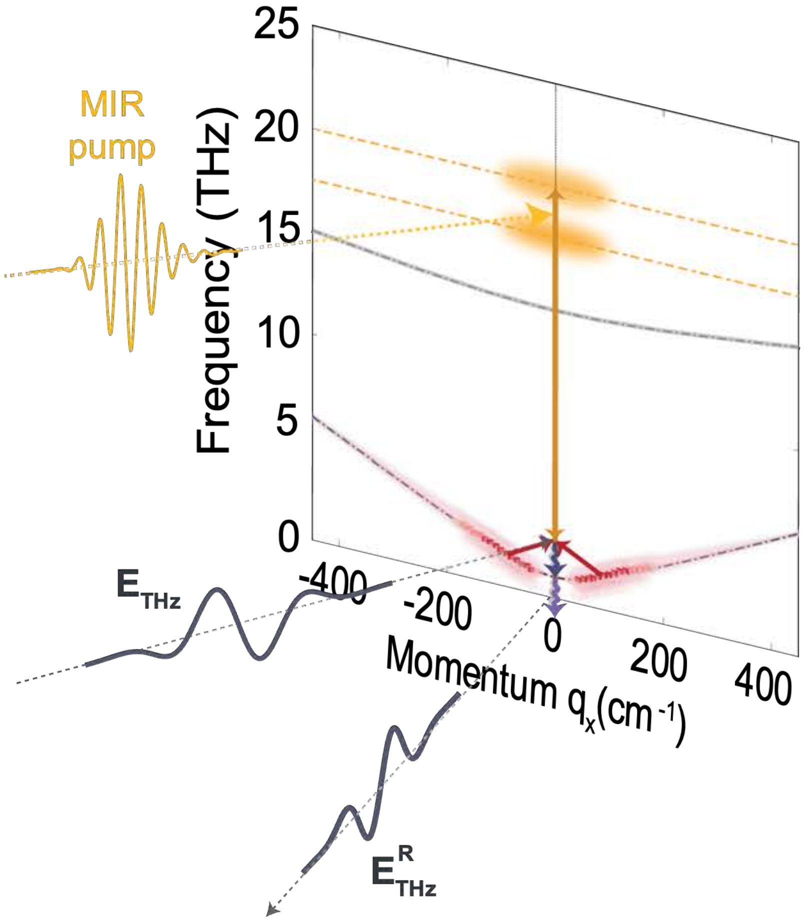


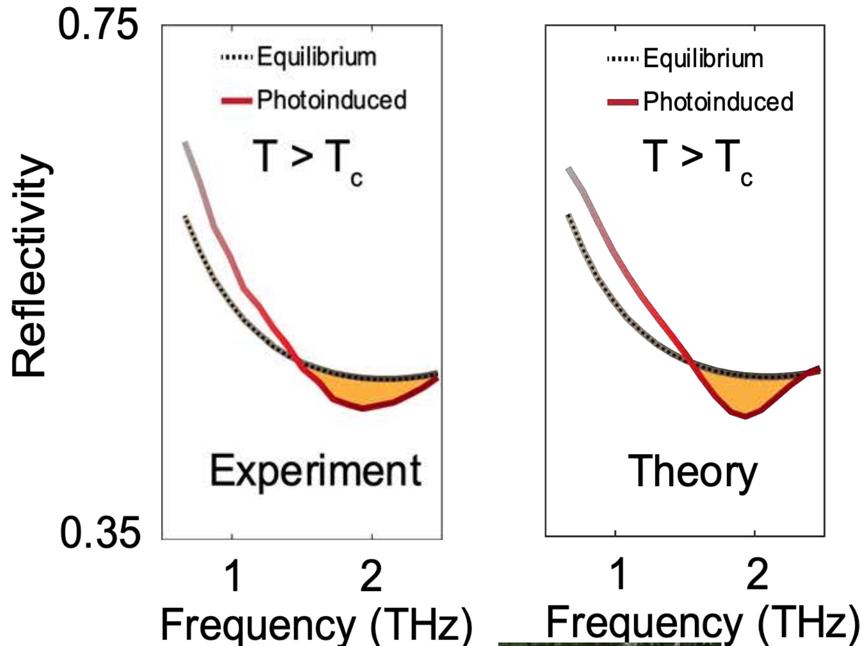
Squeezed Josephson Plasmons

$$\mathbf{g(Q_{1,IR} + Q_{2,IR})^2 J_1^2}$$



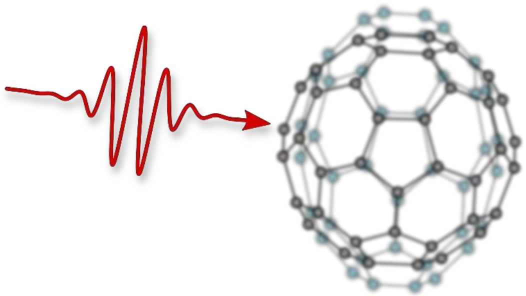
Coherent squeezed mode explains optical properties

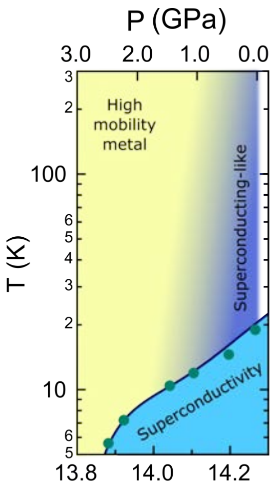




with Marios Michael, Eugene Demler

Do these explain the optical and magnetic properties?





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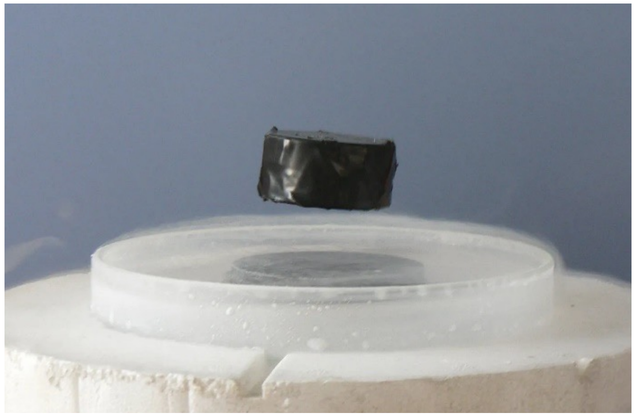
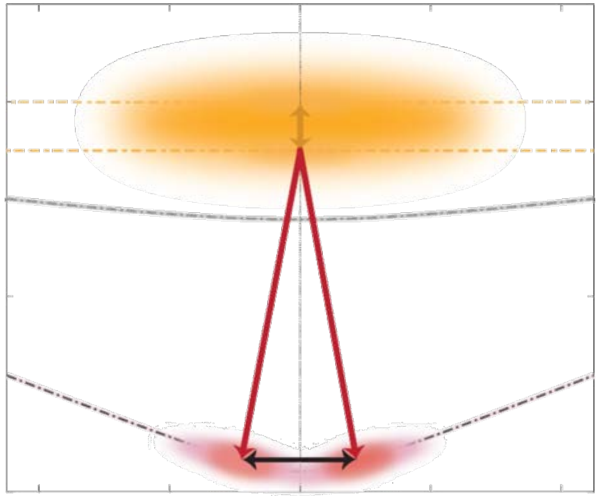
?

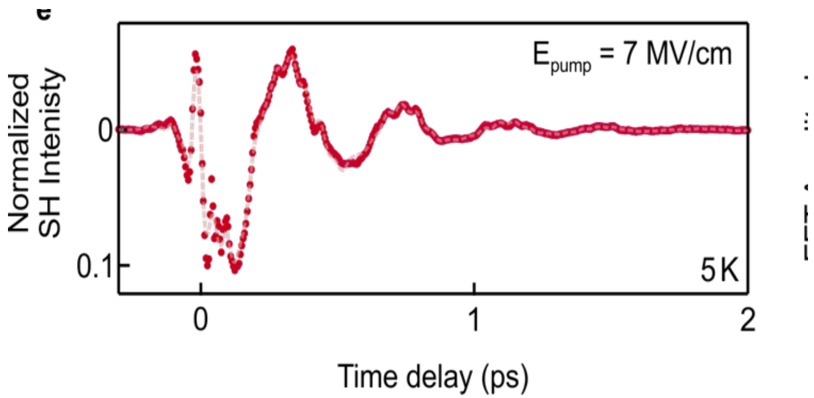


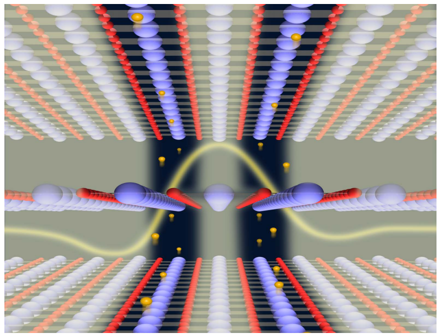
Squeezed current/phase oscillations



Rather than amplification of the superconducting currents $J_{,q_x}$

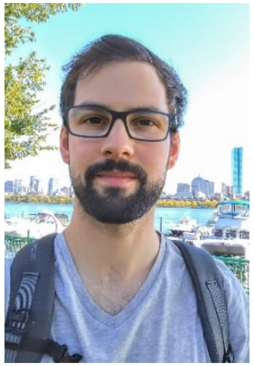
The underlying physcis may be connected to oscillations in the „noise“ of the current $\langle \boldsymbol{J_{q_x} J_{-q_x}} \rangle$





Acknowledgements


N. Taherian


Alexander von Hoegen


Michael Först


Albert Liu


Michael Fechner


Bernhard Keimer


Sebastian Fava


Giovanni De Vecchi


Michele Buzzi


Gregor Jotzu


Marios H. Michael


Eugene Demler