

Nonequilibrium Superconductivity in High- T_c Cuprates: Recent Advances

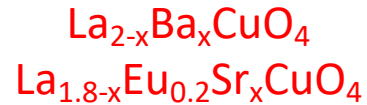
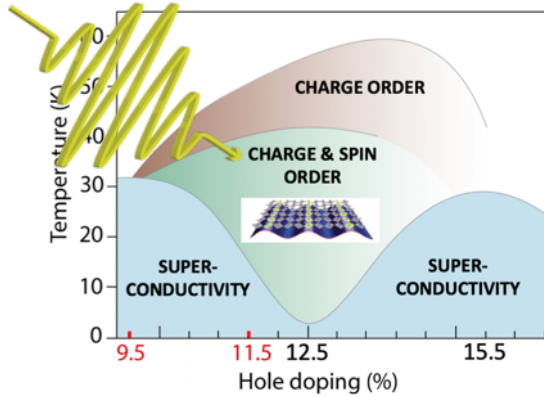
Daniele Nicoletti

Max Planck Institute for the Structure and Dynamics of Matter
Hamburg, Germany

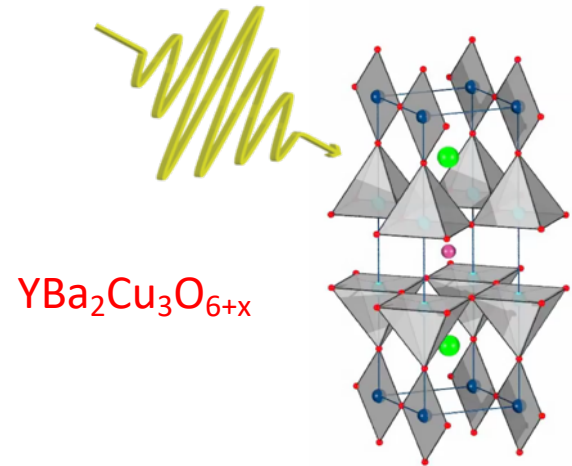
Conference on Nonequilibrium Superconductivity
CCQ – Flatiron Institute – New York – January 14th 2020

Optical Control of Superconductivity: Different approaches

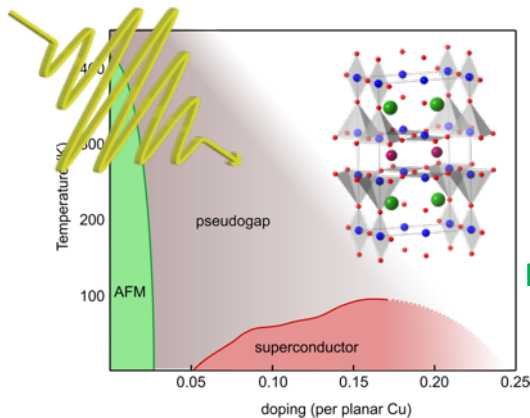
Melt competing orders



Displace the lattice

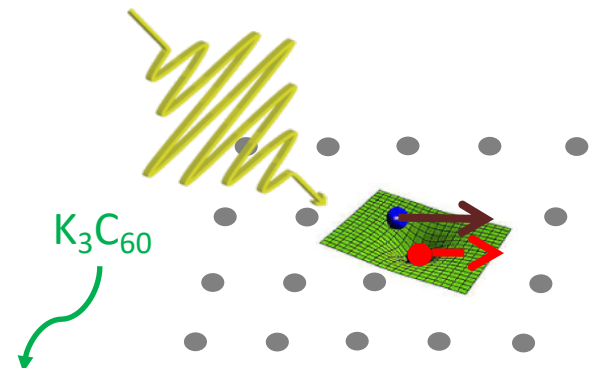


Synchronize pre-formed pairs



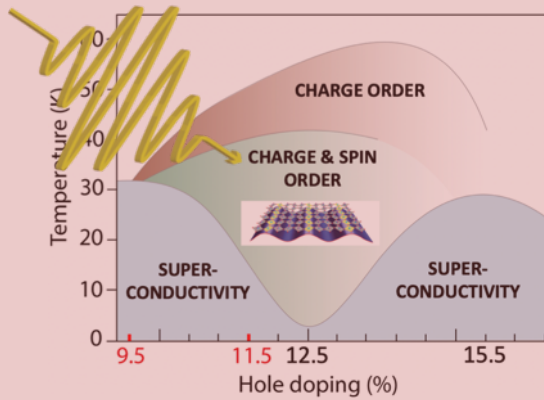
See Michele Buzzi's talk on Thursday

Modulate pairing directly

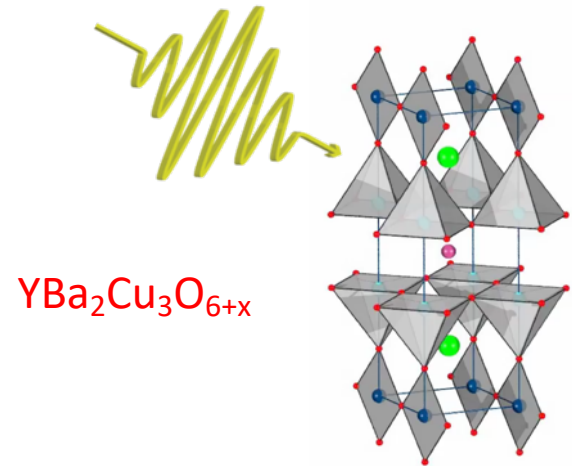


Optical Control of Superconductivity: Different approaches

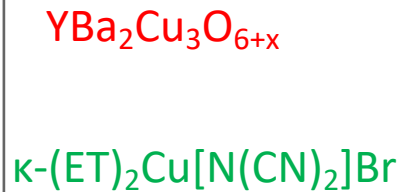
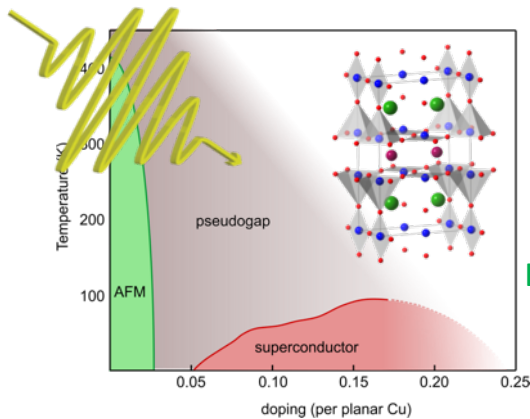
Melt competing orders



Displace the lattice

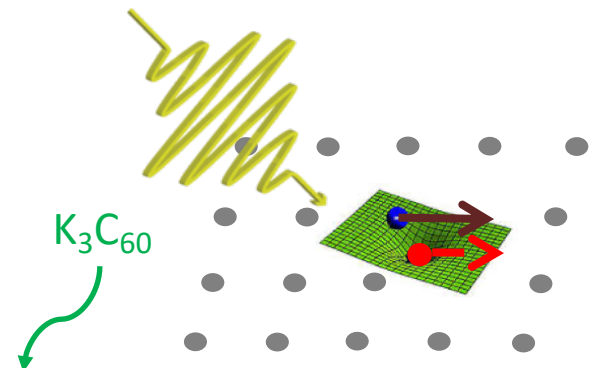


Synchronize pre-formed pairs



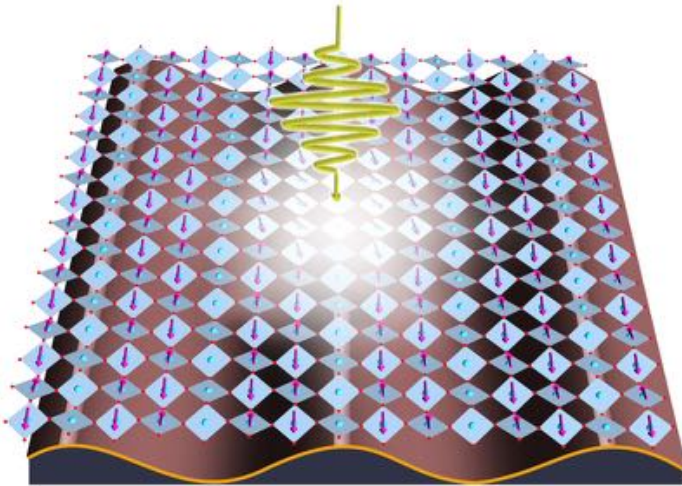
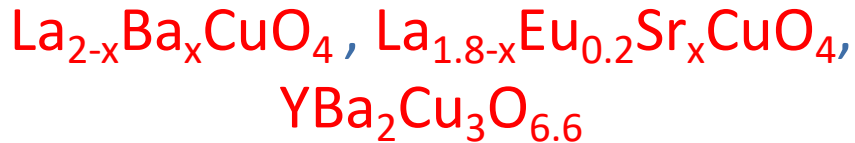
See Michele Buzzi's talk on Thursday

Modulate pairing directly



1: Competing Orders

Melting of Competing Orders



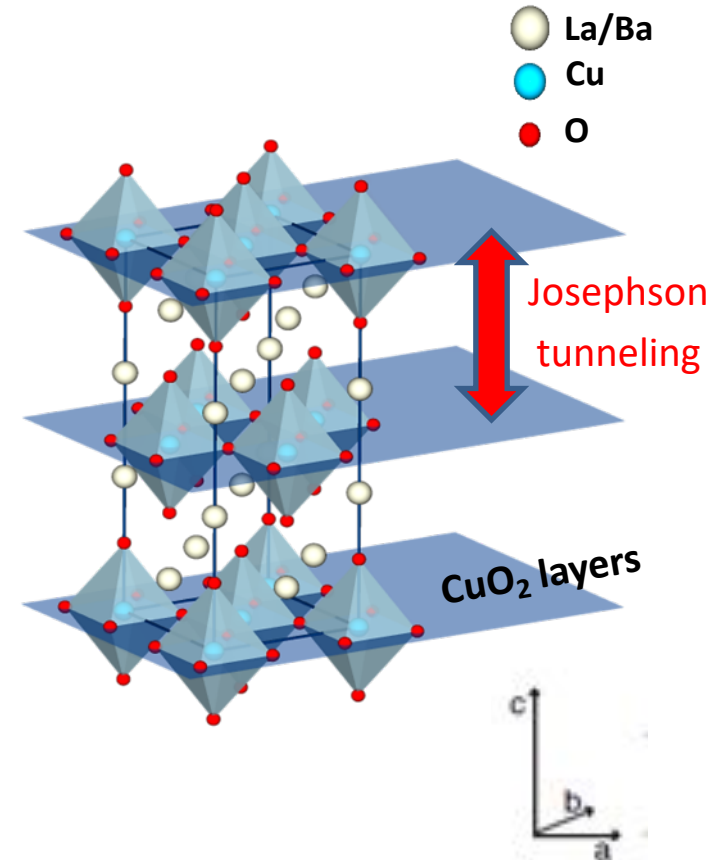
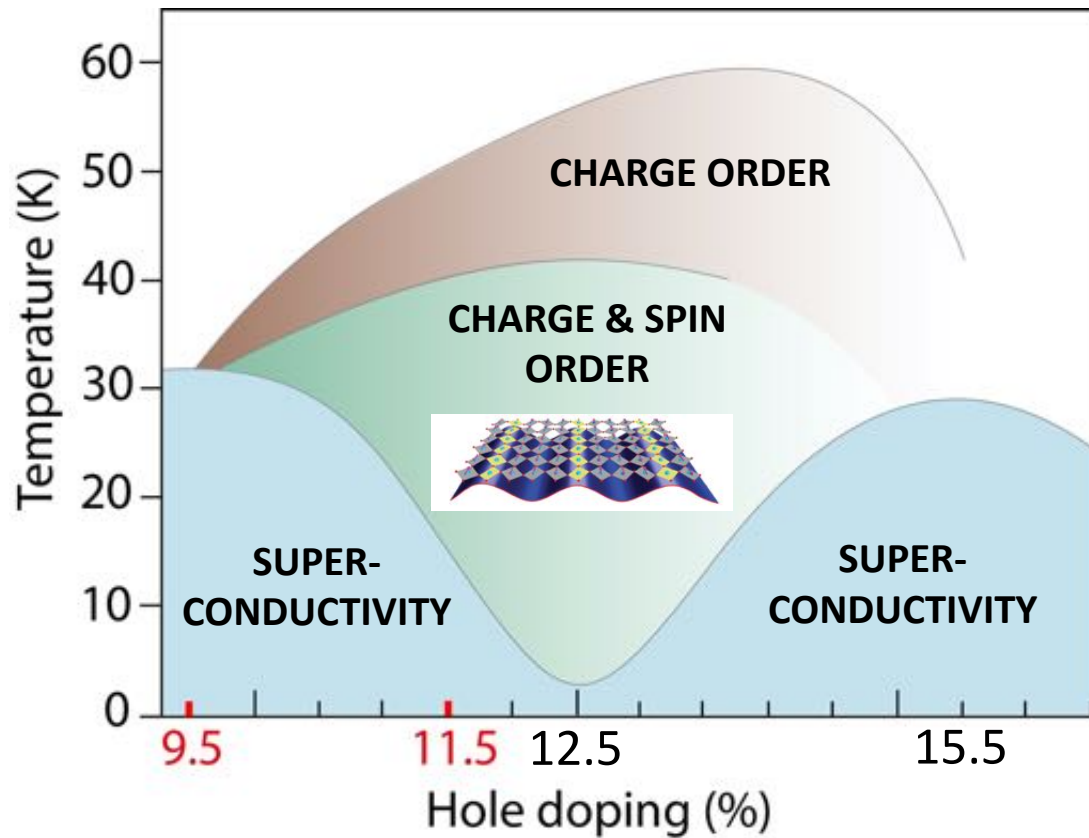
- D. Fausti *et al.*, Science **331**, 189 (2011)
C. R. Hunt *et al.*, Phys. Rev. B **91**, 020505 (2015)
M. Först *et al.*, Phys. Rev. Lett. **112**, 157002 (2014)
M. Först *et al.*, Phys. Rev. B **90**, 184514 (2014)
D. Nicoletti *et al.*, Phys. Rev. B **90**, 100503 (2014)
E. Casandruc *et al.*, Phys. Rev. B **91**, 174502 (2015)
V. Khanna *et al.*, Phys. Rev. B **93**, 224522 (2016)
D. Nicoletti *et al.*, Phys. Rev. Lett. **121**, 267003 (2018)

K. A. Cremin *et al.*, PNAS **116**, 19875 (2019)
S. J. Zhang *et al.*, Phys. Rev. B **98**, 020506 (2018)



Stripe order and high- T_c superconductivity

High- T_c cuprate $\text{La}_{2-x}\text{Ba}_x\text{CuO}_4$

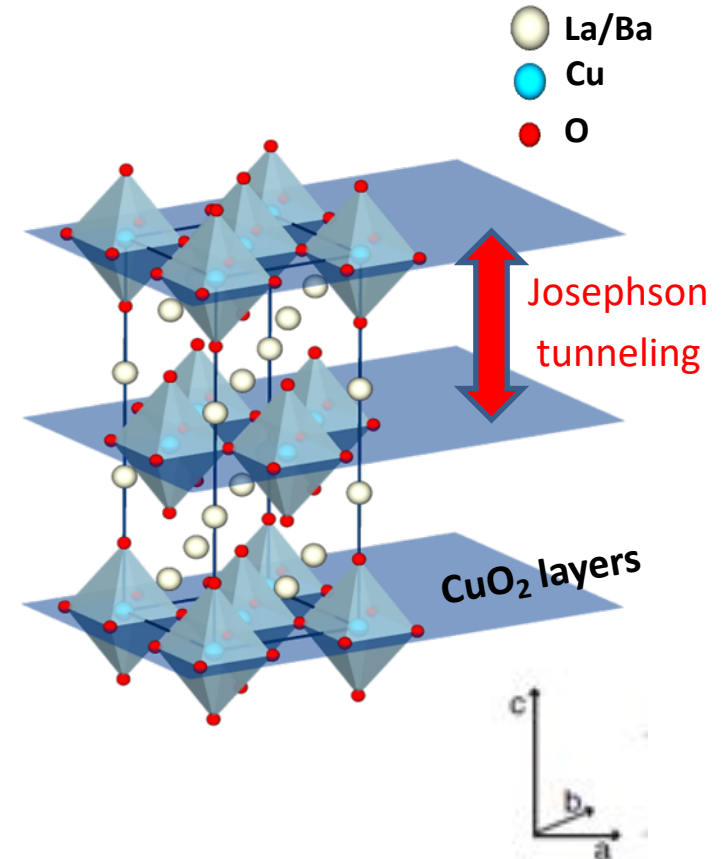
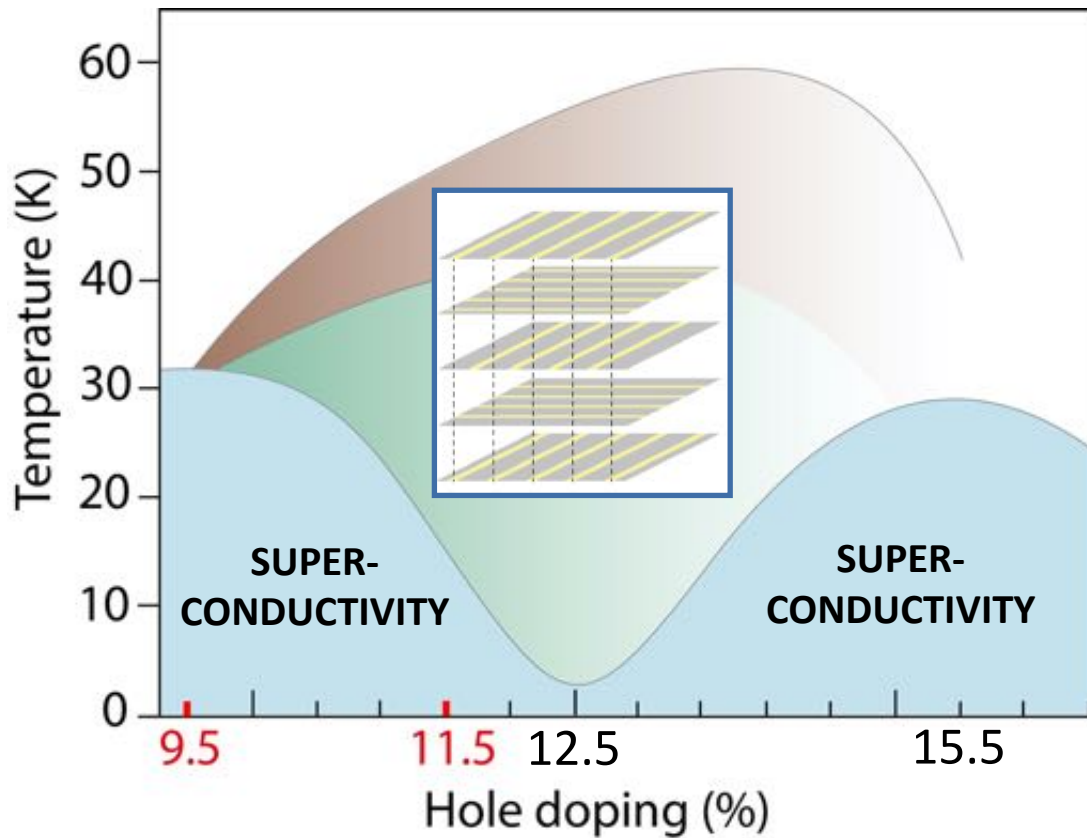


M. Hücker *et al.*, Phys. Rev. B **83**, 104506 (2011)
H.-H. Klauss *et al.*, Phys. Rev. Lett. **85**, 4590 (2000)



Stripe order and high- T_c superconductivity

High- T_c cuprate $\text{La}_{2-x}\text{Ba}_x\text{CuO}_4$



M. Hücker *et al.*, Phys. Rev. B **83**, 104506 (2011)
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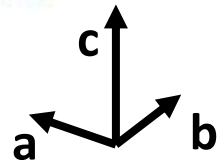
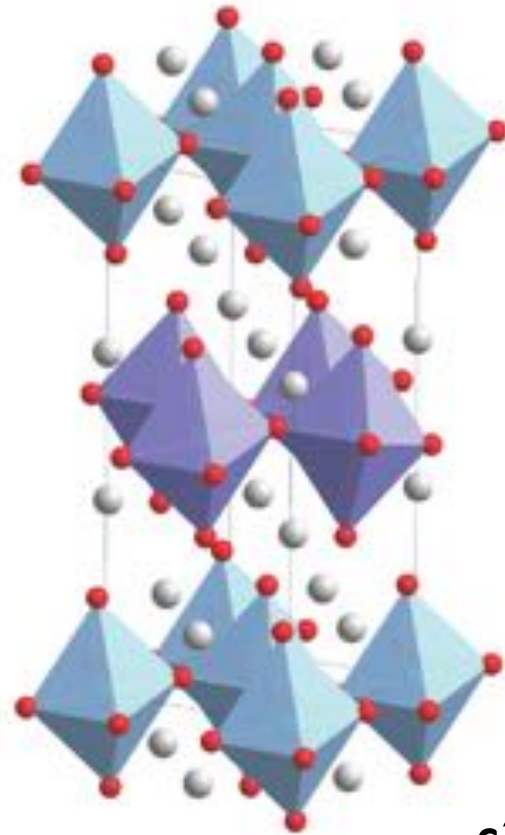
Time-resolved THz spectroscopy



THz probe
(pol. along c)



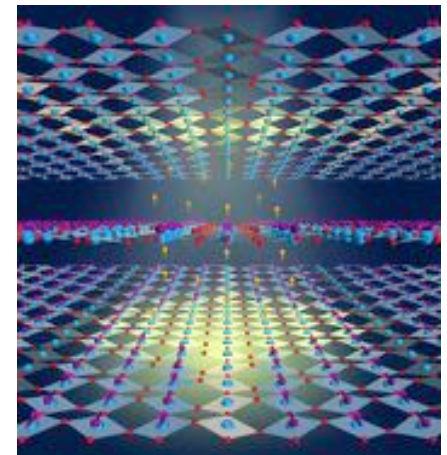
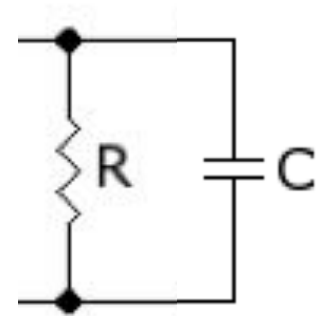
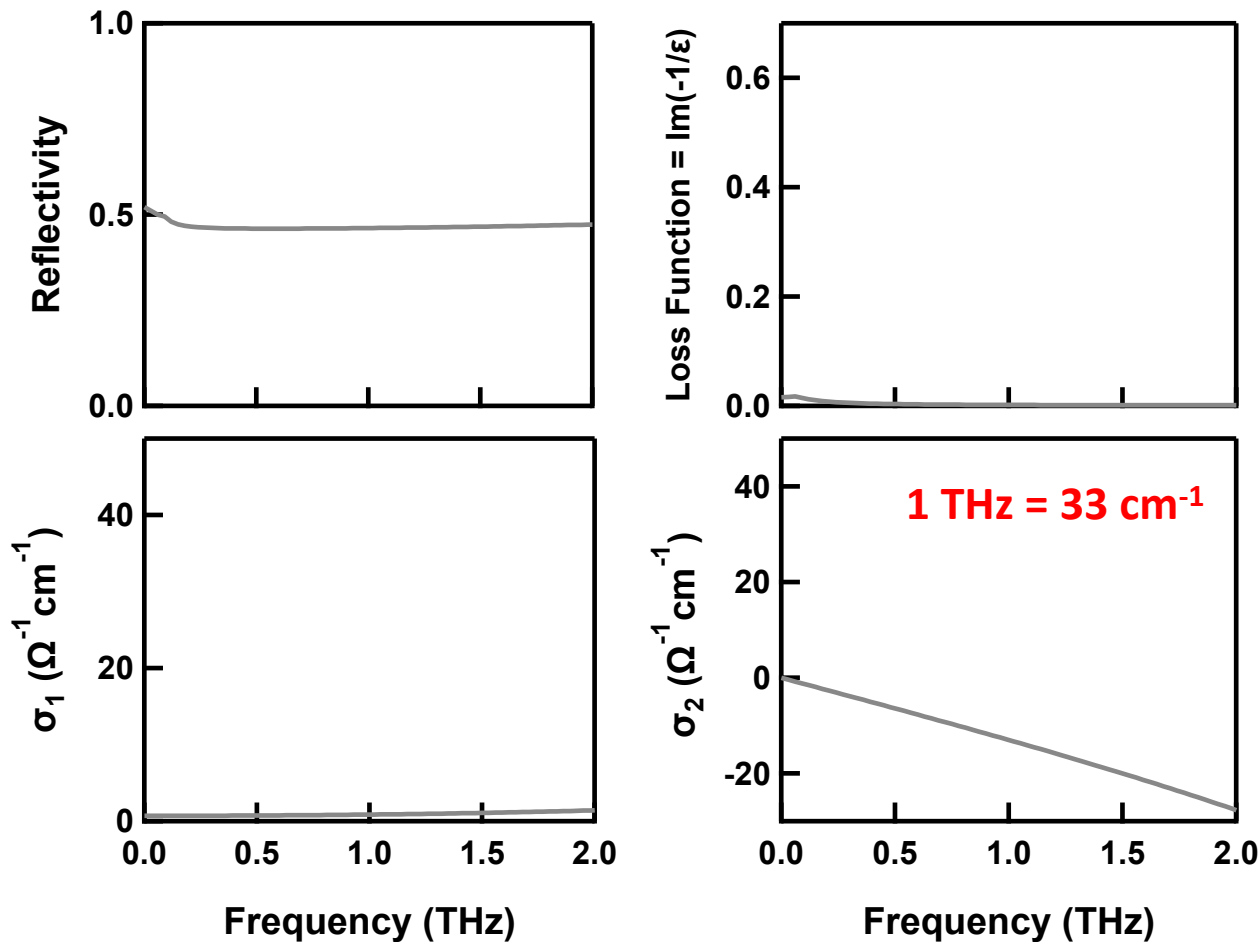
Optical/IR
Pump



Probing c-axis optical properties

Insulating response

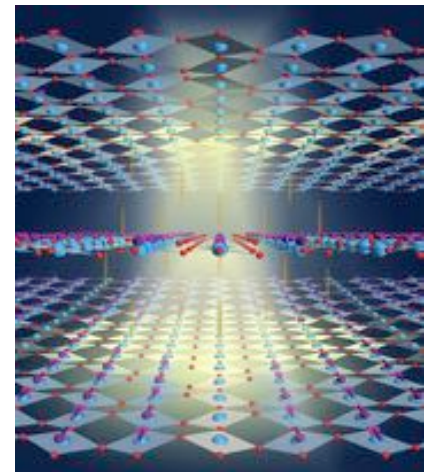
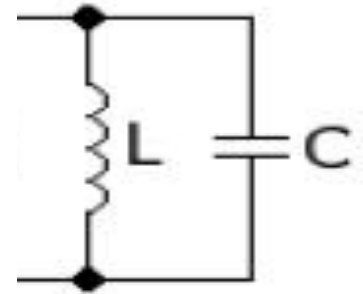
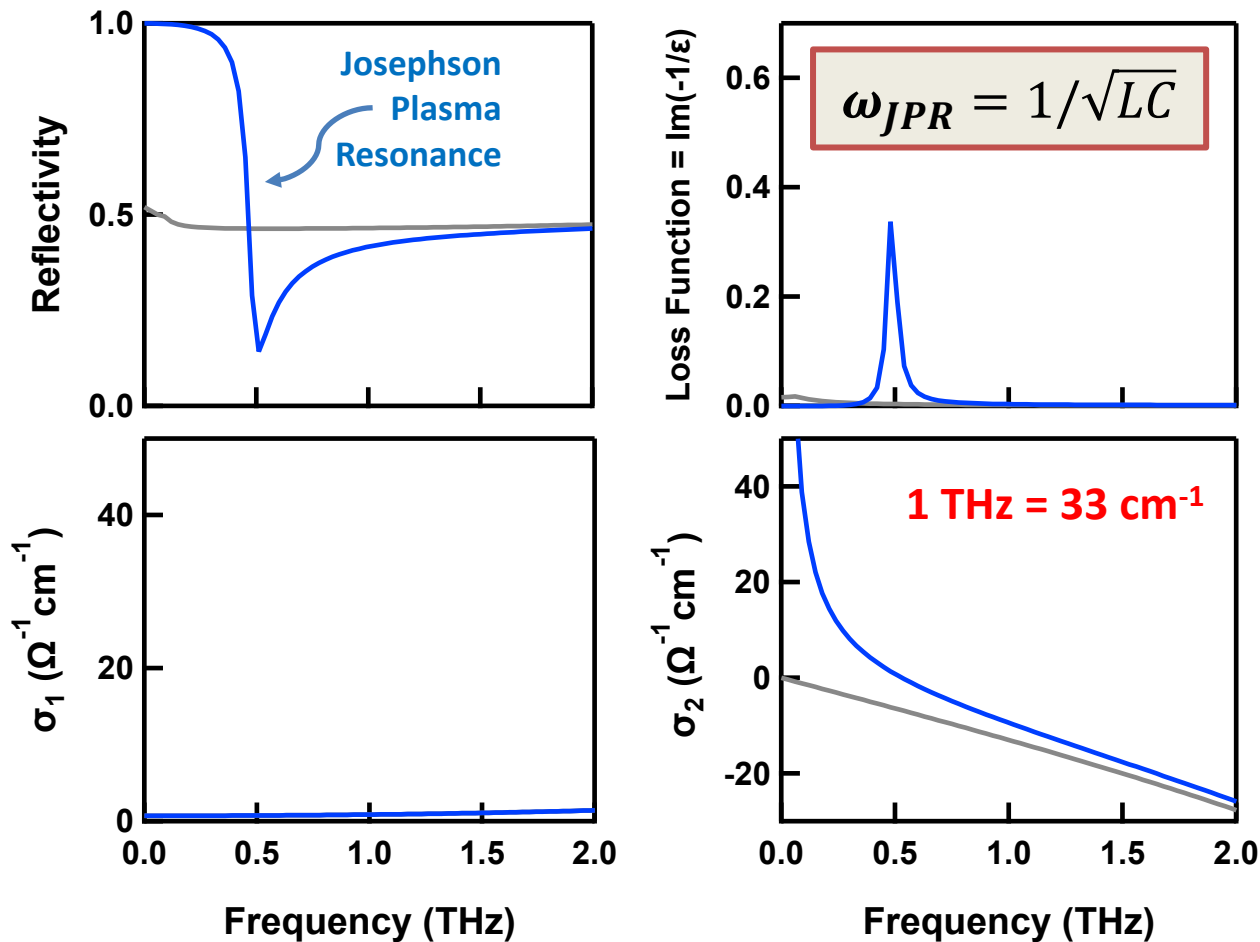
$$T > T_c$$



Probing c-axis optical properties

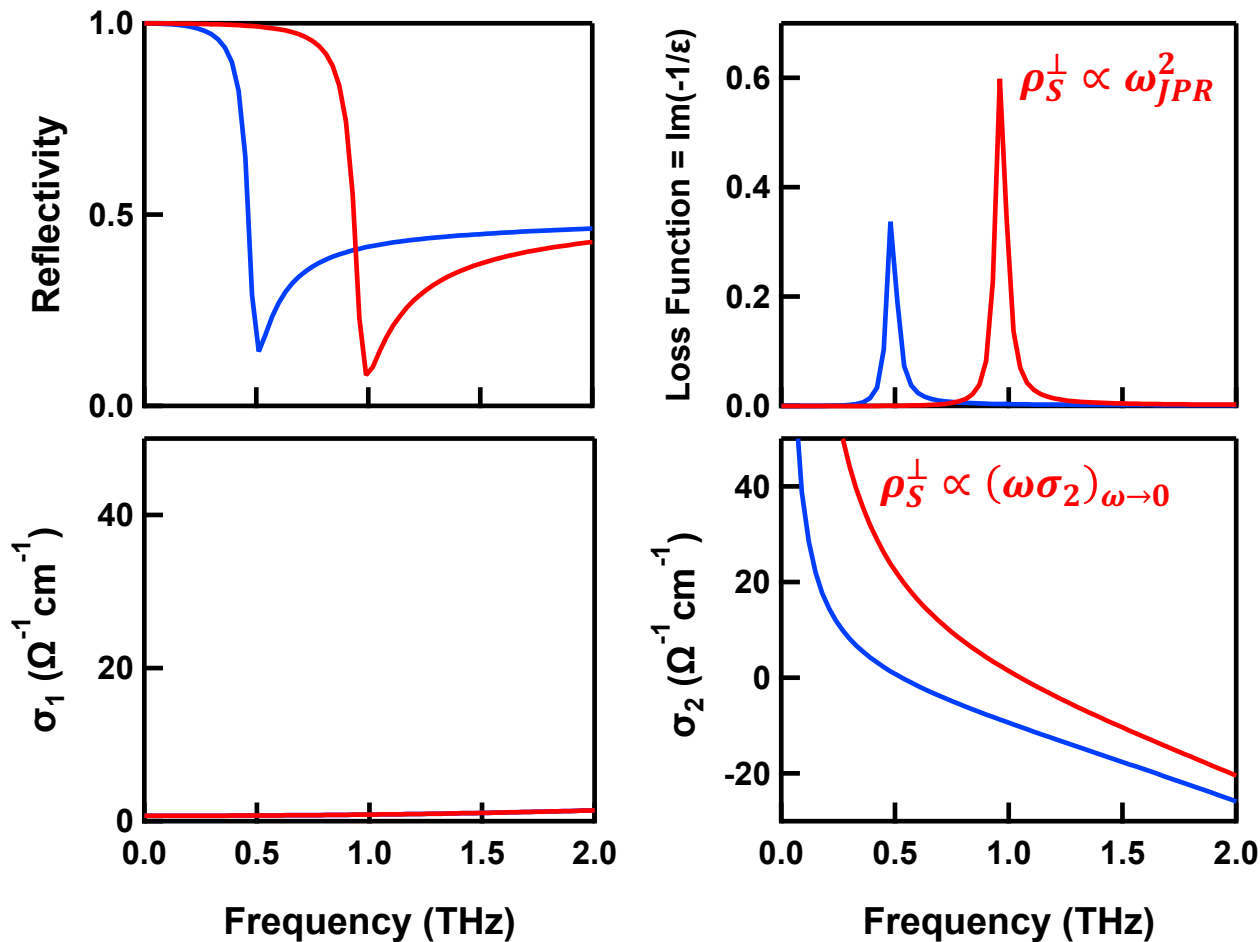
Superconducting response

$$T < T_c$$



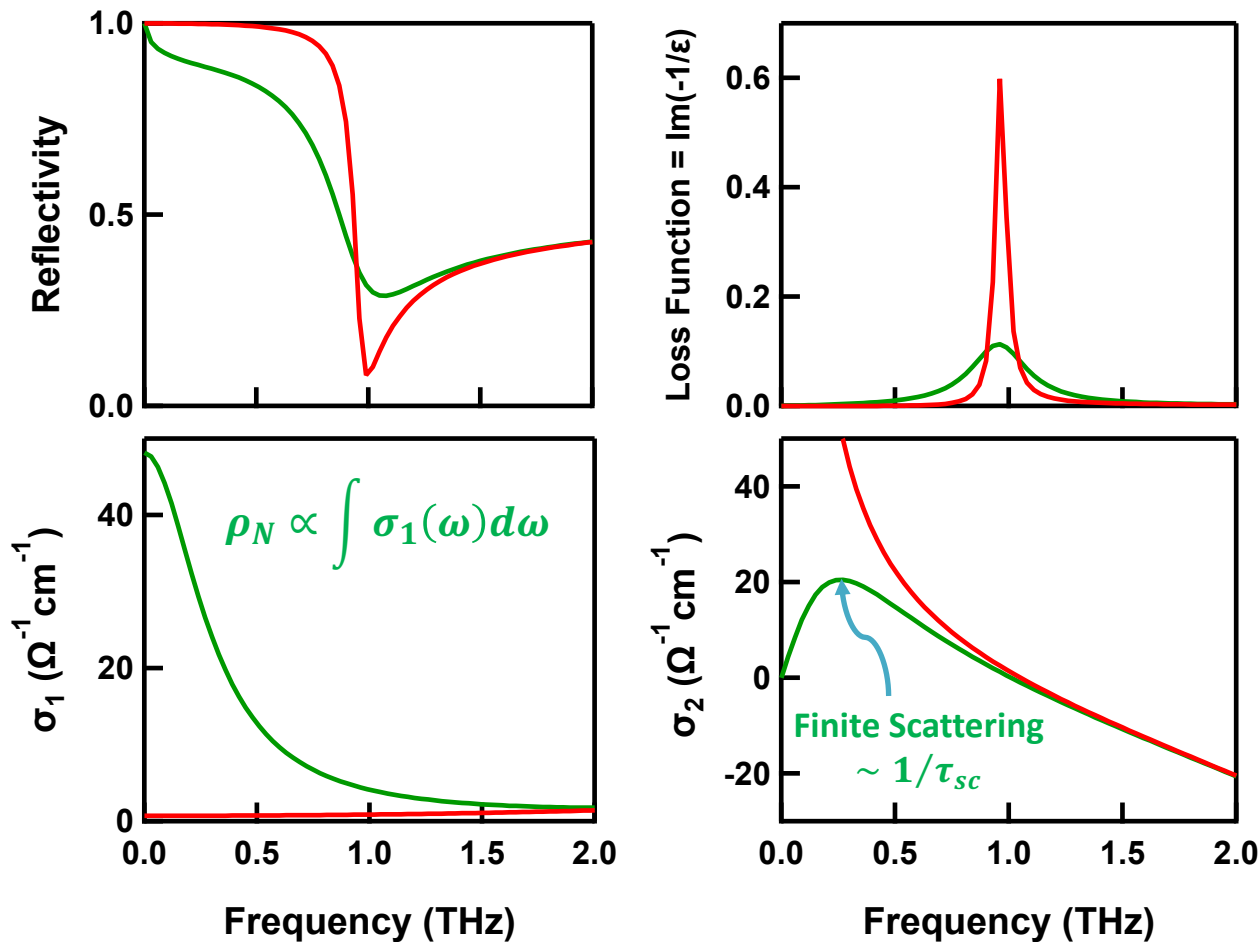
Probing c-axis optical properties

Enhanced superfluid stiffness

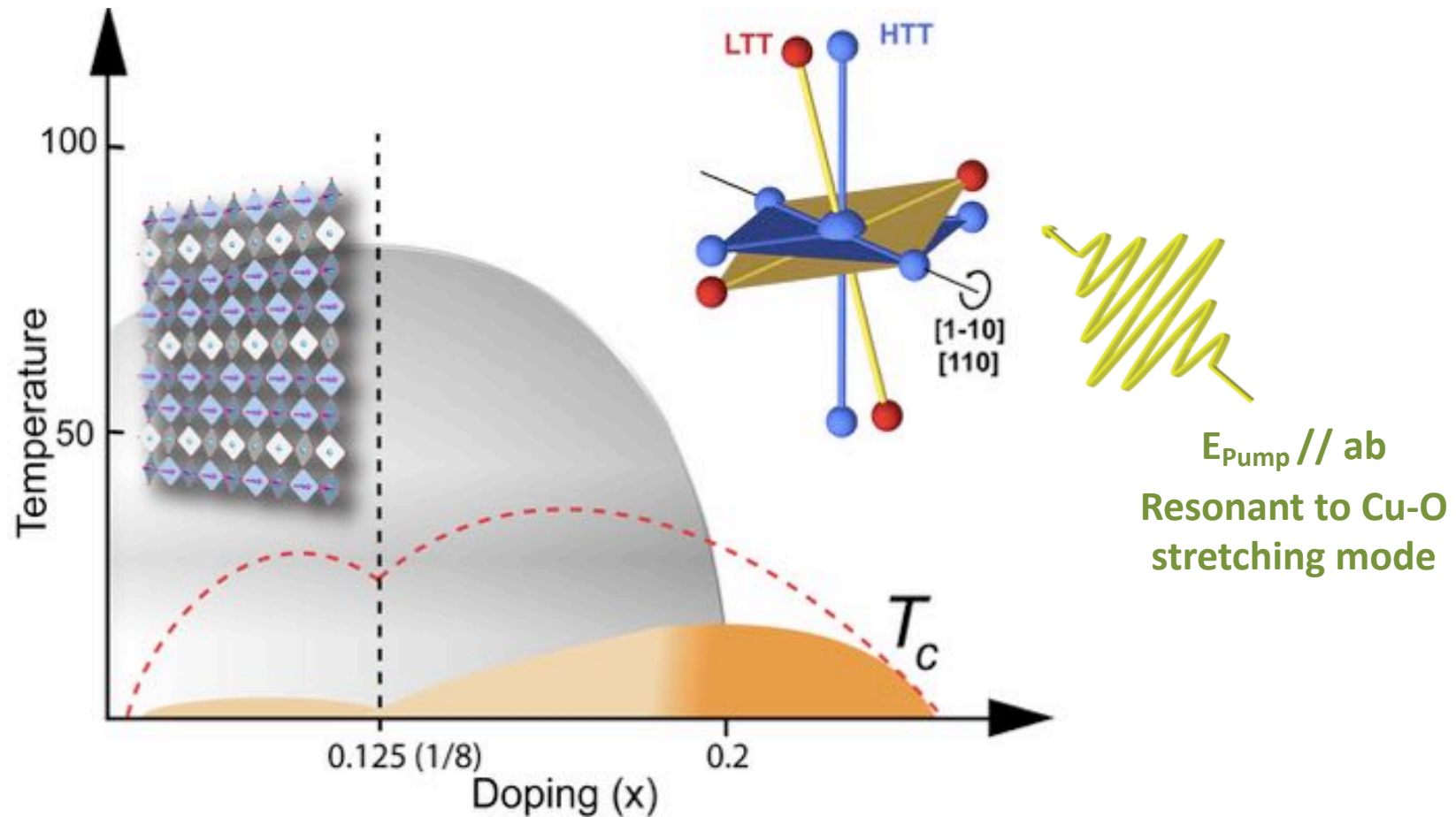


Probing c-axis optical properties

Dissipative response



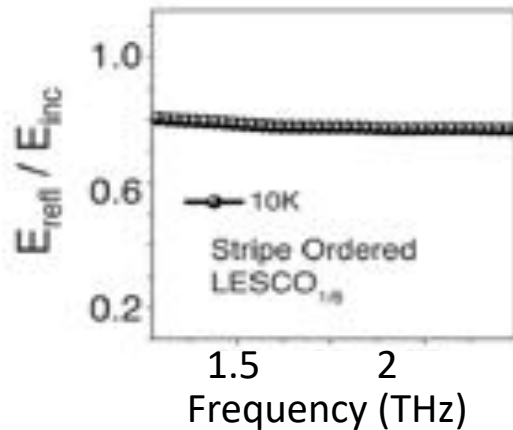
Phonon pump in the striped cuprate $\text{La}_{1.8-x}\text{Eu}_{0.2}\text{Sr}_x\text{CuO}_4$



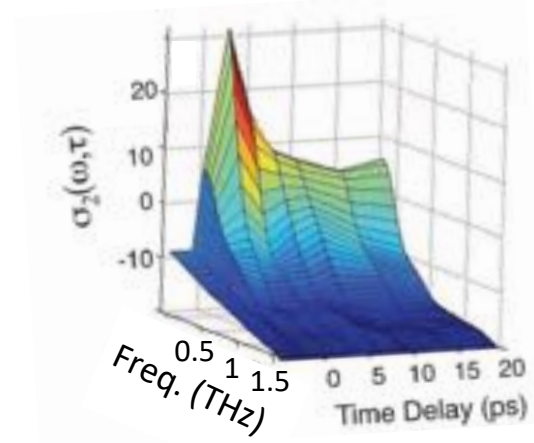
D. Fausti et al., Science 331, 6014 (2011)

Light-induced Josephson Plasma Resonance

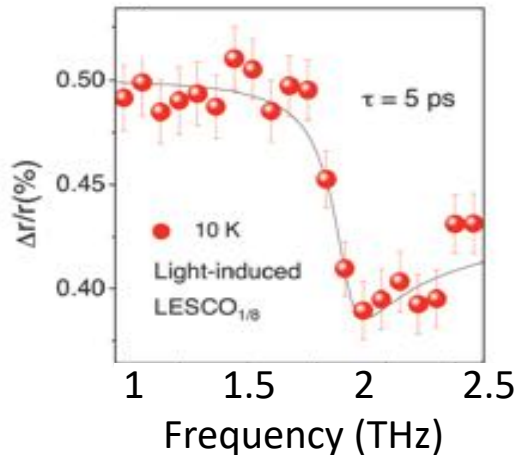
Equilibrium Reflectivity



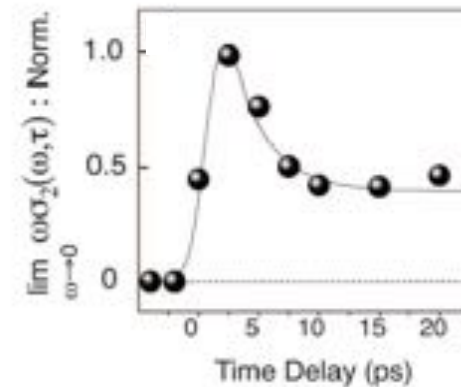
Transient Imaginary Conductivity



Light-Induced Reflectivity



Superfluid Stiffness

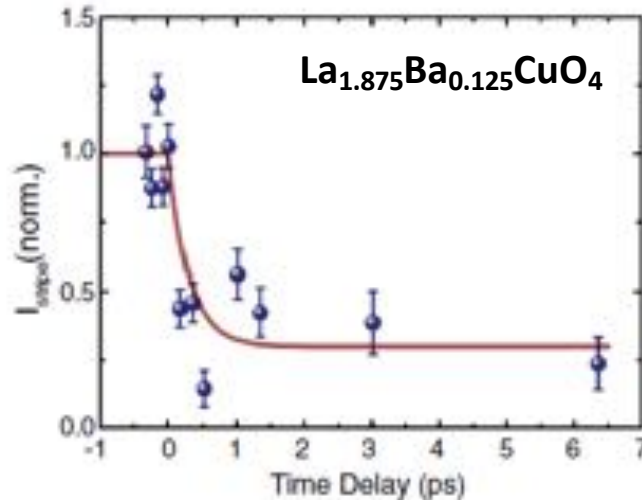


D. Fausti et al., Science 331, 6014 (2011)

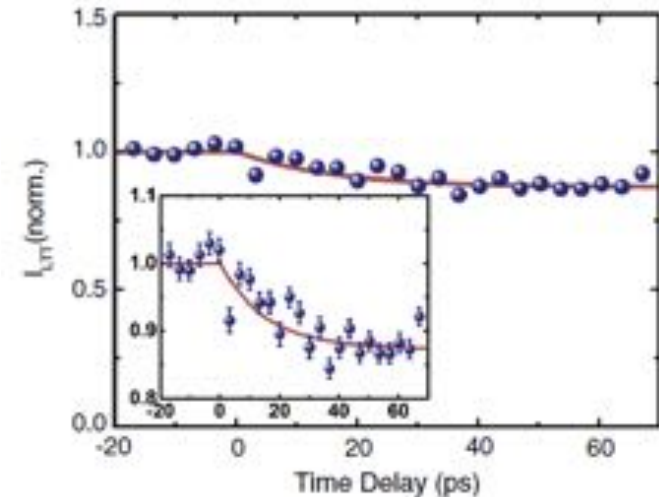


Soft X-ray diffraction probe: Stripe melting

Charge order peak



Structural peak

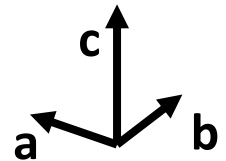
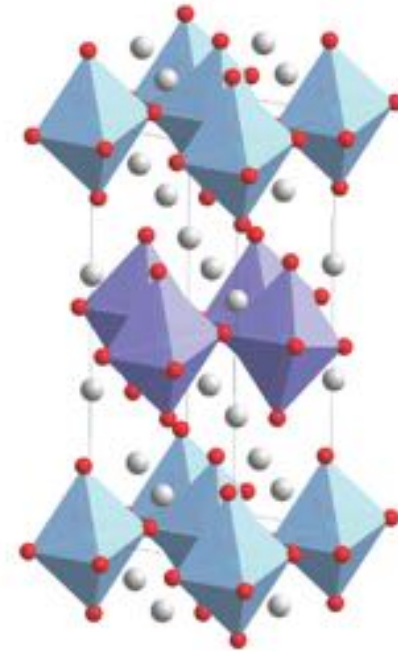


Charge order and lattice dynamics are decoupled on ultrafast timescale
Lattice may not play an important role in light-induced dynamics

M. Först *et al.*, Phys. Rev. Lett. 112, 157002 (2014)



NIR pump / THz probe spectroscopy



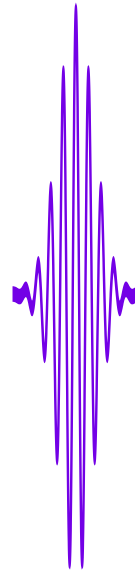
Yesterday's talk by Rick Averitt

K. A. Cremin *et al.*,

PNAS **116**, 19875 (2019)



THz probe
(pol. out-of-plane)



Pump 1.5 eV
(pol. out-of-plane)

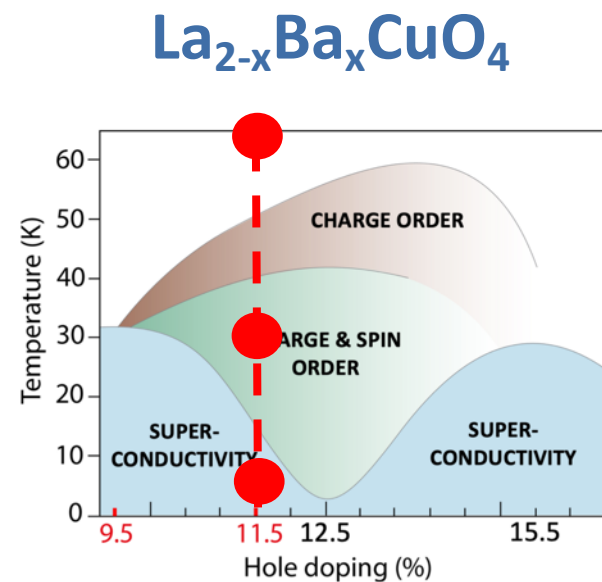
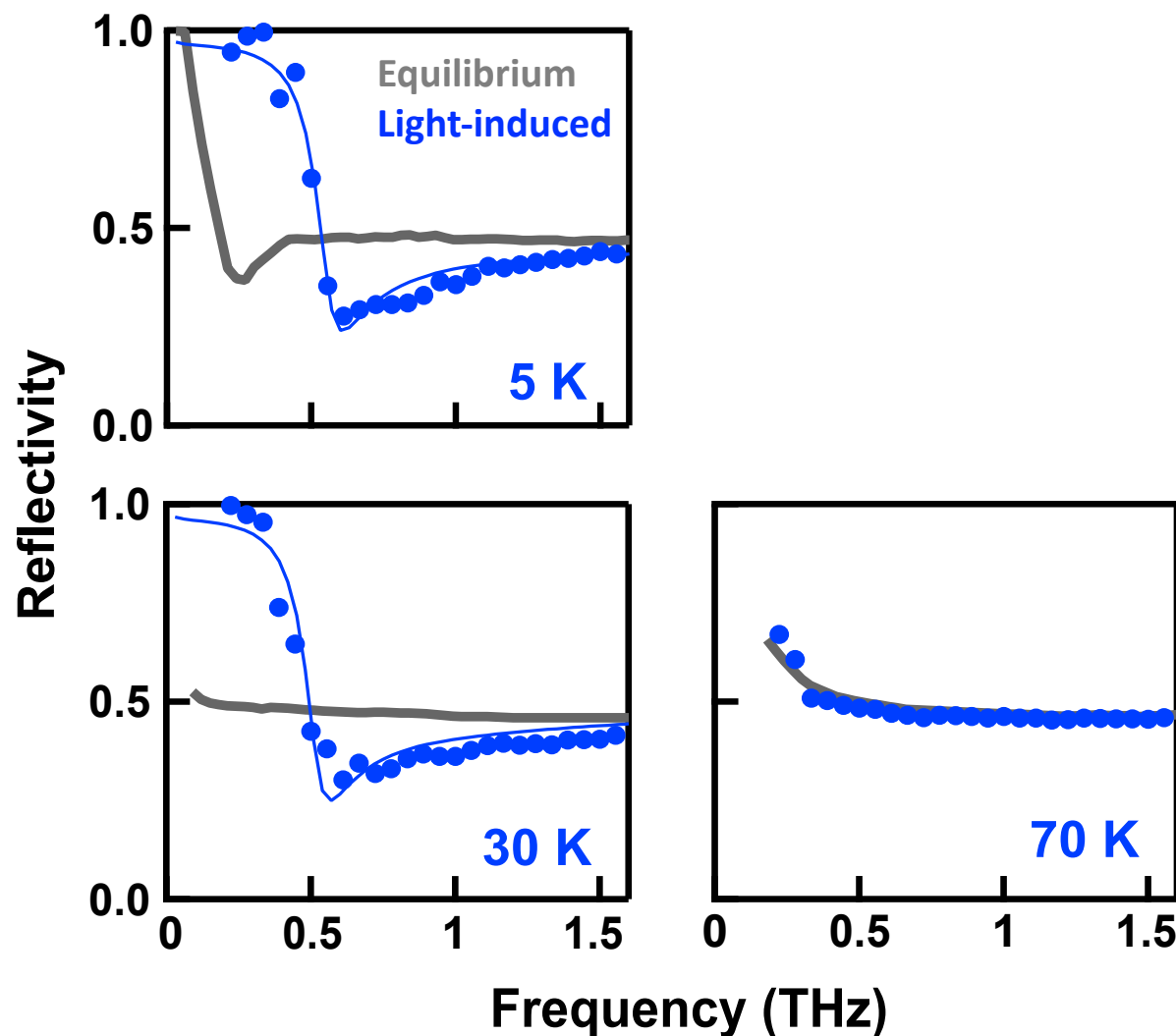


Perturbs mainly the stripe order

In-plane superconducting condensate only weakly affected



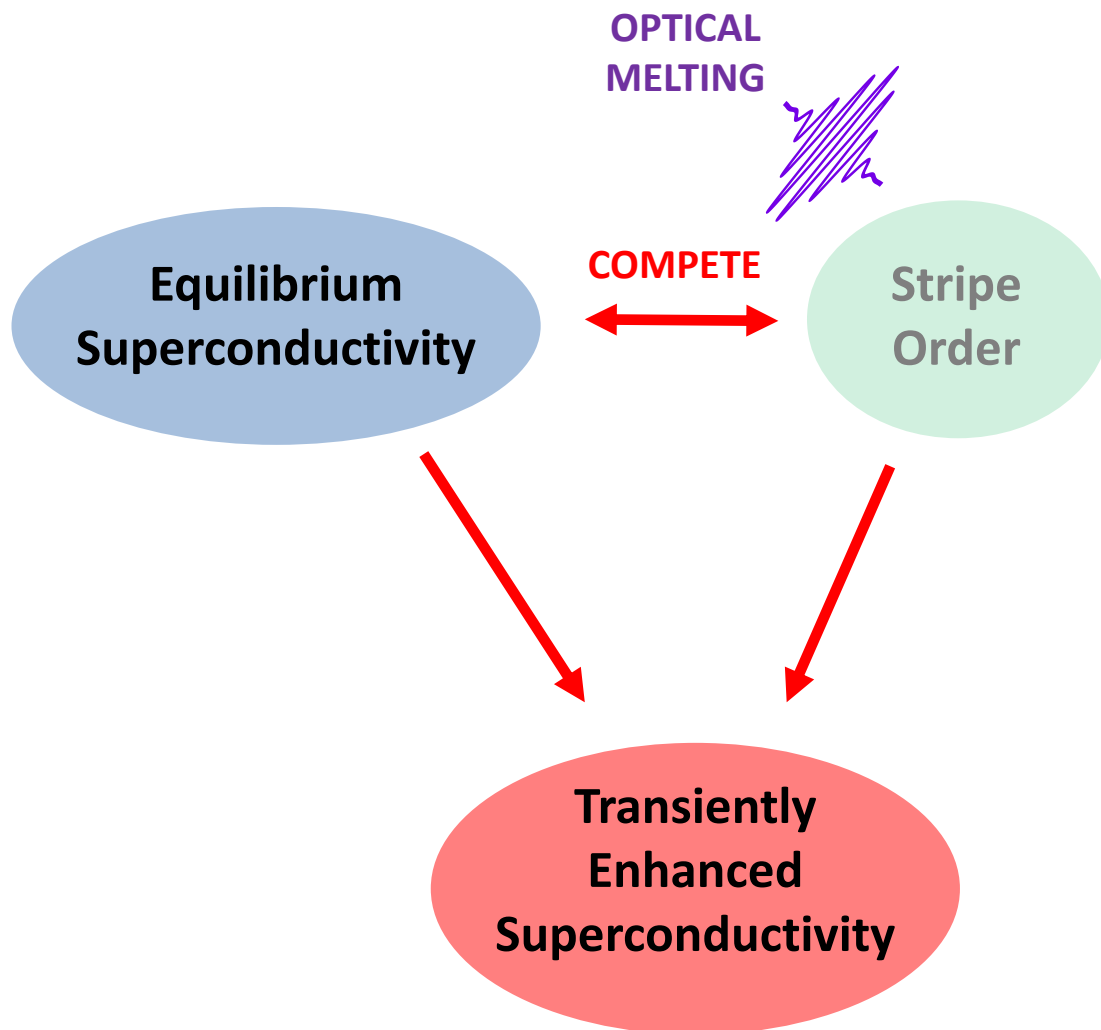
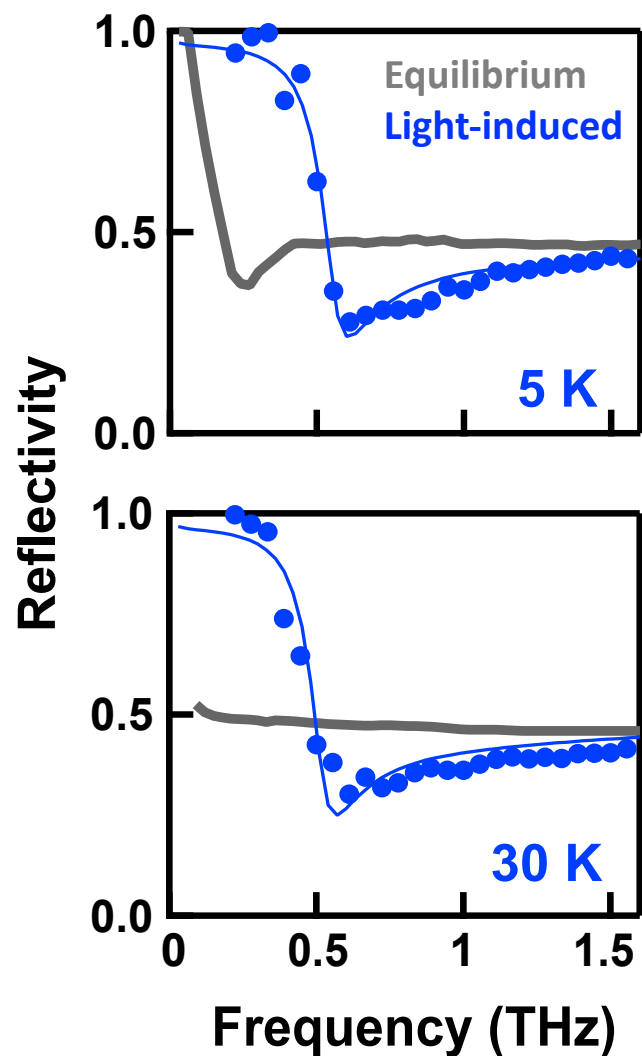
No effect above the stripe order temperature



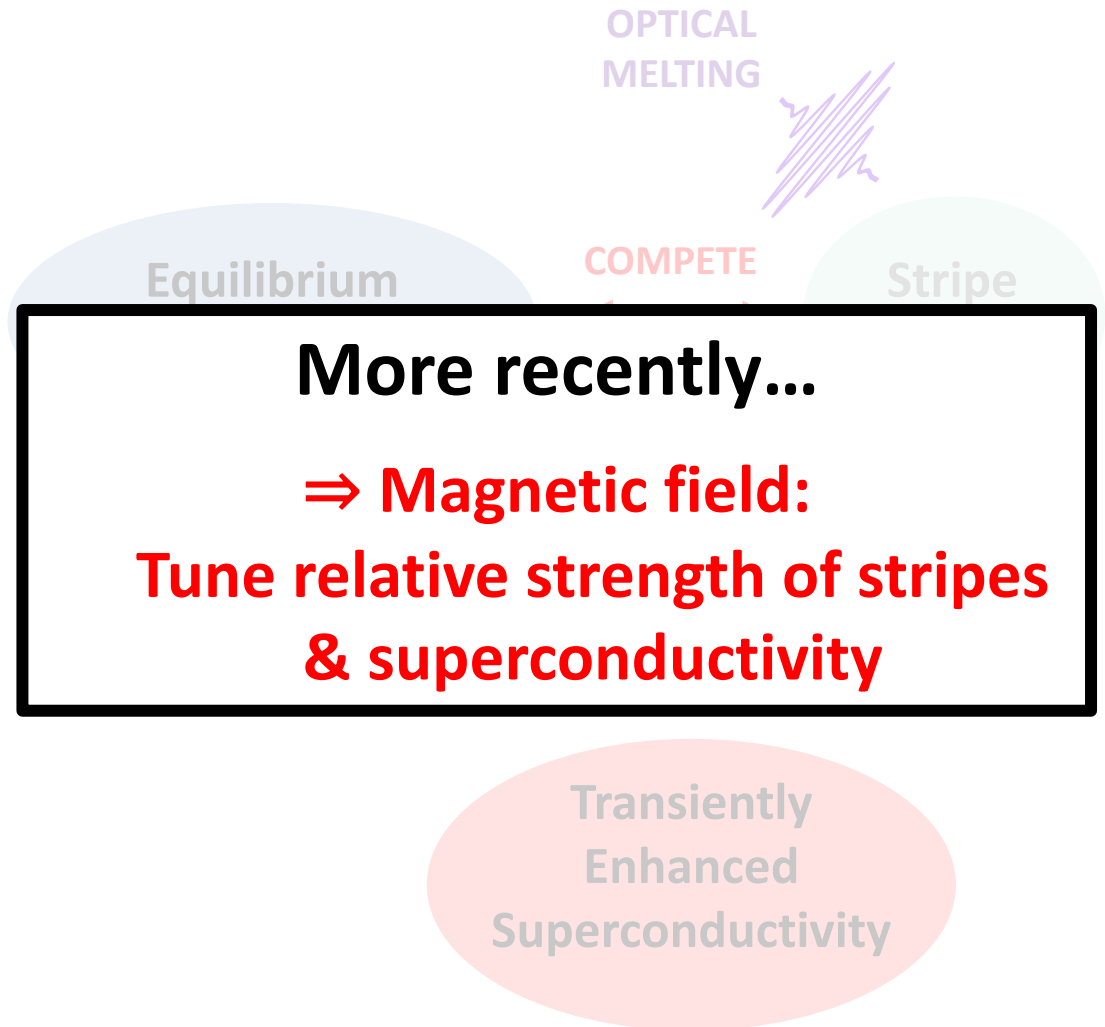
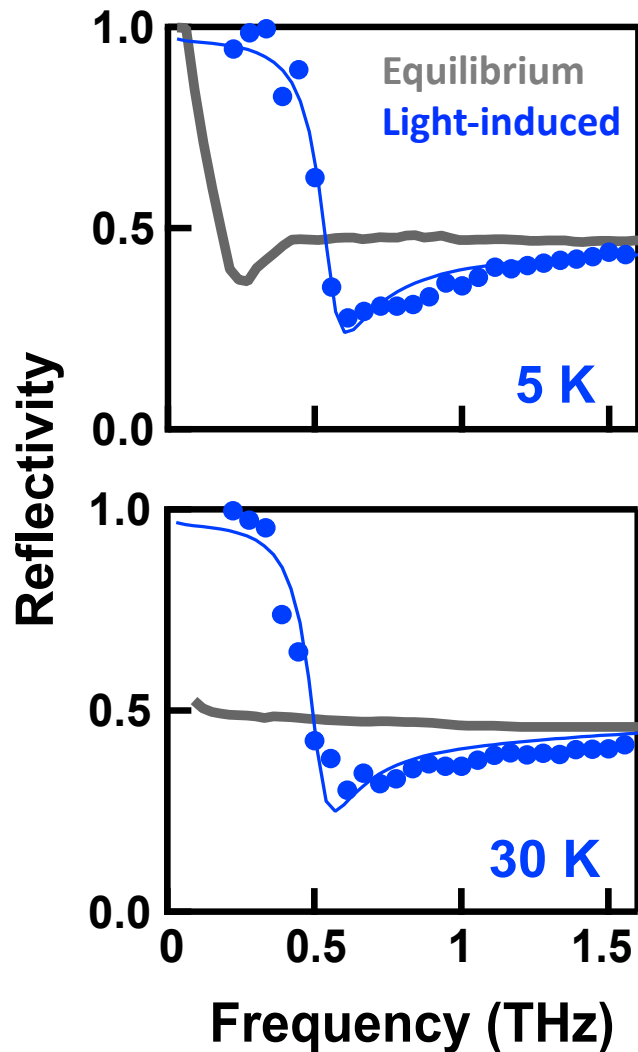
D. Nicoletti et al., Phys. Rev. B 90, 100503 (2014)



Optically enhanced superconductivity via stripe melting



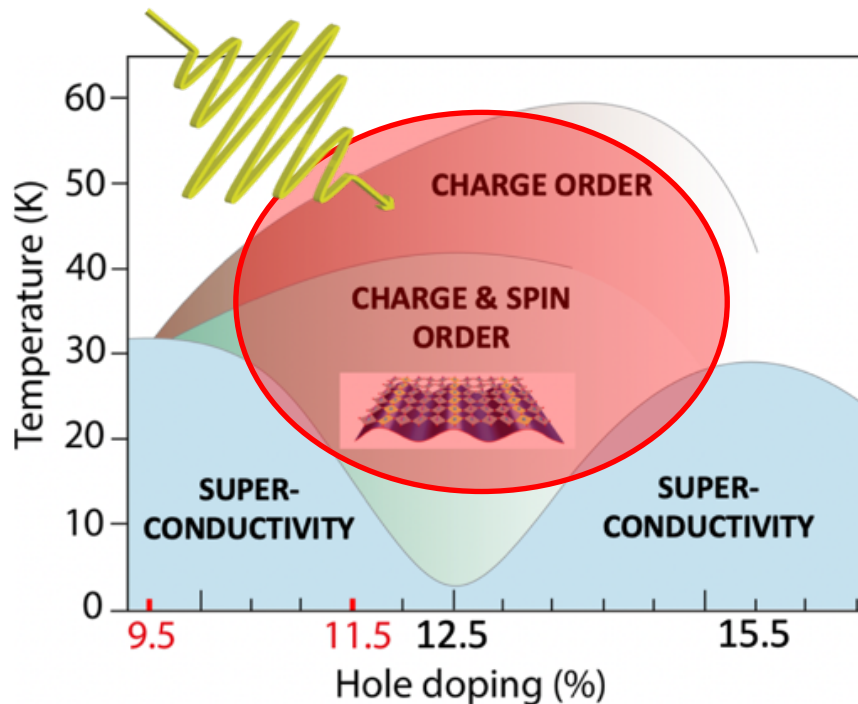
Optically enhanced superconductivity via stripe melting



D. Nicoletti *et al.*, Phys. Rev. Lett. 121, 267003 (2018)



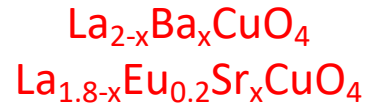
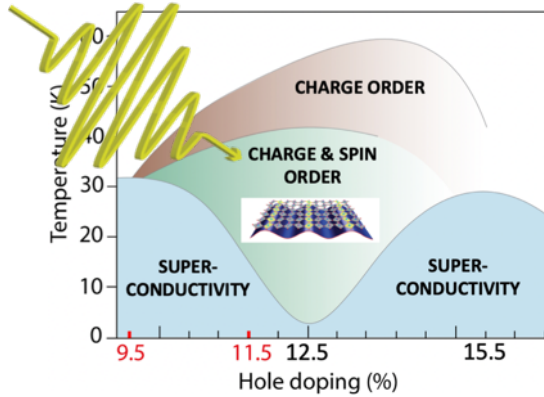
Melting of competing order: Summary



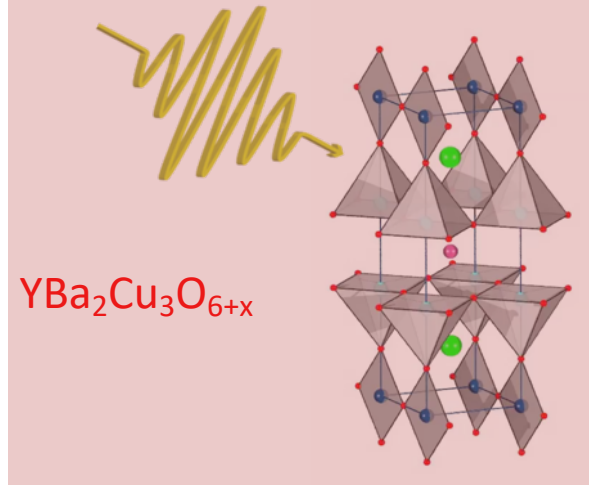
- Limited to $T < T_{\text{Charge Order}}$
- Works for a broad range of pump wavelengths
- “Understood” in terms of optical melting of competing stripe phase

Optical Control of Superconductivity: Different approaches

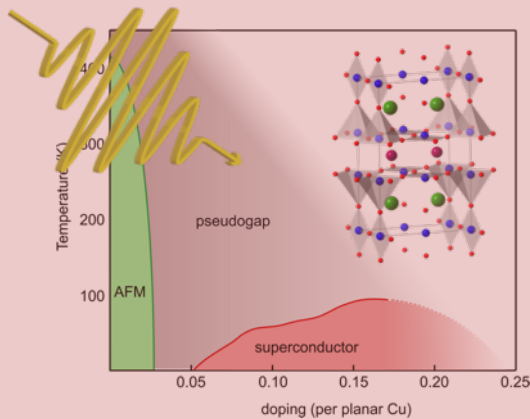
Melt competing orders



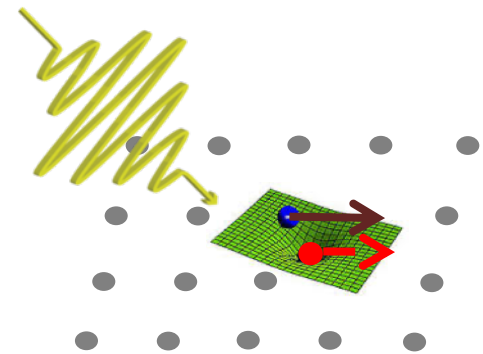
Displace the lattice



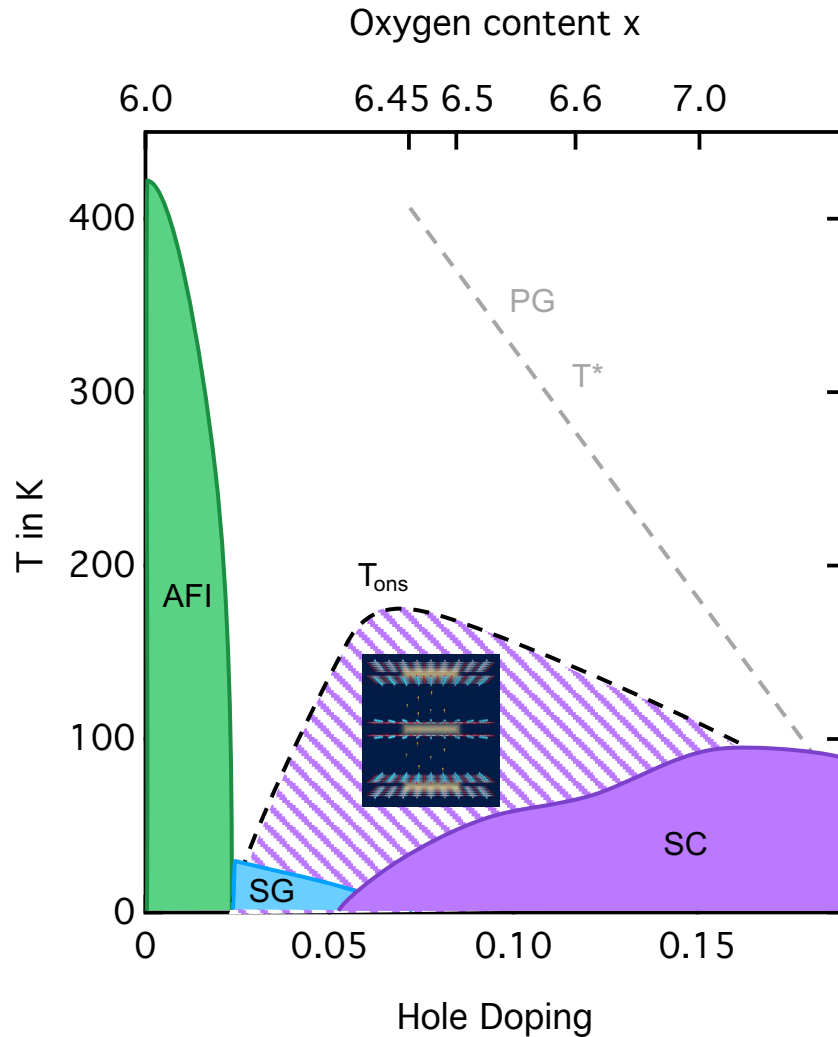
Synchronize pre-formed pairs



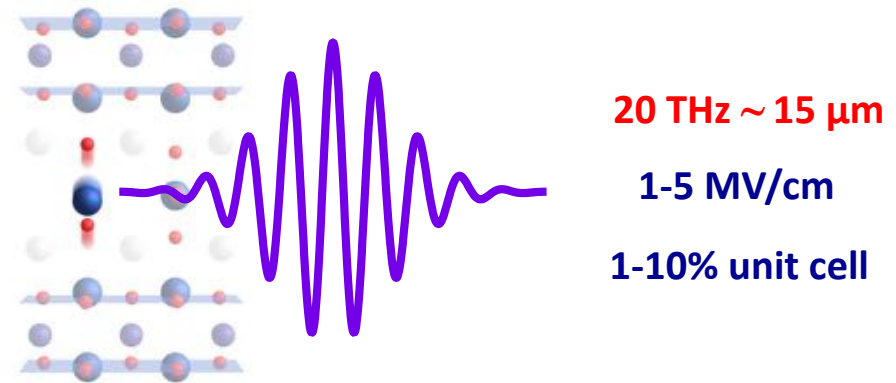
Modulate pairing directly



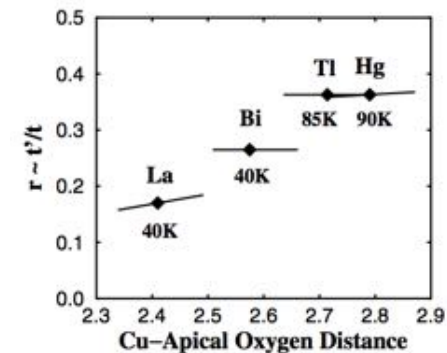
Driving the apical oxygen phonon in YBCO



E. Uykur et al., Phys. Rev. Lett. 112, 127003 (2014)
 A. Dubroka et al., Phys. Rev. Lett. 107, 047006 (2011)



Apical oxygen position correlates with T_c at equilibrium



E. Pavarini et al., Phys. Rev. Lett. 87, 047003 (2001)
 C. Weber et al. Phys. Rev. B 82, 125107 (2010)

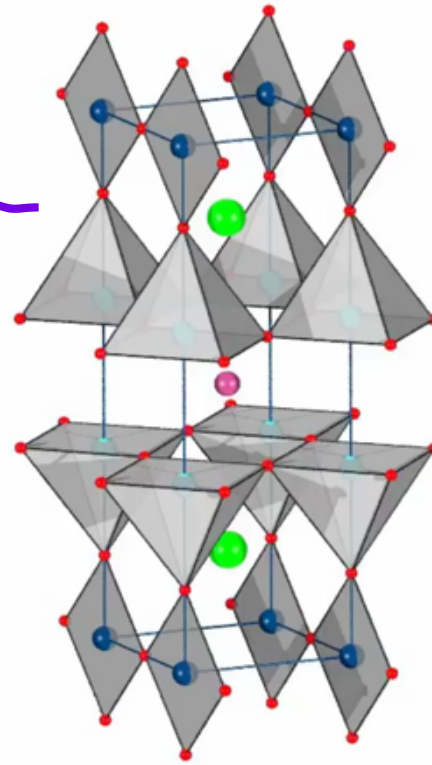
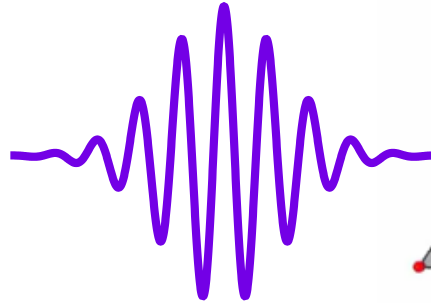


Driving the apical oxygen phonon in YBCO

Pump
20 THz $\sim$ 15 μ m

1-5 MV/cm

1-10% unit cell



YBa₂Cu₃O_{6+x}

Many different probes...

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

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

C. Hunt *et al.*, Phys. Rev. B **94**, 224303 (2016)

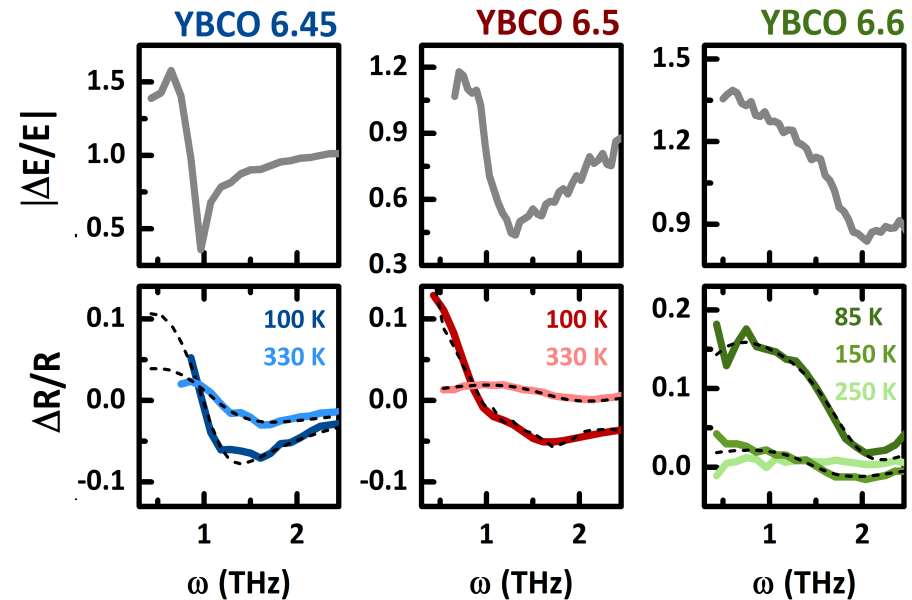
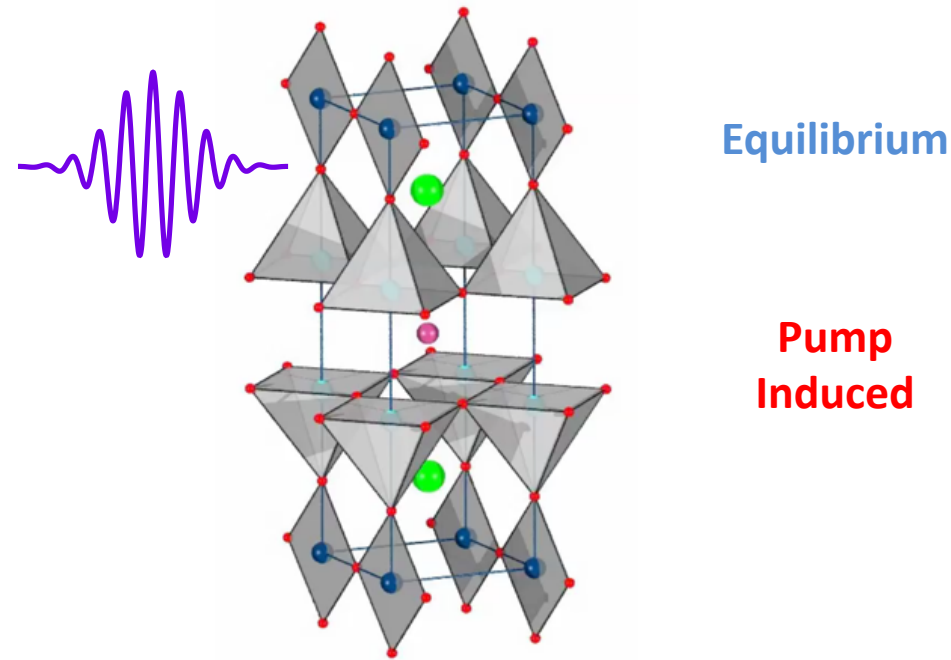
R. Mankowsky *et al.*, Nature **516**, 71 (2014)

M. Först *et al.*, Phys. Rev. B **90**, 184514 (2014)

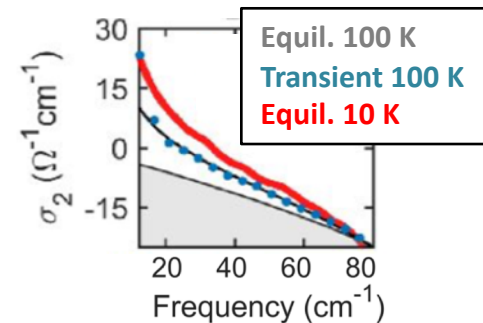
R. Mankowsky *et al.*, Phys. Rev. B **91**, 094308 (2015)

A superconducting-like response up to room T

1) Transient Plasma Resonance



2) Divergent imaginary conductivity

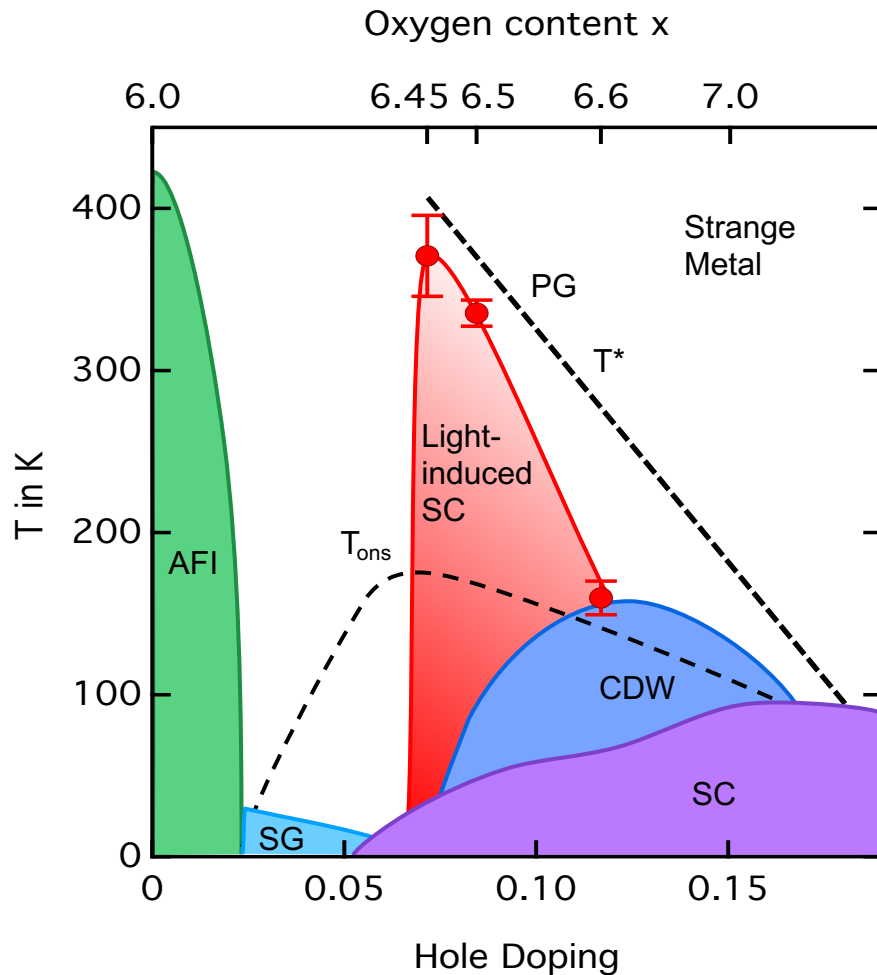


S. Kaiser *et al.*, Phys. Rev. B **89**, 184516 (2014)

C. Hunt *et al.*, Phys. Rev. B **94**, 224303 (2016)

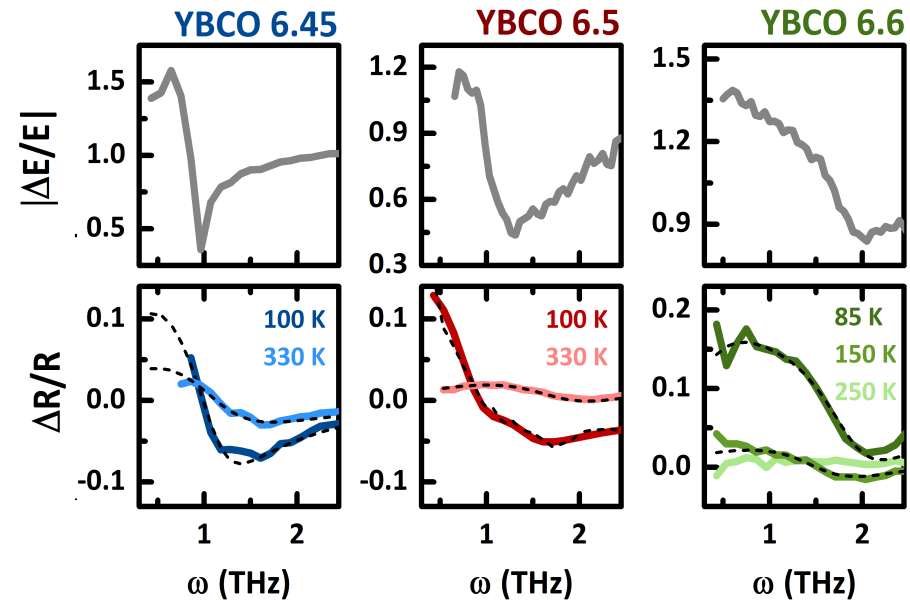


Signatures all the way up to the Pseudogap temperature T^*

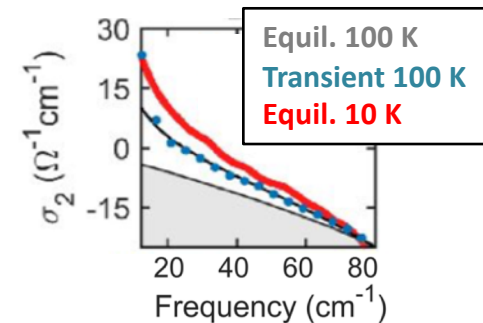


S. Kaiser *et al.*, Phys. Rev. B **89**, 184516 (2014)
 C. Hunt *et al.*, Phys. Rev. B **94**, 224303 (2016)

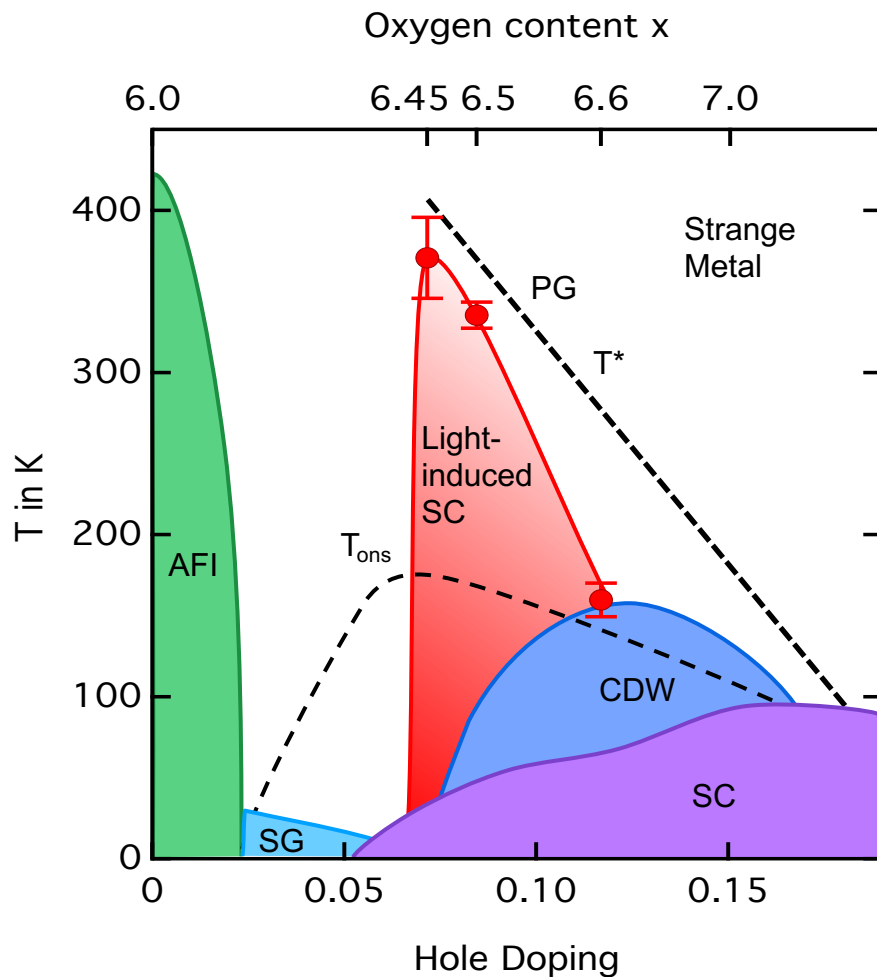
1) Transient Plasma Resonance



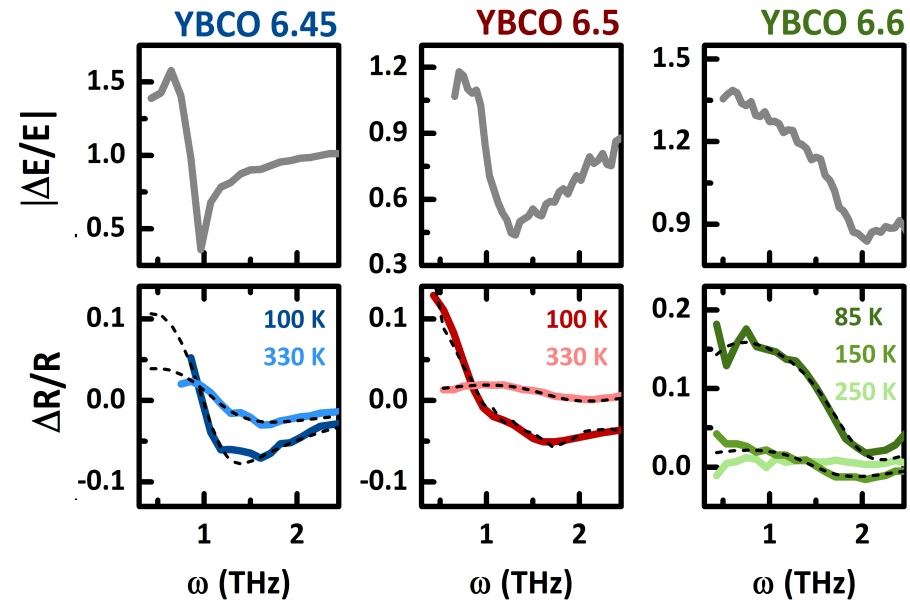
2) Divergent imaginary conductivity



Signatures all the way up to the Pseudogap temperature T^*



1) Transient Plasma Resonance



What is going on?

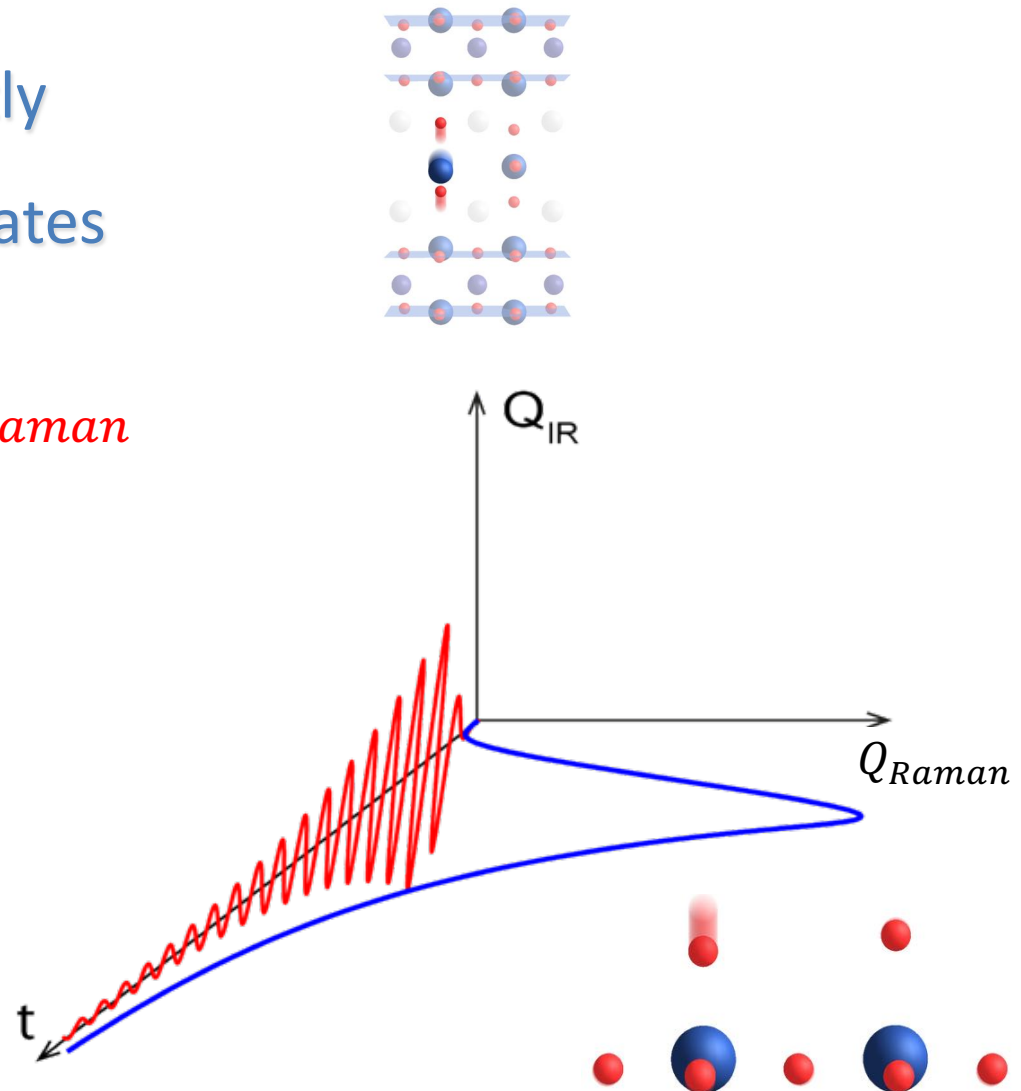
S. Kaiser *et al.*, Phys. Rev. B **89**, 184516 (2014)
C. Hunt *et al.*, Phys. Rev. B **94**, 224303 (2016)



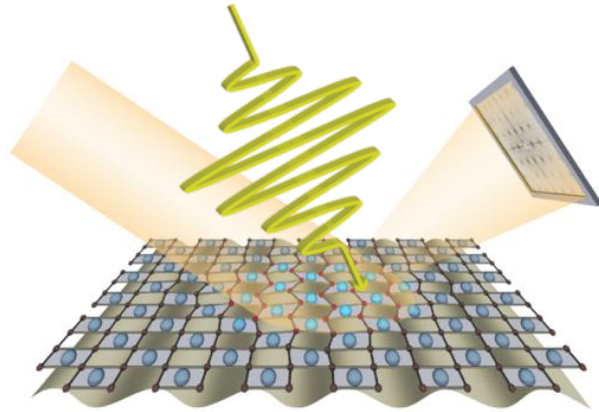
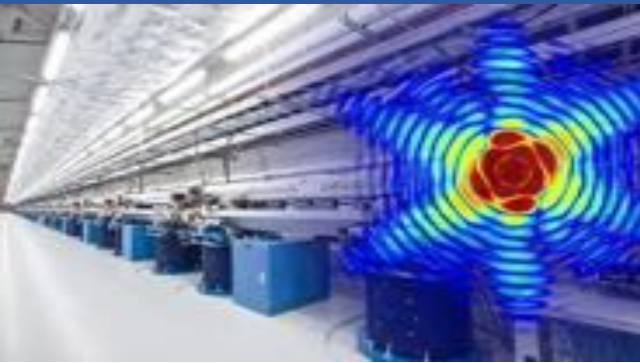
Nonlinear phonon coupling

Lattice displaces transiently
along Raman mode coordinates

$$V = \frac{1}{2} \mu_{IR} \omega_{IR}^2 Q_{IR}^2 + NA Q_{IR}^2 Q_{Raman}$$

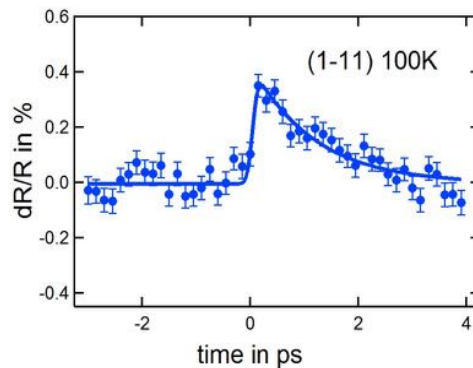


Femtosecond X-ray Crystallography

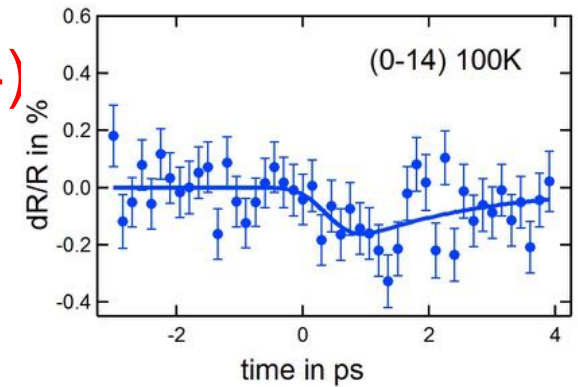


$(-1,1,1)$

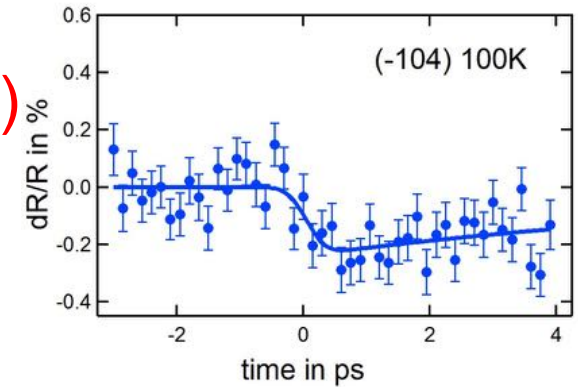
R. Mankowsky *et al.*,
Nature **516**, 71 (2014)



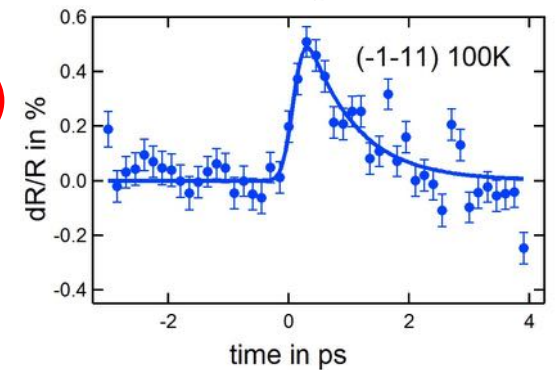
$(0,-1,4)$



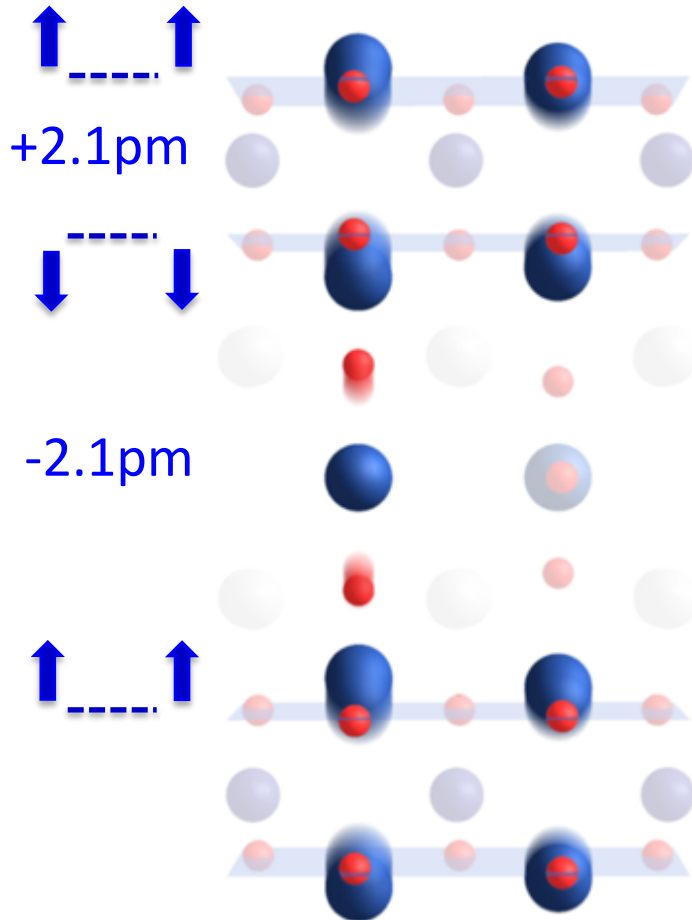
$(-1,0,4)$



$(1,-1,1)$

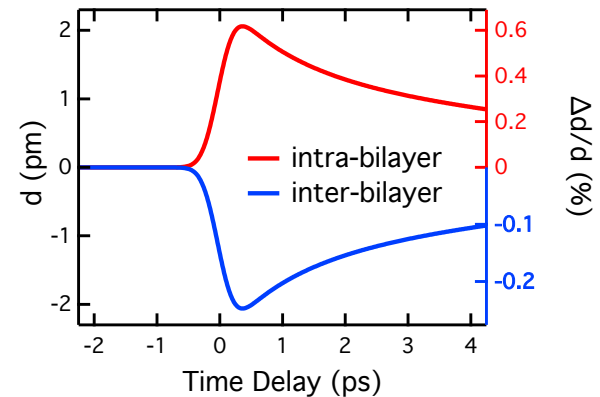


A new, transient crystal structure



Staggered motion of the layers

- Inter-bilayer tunneling is enhanced at the expenses of the coupling within the bilayers

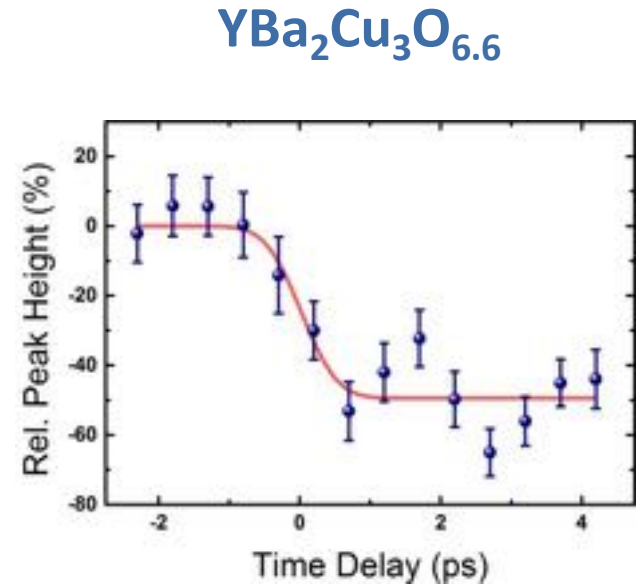
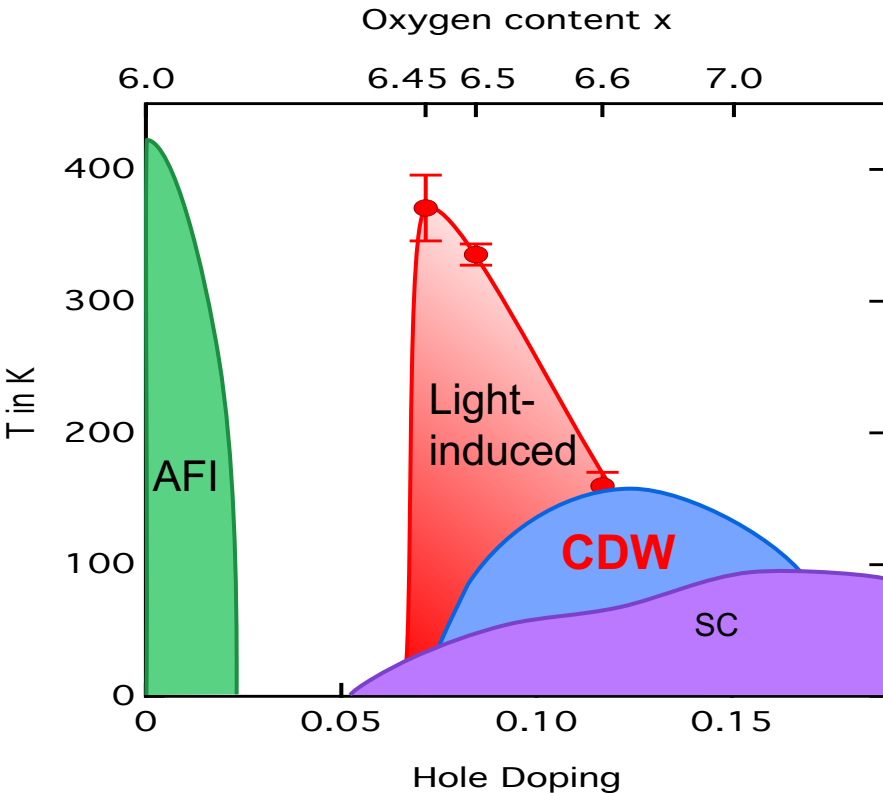


R. Mankowsky *et al.*,
Nature **516**, 71 (2014)

See also:
W. Hu *et al.*, Nat. Mater. **13**, 705 (2014)



But also: Partial Melting of competing CDW phase

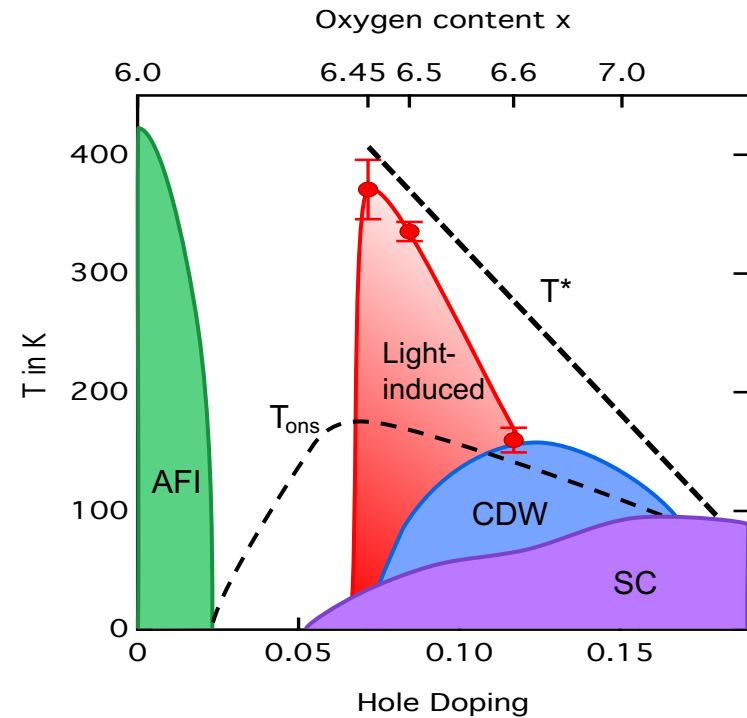
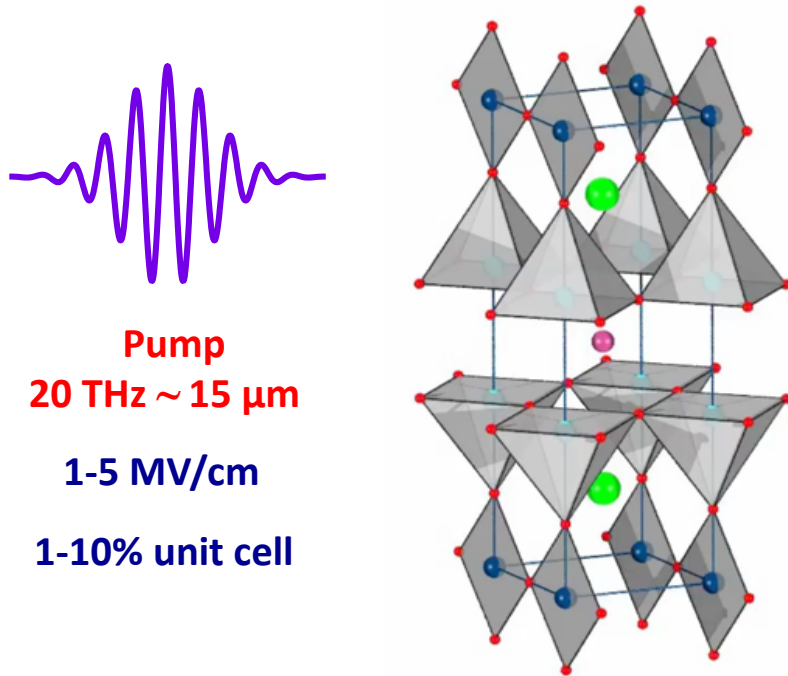


Soft X-Ray Diffraction Probe

M. Först et al., Phys. Rev. B 90, 184514 (2014)



Optically-Driven Superconductivity in YBCO: The status in 2016



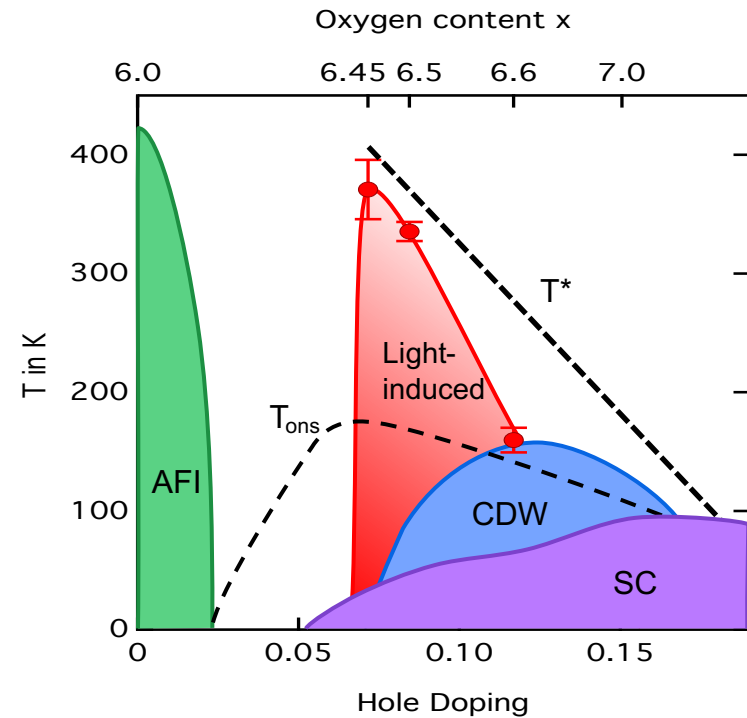
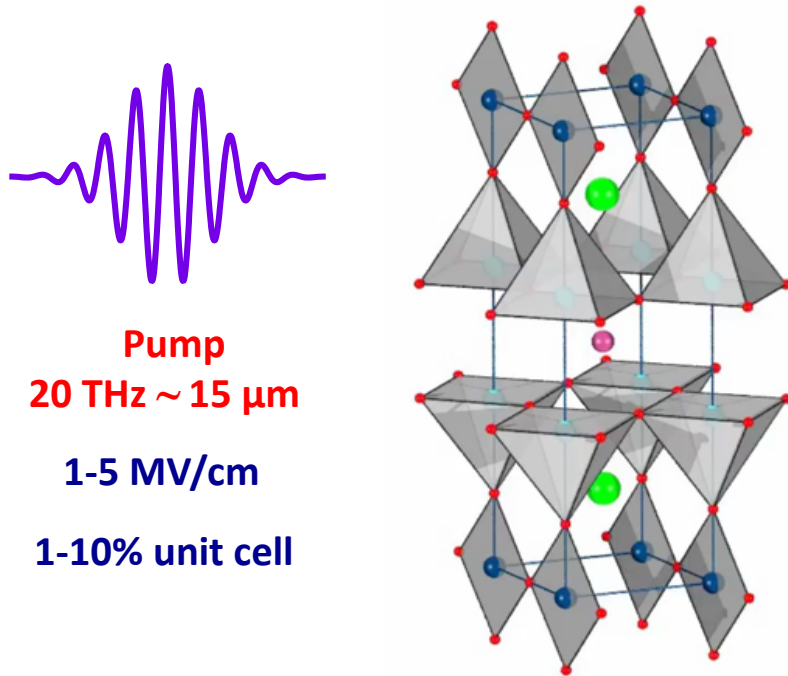
Resonant excitation of apical oxygen phonon $\rightarrow$
optically-driven superconductivity in underdoped YBCO

Lattice is transiently displaced $\rightarrow$
Staggered motion of the layers

Optical melting of competing
Charge-density-wave



Optically-Driven Superconductivity in YBCO: The status in 2016

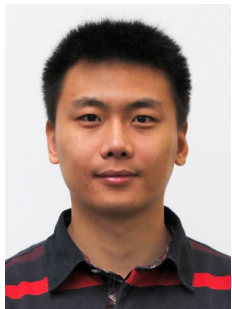
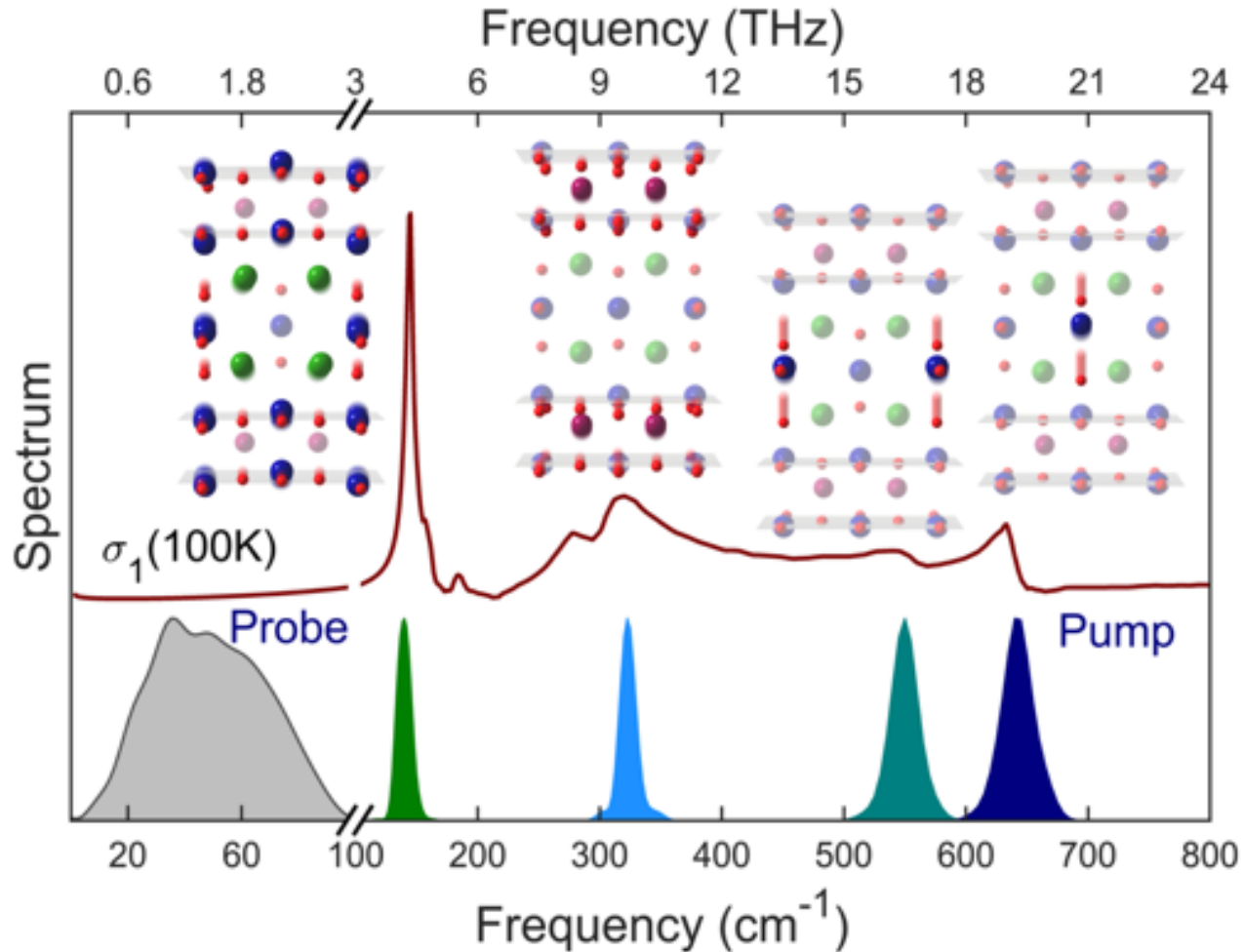


Resonant excitation of apical oxygen phonon $\rightarrow$
optically-driven superconductivity in underdoped YBCO

Is this response specific to apical oxygen excitation?

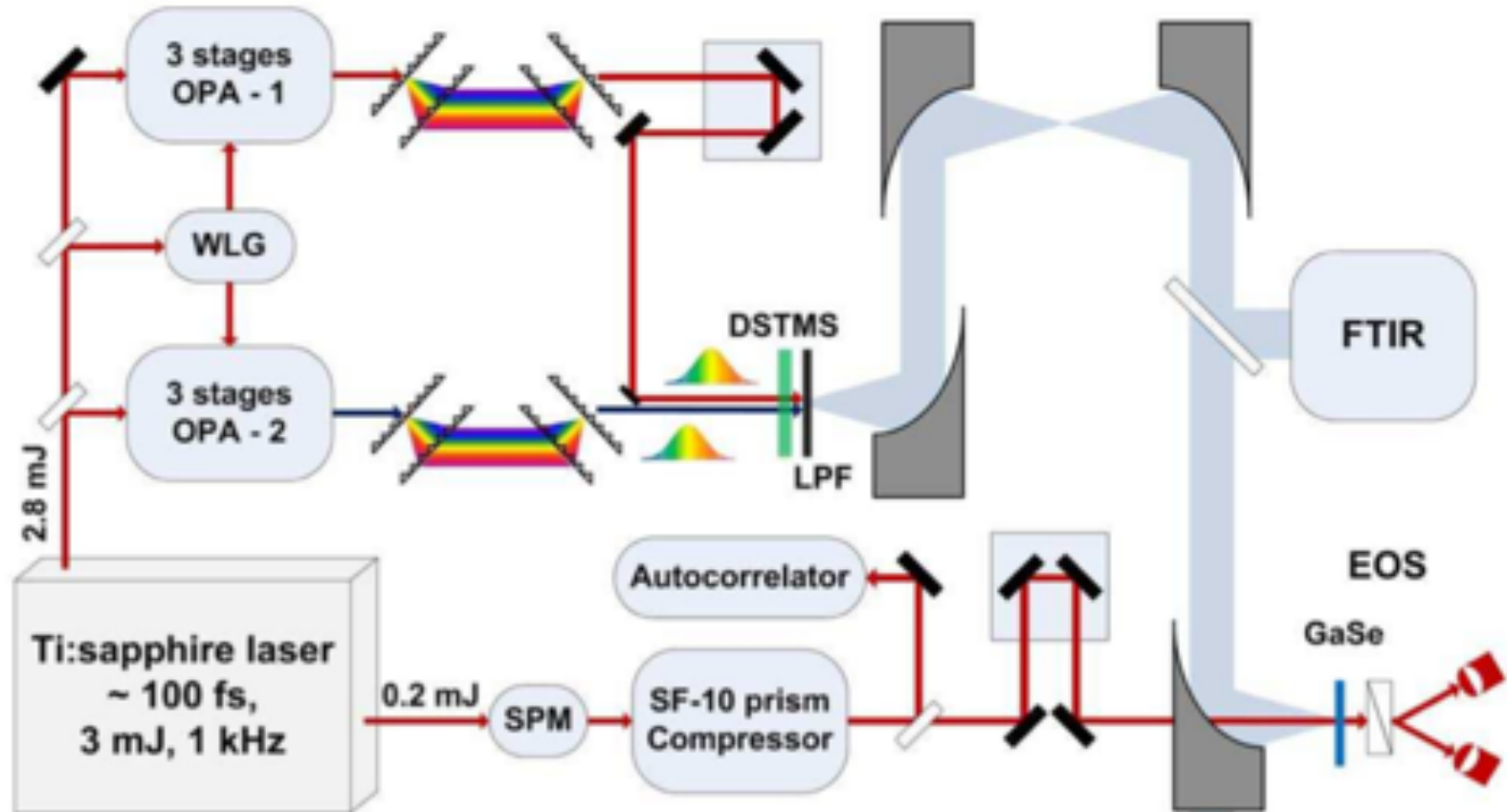
Recent Advance #1

Goal: Tune the pump wavelength widely and selectively

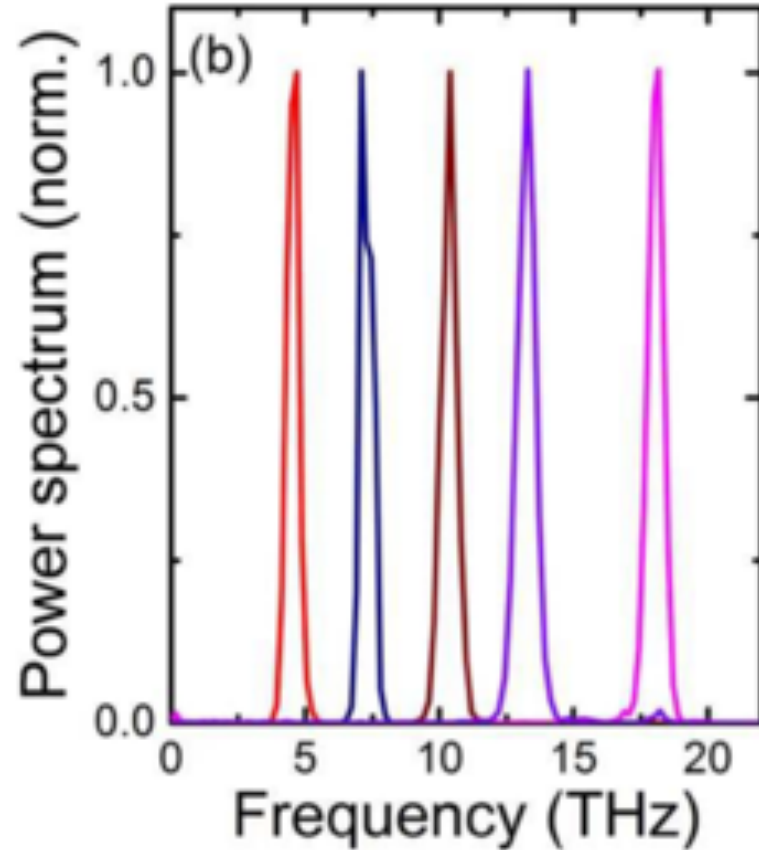
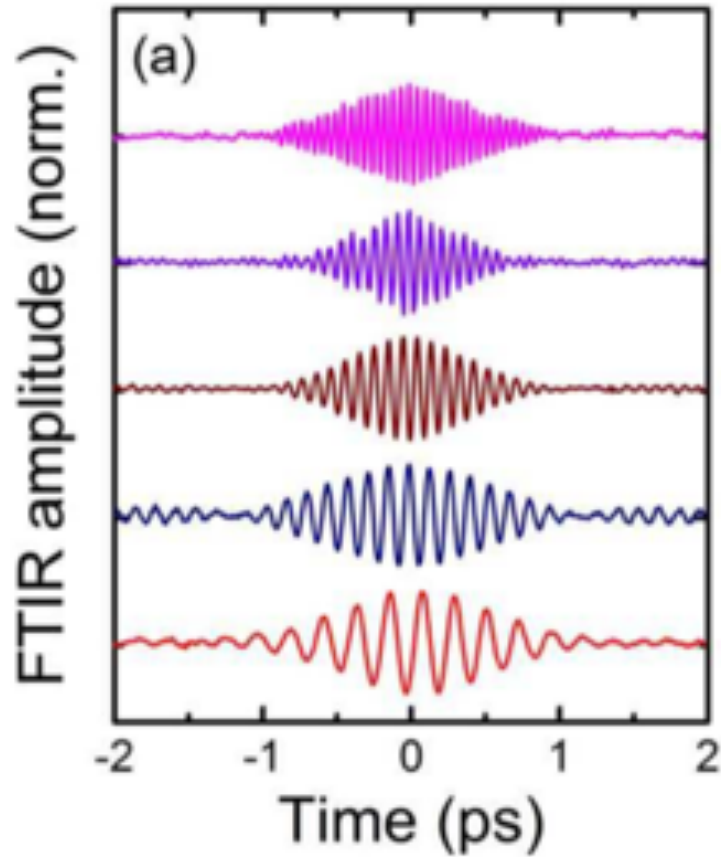


Biaolong Liu

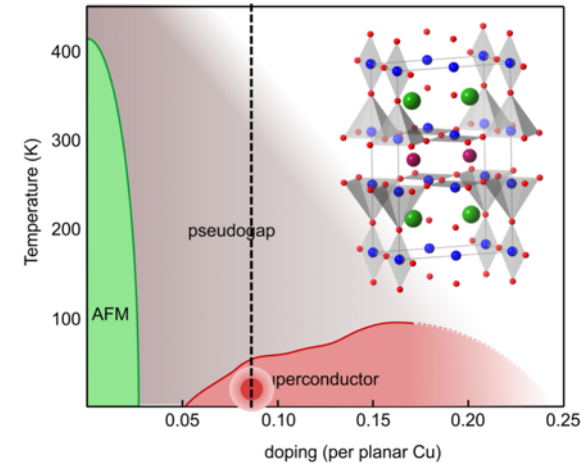
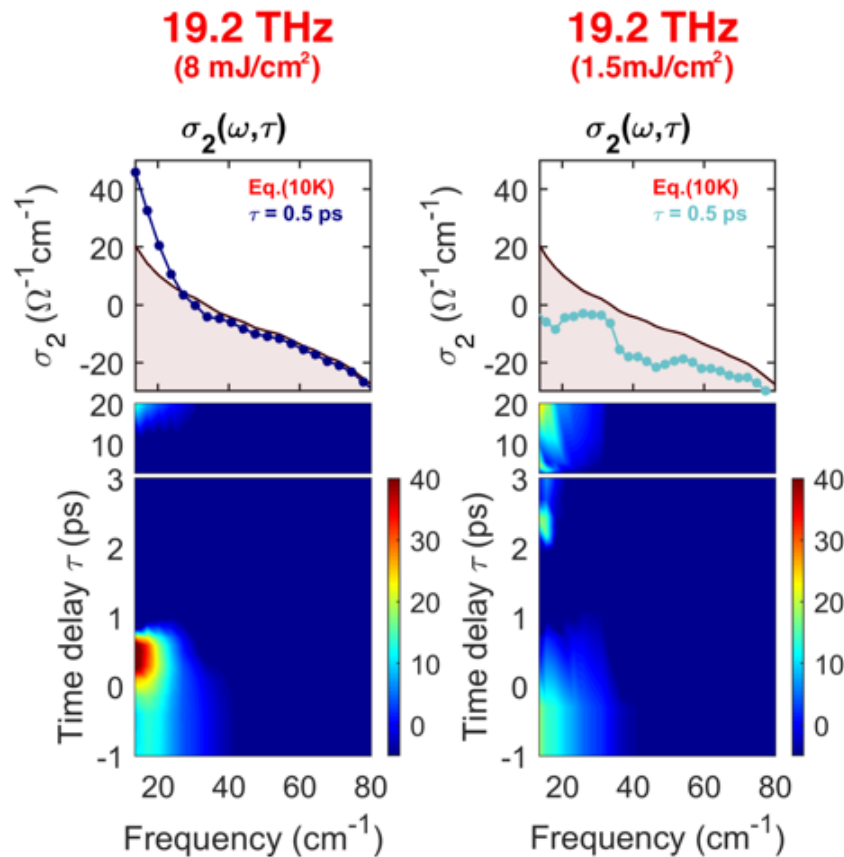
A tunable, narrowband THz pump



A tunable, narrowband THz pump



Check #1 - Transiently enhanced superconductivity below T_C : Short-lived and only for fluences $\gtrsim 4 \text{ mJ/cm}^2$



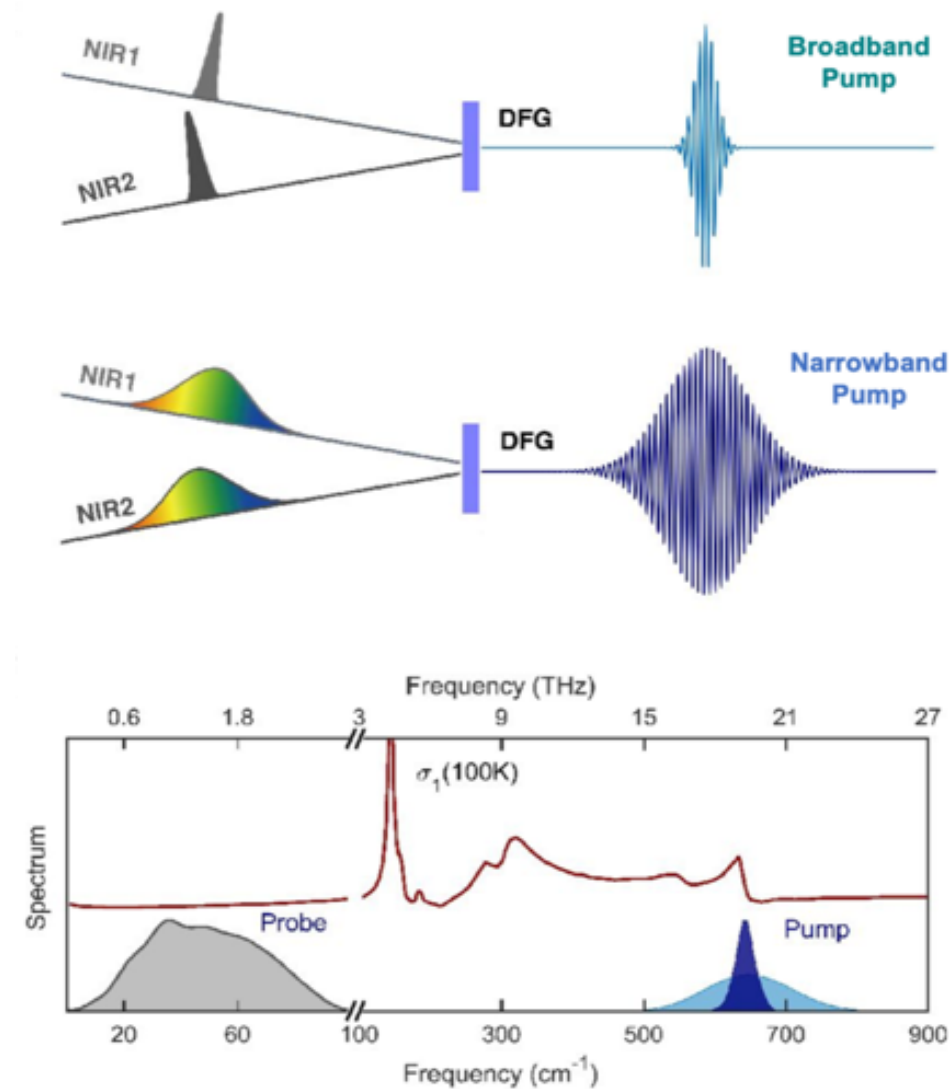
Different excitation regime than in S. J. Zhang et al., arXiv:1904.10381 (2019)

See talk by N. L. Wang later today

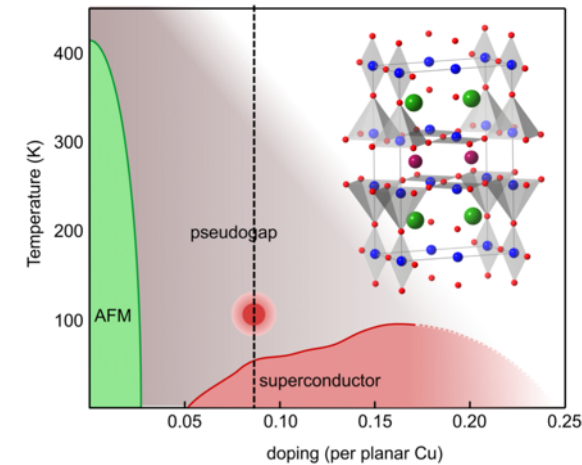
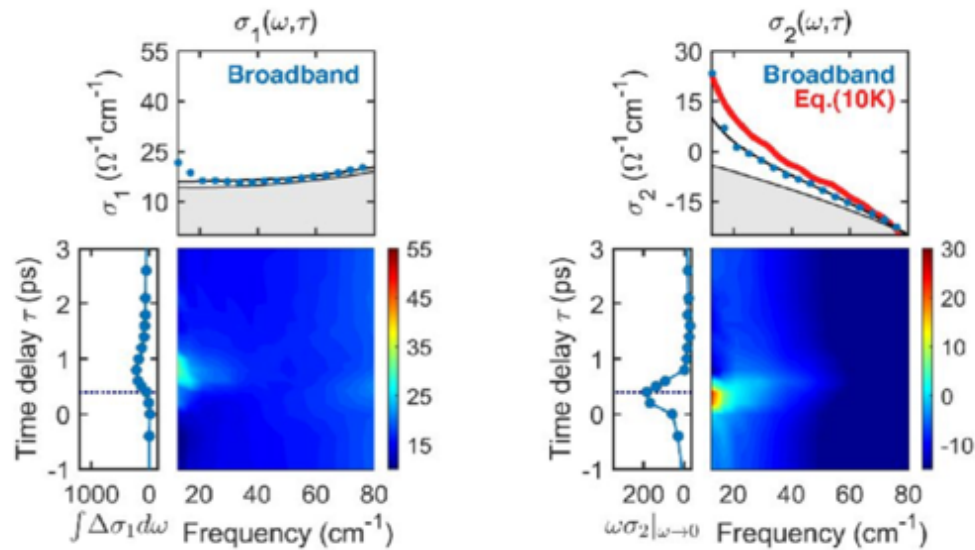
B. Liu et al., arXiv:1905.08356 (2019)



Check #2 - Apical oxygen excitation above T_C broadband vs narrowband



Check #2 - Apical oxygen excitation above T_C broadband vs narrowband



Dissipative Response

$$\propto \int \sigma_1(\omega) d\omega$$

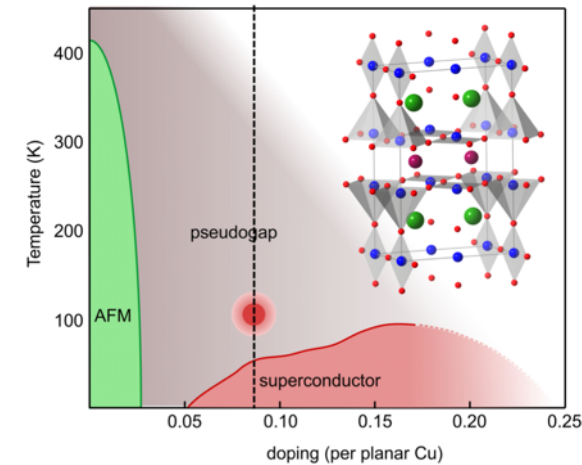
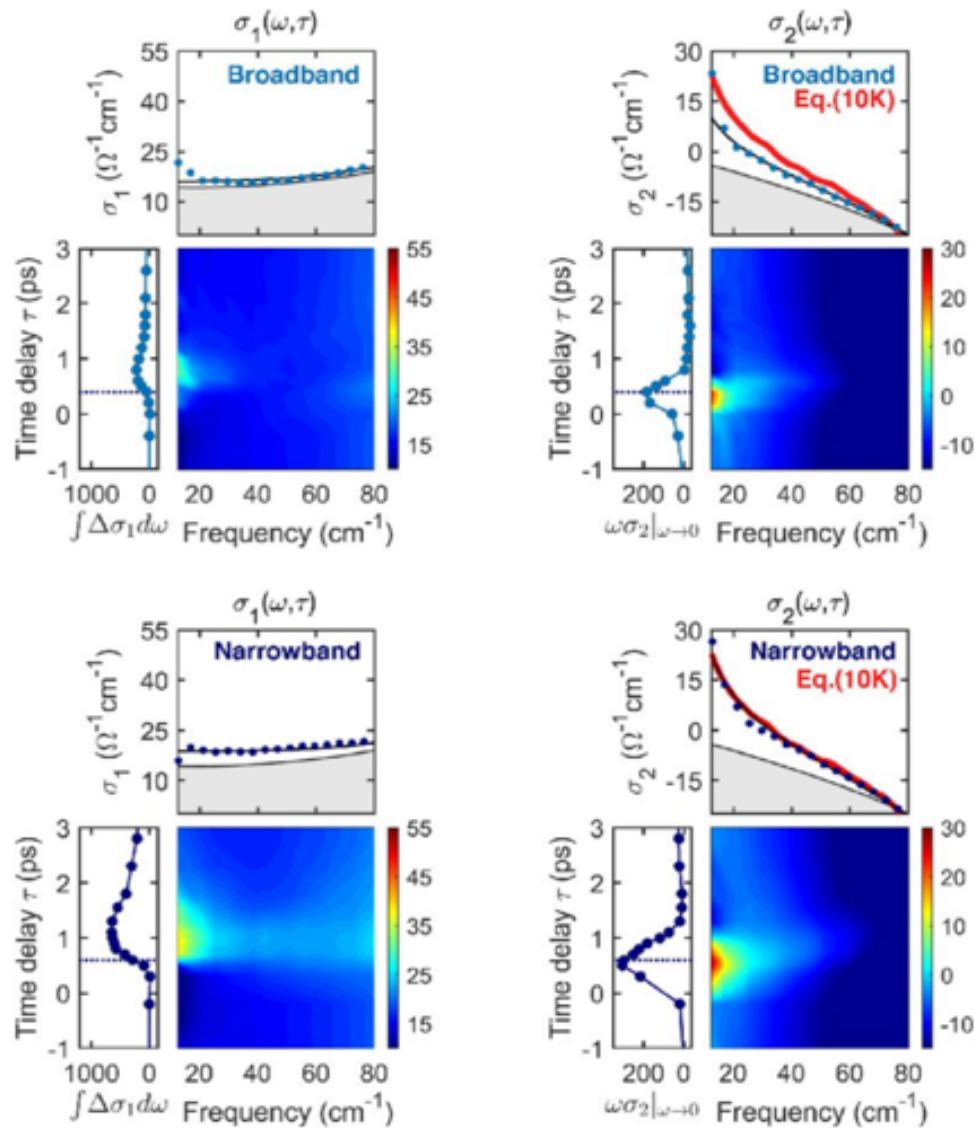
Superconducting – like
Coherent Response

$$\propto (\omega \sigma_2)_{\omega \rightarrow 0}$$



Check #2 - Apical oxygen excitation above T_C

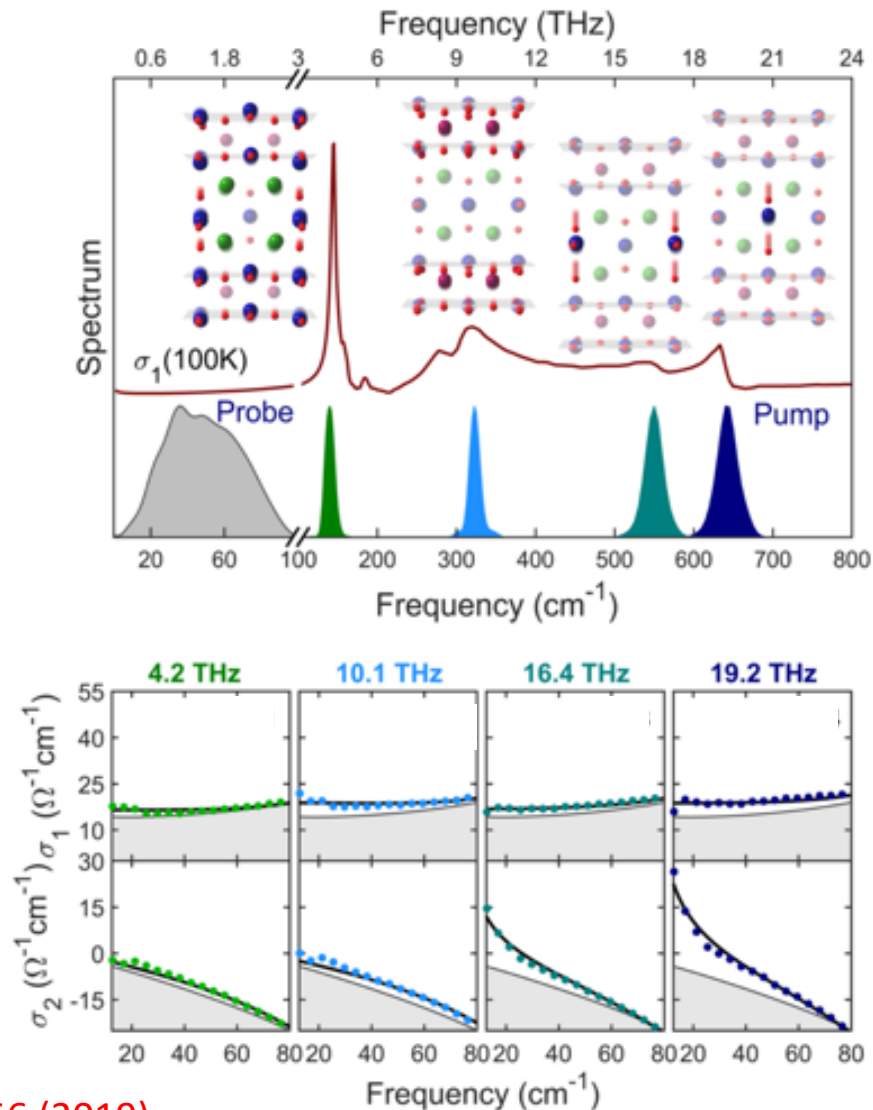
Resonant narrowband excitation more effective



Same pump fluence
 $\sim 8 \text{ mJ/cm}^2$

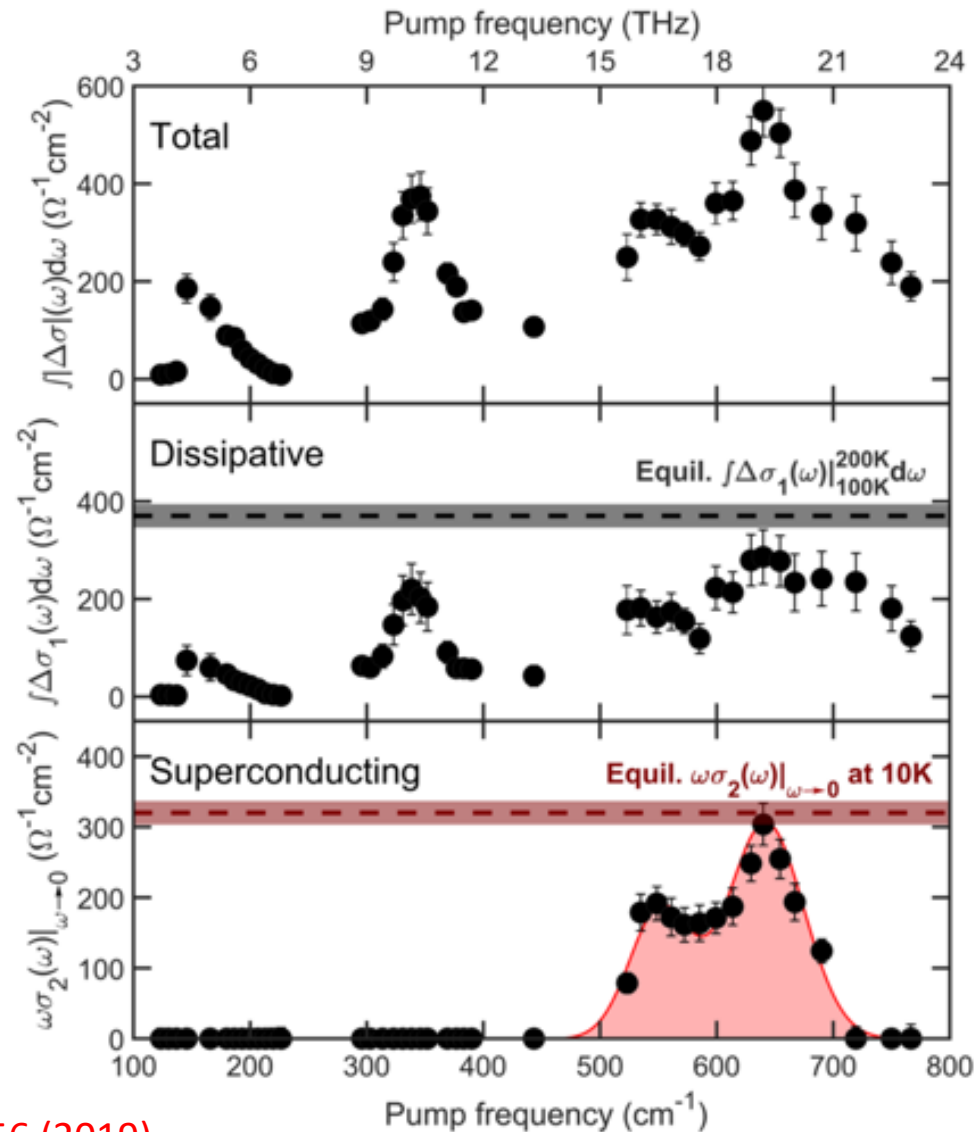


Which phonons enhance superconductivity ?

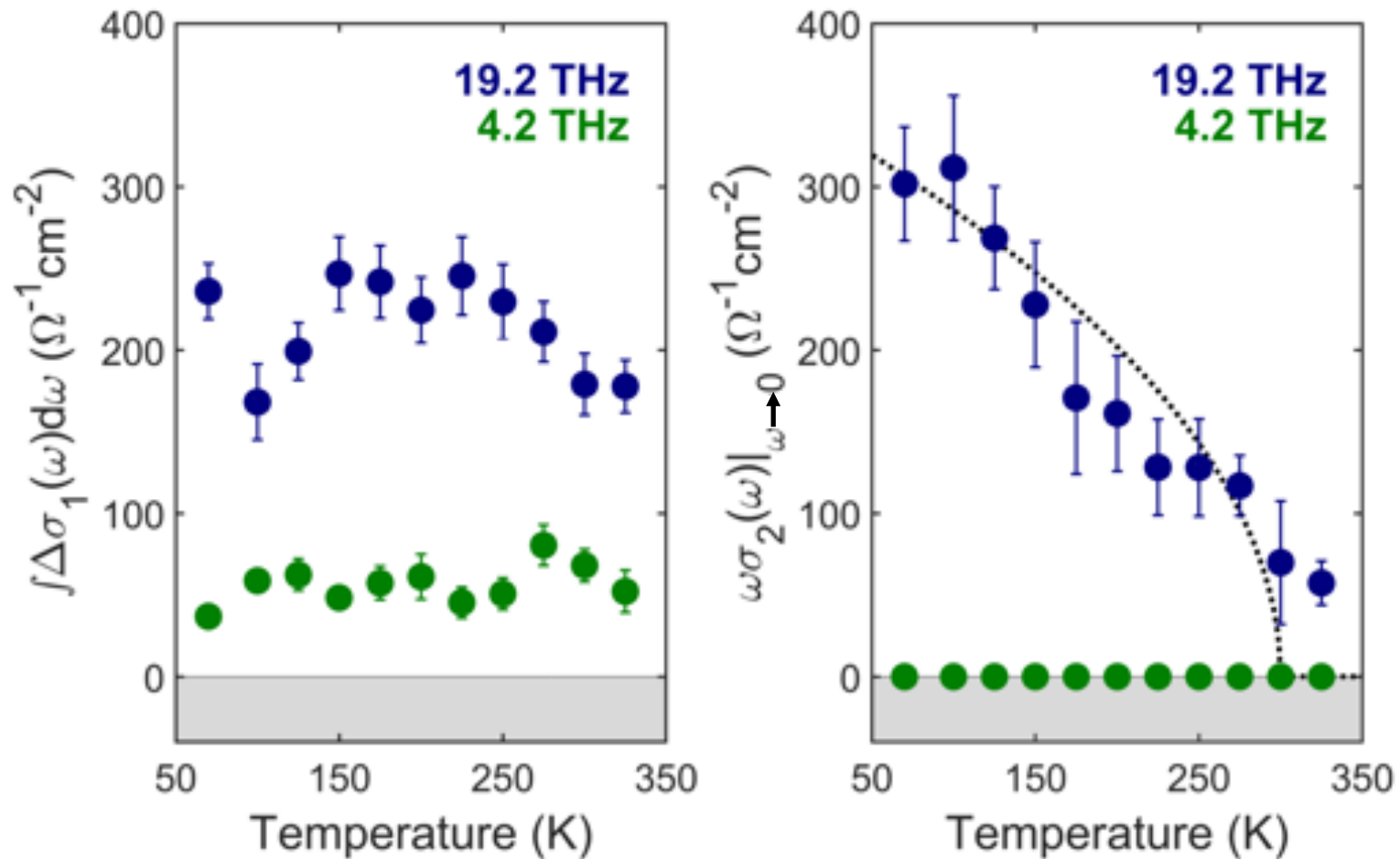


Only apical oxygen phonons work

Constant pump fluence
($\sim 8 \text{ mJ/cm}^2$)
& peak electric field
($\sim 3 \text{ MV/cm}$)

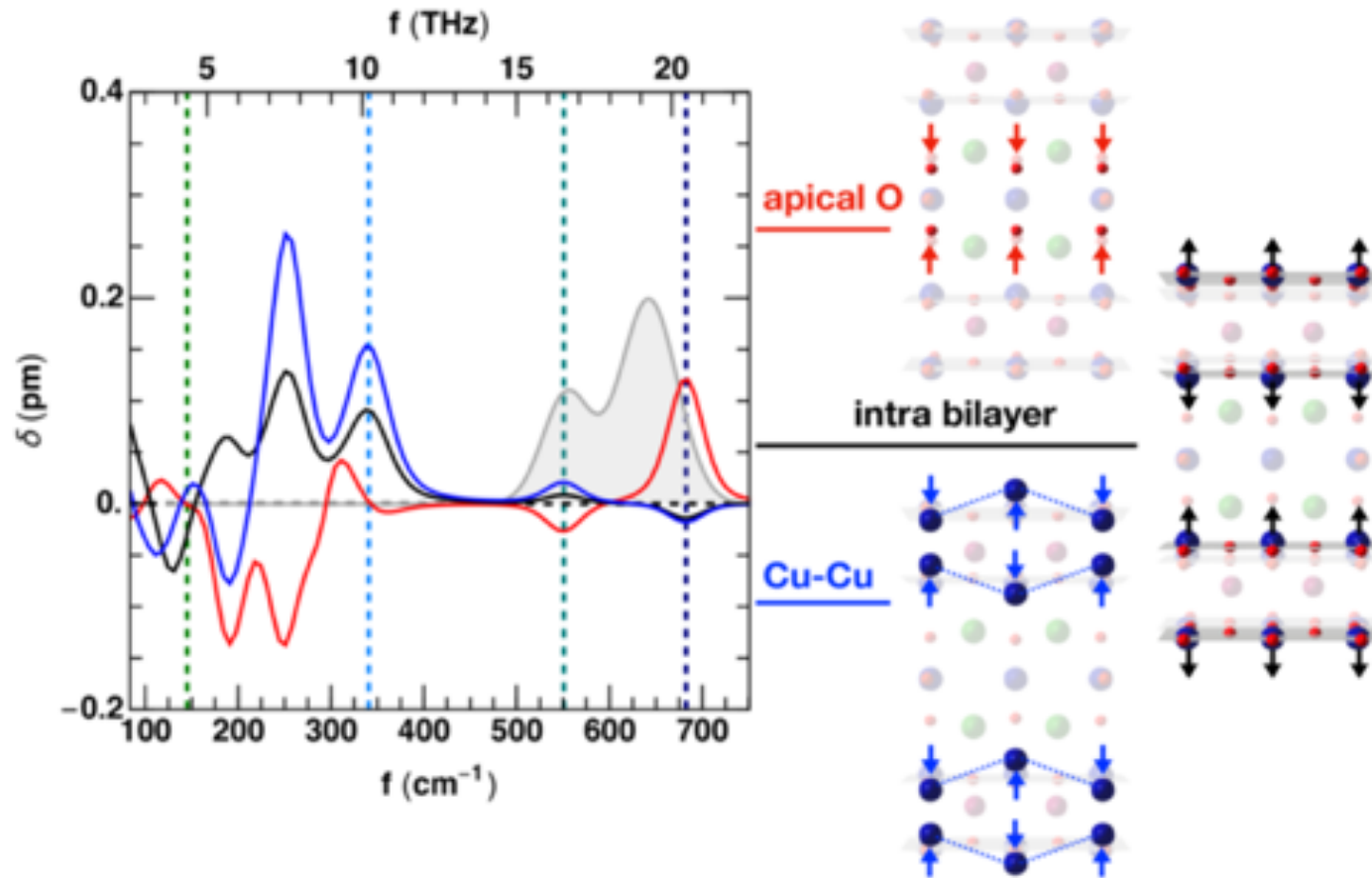


Only apical oxygen phonons work



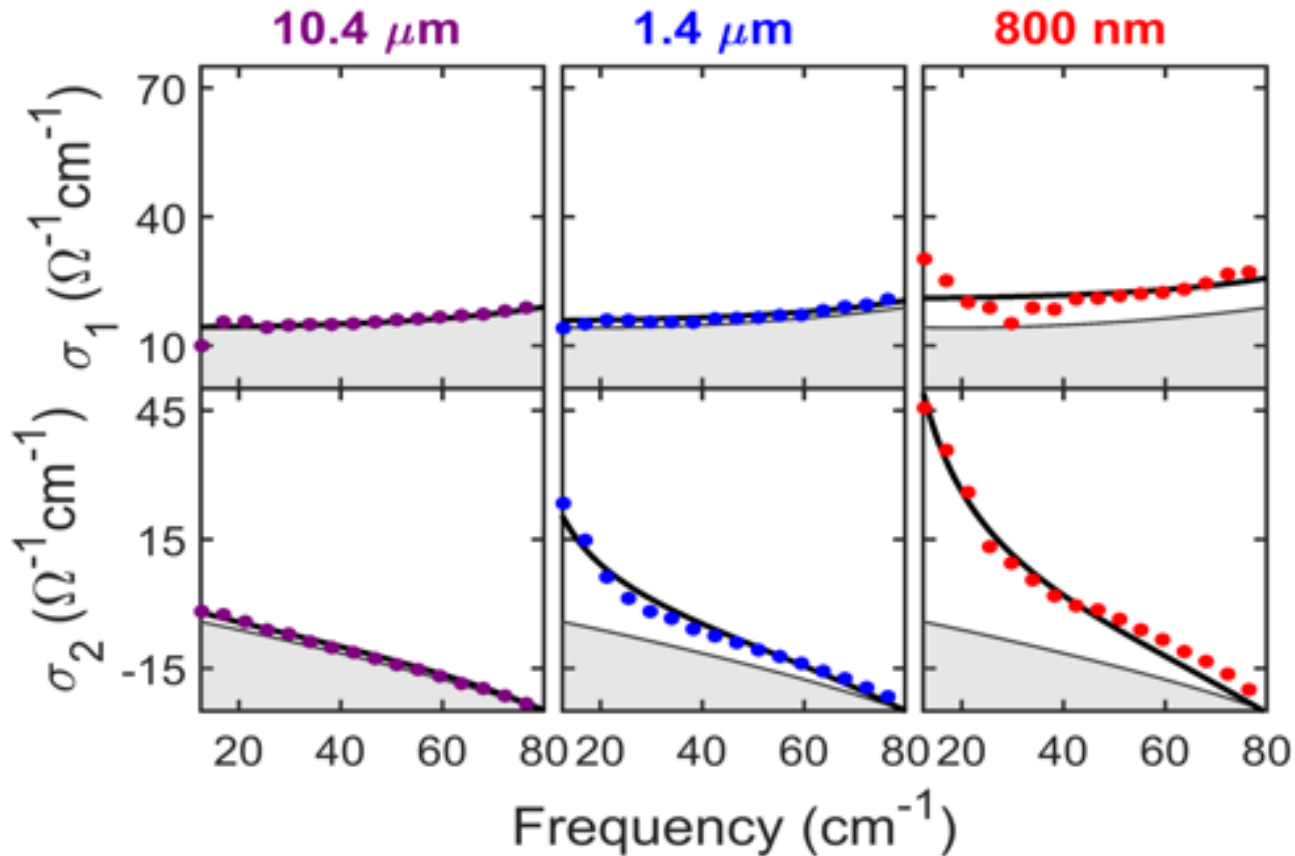
but... Calculated lattice displacements: no clear trend

Ab-initio calculation of $Q_{\text{IR}}^2 Q_{\text{Raman}}$ coupling



Calculations by Michael Fechner

and... high-energy charge excitation in the near-IR also works



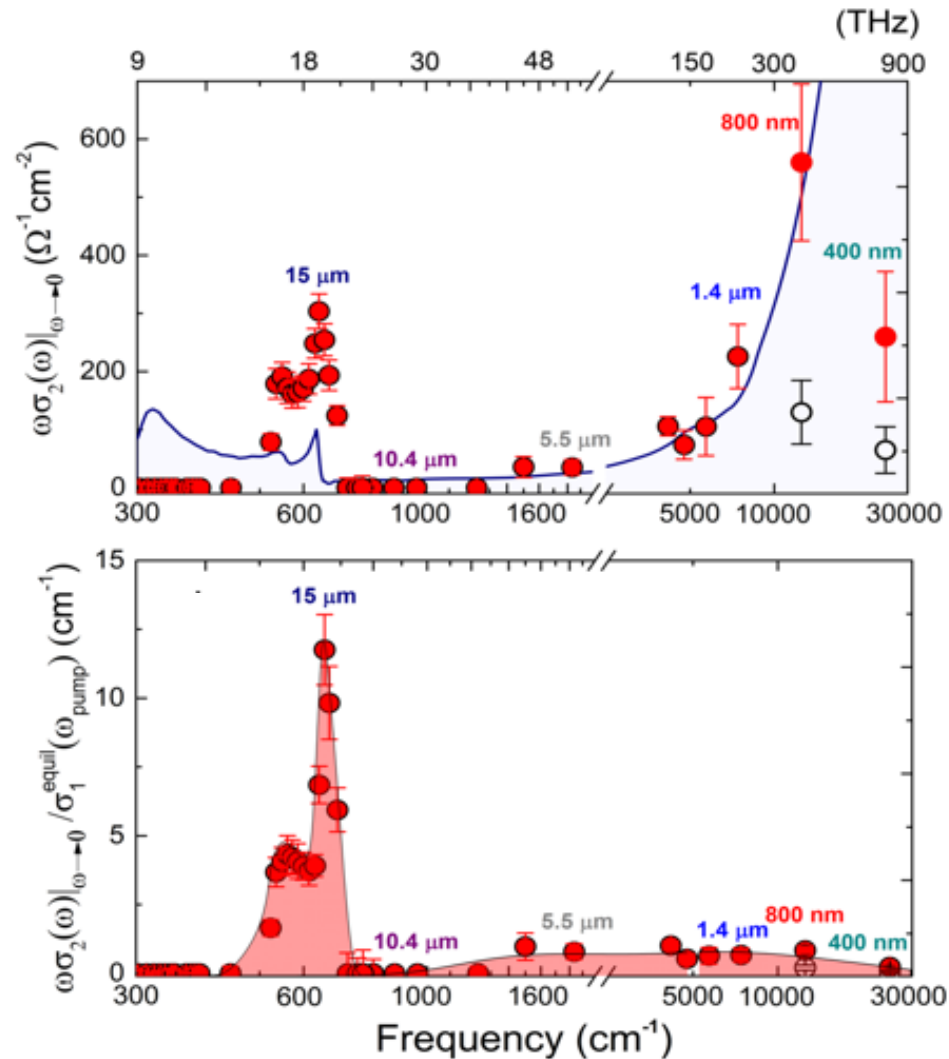
See also:

S. J. Zhang et al., arXiv:1904.10381 (2019)

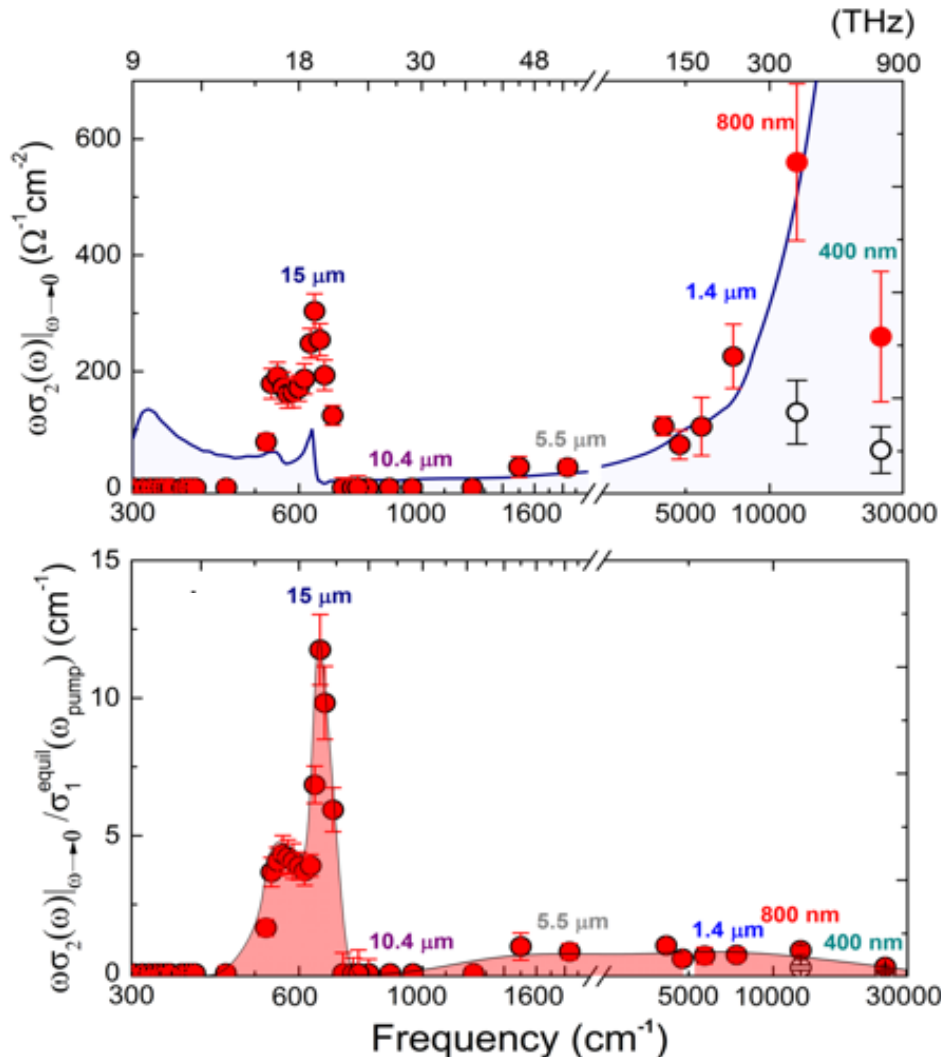
B. Liu *et al.*, arXiv:1905.08356 (2019)



A new pump frequency resonance in the near-IR



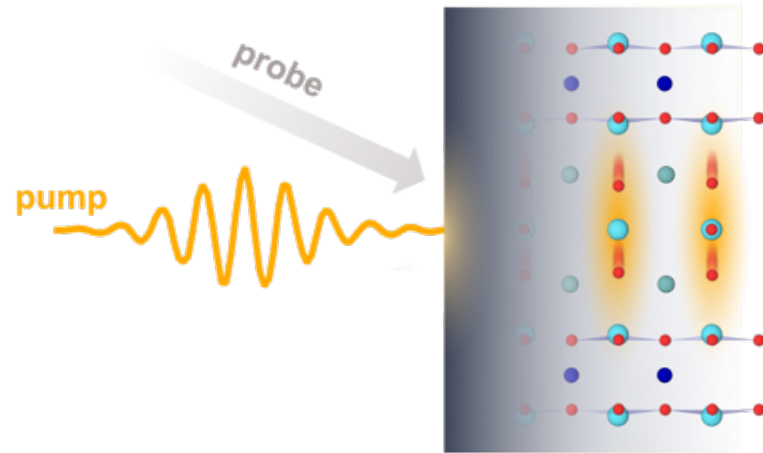
Optically-driven superconductivity in YBCO: Summary



- Two pump frequency resonances
- CDW melting & Lattice displacement may not play a fundamental role
- Key: Changes in the electronic properties of the planes?



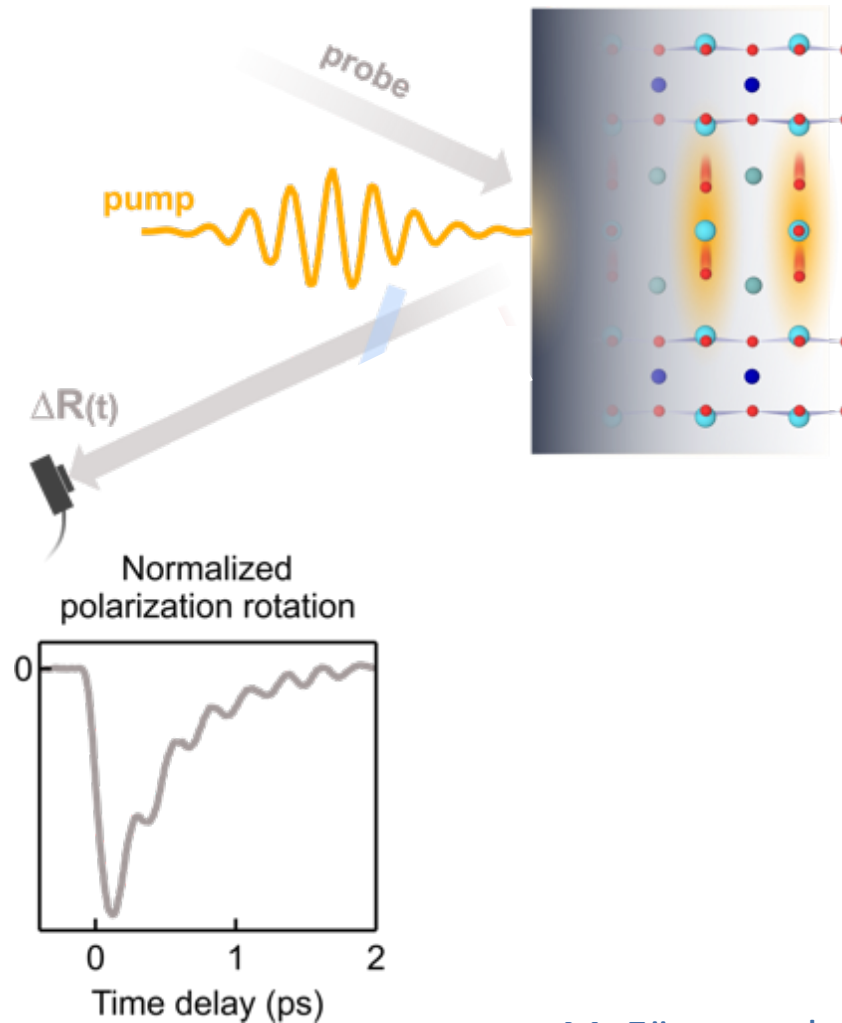
Recent Advance #2



How do the apical oxygen phonons couple to electronic coherences?

Can one observe coherently-driven supercurrents in real time?

Time-resolved Optical Reflectivity: Raman Modes

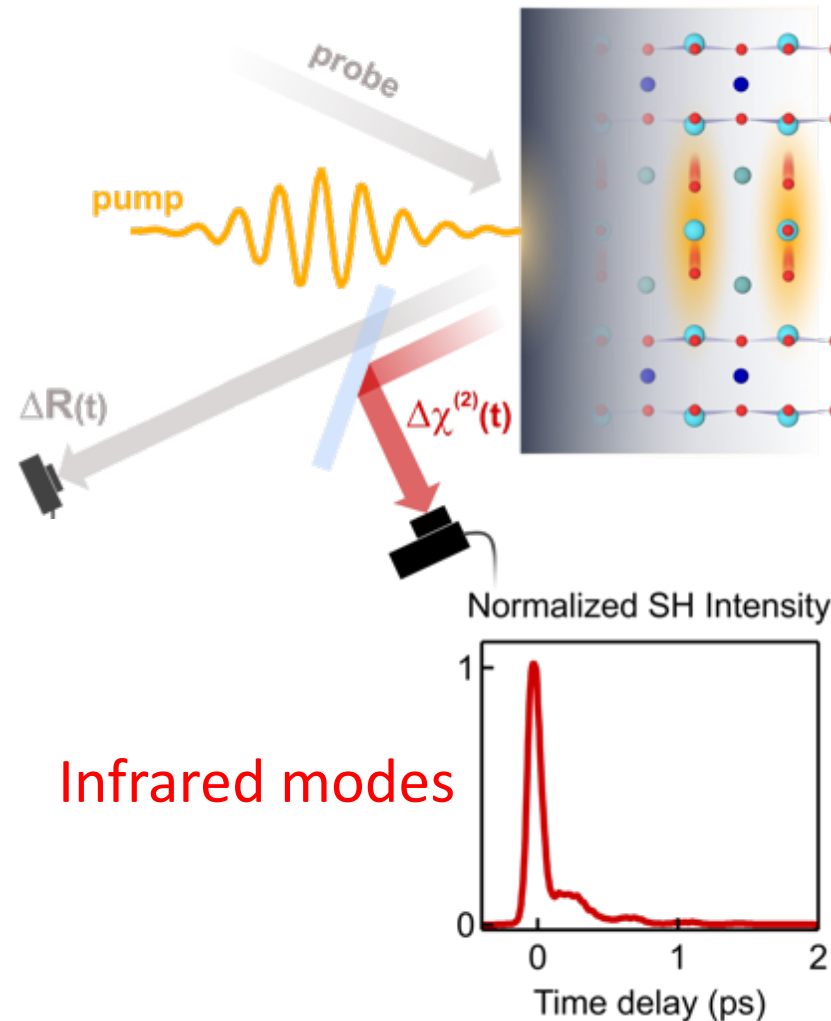


Raman modes

M. Först et al. *Nature Physics* **7**, 854 (2011)
R. Mankowsky *et al.*, *Nature* **516**, 71 (2014)



Time-resolved Second Harmonic Generation: Coherent IR-active modes



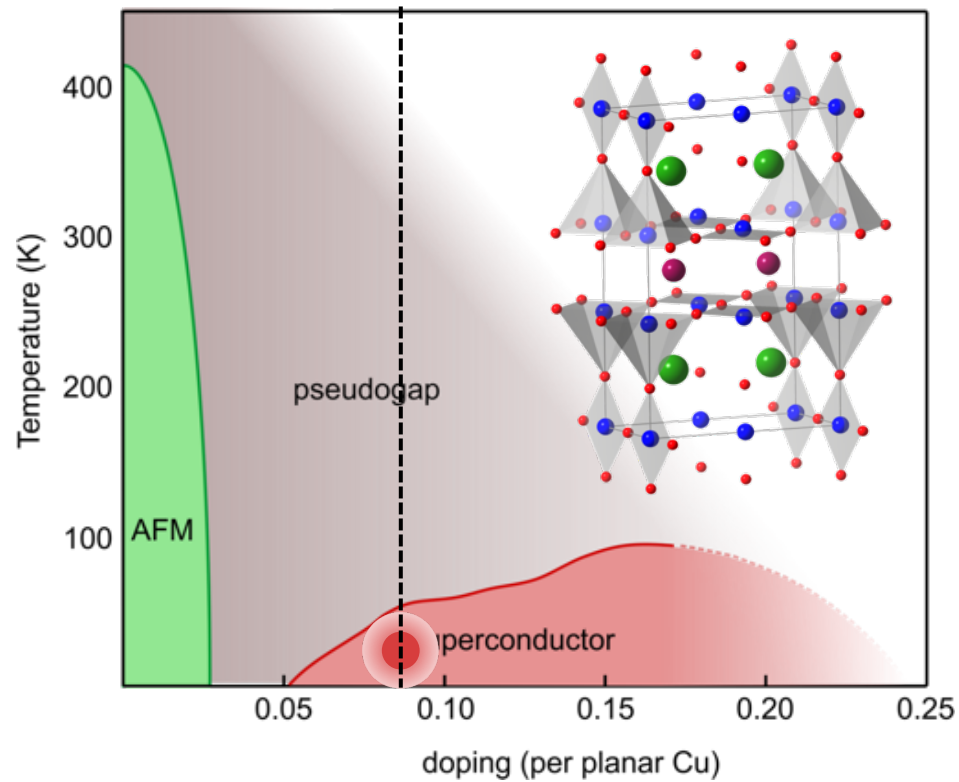
Alex von Hoegen

Infrared modes

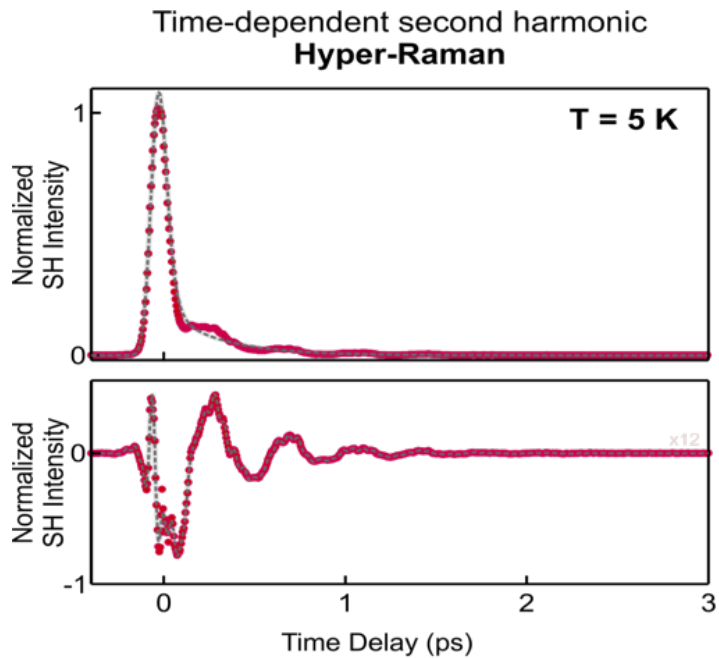
Static SHG on YBCO:
L. Zhao *et al.*,
Nat. Phys. 13, 250 (2017)



$\text{YBa}_2\text{Cu}_3\text{O}_{6.5}$ at $T < T_c$

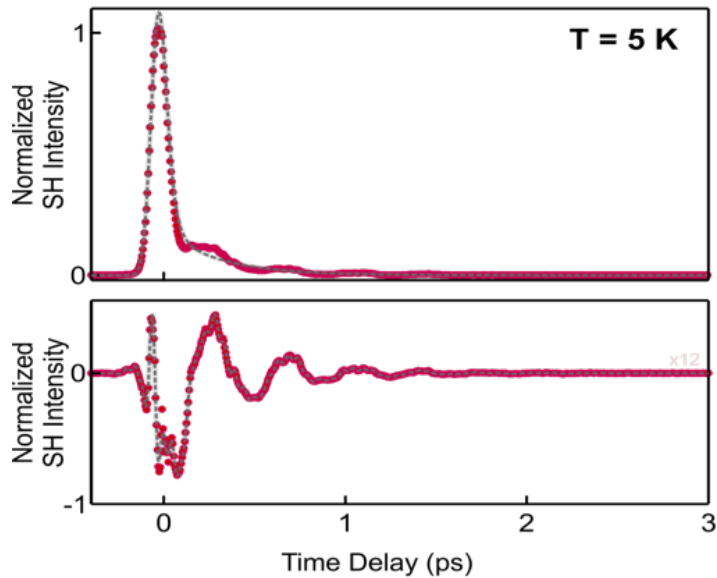


Coherent infrared modes

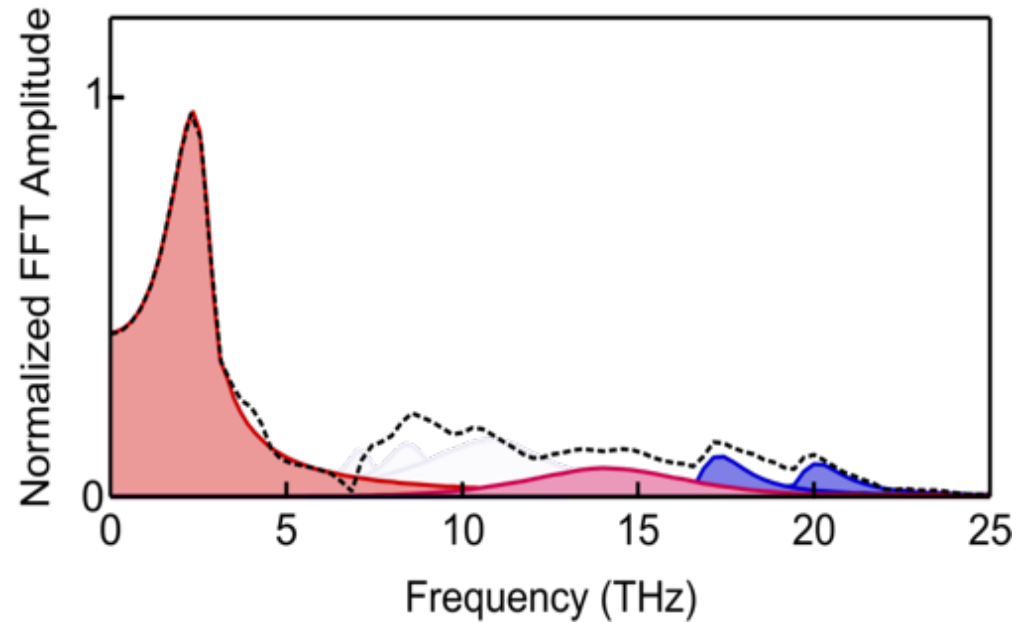


Coherent infrared modes

Time-dependent second harmonic
Hyper-Raman

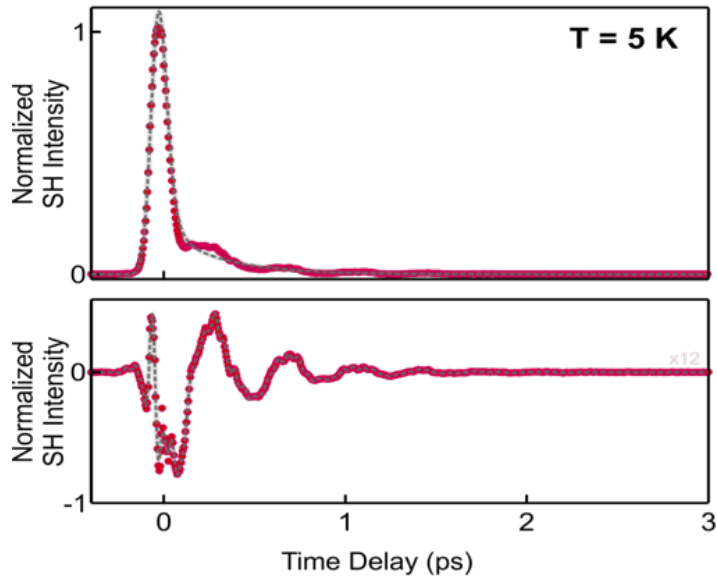


Coherent infrared mode spectrum

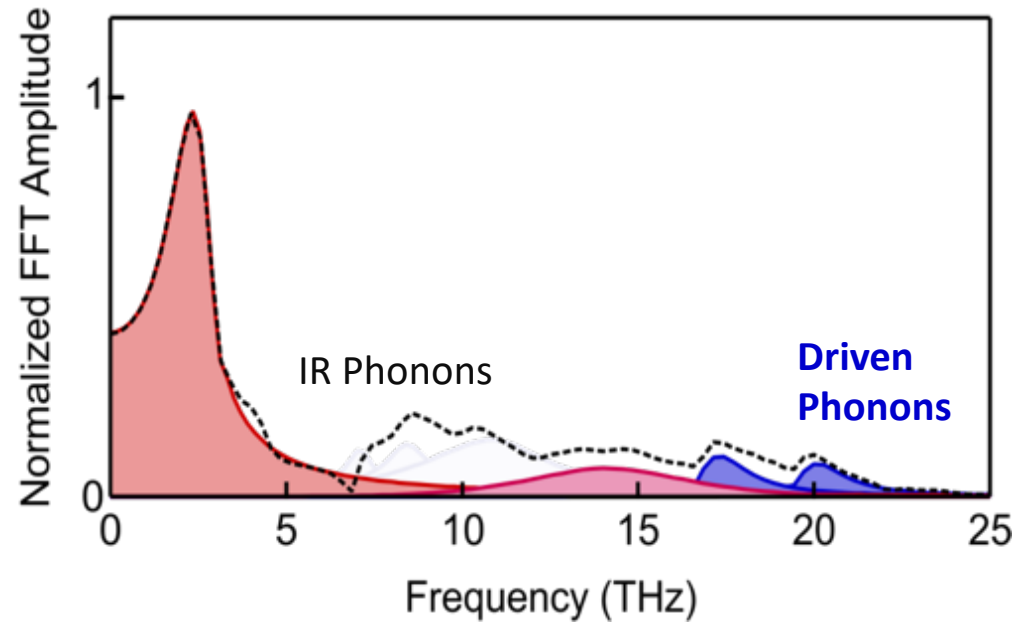


I see odd phonons...

Time-dependent second harmonic
Hyper-Raman

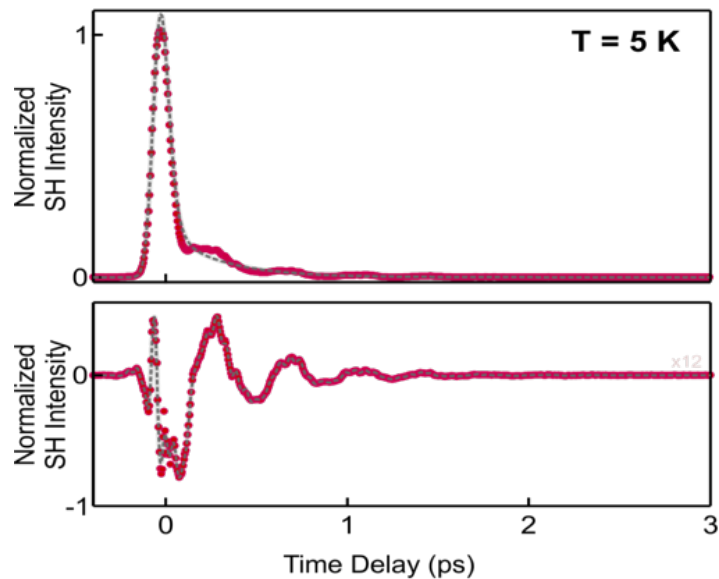


Coherent infrared mode spectrum

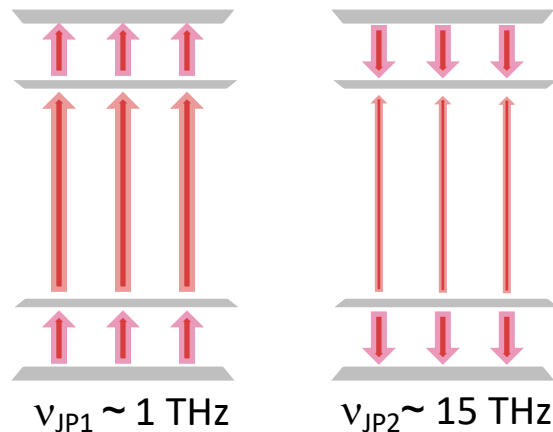
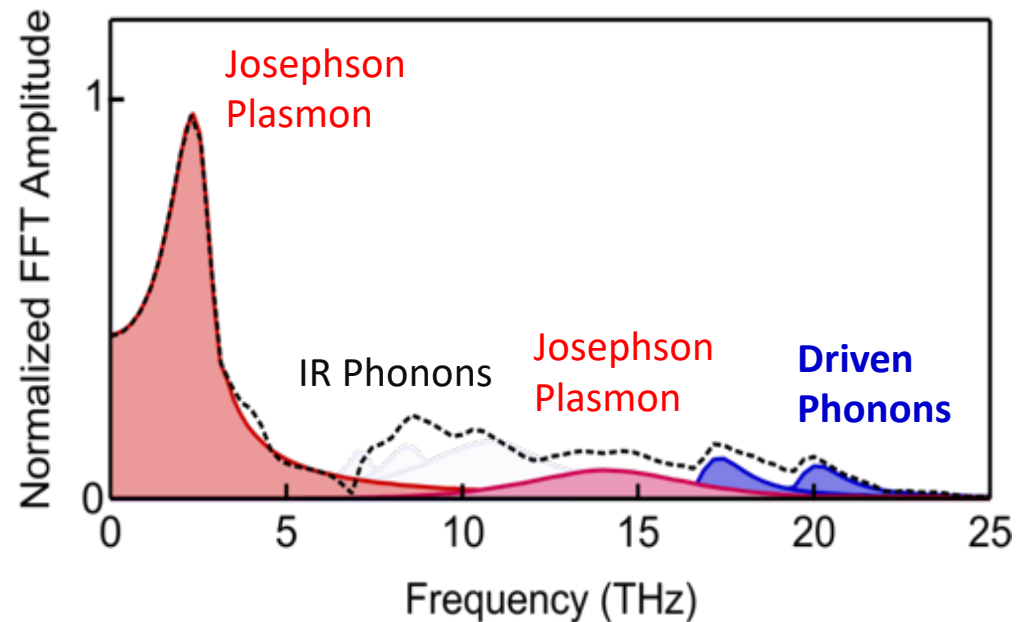


I see odd phonons and Josephson Plasma modes

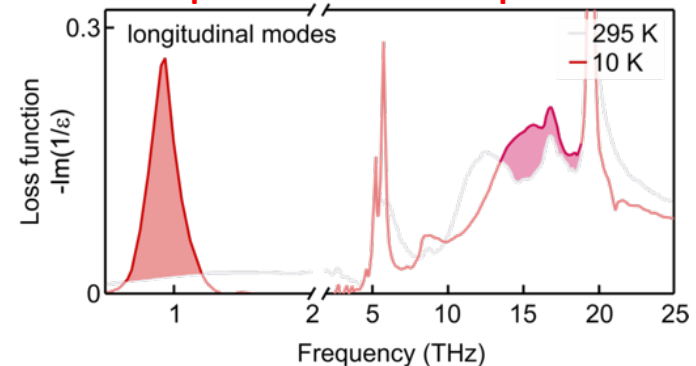
Time-dependent second harmonic
Hyper-Raman



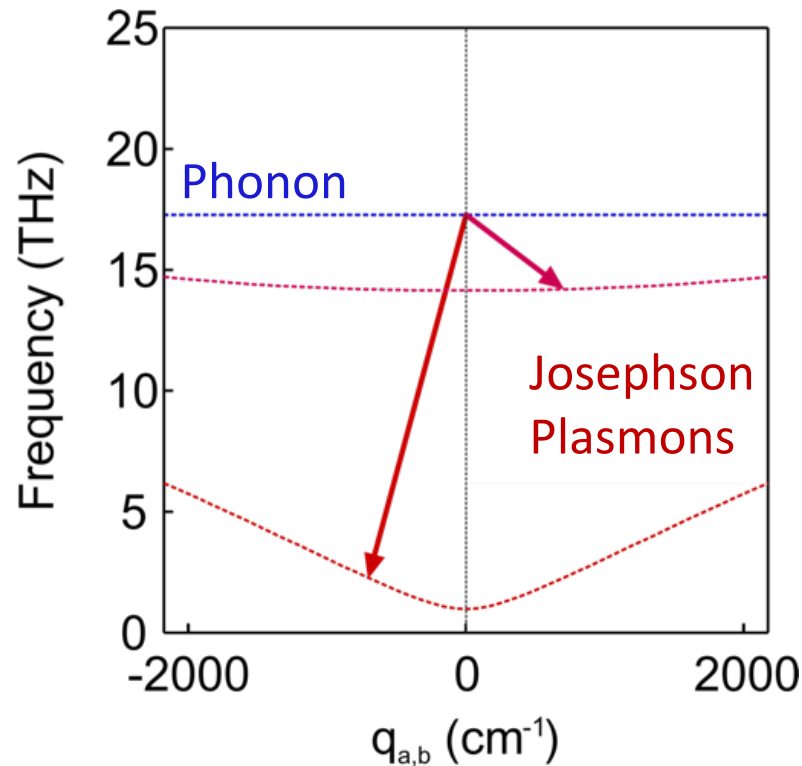
Coherent infrared mode spectrum



Equilibrium Infrared Spectrum



Driven phonon mixes with two plasmons at finite q?



$$\omega_{J1}(q_{plas}) + \omega_{J2}(-q_{plas}) = \omega_{phonon}$$

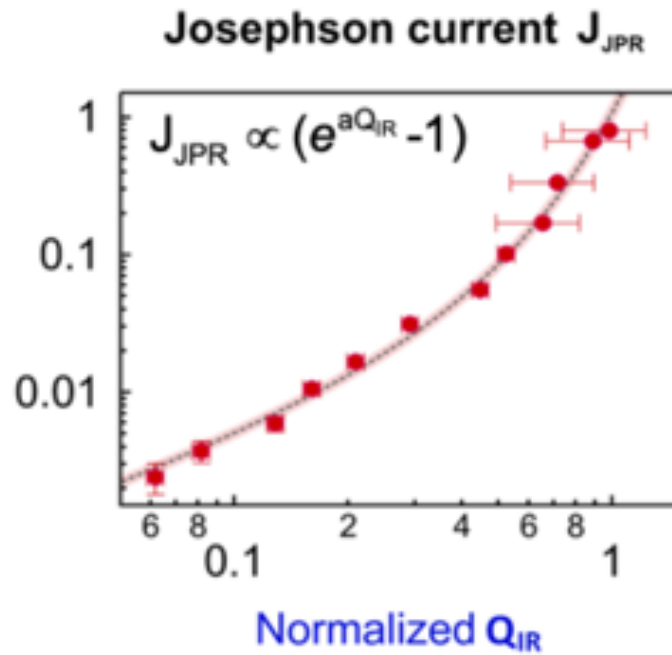
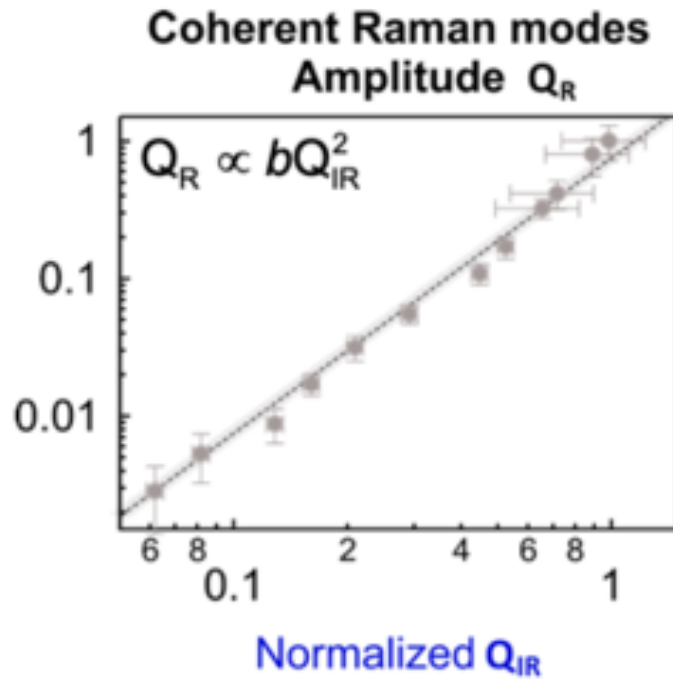
with Michael Fechner,
Marios Michael, Eugene Demler

see also:
S. Denny et al. Phys. Rev. Lett **114**, 137001 (2016)

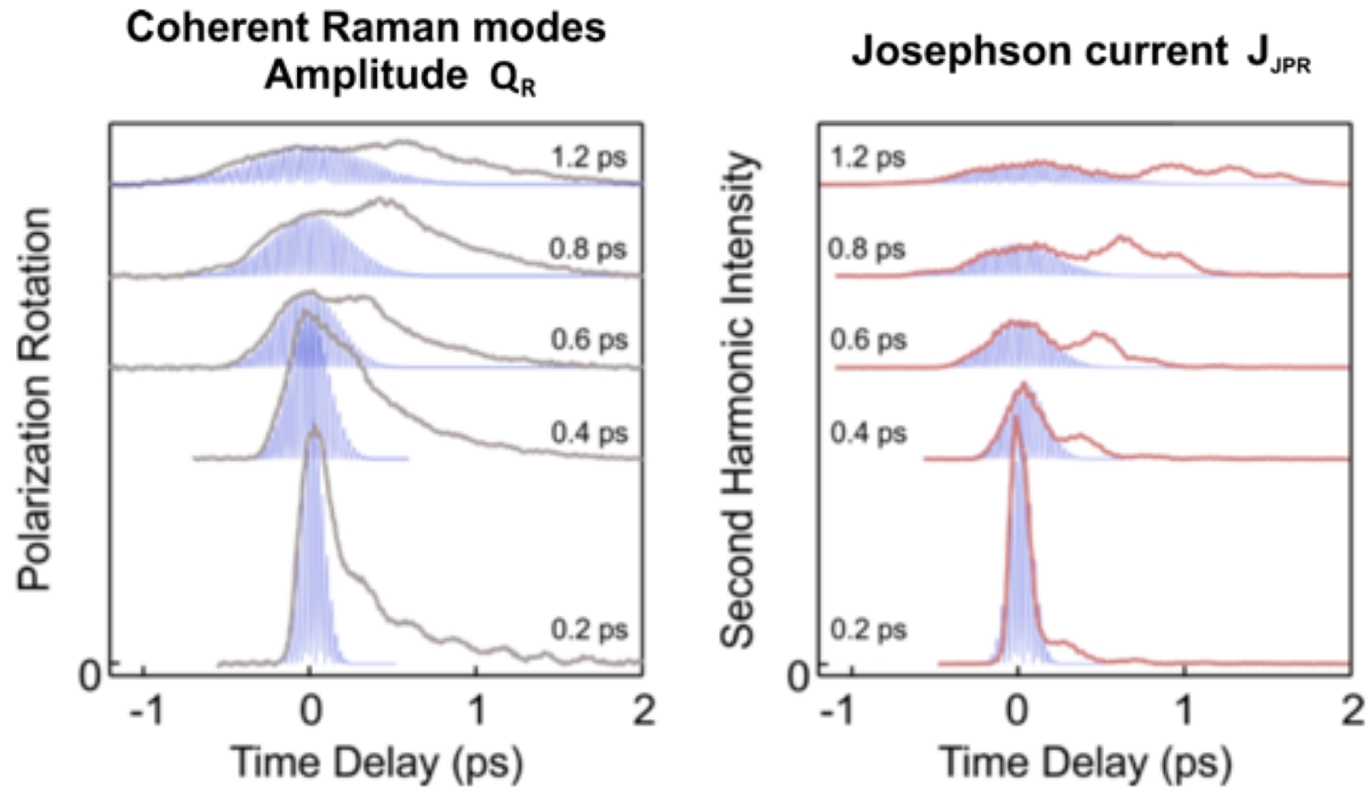
See talk by Marios Michael on Thursday



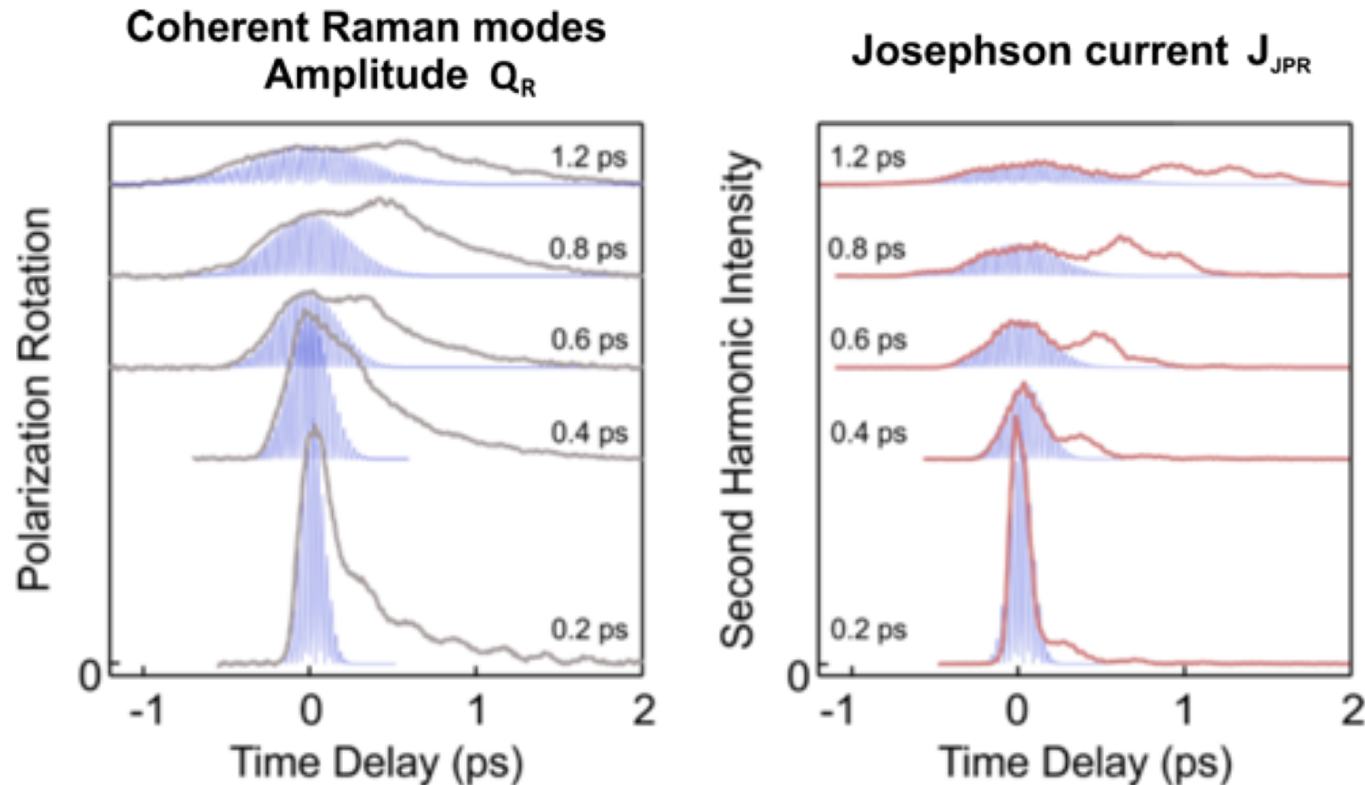
Exponential gain vs Q_{IR} amplitude



Oscillations survive for increasing pulse length

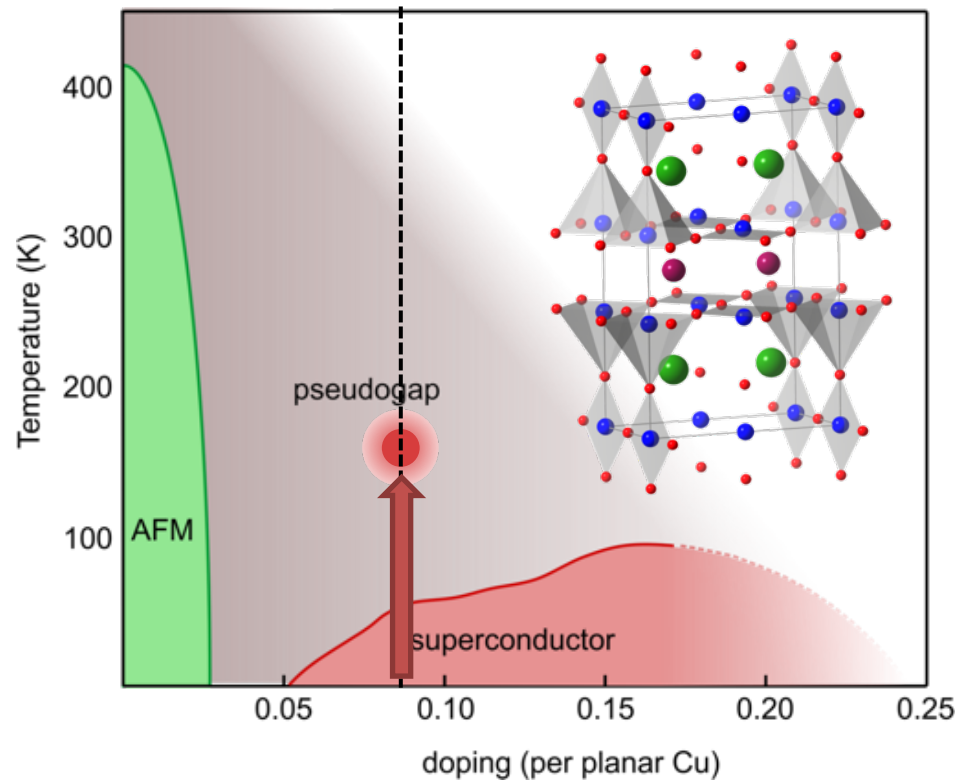


Oscillations survive for increasing pulse length

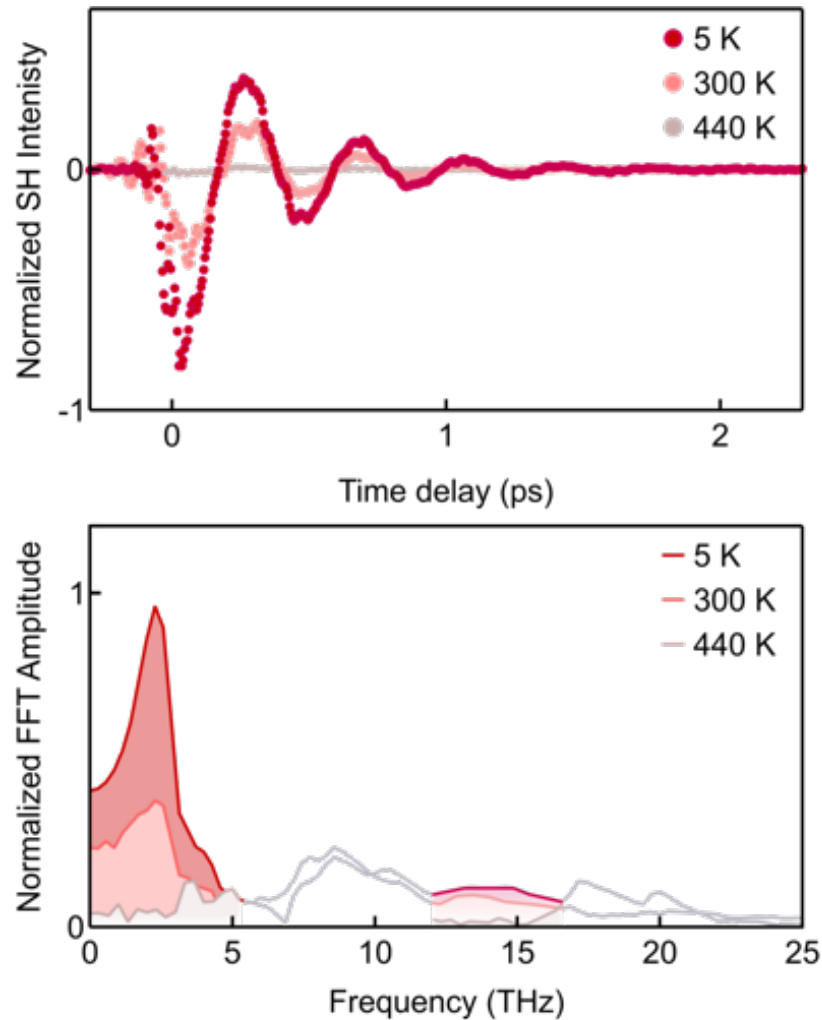


Parametrically driven Josephson oscillations?

Same experiment at higher temperatures



Josephson oscillations persist in the normal state



See also:

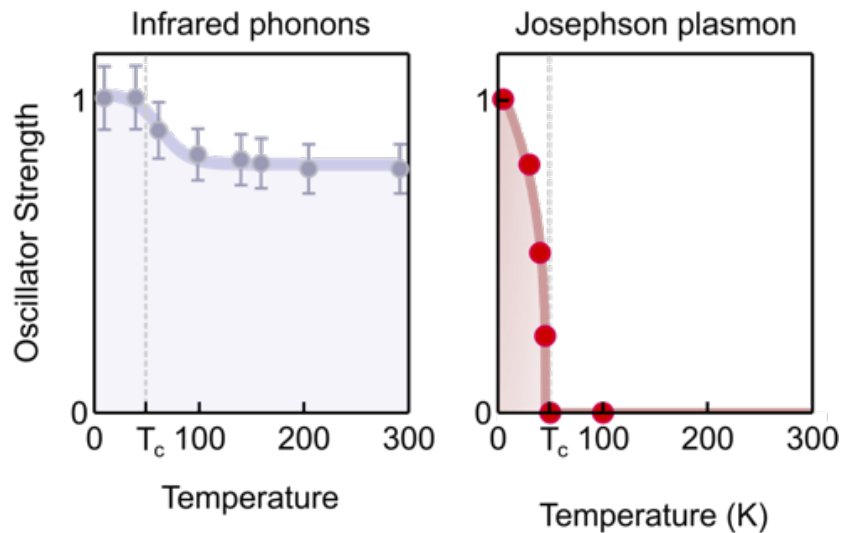
A. von Hoegen et al., arXiv:1911.08284 (2019)

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

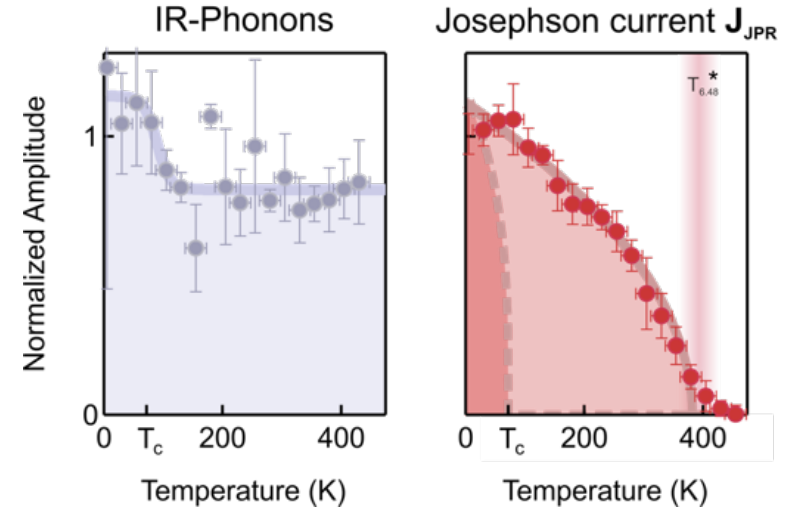


Equilibrium vs. Coherently Driven

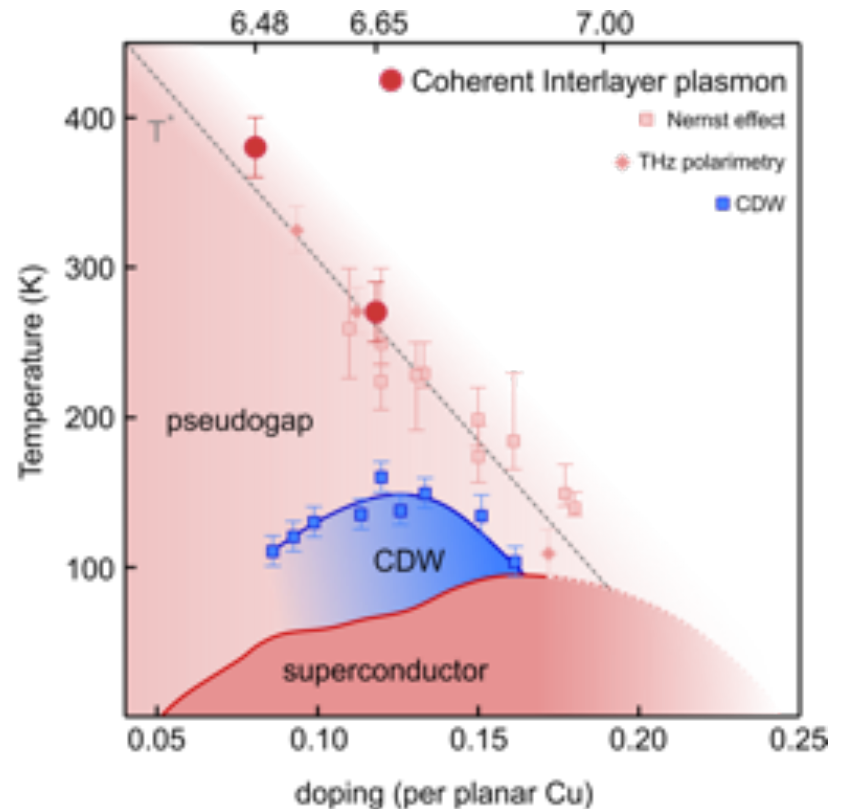
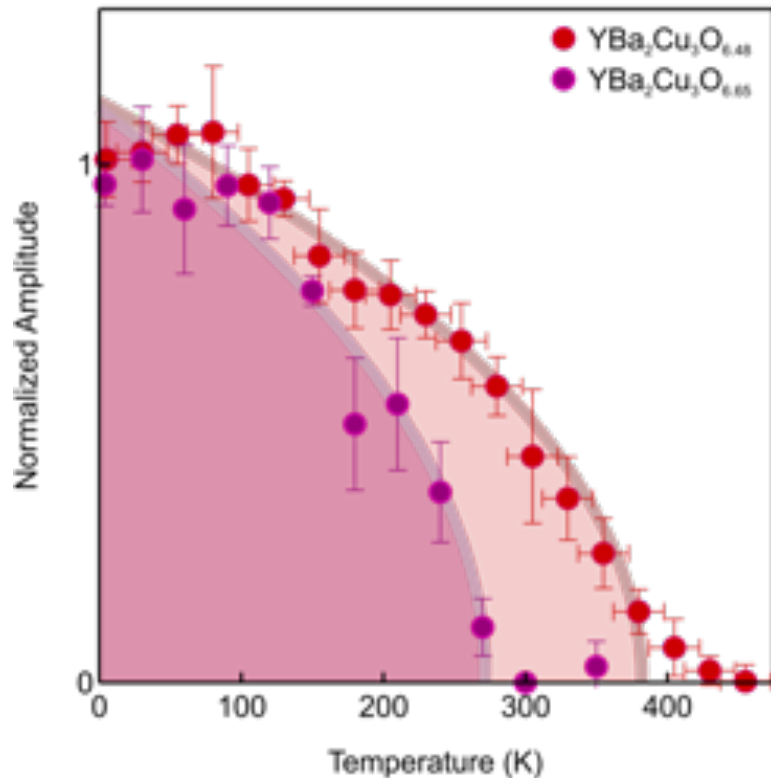
Equilibrium



Coherently Driven



Doping dependence consistent with T^*

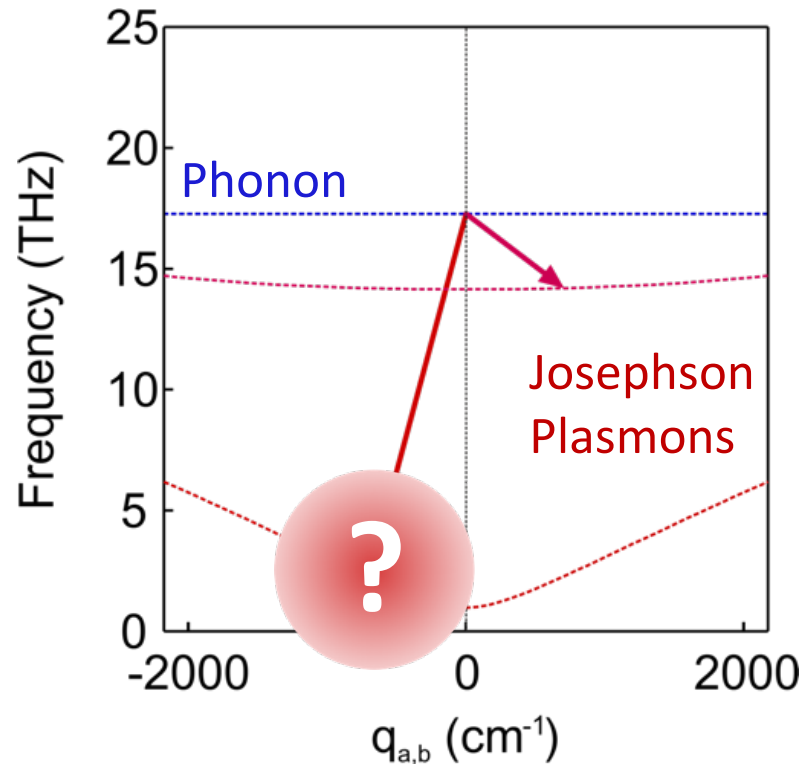


W. Hu *et al.*, Nat. Materials **13**, 705 (2014)
S. Kaiser *et al.*, Phys. Rev. B **89**, 184516 (2014)

A. von Hoegen *et al.*, arXiv:1911.08284 (2019)



What am I driving in the normal state ?



$$\omega_{J1}(q_{plas}) + \omega_{J2}(-q_{plas}) = \omega_{phonon}$$

with Michael Fechner,
Marios Michael, Eugene Demler

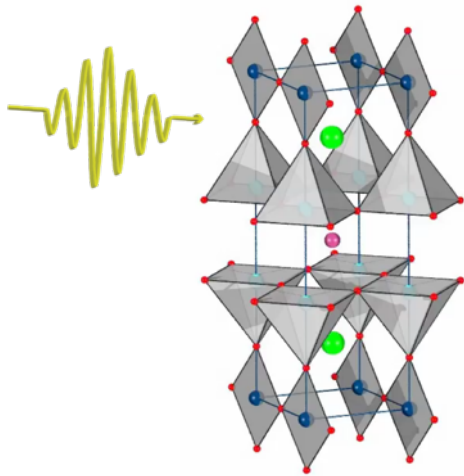
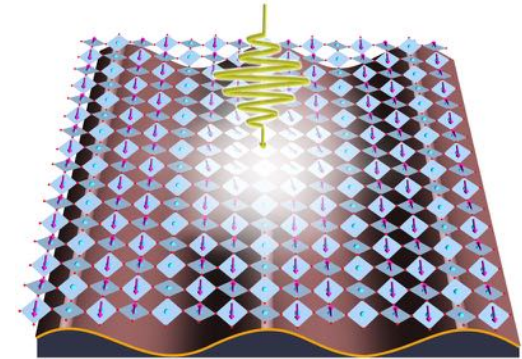
S. Denny et al. Phys. Rev. Lett **114**, 137001 (2015)
J. Okamoto et al. Phys. Rev. Lett **117**, 227001 (2016)

See talk by Marios Michael on Thursday



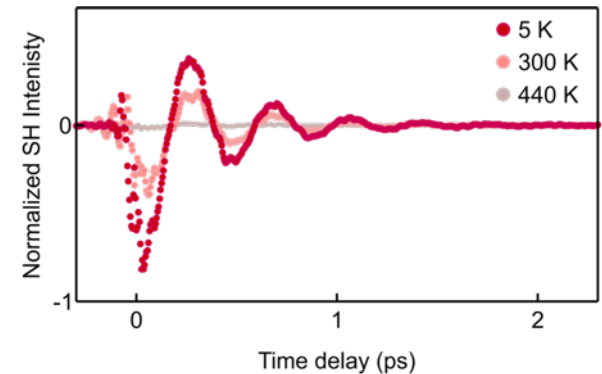
Summary

Stripe melting & optically-enhanced superconductivity in single layer cuprates



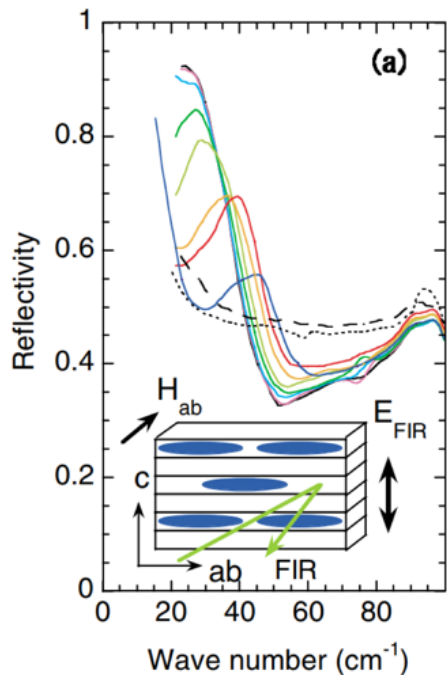
Pump frequency resonances for optically-stimulated superconductivity in $\text{YBa}_2\text{Cu}_3\text{O}_{6+x}$

Coherently driven Josephson currents detected in time domain via second harmonic generation



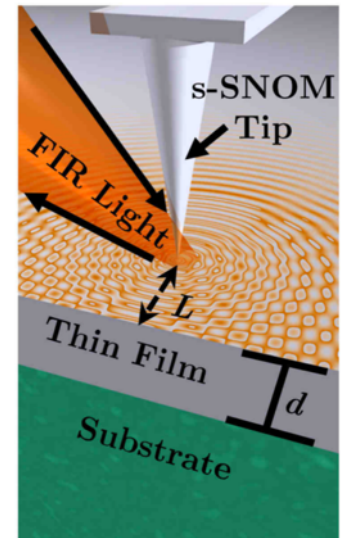
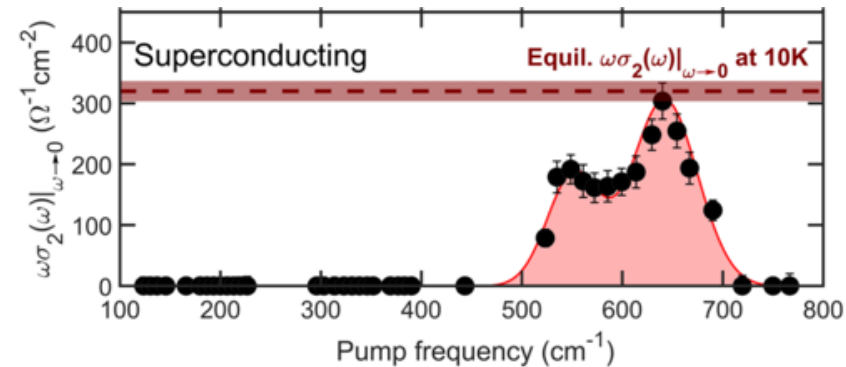
Outlook

Second harmonic probe of coherent Josephson currents under narrowband selective phonon excitation



Magnetic field dependence of coherent plasma oscillations in second harmonic

Study driven Josephson plasmons at finite momenta with near-field techniques



H. T. Stinson *et al.*, Phys. Rev. B **90**, 014502 (2014)

D. Basov's talk yesterday

K. M. Kojima *et al.*, Phys. Rev. Lett. **89**, 247001 (2002)



Acknowledgments

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