Enhancing Superconductivity using Light

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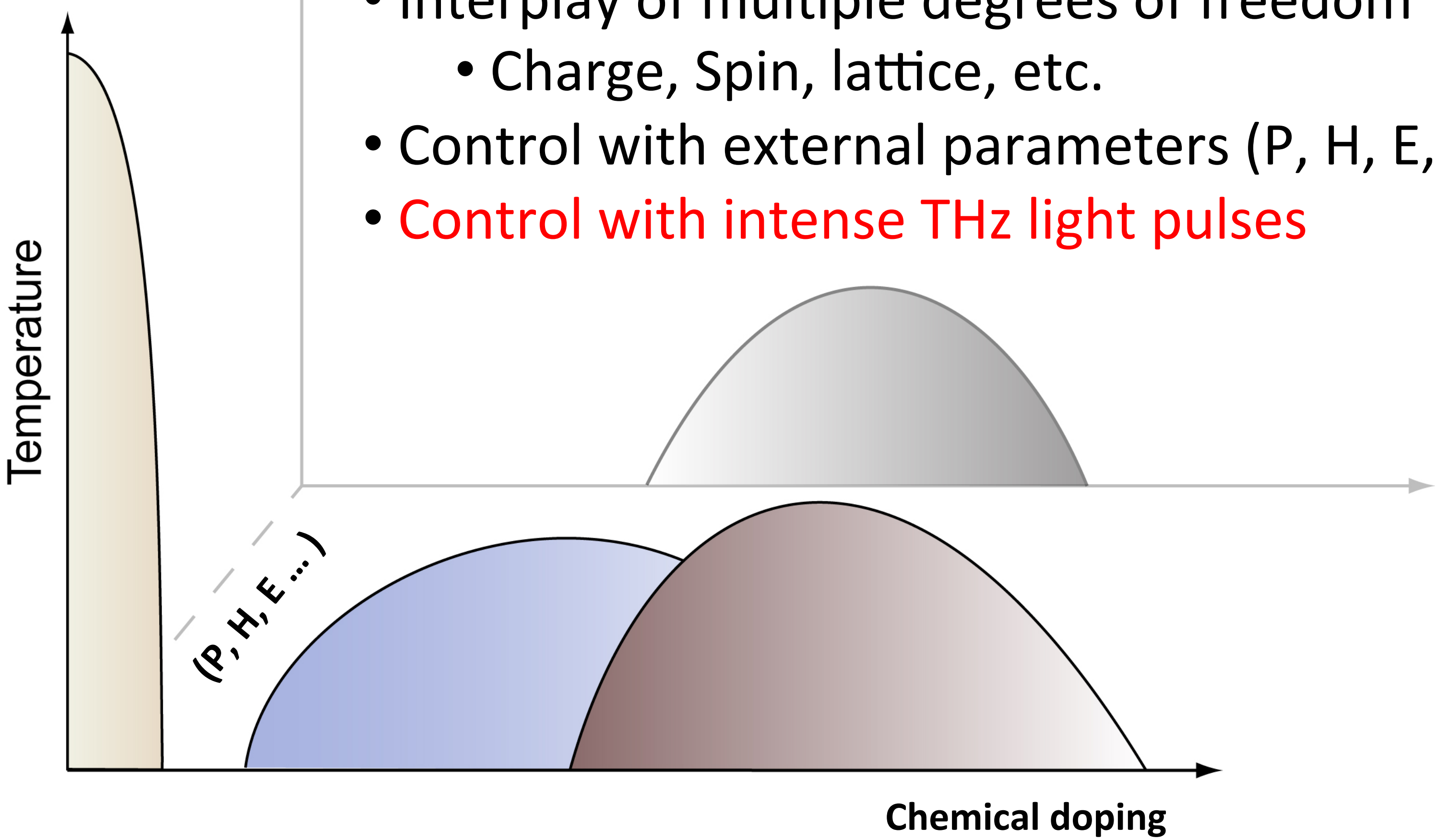
Controlling complex matter

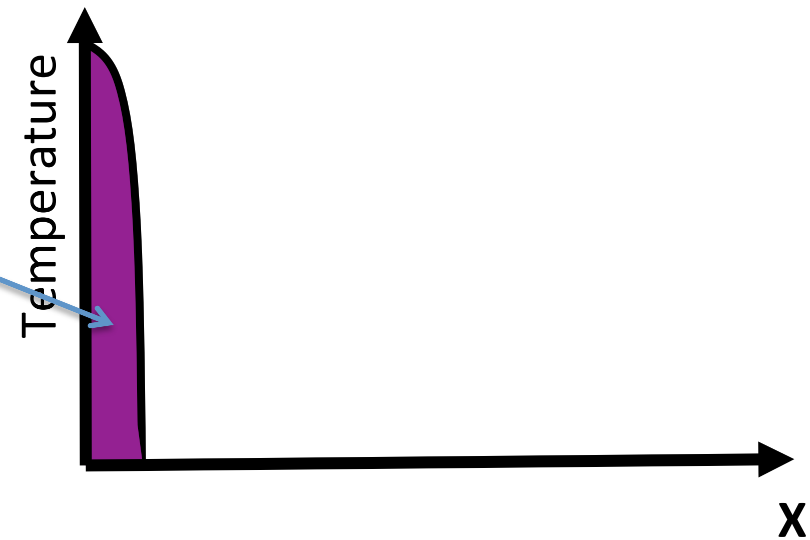
Competition of different stable phases

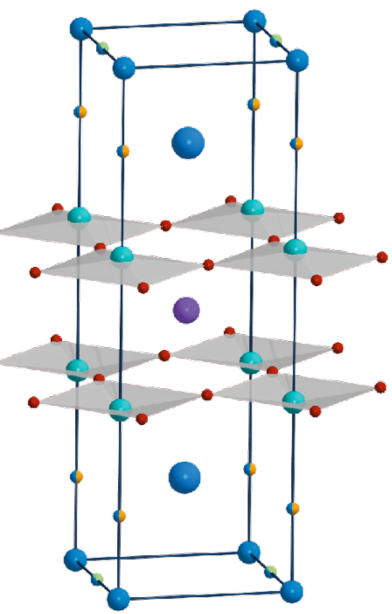
- Interplay of multiple degrees of freedom
  - Charge, Spin, lattice, etc.
- Control with external parameters (P, H, E, x, …)
- Control with intense THz light pulses



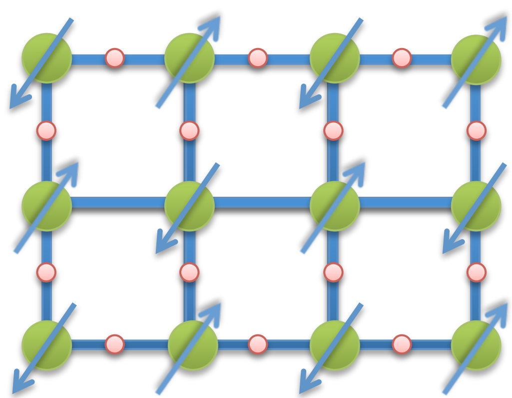
Cuprate-Supercondutors

- Layered materials
- 2D-doped Mott insulator





CuO-plane



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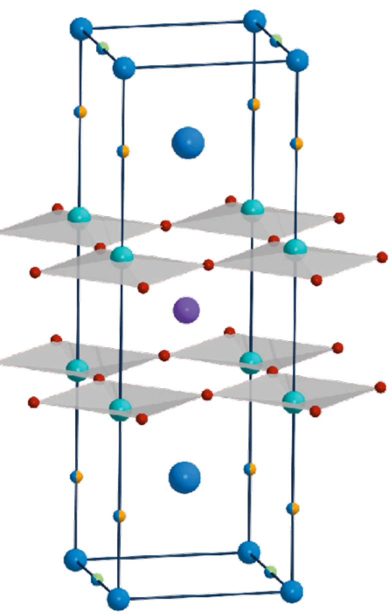

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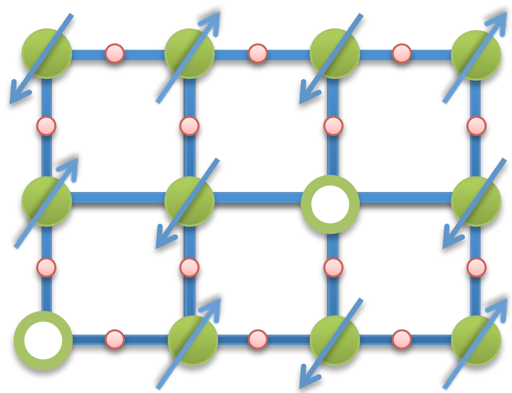
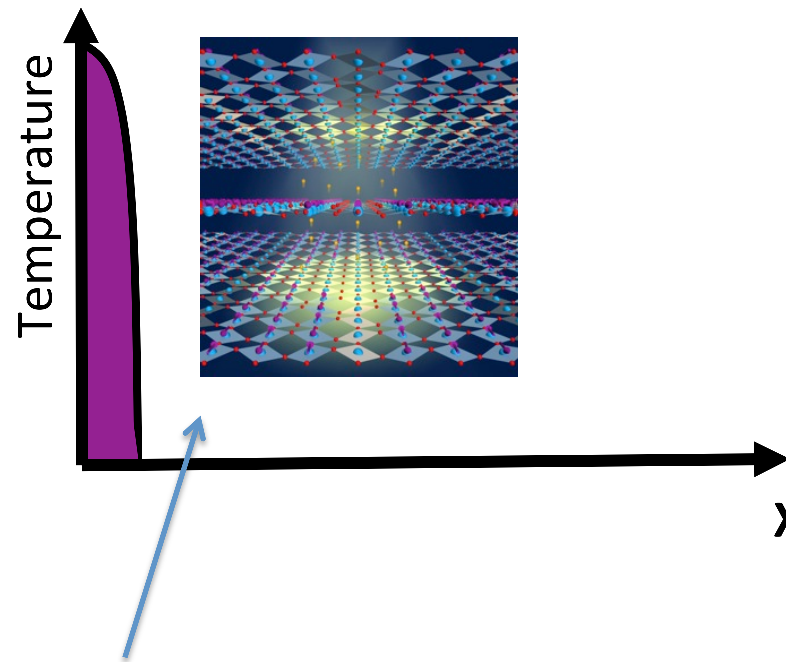
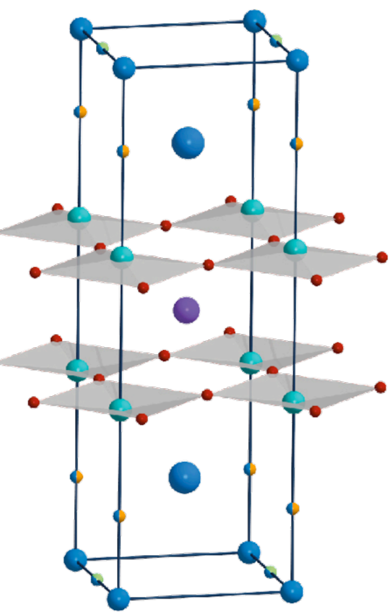




- Unconventional 2D metallic phase

Cuprate-Superconductors

- Layered materials
- 2D-doped Mott insulator



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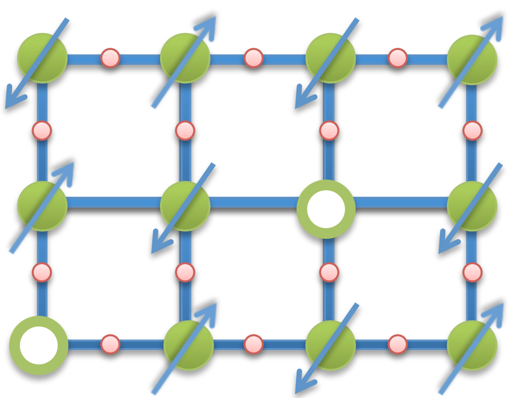
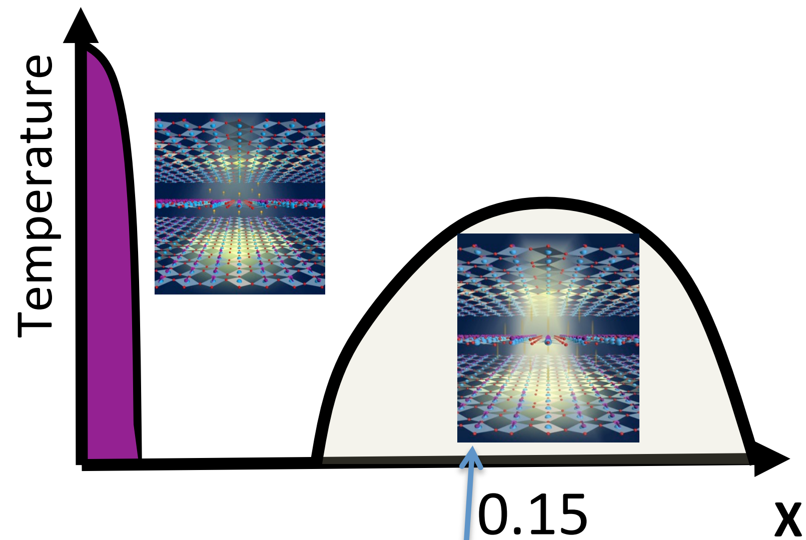


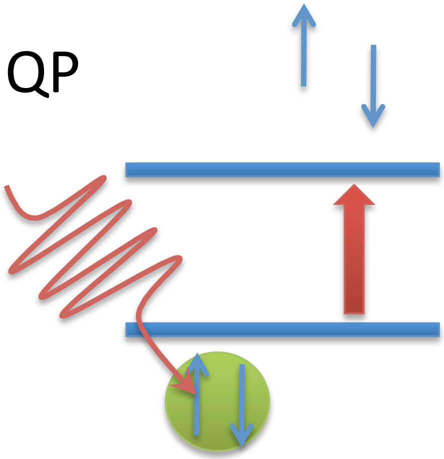


- Unconventional 2D metallic phase

- 3D-Superconductivity

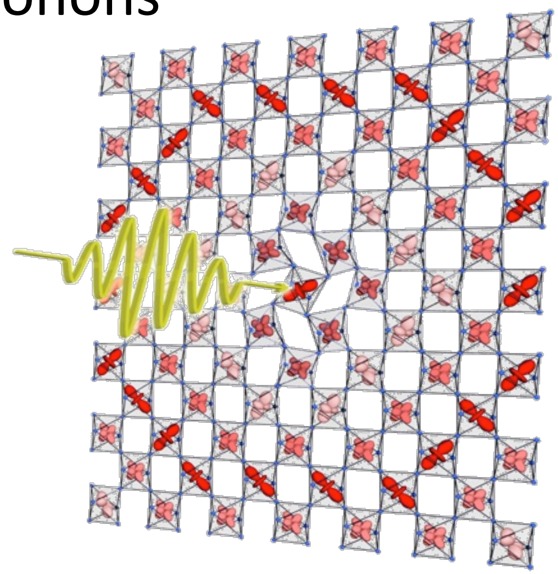
Time resolved pump-probe spectroscopy

- Spectroscopy of non equilibrium QP



1.5 eV ~ 20,000 K

- THz control: Collective excitations, phonons



1 THz ~ 4 meV ~ 50 K

mpsd

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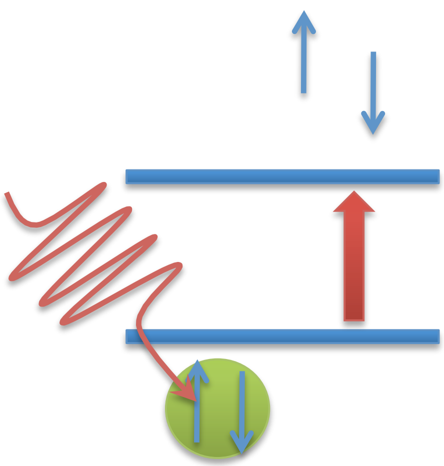
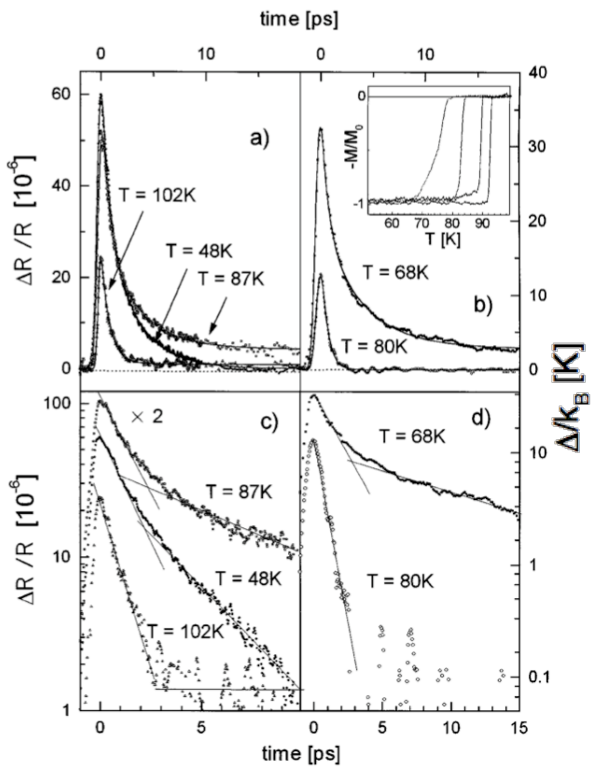
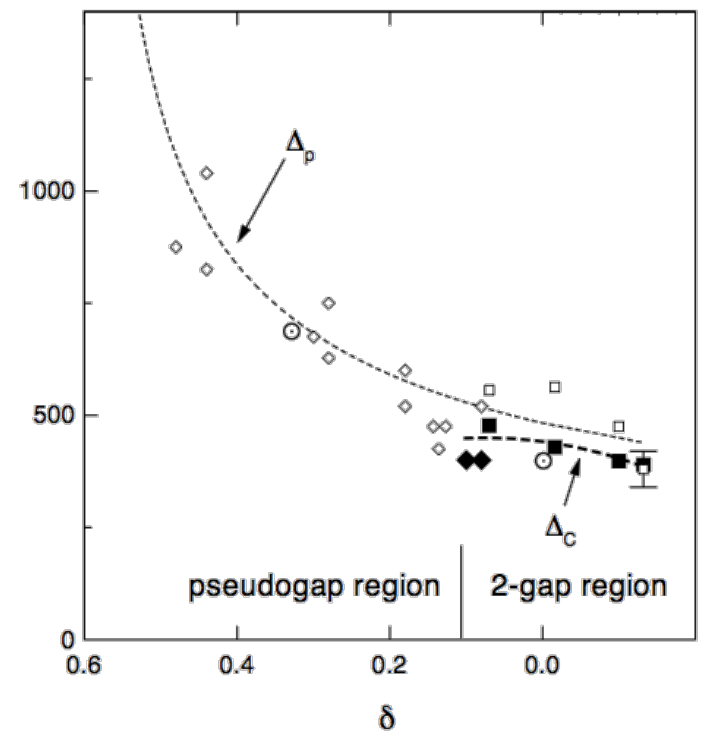
Photo-doping dynamics of cuprates

- Recombination dynamics



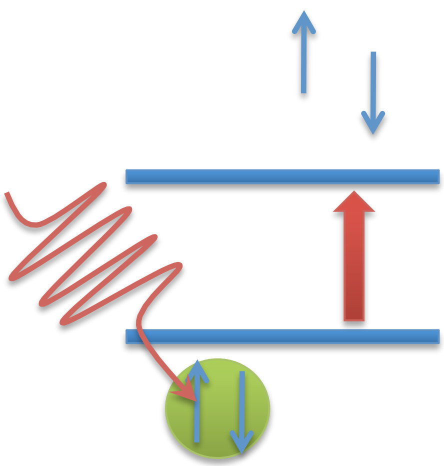


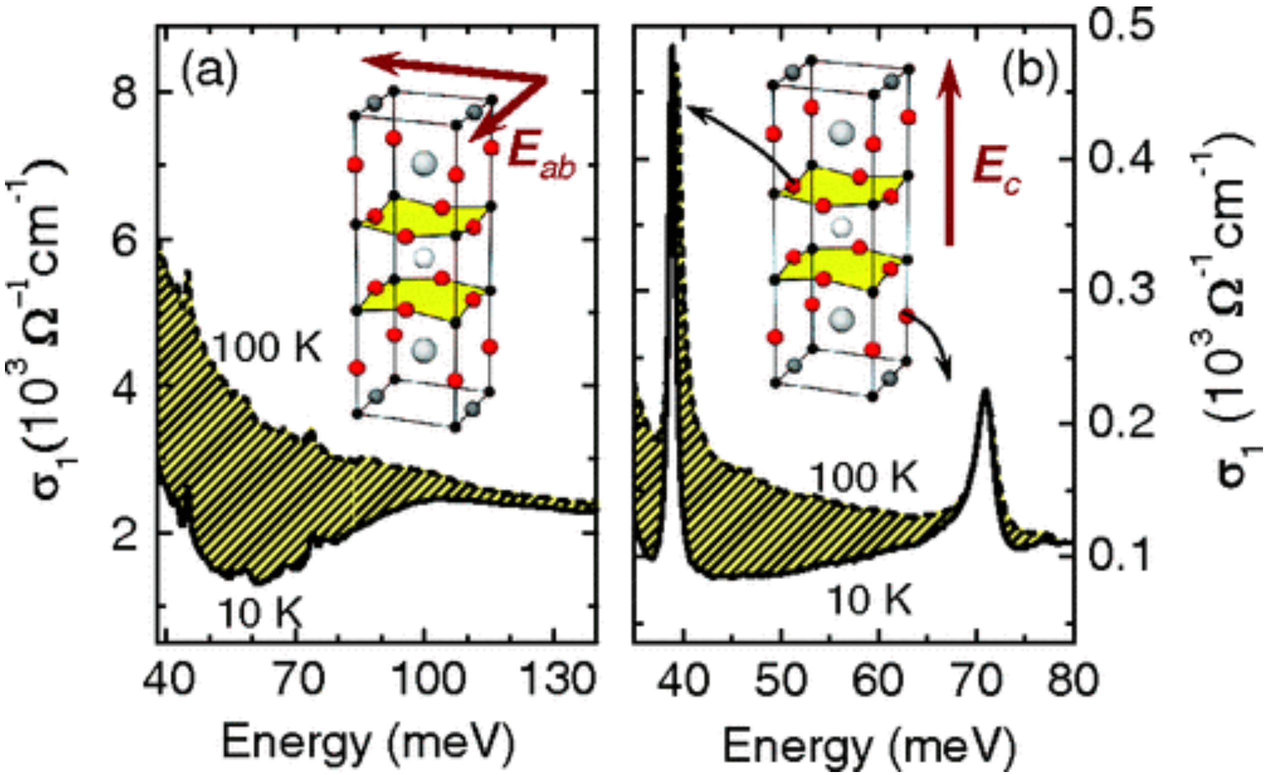


J. Demsar et al. PRL (1999)

Photo-doping the SC gap

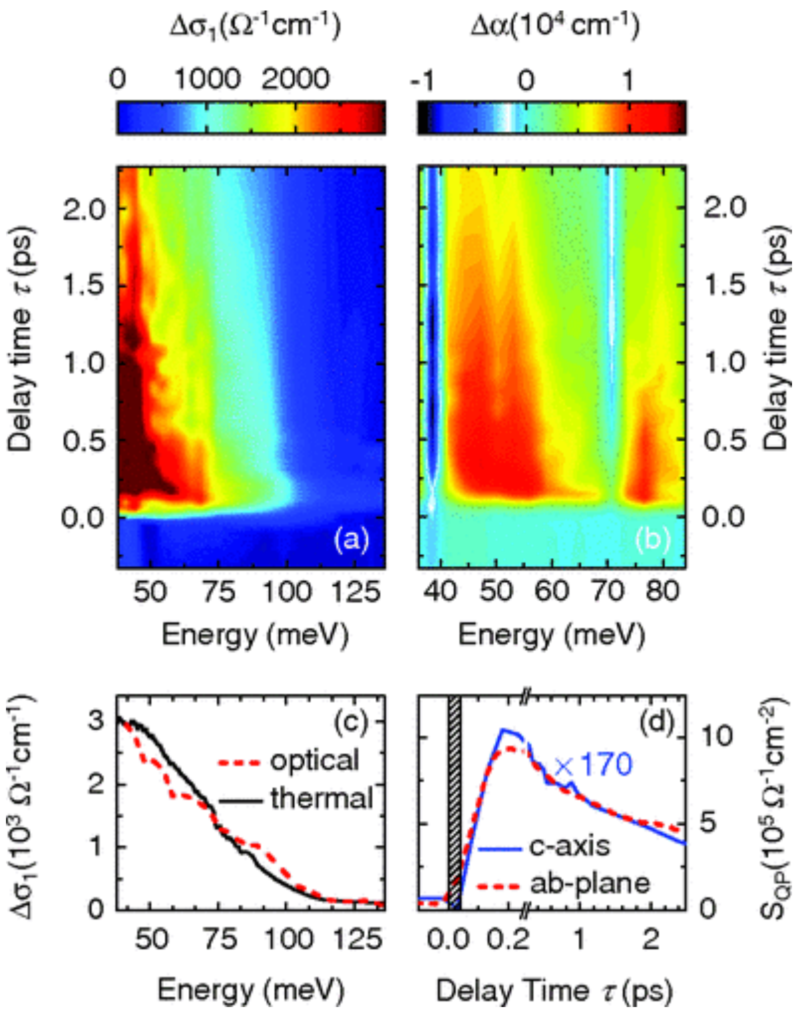
- Optical gap in YBCO





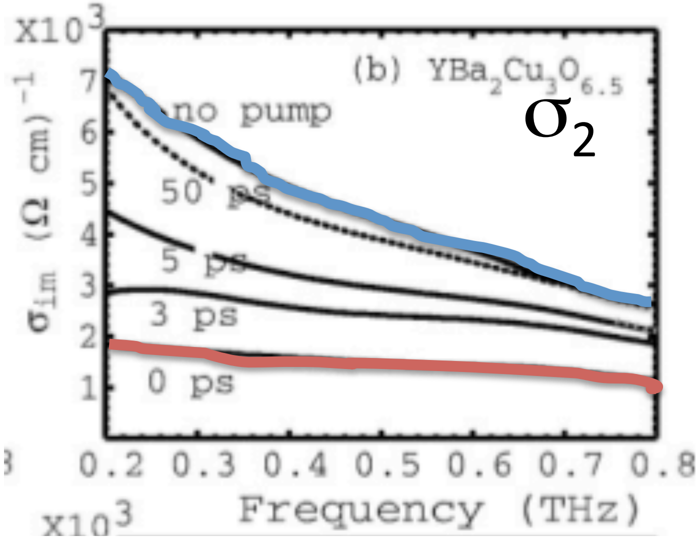
A. Pashkin et al. PRL (2010)

Spectroscopy of the gaps



A. Pashkin et al. PRL (2010)

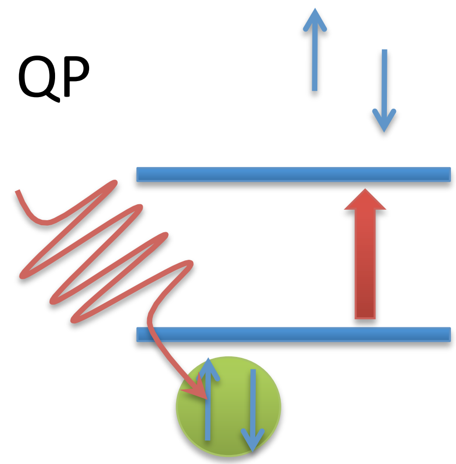
- Full optical response



R. Averitt PRB (2001)

Time resolved pump-probe spectroscopy

- Spectroscopy of non equilibrium QP



1.5 eV ~ 20,000 K

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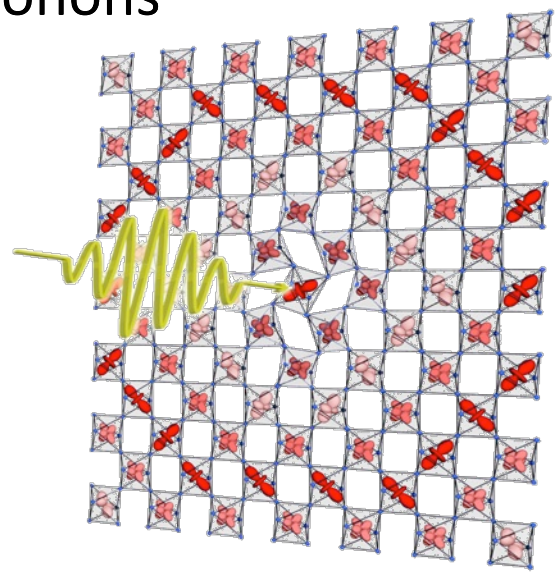
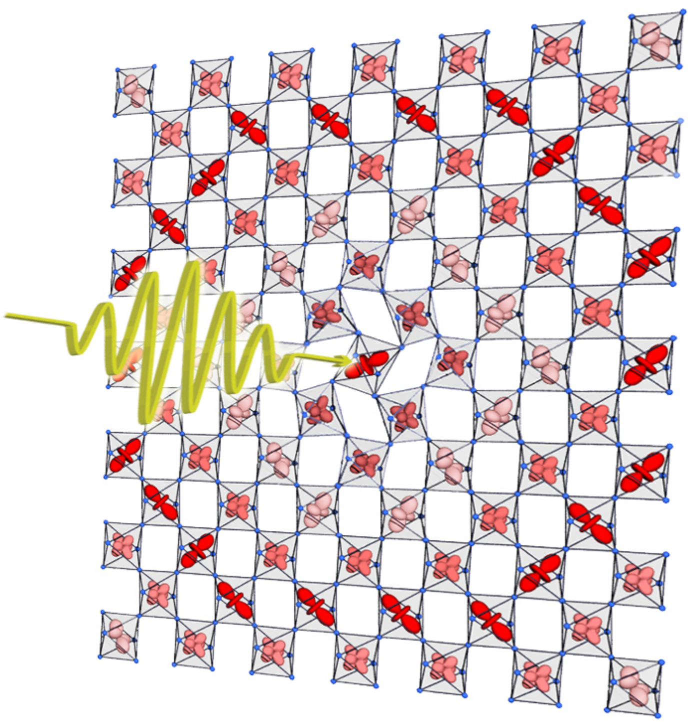
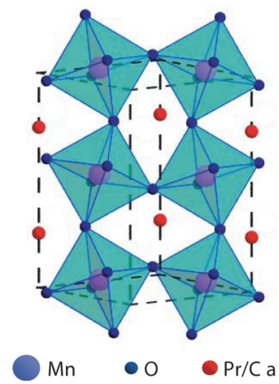


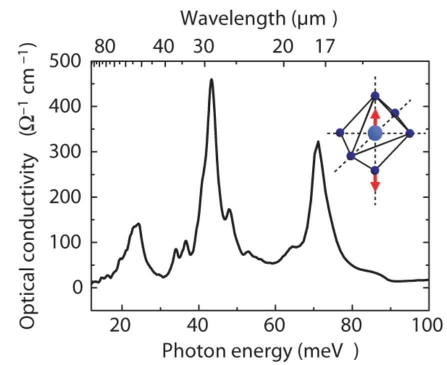
1 THz ~ 4 meV ~ 50 K

Selective lattice deformation

Resonant phonon excitation







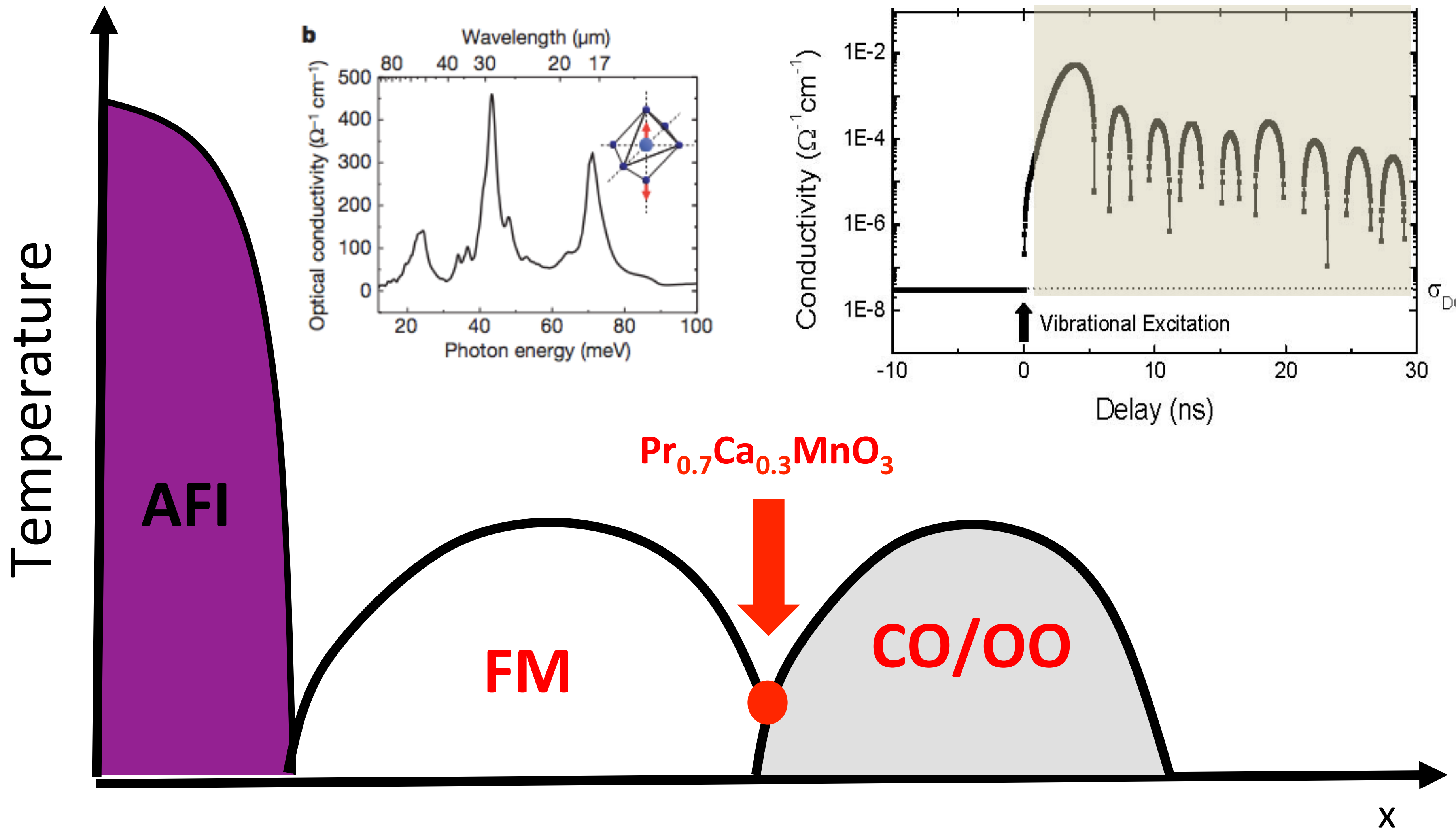
17 μm

17 THz

70 meV

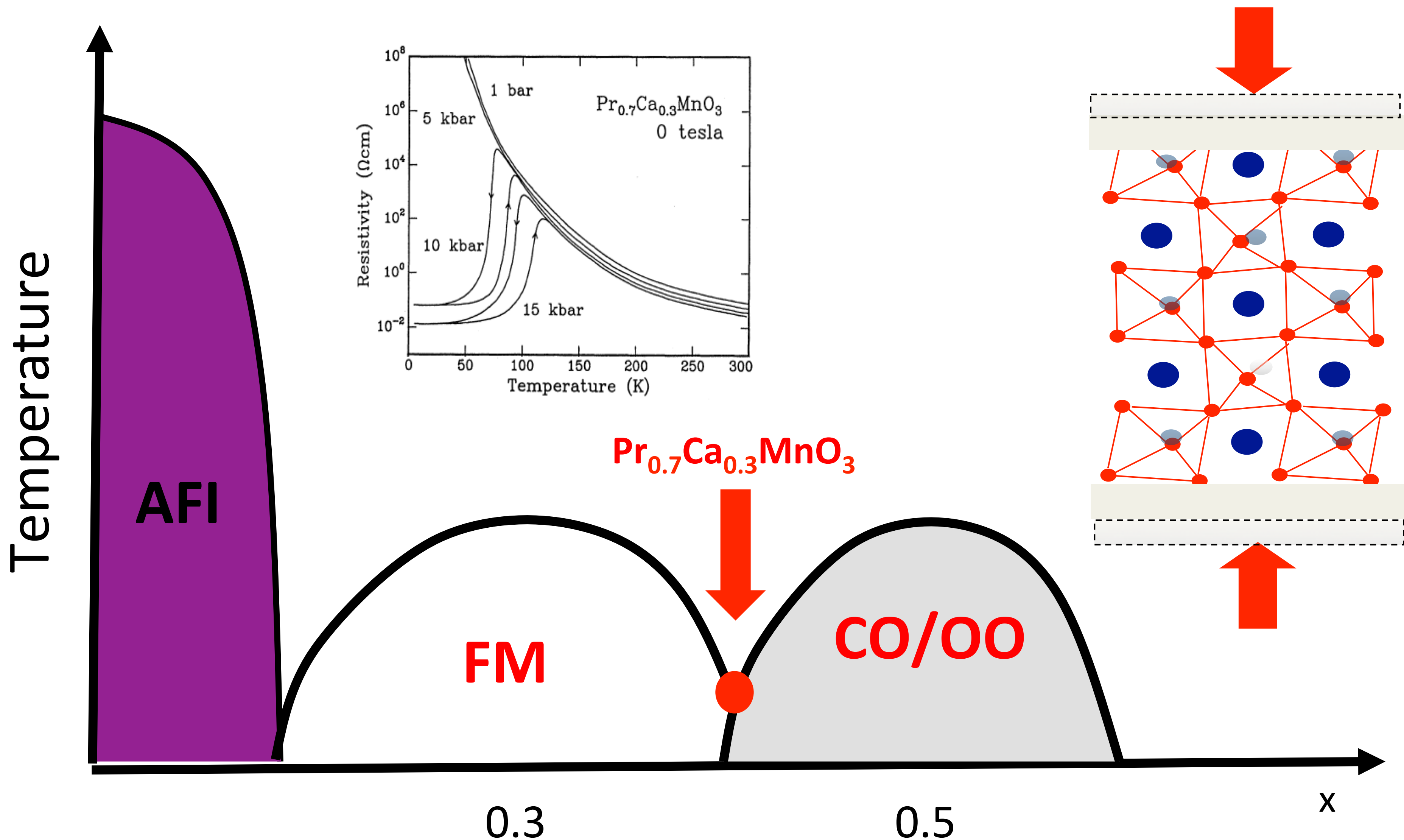
M. Rini et al., Nature 449, 72 (2007)

Non-thermal switching in $Pr_{0.7}Ca_{0.3}MnO_3$



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

Pressure tuning of a metal insulator transition in PCMO

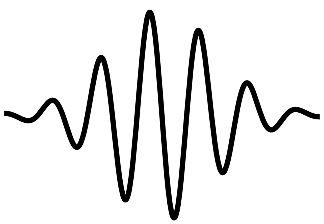


H. Hwang et al., Phys. Rev. Lett. 52, 15046 (1995)

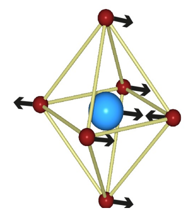
How does an optical pulse exert pressure ?

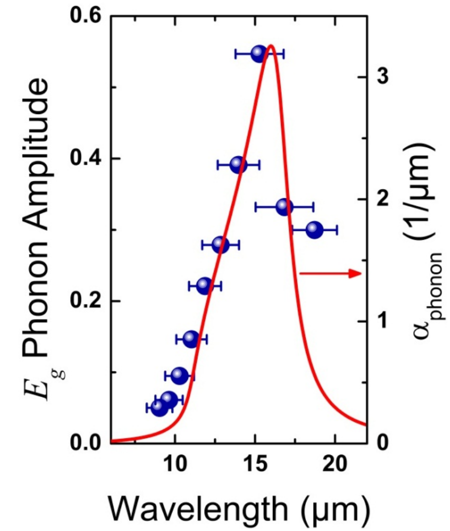
- resonant excitation at the 15 μm Mn-O mode

$\propto Q_{IR}$



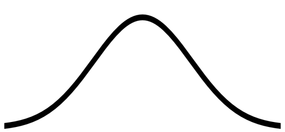
E_{1u}



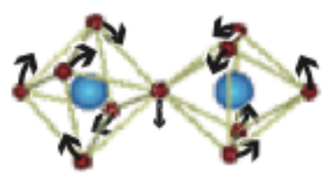


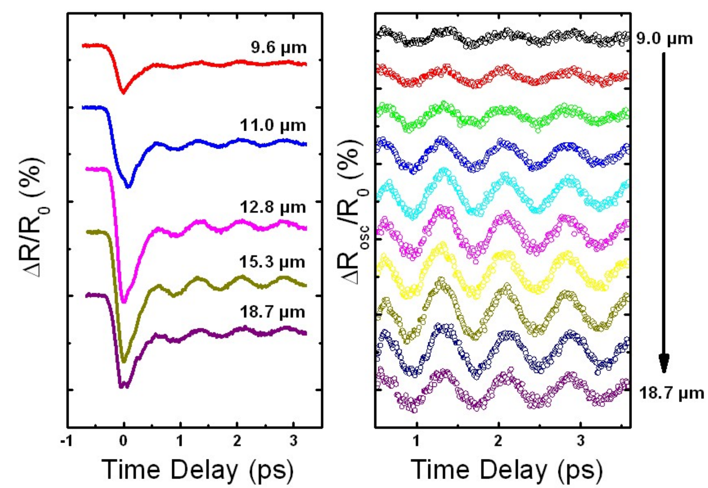
- Ionic Raman Scattering: Rectification into 1.2 THz mode

$\propto Q_{IR} \bullet Q_{IR}$



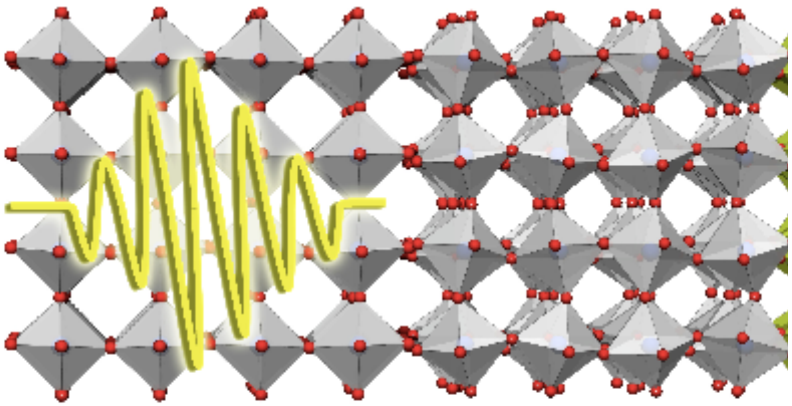
$E_{1g} \subset E_{1u} \bullet E_{1u}$



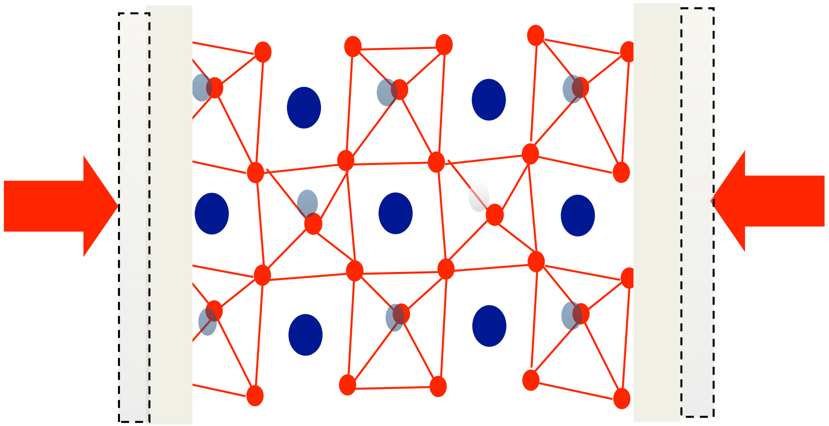


M. Foerst et al., Nature Physics 7, 854 (2011)

Mode selective pressure



$La_{0.7}Sr_{0.3}MnO_3$



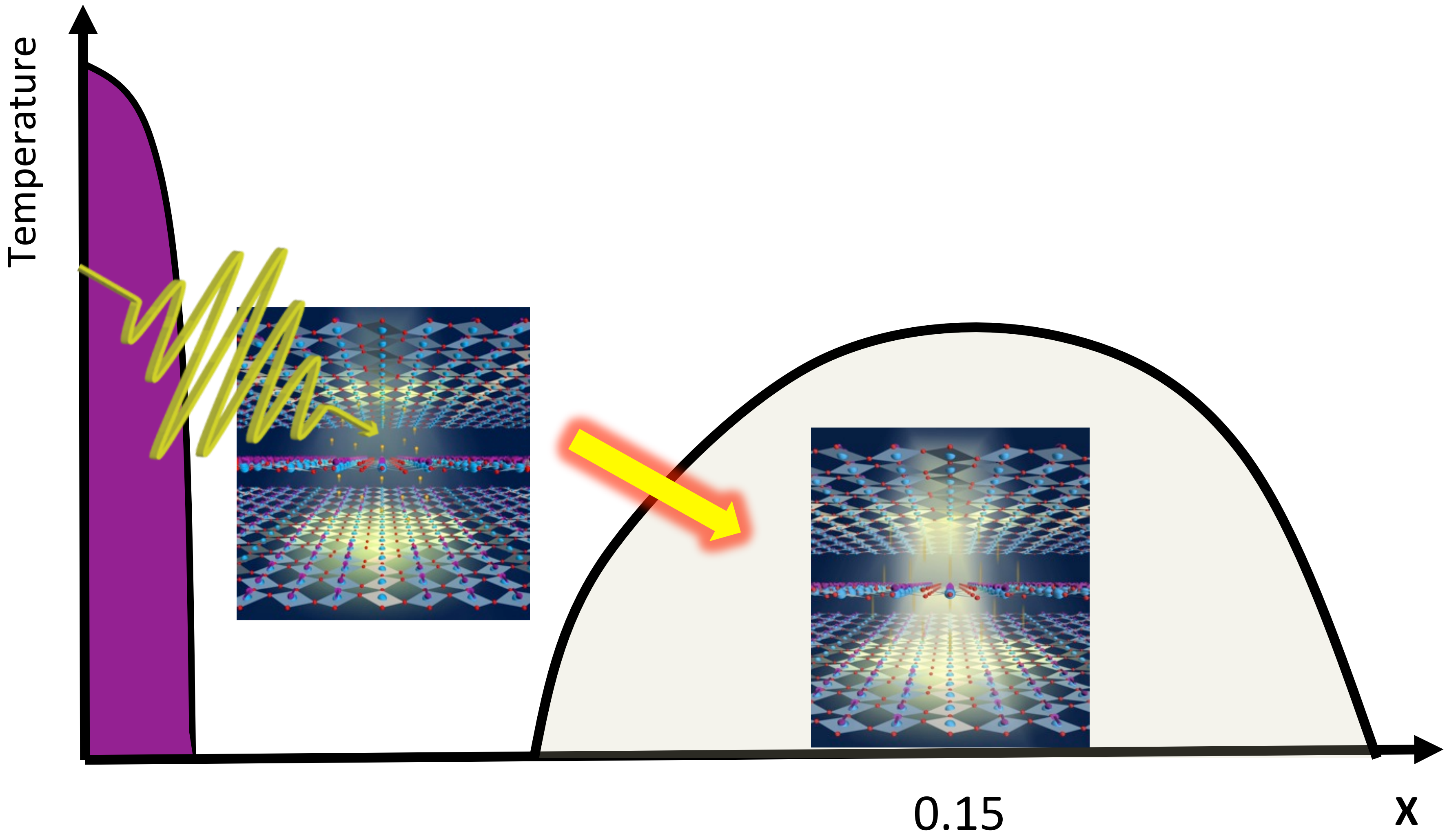
M. Rini et al., Nature (2007)
R. Tobey et al, PRL (2008)
M. Foerst et al., Nature Physics (2011)
M. Foerst et al., PRB (2011)
A. Caviglia et al, PRL (2011)

$Pr_{0.7}Ca_{0.3}MnO_3$

$La_{0.5}Sr_{1.5}MnO_4$

$NdNiO_3$ / $LaAlO_3$

Can we control SC with light?

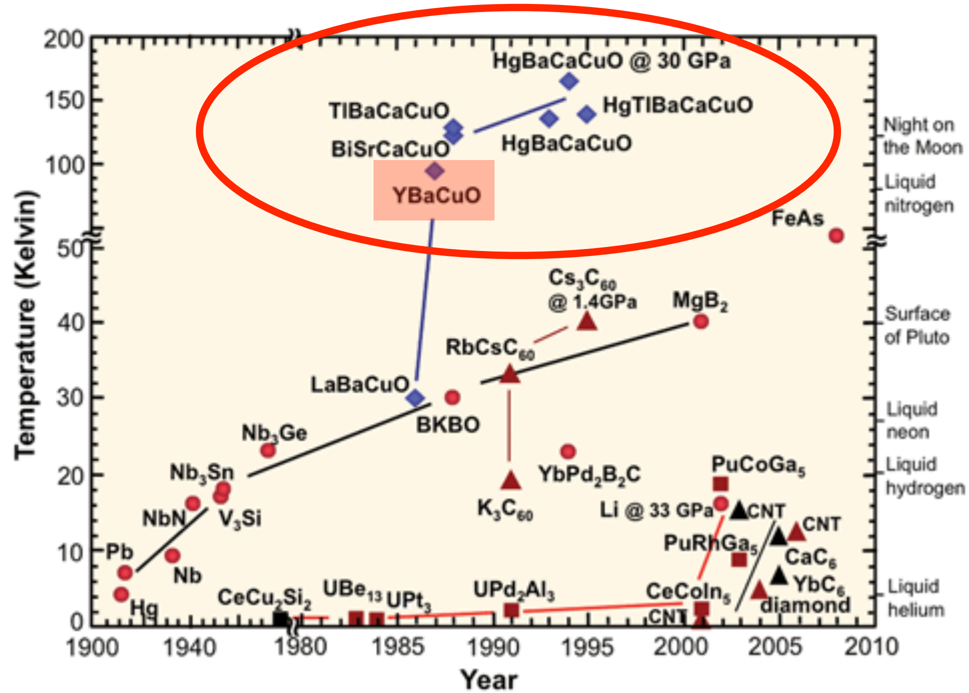


History of higher T_c

Increase of Tc:
Materials discovery

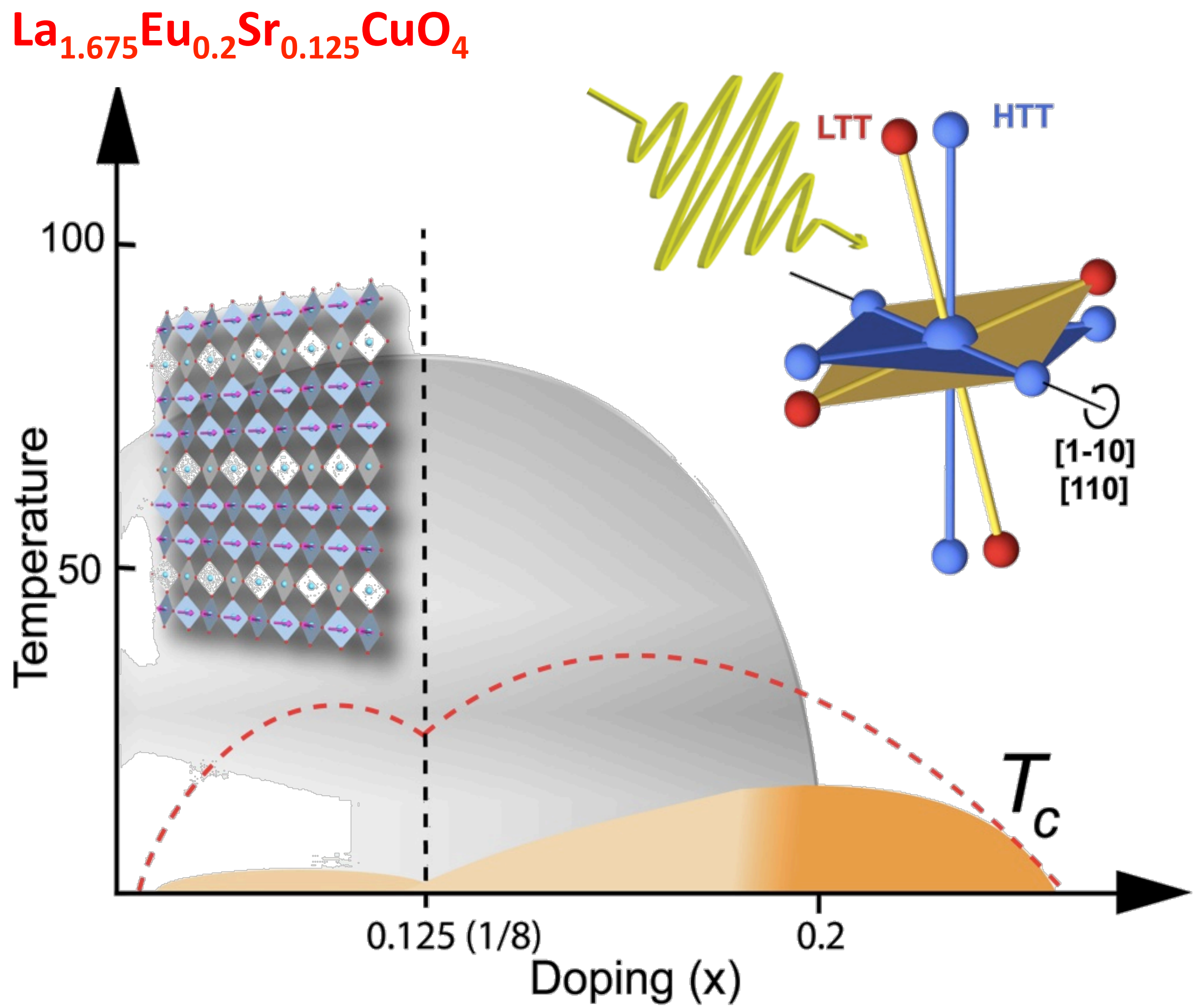
Layered Copper Oxides

$T_{c,max} \ll T_{room}$



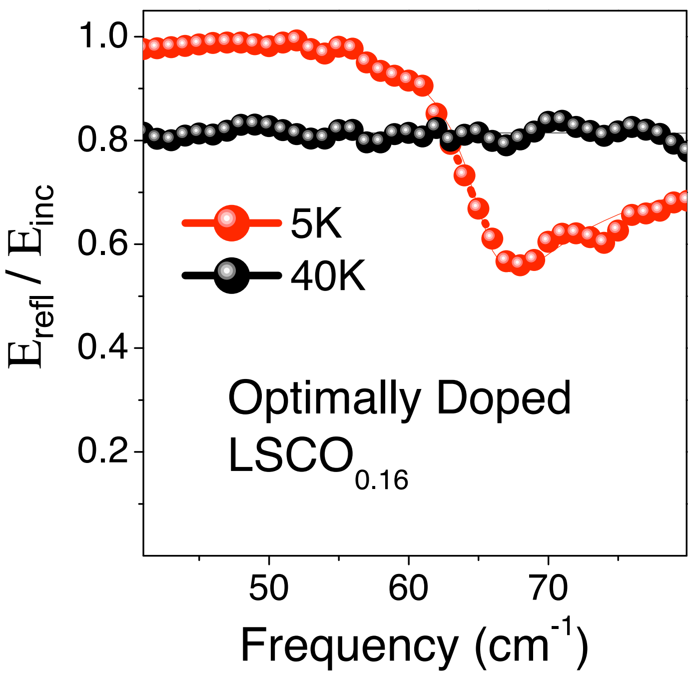
Can light induced phase transitions help us reaching room-temperature?

Stripe phase: Competing order to SC

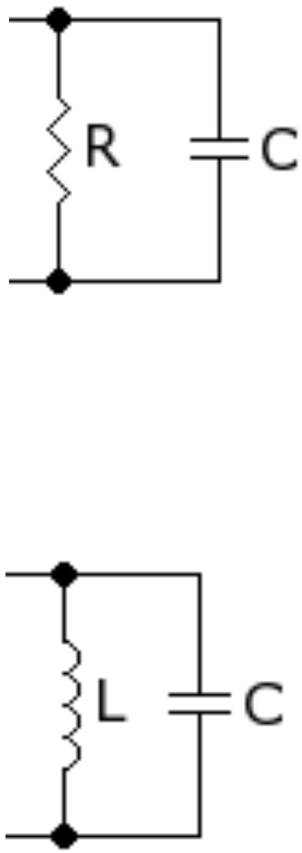


D. Fausti et al., Science 331, 6014 (2011)

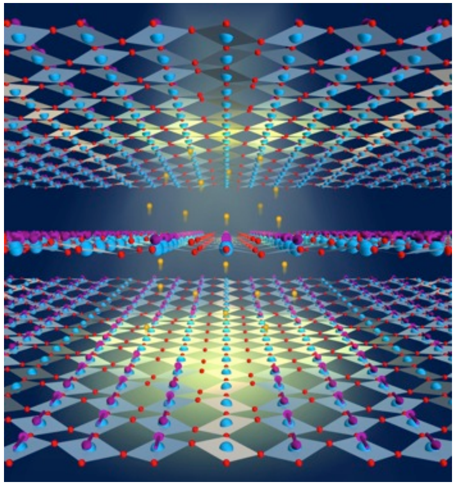
How do we recognize a superconductor?



Josephson Plasma edge of a superconductor



T > T_c



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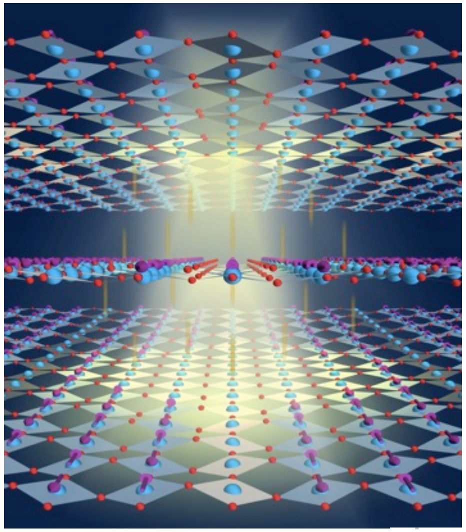
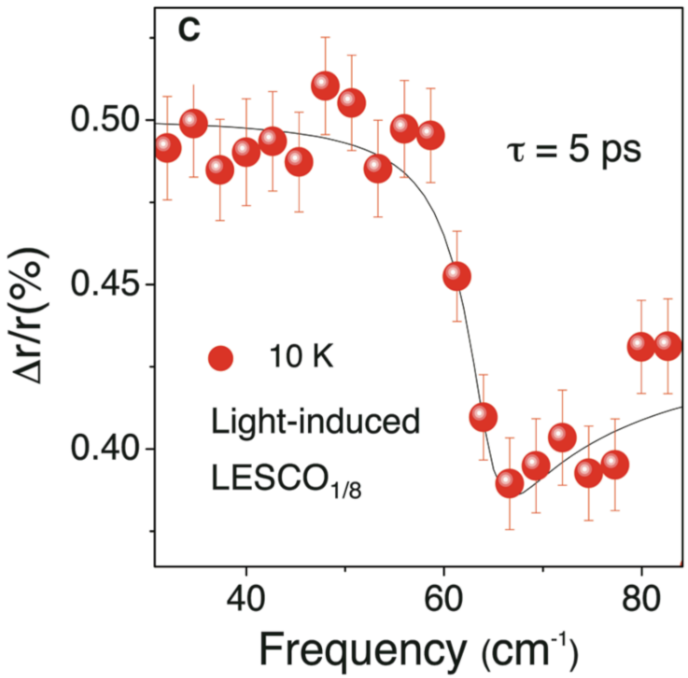
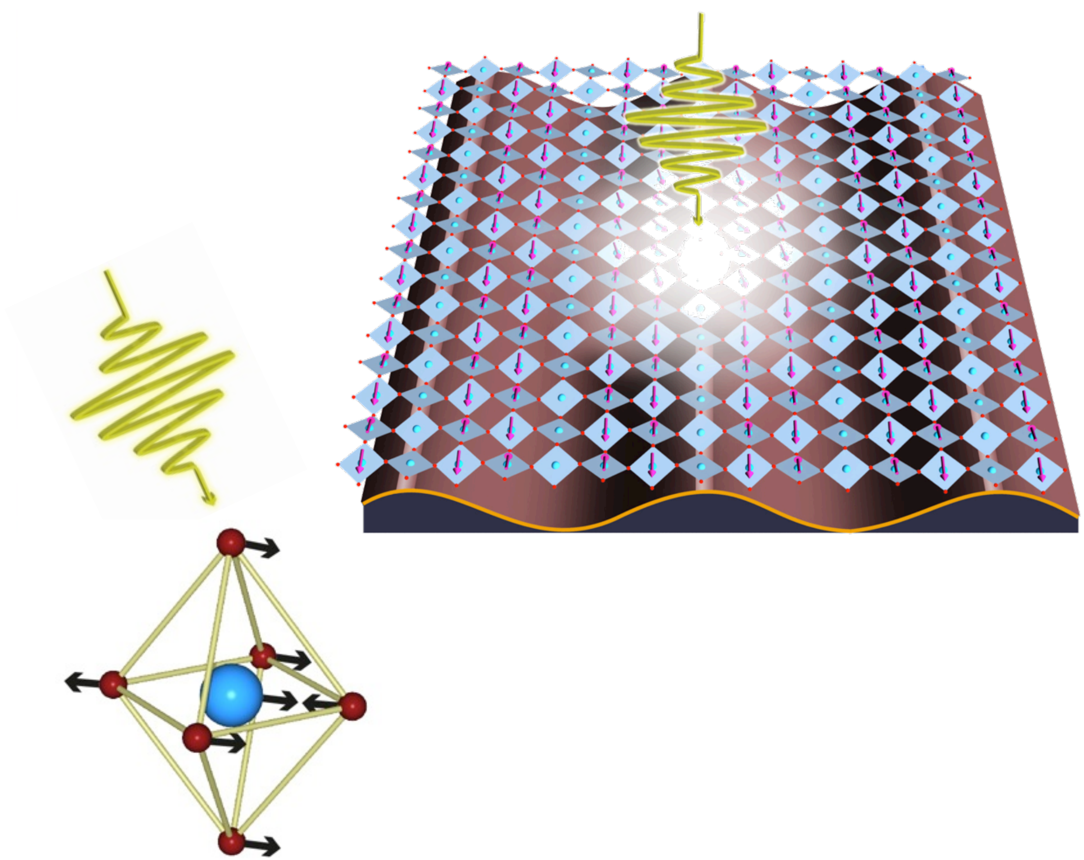


Light-induced superconductivity

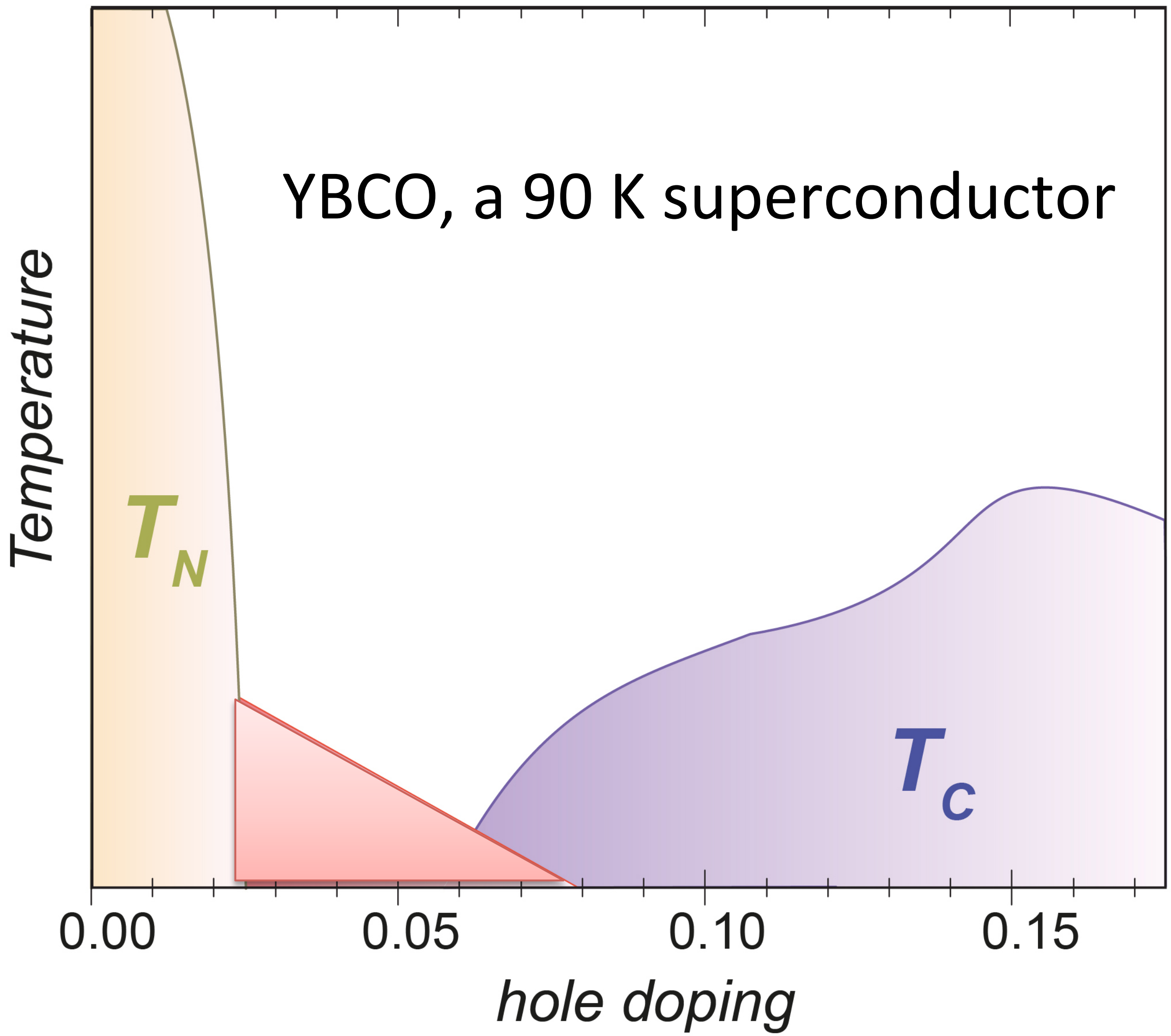
Photo-induced JPR from the stripe phase





D. Fausti et al., Science 2011

$YBa_2Cu_3O_{6+x}$



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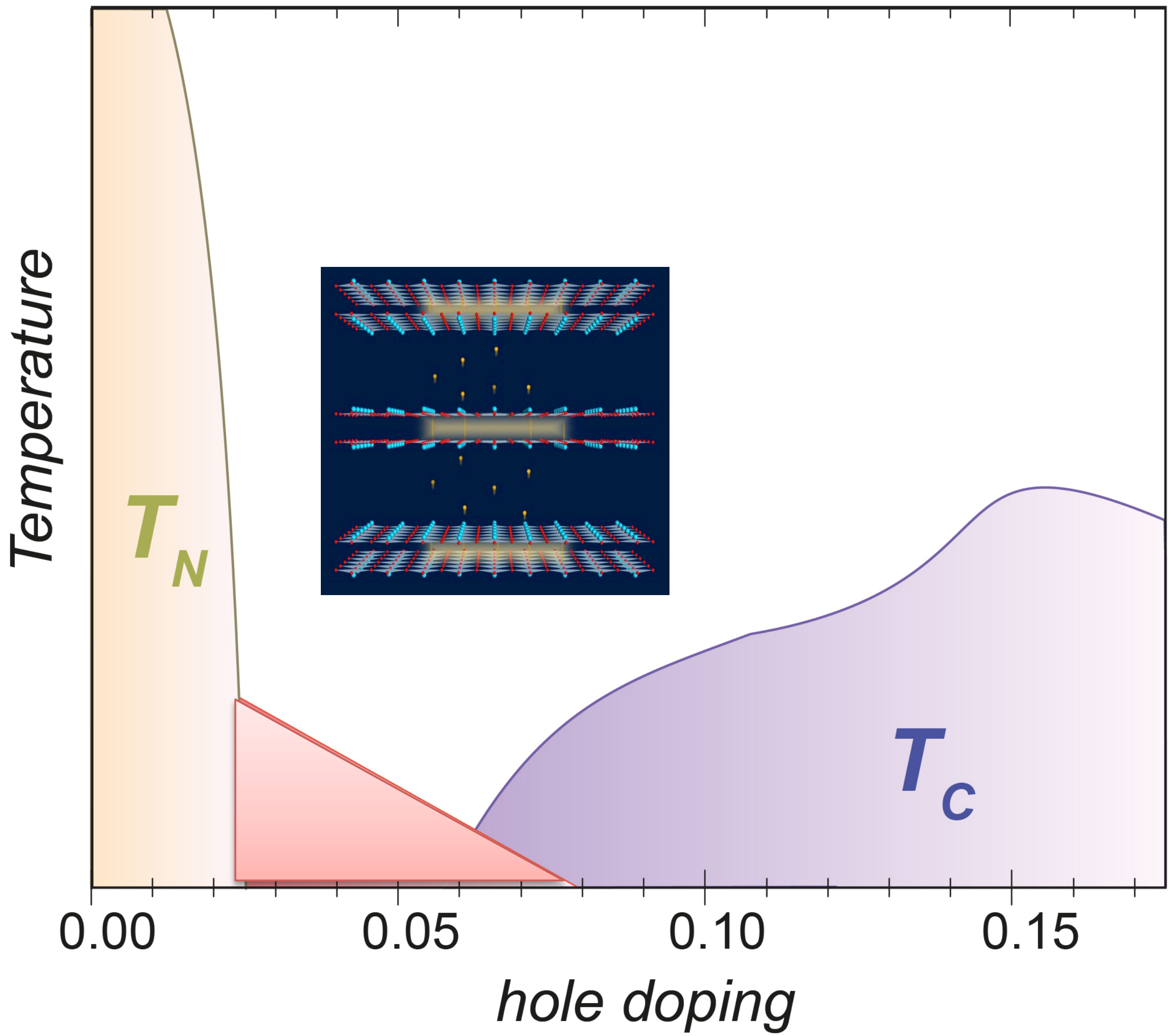
Is there superconducting coherence above T_c?

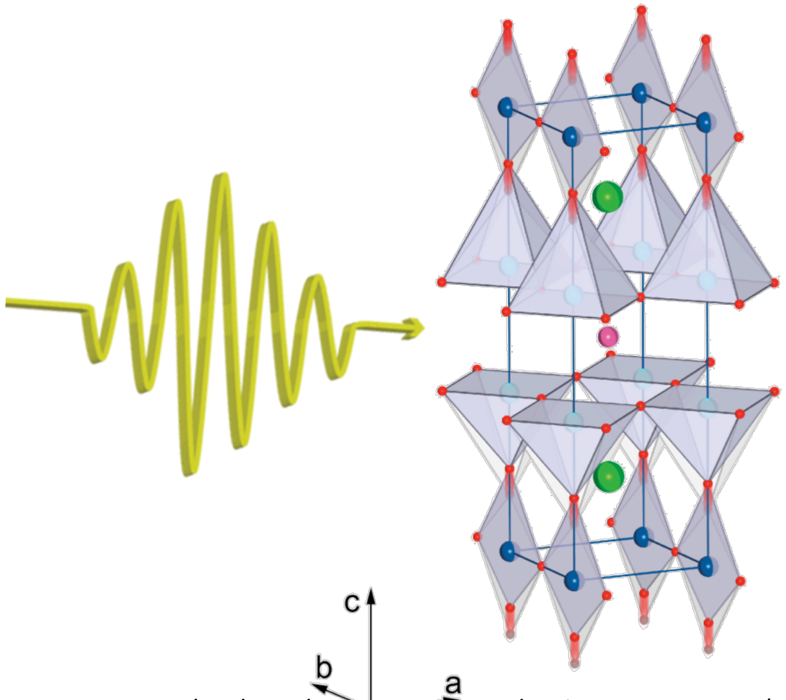


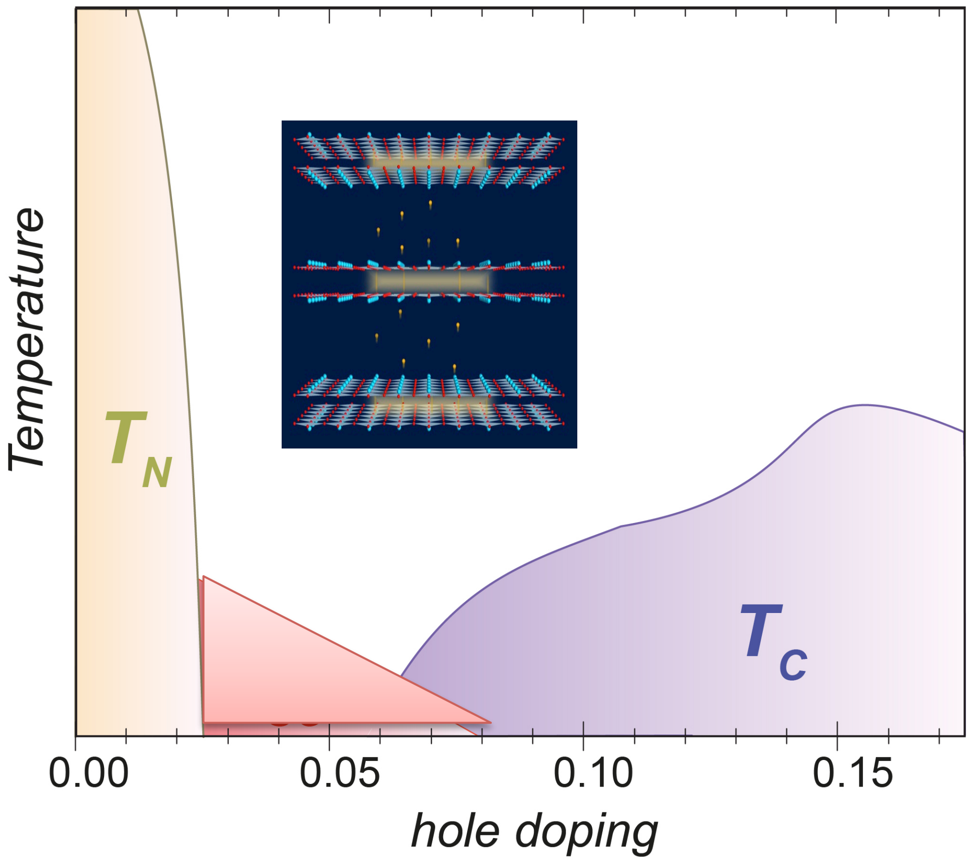
A. Dubroka et al., Phys. Rev. Lett. 107, 047006 (2011)

Can we modulate coherence in YBCO?

Apical oxygen in cuprates: stretching mode at 15.5 μm

Direct control of
- In-plane hopping
- Exchange interaction



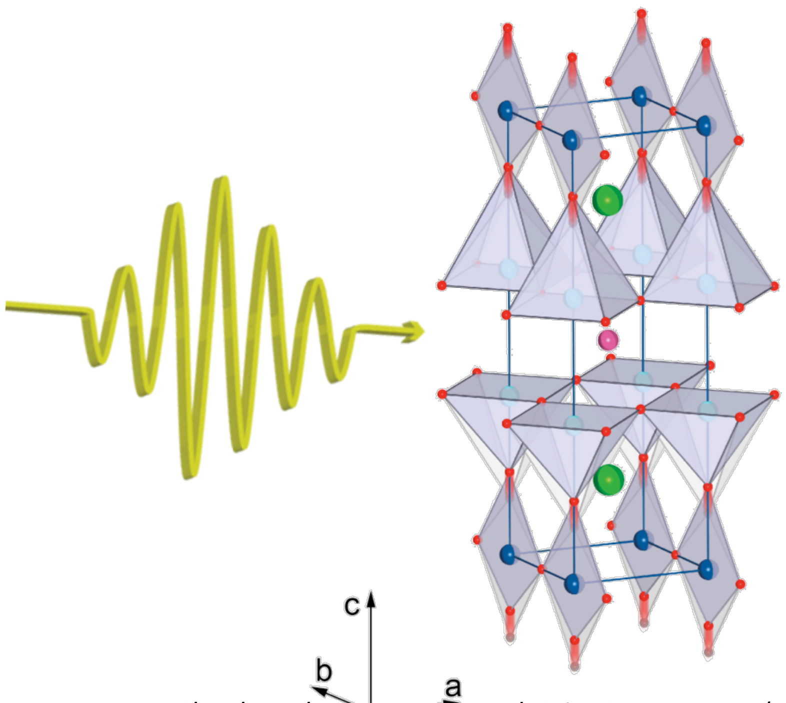


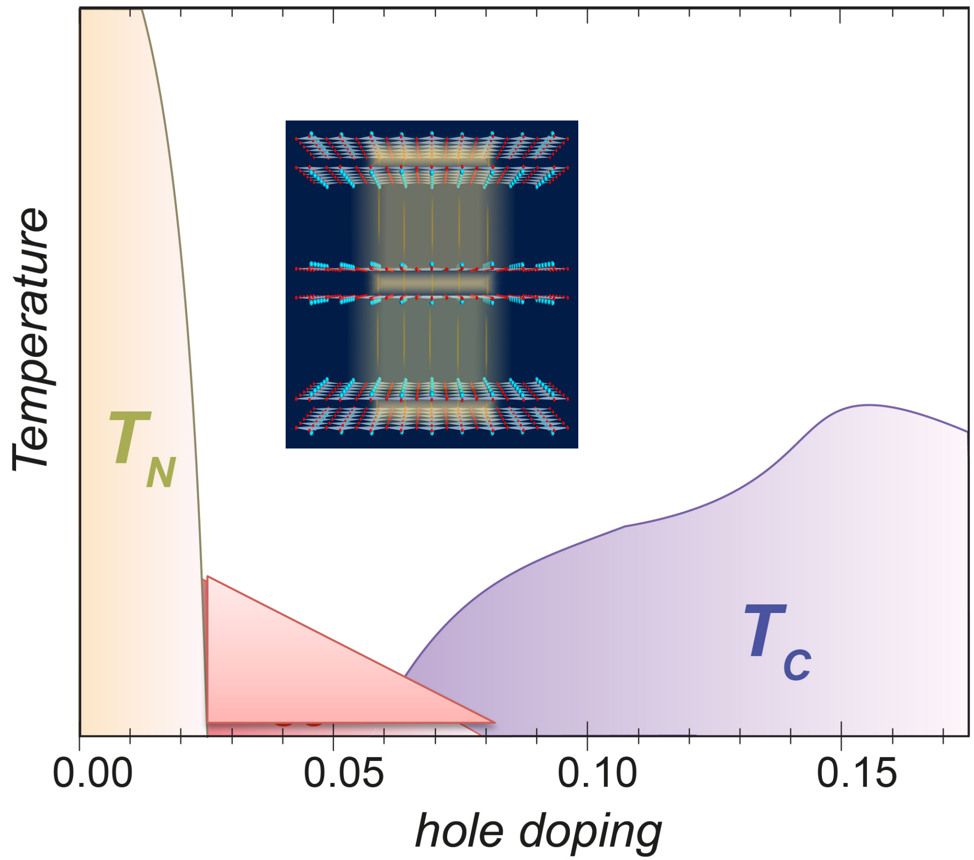
J.K. Slezak et al., Proc. Nat'l Acad. Sci. USA 105, 3203 (2008).

E. Pavarini et al. Phys. Rev. Lett. 87, 047003 (2001).

Dynamically modulated state in YBCO

Is the modulated state more coherent ?





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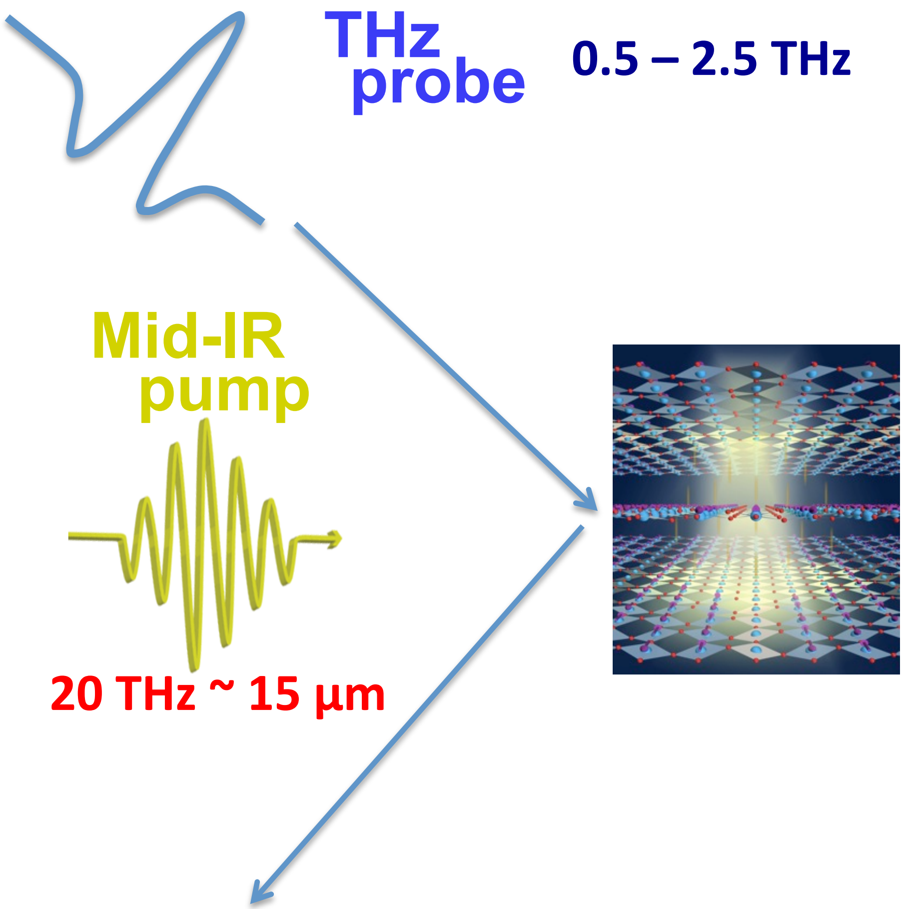
Vibrational modulation of a superconductor



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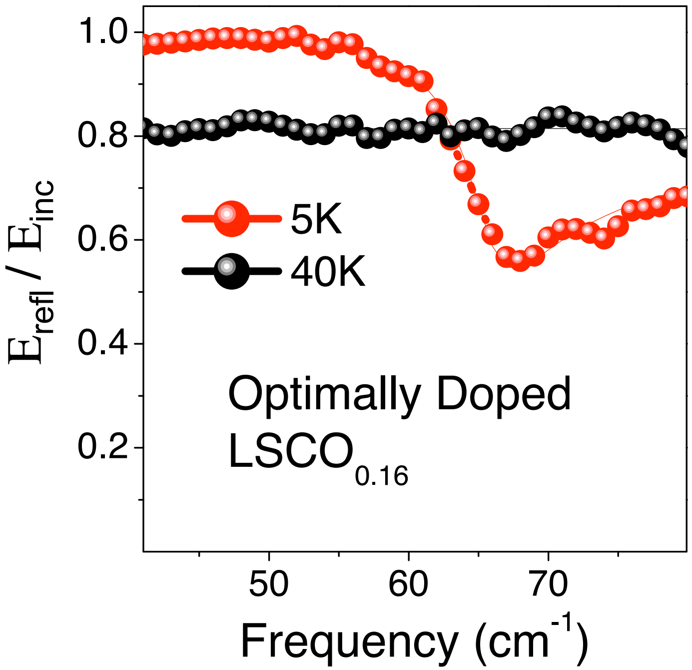
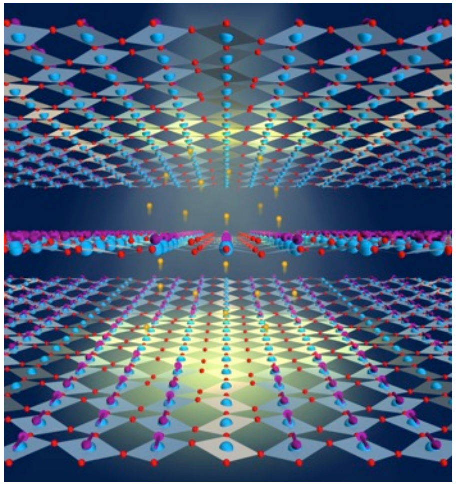


$T > T_c$



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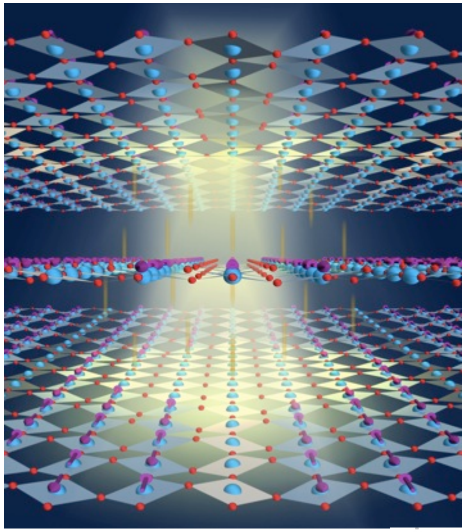

Josephson Plasma edge of a superconductor

Signatures of superconductivity

- Zero resistivity ρ_{DC}=0
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Signatures of superconductivity

- Zero resistivity $\rho_{DC}=0$
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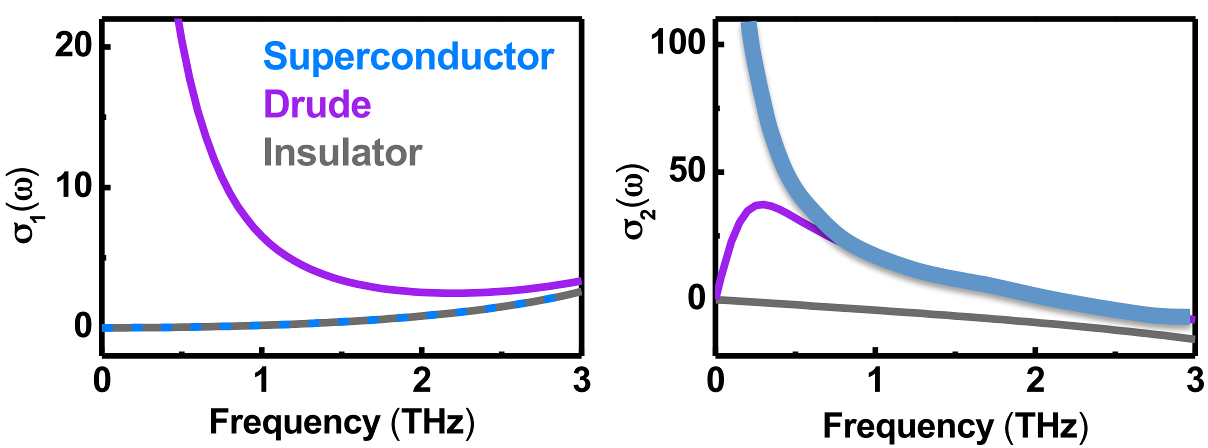
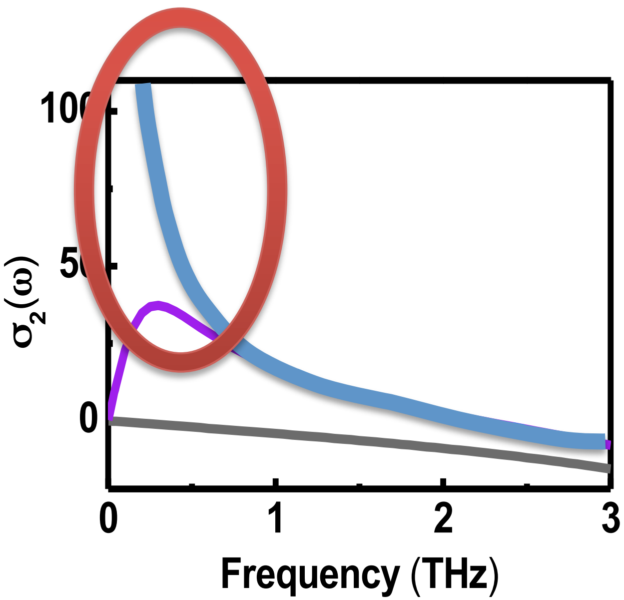
- Fingerprints in the ac-optical conductivity
  - Delta peak at $\omega = 0$
  - London $1/\omega$ in σ_2



Signatures of superconductivity

- Zero resistivity $\rho_{DC}=0$
- Meissner effect
- Fingerprints in the ac-optical conductivity
  - Delta peak at $\omega = 0$
  - London $1/\omega$ in σ_2

→ Superfluid density: $\omega\sigma_{2\ \omega\to 0}$



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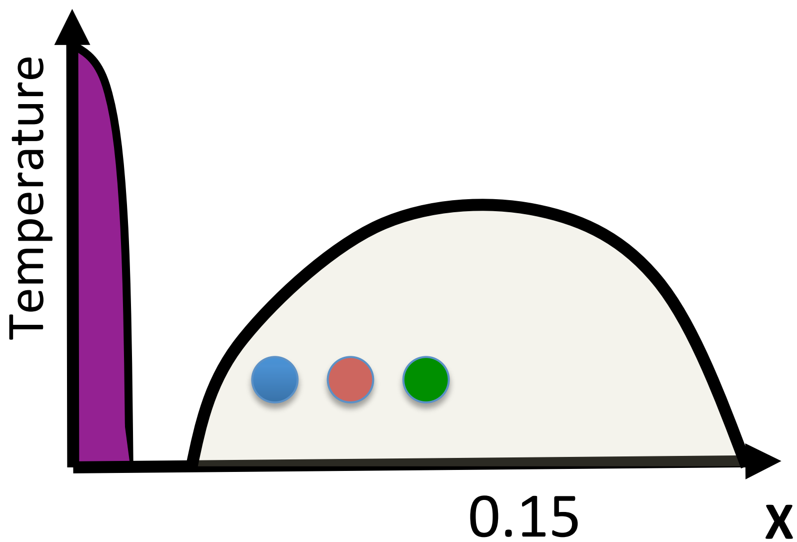
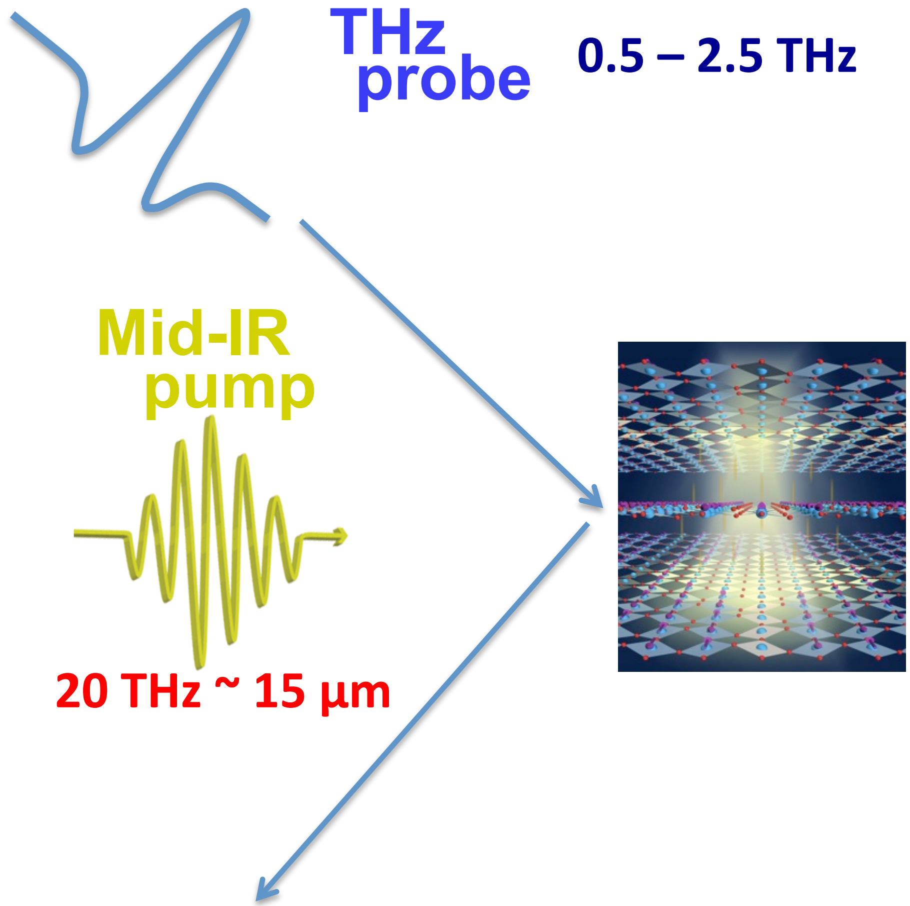
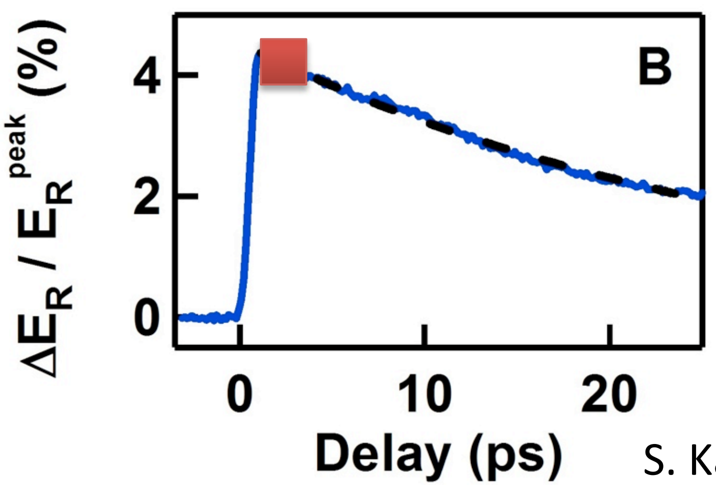
Vibrational modulation of a superconductor

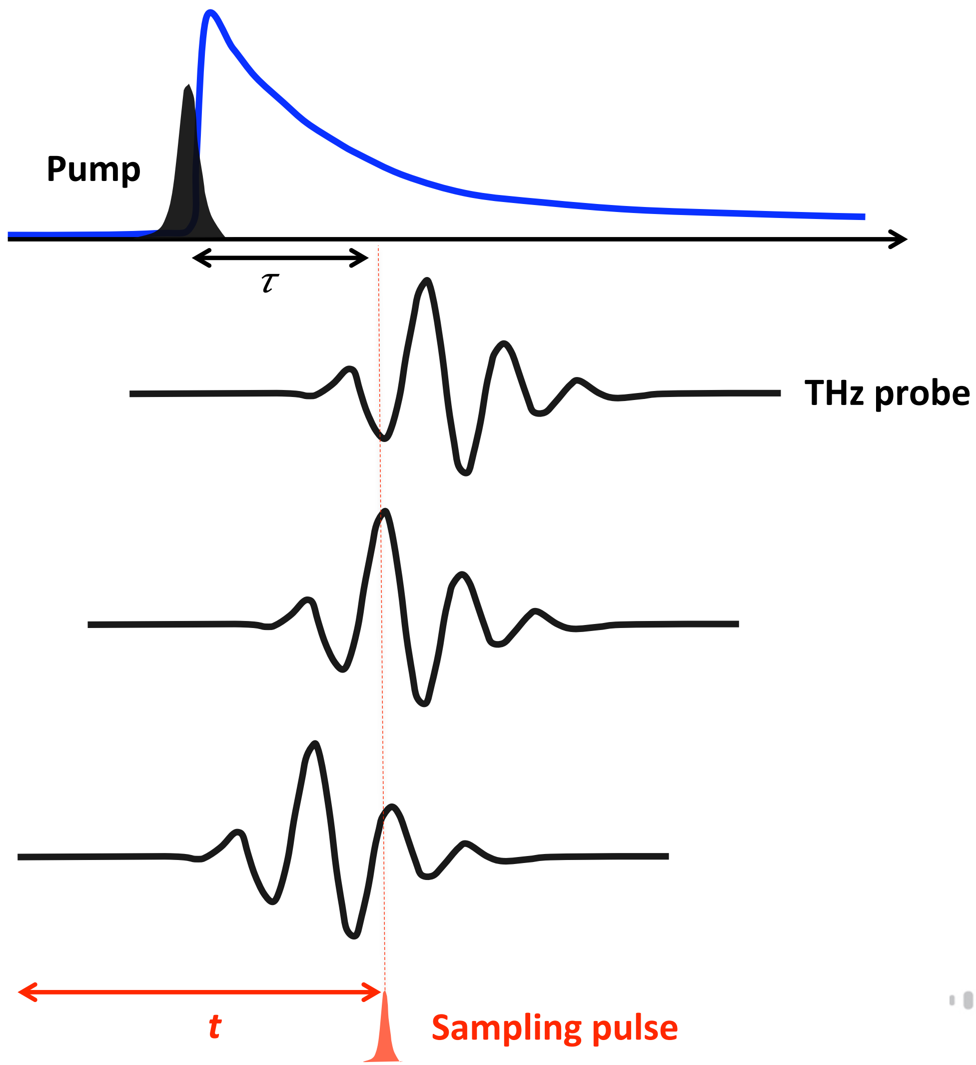




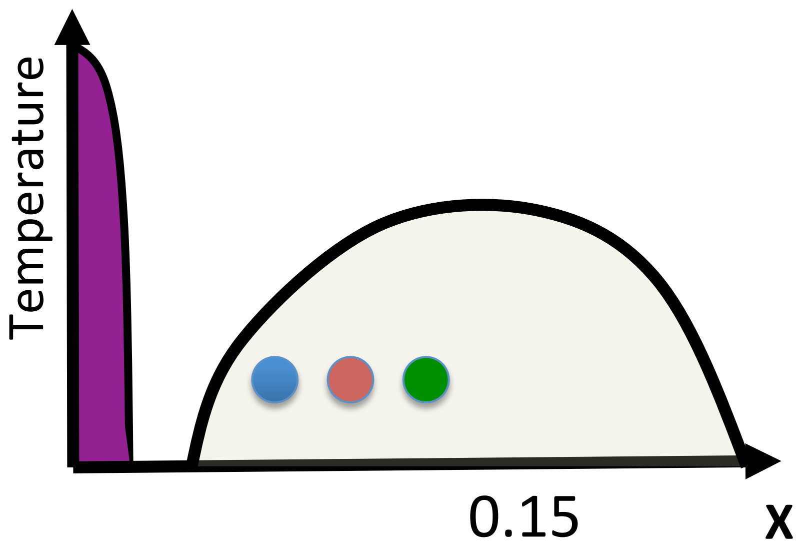


S. Kaiser et al., Phys. Rev. B **89**, 184516 (2014)

Electro optical sampling of the probe pulse

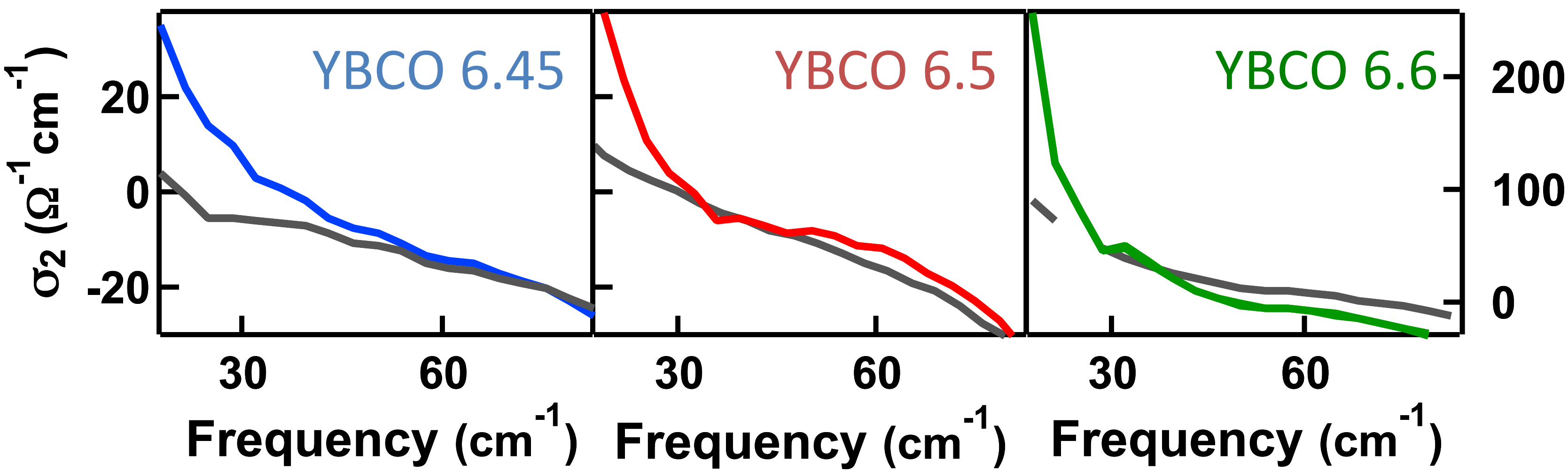


Enhanced coherence below T_c



Increase of superfluid density:

enhanced low frequency JPR

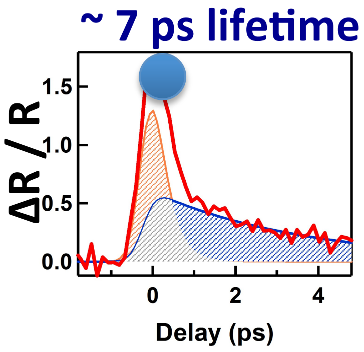


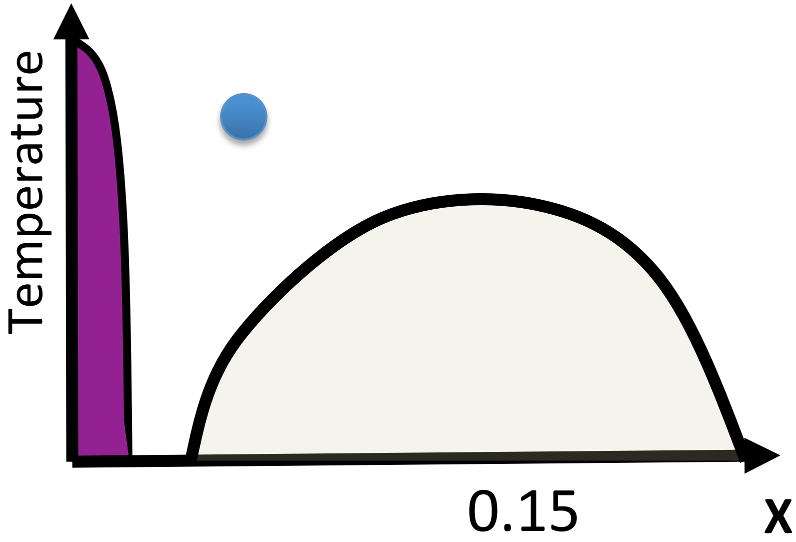
S. Kaiser et al., Phys. Rev. B **89**, 184516 (2014)

Dynamically modulated state above T_c

YBCO 6.45 (T_c=35 K)

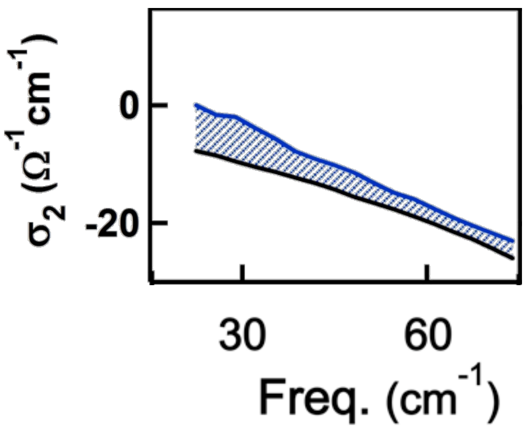
Base temperature 100 K

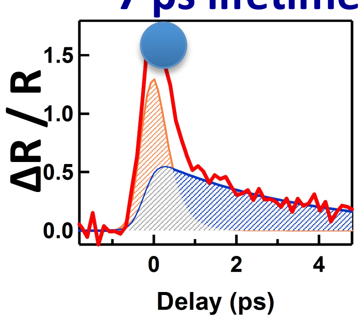




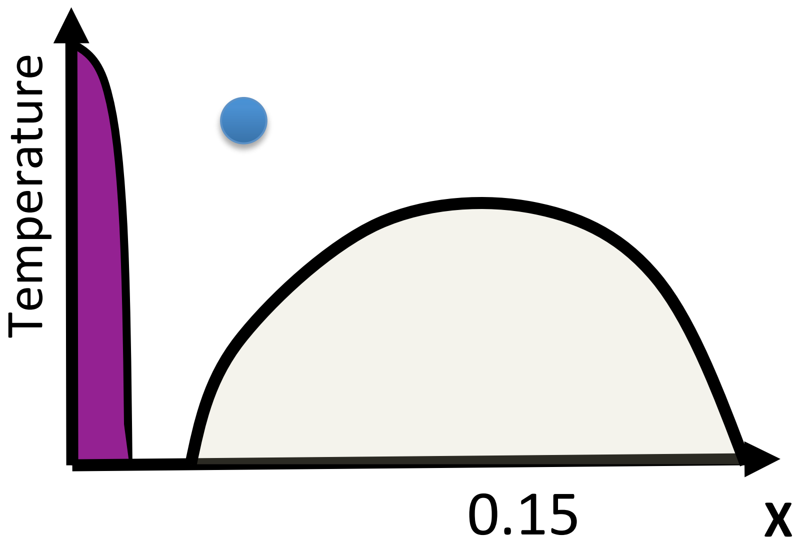
S. Kaiser et al., Phys. Rev. B **89**, 184516 (2014)

Optical response at 100 K YBCO 6.45 (T_c=35 K)



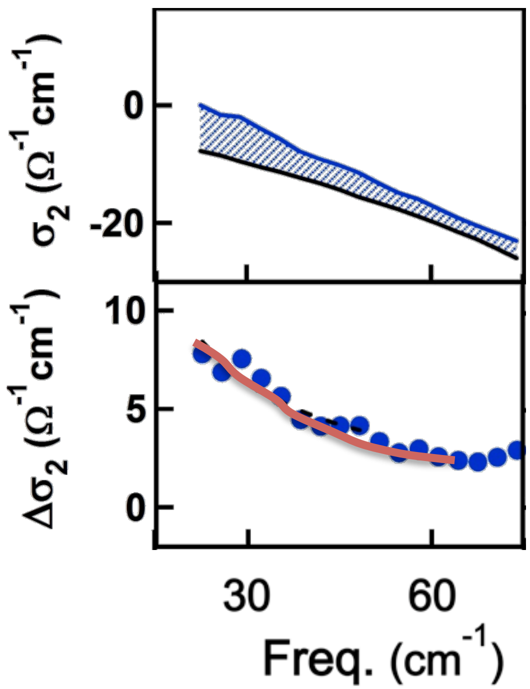


(1) Increased inductive response



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

Optical response at 100 K YBCO 6.45 (T_c=35 K)

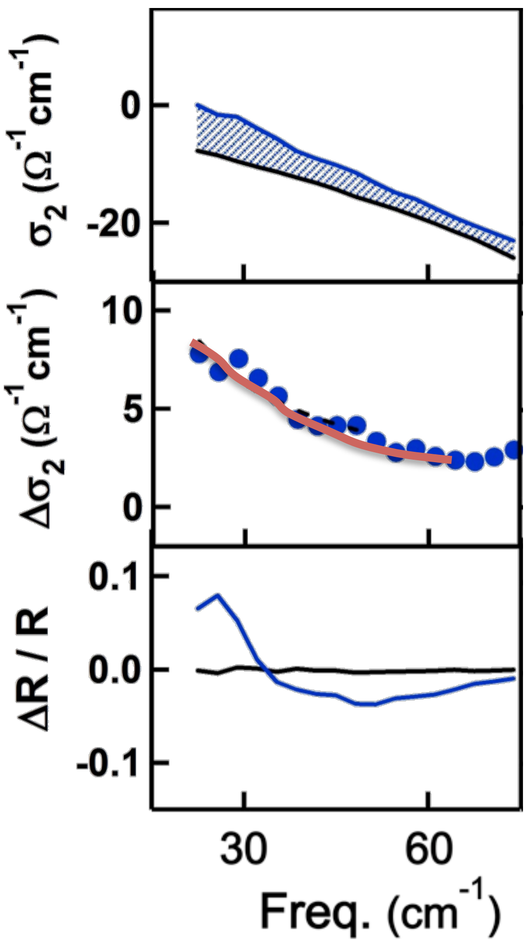


(1) Increased inductive response

(2) $1/\omega$ response in the σ_2 changes

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

Optical response at 100 K YBCO 6.45 (T_c=35 K)



(1) Increased inductive response

(2) $1/\omega$ response in the σ_2 changes

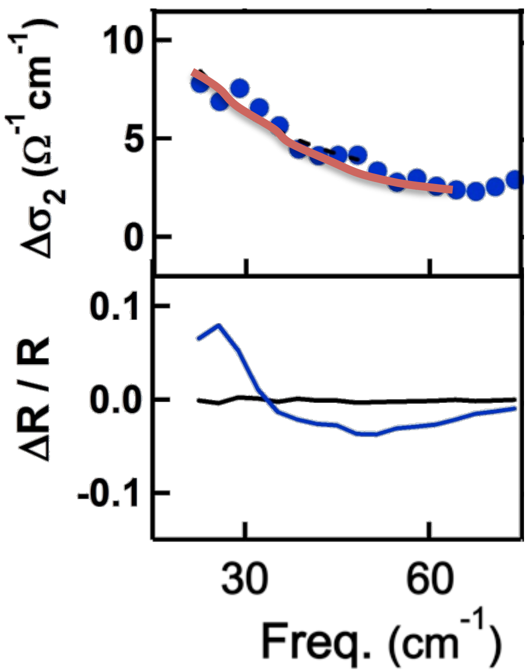
(3) Photoinduced plasma edge

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

Temperature dependence YBCO 6.45 (T_c=35 K)

Increase temperature:

100 K

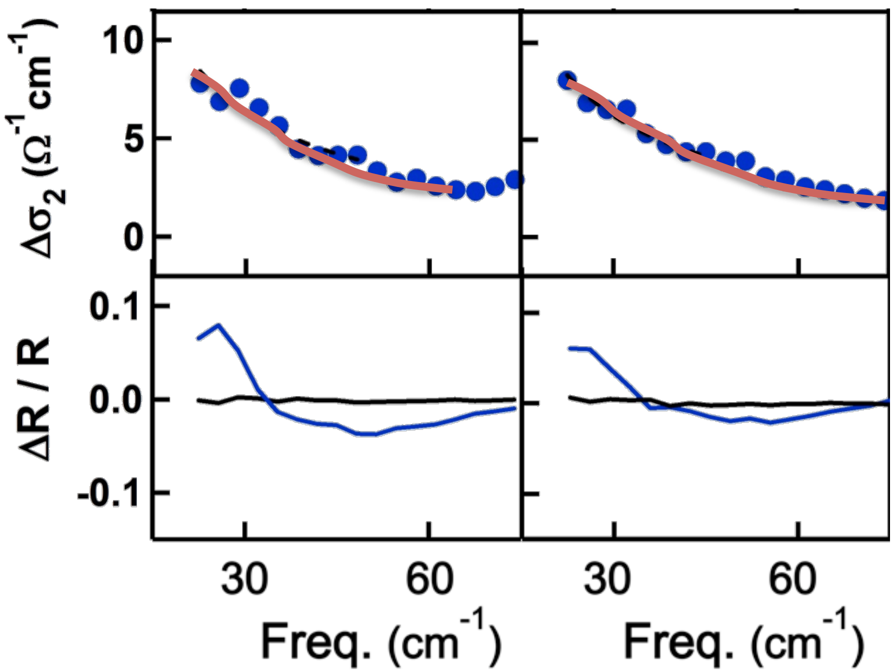


S. Kaiser et al., Phys. Rev. B **89**, 184516 (2014)

Temperature dependence YBCO 6.45 (T_c=35 K)

Increase temperature:

100 K 200 K



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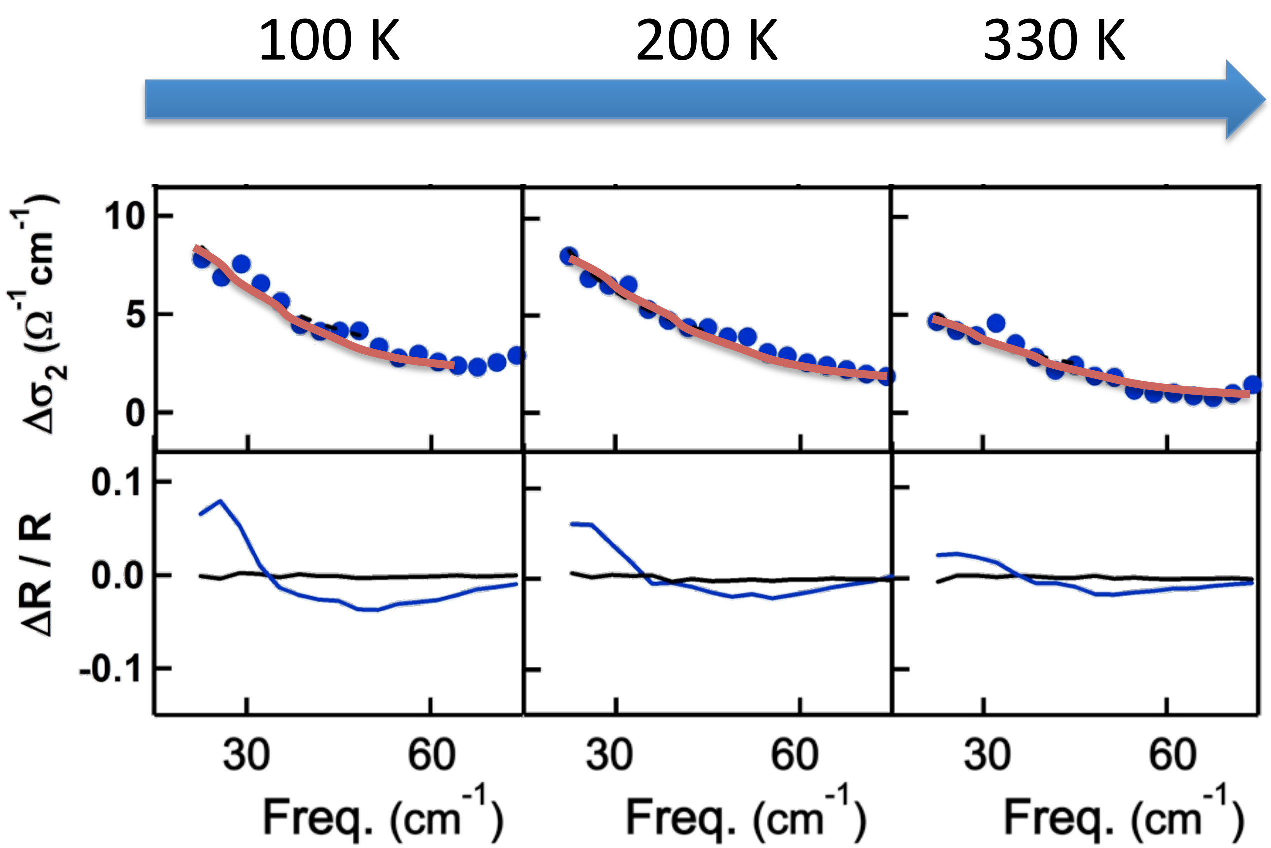
S. Kaiser et al., Phys. Rev. B **89**, 184516 (2014)

CFEL SCIENCE

Temperature dependence YBCO 6.45 (T_c=35 K)

Increase temperature: **All effects persist!**

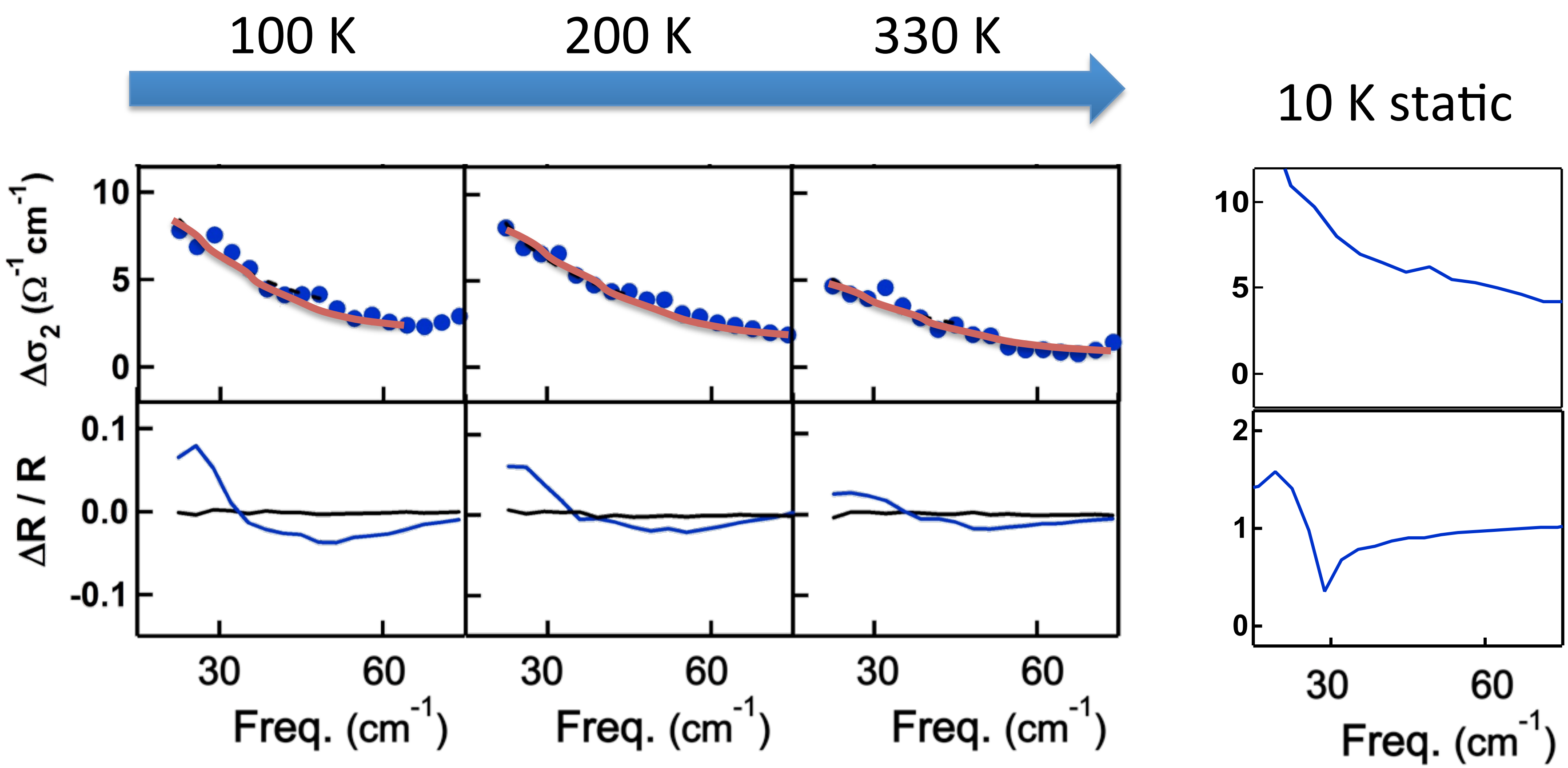


S. Kaiser et al., Phys. Rev. B **89**, 184516 (2014)

Temperature dependence YBCO 6.45 (T_c=35 K)

Increase temperature:

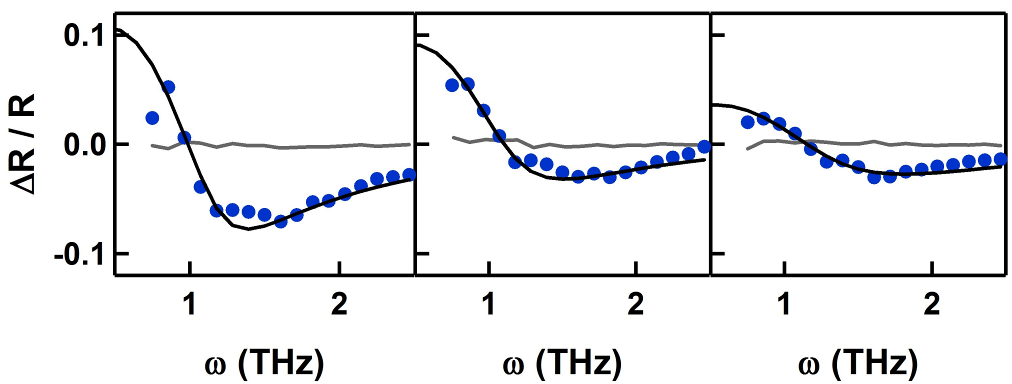
All effects persist!

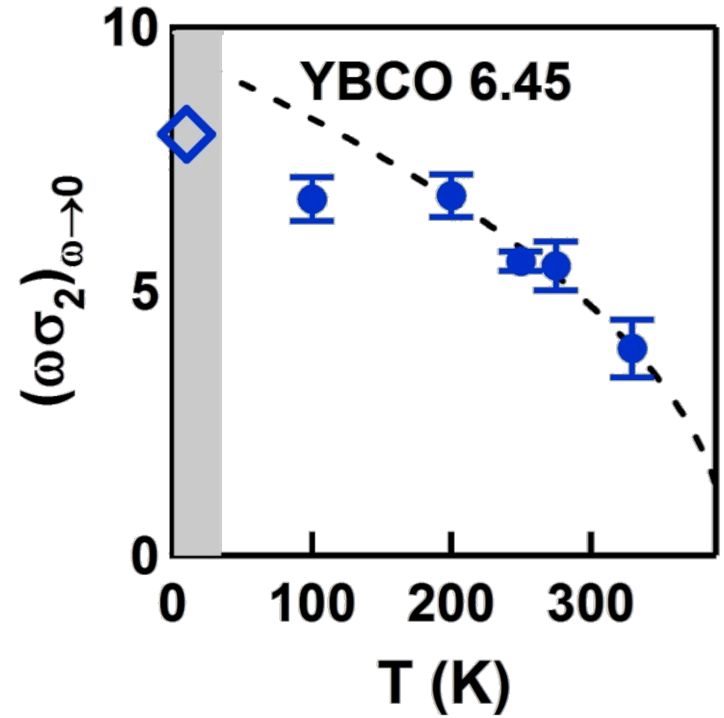


S. Kaiser et al., Phys. Rev. B **89**, 184516 (2014)

Evaluating the "Superfluid" density

100 K 200 K 330 K





$$D^{SF} \propto (\omega\sigma_2)_{\omega\to 0}$$

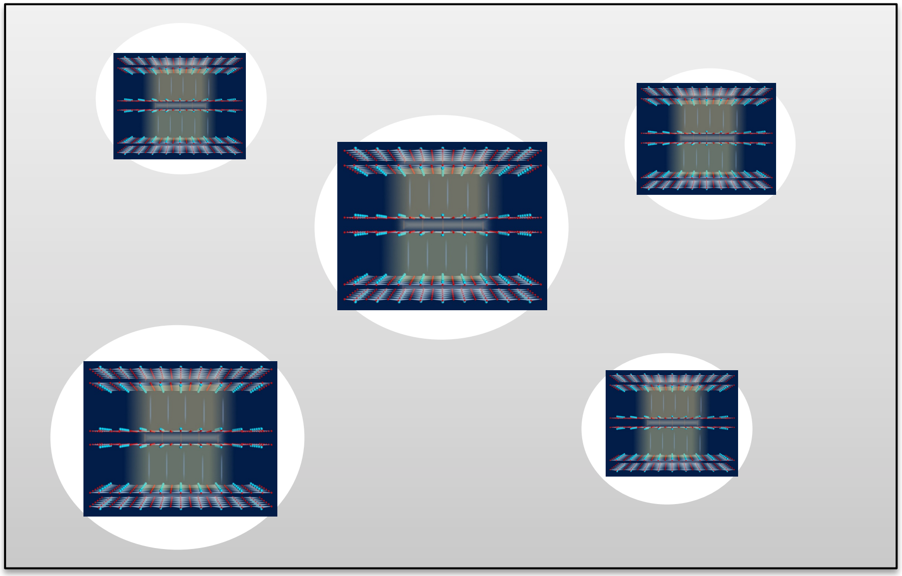
$$D^{SF} \propto \sqrt{1 - \frac{T}{T'}}$$

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

Inhomogeneous nature of the SC state

Bruggeman Effective Medium

$$f\,\frac{\tilde{\varepsilon}_S(\omega)-\tilde{\varepsilon}_E(\omega)}{\tilde{\varepsilon}_S(\omega)+2\tilde{\varepsilon}_E(\omega)}+(1-f)\,\frac{\tilde{\varepsilon}_{NS}(\omega)-\tilde{\varepsilon}_E(\omega)}{\tilde{\varepsilon}_{NS}(\omega)+2\tilde{\varepsilon}_E(\omega)}=0,$$



ε_E : Effective medium dielectric function

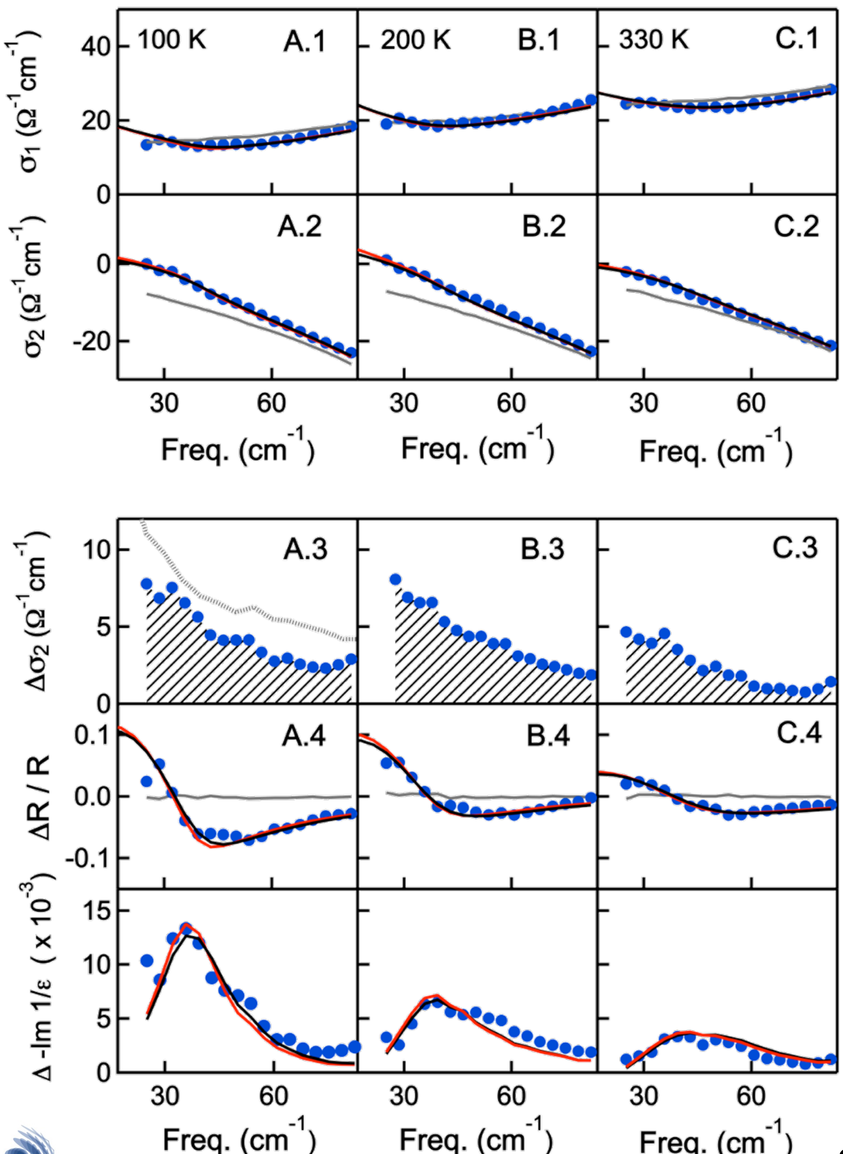
ε_S : Superconductor dielectric function (Plasmafrequency defines edge pos.)

ε_{NS}: Normal-state dielectric function

f : Superconducting volume fraction (only free fit parameter)

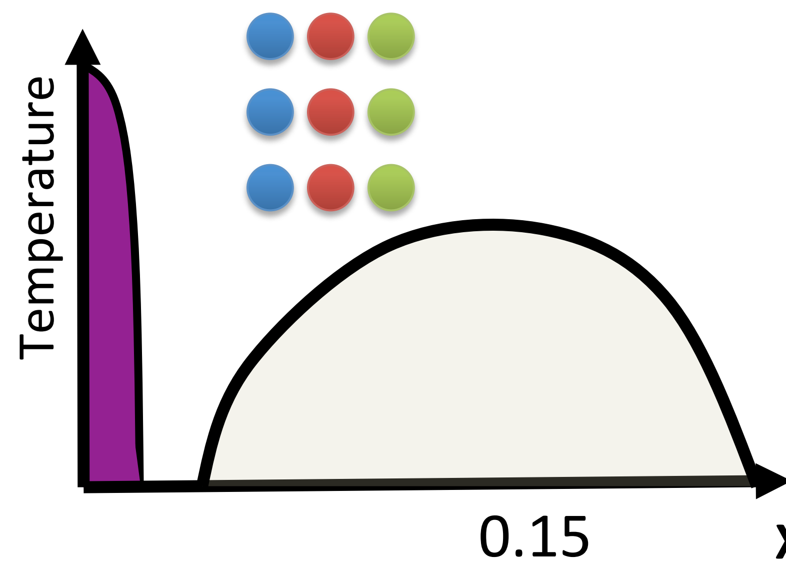
S. Kaiser et al., Phys. Rev. B **89**, 184516 (2014)

Effective medium fits to YBCO 6.45 (T_c=35 K)



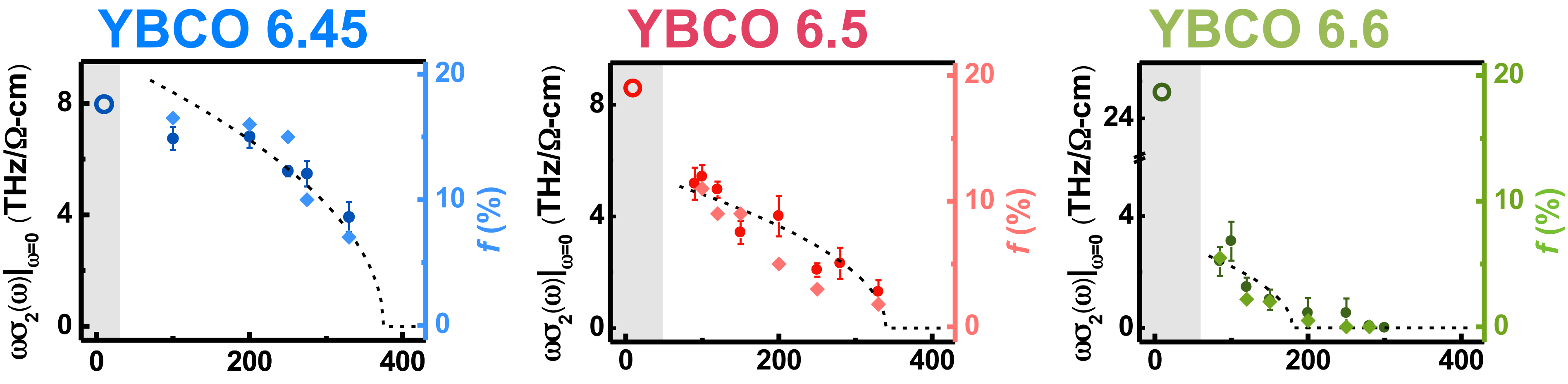
Excellent fit to all optical properties

All temperatures, all doping levels!



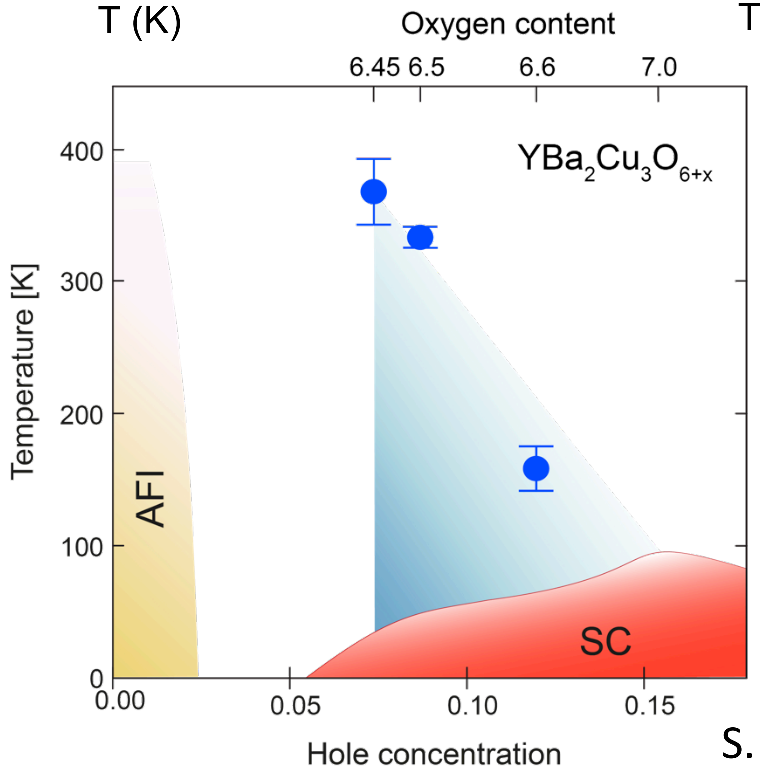
S. Kaiser et al., Phys. Rev. B **89**, 184516 (2014)

Temperature dependence of the superconducting properties



Filling fraction:

$$f(T) \propto \sqrt{1 - \frac{T}{T'}}$$



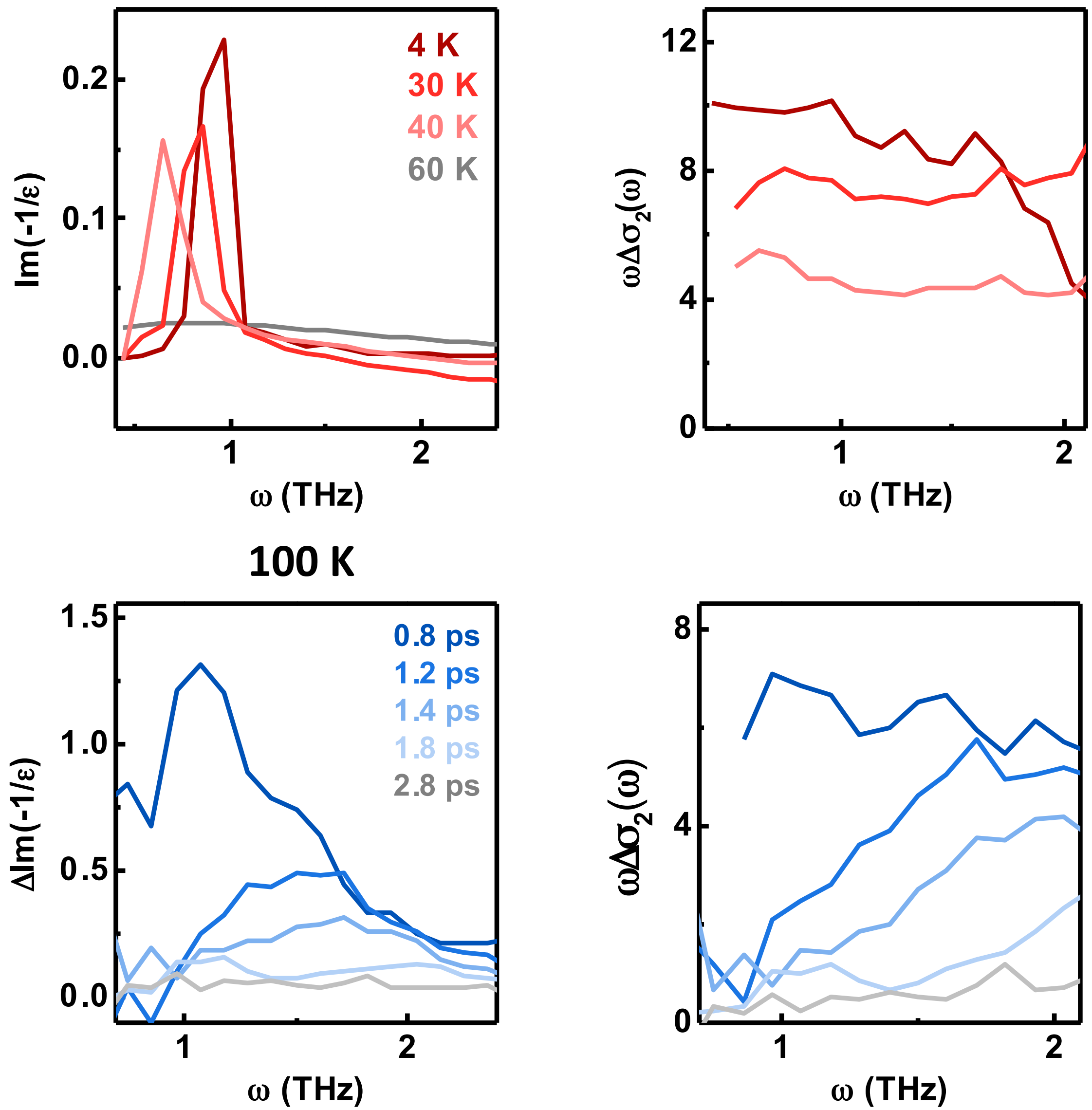
Phase diagram for photo-induced transient superconductivity

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

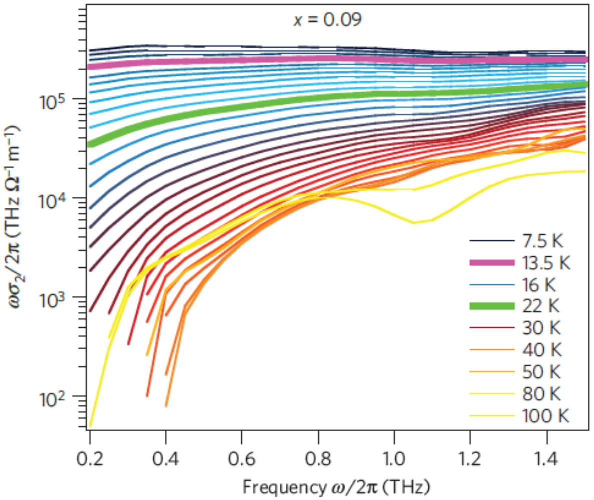
Relaxation of the transient state

Equilibrium:

Transient:



Relaxation of the transient state



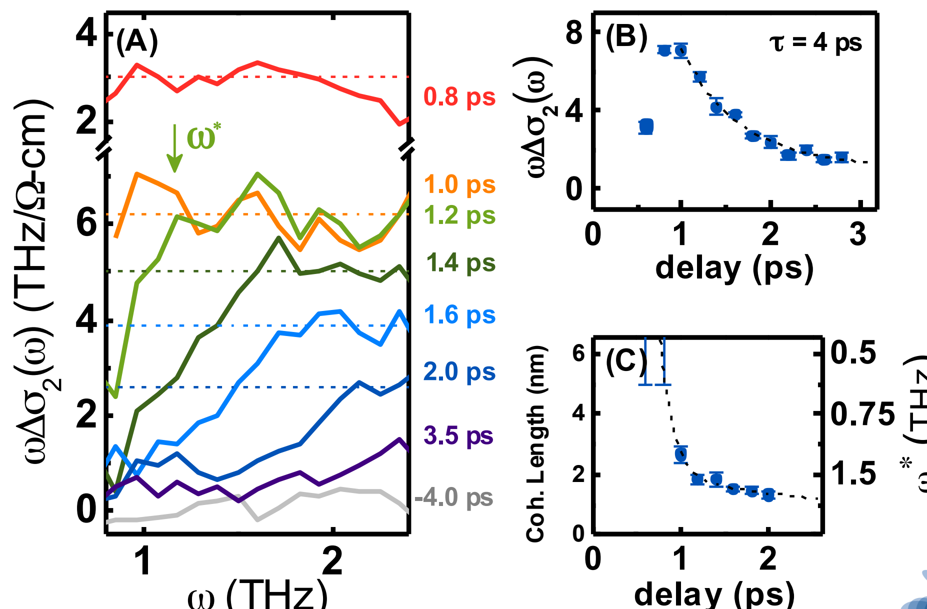
Divergence of σ2 a measure of coherence

For instance, LSCO—fluctuations above the KTB temperature. [L. S. Bilbro, *et al*. *Nature Physics*, **7** 298 (2011).]

Fluctuations on long time/length scales → divergence in 1/ω behavior seen at low frequencies.

Can use "roll off" frequency as a measure of the coherence length scale.

$$d_{coh} \sim 2 d_{jctn} \omega_J / \omega^*$$



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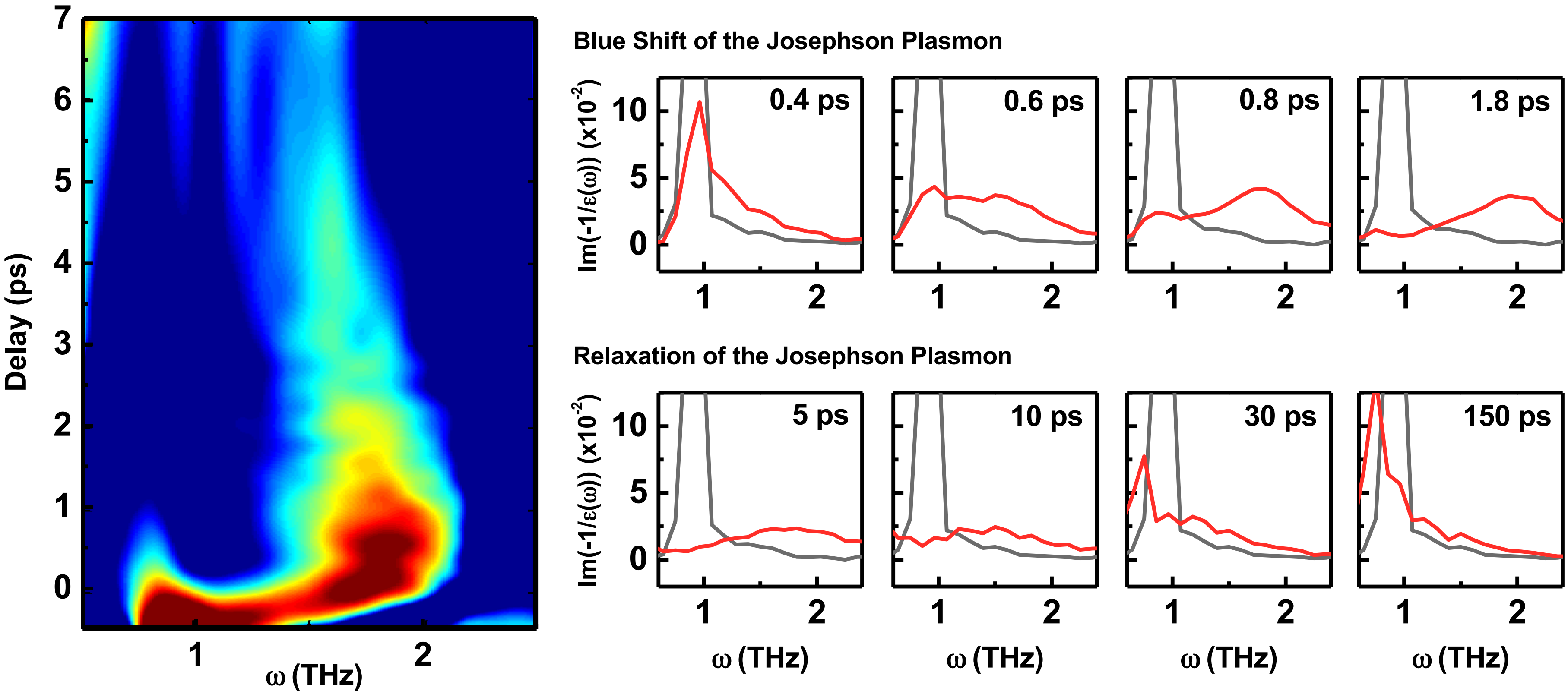
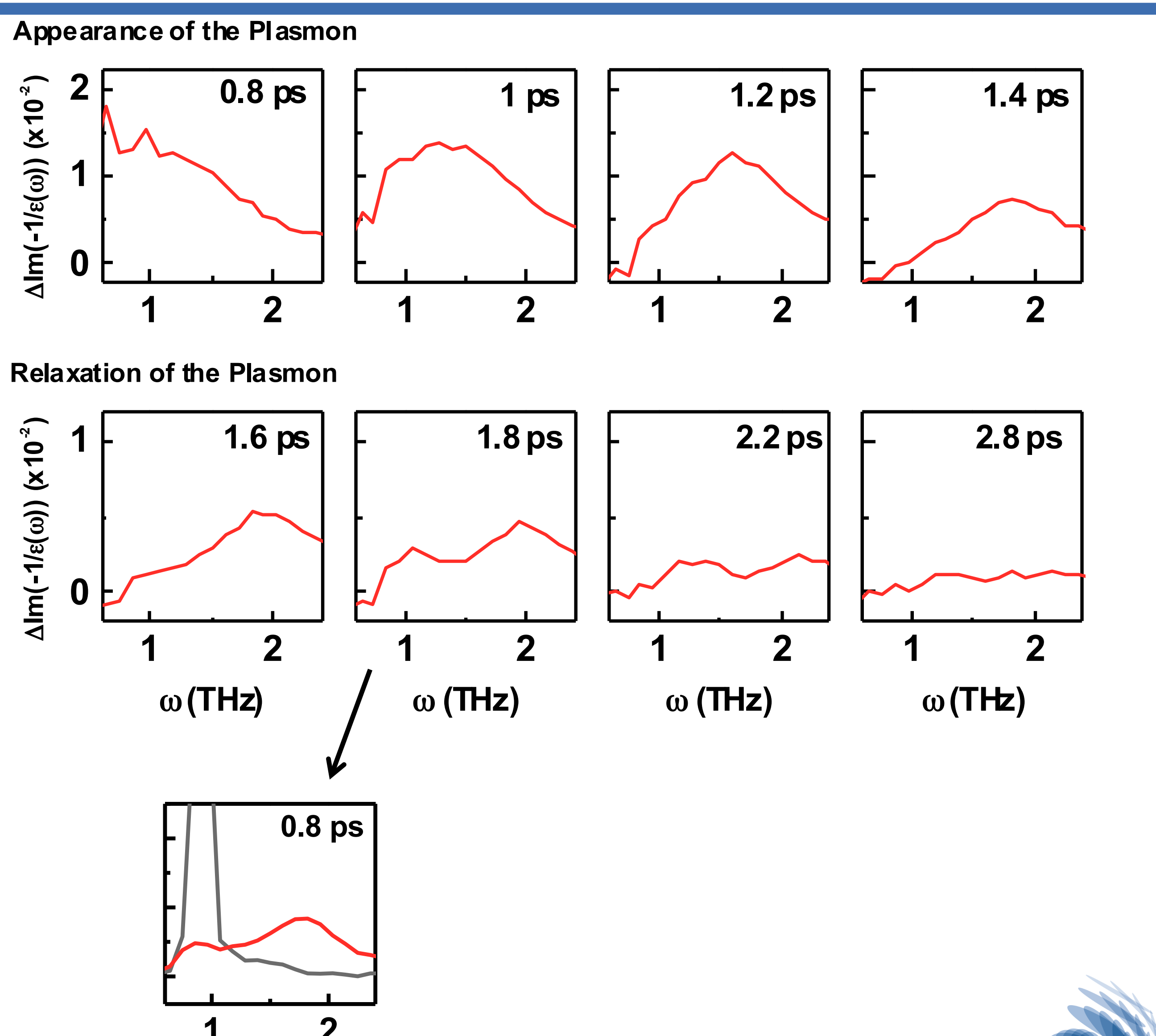
Relaxation of the transient plasmon, T < Tc



mpsd

Relaxation of the transient plasmon, T > Tc



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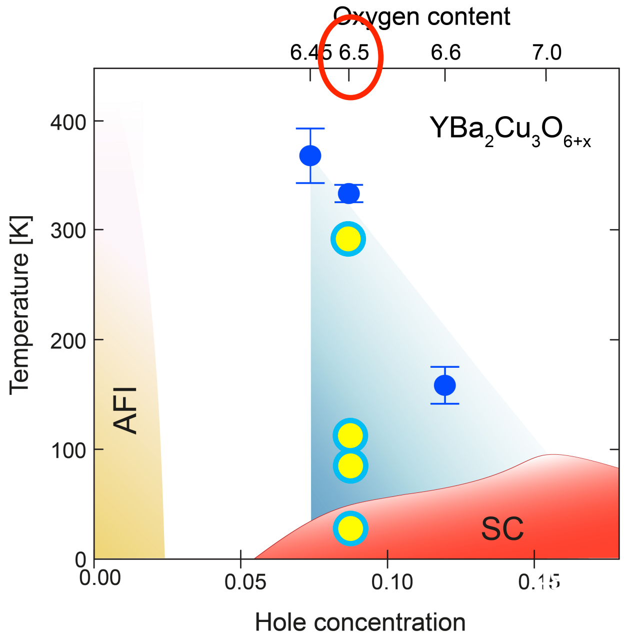
Light-induced superconductivity can be found up to room temperature

- **Where are the transient superconducting carriers coming from?**



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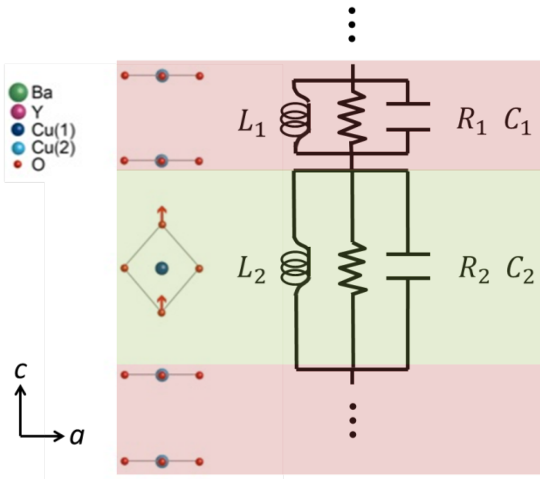
Where are the carriers coming from?

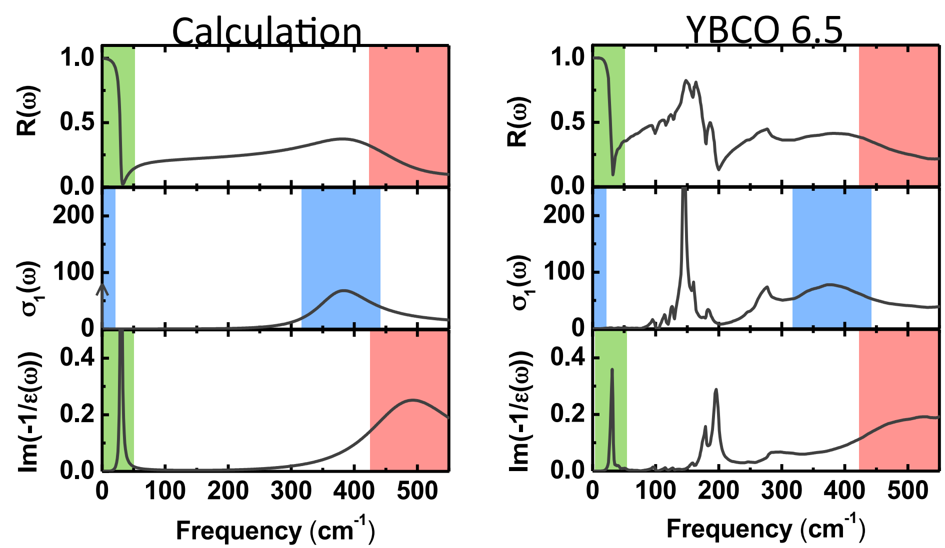


Consider below Tc again.

A second equilibrium Josephson plasma resonance (JPR) at high frequency.

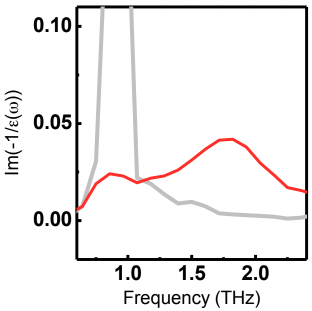
Two modes share spectral weight

- **DC delta function**
- **Finite frequency transverse mode**

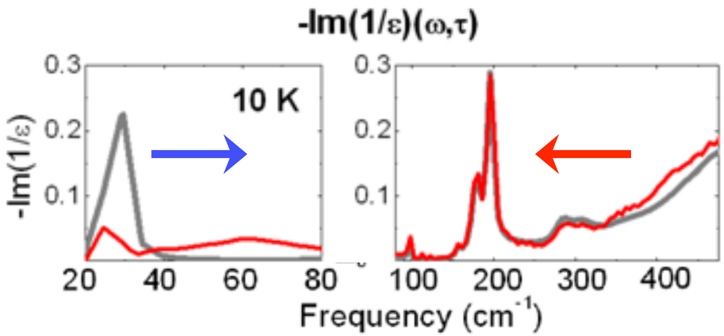


[calculation based on: D. van der Marel, and A. Tsvetkova. Czech. Journal of Physics 46, 3165]

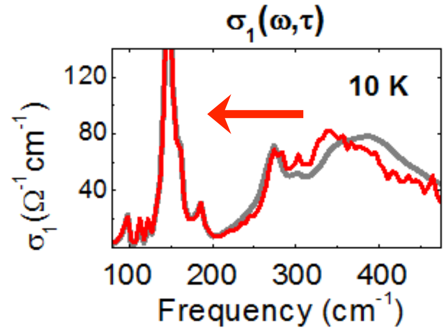
Broadband Response at T < T_c: High frequency plasmon weakens



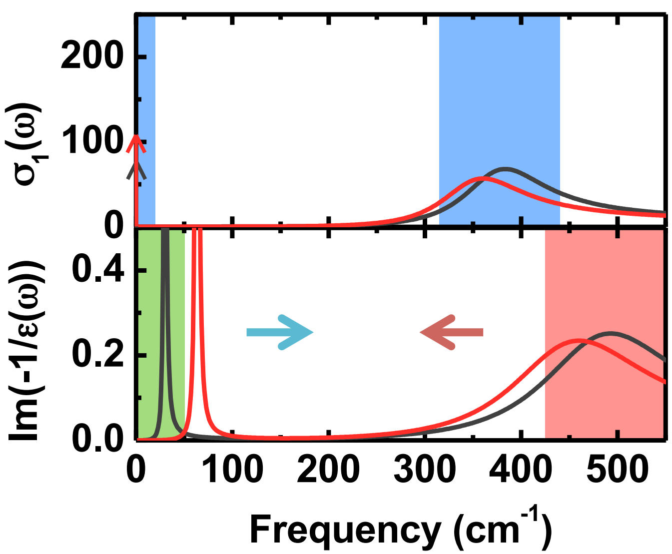
ω_{JPR1} **blue shifts** ω_{JPR2} **red shifts**

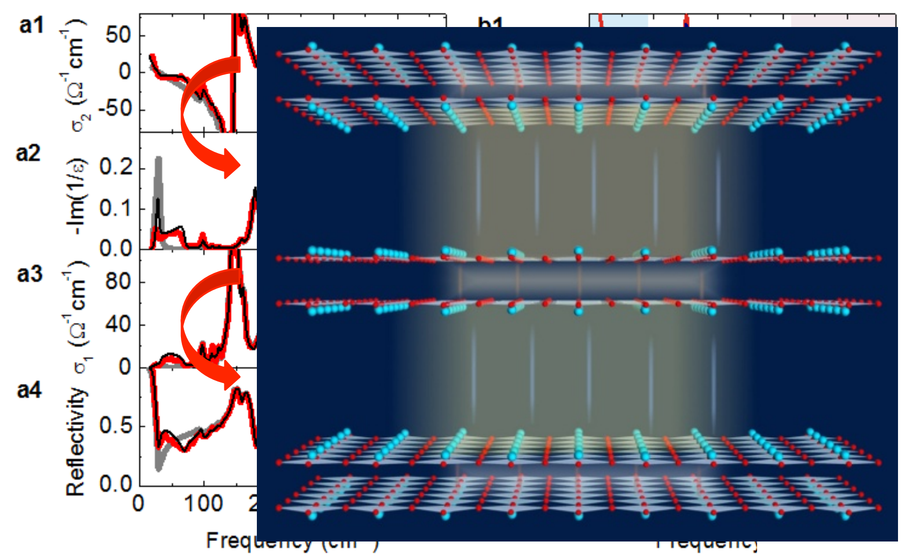


Transverse mode
ω_T **red shifts**



Calculation

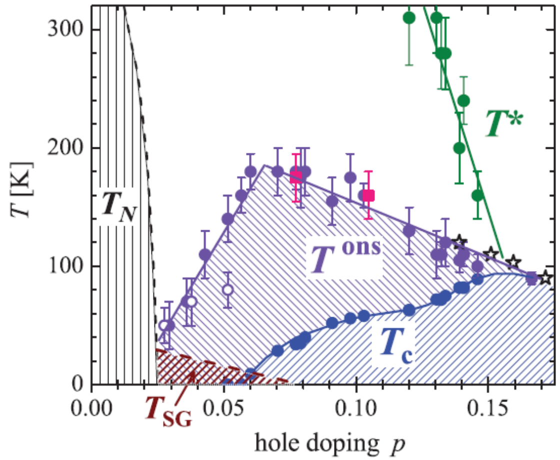




W. Hu et al., Nature Materials **13**, 705–711 (2014)

mpsd

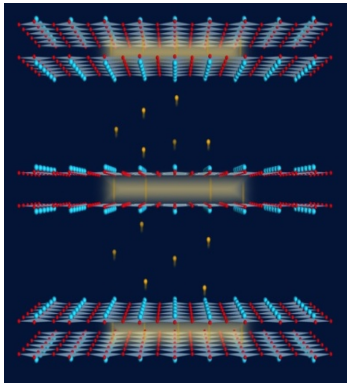
What about above T_c?

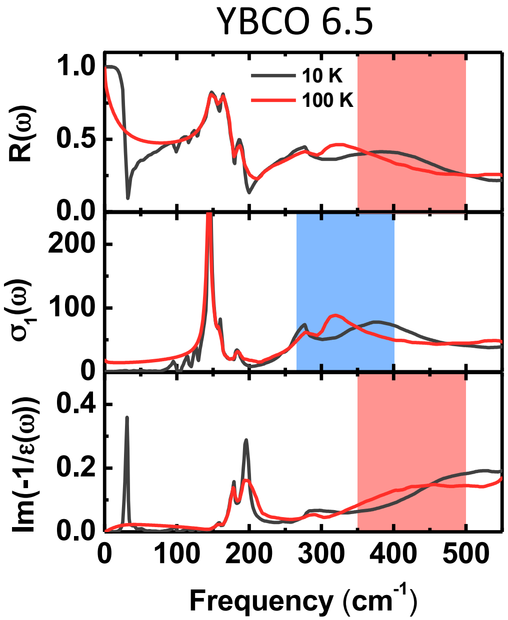


[A. Dubroka, *et al.*, PRL **106**, 047006 (2011).]

Precursor superconductivity far above T_c
YBCO 6.6: up to 180 K!

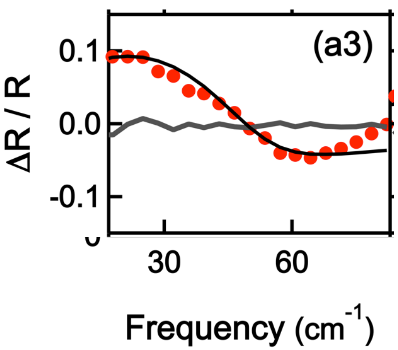
Effect attributed to conductivity across **bilayers** only

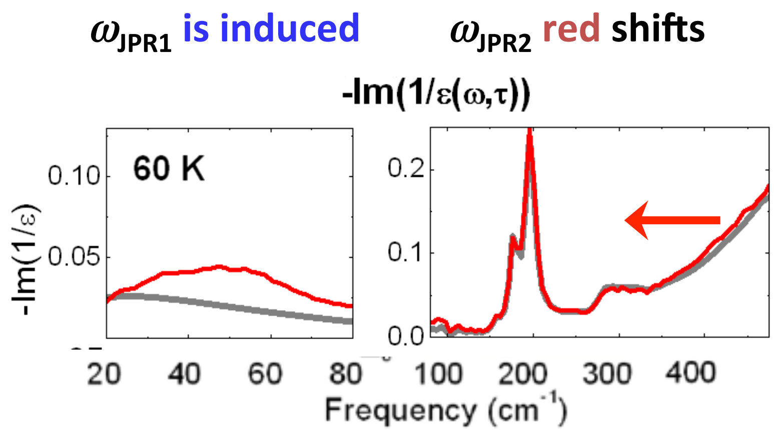


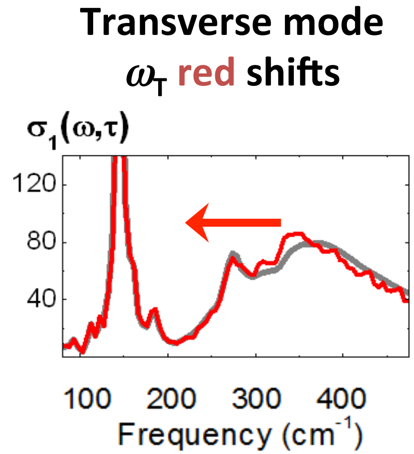


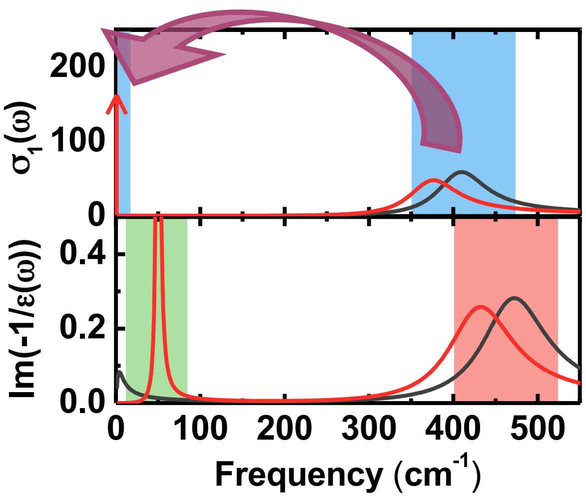
W. Hu et al., Nature Materials **13**, 705–711 (2014)

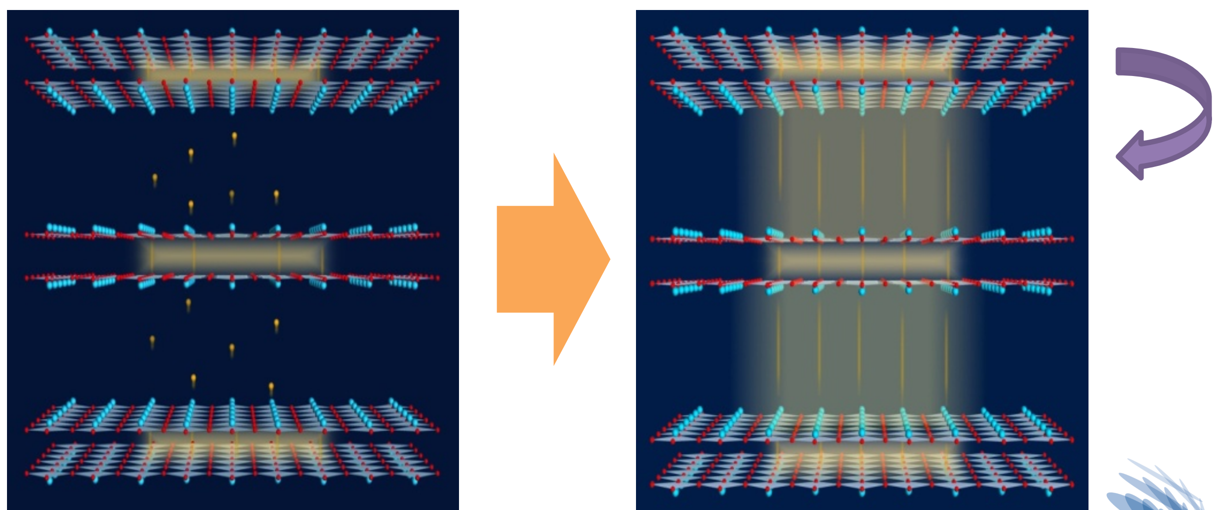
Broadband Response at T > $T_{c:}$ Redistribution of coherence











W. Hu et al., Nature Materials **13**, 705–711 (2014)

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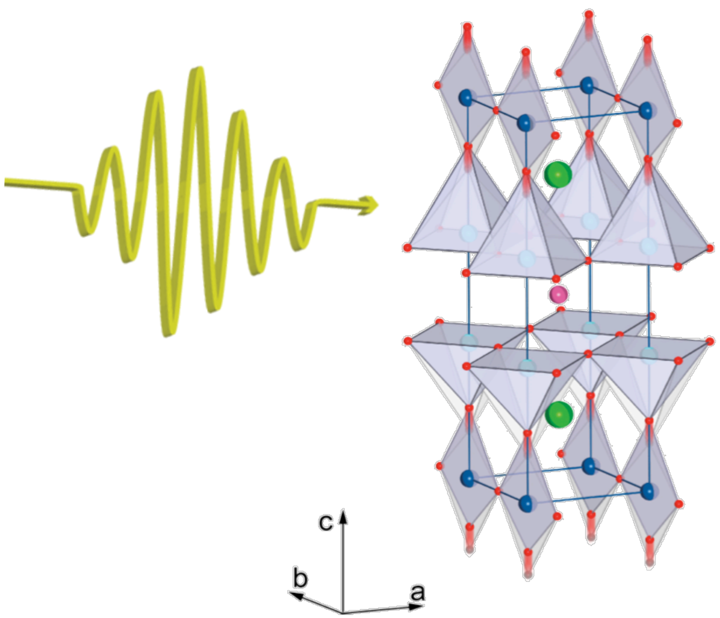
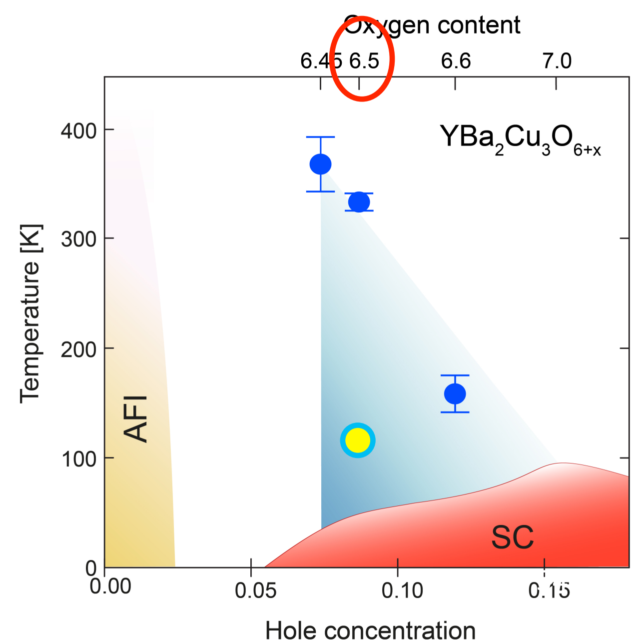
Light-induced superconductivity can be found

Cooper pairs transfer between the bilayers

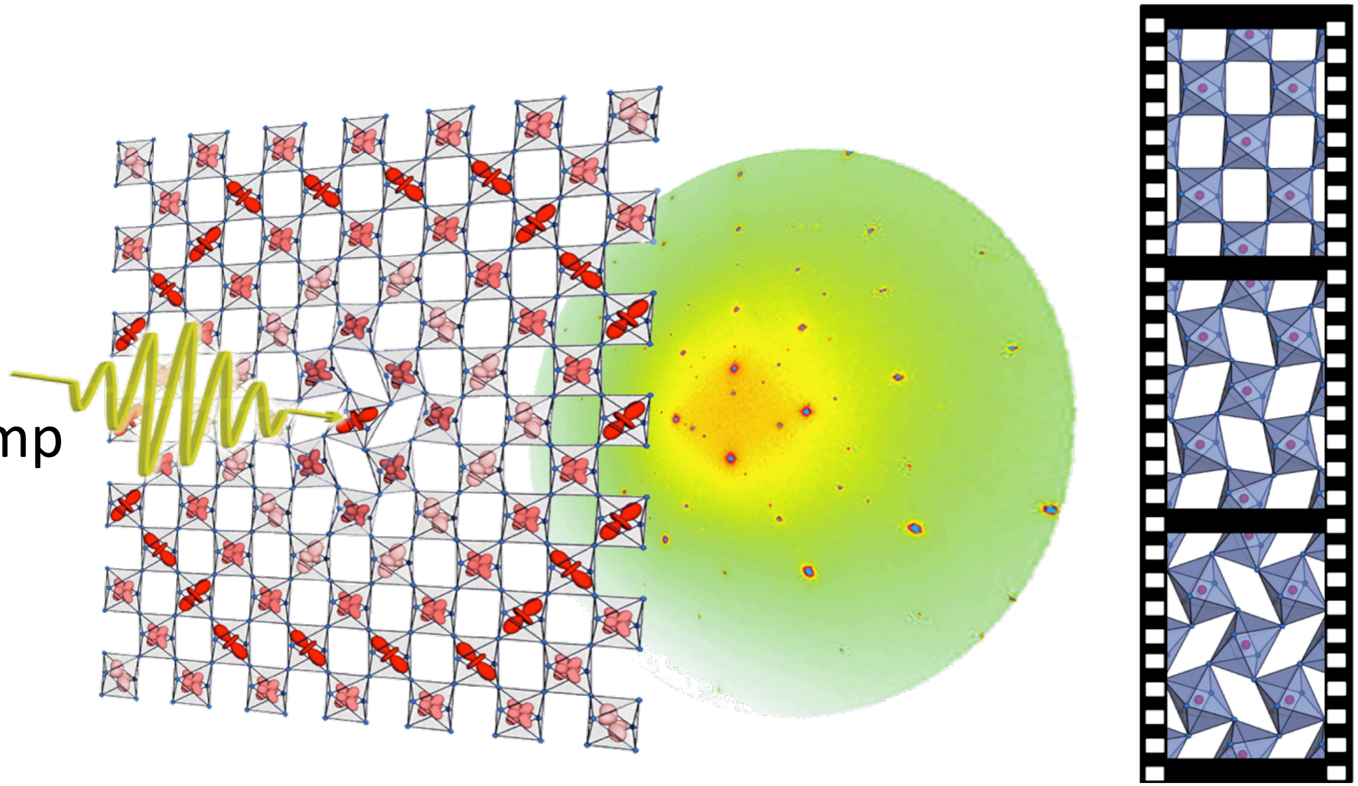
What are the atoms doing?





fs-crystallography

15 μm
phonon pump



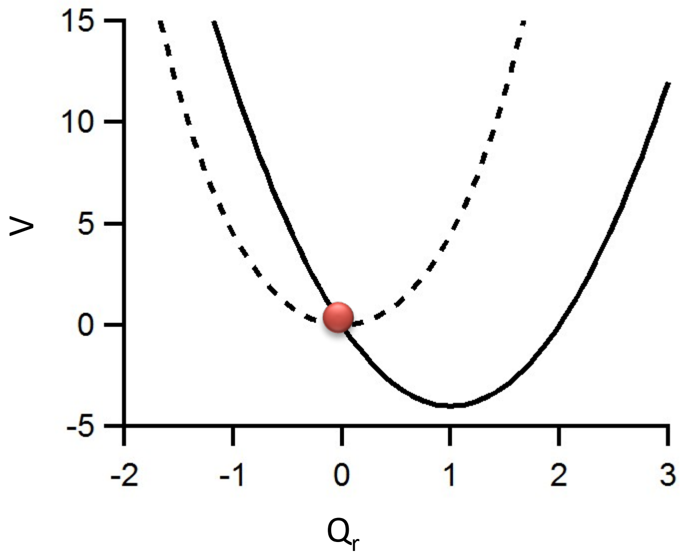
Q^2Q – coupling

•Simple Classical Model of Nonlinear Phononics

- Potential energy of the Raman mode as function of IR mode Amplitude

$$V_r = \frac{1}{2}\mu_r\omega_r^2 Q_r^2 - AQ_{ir}^2 Q_r$$

Displacement of Raman mode



Nonlinear Phononics in Bulk

- Equation of Motion $\mu_r \ddot{Q}_r + 2\gamma_r \mu_r \dot{Q}_r + \mu_r \omega_r^2 Q_r = A Q_{ir}^2$

Nonlinear Phononics in Bulk

- Equation of Motion $\mu_r \ddot{Q}_r + 2\gamma_r \mu_r \dot{Q}_r + \mu_r \omega_r^2 Q_r = A Q_{ir}^2$

damped harmonic oscillator

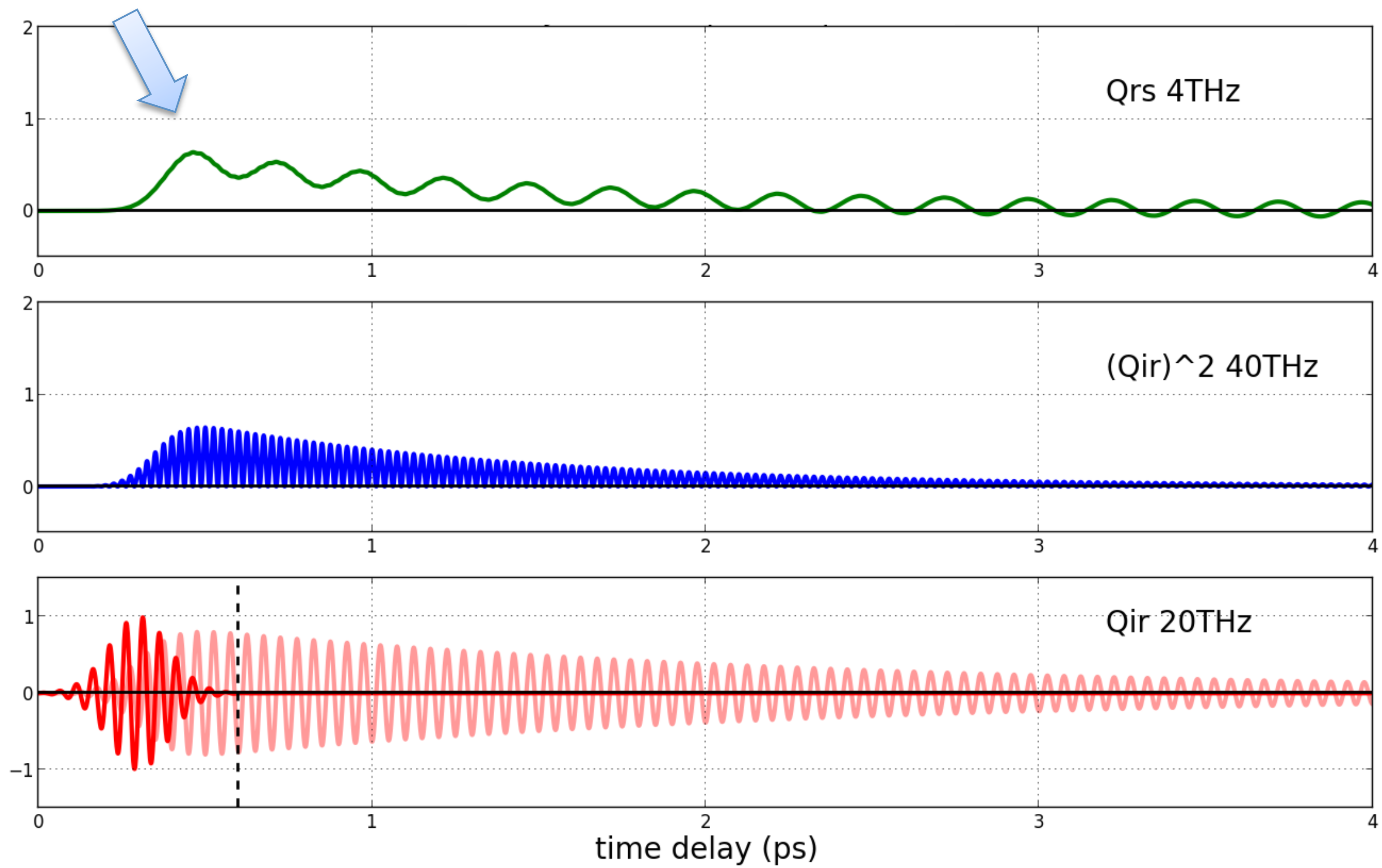
Nonlinear Phononics in Bulk

- Equation of Motion $$\mu_r \ddot{Q}_r + 2\gamma_r \mu_r \dot{Q}_r + \mu_r \omega_r^2 Q_r = A Q_{ir}^2$$

damped harmonic oscillator   driving force

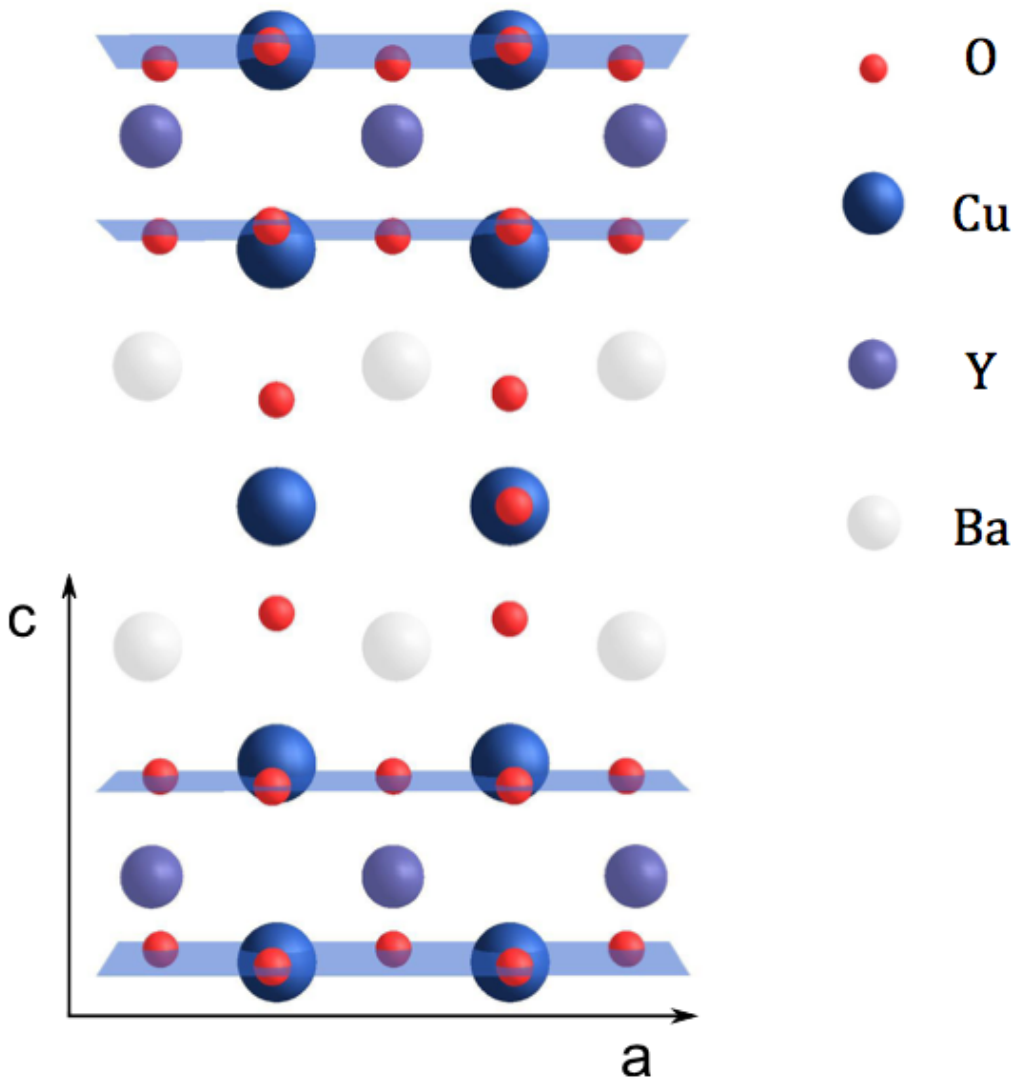
- Equation of Motion $\mu_r \ddot{Q}_r + 2\gamma_r \mu_r \dot{Q}_r + \mu_r \omega_r^2 Q_r = A Q_{ir}^2$

$Q_r(t)$

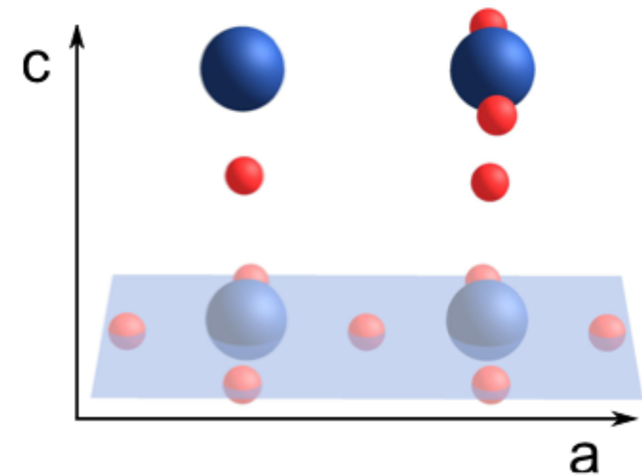


Atomic Motions

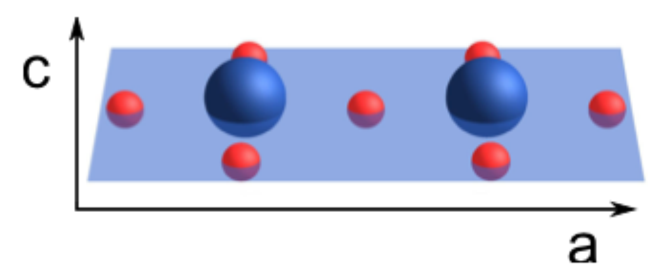
- YBCO6.5 OrthoII



Chains

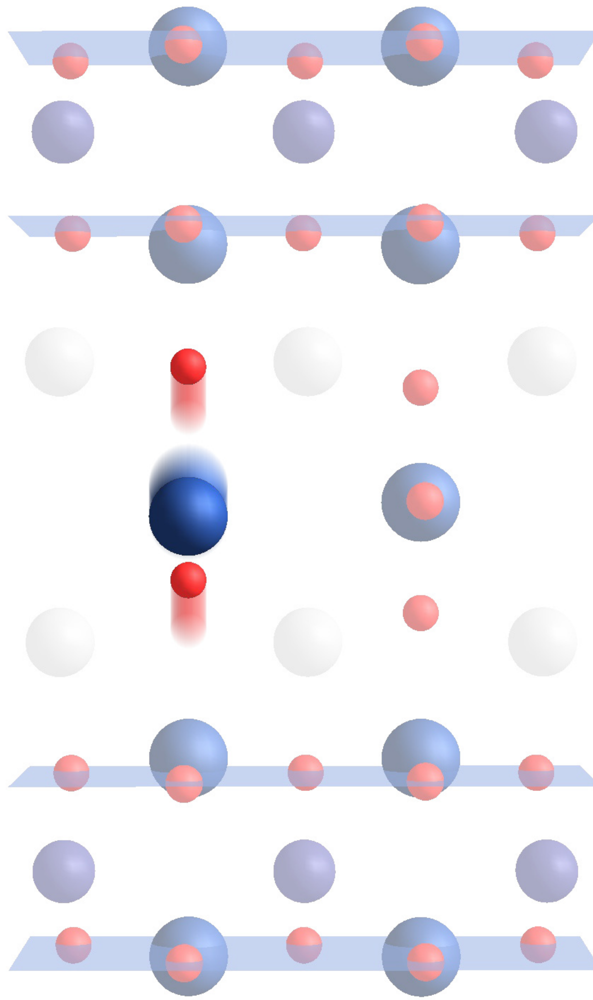


CuO_2 Planes



Atomic Motions

B1u Mode



Symmetry table

- Symmetry Analysis of YBCO

⊗	A_g	B_{1g}	B_{2g}	B_{3g}	A_u	B_{1u}	B_{2u}	B_{3u}
A_g	A_g	B_{1g}	B_{2g}	B_{3g}	A_u	B_{1u}	B_{2u}	B_{3u}
B_{1g}	B_{1g}	A_g	B_{3g}	B_{2g}	B_{1u}	A_u	B_{3u}	B_{2u}
B_{2g}	B_{2g}	B_{3g}	A_g	B_{1g}	B_{2u}	B_{3u}	A_u	B_{1u}
B_{3g}	B_{3g}	B_{2g}	B_{1g}	A_g	B_{3u}	B_{2u}	B_{1u}	A_u
A_u	A_u	B_{1u}	B_{2u}	B_{3u}	A_g	B_{1g}	B_{2g}	B_{3g}
B_{1u}	B_{1u}	A_u	B_{3u}	B_{2u}	B_{1g}	A_g	B_{3g}	B_{2g}
B_{2u}	B_{2u}	B_{3u}	A_u	B_{1u}	B_{2g}	B_{3g}	A_g	B_{1g}
B_{3u}	B_{3u}	B_{2u}	B_{1u}	A_u	B_{3g}	B_{2g}	B_{1g}	A_g

A_g modes

$B_{1u} \times B_{1u} = A_g$

•Symmetry Analysis of YBCO

⊗	A_g	B_{1g}	B_{2g}	B_{3g}	A_u	B_{1u}	B_{2u}	B_{3u}
A_g	A_g	B_{1g}	B_{2g}	B_{3g}	A_u	B_{1u}	B_{2u}	B_{3u}
B_{1g}	B_{1g}	A_g	B_{3g}	B_{2g}	B_{1u}	A_u	B_{3u}	B_{2u}
B_{2g}	B_{2g}	B_{3g}	A_g	B_{1g}	B_{2u}	B_{3u}	A_u	B_{1u}
B_{3g}	B_{3g}	B_{2g}	B_{1g}	A_g	B_{3u}	B_{2u}	B_{1u}	A_u
A_u	A_u	B_{1u}	B_{2u}	B_{3u}	A_g	B_{1g}	B_{2g}	B_{3g}
B_{1u}	B_{1u}	A_u	B_{3u}	B_{2u}	B_{1g}	A_g	B_{3g}	B_{2g}
B_{2u}	B_{2u}	B_{3u}	A_u	B_{1u}	B_{2g}	B_{3g}	A_g	B_{1g}
B_{3u}	B_{3u}	B_{2u}	B_{1u}	A_u	B_{3g}	B_{2g}	B_{1g}	A_g

YBCO OrthoII – 11Ag modes

A_g modes

B_g modes

B_{1u} x B_{1u} = A_g

DFT Calculations

(Alaska Subedi, Antoine Georges)

DFT Calculations

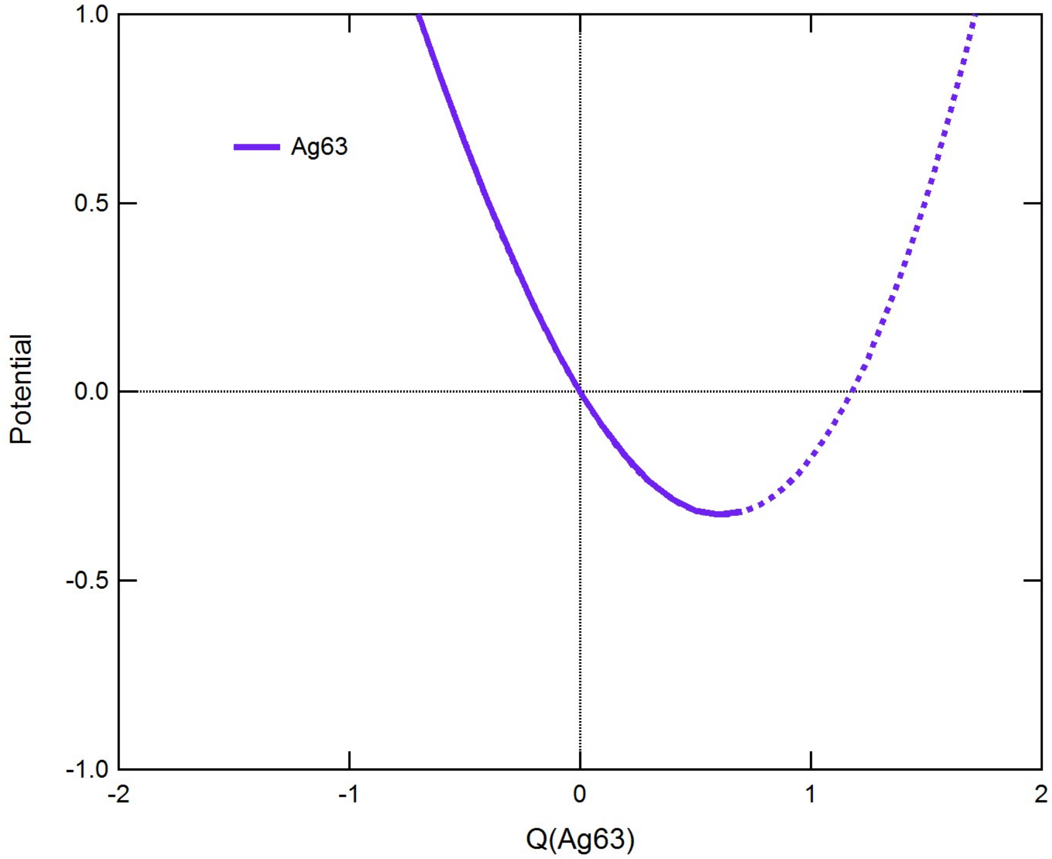
(Alaska Subedi, Antoine Georges)

Input B1u amplitude

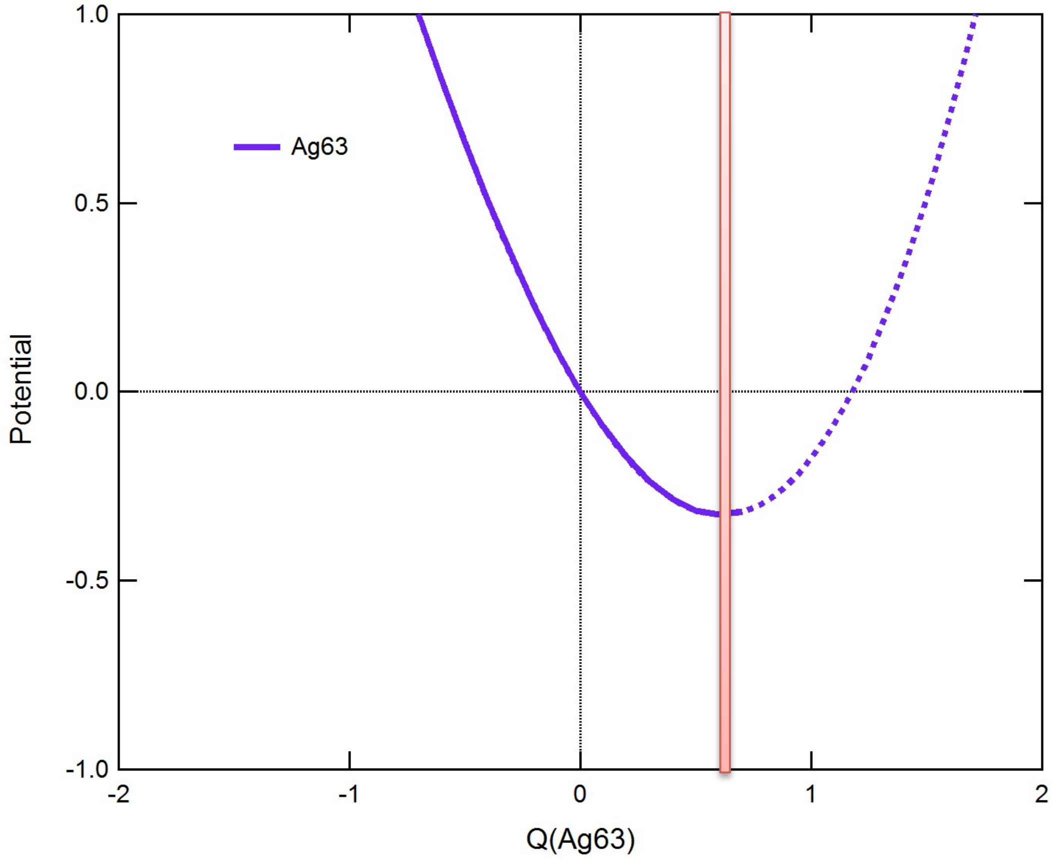
↓

Output Raman mode coupling strengths

- Results of DFT calculations

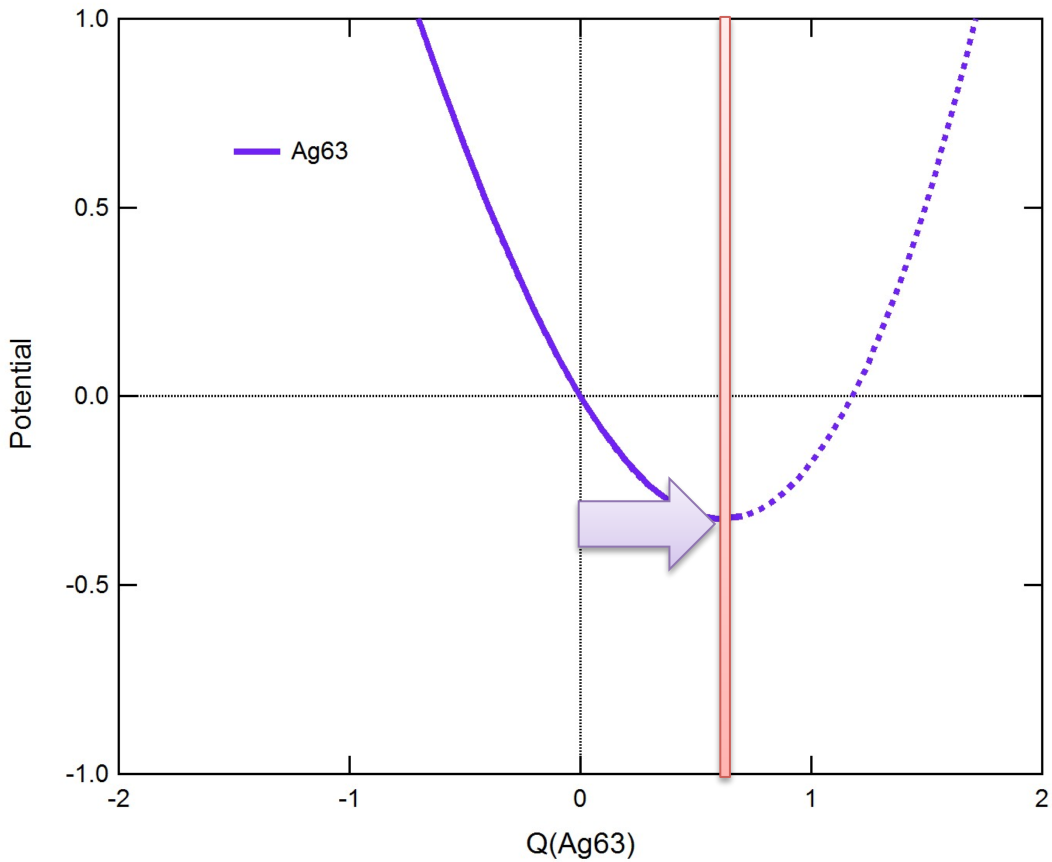


•Example for determination of coupling strength



Raman mode Energy potential shifts

•Example for determination of coupling strength

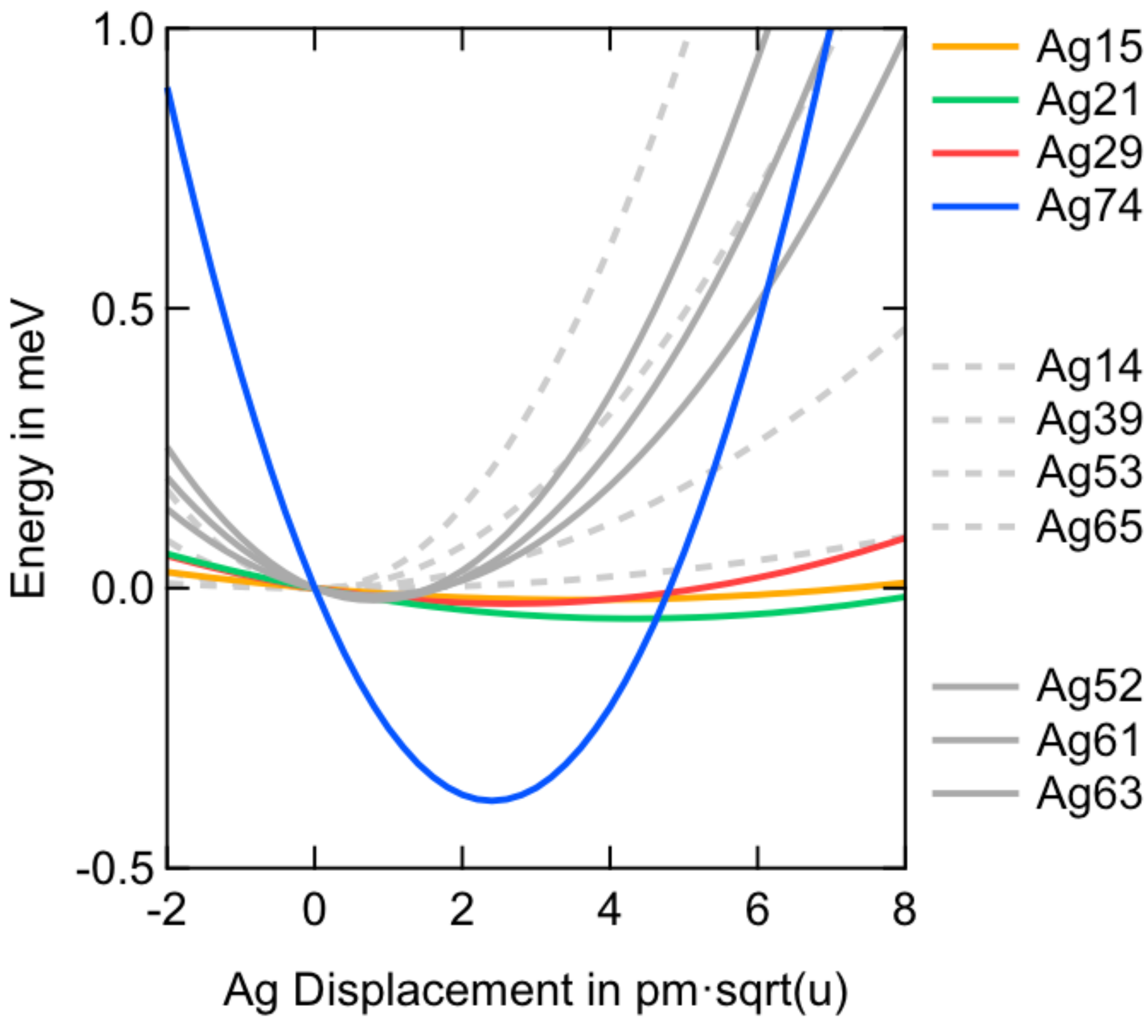


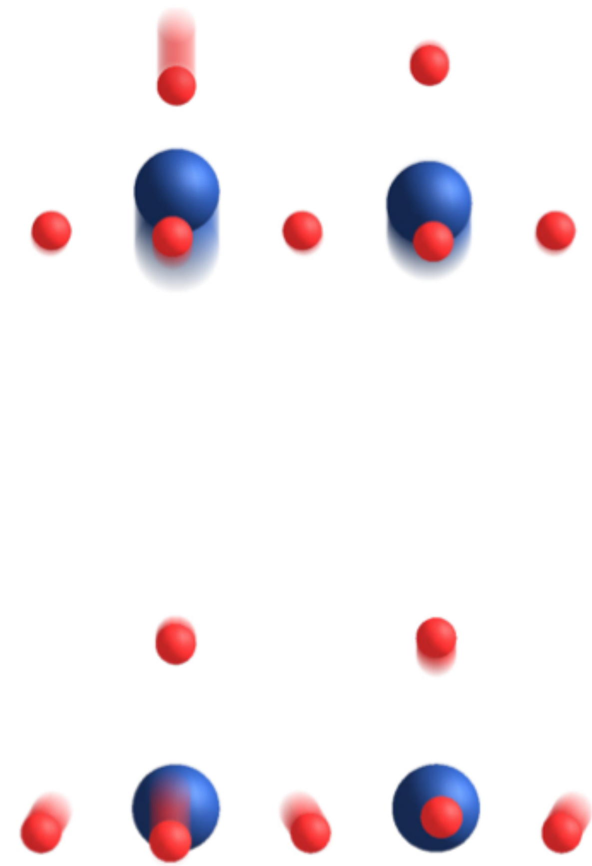
Raman mode Energy potential shifts

Size of the shift gives coupling strength

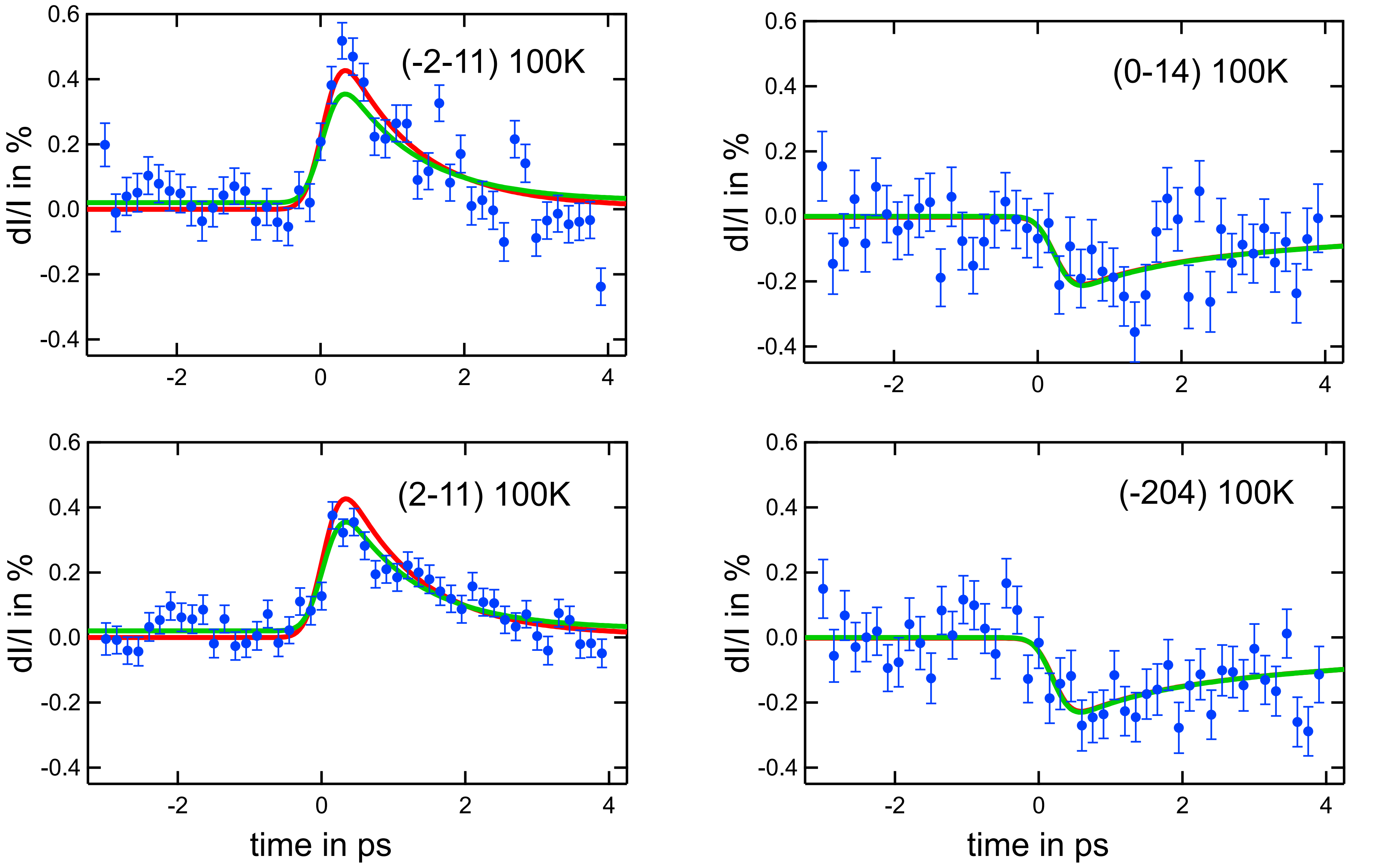
Fit only one Amplitude to experimental Data

•Relative coupling strengths



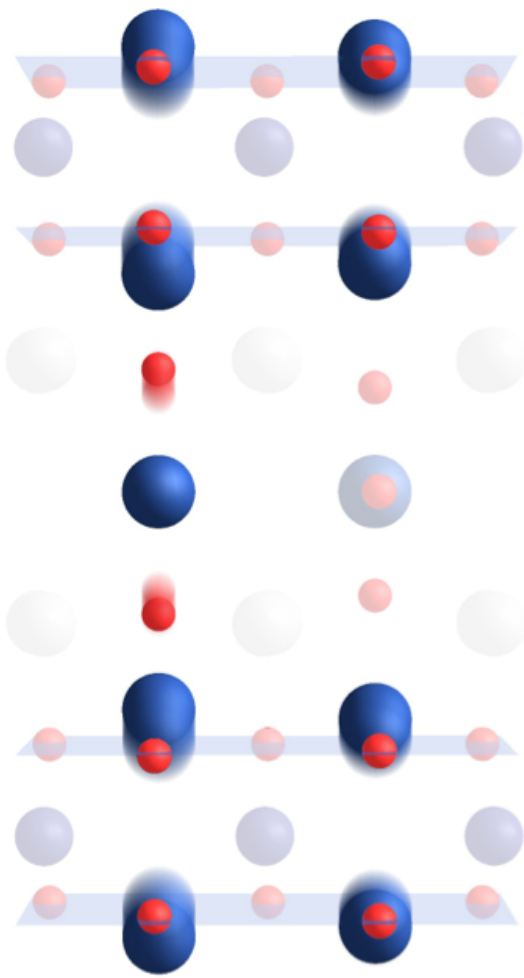


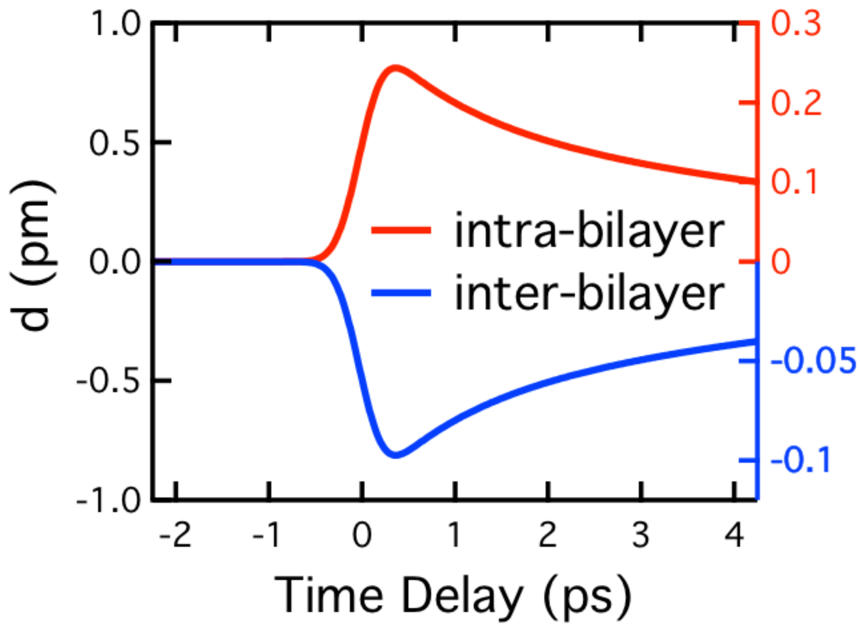
How much are the normal modes moving?



Lattice Shift

- Lattice Rearrangement



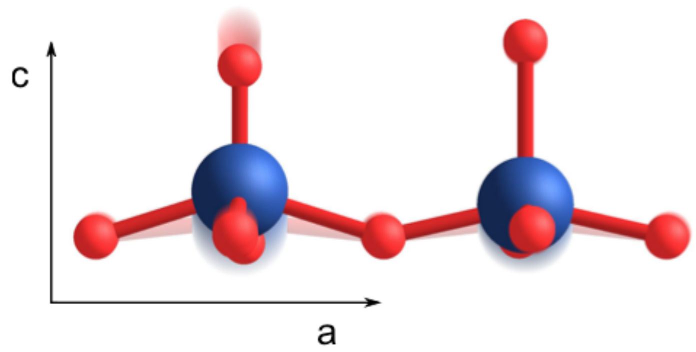


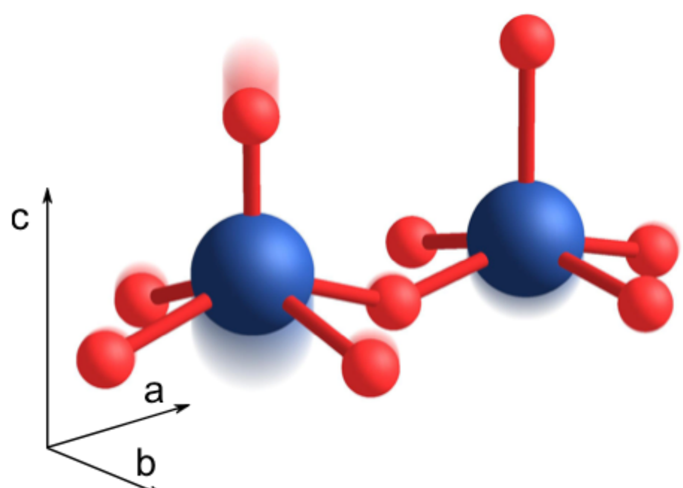
R. Mankowsky *et al.*, arXiv:1405.2266

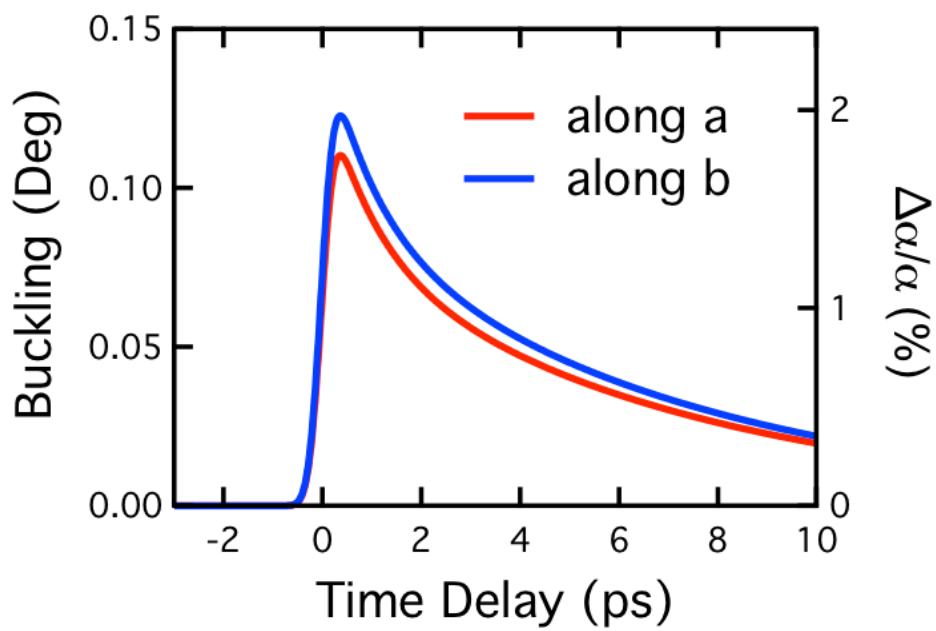
Is this the (unstable) atomic structure of a room temperature superconductor?

Lattice Shift

- Buckling

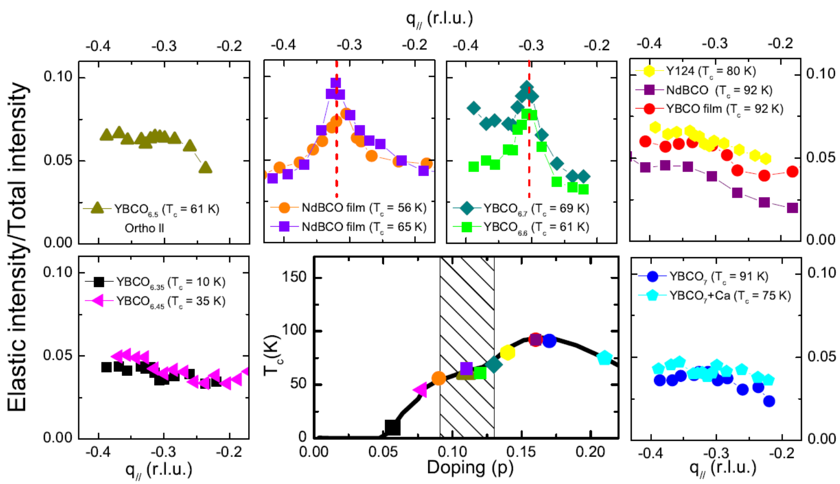






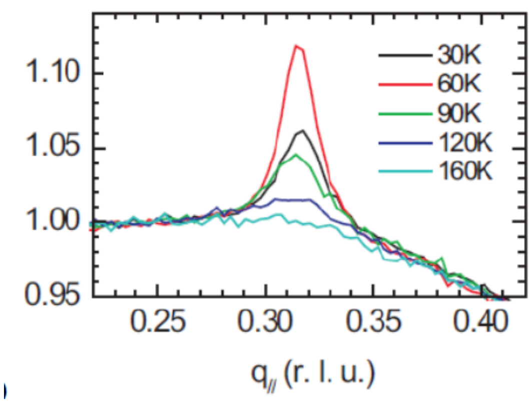
R. Mankowsky *et al.*, arXiv:1405.2266

Microscopic Physics: Hypothesis nr. 2



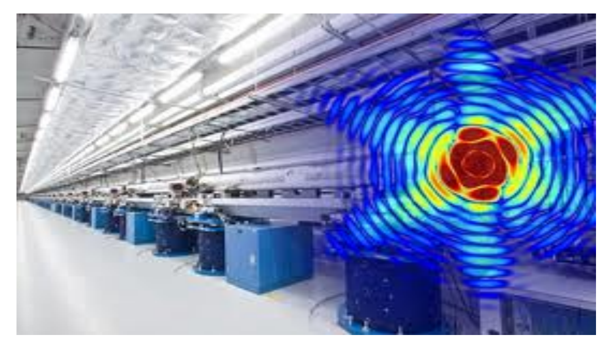
Is this atomic motion melting competing orders ?

Ghiringhelli et al. Science 337, 821 (2012)



Resonant Soft X-ray Diffraction (Cu L-edge) reveals bi-axial in-plane charge density wave, peaking at T_C

LCLS soft x-ray experiments



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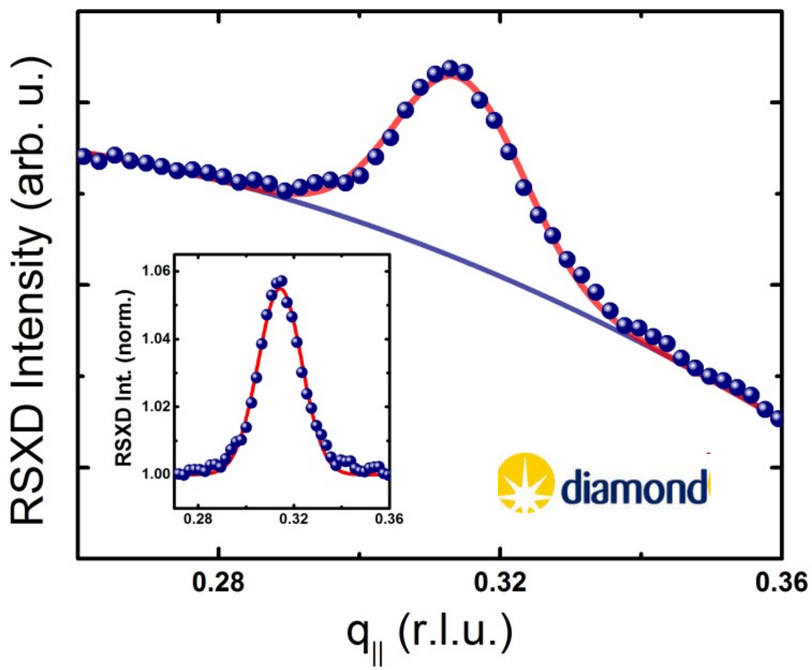
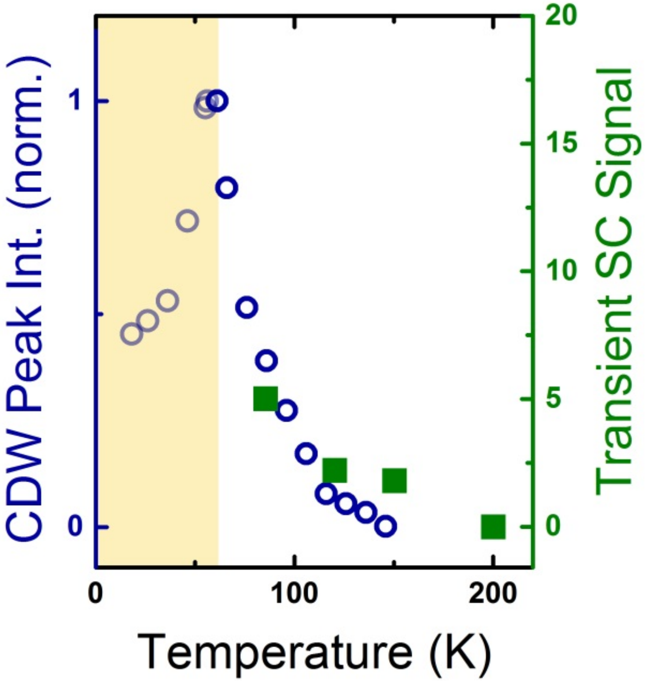
Temperature dependence of the coherent and CDW state

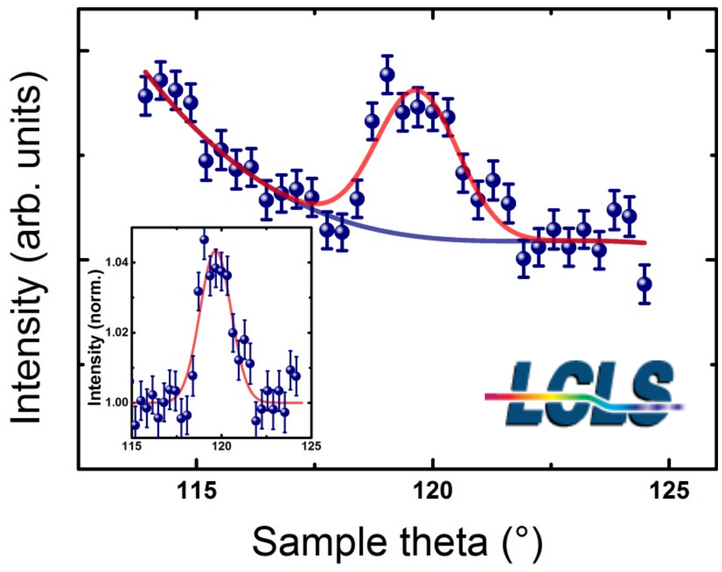
Comparison to the strength of charge correlations above T_C

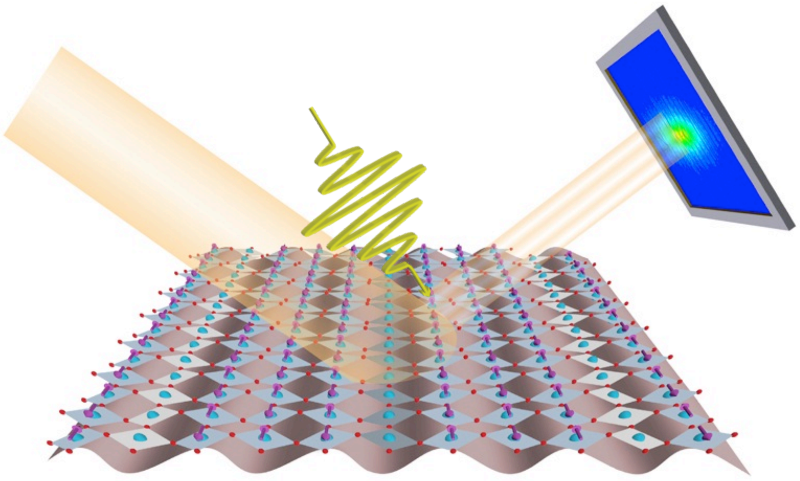


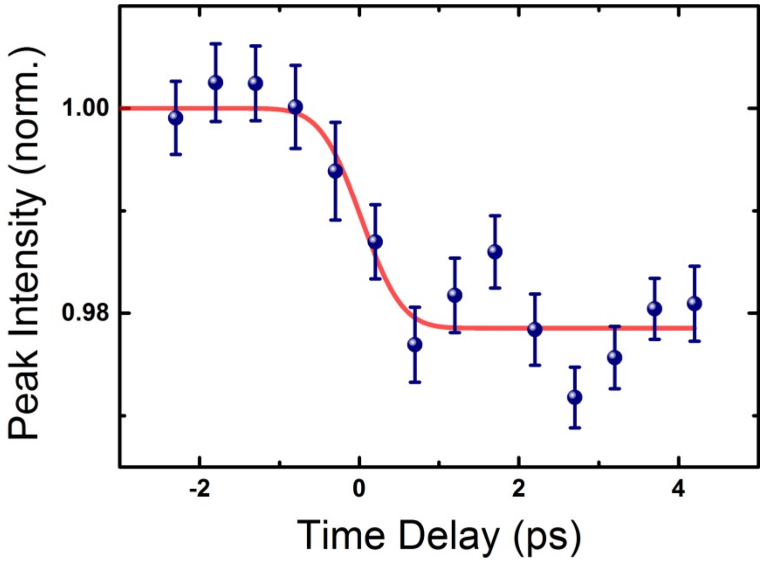


YBCO 6.6, Tc=60 K

Transient reduction of the CDW order







- We observe 50% melting of the CDW peak
- Time scale comparable to the appearance of transient SC
- Lifetime exceeds the lifetime of transient SC

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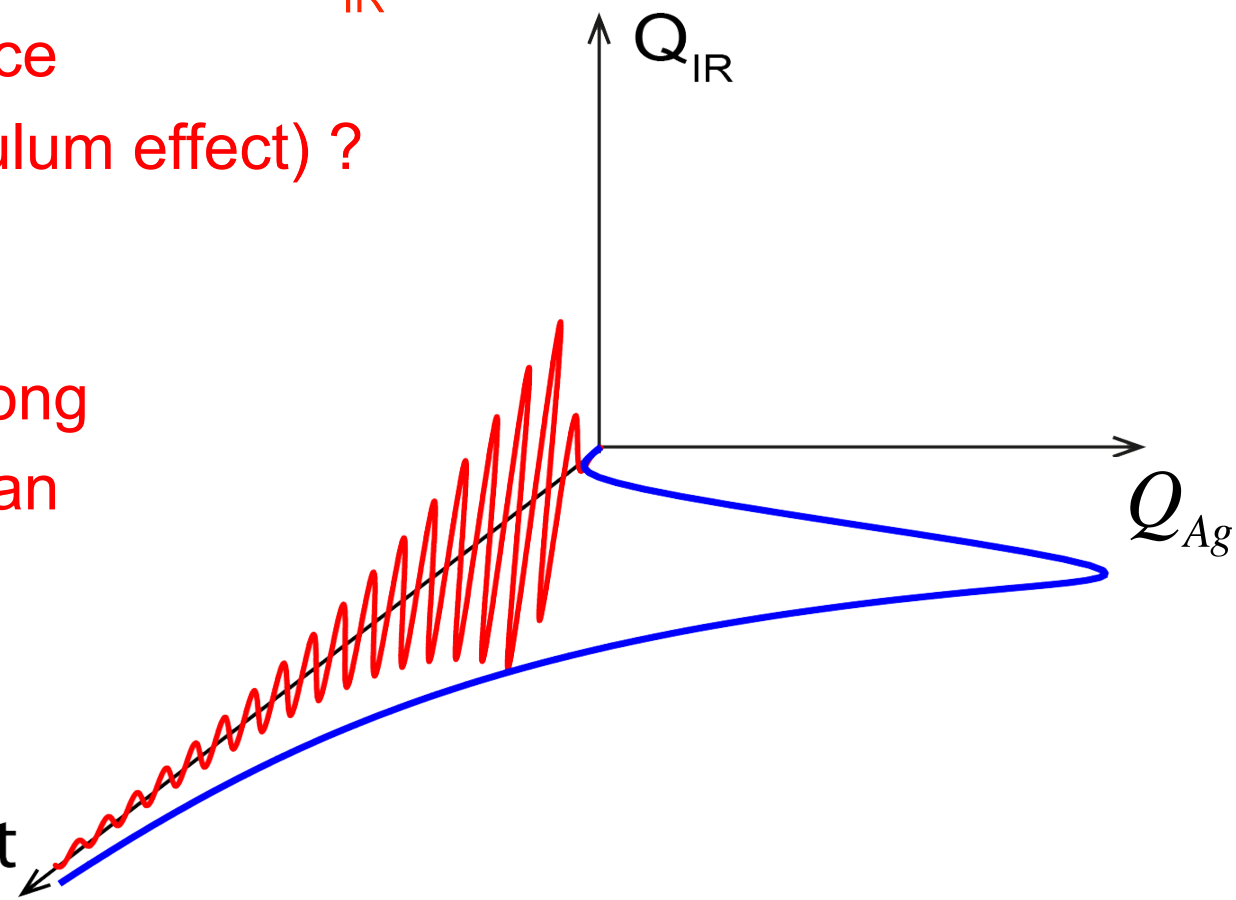
Microscopic Physics: Hypothesis nr. 3

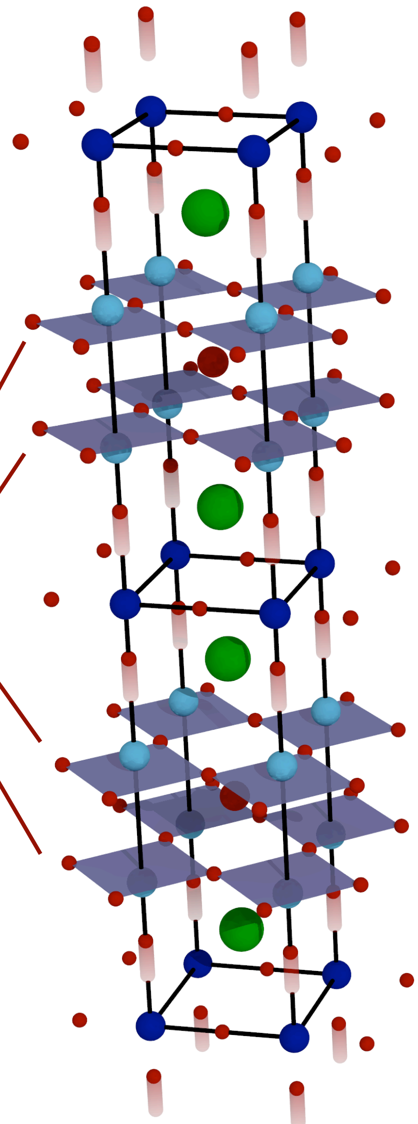
Is the dynamic modulation of Q_{IR} stabilizing coherence

(see Kaptiza pendulum effect) ?

Is the distortion along the A_g coordinate an epiphenomenon ?



Reducing phase fluctuations via driving

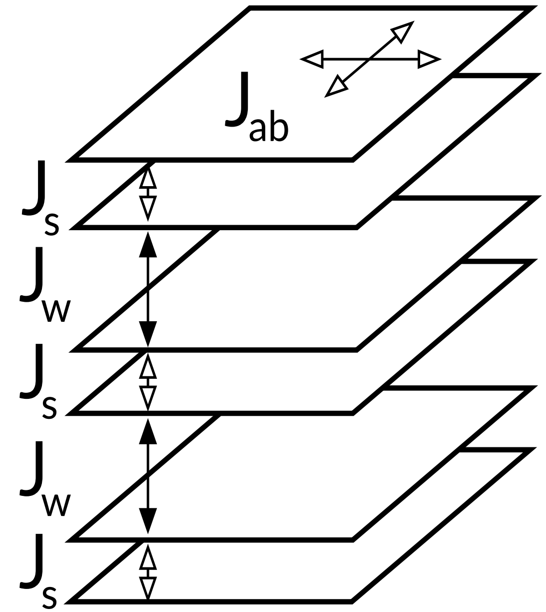


Modeled via a layered system of coupled Josephson junctions

$$H_\theta = -\sum_{<ij>} J_{ij} \cos(\theta_i - \theta_j)$$

Anisotropy:

$$J_{ab} : J_s : J_w \sim 1000 : 100 : 1$$

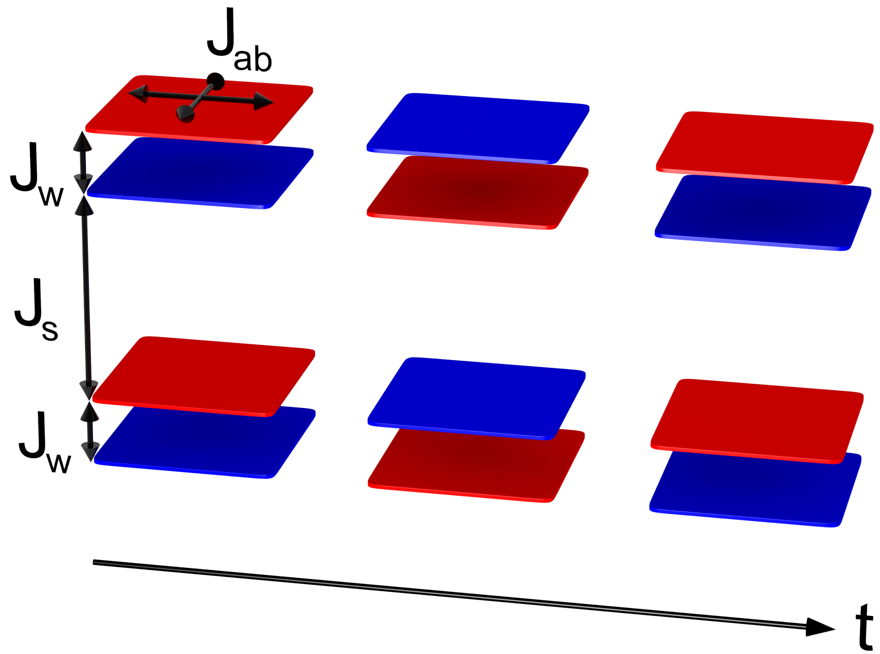


Arxiv:1406.3609

Robert Höppner, Beilei Zhu, Tobias Rexin, Ludwig Mathey

Driving

Modelled by a staggered potential, oscillating with frequency ω_m



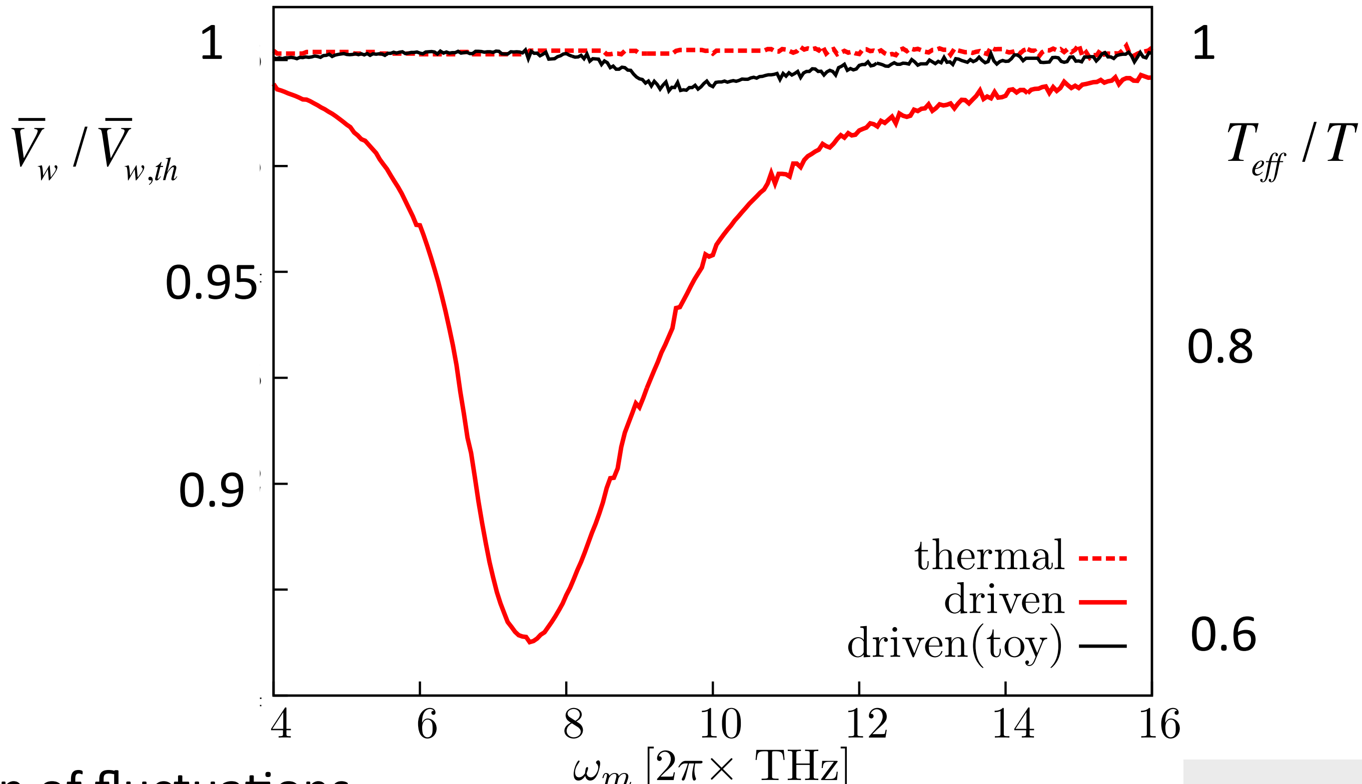
Current across the weak junctions: $j_w = 2J_w \sin\theta$

Arxiv:1406.3609

Robert Höppner, Beilei Zhu, Tobias Rexin, Ludwig Mathey

Frequency scan

Current fluctuations: $V_w(t) = \overline{(j_w(t))^2} - \left(\overline{j_w(t)}\right)^2$ $\xrightarrow{\text{time-averaged}}$ $\bar{V}_w$



- ✓ Reduction of fluctuations
- ✓ Plasmon mode of the strong layers serve as an amplifier of the driving

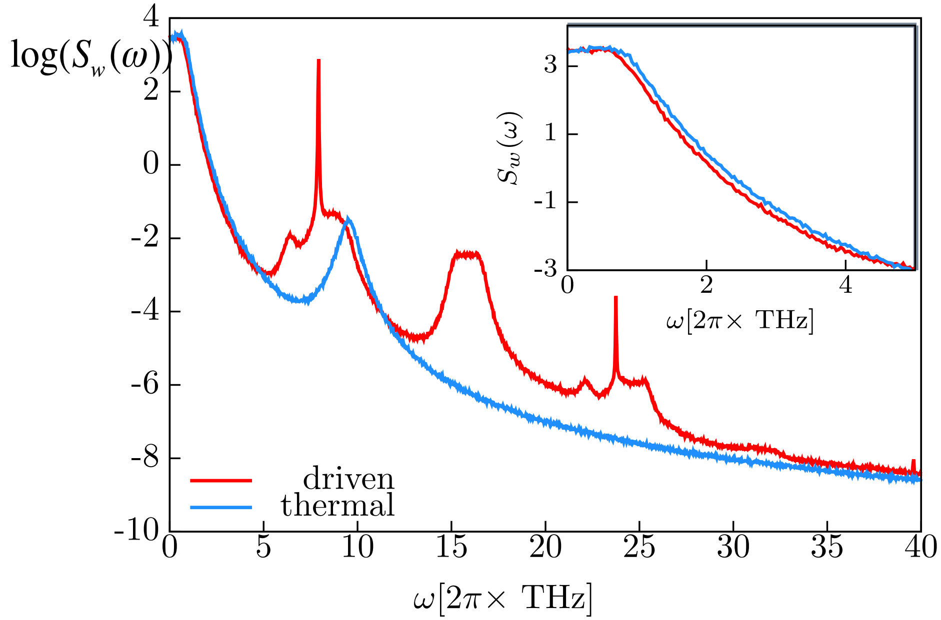
Arxiv:1406.3609

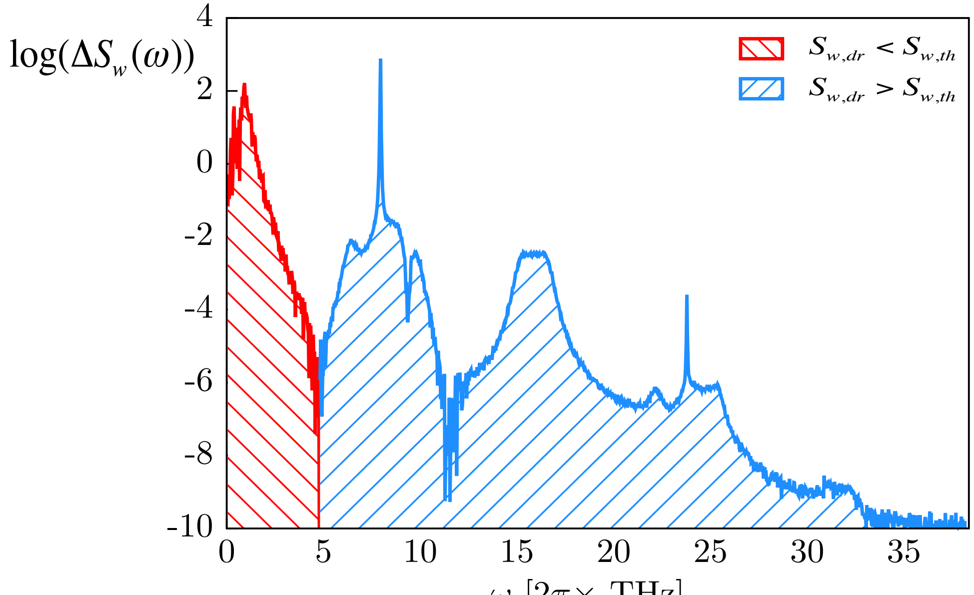
Power spectrum

$$S_w(\omega) = \langle j_w(-\omega) j_w(\omega) \rangle$$

- ✓ Low-frequency modes suppressed
- ✓ High-frequency modes enhanced

Up-conversion of spectral weight!

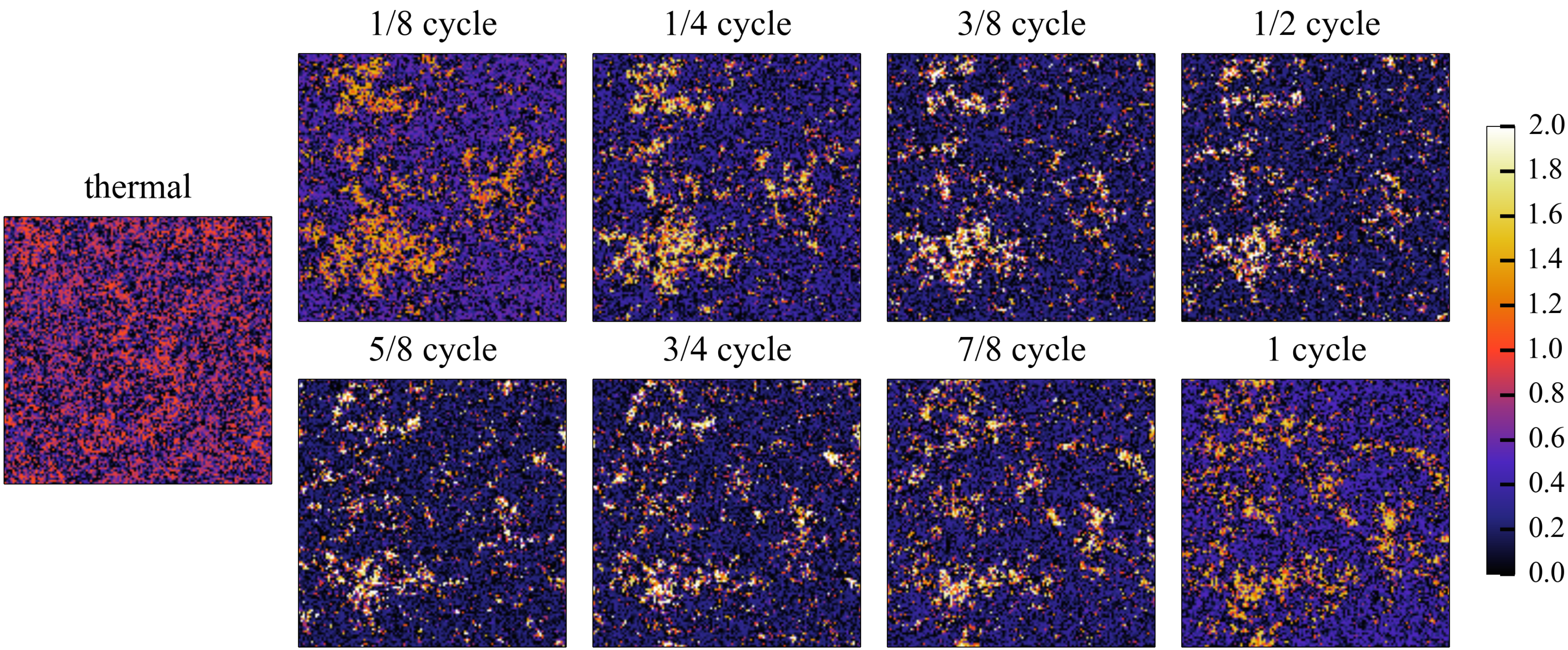




Arxiv:1406.3609

In-plane dynamics

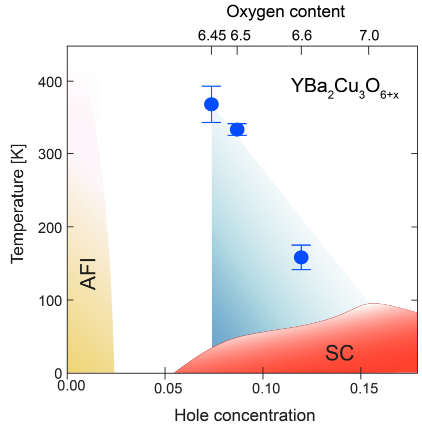
Spatially resolved fluctuations: $\left(j_w(\vec{r},t) - \bar{j}_w(t)\right)^2$ Spatial average $j_w(t)$



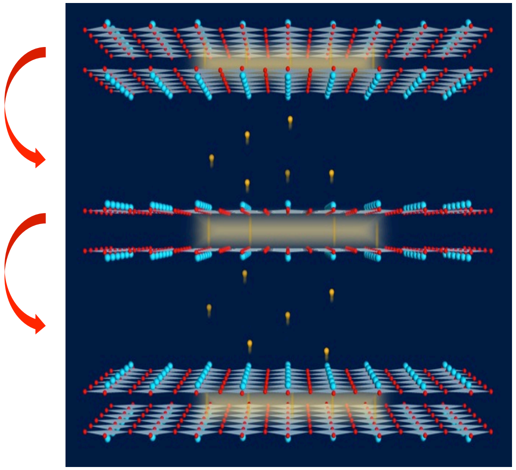
Arxiv:1406.3609

- ✓ Fluctuations reduced overall
- ✓ Local hotspots: short range fluctuations increased, long-range reduced

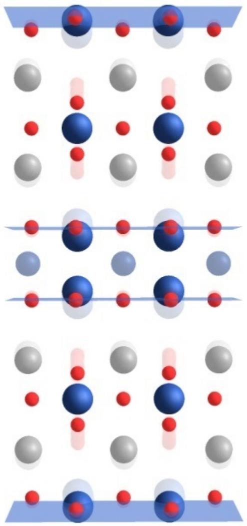
Summary



Transient Light Induced Superconductivity at Room Temperature in $YBa_2Cu_3O_{6+d}$



Coherence at low frequency appears at the expense of coupling within the bilayers



Non-linear lattice dynamics, CDW dynamics and dynamical stabilization offer hints to possible microscopic mechanisms

People

Mid-IR pump / THz probe experiments

Daniele Nicoletti

Cassi Hunt

Wanzheng Hu

Isabella Gierz

Mid-IR pump / X-Ray probe

Roman Mankowsky

Michael Först

Andrea Cavalleri

M. LeTacon
T. Loew
A. Frano
B. Keimer
MPI Stuttgart

A. Subedi
A. Georges
Paris

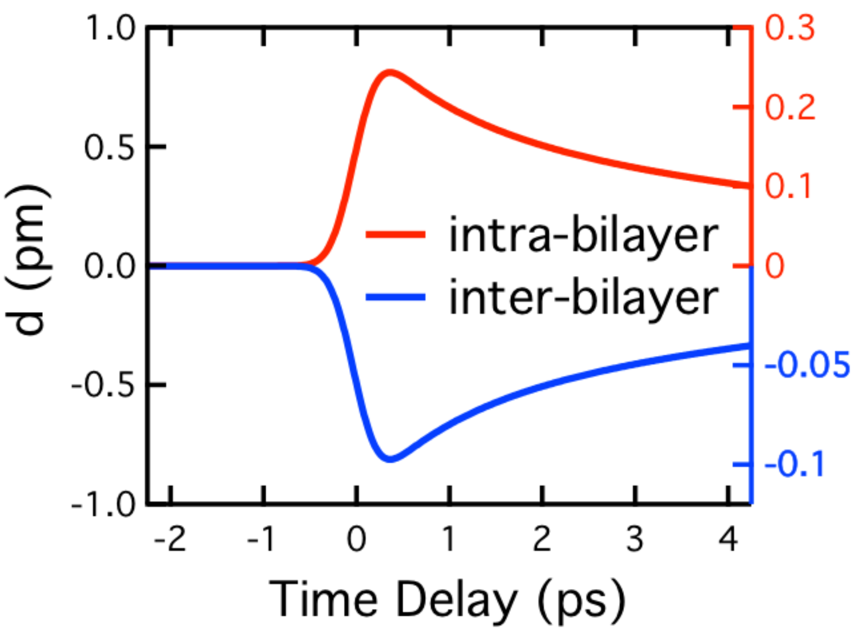
S. DHESI
DIAMOND
Light Source

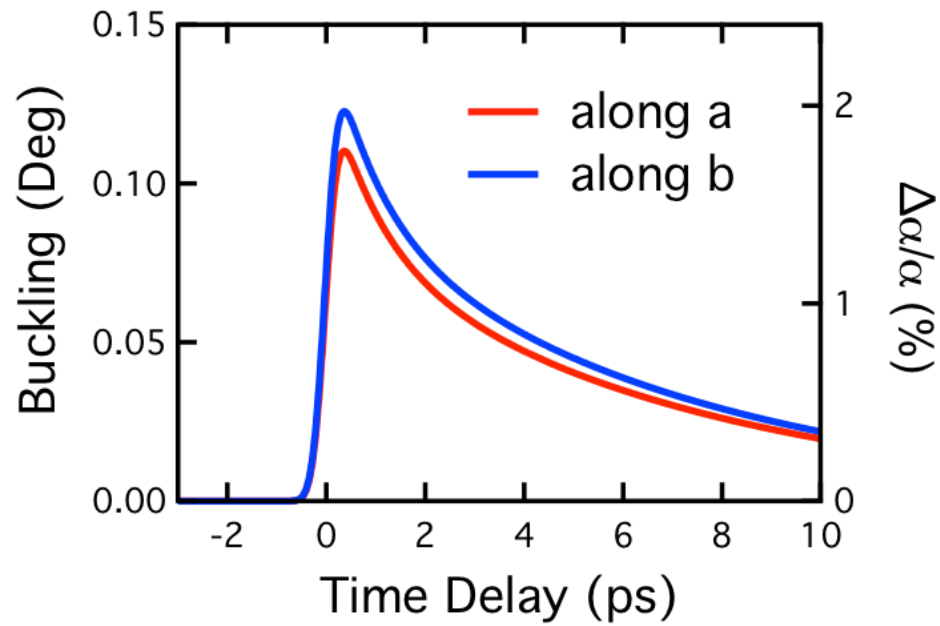
J. Turner
D. Dakovski
M. Miniti
J. Robinson
LCLS

Thank you for your attention!

- Change in Bilayer Distance

Change in Buckling

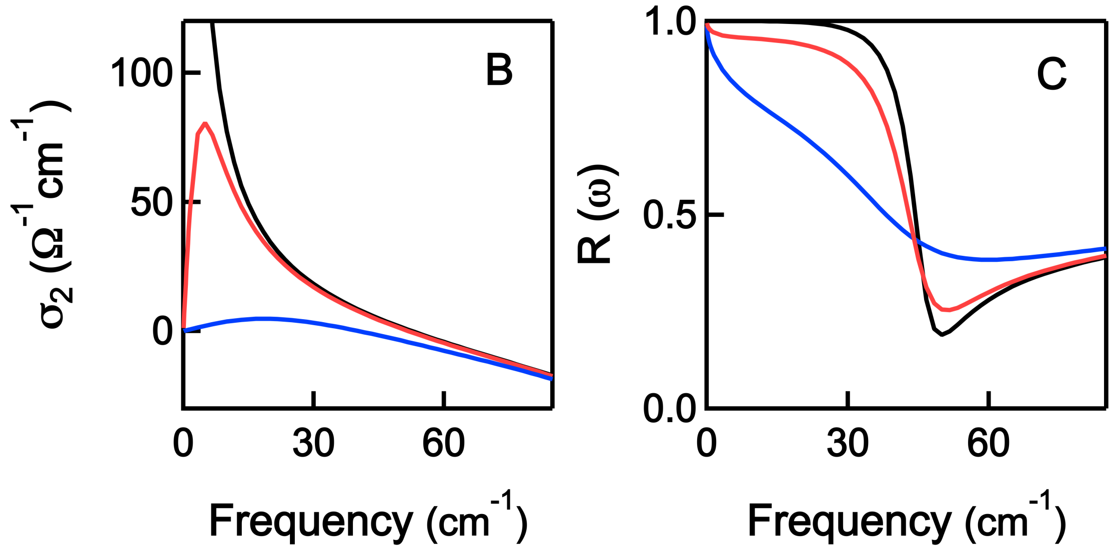




Transient Perfect Metal vs Superconductor

Transient metal:

- Finite scattering time τ (as large as the lifetime of the transient state)
- Can not be distinguished from a SC at frequencies above 1/τ



Induced coherence above T_c

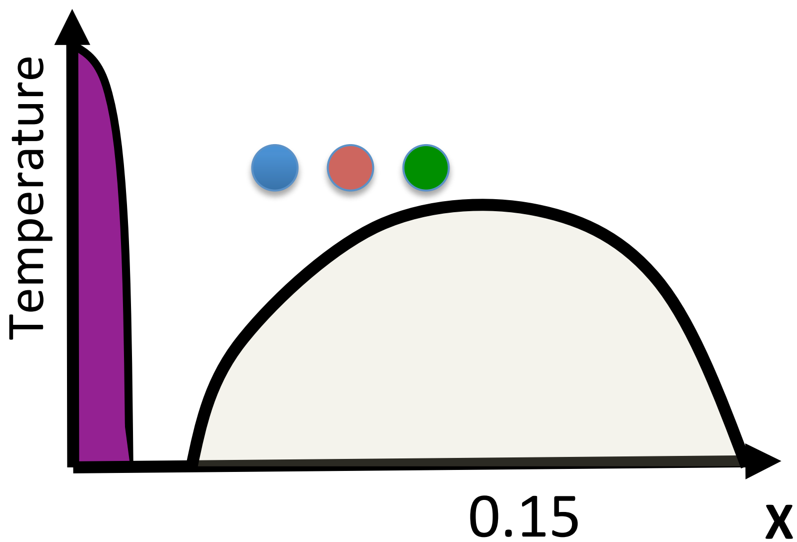
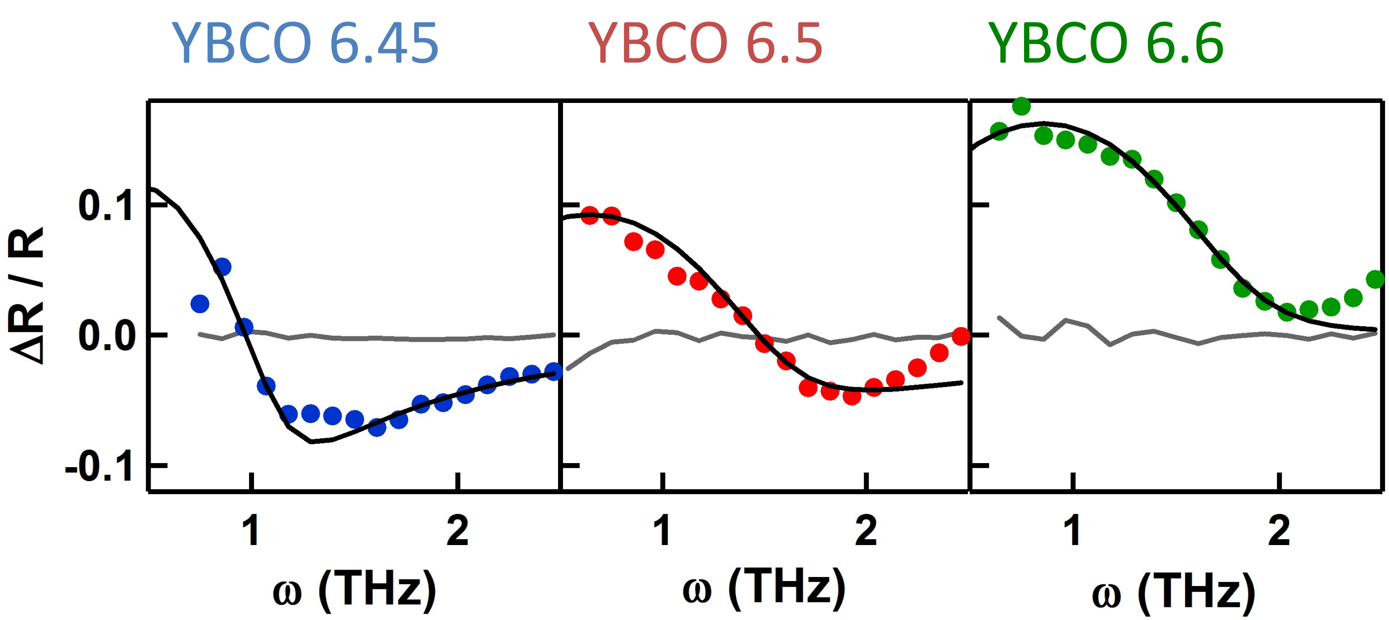


Photo-induced low frequency JPR



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Induced coherence above T_c

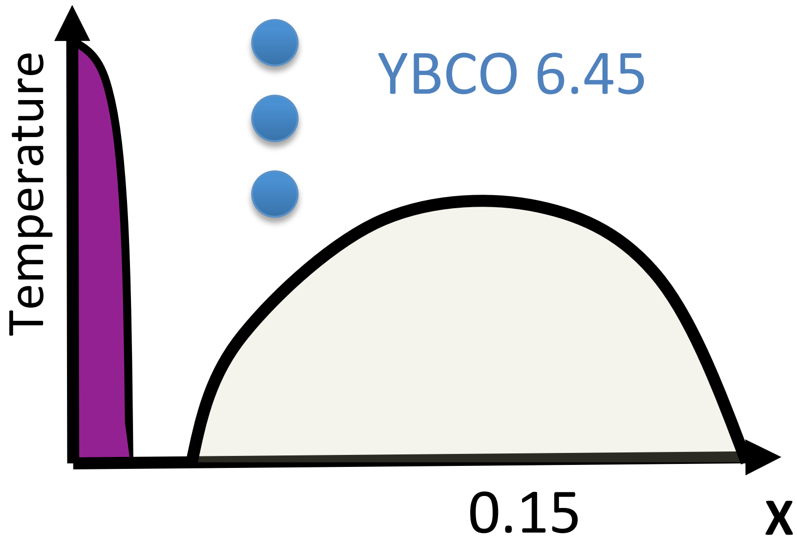
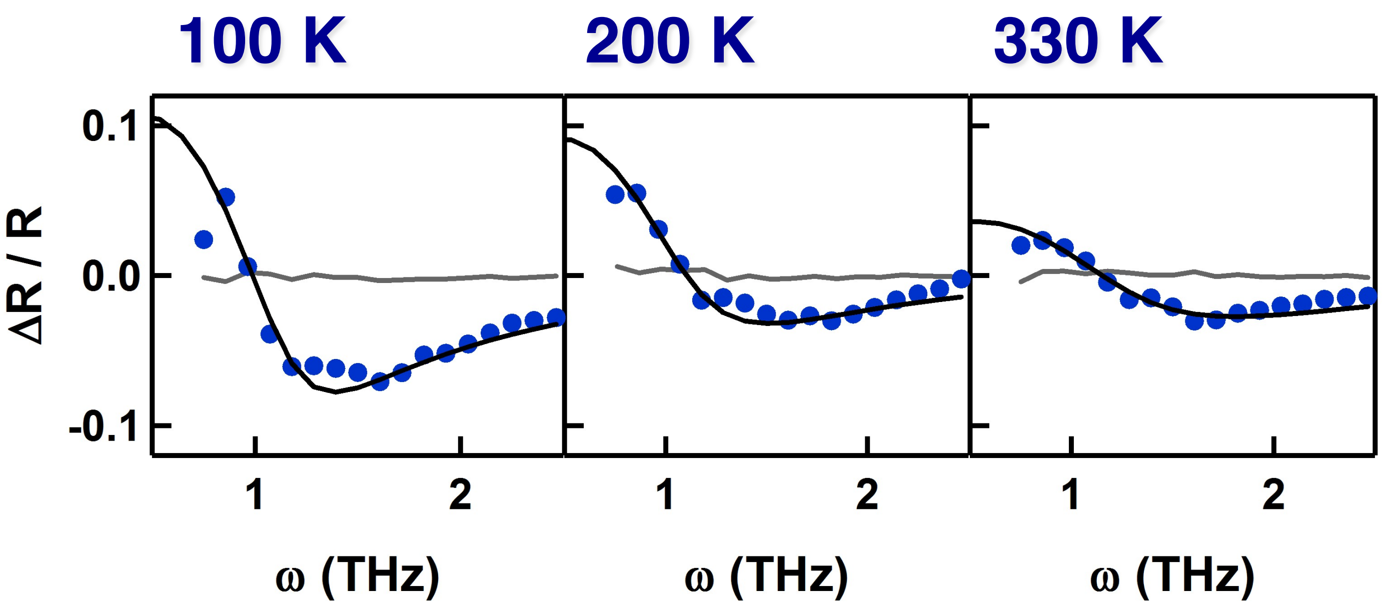
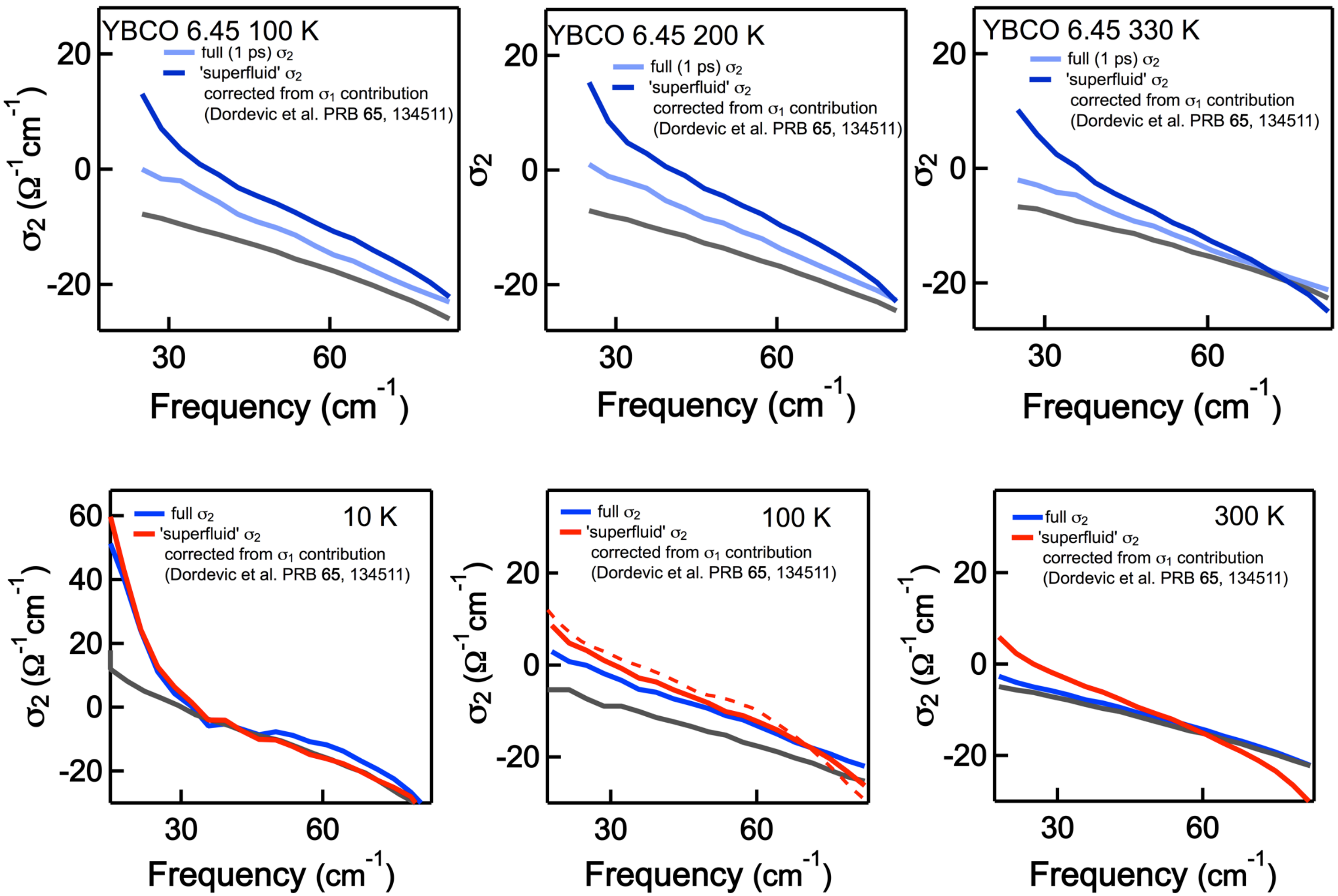


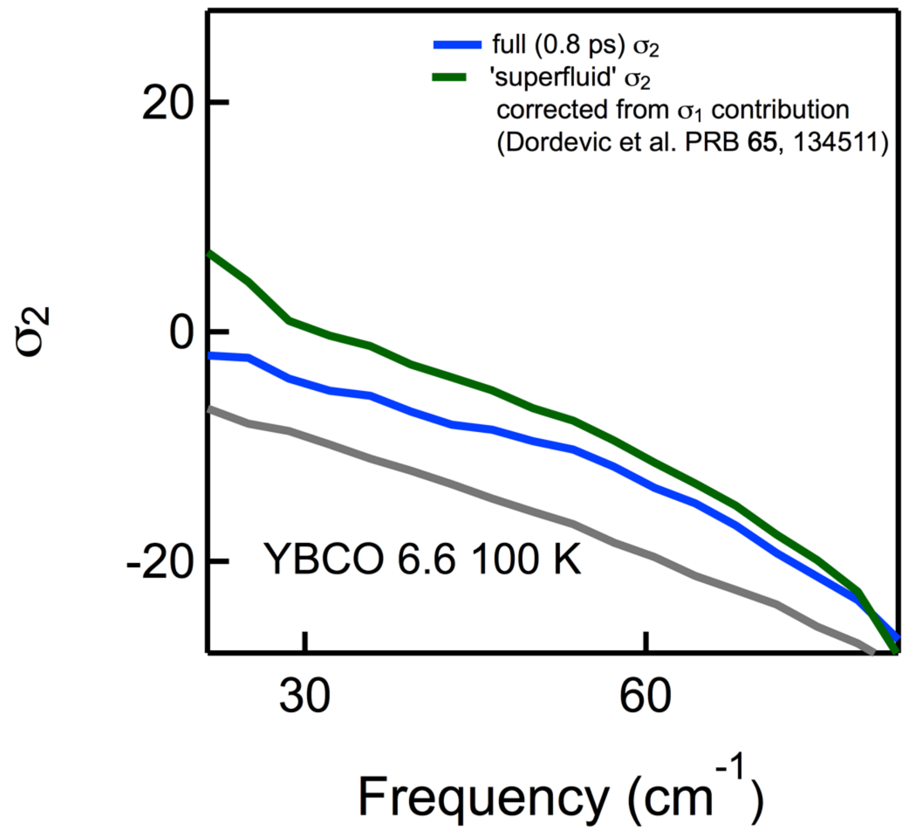
Photo-induced low frequency JPR



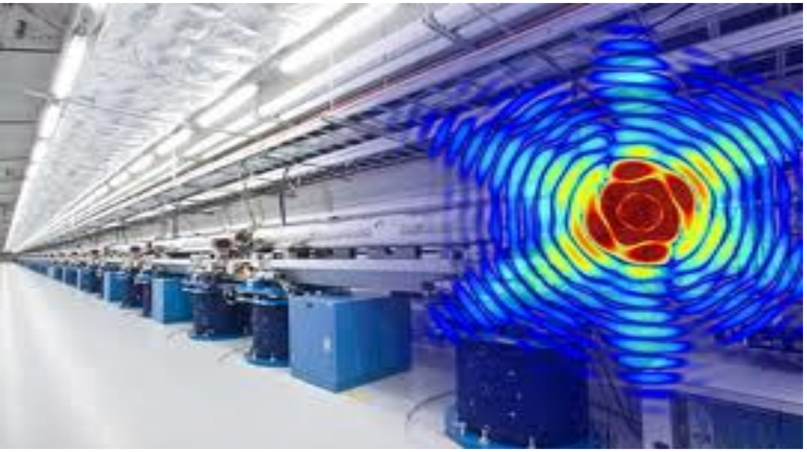
Correction of sigma2



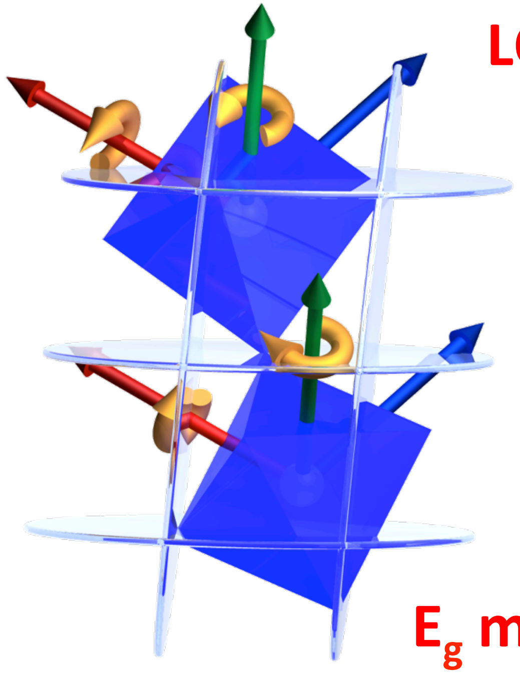
Correction of sigma2



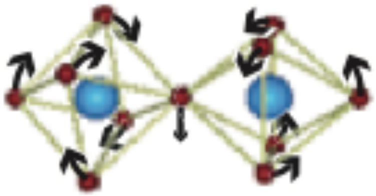
Displacive Eg excitation: (012) up and (201) down

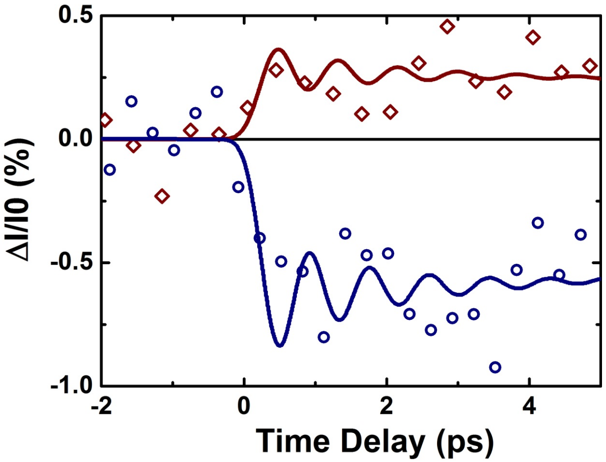


LCLS



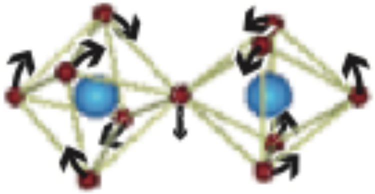
E_g mode





(012)

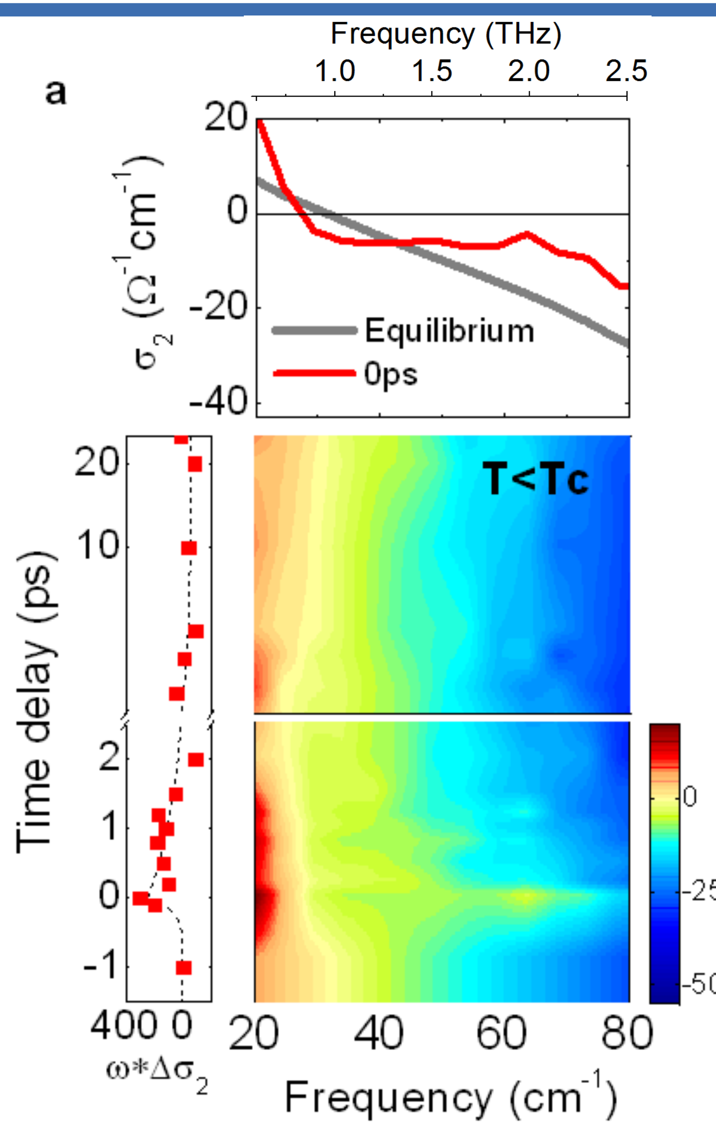
(201)



M. Foerst , R. Mankowski et al.

Below Tc: Enhancement of Superconductivity

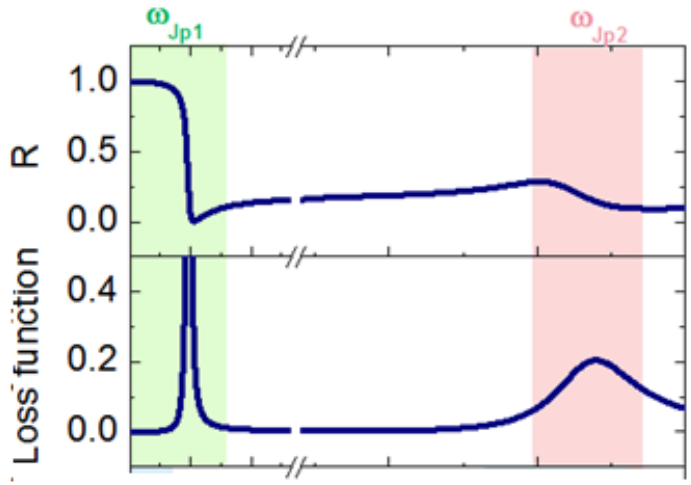
Enhancement of divergent σ_2

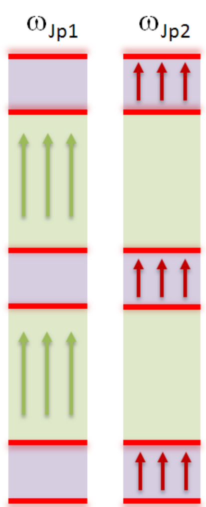


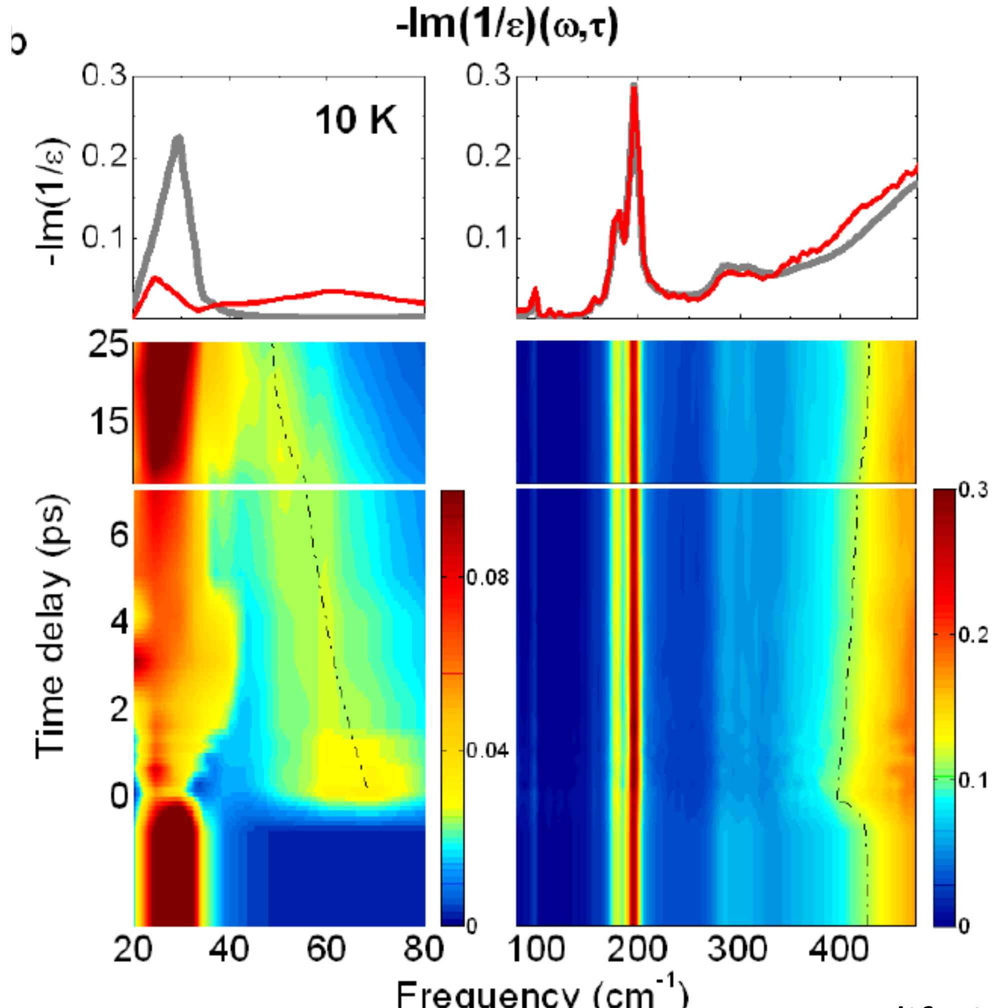
1 THz = 33 cm^{-1}

Wanzheng Hu et al., arXiv 1308.3204

Two longitudinal Josephson plasma modes



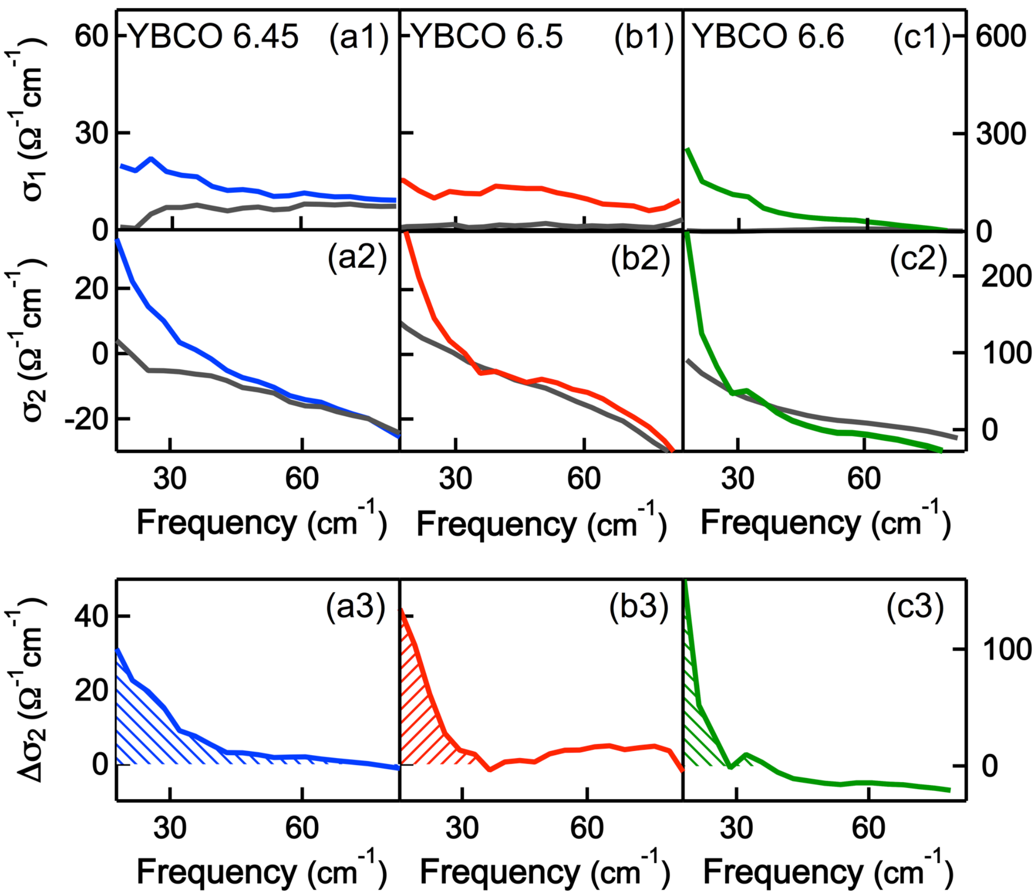




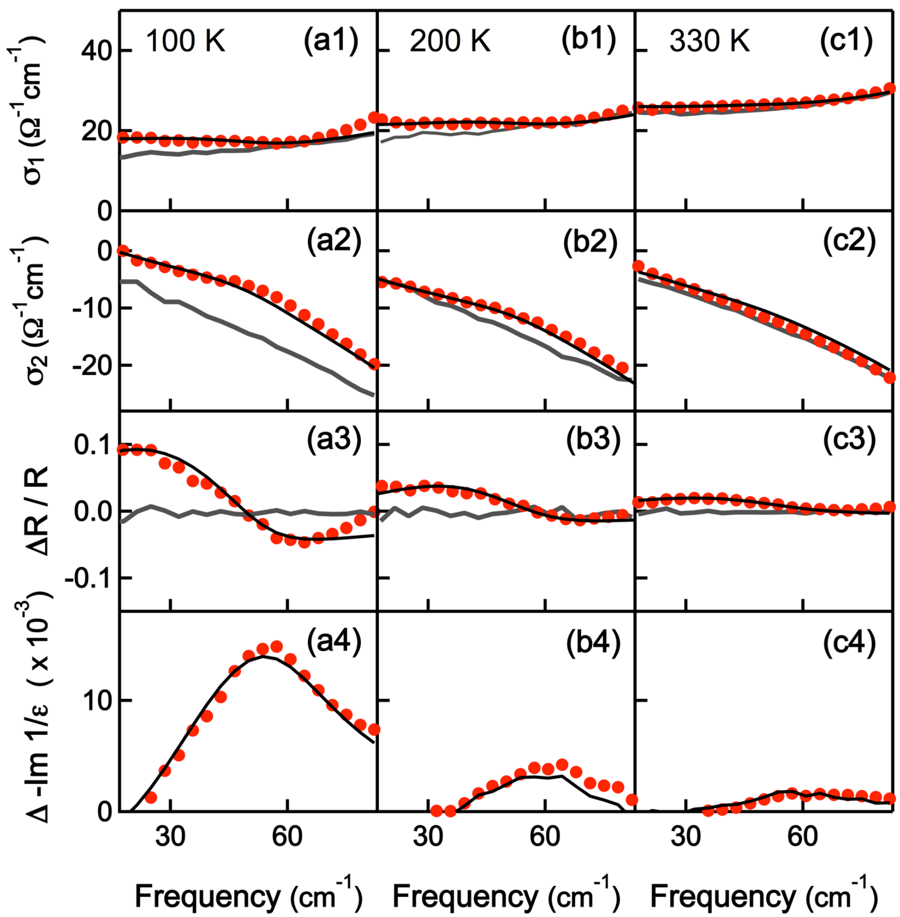
7 ps lifetime

Wanzheng Hu et al., arXiv 1308.3204

YBCO below Tc

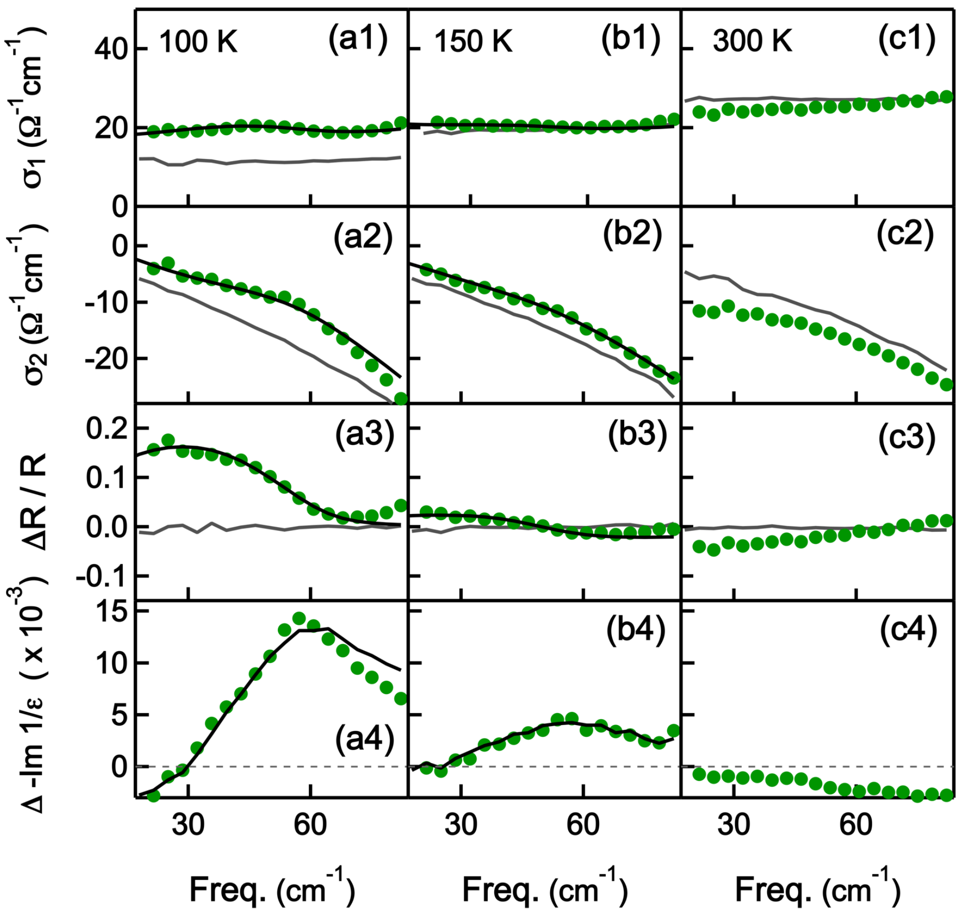


YBCO 6.5



100 K
(a1)
200 K
(b1)
330 K
(c1)
(a2)
(b2)
(c2)
(a3)
(b3)
(c3)
(a4)
(b4)
(c4)
σ1 (Ω-1cm-1)
σ2 (Ω-1cm-1)
ΔR / R
Δ -Im 1/ε (x 10-3)
40
20
0
-10
-20
0.1
0.0
-0.1
10
30
60
Frequency (cm-1)
Frequency (cm-1)
Frequency (cm-1)

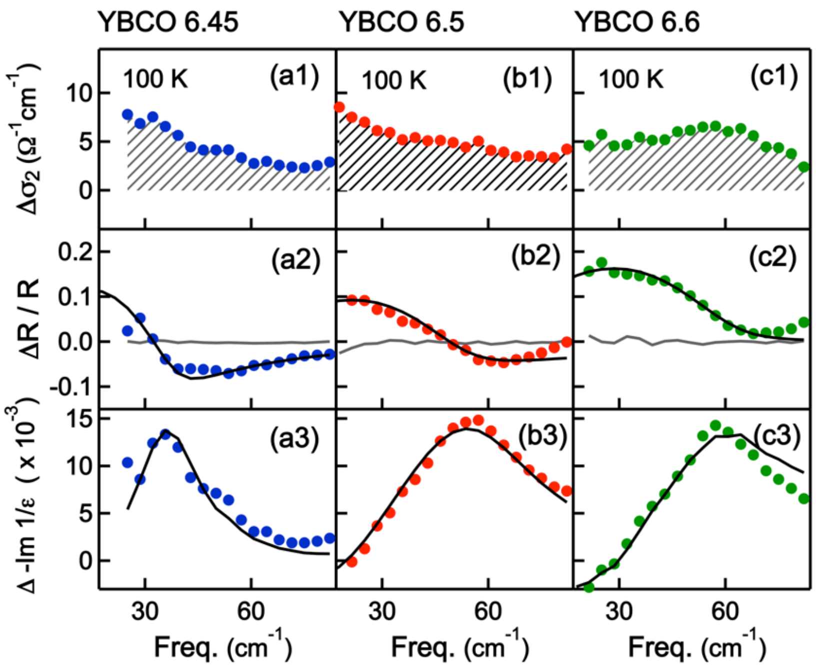
YBCO 6.6



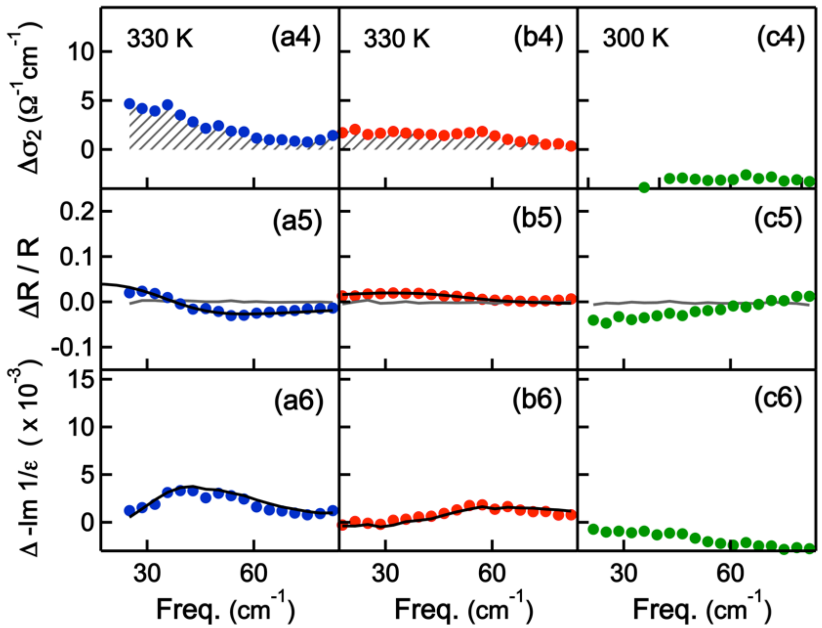
100 K
(a1)
150 K
(b1)
300 K
(c1)
(a2)
(b2)
(c2)
(a3)
(b3)
(c3)
(a4)
(b4)
(c4)
σ1 (Ω-1cm-1)
σ2 (Ω-1cm-1)
ΔR / R
Δ -Im 1/ε (x 10-3)
Freq. (cm-1)
Freq. (cm-1)
Freq. (cm-1)

YBCO above Tc

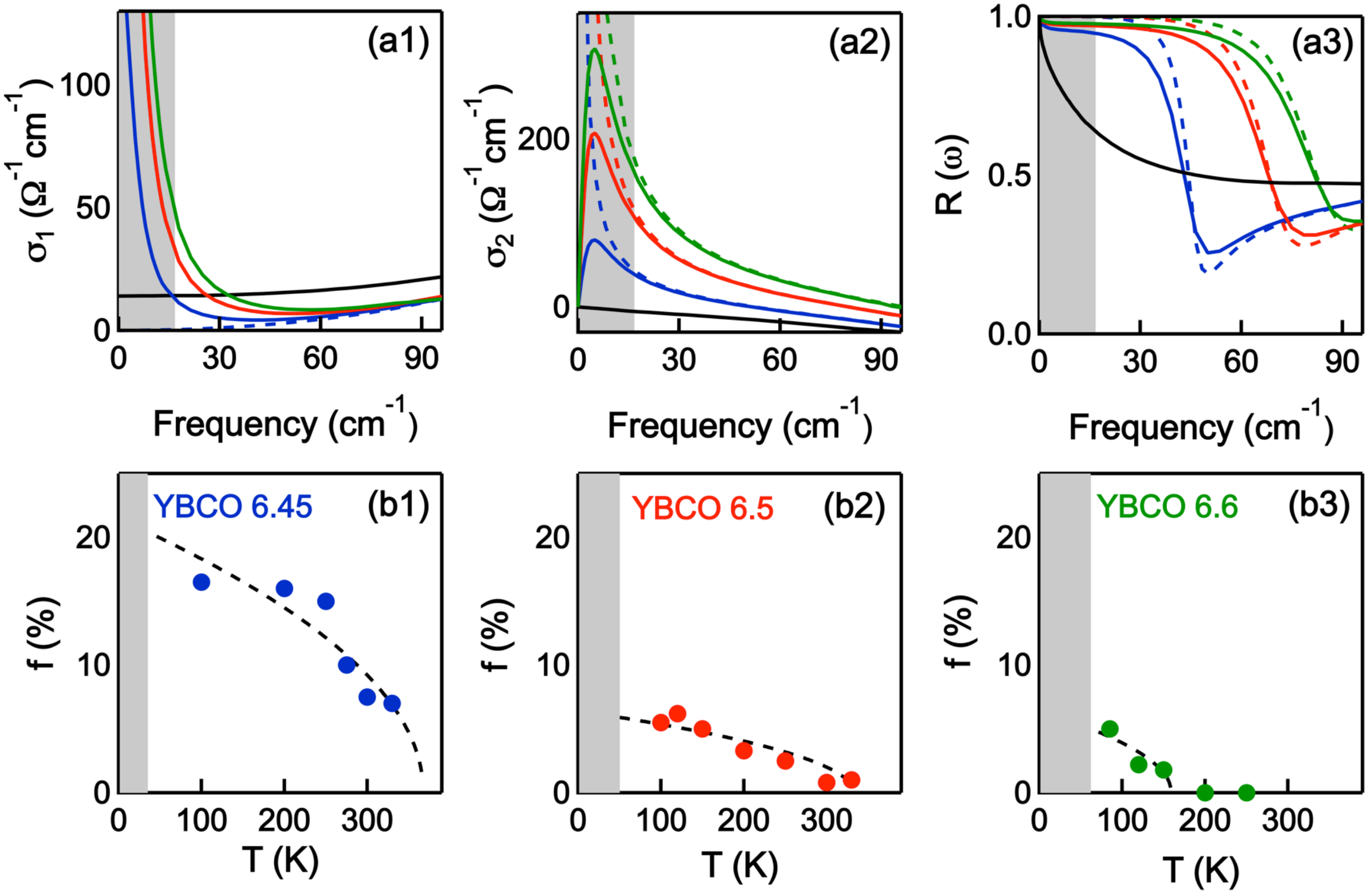
100 K



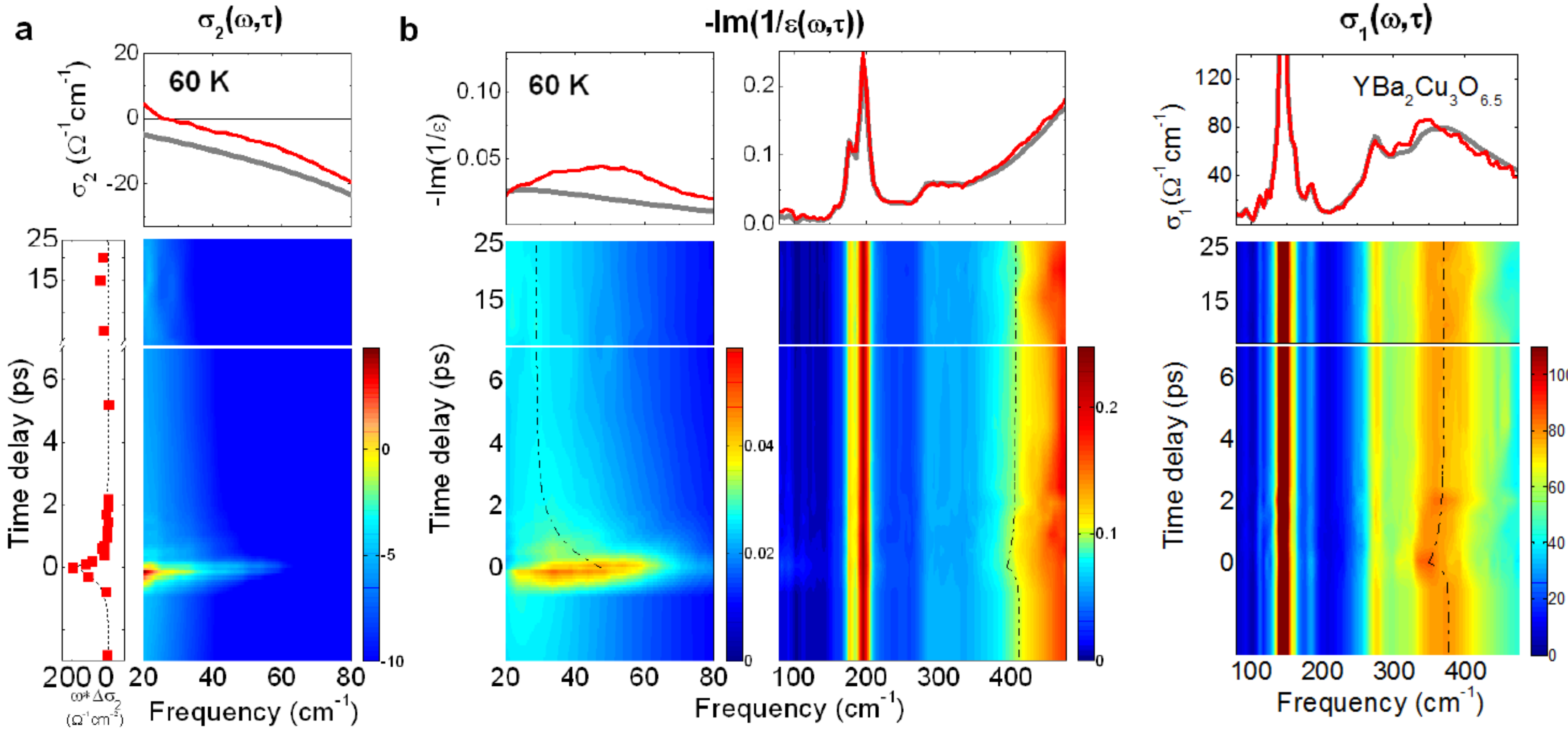
330 K / 300 K



Extracted SC properties

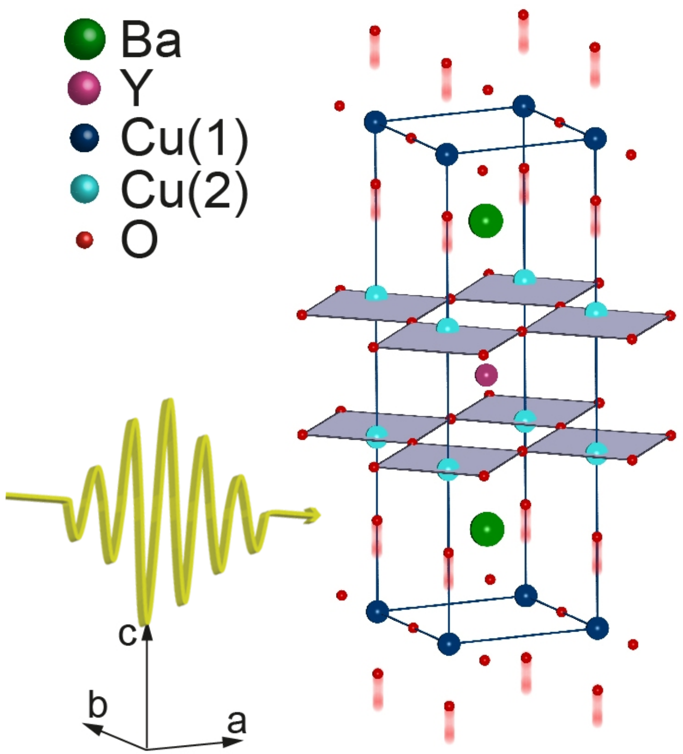


Above Tc

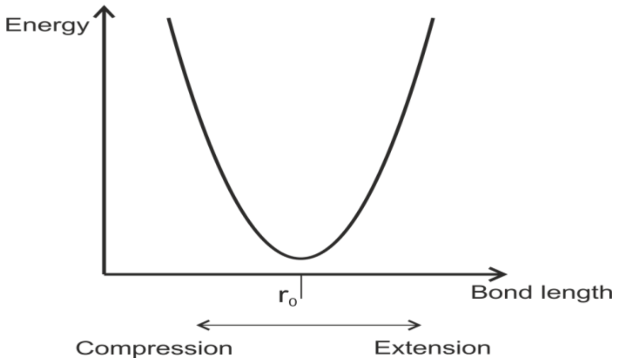


Wanzheng Hu et al., arXiv 1308.3204

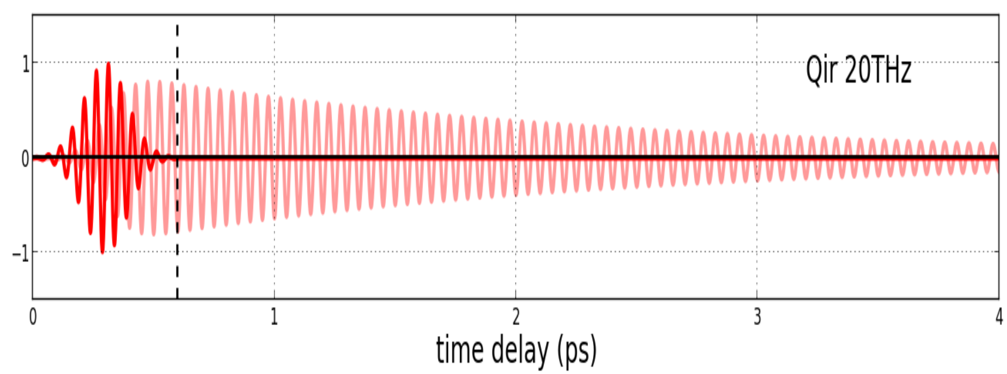
Linear response: no average displacement



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



$$\ddot{Q}_{IR} + 2\gamma\dot{Q}_{IR} + \omega_{IR}^2 Q_{IR} = f(t)$$



mpsd

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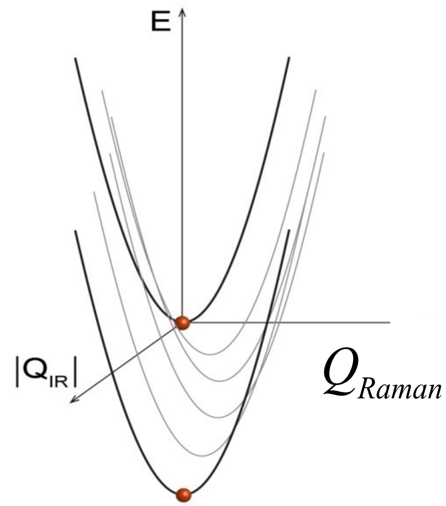
Anharmonic coupling

$$V = \frac{1}{2}\mu_{IR}\omega_{IR}^2 Q_{IR}^2 + NAQ_{IR}^2 Q_2$$

$$\mu_{IR}(\ddot{Q}_{IR} + 2\gamma\dot{Q}_{IR} + \omega_{IR}^2 Q_{IR}) = Q_{IR}Q_2 + f(t)$$

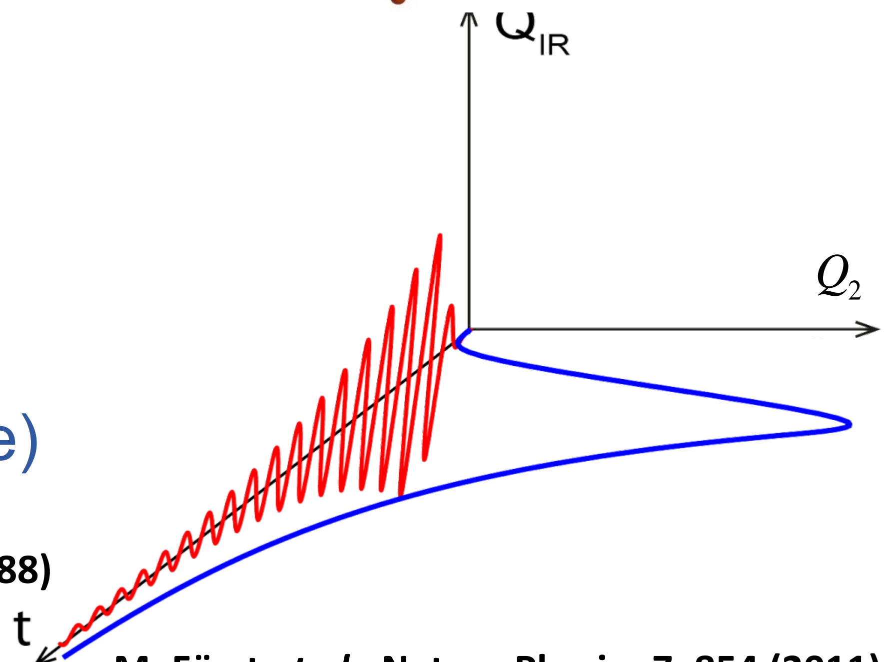
$$\mu_2(\ddot{Q}_2 + 2\gamma\dot{Q}_2 + \omega_2^2 Q_2) = AQ_{IR}^2$$



Q_{IR} (B_{1u})

$Q_{IR}^2\ Q_2$ not zero

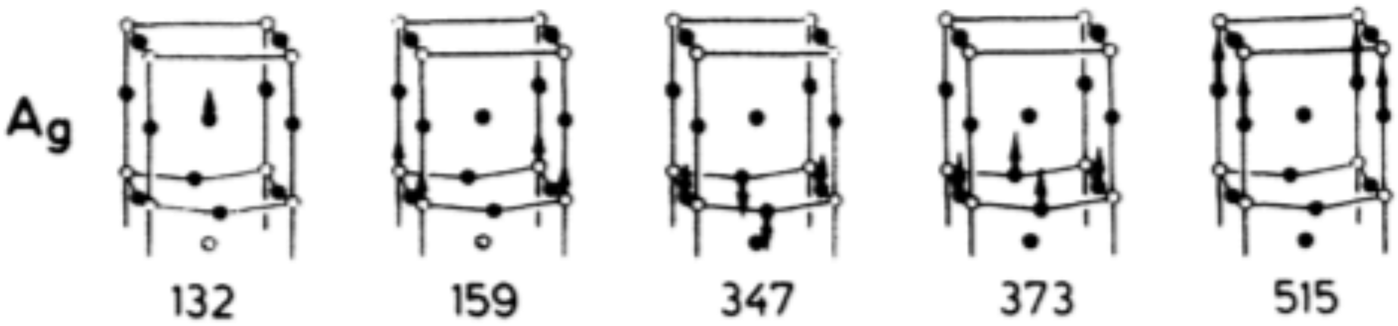
only for Q_2 (A_g, Raman active)

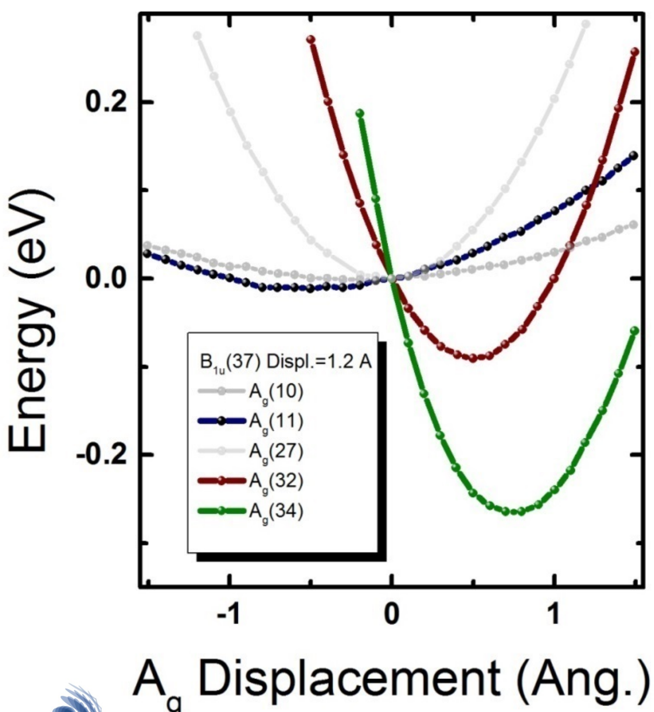


R. Liu et et al., *Phys. Rev. B* 37, 7971 (1988)

M. Först *et al.*, Nature Physics 7, 854 (2011)

3 coupled Raman modes





DFT Calculations

Frozen B_{1u} distortion (1 Å)

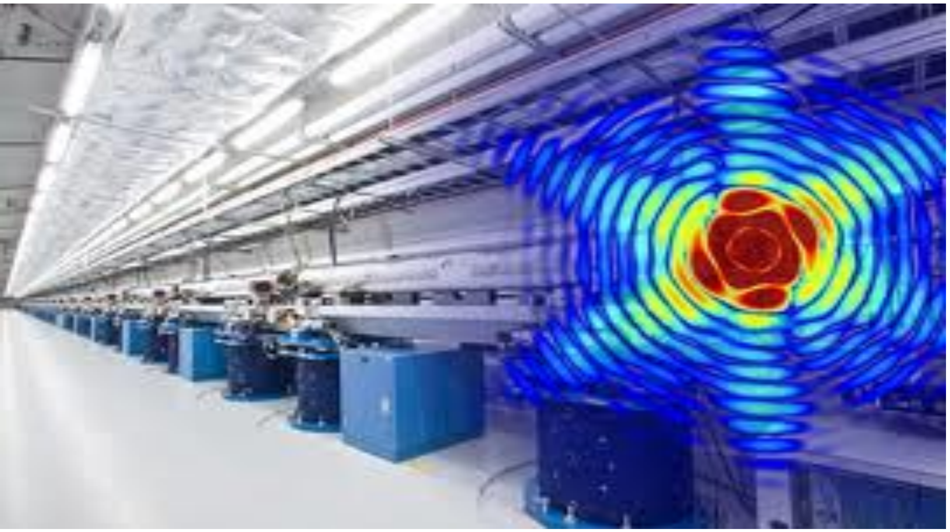
3 coupled modes (out of 5)

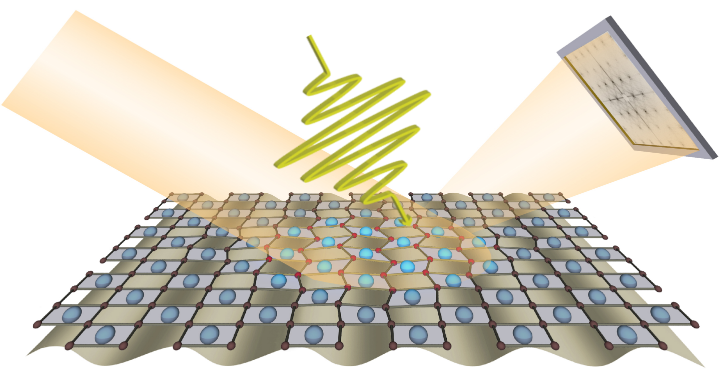
Alaska Subedi – Antoine Georges (Ecole Polytechnique)

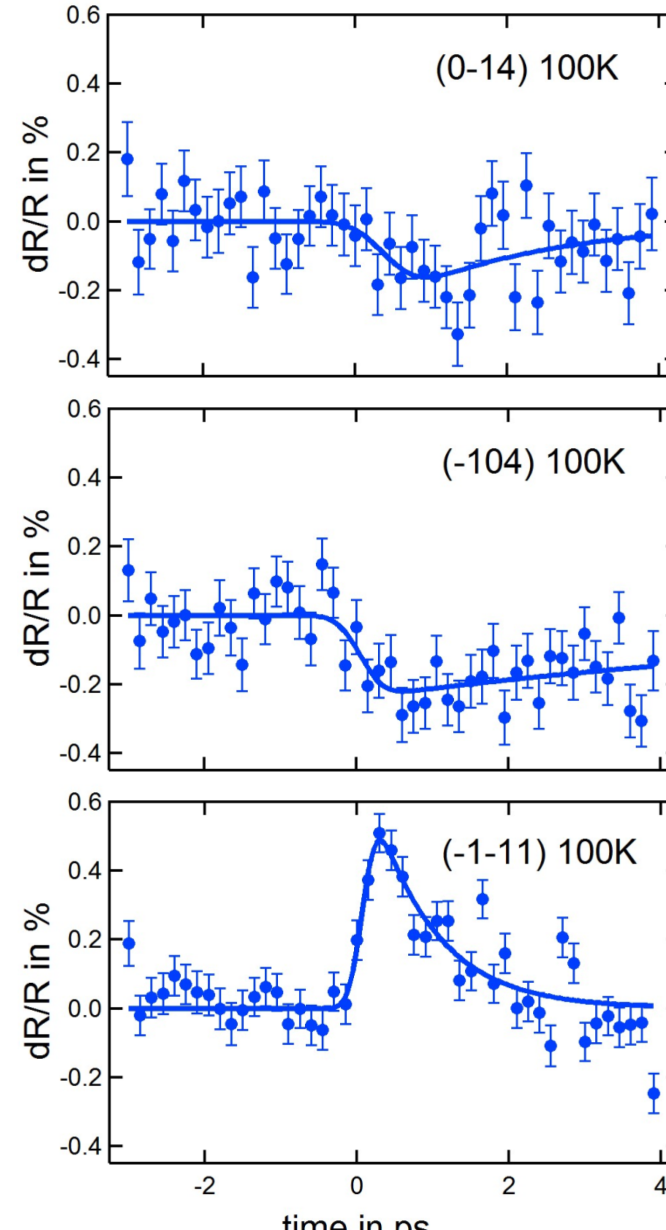
Michael Fechner - Nicola Spaldin (ETH)

How much is each mode moving ?

LCLS: Femtosecond Crystallography





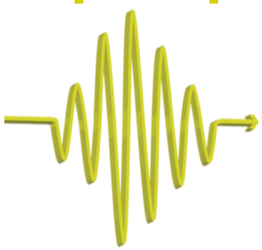


mpsd

R. Mankowsky *et al.*, forthcoming

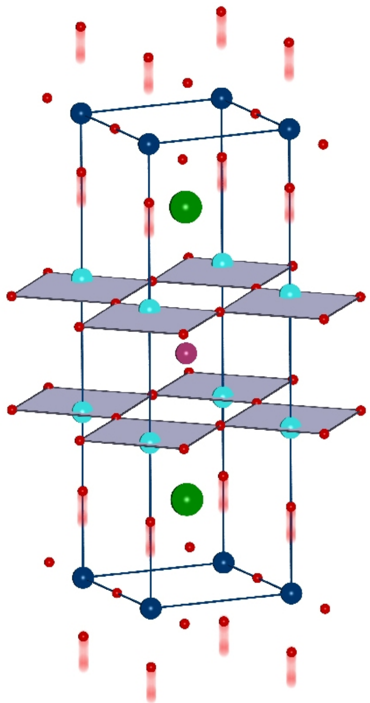
Direct Excitation of the Lattice in YBCO

Mid-IR pump

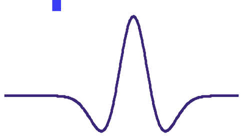


20 THz ~ 15 μm

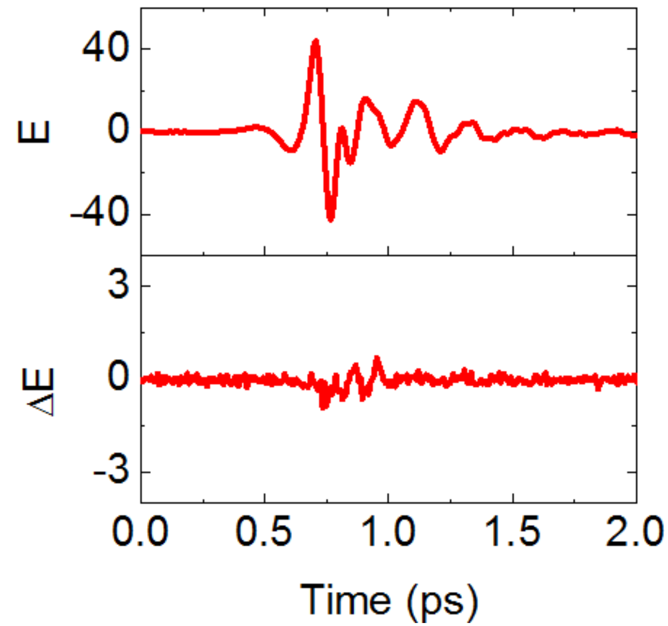
$YBa_2Cu_3O_{6+x}$



THz probe

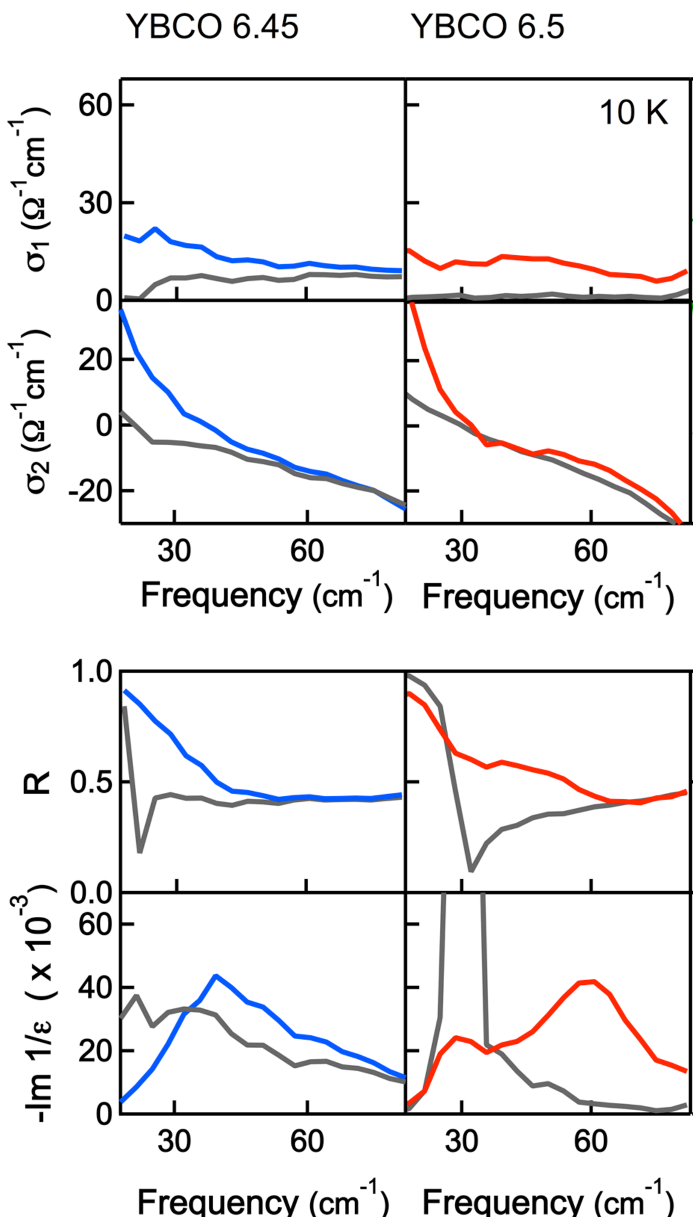


0.5 – 2.5 THz



$$\frac{\Delta \tilde{E}_R(\omega,\tau)}{\tilde{E}_R(\omega)} = \frac{\tilde{r}(\omega,\tau) - \tilde{r}_0(\omega)}{\tilde{r}_0(\omega)}$$

Enhanced coherence below T_c



Increase of superconductivity

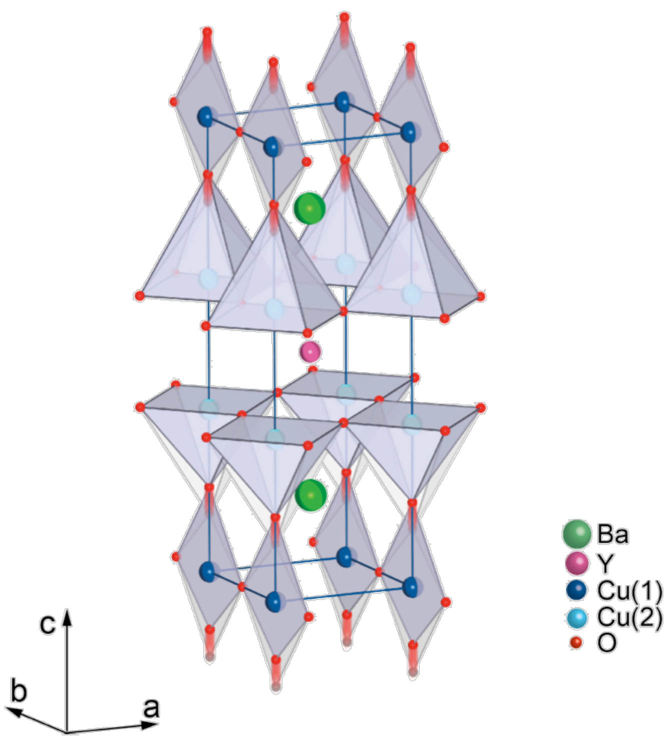
enhanced σ_2

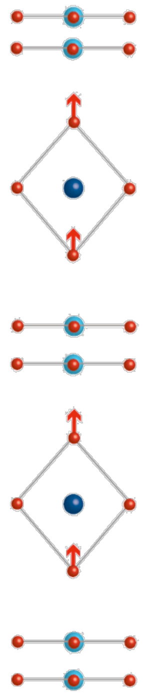
Blue shift of the

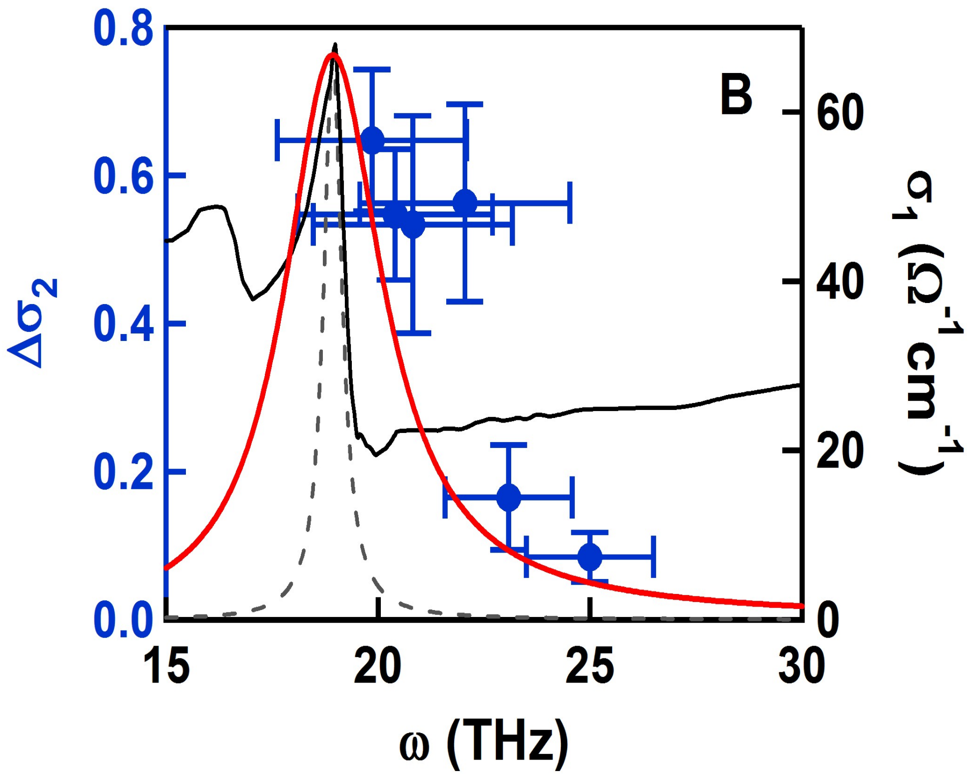
- reflectivity edge
- Loss function

mpsd

Fluence and wavelength dependence



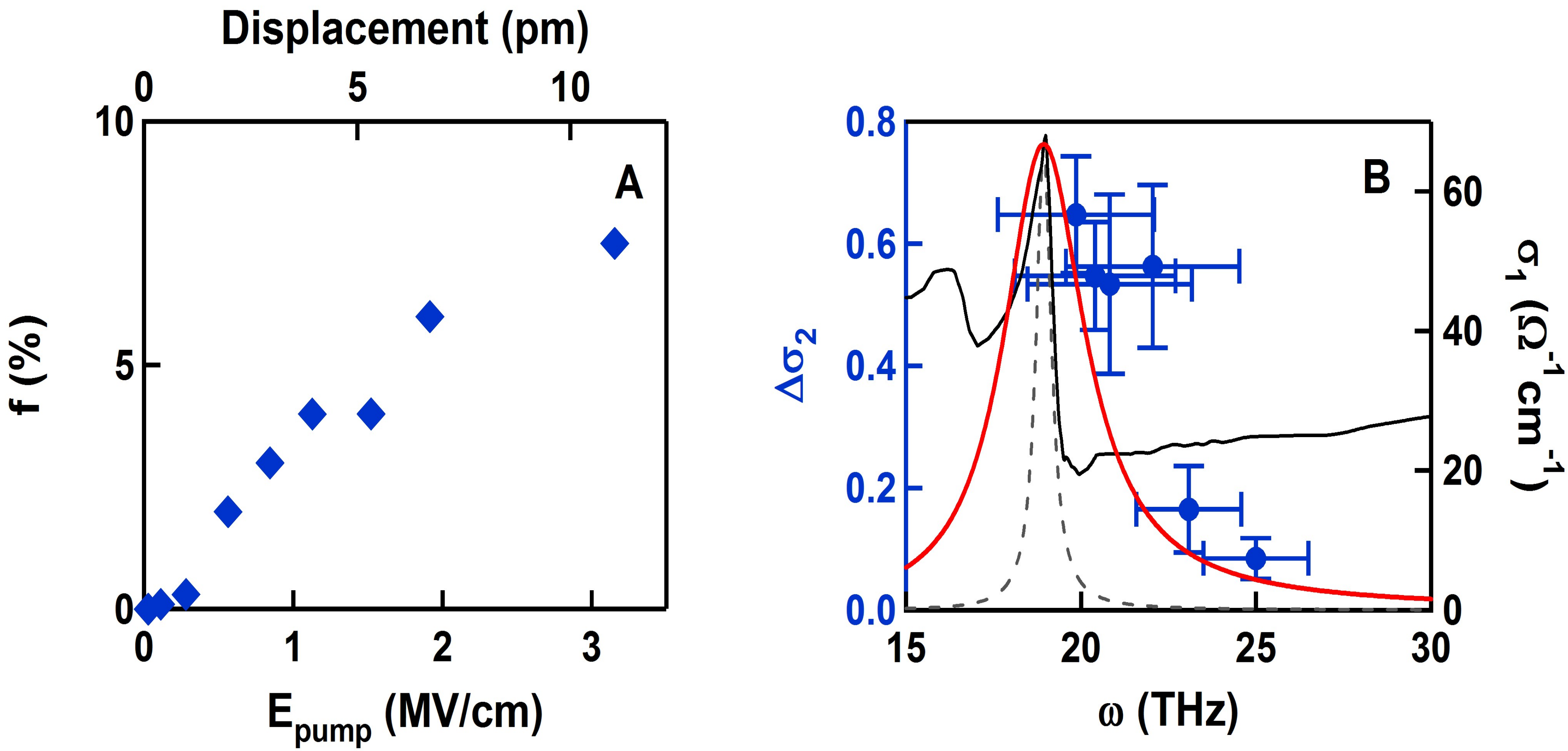




Resonant to apical oxygen phonon

mpsd

Fluence and wavelength dependence

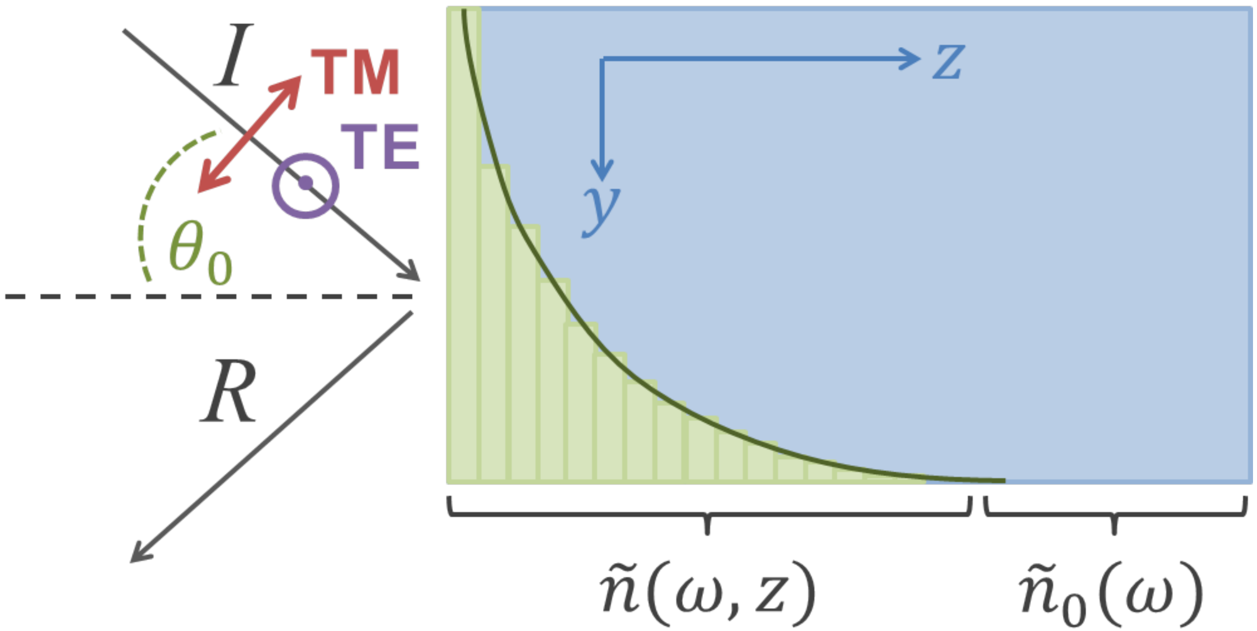


Linear field dependence
No percolation behavior found

Resonant to apical oxygen phonon

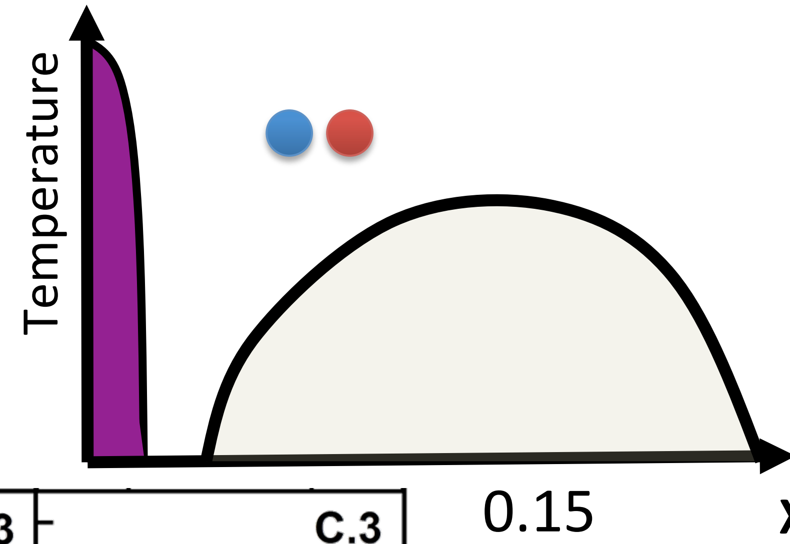
Penetration depth mismatch

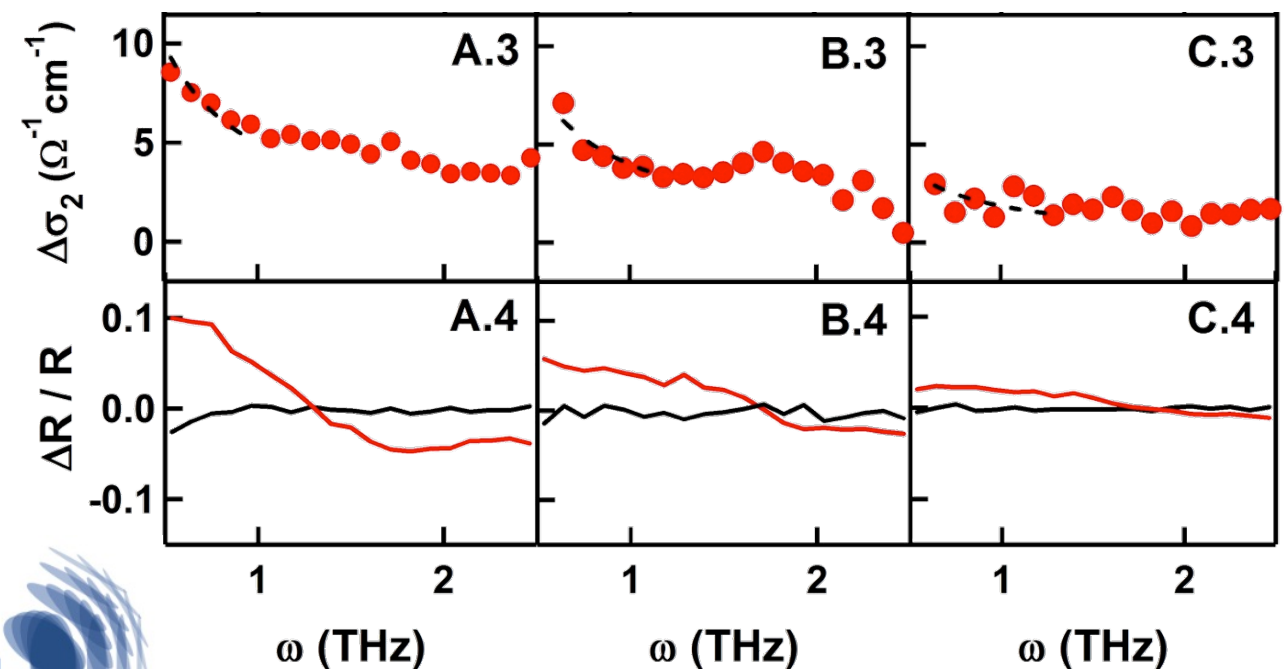
$$\tilde{n}(\omega, z) = \tilde{n}_0(\omega) + \Delta\tilde{n}(\omega)e^{-\alpha z}$$



Multilayer model to calculate the optical properties

Temperature dependence YBCO 6.5 (T_c=50 K)





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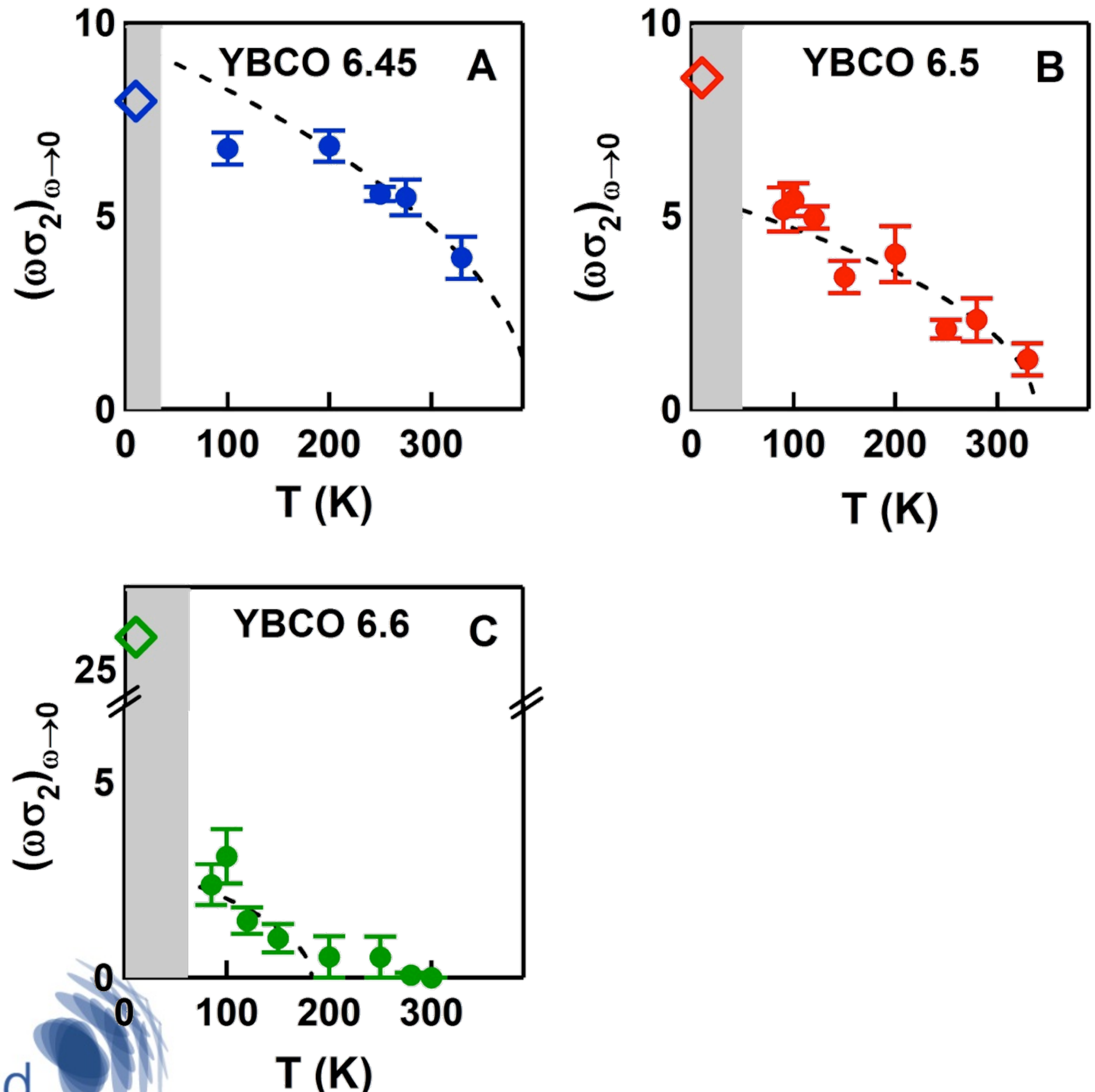
CFEL SCIENCE

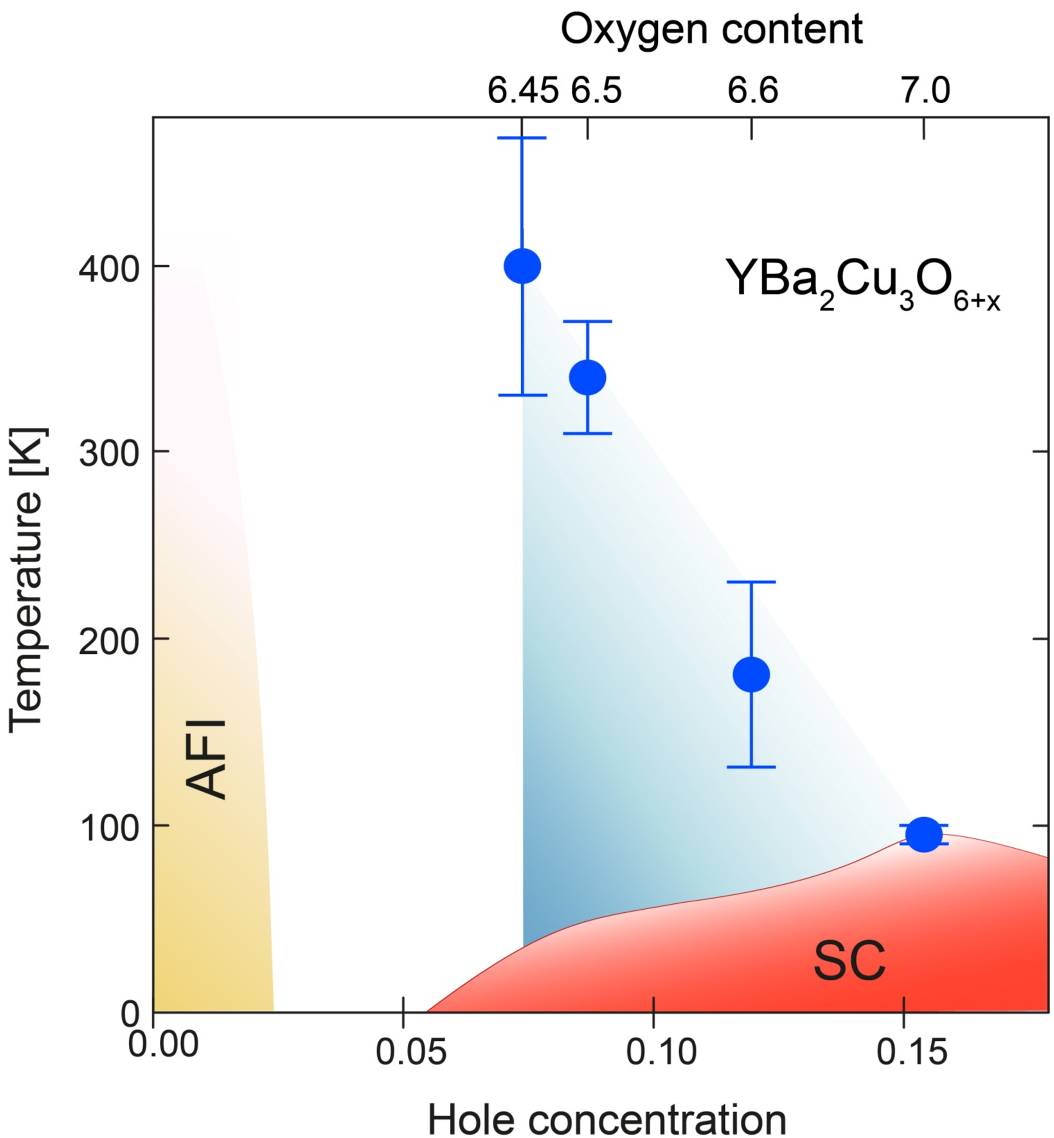
Temperature dependence of superfluid density



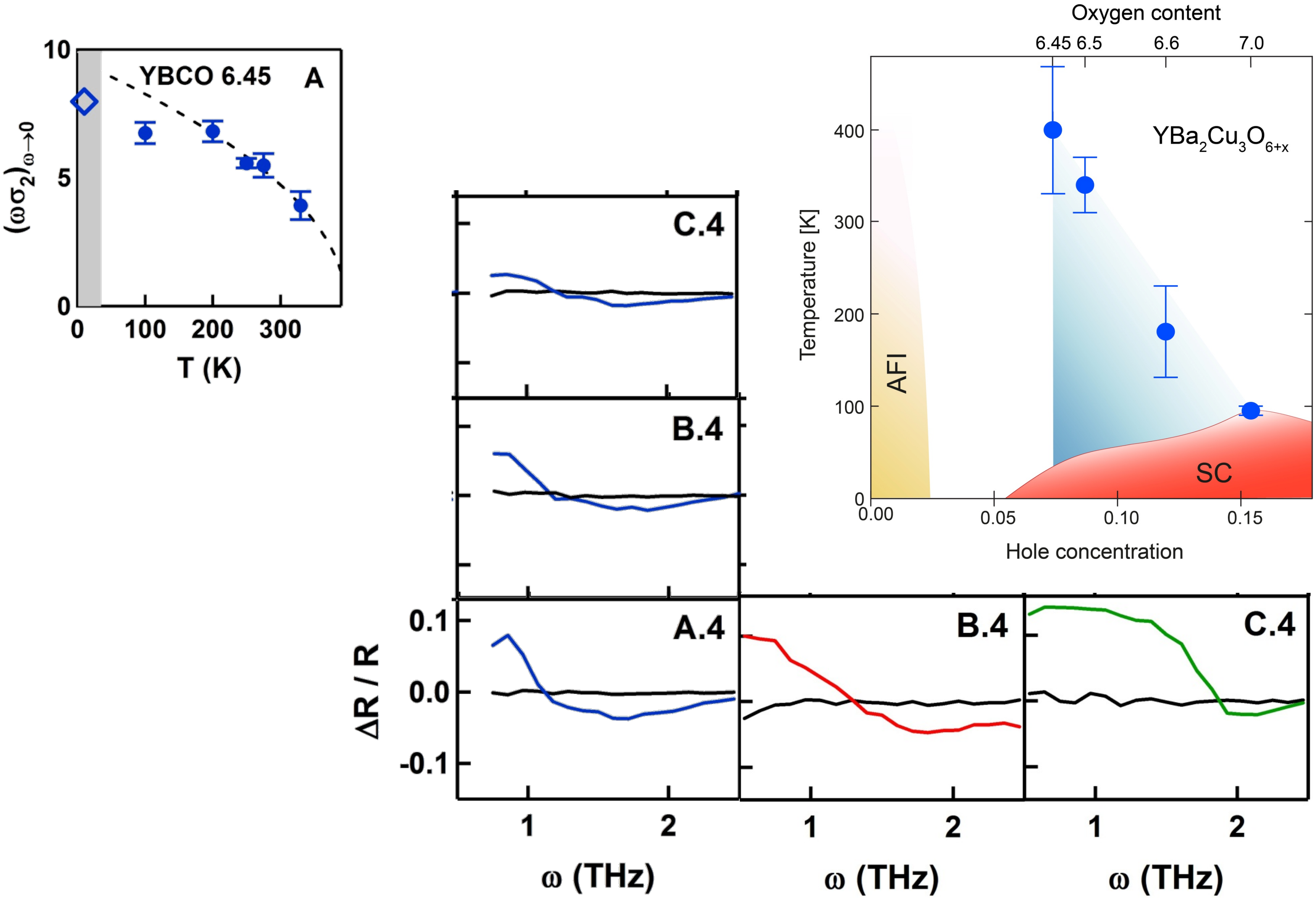
$$D^{SF} \propto (\omega\sigma_2)_{\omega\to 0}$$

$$D^{SF} \propto \sqrt{1 - \frac{T}{T'}}$$

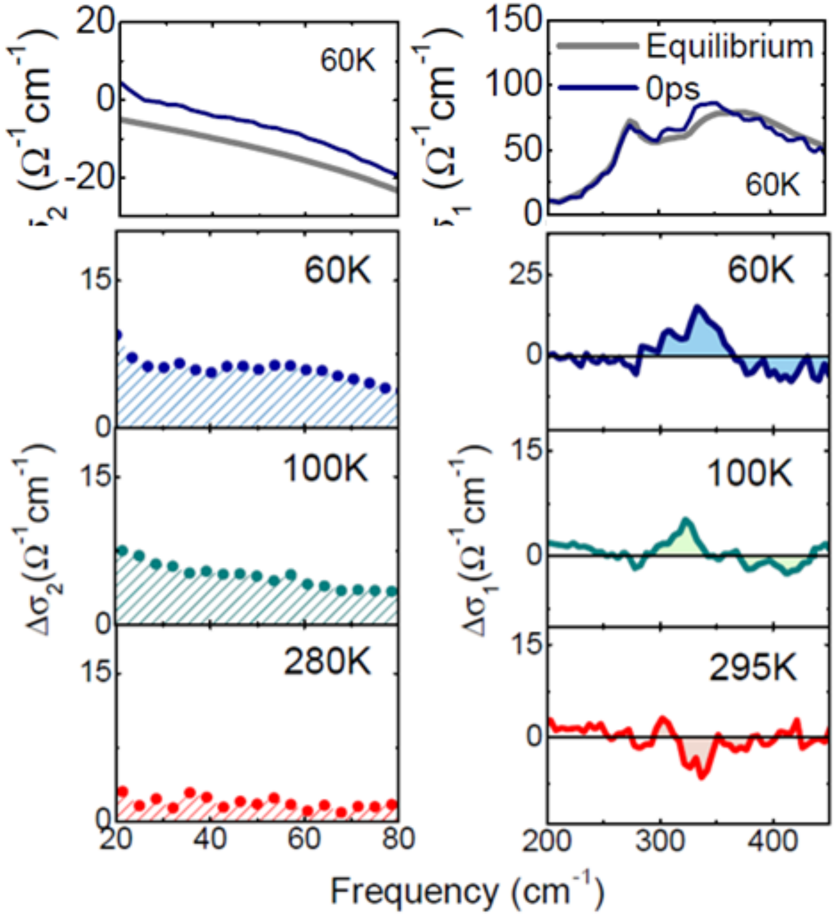
Induced Inductive Coupling far above T_c

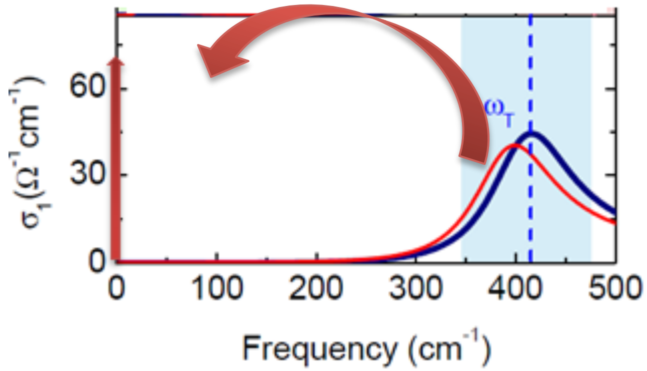


Inhomogeneous nature of the SC state

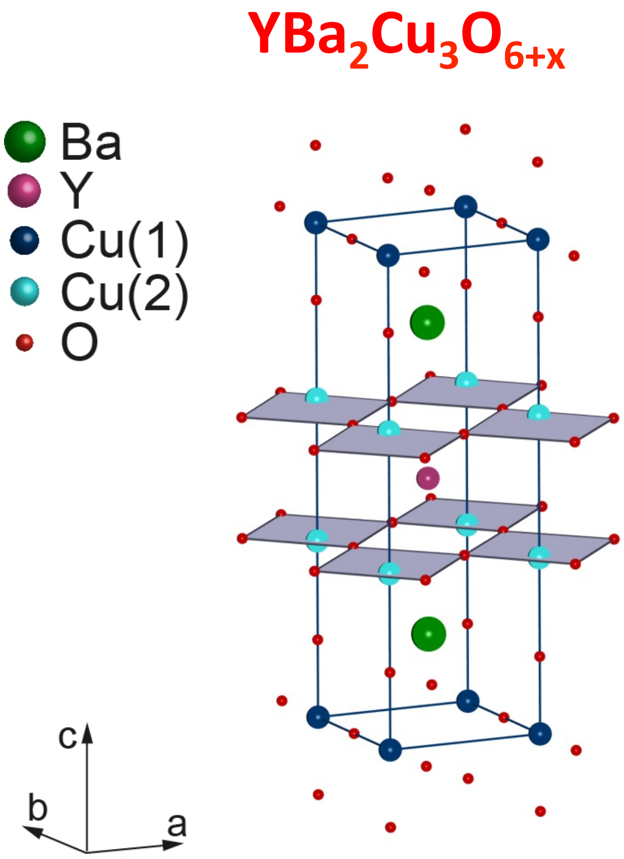


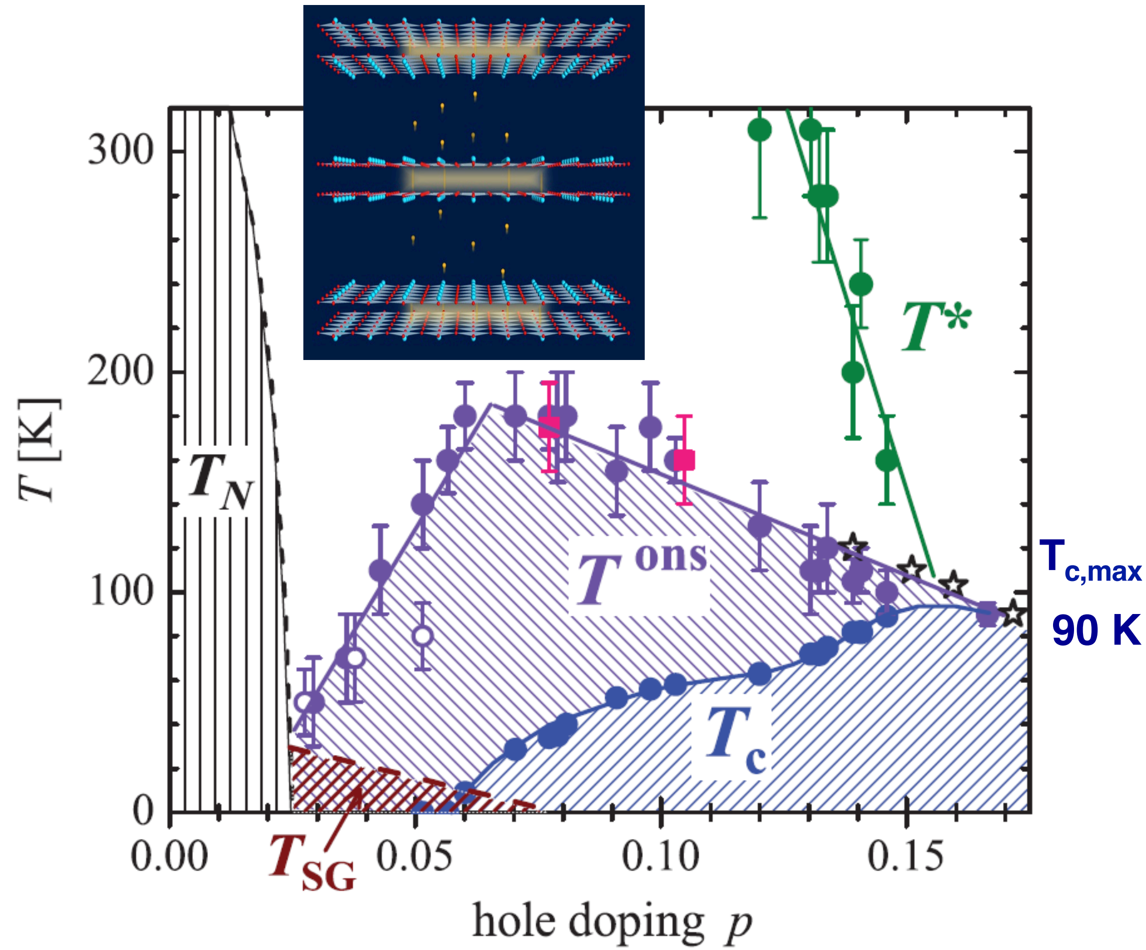
Temperature dependence





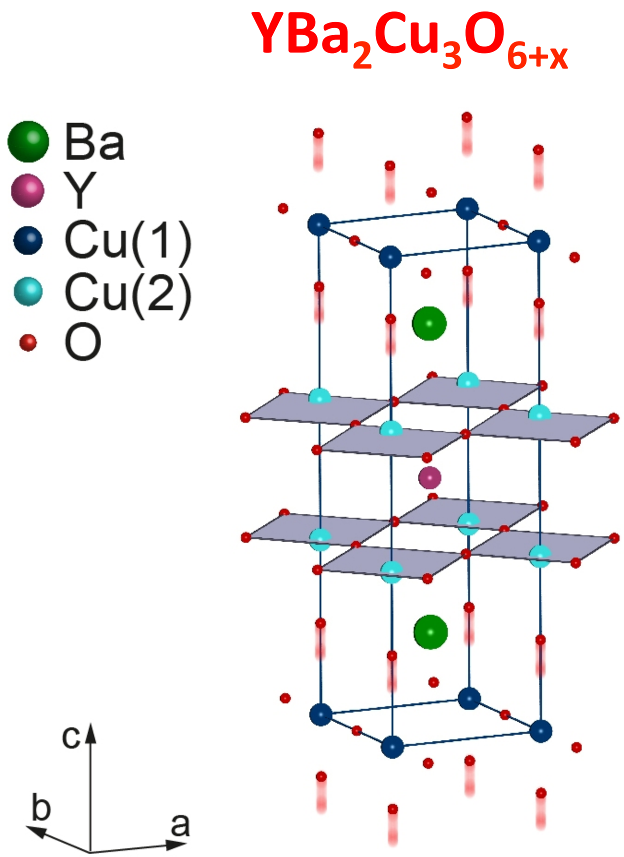
Precursor superconducting state above Tc

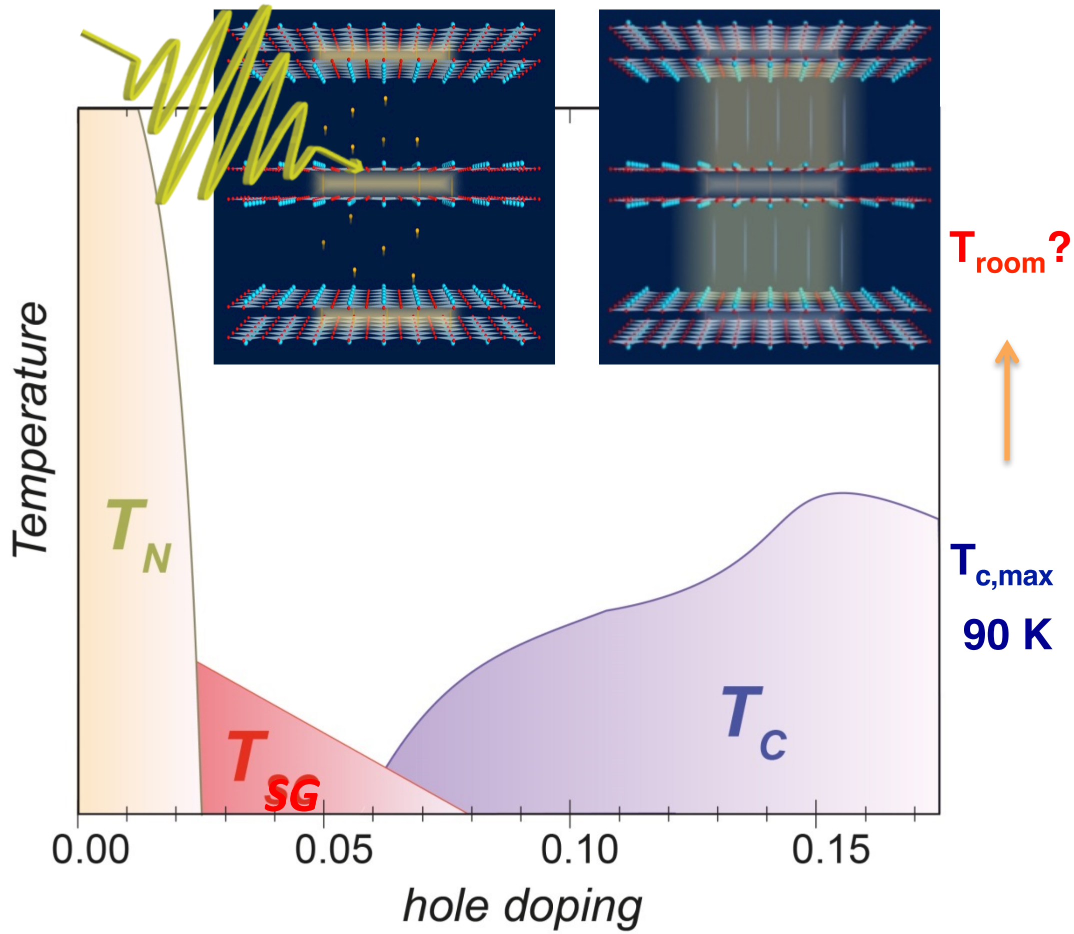




A. Dubroka *et al.*,
Phys. Rev. Lett. 107, 047006 (2011)

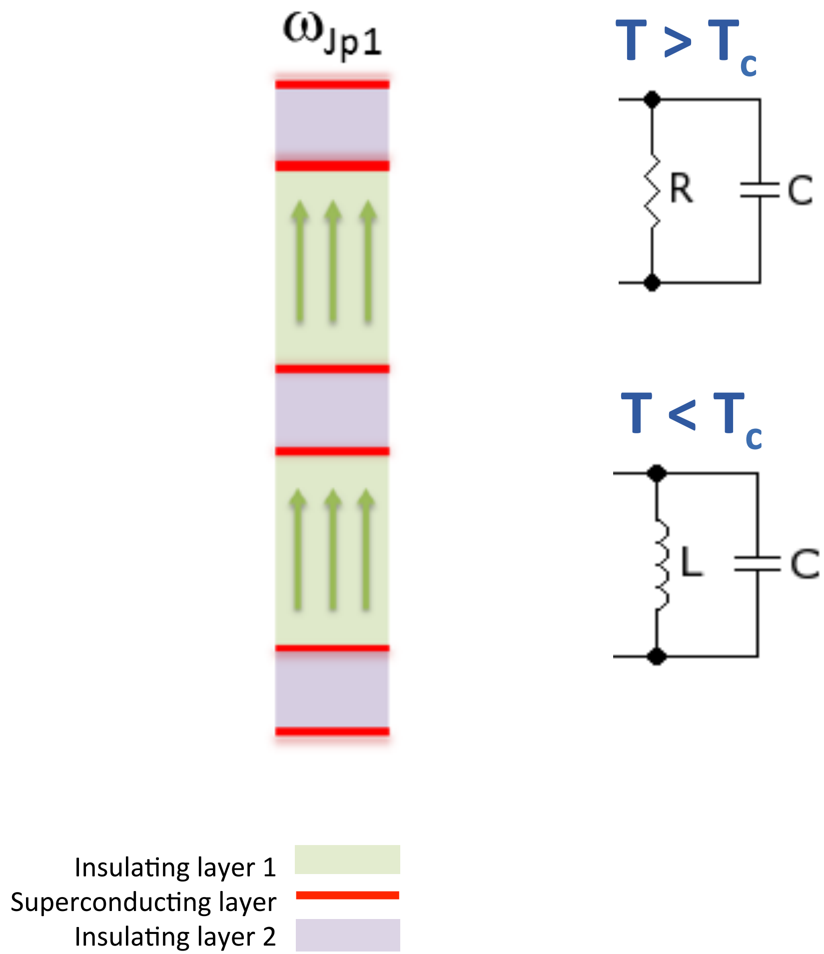
Coherent control of superconductivity



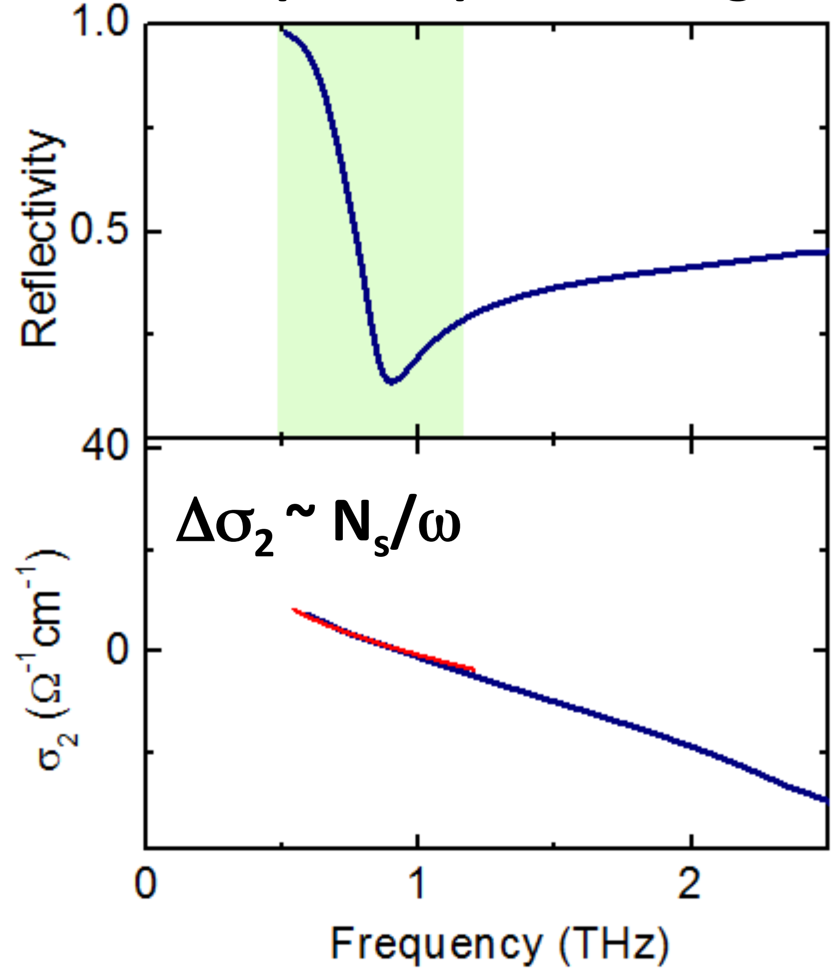


Signature of superconductivity

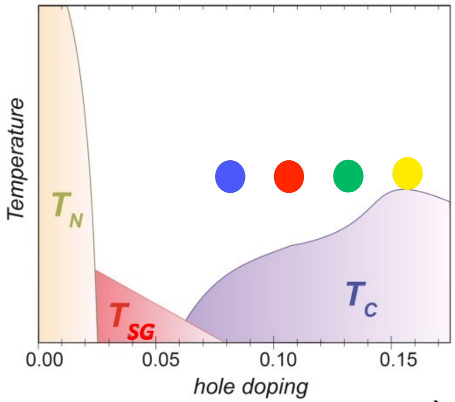
$YBa_2Cu_3O_{6+x}$ c-axis



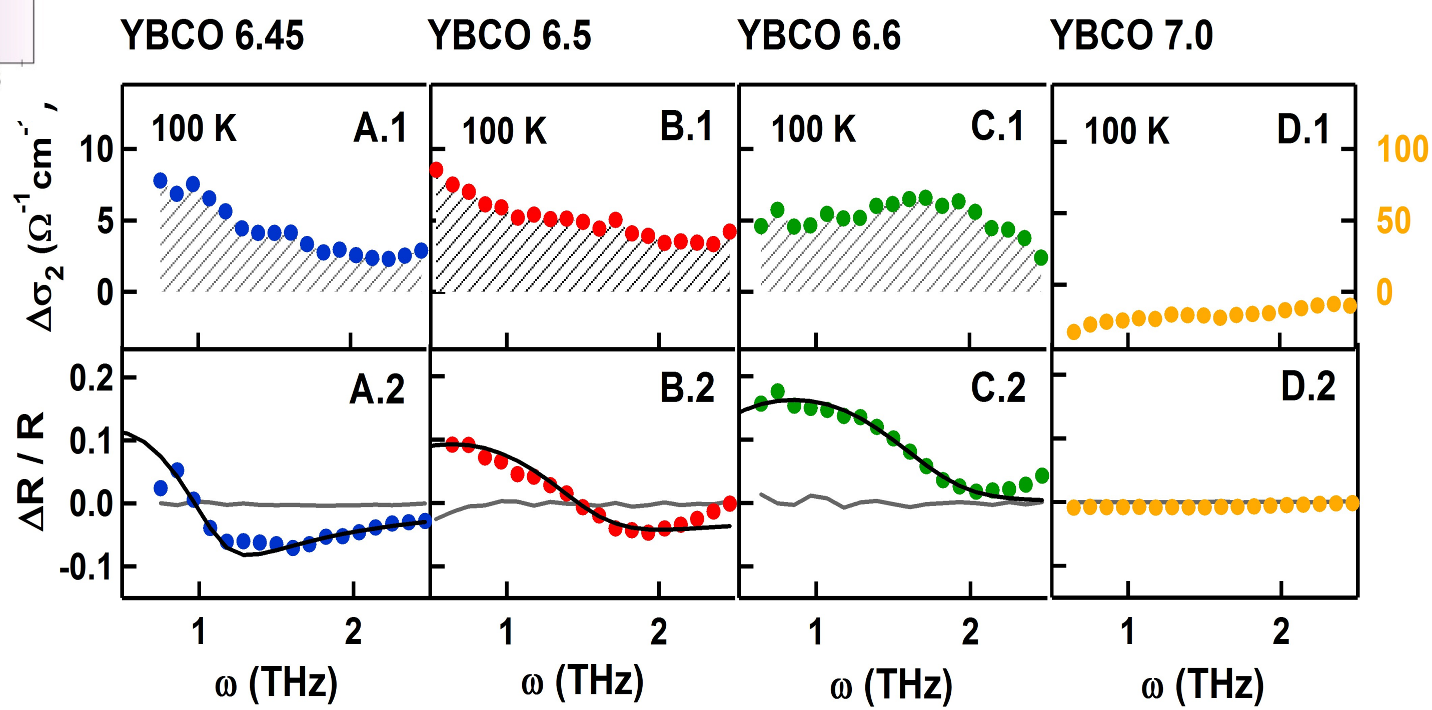
Josephson plasma edge



Transient Superconductivity above Tc

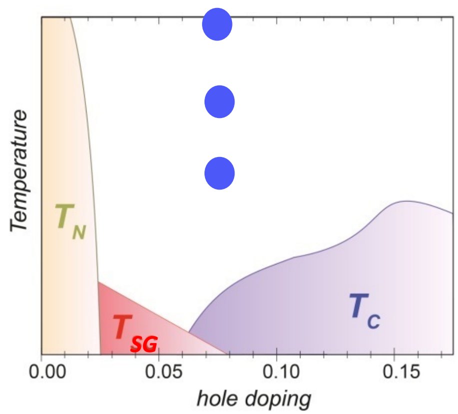


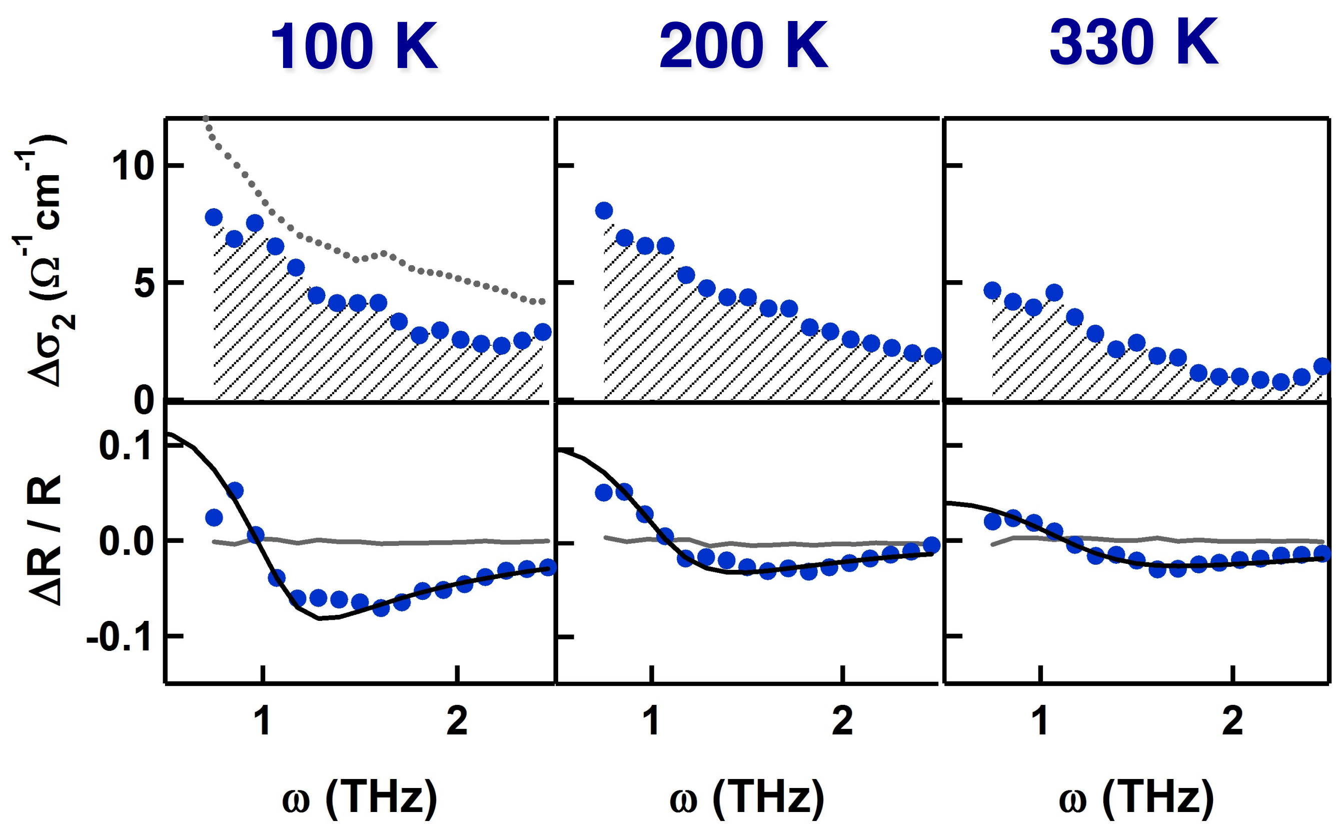
T = 100 K



S. Kaiser, D. Nicoletti, C. Hunt et al., arXiv 1205.4661v5

YBCO$_{6.45}$: Temperature Dependence

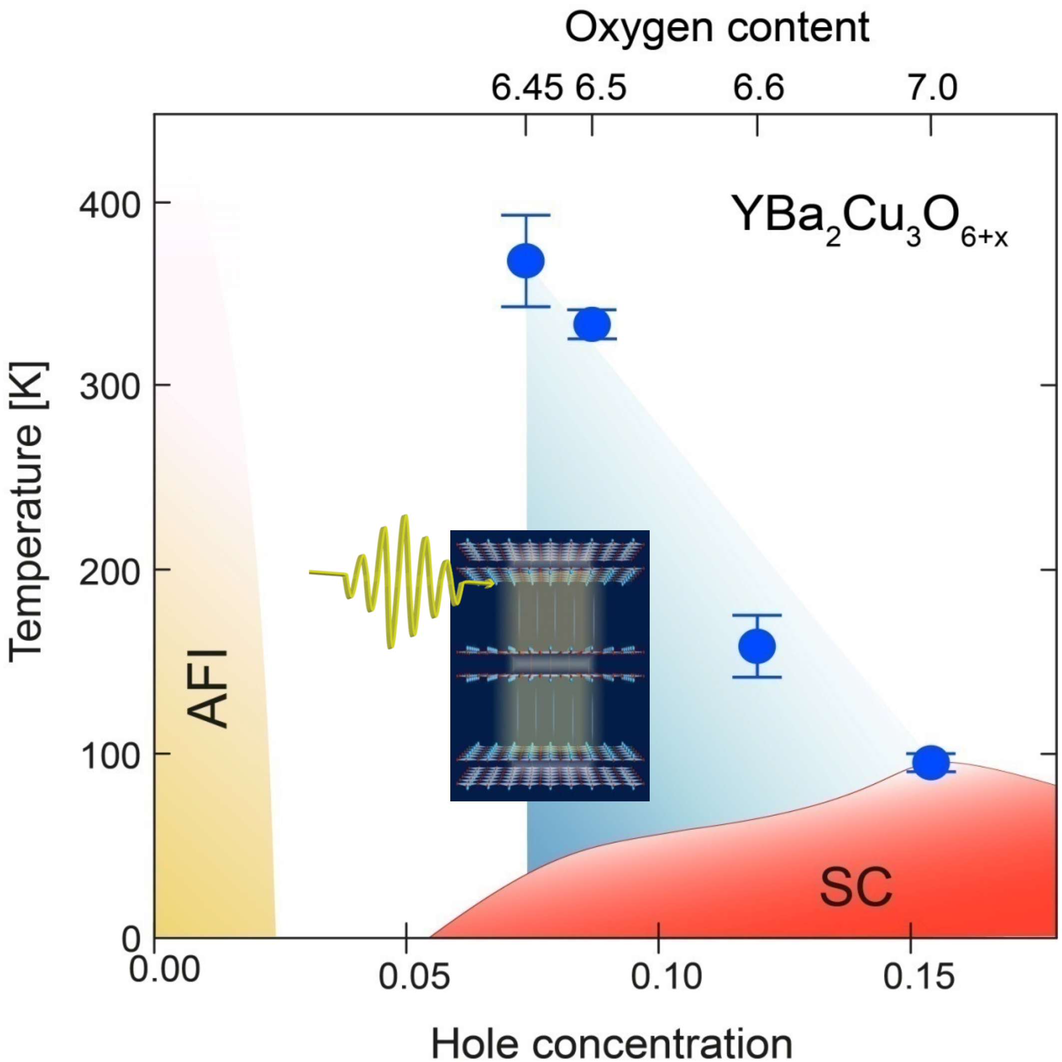




Light-induced Superconductivity up to Room Temperature

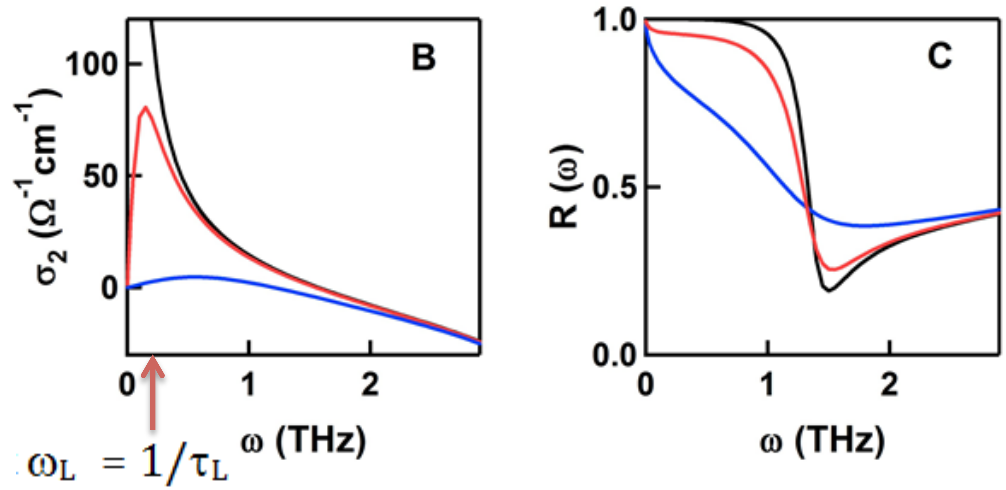
S. Kaiser, D. Nicoletti, C. Hunt et al., arXiv 1205.4661v5

Phase Diagram

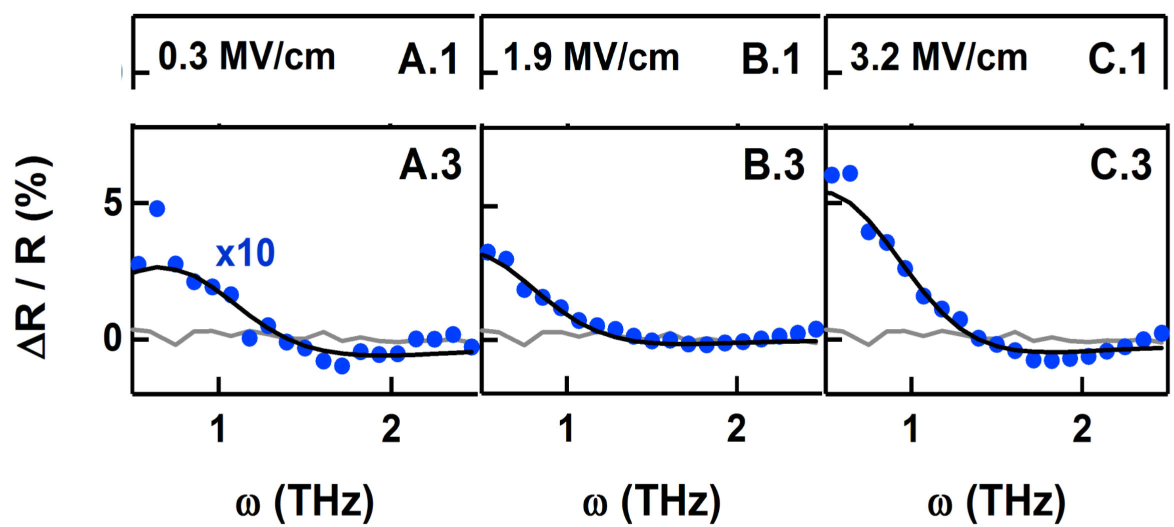


S. Kaiser, D. Nicoletti, C. Hunt et al., arXiv 1205.4661v5

Other possible explanation



high-mobility Drude conductor ? Photo-carriers with a long τ?



The position of the edge exhibited no fluence dependence

S. Kaiser, D. Nicoletti, C. Hunt et al., arXiv 1205.4661v5