Light-Induced High-Temperature Superconductivity

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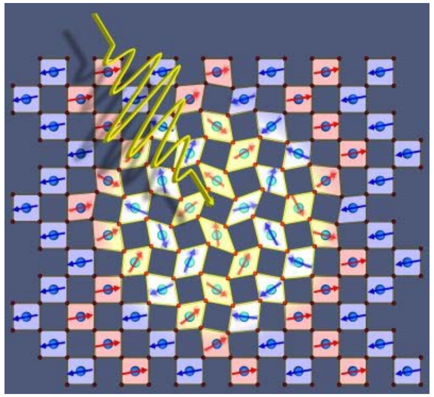
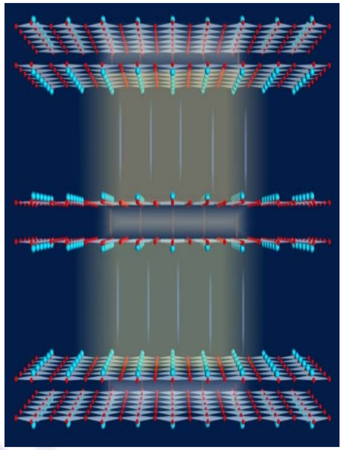
SYNQUANT – Designer Quantum Systems Out of Equilibrium

KITP Santa Barbara – November 15th 2016

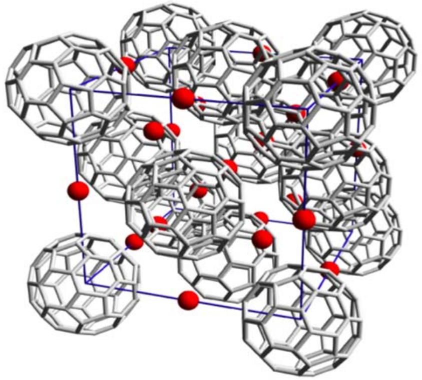
Outline

- Resonant excitation of lattice vibrations with femtosecond mid-infrared pulses





- Light control of interlayer superconducting transport in high-T_c cuprates



- Evidence of light-induced superconductivity in the alkali-doped fulleride K_3C_{60}

People

Andrea Cavalleri's Group – Max Planck Institute for the Structure and Dynamics of Matter, Hamburg

Matteo Mitrano

Roman Mankowsky

Cassi Hunt

Alice Cantaluppi

Michael Först

Stefan Kaiser

Wanzheng Hu

Michele Buzzi

Theory

Stephen Clark
Dieter Jaksch
Oxford

Alaska Subedi
Antoine Georges
Paris

Samples

Bernhard Keimer
Hide Takagi
Stuttgart

Genda Gu
Brookhaven

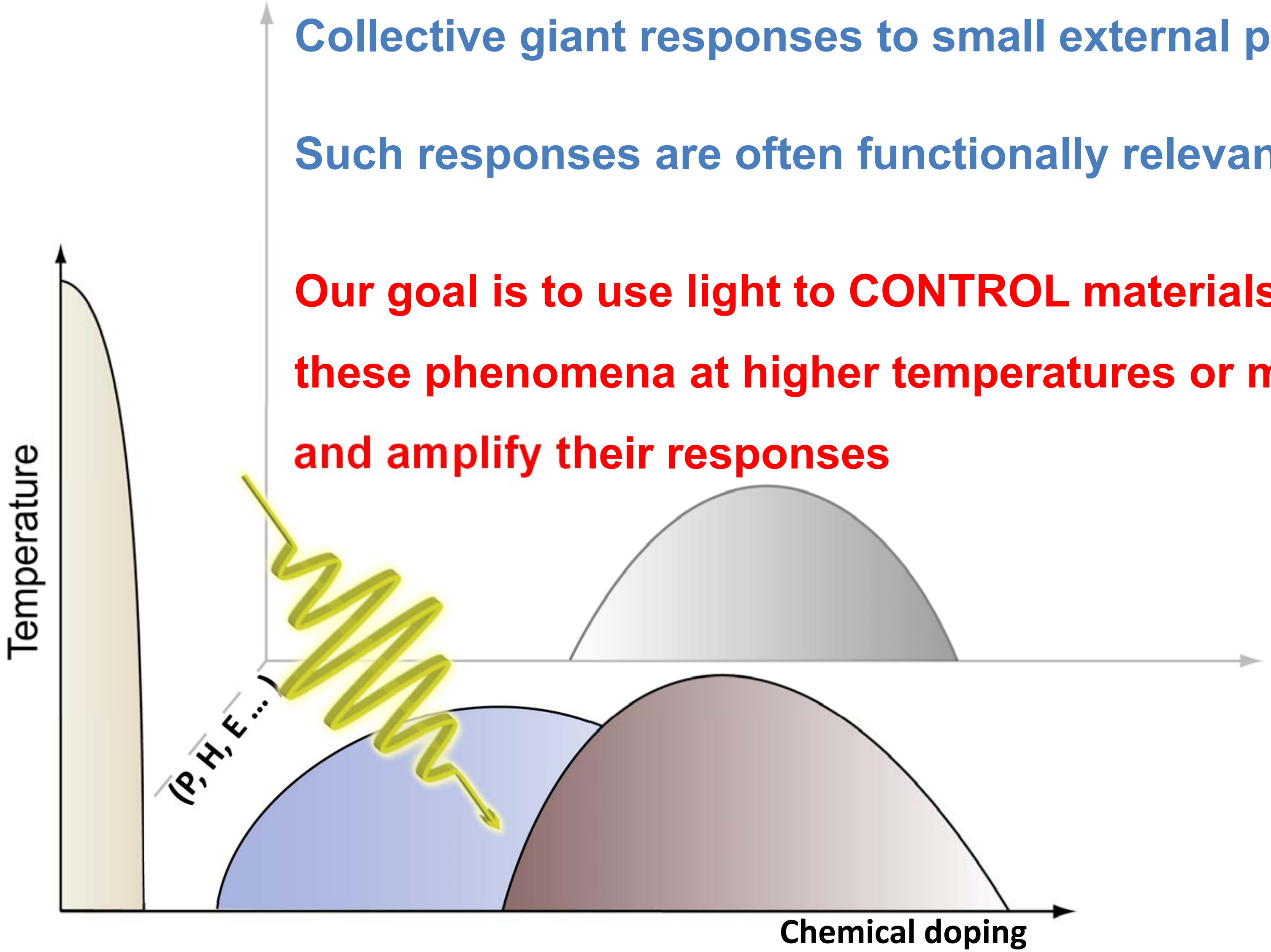
Mauro Riccò
Parma

Complex solids: many competing phases

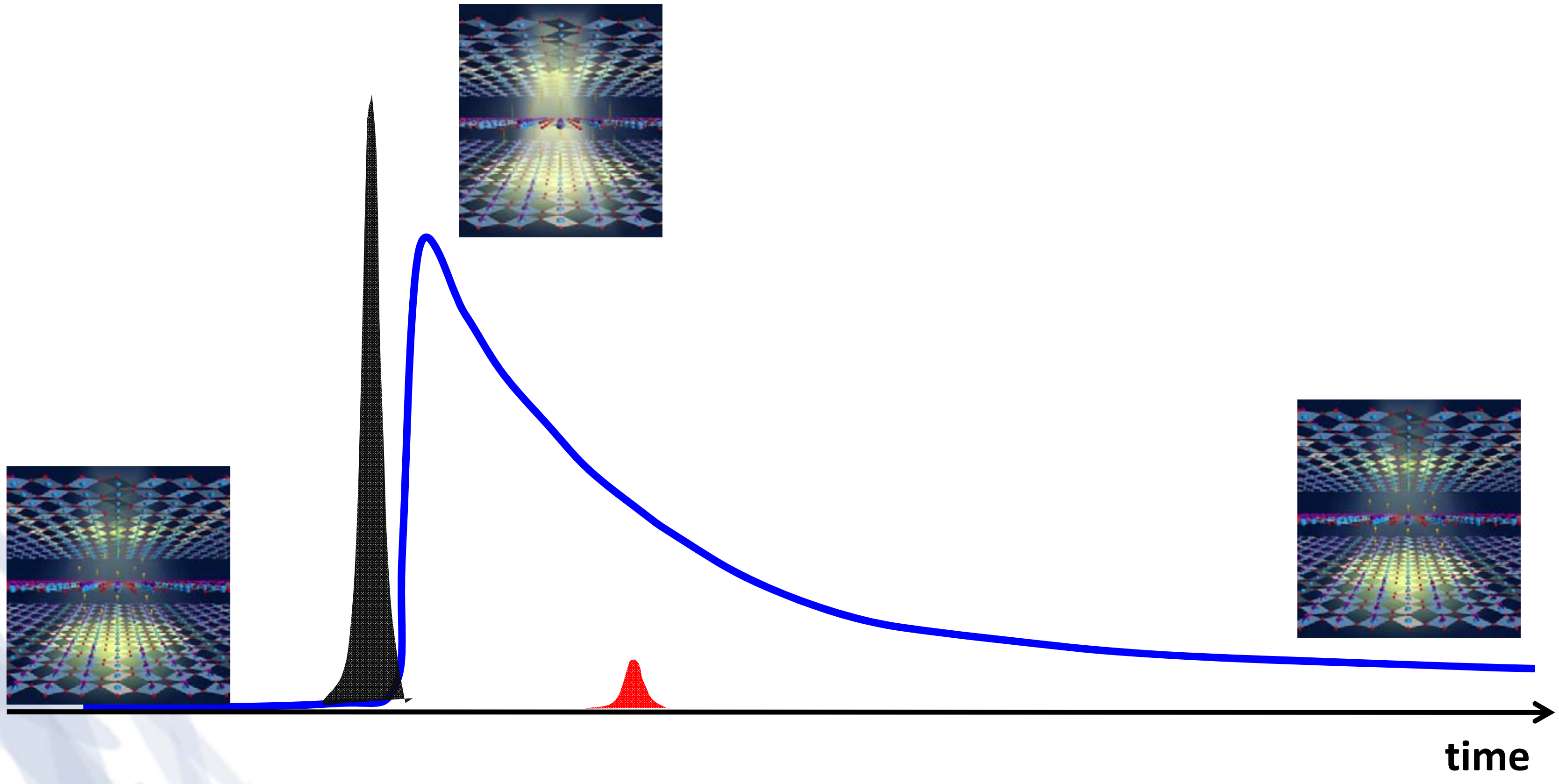
Collective giant responses to small external perturbations

Such responses are often functionally relevant

Our goal is to use light to CONTROL materials, induce these phenomena at higher temperatures or modulate and amplify their responses

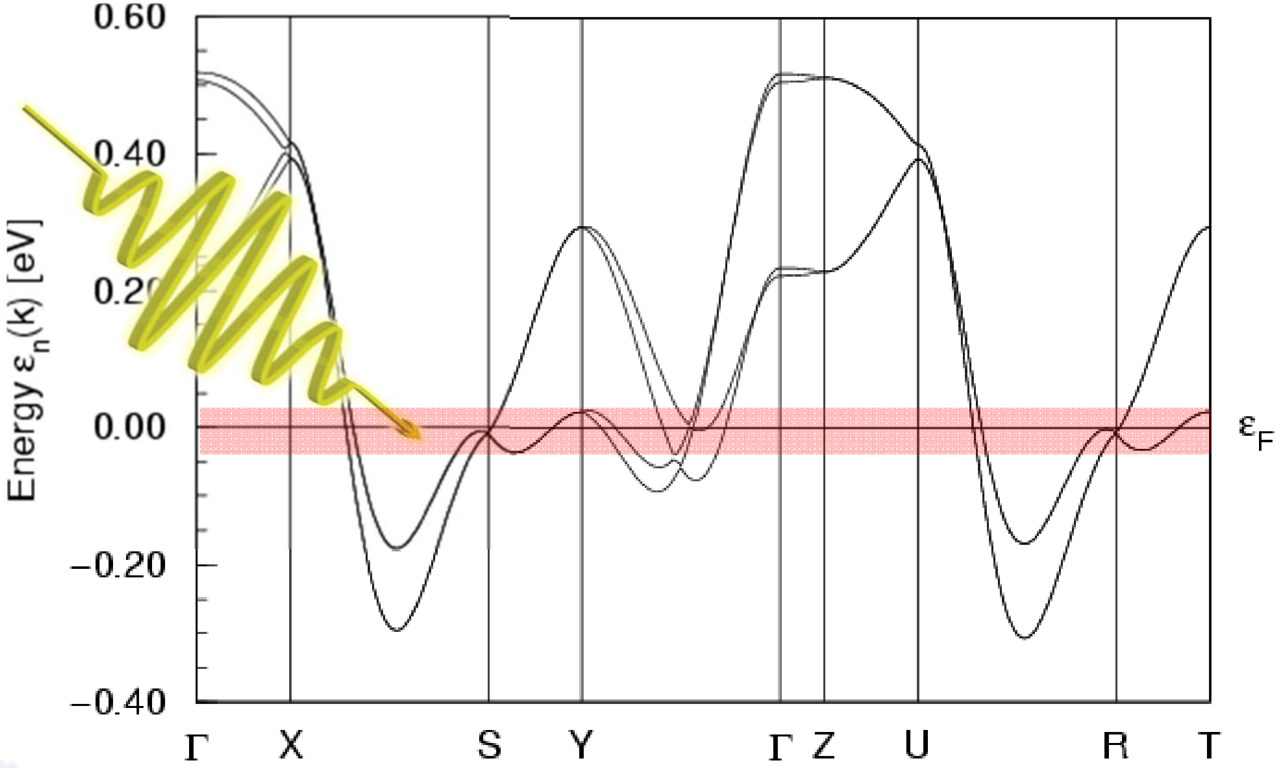


Pump-probe experiments



Control at THz frequencies: natural energy scales

1 THz ~ 50 K ~ 4 meV



Low energy scales

Coherent dynamics

No increase in entropy

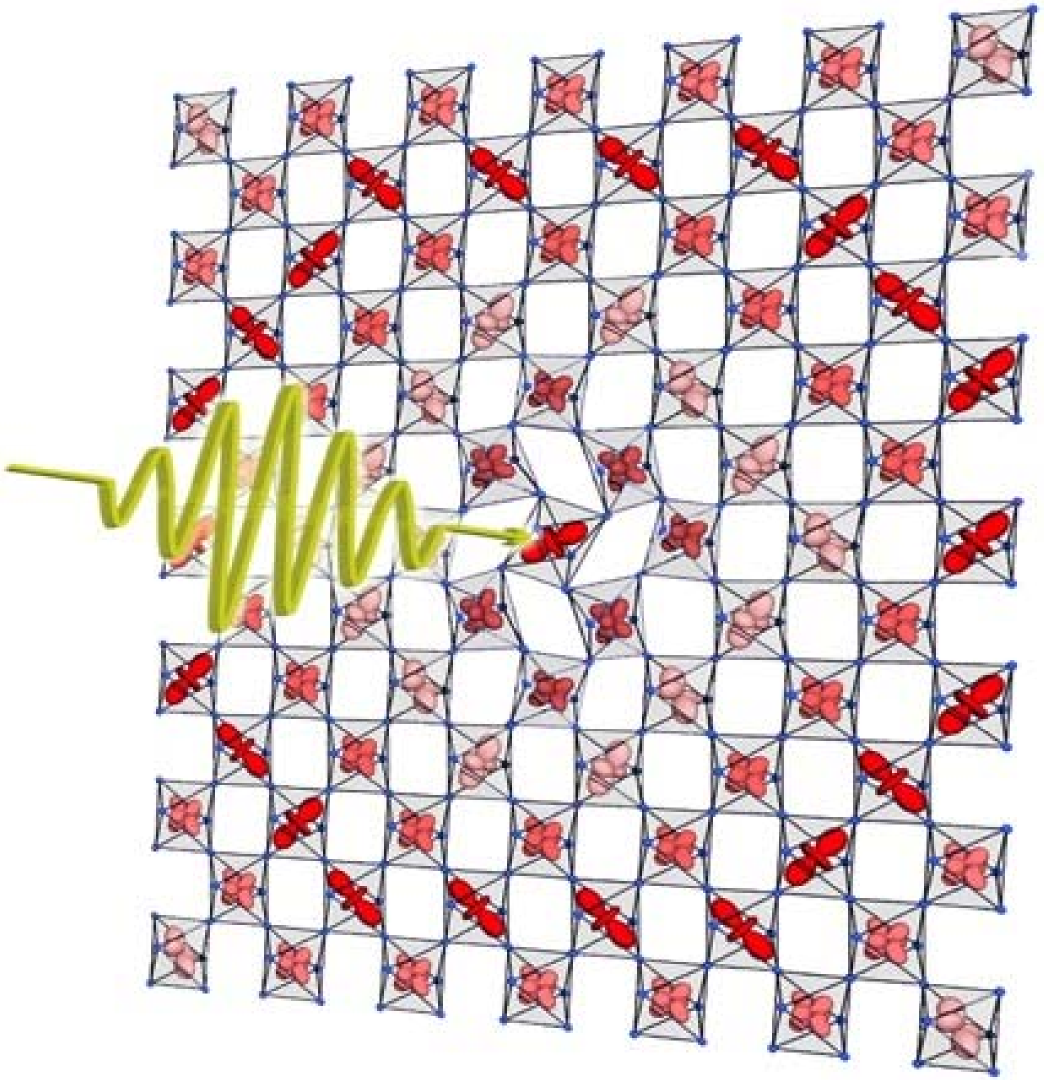
This Talk: Optical control of the lattice

mid-IR
excitation

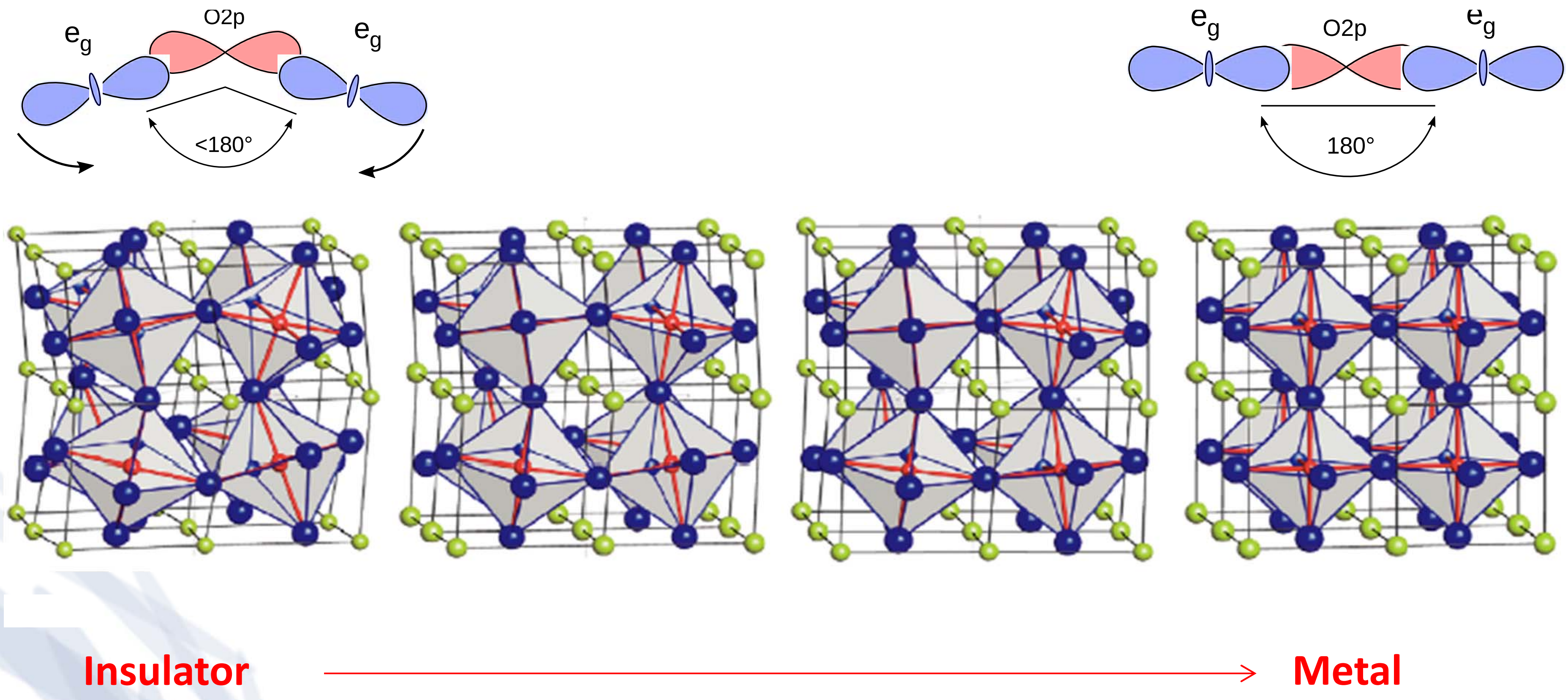
30 THz ~ 10 µm

1-5 MV/cm

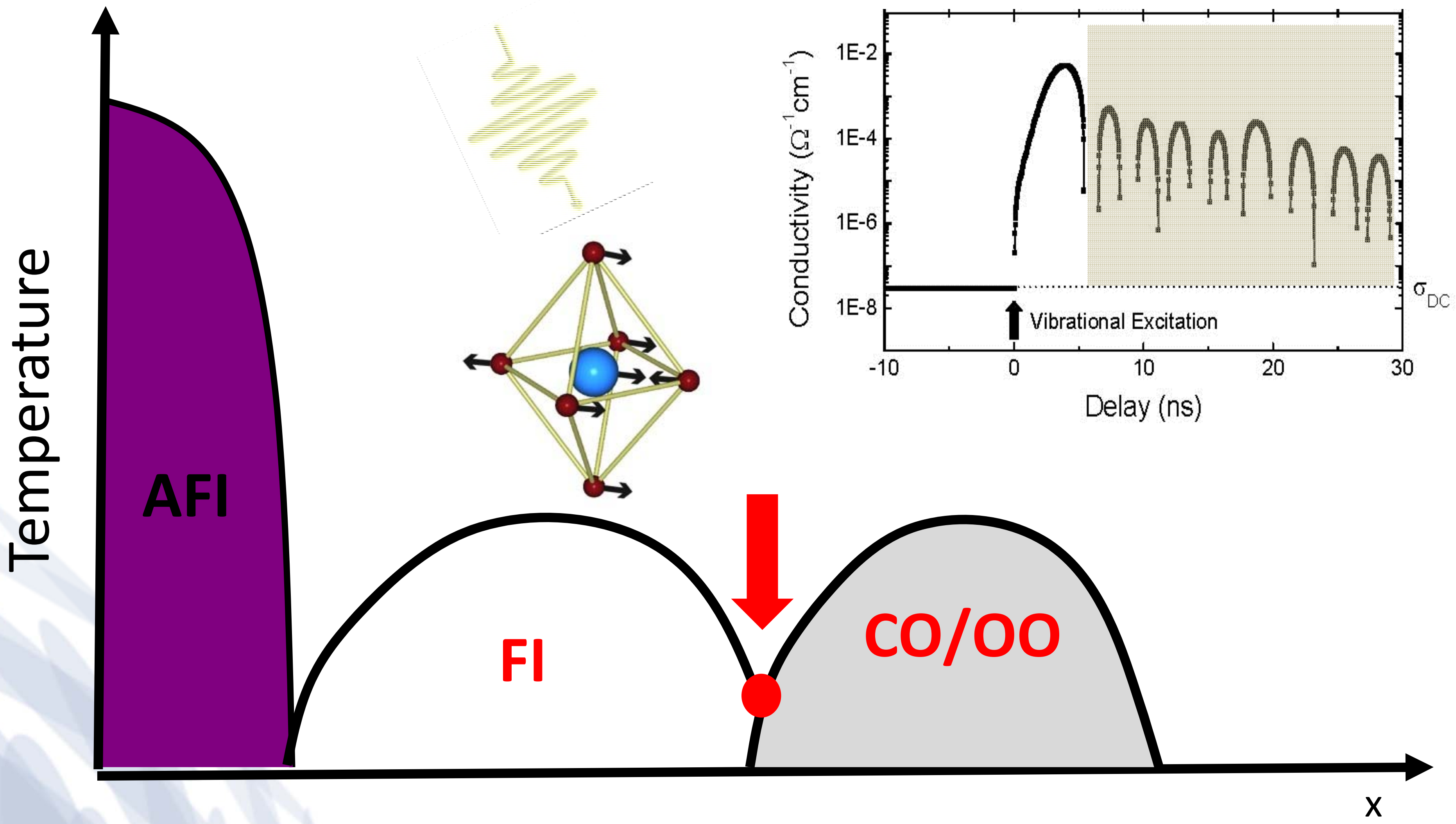
1-10% unit cell



Why? e.g. controlling bond angles in oxides



$Pr_{0.7}Ca_{0.3}MnO_3$: phonon-driven insulator-to-metal transition



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

Lattice displacement ?

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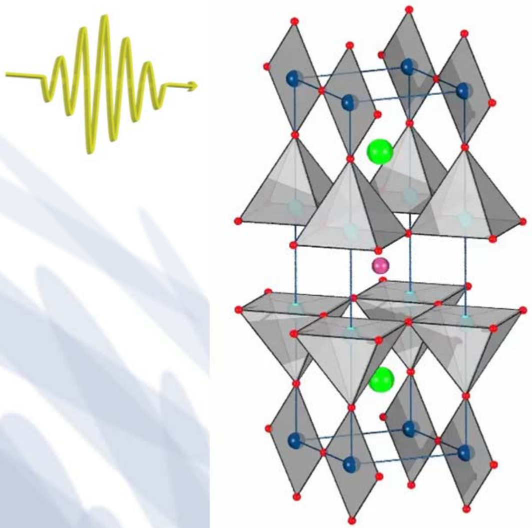
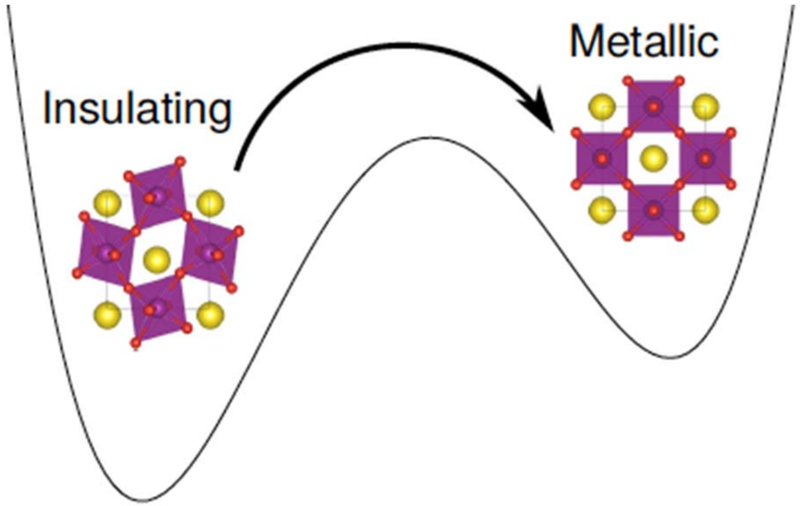
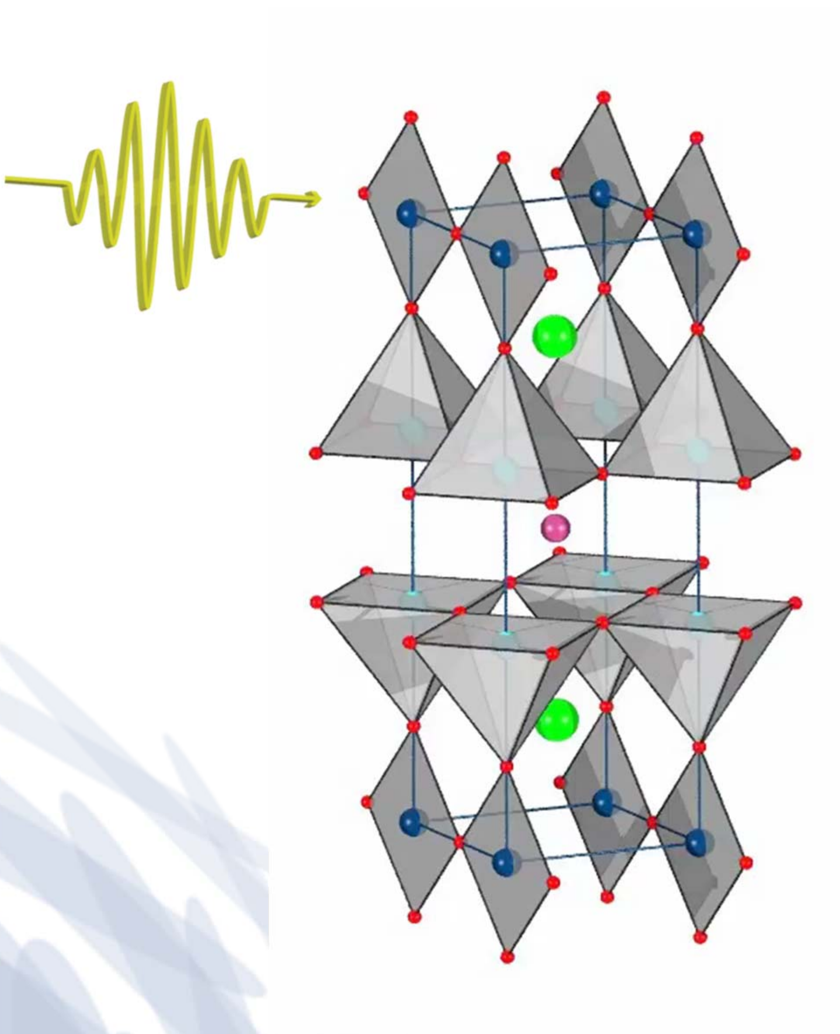
How can optical excitation

displace the crystal bond angles?



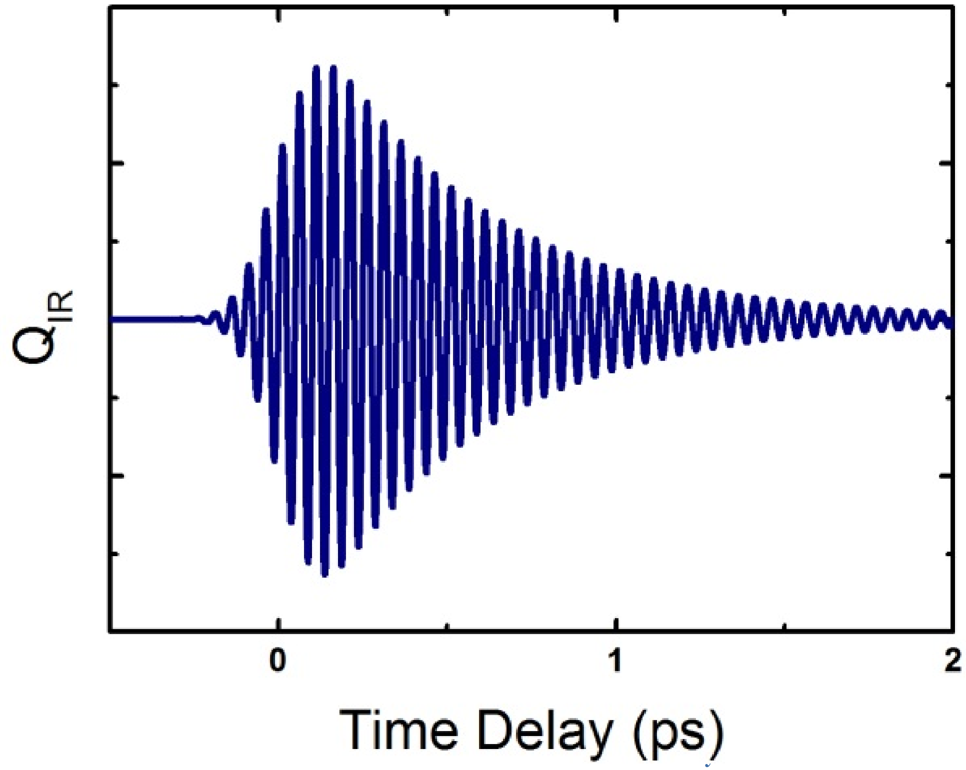


Linear response: no average displacement



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

$$\ddot{Q}_{IR} + 2\gamma\dot{Q}_{IR} + \omega_{IR}^2 Q_{IR} = A\exp(i\omega t)$$



Anharmonic coupling to a second mode

mpsd

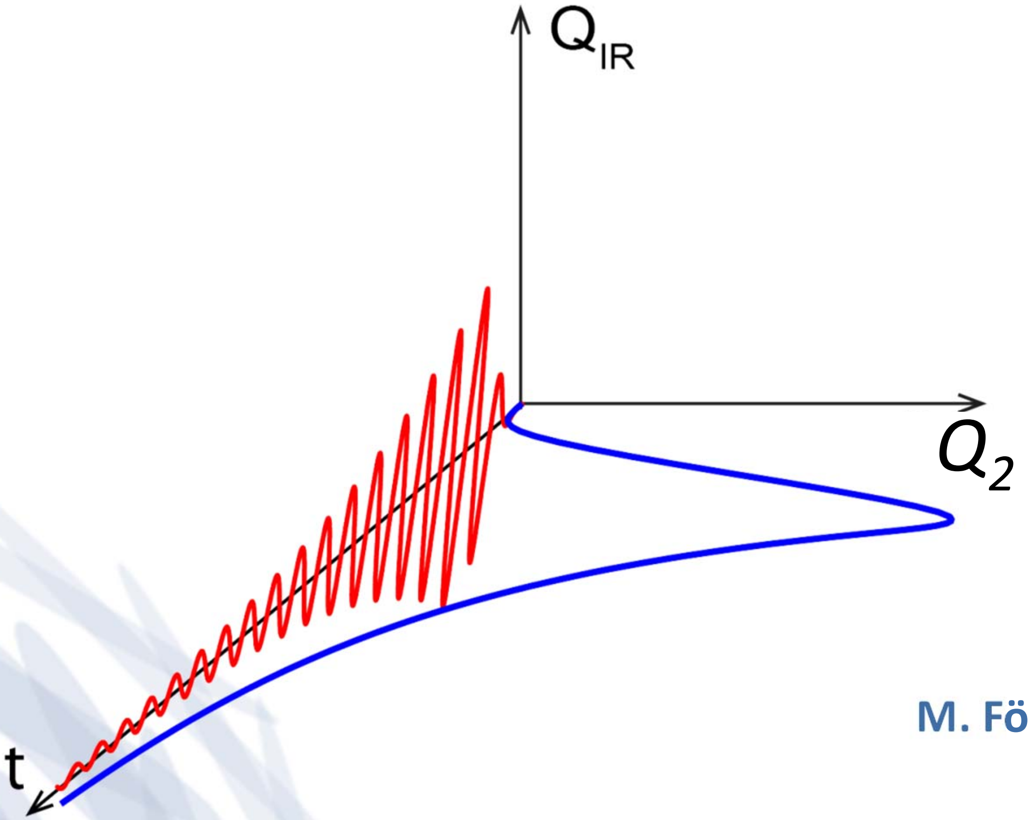
$$V = \frac{1}{2}\omega_{IR}^2 Q_{IR}^2 + \frac{1}{2}\omega_2^2 Q_2^2 - A Q_{IR}^2 Q_2$$

$Q_{IR}^2 Q_2 \neq 0$
only if Q_2 is a Raman mode

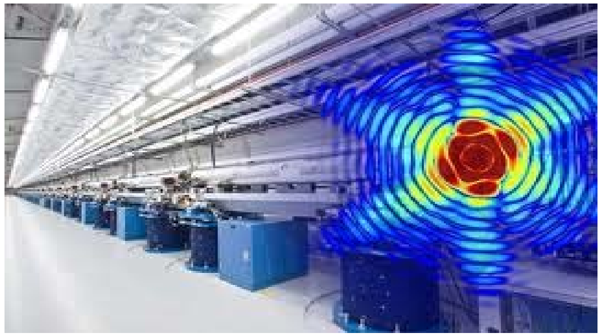
M. Först et al., Nature Physics 7, 854 (2011)
A. Subedi et al., Phys. Rev. B 89, 220301 (2014)

Lattice displacement via Nonlinear Phononics

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



Atomic displacement measured with femtosecond X-ray diffraction

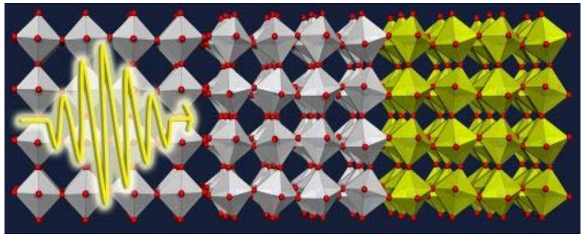


M. Först et al., Sol. State Comm. 169, 24 (2013)

M. Först et al., Nature Physics 7, 854 (2011)
A. Subedi et al., Phys. Rev. B 89, 220301 (2014)

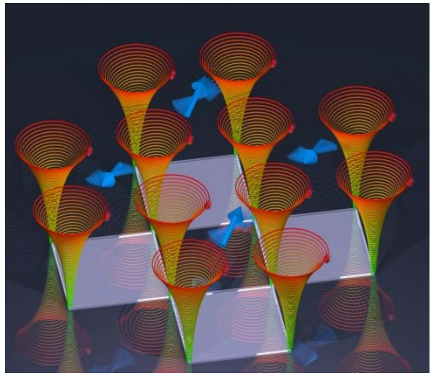
Other examples of lattice control in complex solids

Ultrafast Phase Control across Heterostructured Interfaces



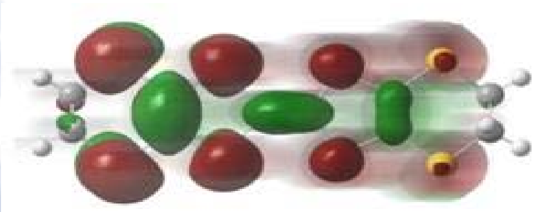
A. Caviglia et al., Phys. Rev. Lett. 108, 136801 (2012)

Phonon-induced effective magnetic field



T. Nova et al., Nature Physics, AOP (2016)

Vibrational control of Hubbard U in organic molecular solid

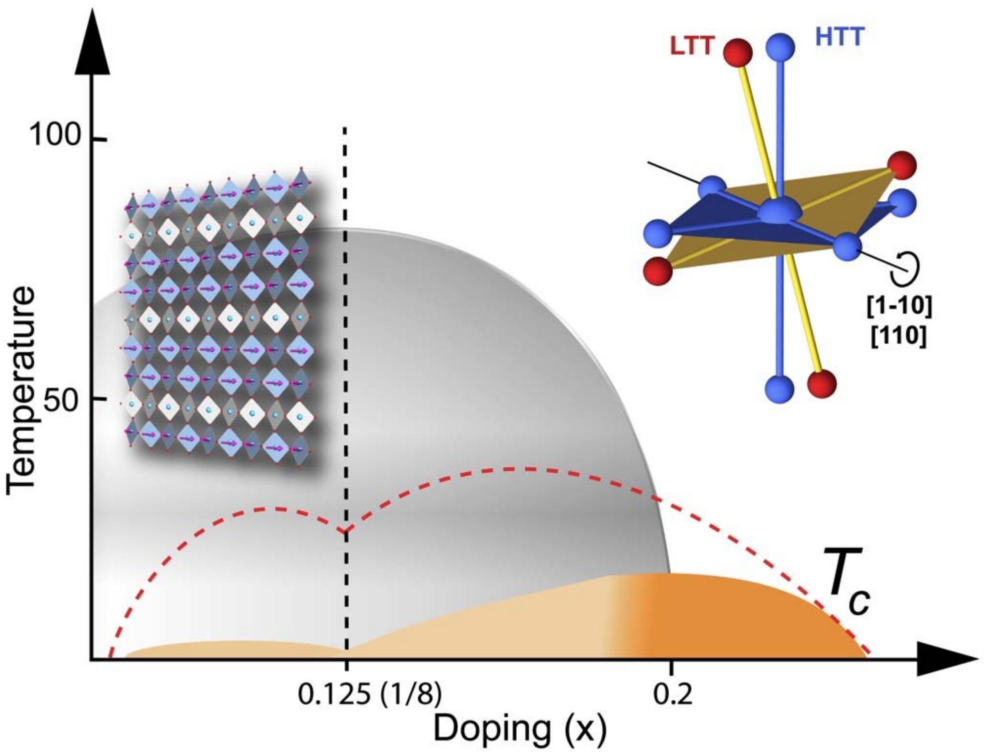


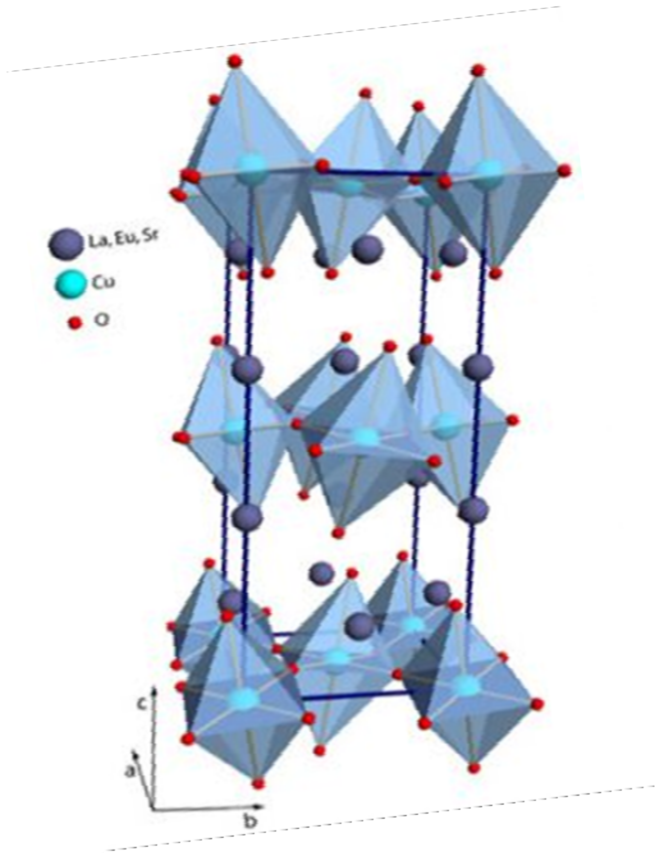
S. Kaiser et al., Sci. Rep. 4, 3823 (2014)
R. Singla et al., Phys. Rev. Lett. 115, 187401 (2015)

For a review see:
M. Först et al., Acc. Chem. Res. 48, 380 (2015)
R. Mankowsky et al., Rep. Prog. Phys. 79, 6 (2016)
D. Nicoletti & A. Cavalleri, Adv. Opt. Phot. 8, 401 (2016)

Can we apply this approach to control superconductivity in high-T_c cuprates ?

Example #1: The striped cuprate $La_{1.675}Eu_{0.2}Sr_{0.125}CuO_4$



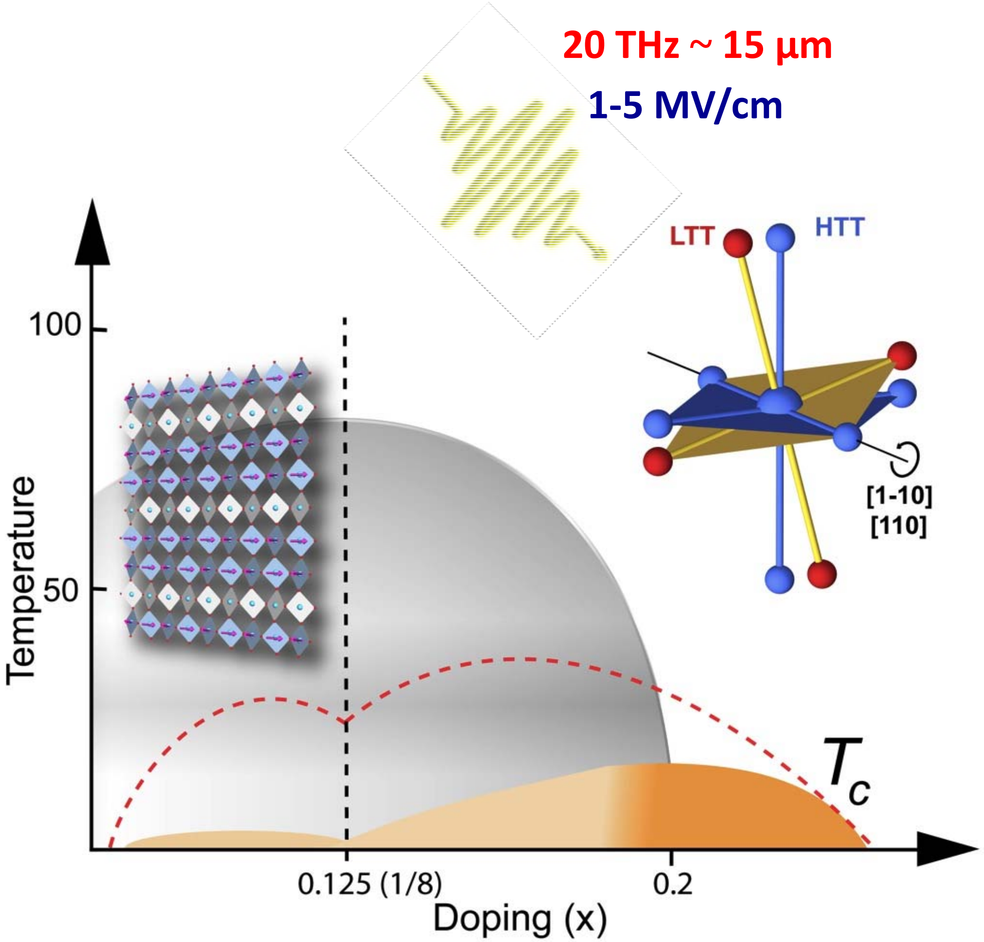


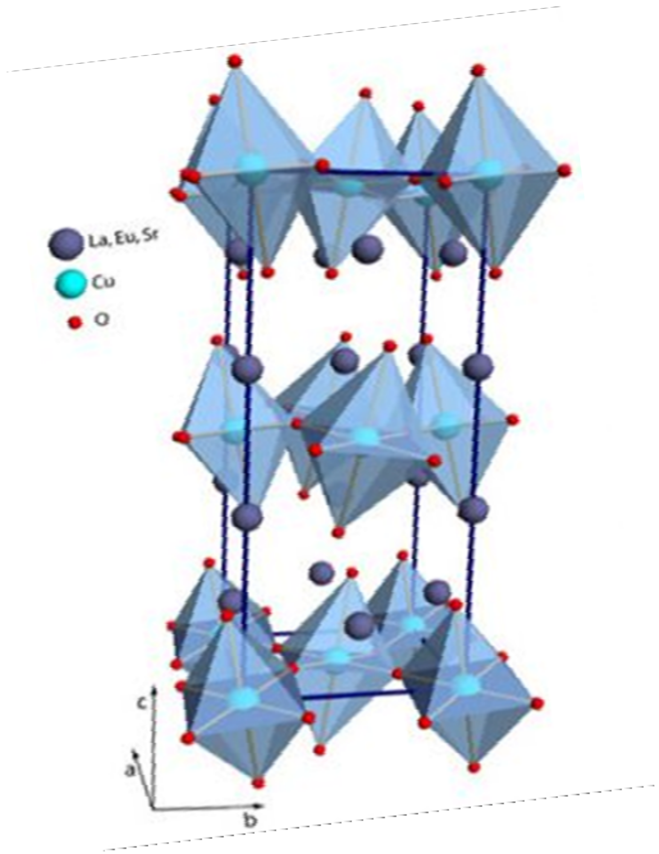
D. Fausti et al., Science 331, 6014 (2011)

Pumping the in-plane Cu-O stretching mode

20 THz ~ 15 µm

1-5 MV/cm





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

Probing the interlayer Josephson coupling

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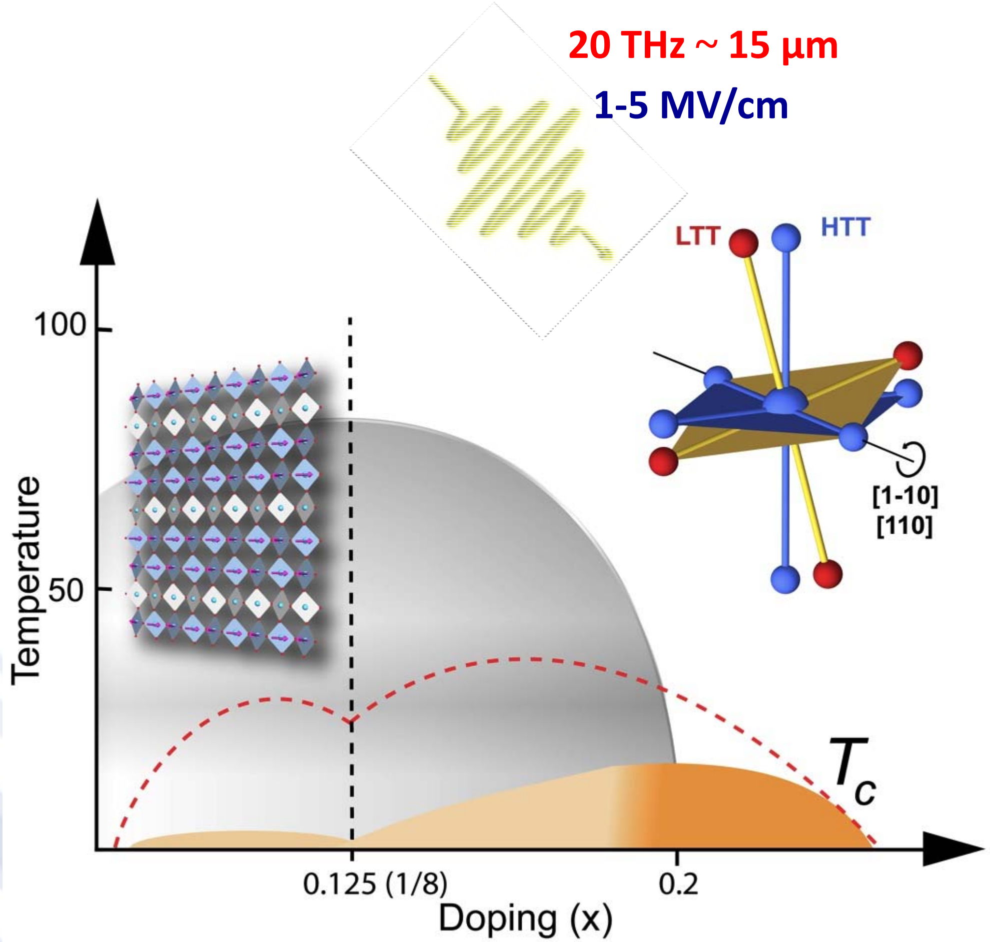
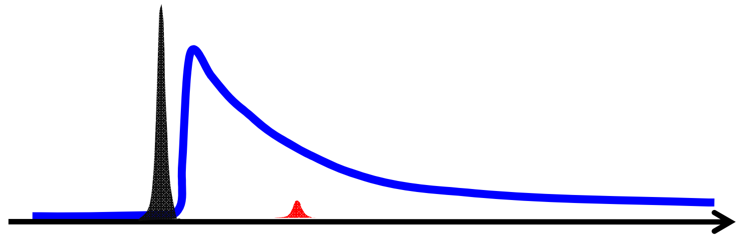
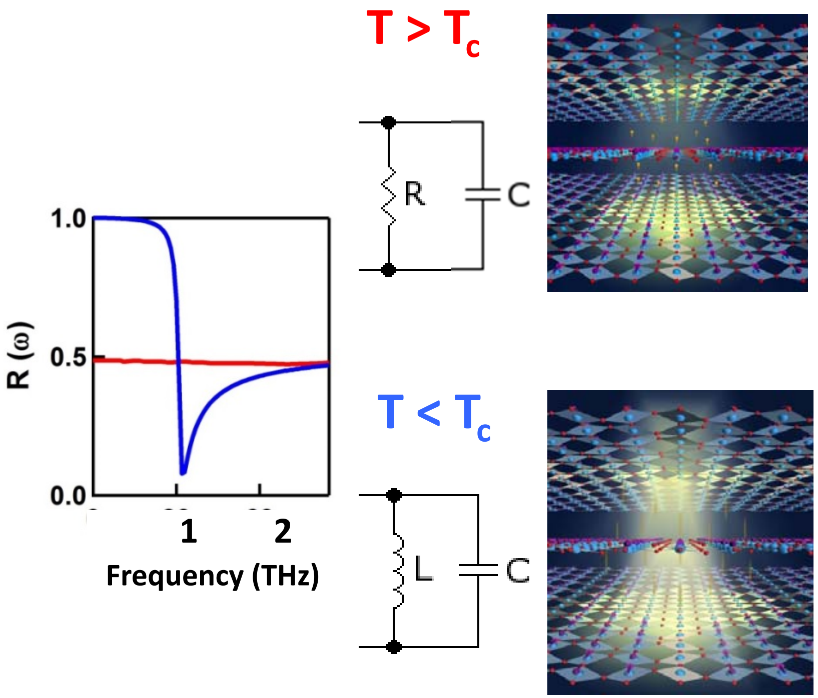


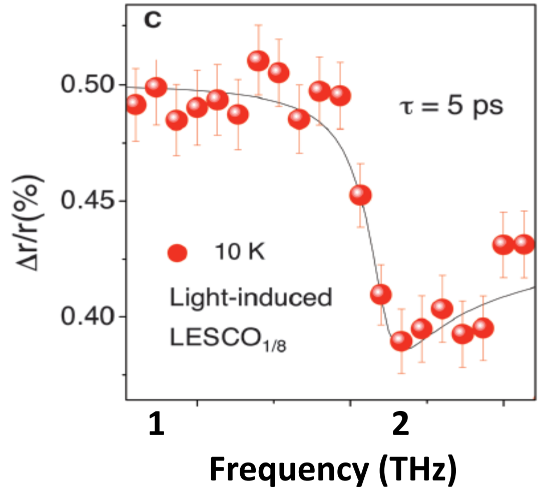


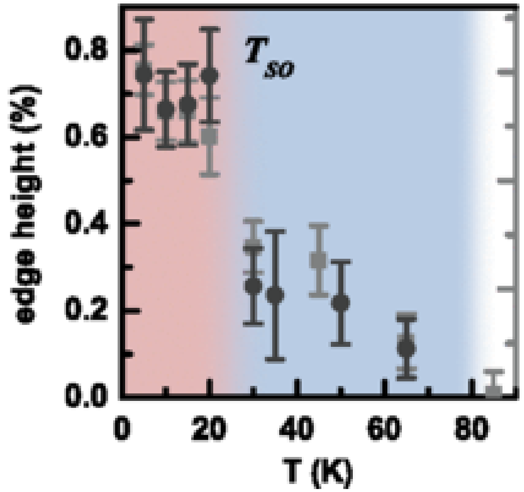


D. Fausti et al., Science 331, 6014 (2011)

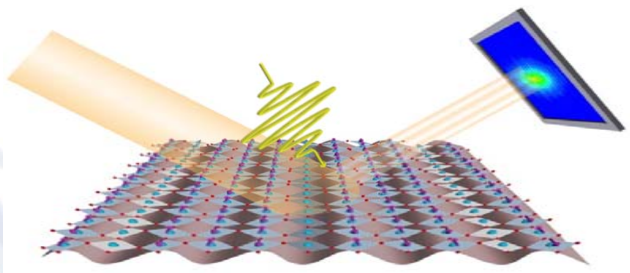
Light-induced superconductivity via stripe melting

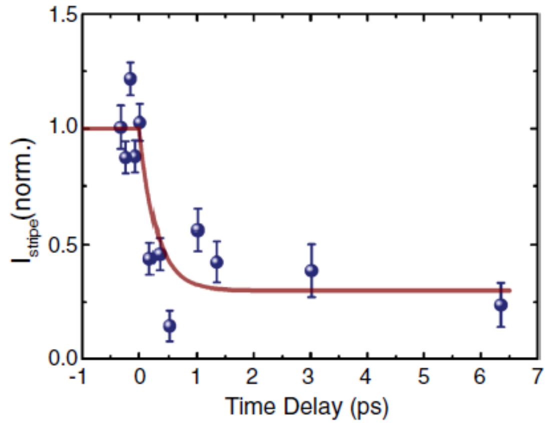
Transient Josephson Plasma Resonance measured up to T_{CO} = 70 K





Soft X-ray probe reveals stripe melting on the same time scale





D. Fausti et al., Science 331, 6014 (2011)
C. R. Hunt et al., Phys. Rev. B 91, 020505(R) (2015)
M. Först et al., Phys. Rev. Lett. 112, 157002 (2014)

Light-induced superconductivity via stripe melting

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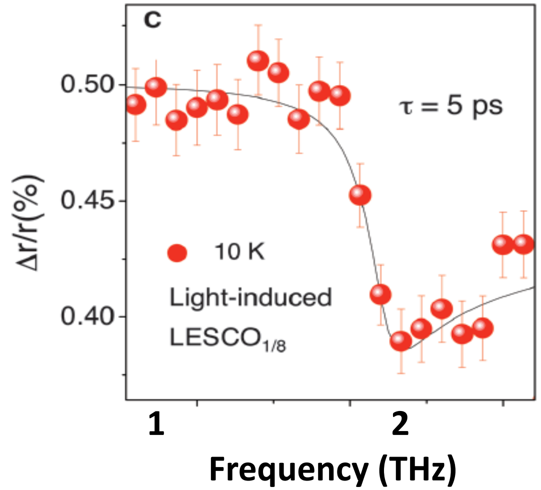

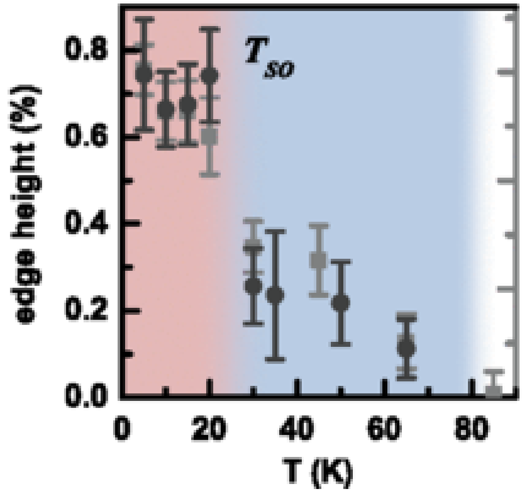

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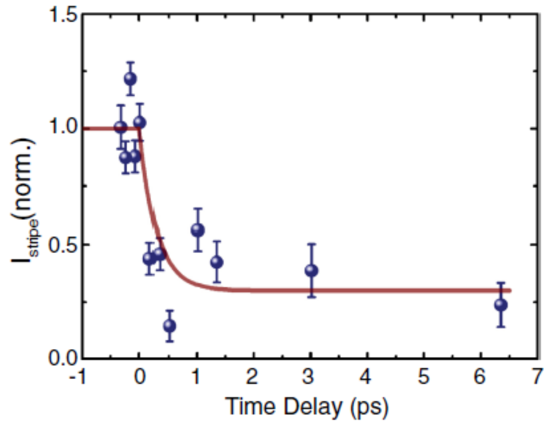


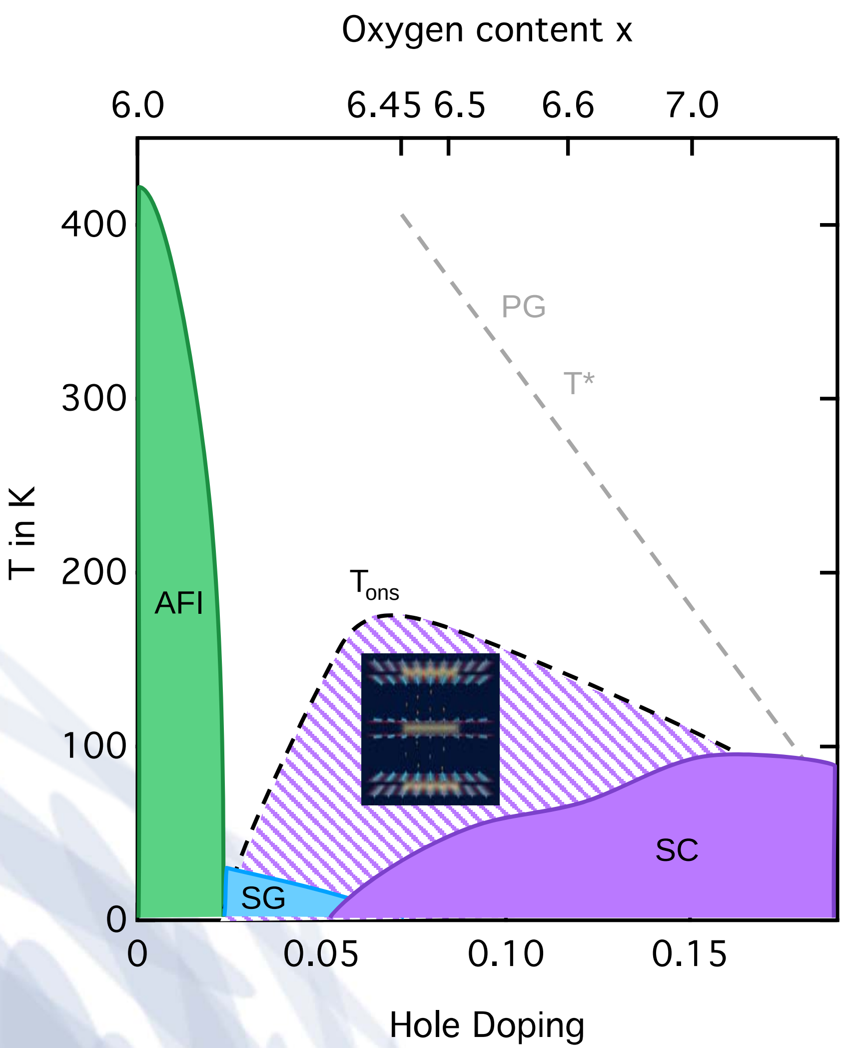
See also:

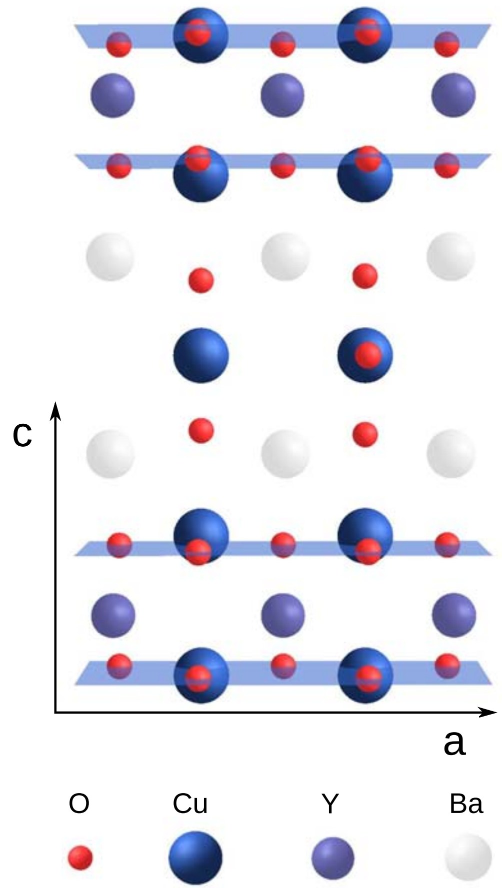
D. Nicoletti et al., Phys. Rev. B 90, 184514 (2014)

E. Casandruc et al., Phys Rev. B 91, 174502 (2015)

V. Khanna et al., Phys. Rev. B 93, 224522 (2016)

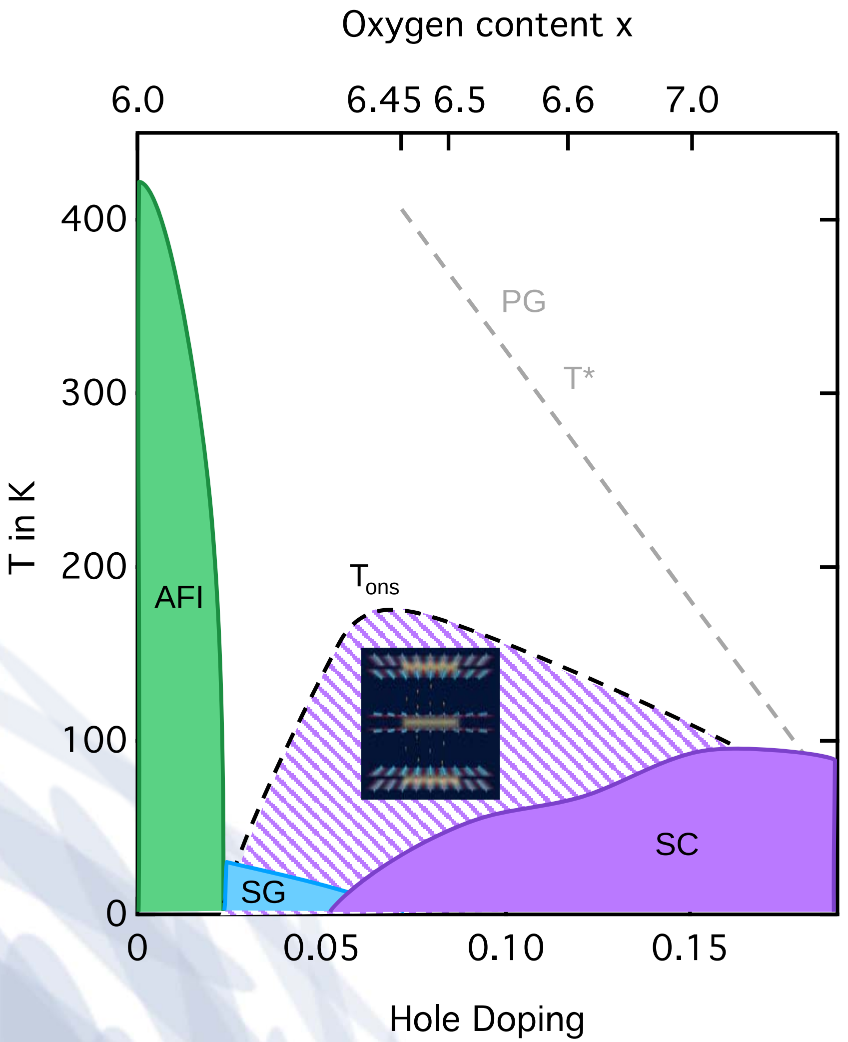
Example #2: The bi-layer cuprate $YBa_2Cu_3O_{6+x}$

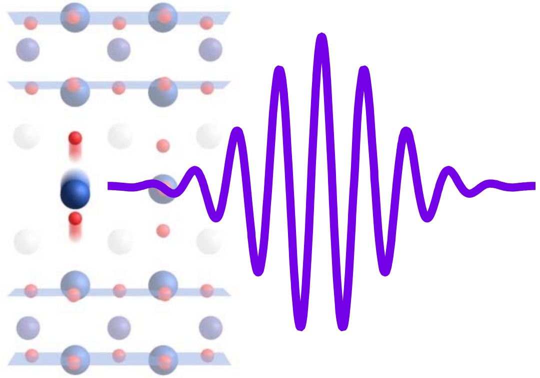




E. Uykur et al., Phys. Rev. Lett. 112, 127003 (2014)
A. Dubroka *et al.*, Phys. Rev. Lett. 107, 047006 (2011)

Pumping the apical oxygen mode



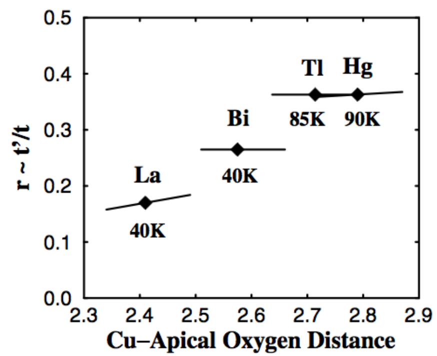


20 THz ~ 15 μm

1-5 MV/cm

1-10% unit cell

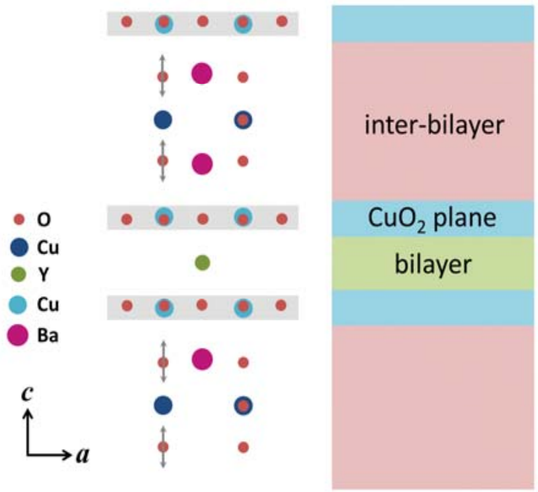
Apical oxygen position correlates with T_c at equilibrium



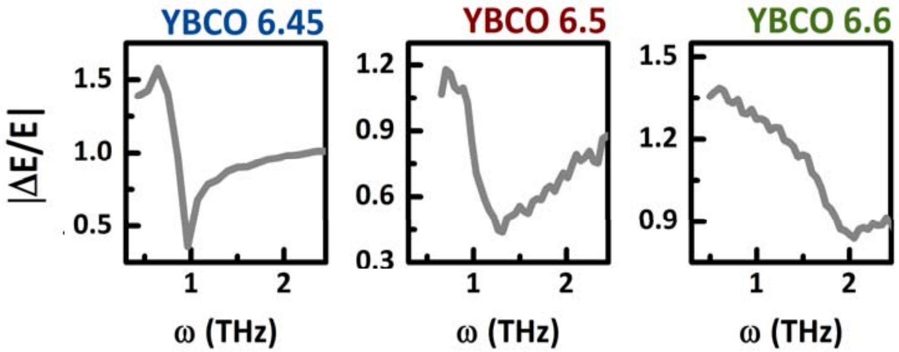
E. Uykur et al., Phys. Rev. Lett. 112, 127003 (2014)
A. Dubroka et al., Phys. Rev. Lett. 107, 047006 (2011)

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

Probing the inter-bilayer transport

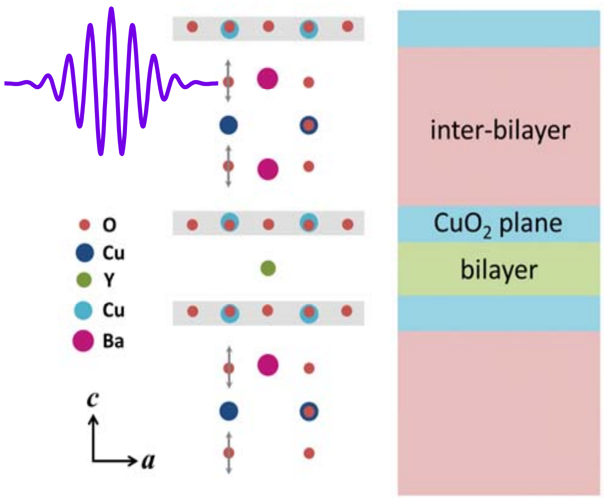


Equilibrium



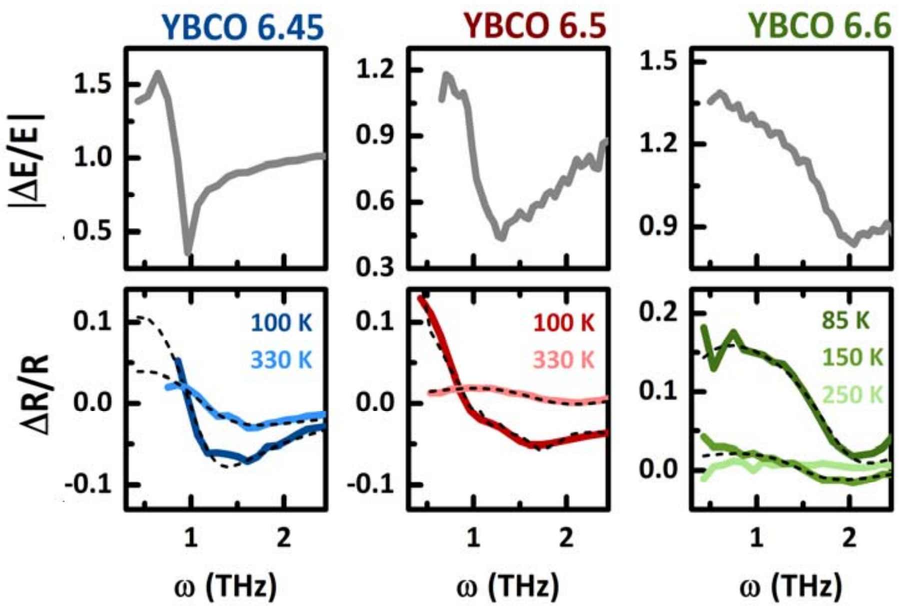
W. Hu. et al. Nature Materials 13, 705 (2014)
S. Kaiser et al., Phys. Rev. B 89, 184516 (2014)
C. R. Hunt et al., Phys. Rev. B *in press* (2016)

A superconducting-like response up to room T



Equilibrium

Pump Induced



W. Hu. et al. Nature Materials 13, 705 (2014)
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A superconducting-like response up to room T

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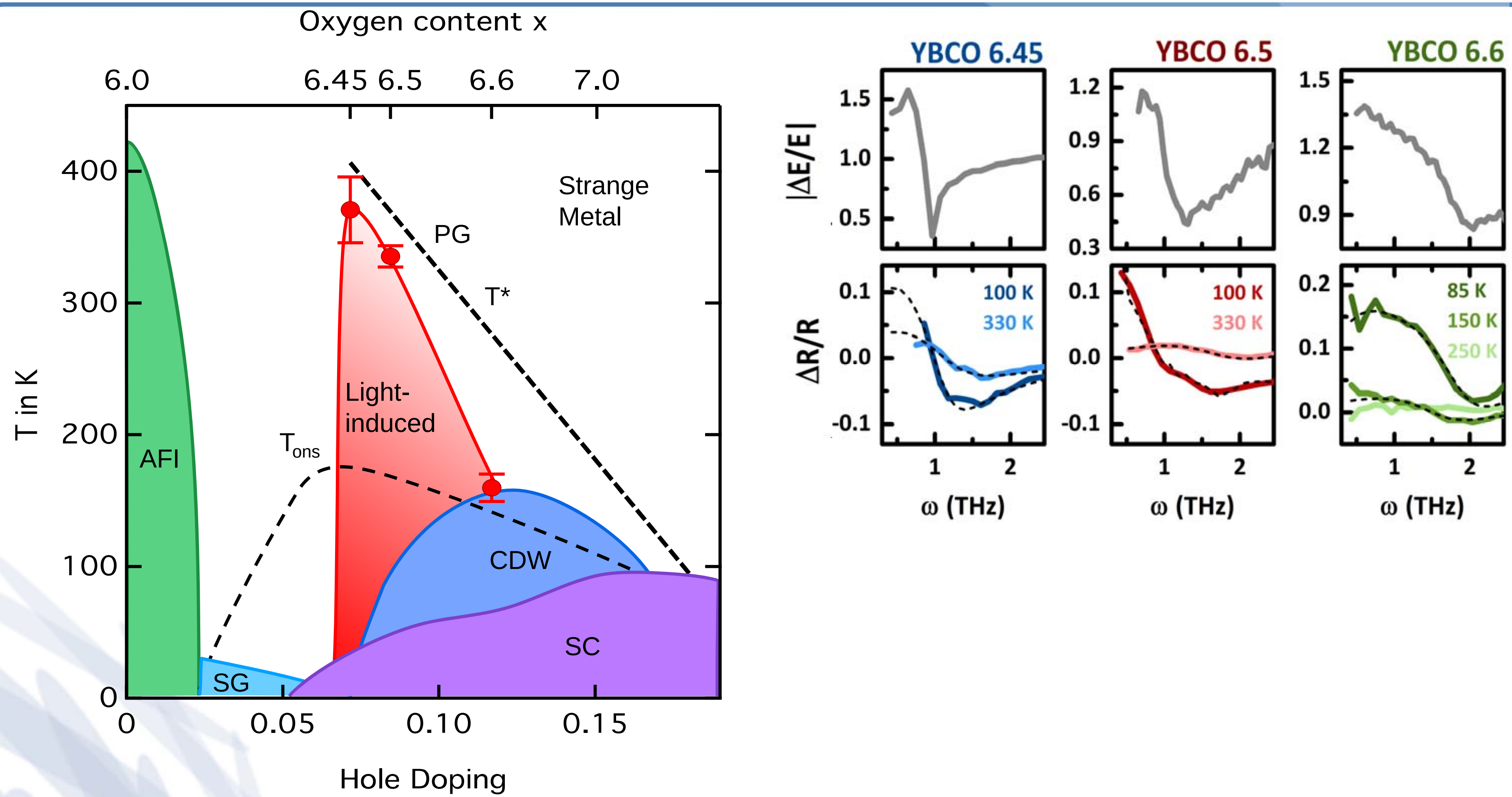


W. Hu. et al. Nature Materials 13, 705 (2014)
S. Kaiser et al., Phys. Rev. B 89, 184516 (2014)
C. R. Hunt et al., Phys. Rev. B *in press* (2016)

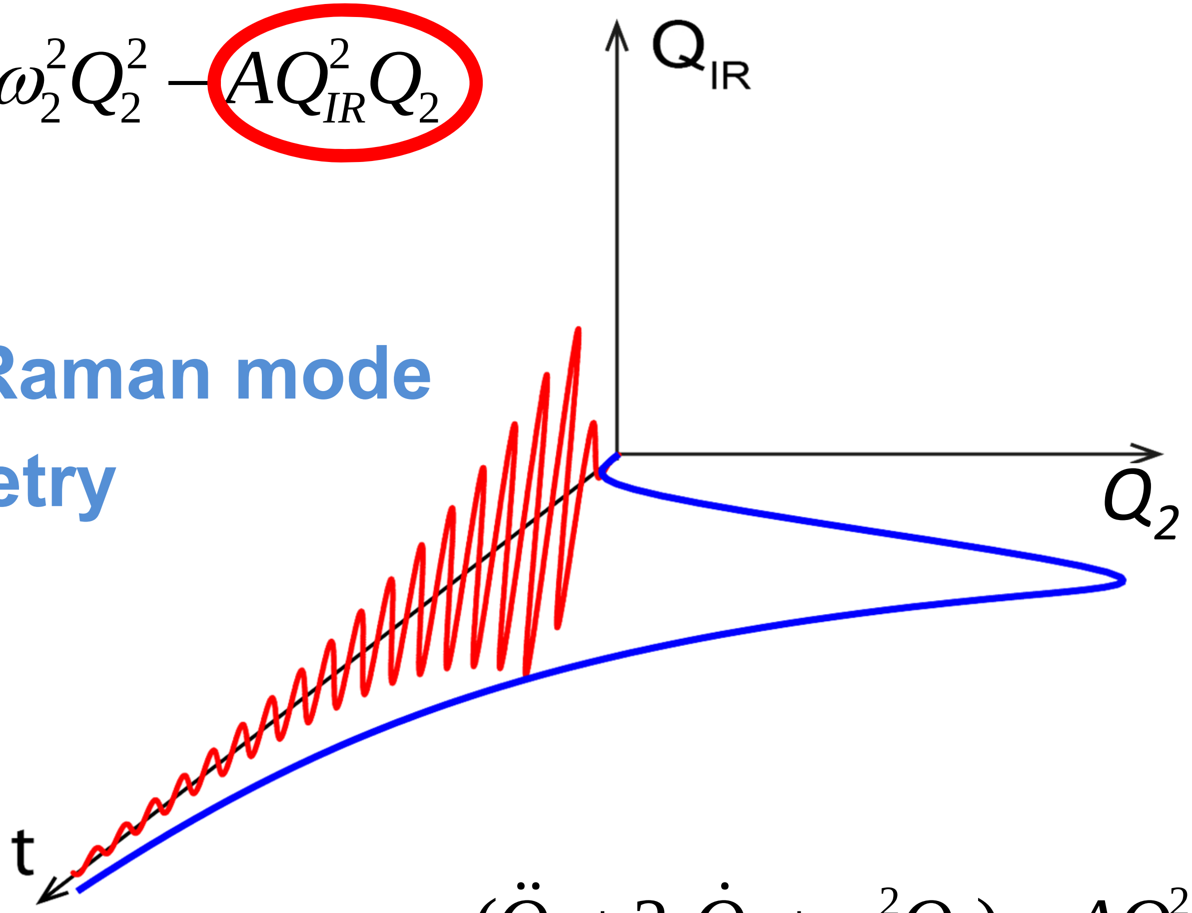
How does this work ?

What is the lattice doing ?

Nonlinear Phononics

$$V = \frac{1}{2}\omega_{IR}^2 Q_{IR}^2 + \frac{1}{2}\omega_2^2 Q_2^2 - AQ_{IR}^2 Q_2$$

$Q_{IR}^2 Q_2 \neq 0$
only if Q_2 is a Raman mode with A_g symmetry



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

11 A_g Raman modes

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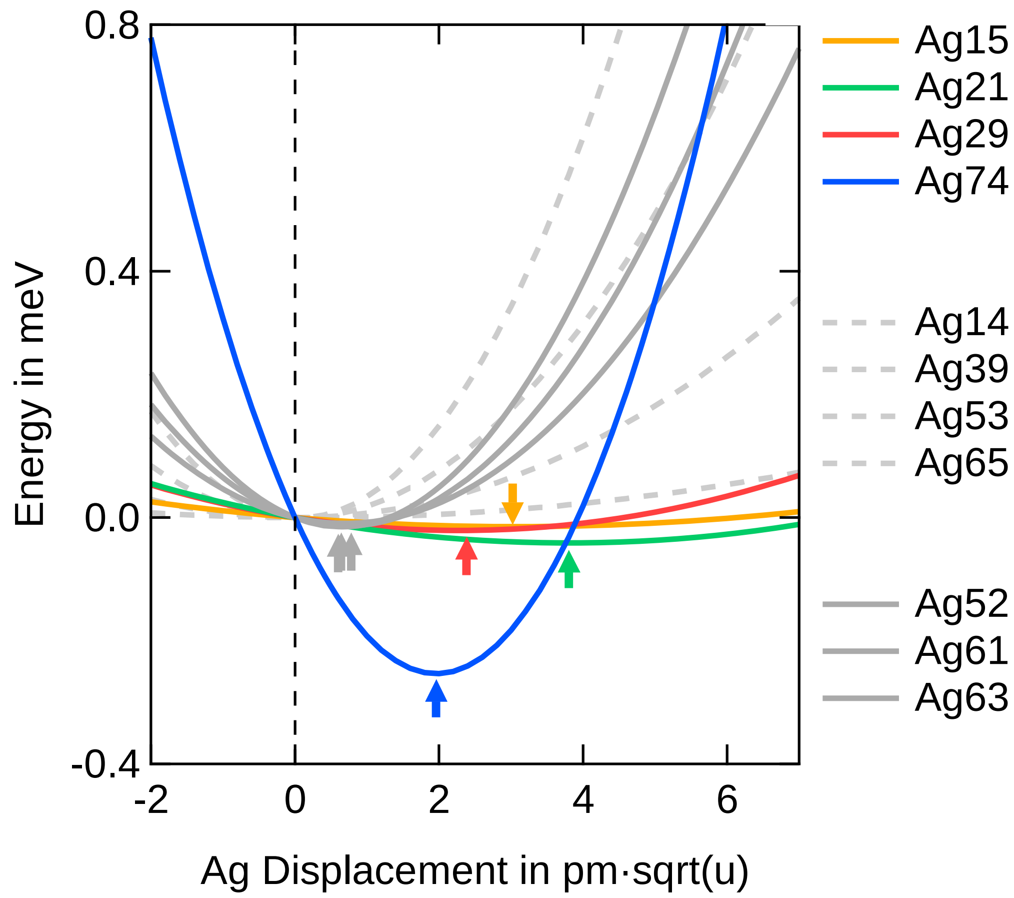
Only four A_g modes are coupled strongly with B_{1u}



Alaska Subedi – Antoine Georges (Ecole Polytechnique, Paris)

Femtosecond X-ray crystallography

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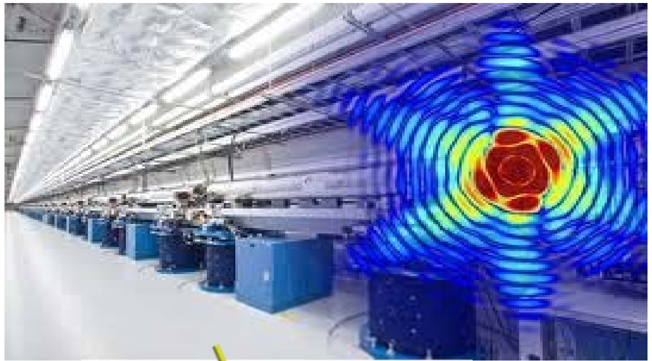
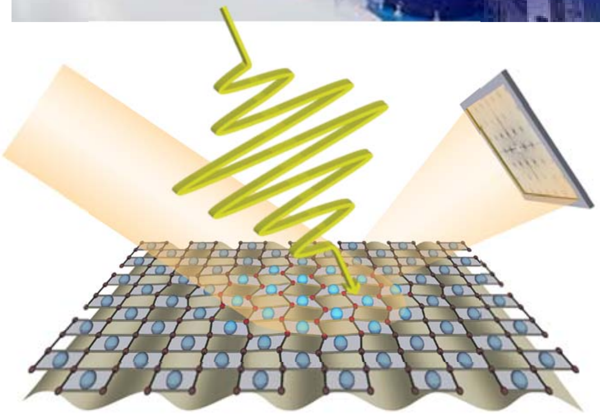
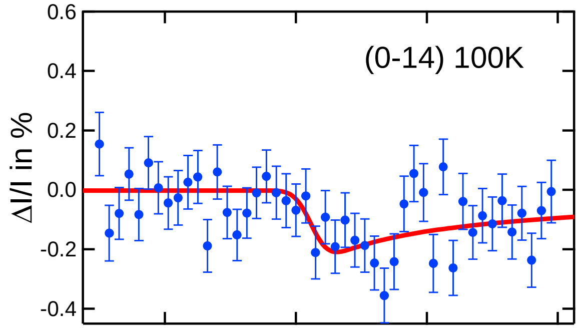
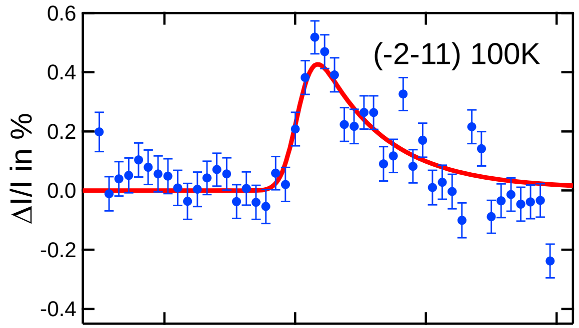
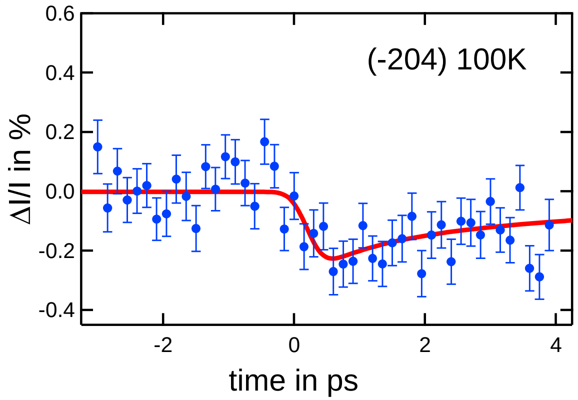


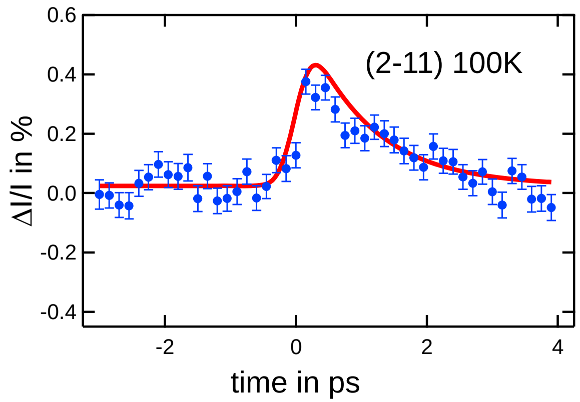
XPP @ LCLS







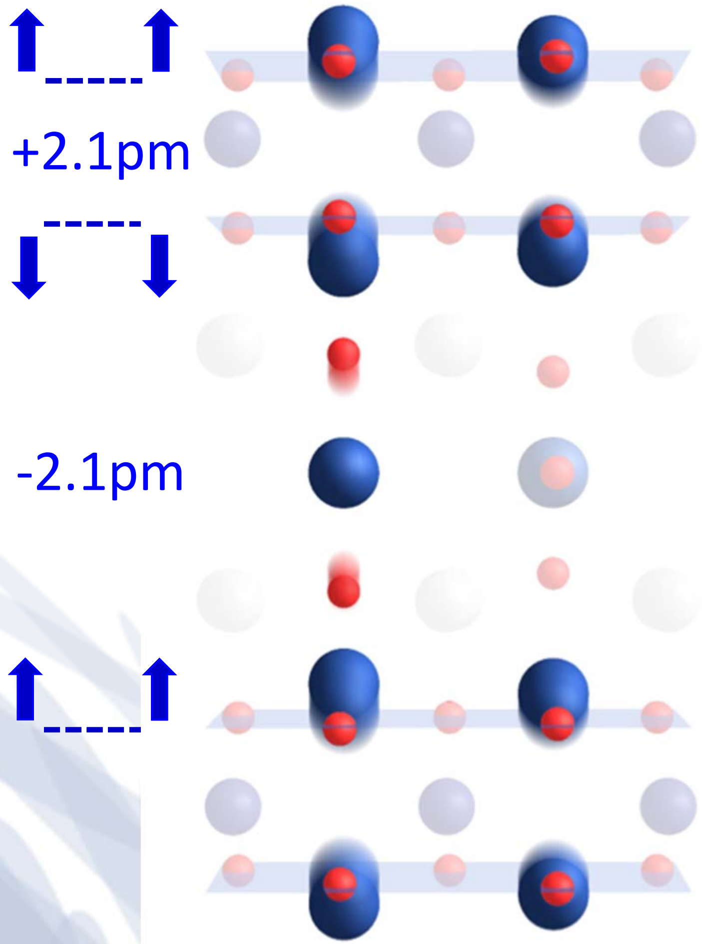




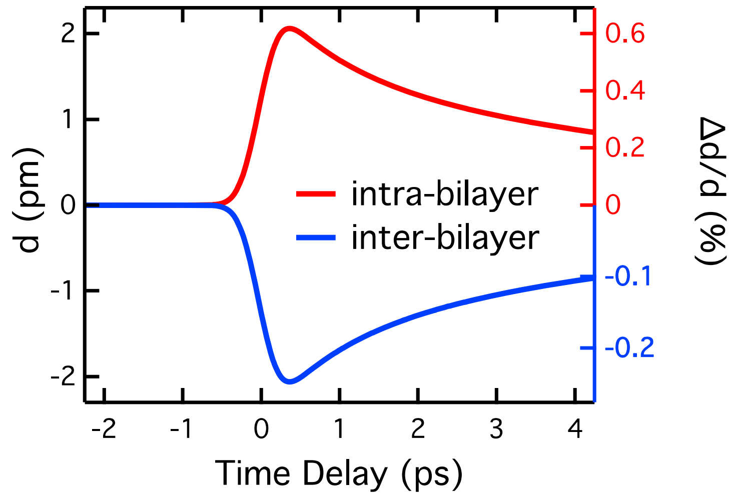
R. Mankowsky et al. Nature 516, 71 (2014)

A new, transient crystal structure

Lattice Rearrangement



Staggered motion of the layers



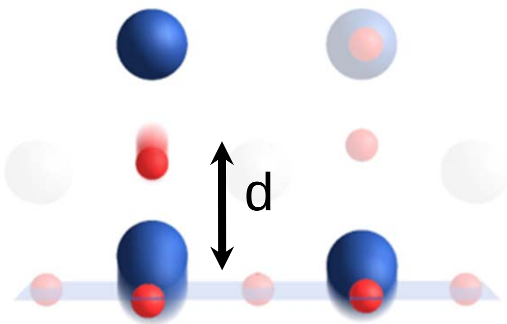
Is this the structure of a room temperature superconductor ?

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

Similar to external pressure?

Light-Induced

d reduces by > 3%

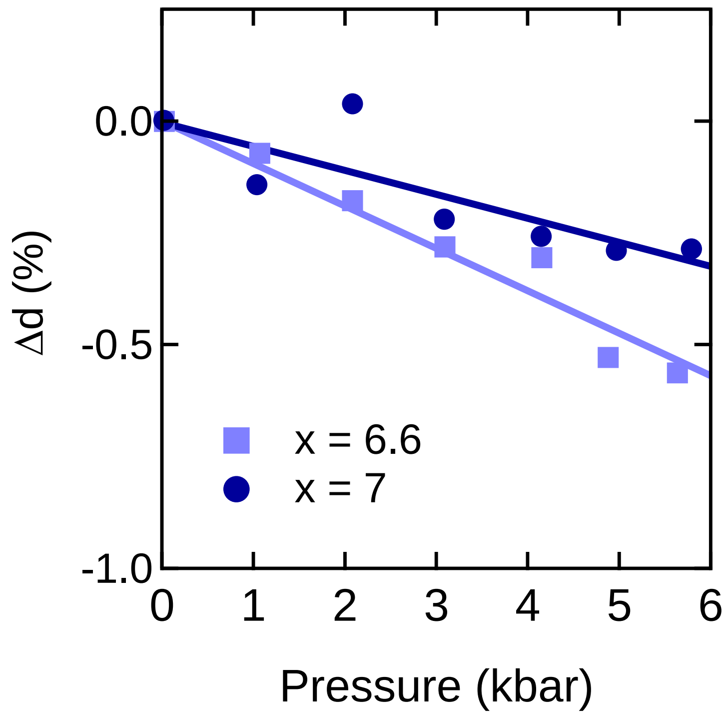


R. Mankowsky et al. Nature 516, 71 (2014)

J. Jorgensen et al. Physica C 171, 93 (1990)

Pressure

d reduces by few %

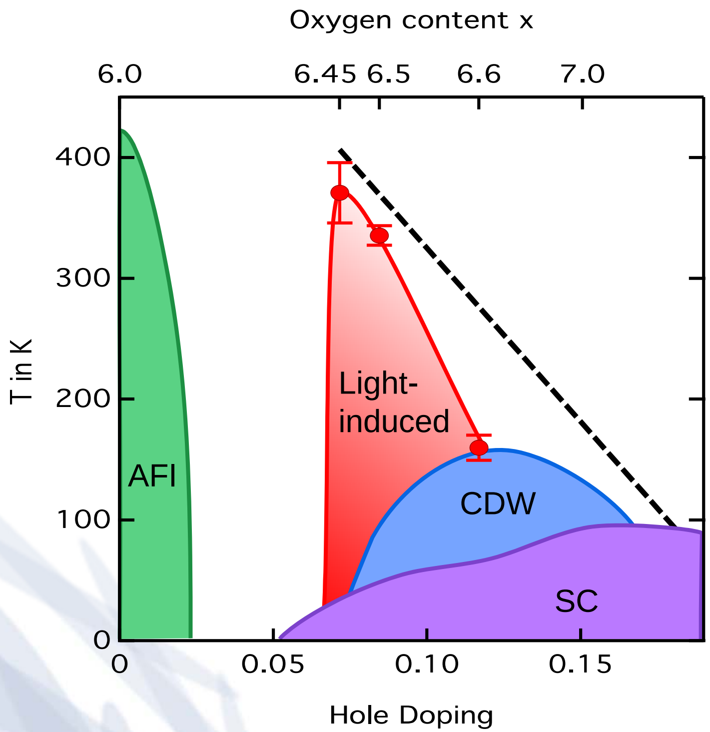


Similar to external pressure?

mpsd

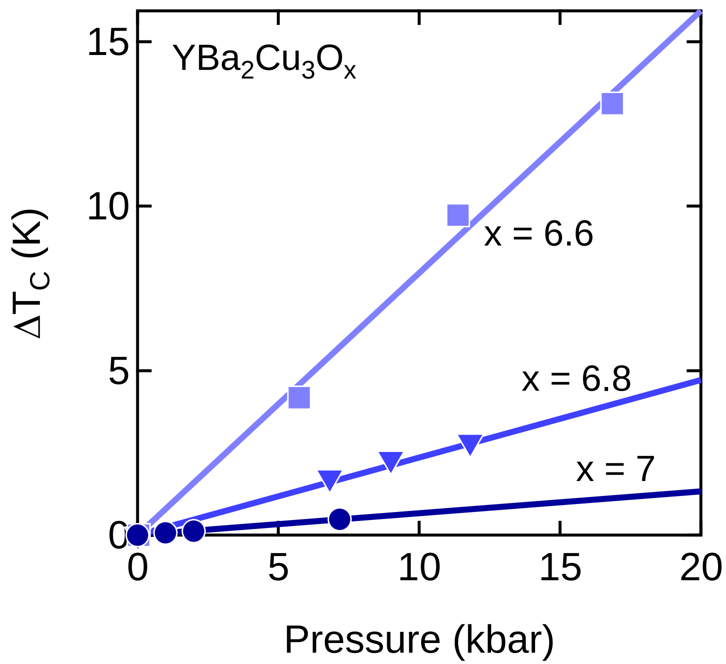
Light-Induced

“T_C increases by > 100 K”



Pressure

T_C increases by ~10 K

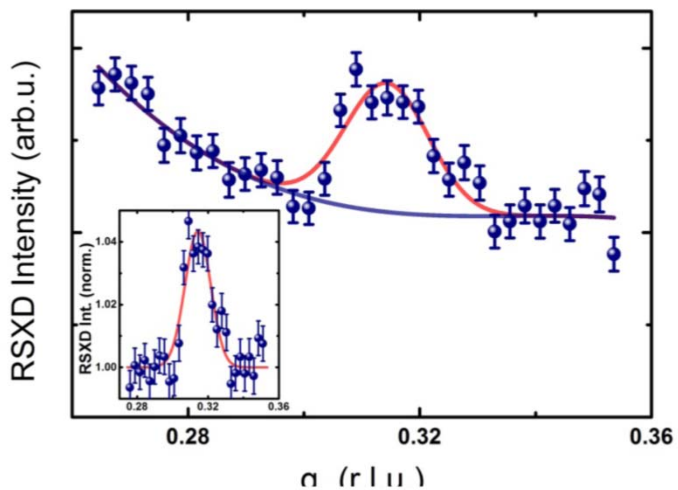


W. Hu. et al. Nature Materials **13**, 705 (2014)
L. E. Schirber et al. Phys. Rev. B **35**, 8709 (1987)

J. G. Huber et al. Phys. Rev. B **41**, 8757 (1990)
B. Bucher et al. Journal of Less-Common Metals **164, 165**, 20 (1990)

Open Questions

Role of Charge Order (partial melting)



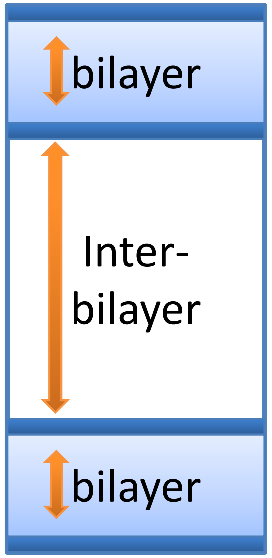
M. Först et al., Phys. Rev. B **90** 184514 (2014)

Theory

Z. M. Raines et al., Phys. Rev. B 91 184506 (2015)

A. Patel & A. Eberlein, Phys. Rev. B 93, 195139 (2016)

Role of the directly-driven IR-active mode



Parametric driving

Decrease phase fluctuations

Enhancement of Josephson coupling

Theory

R. Höppner et al., Phys. Rev. B 91 104507 (2015)

J. Okamoto et al., Phys. Rev. Lett. *in press* (2016)

S. J. Danny et al., Phys. Rev. Lett. 114 137001 (2015)

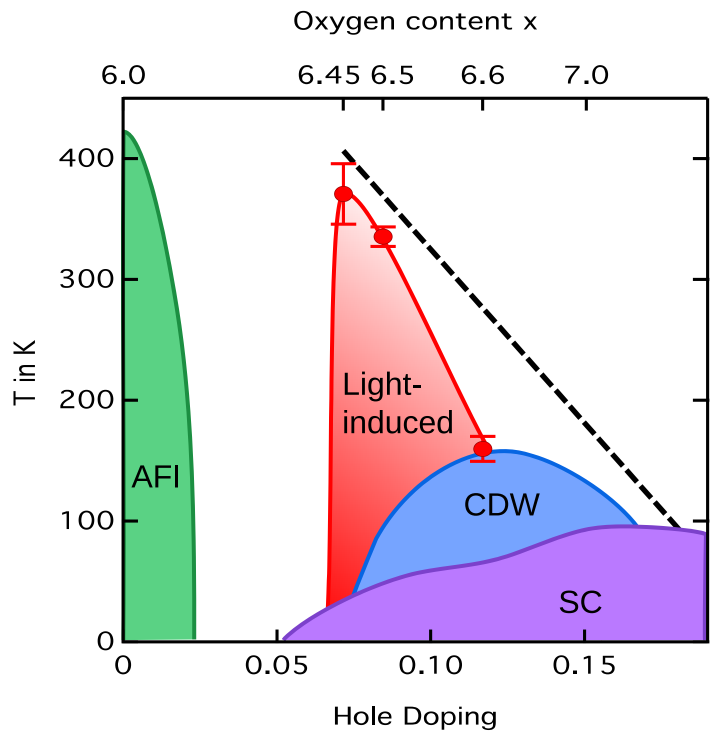
There are limitations…

mpsd

Transient state is inhomogeneous

Equilibrium physics not understood

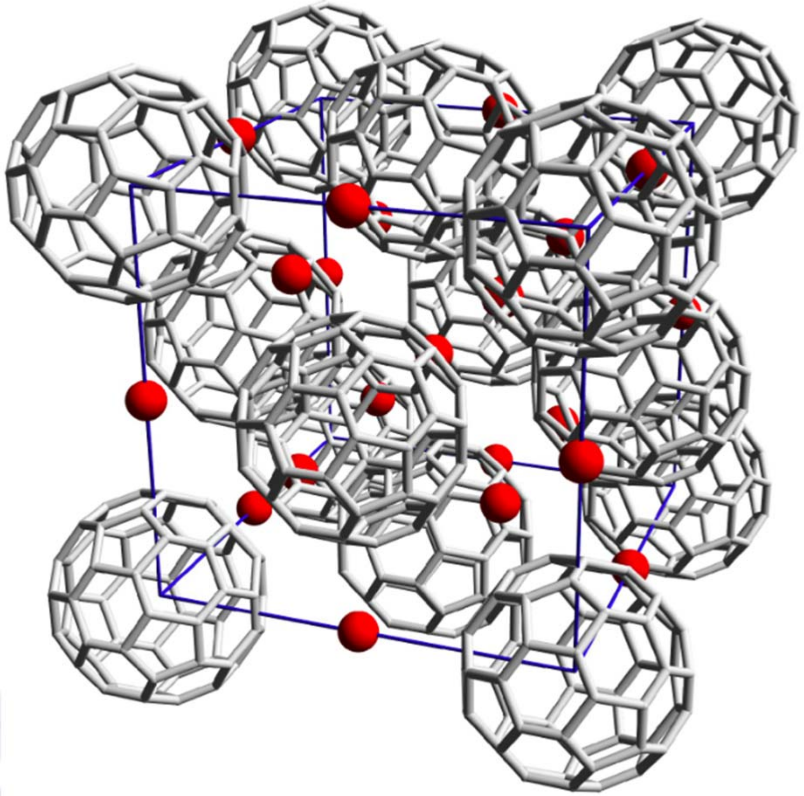
Short lifetime (few picoseconds)

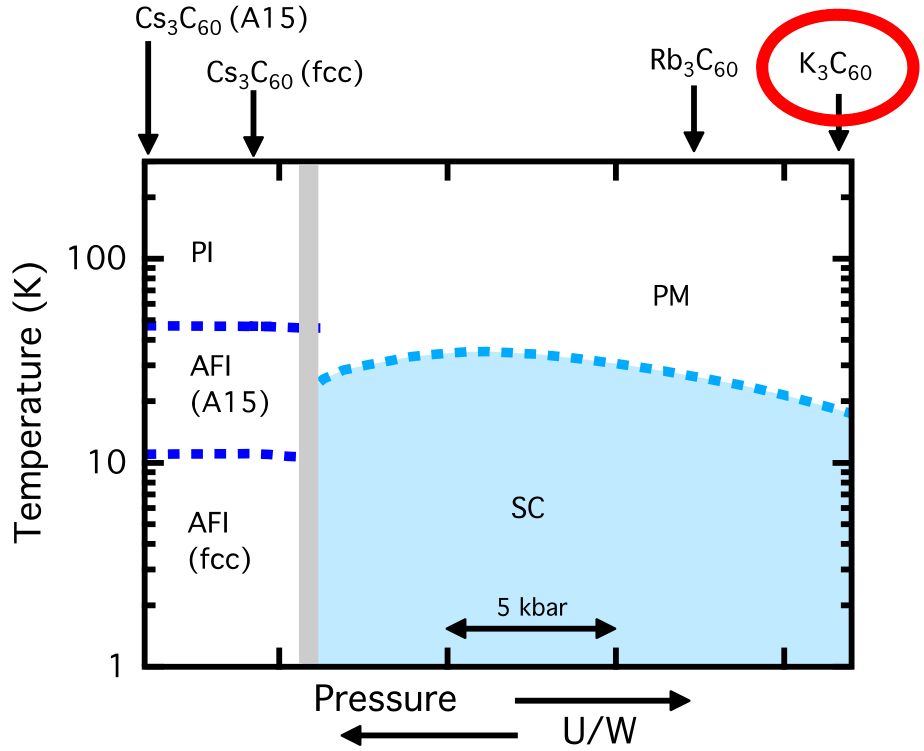


Is light-induced superconductivity specific to cuprates ?

K_3C_{60}: a 20 K superconductor

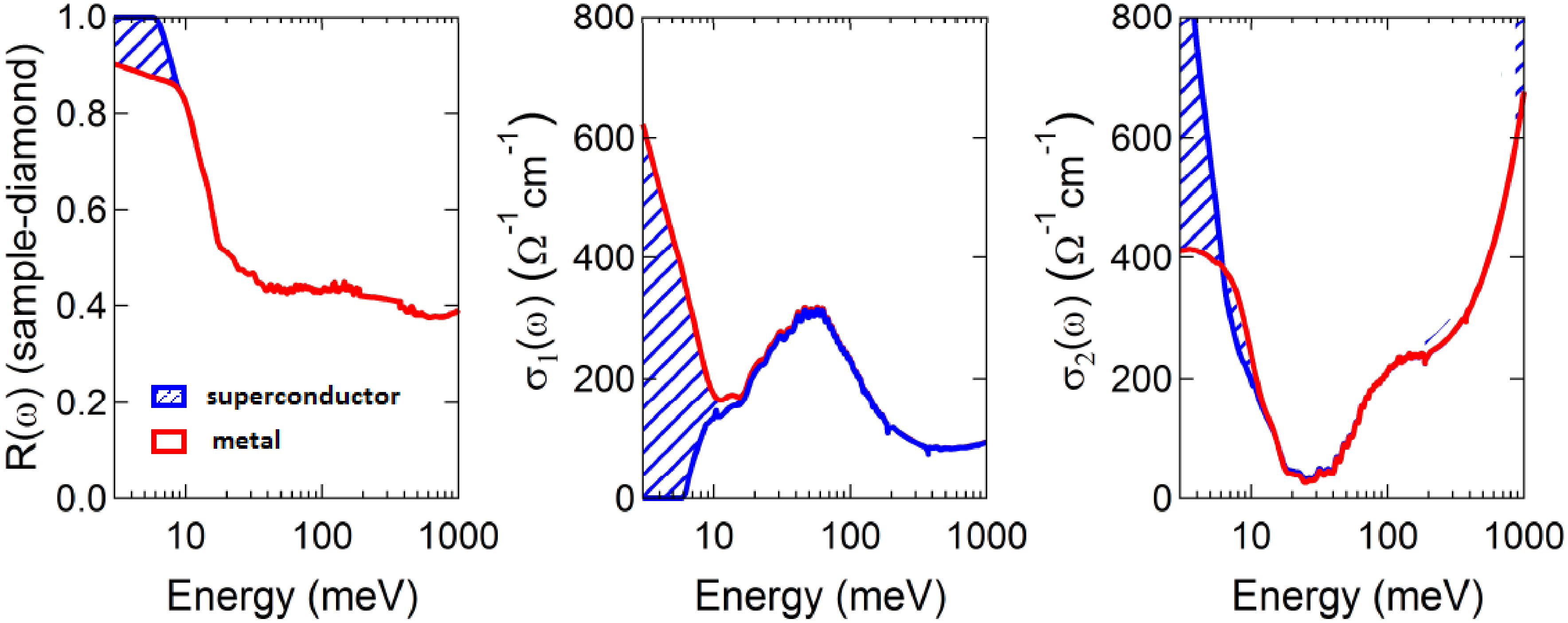
mpsd





- **3D electronic structure**
- **"Conventional" superconductivity (s-wave)**
- **High T_C (20 K)**

Equilibrium Superconducting Transition



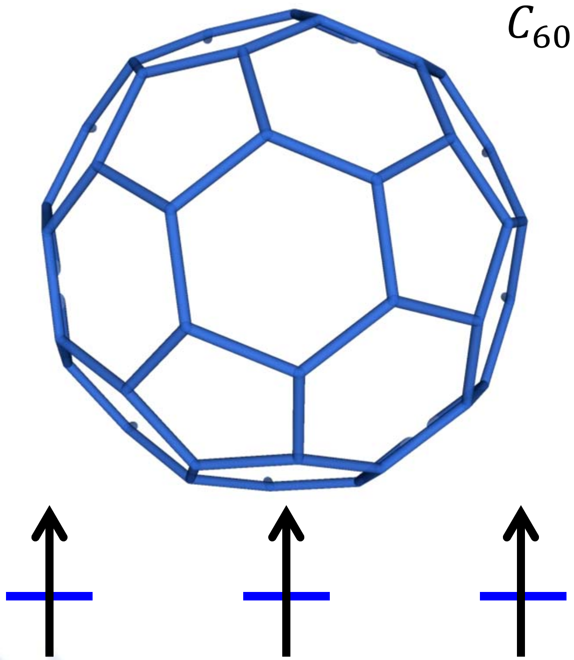
- **Reflectivity saturates to 1**
- **Gap opening in $\sigma_1(\omega)$**
- **Low-frequency divergence in $\sigma_2(\omega)$**

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

Mechanism for Superconducting Pairing

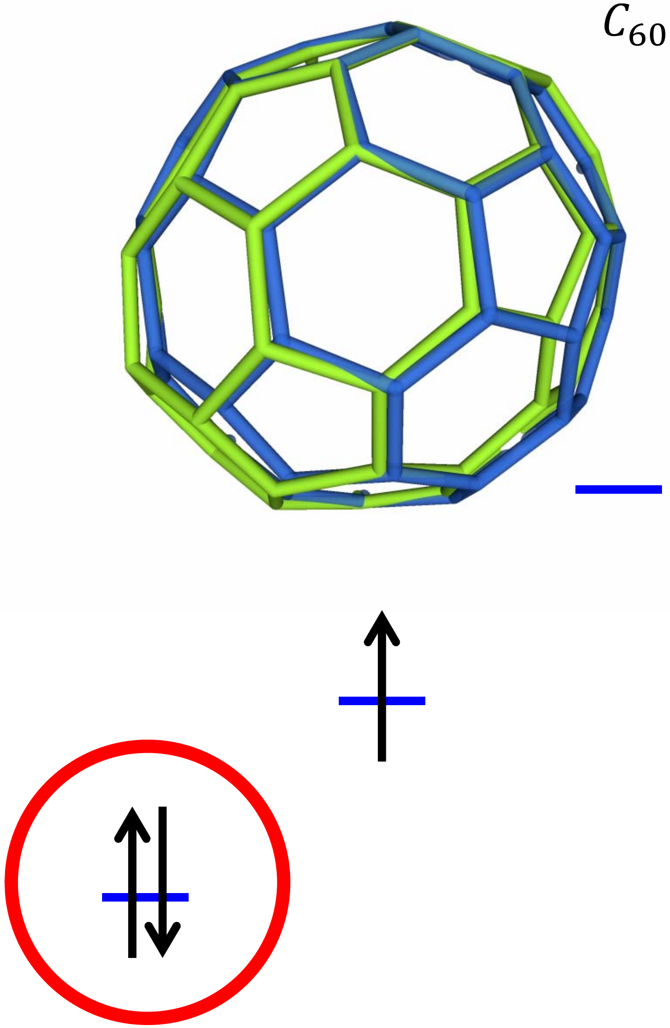
Undistorted

$C_{60}{}^{3-}$



Distorted

$C_{60}{}^{3-}$

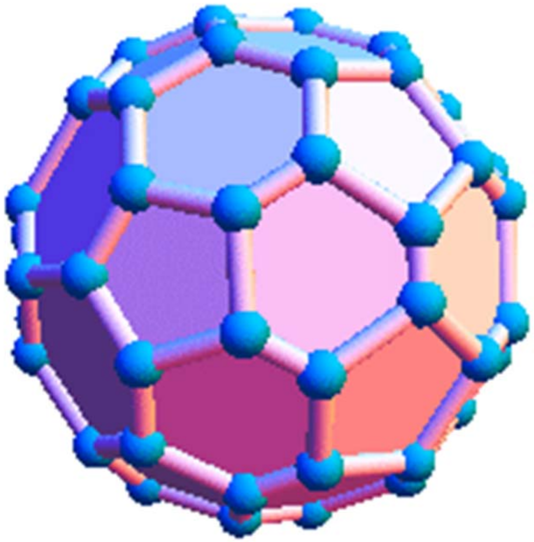


"On ball" distortions favor local pairing

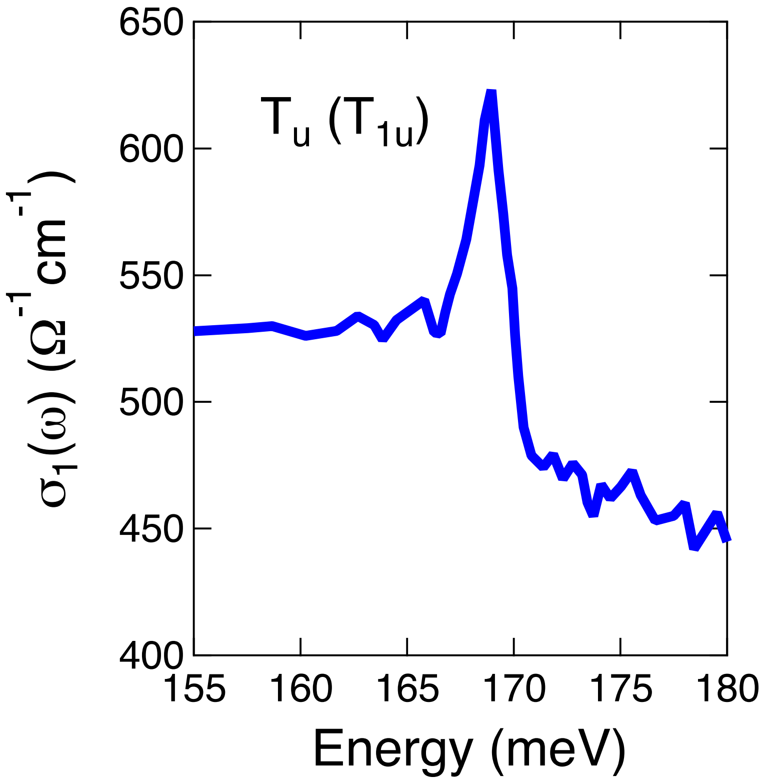
O. Gunnarsson, Rev. Mod. Phys. 69, 575 (1997)

Resonant Vibrational Excitation

$T_{1u}(4)$
170 meV



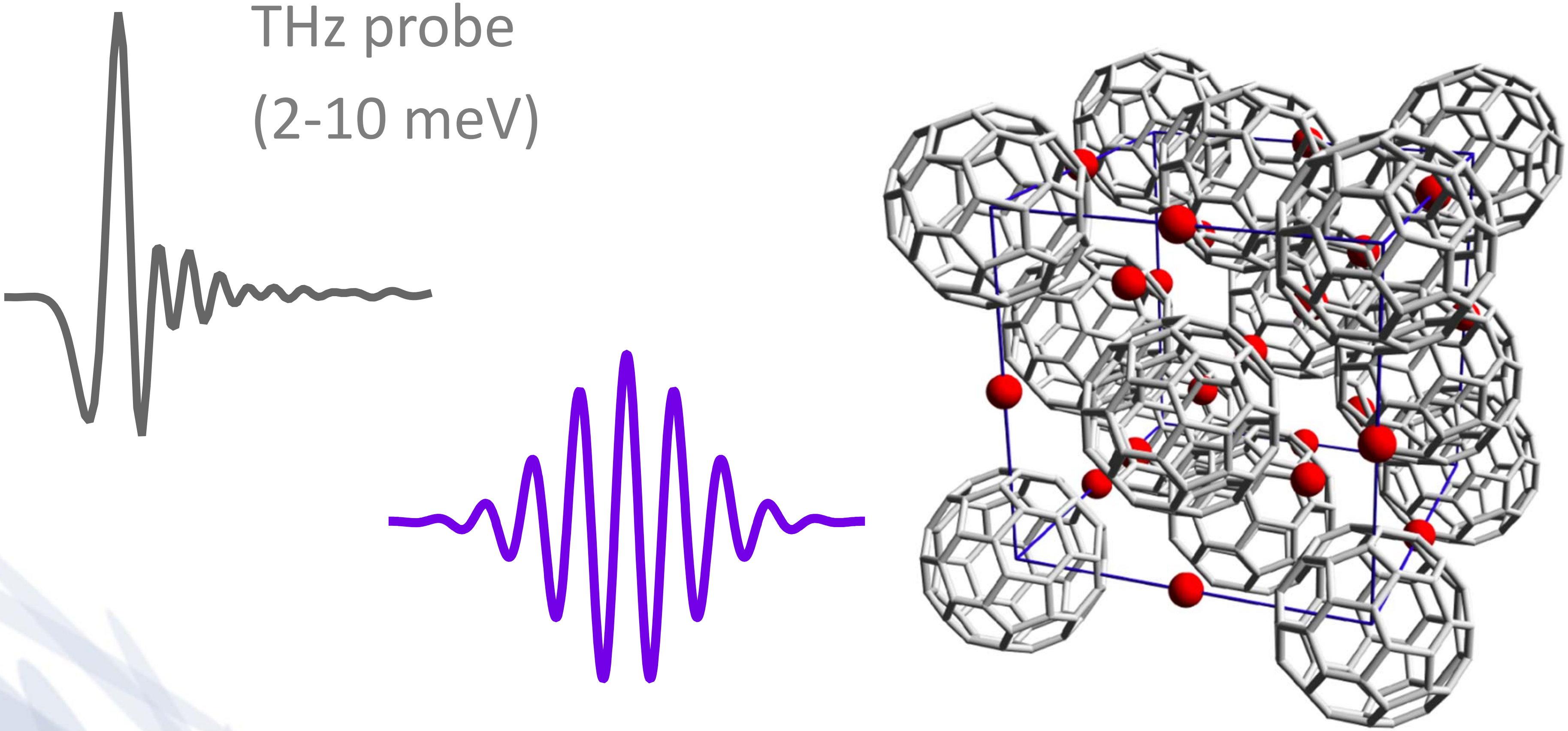
mid-IR pump 170 meV



Iwasa et al. PRB **51,** 3678 (1995)

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

Vibrational pump / THz probe in K_3C_{60}



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

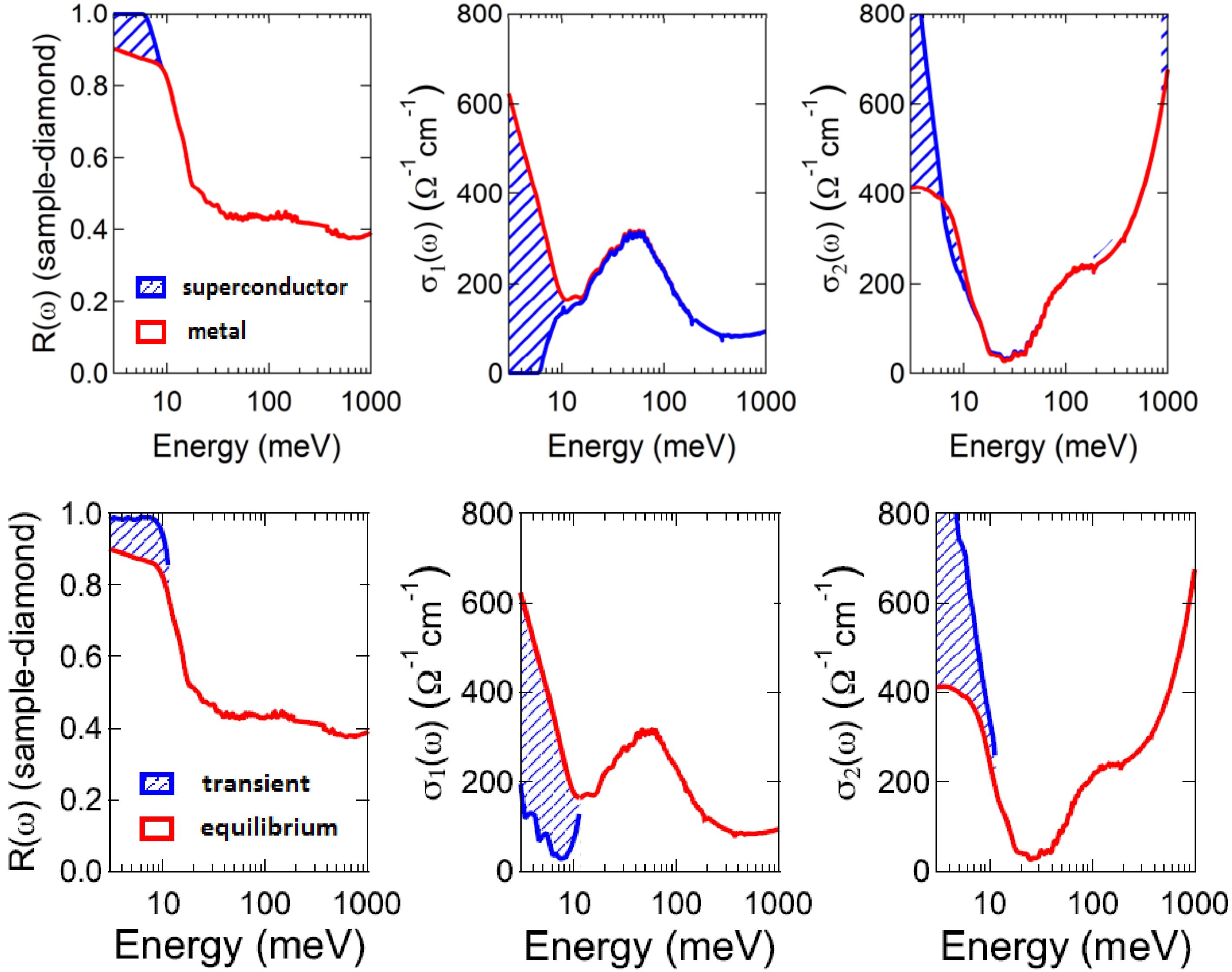
Striking similarity with equilibrium superconductor

Equilibrium

$T < T_c$

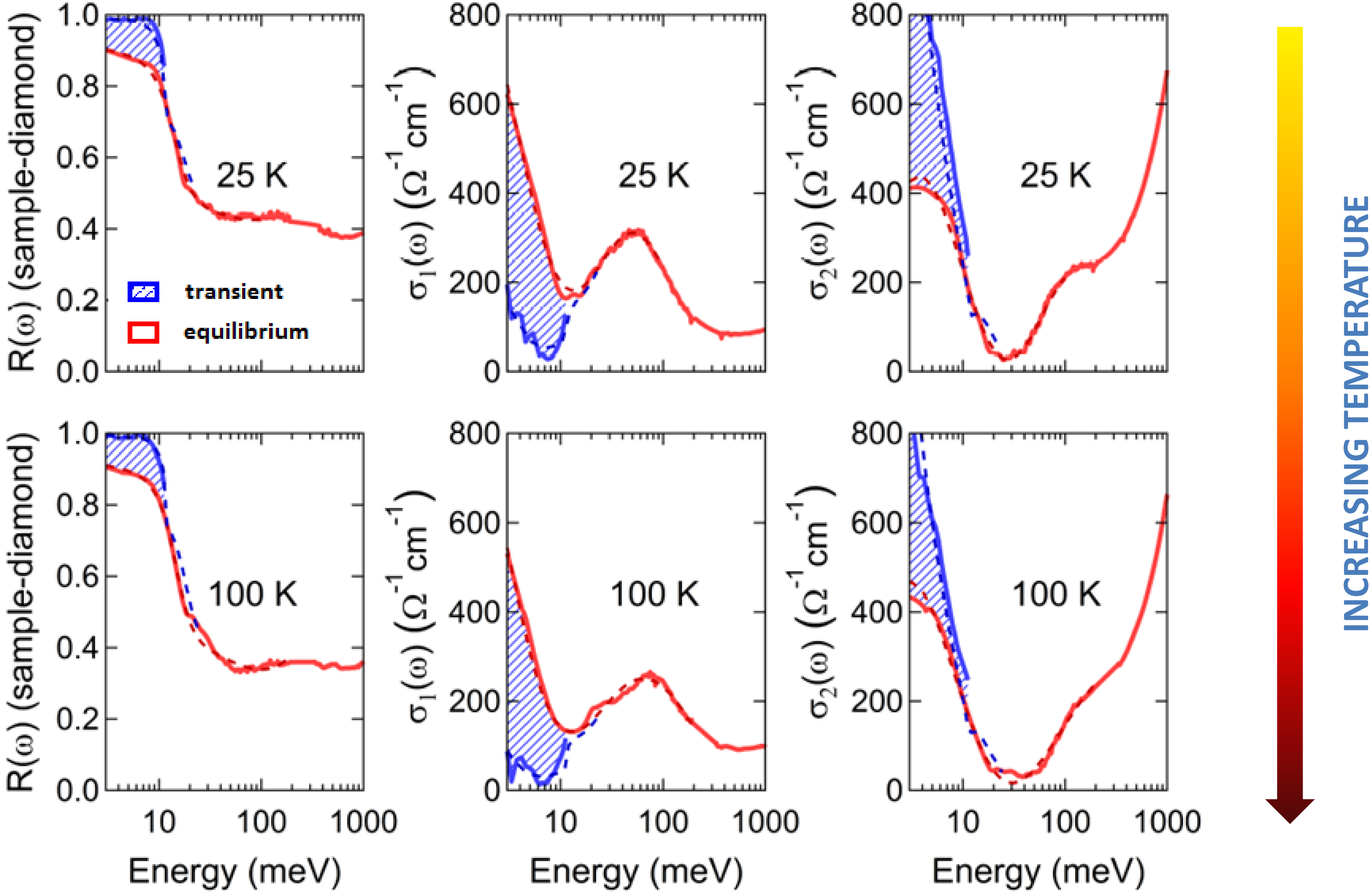
Light-Induced

$T > T_c$



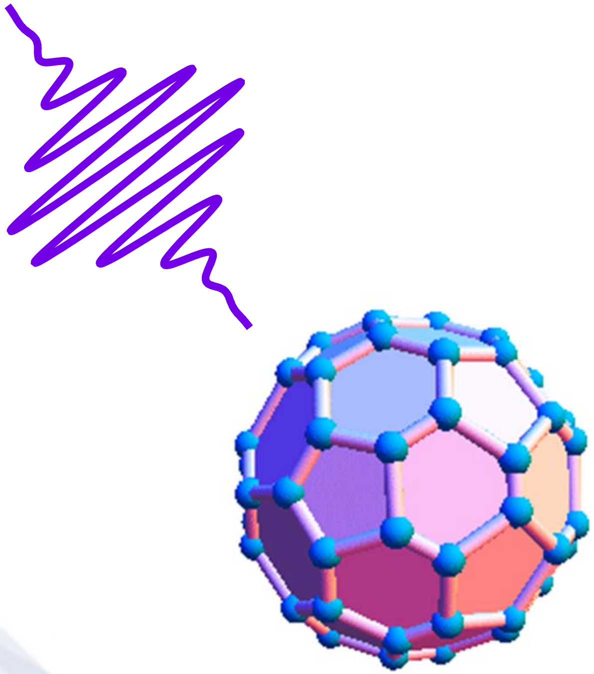
M. Mitrano *et al.*, Nature 530, 461 (2016)

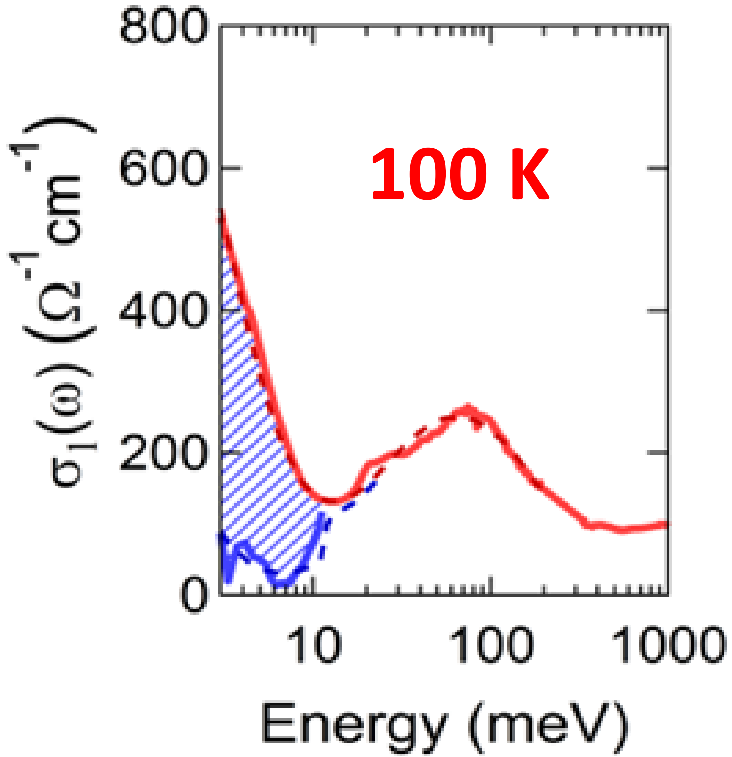
Temperature dependence



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

K_3C_{60} : Stimulated superconductivity ?

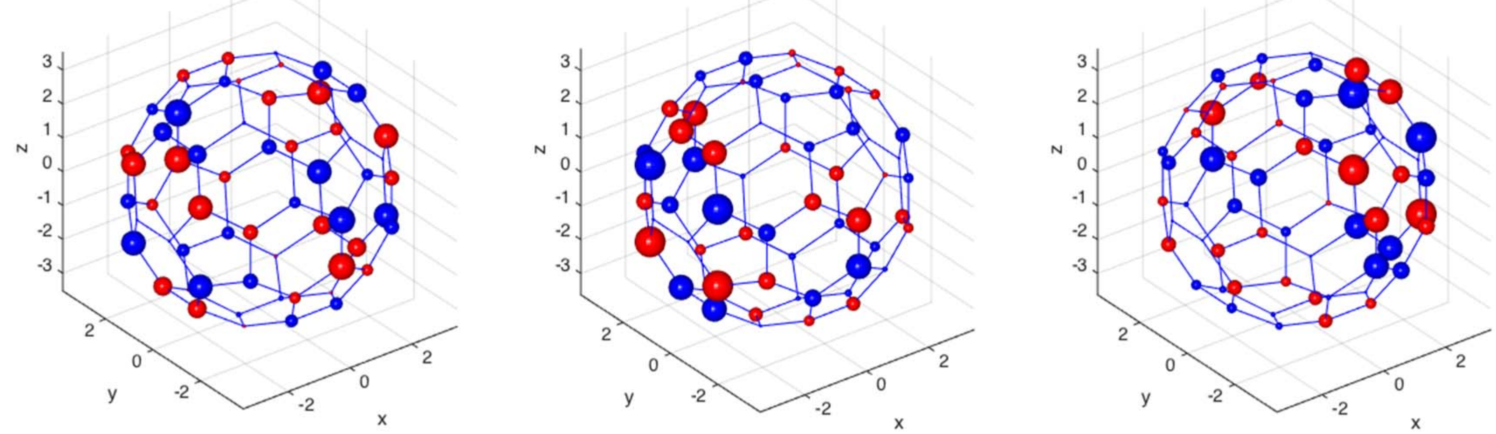


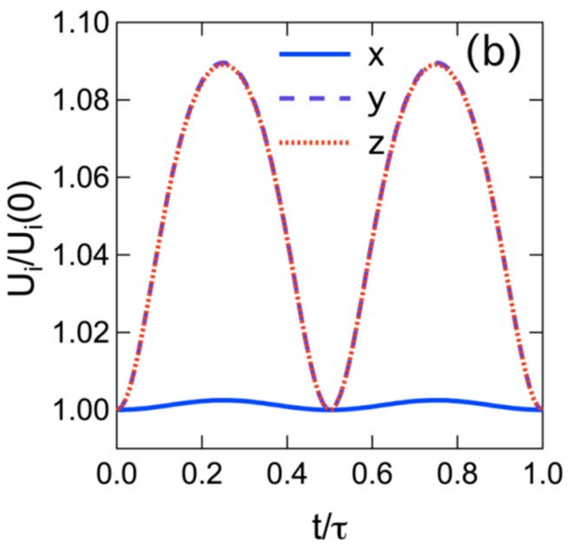


What is going on?

Scenario #1: Modulation of U via Q^2U coupling ?

t/τ=0 t/τ=1/4 t/τ=3/4





S. Clark & D. Jaksch, Oxford

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

Theory:

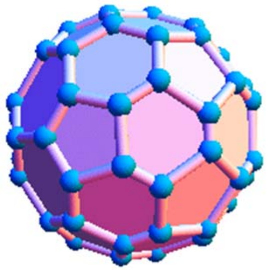
M. Kim et al., Phys. Rev. B 94, 155152 (2016)

D. M. Kennes et al., arXiv:1609.03802 (2016)

Scenario #2: Anharmonic coupling to Raman mode?

mpsd

T_{1u}^2

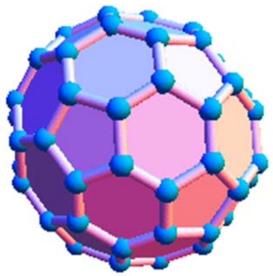


$T_{1u}(4)$

170 meV

$Q^2_{T1u}Q_{Hg}$

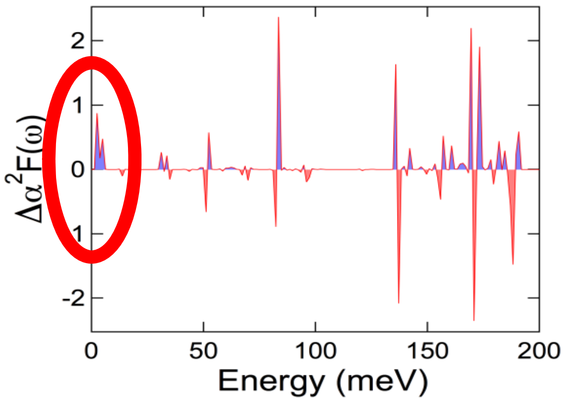
H_g



$H_g(1)$

32 meV

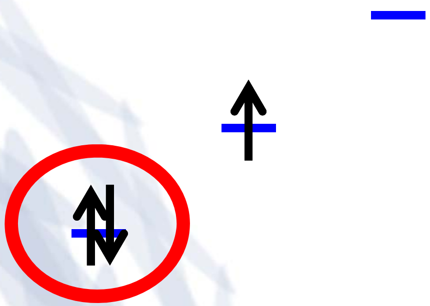
Electron-phonon coupling



A. Subedi, Paris

M. Mitrano, Nature 530, 461 (2016)

Dynamical enhancement of pairing ?



Theory:

M. Sentef et al., Phys. Rev. B 93, 144506 (2016)

M. Knap et al., arXiv:1511.07874 (2016)

A. Komnik & M. Thorwart, arXiv:1607.03858 (2016)

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