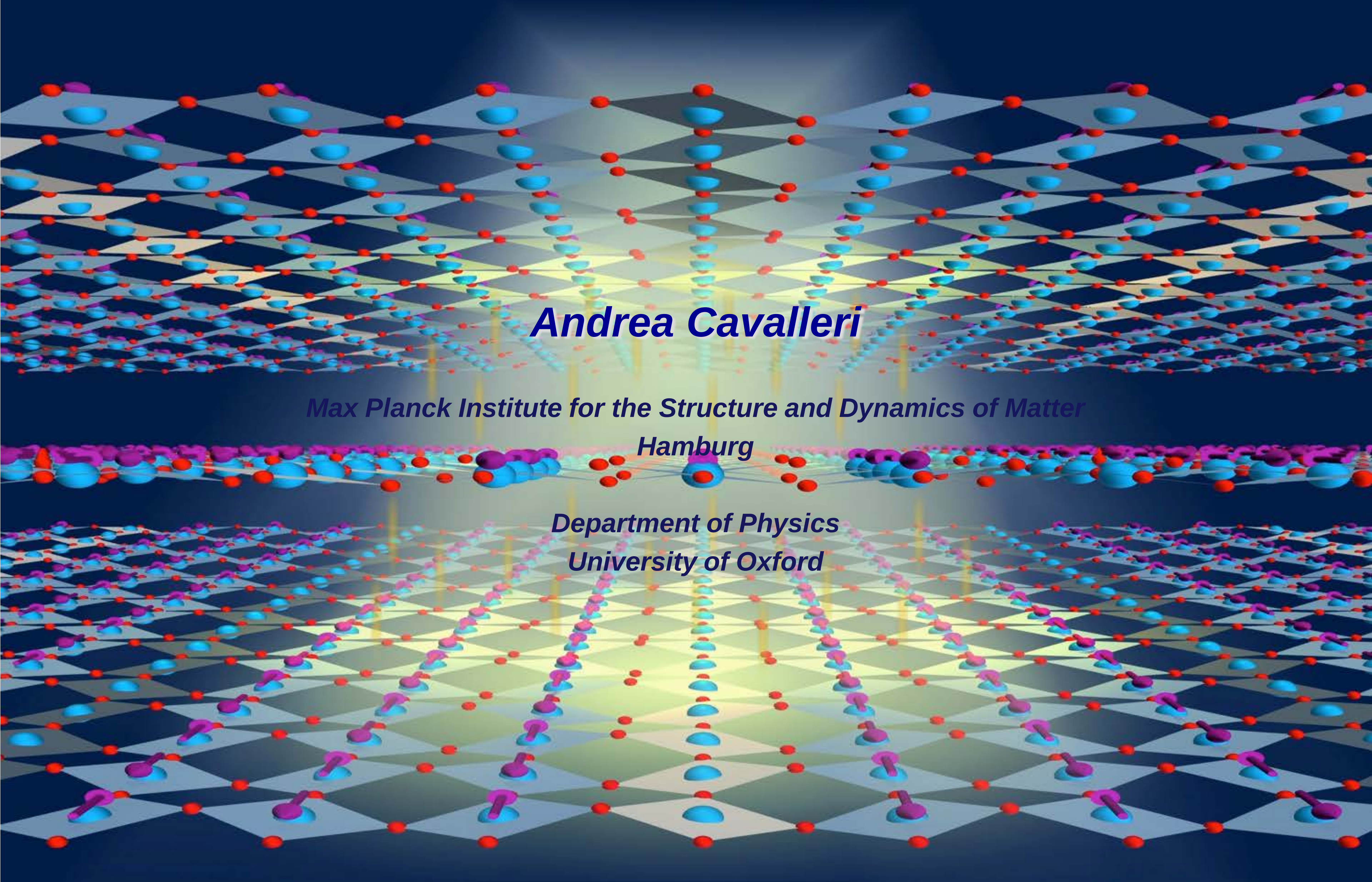
Light-control of quantum solids



Andrea Cavalleri

Max Planck Institute for the Structure and Dynamics of Matter
Hamburg

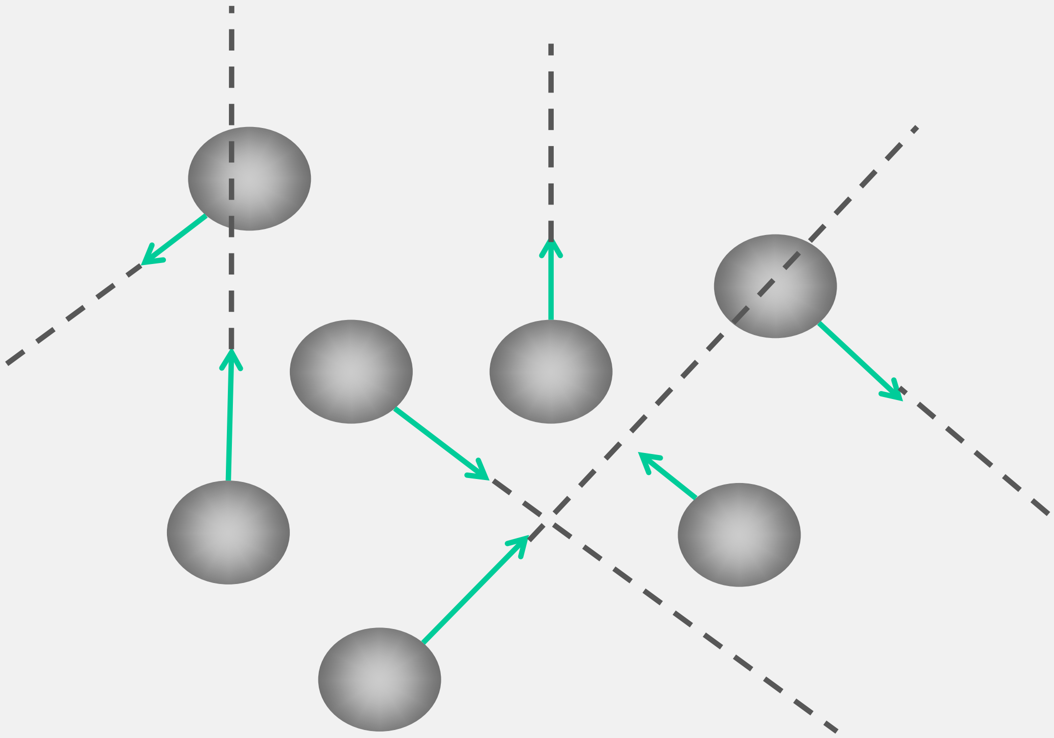
Department of Physics
University of Oxford

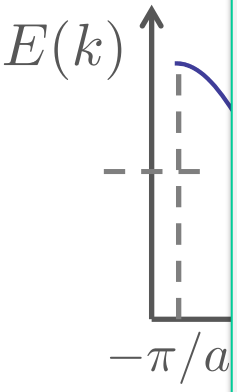
Conventional view of a solid

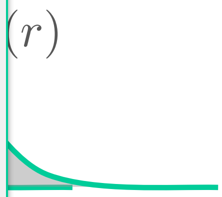
Many … ly free

weak effective interactions

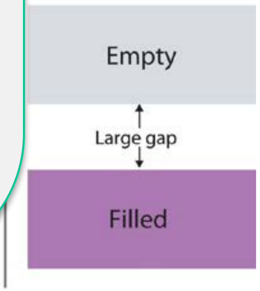
can extrapolate *en masse* behaviour from one particle







Band stru… metals, s… and ins…



Strong correlations

This picture fails for materials like transition metal oxides, which a

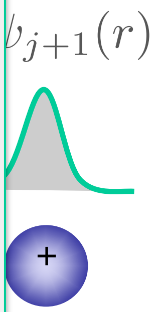
eason is:

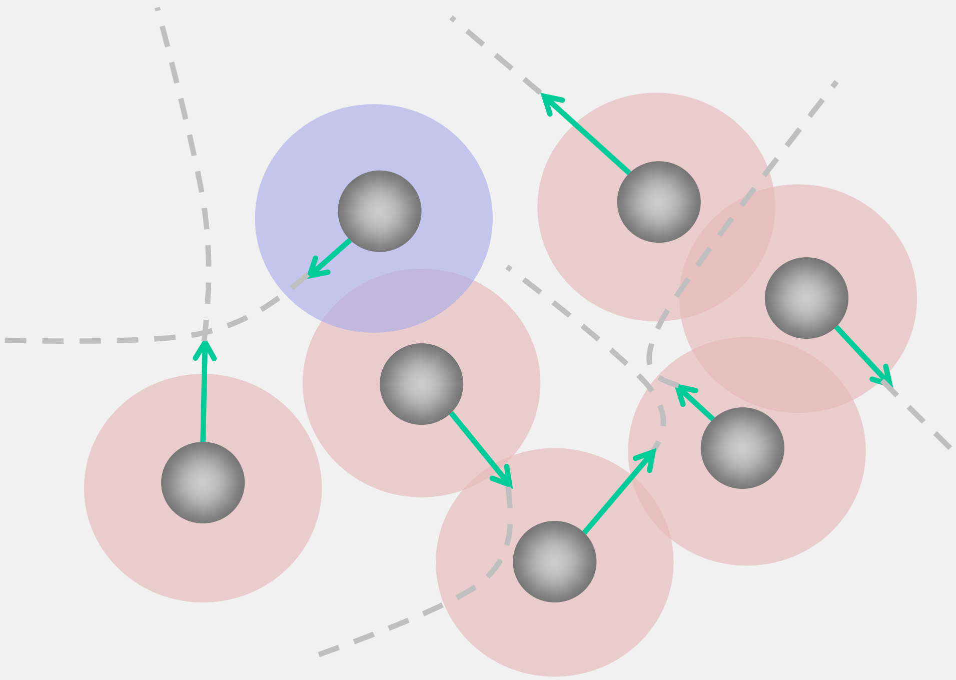
“core-l

small

confi

Mott insula



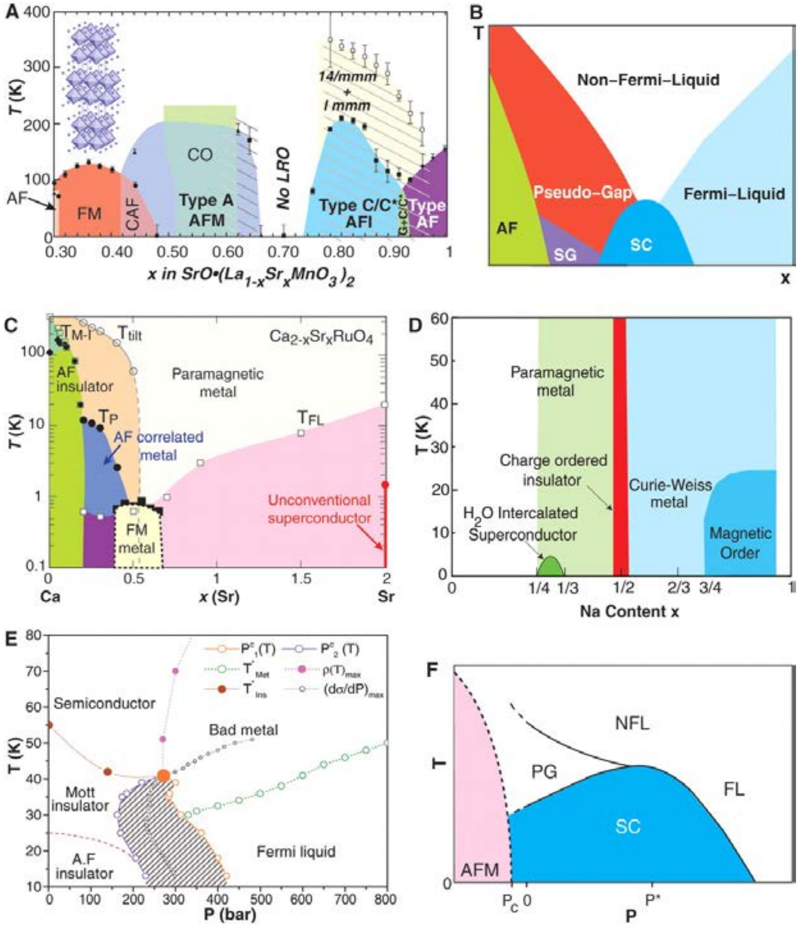


strong effective interactions

- particles do not move independently

Big consequences

Materials with strong correlations possess a wide variety of competing phases with different and unconventional properties:



Metal-insulator transitions

Colossal magnetoresistance

High-temperature superconductivity

E. Dagotto, Science 309, 257 (2005)

Complex Materials

Complex materials

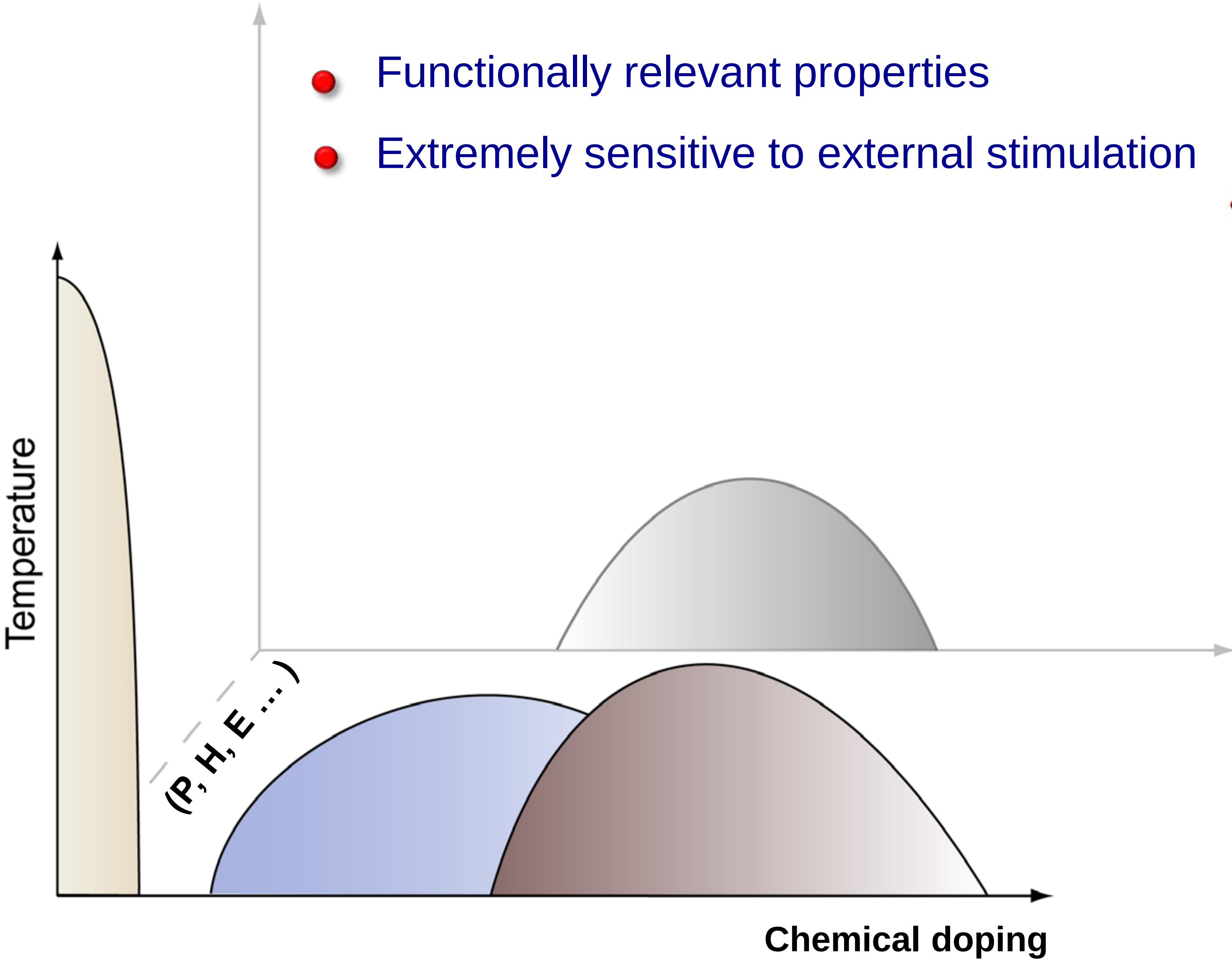
Strong correlations produce collective giant responses to small external perturbations.

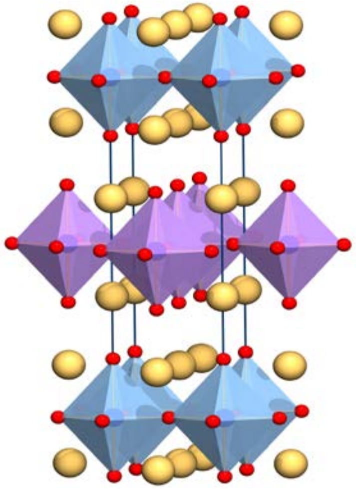
Such responses are often *functionally* relevant.

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

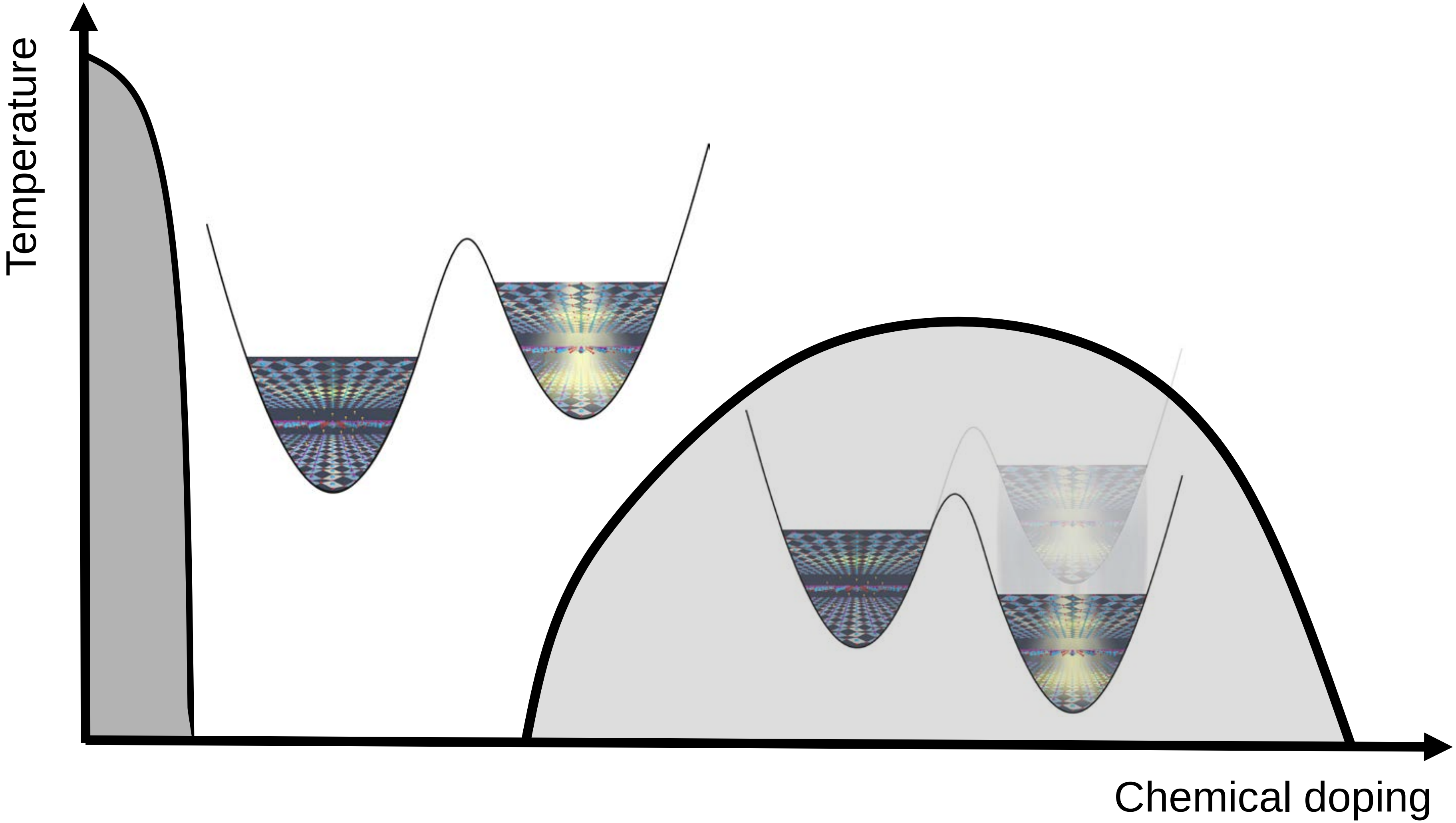
Complex solids: many competing phases

- Functionally relevant properties
- Extremely sensitive to external stimulation

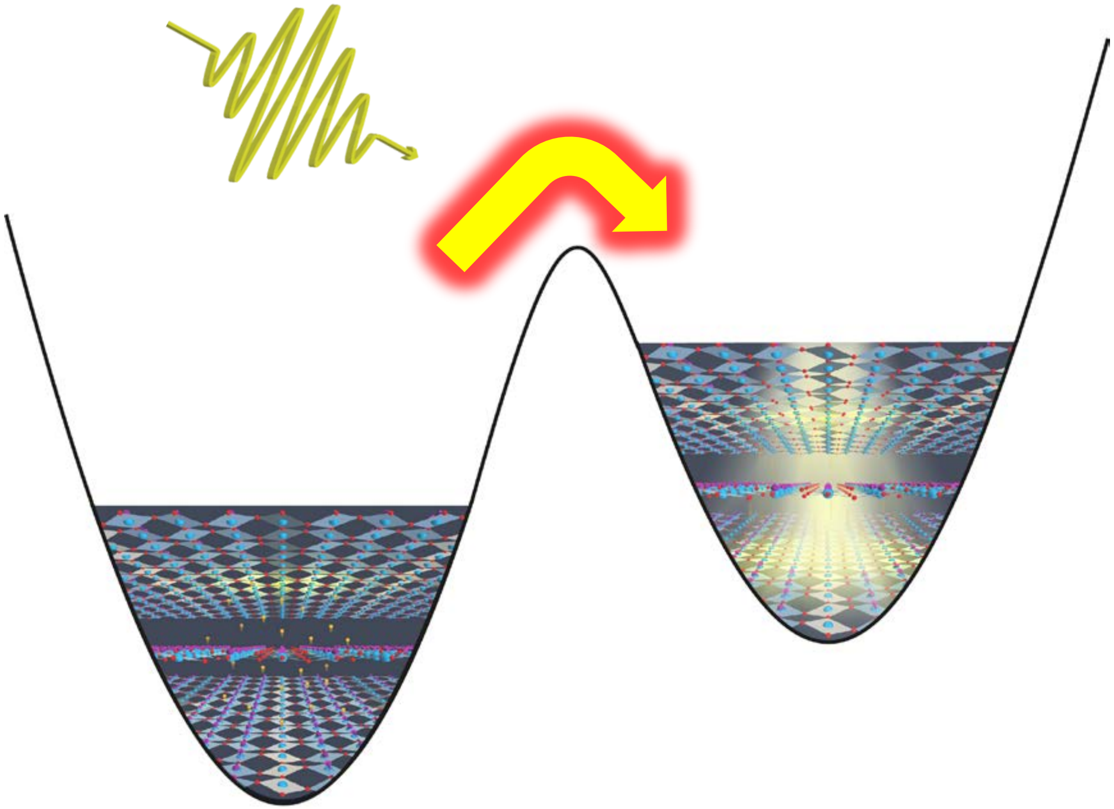




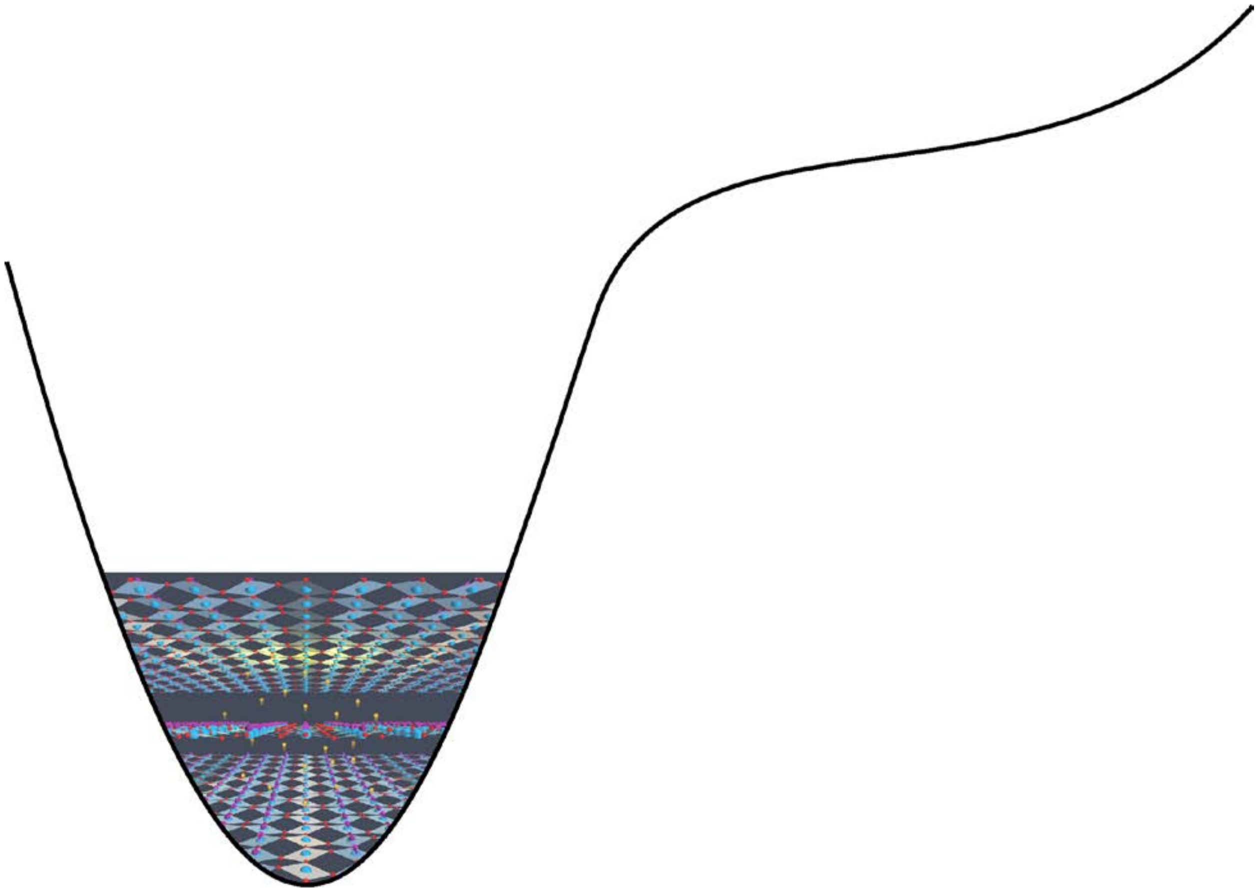
Ground states and hidden phases



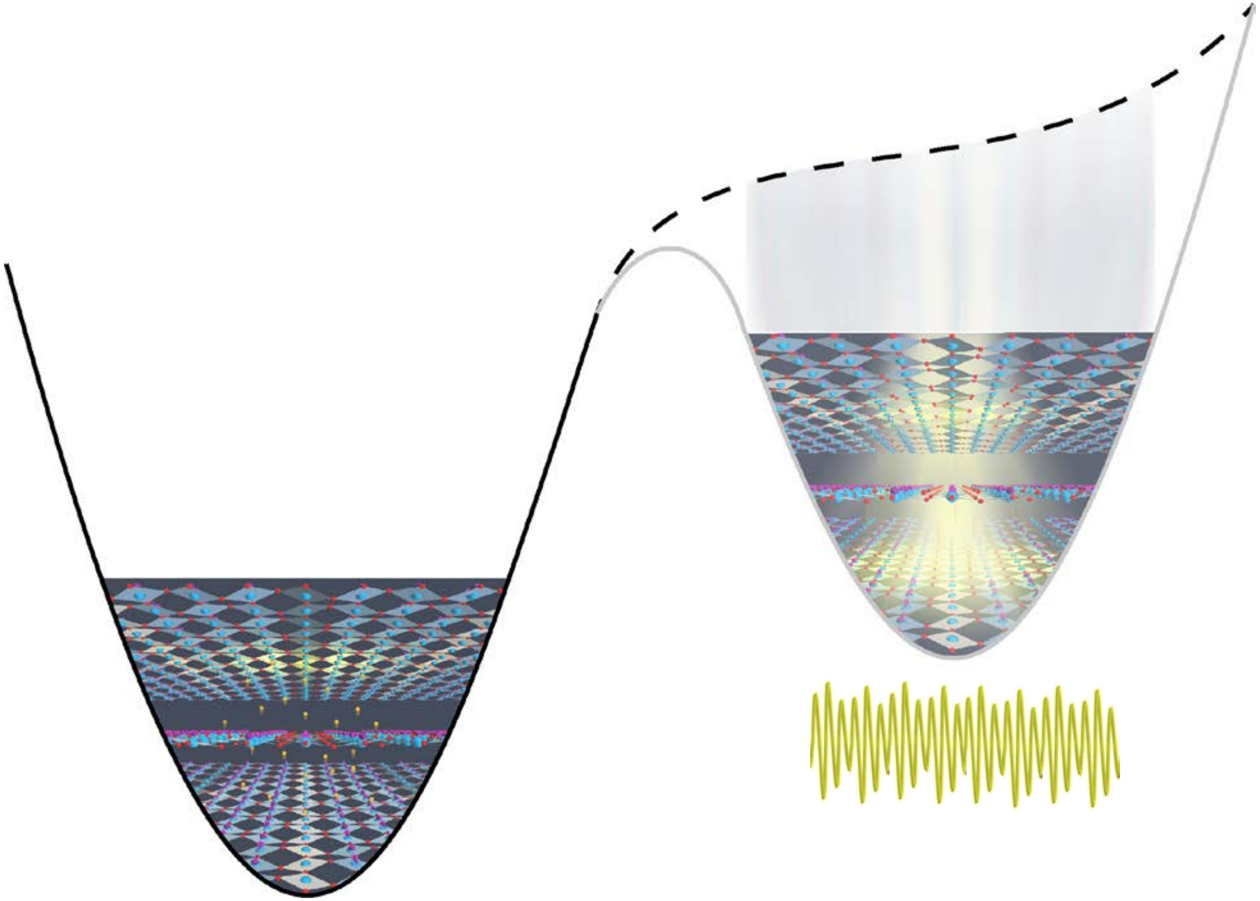
Dynamical control (1): switching into hidden phases



Dynamical control (2): creating new order by driving



Dynamical control (2): creating new order by driving



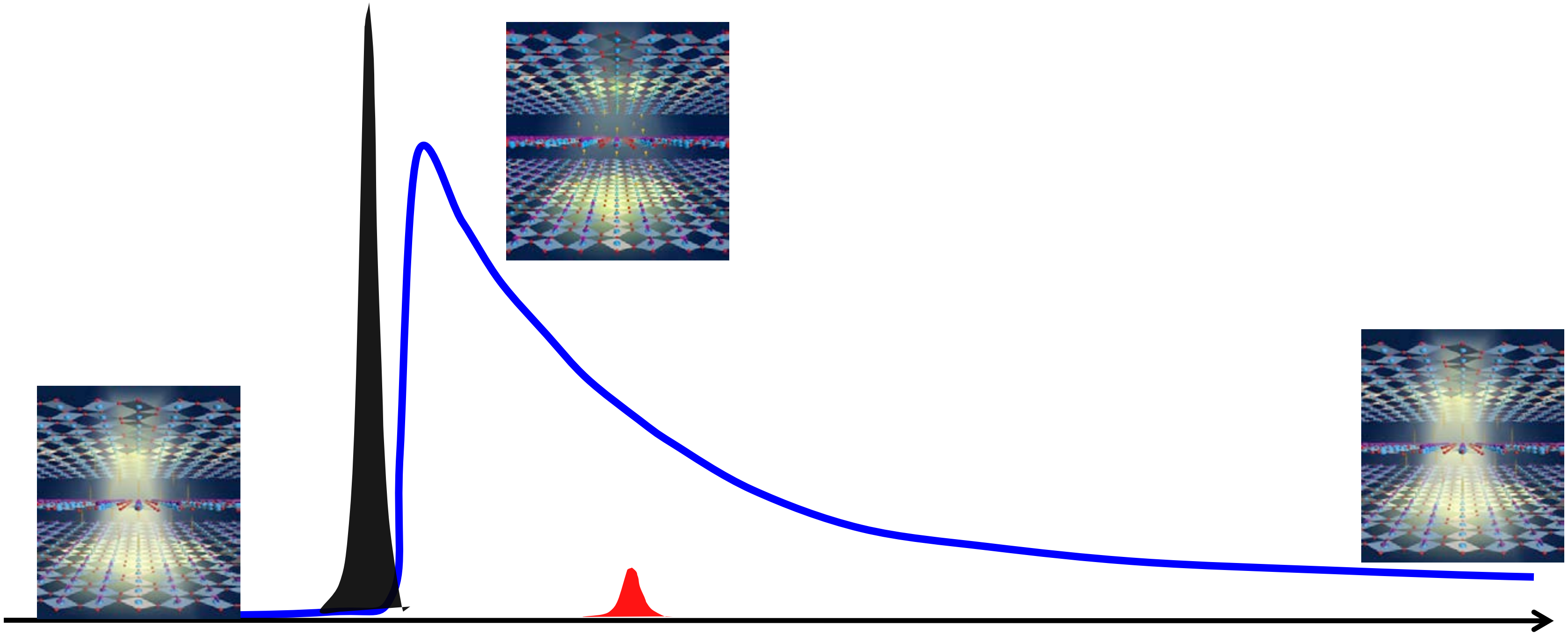
Periodically driven systems ARE different

Driven systems often exhibit new regions of stability. A famous example – take a pendulum and vibrate its pivot point:

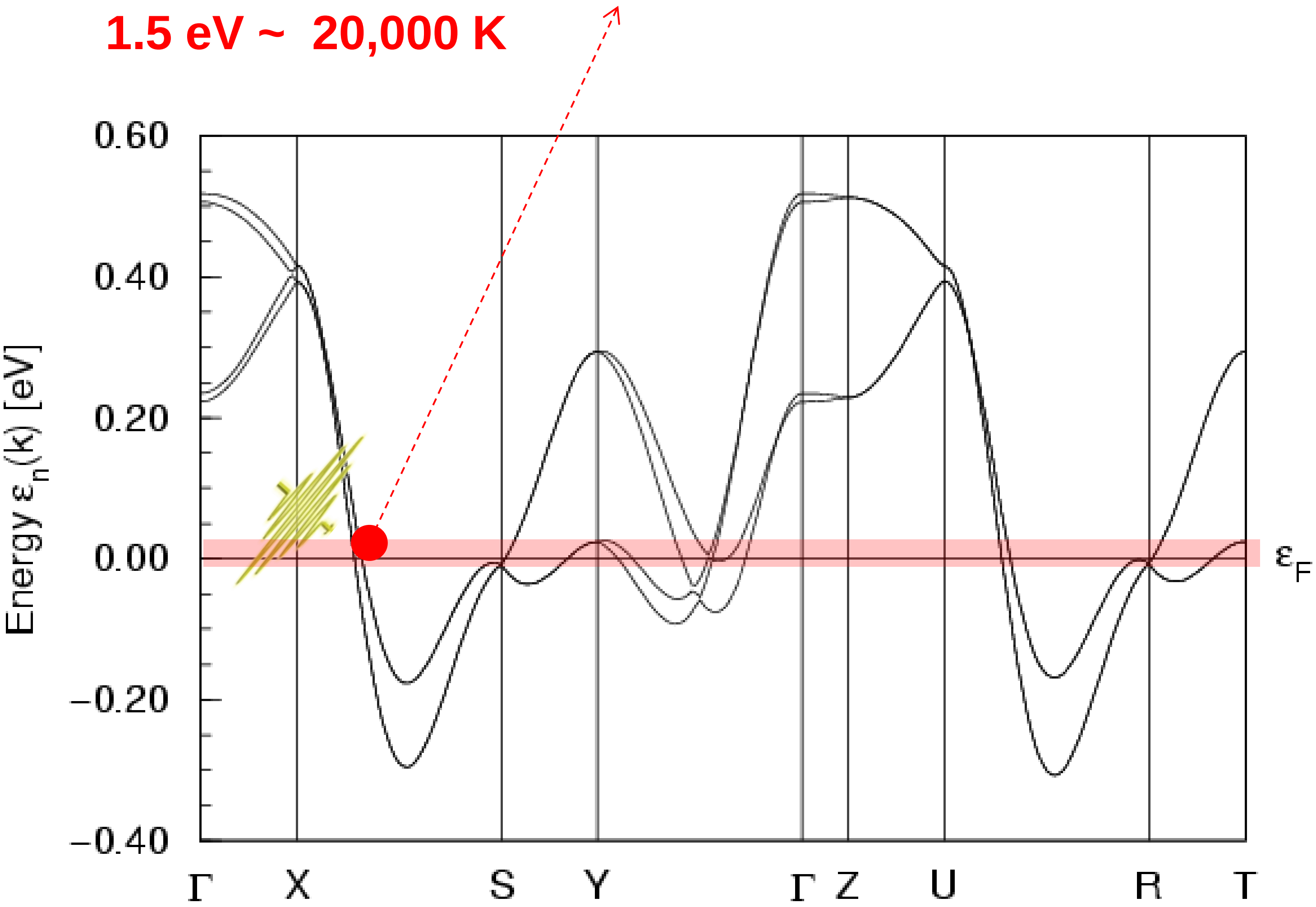
P.L. Kapitza, "Dynamic stability of a pendulum with an oscillating point of suspension," *Zh. Eksp. Teor. Fiz.* 21, 588 (1951)

L.D. Landau and E.M. Lifschitz *Mechanics* (Pergamon, Oxford 1976)

Dynamical phenomena: experiments



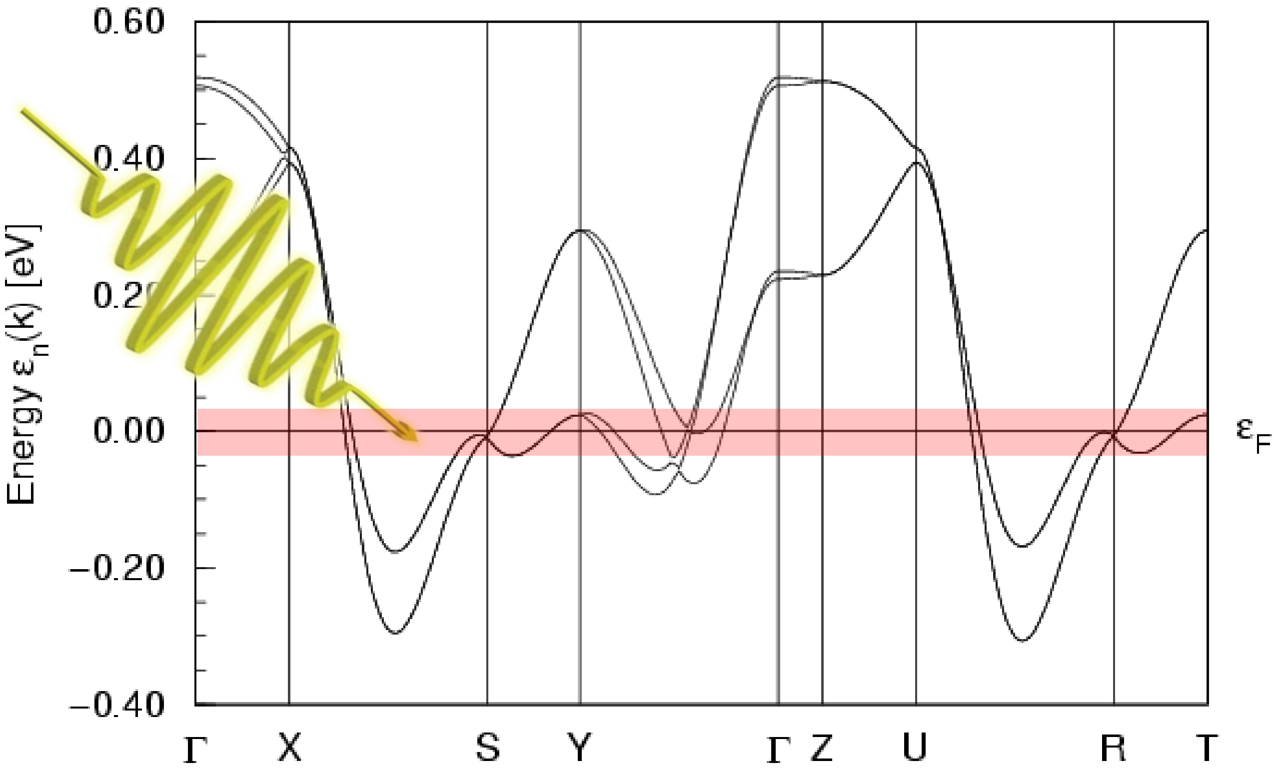
Stay away from visible light !



High energy scales **Incoherent** **Entropy**

Control at THz frequencies: natural energy scales

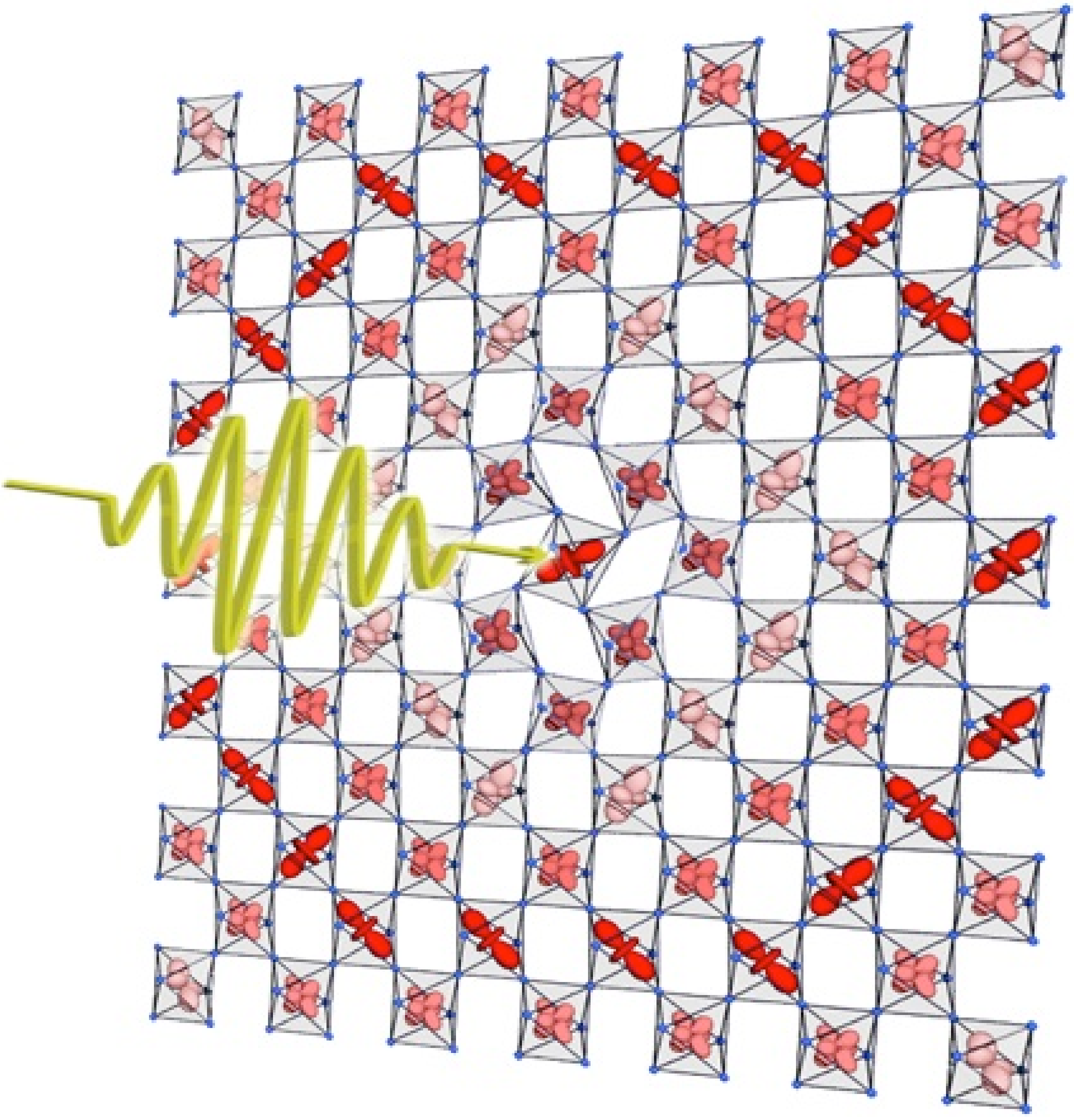
1 THz ~ 50 K ~ 4 meV



Low energy scales

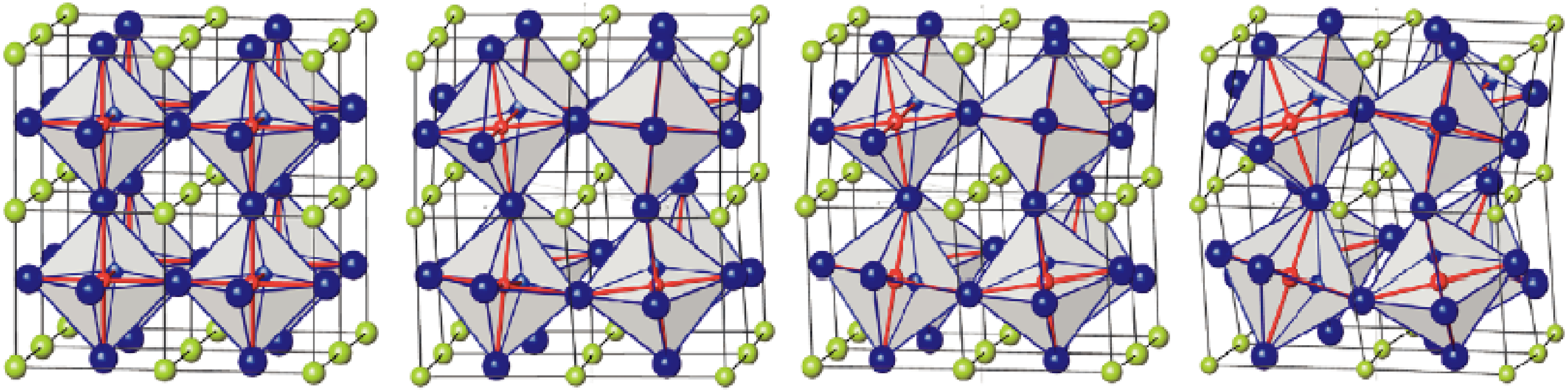
Long coherence times

Coherent control of the lattice

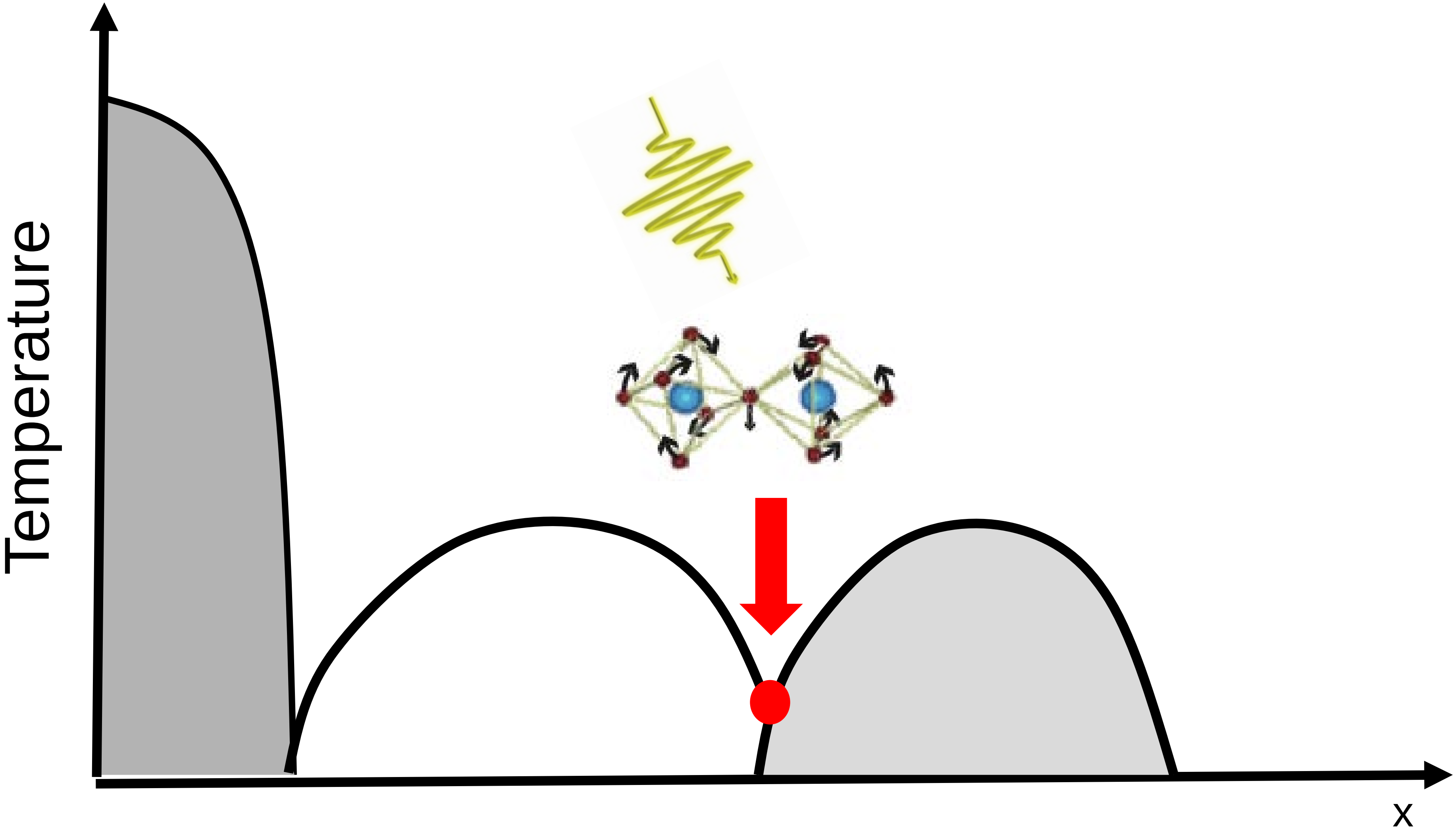


Why? e.g. controlling bond angles in oxides

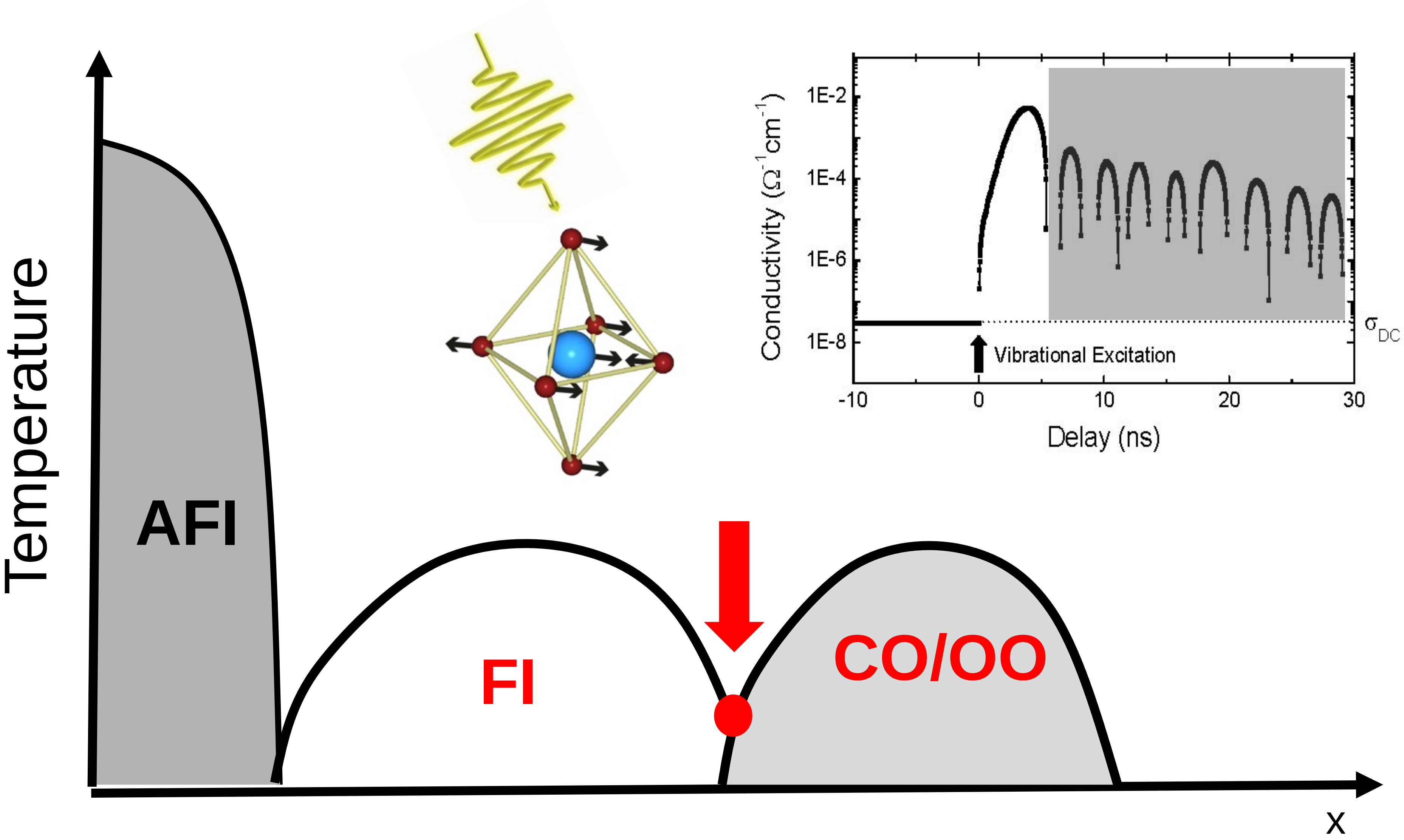
Metal → Insulator



Can I control a bond angle with light



$Pr_{0.7}Ca_{0.3}MnO_3$: Phonon Driven I-M Transition

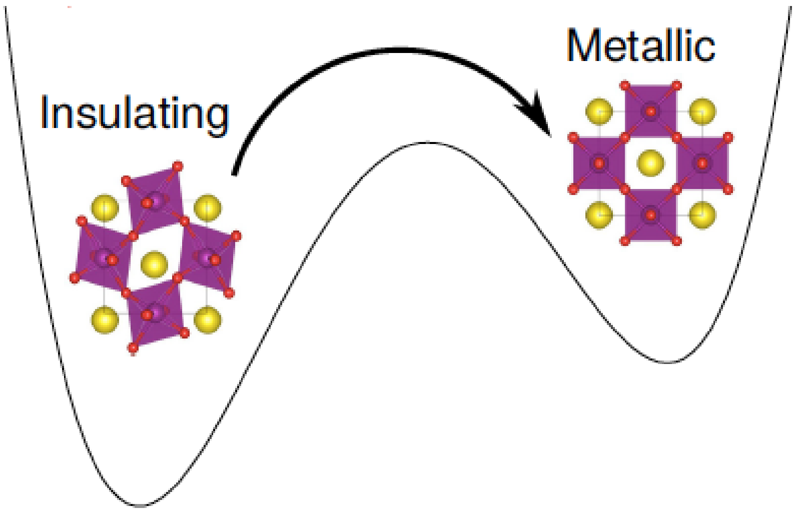


M. Rini et al., Nature 449, 72 (2007)

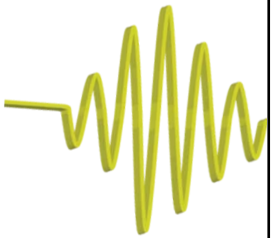
Displacive ?

How can optical excitation

displace the crystal bond angles?

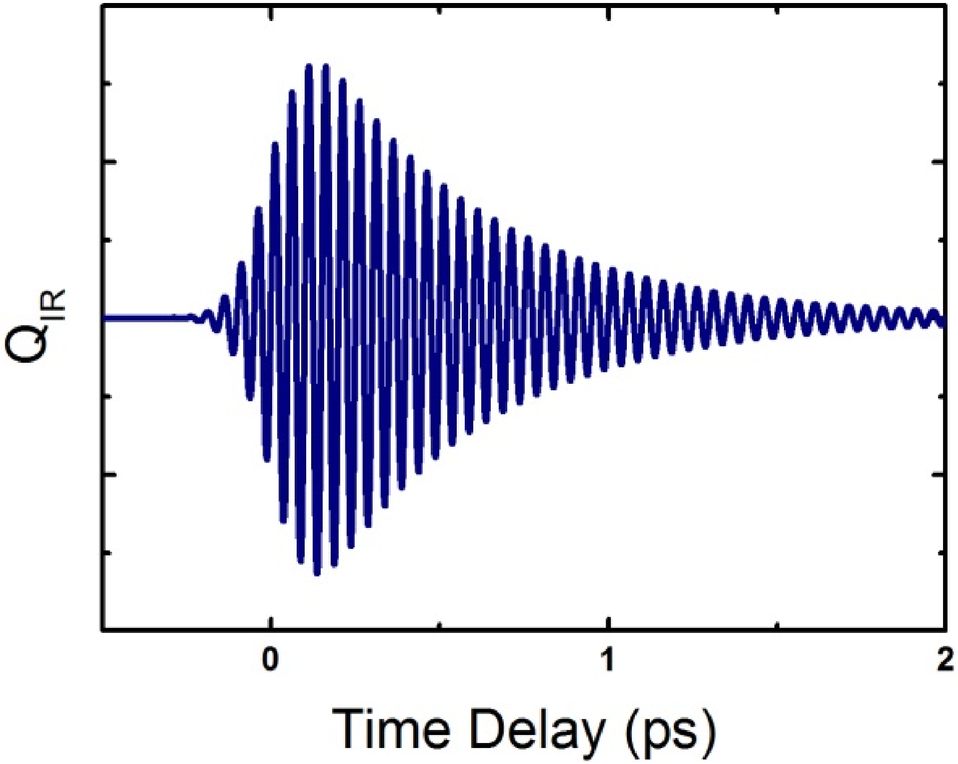


Linear response: no average displacement



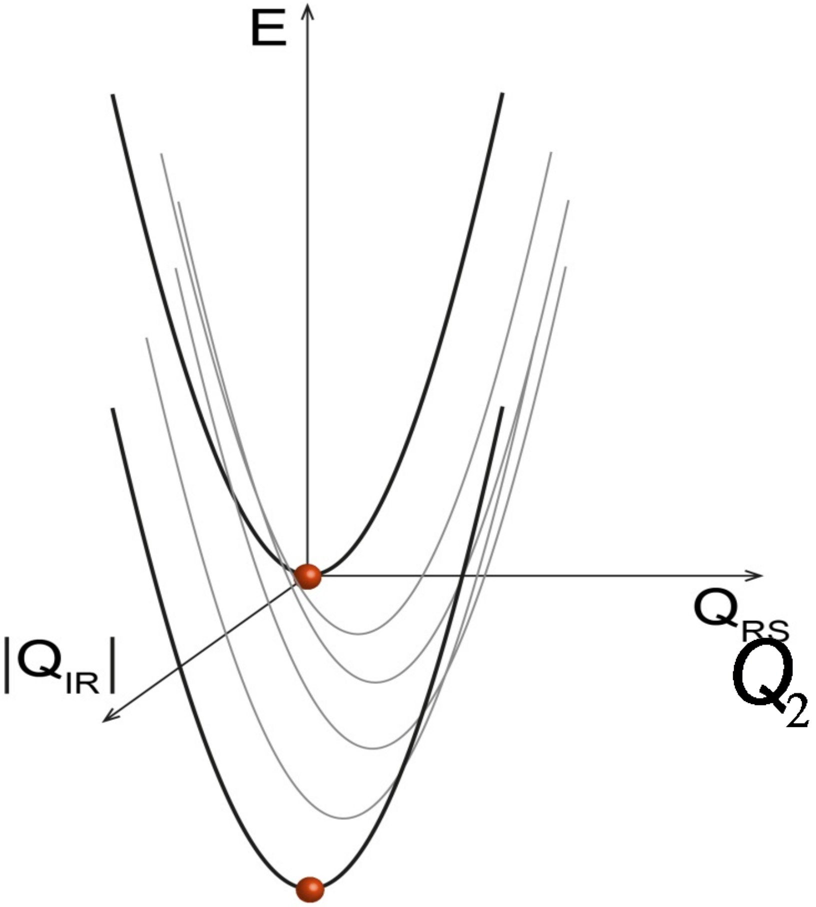
$$V = \frac{1}{2}\mu_{IR}\omega_{IR}^2 Q_{IR}^2$$

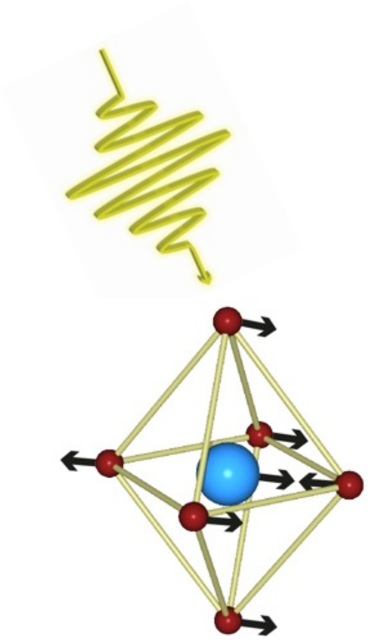
$$\ddot{Q}_{IR} + 2\gamma\dot{Q}_{IR} + \omega_{IR}^2 Q_{IR} = A\exp(i\omega t)$$



Anharmonic coupling to a second mode

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





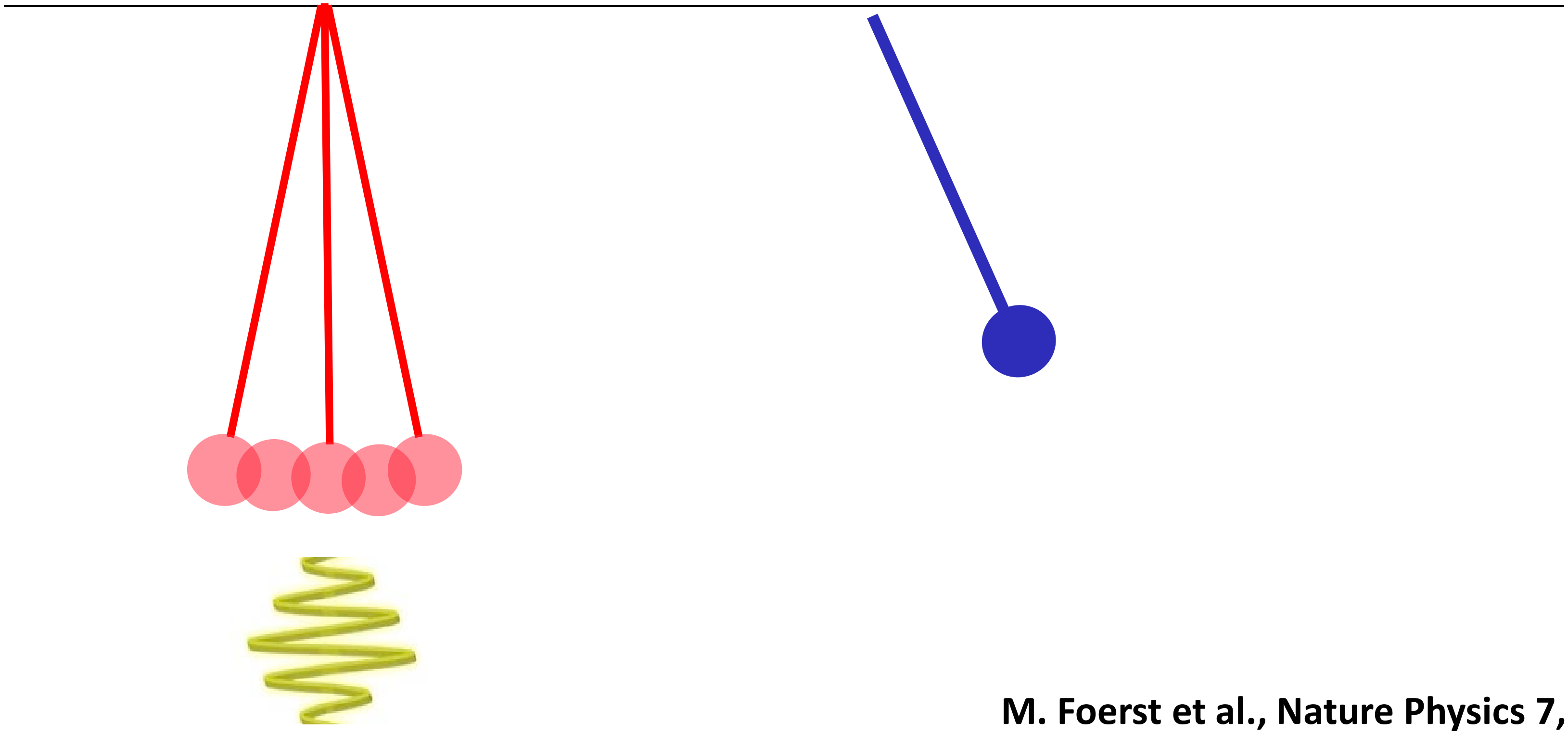
With Roberto Merlin, Univ. of Michigan

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

Equations of Motion: Two coupled oscillators

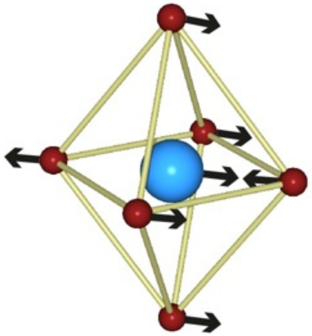
$$(\ddot{Q}_{IR} + 2\gamma\dot{Q}_{IR} + \omega_{IR}^2 Q_{IR}) = A\exp(i\omega t)$$

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



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

Selection rules



Q_{IR} of B_{1u} symmetry

As in: $Pr_{0.7}Ca_{0.3}MnO_3$

$La_{1.5}Ca_{0.5}MnO_4$

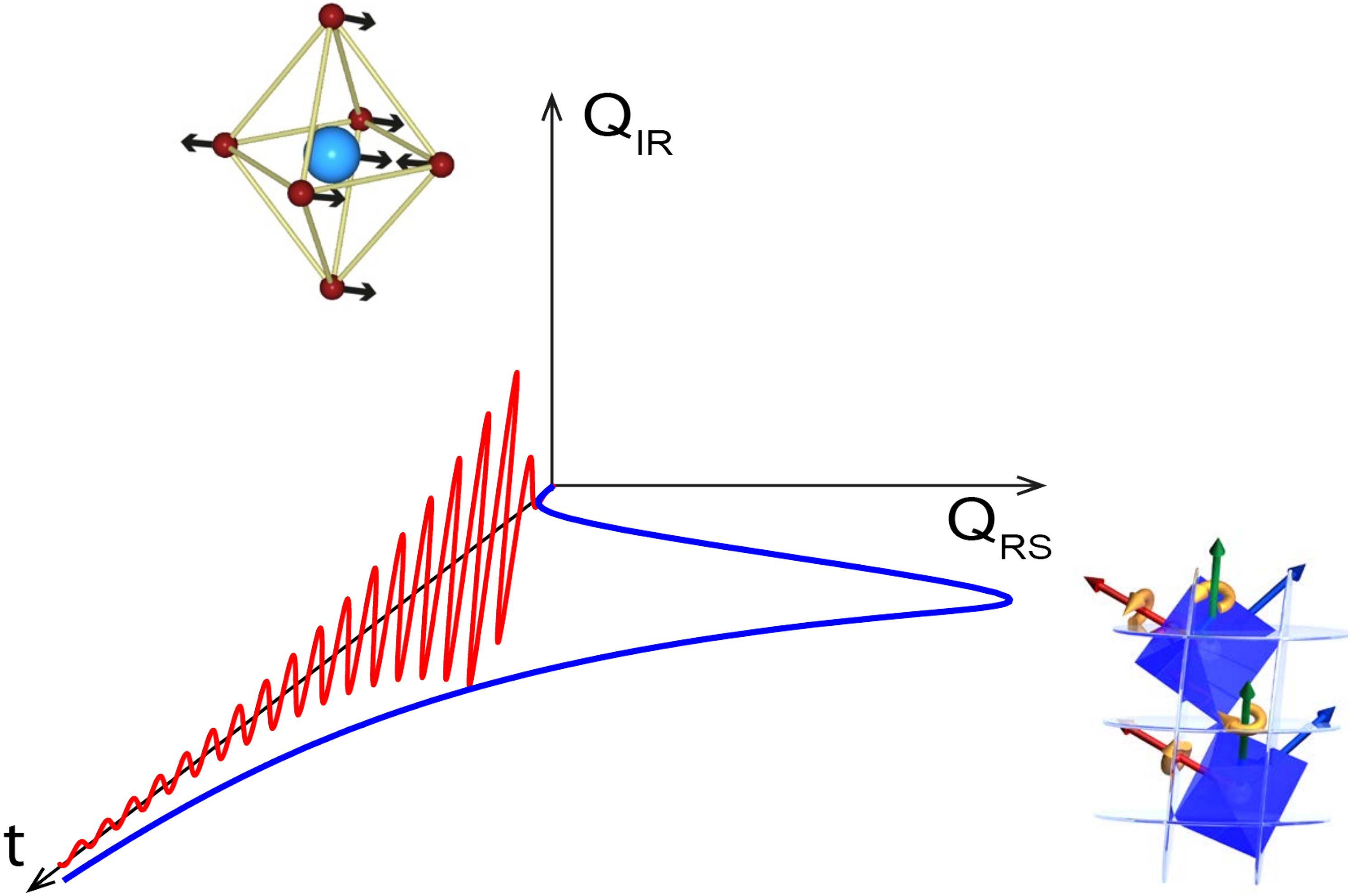
$YBa_2Cu_3O_{6+x}$

$Q_{IR}^2 Q_2 \neq 0$

only if Q_2 is a Raman mode of A_g symmetry

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

Rectified stretching leads to bending

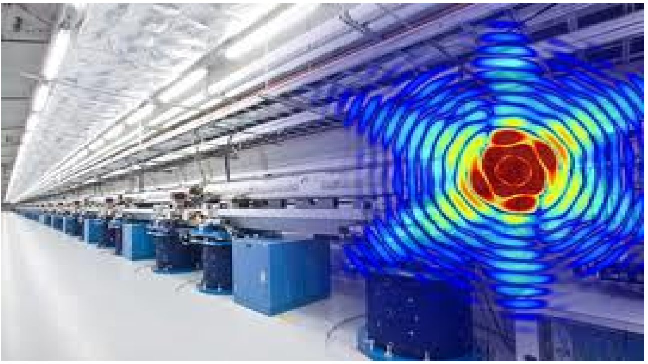


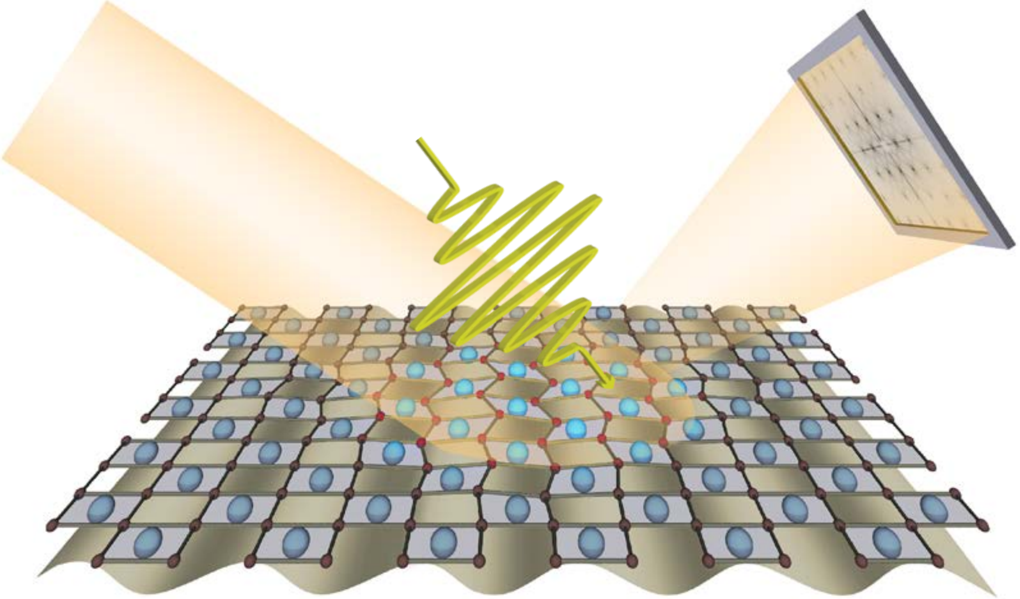
Is this true ?

Is there a nonzero average displacement ?

How far are the atoms being displaced ?

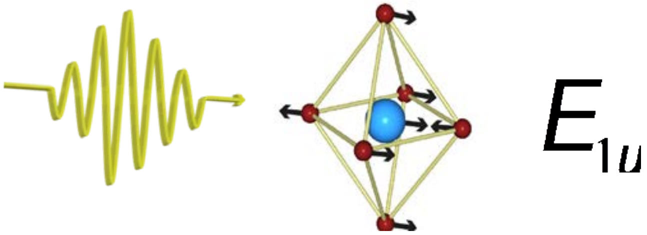
THz pump - Ultrafast x-ray diffraction probe



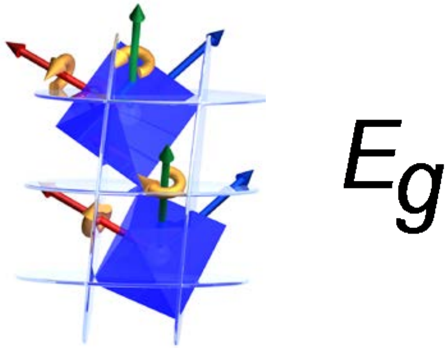


Femtosecond x-rays: quantify displacement

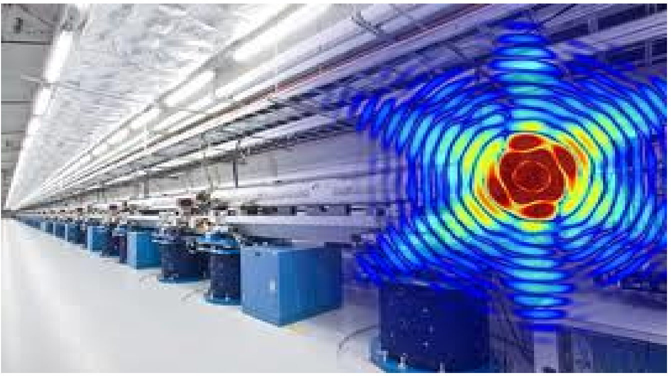
Mid-IR pump (E_{1u} mode)

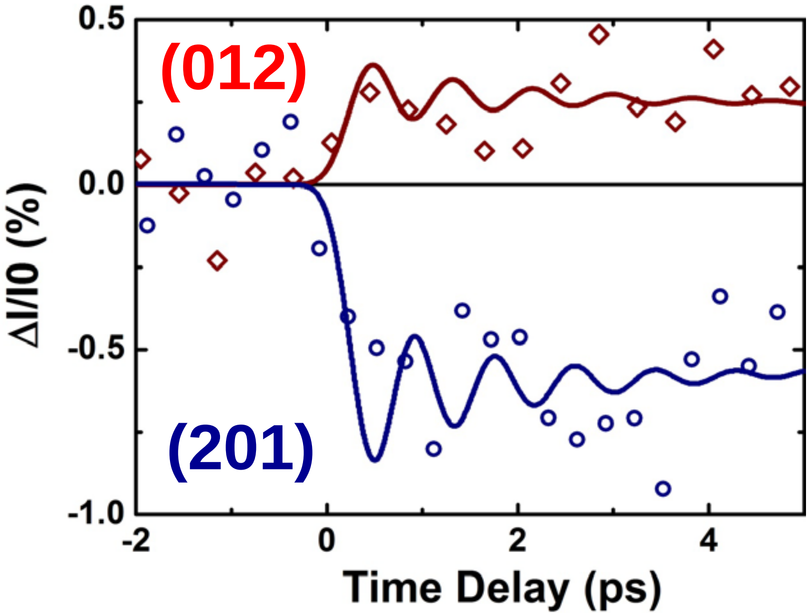


Displacive field (E_g mode)



X-ray probe



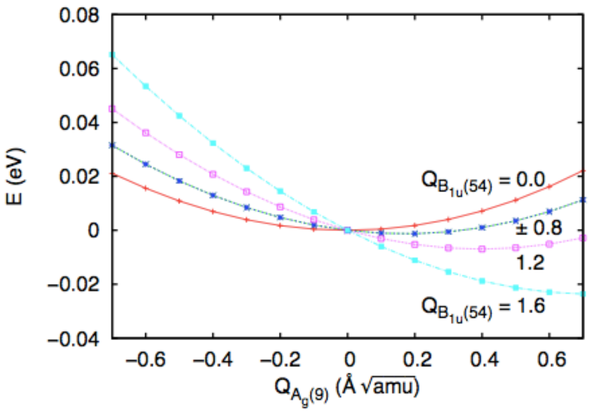


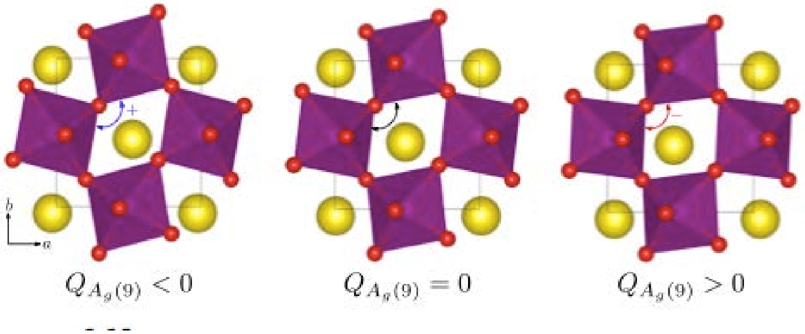
M. Foerst et al. Solid State Comm. 169, 4 (2013)

With Steve Johnson, ETH

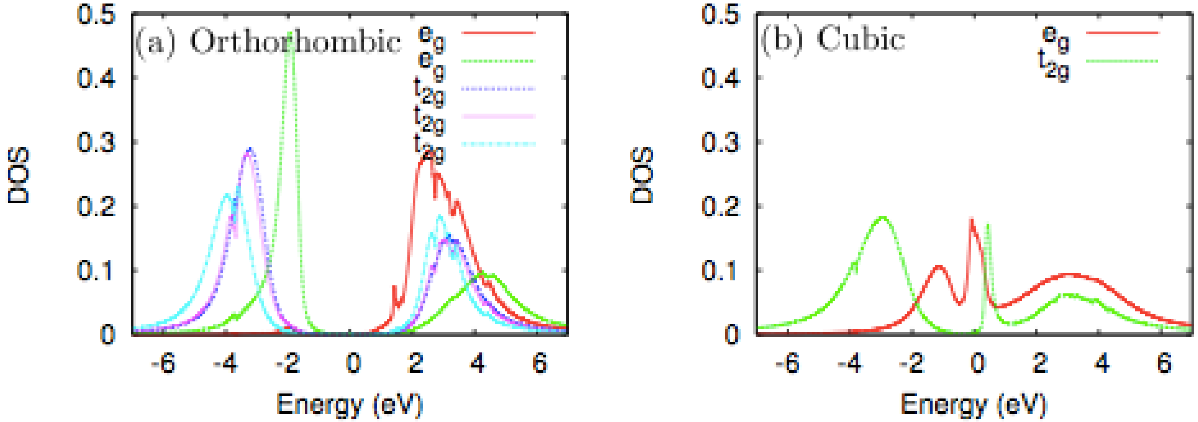
Theory: octahedral rotations make a metal

Frozen Phonon





Electronic Structure in the distorted state -> metallic



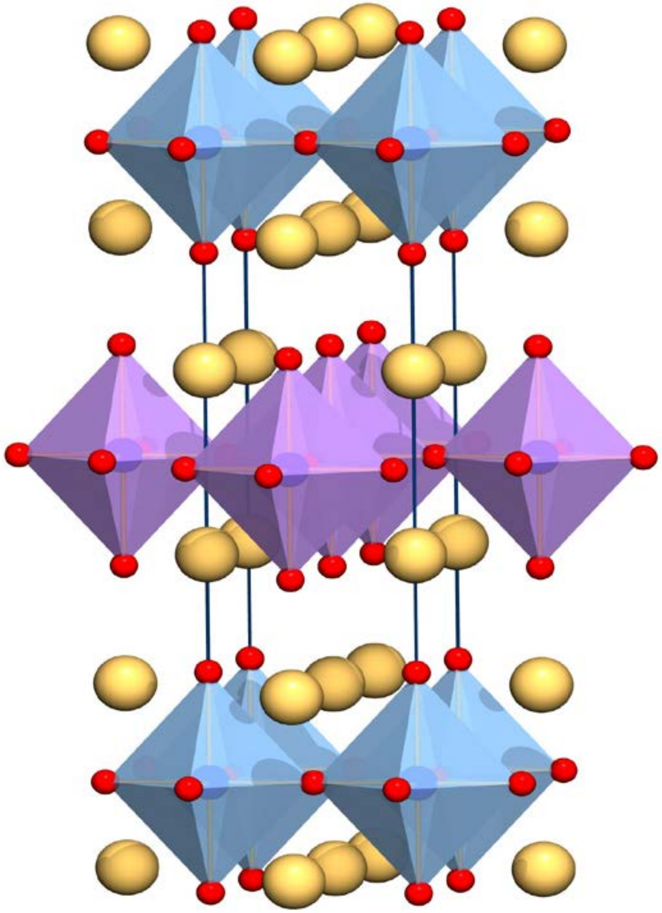
A. Subedi, A. Cavalleri, A. Georges *Phys Rev B 89,* 220301 (2014)

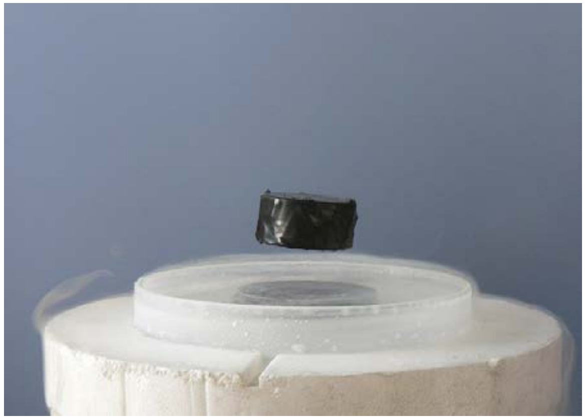
Optical control of the lattice

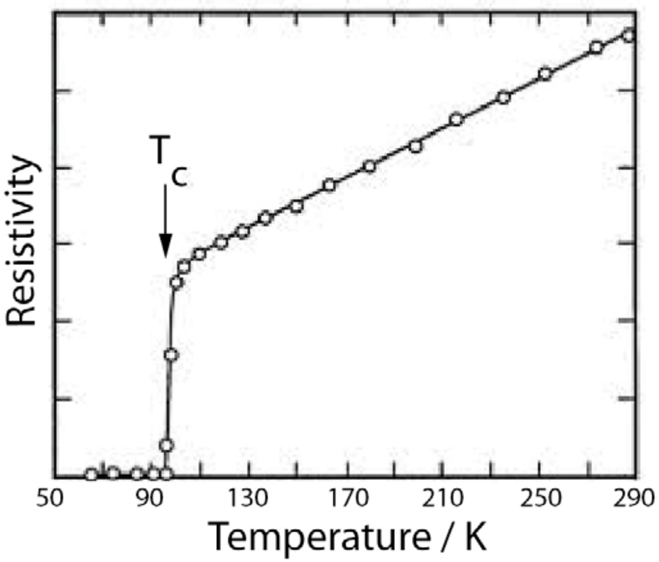
What else can I control ?

High Temperature Cuprate Superconductivity

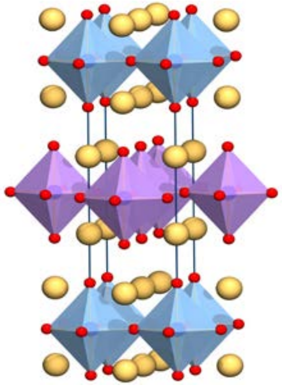
Below a critical temperature T_c resistivity vanishes

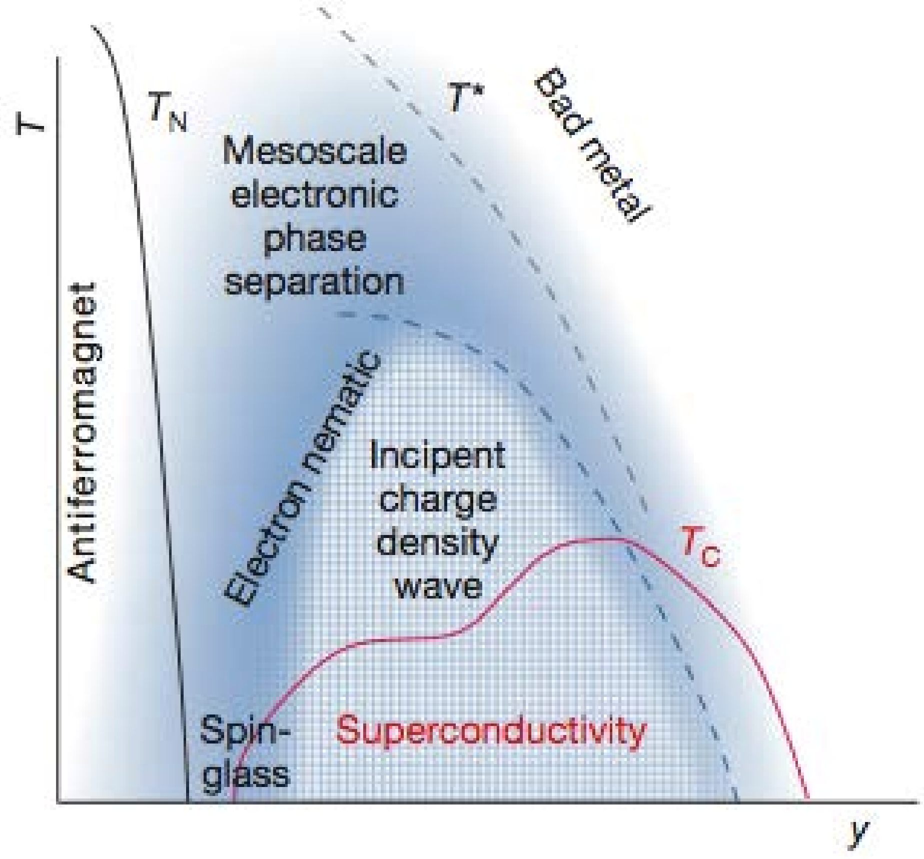


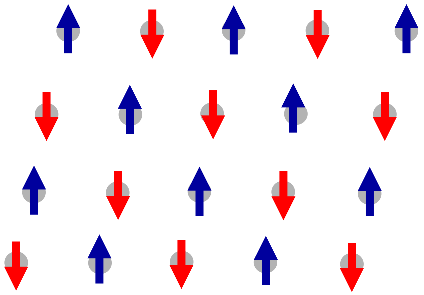


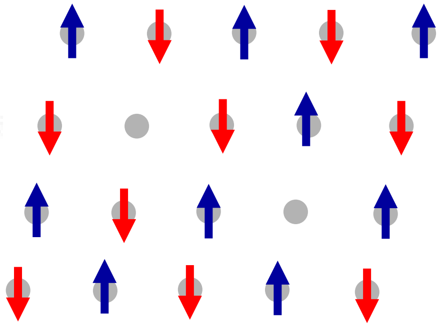


Competing orders can quench T_c



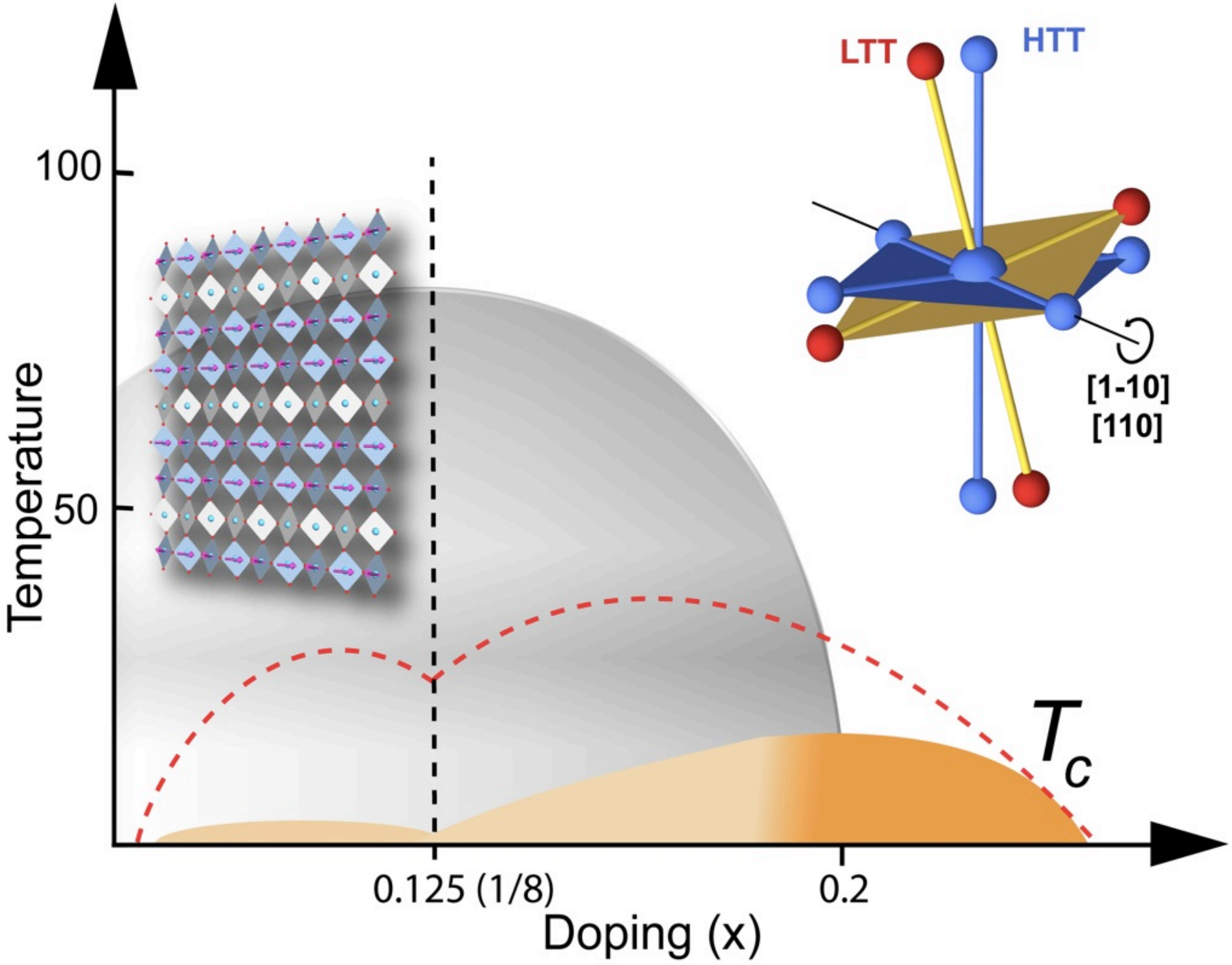






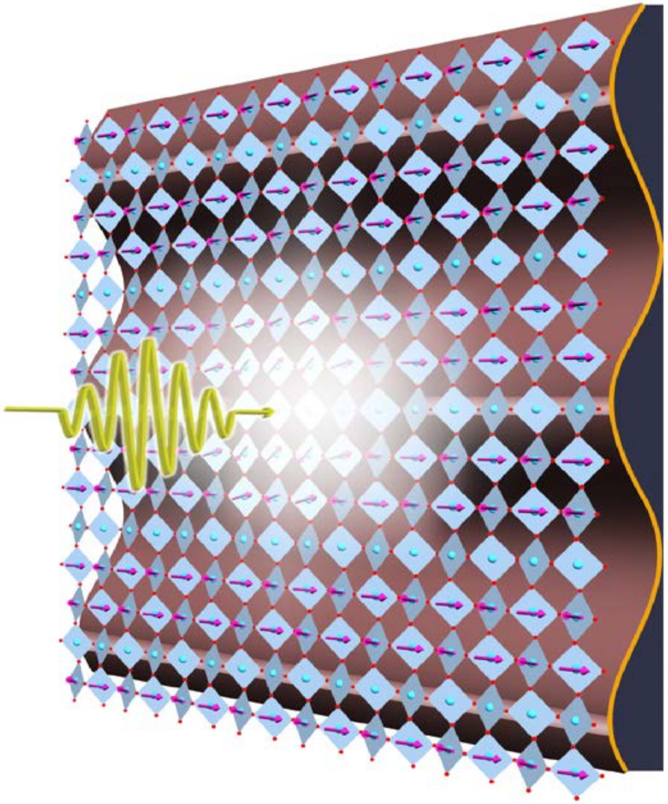
Fradkin and Kivelson, Nature Physcs (2012)

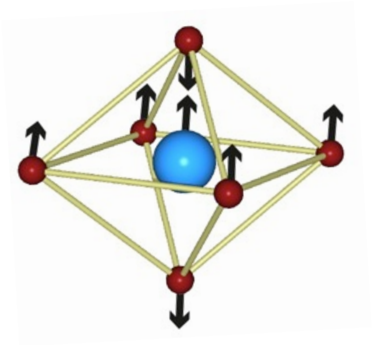
Eu:LSCO$_{1/8}$ stripe charge order



With Hide Takagi
MPI Stuttgart

Excitation of in plane Cu-O stretch





600 cm^{-1}

16 μm wavelength

μJ pulses

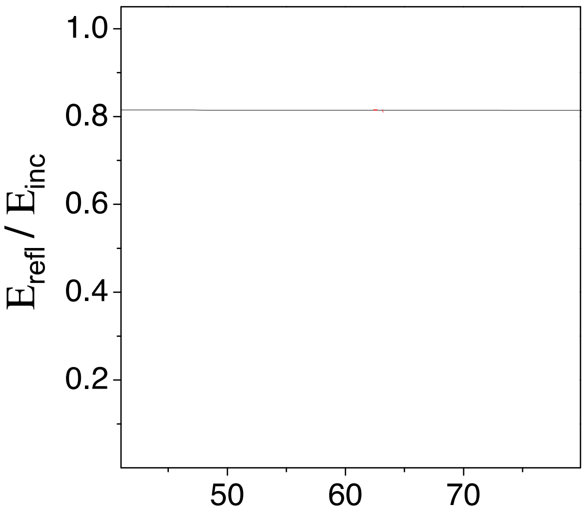
MV/cm fields

With Hide Takagi
MPI Stuttgart

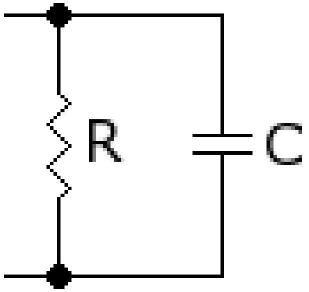
Probing the transient state

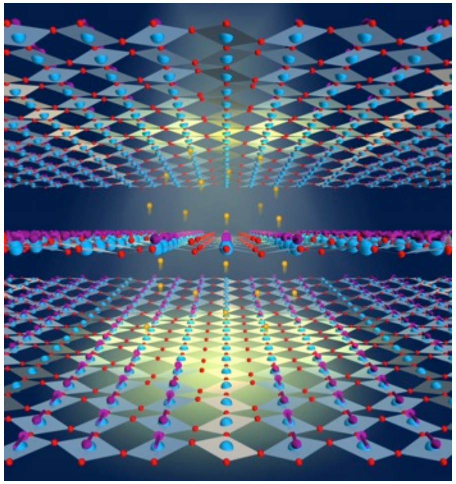
How do I recognize a transient superconductor ?

Josephson Plasmon

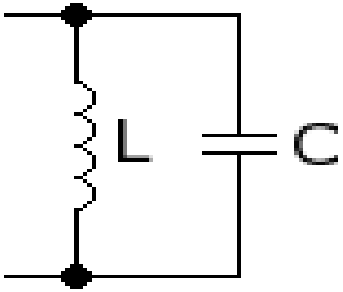


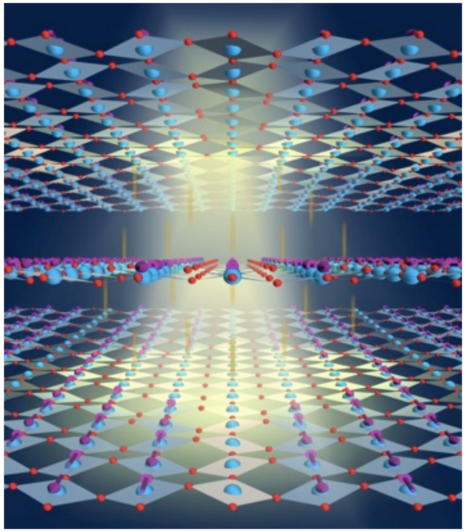
$T > T_c$





$T < T_c$

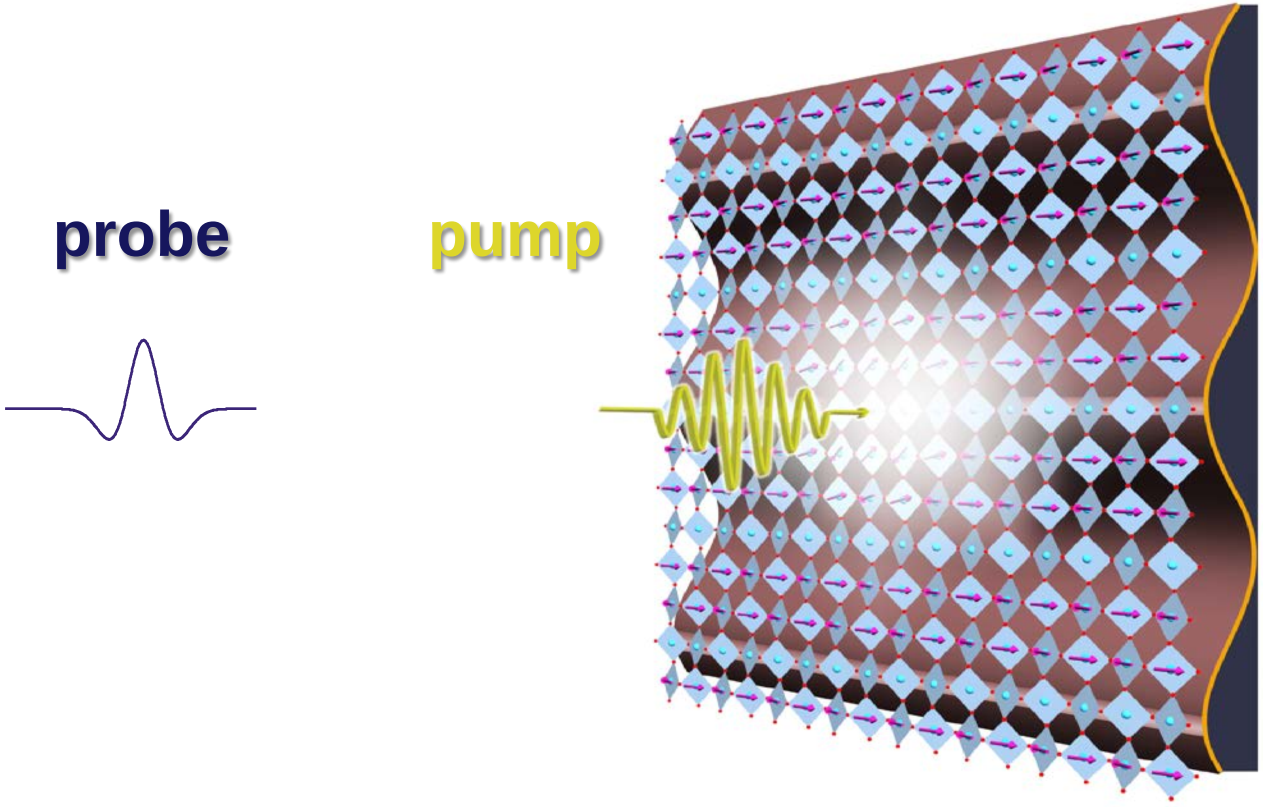




Kresin and Morawitz PRB (1988)

van der Marel and A. A. Tsvetkov Czech. J. Phys. (1996)

Mid-IR pump / THz Probe Spectroscopy



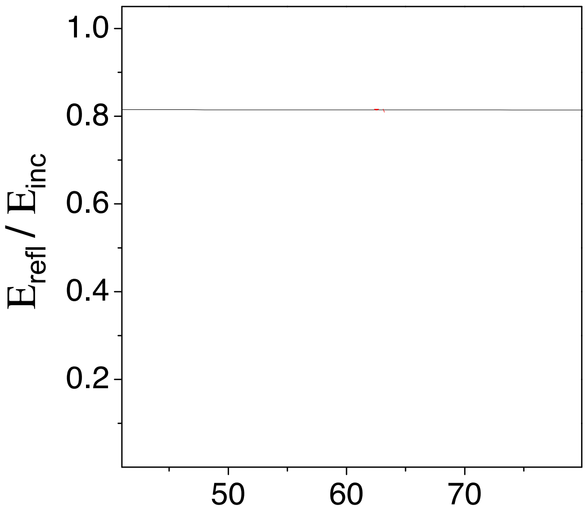
A light Induced Josephson plasma edge

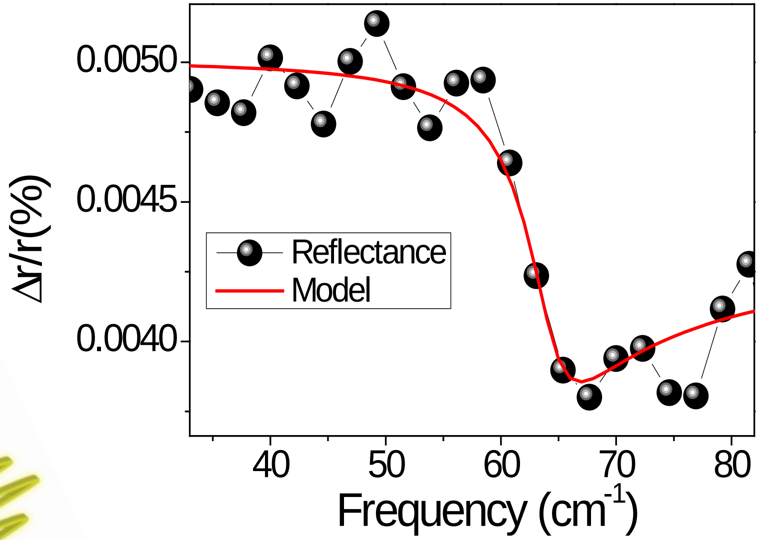
Equilibrium LSCO

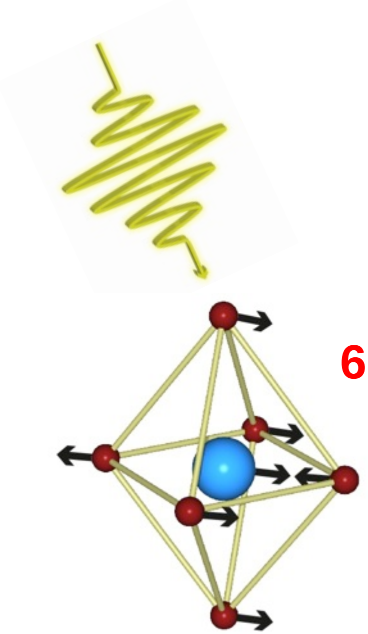
Superconducting (eq.)

Photo-induced LESCO

Superconducting (non eq.)







600 cm^{-1}

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

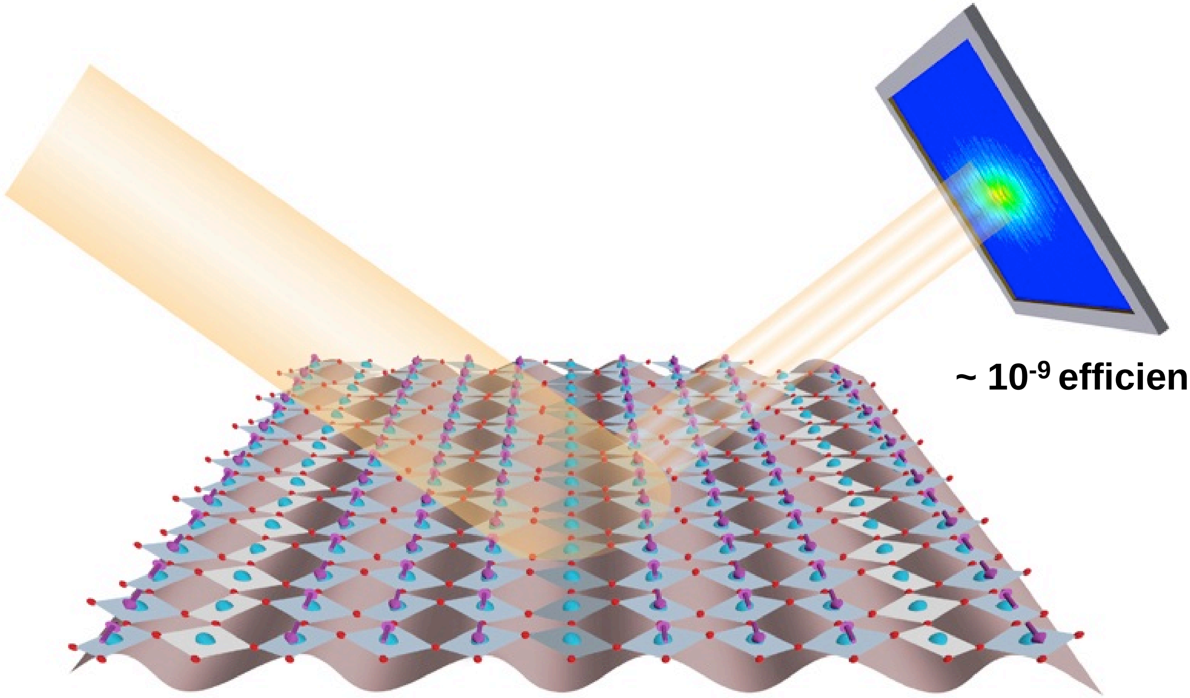
Probing the transient state

Am I melting charge stripes with light ?

Charge stripes are seen by soft x-ray scattering

O Kedge

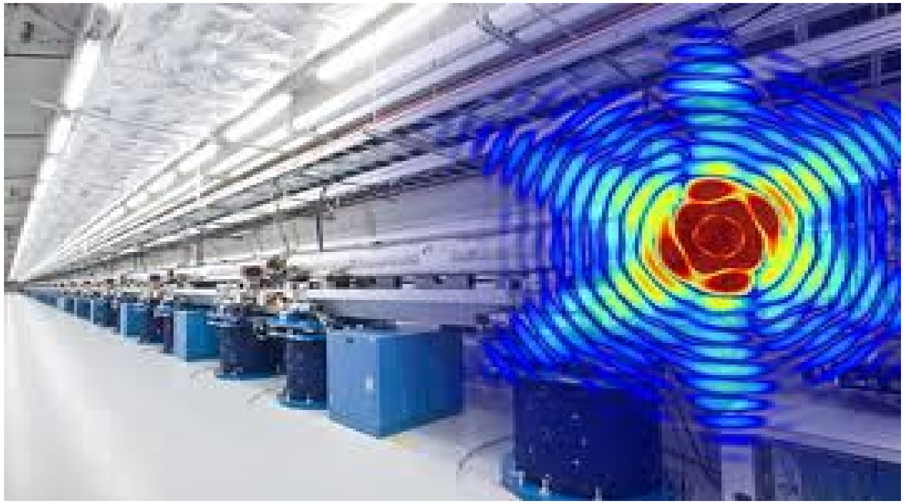
(0.25, 0, 0.65)

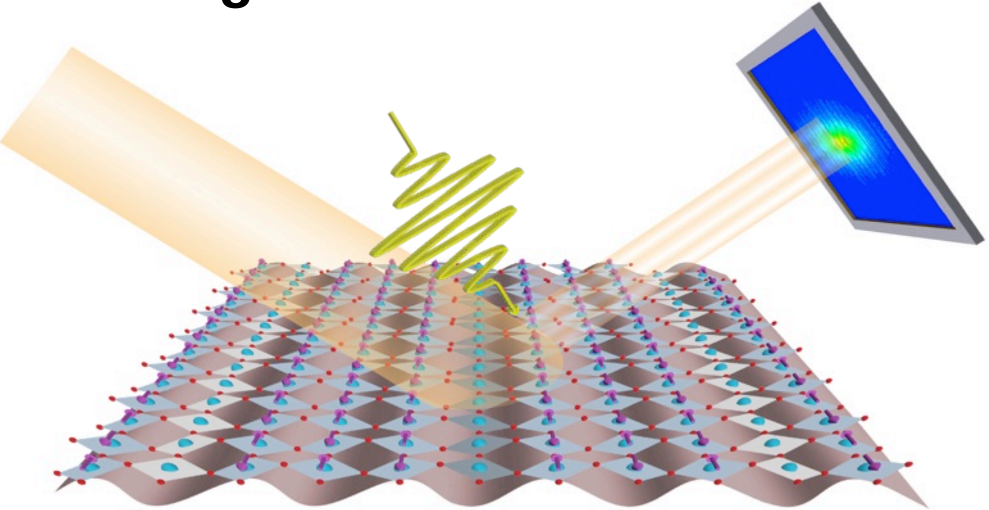


~ 10^{-9} efficiency

Abbamonte et al *Nature Physics 1, 155* (2005)

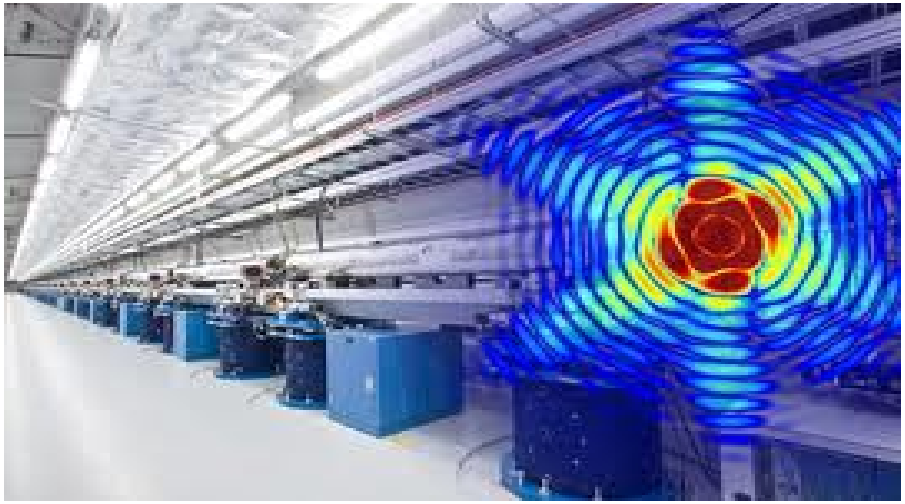
Ultrafast soft X-ray diffraction





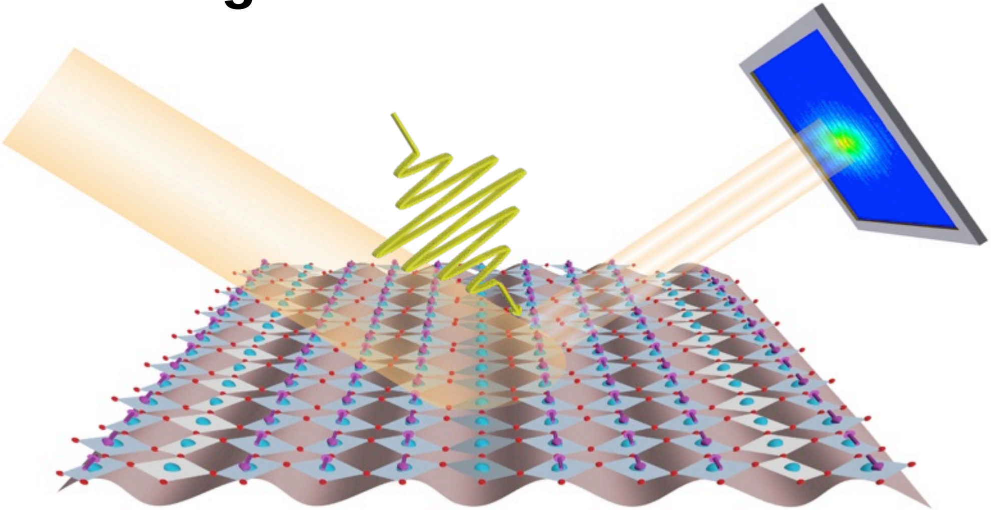
With John Hill, BNL

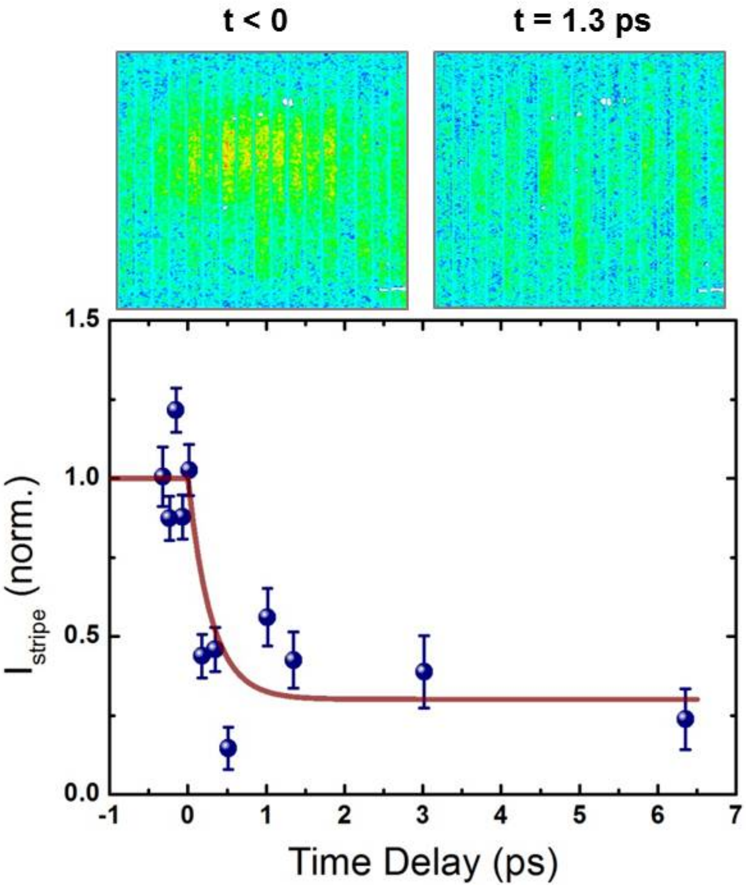
Ultrafast soft X-ray diffraction



O Kedge

(0.25, 0, 0.65)



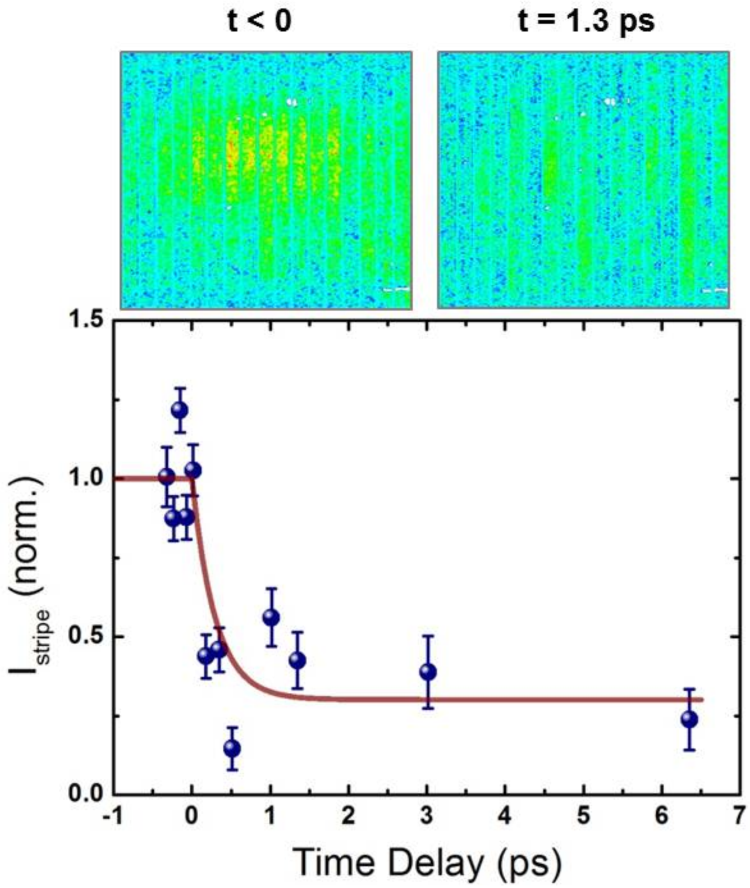


M. Foerst et al., Phys Rev Lett 112, 157002 (2014)

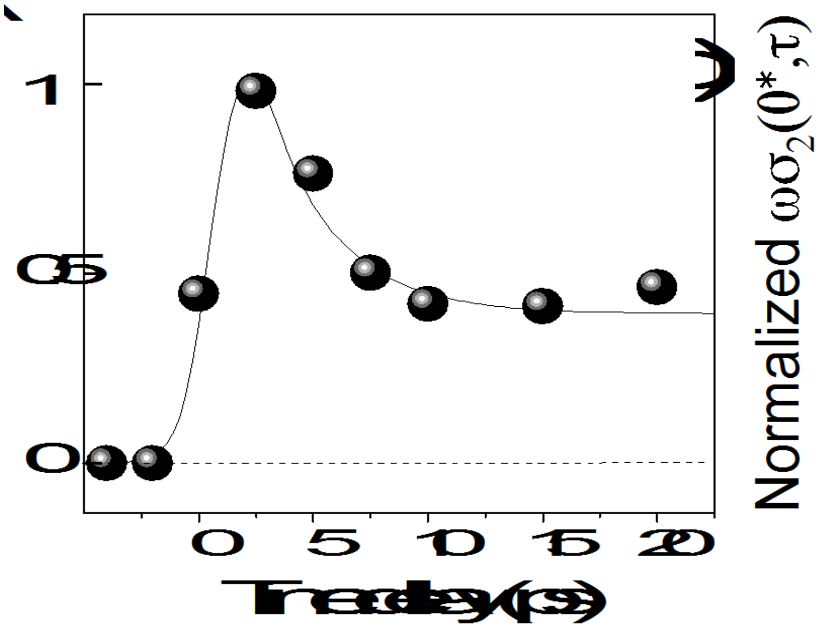
With John Hill, BNL

Charge stripe melting - superconductivity

- Charge Stripes melt concomitantly with the formation of the SC



superconductivity

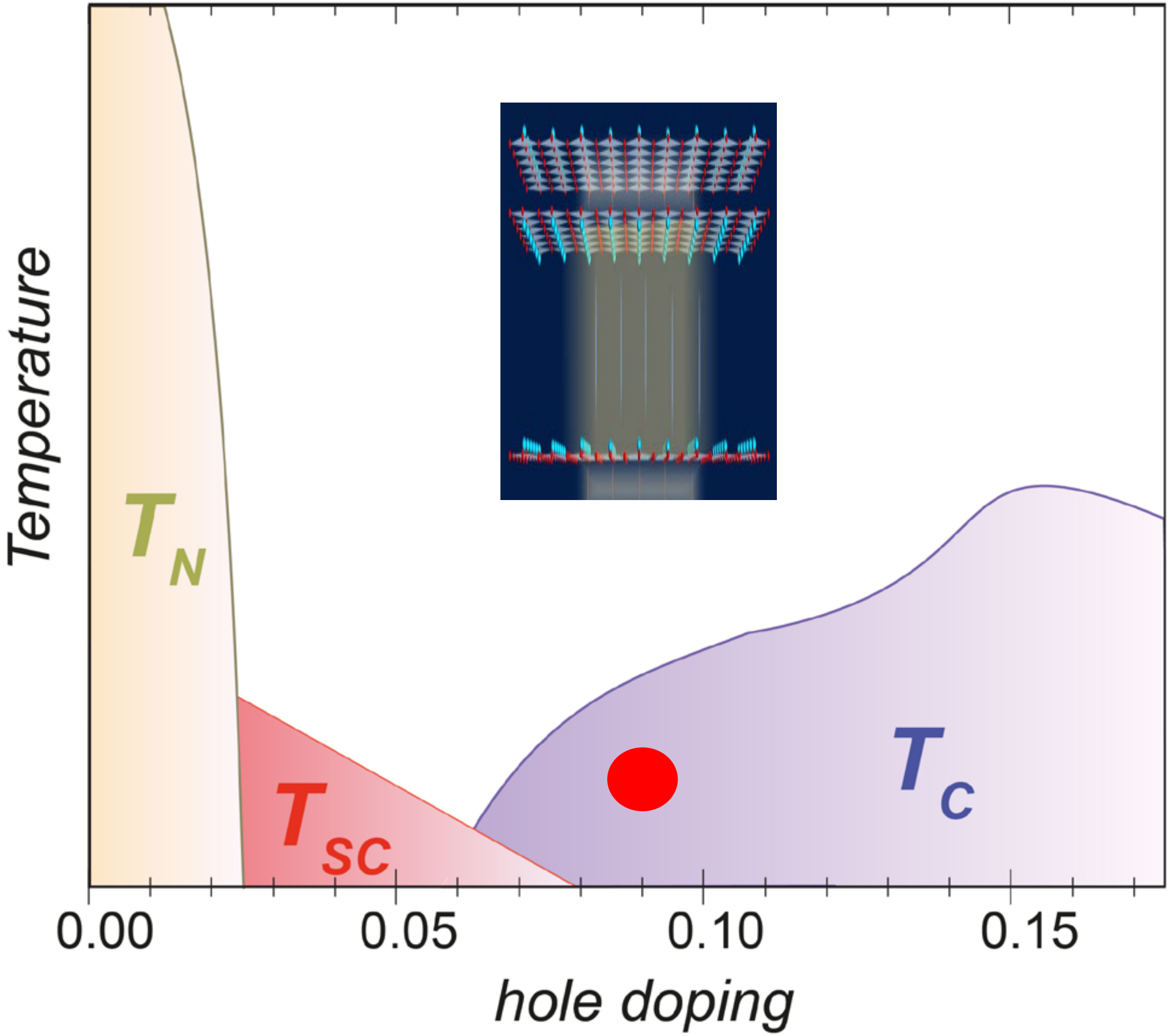


M. Foerst et al., Phys Rev Lett 112, 157002 (2014)

Other systems

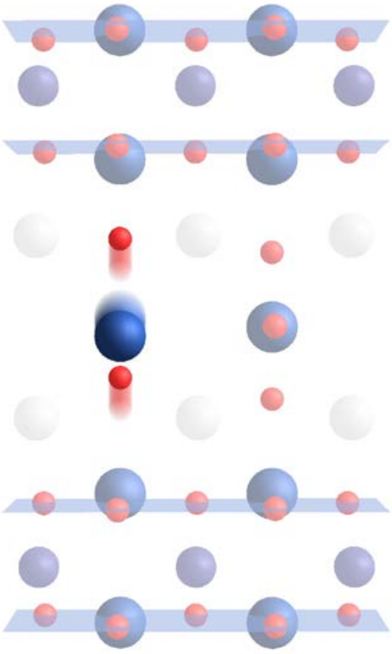
Can I do this in other cuprates ?

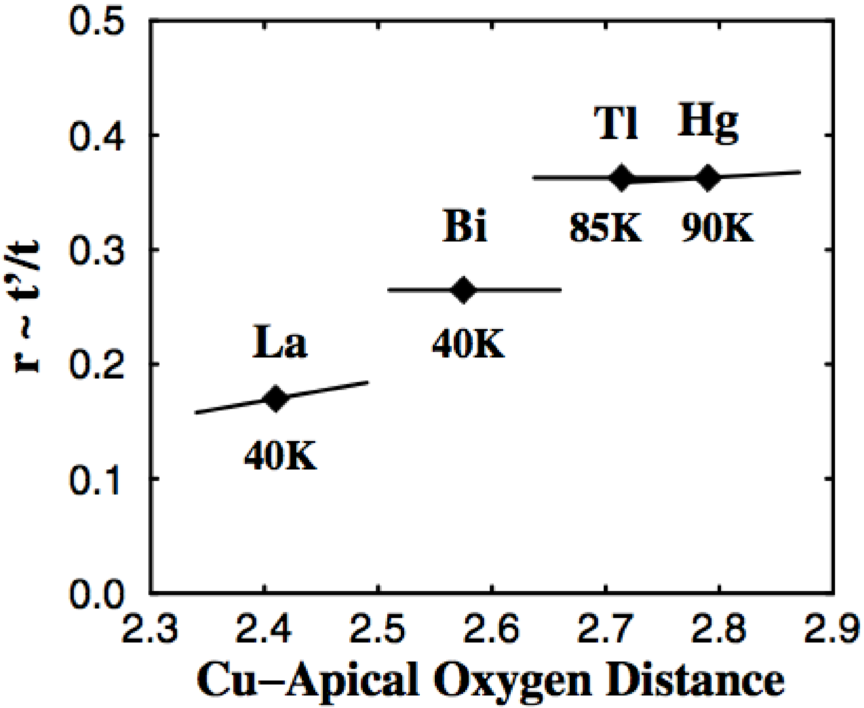
Bilayer cuprates: YBCO



With B. Keimer
MPI Stuttgart

Apical oxygen correlates with T_c at equilibrium

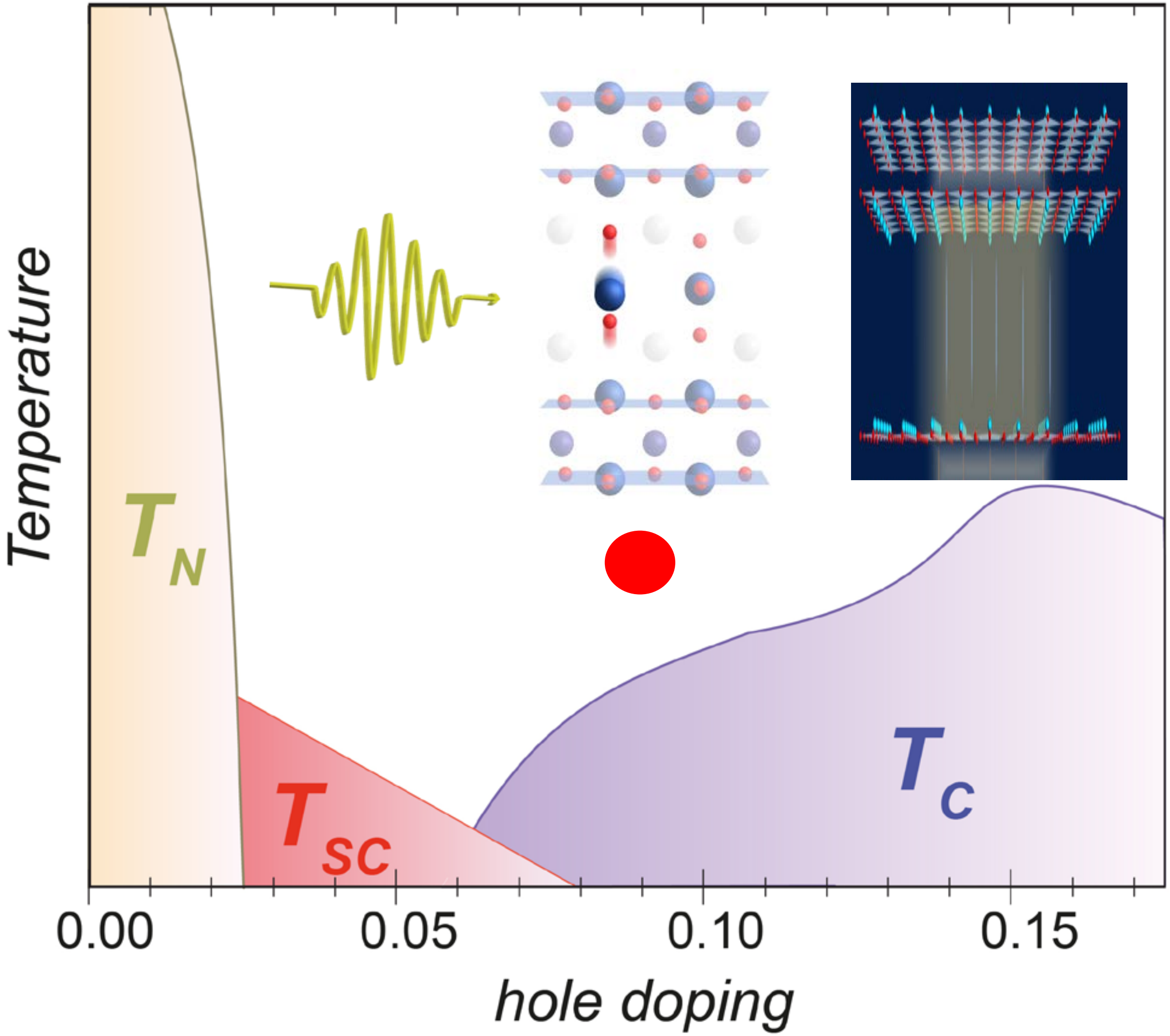




E. Pavarini et al., *PRL 8*7, 047003 (2001)

C. Weber et al. Phys. Rev. B 82, 125107 (2010).

Can I induce coherence above T_c ?



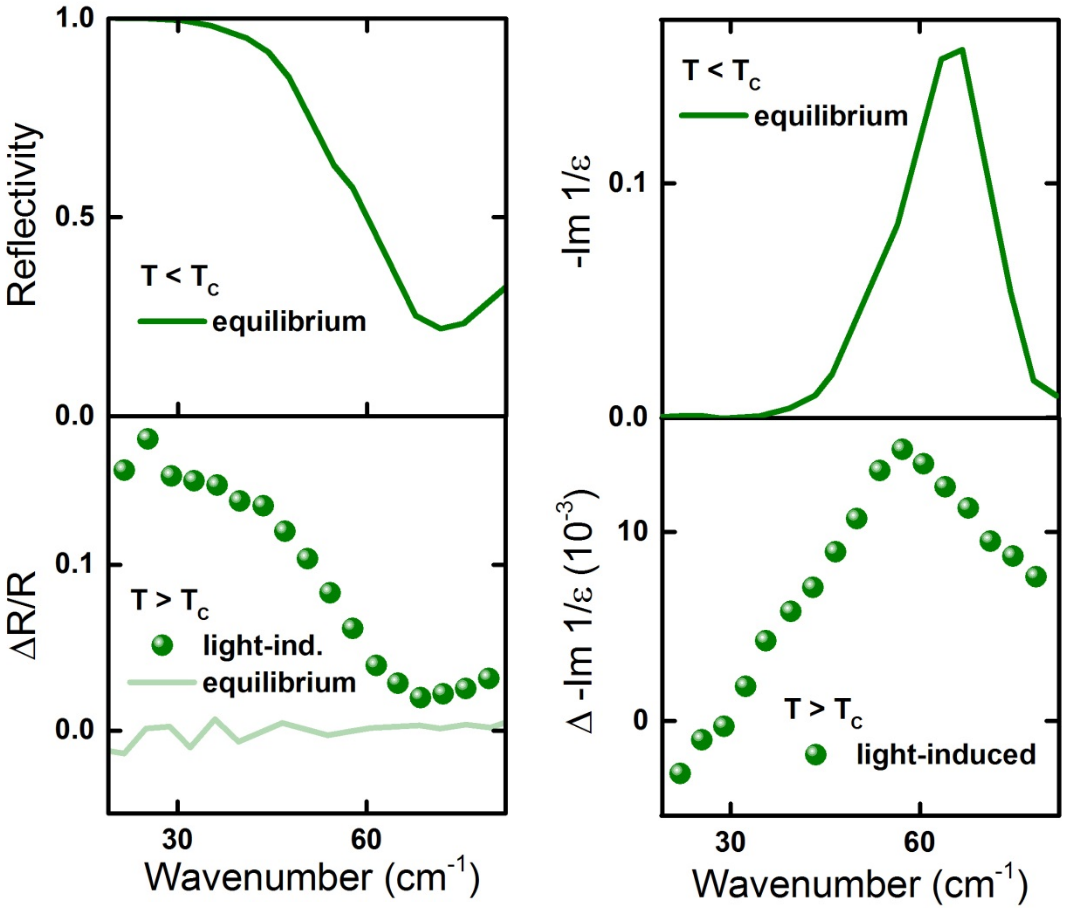
With B. Keimer
MPI Stuttgart

Light induced Josephson Coupling – 2 X Tc

Plasma edge

$\varepsilon_1(\omega_{JPR}) = 0$

$YBCO_{6.6}$ – 100 K

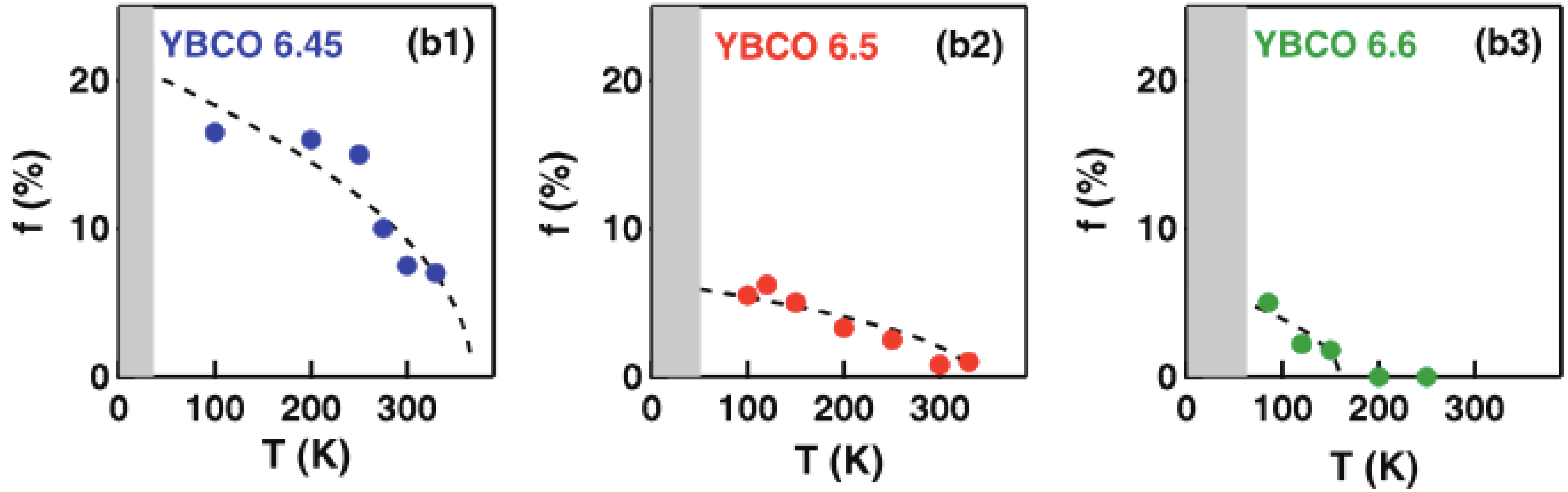


Equilibrium $T<T_c$

Light induced $T>T_c$

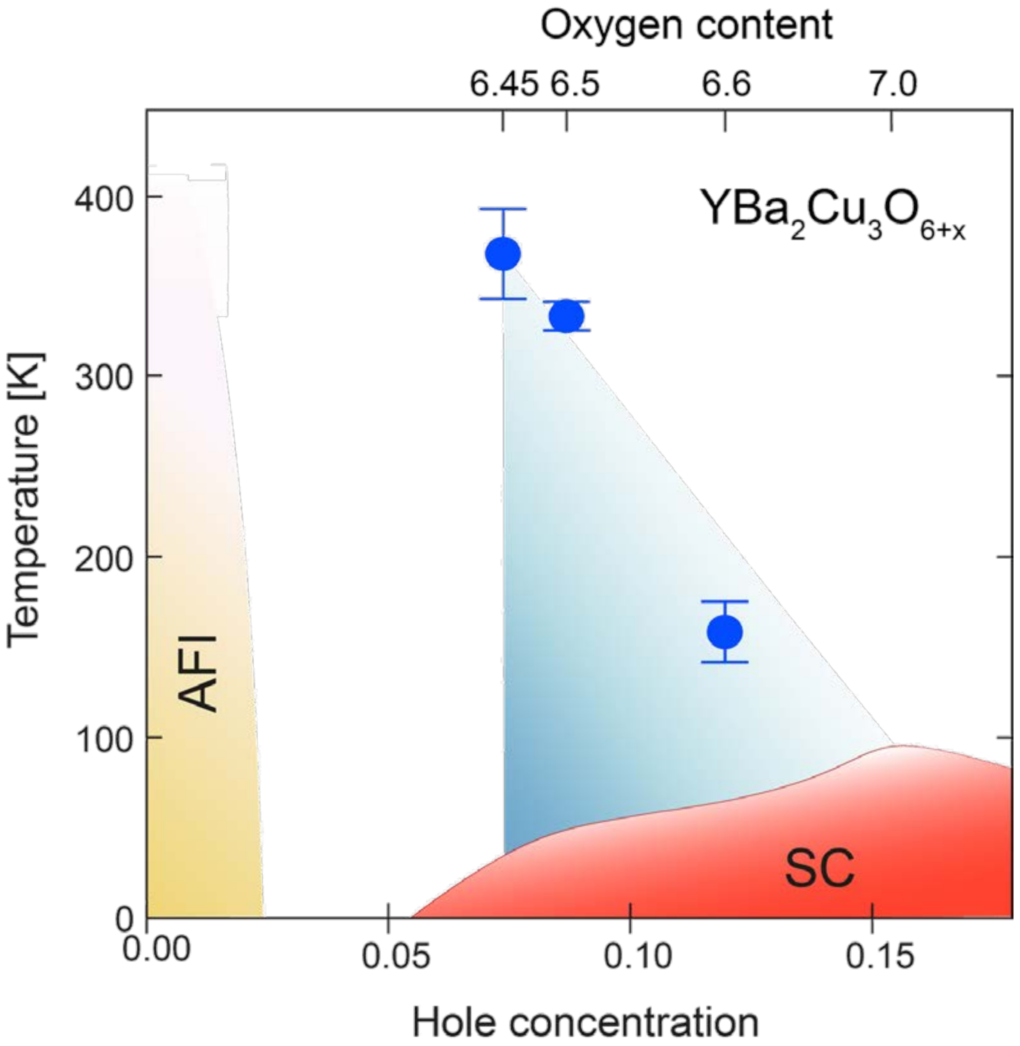
W. Hu. et al. *Nature Materials* 13, 705 (2014)

Surprise….. Up to room temperature



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

Throughout the pseudogap phase

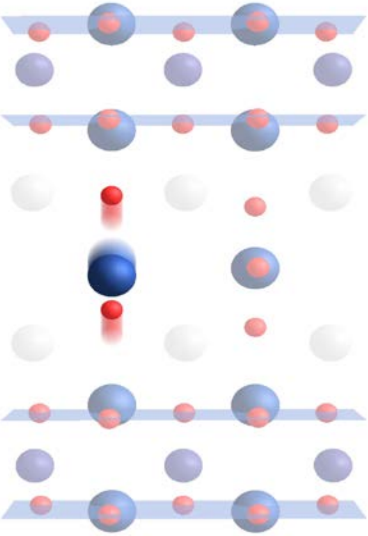


W. Hu. et al. *Nature Materials* 13, 705 (2014)

Underdoped YBCO

What is the lattice doing ?

Nonlinear Phononics: YBCO

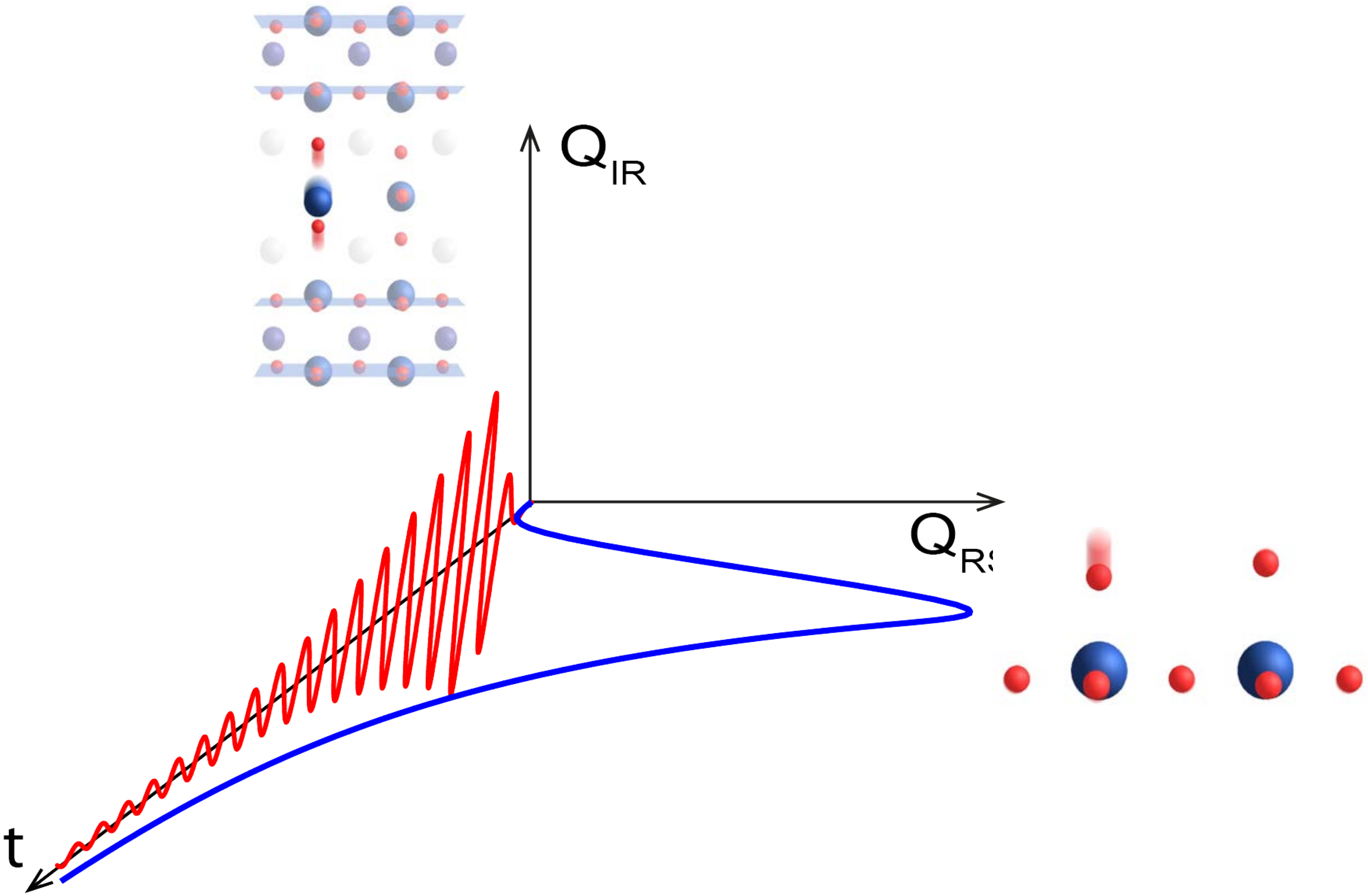


Q_{IR} of B_{1u} symmetry

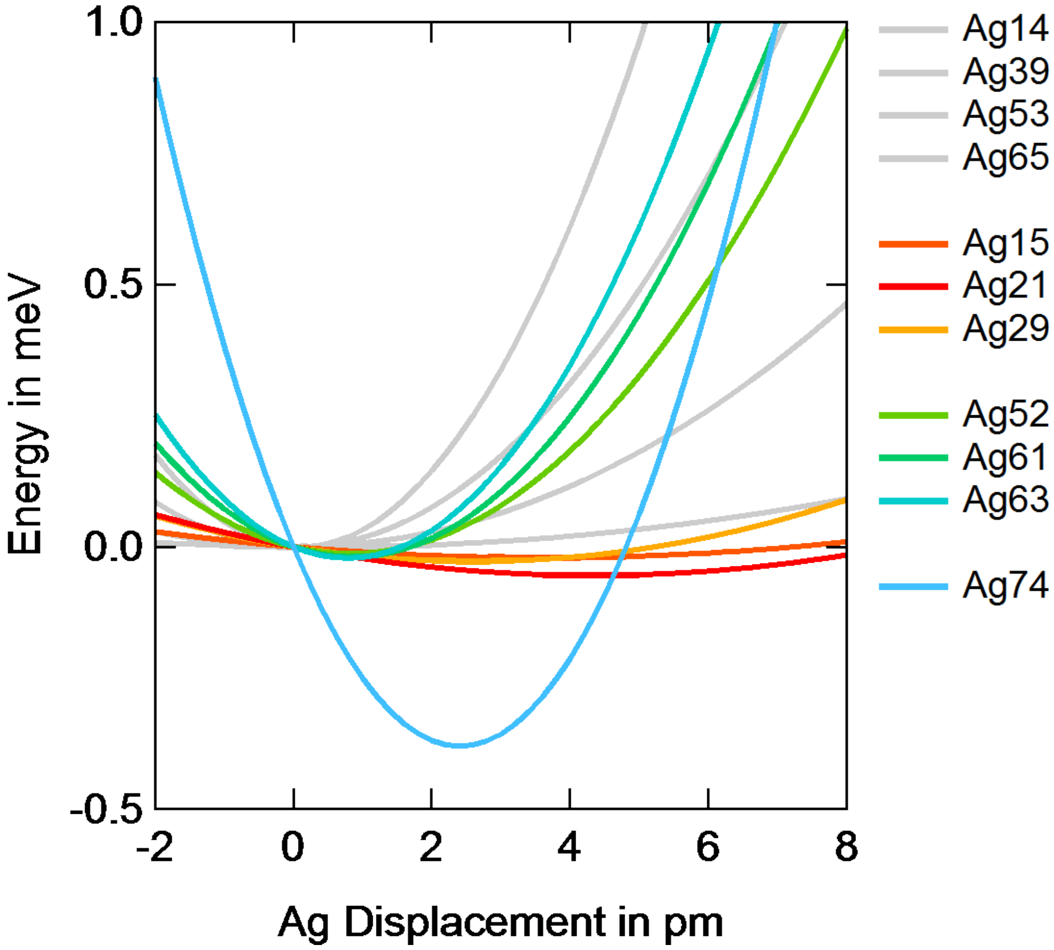
$Q_{IR}^2 Q_2 \neq 0$

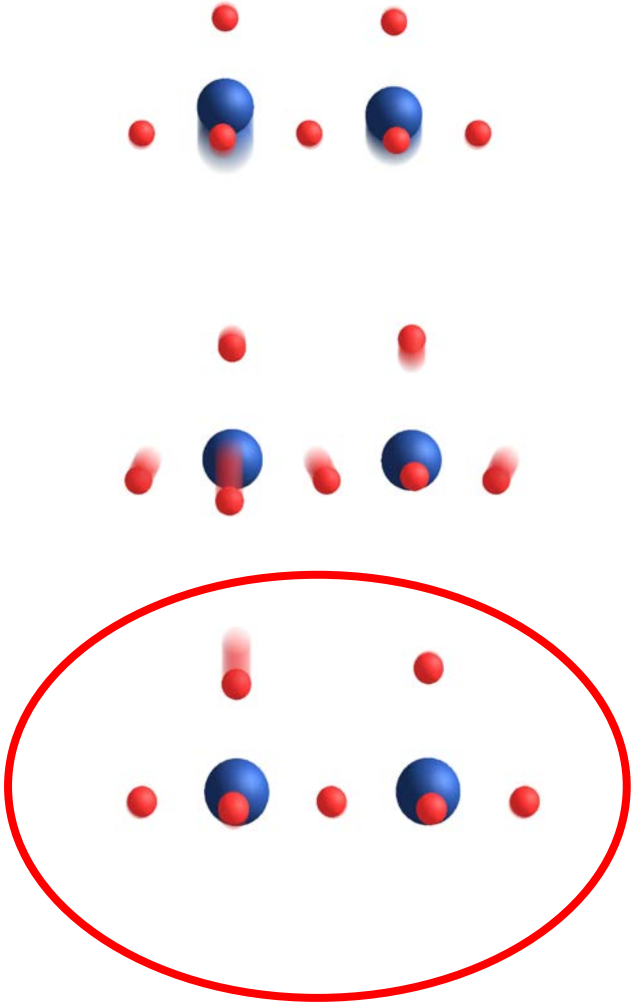
only if Q_2 is a Raman mode of A_g symmetry

Excite B_{1u} and displace along A_g



Doped YBCO: 11 A$_g$ Raman modes

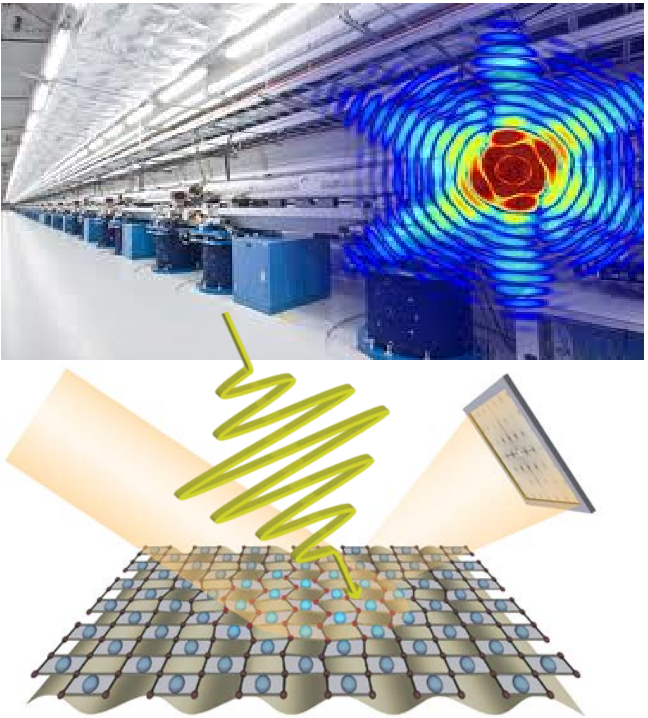




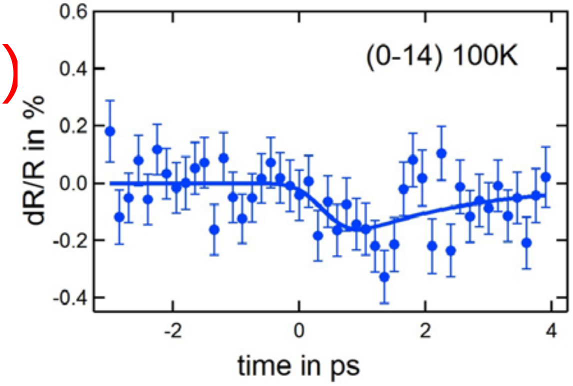
Only three Ag modes are coupled strongly with B1u

Alaska Subedi – Antoine Georges (Ecole Polytechnique)

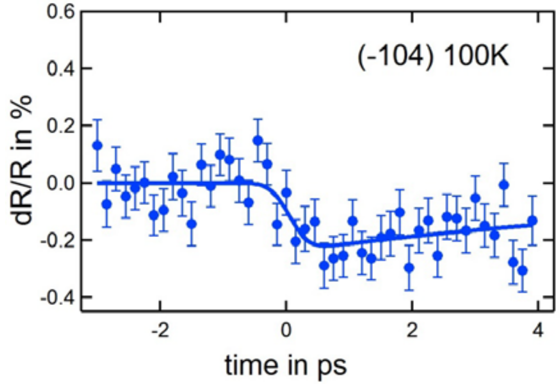
Femtosecond X-ray Scattering



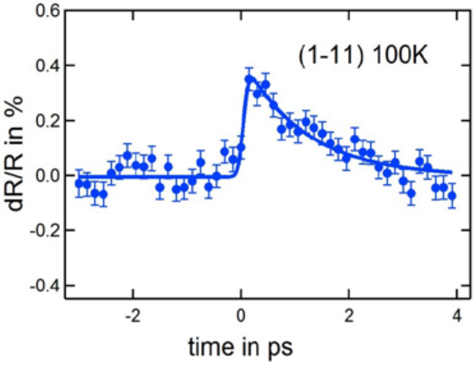
(0,-1,4)



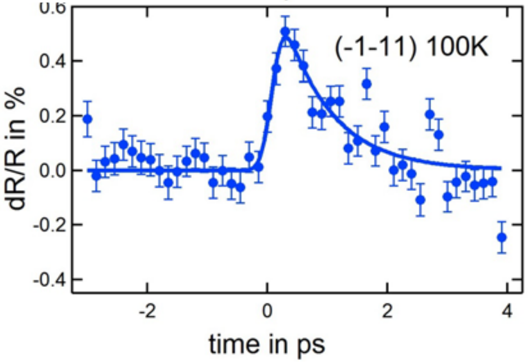
(-1,0,4)



(-1,1,1)

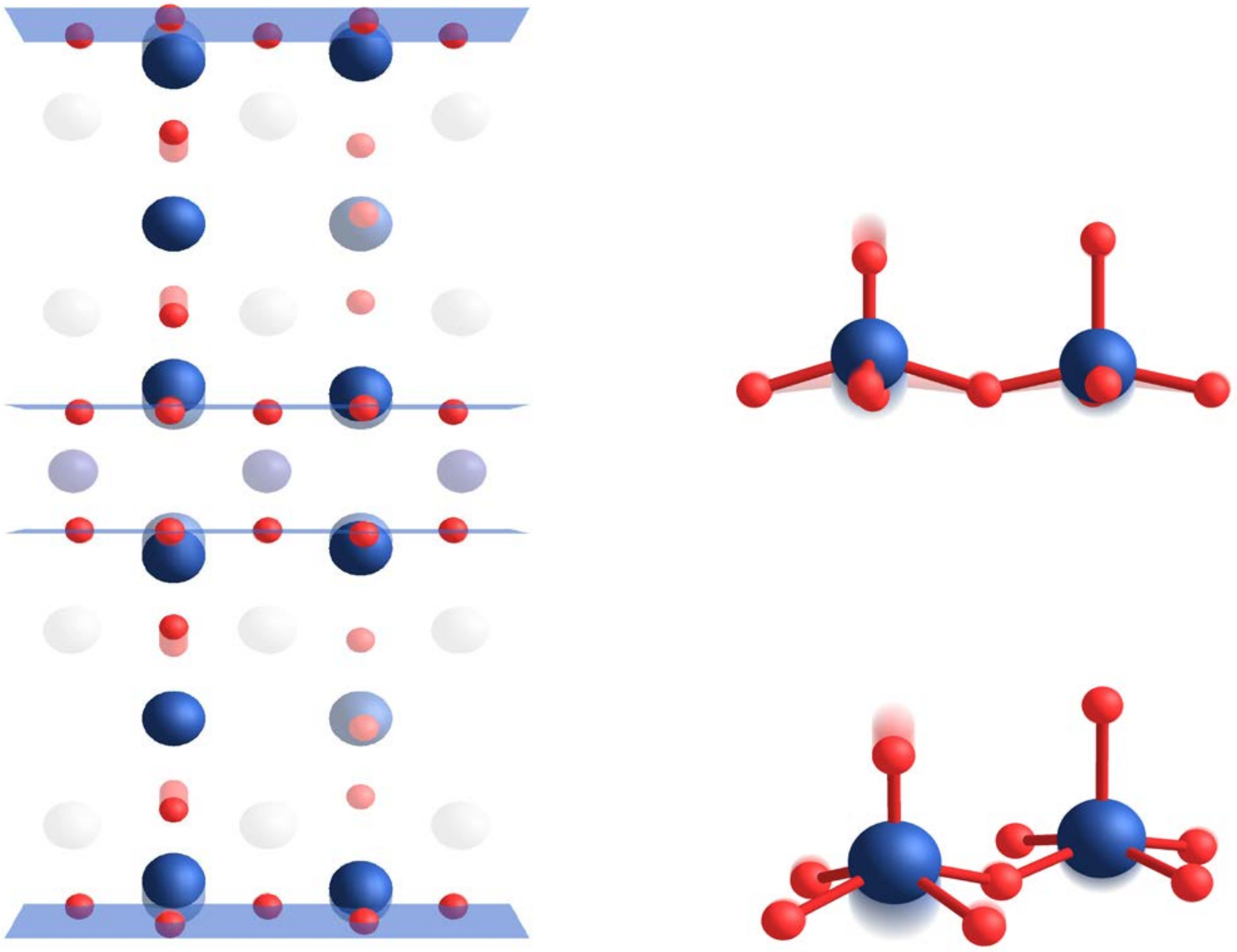


(1,-1,1)



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

A new, transient crystal structure

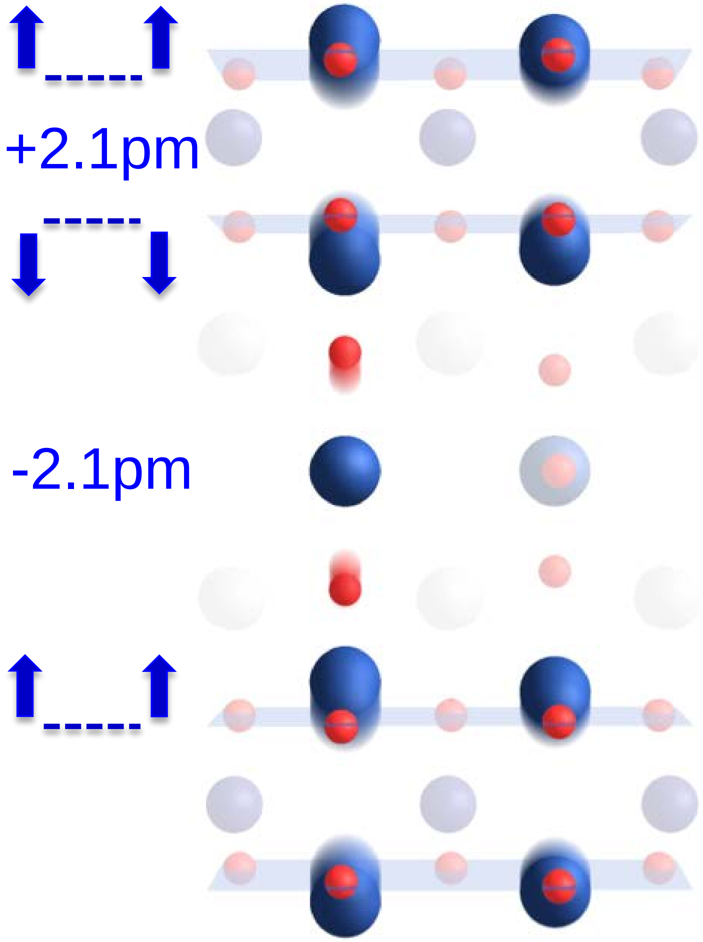


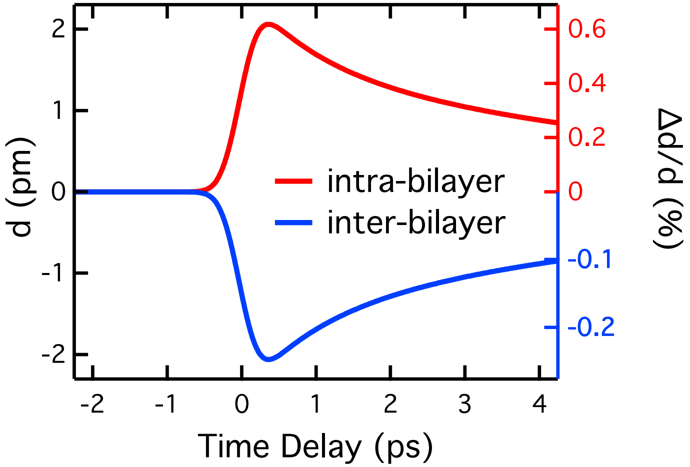
R. Mankowski et al. *Nature 516,71 (2014)*

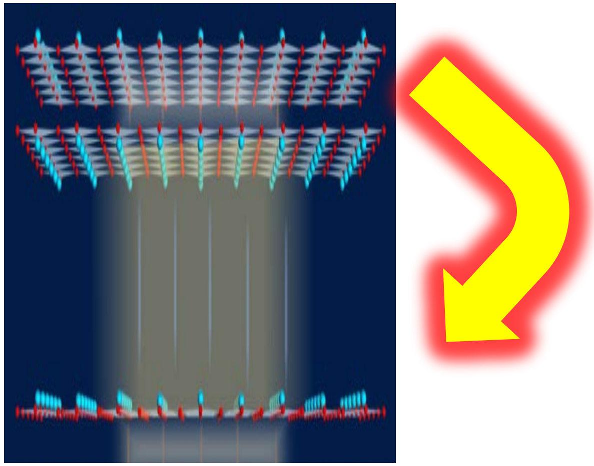
Dynamical materials discovery

Is this the structure of a room temperature superconductor ?

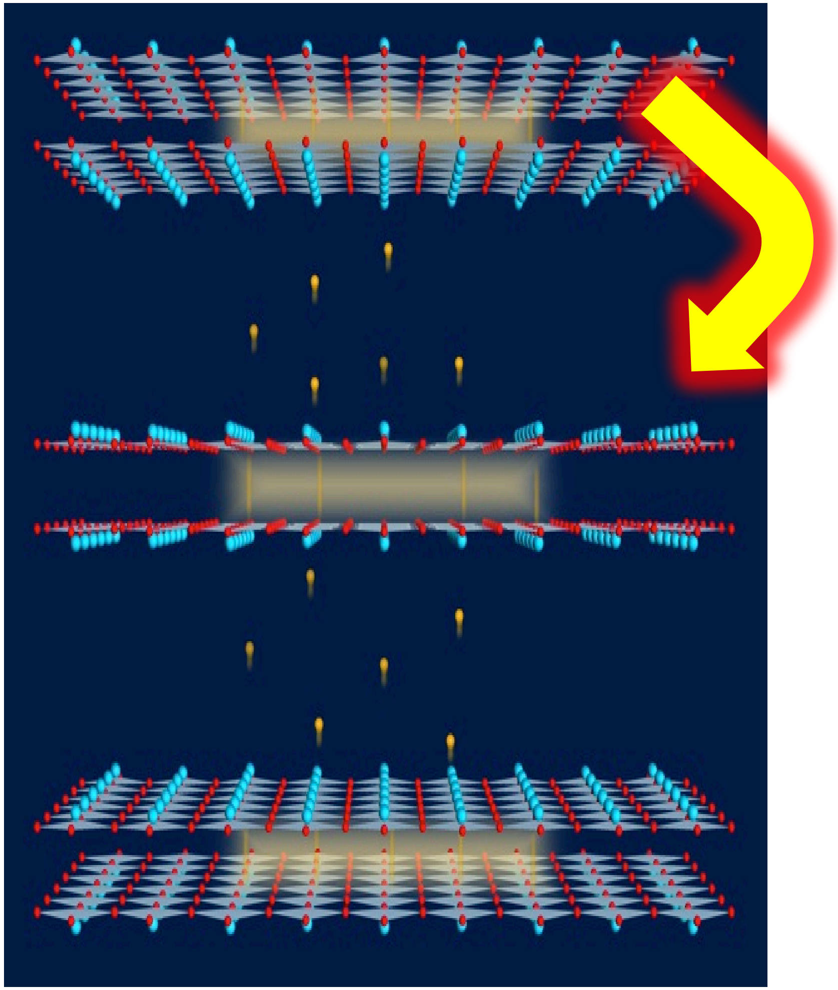
1) Staggered motion of the planes

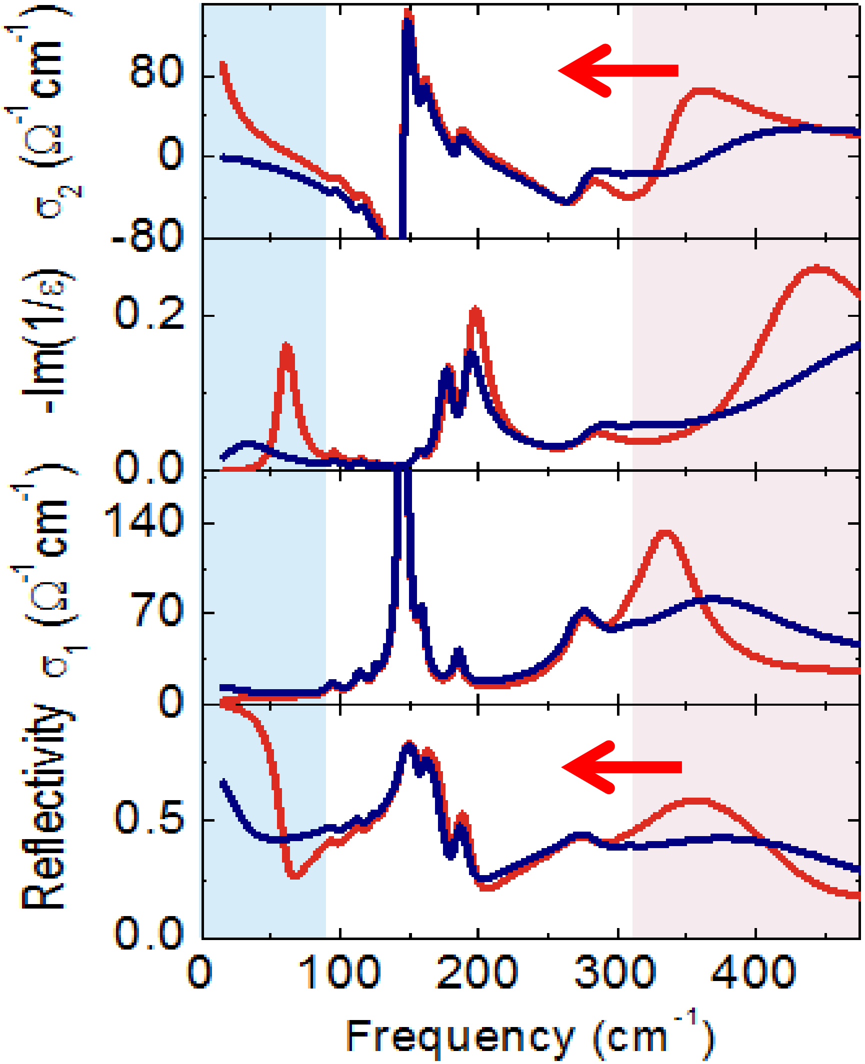






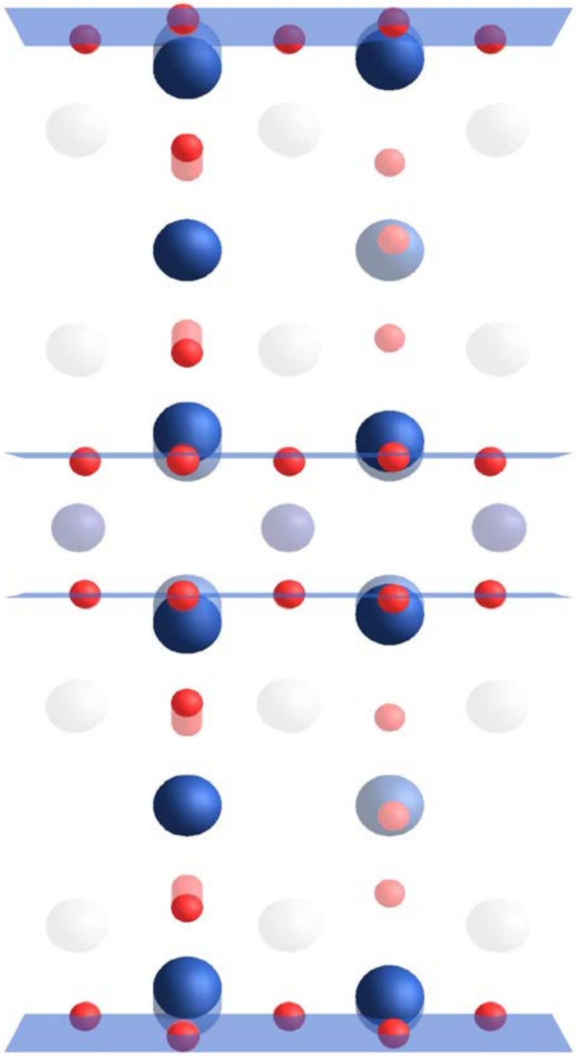
Spectral weight from high frequency

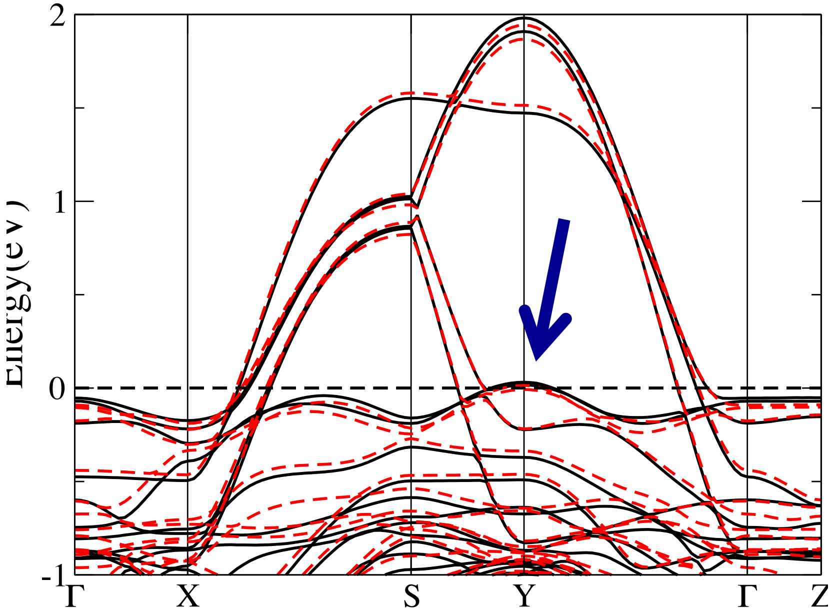


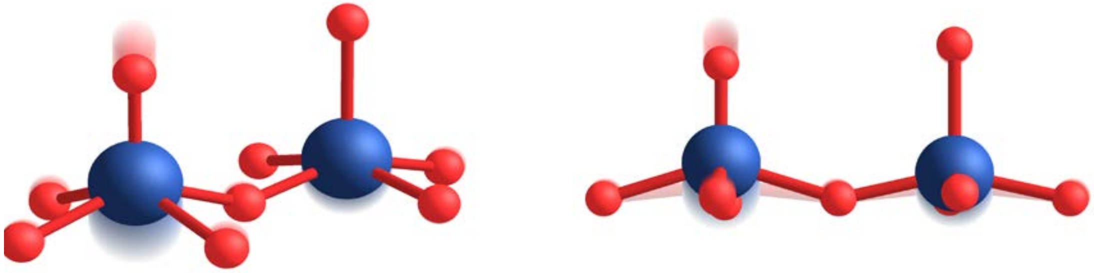


W. Hu. et al. *Nature Materials* 13, 705 (2014)

2) Empty chain band moves down in energy

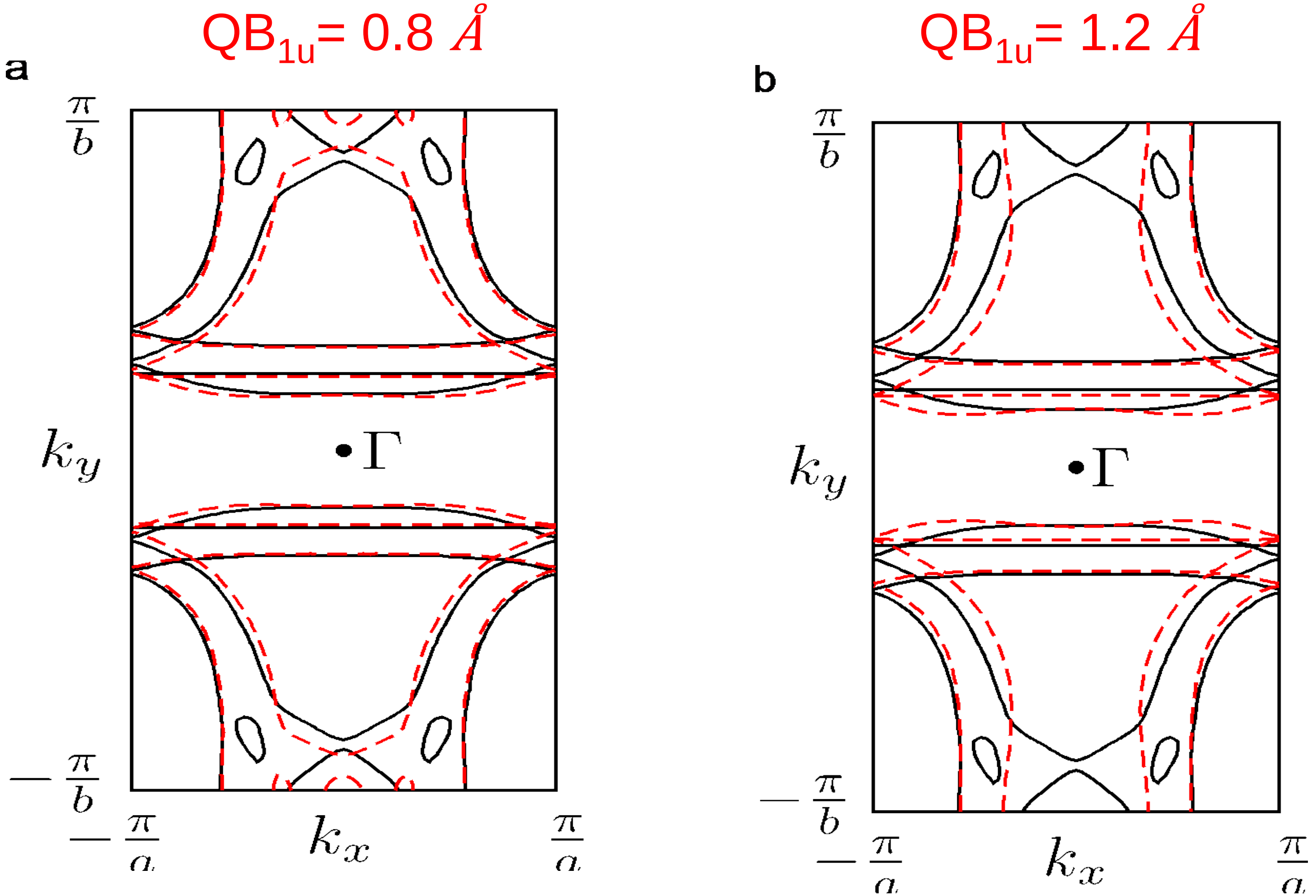






R. Mankowski et al. *Nature 516,71 (2014)*

3) A “cleaner” LDA electronic structure

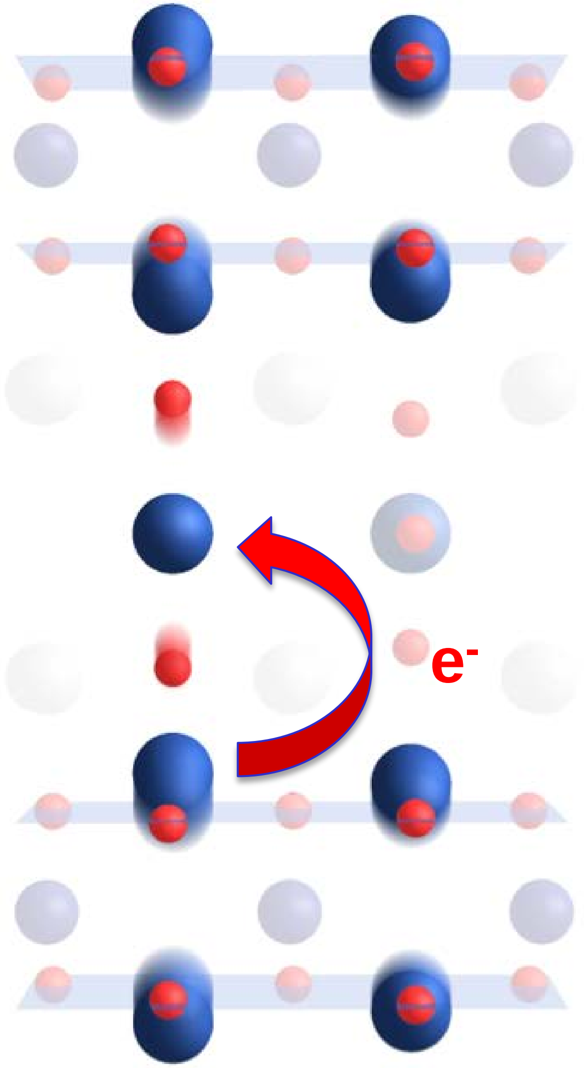


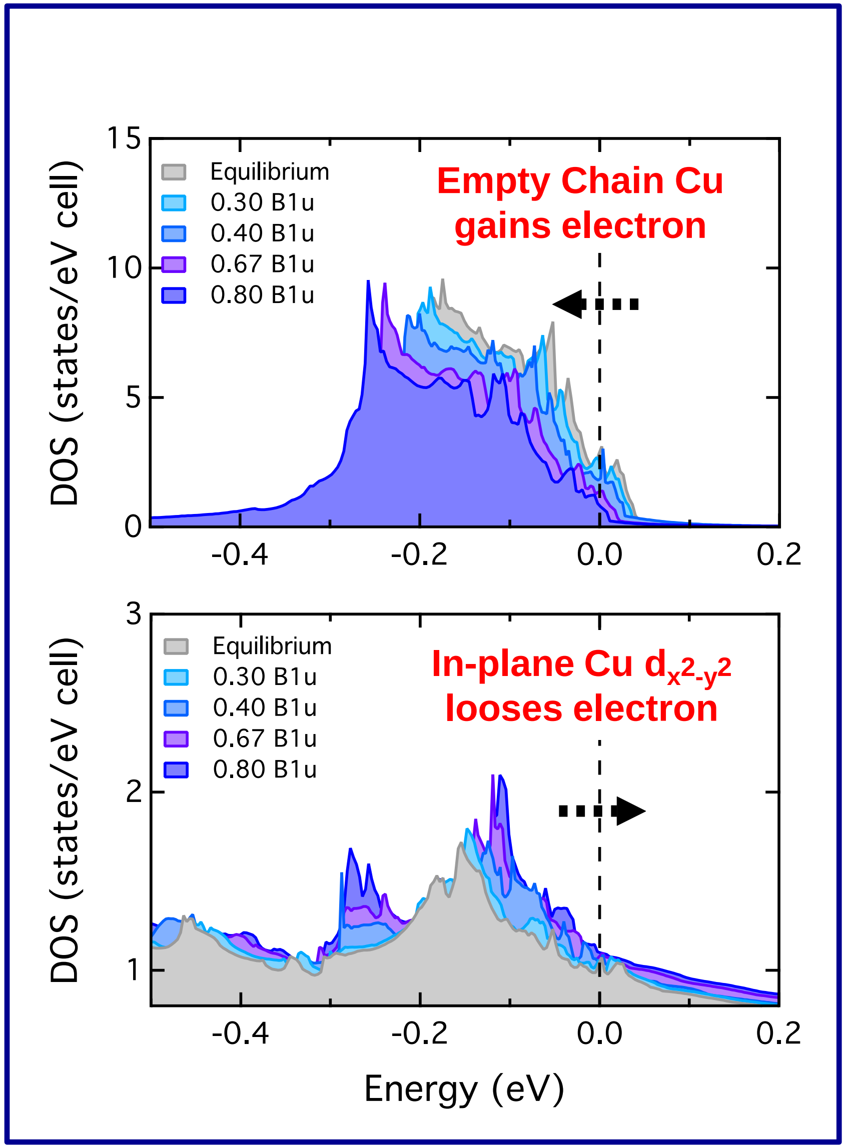
QB_{1u}= 0.8 $\AA$

QB_{1u}= 1.2 $\AA$

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

3) Charge transfer from the planes to the chains

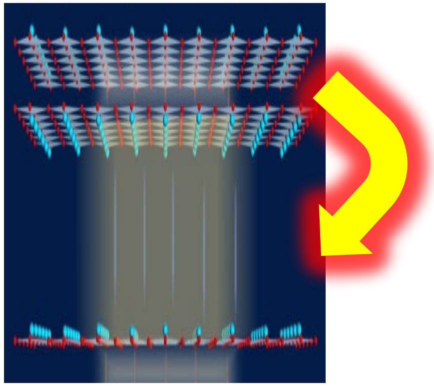




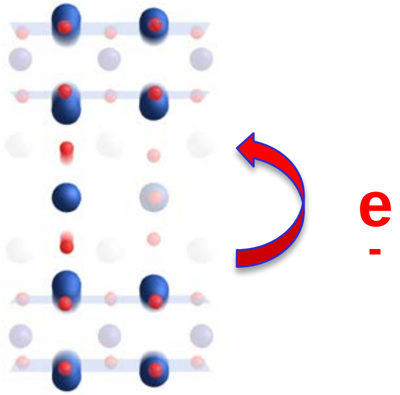
R. Mankowski et al. *Nature 516,71 (2014)*

Summary: three good things

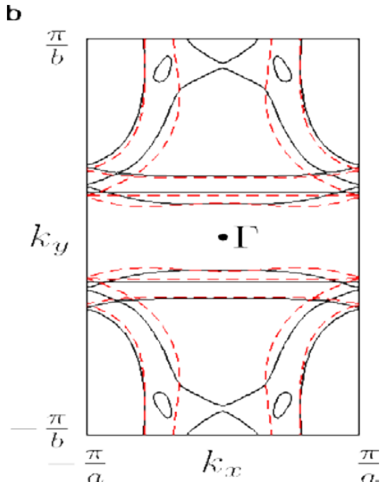
1) Staggered motion of the layers



2) Charge transfer from to chains



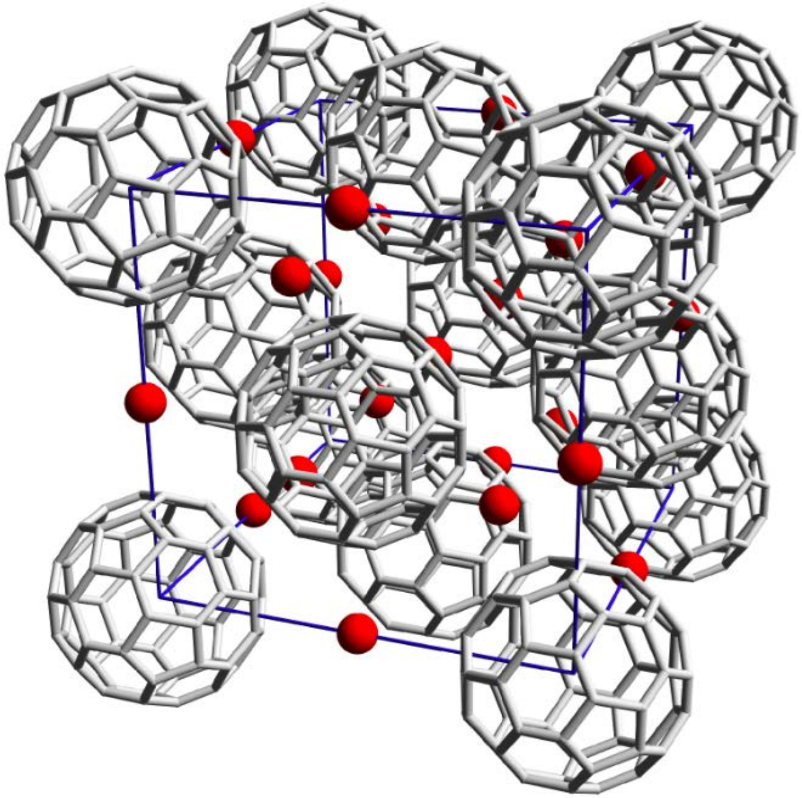
3) dx^2-y^2 Fermi surface

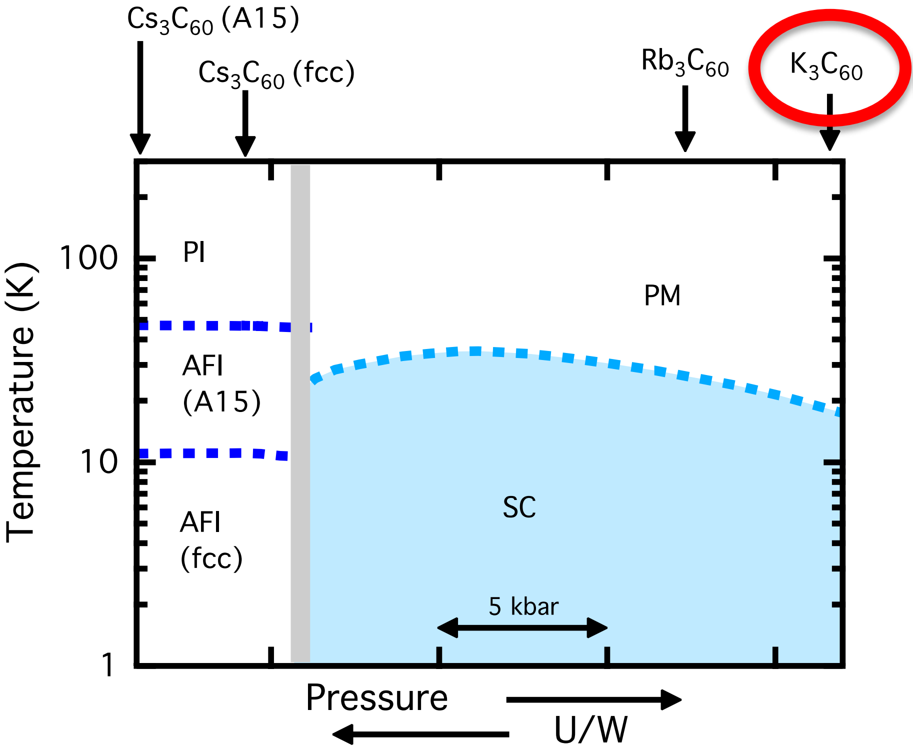


Light enhanced superconductivity

Is this a phenomenon specific to cuprates or is it more general ?

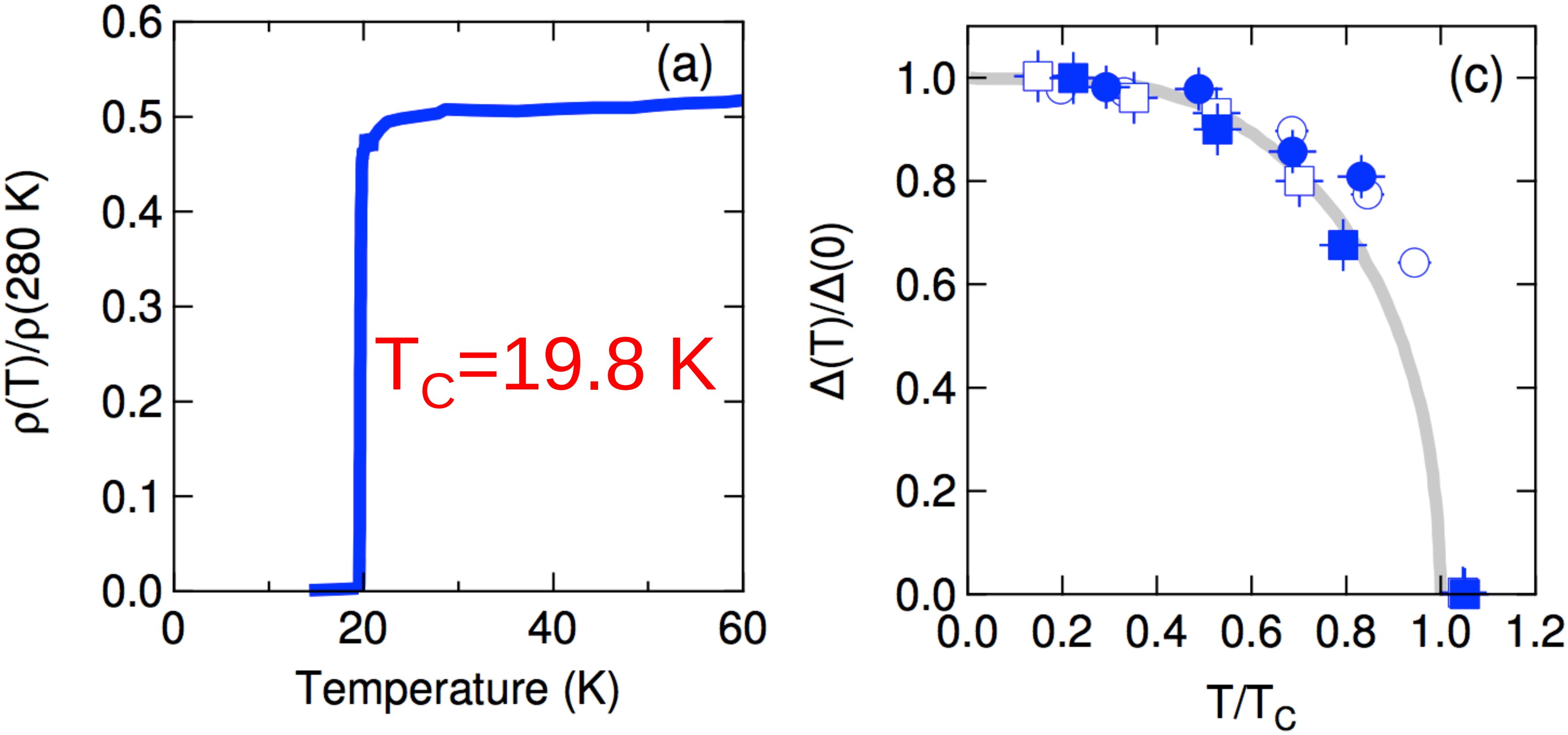
K_3C_{60}: a 20 K superconductor





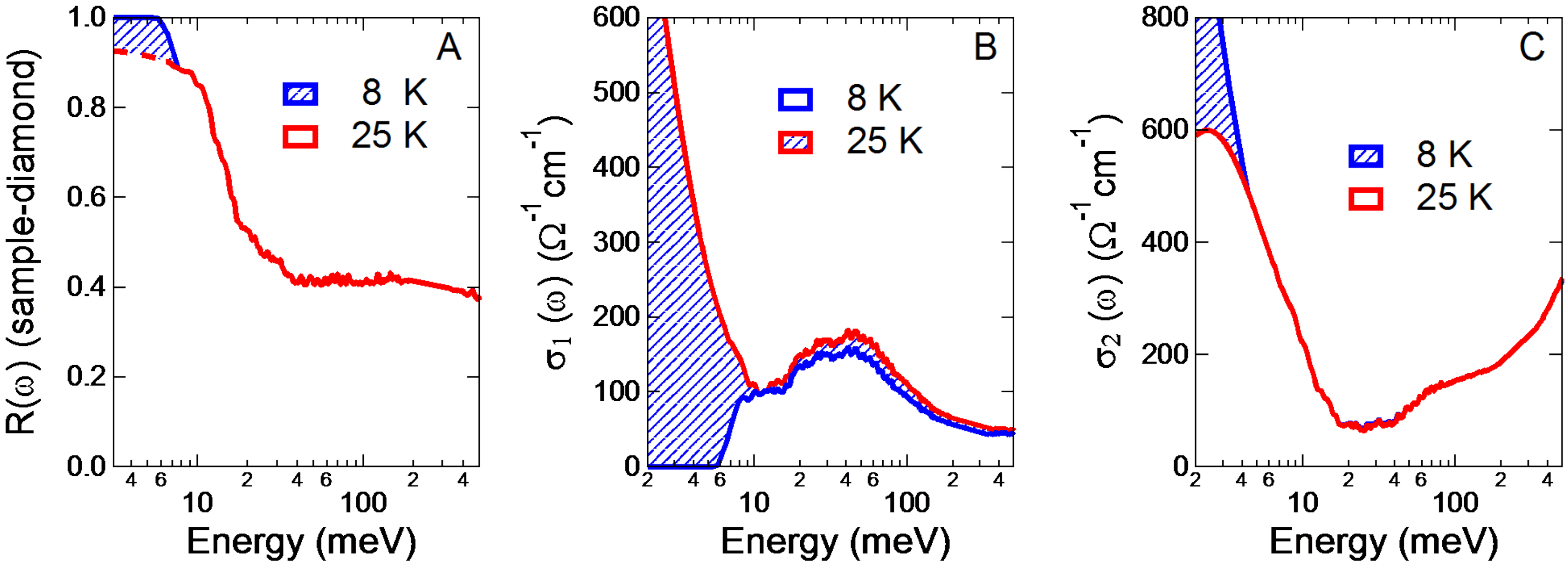
- Organic molecular solid
- High T_C (20 K)
- 3D electronic structure

Equilibrium Superconductivity in K_3C_{60}



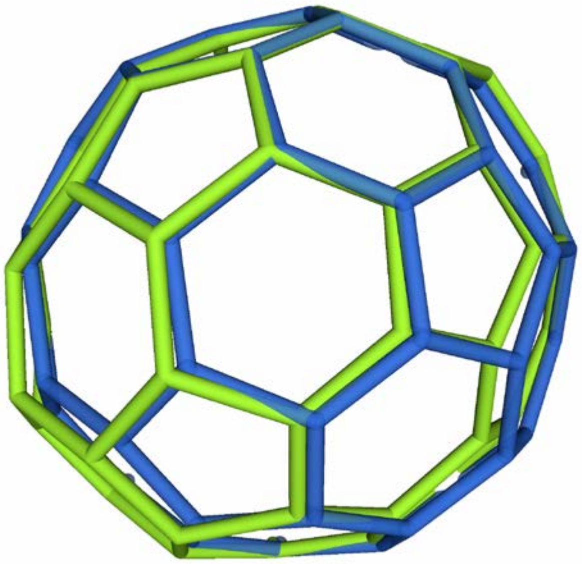
From literature data, MM PhD thesis

Equilibrium Superconducting Transition



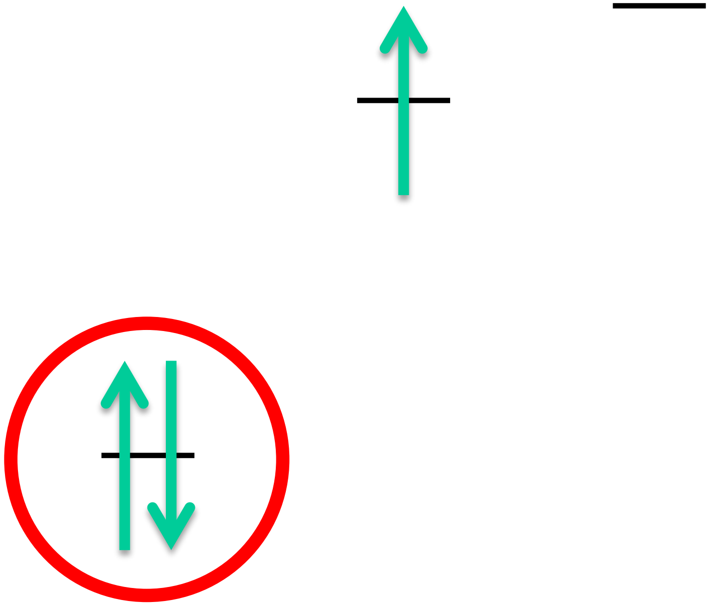
- Increase in R(ω)
- Gap opening in $\sigma_1(\omega)$
- Increase in $\sigma_2(\omega)$

Pairing Interaction in K_3C_{60}



🟩 H_g mode (JT distortion)

🟦 Undistorted



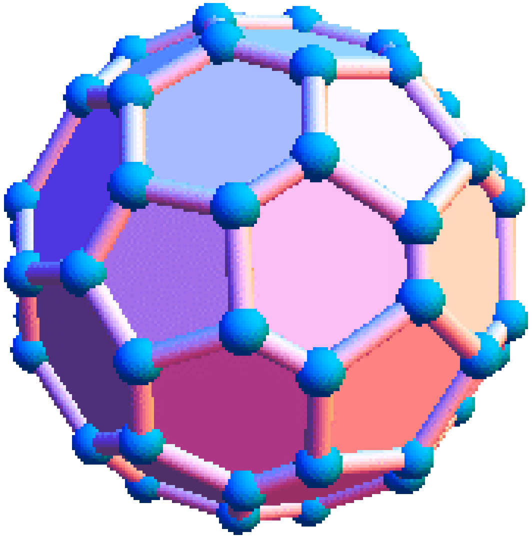
"On ball" vibrations plus correlations favor local pairing

Schluter, Varma, Tosatti, Capone, Gunnarson…….

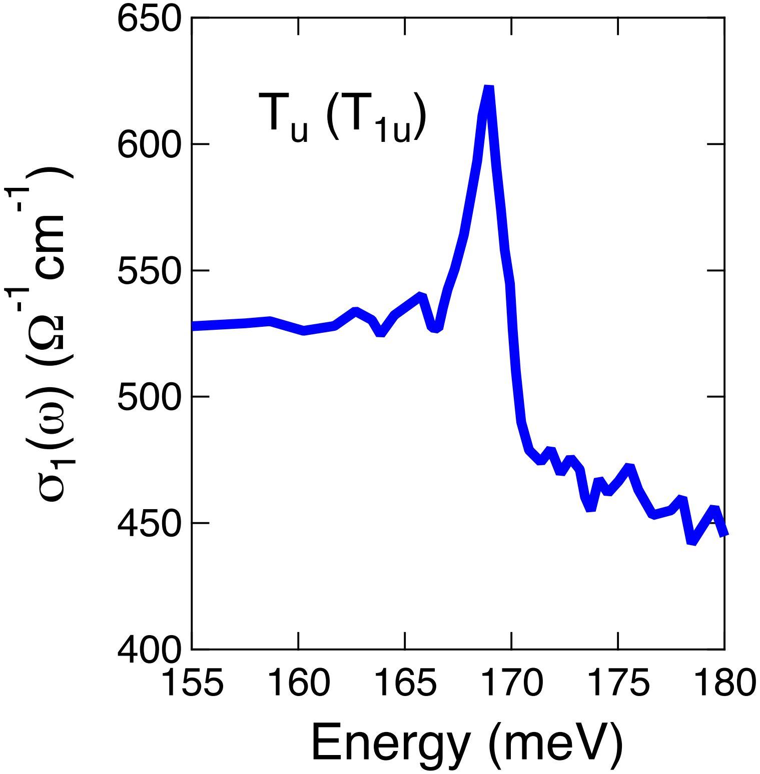
Kivelson, Chakravarty

Vibrational pump

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

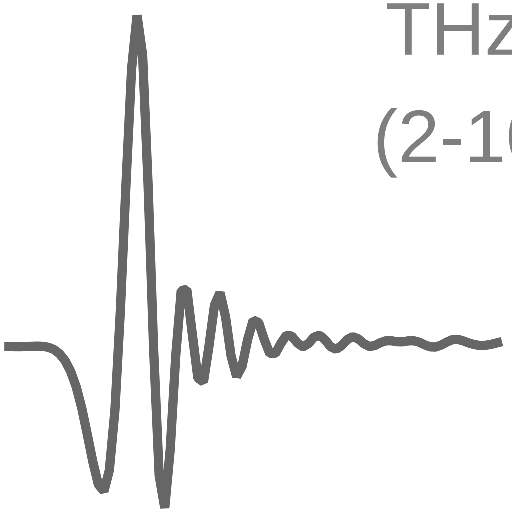


MIR pump 170 meV (7.3 μm)



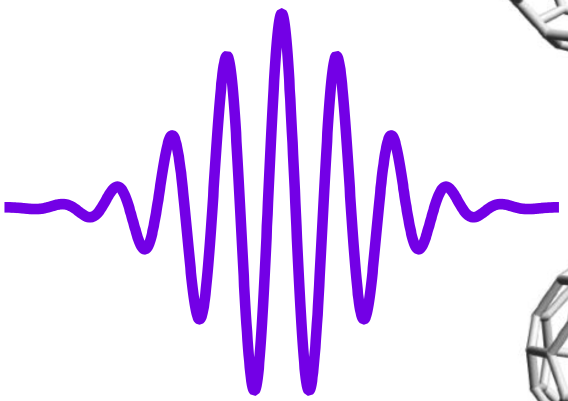
Iwasa et al. PRB **51,** 3678 (1995)

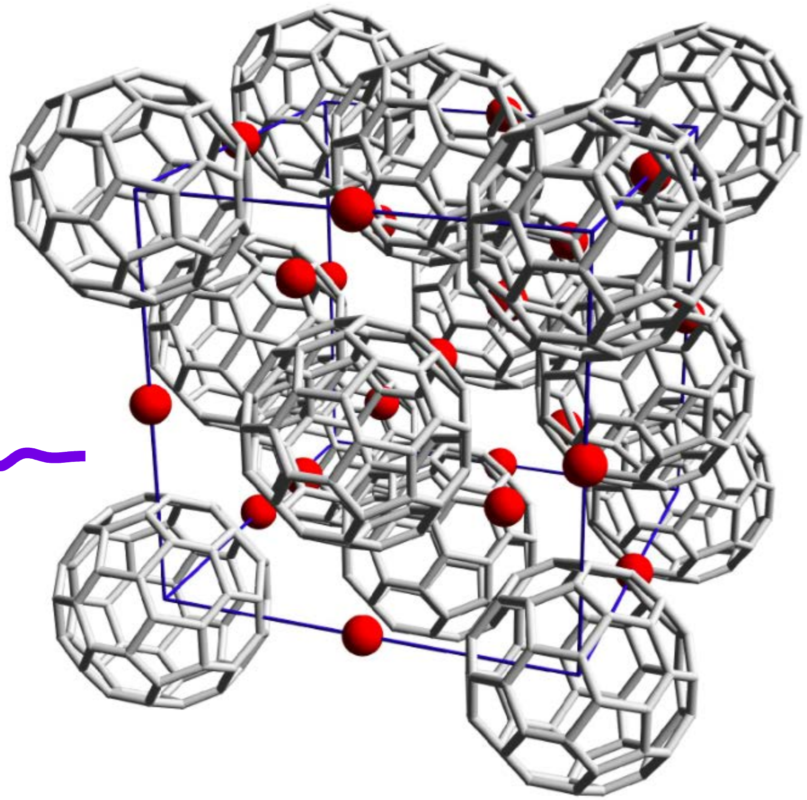
Vibrational pump THz probe in K_3C_{60}



THz probe

(2-10 meV)

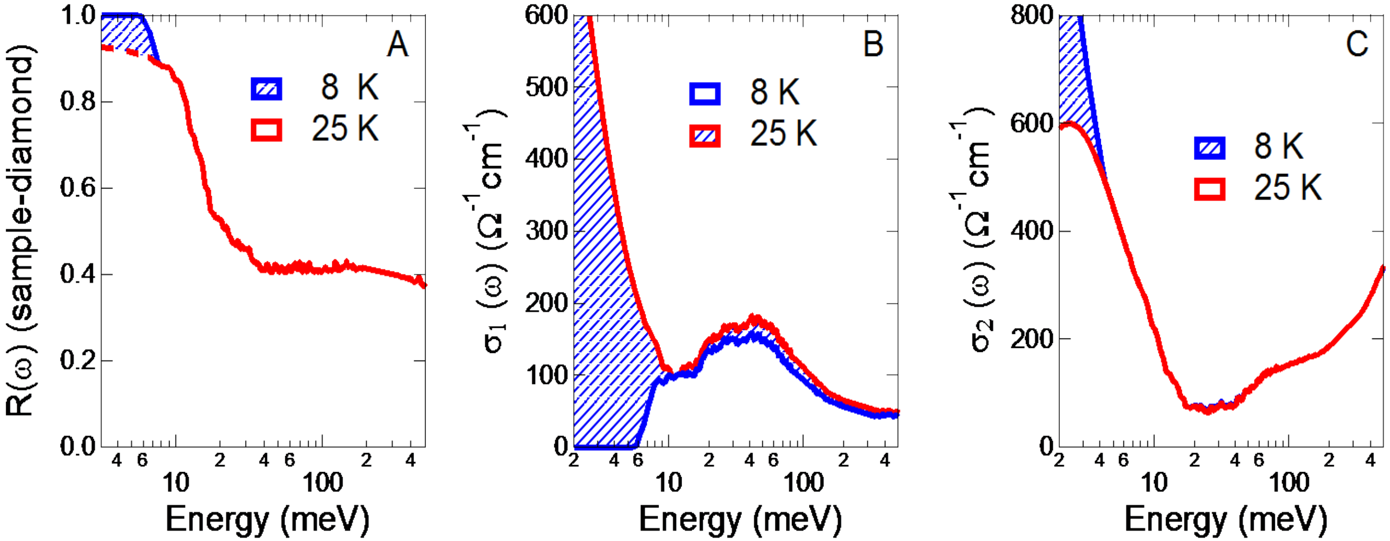




MIR pump 170 meV (7.3 μm)

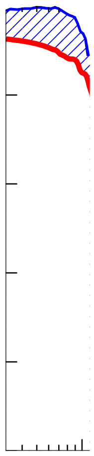
Striking similarity with the low temperature SC

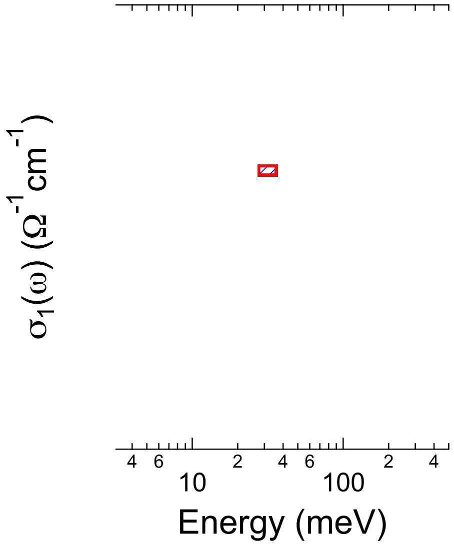
Cooling



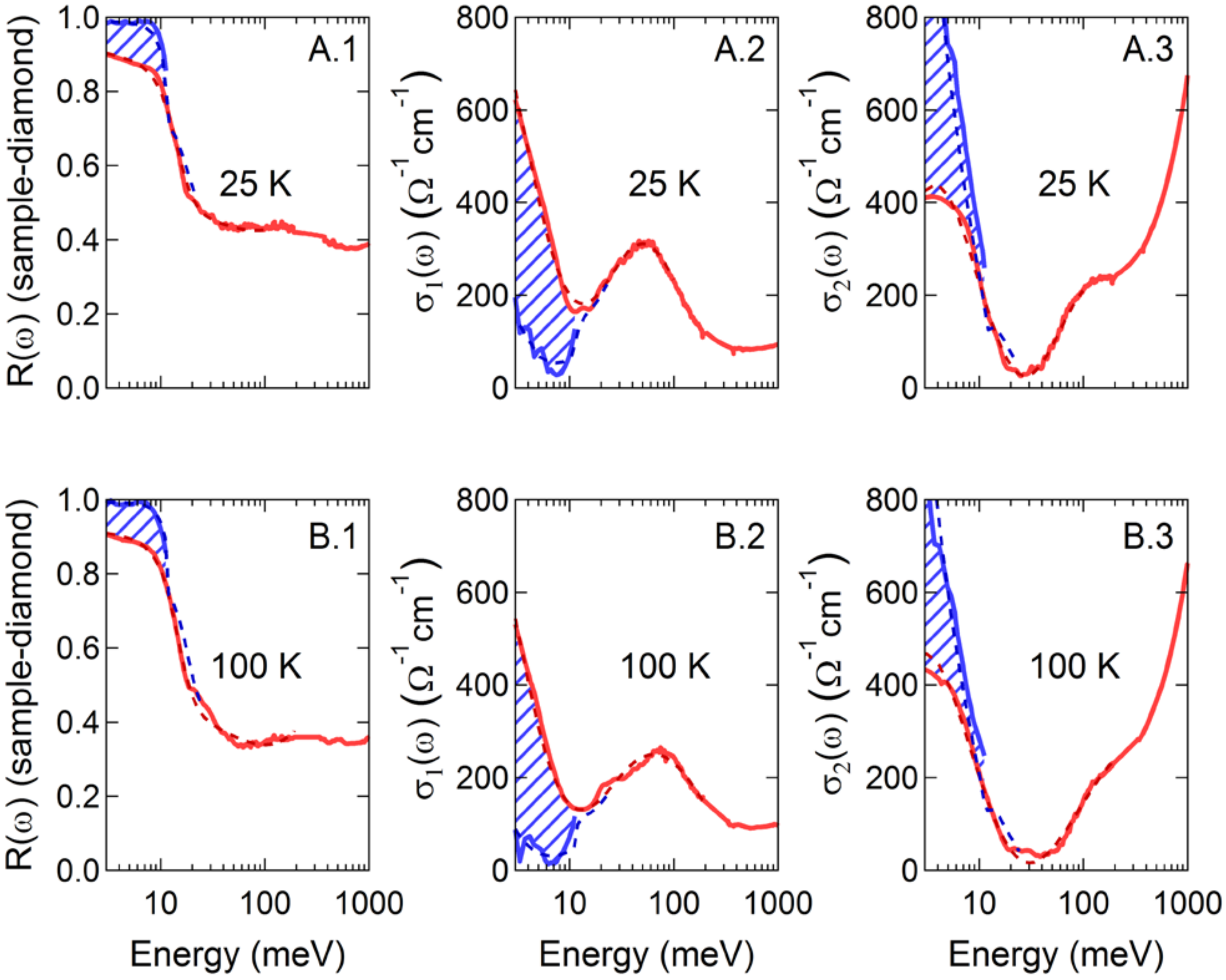
Light-induced

T=25 K

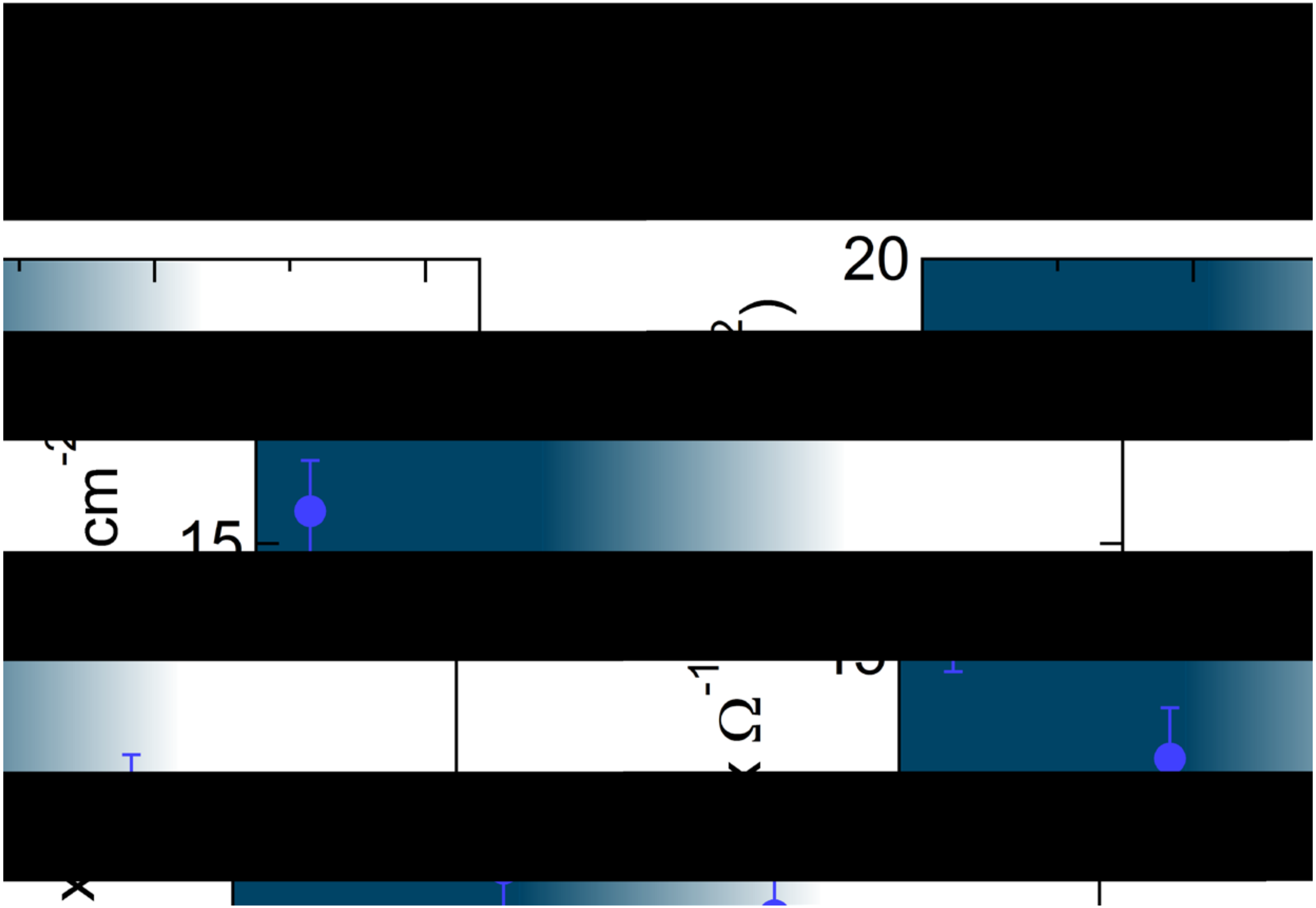




Temperature dependence



Crossover at ~10 times T_c



[redacted]

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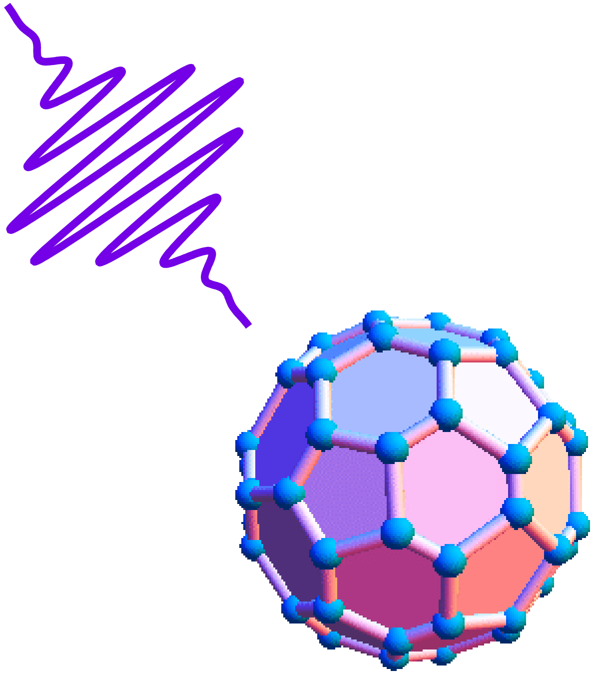
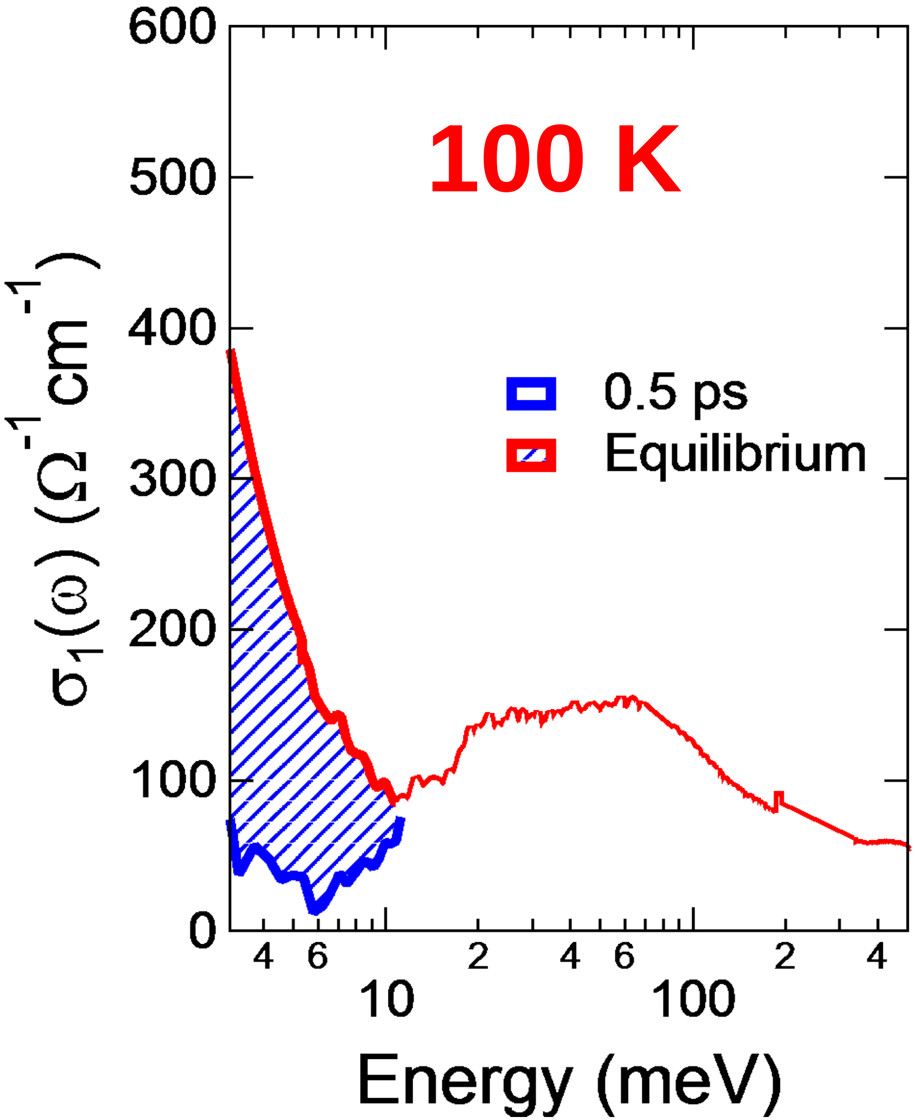
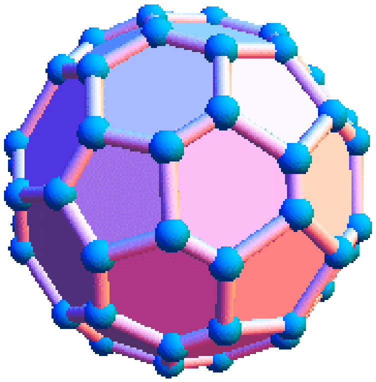
K_3C_{60} : Stimulated superconductivity ?



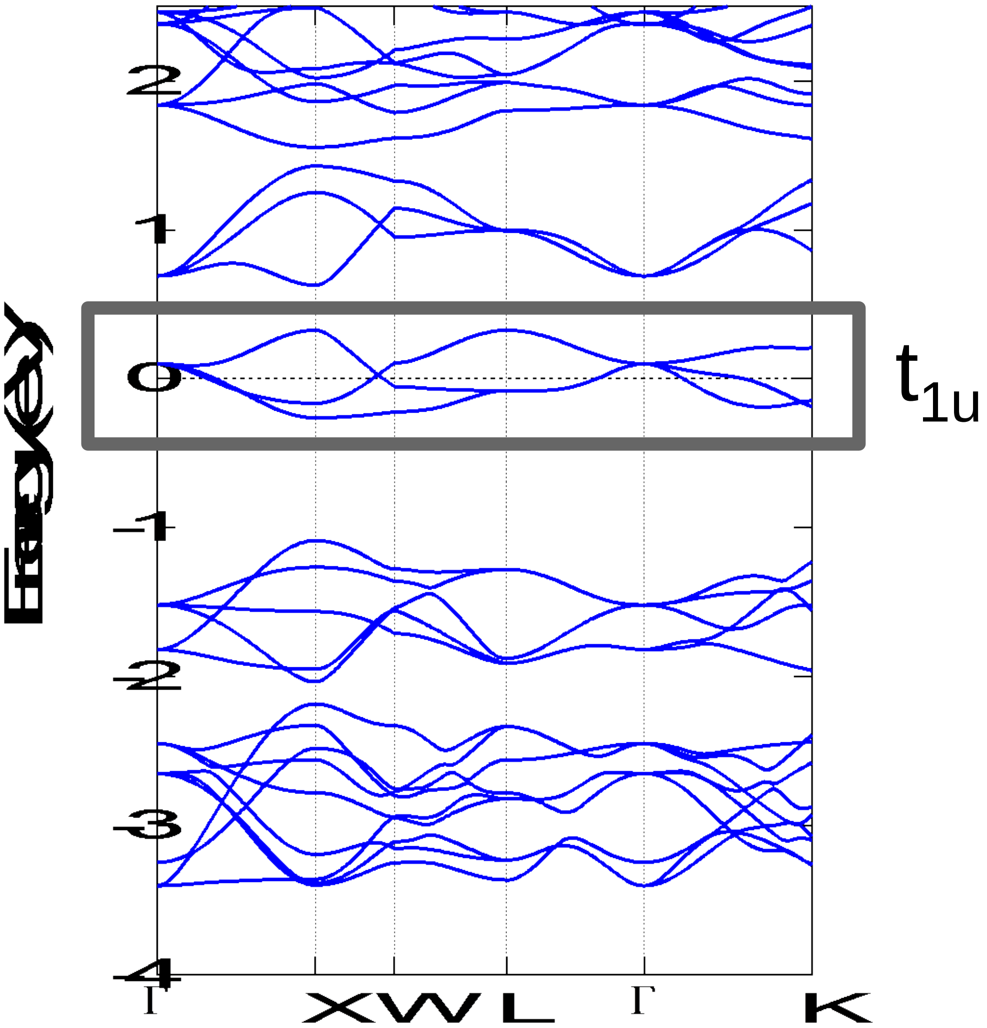


What is going on?

T_{1u} vibration: no linear e-ph coupling



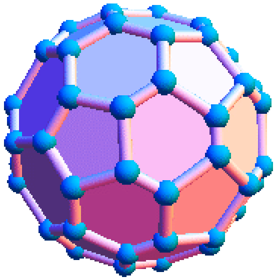
T_{1u}(4)
1370 cm^{-1}



Nonlinear Coupling to Jahn Teller Phonon

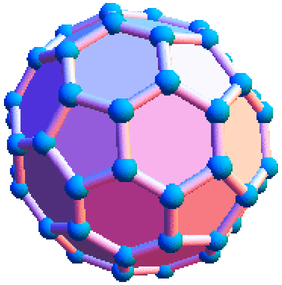
$Q^2_{T1u}Q_{Hg}$

$T_{1u}{}^2$



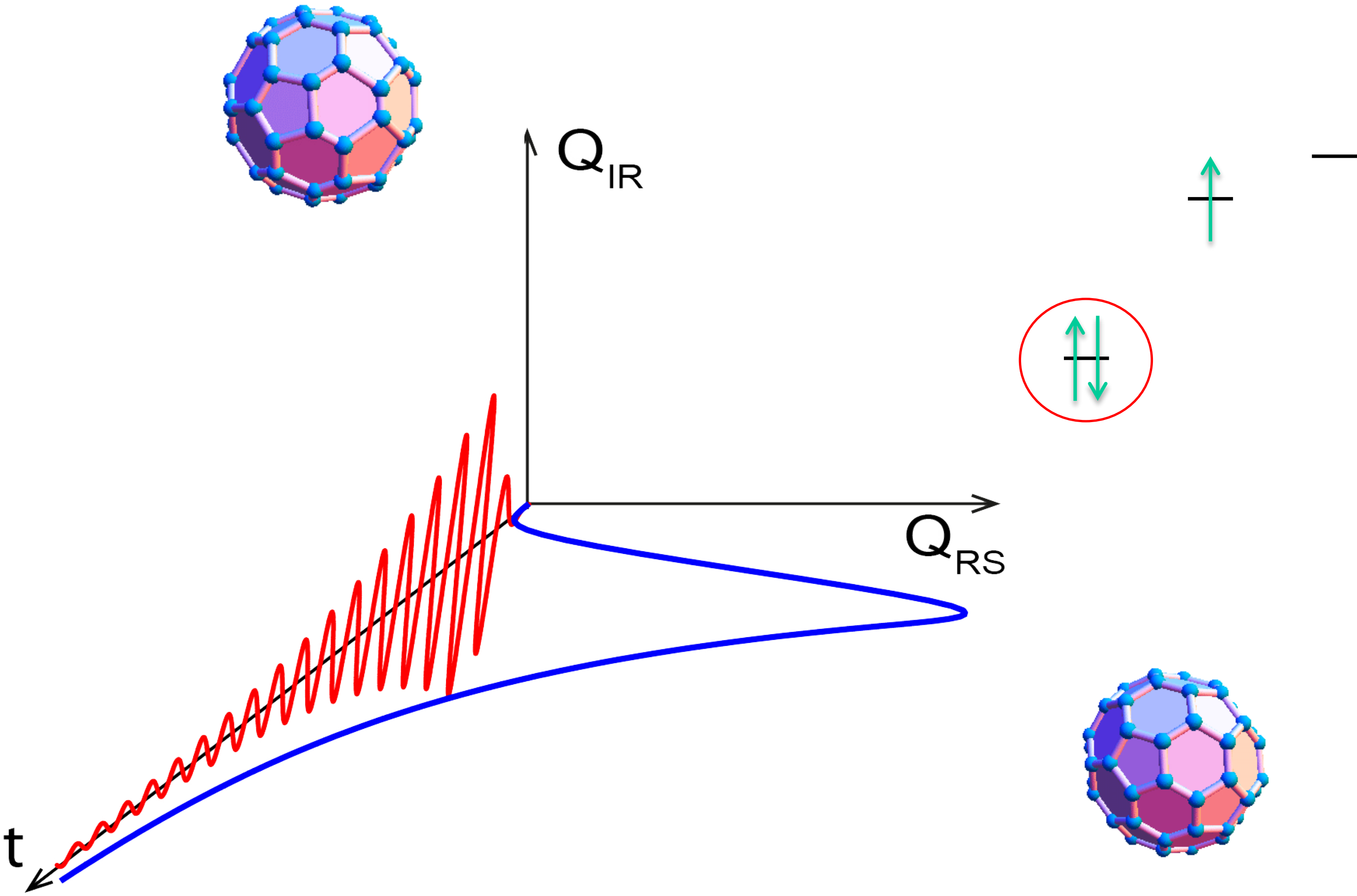
$T_{1u}(4)$
1370 cm^{-1}

H_g



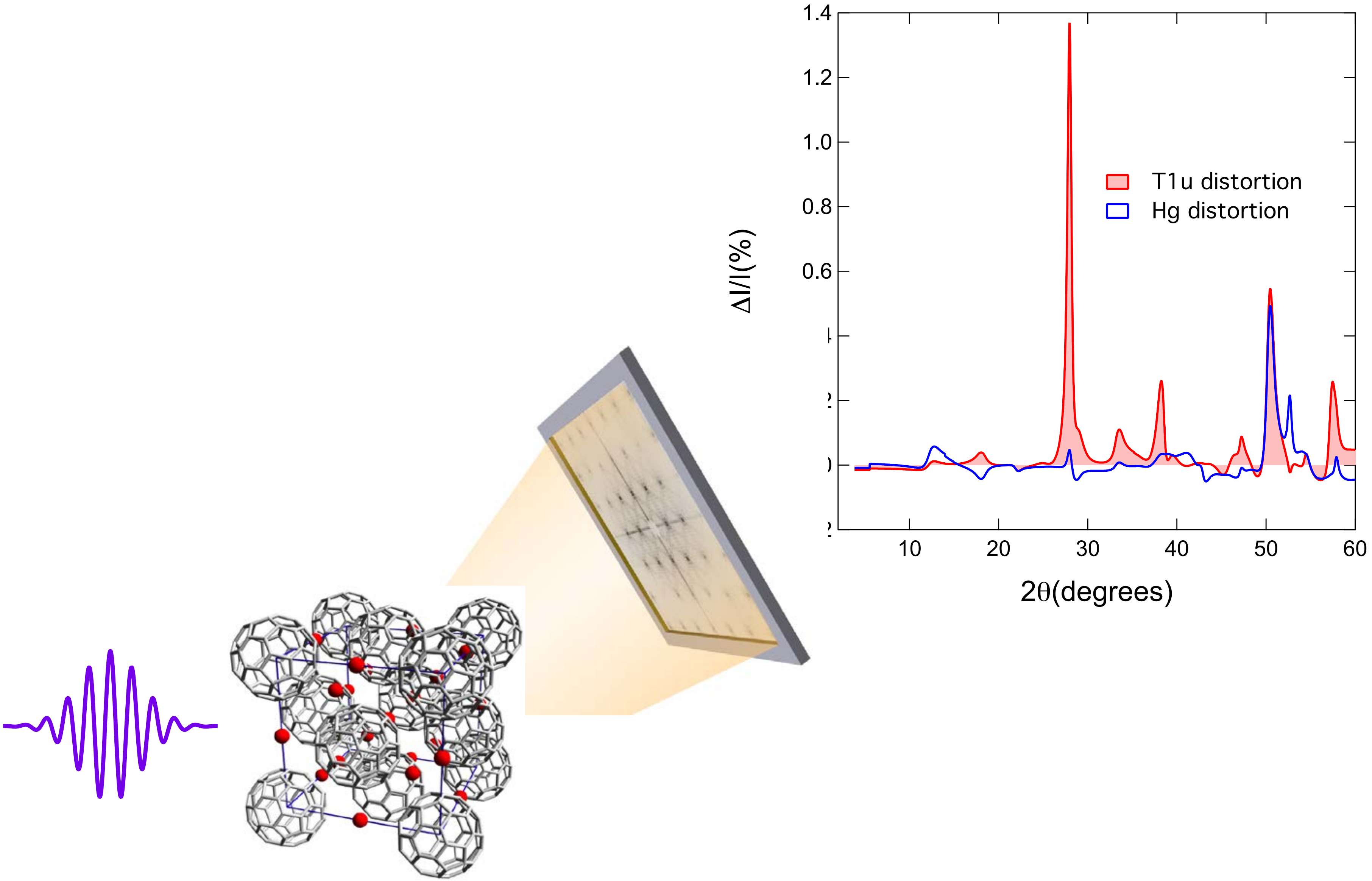
$H_g(1)$
261 cm^{-1}

Dynamical enhancement of pairing ?



Or something else……….

Our new LCLS proposal



People

Matteo Mitrano

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Stefan Kaiser

Alaska Subedi

Cassi Hunt

Theory

Stephen Clark
Dieter Jaksch
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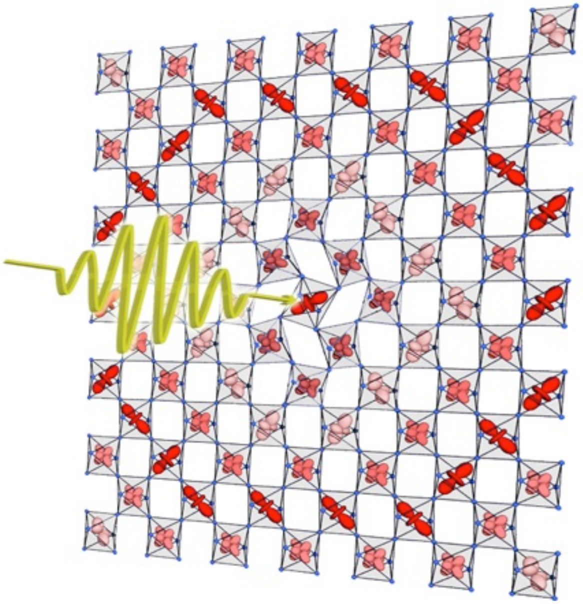
Samples

B. Keimer
Stuttgart

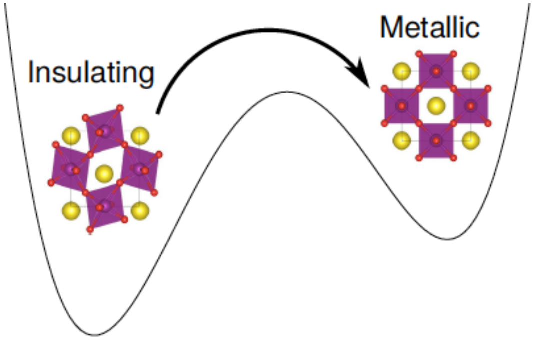
G. Gu
Brookhaven

H. Takagi
Stuttgart

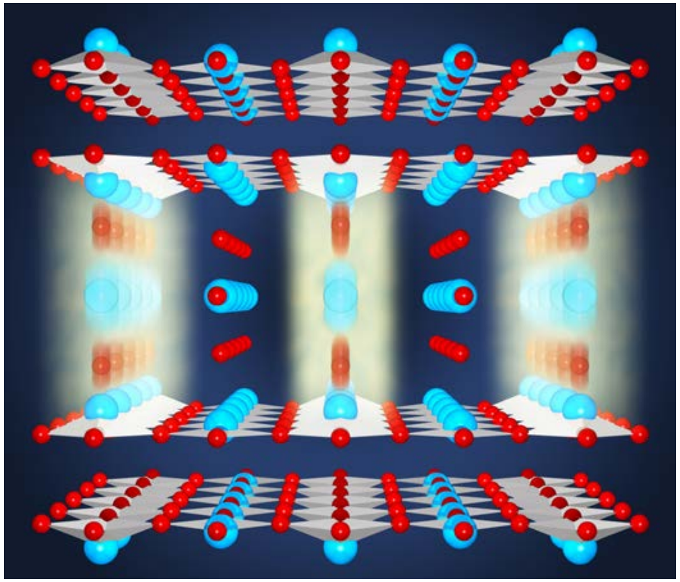
Controlling solids with light

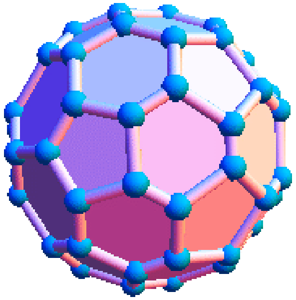


Driving competing orders



Dynamical materials discovery





Non-equilibrium order

Non-equilibrium superconductivity