Quantum Condensed Matter Dynamics

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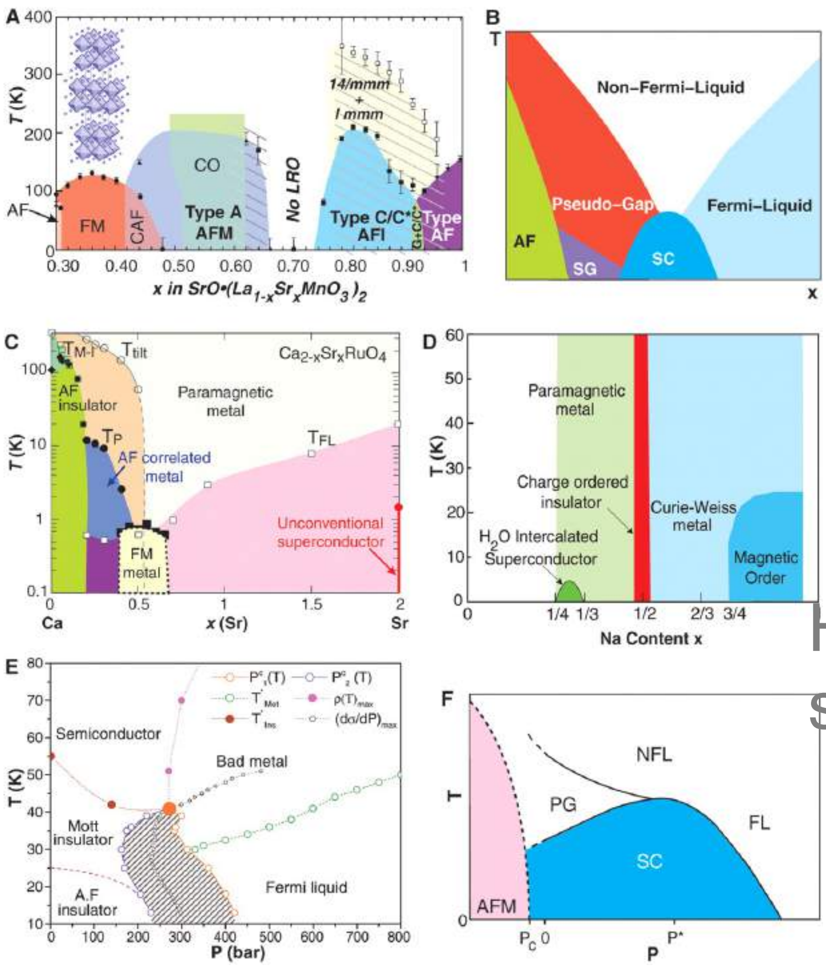
Lecture 3: Nonlinear Phononics I

Lecture 4: Nonlinear Phononics II

Quantum Materials

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



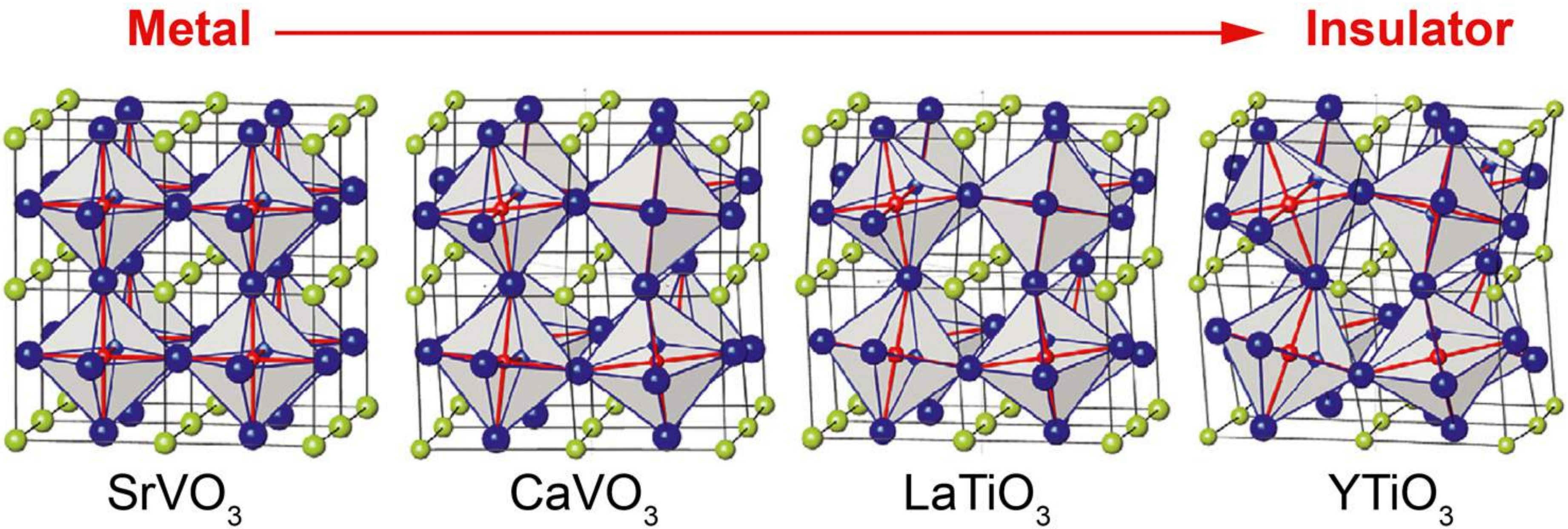
Metal-insulator transitions

Colossal magnetoresistance

High-temperature superconductivity

E. Dagotto, Science 309, 257 (2005)

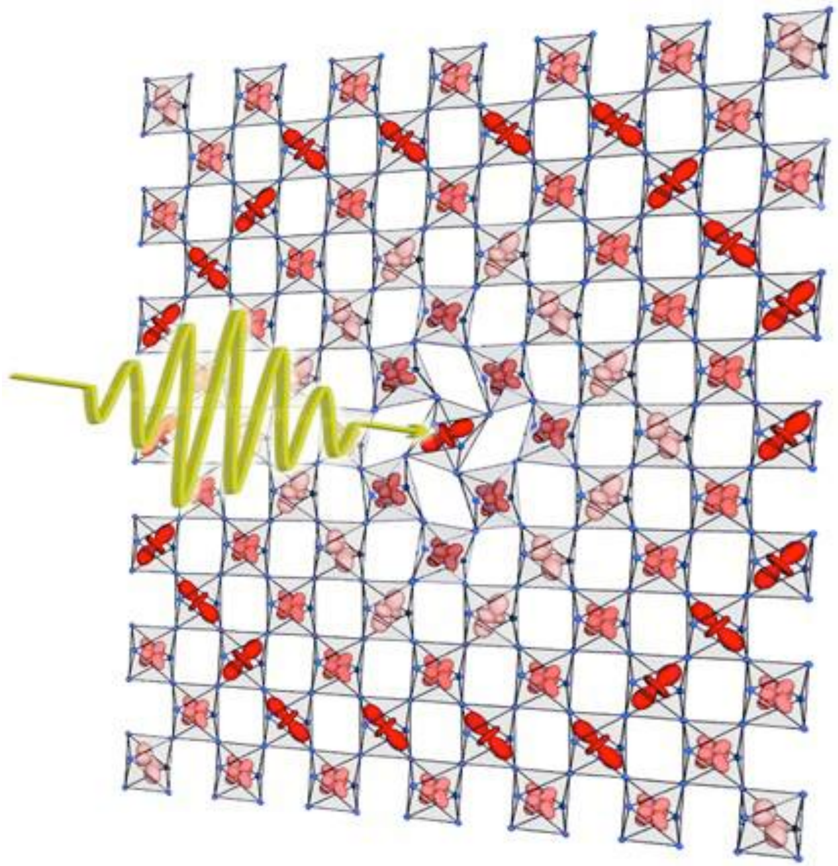
Structure-function in Quantum Materials



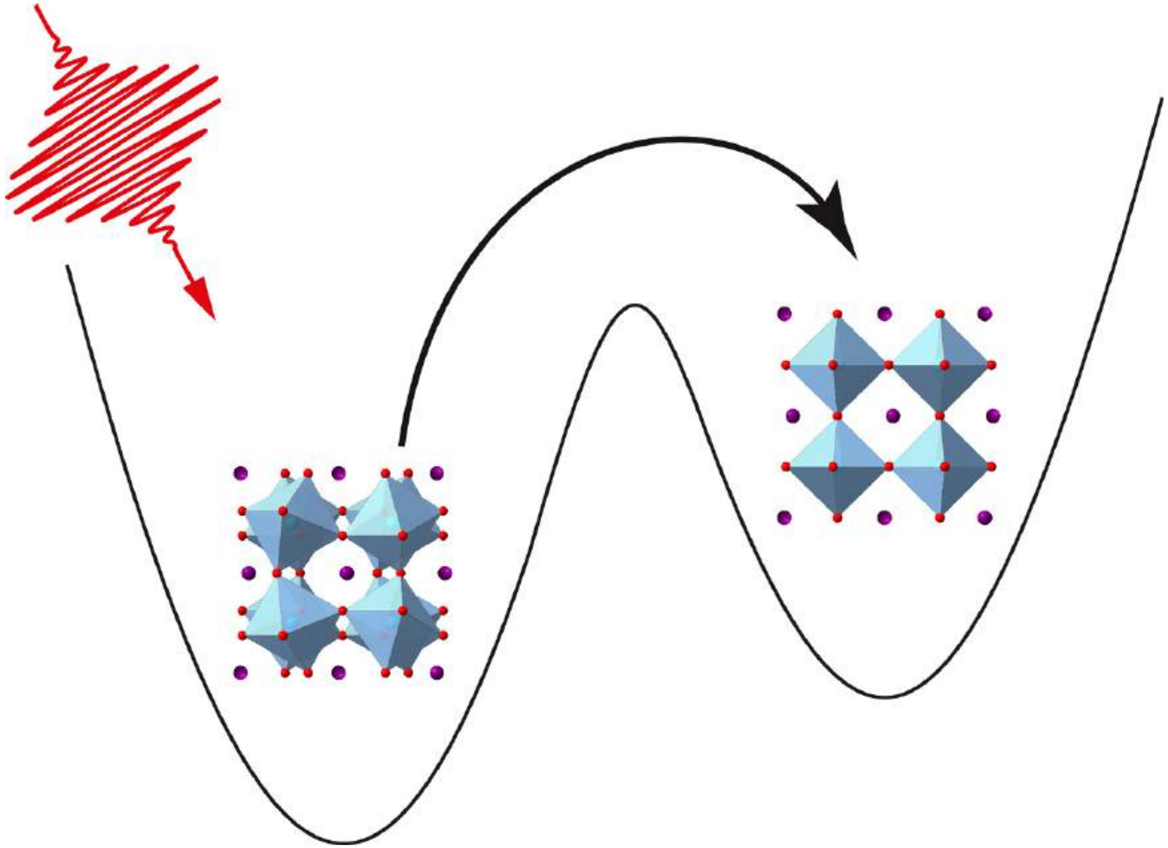
Selective control: single lattice coordinate

Mid infrared and THz light: lattice distortions along one (or few) normal mode coordinates

Displacements ~ 1-10 %



Can one control specific bond angles with light ?

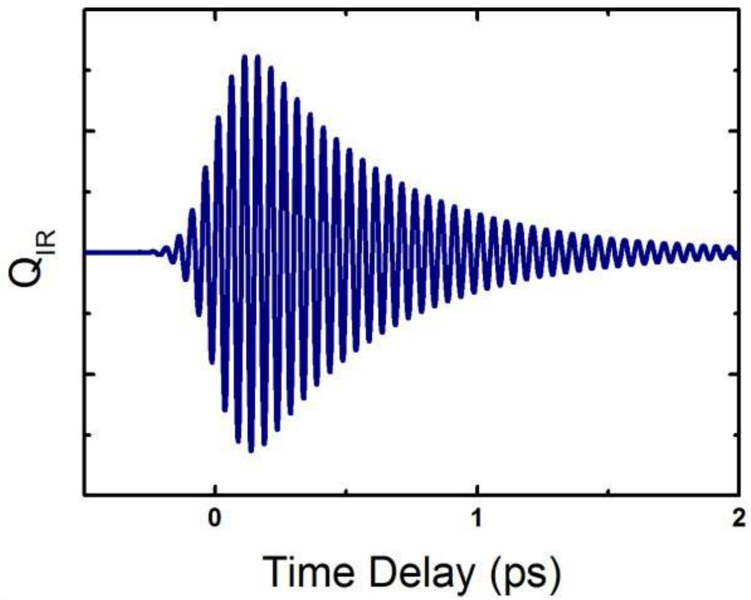


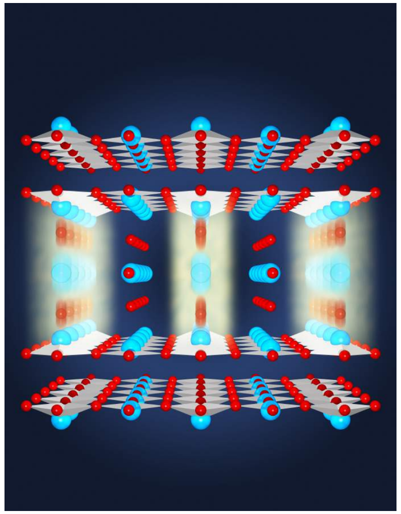
Linear coupling

Light couples to IR active phonons − whose coordinates that are odd against inversion

Linear optical excitation of IR-active modes does nothing on average

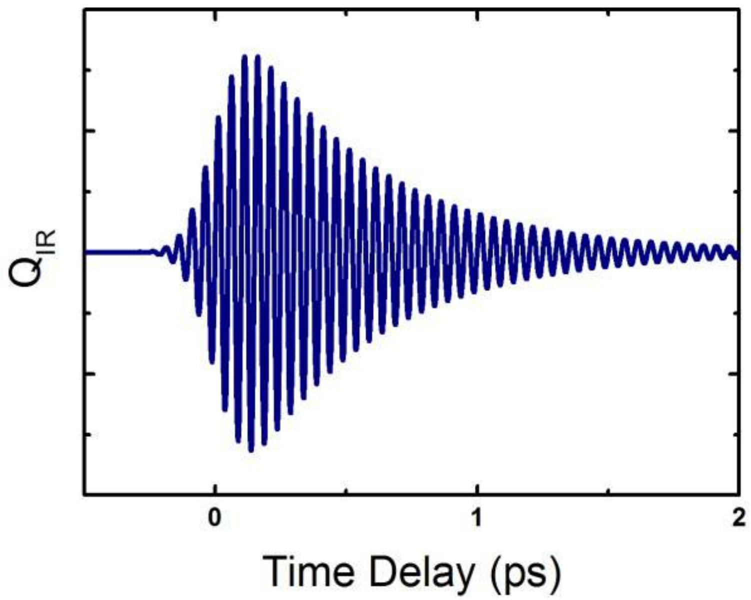
LINEAR - Q_{IR}



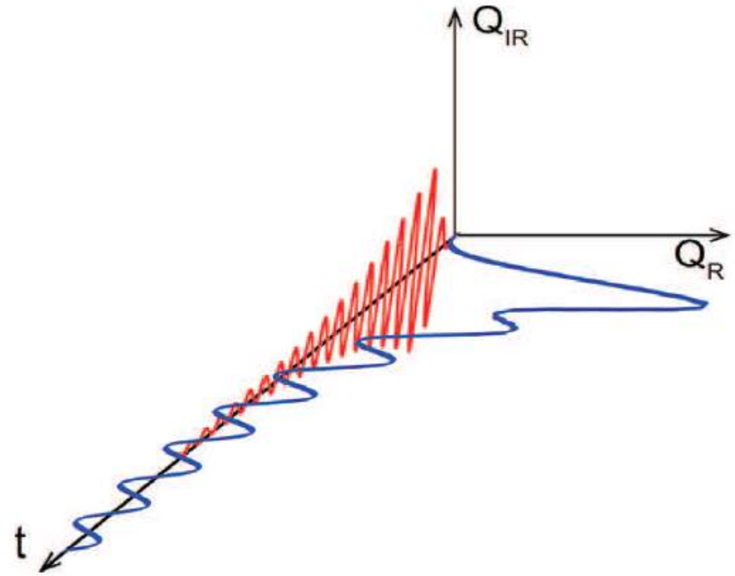


Today's lecture: beyond linear coupling

LINEAR - Q_{IR}



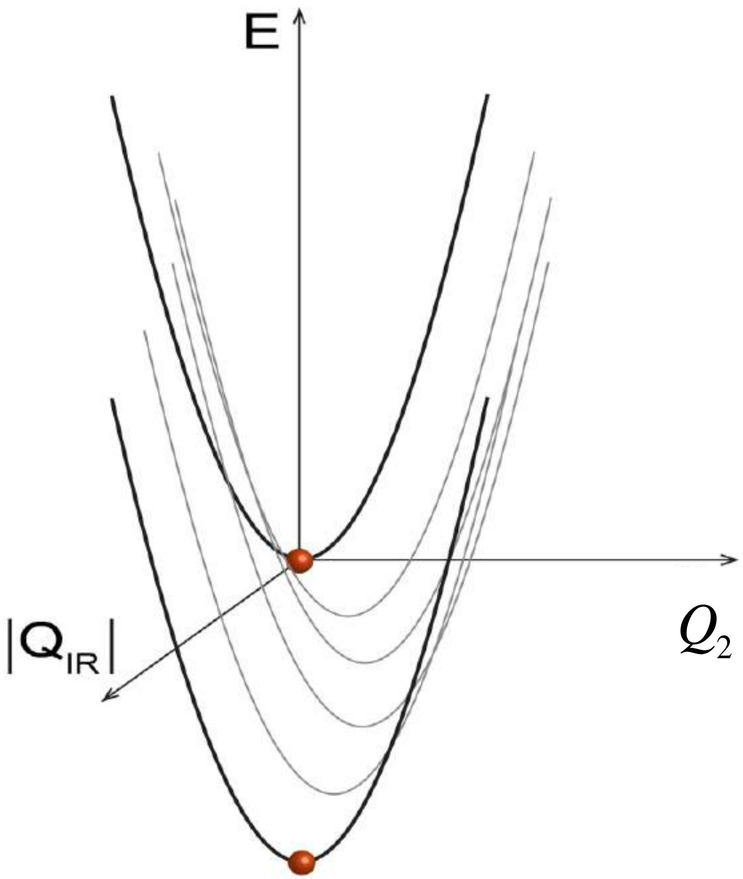
NONLINEAR – Q_2

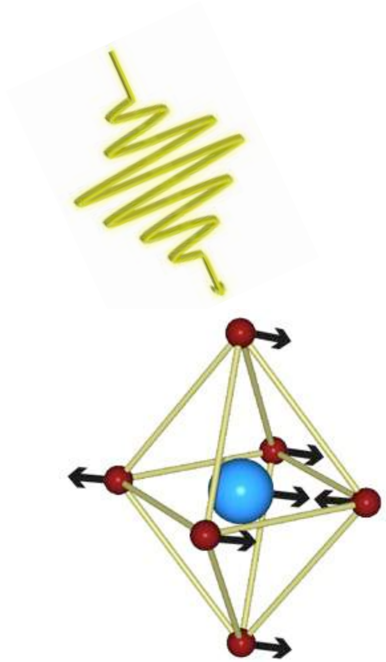


M. Först et al.*, Nature Physics* 7, 854 (2011)

Lowest order non-linear coupling

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





If material centrosymmetric

$$U_{\text{int}} = A Q_{ir}^2 Q_2$$

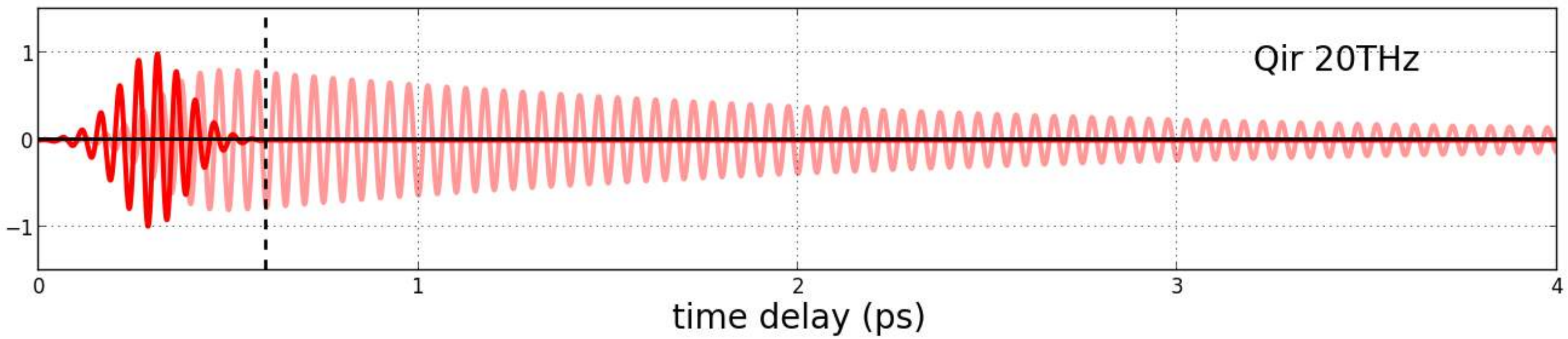
$$even \qquad odd^2 even$$

Interaction is always between a driven odd mode and an even mode

Equations of motion: oscillations in Q_{IR}

$$\ddot{Q}_{IR} + \gamma_{IR}\dot{Q}_{IR} + \omega_{IR}^{2}Q_{IR} = AE_{laser}^{i\omega t}$$

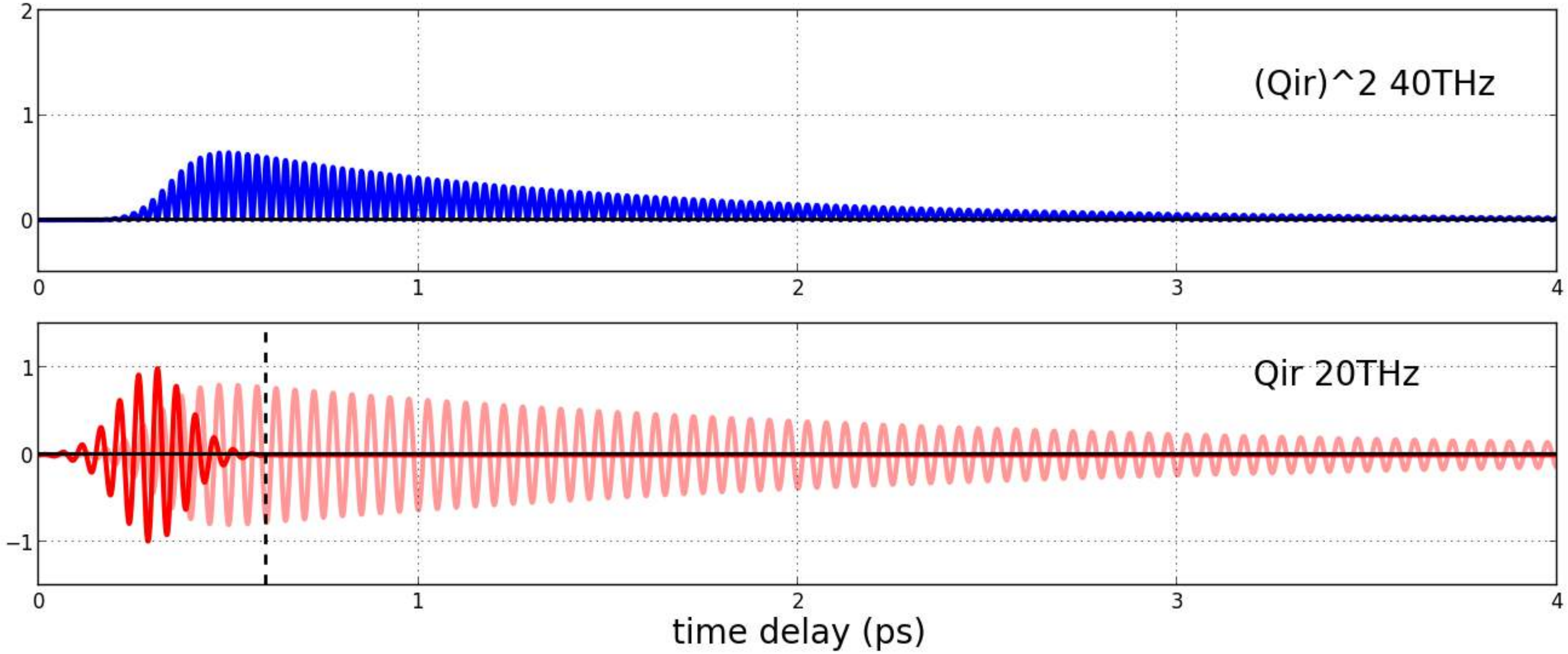
harmonic oscillator   Laser field



Equations of motion: oscillations in $(Q_{IR})^2$

$$\ddot{Q}_{IR} + \gamma_{IR}\dot{Q}_{IR} + \omega_{IR}^2 Q_{IR} = AE_{laser}^{i\omega t}$$

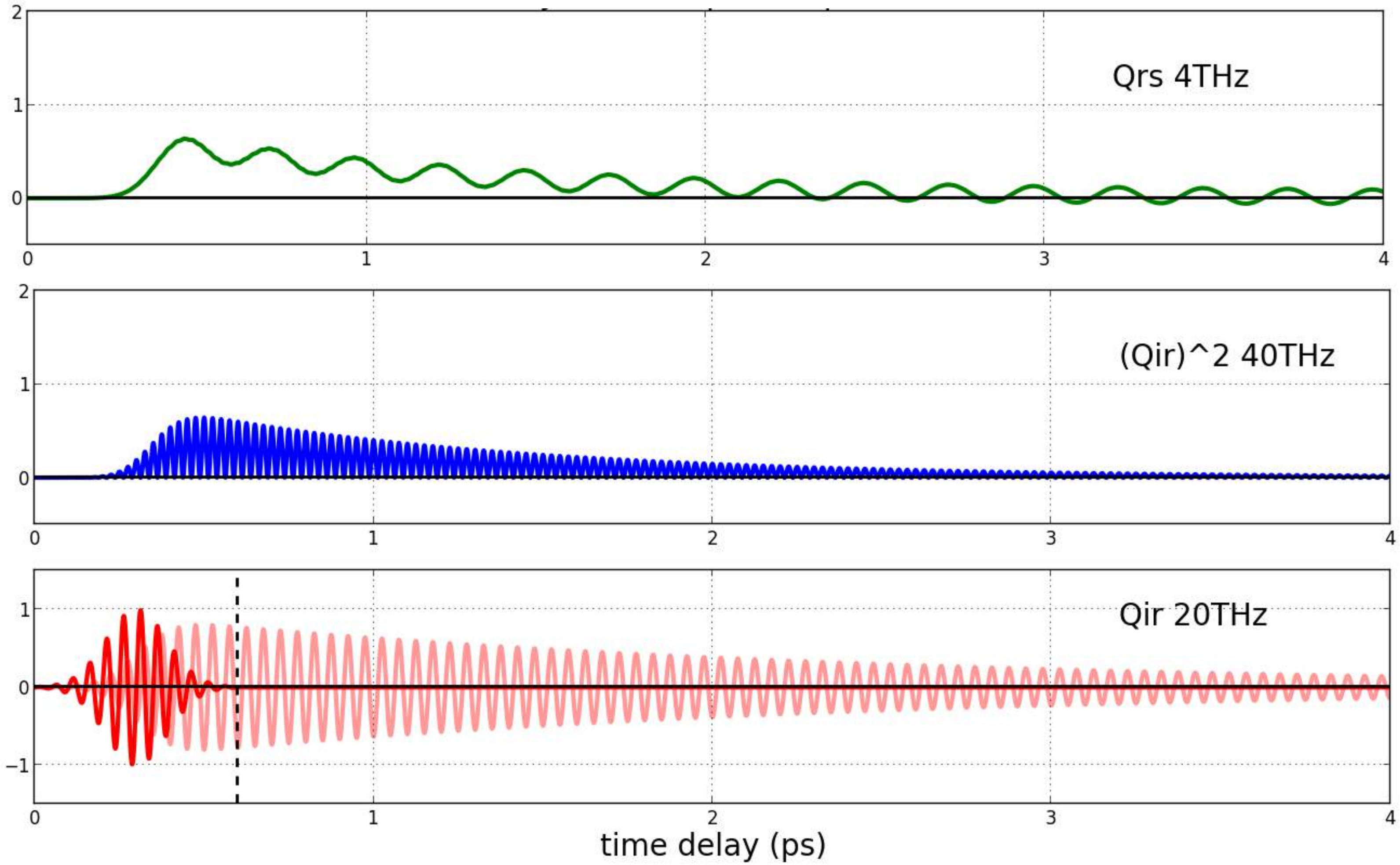
$$(\ddot{Q}_2 + \gamma\dot{Q}_2 + \omega_2^2 Q_2) = BQ_{IR}^2$$



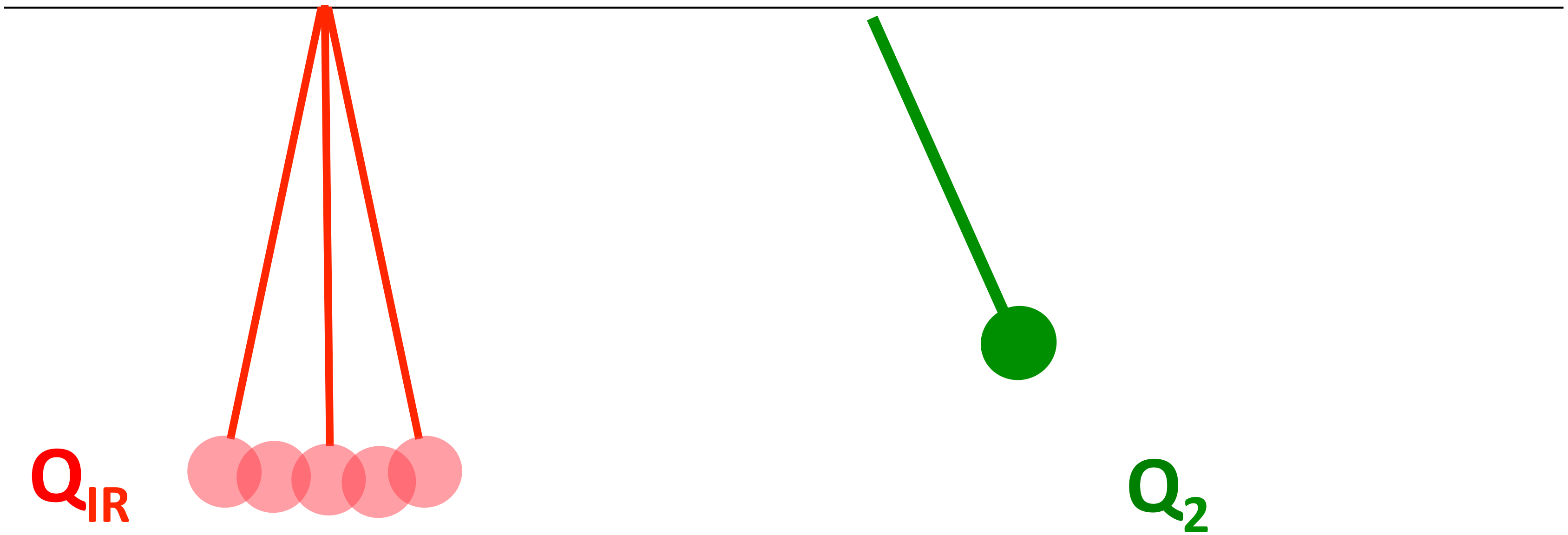
Oscillations in Q_{IR} displace Q_2

$$\ddot{Q}_{IR} + \gamma_{IR}\dot{Q}_{IR} + \omega_{IR}^2 Q_{IR} = AE_{laser}^{i\omega t}$$

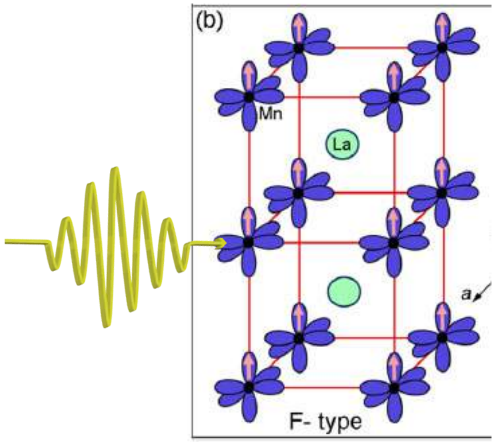
$$(\ddot{Q}_2 + \gamma\dot{Q}_2 + \omega_2^2 Q_2) = BQ_{IR}^2$$

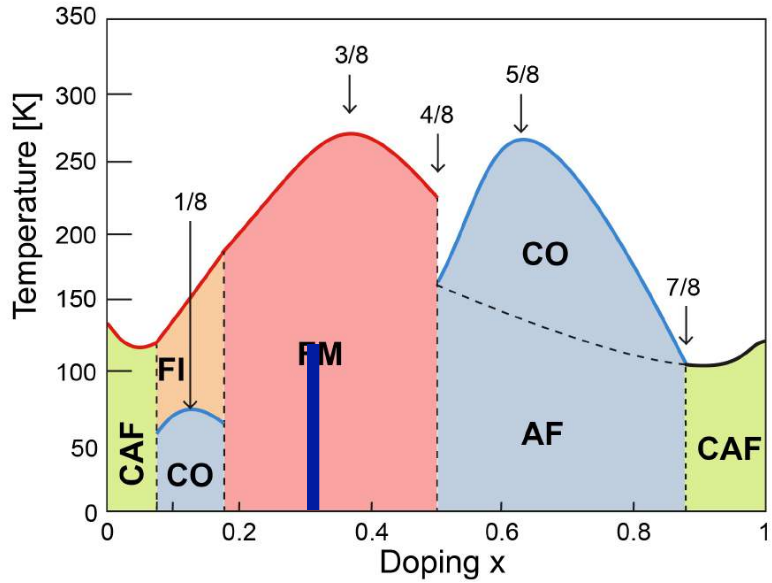


Q_{IR} Q_2 term: Oscillations in Q_{IR} displace Q_2

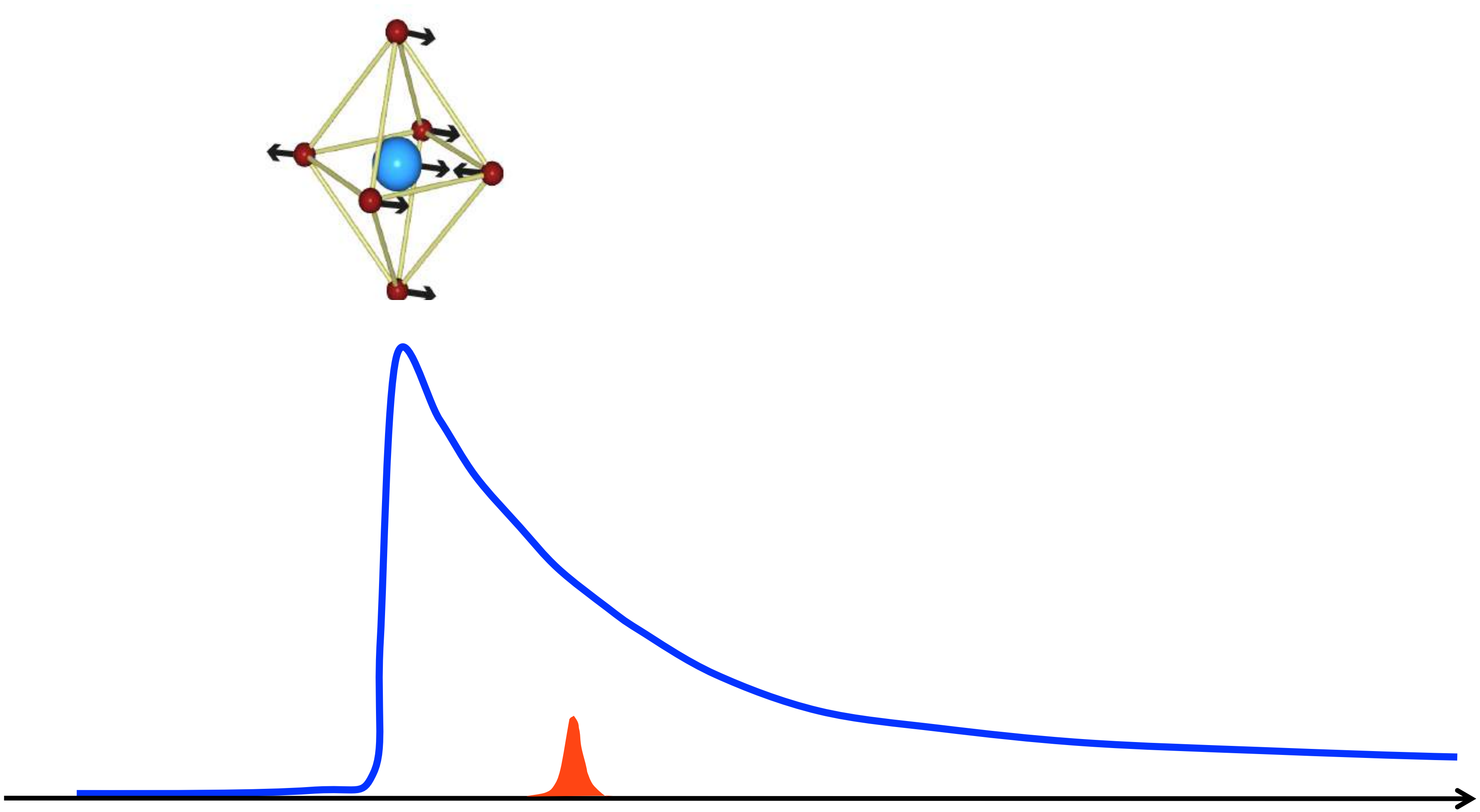


Example: $La_{0.3}Sr_{0.3}MnO_3$

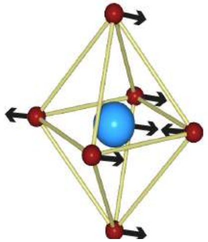


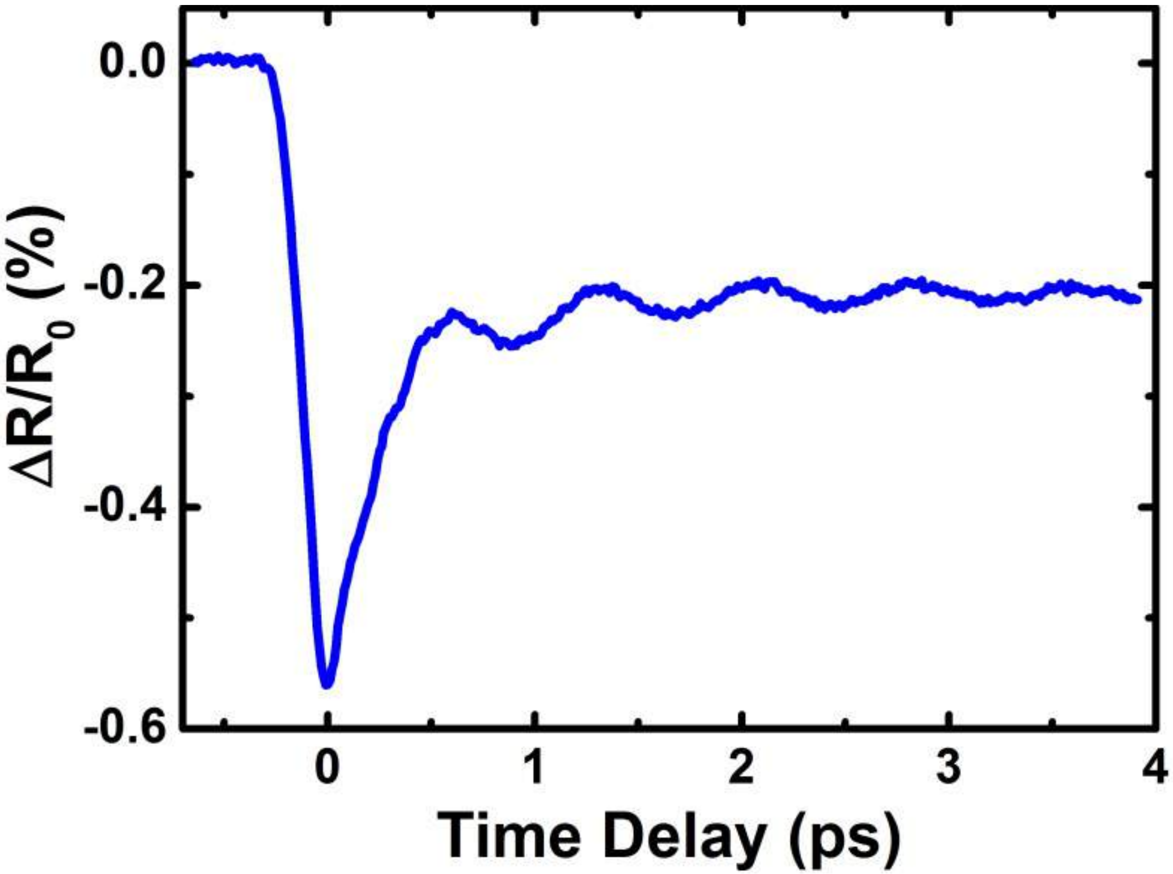


Excite Oxygen Stretch of E_u symmetry

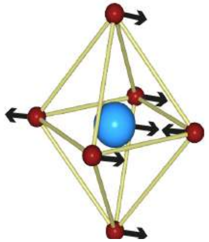


Time resolved reflectivity oscillates

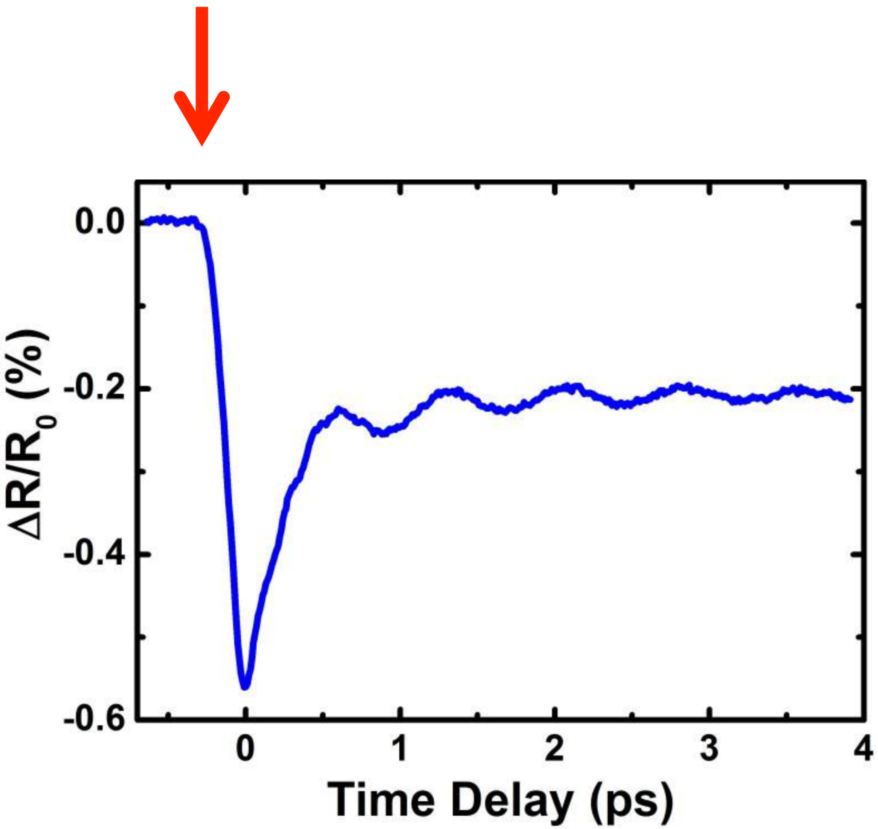


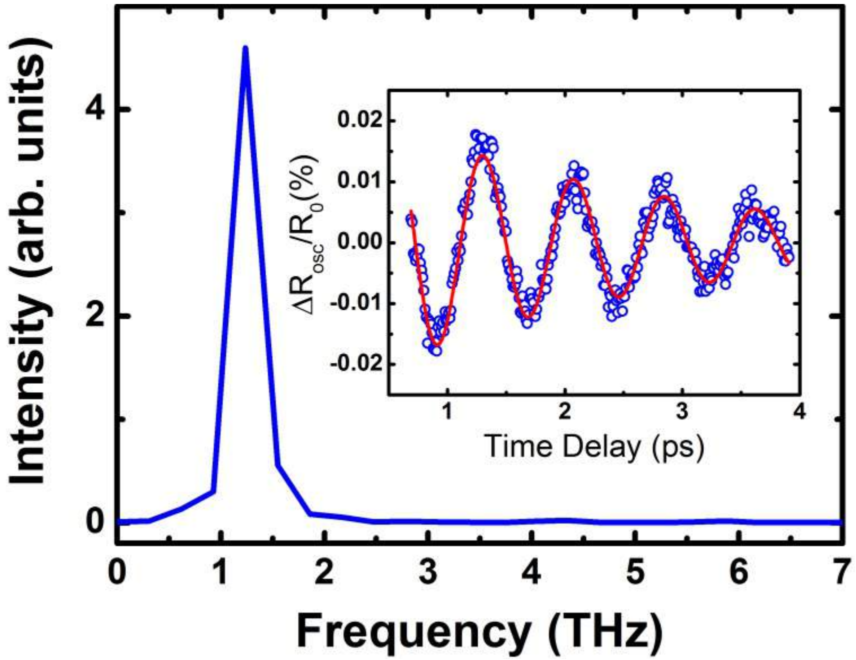


Oscillations indicate excitation of E_g mode



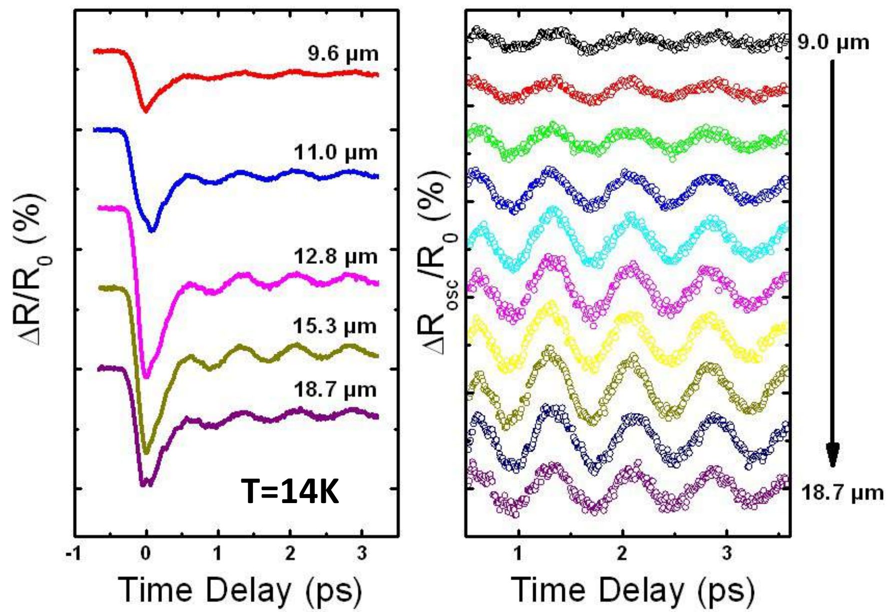
E_{1u}

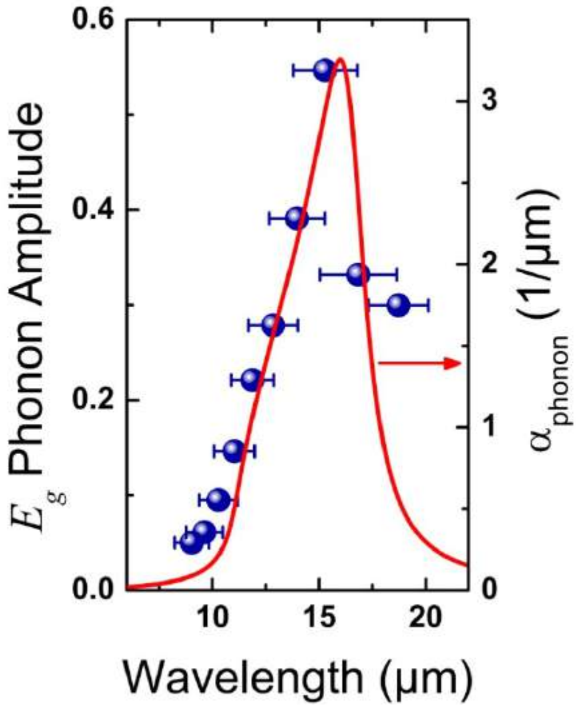




M. Foerst et al., Nature Physics 7, 854 (2011)

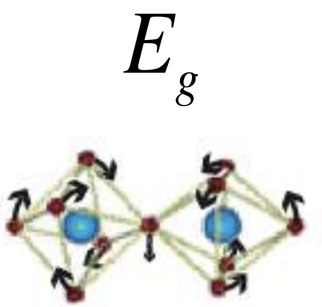
E_g only there if light resonant with E_u

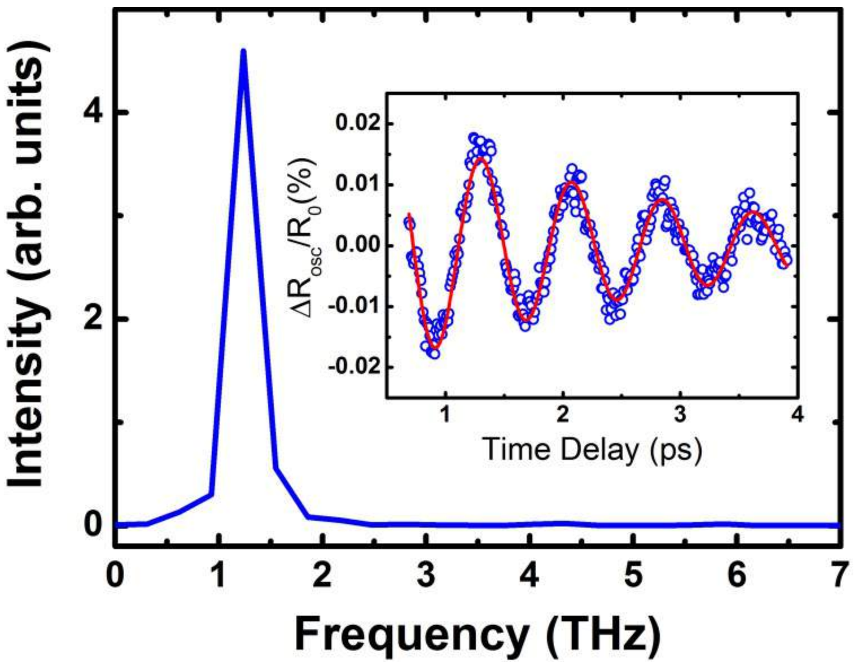


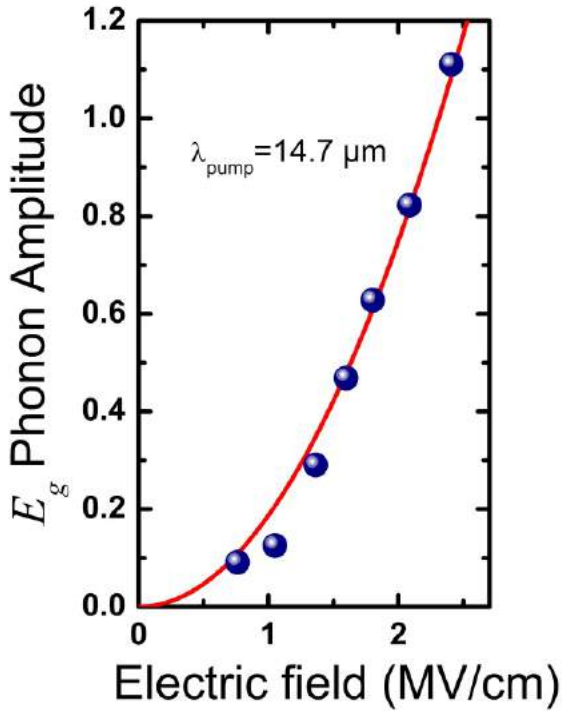


M. Foerst et al., Nature Physics 7, 854 (2011)

E_g amplitude follows $(E_{laser})^2$







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

E_g mode has the correct symmetry

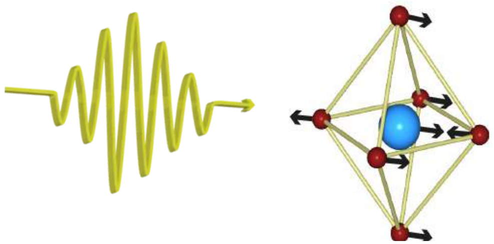
$$U_{\text{int}} = AQ_{ir}^2 Q_2$$

$$E_{1u}^2 E_g$$

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

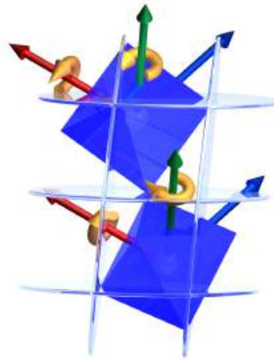
Is there an average displacement along E_g ?

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



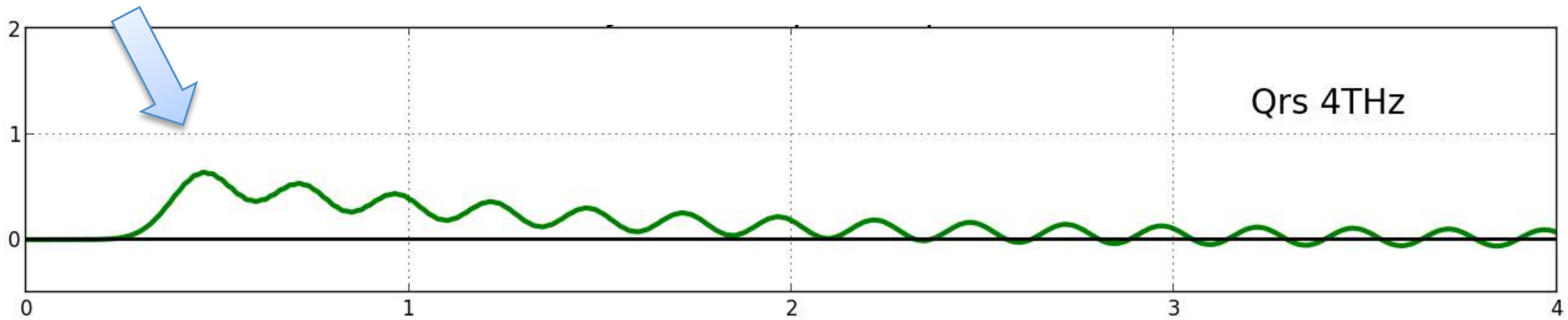
E_{1u}

Displacive field (E_g mode)

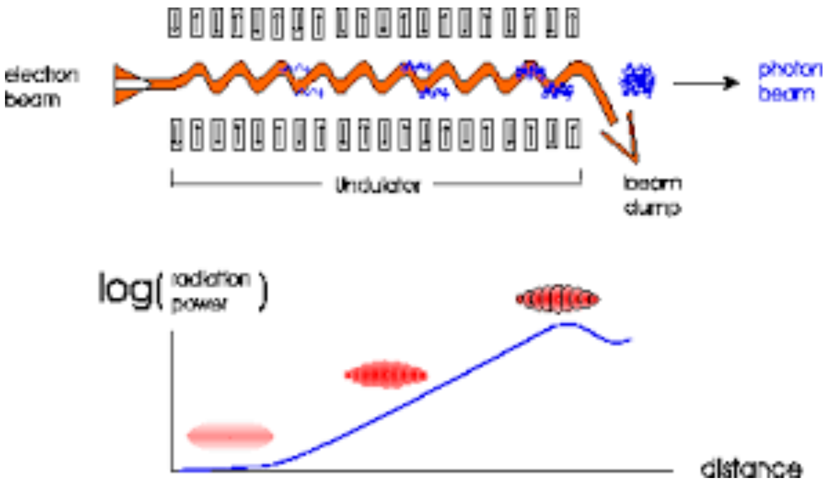


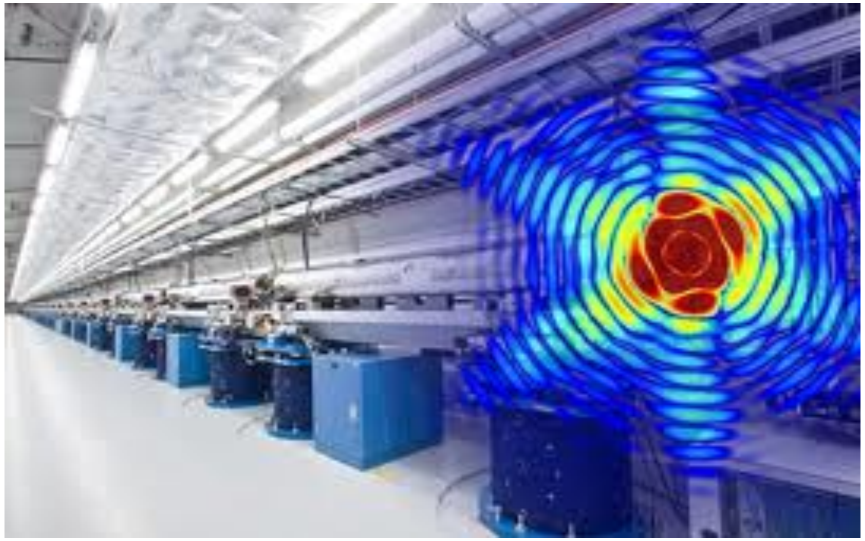
E_g

$Q_r(t)$



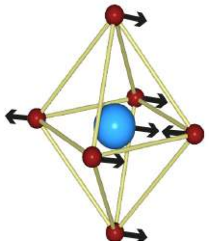
Pump probe experiment using X-ray FEL

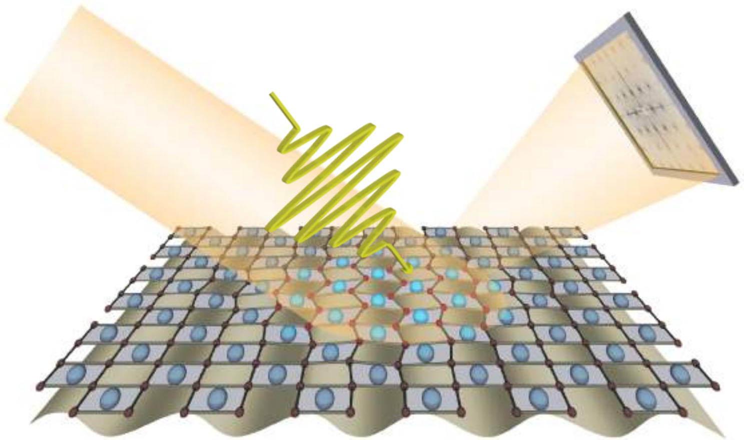




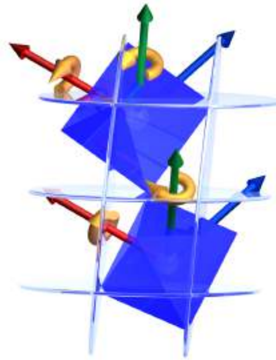
Step change in structure factor

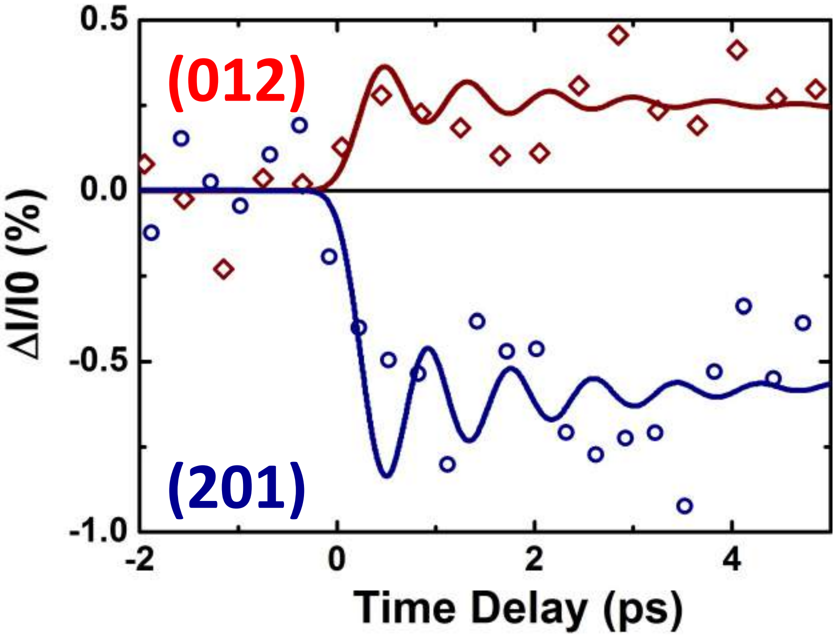
Mid-IR pump (E_{1u} mode)





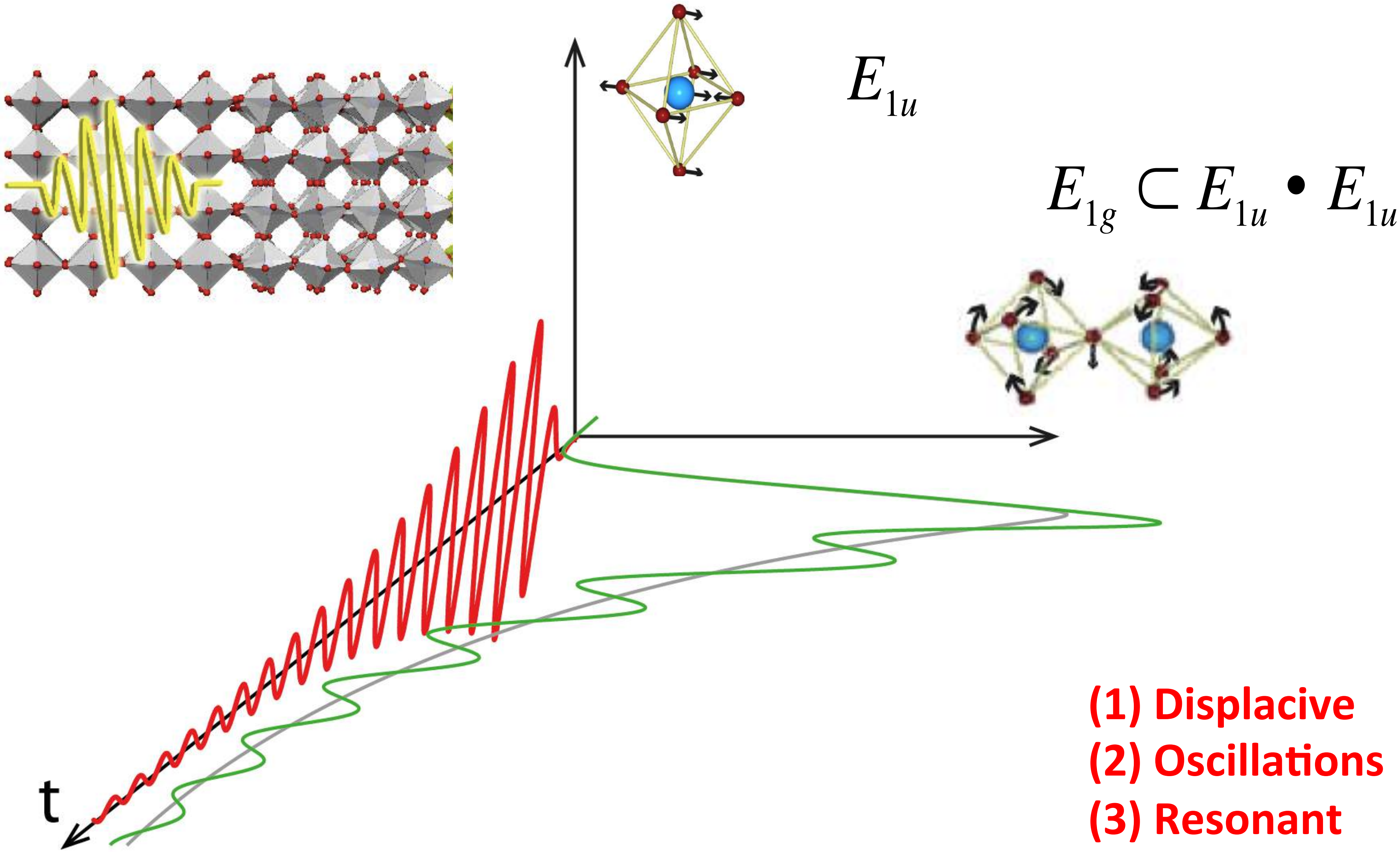
Displacive field (E_g mode)





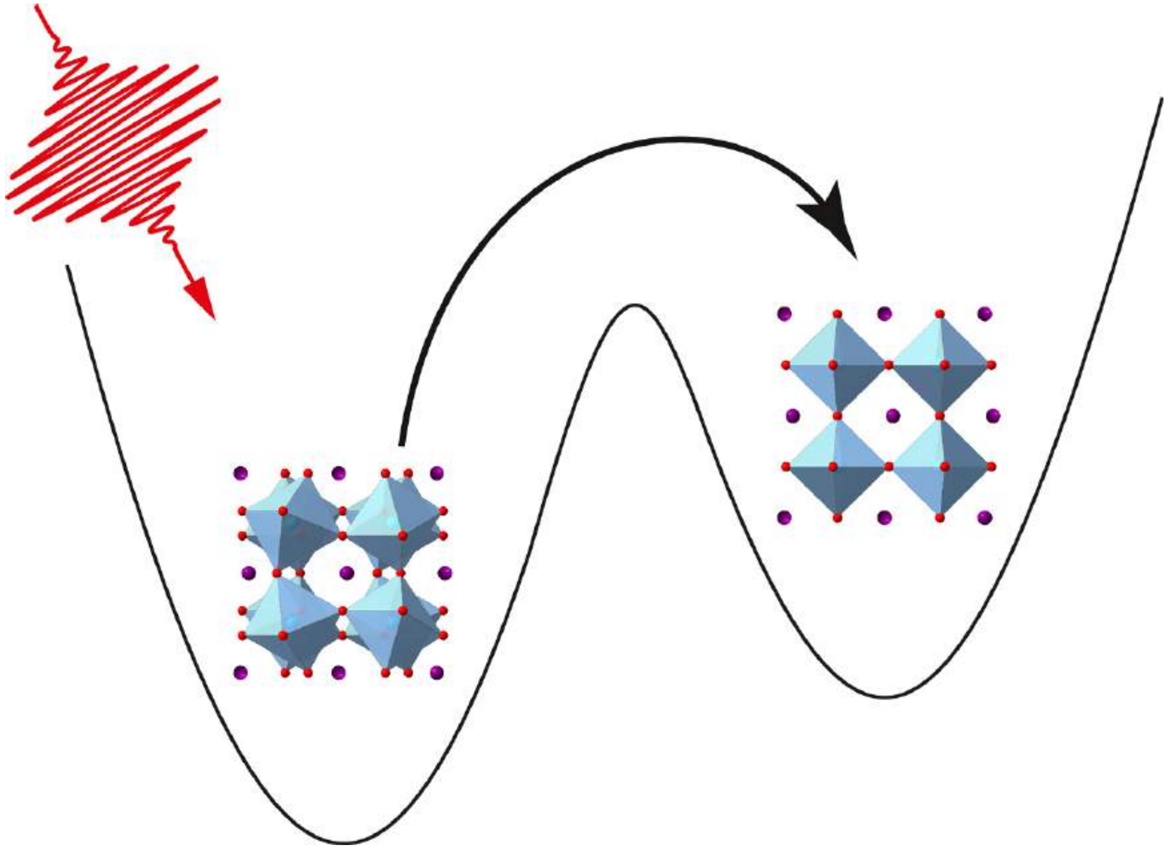
M. Foerst et al. Solid State Comm. 169, 4 (2013)

Lowest order nonlinear phononics

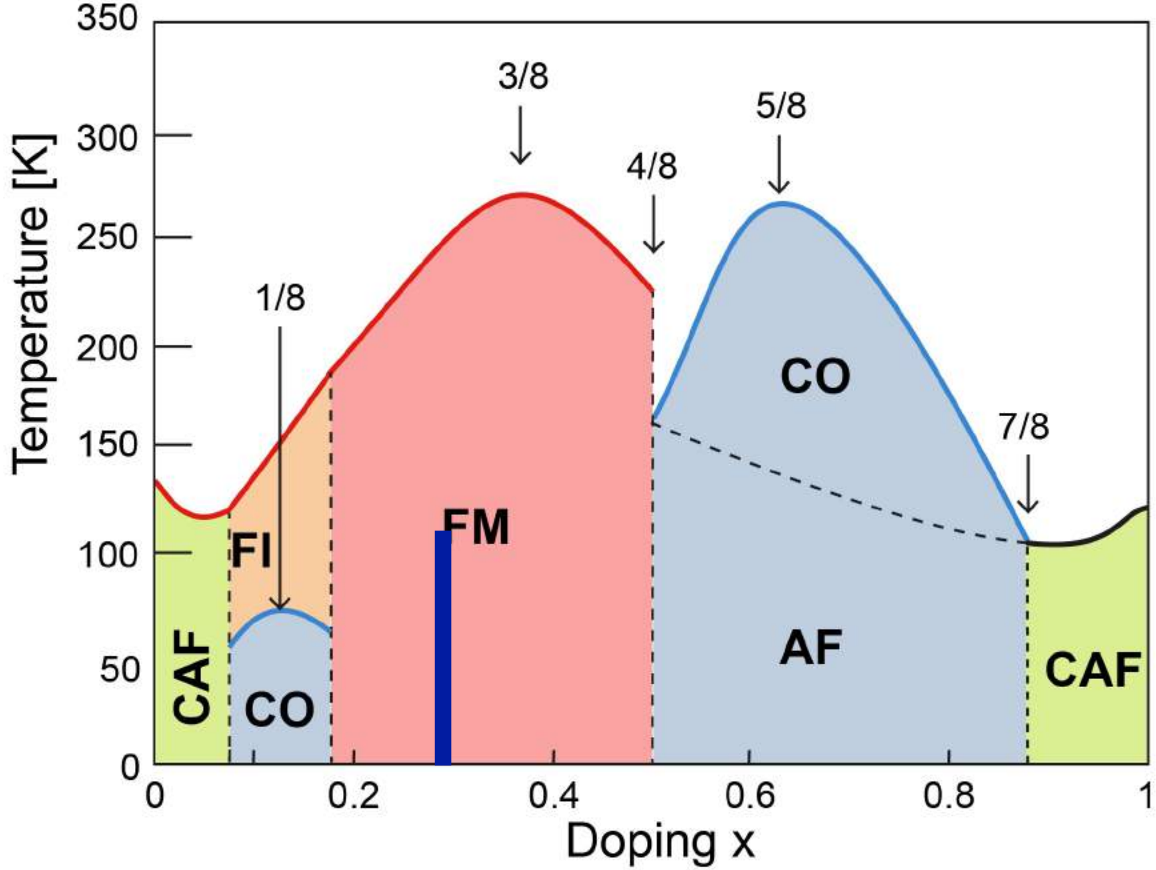


(1) Displacive
(2) Oscillations
(3) Resonant
(4) Quadratic

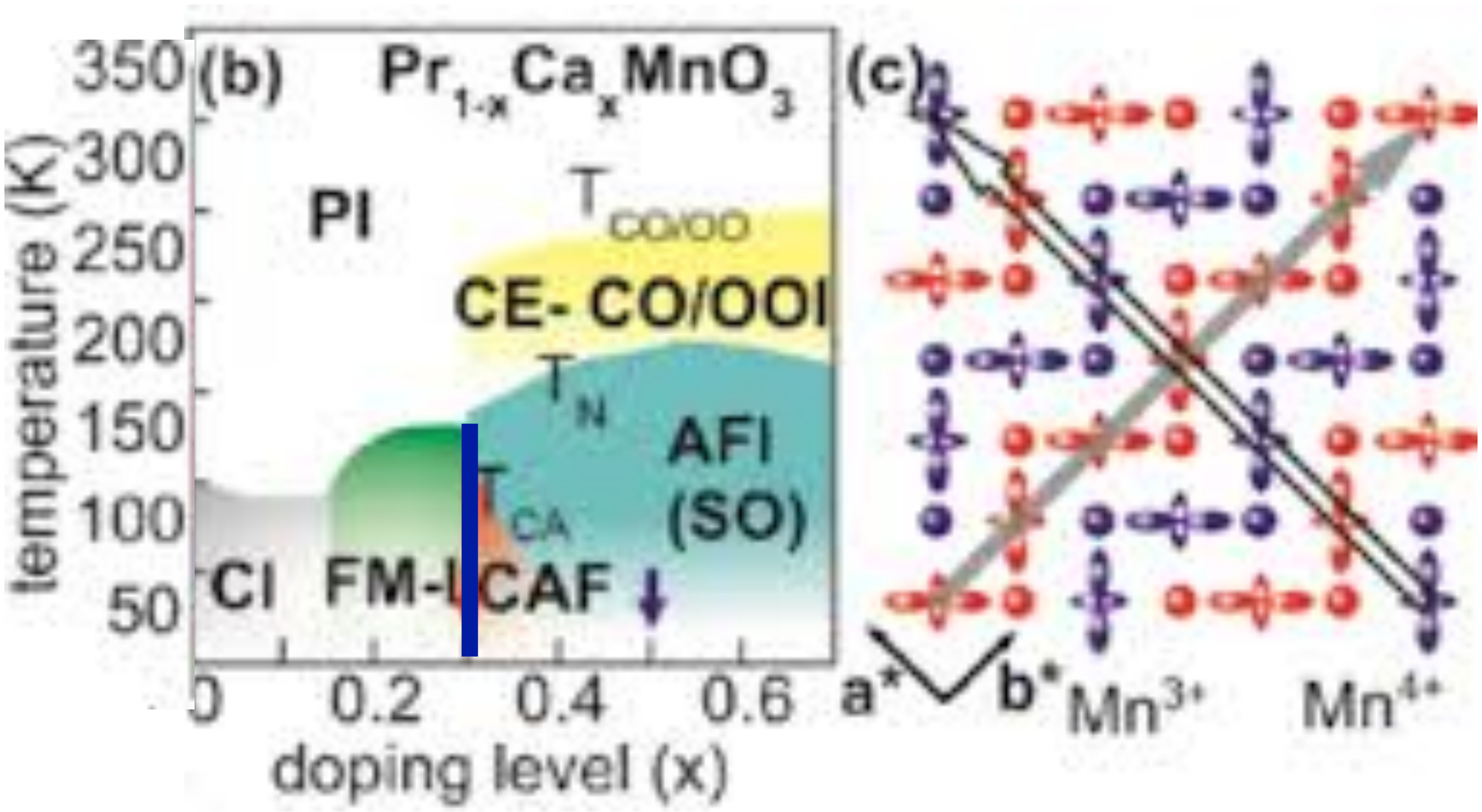
Can one control specific bond angles with light ?



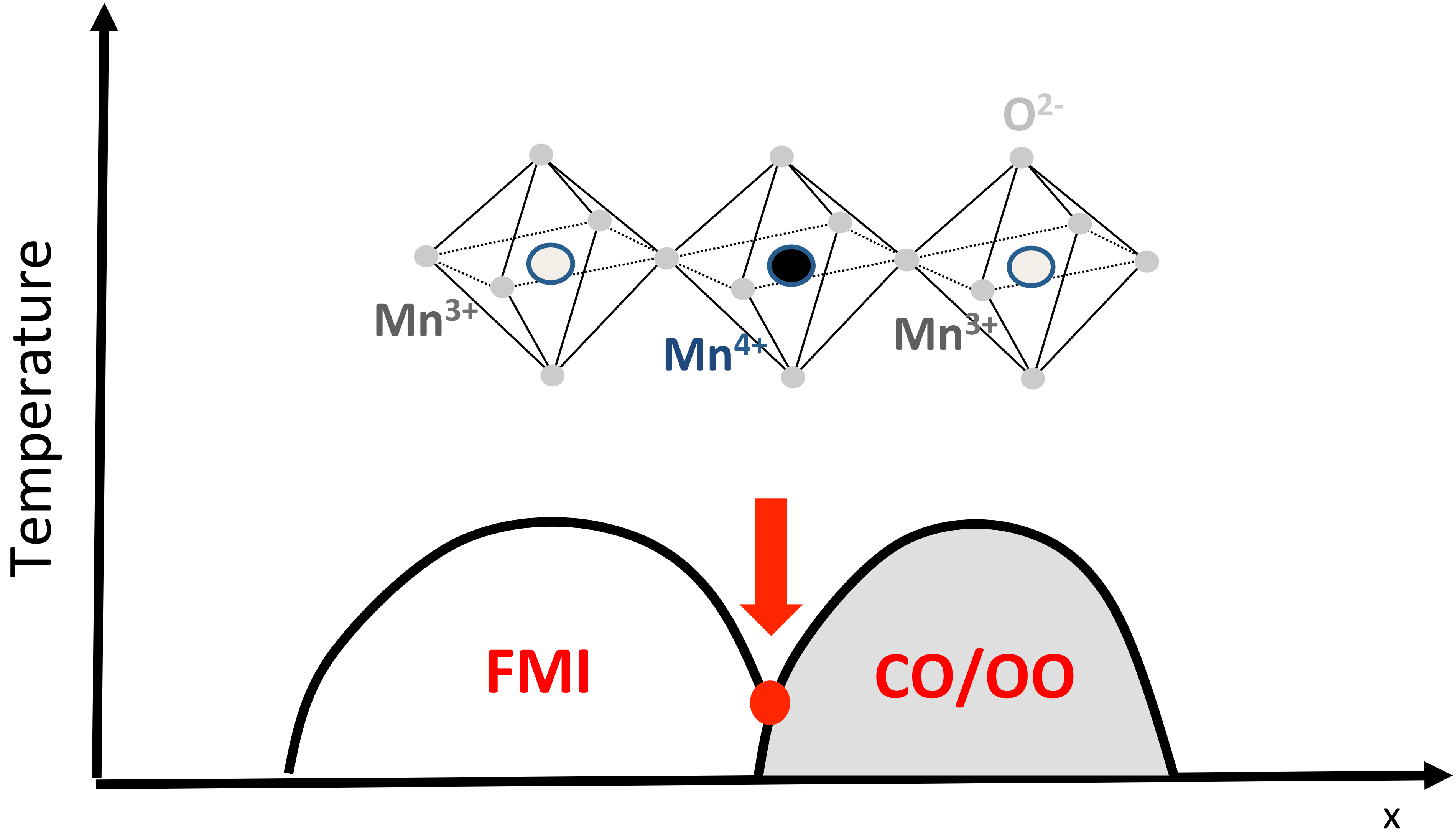
Demonstration away from phase boundary



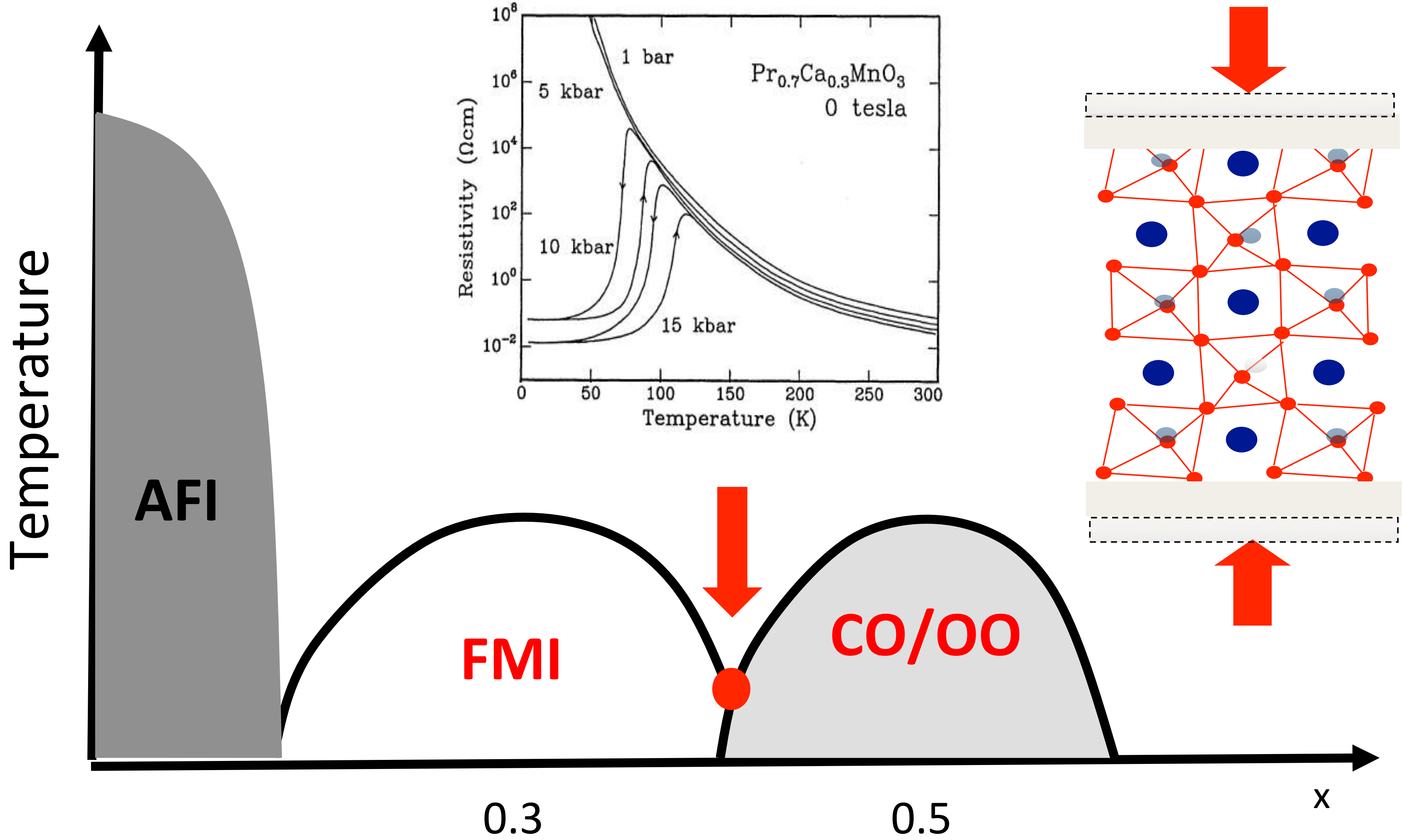
Close to a Phase Boundary: $Pr_{0.3}Ca_{0.3}MnO_3$



$Pr_{0.3}Ca_{0.3}MnO_3$: competition between two insulators

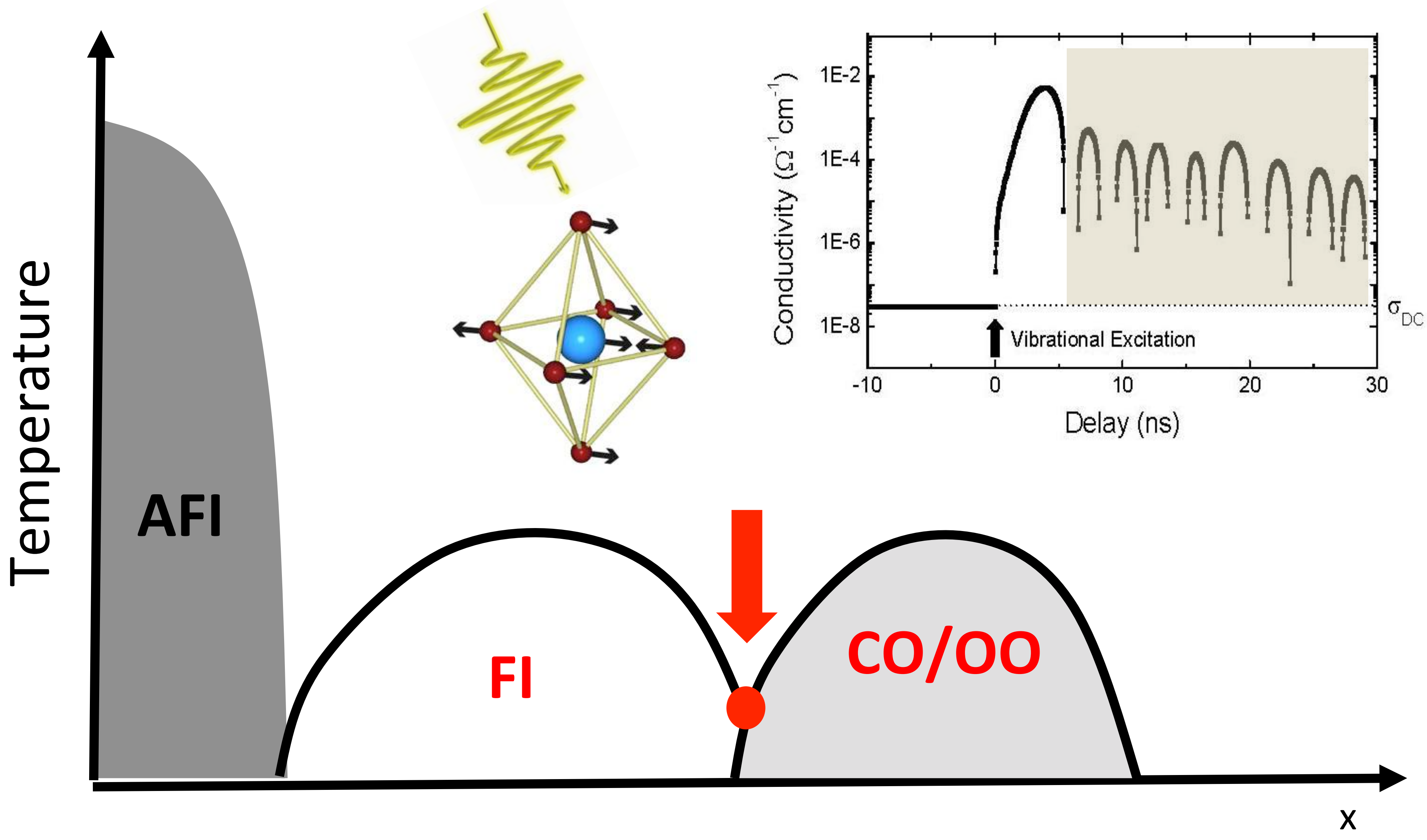


$Pr_{0.3}Ca_{0.3}MnO_3$: a hidden metallic phase



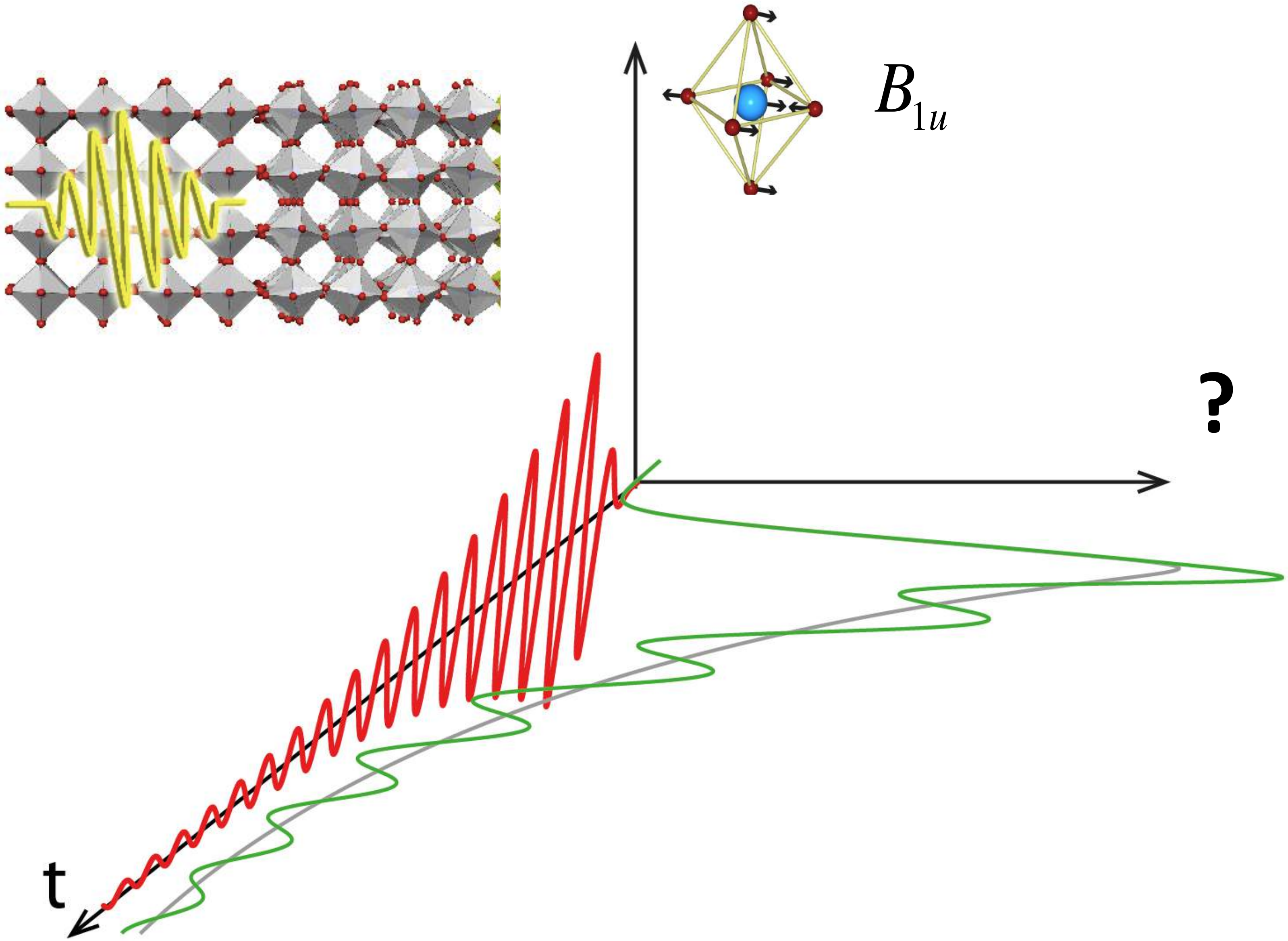
H. Hwang et al., Phys. Rev. Lett. 52, 15046 (1995)

$Pr_{0.3}Ca_{0.3}MnO_3$: excite B_{1u} mode induces hidden metal



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

What is the dynamical lattice distortion ?



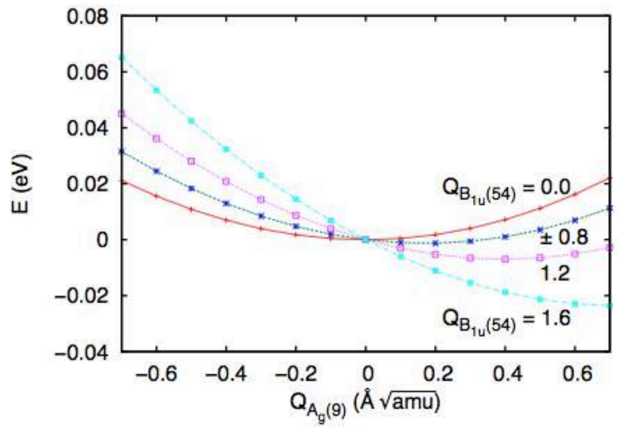
B_{1u} drives A_{1g} mode

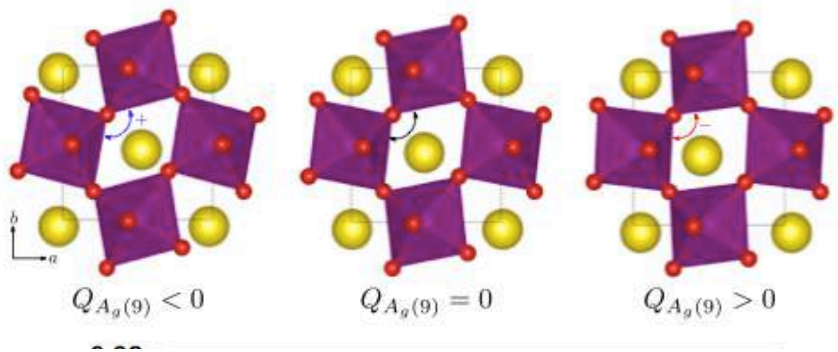
$$U_{\text{int}} = AQ_{ir}^{2}Q_{2}$$

$$B_{1u}^{2}A_{1g}$$

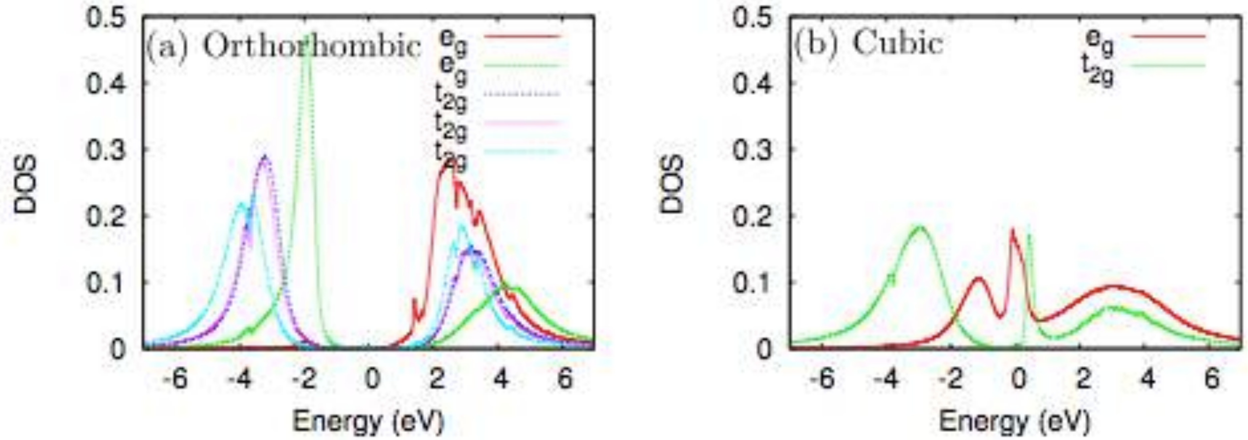
B_{1u} stretch drives A_{1g} rotations

Frozen Phonon



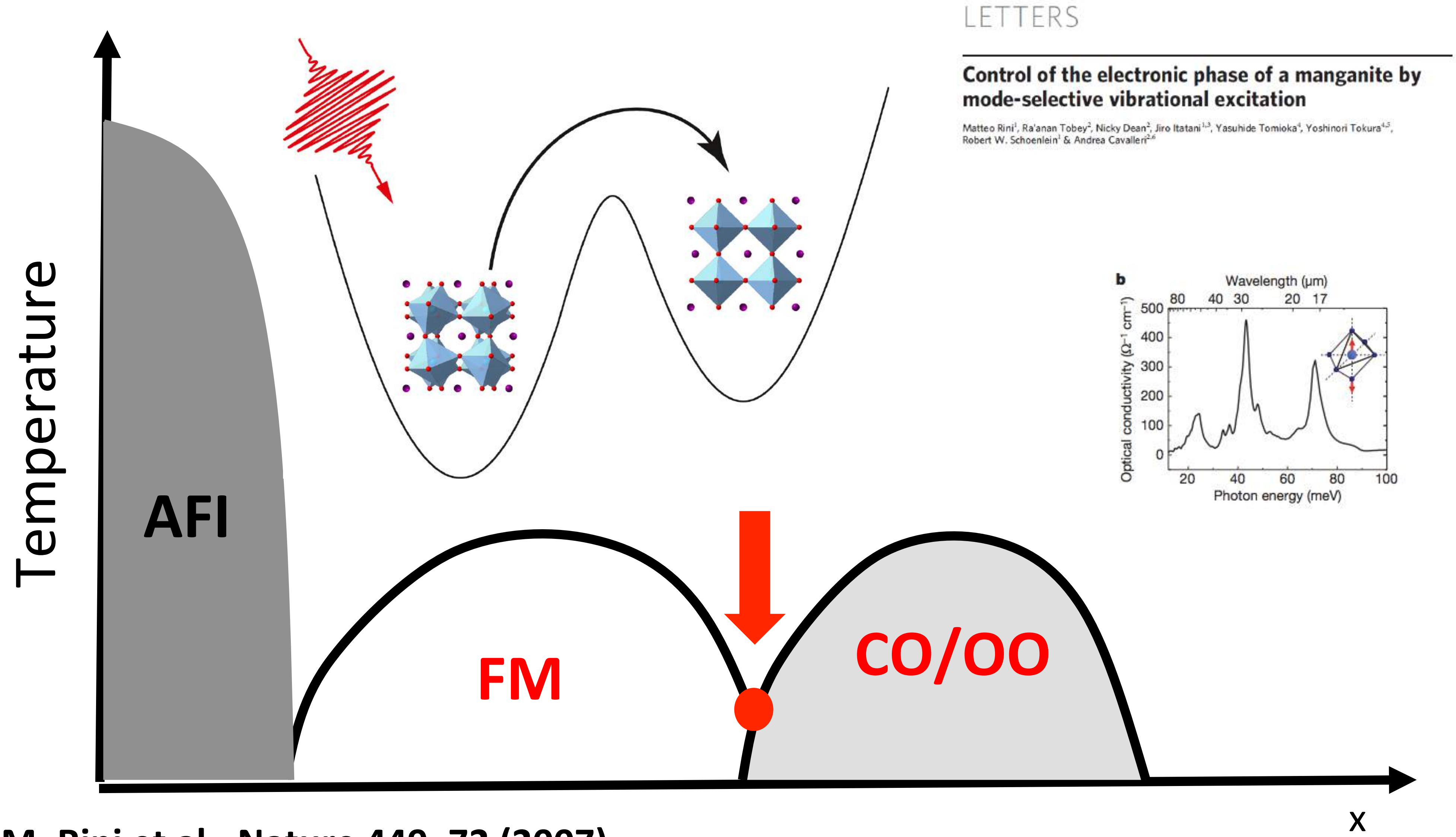


Electronic Structure in the distorted state -> metallic



A. Subedi, A. Cavalleri, A. Georges *Phys. Rev B* 89, 330301 (2014)

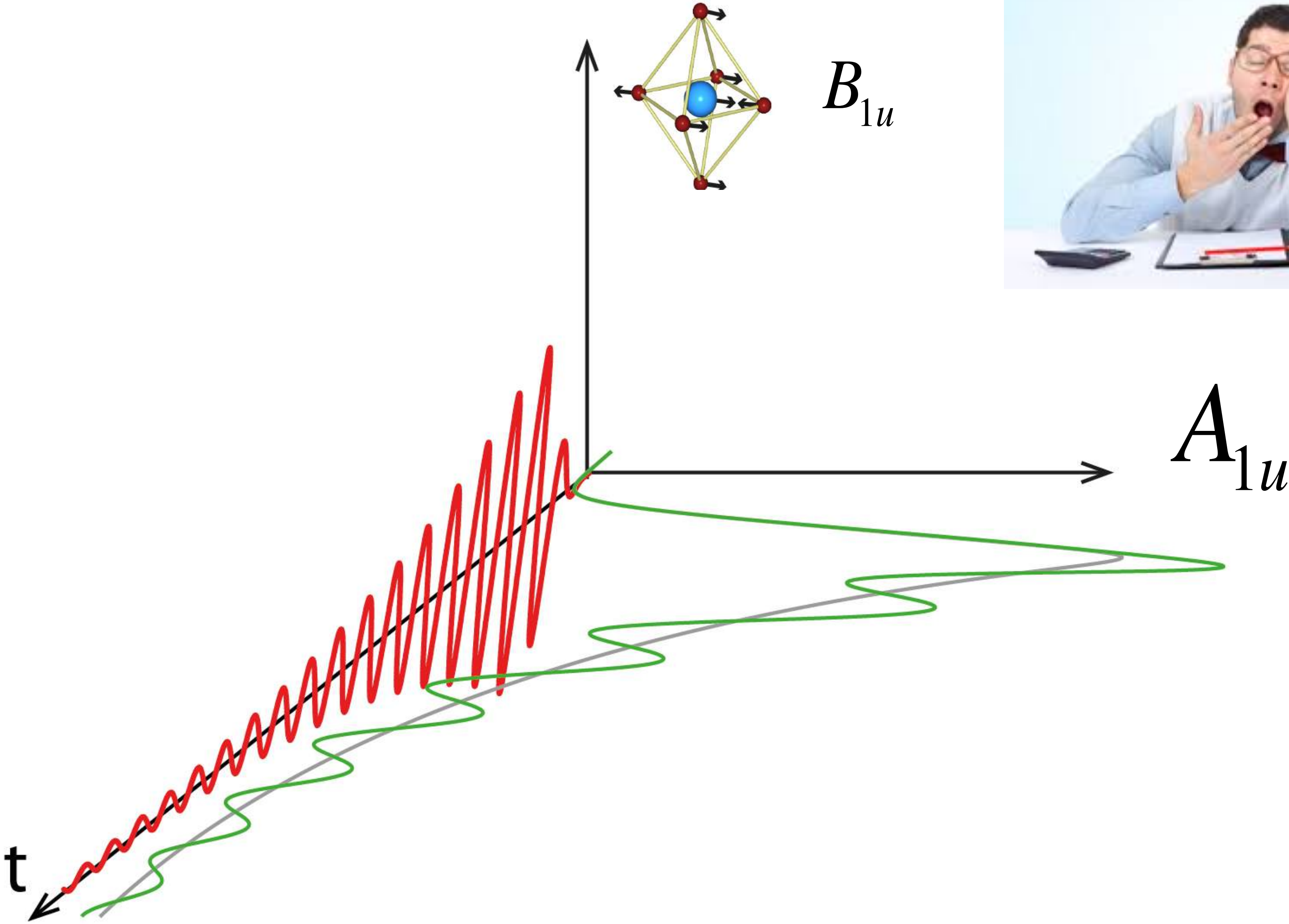
$Pr_{0.3}Ca_{0.3}MnO_3$: control of bond tilt…after all



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

A. Subedi, A. Cavalleri, A. Georges *Phys. Rev B* 89, 330301 (2014)

Centrosymmetric – only A modes



What else can I do ?

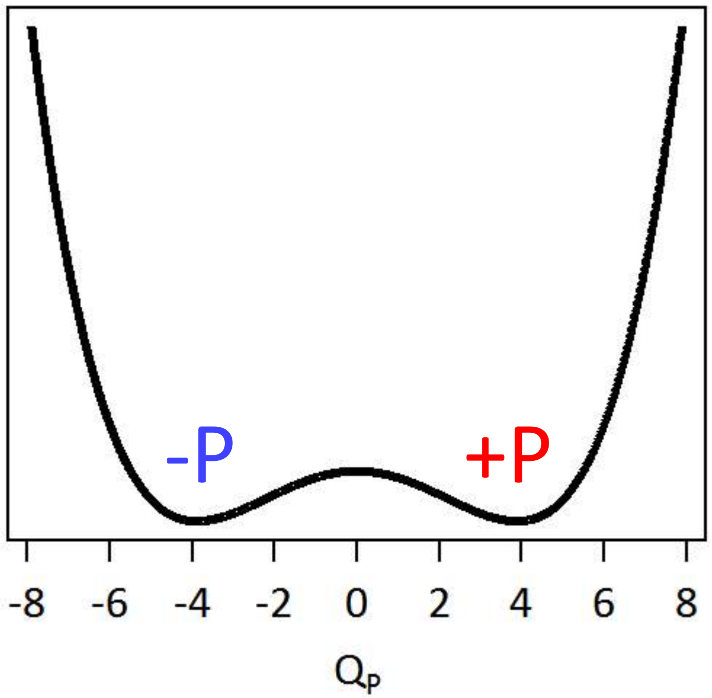
Manipulate inversion symmetry

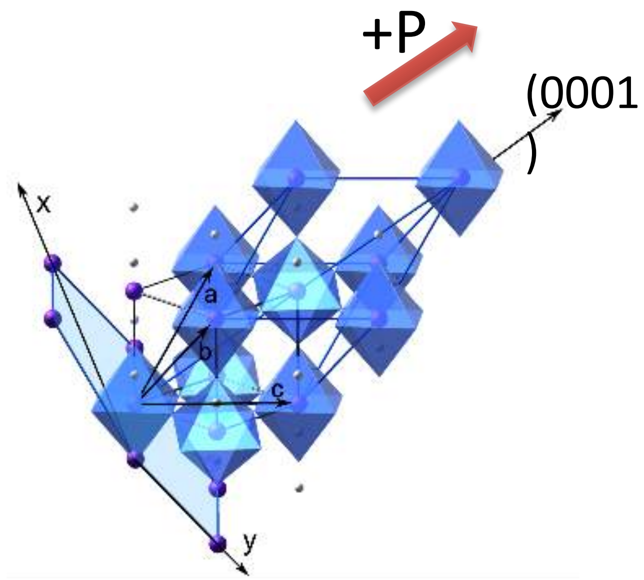
Manipulate time reversal symmetry

Ferroelectric: no centre of inversion

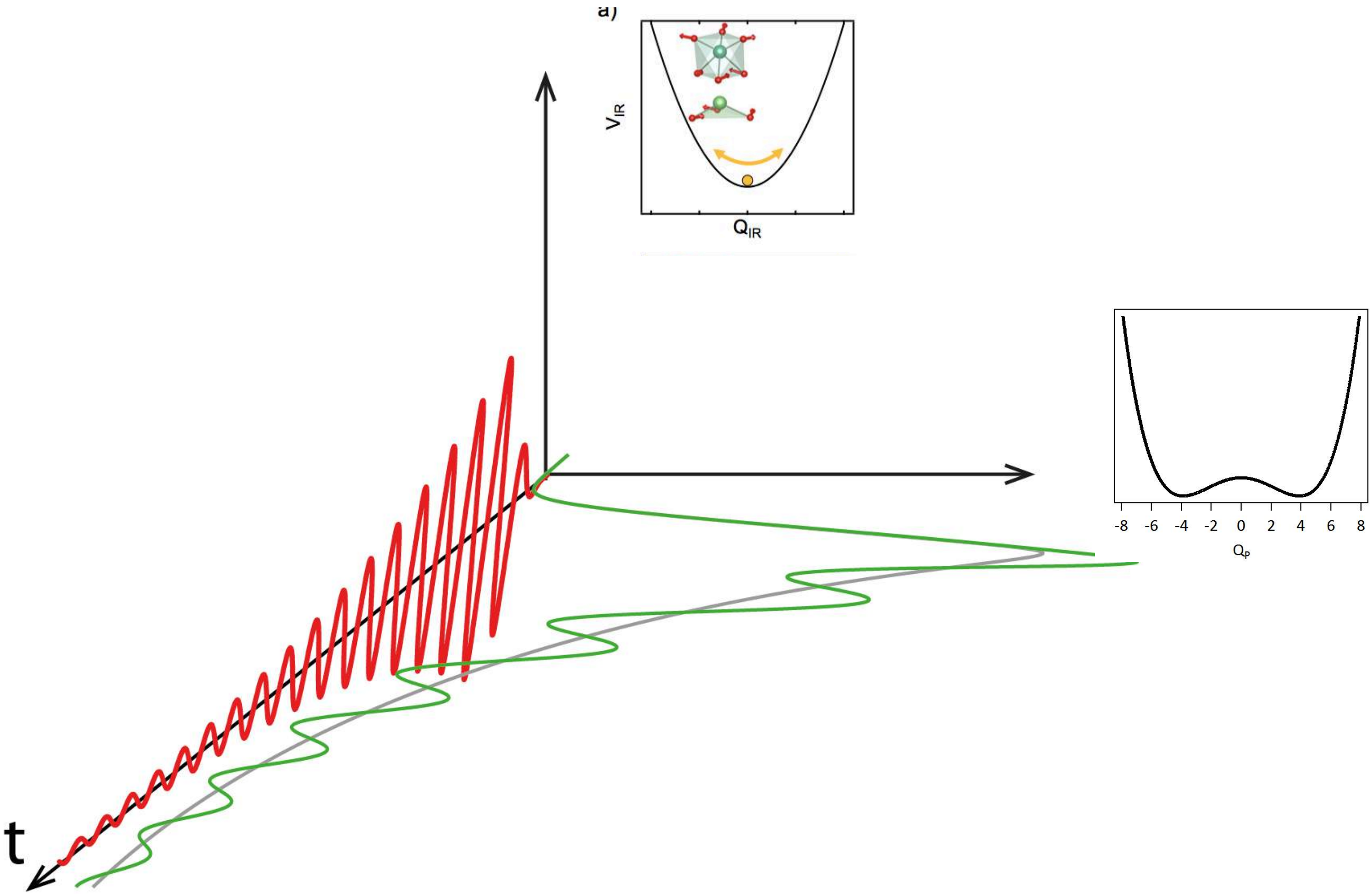
$$V_P = \frac{1}{2}\omega_P^2 Q_P^2 + aQ_P^3 + bQ_P^4$$

$LiNbO_3$

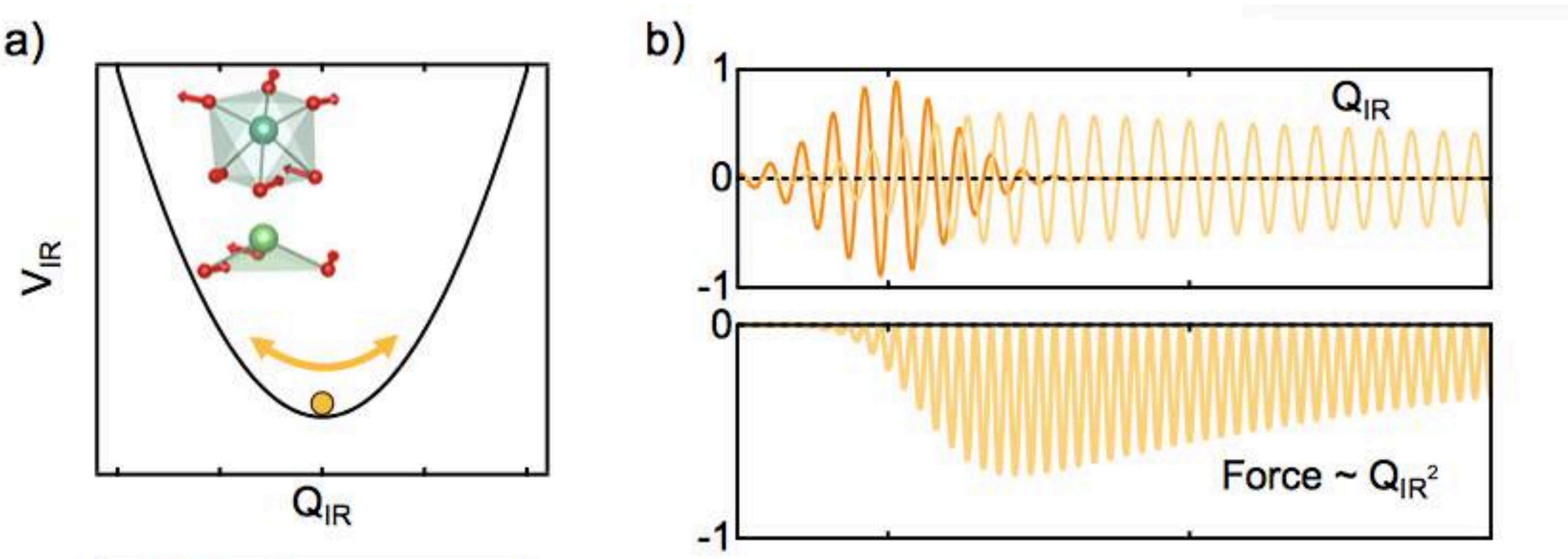




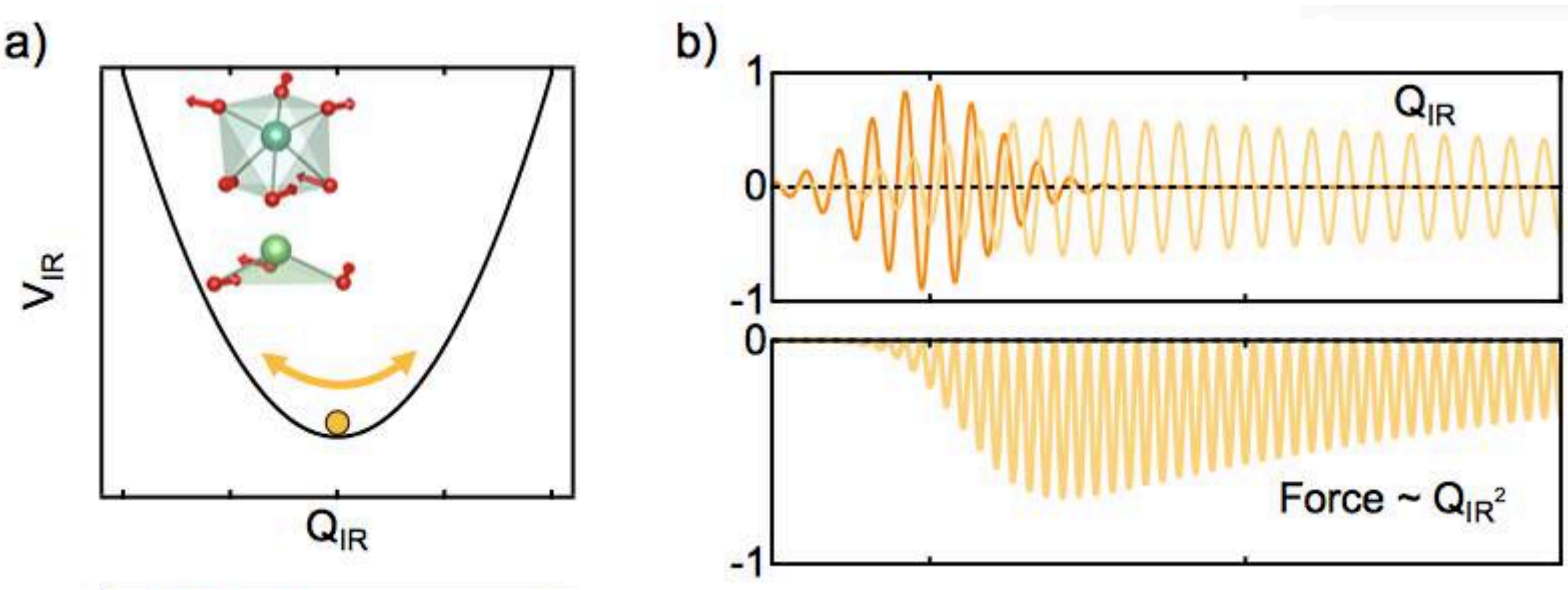
Not centrosymmetric – coupling odd modes



Pump an auxilliary mode



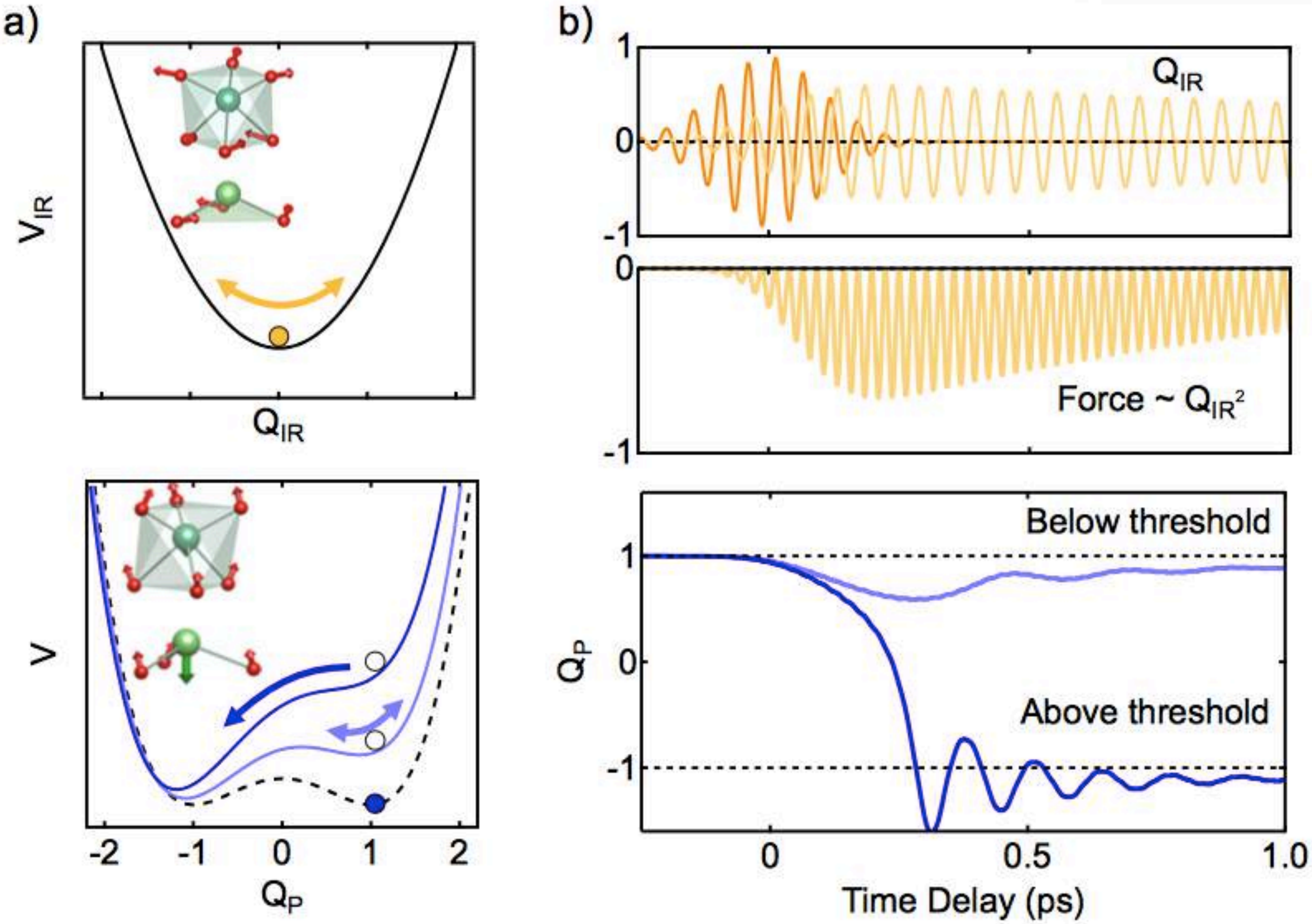
Force on ferroelectric mode



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

$$\ddot{Q}_P + \gamma_P \dot{Q}_P - \omega_P^2 Q_P + c_P Q_P^3 = aQ_{IR}^2,$$

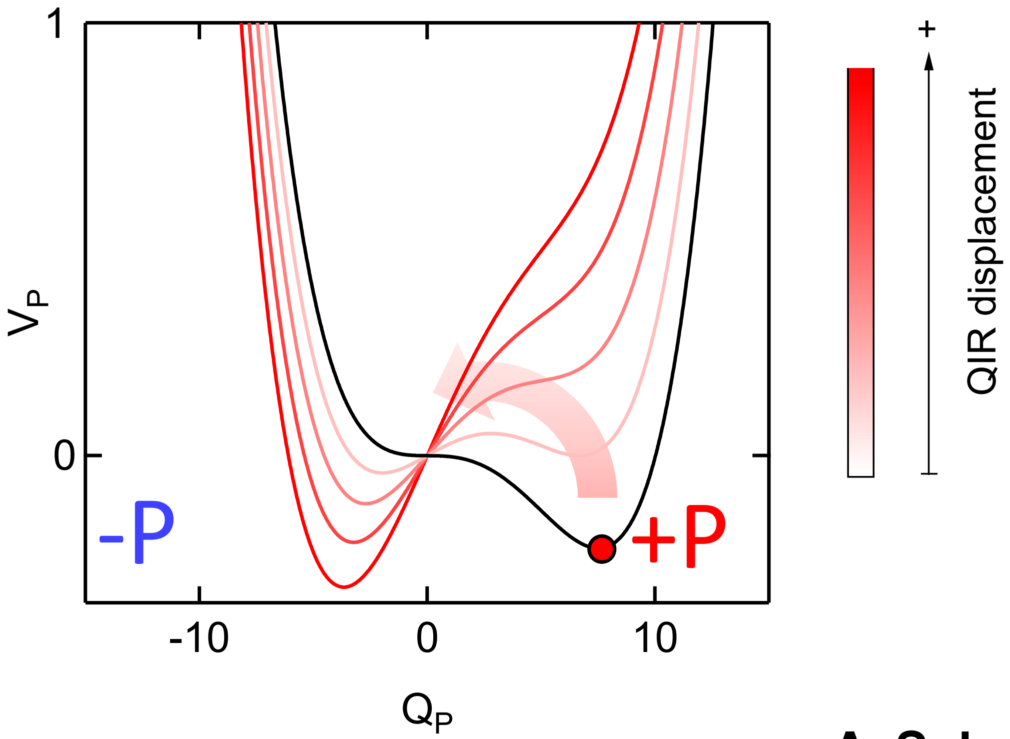
Force on ferroelectric mode

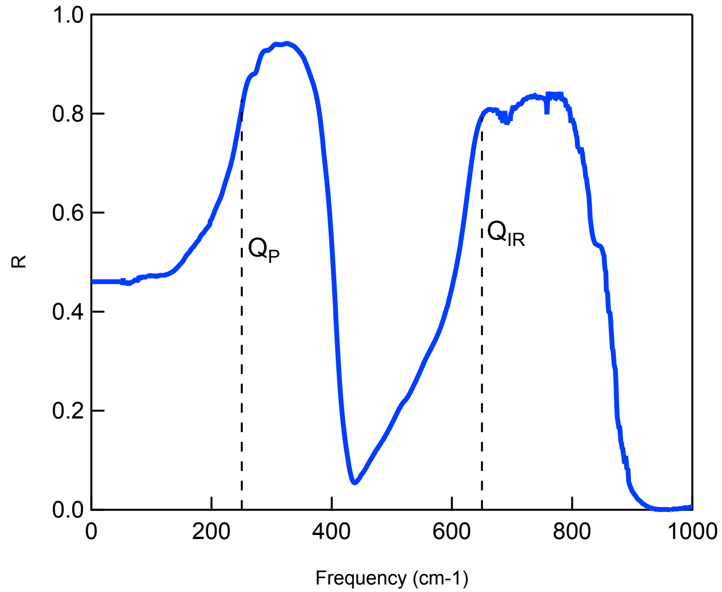


A. Subedi *Phys. Rev B* 92, 214303 (2014)

Coupling to Ferroelectric polarization

$$V_P = \frac{1}{2}\omega_P^2 Q_P^2 + aQ_P^3 + bQ_P^4 + AQ_{ir}^2 Q_P$$





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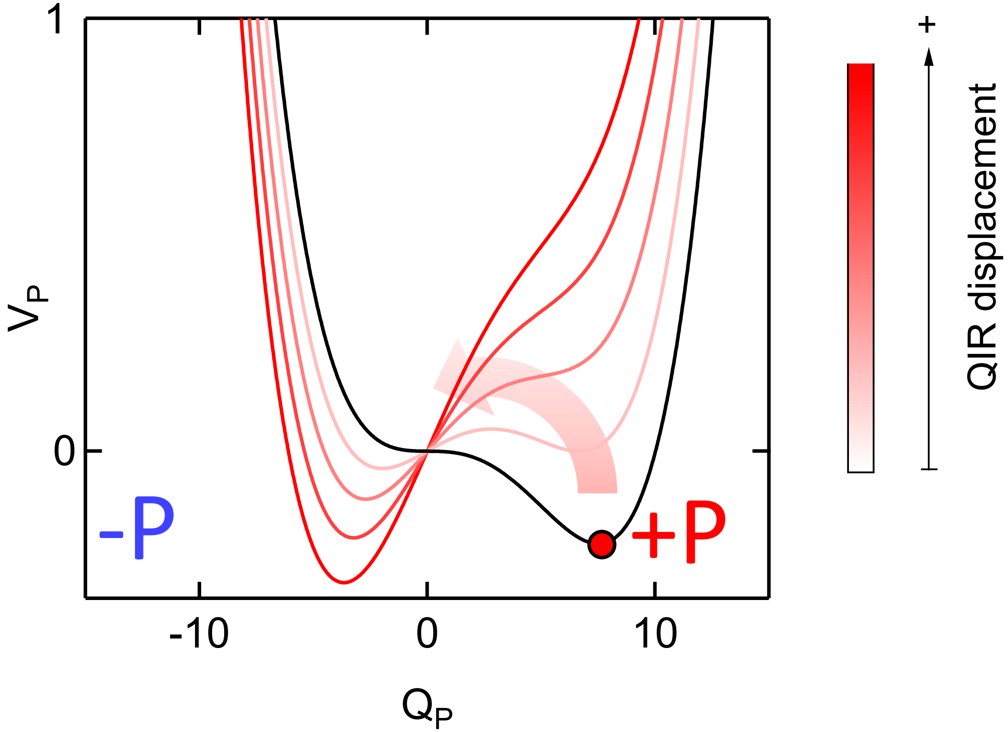
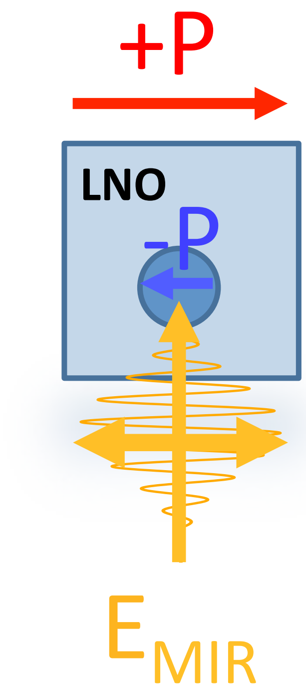
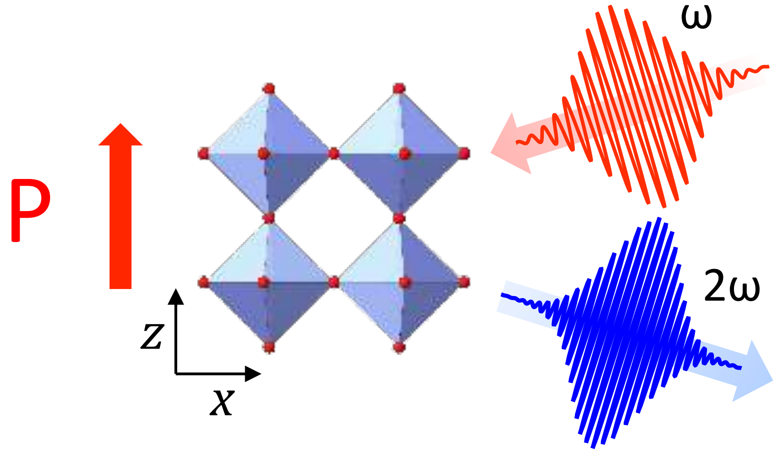
Coupling to Ferroelectric polarization

$$V_P = \frac{1}{2}\omega_P^2 Q_P^2 + aQ_P^3 + bQ_P^4 - AQ_{ir}^2 Q_P$$





Probing Ferroelectric polarization

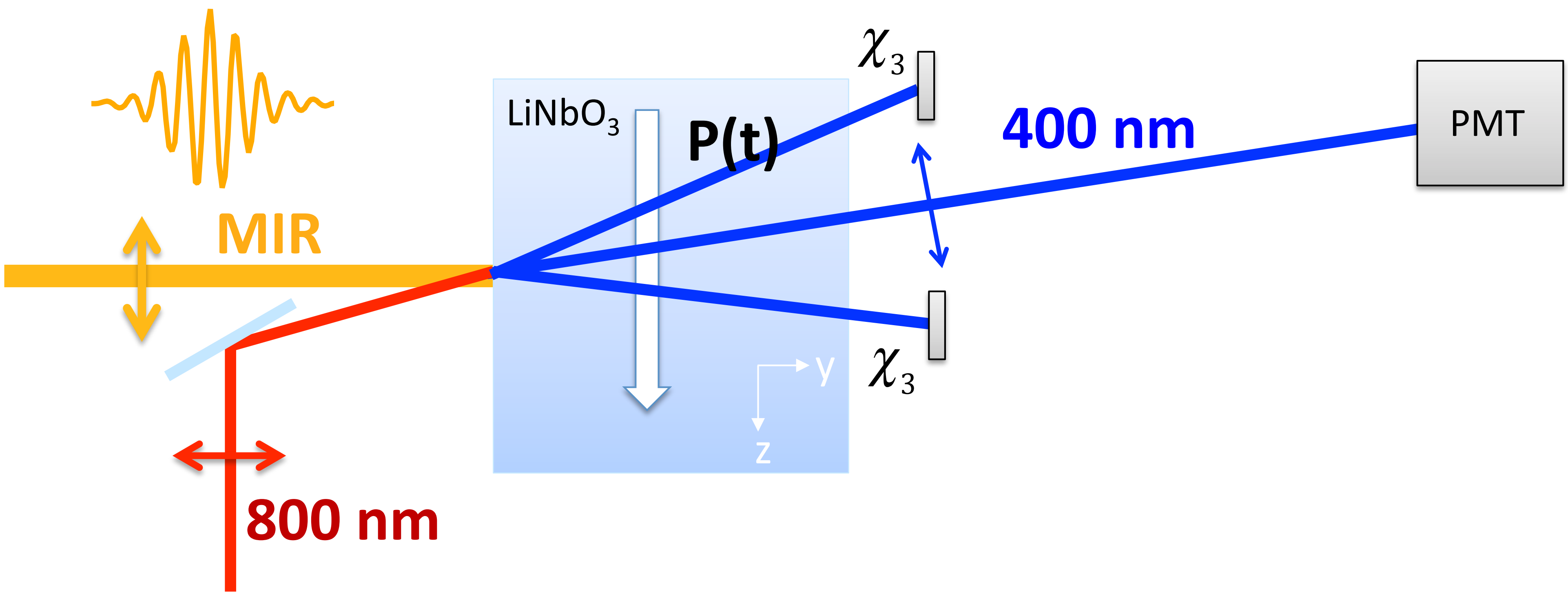


SHG only possible in non-centrosymmetric materials

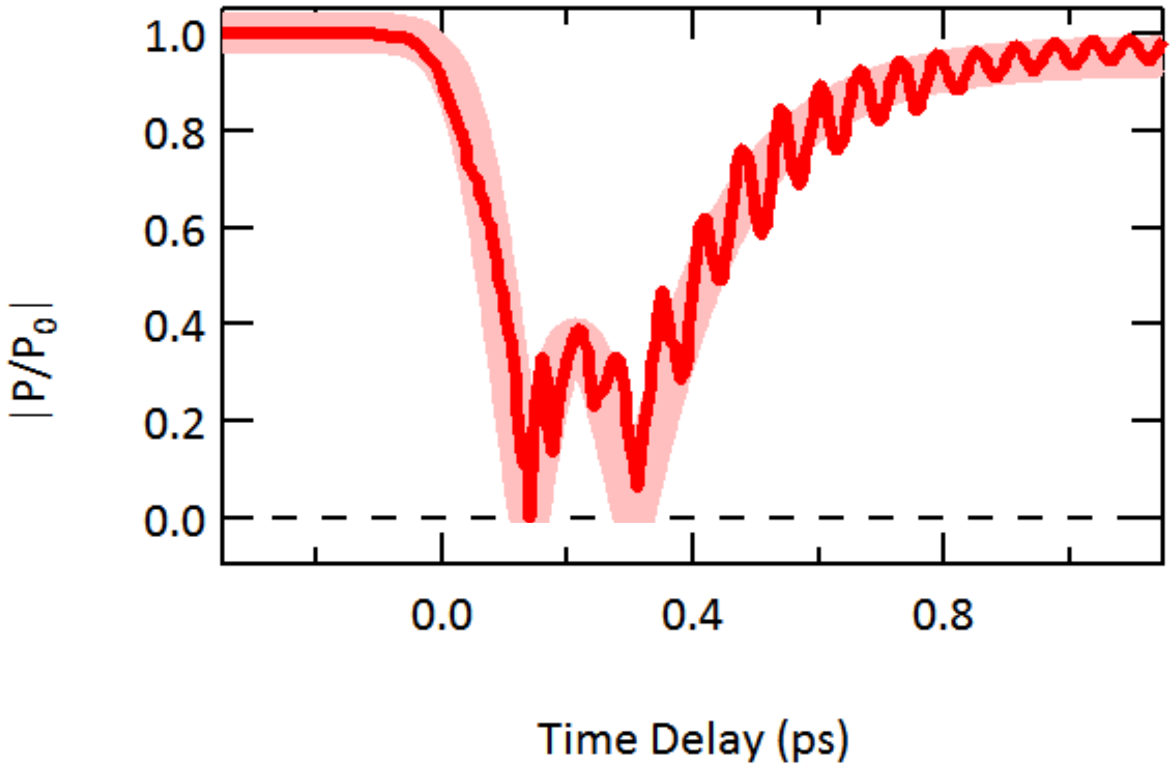
$$P^{(2)} = \varepsilon_0 \cdot \chi^{(2)} \cdot E^2_{(800nm)}$$

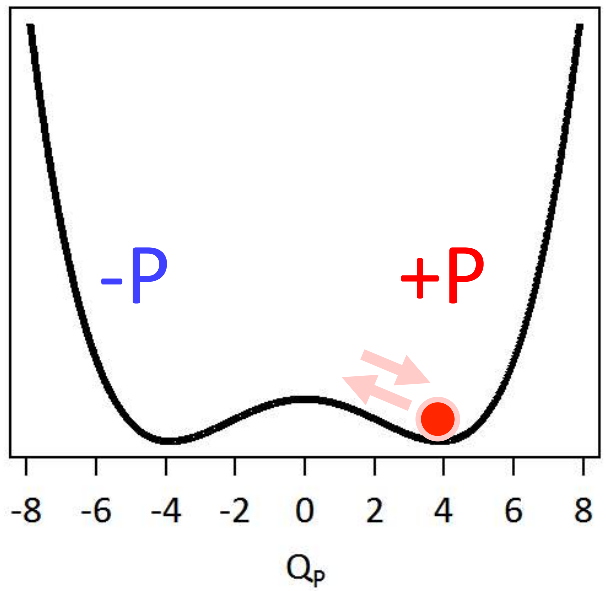
Probing Ferroelectric polarization

Measure time-resolved second harmonic intensity

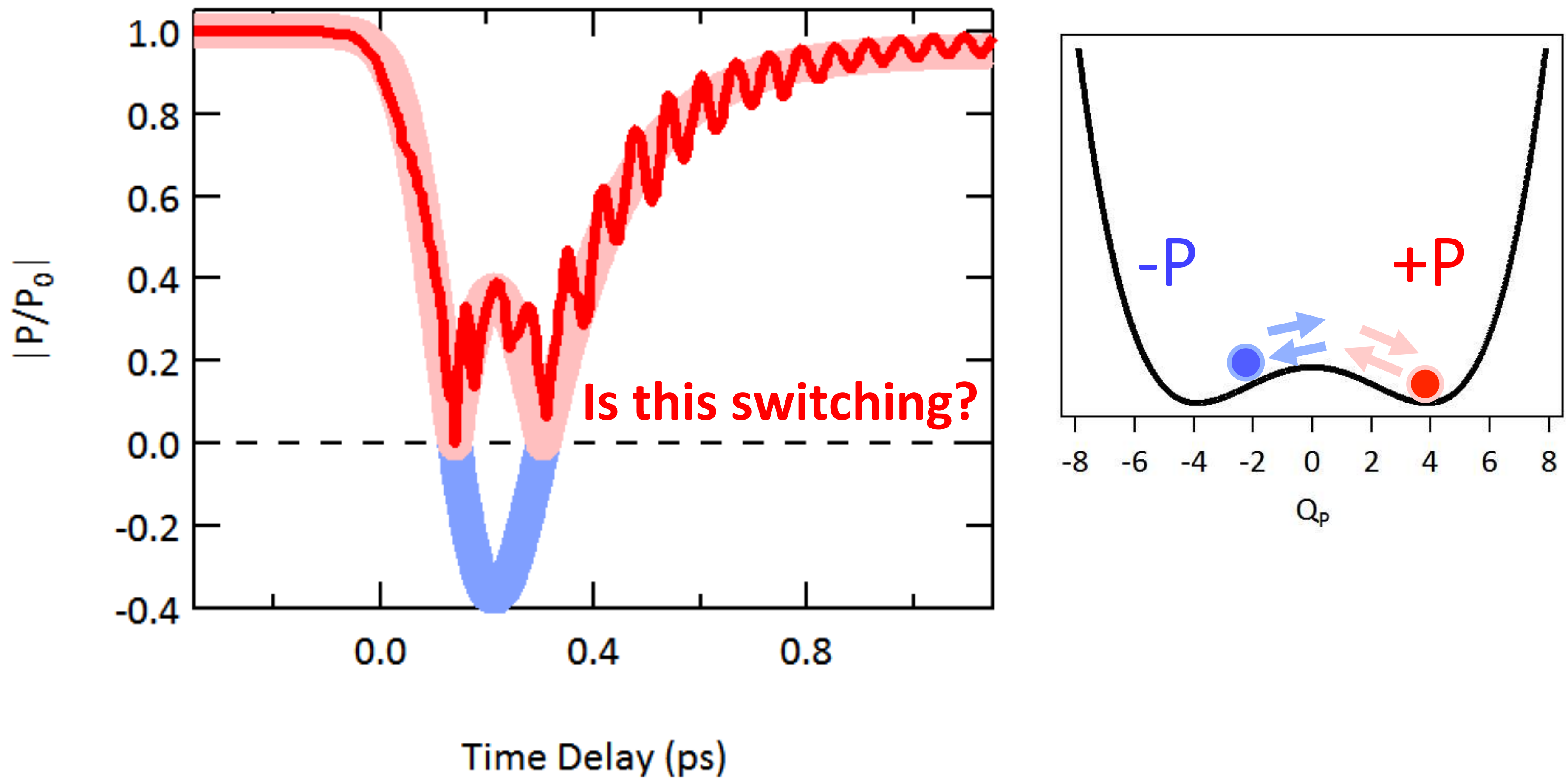


drops to zero...bounces....goes back to zero

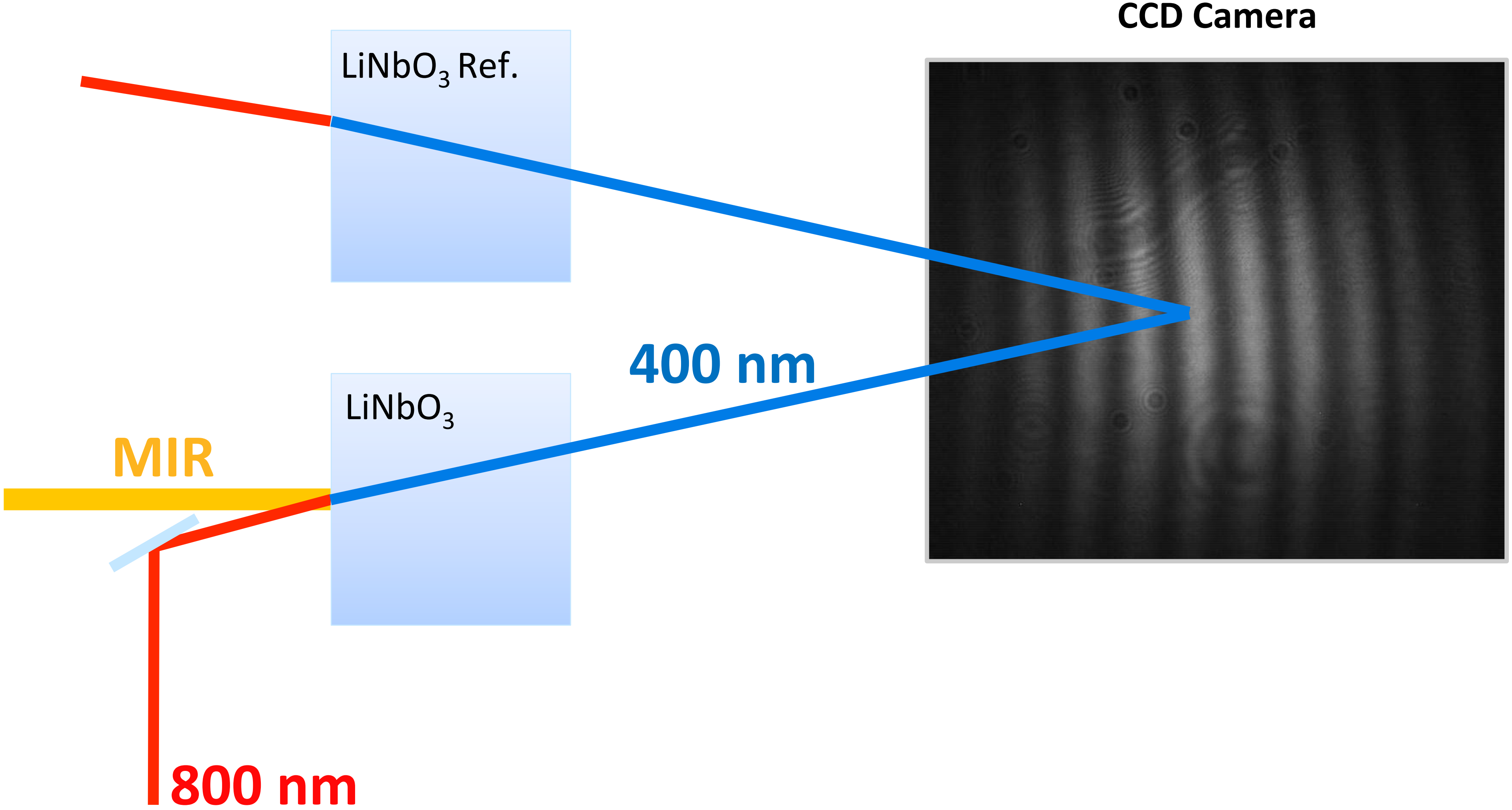




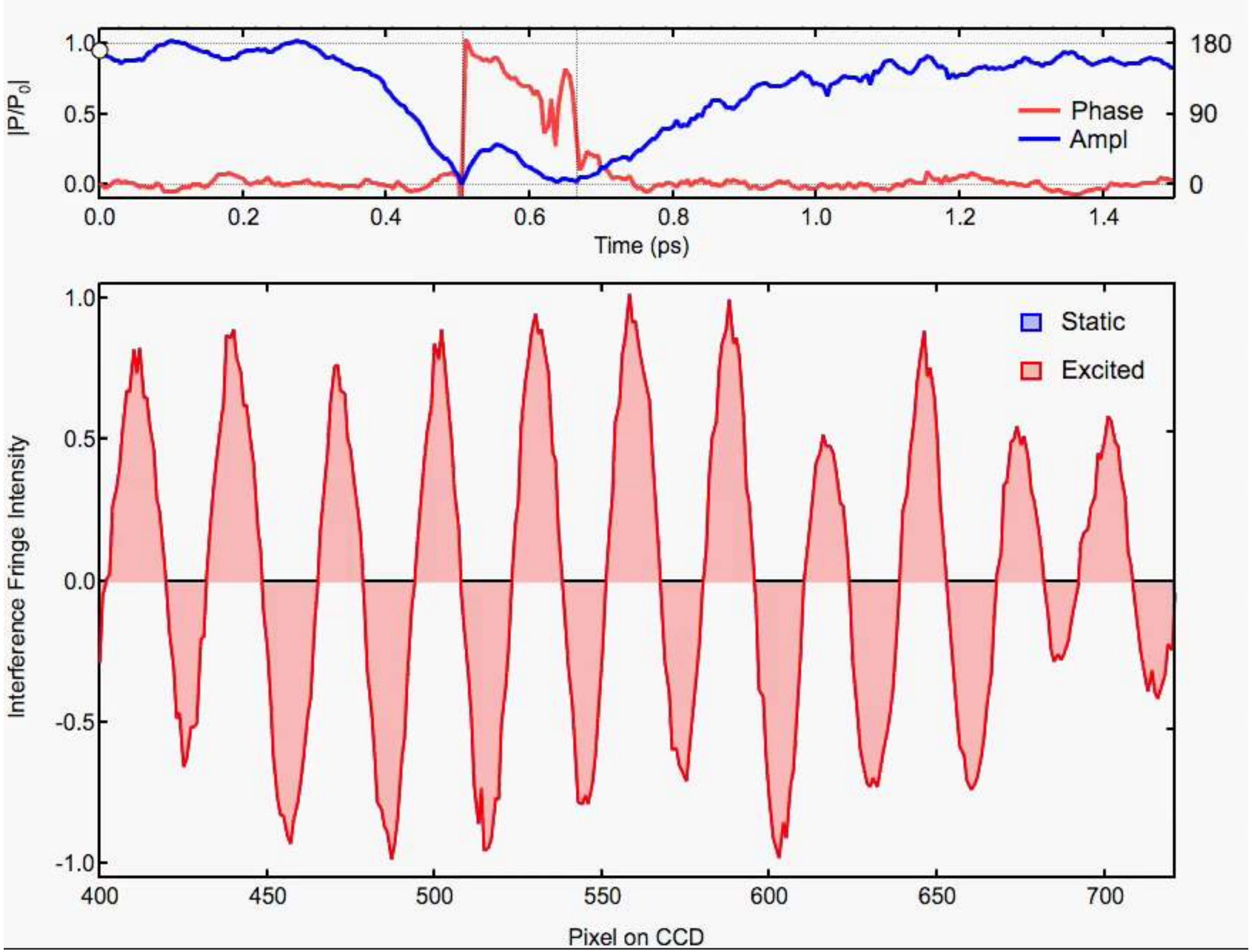
Is this switching?



Phasing Ferroelectric Polarization

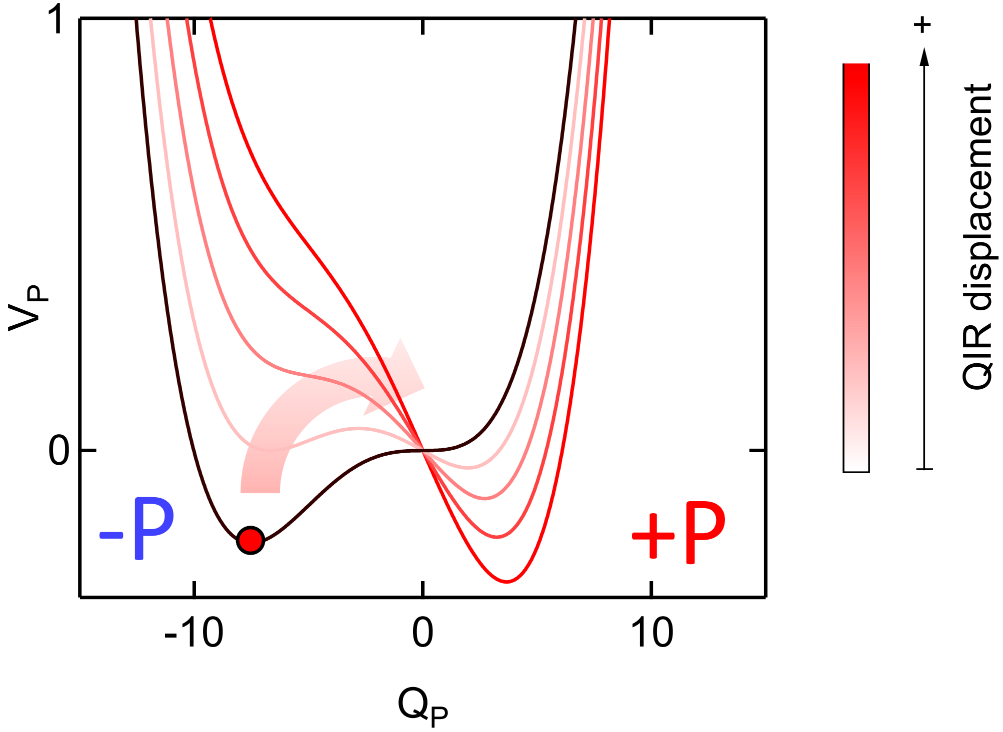


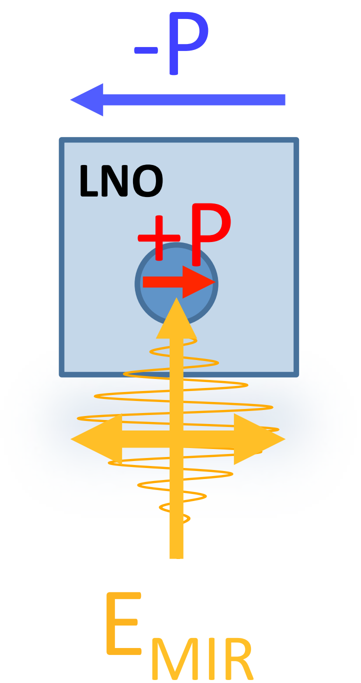
Phasing Ferroelectric Polarization



Ferroelectric Switching in LNO

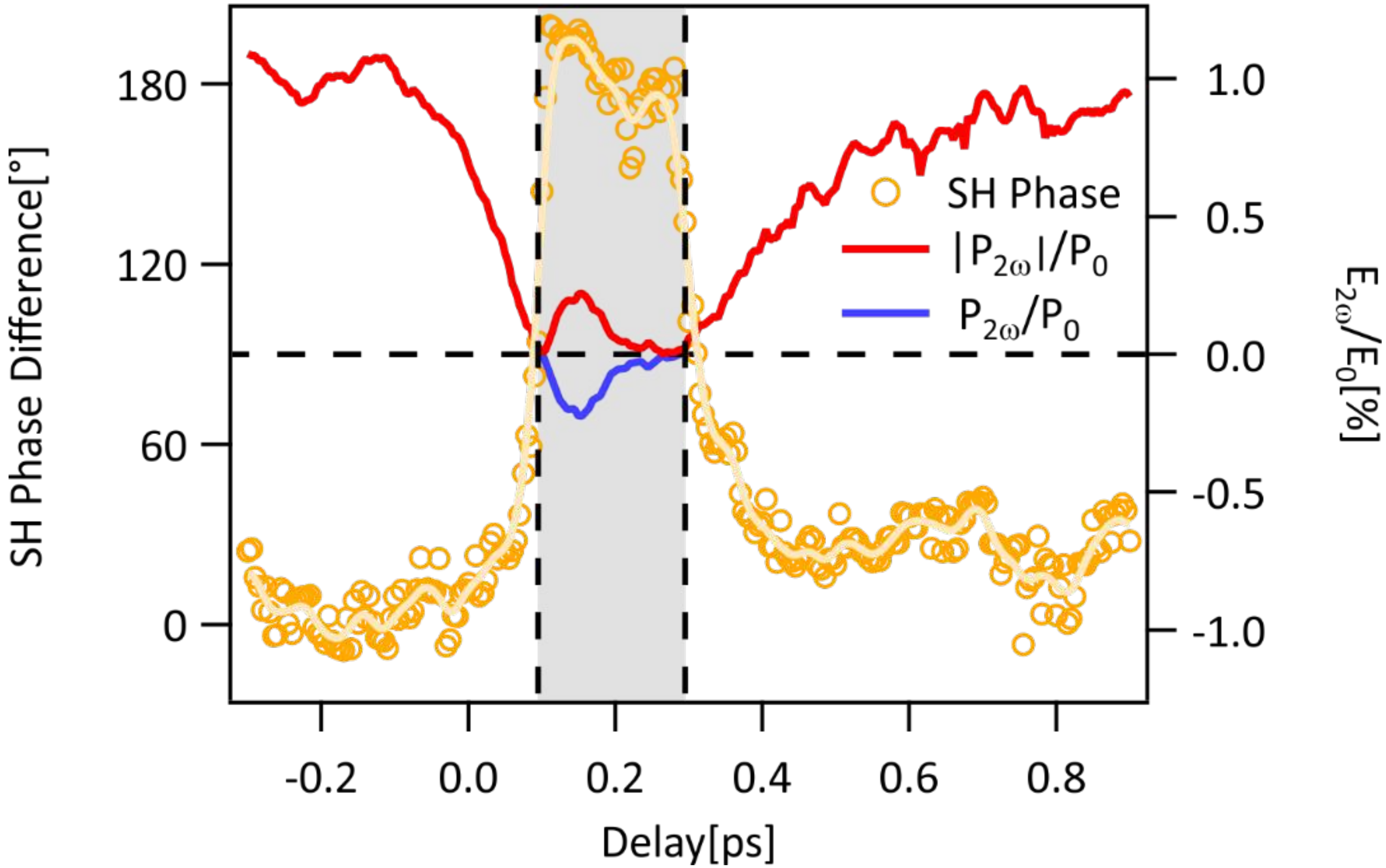
$$V_P = \frac{1}{2}\omega_P^2 Q_P^2 + aQ_P^3 + bQ_P^4 - AQ_{ir}^2 Q_P$$





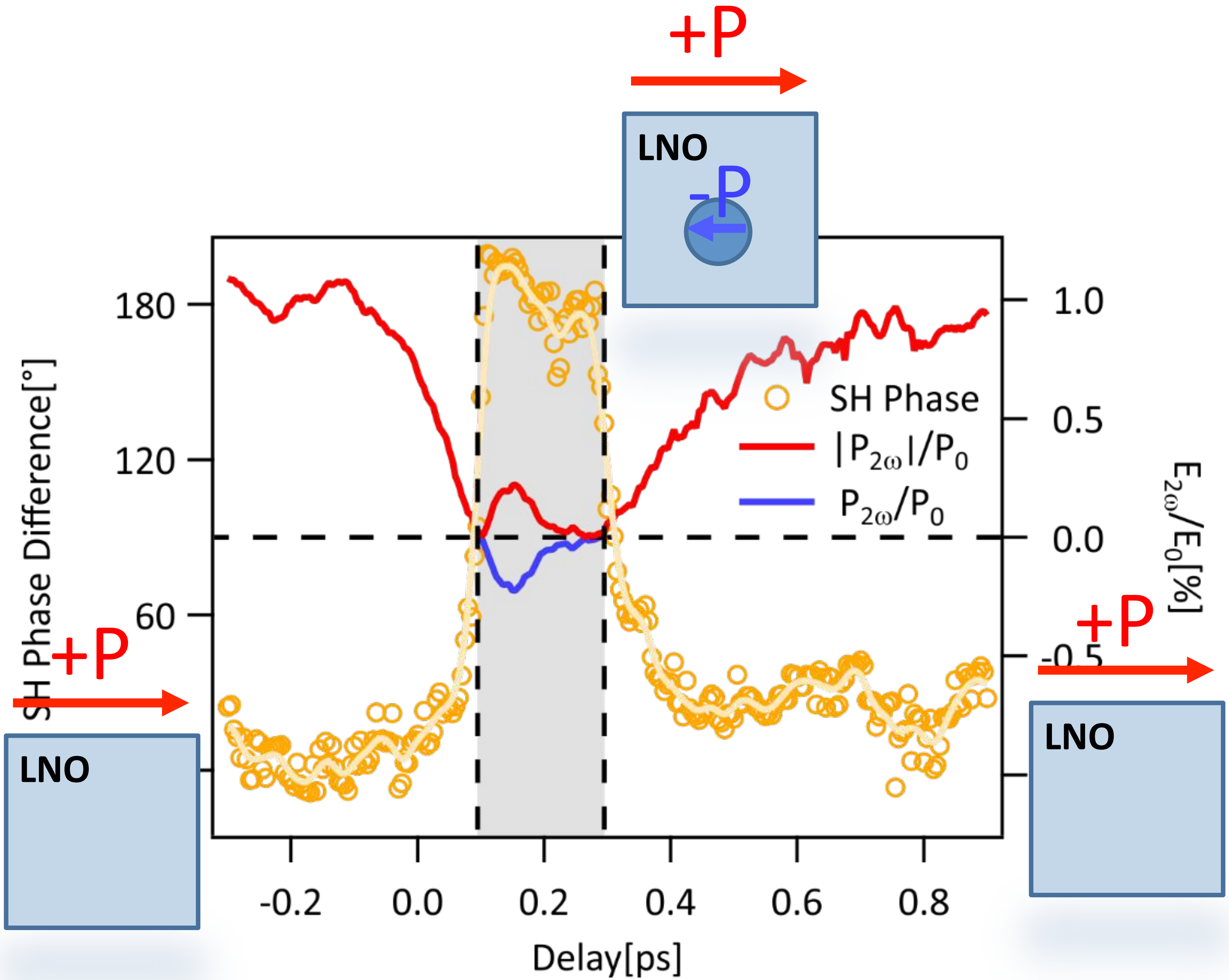
"Direction" given by initial state

Phasing Polarization Switching



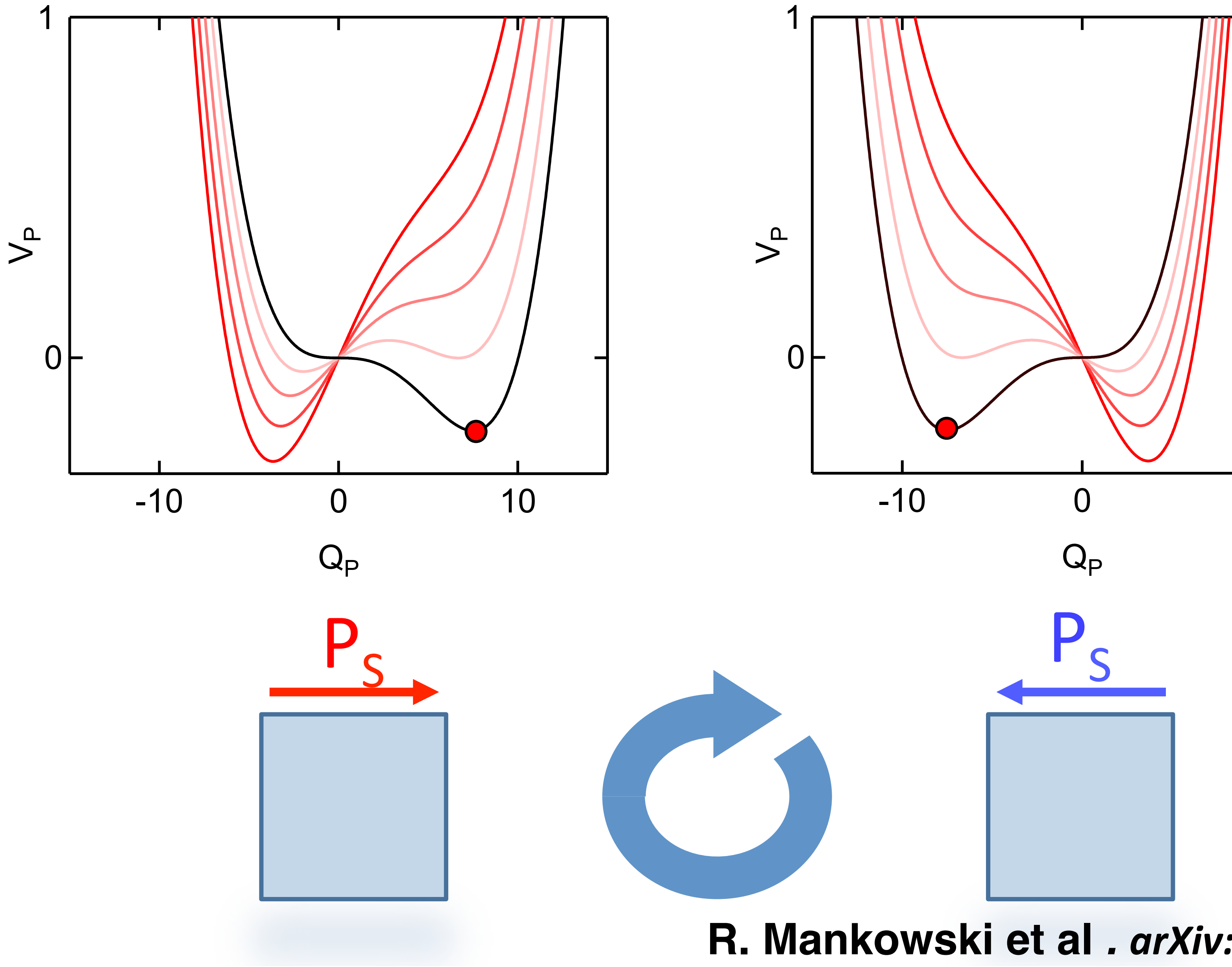
R. Mankowski et al ***. arXiv:1701.06312***

Phasing Ferroelectric Polarization



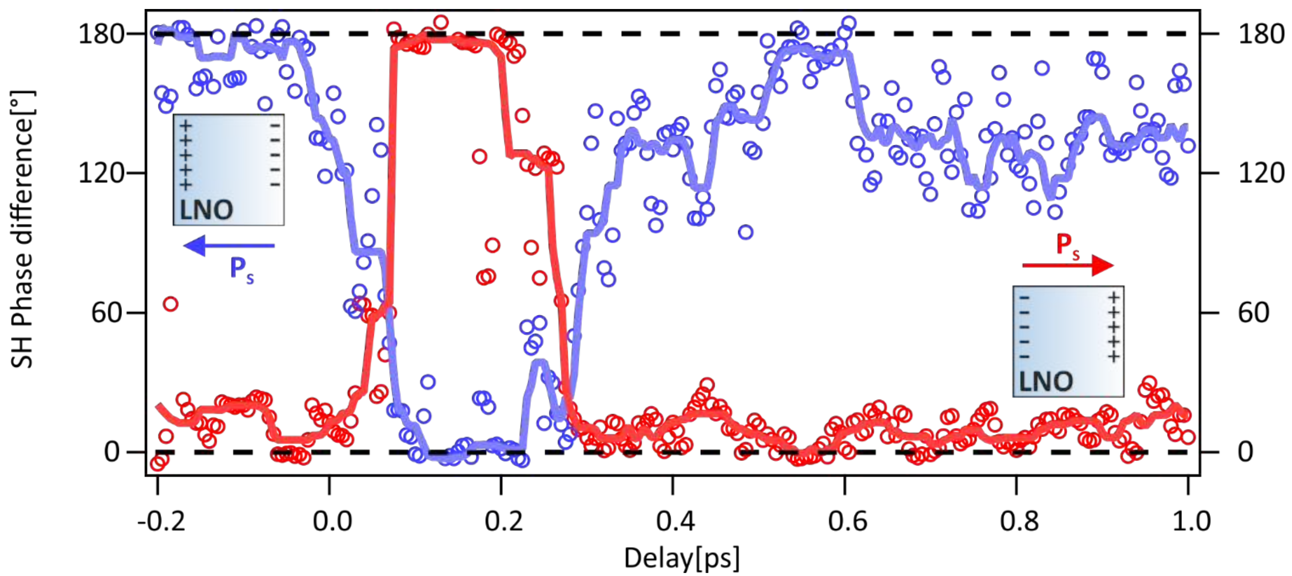
R. Mankowski et al . ***arXiv:1701.06312***

Starting from different direction



R. Mankowski et al . *arXiv:1701.06312*

Bi-directional switching



R. Mankowski et al . ***arXiv:1701.06312***

Up to now I discussed only lowest order

In analogy with nonlinear optics

$Q_{IR}^2 \cdot Q_2$ (lattice control)

$Q_{IR}^2 \cdot Q_2^2$ (phonon squeezing)

Q_{IR}^4 (parametric phonon amplification)

$Q_{IR1} \cdot Q_{IR2} e^{i\Theta} \cdot s$ (controlling time reversal invariance)

$Q_{IR}^2 \cdot U$ (controlling correlations)

What else?

In analogy with nonlinear optics

$Q_{IR}^2 \cdot Q_2$ (lattice control)

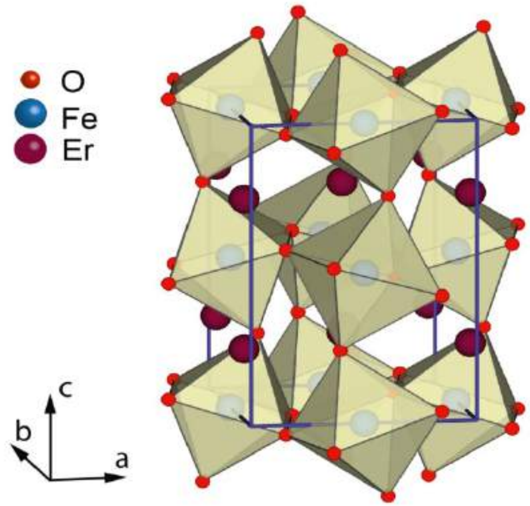
$Q_{IR}^2 \cdot Q_2^2$ (phonon squeezing)

Q_{IR}^4 (parametric phonon amplification)

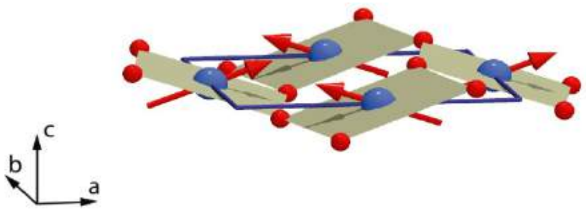
$Q_{IR1} \cdot Q_{IR2} e^{i\Theta} \cdot s$ (controlling time reversal invariance)

$Q_{IR}^2 \cdot U$ (controlling correlations)

Can we break time reversal symmetry ?

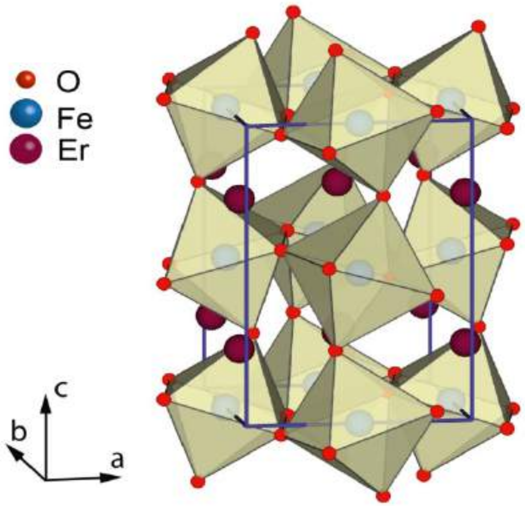


ErFeO$_3$



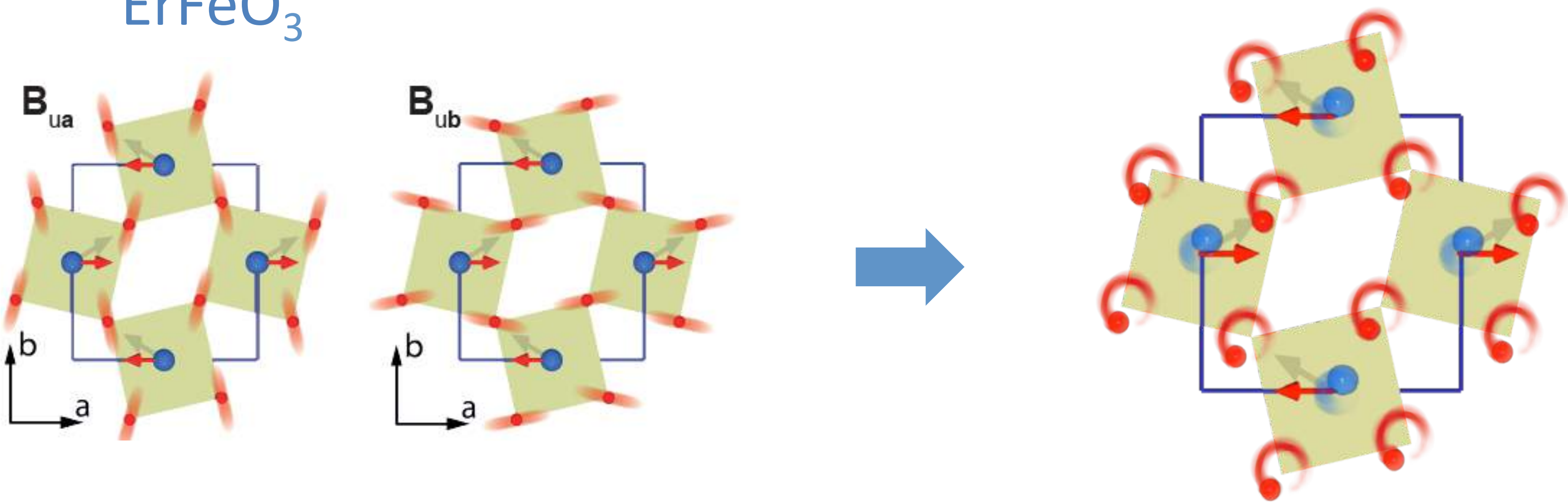
Orthorombically distorted perovskite
Antiferromagnetic insulator

Exciting more than one mode

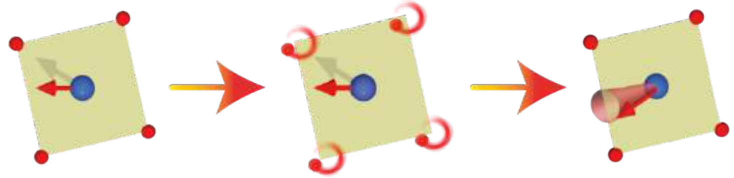


Simultaneous excitation of **two lattice modes** with controlled **relative phase**.

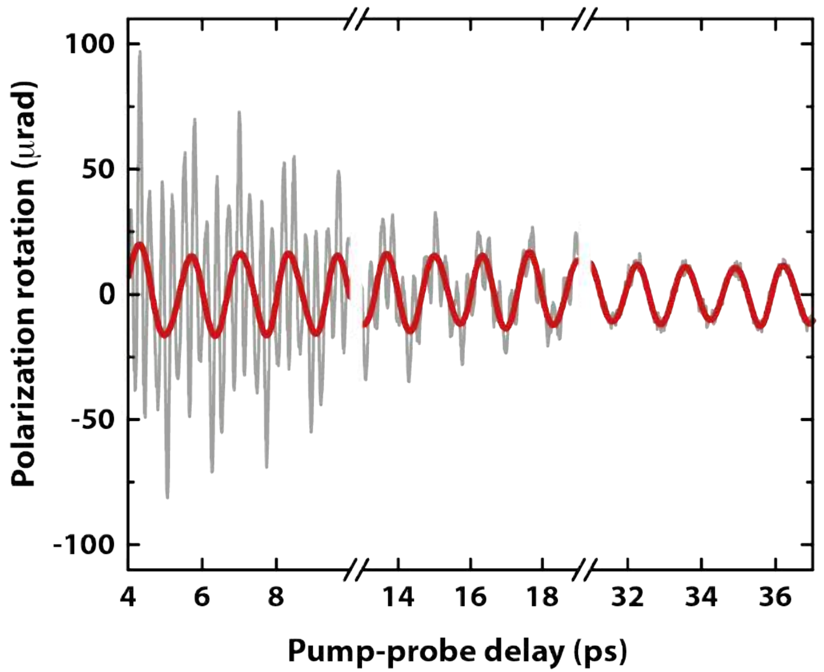
$ErFeO_3$

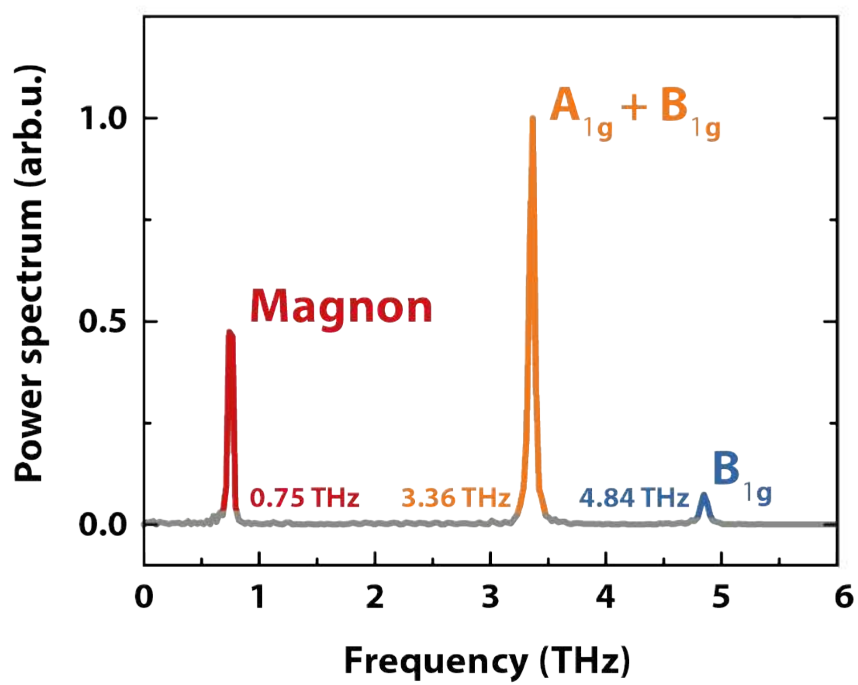


Break time reversal symmetry



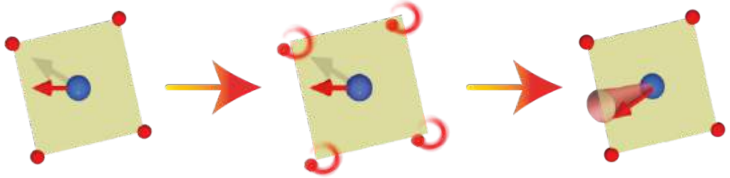
$$H_{eff} = i\alpha\, Q_{IR1} Q^{*}_{IR2} M$$



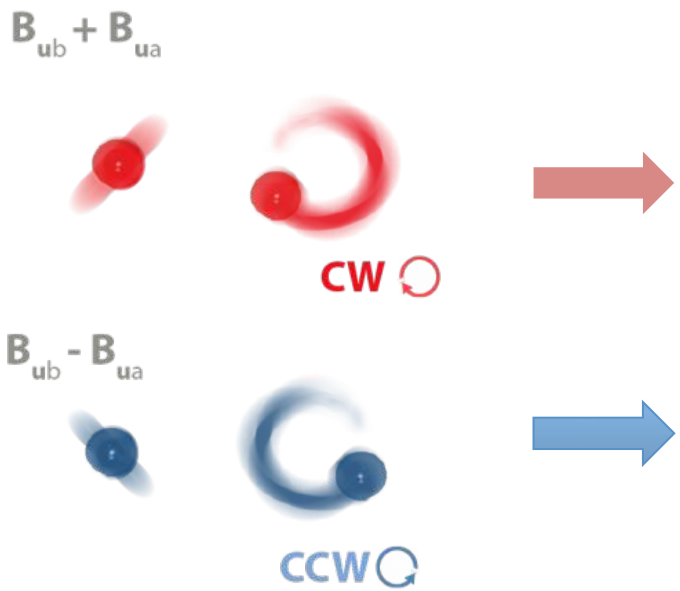


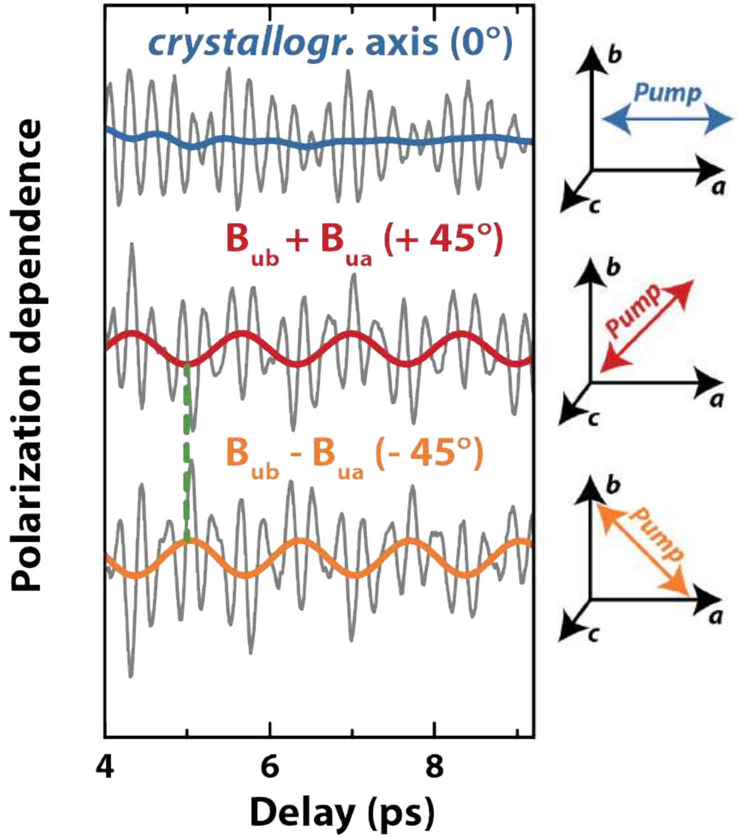
T. F. Nova et al., *Nature Physics* 13, 132 *(2017)*

Coherent control of magnetic mode



$$H_{eff} = i\alpha\, Q_{IR1} Q^{*}_{IR2} M$$

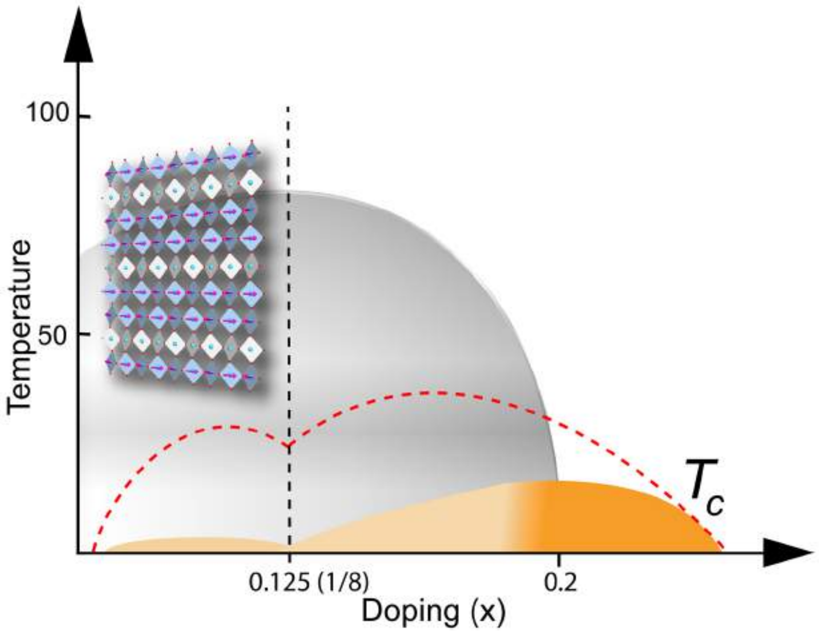




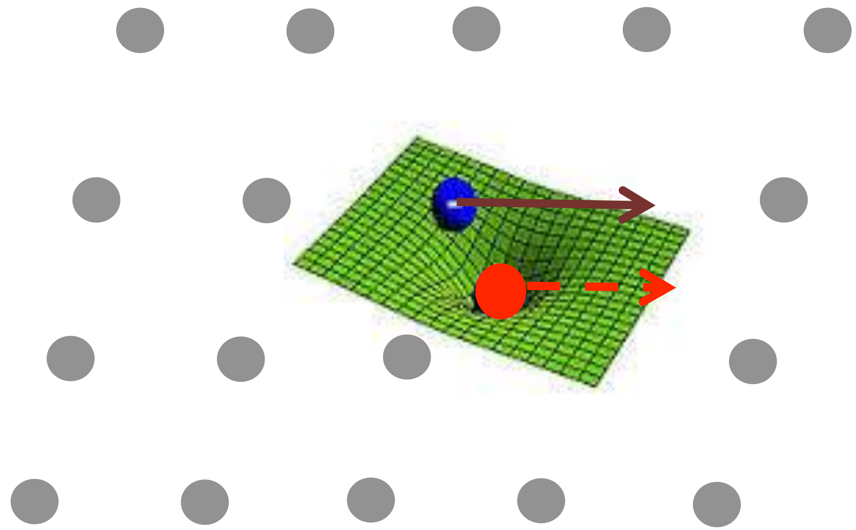
T. F. Nova et al., *Nature Physics* 13, 132 *(2017)*

Controlling superconductivity

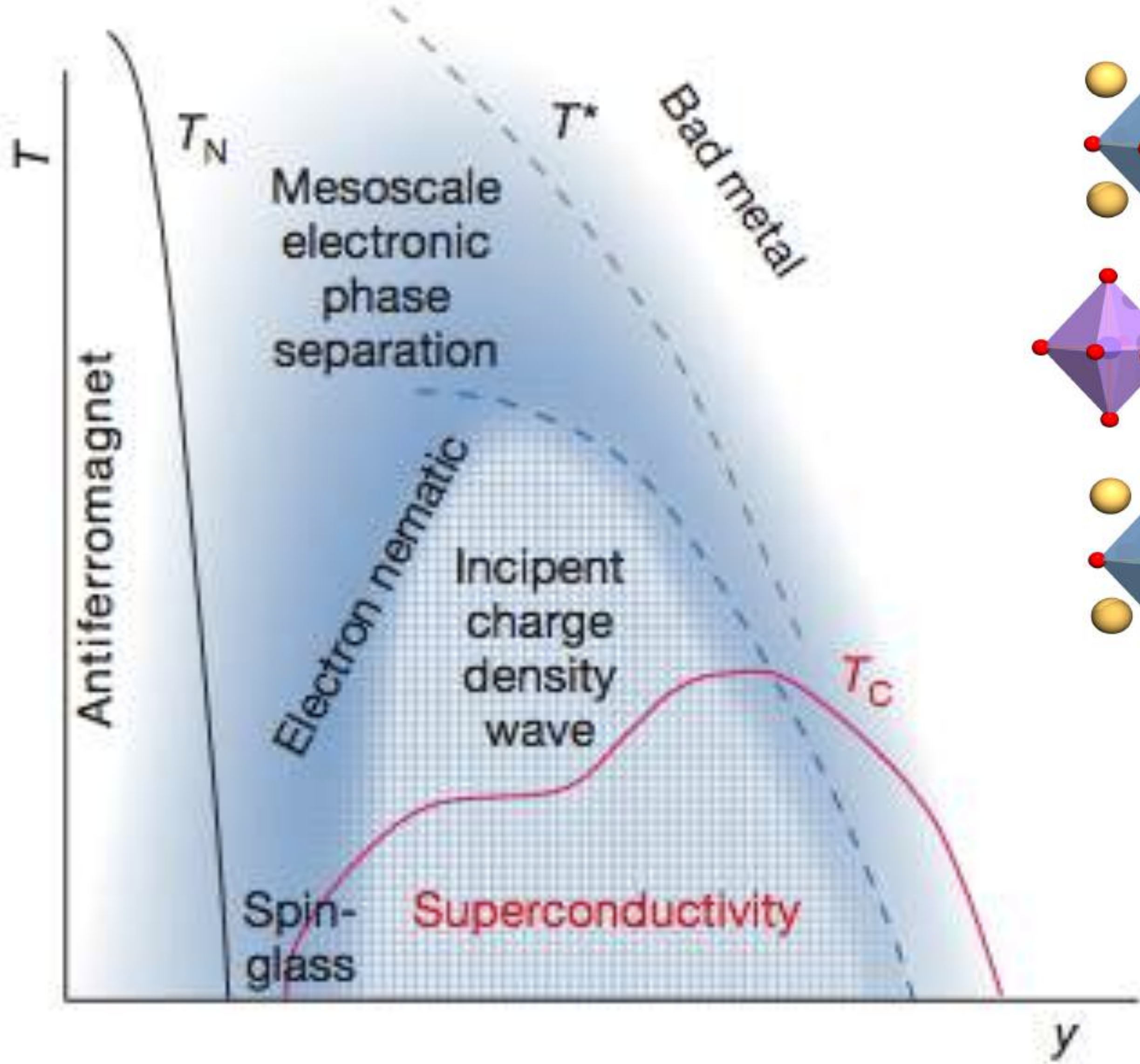
Lattice distortions may quench SC

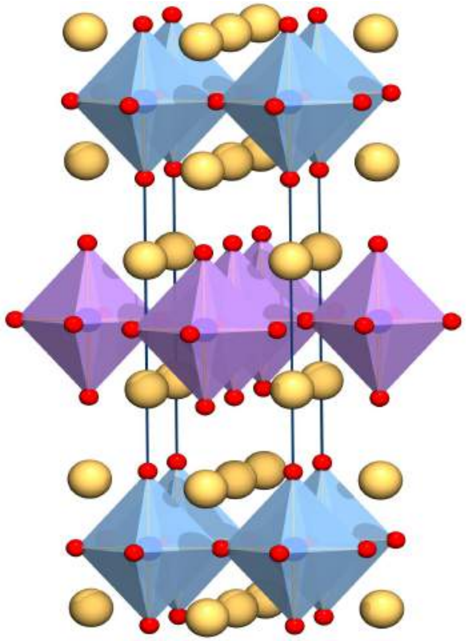


Lattice distortions may promote SC



Cuprate superconductors: competing orders and hidden phases

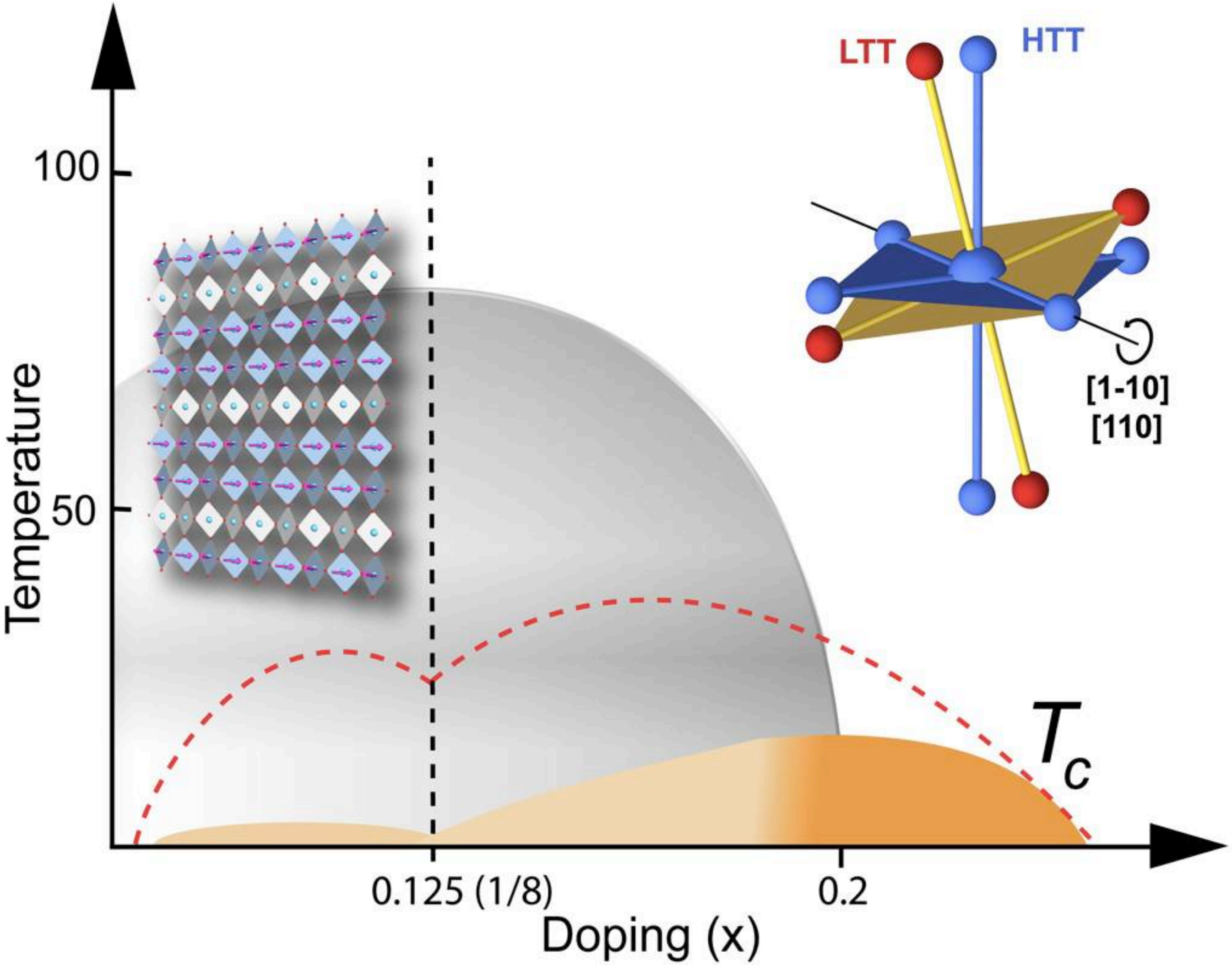




doping

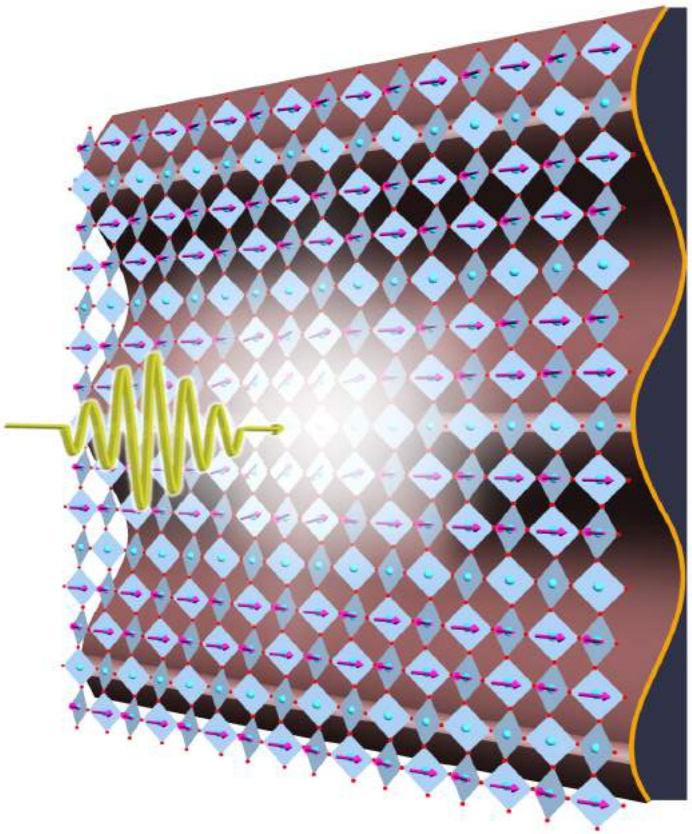
Fradkin and Kivelson, Nature Physcs (2012)

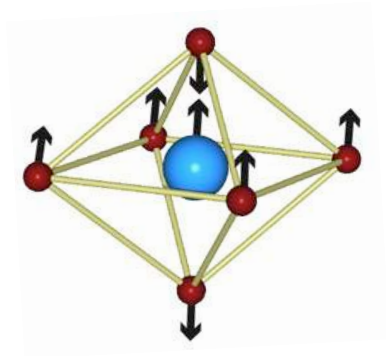
Eu:LSCO$_{1/8}$ stripe charge order



With Hide Takagi
MPI Stuttgart

Excitation of in plane Cu-O stretch





600 cm^{-1}

16 μm wavelength

μJ pulses

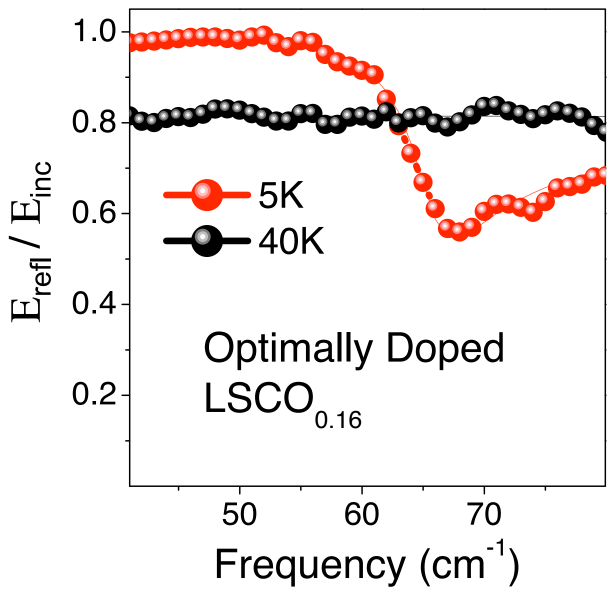
MV/cm fields

With Hide Takagi
MPI Stuttgart

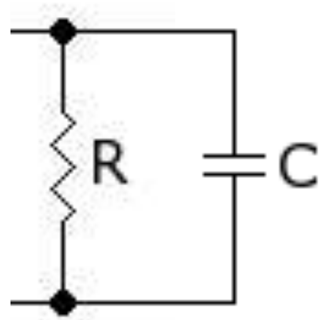
Probing the transient state

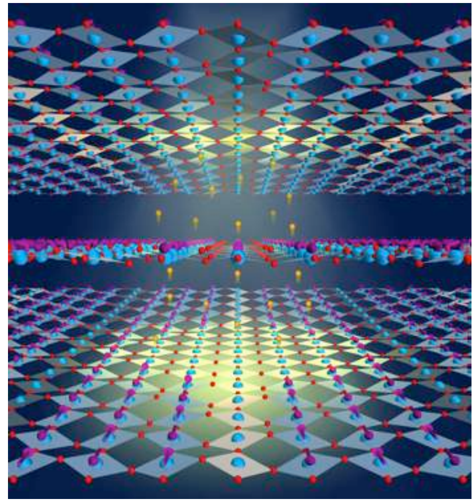
How do I recognize a transient superconductor ?

Josephson Plasmon

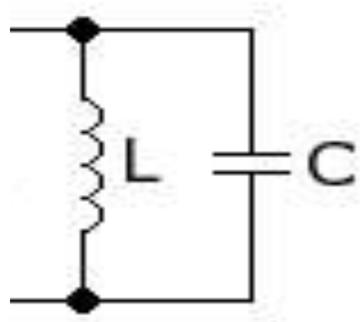


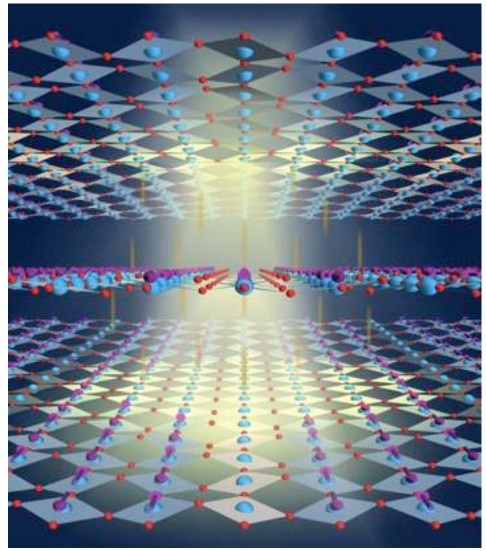
$T > T_c$





$T < T_c$

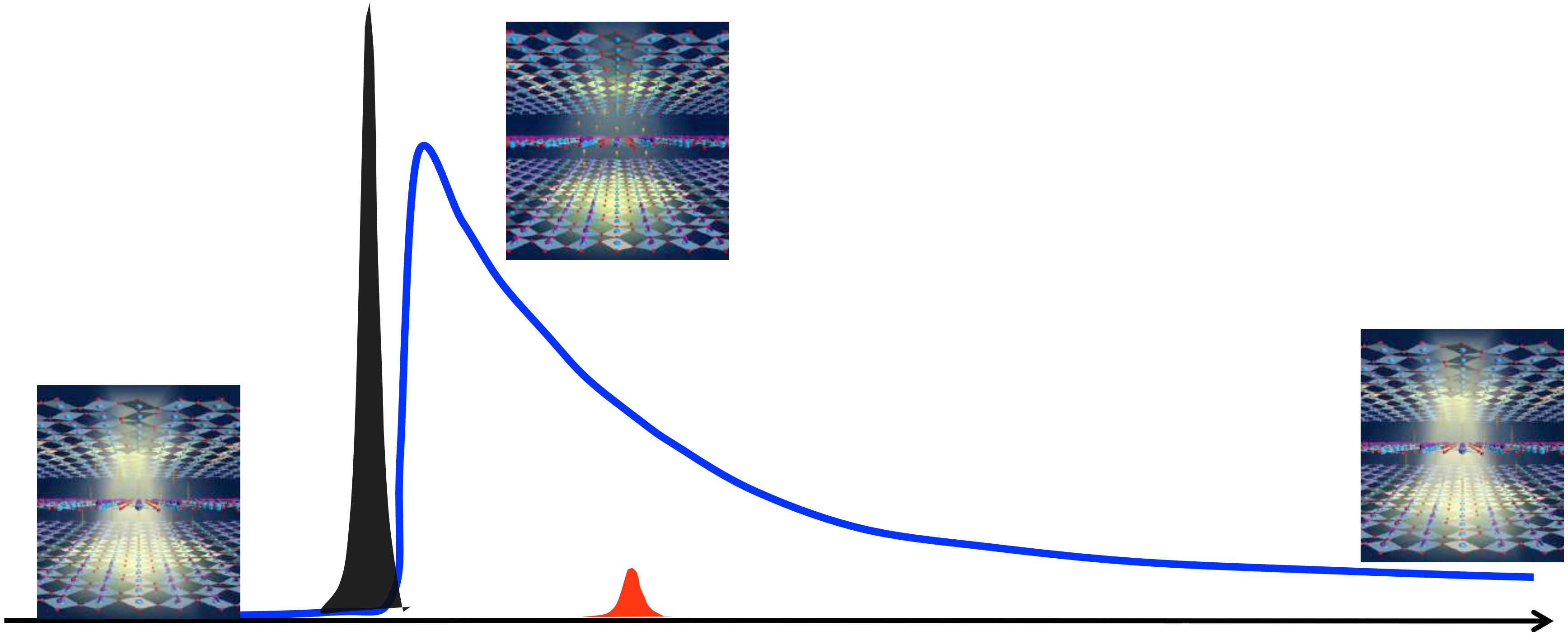




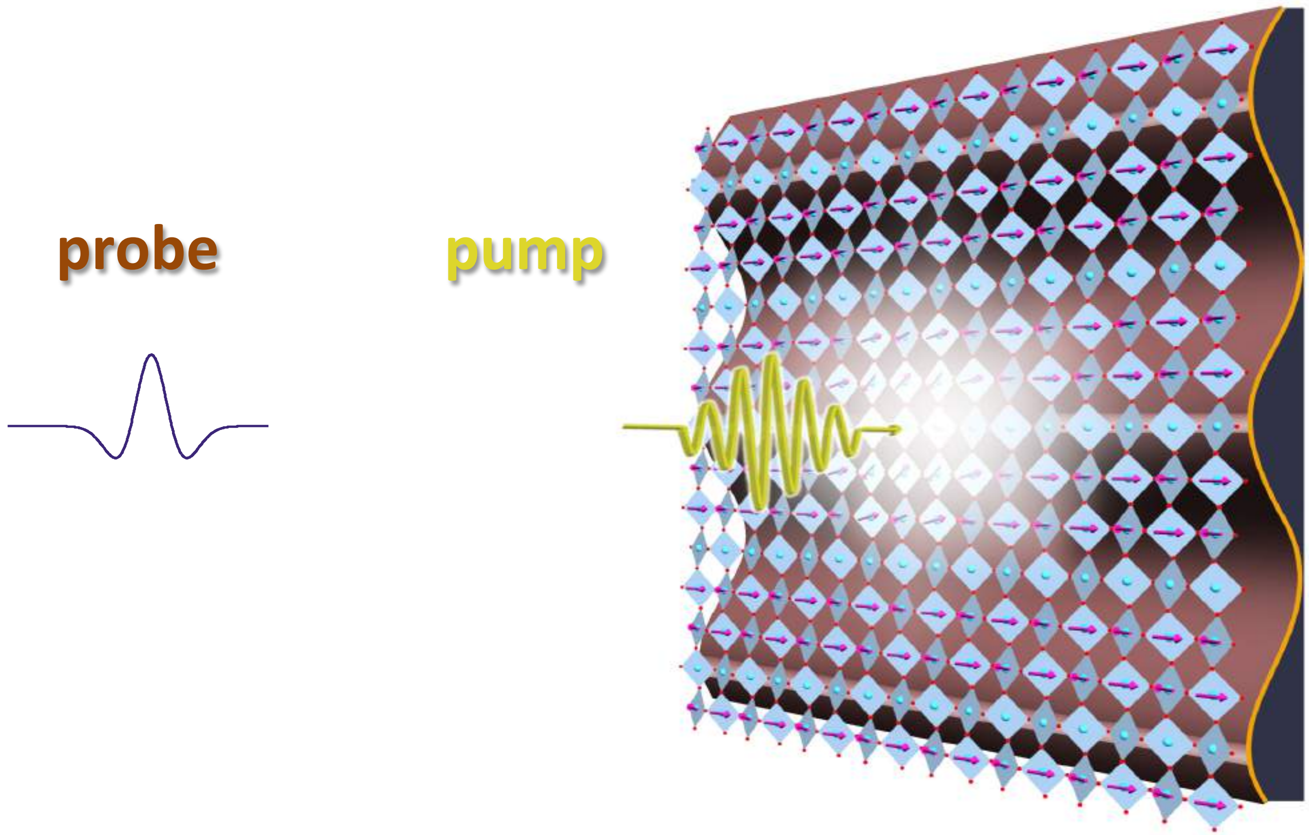
Kresin and Morawitz PRB (1988)

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

Probing the transient state



Mid-IR pump / THz Probe Spectroscopy



A light Induced Josephson plasma edge

Equilibrium LSCO

Superconducting (eq.)

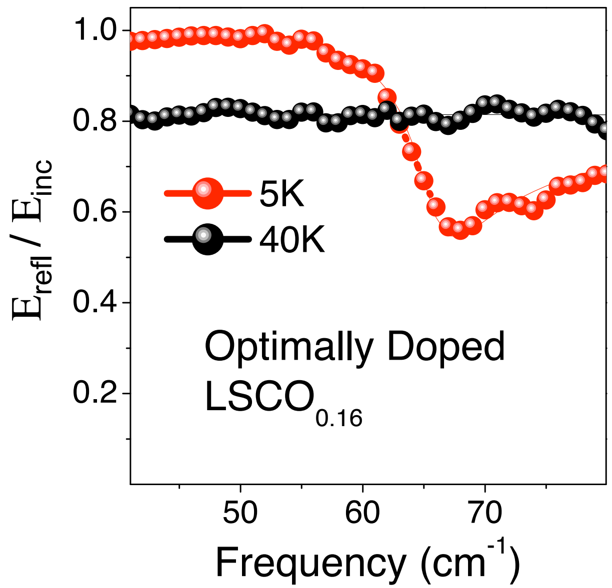
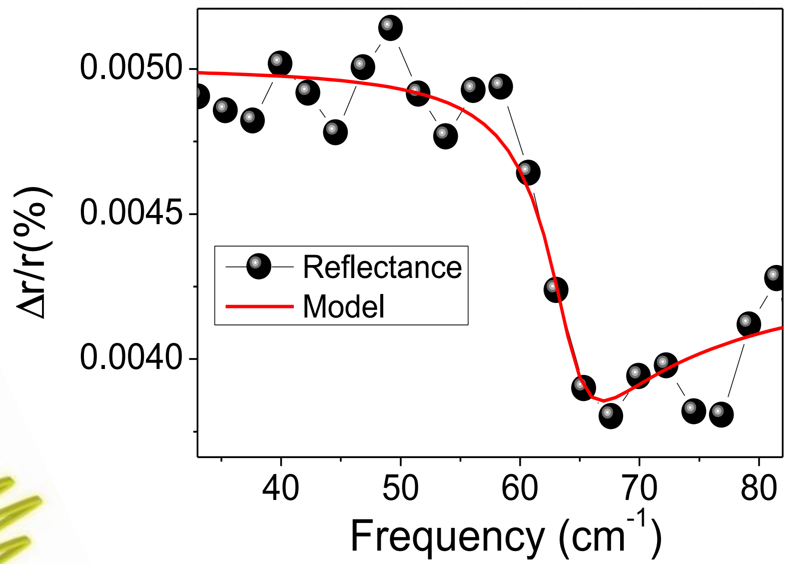
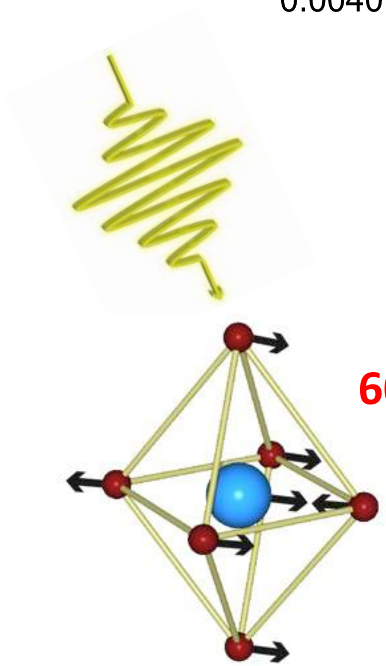


Photo-induced LESCO

Superconducting (non eq.)

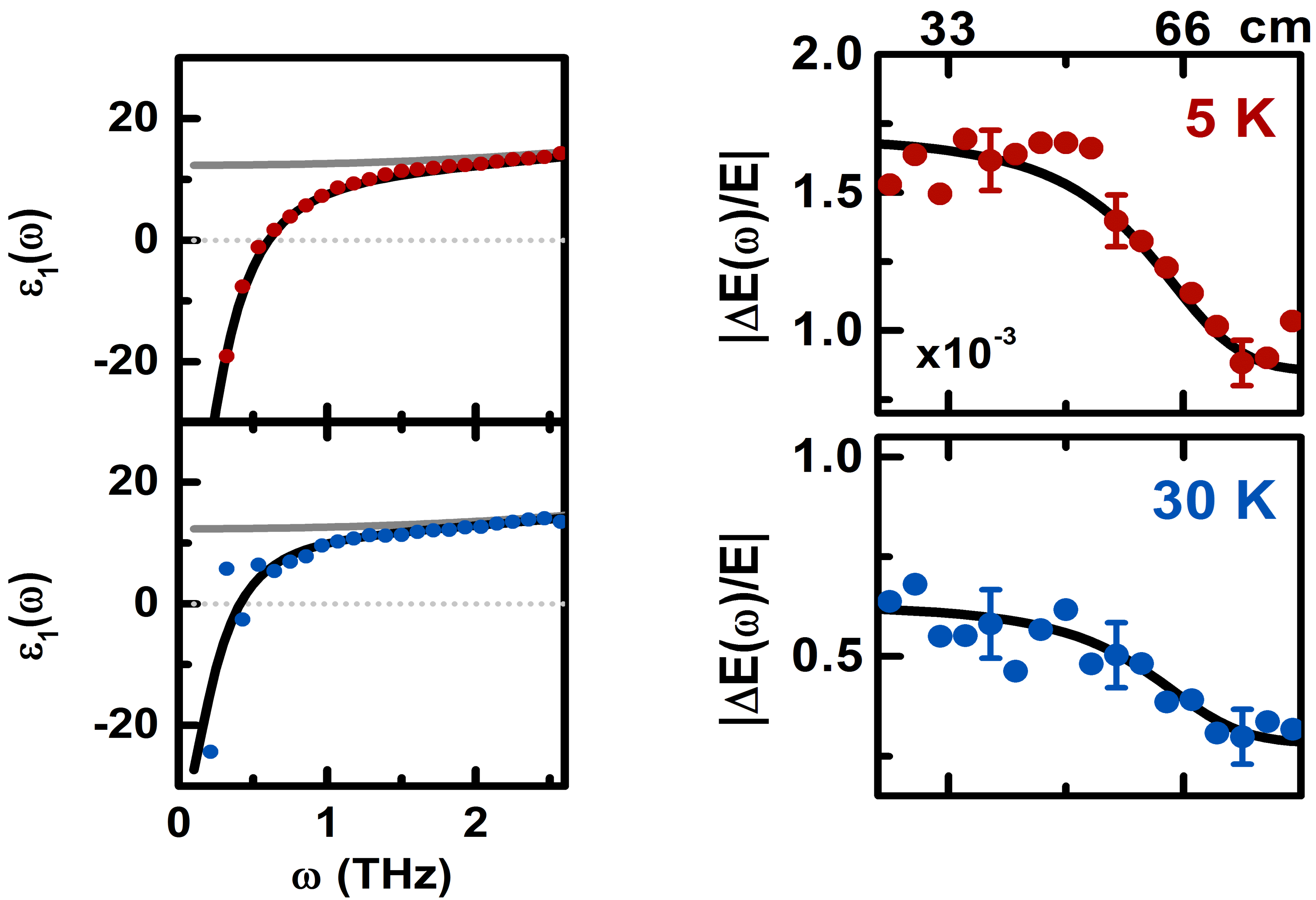




600 cm^{-1}

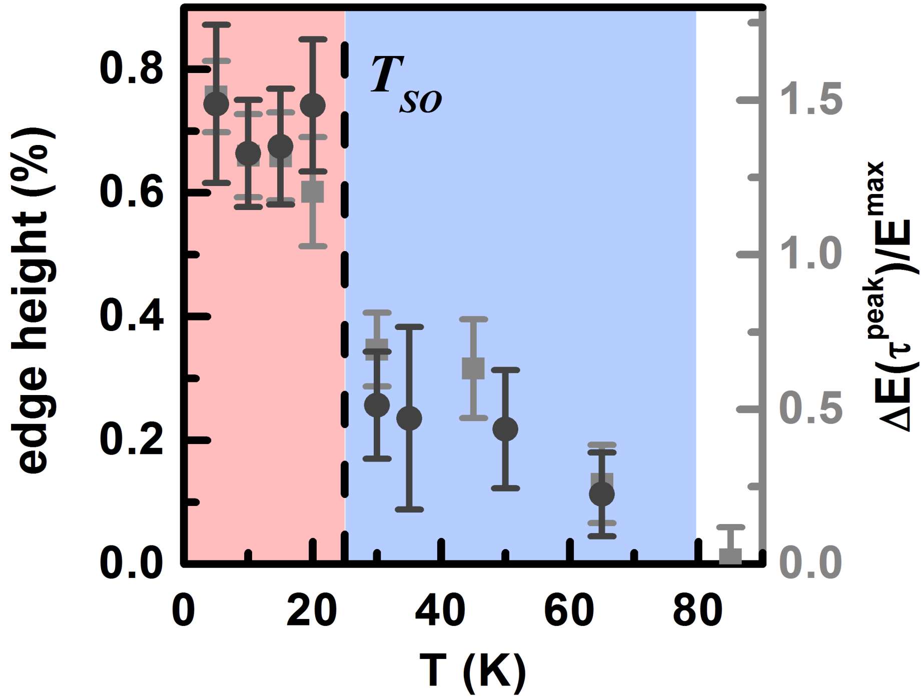
D. Fausti et al., Science 331, 6014 (2011)

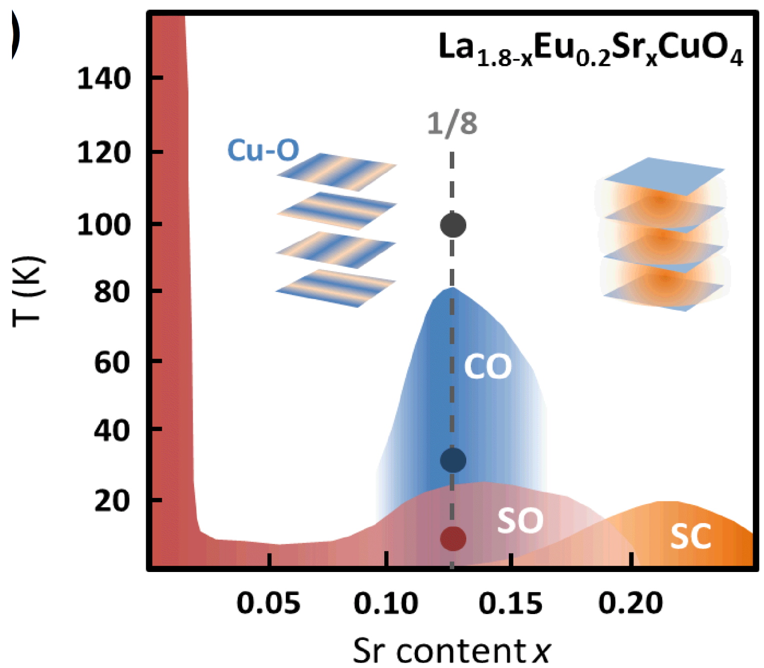
Plasma mode where $\varepsilon_1(\omega)$ crosses zero



C.R. Hunt et al., Physical Review B 91, 020505(R) (2015)

Plasma mode up to T_{CO} = 80 K





C.R. Hunt et al., Physical Review B 91, 020505(R) (2015)

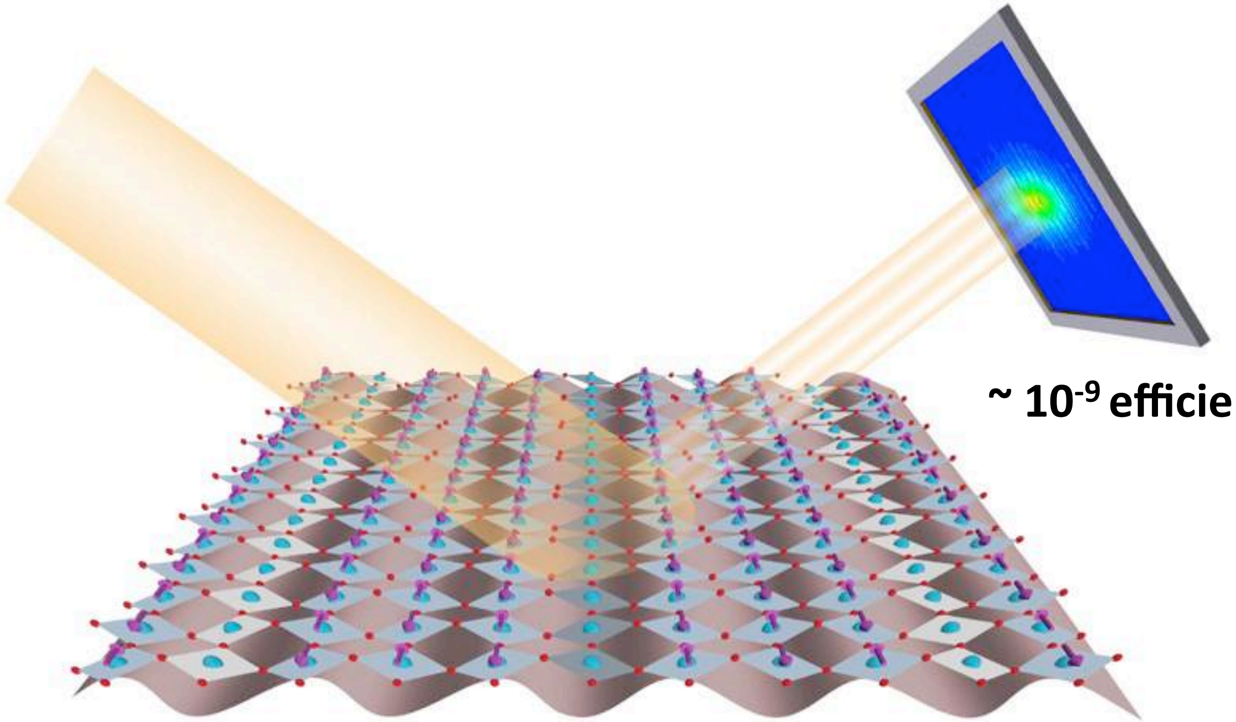
Probing the transient state

Am I melting charge stripes with light ?

Charge stripes are seen by soft x-ray scattering

O Kedge

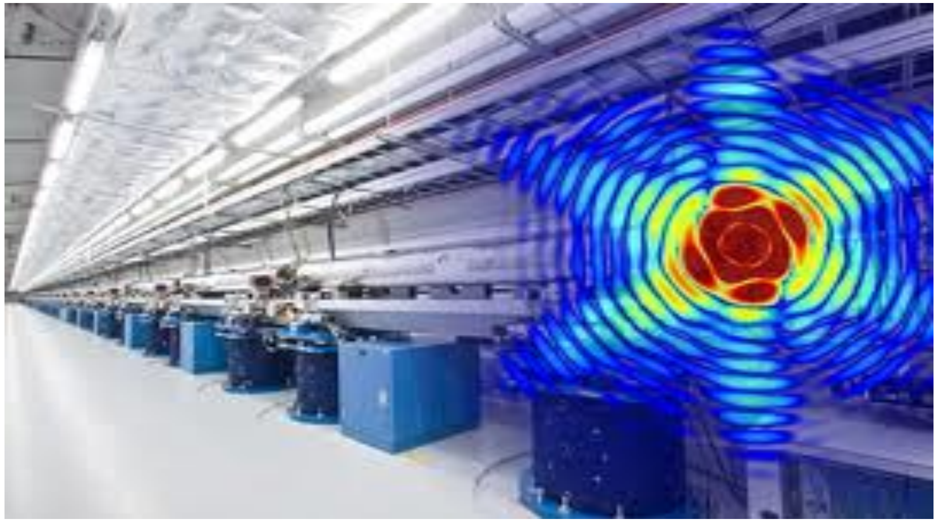
(0.25, 0, 0.65)



~ 10^{-9} efficiency

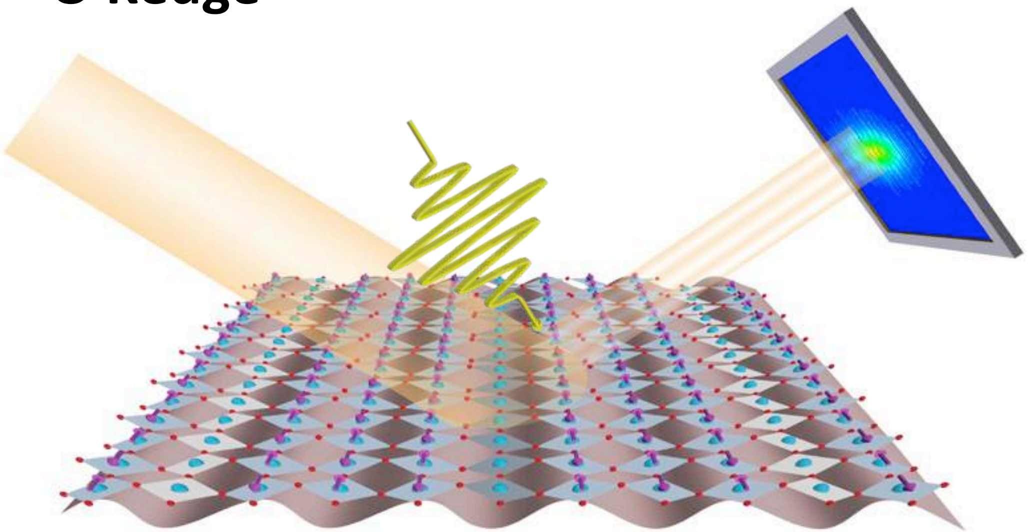
Abbamonte et al *Nature Physics 1, 155* (2005)

Ultrafast soft X-ray diffraction



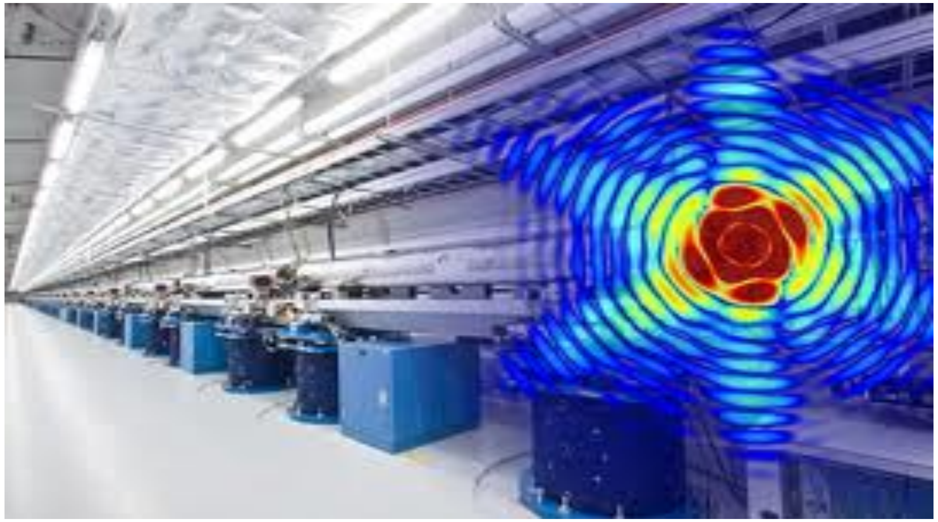
O Kedge

(0.25, 0, 0.65)



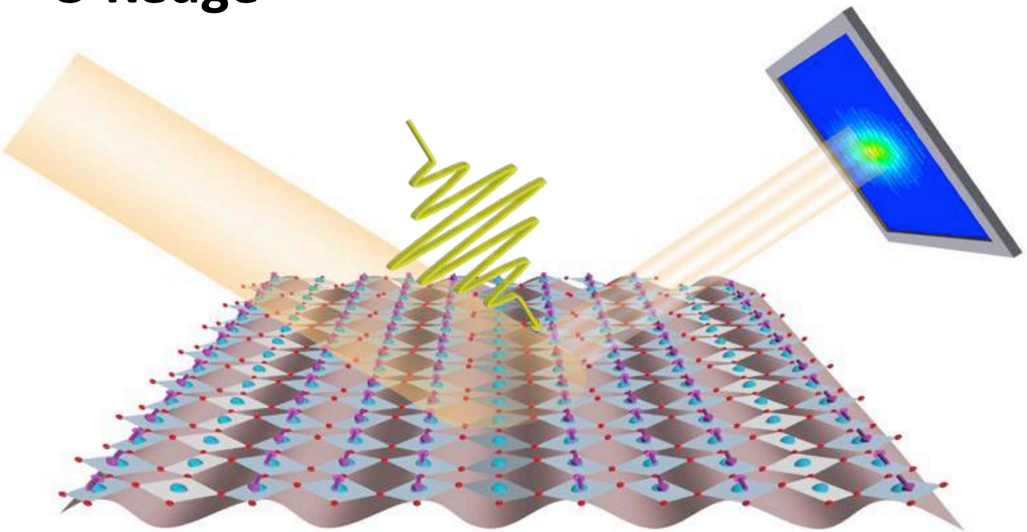
With John Hill, BNL

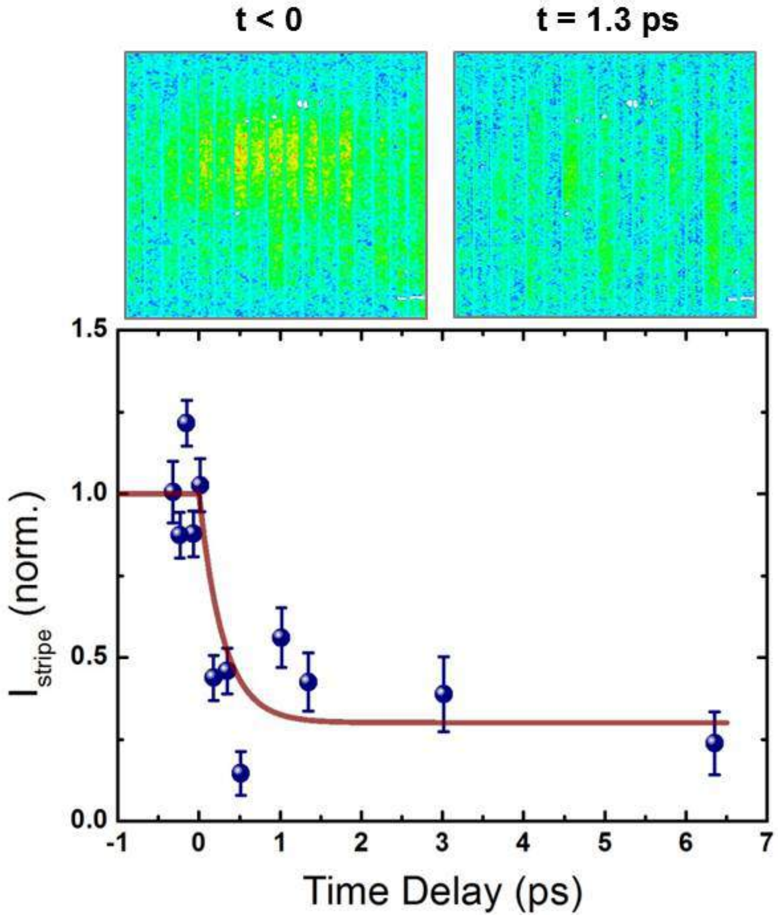
Ultrafast soft X-ray diffraction



O Kedge

(0.25, 0, 0.65)



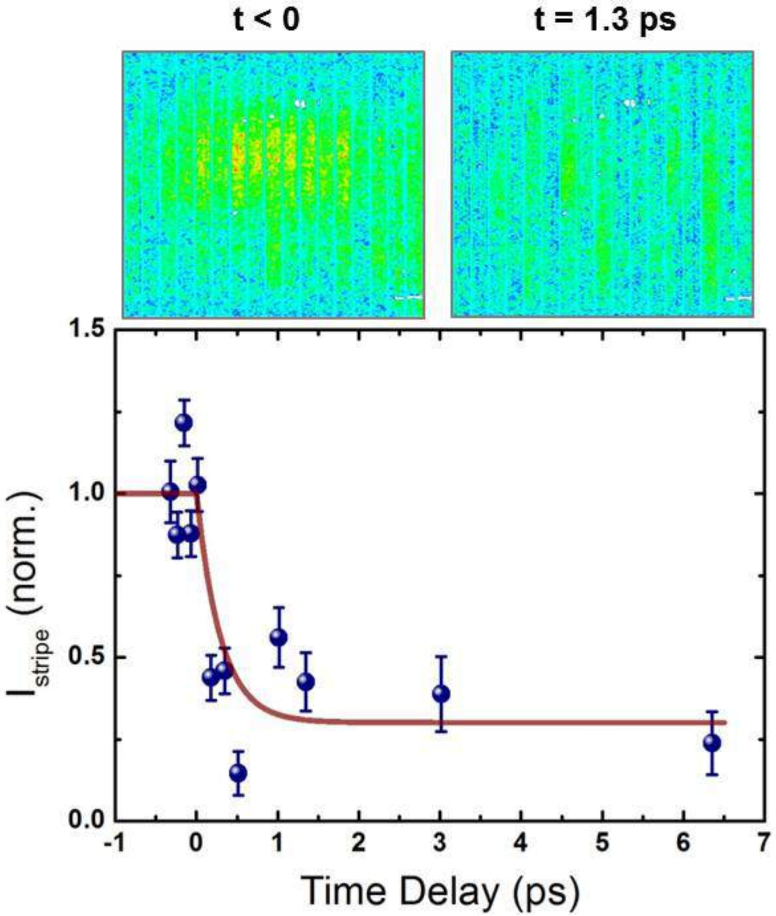


M. Foerst et al., Phys Rev Lett 112, 157002 (2014)

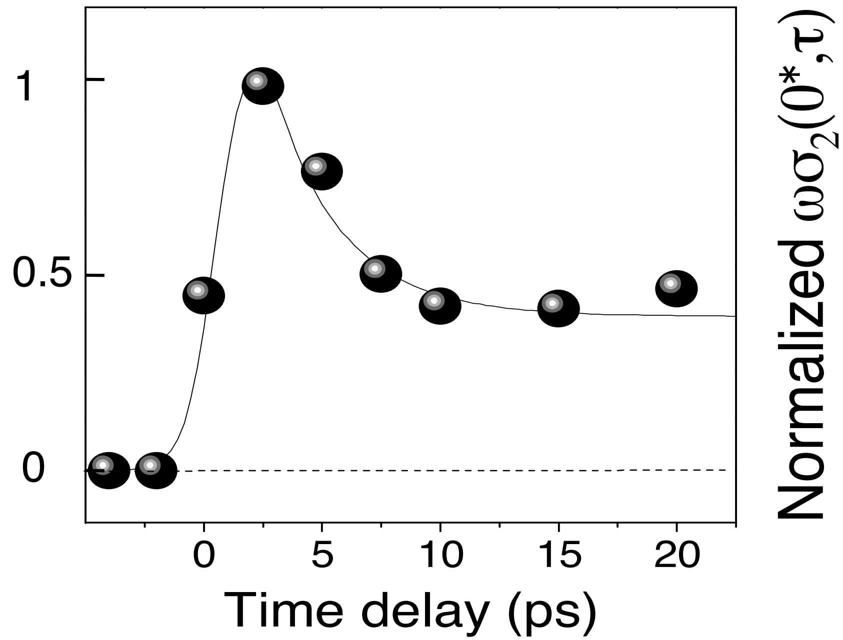
With John Hill, BNL

Charge stripe melting - superconductivity

- Charge Stripes melt concomitantly with the formation of the SC

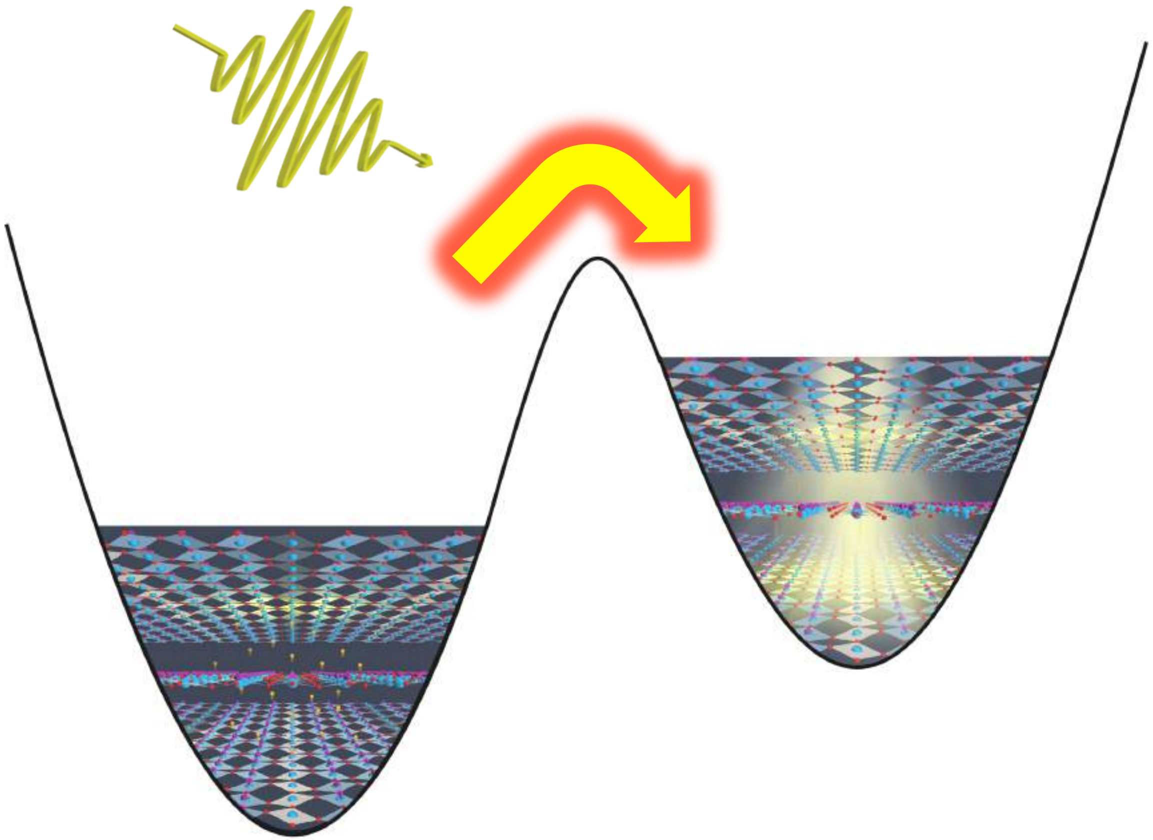


superconductivity



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

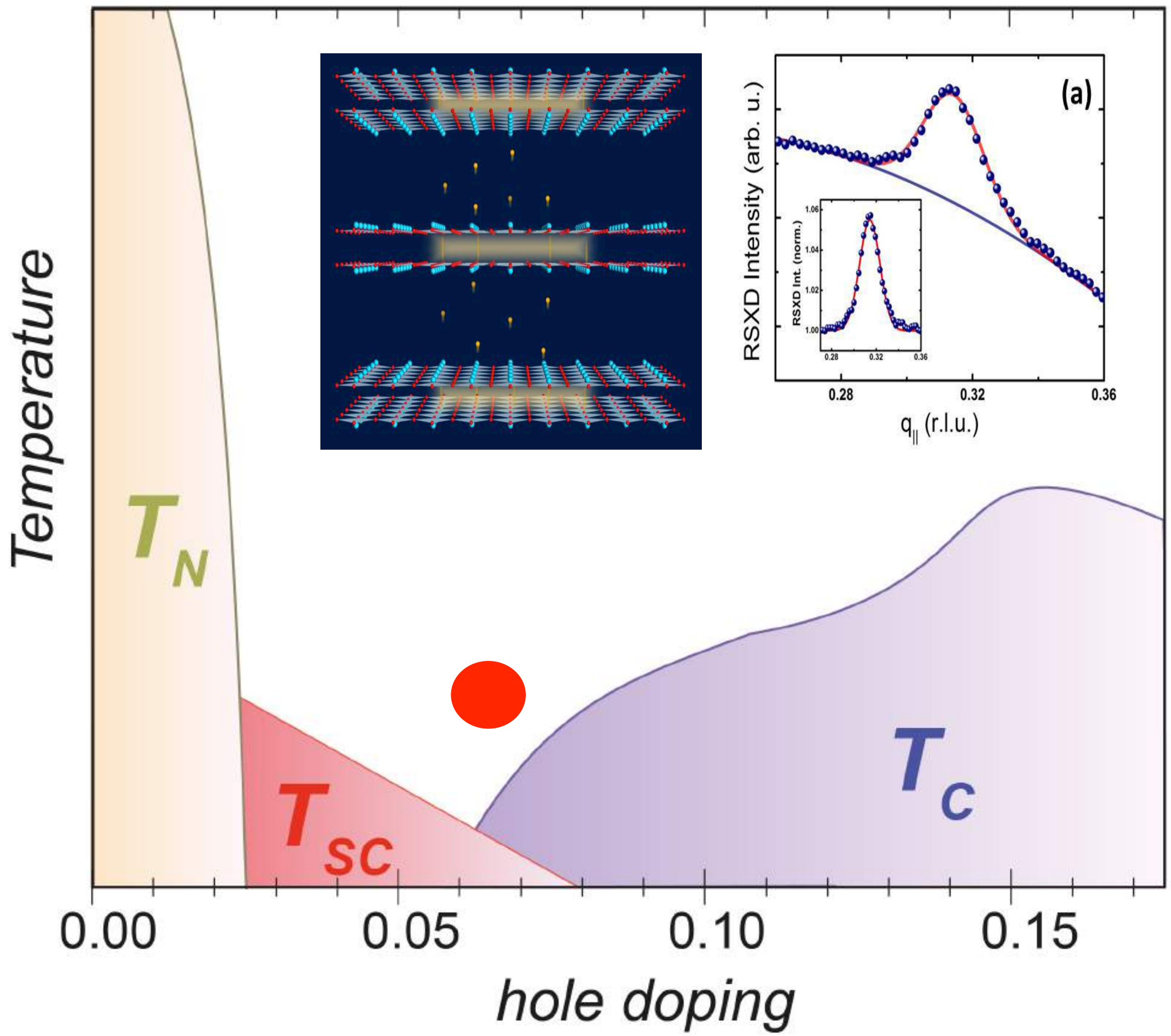
…………switching into a hidden phase



Other systems

Can I do this in other cuprates ?

YBCO: Coherence above T_c and a CDW

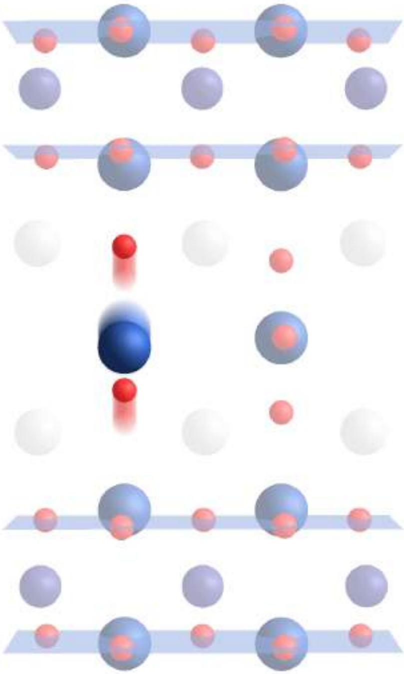


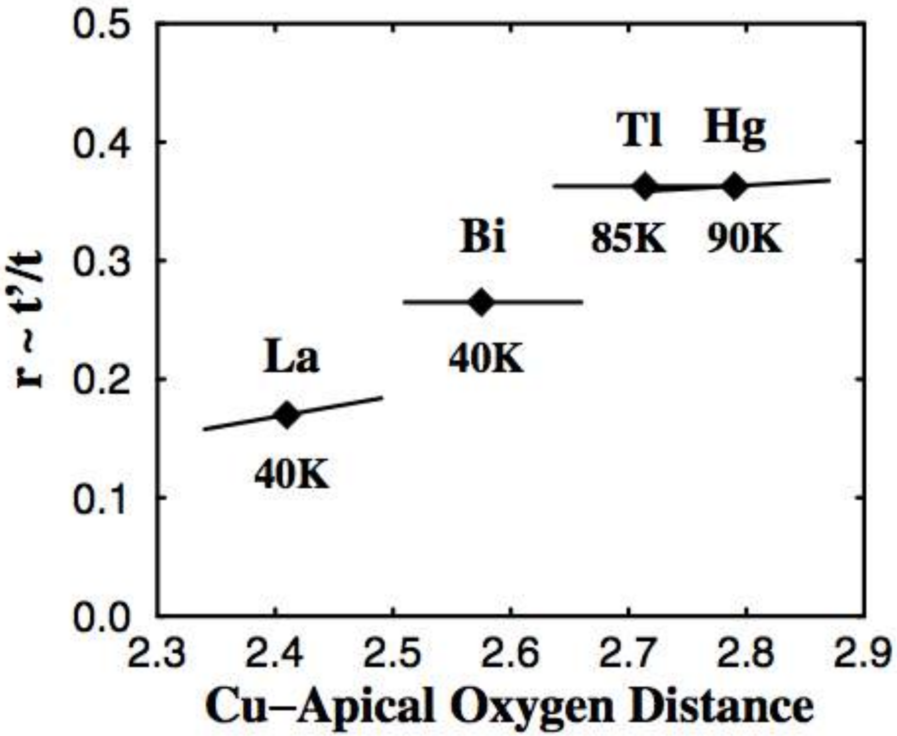
G. Ghiringhelli et al., *Science 337*, 821 (2012)

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

With B. Keimer
MPI Stuttgart

Apical oxygen correlates with T_c at equilibrium

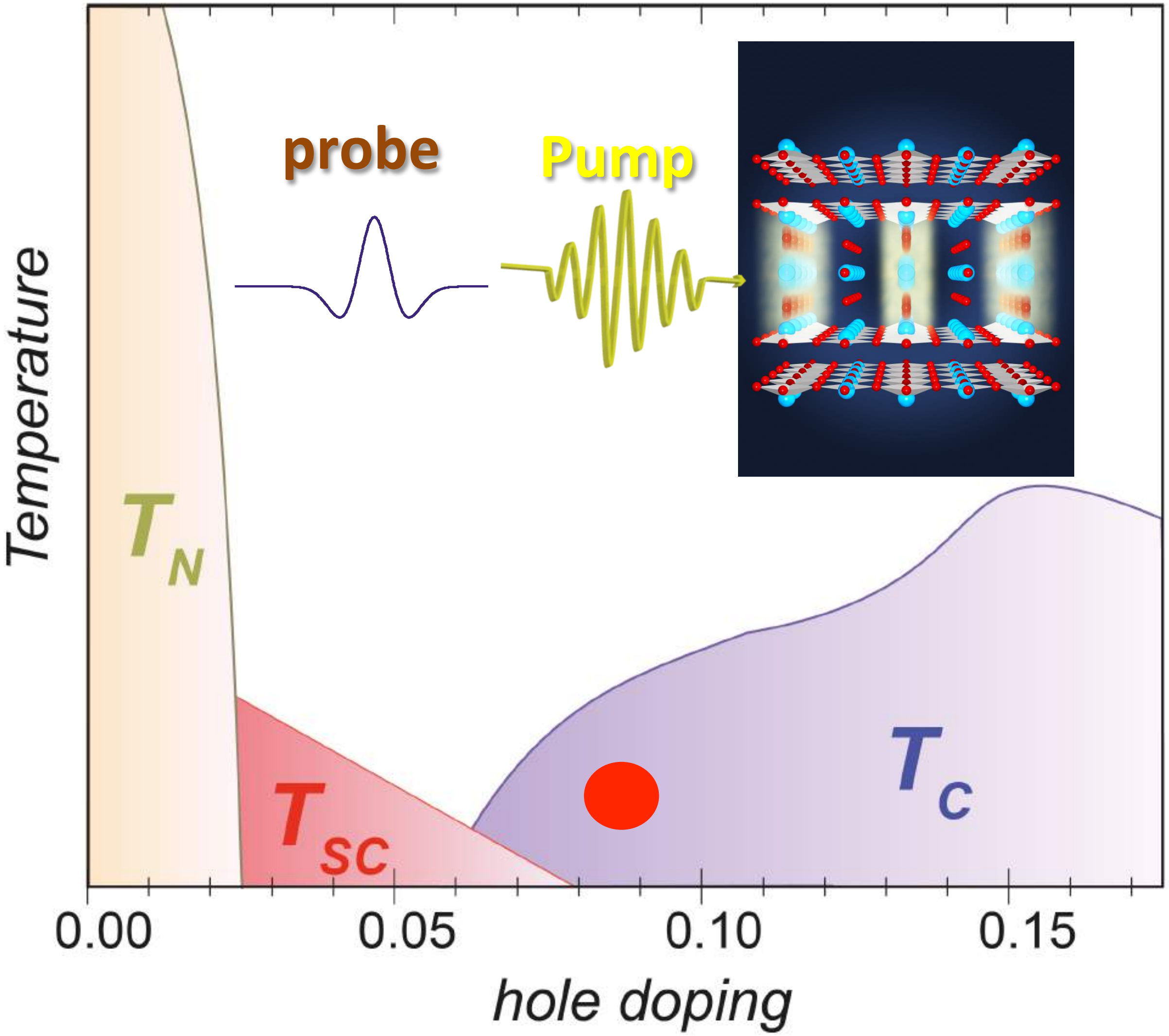




E. Pavarini et al., *PRL 8*7, 047003 (2001)

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

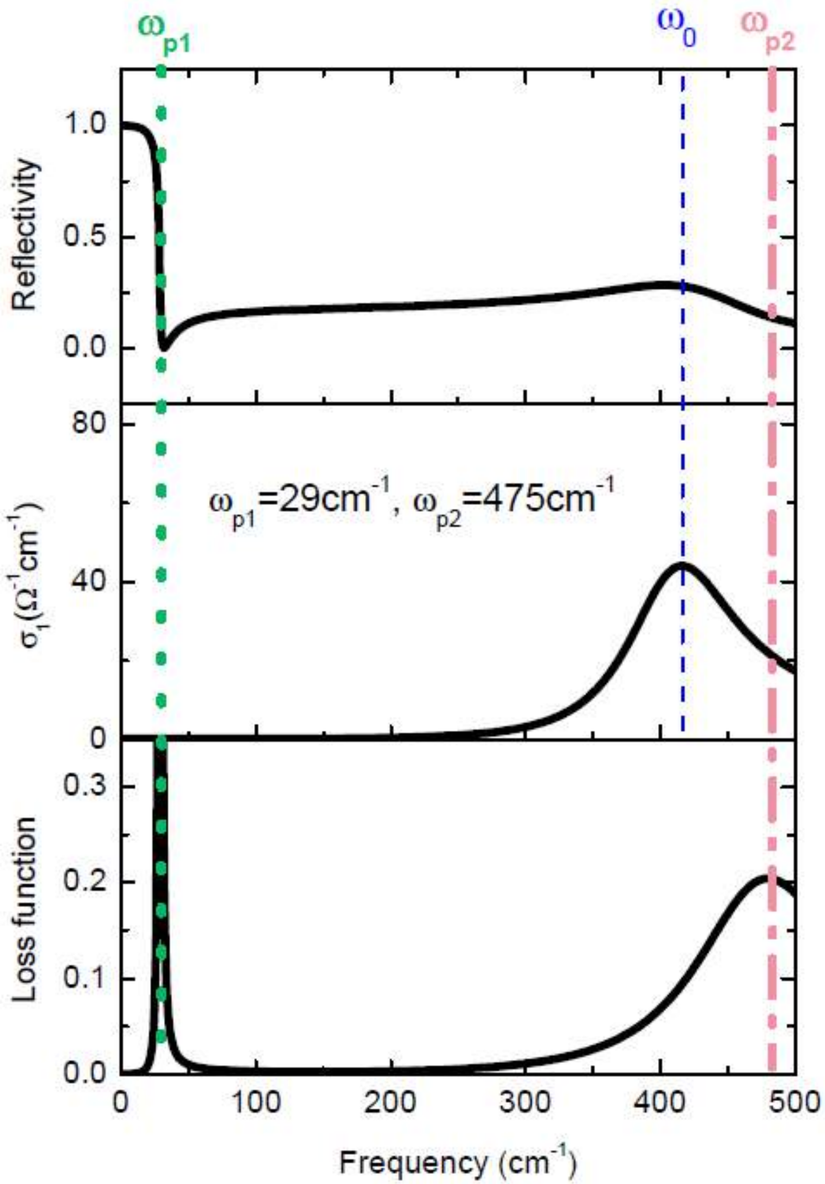
Pump apical oxygen probe c-axis plasma

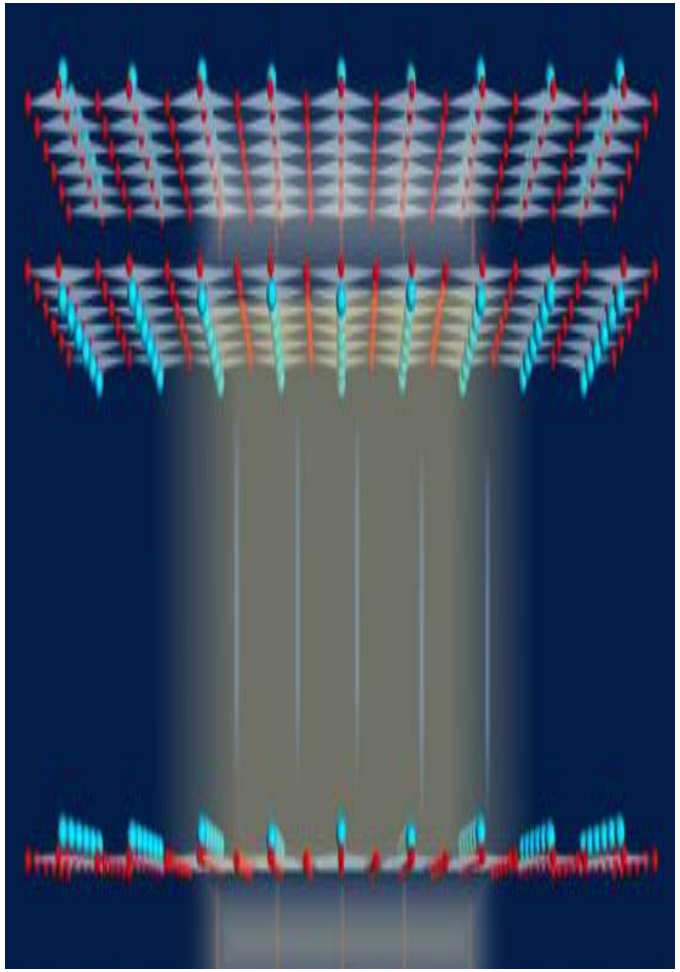


W. Hu et al. *Nature Materials* 13, 705 (2014)

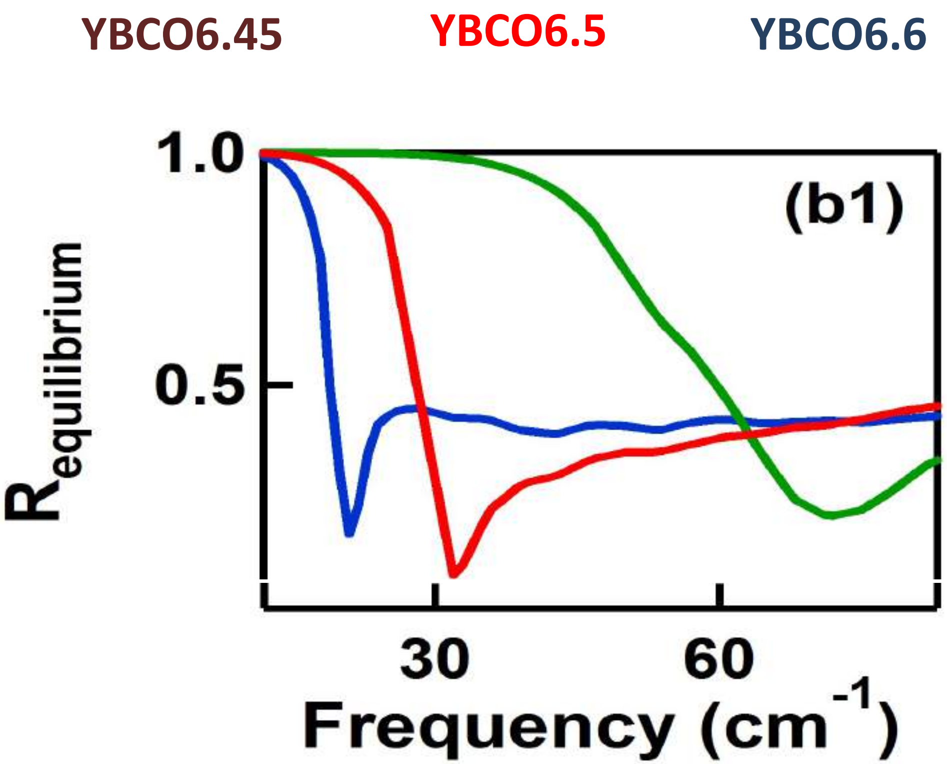
S. Kaiser, D. Nicoletti, C. Hunt et al., *Phys. Rev. B* 89, 184516 (2014)

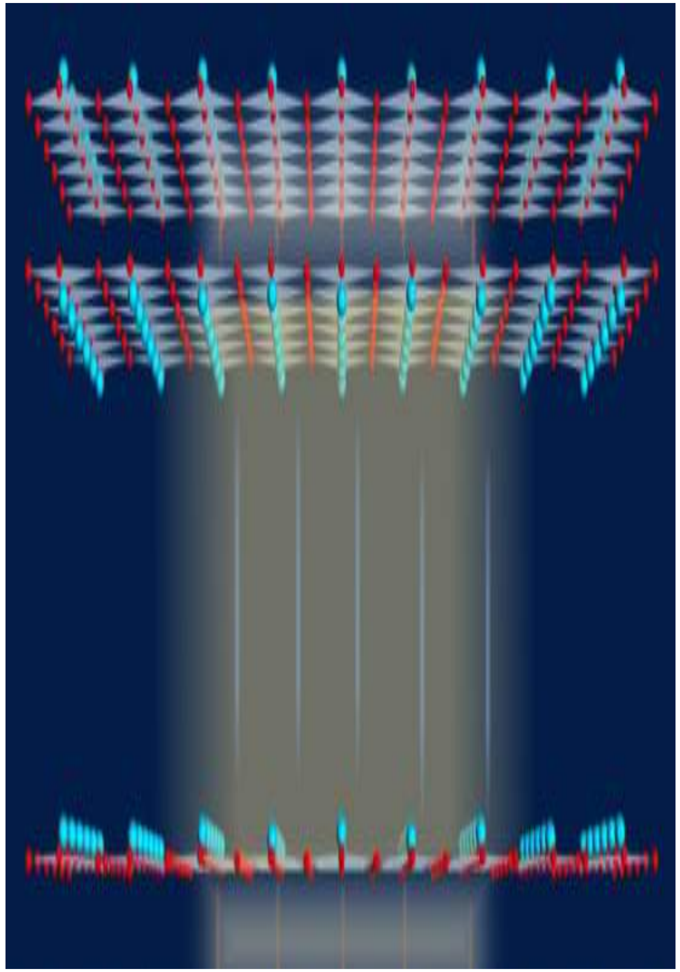
Below Tc: two plasma plasma edges



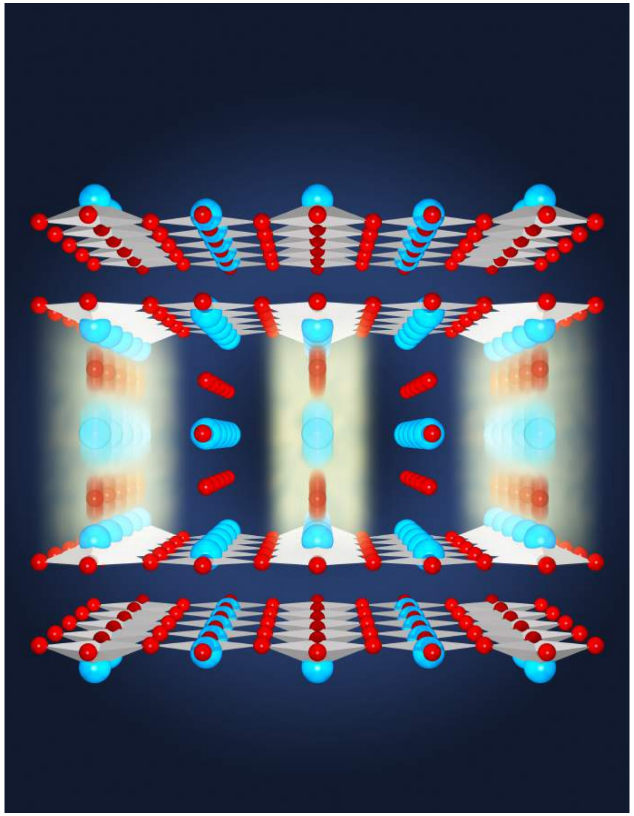


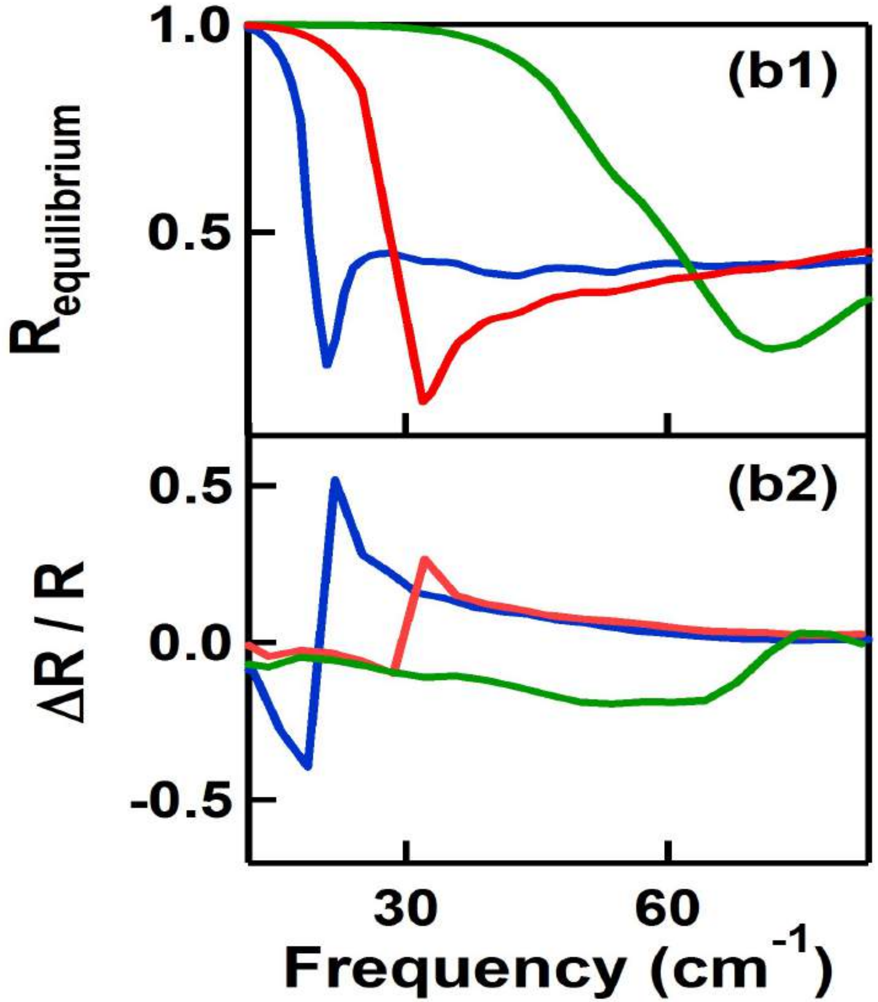
Low frequency inter-bilayer plasma edge





Below Tc: Light-induced blue shift of the edge

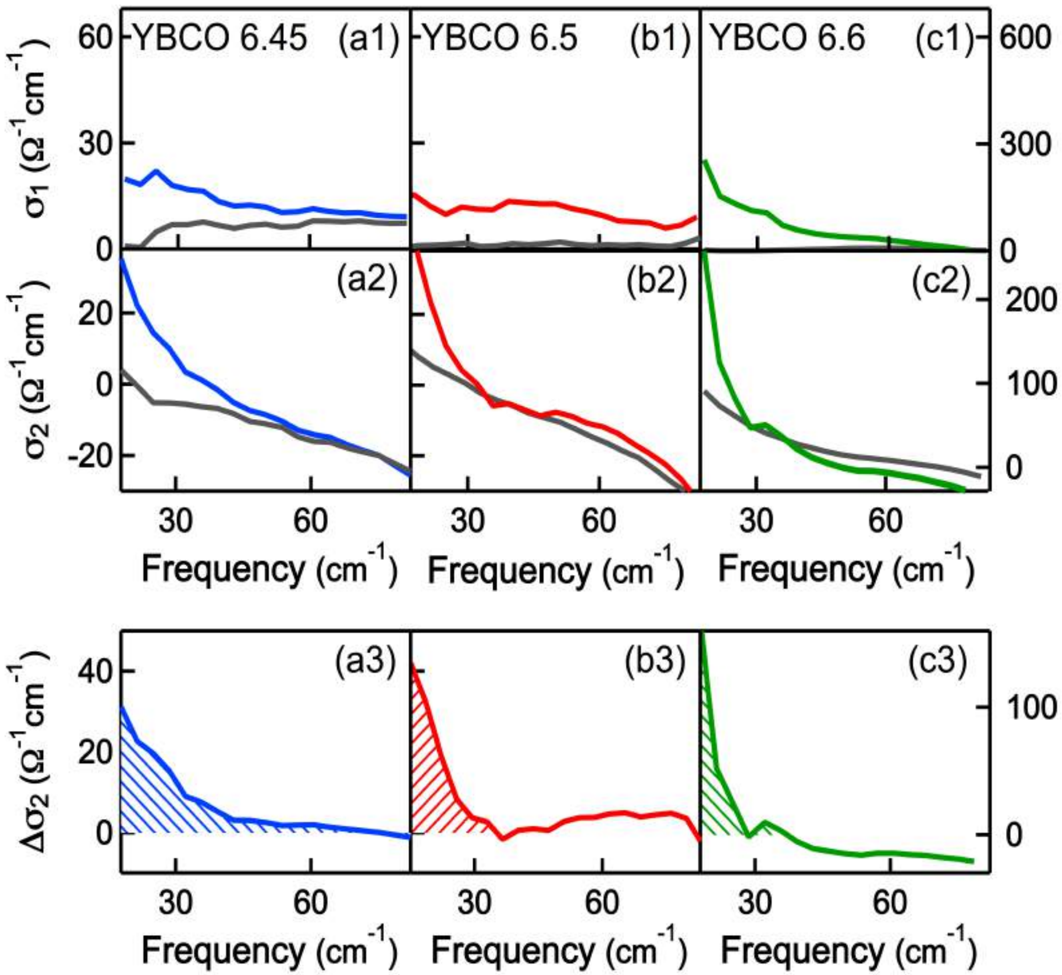




W. Hu et al. *Nature Materials* 13, 705 (2014)

S. Kaiser, D. Nicoletti, C. Hunt et al., *Phys. Rev. B* 89, 184516 (2014)

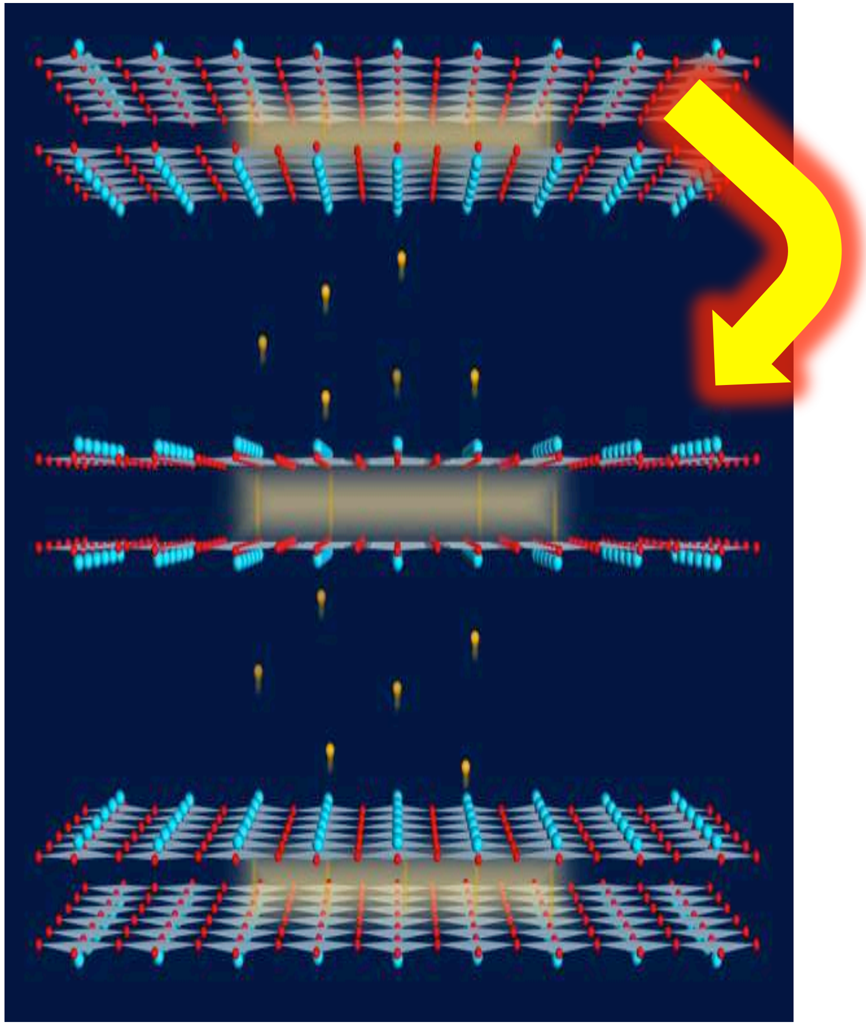
Below T_c: Enhancement of "superconductivity"

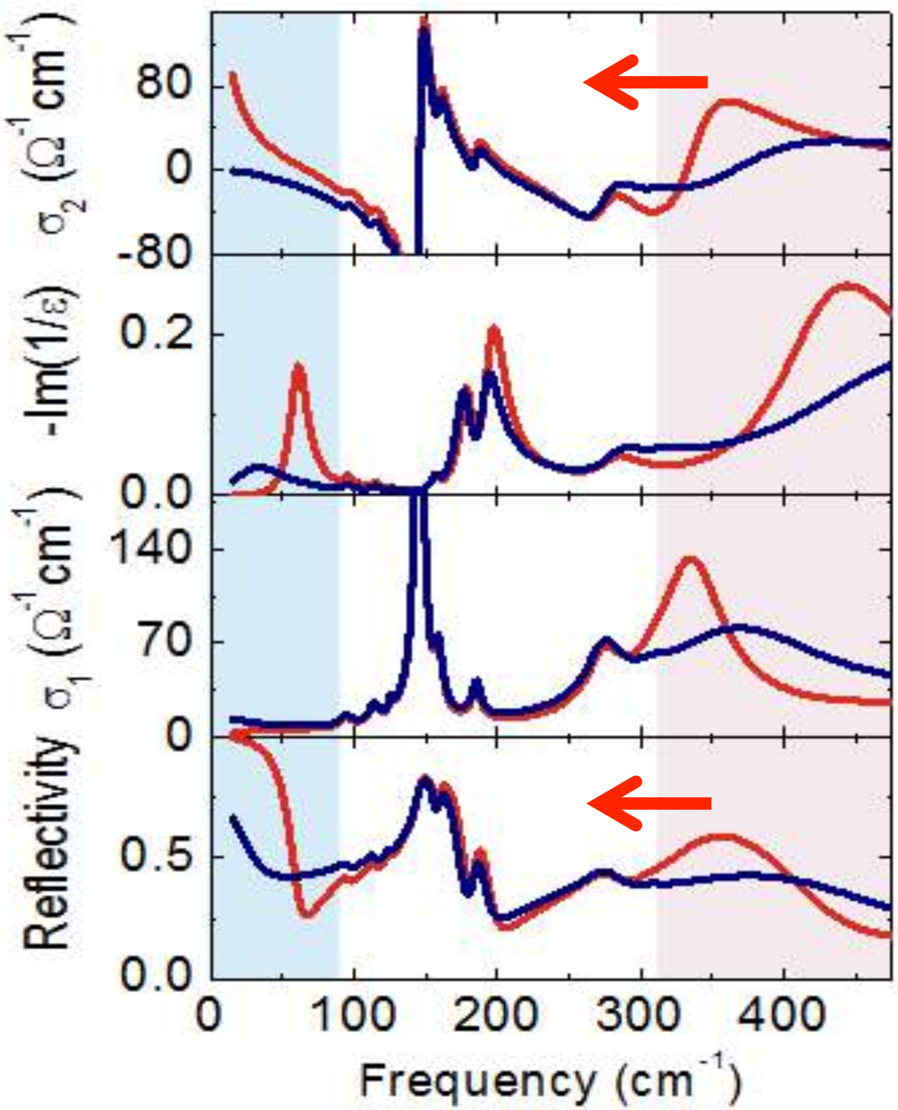


W. Hu. S. Kaiser, D. Nicoletti, C.S. Hunt et al. *Nature Materials* 13, 705 (2014)

S. Kaiser, D. Nicoletti, C. Hunt et al., *Phys. Rev. B* 89, 184516 (2014)

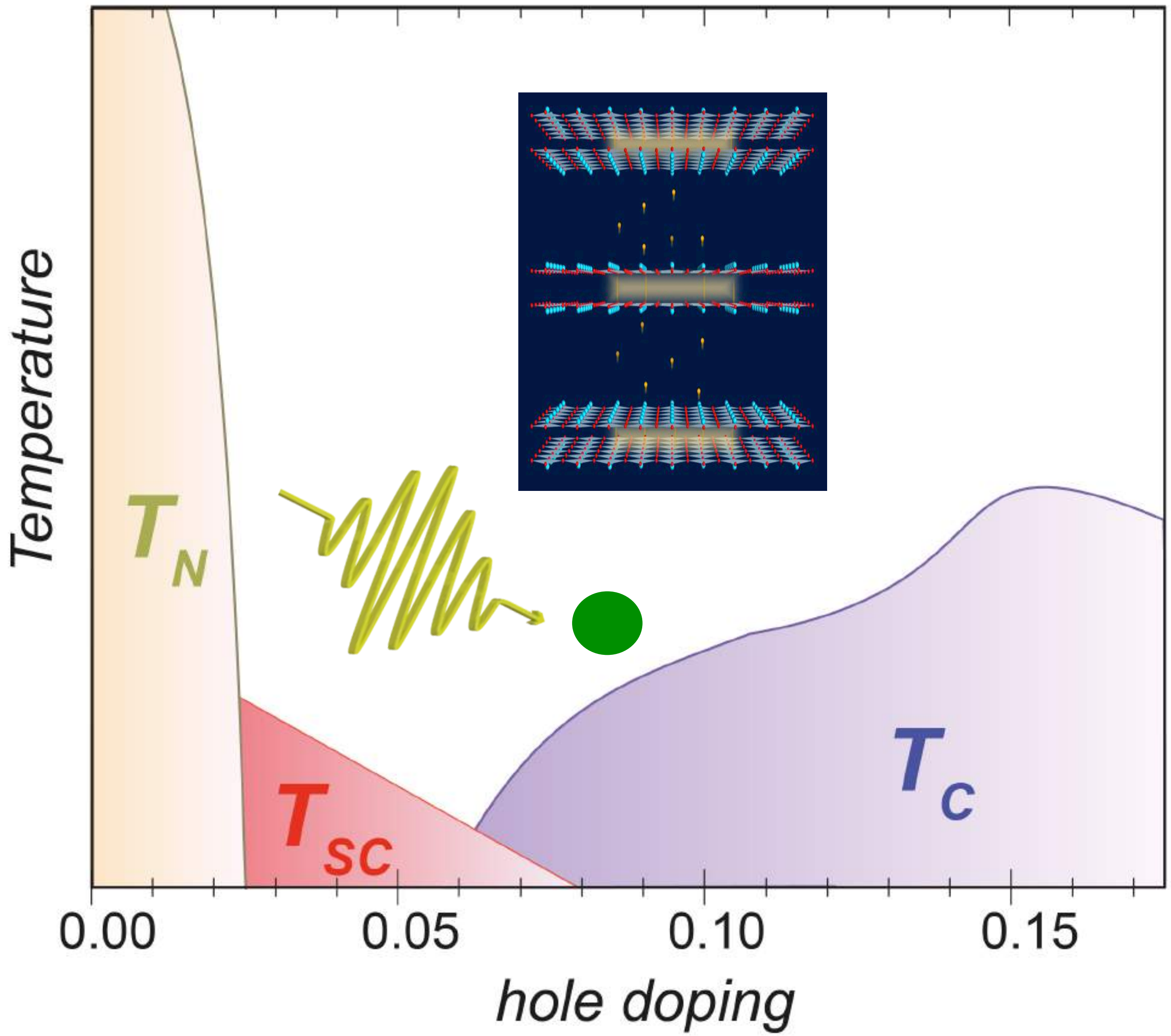
Spectral weight from high frequency





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

Above T_c



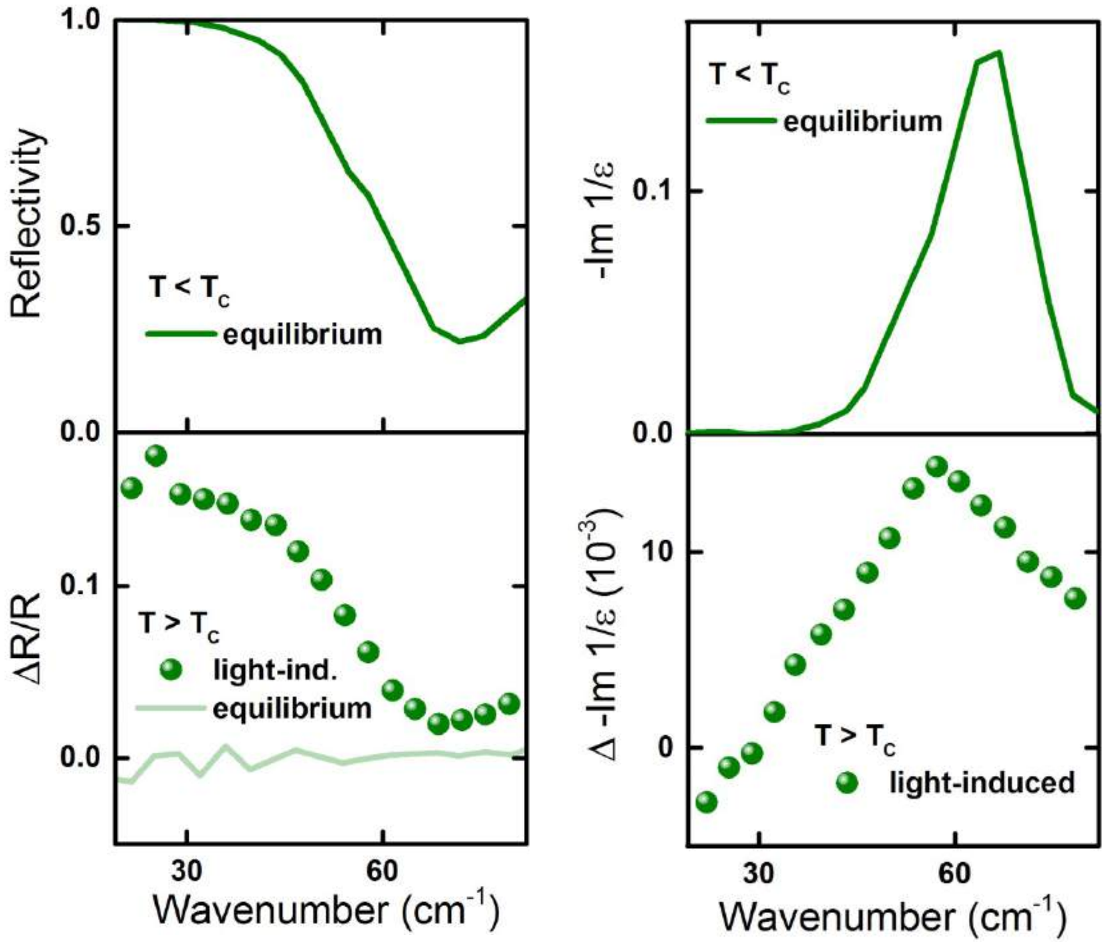
With B. Keimer
MPI Stuttgart

Light induced Plasma Mode – 2 X Tc

Plasma edge

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

$YBCO_{6.6}$ – 100 K

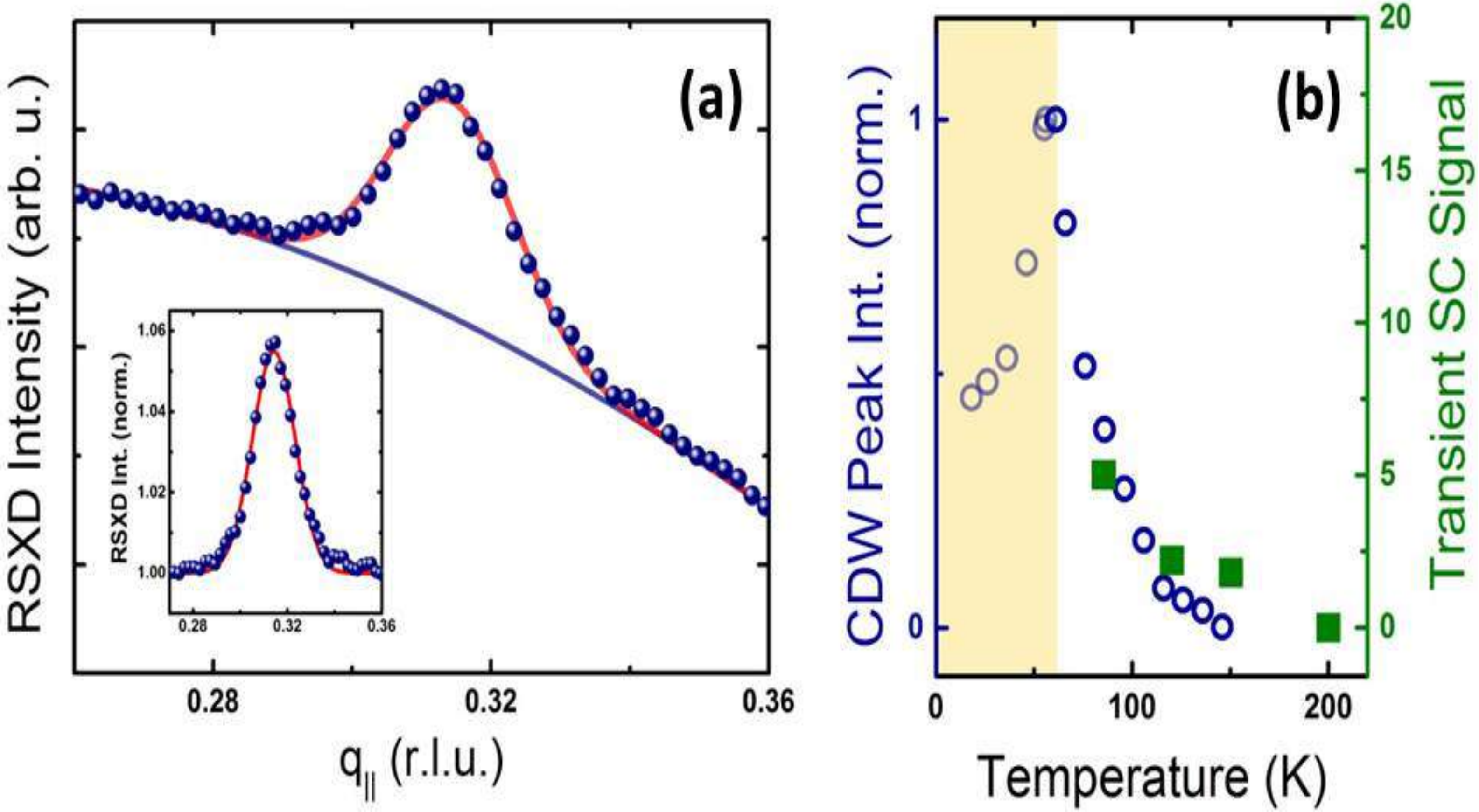


Equilibrium $T<T_c$

Light induced $T>T_c$

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

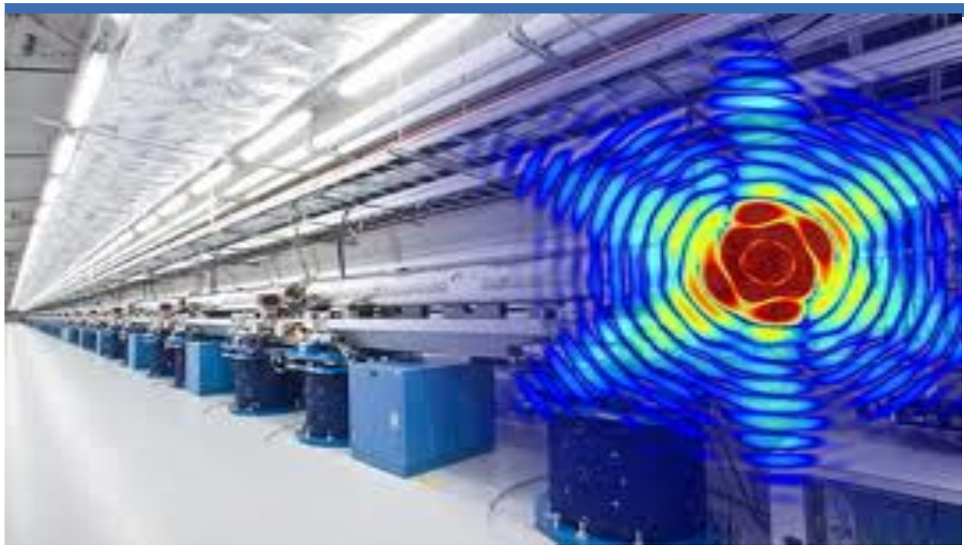
Light induced edge – follows charge order

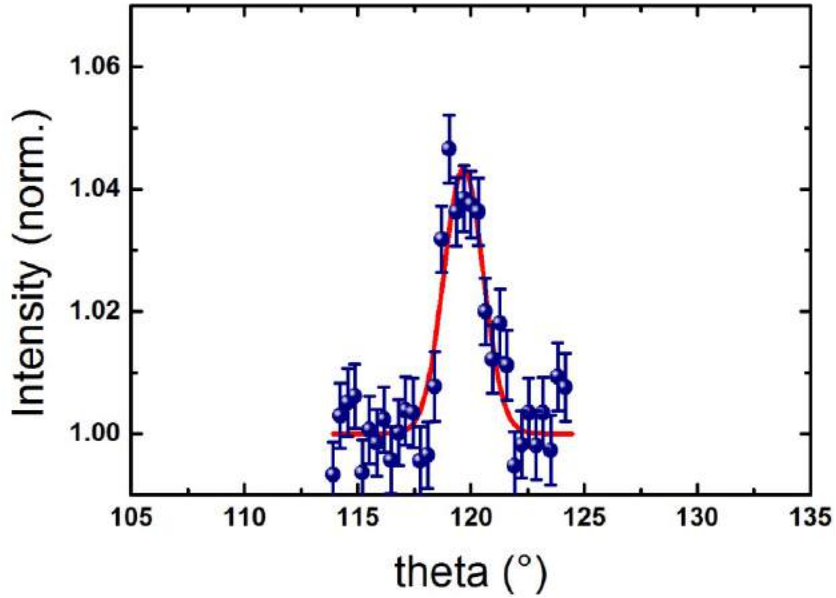


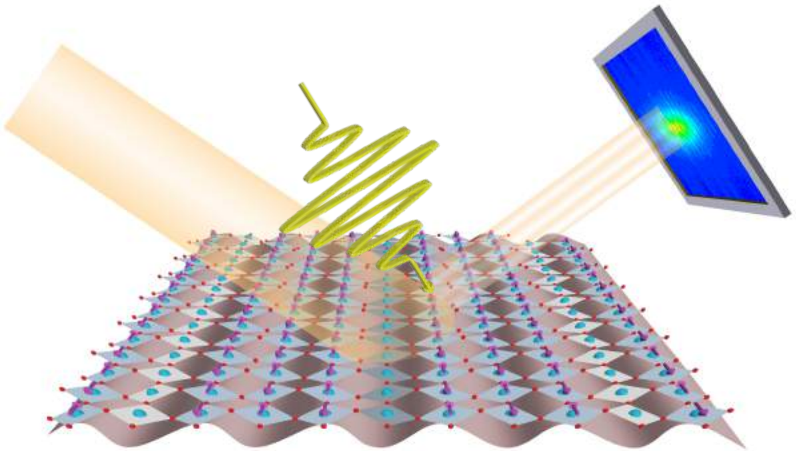
G. Ghiringhelli et al., *Science 337*, 821 (2012)

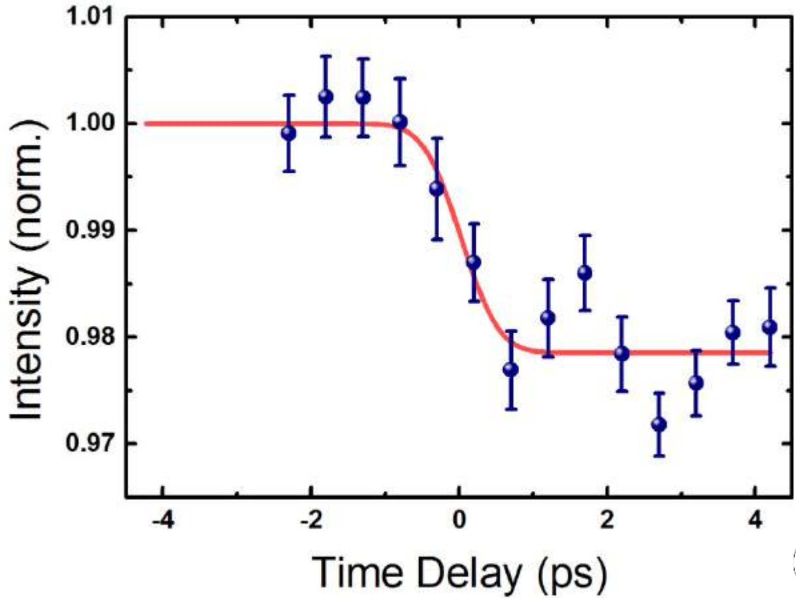
S. Kaiser, D. Nicoletti, C. Hunt et al., *Phys. Rev. B* 89, 184516 (2014)

YBCO$_{6.6}$: Light induced CDW melting







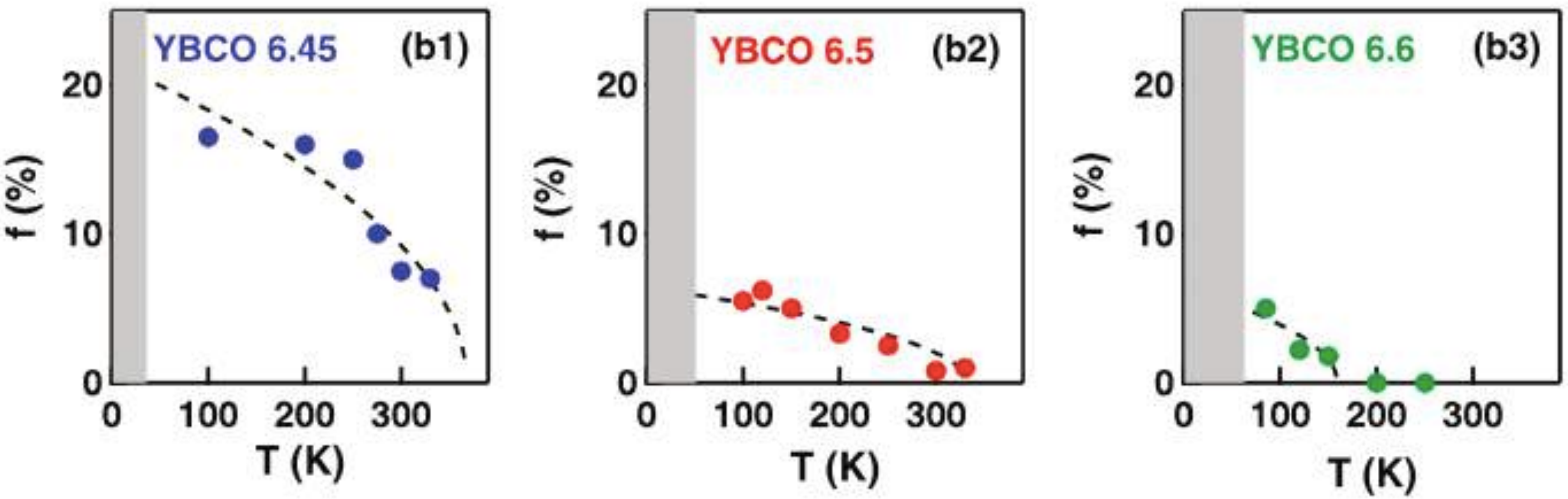


M. Foerst et al., *Phys. Rev. B* (2014)

Underdoped YBCO

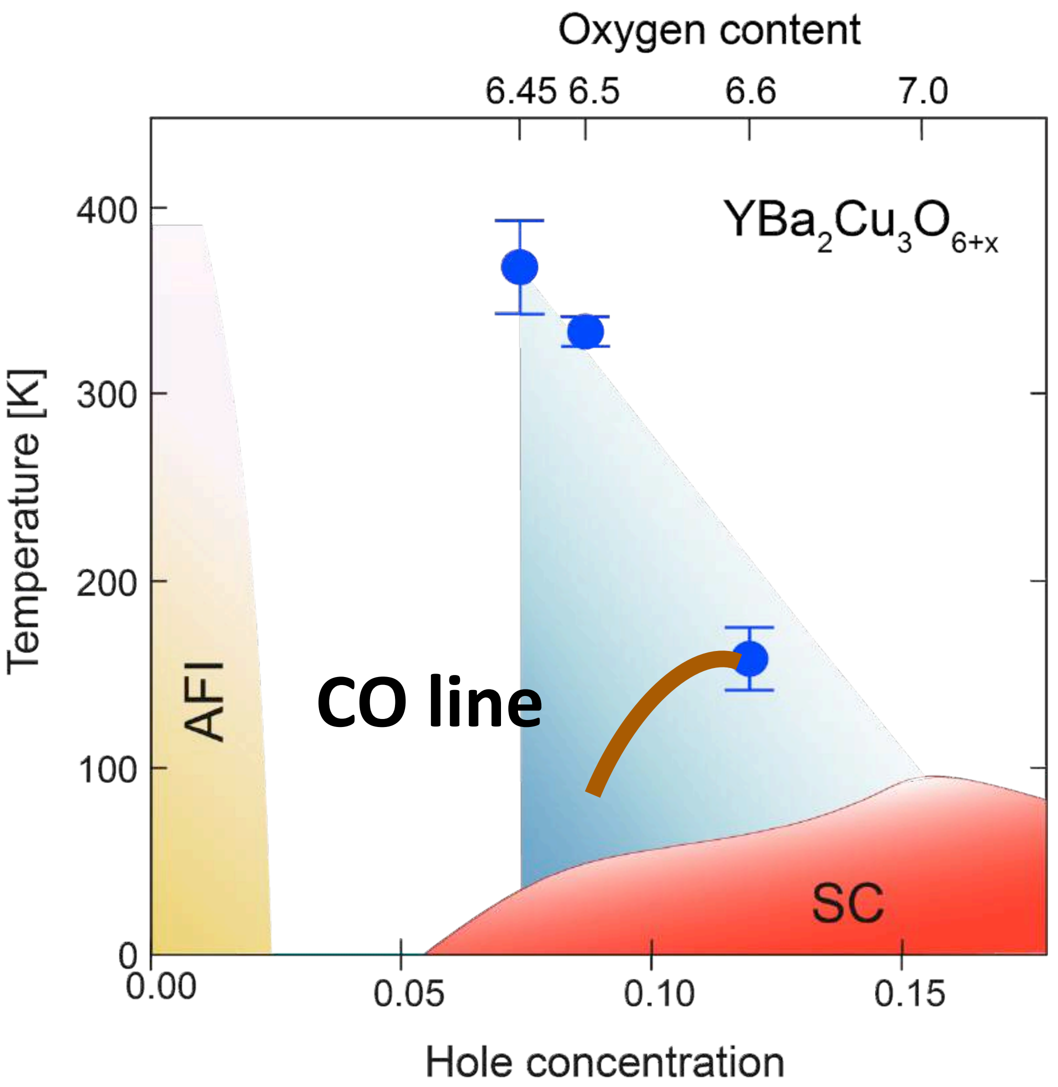
So far everything like in $LESCO_{1/8}$

Other dopings - Surprise….. Follows T*



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

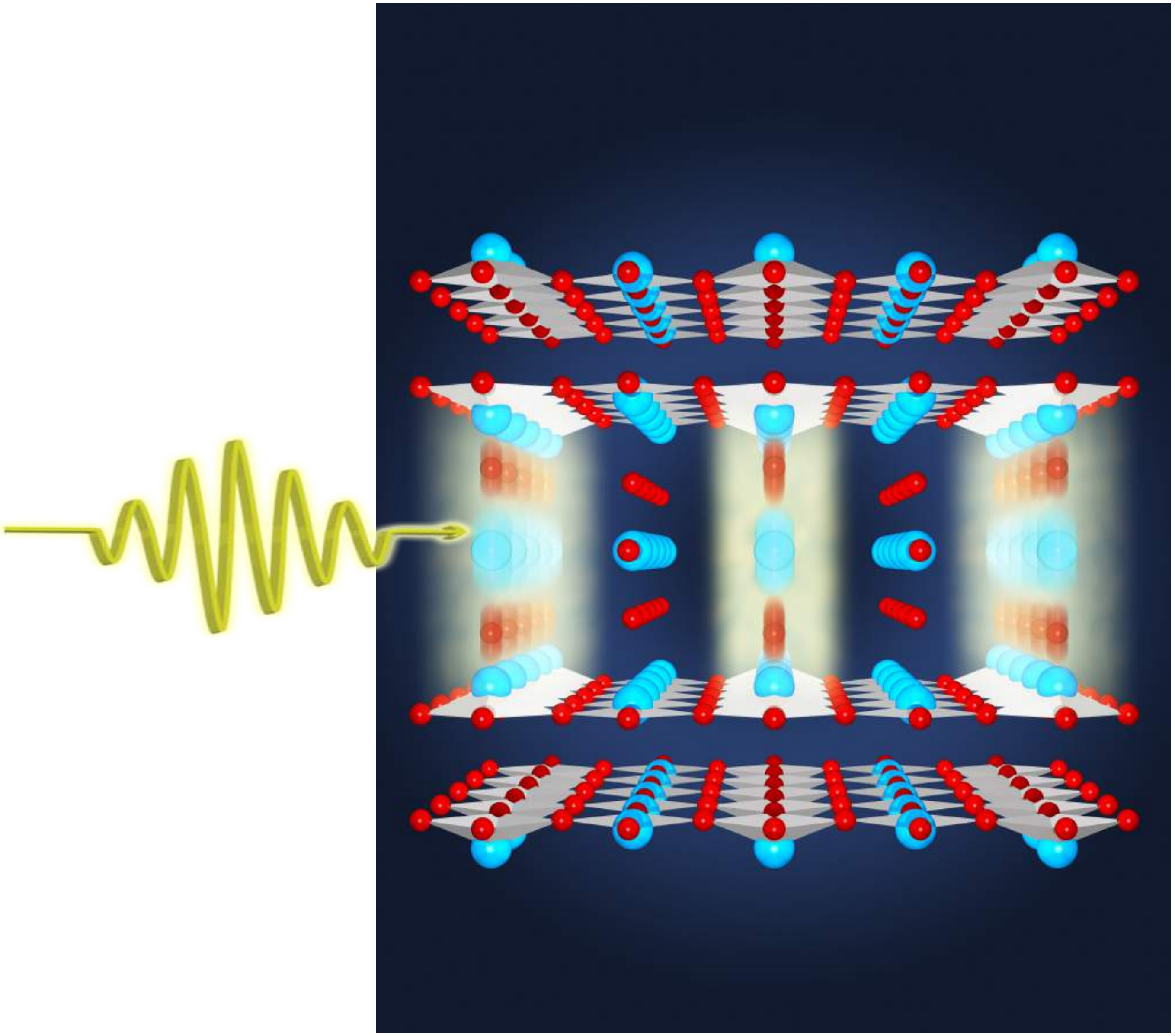
Follows T*



W. Hu. S. Kaiser, D. Nicoletti, C.S. Hunt et al. Nature Materials (2014)

S. Kaiser, D. Nicoletti, C. Hunt et al., *Phys. Rev. B* 89, 184516 (2014)

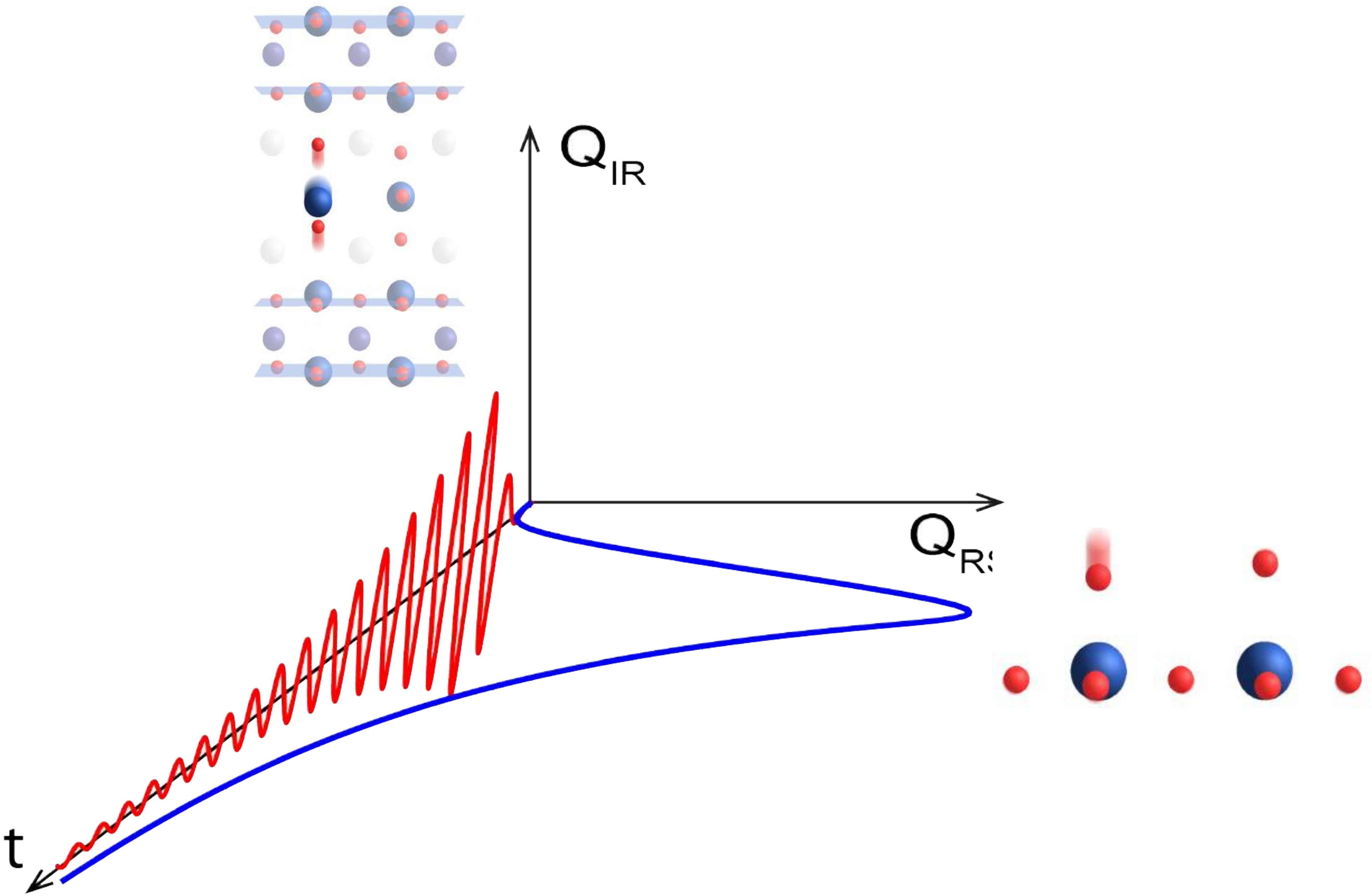
Dynamical modulation: what is going on ?



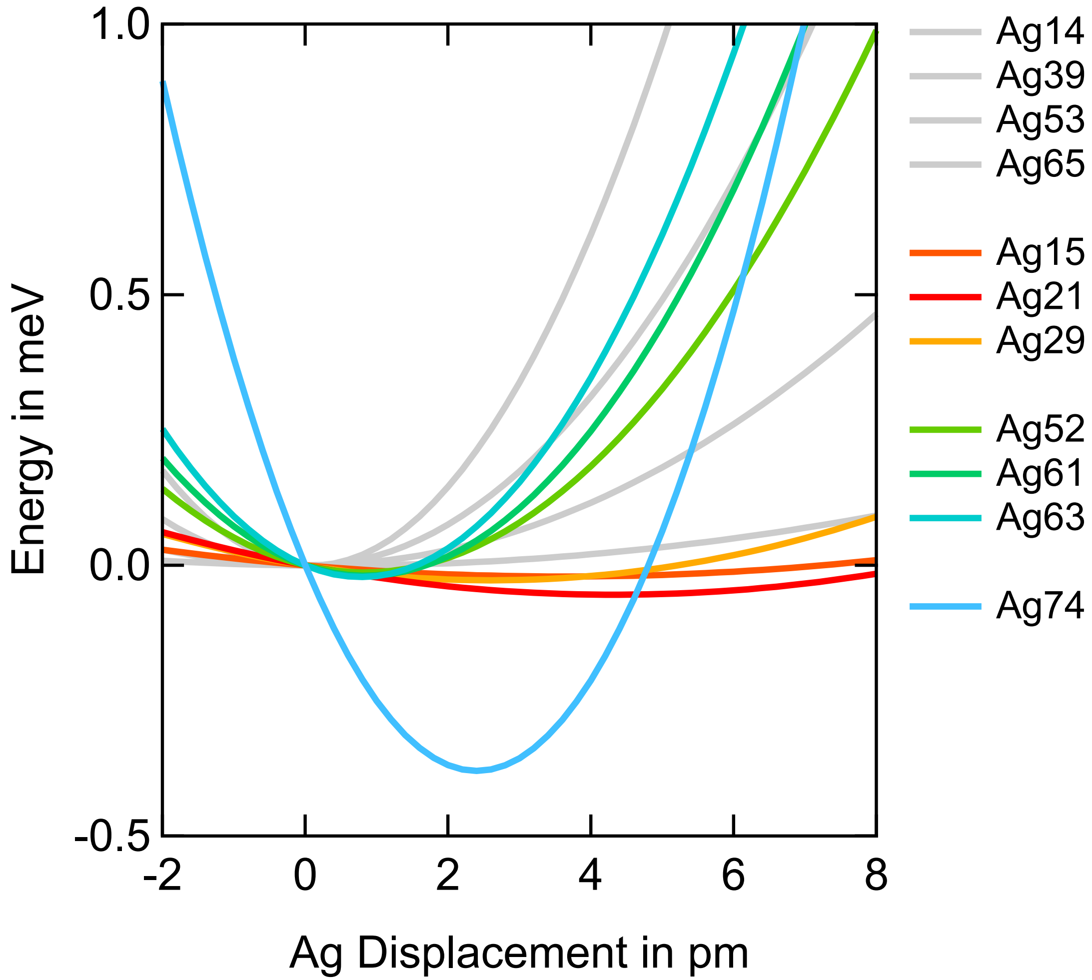
Underdoped YBCO

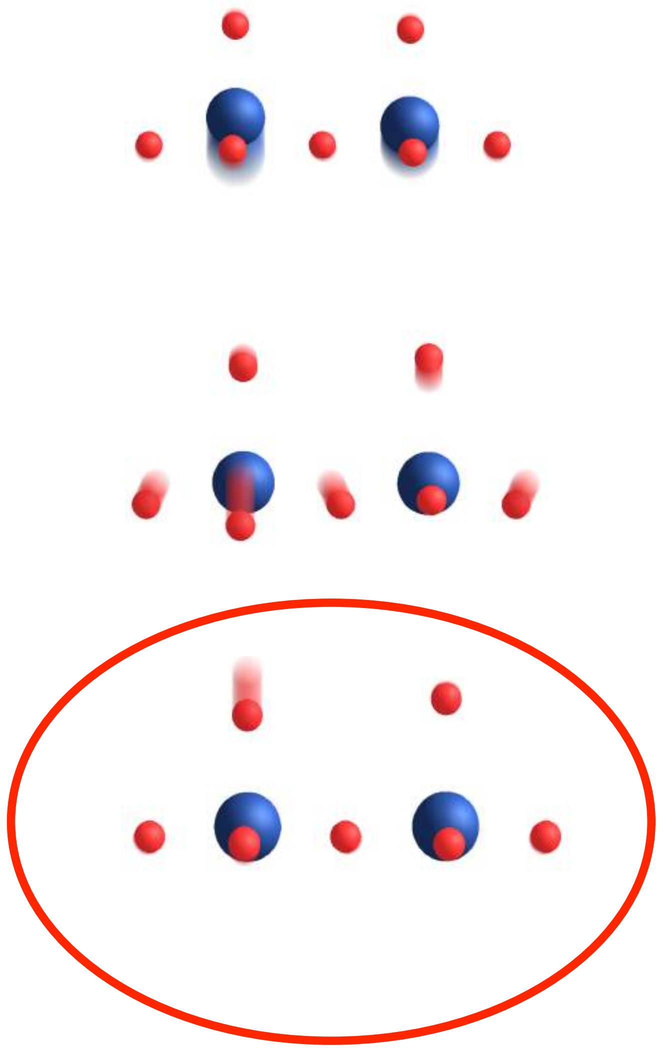
What is the lattice doing ?

Excite B_{1u} and displace along A_g



Doped YBCO: 11 A_g Raman modes

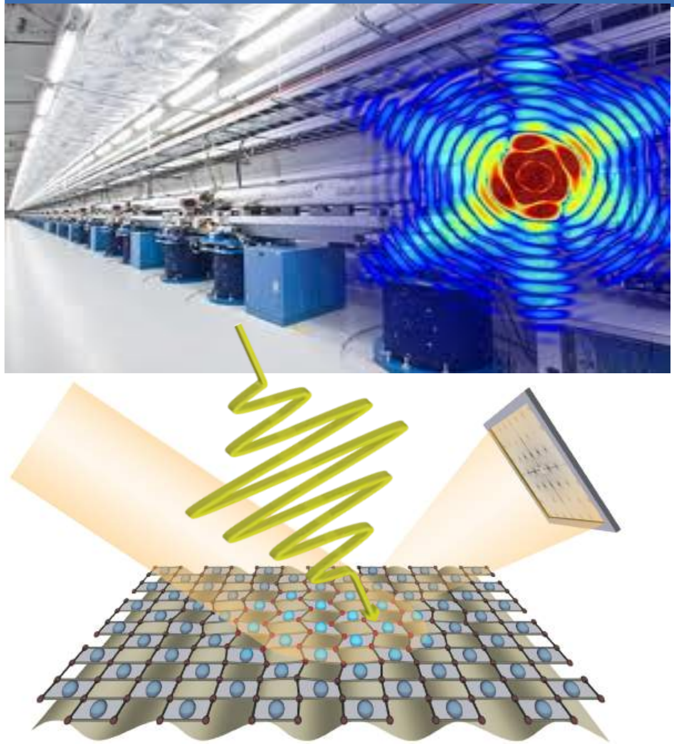




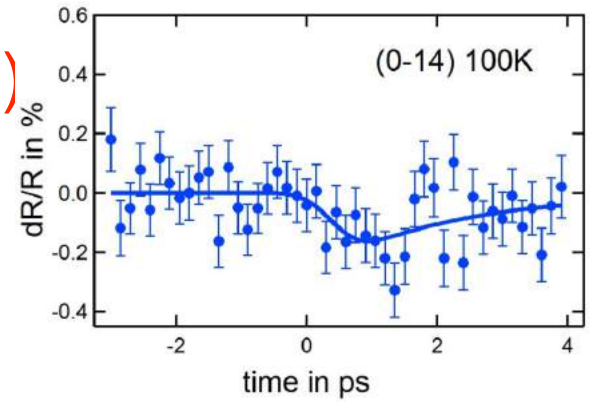
Only three Ag modes are coupled strongly with B1u

Alaska Subedi – Antoine Georges

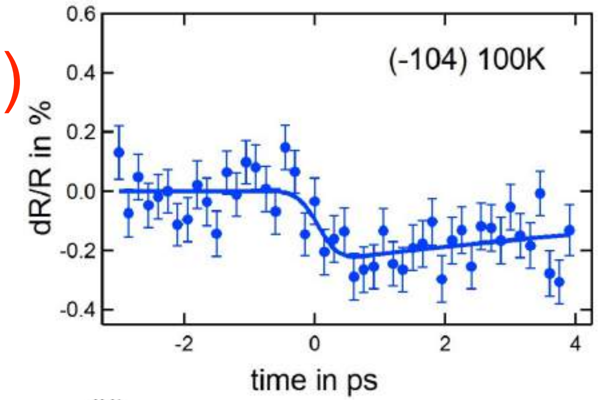
Femtosecond X-ray Scattering



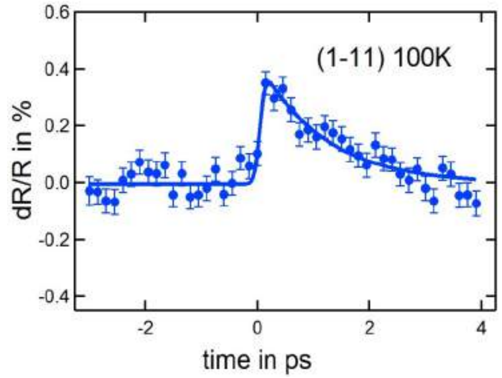
(0,-1,4)



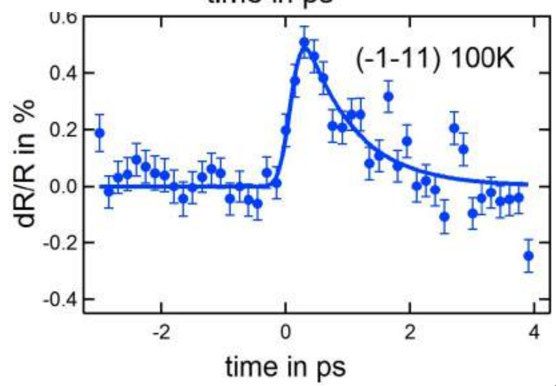
(-1,0,4)



(-1,1,1)

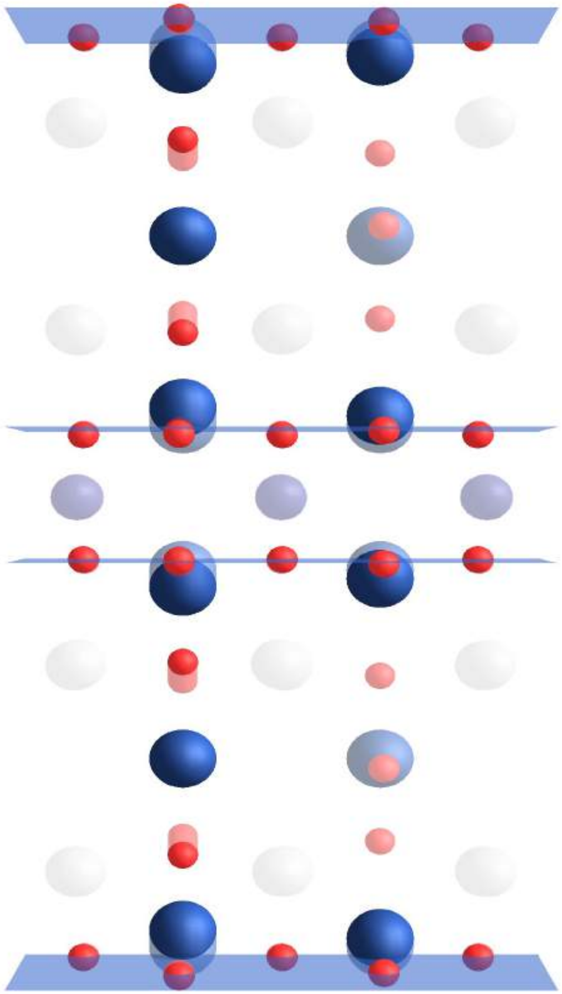


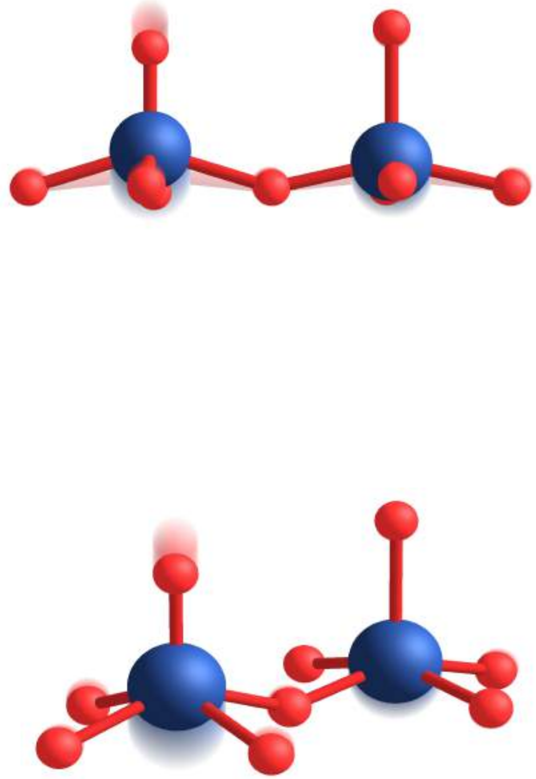
(1,-1,1)



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

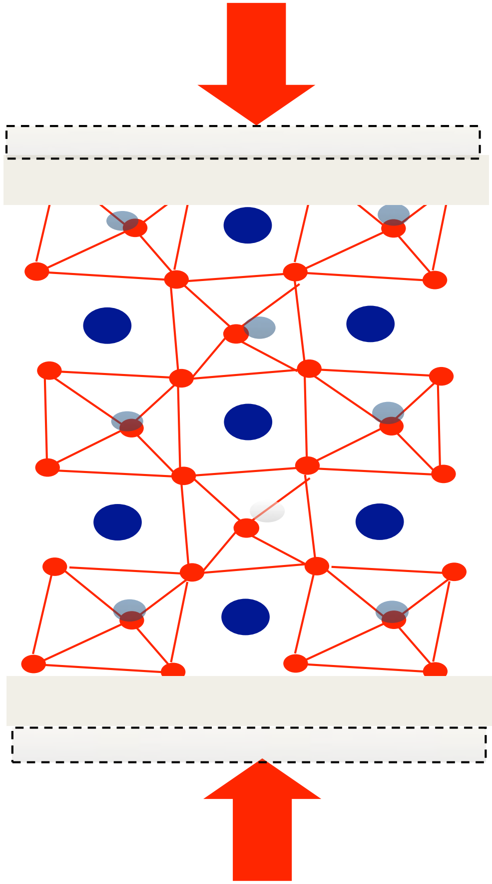
A new, transient crystal structure

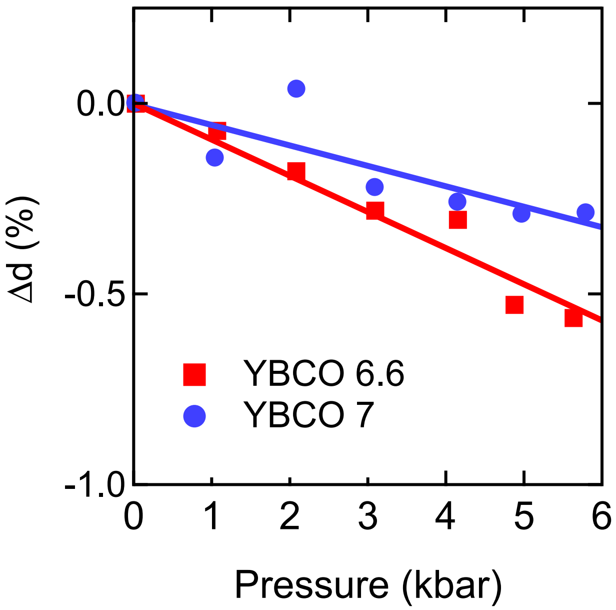


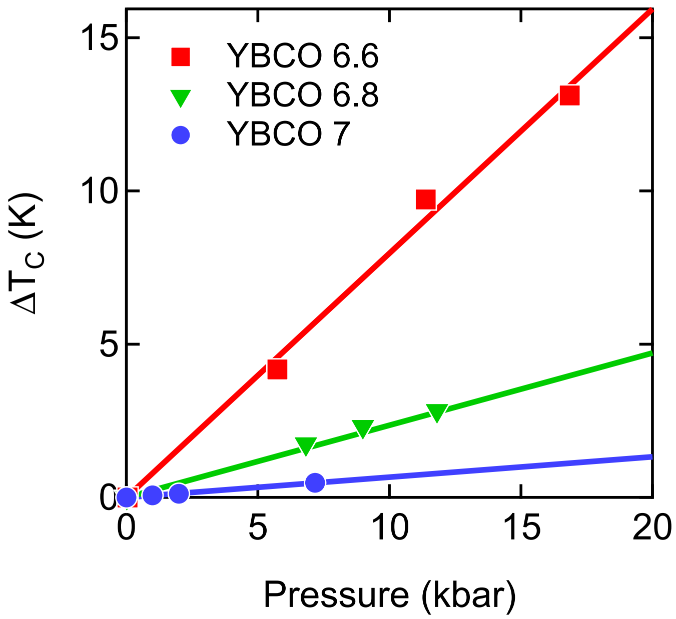


R. Mankowski et al. *Nature 516,71 (2014)*

Same distortions observed under pressure







Pressure
d ~ 0.5 %
ΔT_c ~ 5 - 15 K

Phononics
d ~ 3 %

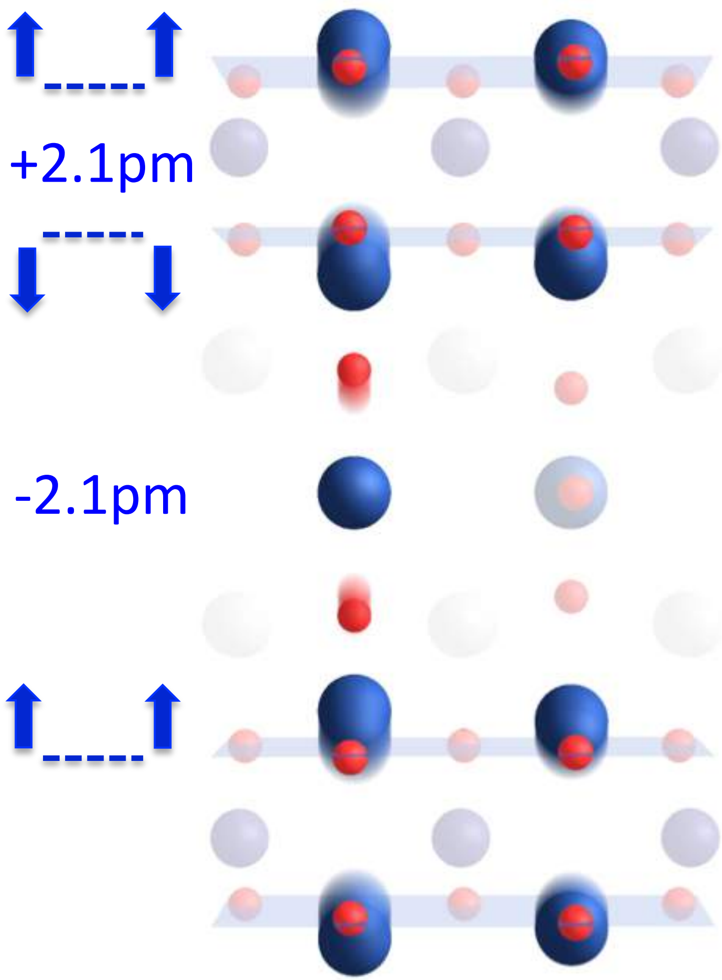
J. G. Huber et al. *Phys. Rev. B 41*, 8757 (1990)

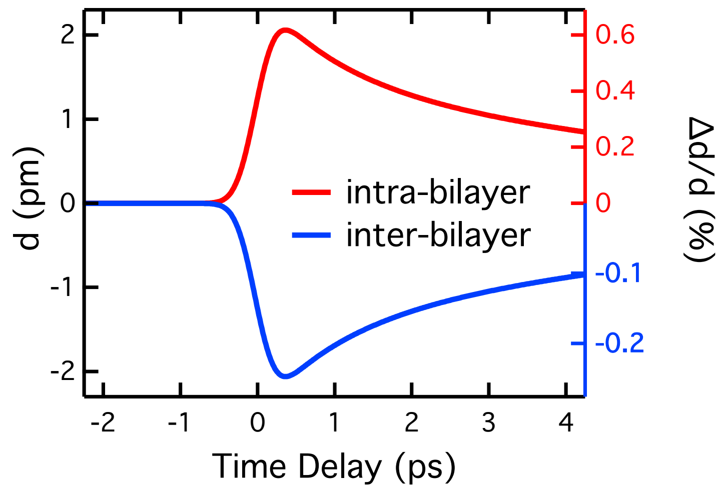
L. E. Schirber et al. *Phys. Rev. B 35*, 8709 (1987)

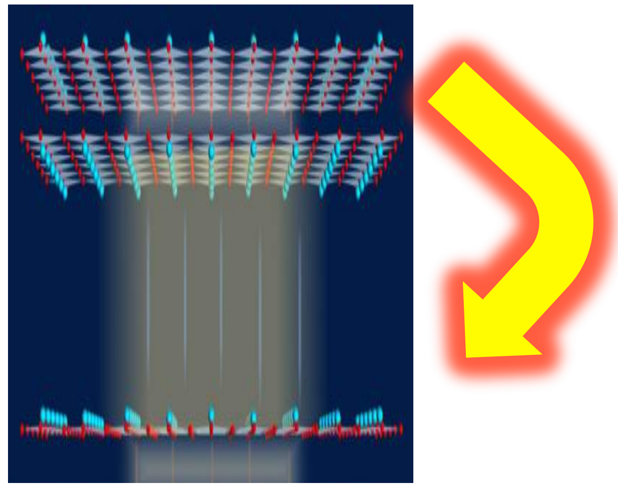
B. Bucher et al. *Journal of Less-Common Metals 164, 165*, 20 (1990)

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

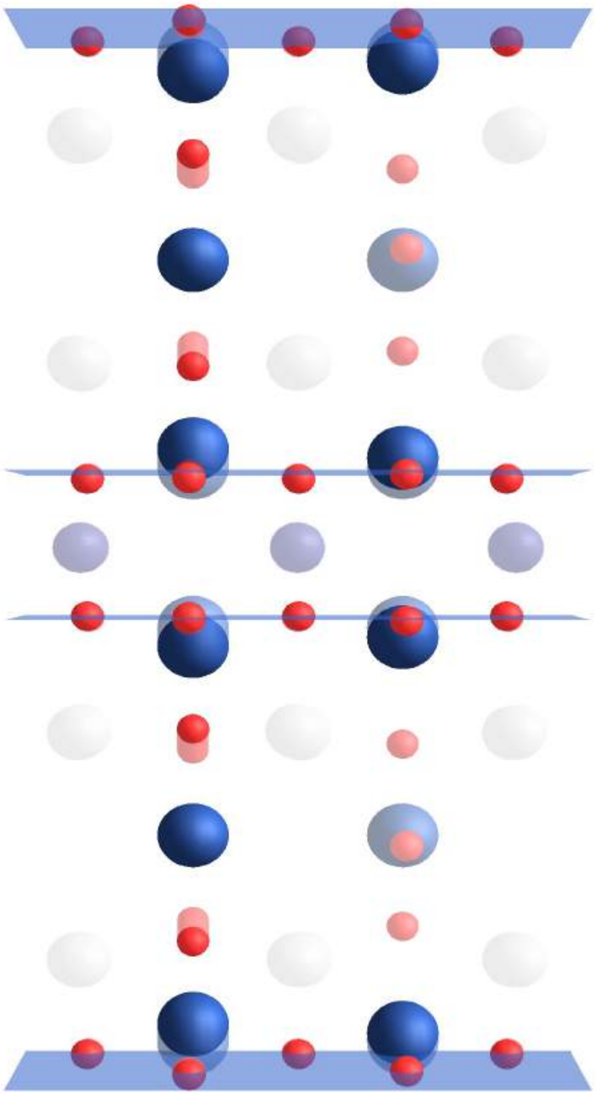
1) Staggered motion of the planes

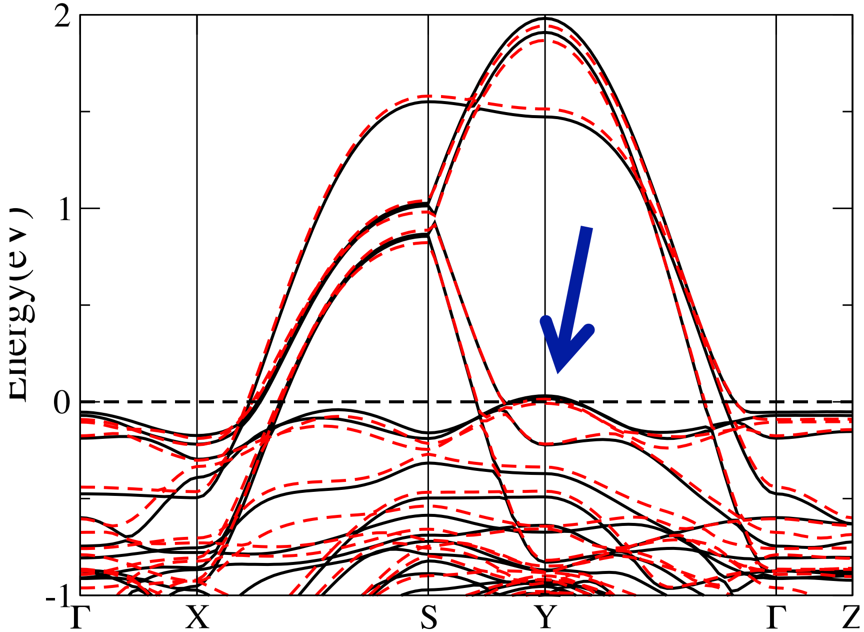


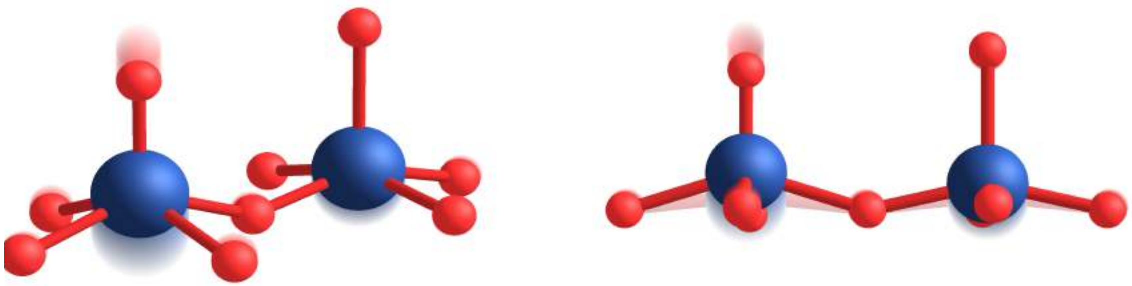




2) Empty chain band moves down in energy

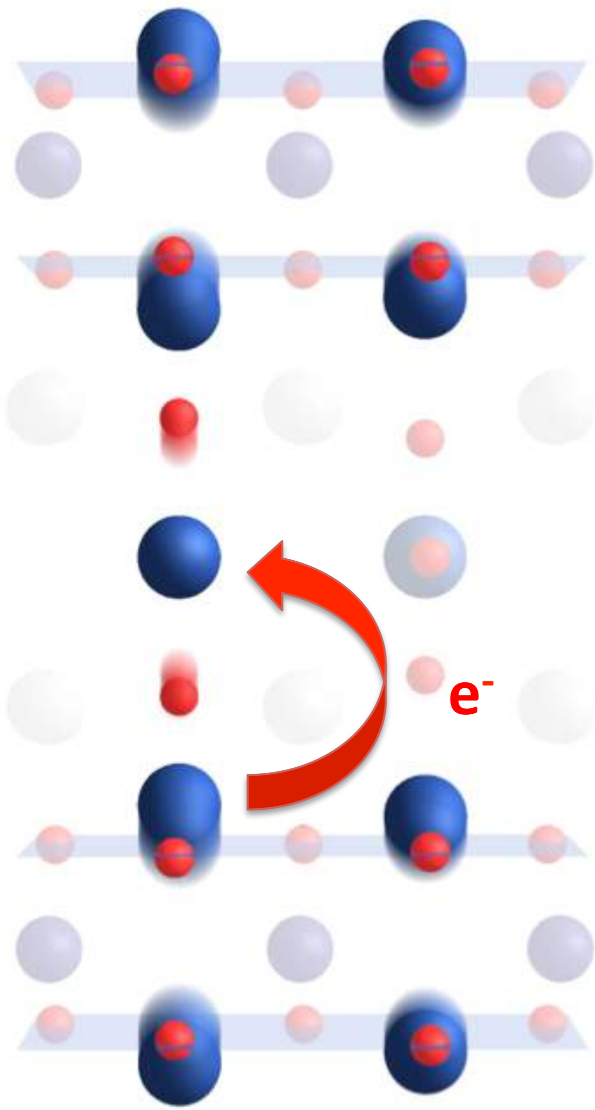


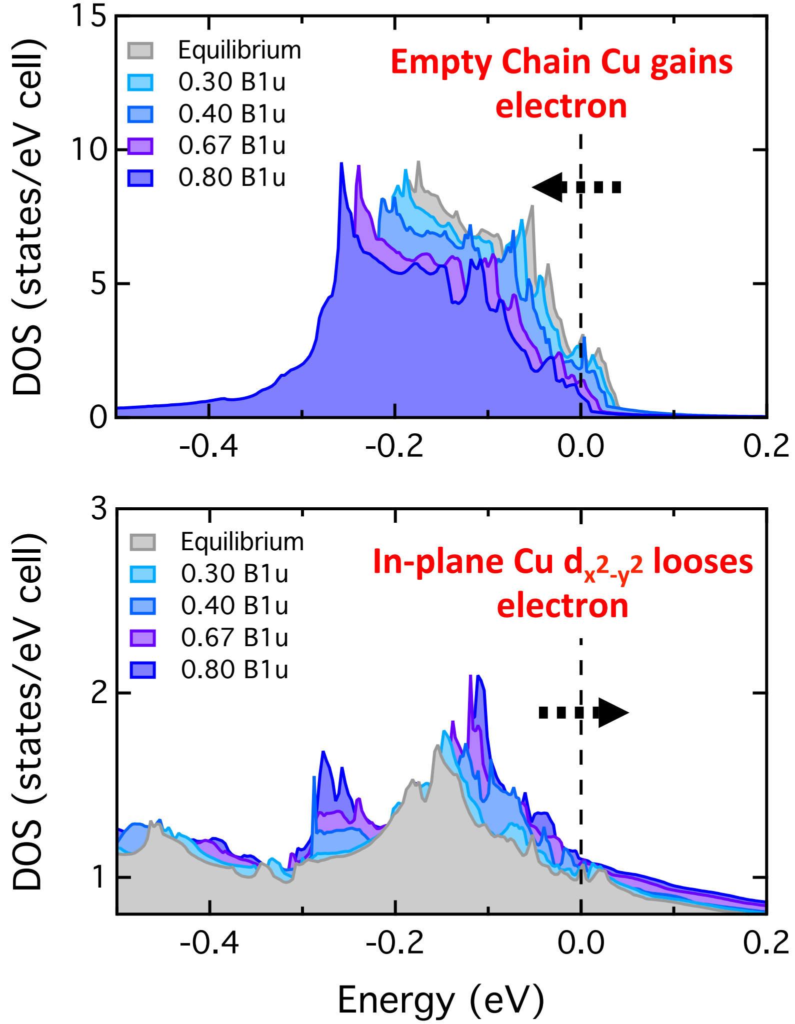




R. Mankowski et al. *Nature 516,71 (2014)*

3) Charge transfer from the planes to the chains

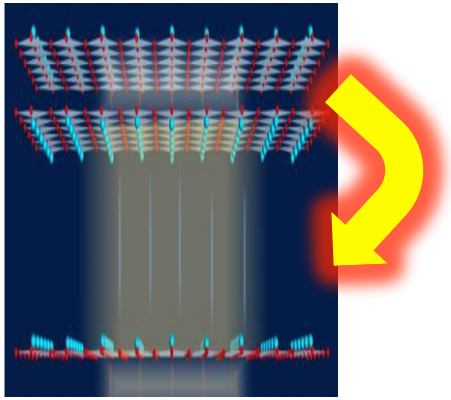




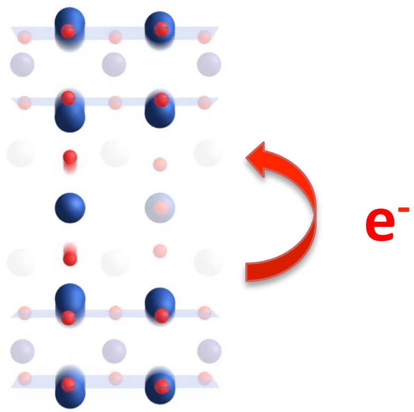
R. Mankowski et al. *Nature 516,71 (2014)*

Summary: three good things

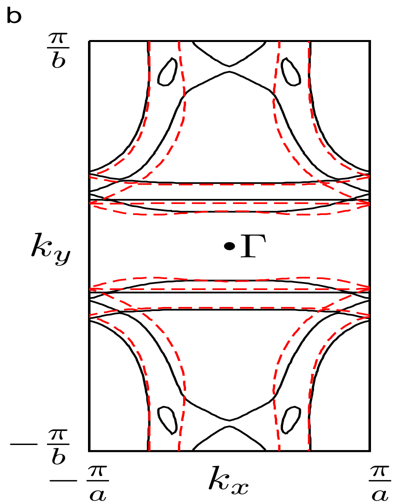
1) Staggered motion of the layers



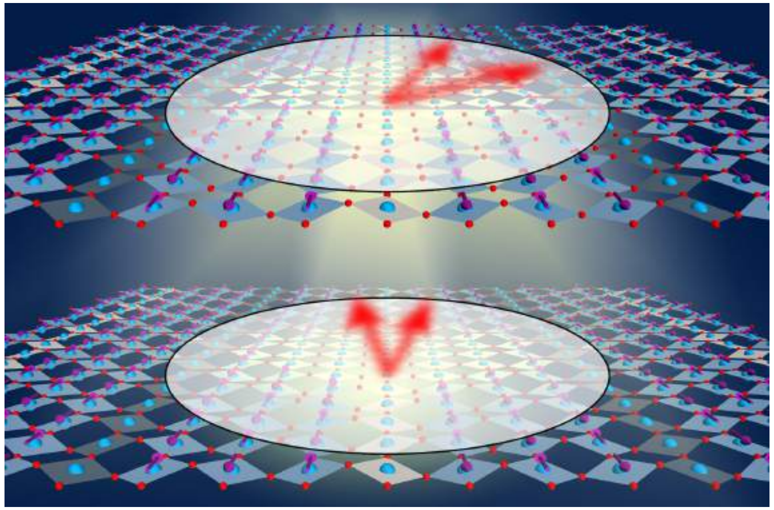
2) Charge transfer from to chains

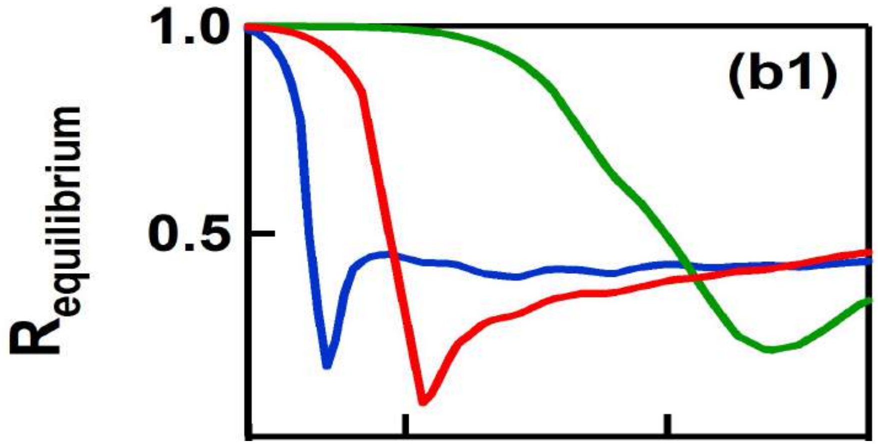


3) dx^2-y^2 Fermi surface



Let's think about YBCO again: below Tc





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

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

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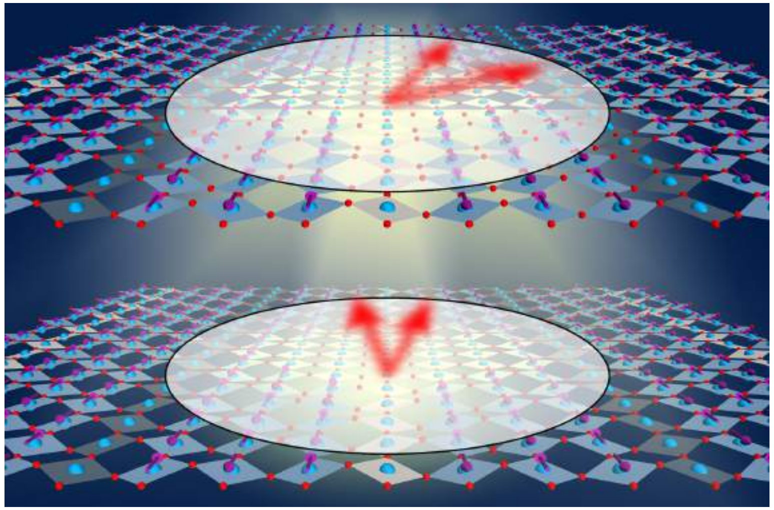

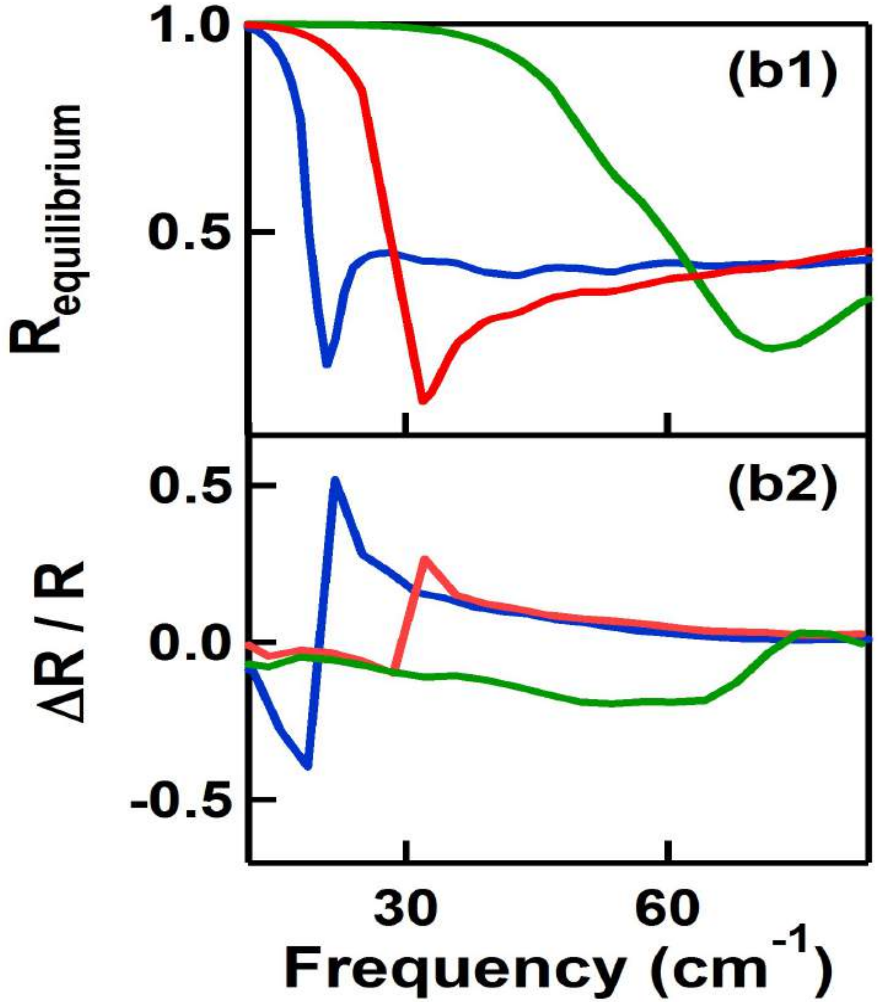

S. Kaiser, et al., *Phys. Rev. B* 89, 184516 (2014)

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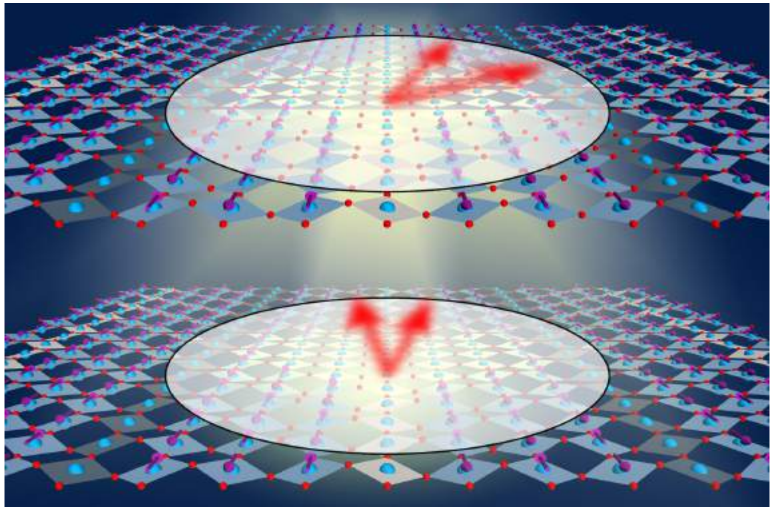
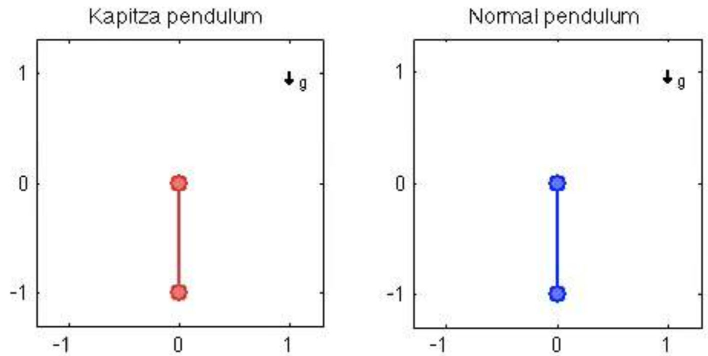
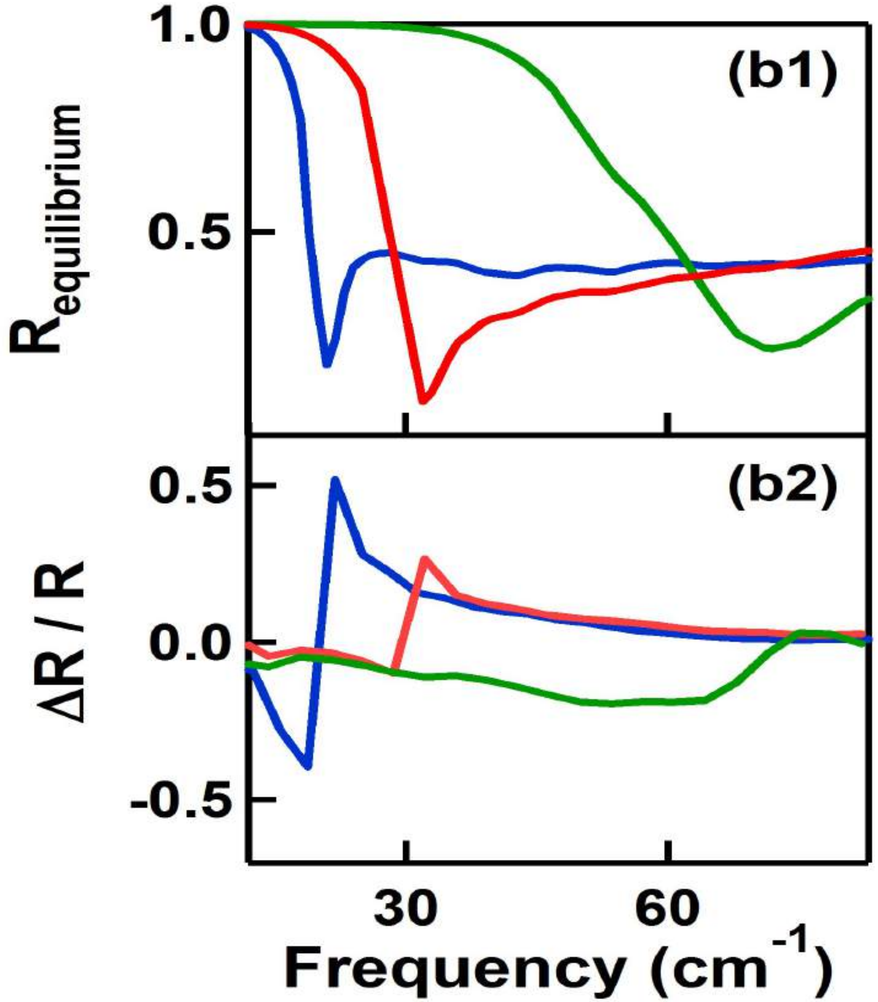


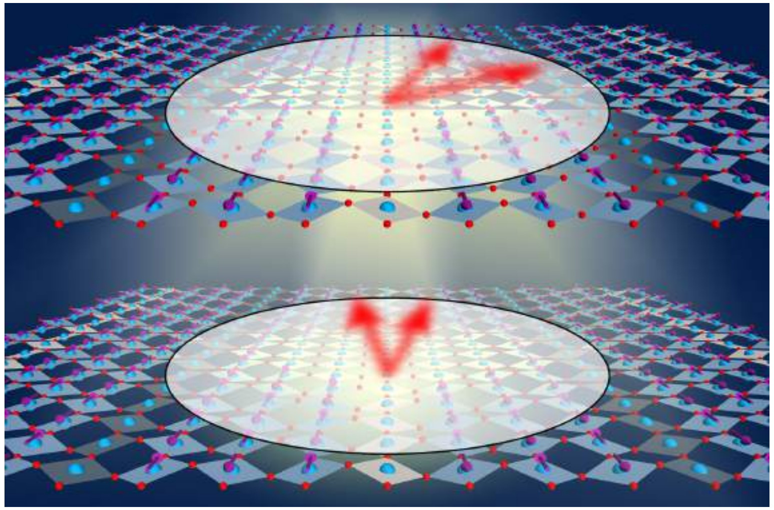


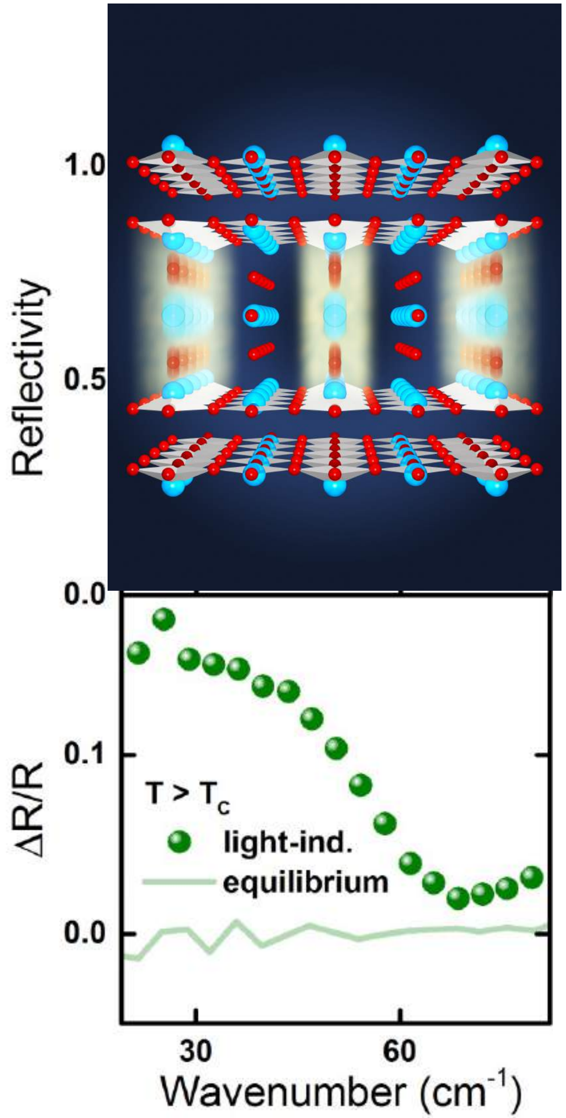


P.L. Kapitza, "Dynamic stability of a pendulum with an oscillating point of suspension," *Zh. Eksp. Teor. Fiz.* 21, 588 (1951)

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

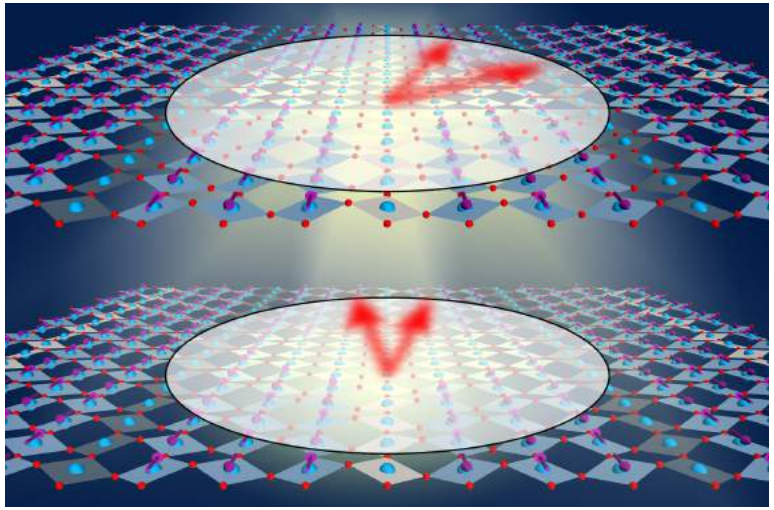
Let’s think about YBCO again: above Tc

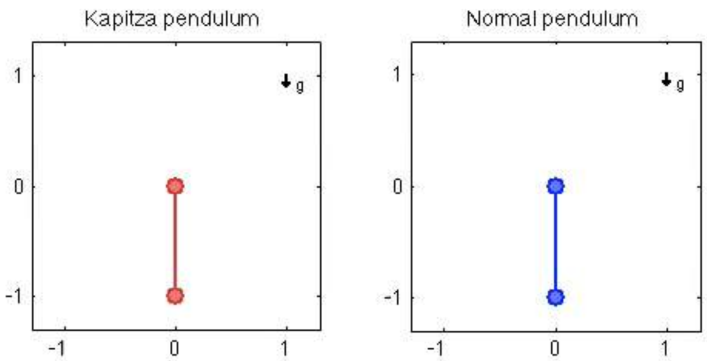


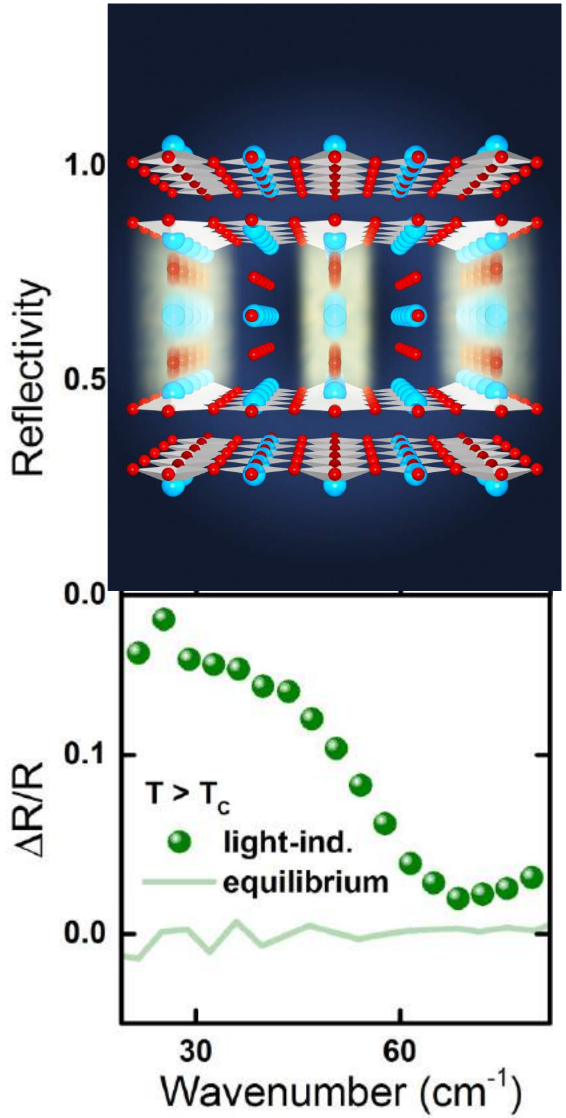


100 K
driven

Let's think about YBCO again: above Tc







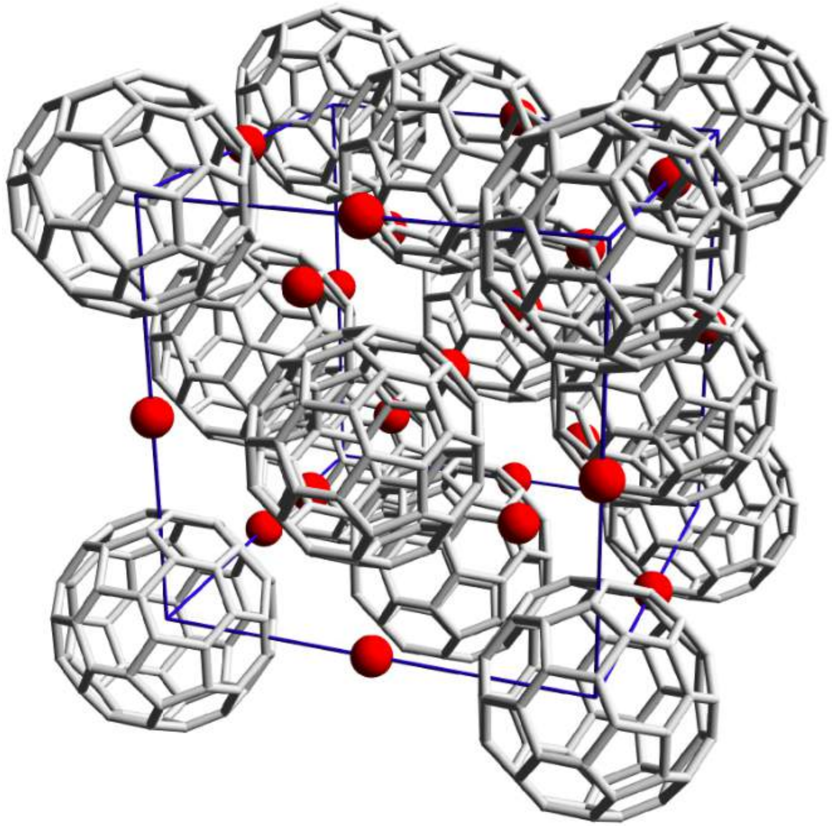
100 K
driven

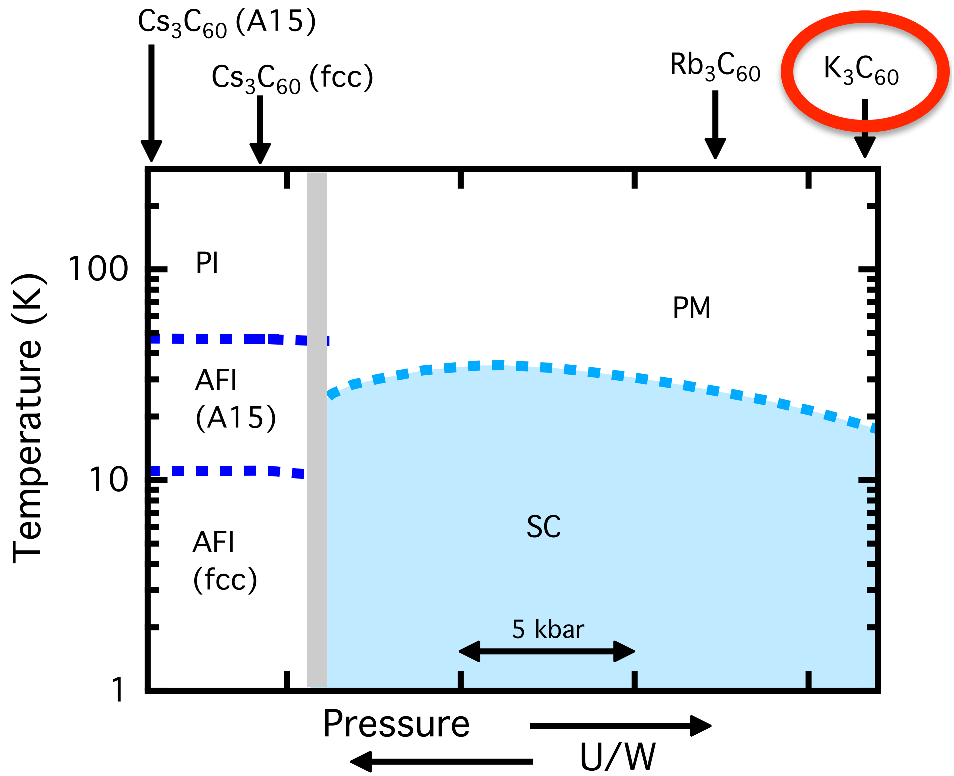
P.L. Kapitza, "Dynamic stability of a pendulum with an oscillating point of suspension," ***Zh. Eksp. Teor. Fiz.*** **21, 588 (1951)**

Light enhanced superconductivity

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

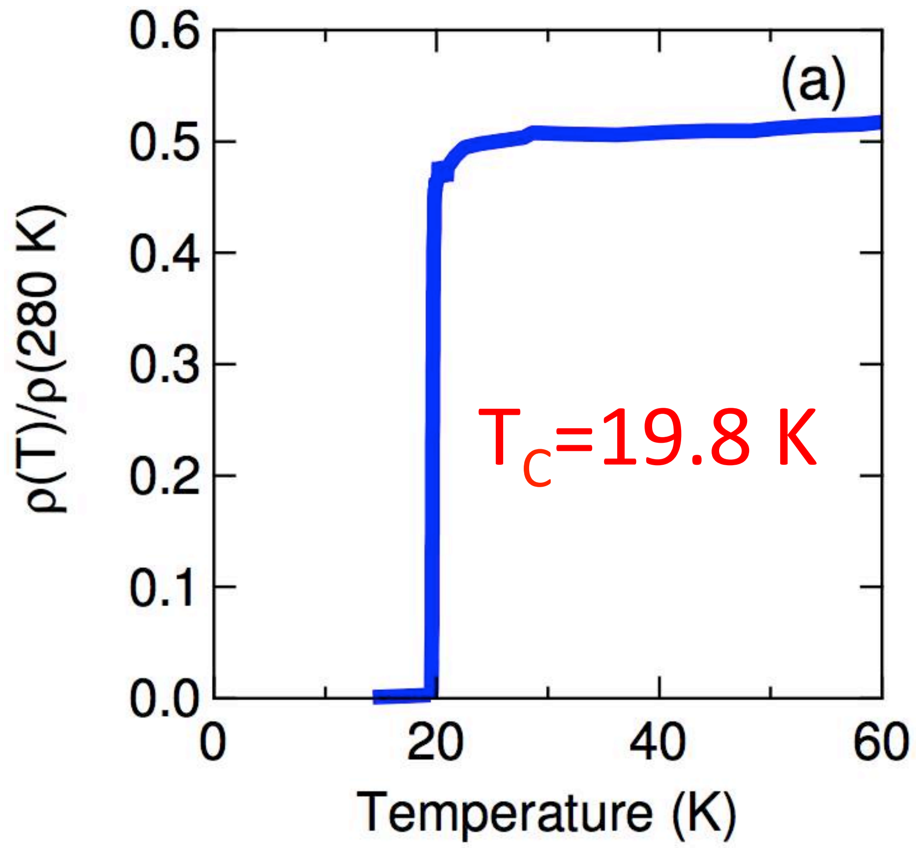
K_3C_{60}: a 20 K superconductor

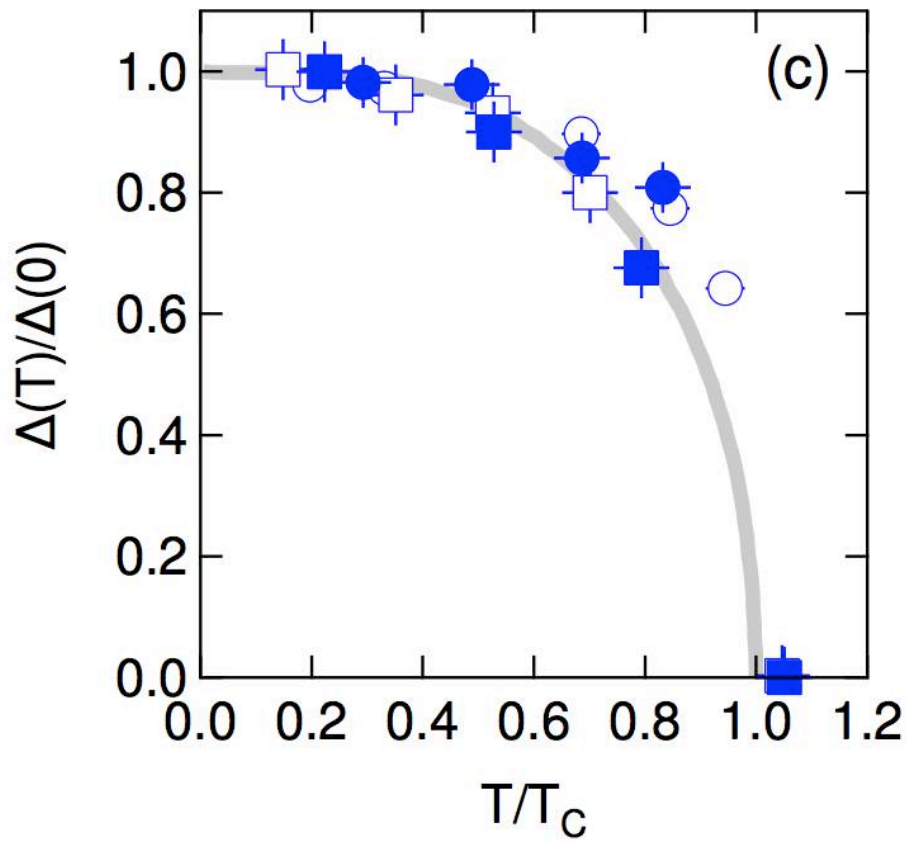




- Organic molecular solid
- High T_C (20 K)
- 3D electronic structure

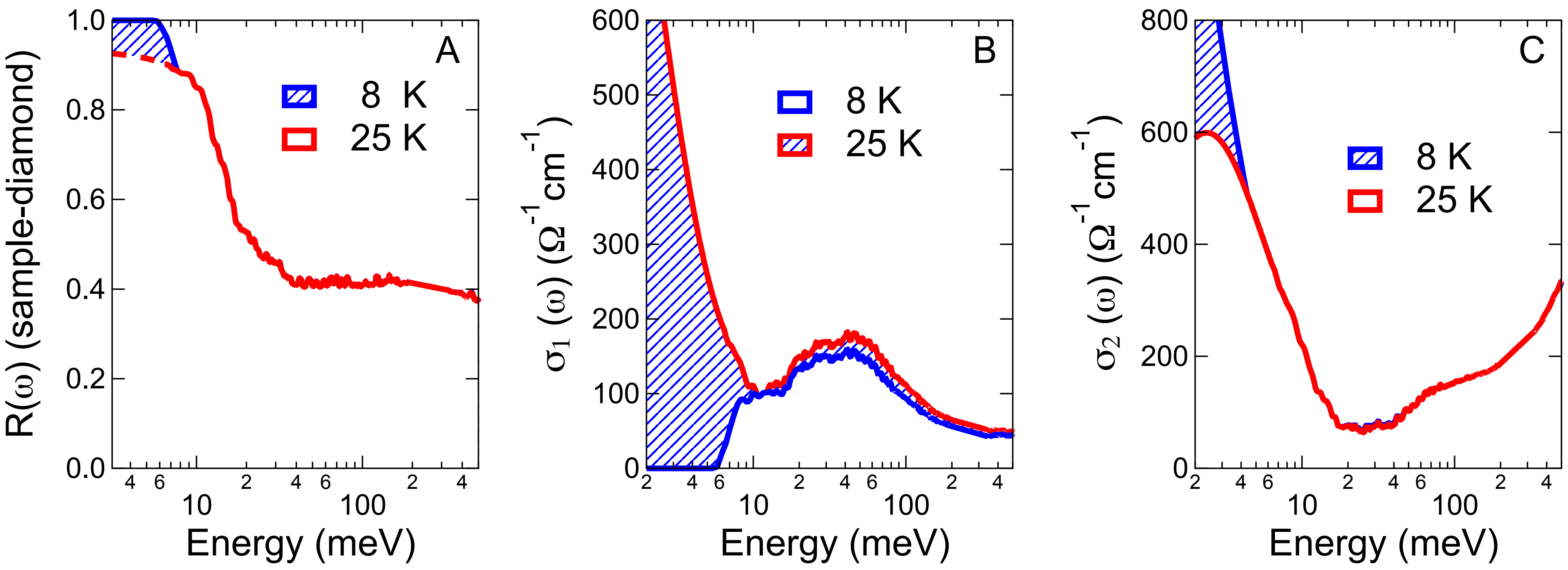
Equilibrium Superconductivity in K_3C_{60}





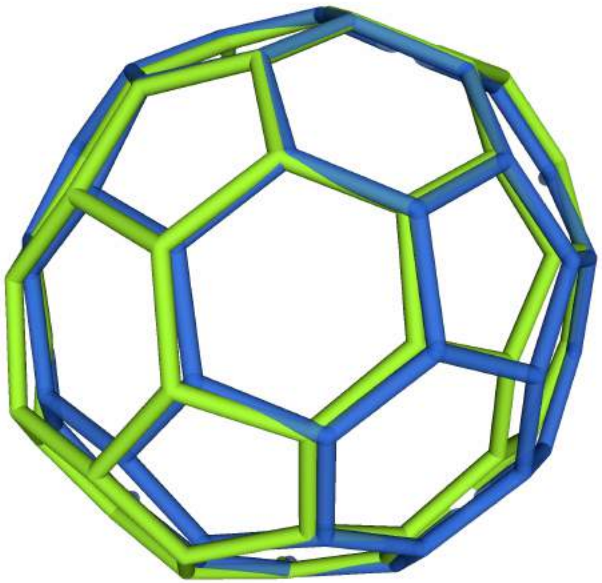
From literature data, MM PhD thesis

Equilibrium Superconducting Transition



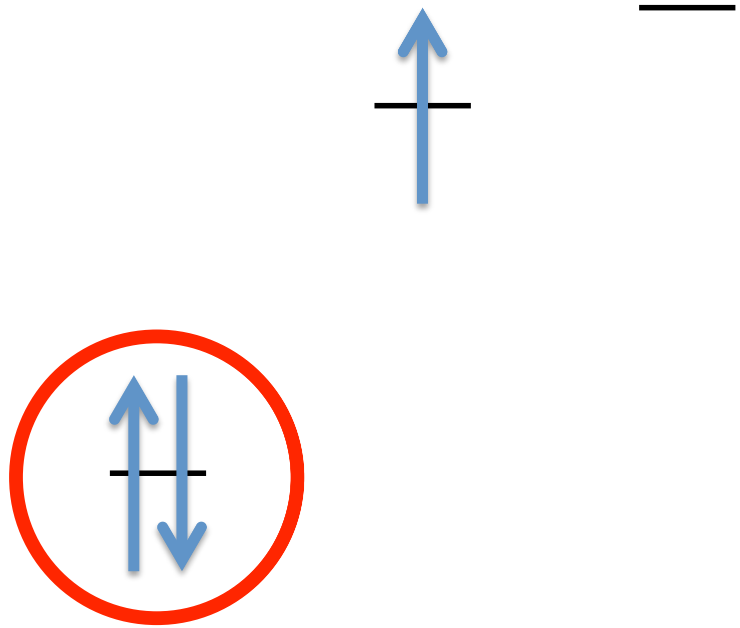
- Increase in $R(\omega)$
- Gap opening in $\sigma_1(\omega)$
- Increase in $\sigma_2(\omega)$

Pairing Interaction in K_3C_{60}



H_g mode (JT distortion)

Undistorted



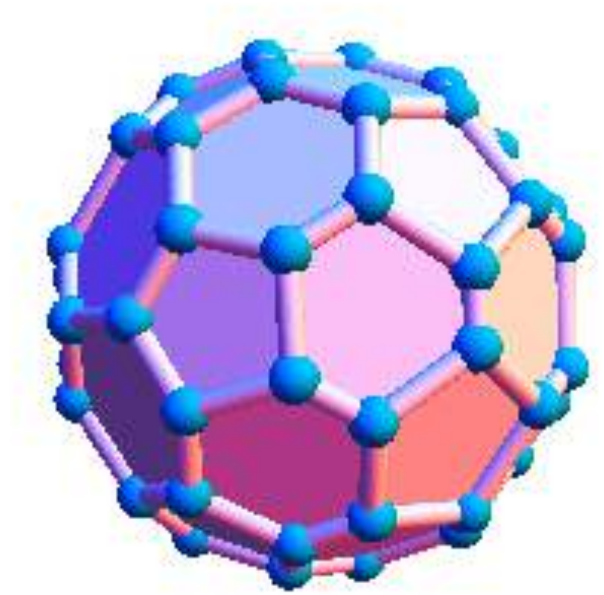
"On ball" vibrations plus correlations favor local pairing

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

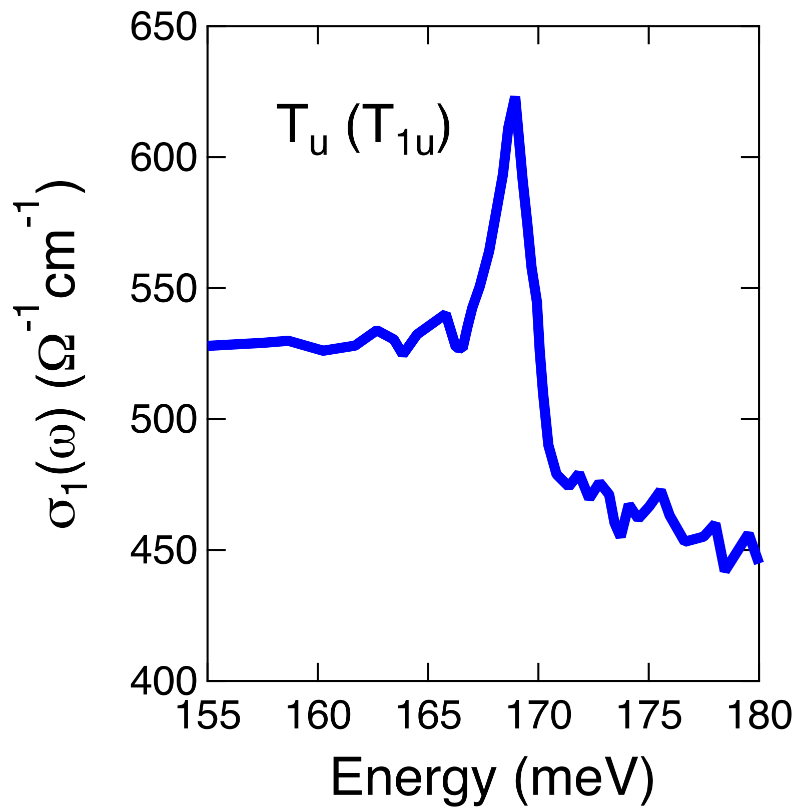
Kivelson, Chakravarty

Vibrational pump

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

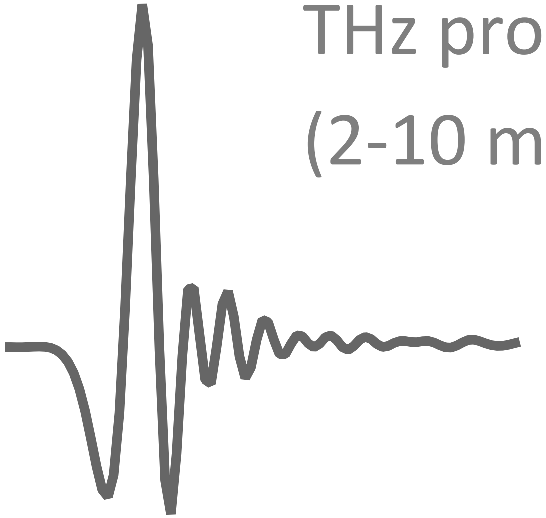


MIR pump 170 meV (7.3 μm)



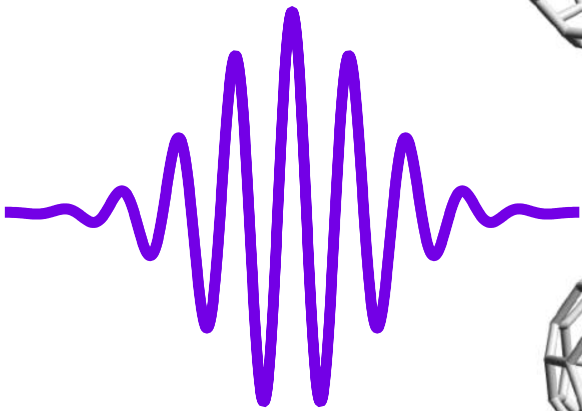
Iwasa et al. PRB **51,** 3678 (1995)

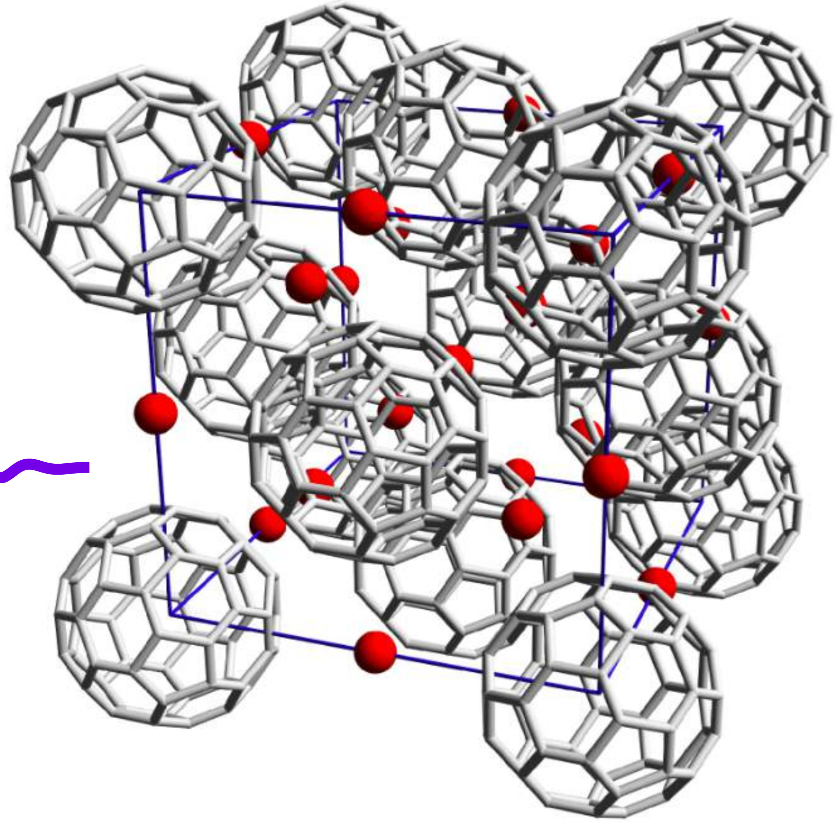
Vibrational pump THz probe in K_3C_{60}



THz probe

(2-10 meV)





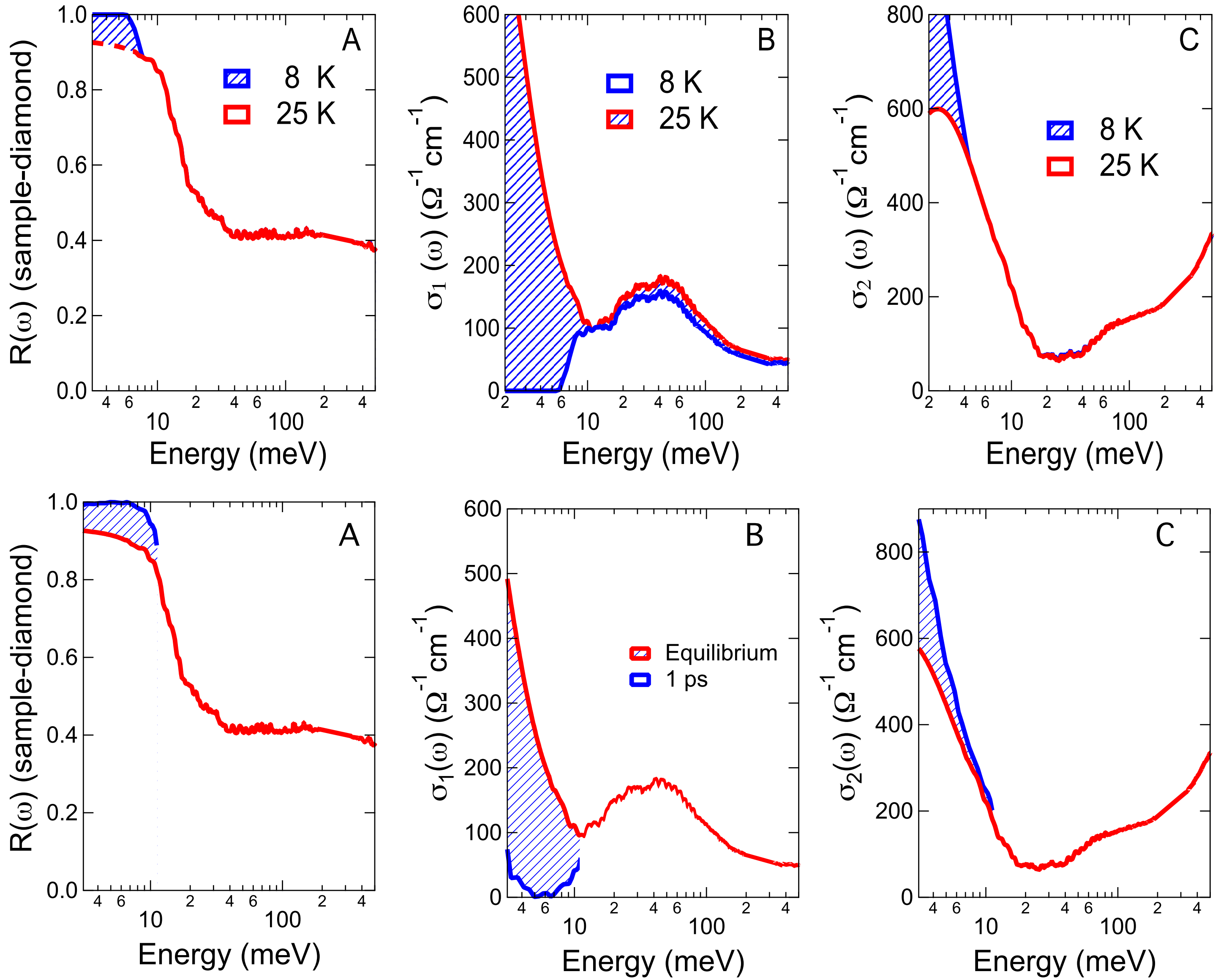
MIR pump 170 meV (7.3 μm)

Striking similarity with the low temperature SC

Cooling

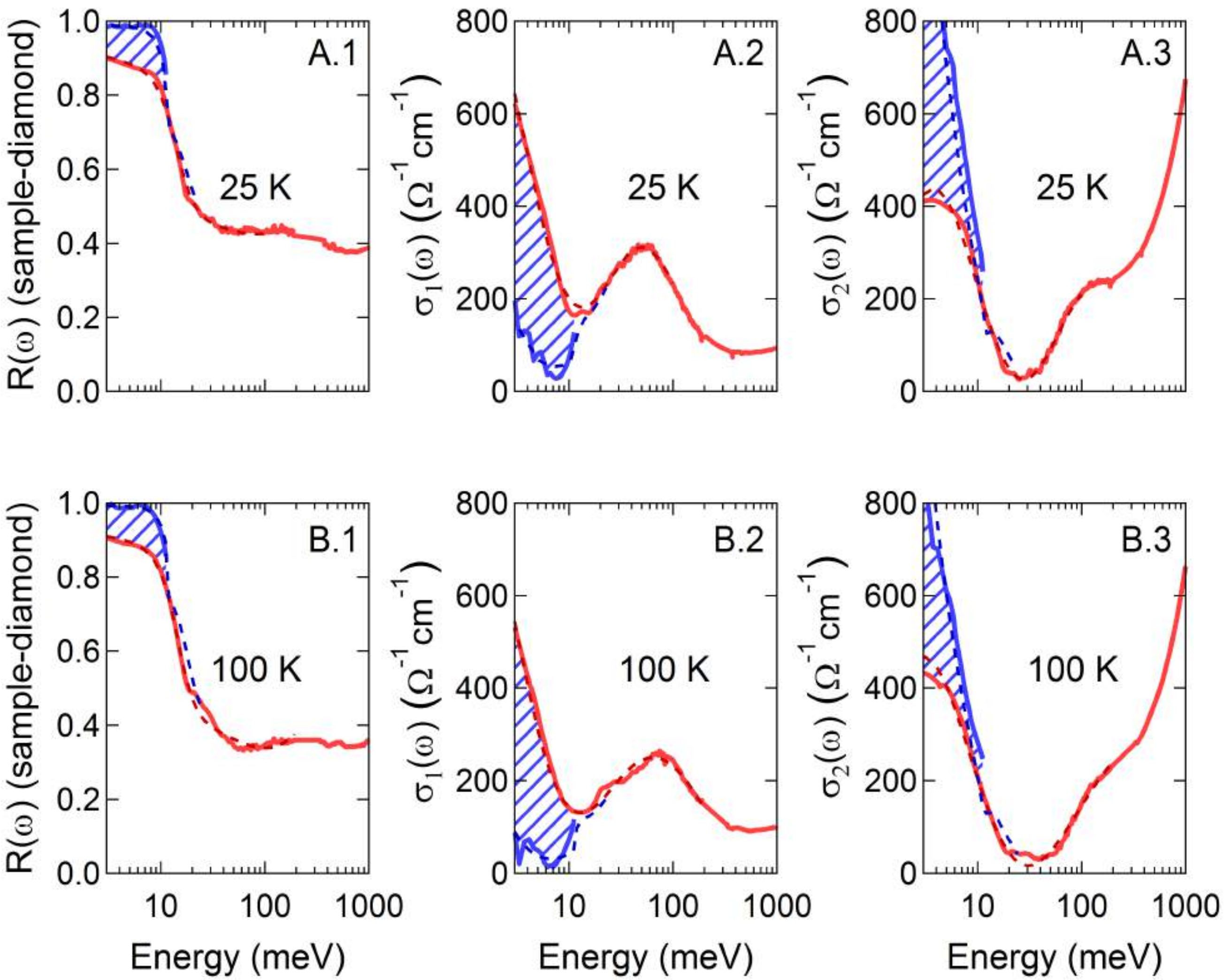
Light-induced

T=25 K



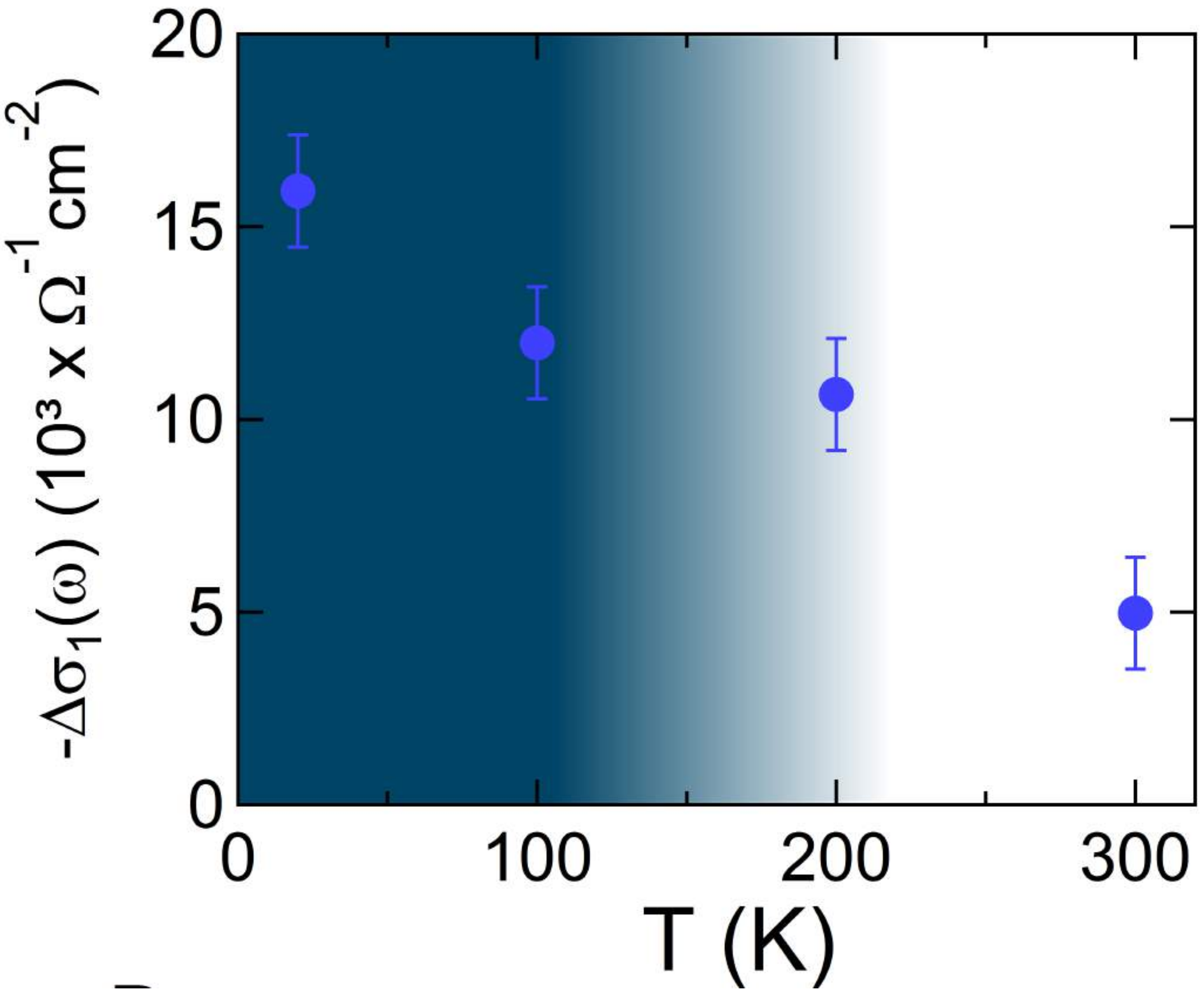
M. Mitrano et al. 530, 461 *Nature* (2016)

Temperature dependence



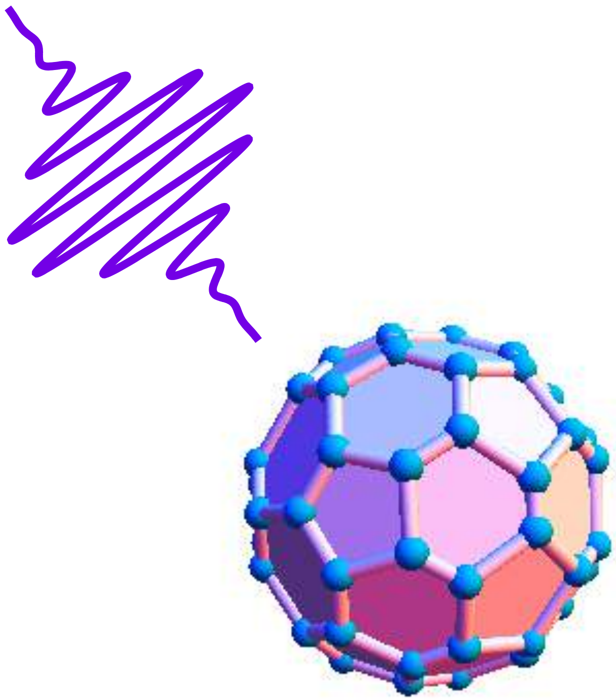
M. Mitrano et al. 530, 461 *Nature* (2016)

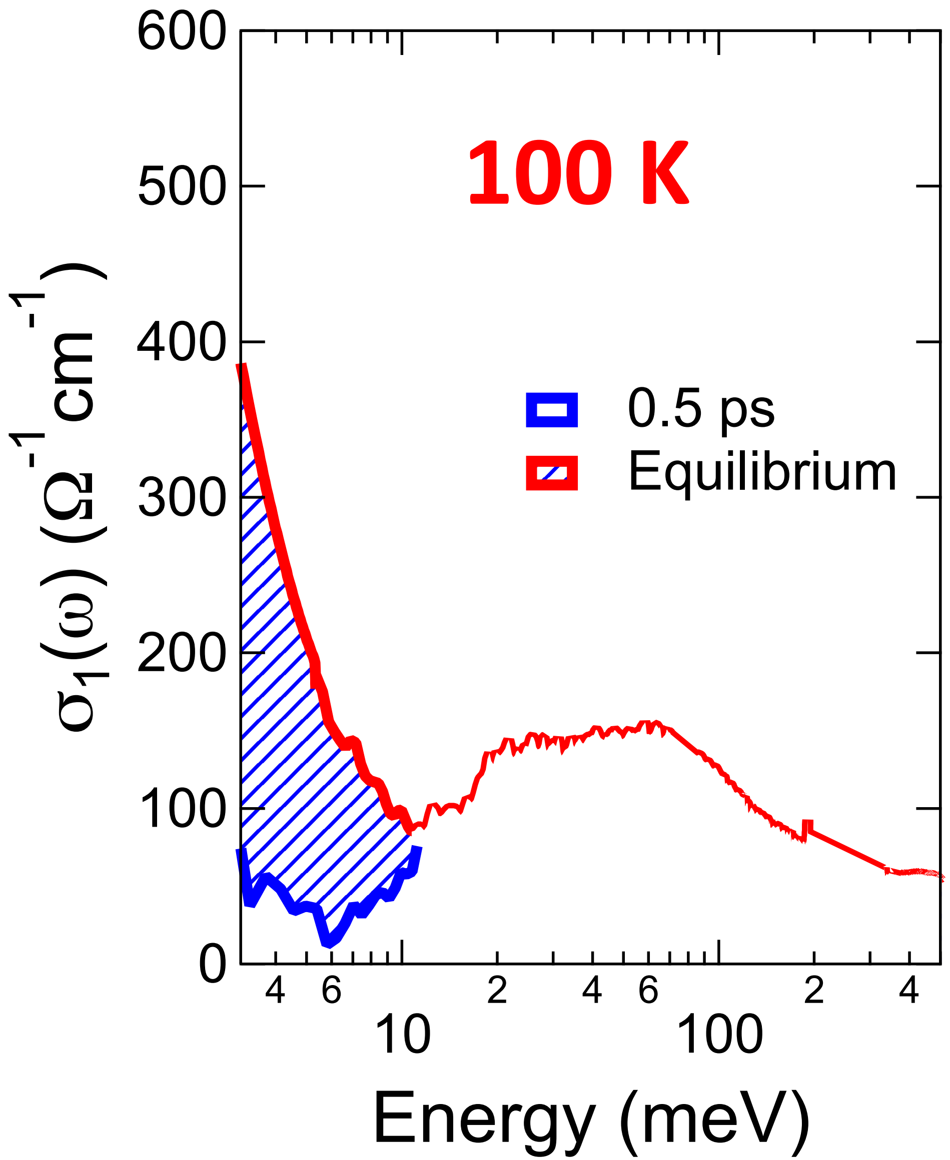
Crossover at ~10 times T_c



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

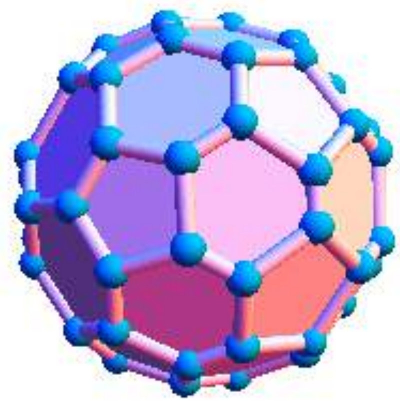
K_3C_{60} : Stimulated superconductivity ?



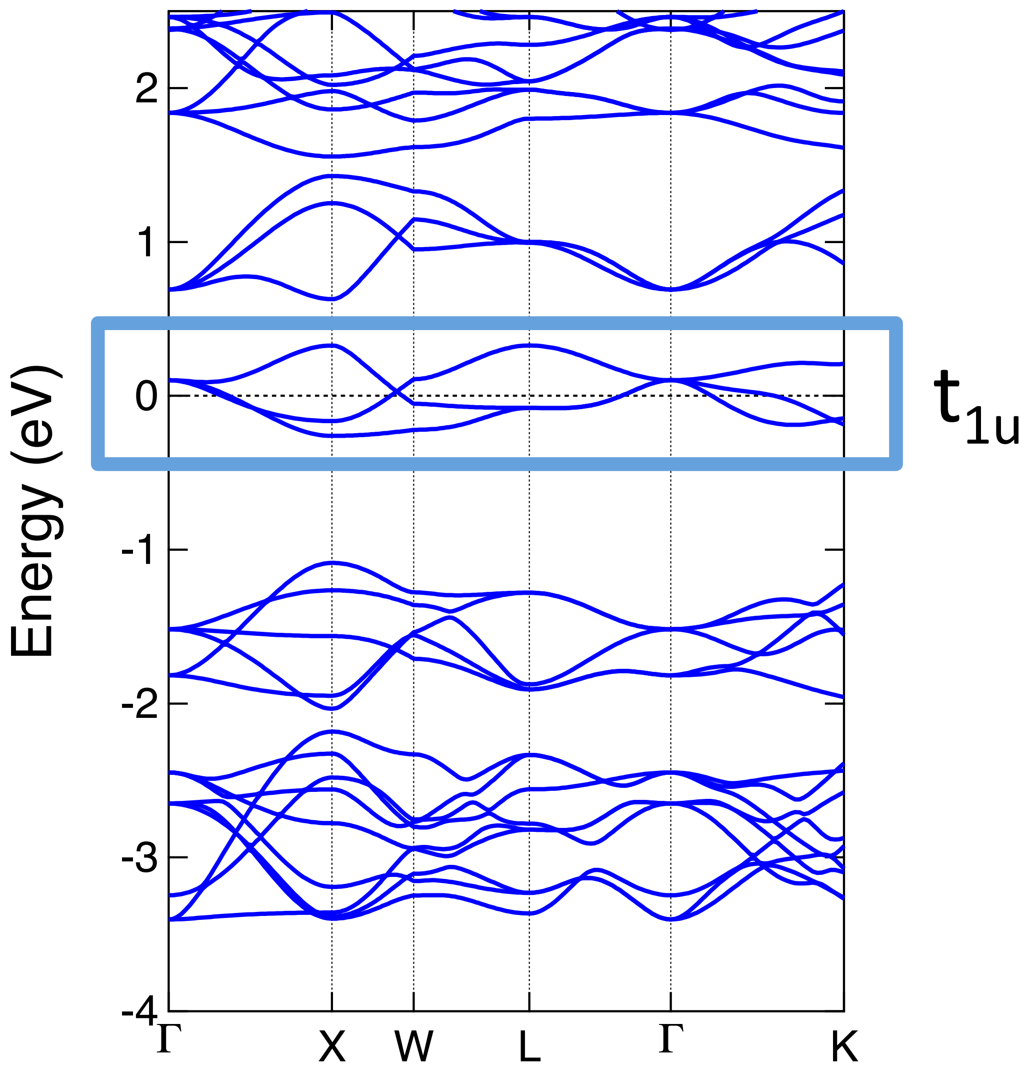


What is going on?

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



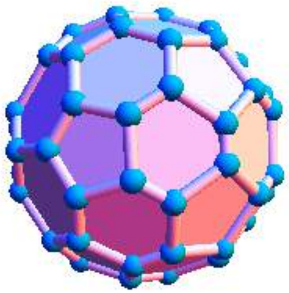
$T_{1u}(4)$
1370 cm^{-1}



Nonlinear coupling to Jahn Teller Phonon?

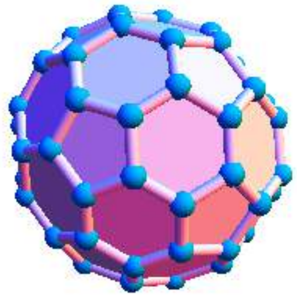
$Q^2_{T1u} Q_{Hg}$

$T_{1u}{}^2$



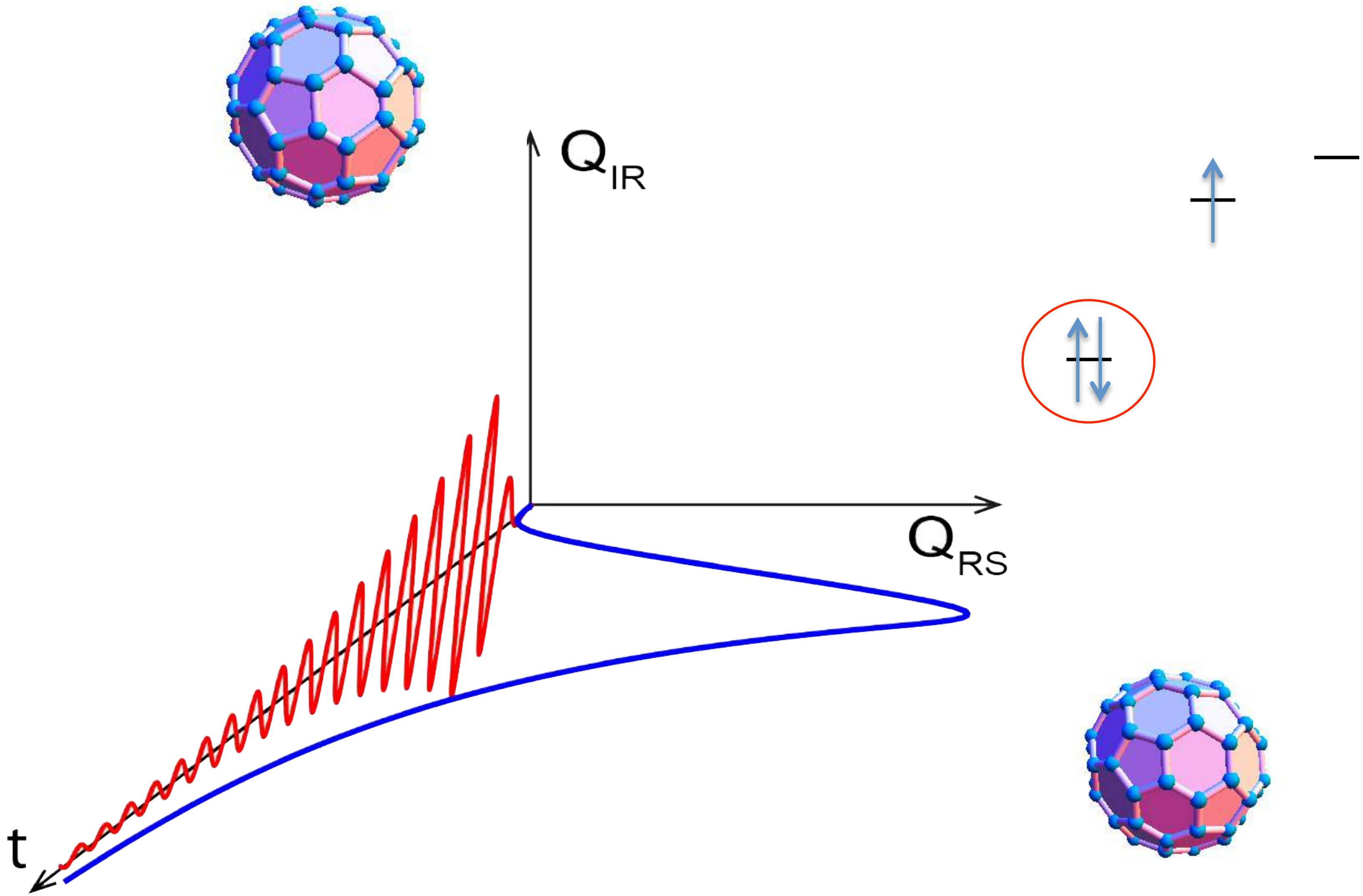
$T_{1u}(4)$
1370 cm^{-1}

H_g



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

Enhancement of pairing distortions ?



Or…..new types of coupling

In analogy with nonlinear optics

$Q_{IR}^2 \cdot Q_2$ (lattice control)

$Q_{IR}^2 \cdot Q_2^2$ (phonon squeezing)

Q_{IR}^4 (parametric phonon amplification)

$Q_{IR1} \cdot Q_{IR2} e^{i\Theta} \cdot s$ (controlling time reversal invariance)

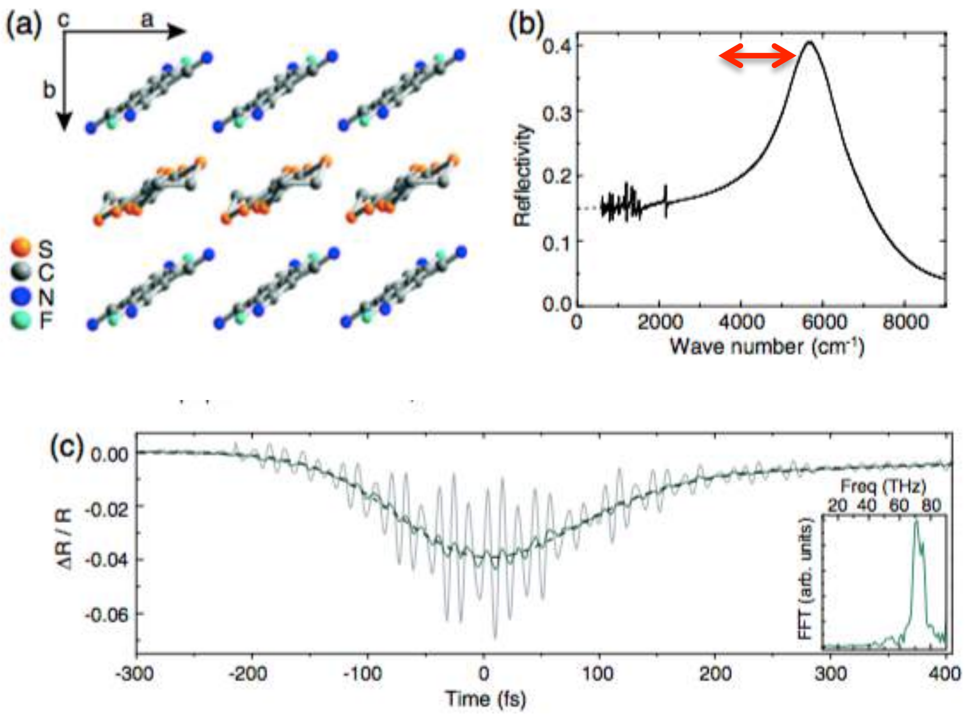
$Q_{IR}^2 \cdot U$ (controlling correlations)

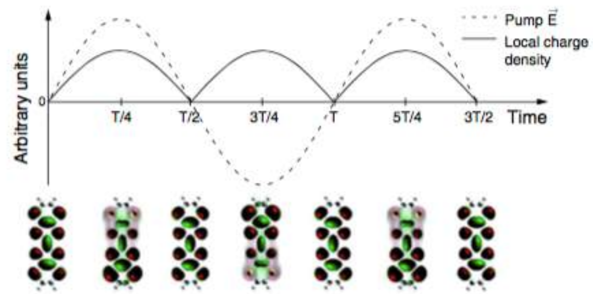
Modulation of U in organics

PRL **115**, 187401 (2015) PHYSICAL REVIEW LETTERS week ending 30 OCTOBER 2015

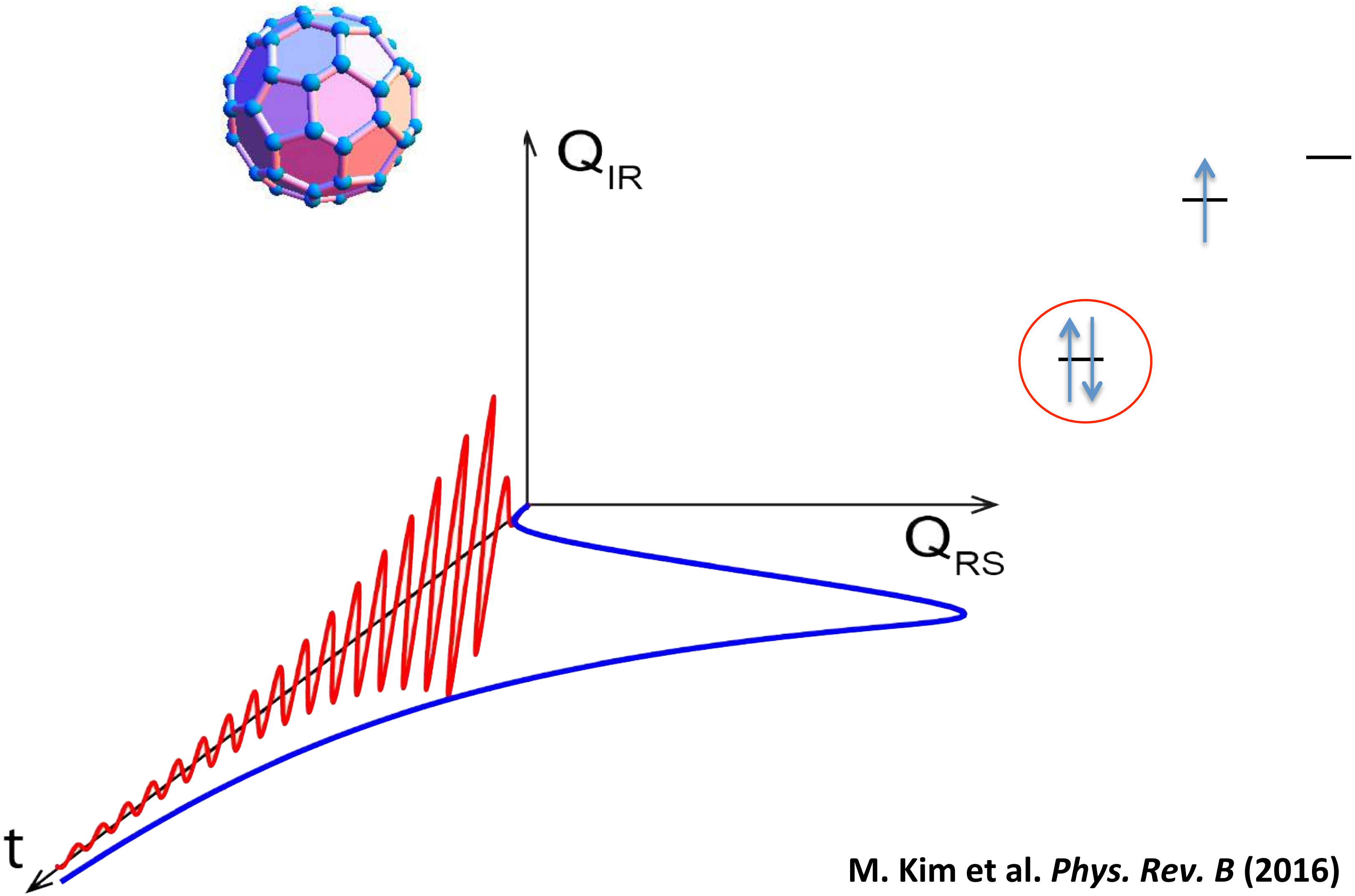
THz-Frequency Modulation of the Hubbard *U* in an Organic Mott Insulator

R. Singla,[1,*] G. Cotugno,[1,2] S. Kaiser,[1,7,8,†] M. Först,[1] M. Mitrano,[1] H. Y. Liu,[1] A. Cartella,[1] C. Manzoni,[1,4] H. Okamoto,[5] T. Hasegawa,[6] S. R. Clark,[2,9] D. Jaksch,[2,3] and A. Cavalleri[1,2,‡]





Nonlinear coupling to correlation energy ?



M. Kim et al. *Phys. Rev. B* (2016)

G. Mazza, A. Georges (2017)

Nonlinear phononic control