Photo-induced Superconductivity

and all that…

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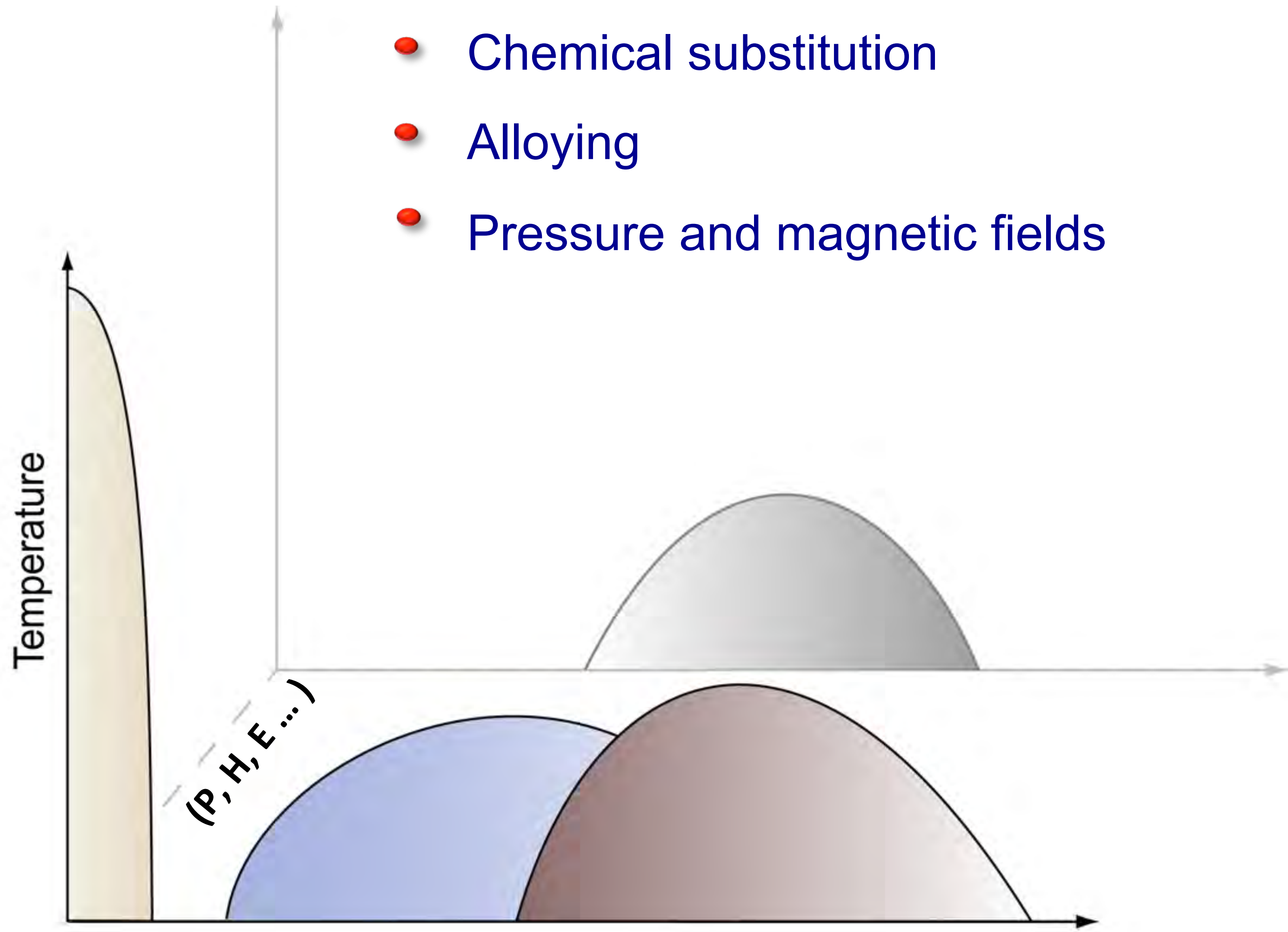
Materials control: conventional routes

- Chemical substitution
- Alloying
- Pressure and magnetic fields

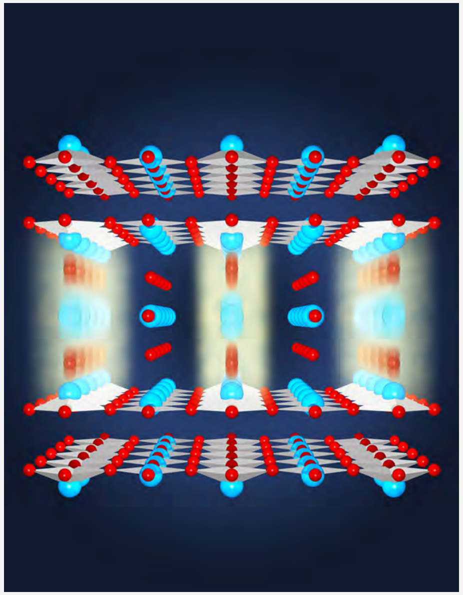


Chemical doping

Driven Systems

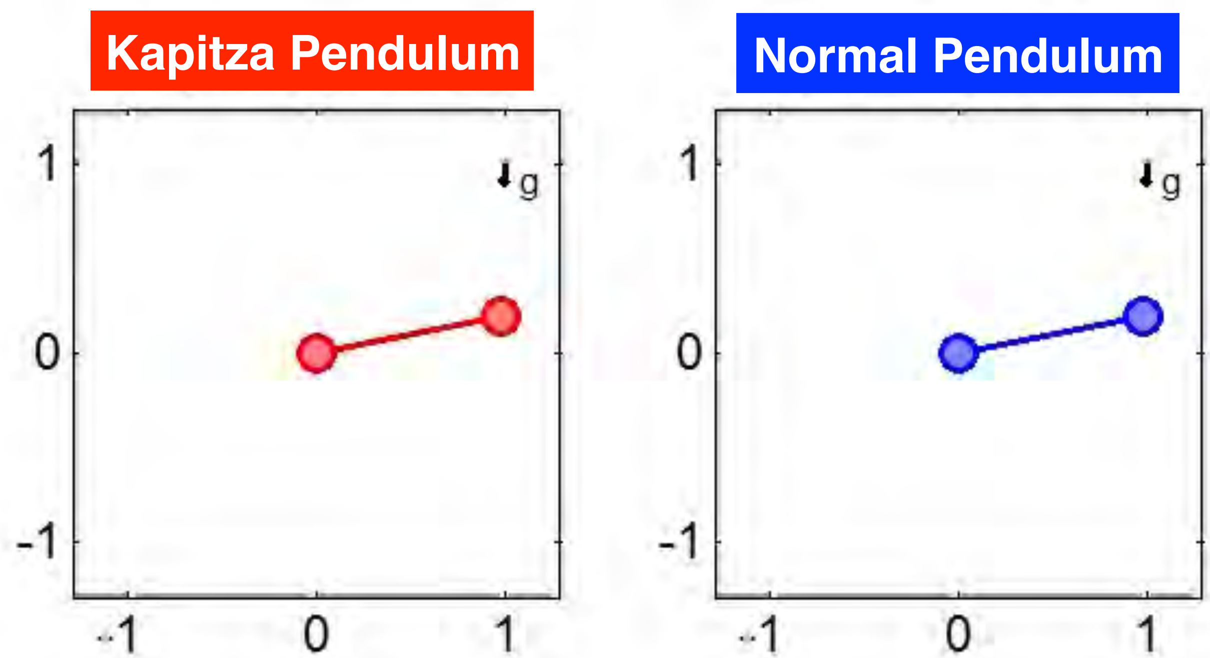
Driven solids are different

Dynamical modulation can create effective energy landscapes and new functionalities in quantum solids



Driven Systems: New Energy Landscapes

Take a pendulum and vibrate its pivot point:



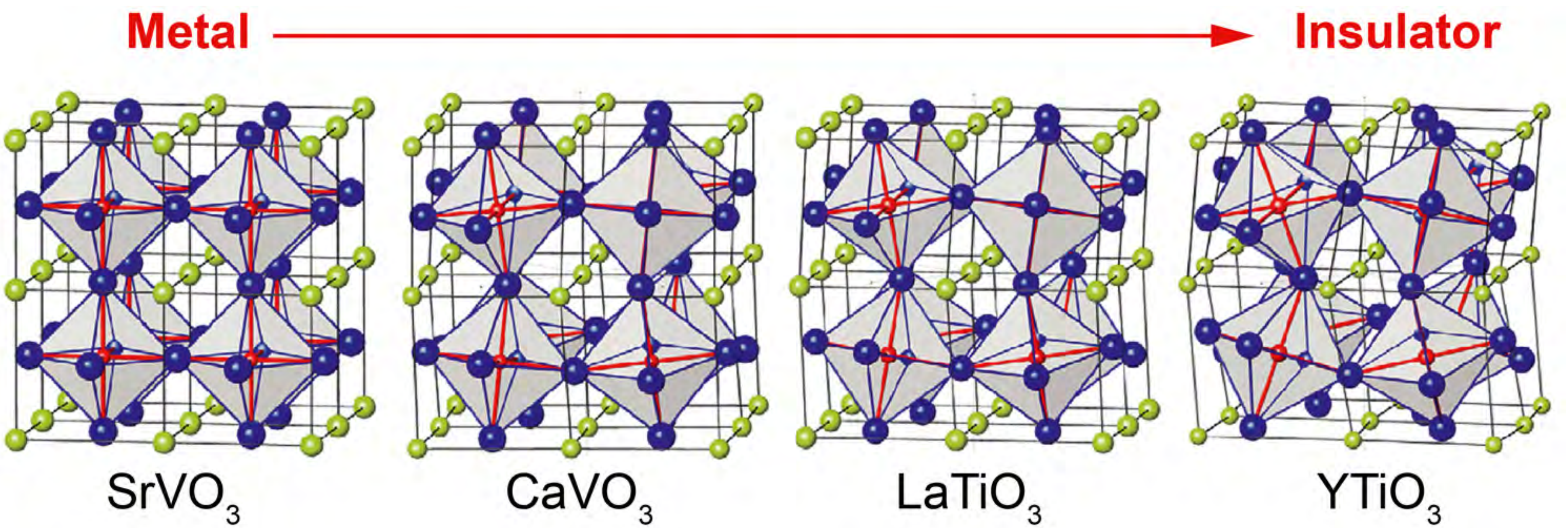
P.L. Kapitza, "Dynamic stability of a pendulum with an oscillating point of suspension,"
Zh. Eksp. Teor. Fiz. **21, 588 (1951)**

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

Driven Systems: New Energy Landscapes

Take a saddle and spin it:

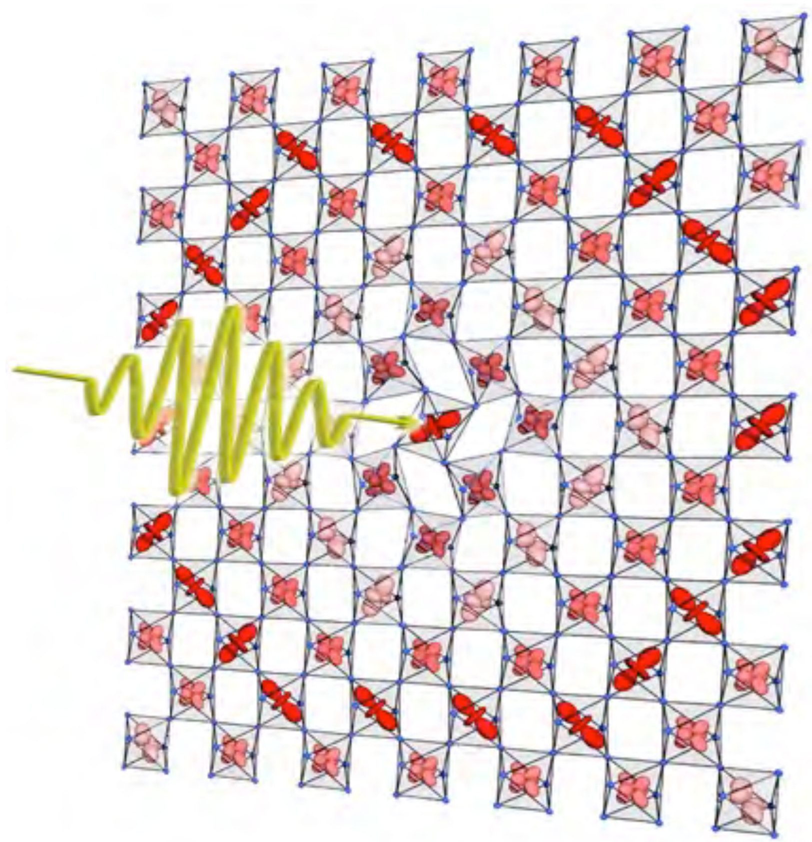
Structure-function in solids



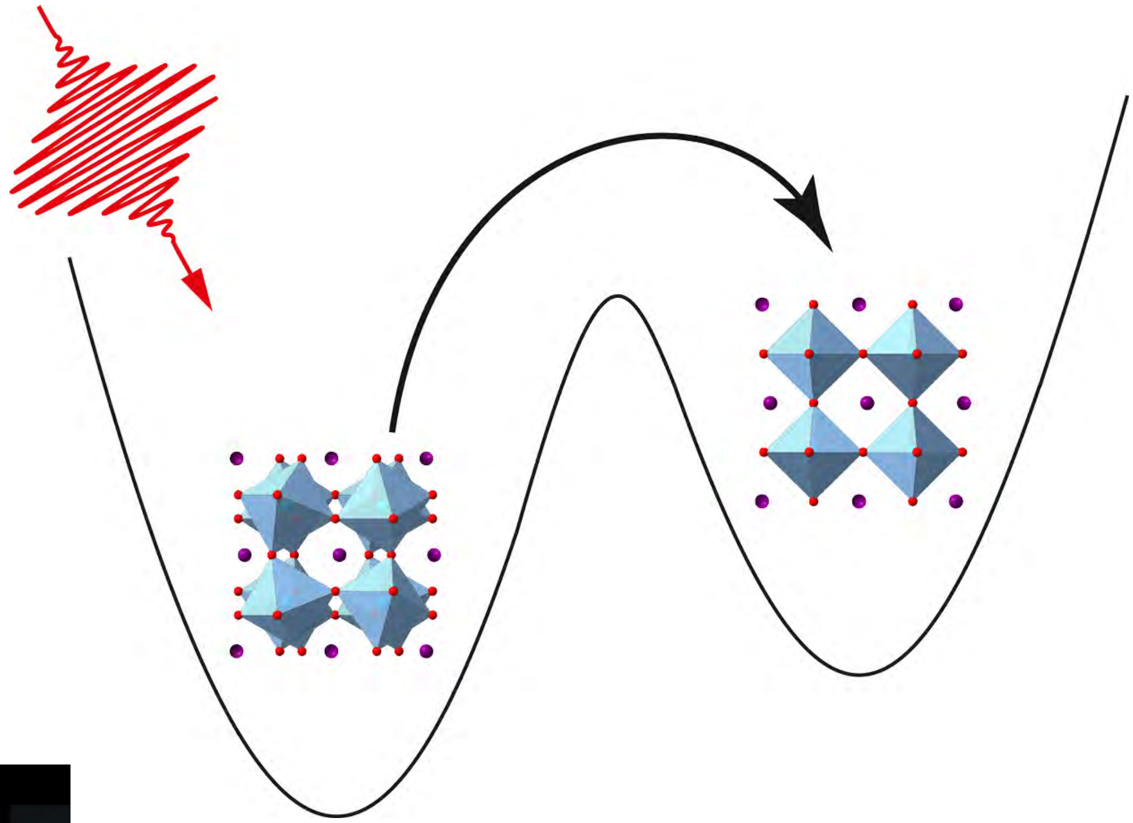
Resonant excitation of the lattice

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

Displacements ~ 1-10 %



Can I dynamically stabilize new lattice structures?

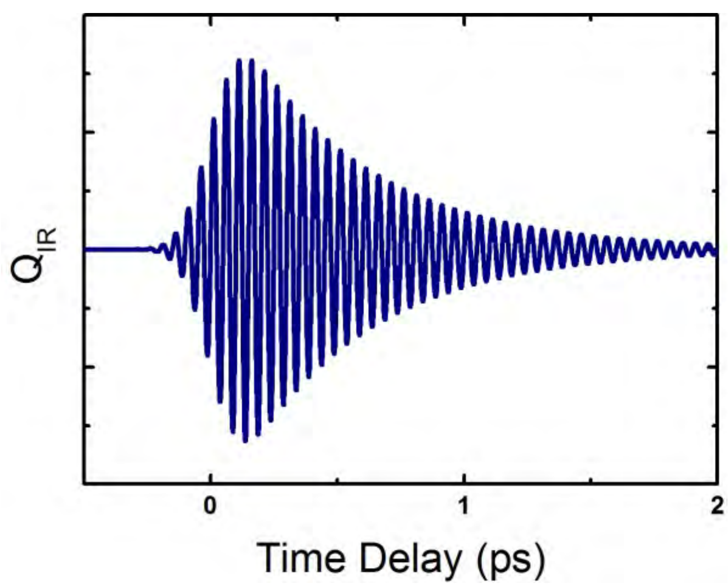


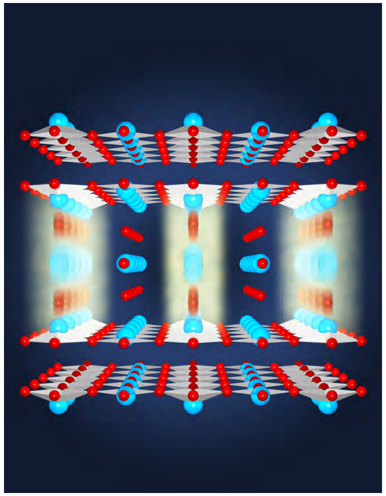
Linear coupling

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

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

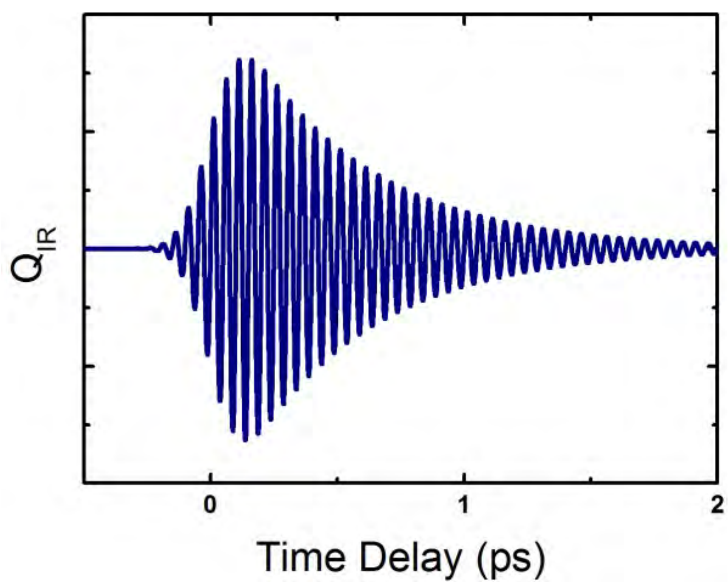
LINEAR - Q_{IR}



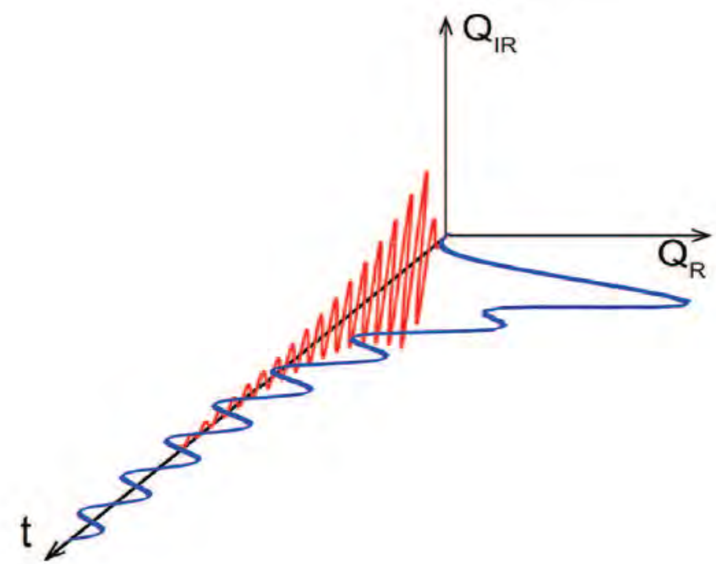


Today's lecture: beyond linear coupling

LINEAR - Q_{IR}



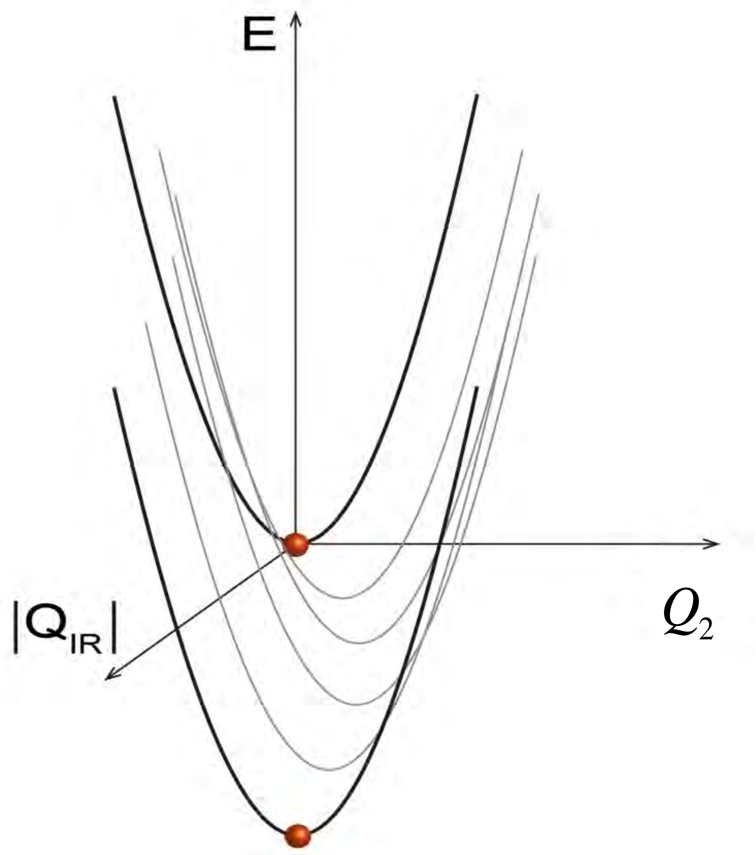
NONLINEAR – Q_2

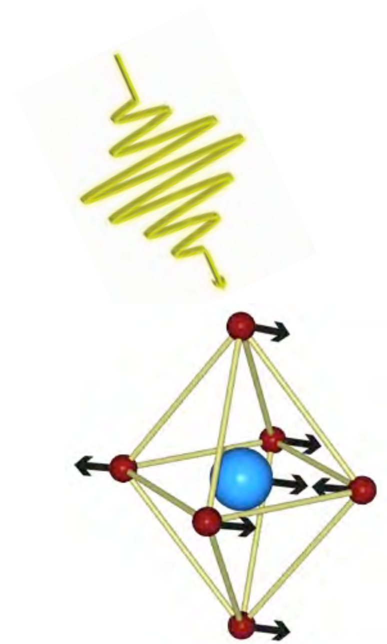


M. Först et al., *Nature Physics* 7, 854 (2011)

Lowest order non-linear coupling

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

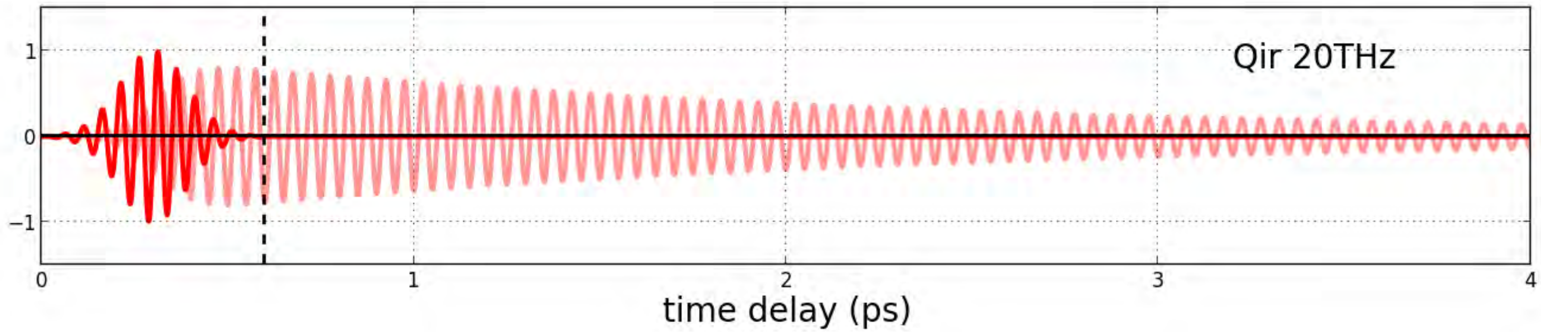




Equations of motion: oscillations in Q_{IR}

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

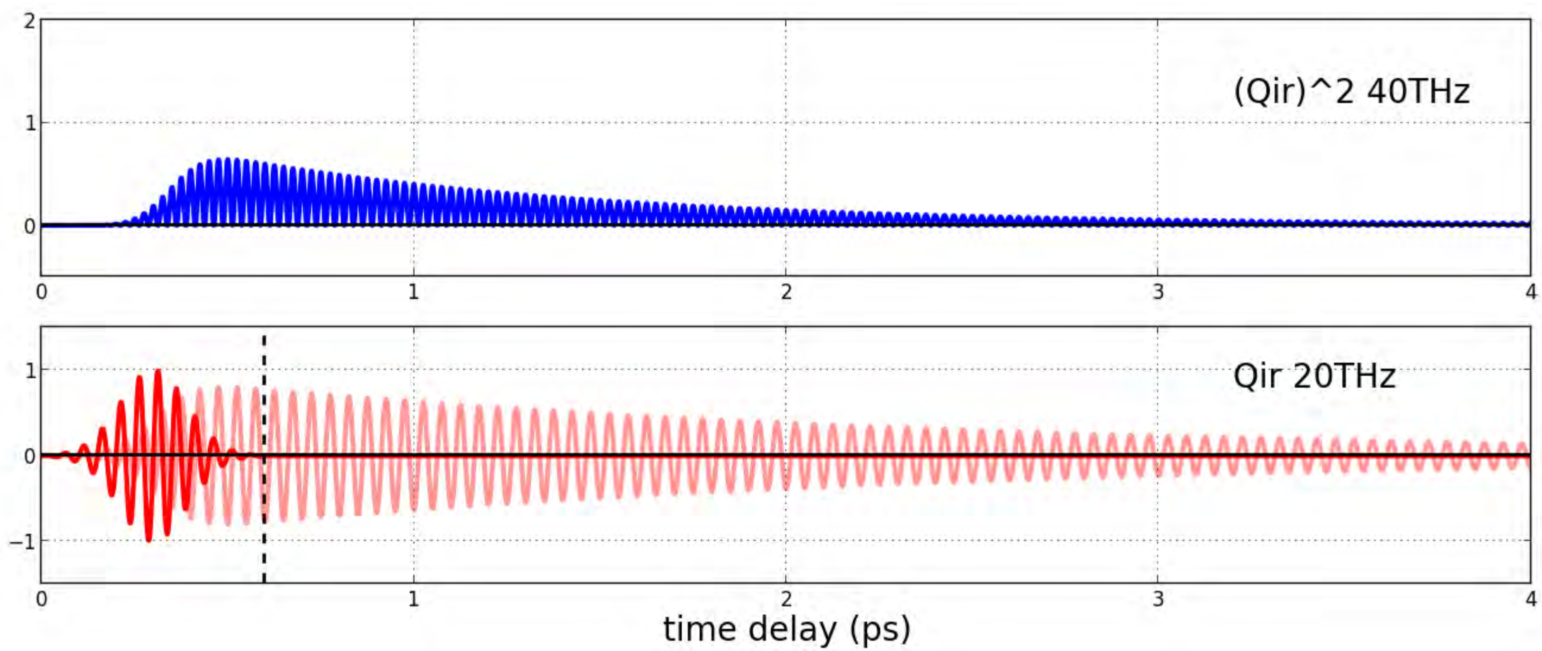
harmonic oscillator   Laser field



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

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

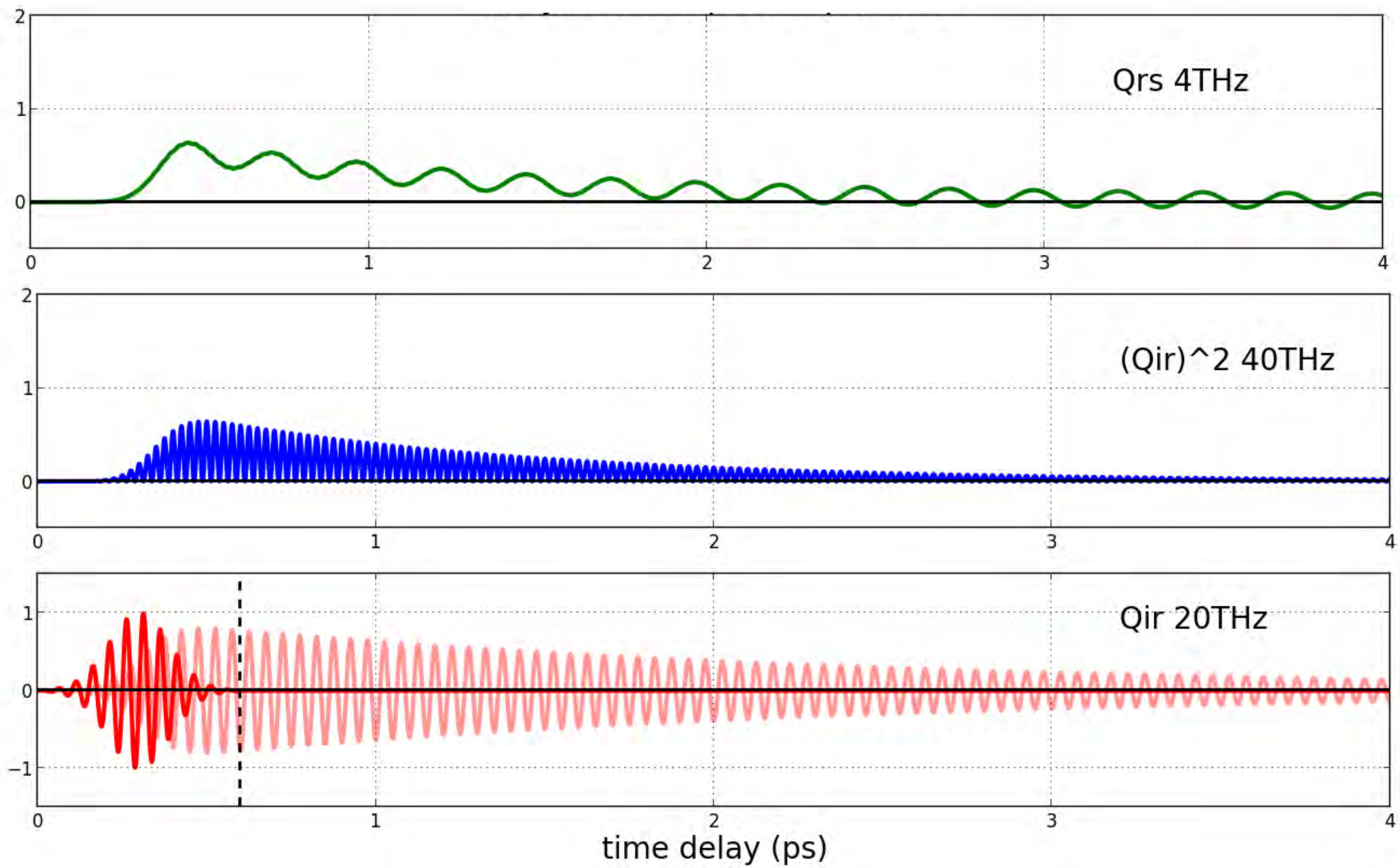
$$(\ddot{Q}_2 + \gamma\dot{Q}_2 + \omega_2^2 Q_2) = \boxed{BQ_{IR}^2}$$



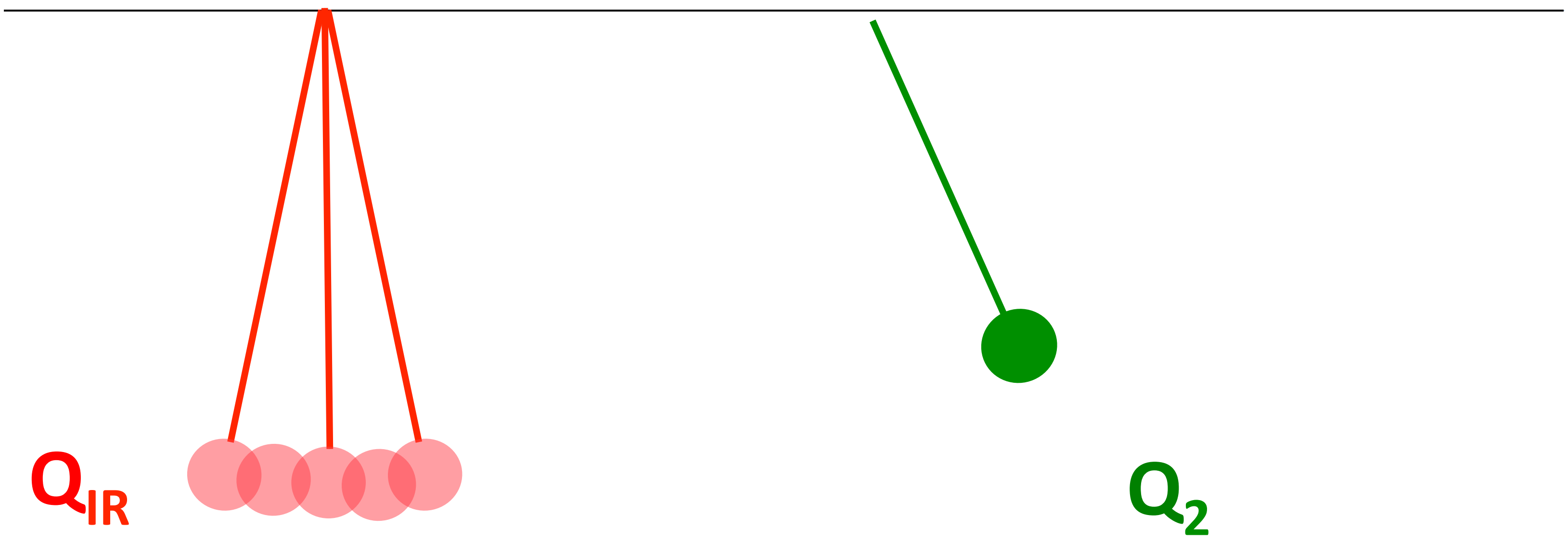
Oscillations in Q_{IR} displace Q_2

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

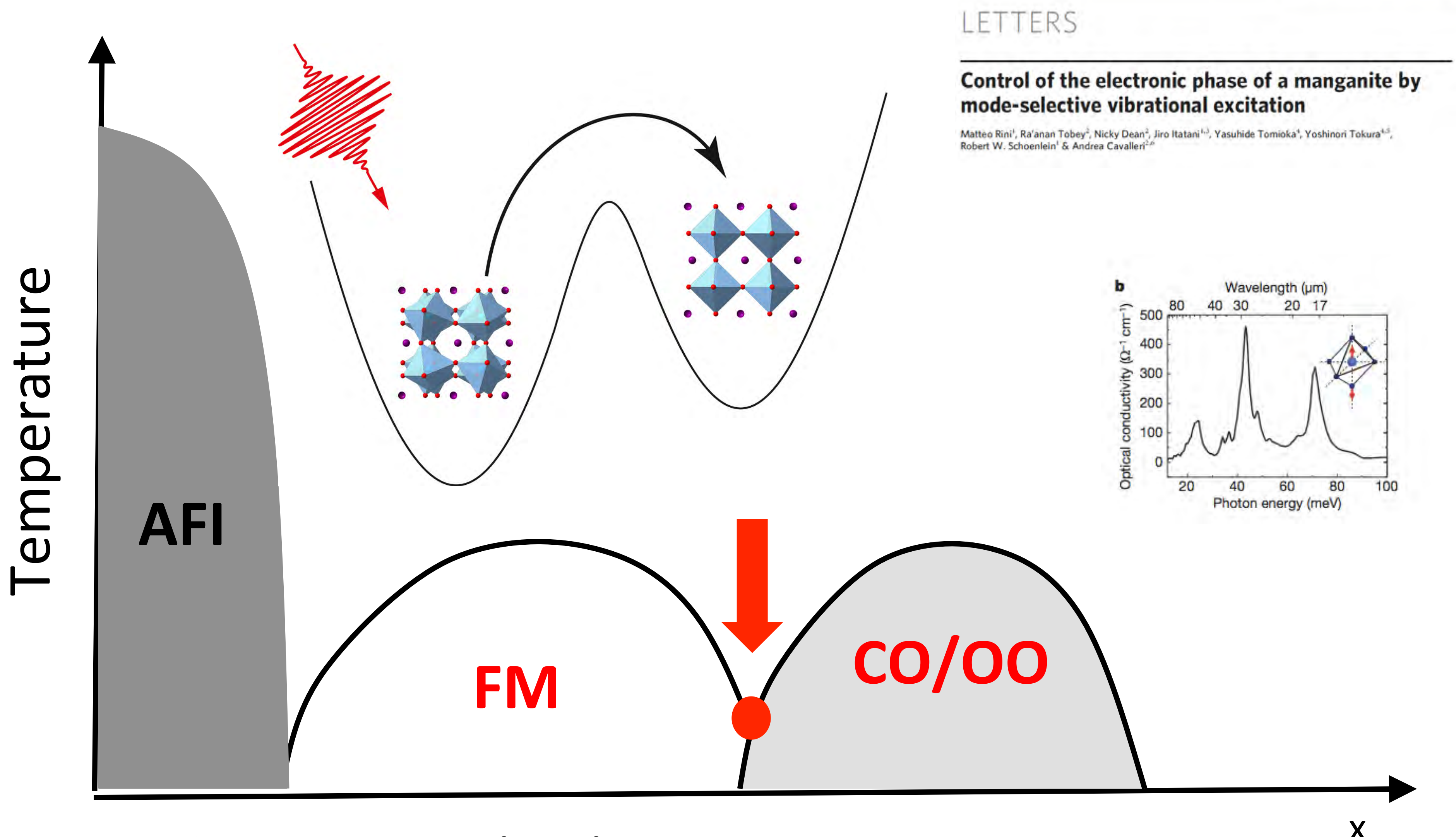
$$(\ddot{Q}_2 + \gamma\dot{Q}_2 + \omega_2^2 Q_2) = BQ_{IR}^2$$



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



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

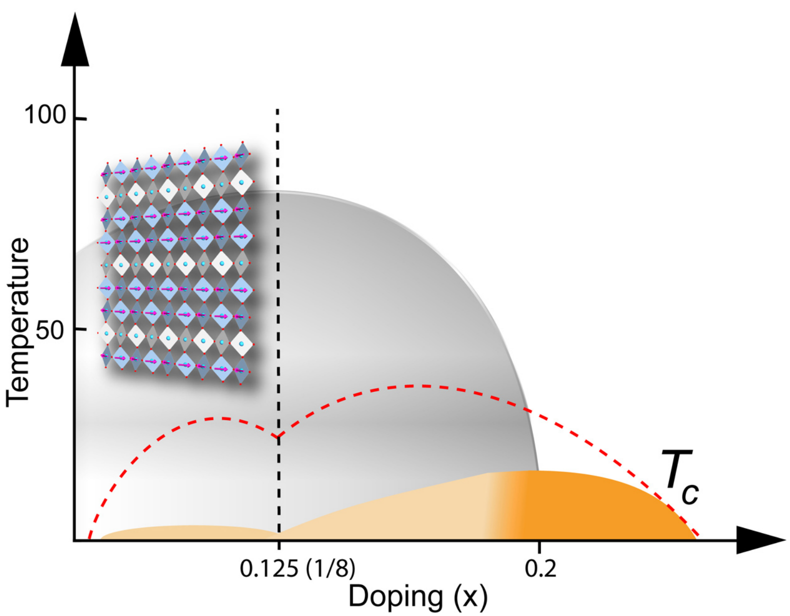


M. Rini et al., Nature 449, 72 (2007)

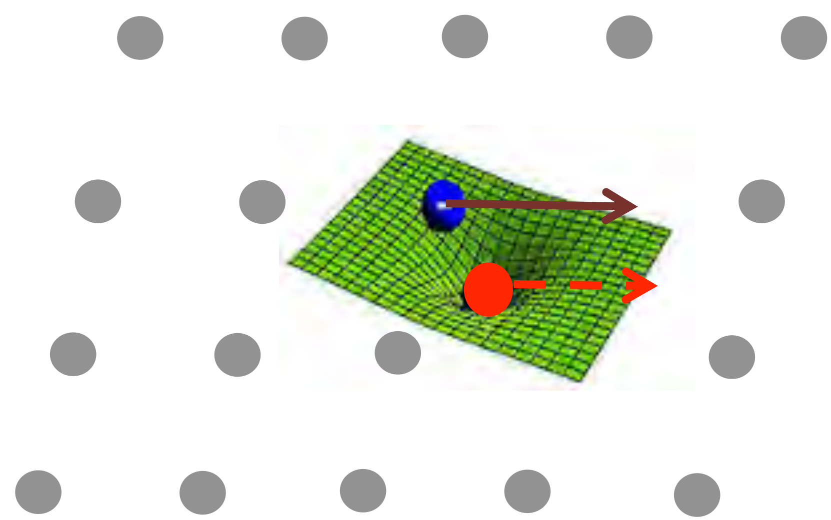
A. Subedi, A. Cavalleri, A. Georges *Phys. Rev B* 89, 330301 (2014)

Controlling Superconductivity

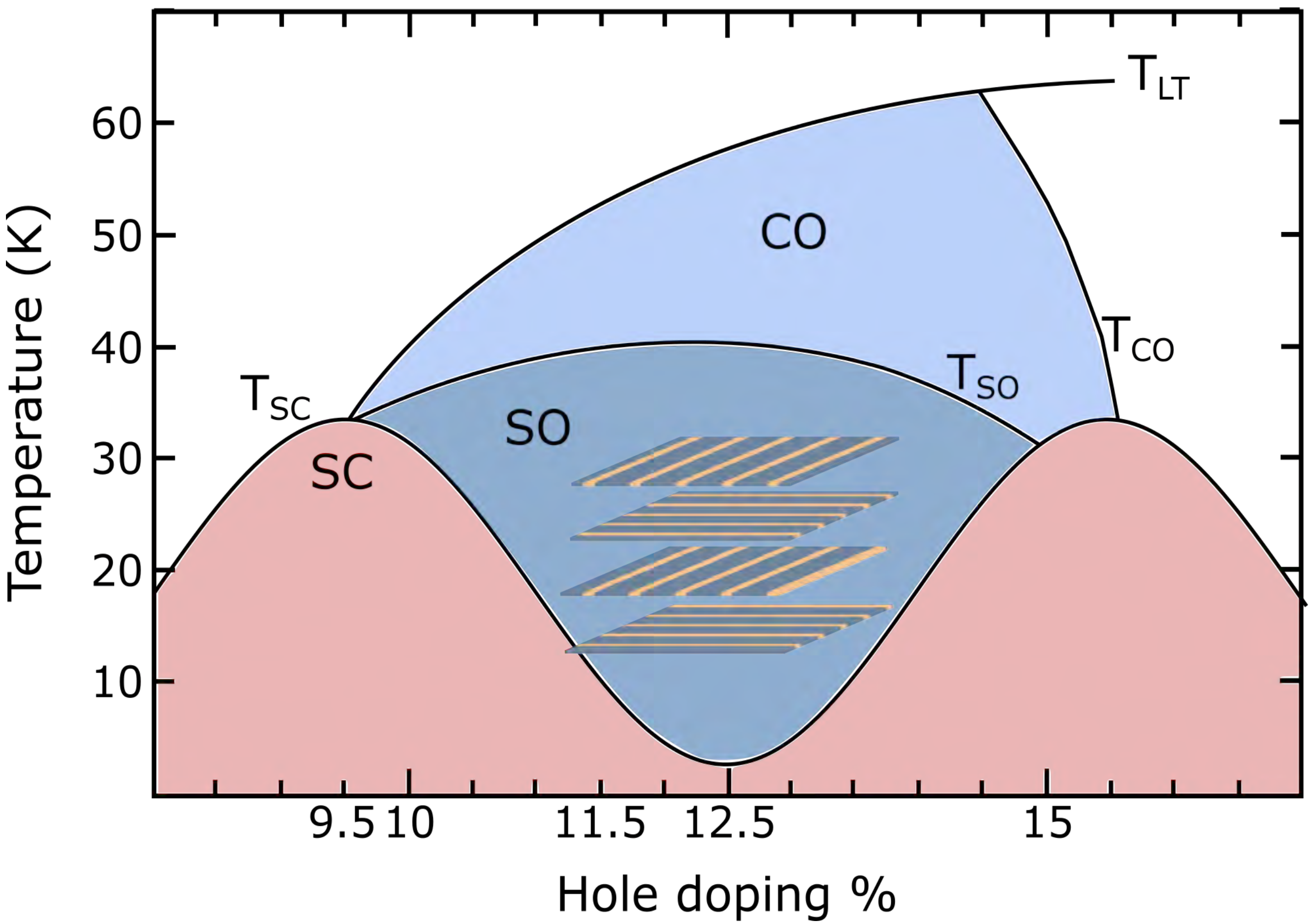
Lattice distortions may quench SC

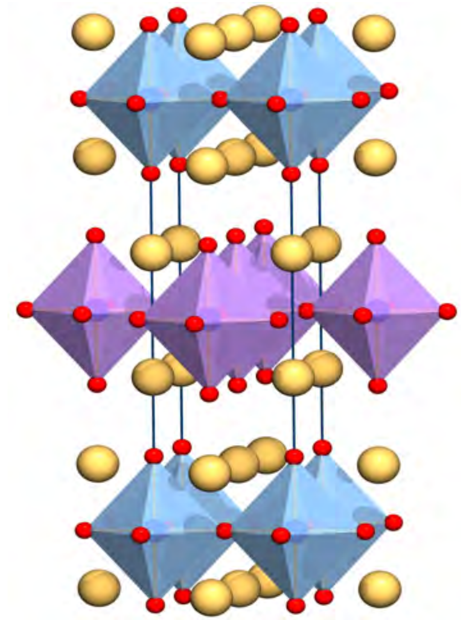


Lattice distortions may promote SC



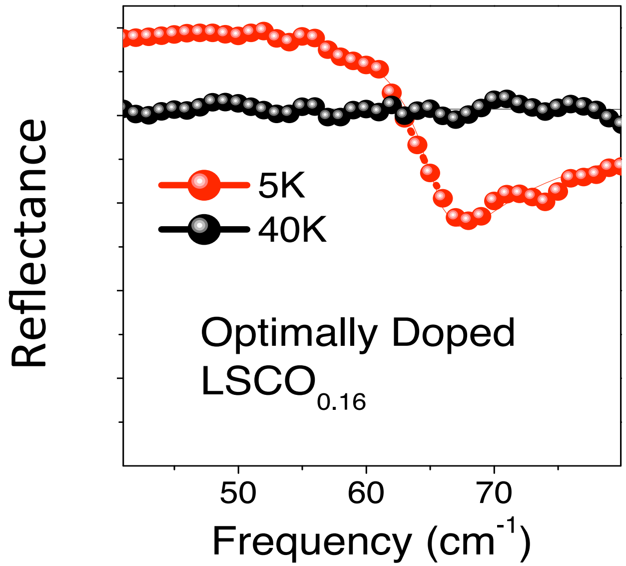
Cuprate superconductors: competing orders and hidden phases

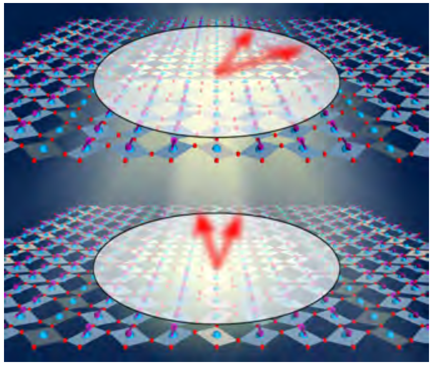




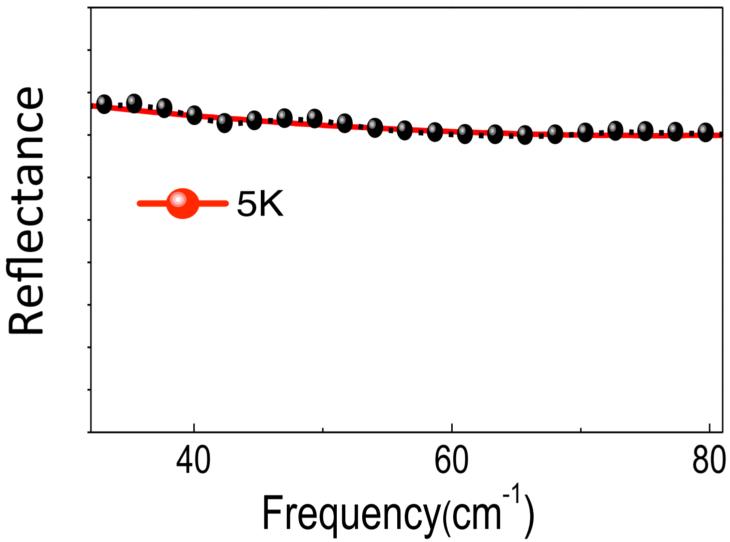
Stripes: Frustrated Interlayer tunnelling

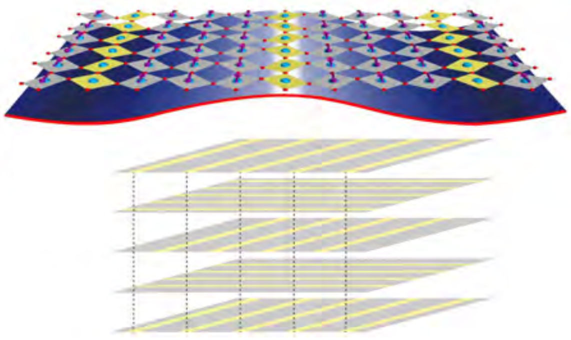
Cooling: $La_{1.84}Sr_{0.16}CuO_4$



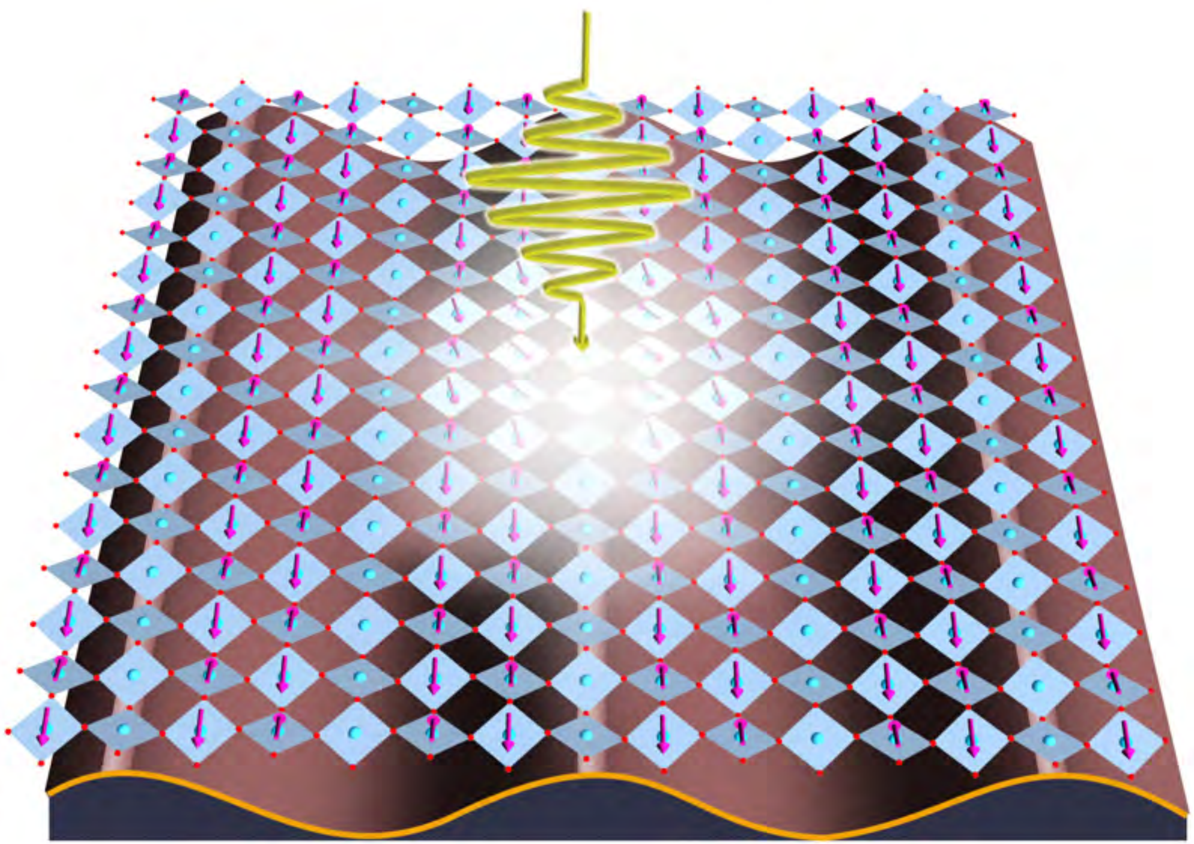


Cooling: $La_{1.675}Eu_{0.2}Sr_{0.125}CuO_4$





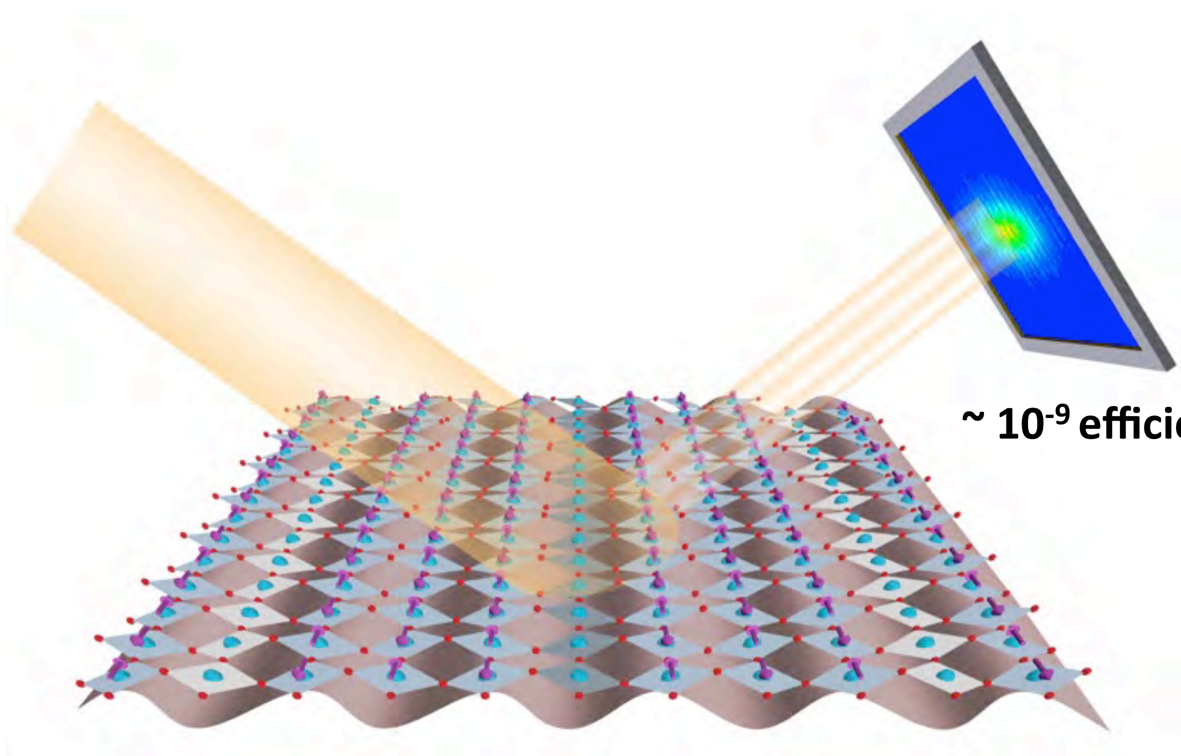
First step: Melt Stripes Optically



Seeing Stripes: Resonant Soft X-rays

O Kedge

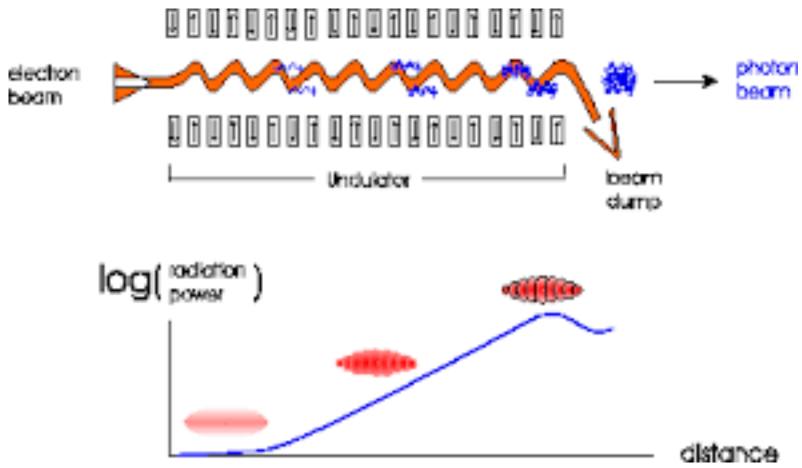
(0.25, 0, 0.65)

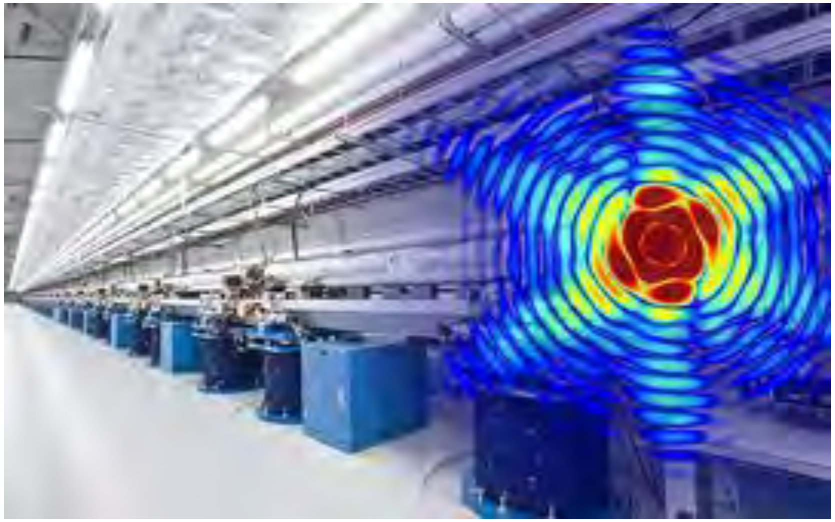


~ 10^{-9} efficiency

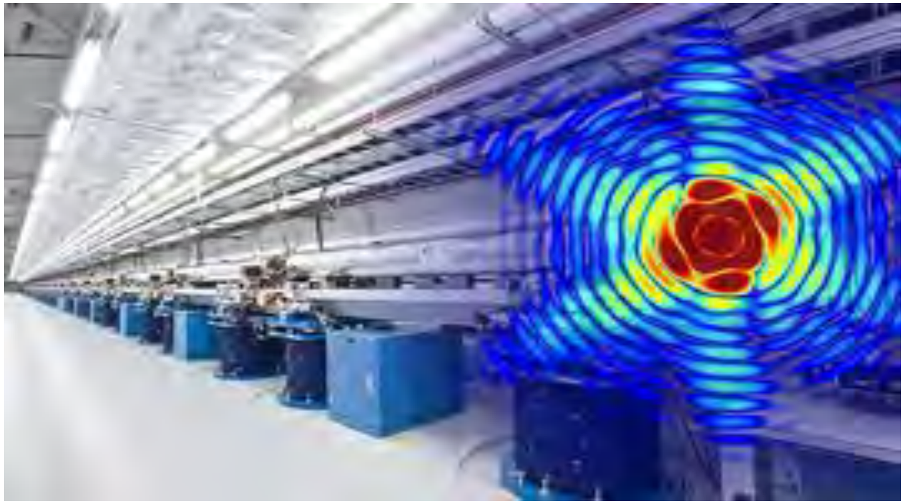
Abbamonte et al *Nature Physics 1, 155* (2005)

Pump probe experiment using X-ray FEL

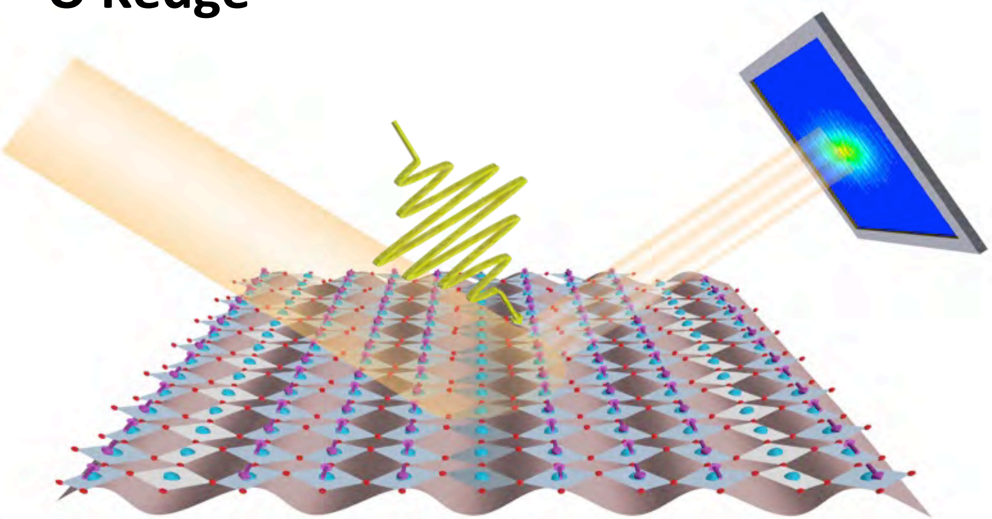




Ultrafast Resonant Soft X-rays

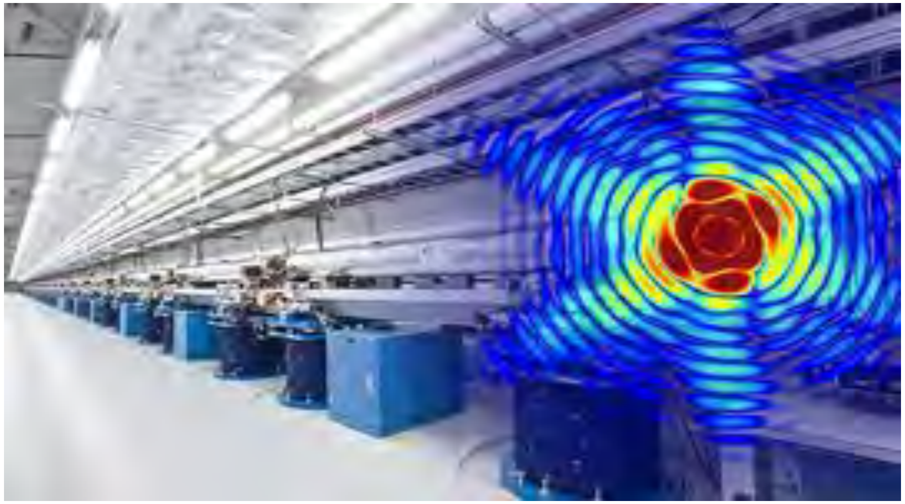


O Kedge **(0.25, 0, 0.65)**



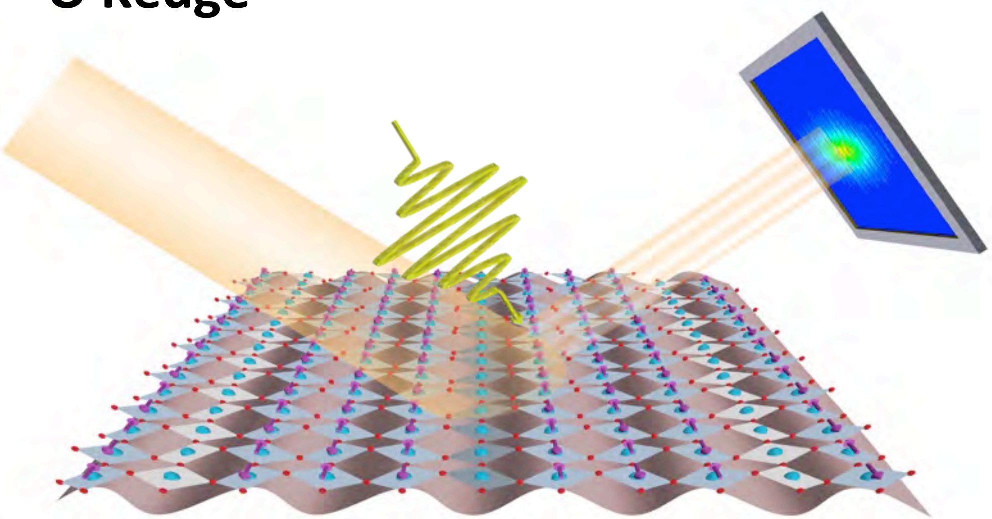
With John Hill, BNL

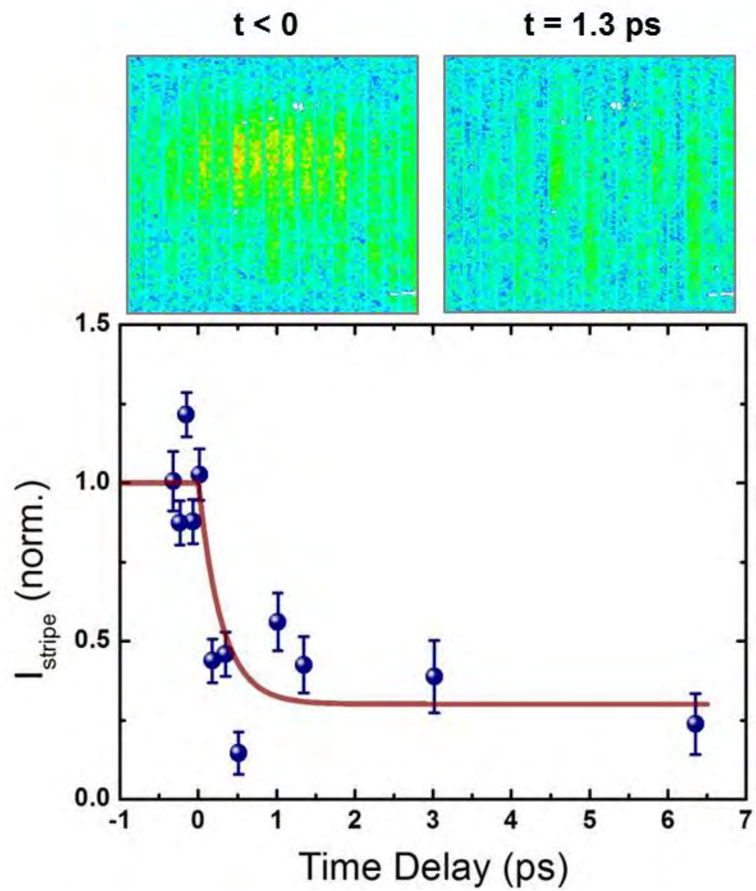
Ultrafast Resonant Soft X-rays



O Kedge

(0.25, 0, 0.65)



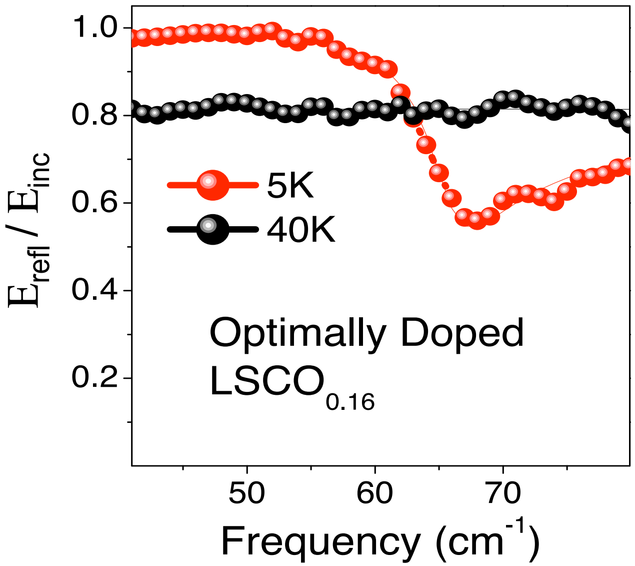


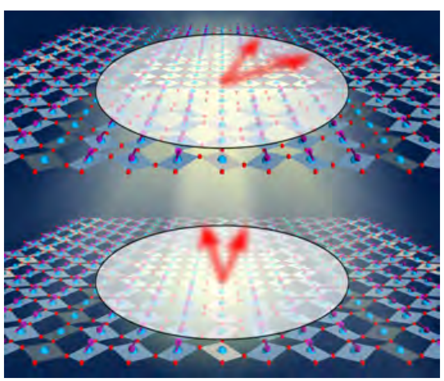
M. Foerst et al., Phys Rev Lett 112, 157002 (2014)

With John Hill, BNL

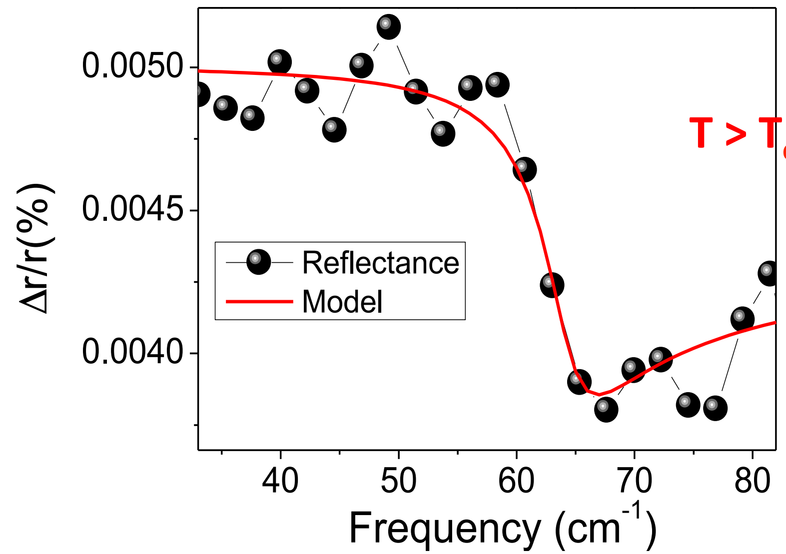
Light Induced "superconductivity"

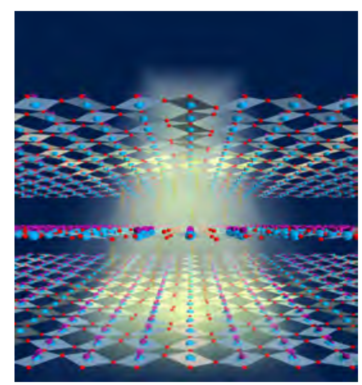
Cooling: $La_{1.84}Sr_{0.16}CuO_4$





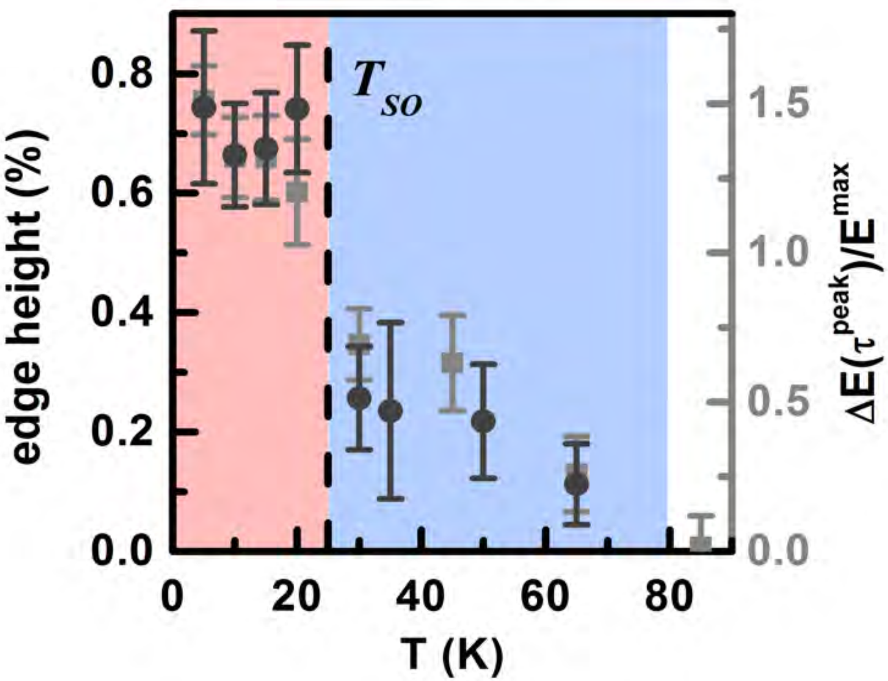
Light: $La_{1.675}Eu_{0.2}Sr_{0.125}CuO_4$

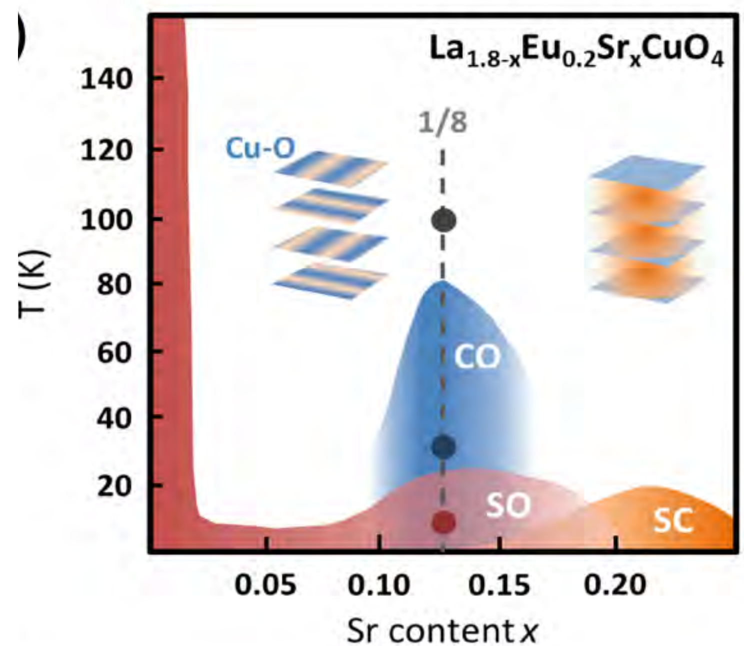




D. Fausti et al., *Science* 331, 6014 (2011)

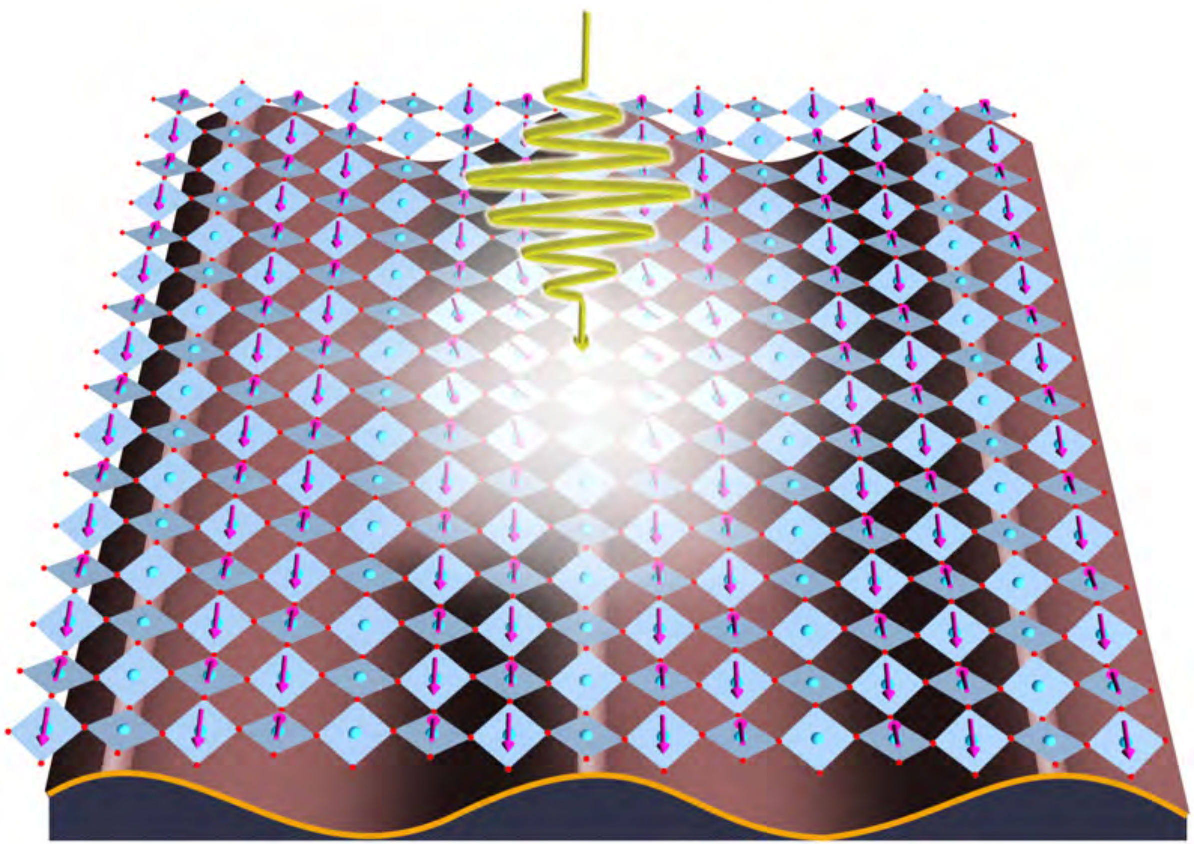
Light Induced "superconductivity" – up to T_{CO} = 80 K



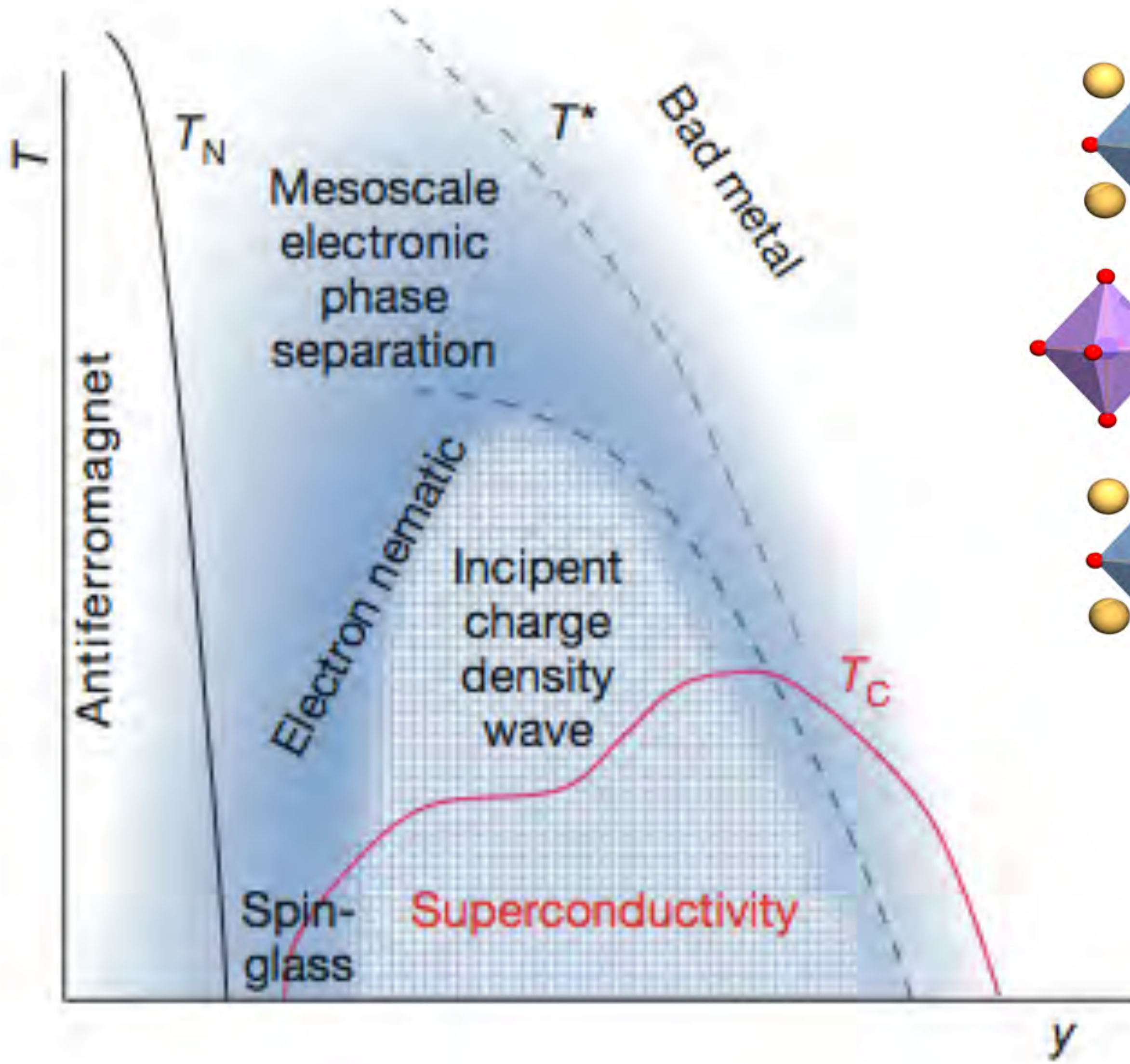


C.R. Hunt et al., Physical Review B 91, 020505(R) (2015)

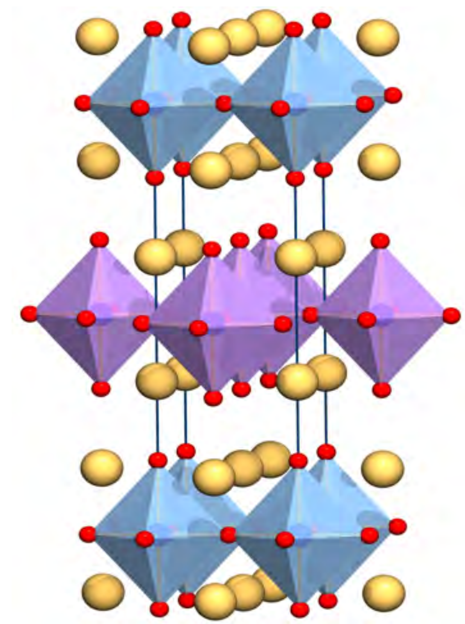
Hypothesis: Melt Stripes Optically



Bi-layer Cuprates: more competing orders and hidden phases

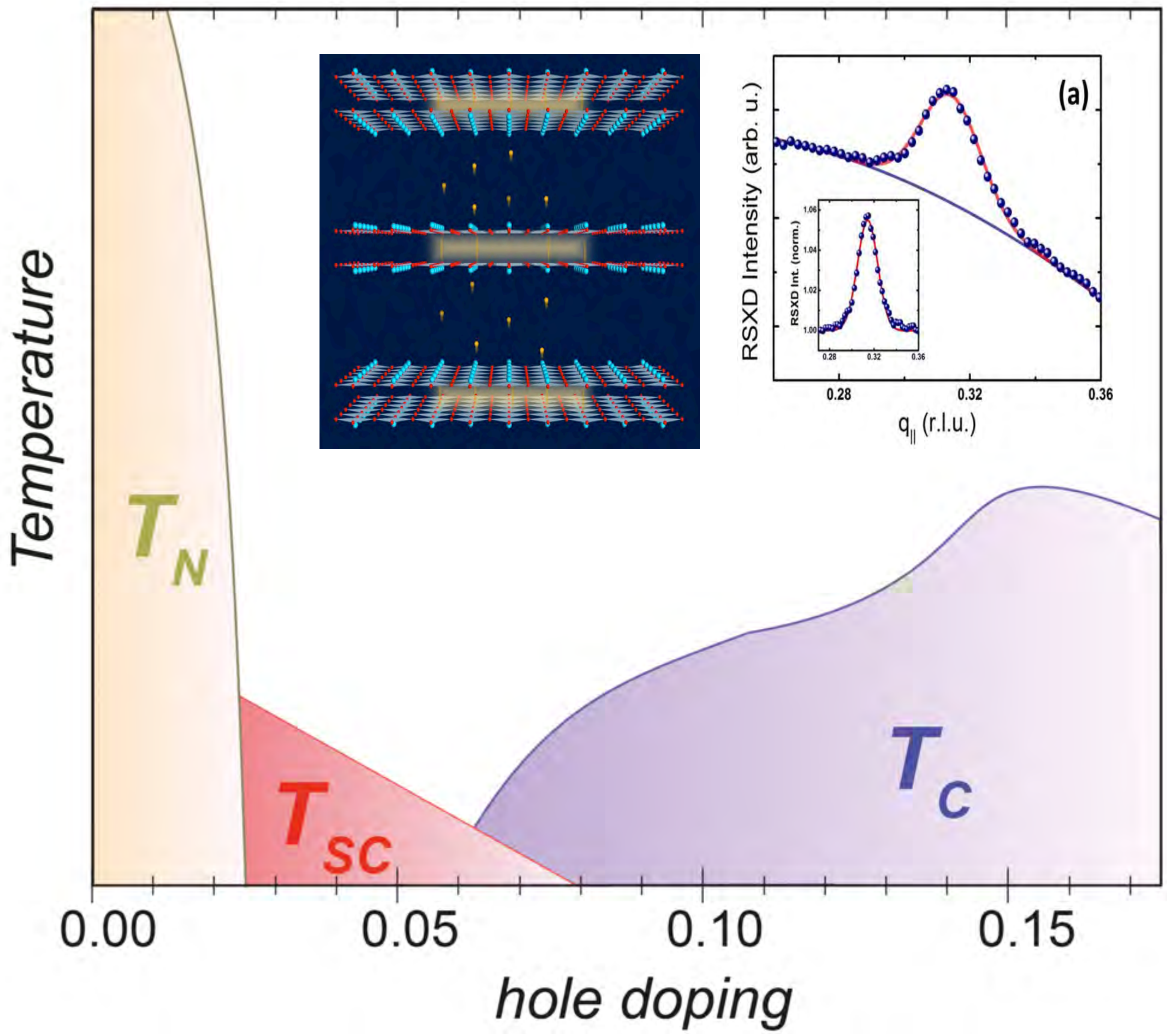


doping



Fradkin and Kivelson, Nature Physcs (2012)

$YBa_2Cu_3O_{6+x}$: Coherence above T_c and a CDW

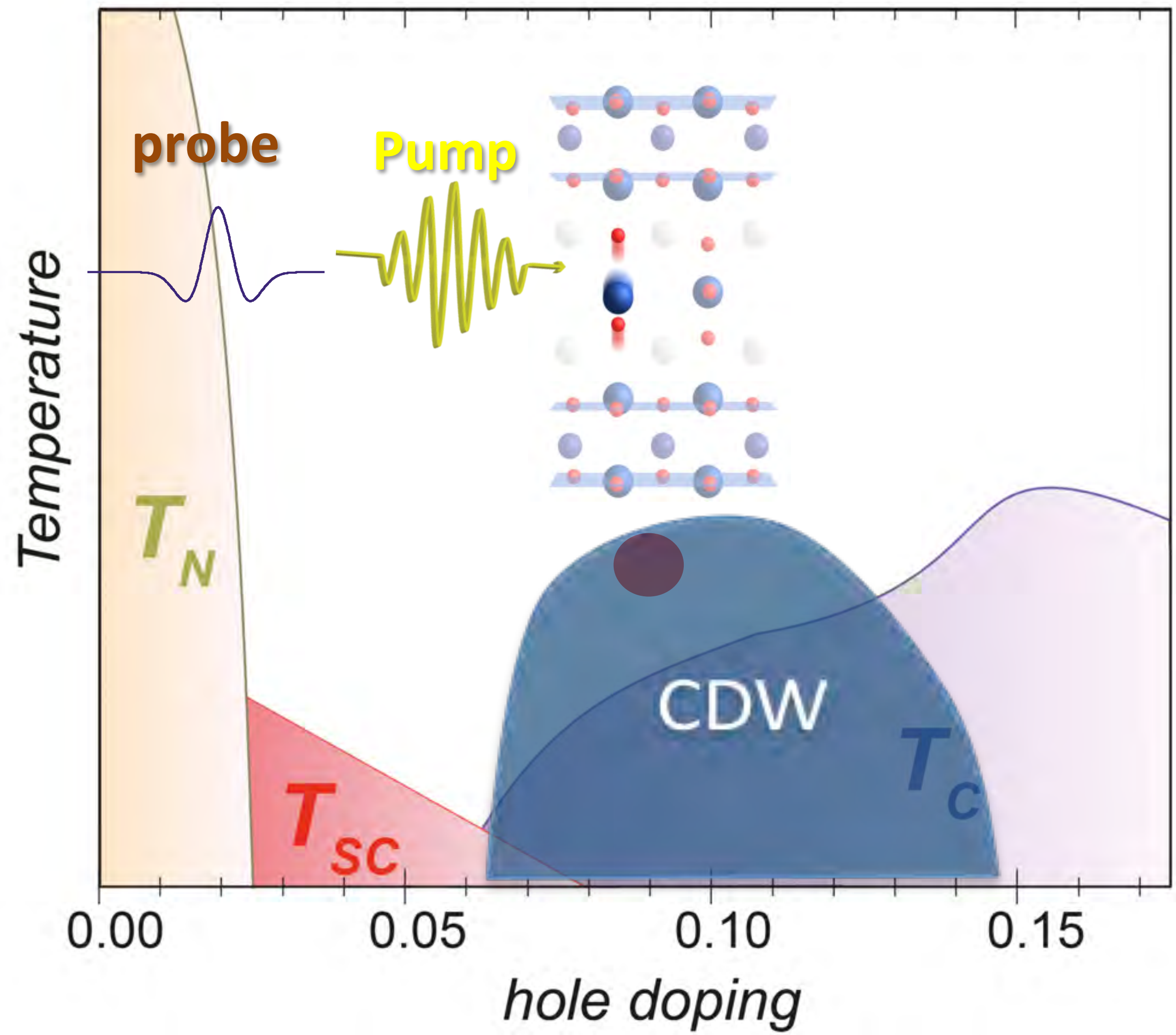


G. Ghiringhelli et al., *Science 337*, 821 (2012)

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

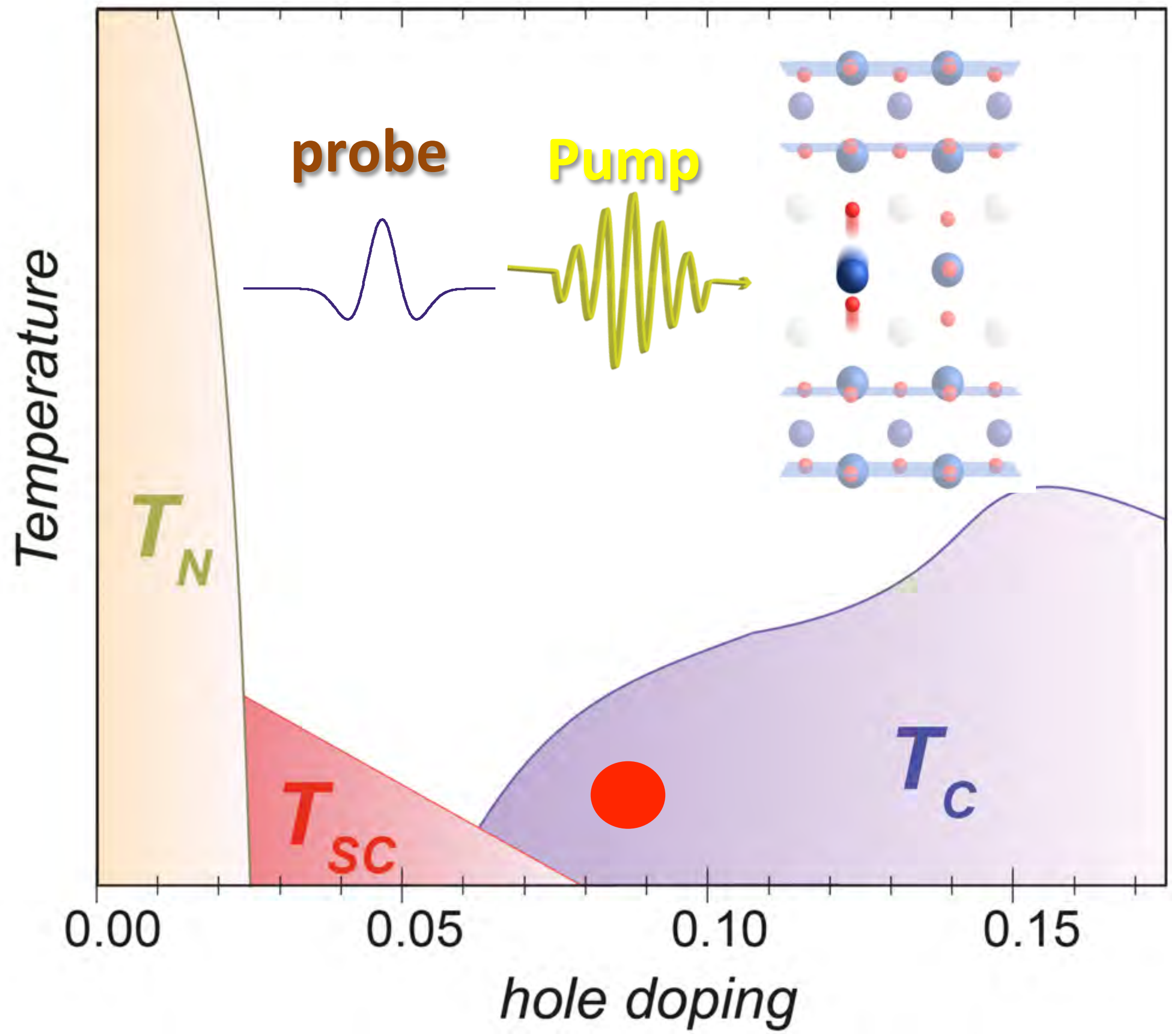
With B. Keimer
MPI Stuttgart

$YBa_2Cu_3O_{6.6}$



probe
Pump
Temperature
T_N
T_{SC}
CDW
T_c
0.00
0.05
0.10
0.15
hole doping

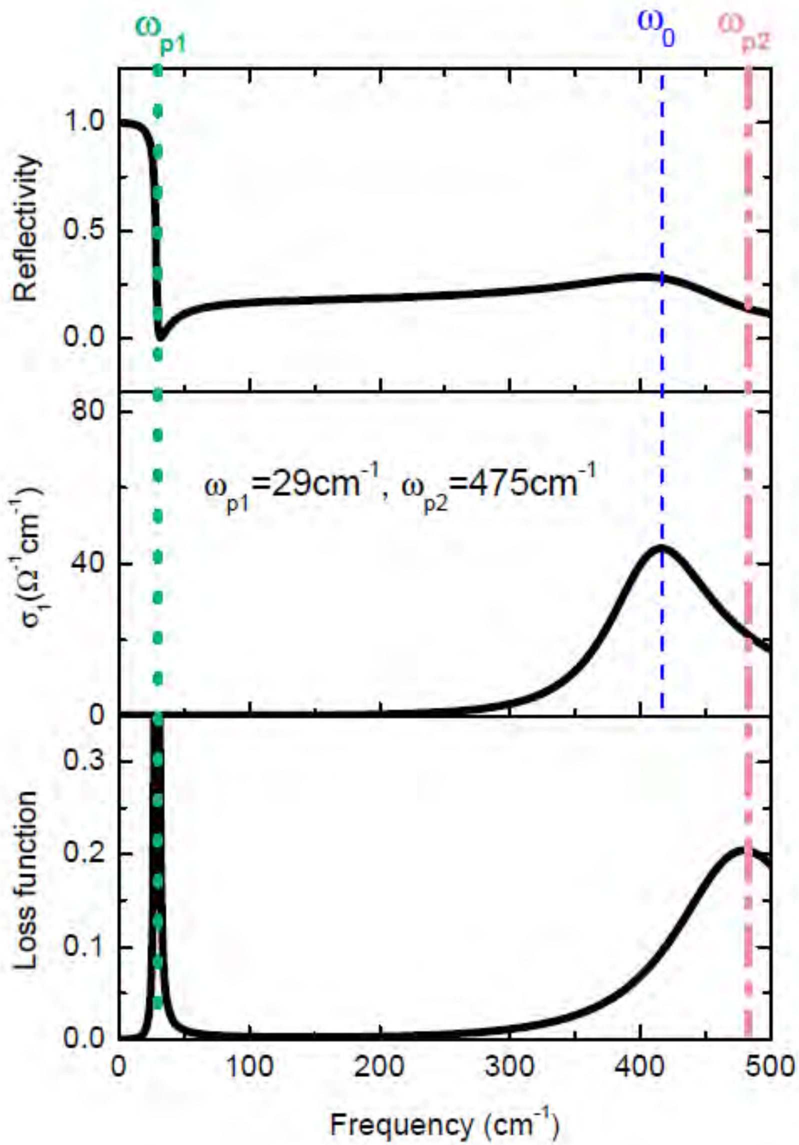
Below T_c

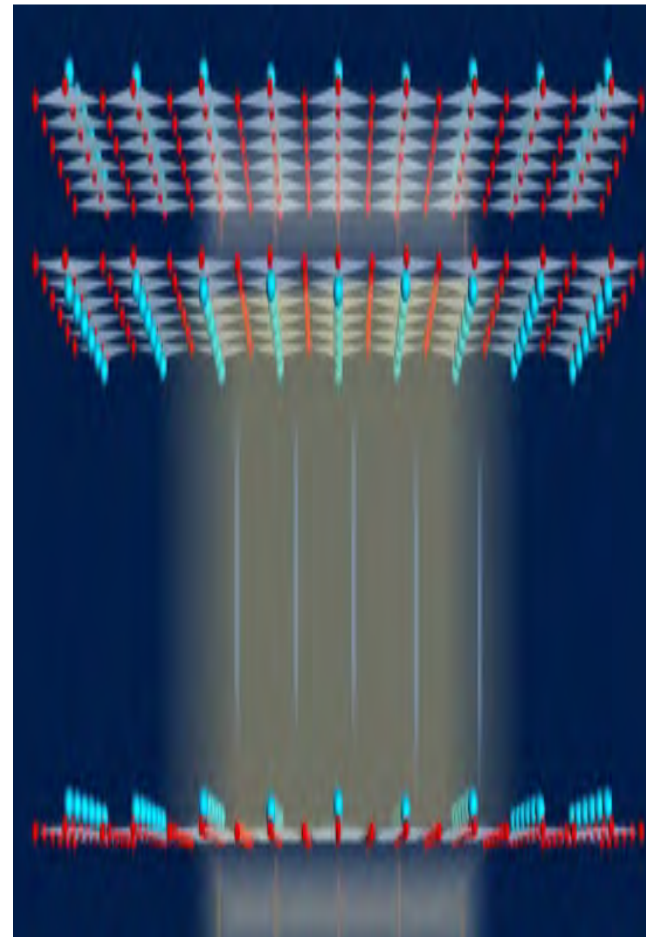


W. Hu et al. *Nature Materials* 13, 705 (2014)

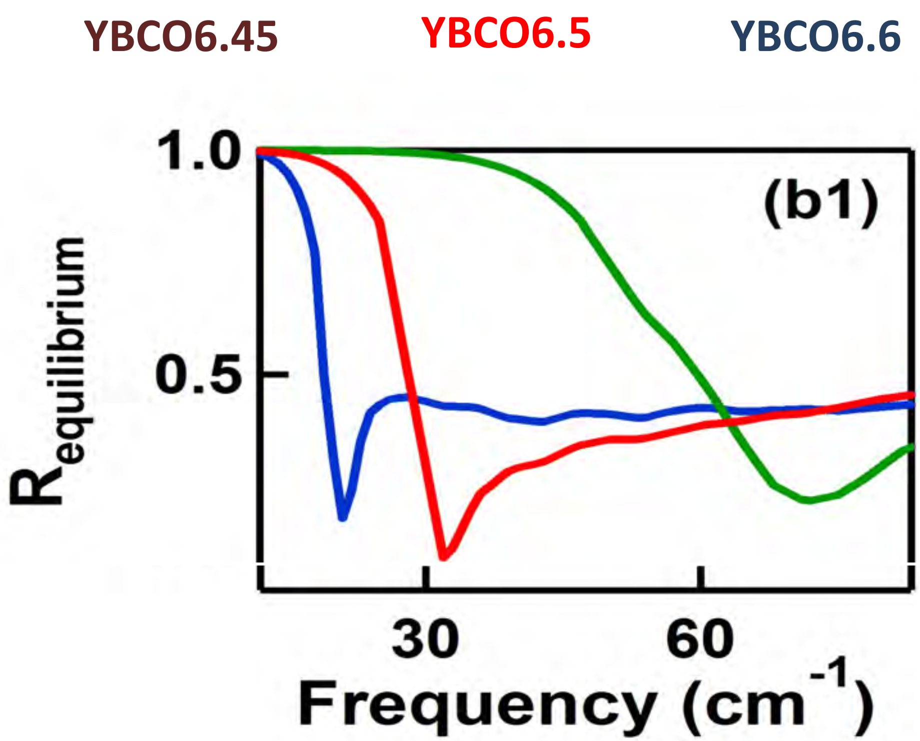
S. Kaiser, D. Nicoletti, C. Hunt et al., *Phys. Rev. B* 89, 184516 (2014)

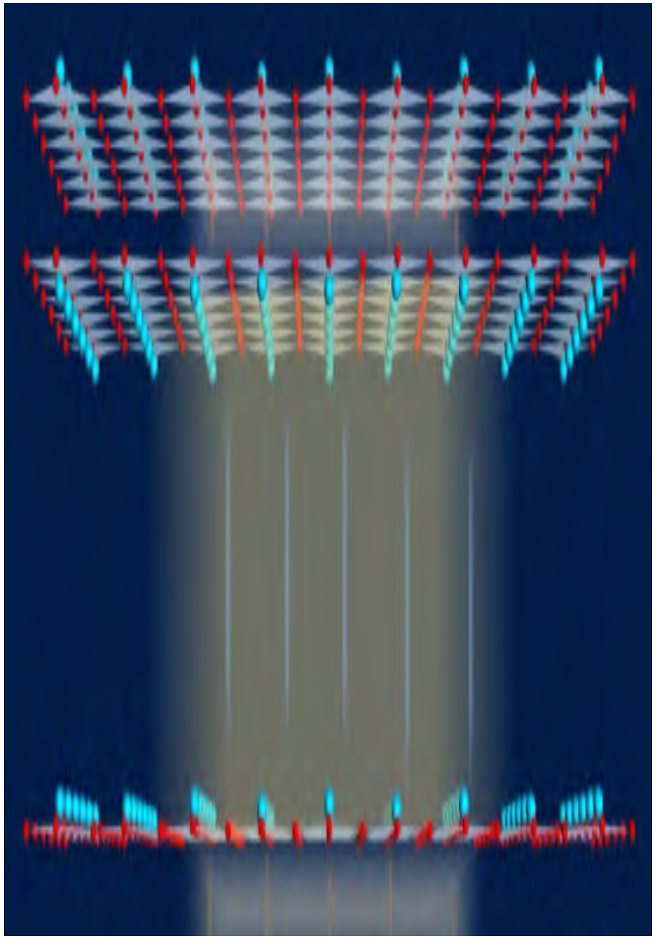
Below Tc: two plasma plasma edges





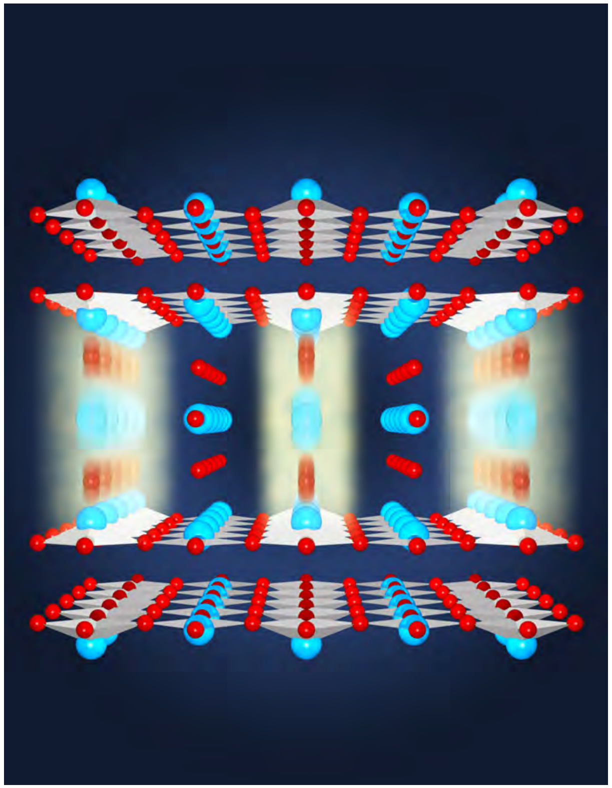
Low frequency inter-bilayer plasma edge

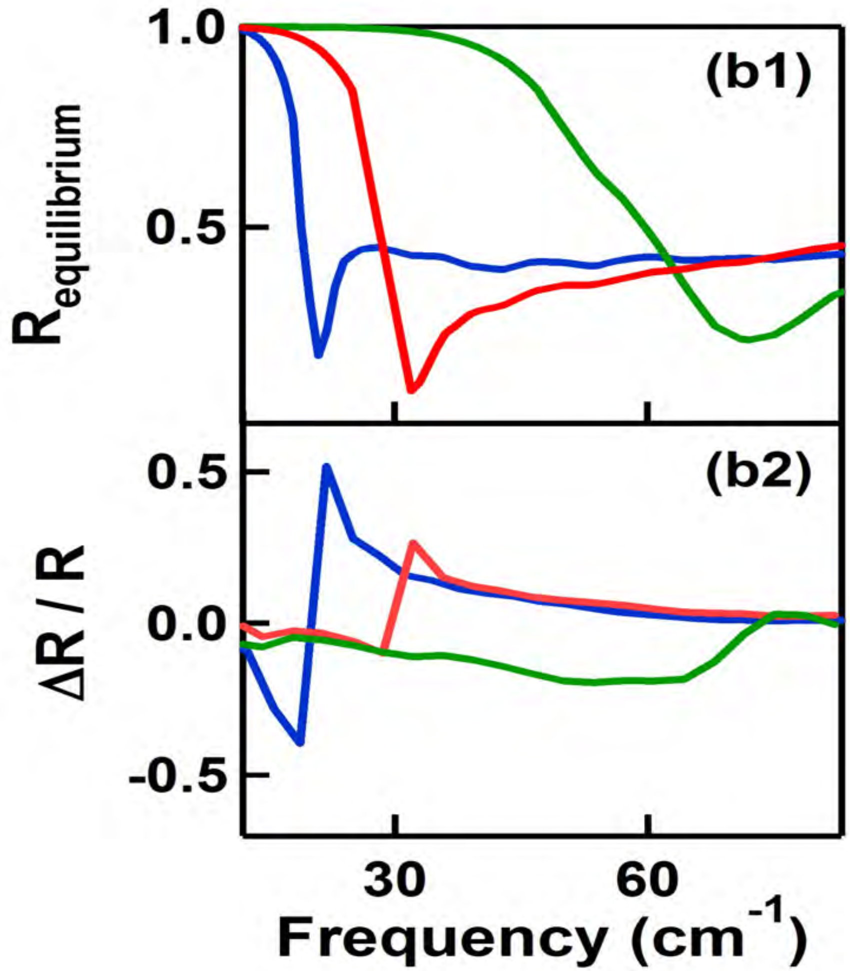




W. Hu et al. *Nature Materials* 13, 705 (2014)

Below Tc: Light-induced blue shift of the edge

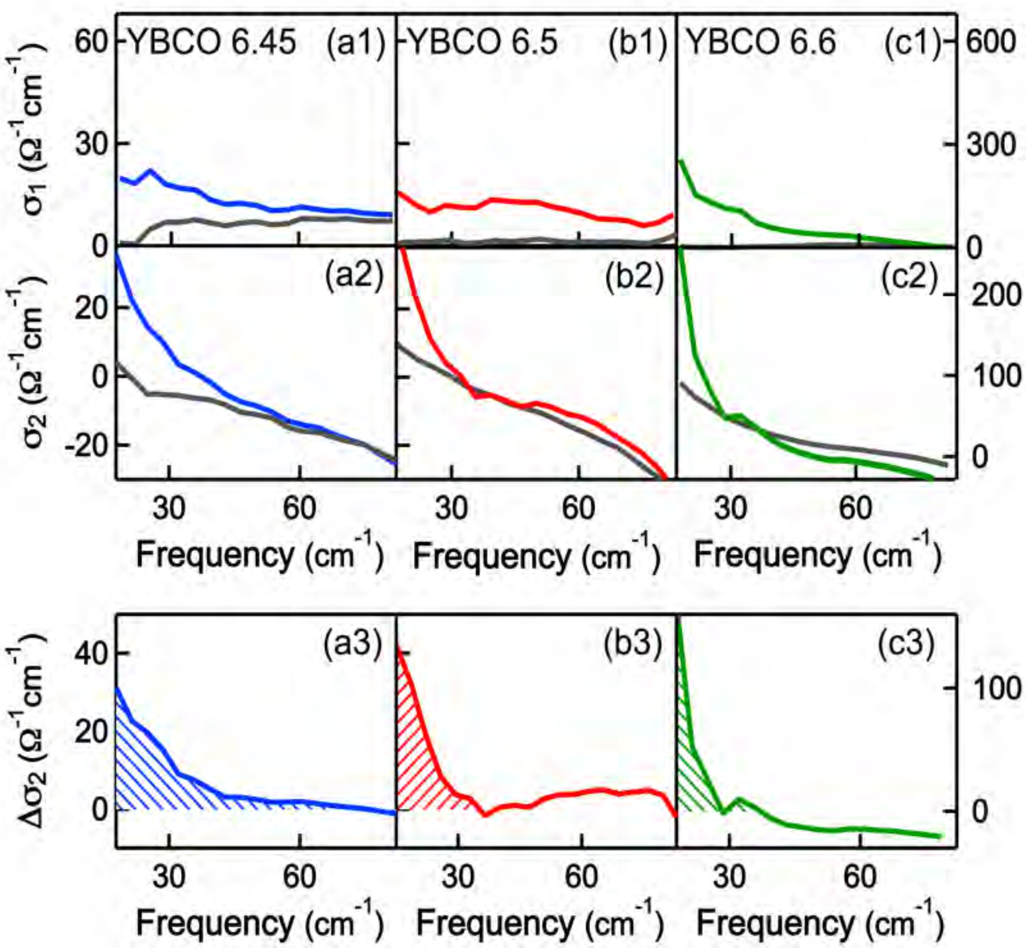




W. Hu et al. *Nature Materials* 13, 705 (2014)

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

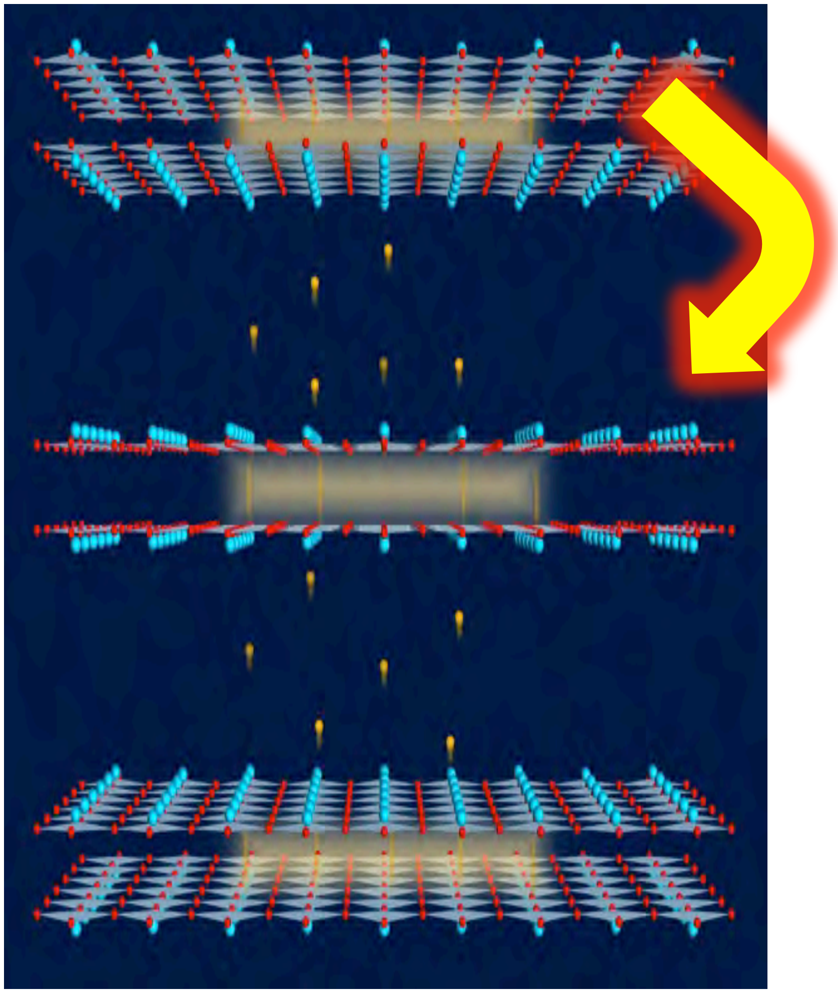
Below T_c: Enhancement of "superconductivity"

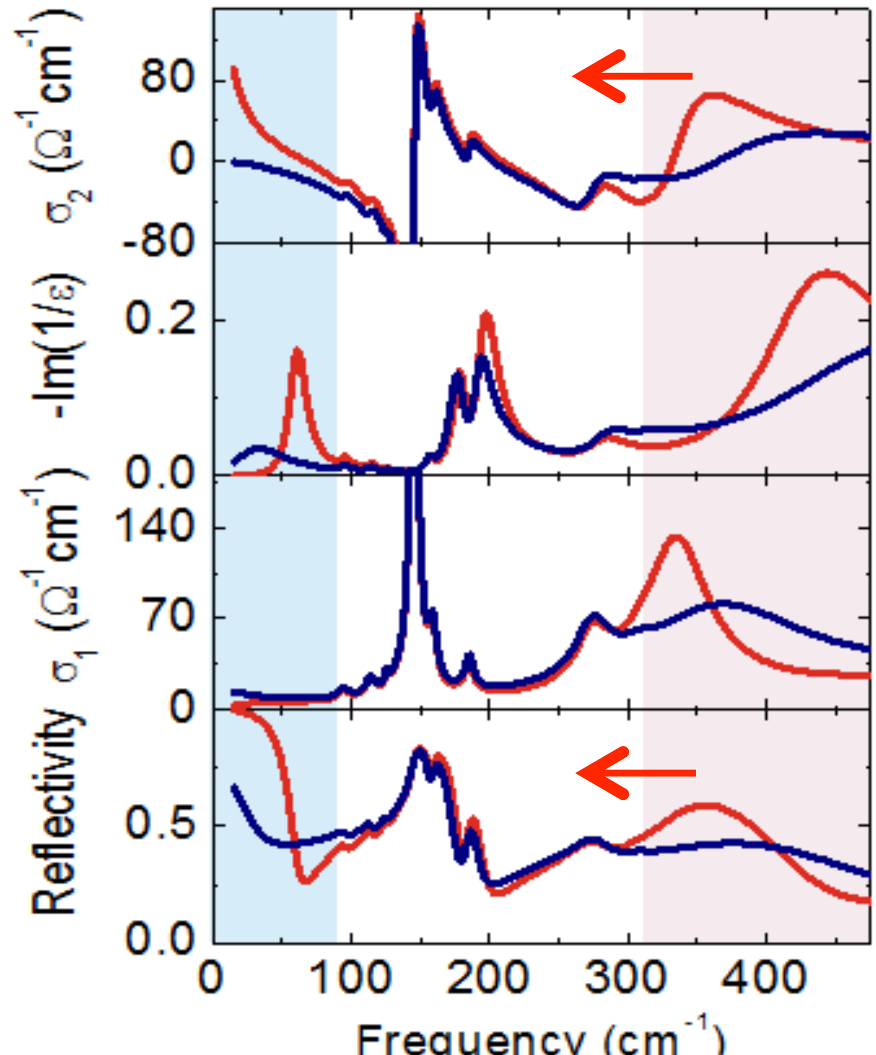


W. Hu. S. Kaiser, D. Nicoletti, C.S. Hunt et al. *Nature Materials* 13, 705 (2014)

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

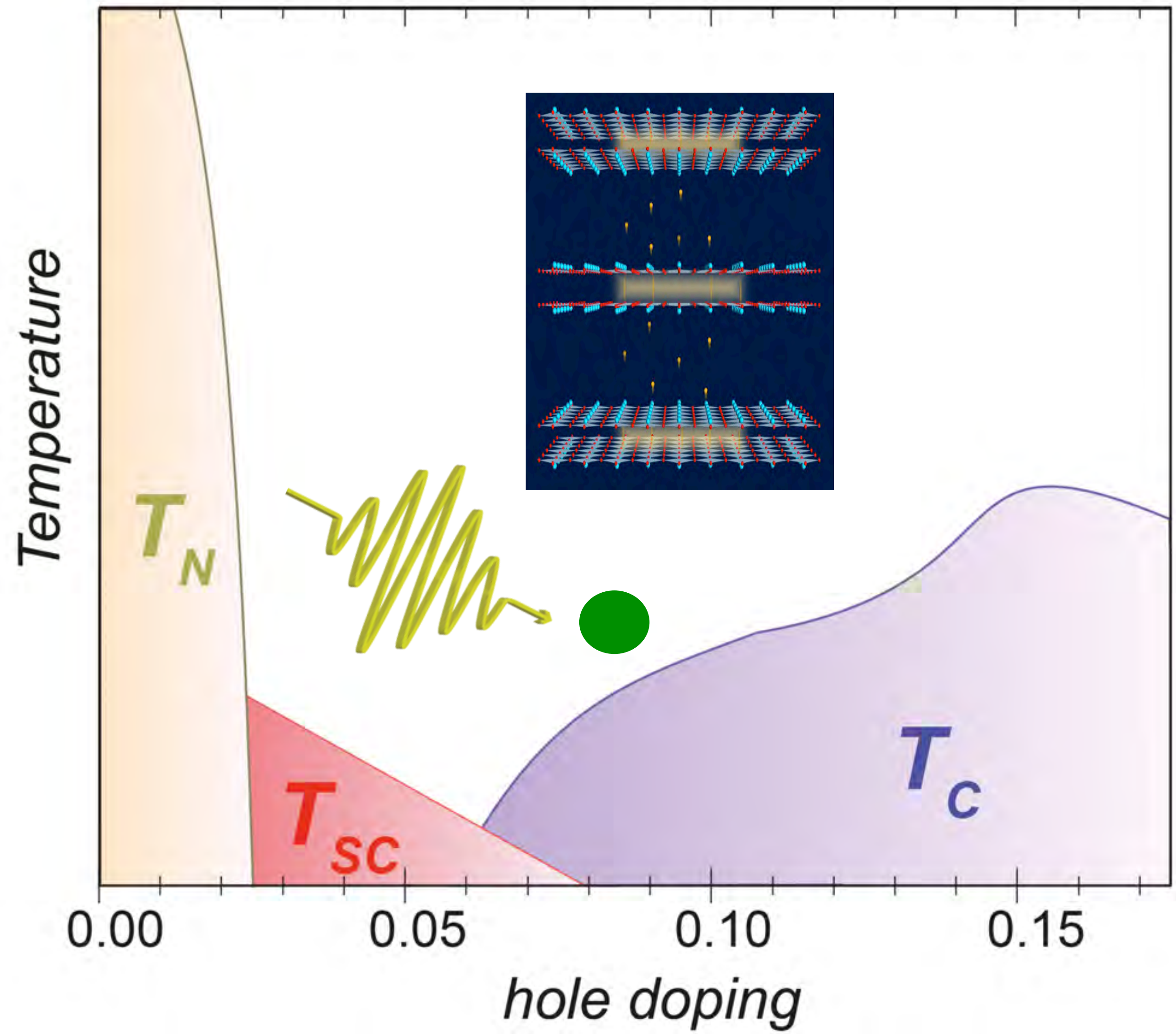
Spectral weight from high frequency





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

Above T_c



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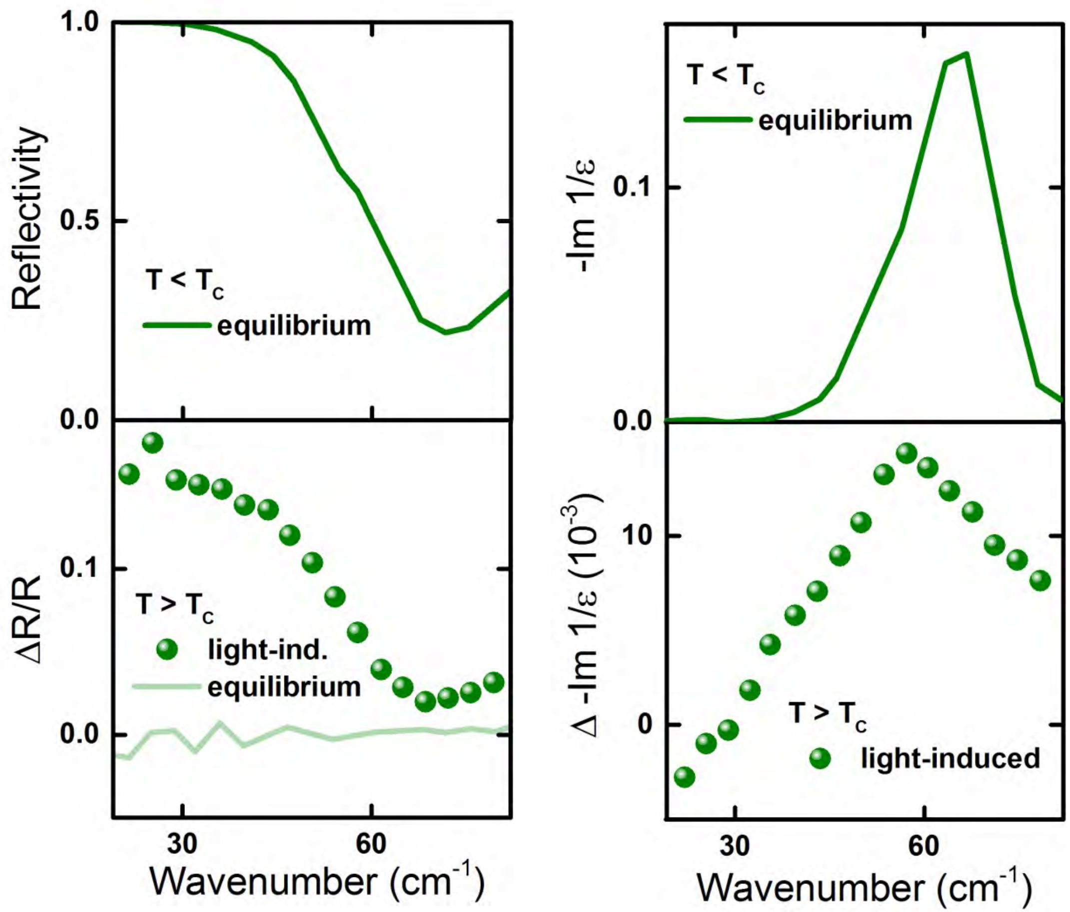
Light induced “Superconductivity”

Plasma edge **$\varepsilon_1(\omega_{JPR}) = 0$** **$YBCO_{6.6}$ – 100 K**

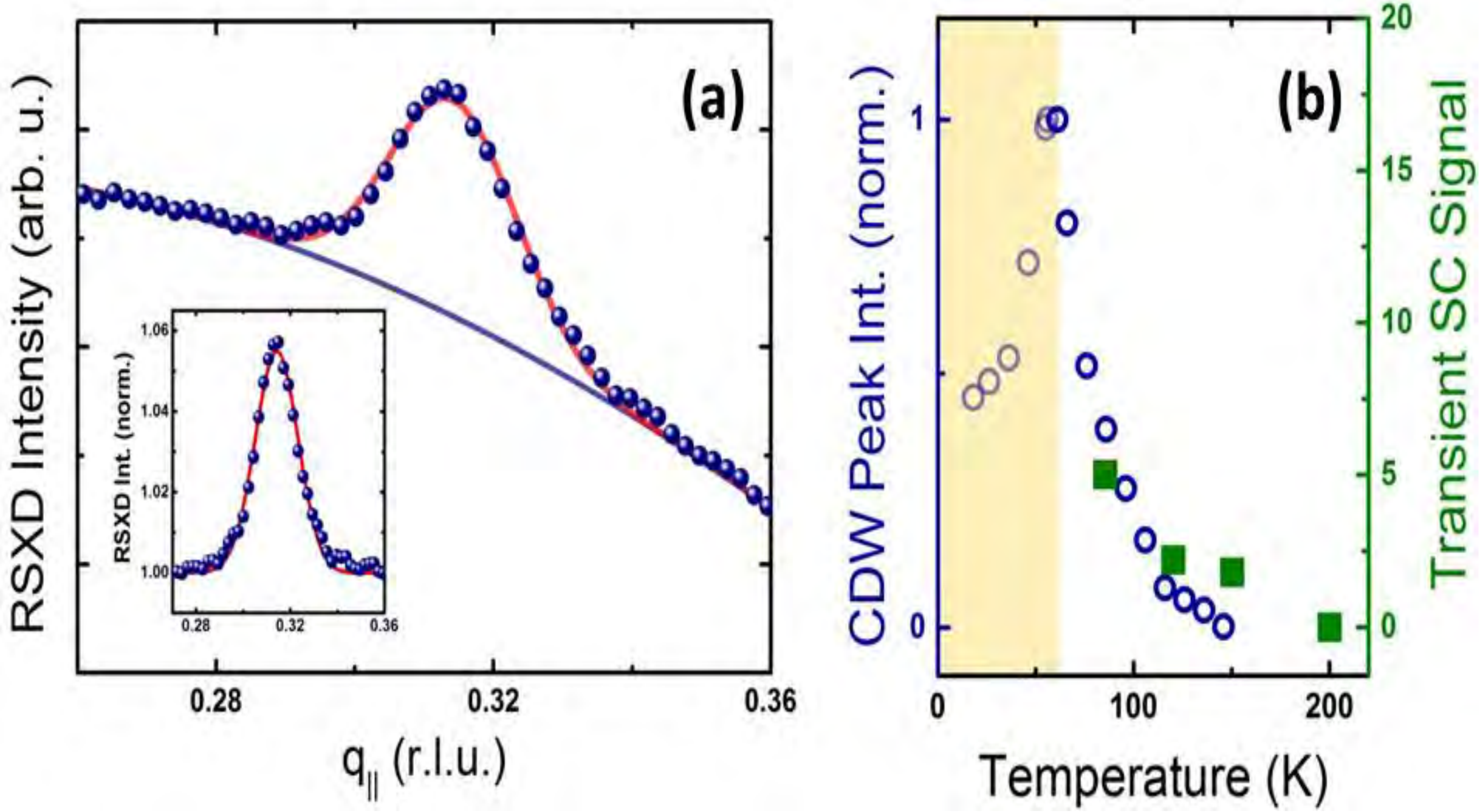


Equilibrium $T<T_c$

Light induced $T>T_c$

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

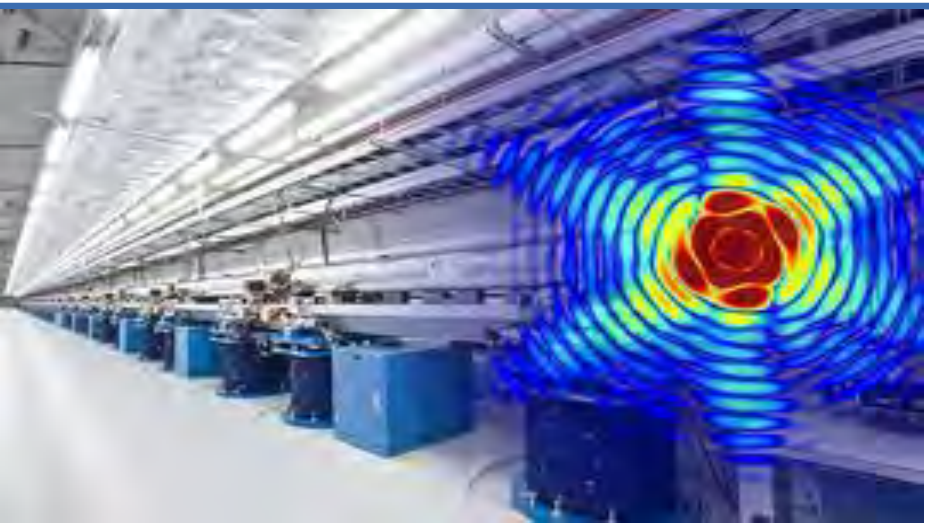
Light induced edge in $YBa_2Cu_3O_{6.6}$: only up to T_{CO}

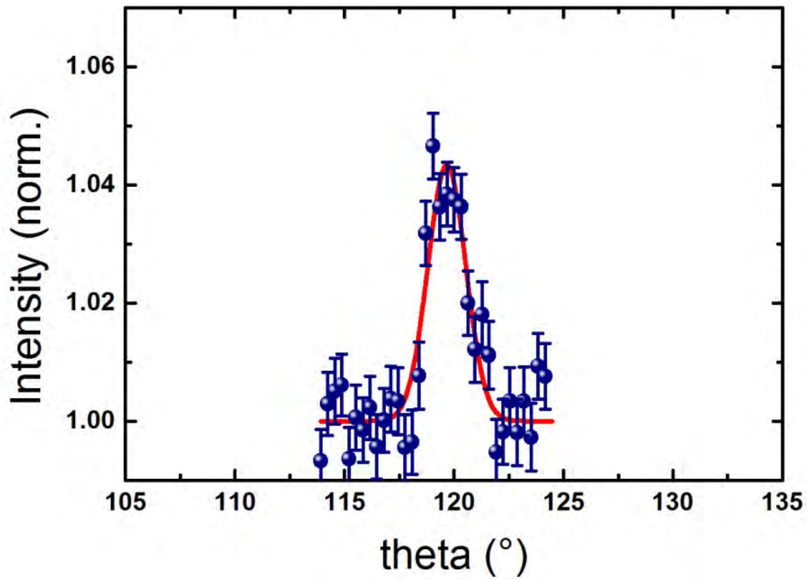


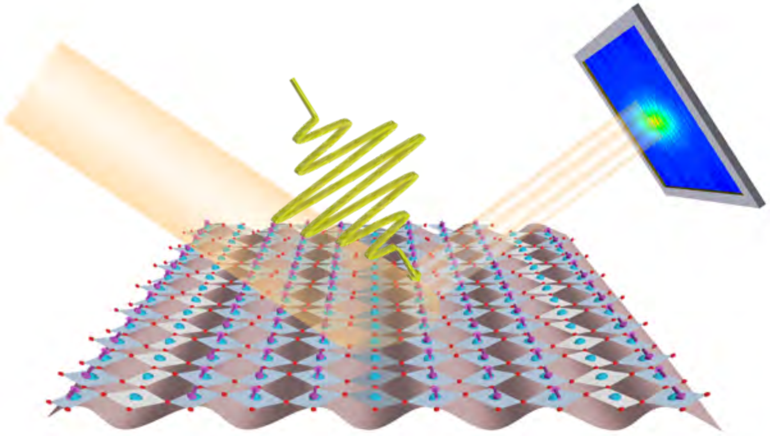
G. Ghiringhelli et al., *Science 337*, 821 (2012)

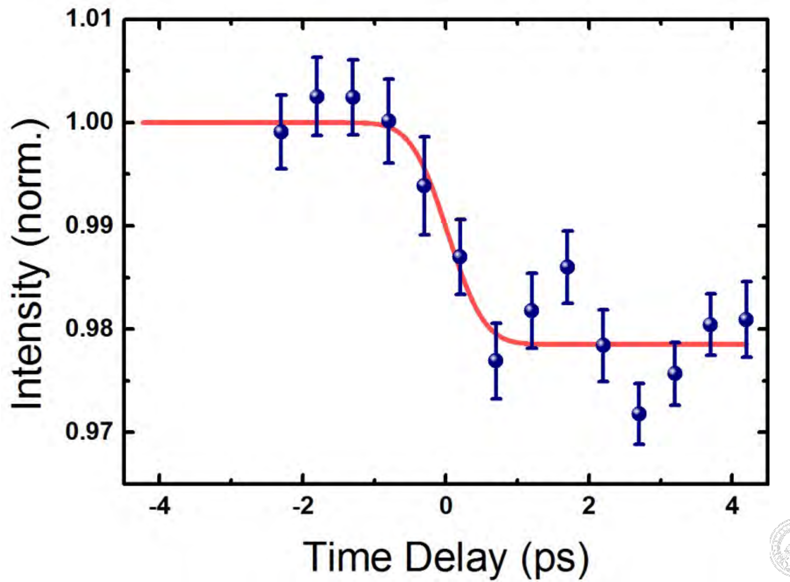
S. Kaiser, D. Nicoletti, C. Hunt et al., *Phys. Rev. B* 89, 184516 (2014)

Light induced edge in $YBa_2Cu_3O_{6.6}$: CO melts



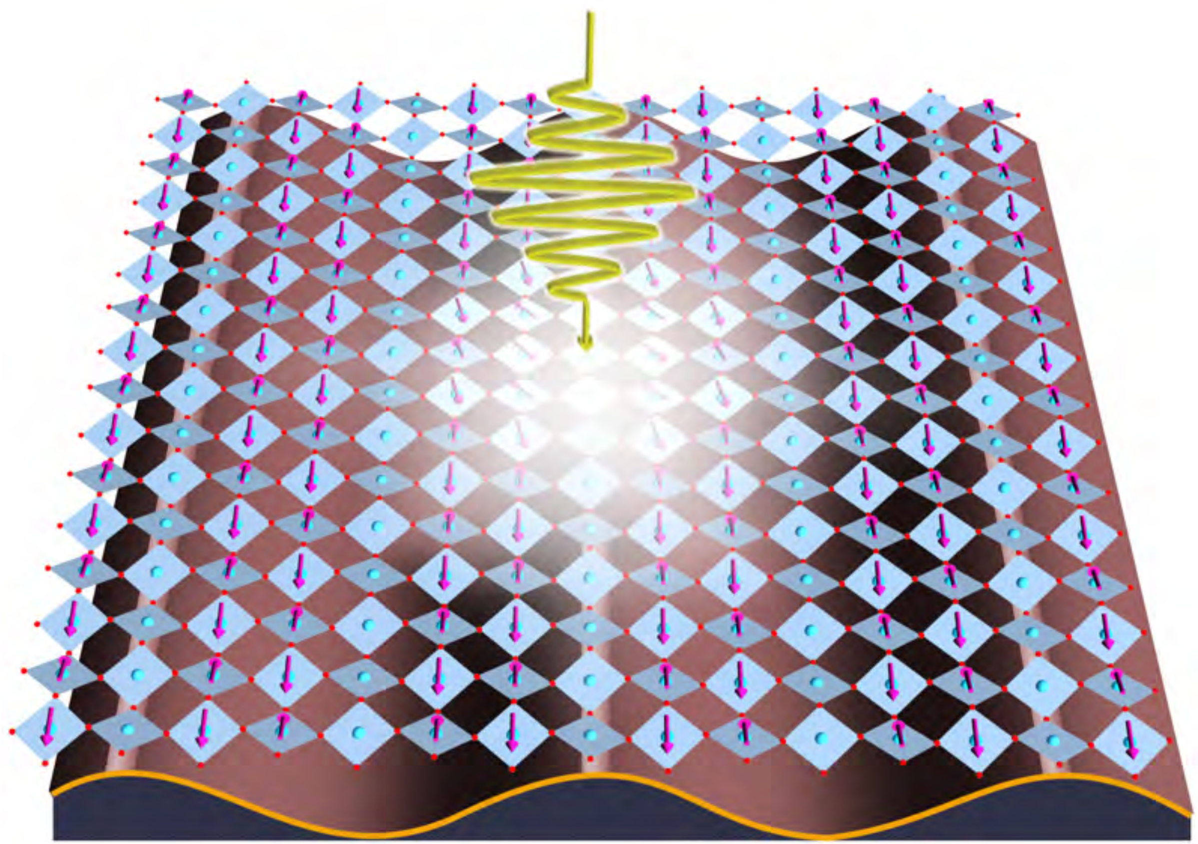




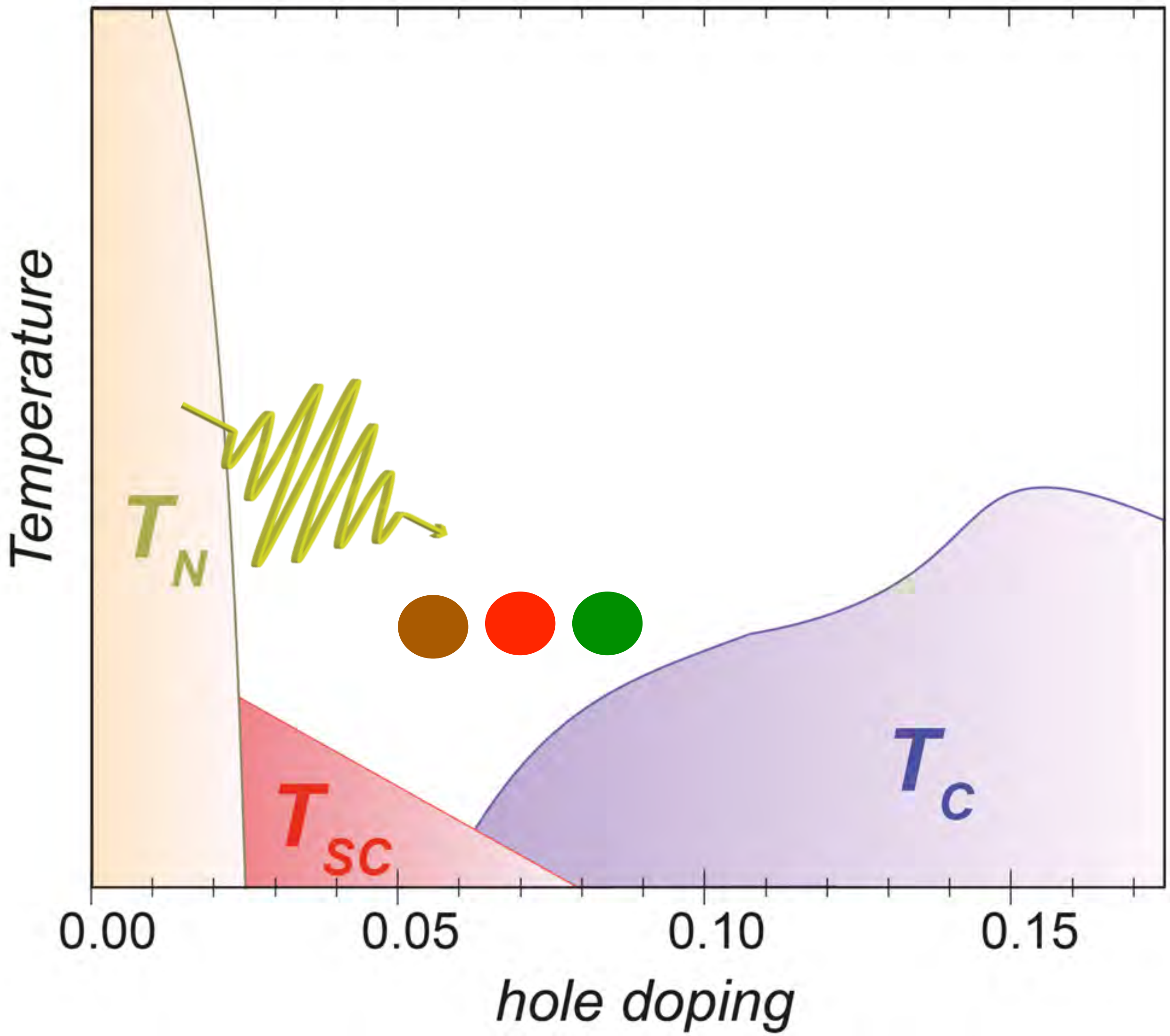


M. Foerst et al., *Phys. Rev. B* (2014) – in press

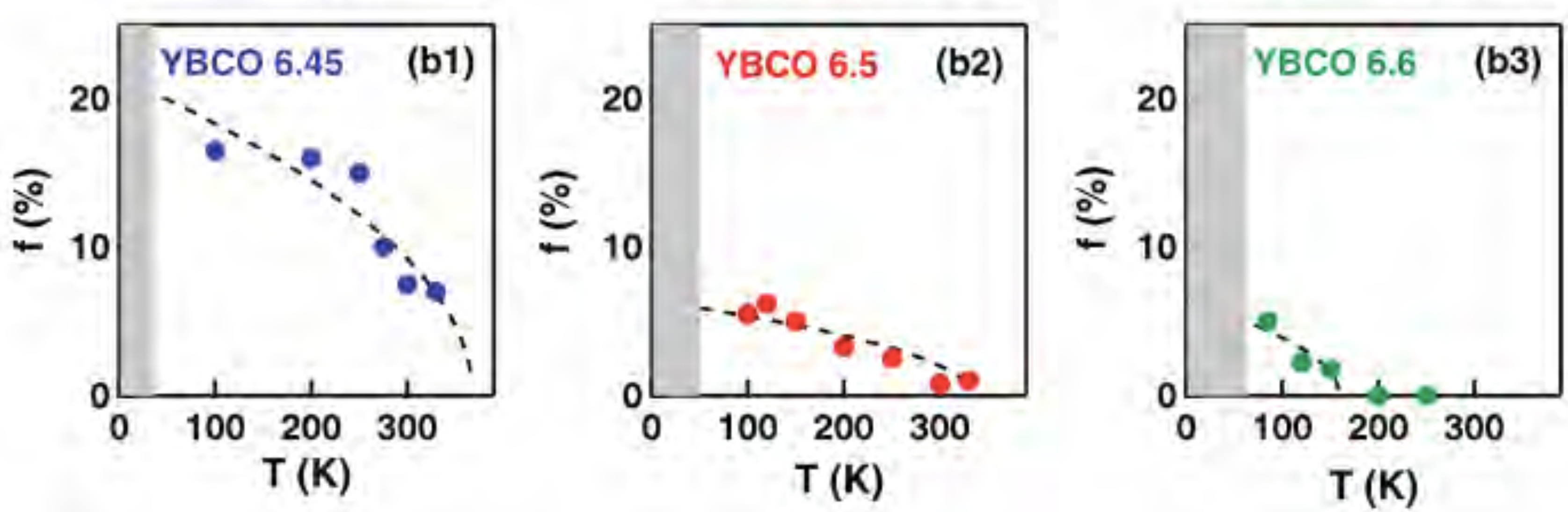
Hypothesis: I Melt Stripes Optically



Lower doping values

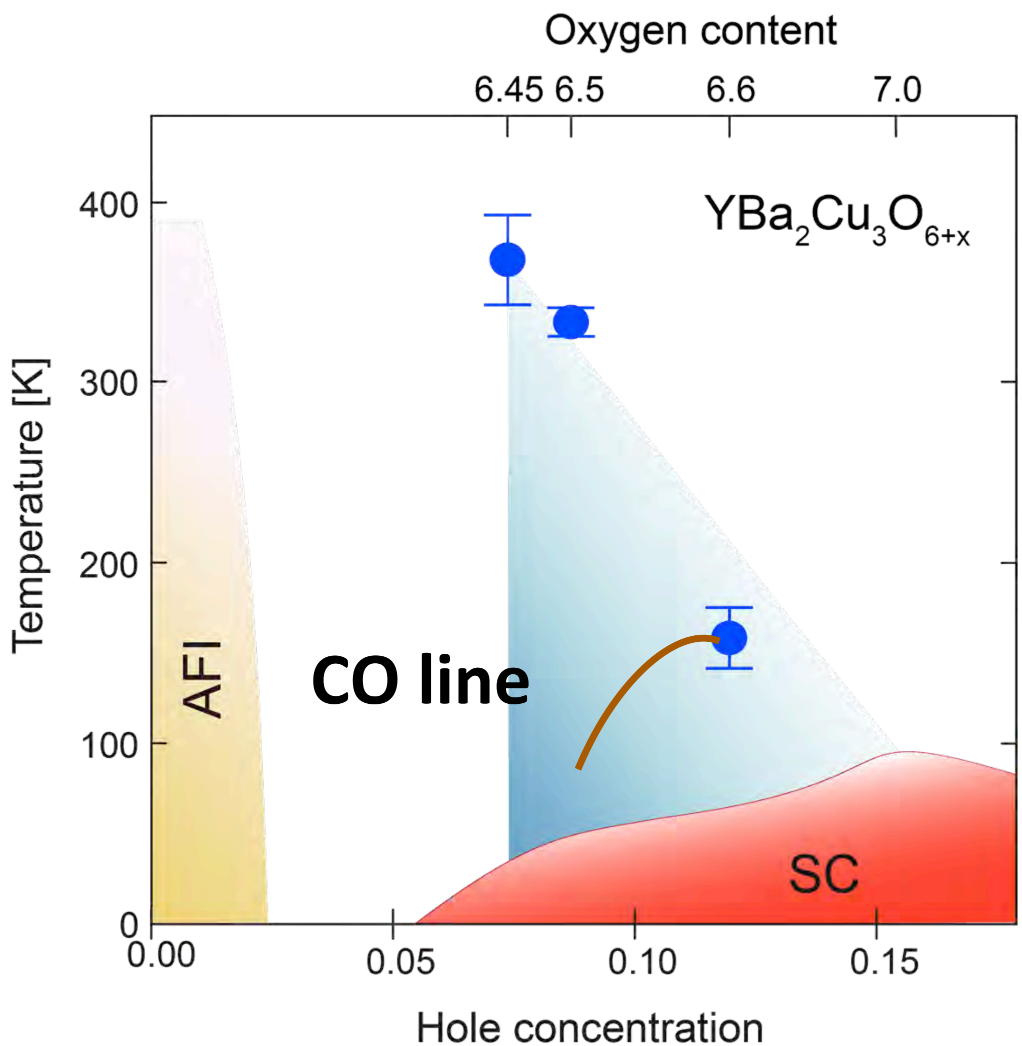


larger effect for lower dopings….



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

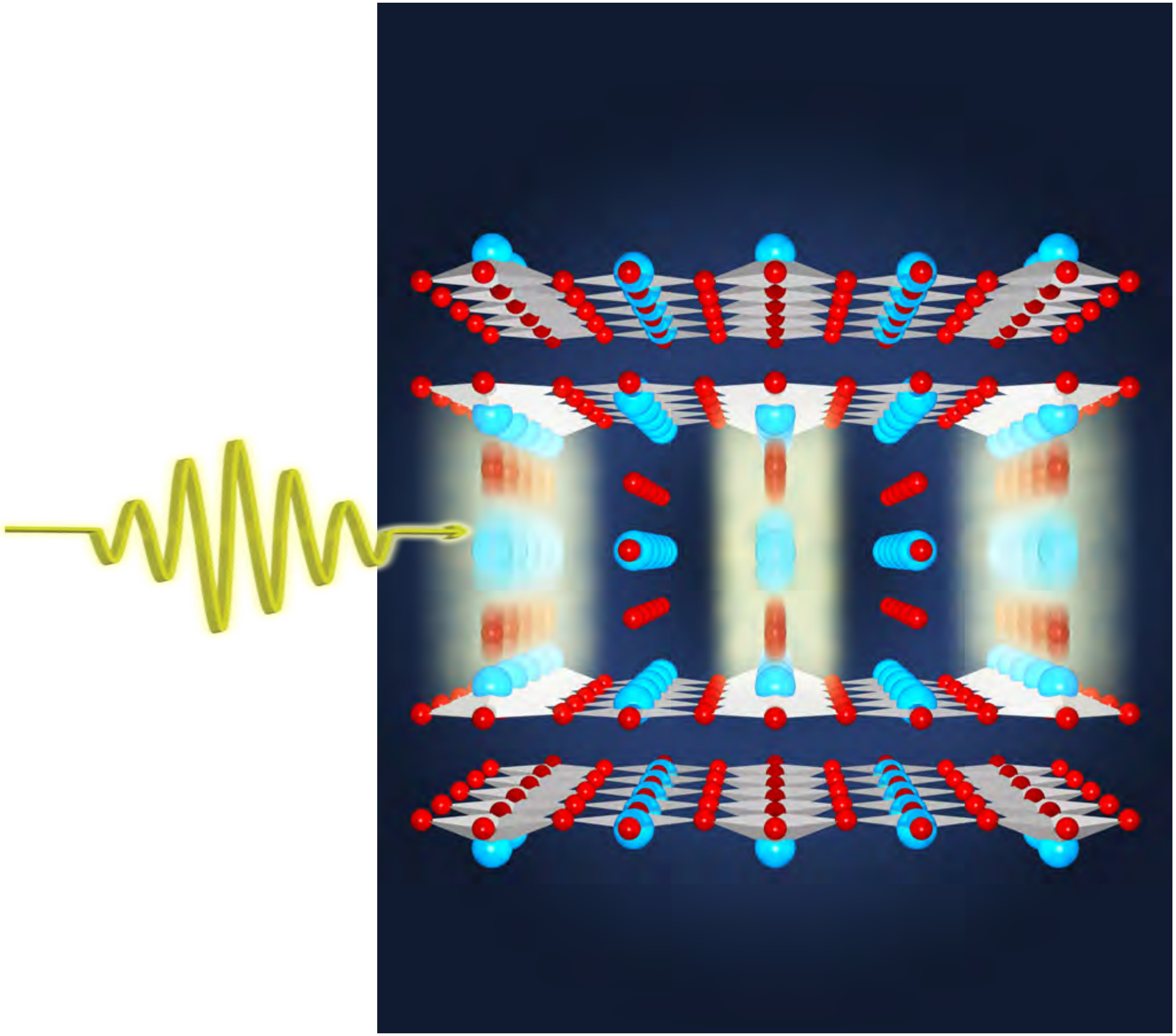
Follows T*



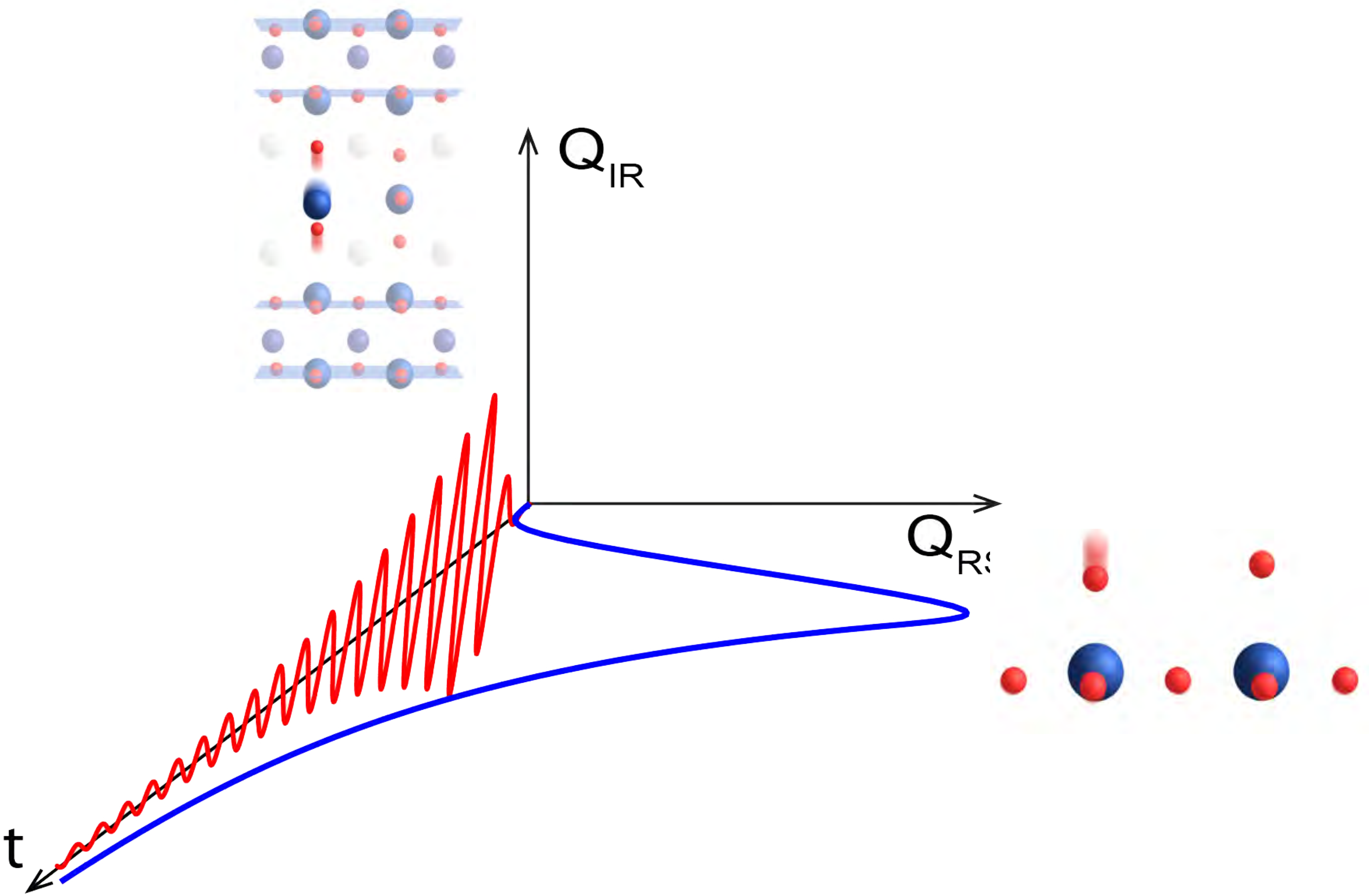
W. Hu. S. Kaiser, D. Nicoletti, C.S. Hunt et al. Nature Materials (2014)

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

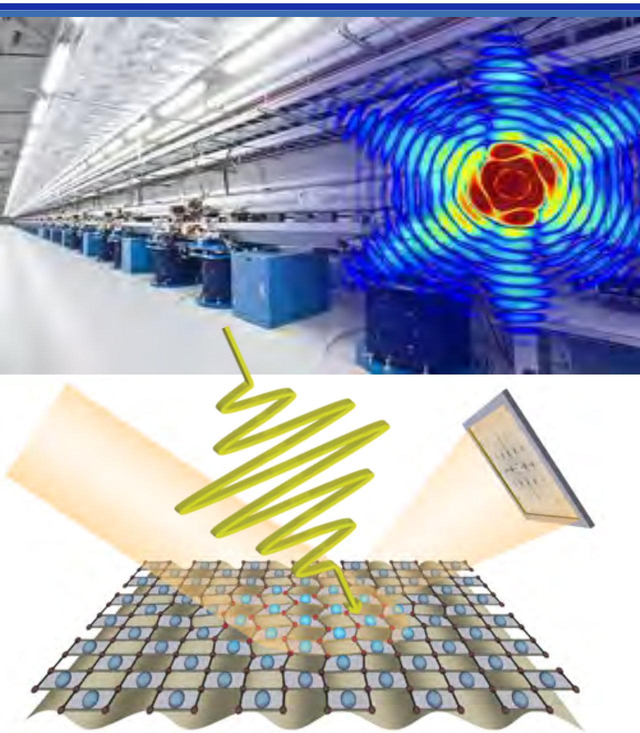
Dynamical modulation: what is going on ?



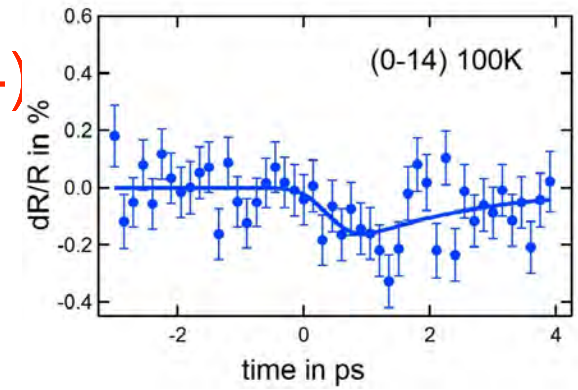
Excite B_{1u} and displace along A_g



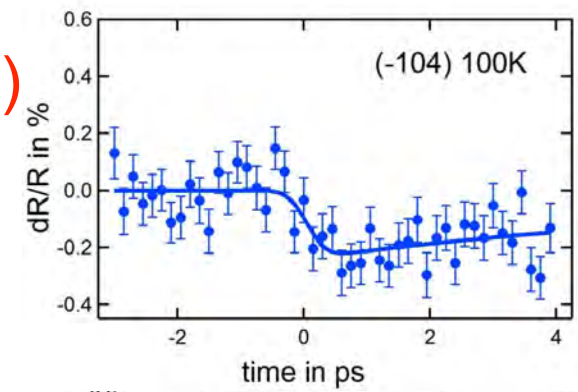
Femtosecond X-ray Scattering



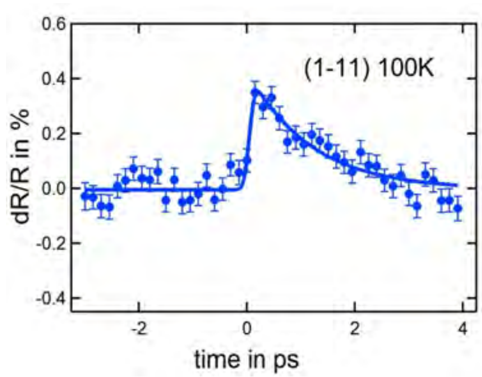
(0,-1,4)



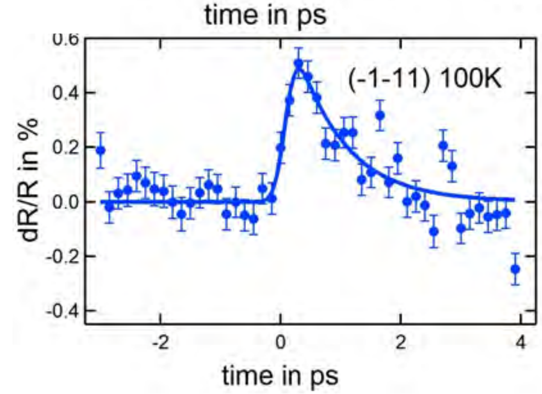
(-1,0,4)



(-1,1,1)

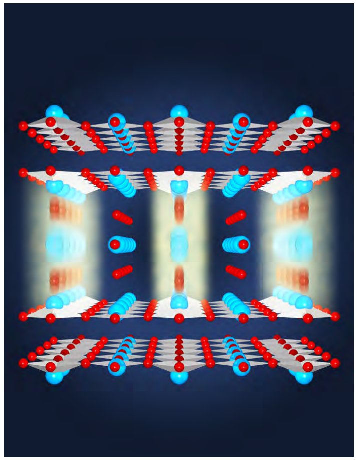


(1,-1,1)

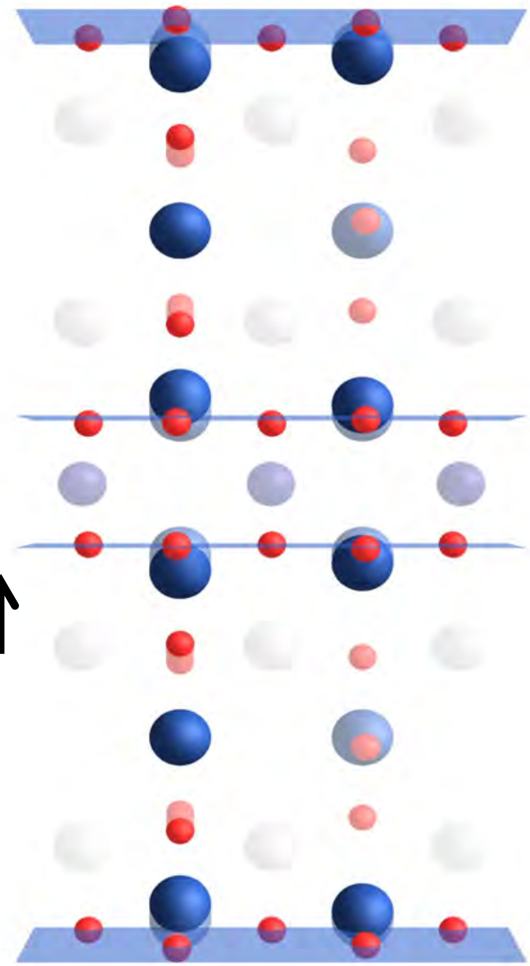


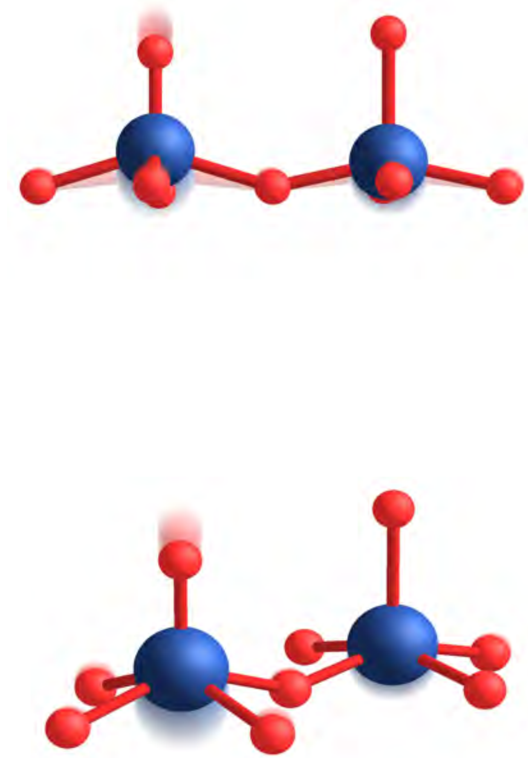
R. Mankowski et al. *Nature 516,71 (2014)*

New bond lengths in $YB_2Cu_3O_{6+x}$



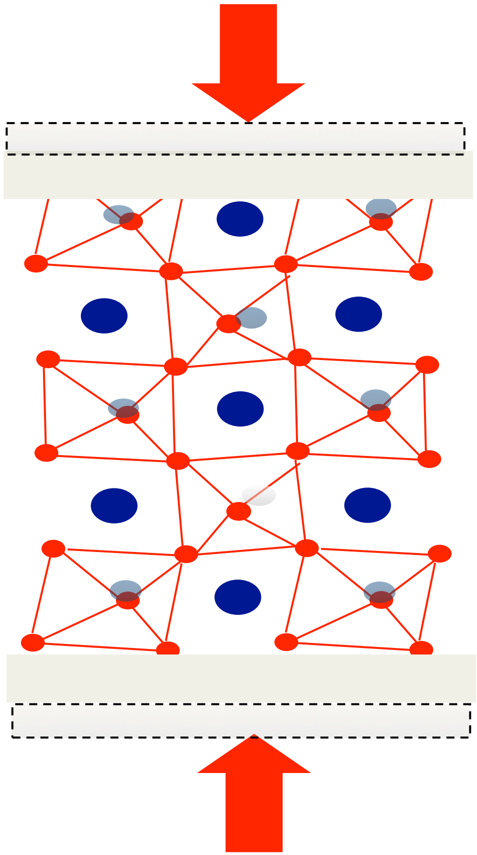
d ~ 3 % ↑

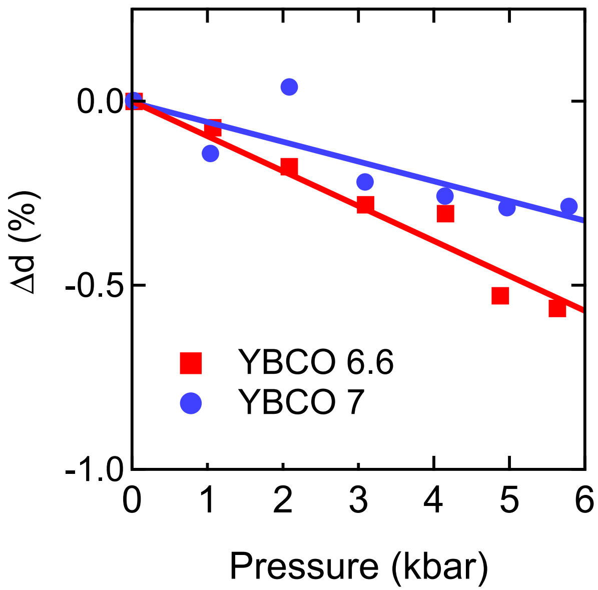


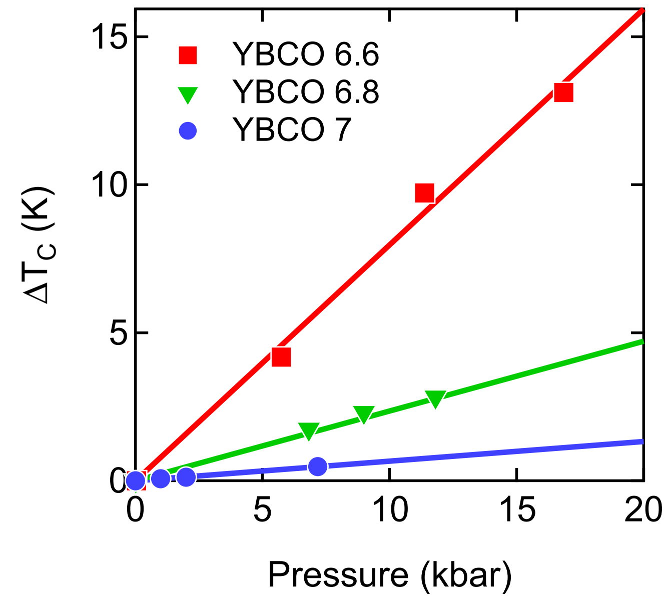


R. Mankowski et al. *Nature* 516, 71 (2014)

Pressure does the same…. only less







Pressure
d ~ 0.5 %
ΔT_c ~ 5 - 15 K

Phononics
d ~ 3 %

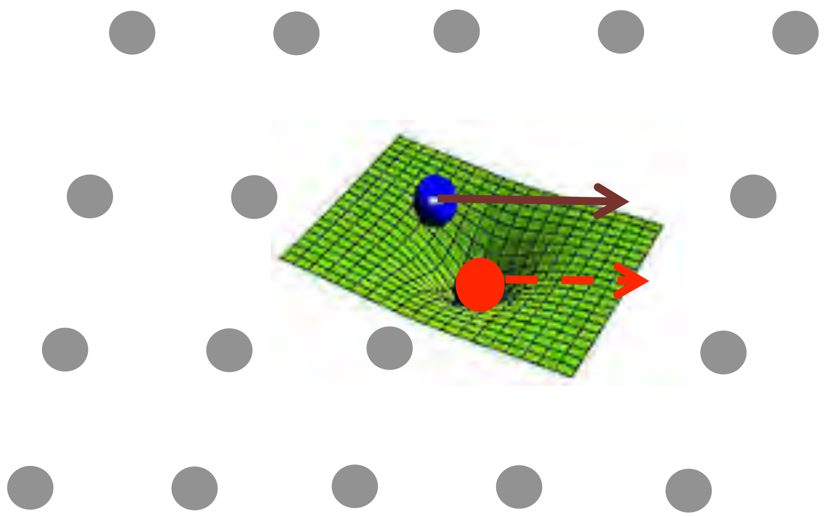
J. G. Huber et al. *Phys. Rev. B 41*, 8757 (1990)

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

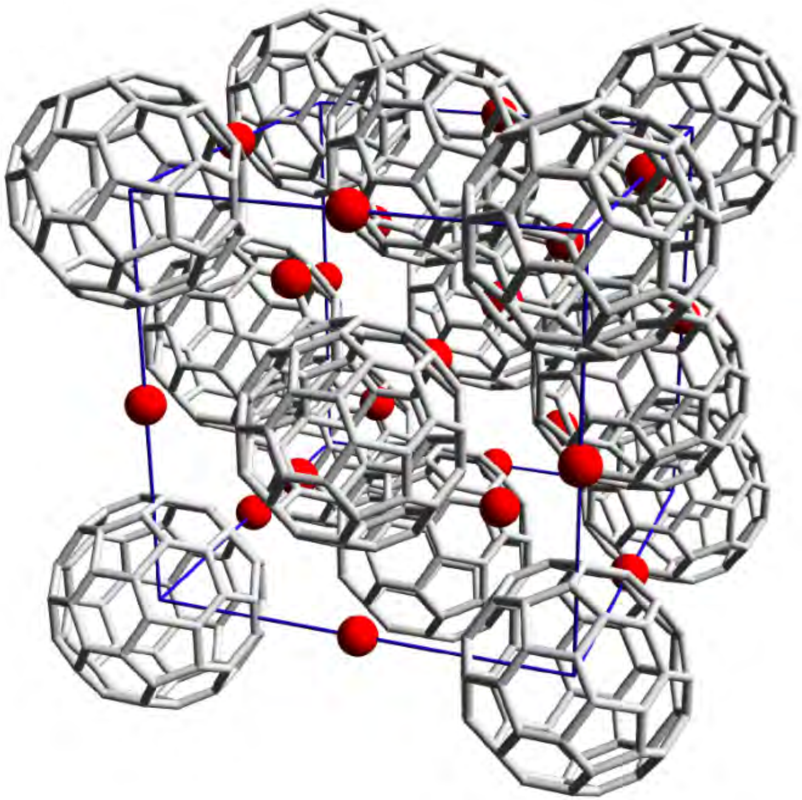
B. Bucher et al. *Journal of Less-Common Metals 164, 165*, 20 (1990)

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

Is this phenomenon general ?

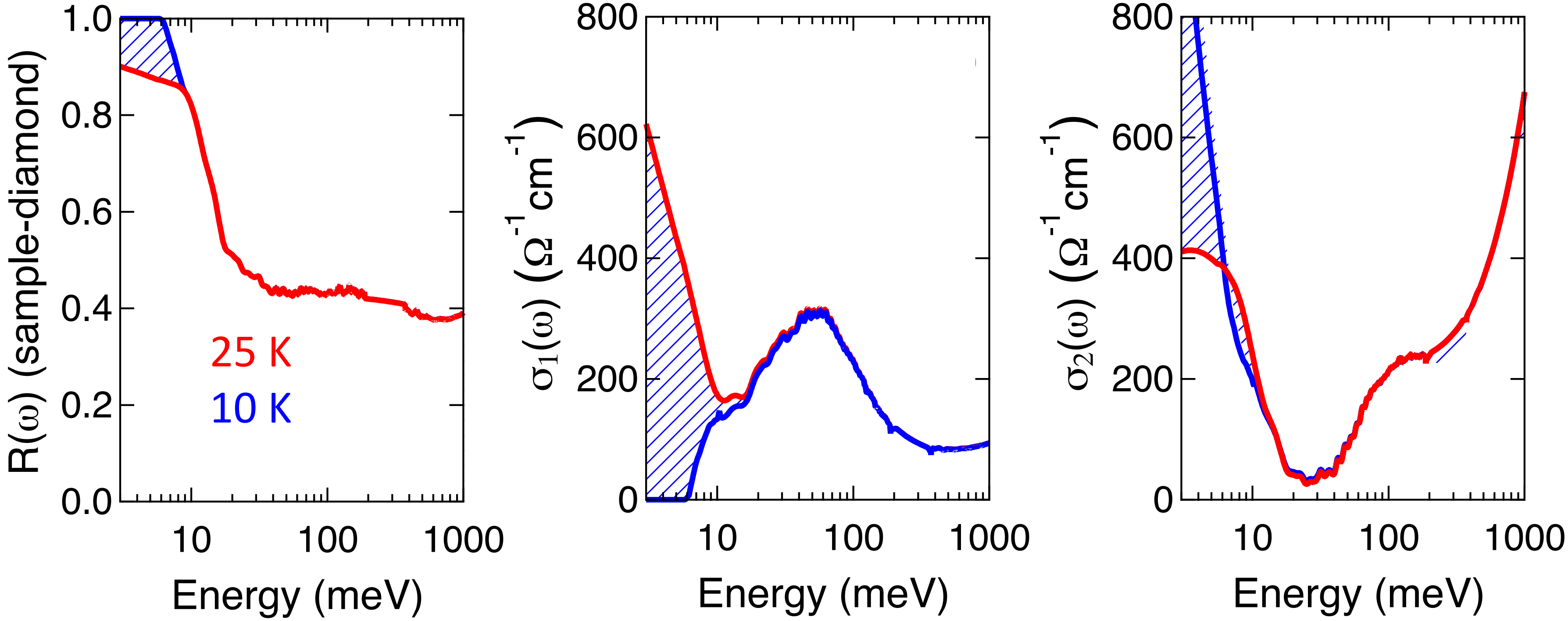


The K_3C_{60} superconductor

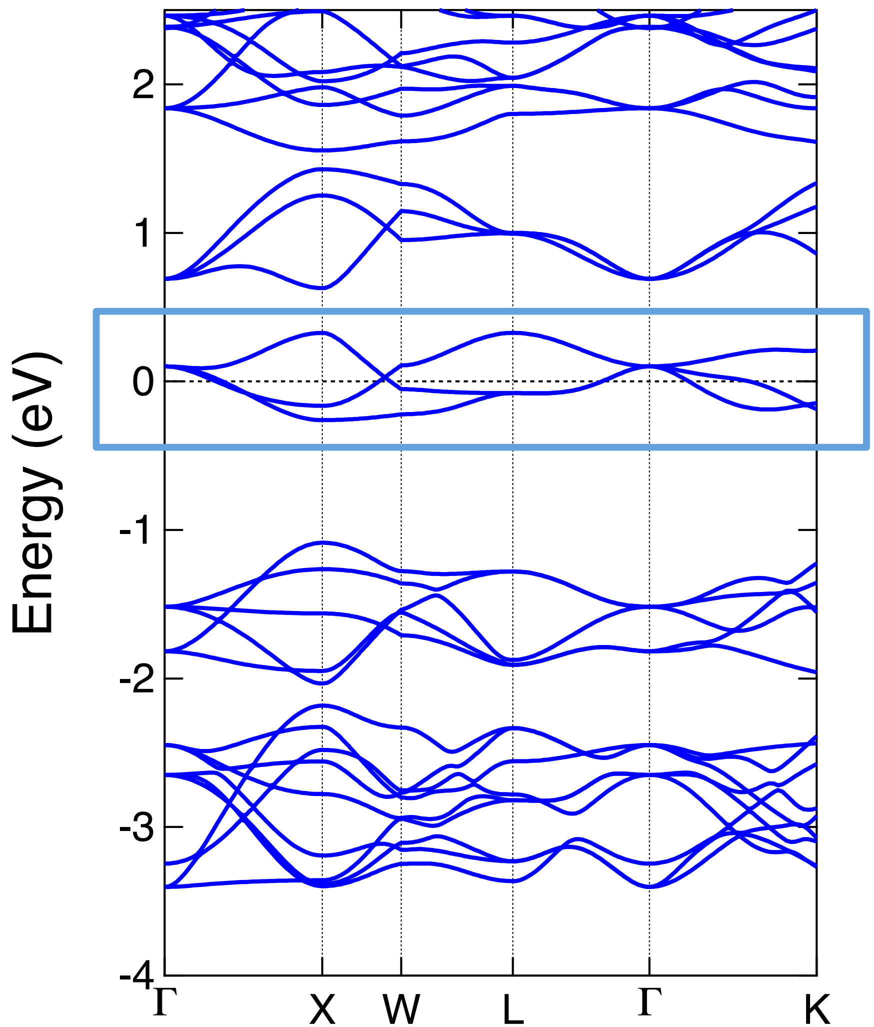


- Lattice mediated superconductivity
- T_C (20 K)

Superconducting transition: cooling



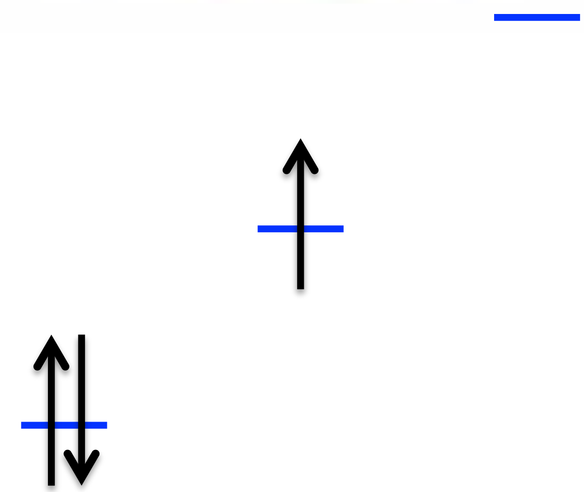
Pairing aided by a molecular Jahn-Teller distortion



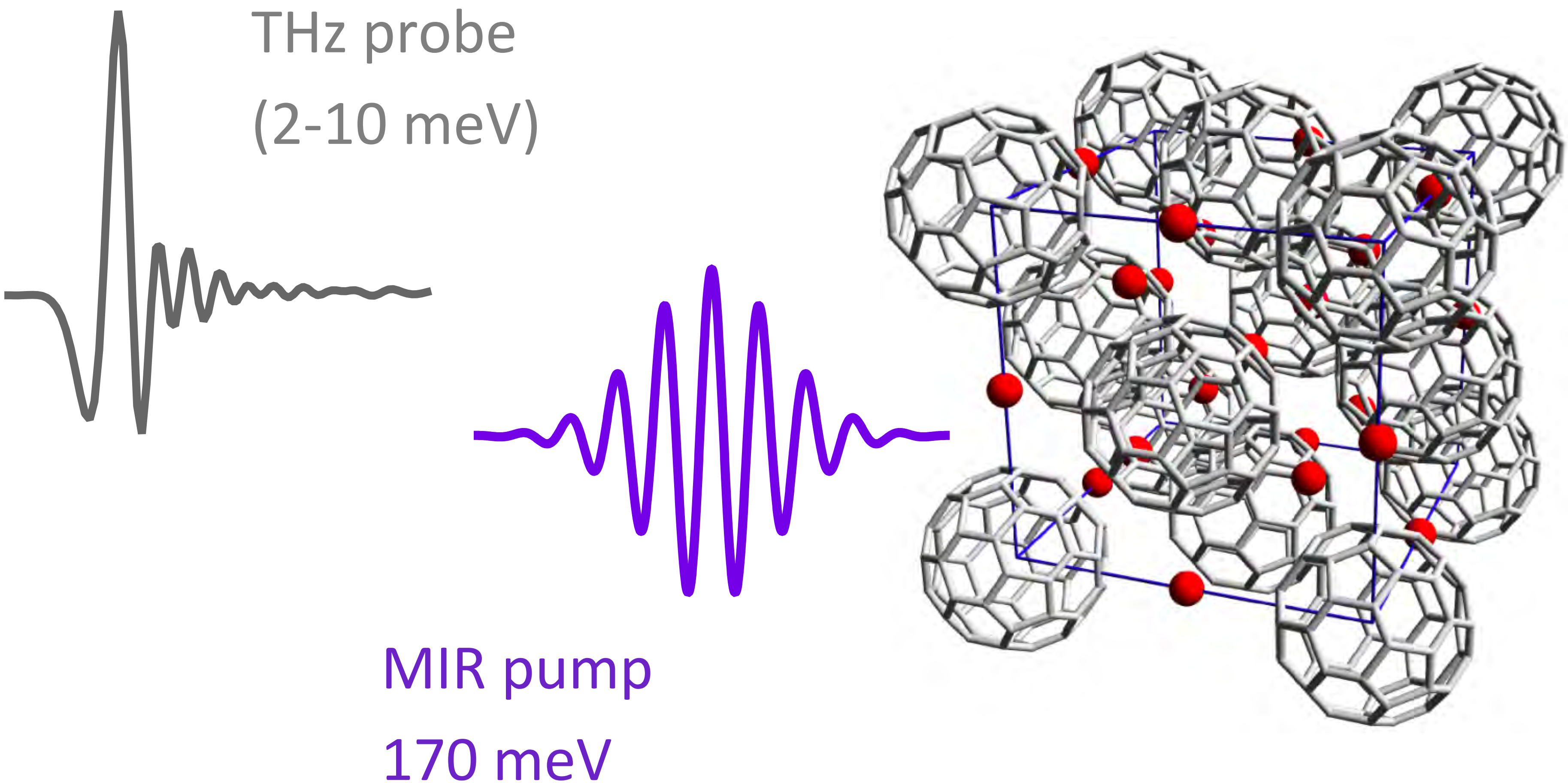
Courtesy of A. Subedi

t_{1u}

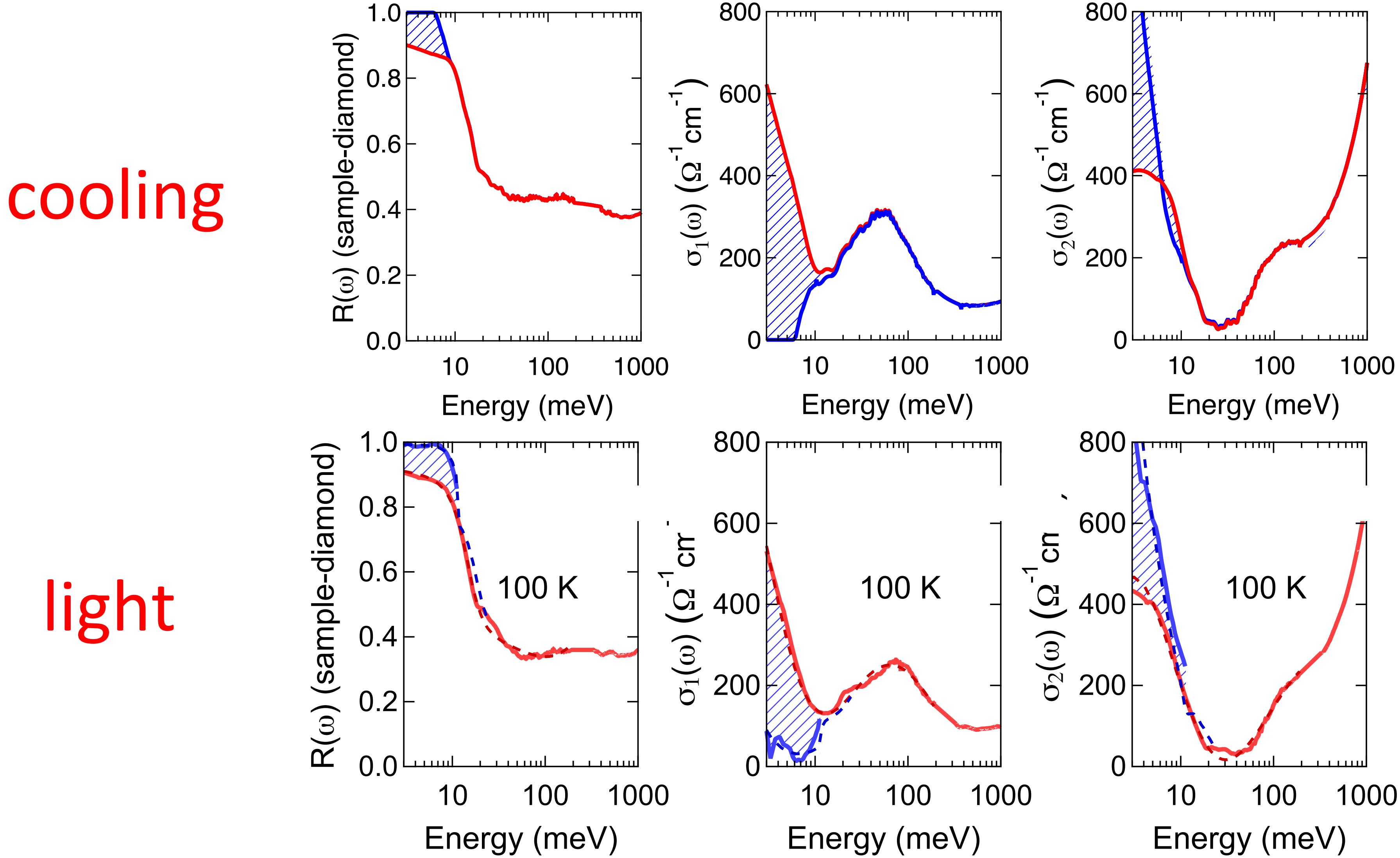
Narrow bandwidth 0.5 eV



Optical excitation of molecular vibrations

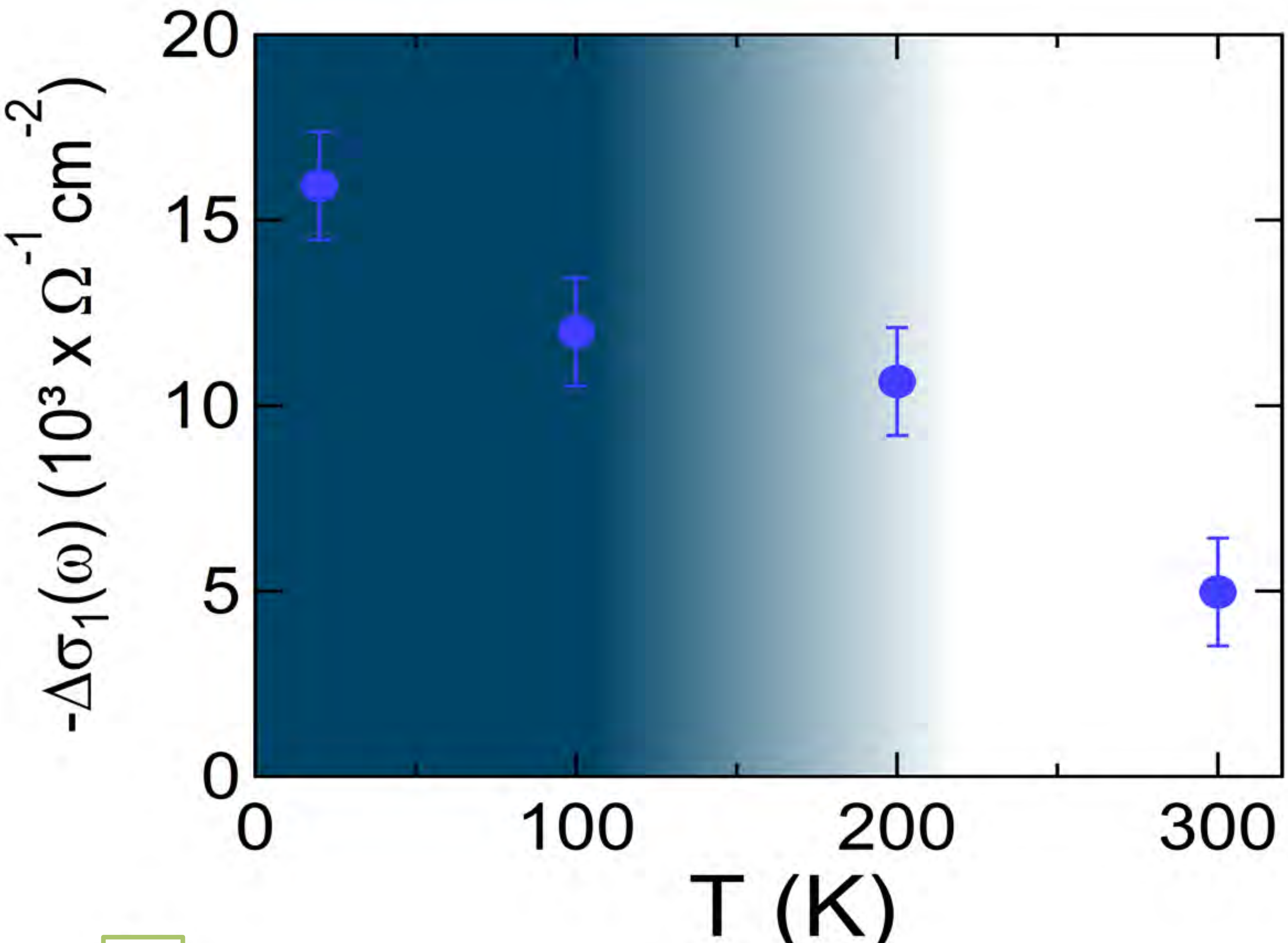


A light-induced superconducting like phase



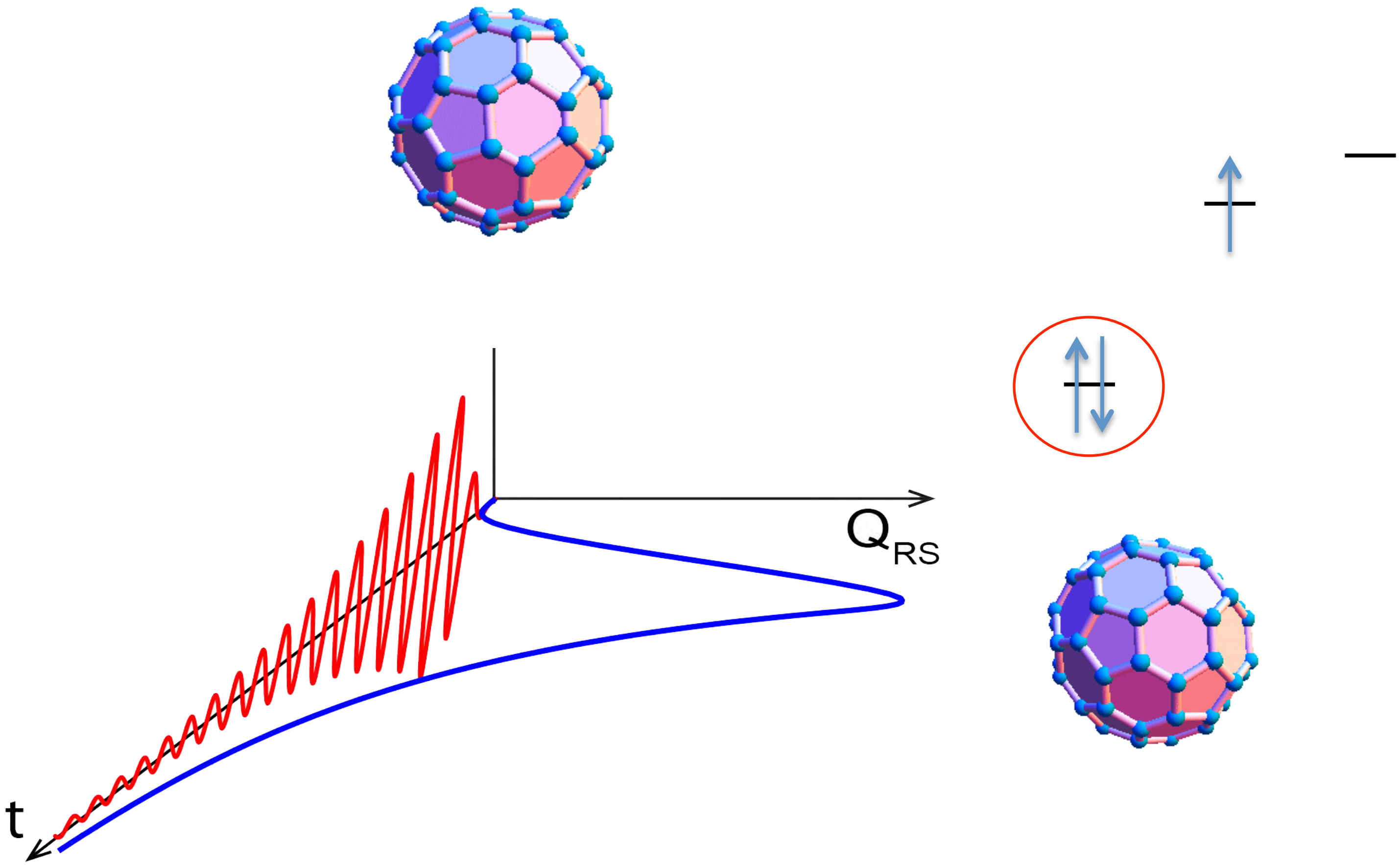
M. Mitrano et al. *Nature 530, 461* (2016)

Up to > 100 K

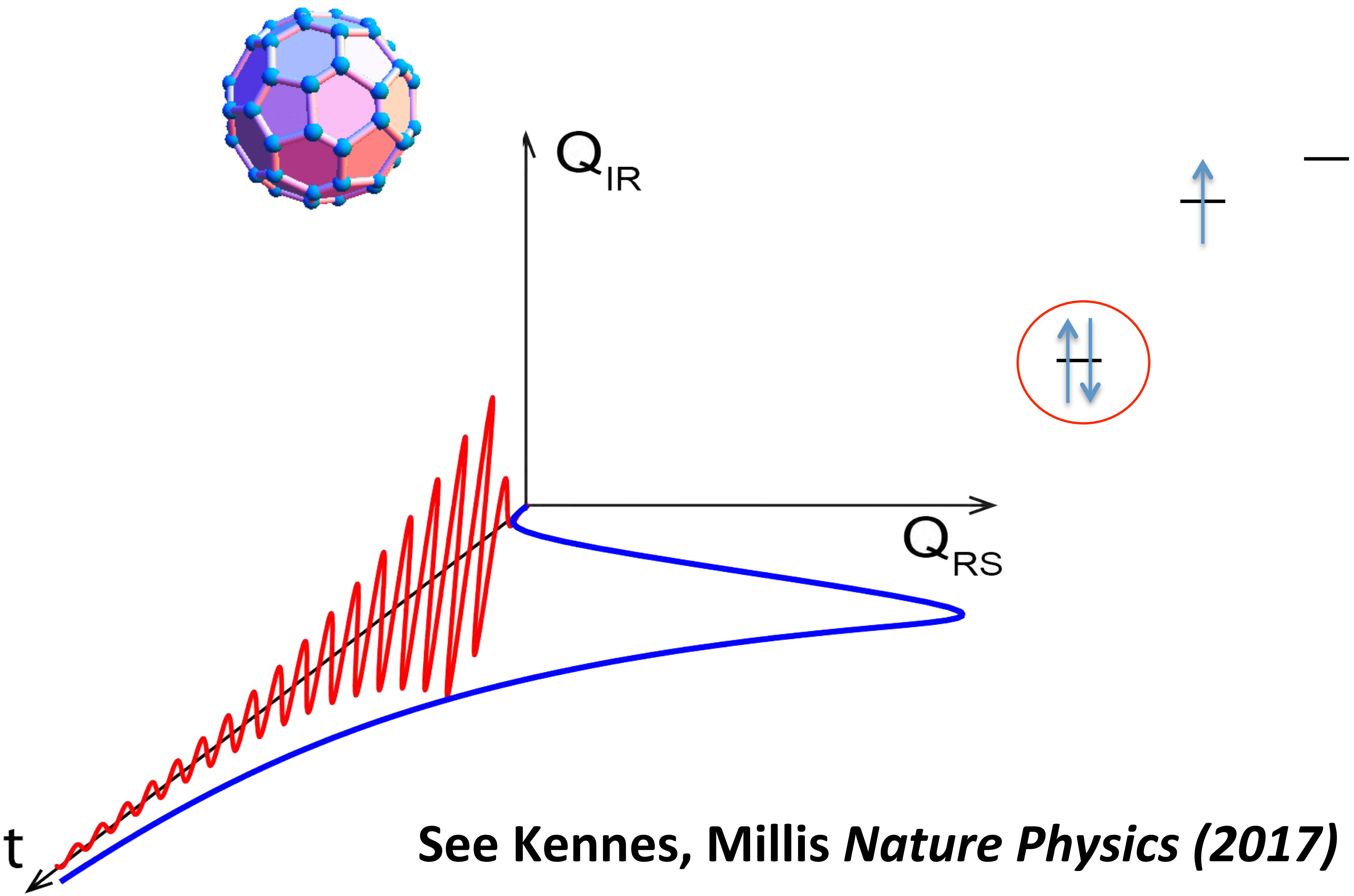


$-\Delta\sigma_1(\omega)$ $(10^3 \times \Omega^{-1} cm^{-2})$
20
15
10
5
0
0
100
200
300
T (K)

Quasi-static lattice distortion ?



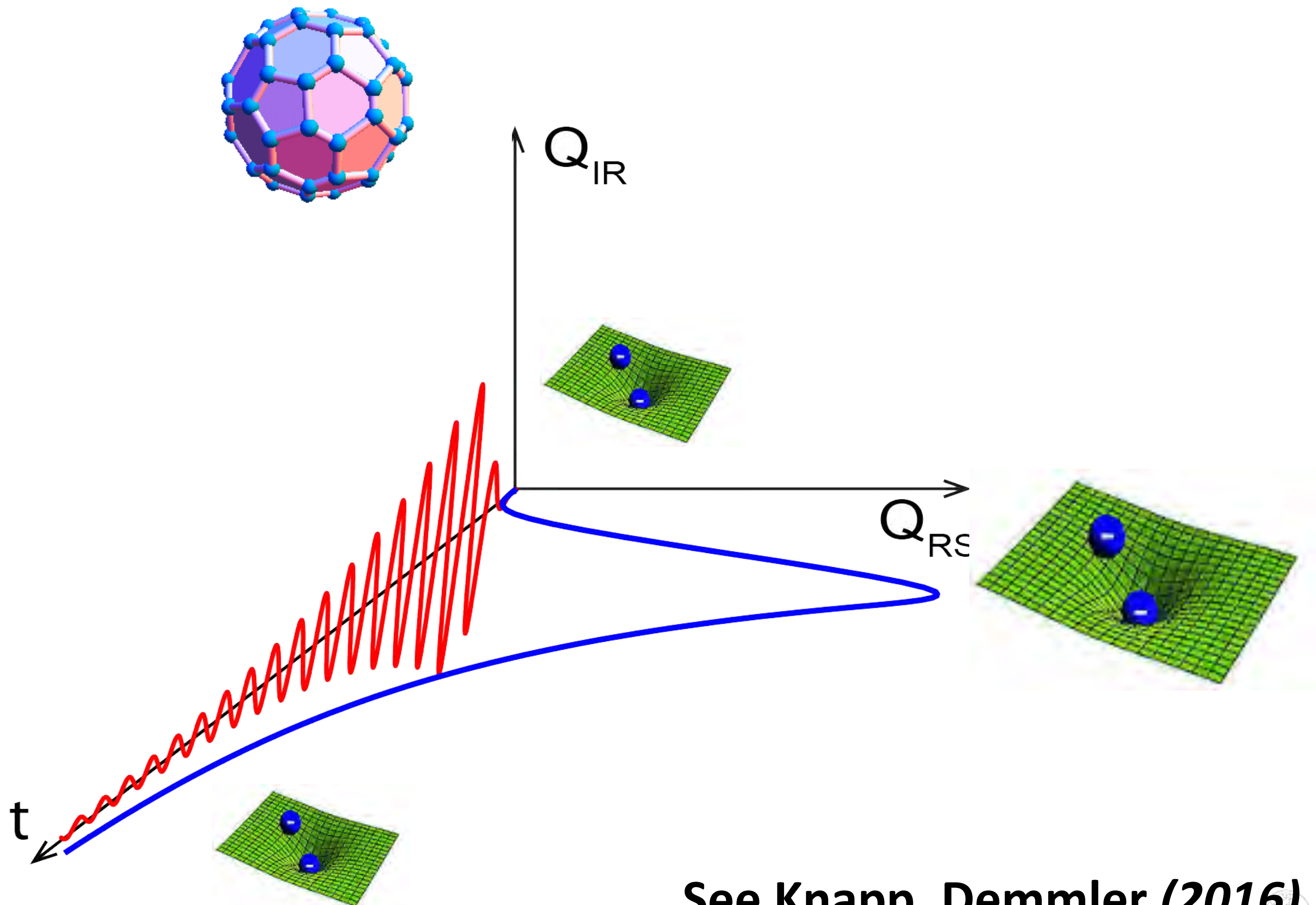
Light induced negative U?



See Kennes, Millis *Nature Physics (2017)*

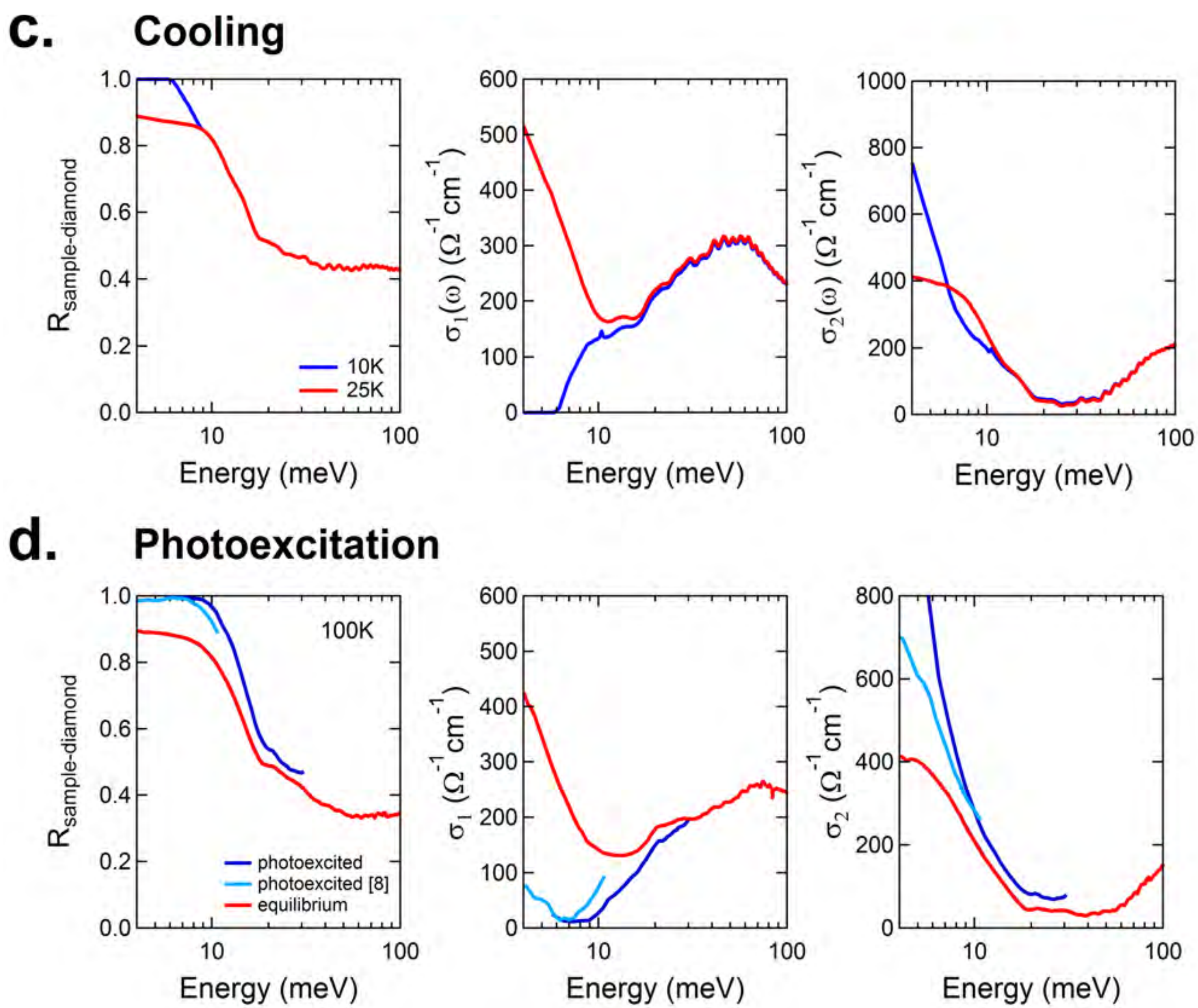
See Kim,, Mazza, Georges *(2017)*

Parametric amplification of the pairing instability ?

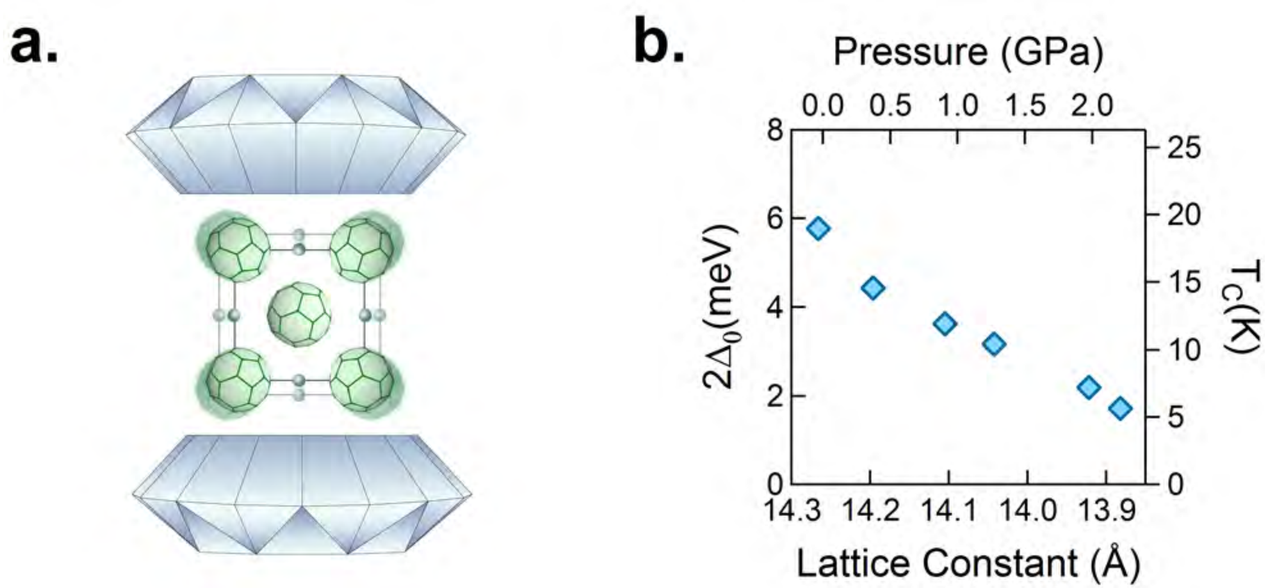


See Knapp, Demmler *(2016)*

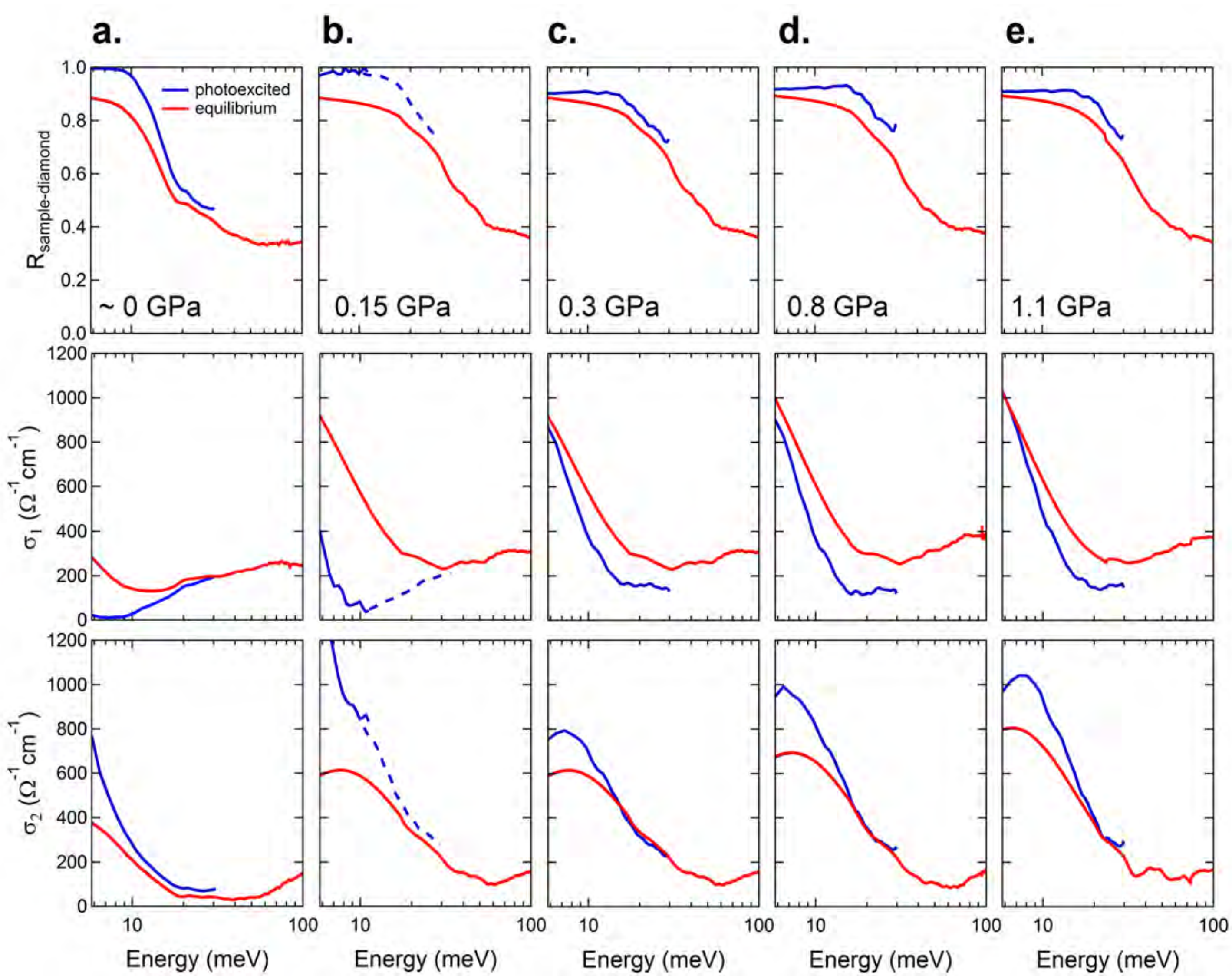
New data (2017 +): fluence dependent gap



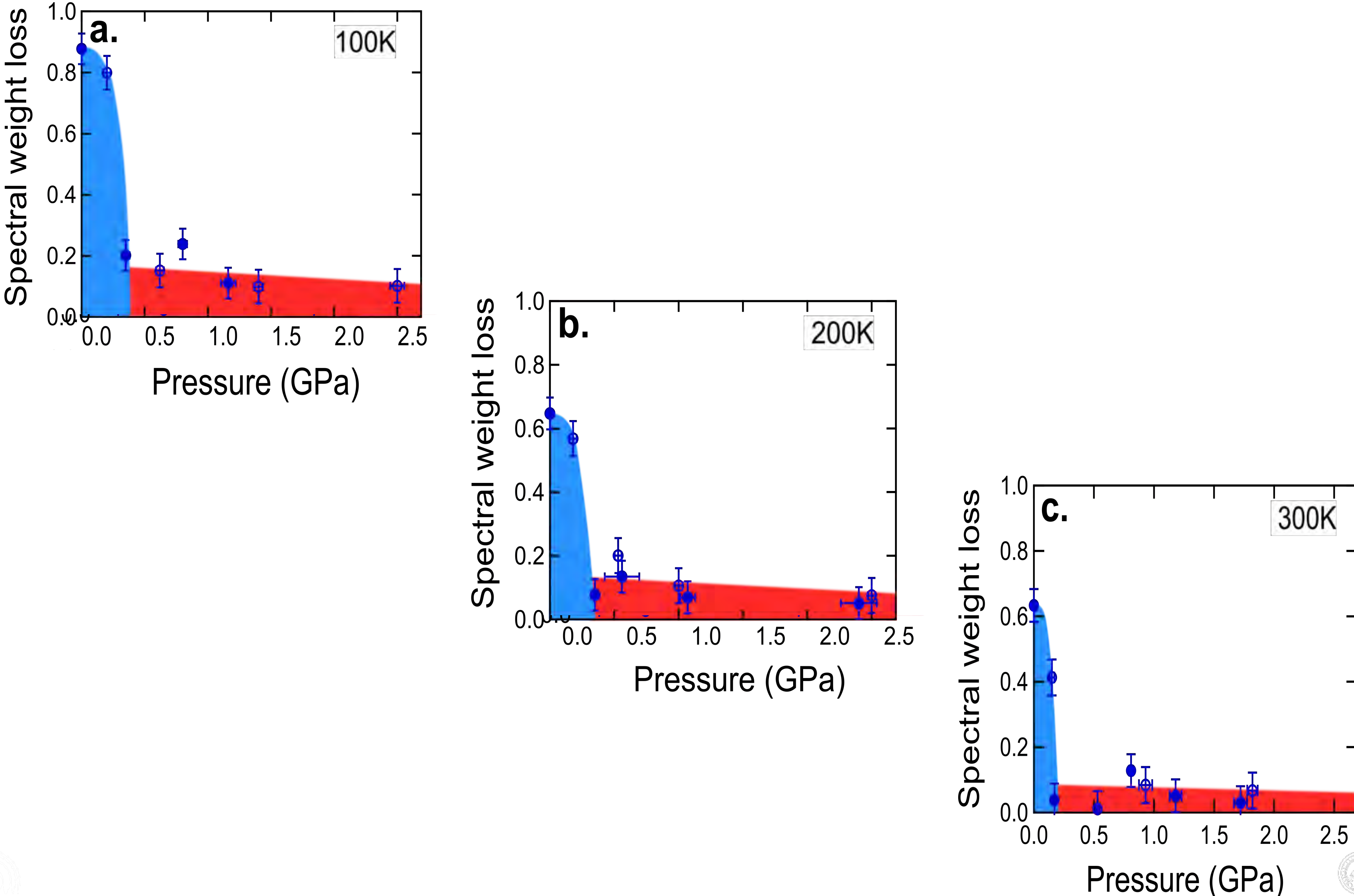
Other parameters: e.g. pressure



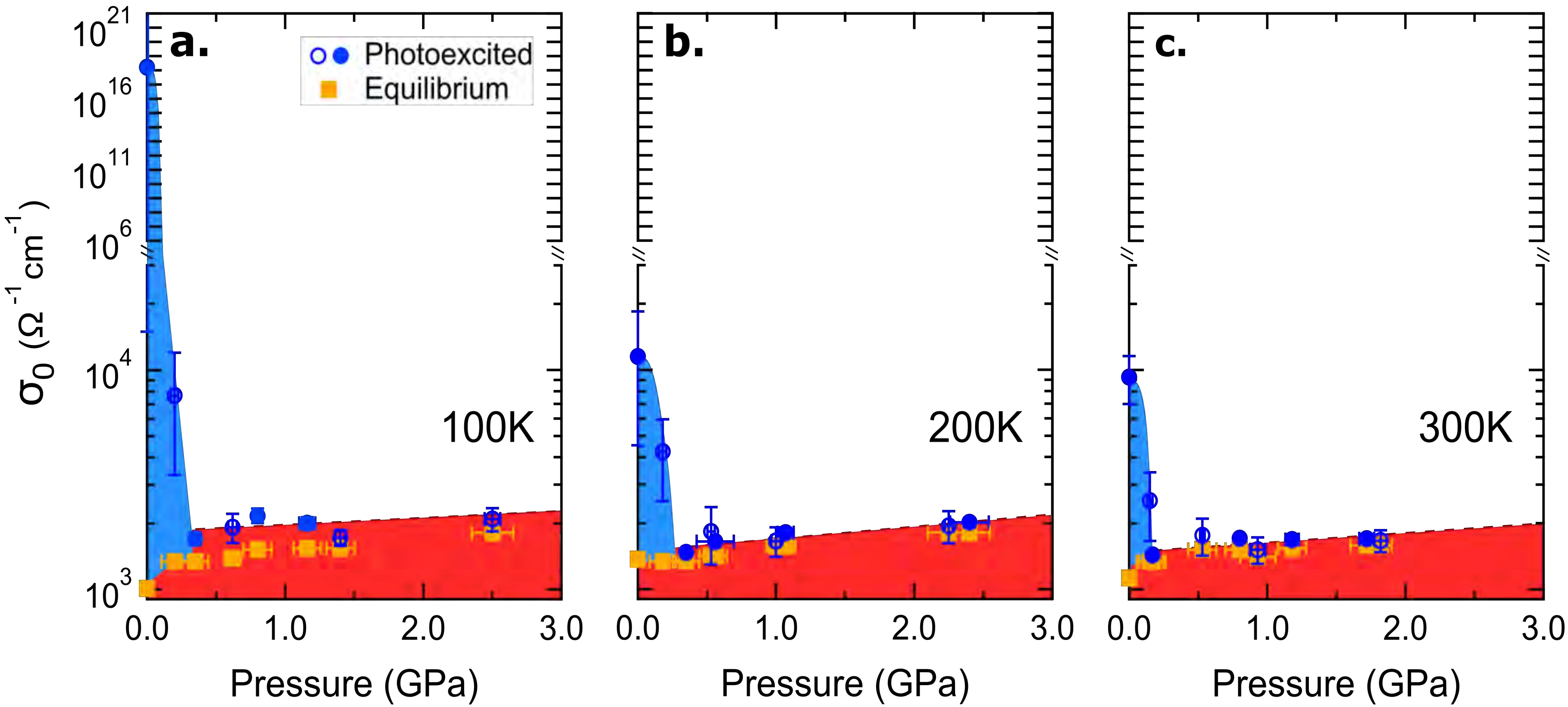
New data (2017 +): pressure dependent gap



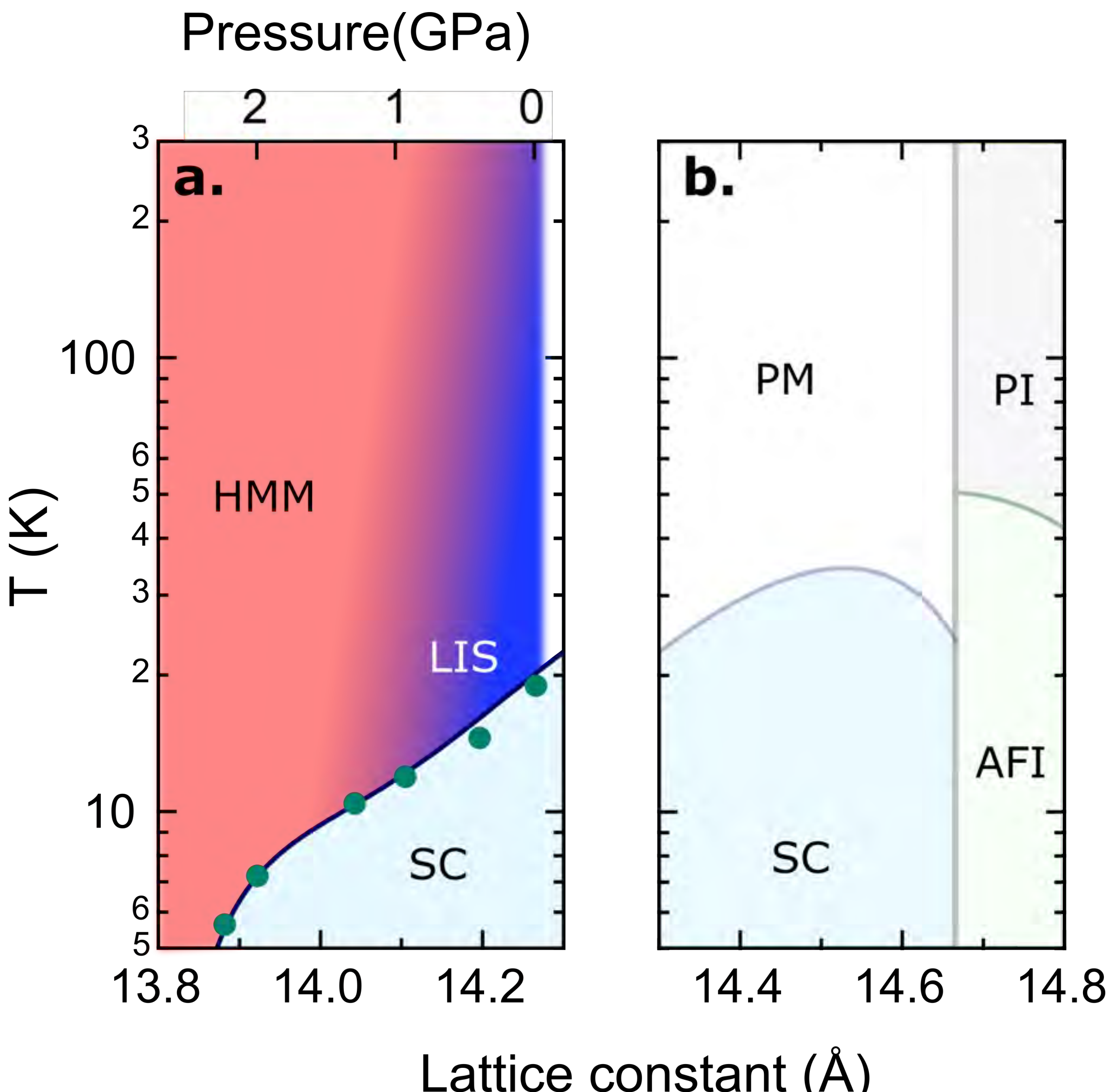
New data (2017 +): pressure dependent gap



New data (2017 +): pressure dependent conductivity



New data (2017 +): non-equilibrium phase diagram



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G. Gu
Brookhaven National Laboratory

Experimental Team
LCLS - SLAC

M. Ricco'
Universita' di Parma

Summary

Dynamical control of the crystal lattice

Use coherent radiation to drive quantum materials, discover new non-equilibrium phases of matter not found near equilibrium

Understand the non-equilibrium emergent phenomena

Explore new paradigms for device applications