

What can we learn about strongly coupled system by time-domain spectroscopy?

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SLAC

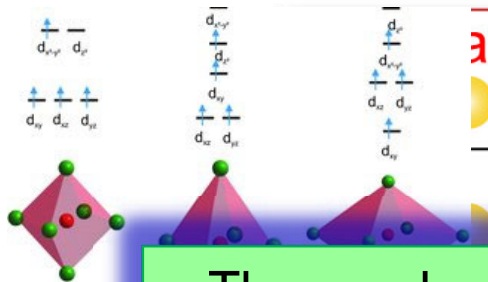


Challenge – complex electronic orders

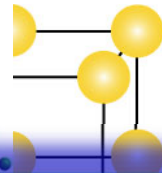


Ming Yi

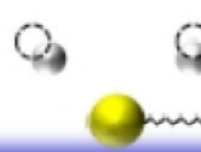
Jahn-Teller distortion



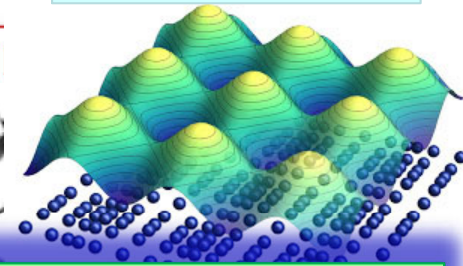
lattice



Cha



charge density wave



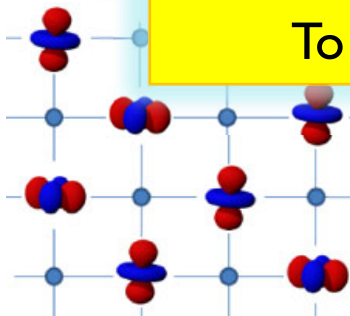
These orders interact such that small perturbations lead to large changes in material properties.

Interplay

→ Need a way to systematically study low lying excitations, to gain insights on how these orders interact

To understand the underlying microscopic ingredients

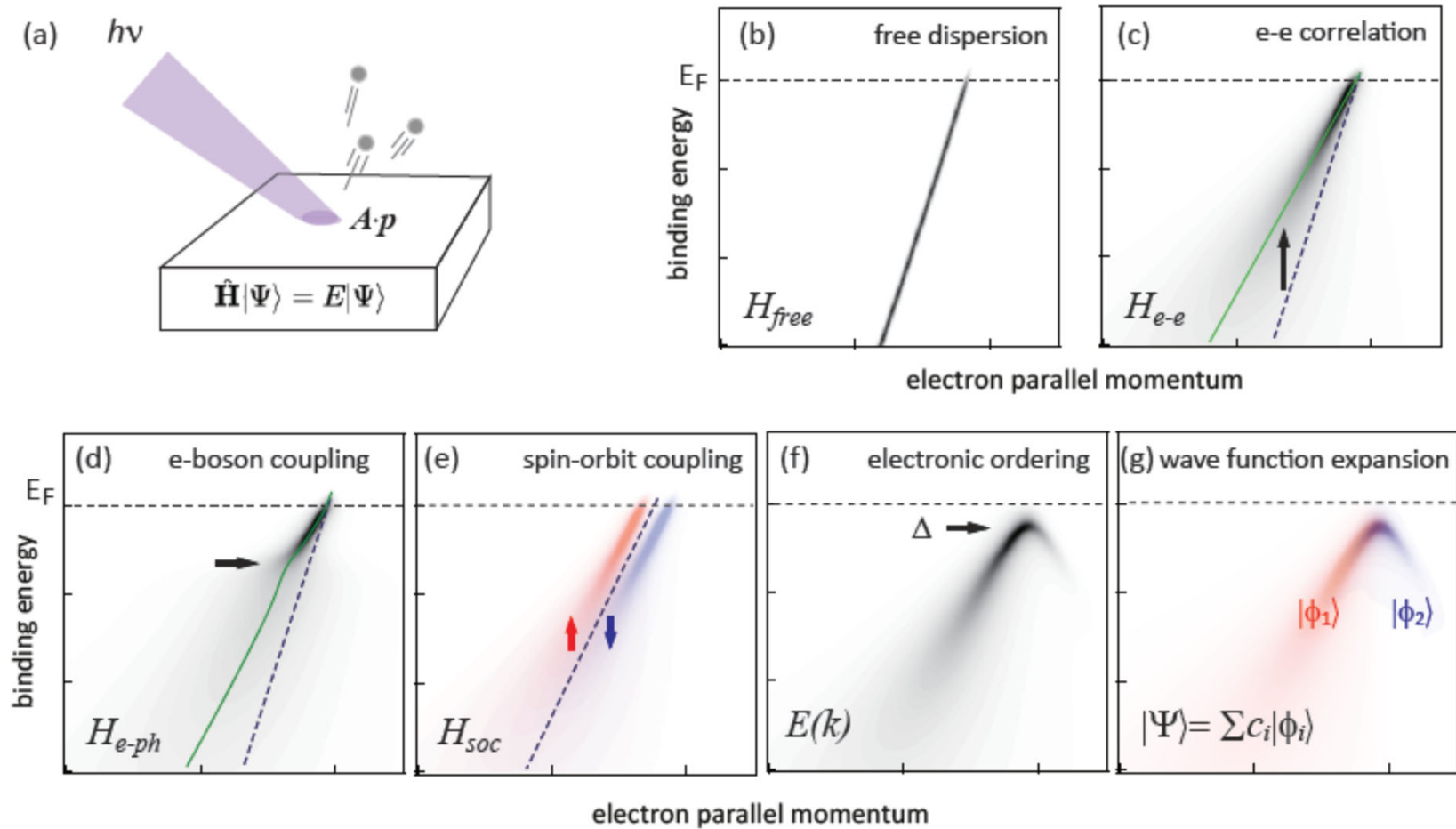
orb



U



Modalities of ARPES

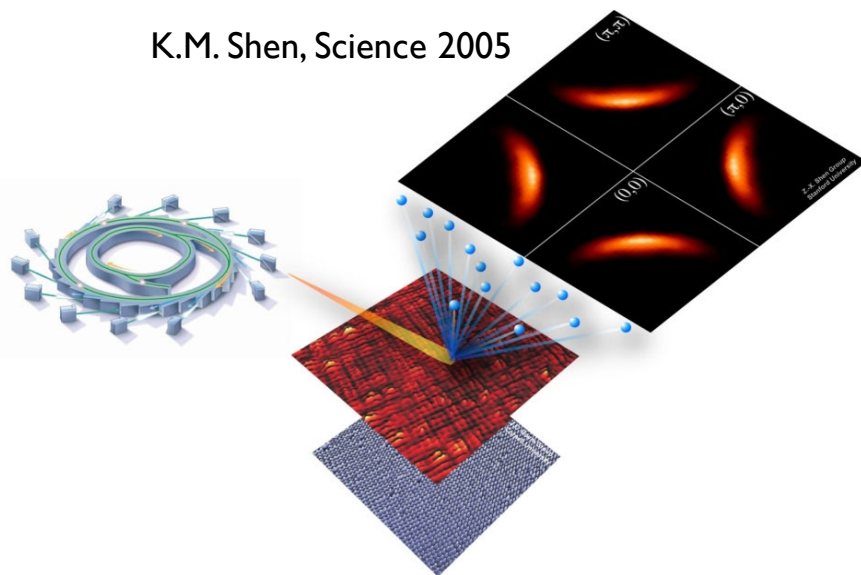


Sobota, He, Shen, RMP, 2019

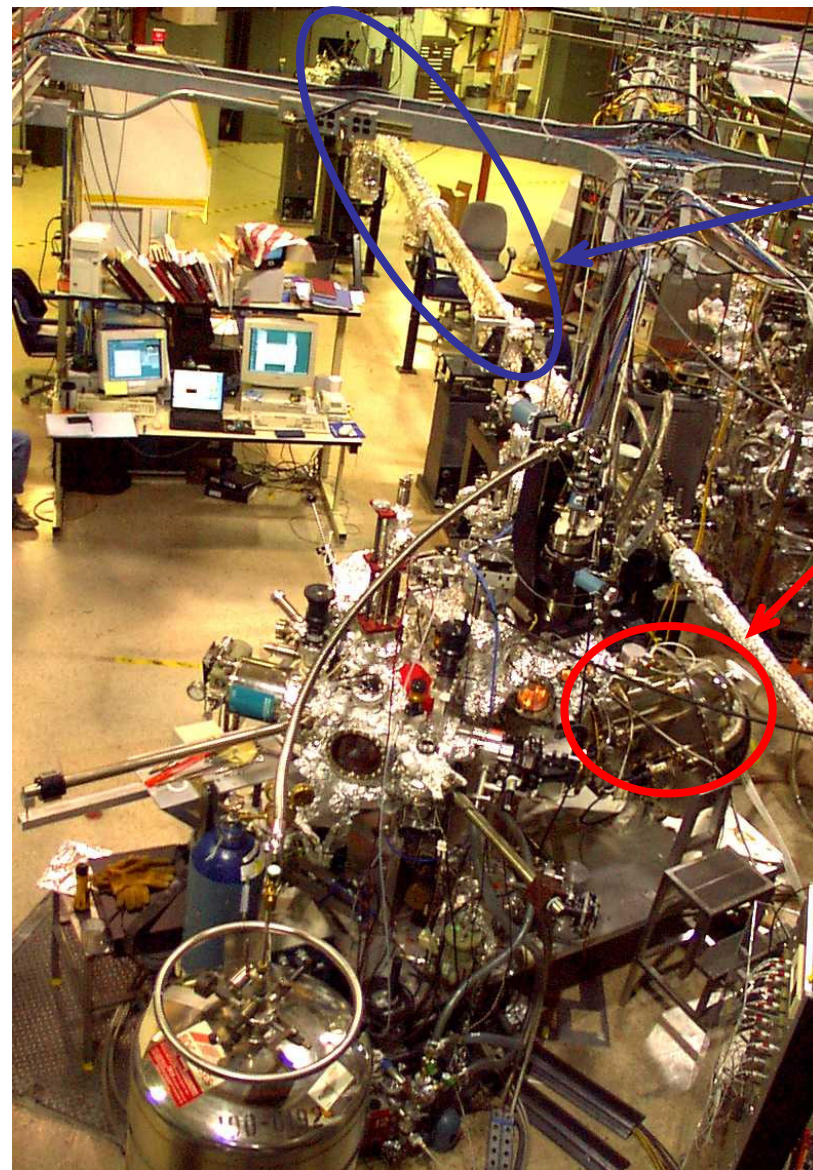


Angle-Resolved Photoemission Spectroscopy

K.M. Shen, Science 2005



STANFORD SYNCHROTRON RADIATION LABORATORY

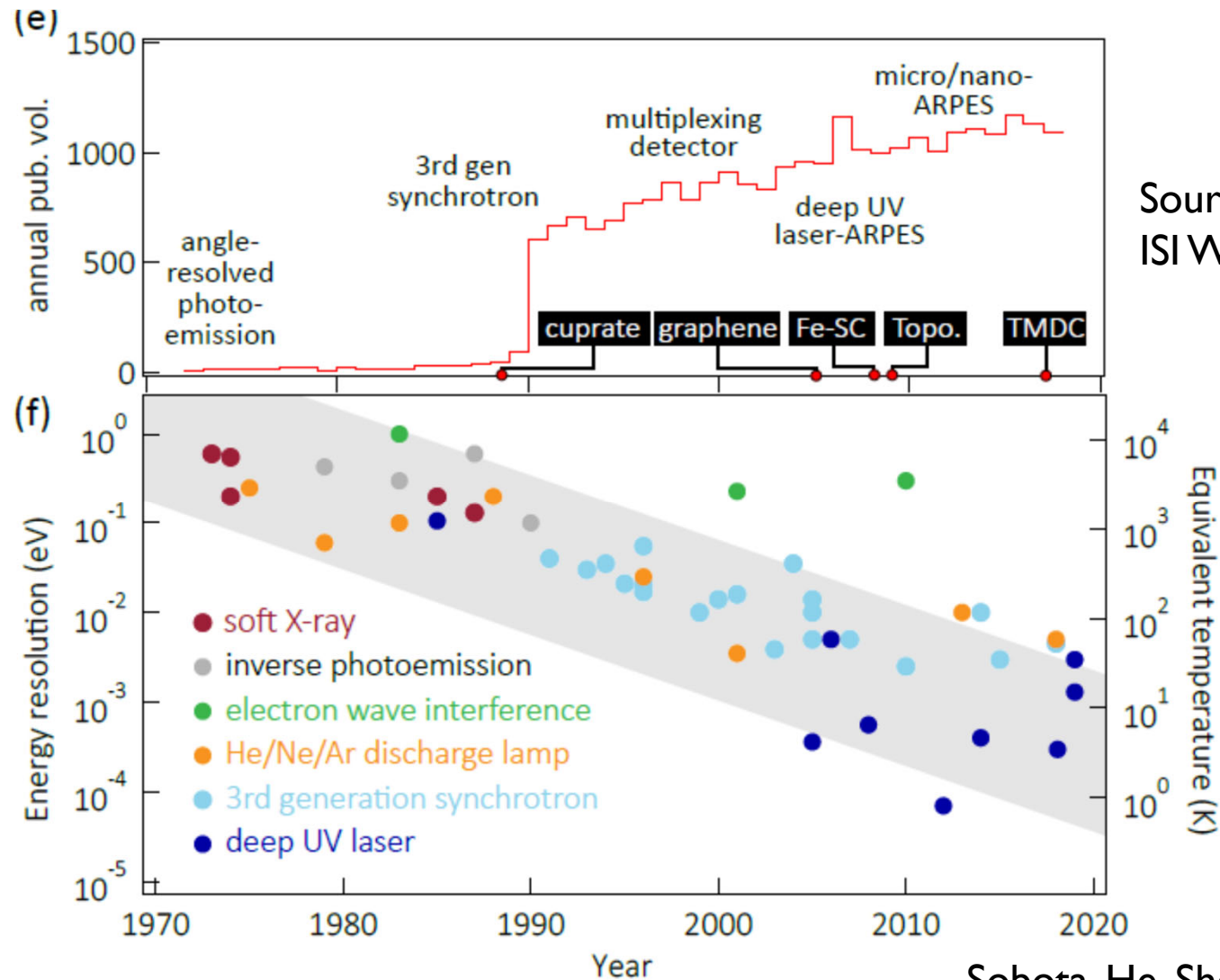


NIM

SES-200



Science and ARPES Tool Development

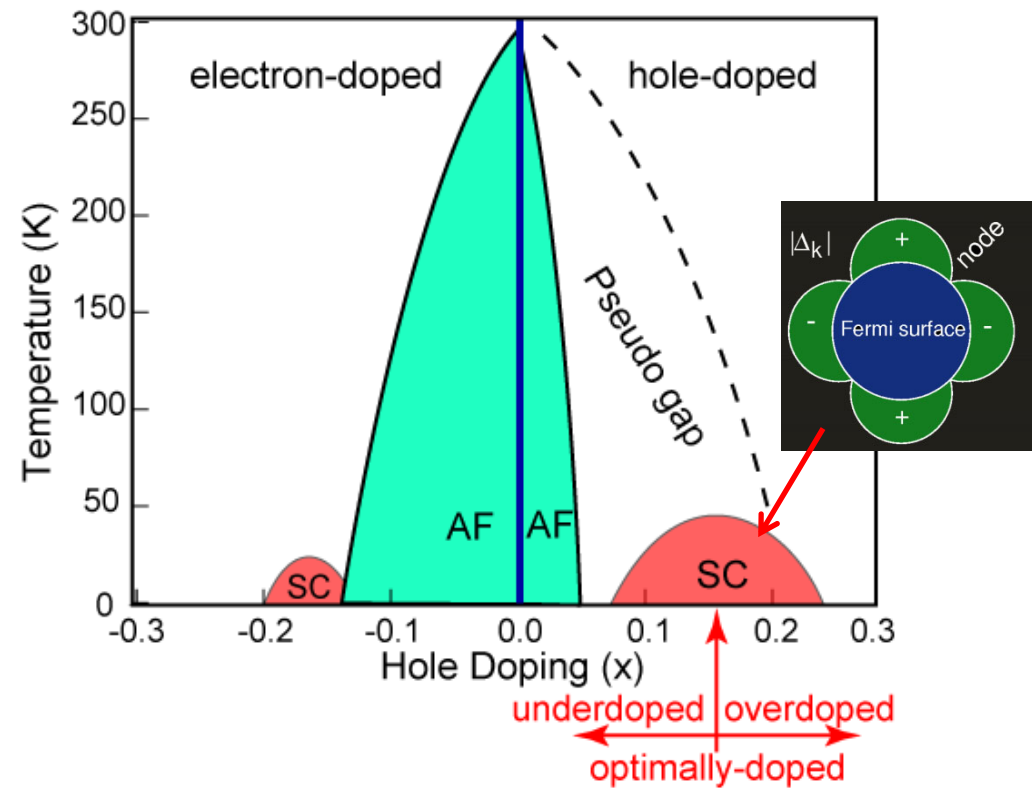
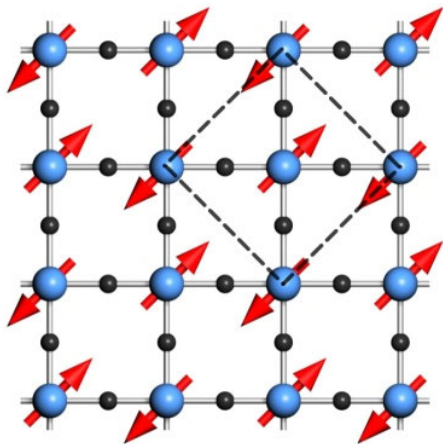
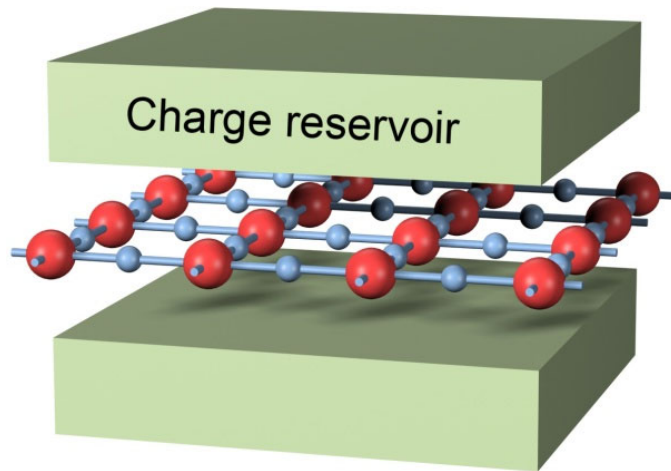


Source
ISI Web of Science

Sobota, He, Shen, RMP, 2019



High- T_c Cuprate Superconductors



Courtesy of G.Yu



Enhanced Pairing in 1 UC FeSe on STO

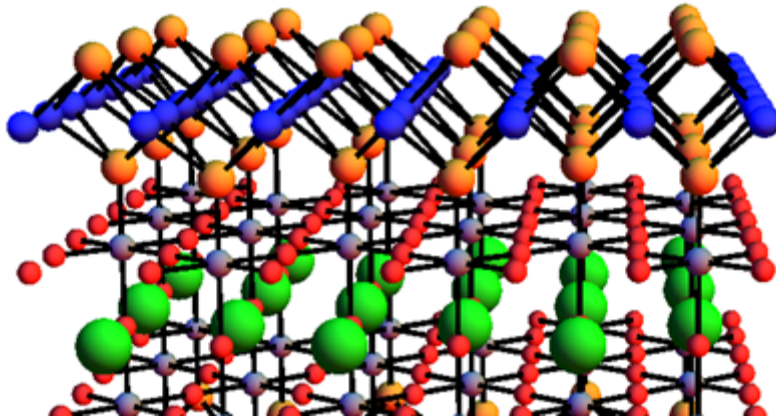
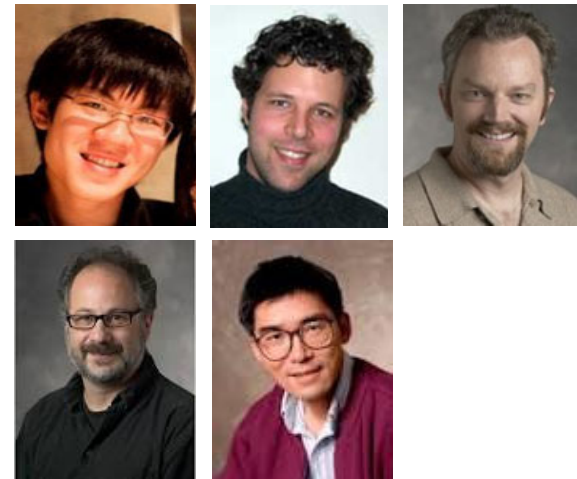
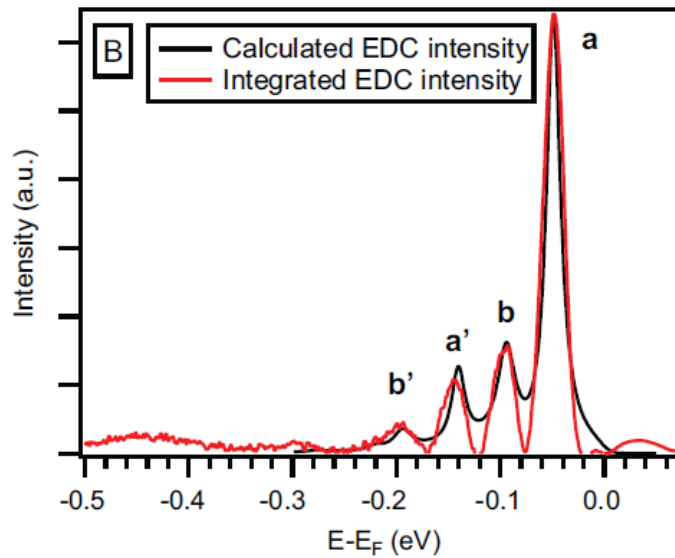


Figure courtesy – Dunghai Lee

1 UC FeSe
TiO _{2-x}
SrO
TiO _{2-x}



Electron-Phonon problem in Strongly Correlated Materials

- ▣ *Frequency domain – progress and challenge*
 - *Overview and Recent updates from cuprates*
- ▣ *Time domain – complementary tool*

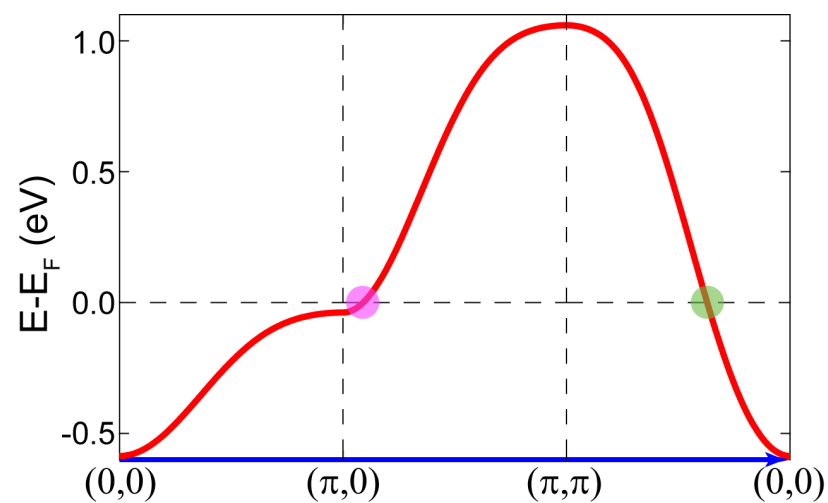
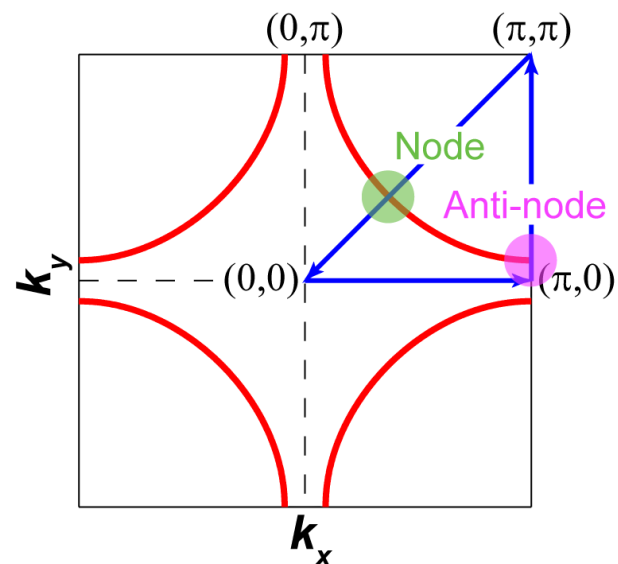
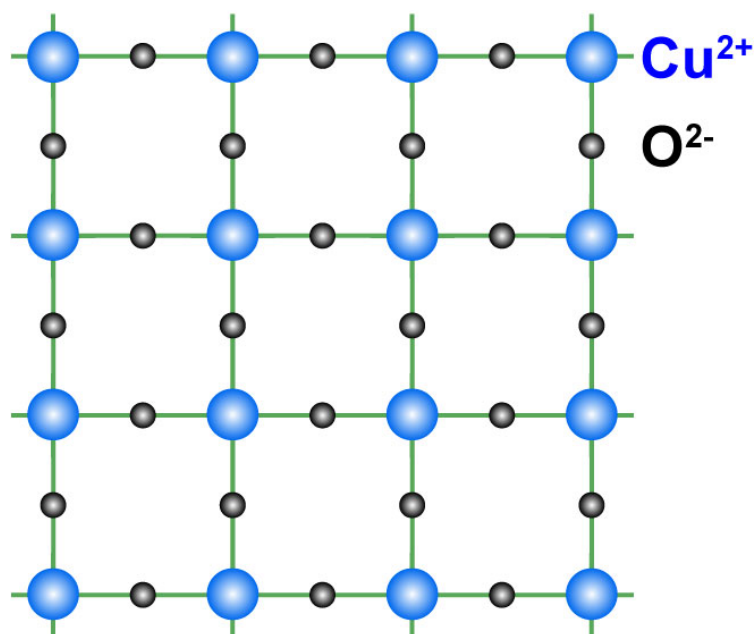


Reasons to consider electron-phonon interaction in novel superconductor

- ❑ Direct spectral signature of mode coupling
- ❑ Chemical potential puzzle
- ❑ Single hole in AFM state
- ❑ Polaron signature
- ❑ Enhanced superconductivity
- ❑ Electronic phase diagram – From global entanglement to Fermi liquid



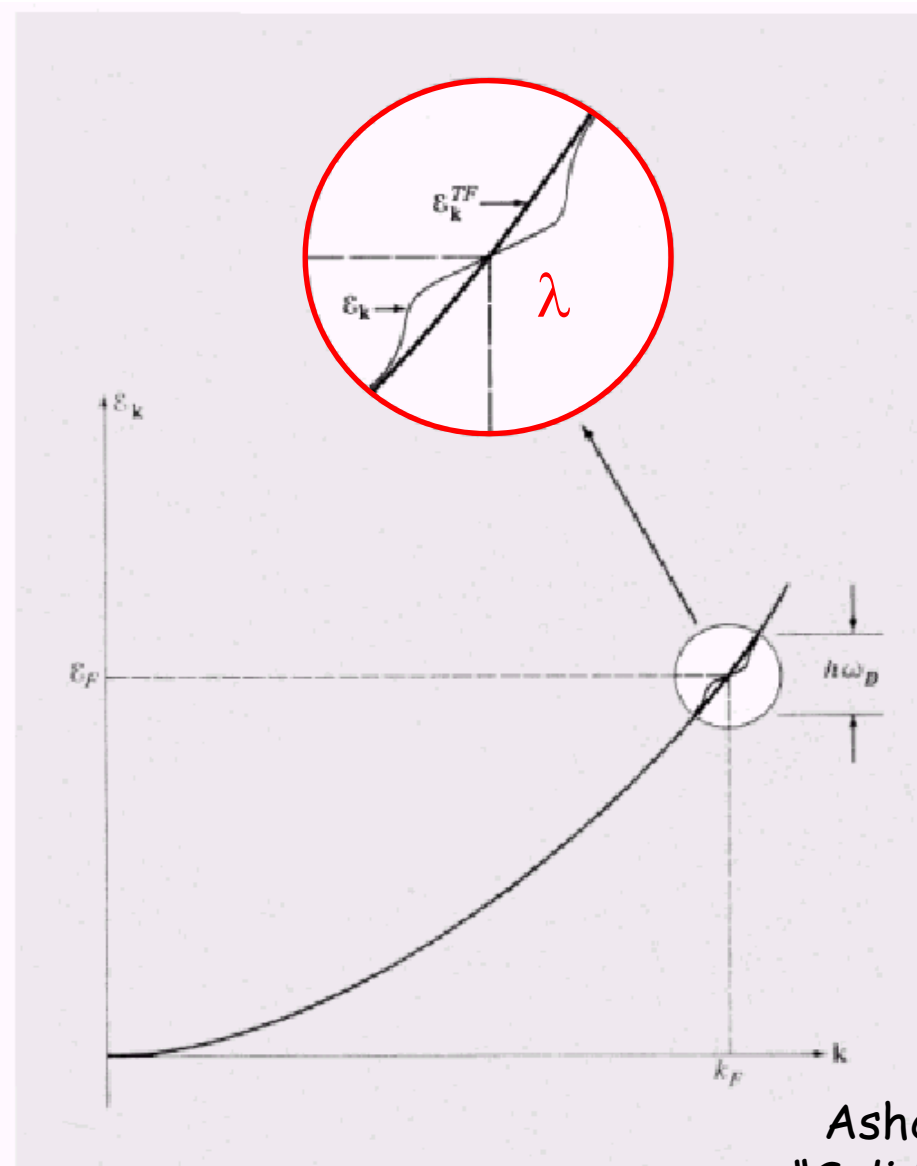
Electronic Structure and Fermi Surface



Coupling to a collective mode: e.g. phonons

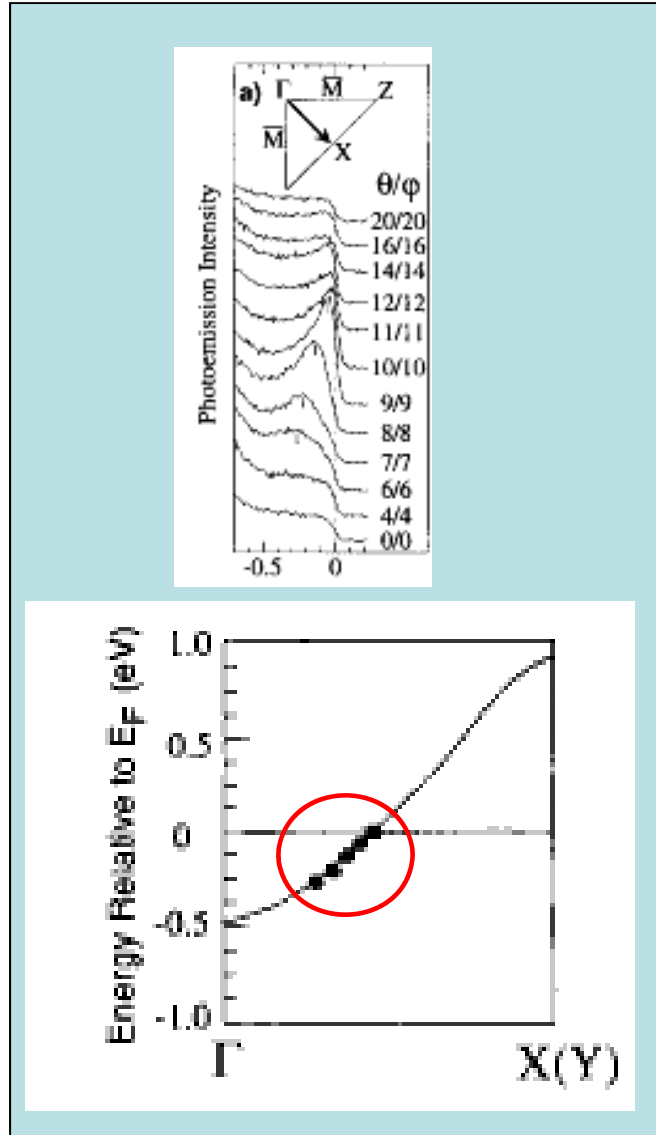
λ
electron-mode
coupling constant

Screening of electrons
due to ions $\rightarrow m^*$

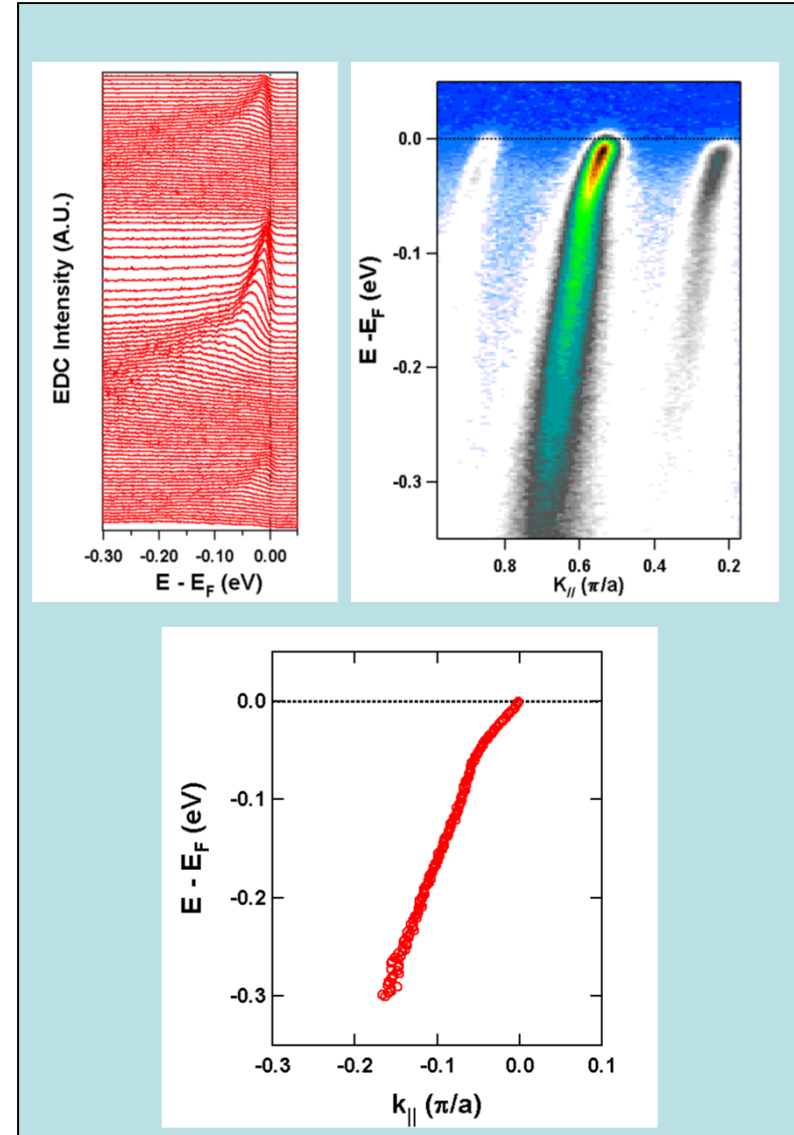


Better Resolution Reveals Electron Kinkiness in High-Tc Materials

Angular Resolution: 2 degrees

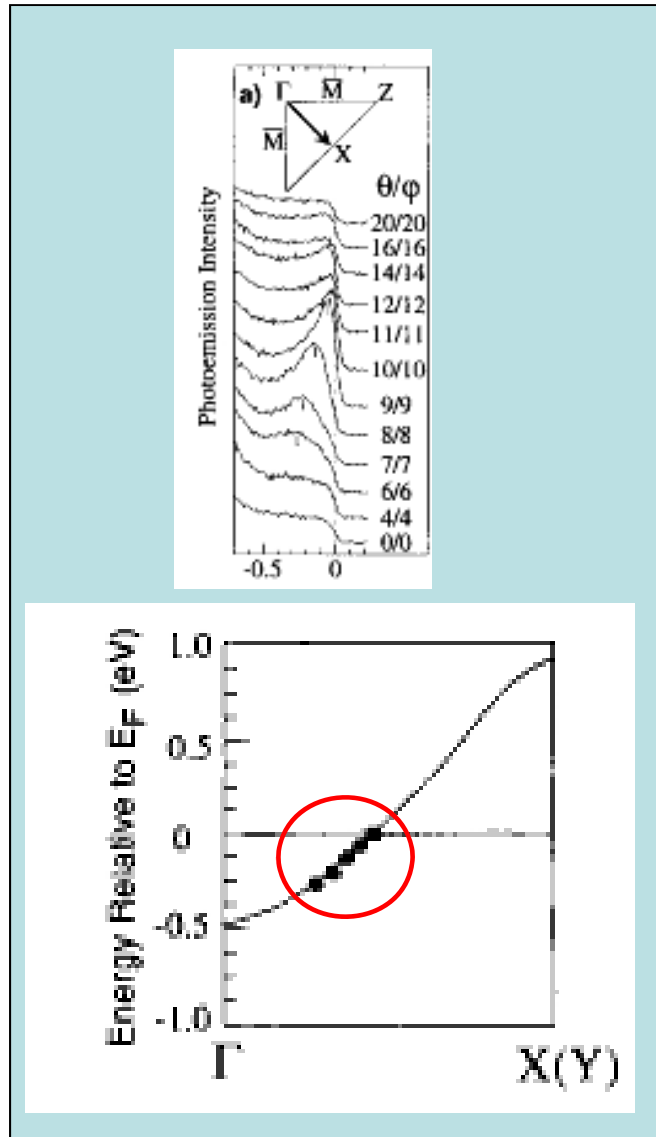


Angular Resolution: 0.3 degree

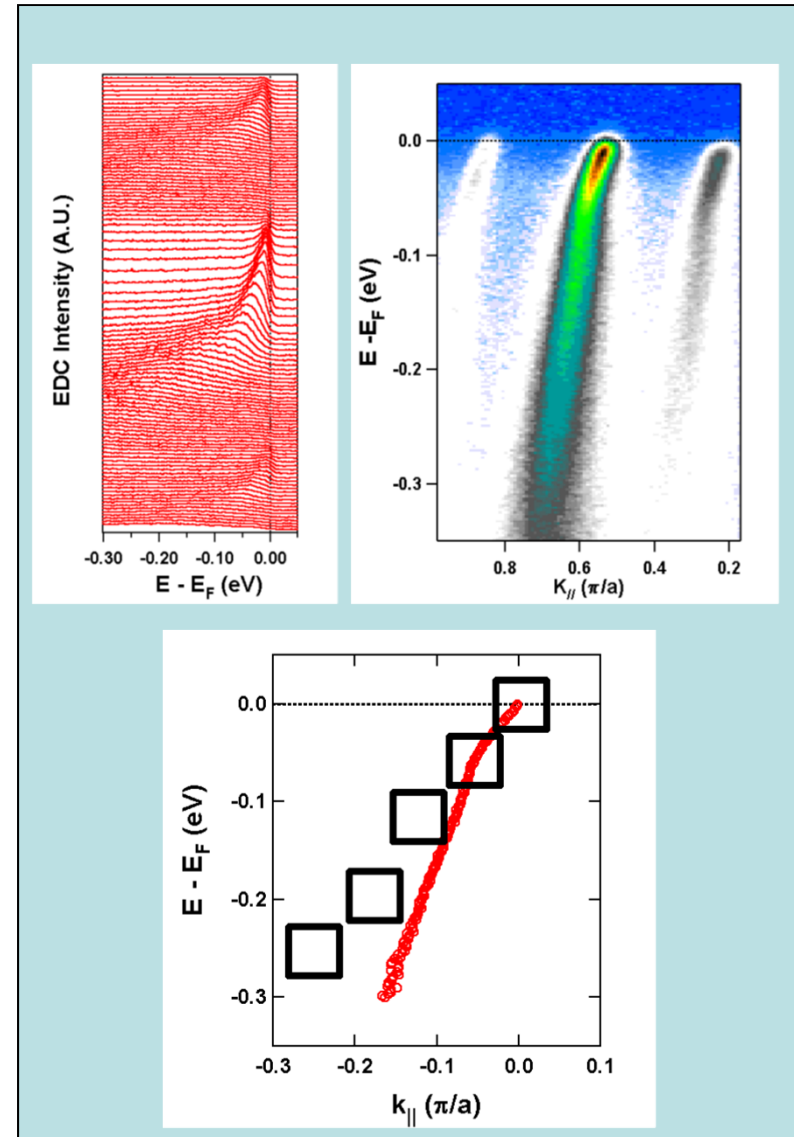


Better Resolution Reveals Electron Kinkiness in High-Tc Materials

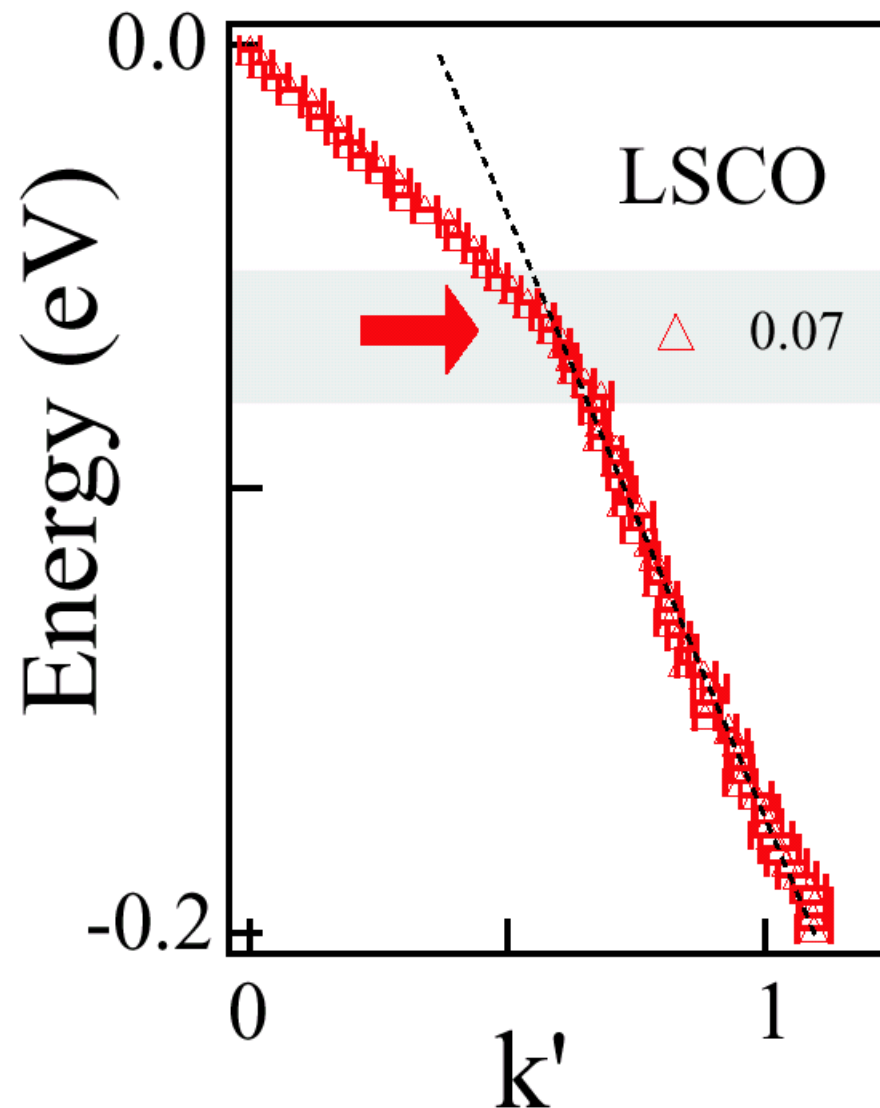
Angular Resolution: 2 degrees



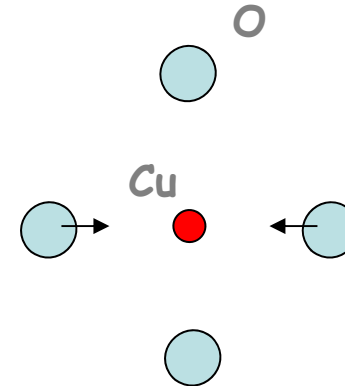
Angular Resolution: 0.3 degree



Coupling to High energy phonons?



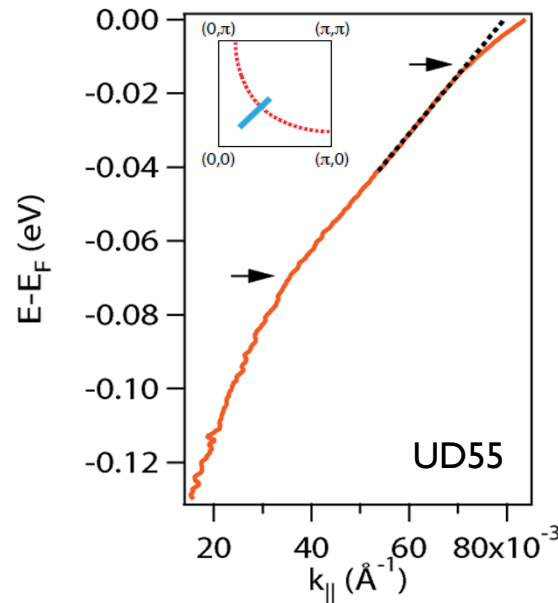
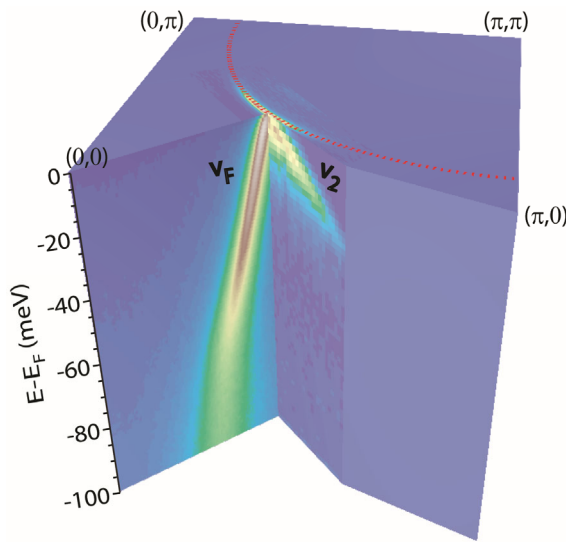
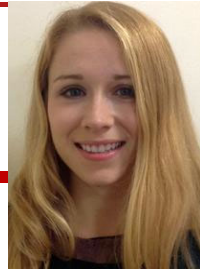
Zone edge
Half-breathing mode



- LO phonon in LSCO at 70meV (McQueeney et al., L. Pintschovius and Braden).

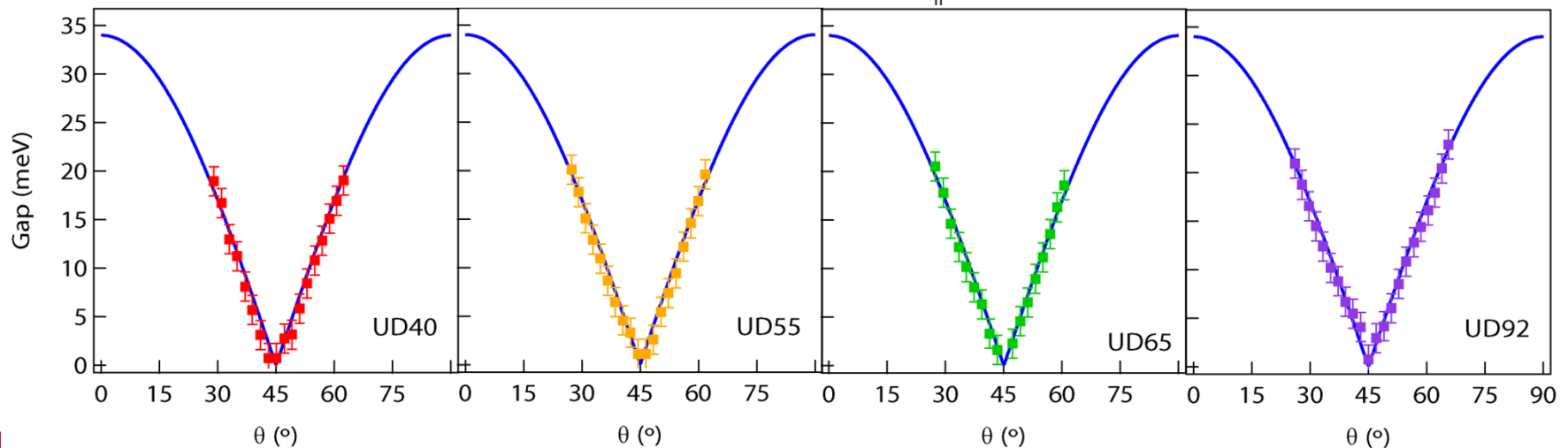


Precision Measurement of the Node

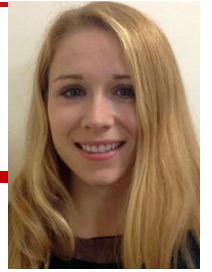


**Fundament
thermodynamic
Quantity**

$$\frac{\kappa_0}{T} \propto \frac{v_F}{v_\Delta}$$

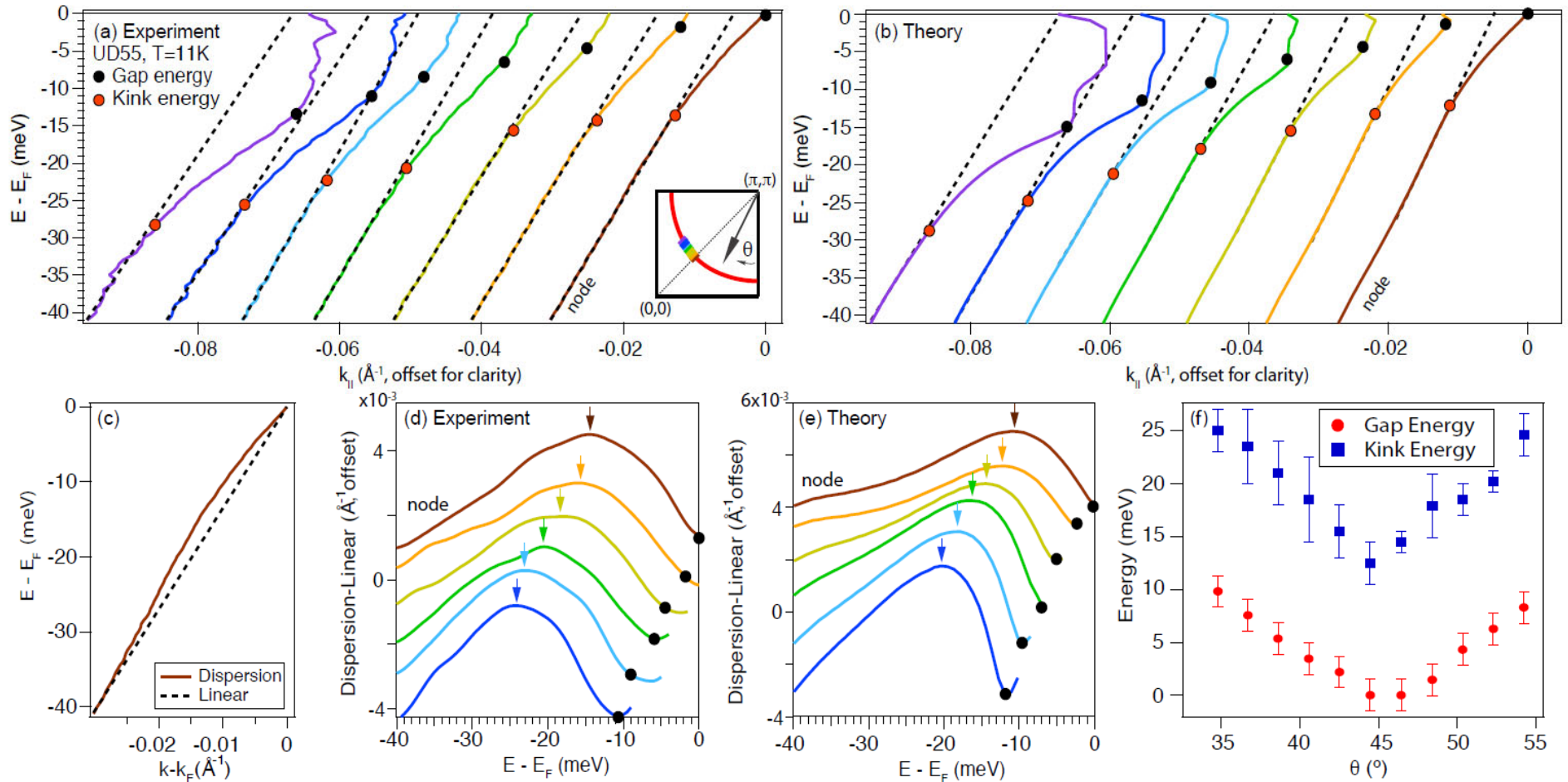


Experiment and Theory – forward scattering

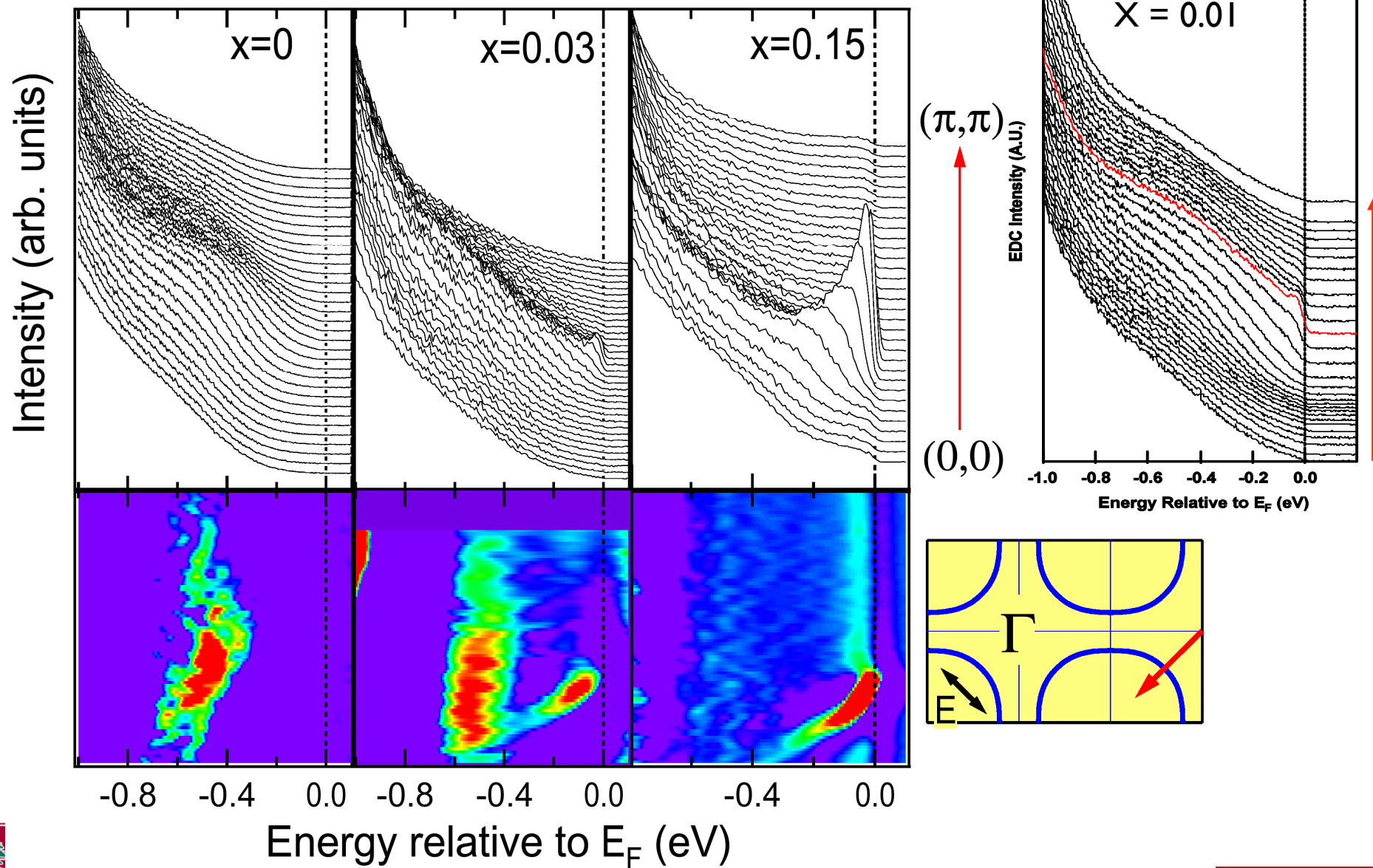


Insight from simulation: Importance of Long Range Coulomb Interaction

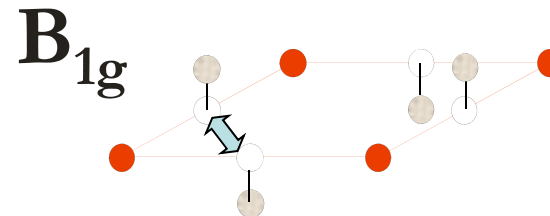
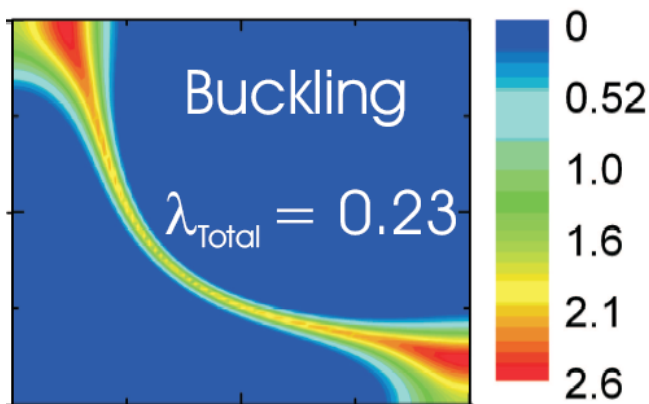
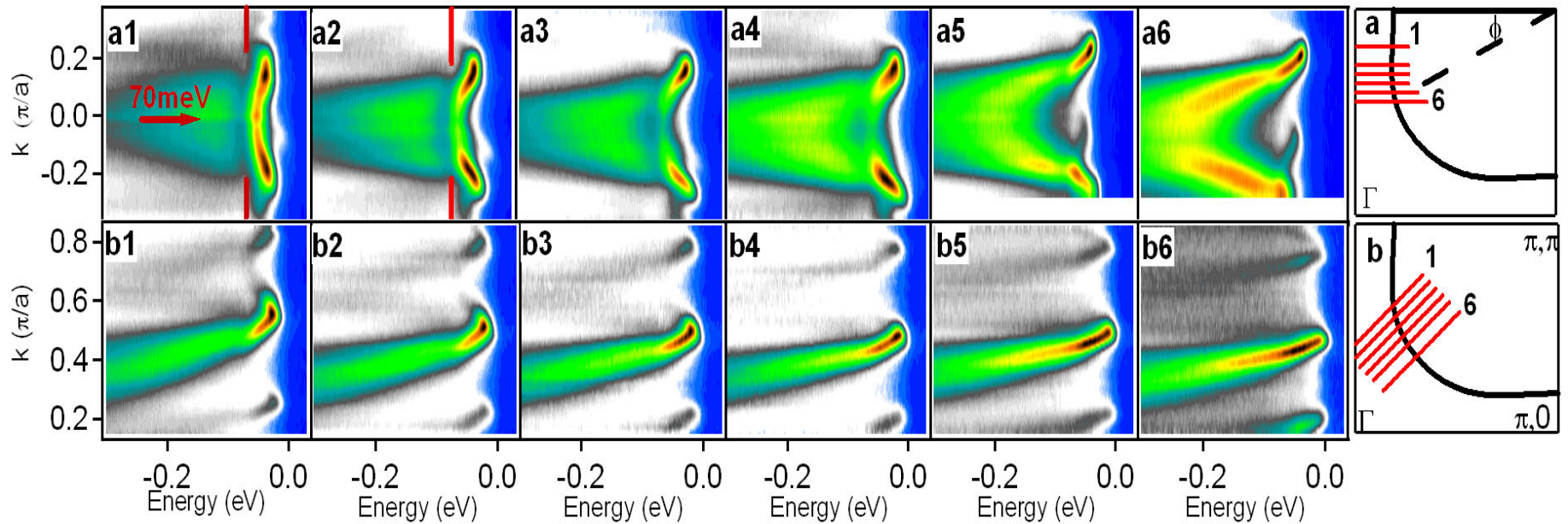
Vishik, Johnston, **Devereaux**, Shen, Lu, Moore et al., Physical Review Letters, 104, 207002 (2010); 108, 166404 (2012)



Samples of LSCO Data



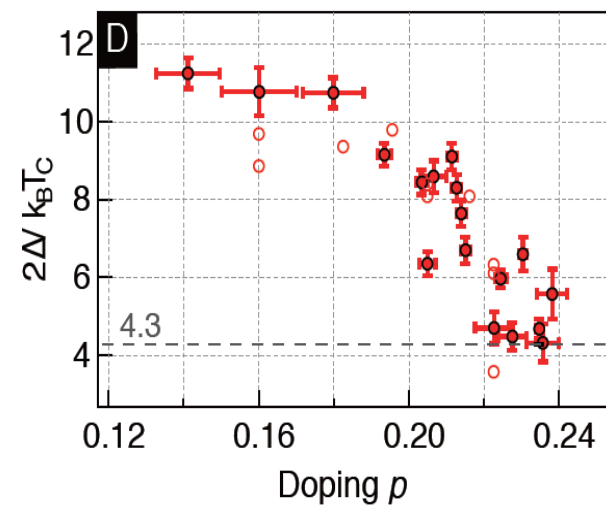
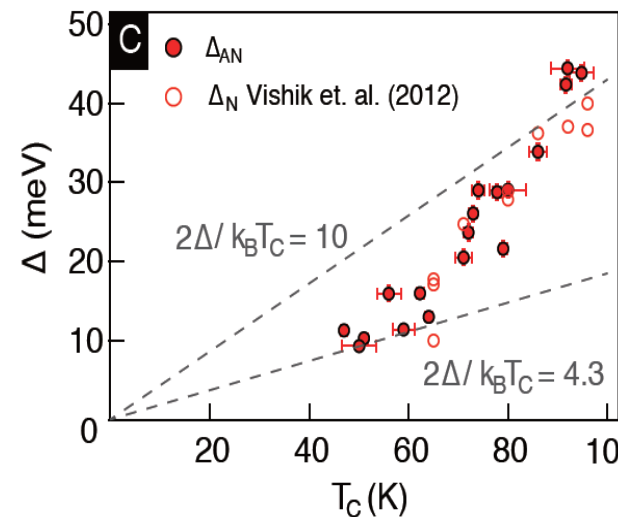
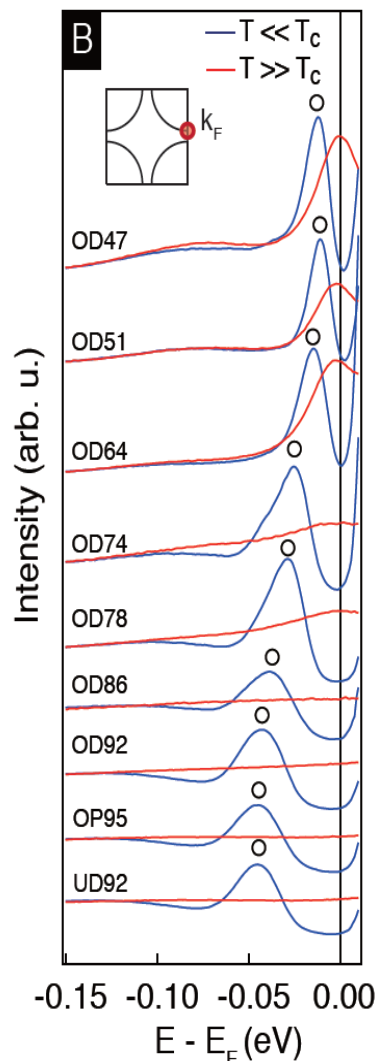
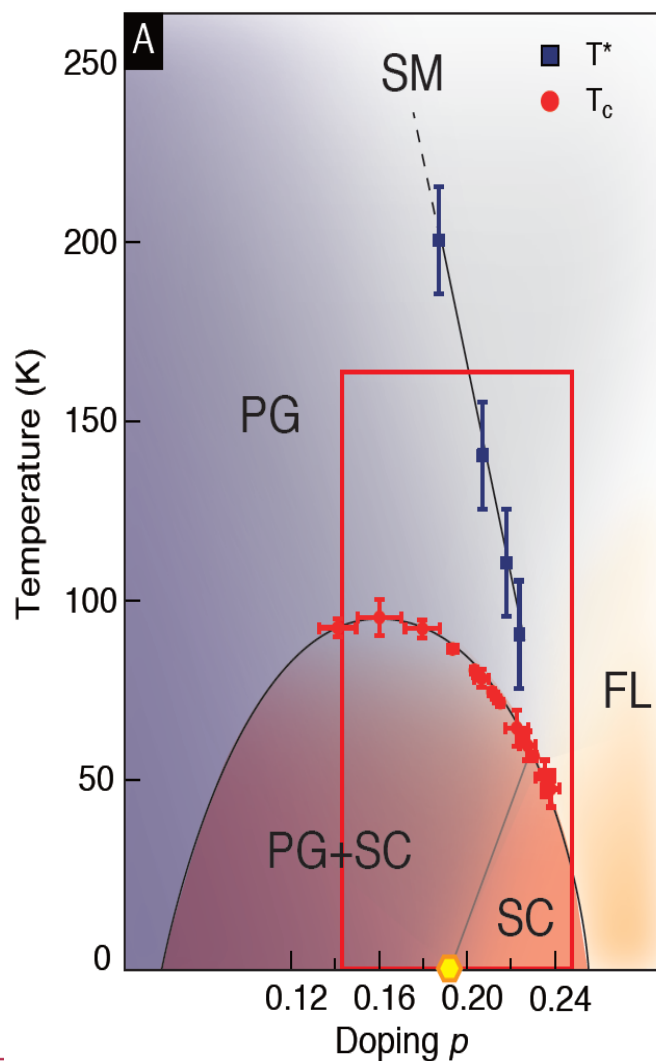
An example of anisotropic el-ph interaction



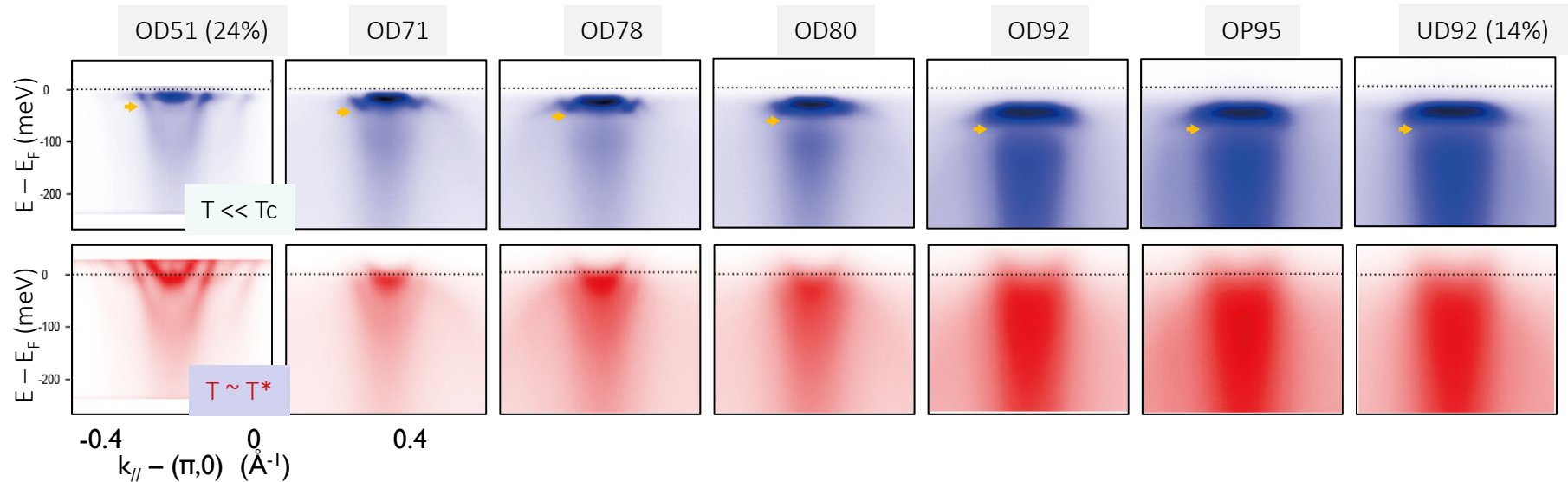
T. Cuk et al., cond-mat/0403521, PRL04
T. Devereaux et al. cond-mat/0403766, PRL04



Change of the superconducting gap and character



Emergence of the antinodal “dip”

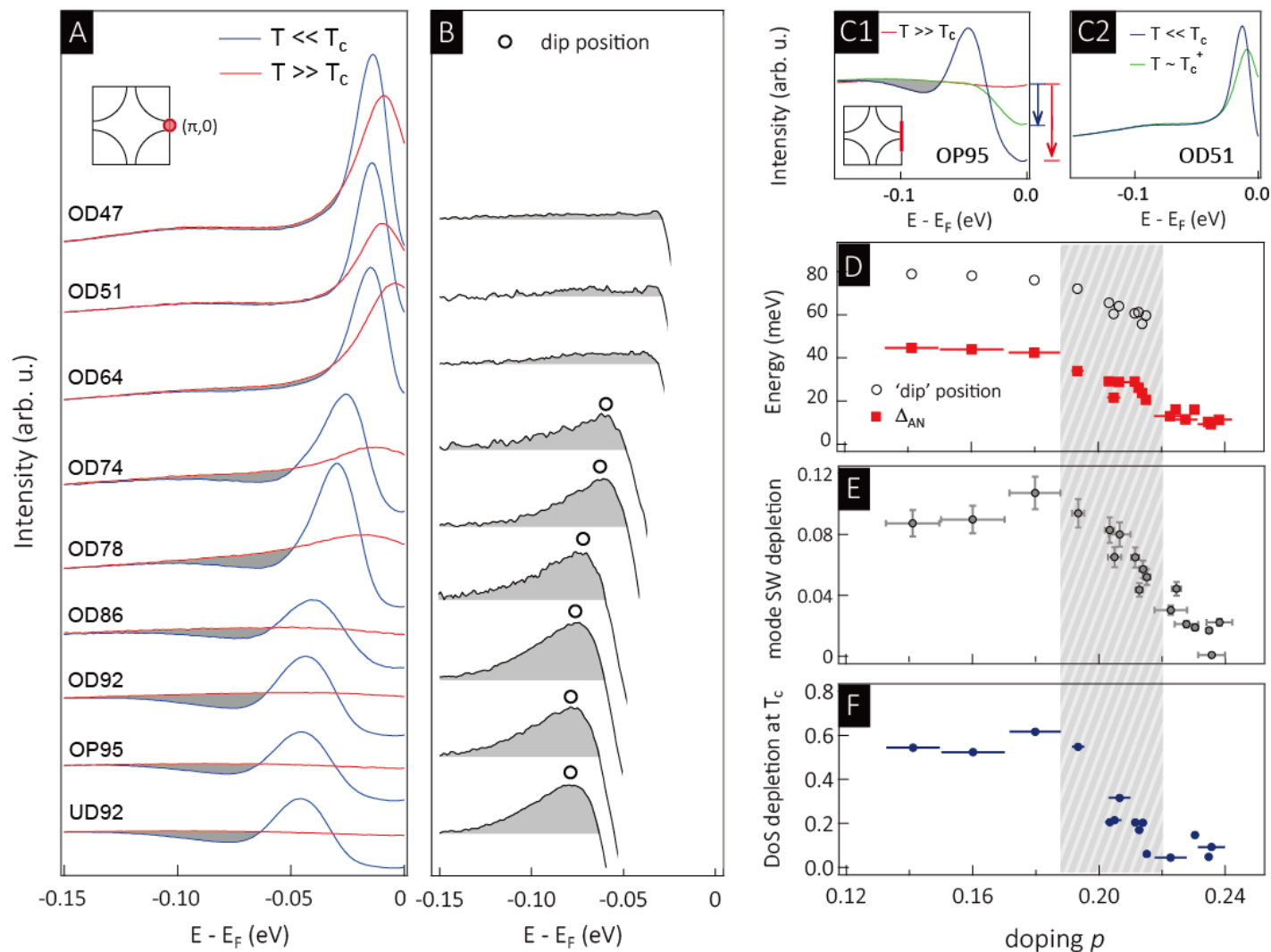


Dip strength and energy quickly increases after $T_c \geq 70\text{K}$

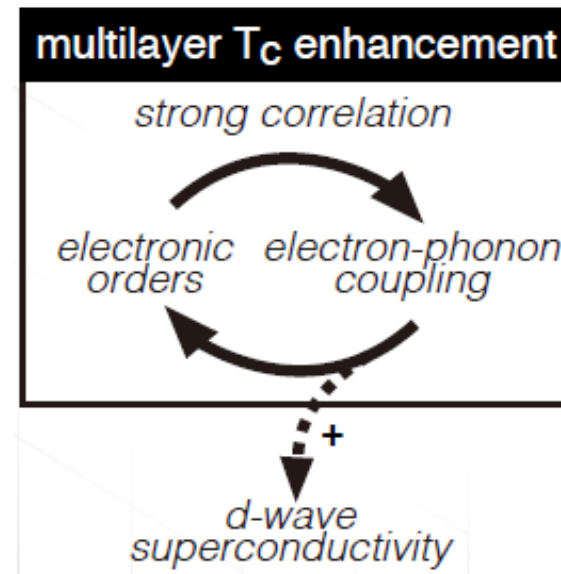
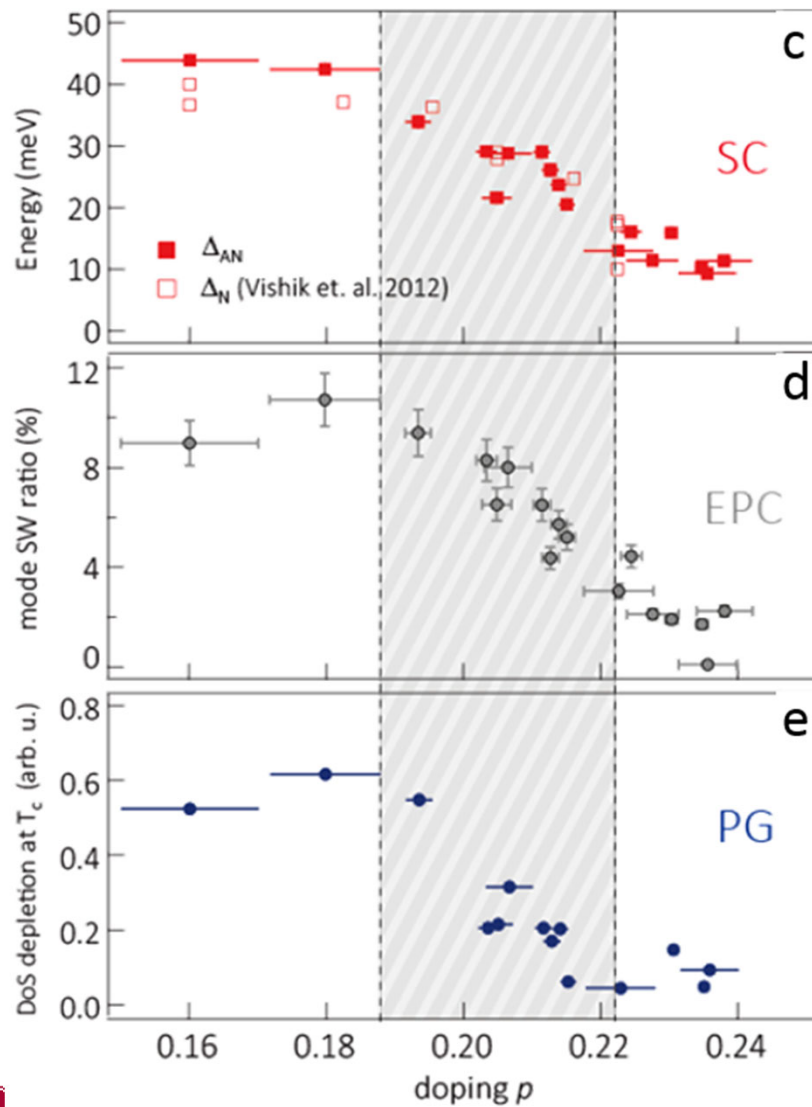
Superconducting gap monotonically increases with underdoping



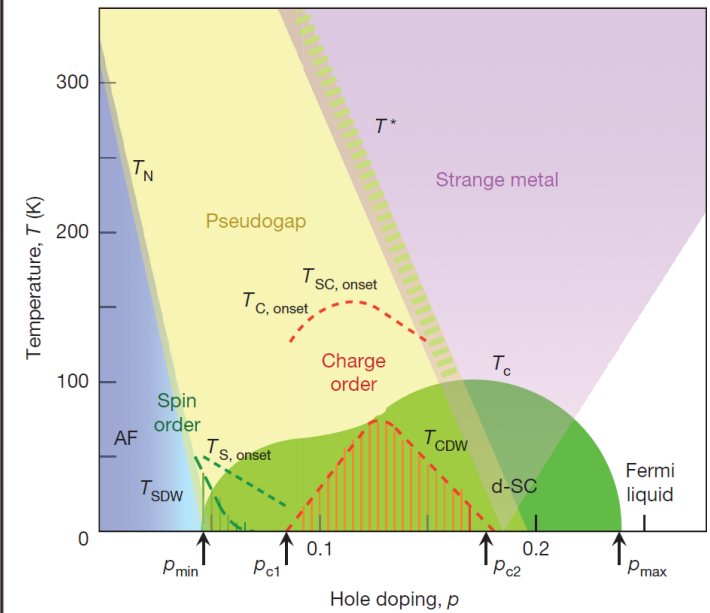
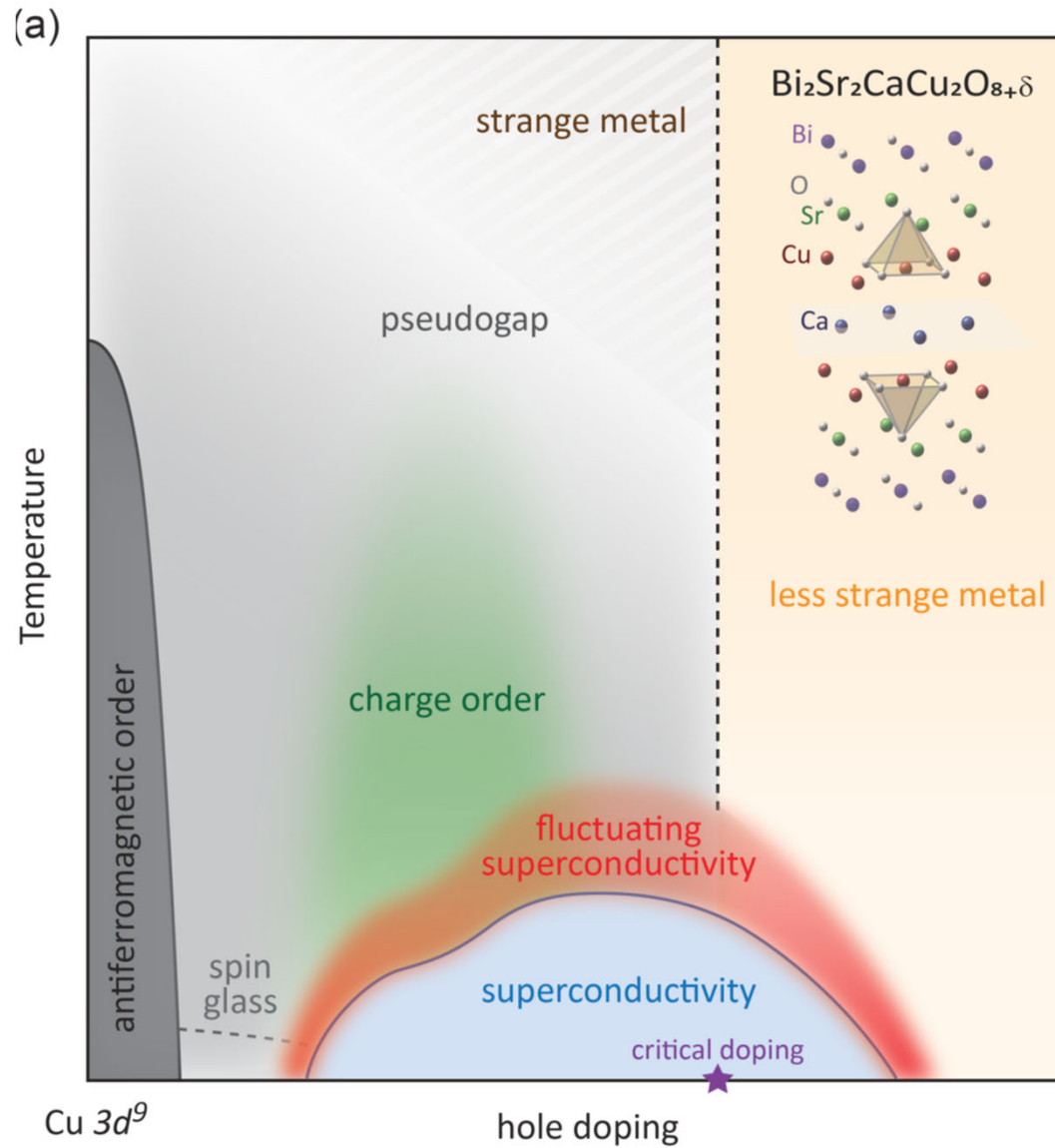
Evolution of the mode coupling “dip”

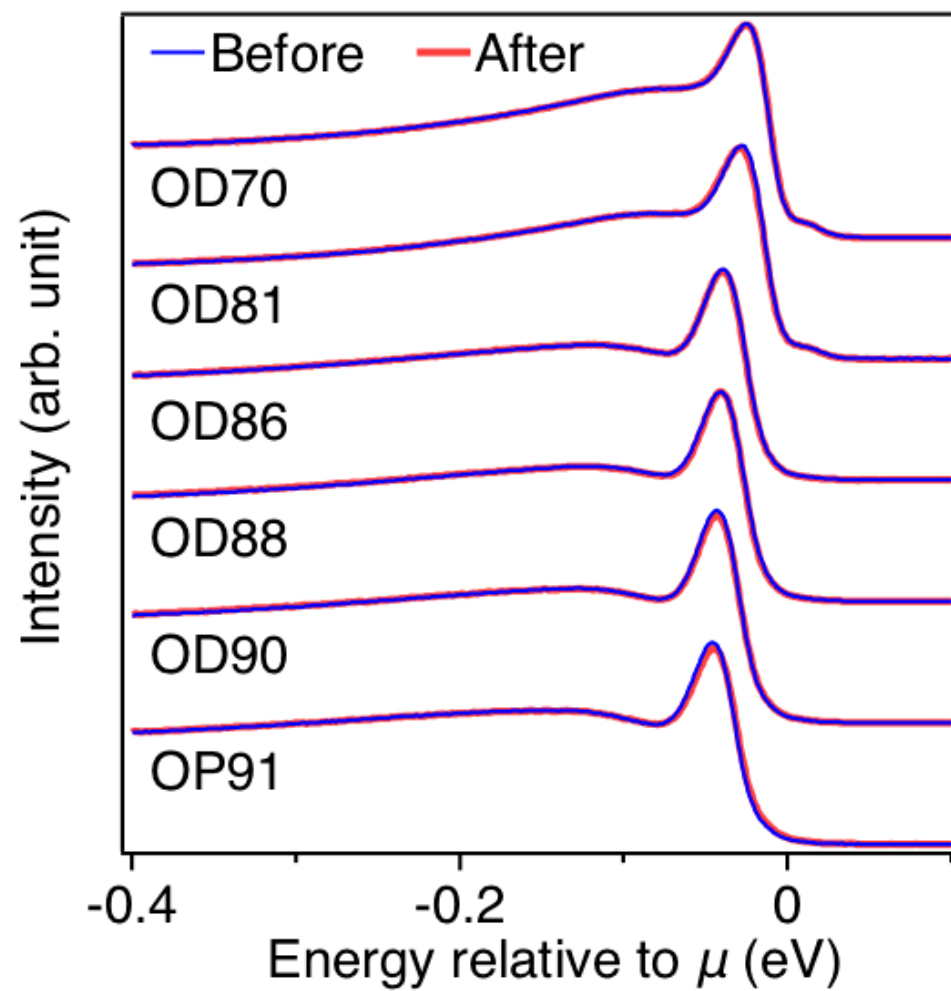


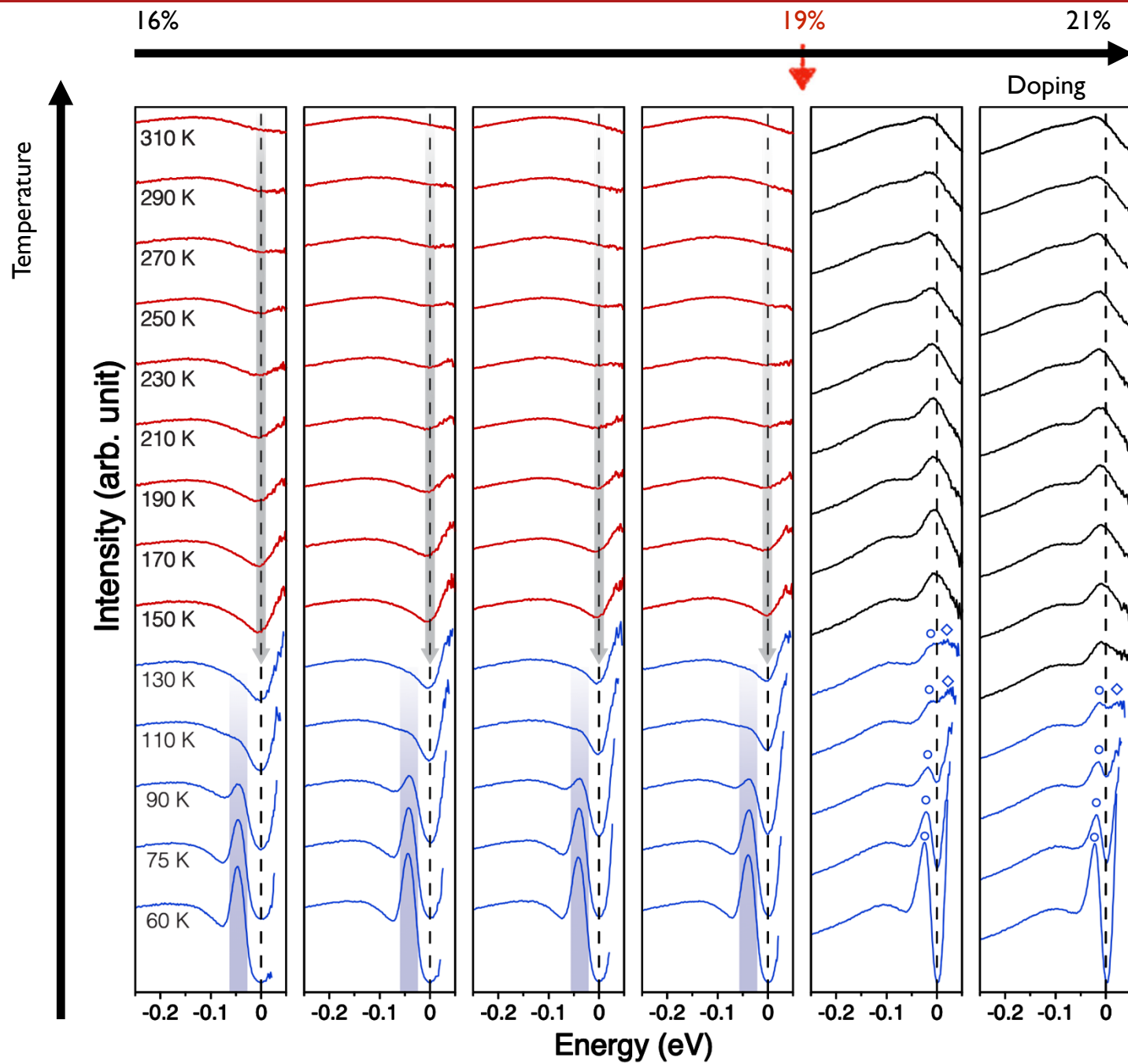
Coordinated change in EPC and correlation



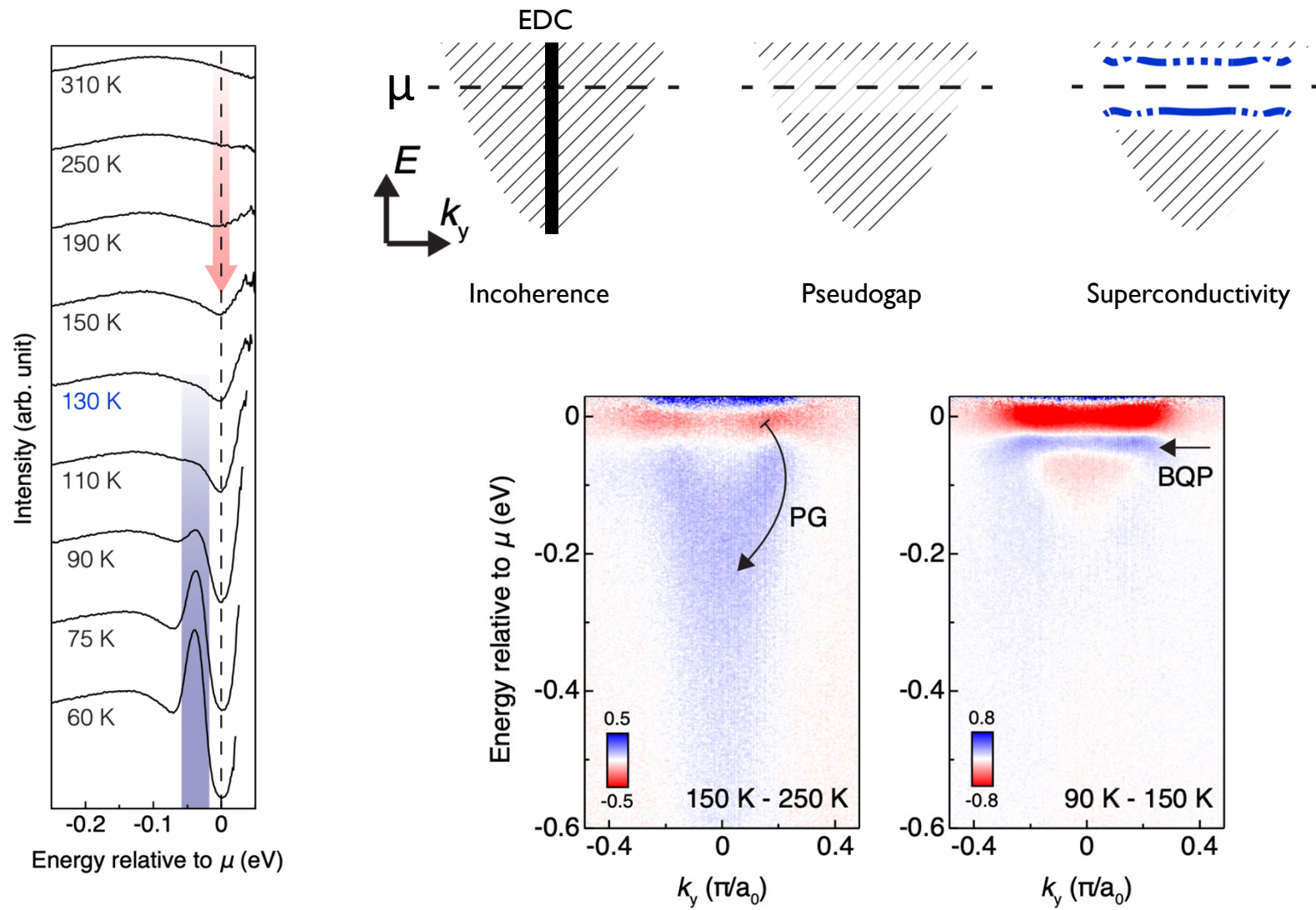
Phase Diagram



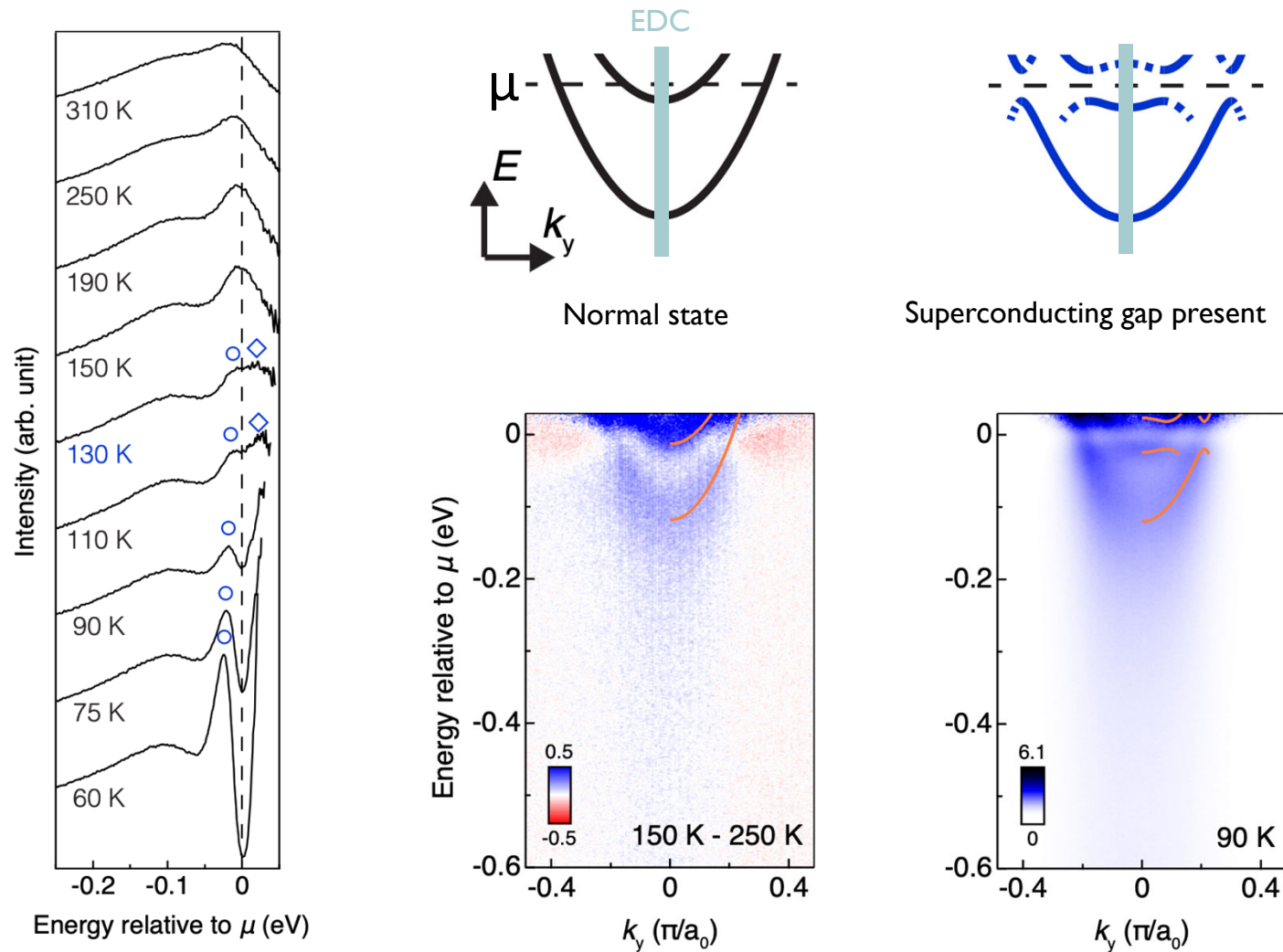




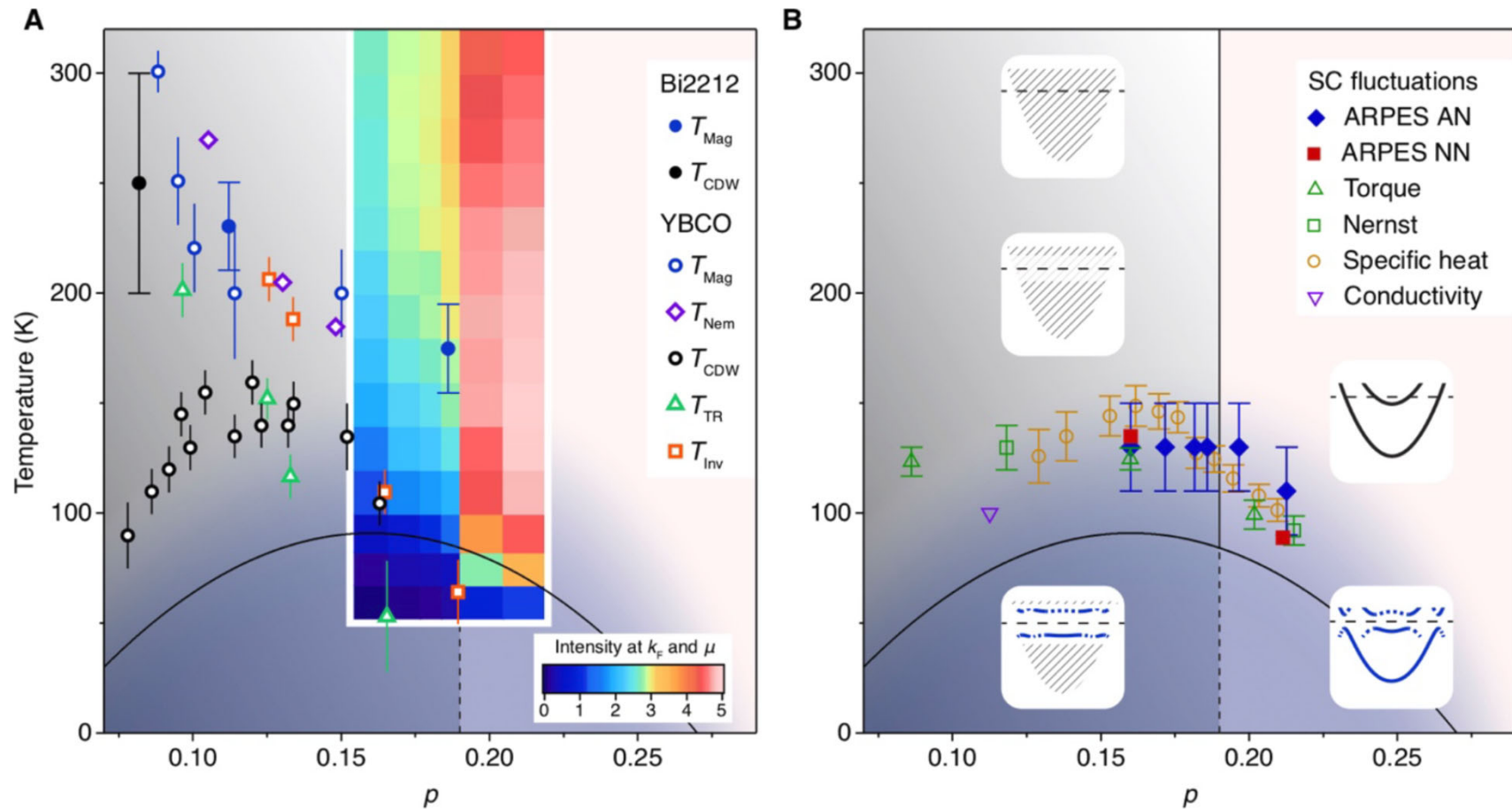
Two “gaps” for $p < 0.19$ ($T_c \sim 86$ K)



One gap for $p > 0.19$ ($T_c \sim 81$ K)



ARPES – as a Many-Body Spectroscopy

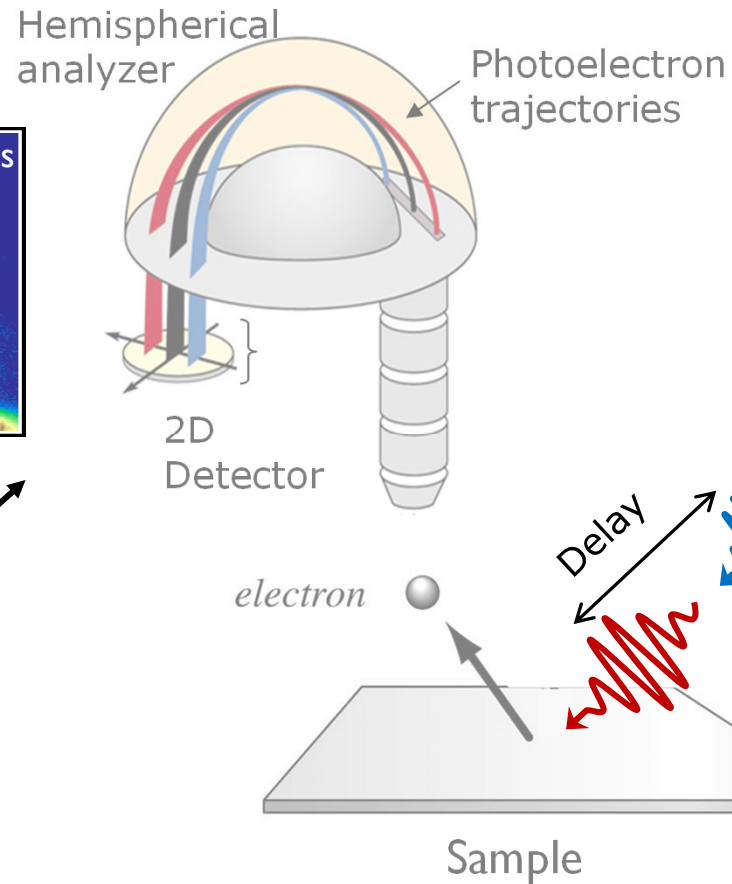
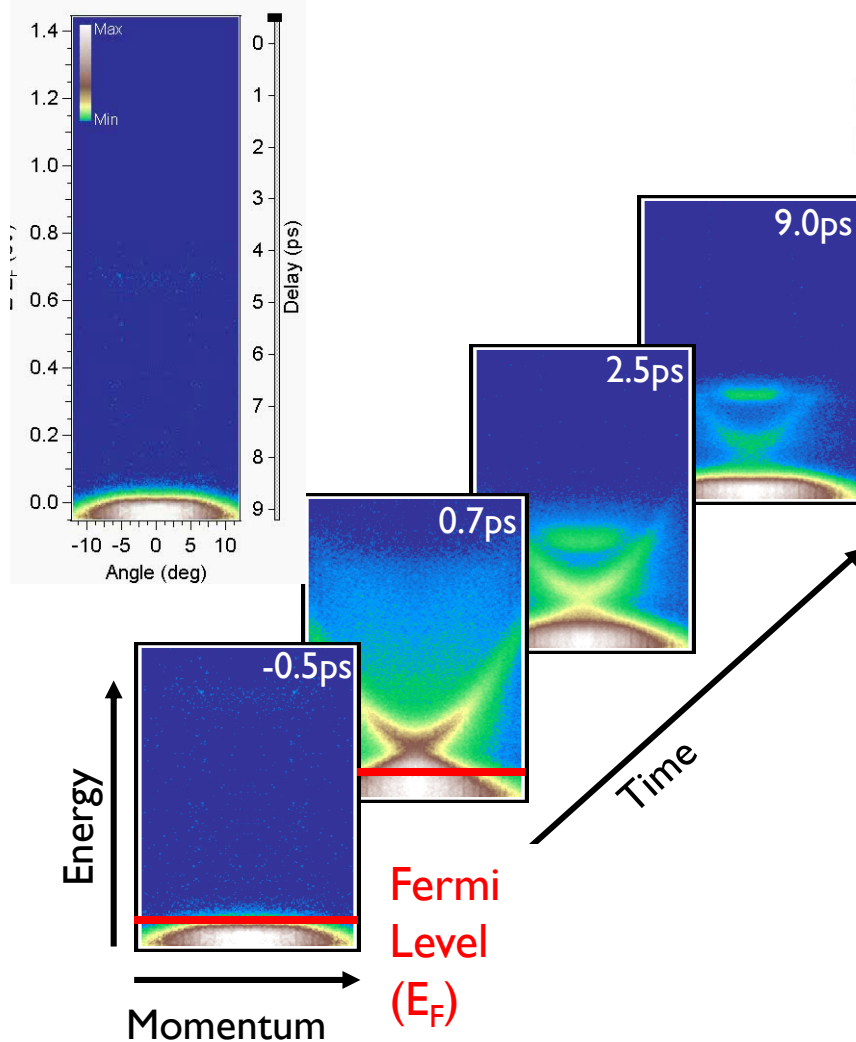


Electron-Phonon problem in Strongly Correlated Materials

- ▣ *Frequency domain – progress and challenge*
 - *Overview and Recent updates from cuprates*
- ▣ *Time domain – complementary tool*



Time-Resolved ARPES (trARPES)

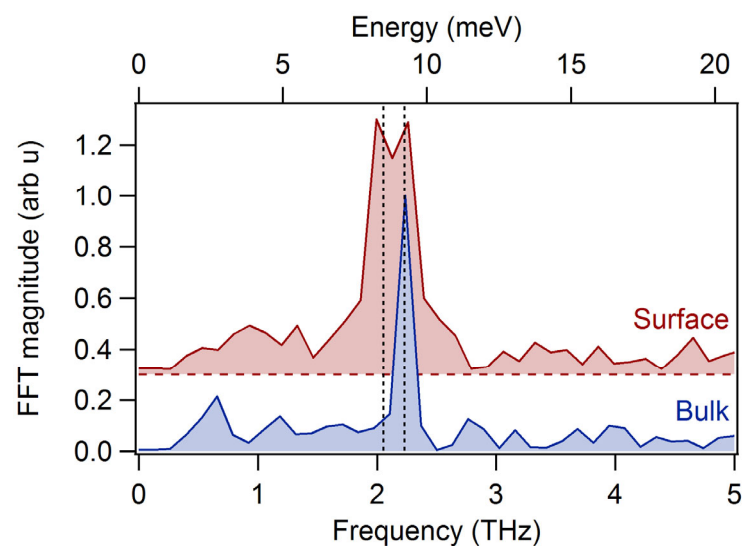
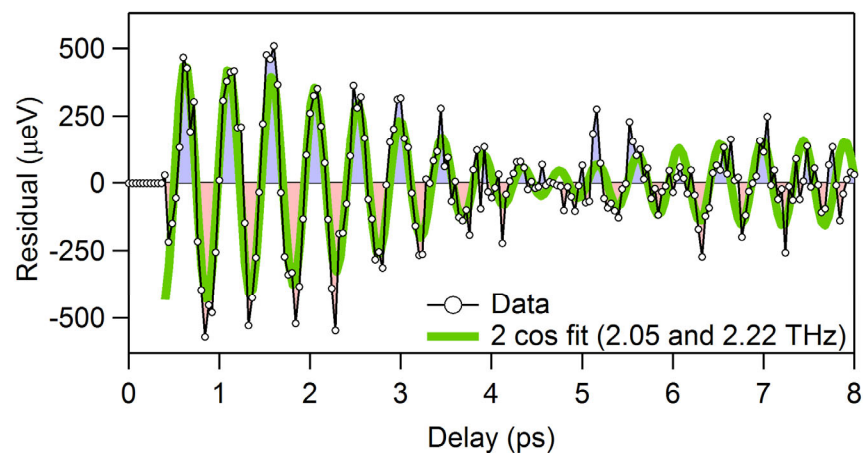
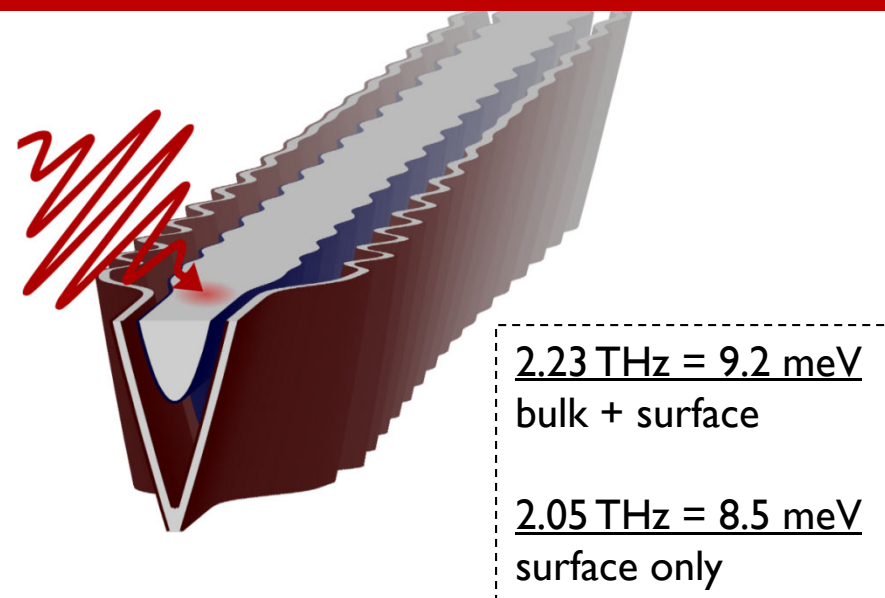
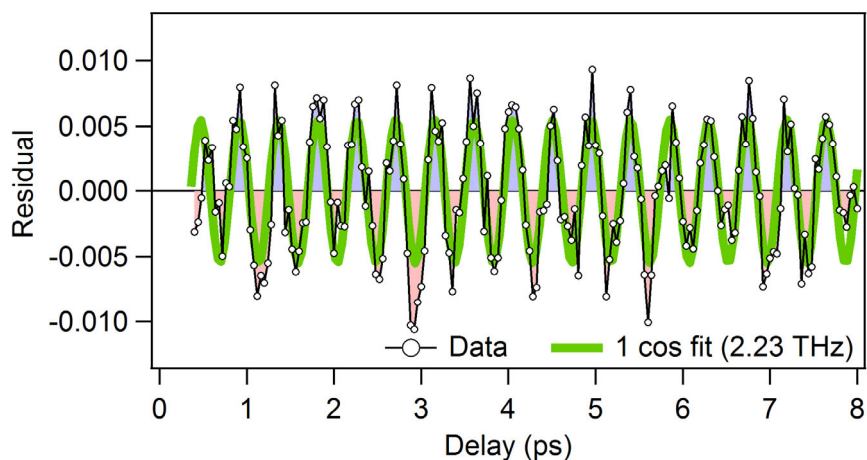


Sobota et al., PRL (2012)

- Precision measurements of ground state property

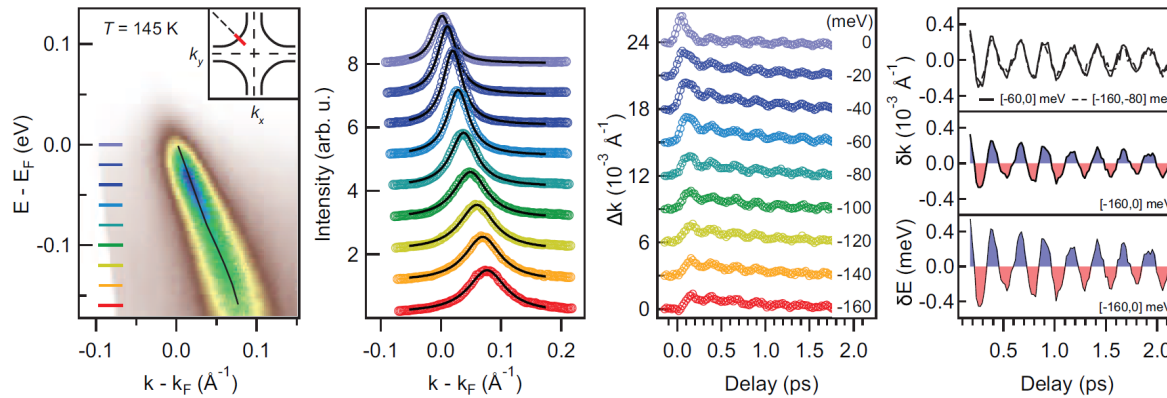


trARPES measurement - Bulk and Surface Comparison

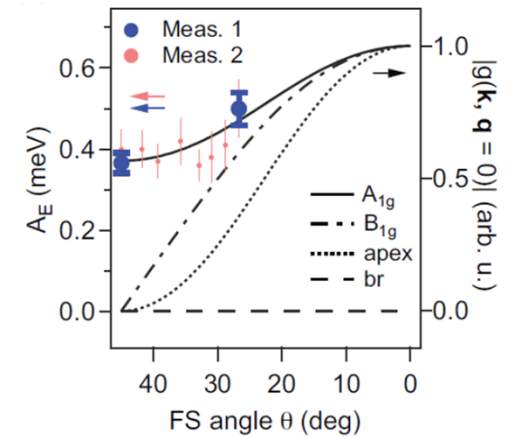
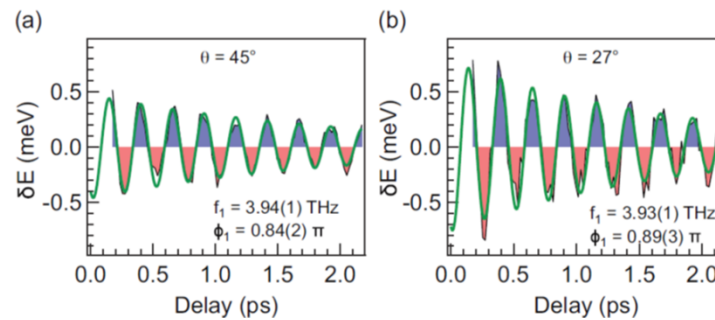
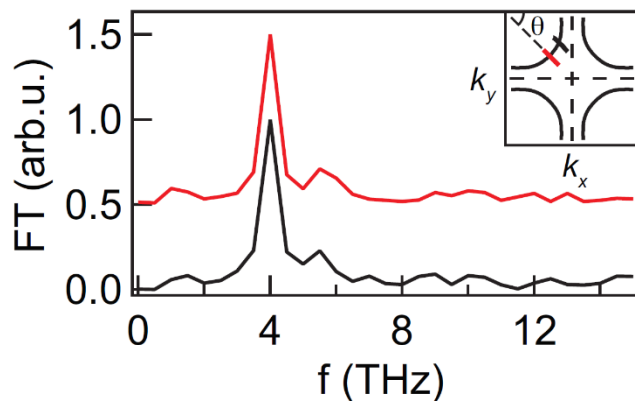


Band and momentum dependent response to lattice distortions

Coherent Phonons in Bi2212

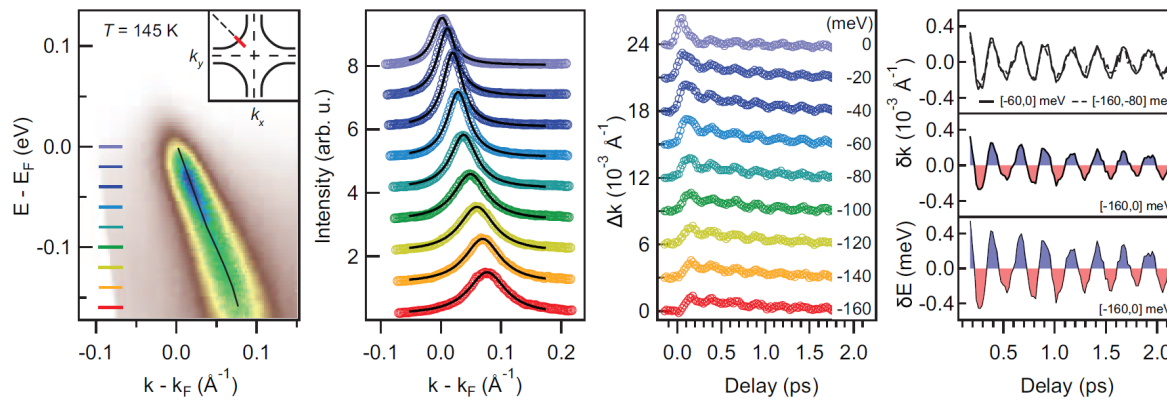


Shuolong Yang
PRL 122, 176403
(2019)

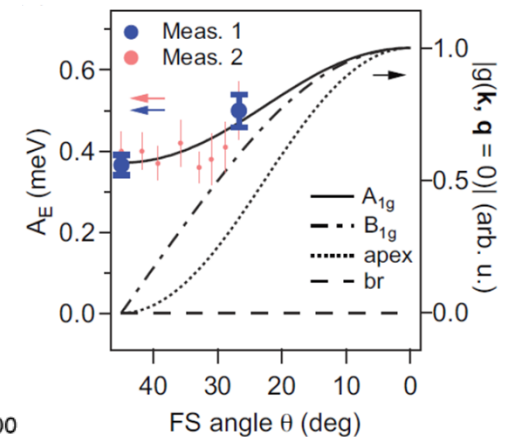
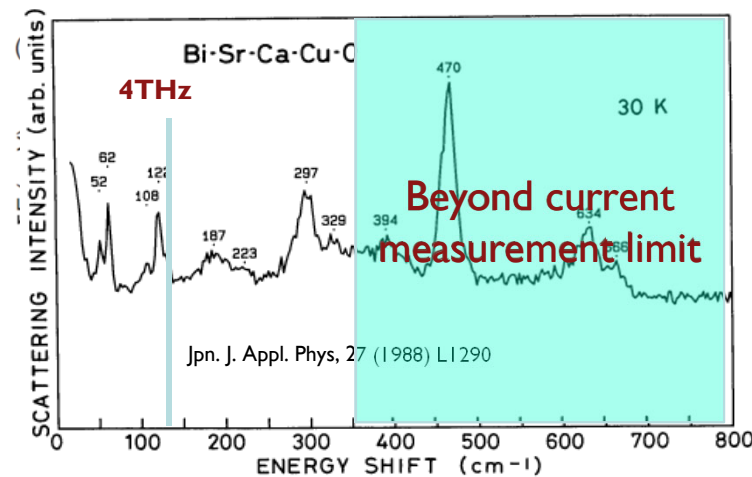
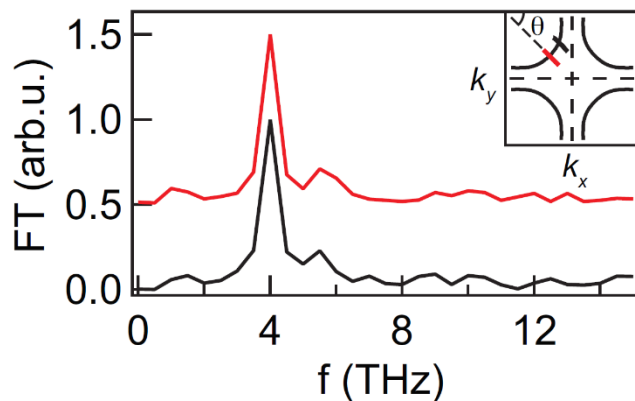


Band and momentum dependent response to lattice distortions

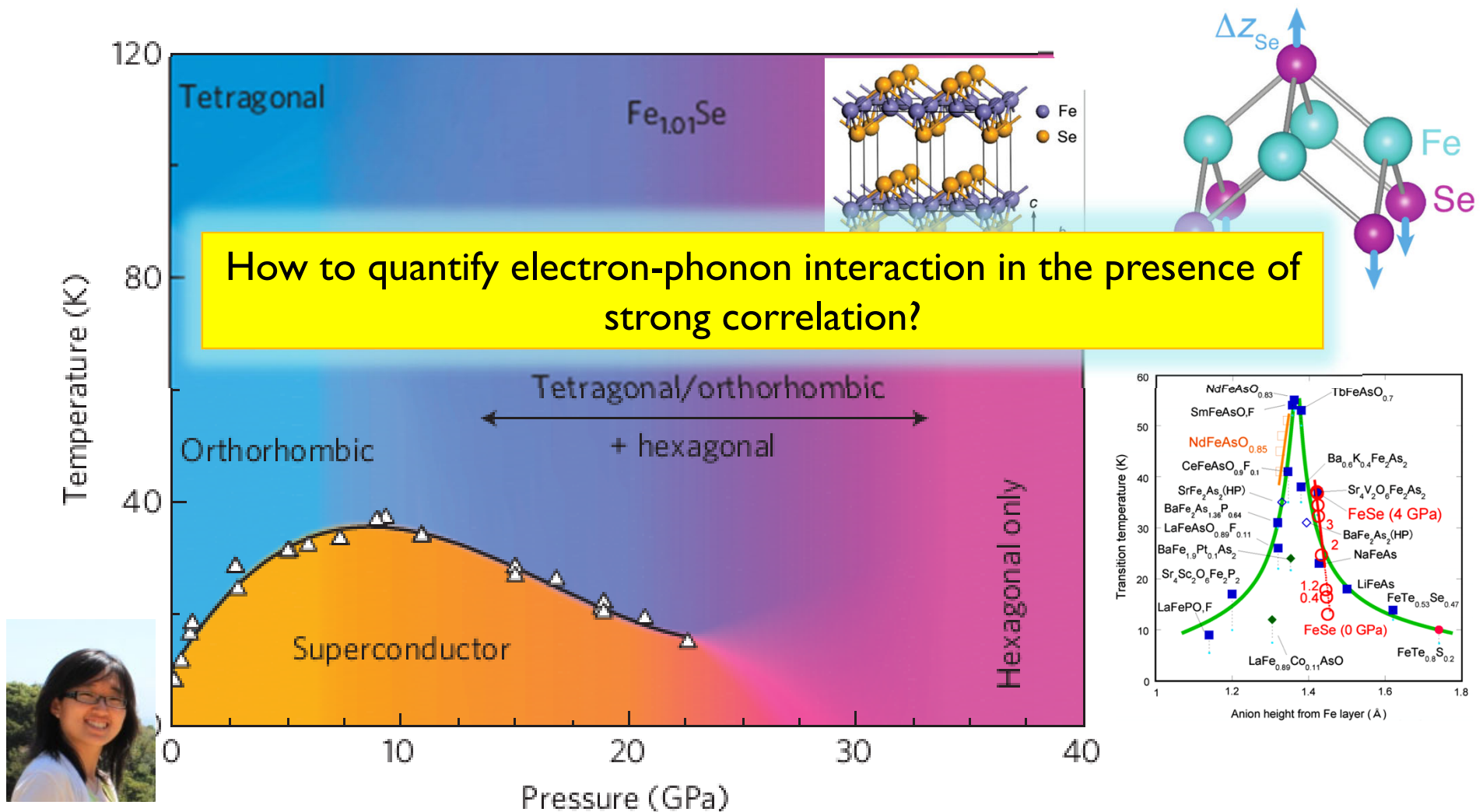
Coherent Phonons in Bi2212



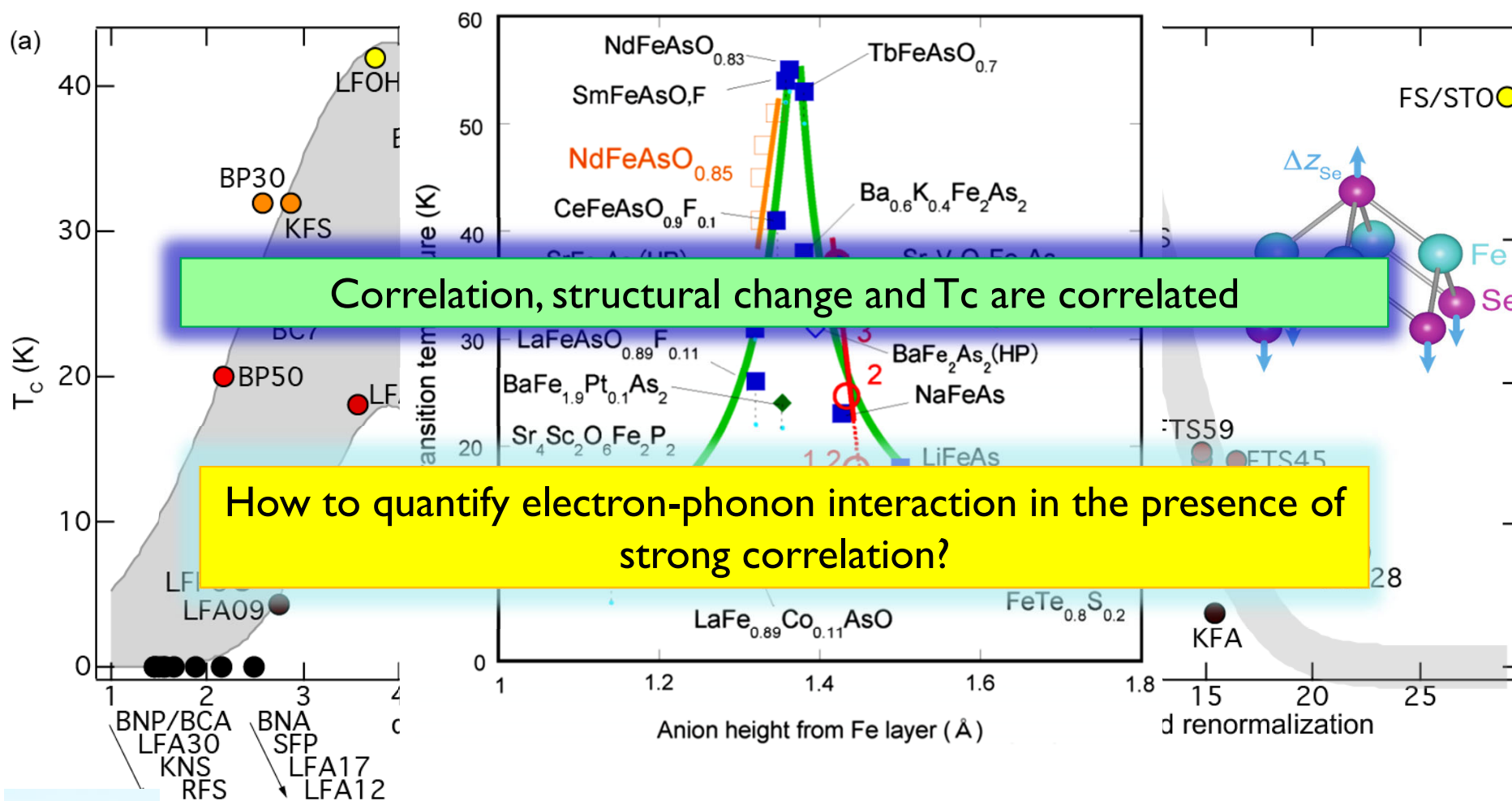
Shuolong Yang
PRL 122, 176403
(2019)



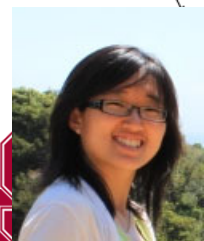
Pressure dependence of Superconductivity in FeSe



Relationship between correlation and T_c



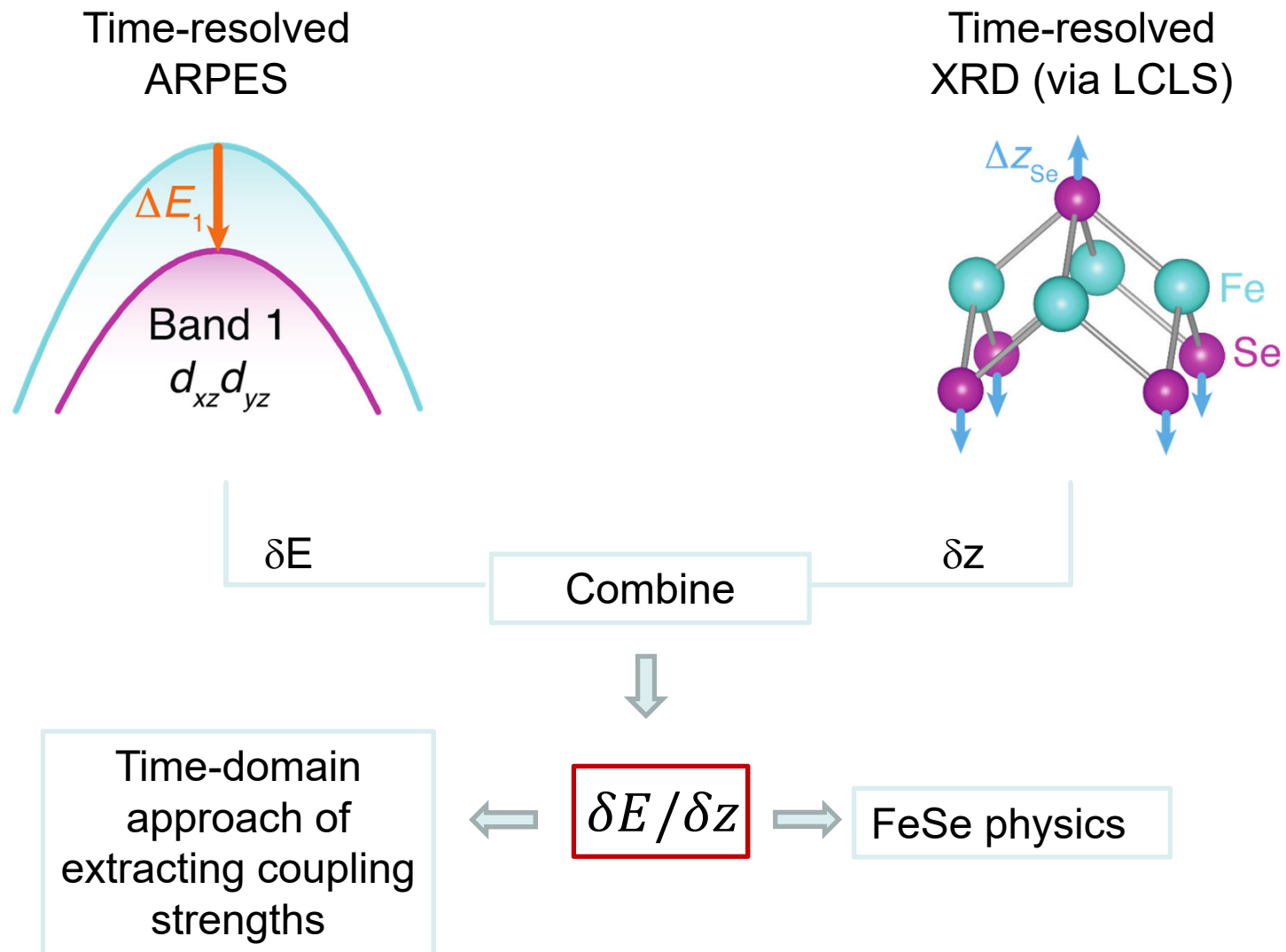
**compounds with T_N/T_S not included*



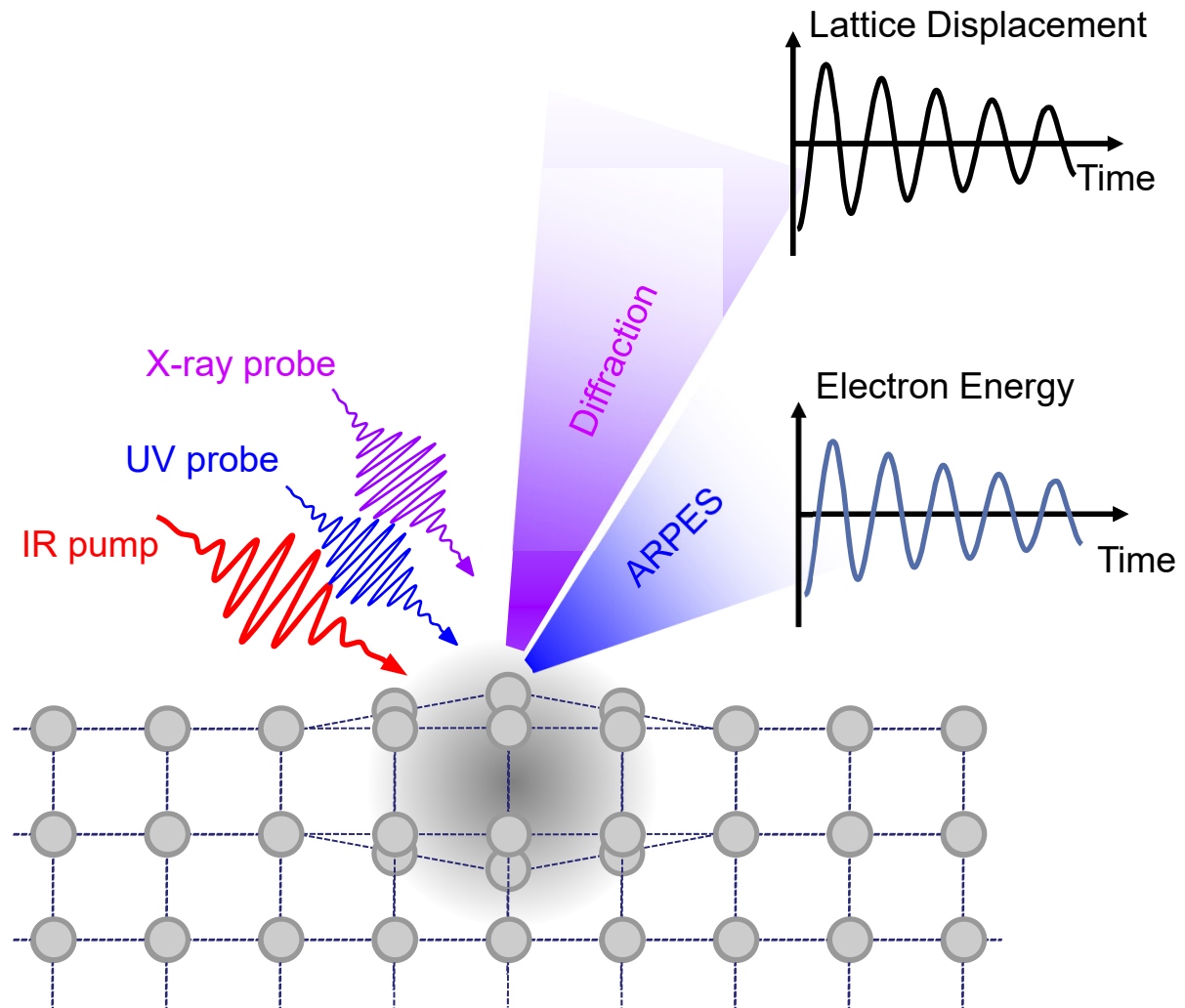
Y. Mizuguchi et al. Supercond Sci Tech 2010.

M.Yi et al., Nature Quantum Materials, 2017

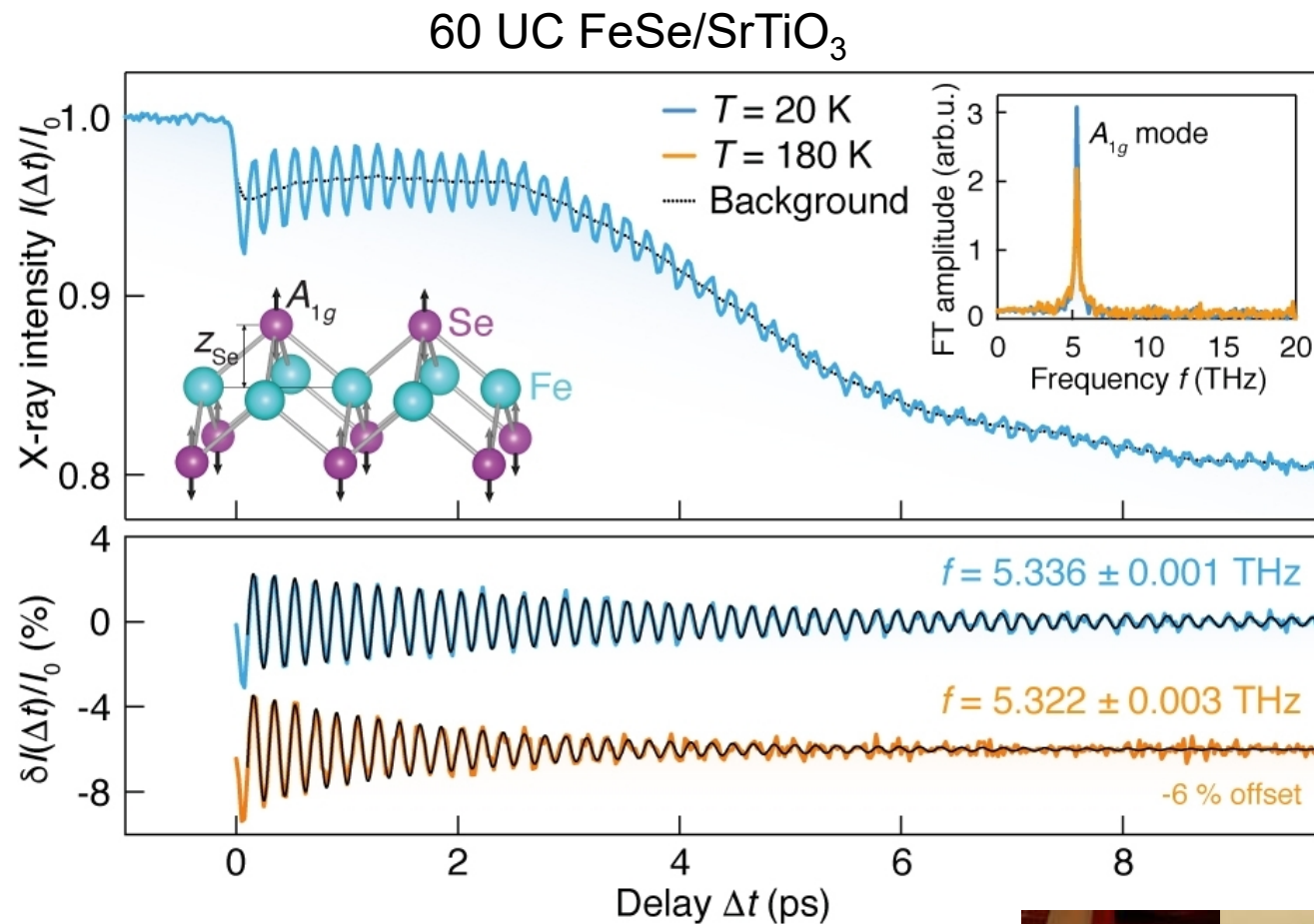
Steps forward: quantifying electron-phonon coupling in time domain



A New Paradigm: Ultrafast “Lock-in”



Time-resolved X-ray diffraction measurement



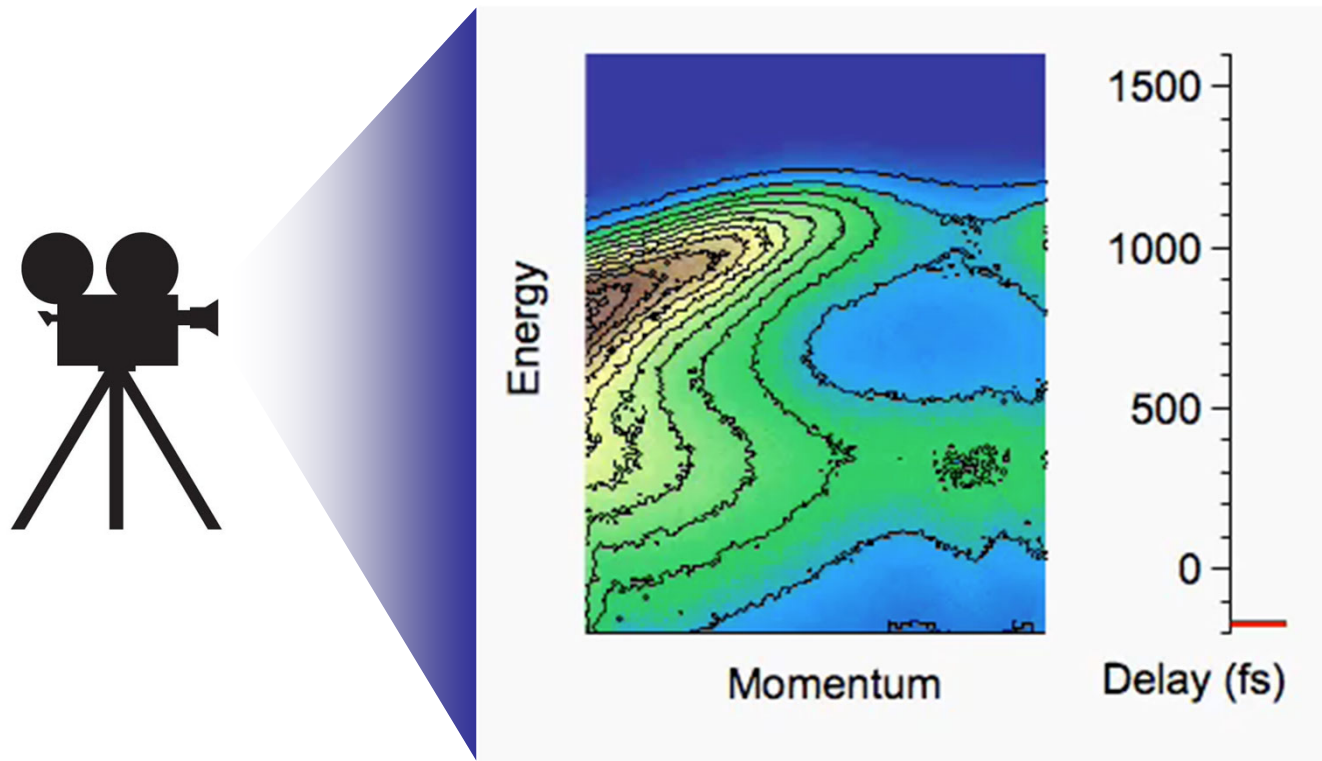
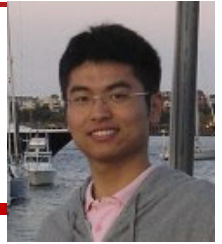
- $\omega_{ph}: 5.334 \pm 0.001$ THz



S. Gerber*, S.-L. Yang* *et al. Science*, 357, 71 (2017)



Movie of electronic band structure



- ω_{ph} : 5.334 ± 0.001 THz

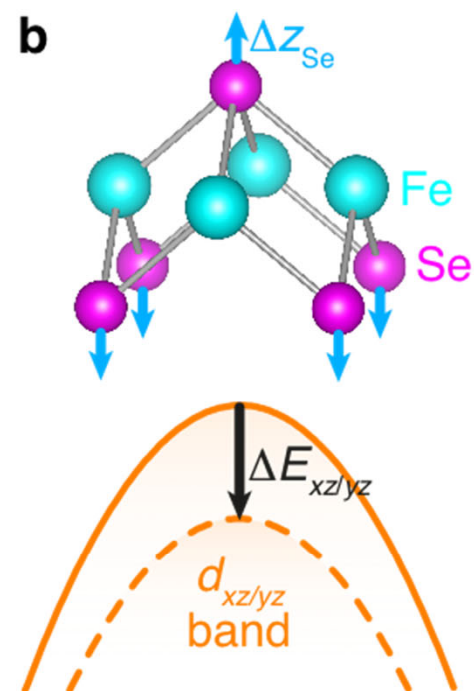
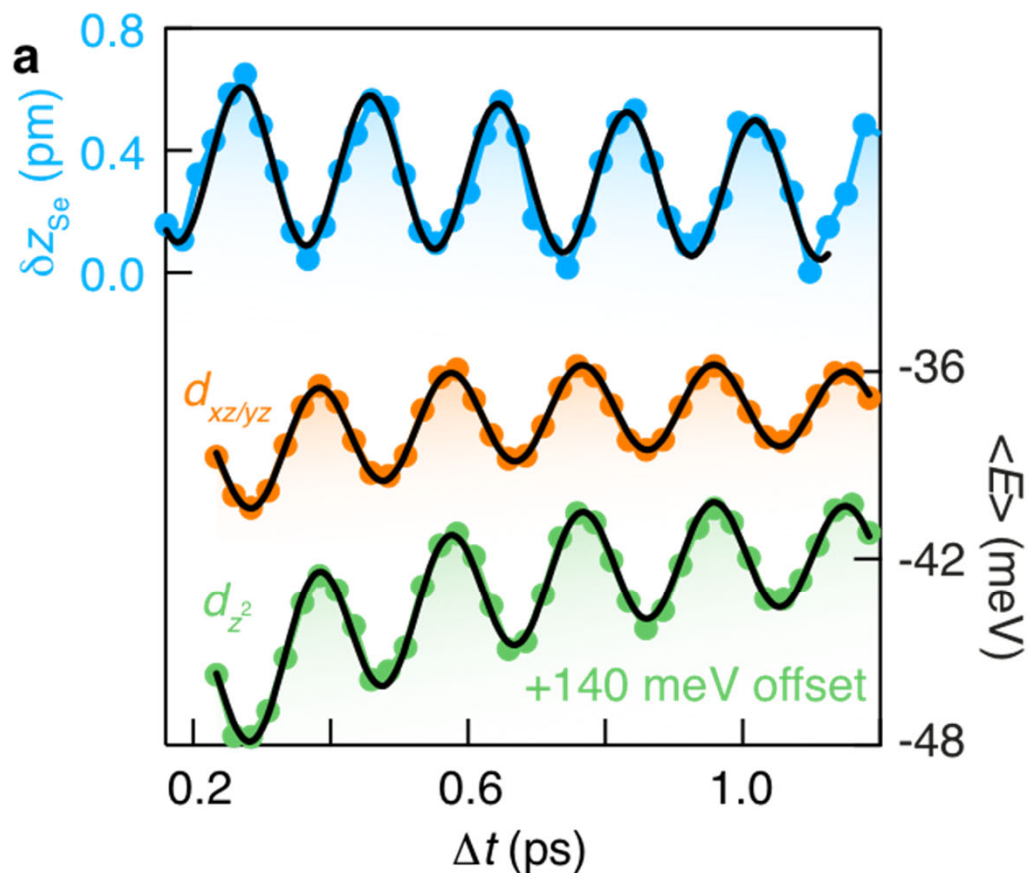


S.-L. Yang *et al.* *Nano Lett.* **15**, 4150 (2015)

S.L. Yang, thesis 2016

Comparison between trXRD and trARPES measurements --- Orbital dependent coupling

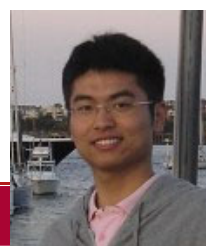
- $\omega_{ph}: 5.334 \pm 0.001$ THz



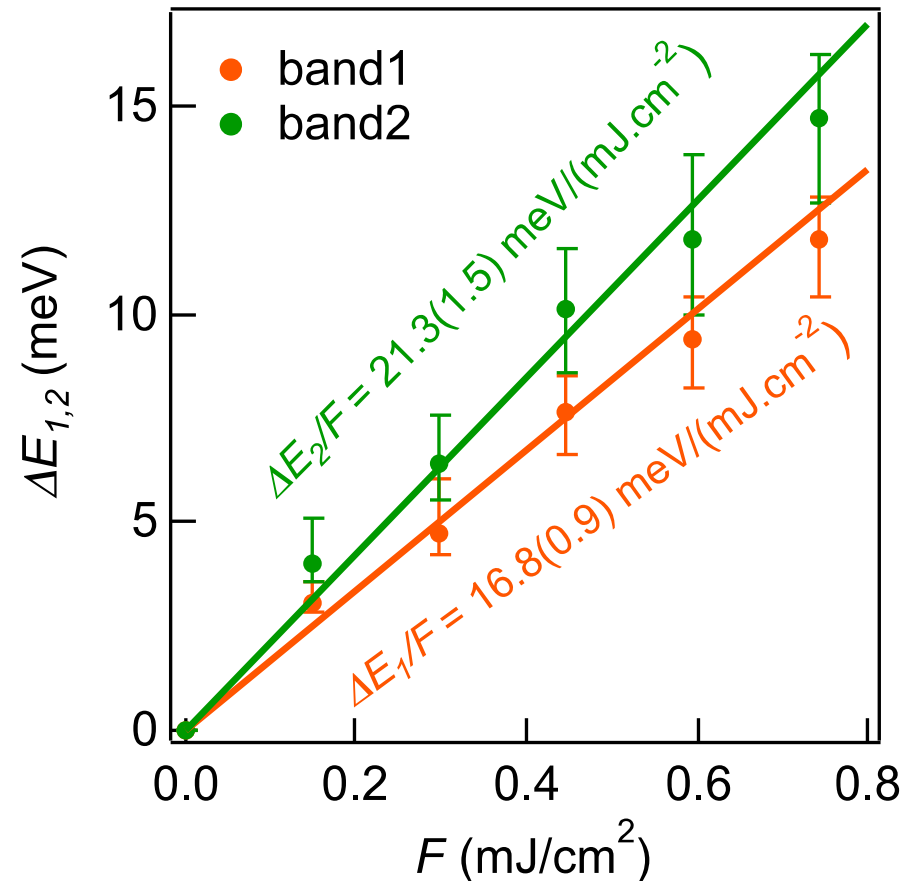
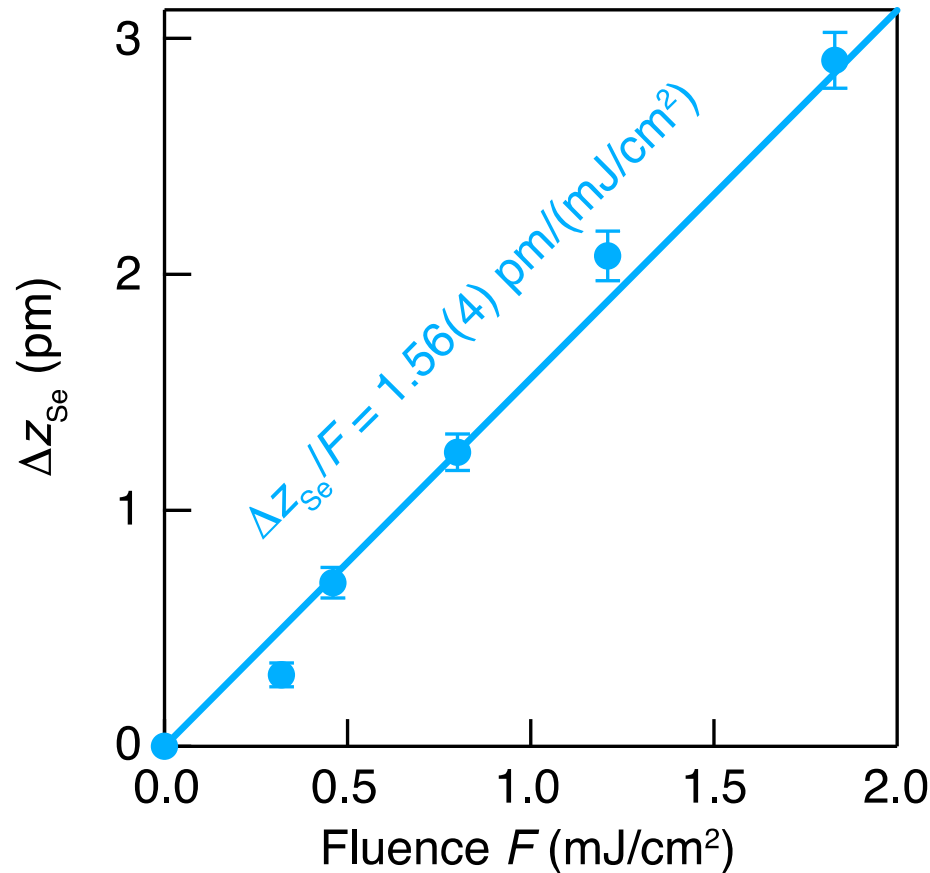
Simultaneous sensitivity to space (10^{-13} meter) and time (10^{-14} second)



S. Gerber*, S.-L. Yang* *et al. Science*, 357, 71 (2017)



Fluence dependence – Linear Response Regime

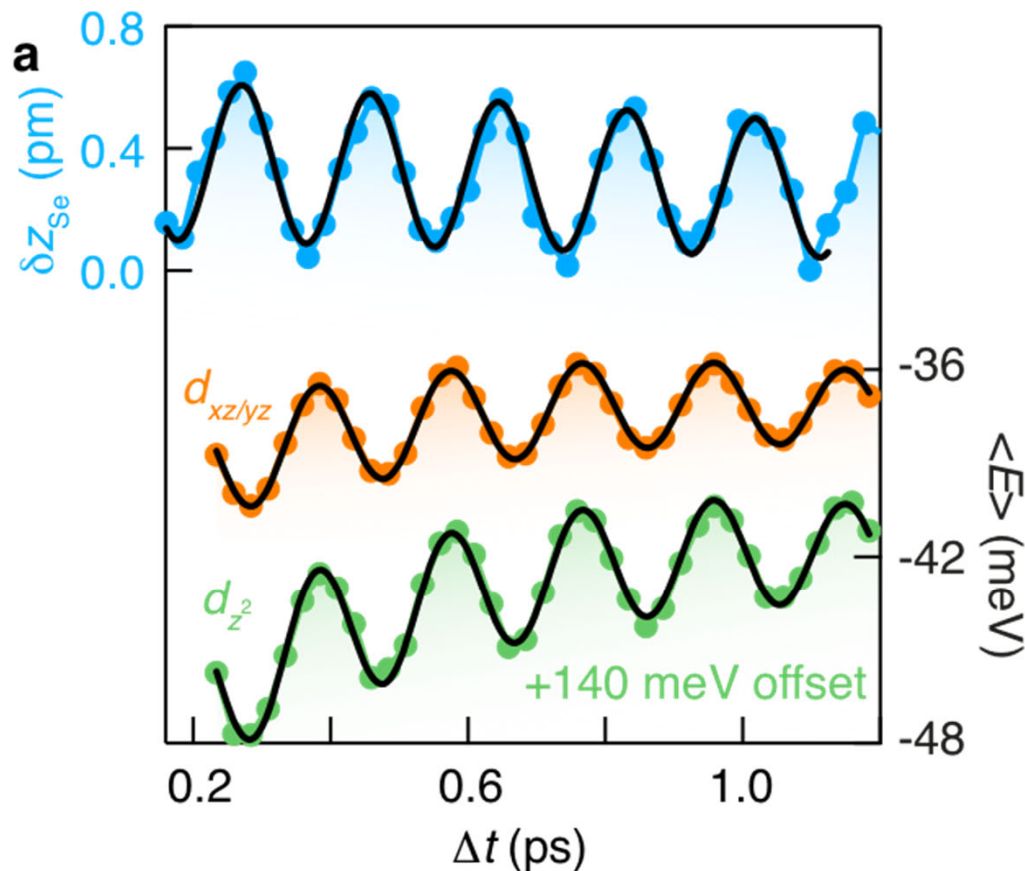


- Linear-response regime: deformation potential not modified by the pump

S. Gerber*, S.-L. Yang* *et al. Science*, 357, 71 (2017)



Precision Measurement of Electron-Phonon Coupling in Correlated Superconductor FeSe



Time Resolved X-ray Diffraction
Tracks Atomic Motion

**Electron correlation
modulates the
deformation potential
by an order magnitude**

$\Delta E_{xz/yz} / \Delta z_{\text{Se}}$ (meV/pm)	
DFT	-1.6 ± 0.2 ←
DMFT	$-10.3 \text{ to } -13.4$
Experiment	-13.0 ± 2.5 ←

Time Resolved Photoemission
Tracks Electron Energy Change

Mandal *et al.*, Phys. Rev. B.
89, 220502 (R) (2014)



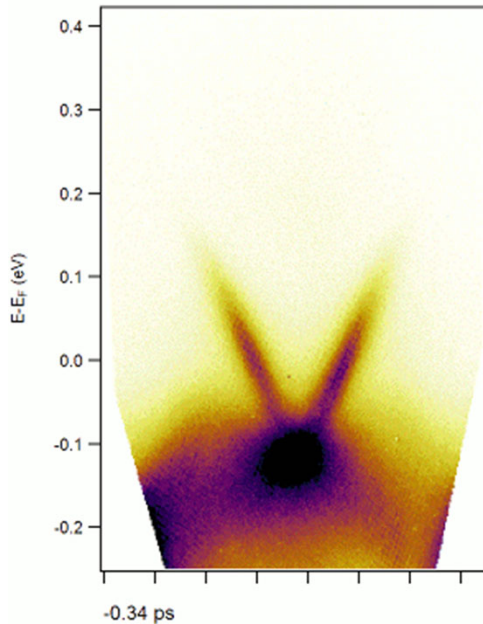
A less correlated material:

Quantify how topological states respond to lattice distortions

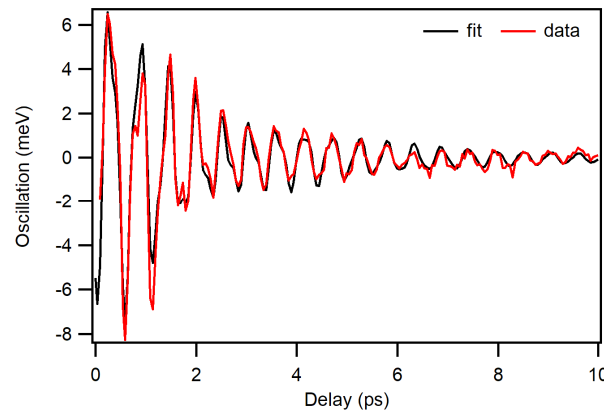


J.A. Sobota
(unpublished)

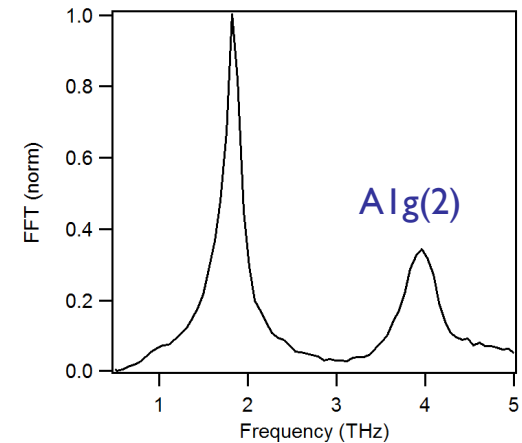
Time-resolved ARPES and time-resolved XRD on Bi_2Te_3



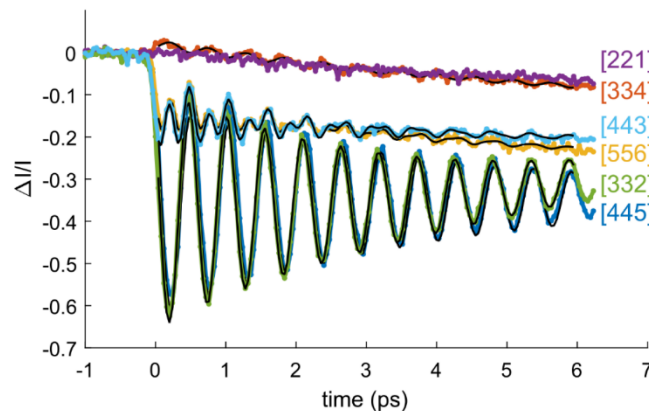
Band oscillation (trARPES)



$A_{1g}(1)$



Lattice oscillation (trXRD)



Collaborators:

XRD: S.W. Teitelbaum, Y. Huang, T. Sato, M. Chollet, J.M. Glownia, T. Henighan, M. Trigo, D. A. Reis; ARPES: J.A. Sobota, H. Soifer, P.S. Kirchmann, Z.-X. Shen; Theory: J. Querales-Flores, I. Savic, E. Murray, S.B. Fahy; Sample synthesis: C. Rotundu, T.P. Bailey, C. Uher



Coupled Interactions – Relevance?

- *Feedback loop of enhanced superconductivity*
 - *Forwardly scattered phonons*
 - *Interface enhanced superconductivity*
 - *Cooperative feedback loop and enhanced superconductivity*
 - *Incoherent (“entangled”) state sharply bounded by vertical boundary*
- *Time domain provides new opportunity*
 - *High energy resolution for bosons*
 - *State and mode specific coupling*
 - *Precision measurements*

