Phase fluctuation in AF order and its effect on the pseudo-gap in electron doped cuprates

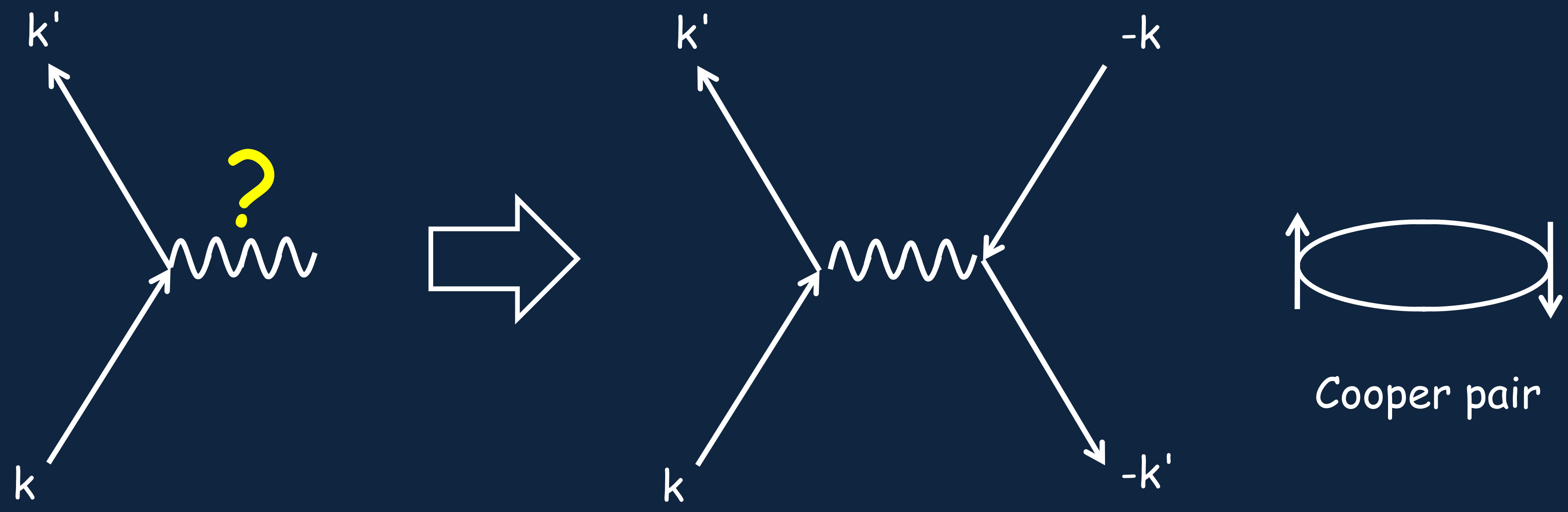
Chang Young Kim

Yonsei University

Outline

1. Review
2. ARPES results
3. Spin-fermion model
4. AF phase fluctuation model
5. Conclusion

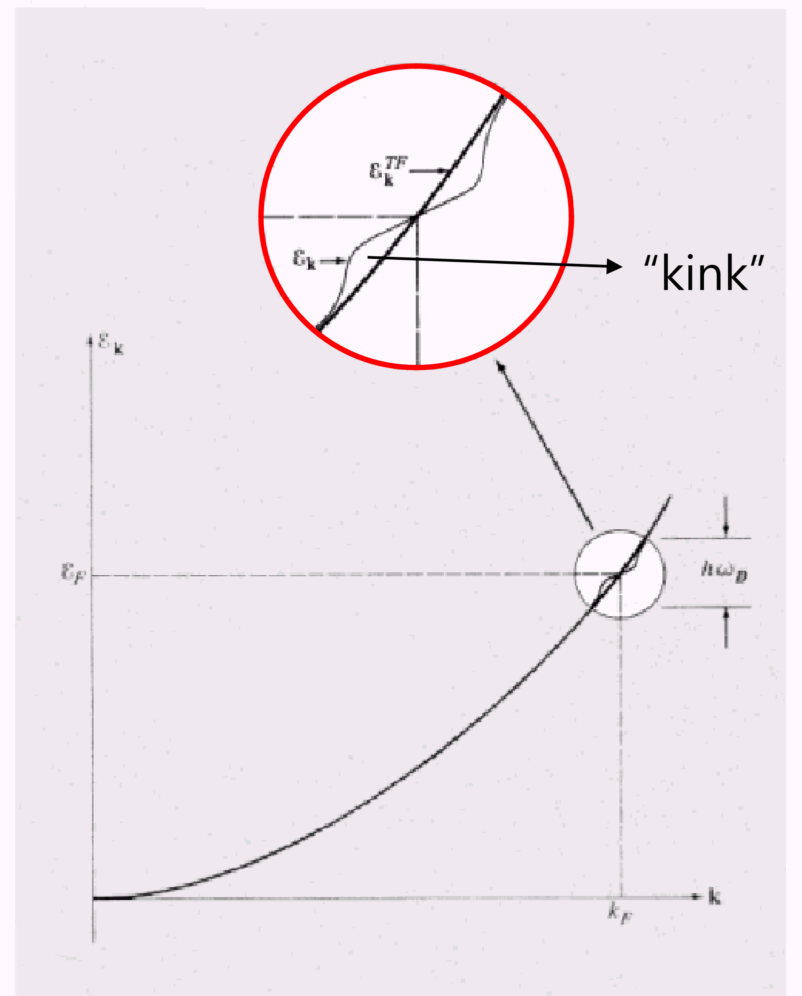
What interacts with electrons in HTSCs?



Lattices, spins, etc

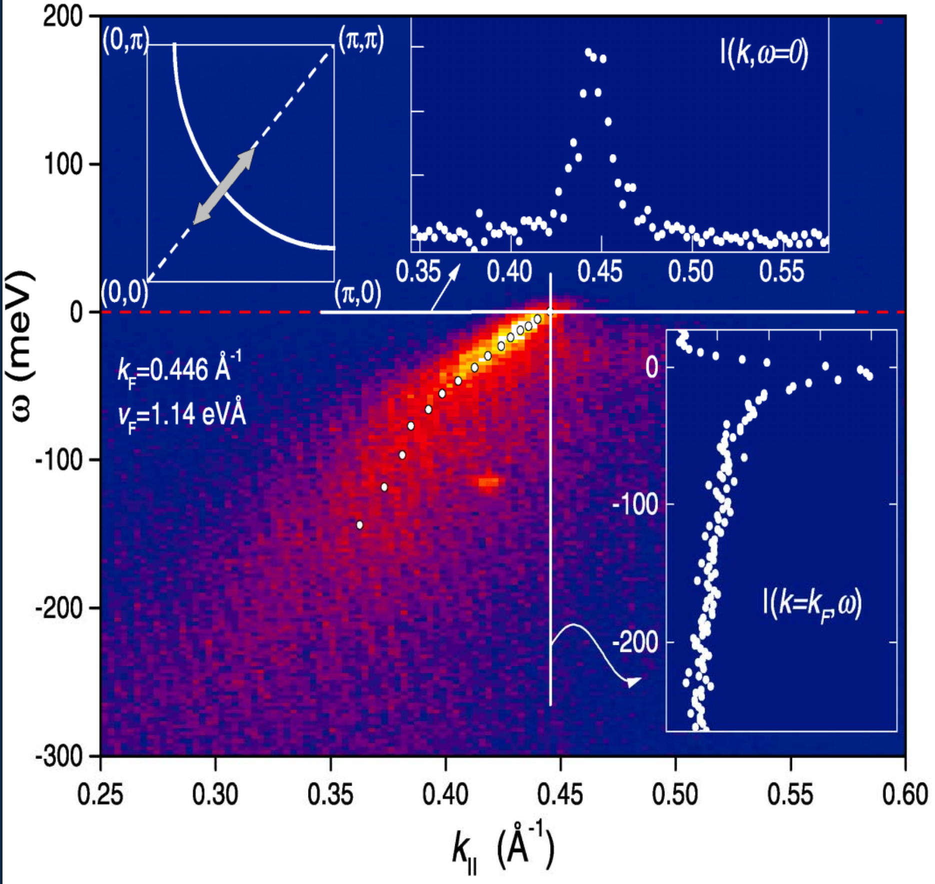
Information in spectral functions

Electron-phonon coupling



Ashcroft, Mermin "Solid State Physics"

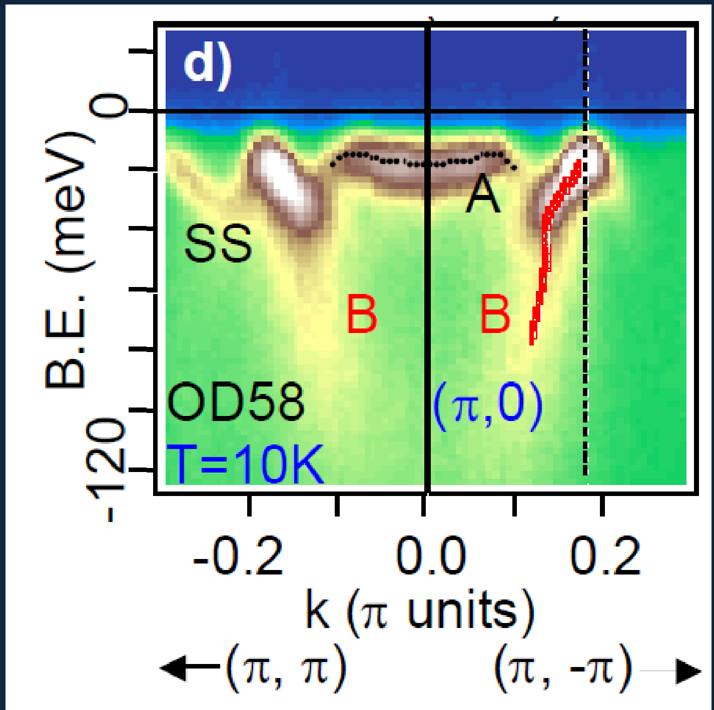
'kink' in the spectral function



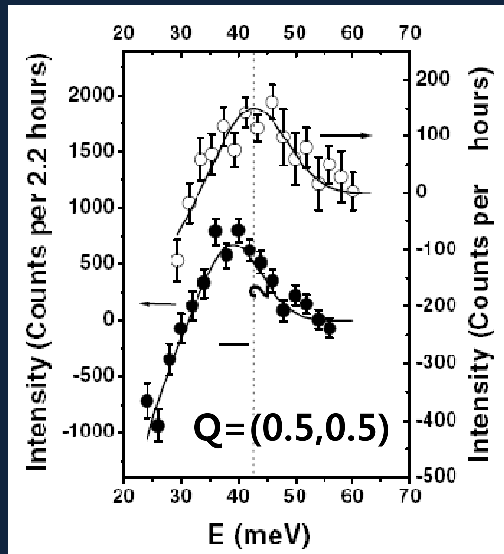
T. Valla, Science, 1999

Controversies in h-doped HTSCs

Strong kink in Bi2212



A. Gromko et al., PRB



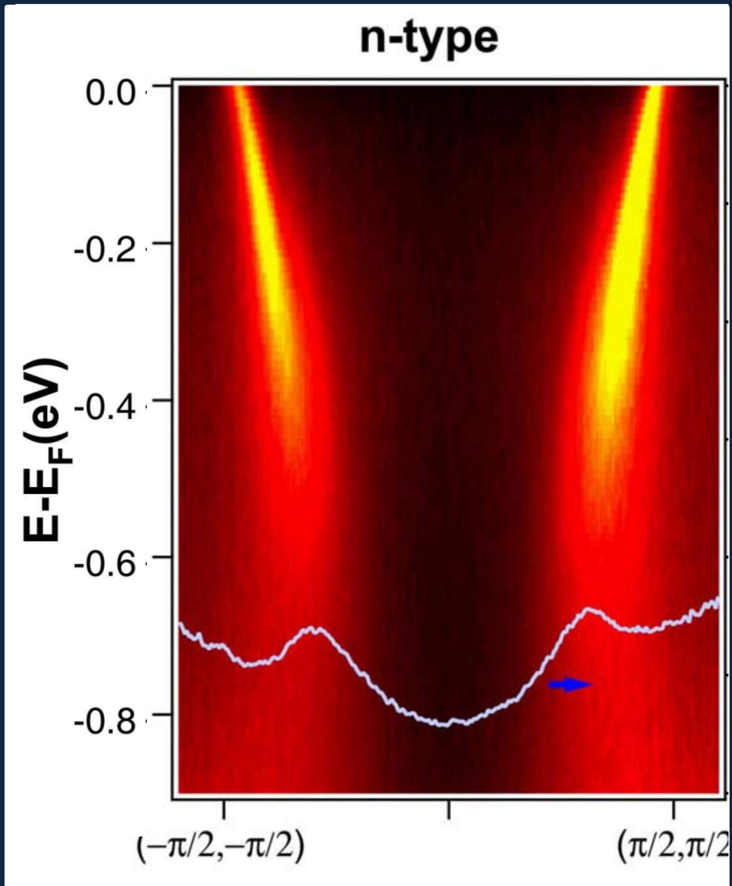
H. He *et al.* PRL (2001)

- Similar energy scales

  Superconducting gap, Pseudo gap,

  Phonons, Magnetic resonance mode

Energy scales in e-doped HTSCs

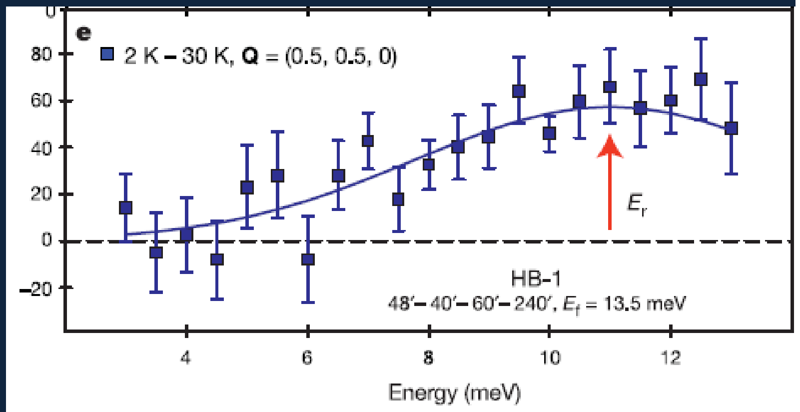


← Superconducting gap (~3 meV)
← Magnetic resonance mode (~10 meV?)
← Low E kink (~50 meV)
← Pseudo gap (~ 100 meV)

← High E kink (~500 meV)

B. Moritz et al., NJP

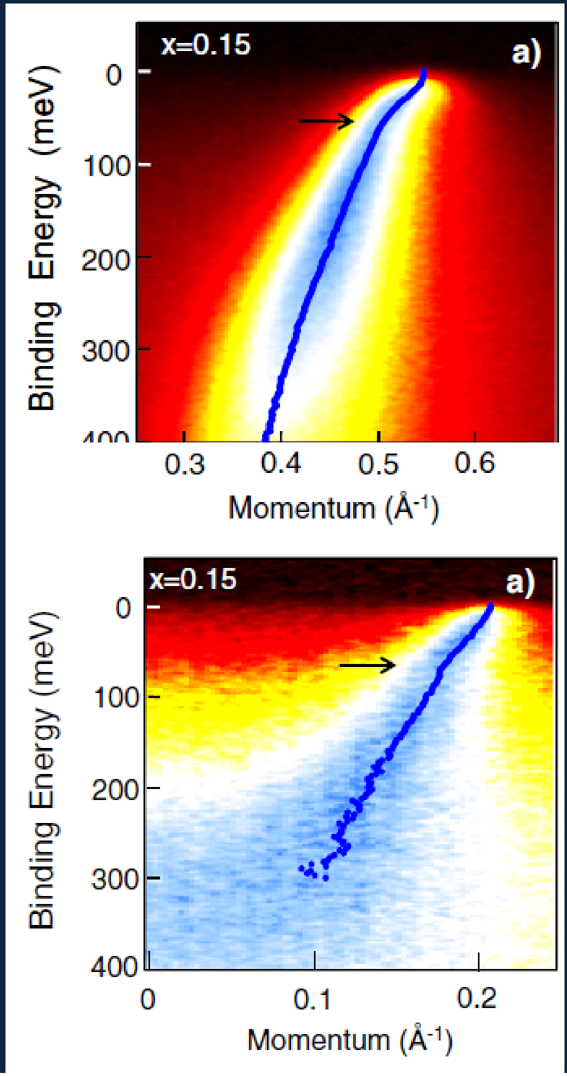
Spin resonance mode?



S. Wilson, Nature **442**, 59 (2006)

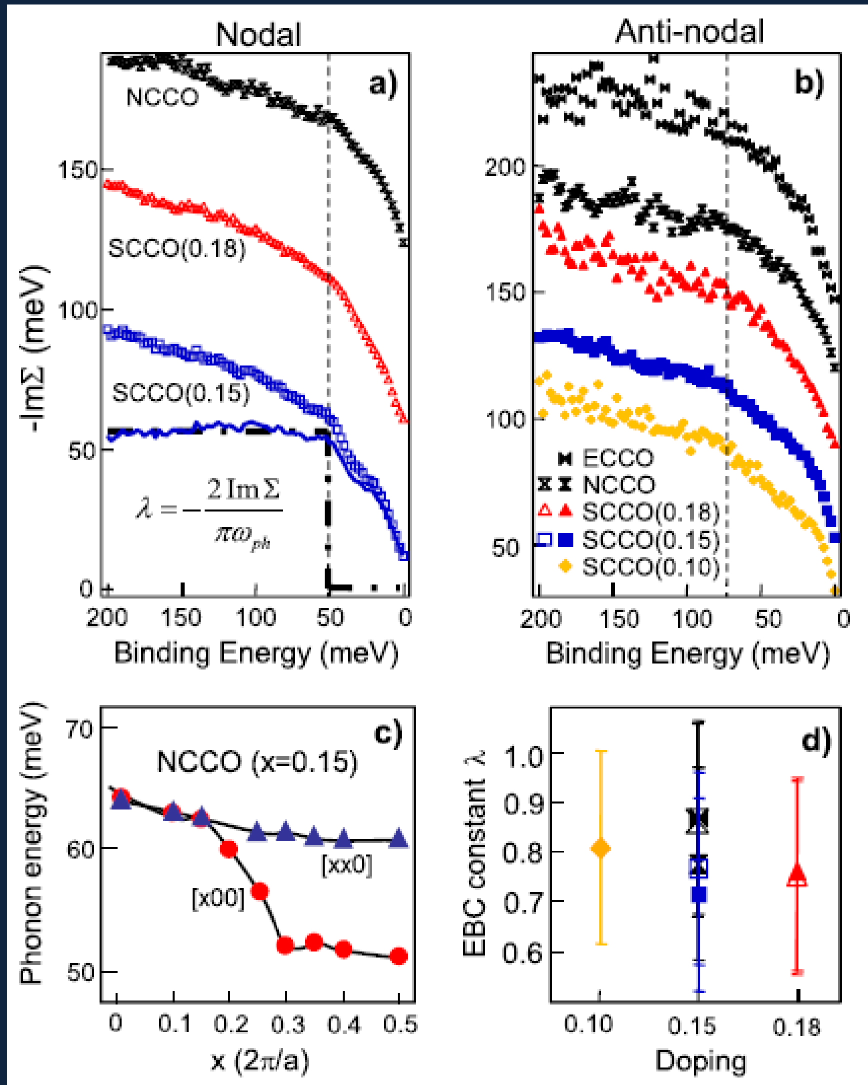
Phonons in e-doped HTSCs

Isotropic e-phonon coupling (S. R. Park, PRL **101**, 117006 (2008))

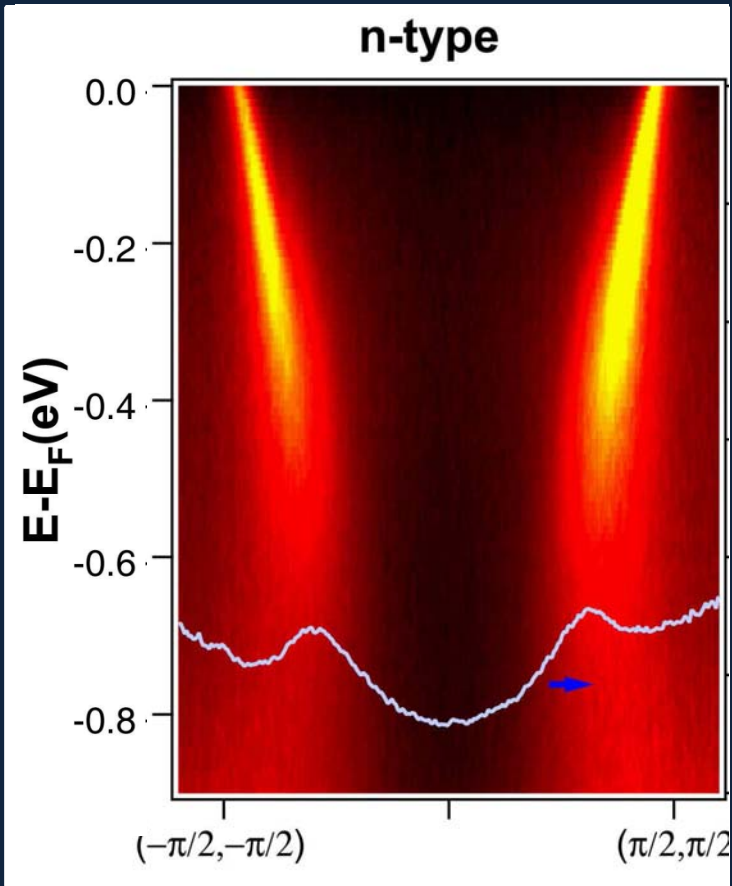


Nodal

Anti-nodal

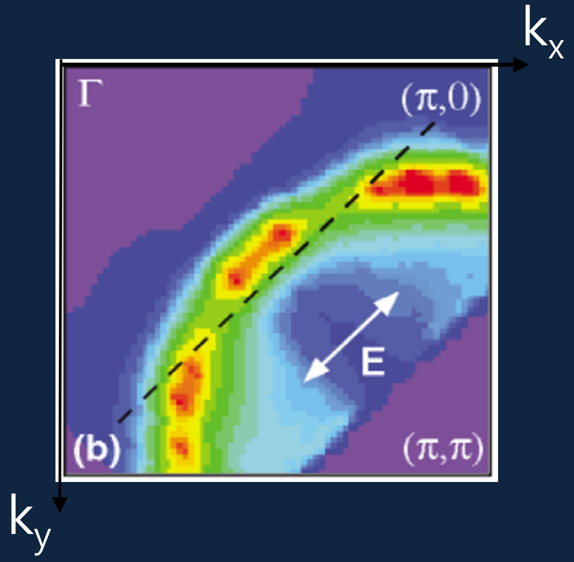


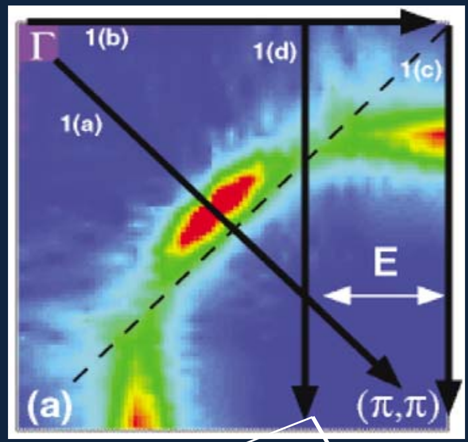
Wish to look at pseudo-gap

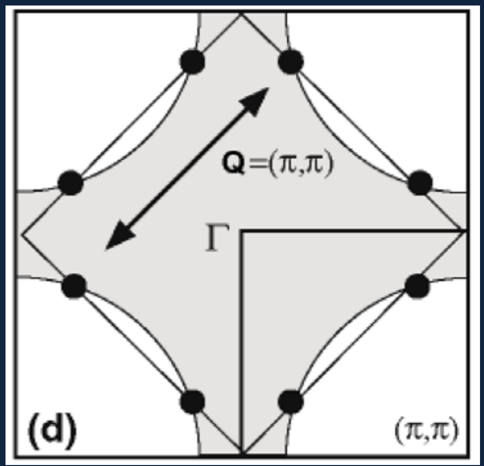


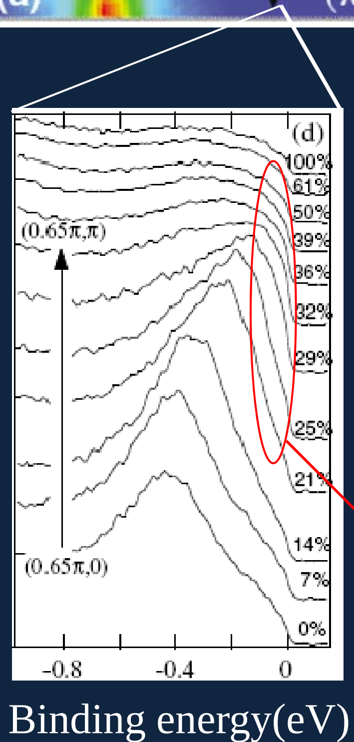
Superconducting gap (~3 meV)
Spin resonance mode (~10 meV?)
Low E kink (~50 meV)
Pseudo gap (~ 100 meV)
High E kink (~500 meV)

PG in electron doped cuprates









Pseudo-gap effect

- Spectral weight suppression near E_F at the intersection of AF Billiouin Zone Boundary (AFBZ) and the underlying FS

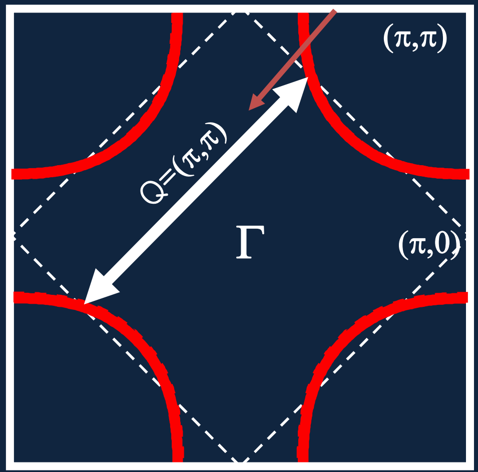
- Coupling to a bosonic mode localized at Q=(π,π)?

N. P. Armitage

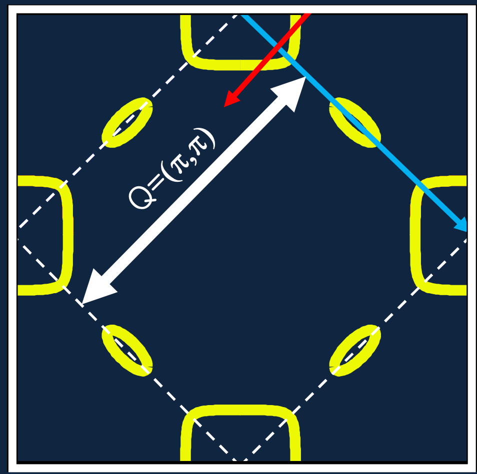
PRL (2001)

Static $\sqrt{2} \times \sqrt{2}$ order

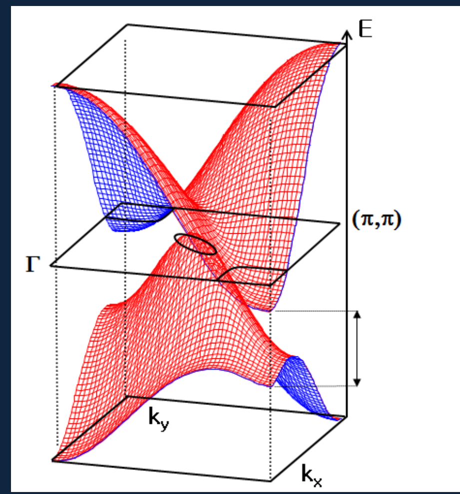
(π, π) scattering from √2 x √2 order?

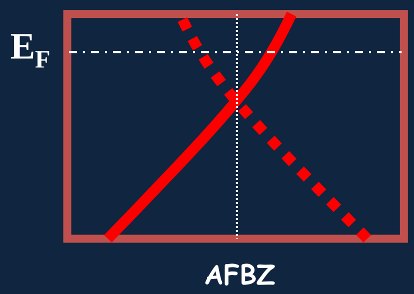


Original
Fermi surface

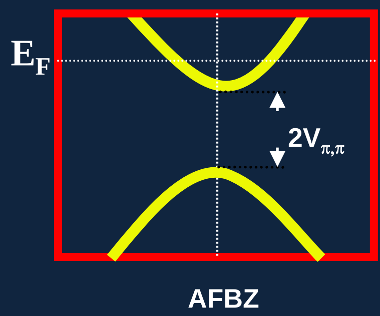


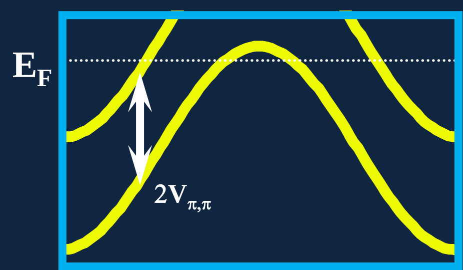
Reconstructed
Fermi surface



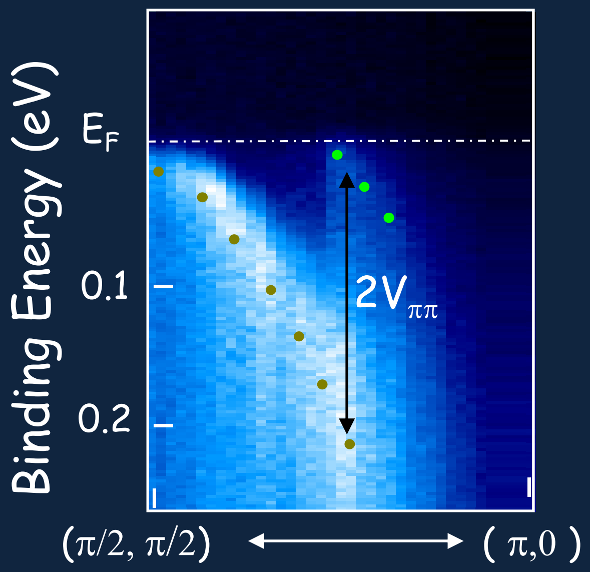


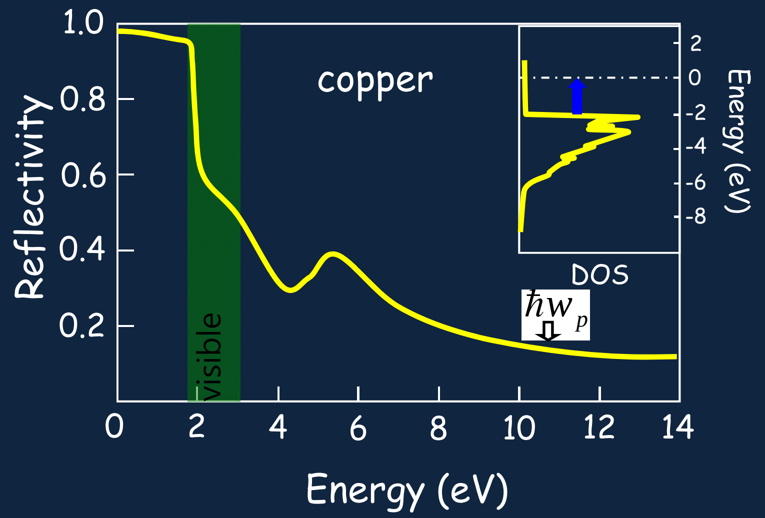
Band Structure

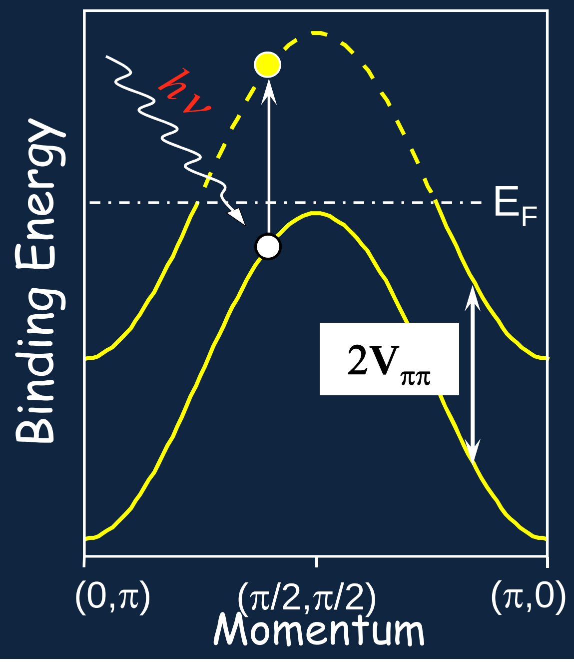


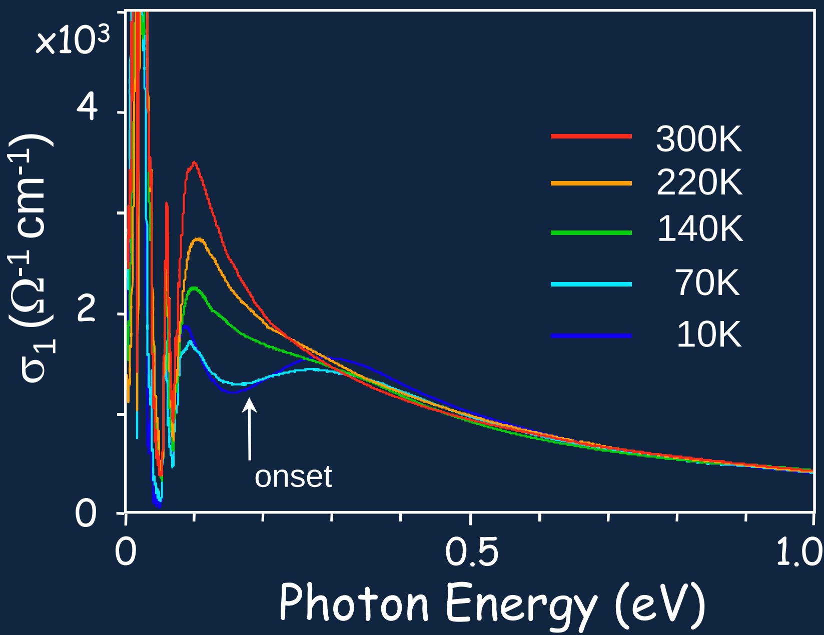


Inter-band transition





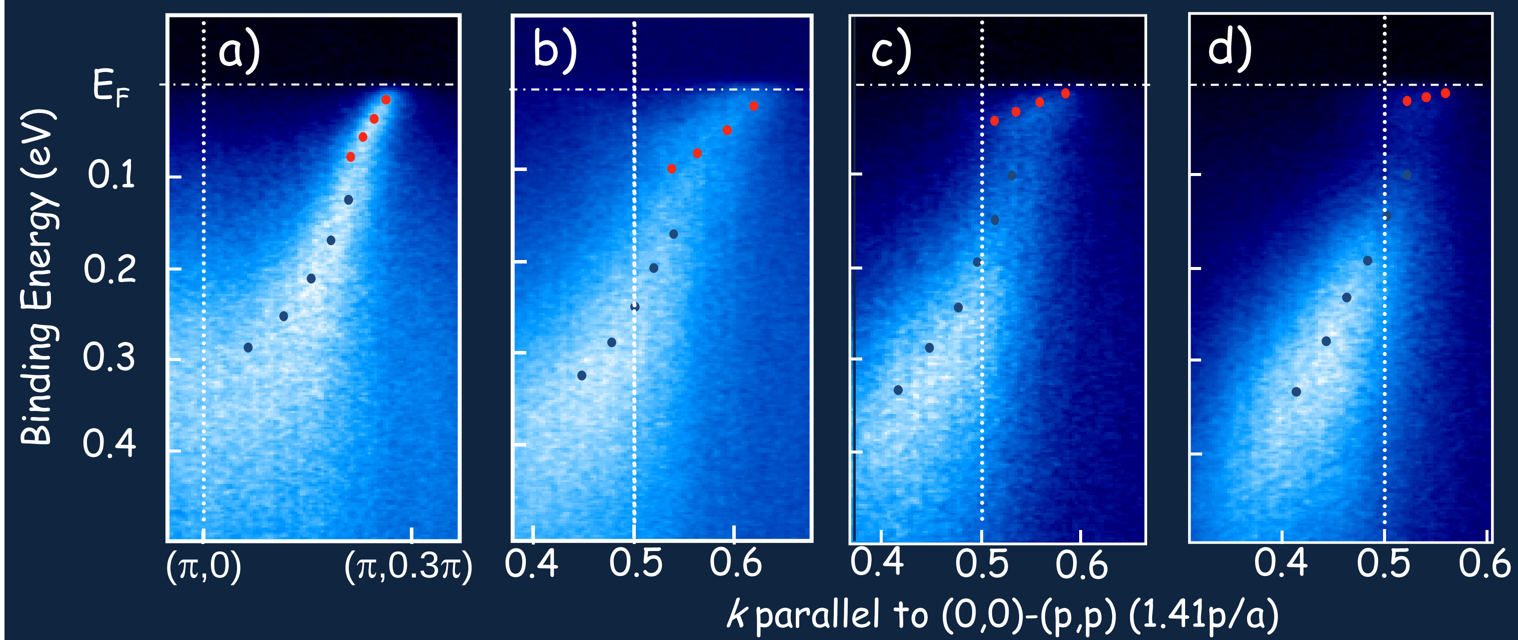


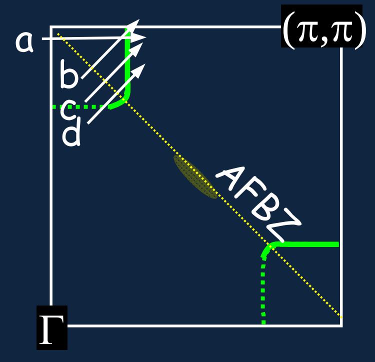


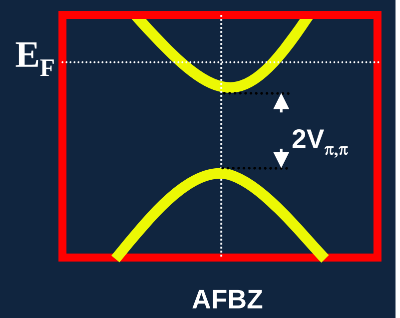
S. R. Park
PRB 2007

Overshooting problem

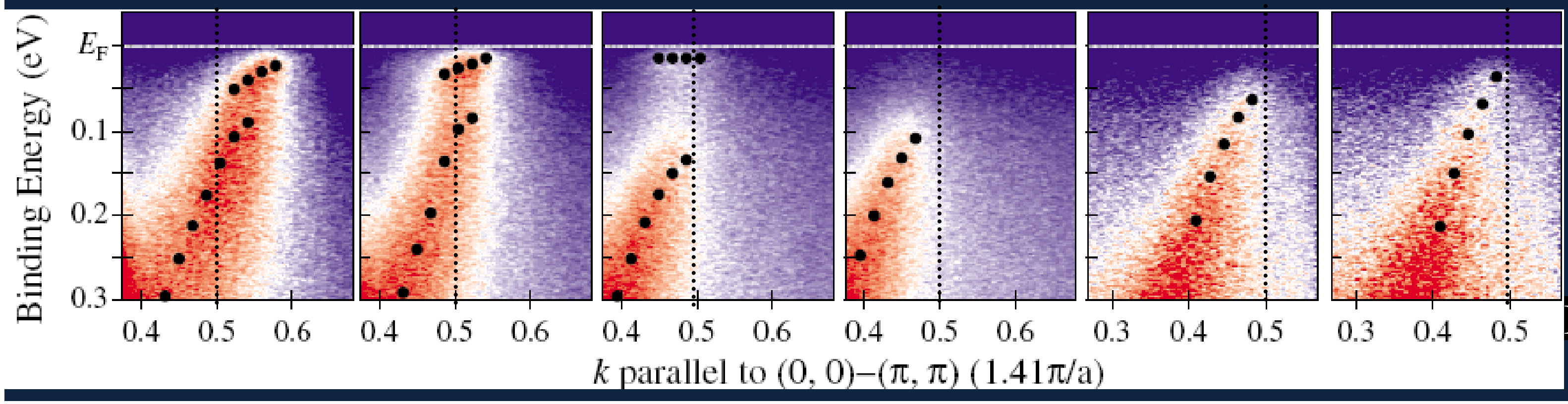
S. R. Park *et al.*, PRB® (2007) <u>SCCO(x=0.15)</u>

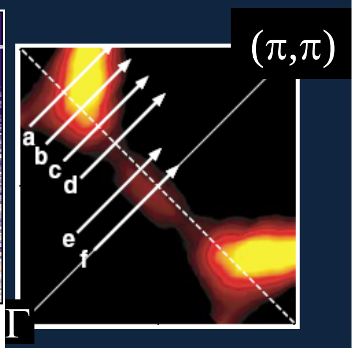






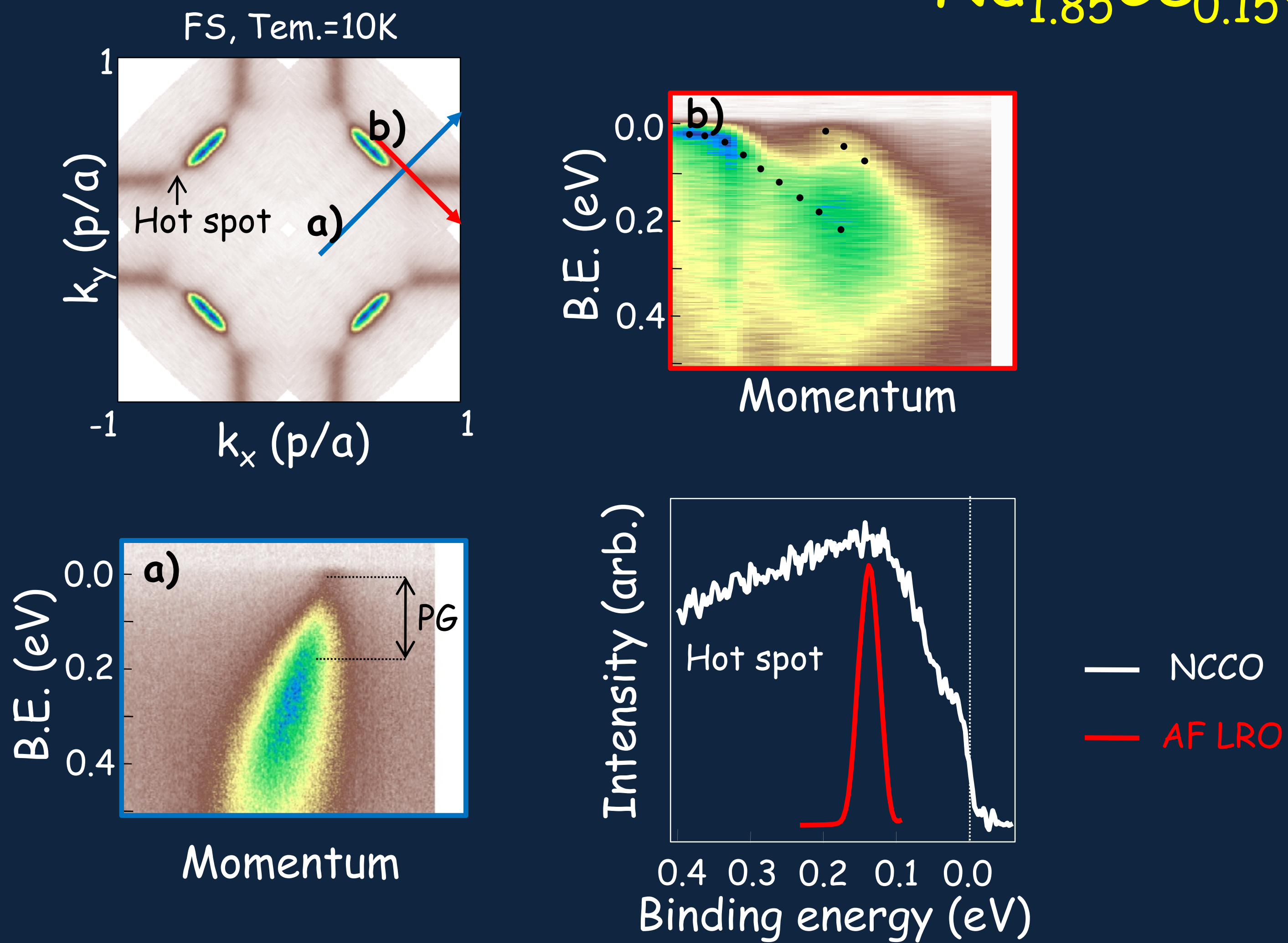
H. Matsui *et al.*, PRL (2005) <u>NCCO(x=0.13)</u>





E_F spectral weight at hot spot

$Nd_{1.85}Ce_{0.15}CuO_4$



Two problems:

1. Band overshoots across AFZB
2. E_f Spectral weight @ hot spot

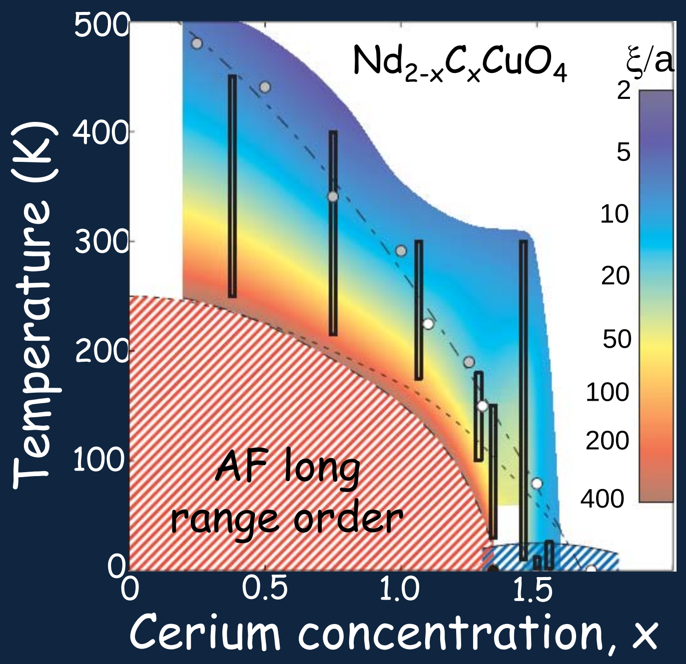
In addition:

What is the origin of scattering?

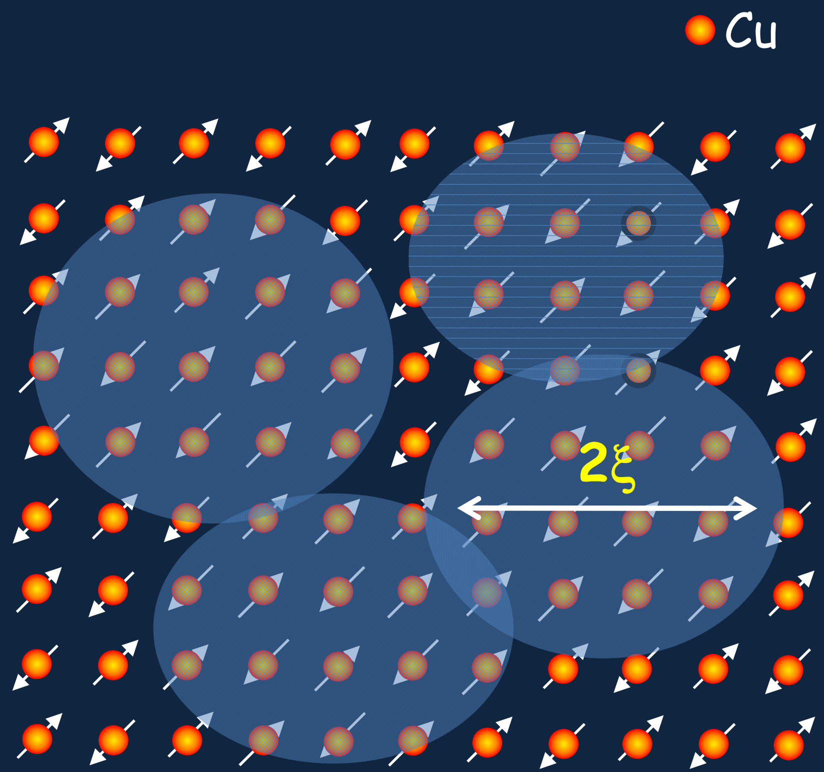
(Spin-fermion, localized moments, ...)

Effect of short range order?

AF correlation length
by INS



E. M. Motoyama *et al.*, nature (2007)

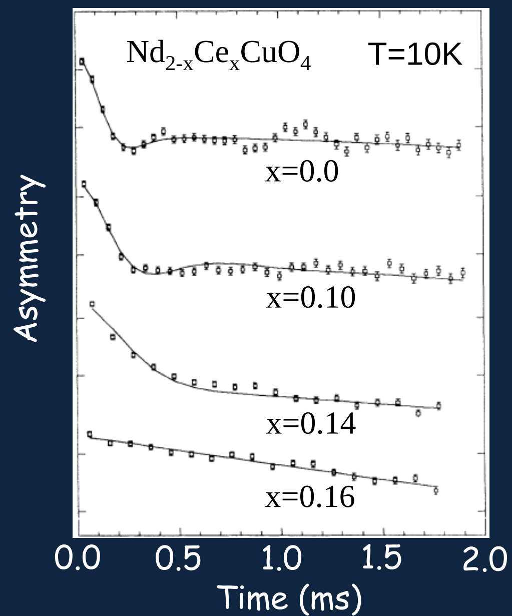


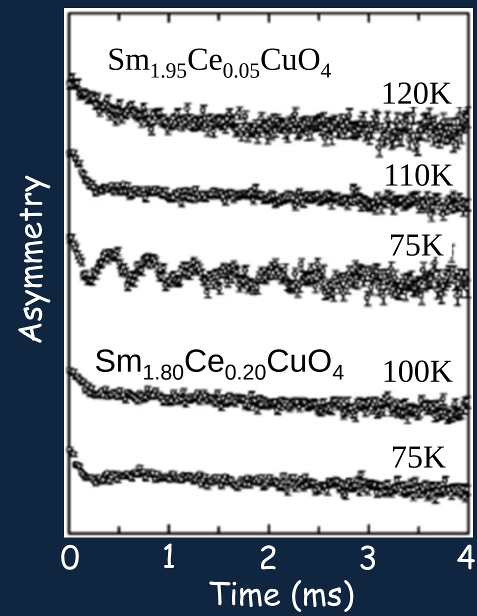
How to control the ordering length?

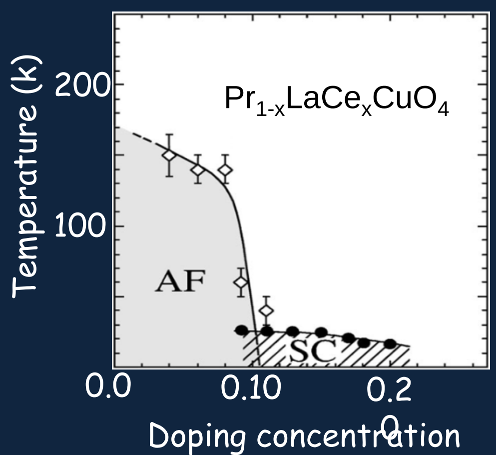
Rare earth element dependent AF

: muon spin relaxation

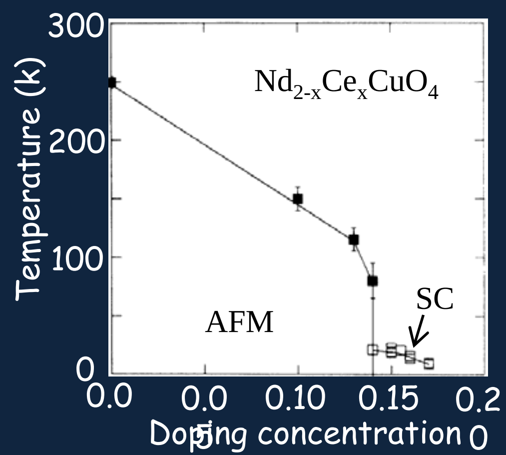
- heavier rare-earth element, stronger AF
- static AF cover all SC dome in SCCO



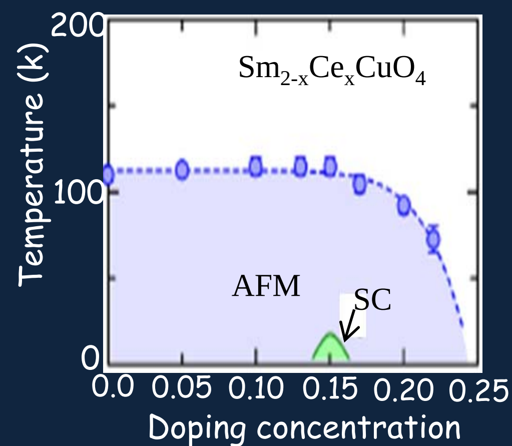




M. Fujita *et al.*, PRB, 2003



G. M. Luke *et al.*, PRB, 1990

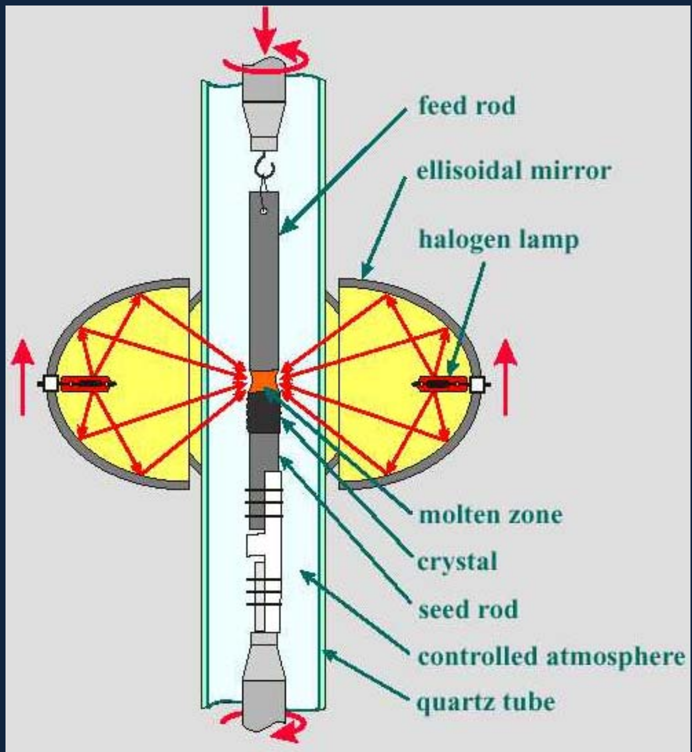


T. Sasakawa, unpublished

Samples

NATIONAL INSTITUTE OF ADVANCED INDUSTRIAL SCIENCE AND TECHNOLOGY (AIST)

Floating zone



$Rn_{2-x}Ce_xCuO_4$

57 $^2D_{3/2}$ **La** Lanthanum 138.9055 $[Xe]5d6s^2$ 5.5769	58 $^1G^\circ_4$ **Ce** Cerium 140.116 $[Xe]4f5d6s^2$ 5.5387	59 $^4I^\circ_{9/2}$ **Pr** Praseodymiu 140.90765 $[Xe]4f^36s^2$ 5.473	60 $^5I_4$ **Nd** Neodymium 144.24 $[Xe]4f^46s^2$ 5.5250	61 $^6H^\circ_{5/2}$ **Pm** Promethium (145) $[Xe]4f^56s^2$ 5.582	62 $^7F_0$ **Sm** Samarium 150.36 $[Xe]4f^66s^2$ 5.6437	63 $^8S^\circ_{7/2}$ **Eu** Europium 151.964 $[Xe]4f^76s^2$ 5.6704	64 $^9D^\circ_2$ **Gd** Gadolinium 157.25 $[Xe]4f^75d6s^2$ 6.1498	65 $^6H^\circ_{15/2}$ **Tb** Terbium 158.92534 $[Xe]4f^96s^2$ 5.8638
89 $^2D_{3/2}$ **Ac** Actinium (227) $[Rn]6d7s^2$ 5.17	90 $^3F_2$ **Th** Thorium 232.0381 $[Rn]6d^27s^2$ 6.3067	91 $^4K_{11/2}$ **Pa** Protactinium 231.03588 $[Rn]5f^26d7s^2$ 5.89	92 $^5L^\circ_6$ **U** Uranium 238.02891 $[Rn]5f^36d7s^2$ 6.1941	93 $^6L_{11/2}$ **Np** Neptunium (237) $[Rn]5f^46d7s^2$ 6.2657	94 $^7F_0$ **Pu** Plutonium (244) $[Rn]5f^67s^2$ 6.0260	95 $^8S^\circ_{7/2}$ **Am** Americium (243) $[Rn]5f^77s^2$ 5.9738	96 $^9D^\circ_2$ **Cm** Curium (247) $[Rn]5f^76d7s^2$ 5.9914	97 $^6H^\circ_{15/2}$ **Bk** Berkelium (247) $[Rn]5f^97s^2$ 6.1979

$Nd_{1.85}Ce_{0.15}CuO_4 (T_c=23K)$

$Sm_{1.90}Ce_{0.10}CuO_4 (T_c=0K)$

$Sm_{1.85}Ce_{0.15}CuO_4 (T_c=17K)$

$Sm_{1.82}Ce_{0.18}CuO_4 (T_c=9K)$

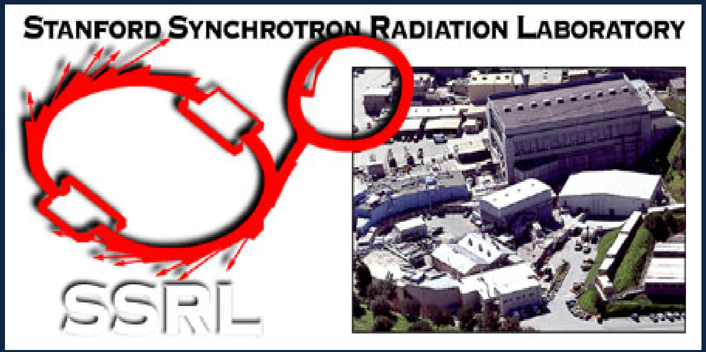
$Eu_{1.85}Ce_{0.15}CuO_4 (T_c=0K)$

$Gd_{1.85}Ce_{0.15}CuO_4 (T_c=0K)$

Experiments

- **ARPES experiments**: Stanford Synchrotron Radiation Lab.
- **Energy resolution** : 15 meV
- **Temperature** : 15K

➢ ARPES

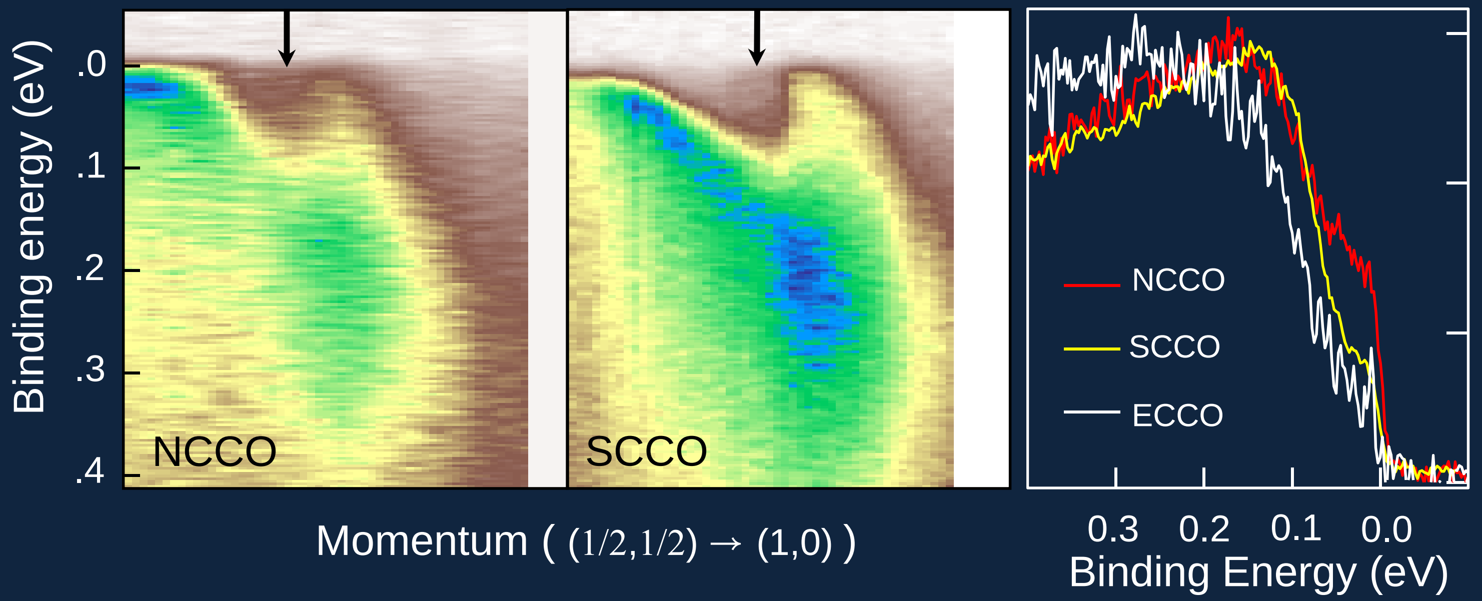


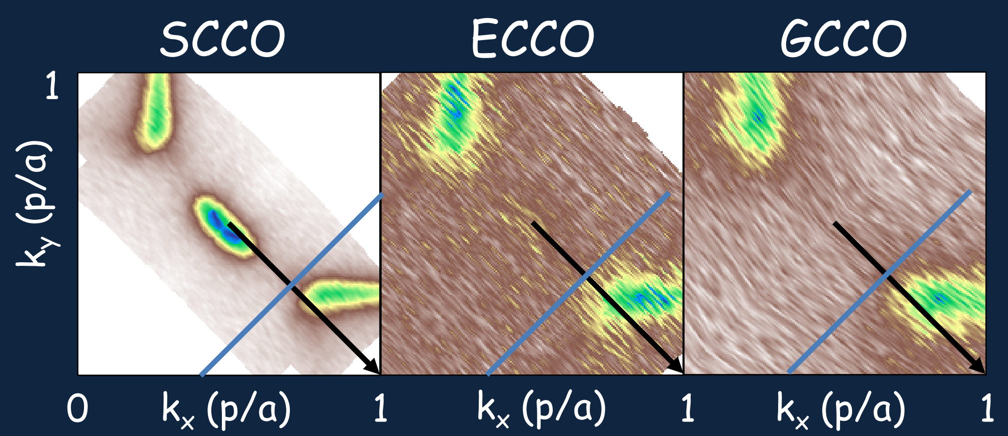
SSRL, Stanford, USA

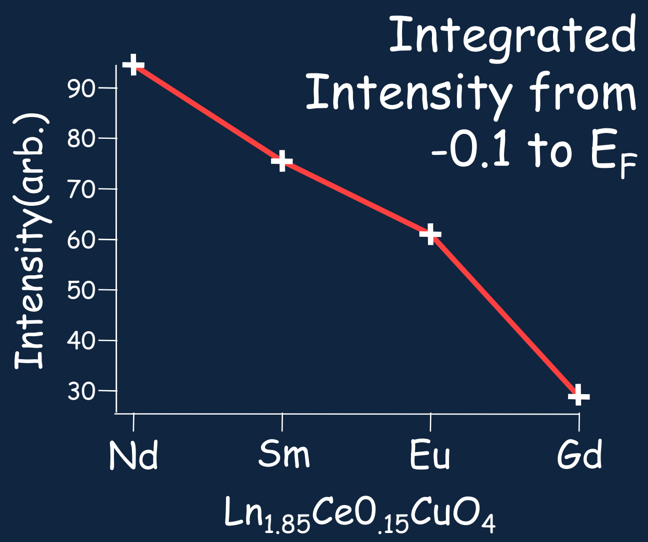
B.L. 5-4
high resolution ARPES

➢ Optical

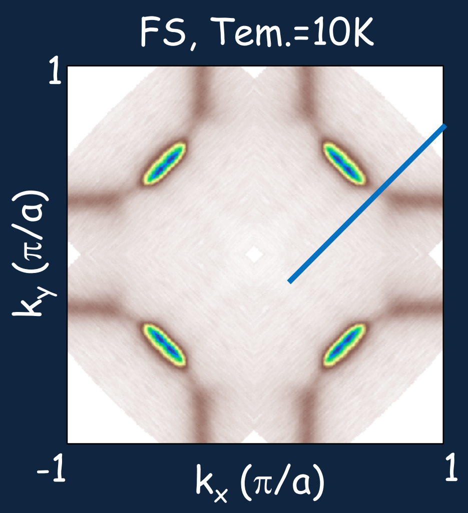
Rare-earth elements dependent

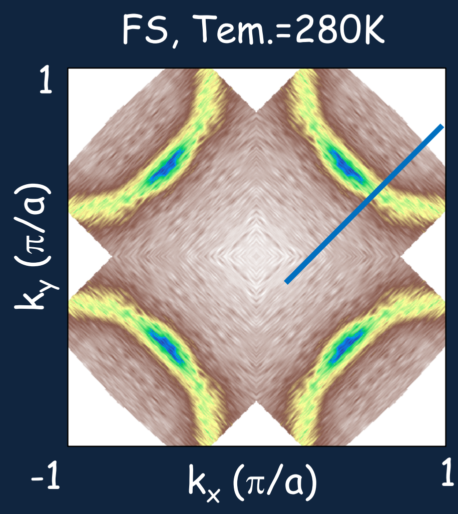


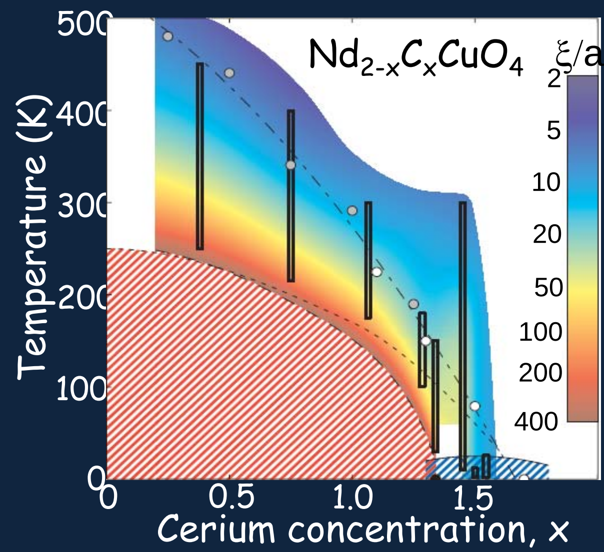


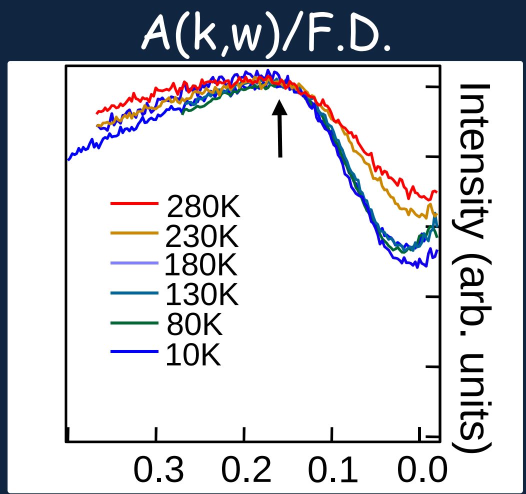


Tem. Dep. Spectral weight



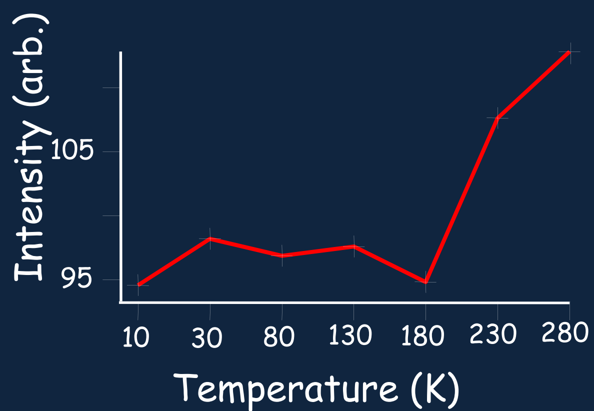






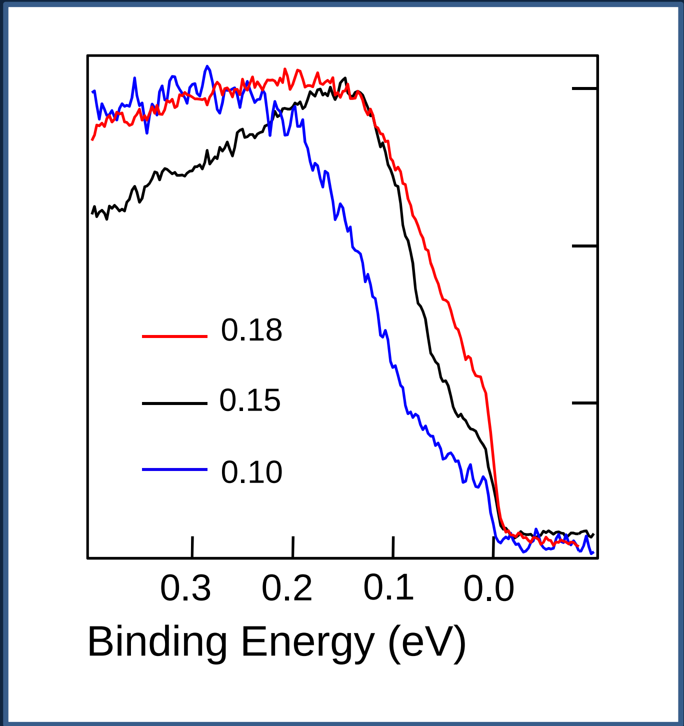
Integrated intensity from -0.1 to E_F

~1/correlation length(ξ)



Doping dep. spectral weight

$Sm_{2-x}Ce_xCuO_4$



Previously also seen in NCCO
H. Matsui et al., PRB (2007)

Doping, temperature, rare earth dependences all show that:

1. Overall, gap size does not change much
2. Gap is filled up as AF ordering length decreases

⇒Similar to pseudo-gap in hole doped & reminiscence of phase fluctuation.

Spin-fermion model

Coupling to spin excitations

nature physics

LETTERS

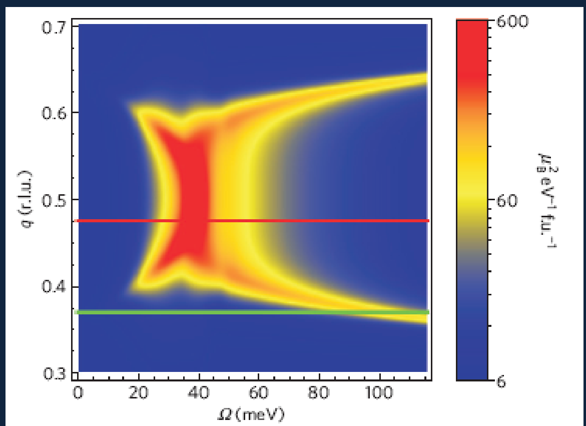
PUBLISHED ONLINE: 18 JANUARY 2009 | DOI: 10.1038/NPHYS1180

Strength of the spin-fluctuation-mediated pairing interaction in a high-temperature superconductor

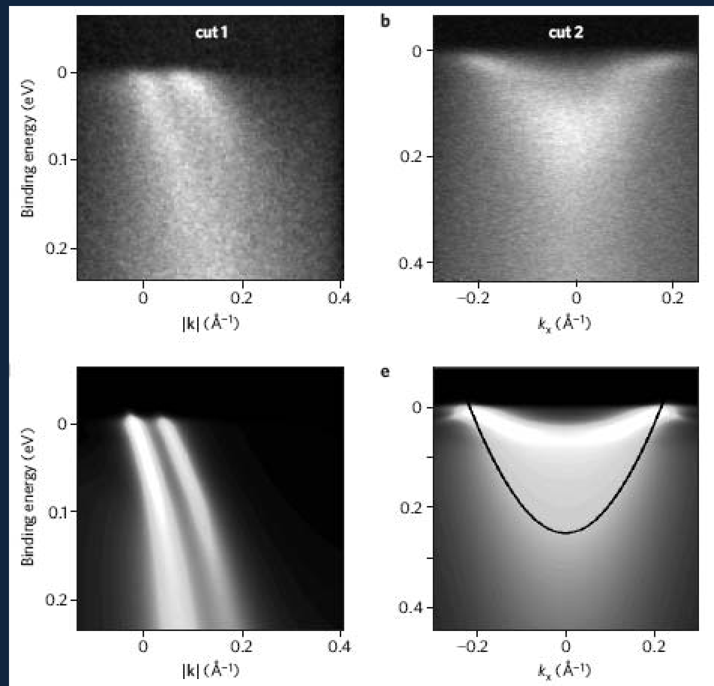
T. Dahm[1], V. Hinkov[2], S. V. Borisenko[3], A. A. Kordyuk[3], V. B. Zabolotnyy[3], J. Fink[3,4], B. Büchner[3], D. J. Scalapino[5], W. Hanke[6] and B. Keimer[2]*

$$V_{\text{eff}}(\mathbf{Q},\Omega) = \frac{3}{2}\,\bar{U}^2\,\chi(\mathbf{Q},\Omega)$$

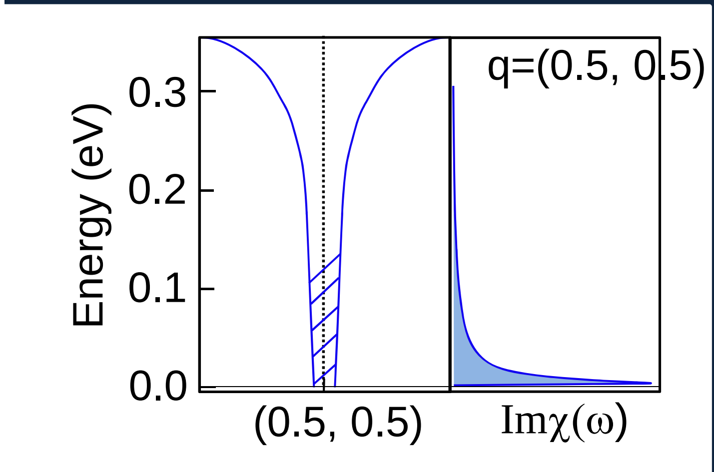
U = 1.59 eV



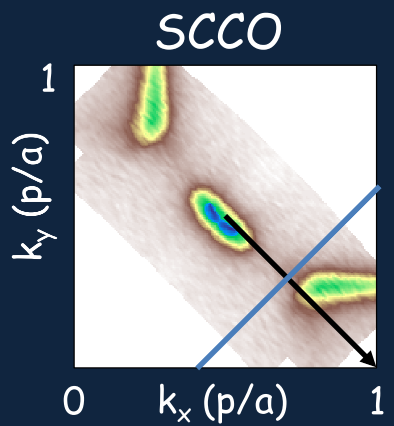
χ''

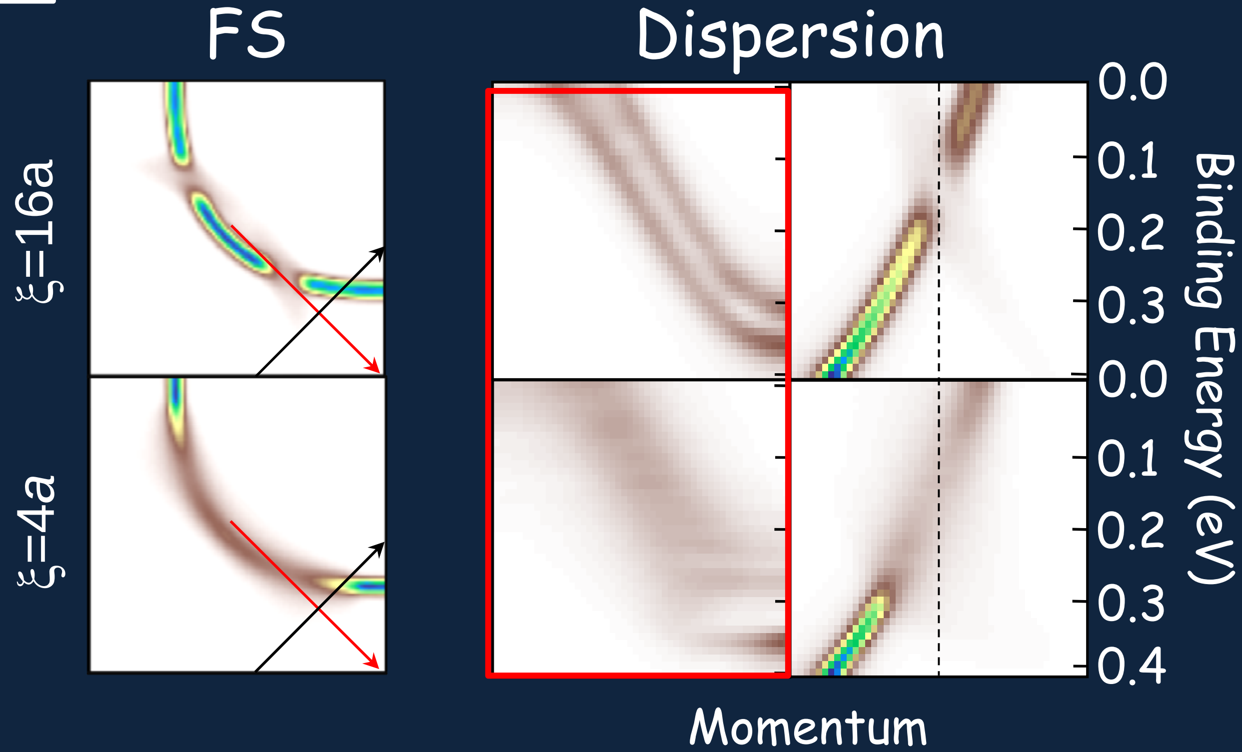


Electron doped case

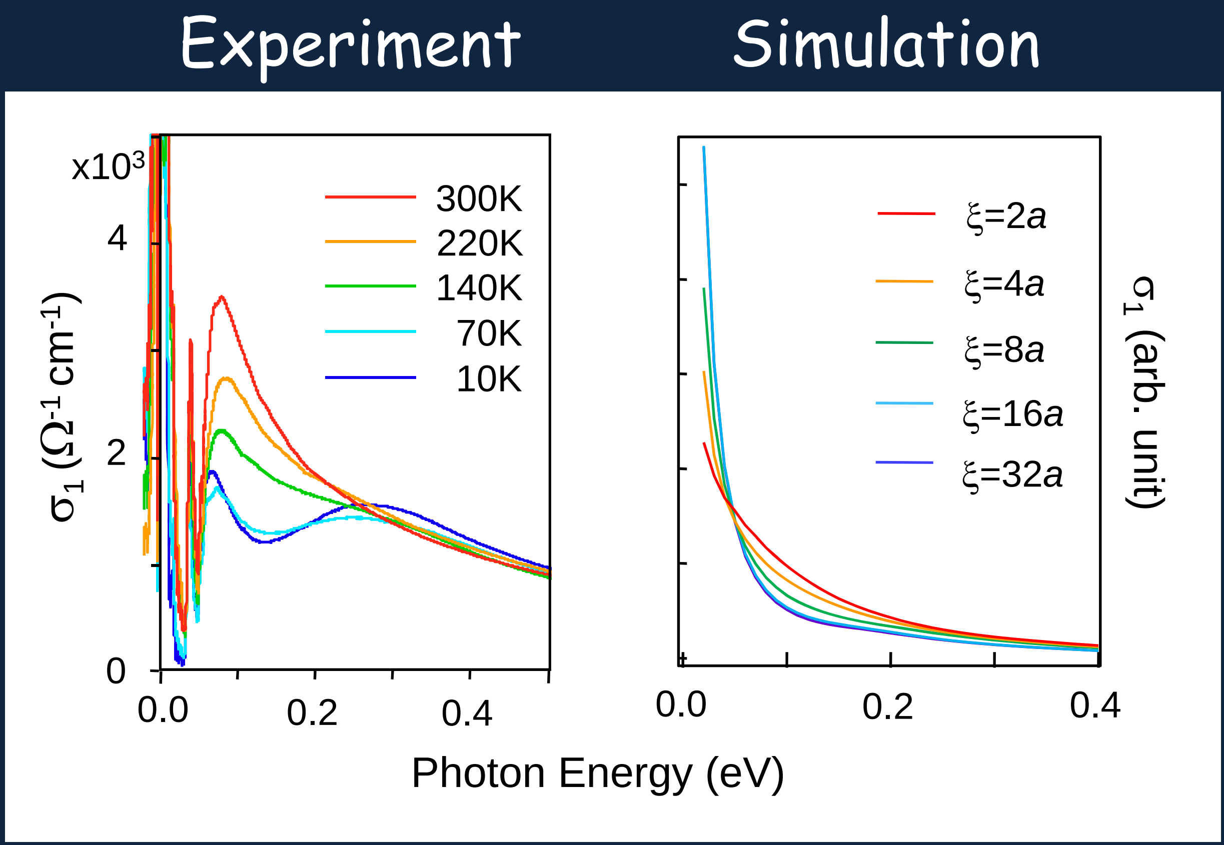


Wilson et al., PRL 96, 157001 (2006)





Optical conductivity



AF phase fluctuation model

("Yet another spin-fermion model",
A. Chubukov)

Subject to potential from AF order

$$H = \sum_{ij} t_{ji} c_{j\sigma}^{+} c_{i\sigma} + \lambda \sum_{i} \mathbf{m}_i \cdot \mathbf{S}_i$$

m_i = local magnetic moment
S_i = electron spin
λ = coupling constant

$$S_i^{+} = c_{i\uparrow}^{+} c_{i\downarrow}, \quad S_i^{-} = c_{i\downarrow}^{+} c_{i\uparrow}, \quad S_i^{z} = \frac{1}{2}(c_{i\uparrow}^{+} c_{i\uparrow} - c_{i\downarrow}^{+} c_{i\downarrow})$$

$$H = \sum_{ij} t_{ji} c_{j\sigma}^{+} c_{i\sigma} + \lambda \sum_{i} (m_i^{+} c_{i\downarrow}^{+} c_{i\uparrow} + m_i^{-} c_{i\uparrow}^{+} c_{i\downarrow}), \quad m_i^{+} = m_i^{x} + i m_i^{y}$$

$$m_i^{+} = (-1)^i m e^{i\phi_i}$$

<= AF phase fluctuation

$$G_k = G_{k\uparrow} + G_{k\downarrow} = \frac{\cos^2\theta_{k-p\uparrow}}{E_{k-p\uparrow}^{+} - i\omega} + \frac{\sin^2\theta_{k-p\uparrow}}{E_{k-p\uparrow}^{-} - i\omega} + \frac{\cos^2\theta_{k+p\downarrow}}{E_{k+p\downarrow}^{+} - i\omega} + \frac{\sin^2\theta_{k+p\downarrow}}{E_{k+p\downarrow}^{-} - i\omega},$$

$$A_k = \cos^2\theta_{k-p\uparrow}\delta(E_{k-p\uparrow}^{+} - \omega) + \sin^2\theta_{k-p\uparrow}\delta(E_{k-p\uparrow}^{-} - \omega) + \cos^2\theta_{k+p\downarrow}\delta(E_{k+p\downarrow}^{+} - \omega) + \sin^2\theta_{k+p\downarrow}\delta(E_{k+p\downarrow}^{-} - \omega)$$

$$G_k = G_{k\uparrow} + G_{k\downarrow} = \frac{\cos^2\theta_{k-p\uparrow}}{E^+_{k-p\uparrow} - i\omega} + \frac{\sin^2\theta_{k-p\uparrow}}{E^-_{k-p\uparrow} - i\omega} + \frac{\cos^2\theta_{k+p\downarrow}}{E^+_{k+p\downarrow} - i\omega} + \frac{\sin^2\theta_{k+p\downarrow}}{E^-_{k+p\downarrow} - i\omega},$$

$$A_k = \cos^2\theta_{k-p\uparrow}\delta(E^+_{k-p\uparrow} - \omega) + \sin^2\theta_{k-p\uparrow}\delta(E^-_{k-p\uparrow} - \omega) + \cos^2\theta_{k+p\downarrow}\delta(E^+_{k+p\downarrow} - \omega) + \sin^2\theta_{k+p\downarrow}\delta(E^-_{k+p\downarrow} - \omega)$$

with

$$\cos 2\theta_{k-p\uparrow} = \frac{\varepsilon_k - \varepsilon_{k+Q-2p}}{\sqrt{(\varepsilon_k - \varepsilon_{k+Q-2p})^2 + 4\lambda^2 m^2}}, \qquad \cos 2\theta_{k+p\downarrow} = \frac{\varepsilon_k - \varepsilon_{k+Q+2p}}{\sqrt{(\varepsilon_k - \varepsilon_{k+Q+2p})^2 + 4\lambda^2 m^2}}$$

and

$$E^\pm_{k-p\uparrow} = \frac{1}{2}(\varepsilon_k + \varepsilon_{k+Q-2p}) \pm \sqrt{(\lambda m)^2 + \frac{1}{4}(\varepsilon_k - \varepsilon_{k+Q-2p})}$$

$$E^\pm_{k+p\downarrow} = \frac{1}{2}(\varepsilon_k + \varepsilon_{k+Q+2p}) \pm \sqrt{(\lambda m)^2 + \frac{1}{4}(\varepsilon_k - \varepsilon_{k+Q+2p})}.$$

Finally:

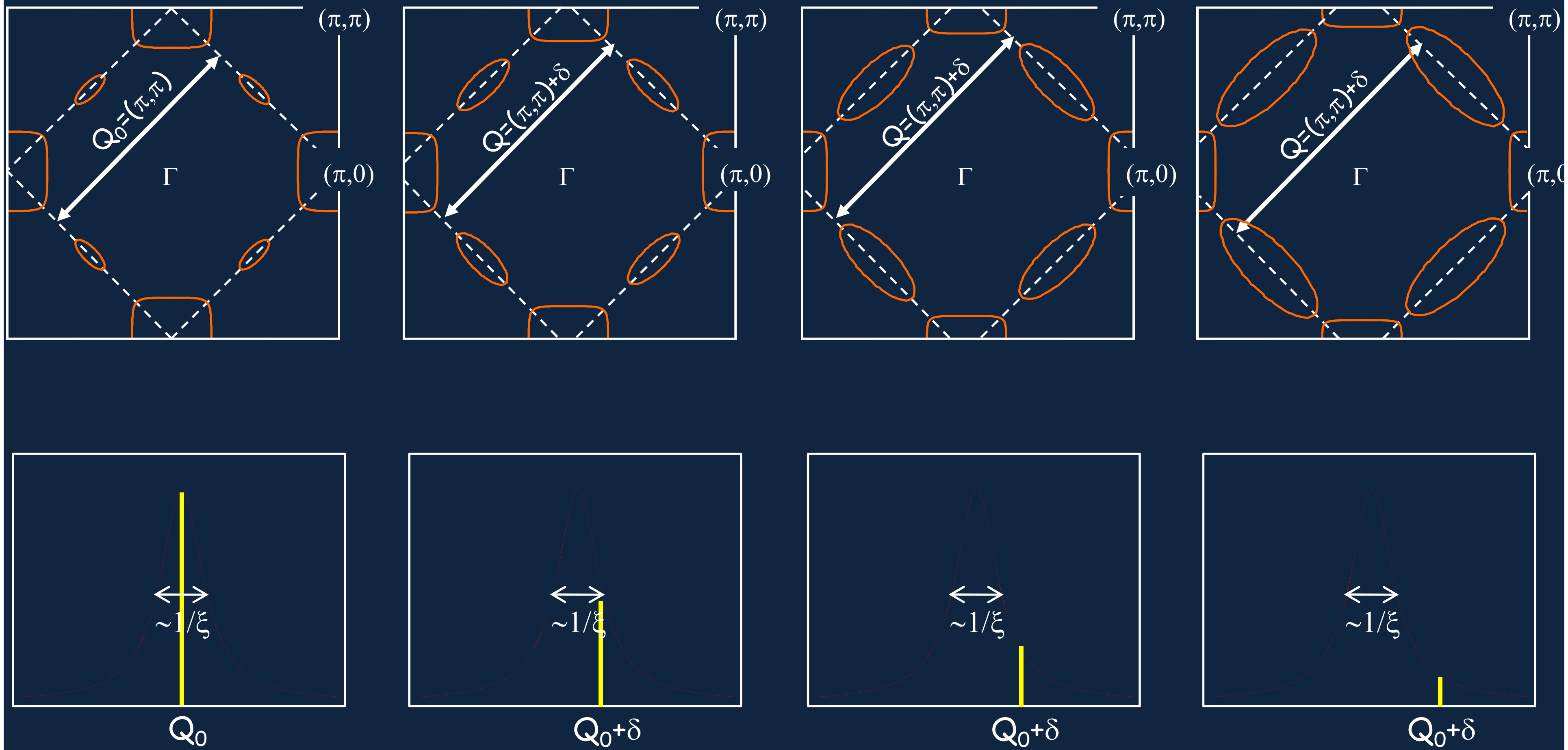
$$\langle A_k \rangle = \int \left(\cos^2\theta_{k-p\uparrow}\delta(E^+_{k-p\uparrow} - \omega) + \sin^2\theta_{k-p\uparrow}\delta(E^-_{k-p\uparrow} - \omega)\right)\rho(p)d^2p.$$

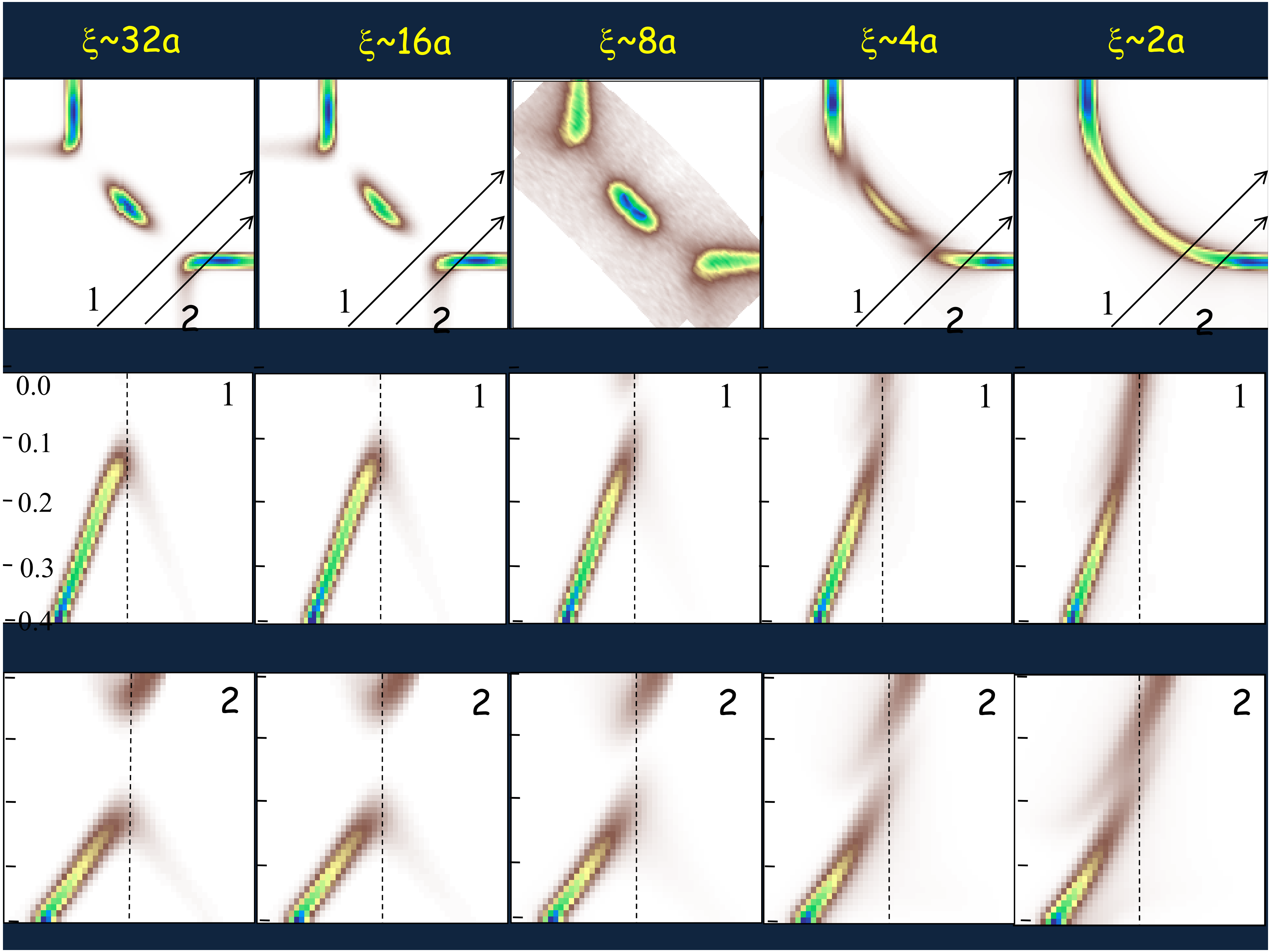
with

$$\langle A_k \rangle = \int \frac{A_k(\omega)}{p^2\xi^2 + 1} d^2p$$

* ξ = ordering length

AF phase fluctuation effect
(averaging over different Q's)

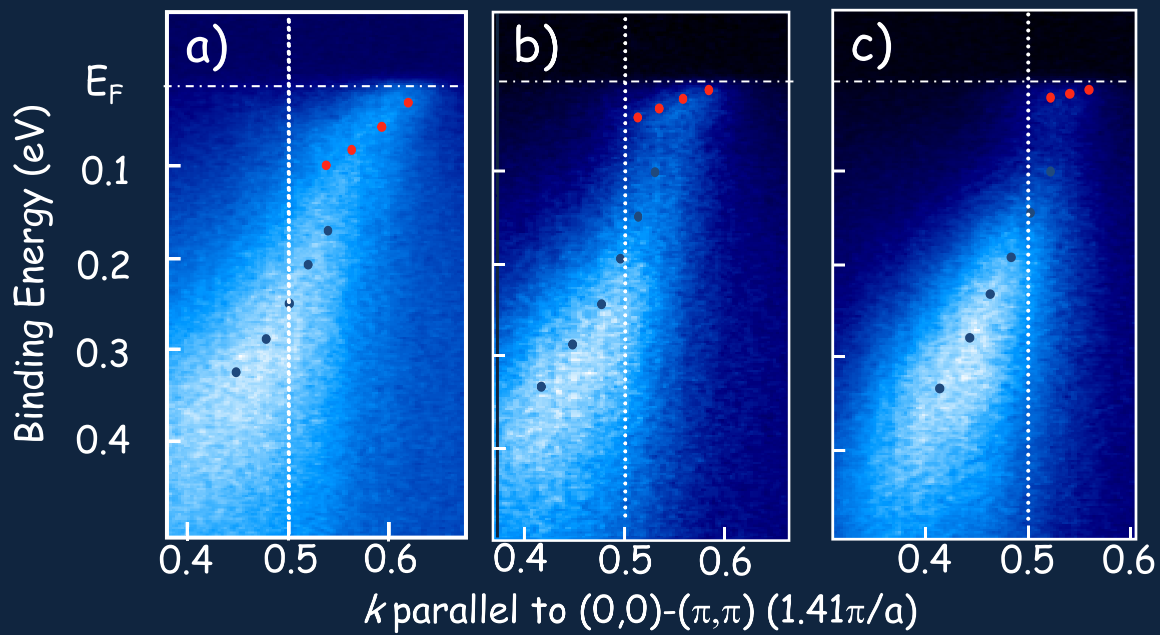


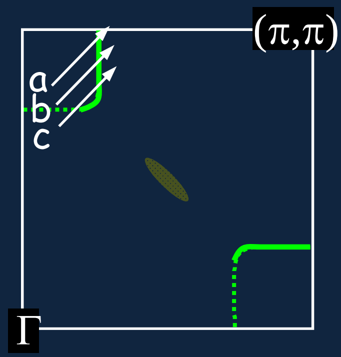


ξ~32a
ξ~16a
ξ~8a
ξ~4a
ξ~2a
1
2
0.0
0.1
0.2
0.3
0.4

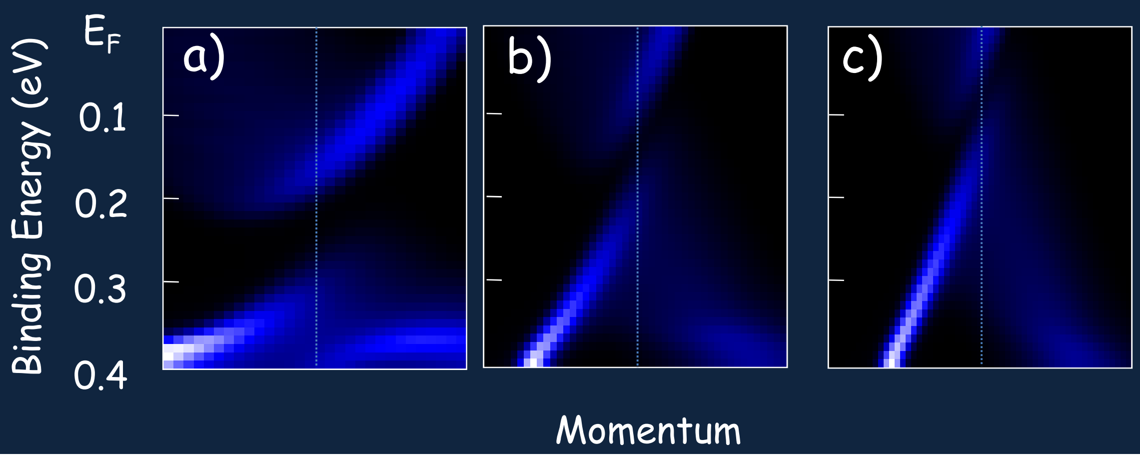
Electron-AF SRO coupling

$Sm_{1.85}Ce_{0.15}CuO_4$

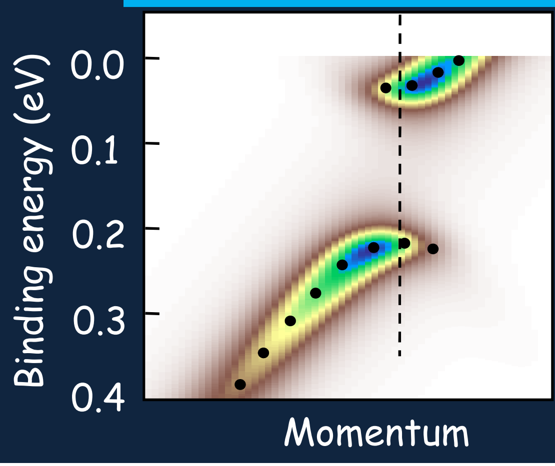




Short Range Order(SRO) , ξ~4a

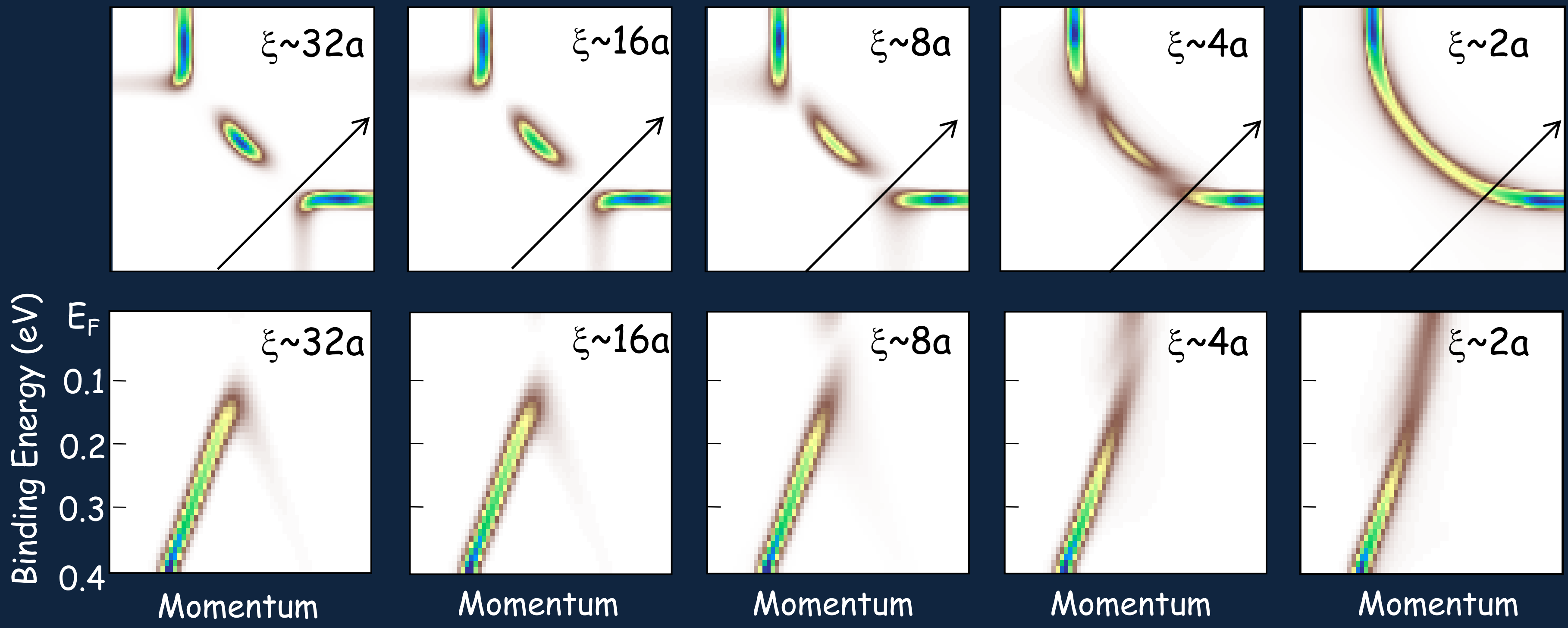


Long Range order

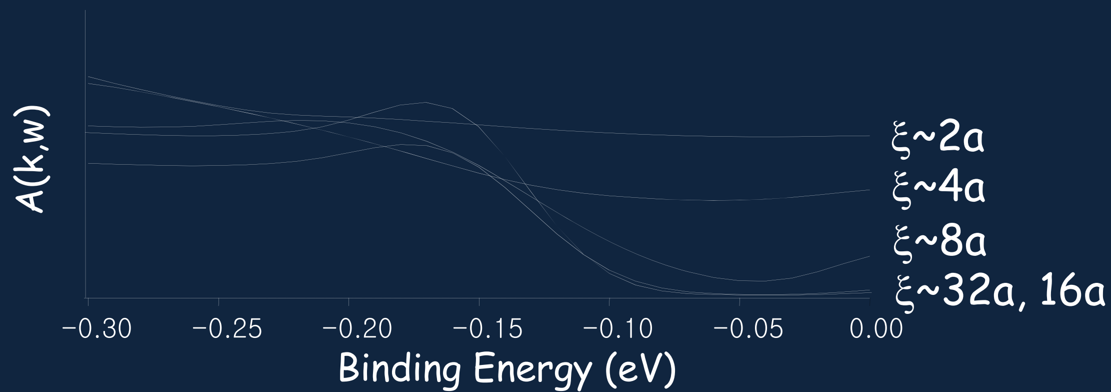


Gap filling and E_F weight

➢ <u>Fermi surface</u>



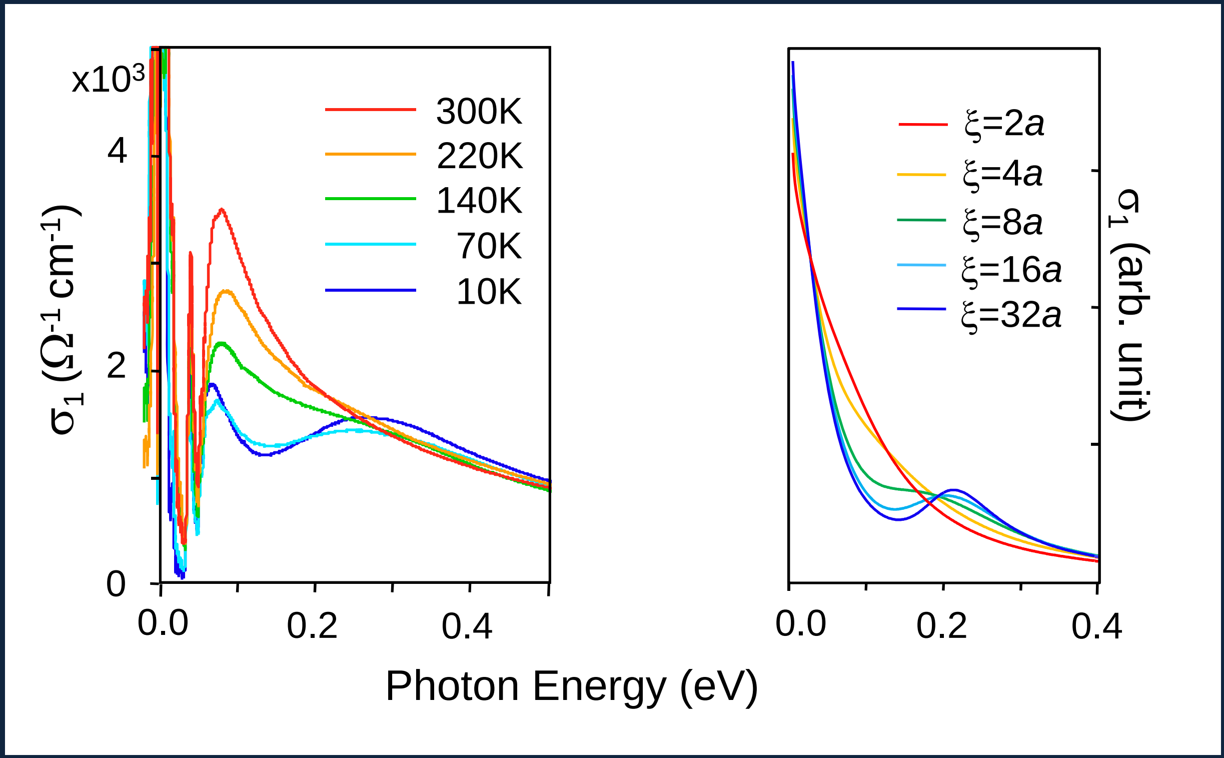
Spectral weight near E_F



Optical conductivity

Experiment

Simulation



The model....

1. Not spin-boson but phase gradient ($\nabla\phi$) couples to electron.
2. T_c can be estimated based within the model.
3. The parameter λm can be obtained by fitting exp data.

$$H = \sum_{ij} t_{ji} c^{+}_{j\sigma} c_{i\sigma} + \lambda \sum_{i} \mathbf{m}_i \cdot \mathbf{S}_i$$

Summary

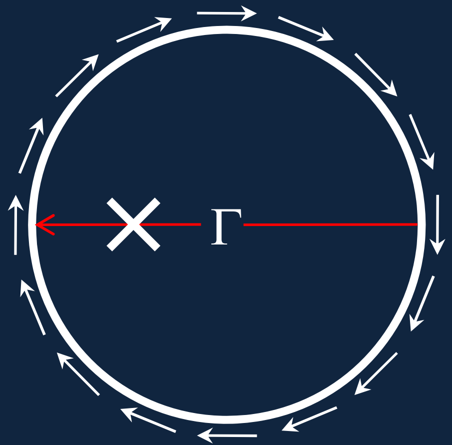
1. Correlation between pseudo-gap behavior and AF ordering
2. Pseudo-gap does not close but fills up as AF ordering decreases
3. ARPES spectral function and optical conductivity are well explained within AF phase fluctuation model

Quasi-particle dynamics in topological insulator Bi_2Se_3

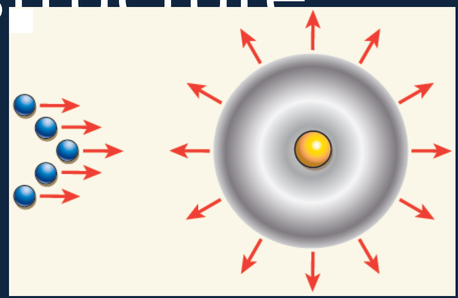
S. R. Park, W. S. Jung, Chul Kim, D. J. Song, C. Kim,
S. Kimura, K. D. Lee and N. Hur

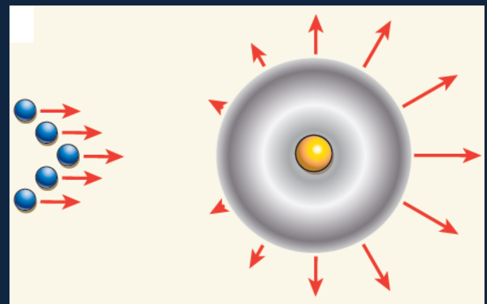
Importance

1. Long lifetime of surface metallic states due to helical spin structure



FS of surface state and spin structure





2. Protected surface metallic states

- No Fermi surface instability

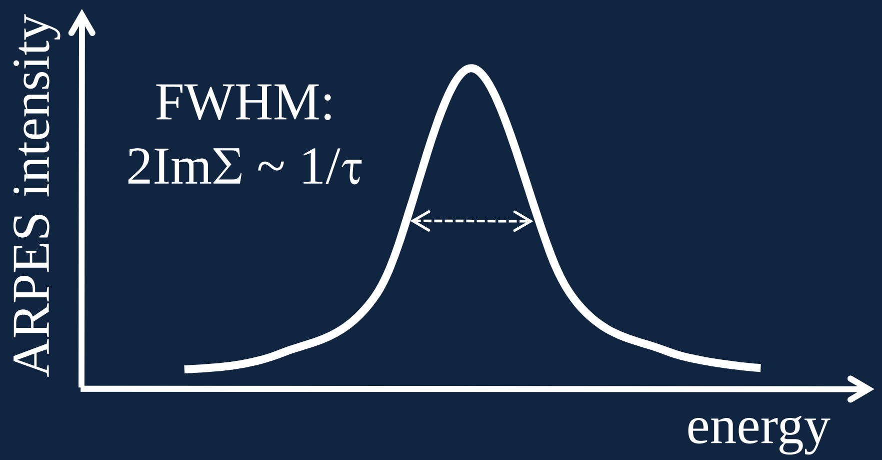
➡ Dissipationless nano-device and spinstronics

Long lifetime?
- ARPES studies

ARPES for lifetime measurement

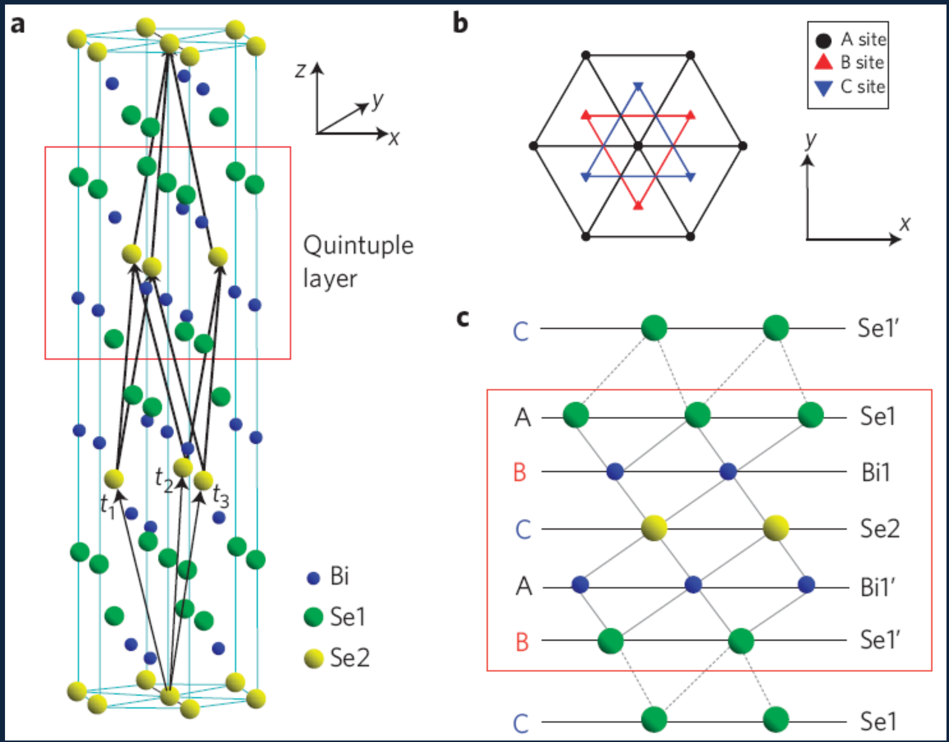
Spectral function

$$A(k,\omega) = \frac{1}{\pi} \frac{\mathrm{Im}\Sigma(k,\omega)}{(\omega - \varepsilon_k - \mathrm{Re}\Sigma(k,\omega))^2 + \mathrm{Im}\Sigma(k,\omega)^2}$$



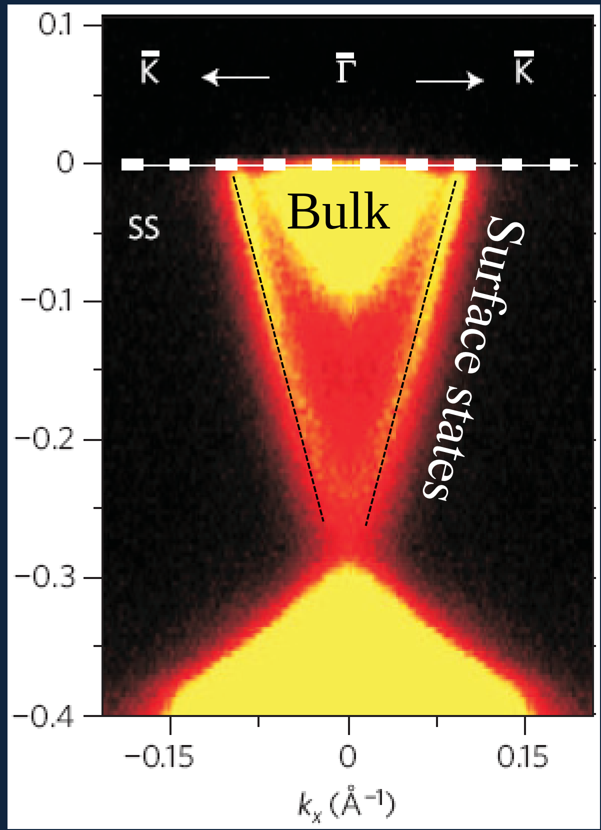
ARPES on TI "Bi_2Se_3"

Crystal structure



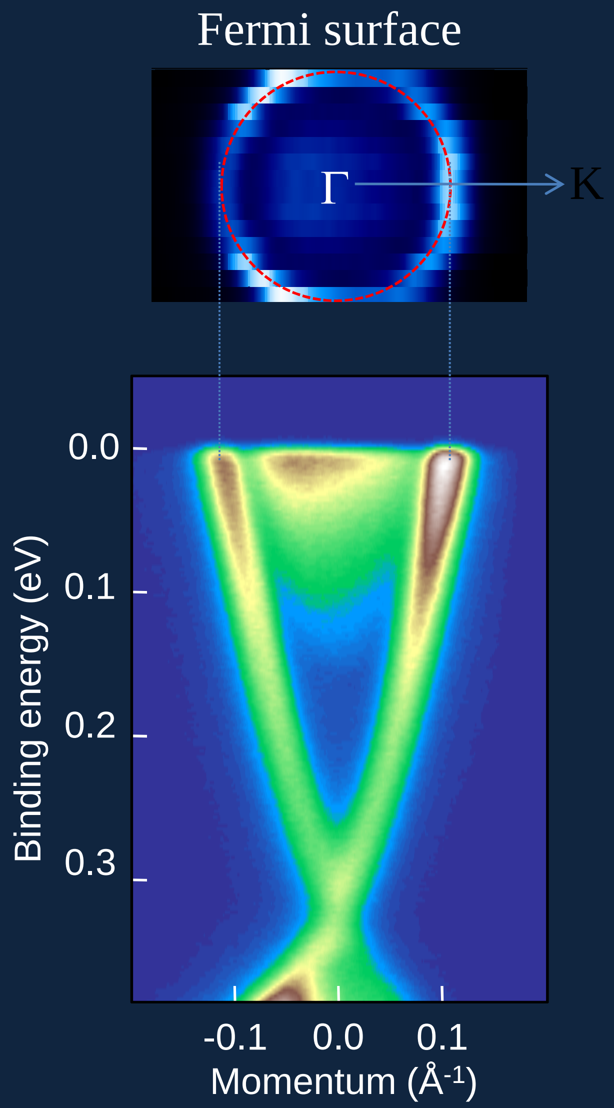
H. Zhang *et al*., Nat. Phys. (2009)

Surface states

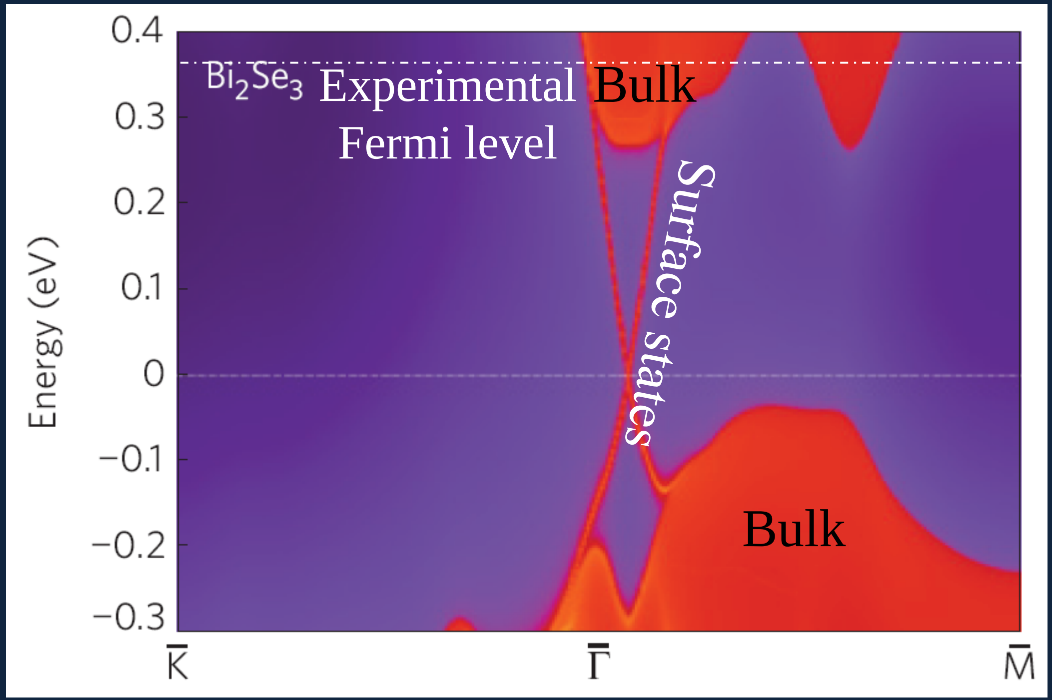


Y. Xia *et al*., Nat. Phys. (2009)

Our ARPES data (15 K, 8eV P. E.)



- Transport measurements as a bulk sensitive tool also report metallic behavior

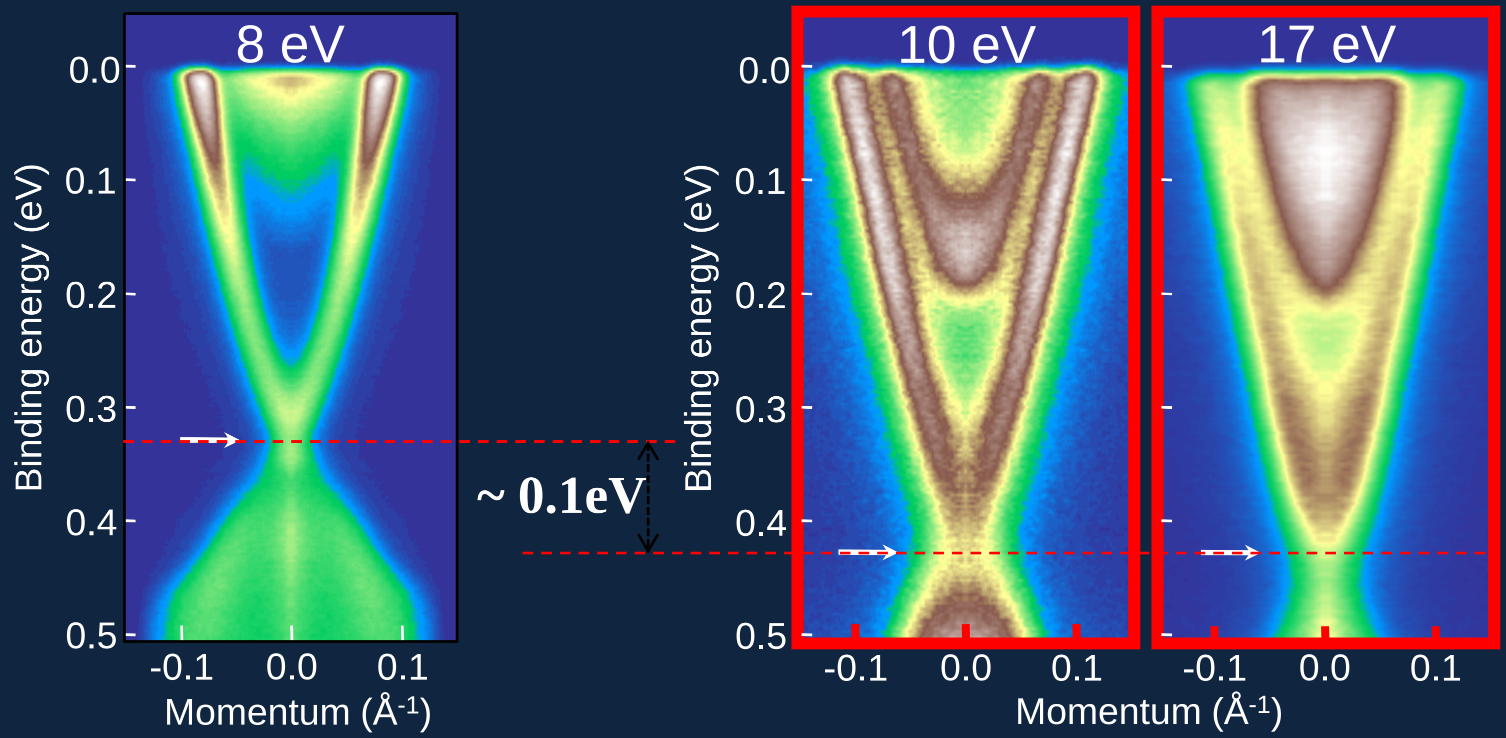


H. Zhang *et al.*, Nat. Phys. (2009)

Time dependence

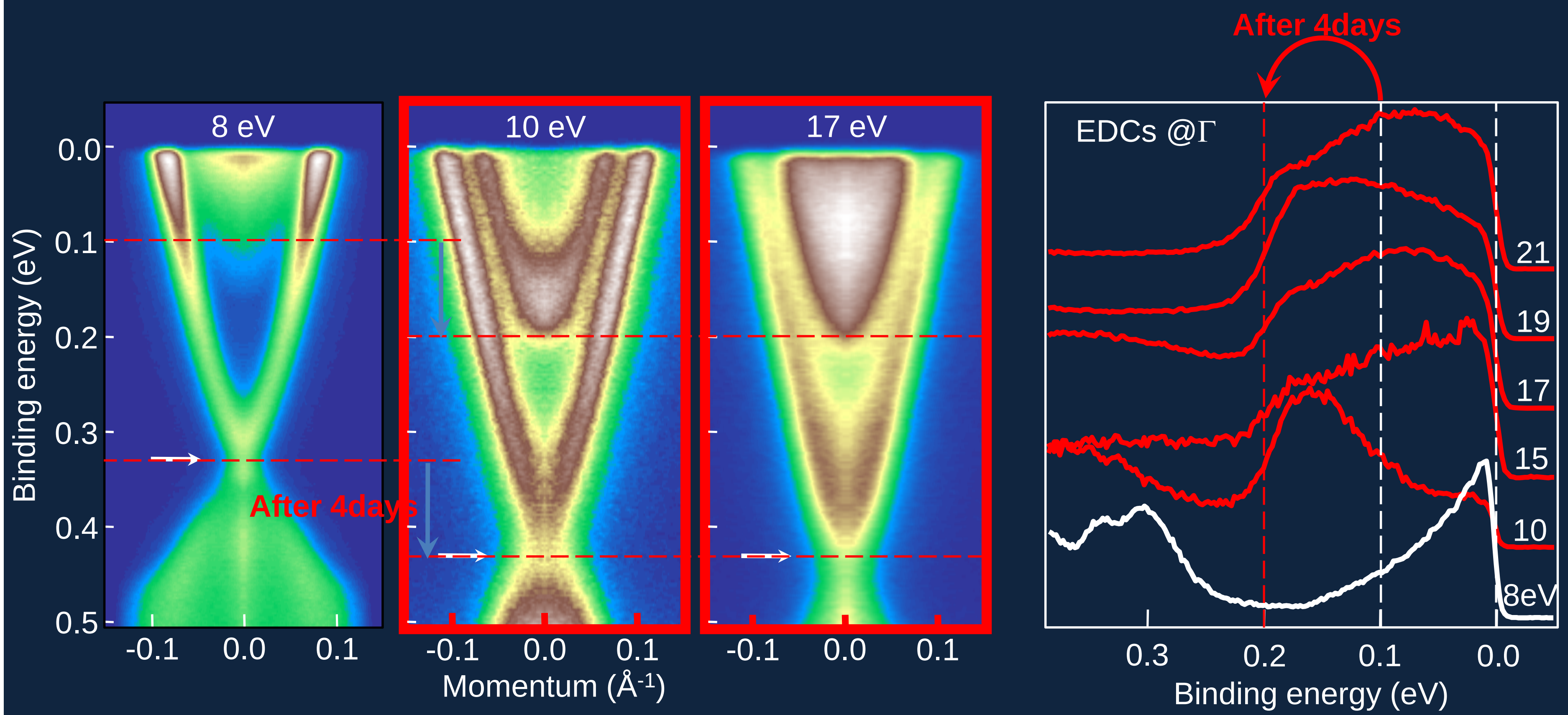
Fresh surface

4 days later



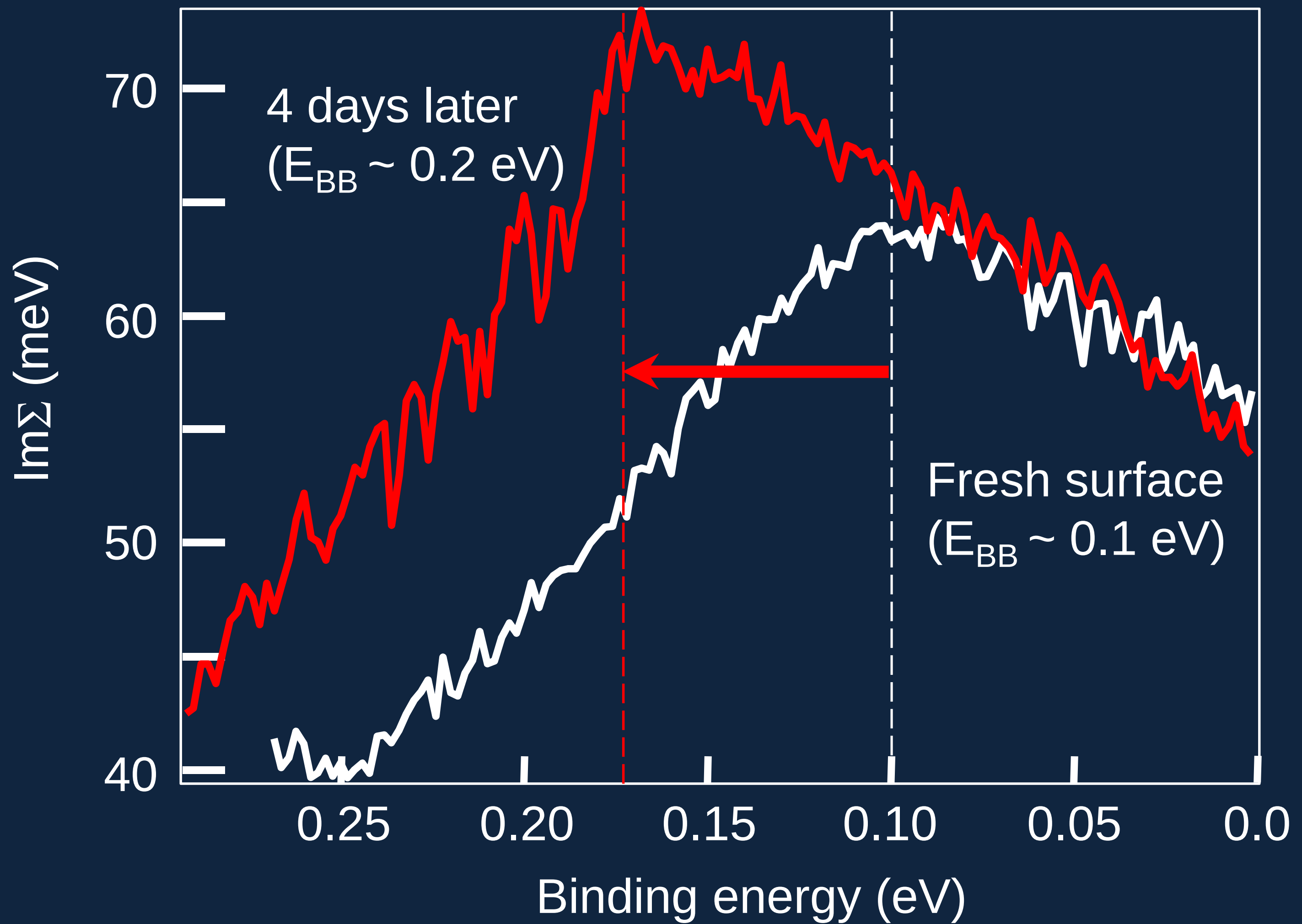
Surface (electron) doping effect with time

Photon energy dependence

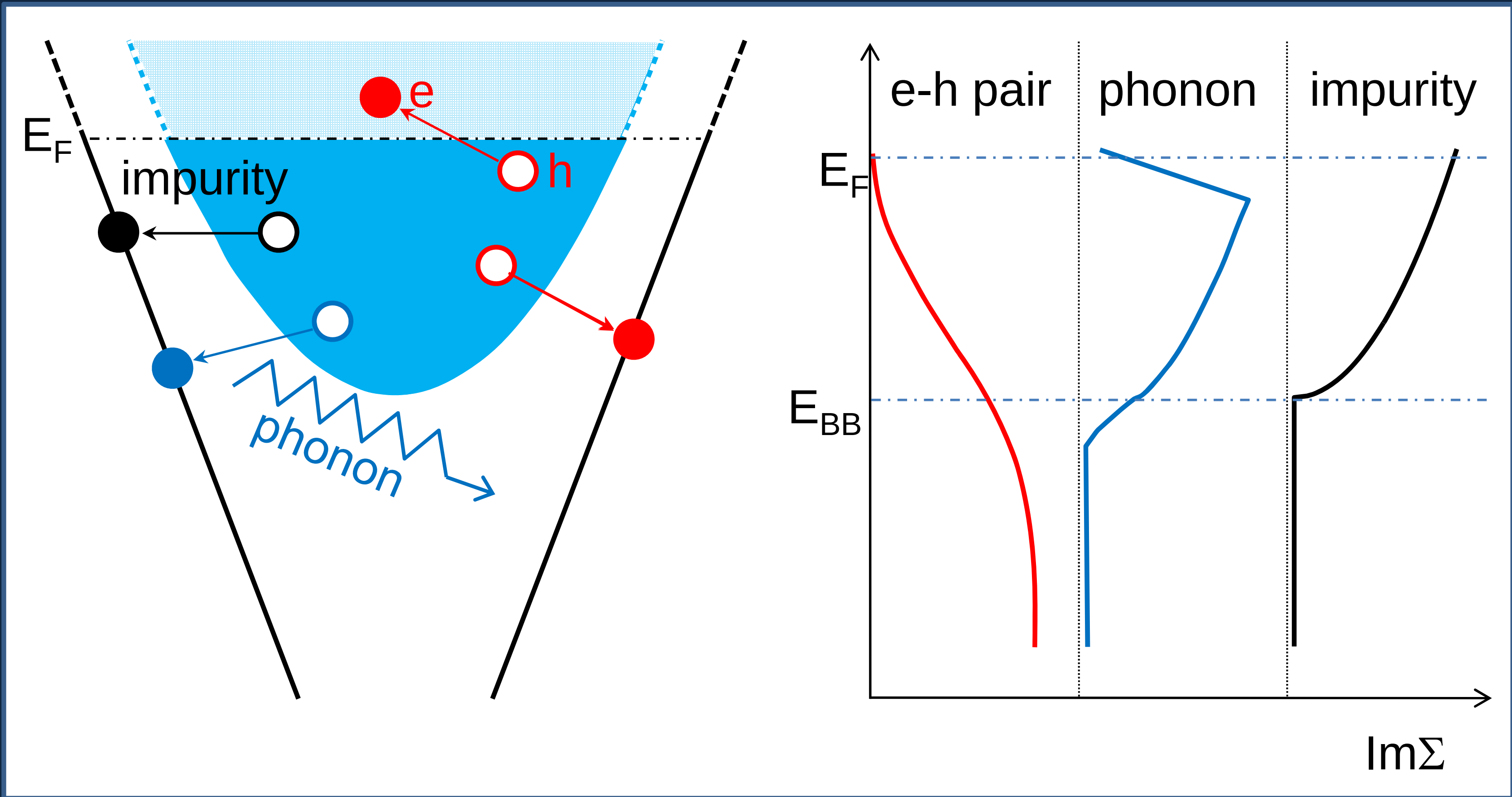


- Bulk states taken with 8 eV are suppressed due to k_z-selection rule.
- B. E. of bulk conduction band (E_{BB}) ~ 0.1eV

Life time : kink in ImΣ at ~E_{BB}

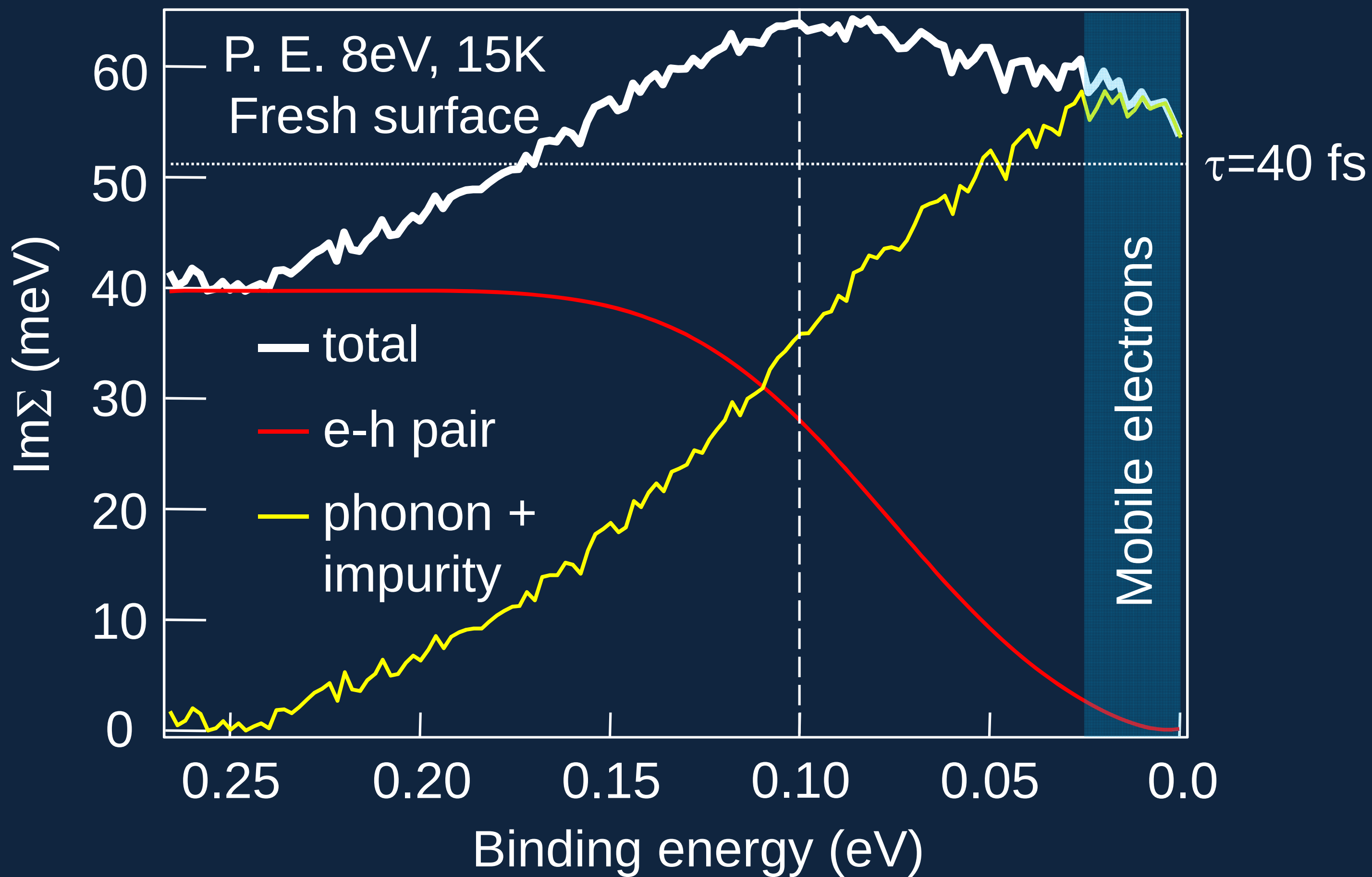


Scattering channels



• Kink in ImΣ at around E_{BB} is originated from scattering due to phonon or impurity

Surface electron lifetime



$$l_m = \tau \times \upsilon_g = 40 \cdot 10^{-15}(s) \times 5 \cdot 10^{5}(m/s) = 0.02(\mu m)$$

- Scattering to bulk states due to impurity is the main scattering channel for TM states.

Quasi-particle scattering and protected nature of topological states in a parent topological insulator Bi_2Se_3

S. R. Park[1], W. S. Jung[1], Chul Kim[1], D. J. Song[1], C. Kim[1,*], S. Kimura[2], K. D. Lee[3] and N. Hur[3]
[1]*Institute of Physics and Applied Physics, Yonsei University, Seoul, Korea*
[2]*UVSOR Facility, Institute for Molecular Science and The Graduate University for Advanced Studies, Okazaki 444-8585, JAPAN and*
[3]*Department of Physics, Inha University, Incheon 402-751, Korea*
(Dated: November 24, 2009)

We report on angle resolved photoemission spectroscopic studies on a parent topological insulator (TI), Bi_2Se_3. The line width of the spectral function (inverse of the quasi-particle lifetime) of the topological metallic (TM) states shows an anomalous behavior. This behavior can be reasonably accounted for by assuming decay of the quasi-particles predominantly into bulk electronic states through electron-electron interaction and defect scattering. Studies on aged surfaces reveal that topological metallic states are very much unaffected by the potentials created by absorbed atoms or molecules on the surface, indicating that topological states could be indeed protected against weak perturbations.

. To appear in PRB(R)

Summary

Experimental observation

- Kink in scattering rate at around bulk conduction band bottom

Interpretation

- Strong scattering between surface and bulk electrons due to electron-phonon coupling or impurity near E_F
- Carrier life time in TM states hardly affected by adsorbate created disorder potential