光電子および中性子分光の相補的利用による高温超伝導体の研究

Cooperative photoemission and neutron spectroscopy study of high-temperature superconductors

理学研究科物理学専攻
高橋　隆　山田和芳

Department of Physics
T. Takahashi & K. Yamada

東北大学
２１世紀COEプログラム「物質階層融合科学の構築」

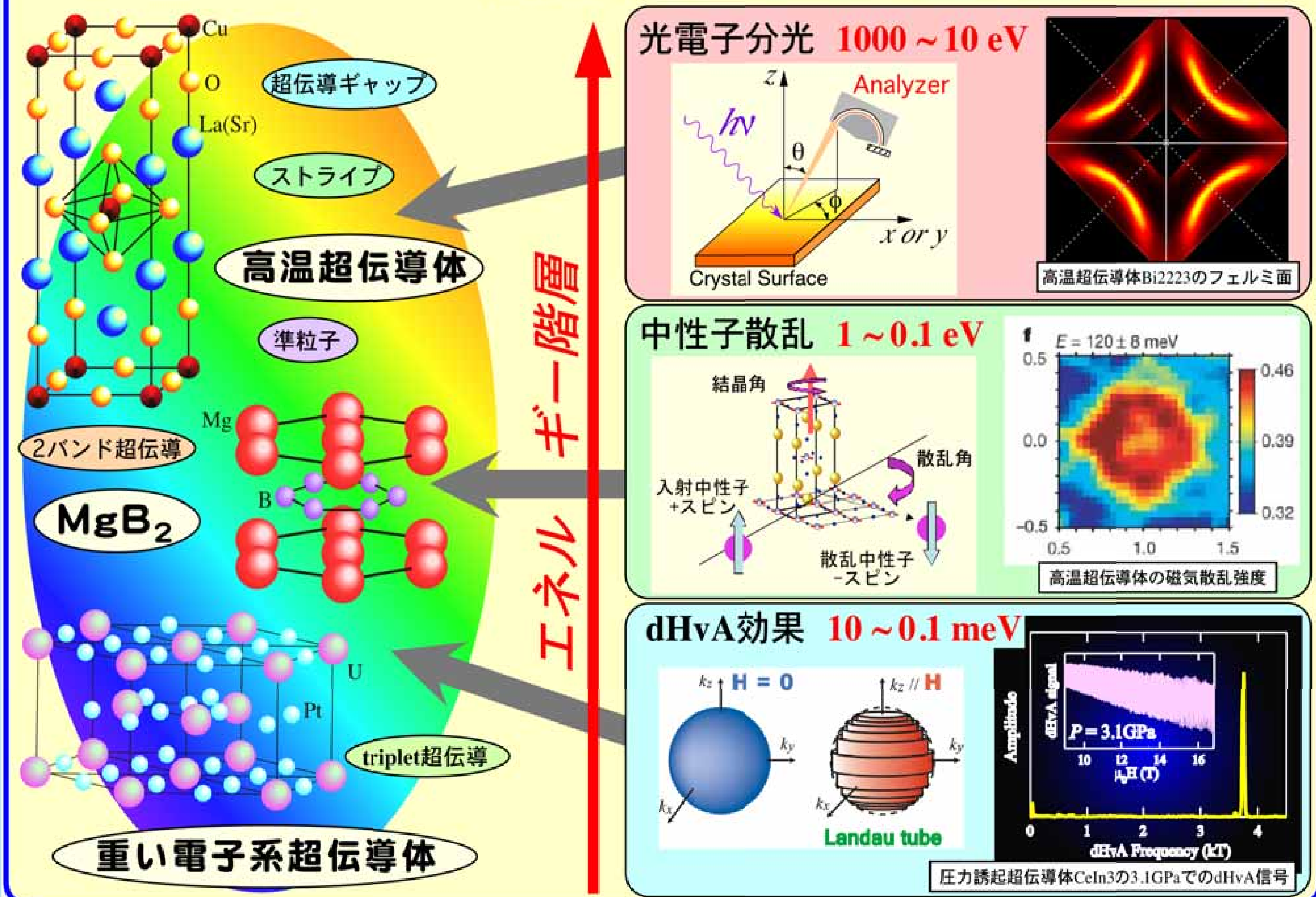
多重エネルギー階層分光による
超伝導固体内素励起の研究

代表研究者：高橋　隆

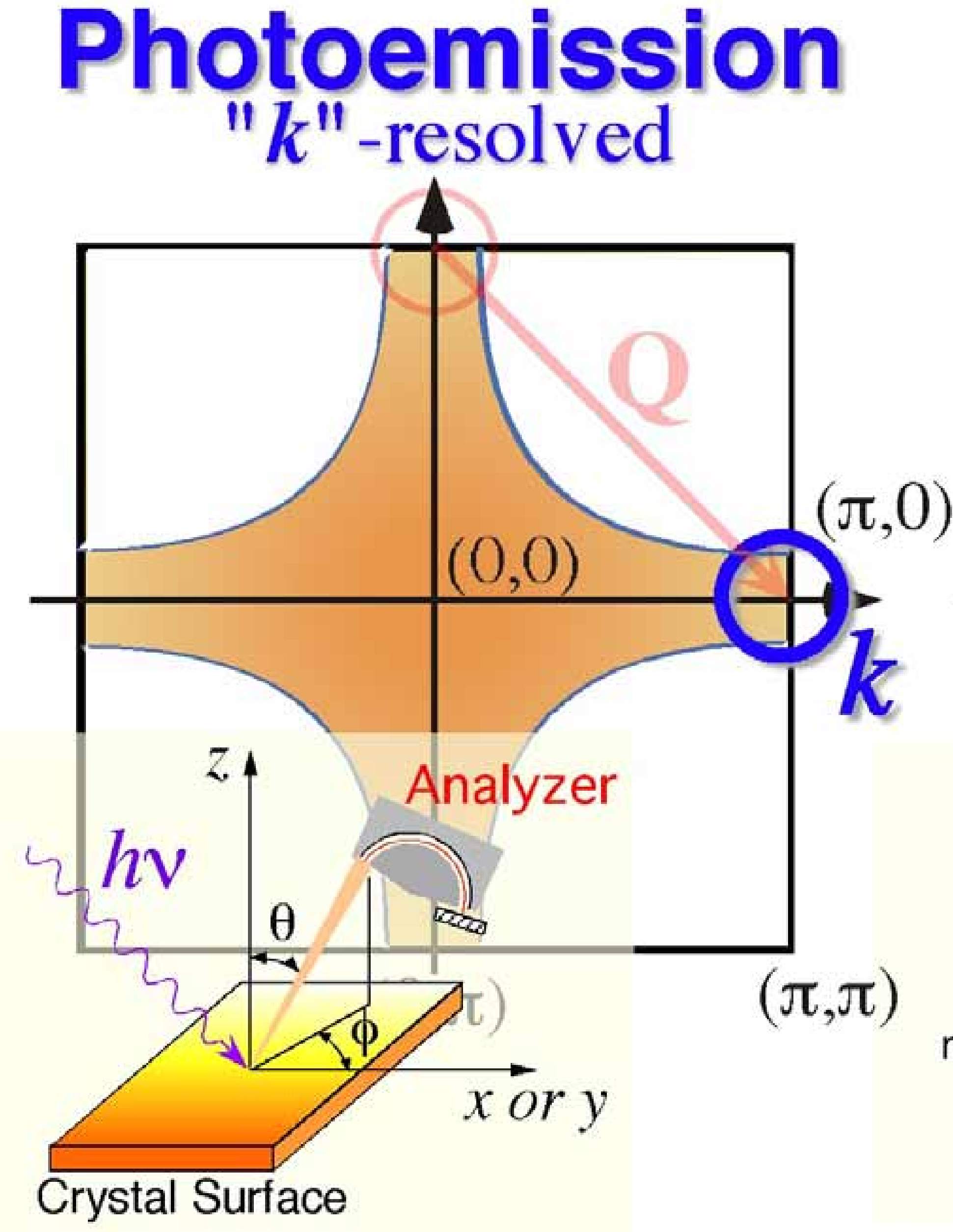
研究分担者：青木晴善、山田和芳、落合　明、佐藤宇史
木村憲彰、藤田全基、平賀晴弘

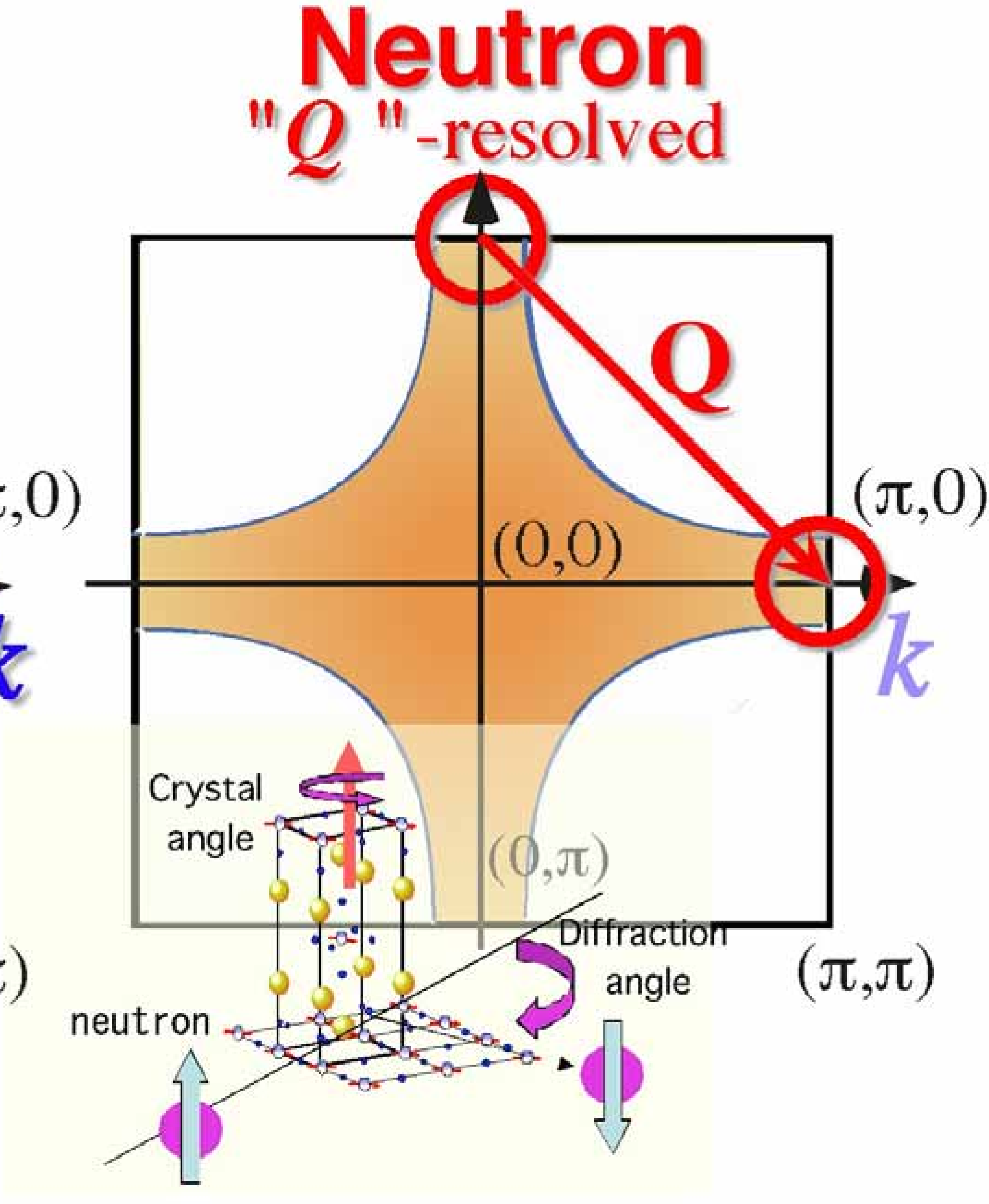
研究協力者： Satyabrata Raj

多重エネルギー階層分光による超伝導体の研究



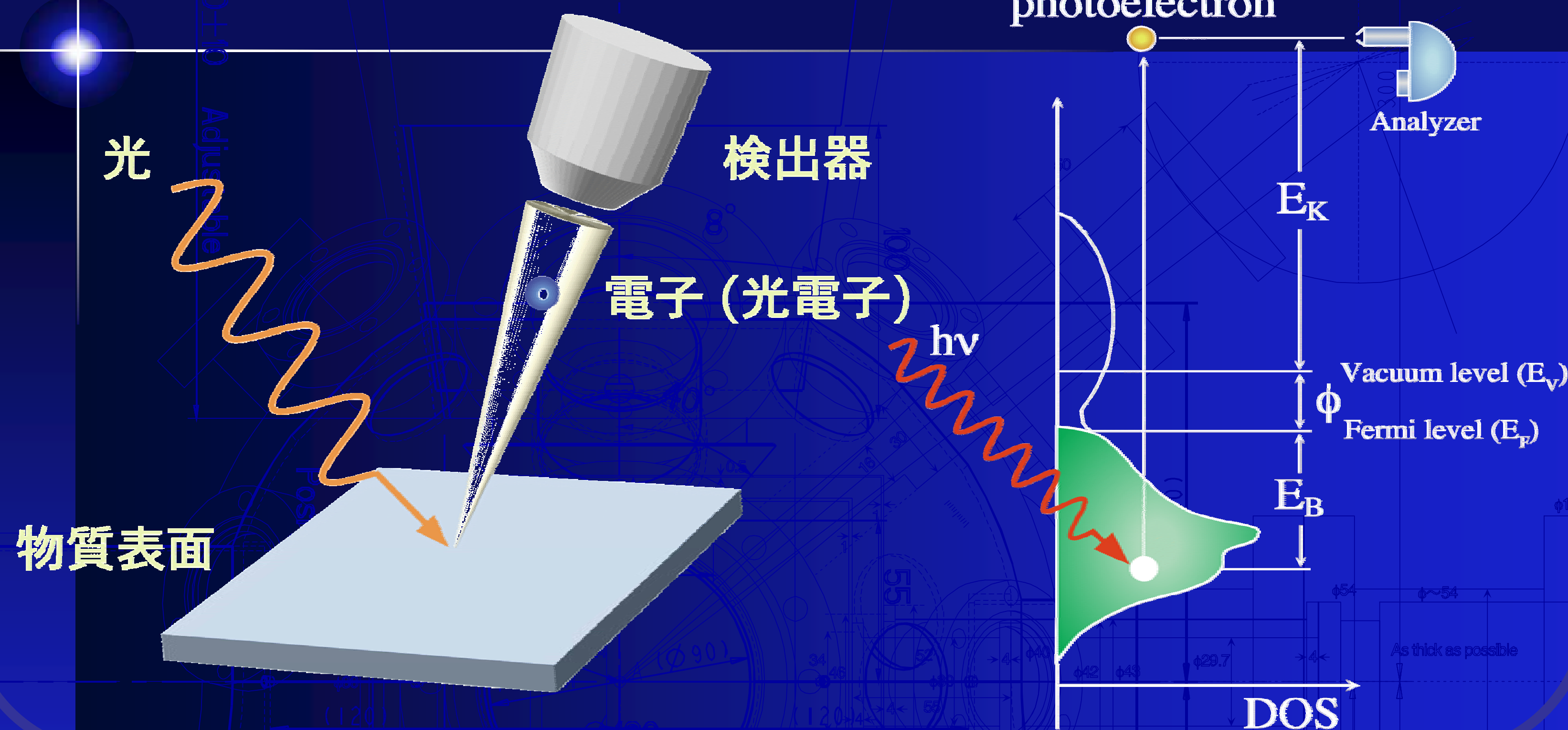
Two "momentum"-resolved experiments





Angle-Resolved Photoemission Spectroscopy (ARPES)

光電効果 (Einstein1905, Siegbahn 1981)



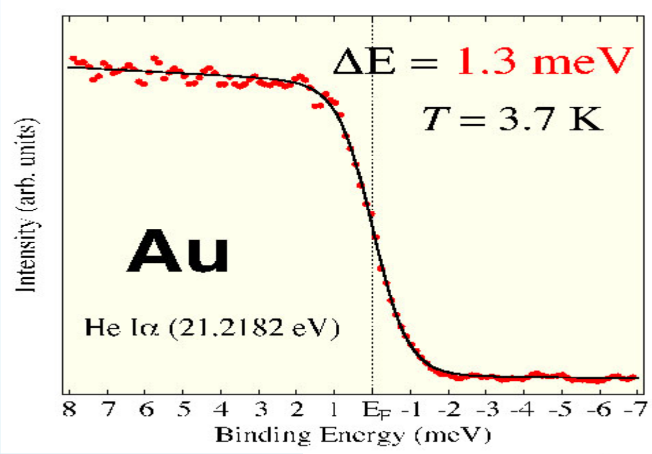
○角度分解光電子分光 ── 固体の**電子状態**の直接決定

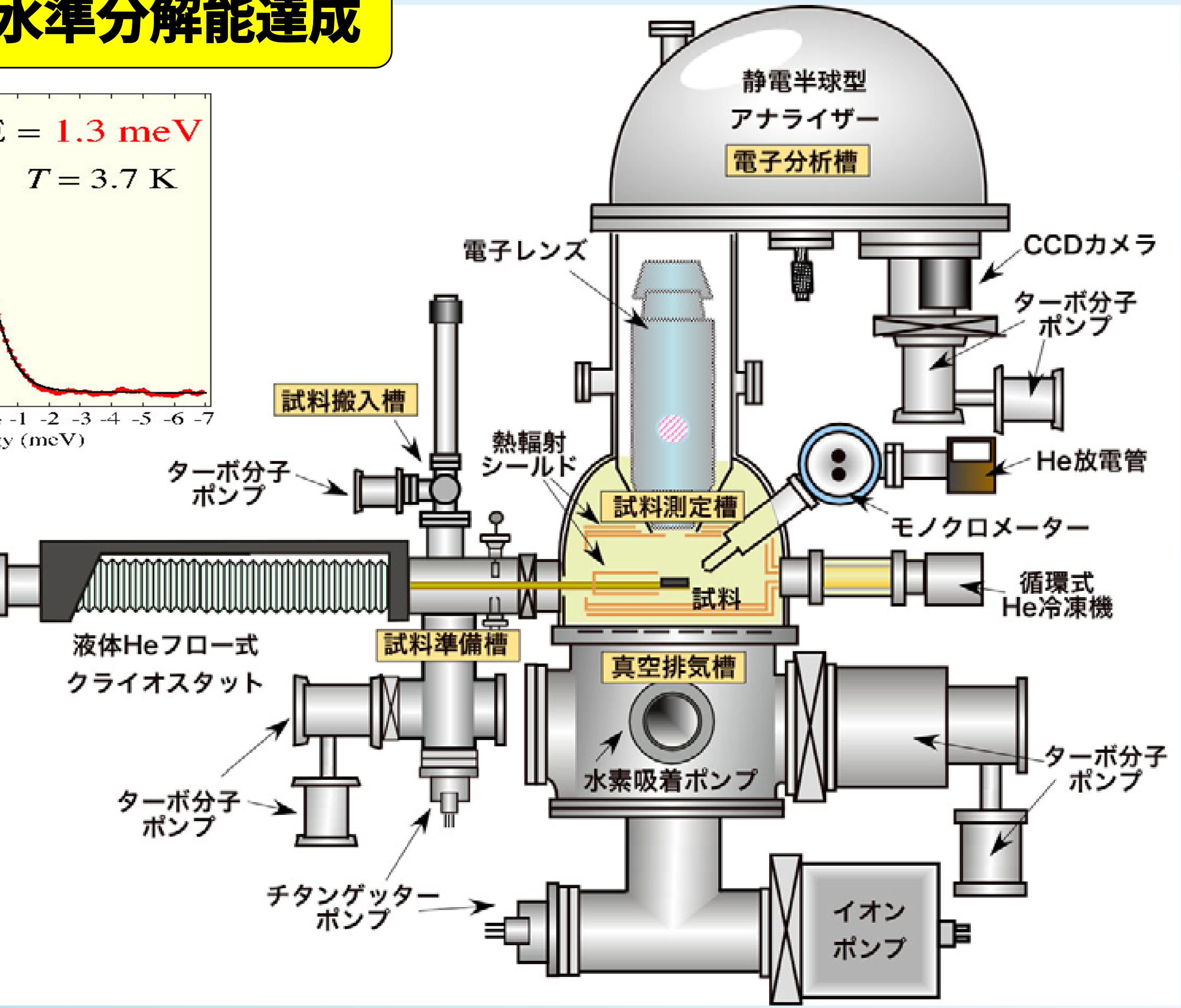
(ARPES: **A**ngle-**R**esolved **P**hoto**E**mission **S**pectroscopy)

- 状態密度
- バンド構造
- 多体相互作用

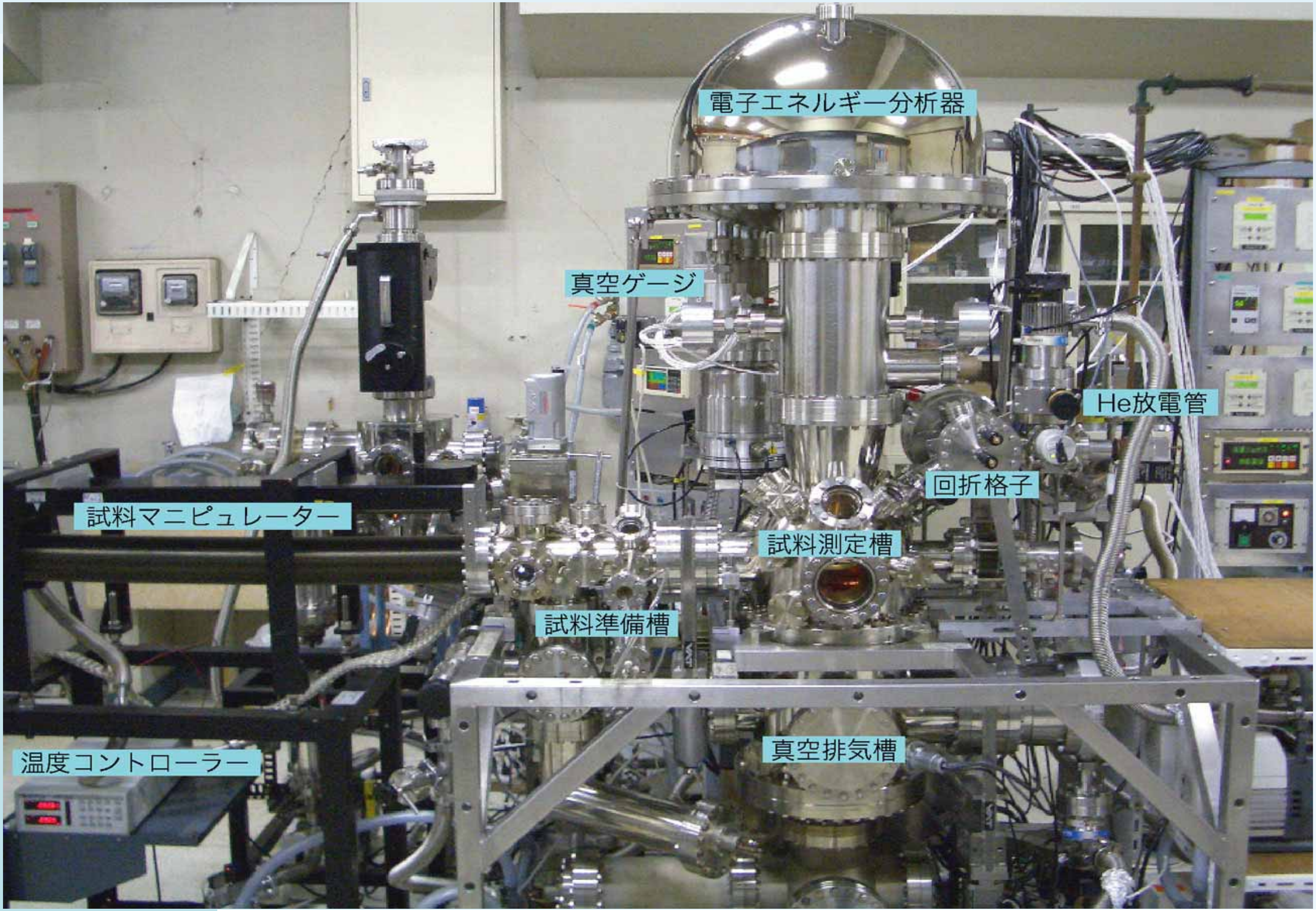
Ultrahigh-resolution photoemission spectrometer

世界最高水準分解能達成

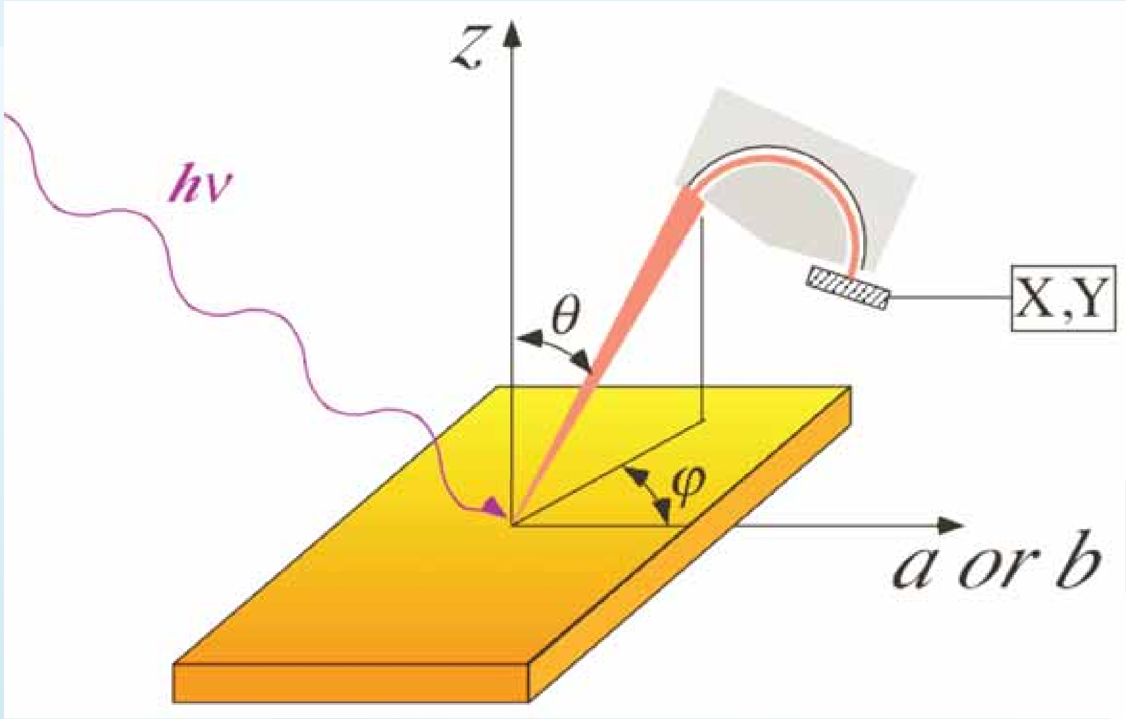


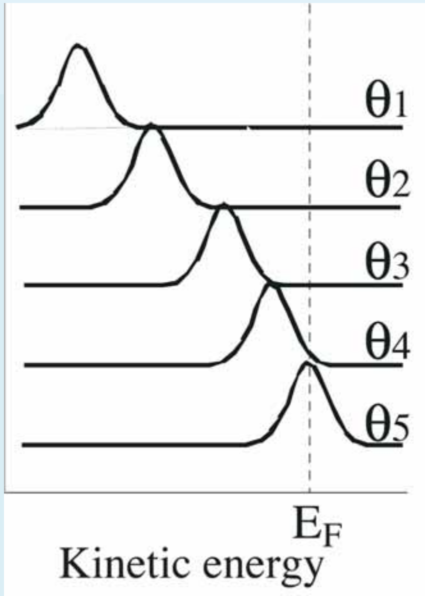


Ultrahigh-resolution photoemission spectrometer constructed at Tohoku University



Schematic view of ARPES





$$E_B = h\nu - \Phi - E_k$$

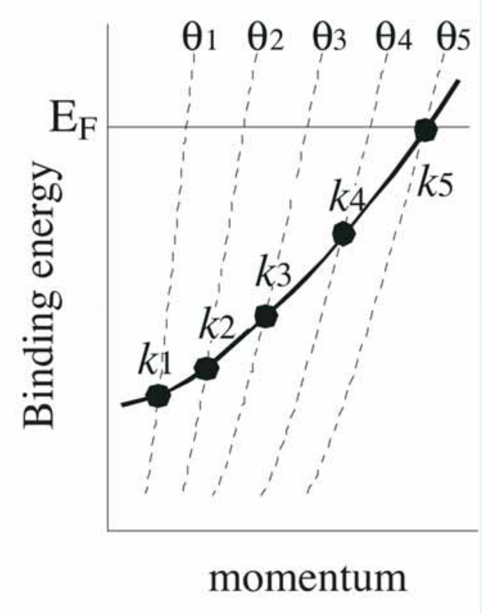
$$k_{//} = \sqrt{\frac{2mE_k}{\hbar^2}} sin\theta$$

E_B : **Binding energy**

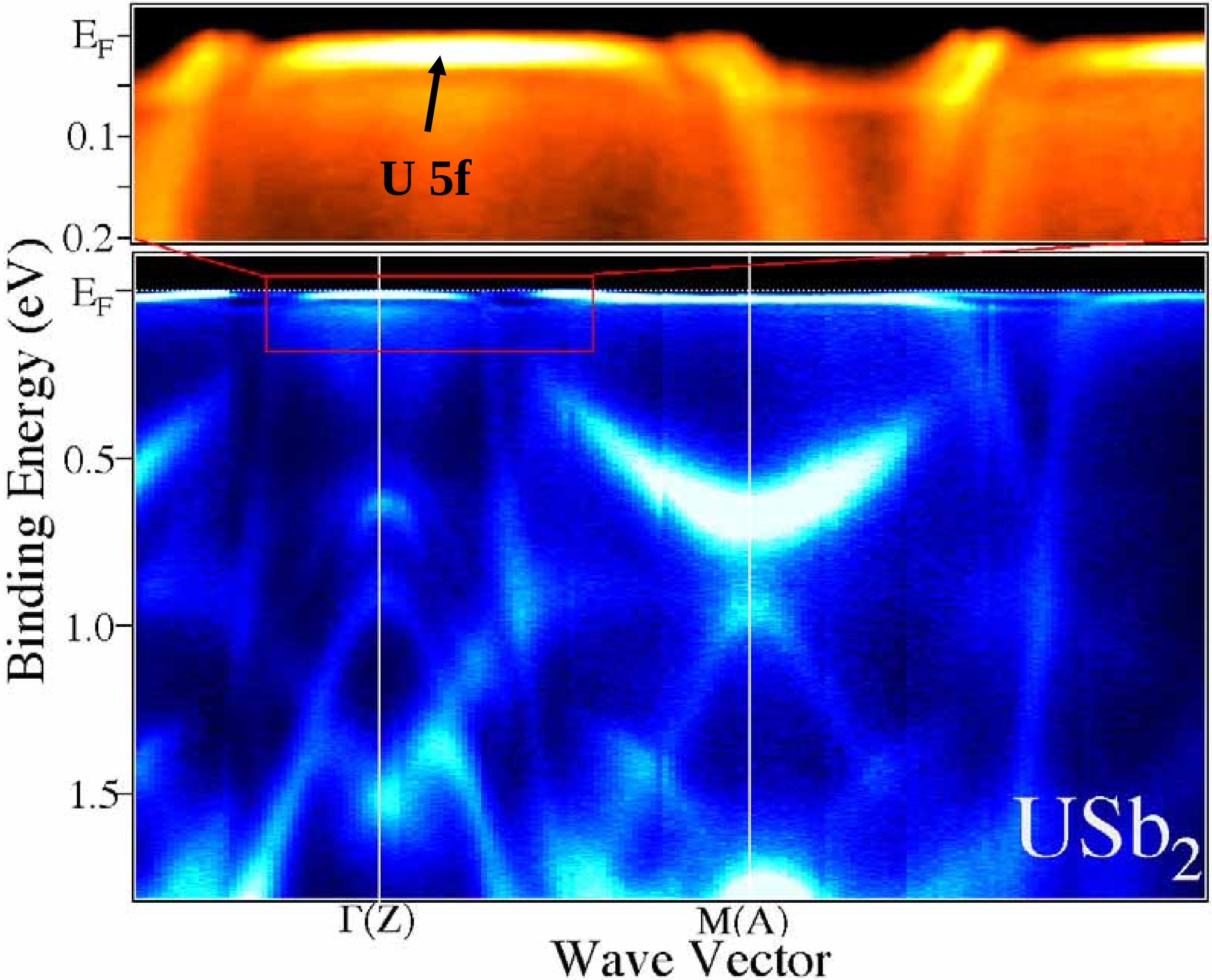
E_k : **Kinetic energy**

Φ : **Work function**

$h\nu$: **Photon energy**

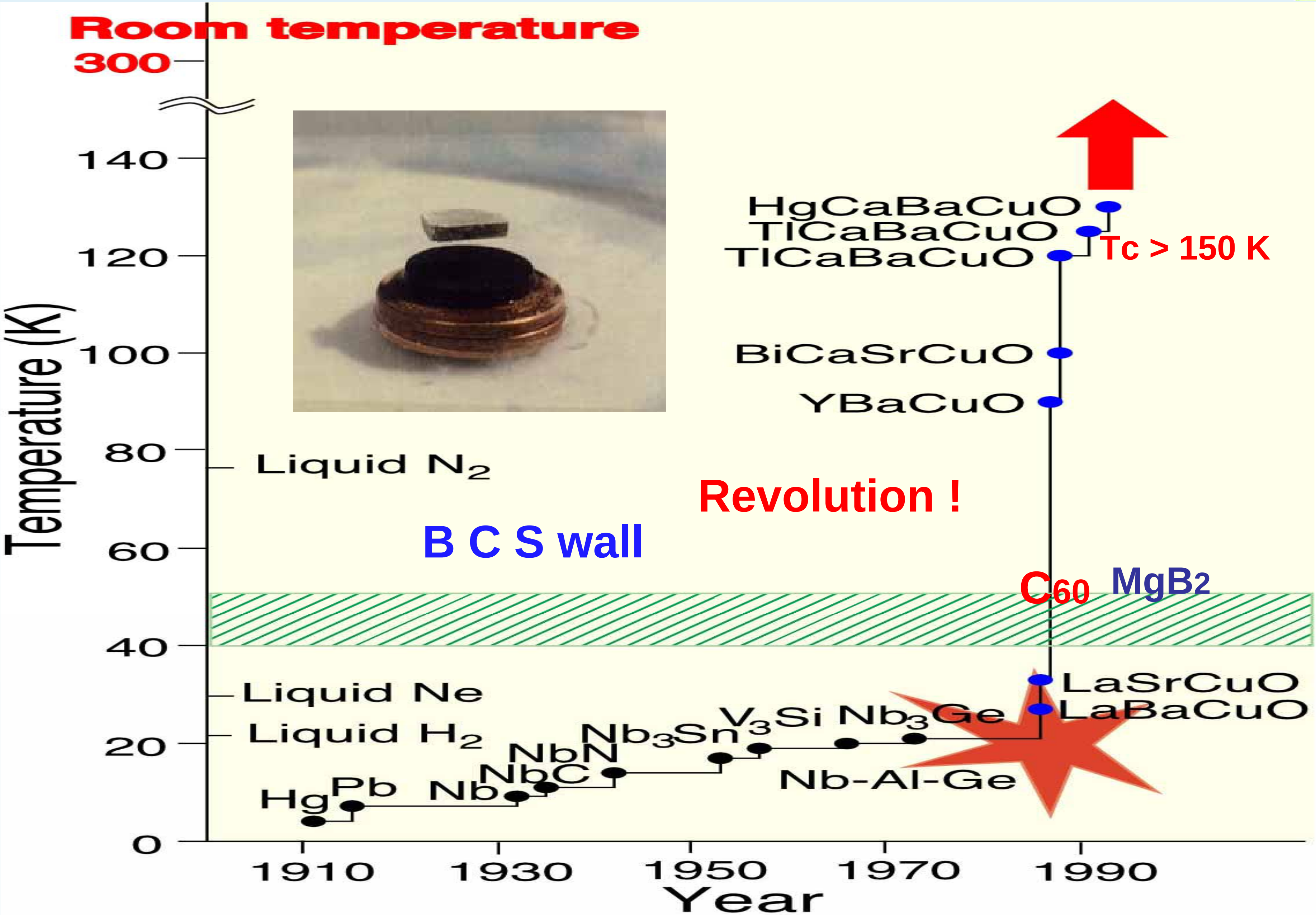


High-resolution ARPES of USb_2



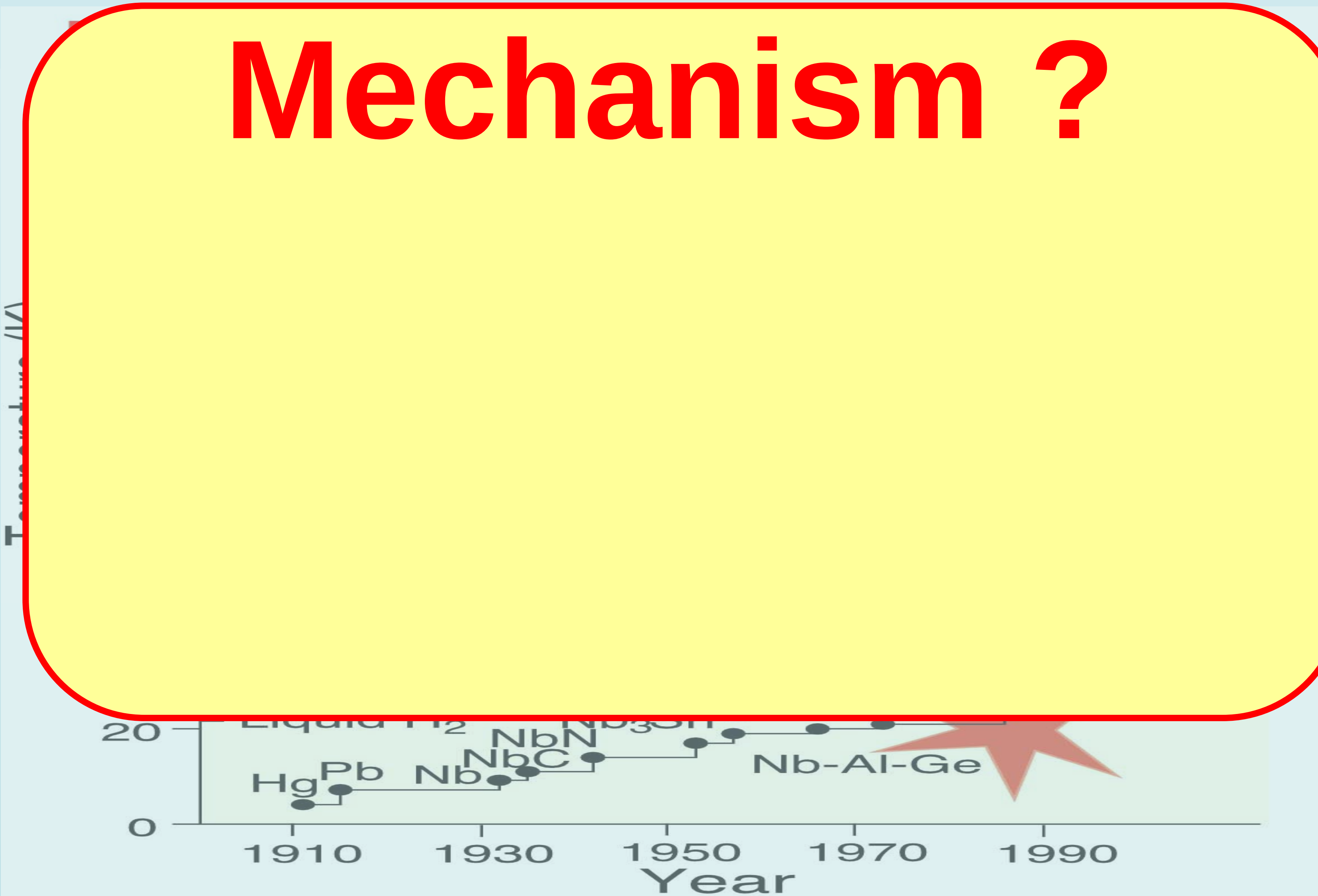
高温超伝導

High-Tc superconductors



High-Tc superconductors

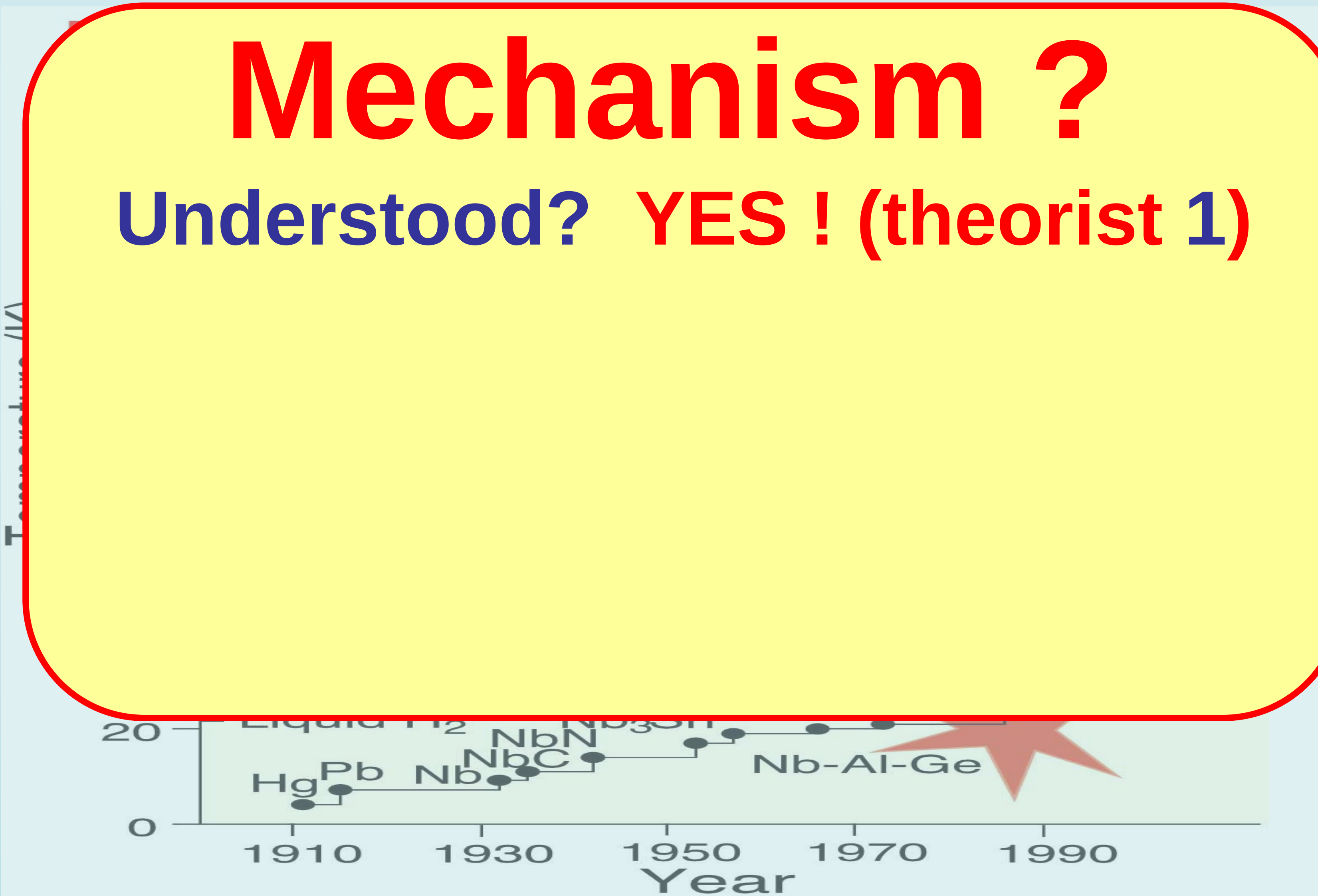
Mechanism ?



Bednorz & Müller (1986)

Nobel Prize (1987)

High-Tc superconductors

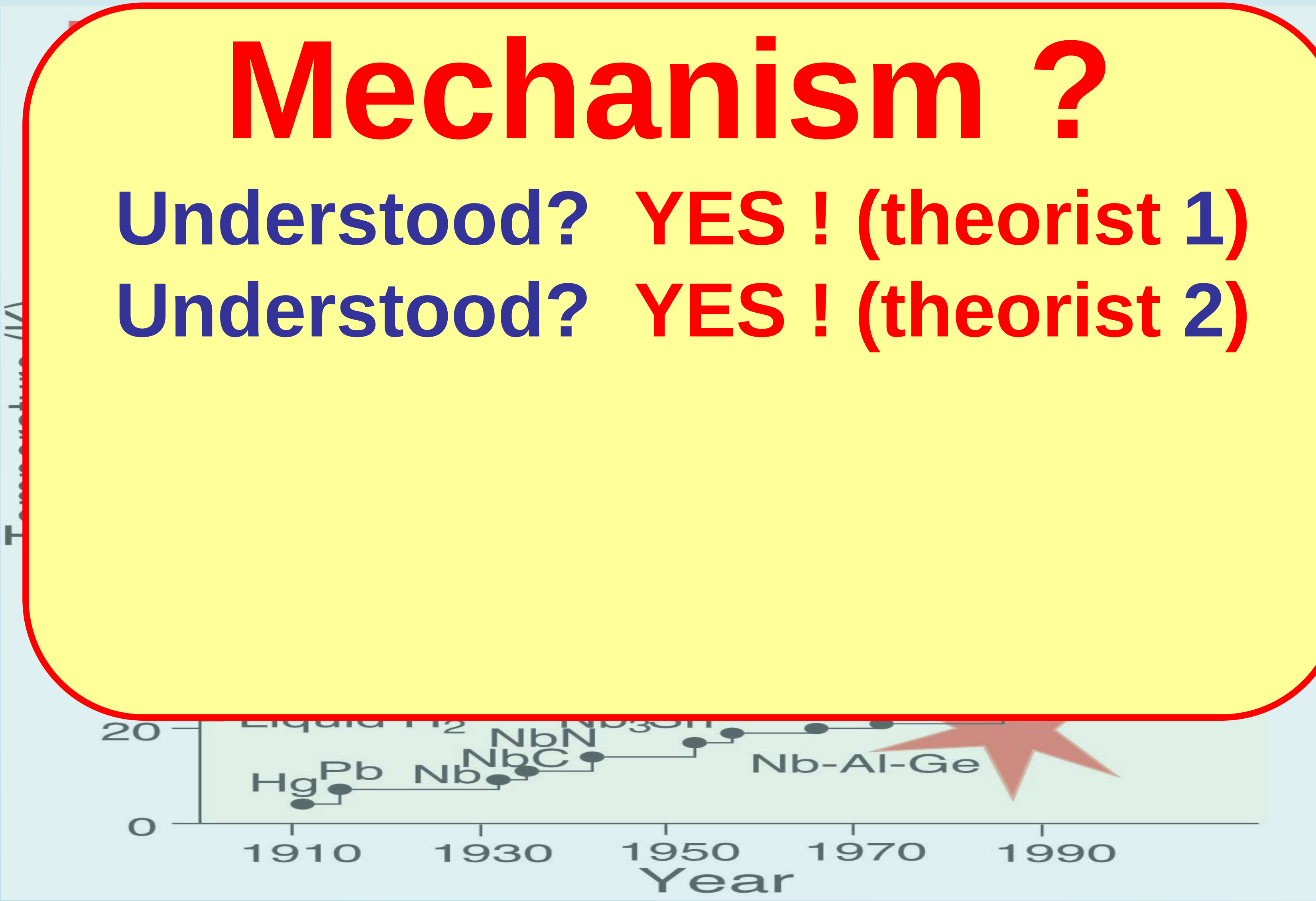


Mechanism ?

Understood? YES ! (theorist 1)

Bednorz & Müller (1986)
Nobel Prize (1987)

High-Tc superconductors



Mechanism ?

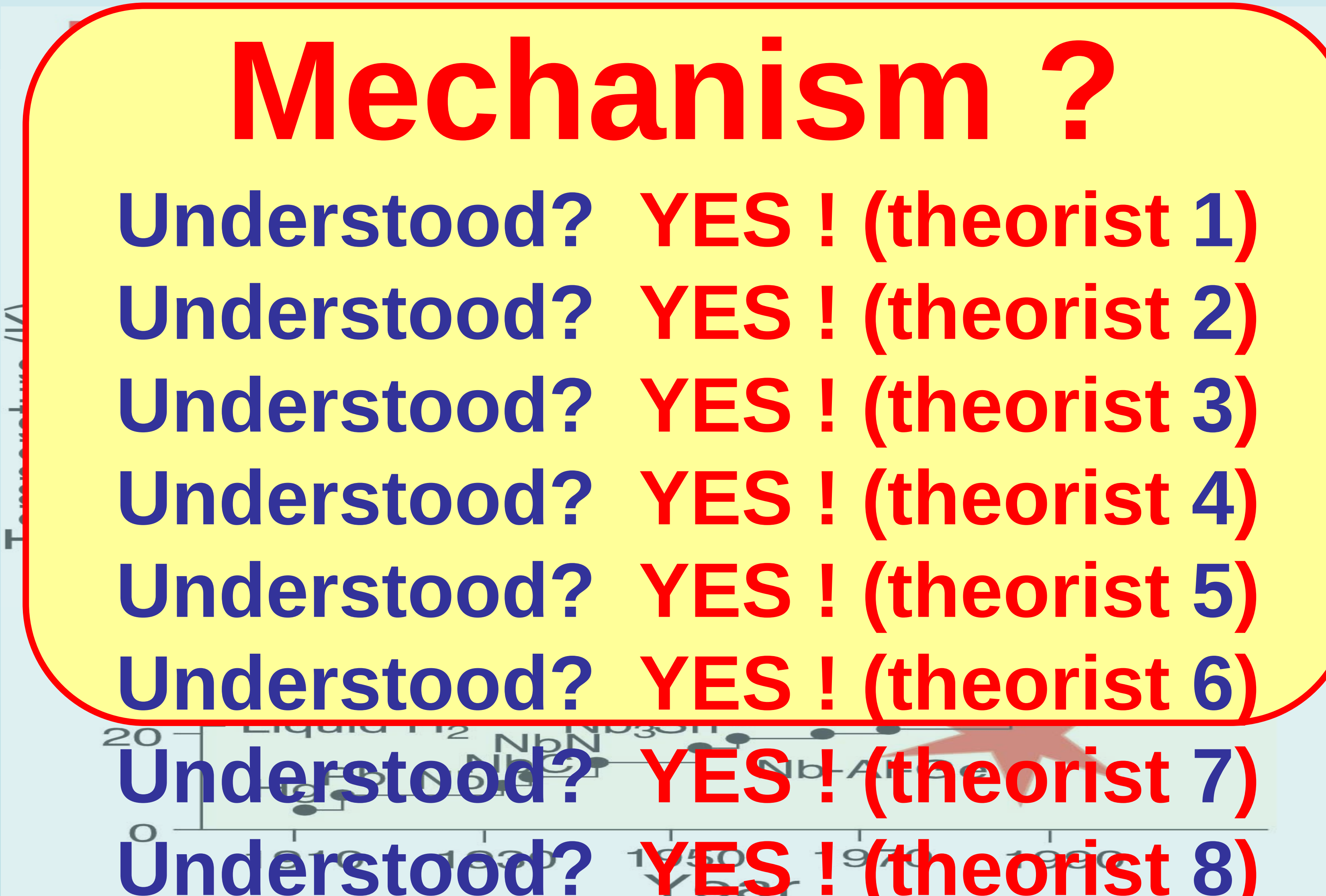
Understood? YES ! (theorist 1)

Understood? YES ! (theorist 2)

Bednorz & Mϋller (1986)

Nobel Prize (1987)

High-Tc superconductors



Mechanism ?

Understood? YES ! (theorist 1)
Understood? YES ! (theorist 2)
Understood? YES ! (theorist 3)
Understood? YES ! (theorist 4)
Understood? YES ! (theorist 5)
Understood? YES ! (theorist 6)
Understood? YES ! (theorist 7)
Understood? YES ! (theorist 8)
Understood? YES ! (theorist 9)

Bednorz & Muller (1986)
Nobel Prize (1987)

High-Tc superconductors

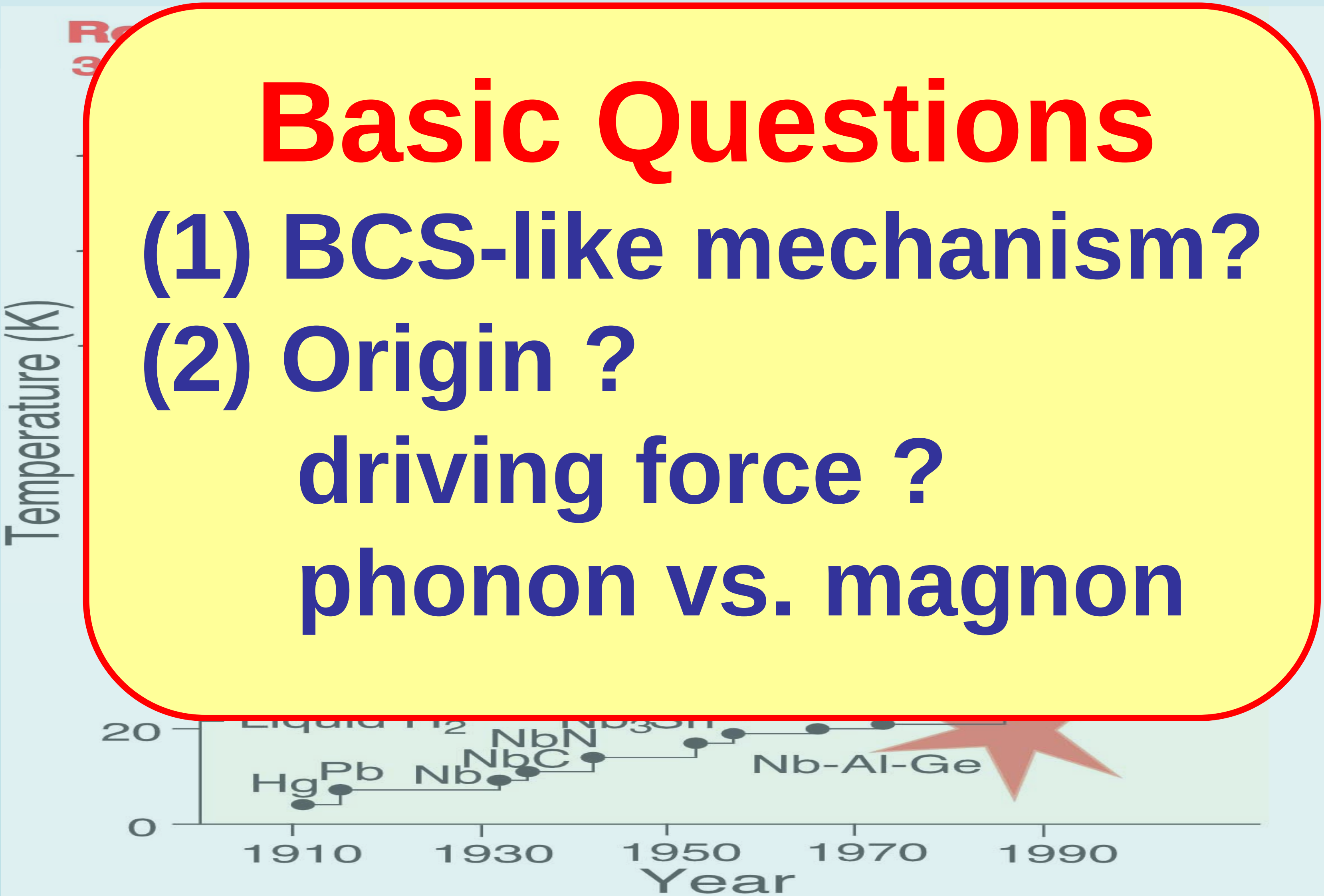
Mechanism ?

Understood? YES ... t 1)
Understood? ... 2)
Understo... ist 3)
Under... theorist 4)
Ur... S ! (theorist 5)
Unc... YES ! (theorist 6)
Unde... ood? YES ! (theorist 7)
Understood? YES ! (theorist 8)
Understood? YES ! (theorist 9)

UNKNOWN !

Bednorz & Muller (1986)
Nobel Prize (1987)

High-Tc superconductors



Basic Questions

(1) BCS-like mechanism?

(2) Origin ?

driving force ?

phonon vs. magnon

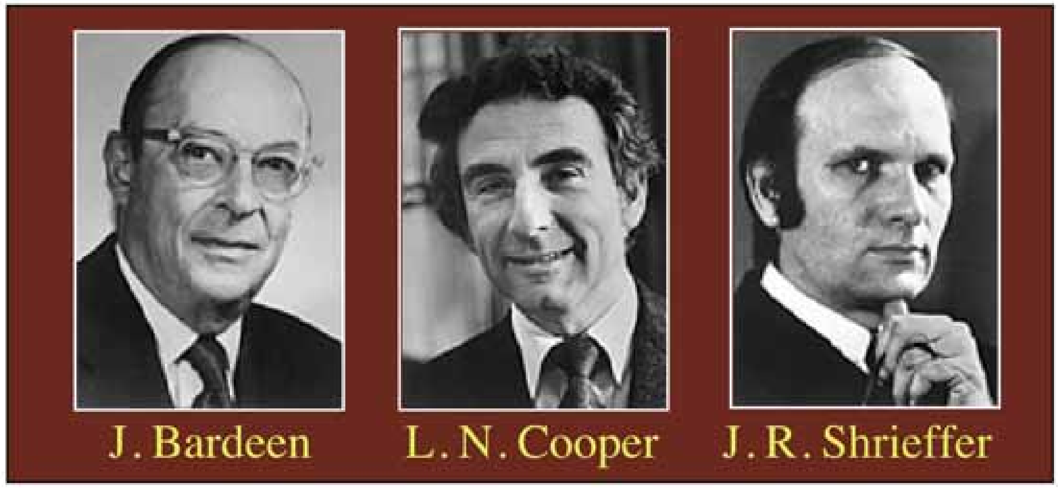
Bednorz & Muller (1986)

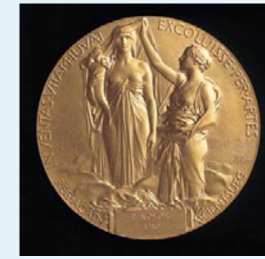
Nobel Prize (1987)

B C S theory

$$\psi_{BCS} = \Pi_k(u_k+v_k a^\dagger_{k\uparrow} a^\dagger_{-k\downarrow})|0\rangle$$

Phys. Rev. 108 (1958) 1175.

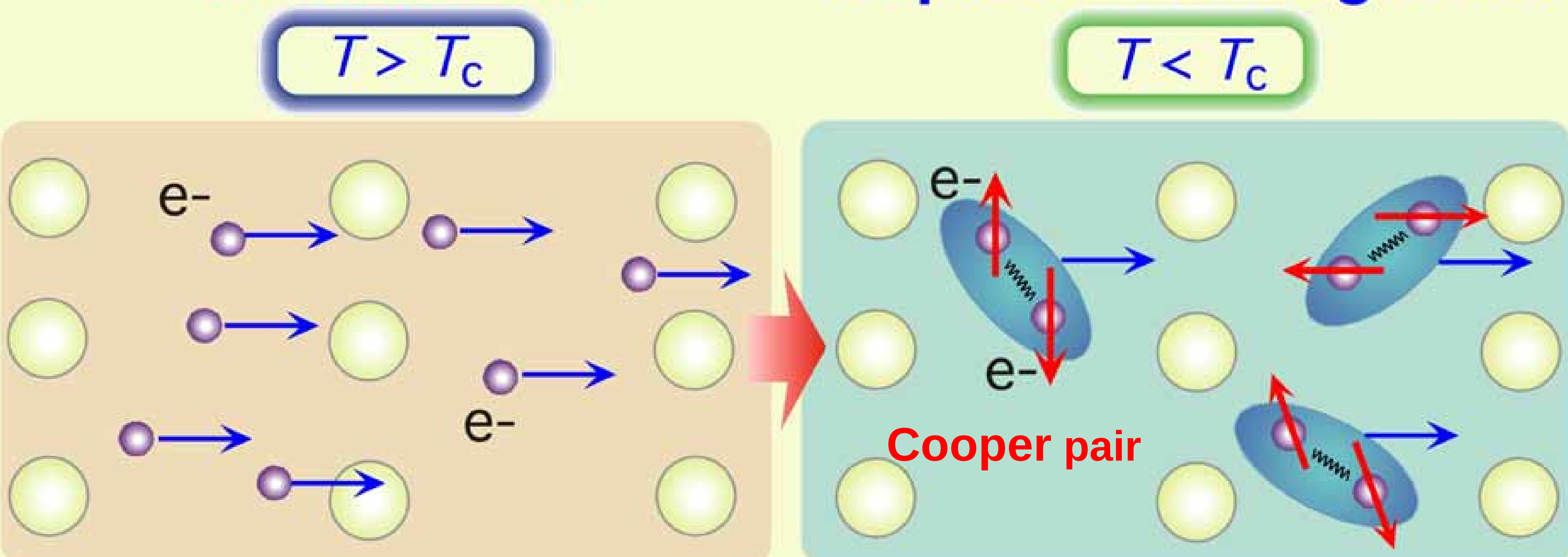




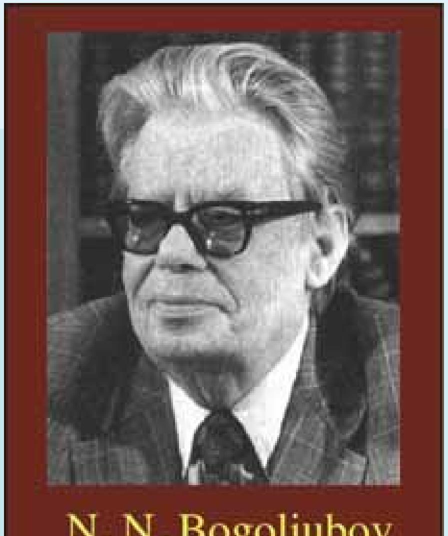
Nobel Prize (1972)

Normal state

Superconducting state



Bogoliubov quasiparticles (BQPs)



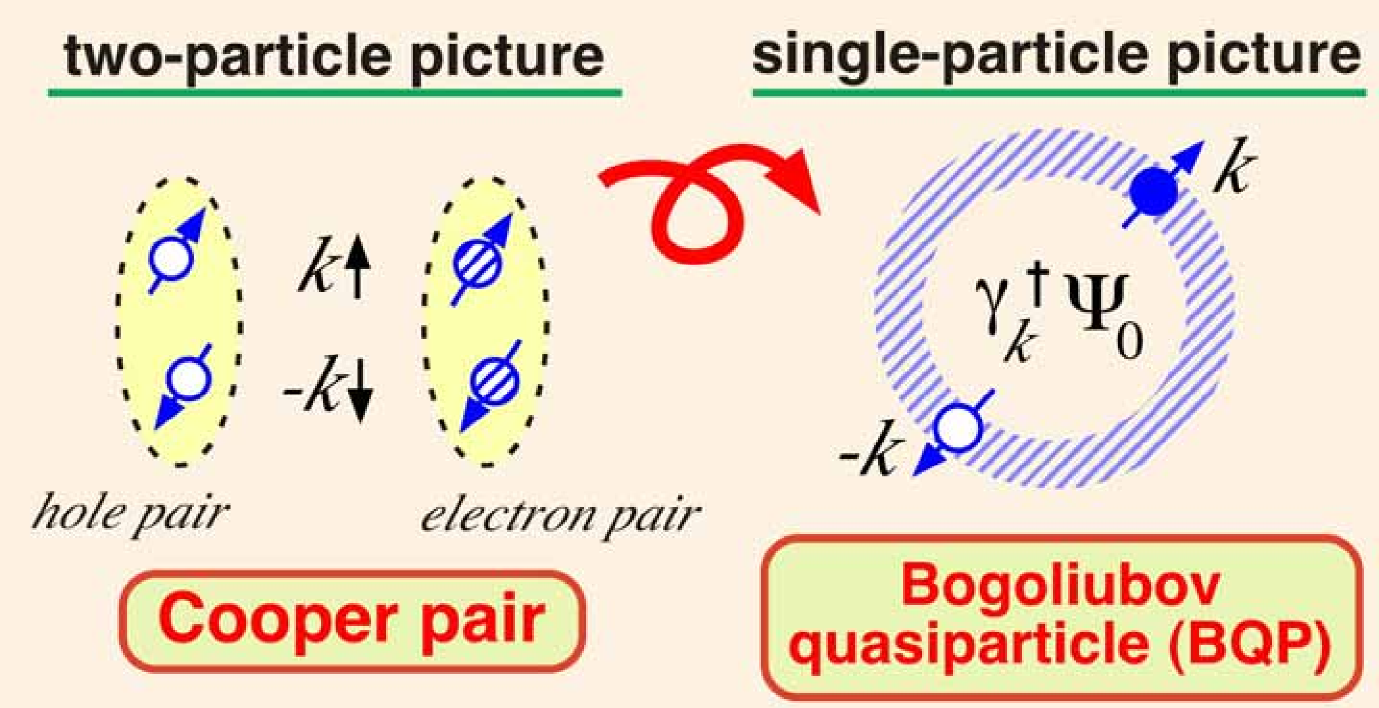
N. N. Bogoliubov

Bogoliubov transformation

$$\gamma_{k0} = u_k c_{k\uparrow} - v_k c^{\dagger}_{-k\downarrow}$$
$$\gamma^{\dagger}_{k1} = v^{*}_k c_{k\uparrow} + u^{*}_k c^{\dagger}_{-k\downarrow}$$

J. Phys. USSR 11 (1947) 23

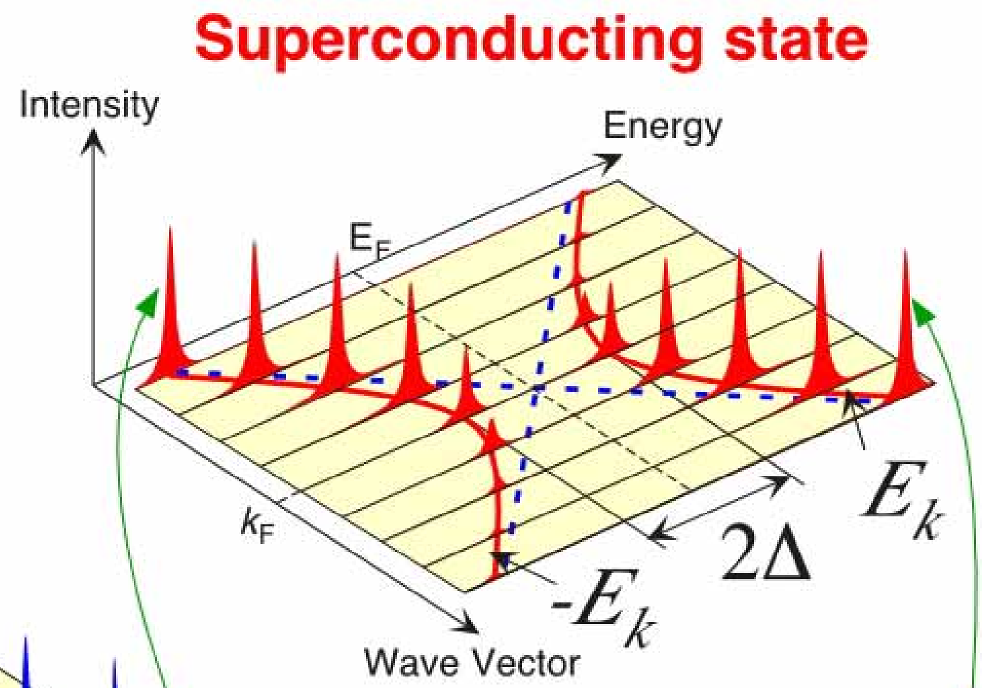
Nuovo Cimento 7 (1958) 794

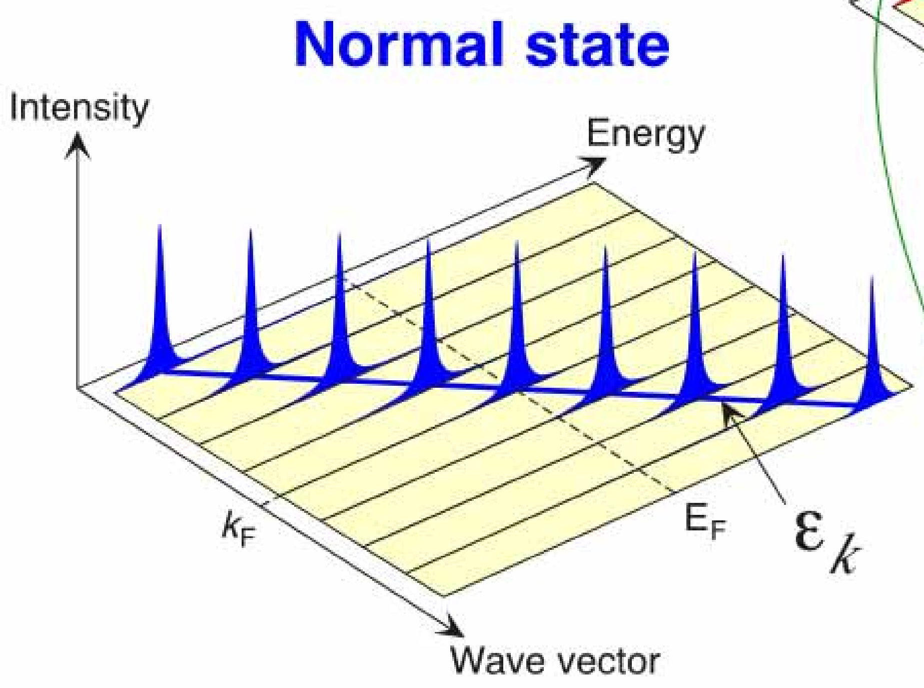


Formation of Bogoliubov quasiparticle band

energy dispersion

$$(E_k)^2 = (\varepsilon_k)^2 + (\Delta_k)^2$$



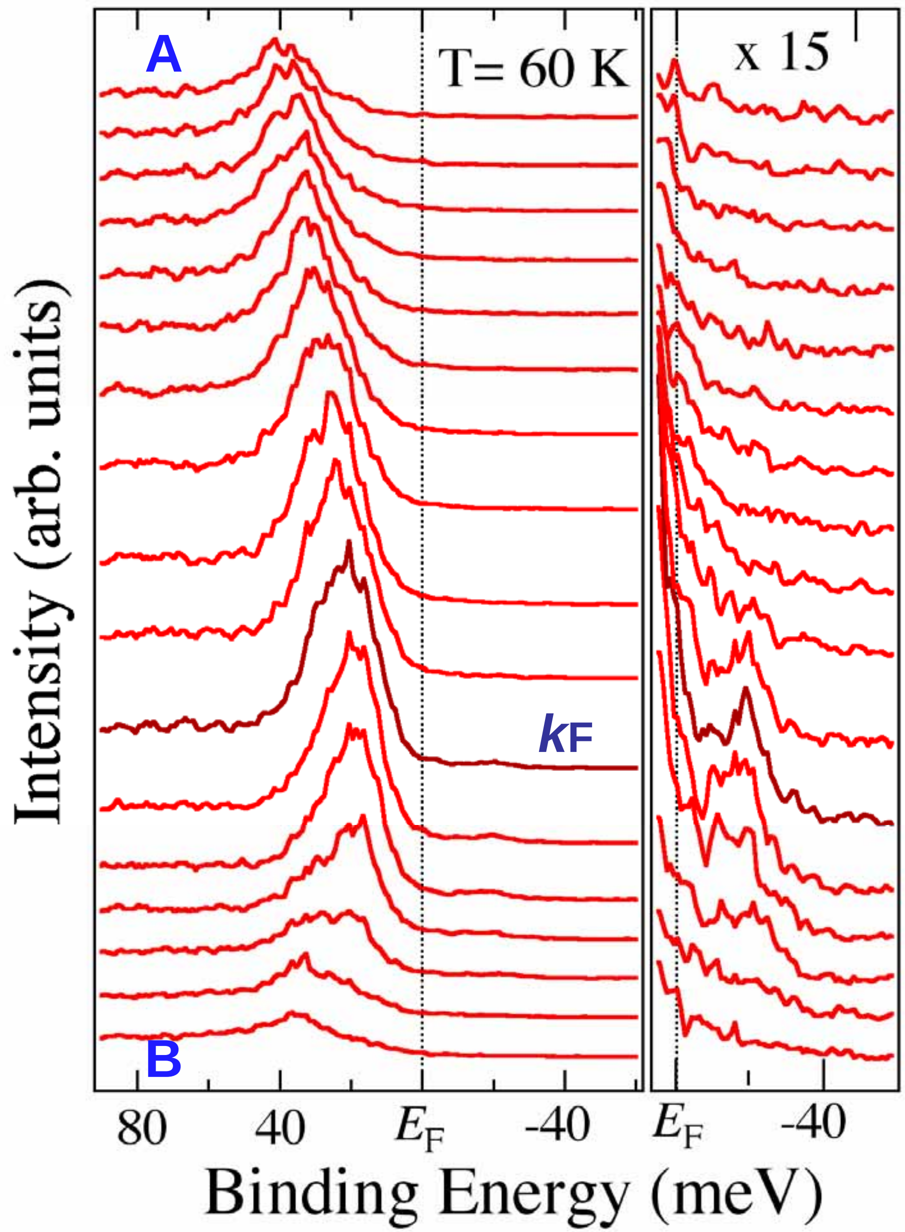


coherence factors

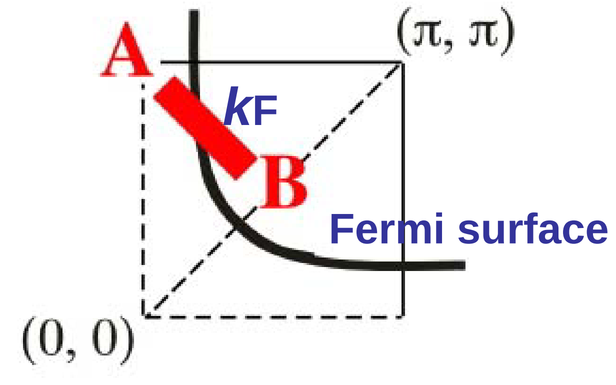
$$|u_k|^2 = \frac{1}{2}(1+\varepsilon_k/E_k)$$

$$|v_k|^2 = \frac{1}{2}(1-\varepsilon_k/E_k)$$

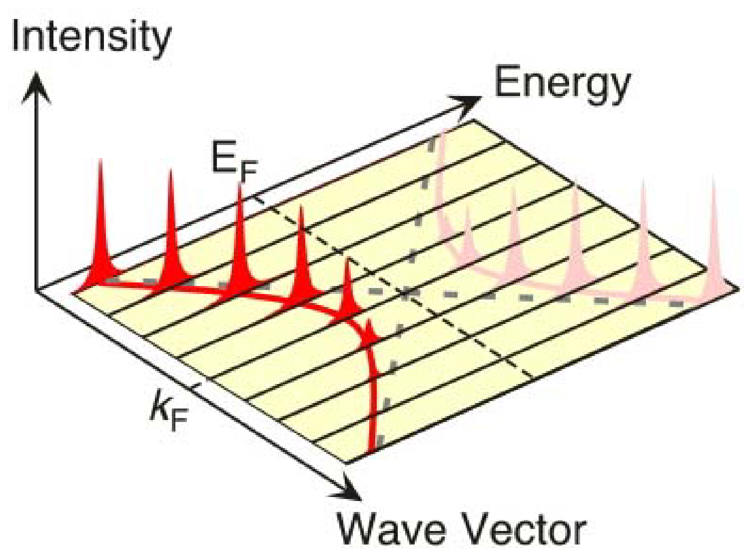
High-resolution ARPES spectra of Bi2223



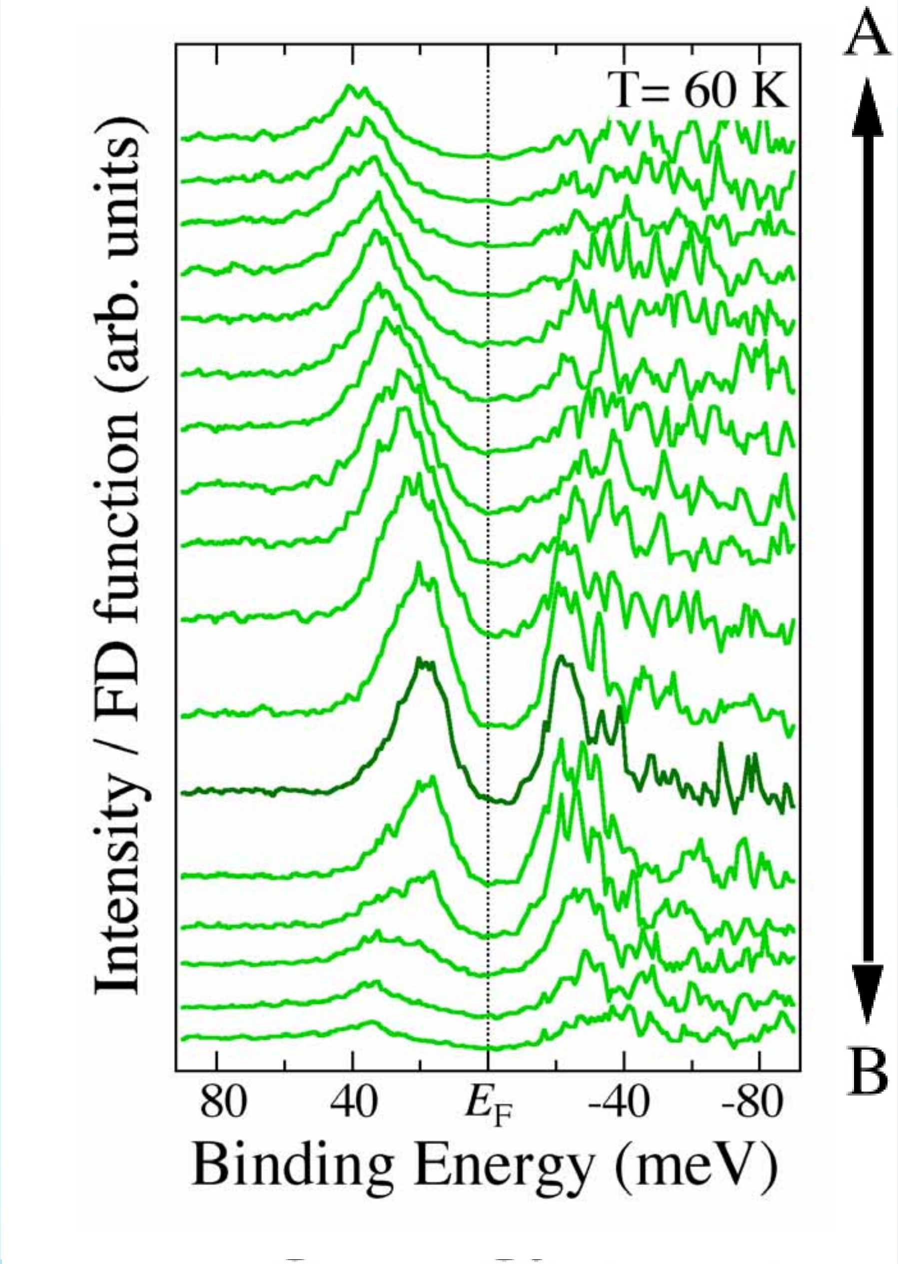
Matsui et al. PRL 90 (2003) 217001



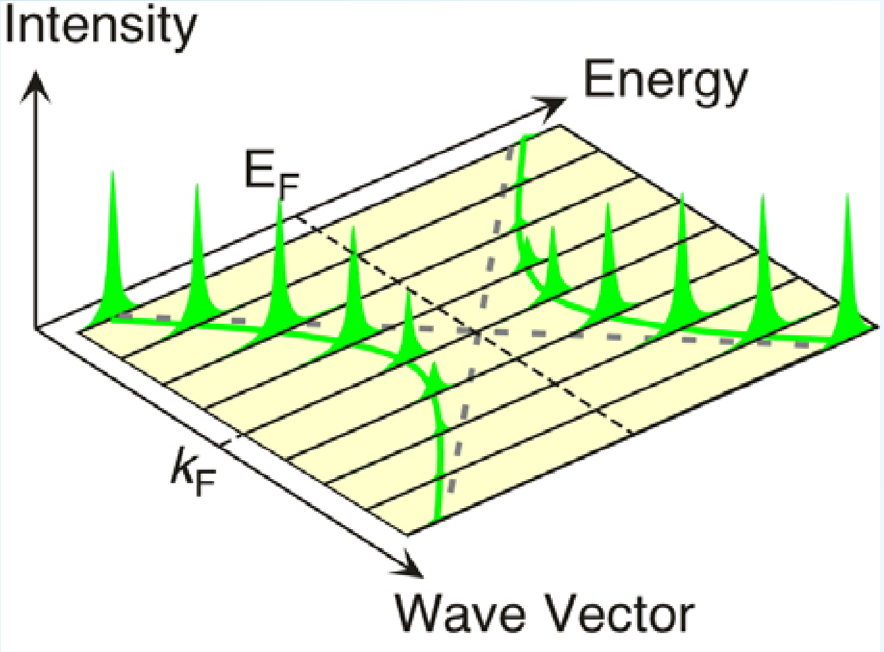
Electron branch of BQP band



ARPES spectra of Bi2223 divided by FD function

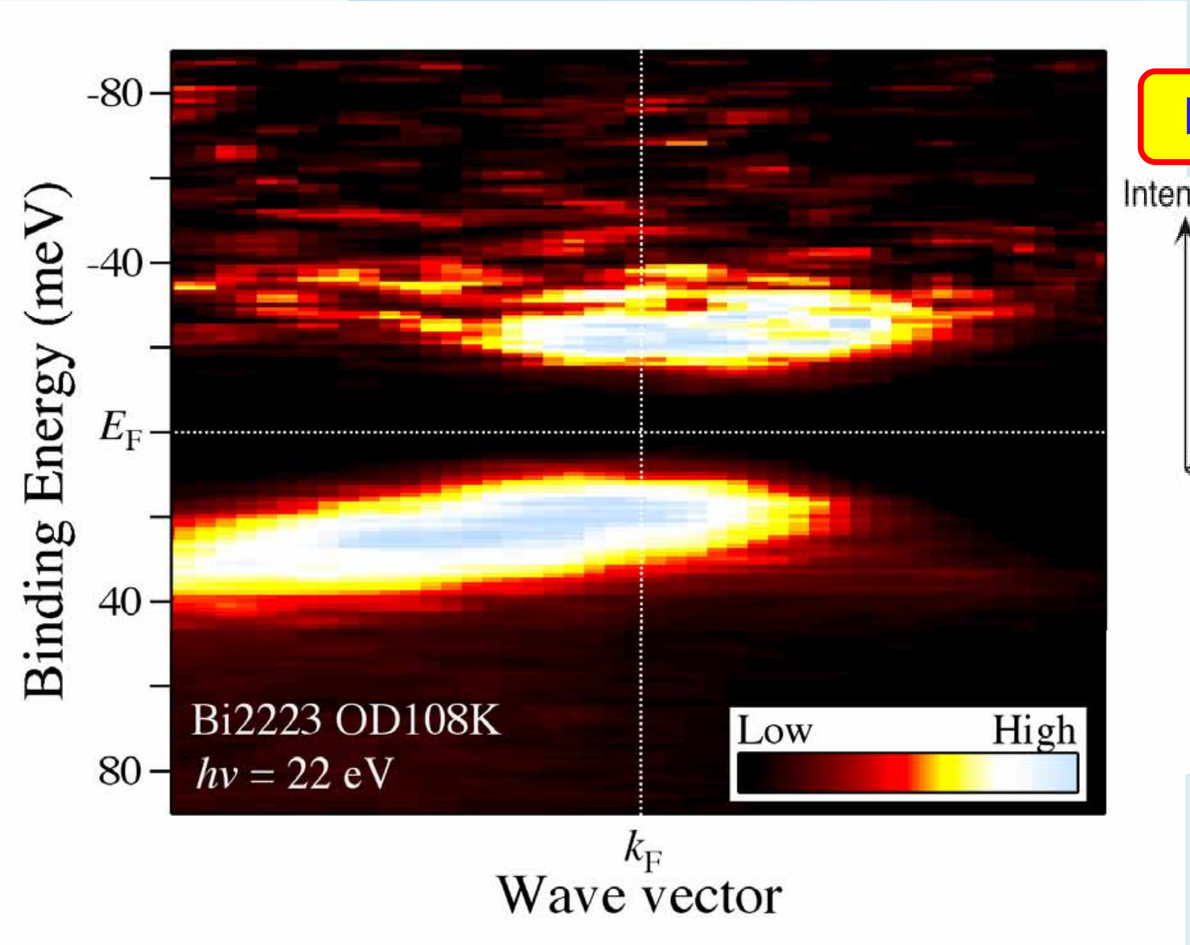


Hole branch of BQP band

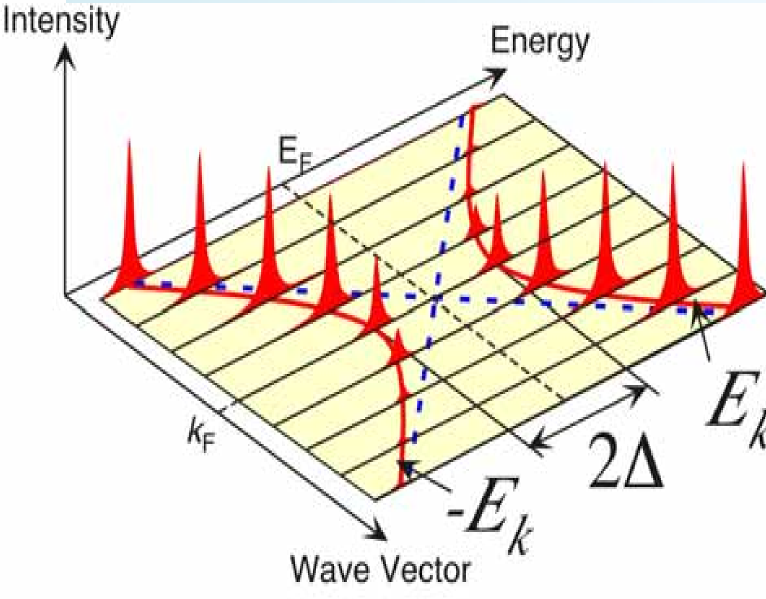


Evidence for BQP band in Bi2223

FD-divided ARPES intensity plot near E_F



Full branch of BQP band

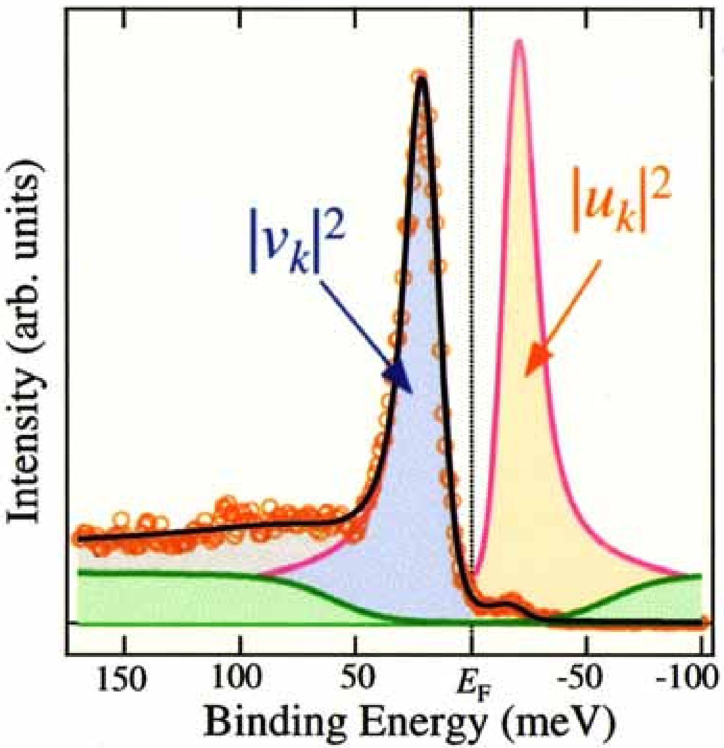


BQP picture is qualitatively established.

How abut the coherence factors ?

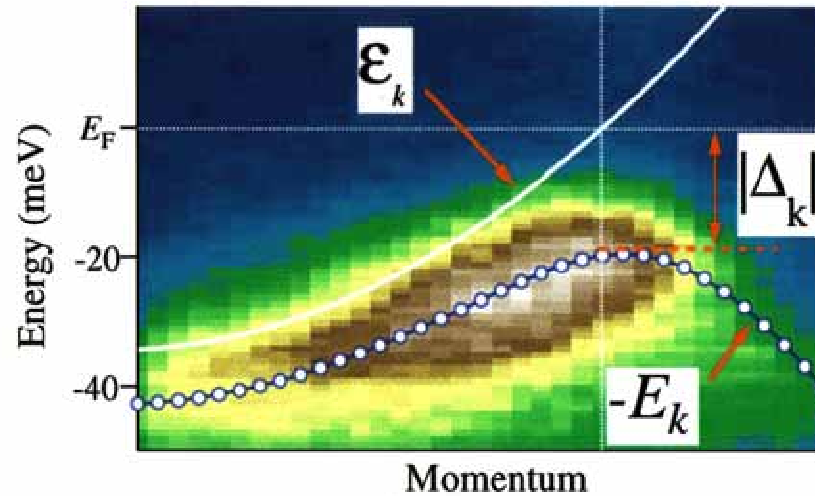
Coherence factors $|u_k|^2$ and $|v_k|^2$

Experimental



$$A(k,\omega) = \frac{1}{\pi}\left(\frac{|u_k|^2\Gamma}{(\omega-E_k)^2+\Gamma^2} + \frac{|v_k|^2\Gamma}{(\omega+E_k)^2+\Gamma^2}\right)$$

Theoretical



$$|v_k|^2 = 1 - |u_k|^2 = \frac{1}{2}\left(1 - \frac{\varepsilon_k}{E_k}\right)$$

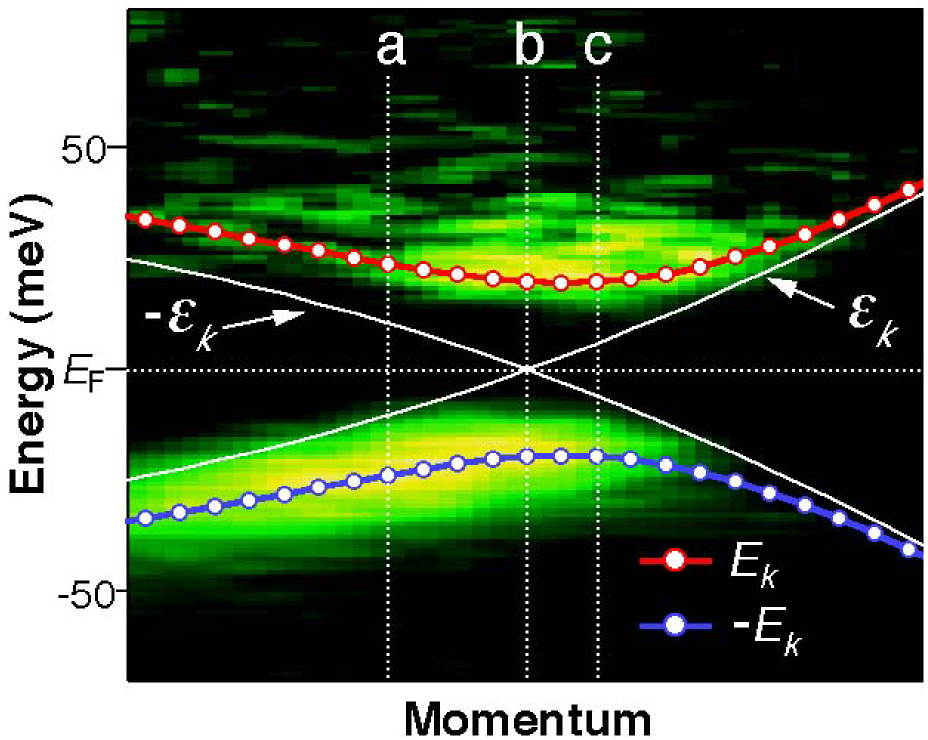
E_k : BQP band

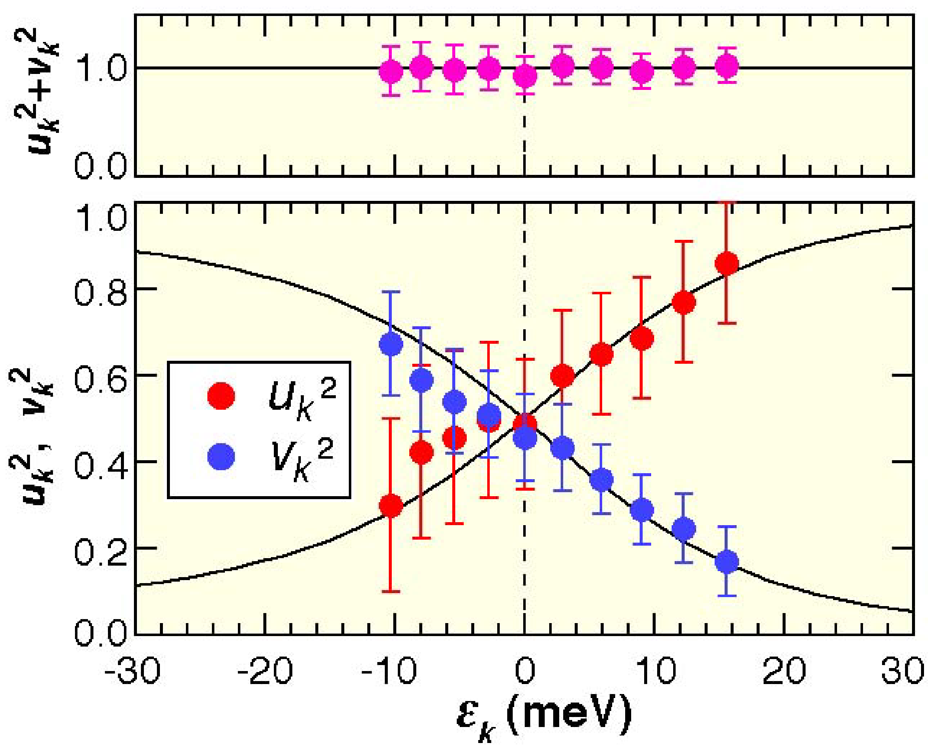
$\varepsilon_k = \sqrt{E_k^2 - |\Delta_k|^2}$: normal state band

$\Delta_k = \Delta_0 \, |\cos(k_x)-\cos(k_y)| \, / \, 2$

Comparison of BQP dispersion and coherence factors between "experiment" and "theory"

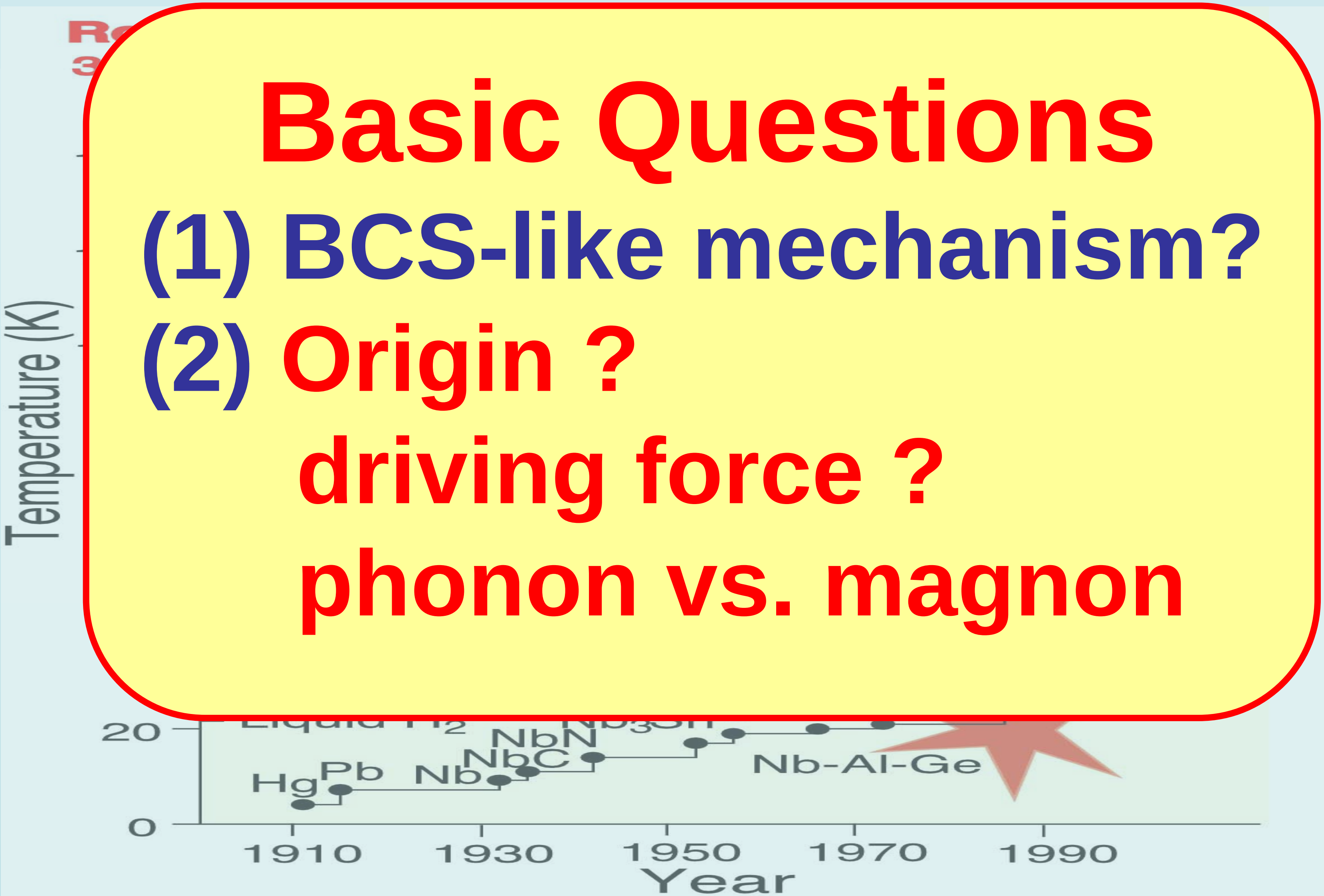
Excellent quantitative agreement !





BCS theory is quantitatively verified.

High-Tc superconductors



Basic Questions

(1) BCS-like mechanism?

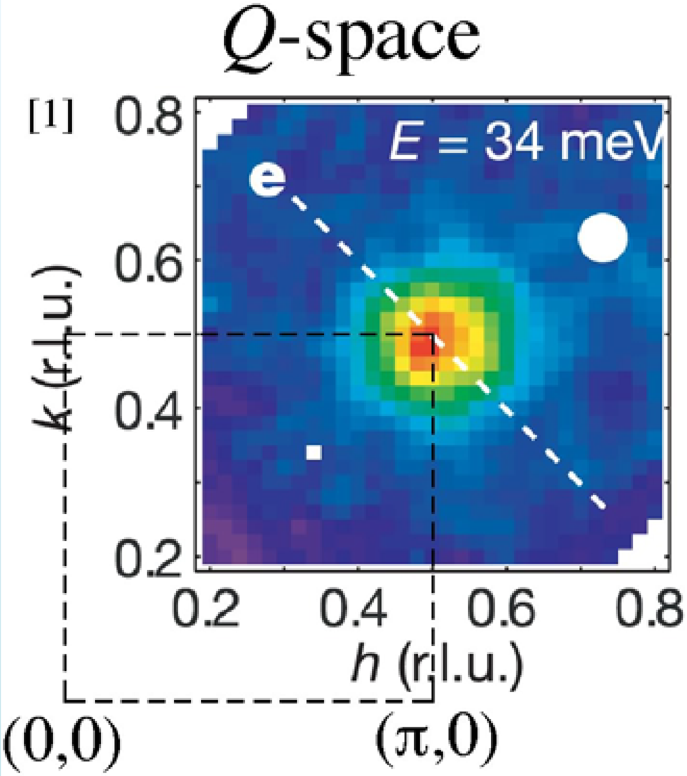
(2) Origin ?

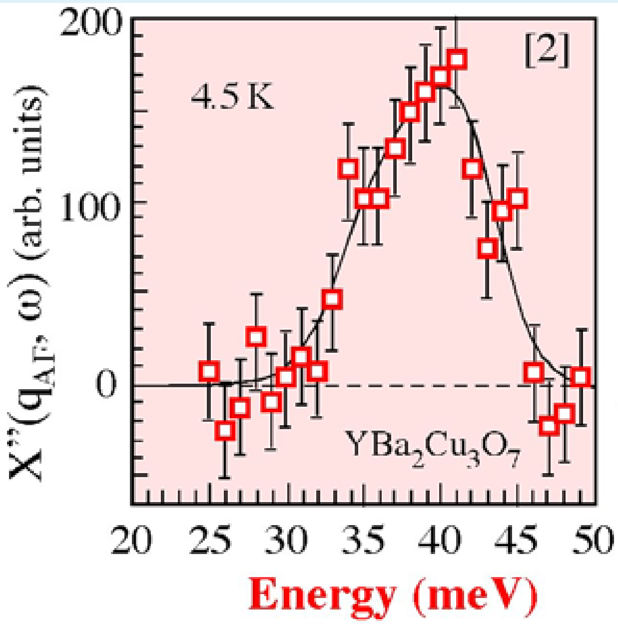
driving force ?

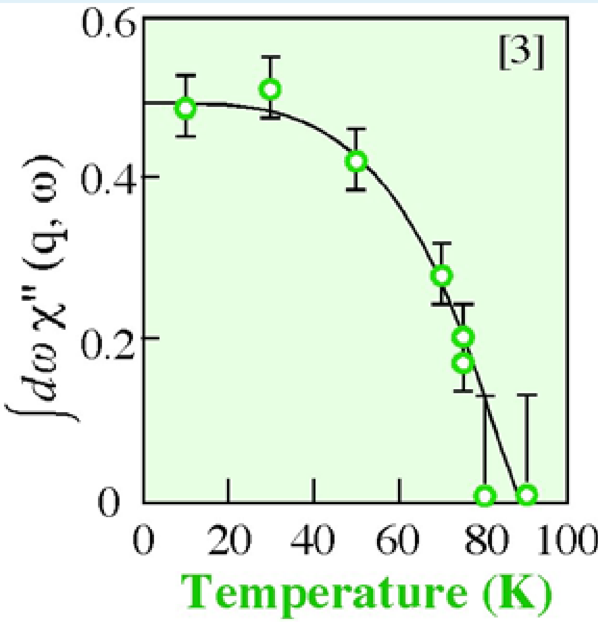
phonon vs. magnon

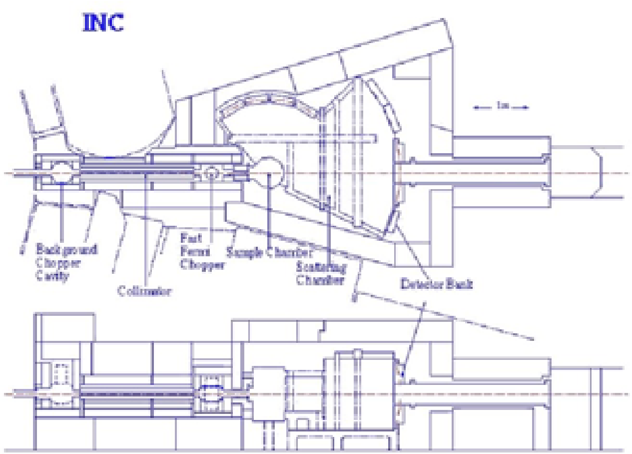
Bednorz & Müller (1986)
Nobel Prize (1987)

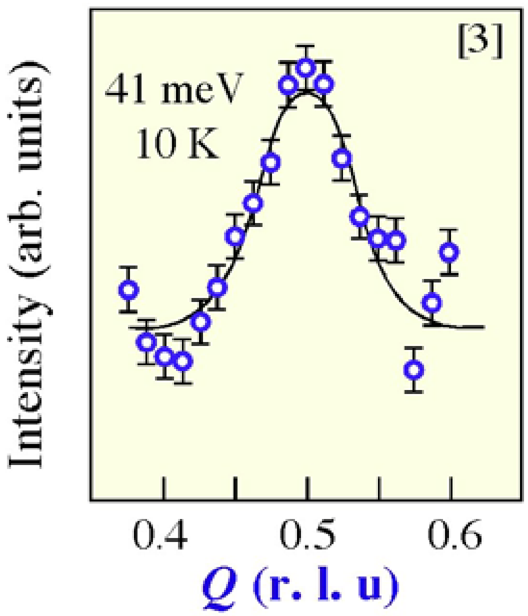
Magnetic resonance mode









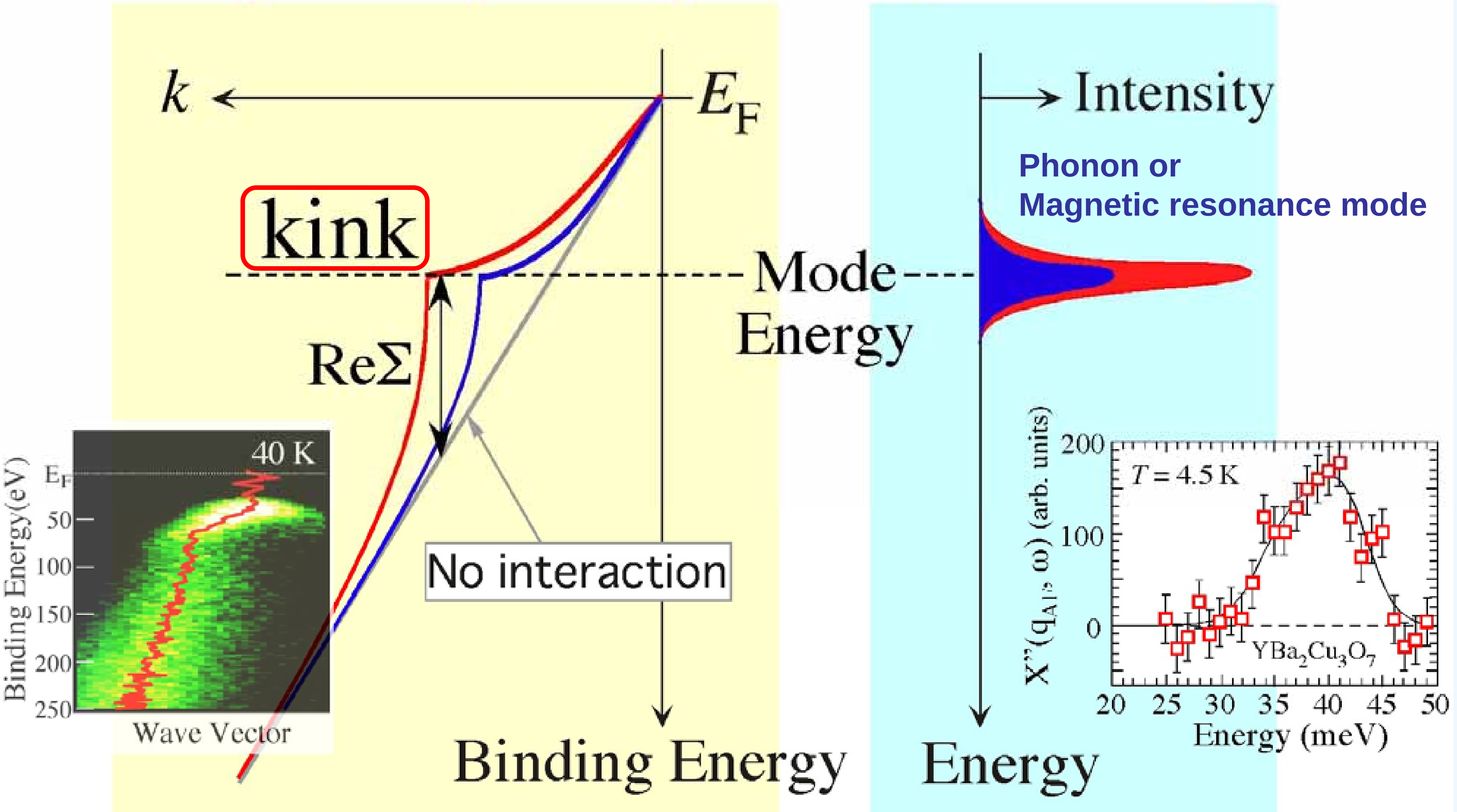


[1] S. M. Hayden *et al.*, Nature **429**, 531 (2004).
[2] P. Bourges *et al.*, Phys. Rev. B **53**, 876 (1996).
[3] H. F. Fong *et al.*, Phys. Rev. B **54**, 6708 (1996).

Relation between dispersion kink and mode

Photoemission [band dispersion]

Bosonic excitation



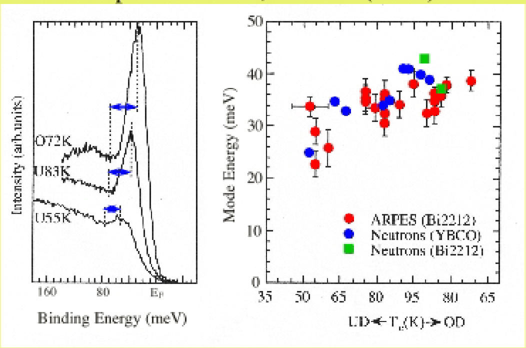
Dispersion "kink" in ARPES spectra

Dispersion kink in high-Tc cuprates ⟶ Strong coupling of electrons with mode(s)

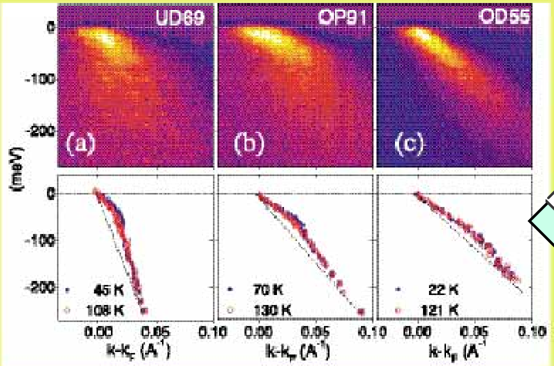
⟶ Mechanism of high-Tc superconductivity

Magnetic

J. C. Campuzano *et al.*, PRL 83 (1999) 3709.

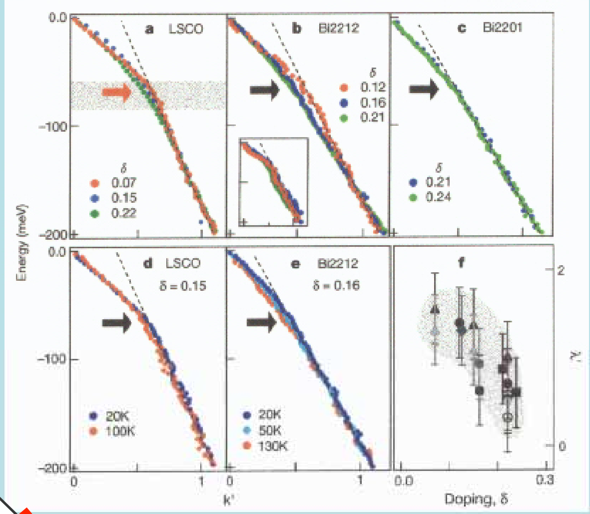


P. D. Johnson *et al.*, PRL 87 (2001) 177007.



Phonon

A. Lanzara *et al.*, Nature 412 (2001) 510.



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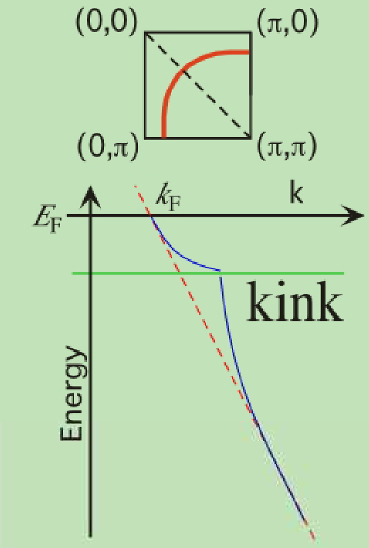
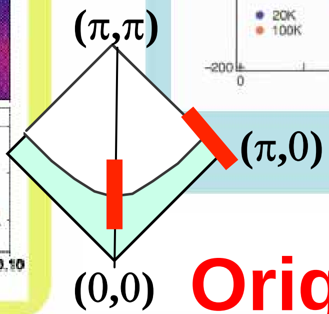
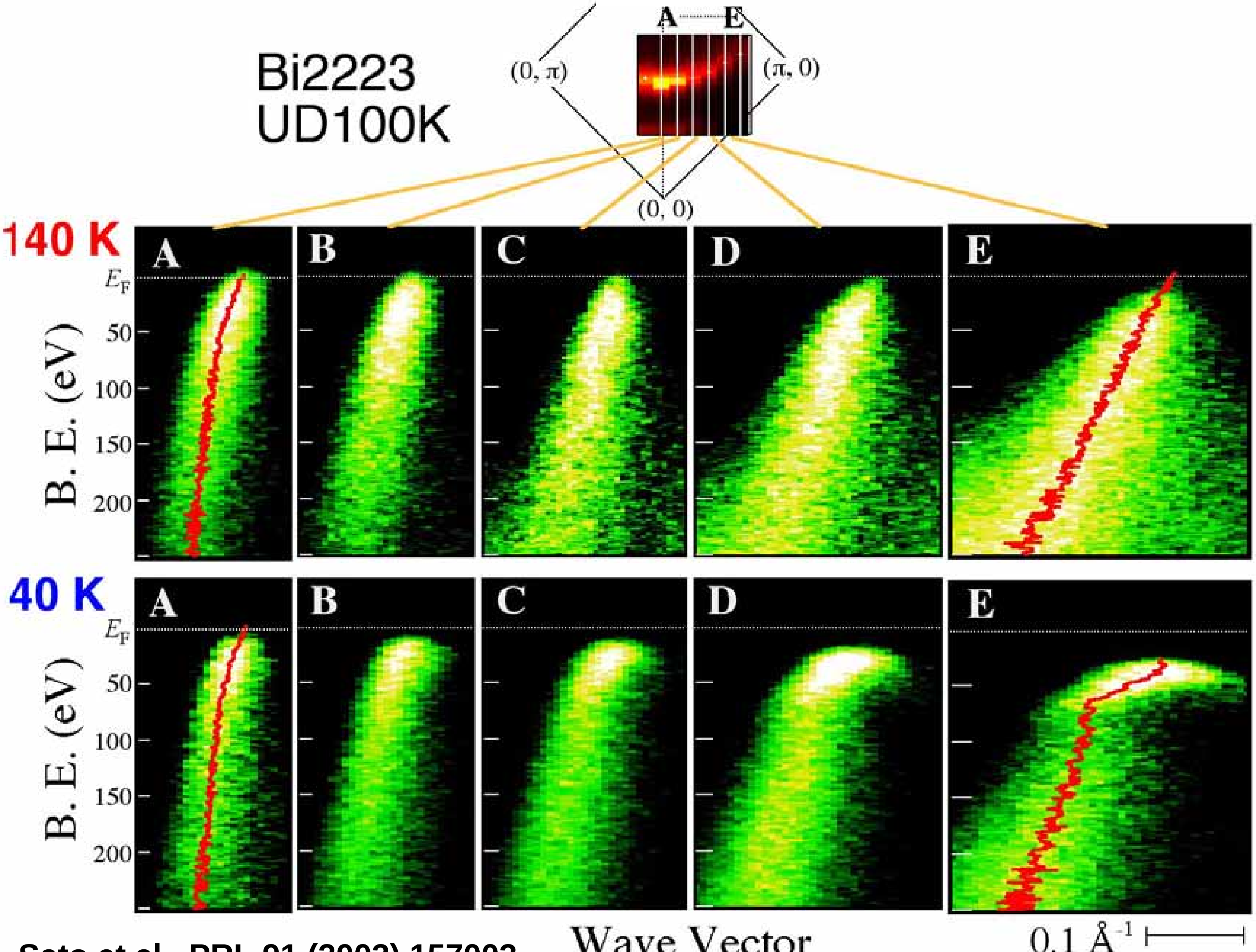




Origin of kink is controversial

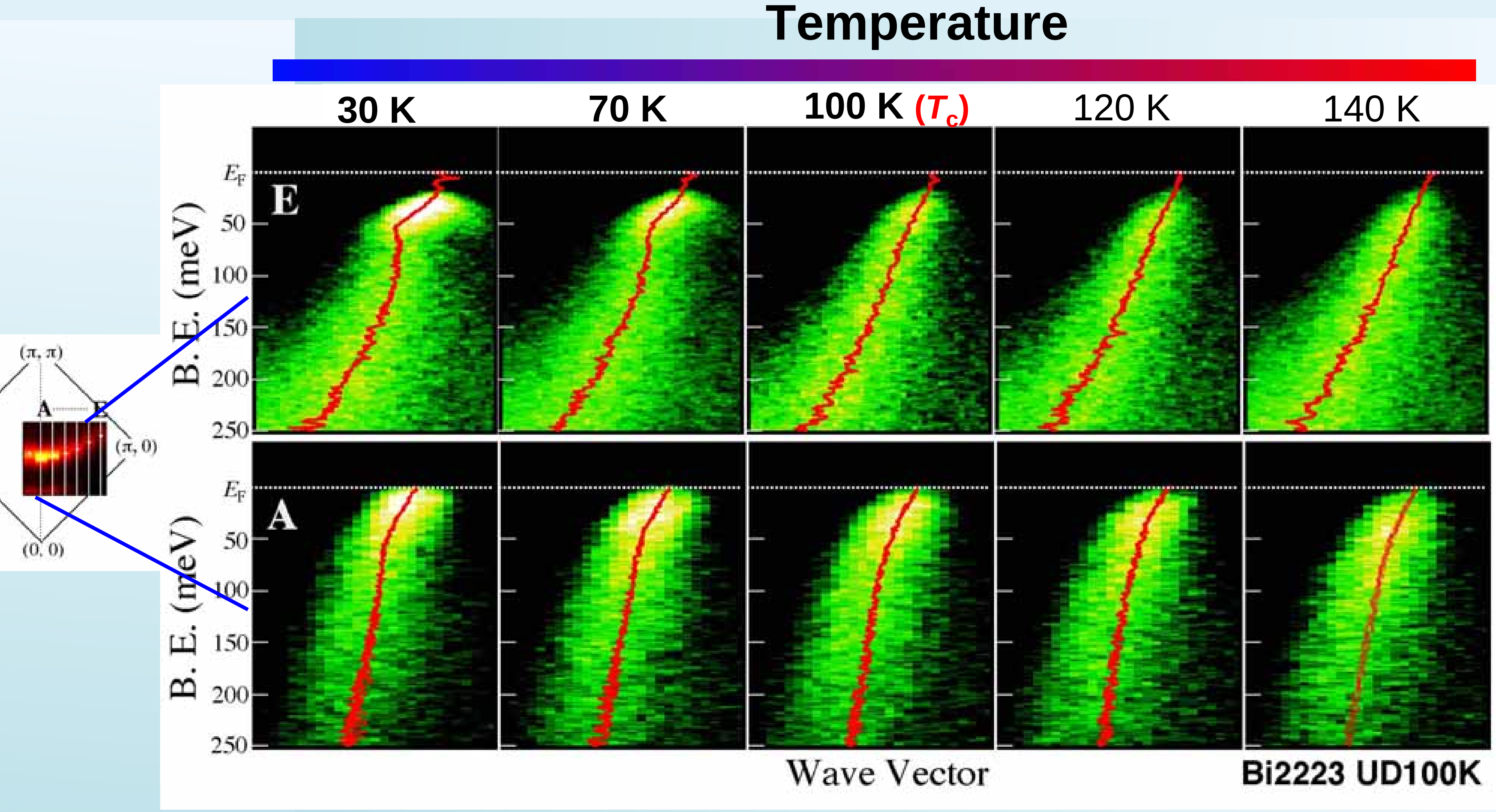
Systematic ARPES of BSCCO and NCCO

Momentum-dependence of kink in Bi2223



Sato et al., PRL 91 (2003) 157003

Temperature-dependence of kink in Bi2223



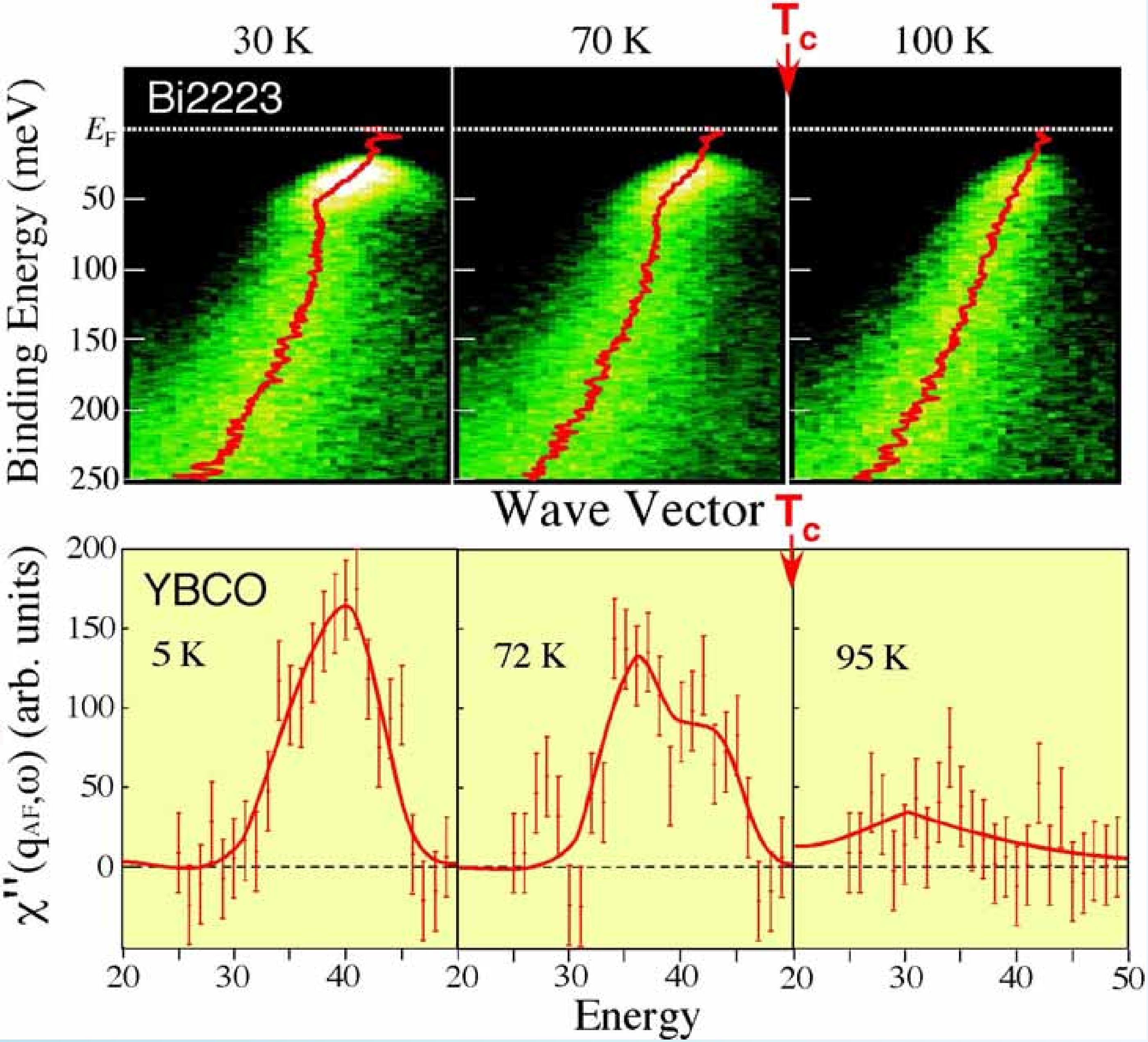
Sato et al., PRL 91 (2003) 157003

Comparison of temperature dependence

Photoemission

Dispersion kink

T. Sato *et al.*,
PRL 91(2003)157003



Neutron

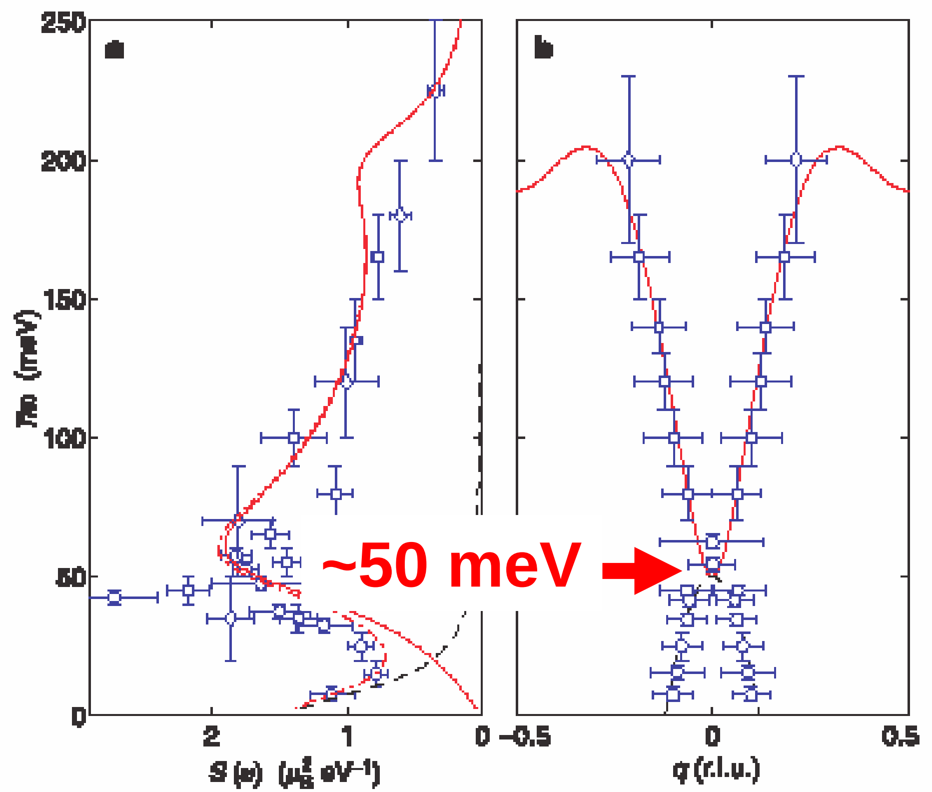
Magnetic resonance

P. Bourges *et al.*,
PRB 53 (1996) 876

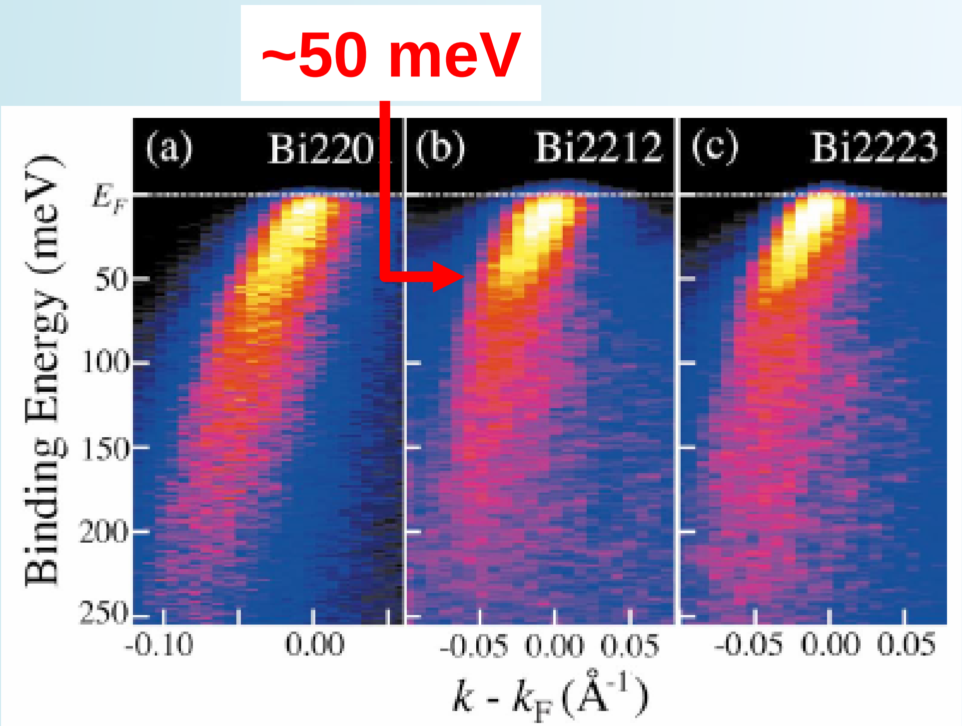
Energy Scale of Spin Excitation and ARPES kink in HTSCs

NEUTRON

ARPES



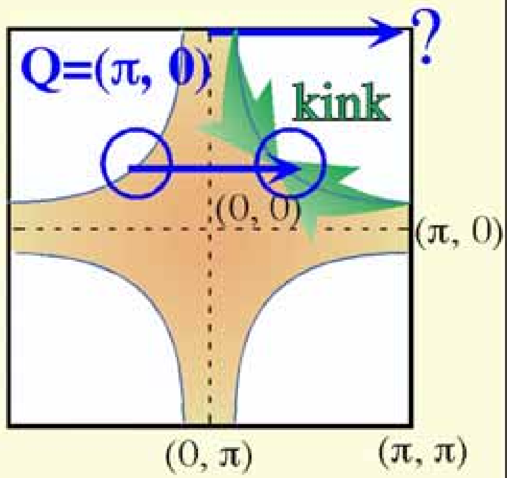
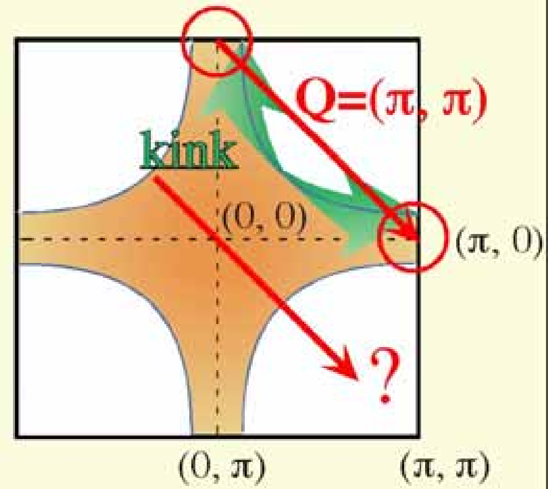
K. Yamada *et al*. (2004)

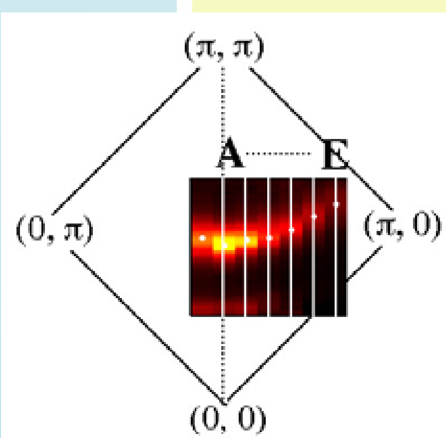


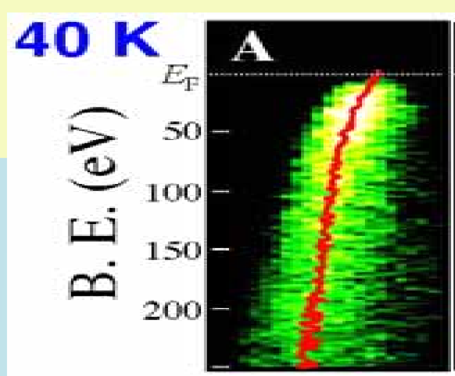
T. Takahashi *et al*. (2003)

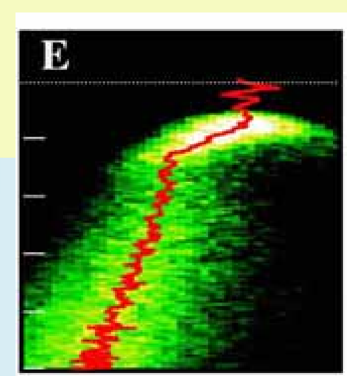
Strong electron coupling to the spin excitation in HTSCs

Phonon v.s. Magnetic mode

	LO phonon	Magnetic resonance
Momentum dependence		
Temperature dependence	Weak	Prominent below T_c





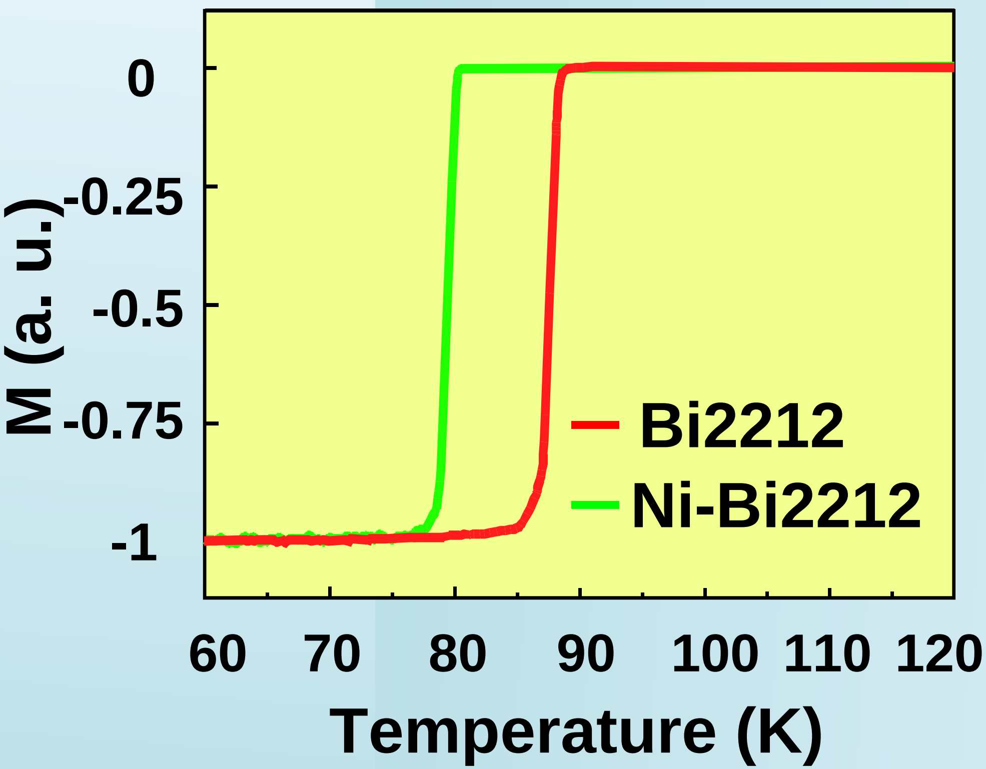


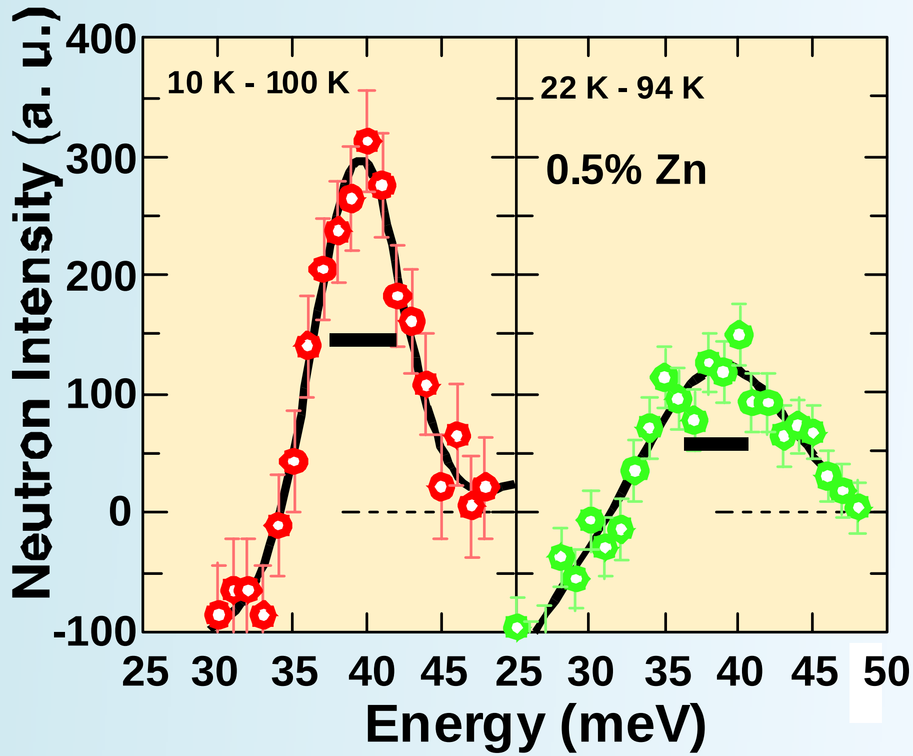
Impurity effects on superconductivity

Zn, Ni, Co

Transition temperature

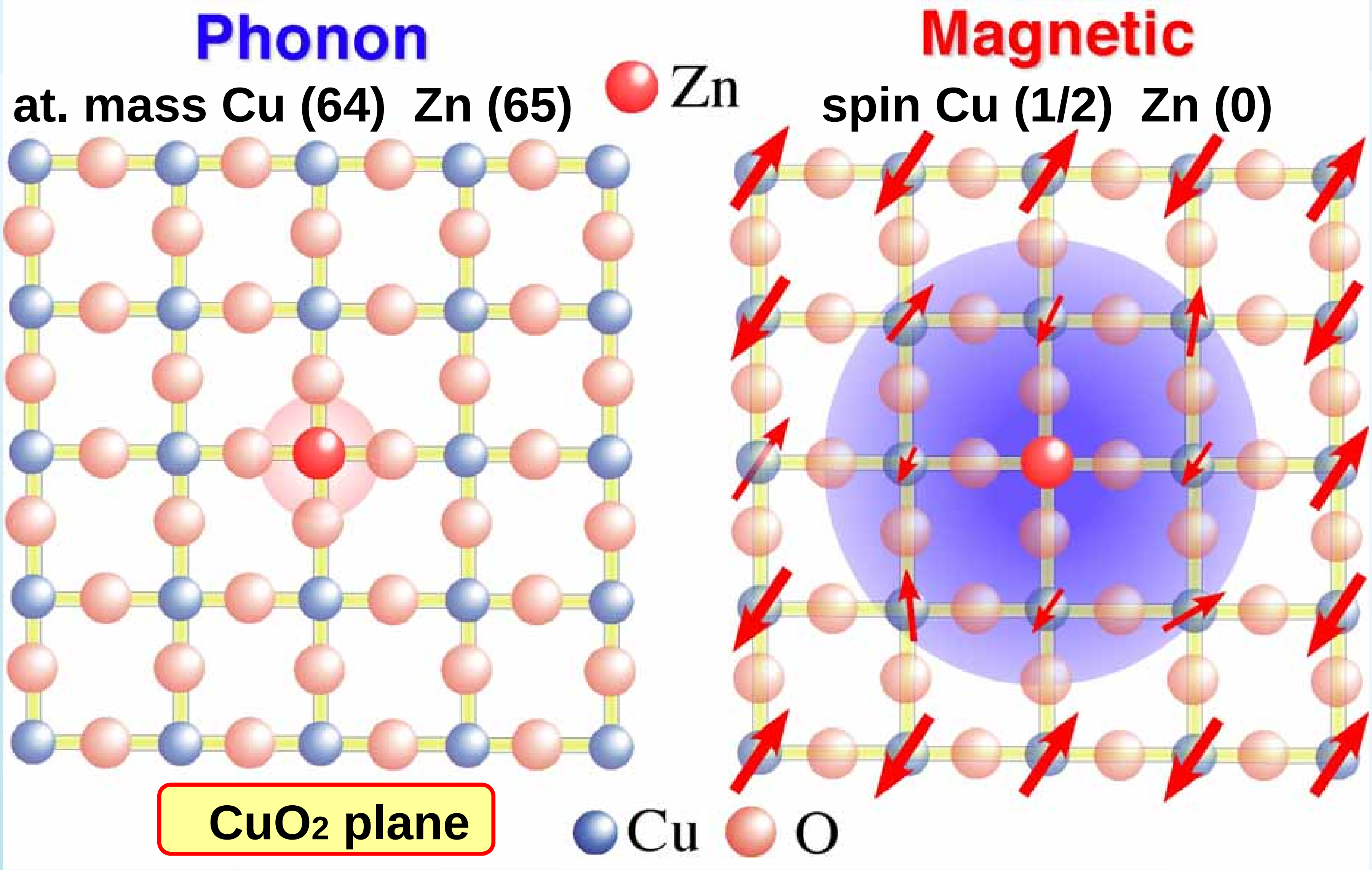
Resonance mode



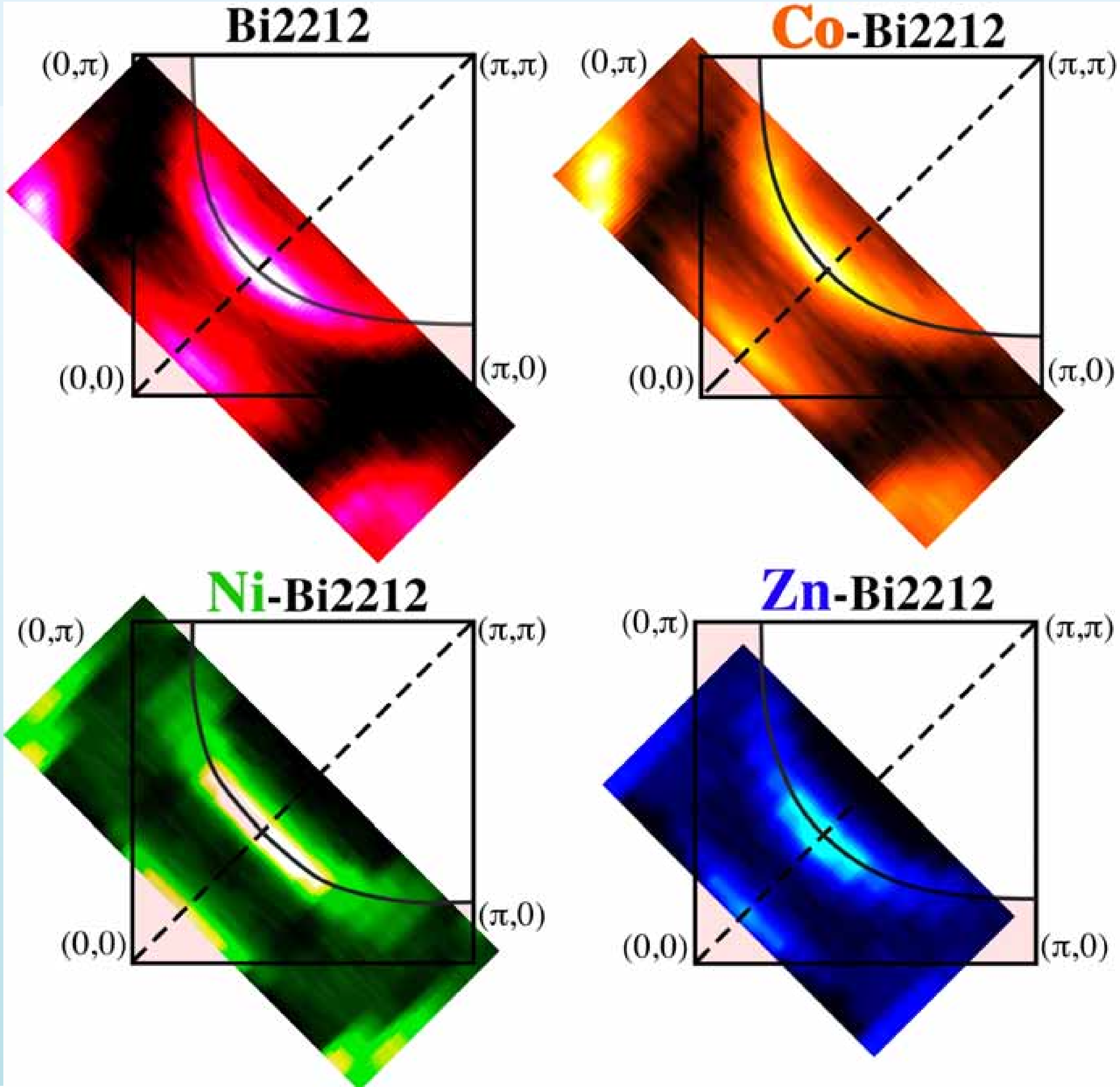


Y. Sidis et al., cond-mat/0006265

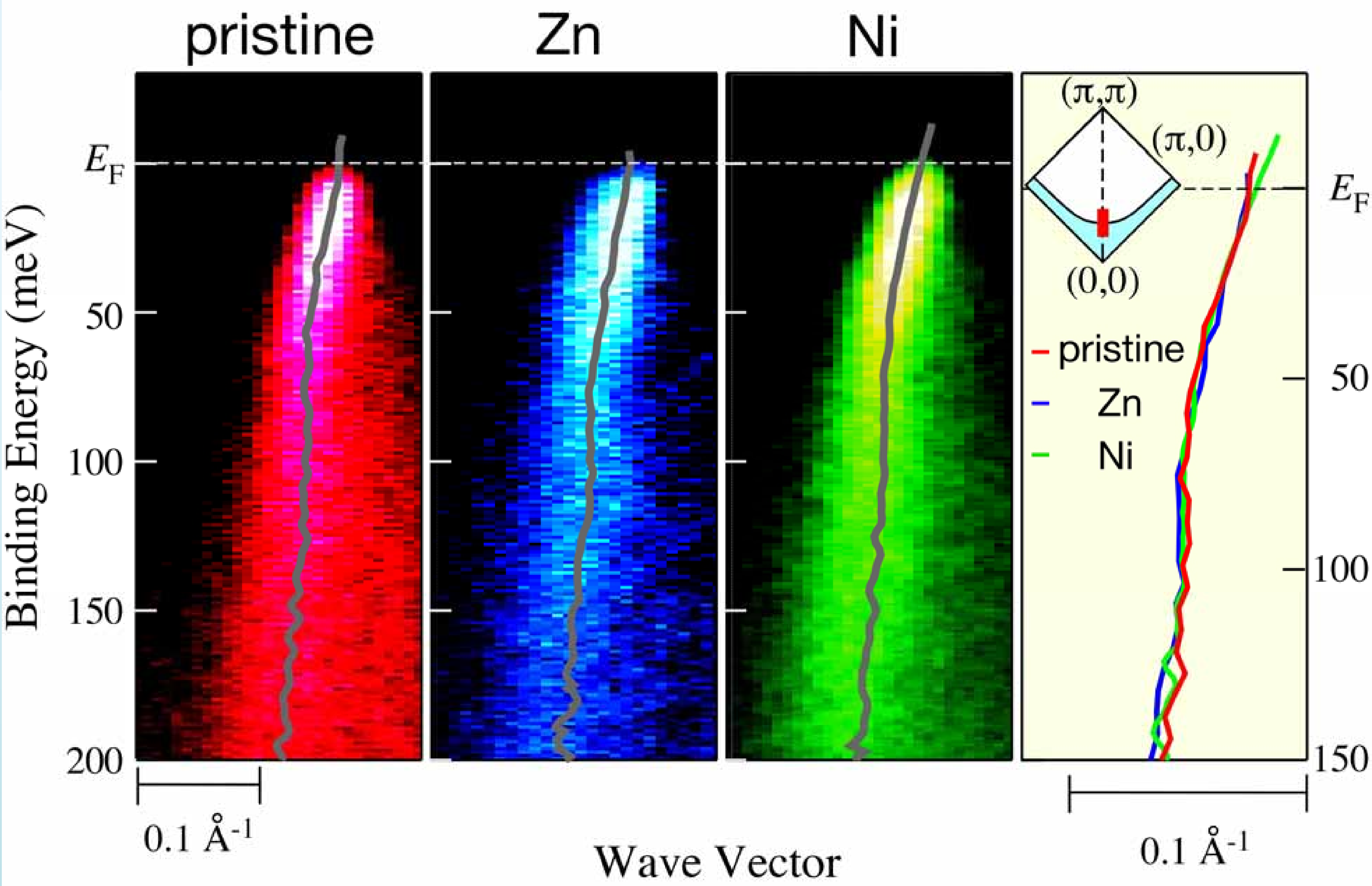
Zn-impurity in CuO_2 plane



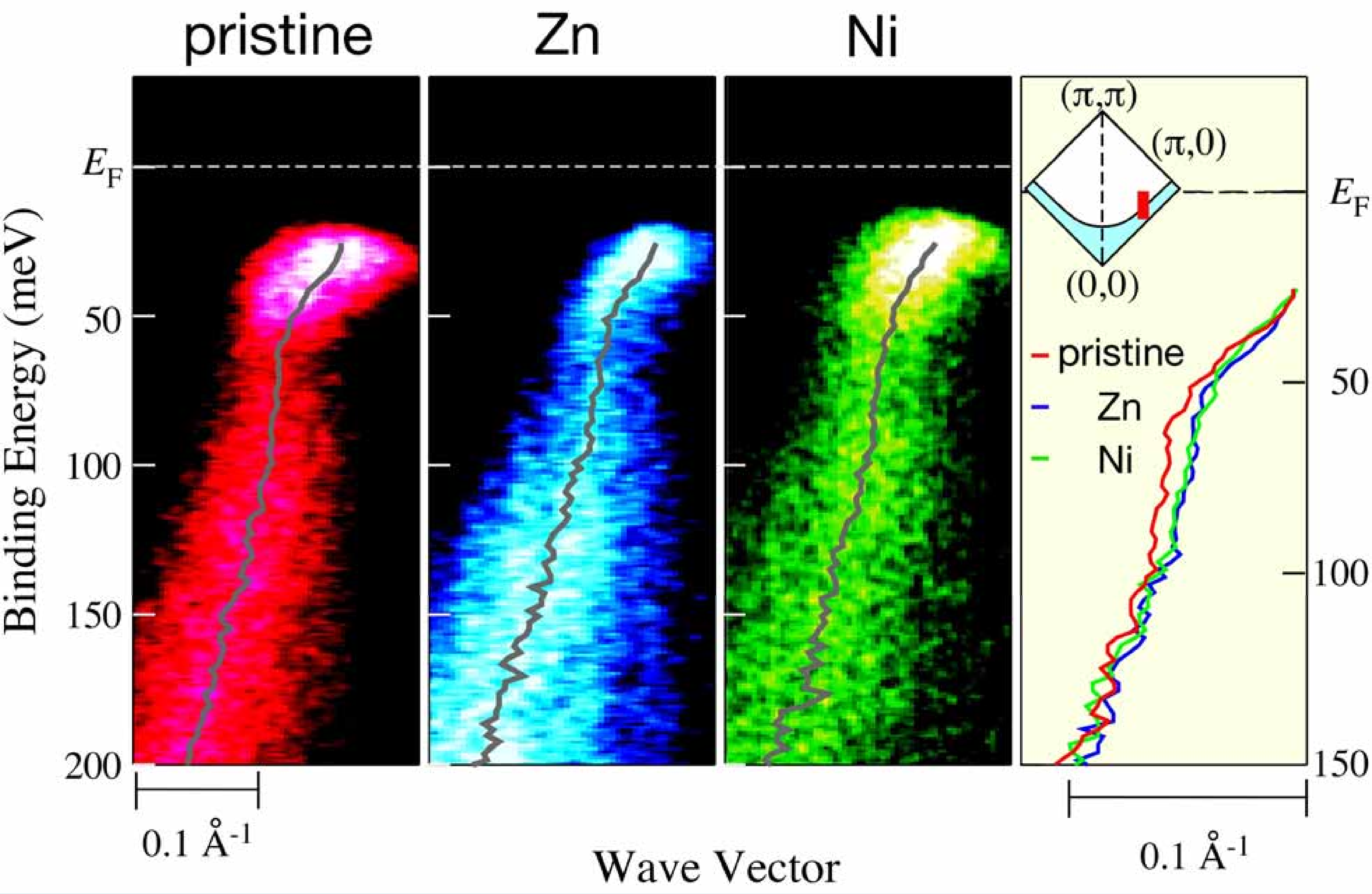
No impurity effect on Fermi surface of Bi2212



Impurity effect on kink along nodal cut



Impurity effect on kink at off-nodal cut



High-Tc superconductors

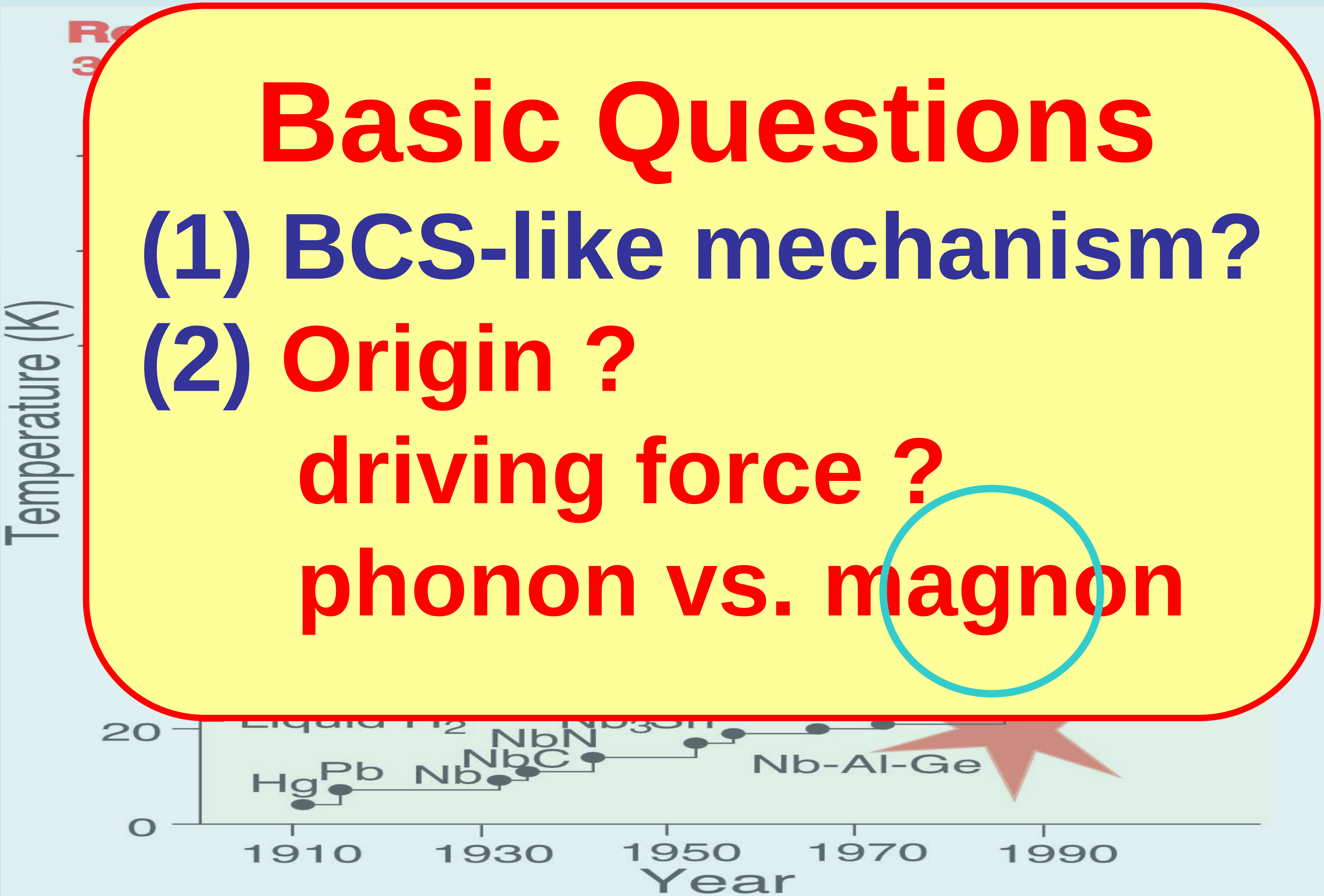
Basic Questions

(1) BCS-like mechanism?

(2) Origin ?

driving force ?

phonon vs. magnon



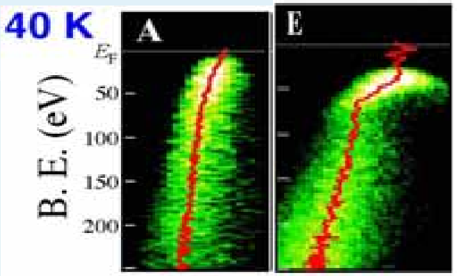
Bednorz & Muller (1986)

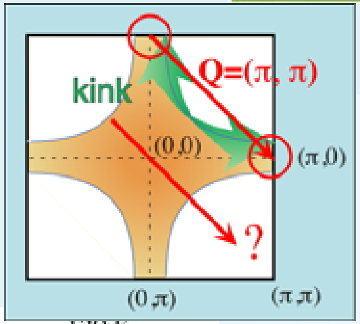
Nobel Prize (1987)

Summary of ARPES study on kink

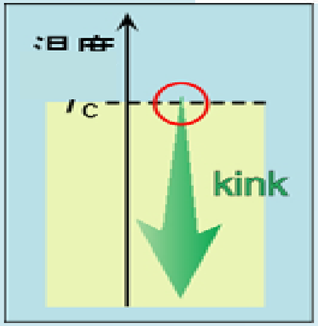
- **Kink around (π, 0)**

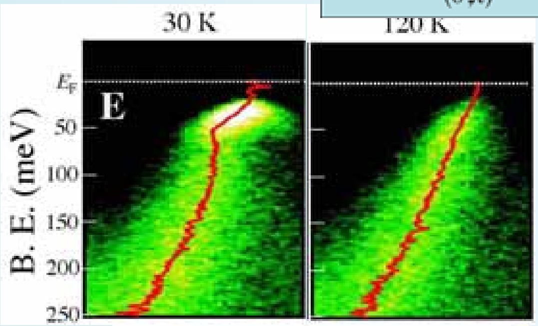
① **Strong k-dependence in the SC state**





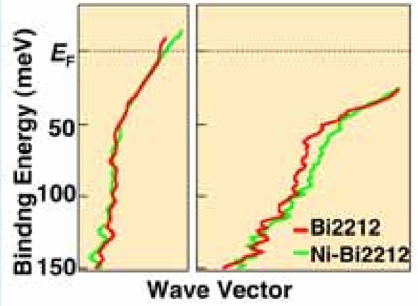
② **Appears below T_c Strong temp. dependence**





③ **Strong in multi-layered HTSCs Weak in single-layered HTSC**

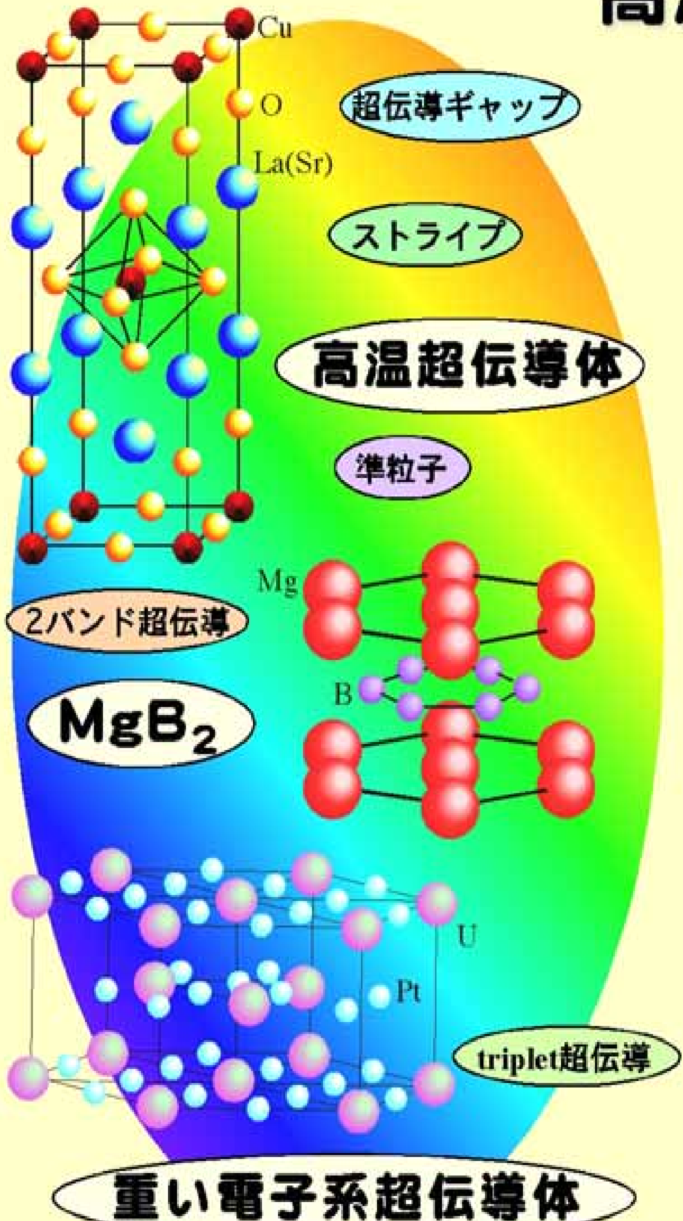
④ **Strong impurity effect**



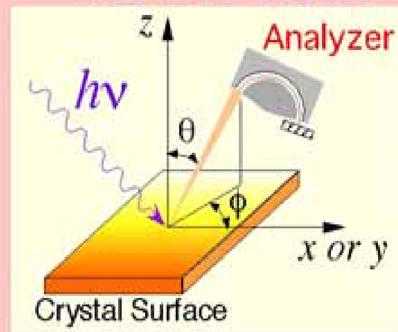
Coupling of electrons with Q=(π, π) magnetic mode is essential for superconductivity

- **Kink at the nodal direction Phonon ?**

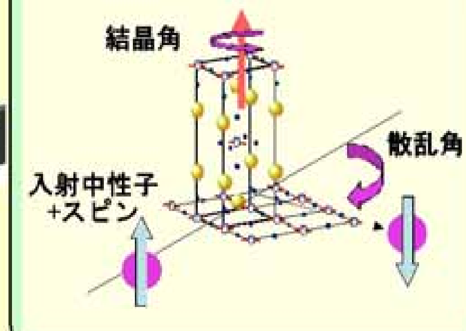
光電子および中性子分光の相補的利用による高温超伝導体の研究



光電子分光



中性子散乱



高温超伝導体発現機構

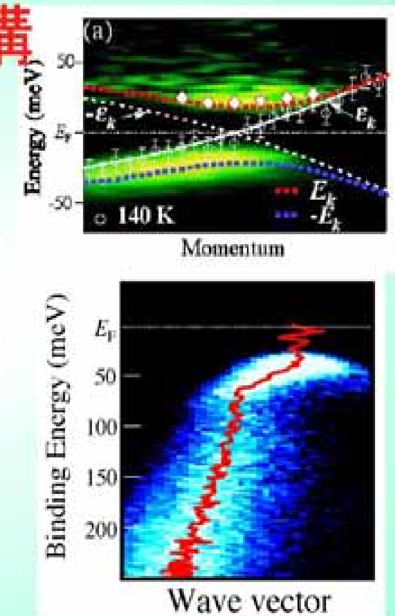
- 超伝導機構

  BCS的

  ボゴリューボフ準粒子

- 超伝導起源

  磁気的相互作用



東北大学
21世紀COEプログラム「物質階層融合科学の構築」

多重エネルギー階層分光による
超伝導固体内素励起の研究

代表研究者：高橋　隆

研究分担者：青木晴善、山田和芳、落合　明、佐藤宇史
木村憲彰、藤田全基、平賀晴弘

研究協力者： Satyabrata Raj