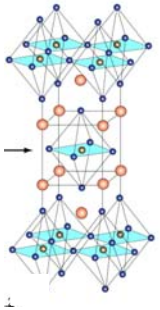
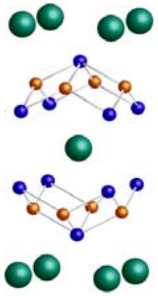
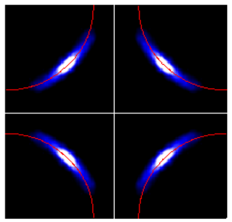
Cheiron school 2013

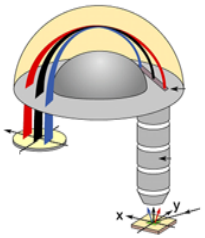
# Photoemission Spectroscopy (2)

## Strongly correlated electron systems





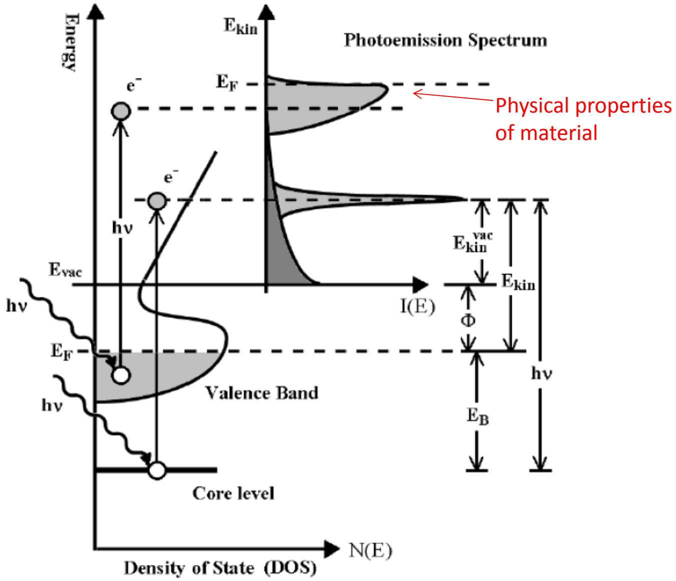




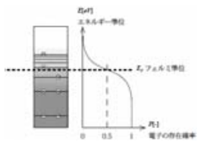

Teppei Yoshida

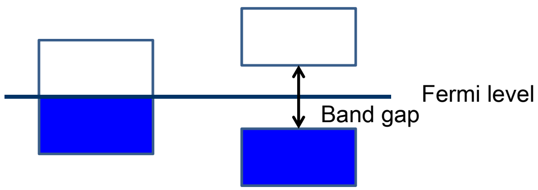
*Graduate School of Human and Environmental Studies, Kyoto University*


# Principle of photoemission spectroscopy

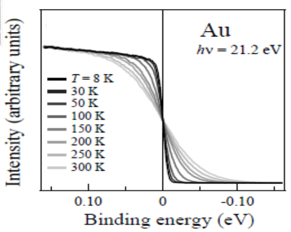


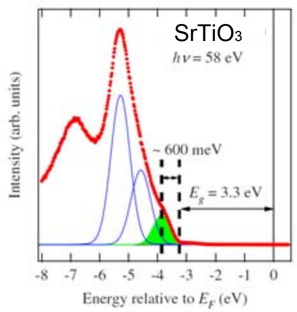

# Electronic structure near the Fermi level






Photoemission spectra

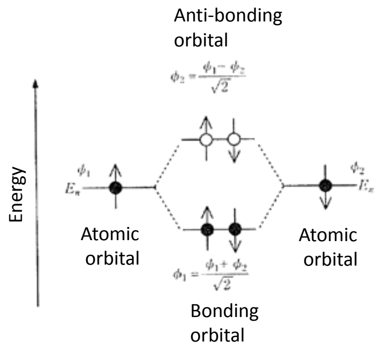


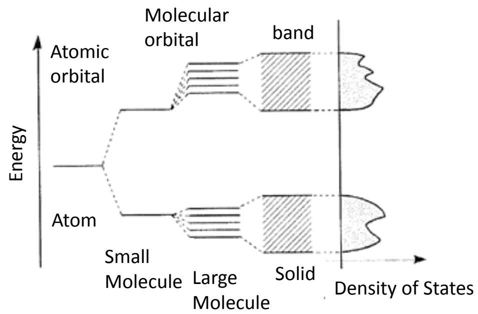




Takizawa *et al.*, PRB '09

# Electronic structure

## from molecular orbital to solid state band

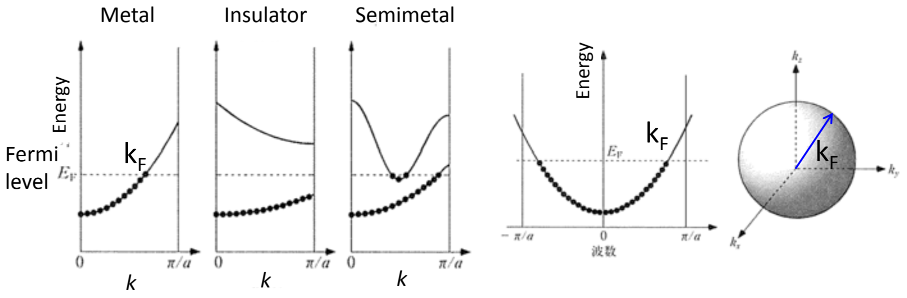



「光電子固体物性」T. Takahashi

# Electronic structure

## Band dispersion and Fermi surface

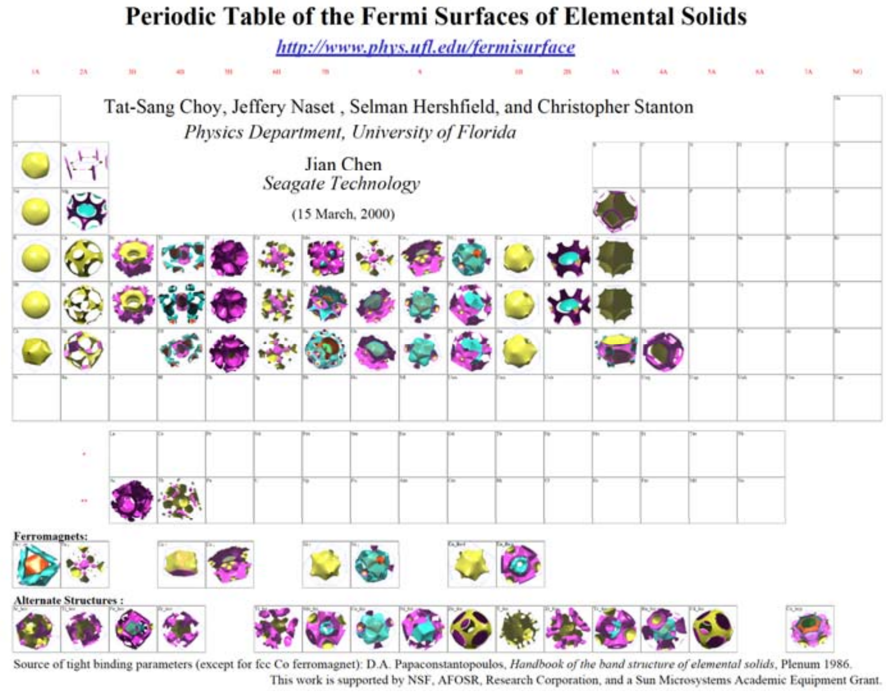



Quantum number: wave number *k*

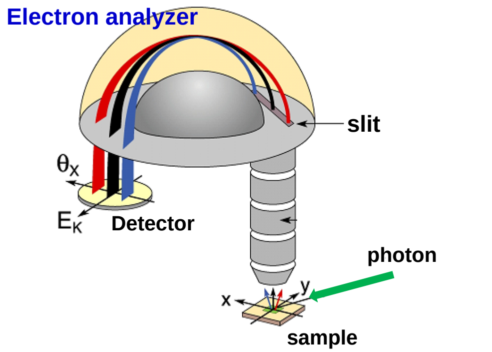
*Momentum hk*

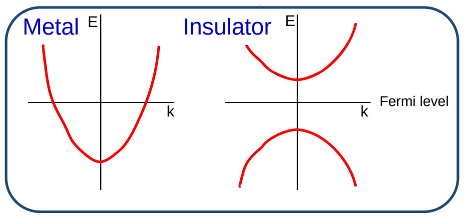
E= $h^2k^2/2m$

「光電子固体物性」T. Takahashi

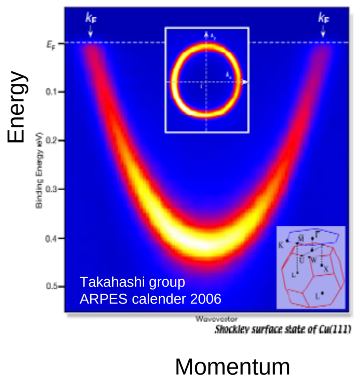



# Angle-resolved photoemission spectroscopy (ARPES)

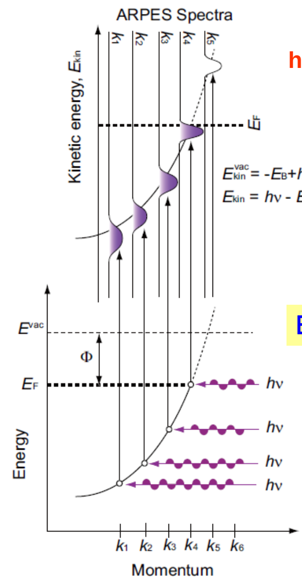


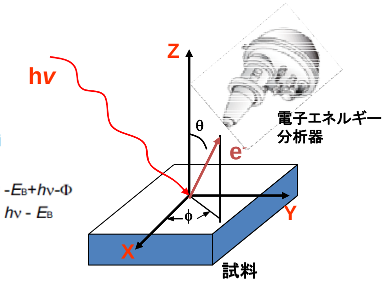



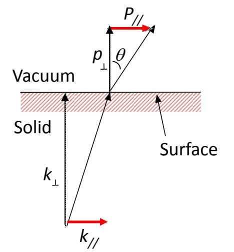

**Band dispersion and Fermi surface**




# Principle of ARPES




**Energy conservation**

$E_{kin} = -E_B + h\nu - \Phi$

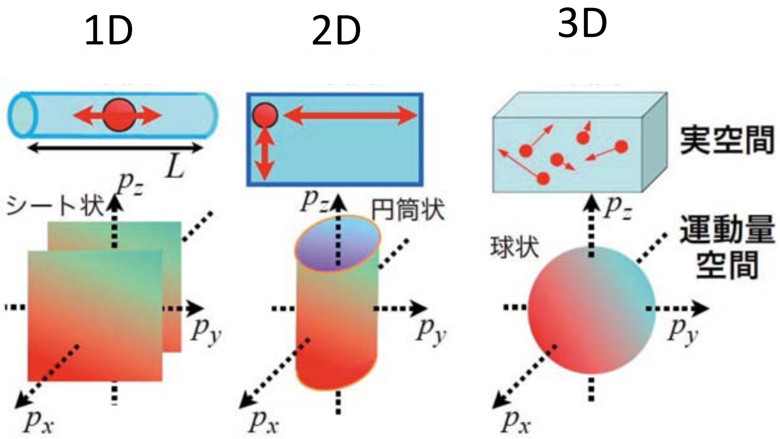
**Momentum conservation ( parallel to the surface )**

$$p_{//} = \hbar k_{//}$$

$$p_{//} = \sqrt{2mE_{kin}}\sin\theta$$

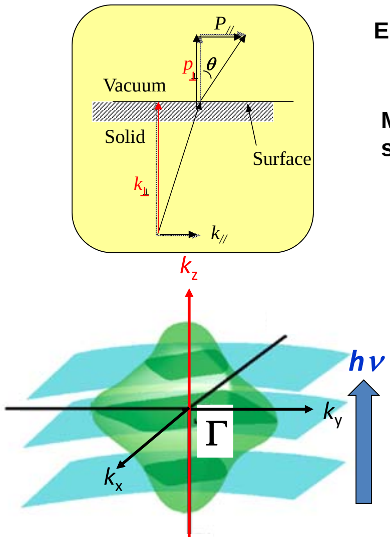
$$\hbar k_{//} = \sqrt{2mE_{kin}}\sin\theta = \sqrt{2m(-E_B + h\nu - \Phi)}\sin\theta$$

## Dimension of Fermi surface




関山明ほか Spring-8 最近の研究から

## Three-dimensional Fermi surface mapping




**Energy conservation**

$$E_{kin} = -E_B + h\nu - \Phi$$

**Momentum conservation （Parallel to surface）**

$$p_{//} = \hbar k_{//}$$

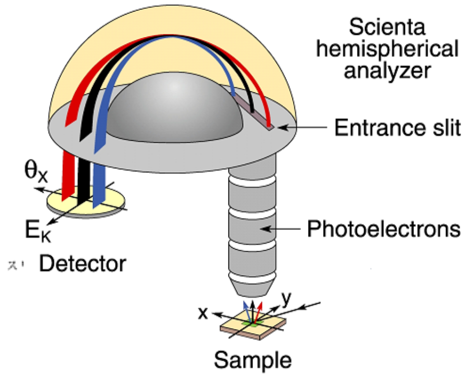
$$p_{//} = \sqrt{2mE_{kin}}\sin\theta$$

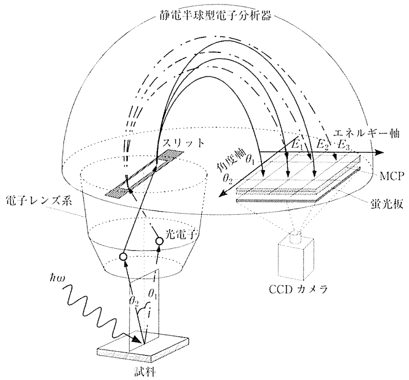
$$\hbar k_{//} = \sqrt{2mE_{kin}}\sin\theta = \sqrt{2m(-E_B + h\nu - \Phi)}\sin\theta$$

$$\hbar k_{\perp} = \sqrt{2m(E_{kin}\cos^2\theta + V)}$$

**V: Inner potential**

## Electron Analyzer

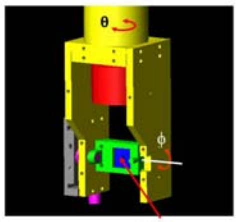


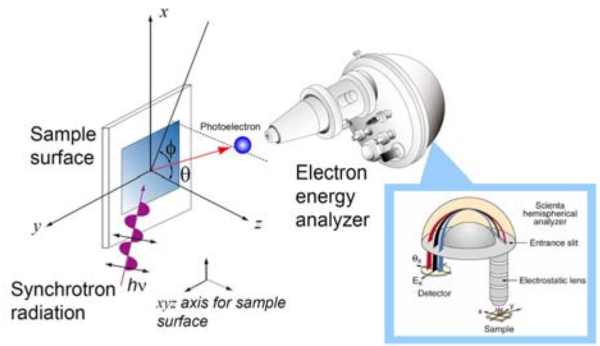

「光電子固体物性」T. Takahashi

## Multi-axis manipulator

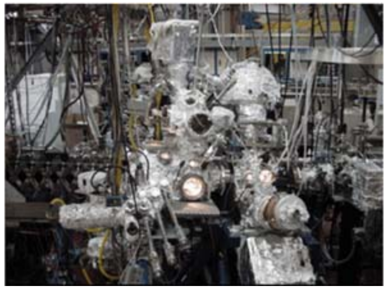
2軸マニピュレーター




試料

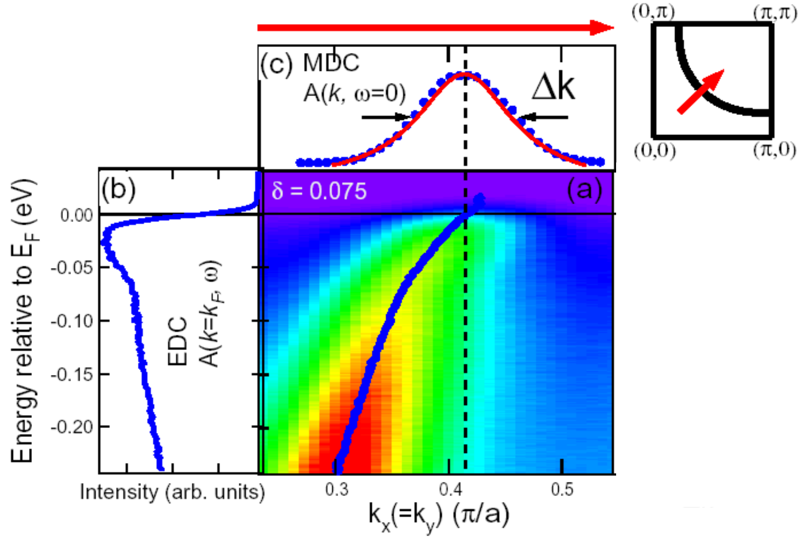


# ALS BL10.0.01



**Advanced Light Source**

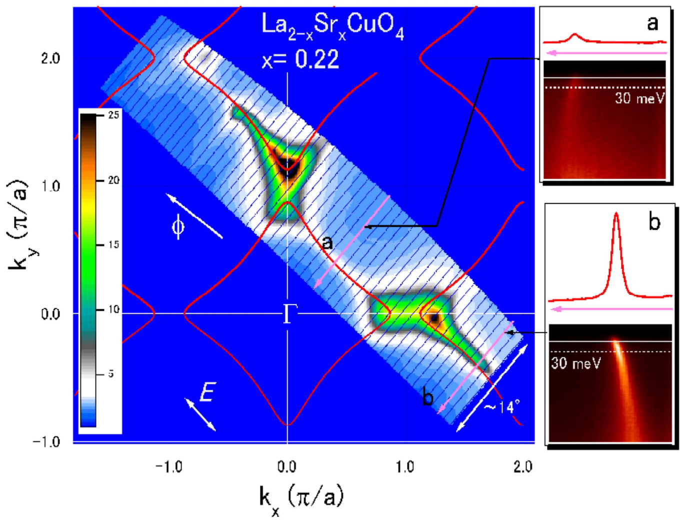
# EDC and MDC



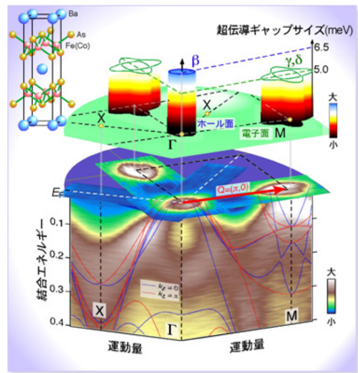

EDC (energy distribution curve)
MDC (momentum distribution curve)

# Spectral weight mapping

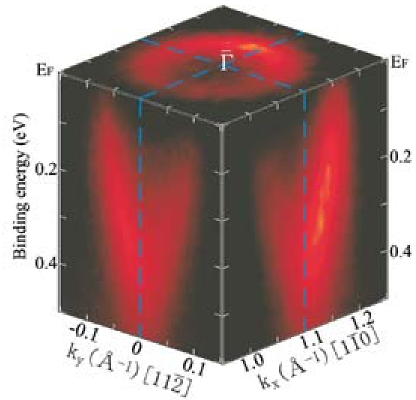
Intensity at Fermi level




# Fermi surface and band dispersion

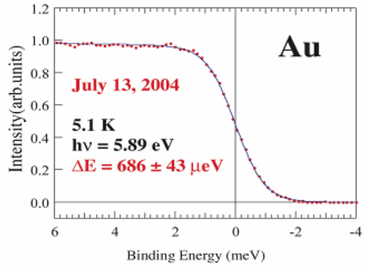


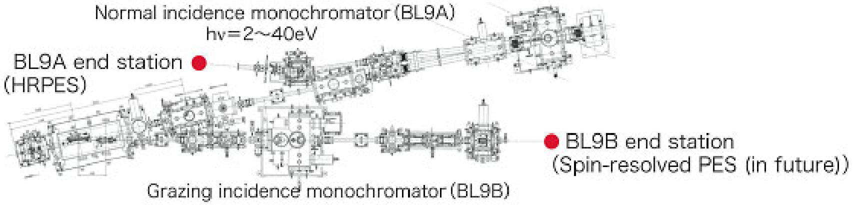

東北大　高橋研




東大　長谷川研

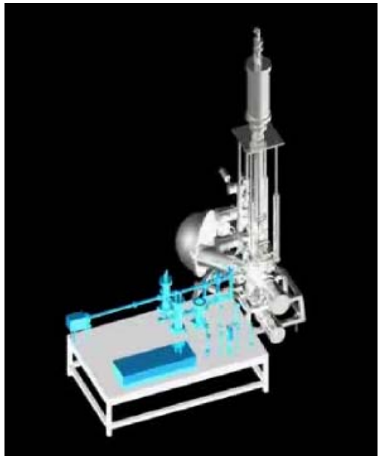
# HiSOR BL9



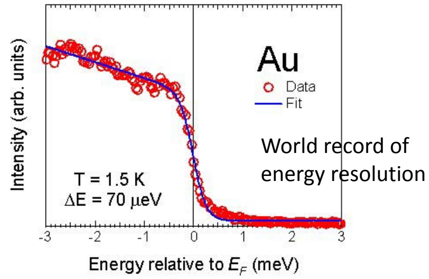

http://www.hsrc.hiroshima-u.ac.jp/english/bl9.htm

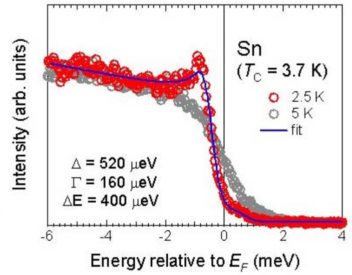
# Very High resolution photoemission spectroscopy



Shin Group
ISSP, University of Tokyo

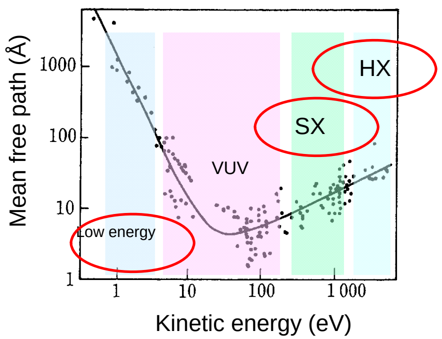
http://shin.issp.u-tokyo.ac.jp/souchi/3gouki/




# Probing depth

**Escape depth of photoelectrons**




**VUV -> surface sensitive**

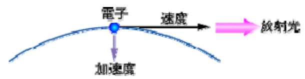
**SX**

- Energy resolution < 100meV
- Quick mapping in momentum space

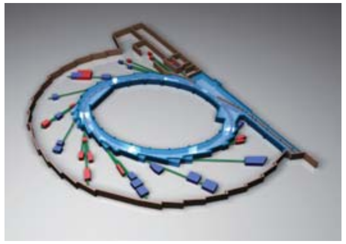
**Low energy photons (SOR, laser)**

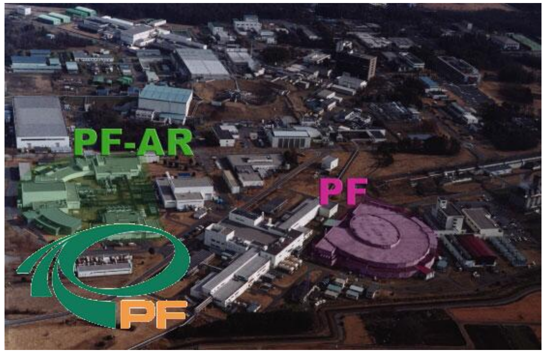
- Resolution < 5meV
- It takes a time to map in momentum space.

# Hiroshima Synchrotron（HiSOR）



# Photon Factory





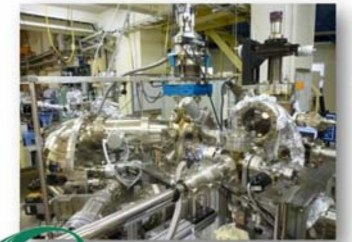

KEK (High energy …)

Tsukuba, Japan

Tsukuba, Japan

KEK, PF information
From HP

# ARPES experimental end station



高エネ研フォトンファクトリー
PF BL-28A

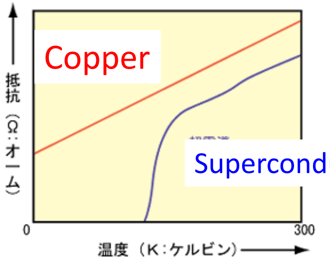
広島大学放射光センター
HiSOR BL- 9A

バークレー国立研究所
ALS BL-10


スタンフォード大学放射光研究所
SSRL BL 5-4

励起光エネルギー可変
直線偏光、円偏光

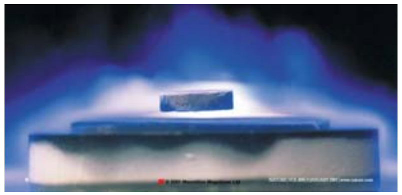
# What is superconductivity?

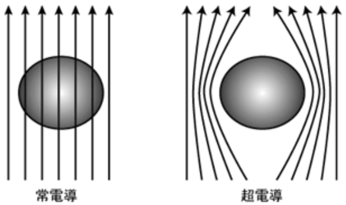



Zero resistance
→ no thermal loss

住友電工のHPより

Misner Effects

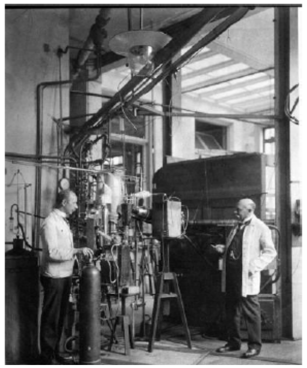





# Discovery of superconductivity

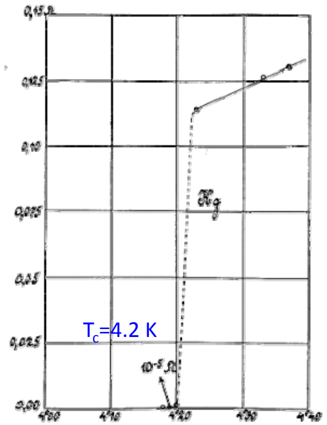
Liquid He（1908）

Discovery of superconductivity
in Hg（1911）



Kamerlingh Onnes

Nobel prize in 1913

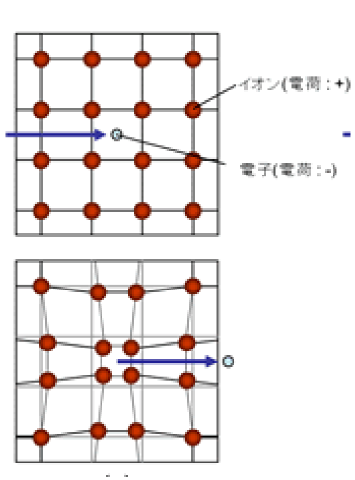


# BCS (Bardeen, Cooper, Schrieffer ) theory

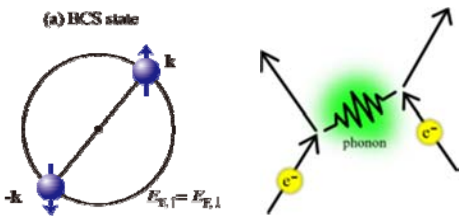
John Bardeen    Leon Neil Cooper    John Robert Schrieffer

BCS theory 1957    Nobel Prize in 1972

Electron-Phonon interaction




**Cooper pairs**




Electrons make pairs mediated by lattice vibrations (phonon)

# High-Tc cuprate superconductor

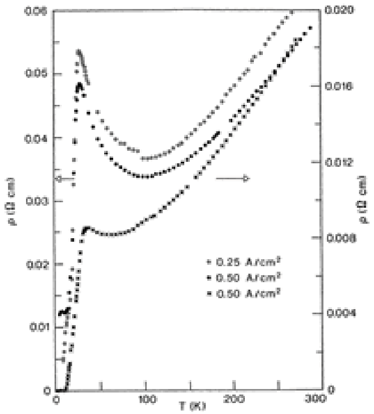



Fig.1 La-Ba-Cu-Oの最初の報告

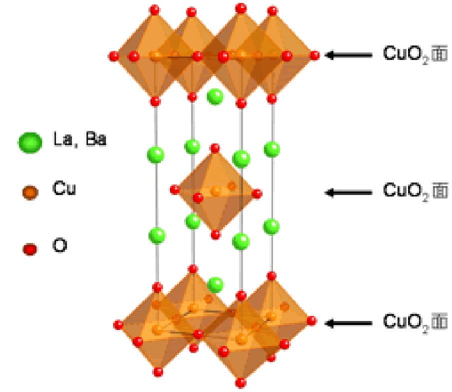
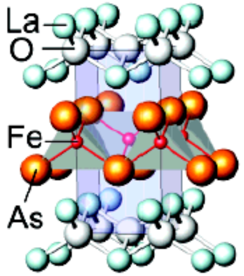



Fig.2 $La_{2-x}Ba_xCuO_4$の結晶構造

J. G. Bednorz and K. A. Müller, *Z. Phys*. **B64** (1986) 189

# Discovery of iron-based superconductors (2008)




LaFeAsO

J|A|C|S COMMUNICATIONS

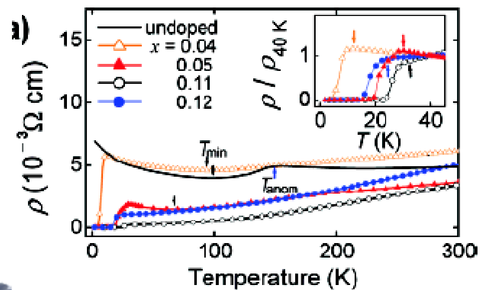
Published on Web 02/23/2008

**Iron-Based Layered Superconductor $La[O_{1-x}F_x]FeAs$ ($x$ = 0.05−0.12) with $T_c$ = 26 K**

Yoichi Kamihara,*,† Takumi Watanabe,‡ Masahiro Hirano,†,§ and Hideo Hosono†,‡,§

*ERATO-SORST, JST, Frontier Research Center, Tokyo Institute of Technology, Mail Box S2-13, Materials and Structures Laboratory, Tokyo Institute of Technology, Mail Box R3-1, and Frontier Research Center, Tokyo Institute of Technology, Mail Box S2-13, 4259 Nagatsuta, Midori-ku, Yokohama 226-8503, Japan*

Received January 9, 2008; E-mail: hosono@msl.titech.ac.jp

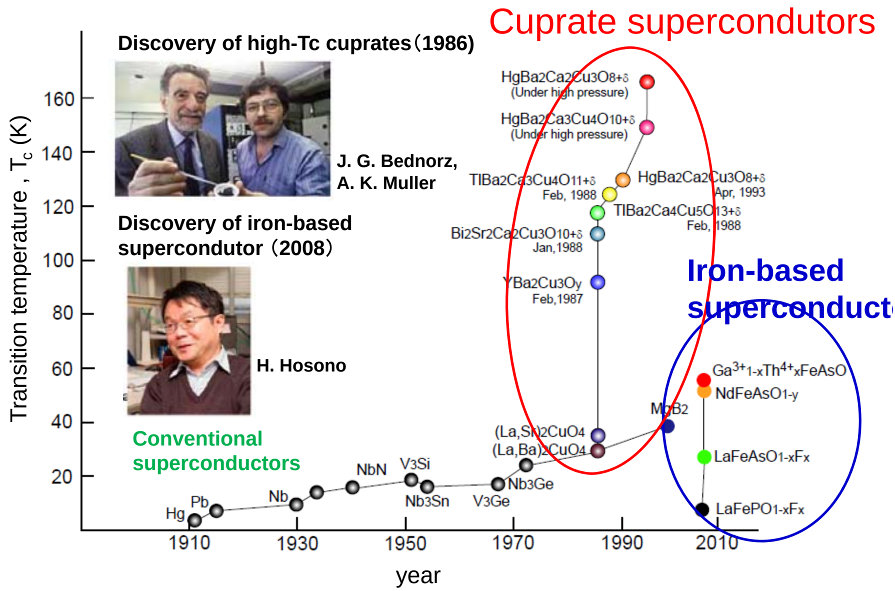



H. Hosono

Y. Kamihara

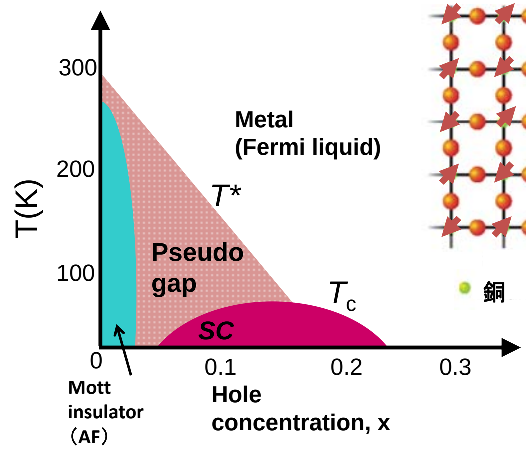
High transition temperature next to the cuprates family

# History of superconductivity

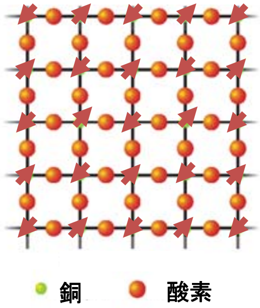


# High-Tc cuprate superconductors

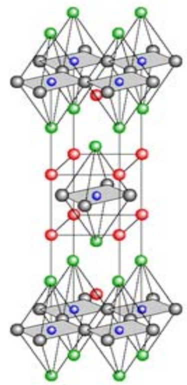
**Phase diagram**



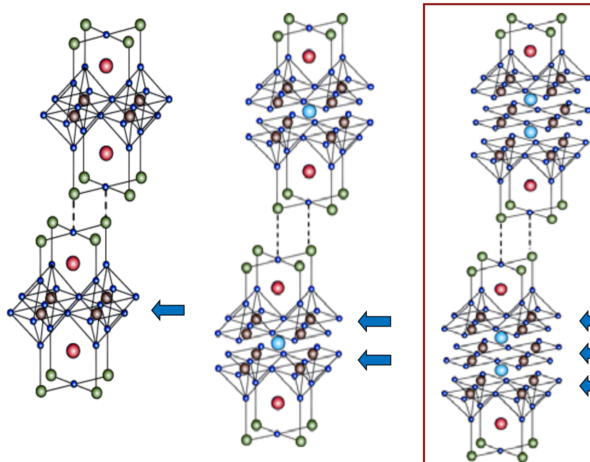

**$CuO_2$ plane**



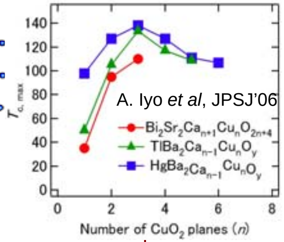

**Crystal structure**



# Single-, double-, and triple layer cuprates




**$T_c$ of multilayer cuprates**




$Bi_2Sr_2CuO_{6+\delta}$
Bi2201 $T_{c,max}$=34 K
c=24.6 Å

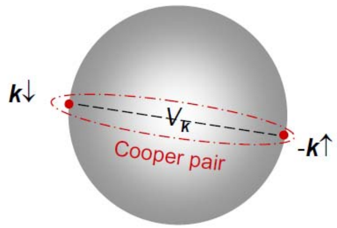
$Bi_2Sr_2CaCu_2O_{8+\delta}$
Bi2212 $T_{c,max}$=95 K
c=30.7 Å

$Bi_2Sr_2Ca_2Cu_3O_{10+\delta}$
Bi2223 $T_{c,max}$=110 K
c=37.1 Å

$CuO_2$面の枚数と$T_c$の間に相関がある。

# BCS theory

**Cooper pair formation**

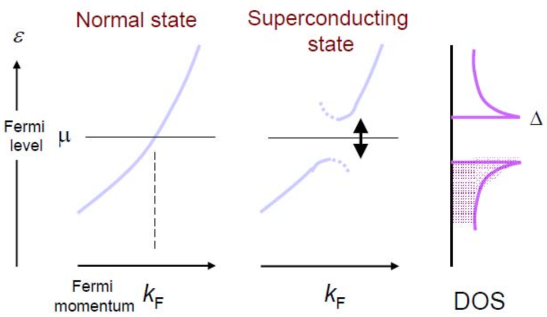



$$\Psi_{BCS} = \prod_k (u_k + v_k a^+_{k,\uparrow} a^+_{-k,\downarrow})|0\rangle$$

$u_k / v_k$ ~ constant

Order parameter: $\Delta(\boldsymbol{k}) = \Delta_0$

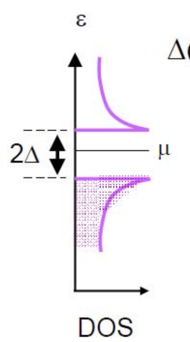
**Superconducting gap**




$\varepsilon = \varepsilon(\mathrm{k})$ $\quad \varepsilon = \pm\sqrt{\varepsilon(\mathrm{k})^2 + \Delta^2}$

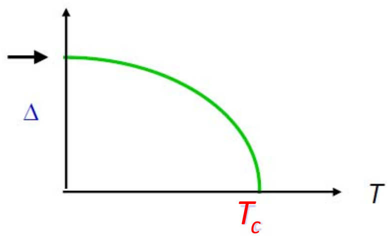
# BCS theory

**Density of states**




$$\Delta(0) = \frac{3.5 k_B T_c}{2}$$

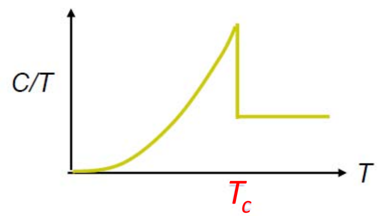
**Superconducting gap Δ(T)**




Order parameter: $\Delta(\boldsymbol{k}) = \Delta_0$

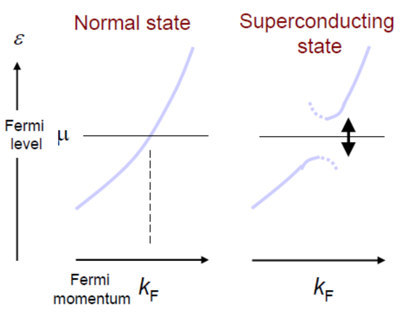
Superfluid density
= Fermi surface volume/$m^*$

**Electronic specific heat**

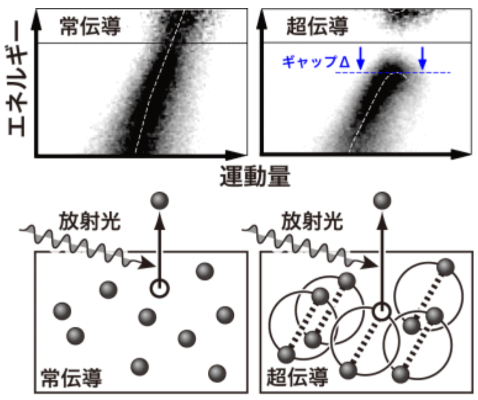


# Observation of SC gap by ARPES

### Superconducting gap



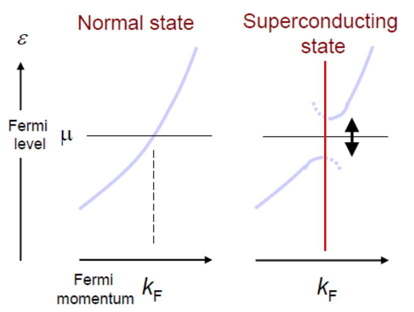

$\varepsilon = \varepsilon(\mathrm{k})$ $\quad \varepsilon = \pm\sqrt{\varepsilon(\mathrm{k})^2 + \Delta^2}$



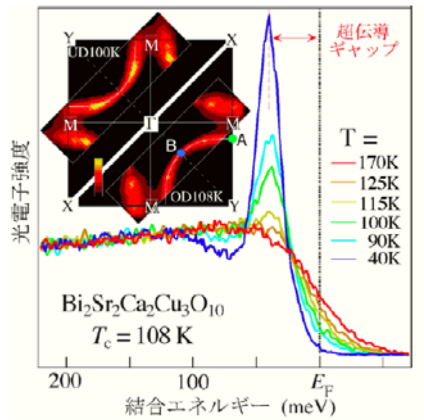

http://www.hsrc.hiroshima-u.ac.jp/temperature.htm

# Observation of SC gap by ARPES

### Superconducting gap



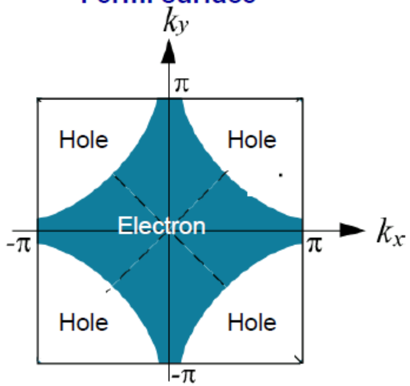

$\varepsilon = \varepsilon(\mathrm{k})$ $\quad \varepsilon = \pm\sqrt{\varepsilon(\mathrm{k})^2 + \Delta^2}$



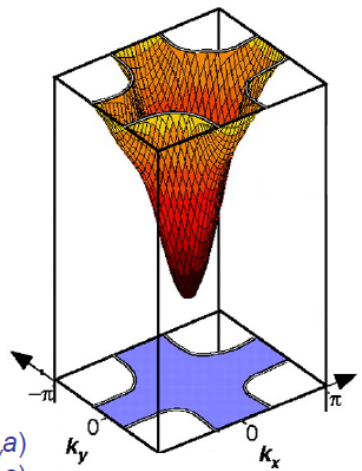

http://arpes.phys.tohoku.ac.jp/contents/study/CuO.html

# Fermi surface and band dispersions in high-Tc cuprates

### Fermi surface



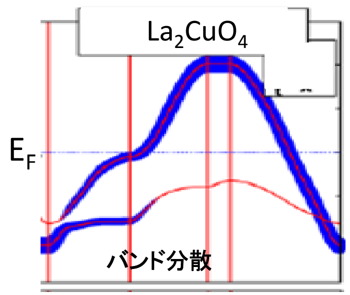

### Band dispersion

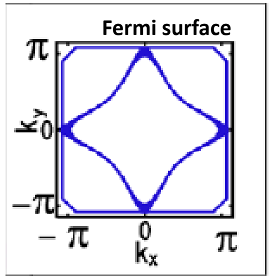



Band structure: $E(\mathbf{k}) = -2t(\cos k_x a + \cos k_y a)$
$- 4t'\cos k_x a \cos k_y a - 2t''(\cos 2k_x a + \cos 2k_y a)$

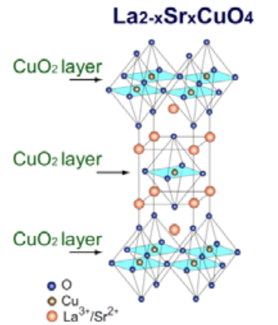
# Band structure and Fermi surface of high-Tc cuprates (Overdoped sample)

**Theory**

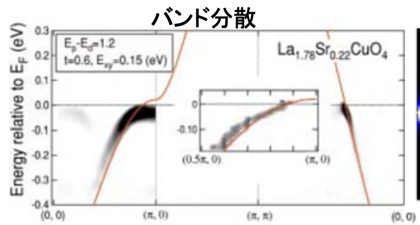


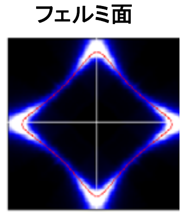



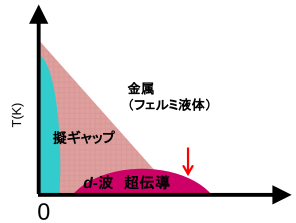

H. Sakakibara *et al.*, PRL '09




**ARPES**

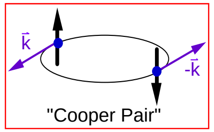


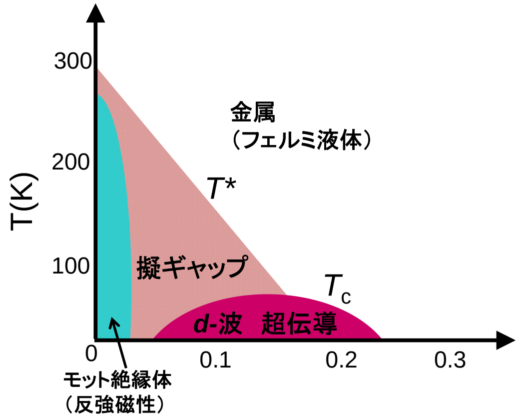



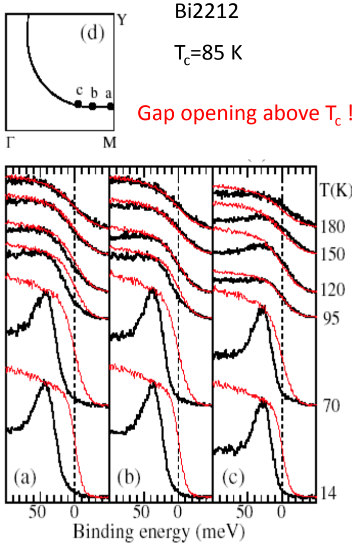

T. Yoshida *et al.*, PRB '01

# Pseudogap issue




Preformed
Cooper pairs?




Bi2212

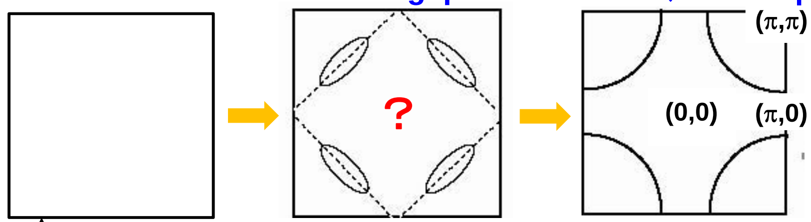
$T_c$=85 K

Gap opening above $T_c$ !?

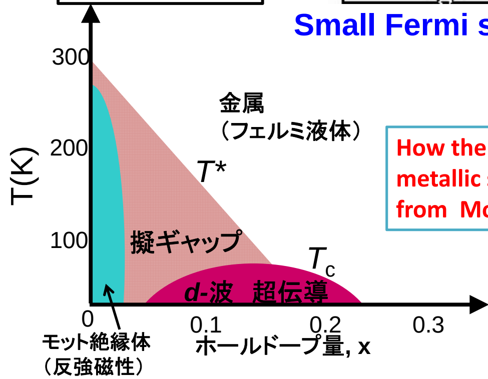
Ding et al.

# Evolution of "Fermi surface"

Mott insulator　Pseudogap state　Metal（Fermi liquid）

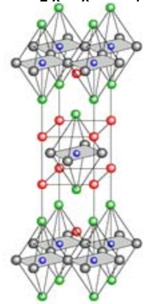



Small Fermi surface　Large Fermi surface



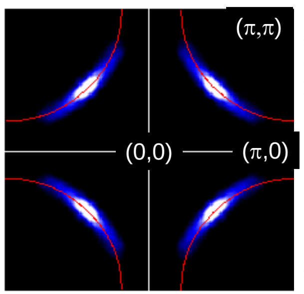

How the psedogap and metallic states are formed from Mott insulator ?

$La_{2-x}Sr_xCuO_4$



# Fermi arc

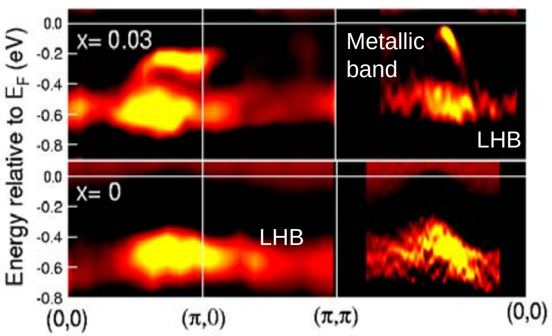
Fermi surface mapping




"truncated Fermi surface"
（Fermi arc)

Relation between SC gap and pseudogap ?

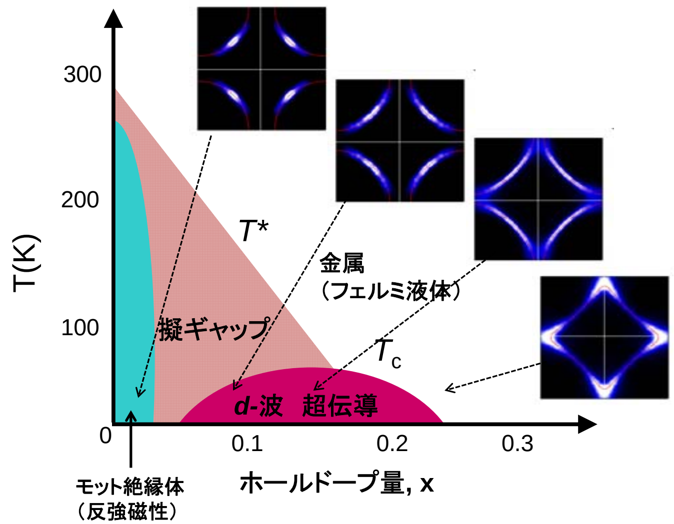
QP band dispersions　LSCO x=0.03




T. Yoshida *et al*. PRL. '03.

**QP band structure in node direction**
**⇒　Origin of metallic conductivity**

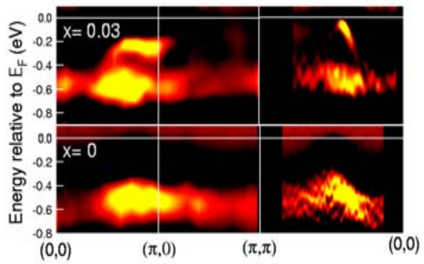
# Pseudogap and Fermi arc




T. Yoshida　*et al*. PRB. '06.

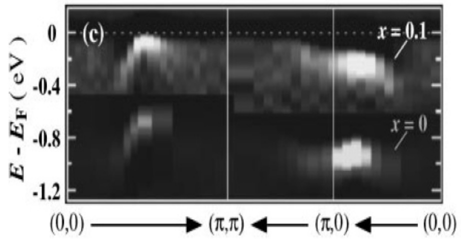
## Formation of quasi-particle band

LSCO

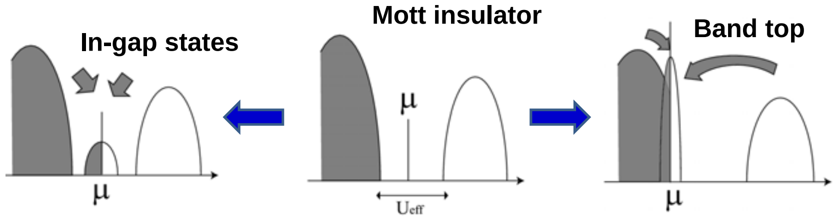



T. Yoshida *et al*., PRL '03.

$Ca_{2-x}Na_xCuO_2Cl_2$ (Na-CCOC)

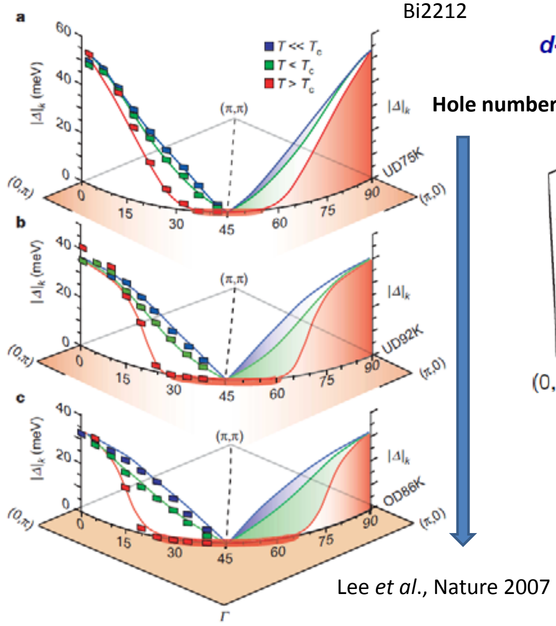


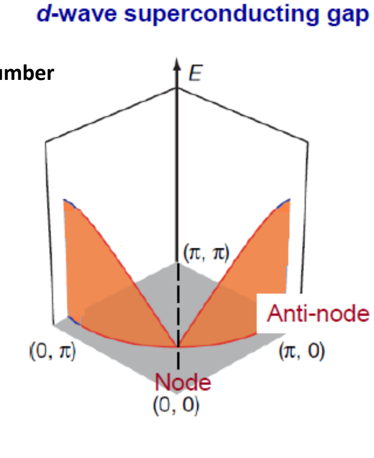

Y. Kohsaka *et al*., JPSJ '03.




There are two kinds of evolution process of QP structure.

## Anisotropic SC gap in Bi2212

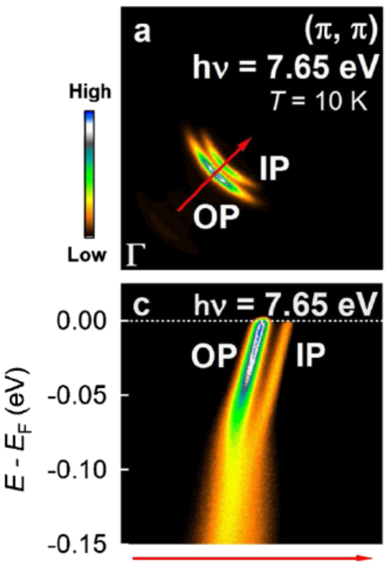


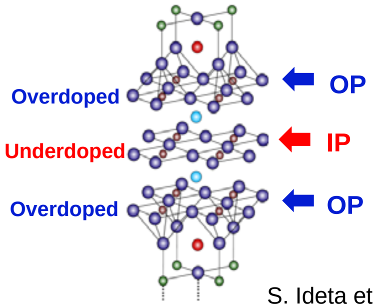




$d_{x2-y2}$ symmetry

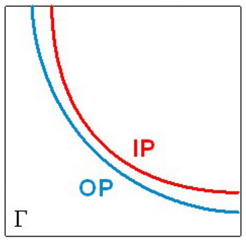
Lee *et al*., Nature 2007

## Band dispersion and Fermi surfaces of Bi2223



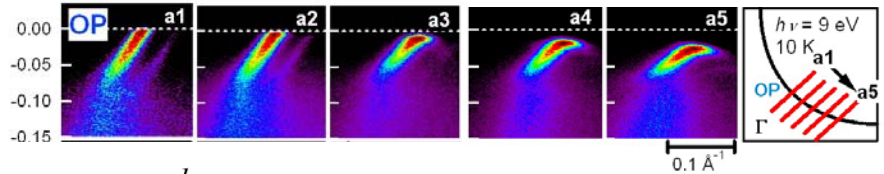



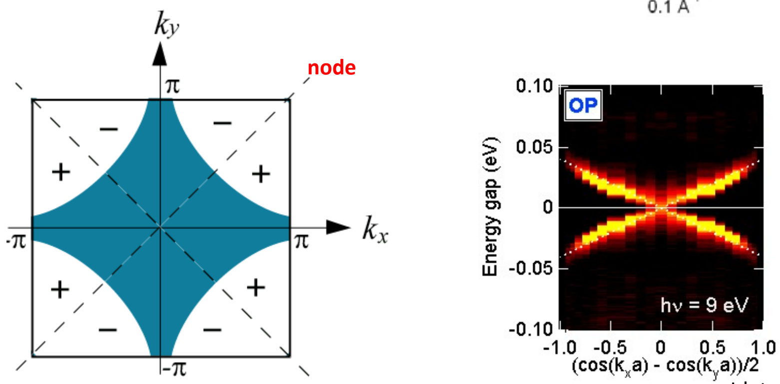

S. Ideta et al., PRL '10




$T_c$=110K

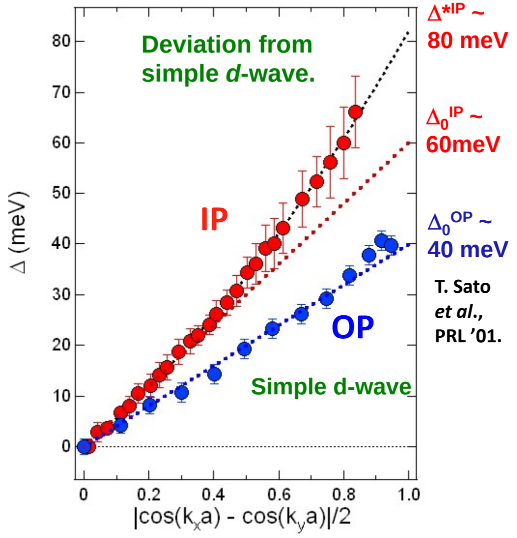
## d-wave superconducting gap

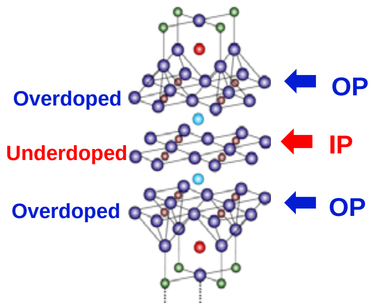


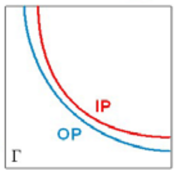

Ideta *et al*., PRL

# Superconducting gaps of Bi2223



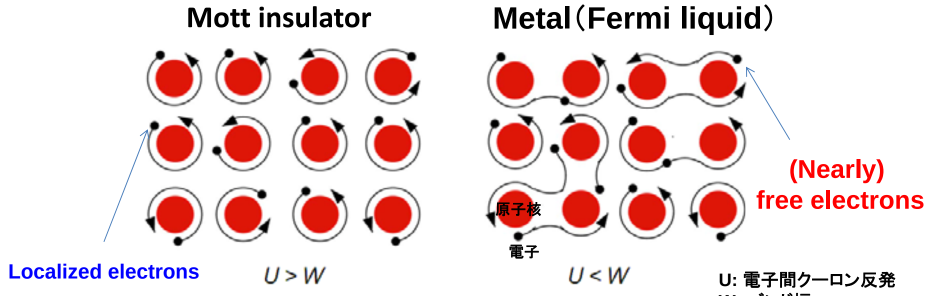

S. Ideta et al., PRL '10

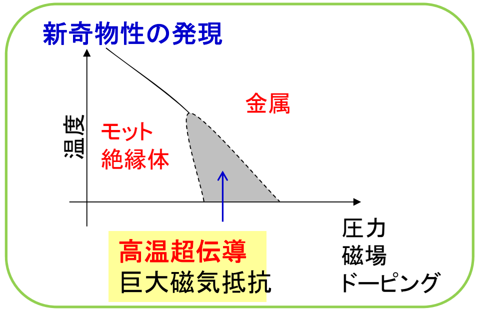



IP: underdoped
OP:overdoped

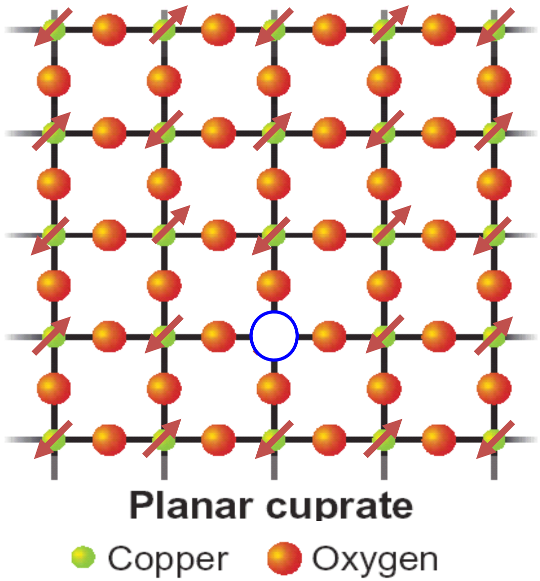
$T_c$=110K

# Strongly correlated electron system




# High-Tc cuprate superconductor




# Correlated electrons

There are three kinds of “electrons”.

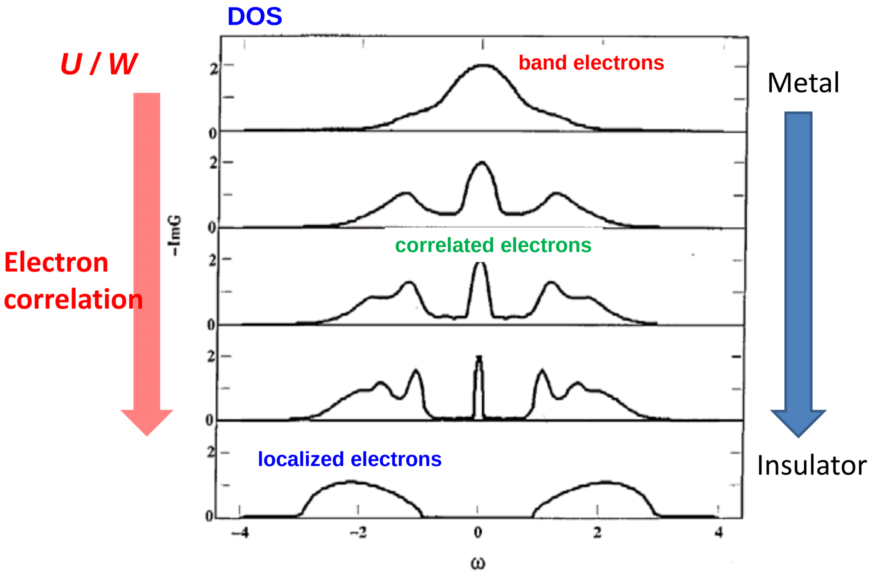
1) Band electrons
Nearly free electrons can move between atoms.

2) Localized electrons
Electrons localized near atom sites due to correlation.

3) Correlated electrons
These electrons can move between atoms but their movements are not so easy as in band electrons.

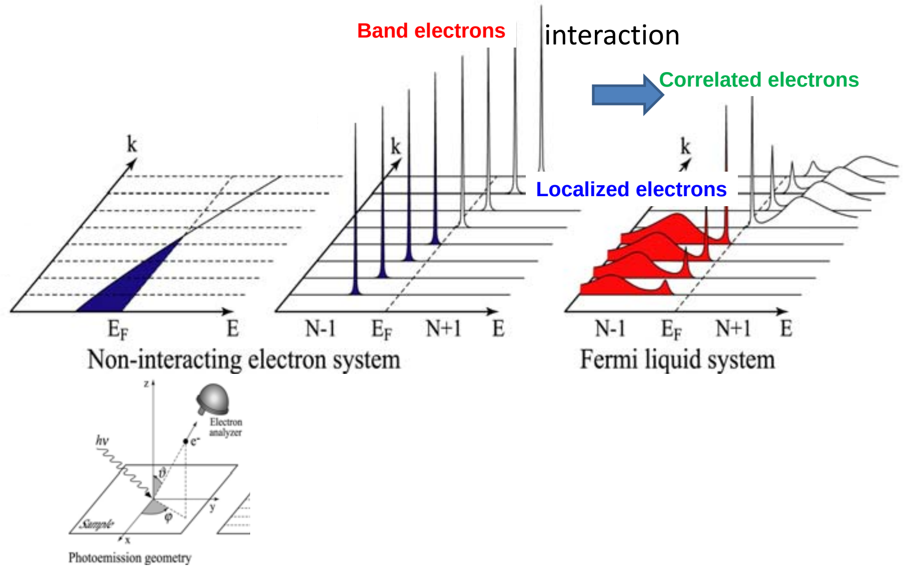
cf. Prof. Nagaosa at Univ. Tokyo

# Correlation effects on DOS

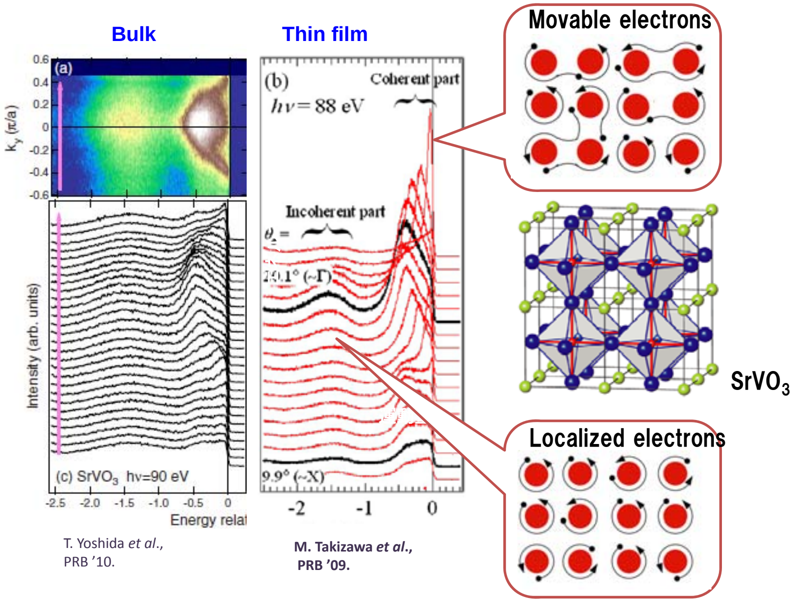



X.Y. Zhang, M.J. Rozenberg and G. Kotliar, PRL '93.

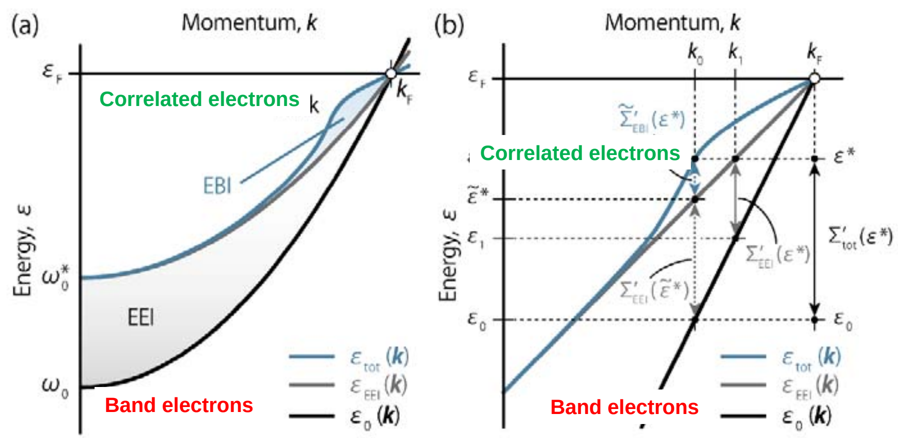
# Correlation effects in ARPES spectra




# Correlated electron system $SrVO_3$




# Kink structure in quasi particle




Eel: electron-electron interaction

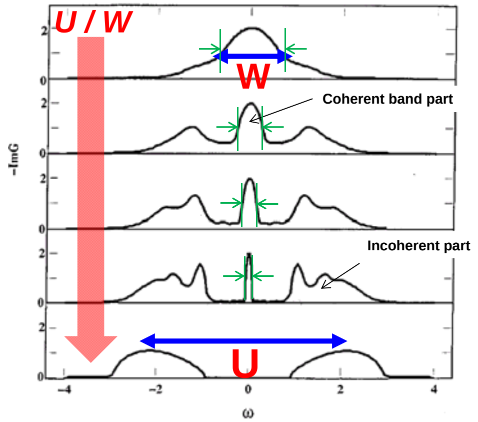
Ebl: electron-boson interaction

$\Sigma(\varepsilon)$: Self-energy

Iwasawa et al., Sci. Rep. 3, 1930 (2012).
JSSRR Journal

# Mass enhancement due to electron correlation

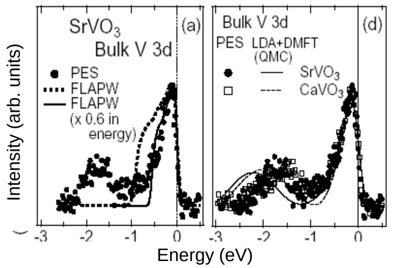
**DOS**



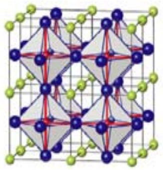

X.Y. Zhang, M.J. Rozenberg and G. Kotliar, PRL '93.

Mass renormalization near MI transition

**PES spectra**

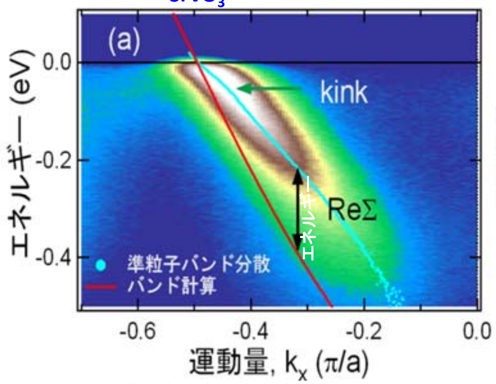


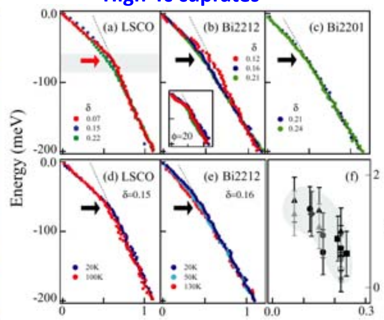

A. Sekiyama *et al*. PRL'04.



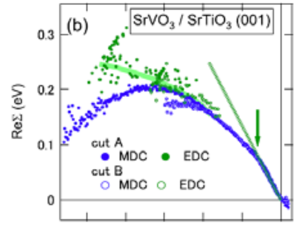
**$SrVO_3$ ($3d^1$)**

# Correlated electron system $SrVO_3$



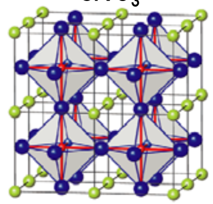

**A. Lanzara *et al*. Nature 2001**




**kink ~ 60meV**
**Electron-phonon interaction?**

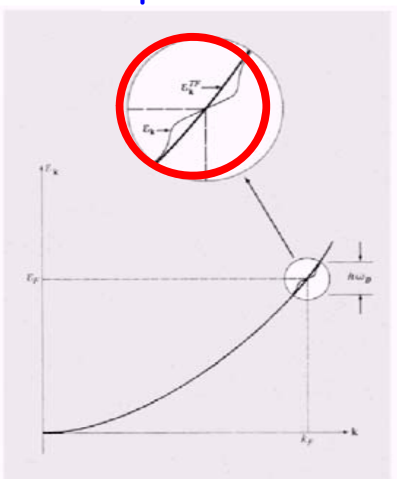
S. Aizaki, T. Y. *et al*. PRL '12.

**$SrVO_3$**



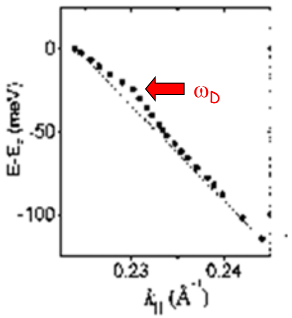
# Electron-phonon interaction

**Band dispersion**



**Ashcroft, Mermin**
***"Solid State Physics"***

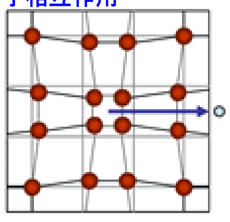
ARPES



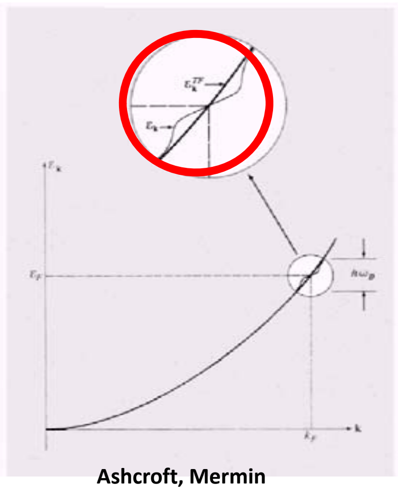

**Mo(110)**

T. Valla *et al.* *PRL*83, 2085 (1999)

電子-格子相互作用

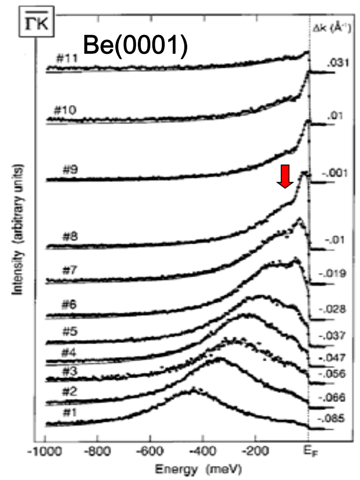


# Electron-phonon interaction



**Ashcroft, Mermin**
***"Solid State Physics"***

ARPES



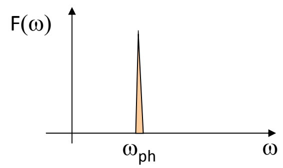

Hengsberger *et al.* **83**, 592 (1999)

## Model of Self-energy

$$\Sigma = \Sigma(el-ph) + \Sigma(el-el) + \Sigma(el-imp)$$

**Einstein model**

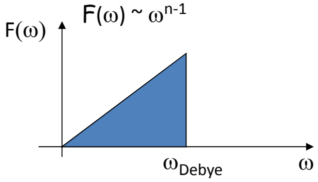
$F(\omega) \sim \delta(\omega - \omega_o)$

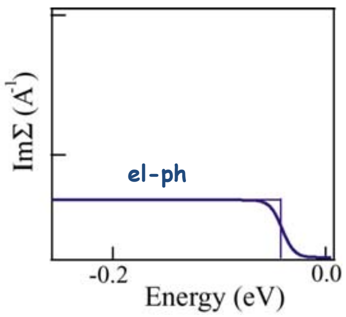



$$\mathrm{Im}\sum_{el-ph}(\omega) = \pi\hbar\int_0^{\omega}\alpha^2 F(\omega')d\omega'$$

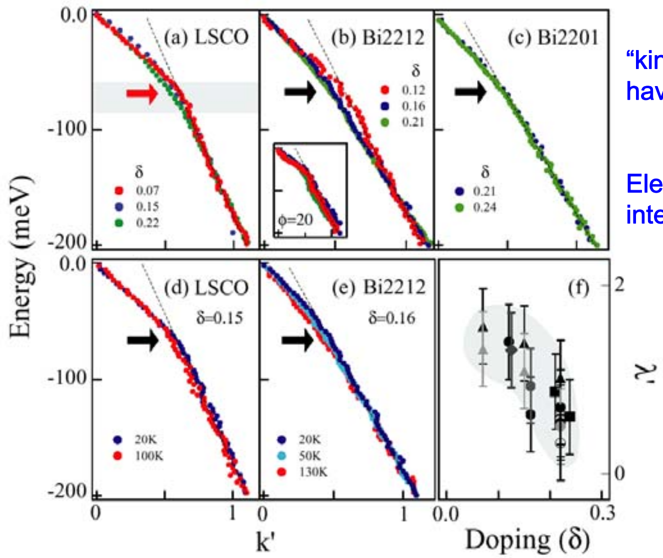
**Debye model**

$F(\omega) \sim \omega^{n-1}$




## Quasi-particle structure of high-Tc cuprates




"kink" in band dispersions have been observed.

Electron-phonon interaction ?

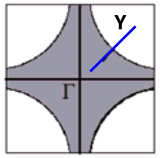
A. Lanzara *et al*. Nature 2001

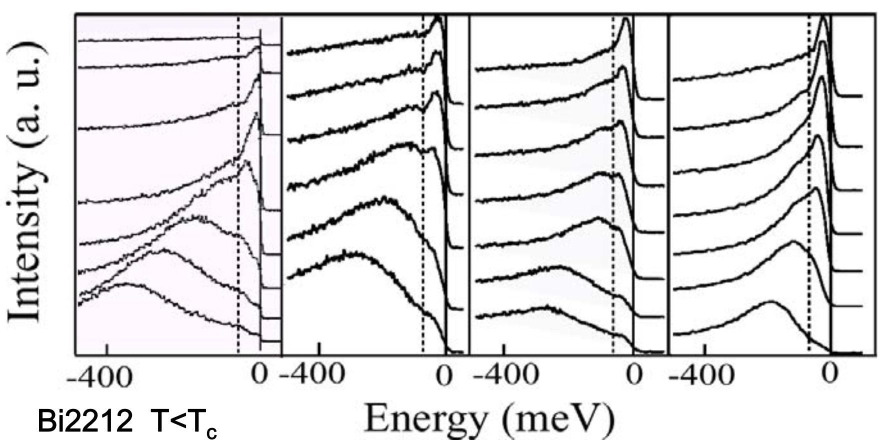
## Quasi-particle structure of high-Tc cuprates

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

"Dip" structure in spectra.

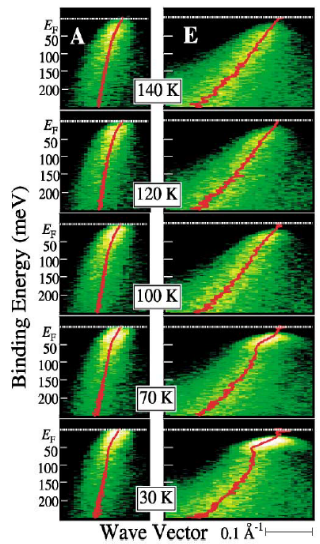
Electron-phonon interaction?

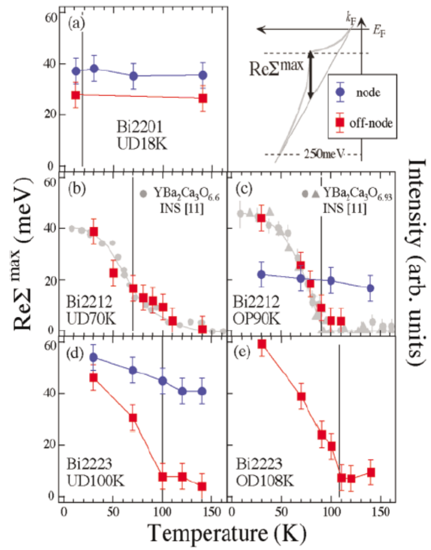



Bi2212 $T<T_c$

## Origin of kink: Spin fluctuations?




T. Sato et al. PRL 03'