The KITS 2017 Forum
New Horizons in Condensed Matter Physics
27-29 March 2017, Beijing, China

Scanning Tunneling Spectroscopy Study of Cuprates and a Topological Superconductor

Dong-lai Feng

Department of Physics, Fudan University

Outline

- ✓ *Cross-Sectional STM Study of $Bi_2Sr_2CaCu_2O_{8+\delta}$ and $YBa_2Cu_3O_{7-x}$*
- ✓ *Nematic (2-fold symmetric) field dependence of the superconducting gap of $Cu_xBi_2Se_3$*

Acknowledgement

- **Fudan STM team: Mingqiang Ren, Yajun Yan, Wei Chen, Chen Chen, Xi Liu, Ran Tao, Tong Zhang**

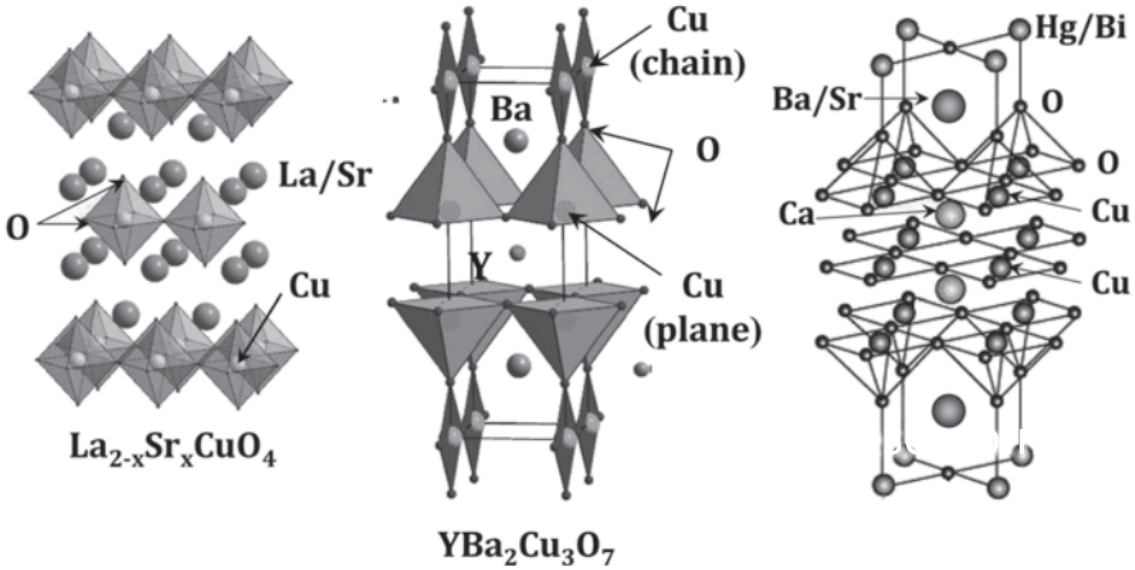
- **Samples: Xin Yao (for YBCO), Hiroshi Eisaki (for Bi2212 and LSCO) Y. Ando ($Cu_xBi_2Se_3$)**

- **Discussions:**
  - **Jiangping Hu, Yan Chen, Tao Xiang, Ruihua He, Darren Peets, Yihua Wang**
  - **Guoqing Zheng, Liang Fu**

Cross-Sectional STM Study of $Bi_2Sr_2CaCu_2O_{8+\delta}$ and $YBa_2Cu_3O_{7-x}$

Cuprates

Crystal structure of cuprates



schematic diagram

charge reservoir

CuO_2 layer

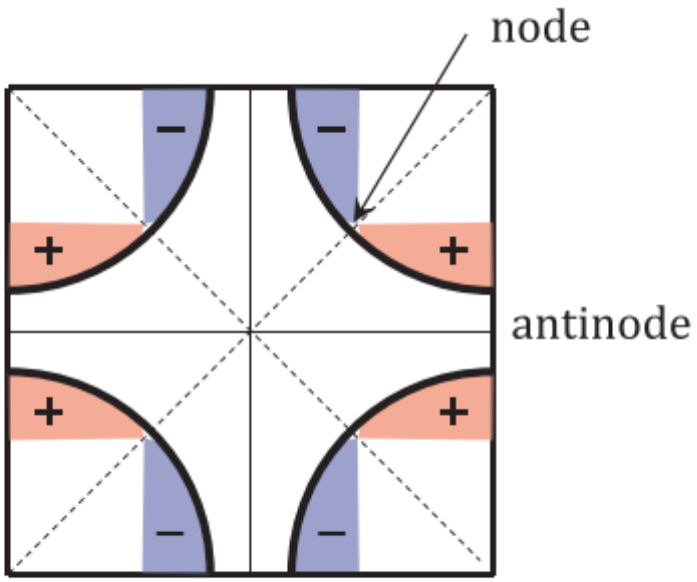
charge reservoir

CuO_2 layer

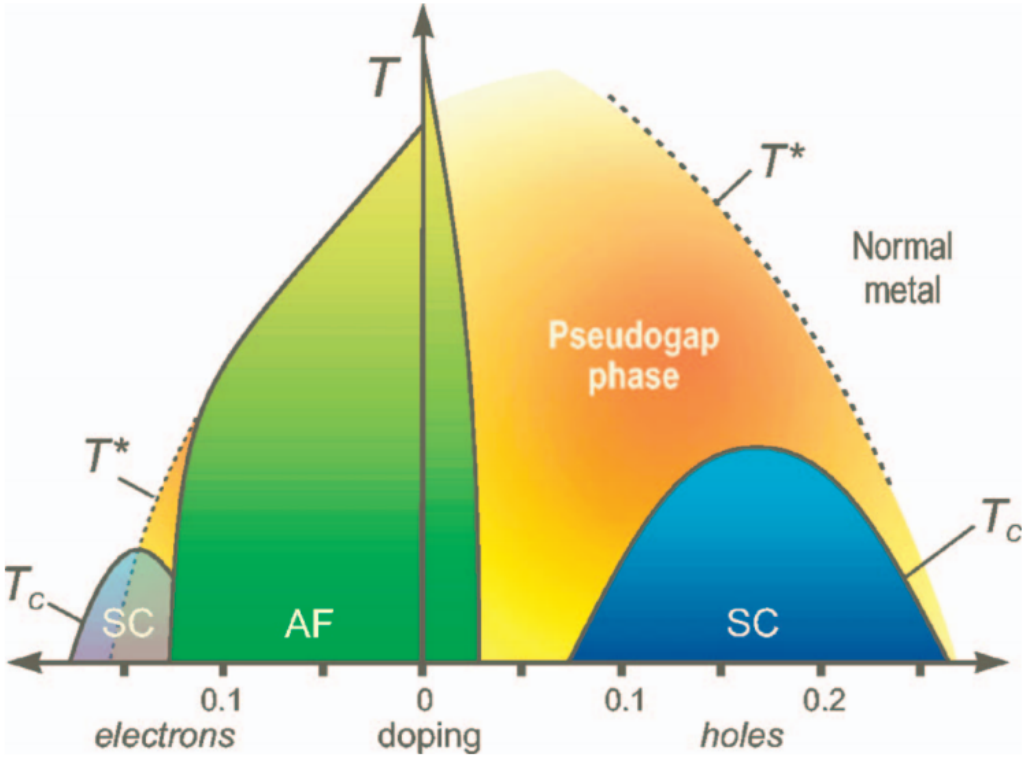
Uchida S I 2015 High Temperature Superconductivity, the Road to High Critical Temperature (New York: Springer)

We are told: The cuprates are made of conducting CuO_2 layers and insulating charge reservoir oxide layers

d –wave gap and pseudogap



$$2\Delta(\boldsymbol{k}) = \Delta_0 \,(\cos k_x a - \cos k_y a)$$



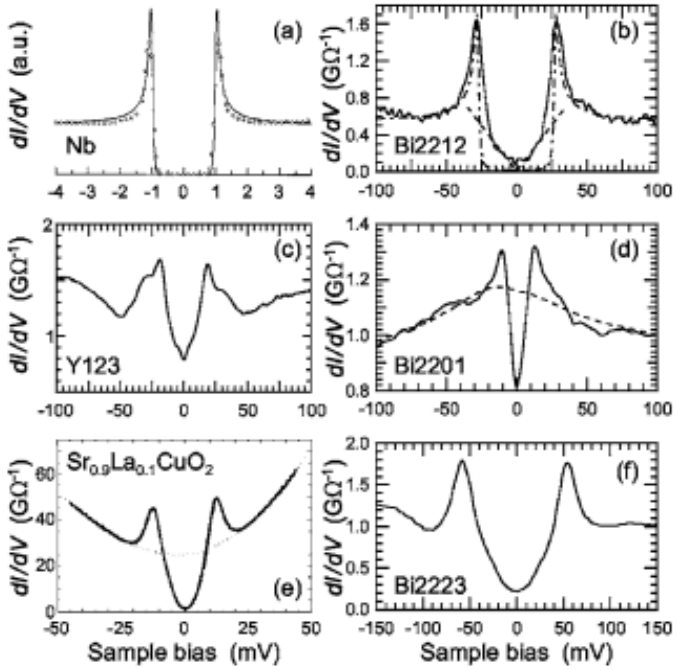
Uchida S I 2015 High Temperature Superconductivity, the Road to High Critical Temperature (New York: Springer)

- the nodal superconducting gap and the pseudogap are critical characteristics of the CuO_2 planes

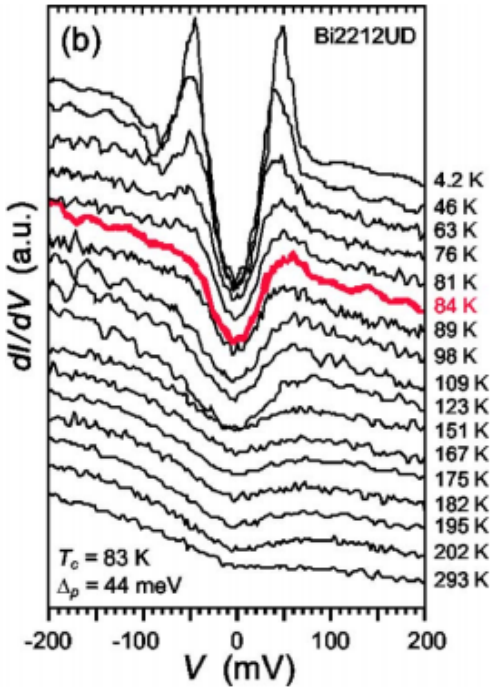
Gap in STS

Spectrum of various cuprates

Optimal doped samples



Under-doped Bi2212

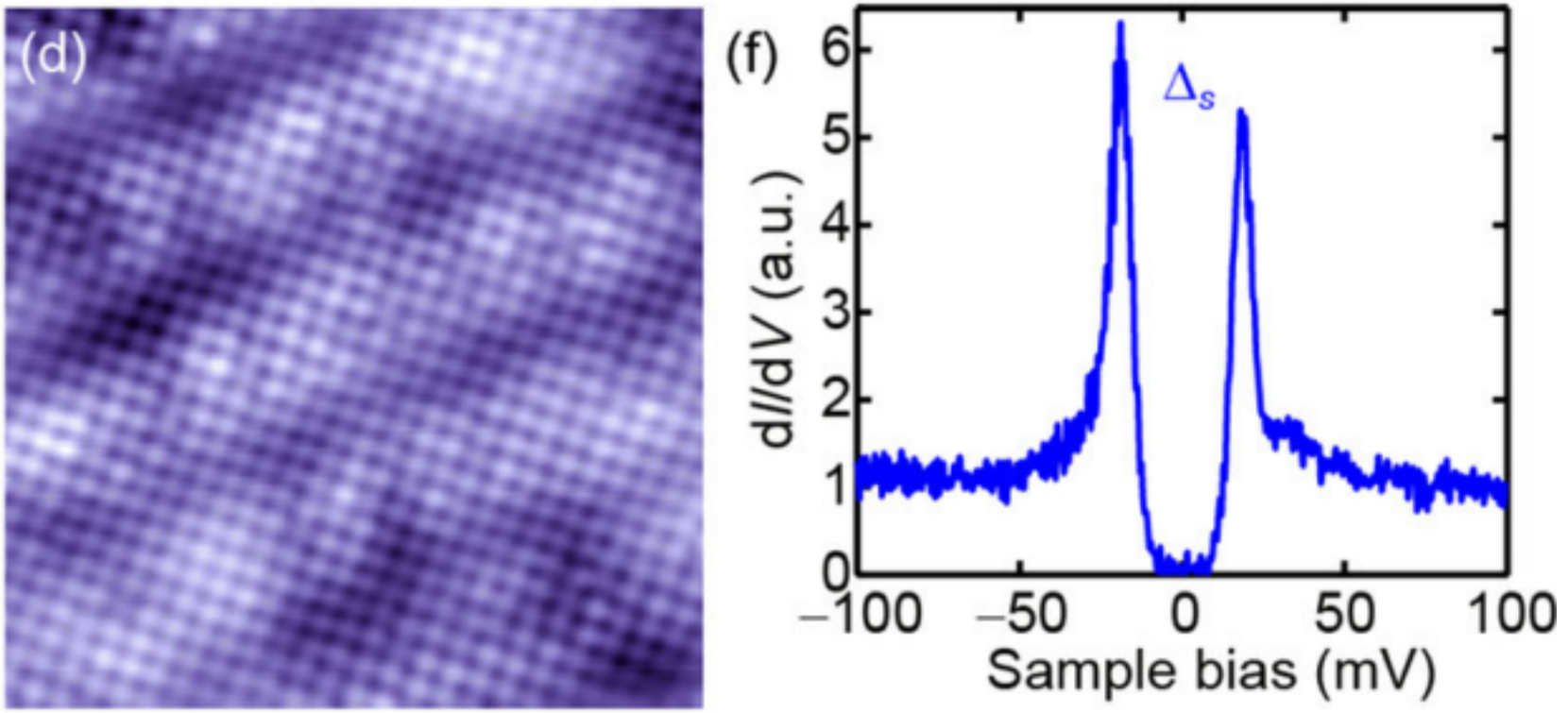


Fischer Ø et al 2007 Rev. Mod. Phys. 79 353

- d-wave nodal superconducting gap behaves as a V-shaped gap and the pseudogap appears as a spectral weight suppression over hundreds of meV in STS.

Possible S-wave Pairing ?

CuO_2 monolayer grown on Bi 2212 substrate



- Pseudogap is inherent to the BiO planes and likely irrelevant to pairing
- CuO_2 films grown on Bi2212 shows a U-shaped gap

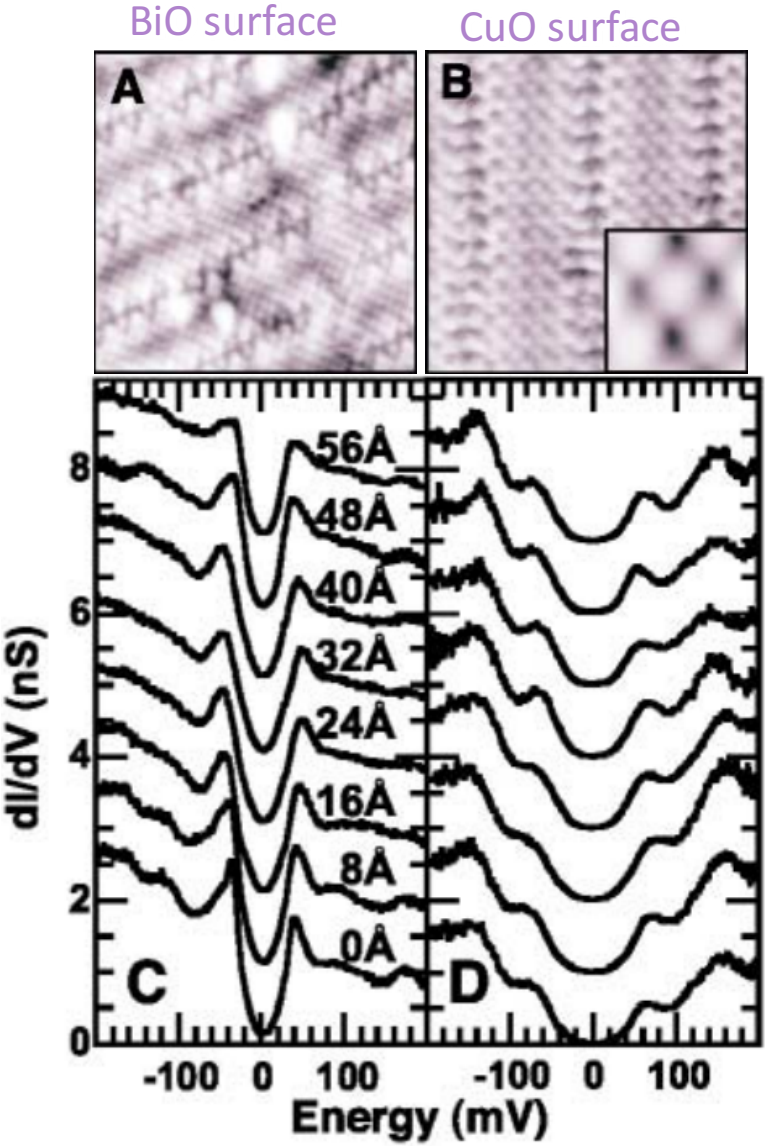
The usual STM and ARPES measurements may contain contributions from both the CuO_2 layers and the charge reservoir layers

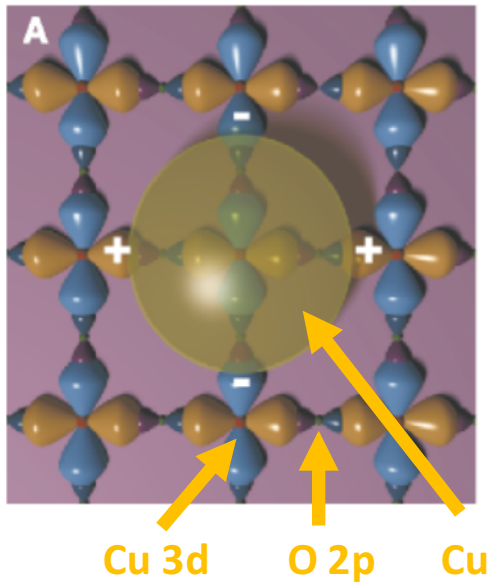
Zhong Y et al 2016 Chin. Sci. Bull. 61 1239
Lv Y F et al 2015 Phys. Rev. Lett. 115 237002
Lv Y F et al 2016 Phys. Rev. B 93 140504

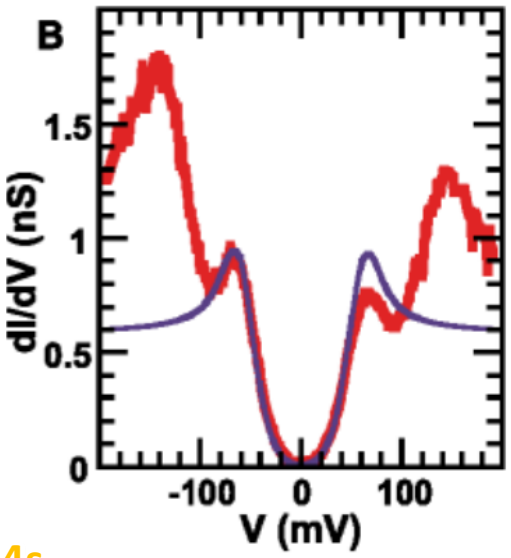
Possible S-wave Pairing ?

Bi2212 thin films (100nm) Tc = 84 K

cleaved mechanically at room temperature in vacuum



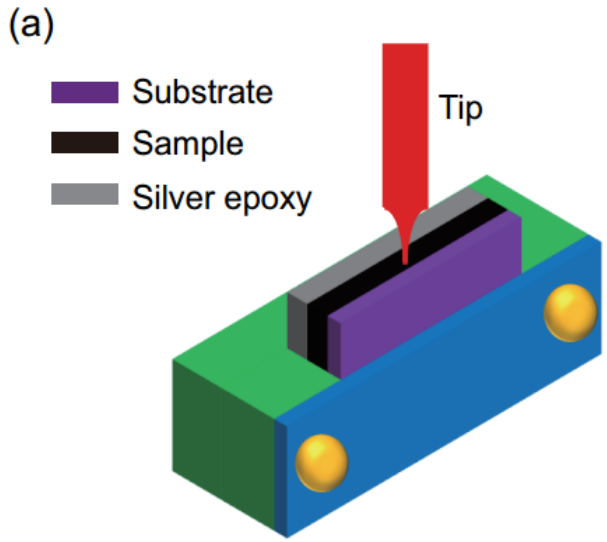




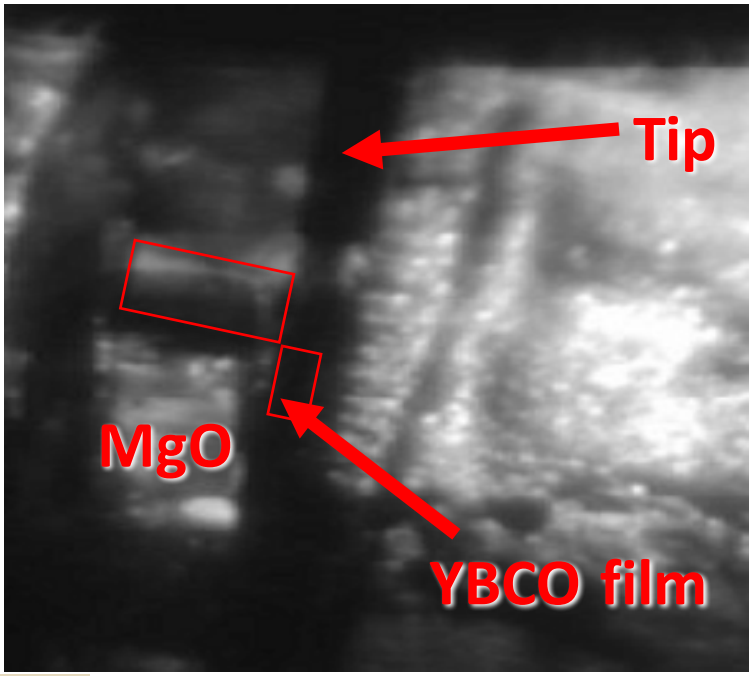
U-gap can be fitted by d-wave pairing considering that the c-axis tunneling is dominated by the $(\pi,0)$ region.

Misra S et al 2002 Phys. Rev. Lett. 89 087002

Experimental Setup



Optical microscope image



Measurement temperature T =4.5K

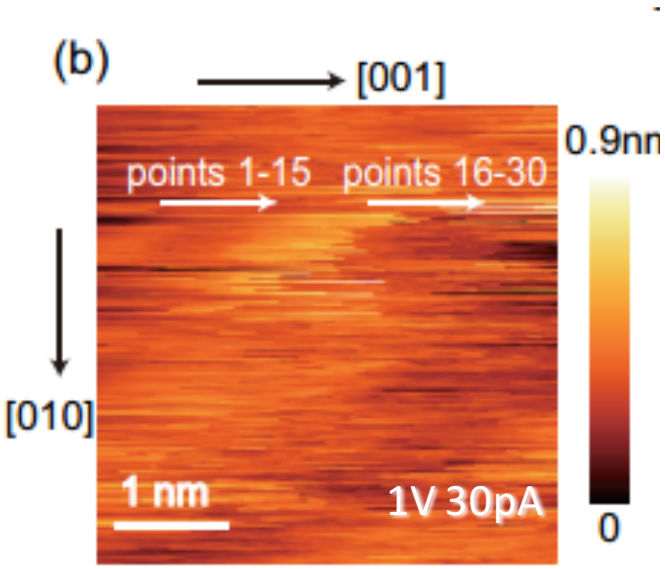
Bi2212: T_c =88K YBCO film （600nm thick）: T_c=88K

Cleavage condition： about 80K in vacuum （1x e^{-10}mbar）

M. Q. Ren, Y. J. Yan, T. Zhang, DLF, CHIN. PHYS. LETT. **33**, 127402 (2016)

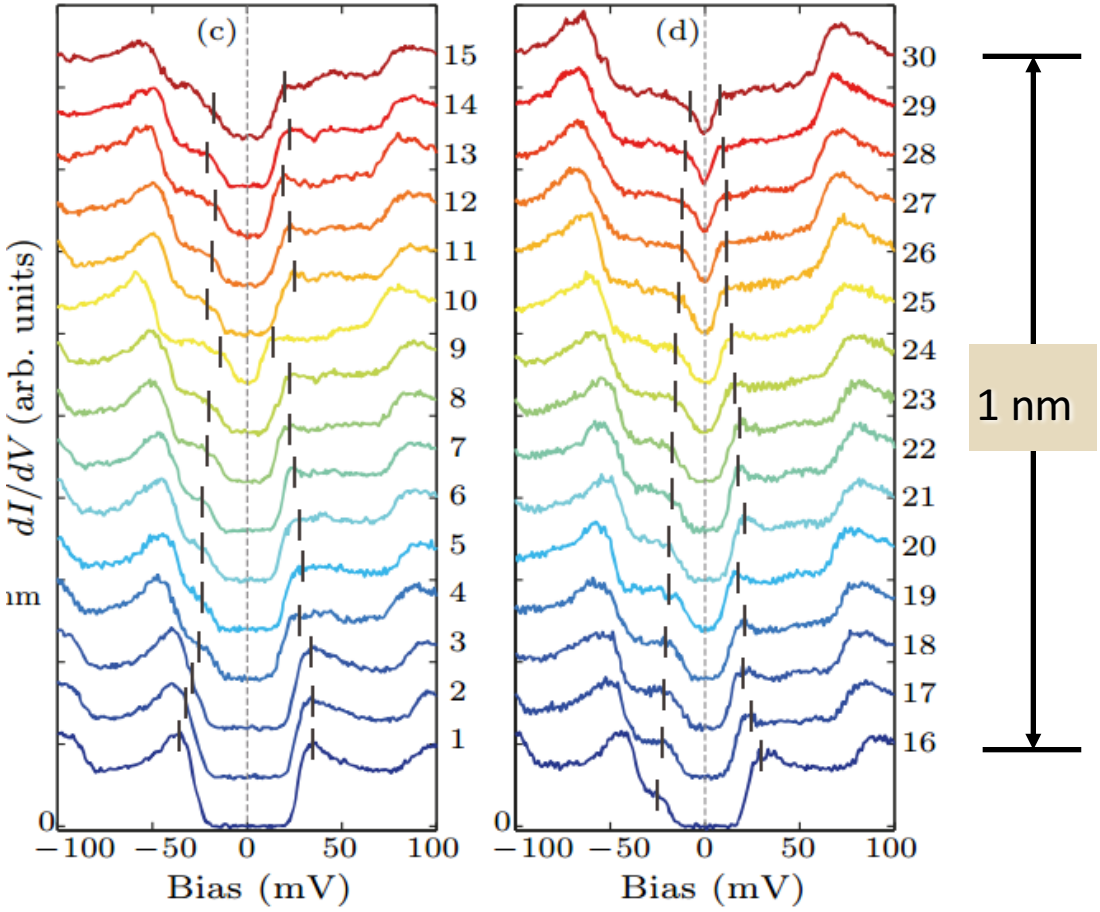
$Bi_2Sr_2CaCu_2O_{8+\delta}$ (100) plane

Bi 2212 single crystal
Tc =88K



- the overall roughness is less than 1 nm
- Tilt from the (100) plane < 7°

Cut along (001) Over 1nm

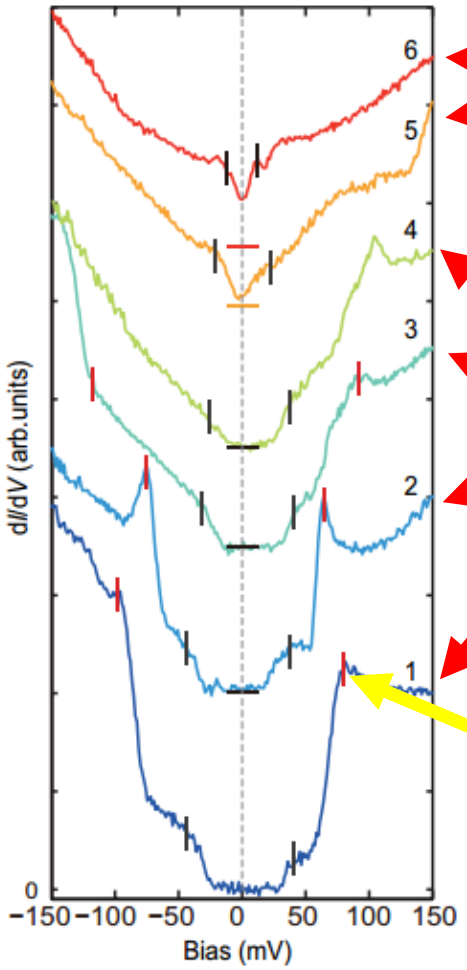


- STS shows strong spatial dependence.
- The U-shaped gap gradually become V-shaped within ~ 1 nm

$Bi_2Sr_2CaCu_2O_{8+\delta}$ (100) plane

Bi 2212 single crystal
Tc =88K

Representative STS spectra



V-shaped gaps

13 -18 meV

U-shaped gaps

a flat bottom

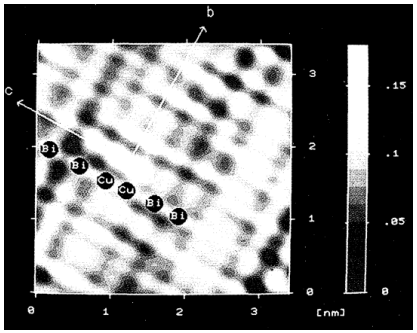
10 -25 meV

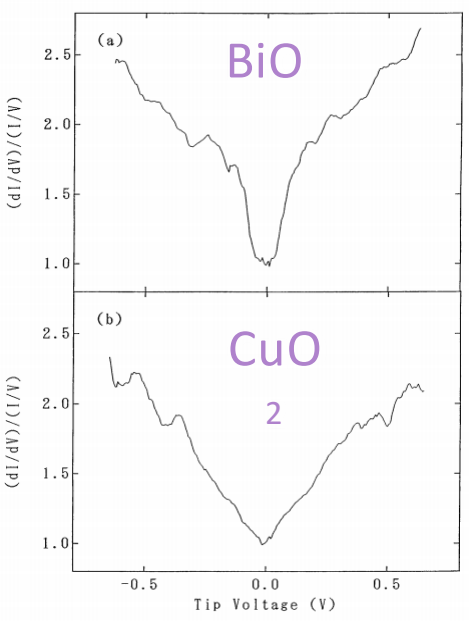
Larger gap?

60 - 90 meV

Early Bi2212 data

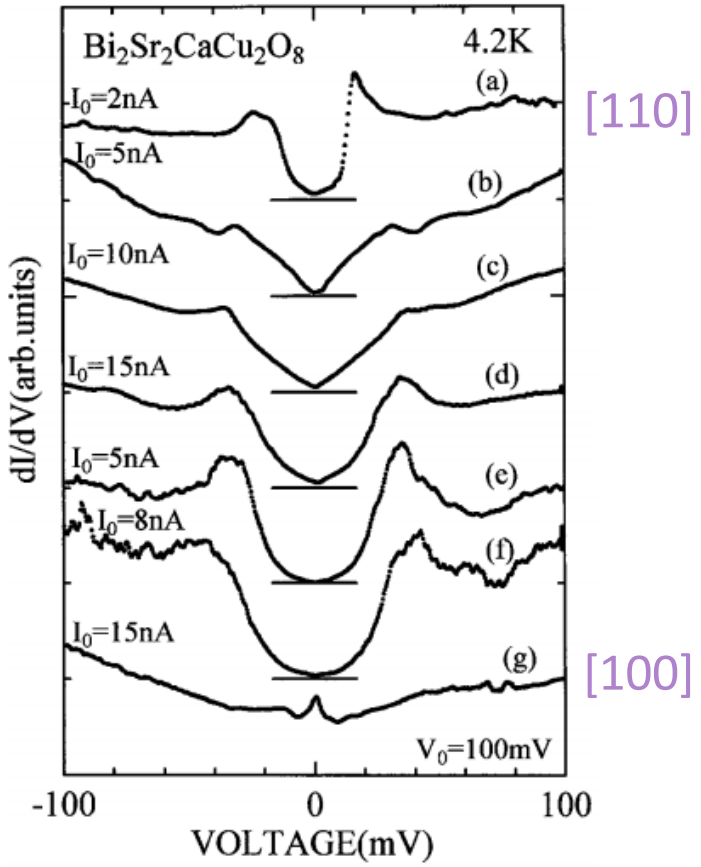
(100) plane of Bi 2212
prepared with diamond-filing in nitrogen





Hasegawa T, Kitazawa K, 1990 Jpn. J. Appl. Phys. 29 L434
Suzuki K et al 1999 Phys. Rev. Lett. 83 (3) 616-619

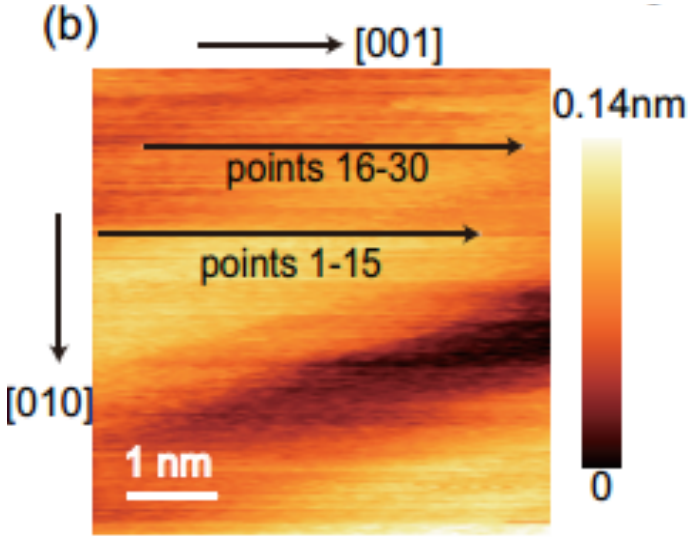
(h,k,0) plane of Bi 2212
prepared with razor blade in air



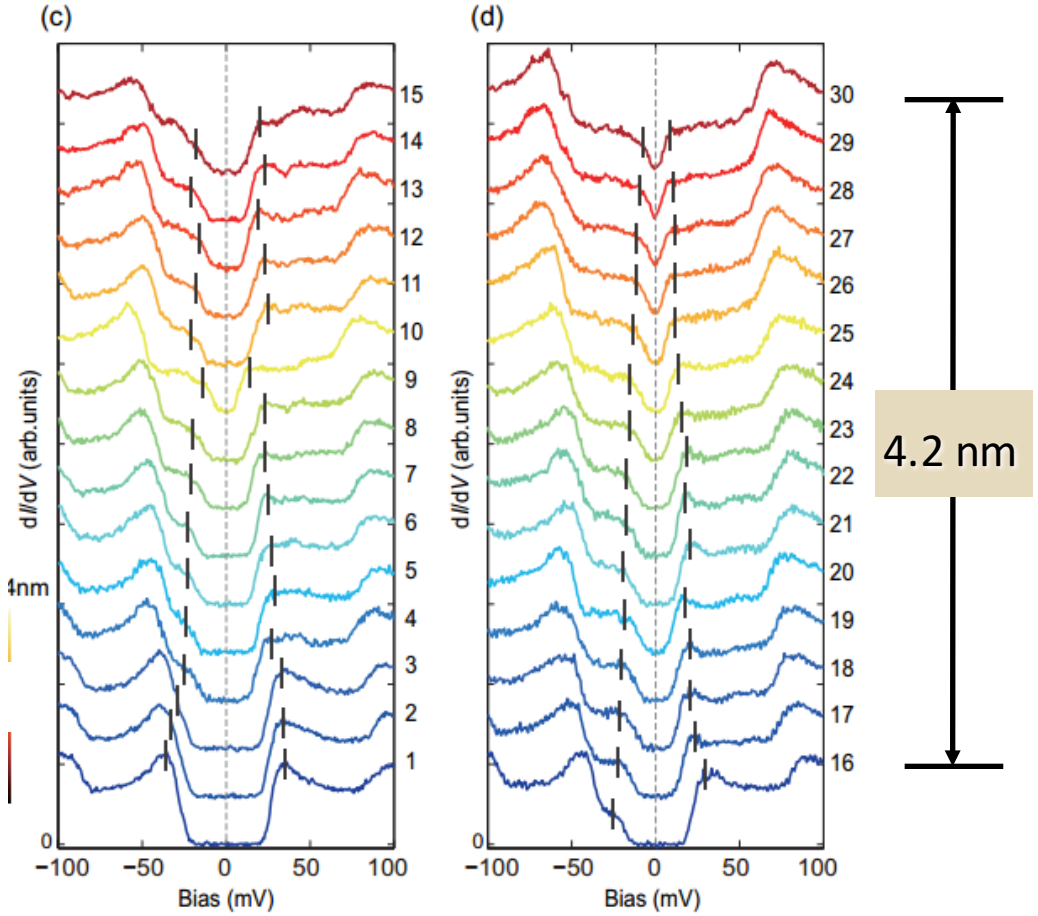
- Previous STM experiments did not observed the U-shaped gap on Bi2212.
- Difference: their samples were prepared outside the vacuum.

$YBa_2Cu_3O_{7-x}$ (100) plane

YBCO thin film grow on MgO
Thickness: 600 nm
Tc =88K



Cuts along [001] direction
Spatial distance : 0.3 nm

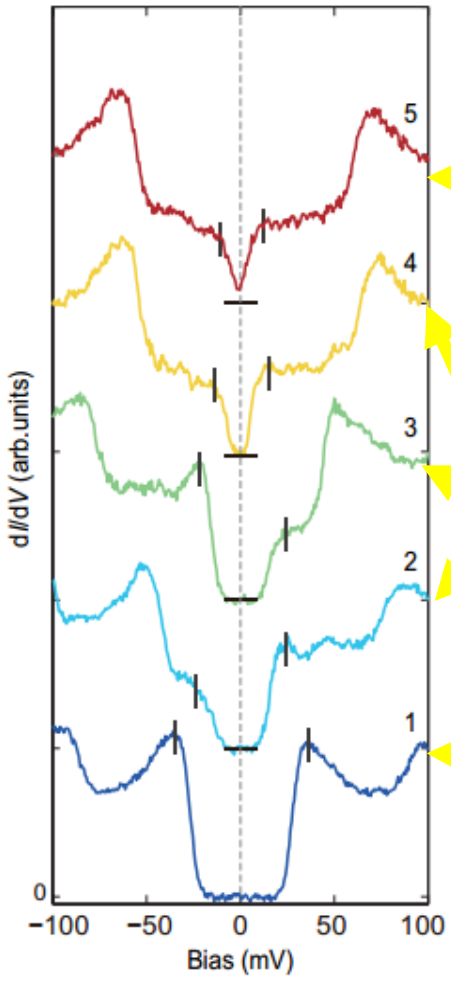


- STS shows strong spatial dependence.
- The U-shaped gap gradually becomes V-shaped.

$YBa_2Cu_3O_{7-x}$ (100) plane

YBCO thin film grow on MgO
Thickness: 600 nm
Tc =88K

Representative STS spectra



V-shaped gap

8 - 10 meV

Smaller U-shaped gap

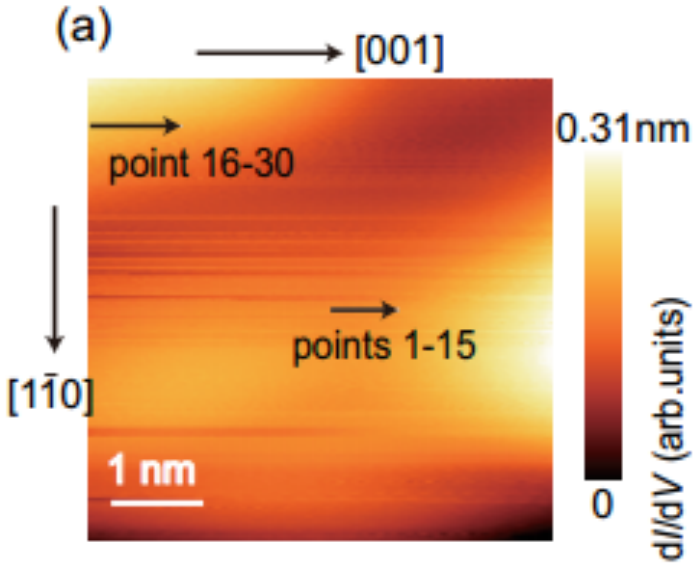
10 - 35 meV

Well defined U-shaped gap

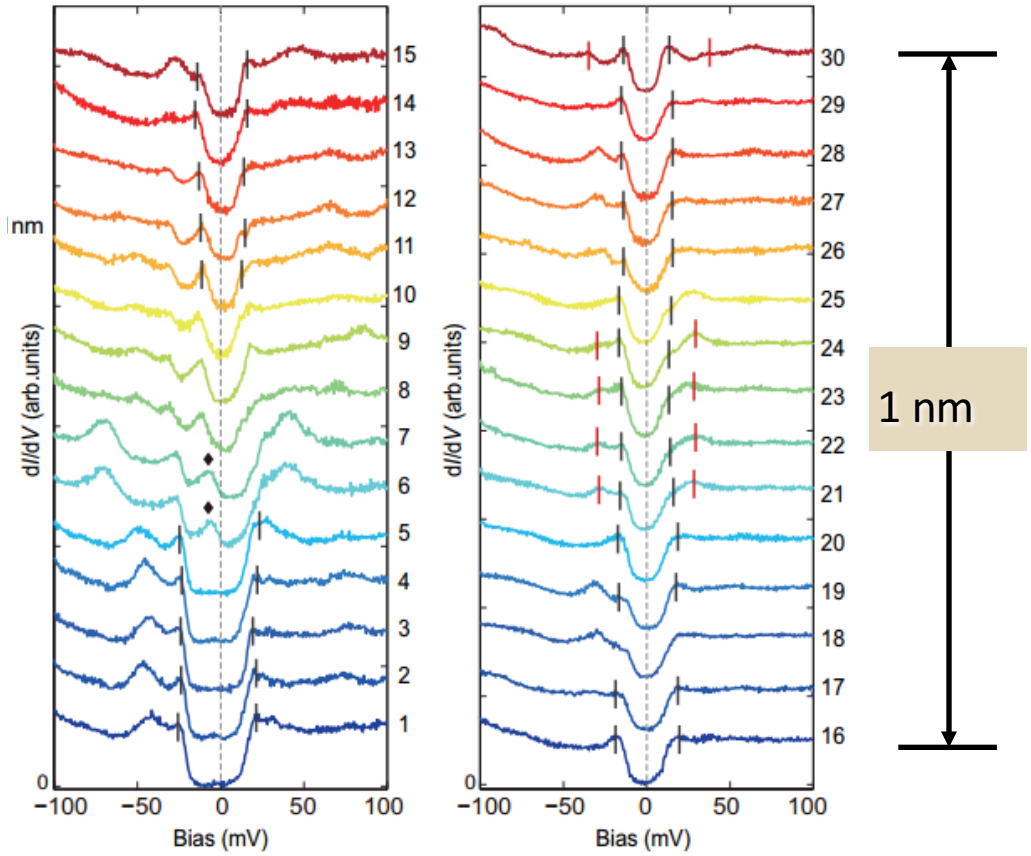
35 meV

$YBa_2Cu_3O_{7-x}$ (110) plane

YBCO thin film grow on MgO
Thickness: 600 nm
Tc =88K



Cuts along [001] direction
Spatial distance ： 0.7 Å

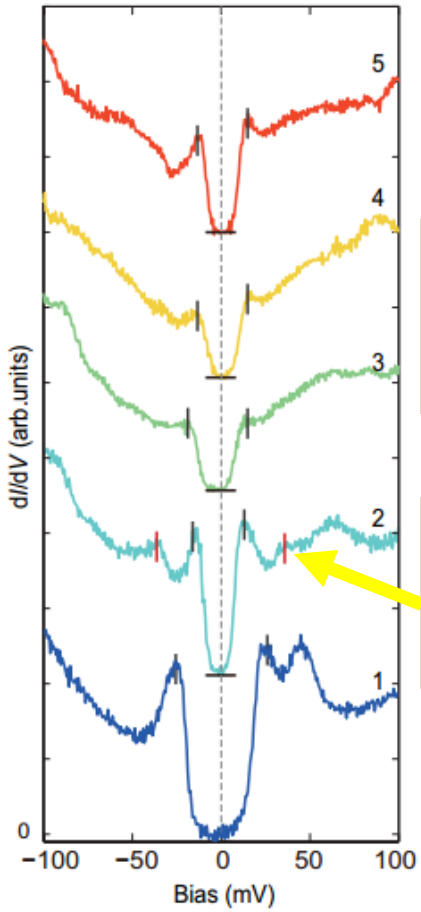


- Well defined U-shaped gap with coherent peaks
- The gap size varies in space
- The maximum gap size on the (110) plane is reduced, compared with that on the (100) plane

$YBa_2Cu_3O_{7-x}$ (110) plane

YBCO thin film grow on MgO
Thickness: 600 nm
Tc =88K

Representative STS spectra



U-shaped gap

10 - 25 meV

double superconducting gap ?

bosonic modes?

Observations:

- The low-energy electronic structure of both Bi2212 and YBCO is strongly spatially dependent.

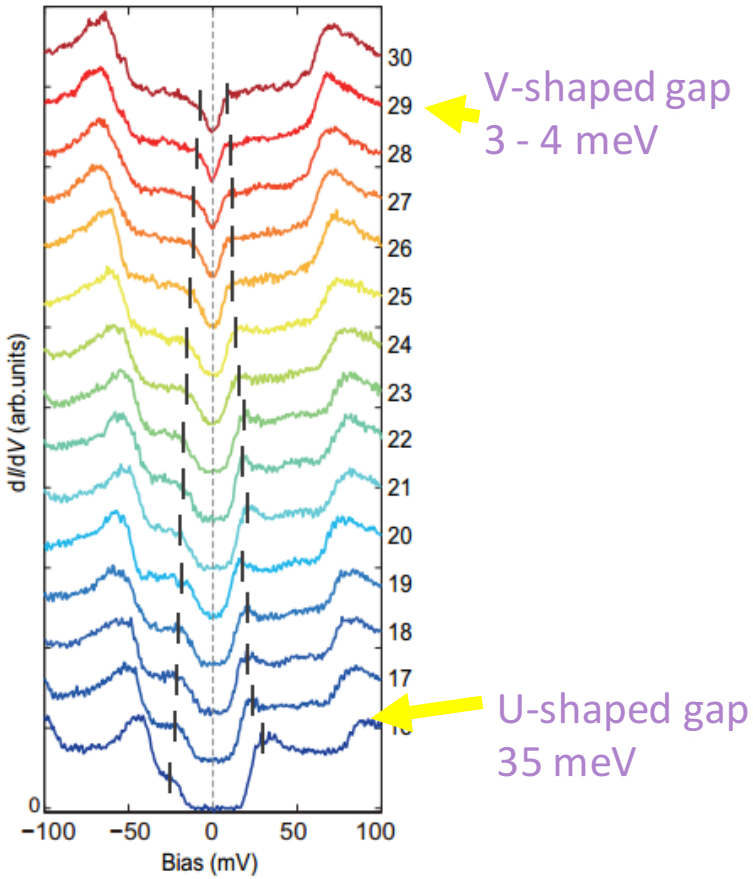
- There are generally two types of gaps: well defined U-shaped gap and small V-shaped gap

Open issues:

- Need atomically resolved cross-sectional images
- The effects of tunneling matrix elements
- Complexity of polar surface
- … …

A possibility: proximity effects

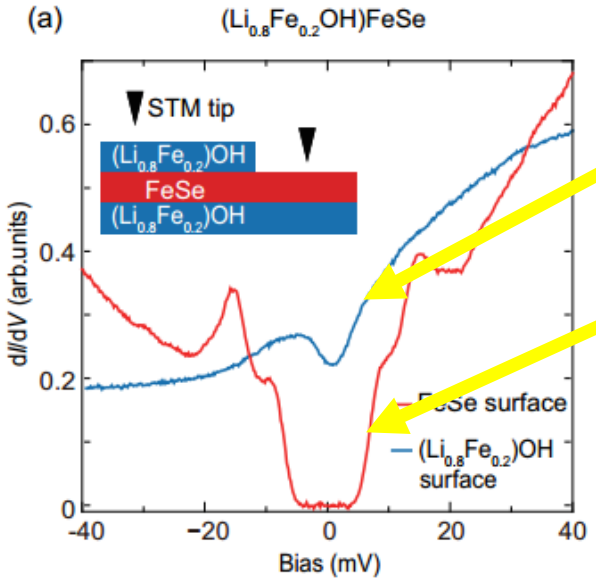
From YBCO (100) plane



V-shaped gap
3 - 4 meV

U-shaped gap
35 meV

STS on different layers of $(Li_{0.8}Fe_{0.2})OHFeSe$



V-shaped gap
3 - 4 meV

U-shaped gap
15 meV

Yan Y J et al 2016 Phys. Rev. B 94 134502

- Proximity effect from the superconducting layer (U - shaped gap) to the charge reservoir layers (V - shaped gap)

Simulation of the tunneling matrix element effects

Empirical model based on WKB approximation

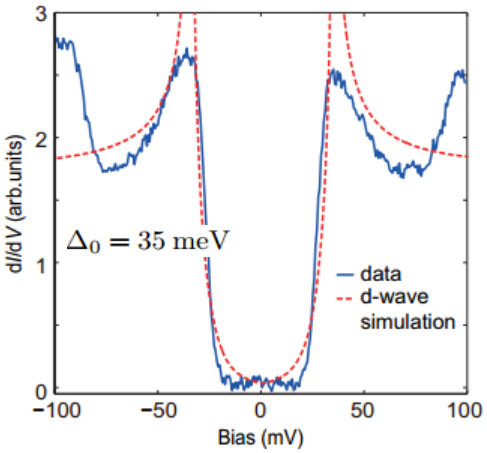
$$\frac{dI}{dV} \propto \int p(\theta)\rho_0(E,\theta)\frac{df(E+eV)}{dV}dEd\theta$$

Tunneling probability: $p(\theta) = \exp[-\beta \sin^2(\theta - \theta_0)]$

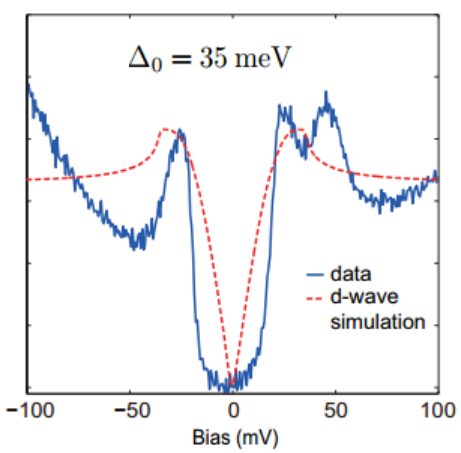
low energy DOS: $\rho_0(E,\theta) = \mathrm{Re}[E/\sqrt{E^2 - \Delta(\theta)^2}]$

gap function: $\Delta(\theta) = \Delta_0 \cos(2\theta)$

YBCO (100) plane



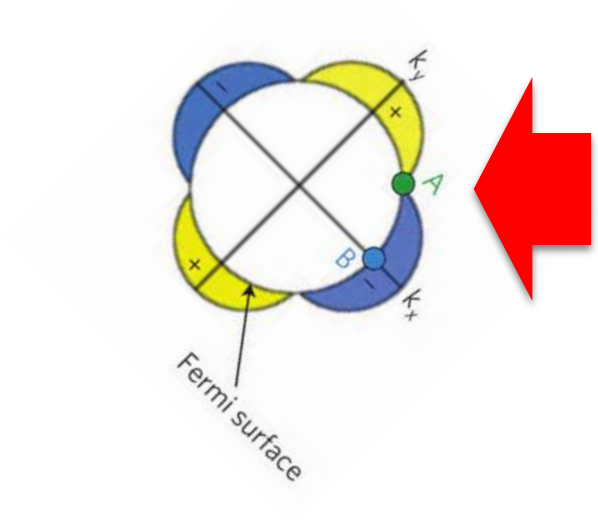
YBCO (110) plane



Simulations based on a *d*-wave gap cannot readily reproduce the measured U-shaped gap

Suzuki K et al 1999 Phys. Rev. Lett. 83 (3) 616-619
E. L. Wolf, Principles of Electron Tunneling Spectroscopy (Oxford University Press, New York, 1989)

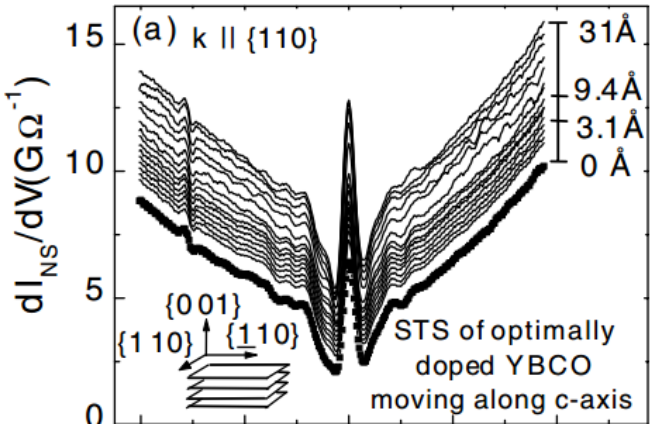
Lack of zero bias peak



- We did not observe a peak at zero bias on cleaved YBCO along the (110) plane
- Maybe due to the different sample preparation and surface conditions ?

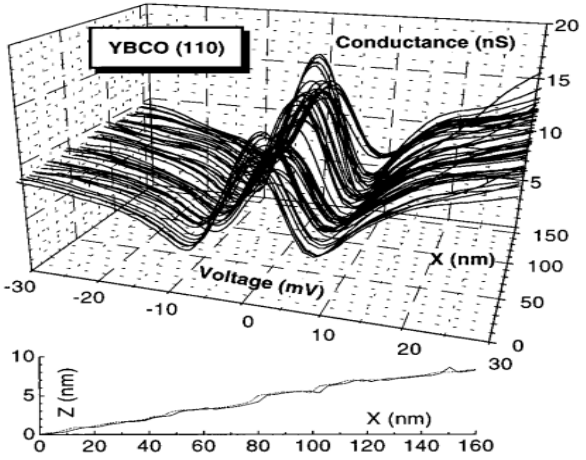
YBCO single crystals with Tc=91K
The surface was prepared by chemical etching

Yeh N C et al 2001 Phys. Rev. Lett. 87 087003



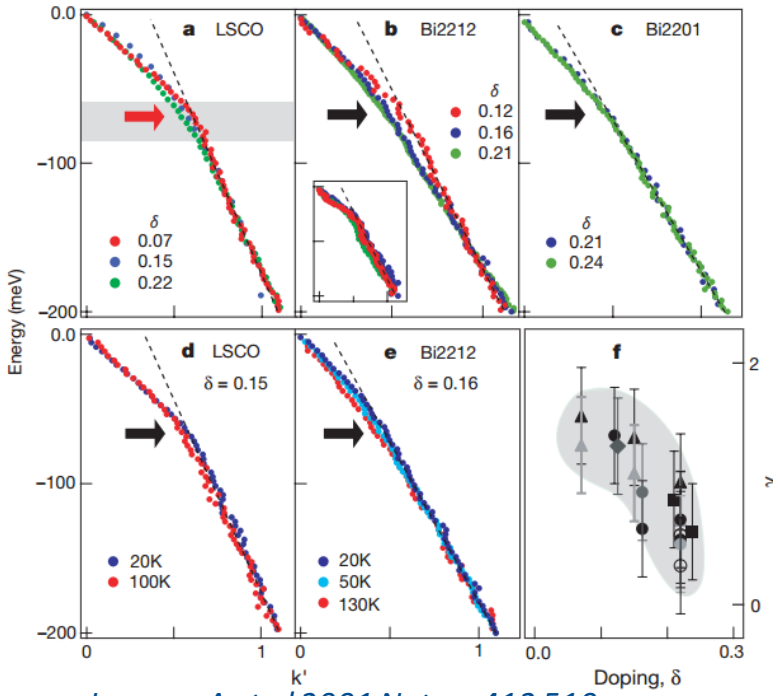
YBCO film (110) plane grown on STO
air-exposure time of about 30 min.

L. Alff et al 1997 Phys. Rev. B 55 R1457



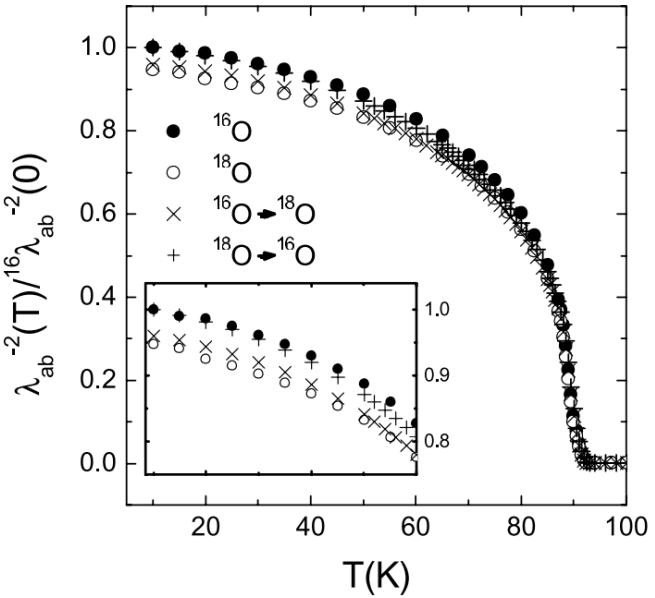
s-wave pairing evidence ?

ARPES study on various cuprates



Lanzara A et al 2001 Nature 412 510

muon-spin rotation study on the nearly optimally doped YBCO



Khasanov R et al 2004 Phys. Rev. Lett. 92 057602

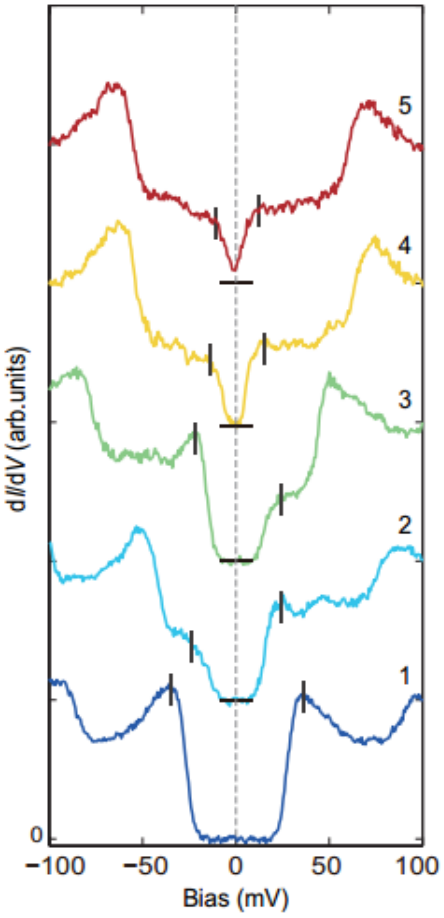
- electron phonon coupling signature in ARPES.
- Isotope effects of the superfluid density

Summary

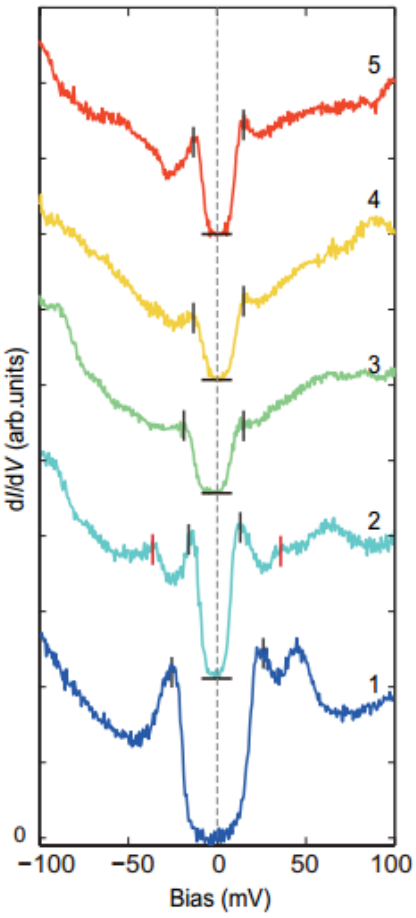
- Electronic states of Bi2212 and YBCO have strong spatial dependence along c.
- U - shaped gap on both YBCO(100) and YBCO (110) plane
- U - shaped gap could not easily understood based on *d* – wave pairing

- V shaped gap maybe in the charge reservoir layers, whose role needs to be checked further.
- There is a long list of experiment supporting d-wave, our findings need further investigations.

YBCO (100) plane



YBCO (110) plane



Nematic (2-fold symmetric) field dependence of the superconducting gap of $Cu_xBi_2Se_3$

Ya-Jun Yan