The KITS 2017 Forum, March 27-29, 2017

# On the pairing mechanism of unconventional high temperature superconductor materials

**Qi-Kun Xue**

**Tsinghua University**

# Acknowledgements

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**ARPES:** Xingjiang Zhou, Hong Ding (IOP), Zhixun Shen (Stanford)

**Optics:** Jimin Zhao (IOP)

**Theory:** Xincheng Xie, Fuchun Zhang (KITP)

**BSCCO Samples:** Genda Gu (Brookhaven)

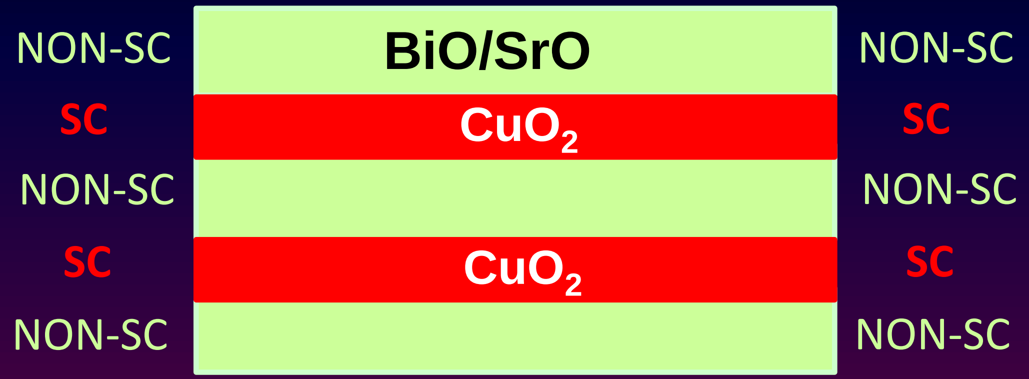
**Financial Supports: NSF, MOST and MOE of China**

*Material View:*
*High-Temperature Superconductivity*

**Layered structure ($Bi_2Sr_2CaCu_2O_{8+\delta}$)**

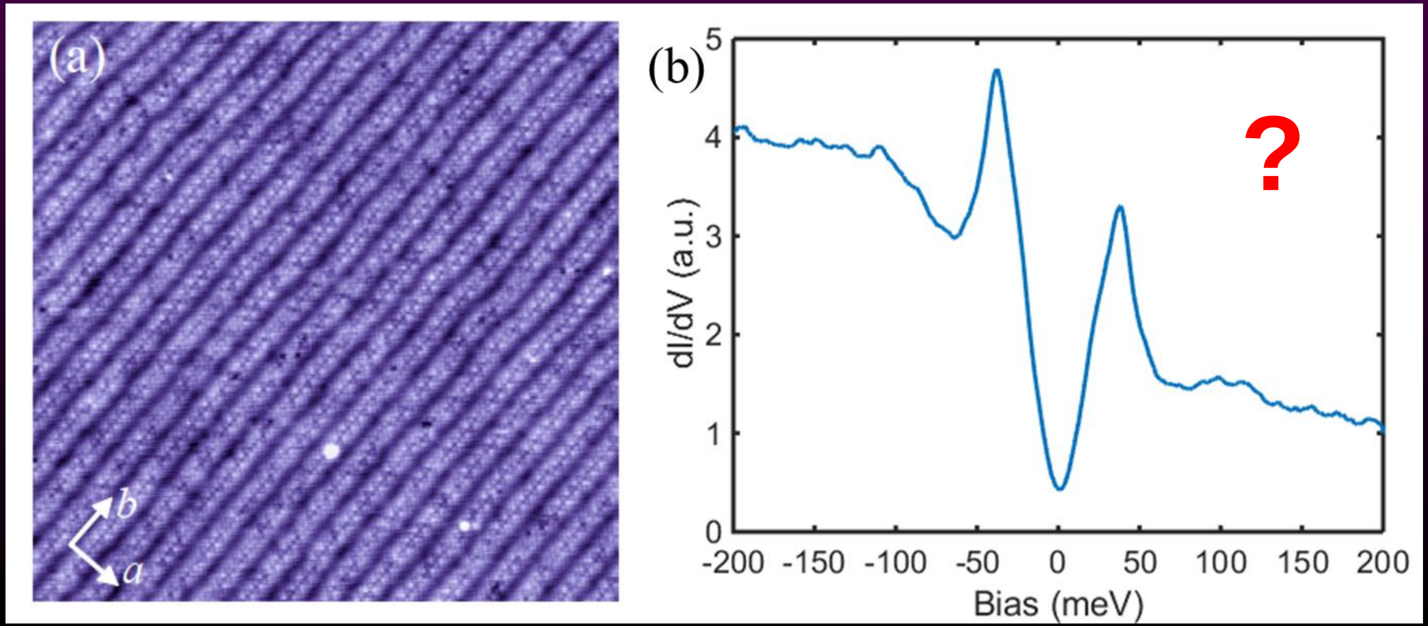
# The most unconventional aspect of HTS

1. Complex layered structure
2. Carrier density in $CuO_2$ (FeAs/FeSe)



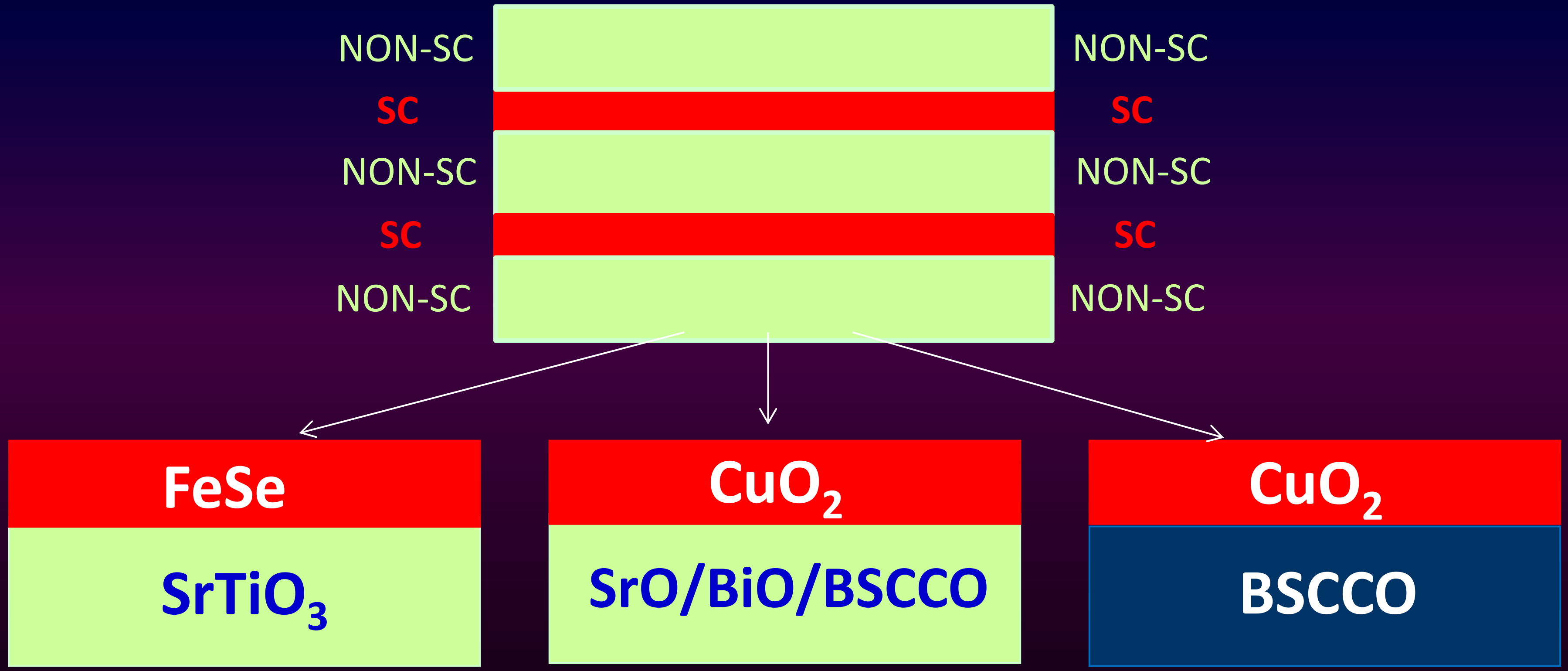

**Bi-2212**

**BiO-terminated surface**



# The most unconventional aspect of HTS

1. Complex layered structure
2. Carrier density in $CuO_2$ (FeAs/FeSe)



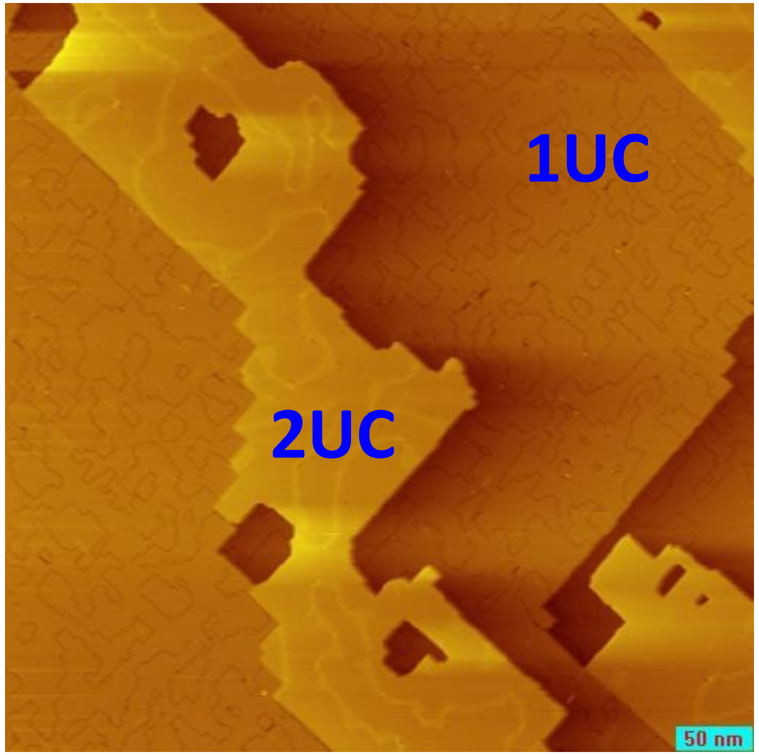

Wang et al., Chin. Phys. Lett. **29**, 037402 (2012)

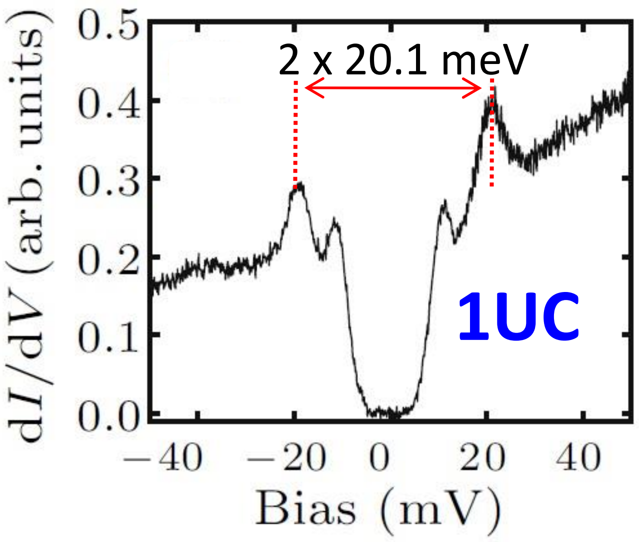
Lv et al., Phys. Rev. Lett. **115**, 237002 (2015)

Zhong and Wang et al., Sci. Bull. 61, 1239 (2016)

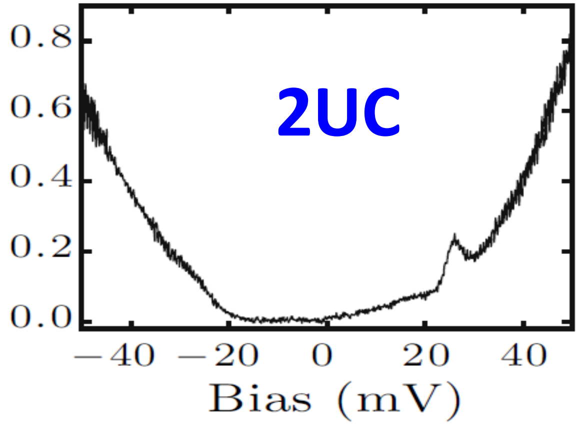
# STM/STS of FeSe on STO

*Q. Y. Wang et al., Chin. Phys. Lett. 29, 037402 (2012)*




**Δ = 20.1 meV**

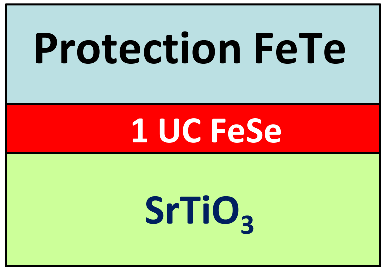


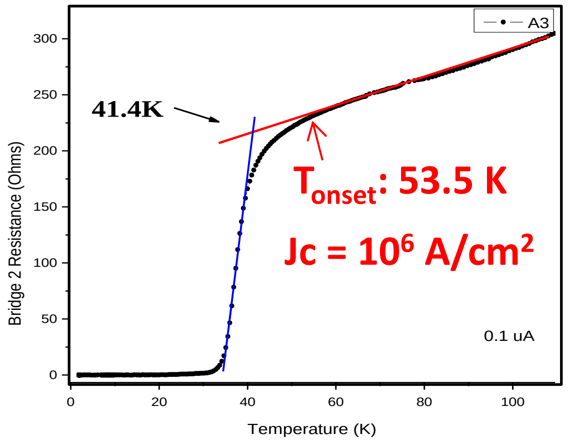

**2UC is not superconducting**

# Monolayer FeSe on STO: Tc ~ 65 K - 100 K

**My group: Chin. Phys. Lett. 29, 037402 (2012)**

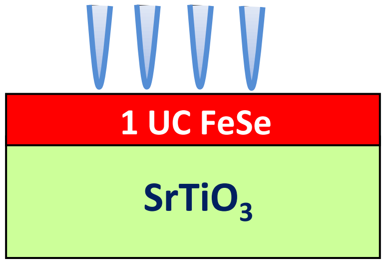
### *Ex situ* transport

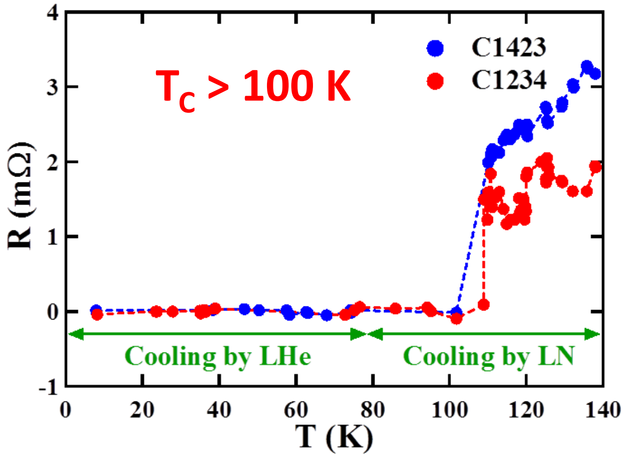



**Q. K. Xue, Jian Wang (PKU): Chin. Phys. Lett. 31, 017401(2014)**

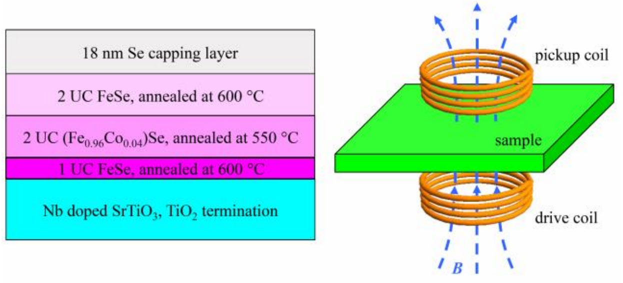
### *In situ* 4PP

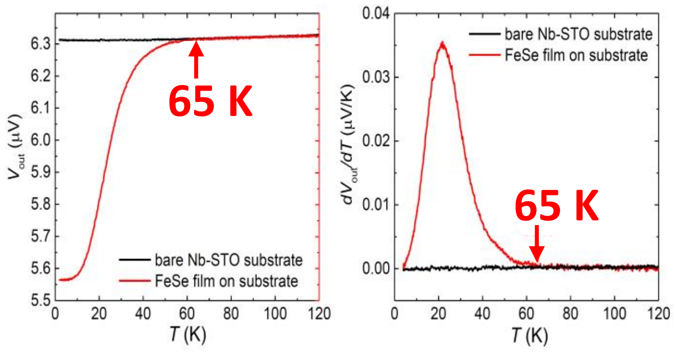



**Jinfeng Jia: Nat. Mater. 14, 285 (2015)**

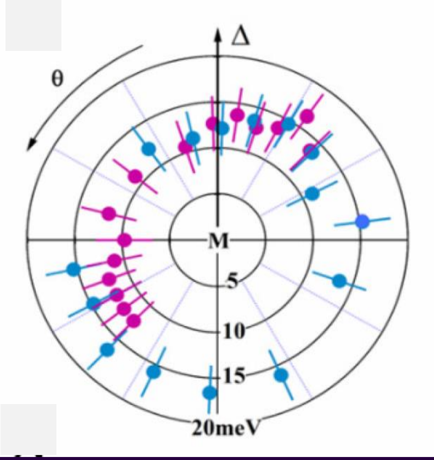
### Two-coil mutual inductance



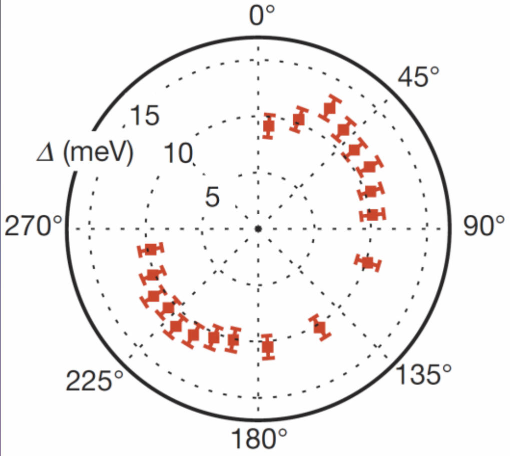




**Yayu Wang, D. L. Feng, K. A. Moler: Sci. Bull. 2016**

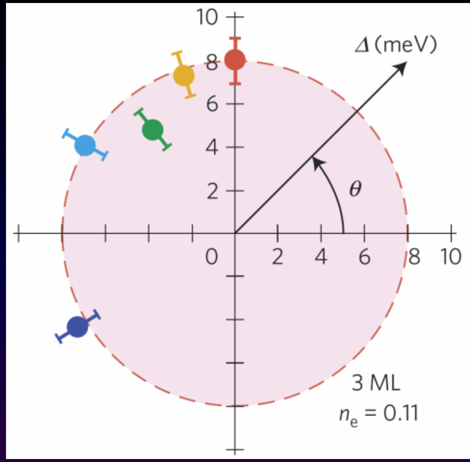
# Gap Symmetry & Tc by ARPES: Isotropic



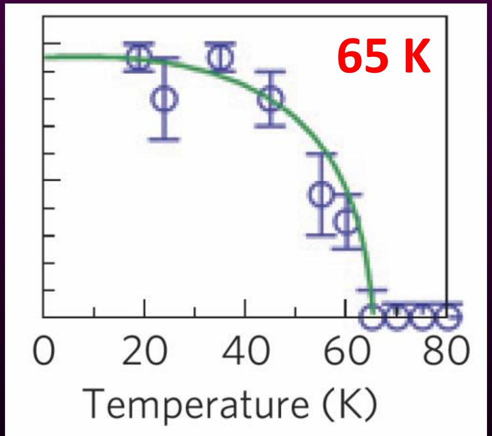

Xingjiang Zhou
*Nat. Mater. 2013*



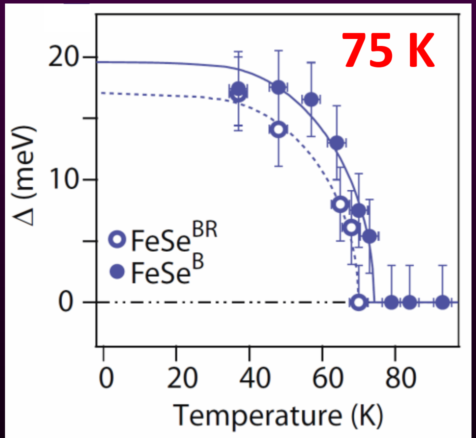

Z. X. Shen
*Nature 2014*




Prof. Takahashi
*Nat. Mater. 2015*



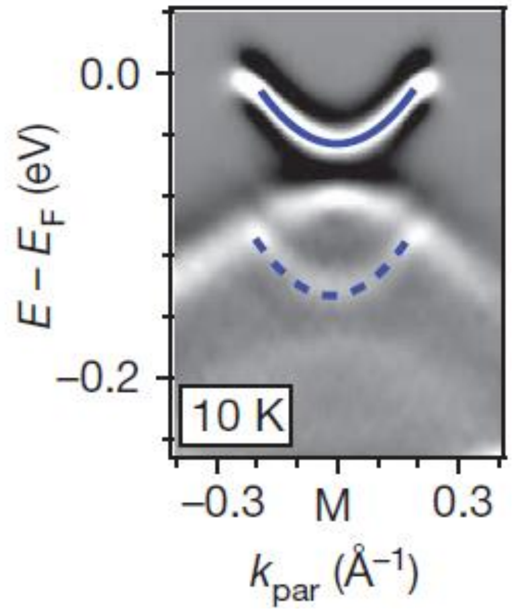

Xingjiang Zhou
*Nat. Comm. 2012*




Donglai Feng
*Nat. Mater. 2013, PRL 2014*

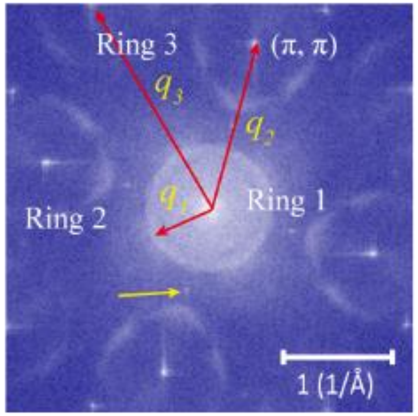
- **Gap closing T follows the BCS theory with $2\Delta_0/k_BT_C$ = 6 (SC gap)**
- **Tc: close to 77 K**

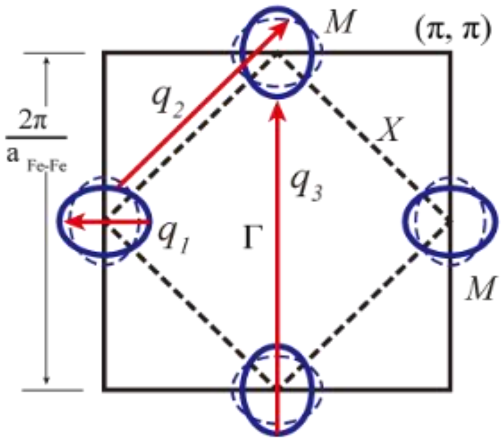
# Plain s-wave pairing + electron-phonon coupling



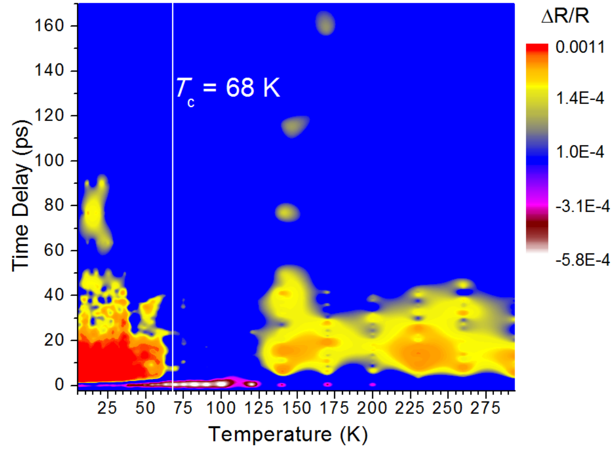

Z. X. Shen & D. H. Lee
Nature 515, 245 (2014)

FFT (B=0)



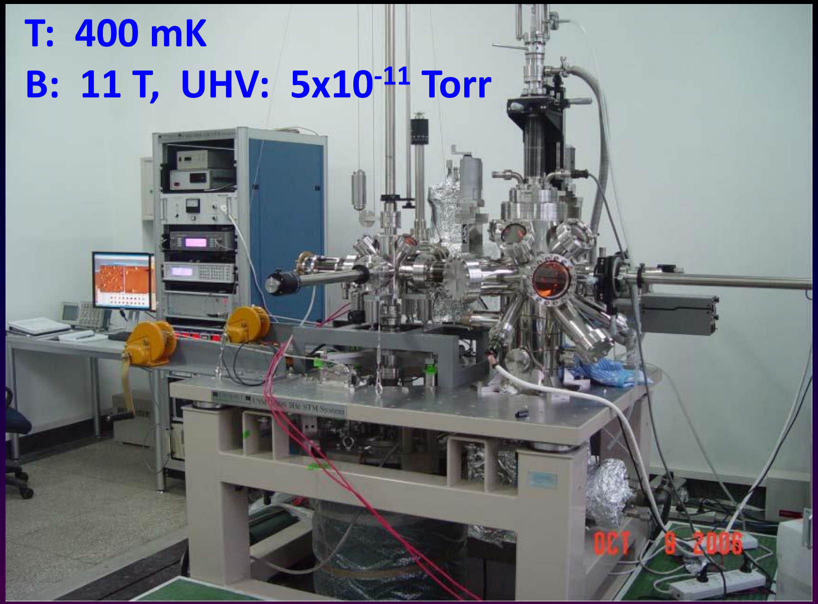




T. Zhang & D. L. Feng
Nature Physics 11, 946 (2015)



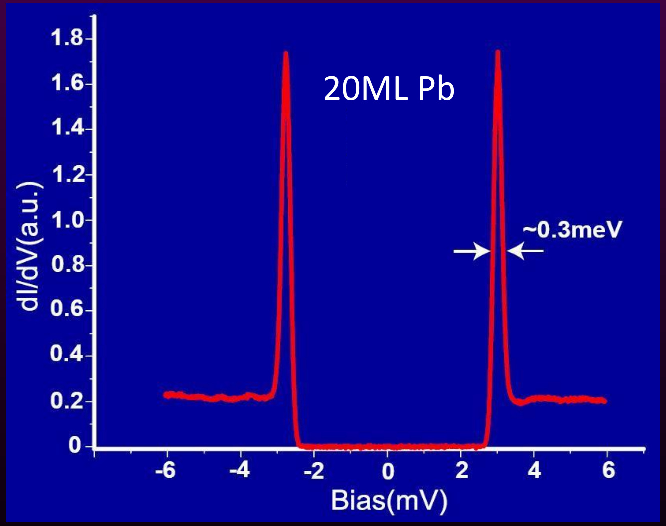

Jimin Zhao
PRL 116, 107001 (2016)

# Ozone-assisted MBE growth of $CuO_2$ films on Bi-2212





*Zhong and Wang et al., Sci. Bull. 61, 1239 (2016)*




*Ji et al., PRL 100, 226801 (2008)*

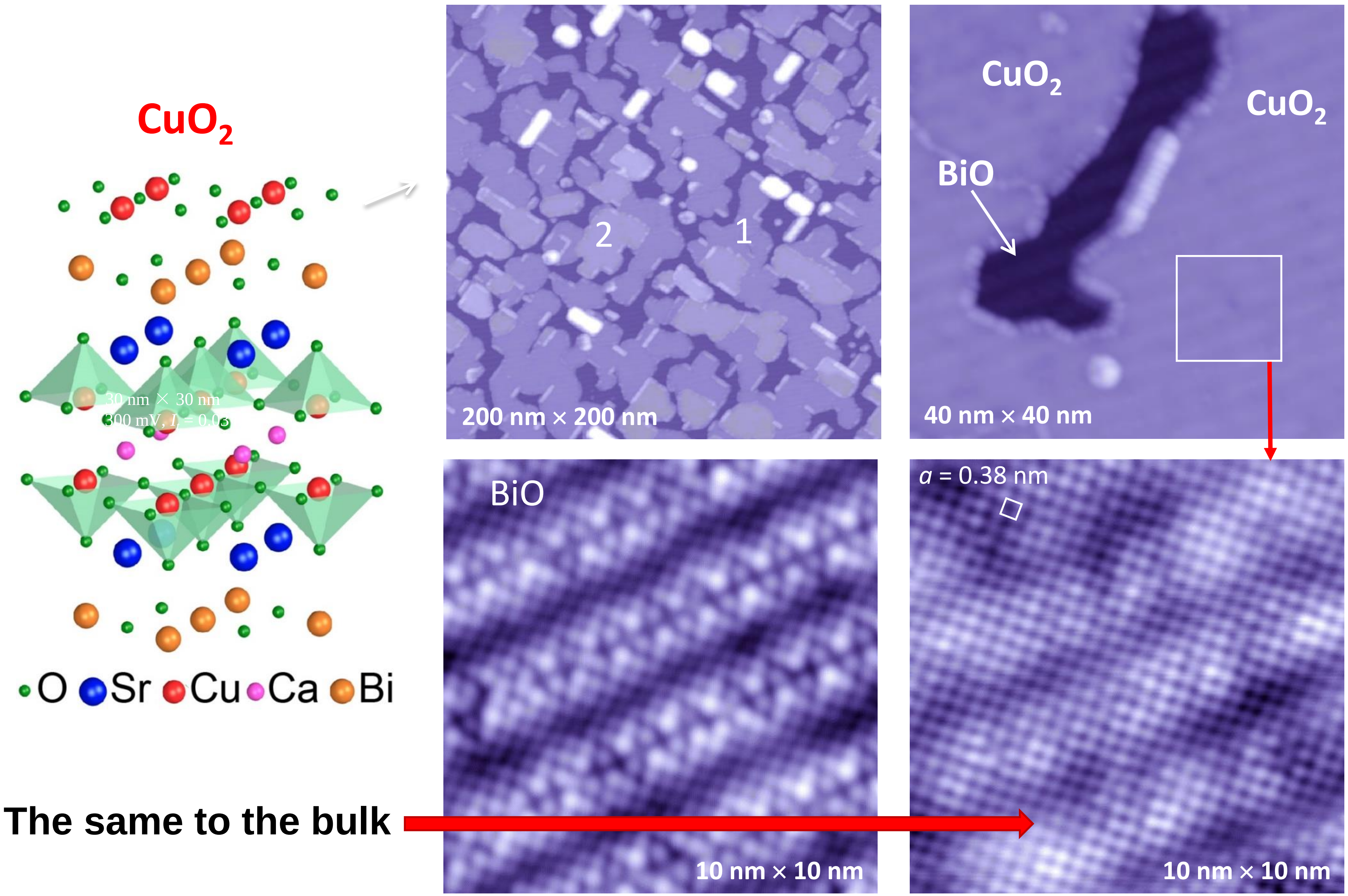
Bi-2212 surface: UHV cleaving

$CuO_2$ growth:

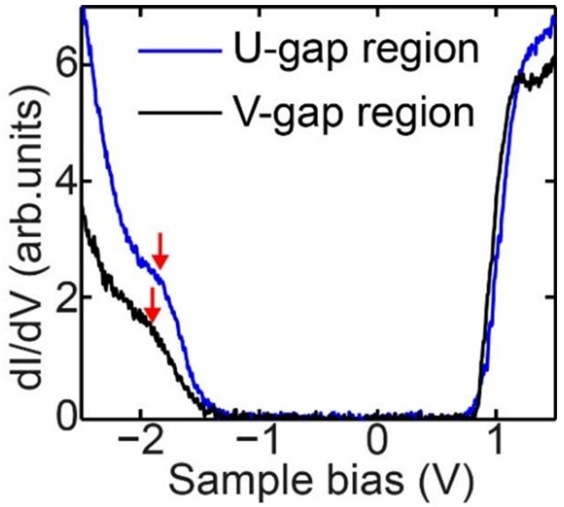
Cu: 99.9%

Ozone flux: $1.0 \sim 5.0 \times 10^{-5}$ Torr

# MBE growth of $CuO_2$ films on $Bi_2Sr_2CaCu_2O_{8+\delta}$



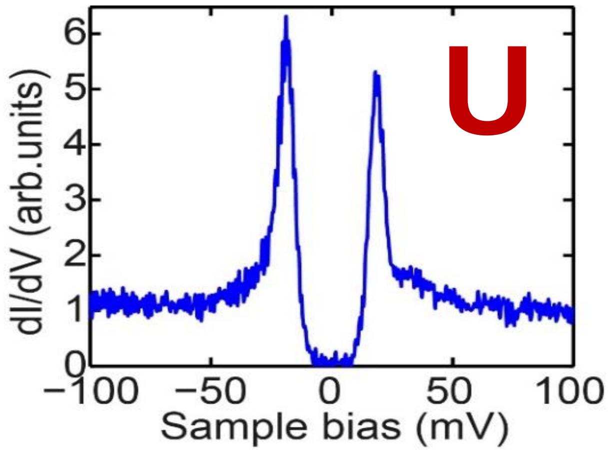
# Two important results from 1UC $CuO_2$ films

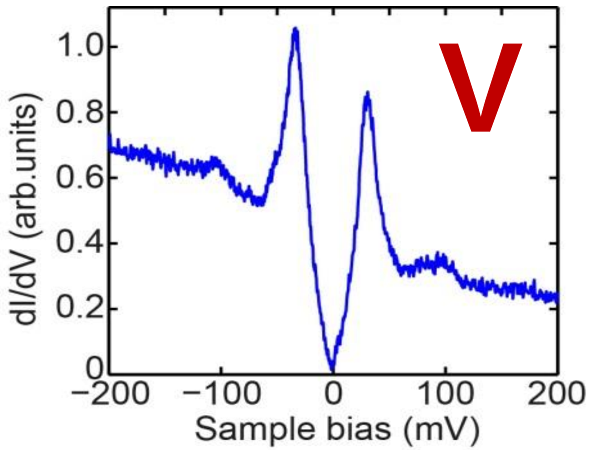


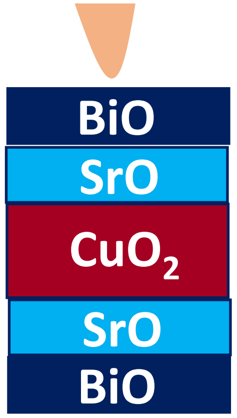

**(1) No change in the Mott-Hubbard band structure of $CuO_2$ (regardless of the doping).**

**(2) U-shaped gap on $CuO_2$, not the V-gap on the cleaved BiO surface.**

**The assumption that the "V" gap is tunneling from the underlying $CuO_2$ is NOT correct.**

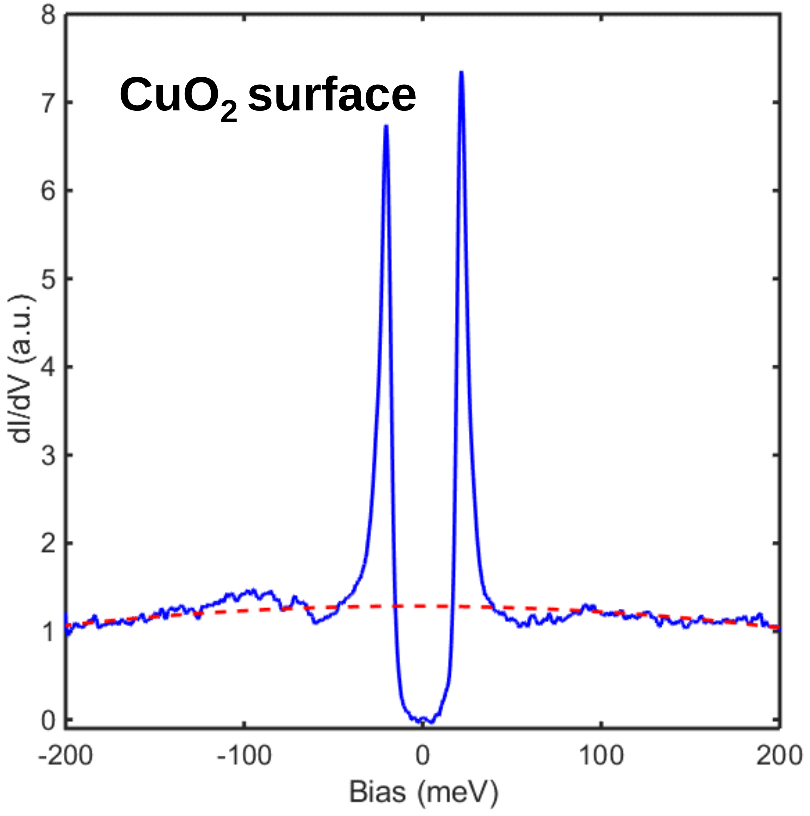


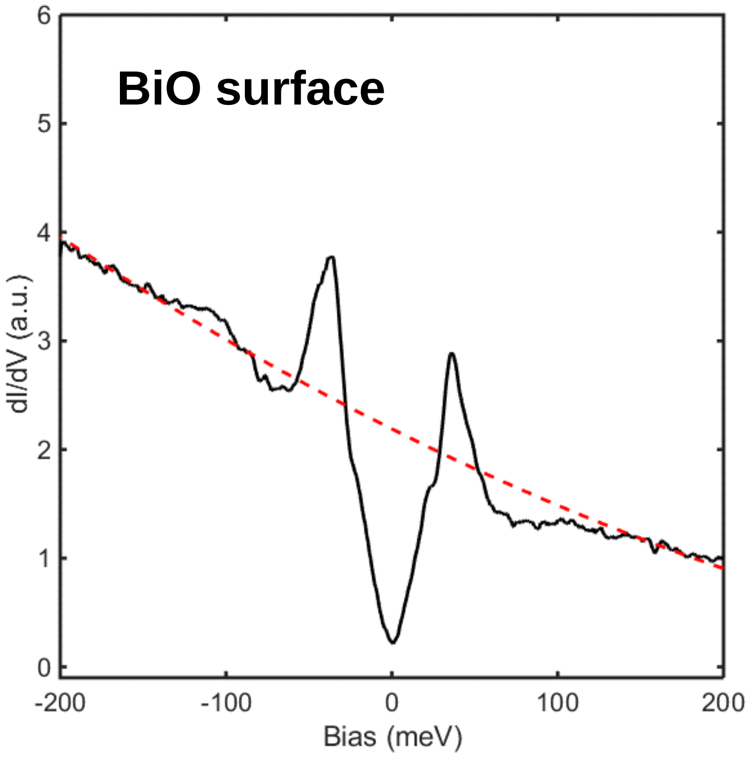




**Cuprates: interface enhanced BCS superconductor?**

# Robust U-Gap of Monolayer $CuO_2$ on Bi-2212 (raw data)



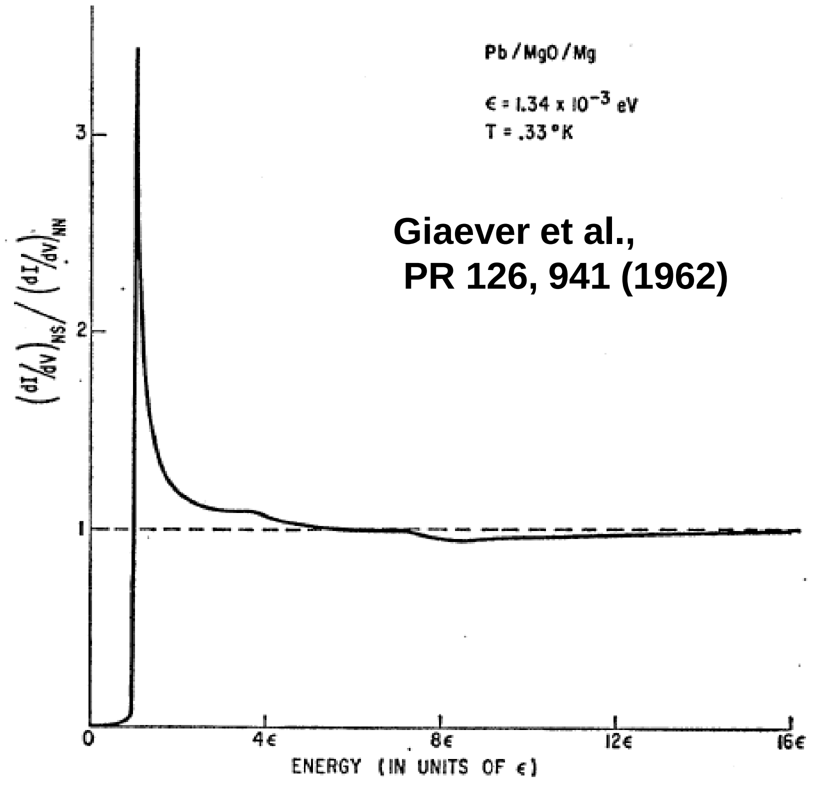



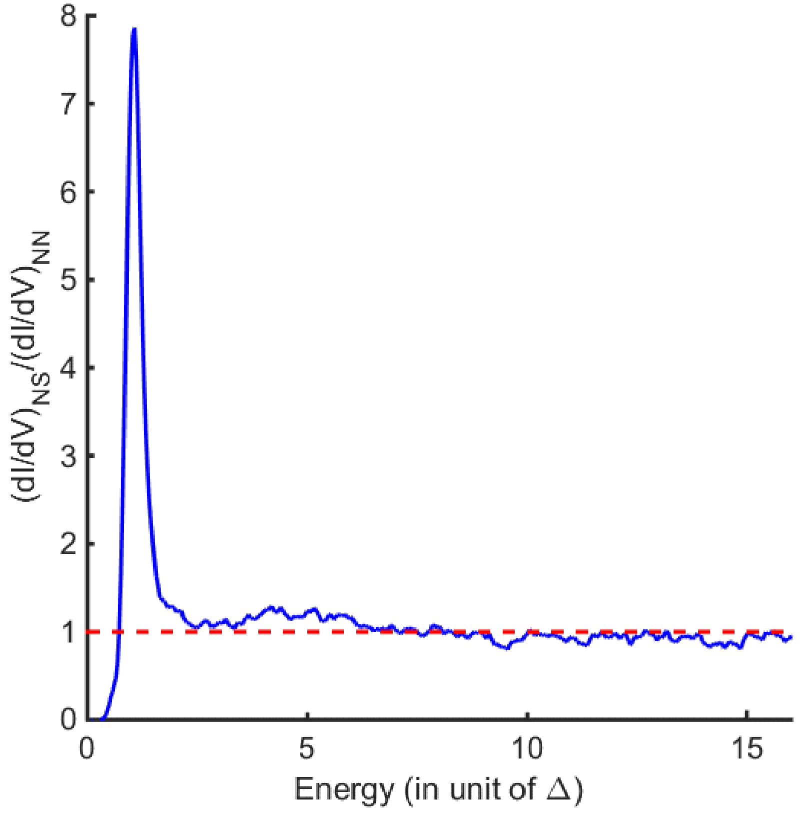

**Red background: normal-state fit**
**The normal state: particle-hole symmetry**
**(Fermi-liquid behavior)**

**Red background: normal-state fit**
**The normal state: particle-hole asymmetry**
**(doped Mott insulator)**

*Zhong et al., unpublished data (2017)*

# Robust U-Gap of Monolayer $CuO_2$ on Bi-2212



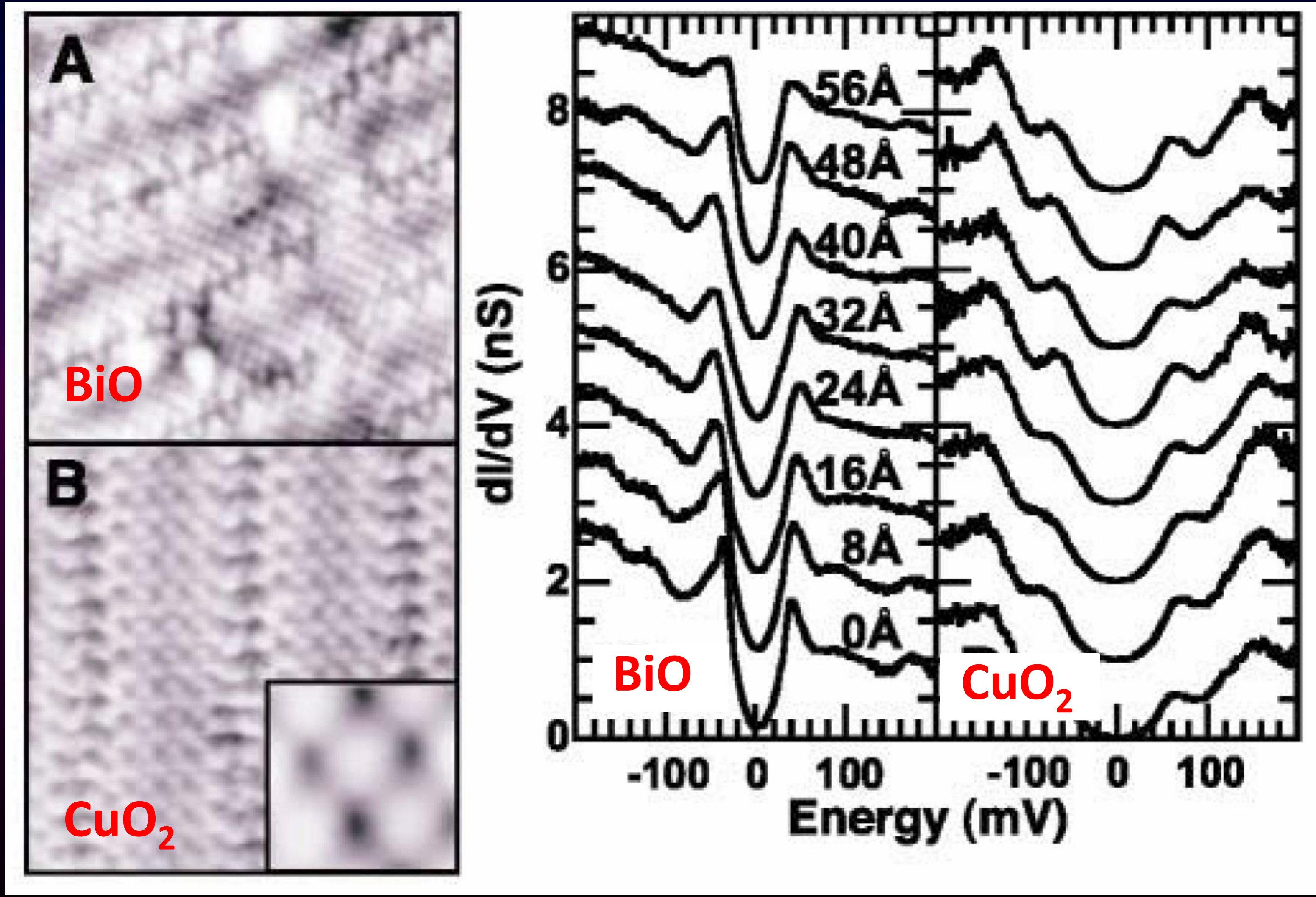

**BCS Pb normalized spectrum** ⟷ **U-gap: normalized spectrum**

**good**

*Zhong et al., unpublished data (2017)*

# STS spectra of the cleaved $CuO_2$ surface of BSCCO

Yazdani Group: PRL 89, 087002(2002)



# Our original proposal for raising $T_C$ (2008)

**BCS Theory**

$$T_c = \frac{w_0}{1.2}\exp\left[-\frac{1.04(1+\lambda)}{\lambda-\mu^*(1+0.62\lambda)}\right]$$

$w_0 \sim 300$ K ⇨ ~ 40 K

*W. L. McMillan, Phys. Rev. B16, 643 (1977)*

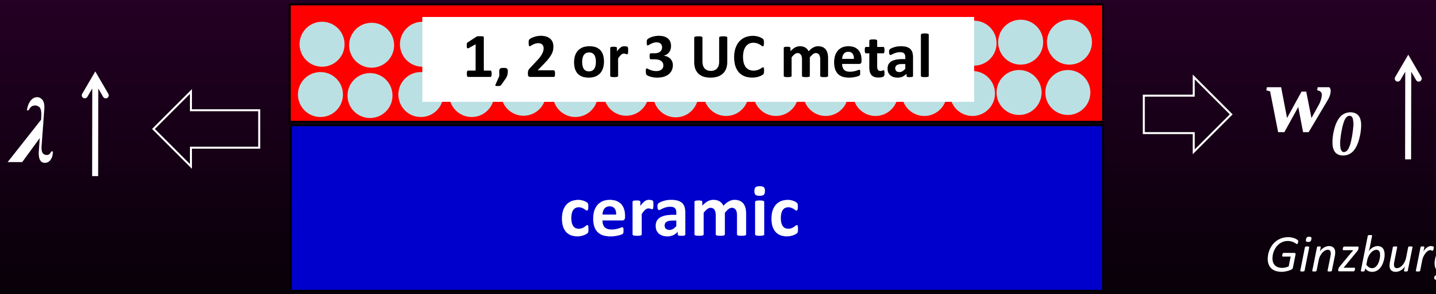
**Metal: conducting, but low Debye $w_0$**

**Ceramic (diamond): high Debye $w_0$, but insulating.**

**(Heavy doping destroys phase coherence)**

## To raise Tc under BCS e-ph coupling scheme

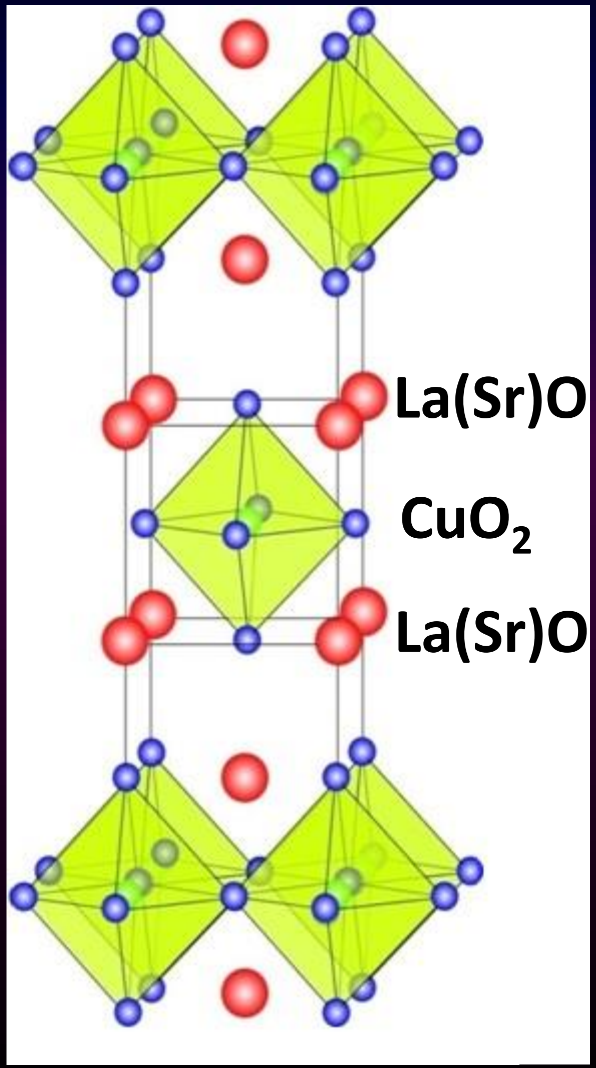
"soft" conductor + "hard" reservoir: heterostructure of two materials may overcome the Tc limit for one material




*Ginzburg, 1964*

# High Tc by doping of a parent insulator

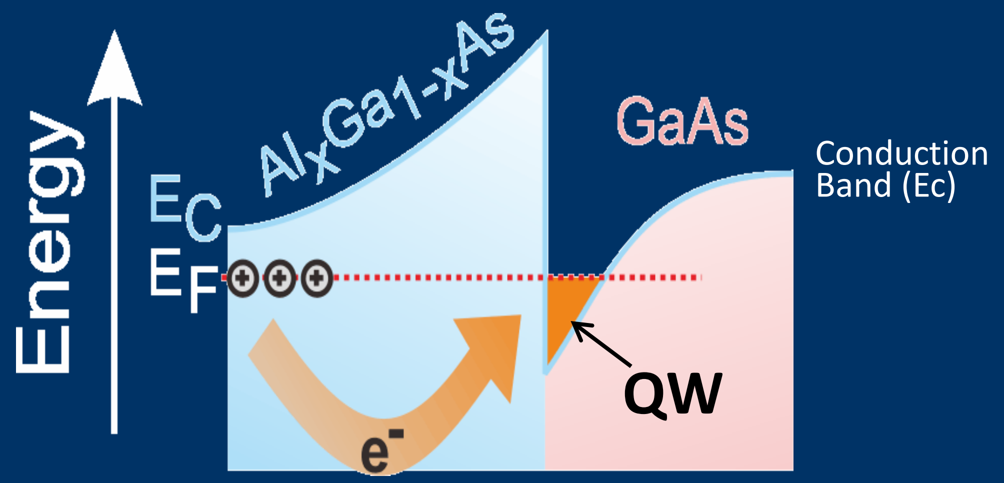
Bednorz & Müller, 1986




La$_{2-x}$

R. Dingle, H. L. Störmer, A. C. Gossard, and W. Wiegmann, **Appl. Phys. Lett. 33**, 665 (1978)

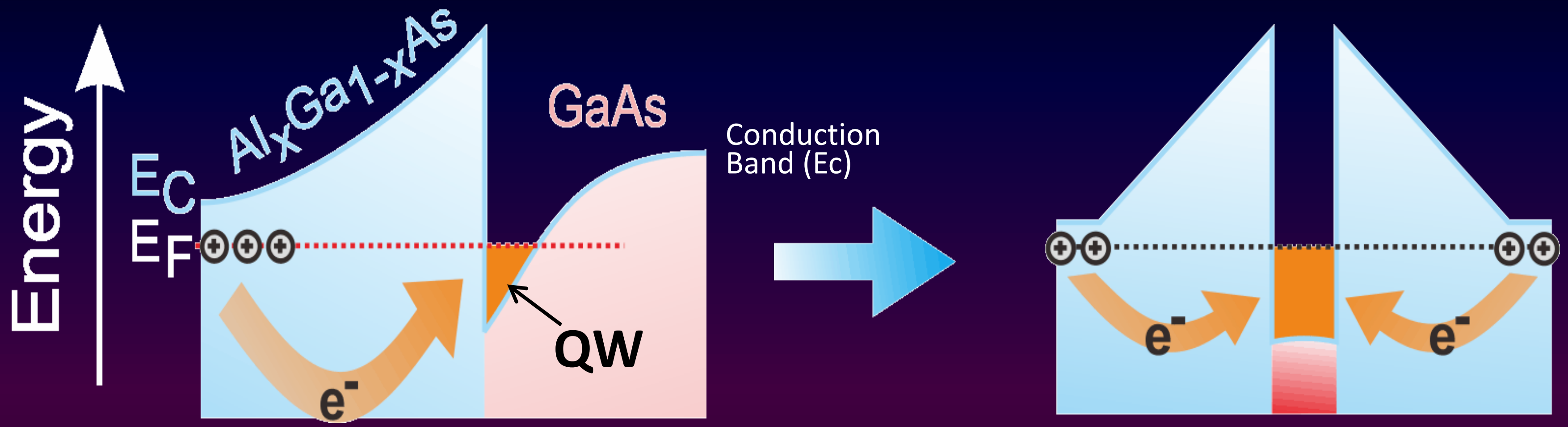
**Modulation-Doping for 2DEG**




**Charge transfer is very important!**

# High mobility 2DEG in modulation-doped semiconductor heterostructures

Dingle, Störmer, Gossard, Wiegmann, APL **33**, 665 (1978)




**No change in GaAs band structure (Rigid band)**

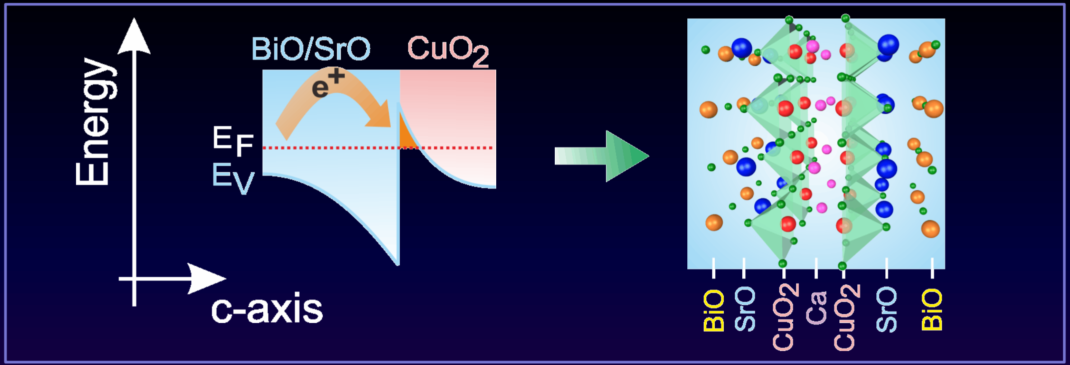
**superlattice**

(1) Charge transfer → Band bending → QW (2DEG).

(2) Without QW formation in its interface side, the GaAs cannot conduct !!!

(3) Spatially separated electrons and their parent atoms.

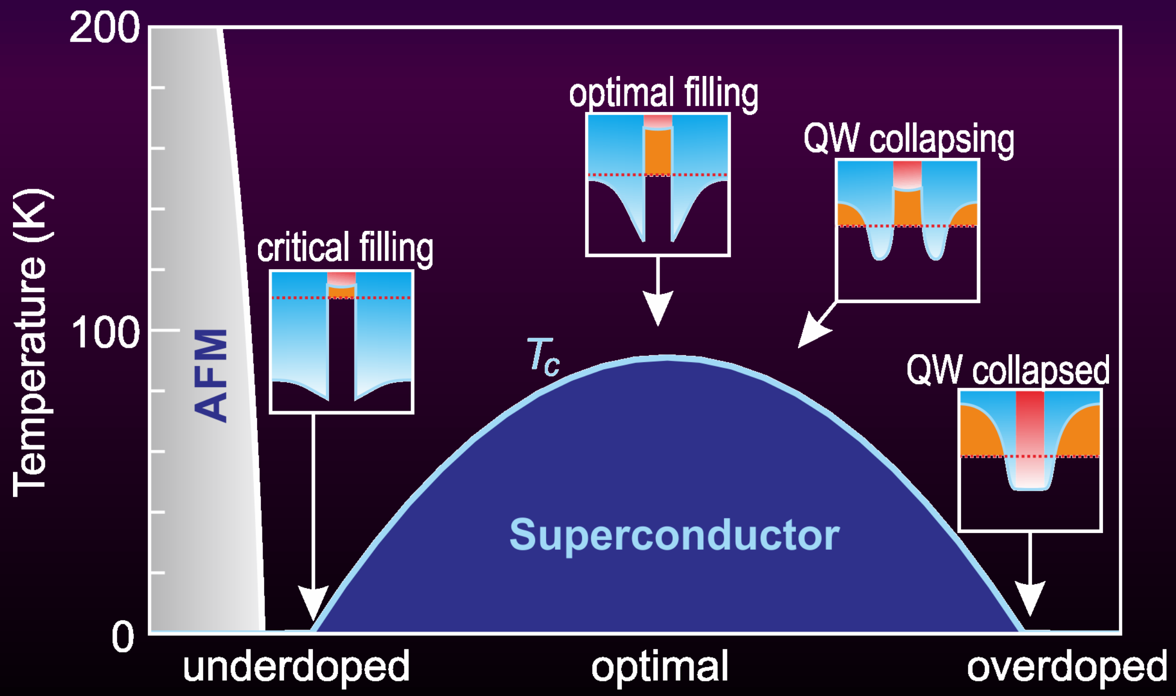
# Our Model: 2D Hole Liquid (2DHL)




*Zhong and Wang et al., Sci. Bull. 61, 1239 (2016)*

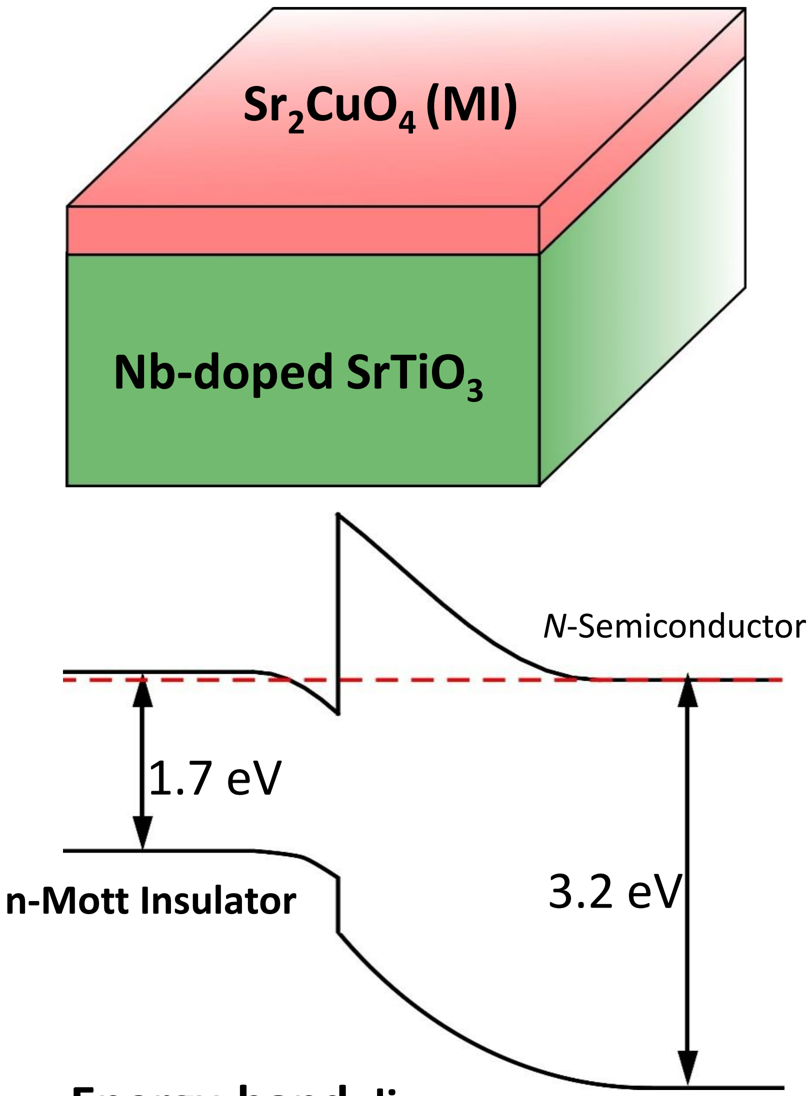
**Our work indicates similar charge transfer at the $BiO/CuO_2$ interface**

**The complex phase diagram**



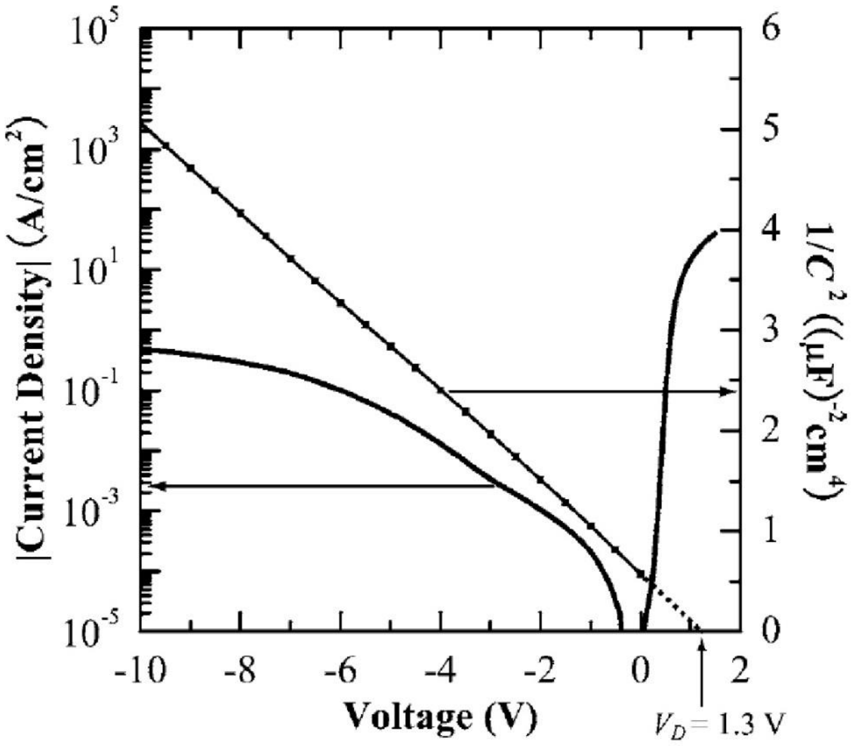
# Band bending occurs at Mott-insulator/STO heterostructure

~ 30 nm $Sr_2CuO_4$ films on STO




**Energy-band diagram**

***Prof. Tokura: PRB 75, 155103 (2007)***




Current-voltage and capacitance-voltage curves

Rectifying *I-V* characteristic with
a diffusion potential of 1.3 V

# BCS superconductors

$T_C$ ~ 40 K (low $w_o$ and limited $\lambda$) — conventional

$T_C > 77$ K
- Interface Enhancement at heterostructures

— unconventional

**Thank you very much!**