

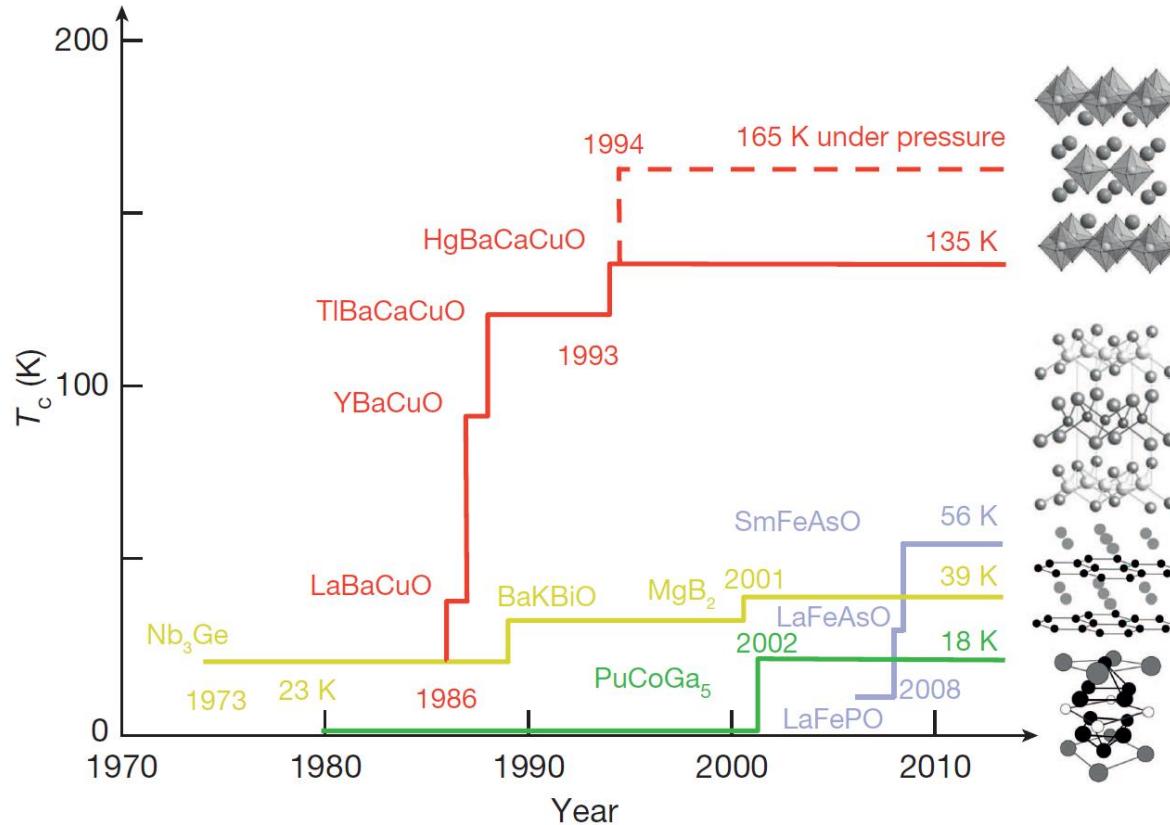
Presence of *s*-wave pairing in twisted $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+x}$ Josephson junctions

Menghan Liao

Acknowledgements: Prof. Qikun Xue, Prof. Ding Zhang, Prof. Yuying Zhu, Prof. Qinghua Zhang, Jin Zhang, Fanqi Meng, Ruidan Zhong, John Schneeloch, Prof. Kaili Jiang, Prof. Genda Gu, Prof. Lin Gu, Prof. Xucun Ma

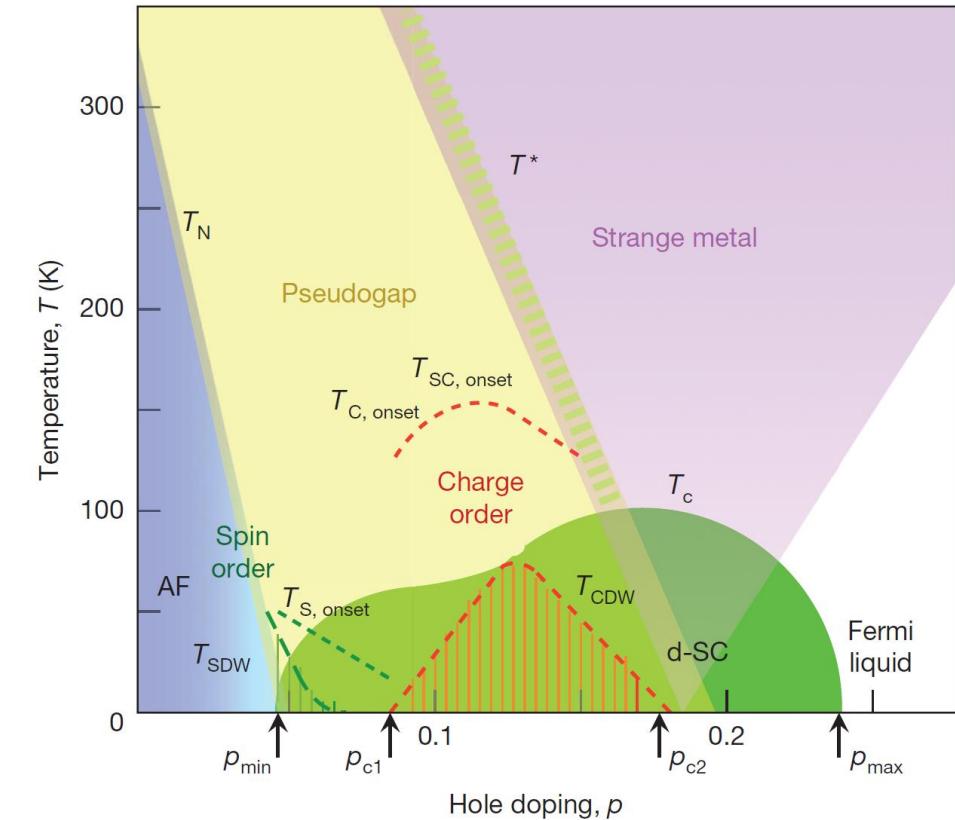
Mechanism of high T_c cuprate superconductors: an open question

- Highest T_c at ambient pressure
- Doped Mott insulator: “dirty” metal



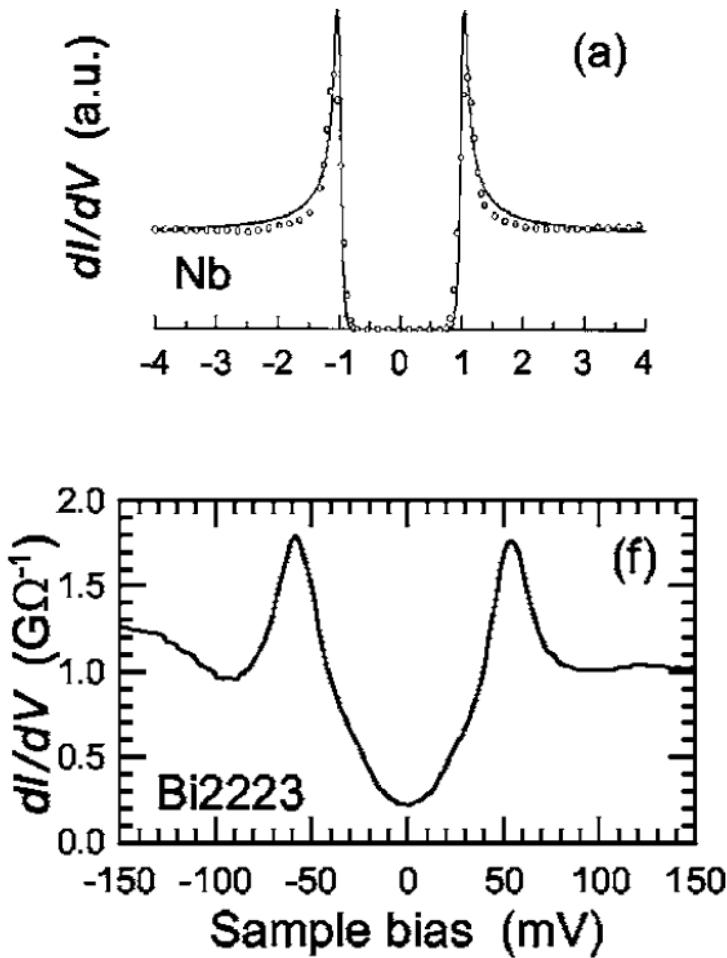
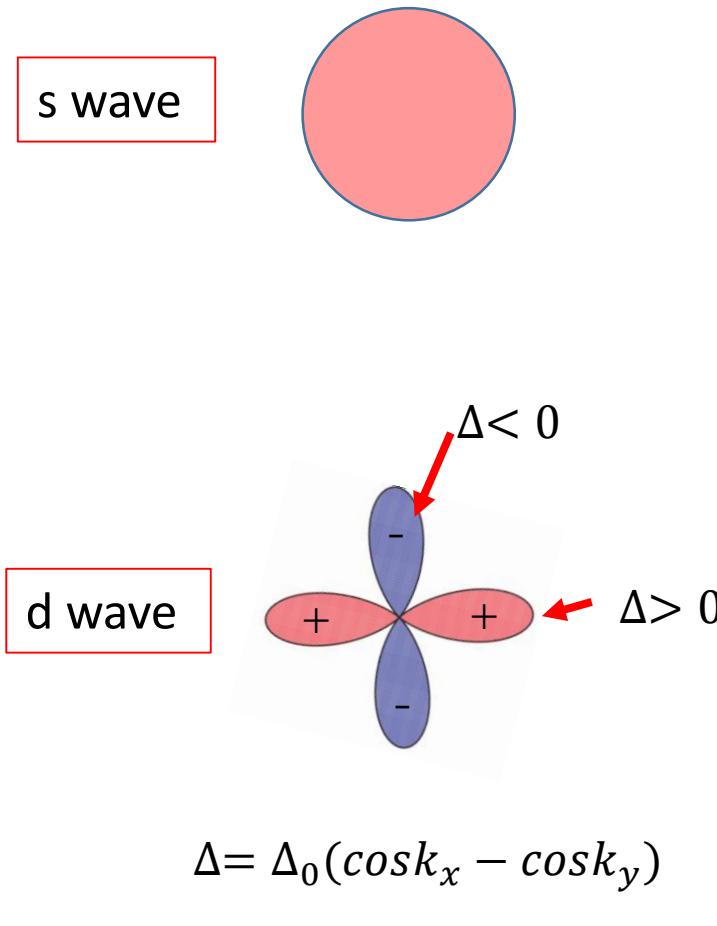
B. Keimer et al. *Nature*, **518**, 179–186 (2015).

Complex phase diagram of cuprates

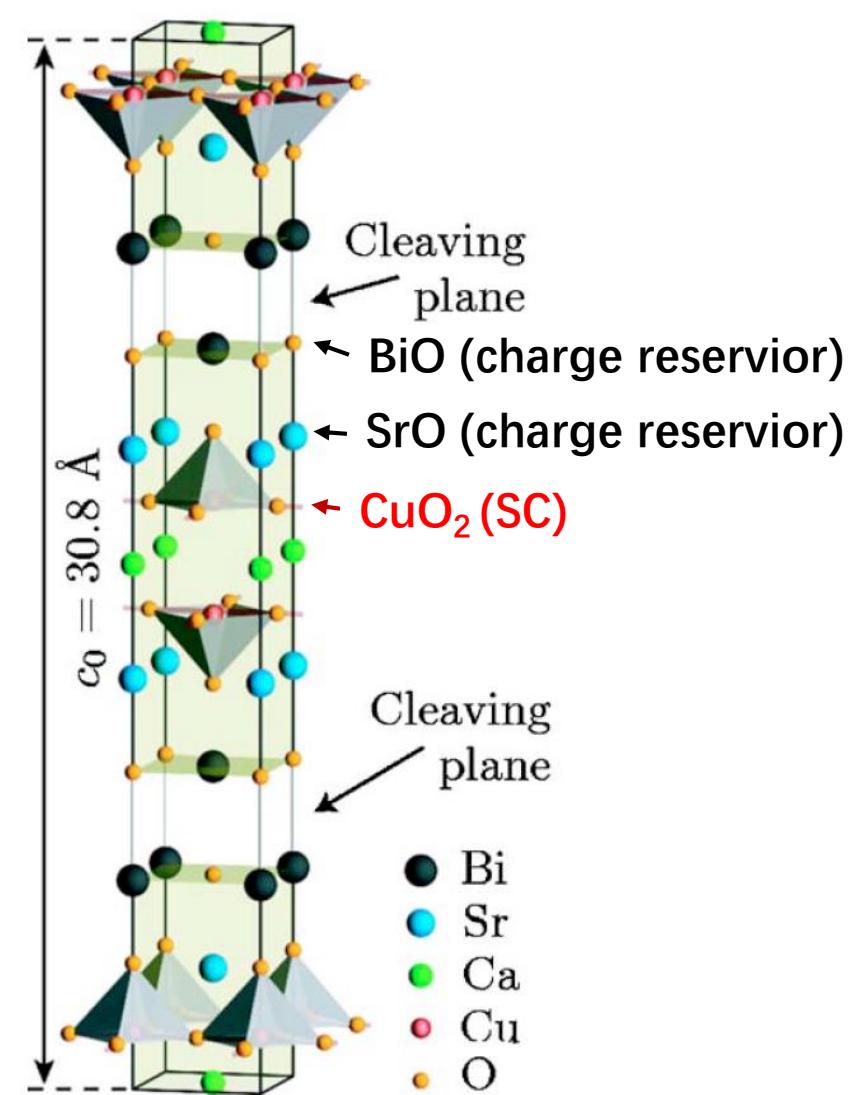


- Pseudogap?
- Competing charge orders?
- Pairing symmetry?
- ...

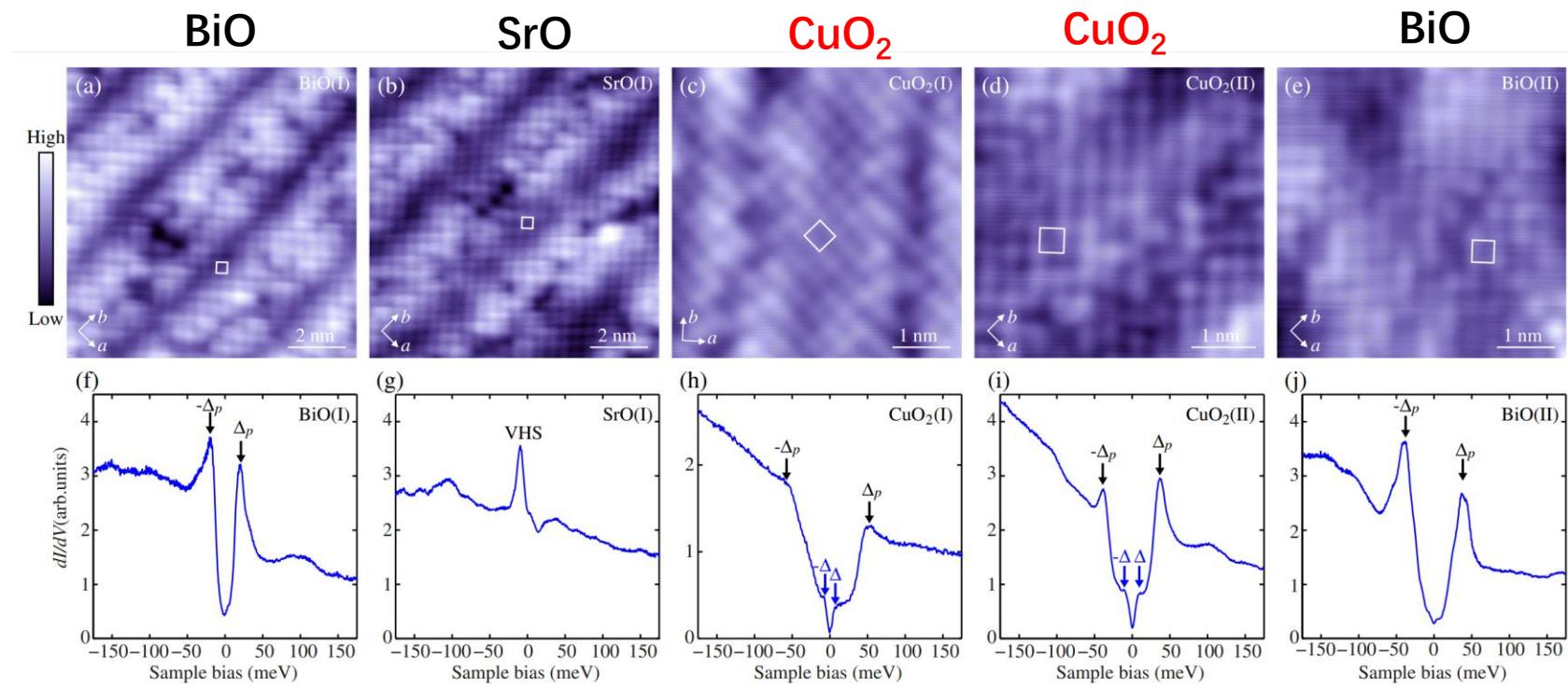
s-wave vs *d*-wave pairing



Structure of $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+x}$ (Bi-2212)



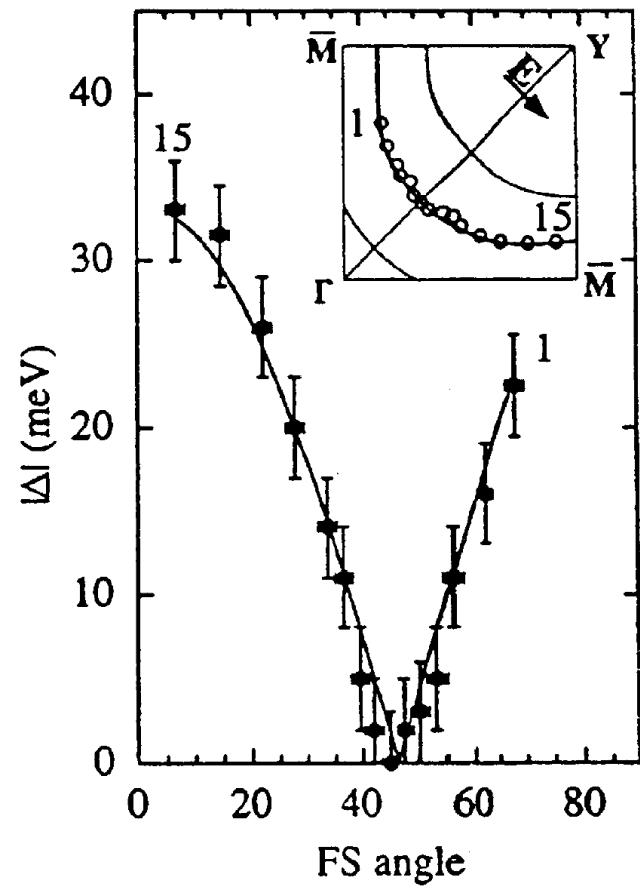
Structure and gap of different layers



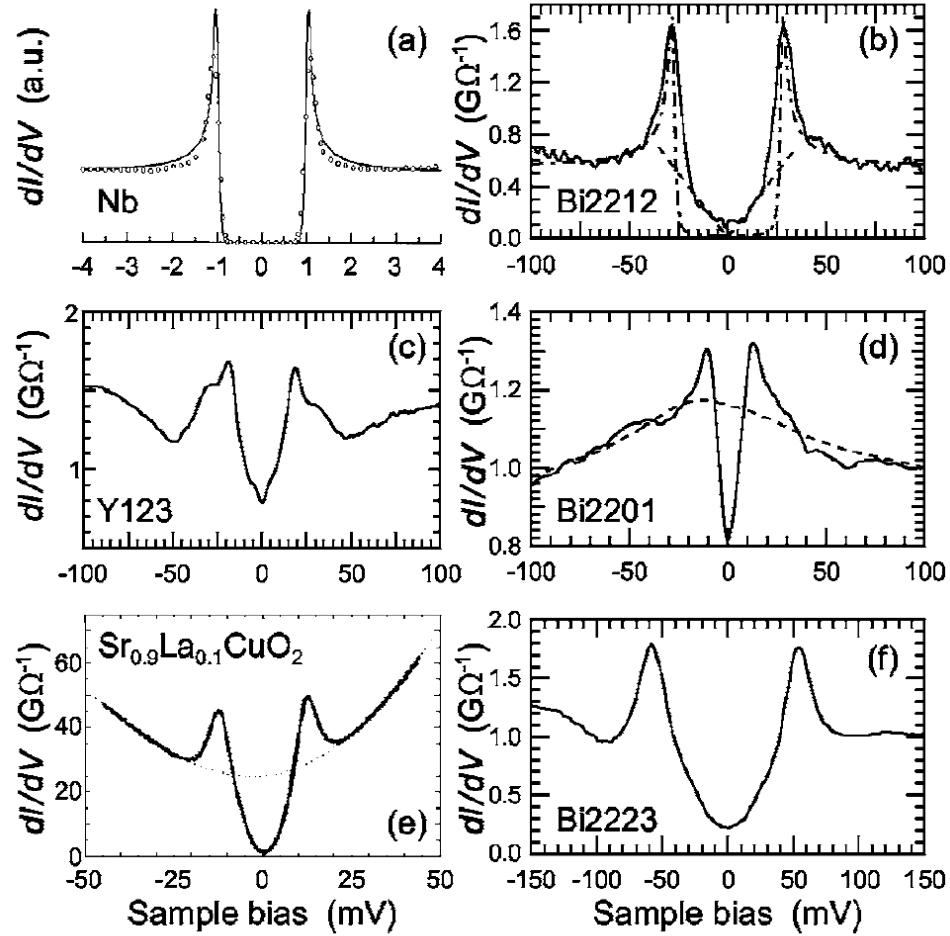
Measurements of SC gap: non-phase sensitive experiments

d-wave like: charge reservoir

ARPES

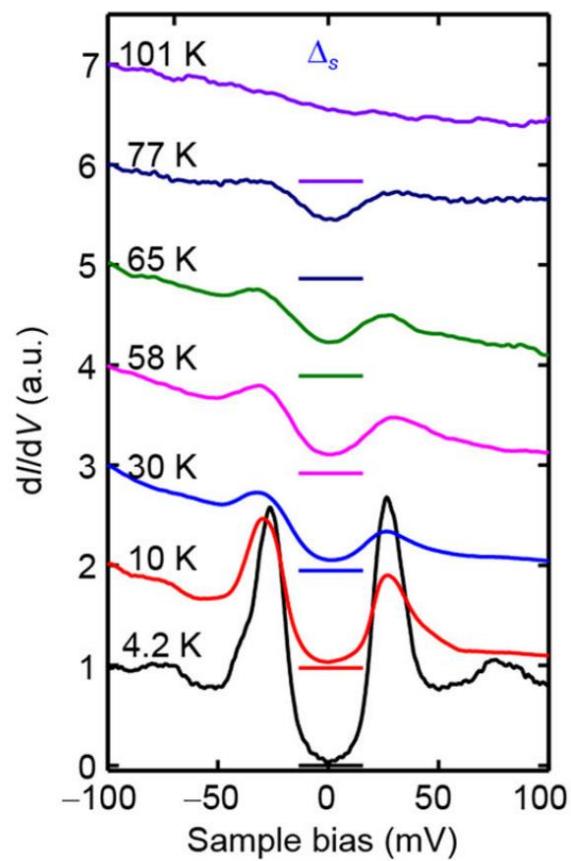


STM



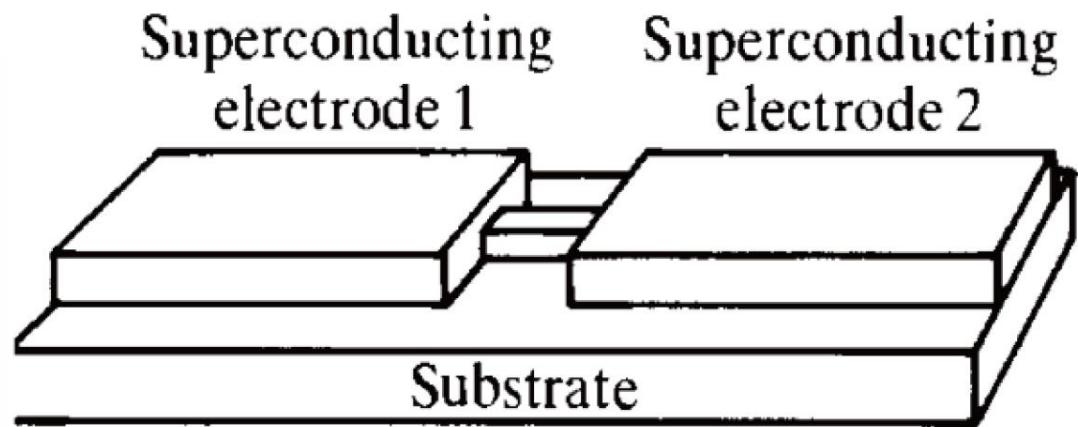
s-wave like: CuO₂ layer

STM



Y. Zhong Y, et al. *Sci. Bull.* **61**, 1239–1247 (2016).

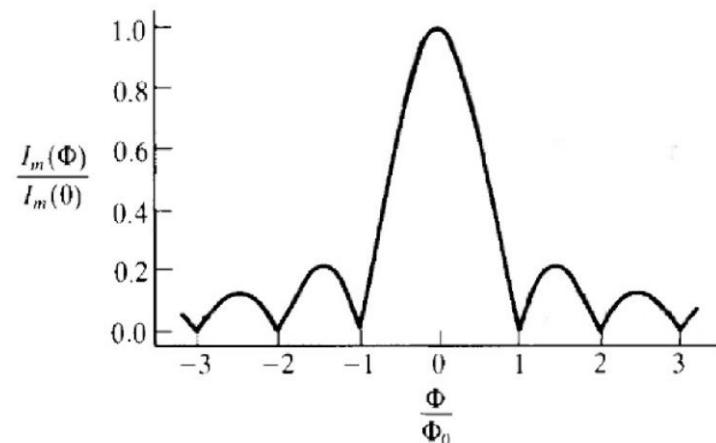
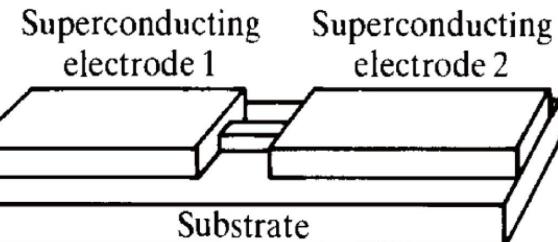
Josephson effect



$$I_s = I_c \sin \gamma$$

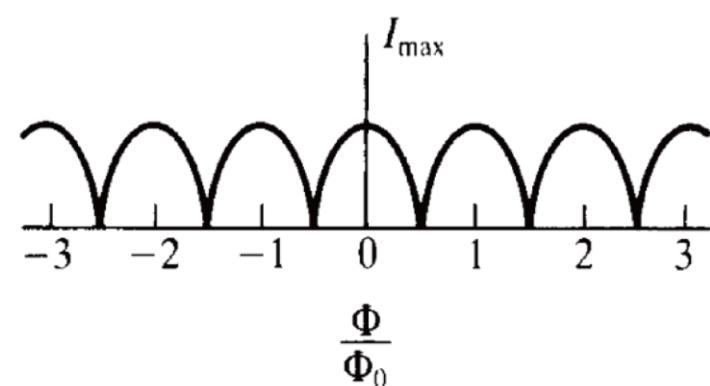
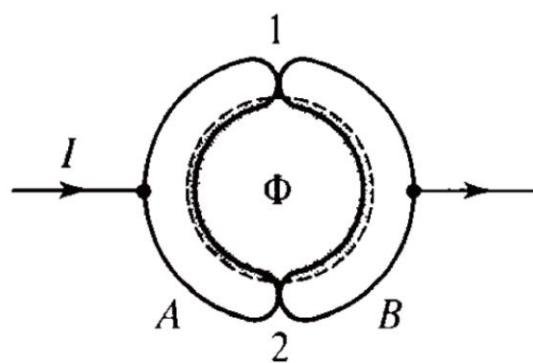
$$\gamma \equiv \Delta\varphi - (2\pi/\Phi_0) \int \mathbf{A} \cdot d\mathbf{s}$$

Josephson Effect



$$I_m(H)/I_m(0) = |\sin(\pi\Phi/\Phi_0)/(\pi\Phi/\Phi_0)|$$

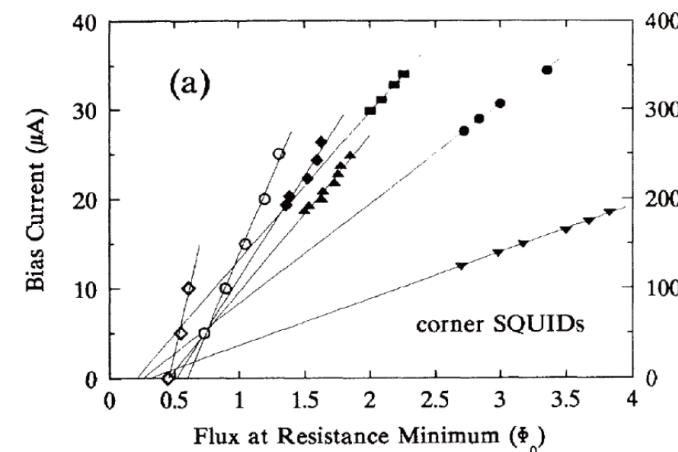
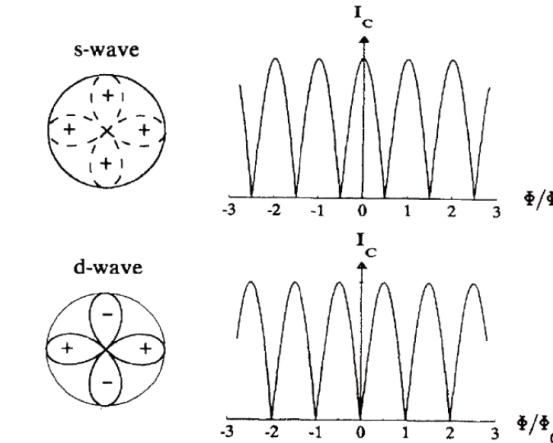
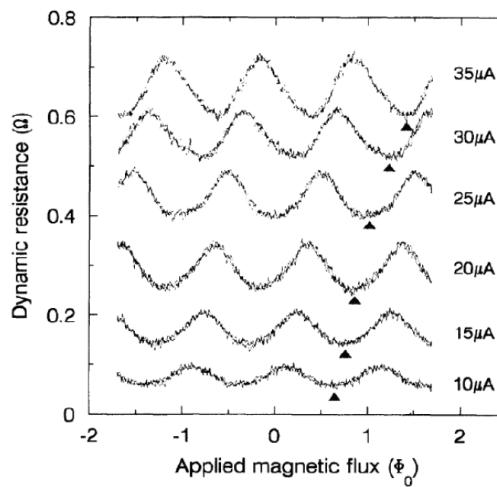
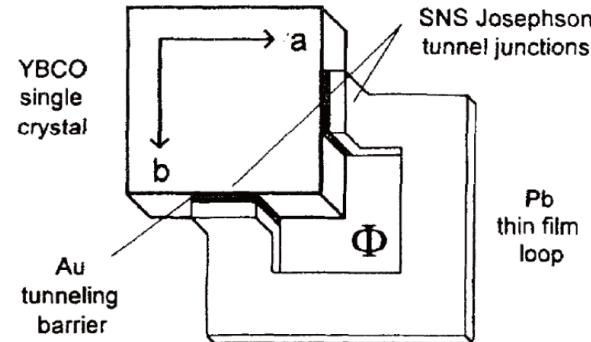
superconducting quantum interference device
(SQUID)



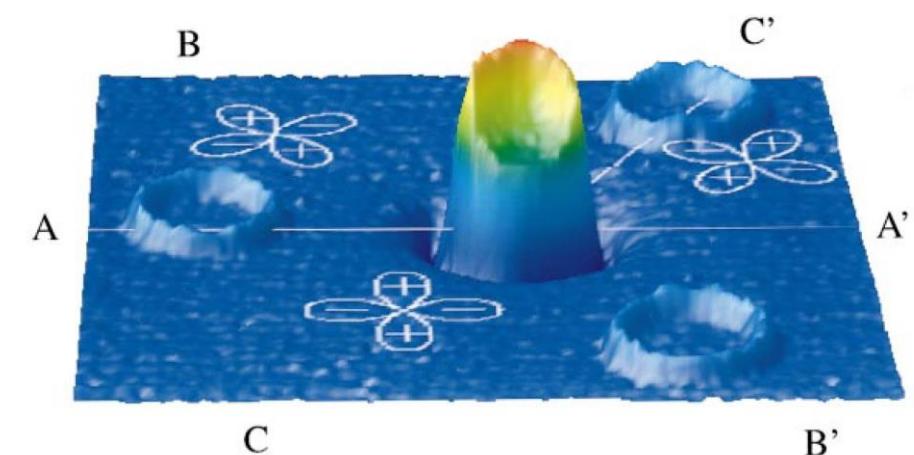
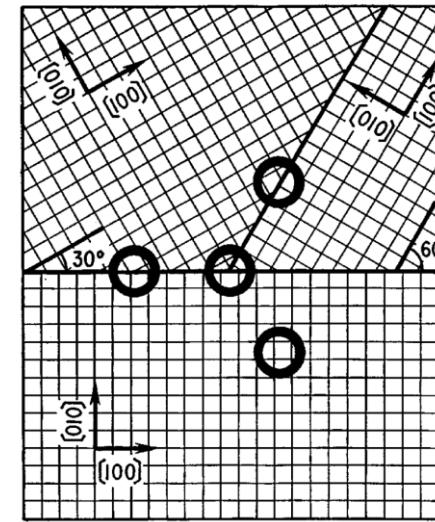
$$I_m = 2I_c|\cos(\pi\Phi/\Phi_0)|$$

Phase sensitive experiments of cuprates: in-plane Josephson junctions

'Corner SQUID': shift of diffraction pattern



Tricrystal experiments: half-flux quantum

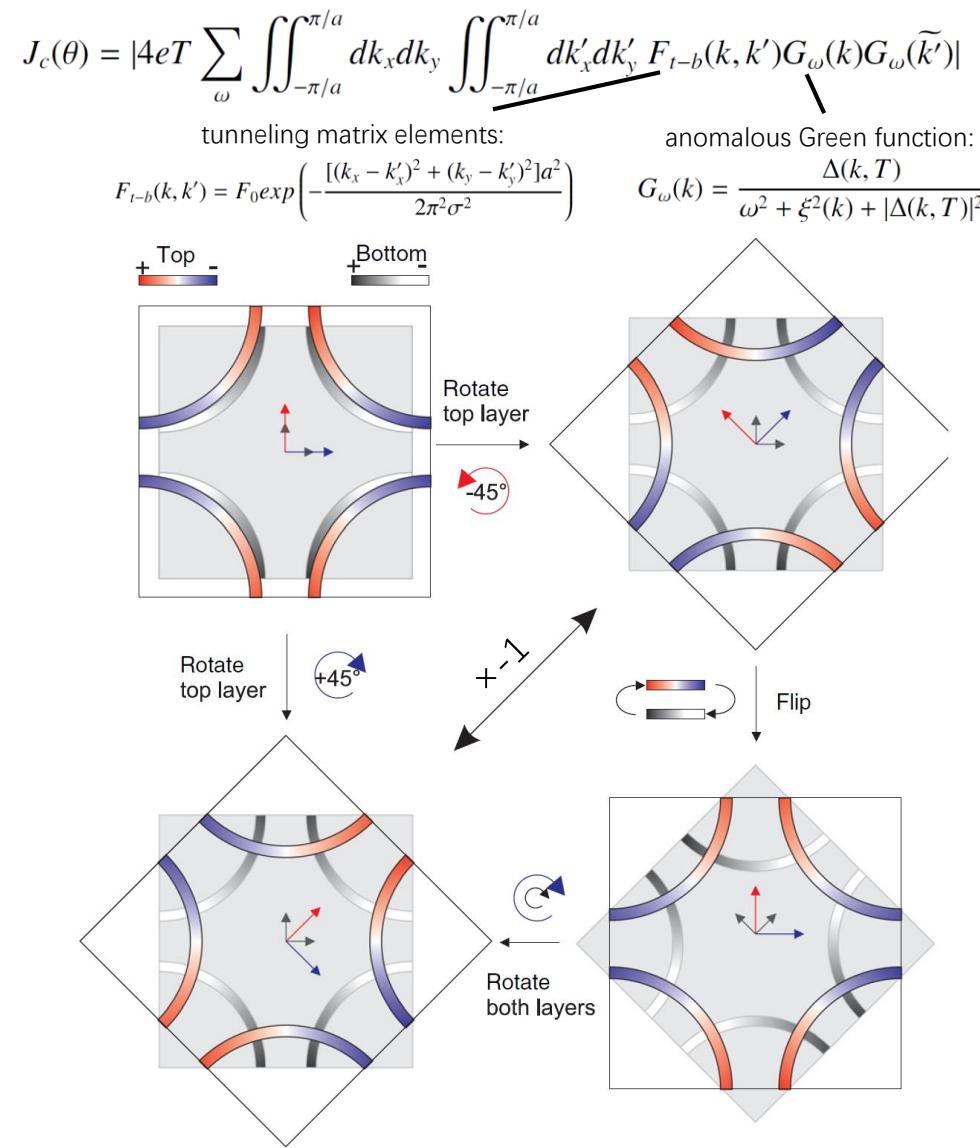
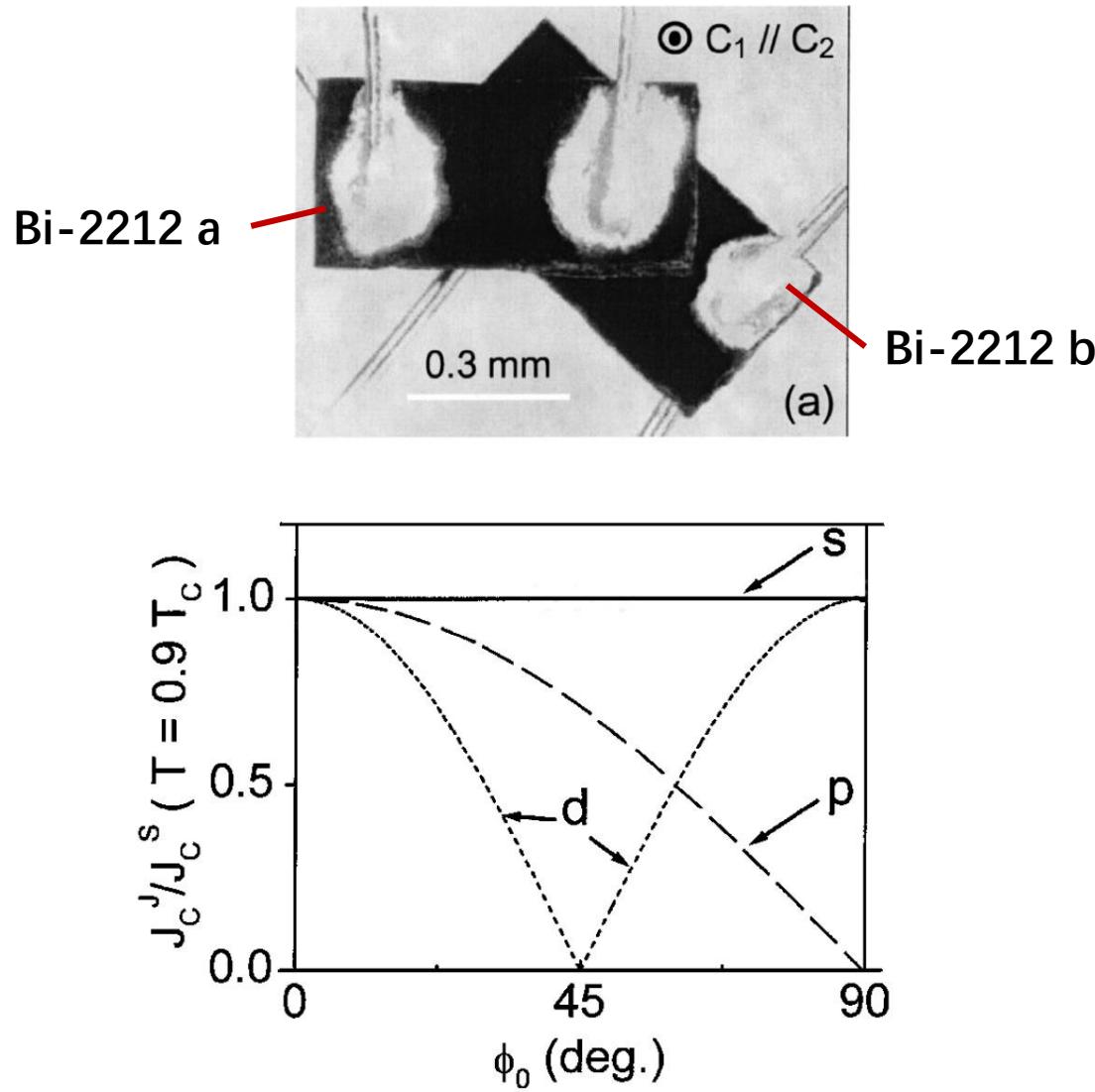


Hardy W N, Bonn D A, Morgan D C,
et al. *Phys. Rev. Lett.* **1993**, 70, 3999.

Tsuei C C, Kirtley J R. *Rev. Mod. Phys.* **2000**, 72, 969.

***d*-wave like**

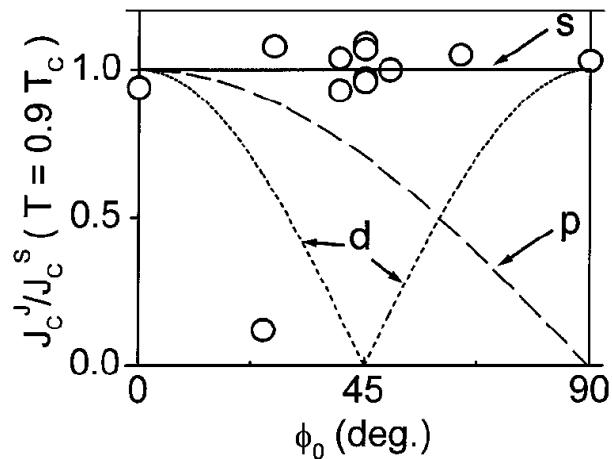
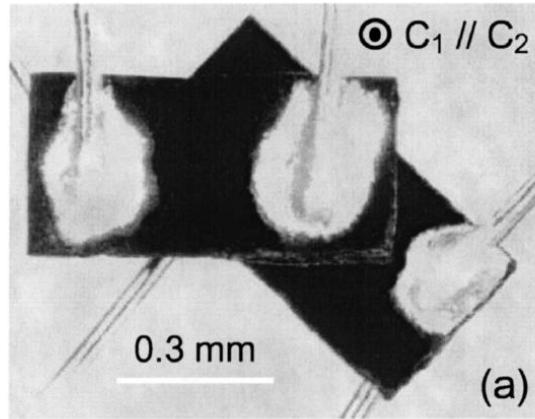
Phase sensitive experiments of cuprates: *c*-axis Josephson junctions



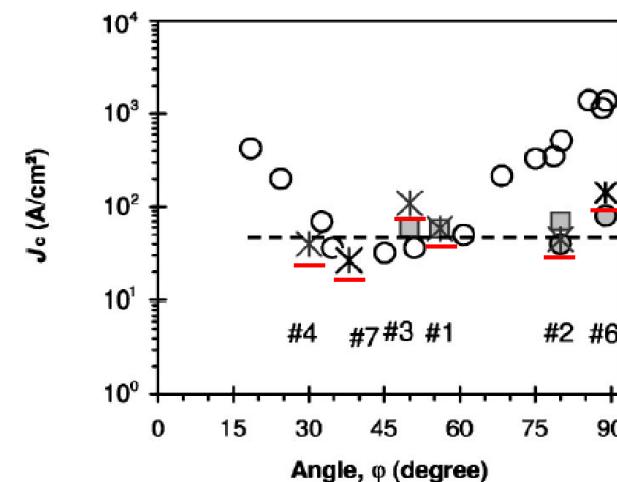
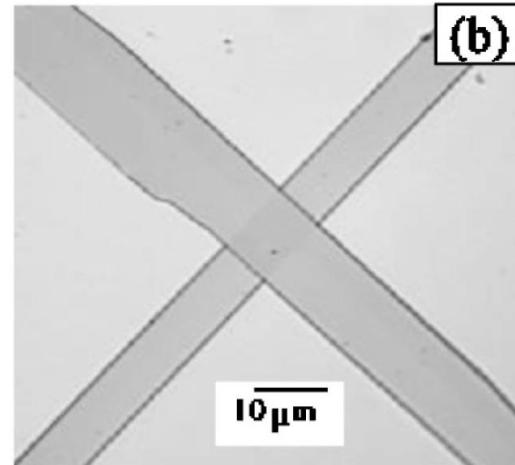
Phase sensitive experiments of cuprates: *c*-axis Josephson junctions

s-wave like

Q. Li, et al.

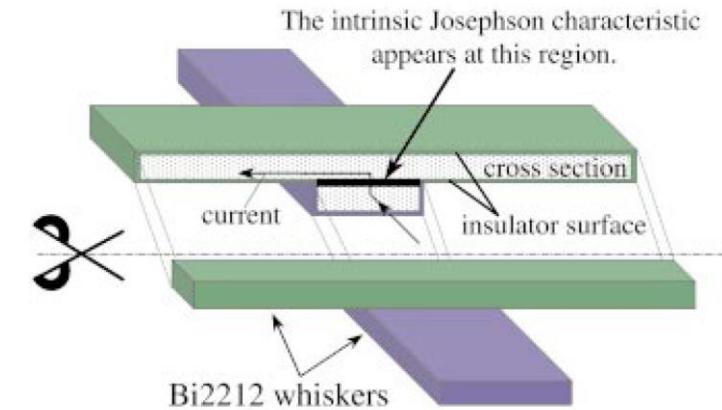


Yu Latyshev, et al.

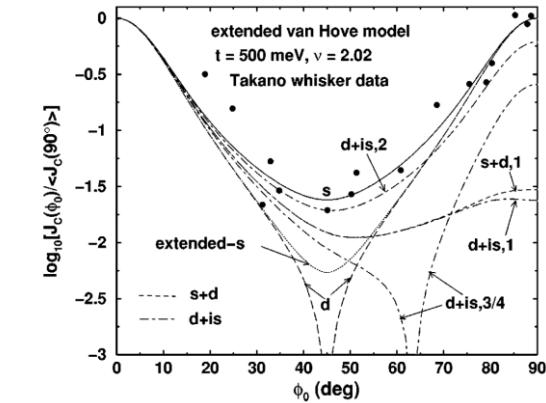
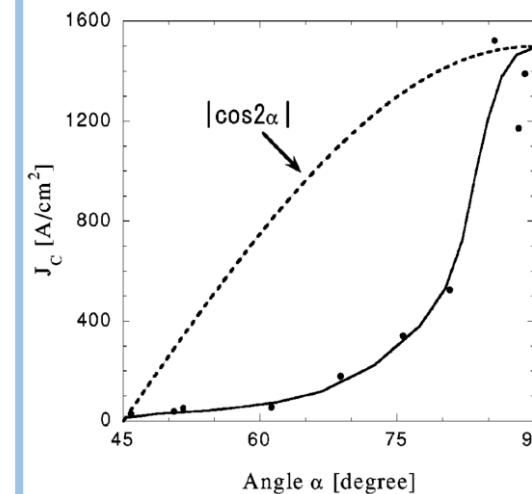


d-wave like

Y. Takano, et al.



R. A. Klemm's explanation with orbital effect in *s*-wave

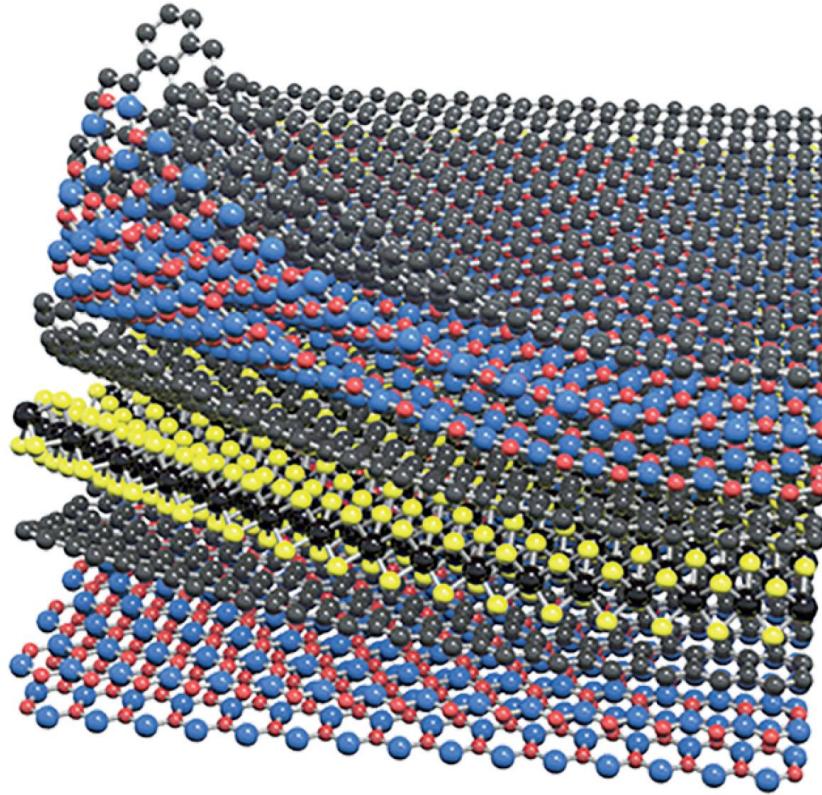
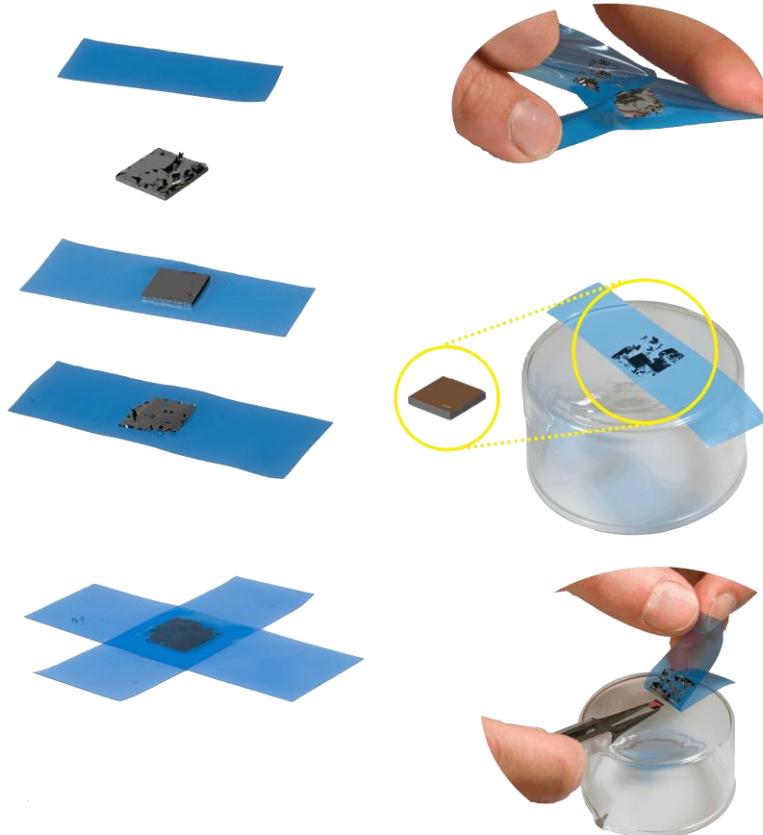


Q. Li et al. *Phys. Rev. Lett.* **83**, 4160 (1999).

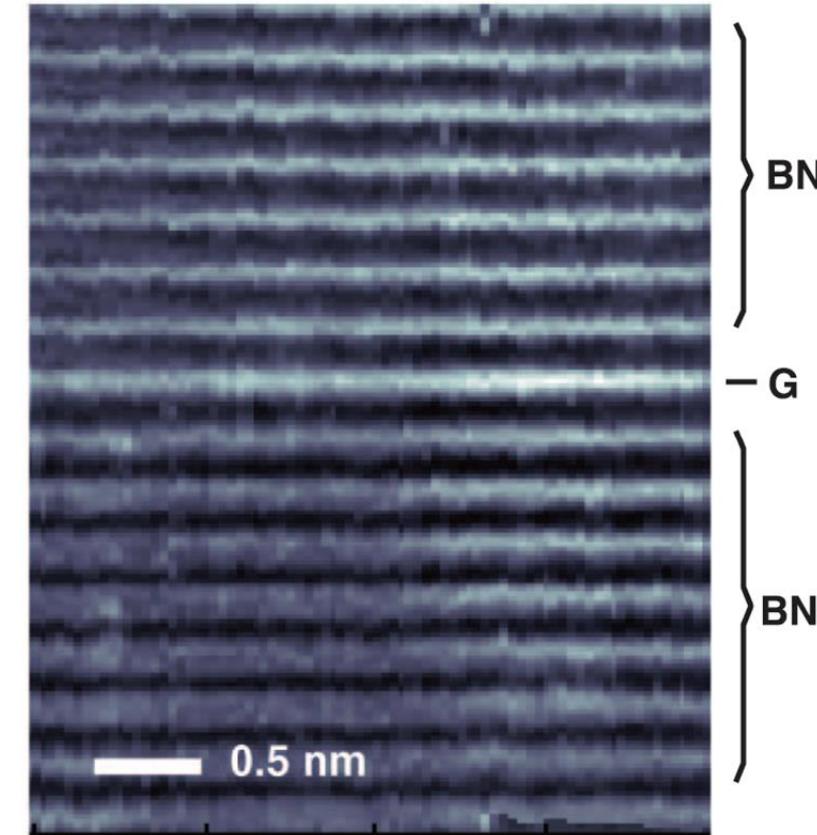
Y. Latyshev et al. *Phys. Rev. B*, **70**, 094517 (2004).

Y. Takano et al. *Phys. Rev. B*, **65**, 140513 (2002).

Van der Waals heterostructures



Atomically flat interfaces

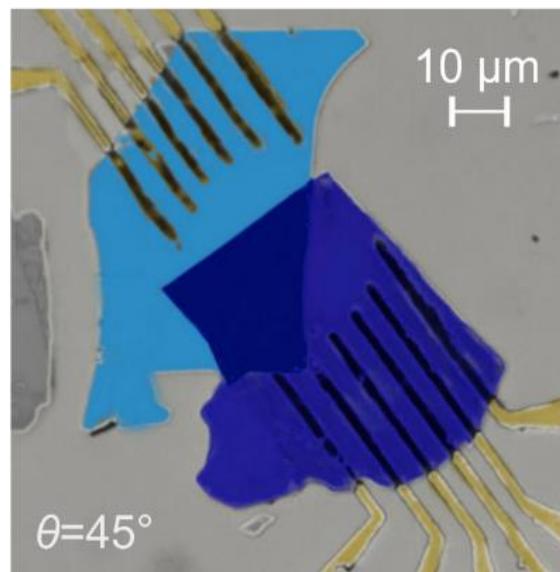
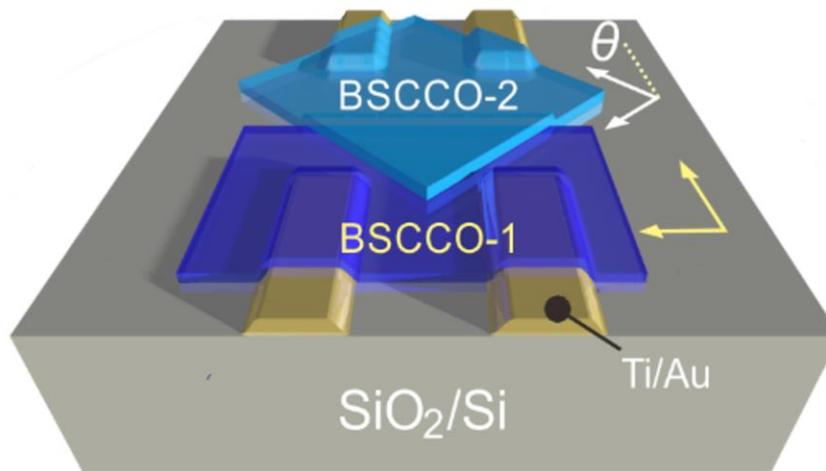


A. K. Geim et al. *Nature*, **499**, 419 (2013).

L. Wang, et al. *Science*, **342**, 614-617 (2013).

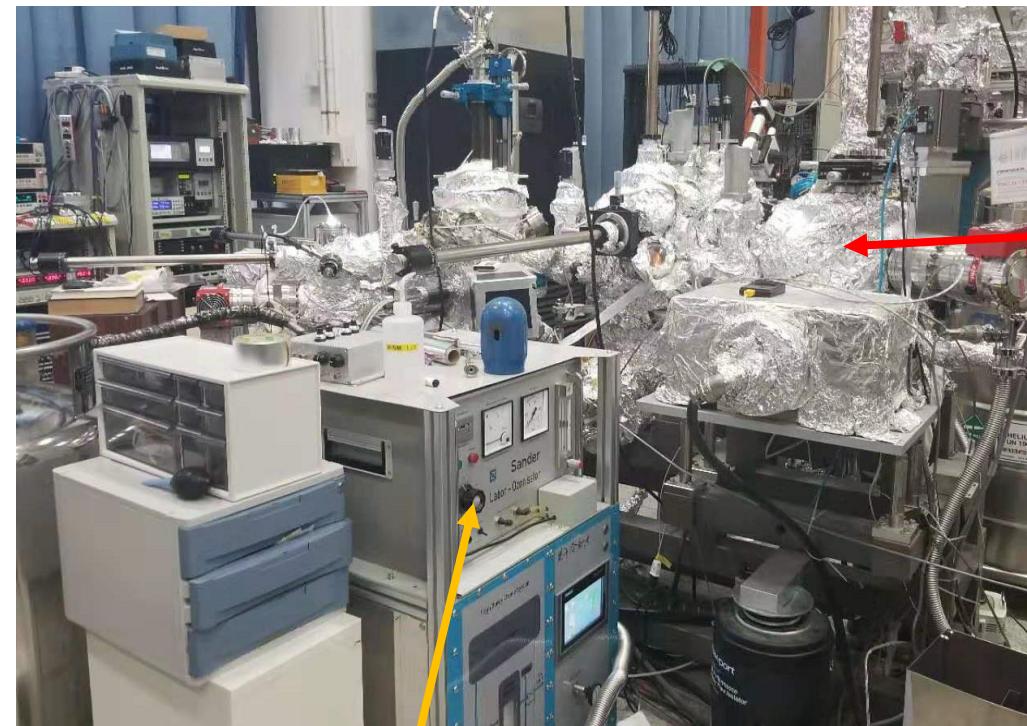
Fabrication of twisted Bi-2212 junctions with vdW stacking and annealing

Van der Waals stacking



Annealing

O_2
tube furnace
 550°C

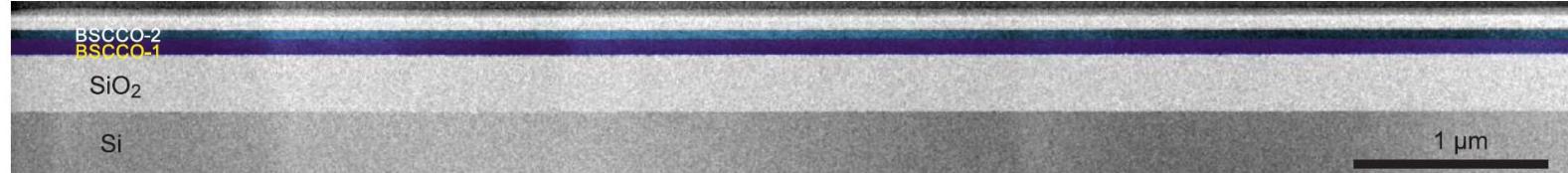


UHV
chamber

ozone generator

Atomic flat junctions at the micrometer scale

(a) No. 0817 $\theta_{\text{nominal}}=45^\circ$



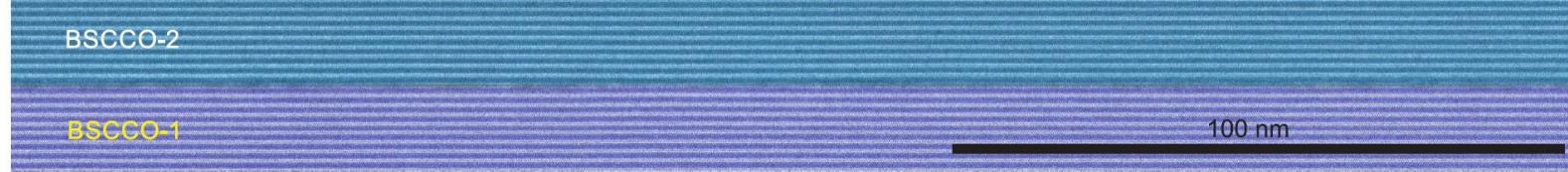
(b) No. 0817 $\theta_{\text{nominal}}=45^\circ$



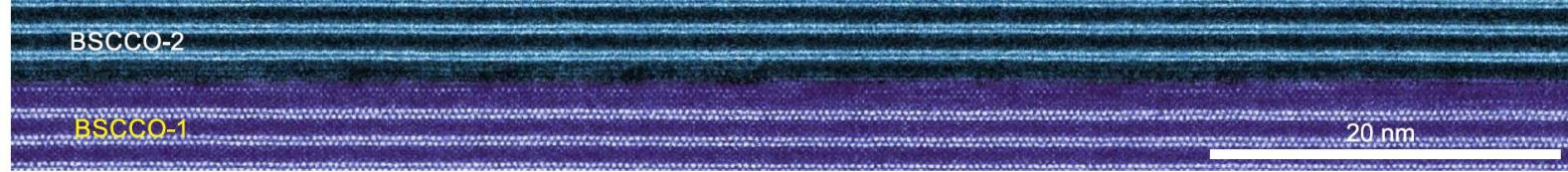
(c) No. 0817 $\theta_{\text{nominal}}=45^\circ$



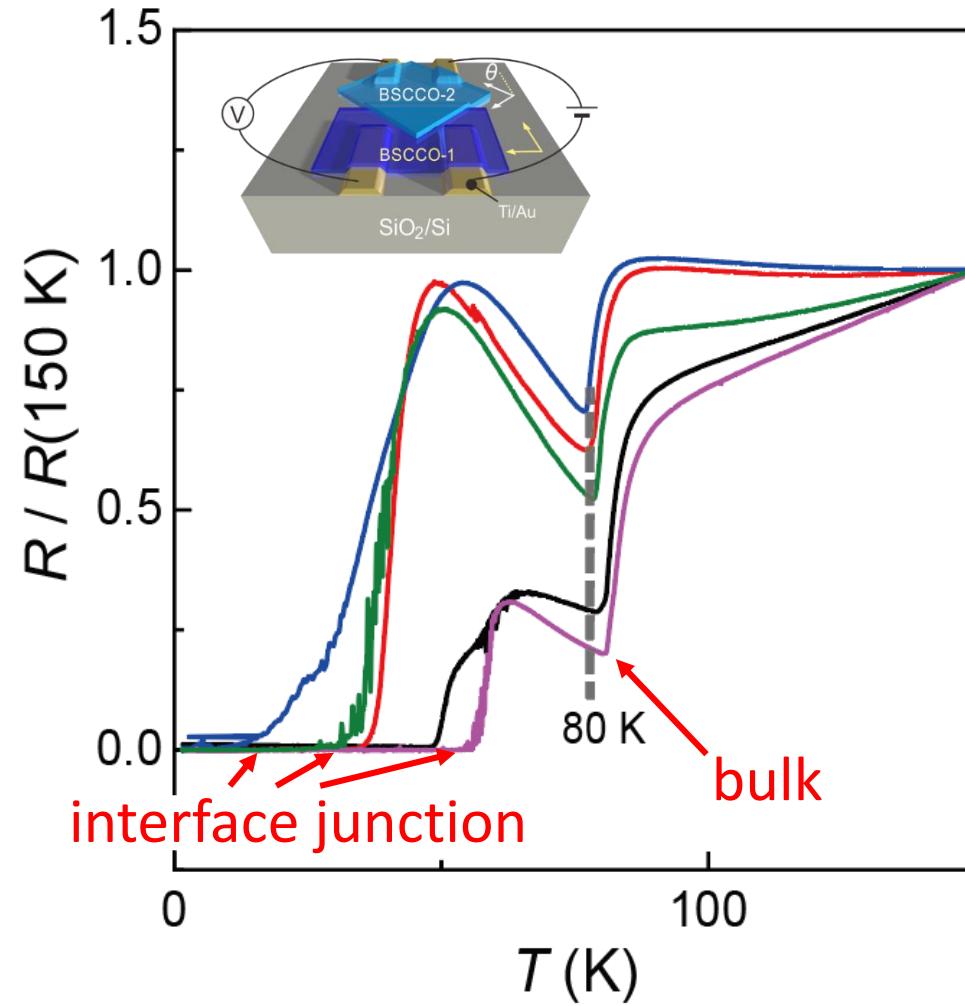
(d) No. 0814 $\theta_{\text{nominal}}=25^\circ$



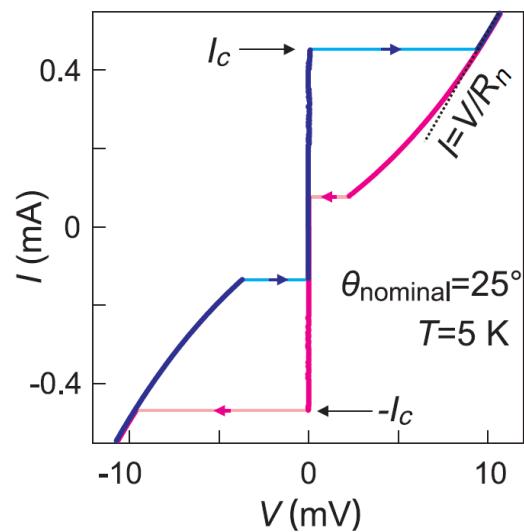
(e) No. 0227 $\theta_{\text{nominal}}=0^\circ$



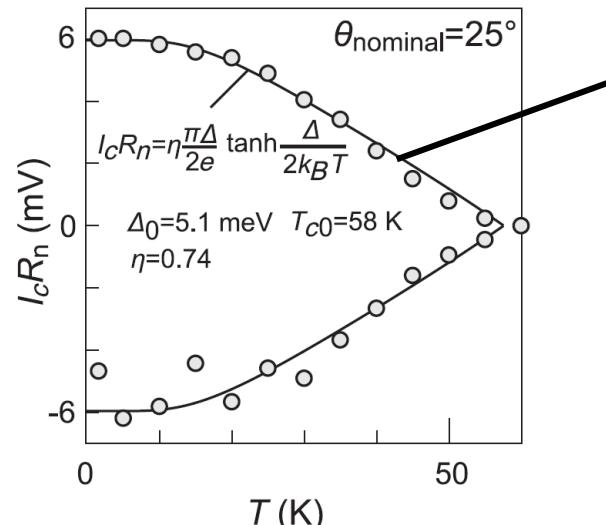
Temperature dependent resistance of the heterostructures



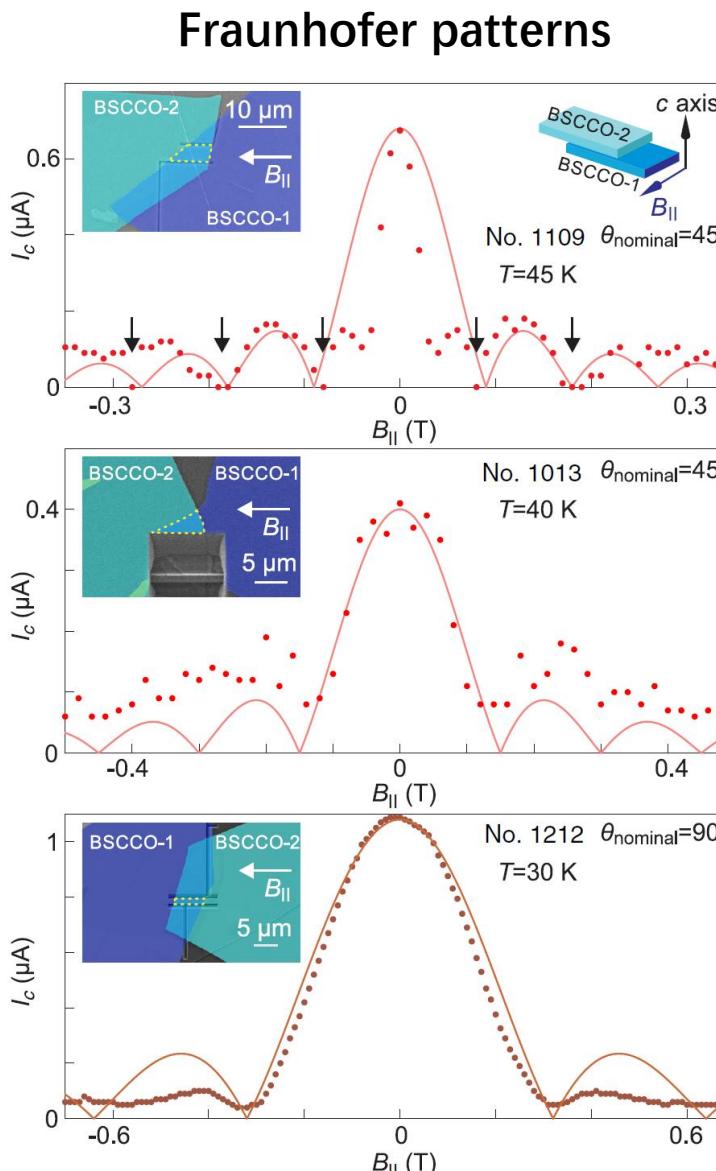
Josephson effect in twisted Bi-2212 junctions



I - V at different temperatures

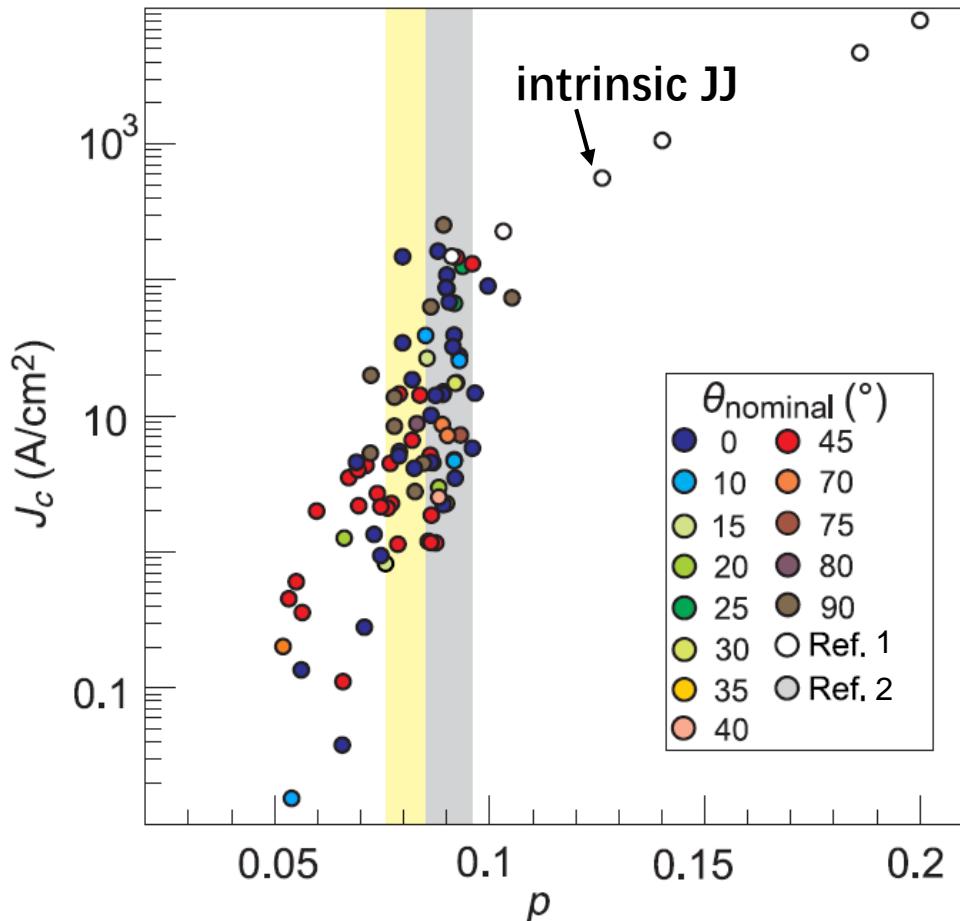


Ambegaokar-Baratoff
formula: S-I-S junction

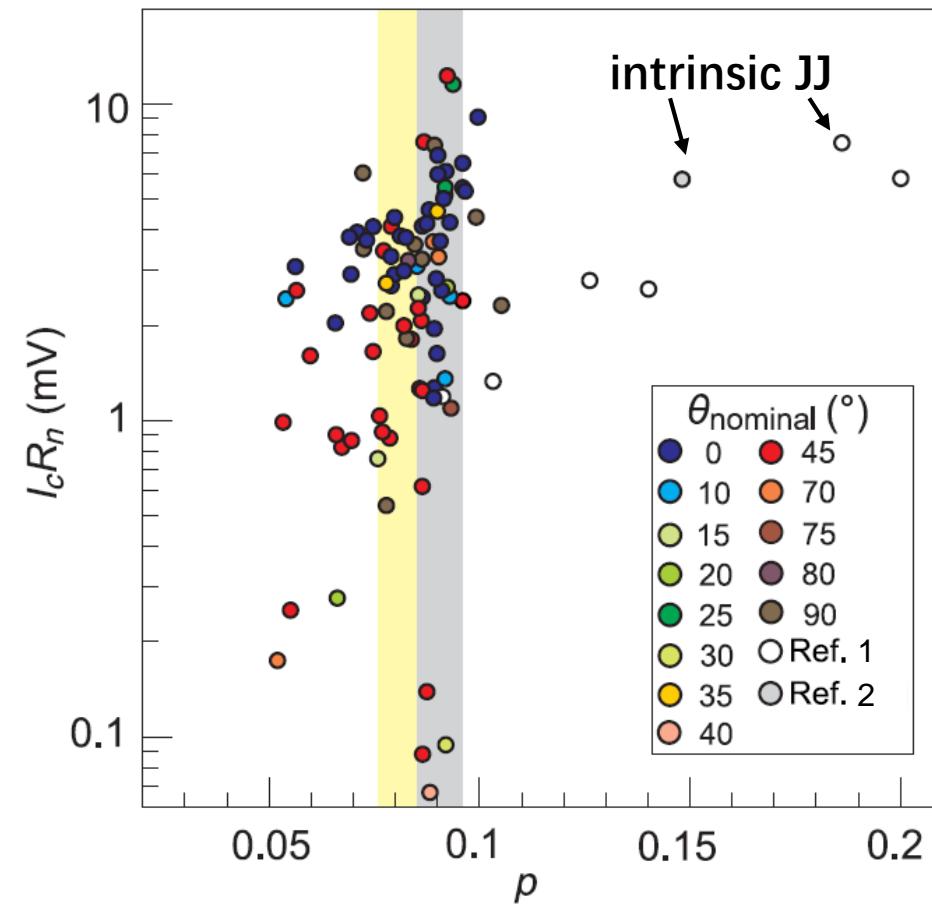


Doping dependent J_c and I_cR_n

J_c : critical current density



I_cR_n : Josephson coupling strength



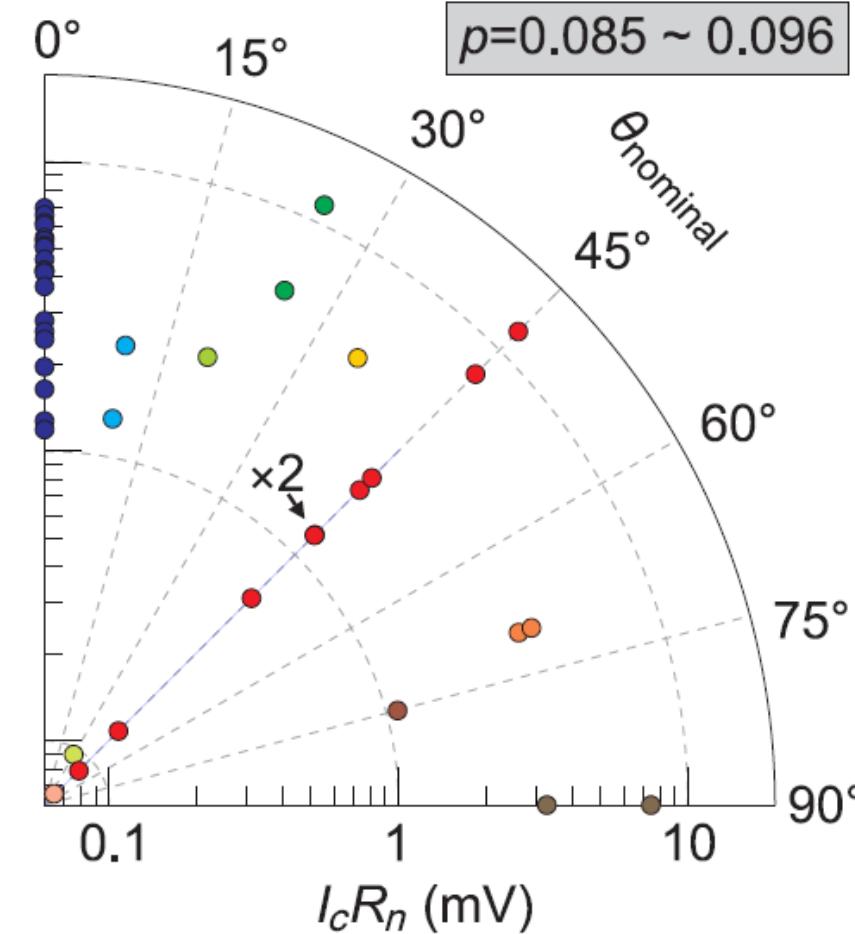
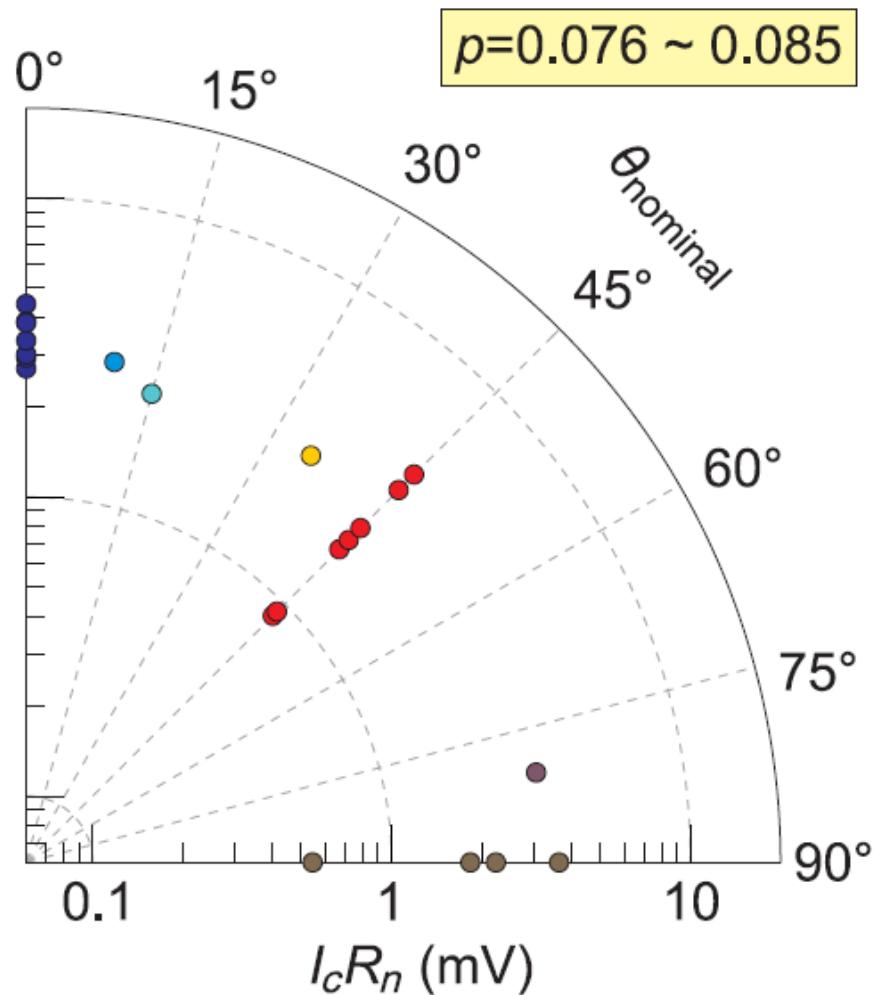
Y. Zhu, et al. *Phys. Rev. X*, **11**, 031011 (2021)

1. M. Suzuki, et al. *Phys. Rev. B* **85**, 214529 (2012).

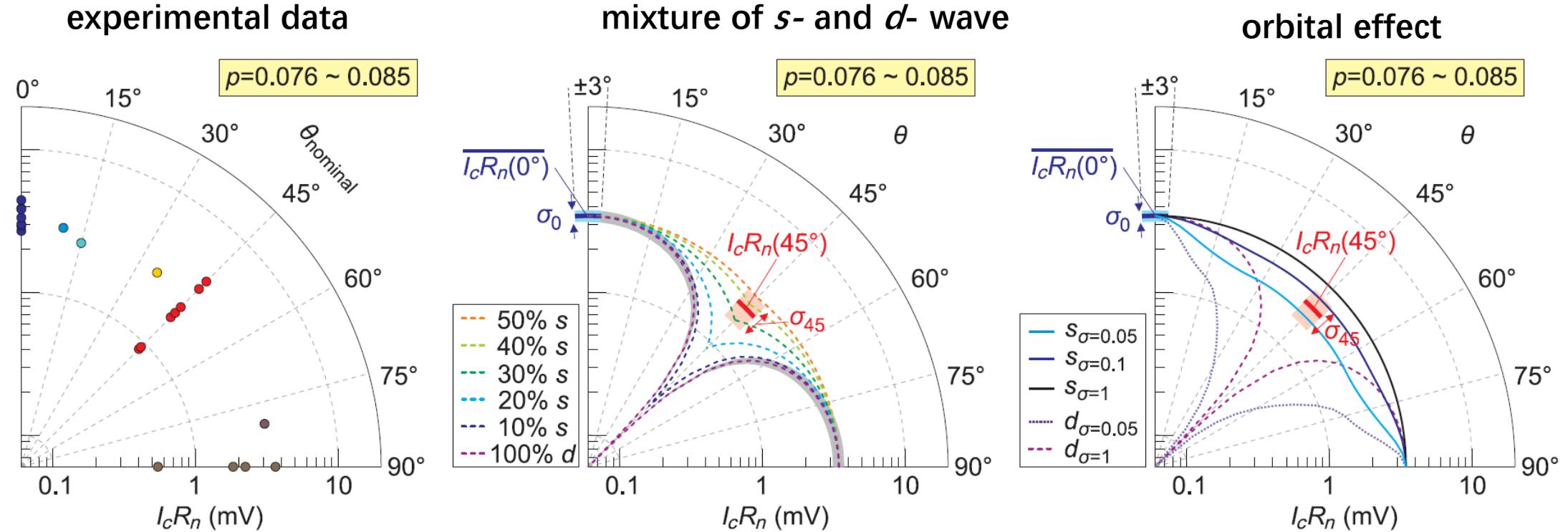
2. Y. Takano, et al. *Phys. Rev. B* **65**, 140513(R) (2002).

Josephson junction quality as high as intrinsic ones

Isotropic Josephson coupling strength at different twist angles



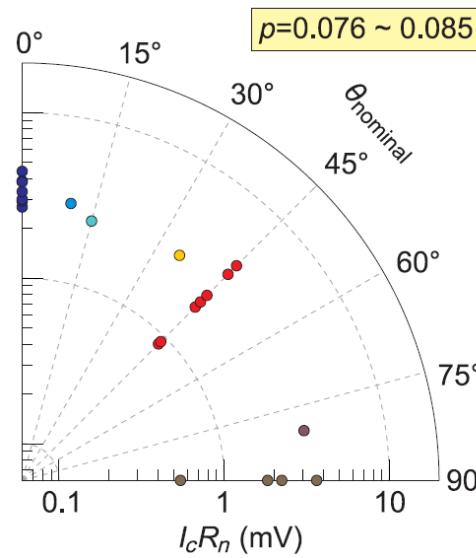
Isotropic Josephson coupling strength at different twist angles



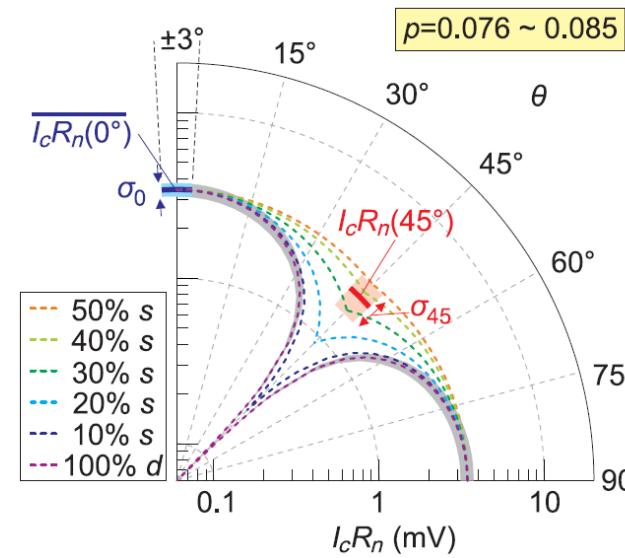
Significant s -wave component

Isotropic Josephson coupling strength at different twist angles

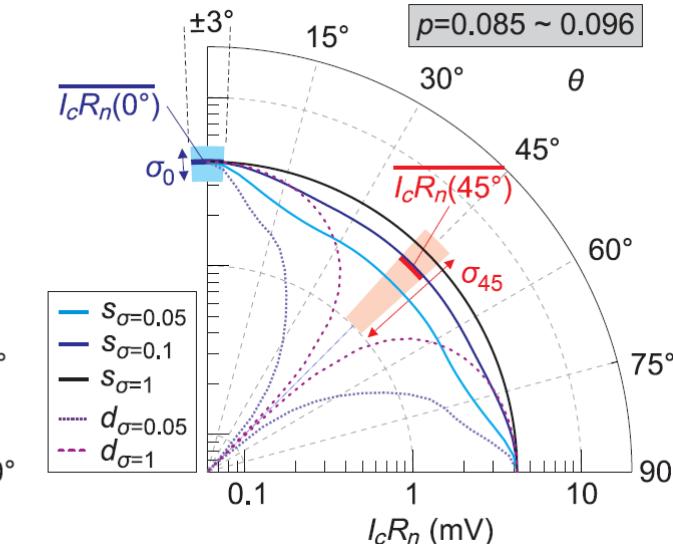
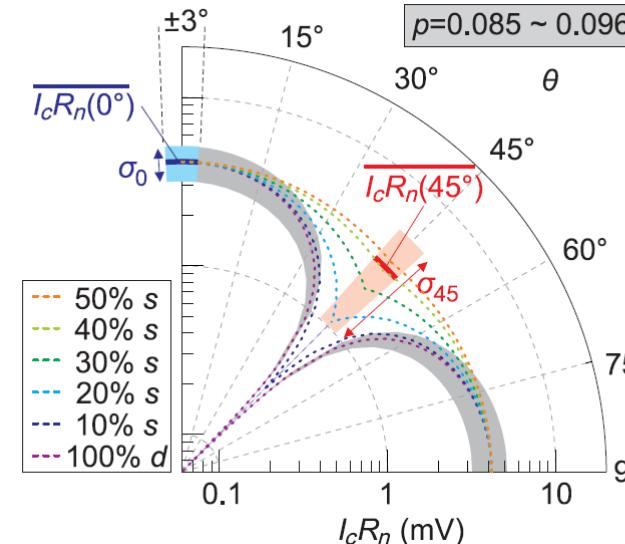
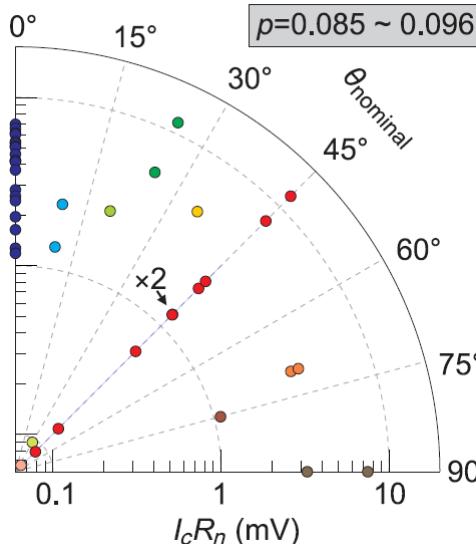
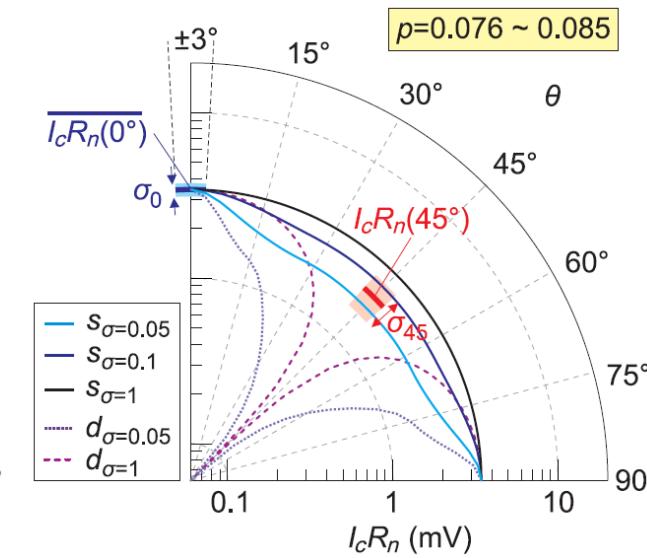
experimental data



mixture of s - and d - wave

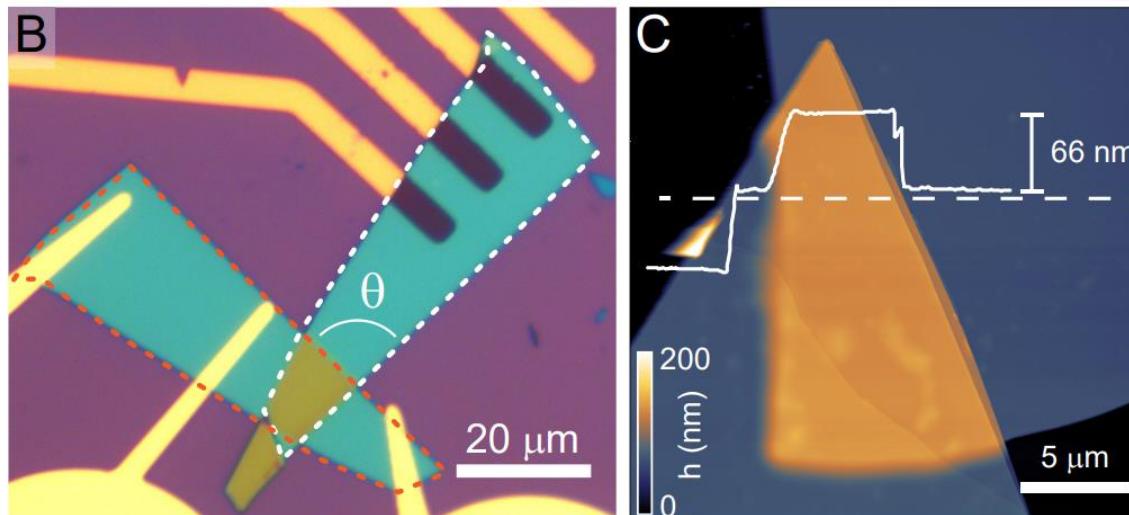
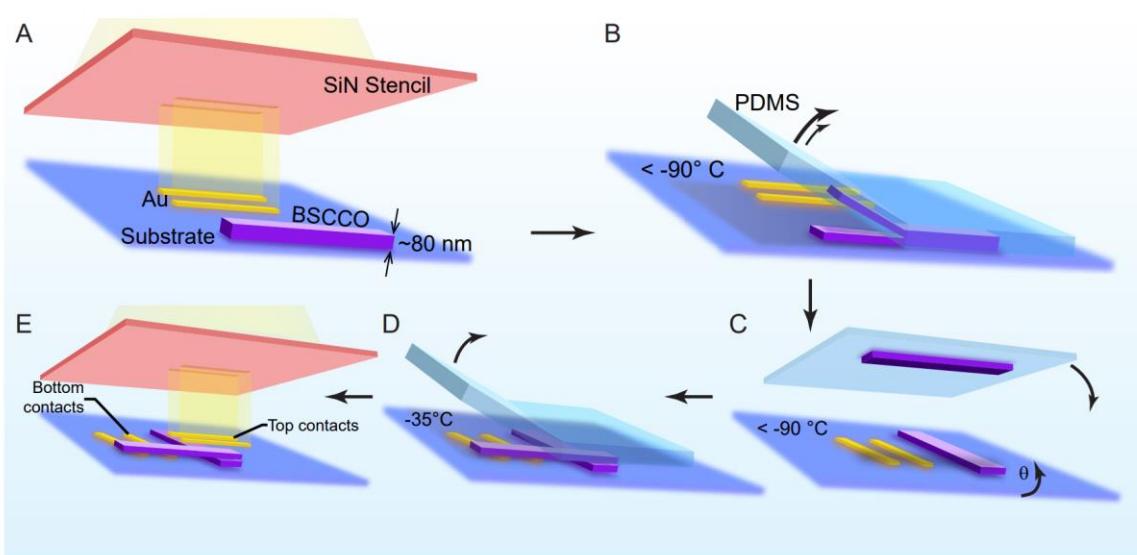


orbital effect

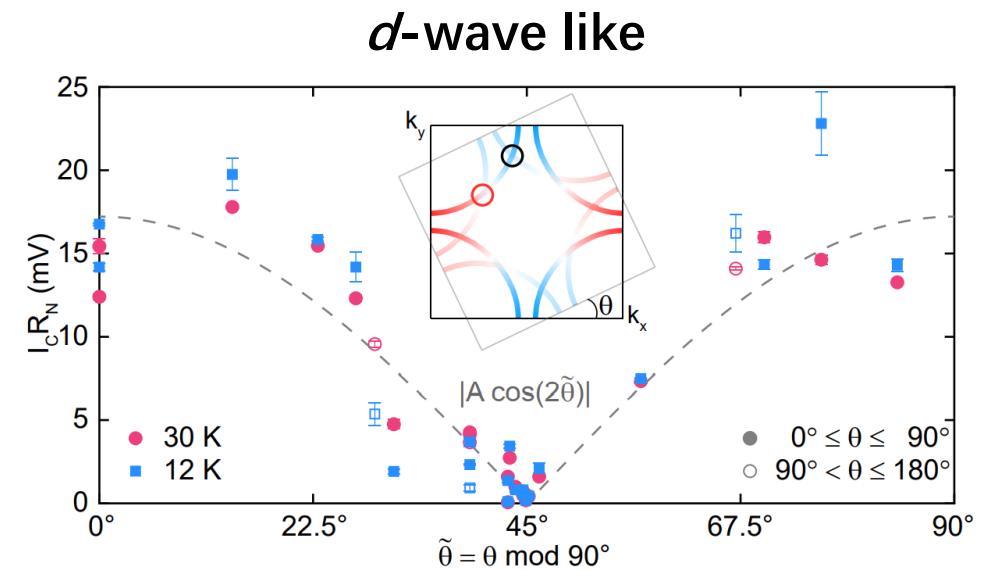


Significant s -wave component

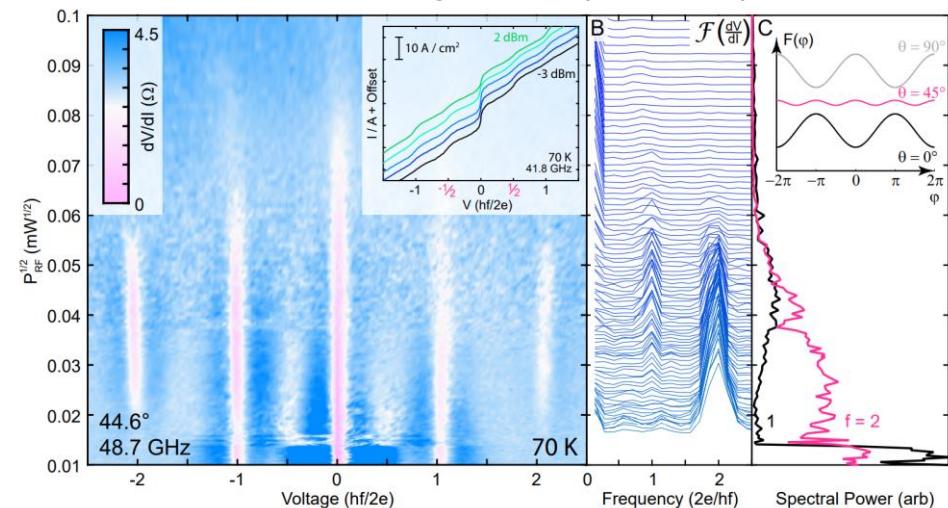
Cold transfer developed by S. Y. Zhao, et al



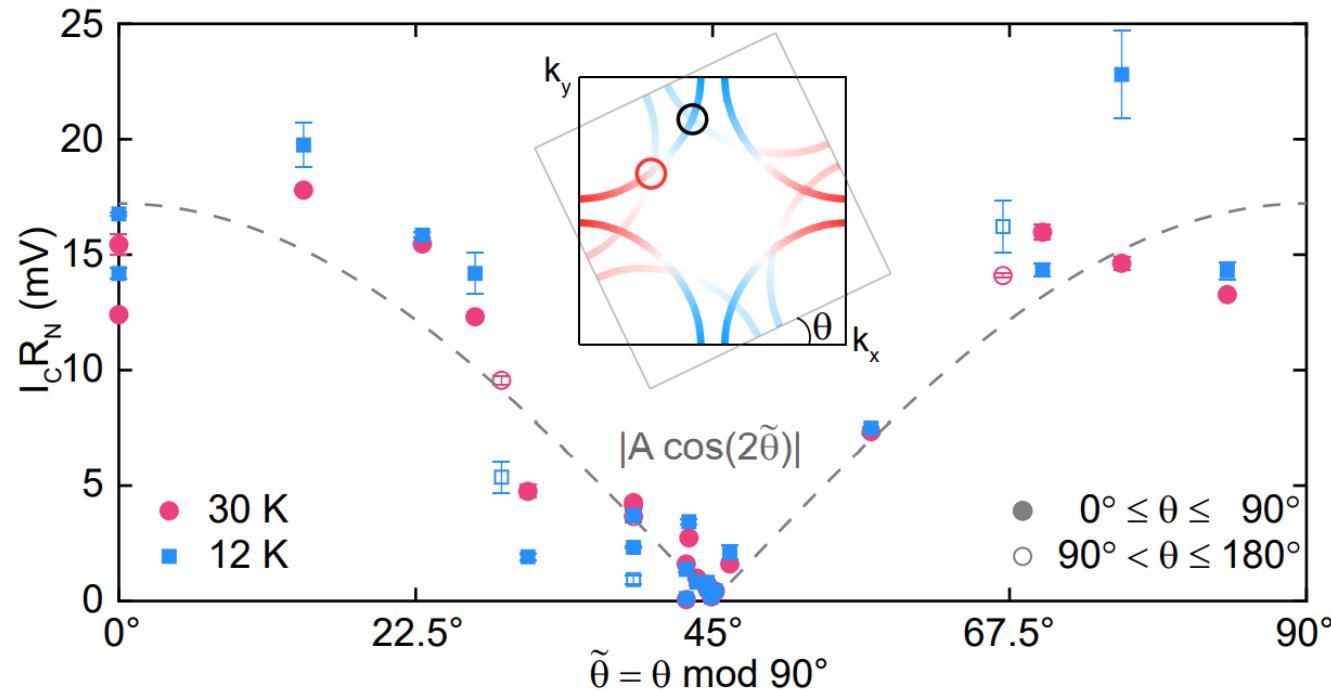
S. Y. Zhao, et al. arXiv:2108.13455, (2021).



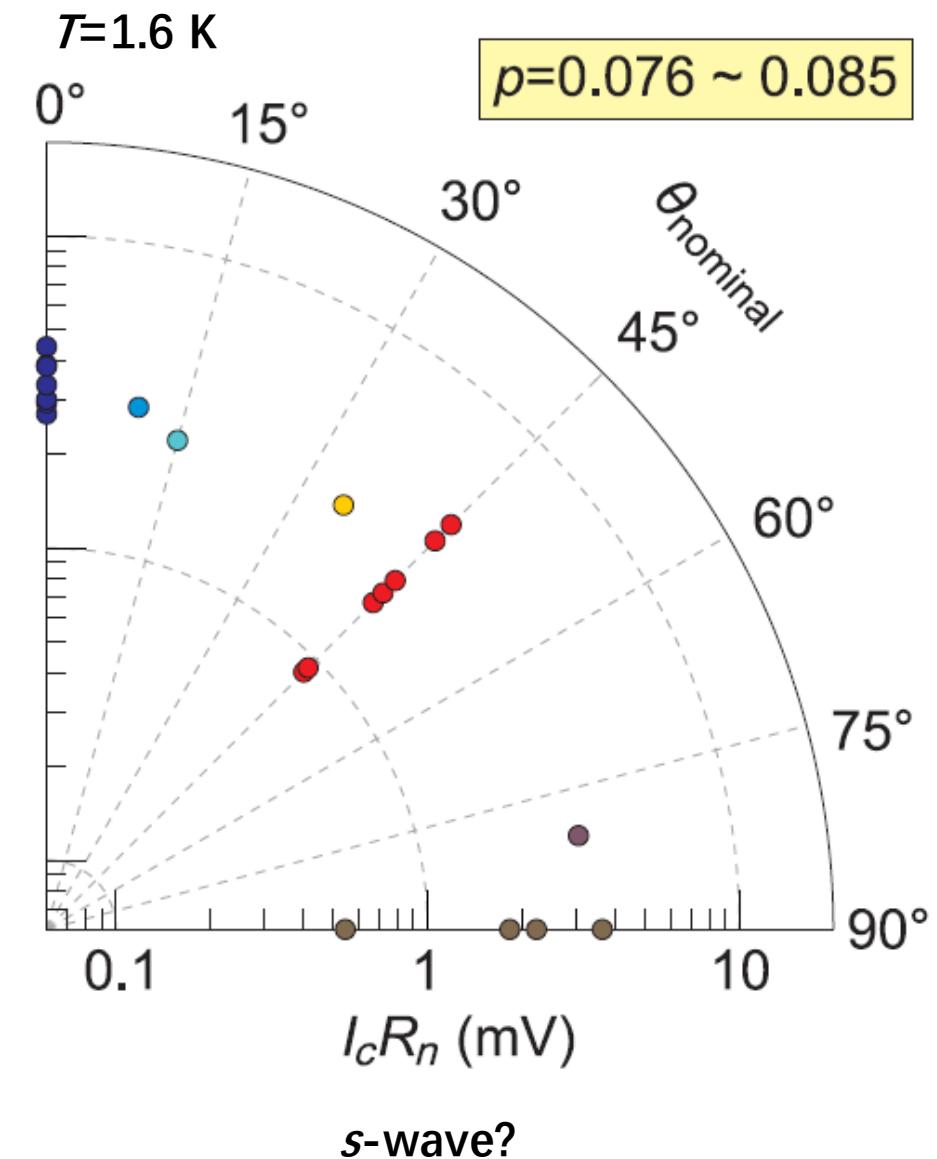
Co-tunneling of cooper pairs
Half-integer Shapiro steps



Twist angle dependent $I_c R_n$ at different temperatures



second order effect?
orbital effect?



s-wave?

Summary

- Atomic flat Bi-2212 Josephson junctions at different doping levels and twist angles
- Isotropic Josephson tunneling
- *s*-wave component