Cuprate twistronics towards a new generation of quantum hardwares

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Superpuddles Lab

Acknowledgments: the members and funding sources

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DAAD
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Terra Quantum

photo in 2023

Collaborators

Thank you to my main current collaborators in this journey that I will present you today


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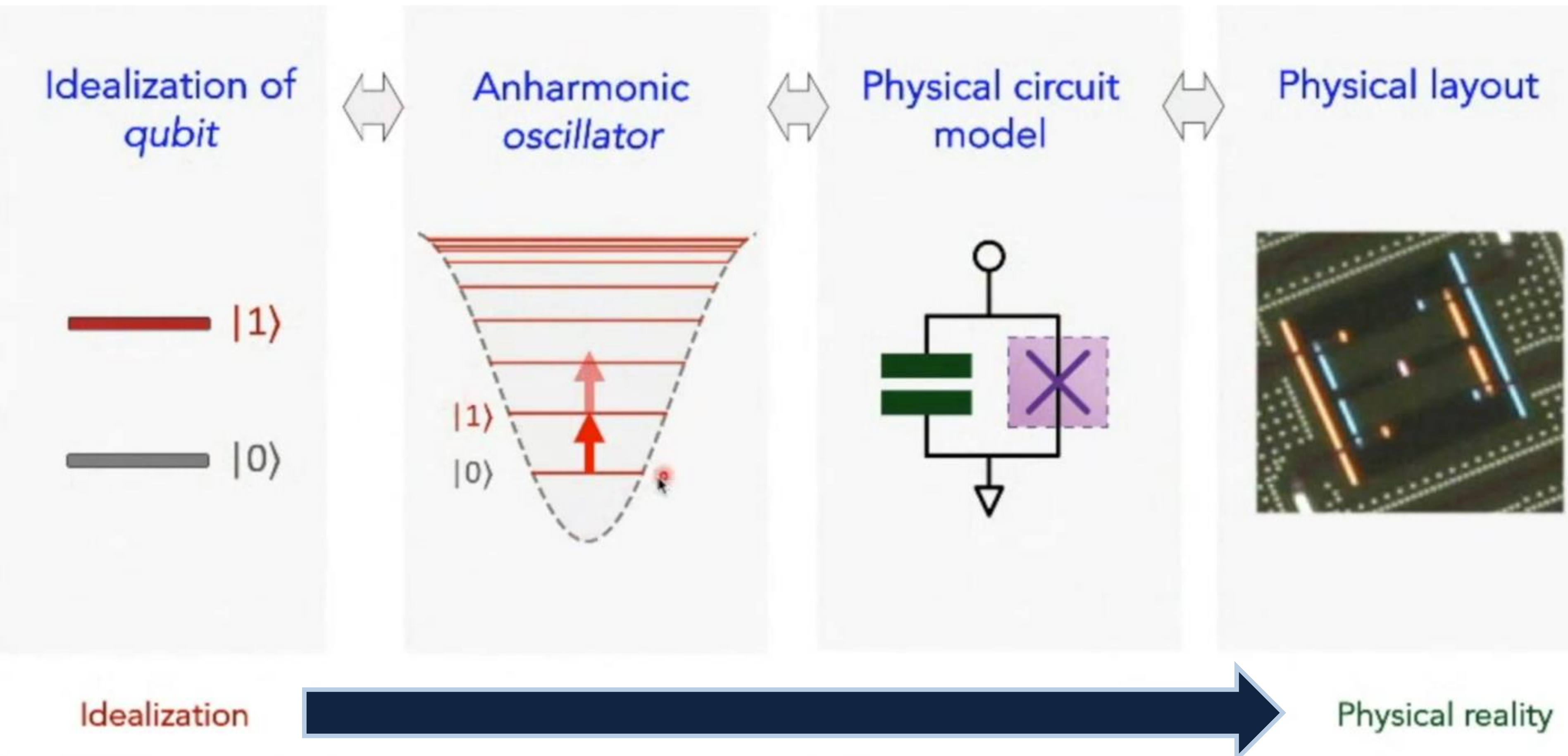
From idealization to physical reality



Krantz, Philip, et al. "A quantum engineer's guide to superconducting qubits." *Applied physics reviews* 6.2 (2019).

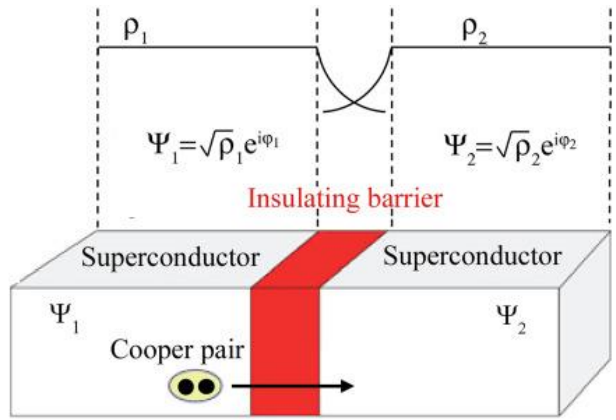
The grand-challenge in the Josephson-effect: the detrimental disorder

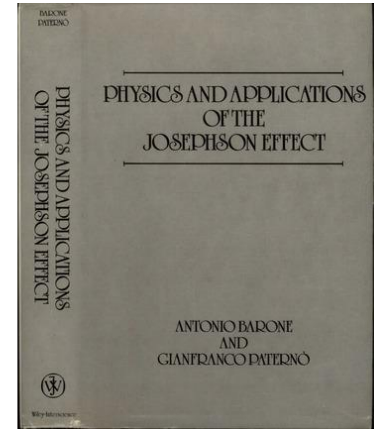
$$I(t) = I_c \sin(\phi(t))$$

$$\frac{\partial \phi}{\partial t} = \frac{2eV(t)}{\hbar}$$

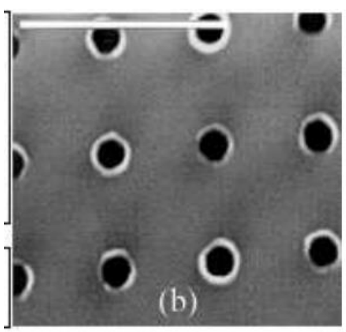
B. D. Josephson, *Physical Letters.* *1*, 251–253 (1962).

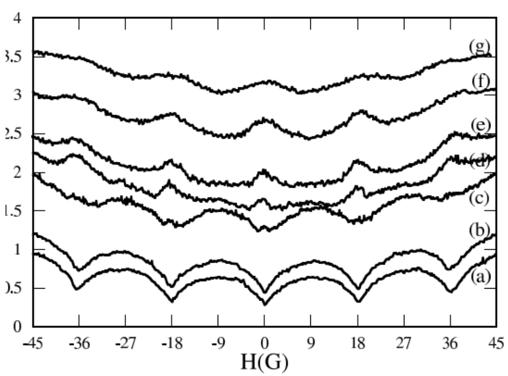
A. Barone, G. Paterno. *Physics and applications of the Josephson effect*. 1982.



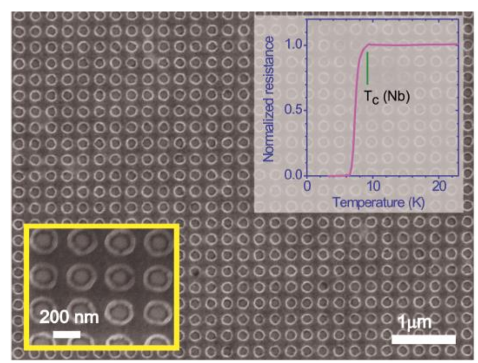


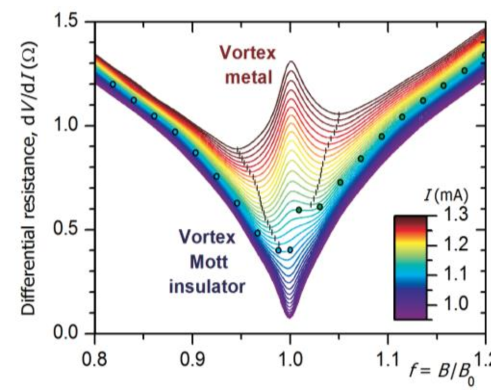
Minimizing detrimental disorder





Z. Jiang, et al. *Applied physics letters* 84 5371-5373 (2004) .

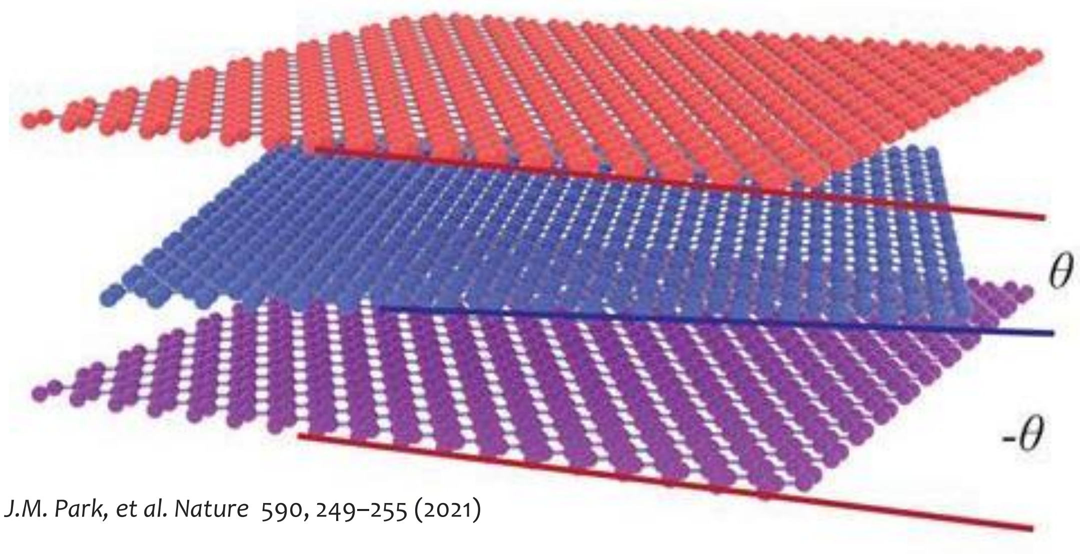




NP et al., *Science* 349, 202-1205 (2015)

A revolution in materials science

Twistronics = 2D materials + twist angle



J.M. Park, et al. Nature 590, 249–255 (2021)

Unprecedented tunability

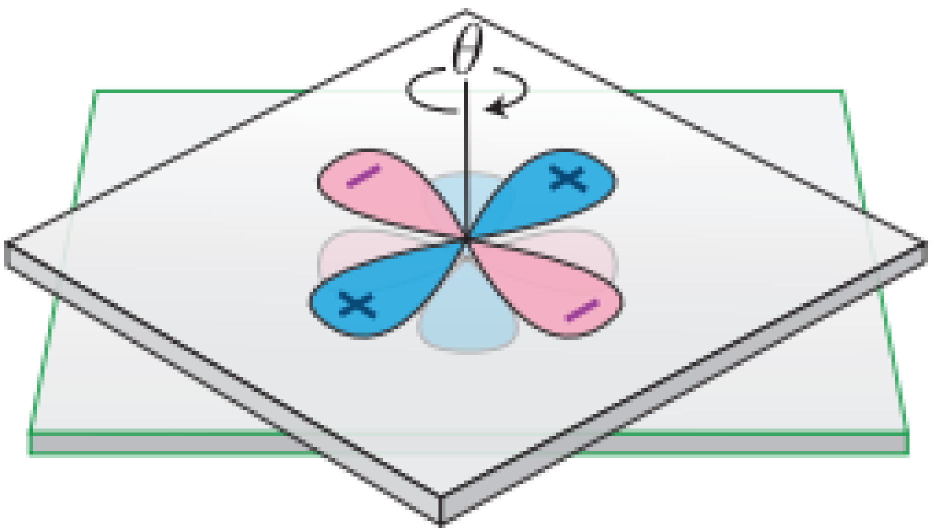
- Correlated physics
- Superconductivity
- Topological matter

- Cuprates materials show an inexplicable macroscopic quantum state.

  J. Bednorz and K.A. Müller Zeitschrift für Physik B Condensed Matter 64, 189-193 (1986).

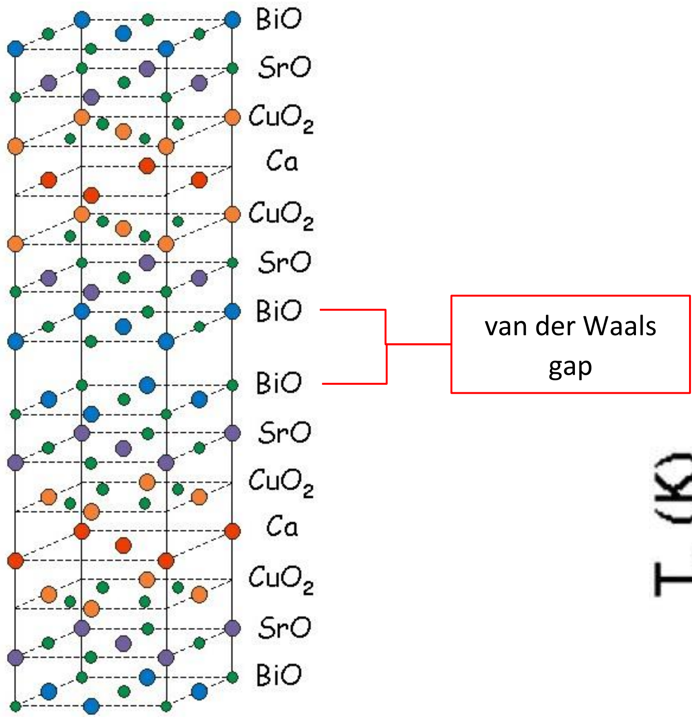
- Twisted cuprate structures proposed for exploring new physics.

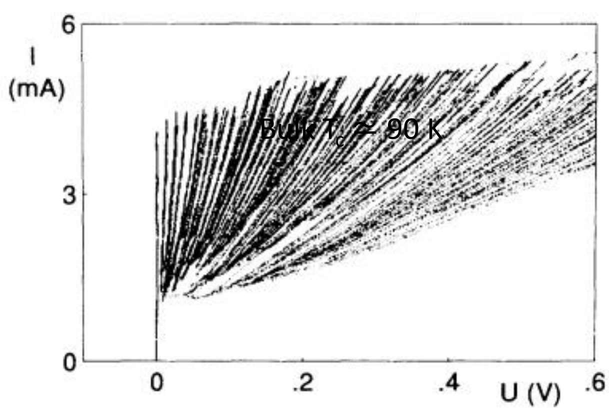
  M. Sigrist, *Progress of theoretical physics 99, 899-929 (1998)*

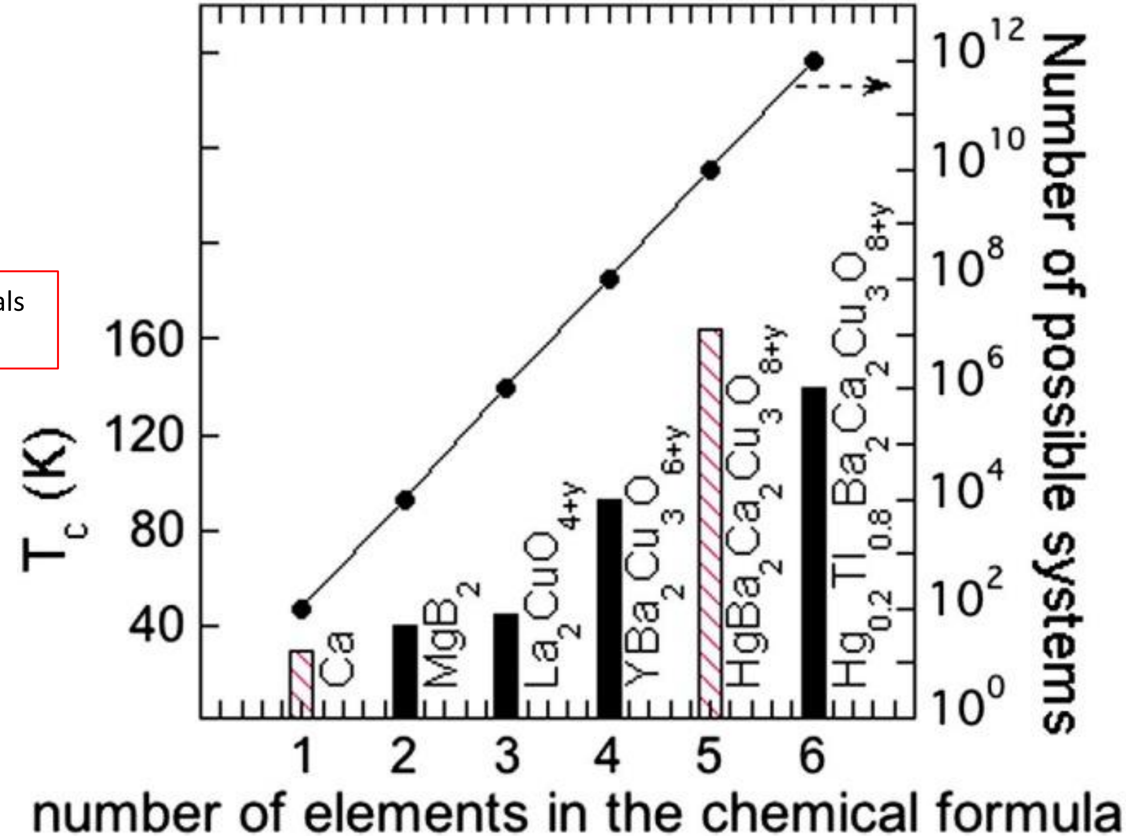


Physics of complexity meet macroscopic quantum states

Wikipedia







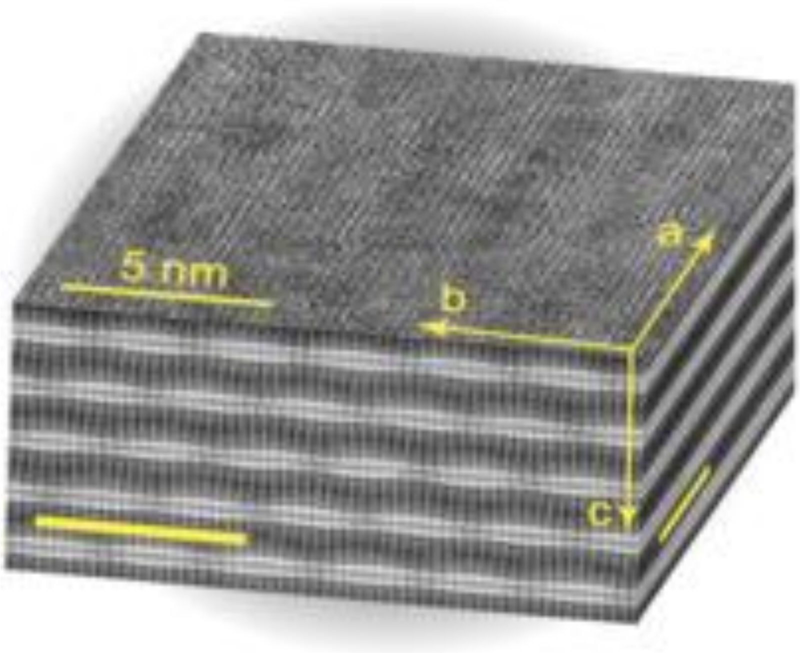
NP et al. *Proceedings of the National Academy of Sciences* 109, 15685-15690 (2012).

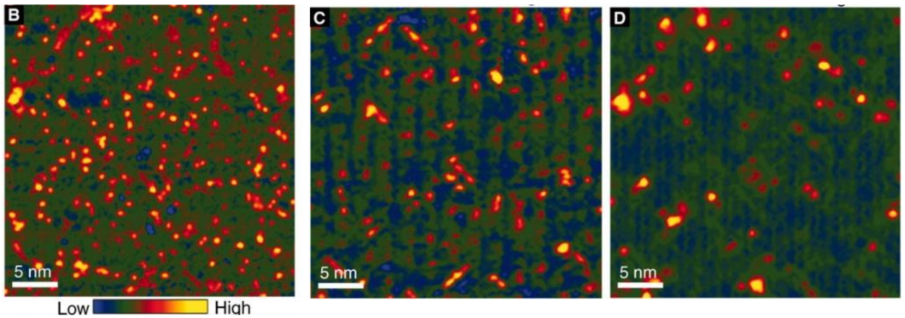
- Intrinsic Josephson junctions in the $Bi_2Sr_2CaCu_2O_{8+x}$ crystal structure

R. Kleiner, et al. *Physical review letters* 68 2394 (1992).

The complexity created by the oxygen interstitials

the most vagabond among the elements





Apical oxygen, O-i near SrO, O-i near BiO,

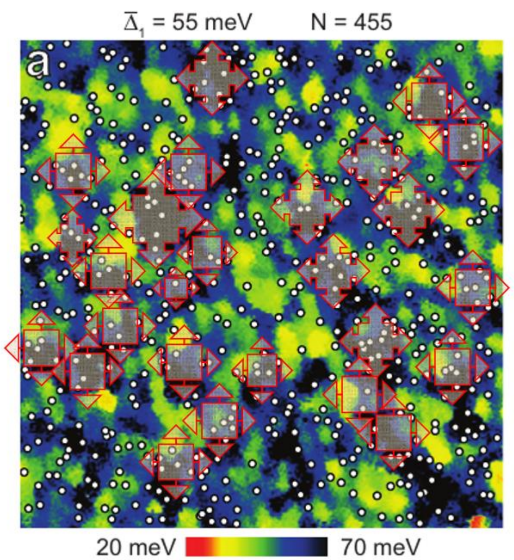
I. Zeljkovic, et al. *Science* 337, 320-323 (2012).

- Incommensurate superlattice modulation

NP et al, *Physical Review Materials* 4, 114007 (2020).

- Oxygen interstitals nanopuddles in Bi2212

V. Velasco, et al. *Journal of Condensed Matter Physics* 35, 415602 (2023)



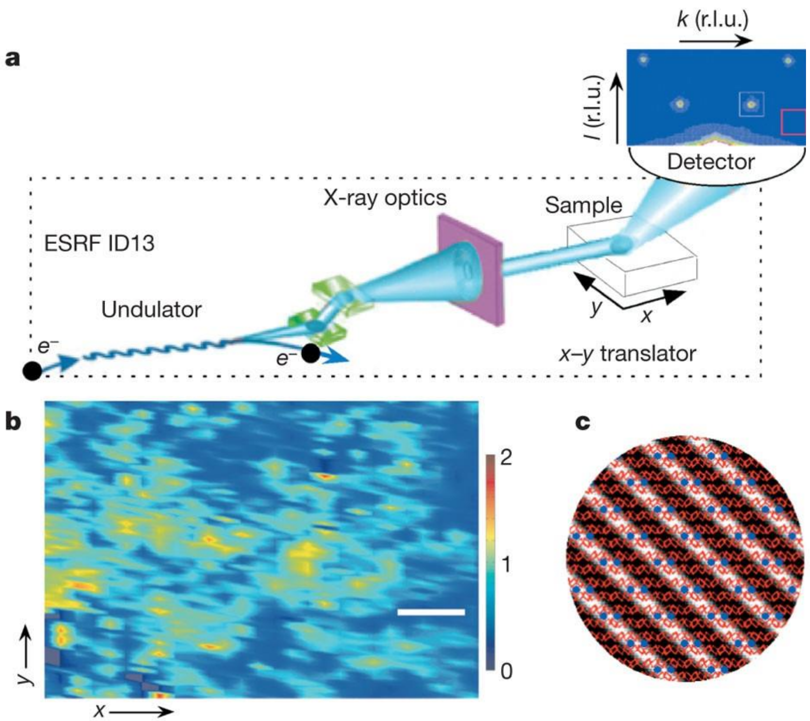
- Superconducting gaps inhomogeneity in Bi2212

Fischer, Øystein, et al. *Reviews of Modern Physics* 79 353 (2007)

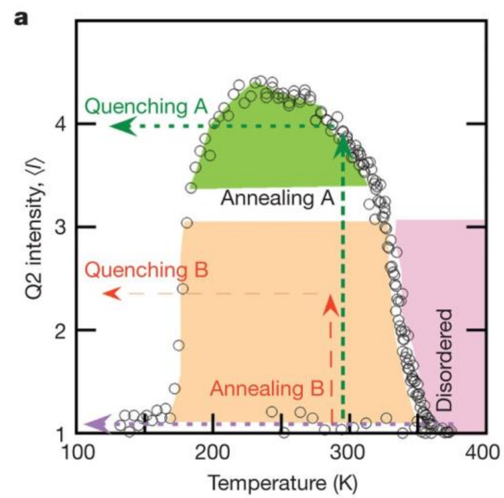
Evolution of oxygen order in cuprate superconductors

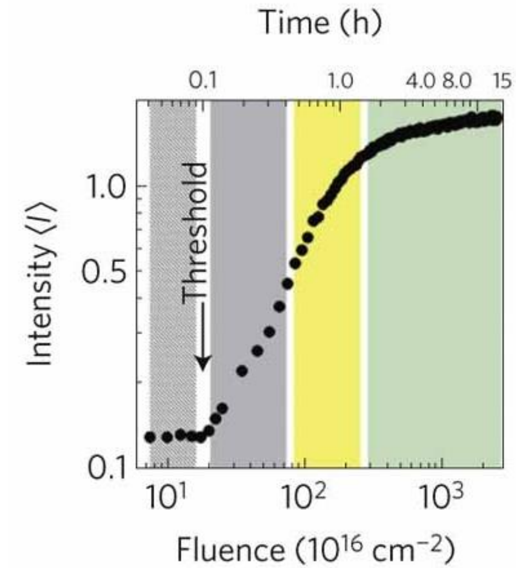
How do we know that oxygen interstitials are frozen below 200K?

- **Oxygen interstitials order form fractal structures** that seem to promote high-temperature superconductivity



M. Fratini, NP, et al. *Nature* 466, 841-844 (2010).





- **Oxygen interstitials order can be tuned** with continuous exposition to synchrotron X-ray light **in between 200-300** K.

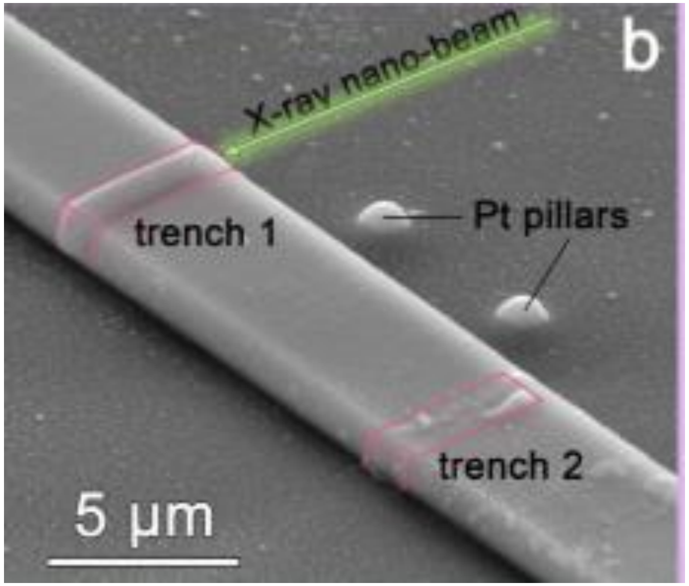
NP et al. *Nature Materials* 10, 733-736.(2011)

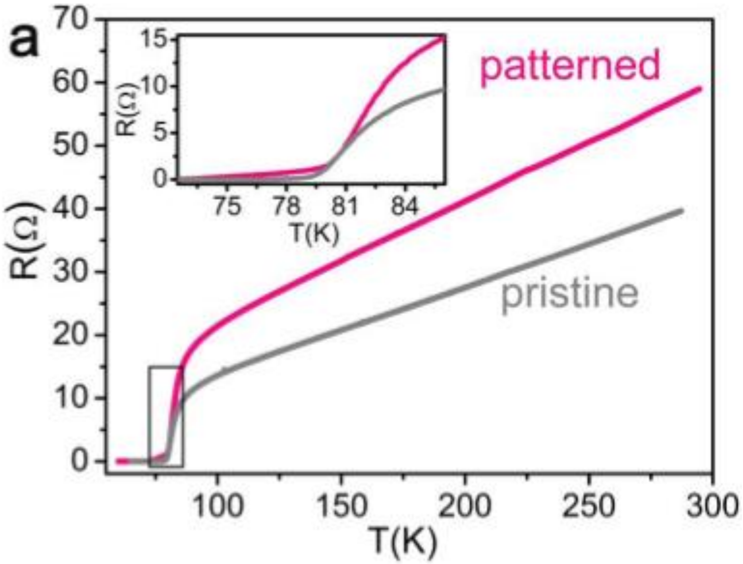
- A solvent-polymer free lithographic process is proposed using continuous X-ray light illumination for creating **Josephson junctions** with a cuprate superconductor.

NP, et al. *Superconductor Science and Technology* 25 124004 (2012)

Solvent-polymer free X-ray lithographic process

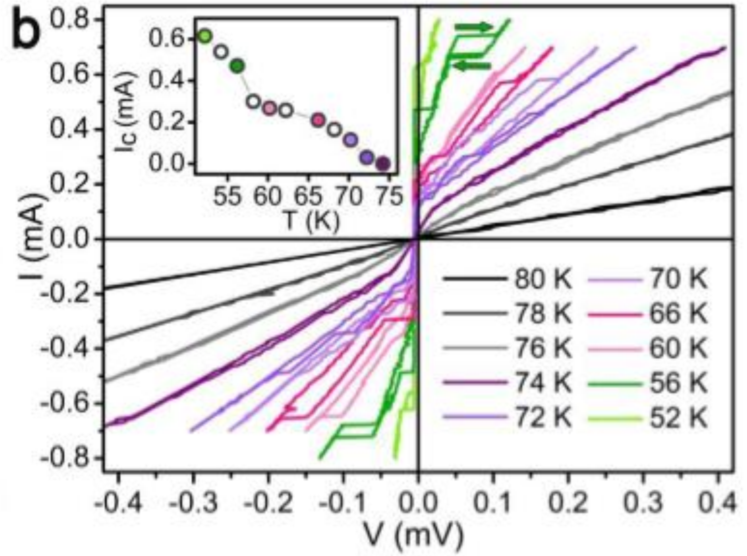
Detrimental disorder created by the depletion and diffusion of oxygen





- Fully functional Josephson junctions devices have been obtained by locally turning the material into a nonsuperconducting state by means of hard nano X-ray exposure.

M. Truccato, *et al. Nano Letters* 16 1669-1674 (2016)

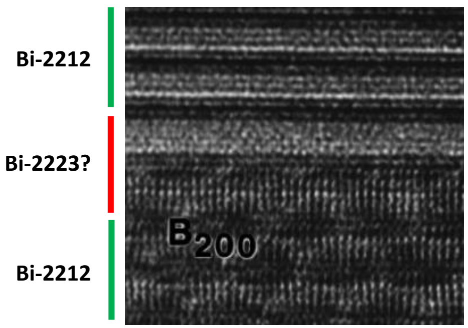


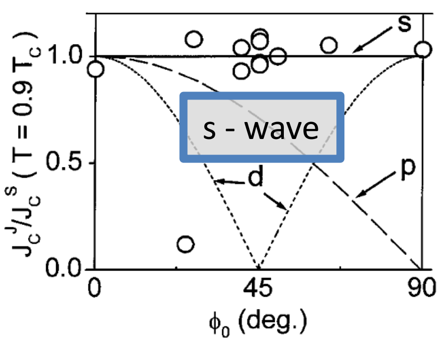
However, I_c and T_c control in the Josephson junction is challenging

Stacked and twisted $Bi_2Sr_2CaCu_2O_{8+x}$ crystals.

The detrimental disorder is introduced by the high temperature (up to 850 °C) oxygen annealing

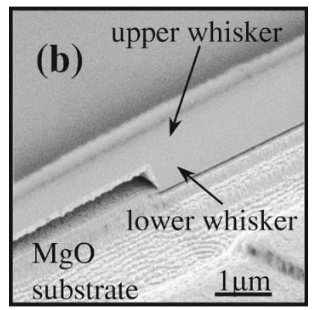
Bulk Crystals

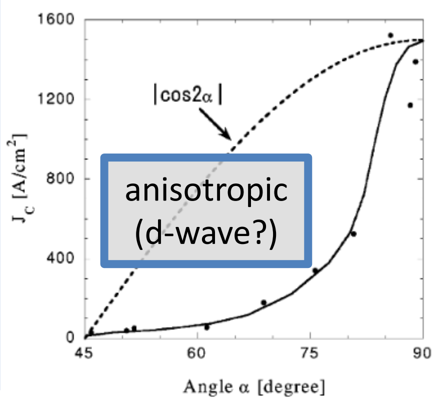




Q. Li, et al. *Physical review letters* 83, 4160 (1999).

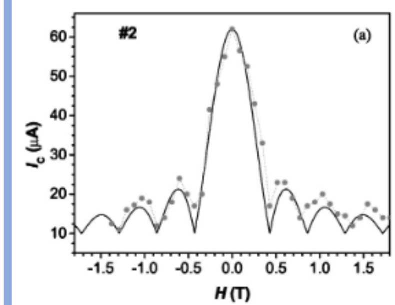
Artificial Whisker Junctions

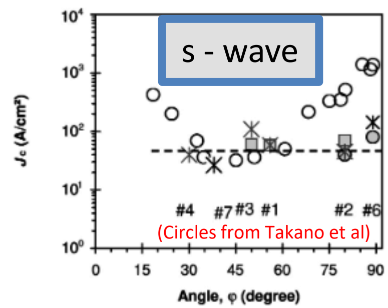




Y. Takano, et al. *Physical Review B* 65, 140513 (2002).

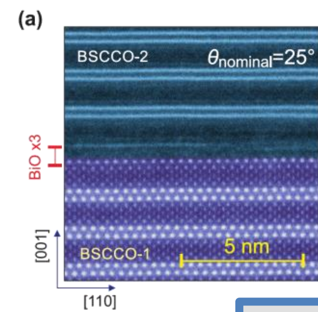
Natural Whisker Junctions



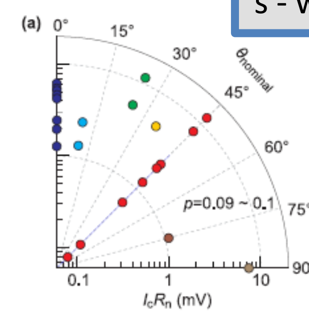


Y. I. Latyshev, et al. *Physical Review B* 70 094517 (2004).

Exfoliated Flakes



s - wave



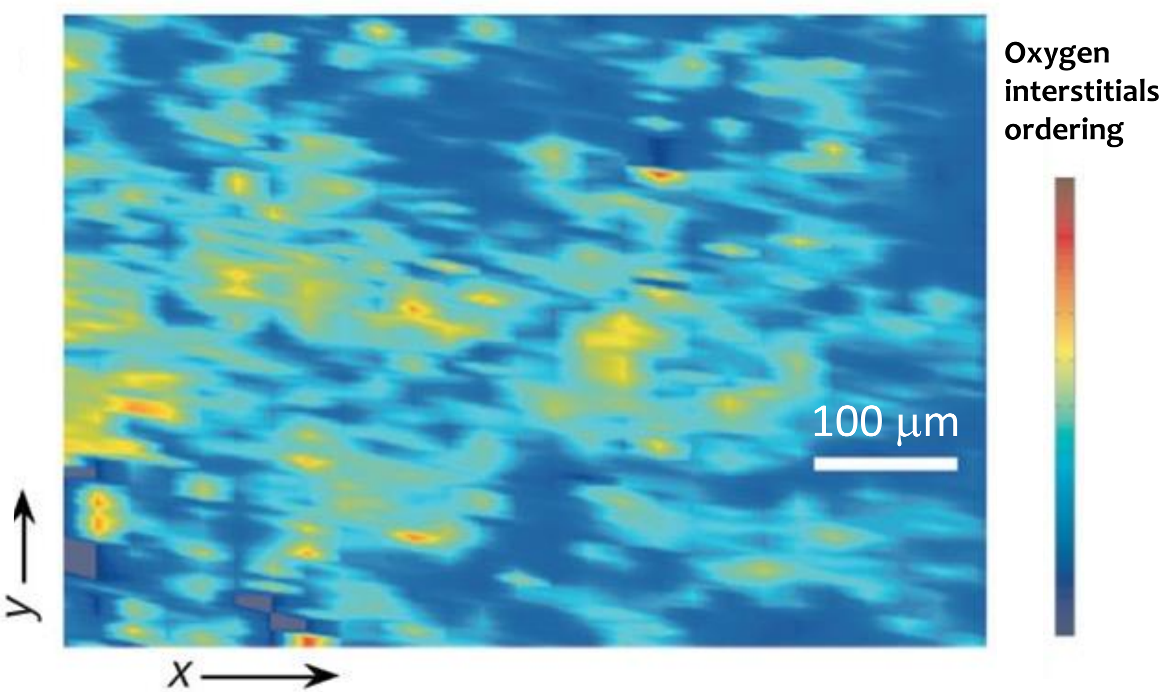
Y. Zhu, et al. *Physical Review X* 11, 031011 (2021).

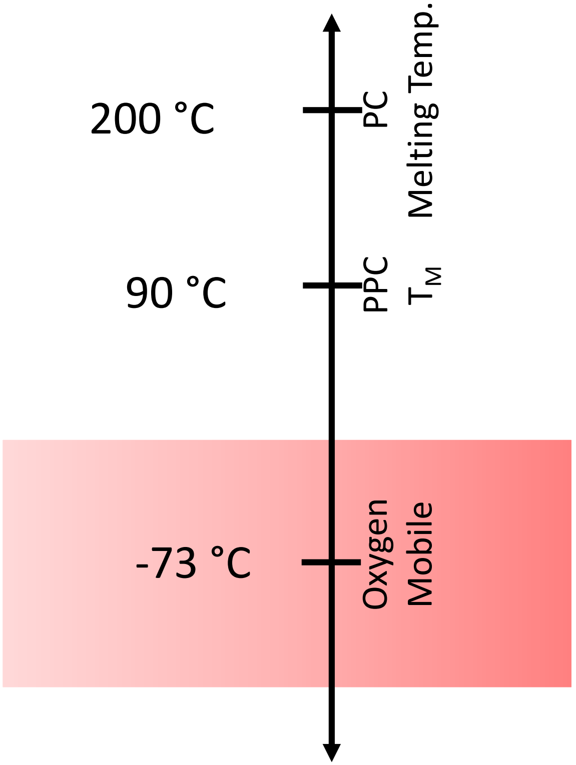
Oxygen diffusion mechanisms are different in the ab-plane (activation 0.9eV) and along the c-axis (activation 2eV).

The c-axis diffusion coefficient increases from 10^{-17} to $10^{-12}\,\frac{cm^2}{s}$ respectively for 400 °C and 700 °C.

M. Runde, et al. *Physical Review B* 45, 7375 (1992)

Minimizing detrimental disorder in twisted cuprate interfaces is a 25 years long challenge.



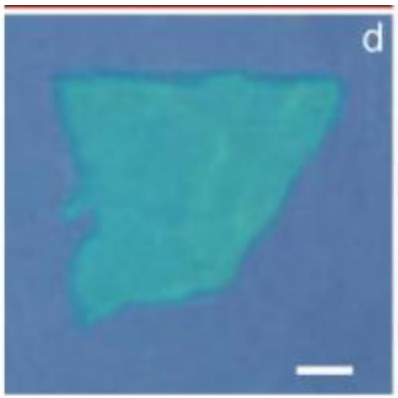


Essential hetereogeneities are determined in cuprates by the oxygen interstitials self-organization which **can be erased at high temperatures.**

M. Fratini, NP, et al. *Nature* 466, 841-844 (2010).
NP et al. *Nature Materials* 10, 733-736.(2011)
NP, et al. *PNAS* 109 15685-15690 (2012).
G. Campi, NP, et al *Nature* 525, 359-362 (2015)

Challenge: Finding a stacking methodology which works below -73 °C .

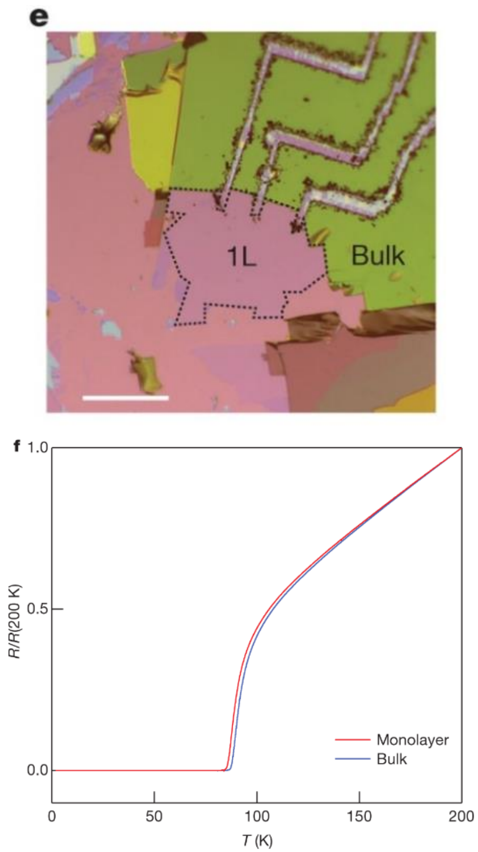
Starting with the isolation of optimally superconducting $Bi_2Sr_2CaCu_2O_{8+x}$ atomically thin crystals.

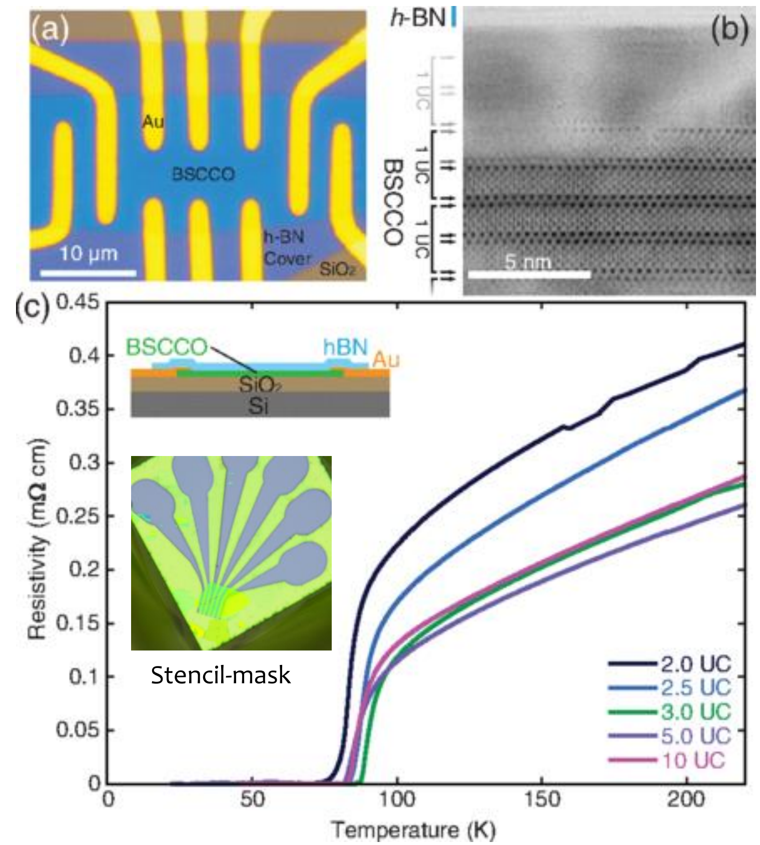


$Bi_2Sr_2CaCu_2O_{8+x}$ crystals are exfoliated on a SiO_2 substrate with the scotch-tape method.

Chemical reactivity turns the crystals insulating.

K.S. Novoselov, et al. *Proceedings of the National Academy of Sciences* 102, 10451-10453 (2005)

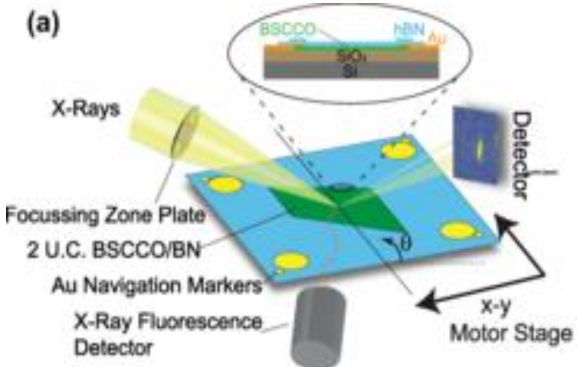


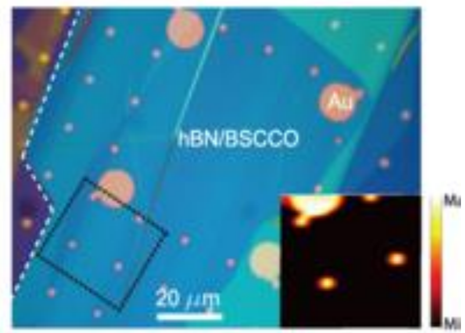


Isolation of optimally superconducting $Bi_2Sr_2CaCu_2O_{8+x}$ atomically thin crystals achieved in 2019.

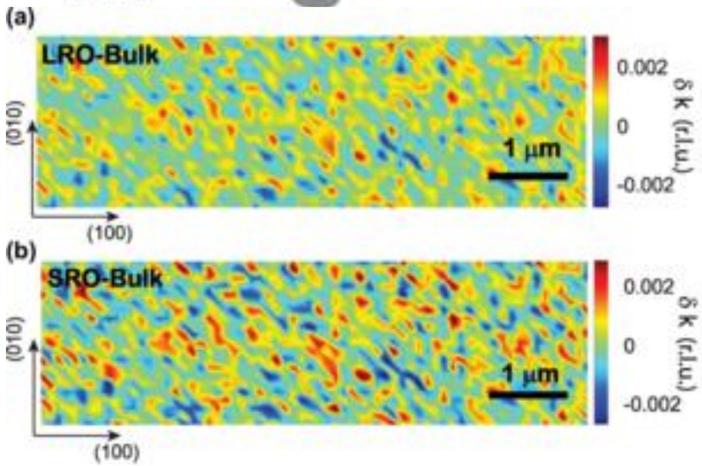
- **Heat sensitivity** during the exfoliation is overcome by cooling the SiO_2 substrate at -40°C.
  Y. Yu, et al. *Nature* 575 156-163 (2019)
- **Chemical reactivity** for the realization of the electrical contacts in a nanodevice is overcome by the stencil mask method
  S.Y. F. Zhao, NP, et al. *Physical review letters* 122 247001 (2019)

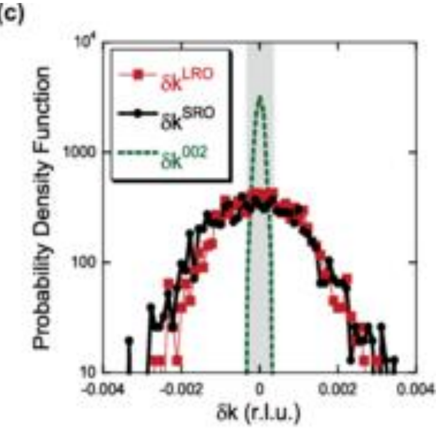
Detrimental dislocations in optimally superconducting $Bi_2Sr_2CaCu_2O_{8+x}$ atomically thin crystals.





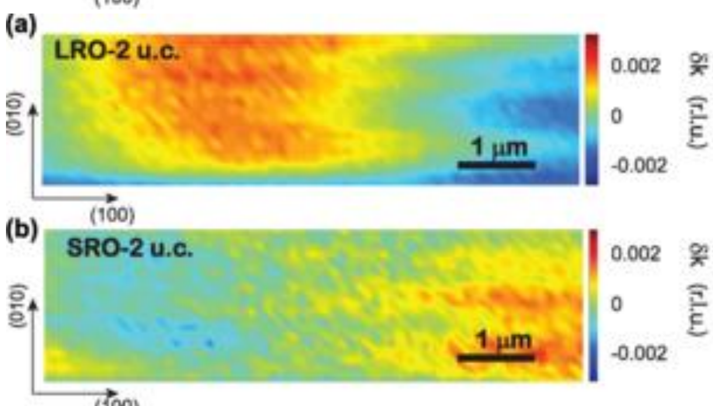
- Lattice must be as frozen as possible during any fabrication involving $Bi_2Sr_2CaCu_2O_{8+x}$ surfaces.

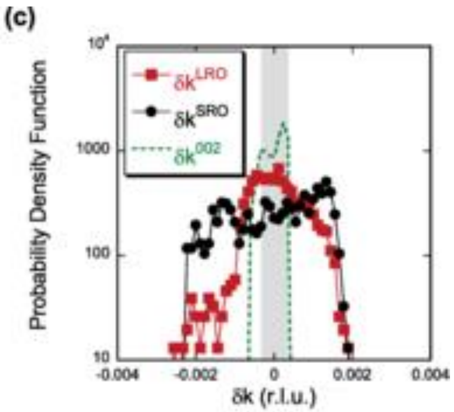




r-k gaussian-like disorder in the incommensurate superlattice

Thinning the crystals

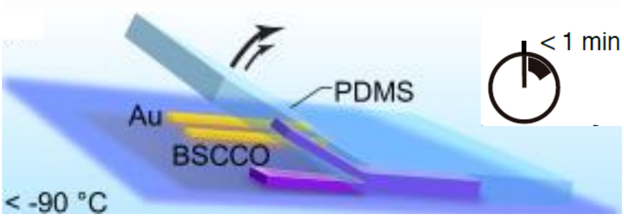


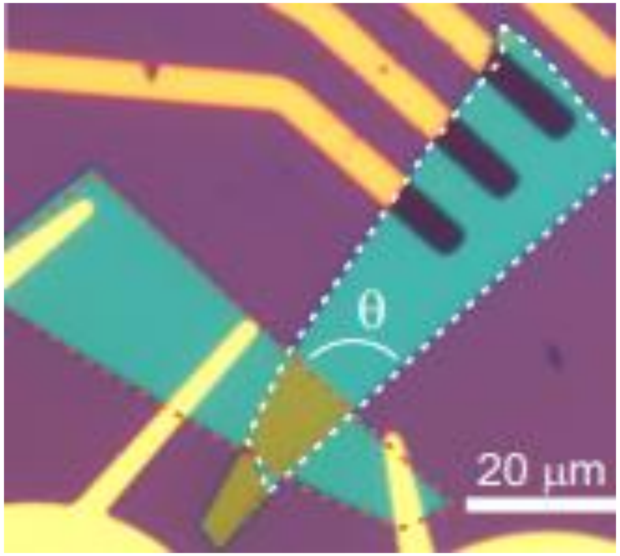


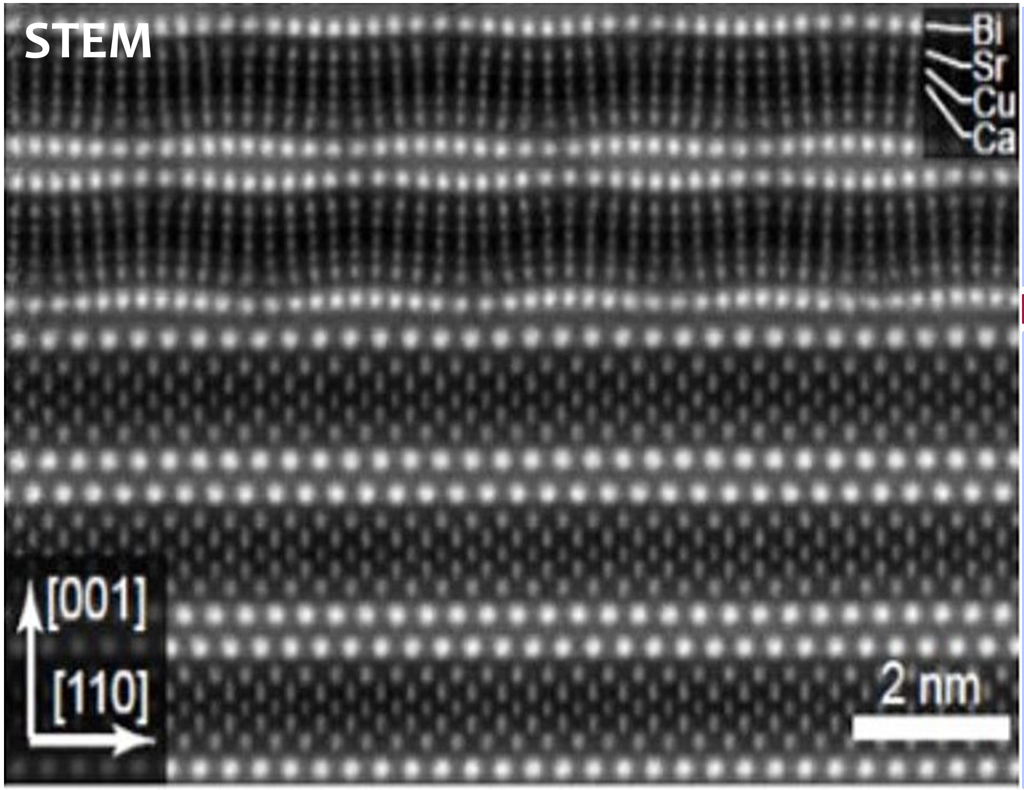
r-k non-gaussian disorder in the incommensurate superlattice

NP et al, *Physical Review Materials* 4, 114007 (2020)

A novel methodology for ultra-clean twisted cuprate interfaces!







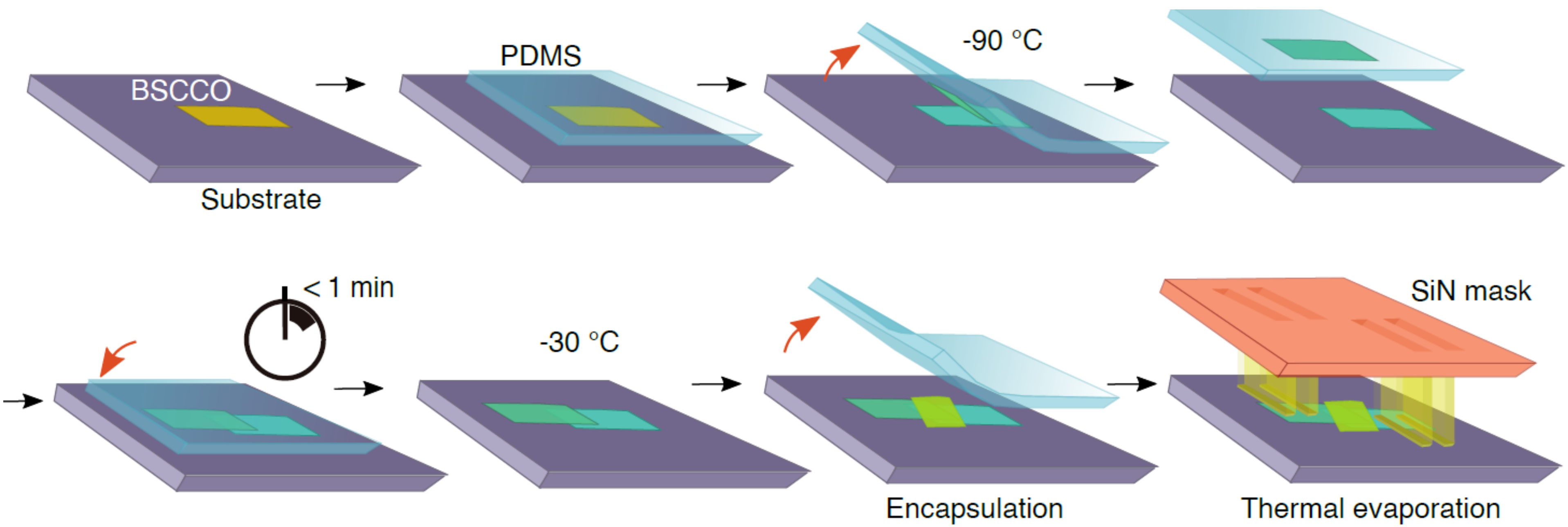
S.Y. F. Zhao, NP et al. *Science* 382, 1422-1427 (2023)

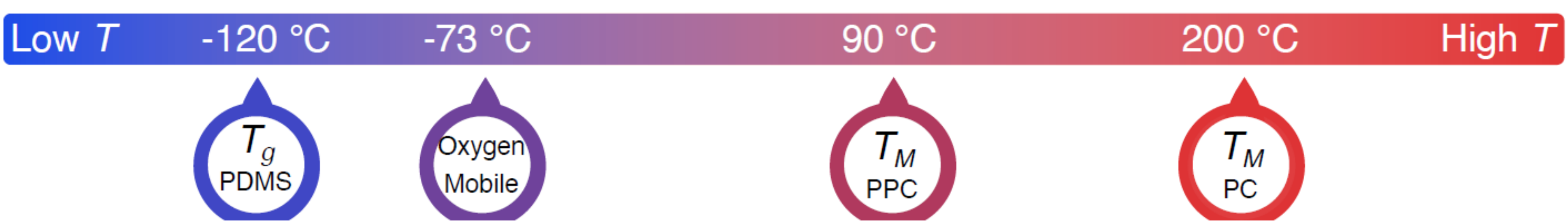
Y. Lee, NP et al. *Advanced Materials* 35, 2209135 (2023)

M. Martini, NP et al. *Materials Today*, 67, 106-112 (2023)

Engineering **complexity, topological** and **strongly correlated physics** in one system and in a wide temperature range

The silicon polymer PDMS becomes stickier close to its glass transition temperature T_g ~ -120 °C

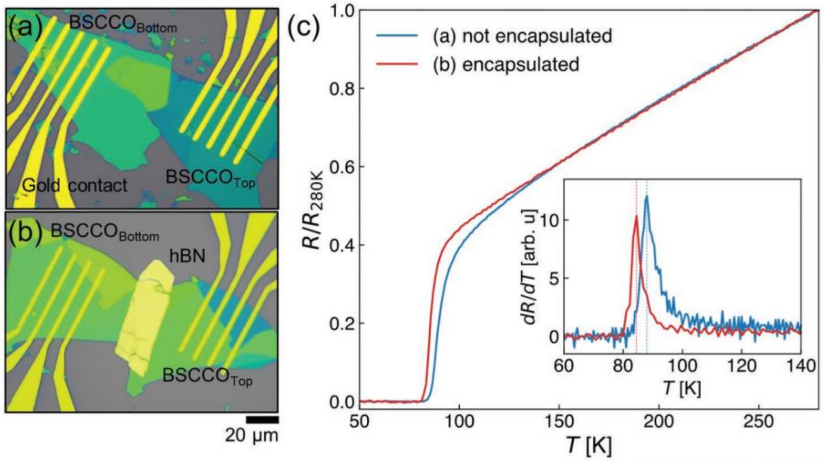


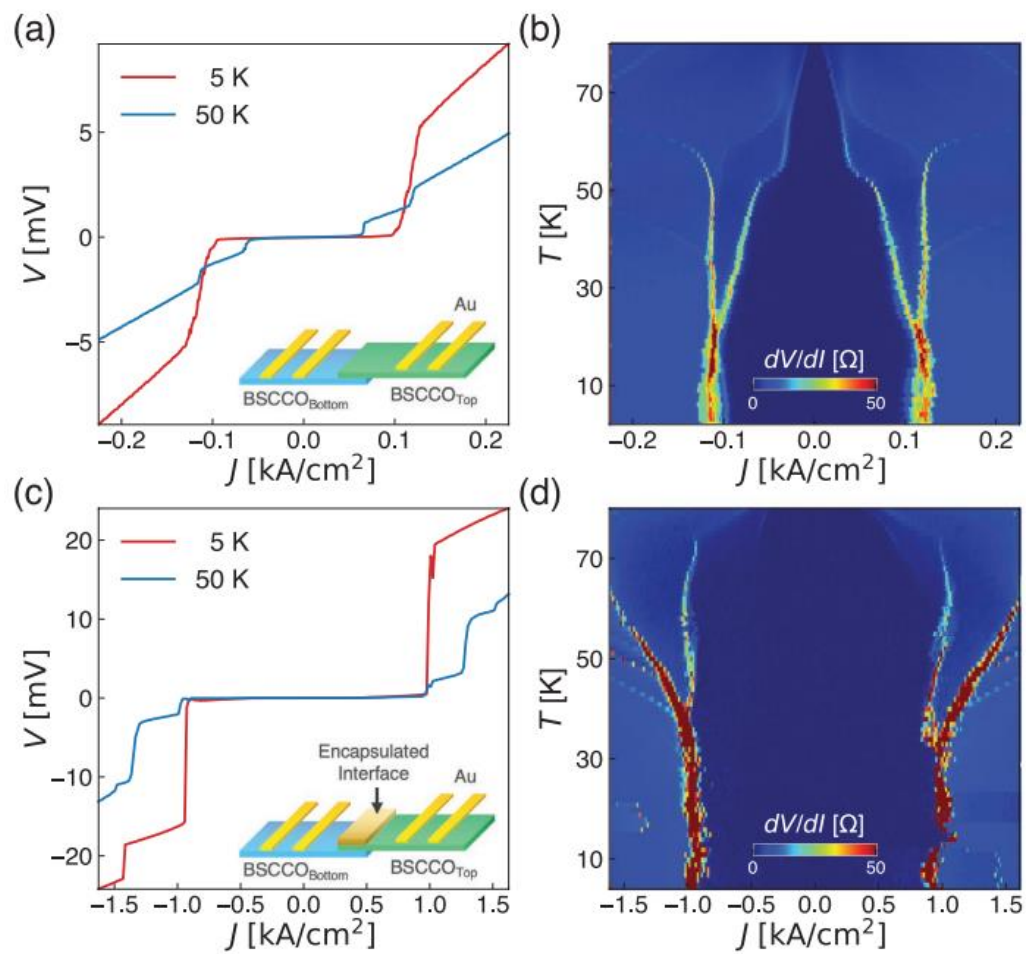


Interfaces are realized with a T_d ~ -100 °C
Measurements of T_d are done with an optical microscope.

S.Y. F. Zhao, NP et al. *Science* 382, 1422-1427 (2023)
Y. Lee, NP et al. *Advanced Materials* 35, 2209135 (2023)
M. Martini, NP et al. *Materials Today*, 67, 106-112 (2023)

Encapsulation protects from detrimental disorder if the electrical contacts are evaporated close to 10^{-6} Torr



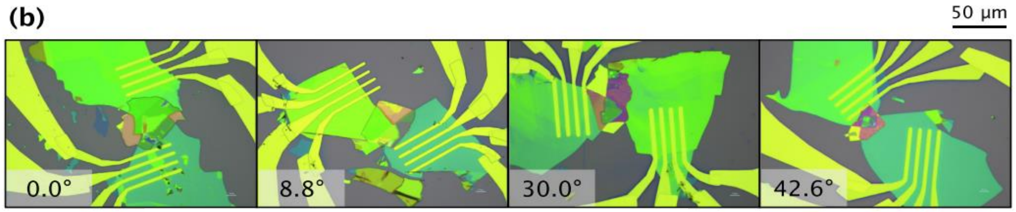


- Optimal superconducting critical transition **(T_c ~ 90 K) is a requirement** for coherence in the twisted cuprate Josephson junctions, **but is not sufficient.**
- An encapsulated and not encapsulated twist junction may share the same T_c, but have very different transport properties for the same angle.

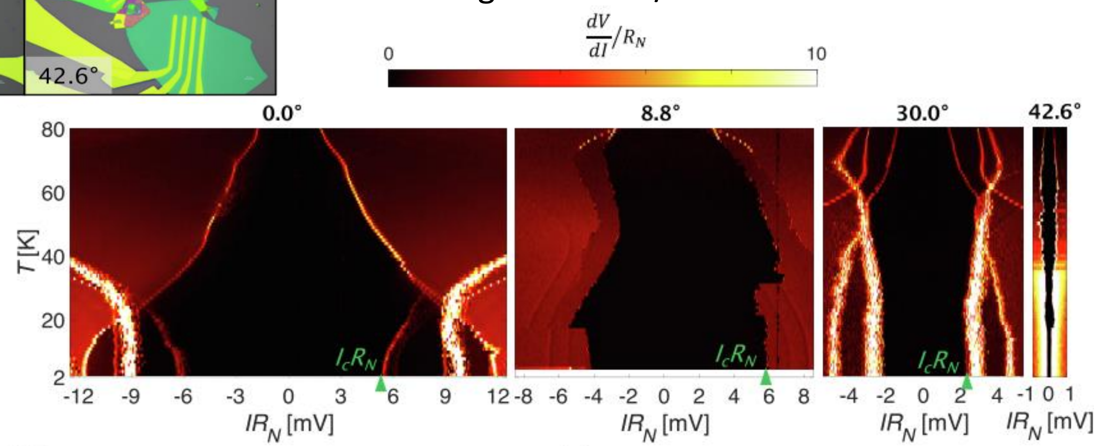
Y. Lee, NP et al. *Advanced Materials* 35, 2209135 (2023)

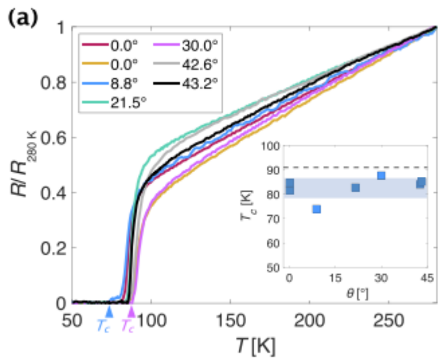
Josephson coupling dependence with the twist in hBN encapsulated junctions

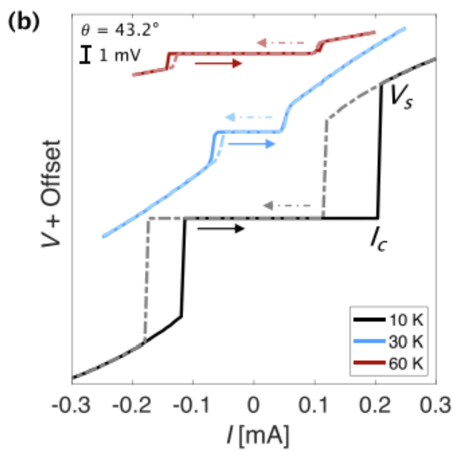
Au contacts are thermally evaporated close to 10^{-6} Torr

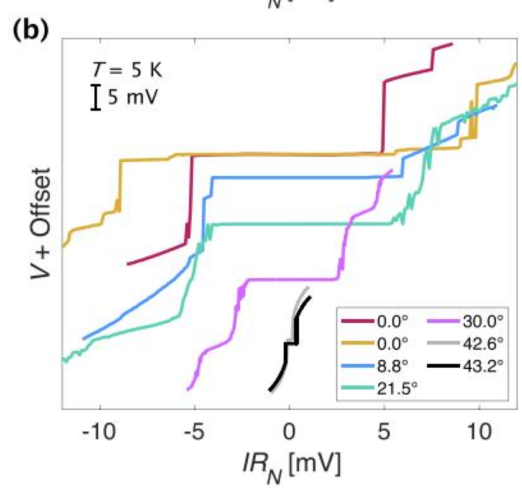


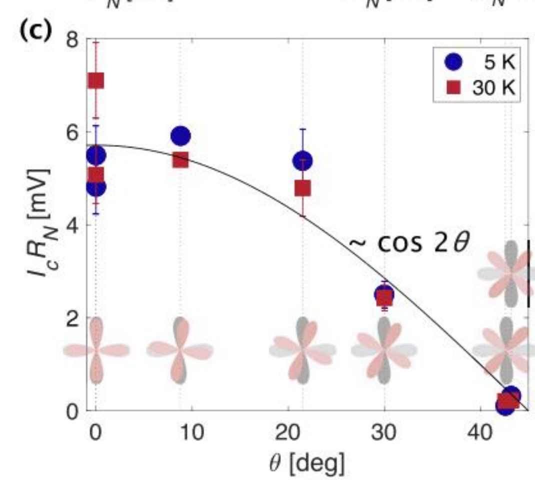
- Intrinsic Josephson junction characteristics at ~ 0° twist angle ~ 1.2 kA/cm^2









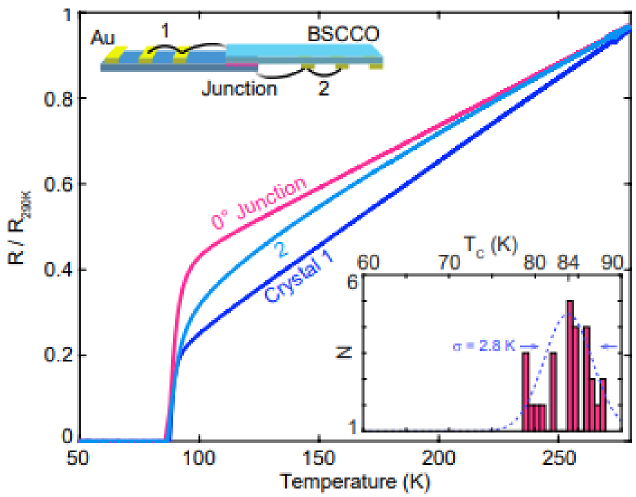


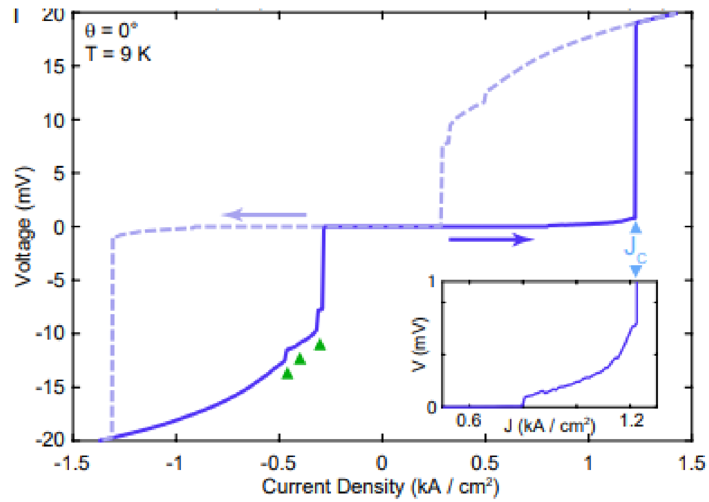
- Two order of magnitude Josephson energy change near 45 ° twist angle consistent with a d-wave angular dependence ~cos(2θ).

M. Martini, NP et al. *Materials Today*, 67, 106-112 (2023)

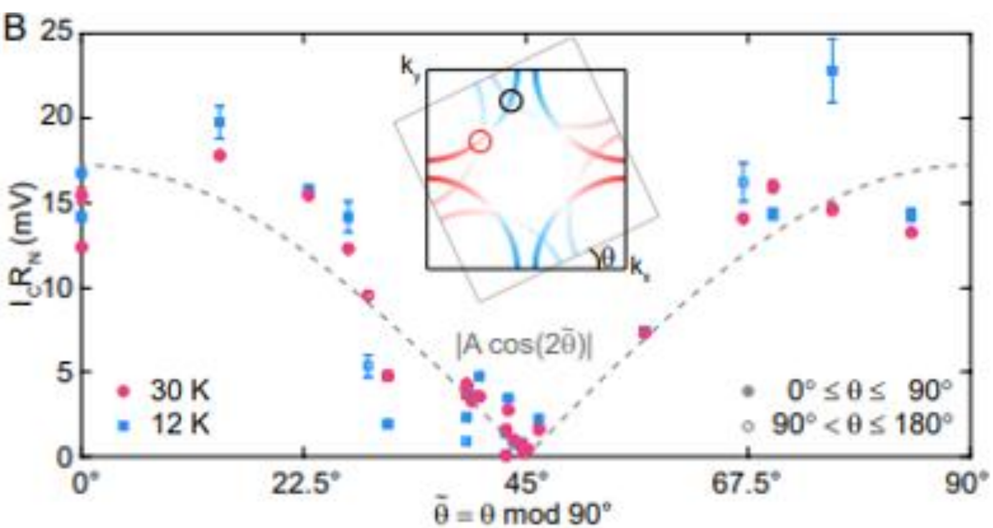
Josephson coupling dependence with the twist

Au contacts are thermally evaporated close to 10^{-8} Torr therefore there is no need of encapsulation.





- Intrinsic Josephson junction characteristics at ~ 0° twist angle ~ 1.2 kA/cm²
- Two order of magnitude Josephson energy change near 45 ° twist angle consistent with a d-wave angular dependence $\sim\cos(2\theta)$.



The d-wave angular dependence can be obtained with same cryogenic transfer technology and alternative methods for electrical contacts fabrication.

Ic(θ) $\sim\cos(2\theta)$ provides evidence for incoherent tunnelling.

Theoretical details in: T. Tummuru et al., *Phys. Rev. B* **105**, 064501 (2022)

S.Y. F. Zhao, NP et al. *Science* 382, 1422-1427 (2023)

Coherent tunnelling in d-wave in twisted Josepshson junctions from the anomalous $I_c(T)$

Theoretical details in: T. Tummuru et al., *Phys. Rev. B* **105**, 064501 (2022)

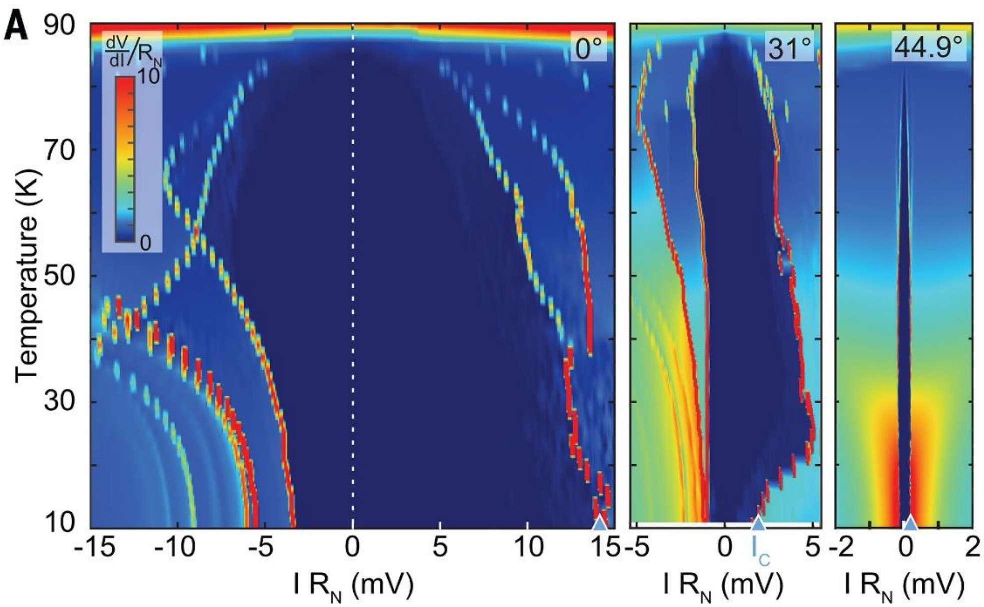
$$I_c(T) \simeq \frac{et^2}{2\hbar} \sum_k \frac{\Delta_{k1}\Delta_{k2}}{D_k(\pi/2)} \sum_{a=\pm} \left[\frac{-a}{E_{ka}} \tanh \frac{1}{2}\beta E_{ka} \right]_{\varphi \to \pi/2}$$

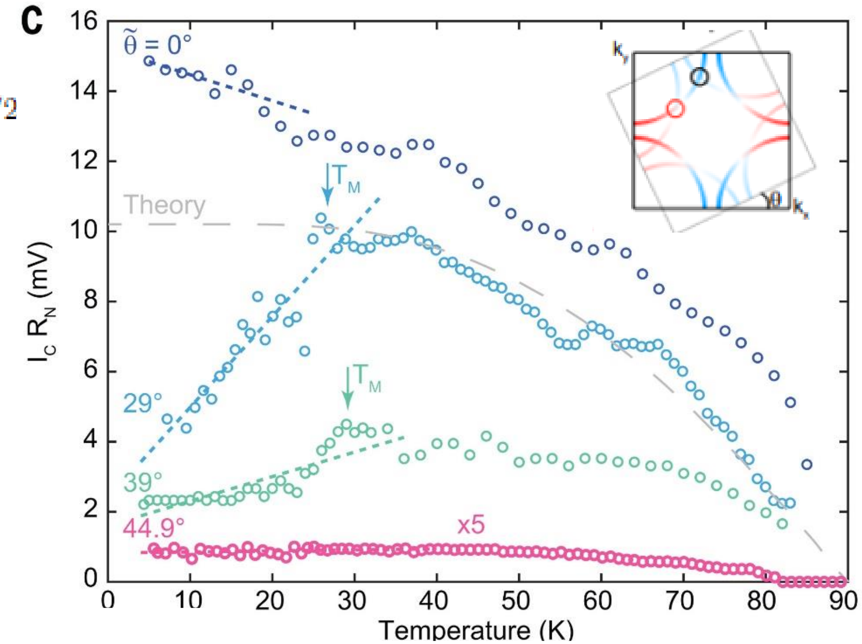
$$E_{k+} > E_{k-}$$

- It is always positive by definition.

$$\Delta_{k1}\Delta_{k2} = \Delta^2 \cos(2\alpha_k + \theta)\cos(2\alpha_k - \theta)$$

- For non-zero twist this product is negative in the vicinity of the Brillouin zone (Bz) diagonals, i.e. the nodal region of the original untwisted d-wave superconductor, and is positive in the rest of the Bz.



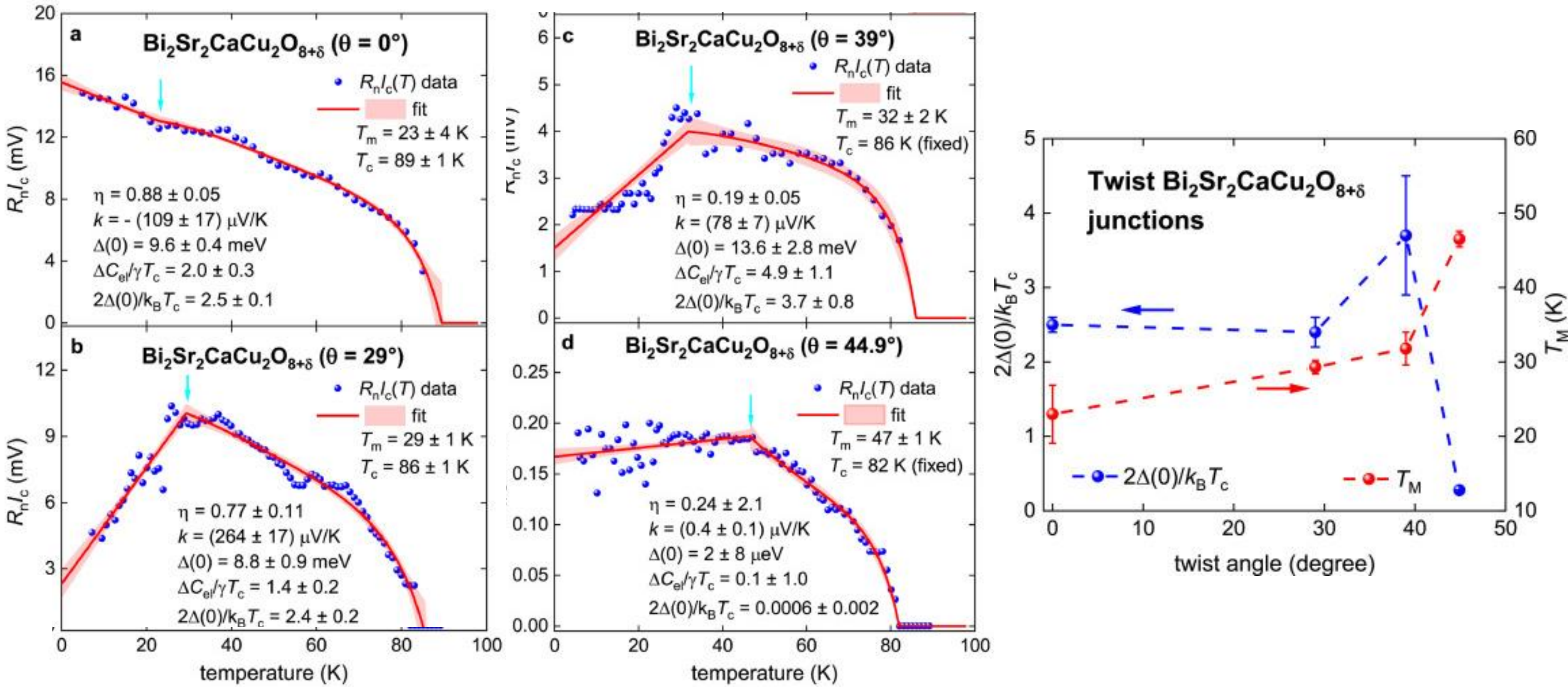


- In a twisted configuration nodal regions give a negative contribution to Ic(0). Reducing this negative contribution by thermal excitations therefore produces a net increase in the total supercurrent.

D-wave coherent tunnelling is consistent with the experimental observations

S.Y. F. Zhao, NP et al. *Science* 382, 1422-1427 (2023)

d-wave symmetry of c-axis superconducting gap



- The implementation of the more accurate gap equation (which allows variable coupling strength and gap symmetry) in the Ambegaokar-Baratoff equation provides further evidence of the d-wave symmetry for the c-axis superconducting gap in twisted Bi-2212 junctions.

Talantsev, Evgeny F. *Physica C: Superconductivity and its Applications* 1354549 (2024)

Supercurrent flowing through second order-mechanisms

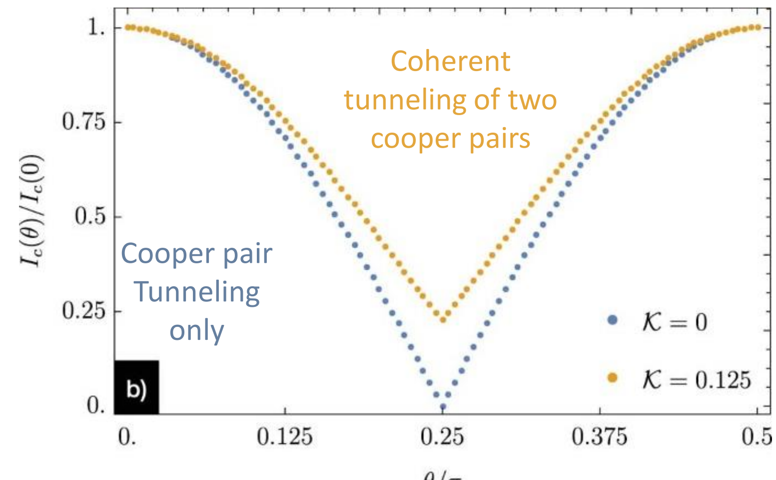
Theory predicts close to $\theta = 45°$.

$j(\varphi) = j_1 \sin(\varphi) + j_2 \sin(2\varphi)$

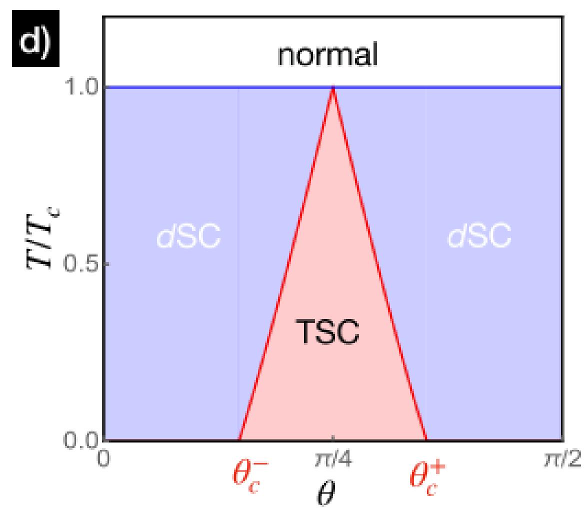
- The maximally mismatched superconducting order parameter phase eliminates the conventional direct Cooper pair tunneling term $j1_1$

$d_{x^2-y^2}$ $\quad + \quad$ id_{xy} $\quad \rightarrow \quad$ $d_{x^2-y^2} + id_{xy}$

- Second-order mechanisms are predicted to support an interfacial superconductivity with **doubly degenerate Josephson energy** owing to the inherent $d_{x^2-y^2} + id_{xy}$ symmetry of the superconducting order parameter within each flake.

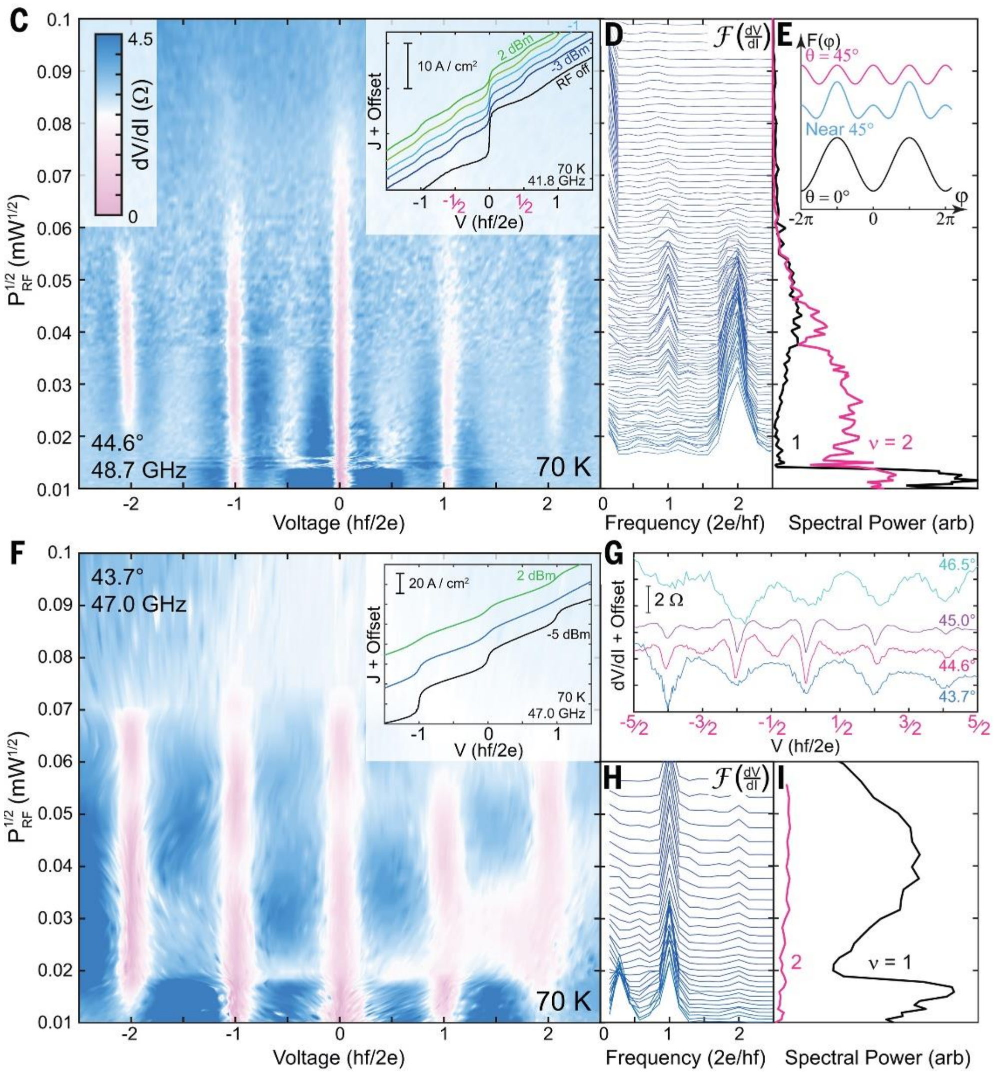


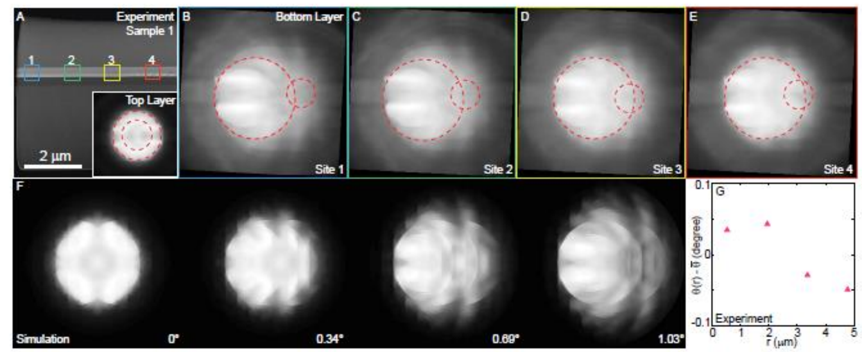
P.A. Volkov., NP et al. *arXiv preprint arXiv:2108.13456* (2021).



O. Can, et al. *Nature Physics* 17 519-524.(2021)

Half-integer Shapiro steps emerge close to θ = 45°.





- Convergent beam electron diffraction measurement of the rotation angle theta provides an upper bound to angular disorder at 0.2°

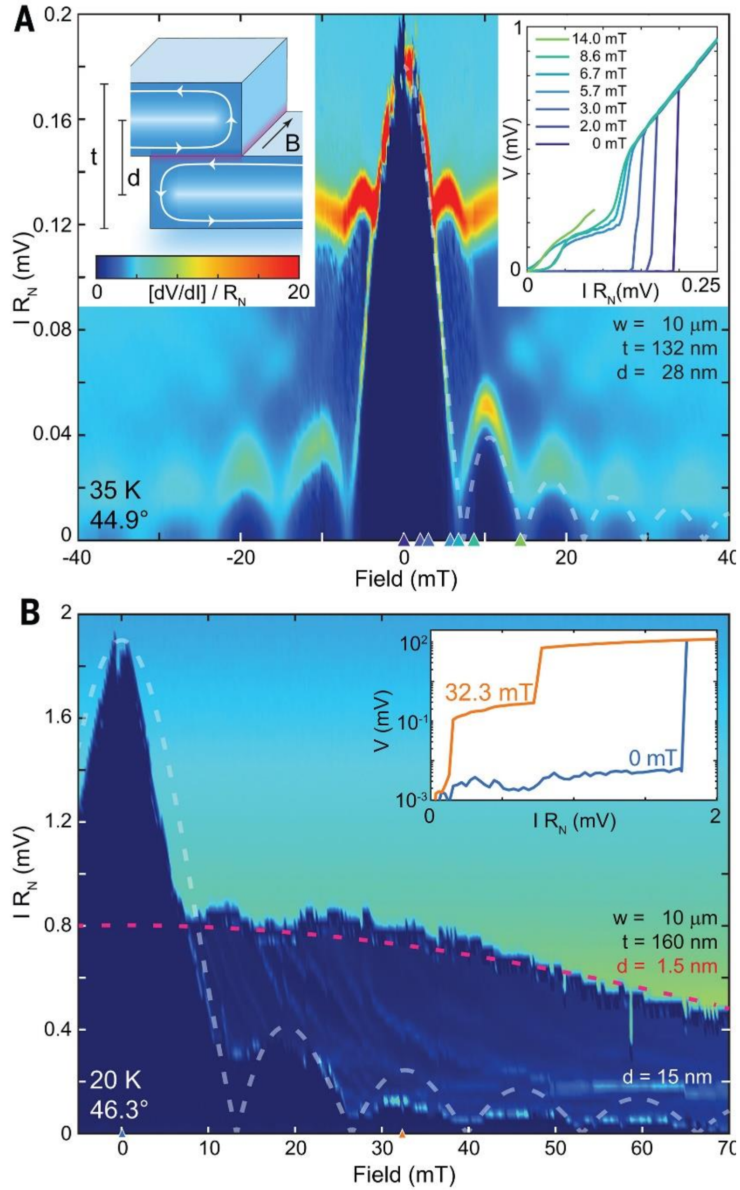
Half-integer Shapiro step signatures observed in our experiments are fully consistent with a dominant second-harmonic Josephson current-phase relation

S.Y. F. Zhao, NP et al. *Science* 382, 1422-1427 (2023)

Fraunhofer patterns near θ = 45°.

- The Meissner currents (white lines) in the flakes affect the phase difference at the twist junction, enhancing its effective thickness d for the magnetic flux .
- θ = 44.9° JJ with IC(B‖) oscillation with a period about 20 times shorter than that expected for intrinsic junctions.
- At a nearby angle θ = 46.3°, the short-period oscillations appear to coexist with a long-period oscillation characteristic of IJJs.

d/t ≈ 0.1 for both devices only if we assume that the 44.9° junction is coupled purely through **the second-order process with a doubled Fraunhofer interference pattern period**.

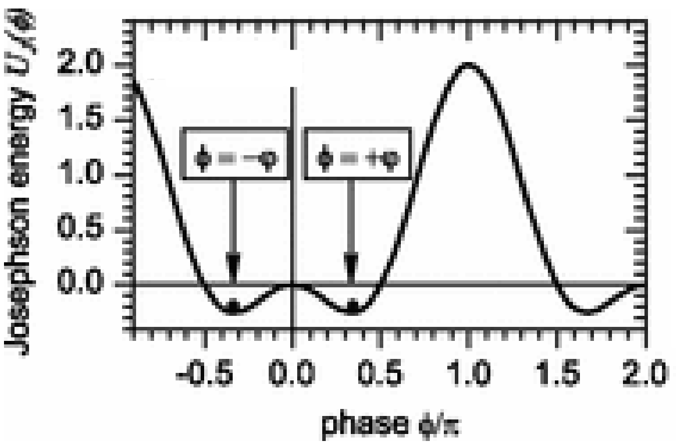


S.Y. F. Zhao, NP et al. *Science* 382, 1422-1427 (2023)

Prepare the Time-Reversal-Symmetry broken initial $\pm\varphi_o$ states by the "training current sequence"

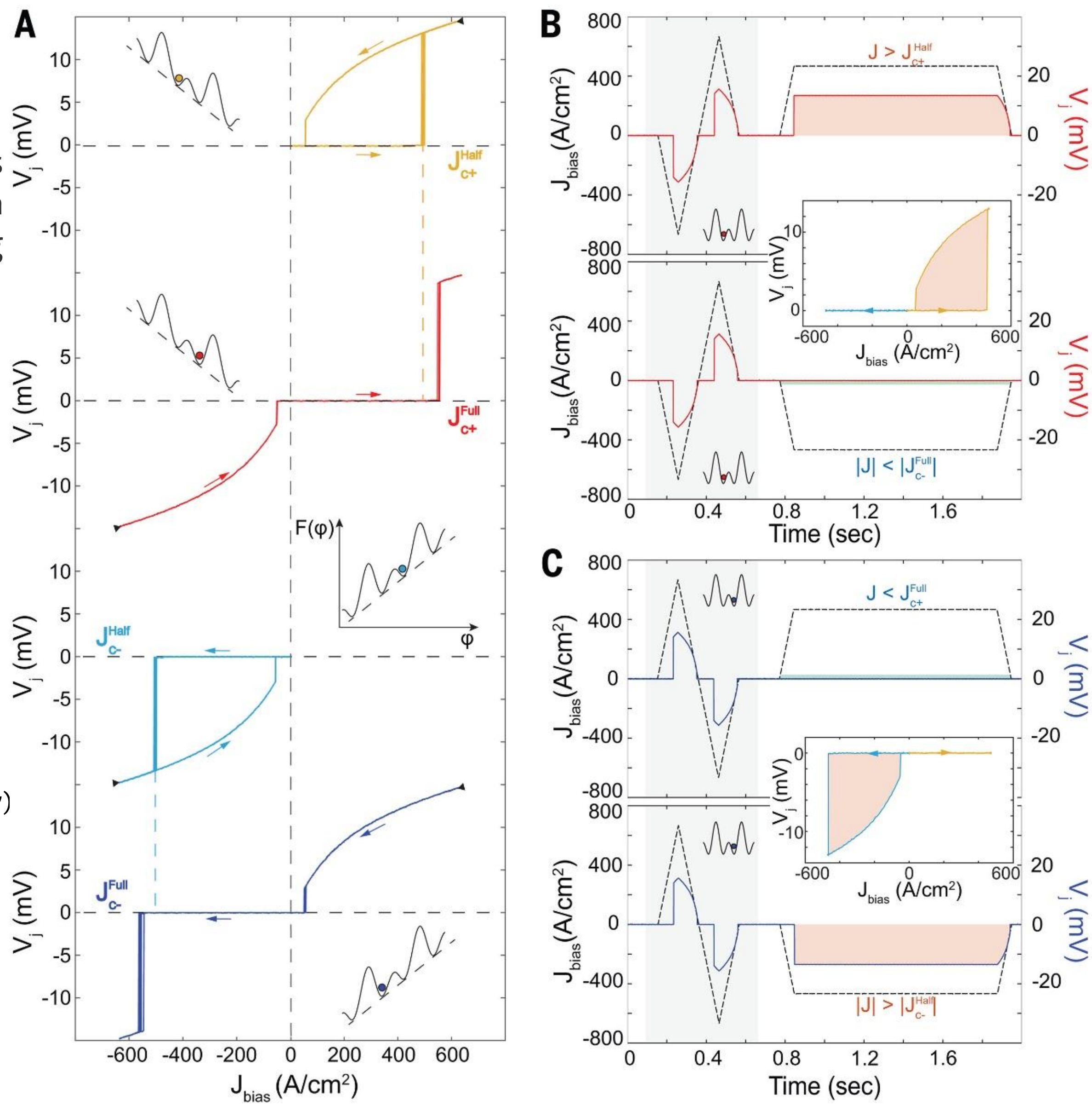
$j(\varphi) = j_1\sin(\varphi) + j_2\sin(2\varphi)$; $J_2 > j_1$

the Josephson junction ground state splits into a pair of degenerate states with complex phase angle $\varphi = \pm\varphi_o$ lying between o and π



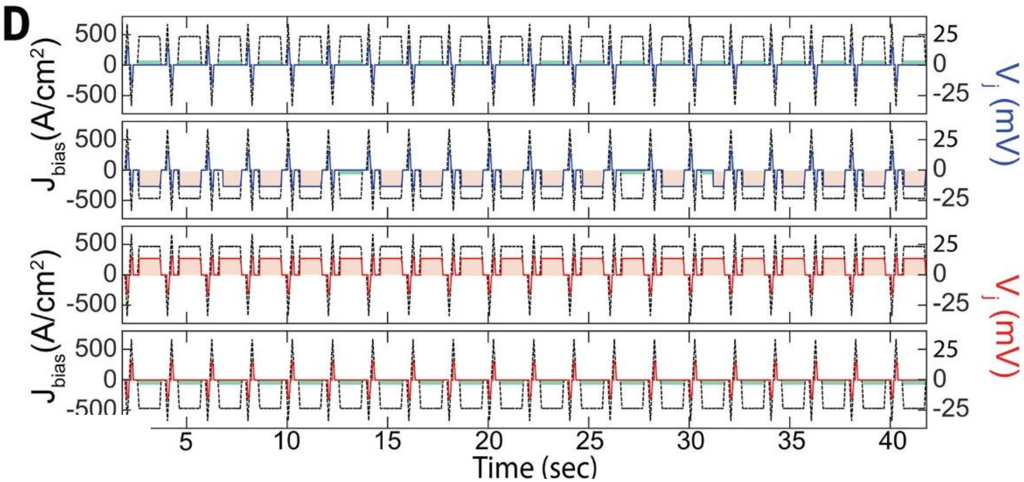
Theory details in: E. Goldobin, et al. Phys. Rev. B **76**, 224523 (2007)

Junction *I-V* characteristics obtained from a JJ with θ = 39.5° at 12 K revealing four distinct J_C accessible via different current sweep directions and histories

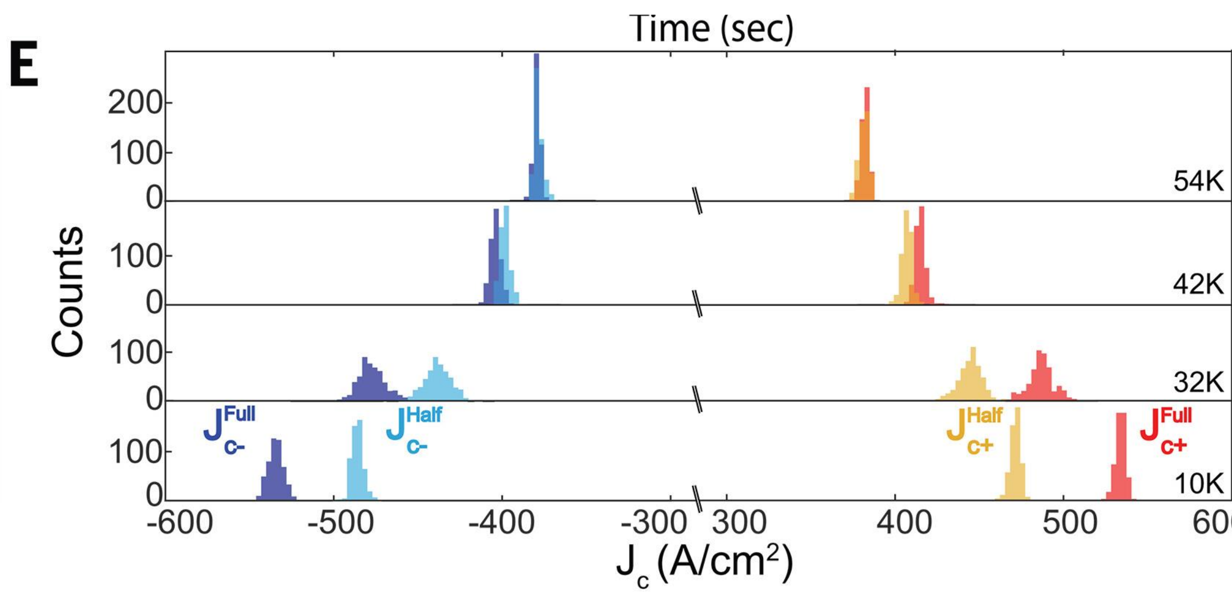


S.Y. F. Zhao, NP et al. *Science* 382, 1422-1427 (2023)

Current-trainable Josephson diode effect



- Junction response to consecutive training and test pulses, showing controllable behavior
- Temperature-dependent switching current distributions of the four different critical currents

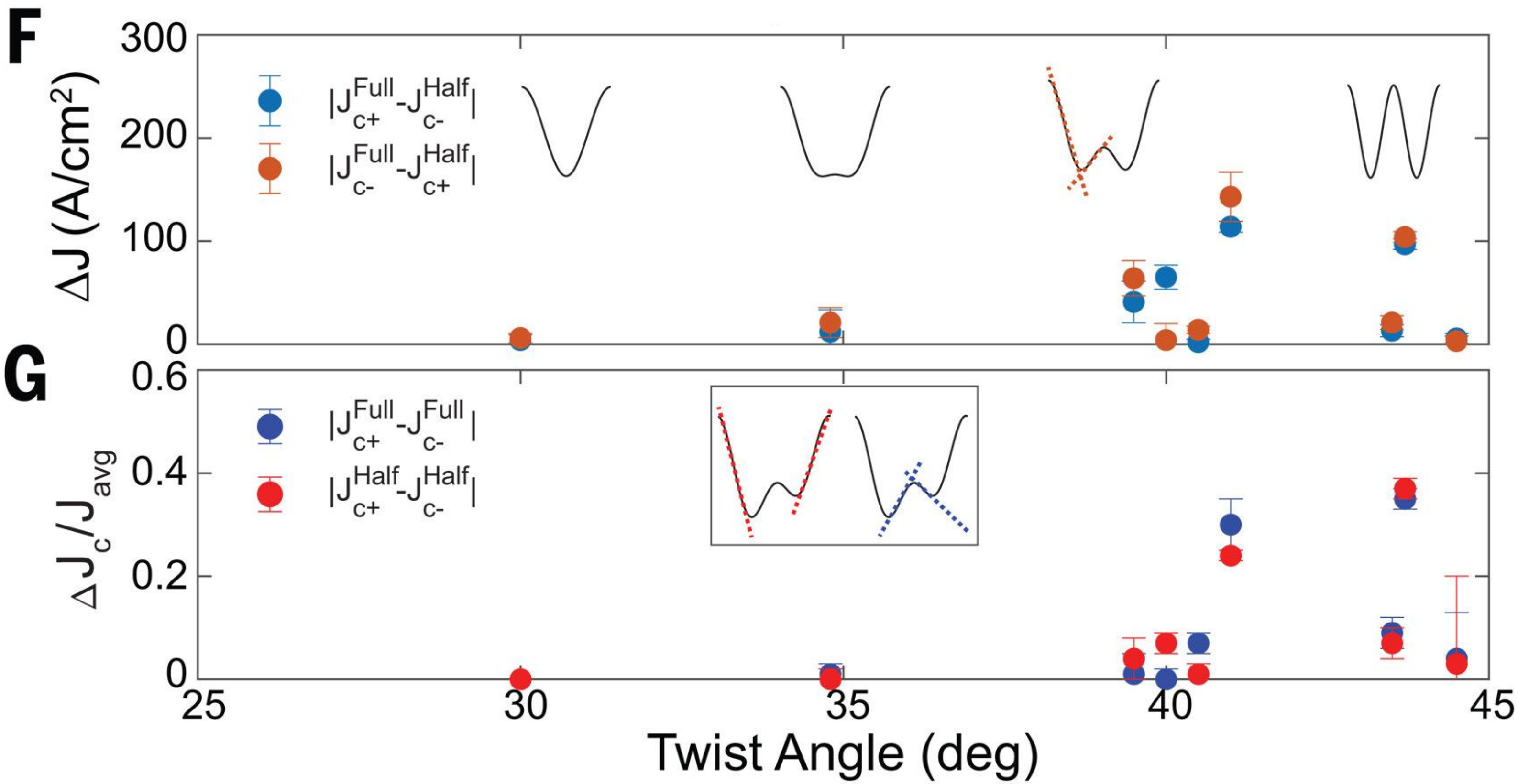


At higher temperature, the phase dynamics become damped, and the **Jc asymmetry becomes less prominent upon heating and vanishes at about 50 K**

S.Y. F. Zhao, NP et al. *Science* 382, 1422-1427 (2023)

Time reversal symmetry breaking superconductivity between twisted cuprate superconductors

Observation of the valley asymmetry in the pair of degenerate states



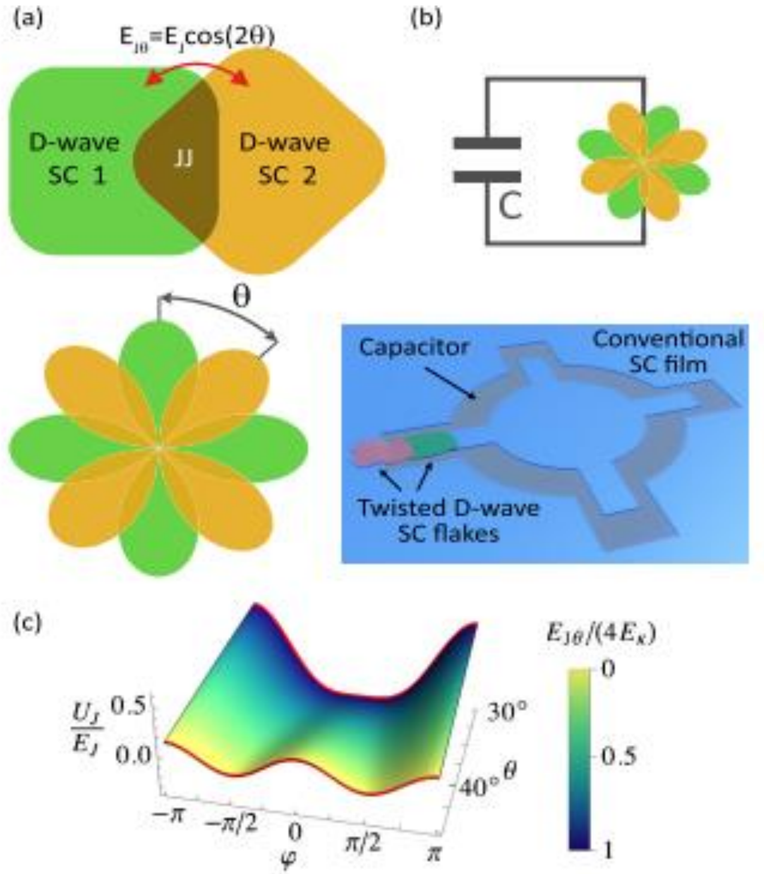
At exact-ly 45°, on the other hand, the purely second-harmonic Josephson potential has an additionalsymmetry around ±φ0: $\pm\varphi_0 \pm \varphi \leftrightarrow \pm\varphi_0 \mp \varphi$,which forbids the diode effect

The observed diode effect is closely related to the free energy land-scape of coexisting first- and second-harmonic Current-Phase relation terms

S.Y. F. Zhao, NP et al. *Science* 382, 1422-1427 (2023)

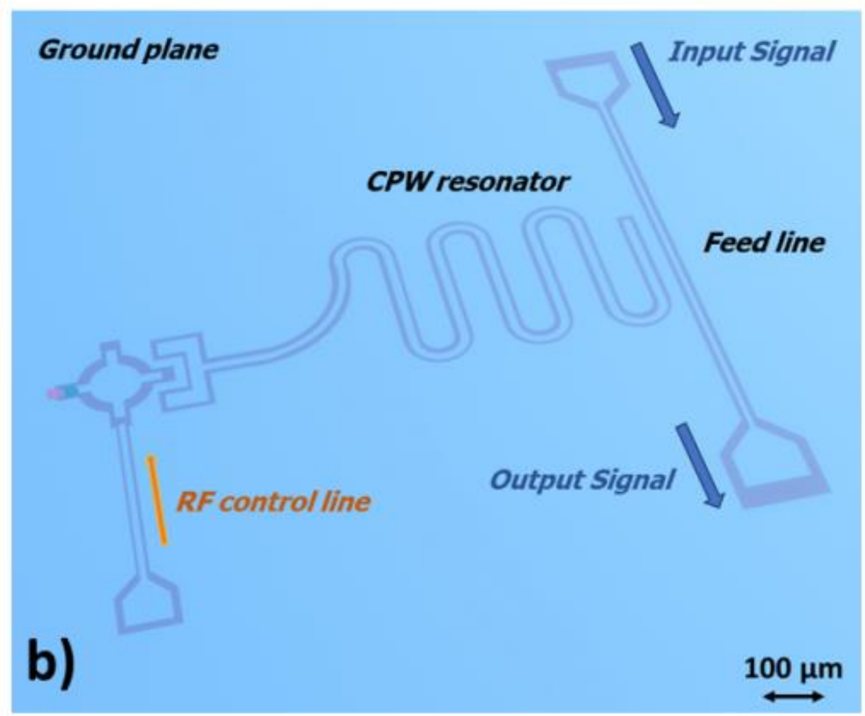
Towards a new generation of macroscopic quantum bit

based on twisted cuprate van der Waals heterostructures



Cuprate twisted junctions to realize a capacitively shunted qubit that we call **flowermon**. The d-wave nature of the order parameter endows the flowermon with inherent protection against charge-noise-induced relaxation and quasiparticle-induced dissipation.

V. Brosco, NP, et al. Physical Review Letters 132, 017003 (2024)



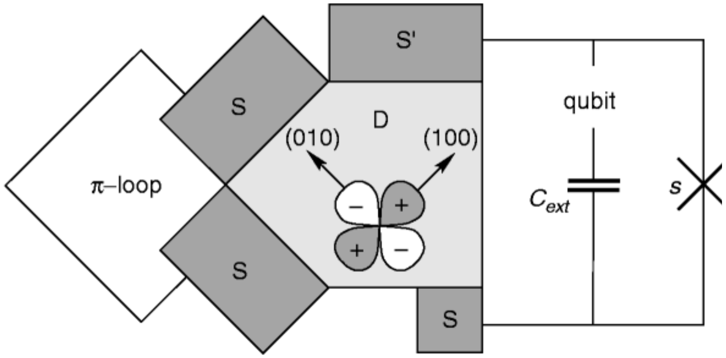
- Hamiltonian for a s-wave junction circuit

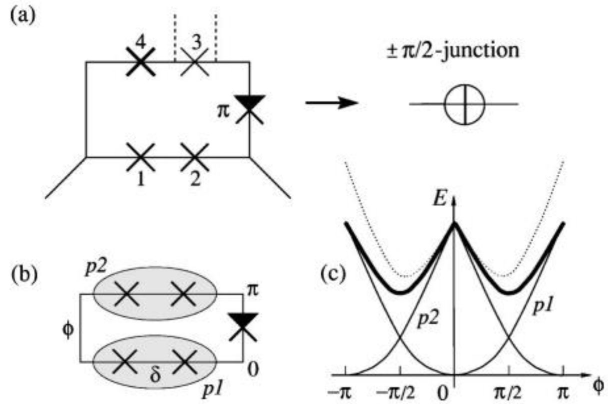
$$H_J = -E_J\cos(\hat{\varphi}),$$

- Hamiltonian of the **flowermon** circuit

$$H = 4E_C(\hat{n}-n_g)^2 - E_{J\theta}\cos(\hat{\varphi}) + E_\kappa\cos(2\hat{\varphi}),$$

Pioneering theoretical and experimental works on cuprates qubits

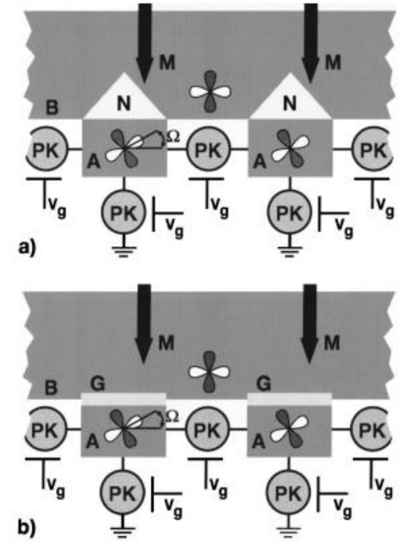




- Proposals for the suppression of tunneling in d-wave based Josephson junctions, based on momentum mismatch, to realize superconducting qubits with an enhanced coherence

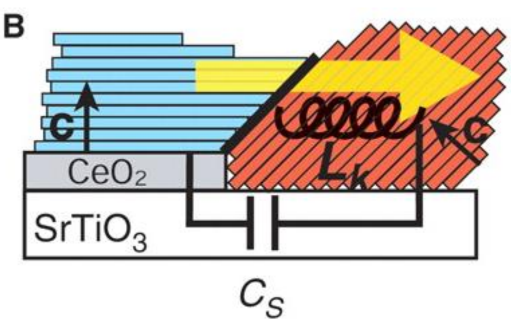
L. B., Ioffe, et al. *Nature* 398 679-681 (1999)

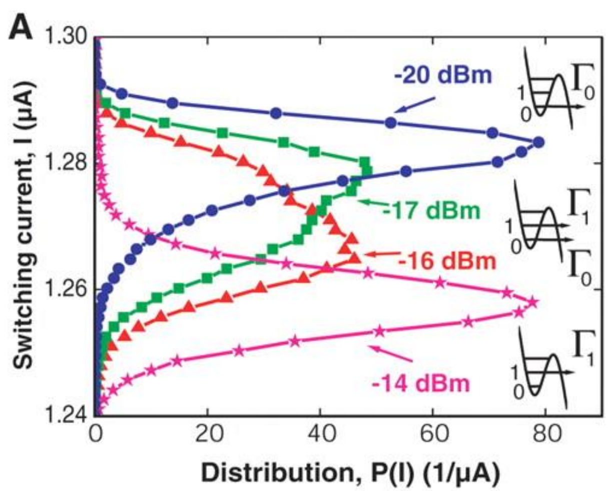
G. Blatter, et al. Phys. Rev. B **63**, 174511 (2001)



- Two d-wave qubits coupled are shown

A. Blais, et al. Phys. Rev. A **61**, 042308 (2000)



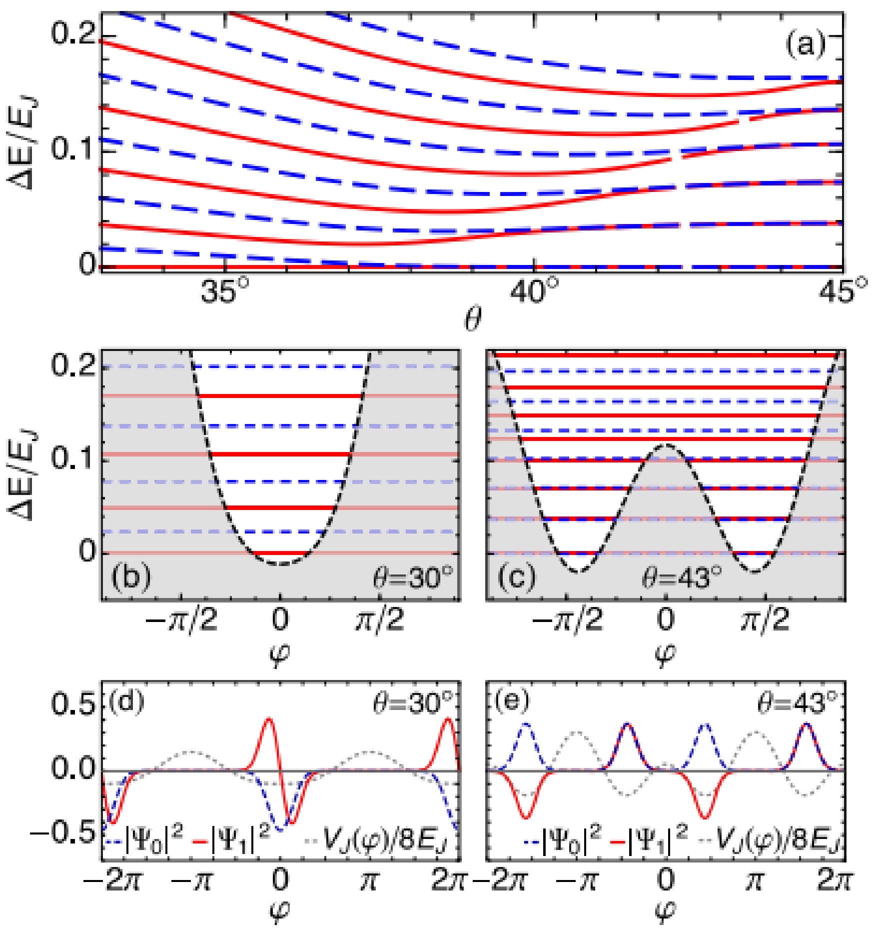


T. Bauch, et al., Science 311, 57 (2006)

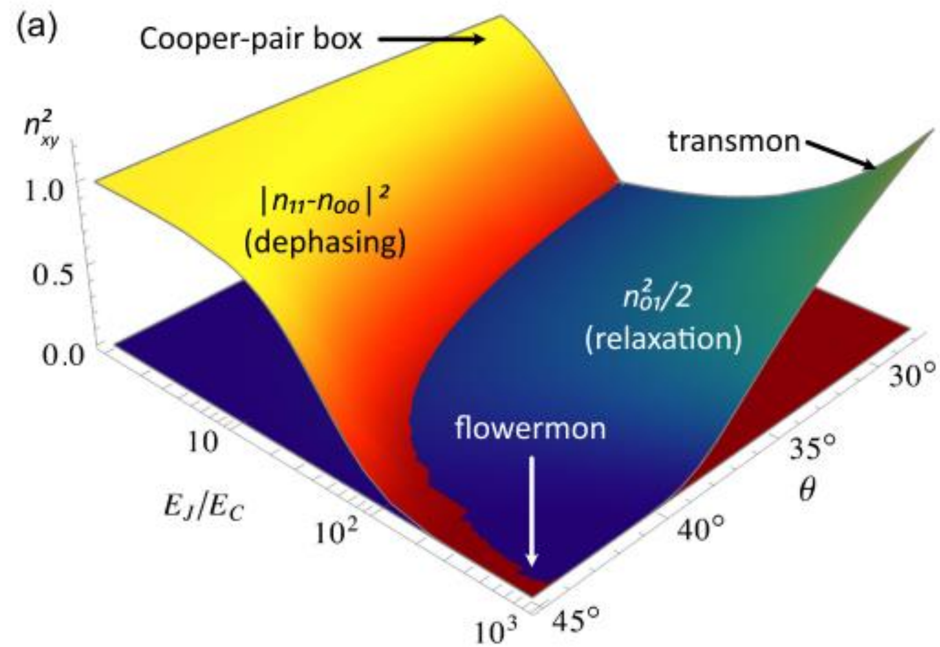
- Experimental early realization of momentum mismatch with grain boundary YBa_2Cu3O_{7-x} indicated the degeneragy of the ground state.

Detrimental disorder and **fabrication complexity** hindered the realization of the qubit based on grain boundary junctions.

New class of hybrid devices which combine the benefits of quantum materials and coherent quantum circuits



Flowermon low-energy spectrum. (a) Energy levels of the flowermon qubit as a function of the angle θ. Even and odd levels are shown in red and blue lines respectively

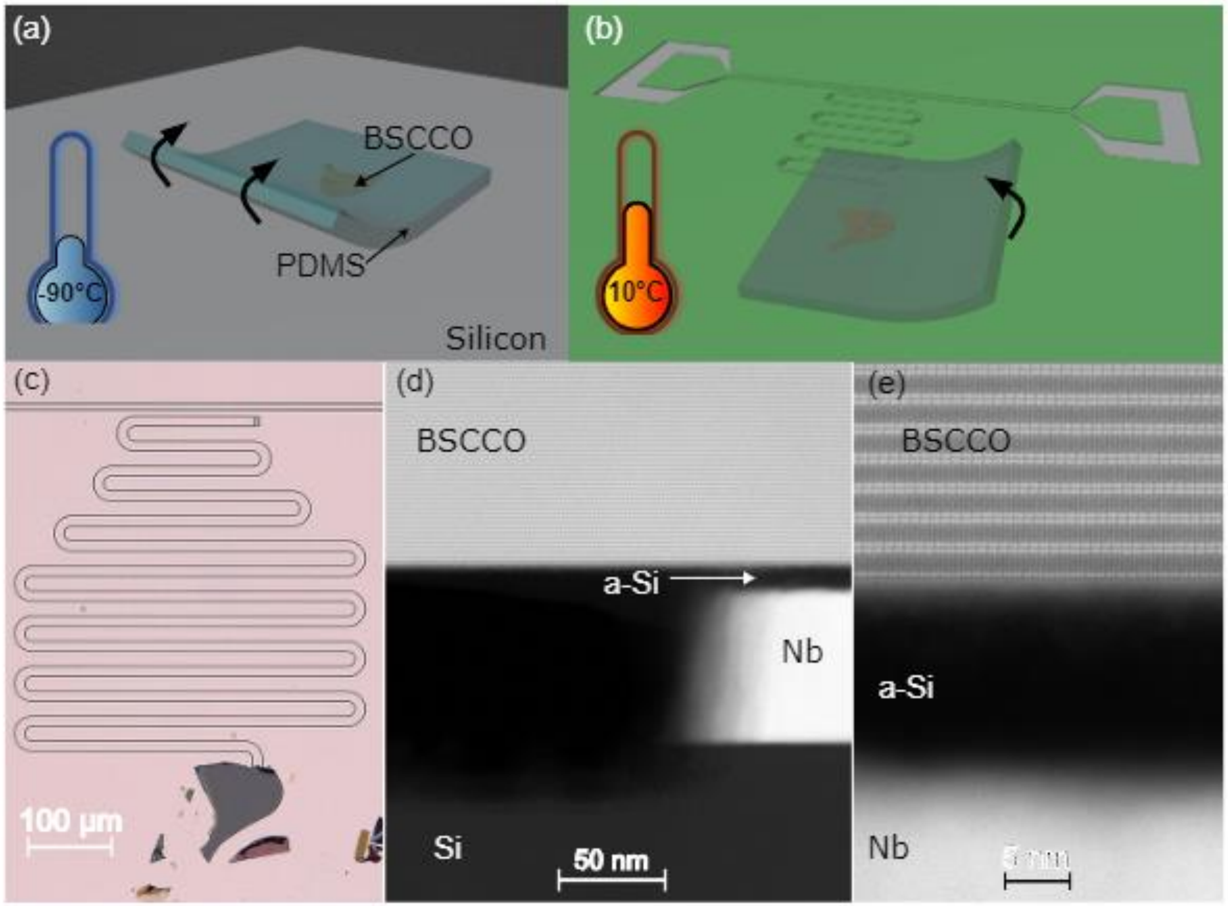


$$\Gamma_{\downarrow,\mathrm{qp}} = t^2 |\langle\psi_0| \sin(\varphi/2) |\psi_1\rangle|^2 S^{\theta}_{\mathrm{qp}}(\omega_{01}),$$

At twisting angles close to 45°, the flowermon **shows exponential suppression of the charge-induced noise**, as well **as protection from nodal quasiparticle tunneling**.

V. Brosco, NP, et al. Physical Review Letters 132, 017003 (2024)

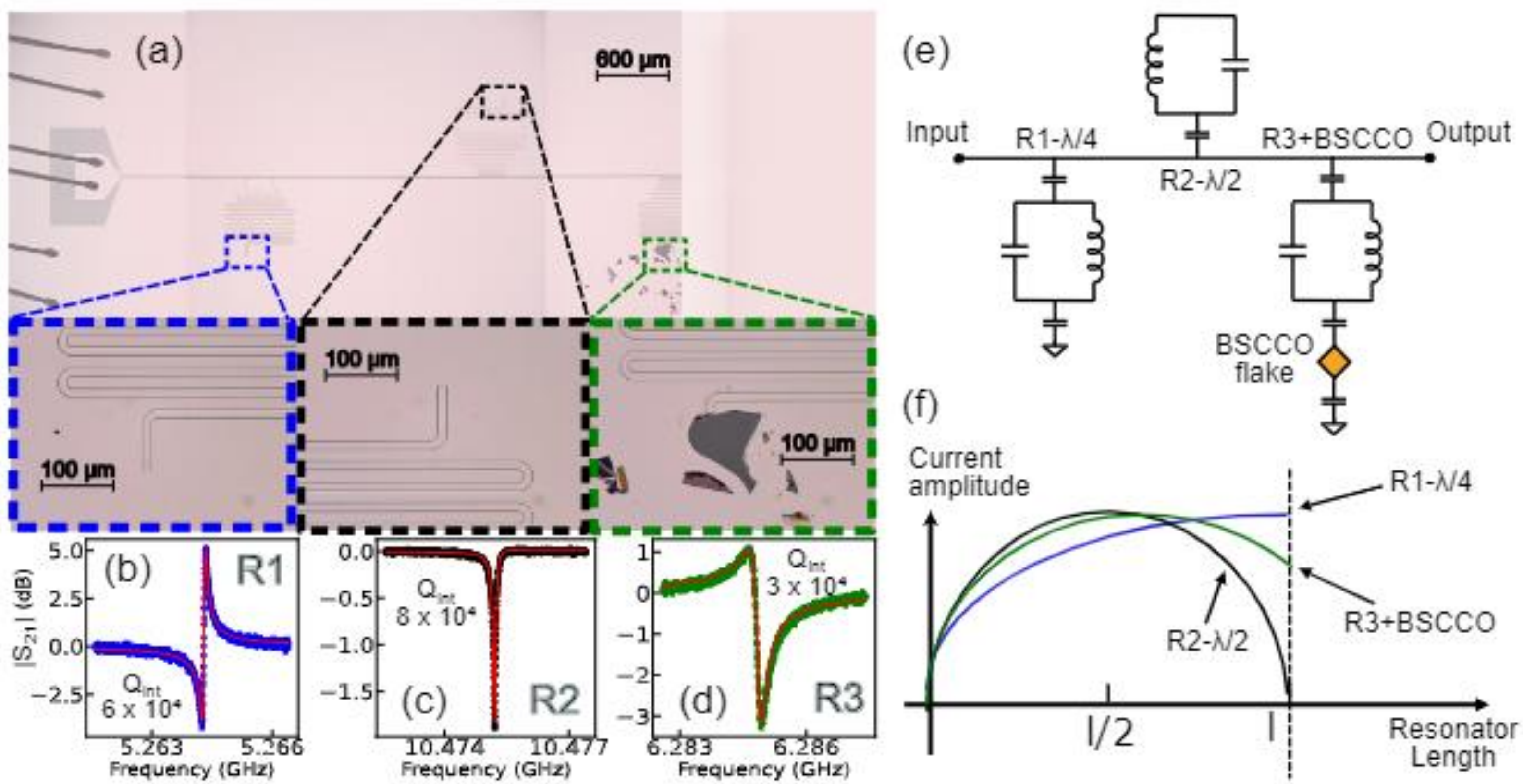
Exploring van der Waals cuprate superconductor using hybrid microwave resonator



Advanced cryogenic stacking technology can be used to integrate fragile complex van der Waals cuprate architectures in superconducting circuits and explore their coupling!

(unpublished data) Submitted

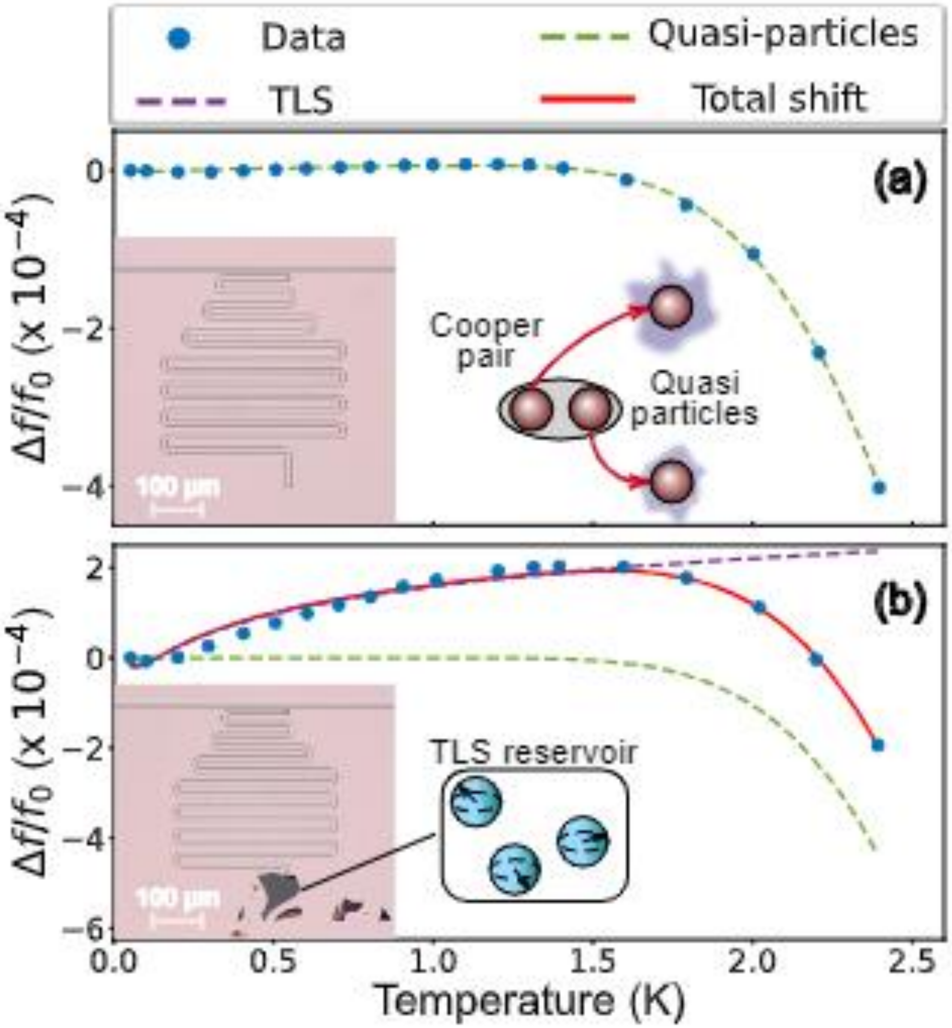
Measuring the coupling



Low-power transmission spectrum of the resonator R1 (left, blue), R2 (middle, black) and R3 (with BSCCO flake, right, green) and their internal quality factors at 50 mK.

(unpublished data) Submitted

Temperature dependence of the resonance frequency.

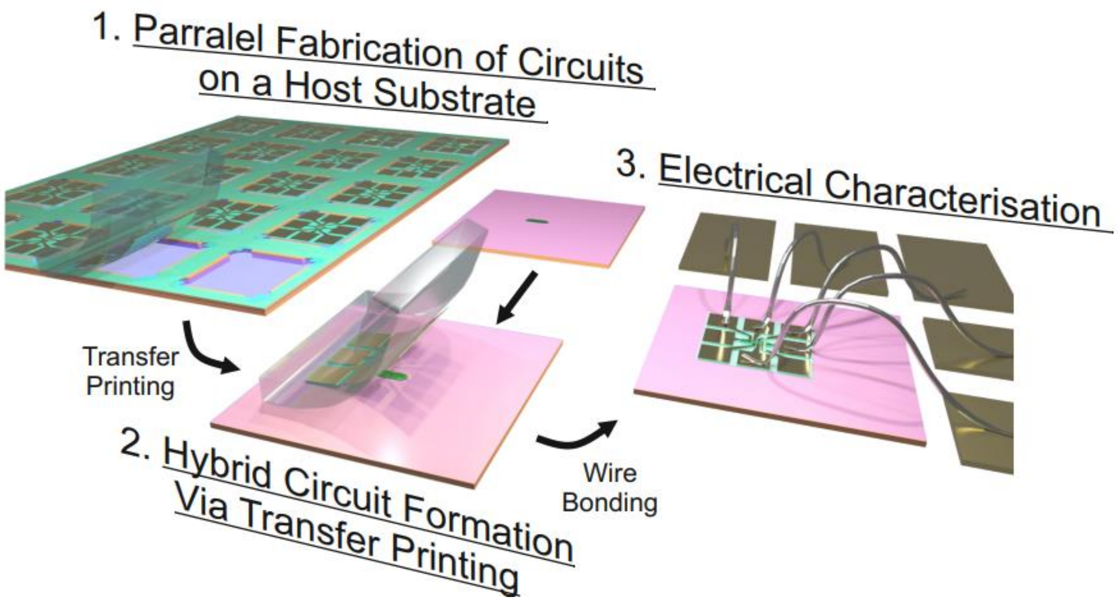


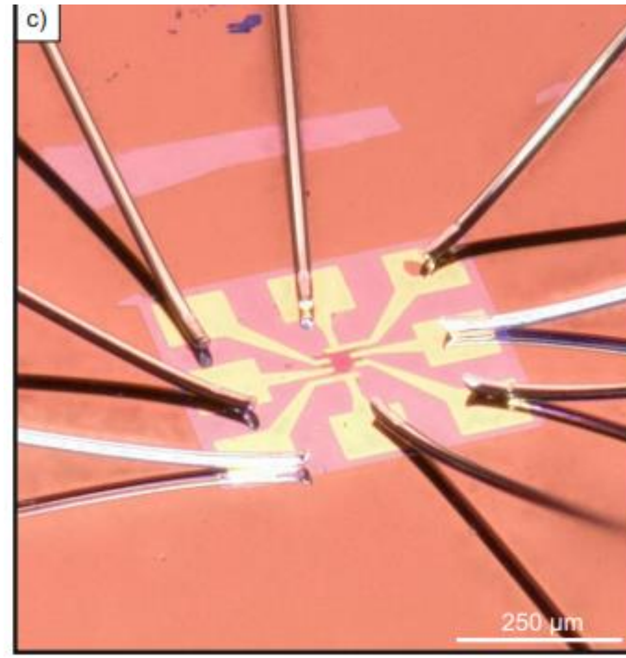
The green dashed line is a fit to a shift due to the thermal generation of quasiparticles, while the purple dashed line is a fit to coupling with a TLS reservoir.

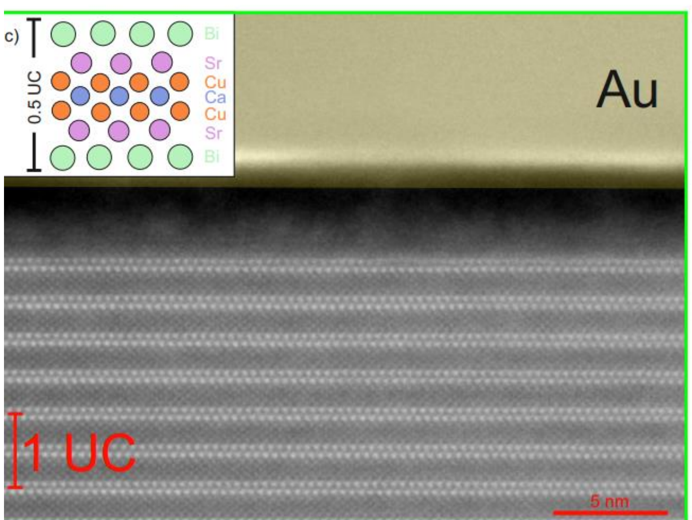
(unpublished data) Submitted

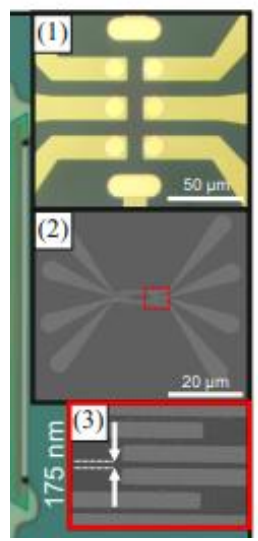
Next generation: Silicon nitride technology for micro-printed circuits

Leading the integration of complex circuits into 2d twisted cuprate junctions







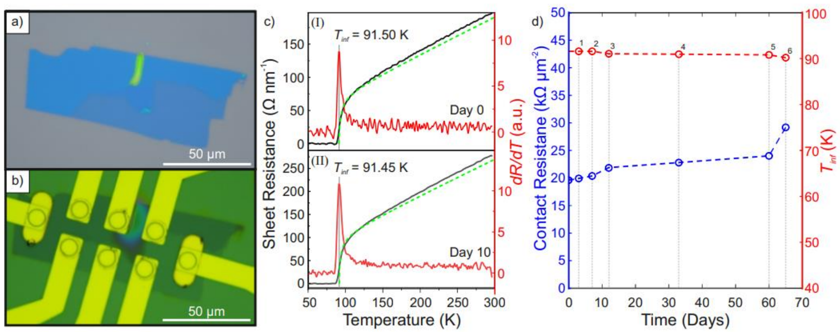


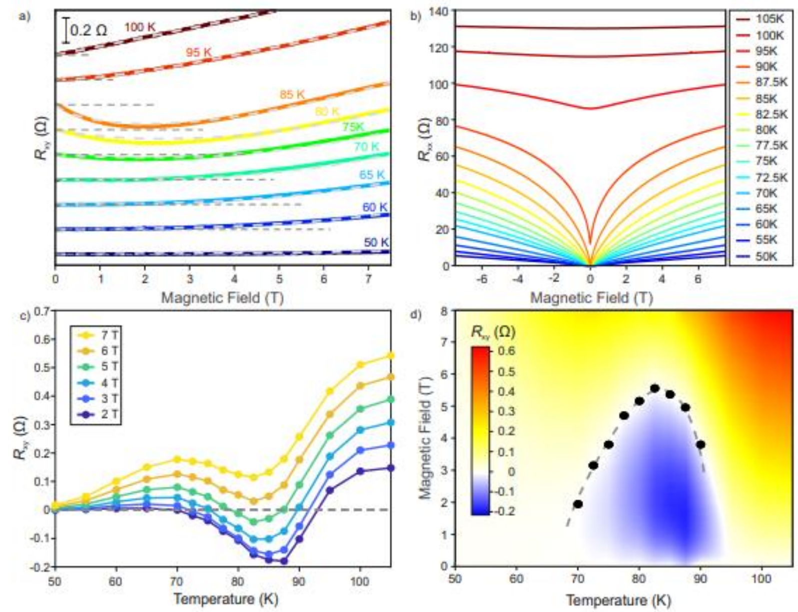
Cryogenically transferred circuit boards **entirely separates the circuit fabrication** stage requiring chemically reactive substances and ionizing physical processes from the creation of the thin superconducting structures.

C.N.Saggau, NP., et al. *ACS Applied Materials & Interfaces* 15 51558-51564 (2023) .

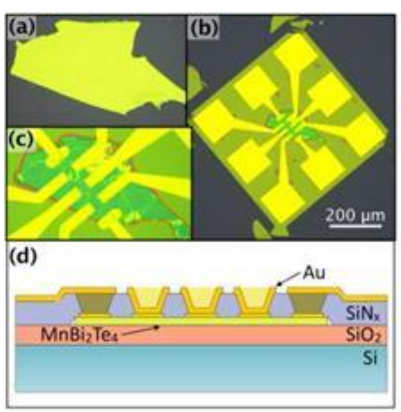
Testing the silicon nitride micro printed circuits boards

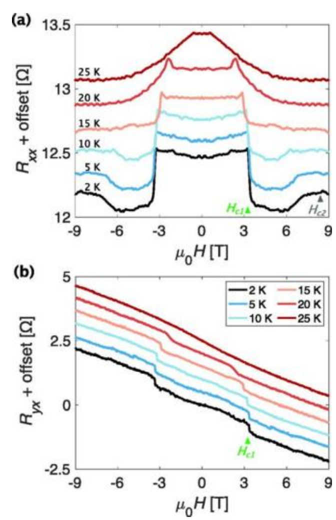
The results show optimal contact resistance, versatility in the choice of materials, nanometerprecision and long-stability





- The technology preserves the superconducting properties of the BSCCO crystal and that the membrane acts as an encapsulation layer, blocking the detrimental effects of disorder over a long time.
- The robustness of the membrane is demonstrated by the numerous thermal cycles performed for our experiments





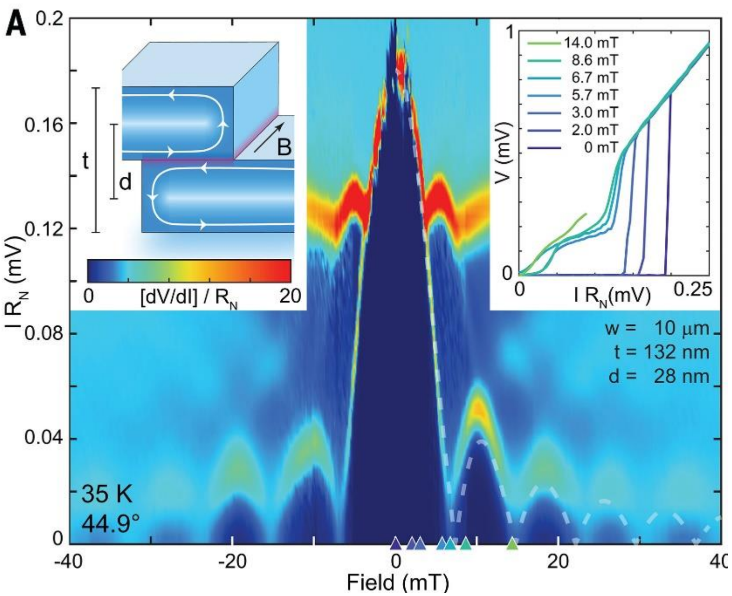
The technological solution will be implemented for integrating quantum electrodynamical circuits for the next generation of nanodevices with the **goal to reduce maximally the detrimental disorder in quantum materials**.

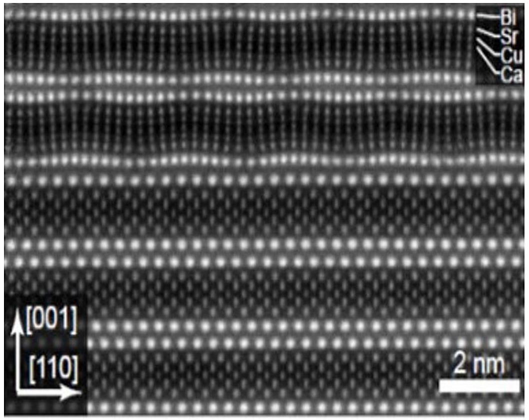
C.N.Saggau, NP., et al. *ACS Applied Materials & Interfaces* 15 51558-51564 (2023) .

M. Martini, NP et al. *Applied Physics Letters* 123 (2023).

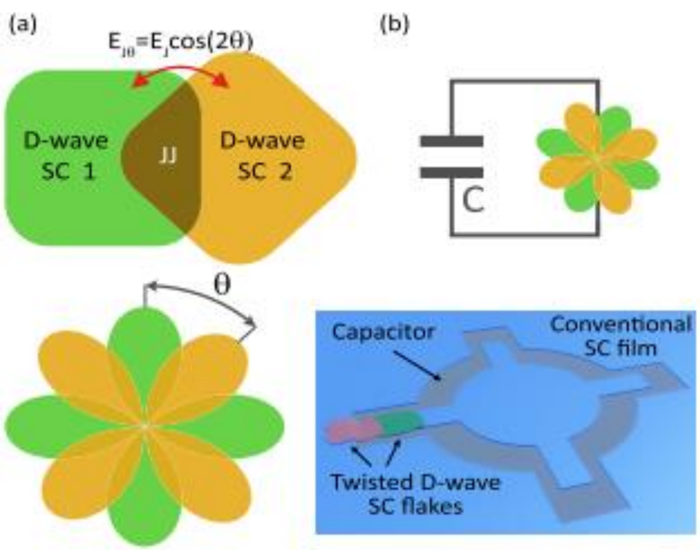
Conclusion. Artificial 2D cuprate heterostructures for:

Engineering **complexity, topological** and **strongly correlated physics** in one system and in a wide temperature range





Advancing methodologies for the fabrication of **artificial 2D complex quantum materials**



Producing a new generation of quantum circuits harnessing the unique quantum complexity created by the geometry.