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Anomalous metal states in cuprate, Fe-based, and nickelate superconducting films

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Outline

- Part I: Background

- Part II: Anomalous metal states in 2D superconductors

  Science 366, 1505 (2019) with a perspective paper: Science 366, 1450 (2019)

- Part III: The high-temperature anomalous metal states in FeSe/STO

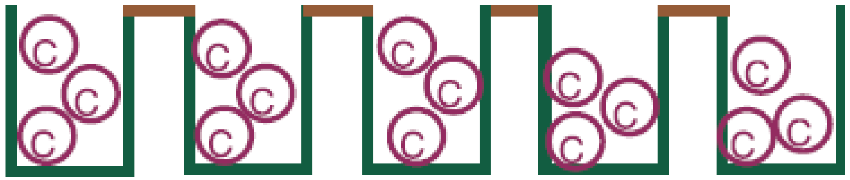
  Physical Review Letters 132, 226003 (2024)

- Part IV: Anomalous metal states in infinite-layer nickelate films

  arXiv: 2603.00670 (2026)

Cooper pairs (considered as bosons in some situations): two ground states in 2D systems

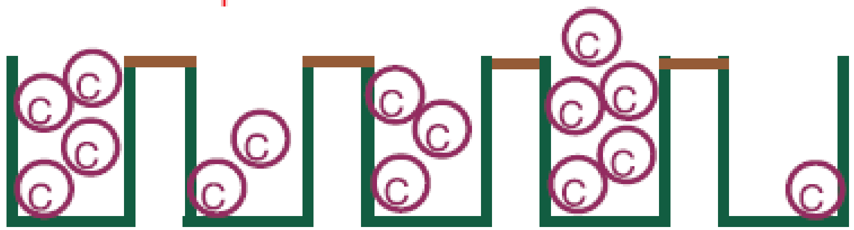
Insulator



Number of Cooper-pairs in each well is fixed

Zero conductance

Superconductor



+ quantum entanglement with other number configurations

Zero resistance

In the insulator, Cooper pair number fluctuations cease, leading to infinite uncertainty in the phase.

In contrast, phase coherence obtains in a superconductor, leading to infinite uncertainty in the Cooper-pair particle number.

***P. Phillips and D. Dalidovich, Science* 302,243 (2003)**

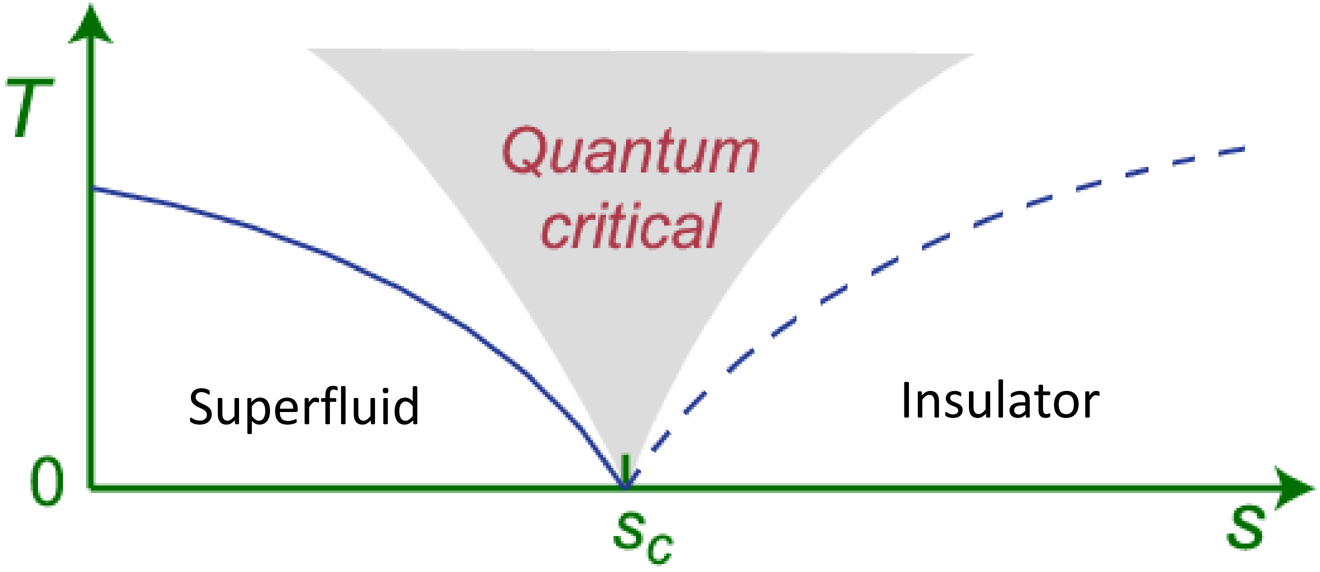
Bosons are thought to exist in one of two ground states: condensed in a superconductor or localized in an insulator.

Two ground states for 2D superconducting system approaching zero temperature:

Coopers (sometime can considered as bosons) are thought to exist in one of two ground states: condensed in a superconductor or localized in an insulator.

Quantum phase transitions

Duality from charge and vortex
there is no intermediate state

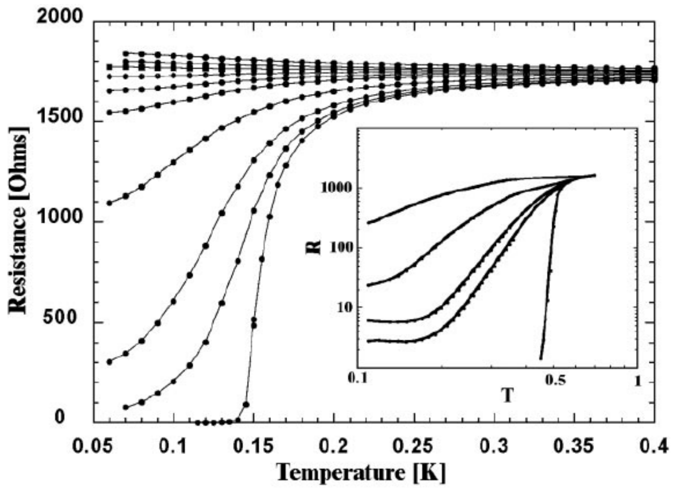


Tuning parameter eg. Doping, disorder, magnetic field B

However, some experiments have revealed a metallic ground state that disrupts the direct transition between the superconductor and the insulator.

Signature of anomalous metallic state (i.e. quantum metal or Bose metal)

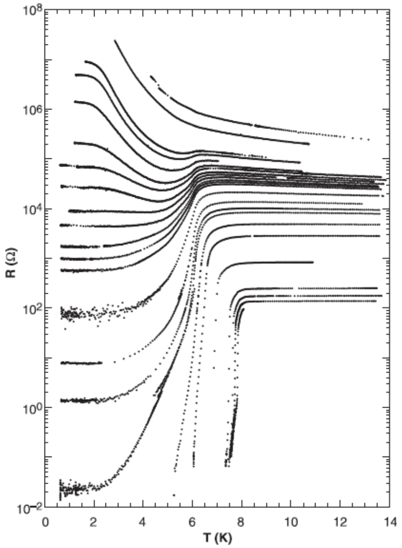
MoGe thin films at different magnetic fields



Kapitulnik group, Phys. Rev. Lett. 74, 3037 (1995)

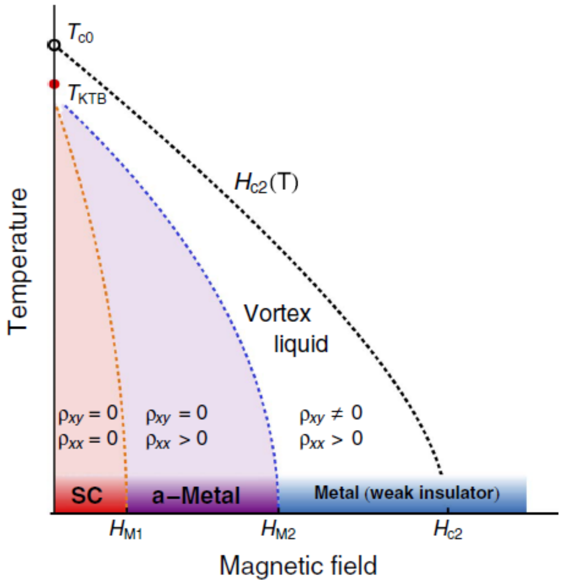
M. R. Beasley group, Phys. Rev. Lett. 76, 1529 (1996)

Ga films from 12.75 to 16.67 Å

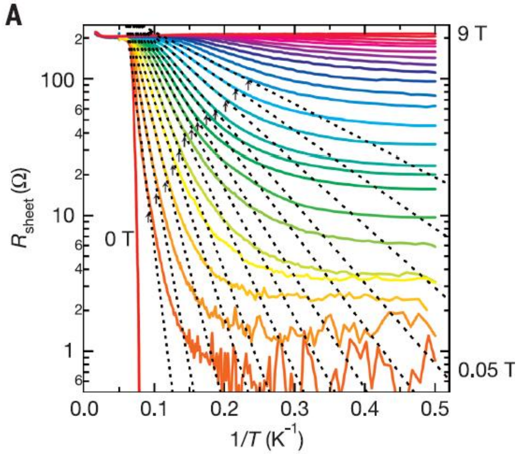


Goldman group, Phys. Rev. Lett. 88, 37004 (2002)

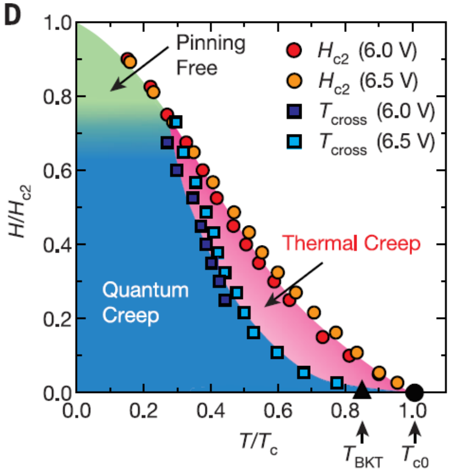
Particle-hole symmetry reveals failed superconductivity in the metallic phase of 2D amorphous superconducting films.



Kapitulnik group, Science Advances 3, e1700612 (2017)



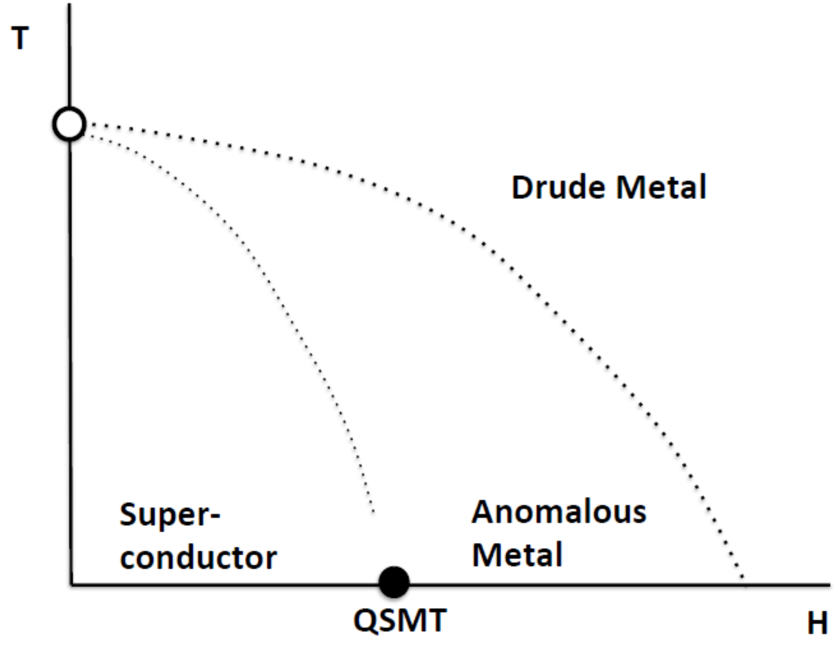
ZrNCl by liquid gating



Iwasa group, Science 350, 409(2015)

In low temperature regime, the resistance saturates to a value independent of temperature, showing the signature of anomalous metallic state.

Schematic phase diagram for the magnetic field driven SMT



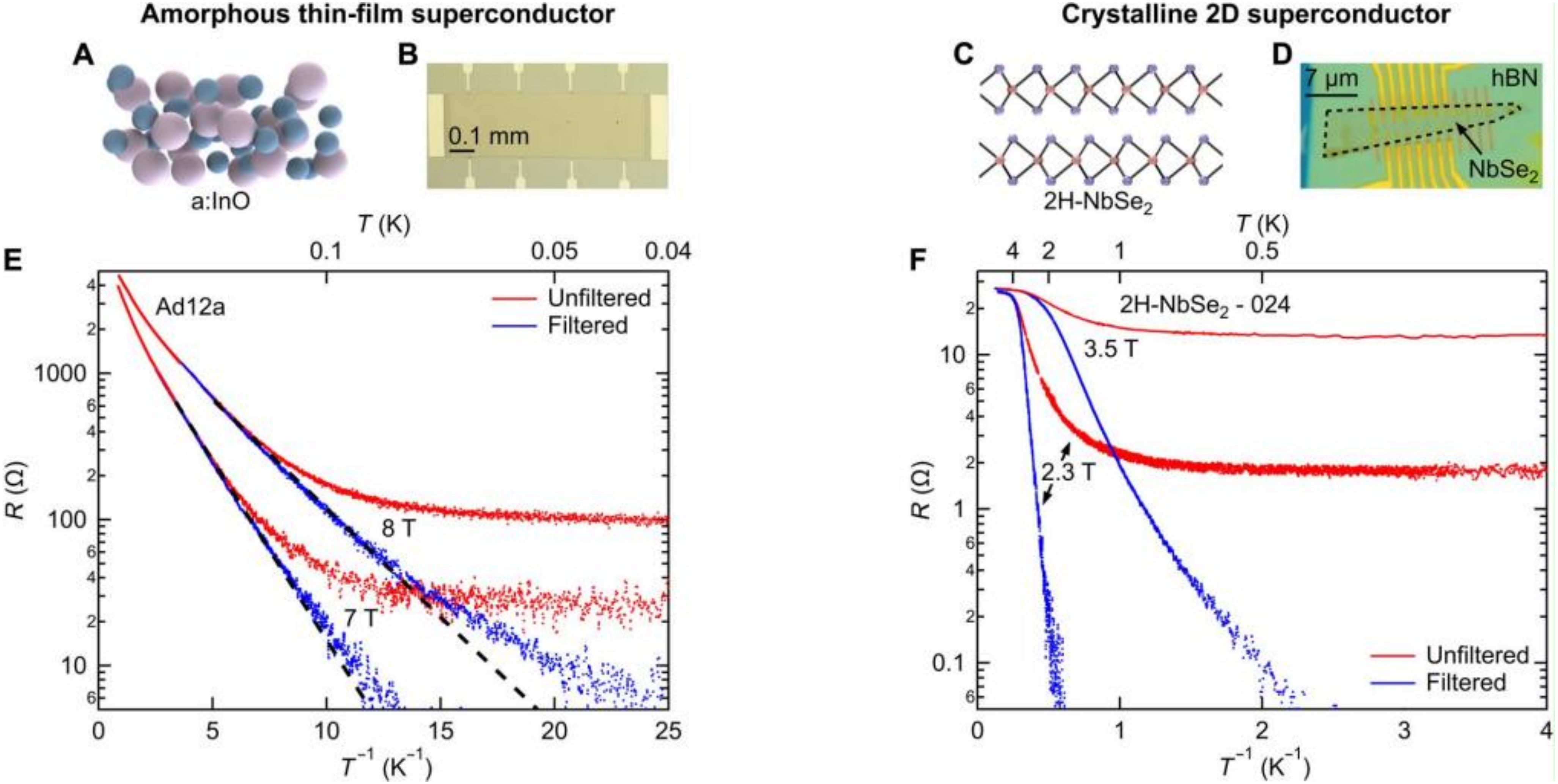
The characteristic of the anomalous metal:

1. Resistance firstly drops and then saturates at low temperatures
2. Suppressed Hall response
3. Giant magnetoresistance

There is currently no satisfactory theory of anomalous metals that accounts for the full set of **key experimental facts**, in particular the robustness of the anomalous metallic state. We view this as **one of the major open problems** in condensed matter physics.

A. Kapitulnik, S. A. Kivelson, B. Spivak, Rev. Mod. Phys. 91, 11002 (2019)

Anomalous metallic state in 2D superconducting system: Problems and challenges



However, one experiment shows that such "anomalous metallic state" is from high frequency noise. When they used the filters, the "anomalous metallic state" became superconducting!

Under debate and challenging!

I. Tamir et al., Sci. Adv. 5:eaau3826 (2019)

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Brown University

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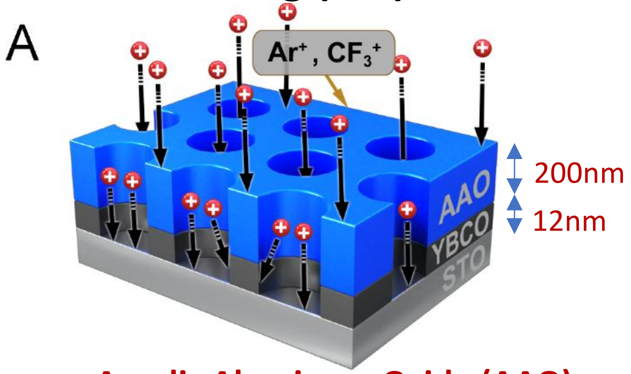
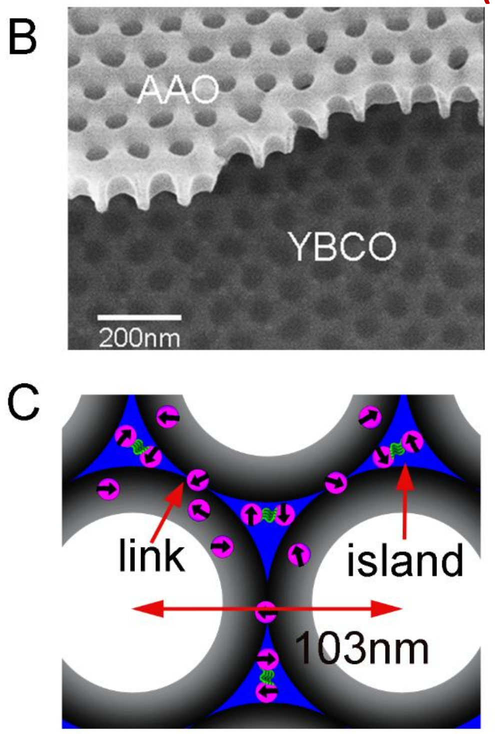
Other collaborators: Yang Wang, Liu Feng, Qianmei He, Jian Sun, Yue Tang, Chunchun Wu, Wanli Zhang, Jie Xiong, Xi Lin, Hong Yao, Haiwen Liu, Gustavo Fernandes, Jimmy Xu

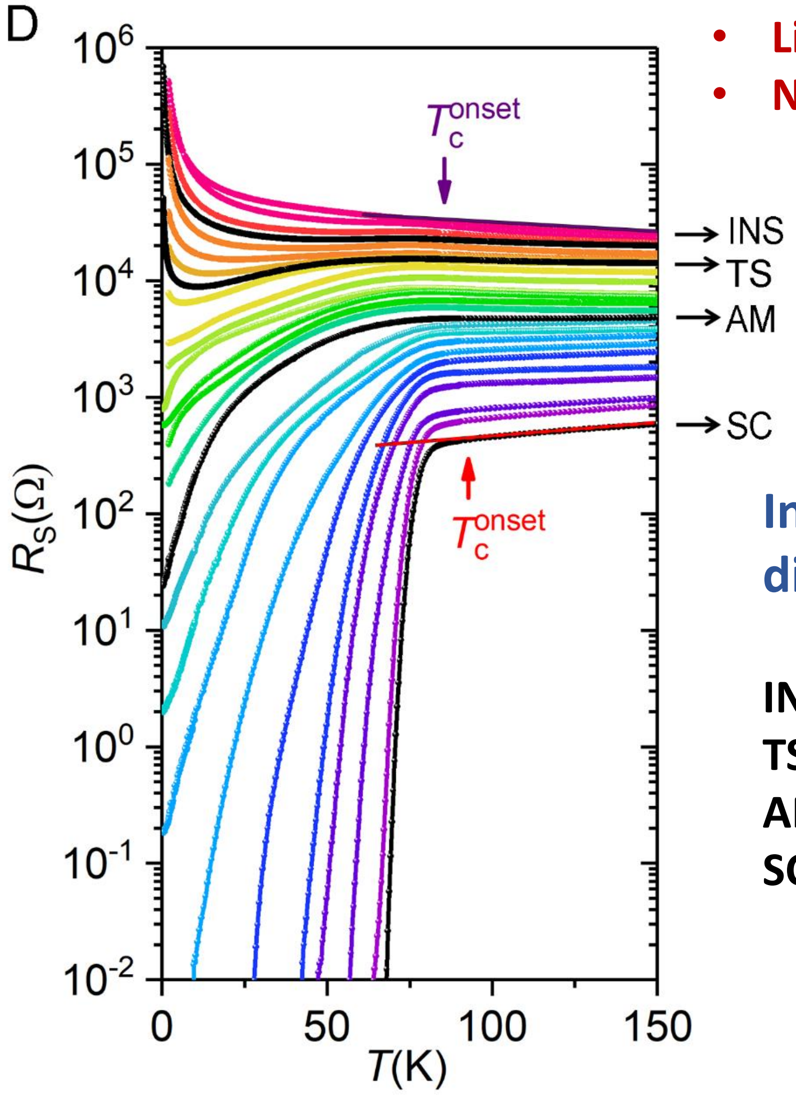
Anomalous metallic state in nano-patterned high Tc YBCO films

Reactive ion beam etching (RIE)



Anodic Aluminum Oxide (AAO)





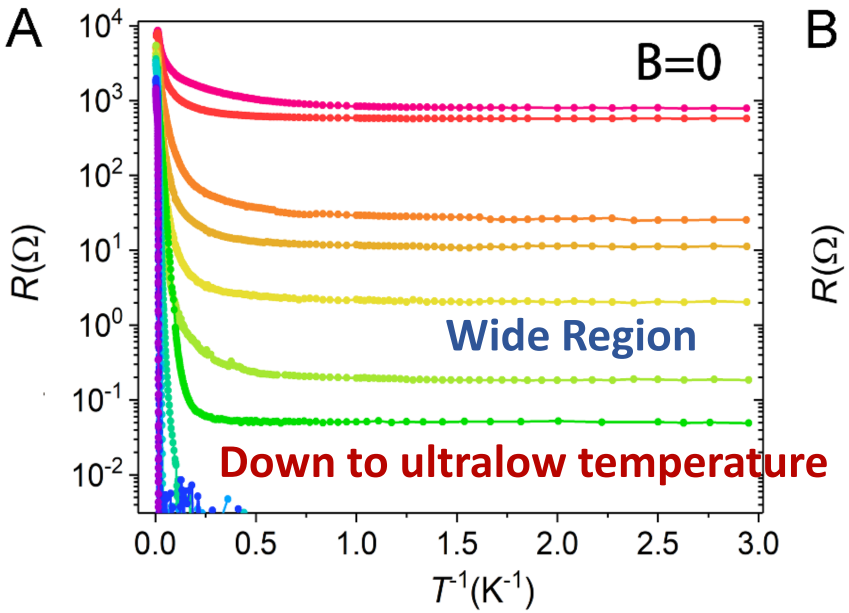
- **Increase etching time**
- **Induce more disorder (halo grows)**
- **Link resistance grows**
- **Normal resistance grows**

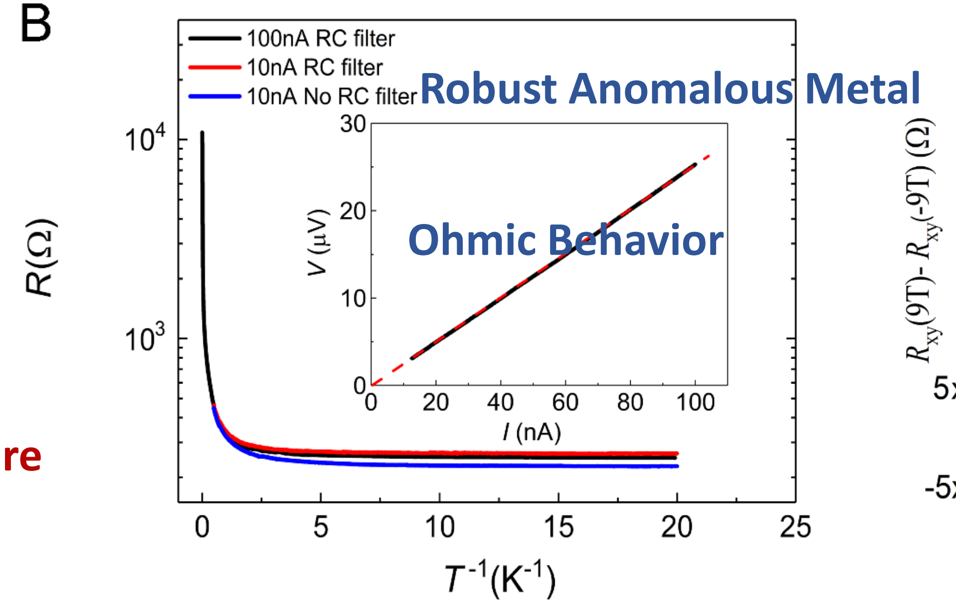
Increasing disorder

INS: insulating state
TS : transitional state
AM: anomalous metal
SC : superconducting state

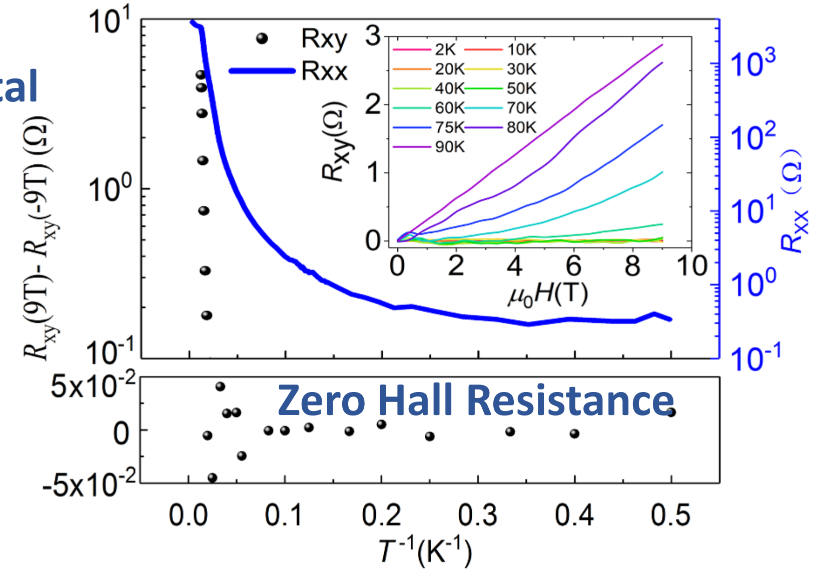
***Science* 366, 1505 (2019)**

Evidences of anomalous metallic state in 2D high Tc films

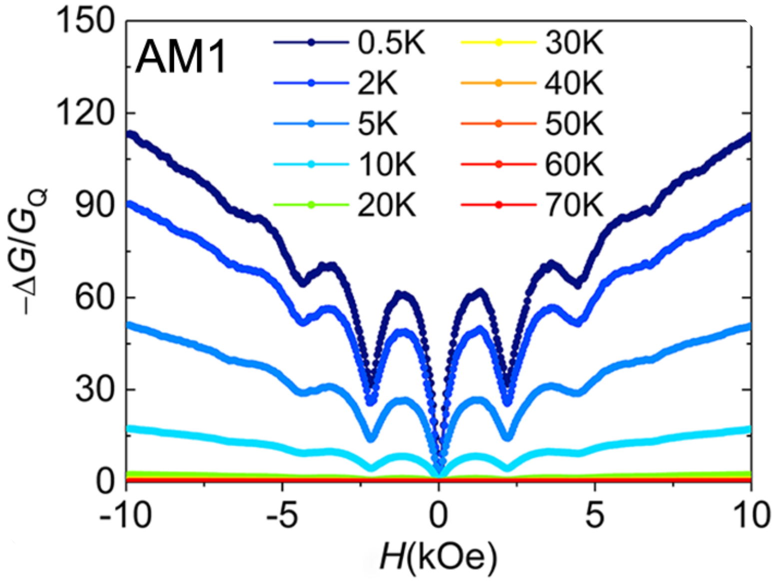




Control experiment of filters



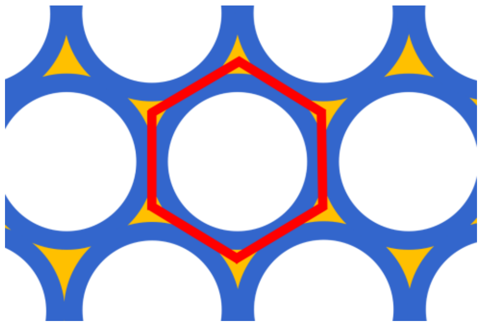
Within measurement resolution



Quantum oscillations of Cooper pairs

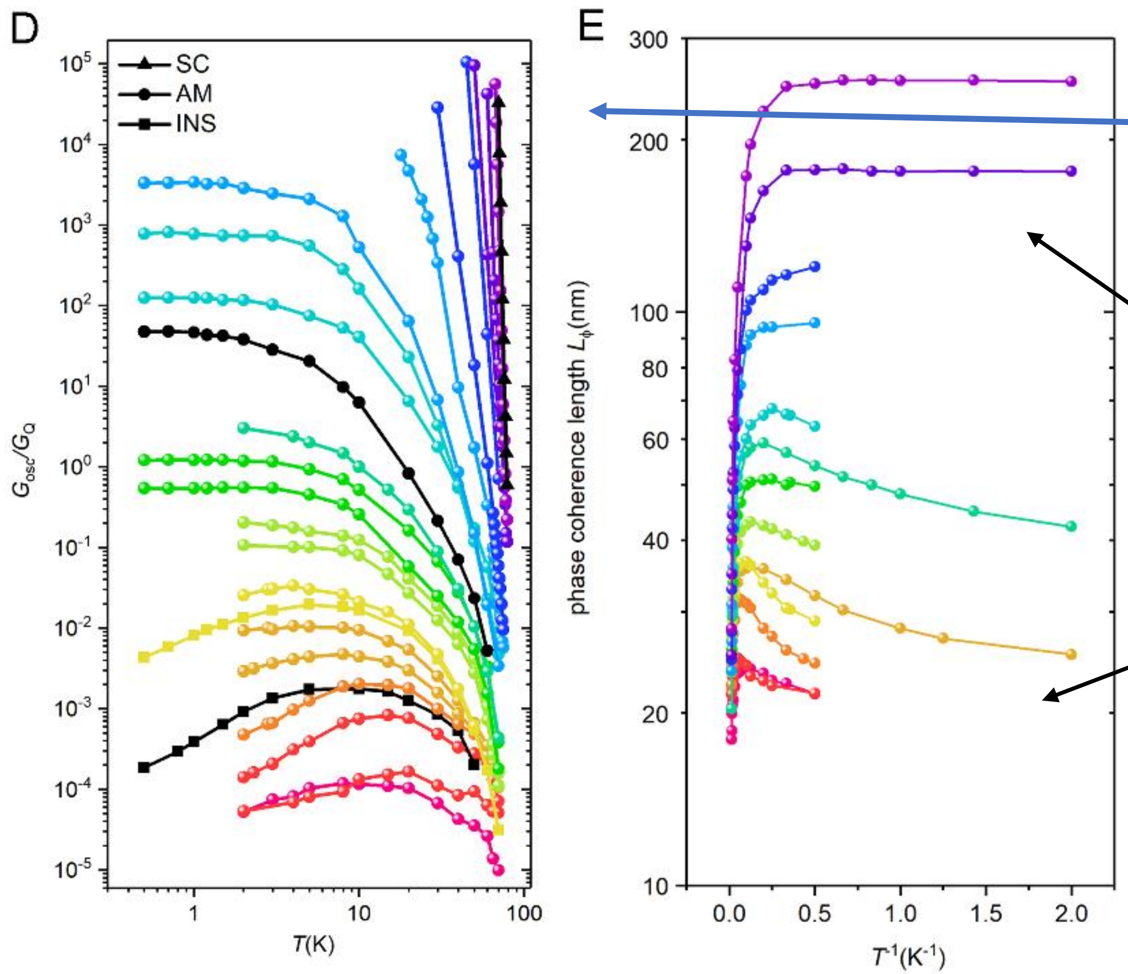
Quantum oscillations with a magnetic field period of 0.225 T.

This period is consistent with one superconducting flux quantum $\Phi_0 = h/2e$ threading an area of one unit-cell of the pattern (around 9200 nm^2).



The transport properties of the anomalous metallic state are dominated by Cooper pairs.

Quantum oscillations amplitude and phase coherence length calculation



- superconducting films,
- G_{osc} grows with decreasing temperature
- phase coherence length diverges when $T \rightarrow 0$

- Anomalous metallic state films, G_{osc} saturates around 5K with decreasing temperature
- phase coherence length saturates

- Insulating state films, G_{osc} first increases then decreases at lower temperatures
- phase coherence length decreases at lower temperatures

Saturation of phase coherence plays a prominent role in the formation of this anomalous metallic state.

Science 366, 1505 (2019)

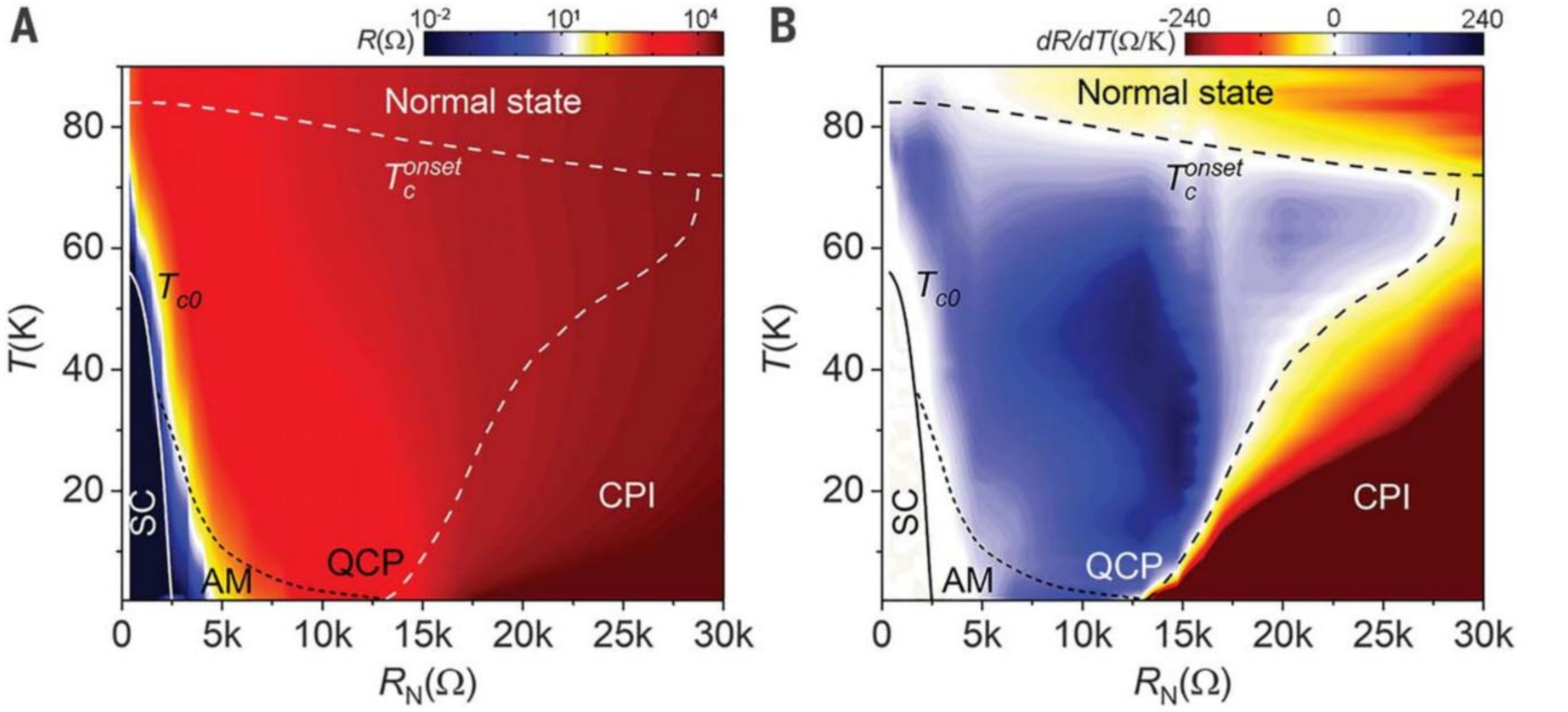
Quasiparticle quantum interference

$$G_{osc} = \frac{4e^2}{h}\left(\frac{L_\phi}{\pi r}\right)^{1.5}\exp\left(-\frac{\pi r}{L_\phi}\right).$$

L_ϕ Phase coherence length

Phys. Rev. B 68, 085413 (2003)

Phase diagram of YBCO films modulated by hexagonal array of holes



Superconducting phase: $R_s = 0$ **(within the measurement resolution)**

Anomalous metal: **Resistance saturates in low temperature regime**

Cooper pair insulator: $dR_s/dT < 0$

Summary

1. The high quality YBCO films were grown on (001)-oriented $SrTiO_3$ substrates by magnetron sputtering. Periodic array of holes were fabricated on YBCO films by reactive ion etching technique through a nano-pattern. With increasing etching time, the nanopatterned YBCO films undergo the disorder induced superconductor-anomalous metal-insulator transition.
2. Anomalous metallic state is observed in the YBCO films, revealed by the robust wide region resistance saturation with or without filters, Ohmic behavior, absence of Hall effect and large magnetoresistance in the low temperature regime etc.
3. We observe pronounced h/2e quantum oscillations in the anomalous metallic states, demonstrating the dominant role of Cooper pairs in the anomalous metallic state. The saturation of phase coherence length derived from quantum oscillations could explain the origin of the anomalous metallic state.
4. Remarkably, our work opens a new avenue for studying anomalous metallic states via nanopatterning and quantum oscillations.

Science 366, 1505 (2019)

Highlight

Journal Club for Condensed Matter Physics JCCM_March_2019_01
https://www.condmatjclub.org

Evidence of an anomalous metallic phase in a high temperature superconducting device

Recommended with a Commentary by Steven A. Kivelson, Stanford University, Stanford, CA 94205

Prof. S. A. Kivelson

There are a number of aspects of the results that are notable:

1. **In the AM regime, the resistivity becomes T independent below temperatures as high as 5K, a 10 to 100 times higher temperature scale than that of other systems.**
2. **Magneto-resistance oscillations with period corresponding to a superconducting flux quantum per hole have been observed in all the regimes.**
3. **The Hall resistivity plummets from its normal state value to become immeasurably small below approximately 50K in the AM regime.**

Steven A. Kivelson, Journal Club for Condensed Matter Physics, March, 2019. Available at https://www.condmatjclub.org/?p=3560

Highlight

INSIGHTS | PERSPECTIVES

PHYSICS

Free at last: Bose metal uncaged

A metallic phase disrupts the classic two-state superconductor-insulator picture

By Philip W. Phillips[1,2]

Even the particle world is not immune to identity politics. Bosons have been in a bit of an identity crisis, or so it has seemed since 1989 (1). Quantum mechanics requires bosons made of two paired electrons to either condense into a superfluid with a well-defined phase with zero electrical resistance or localize in an insulating state with infinite resistance. The direct transition from superconducting to insulating states was widely observed in a range of thin films (2–4). The most popular model for explaining these observations (5) claims that the destruction of superconductivity occurs when the resistance of the thin film exceeds a critical value. For bosons on the brink of localization, electrically insulating behavior is observed if the resistance is greater than the quantum of resistance, $R_q = h/4e^2$, otherwise superconductivity persists, where h is Planck's constant and e is the electric charge. On page 1505 of this issue, Yang *et al.* (6) offer a counterexample by establishing that a bosonic metallic phase disrupts the superconductor-insulator transition (SIT) in the high-temperature superconductor $YBa_2Cu_3O_{7-x}$ (YBCO).

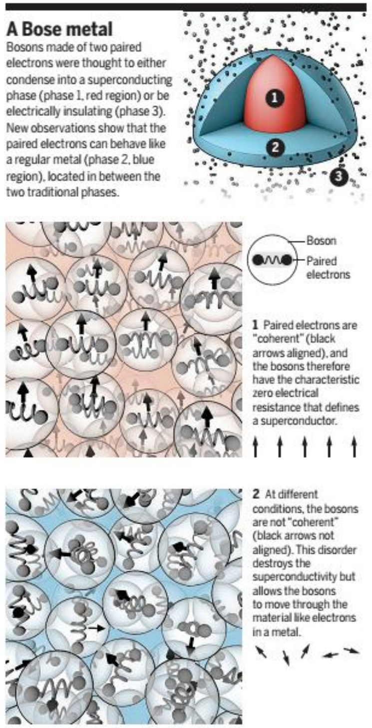
Indeed, bosons have been toying with metallicity since 1989 (2). However, the older data were dismissed by other researchers as being due to a refrigeration problem. The explanation for the observations was that the bosons were not cooling, instead remaining in suspended animation and conducting. Nonetheless, the metallic states were observed at a frequency that kept hope alive for a true 0 K disruption of the SIT. In the magnetic field–tuned transition in molybdenum germanide (MoGe) (4), the resistance flattened at an onset temperature that decreased with increasing field. If the metallicity was due to a heating effect, then the failure to cool the sample would occur at the same temperature, not a temperature determined by the magnetic field (4). Similar observations were made on tantalum (7) and in single crystals of ion-gated zirconium nitride chloride (ZrNCl) (8).

A direct attack on the refrigeration problem came from the experiments that showed that the metallic states in amorphous indium oxides (InO_x) (3) and crystalline 2H-phase niobium diselenide (2H-$NbSe_2$) (9) were artifacts (10) because they vanished by eliminating all sources of electromagnetic radiation. Yang *et al.* used this now-standard electromagnetic radiation–filtering scheme to avoid artifacts and directly address what is carrying the current in the metallic phase.

The experiment utilized a series of high-temperature superconducting YBCO films, which were tuned through the SIT by reactive ion etching. This technique transfers a patterned array of hexagonally plated holes to YBCO. Yang *et al.* observed that the normal-state thin-film resistance increases with increasing etching time. The etching time controls the thickness of the resulting pores' sidewalls, straining the YBCO shell and creating structural defects. The defects increase the resistance of the thin-film sheet. The transition the authors observed is an example of disorder-tuned SIT and similar to the 1989 experiments (2).

Yang *et al.* observed three phases with a critical value for the resistance roughly twice the quantum of resistance, R_q (5). The metallic phase persisted down to a temperature of 50 mK. To characterize this phase, the authors confirmed previous reports (11) of a vanishing Hall resistance. This type of response of the resistance to a magnetic field is an indication of emergent particle-hole symmetry. The ingenuity in the authors' experiments is their measurement of the resistance oscillations as a function of magnetic field. In a typical metal in which electrons are the charge carriers, the oscillations have a period of h/e. Instead, the authors found an $h/2e$ periodicity. This behavior indicates that the charge carriers are two electrons. This experiment thereby proves definitively that bosons are free to roam in a metallic phase, invalidating the standard picture of the two-phase model (5).

Hence, the teasing is over. Bosons can exist as a metal. Furthermore, Yang *et al.* observed that the amplitude of the conductance oscillations grows in the superconducting state, remains constant in the metal, and decreases in the insulator. This



A Bose metal
Bosons made of two paired electrons were thought to either condense into a superconducting phase (phase 1, red region) or be electrically insulating (phase 3). New observations show that the paired electrons can behave like a regular metal (phase 2, blue region), located in between the two traditional phases.

[1]Department of Physics, University of Illinois, 1110 W. Green Street, Urbana, IL 61801, USA. [2]Institute for Condensed Matter Theory, University of Illinois, 1110 W. Green Street, Urbana, IL 61801, USA. Email: dimer@illinois.edu

GRAPHIC: V. ALTOUNIAN/SCIENCE

Hence, the teasing is over. Bosons can exist as a metal. Furthermore,

Prof. P. W. Phillips

RESEARCH

SOLID-STATE PHYSICS

Intermediate bosonic metallic state in the superconductor-insulator transition

Chao Yang[1]*, Yi Liu[2,3]*, Yang Wang[1], Liu Feng[1], Qianmei He[1], Jian Sun[2,3], Yue Tang[2,3], Chunchun Wu[1], Jie Xiong[1]†, Wanli Zhang[1], Xi Lin[2,3,4,5], Hong Yao[3,6,7], Haiwen Liu[8], Gustavo Fernandes[9], Jimmy Xu[9,10], James M. Valles Jr.[10]†, Jian Wang[2,3,4,5,7]†, Yanrong Li[1]

Whether a metallic ground state exists in a two-dimensional system beyond Anderson localization remains an unresolved question. We studied how quantum phase coherence evolves across superconductor–metal–insulator transitions through magnetoconductance quantum oscillations in nanopatterned high-temperature superconducting films. We tuned the degree of phase coherence by varying the etching time of our films. Between the superconducting and insulating regimes, we detected a robust intervening anomalous metallic state characterized by saturating resistance and oscillation amplitude at low temperatures. Our measurements suggest that the anomalous metallic state is bosonic and that the saturation of phase coherence plays a prominent role in its formation.

*These authors contributed equally to this work.
†Corresponding author. E-mail: jianwangphysics@pku.edu.cn (J.W.); james_valles_jr@brown.edu (J.M.V.); jiexiong@uestc.edu.cn (J.X.)

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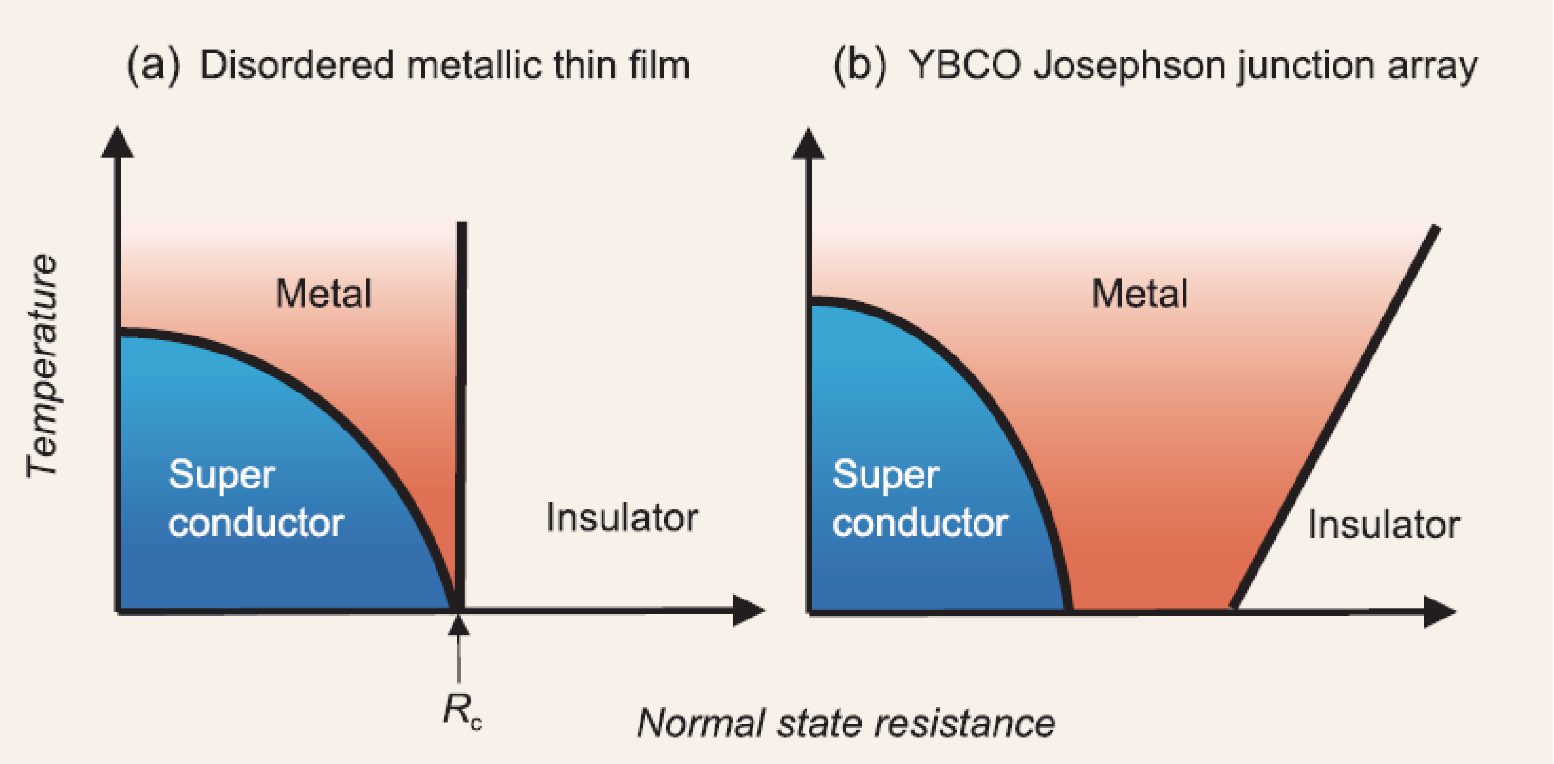
Yang *et al.*, *Science* **366**, 1505–1509 (2019)   20 December 2019

Highlight

PHYSICS

Do bosons always condense?

Yoshihiro Iwasa[1,2]



Schematic phase diagram of (a) disordered 2D superconductor and (b) YBCO Josephson-junction arrays.

Prof. Y. Iwasa

Natl. Sci. Rev. 8, nwaa219 (2021)

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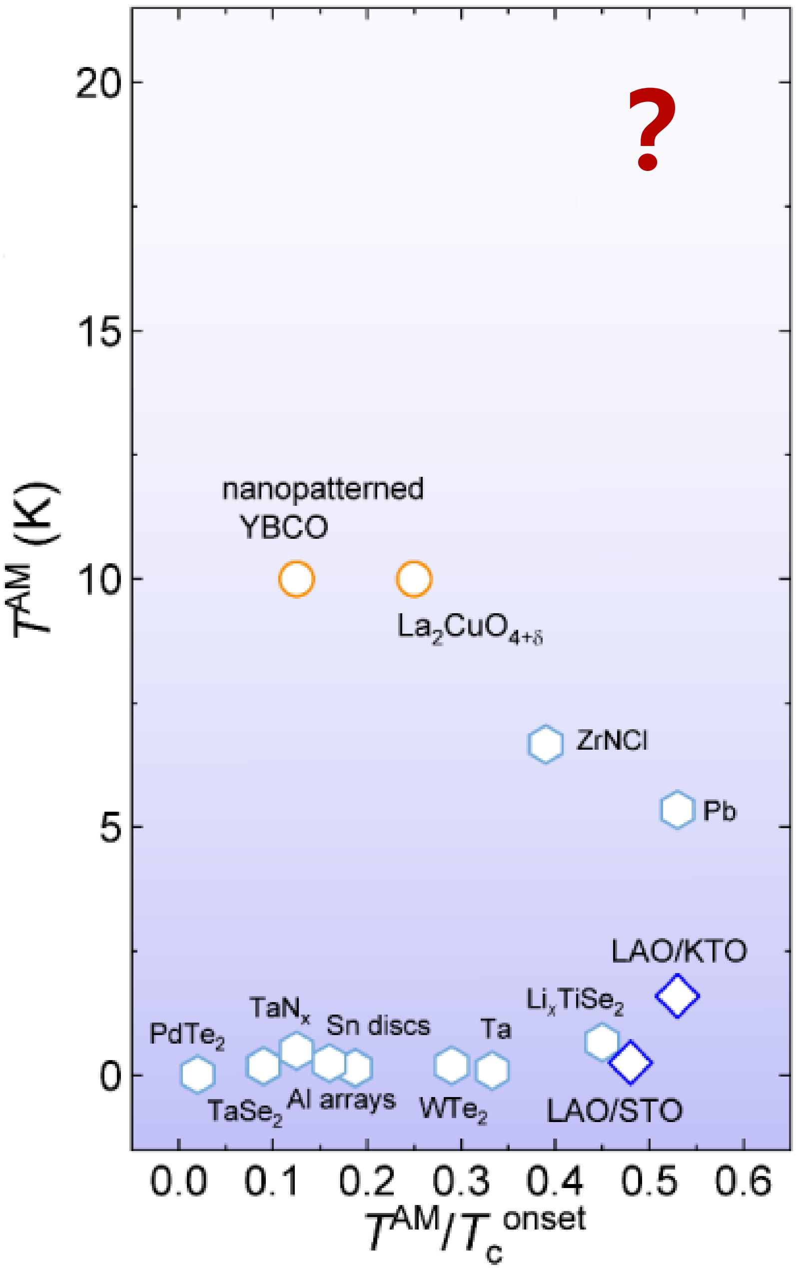
Other collaborators: Chengcheng Ji, Shichao Qi, Xiaotong Jiao, Wenfeng Dong, Yi Sun, Wenhao Zhang, Zihan Cui, Minghu Pan, Nitin Samarth, Lili Wang, X.C. Xie, Qi-Kun Xue

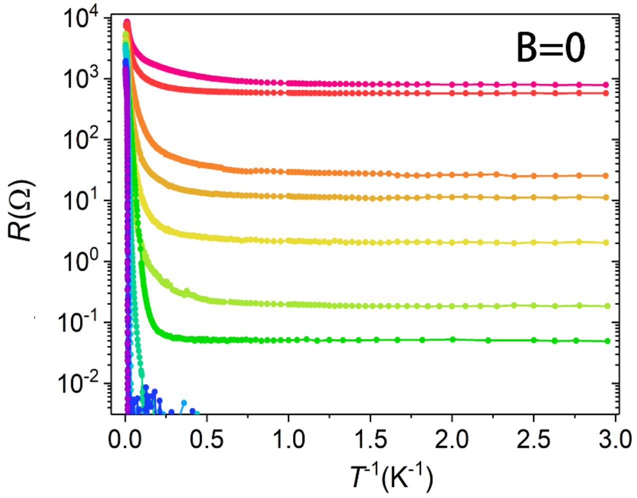
High-temperature anomalous metallic state



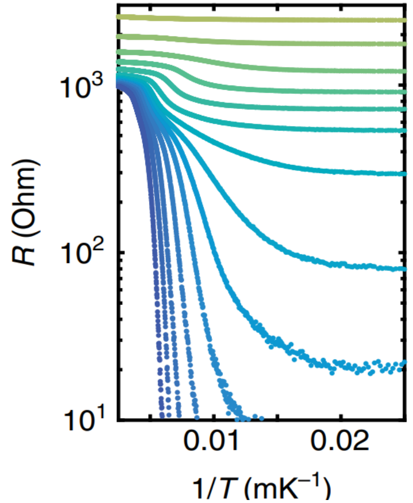
1. High temperature superconductors show high T_{AM}

2. Interface superconductors manifest high T_{AM}/T_c^{onset}

High temperature superconductor YBCO

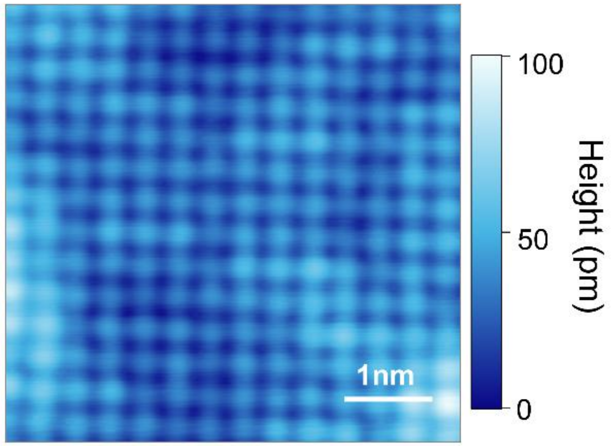


$LaAlO_3/SrTiO_3$ interface

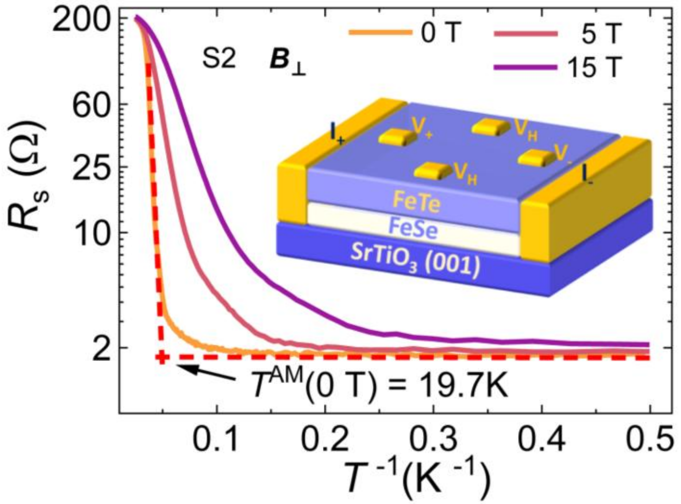


How about high temperature interface superconductors FeSe/STO?

High-temperature anomalous metallic state in crystalline FeSe/STO

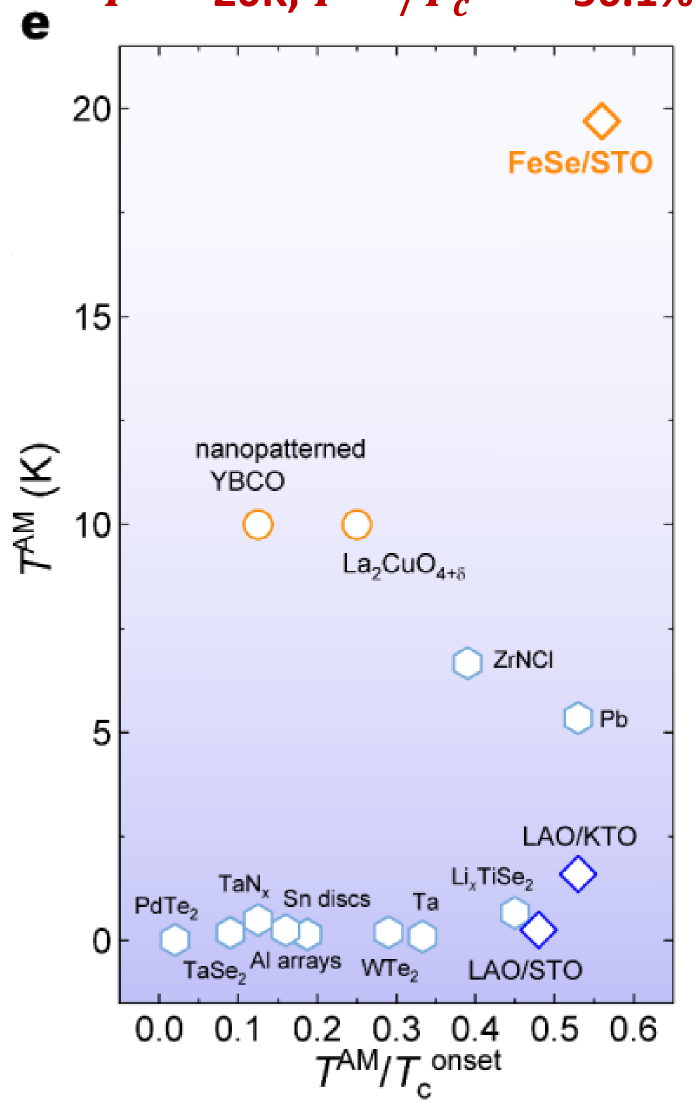


Ultrathin crystalline FeSe films down to one unit-cell thickness grown on STO (001) substrates by molecular beam epitaxy.



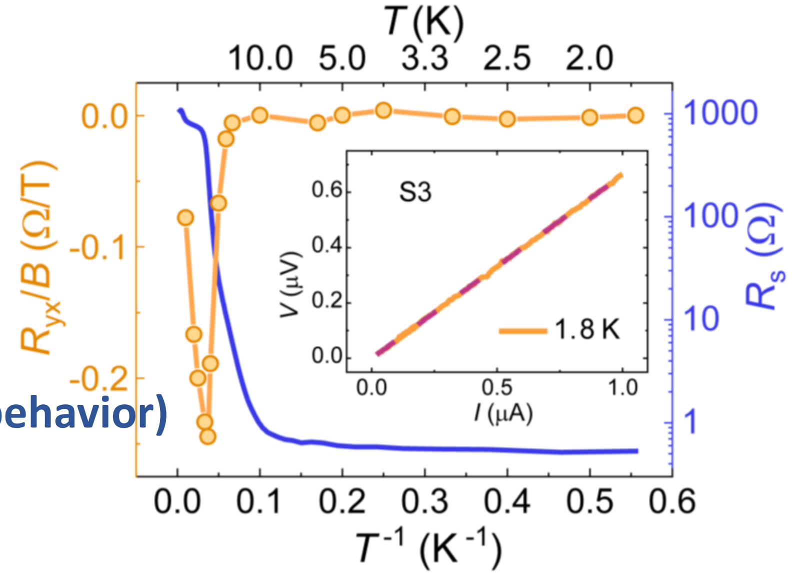
The highest characteristic temperature T^{AM} of the anomalous metal state is around 20K.

T^{AM}~20K, T^{AM}/T_c^{onset}~56.1%



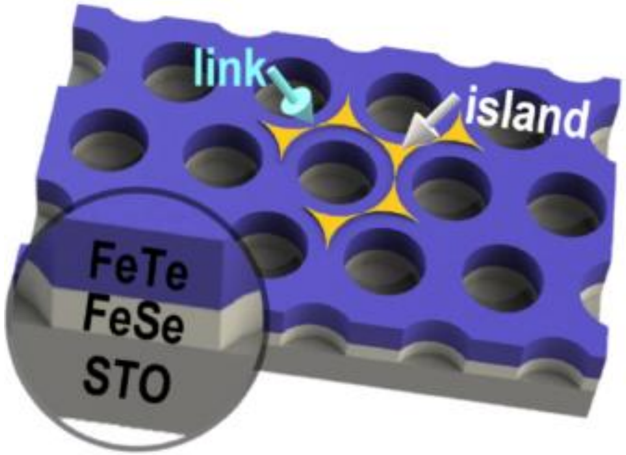
Zero Hall resistance within measurement resolution

The linear IV curve (ohmic behavior)

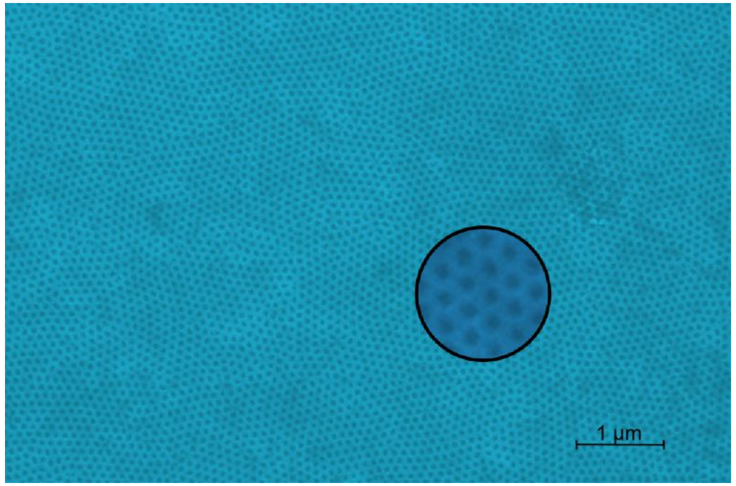


Bosonic strange metal state?

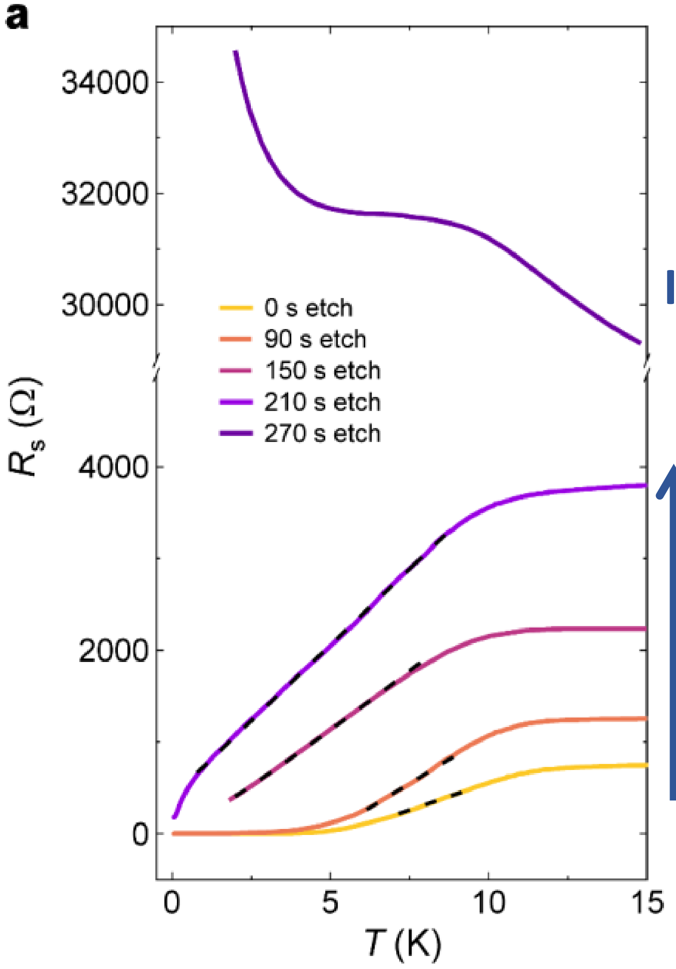
Reactive ion etching



Typical scanning electron microscope image of a nanopatterned FeSe film.

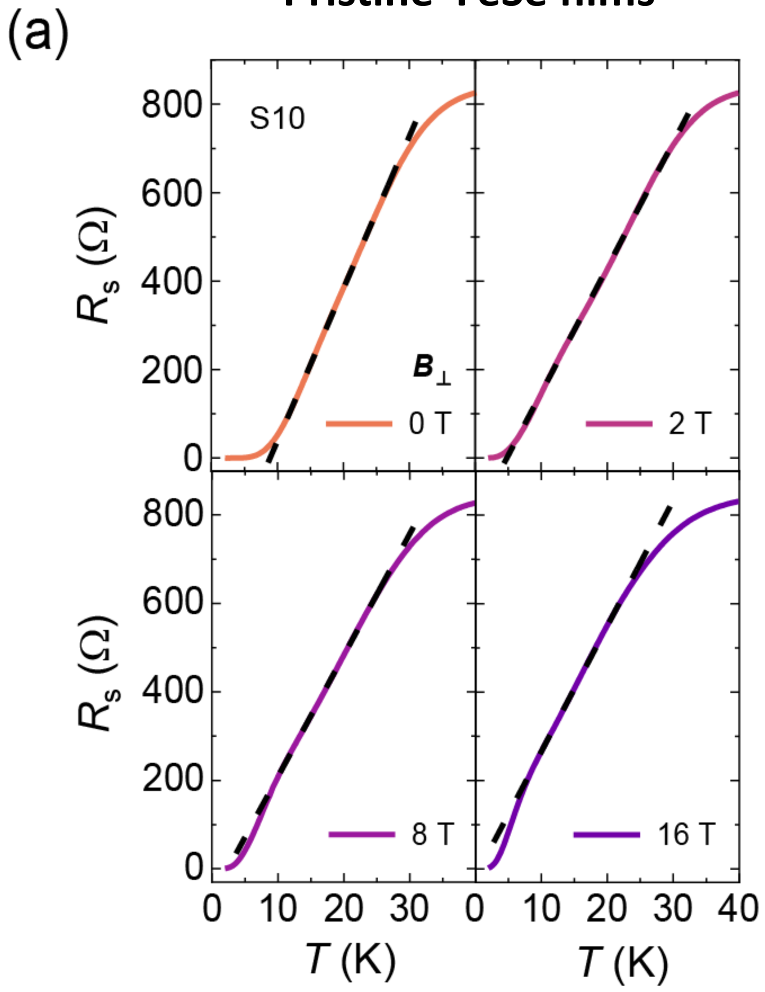


Nanopatterned FeSe films



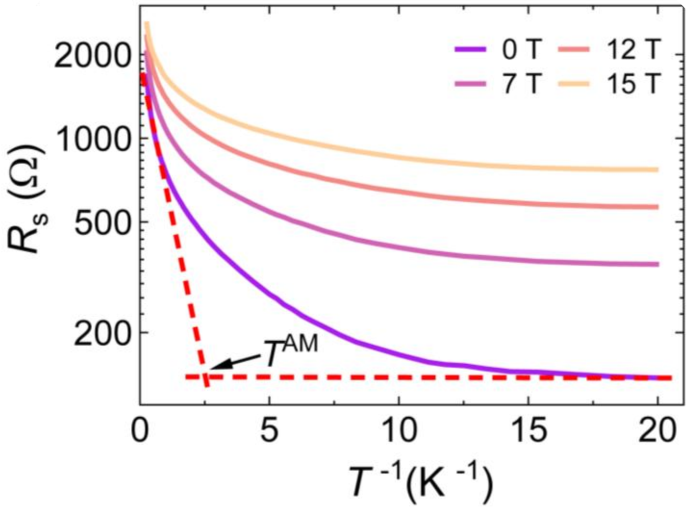
Increasing etching time

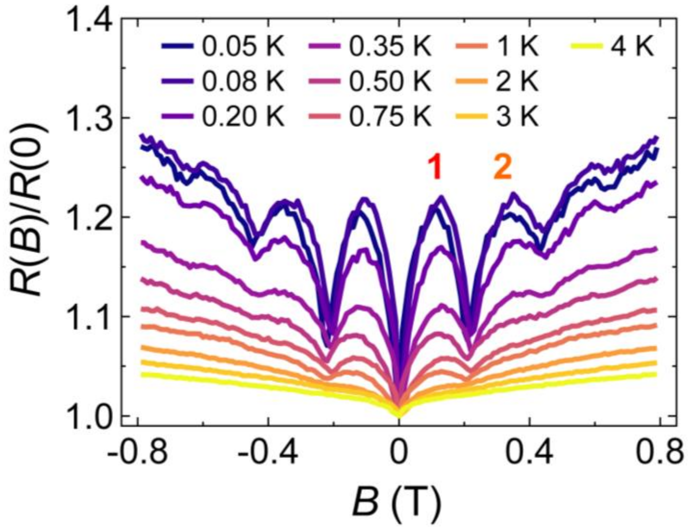
Pristine FeSe films



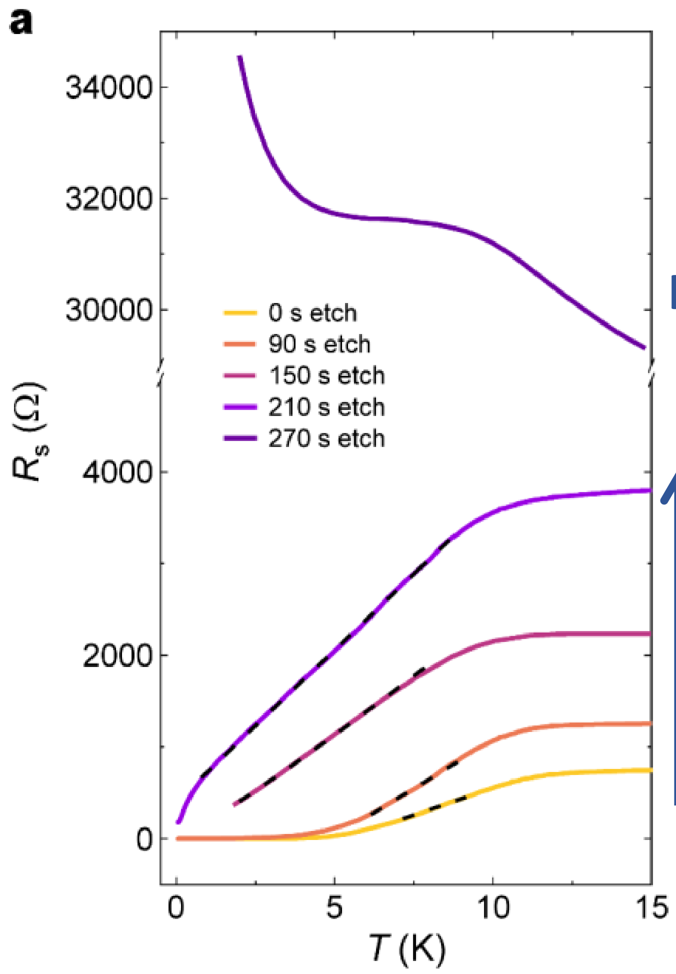
For both pristine and nanopatterned FeSe films, a remarkable linear-in-temperature resistance in a wide temperature regime below T_c^{onset} is detected, reminiscent of the strange metal behavior.

Anomalous metallic state in nanopatterned FeSe/STO



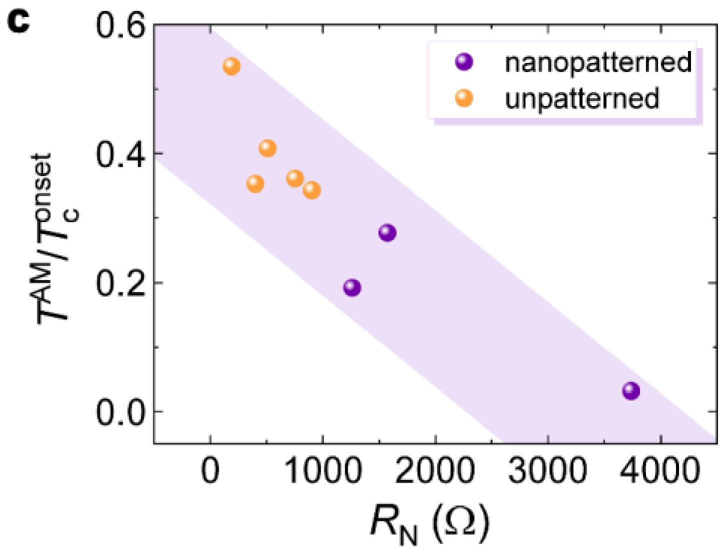


$h/2e$ quantum oscillations



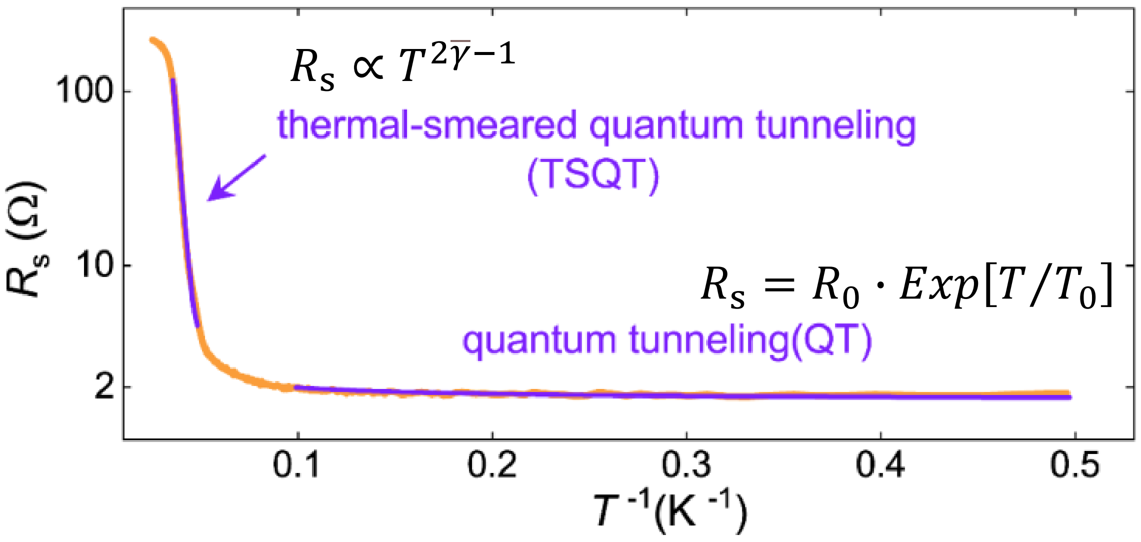
Increasing etching time

The FeSe/STO samples undergo **a superconductor to insulator transition** with increasing etching time.

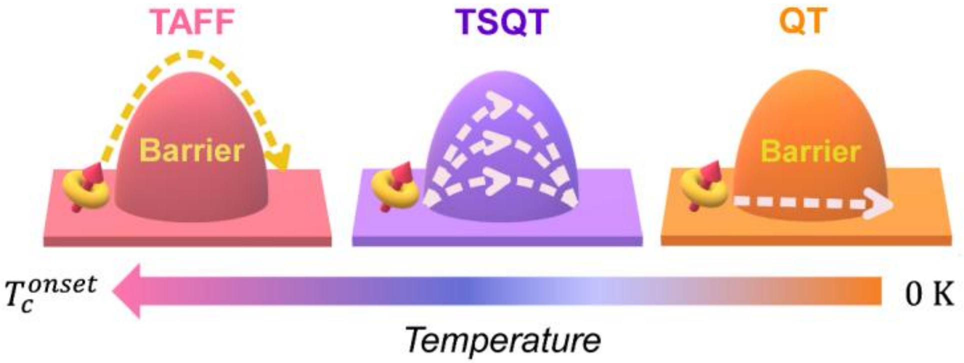


The T^{AM}/T_c^{onset} shows a negative relation to the normal state resistance.

The anomalous metal state in FeSe/STO

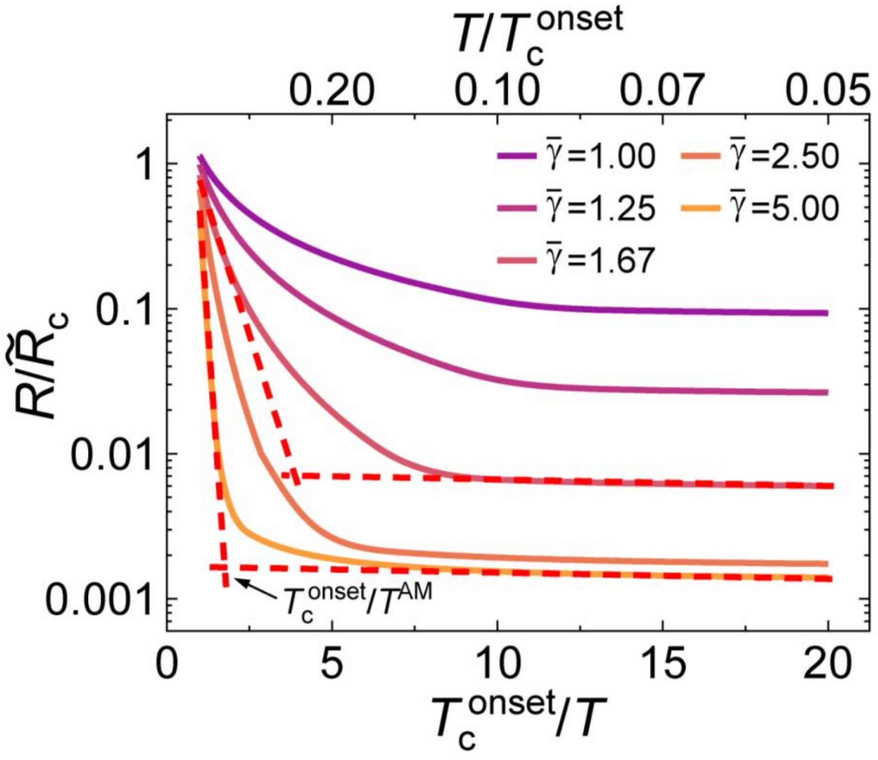


We analyze the behavior of anomalous metal states considering **the quantum tunneling of vortices** in the Josephson junction array **with the ohmic dissipation.**



In collaboration with Prof. Haiwen Liu at BNU

Theoretical simulation



The average flux or phase dissipation strength $\bar{\gamma} = \frac{h}{4e^2 \overline{R_L}}$ and $\overline{R_L}$ is the average link resistance of the weakly coupled Josephson junction. $\overline{R_L}$ is roughly proportional to R_N. Thus, $\bar{\gamma}$ is proportional to $1/R_N$.

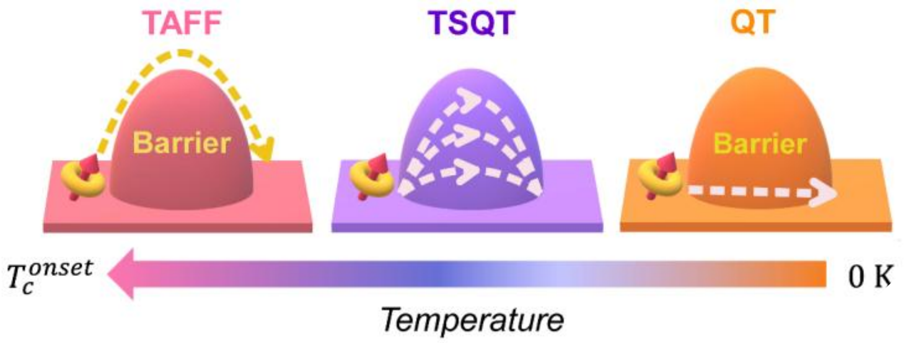
When R_N increases, $\bar{\gamma}$ decreases and then T^{AM}/T_c^{onset} decreases.

Summary

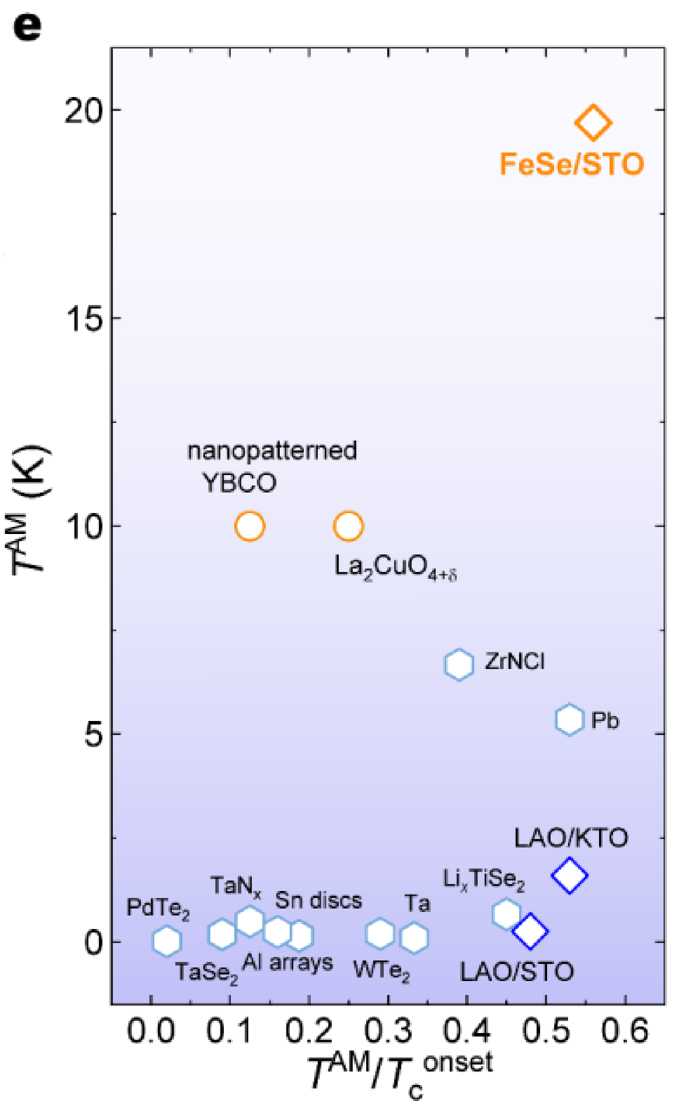
1. We report the observation of high temperature anomalous metallic state in crystalline FeSe/STO interface superconducting system.

2. The zero Hall resistance and pronounced h/2e quantum oscillations demonstrate the bosonic nature of the anomalous metallic state.

3. We develop a model under zero magnetic field based on the quantum tunneling of vortices influenced by the ohmic dissipation, which gives the quantitative explanation for the anomalous metallic state.



T^{AM}~20K, T^{AM}/T_c^{onset}~56.1%



Physical Review Letters 132, 226003 (2024)

Outline

- Part I: Background

- Part II: Anomalous metal states in 2D superconductors

  Science 366, 1505 (2019) with a perspective paper: Science 366, 1450 (2019)

- Part III: The high-temperature anomalous metal states in FeSe/STO

  Physical Review Letters 132, 226003 (2024)

- **Part IV: Anomalous metal states in infinite-layer nickelate films**

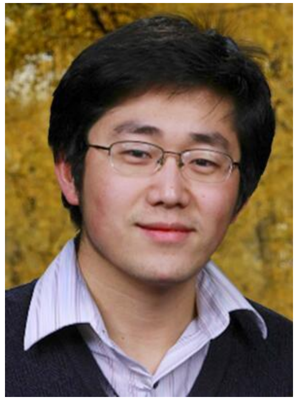
  arXiv: 2603.00670 (2026)

Acknowledgement

Peking University

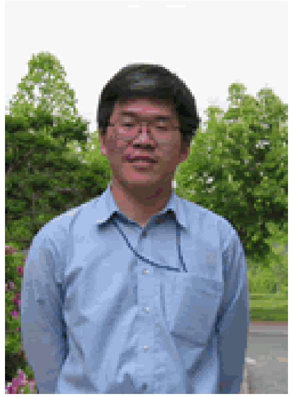
Dr. Haoran Ji

University of Electronic Science and Technology of China



Prof. Liang Qiao

Tsinghua University

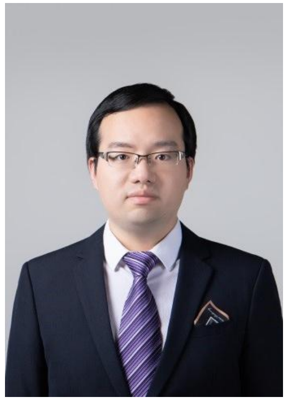


Prof. Guangming Zhang

Institute of Physics Chinese Academy of Sciences

Prof. Yifeng Yang

Renmin University of China



Prof. Yi Liu

Beijing Normal University

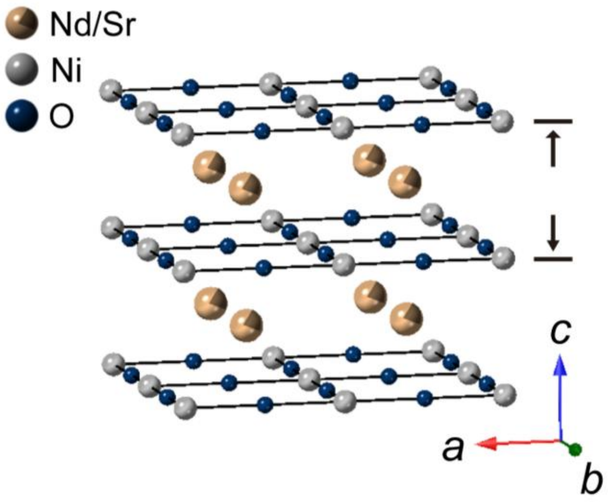
Prof. Haiwen Liu

Other collaborators: Zheyuan Xie, Xiaofang Fu, Zihan Cui, Minghui Xu, etc

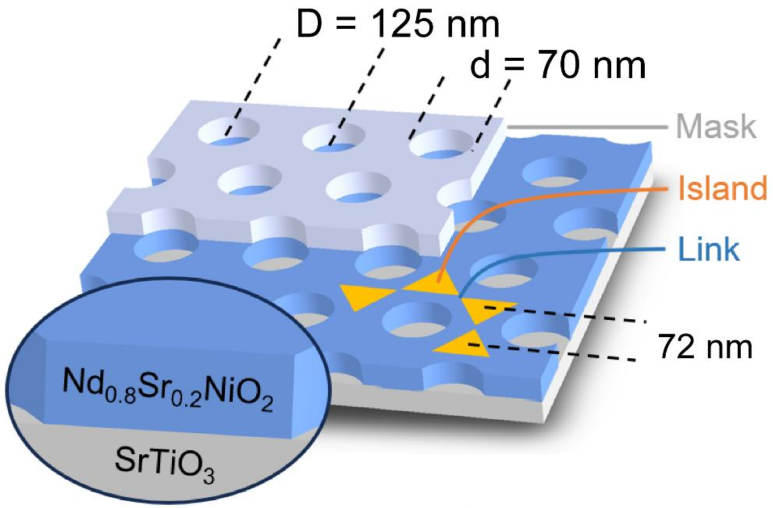
Infinite-layer nickelate films

5s-etched

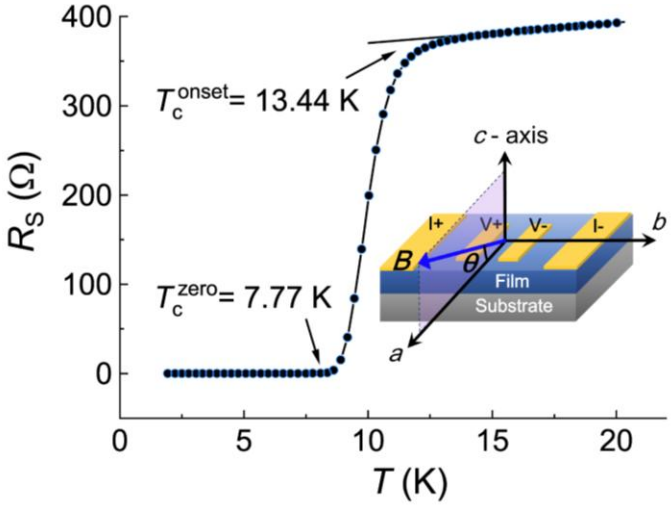
Infinite-layer nickelate $Nd_{0.8}Sr_{0.2}NiO_2$ film

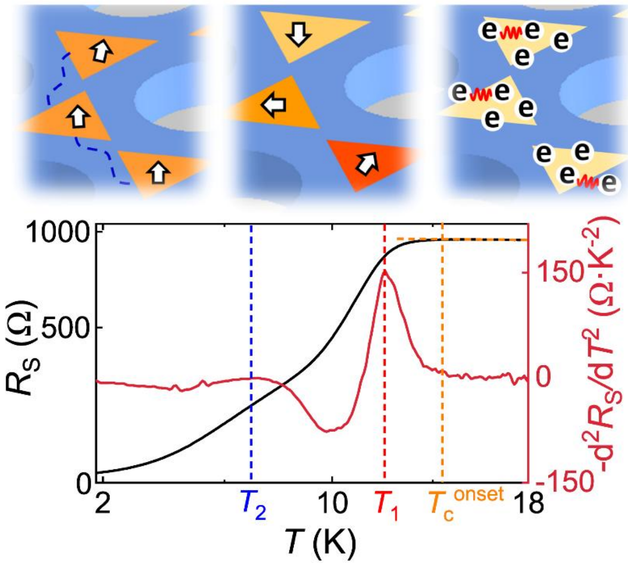


Nano-patterned Josephson-junction array (JJA)



Unpatterned $Nd_{0.8}Sr_{0.2}NiO_2$ film (15 nm thick)





Two-stage transition:

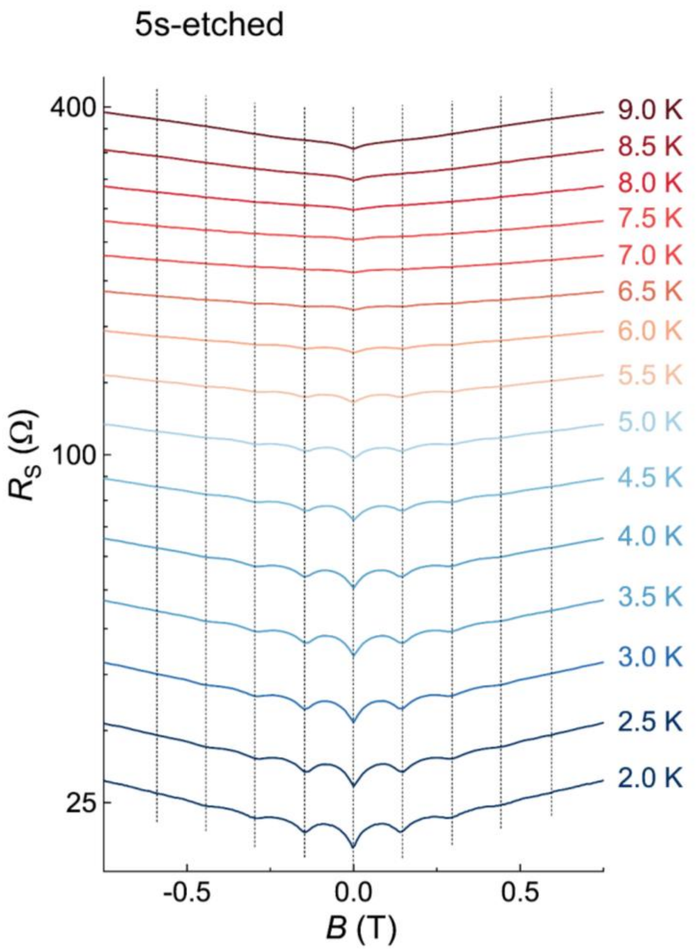
- T_c^{onset} : onset of SC.
- T_1 : local SC in the individual islands.
- T_2 : inter-island phase coherence across the array.

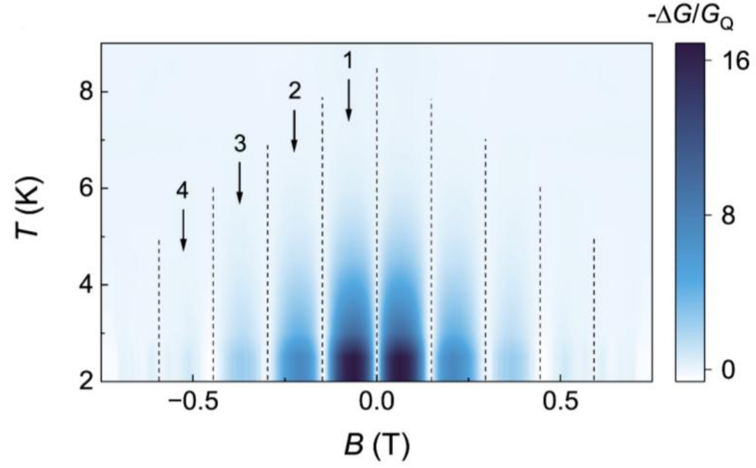
arXiv: 2603.00670 (2026)

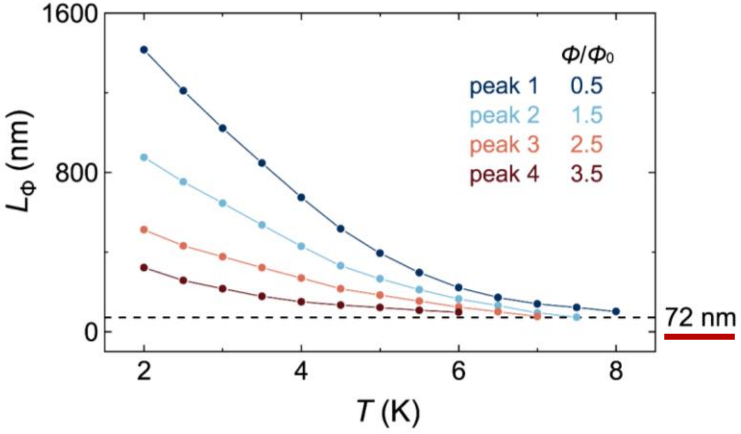
Inter-island phase coherence among the JJA

5s-etched

Robust charge-2*e* quantum oscillations
around the inter-island coherence temperature T_2

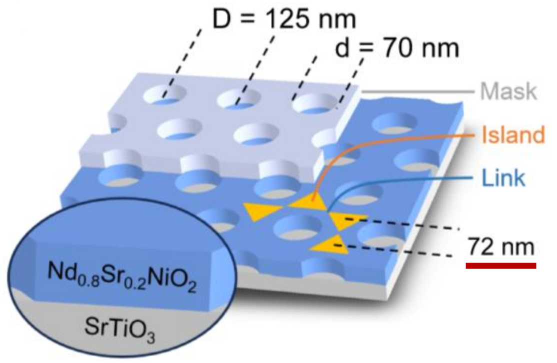






- **Long phase coherence length (L_ϕ)**
- **Charge-2*e* quantum oscillations due to the inter-island phase coherence (L_ϕ >72 nm)**

$$G_{osc} = G_Q \left({}^{2L_\Phi}/_{\pi d} \right)^{1.5} \exp\left(- {}^{\pi d}/_{2L_\Phi} \right)$$

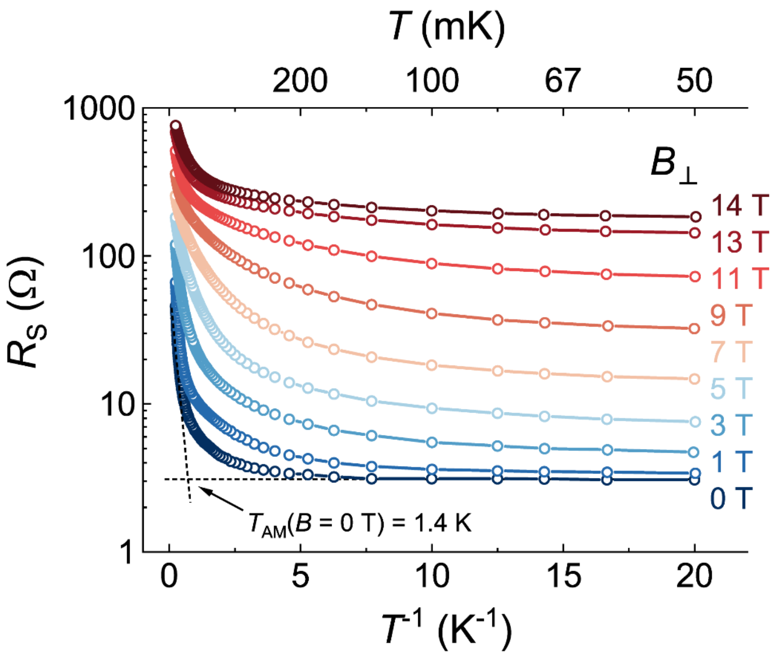


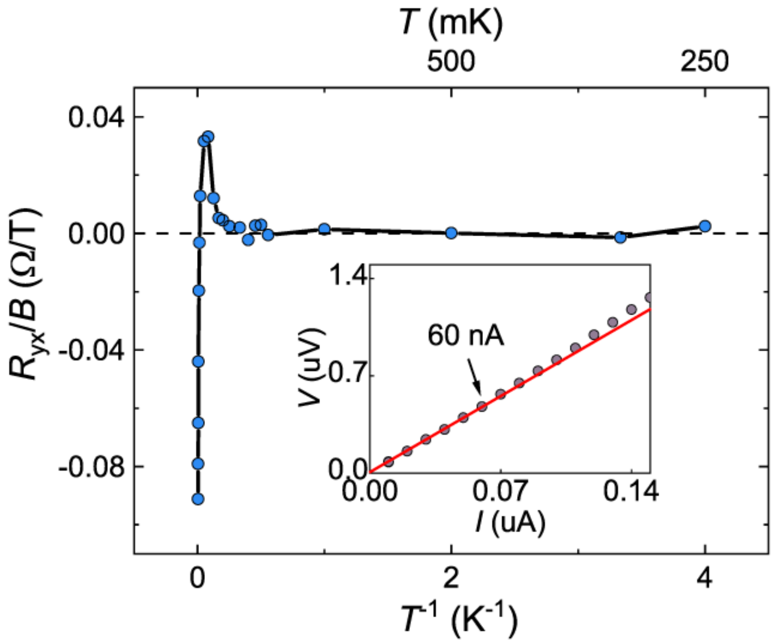
arXiv: 2603.00670 (2026)

Anomalous metallic state in nanopatterned $Nd_{0.8}Sr_{0.2}NiO_2$

At ultralow temperatures down to 50 mK:

5s-etched





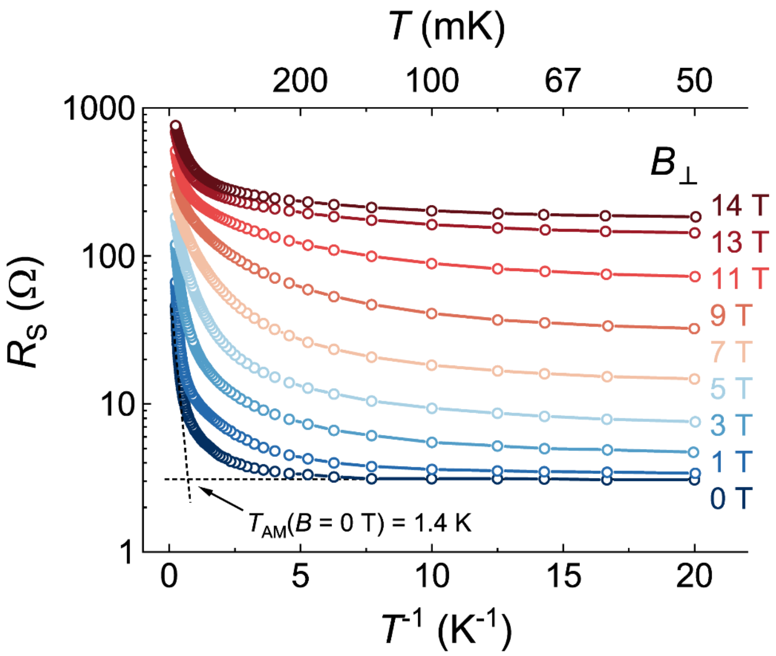
- **Anomalous metallic state below ~ T_{AM} = 1.4 K**

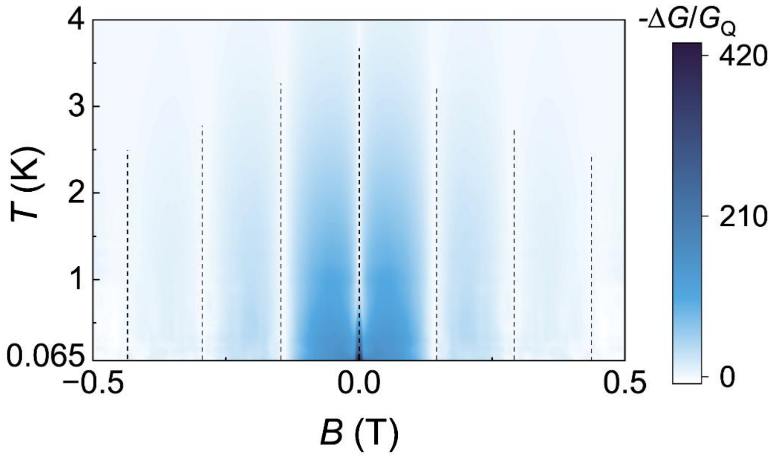
- **Zero Hall coefficient in the anomalous metallica states: Bosonic nature**

Anomalous metallic state in nanopatterned $Nd_{0.8}Sr_{0.2}NiO_2$

At ultralow temperatures down to 50 mK:

5s-etched



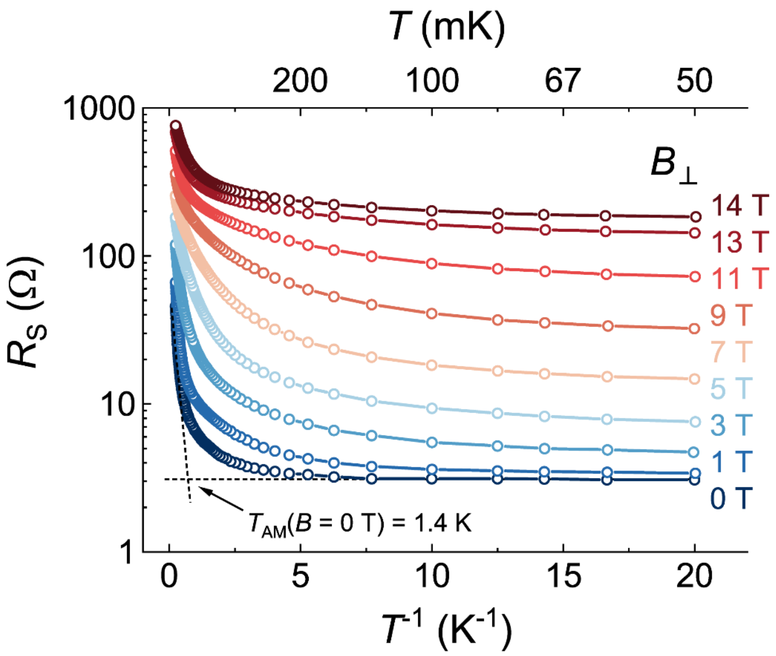


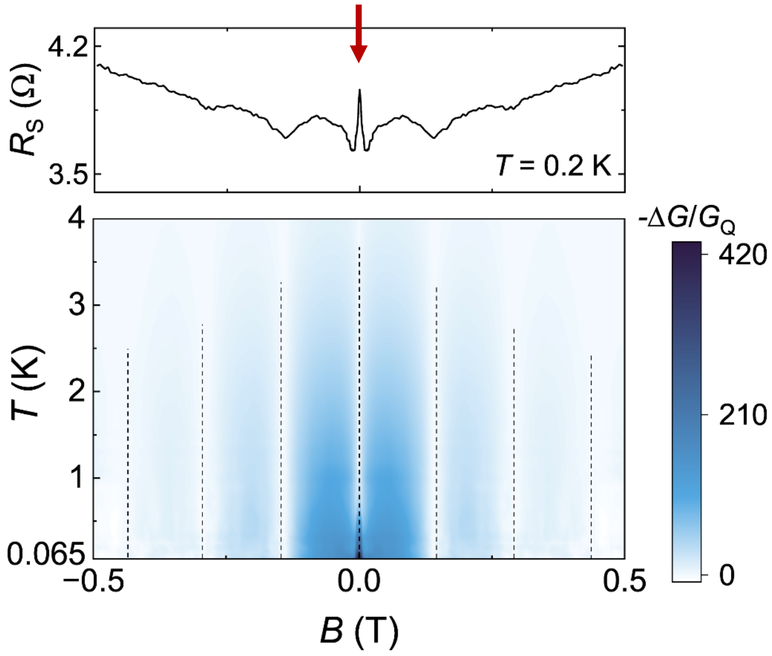
- **Anomalous metallic state below ~ T_{AM} = 1.4 K**
- **Quantum oscillations: Cooper pairs-dominated**

Anomalous metallic state in nanopatterned $Nd_{0.8}Sr_{0.2}NiO_2$

At ultralow temperatures down to 50 mK:

5s-etched





- **Anomalous zero-field peak: superconductivity enhanced by fields, possibly due to strong fluctuations or repulsive Coulomb interactions across the islands?**

S. A. Kivelson, and B. Z. Spivak,
***Phys. Rev. B* 45, 10490-10495 (1992)**

- **Anomalous metallic state below ~ T_{AM} = 1.4 K**

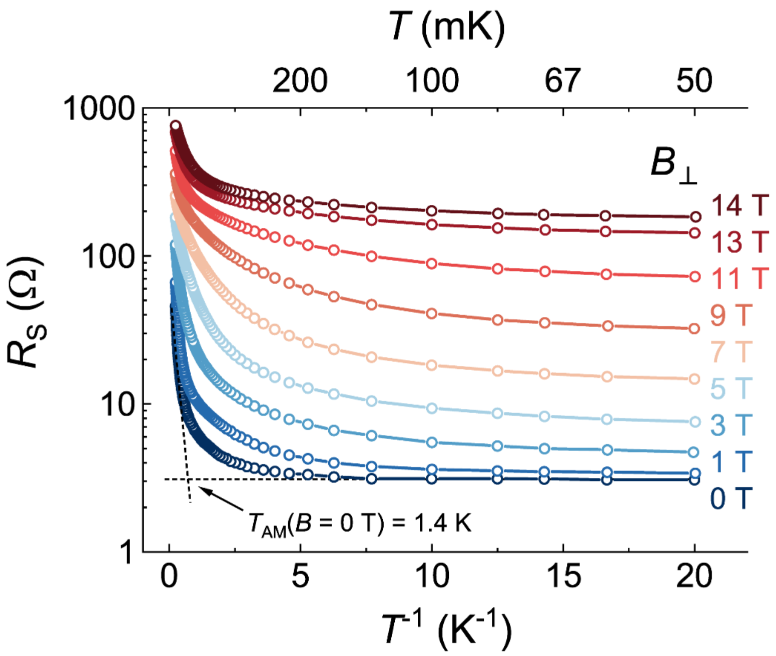
- **Quantum oscillations: Cooper pairs-dominated**

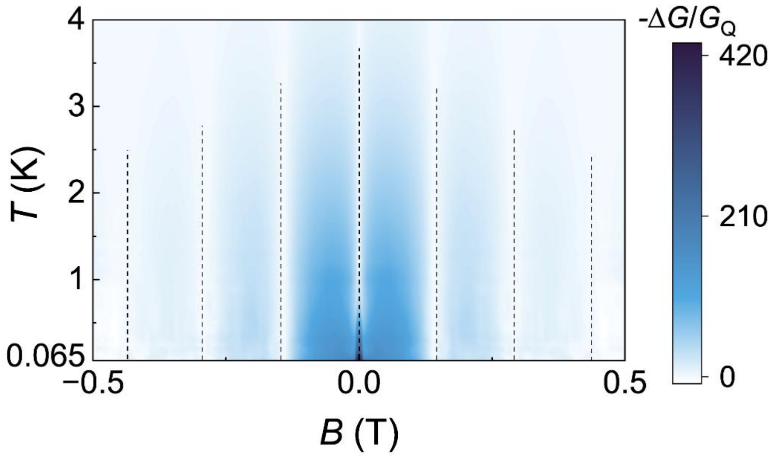
M. A. Skvortsov, A. I. Larkin, and M. V. Feigel'Man,
***Phys. Rev. B* 63, 134507 (2001)**

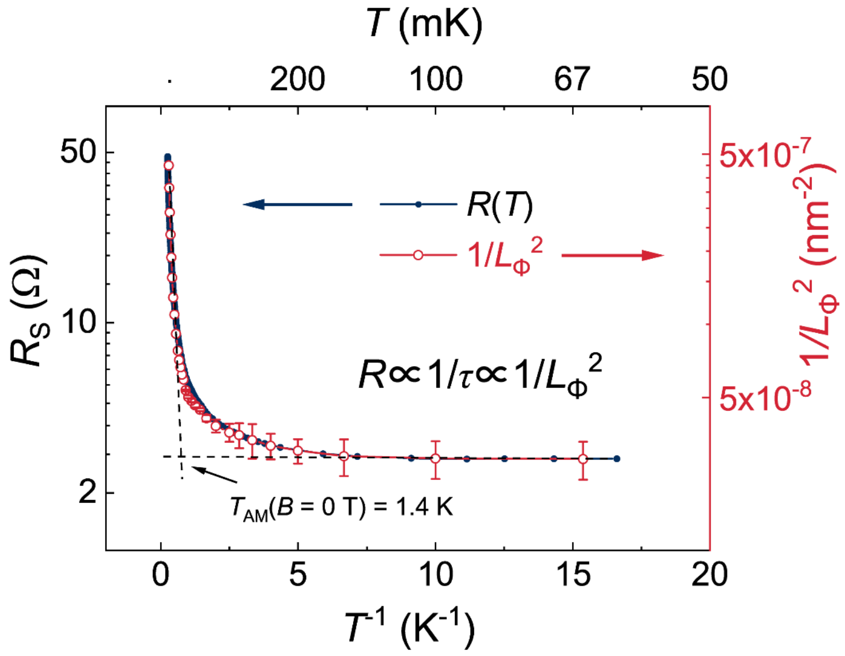
Anomalous metallic state in nanopatterned $Nd_{0.8}Sr_{0.2}NiO_2$

At ultralow temperatures down to 50 mK:

5s-etched







- **Anomalous metallic state below ~ T_{AM} = 1.4 K**
- **Quantum oscillations: Cooper pairs-dominated**
- **Phase coherence length scales with resistance saturations:**

$$R_s \propto \frac{1}{L_\Phi^2} \propto \frac{1}{\tau_\Phi}$$

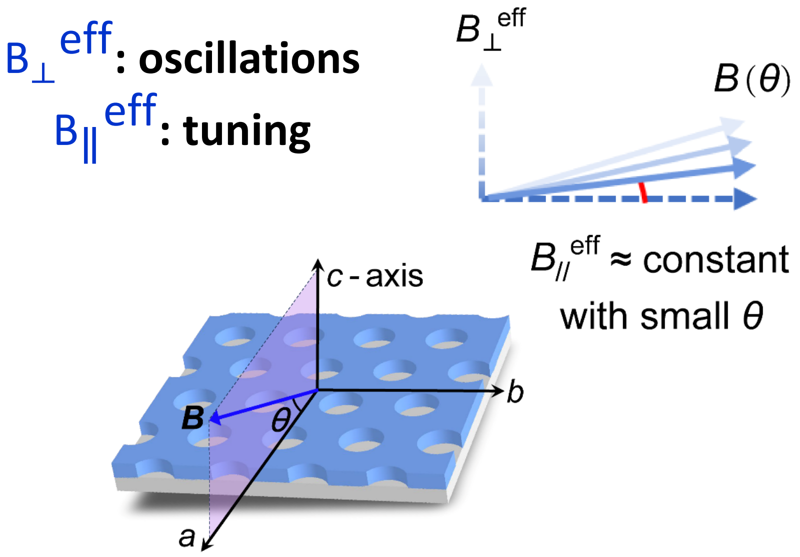
τ_Φ: **dephasing time of Cooper pairs**

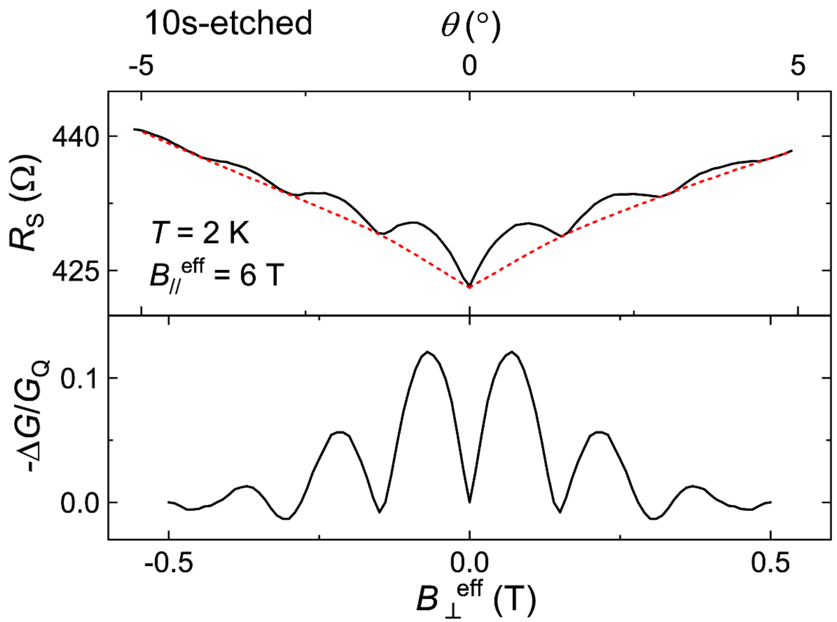
arXiv: 2603.00670 (2026)

Superconducting anisotropy in $Nd_{0.8}Sr_{0.2}NiO_2$

Quantum oscillations under an effective in-plane magnetic field

10s-etched





New method: rotate the magnetic field *B* around $\boldsymbol{\theta}$ = 0°:

- **Investigate the quantum oscillations under $B_{||}^{eff}$ that suppresses the SC stiffness**
- **Study the quantization phenomena during quantum melting of a macroscopic SC state**

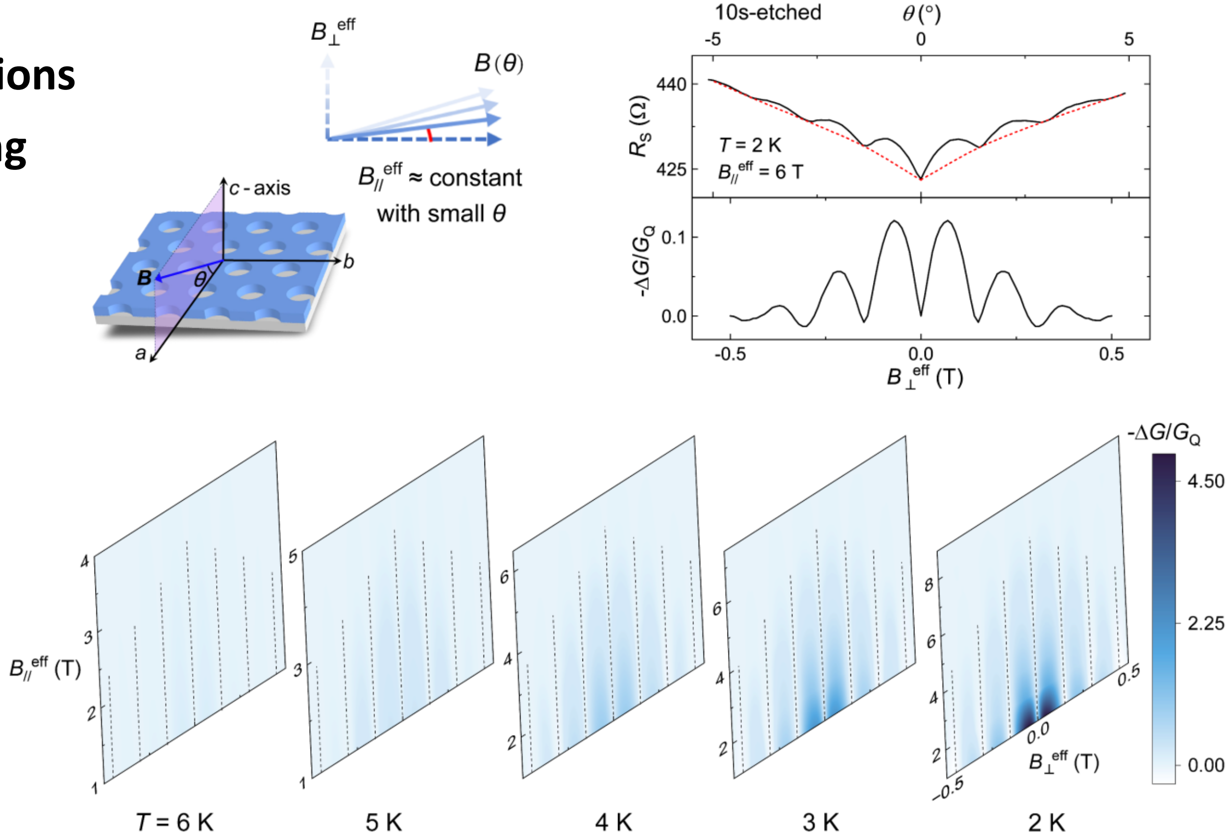
Superconducting anisotropy in $Nd_{0.8}Sr_{0.2}NiO_2$

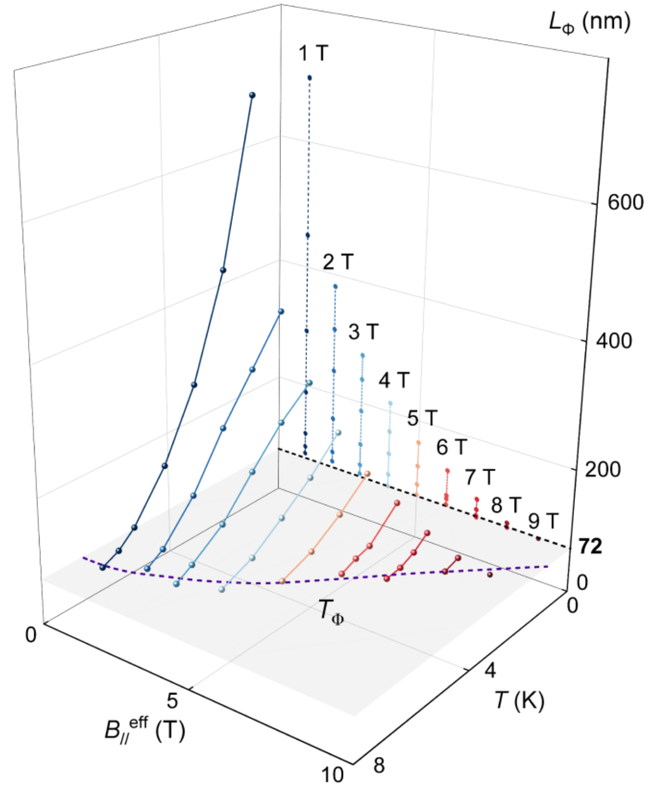
Quantum oscillations under an effective in-plane magnetic field

10s-etched

$B_{\perp}^{eff}$: **oscillations**

$B_{\parallel}^{eff}$: **tuning**





- **3D plot of phase coherence length L_{Φ} as a function of *T* and $B_{\parallel}^{eff}$**
- **$B_{\parallel}^{eff}$ - *T* boundary of inter-island phase coherence**

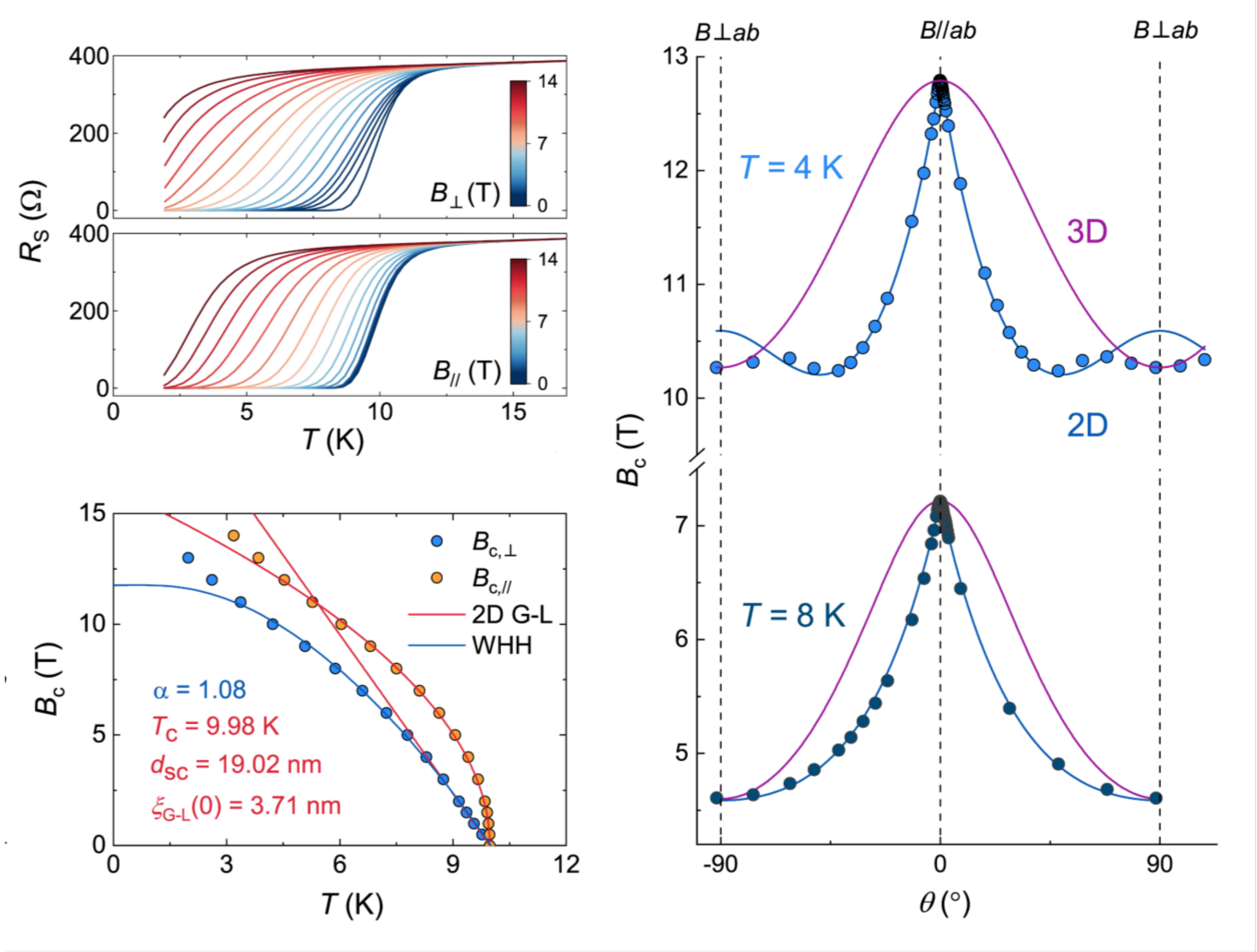
arXiv: 2603.00670 (2026)

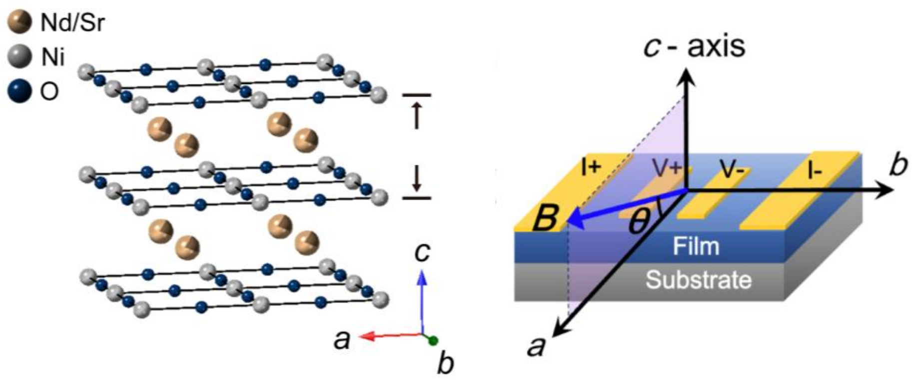
Superconducting anisotropy in $Nd_{0.8}Sr_{0.2}NiO_2$

unpatterned

Complex superconducting dimensionality: 2D + 3D

Unique characteristics of $Nd_{0.8}Sr_{0.2}NiO_2$ nickelate films





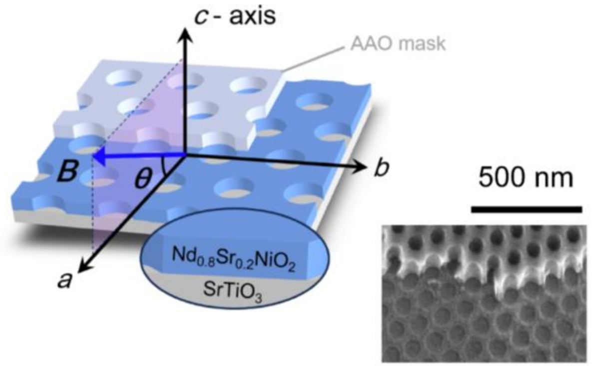
➤ **Complex SC dimensionality: dominant 2D + subtle 3D**

- **Small SC anisotropy ratio**
- **Maki parameter**
  $\alpha = \sqrt{2}B_{orbital} / B_{pauli} = 1.08$

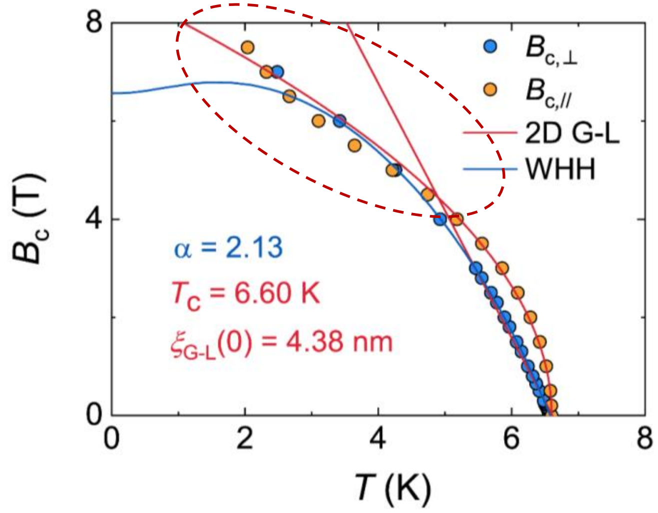
Reversal of superconducting anisotropy

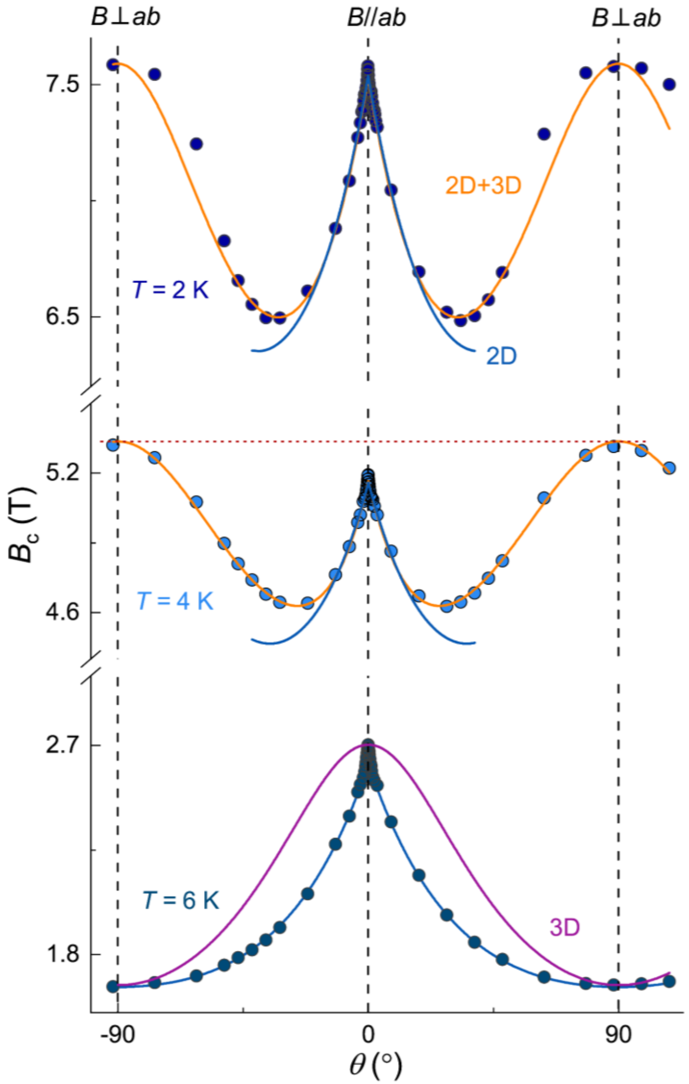
Complex superconducting dimensionality: 2D + 3D
Nano-patterning to modulate the macroscopic SC states

10s-etched



Reversal of SC anisotropy



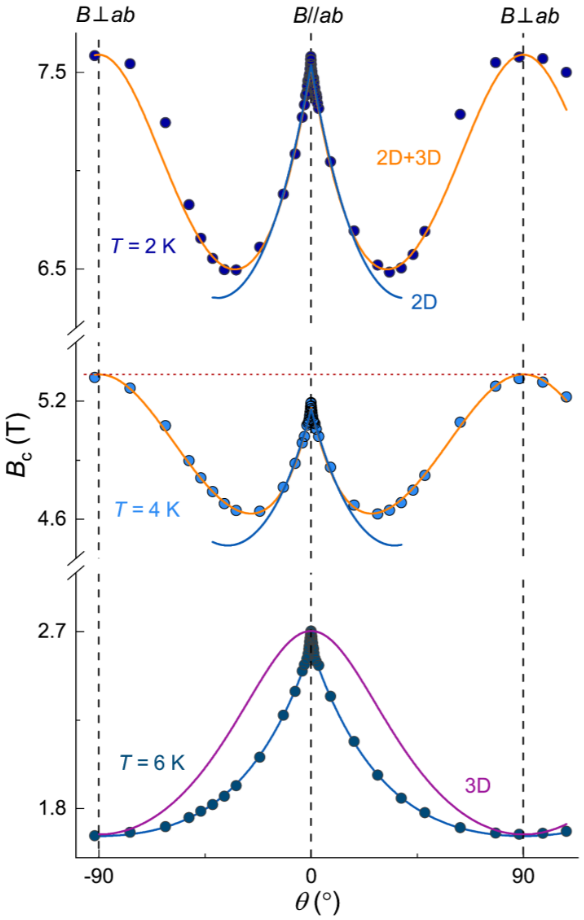


Upon nanopattern engineering:

- ➢ **Complex SC dimensionality: 2D + 3D**
- **Reversal of SC anisotropy:** $B_{c\parallel} < B_{c\perp}$
- **Orbital effect is geometrically quenched by nano-holes.**
- **Pauli paramagnetic effect becomes dominant: role of rare-earth magnetism.**

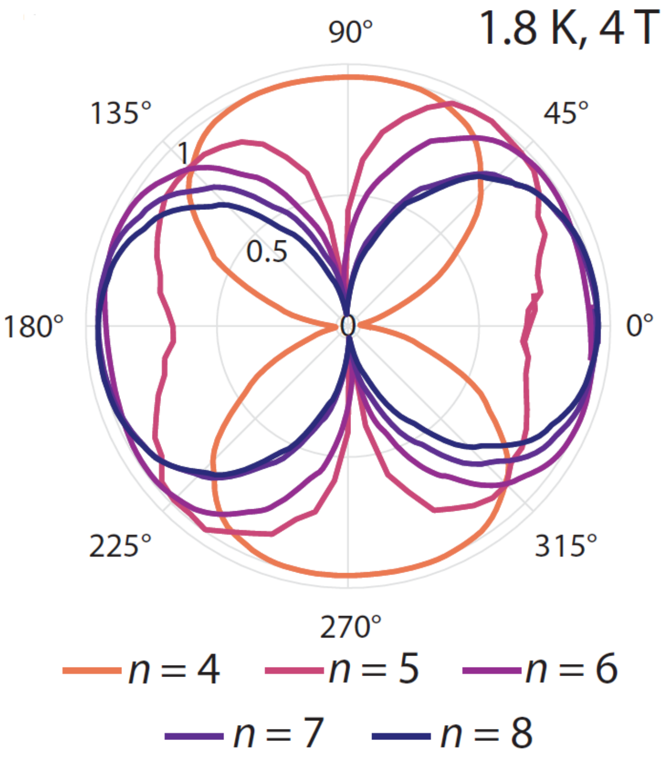
Reversal of superconducting anisotropy

By nanopattern engineering, unchanged stoichiometry



arXiv: 2603.00670 (2026)

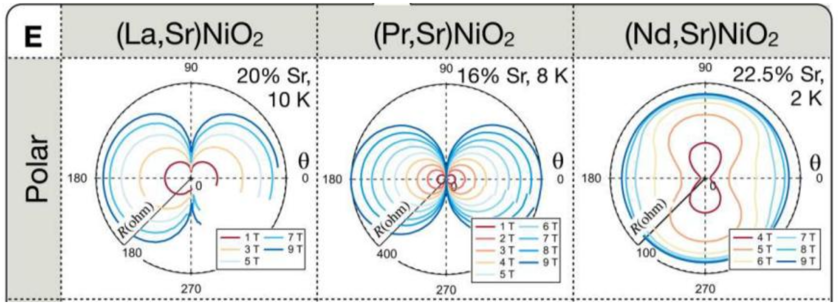
By tuning Ni-O layers *n* in $Nd_{n+1}Ni_nO_{2n+2}$



Reversal in the most structurally 2D n = 4

Science 392, 1390 (2026)

By changing rare-earth element from La, Pr to Nd



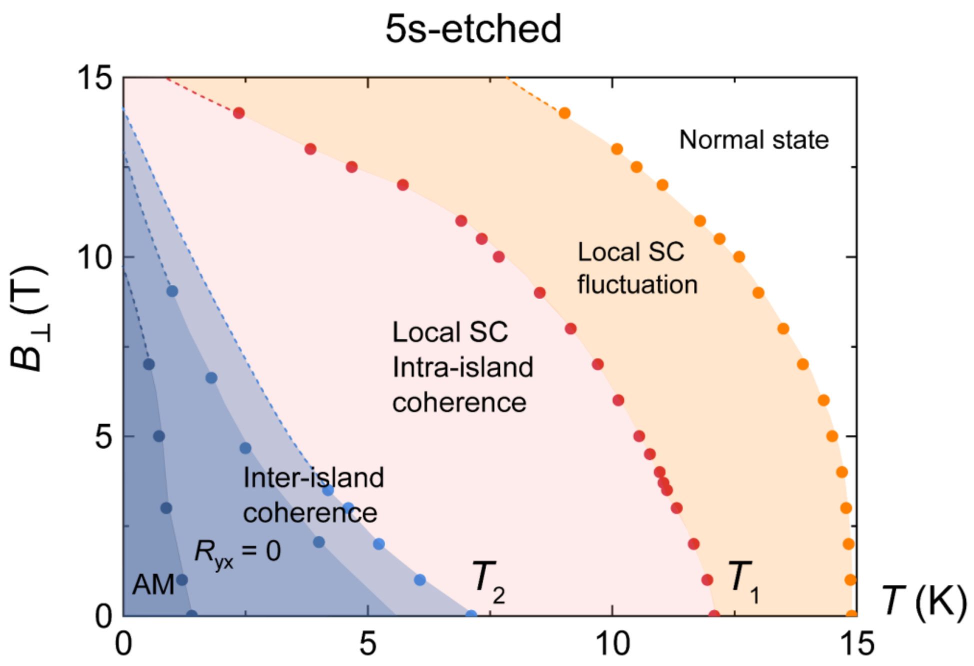
Reversal in Nd-nickelate

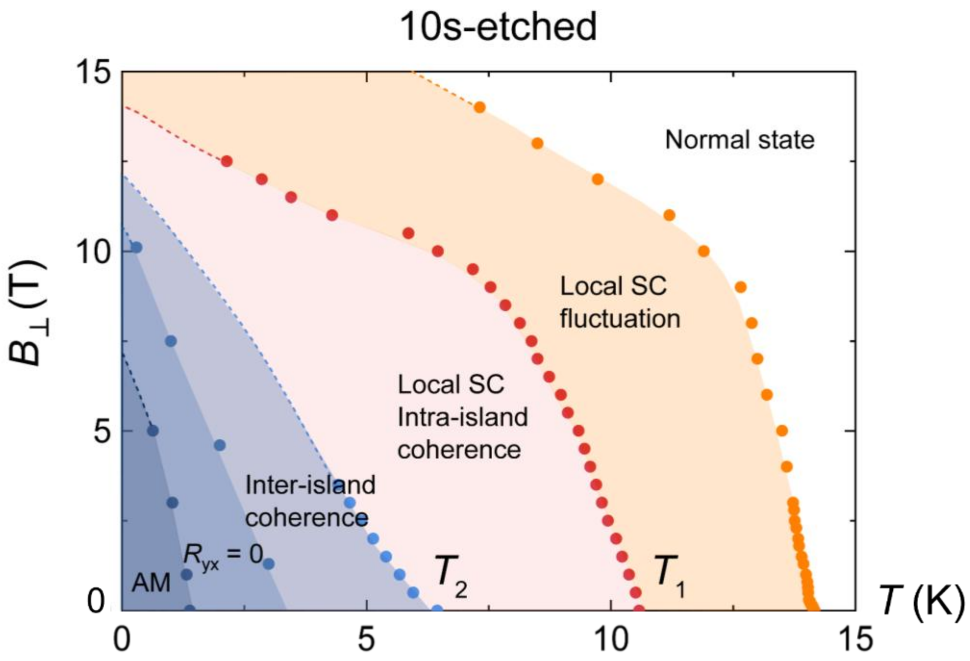
Sci. Adv. 9, eadf665 (2023)

Phase diagrams and Summary

arXiv: 2603.00670 (2026)

- **Global phase diagrams: establishment of superconductivity in the presence of significant phase fluctuations.**



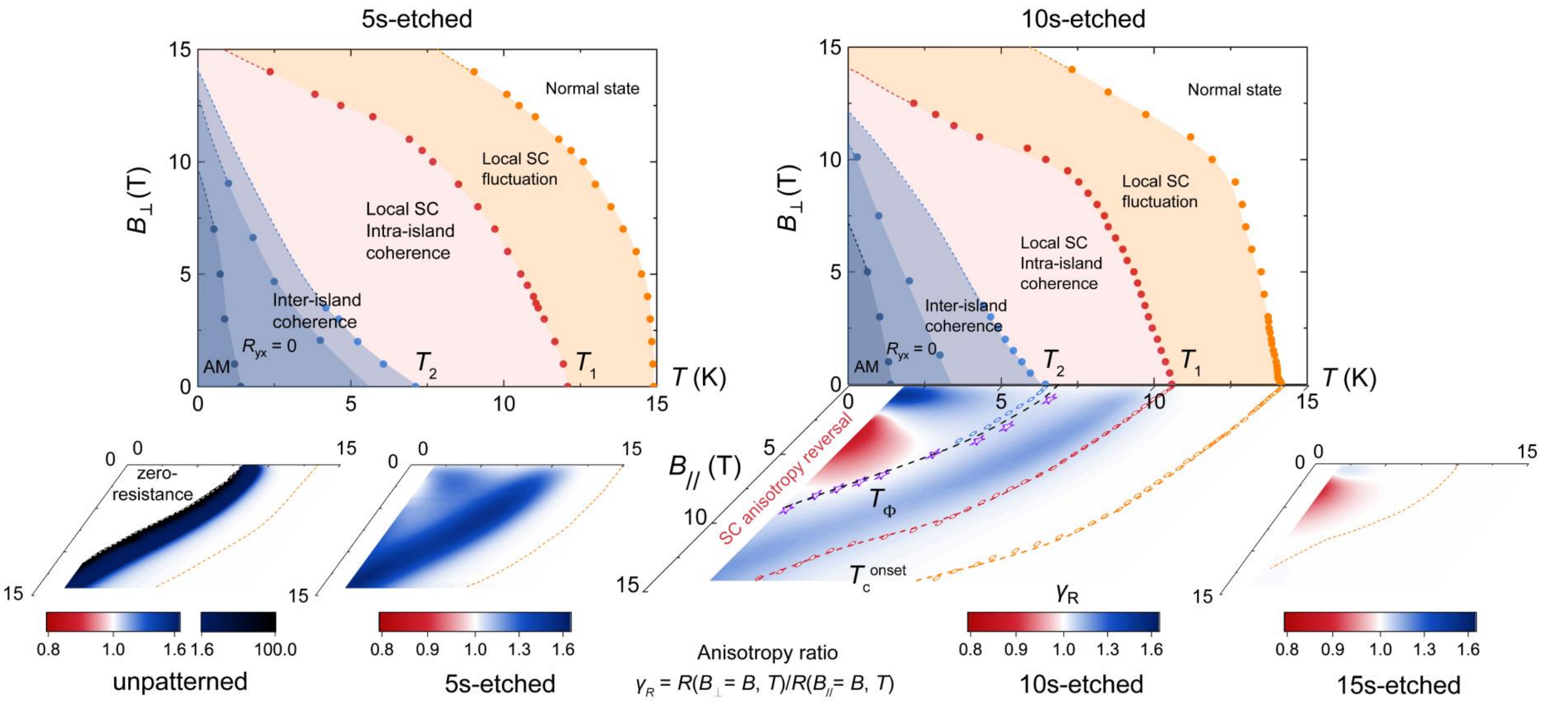


Anomalous metallic state ← Inter-island phase coherence ← Local superconductivity

Phase diagrams and Summary

arXiv: 2603.00670 (2026)

- **Global phase diagrams: evolution of unconventional superconductivity in response to phase fluctuations.**



- **A general method to unravel the intertwined orders (e.g., hidden rare-earth magnetic correlations in nickelate family) via phase coherence engineering, without altering the as-grown sample stoichiometry.**

Take home message

- **Anomalous metal states are observed in high-T_c superconducting films, including cuprates, iron-chalcogenides, nickelates.**

- **Bosonic anomalous metallic state in nanopatterned YBCO films** **Science 366, 1505 (2019)**
  - ❑ **We demonstrate the existence of anomalous metallic state via various experimental evidence.**
  - ❑ **This work opens a new avenue for studying anomalous metallic states via nanopatterning and quantum oscillations.**

- **High temperature anomalous metallic state in FeSe/STO** **Physical Review Letters 132, 226003 (2024)**
  - ❑ **The exceptionally high T^{AM} and T^{AM}/T_c^{onset} of the anomalous metallic state.**
  - ❑ **The quantitative explanation of the anomalous metallic state based on the quantum tunnelling of vortices influenced by ohmic dissipation.**

- **Anomalous metal states in infinite-layer nickelate films** **arXiv: 2603.00670 (2026)**
  - ❑ **Quantitative correlations of the saturation between resistance and phase coherence length $R_s \propto 1/L_\Phi{}^2$.**
  - ❑ **Nano-patterning to modulate the macroscopic SC state, uncovering emergent quantum phenomena via phase coherence engineering.**

Take home message

High-T_c superconducting films

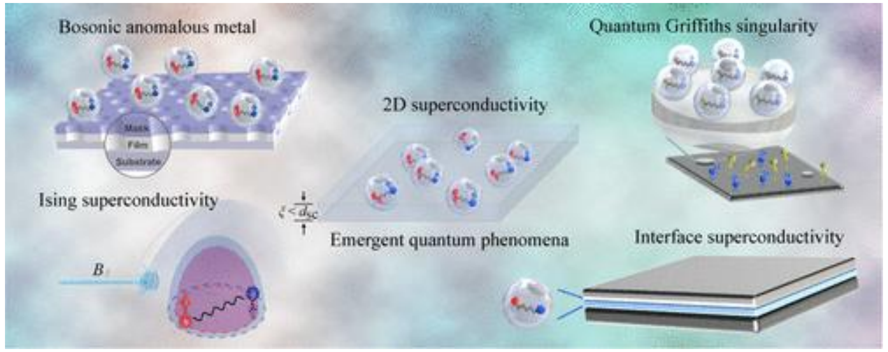
- Bosonic anomalous metallic state in nanopatterned YBCO films Science 366, 1505 (2019) with a perspective paper: Science 366, 1450 (2019)
- High temperature anomalous metallic state in FeSe/STO Physical Review Letters 132, 226003 (2024)
- Anomalous metal states in infinite-layer nickelate films arXiv: 2603.00670 (2026)

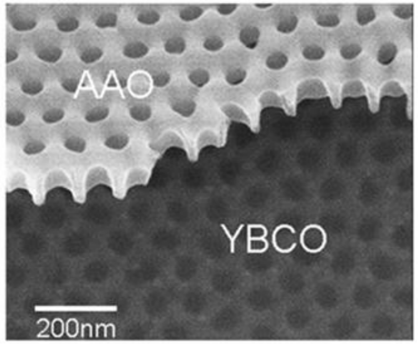
Transition Metal Dichalcogenide films/flakes

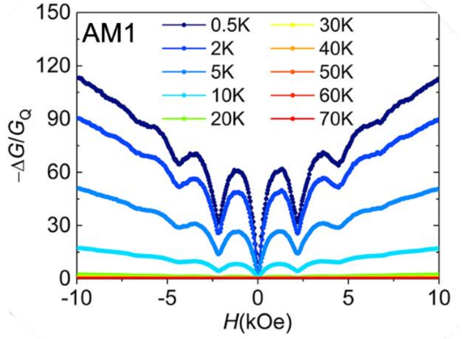
- Anomalous metallic state in crystalline ultrathin $PdTe_2$ film Nano Letters 20, 5728 (2020) highlighted by Editors' Choice in Science: Science 369, 388 (2020)
- Extrinsic and intrinsic anomalous metallic states in 4Ha-$TaSe_2$ nanodevices Nano Letters 21, 7486 (2021)

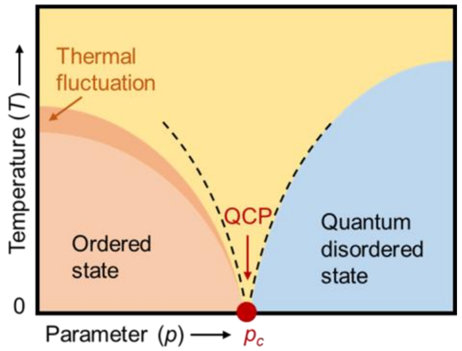
Review articles

- Quantum phase transition in 2D superconductors: a review on recent experimental progress Rep. Prog. Phys. 87, 014502 (2024)
- Two-dimensional and interface superconductivity in crystalline systems Acc. Mater. Res. 5, 1146-1157 (2024)







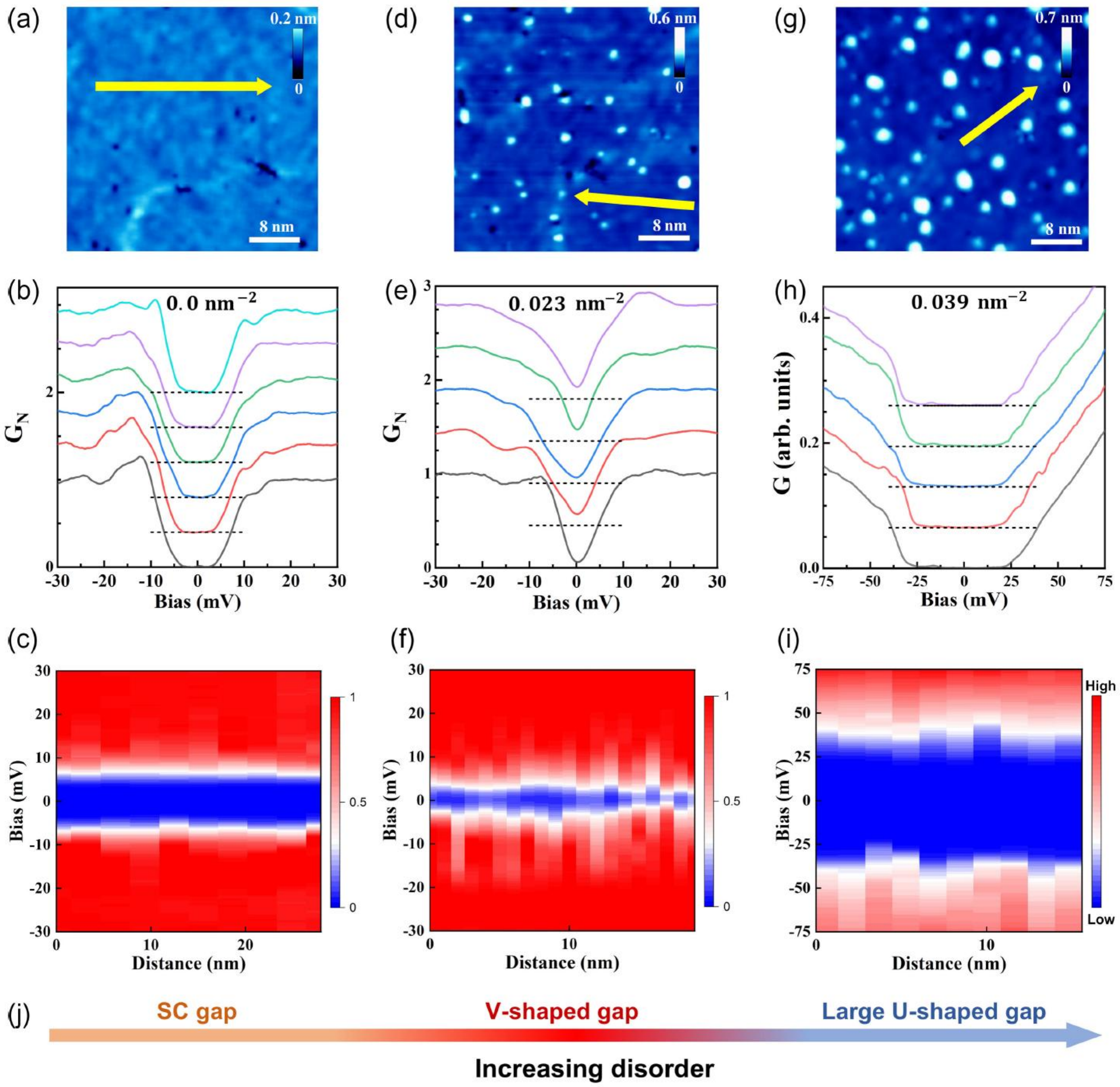


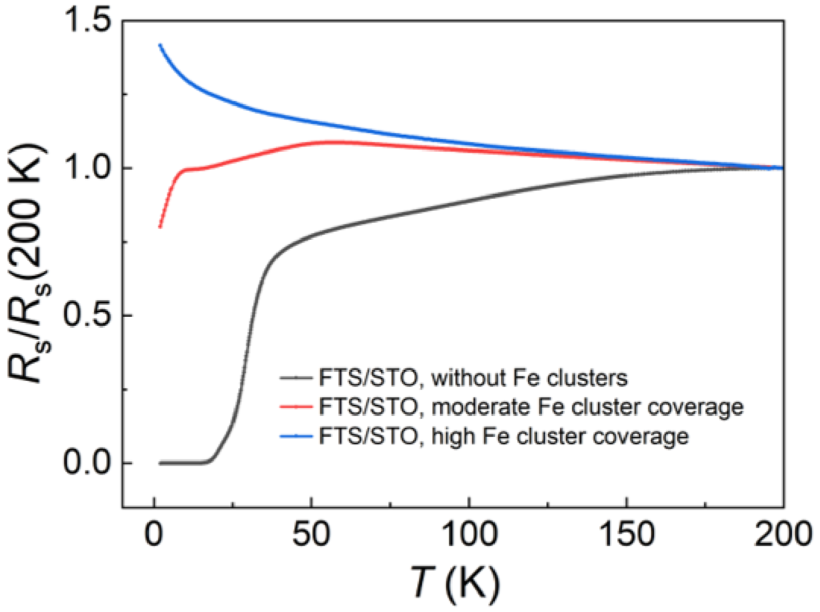
Anomalous metallic state in 2D superconducting system

System	Reference
Al, In, Ga and Pb thin films	*Phys. Rev. B* 40, 182 (1989)
α-MoGe thin films	*Phys. Rev. Lett.* 82, 5341 (1990)
InO_x thin films	*Sci. Adv.* 3 e1700612 (2017), *Phys. Rev. Lett.* 120, 167002 (2018)
Sn disks array on graphene, Al islands array coupled with InAs quantum well	*Nat. Phys.* 10, 380 (2014), *Nat. Phys.* 14, 1138 (2018)
ZrNCl nanoflakes	*Science* 350, 409 (2015)
WTe_2 monolayer	*Science* 362, 922 (2018)
1T-$TiSe_2$ nanoflakes	*Nano Lett.* 19, 4126 (2019)
MoS_2 nanoflakes	*Phys. Rev. Res.* 2, 023127 (2020)
4Ha-$TaSe_2$ nanodevices	*Nano Lett.* 21, 7486 (2021)
Lithium intercalated $TiSe_2$ nanoflakes	*Nat. Commun.* 12, 5342 (2021)
Few-layer 1T'-WS_2	*Phys. Rev. B* 105, L161402 (2022)
Nano-patterned YBCO thin films	*Science* 366, 1505 (2019)
$La_2CuO_{4+\delta}$ thin films	*Phys. Rev. B* 87, 024509 (2013)
$LaAlO_3/SrTiO_3$ interfaces	*Nat. Commun.* 9, 4008 (2021)
$LaAlO_3/KTaO_3$ interfaces	*Science* 372, 721 (2021)
$PdTe_2$ thin films	*Nano Lett.* 20, 5728 (2020)
$FeSe/SrTiO_3$	*Phys. Rev. Lett.* 132, 226003 (2024)
Mono-unit-layer $NbSe_2$	*Phys. Rev. B* 99, 220501(R) (2019)

Briefly summarized in
Rep. Prog. Phys. 87, 014502 (2024)

Spectroscopic Evidence of Quantum Phase Transition in 1-UC Fe(Te,Se)





- **The formation of large gap in the strong disorder regime could be related to the theoretically predicted enhanced pairing correlation within the localization length.**
- **Physical Review Letters 136, 176001 (2026)**

Thank you!