TIDES2026

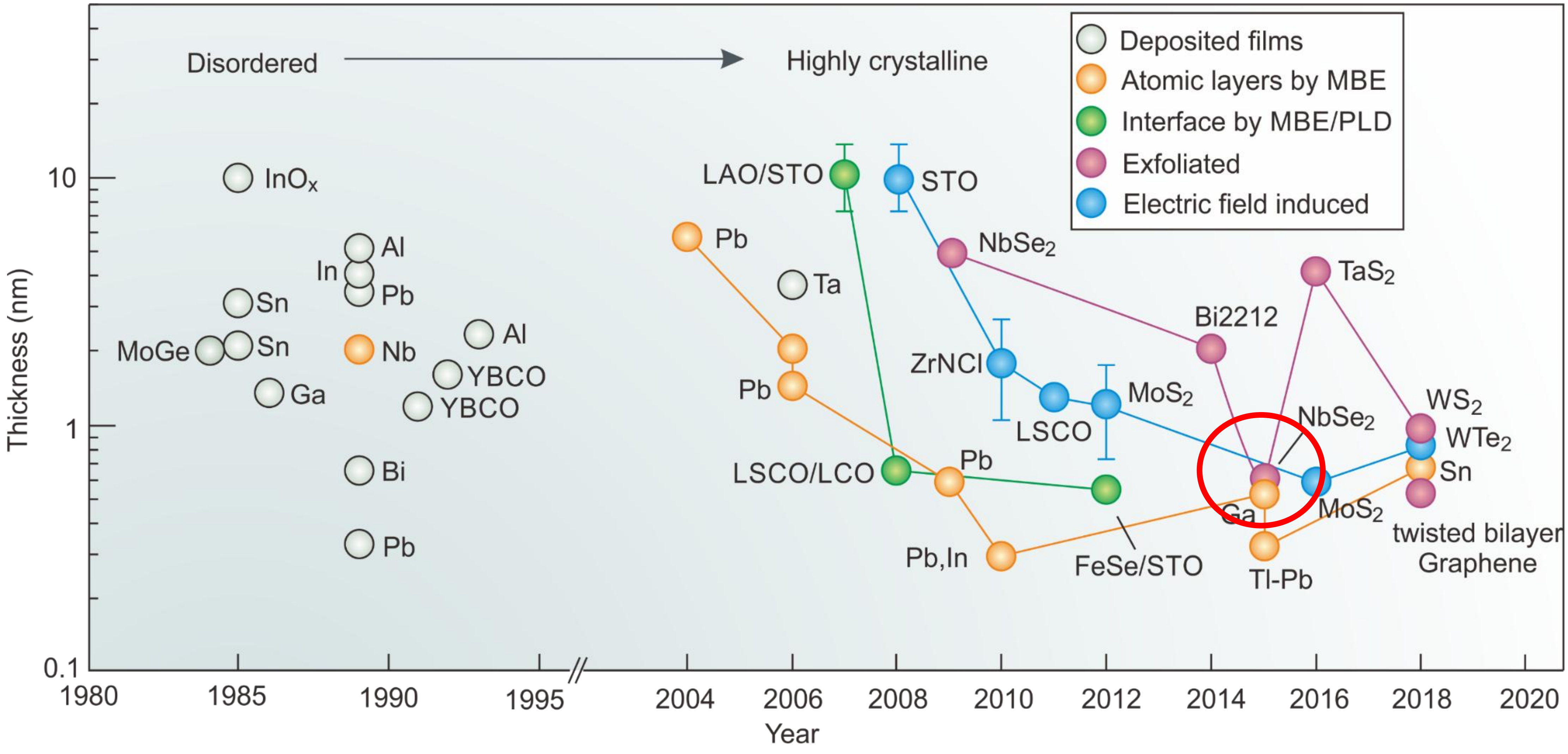
Experimental aspects of 2D superconductivity and topology

Ding Zhang

Department of Physics, Tsinghua University, Beijing, China

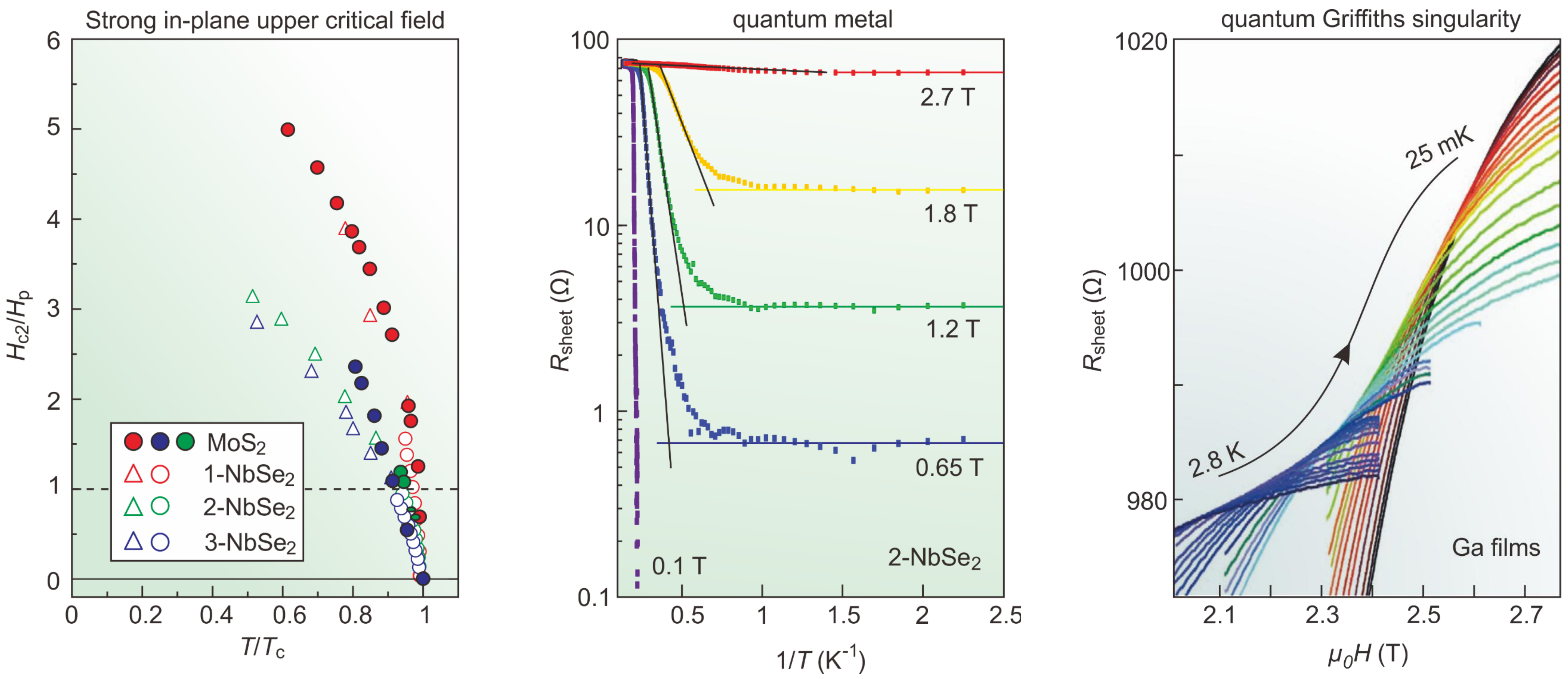
dingzhang@tsinghua.edu.cn

2D superconductors



Adapted from: Y. Saito, T. Nojima and Y. Iwasa, *Nature Reviews Materials* **2**, 16094 (2017)

Interesting physics in 2D superconductors



Adapted from: Y. Saito, T. Nojima and Y. Iwasa, *Nature Reviews Materials* **2**, 16094 (2017)

Latest development 1: chiral superconductivity

Article

Signatures of chiral superconductivity in rhombohedral graphene

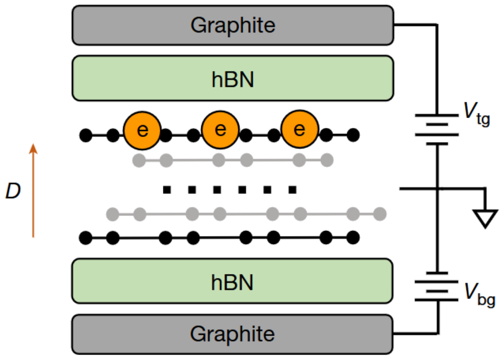
https://doi.org/10.1038/s41586-025-09169-7

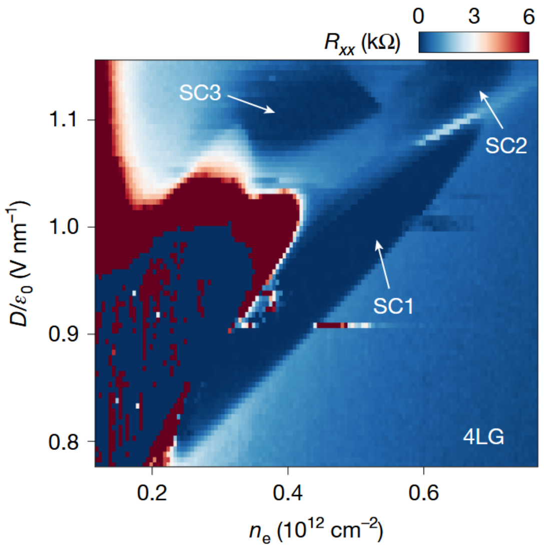
Received: 1 September 2024

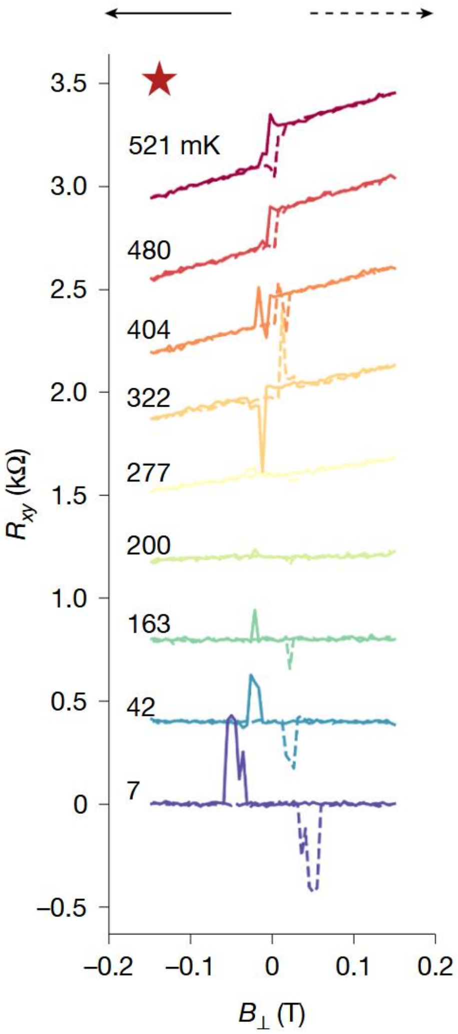
Accepted: 16 May 2025

Published online: 22 May 2025

Tonghang Han[1,6], Zhengguang Lu[1,2,6], Zach Hadjri[1,6], Lihan Shi[1], Zhenghan Wu[1], Wei Xu[1], Yuxuan Yao[1], Armel A. Cotten[3], Omid Sharifi Sedeh[3], Henok Weldeyesus[3], Jixiang Yang[1], Junseok Seo[1], Shenyong Ye[1], Muyang Zhou[1], Haoyang Liu[2], Gang Shi[2], Zhenqi Hua[2], Kenji Watanabe[4], Takashi Taniguchi[5], Peng Xiong[2], Dominik M. Zumbühl[3], Liang Fu[1] & Long Ju[1]✉







T. Han, *et al.*, *Nature* **643,** 654 (2025)

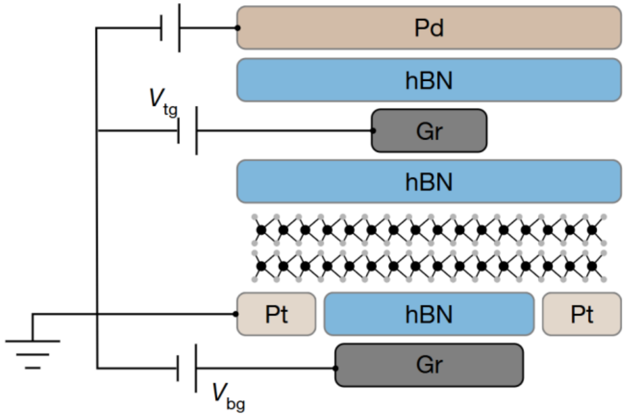
Latest development 2: twisted TMD

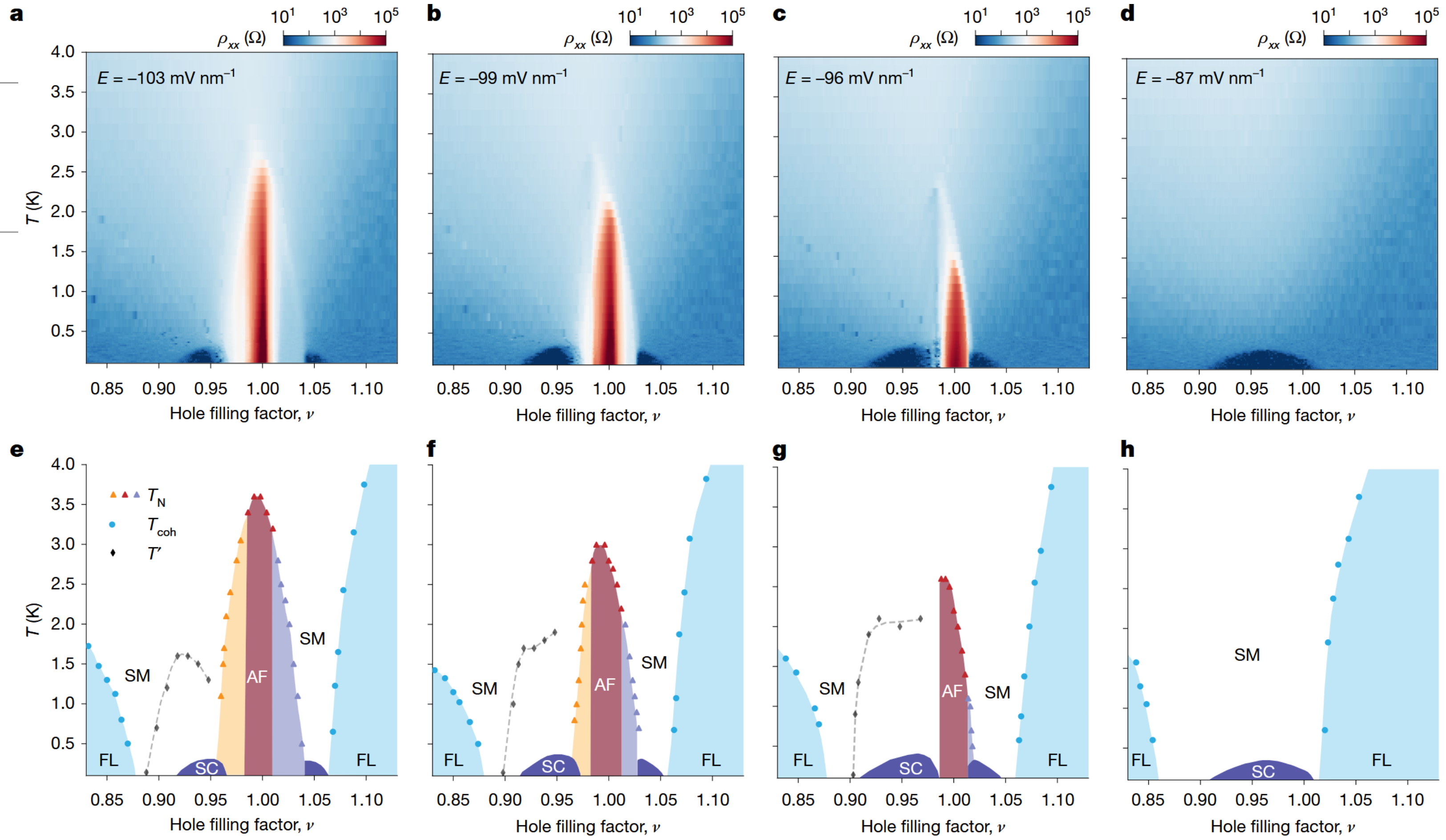

Article

Bandwidth-tuned Mott transition and superconductivity in moiré WSe_2

https://doi.org/10.1038/s41586-025-10049-3
Received: 23 June 2025

Yiyu Xia[1,6✉], Zhongdong Han[2,3,6✉], Jiacheng Zhu[1], Yichi Zhang[2], Patrick Knüppel[2], Kenji Watanabe[4], Takashi Taniguchi[4], Kin Fai Mak[1,2,3,5✉] & Jie Shan[1,2,3,5✉]





Y. Xia, *et al.*, *Nature* **650,** 585 (2026)

Latest development 3: nickelate

Article

Signatures of ambient pressure superconductivity in thin film $La_3Ni_2O_7$

https://doi.org/10.1038/s41586-024-08525-3
Received: 30 July 2024
Accepted: 12 December 2024

Eun Kyo Ko[1,2,8]✉, Yijun Yu[1,2,8]✉, Yidi Liu[1,3], Lopa Bhatt[4], Jiarui Li[1,2], Vivek Thampy[5], Cheng-Tai Kuo[5], Bai Yang Wang[1,3], Yonghun Lee[1,2], Kyuho Lee[1,3], Jun-Sik Lee[5], Berit H. Goodge[6], David A. Muller[4,7] & Harold Y. Hwang[1,2]✉

E. Ko, *et al.*, *Nature* **638,** 935 (2025)

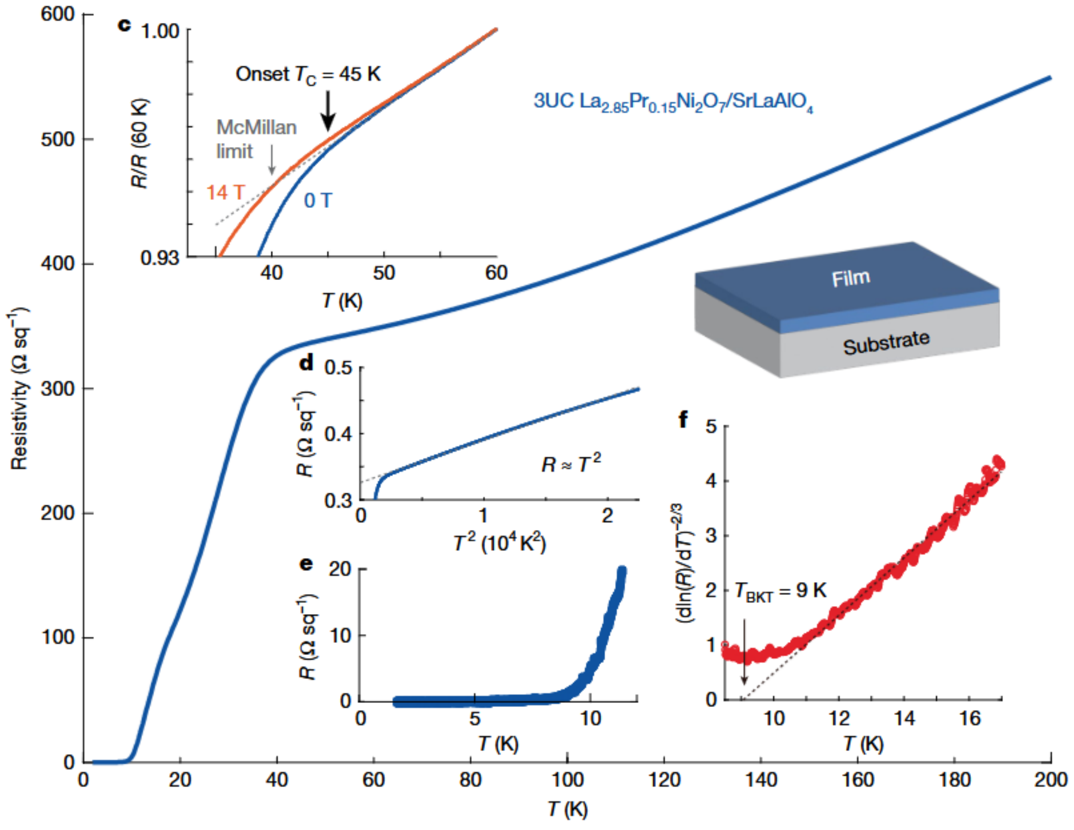
Article

Ambient-pressure superconductivity onset above 40 K in $(La,Pr)_3Ni_2O_7$ films

https://doi.org/10.1038/s41586-025-08755-z
Received: 16 November 2024

Guangdi Zhou[1,4], Wei Lv[1,4], Heng Wang[1,4], Zihao Nie[1,4], Yaqi Chen[1], Yueying Li[1], Haoliang Huang[1,2], Wei-Qiang Chen[1,2], Yu-Jie Sun[1,2], Qi-Kun Xue[1,2,3]✉ & Zhuoyu Chen[1,2]✉

G. Zhou, *et al.*, *Nature* **640,** 641 (2025)



Outline

1. $NbSe_2$—a case study of highly crystalline 2D superconductors

1.1 Dimensionality effect on SC and CDW

1.2 Ising superconductivity: from 3D to 2D and back

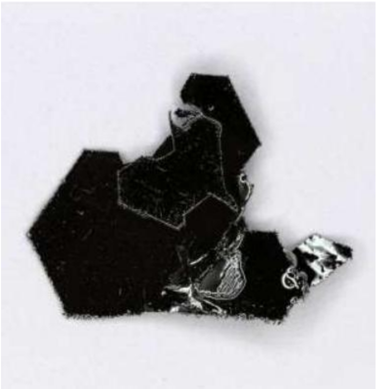
1.3 Anomalous metal phase: intrinsic vs. extrinsic effects

2. 2D superconductors with topology

2.1 WTe_2 and stanene

2.2 Twisted cuprates

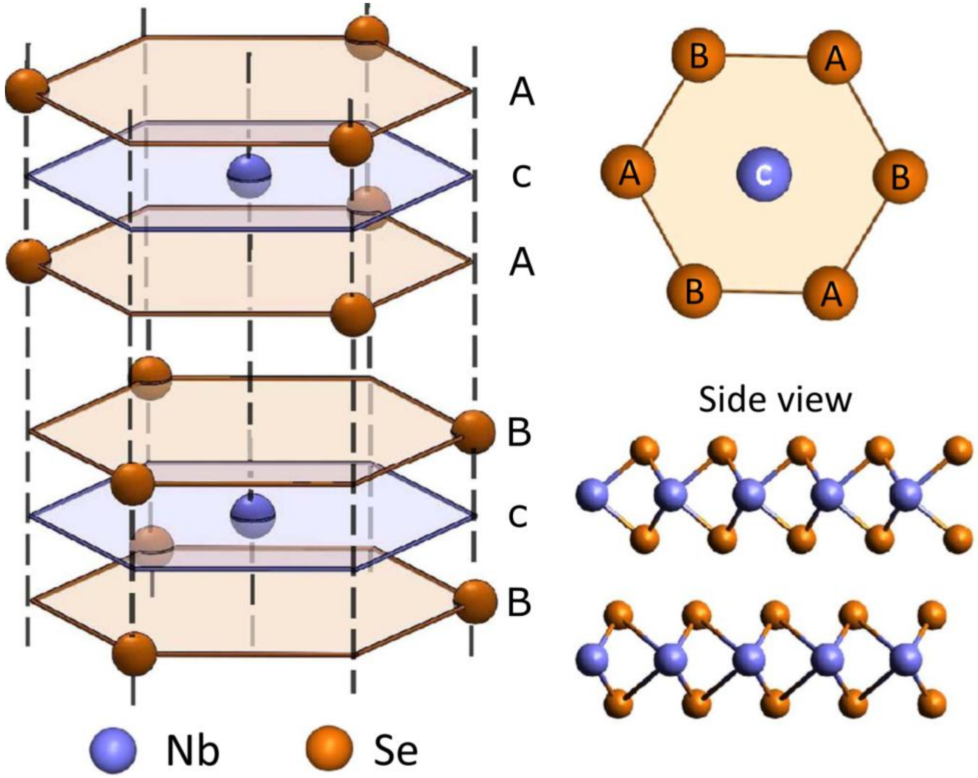
Introduction to 2H-$NbSe_2$



From hq graphene

2Ha stacking

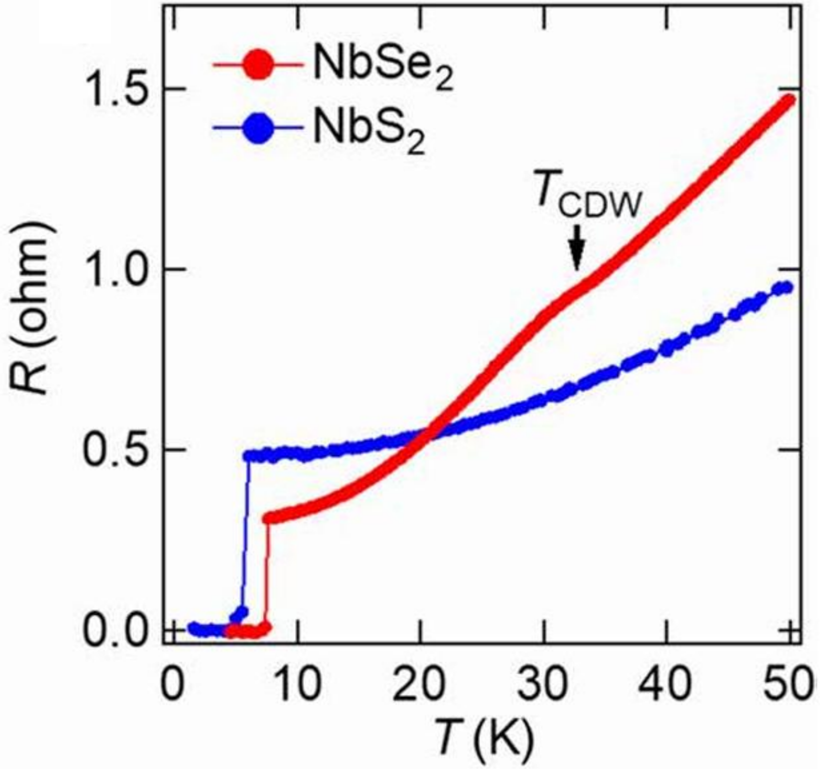
a=b=0.344 nm, c=1.255 nm



R. He, *et al.*, *2D Mater.* **3,** 031008 (2016)

$T_{CDW} = 33$ K

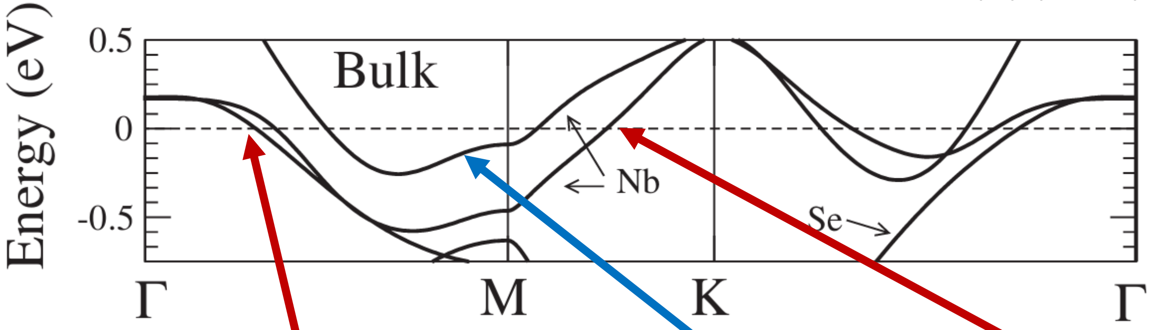
$T_{sc} = 7.2$ K



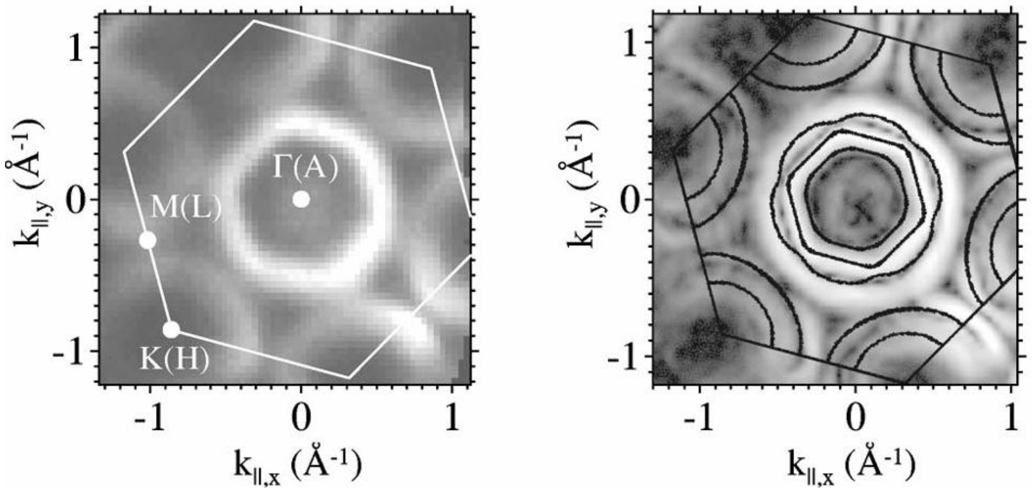
M. Yokoi, *et al.*, *Sci. Adv.* **6,** eaba1377 (2020)

Introduction to 2H-$NbSe_2$

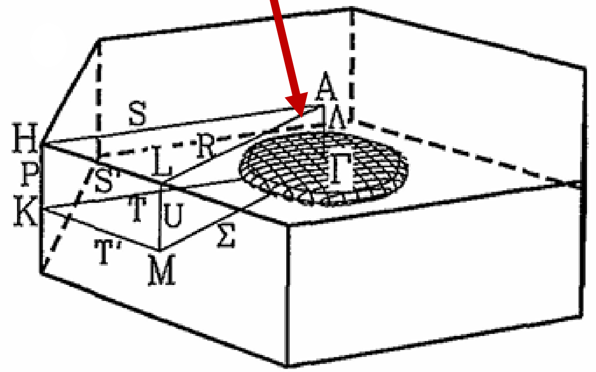
M. Calandra, I. Mazin, F. Mauri, *PRB* **80**, 241108(R) (2009)



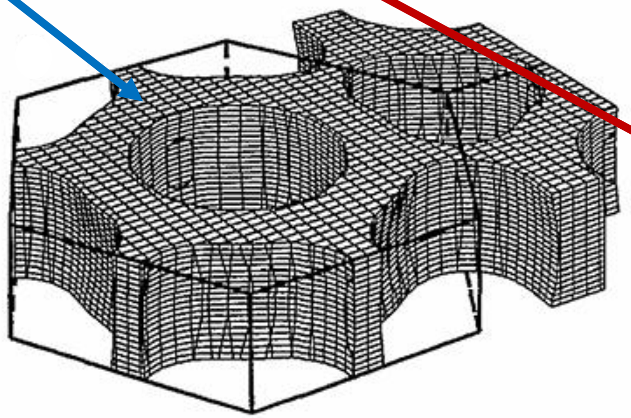
ARPES measurements



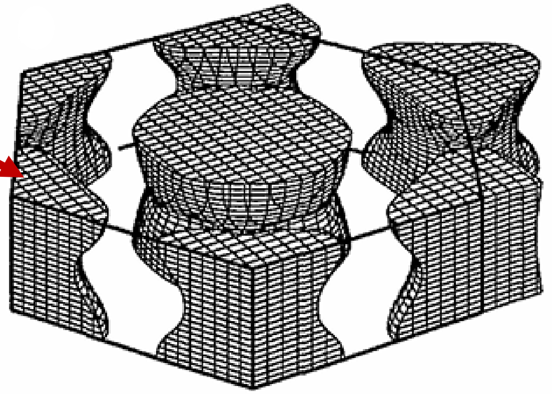
K. Rossnagel, *et al.*, *PRB* **64,** 235119 (2001)



Hole band



Electron band



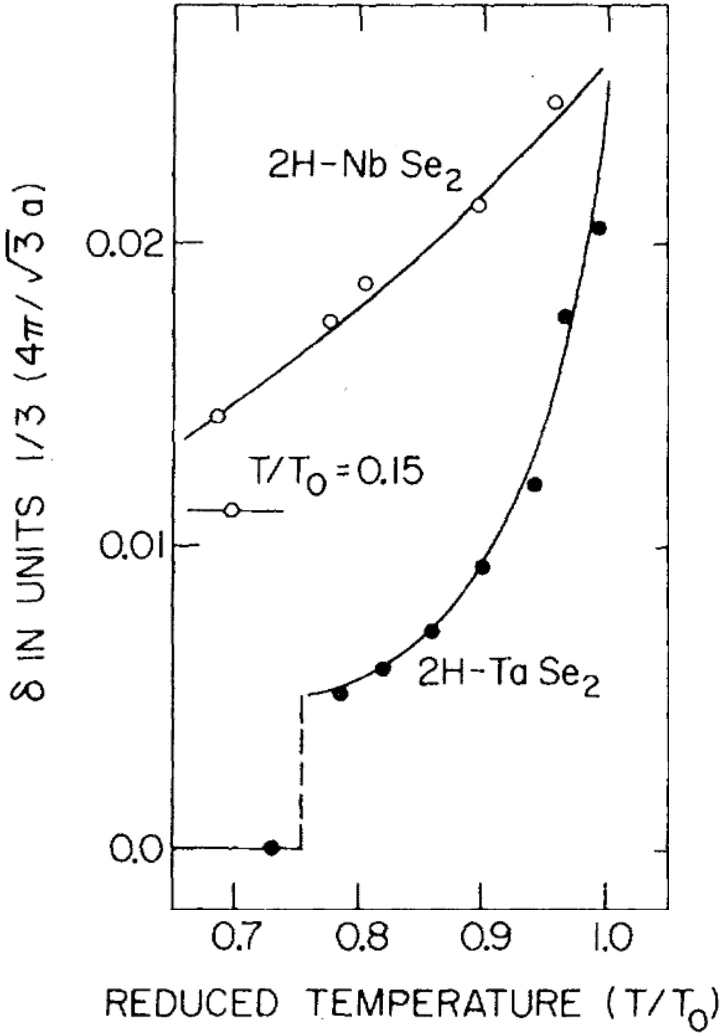
Hole band

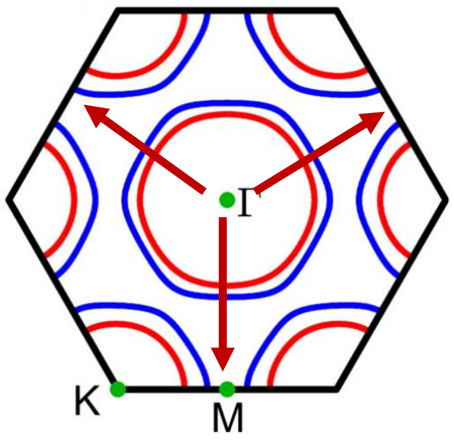
R. Corcoran, *et al.*, *JPCM* **6,** 4479 (1994)

CDW in bulk 2H-$NbSe_2$

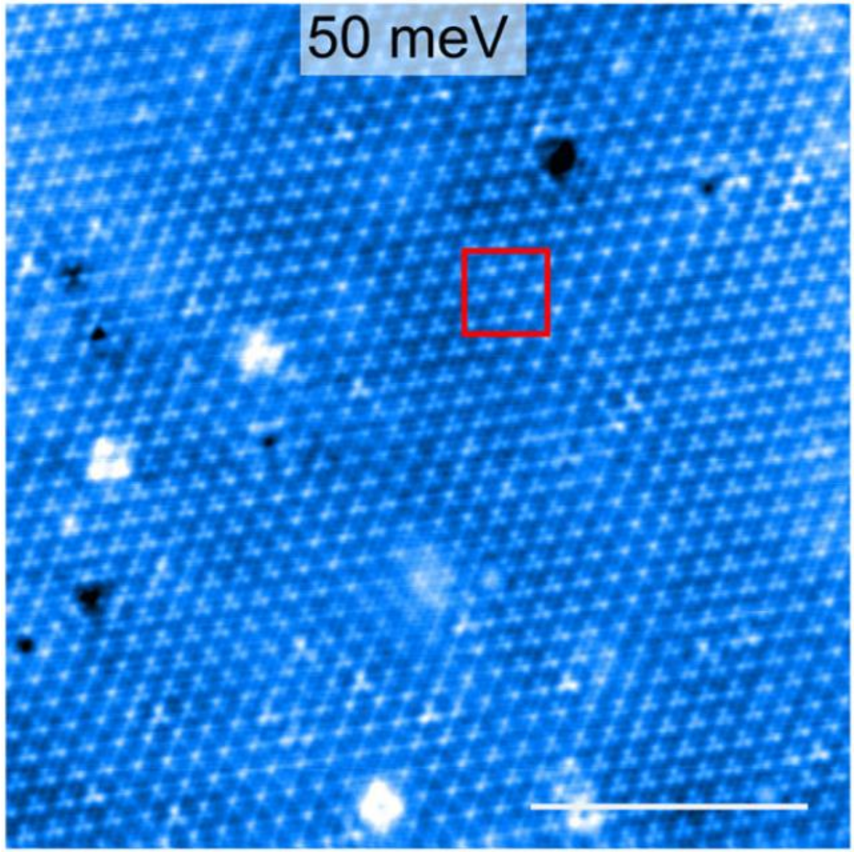
- **Neutron scattering**

$$q = (1-\delta)\frac{2}{3}\,|\Gamma M|$$





$T = 1.2$ K



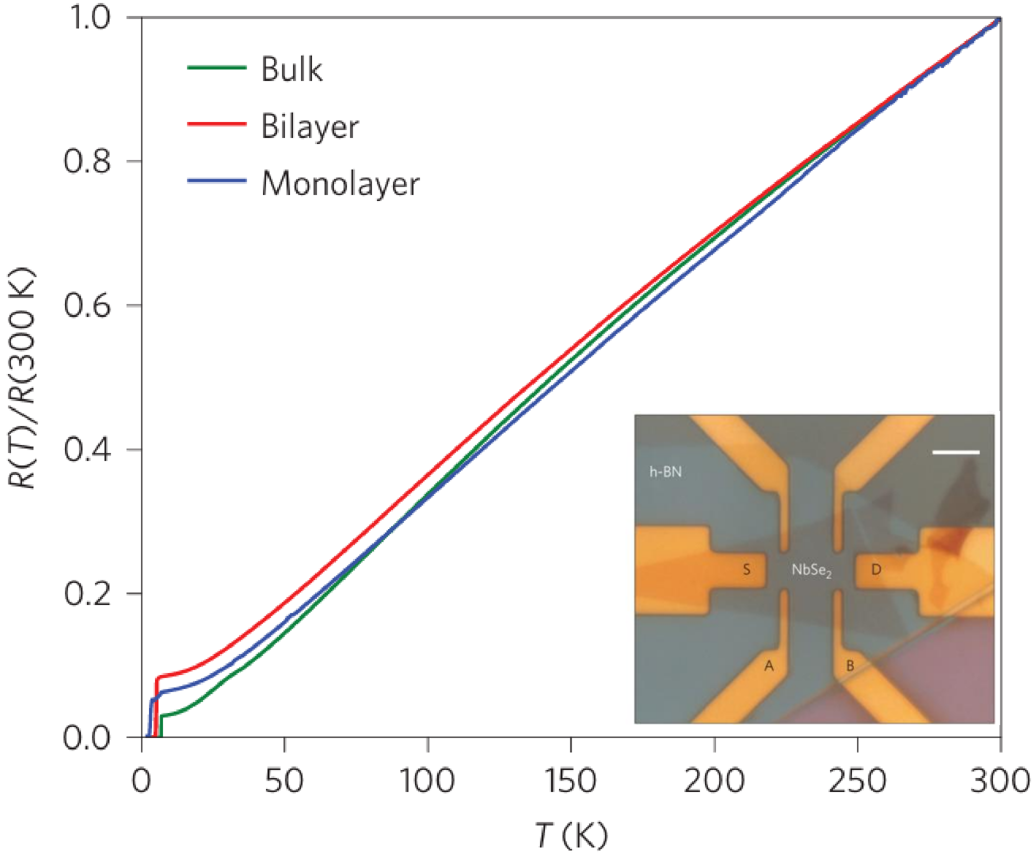
- **CDW appears to be 3x3 in STM**

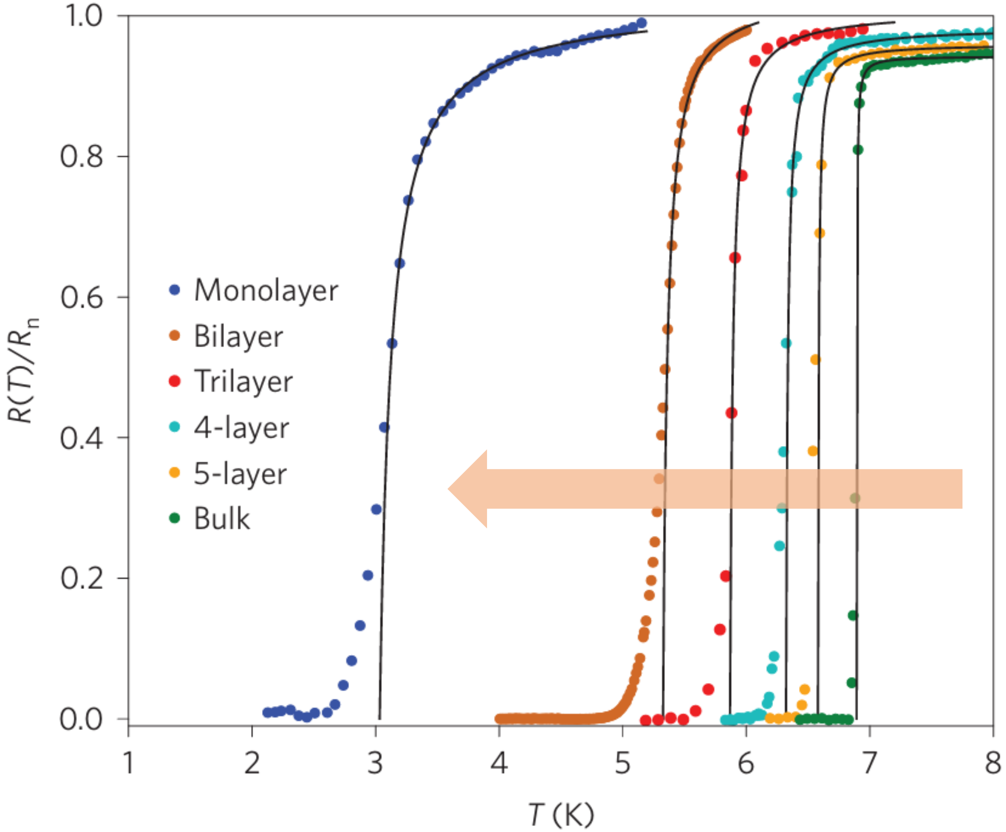
D. Moncton, J. Axe, & F. DiSalvo, *Phys. Rev. Lett.* **34,** 734 (1975)

A. Pasztor, *et al.*, *Nat. Commun.* **12,** 6037 (2021)

Ultrathin $NbSe_2$

Superconductivity of ultrathin $NbSe_2$





- **Dimensionality effect: weakening of interlayer Cooper pairing**

nature physics

LETTERS

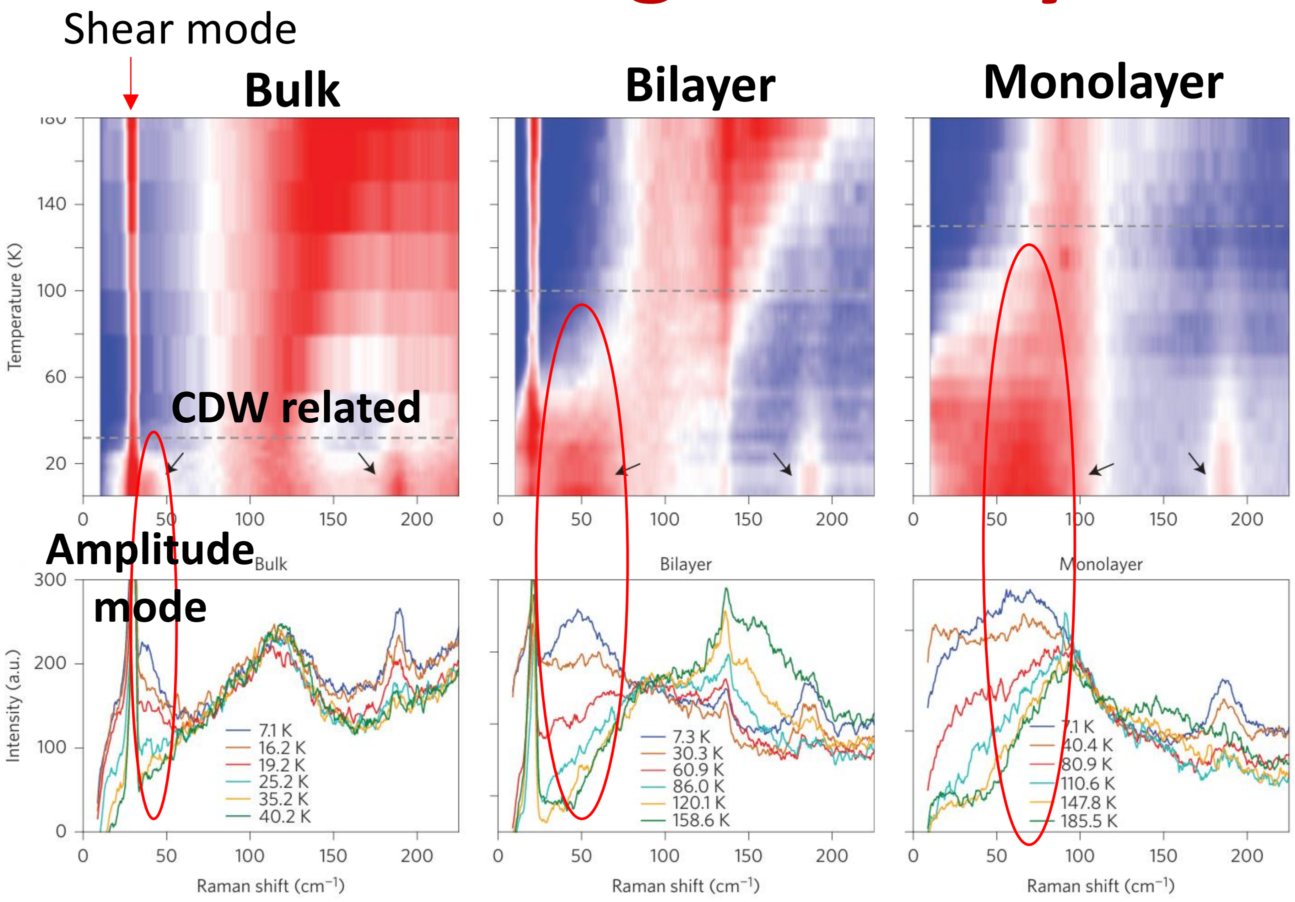
PUBLISHED ONLINE: 9 NOVEMBER 2015 | DOI: 10.1038/NPHYS3538

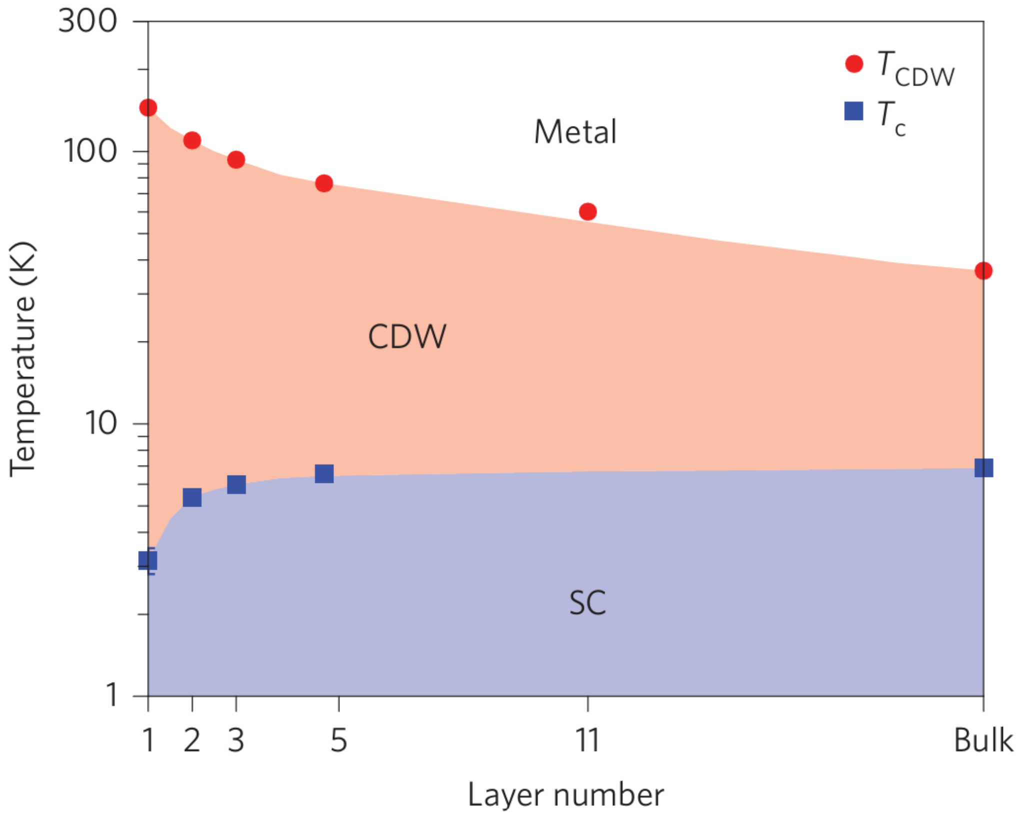
Ising pairing in superconducting $NbSe_2$ atomic layers

Xiaoxiang Xi[1†], Zefang Wang[1†], Weiwei Zhao[1], Ju-Hyun Park[2], Kam Tuen Law[3], Helmuth Berger[4], László Forró[4], Jie Shan[1*] and Kin Fai Mak[1*]

X. Xi, *et al.*, *Nat. Phys.* **12,** 139 (2016)

Charge density wave of ultrathin $NbSe_2$





nature nanotechnology LETTERS
PUBLISHED ONLINE: 20 JULY 2015 | DOI: 10.1038/NNANO.2015.143

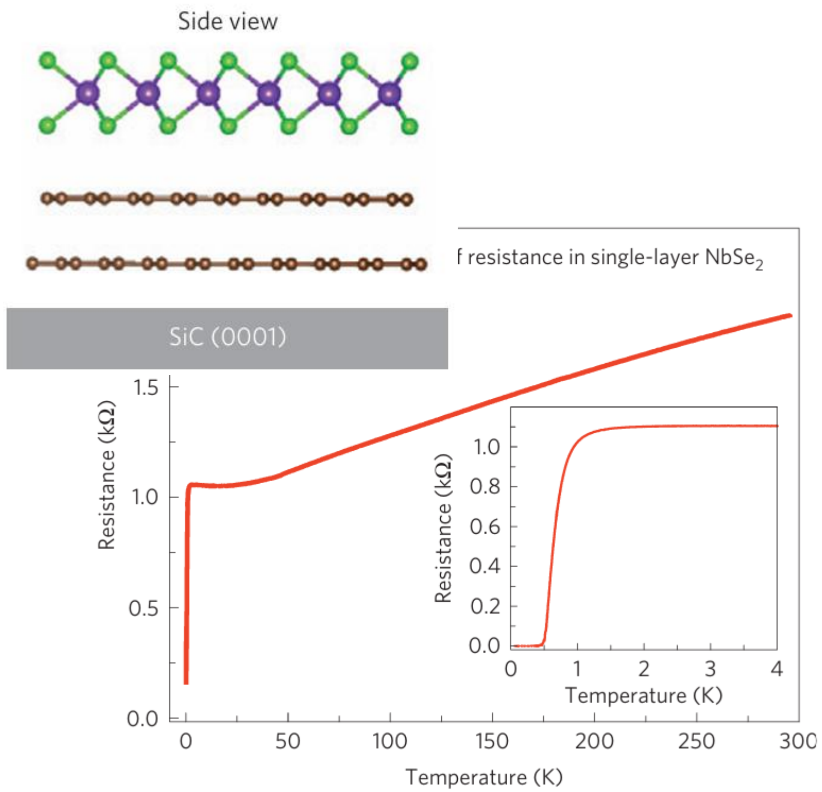
Strongly enhanced charge-density-wave order in monolayer $NbSe_2$

Xiaoxiang Xi[1], Liang Zhao[2], Zefang Wang[1], Helmuth Berger[3], László Forró[3], Jie Shan[1,2]* and Kin Fai Mak[1]*

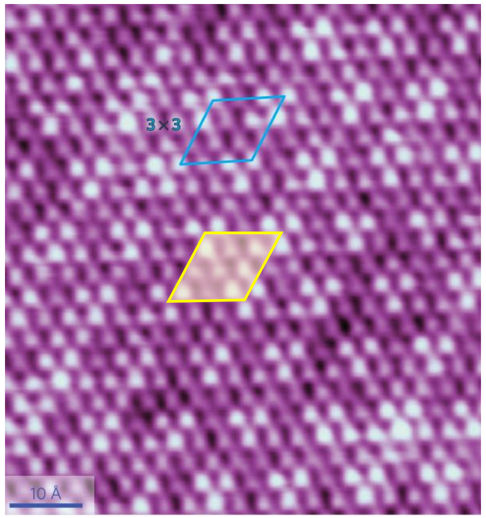
- **CDW enhances as thickness decreases**

X. Xi, *et al.*, *Nat. Nano.* **10,** 765 (2015)

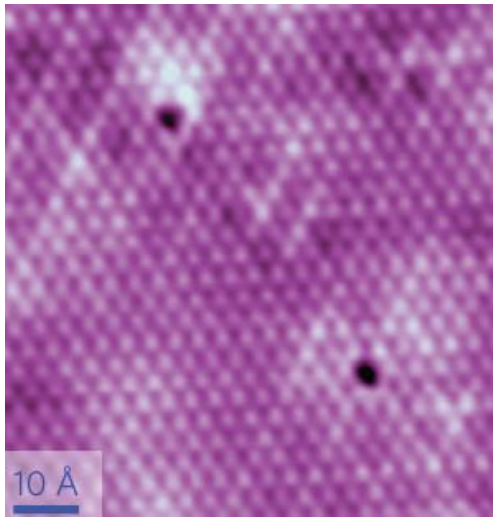
CDW of monolayer $NbSe_2$ on bilayer grahpene



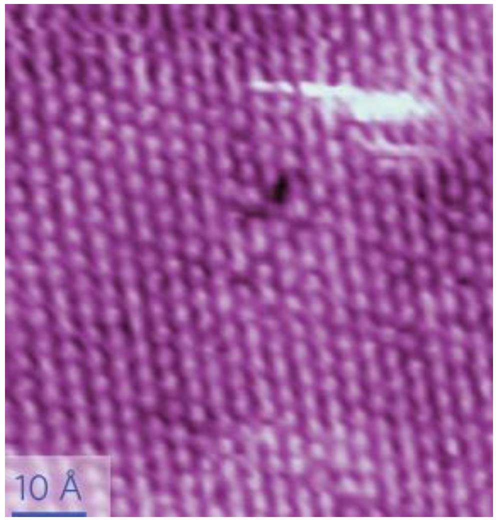
5 K



25 K



45 K



nature physics
ARTICLES
PUBLISHED ONLINE: 2 NOVEMBER 2015 | DOI: 10.1038/NPHYS3527

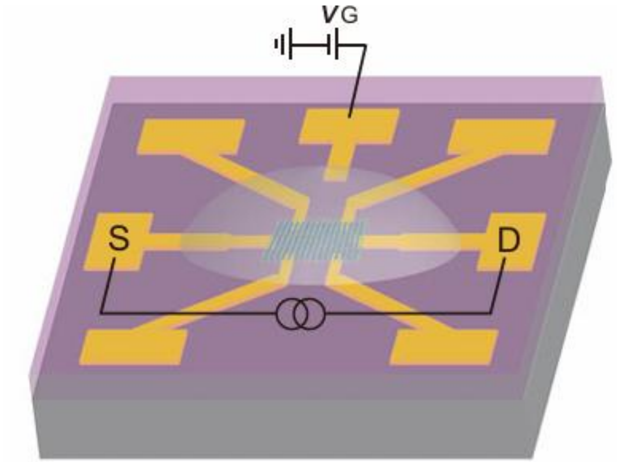
Characterization of collective ground states in single-layer $NbSe_2$

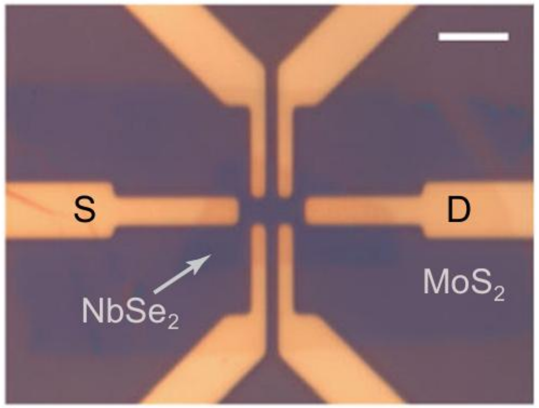
Miguel M. Ugeda[1,2,3]*, Aaron J. Bradley[1], Yi Zhang[4,5,6], Seita Onishi[1], Yi Chen[1], Wei Ruan[1,7], Claudia Ojeda-Aristizabal[1,8,9], Hyejin Ryu[4], Mark T. Edmonds[1,10], Hsin-Zon Tsai[1], Alexander Riss[1,11], Sung-Kwan Mo[4], Dunghai Lee[1], Alex Zettl[1,8,12], Zahid Hussain[4], Zhi-Xun Shen[5,13] and Michael F. Crommie[1,8,12]*

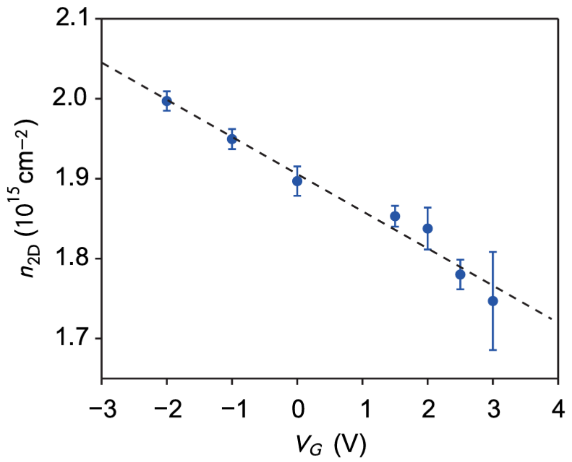
- **CDW occurs only around 25 K or below**

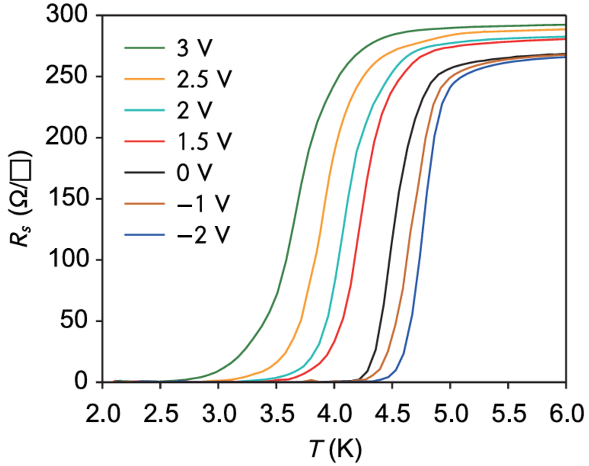
M. Ugeda, *et al.*, *Nat. Phys.* **12,** 92 (2016)

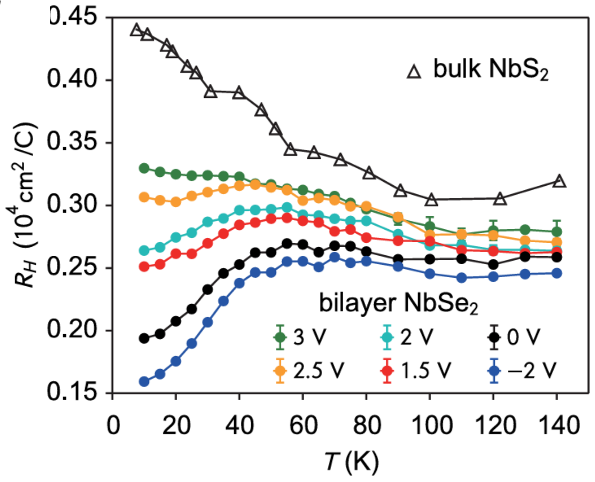
Gate tuning of bilayer $NbSe_2$











- **Electron doping weakens superconductivity and CDW**

PRL **117,** 106801 (2016) PHYSICAL REVIEW LETTERS week ending 2 SEPTEMBER 2016

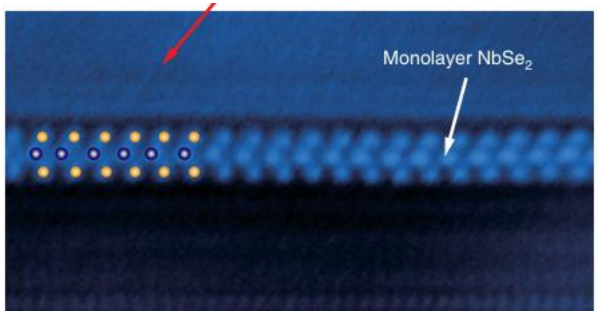
Gate Tuning of Electronic Phase Transitions in Two-Dimensional $NbSe_2$

Xiaoxiang Xi,[1] Helmuth Berger,[2] László Forró,[2] Jie Shan,[1,*] and Kin Fai Mak[1,†]
[1]*Department of Physics and Center for 2-Dimensional and Layered Materials, The Pennsylvania State University, University Park, Pennsylvania 16802-6300, USA*
[2]*Institute of Condensed Matter Physics, Ecole Polytechnique Fédérale de Lausanne, 1015 Lausanne, Switzerland*
(Received 12 April 2016; published 29 August 2016)

X. Xi, *et al.*, *Phys. Rev. Lett.* **117,** 106801 (2016)

Disorder enhanced superconductivity in monolayer $NbSe_2$

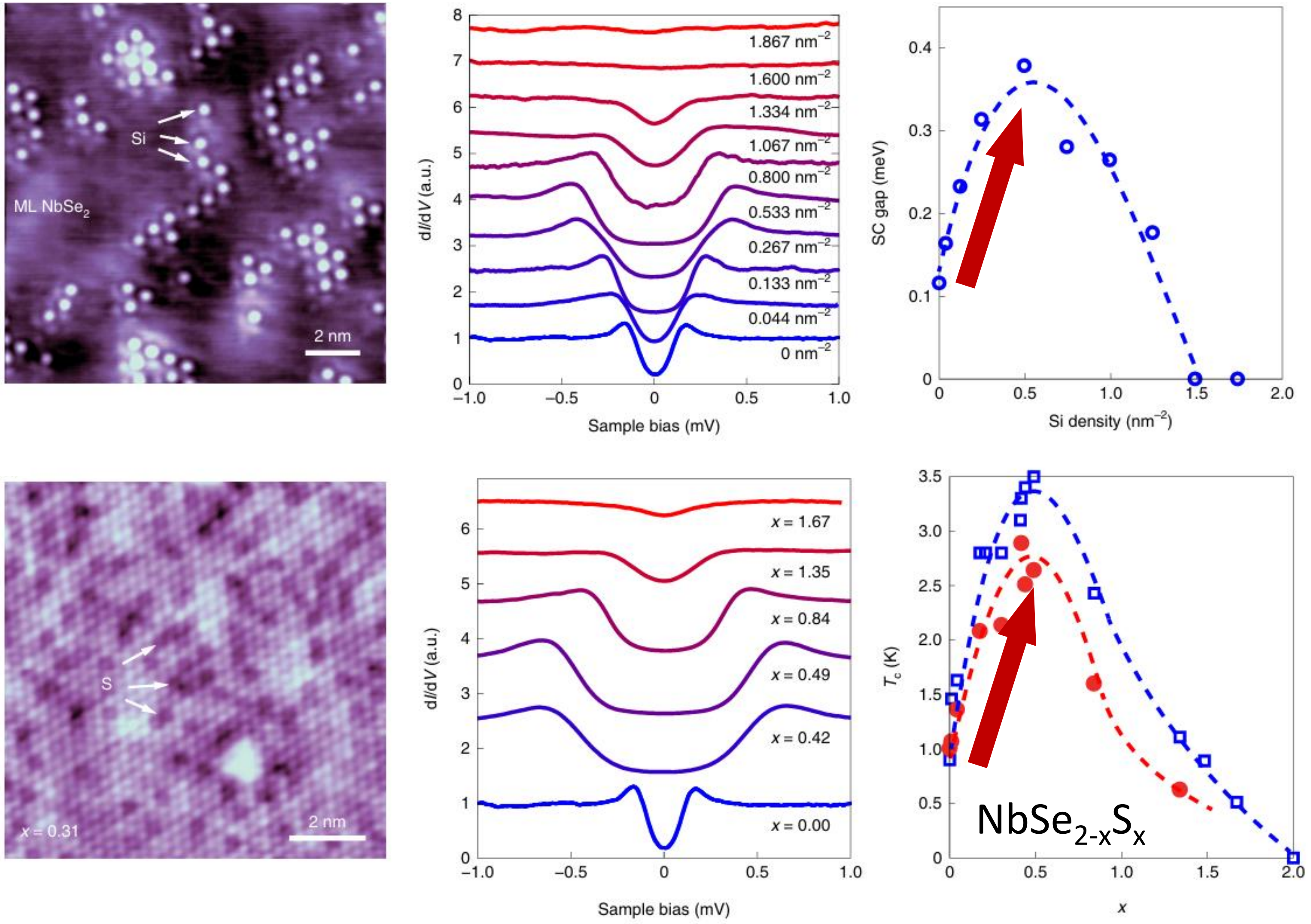
- **Charge transfer?**
  minimalized
- **Weakening of CDW?**
- **Proposal: wavefunction multifractality**



LETTERS
https://doi.org/10.1038/s41567-019-0570-0
nature physics

Disorder-induced multifractal superconductivity in monolayer niobium dichalcogenides

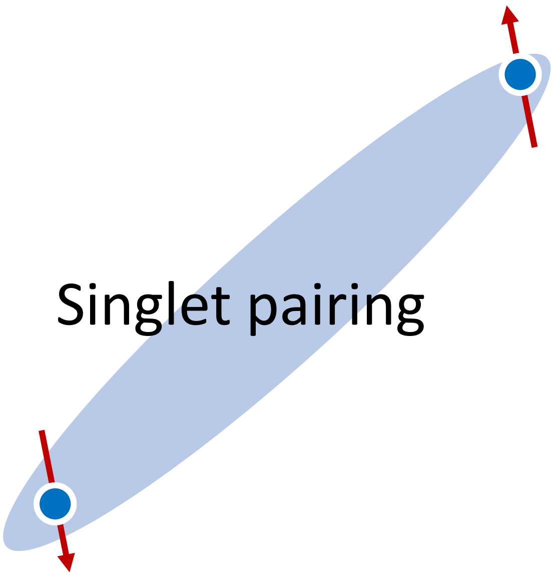
Kun Zhao[1,8], Haicheng Lin[1,8], Xiao Xiao[2,8], Wantong Huang[1], Wei Yao[1], Mingzhe Yan[1], Ying Xing[3], Qinghua Zhang[4], Zi-Xiang Li[1,5], Shintaro Hoshino[6], Jian Wang[3], Shuyun Zhou[1], Lin Gu[4], Mohammad Saeed Bahramy[6,7], Hong Yao[1,5], Naoto Nagaosa[6,7], Qi-Kun Xue[1], Kam Tuen Law[2], Xi Chen[1*] and Shuai-Hua Ji[1,6*]



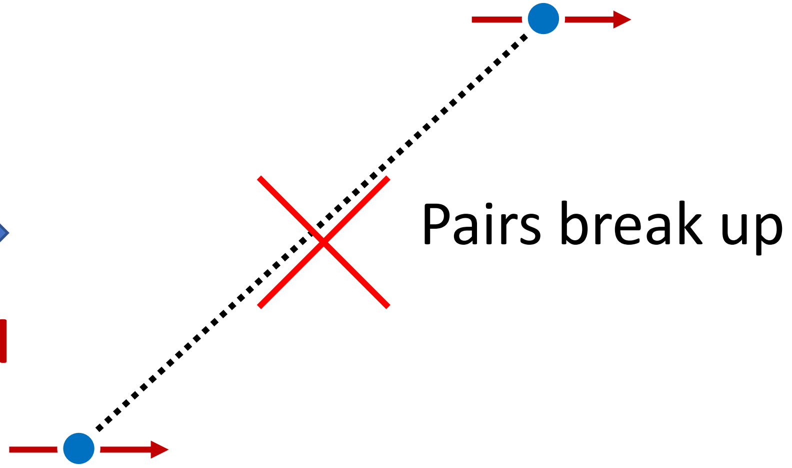
K. Zhao, *et al.*, *Nat. Phys.* **15,** 904 (2019)

Ising superconductivity

Zeeman effect on superconductivity



***Vortex effect neglected**



$$F_N - F_S = \frac{1}{2} D(0)\Delta^2$$

Normal state free energy

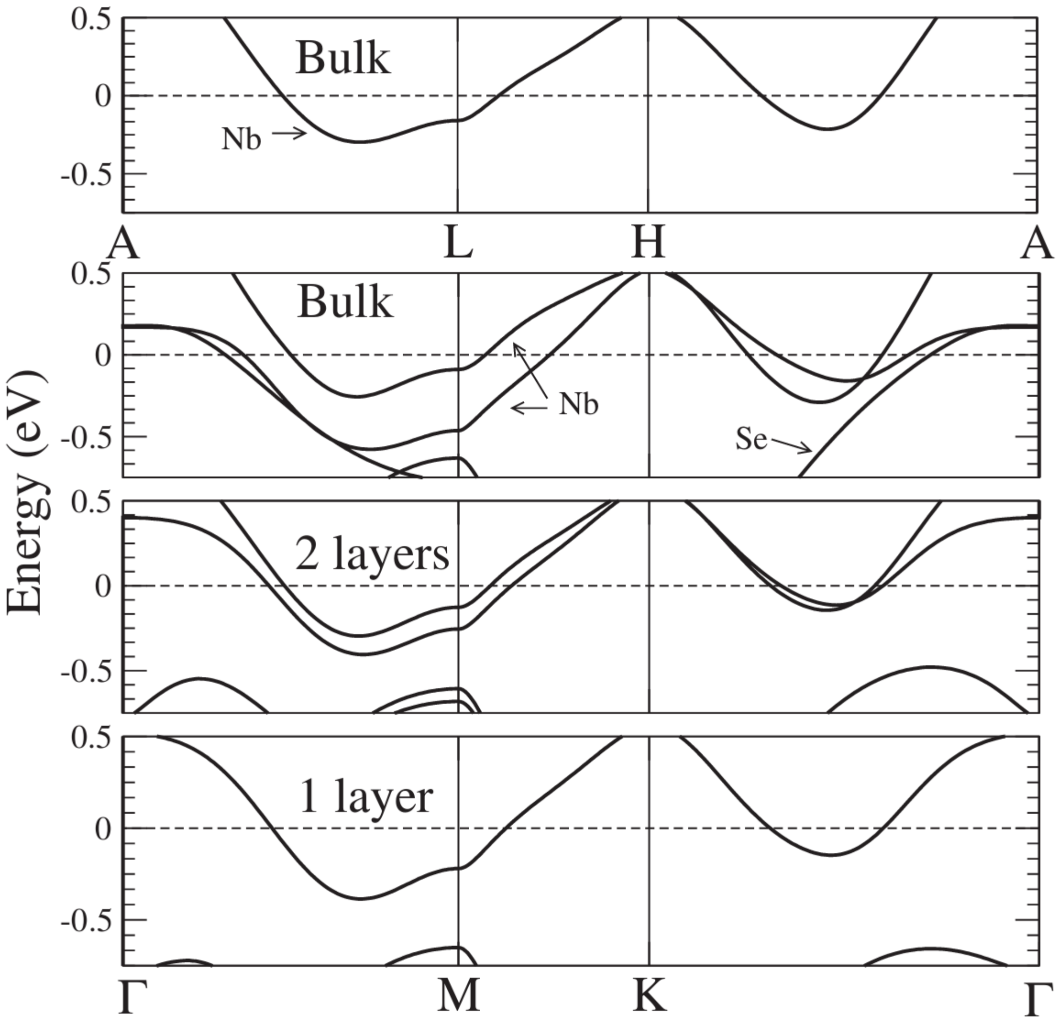
Superconducting state free energy

$$F_N - \frac{1}{2}\chi_P H^2 = F_S$$

- $2\Delta = 3.53 k_B T_c$
- **Pauli paramagnetic limit: $\boldsymbol{B = 1.86 T_c}$**

A. Clogston, *PRL* **9**, 266 (1962); B. Chandrasekhar, *APL* **1**, 7 (1962)

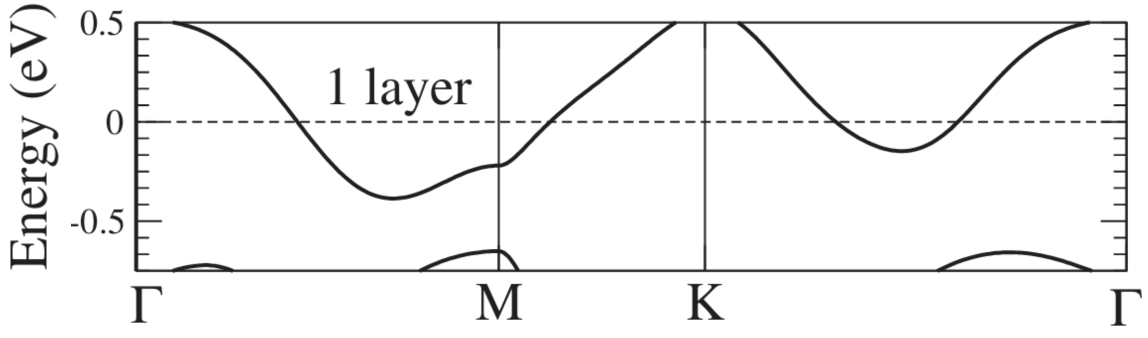
Band structure of monolayer $NbSe_2$

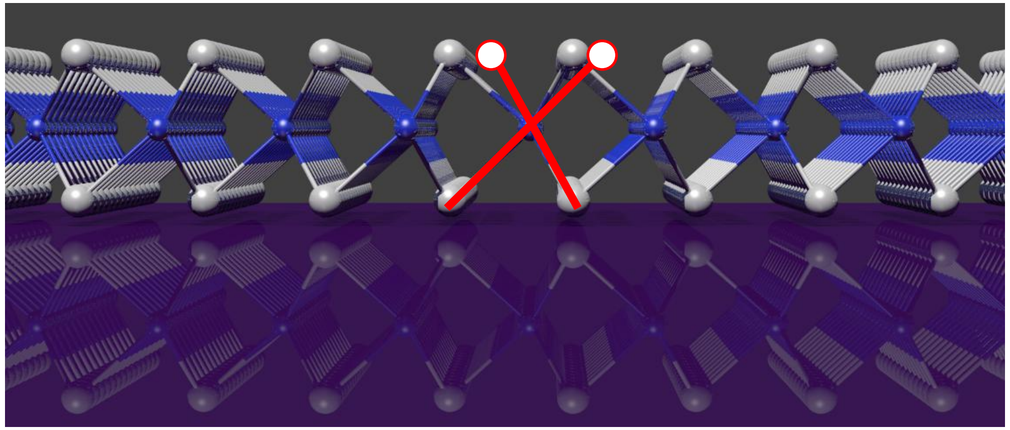


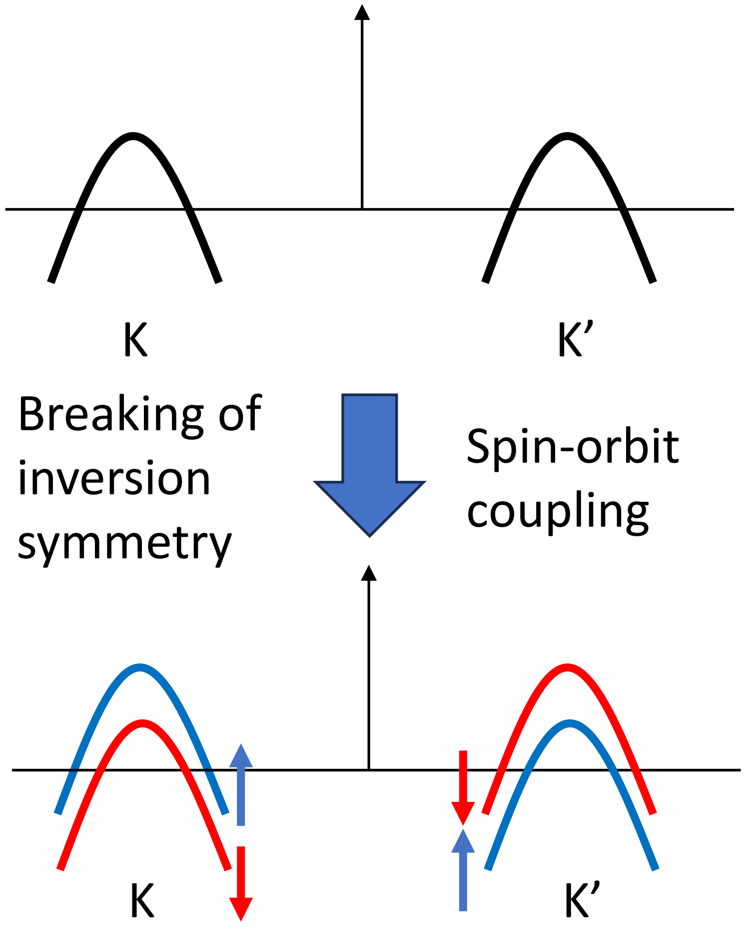
M. Calandra, I. Mazin, F. Mauri, *PRB* **80**, 241108(R) (2009)

Band structure of monolayer $NbSe_2$

M. Calandra, I. Mazin, F. Mauri, *PRB* **80**, 241108(R) (2009)

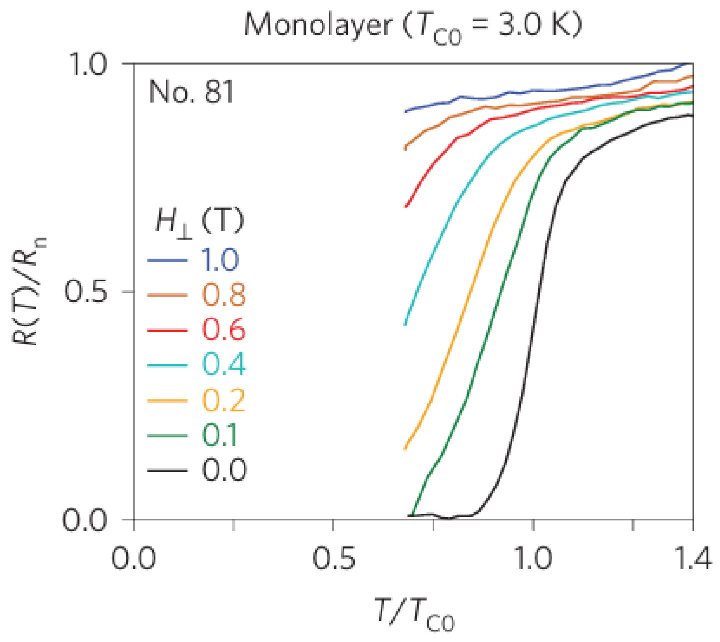


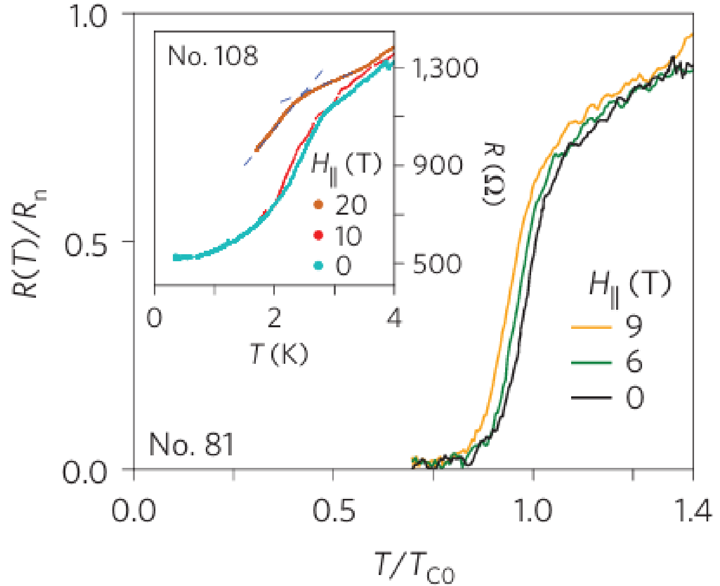


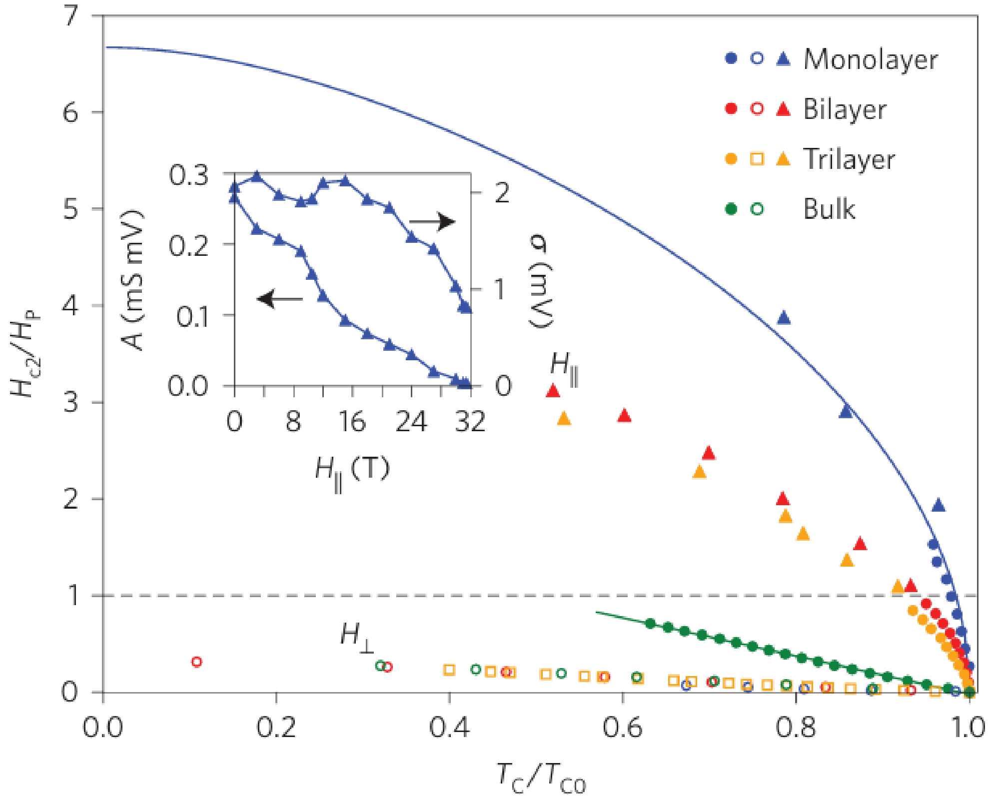


- **Effective Zeeman splitting: spins are locked to the out-of-plane direction**

Ising superconductivity in $NbSe_2$





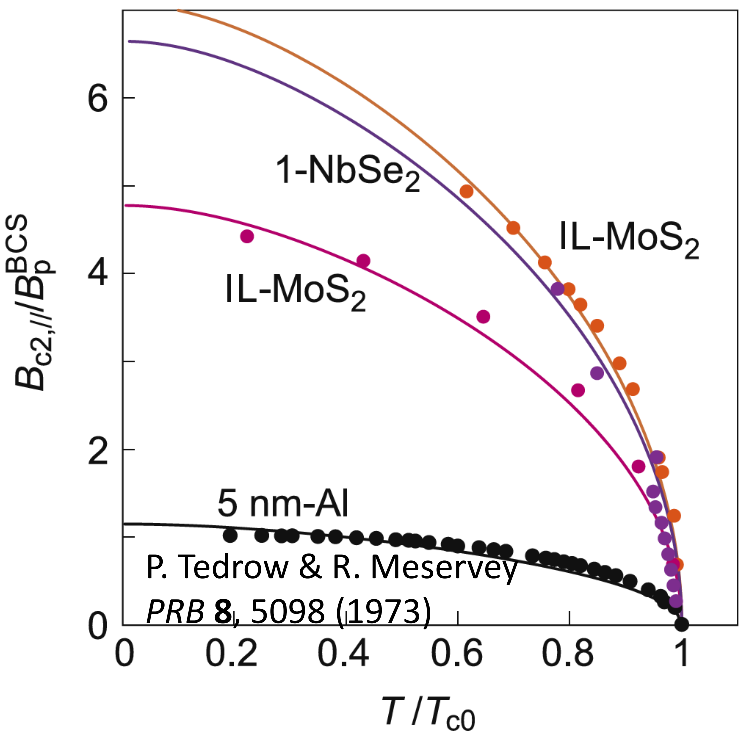


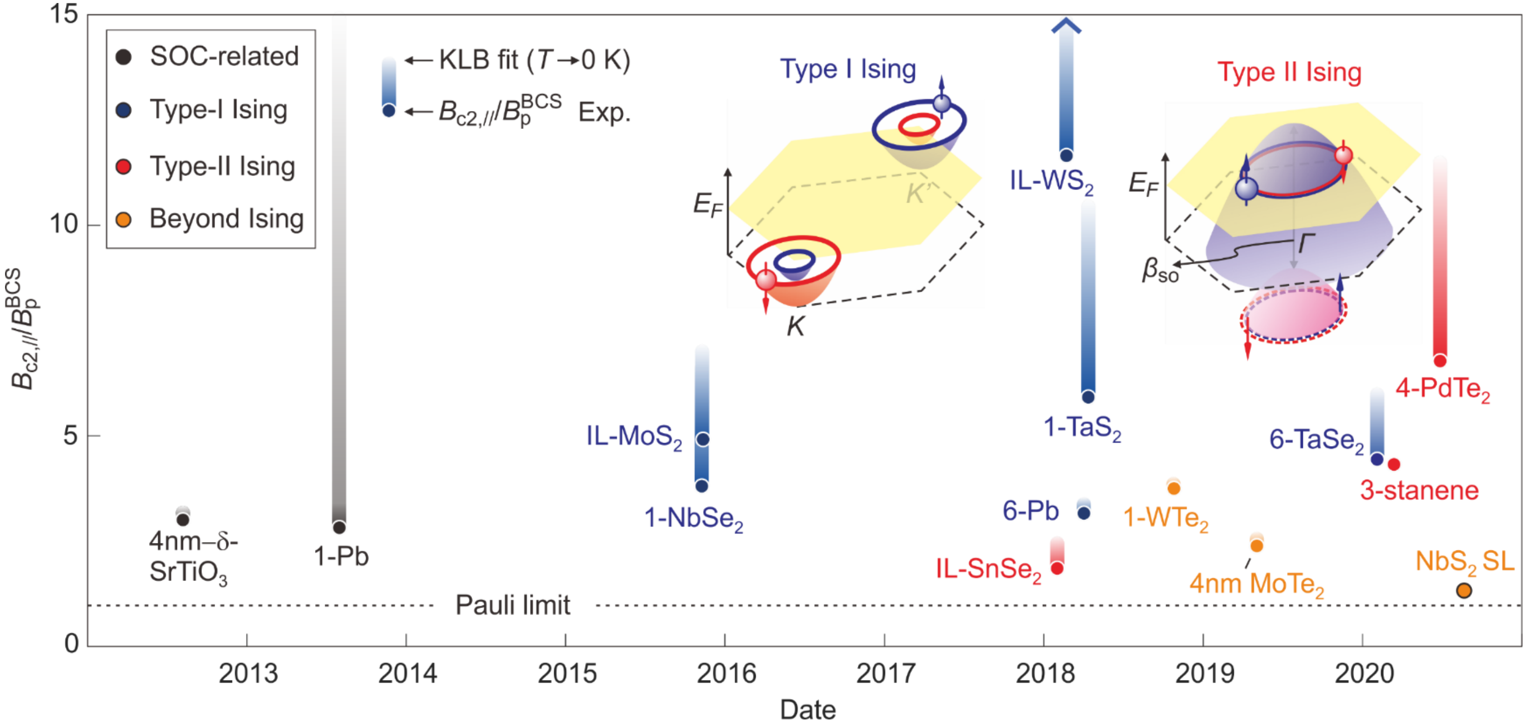
- **Large in-plane upper critical field in few-layer $NbSe_2$**

X. Xi, *et al.*, *Nat. Phys.* **12,** 139 (2016)

Ising superconductors

- **Ising superconductivity in spin-orbit coupled two-dimensional superconductors**

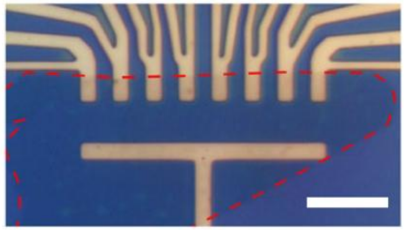


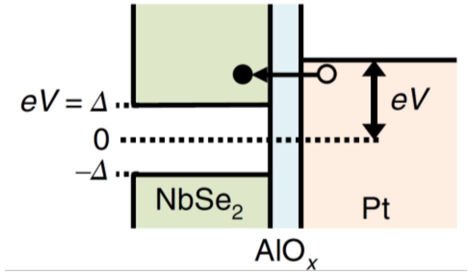


DZ* & J. Falson*, *Nanotechnology* **32,** 502003 (2021)

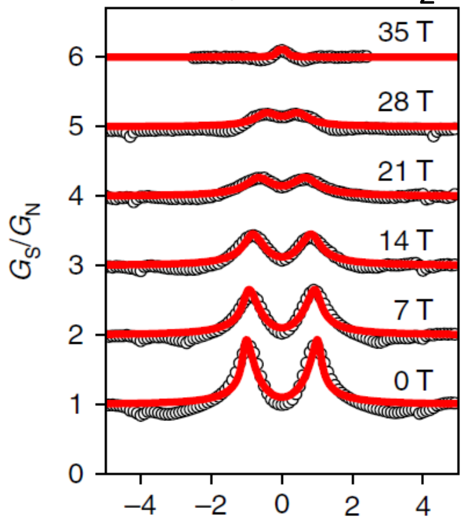
Continuous phase transition under $B_{//}$

- **No Zeeman splitting in tunneling gap**
- **Continuous decrease of gap with $B_{//}$**

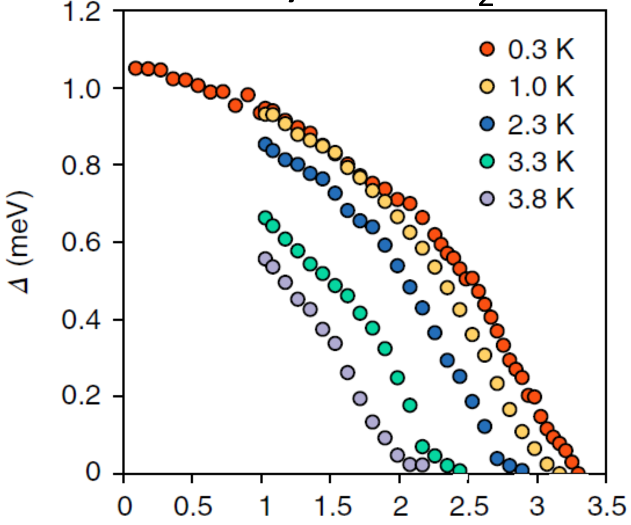




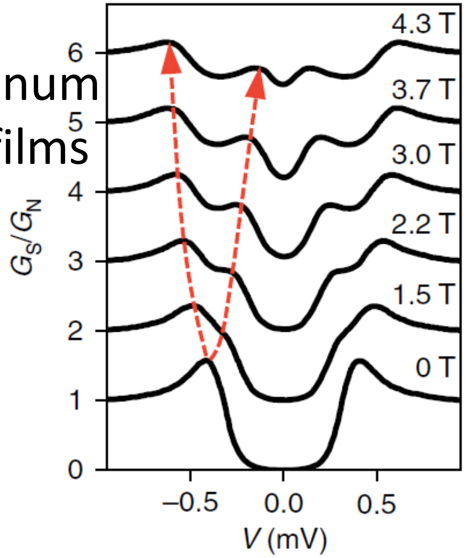
Trilayer $NbSe_2$

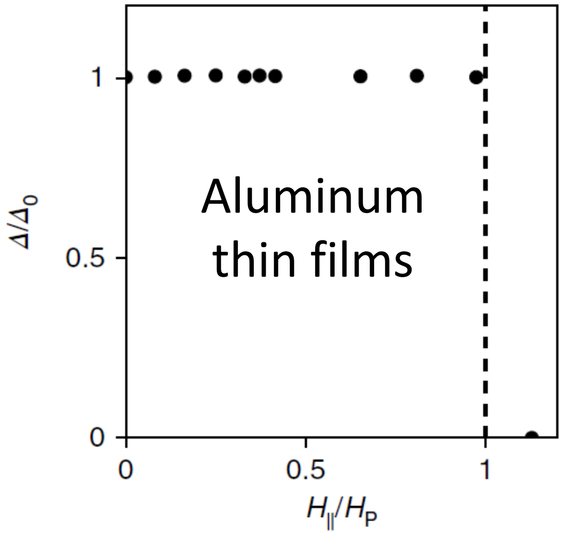


Trilayer $NbSe_2$



Aluminum thin films





nature materials LETTERS
https://doi.org/10.1038/s41563-018-0061-1

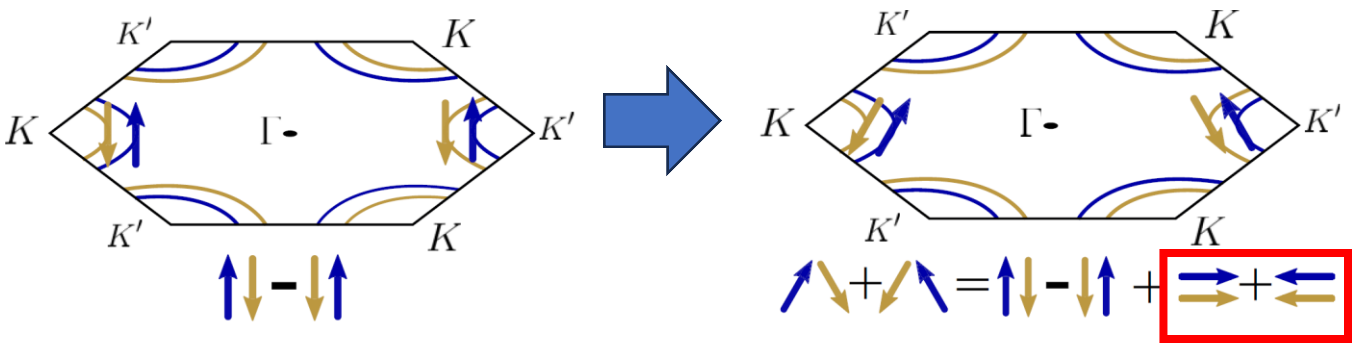
An unusual continuous paramagnetic-limited superconducting phase transition in 2D $NbSe_2$

Egon Sohn[1,2], Xiaoxiang Xi[1,3], Wen-Yu He[4], Shengwei Jiang[1,2], Zefang Wang[1,2], Kaifei Kang[1,2], Ju-Hyun Park[5], Helmuth Berger[6], László Forró[6], Kam Tuen Law[4], Jie Shan[1,2,7*] and Kin Fai Mak[1,2,7*]

E. Sohn, *et al.*, *Nat. Mater.* **17,** 504 (2018)

Possible spin-triplet pairing under large $B_{//}$

With in-plane magnetic field



PHYSICAL REVIEW B **106**, 184514 (2022)

Editors' Suggestion

Tunneling spectroscopy of few-monolayer $NbSe_2$ in high magnetic fields: Triplet superconductivity and Ising protection

M. Kuzmanović,[1,2,*] T. Dvir,[3,4,*] D. LeBoeuf,[5] S. Ilić,[6,7] M. Haim,[3] D. Möckli,[3,8] S. Kramer,[5] M. Khodas,[3] M. Houzet,[6] J. S. Meyer,[6] M. Aprili,[1] H. Steinberg,[3] and C. H. L. Quay[1,†]

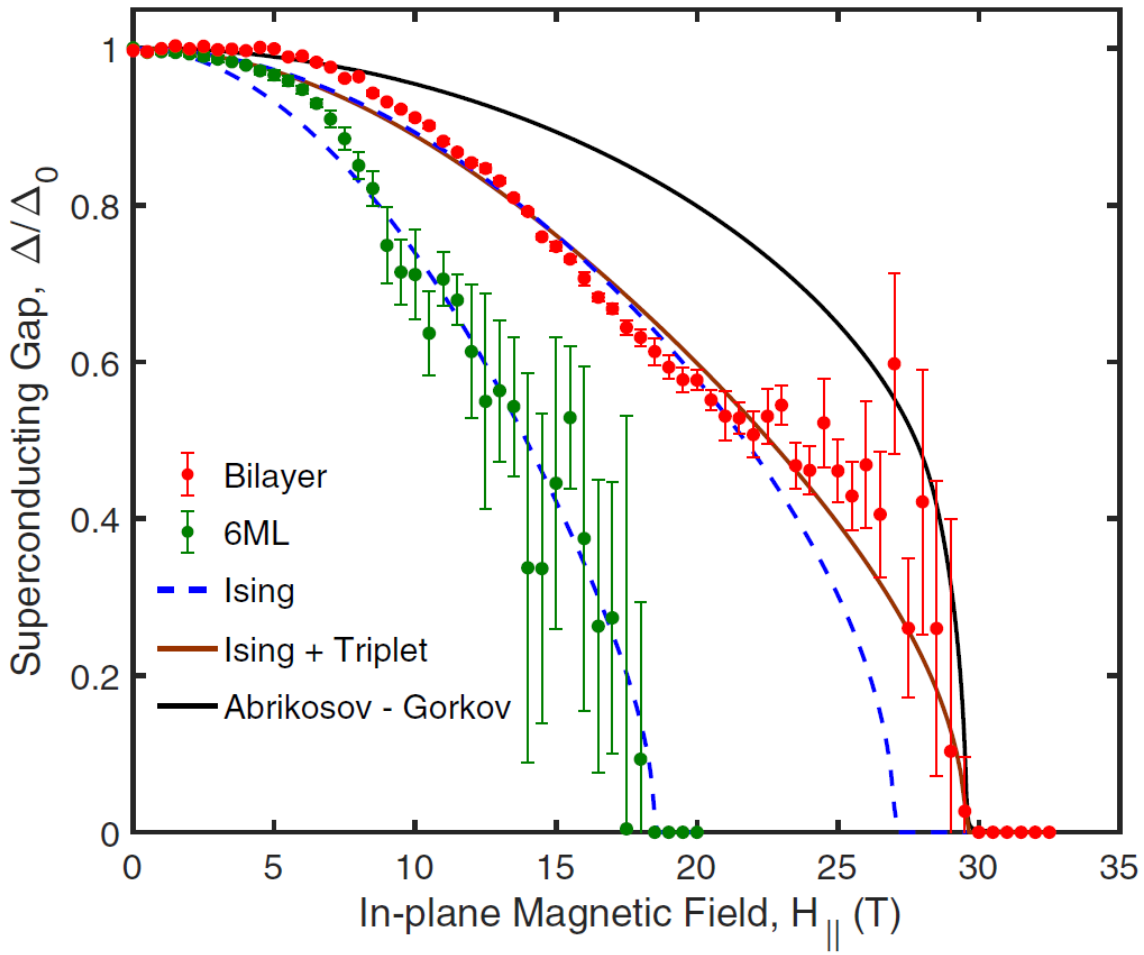
ARTICLE

DOI: 10.1038/s41467-018-03000-w

OPEN

Spectroscopy of bulk and few-layer superconducting $NbSe_2$ with van der Waals tunnel junctions

T. Dvir[1], F. Massee[2], L. Attias[1], M. Khodas[1], M. Aprili[2], C.H.L. Quay[2] & H. Steinberg[1]

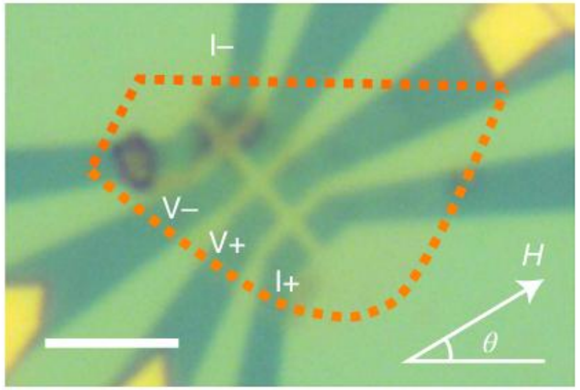


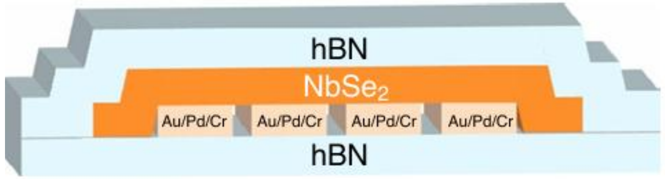
M. Kuzmanovic, *et al.*, *PRB* **106,** 184514 (2022)

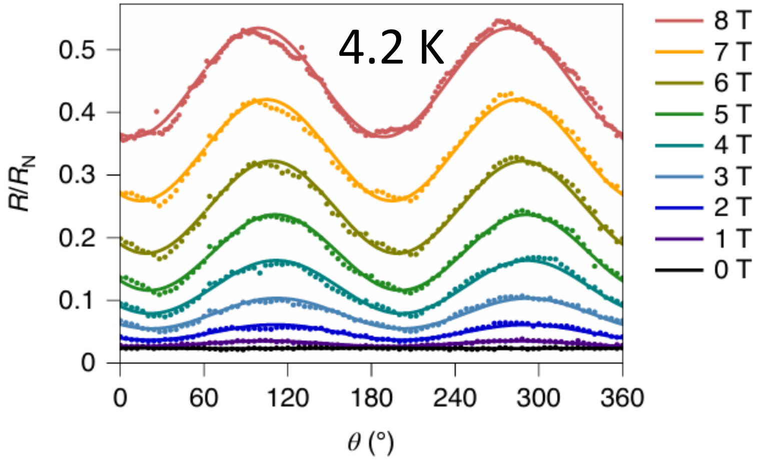
T. Dvir, *et al.*, *Nat. Commun.* **9,** 598 (2018)

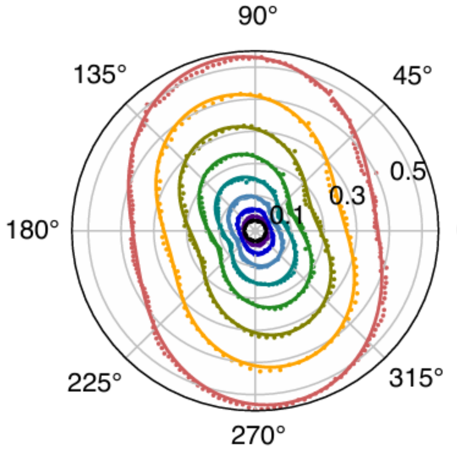
In-plane anisotropy

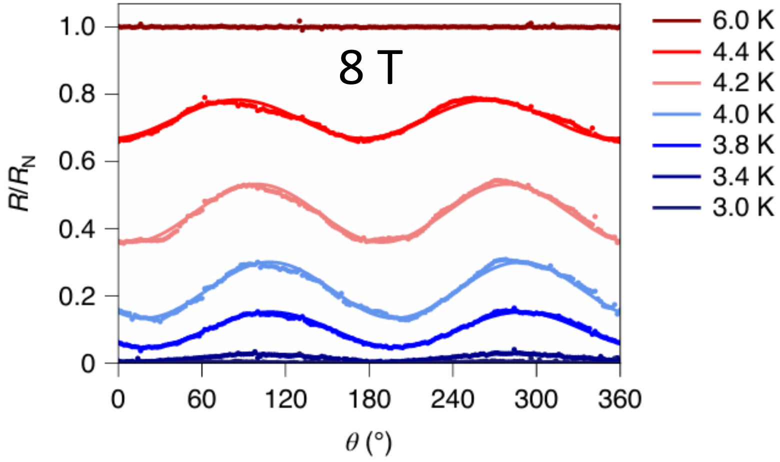
- Rotating the sample in the magnetic field

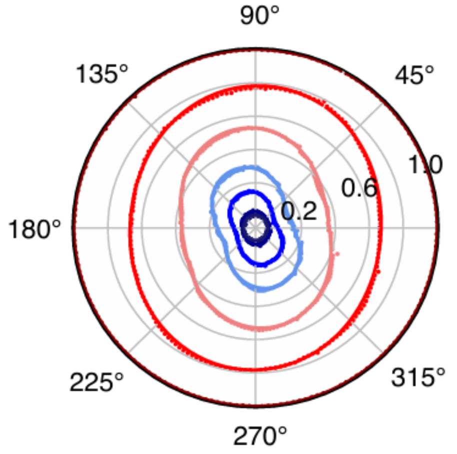












nature physics

ARTICLES

https://doi.org/10.1038/s41567-021-01219-x

Check for updates

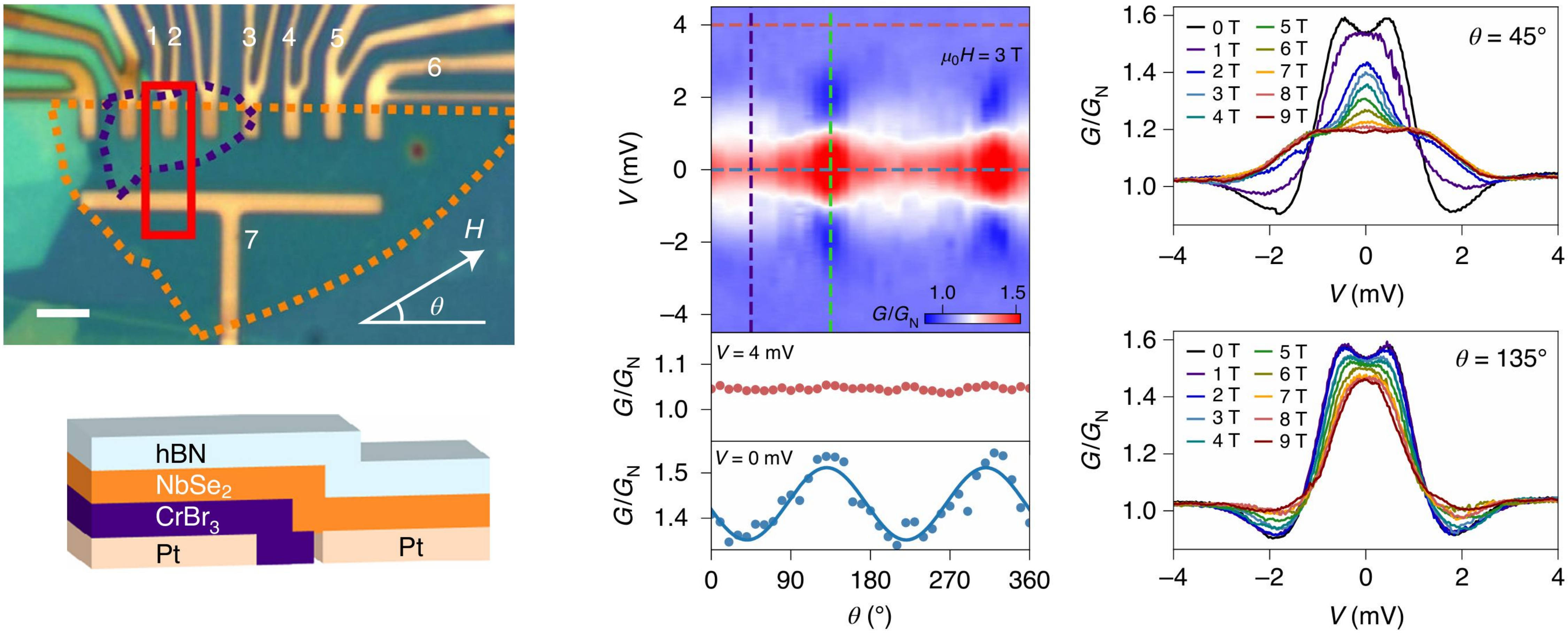
Two-fold symmetric superconductivity in few-layer $NbSe_2$

Alex Hamill[1,8], Brett Heischmidt[1,8], Egon Sohn[2,3,8], Daniel Shaffer[1], Kan-Ting Tsai[1], Xi Zhang[1], Xiaoxiang Xi[4], Alexey Suslov[5], Helmuth Berger[6], László Forró[6], Fiona J. Burnell[1], Jie Shan[3,7], Kin Fai Mak[3,7], Rafael M. Fernandes[1], Ke Wang[1] and Vlad S. Pribiag[1]

A. Hamill, *et al.*, *Nat. Phys.* **17,** 949 (2021)

In-plane anisotropy

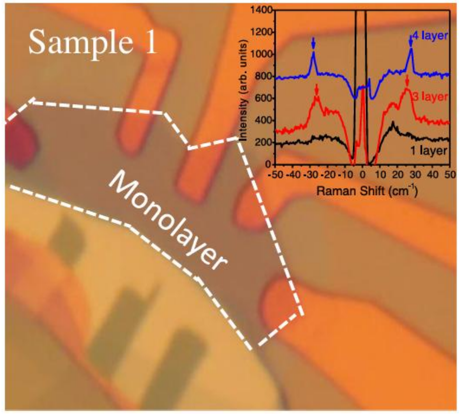
- Two-fold symmetry in the gap response

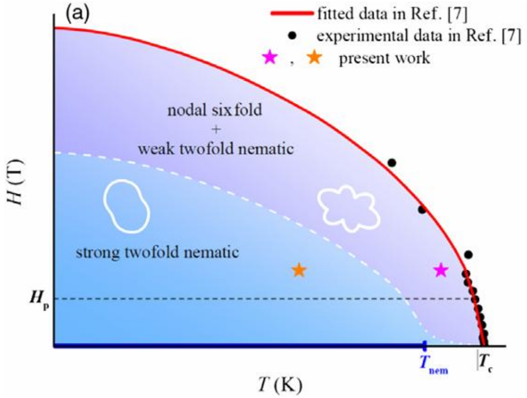


A. Hamill, *et al.*, *Nat. Phys.* **17,** 949 (2021)

In-plane anisotropy in $NbSe_2$ monolayers

- Two-fold symmetry: nematic phase
- Six-fold symmetry: nodal phase



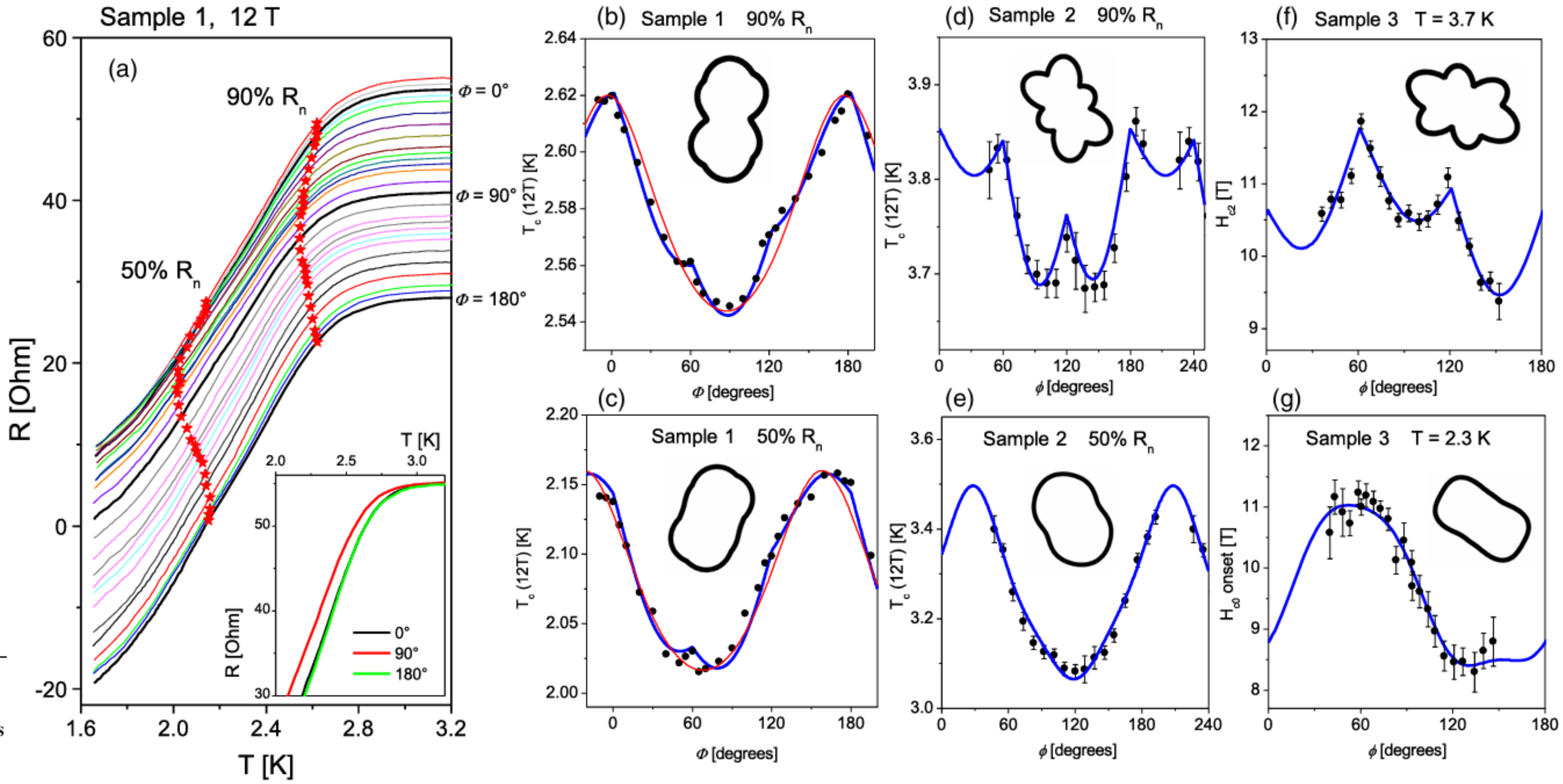


PHYSICAL REVIEW LETTERS **129**, 087002 (2022)

Nodal and Nematic Superconducting Phases in $NbSe_2$ Monolayers from Competing Superconducting Channels

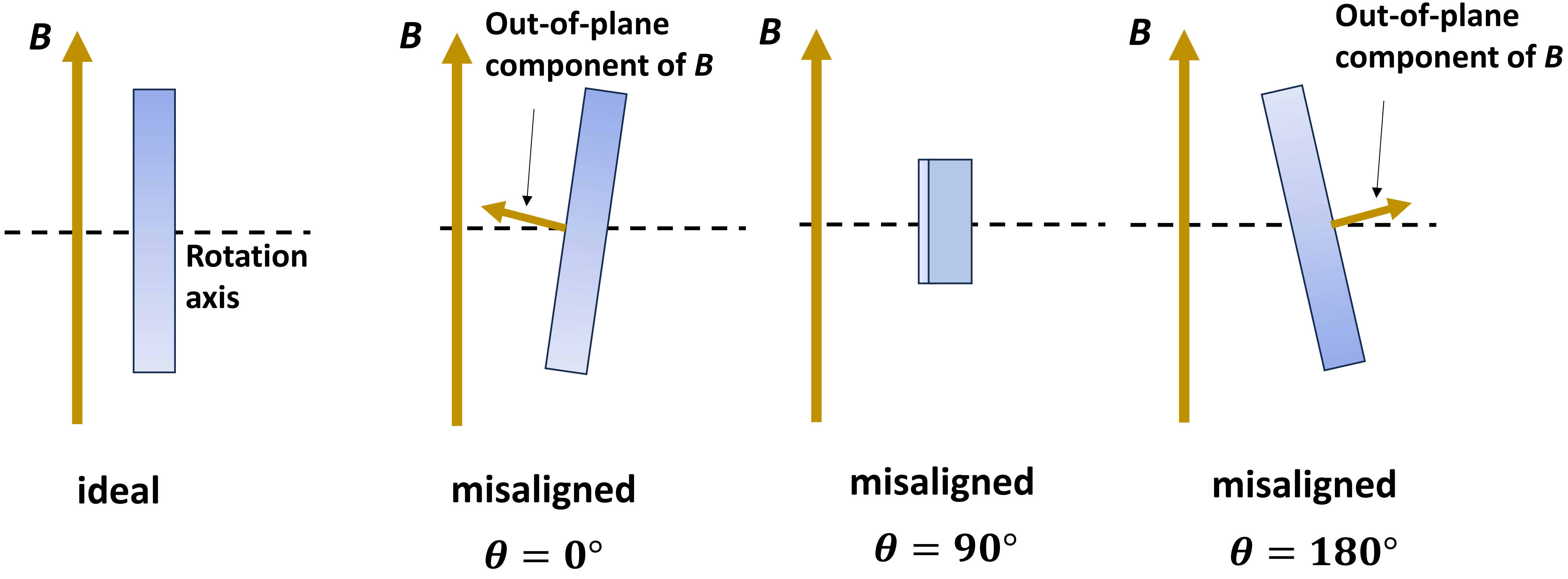
Chang-woo Cho,[1] Jian Lyu,[1,2] Liheng An,[1] Tianyi Han,[1] Kwan To Lo,[1] Cheuk Yin Ng,[1] Jiaqi Hu,[1] Yuxiang Gao,[1] Gaomin Li,[2] Mingyuan Huang,[2] Ning Wang,[1] Jörg Schmalian,[3] and Rolf Lortz[1,*]

[1]Department of Physics, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong
[2]Department of Physics, Southern University of Science and Technology, 1088 Xueyuan Road, Nanshan District, 518000 Shenzhen, Guangdong Province, China
[3]Institute for Theory of Condensed Matter and Institute for Quantum Materials and Technologies, Karlsruhe Institute of Technology, 76131 Karlsruhe, Germany

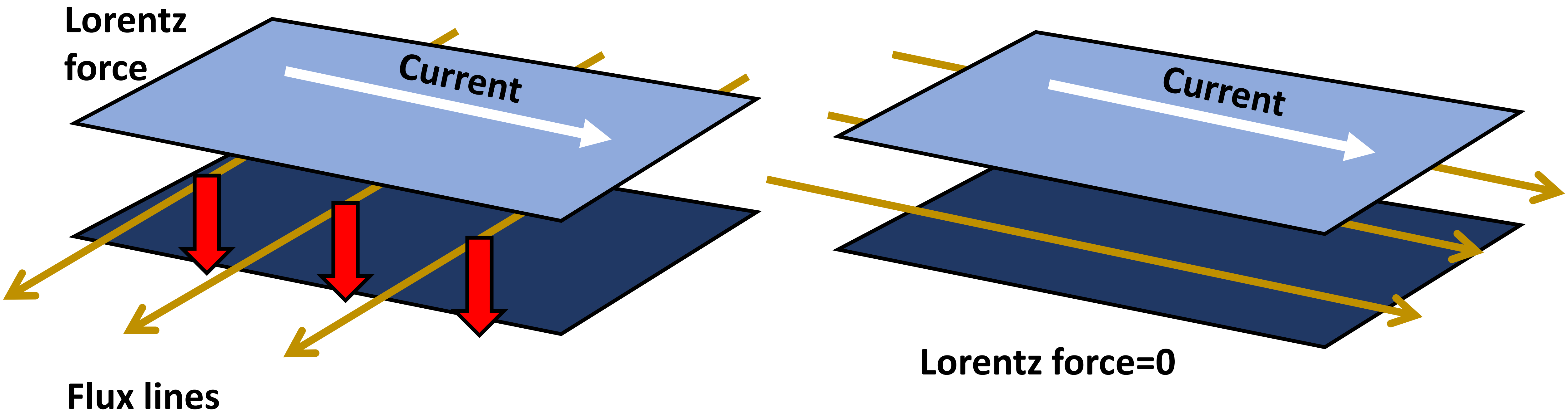


C.-w. Cho, *et al.*, *Phys. Rev. Lett.* **129,** 087002 (2022)

In-plane anisotropy: beware of trivial effect

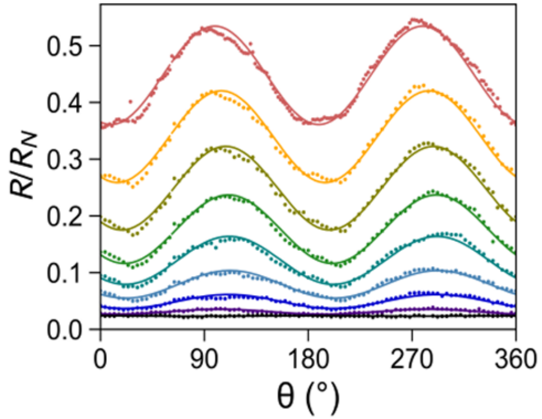


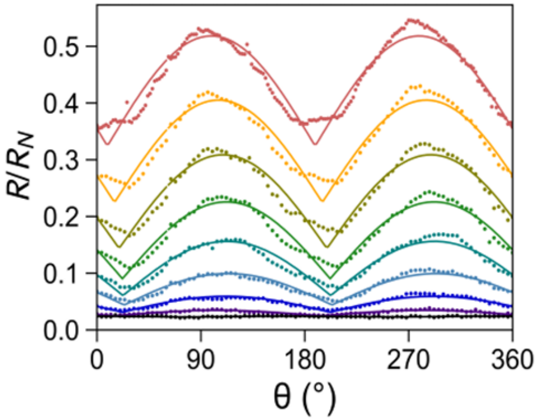
In-plane anisotropy: beware of trivial effect

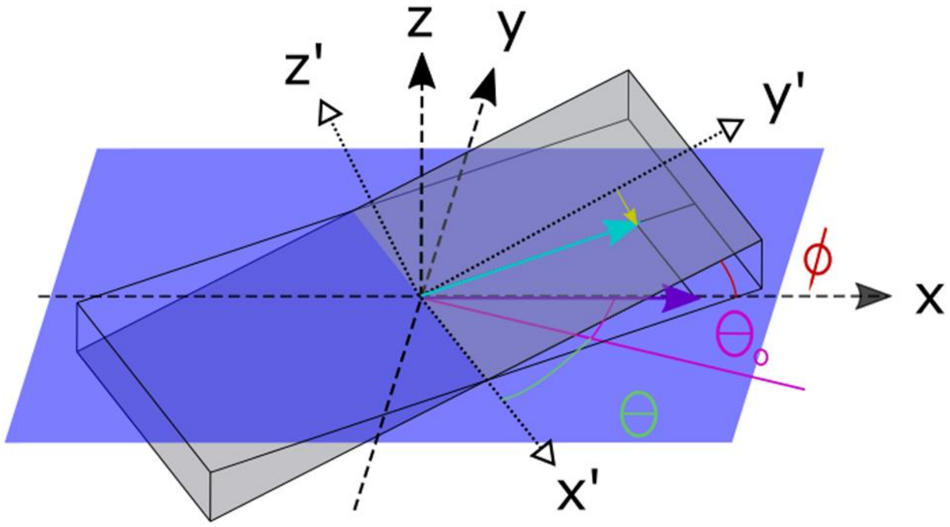


Solid curves: $\sin[2(\theta+\theta_0)]$ | Trivial $|\sin(\theta+\theta_0)|$

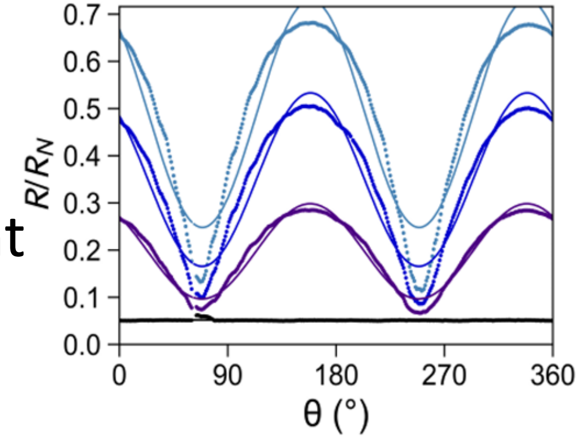
Without intentional misalignment

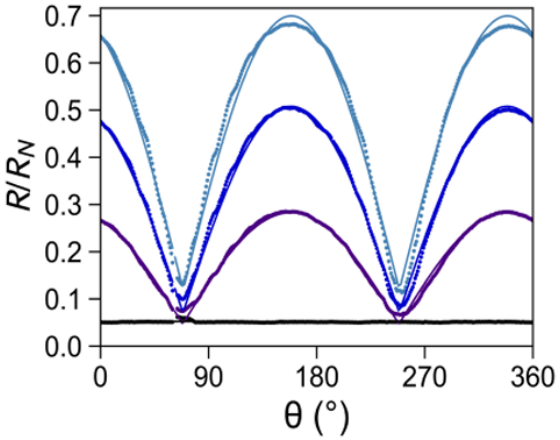




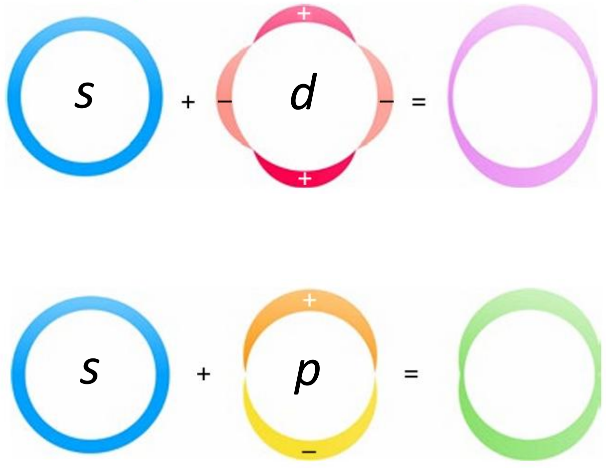


With intentional misalignment of 7 degrees



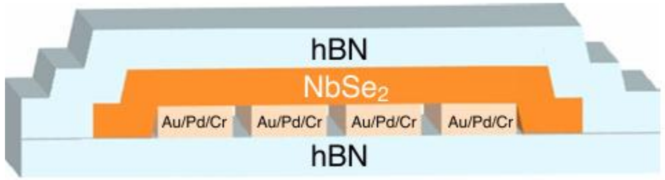


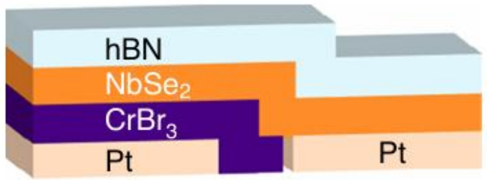
Proposed mechanism



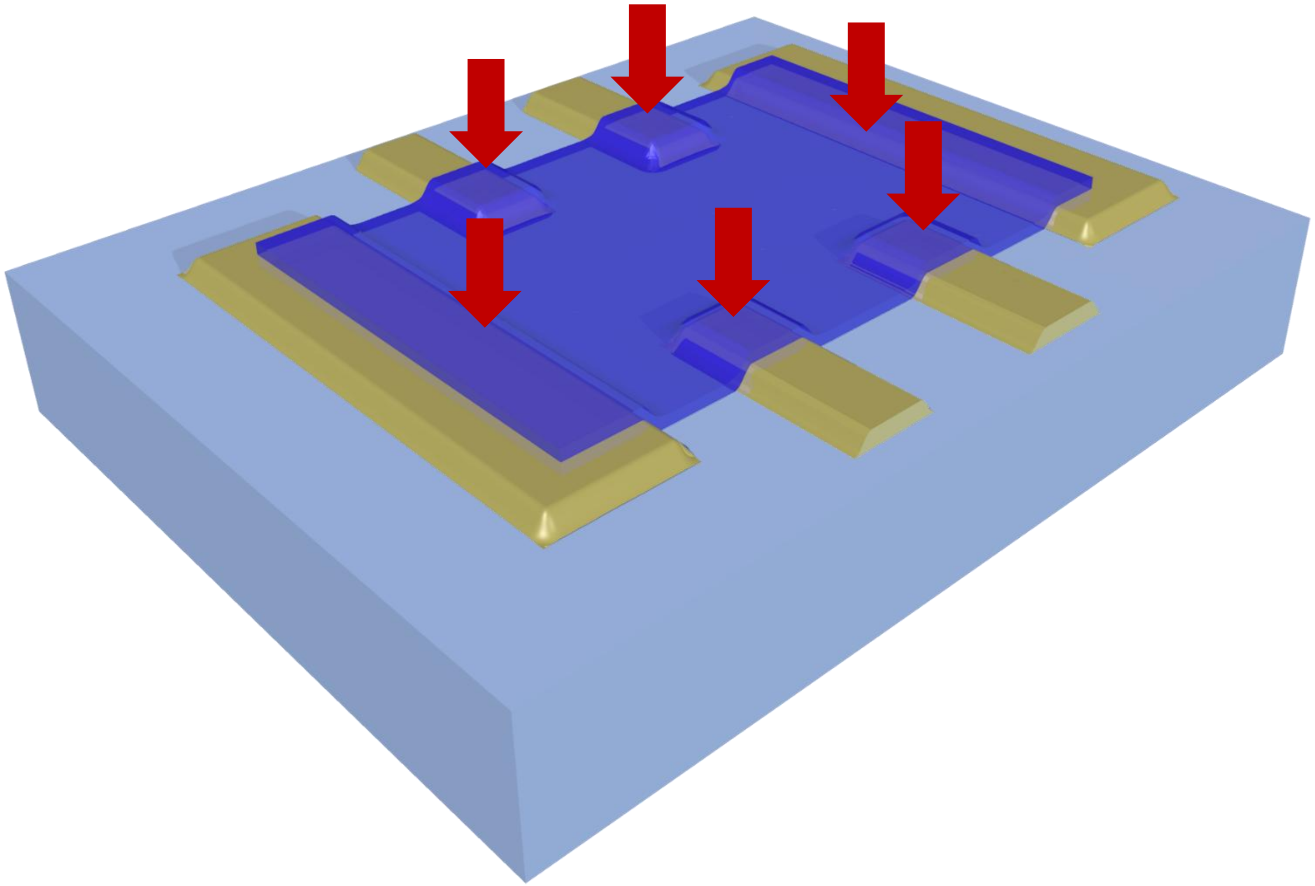
A. Hamill, *et al.*, *Nat. Phys.* **17,** 949 (2021)

In-plane anisotropy: beware of trivial effect

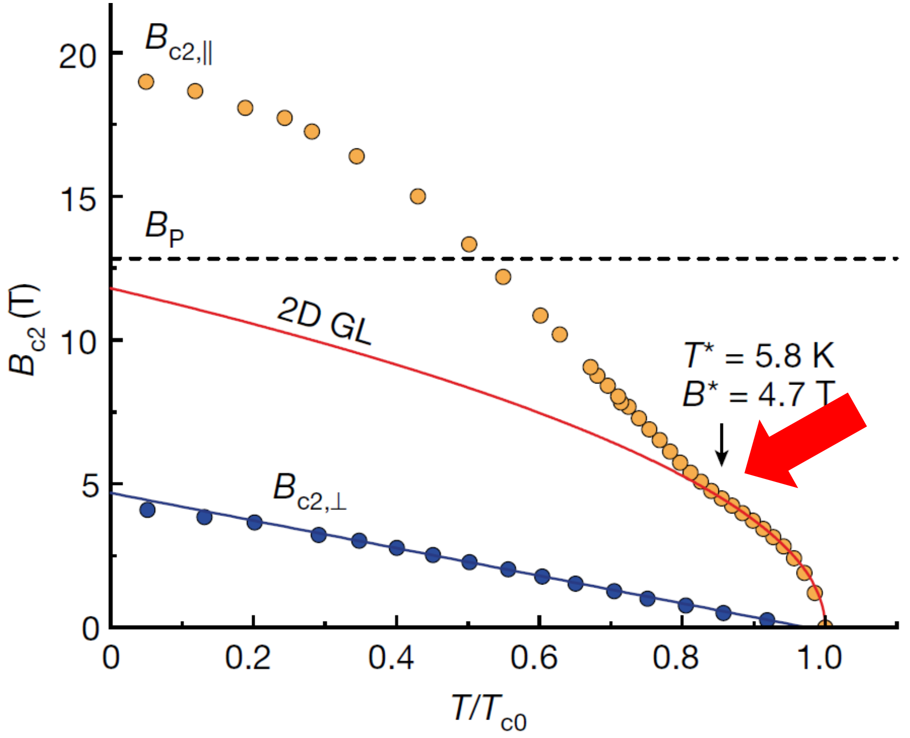


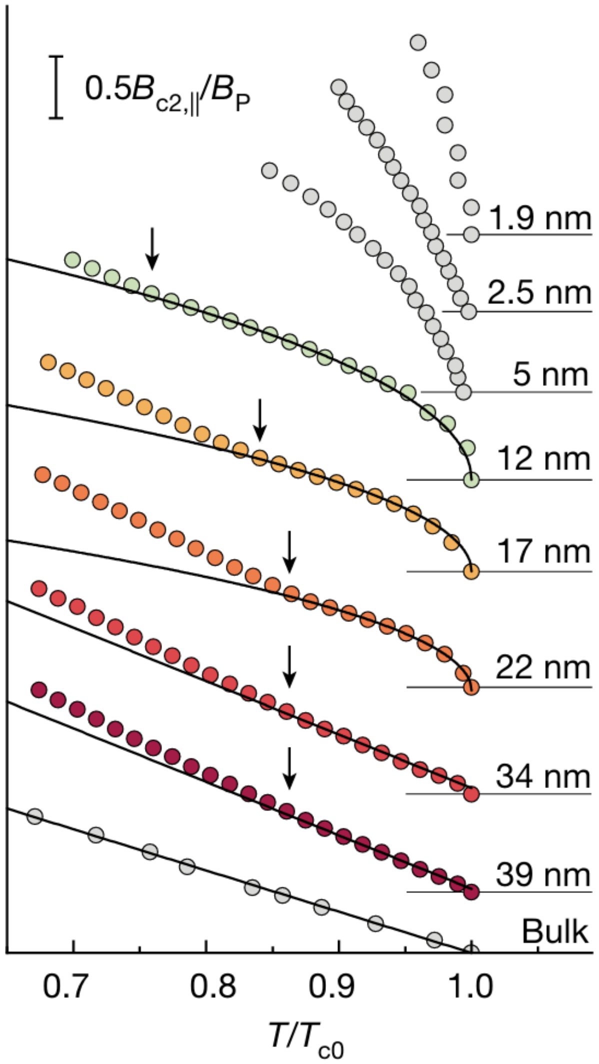


Bottom contacts
may induce strain



Orbital Fulde-Ferrell-Larkin-Ovchinnikov state





Article

Orbital Fulde–Ferrell–Larkin–Ovchinnikov state in an Ising superconductor

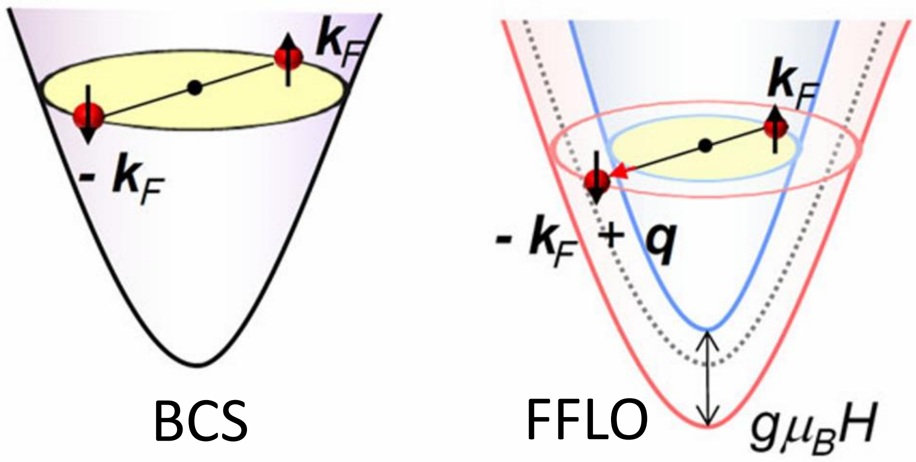
https://doi.org/10.1038/s41586-023-05967-z
Received: 1 November 2022
Accepted: 17 March 2023
Published online: 24 May 2023
Check for updates

Puhua Wan[1], Oleksandr Zheliuk[1,2], Noah F. Q. Yuan[3], Xiaoli Peng[1], Le Zhang[1], Minpeng Liang[1], Uli Zeitler[2], Steffen Wiedmann[2], Nigel E. Hussey[2,4], Thomas T. M. Palstra[5] & Jianting Ye[1]✉

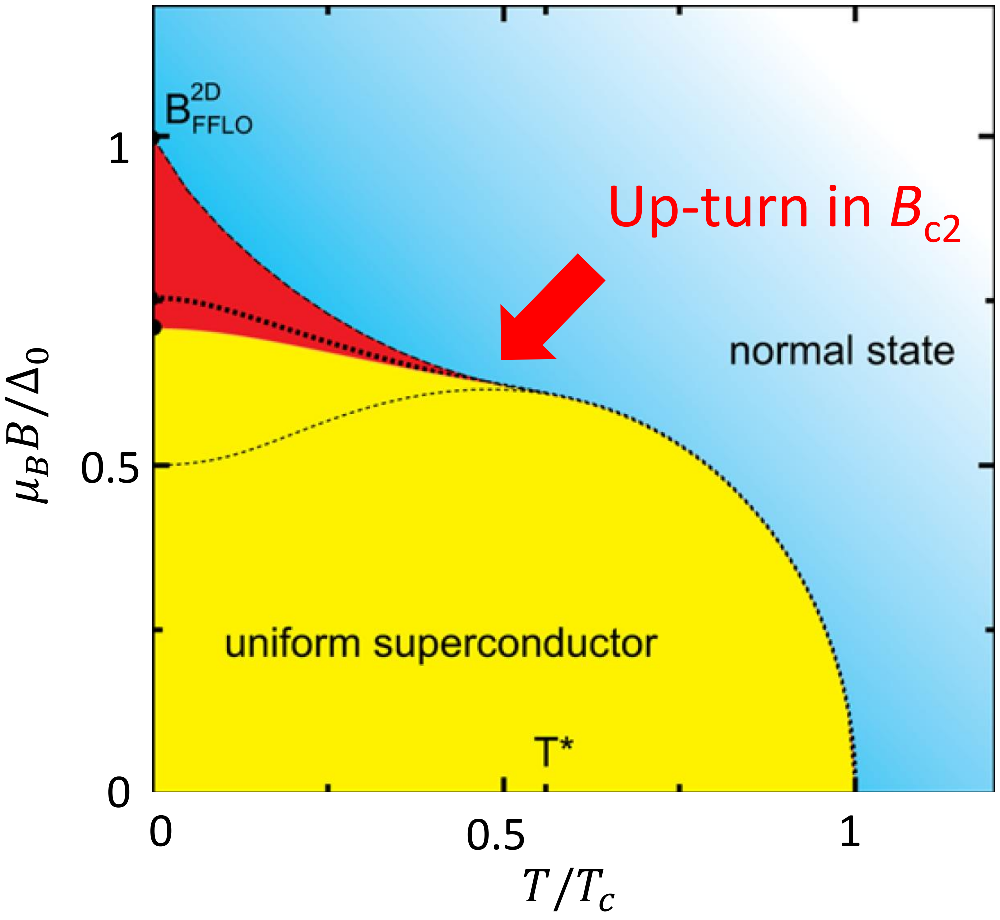
In superconductors possessing both time and inversion symmetries, the Zeeman effect of an external magnetic field can break the time-reversal symmetry, forming a conventional Fulde–Ferrell–Larkin–Ovchinnikov (FFLO) state characterized by

P. Wan, *et al.*, *Nature* **619,** 46 (2023)

Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) state



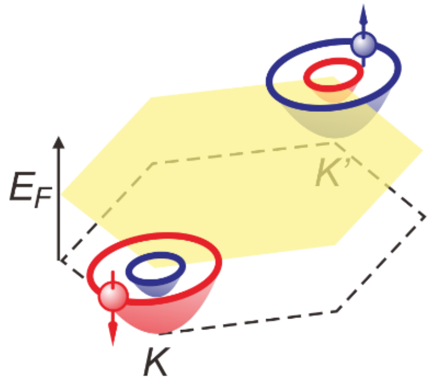
Finite-momentum pairing



- Large Maki parameter ($\alpha = \sqrt{2}\frac{B_{c2}^{orb}}{B_{c2}^{P}} > 1.8$)
- Clean superconductor $l_m > \xi_0$
- Low dimensions

S. Kasahara, *et al.*, *Phys. Rev. Lett.* **124,** 107001 (2020)   J. Wosnitza, *Ann. Phys.* **530,** 1700282 (2017)

Ising superconductivity in $NbSe_2$ and orbital FFLO

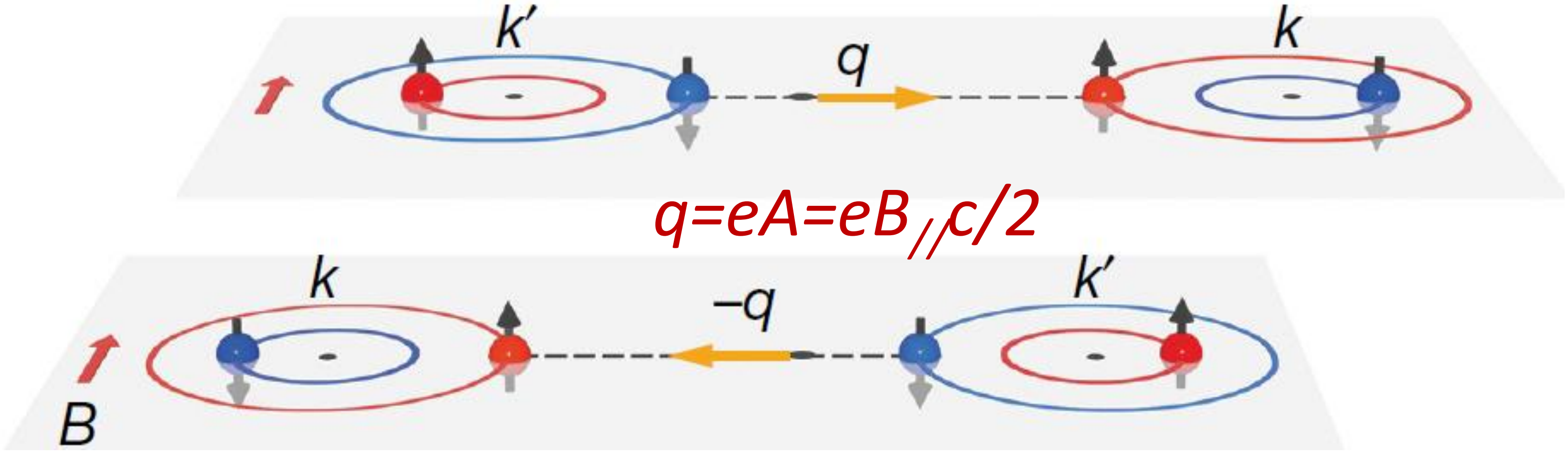


Spin-orbit coupling + inversion symmetry breaking

Spins locked out-of-plane

J. Lu, *et al., Science* **350,** 1353 (2015) X. Xi, *et al., Nat. Phys.* **12,** 139 (2016) Y. Saito, *et al., Nat. Phys.* **12,** 144 (2016)

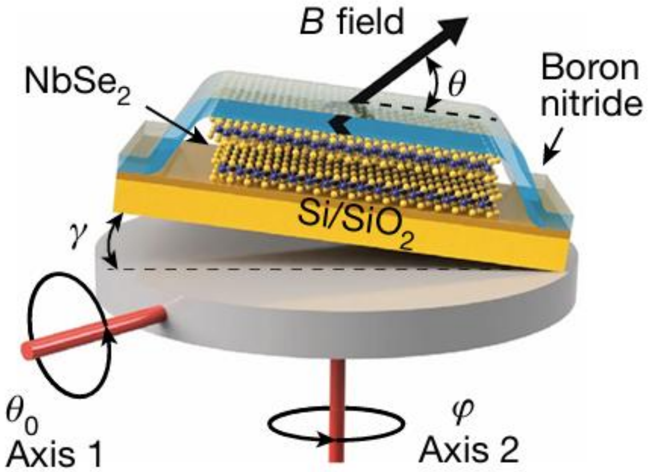
Ising superconductivity + layer degree of freedom

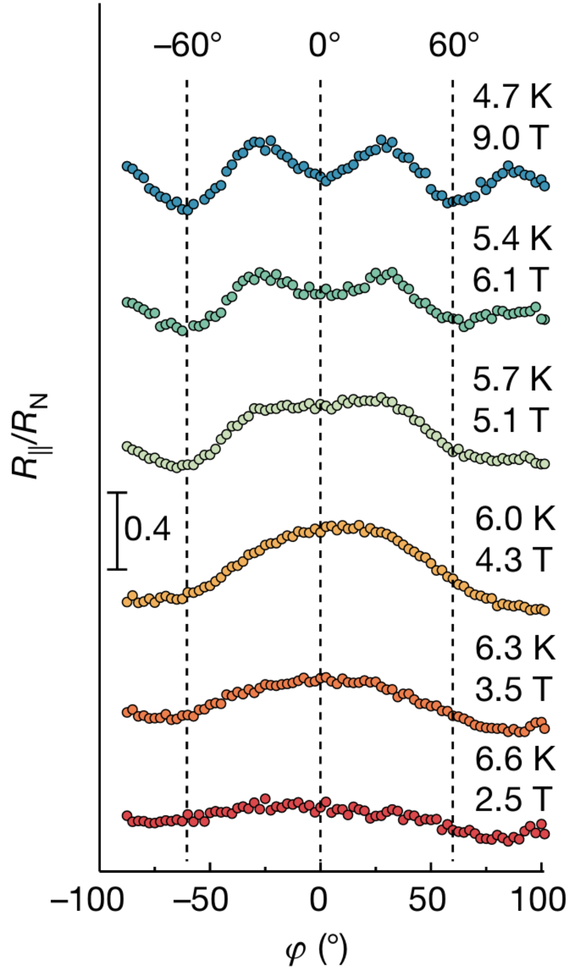


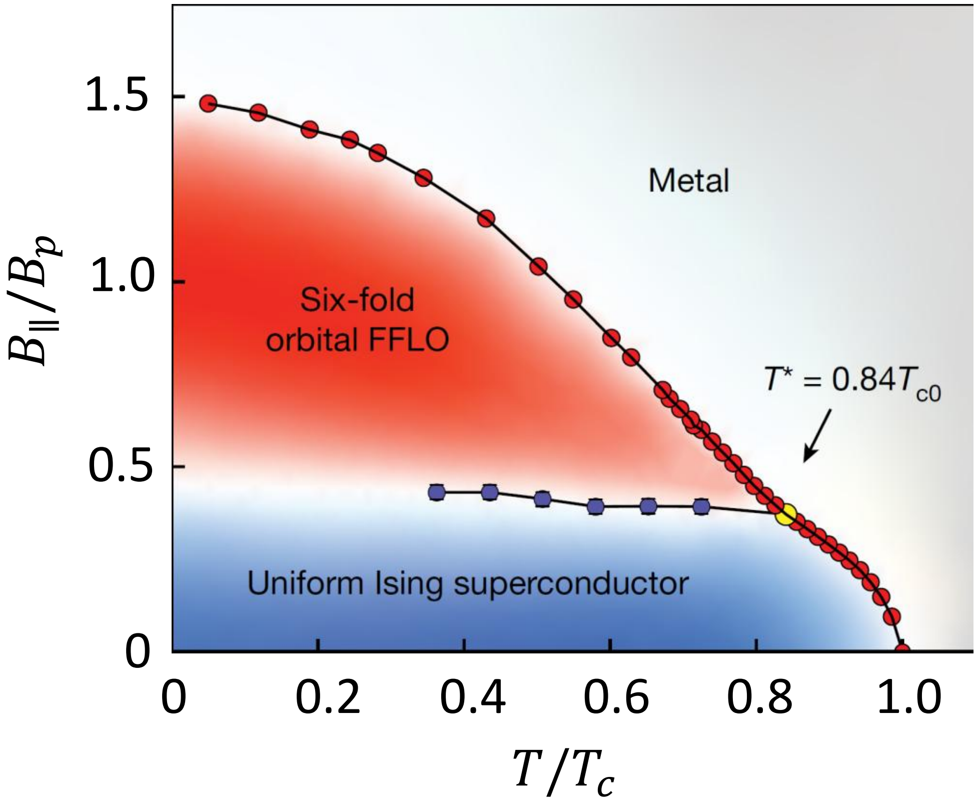
C. Liu, *PRL* **118,** 087001 (2017)

Orbital Fulde-Ferrell-Larkin-Ovchinnikov state

- Six-fold symmetry at low T, high $B_{//}$

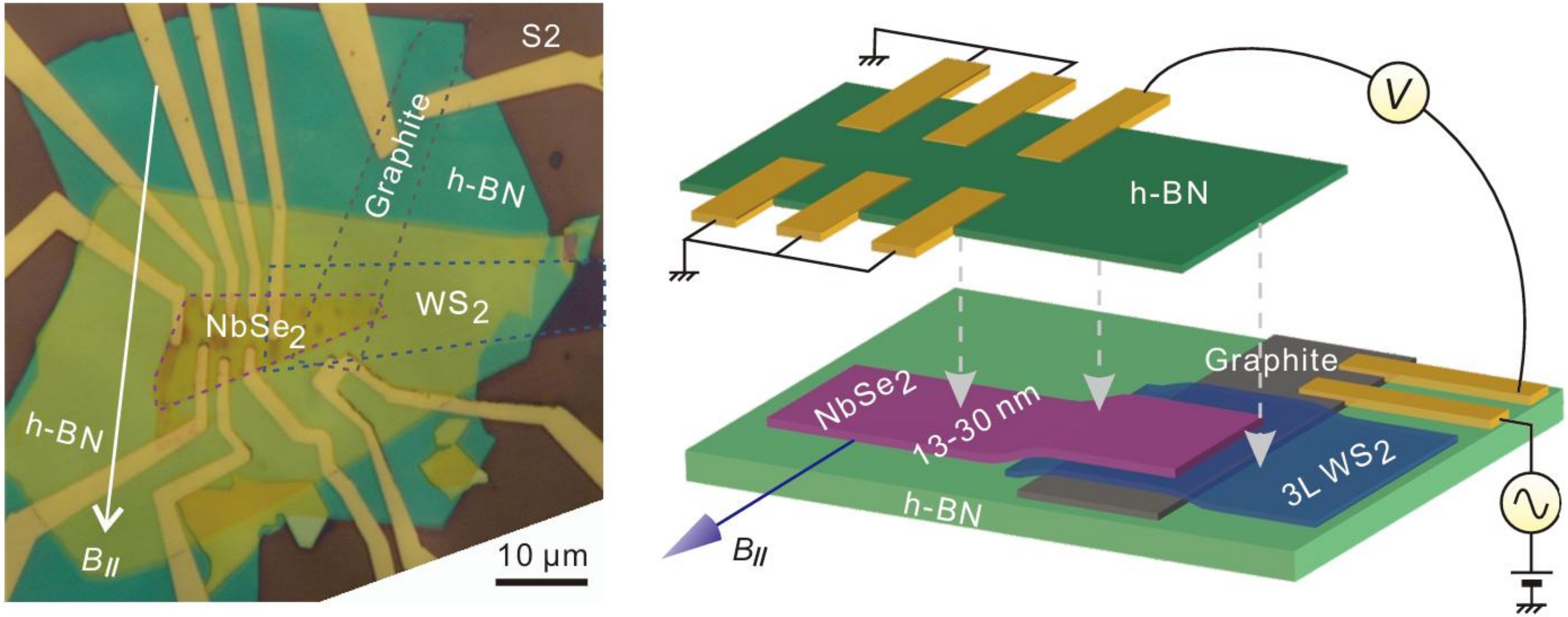






P. Wan, *et al.*, *Nature* **619,** 46 (2023)

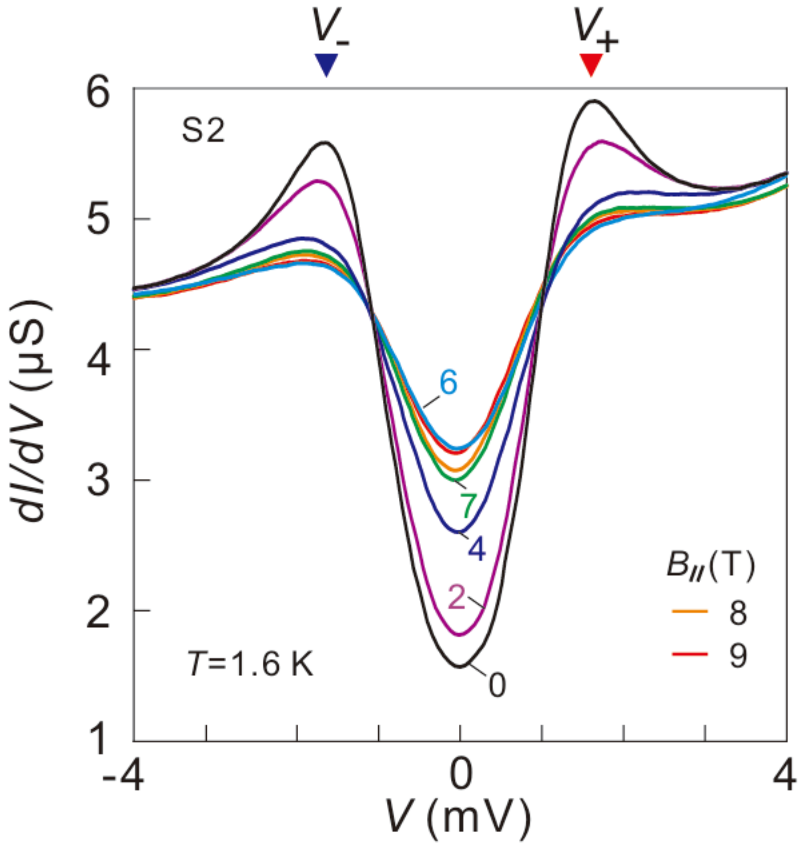
Tunneling spectroscopy under in-plane *B*

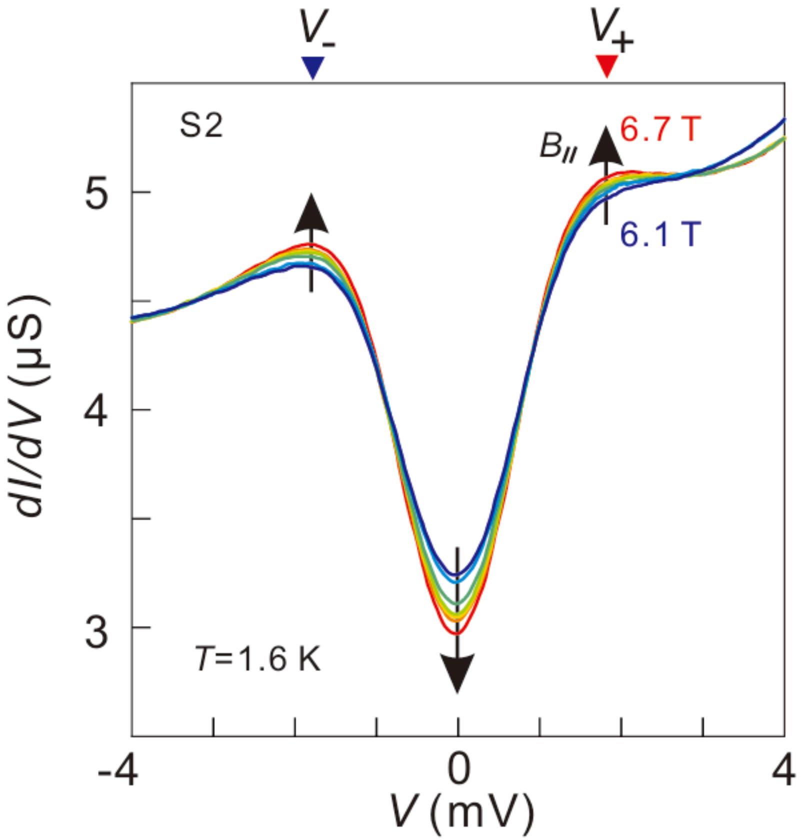


Z. Cao, *et al.*, *Nat. Commun.* (2026) 10.1038/s41467-026-72134-z

Non-monotonic gap evolution with $B_{//}$

- Gap at 7 T > gap at 6 T
- Enhanced gap: $B_{//}$ from 6.1 to 6.7 T

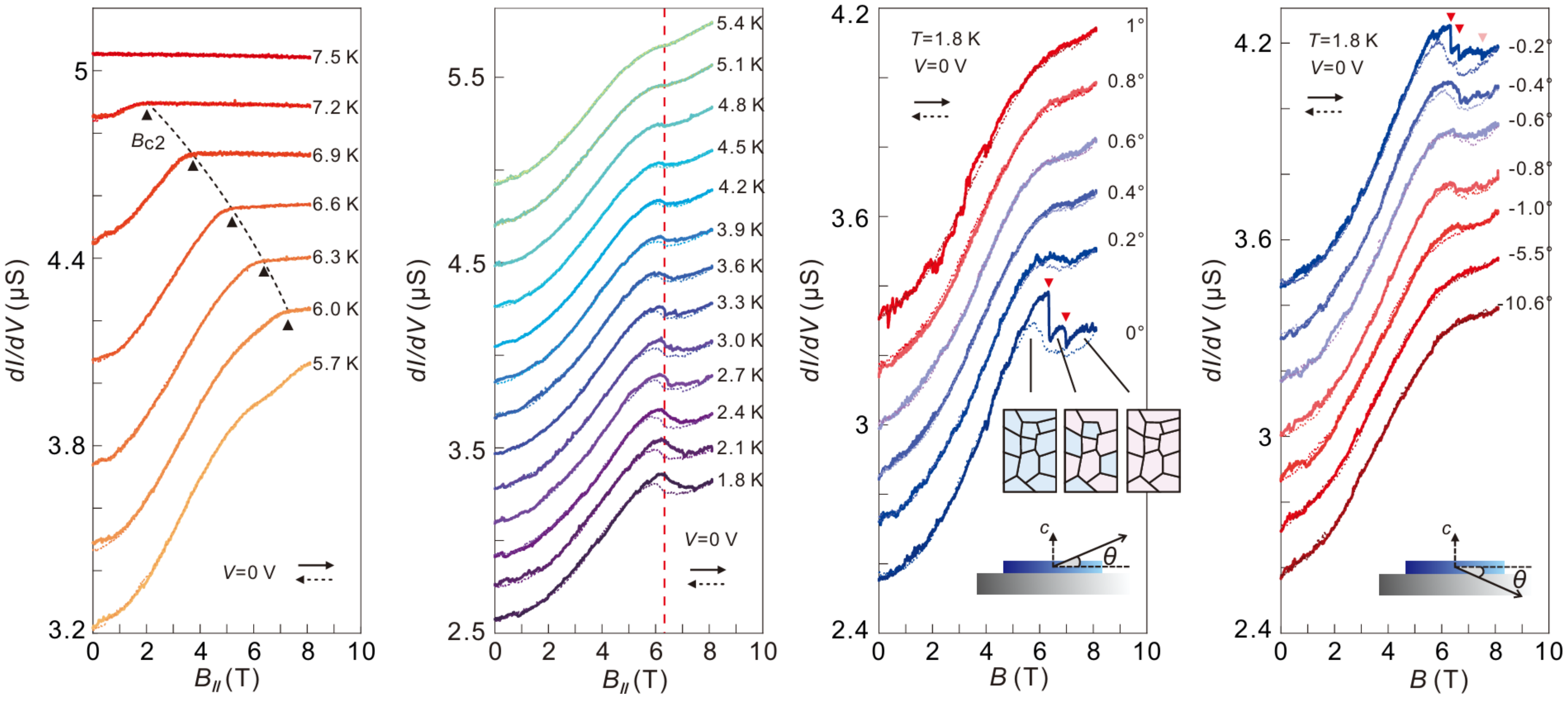




Z. Cao, *et al., Nat. Commun.* (2026) 10.1038/s41467-026-72134-z

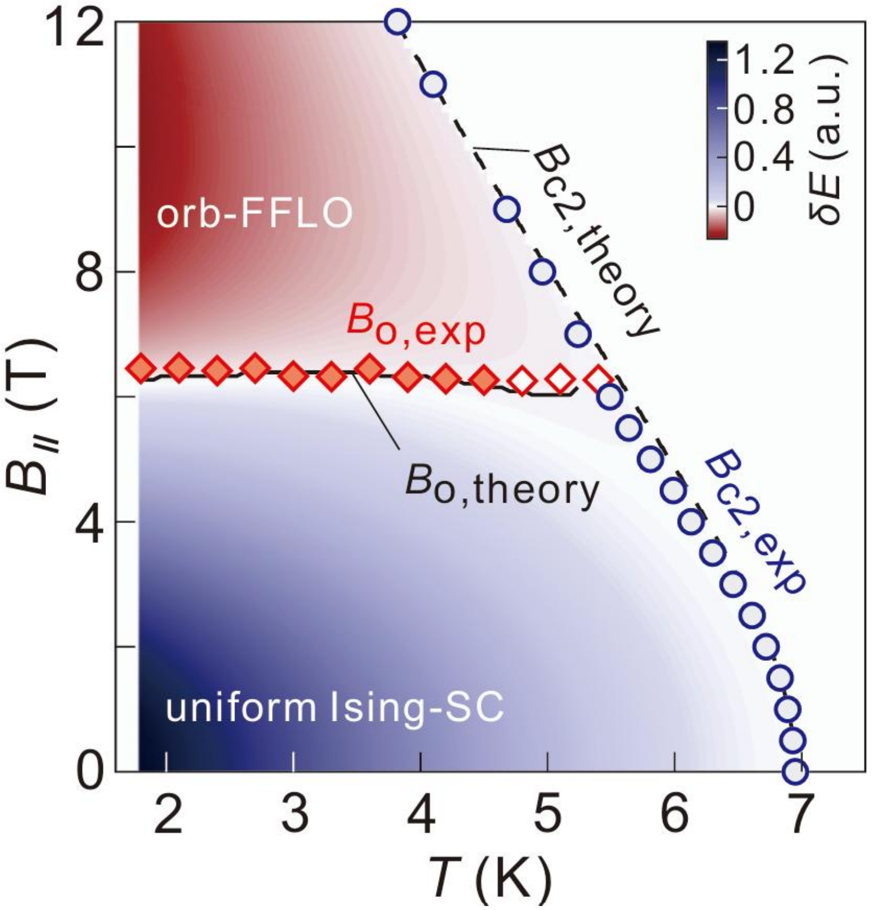
First-order phase transition with $B_{//}$

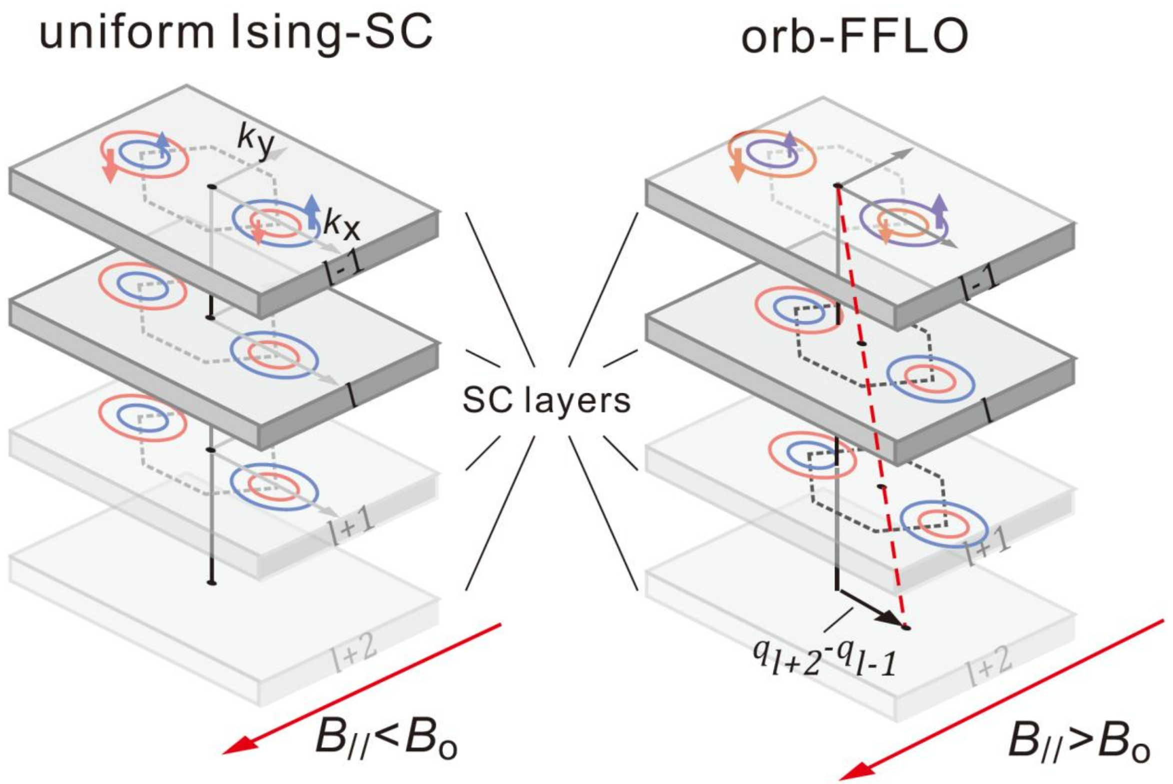
- Below 6 K: an extra kink at around 6 T, hysteresis in pos./neg. sweeps
- Hysteresis with multiple jumps only occurs when the magnetic field is well aligned in-plane



Z. Cao, *et al., Nat. Commun.* (2026) 10.1038/s41467-026-72134-z

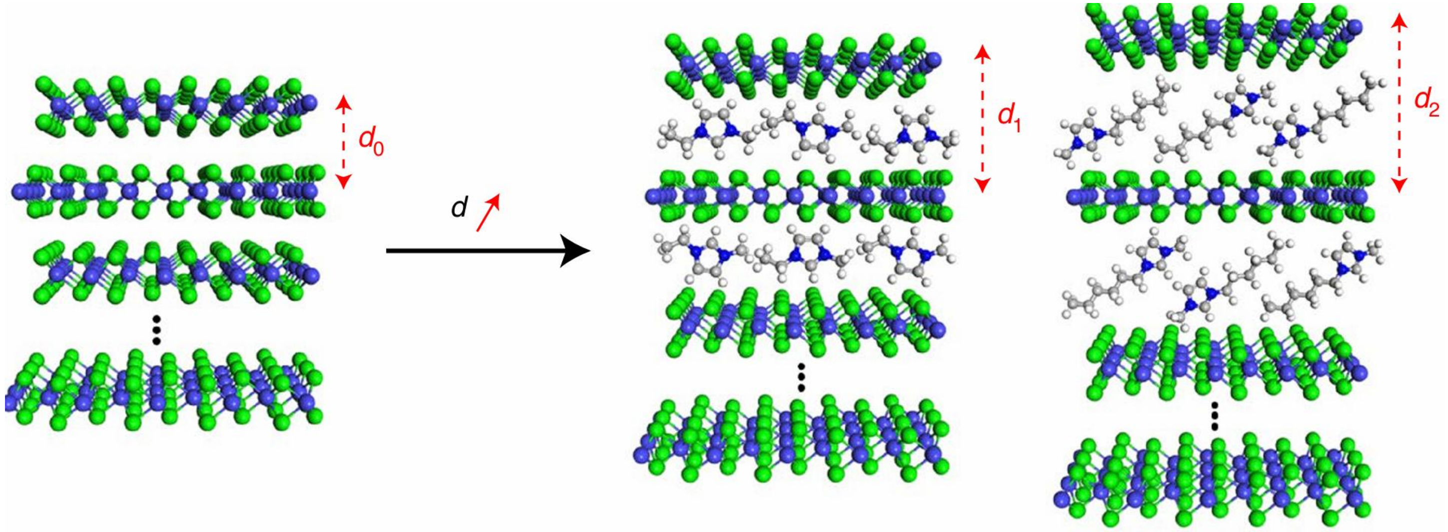
Phase diagram for orbital FFLO state in $NbSe_2$





Z. Cao, *et al.*, *Nat. Commun.* (2026) 10.1038/s41467-026-72134-z

Ising superconductivity in intercalated bulk $NbSe_2$



nature physics

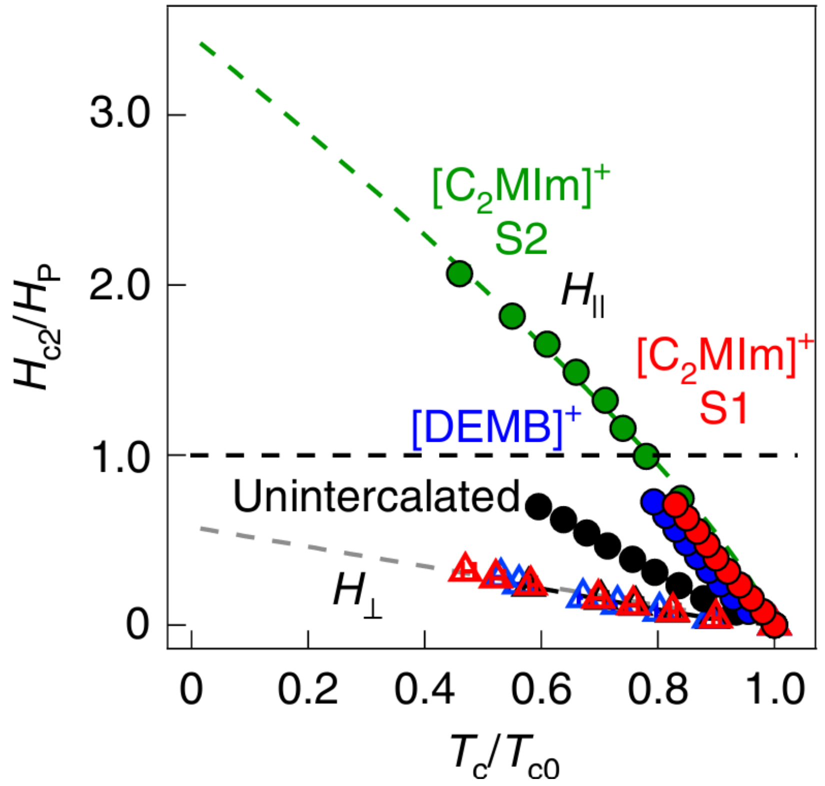
Letter
https://doi.org/10.1038/s41567-022-01778-7

Tailored Ising superconductivity in intercalated bulk $NbSe_2$

Received: 5 February 2020
Accepted: 1 September 2022
Published online: 13 October 2022

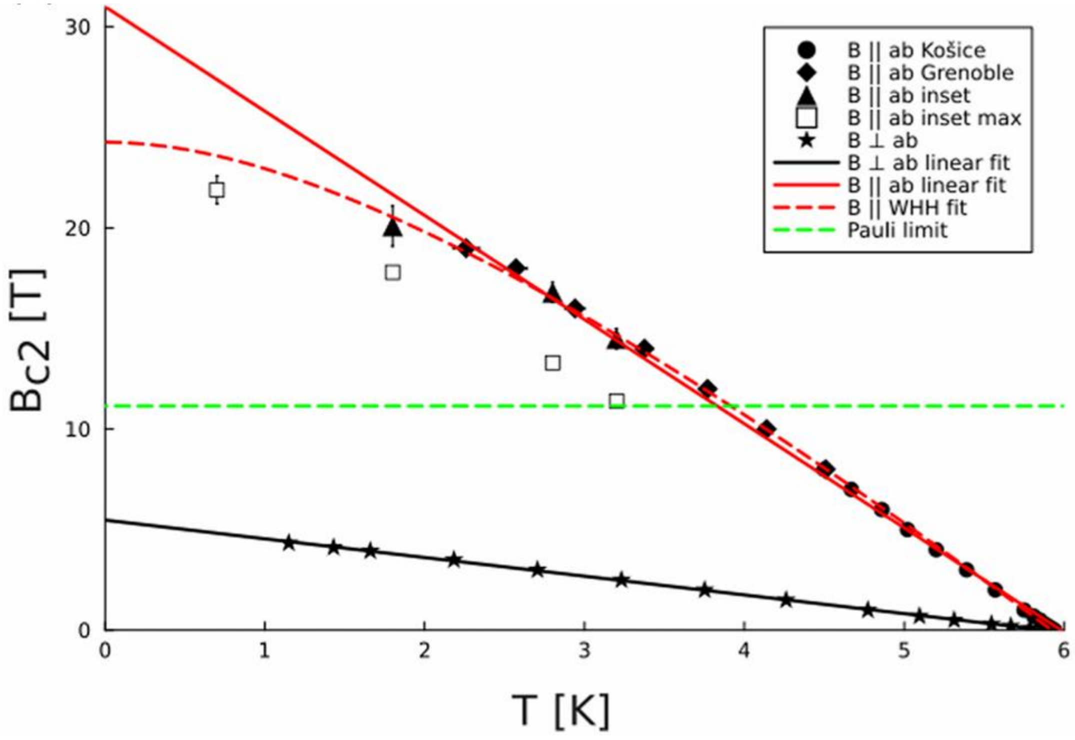
Check for updates

Haoxiong Zhang[1], Awabaikeli Rousuli[1], Kenan Zhang[1], Laipeng Luo[1], Chenguang Guo[1], Xin Cong[2], Zuzhang Lin[1], Changhua Bao[1], Hongyun Zhang[1], Shengnan Xu[1], Runfa Feng[1], Shengchun Shen[1], Kun Zhao[1], Wei Yao[1], Yang Wu[3], Shuaihua Ji[1,4], Xi Chen[1,4], Pingheng Tan[2], Qi-Kun Xue[1,4], Yong Xu[1,4], Wenhui Duan[1,4], Pu Yu[1,4] and Shuyun Zhou[1,4]



H. Zhang, *et al.*, *Nat. Phys.* **18,** 1425 (2022)

Ising superconductivity in bulk $4H_a$-$NbSe_2$



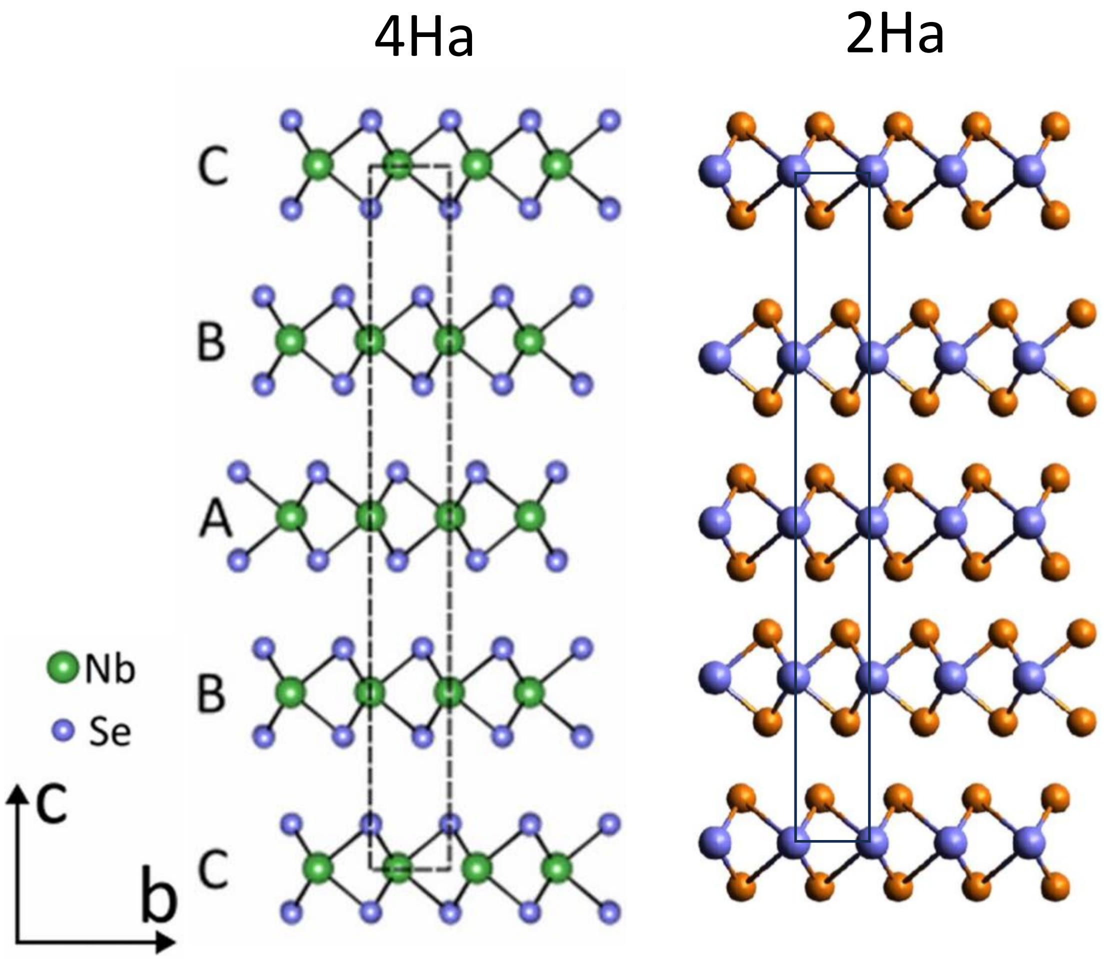
PHYSICAL REVIEW LETTERS **136,** 016002 (2026)

Ising Superconductivity in Noncentrosymmetric Bulk $NbSe_2$

Dominik Volavka,[1,*] Jozef Kačmarčík,[2,*] Timon Moško,[1,*] Zuzana Pribulová,[2] Branislav Stropkai,[1] Jozef Bednarčík,[1,2] Yingzheng Gao,[3] Owen Moulding,[3] Marie-Aude Méasson,[3] Christophe Marcenat,[4] Thierry Klein,[3] Shunsuke Sasaki,[5] Laurent Cario,[5] Martin Gmitra,[1,2,†] Peter Samuely,[2,‡] and Tomas Samuely[1,§]

[1]*Centre of Low Temperature Physics, Faculty of Science, Pavol Jozef Šafárik University in Košice, 04001 Košice, Slovakia*
[2]*Centre of Low Temperature Physics, Institute of Experimental Physics, Slovak Academy of Sciences, 04001 Košice, Slovakia*
[3]*Université Grenoble Alpes, CNRS, Grenoble INP*, Institut Néel, 38000 Grenoble, France*
[4]*Université Grenoble Alpes, CEA, Grenoble INP, IRIG, Pheliqs, 38000 Grenoble, France*
[5]*Institut des Matériaux Jean Rouxel, Université de Nantes and CNRS-UMR 6502, Nantes 44322, France*

(Received 10 June 2025; accepted 16 December 2025; published 9 January 2026)



D. Volavka, *et al.*, *Phys. Rev. Lett.* **136,** 016002 (2026)

Ising superconductivity: a summary

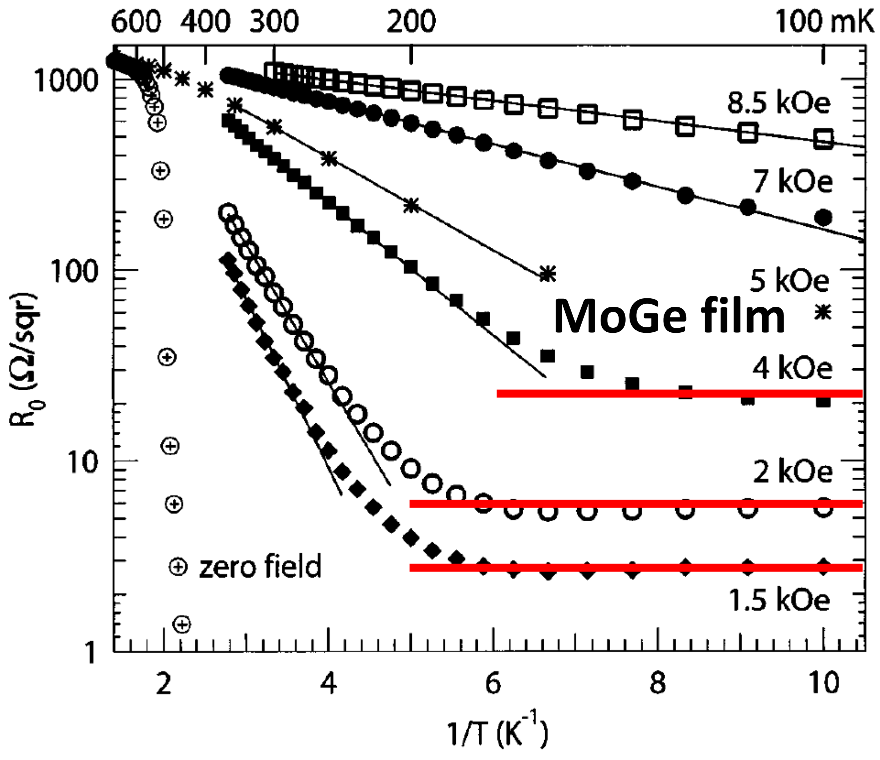
- **Experimental features:**
  - In-plane upper critical fields greatly exceed the Pauli limit
  - Continuously decreasing superconducting gap
  - 2-fold, 6-fold in-plane symmetry (intrinsic?)

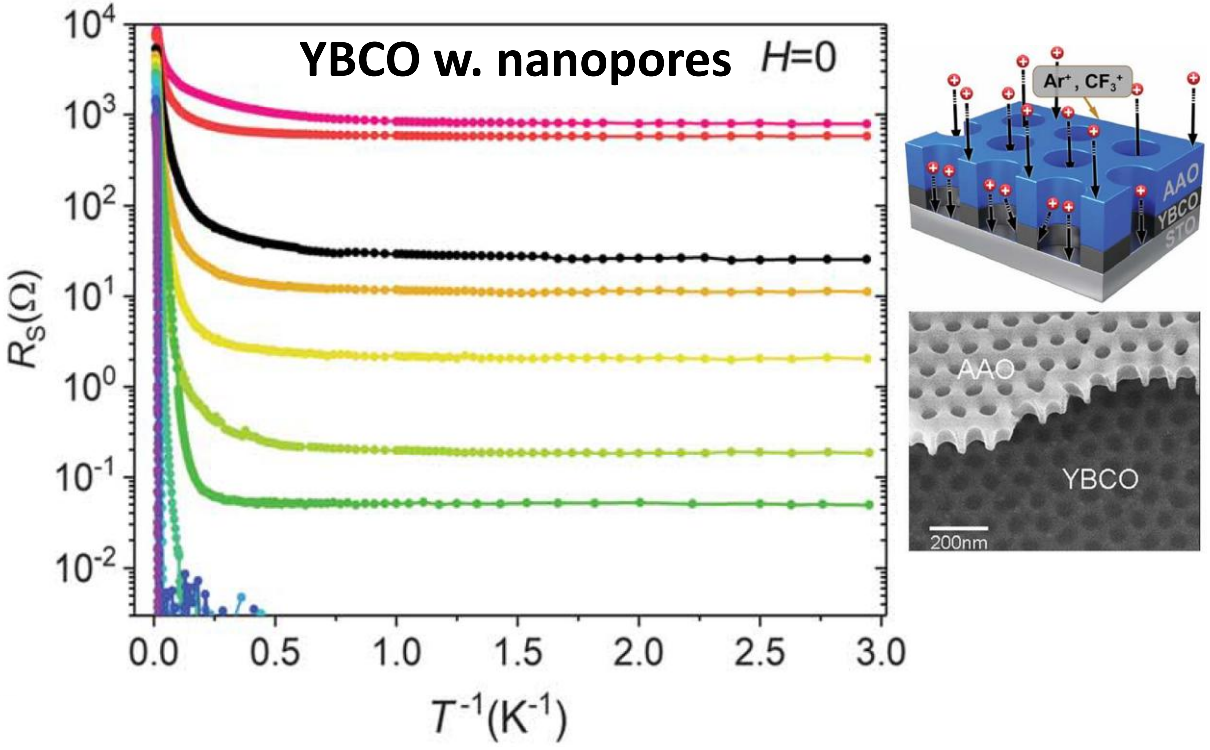
- **Multi-layers:**
  - Orbital FFLO state
  - Large in-plane upper critical fields after intercalation or with special stacking

Anomalous metal phase

Introduction to anomalous metal (AM) phase

- Many 2D superconductors show AM behavior
- Superconducting fluctuations play a major role
- A quantitative theoretical understanding is missing



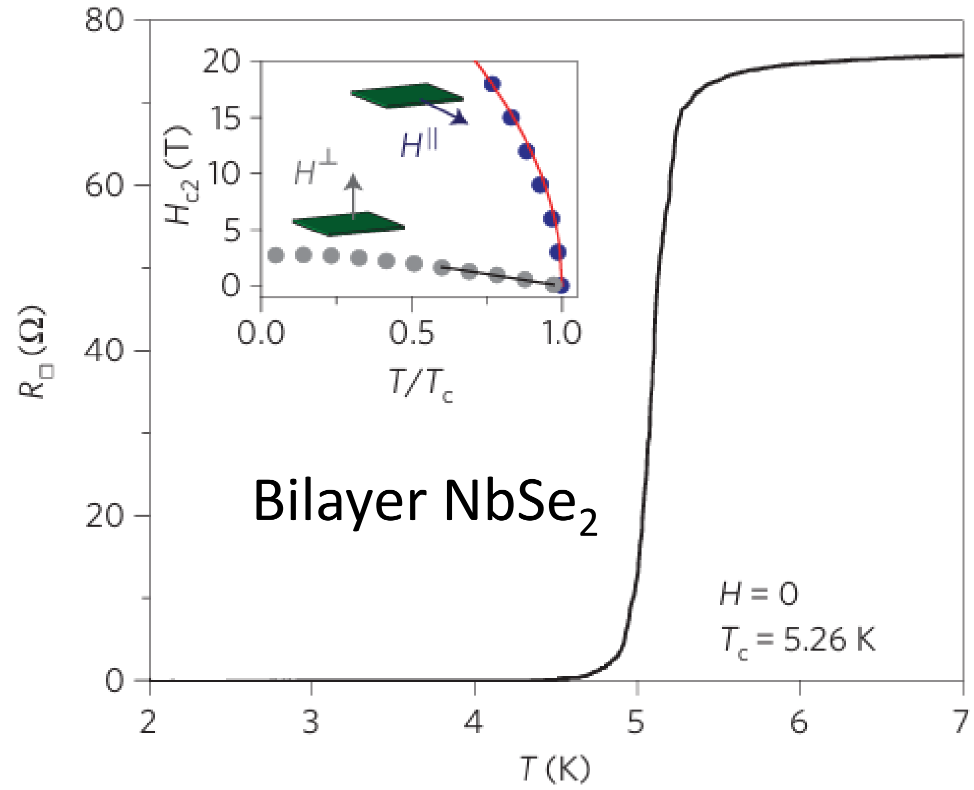


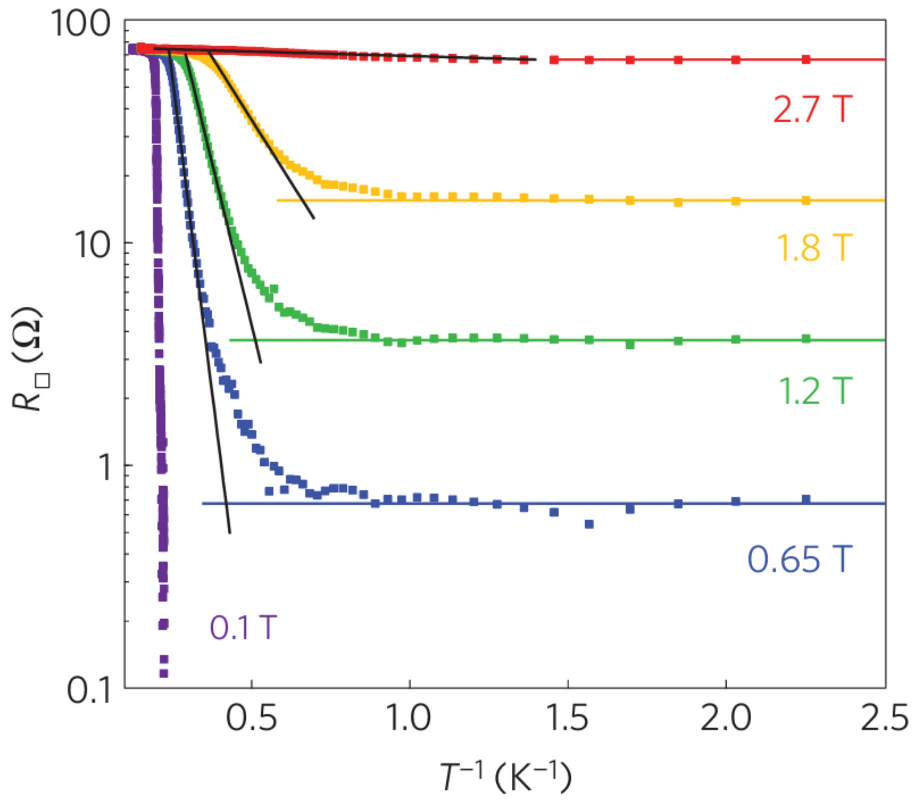
D. Ephron, *et al., Phys. Rev. Lett.* **76**, 1529 (1996)

C. Yang, *et al., Science* **366**, 1505 (2019)

AM phase in bilayer $NbSe_2$

- **Saturated resistance after SC transition**





nature physics

LETTERS

PUBLISHED ONLINE: 7 DECEMBER 2015 | DOI: 10.1038/NPHYS3579

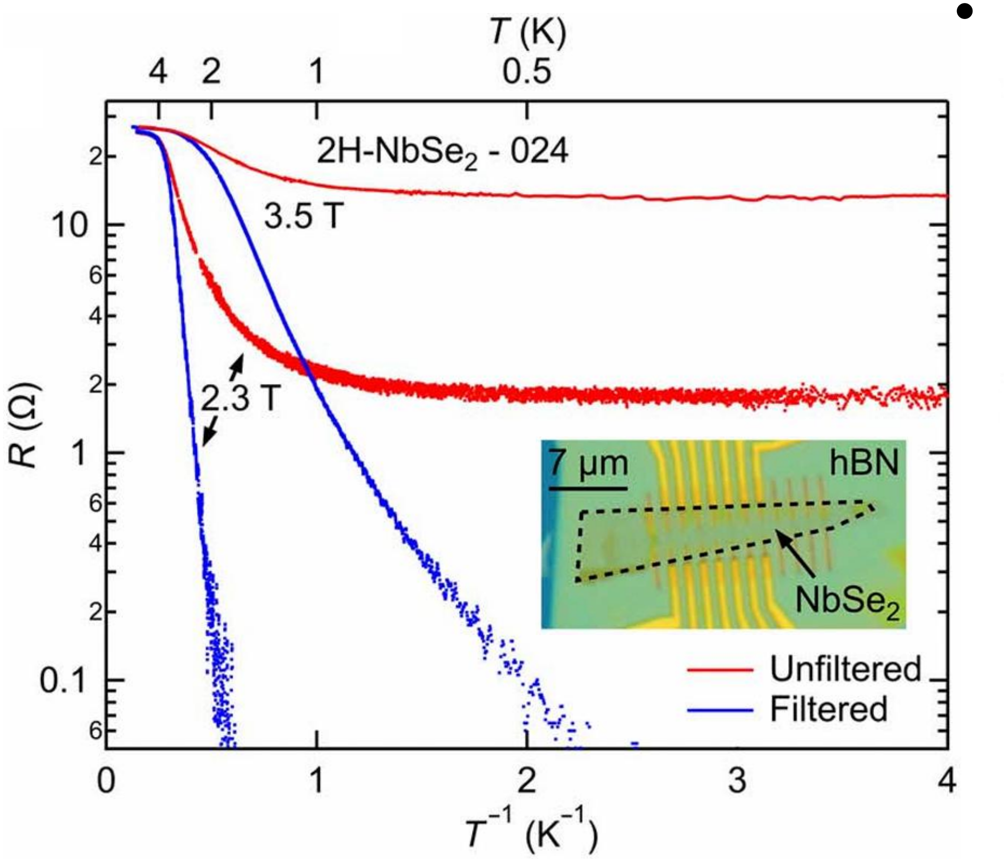
Nature of the quantum metal in a two-dimensional crystalline superconductor

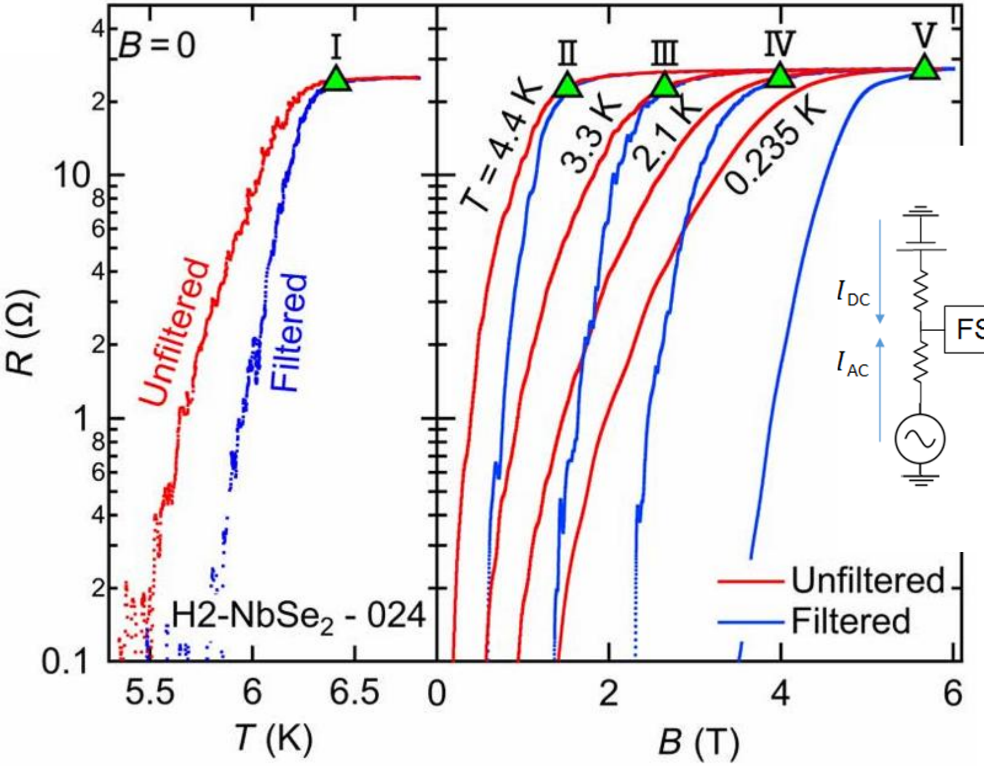
A. W. Tsen[1], B. Hunt[1†], Y. D. Kim[2], Z. J. Yuan[3], S. Jia[3,4], R. J. Cava[5], J. Hone[2], P. Kim[6], C. R. Dean[1*] and A. N. Pasupathy[1*]

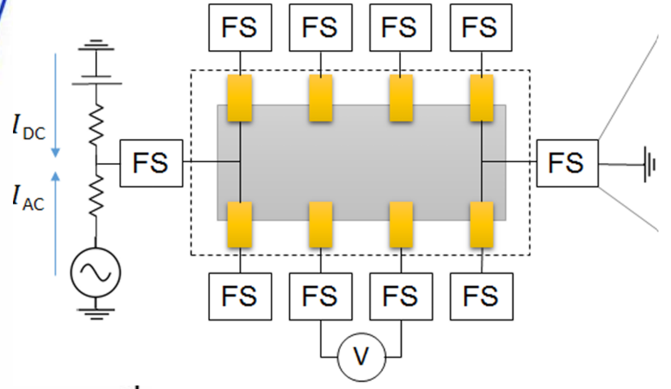
A. W. Tsen, *et al.*, *Nat. Phys.* **12,** 208 (2016)

Intrinsic origin or problem of cooling?

- **Resistance saturation gone after proper filtering**







SCIENCE ADVANCES | RESEARCH ARTICLE

CONDENSED MATTER PHYSICS

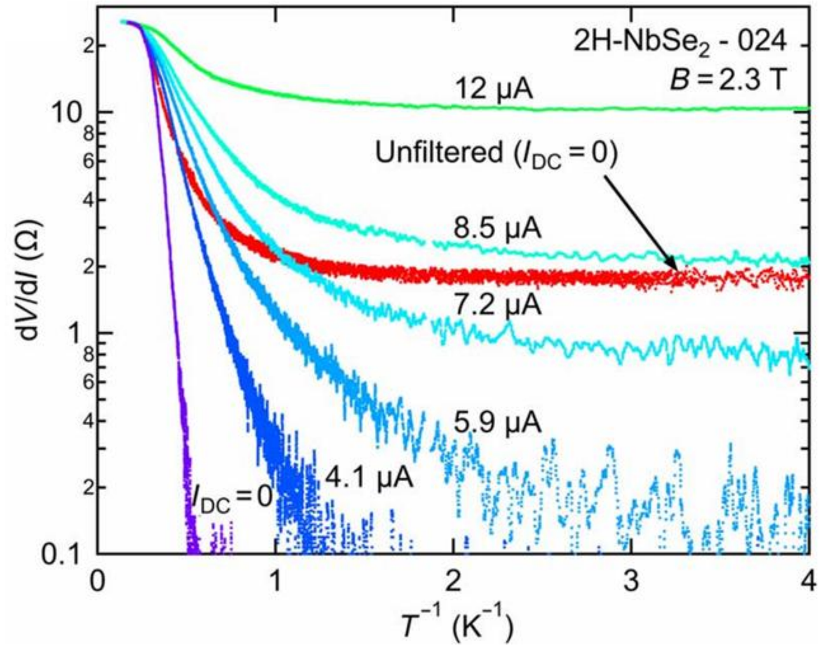
Sensitivity of the superconducting state in thin films

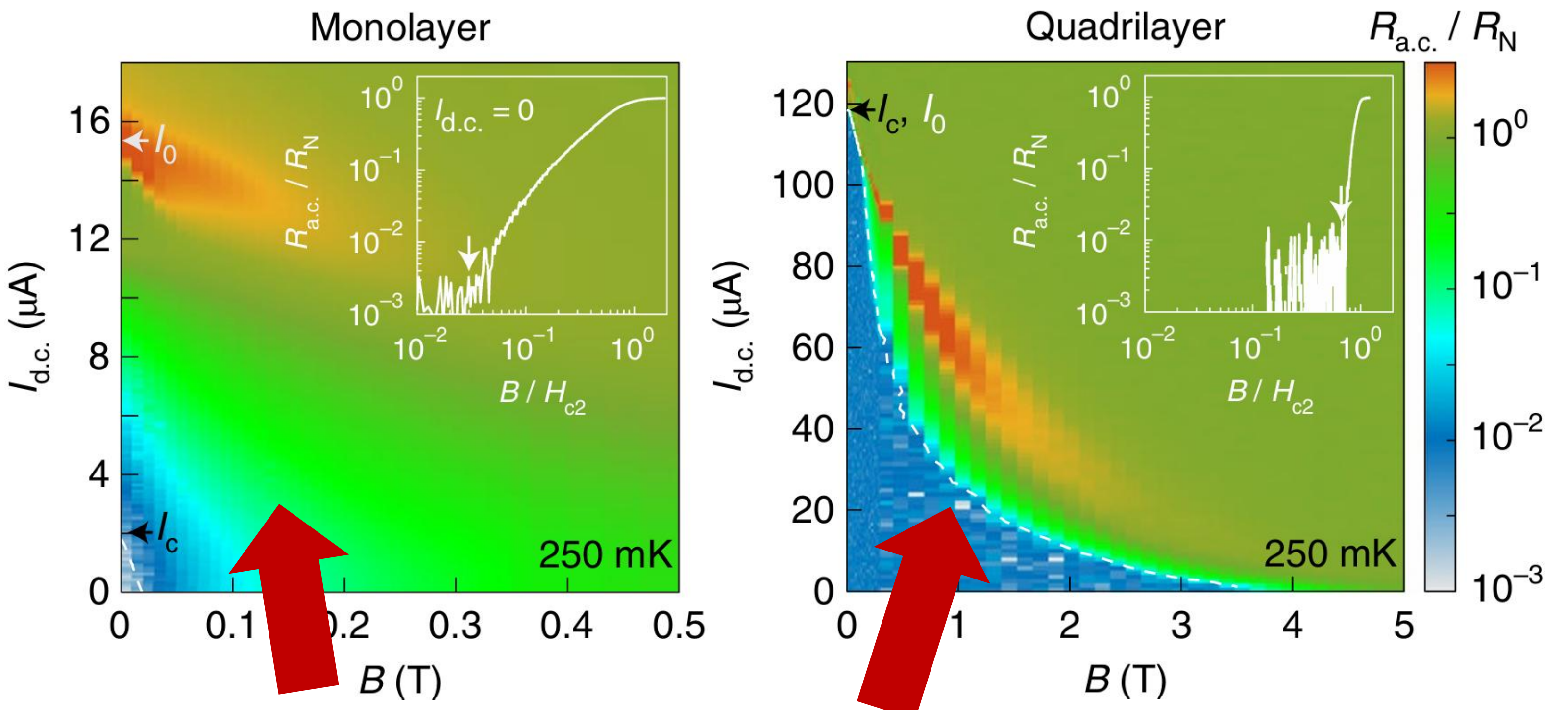
I. Tamir[1,2]*, A. Benyamini[3], E. J. Telford[4], F. Gorniaczyk[1], A. Doron[1], T. Levinson[1], D. Wang[4], F. Gay[5], B. Sacépé[5], J. Hone[3], K. Watanabe[6], T. Taniguchi[6], C. R. Dean[4], A. N. Pasupathy[4], D. Shahar[1,4]

I. Tamir, *et al.*, *Sci. Adv.* **5,** aau3826 (2019)

Intrinsic origin or problem of cooling?

- **Resistance saturation reappears under large dc current**





No sharp drop of *R* as I_{dc} drops **Well-defined dissipationless region**

- **Dissipationless transport in clean monolayer exists only in the limit of *I*=*B*=*T*=0**

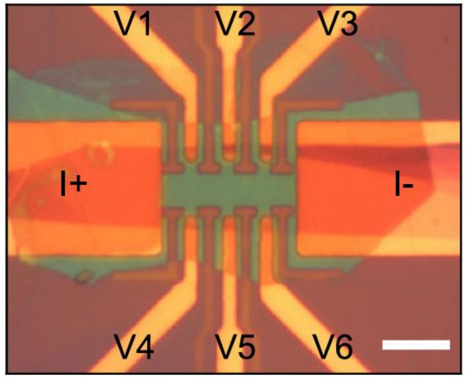
I. Tamir, *et al.*, *Sci. Adv.* **5,** aau3826 (2019) A. Benyamini, *et al.*, *Nat. Phys.* **15,** 947 (2019)

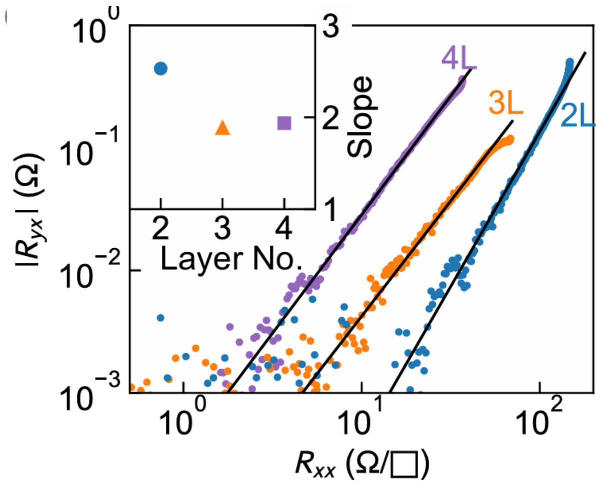
AM in $NbSe_2$: recent development

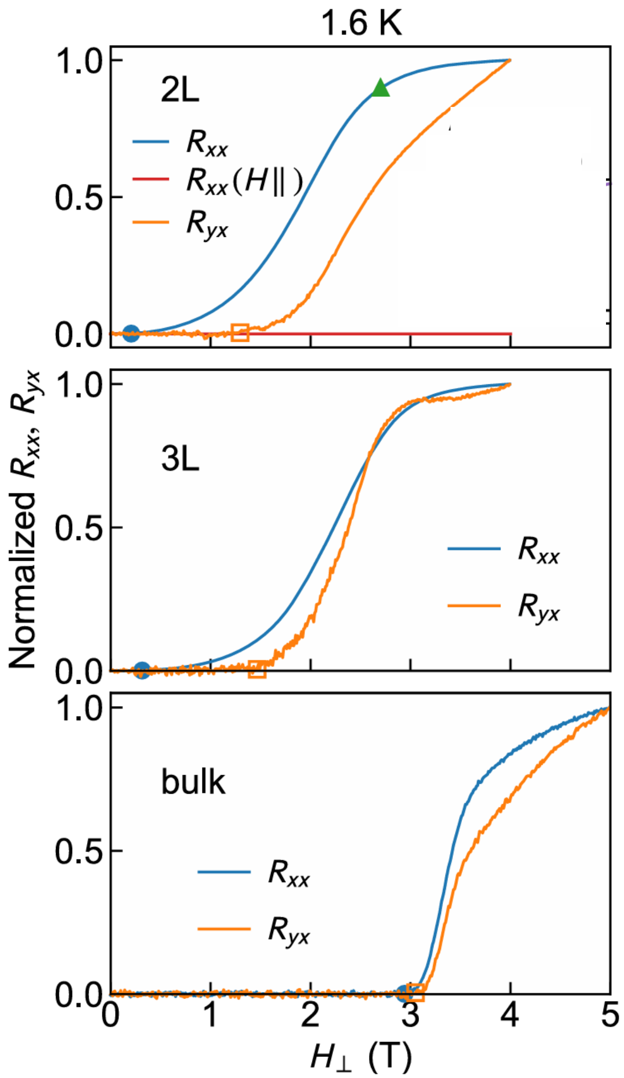
- **Absence of Hall signal in the AM phase**

- **Particle-hole symmetry**

Trilayer $NbSe_2$ on Au electrodes and capped by h-BN







PHYSICAL REVIEW LETTERS **134,** 066002 (2025)

Editors' Suggestion
Featured in Physics

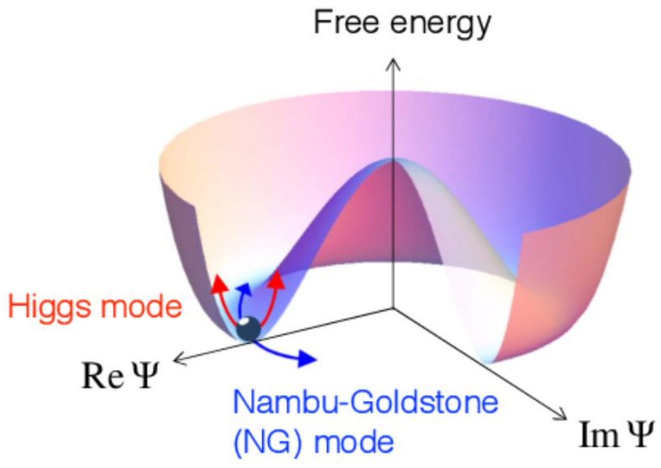
Unveiling Resilient Superconducting Fluctuations in Atomically Thin $NbSe_2$ through Higgs Mode Spectroscopy

Yu Du,[1,*] Gan Liu,[1,*] Wei Ruan,[1,*] Zhi Fang,[1] Kenji Watanabe,[2] Takashi Taniguchi,[3] Ronghua Liu,[1,4] Jian-Xin Li,[1,4,5] and Xiaoxiang Xi[1,4,5,†]

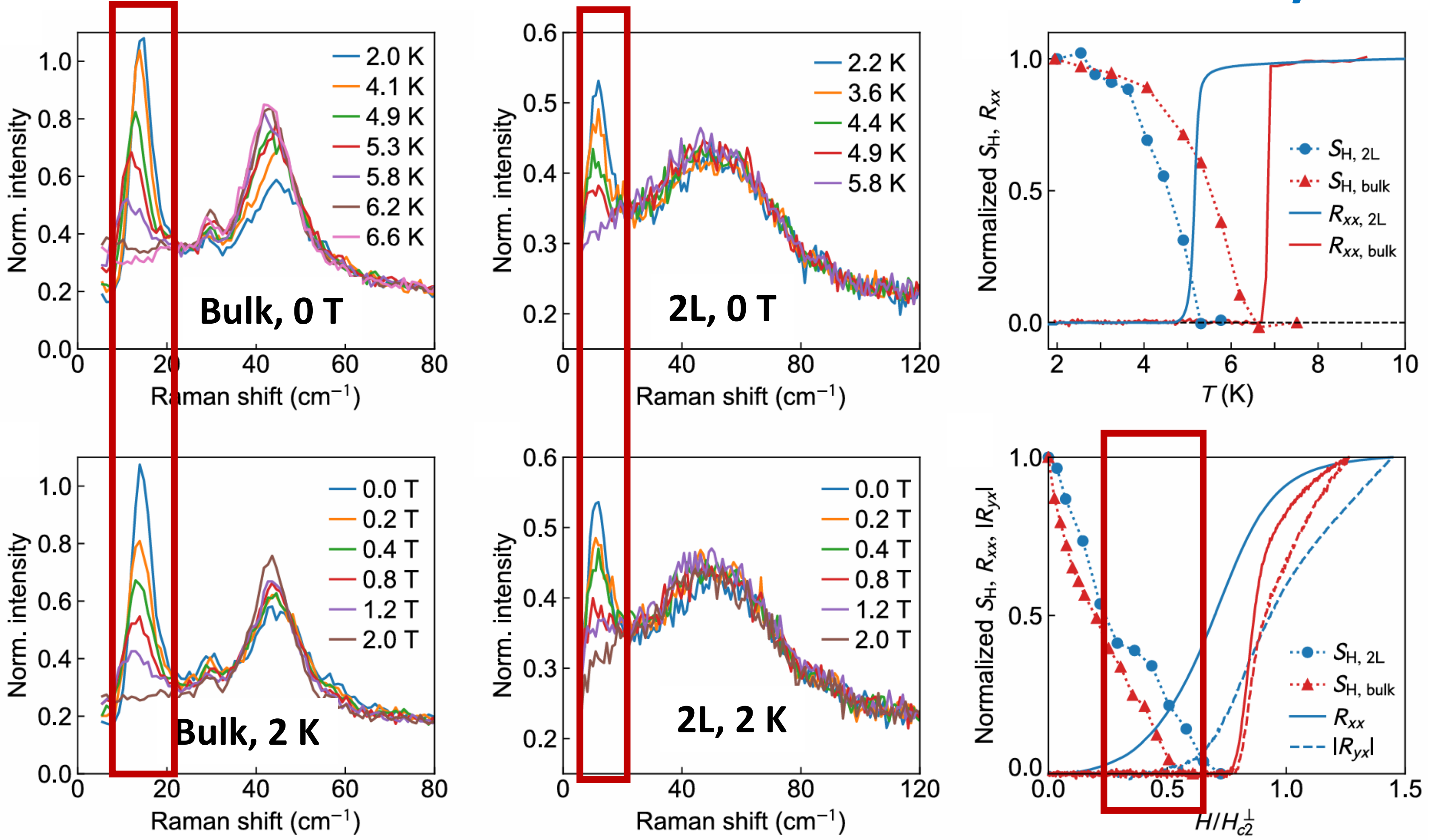
Y. Du, *et al.*, *Phys. Rev. Lett.* **134,** 066002 (2025)

AM in $NbSe_2$: recent development

- **Higgs mode persists in the anomalous metal phase**
  - **Fluctuating Cooper pairs**



Higgs mode　　Higgs mode　　**Blue: bilayer**

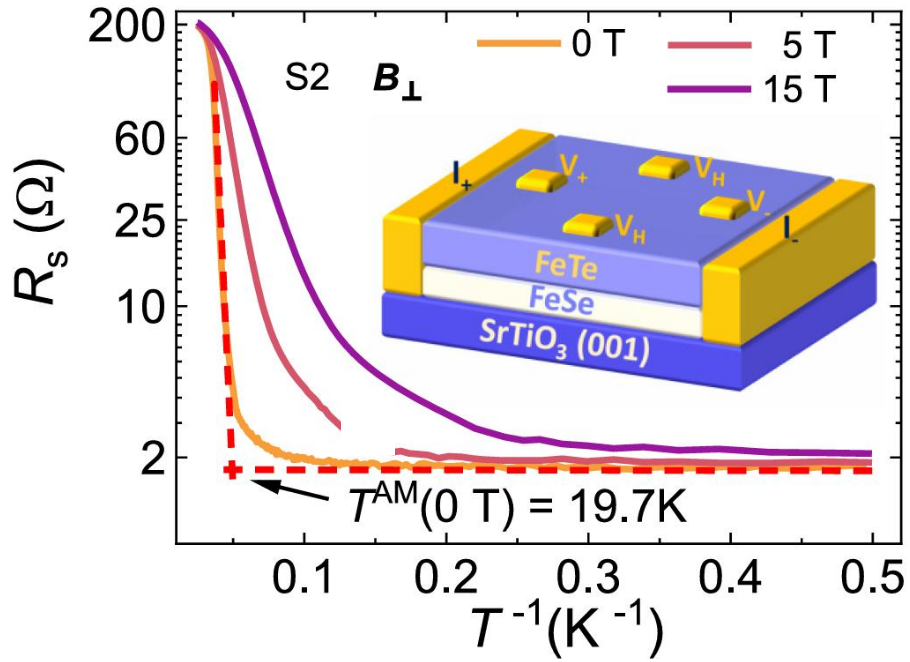


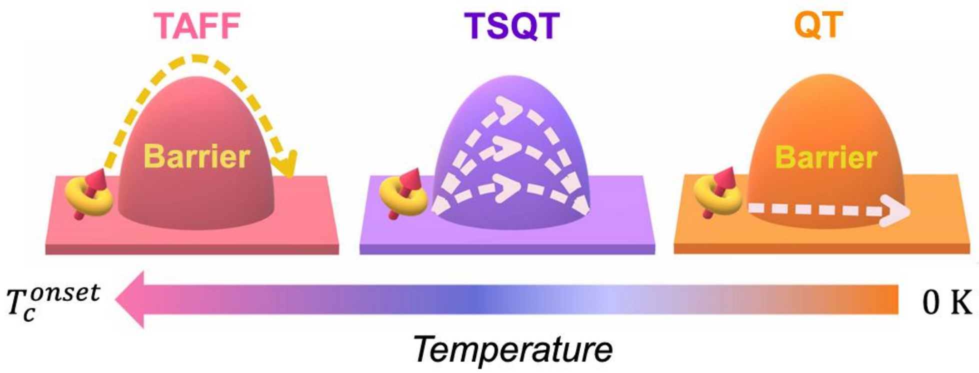
R. Shimano & N. Tsuji *Annu. Rev. Condens. Matter Phys.* **11,** 103 (2020)

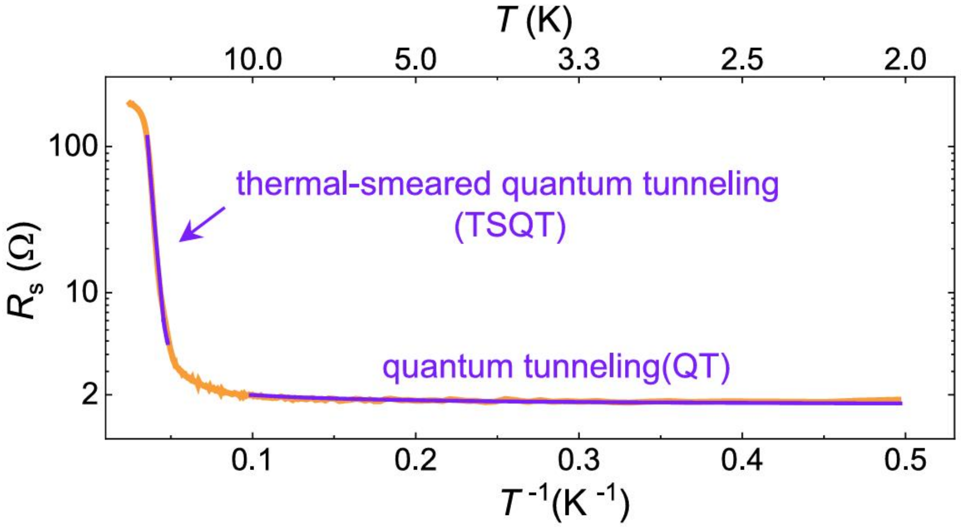
Y. Du, *et al.*, *Phys. Rev. Lett.* **134,** 066002 (2025)

Other recent studies on AM

- **High-temperature AM in FeSe/$SrTiO_3$**





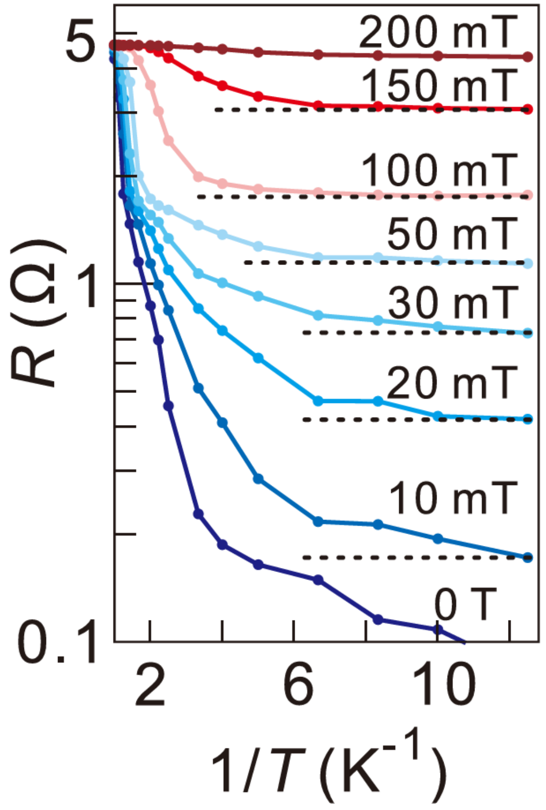


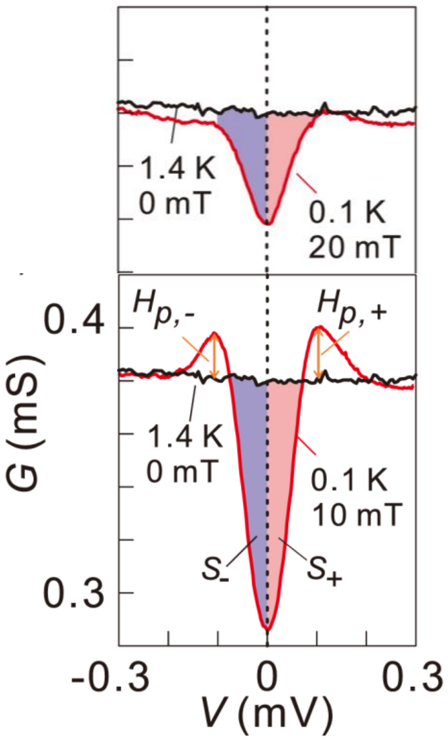
Y. Li, *et al.*, *Phys. Rev. Lett.* **132,** 226003 (2024)

Other recent studies on AM

- **Symmetric gap in the AM phase (with low-pass filters)**

Li_xTiSe_2 (70 nm but 2D like)

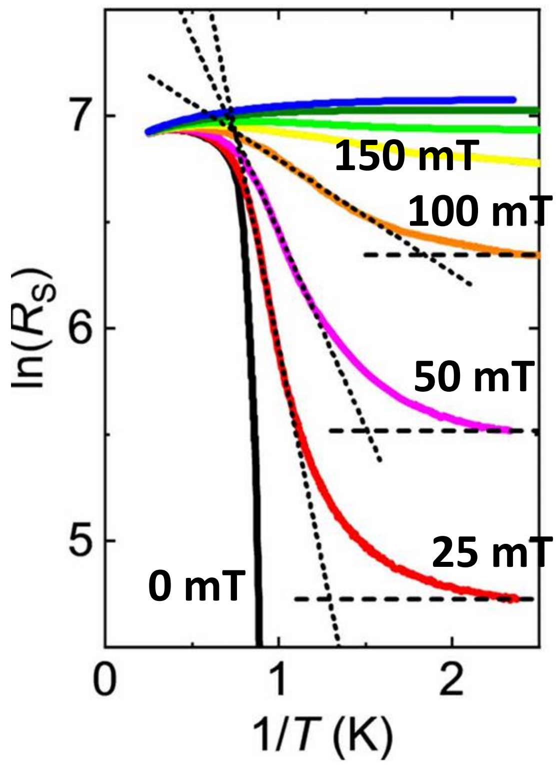


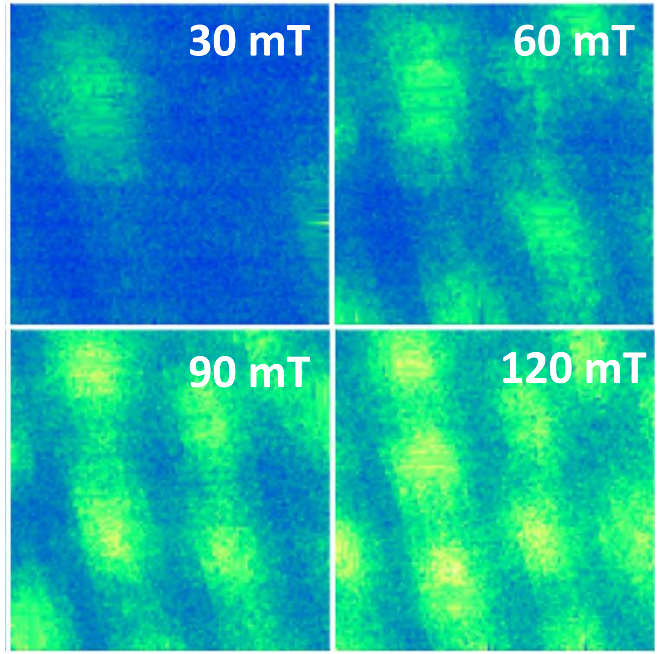


J.-Y. Ji, *et al.*, *Nano Lett.* **25,** 10641 (2025)

- **Gap and stable vortices in the AM phase**

Monolayer Pb on Si(111)





Y. Sato, *et al.*, *Sci. Adv.* **12,** eadu9610 (2026)

Anomalous metal phase: a summary

- **Experimental features:**
  - Saturated R_{xx} below T_{sc} (even after proper filtering for some systems)
  - R_{xy}=0 and persistence of gap opening, indicating particle-hole symmetry
  - Persistence of Higgs mode (2L-4L $NbSe_2$)
  - Stable vortices (Monolayer Pb)

Outline

1. $NbSe_2$—a case study of highly crystalline 2D superconductors

    1.1 Dimensionality effect on SC and CDW

    1.2 Ising superconductivity: from 3D to 2D and back

    1.3 Anomalous metal phase: intrinsic vs. extrinsic effects

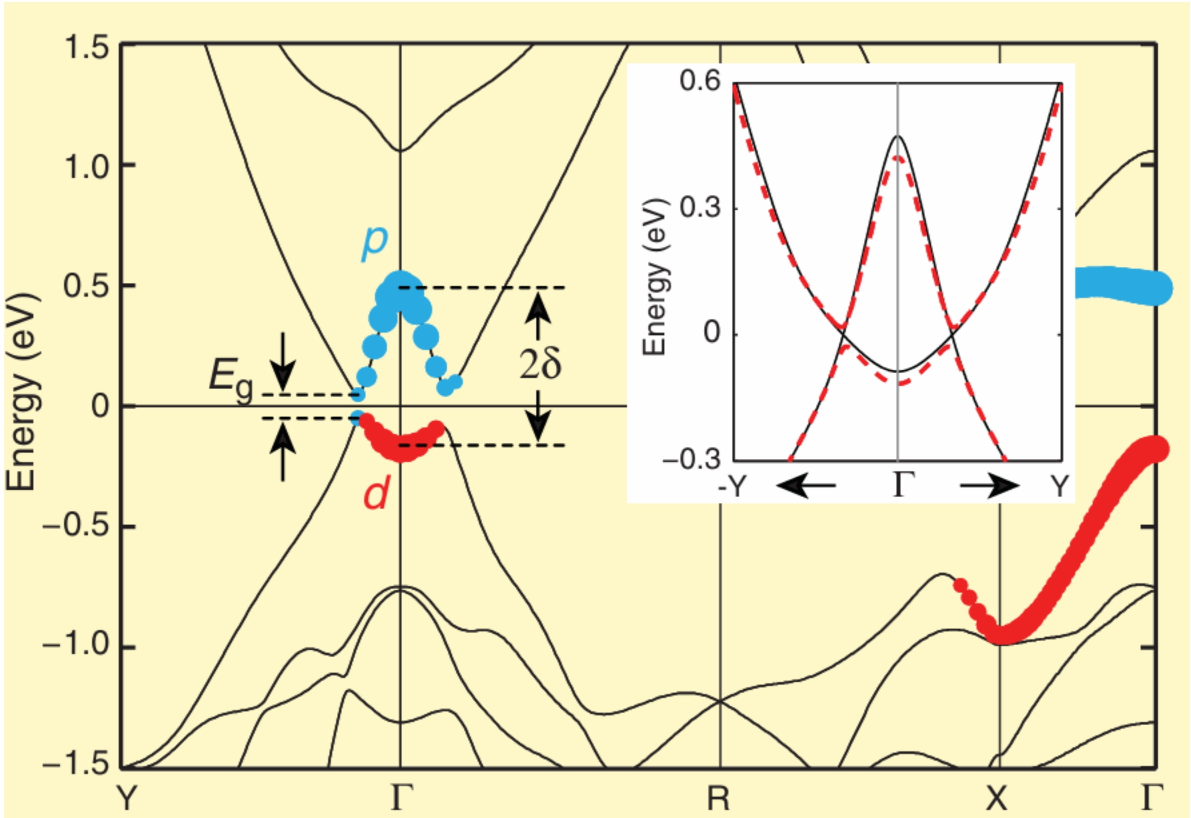
2. 2D superconductors with topology

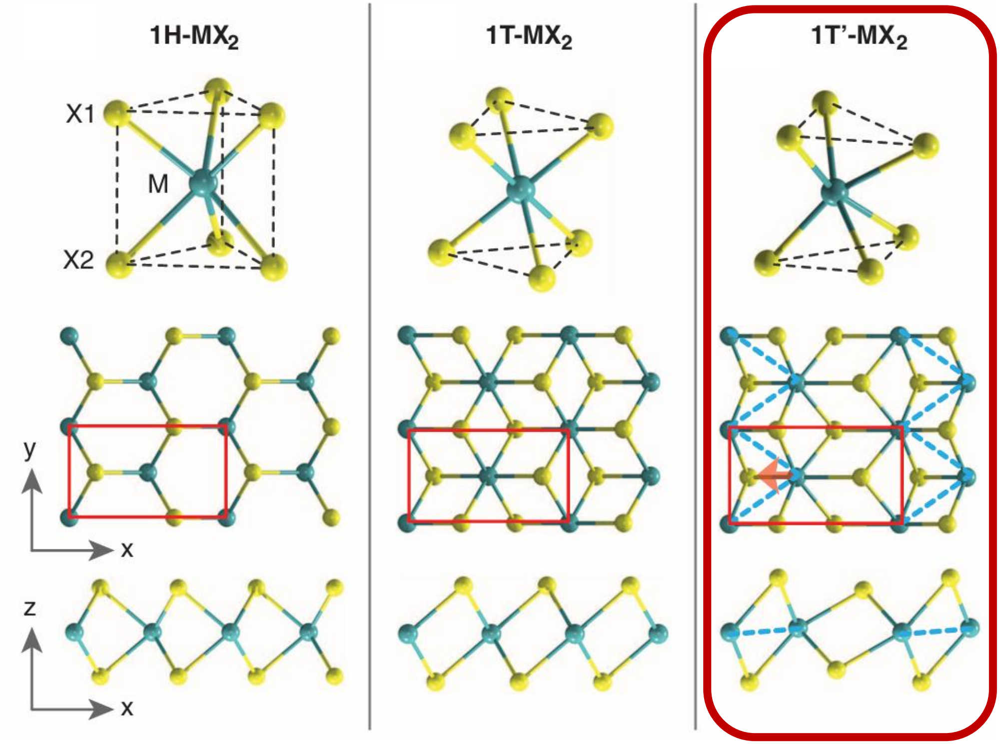
    2.1 WTe_2 and stanene

    2.2 Twisted cuprates

Topological physics in 2D transition metal dichalcogenides

- **Opening of topological gap in the bulk**
- **Formation of edge states**





X. Qian, *et al.*, *Science* **346,** 1344 (2014)

SOLID STATE THEORY

Quantum spin Hall effect in two-dimensional transition metal dichalcogenides

Xiaofeng Qian,[1*] Junwei Liu,[2*] Liang Fu,[2†] Ju Li[1†]

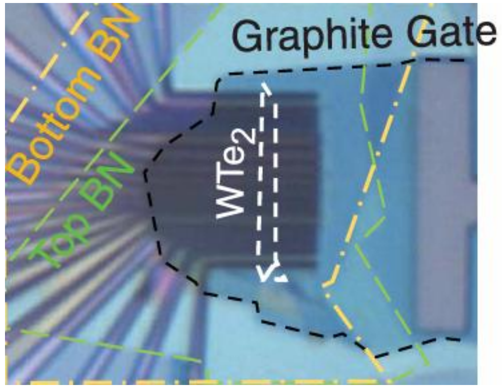
RESEARCH

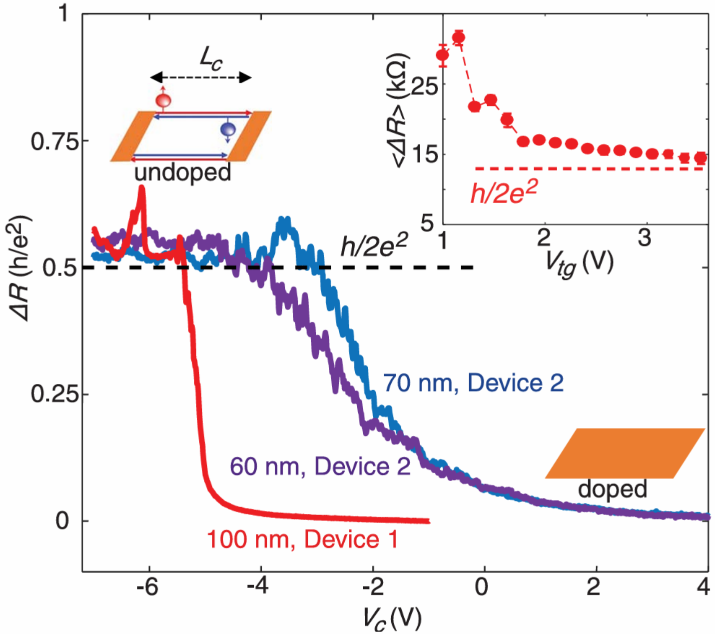
TOPOLOGICAL MATTER

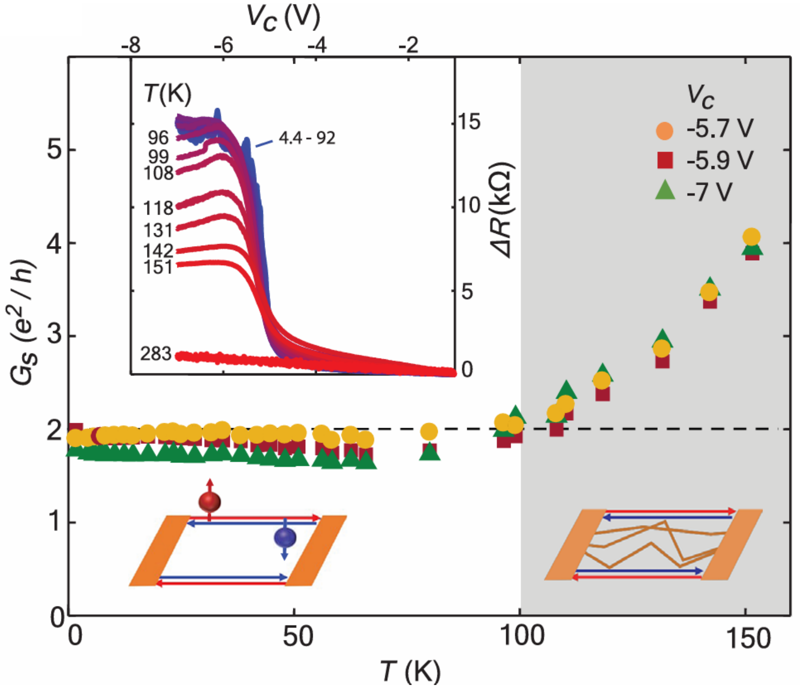
Observation of the quantum spin Hall effect up to 100 kelvin in a monolayer crystal

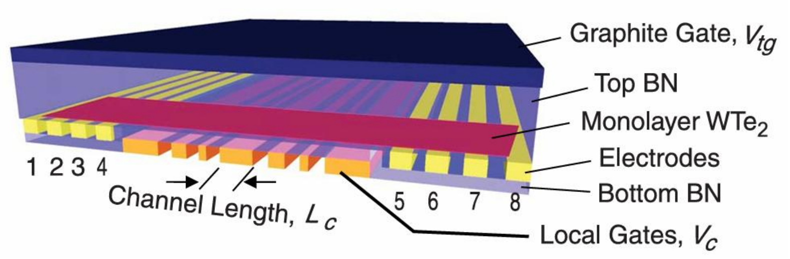
Sanfeng Wu,[1*†] Valla Fatemi,[1*†] Quinn D. Gibson,[2] Kenji Watanabe,[3] Takashi Taniguchi,[3] Robert J. Cava,[2] Pablo Jarillo-Herrero[1†]

- **Monolayer WTe_2**









S. Wu, *et al.*, *Science* **359,** 76 (2018)

RESEARCH

SUPERCONDUCTIVITY

Electrically tunable low-density superconductivity in a monolayer topological insulator

Valla Fatemi[1]*, Sanfeng Wu[1]*†, Yuan Cao[1], Landry Bretheau[2], Quinn D. Gibson[3], Kenji Watanabe[4], Takashi Taniguchi[4], Robert J. Cava[5], Pablo Jarillo-Herrero[1]†

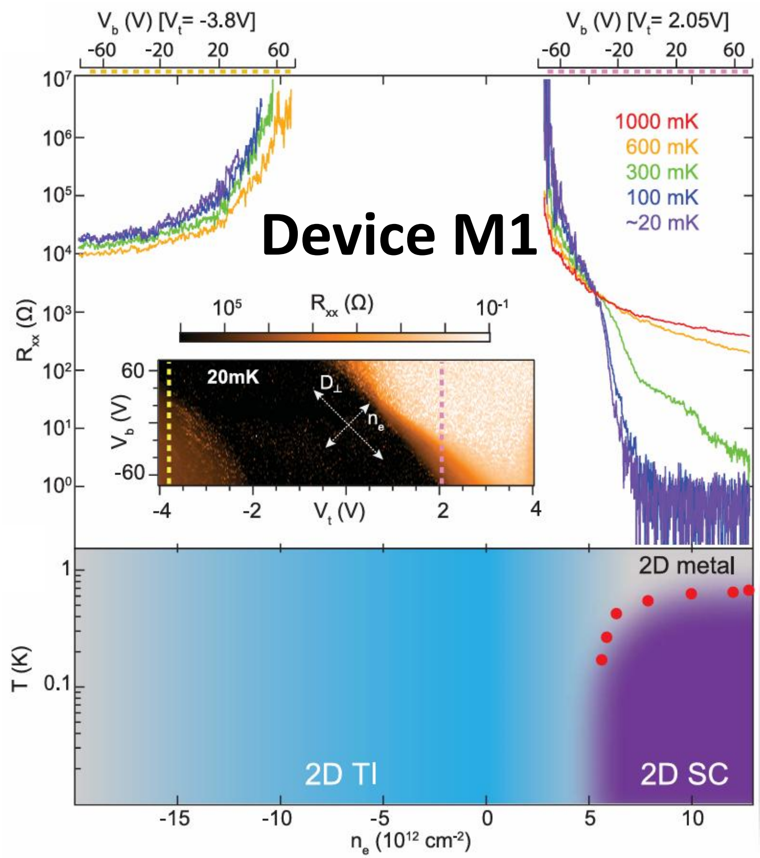
RESEARCH

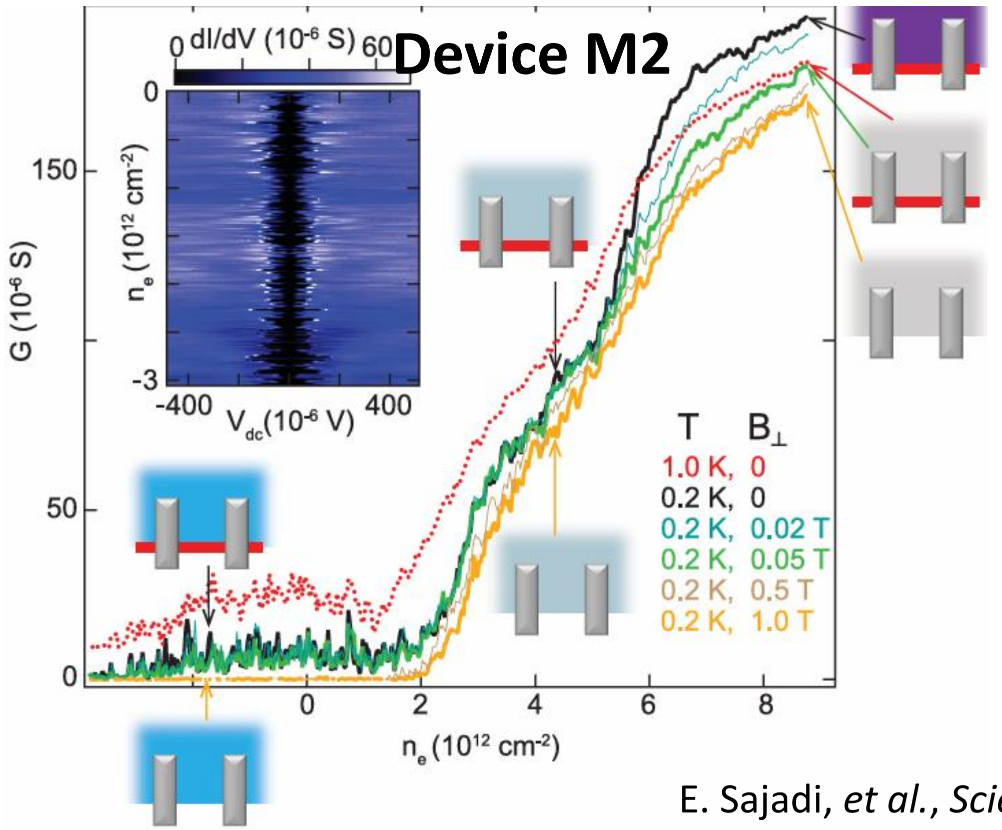
SUPERCONDUCTIVITY

Gate-induced superconductivity in a monolayer topological insulator

Ebrahim Sajadi[1], Tauno Palomaki[2], Zaiyao Fei[2], Wenjin Zhao[2], Philip Bement[1], Christian Olsen[1], Silvia Luescher[1], Xiaodong Xu[2,3], Joshua A. Folk[1]*, David H. Cobden[2]*

- **Coexistence of helical edge and SC bulk**



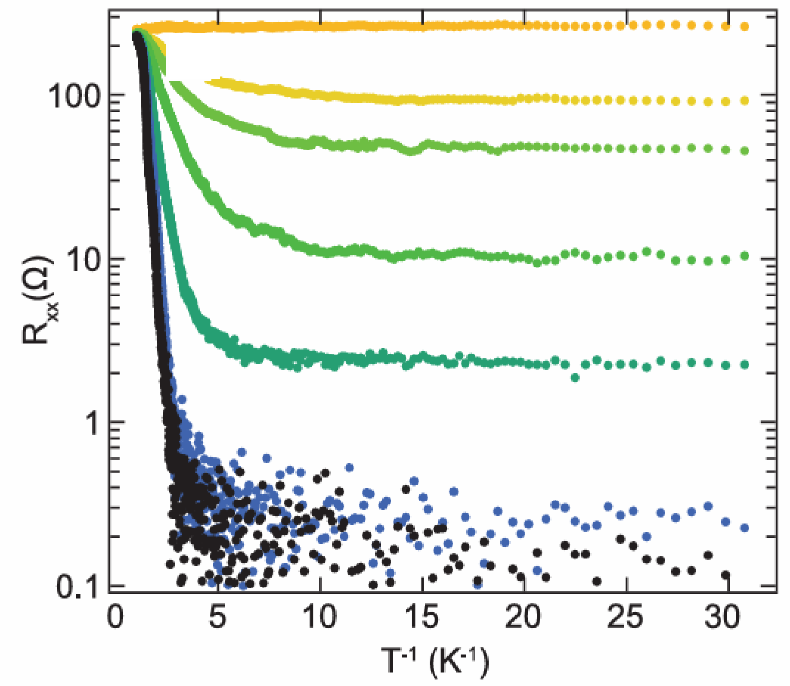


***B* quenches SC**

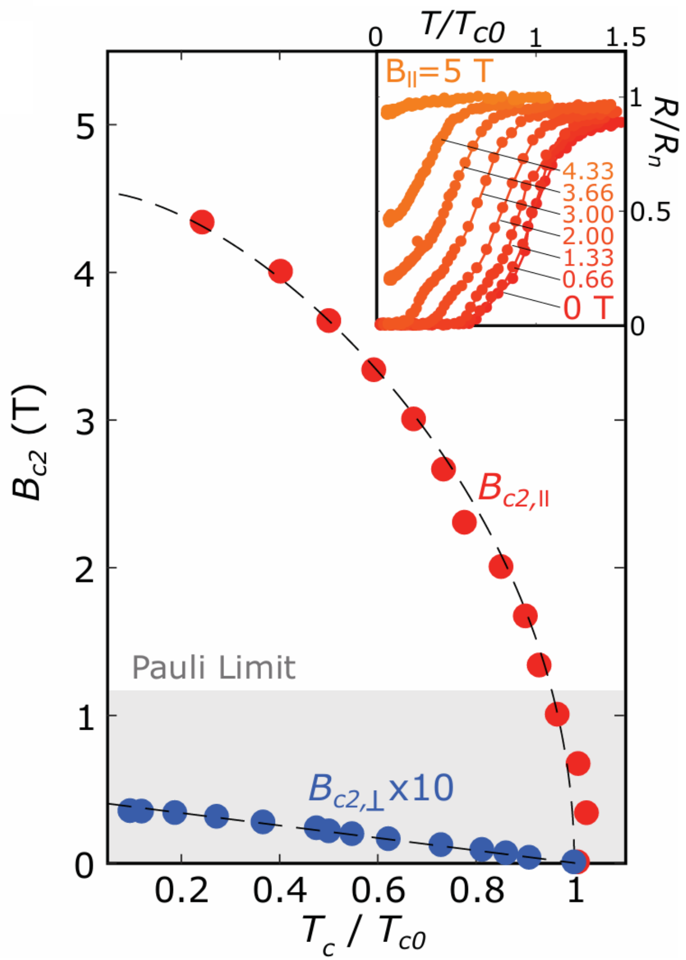
E. Sajadi, *et al.*, *Science* **362,** 922 (2018)

V. Fatemi, *et al.*, *Science* **362,** 926 (2018)

- **Monolayer WTe_2 also hosts anomalous metal state and large $B_{c2,//}$ over B_p**

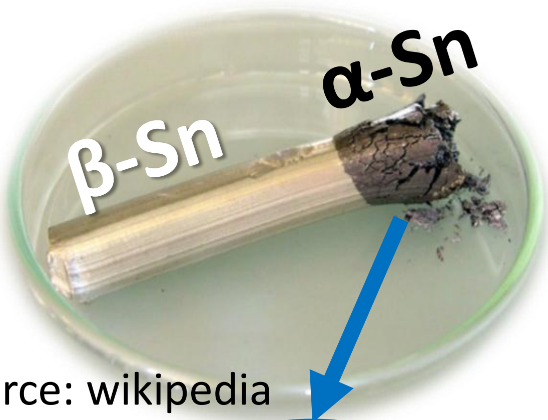


E. Sajadi, *et al.*, *Science* **362,** 922 (2018)

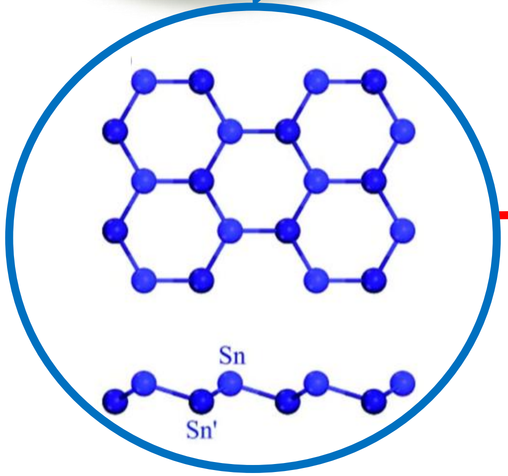


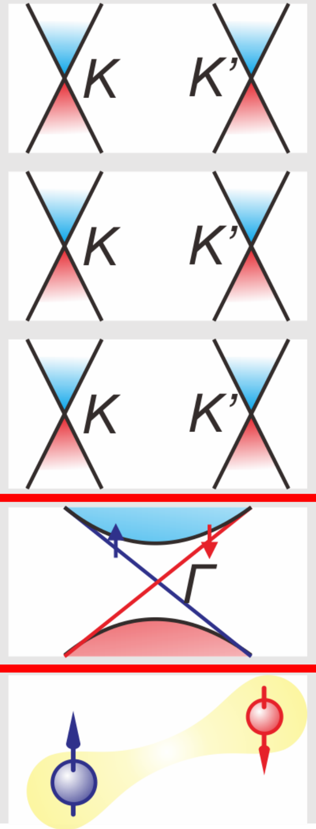
V. Fatemi, *et al.*, *Science* **362,** 926 (2018)

Stanene



Source: wikipedia



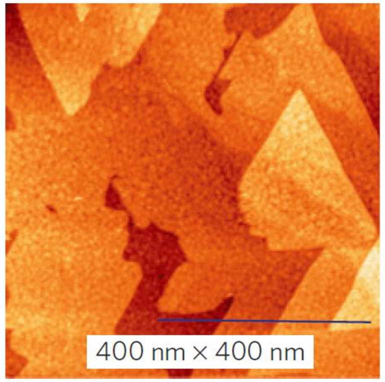


6 C	Graphene	K. Novoselov, et al. *Science* **306**, 666 (2004)
14 Si	Silicene	B. Aufray, et al. *APL* **96**, 183102 (2010)
32 Ge	Germanene	M. E. Davila, et al. *New J. Phys.* **16**, 095002 (2014)
50 Sn	Stanene	F.-F. Zhu, et al. *Nat. Mater.* **14**, 1020 (2015)
82 Pb	Monolayer Pb	T. Zhang, et al. *Nat. Phys.* **6**, 104 (2010)

- **Stanene: monolayer α-Sn (111)**
- **Graphene-like structure + buckling** — C.-C. Liu, H. Jiang & Y. G. Yao *PRB* **84**, 195430 (2011)
- **Room temperature quantum spin Hall** — Y. Xu, S.C. Zhang et al. *PRL* **111**, 136804 (2013)

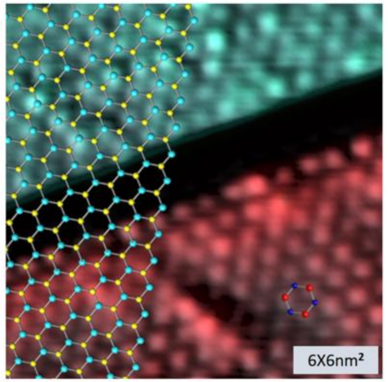
Realization of stanene

Bi_2Te_3



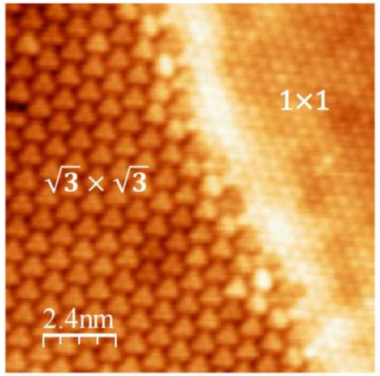
F.-F. Zhu, et al., *Nat. Mater.* **14**, 1020 (2015)

Sb (111)



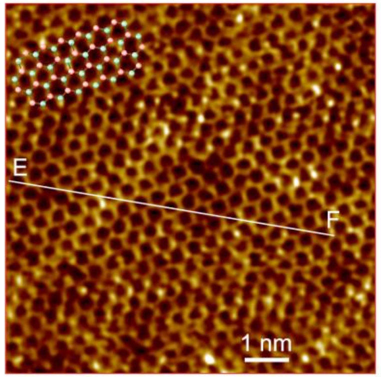
J. Gou et al., *Phys. Rev. Mater.* **1**, 054004 (2017)

Bi(111)



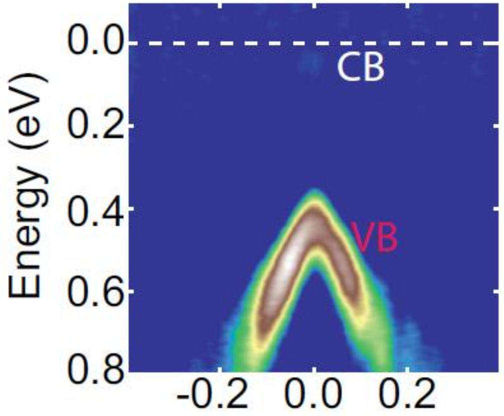
Y.-H. Song et al., *arXiv:* 1707.08657

Ag (111)



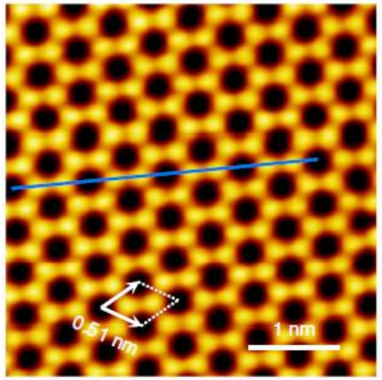
J. Yuhara et al. *2D Mater*. **5**, 025002 (2018)

InSb (111)



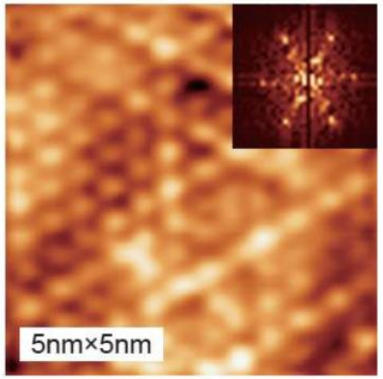
C. Z. Xu et al. *Phys. Rev. B* **97**, 035122 (2018)

Cu (111)



J. Deng et al., *Nat. Mater.* **17**, 1081 (2018)

- **Stanene/Cu: topological**

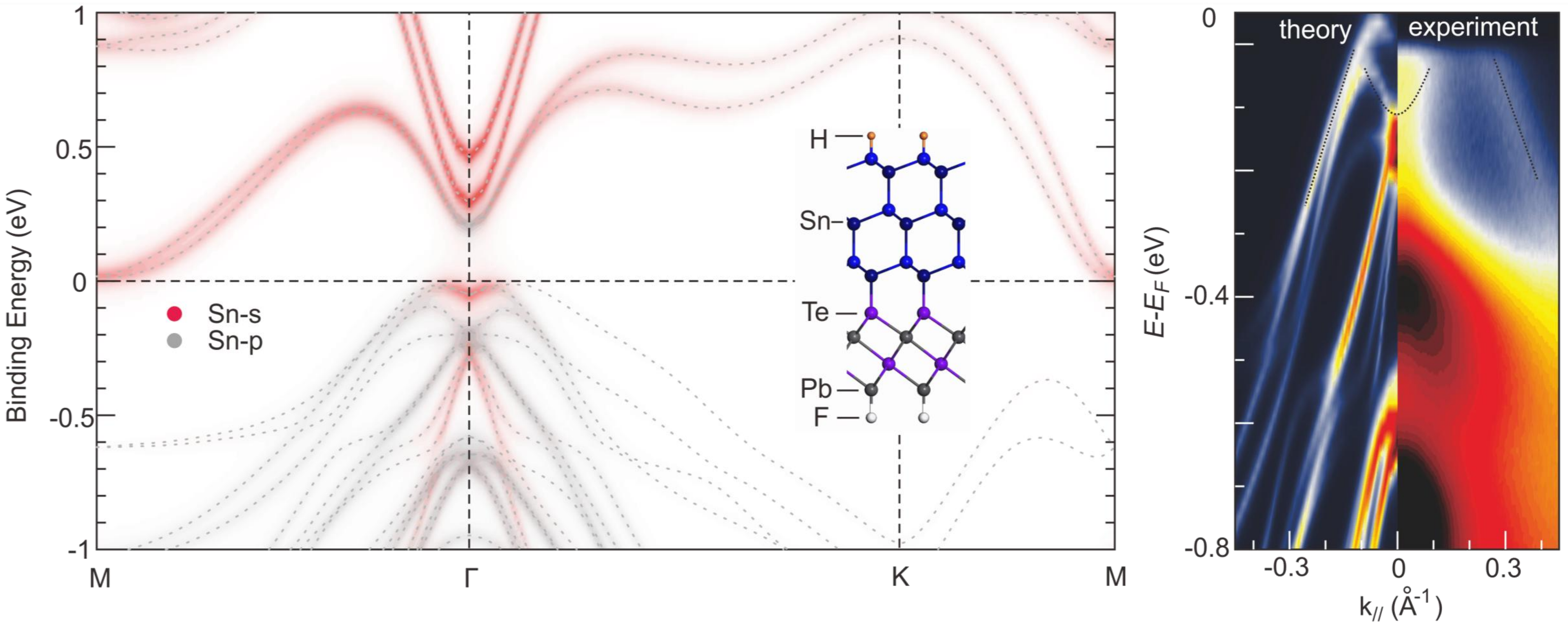


stanene/ PbTe (111)

Y. Zang et al., *Adv. Funct. Mater.* **28,** 1802723 (2018)

- **Few-layer stanene/PbTe: topological**

Band structure of few-layer stanene

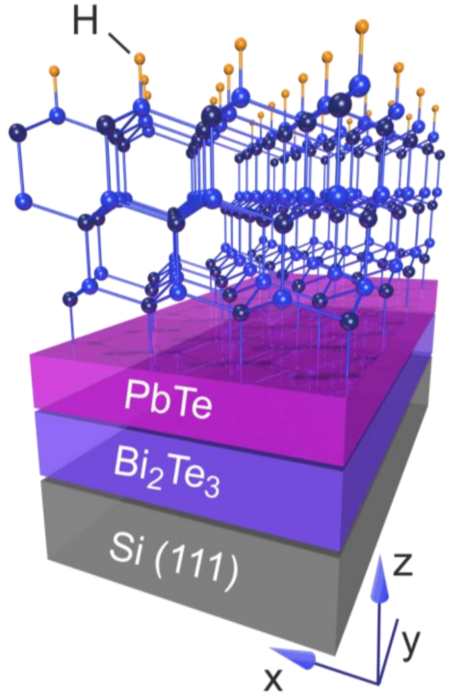


- **M-shaped bands at Γ point**
- **Inverted band structure**
- **Qualitative agreement between theory & experiment**

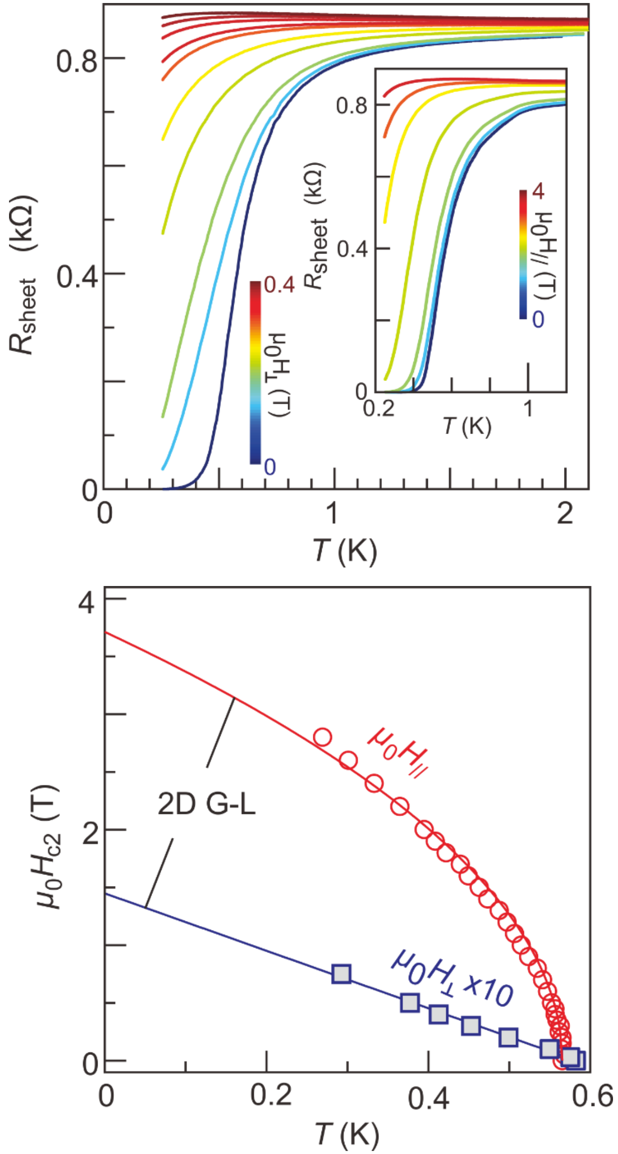
M. Liao, et al.,
Nat. Phys. **14**, 344 (2018)

2D superconductivity of few-layer stanene

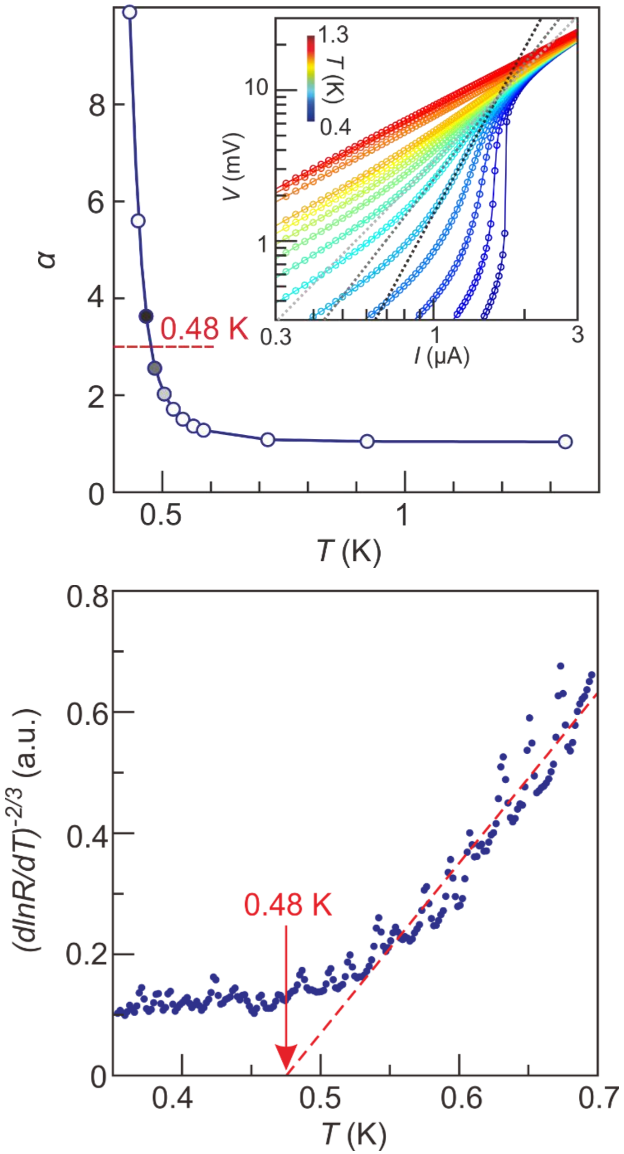
3-Sn/6-PbTe



Anisotropic critical fields



BKT transition

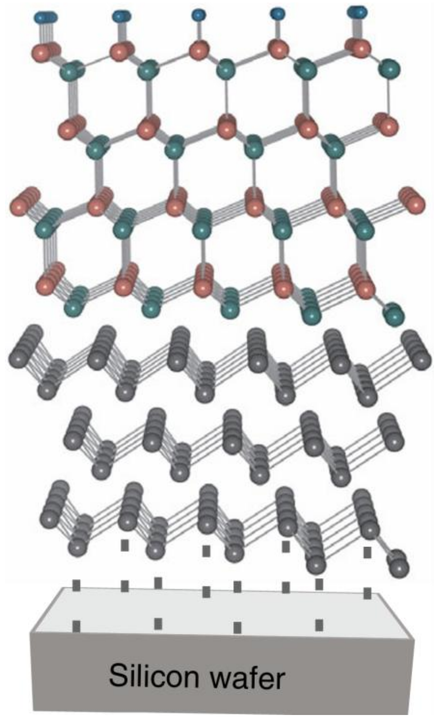


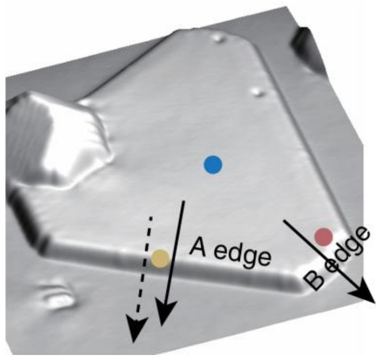
M. Liao, et al.,
Nat. Phys. **14**, 344 (2018)

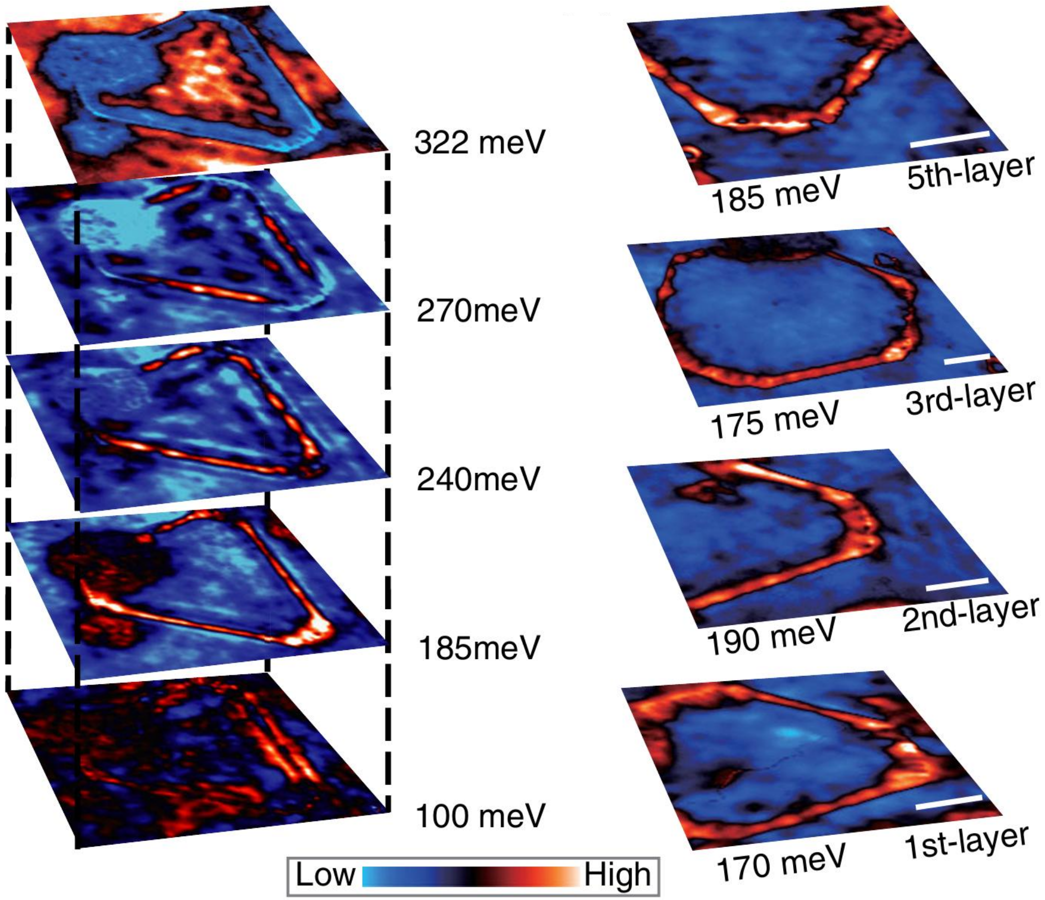
Few-layer stanene on Bi(111)

- **Enhanced density of states at the edge of few-layer stanene islands**

Bi

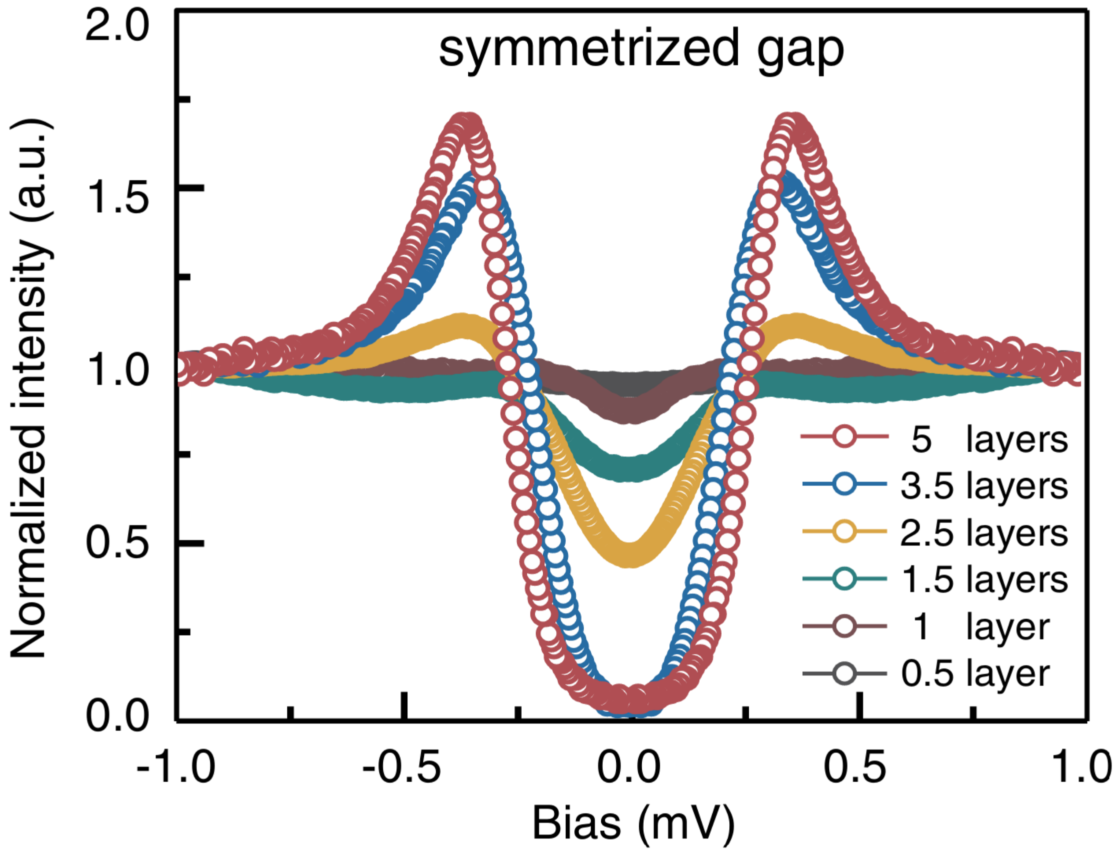






C. Zhao, *et al.*, *Phys. Rev. Lett.* **128**, 206802 (2022)

Few-layer stanene on Bi(111)

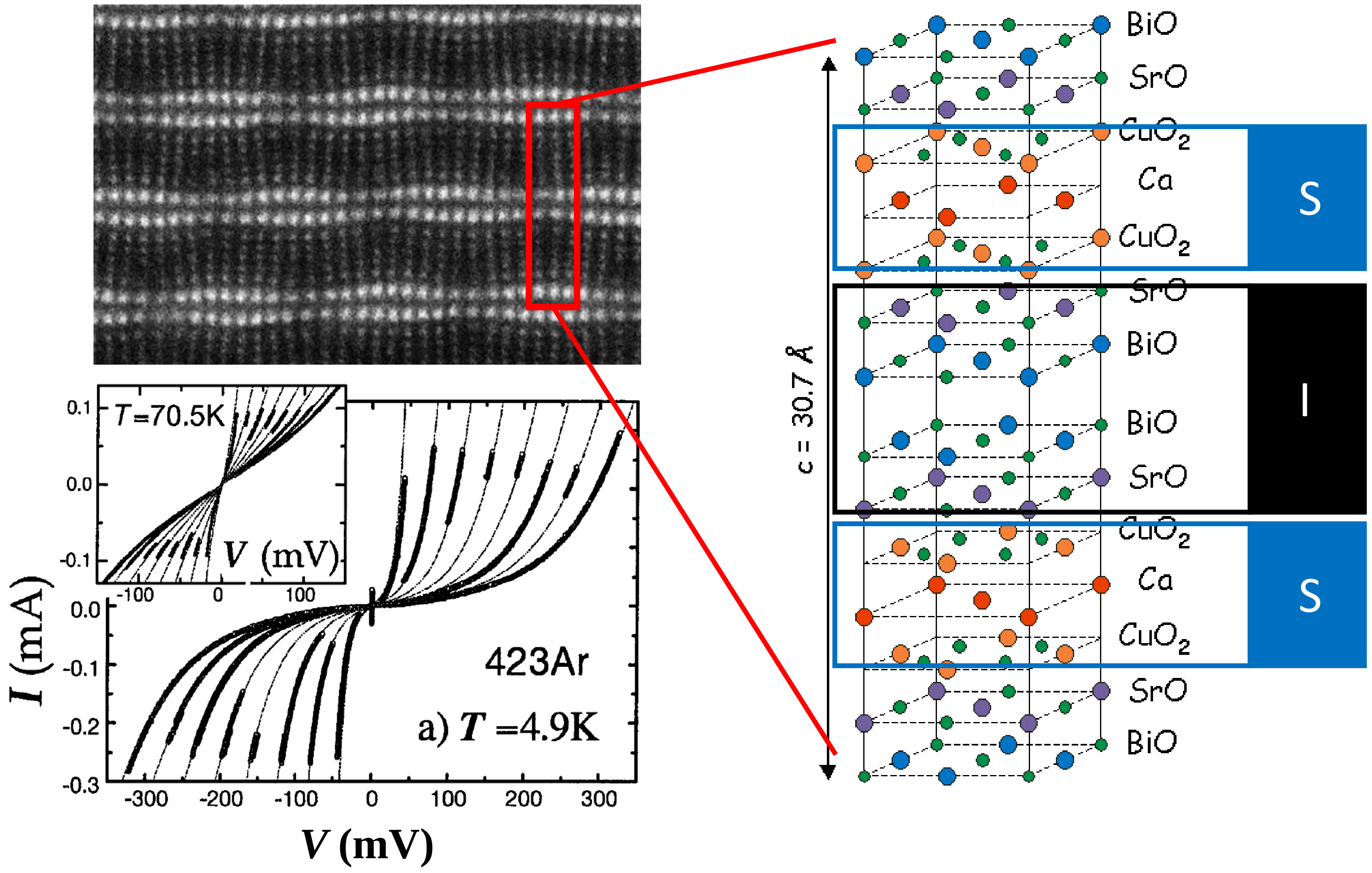


- **Superconducting gap observed down to a monolayer**

C. Zhao, *et al.*, *Phys. Rev. Lett.* **128**, 206802 (2022)

Twisted cuprates

$Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO)

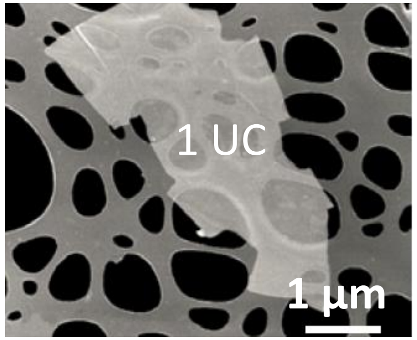


Intrinsic Josephson junction (JJ)

R. Kleiner *et al.* *PRL* **68,** 2394 (1992) V. M. Krasnov *et al.* *PRL* **84**, 5860 (2000) M. Suzuki & T. Watanabe *PRL* **85**, 4787 (2000)

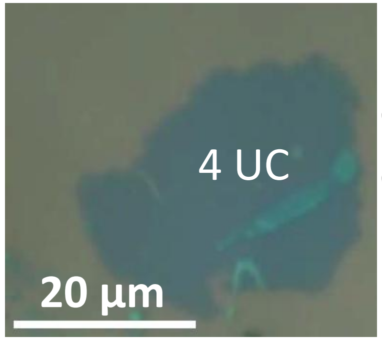
Exfoliation of BSCCO

$Bi_2Sr_2CaCu_2O_x$



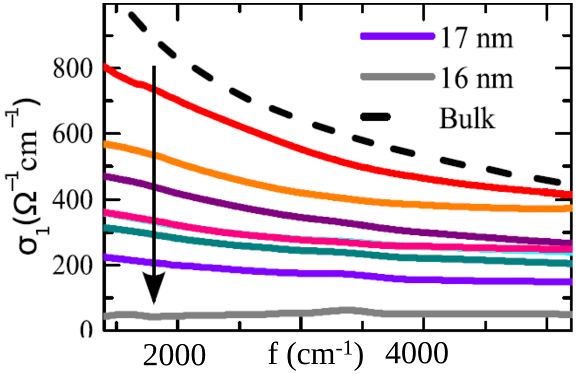
K. S. Novoselov *et al.*
PNAS **102**, 10451 (2005)

$Bi_2Sr_2Ca_{1-x}Dy_xCu_2O_y$

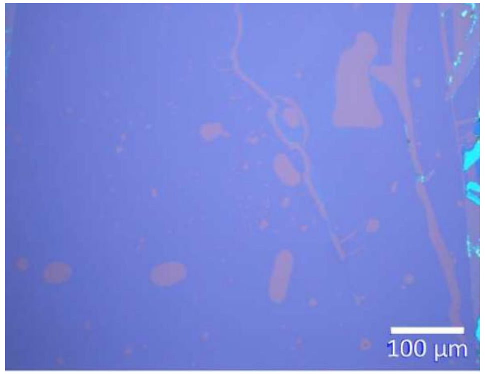


L. J. Sandilands *et al.*
PRB **82**, 064503 (2010)

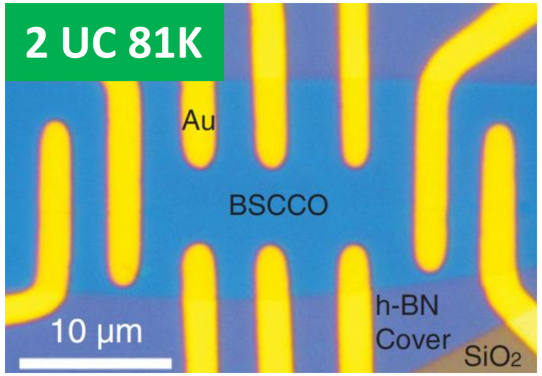
<15 nm: insulating



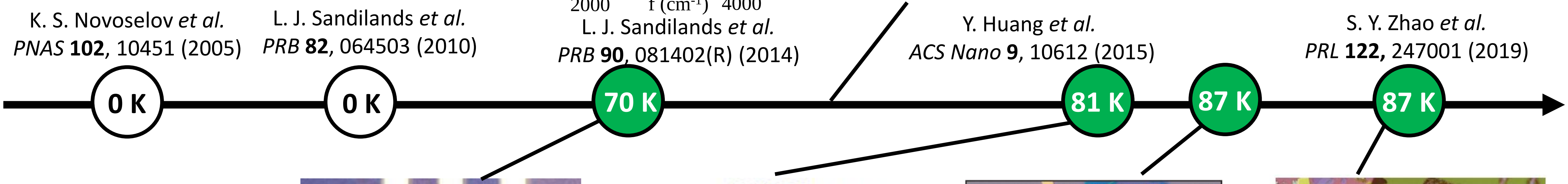
L. J. Sandilands *et al.*
PRB **90**, 081402(R) (2014)

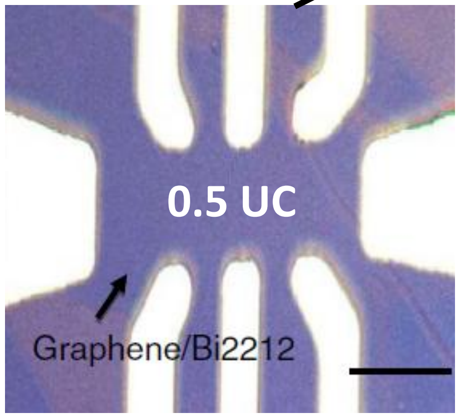


Y. Huang *et al.*
ACS Nano **9**, 10612 (2015)

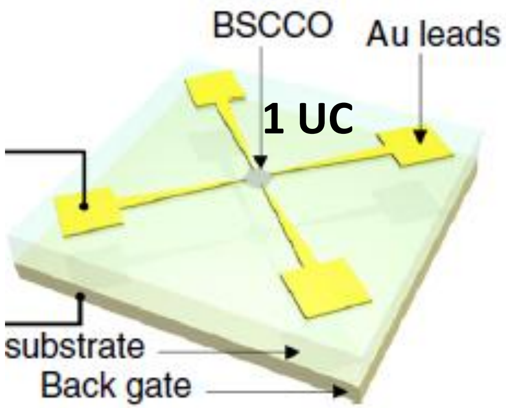


S. Y. Zhao *et al.*
PRL **122,** 247001 (2019)

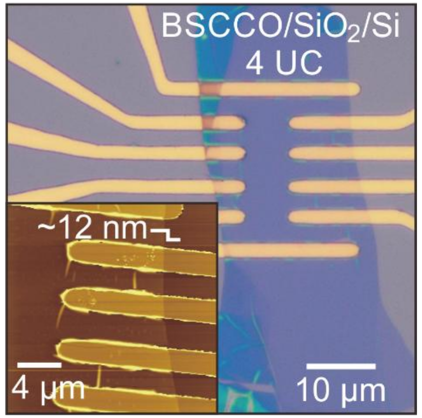




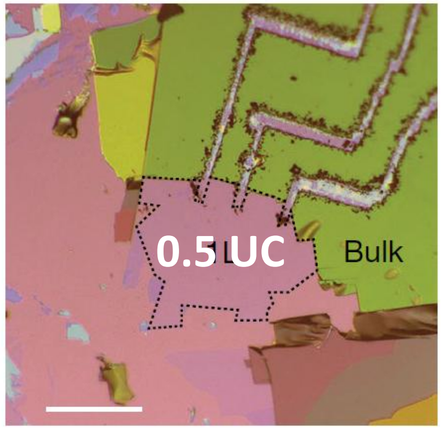
D. Jiang *et al.*
Nat. Commun. **5**, 5708 (2014)



E. Sterpetti *et al.*
Nat. Commun. **8**, 2060 (2017)



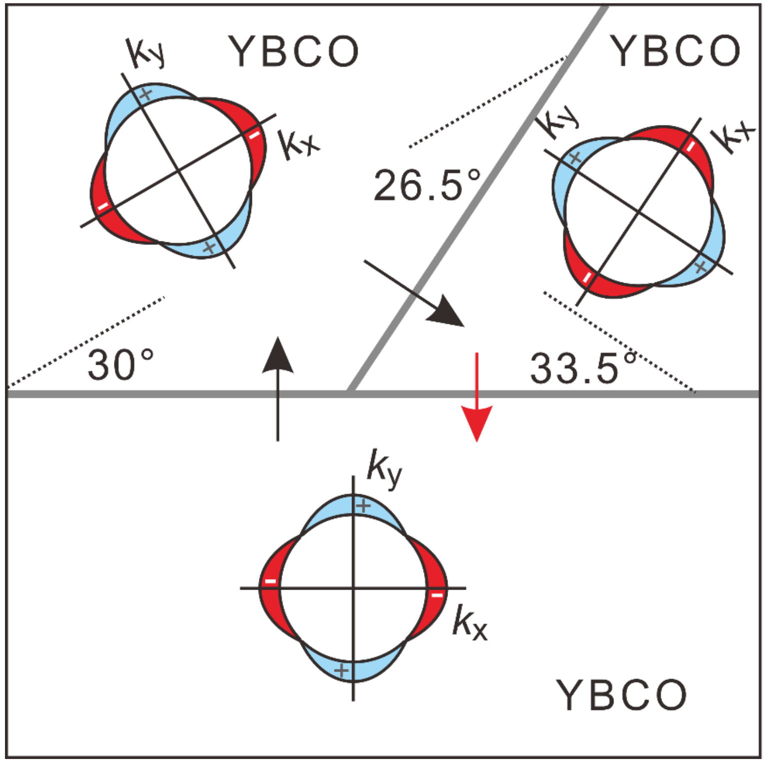
M. Liao, **DZ*** *et al.*
Nano Lett. **18**, 5660 (2018)



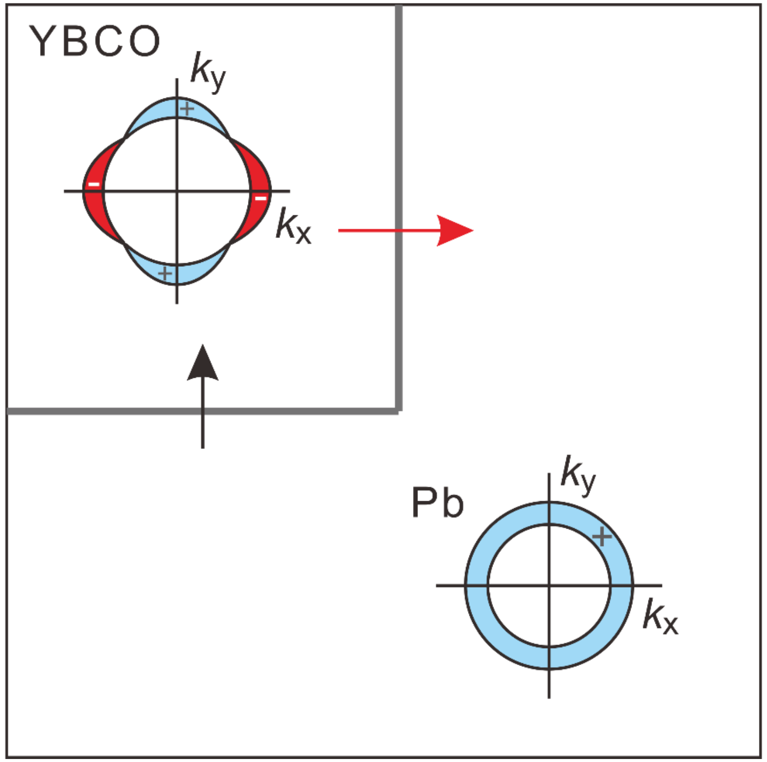
Y. Yu *et al.*
Nature **575,** 156 (2019)

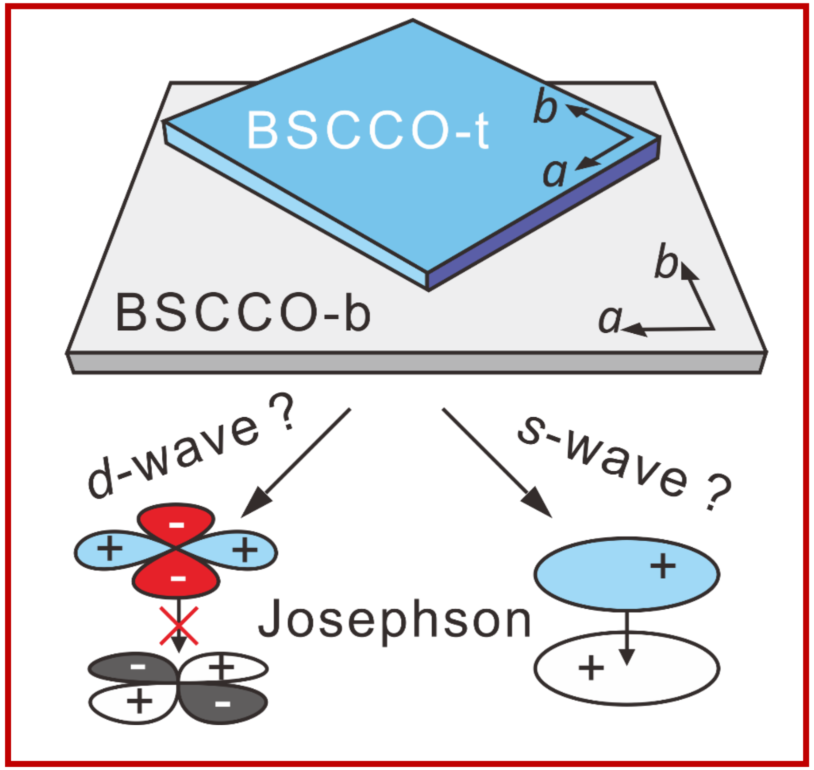
Phase sensitive experiments

Tricystal experiment



Corner junction experiment





C. C. Tsuei
IBM

J. R. Kirtley
IBM

Phys. Rev. Lett. **73,** 593 (1994)

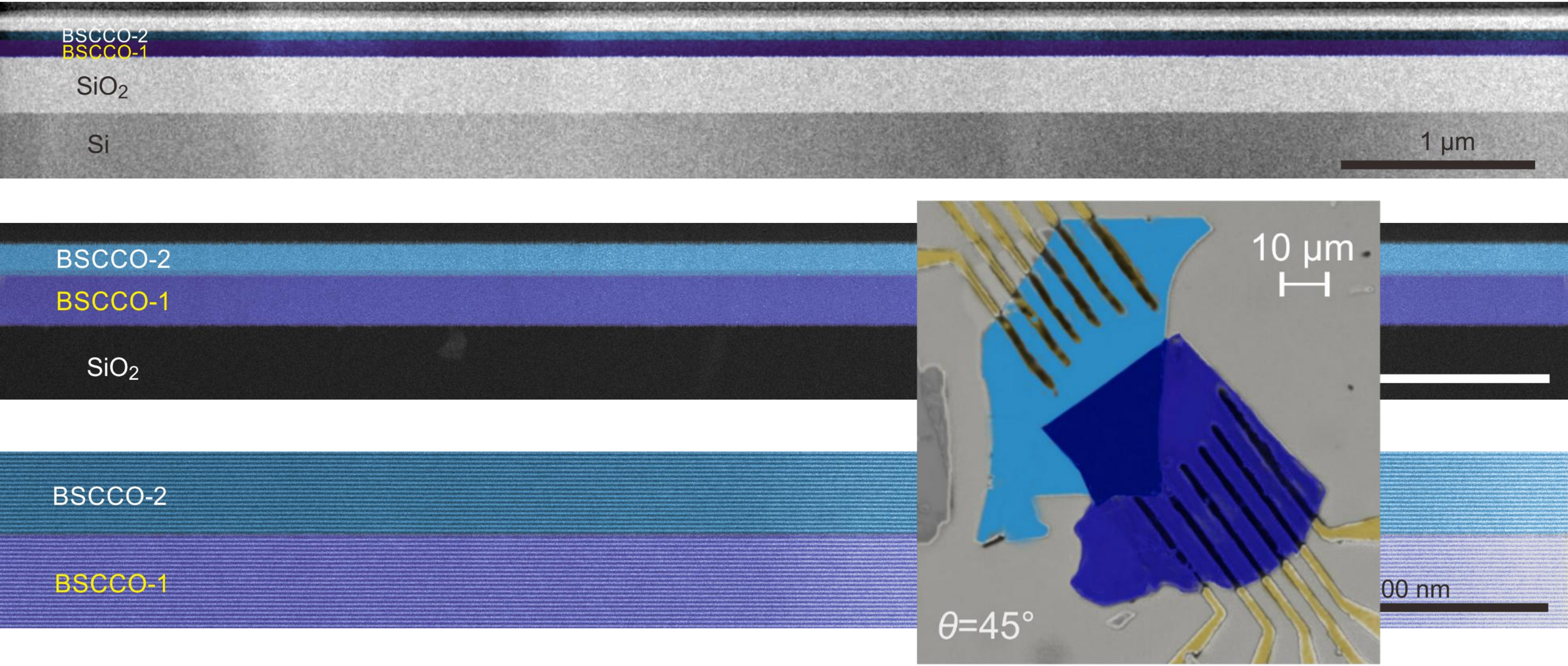
D. J. Van Harlingen
U. Illinois

D. M. Ginsberg
U. Illinois

Phys. Rev. Lett. **71,** 2134 (1993)

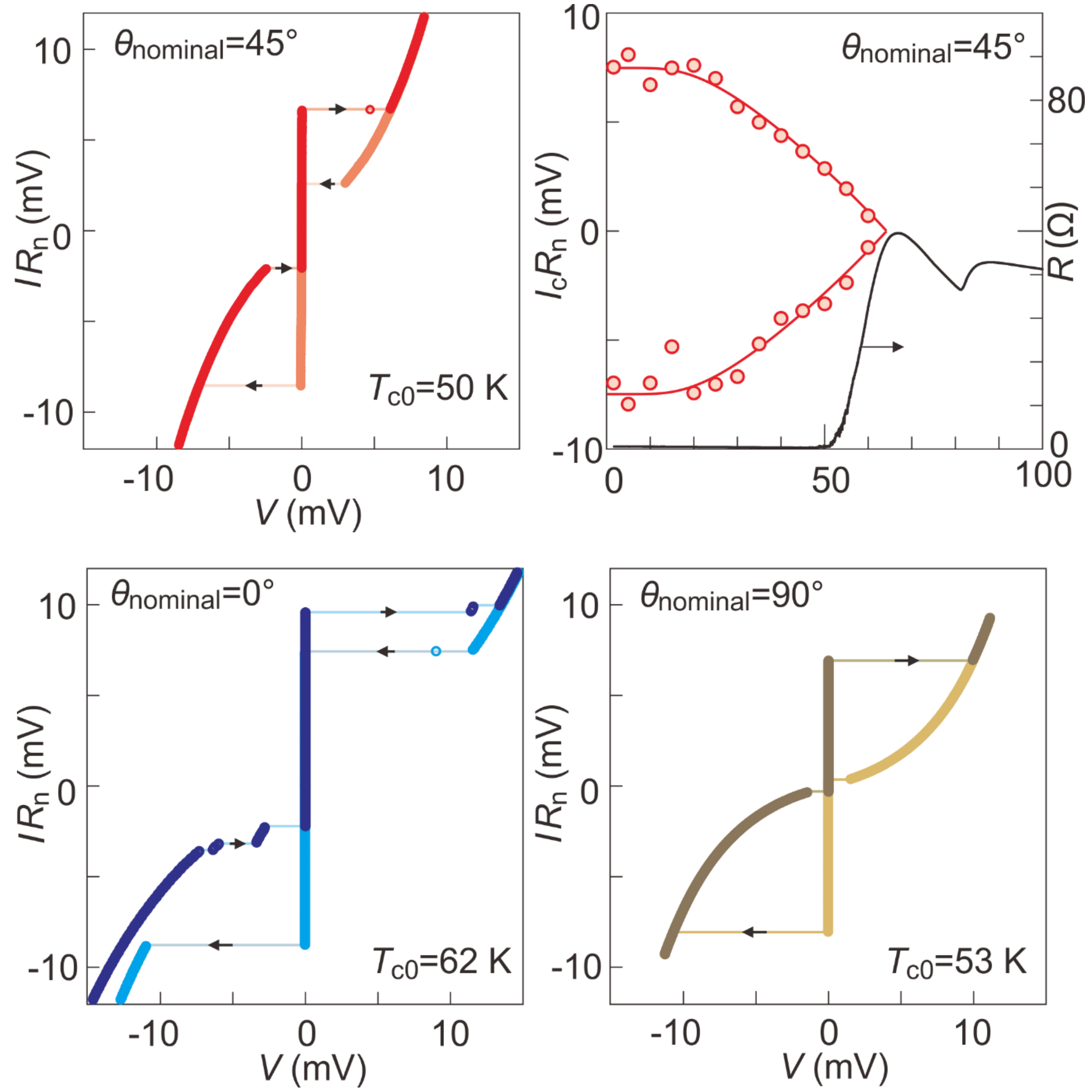
Q. Li *et al. Phys. Rev. Lett.* **83** 4160 (1999)
R. Klemm, *Philo. Mag.* **85**, 801 (2005)

Twisted cuprates by van der Waals stacking



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

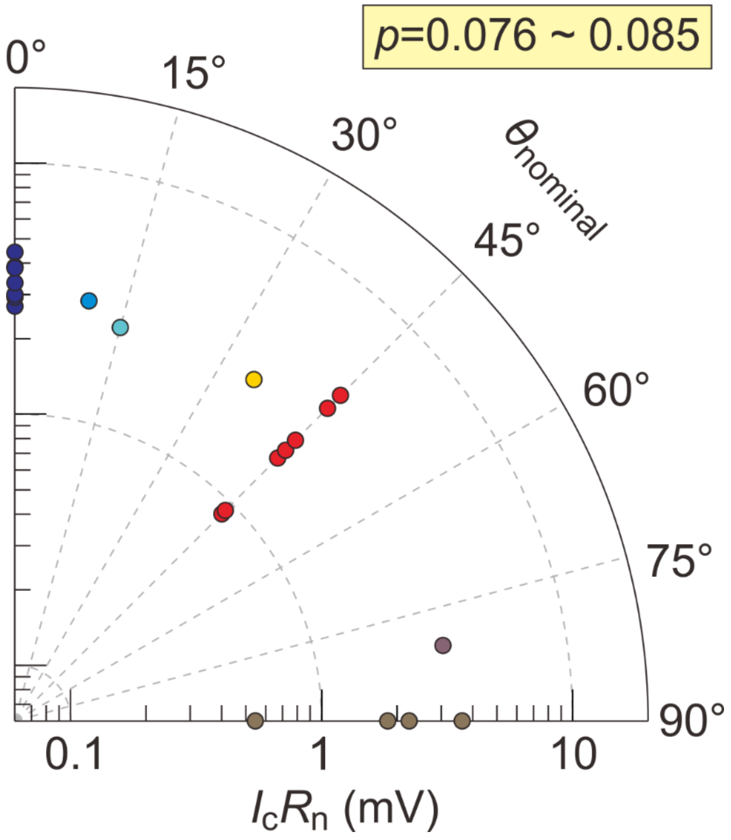
Josephson effect

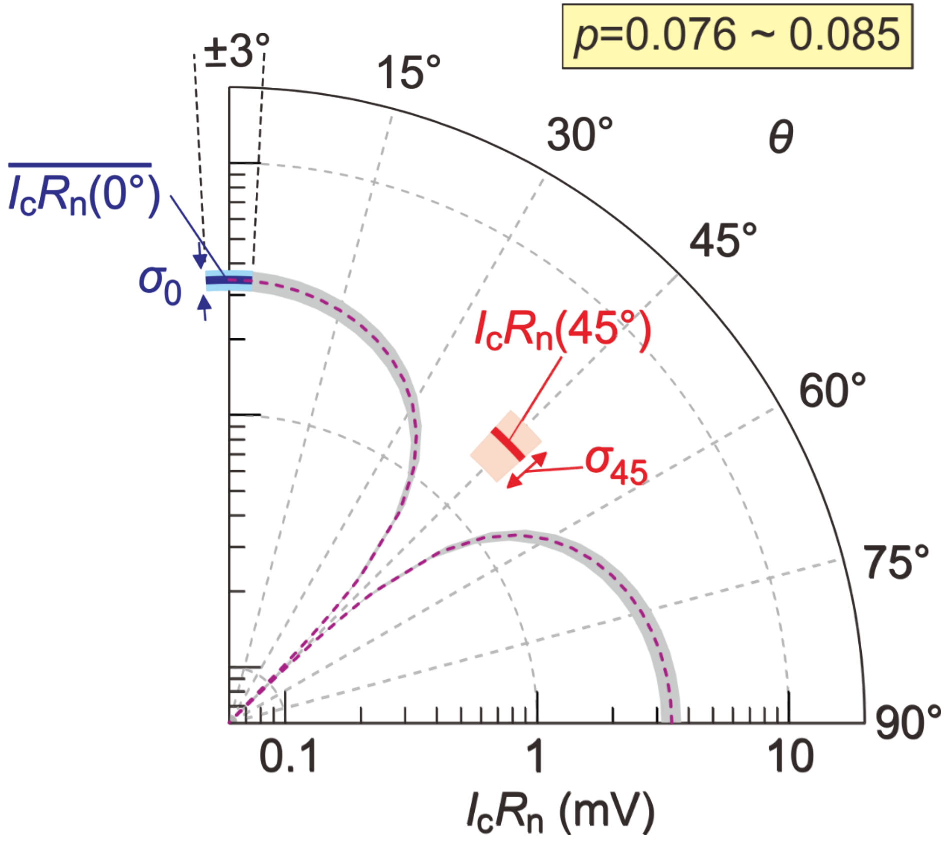


- Bulk T_c: 80 K
  Junction T_c: 50 K
- **A single junction:**
  0.5 UC-BSCCO-1 + 0.5 UC BSCCO-2
- **Josephson coupling @ 45-deg twist**
- $I_c\, R_n$ can reach the same level at various θ
- **Not *d*-wave, just *s*-wave**

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

Angular dependence



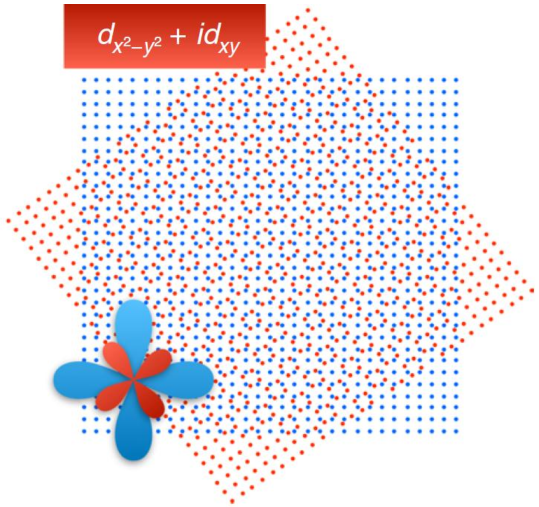


- Average values: slightly smaller at 45°
- Clear deviation from *d*-wave

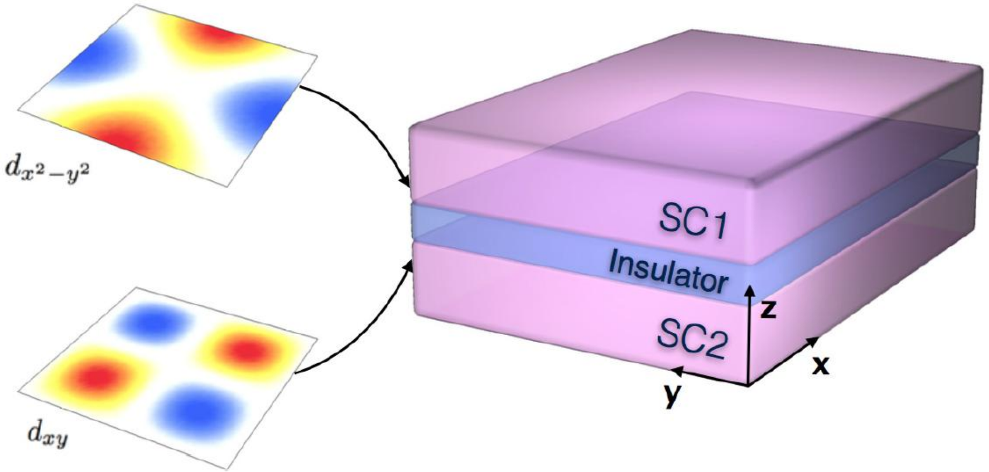
Y. Zhu, *et al., Phys. Rev. X* **11,** 031011 (2021)

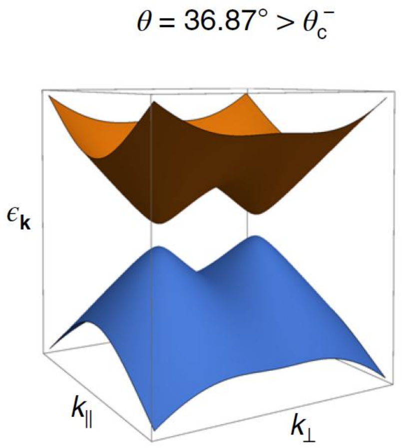
Topological superconductivity?

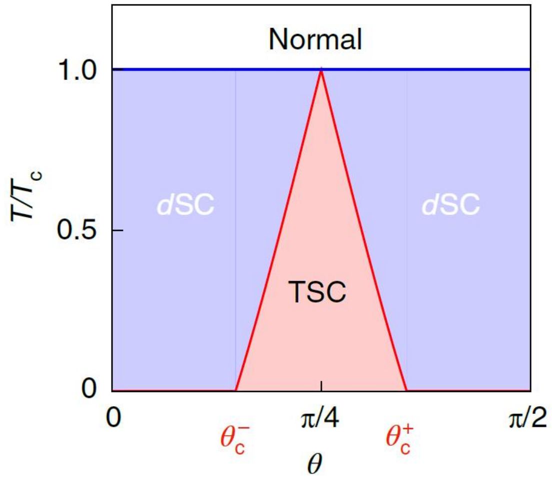
- Coupling between $d_{x^2-y^2}$ and d_{xy} waves: π/2 Josephson junction



- ***d*+*id*-wave** pairing in twisted cuprate bilayers
- Co-tunneling: 4*e*





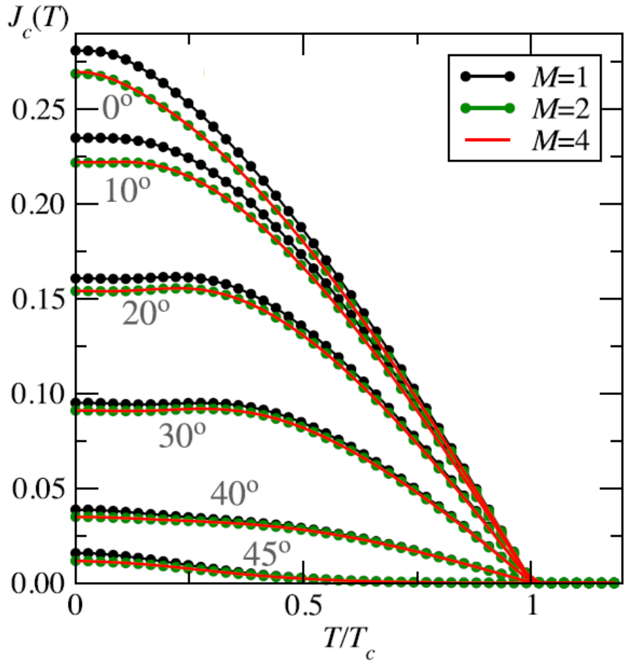


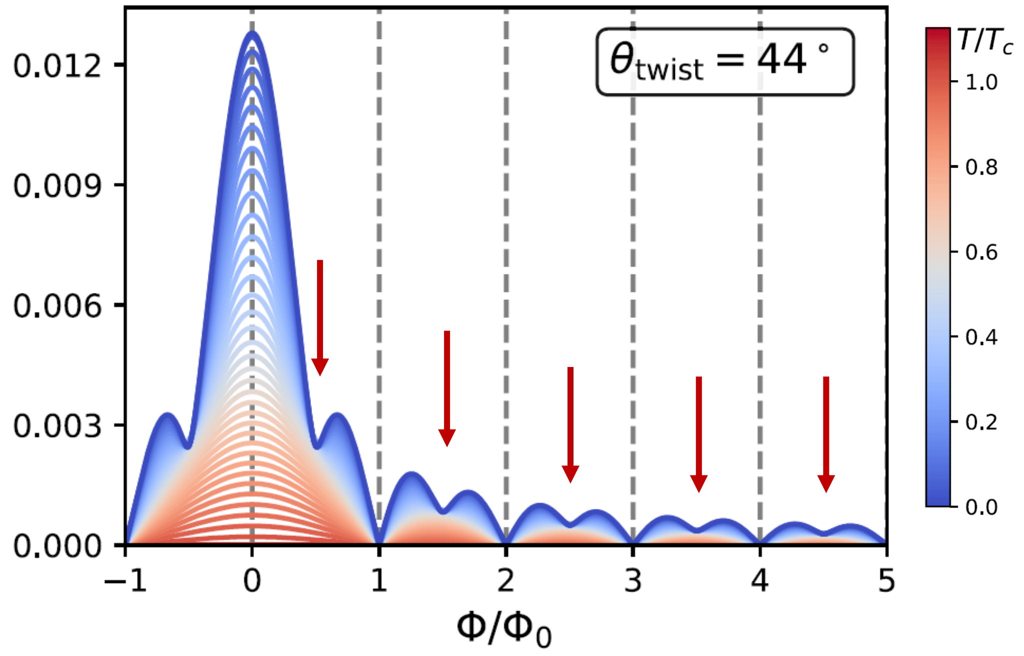
Z. Yang *et al. Phys. Rev. B* **98,** 104515 (2018)

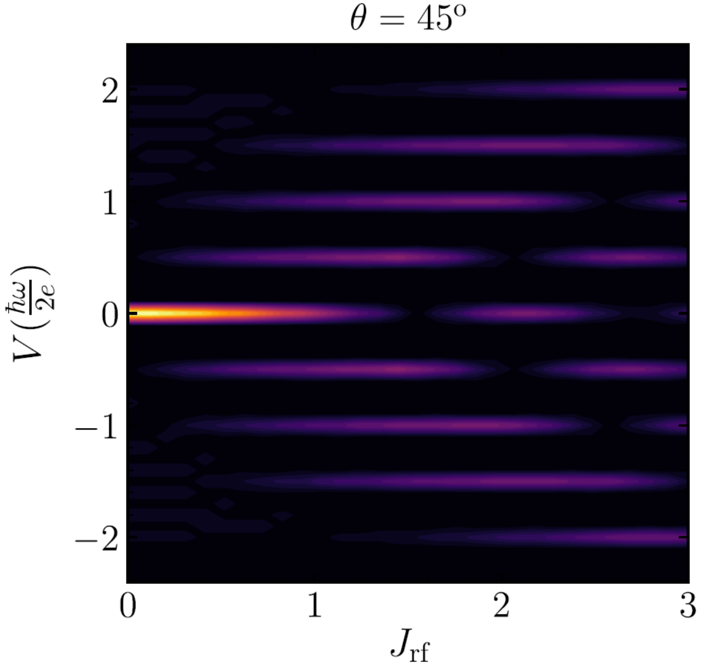
O. Can *et al. Nat. Phys.* **17,** 519 (2021)

Predictions

1. unconventional temperature dependence of I_c
2. Fraunhofer pattern: ***h/2e*** ➡ ***h/4e***
3. Shapiro steps at half integers: ***hf/4e***

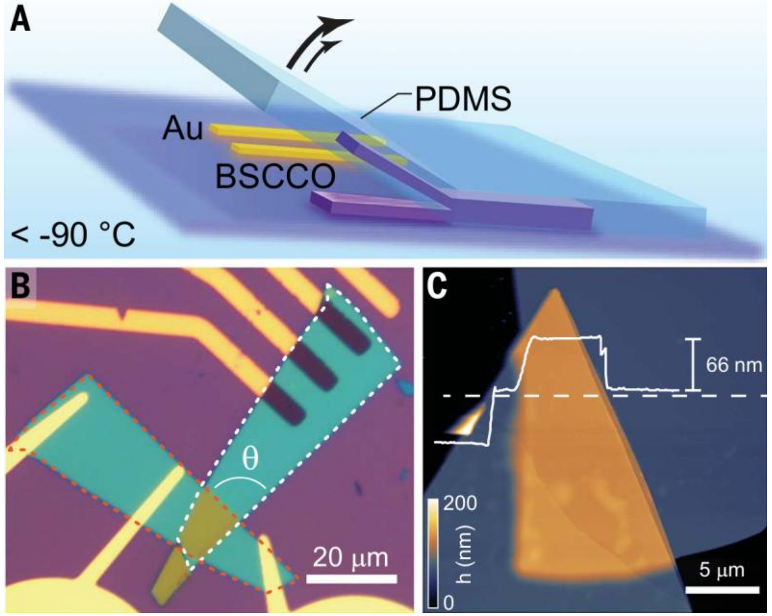


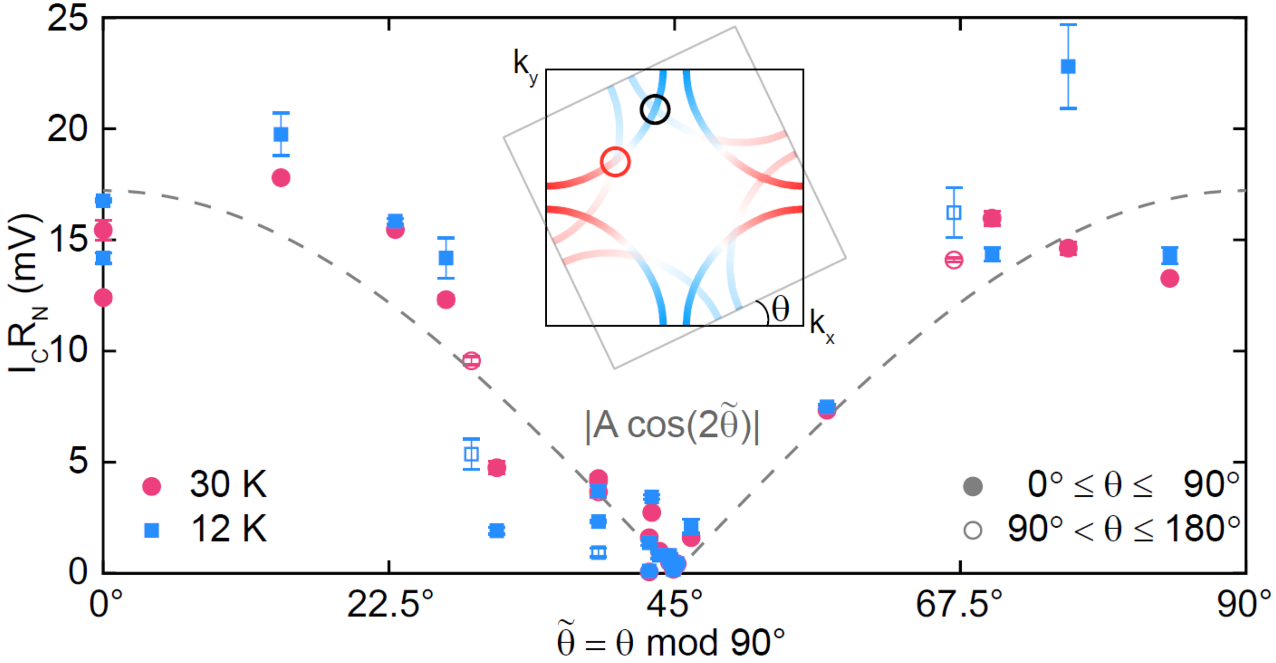




Z. Yang *et al., PRB* **98,** 104515 (2018) O. Can *et al. Nat. Phys.* **17,** 519 (2021) T. Tummuru, S. Plugge, M. Franz, *PRB* **105,** 064501 (2022)

Experiments supporting novel pairing





RESEARCH

SUPERCONDUCTIVITY

Time-reversal symmetry breaking superconductivity between twisted cuprate superconductors

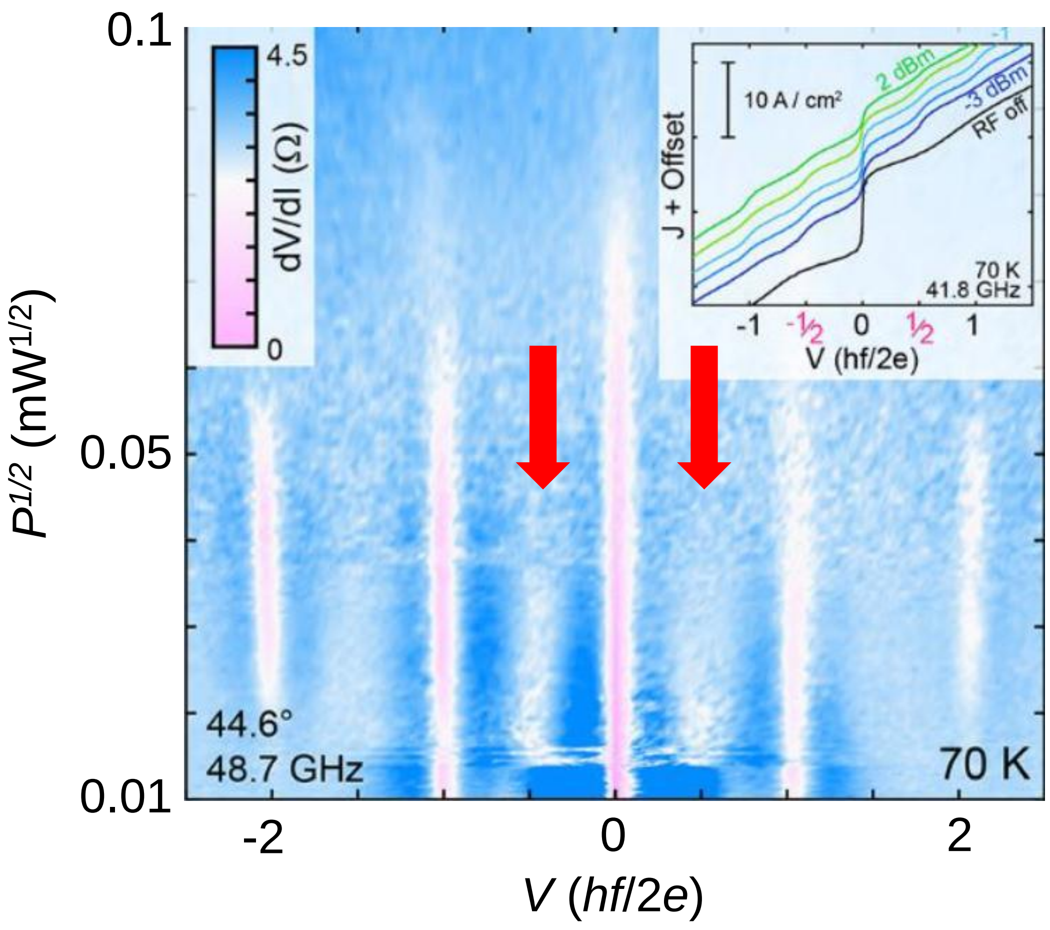
S. Y. Frank Zhao[1]†, Xiaomeng Cui[1]†, Pavel A. Volkov[1,2,3], Hyobin Yoo[4], Sangmin Lee[5], Jules A. Gardener[6], Austin J. Akey[6], Rebecca Engelke[1], Yuval Ronen[1], Ruidan Zhong[7]‡, Genda Gu[7], Stephan Plugge[8], Tarun Tummuru[8], Miyoung Kim[5], Marcel Franz[8], Jedediah H. Pixley[2], Nicola Poccia[1,9]*, Philip Kim[1]*

- Strong suppression of Josephson coupling with increasing twist angle toward 45 degrees

S. Zhao, *et al., Science* **382,** 1422 (2023)

Experiments supporting novel pairing

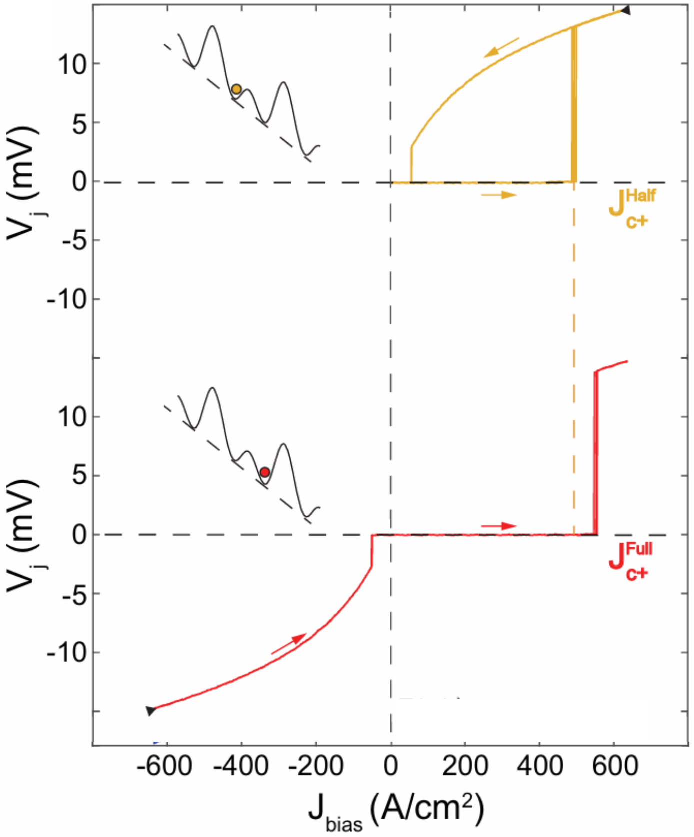
- Shapiro steps at ±1/2

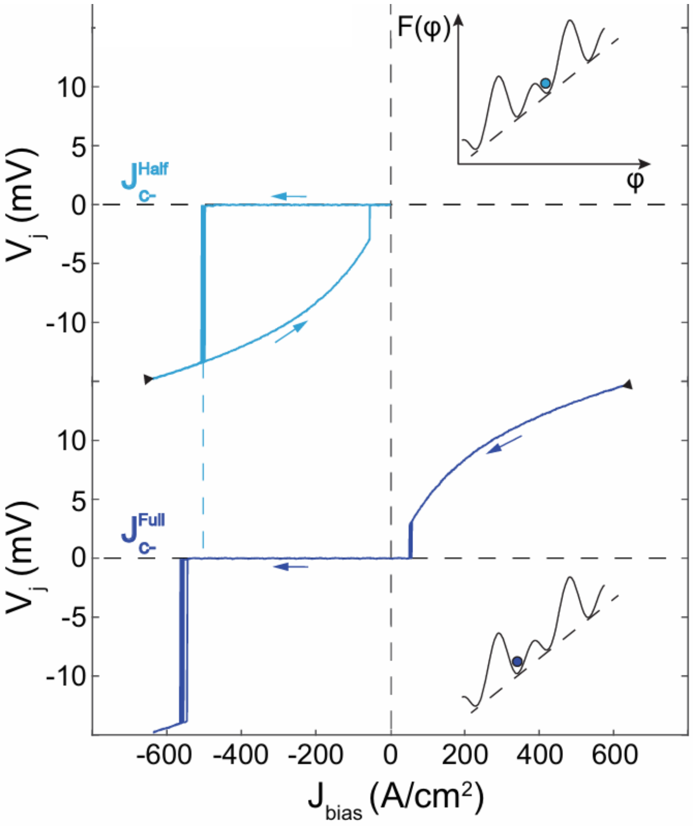


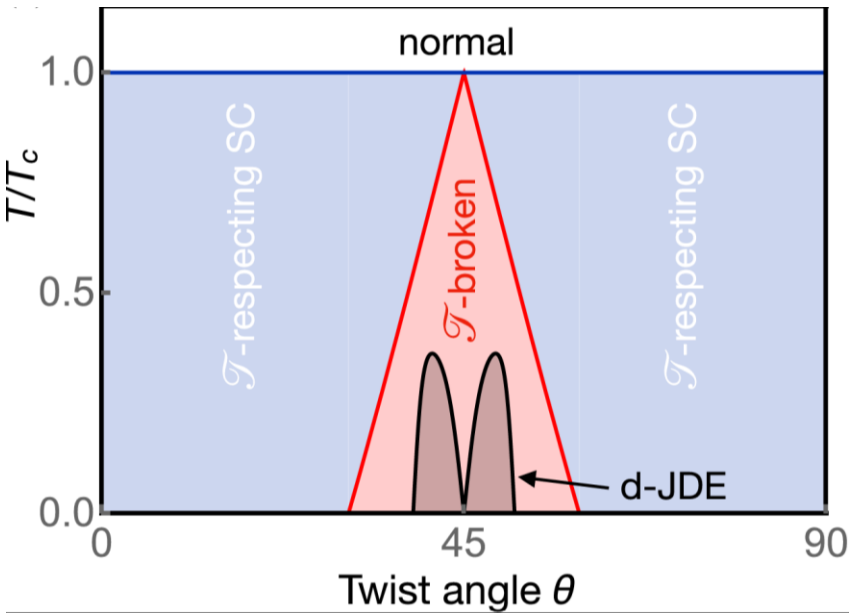
S. Zhao, *et al.*, *Science* **382,** 1422 (2023)

Experiments supporting novel pairing

- Josephson diode effects





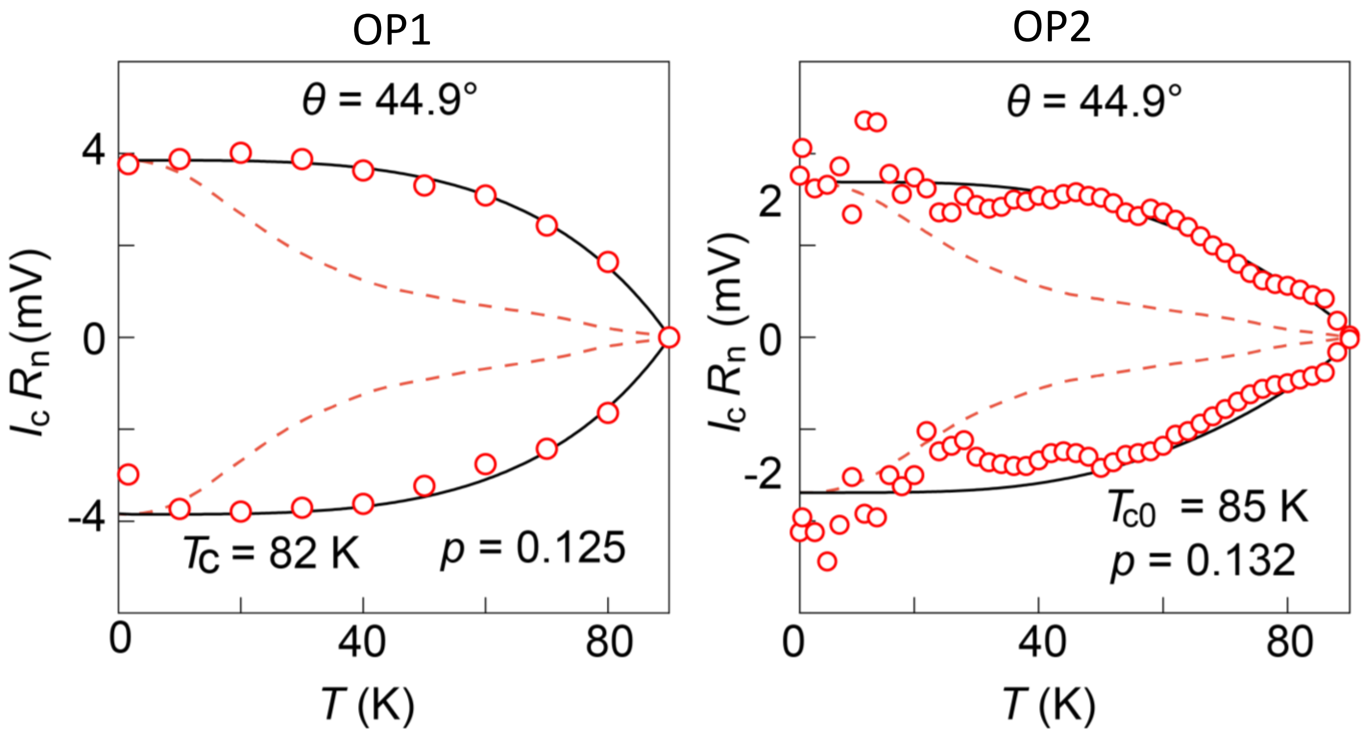


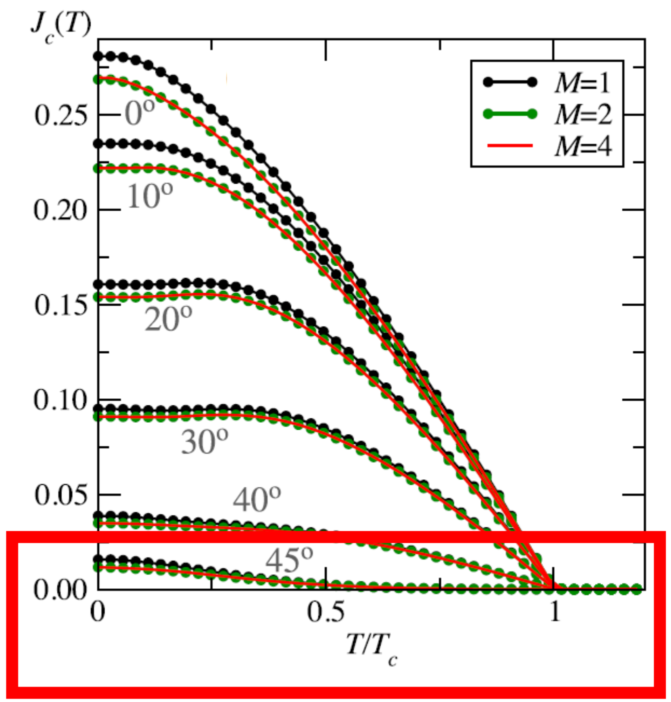
S. Zhao, *et al., Science* **382,** 1422 (2023)

P. Volkov *et al., PRB* **109,** 094518 (2024)

Experiments questioning novel pairing

- Conventional *T*-dependence of the critical current





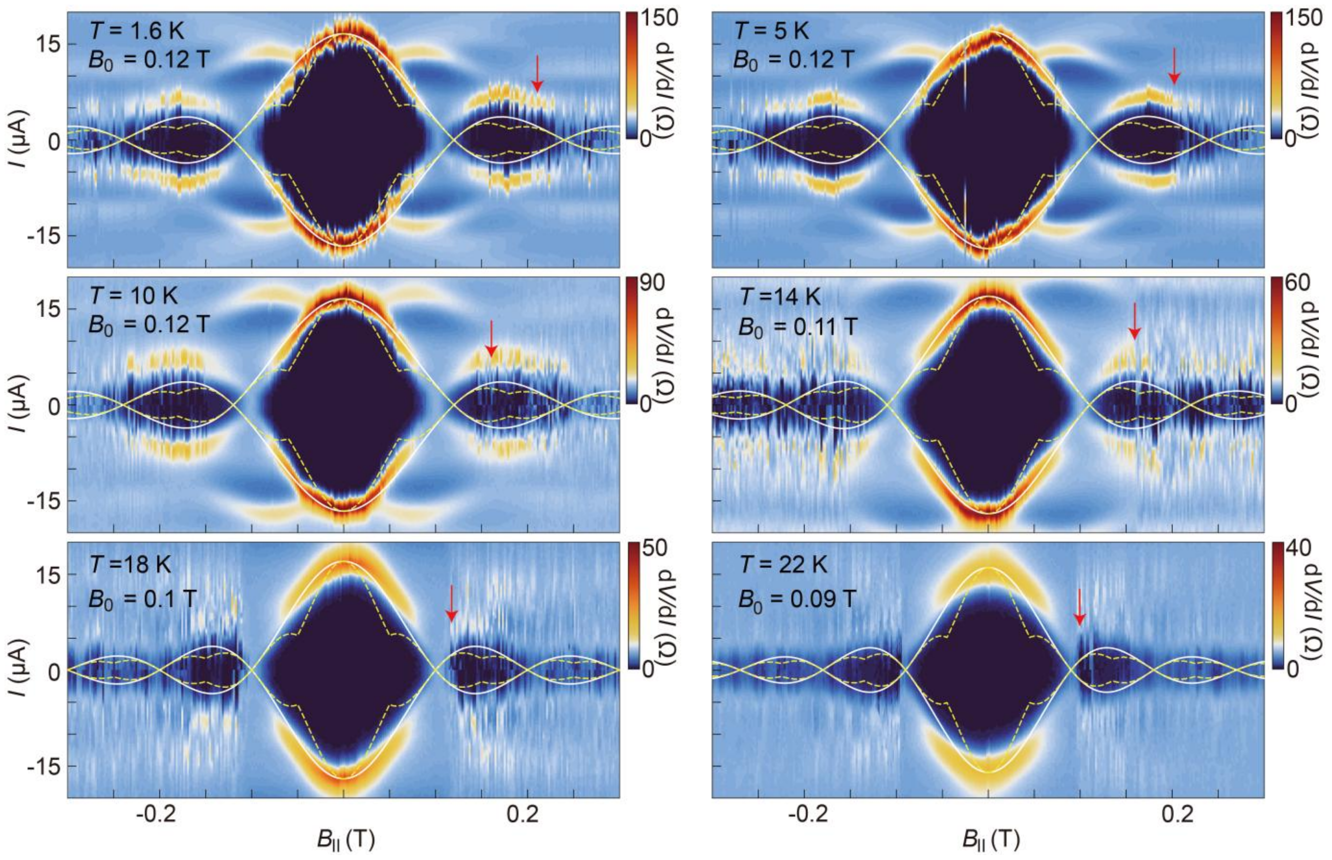
- 45°: Sudden rise at around 0.5 T_c

Y. Zhu, *et al., Phys. Rev. B* **108,** 174508 (2023)

T. Tummuru, S. Plugge, M. Franz, *Phys. Rev. B* **105,** 064501 (2022)

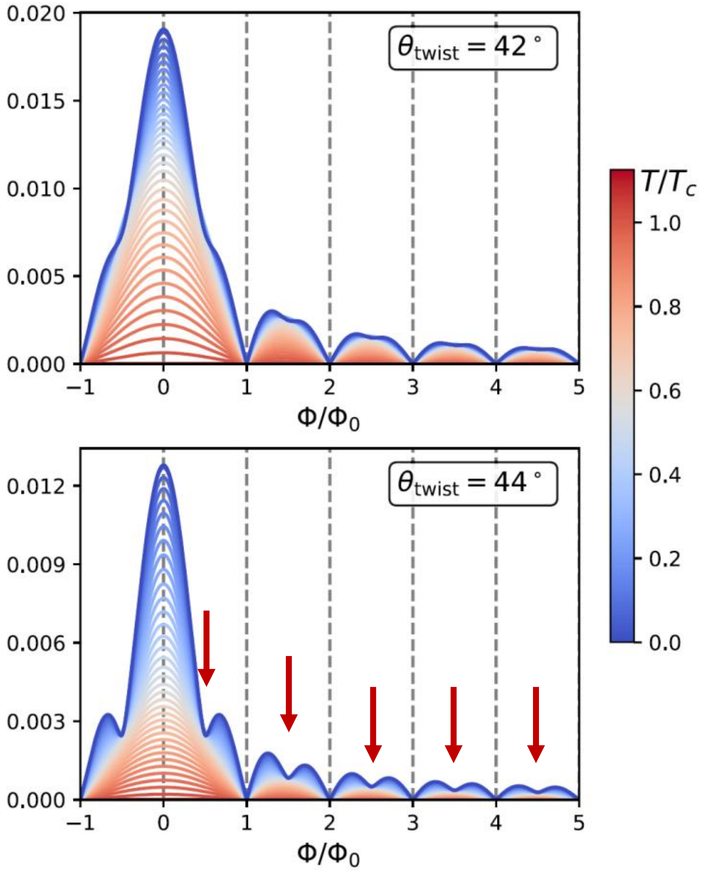
Experiments questioning novel pairing

- Standard Fraunhofer pattern



H. Wang, *et al., Nat. Commun.* **14,** 5201 (2023)

Prediction: doubling of frequency due to emergence of co-tunneling



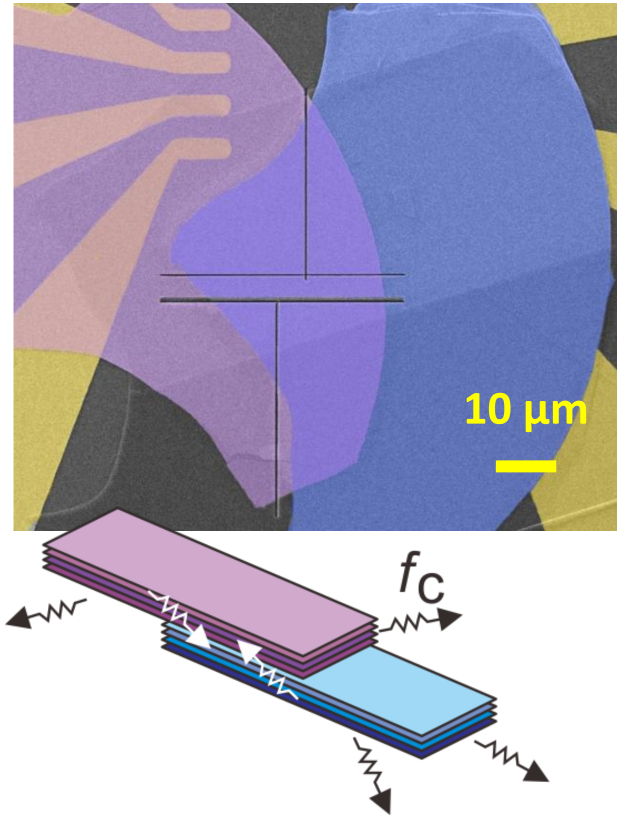
T. Tummuru, S. Plugge, M. Franz, *Phys. Rev. B* **105,** 064501 (2022)

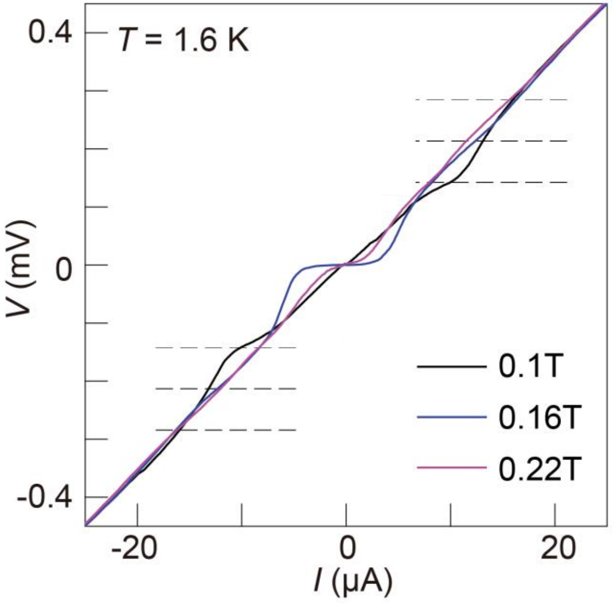
Experiments questioning novel pairing

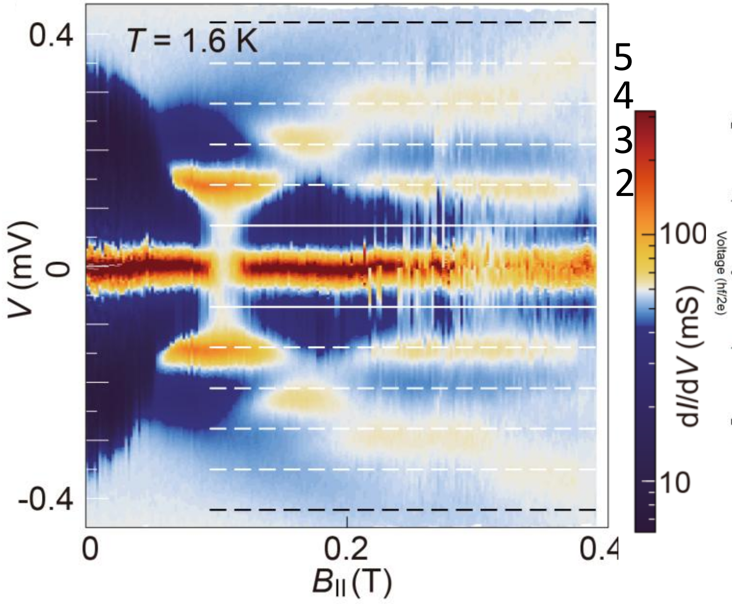
- 44.8°-twisted Bi-2201 junction
- Irradiation on the twisted interface from the cavity

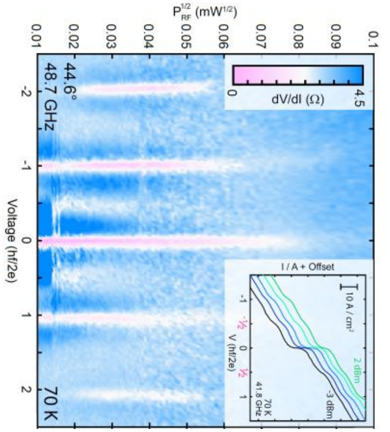
Steps at: $V = k\Phi_0 f_c, k = 1, 2, 3, \ldots$

- **No half-integer steps: absence of co-tunneling**









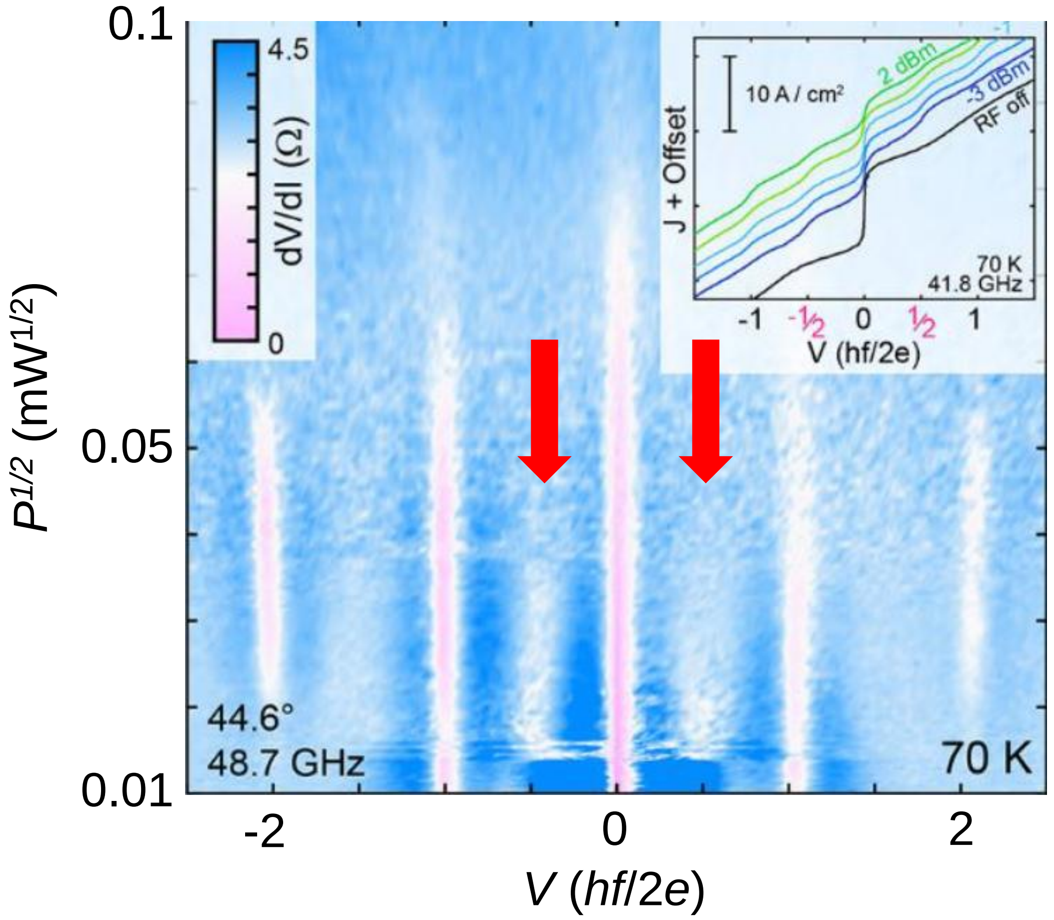
S. Y. Zhao *et al.* arXiv 2108.13455 (2021)

- Consecutively decreasing order of the steps
- First step missing due to dissipation at small bias

H. Wang, *et al., Nat. Commun.* **14,** 5201 (2023)

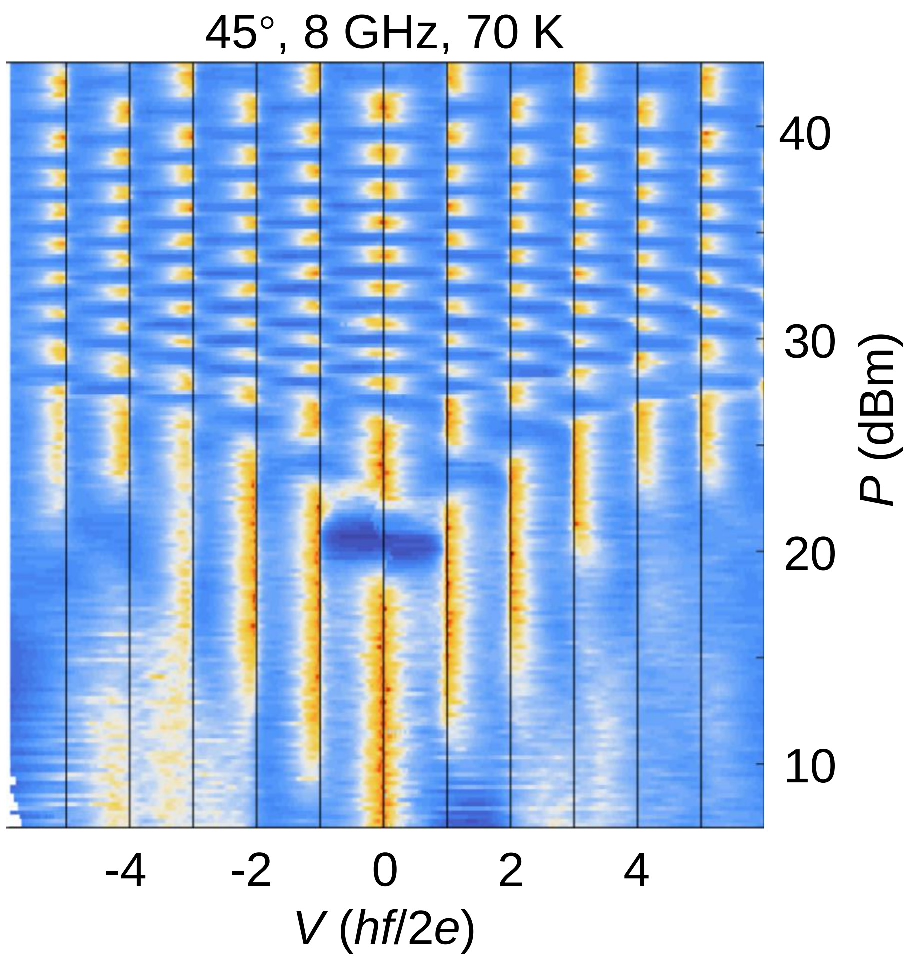
Contrasting results

Shapiro steps at ±1/2



S. Zhao, *et al.*, *Science* **382,** 1422 (2023)

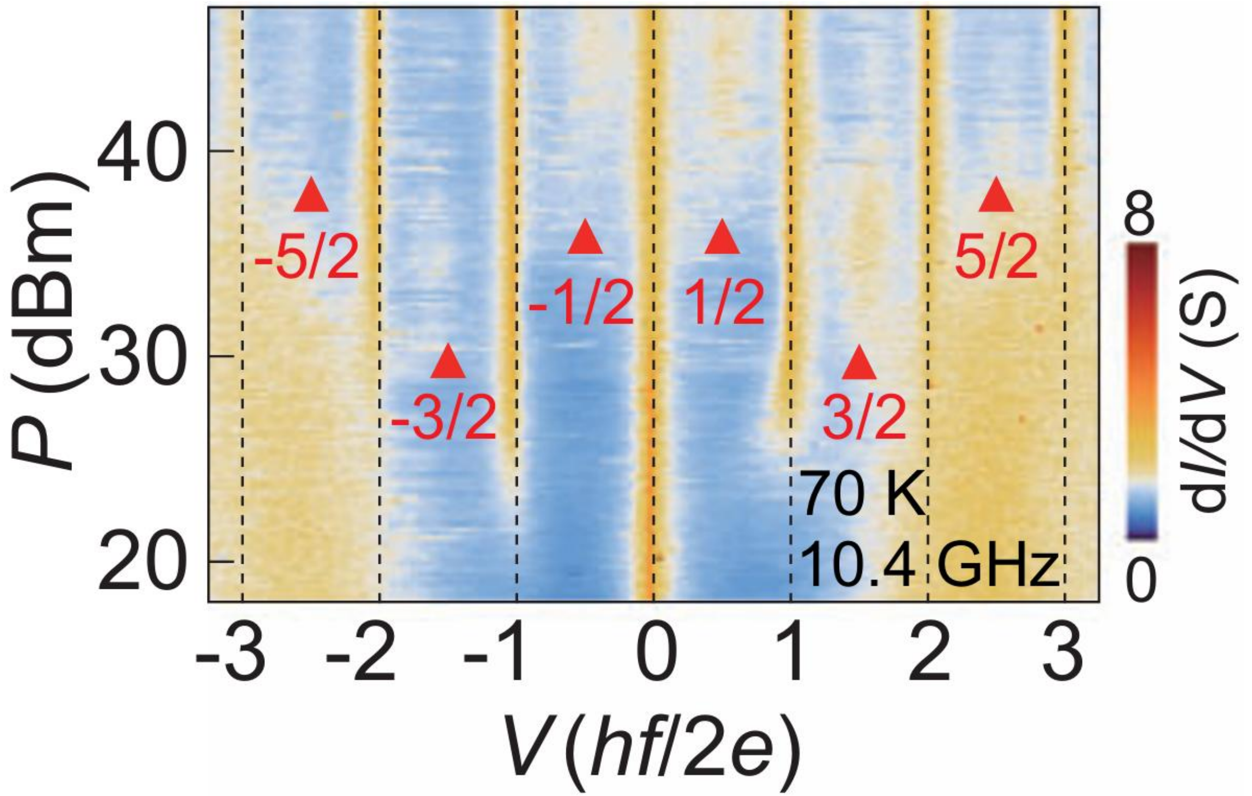
Absence of fractional steps



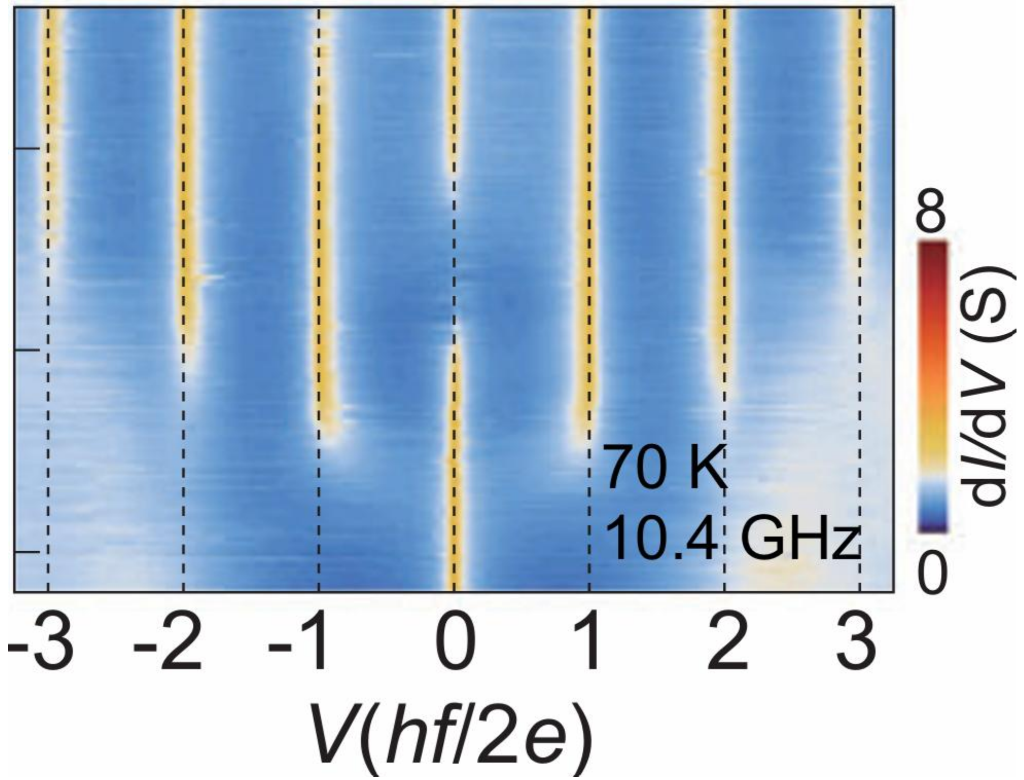
Y. Zhu, *et al.*, *Natl. Sci. Rev.* **13,** nwaf569 (2026)

Metastable fractional Shapiro steps

- 45°-twisted Bi-2212 junction
- 70 K: half integer steps

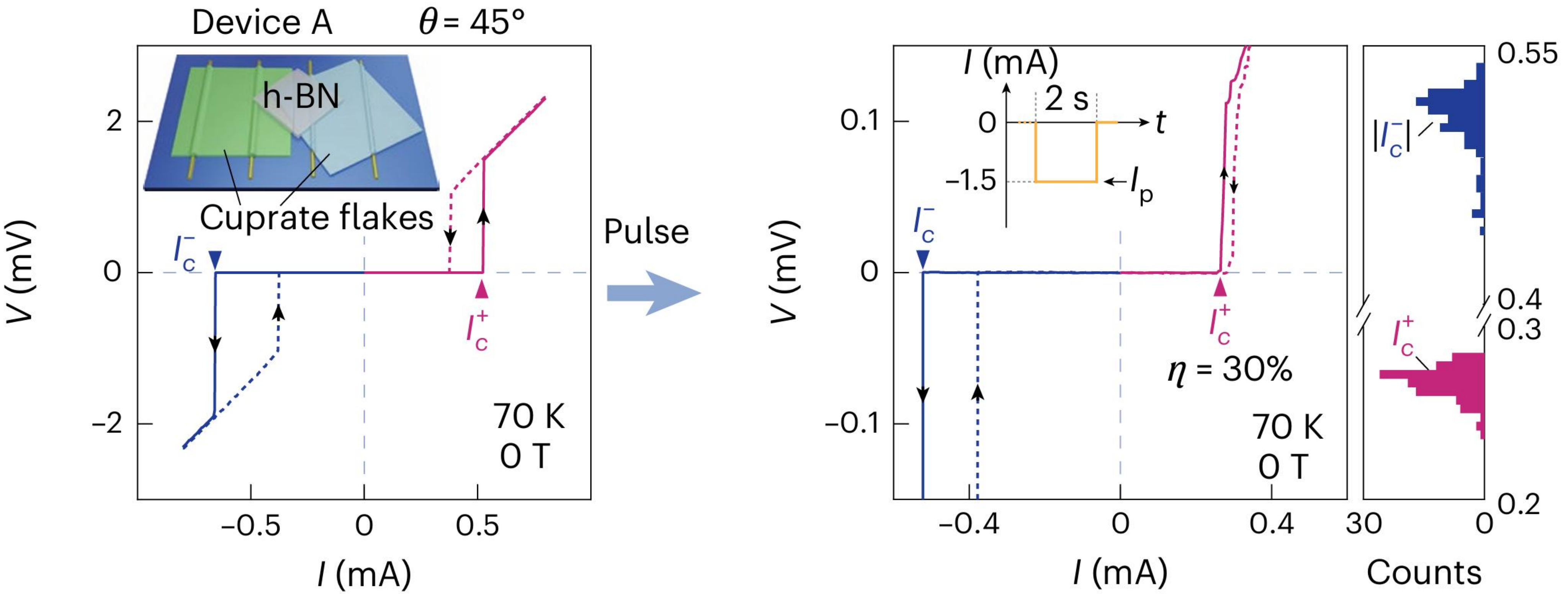


vanish after thermal cycling



Y. Zhu, *et al.*, *Natl. Sci. Rev.* **13,** nwaf569 (2026)

Pulse induced Josephson diode effect



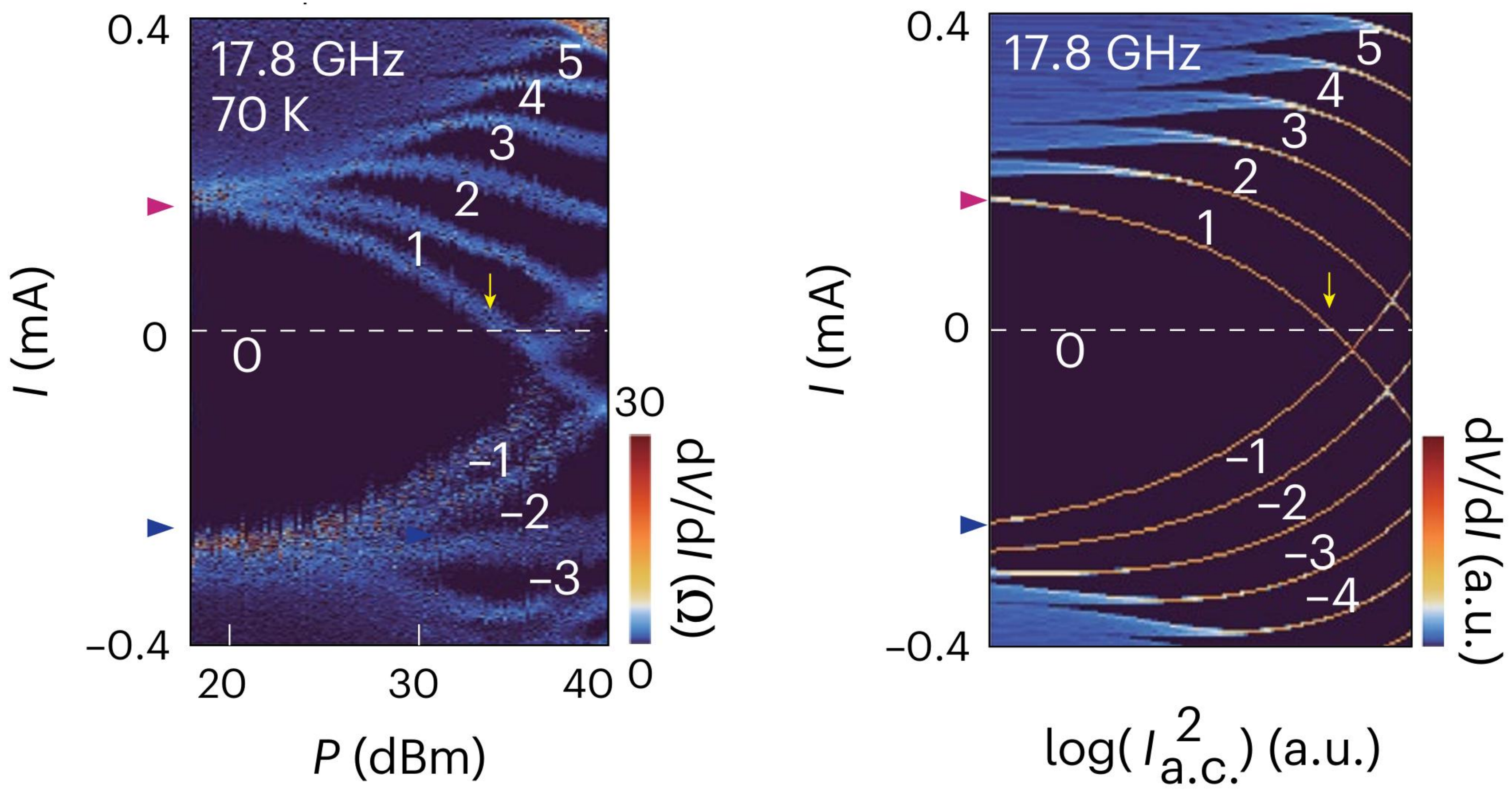
H. Wang, *et al., Nat. Phys.* **22,** 47 (2026)

Pulse induced Josephson diode effect

Experimental data

Simulation

$$J = J_{c1}\sin\varphi + J_{c2}\sin 2\varphi - J_m\cos\varphi$$



H. Wang, *et al., Nat. Phys.* **22,** 47 (2026)

Summary on 2D superconductors with topology

- WTe_2 and stanene show possible coexistence of edge state and superconducting bulk
- Twisted cuprate bilayer is theoretically predicted to be a high-temperature topological superconductor, yet experimentally its pairing symmetry is still under debate

Thanks!

dingzhang@tsinghua.edu.cn