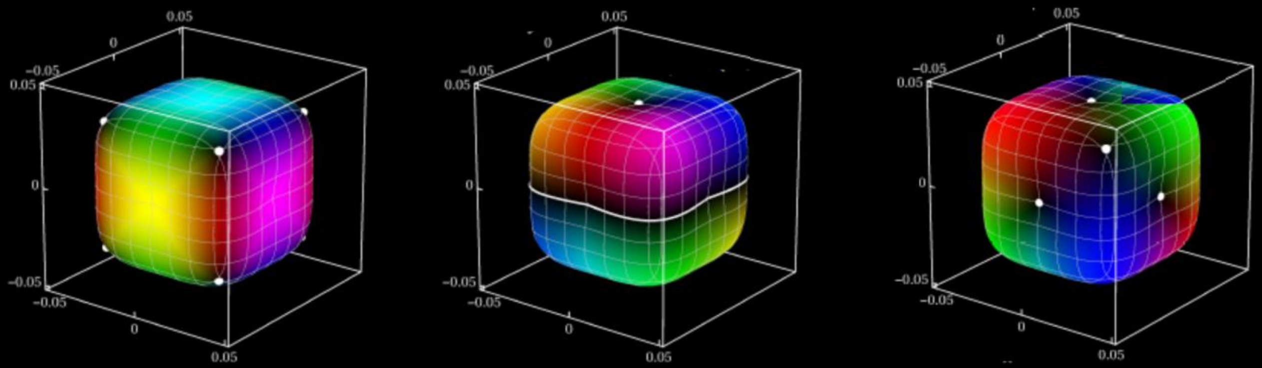
Quantum Materials Center



ECMP Career Paths:

Superconductivity in Strong Spin-Orbit Materials

Johnpierre Paglione

Maryland Quantum Materials Center
Department of Physics
University of Maryland

UNIVERSITY OF MARYLAND

GORDON AND BETTY MOORE FOUNDATION

NSF

DOE – ARRA: EARLY CAREER RESEARCH PROGRAM
Funding Opportunity: DE-FOA-0000751
CDFA: 81.049

Non-Centrosymmetric Topological Superconductivity

Principal Investigator (PI):	Dr. Johnpierre Paglione
Position Title of PI:	Assistant Professor
Applicant/Institution:	University of Maryland, College Park
DOE/Office of Science Program Office:	Basic Energy Sciences (BES)

Awarded Summer 2013

Project Summary

Topological insulators (TIs) are a newly discovered class of materials with strong potential for impact in both fundamental science and future technologies. Differing from conventional insulators by the presence of a metallic, topologically-protected surface state that is completely spin-polarized, these materials offer a new avenue for technologies based on the manipulation of electron spin (rather than charge) in solids, as well as potential for other advances in high-mobility devices, spintronics and fault-tolerant quantum computation. Coupling these protected states with the perfect conductivity found in a superconductor has the potential to not only help elucidate new physics, but also to establish the groundwork for new ways to exploit the potential of technologies that combine the unique features of each state of matter. This proposal presents a research program focused on the synthesis, characterization and optimization of topological superconductors to help elucidate the scientific and technological potential of these materials, as well as provide new routes to realizing exotic phenomena such as Majorana fermion physics. Our plan is to establish a materials synthesis and measurement program to produce and characterize new topological superconductor compounds, exploring the junction between TI, superconducting and magnetic ground states and the potential for stabilization of new cooperative phenomena utilizing both symmetry (topological protection) and thermodynamics (superconducting energy gap). Experiments will also be sought to realize systems with appropriate geometries to observe Majorana fermions, but without the need for proximity effect junctions. Focus will be placed on the exploration of several sub-families of Heusler compounds with the ABC ternary structure. Preliminary work has realized a new family of rare earth-based non-centrosymmetric superconductors with strong spin-orbit coupling, robust thermodynamic superconducting states and the intrinsic ability to tune long range magnetic order by the choice/combination of rare earth species or admixture.

RAPID COMMUNICATIONS

PHYSICAL REVIEW B **84**, 220504(R) (2011)

Superconductivity in the topological semimetal YPtBi

N. P. Butch,* P. Syers, K. Kirshenbaum, A. P. Hope, and J. Paglione

Center for Nanophysics and Advanced Materials, Department of Physics, University of Maryland, College Park, Maryland 20742, USA

(Received 4 December 2011; published 21 December 2011)

The noncentrosymmetric half Heusler compound YPtBi exhibits superconductivity below a critical temperature $T_c = 0.77$ K with a zero-temperature upper critical field $H_{c2}(0) = 1.5$ T. Magnetoresistance and Hall measurements support theoretical predictions that this material is a topologically nontrivial semimetal having a surprisingly low positive charge-carrier density of 2×10^{18} cm^{-3}. Unconventional linear magnetoresistance and beating in Shubnikov–de Haas oscillations point to spin-orbit split Fermi surfaces. The sensitivity of magnetoresistance to surface roughness suggests a possible contribution from surface states. The combination of noncentrosymmetry and strong spin-orbit coupling in YPtBi presents a promising platform for the investigation of topological superconductivity.

RAPID COMMUNICATIONS

PHYSICAL REVIEW B **84**, 220504(R) (2011)

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of topological supercon…

RESEARCH ARTICLE

Nakajima *et al.* Sci. Adv. 2015;1:e1500242 5 June 2015

SUPERCONDUCTORS

Topological *R*PdBi half-Heusler semimetals: A new family of noncentrosymmetric magnetic superconductors

10.1126/sciadv.1500242

Yasuyuki Nakajima,[1] Rongwei Hu,[1] Kevin Kirshenbaum,[1] Alex Hughes,[1] Paul Syers,[1] Xiangfeng Wang,[1] Kefeng Wang,[1] Renxiong Wang,[1] Shanta R. Saha,[1] Daniel Pratt,[2] Jeffrey W. Lynn,[2] Johnpierre Paglione[1]*

We report superconductivity and magnetism in a new family of topological semimetals, the ternary half-Heusler compound *R*PdBi (*R*: rare earth). In this series, tuning of the rare earth *f*-electron component allows for simultaneous control of both lattice density via lanthanide contraction and the strength of magnetic interaction via de Gennes scaling, allowing for a unique tuning of the normal-state band inversion strength, superconducting pairing, and magnetically ordered ground states. Antiferromagnetism with ordering vector (½,½,½) occurs below a Néel temperature that scales with de Gennes factor dG, whereas a superconducting transition is simultaneously supressed with increasing *dG*. With superconductivity appearing in a system with noncentrosymmetric crystallographic symmetry, the possibility of spin-triplet Cooper pairing with nontrivial topology analogous to that predicted for the normal-state electronic structure provides a unique and rich opportunity to realize both predicted and new exotic excitations in topological materials.

RAPID COMMUNICATIONS

PHYSICAL REVIEW B **84**, 220504(R) (2011)

Superconductivity in the topological semimetal YPtBi

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RESEARCH ARTICLE

SUPERCONDUCTORS

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Kim *et al.*, *Sci. Adv.* 2018; **4** : eaao4513 6 April 2018

SCIENCE ADVANCES | RESEARCH ARTICLE

CONDENSED MATTER PHYSICS

Beyond triplet: Unconventional superconductivity in a spin-3/2 topological semimetal

Hyunsoo Kim,[1,2,3]* Kefeng Wang,[1,2] Yasuyuki Nakajima,[1,2,4] Rongwei Hu,[1,2] Steven Ziemak,[1,2] Paul Syers,[1,2] Limin Wang,[1,2] Halyna Hodovanets,[1,2] Jonathan D. Denlinger,[5] Philip M. R. Brydon,[6,7] Daniel F. Agterberg,[8] Makariy A. Tanatar,[3] Ruslan Prozorov,[3] Johnpierre Paglione[1,2]*

In all known fermionic superfluids, Cooper pairs are composed of spin-1/2 quasi-particles that pair to form either spin-singlet or spin-triplet bound states. The "spin" of a Bloch electron, however, is fixed by the symmetries of the crystal and the atomic orbitals from which it is derived and, in some cases, can behave as if it were a spin-3/2 particle. The superconducting state of such a system allows pairing beyond spin-triplet, with higher spin quasi-particles combining to form quintet or septet pairs. We report evidence of unconventional superconductivity emerging from a spin-3/2 quasi-particle electronic structure in the half-Heusler semimetal YPtBi, a low-carrier density noncentrosymmetric cubic material with a high symmetry that preserves the *p*-like $j = 3/2$ manifold in the Bi-based Γ_8 band in the presence of strong spin-orbit coupling. With a striking linear temperature dependence of the London penetration depth, the existence of line nodes in the superconducting order parameter Δ is directly explained by a mixed-parity Cooper pairing model with high total angular momentum, consistent with a high-spin fermionic superfluid state. We propose a $k \cdot p$ model of the $j = 3/2$ fermions to explain how a dominant $J = 3$ septet pairing state is the simplest solution that naturally produces nodes in the mixed even-odd parity gap. Together with the underlying topologically nontrivial band structure, the unconventional pairing in this system represents a truly novel form of superfluidity that has strong potential for leading the development of a new series of topological superconductors.

RAPID COMMUNICATIONS

PHYSICAL REVIEW B **84**, 220504(R) (2011)

Superconductivity in the topological semimetal YPtBi

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PHYSICAL REVIEW LETTERS

Highlights Recent Accepted Collections Authors Referees Search Press About Editor

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Pairing of $j = 3/2$ Fermions in Half-Heusler Superconductors

P. M. R. Brydon, Limin Wang, M. Weinert, and D. F. Agterberg
Phys. Rev. Lett. **116**, 177001 – Published 27 April 2016

Article | References | Citing Articles (124) | Supplemental Material | PDF | HTML | Export Citation

ABSTRACT

We theoretically consider the superconductivity of the topological half-Heusler semimetals YPtBi and
LuPtBi. We show
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materials, the *s*-w
line nodes. Our a
the half-Heuslers.

We acknowledge support from Microsoft Station Q, LPS-CMTC, and JQI-NSF-PFC (P. M. R. B), J. Paglione and the U.S. Department of Energy Early Career Award No. DE-SC-0010605 (L. W.), and the NSF via DMREF-1335215 (D. F. A. and M. W.). The authors thank A. Kapitulnik, H. Kim, and J. Paglione for sharing unpublished experimental data and for stimulating discussions. C. Timm is thanked for helpful comments on the manuscript.

June 2015

CH ARTICLE

Kim *et al.*, *Sci. Adv.* 2018;**4**:eaao4513 6 April 2018

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ajima,[1,2,4] Rongwei Hu,[1,2] Steven Ziemak,[1,2]
[2] Jonathan D. Denlinger,[5]
riy A. Tanatar,[3]

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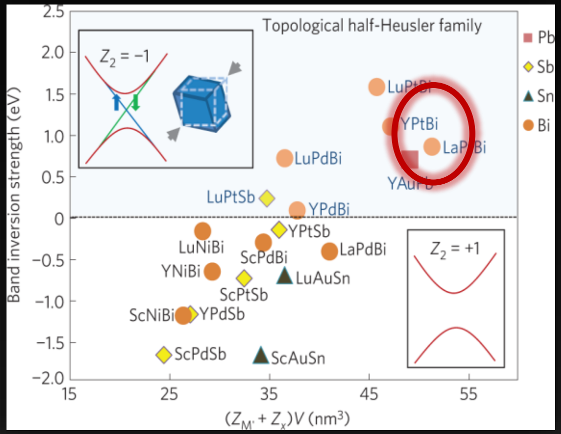
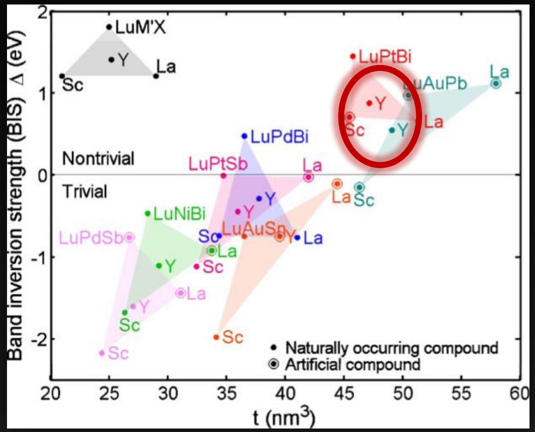
the Heusler family of materials

Band Inversion in *half-Heusler compounds*

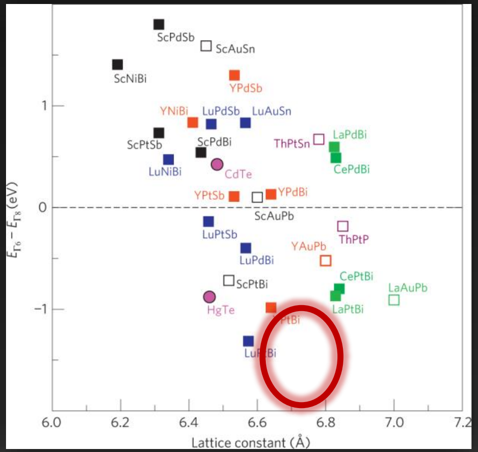
*** Strong band inversion in YPtBi**



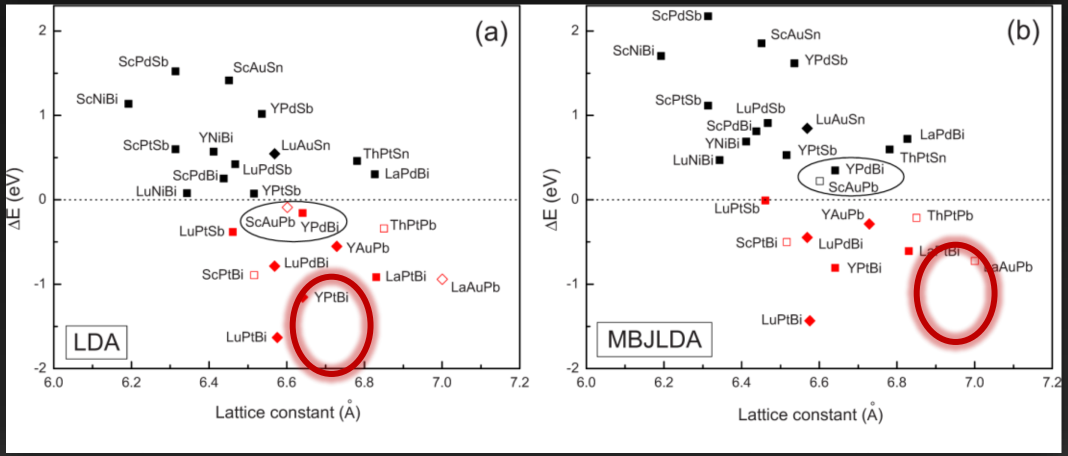
Lin *et* al, Nature Materials (2010)



Al-Sawai *et al*, PRB (2010)



Chadov *et al,* Nature Materials (2010)

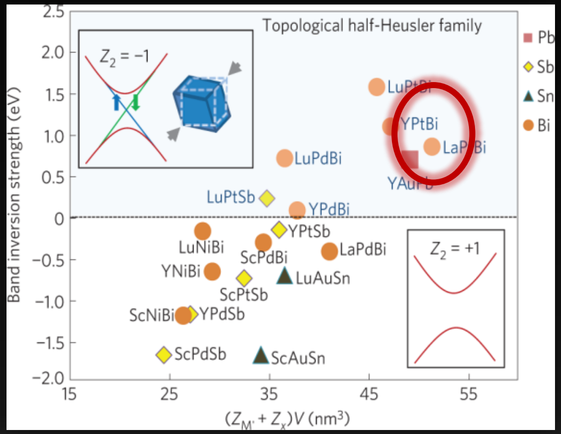


Feng *et* al, PRB (2010) Xiao *et* al, PRL (2010)

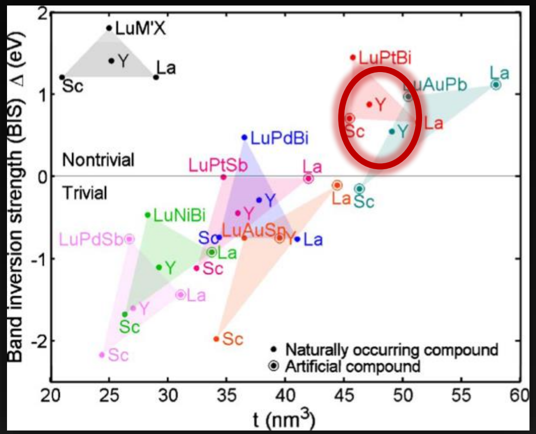
the Heusler family of materials

Band Inversion in *half-Heusler compounds*

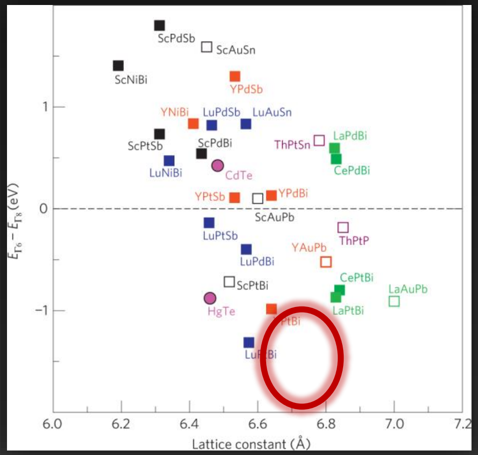
*** Strong band inversion in YPtBi**



Lin *et* al, Nature Materials (2010)



Al-Sawai *et al*, PRB (2010)



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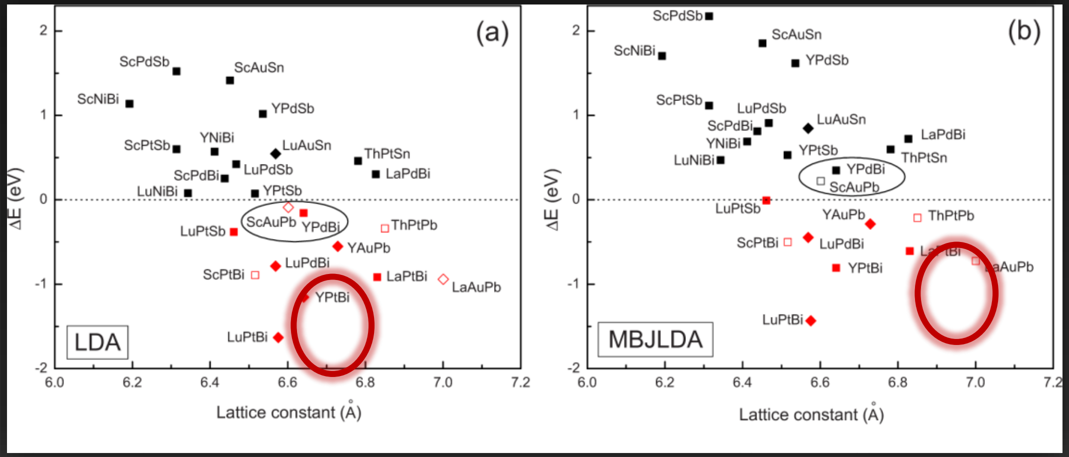
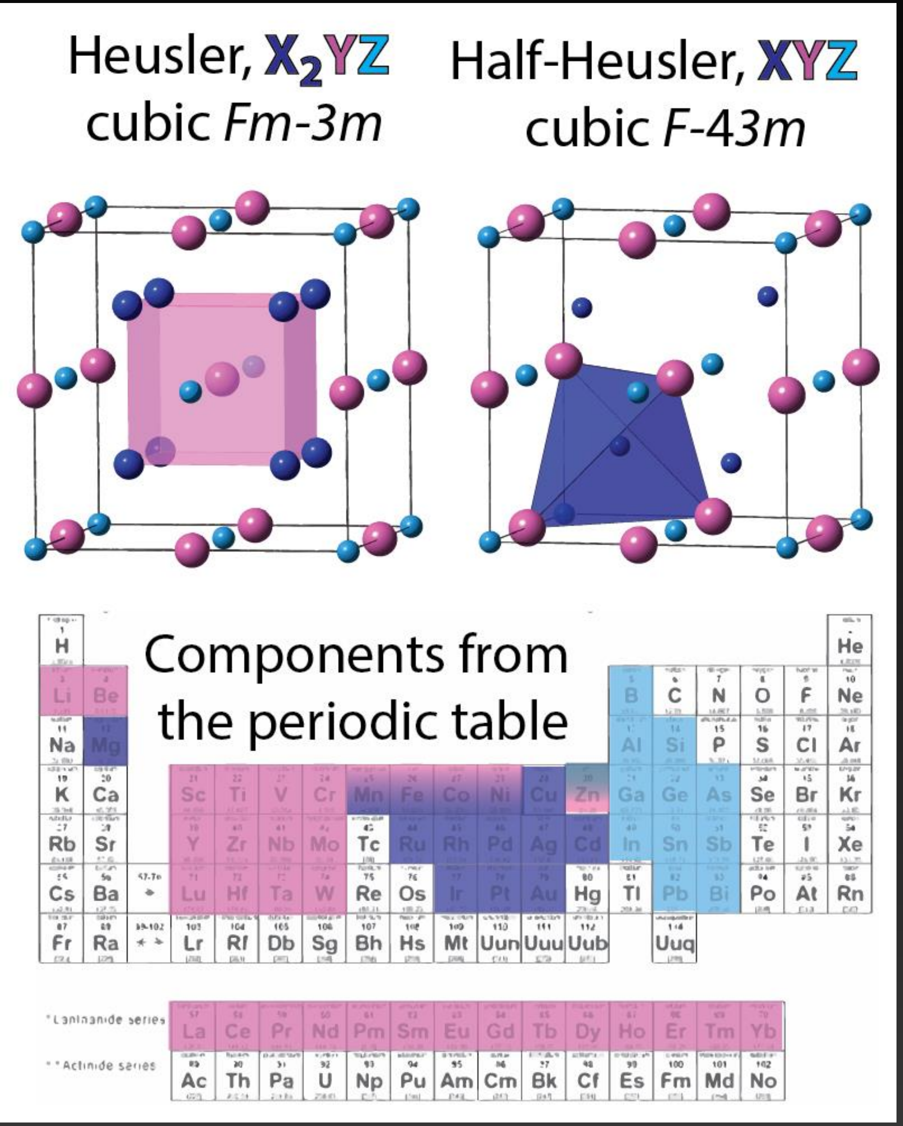


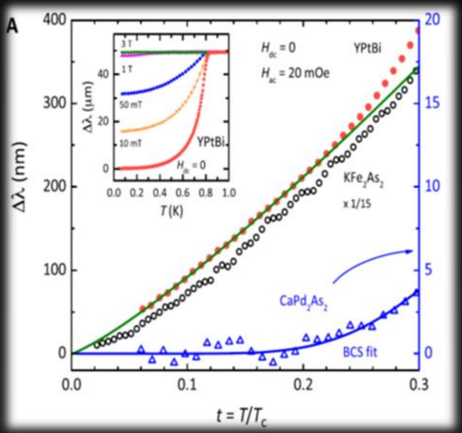
Feng *et* al, PRB (2010) Xiao *et* al, PRL (2010)



~1,250 known intermetallics.

superconductivity in YPtBi

→ *first high-spin superfluid*



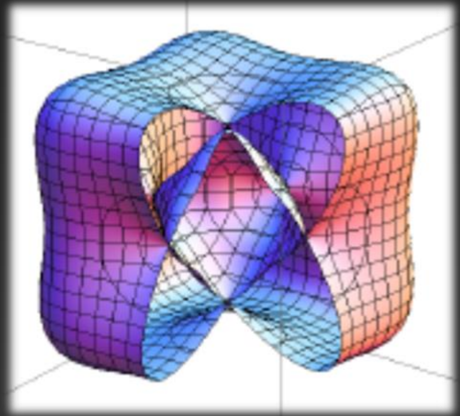
SCIENCE ADVANCES | RESEARCH ARTICLE

CONDENSED MATTER PHYSICS

Beyond triplet: Unconventional superconductivity in a spin-3/2 topological semimetal

Hyunsoo Kim,[1,2,3]* Kefeng Wang,[1,2] Yasuyuki Nakajima,[1,2,4] Rongwei Hu,[1,2] Steven Ziemak,[1,2] Paul Syers,[1,2] Limin Wang,[1,2] Halyna Hodovanets,[1,2] Jonathan D. Denlinger,[5] Philip M. R. Brydon,[6,7] Daniel F. Agterberg,[8] Makariy A. Tanatar,[3] Ruslan Prozorov,[3] Johnpierre Paglione[1,2]*

Science Advances 4, 4513 (2018)



PRL **116,** 177001 (2016) PHYSICAL REVIEW LETTERS week ending 29 APRIL 2016

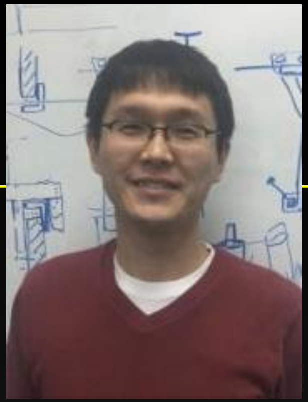
Pairing of $j = 3/2$ Fermions in Half-Heusler Superconductors

P. M. R. Brydon,[1,2,*] Limin Wang,[3] M. Weinert,[4] and D. F. Agterberg[4]

[1]*Condensed Matter Theory Center and Joint Quantum Institute, Department of Physics, University of Maryland, College Park, Maryland 20742, USA*
[2]*Department of Physics, University of Otago, P.O. Box 56, Dunedin 9054, New Zealand*
[3]*Center for Nanophysics and Advanced Materials, Department of Physics, University of Maryland, College Park,*
[4]*Department of Physics, University of Wisconsin, Milwaukee, Wisconsin 53201, USA*

(Received 5 November 2015; published 27 April 2016)

Phys. Rev. Lett. 116, 177001 (2016)

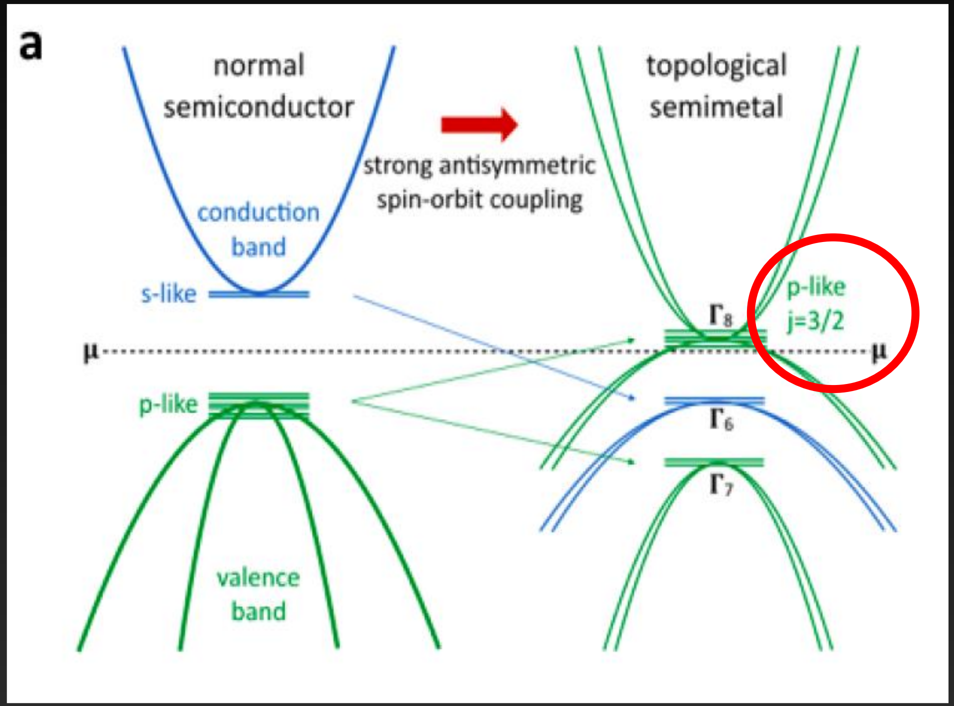


Hyunsoo Kim

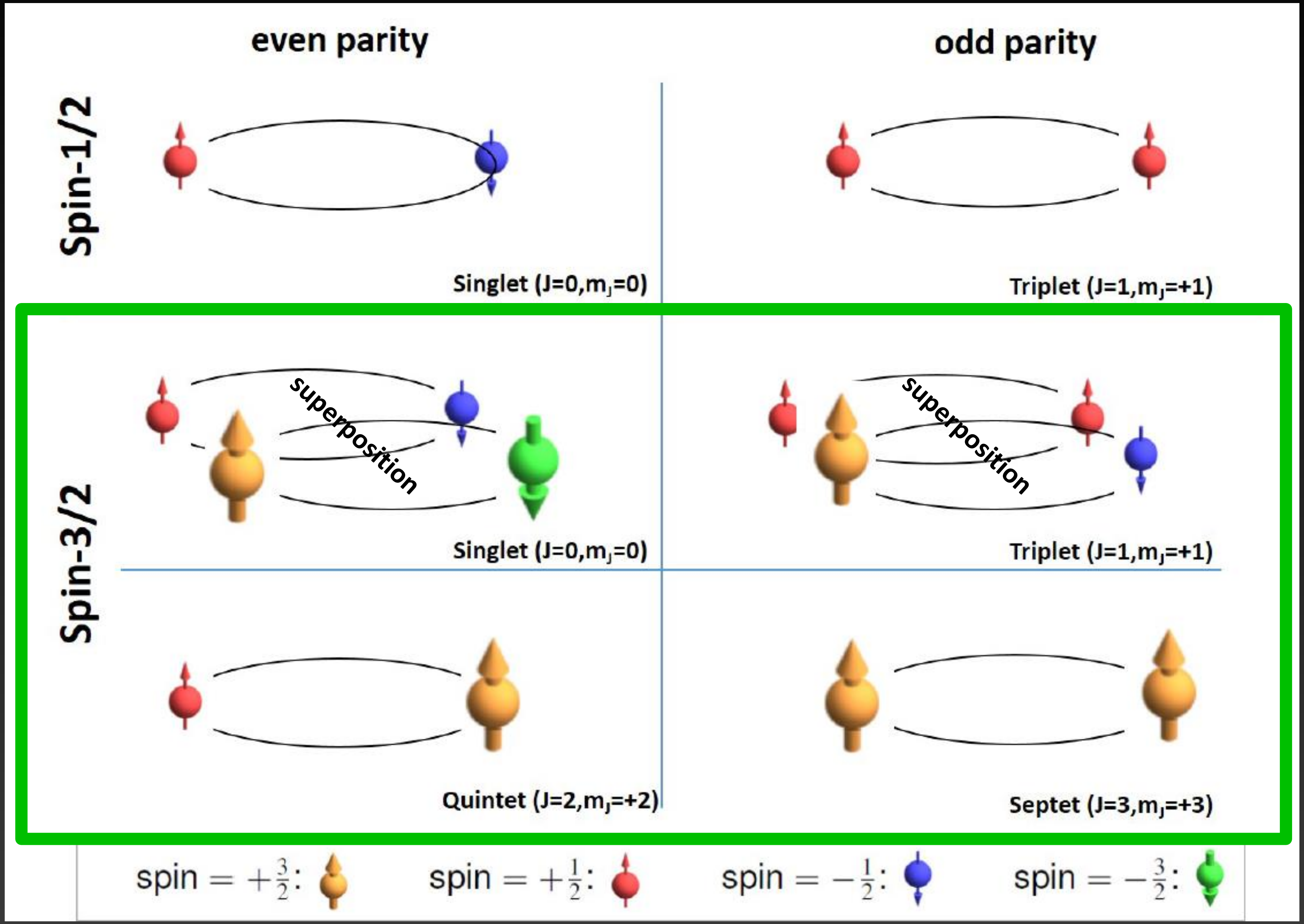
Dan Agterberg (theory)
U Wisconsin Milwaukee
Philip Brydon (theory)
University of Maryland

the Heusler family of materials

spin-3/2 pairing



- p-like states with j=3/2 remain degenerate

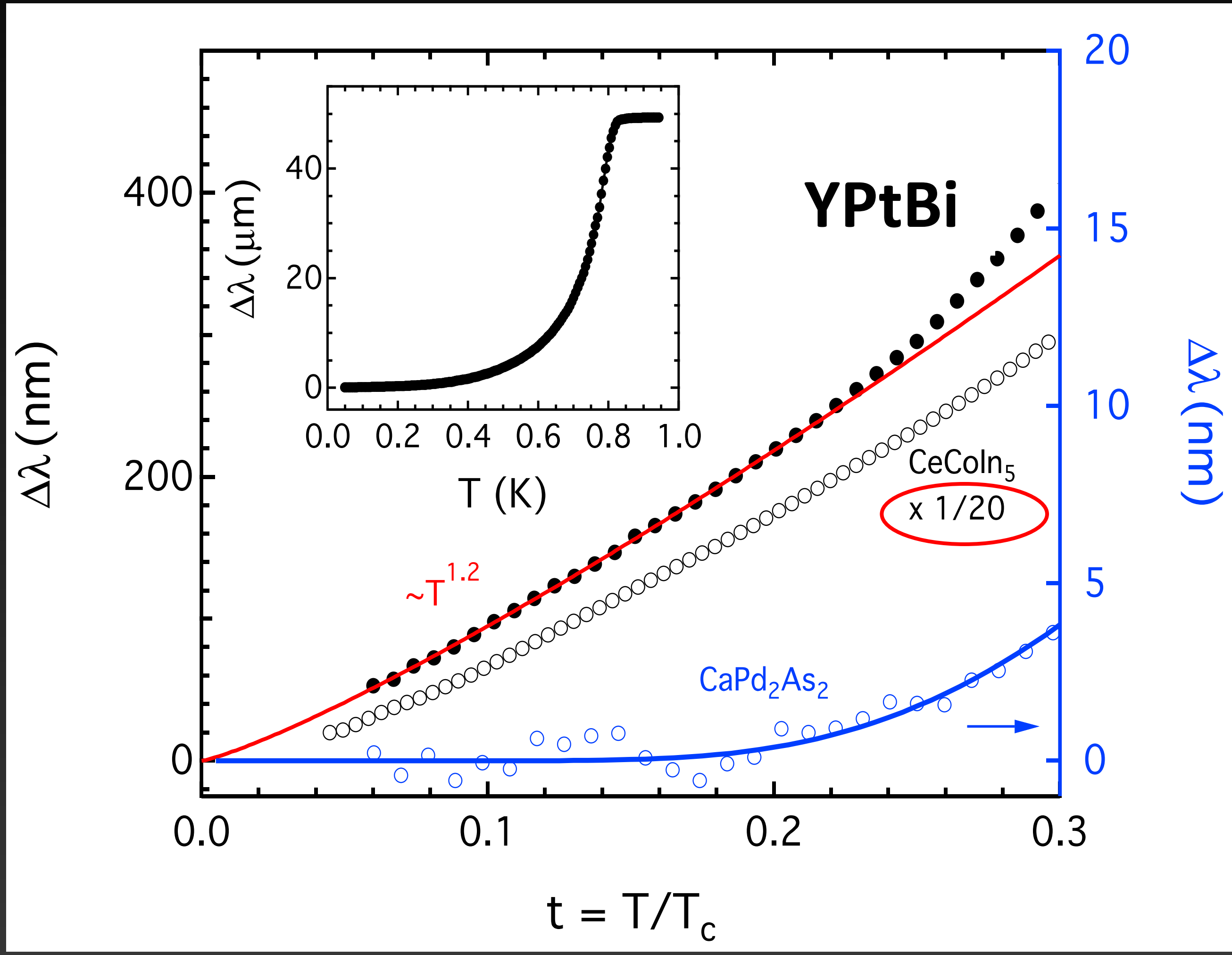


the Heusler family of materials

TDR Penetration Depth

Hyunsoo Kim

- Linear penetration depth ($\Delta\lambda \sim T^{1.2}$): **line nodes**
- Similar to d-wave SCs KFe_2As_2, $CeCoIn_5$…
- Low carrier density – extremely large λ ~2 μm!
- Scattering rate parameter $T^* \sim 0.07T_c$



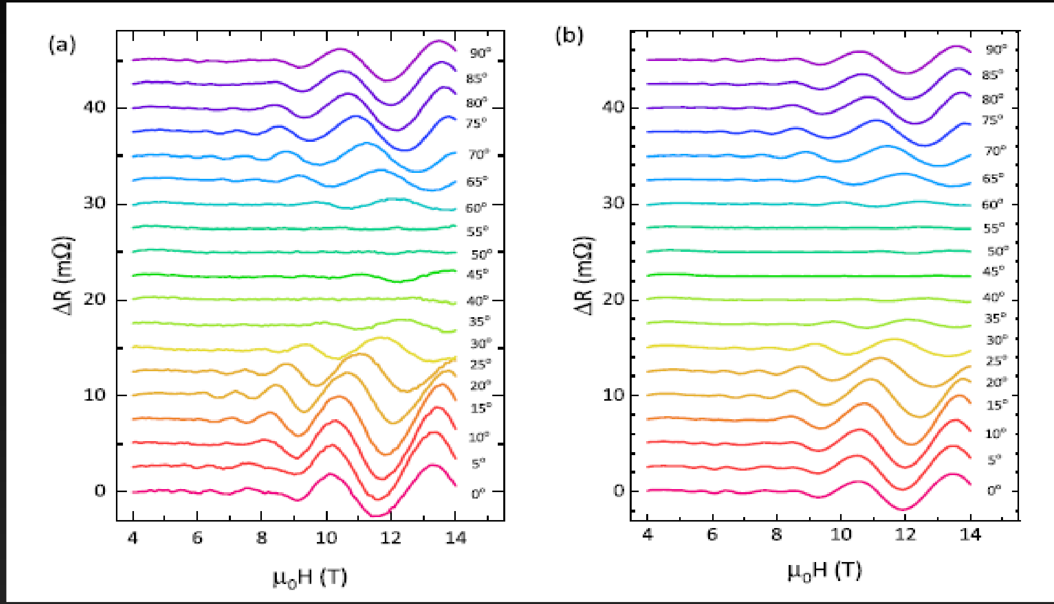
H. Kim et al, Sci. Adv. 2018

the Heusler family of materials

PHYSICAL REVIEW RESEARCH **4**, 033169 (2022)

Quantum oscillations of the $j = 3/2$ Fermi surface in the topological semimetal YPtBi

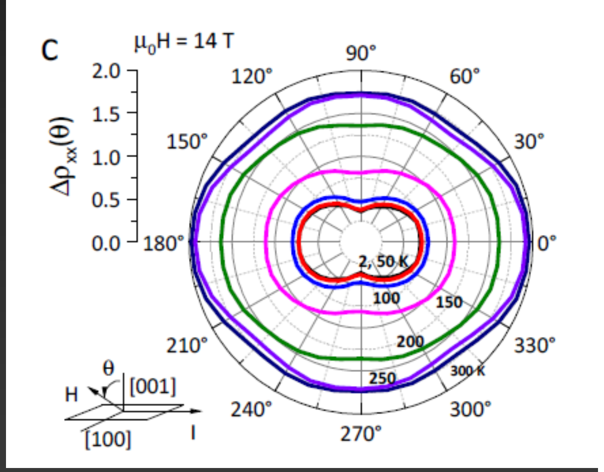
Hyunsoo Kim,[1,2,*] Junhyun Lee,[3,4,*] Halyna Hodovanets,[1,2] Kefeng Wang,[1] Jay D. Sau,[3] and Johnpierre Paglione[1,5,†]
[1] *Maryland Quantum Materials Center, Department of Physics, University of Maryland, College Park, Maryland 20742, USA*
[2] *Department of Physics, Missouri University of Science and Technology, Rolla, Missouri 65409, USA*
[3] *Department of Physics, Condensed Matter Theory Center and the Joint Quantum Institute, University of Maryland, College Park, Maryland 20742, USA*
[4] *Department of Physics and Astronomy, Center for Materials Theory, Rutgers University, Piscataway, New Jersey 08854, USA*
[5] *Canadian Institute for Advanced Research, Toronto, Ontario, Canada M5G 1Z8*

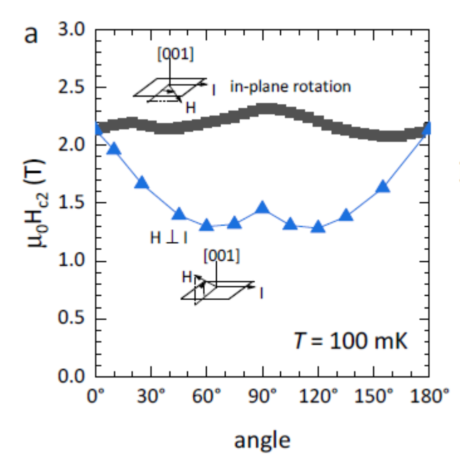


Symmetry-breaking normal state response and surface superconductivity in topological semimetal YPtBi

Hyunsoo Kim,[1,2] Tristin Metz,[1] Halyna Hodovanets,[1,2] Daniel Kraft,[1] Kefeng Wang,[1] Yun Suk Eo,[1,3] and Johnpierre Paglione[1,4]
[1] *Maryland Quantum Materials Center, Department of Physics, University of Maryland, College Park, Maryland 20742, USA*
[2] *Department of Physics, Missouri University of Science and Technology, Rolla, Missouri 65409, USA*
[3] *Department of Physics & Astronomy, Texas Tech University, Lubbock, Texas 79410, USA*
[4] *Canadian Institute for Advanced Research, Toronto, Ontario M5G 1Z8, Canada*

(Dated: March 1, 2024)





UTe_2 – an evolving story!

PHYSICAL REVIEW MATERIALS **6**, 073401 (2022)

Single crystal growth of superconducting UTe_2 by molten salt flux method

H. Sakai,* P. Opletal, Y. Tokiwa, E. Yamamoto, Y. Tokunaga, S. Kambe, and Y. Haga†
Advanced Science Research Center, Japan Atomic Energy Agency, Tokai, Ibaraki 319-1195, Japan

Medical Breakthroughs

Unveiling the Mysteries of Uranium Ditelluride: A New Era for Superconductors

NEWS AND VIEWS | 28 June 2023

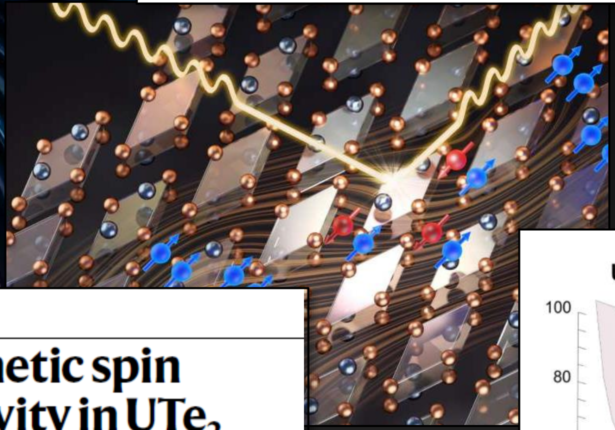
Widespread pair density waves spark superconductor search

Periodic waves of changing electron density are linked to the ability of some materials to conduct electricity without resistance. Four studies reveal that such waves could emerge in more materials than expected.

Hui Chen & Hong-Jun Gao

First Observation of de Haas-van Alphen Effect and Fermi Surfaces in Unconventional Superconductor UTe_2

Dai Aoki[1]*, Hironori Sakai[2], Petr Opletal[2], Yoshifumi Tokiwa[2], Jun Ishizuka[3], Youichi Yanase[4], Hisatomo Harima[5], Ai Nakamura[1], Dexin Li[1], Yoshiya Homma[1] Yusei Shimizu[1], Georg Knebel[6], Jacques Flouquet[6], and Yoshinori Haga[2]



PHYSICAL REVIEW B **106**, L060505 (2022)

Letter | Editors' Suggestion

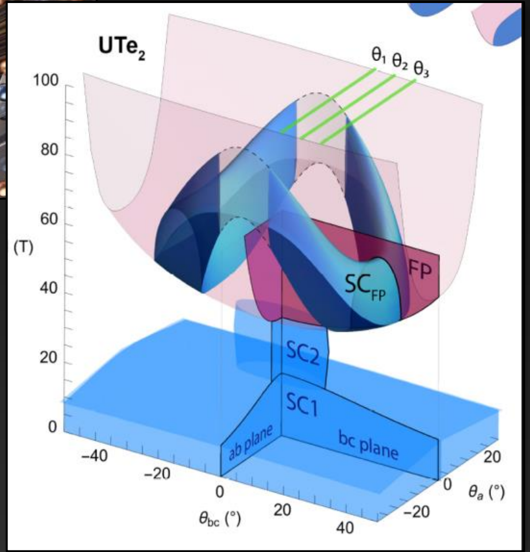
***c*-axis transport in UTe_2: Evidence of three-dimensional conductivity component**

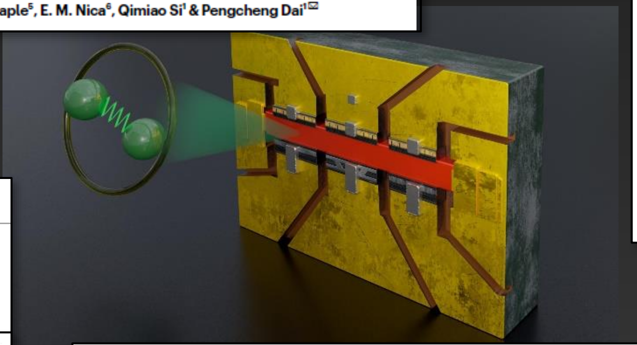
Yun Suk Eo,[1] Shouzheng Liu,[2] Shanta R. Saha,[1] Hyunsoo Kim,[1,*] Sheng Ran,[1,3,†] Jarryd A. Horn,[1] Halyna Hodovanets,[1,*] John Collini,[1] Tristin Metz,[1] Wesley T. Fuhrman,[1] Andriy H. Nevidomskyy,[4] Jonathan D. Denlinger,[5] Nicholas P. Butch,[1,3] Michael S. Fuhrer,[6,7] L. Andrew W

Article

Resonance from antiferromagnetic spin fluctuations for superconductivity in UTe_2

umbach[2,3], Andrey Podlesnyak[4], Yuhang Deng[5], Camilla Moir[5],
M. Brian Maple[5], E. M. Nica[6], Qimiao Si[1] & Pengcheng Dai[1]



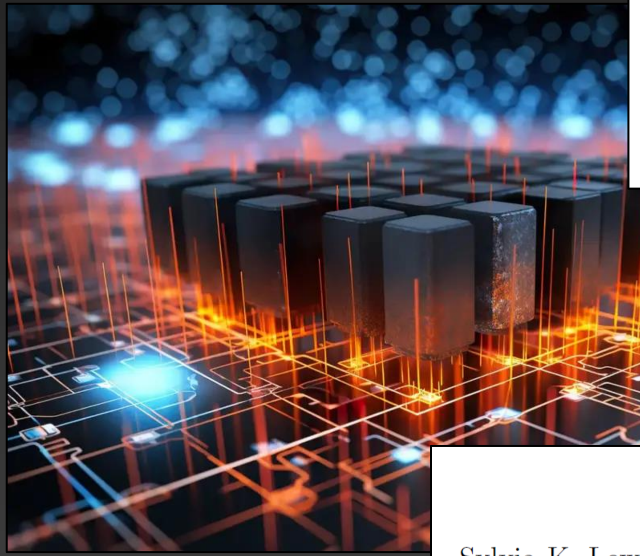


Article

Detection of a pair density wave state in UTe_2

https://doi.org/10.1038/s41586-023-05919-7
Received: 6 September 2022
Accepte

Qiangqiang Gu[1,11], Joseph P. Carroll[1,2,11], Shuqiu Wang[1,3,11], Sheng Ran[4], Christopher Broyles[4], Hasan Siddiquee[4], Nicholas P. Butch[5,6], Shanta R. Saha[5], Johnpierre Paglione[5,7], J. C. Séamus Davis[1,2,3,8] & Xiaolong Liu[1,9,10]



Article

Magnetic-field-sensitive charge density waves in the superconductor UTe_2

https://doi.org/10.1038/s41586-023-06005-8
Received: 27 July 2022
Accepted: 23 March 2023

Anuva Aishwarya[1], Julian May-Mann[1,2], Arjun Raghavan[1], Laimei Nie[1,2], Marisa Romanelli[1], Sheng Ran[3,4,5], Shanta R. Saha[3], Johnpierre Paglione[3,6], Nicholas P. Butch[3,4], Eduardo Fradkin[1,2] & Vidya Madhavan[1,6]

High-Field Superconducting Halo in UTe_2

Sylvia K. Lewin[1,2,*] Peter Czajka[1,2,*] Corey E. Frank[1,2], Gicela Saucedo Salas[2], Hyeok Yoon[2], Yun Suk Eo[2], Johnpierre Paglione[2,3], Andriy H. Nevidomskyy[4], John Singleton[5], and Nicholas P. Butch[1,2]

ARTIFICIAL INTELLIGENCE

A Quantum Leap: Potential Key to Quantum Computing's Future

Published 3 months ago on July 11, 2023
By Alex McFarland

superconductivity in UTe_2

Sheng Ran
WU St. Louis

RESEARCH | *Science* **365**, 684–687 (2019) | 16 August 2019

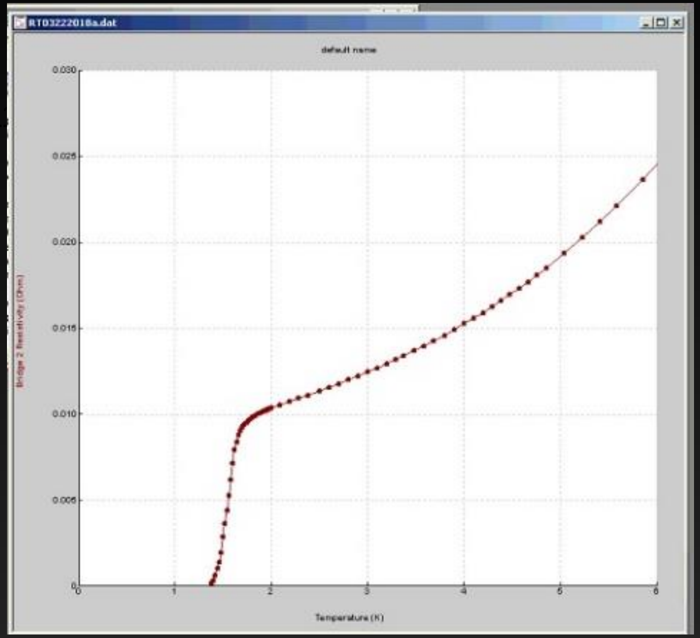
arXiv:181

SUPERCONDUCTIVITY

Nearly ferromagnetic spin-triplet superconductivity

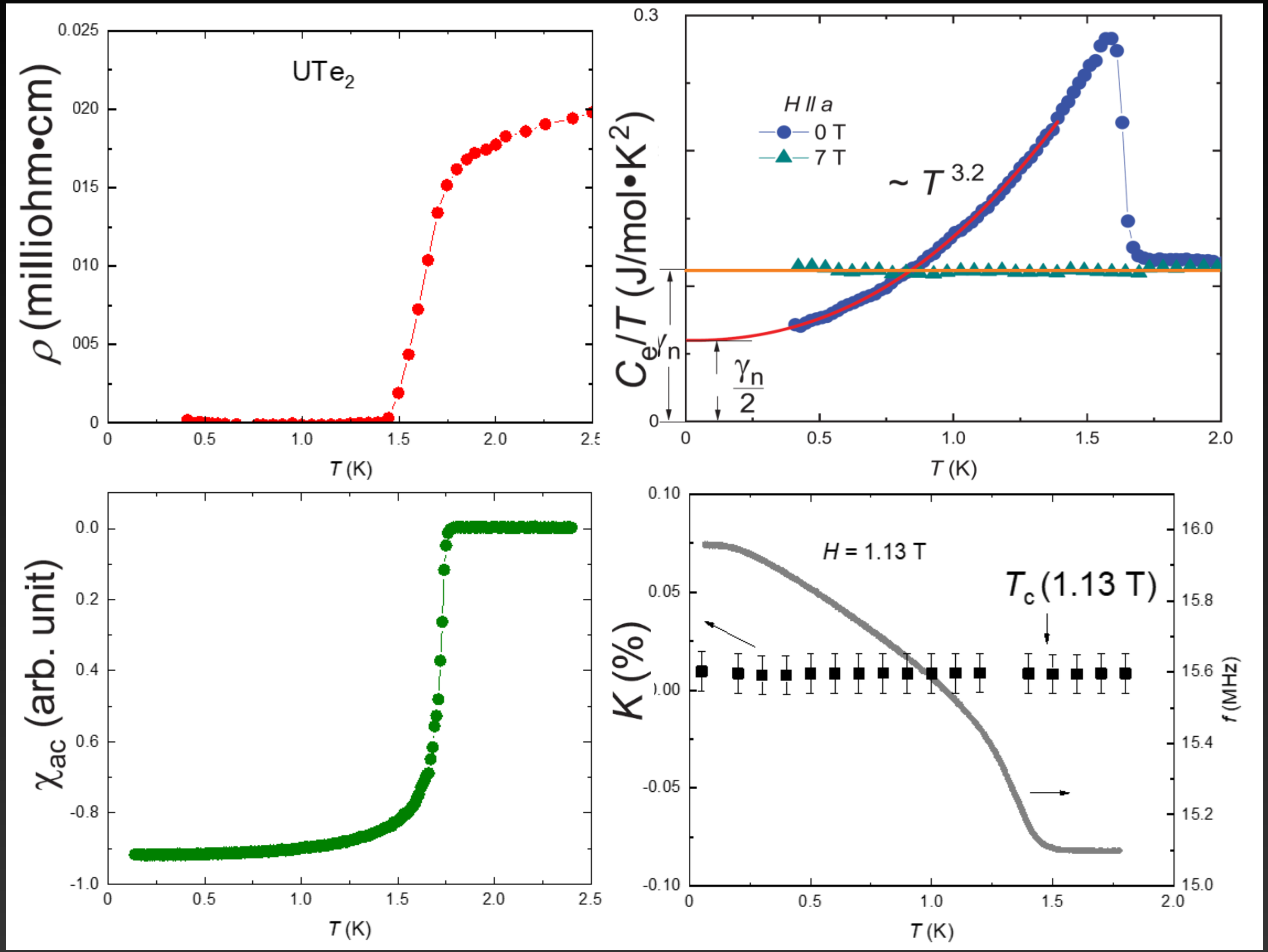
Sheng Ran[1,2*], Chris Eckberg[2], Qing-Ping Ding[3], Yuji Furukawa[3], Tristin Metz[2], Shanta R. Saha[1,2], I-Lin Liu[1,2,4], Mark Zic[2], Hyunsoo Kim[2], Johnpierre Paglione[1,2], Nicholas P. Butch[1,2*]

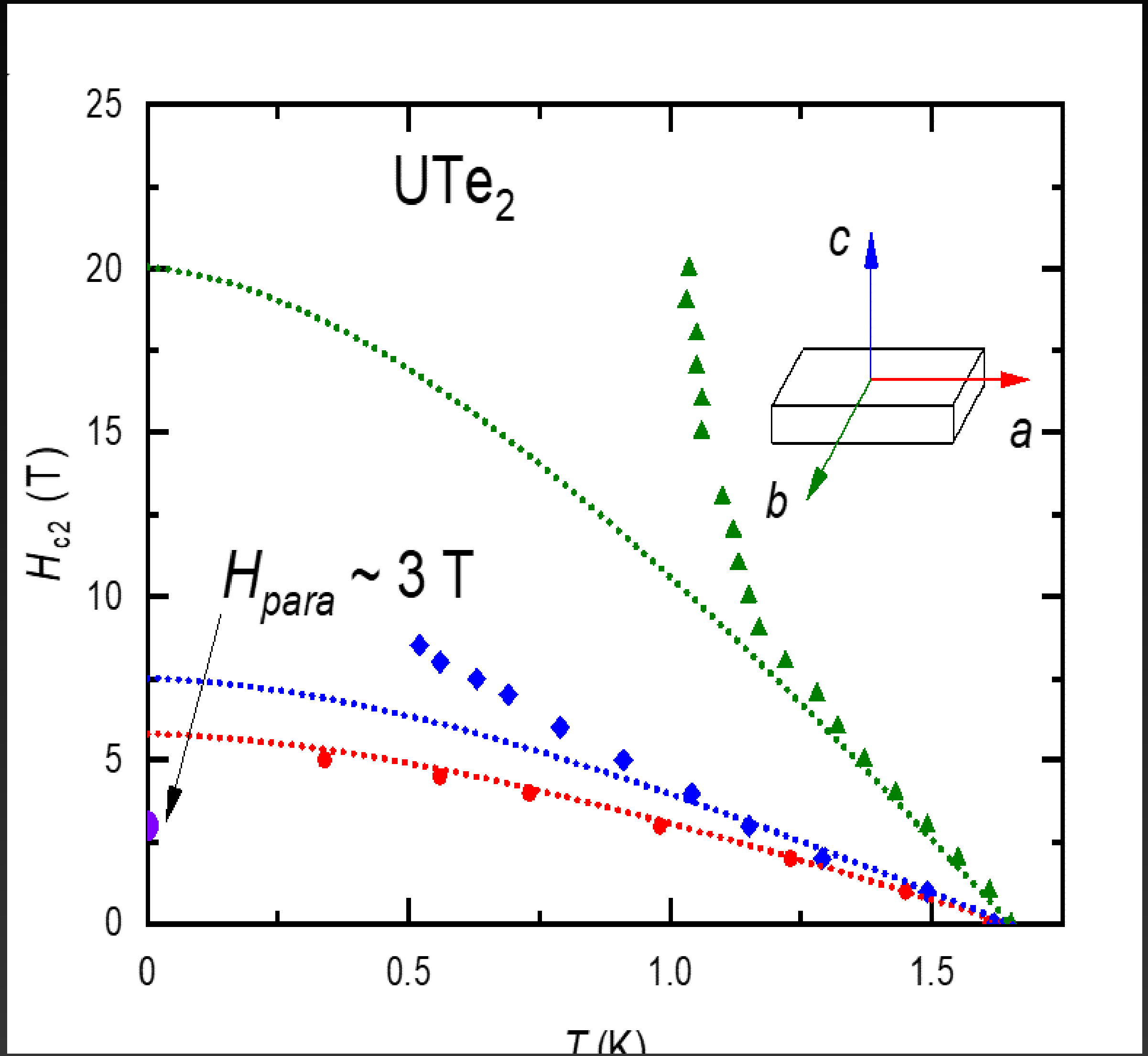
Spin-triplet superconductors potentially host topological excitations that are of interest for quantum information processing. We report the discovery of spin-triplet superconductivity in UTe_2, featuring a transition temperature of 1.6 kelvin and a very large and anisotropic upper critical field exceeding 40 teslas. This superconducting phase stability suggests that UTe_2 is related to ferromagnetic superconductors such as UGe_2, URhGe, and UCoGe. However, the lack of magnetic order and the observation of quantum critical scaling place UTe_2 at the paramagnetic end of this ferromagnetic superconductor series. A large intrinsic zero-temperature reservoir of ungapped fermions indicates a highly unconventional type of superconducting pairing.



- discovery in March 2018
- submission to Science Oct. 2018
- first presented Nov 8, 2018:
- news to Japan Nov 19 2018:
- posted to arXiv Nov 28, 2018:

superconductivity in UTe_2





S. Ran *et al*, Science 365, 684 (2019).

- **full volume SC, no NMR Knight shift**
- **“diverging” H_{c2} along (hard) b-axis**

Robust nodal behavior in the thermal conductivity of superconducting UTe_2

Ian M. Hayes,[1] Tristin E. Metz,[1] Corey E. Frank,[1,2] Shanta R. Saha,[1,2] Nicholas P. Butch,[1,2] Vivek Mishra,[3] P.J. Hirschfeld,[3] and Johnpierre Paglione[1,4,*]

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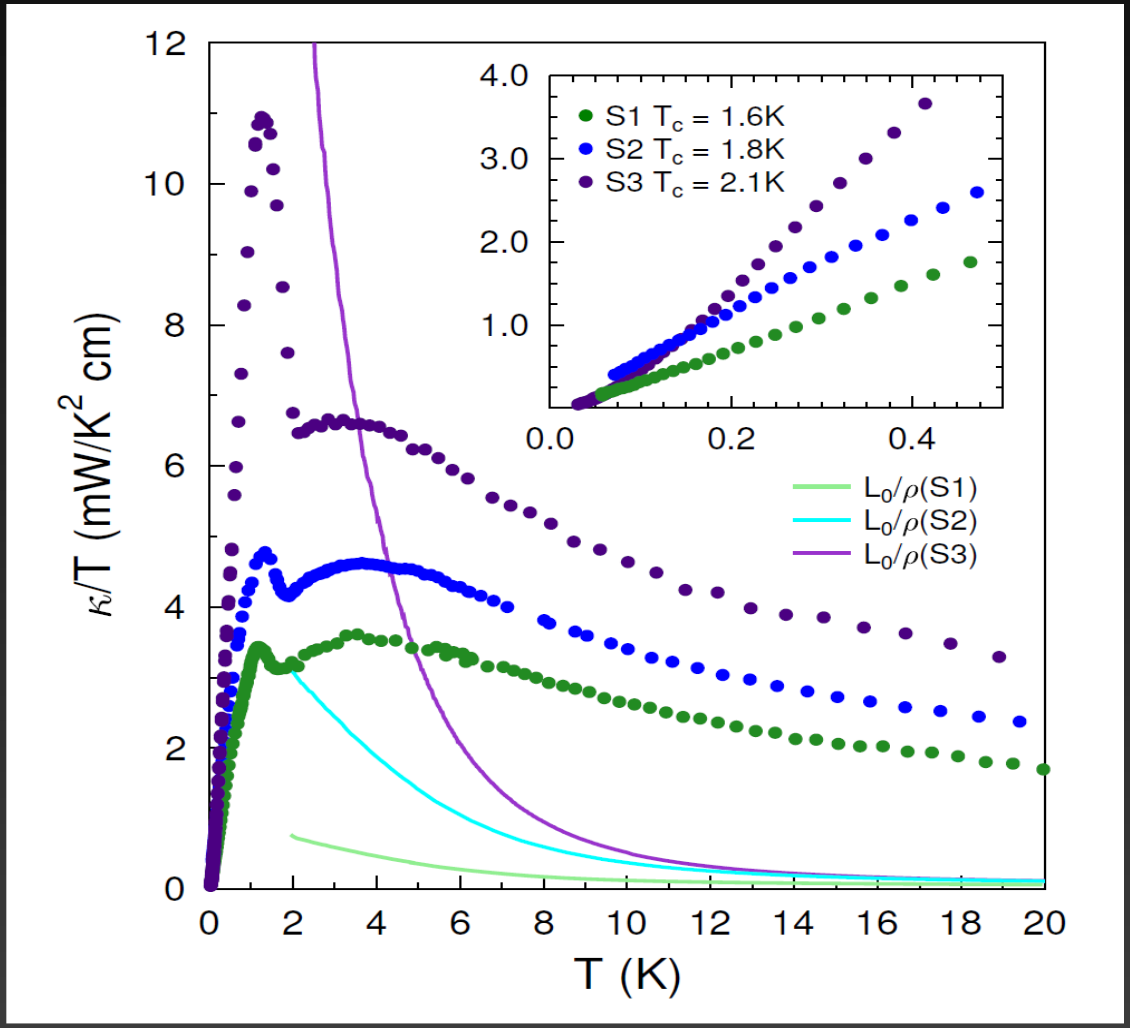
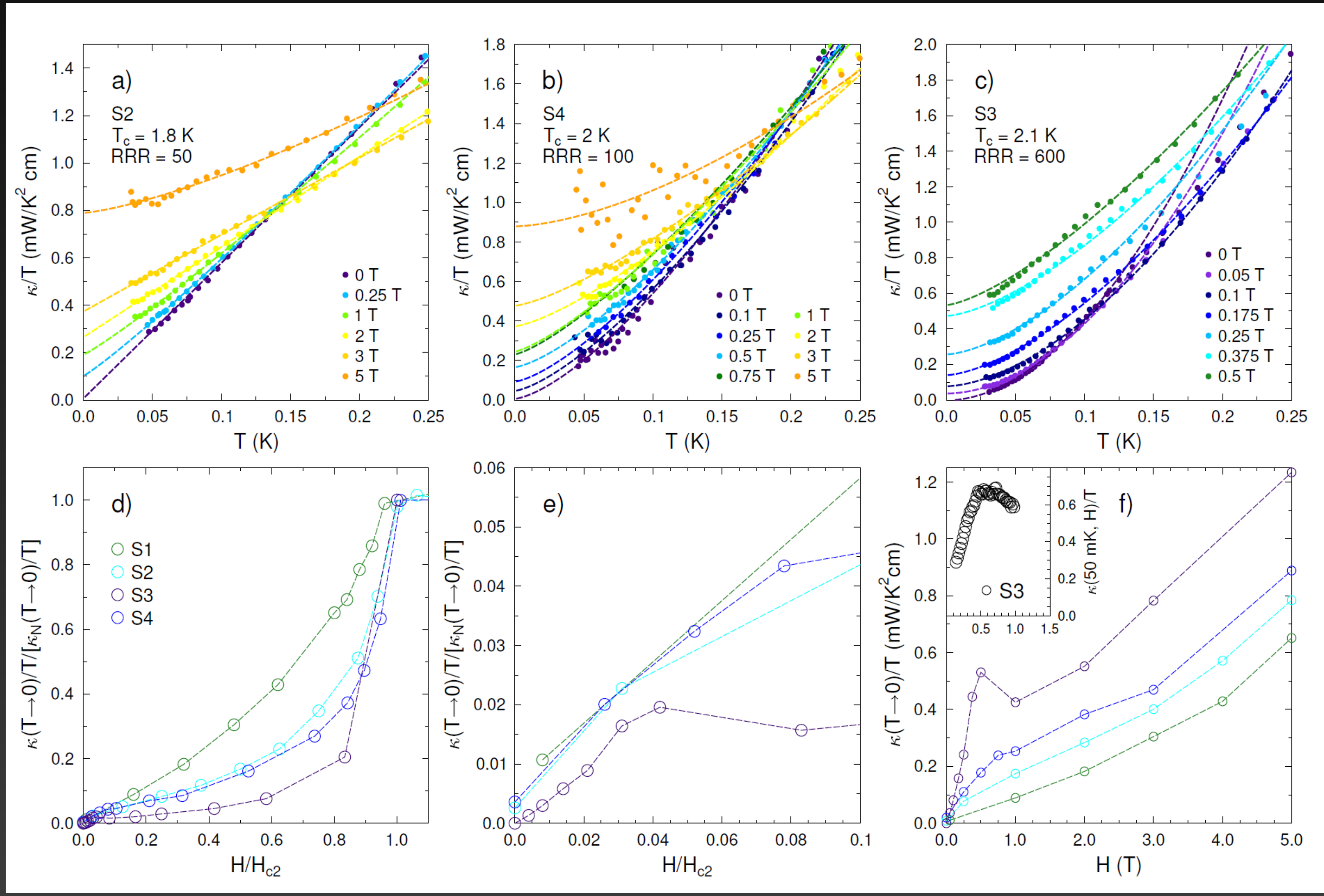
Ian Hayes

I. Hayes et al, arXiv:2402.19353





superconductivity in UTe_2

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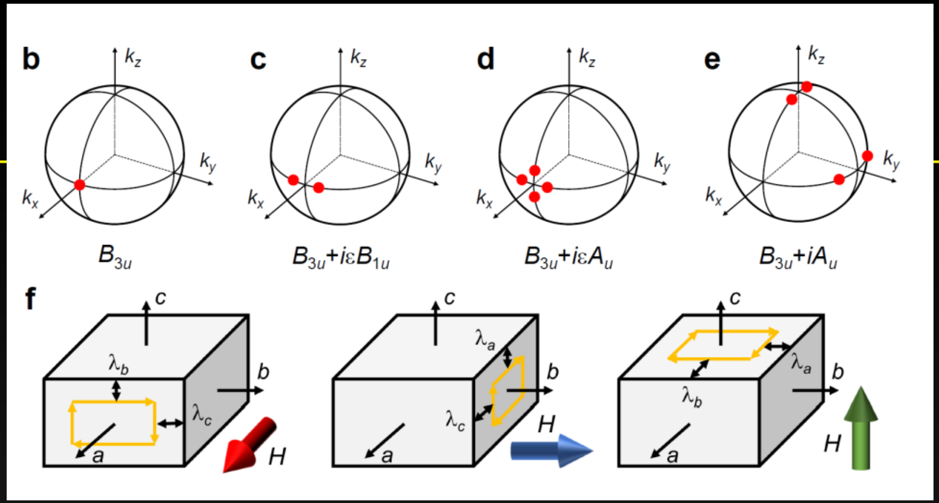
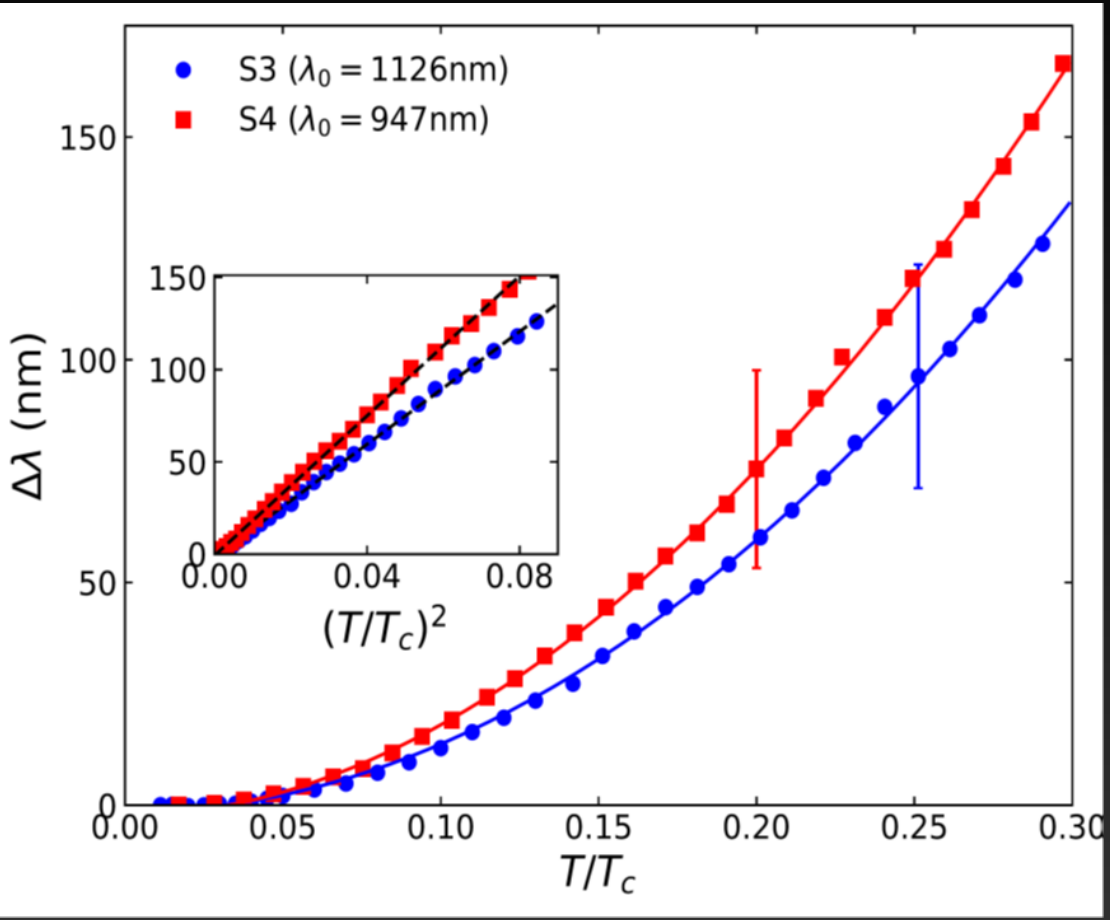
Steve Anlage
University of Maryland

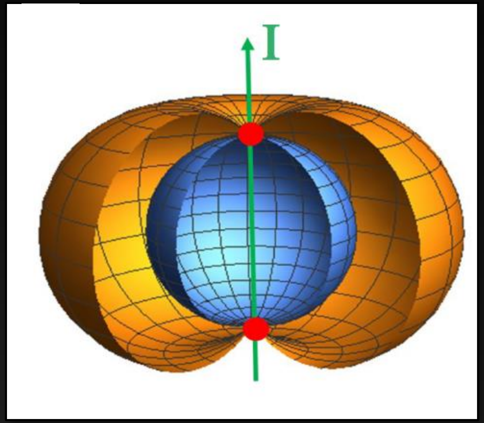


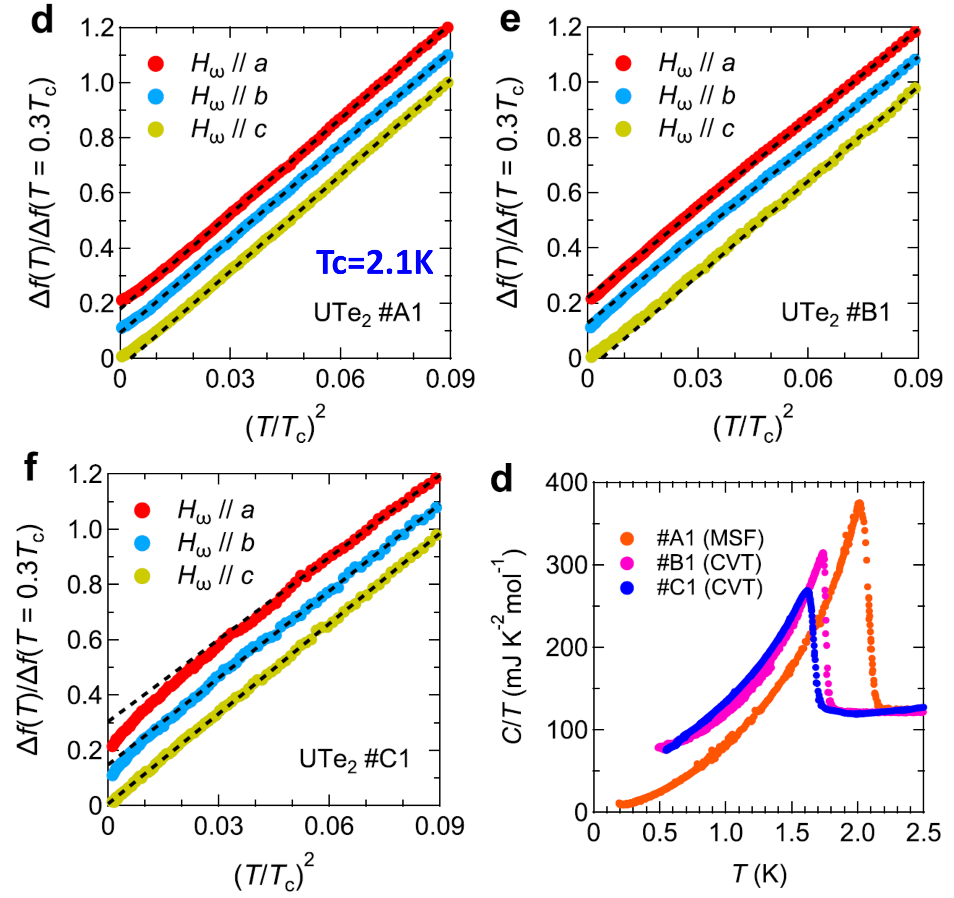
Ishihara *et al*, ncomm (2023)

London penetration depth



T. Metz *et al*, Phys. Rev. B 100, 220504 (2019).

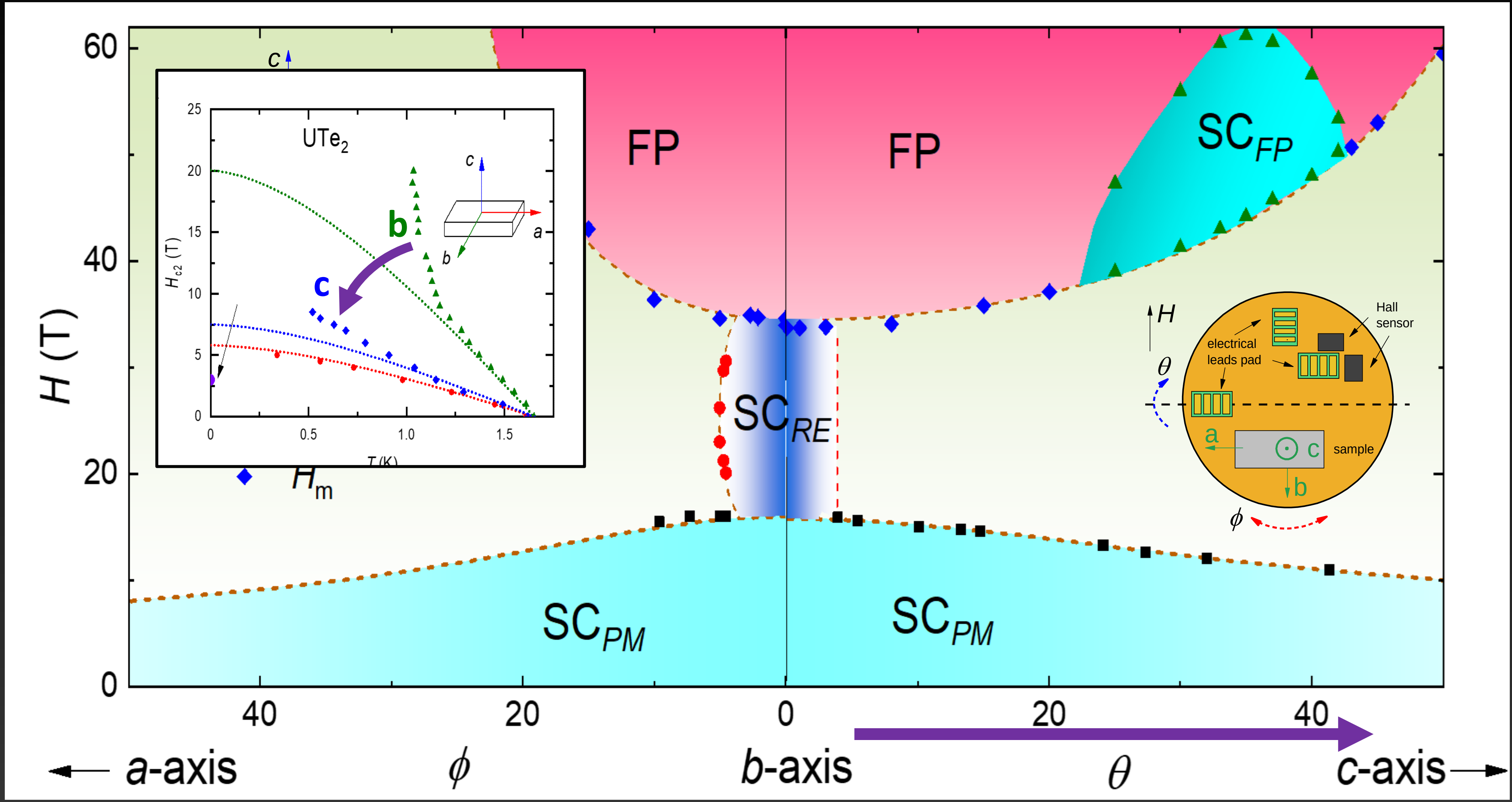




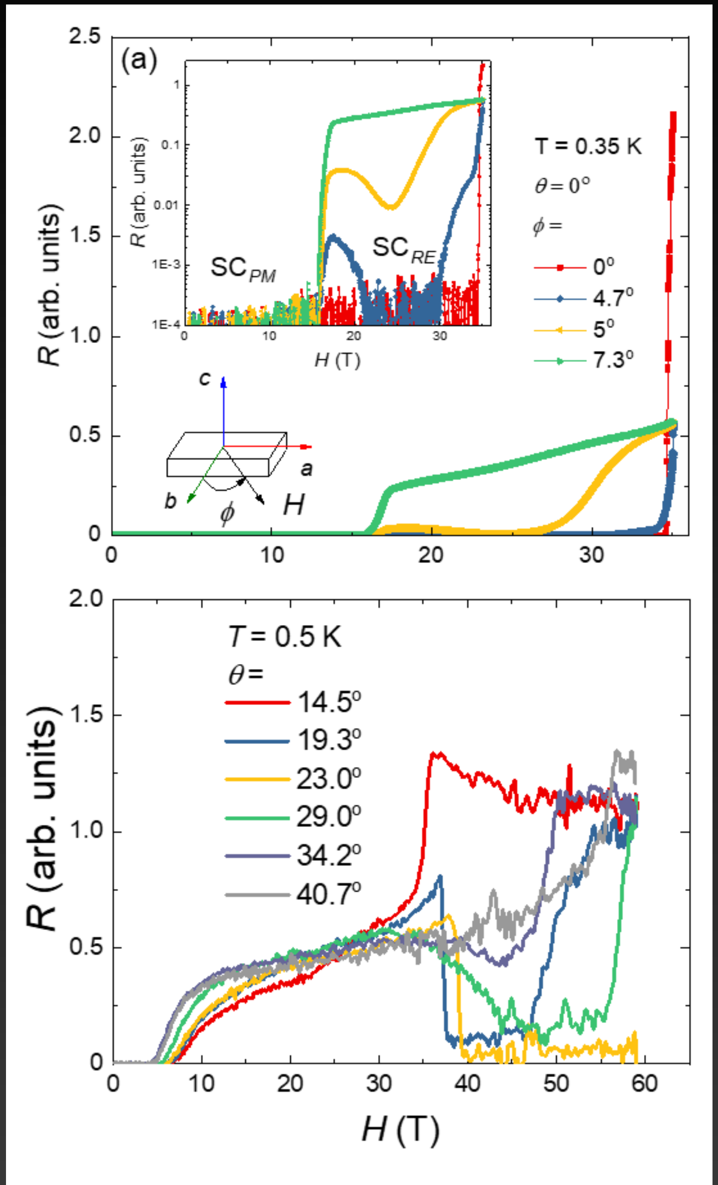
* T^2 in Tc>2K sample also confirmed by Anlage group using microwave technique

- **T^2 penetration depth → point nodes**

UTe_2 in high magnetic fields



S. Ran *et al*, Nature Phys. (2019).



- **Re-entrant superconductivity above 40 T**

superconductivity in UTe_2

Daniel Agterberg (theory)
U Wisconsin-Milwaukee

Aharon Kapitulnik
Stanford

Ian Hayes

Science — REPORTS

Multicomponent superconducting order parameter in UTe_2

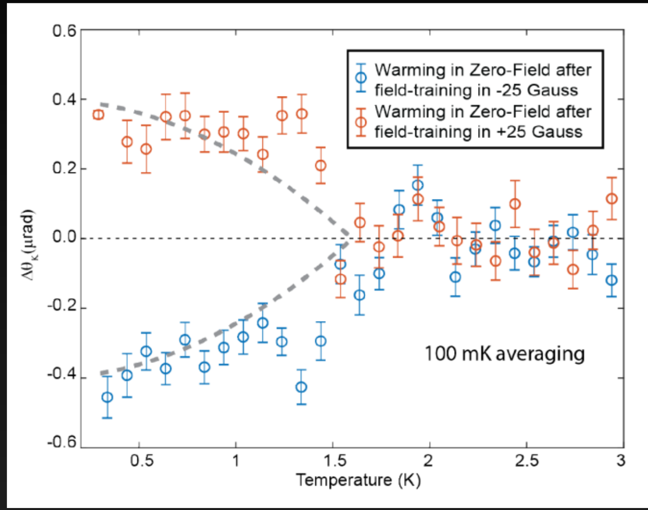
I. M. Hayes[1]†, D. S. Wei[2,3]†, T. Metz[1], J. Zhang[4], Y. S. Eo[1], S. Ran[1,5], S. R. Saha[1,5], J. Collini[1], N. P. Butch[1,5], D. F. Agterberg[6], A. Kapitulnik[2,3,7,8]*, J. Paglione[1,5,9]*

Irrep	E	C_{2z}	C_{2y}	C_{2x}	linear	quadratic $[\psi(\mathbf{k})]$	$\vec{d}(\mathbf{k})$	nodes
A_{1g}	1	1	1	1	-	k_x^2, k_y^2, k_z^2	-	-
B_{1g}	1	1	-1	-1	H_z	$k_x k_y$	-	line
B_{2g}	1	-1	1	-1	H_y	$k_x k_z$	-	line
B_{3g}	1	-1	-1	1	H_x	$k_y k_z$	-	line
A_u	1	1	1	1	-	-	$\hat{x}k_x, \hat{y}k_y, \hat{z}k_z$	-
B_{1u}	1	1	-1	-1	k_z	-	$\hat{x}k_y, \hat{y}k_x, \hat{z}k_x k_y k_z$	point
B_{2u}	1	-1	1	-1	k_y	-	$\hat{x}k_z, \hat{y}k_x k_y k_z, \hat{z}k_x$	point
B_{3u}	1	-1	-1	1	k_x	-	$\hat{x}k_x k_y k_z, \hat{y}k_z, \hat{z}k_y$	point

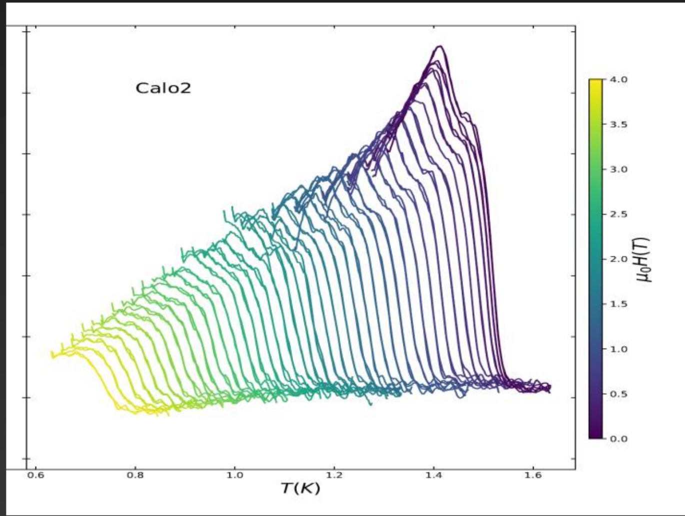
- TRS breaking can be trained by c-axis field, suggesting only **four possible two-component combinations**
- Spin-triplet narrows to first two
- Field dependence of specific heat consistent with #1 and #2

- **Weyl nodes expected** for either state
- 4+ Weyl nodes on k_x=0 or k_y=0 planes
- Consistent with point node gap structure measured experimentally

1 - $\psi_1 \in B_{3u}$ and $\psi_2 \in B_{2u}$
2 - $\psi_1 \in B_{1u}$ and $\psi_2 \in A_u$
3 - $\psi_1 \in B_{3g}$ and $\psi_2 \in B_{2g}$
4 - $\psi_1 \in B_{1g}$ and $\psi_2 \in A_g$



Finite Kerr effect: TRSB at Tc



Split transition: two-component OP

Hayes et al, Science 373, 797 (2021)

high pressure + high field

Sheng Ran
WU St. Louis

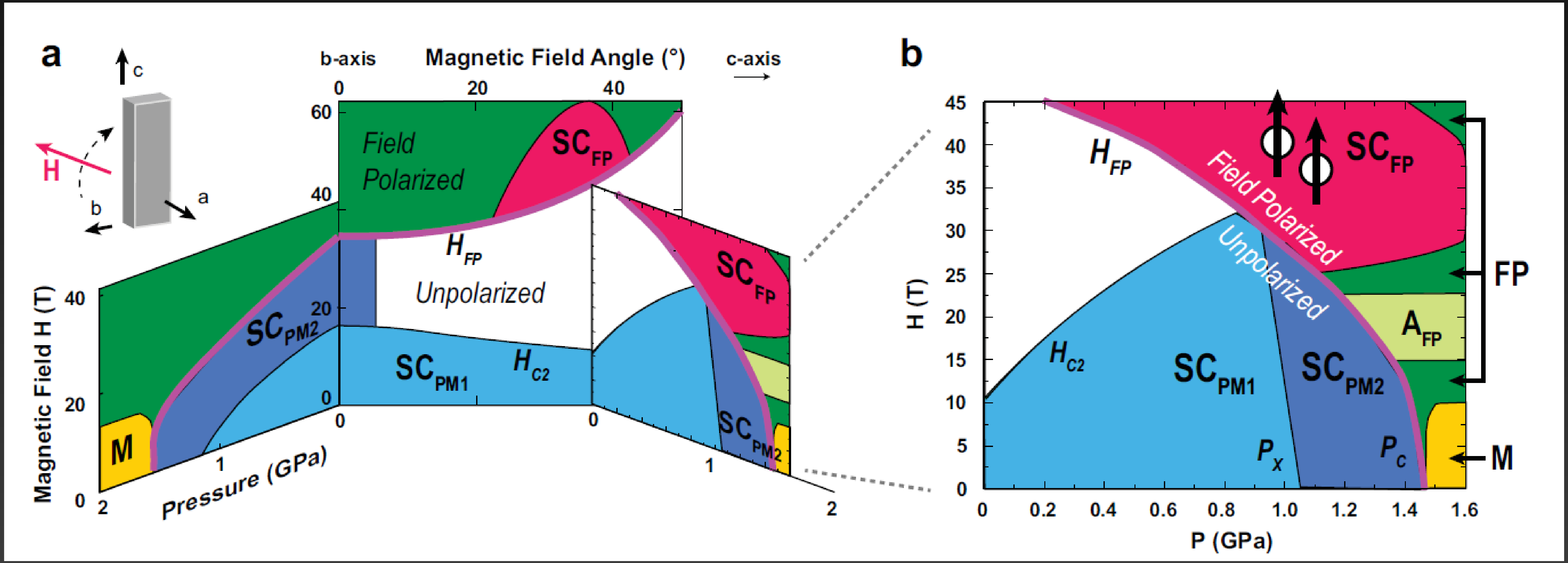
npj | Quantum Materials www.nature.com/npjquantmats

ARTICLE OPEN

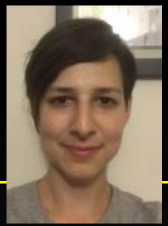
Check for updates

Expansion of the high field-boosted superconductivity in UTe_2 under pressure

Sheng Ran[1,2,3], Shanta R. Saha[1,2], I-Lin Liu[1,2], David Graf[4], Johnpierre Paglione[1,2] and Nicholas P. Butch[1,2]



UTe_2 in high magnetic fields

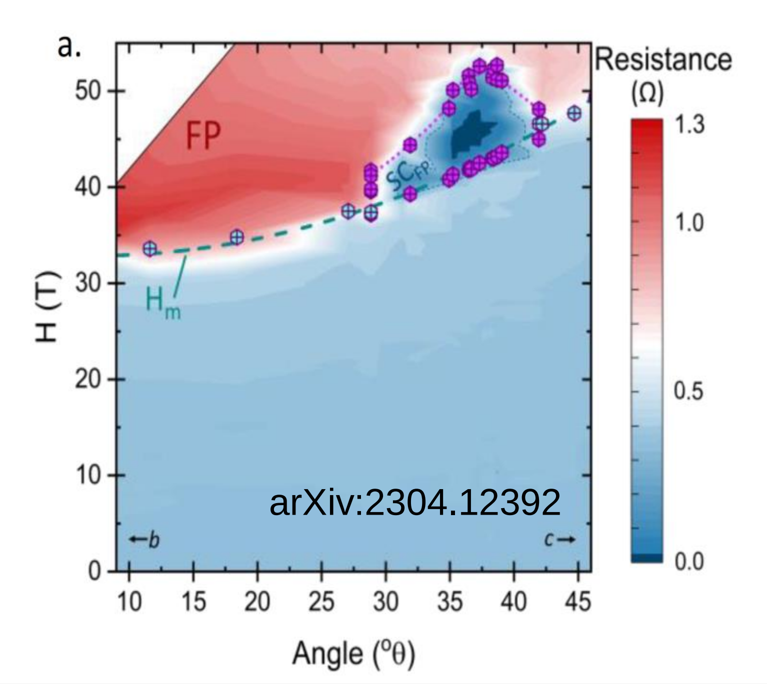


Sylvia Lewin Corey Frank Nick Butch

Lazarus SC phase – more than meets the eye!!

Orphan High Field Superconductivity in Non-Superconducting Uranium Ditelluride

*Corey E. Frank,[1,2] Sylvia K, Lewin,[1,2] Gicela Saucedo Salas,[2,1] Peter Czajka,[1,2] Ian Hayes,[2] Hyeok Yoon,[2] Tristin Metz,[2] Johnpierre Paglione,[2] John Singleton,[3] *Nicholas P. Butch[1,2]



Reports on Progress in **Physics**

REPORT ON PROGRESS

A review of UTe_2 at high magnetic fields

Sylvia K Lewin[4,1,2], Corey E Frank[1,2], Sheng Ran[3], Johnpierre Paglione[2]
Nicholas P Butch[4,1,2]

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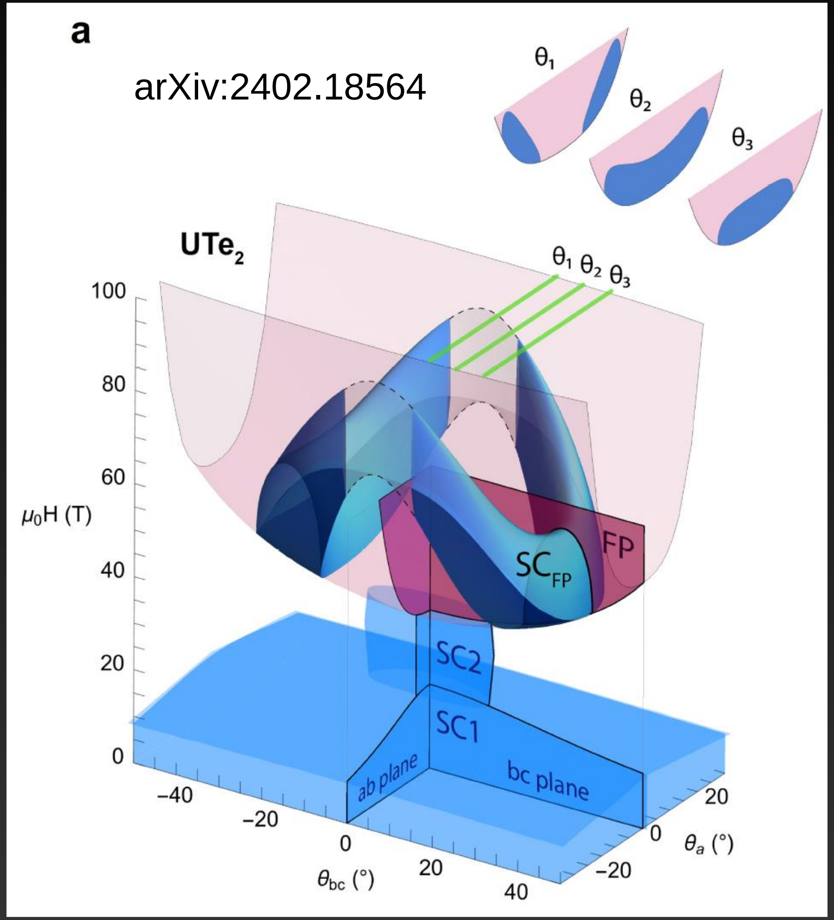

High-Field Superconducting Halo in UTe_2

Sylvia K. Lewin[1,2],* Peter Czajka[1,2],* Corey E. Frank[1,2], Gicela Saucedo Salas[2], Hyeok Yoon[2], Yun Suk Eo[2], Johnpierre Paglione[2,3], Andriy H. Nevidomskyy[4], John Singleton[5], and Nicholas P. Butch[1,2]

Article

Chiral superconductivity in heavy-fermion metal UTe_2

https://doi.org/10.1038/s41586-020-2122-2
Received: 30 July 2019

Lin Jiao[1], Sean Howard[1], Sheng Ran[2,3], Zhenyu Wang[1], Jorge Olivares Rodriguez[1], Manfred Sigrist[4], Ziqiang Wang[5], Nicholas P. Butch[2,3] & Vidya Madhavan[1]✉

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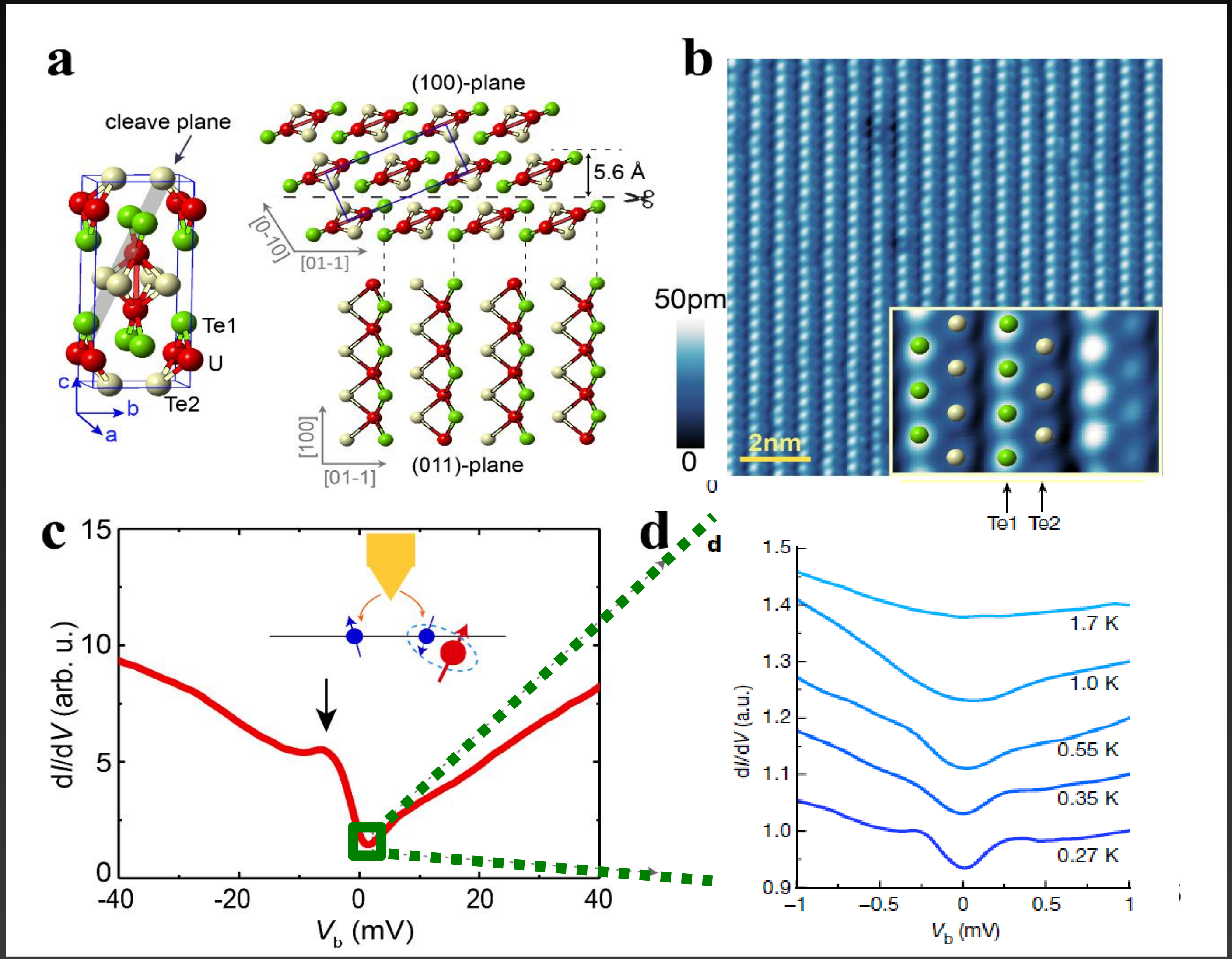

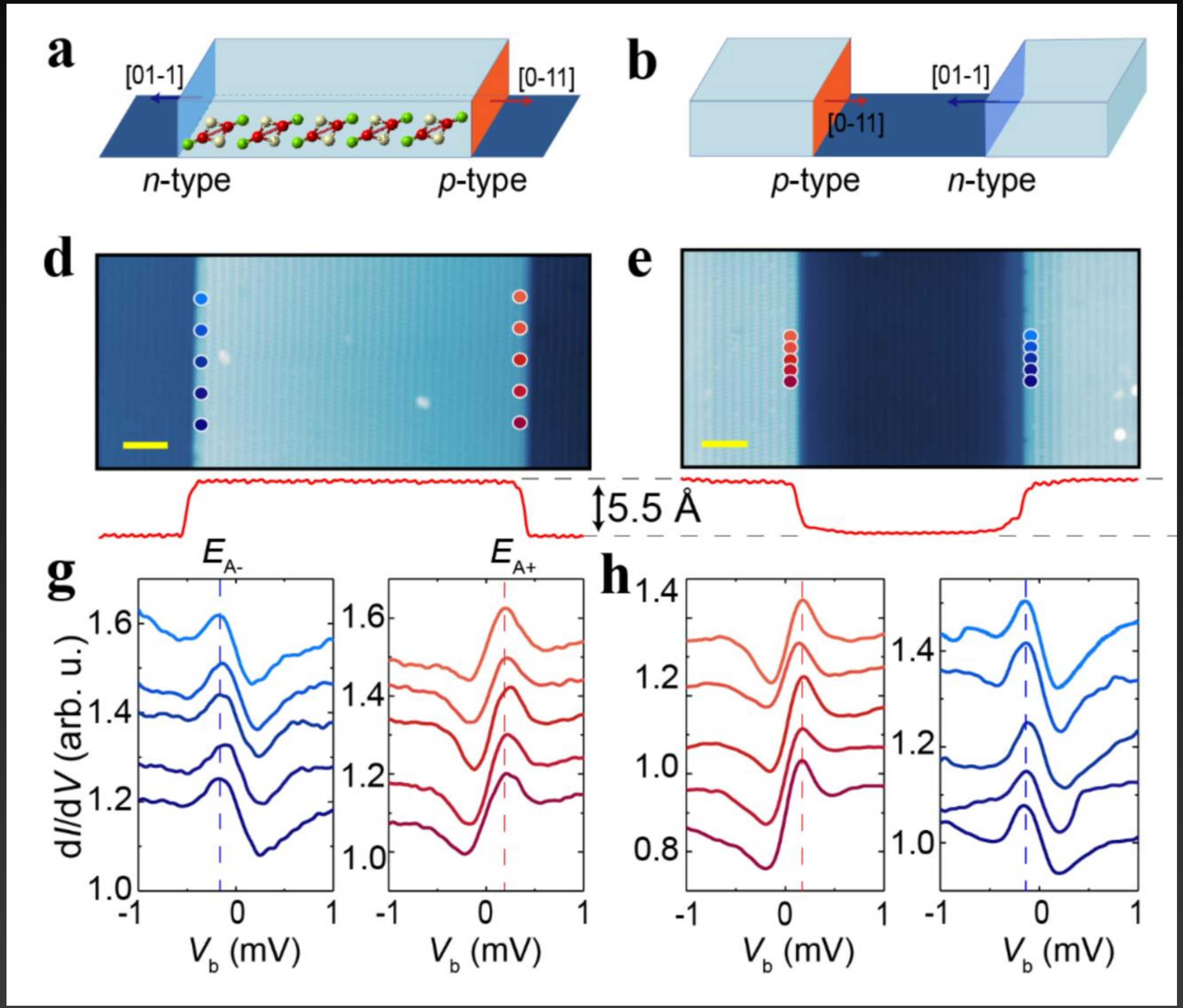

L. Jiao *et al*, Nature (2020)

superconductivity in UTe_2

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Article

Detection of a pair density wave state in UTe_2

https://doi.org/10.1038/s41586-023-05919-7
Received: 6 September 2022
Accepted: 3 March 2023

Qiangqiang Gu[1,11], Joseph P. Carroll[1,2,11], Shuqiu Wang[1,3,11], Sheng Ran[4], Christopher Broyles[4], Hasan Siddiquee[4], Nicholas P. Butch[5,6], Shanta R. Saha[5], Johnpierre Paglione[5,7], J. C. Séamus Davis[1,2,3,8] & Xiaolong Liu[1,9,10]

Article

Magnetic-field-sensitive charge density waves in the superconductor UTe_2

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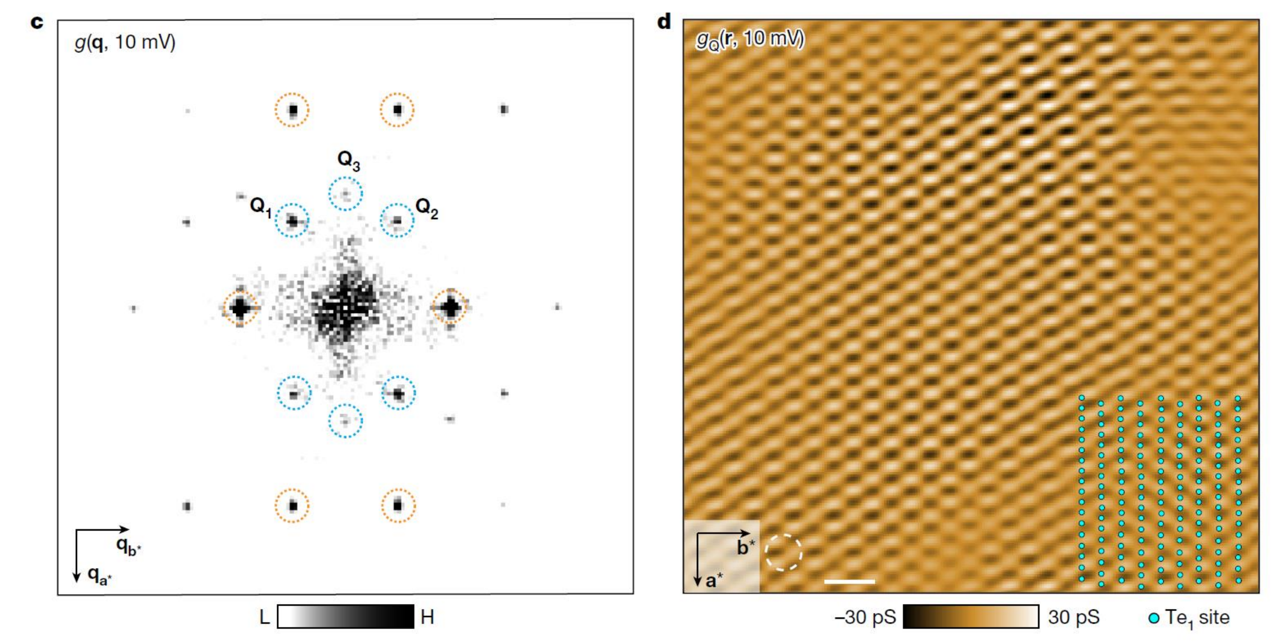
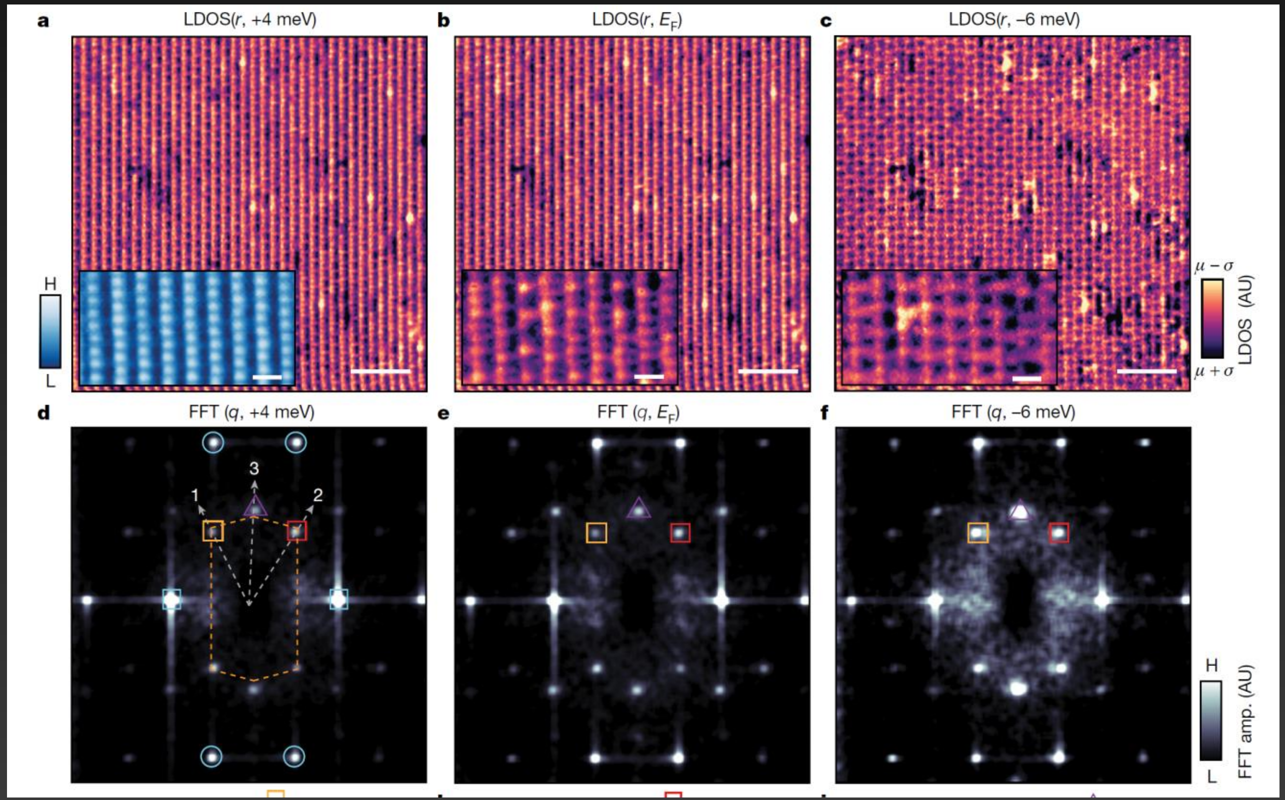
Received: 27 July 2022
Accepted: 23 March 2023

Anuva Aishwarya[1], Julian May-Mann[1,2], Arjun Raghavan[1], Laimei Nie[1,2], Marisa Romanelli[1], Sheng Ran[3,4,5], Shanta R. Saha[3], Johnpierre Paglione[3,6], Nicholas P. Butch[3,4], Eduardo Fradkin[1,2] & Vidya Madhavan[1,6]





- **Pair- and charge-density wave order**

superconductivity in UTe_2

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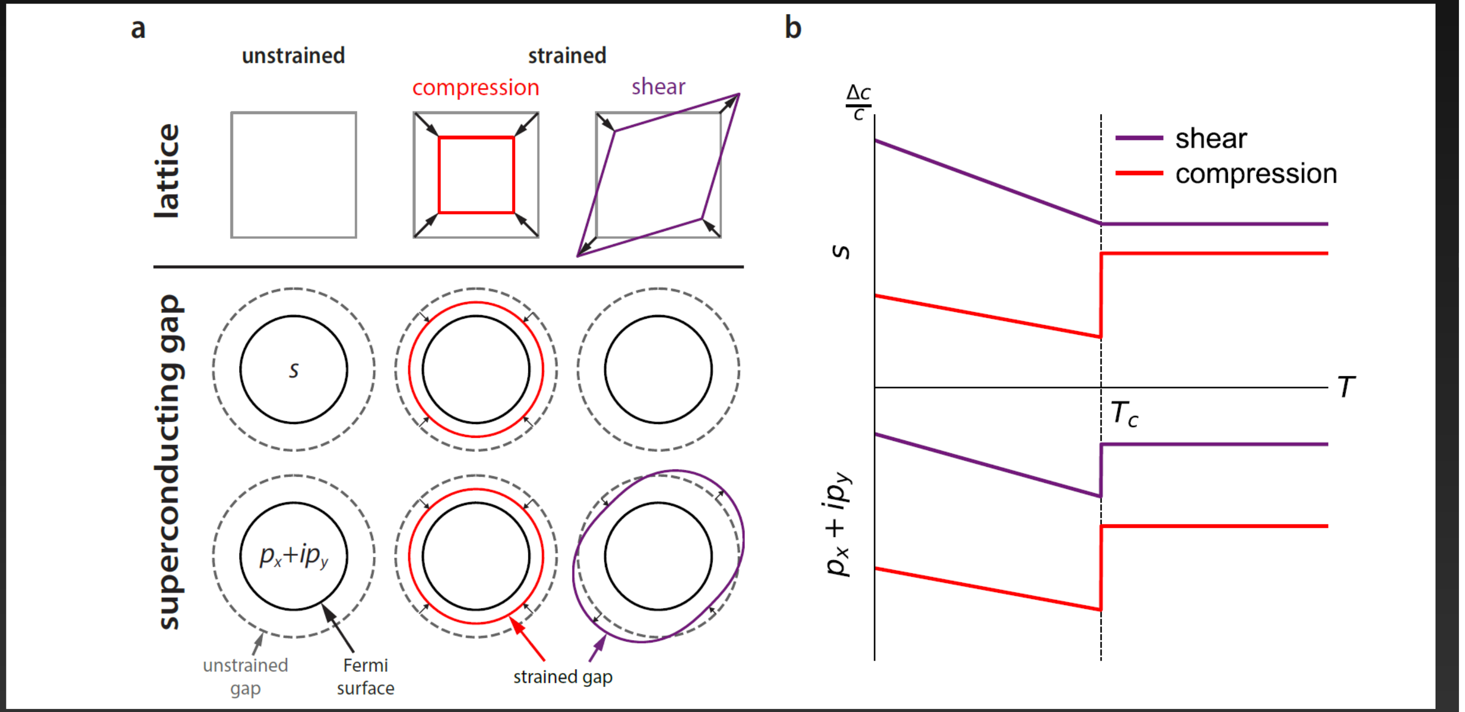
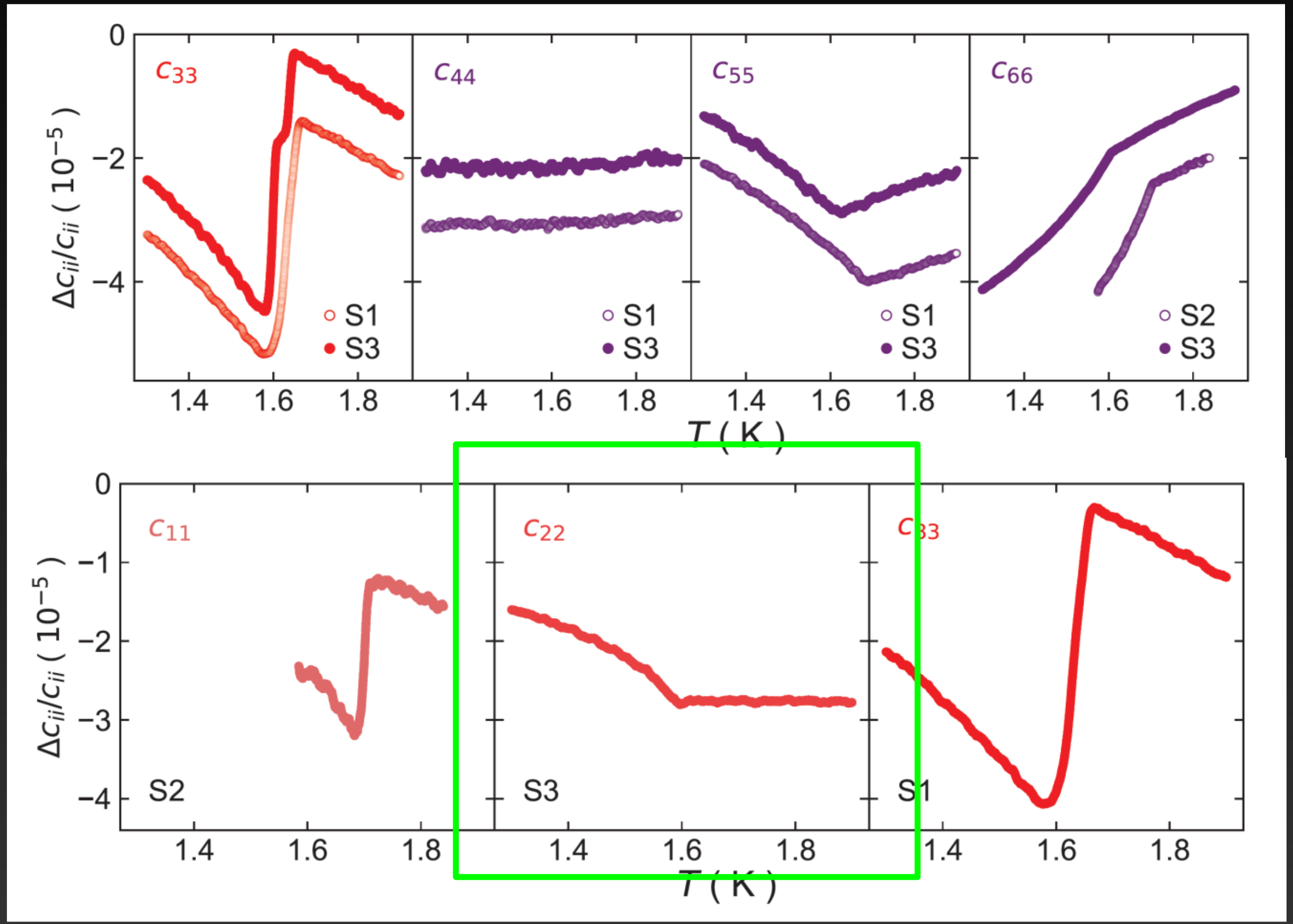


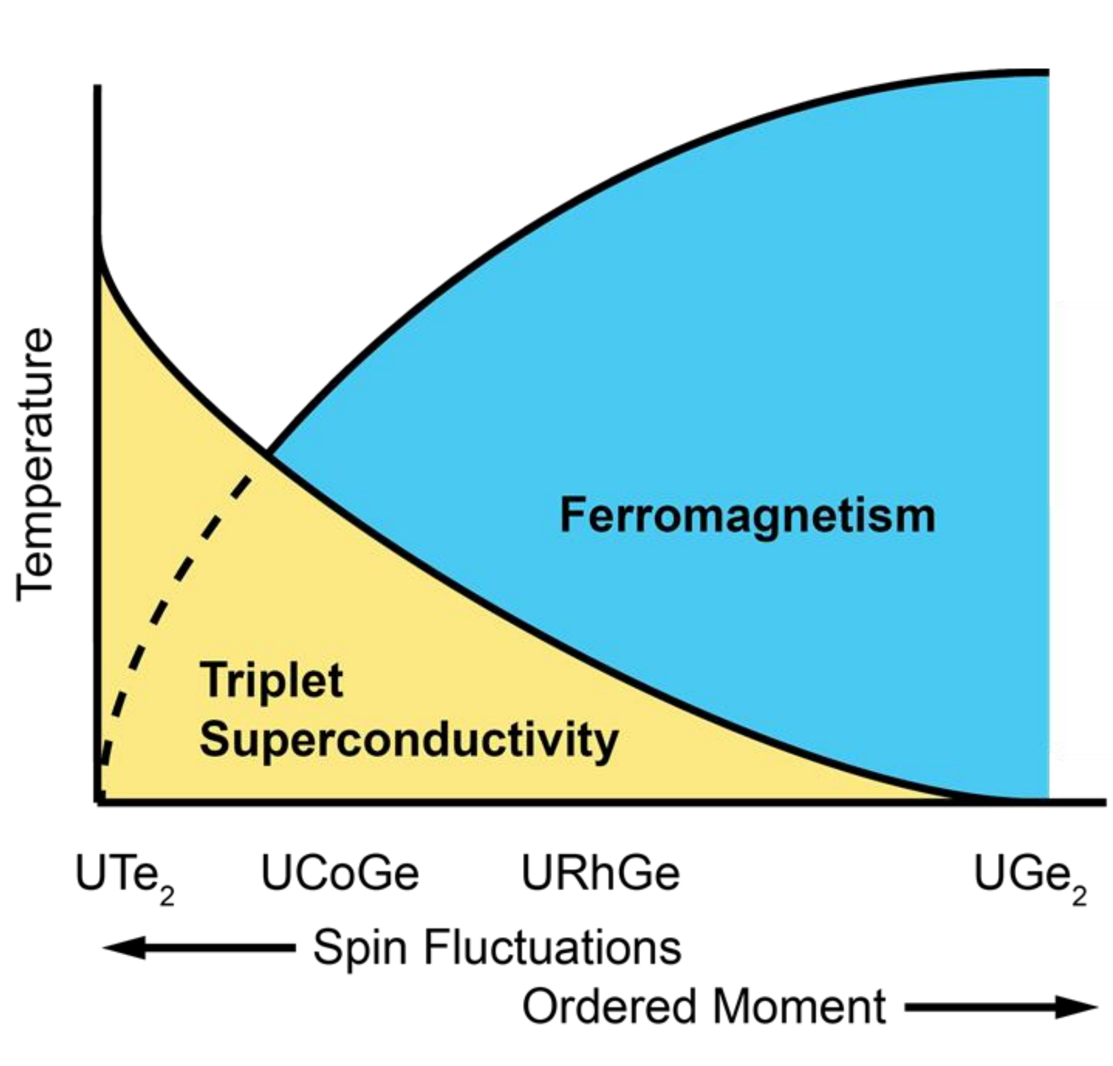


F. Theuss et al, Nature Physics (2024)

conclusions

UTe_2 – exotic spin-triplet superconductor

- **Nearly ferromagnetic superconductor**
  - Paramagnetic U sublattice, Kondo interactions
- **High-field re-entrant pairing**
  - Field-polarized phase above 35 T
  - Re-entrant SC near b-axis
- **Point node gap structure**
  - New experiments point to single-component OP
  - T^2 penetration depth?
- **Topological superconductivty**
  - Chiral bound states (STM)
  - Anomalous normal fluid



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W.C. Lin *et al.*, *"Tuning magnetic confinement of spin-triplet superconductivity,"* npj Quantum Materials 5, 68 (2020)
S. Bae *et al.*, *"Anomalous normal fluid response in a chiral superconductor"*, Nature Communications 12, 2644 (2021).
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D. S. Wei et al., "*Interplay between magnetism and superconductivity in UTe_2*", Phys. Rev. B 105, 024521 (2022).
Y.S. Eo et al., "*Anomalous c-axis transport response of UTe_2*", App. Phys. Lett (2023).
N.P. Butch et al., "*Symmetry of magnetic correlations in spin-triplet superconductor UTe_2*", npj Quantum Matl. 7, 39 (2022).
F. Theuss et al., "*Single-Component Superconductivity in UTe2 at Ambient Pressure*", Nature Physics – to appear (arXiv:2307.10938).

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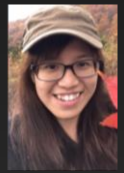
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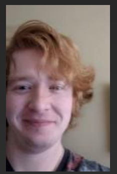
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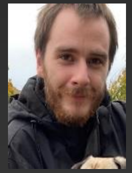
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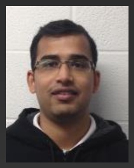
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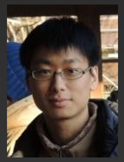
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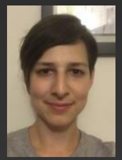
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