Visualizing scattering phase dislocations and the birth of magnetism at a quantum critical point

Hermann Suderow

Laboratorio de Bajas Temperaturas y Altos Campos Magnéticos
Departamento de Física de la Materia Condensada
Instituto de Ciencia de Materiales Nicolás Cabrera

Center for Condensed Matter Physics (IFIMAC)

Universidad Autónoma de Madrid (UAM)

Real-space visualization of scattering phase dislocations in a magnetic semiconductor

and other ongoing work (including a bit of superconductivity)

Hermann Jesús Suderow Rodriguez

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Universidad Autónoma de Madrid (UAM)

Isabel Guillamón

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J. Rusz, Peter M. Oppeneer
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Raquel Sánchez Barquilla, Jose Antonio Moreno, Pablo García, Miguel Águeda, Paula Obladen, Óscar Bou, Jaime Rumeu, Andreu Estrela, Aurora Mang

E. Mascot, D. Morr
Chicago

Jose Baldoví
Masayuki Ochi
Ryotaro Arita
Andrés Martínez
Juan José Palacios

Dai Aoki, Jacques Flouquet, Georg Knebel, Jean Pascal Brison
Tohuku-Grenoble

Linlin Wang, Sergey Bud'ko and Paul C. Canfield
Ames Lab

Samuel Díaz Escribano
Alfredo Levy-Yeyati

Rafael Pineda
Javier Herrera William
José Augusto Galvis
José David Bermúdez
Bogotá

Carmen Munuera, Mar García Hernández
CSIC, Madrid

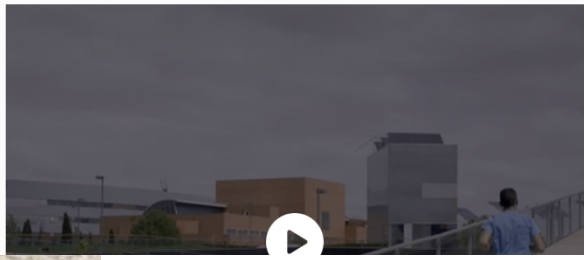
Makoto Shimizu
Youichi Yanase
Kyoto

Anna Böhmer, Amir-Abbas Haghighirad
Bochum, Karlsruhe

Young-Joon Song, Adrian Valadakhni, Roser Valenti, Iksu Yang, Jörg Schmalian
Uni Frankfurt, Uni Karlsruhe

HISTORY OF THE UAM

Con la tecnología de Google Traductor de Google



Severo Ochoa, Margarita Salas, Nicolás Cabrera, Alberto Sols, Francisco Tomás y Valiente, Aurelio Menéndez, Carlos Paris, María Ángeles Durán, José María Segovia de Arana, Diego Figuera Aymerich ... The history of the Autonomous University of Madrid (UAM) has been marked by great na[illegible]nd the humanities since its foun[illegible]ng in 1968, alo[illegible]gside the Autonomous

Real-space visualization of scattering phase dislocations in a magnetic semiconductor

- Quasiparticle interference scattering. Spin orbit scattering.
- Our microscopes and ongoing work
- Scanning Tunneling Spectroscopy of the magnetic semiconductor $EuCd_2As_2$

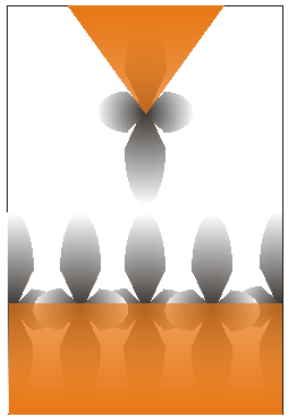
https://arxiv.org/abs/2609.13398

https://sites.google.com/view/hsuderow/

COST Action SUPERQUMAP

Arxiv

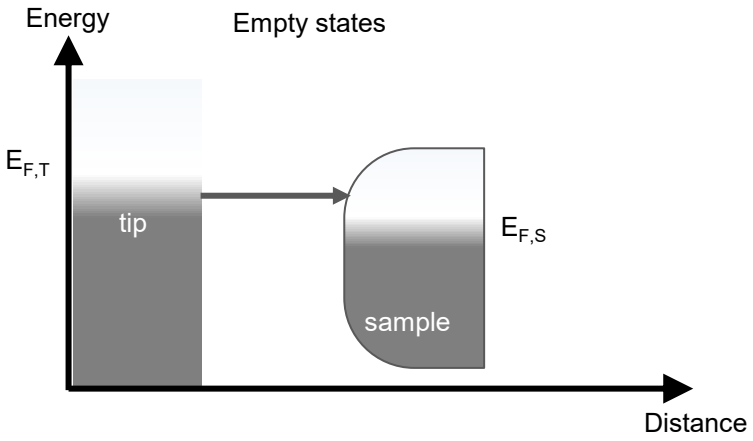
The tunneling current: Chen

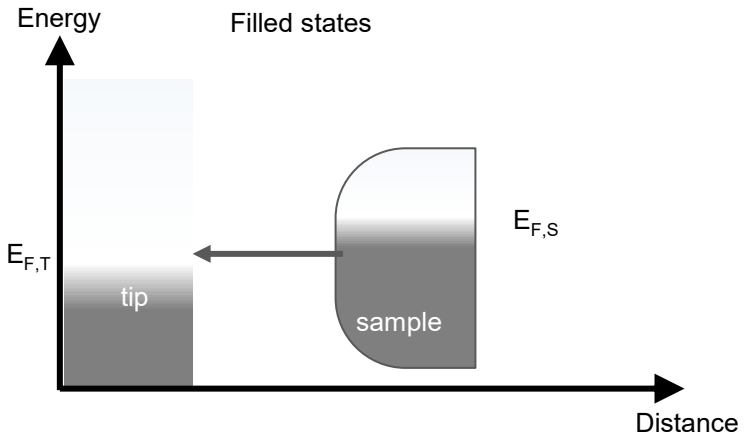


Microscopic (C_p, κ, ρ, …)
Empty + filled states (ARPES, dHvA)
Bandstructure (ARPES)
Real space (neutrons, x-ray)

$$N_{loc}(E, \boldsymbol{r}) = \sum_n |\psi_n(\boldsymbol{r})|^2 \, \delta(E - E_n)$$

$$I(\mathrm{r}_0, V) \propto \int_{E_F}^{E_F+eV} dE \, N_{loc}(\mathbf{d}_0, E) T(\mathbf{d}_0, E, eV)$$

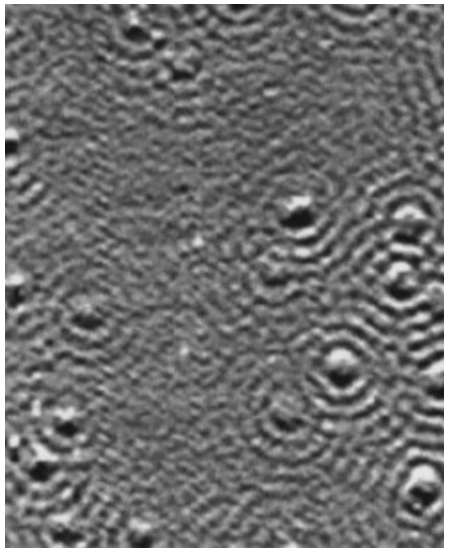




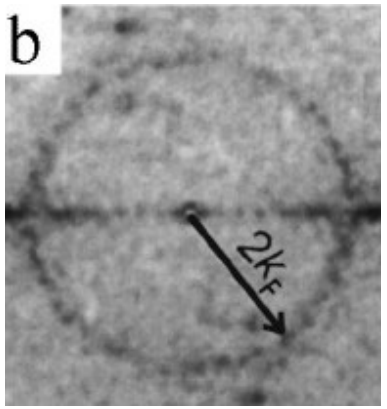
$$\frac{dI}{dV} \propto \int N_{loc}(E) \frac{\partial f(E - eV)}{\partial V} dE$$

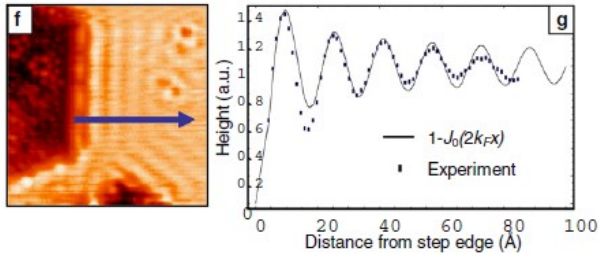
Quasiparticle interference scattering of 2D surface states

Real space conductance map



Fourier transform

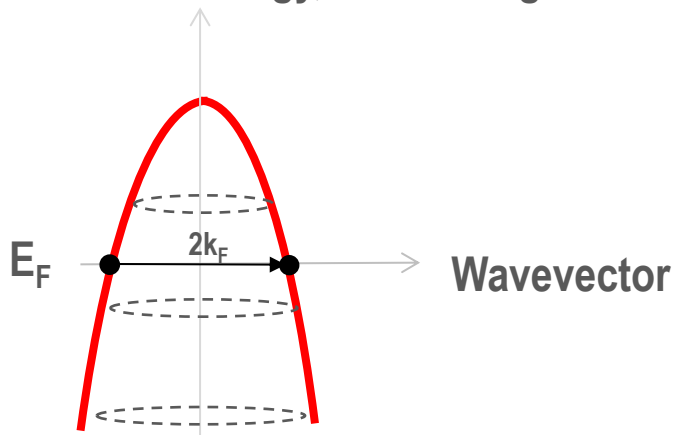




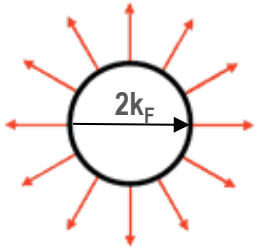


Direct imaging of the two-dimensional Fermi contour: Fourier-transform STM
L. Petersen et al.
Phys. Rev. B, R6858, 57 (1998)
A phenomenological approach of joint density of states for the determination of bandstructure in the case of a semi-metal studied by FT-STS
L. Simon, F. Vonau and D. Aubel
J. Phys. Cond. Matt. 19 (2007) 355009

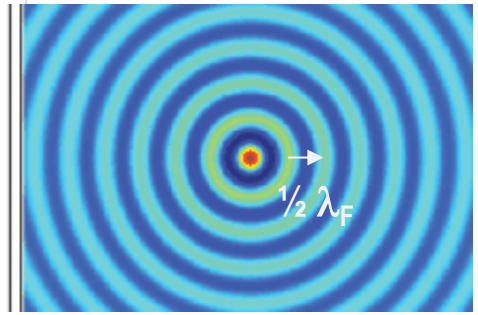
Energy, bias voltage



Fermi surface



Real space DOS



Seeing the Fermi Surface in Real Space by Nanoscale Electron Focusing

ALEXANDER WEISMANN, MARTIN WENDEROTH , SAMIR LOUNIS, PETER ZAHN, NORBERT QUAAS, RAINER G. ULBRICH, PETER H. DEDERICHS, AND STEFAN BLÜGEL Authors Info & Affiliations

SCIENCE · 27 Feb 2009 · Vol 323, Issue 5918 · pp. 1190-1193 · DOI: 10.1126/science.1168738

PHYSICAL REVIEW B **93**, 041109(R) (2016)

Universal signatures of Fermi arcs in quasiparticle interference on the surface of Weyl semimetals

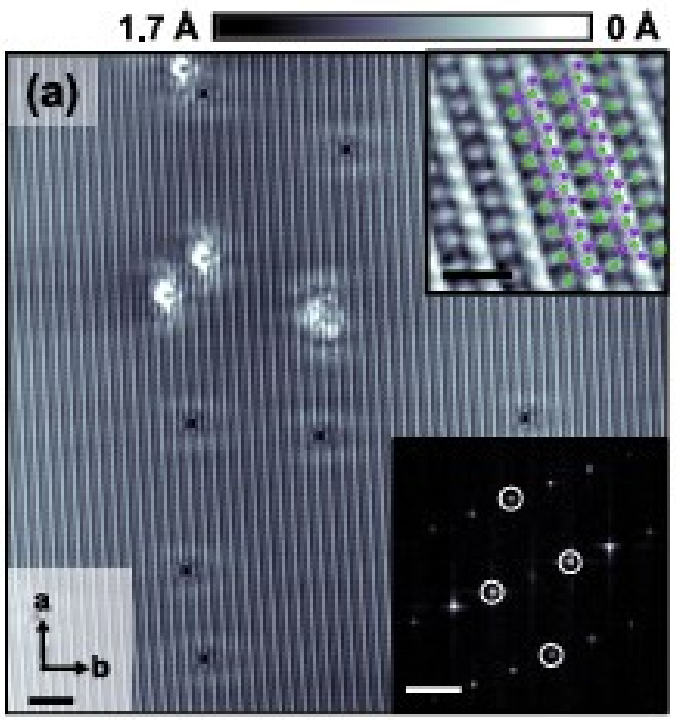
Stefanos Kourtis, Jian Li, Zhijun Wang, Ali Yazdani, and B. Andrei Bernevig

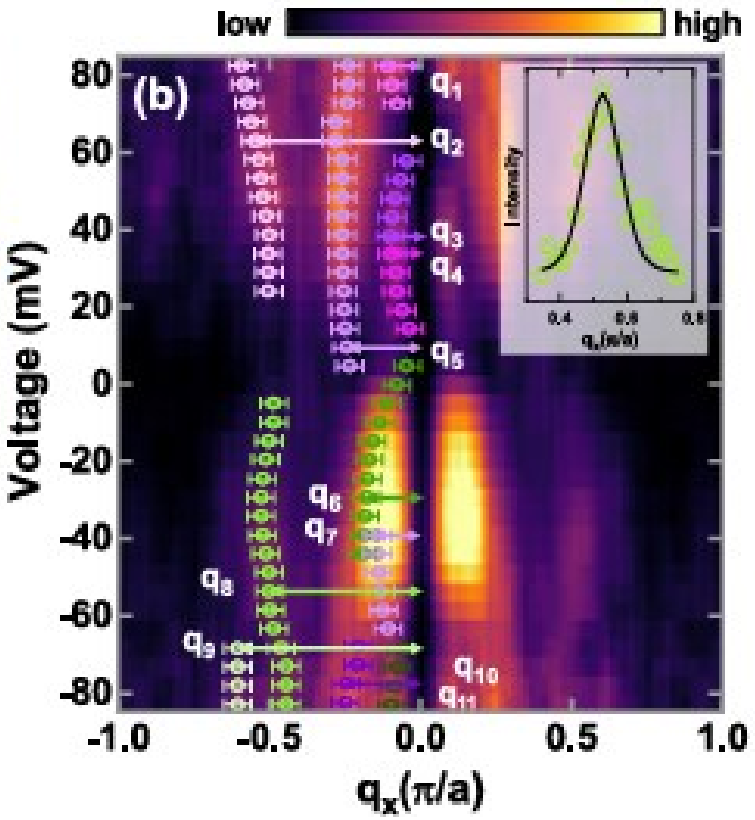
PHYSICAL REVIEW B **93**, 035137 (2016)

Signatures of Weyl semimetals in quasiparticle interference

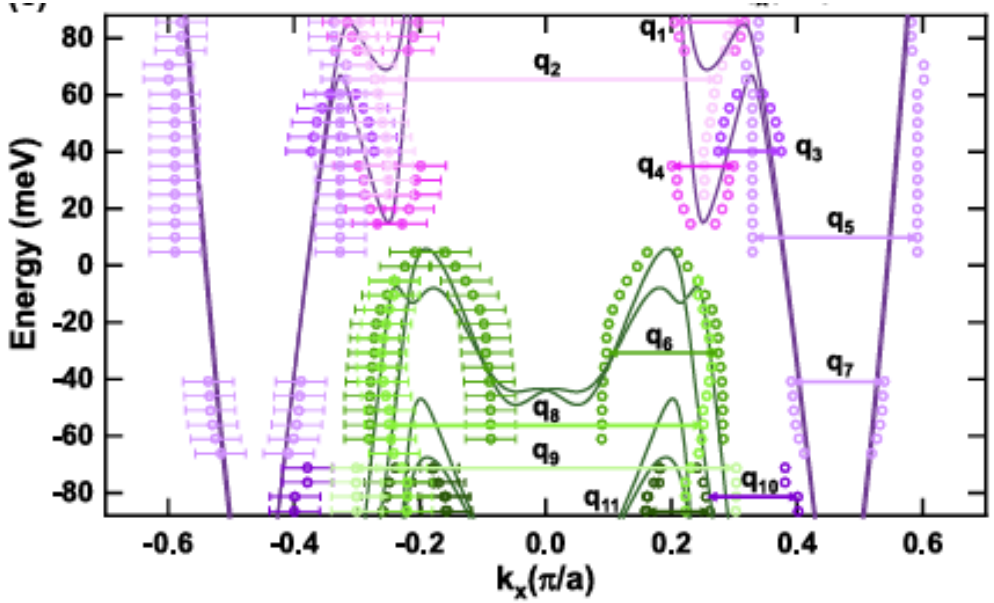
Andrew K. Mitchell and Lars Fritz
Institute for Theoretical Physics, Utrecht University, 3584 CE Utrecht, The Netherlands

Quasiparticle interference scattering in semimetals





(c)



$$N_{loc}(E, \boldsymbol{r}) = \sum_n |\psi_n(\boldsymbol{r})|^2 \, \delta(E - E_n)$$

$$\frac{dI}{dV} \propto \int N_{loc}(E) \frac{\partial f(E - eV)}{\partial V} dE$$

PHYSICAL REVIEW B **112**, 165401 (2025)

Electronic band structure from quasiparticle interference and Landau quantization in WTe_2

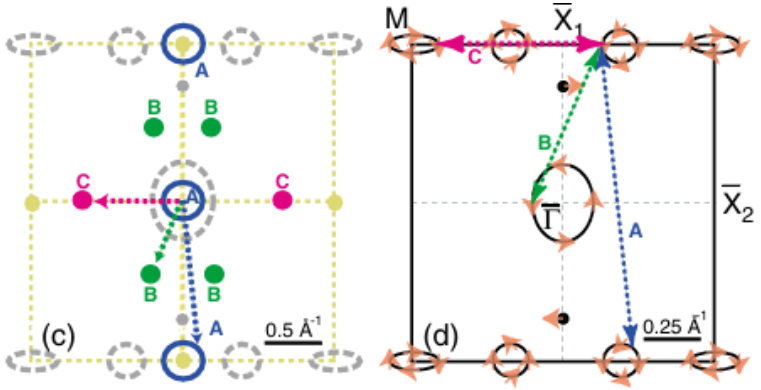
Raquel Sánchez-Barquilla,[1] Francisco Martín Vega,[1] Alberto M. Ruiz,[2] Na Hyun Jo,[3,*] Edwin Herrera,[1] José J. Baldoví,[2] Masayuki Ochi,[4,5] Ryotaro Arita,[6,7] Sergey L. Bud'ko,[3] Paul C. Canfield,[3] Isabel Guillamón,[1] and Hermann Suderow[1,†]

Quasiparticle interference in presence of Spin Orbit Coupling

VOLUME 93, NUMBER 19 PHYSICAL REVIEW LETTERS week ending 5 NOVEMBER 2004

Role of Spin in Quasiparticle Interference

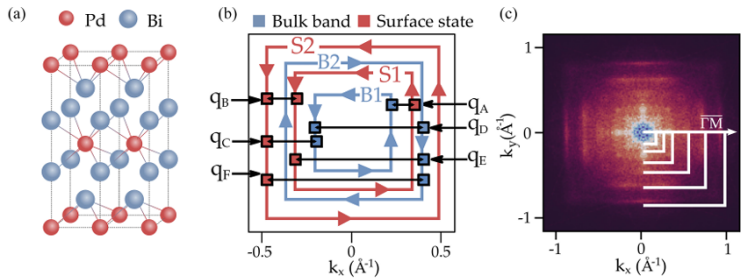
J. I. Pascual,[1,2] G. Bihlmayer,[5] Yu. M. Koroteev,[3,4] H.-P. Rust,[2] G. Ceballos,[2] M. Hansmann,[2] K. Horn,[2] E. V. Chulkov,[3,6] S. Blügel,[5] P. M. Echenique,[3,6] and Ph. Hofmann[7,*]



PHYSICAL REVIEW LETTERS 135, 136201 (2025)

Revealing Band-Hybrid Cooper Pairs on the Surface of a Superconductor with Spin-Orbit Coupling

Javier Zaldívar,[1,*] Jon Ortuzar,[1,*] Miguel Alvarado,[2,3] Stefano Trivini,[1] Julie Baumard,[4] Carmen Rubio-Verdú,[5] Edwin Herrera,[6] Hermann Suderow,[6] Alfredo Levy Yeyati,[3] F. Sebastian Bergeret,[4,7] and Jose Ignacio Pascual[1,8,‡]



Spin Hall effects

Jairo Sinova, Sergio O. Valenzuela, J. Wunderlich, C. H. Back, and T. Jungwirth

Show more

Rev. Mod. Phys. **87**, 1213 – **Published 27 October, 2015**

DOI: https://doi.org/10.1103/RevModPhys.87.1213

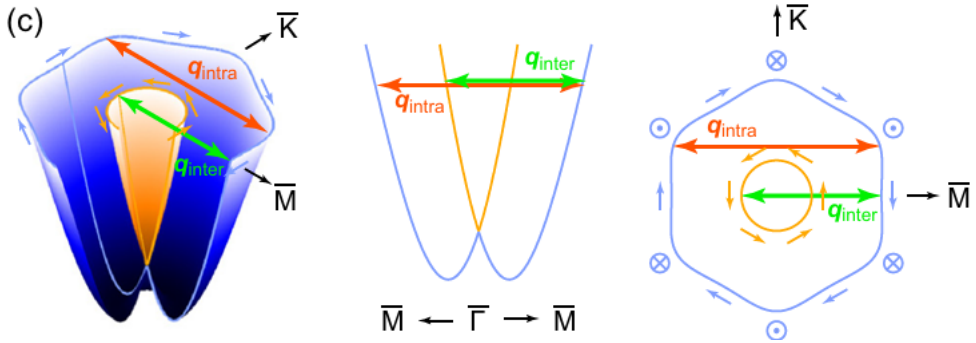
PHYSICAL REVIEW B **95**, 115307 (2017)

Spin-orbit scattering visualized in quasiparticle interference

Y. Kohsaka,[1,*] T. Machida,[1] K. Iwaya,[1] M. Kanou,[2] T. Hanaguri,[1] and T. Sasagawa[2]

[1]*RIKEN Center for Emergent Matter Science, Wako, Saitama 351-0198, Japan*

[2]*Laboratory for Materials and Structures, Tokyo Institute of Technology, Yokohama, Kanagawa 226-8503, Japan*



$$N_{loc}(E, \boldsymbol{r}) = \sum_n |\psi_n(\boldsymbol{r})|^2 \, \delta(E - E_n)$$

$$\frac{dI}{dV} \propto \int N_{loc}(E) \frac{\partial f(E - eV)}{\partial V} dE$$

Spin-orbit scattering

$$H_{SOC} = \frac{\hbar}{4m^2c^2} (\nabla V \times \boldsymbol{p}) \cdot \boldsymbol{\sigma}$$

$$\Psi_{\boldsymbol{k}}(\boldsymbol{r}) = e^{i\boldsymbol{k}\cdot\boldsymbol{r}} \begin{pmatrix} u_+(\boldsymbol{k}) \\ u_-(\boldsymbol{k}) \end{pmatrix}$$

Rashba split bands

$$\Psi_{\boldsymbol{k}}(\boldsymbol{r}) = e^{i\boldsymbol{k}\cdot\boldsymbol{r}} \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ \mp i e^{\varphi_k} \end{pmatrix}$$

$$\varphi_k = arctan\left(\frac{k_y}{k_x}\right)$$

Wavefunction spectroscopy: Phase dislocations occur on complex fields

Macroscopic Cooper pair wavefunction

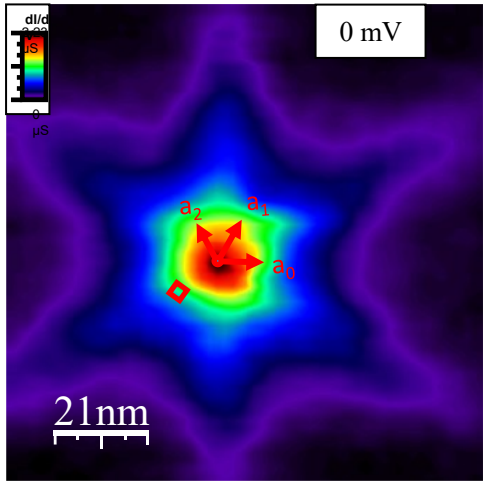
$$\Psi(\mathbf{r}) = \psi_0(\mathbf{r})e^{i\varphi(\mathbf{r})}$$

$$\mathbf{p} = \hbar\nabla\varphi$$

$$v_S = \frac{\hbar}{m}\nabla\varphi$$

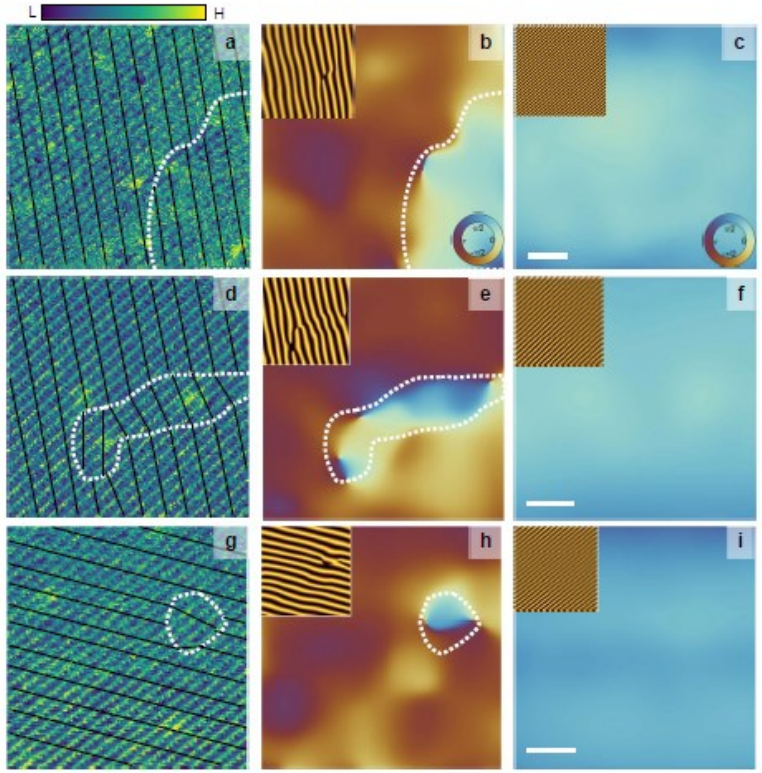
$$\mathbf{p} = \hbar\nabla\varphi = 2m\mathbf{v_s} + 2e\mathbf{A}$$

$$\oint \hbar\nabla\varphi d\mathbf{l} = 2\pi n$$



Charge density wave, macroscopic phase complex field from charge modulation
Dislocations

$$\psi(\mathbf{r}) = \boldsymbol{A}e^{i\phi}$$

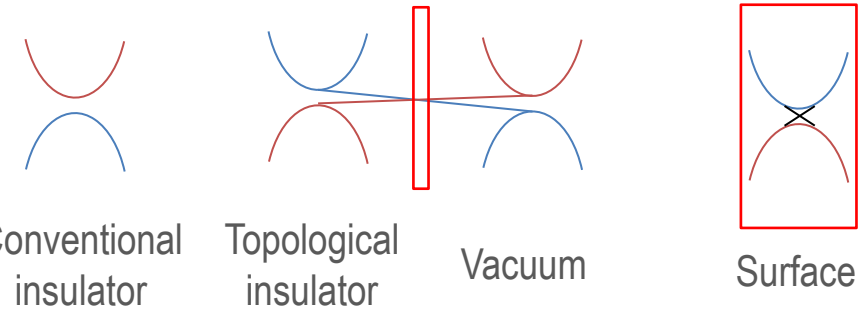


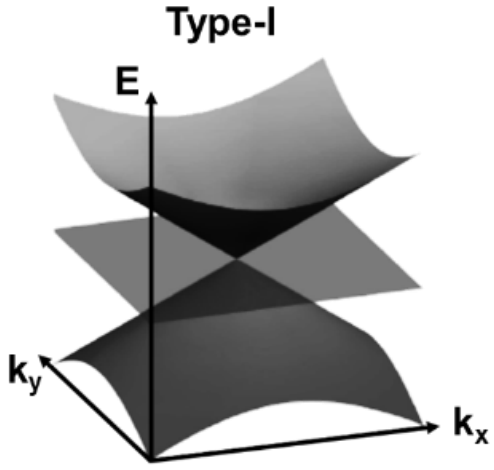
Surface charge density wave in UTe2

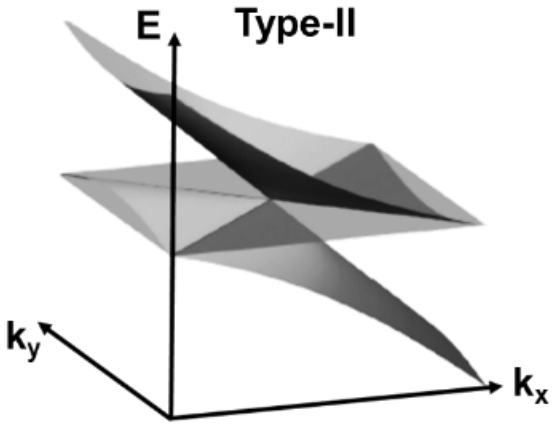
Pablo García Talavera, Miguel Águeda Velasco, Makoto Shimizu, Beilun Wu, Óscar Bou Marqués, Georg Knebel, Midori Amano Patino, Gerard Lapertot, Jacques Flouquet, Jean Pascal Brison, Dai Aoki, Youichi Yanase, Edwin Herrera, Isabel Guillamón, Hermann Suderow

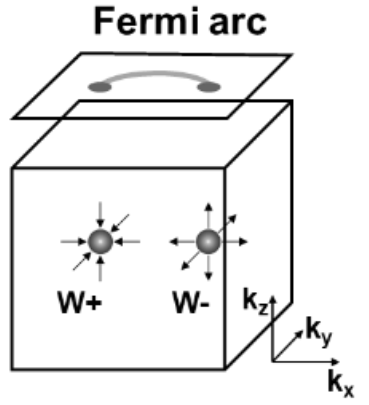
Weyl cones and Fermi arcs

Surface topological states connect Weyl points









$$C = \frac{1}{2\pi}\oint \Omega(\boldsymbol{q})\, d\boldsymbol{S} = \pm 1$$

Nature **527**, 495–498 (2015)

PRL **115,** 217601 (2015) PHYSICAL REVIEW LETTERS week ending 20 NOVEMBER 2015

Observation of Fermi-Arc Spin Texture in TaAs

B. Q. Lv,[1,2] S. Muff,[2,3] T. Qian,[1] Z. D. Song,[1] S. M. Nie,[1] N. Xu,[2] P. Richard,[1,4] C. E. Matt,[2] N. C. Plumb,[2] L. X. Zhao,[1] G. F. Chen,[1,4] Z. Fang,[1,4] X. Dai,[1,4] J. H. Dil,[2,3] J. Mesot,[2,3,5] M. Shi,[2,*] H. M. Weng,[1,4,†] and H. Ding[1,4,‡]

Wavefunction spectroscopy: Phase dislocations

Pseudospin in graphene

Measuring the Berry phase of graphene from wavefront dislocations in Friedel oscillations

C. Dutreix, H. González-Herrero, I. Brihuega, M. I. Katsnelson, C. Chapelier & V. T. Renard

Nature **574**, 219–222 (2019) | Cite this article

Mesurer la phase de Berry du graphène en l'absence de champ magnétique

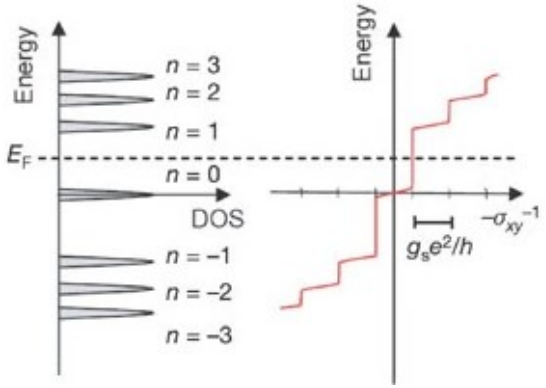
Clément Dutreix[a], Hector González-Herrero[b,c], Ivan Brihuega[b,c,d], Mikhail I. Katsnelson[e], Claude Chapelier[f] and Vincent T. Renard[e,f]

Letter | Published: 10 November 2005

Experimental observation of the quantum Hall effect and Berry's phase in graphene

Yuanbo Zhang, Yan-Wen Tan, Horst L. Stormer & Philip Kim

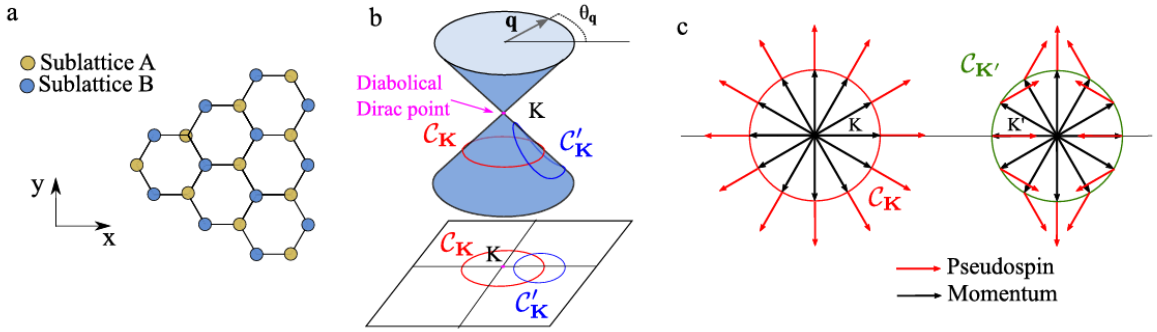
Nature **438**, 201–204 (2005) | Cite this article

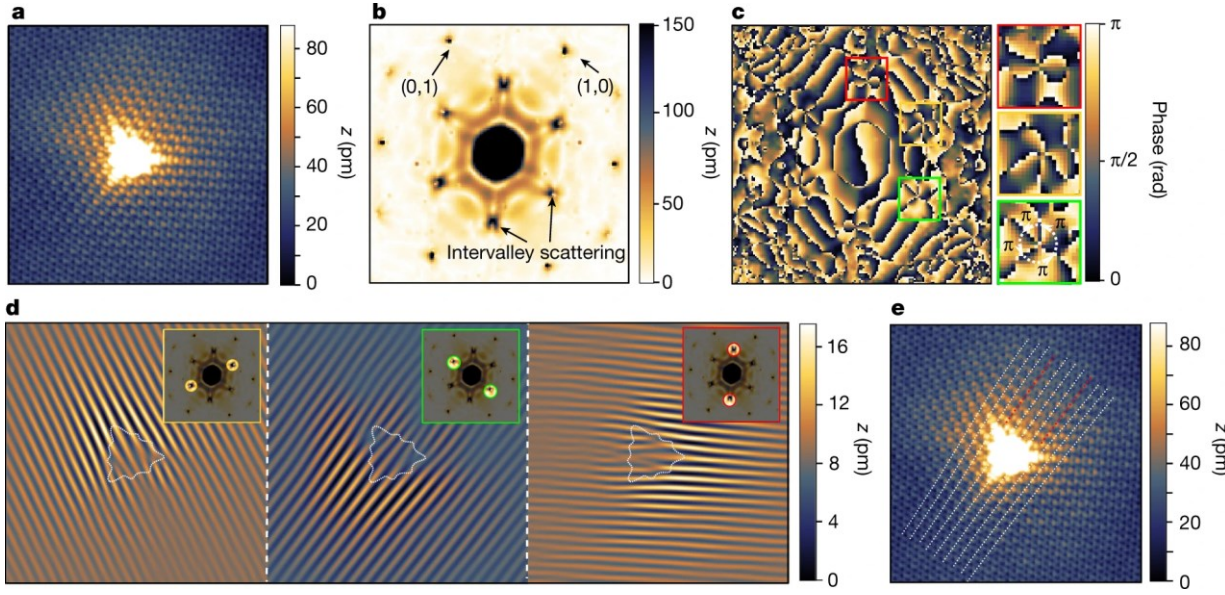


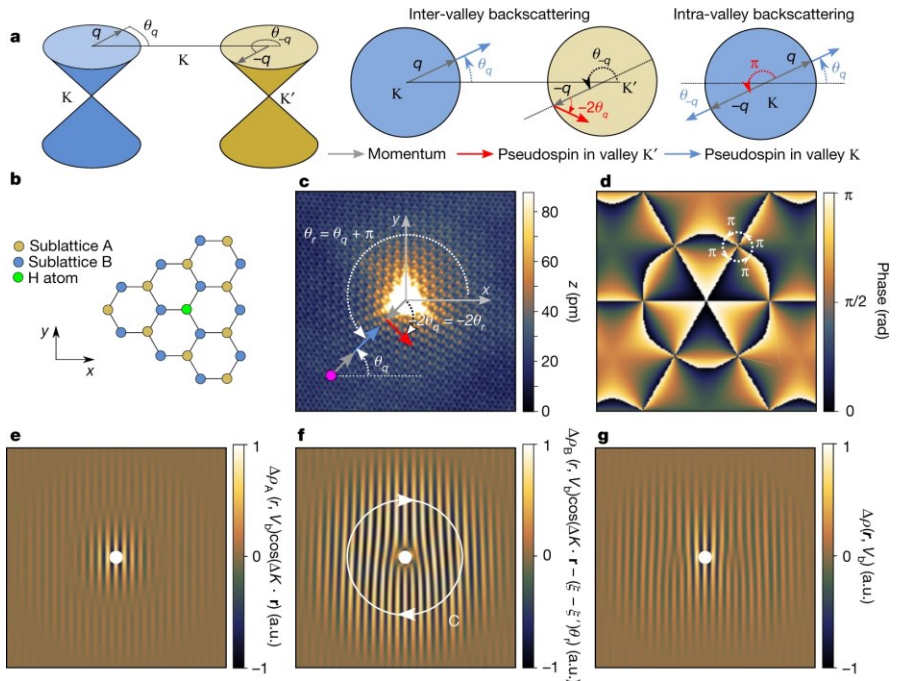
$$A(E_n) = 2\pi \frac{eB}{\hbar}(n+\gamma)$$

$$\gamma = \frac{1}{2} - \frac{\varphi_B}{2\pi}$$

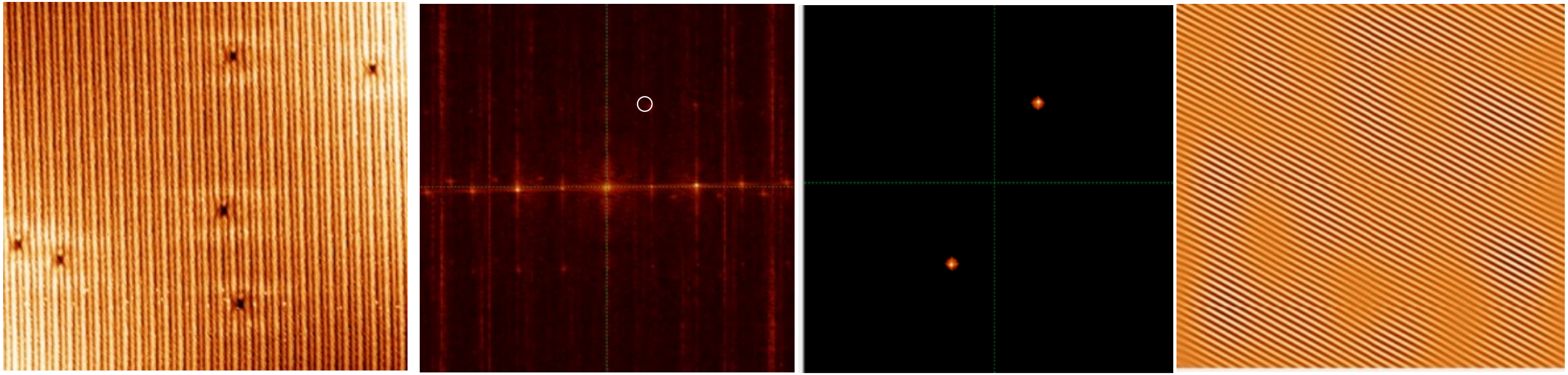
$$\varphi_B = \oint \boldsymbol{A}(\boldsymbol{k})d\boldsymbol{k}$$







Fourier Filter



$$\rho(\boldsymbol{r}) \rightarrow \tilde{\rho}(\boldsymbol{k}) \rightarrow \tilde{\rho}_{Q_0}(\boldsymbol{k}) \rightarrow \rho_{Q_0}(\boldsymbol{r})$$

$$\tilde{\rho}(-\boldsymbol{k}) = \tilde{\rho}(\boldsymbol{k})^*$$

$$\rho(\boldsymbol{r}) = e^{i\boldsymbol{k}\cdot\boldsymbol{r}} + e^{-i\boldsymbol{k}\cdot\boldsymbol{r}} = \cos(\boldsymbol{k}\cdot\boldsymbol{r})$$

$$\rho(\boldsymbol{r}) = \rho(\boldsymbol{r})^*$$

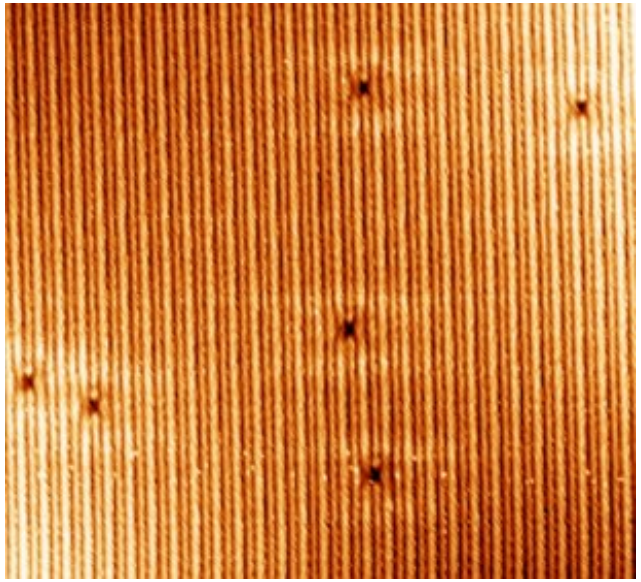
$$\tilde{\rho}(-\boldsymbol{k}) = \tilde{\rho}(\boldsymbol{k})$$

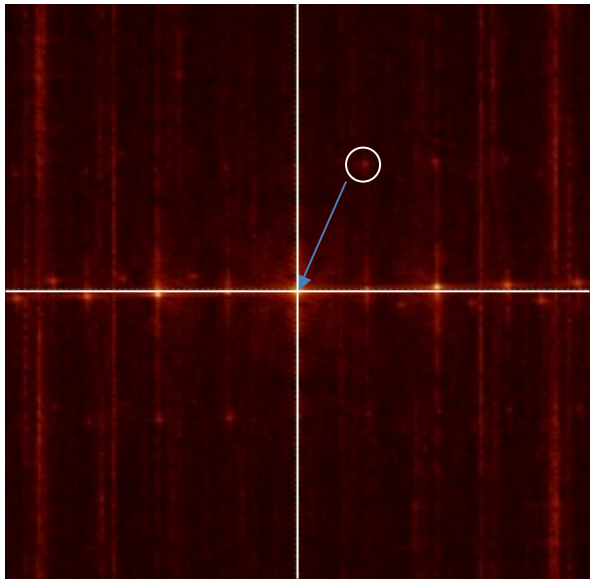
PHYSICAL REVIEW B **112**, 165401 (2025)

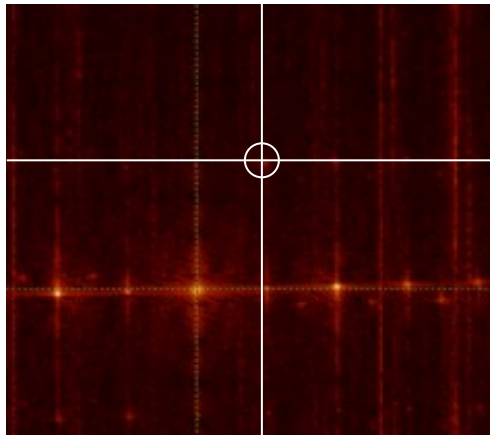
Electronic band structure from quasiparticle interference and Landau quantization in WTe_2

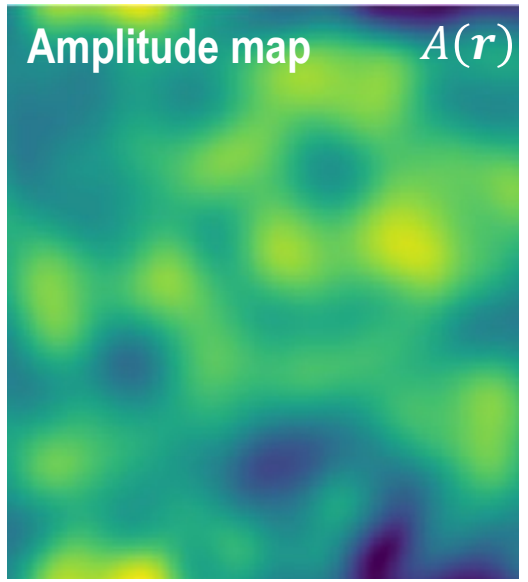
Raquel Sánchez-Barquilla,[1] Francisco Martín Vega,[1] Alberto M. Ruiz,[2] Na Hyun Jo,[3,*] Edwin Herrera,[1] José J. Baldoví,[2] Masayuki Ochi,[4,5] Ryotaro Arita,[6,7] Sergey L. Bud'ko,[3] Paul C. Canfield,[3] Isabel Guillamón,[1] and Hermann Suderow[1,†]

Geometric phase analysis



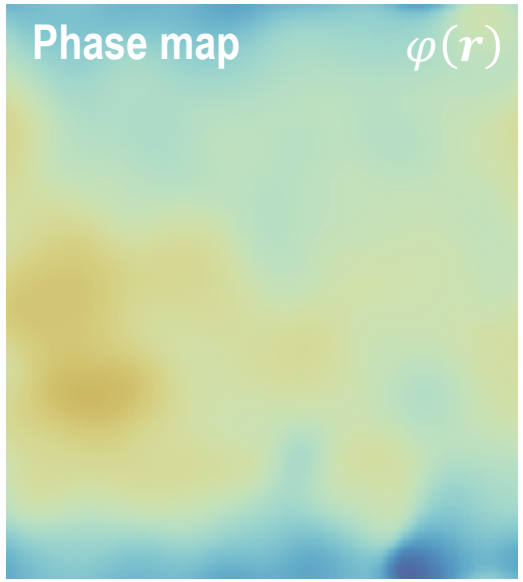






$$\rho(\boldsymbol{r}) \rightarrow \tilde{\rho}(\boldsymbol{k}) \rightarrow \tilde{\rho}_{Q_0}(\boldsymbol{k})$$

$$\tilde{\rho}(-\boldsymbol{k}) \neq \tilde{\rho}(\boldsymbol{k})$$
$$\rho(\boldsymbol{r}) \neq \rho(\boldsymbol{r})^*$$



$$\rho_{Q_0}(\boldsymbol{r}) = A(\boldsymbol{r})\cos\left(\boldsymbol{Q}_0 + \varphi(\boldsymbol{r})\right)$$

1D charge density wave in the hidden order state of URu_2Si_2

Edwin Herrera, Víctor Barrena, Isabel Guillamón, José Augusto Galvis, William J. Herrera, José Castilla, Dai Aoki, Jacques Flouquet & Hermann Suderow

Wave field reconstruction and phase imaging by electron diffractive imaging

Jun Yamasaki[1,2]

[1]Research Center for Ultra-High Voltage Electron Microscopy, Osaka University, 7-1 Mihogaoka, Ibaraki, Osaka, Japan and [2]Institute of Materials and Systems for Sustainability, Nagoya University, Nagoya, Aichi, Japan

Disentangling Coexisting Structural Order Through Phase Lock-In Analysis of Atomic-Resolution STEM Data Get access

Berit H Goodge, Ismail El Baggari, Seung Sae Hong, Zhe Wang, Darrell G Schlom, Harold Y Hwang, Lena F Kourkoutis

Microscopy and Microanalysis, Volume 28, Issue 2, 1 April 2022, Pages 404–411, https://doi.org/10.1017/S1431927622000125

Letter | Published: 15 July 2010

Intra-unit-cell electronic nematicity of the high-T_c copper-oxide pseudogap states

M. J. Lawler, K. Fujita, Jhinhwan Lee, A. R. Schmidt, Y. Kohsaka, Chung Koo Kim, H. Eisaki, S. Uchida, J. C. Davis, J. P. Sethna & Eun-Ah Kim

Nature **466**, 347–351 (2010) | Cite this article

Quantitative measurement of displacement and strain fields from HREM micrographs

M.J. Hÿtch a, E. Snoeck b, R. Kilaas c

Quasiparticle interference in presence of Spin Orbit Coupling

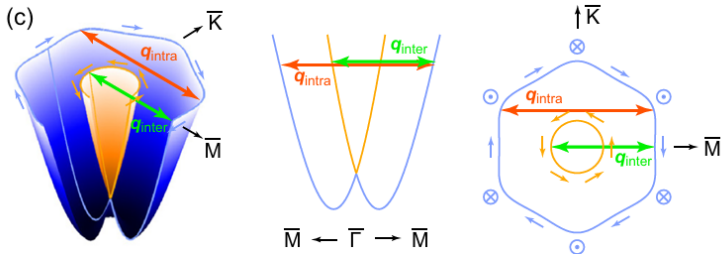
PHYSICAL REVIEW B **95**, 115307 (2017)

Spin-orbit scattering visualized in quasiparticle interference

Y. Kohsaka,[1,*] T. Machida,[1] K. Iwaya,[1] M. Kanou,[2] T. Hanaguri,[1] and T. Sasagawa[2]
[1]*RIKEN Center for Emergent Matter Science, Wako, Saitama 351-0198, Japan*
[2]*Laboratory for Materials and Structures, Tokyo Institute of Technology, Yokohama, Kanagawa 226-8503, Japan*

$$H_{SOC} = \frac{\hbar}{4m^2c^2}(\nabla V \times \boldsymbol{p}) \cdot \boldsymbol{\sigma}$$

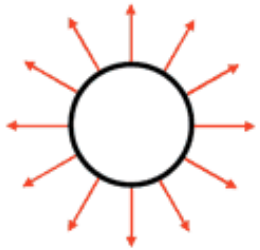
$$QPI(\boldsymbol{k} - \boldsymbol{k}') \propto V_{\boldsymbol{k},\boldsymbol{k}'} N(E, \boldsymbol{k}) N(E, \boldsymbol{k}')$$

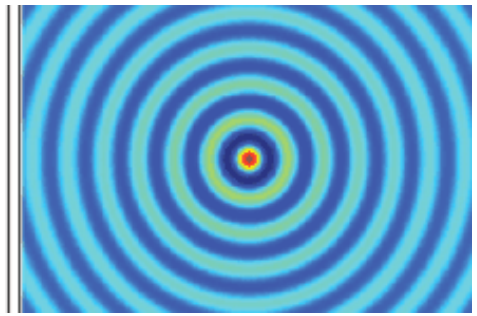


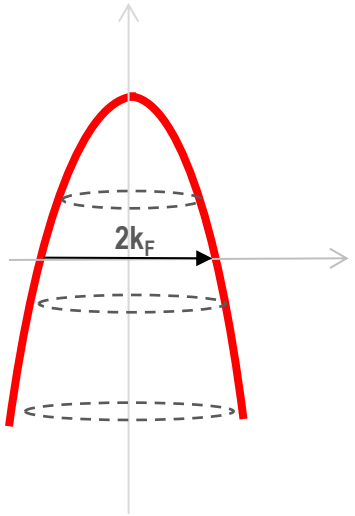
$$V = V_0 \sigma_z$$

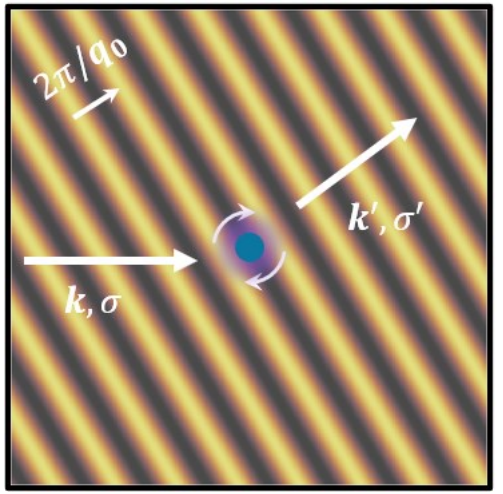
$$V_{\boldsymbol{k},\boldsymbol{k}'} = V_0(I + i\alpha(\boldsymbol{k} \times \boldsymbol{k}') \cdot \boldsymbol{\sigma})$$

Fermi surface

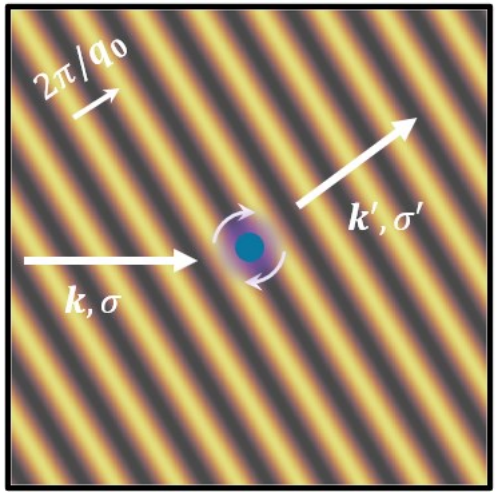






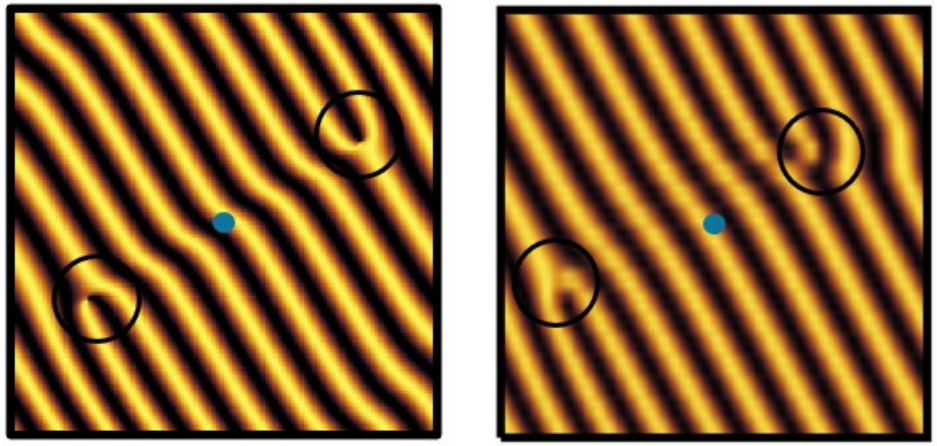


Visualize phase dislocations with geometric phase analysis?



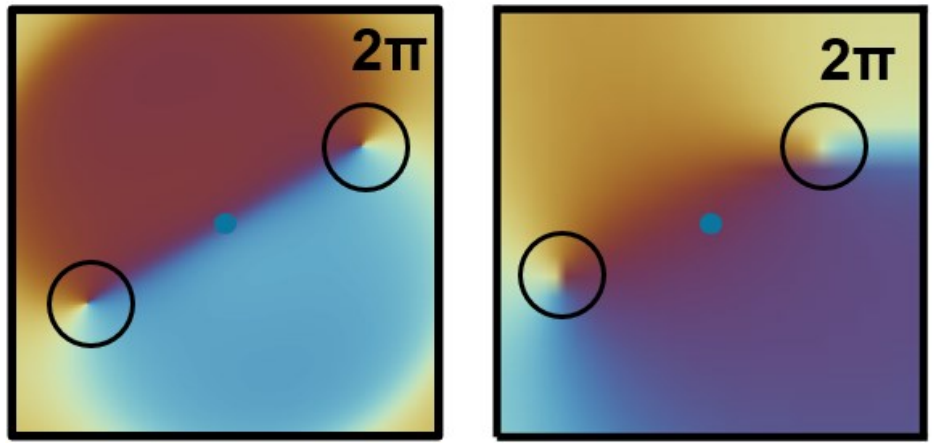
Experiment

Calculations



-π

π



Phase map

Phase map

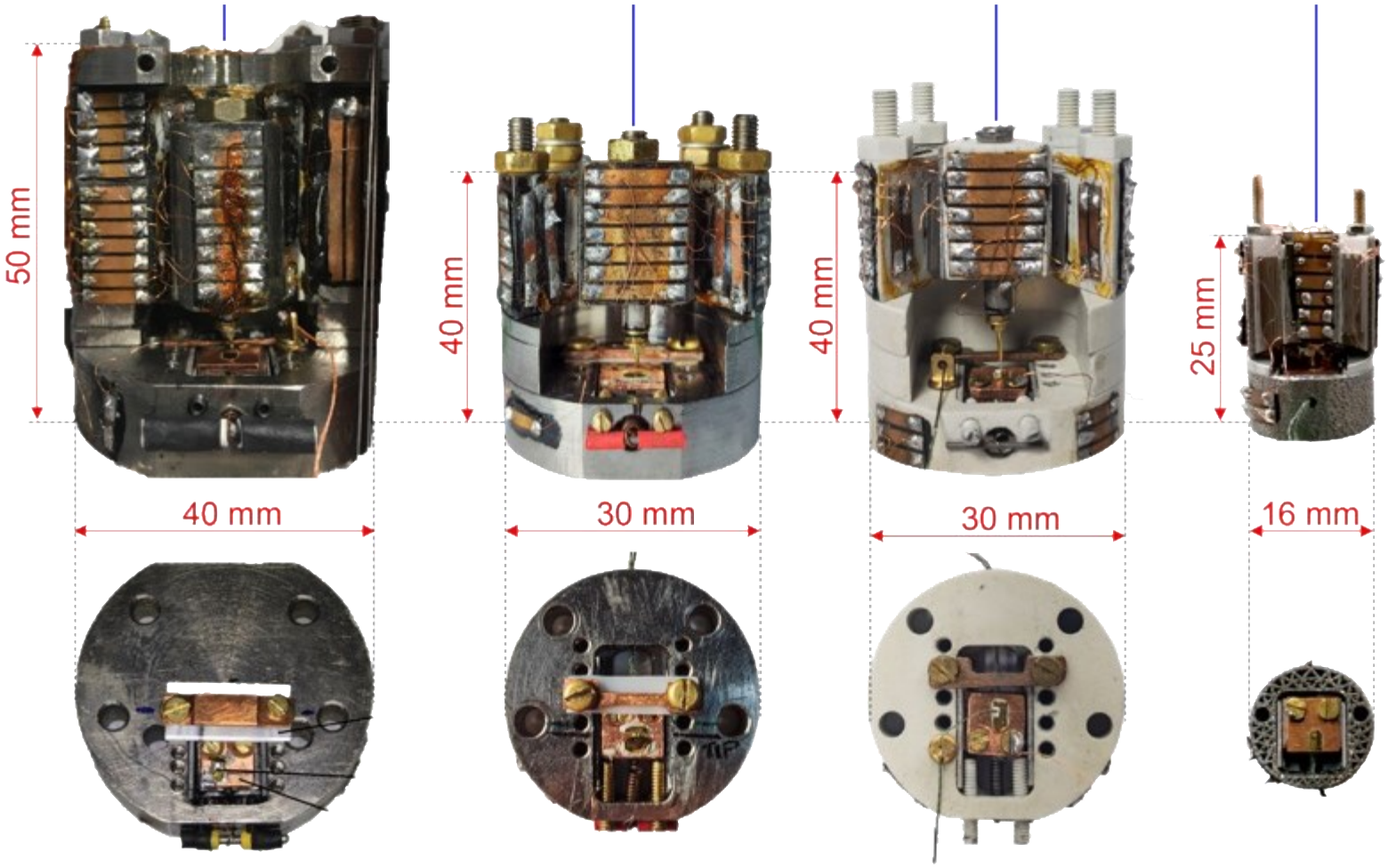
$$V = V_0 \sigma_z$$

$$V_{\boldsymbol{k},\boldsymbol{k}'} = V_0 (I + i\alpha(\boldsymbol{k} \times \boldsymbol{k}') \cdot \boldsymbol{\sigma})$$

Real-space visualization of scattering phase dislocations in a magnetic semiconductor

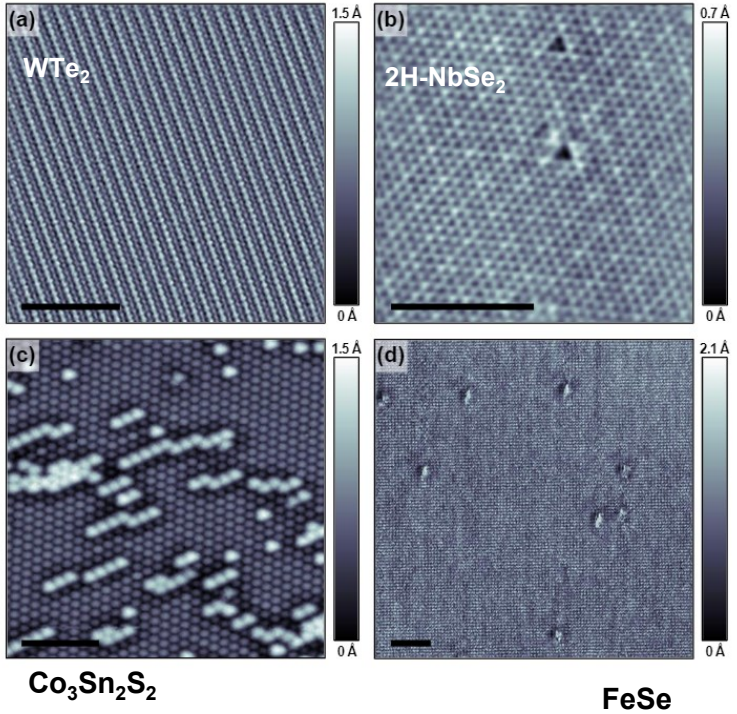
- Quasiparticle interference scattering. Spin orbit scattering.
- Our microscopes and ongoing work
- Scanning Tunneling Spectroscopy of the magnetic semiconductor $EuCd_2As_2$

Self-built microscopes at UAM in nearly self-built ^{3}He-^{4}He dilution refrigerators





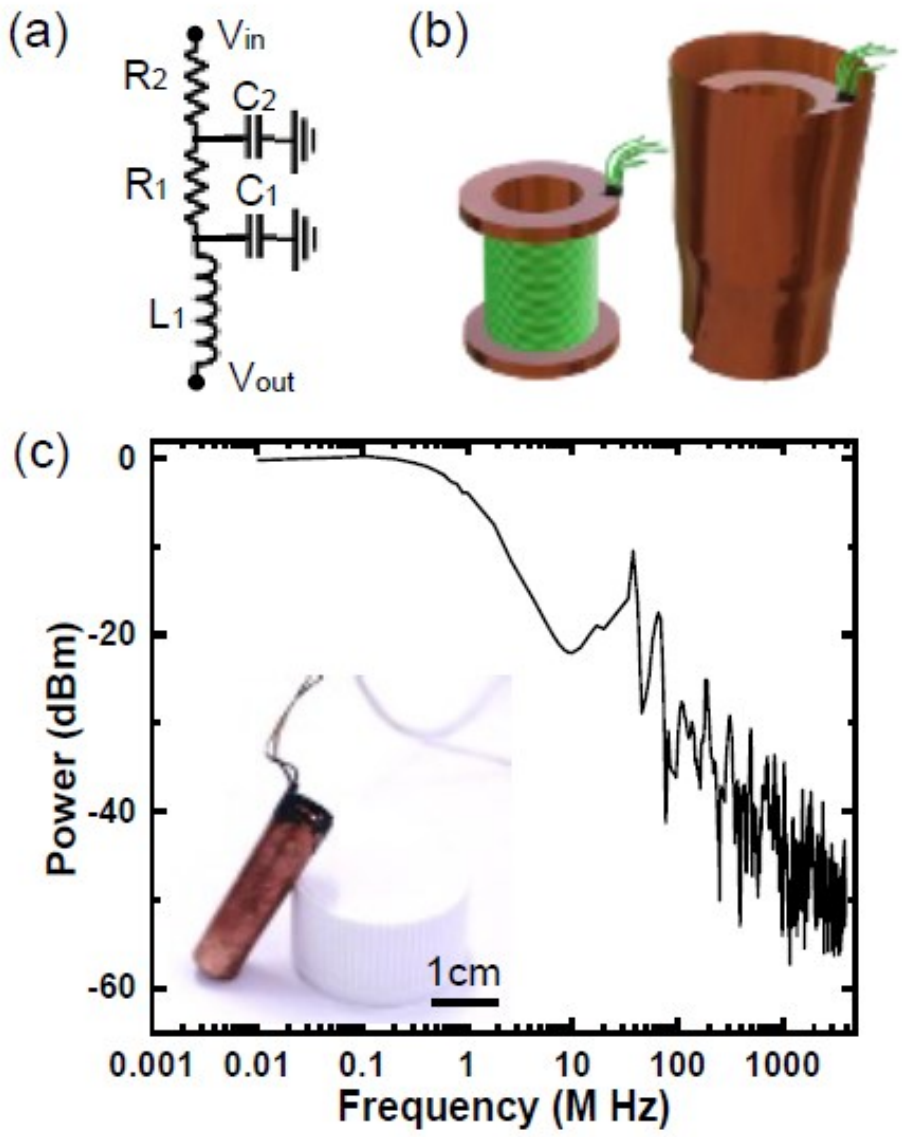
3D printed in grade 5 Titanium alloy



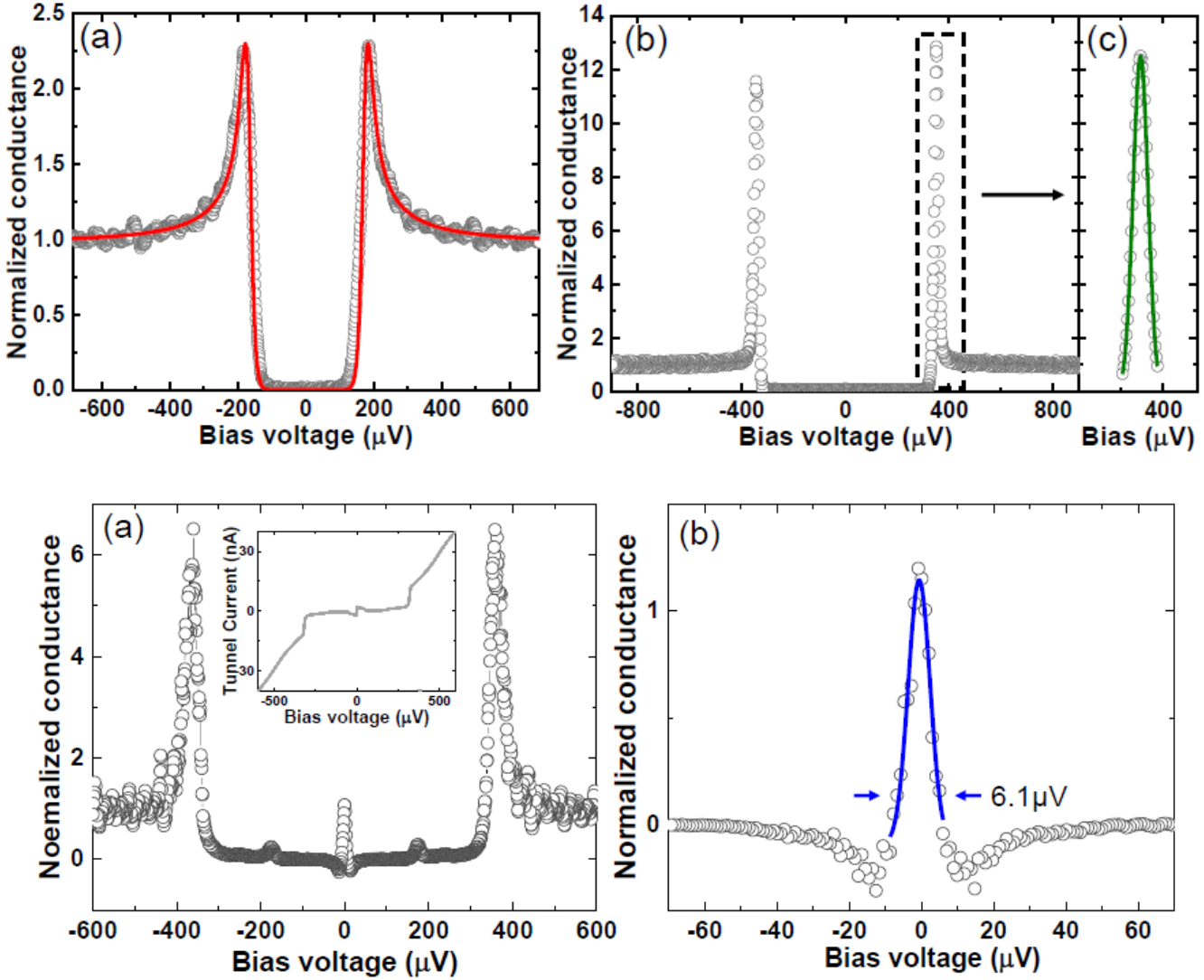
$Co_3Sn_2S_2$

FeSe

Filters and resolution in energy

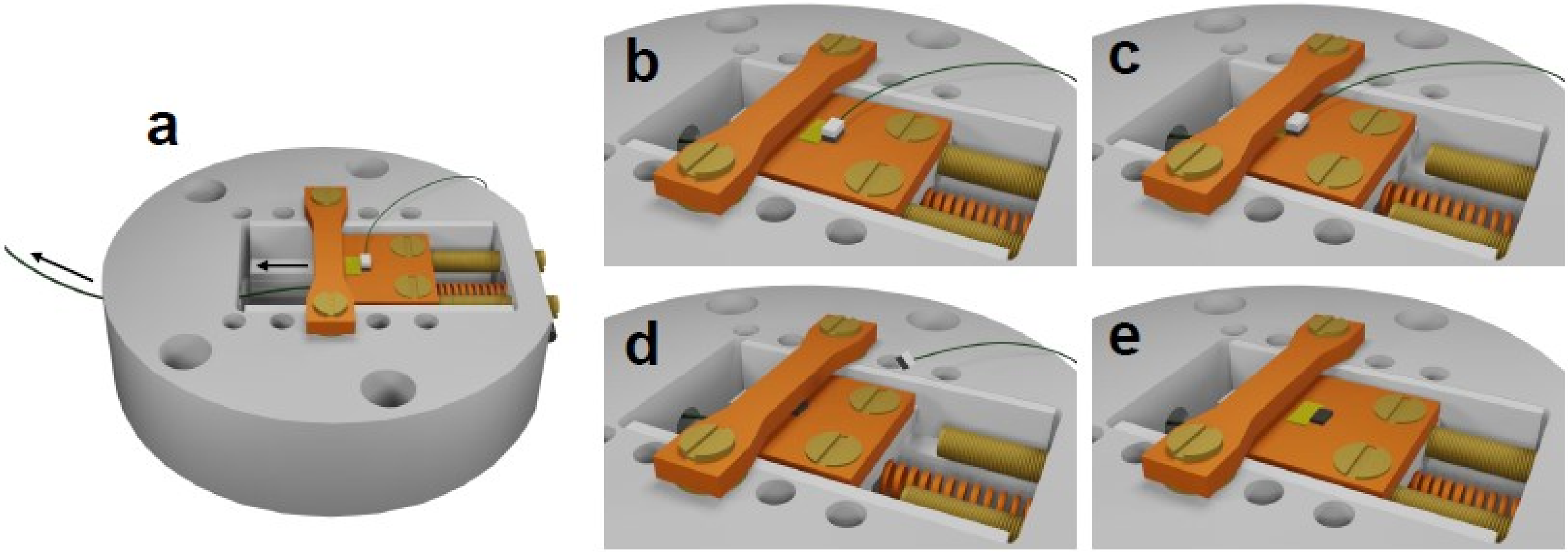


RSI 92, 103705 (2021)



RSI 92, 093701 (2021)

Sample preparation



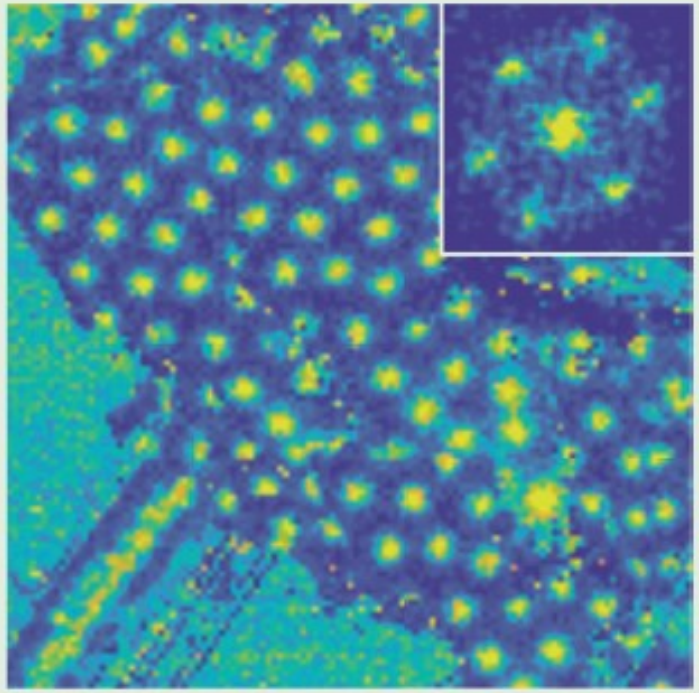
RSI 92, 093701 (2021)



137

PHYSICAL REVIEW LETTERS

Published week ending 21 AUGUST 2026



PRL 137 (8), 080201–088402, 21 August 2026 (430 total pages)

8

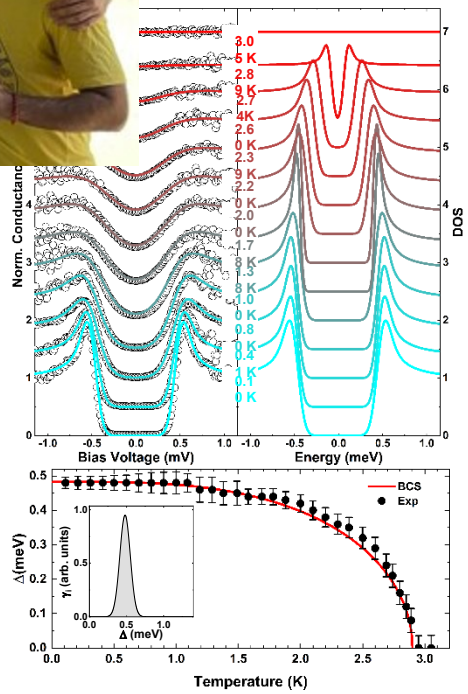
Published by
American Physical Society

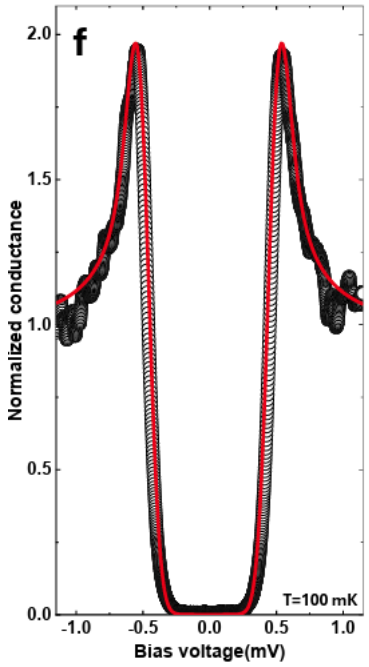
APS

Volume 137, Number 8

Quasiparticle interference: in the Weyl semimetal $PtBi_2$



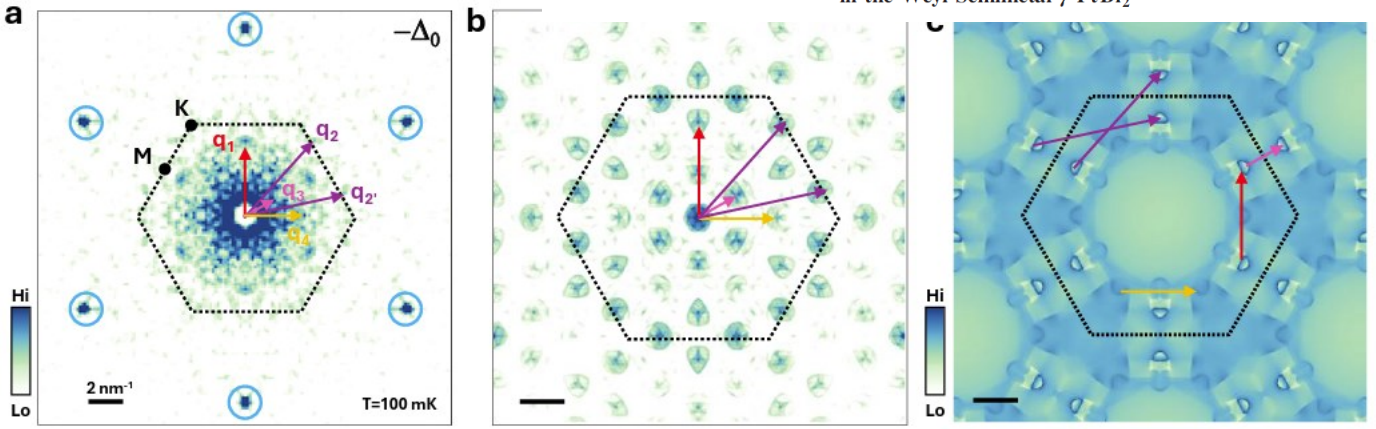




PHYSICAL REVIEW LETTERS **137,** 086001 (2026)

Editors' Suggestion

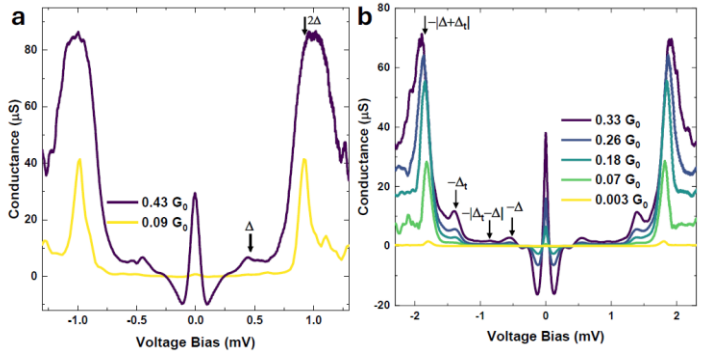
Robust Two-Dimensional Surface Superconductivity and Vortex Lattice in the Weyl Semimetal γ-$PtBi_2$

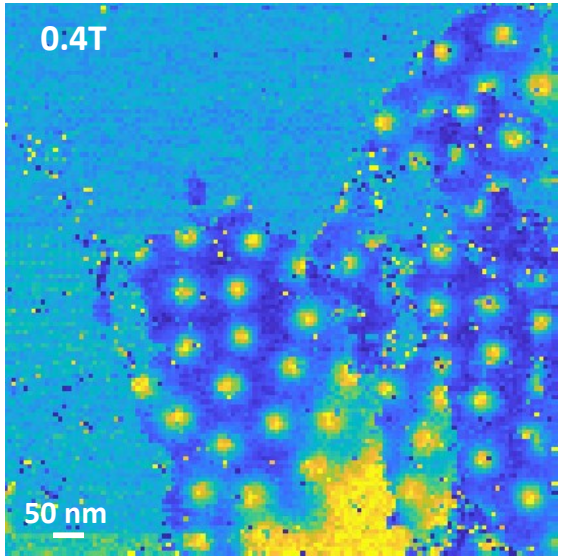


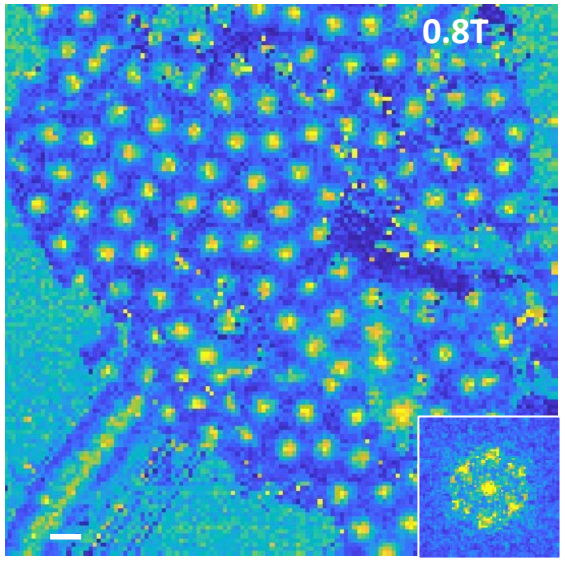
$$\Psi(\mathbf{r}) = \psi_0(\mathbf{r})e^{i\phi(\mathbf{r})}$$

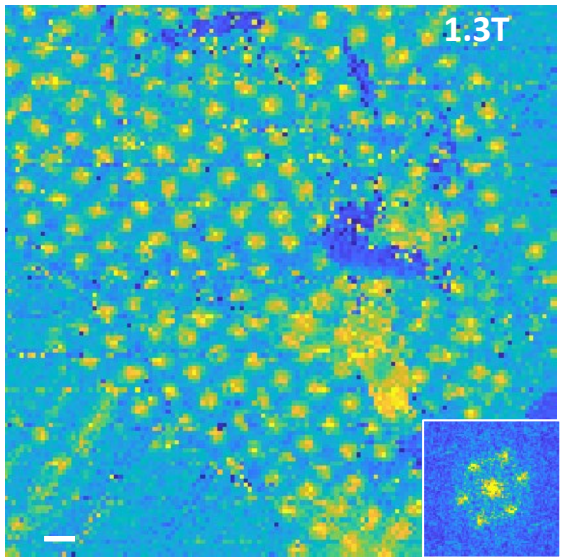
$$\mathbf{p} = \hbar\nabla\phi; \mathrm{v_S} = \frac{\hbar}{m}\nabla\phi$$

PRL, Editors suggestion





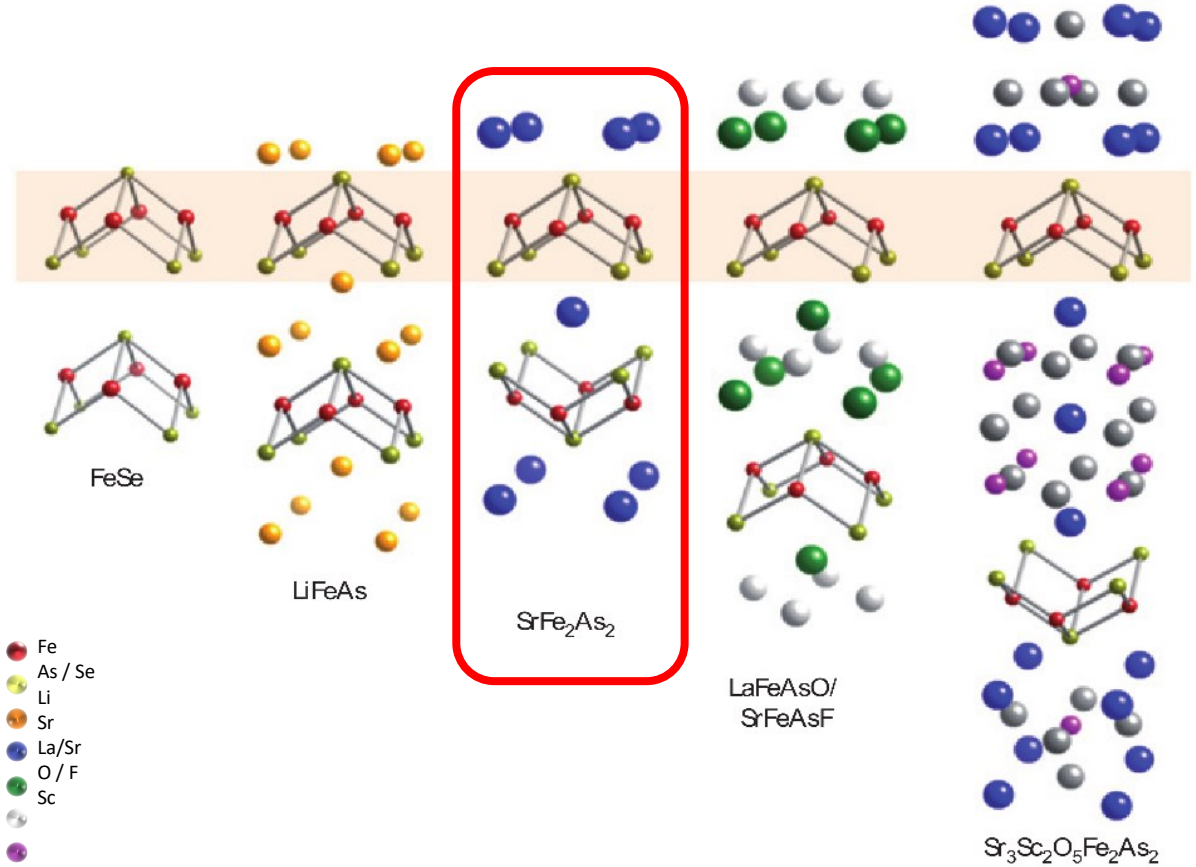


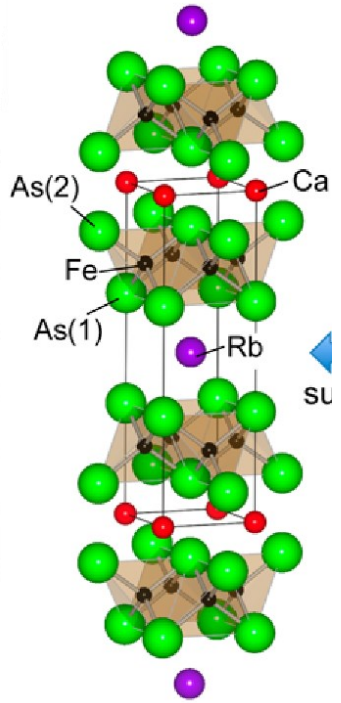


Real-space visualization of scattering phase dislocations in a magnetic semiconductor

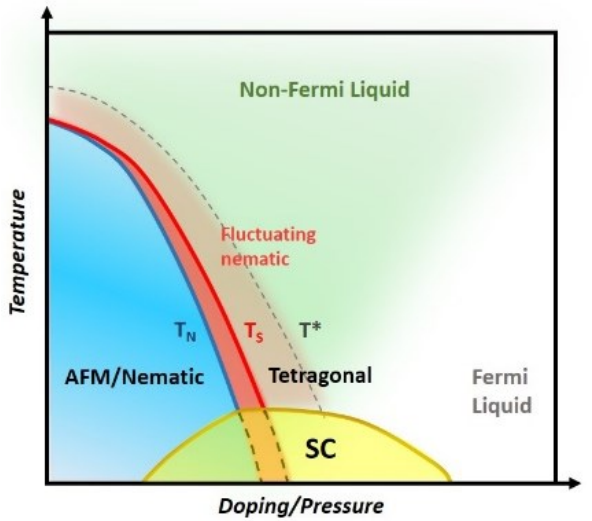
- Quasiparticle interference scattering. Spin orbit scattering.
- Our microscopes and ongoing work
- Scanning Tunneling Spectroscopy of the magnetic semiconductor $EuCd_2As_2$

Crystal structures in the pnictides

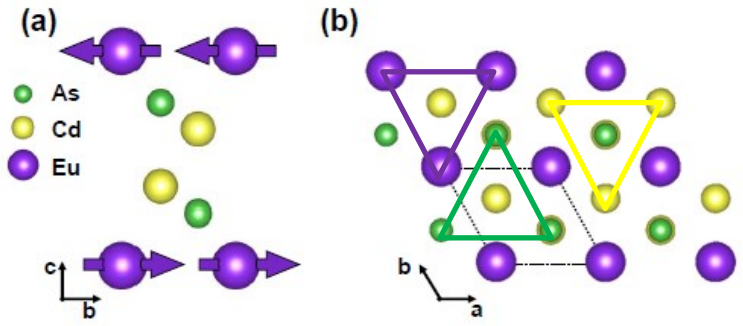


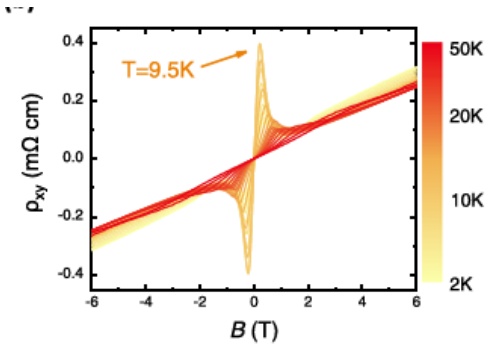


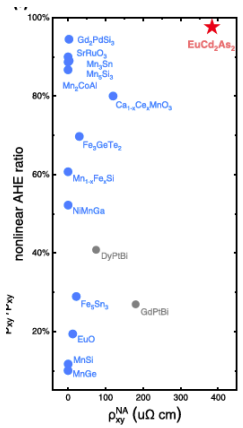
$CaRbFe_4As_4$
(*P4/mmm*)



$EuCd_2As_2$: An “ideal Weyl semimetal”?







PHYSICAL REVIEW B **99**, 245147 (2019)

Single pair of Weyl fermions in the half-metallic semimetal $EuCd_2As_2$

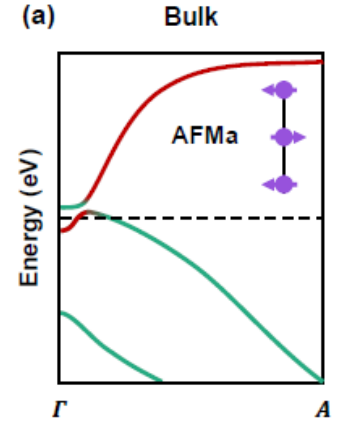
Lin-Lin Wang,[1,*] Na Hyun Jo,[2] Brinda Kuthanazhi,[2] Yun Wu,[2] Robert J. McQueeney,[1,2] Adam Kaminski,[1,2] and Paul C. Canfield[1,2]

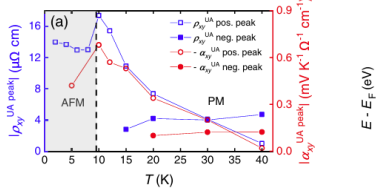
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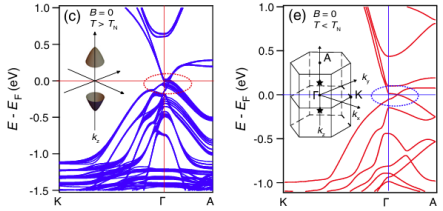
PHYSICS

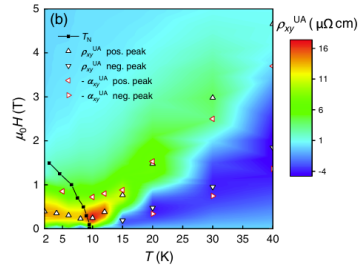
Spin fluctuation induced Weyl semimetal state in the paramagnetic phase of $EuCd_2As_2$

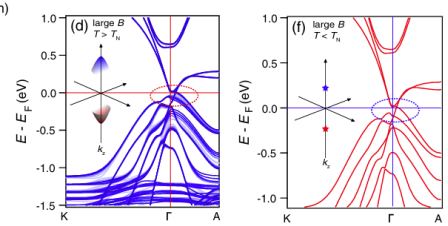
J.-Z. Ma[1,2*], S. M. Nie[2*], C. J. Yi[4,5*], J. Jandke[1], T. Shang[1,2,6], M. Y. Yao[1], M. Naamneh[1], L. Q. Yan[4], Y. Sun[4,5,7], A. Chikina[1], V. N. Strocov[1], M. Medarde[6], M. Song[8,9], Y.-M. Xiong[8,10], G. Xu[11], W. Wulfhekel[12], J. Mesot[1,2,13], M. Reticcioli[14], C. Franchini[14,15], C. Mudry[16,17], M. Müller[16], Y. G. Shi[4,7†], T. Qian[4,7,18†], H. Ding[4,5,7,18], M. Shi[11]











PHYSICAL REVIEW RESEARCH **4**, 023100 (2022)

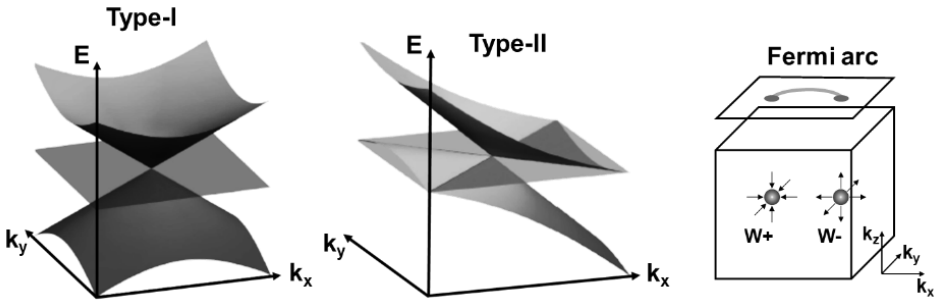
Giant nonlinear anomalous Hall effect induced by spin-dependent band structure evolution

Xiangyu Cao,[1,*] Jie-Xiang Yu,[2,3,*] Pengliang Leng,[1,*] Changjiang Yi,[4,5,*] Xiaoyang Chen,[1,6] Yunkun Yang,[1] Shanshan Liu,[1] Lingyao Kong,[8] Zihan Li,[1] Xiang Dong,[1] Youguo Shi,[4] Manuel Bibes,[7] Rui Peng,[6,11] Jiadong Zang,[2,†] and Faxian Xiu[1,9,10,11,‡]

PHYSICAL REVIEW LETTERS **126,** 076602 (2021)

Unconventional Transverse Transport above and below the Magnetic Transition Temperature in Weyl Semimetal $EuCd_2As_2$

Y. Xu,[1,*] L. Das,[1] J. Z. Ma,[2,3] C. J. Yi,[4] S. M. Nie,[5] Y. G. Shi,[4,6] A. Tiwari,[1,7] S. S. Tsirkin,[1] T. Neupert,[1] M. Medarde,[8] M. Shi,[3] J. Chang,[1,†] and T. Shang[9,1,8,‡]



PHYSICAL REVIEW B **100**, 201102(R) (2019)

Rapid Communications | Editors' Suggestion

Ideal Weyl semimetal induced by magnetic exchange

J.-R. Soh,[1] F. de Juan,[1,2,3] M. G. Vergniory,[2,3] N. B. M. Schröter,[4] M. C. Rahn,[1,*] D. Y. Yan,[5] J. Jiang,[1,6,7] M. Bristow,[1] P. Reiss,[1] J. N. Blandy,[8] Y. F. Guo,[6,9] Y. G. Shi,[5] T. K. Kim,[10] A. McCollam,[11] S. H. Simon,[1] Y. Chen,[1,6] A. I. Coldea,[1] and A. T. Boothroyd[1,†]

ADVANCED SCIENCE Open Access

Research Article | Open Access

Anomalous Hall Conductivity and Nernst Effect of the Ideal Weyl Semimetallic Ferromagnet $EuCd_2As_2$

Subhajit Roychowdhury, Mengyu Yao, Kartik Samanta, Seokjin Bae, Dong Chen, Sailong Ju, Arjun Raghavan, Nitesh Kumar, Procopios Constantinou, Satya N. Guin ... See all authors

First published: 24 February 2023 | https://doi.org/10.1002/advs.202207121 | VIEW METRICS

ADVANCED MATERIALS

Communication

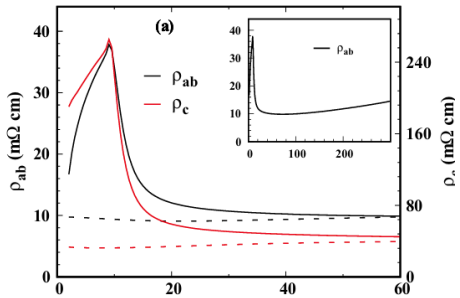
Emergence of Nontrivial Low-Energy Dirac Fermions in Antiferromagnetic $EuCd_2As_2$

Junzhang Ma, Han Wang, Simin Nie, Changjiang Yi, Yuanfeng Xu, Hang Li, Jasmin Jandke, Wulf Wulfhekel, Yaobo Huang, Damien West, Pierre Richard, Alla Chikina, Vladimir N. Strocov, Joël Mesot, Hongming Weng, Shengbai Zhang, Youguo Shi, Tian Qian, Ming Shi, Hong Ding ... See fewer authors

First published: 24 February 2020 | https://doi.org/10.1002/adma.201907565 | VIEW METRICS

Switchable quantum anomalous and spin Hall effects in honeycomb magnet $EuCd_2As_2$

To cite this article: Bingyang Li *et al* 2022 *New J. Phys.* **24** 053038



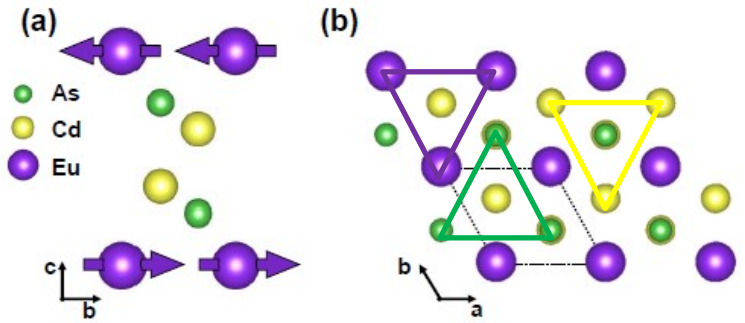
PHYSICAL REVIEW B **94**, 045112 (2016)

Anisotropic transport and optical spectroscopy study on antiferromagnetic triangular lattice $EuCd_2As_2$: An interplay between magnetism and charge transport properties

H. P. Wang,[1] D. S. Wu,[1] Y. G. Shi,[1] and N. L. Wang[2,3,*]

Nature **527**, 495–498 (2015)

$EuCd_2As_2$: A semiconductor …



PHYSICAL REVIEW LETTERS **131,** 186704 (2023)

$EuCd_2As_2$: A Magnetic Semiconductor

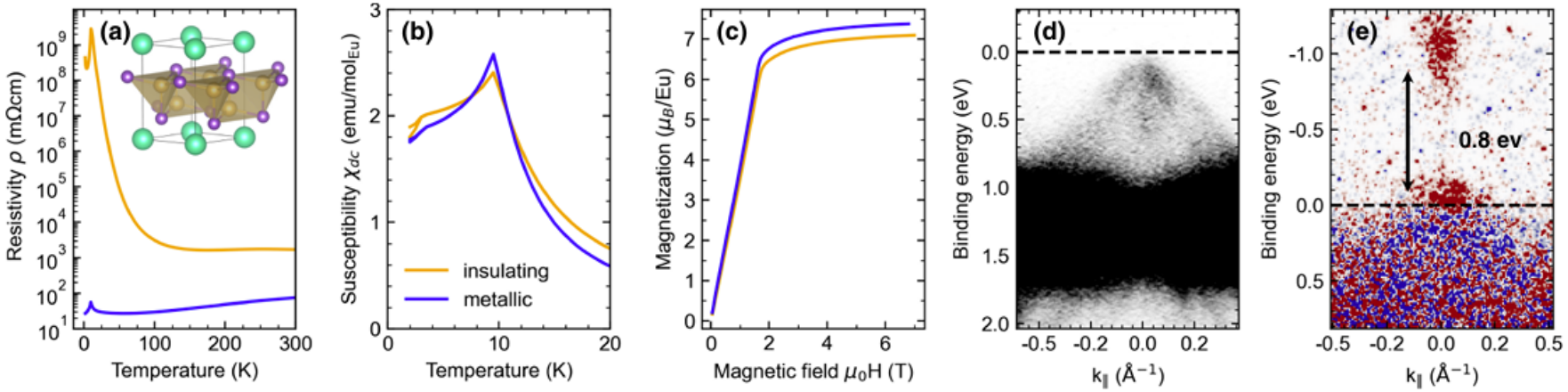
D. Santos-Cottin,[1,*] I. Mohelský,[2] J. Wyzula,[1,2] F. Le Mardelé,[1,2] I. Kapon,[3] S. Nasrallah,[1,4] N. Barišić,[4,5] I. Živković,[6] J. R. Soh,[6] F. Guo,[7,6] K. Rigaux,[7,6] M. Puppin,[7,6] J. H. Dil,[7,6] B. Gudac,[5] Z. Rukelj,[5] M. Novak,[5] A. B. Kuzmenko,[3] C. C. Homes,[8] Tomasz Dietl,[9,10] M. Orlita,[2,11] and Ana Akrap[1,†]

PHYSICAL REVIEW B **109,** 125202 (2024)

Editors' Suggestion

Absence of Weyl nodes in $EuCd_2As_2$ revealed by the carrier density dependence of the anomalous Hall effect

Yue Shi,[1,2] Zhaoyu Liu,[1] Logan A. Burnett,[3] Seokhyeong Lee,[4] Chaowei Hu,[1] Qianni Jiang,[1] Jiaqi Cai,[1] Xiaodong Xu,[1,2] Mo Li,[1,4] Cheng-Chien Chen,[3] and Jiun-Haw Chu[1]



Intrinsic insulating transport characteristics in low-carrier density $EuCd_2As_2$ films

Shinichi Nishihaya; Ayano Nakamura; Mizuki Ohno; Markus Kriener; Yuto Watanabe; Masashi Kawasaki; Masaki Uchida

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Appl. Phys. Lett. 124, 023103 (2024)

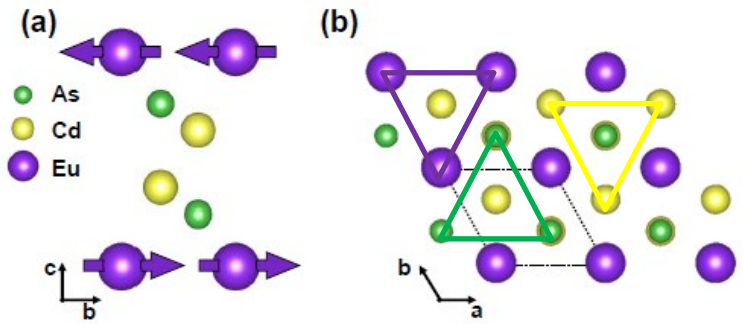
https://doi.org/10.1063/5.0183907 **Article history**

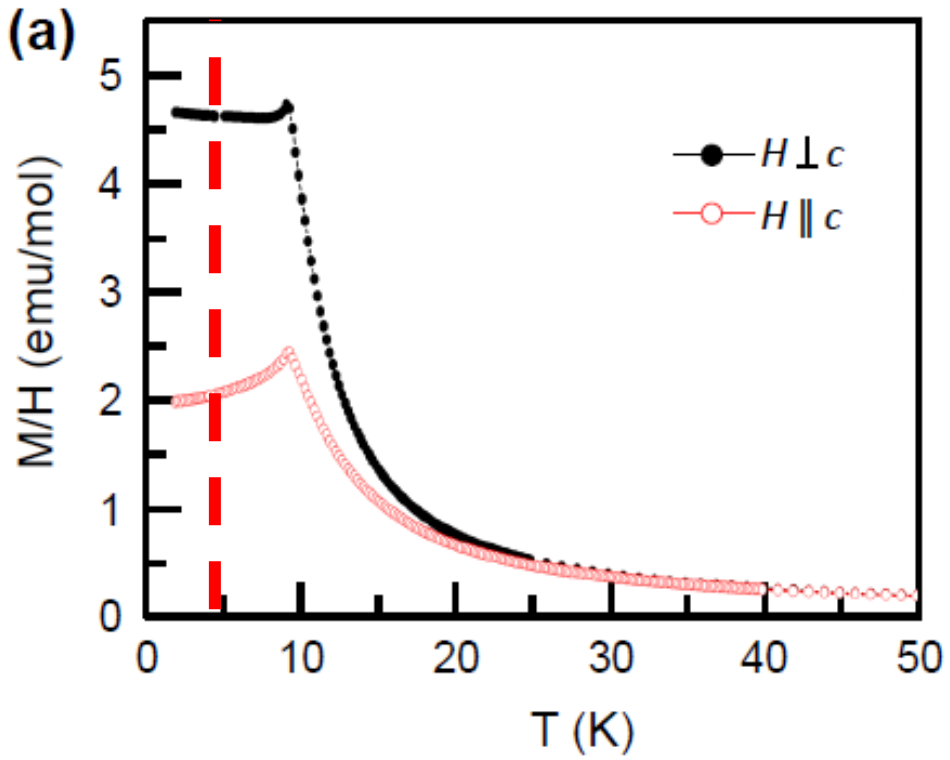
PHYSICAL REVIEW MATERIALS **7,** 034402 (2023)

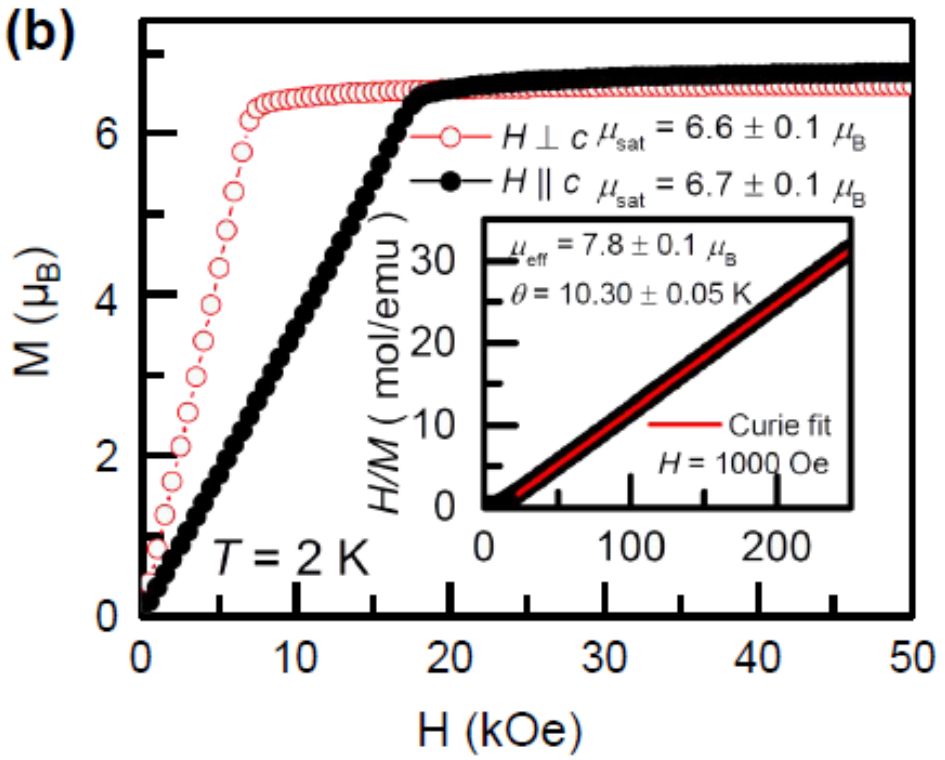
Magnetism and T-x phase diagrams of Na- and Ag-substituted $EuCd_2As_2$

Brinda Kuthanazhi,[1,2] Kamal R. Joshi,[1,2] Sunil Ghimire,[1,2] Erik Timmons,[1,2] Lin-Lin Wang,[1] Elena Gati,[1,2,*] Li Xiang,[1,2,†] Ruslan Prozorov,[1,2] Sergey L. Bud'ko,[1,2] and Paul C. Canfield[1,2,‡]

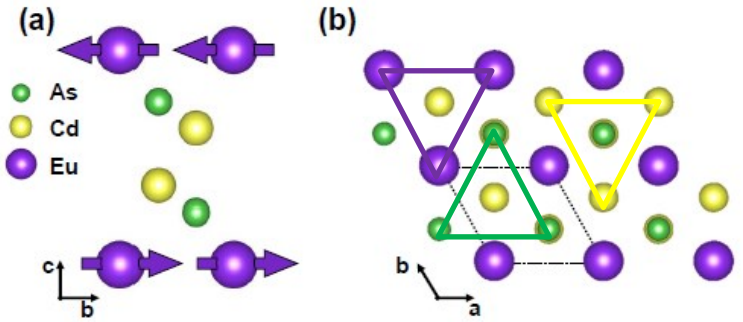
$EuCd_2As_2$: A semiconductor …

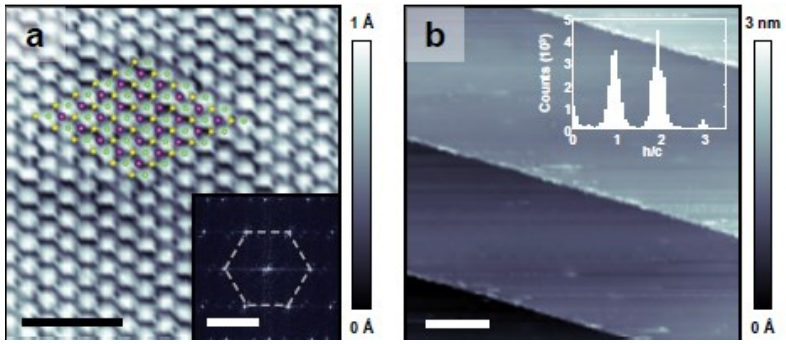


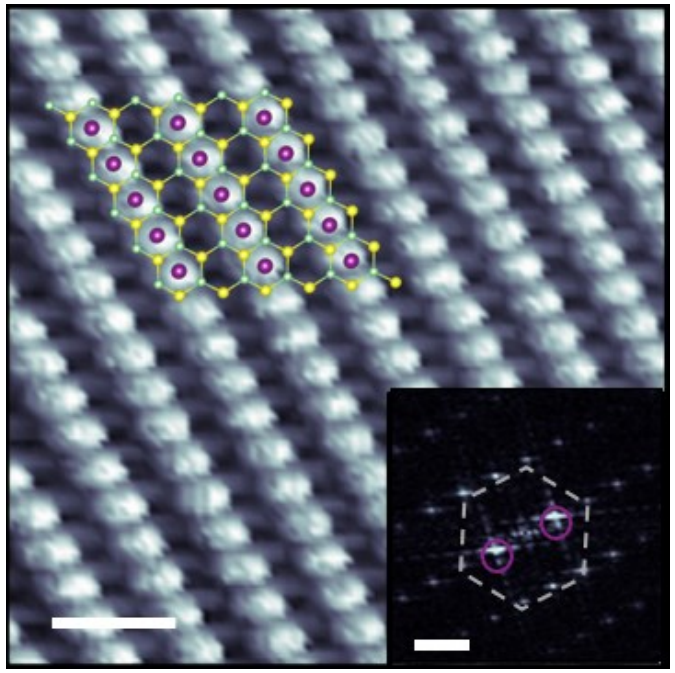


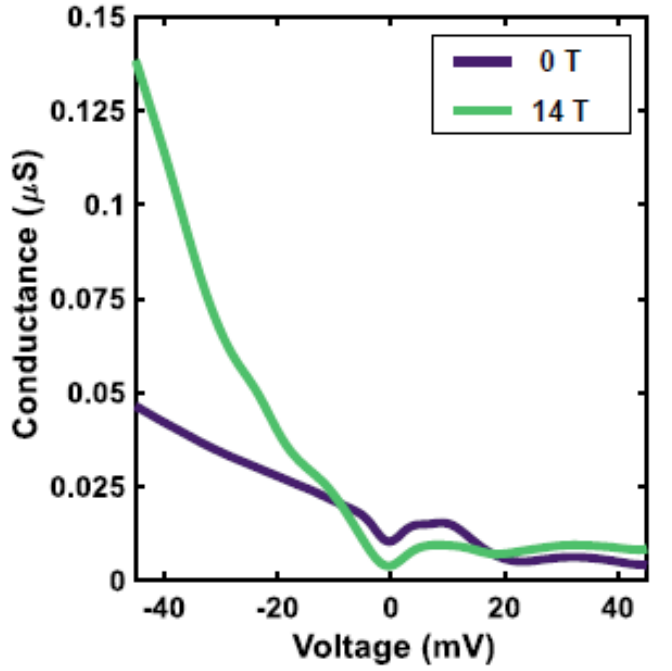


$EuCd_2As_2$



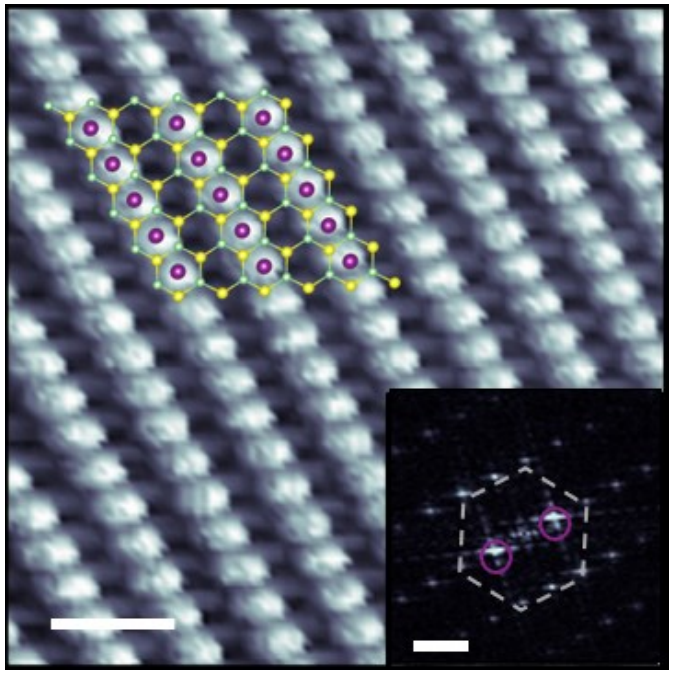


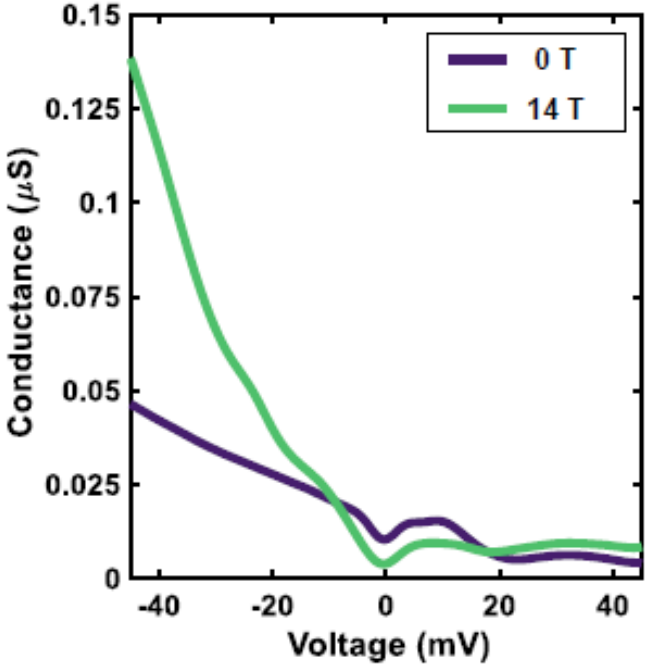


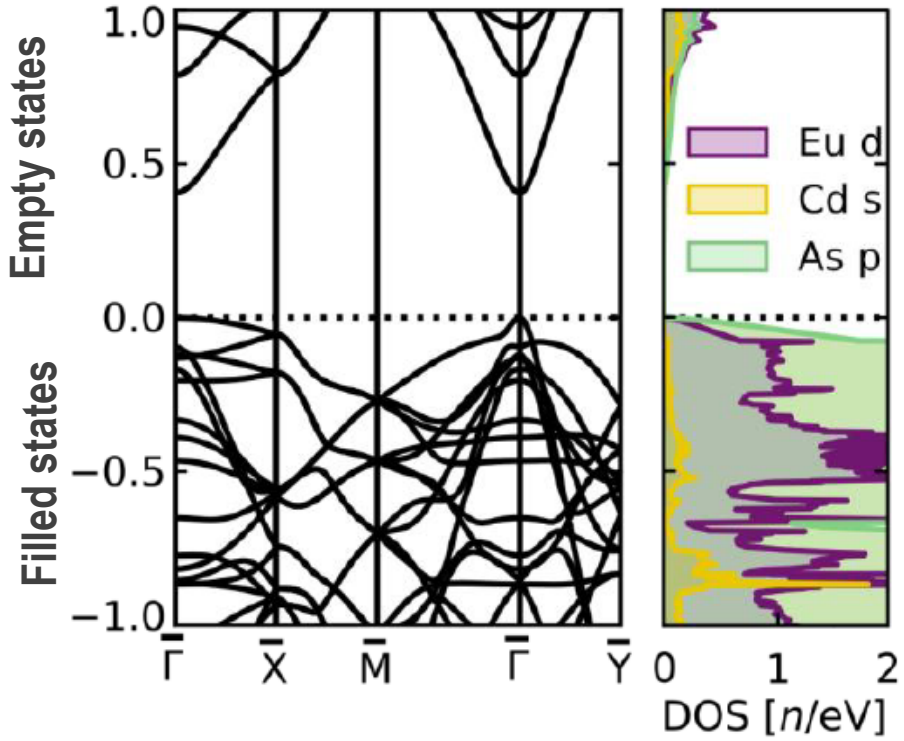


Filled states Empty states

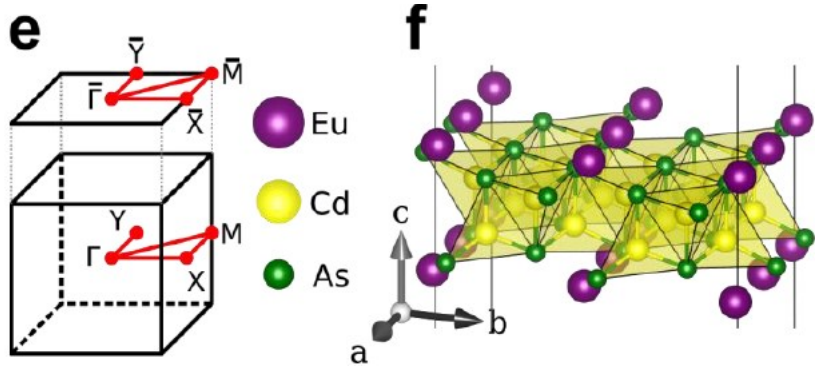
$EuCd_2As_2$





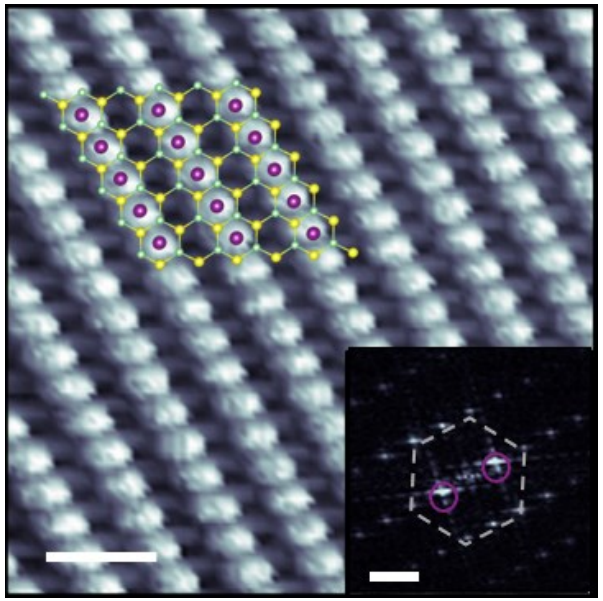


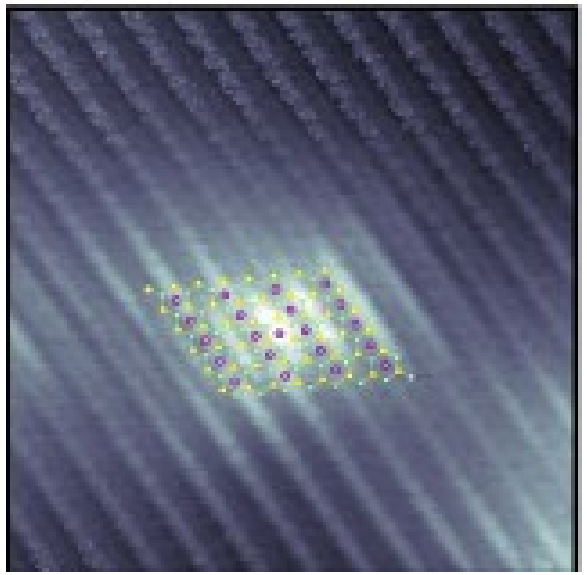
Filled states **Empty states**



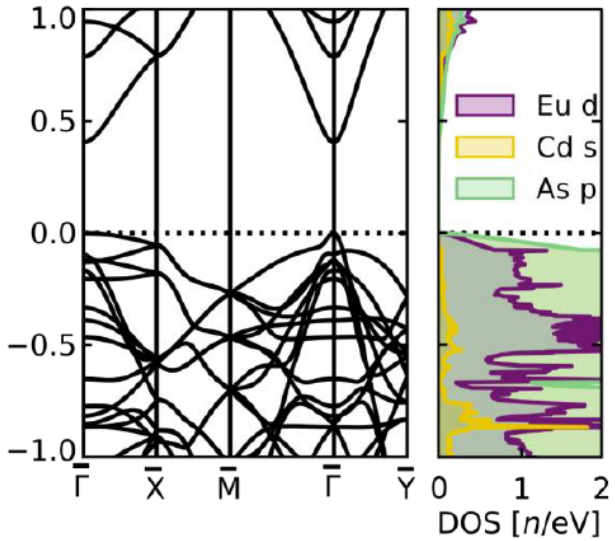
Calculations: Adrian Valadkhni and Roser Valenti

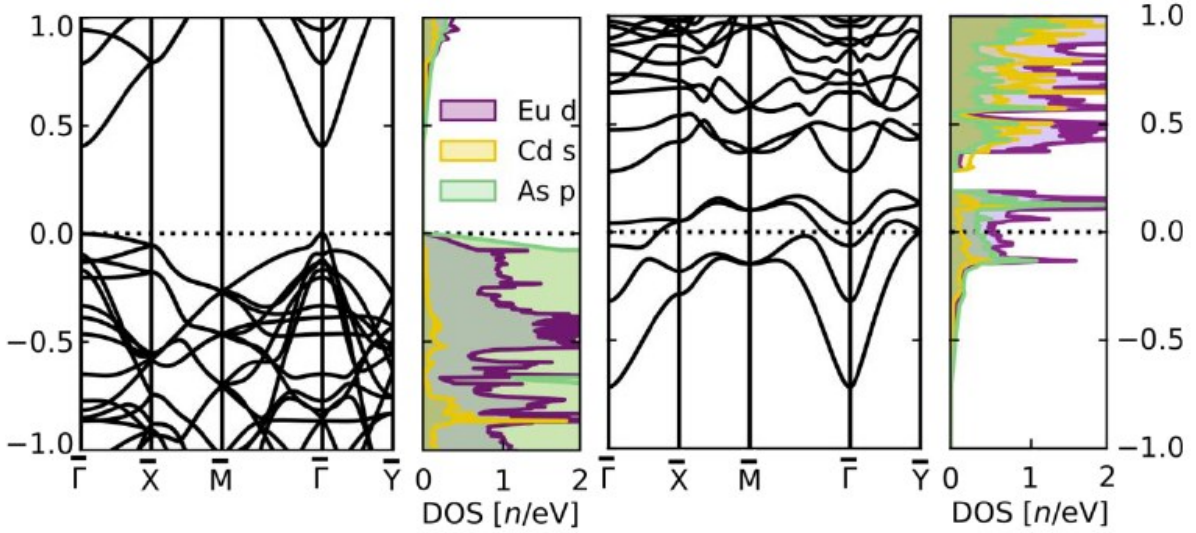
Eu interstitials on $EuCd_2As_2$: localized states at impurities





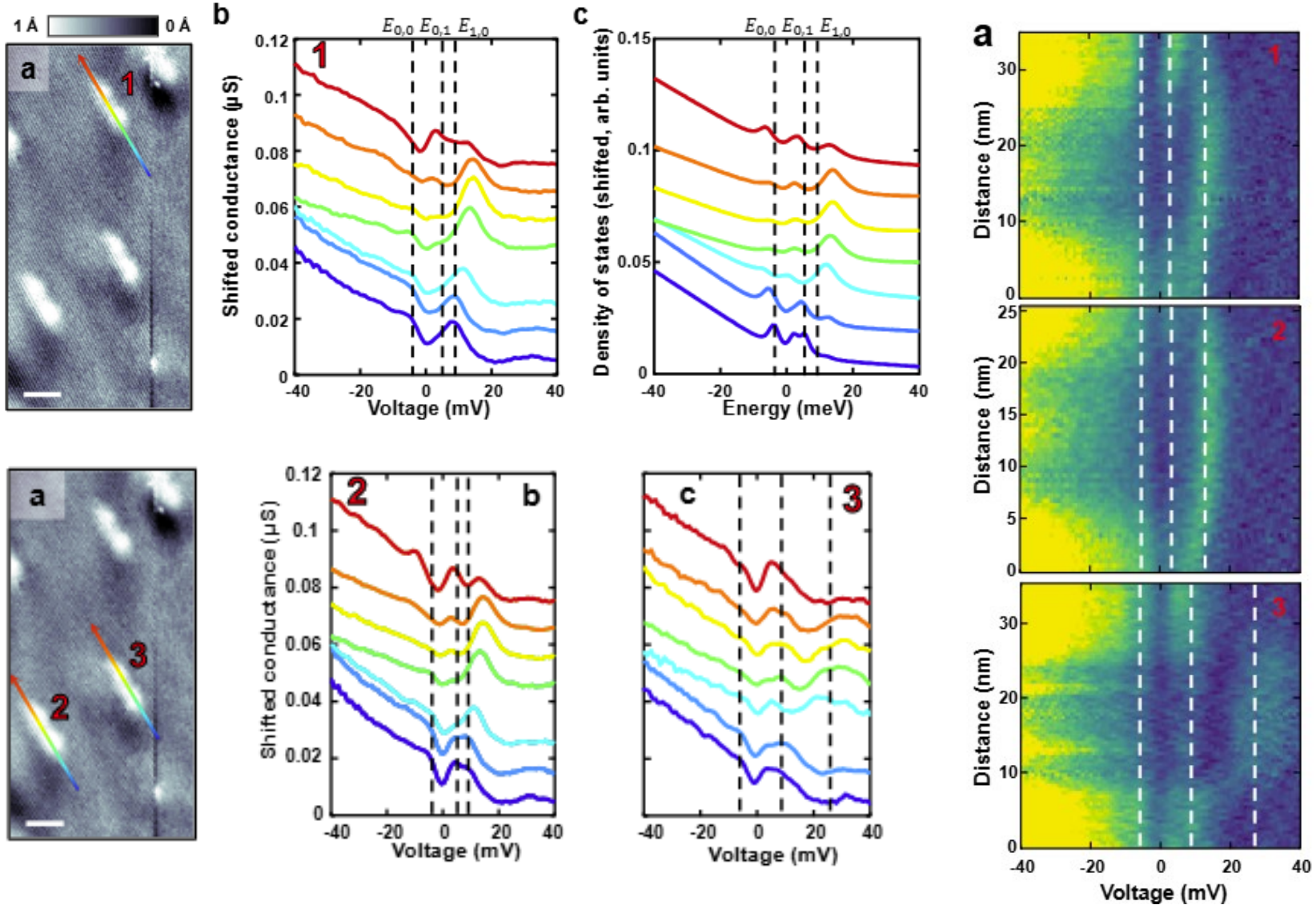
$$I(\mathrm{r}_0, V) \propto \int_{E_F}^{E_F+eV} dE\, N_{loc}(\mathbf{d}_0, E)$$





Calculations: Adrian Valadakhni and Roser Valenti

Eu interstitials on $EuCd_2As_2$: localized states at impurities



2DEG

$$V(\hat{x}) = \omega_0 x^2/2.$$

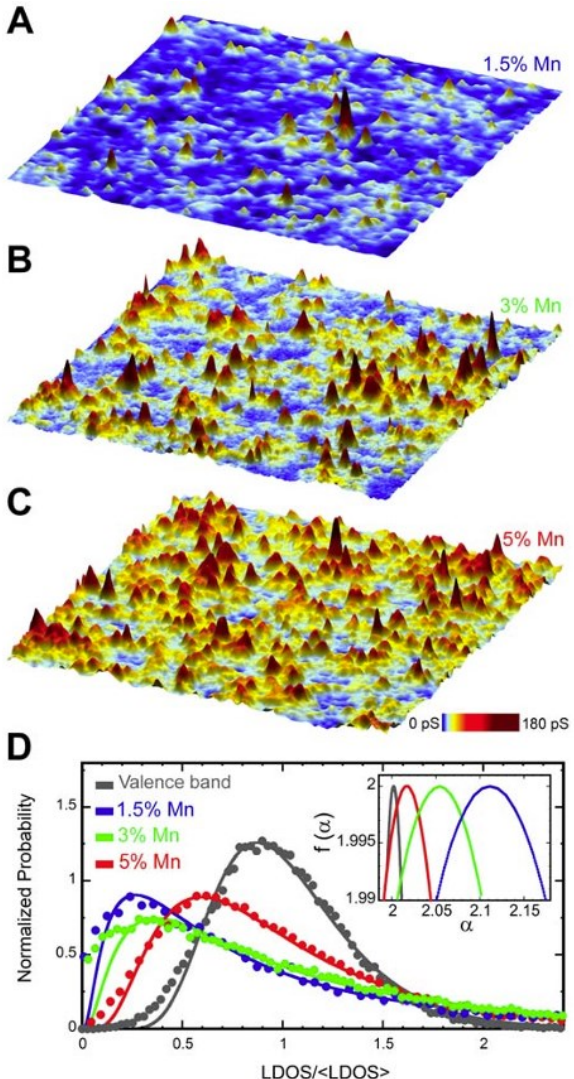
$$j = L, c, \text{ and } R.$$

$$\epsilon_{j,nm} = \left(n + \frac{1}{2}\right)\hbar\omega_0 + \frac{\hbar^2}{2m^*}\left(\frac{m\pi}{W}\right)^2 - E_{j,F}.$$

Calculations: Rafael Pineda, William Herrera (Bogotá) and Alfredo Levy Yeyati (Madrid)

Eu interstitials on $EuCd_2As_2$: Potential landscape

Disordered potential landscape



Visualizing Critical Correlations Near the Metal-Insulator Transition in $Ga_{1-x}Mn_xAs$

ANTHONY RICHARDELLA, PEDRAM ROUSHAN, SHAWN MACK, BRIAN ZHOU, DAVID A. HUSE, DAVID D. AWSCHALOM, AND ALI YAZDANI Authors Info & Affiliations

SCIENCE · 5 Feb 2010 · Vol 327, Issue 5966 · pp. 665-669 · DOI: 10.1126/science.1183640

Visualization of Multifractal Superconductivity in a Two-Dimensional Transition Metal Dichalcogenide in the Weak-Disorder Regime

Carmen Rubio-Verdú; Antonio M. García-García *; Hyejin Ryu; Deung-Jang Choi; Javier Zaldívar; Shujie Tang; Bo Fan; Zhi-Xun Shen; Sung-Kwan Mo; José Ignacio Pascual; Miguel M. Ugeda *

+ Author & Article Information

Nano Lett. (2020) 20 (7): 5111−5118.

Weight $\mu_i = \int_{Box} |\psi(\boldsymbol{r})|^2 \, d\boldsymbol{r}$ **Normalized**

$\mu_i(l) \sim l^{\alpha_i}$

$f(\alpha)$ **How many boxes have an exponent α**

Uniform $\mu_i(l) \propto l^2$

$M_q(l) = \sum {\mu_i}^q$

$M_q(l) \sim l^{\tau(q)}$

$q > 0$ bright regions

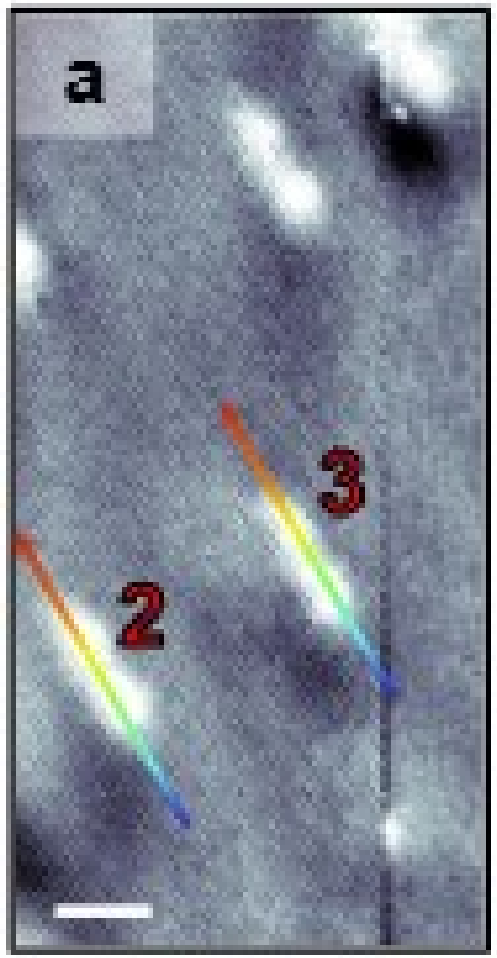
$q < 0$ weak regions

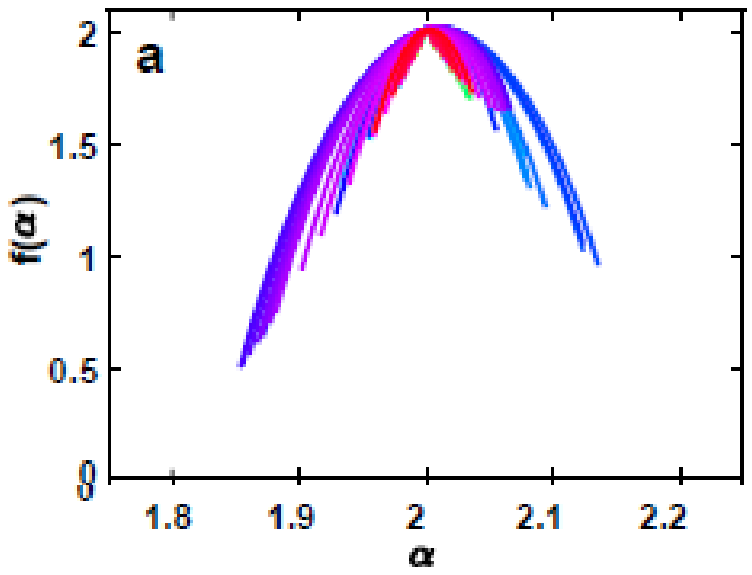
$D_q = \frac{\tau(q)}{q-1}$

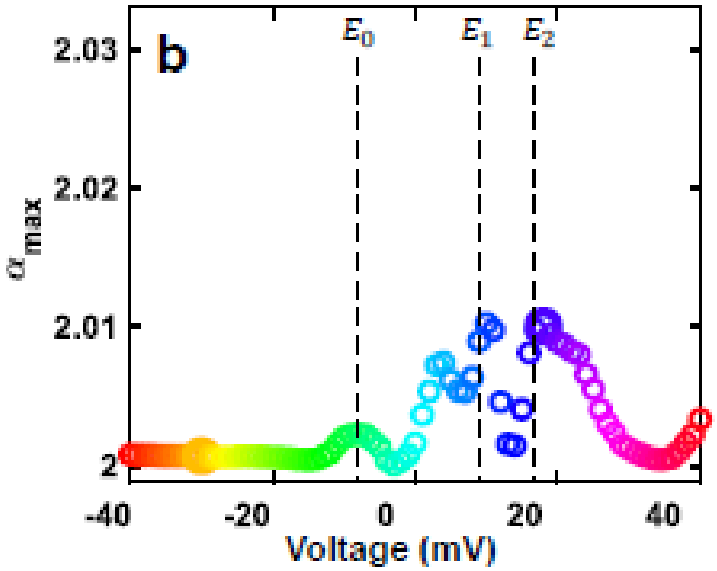
The stronger drop from 2 for increasing q, the more intensity concentrates on spots

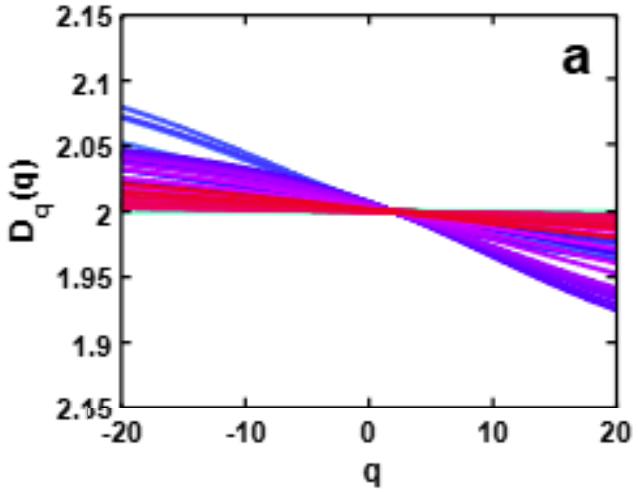
Eu interstitials on $EuCd_2As_2$: Potential landscape

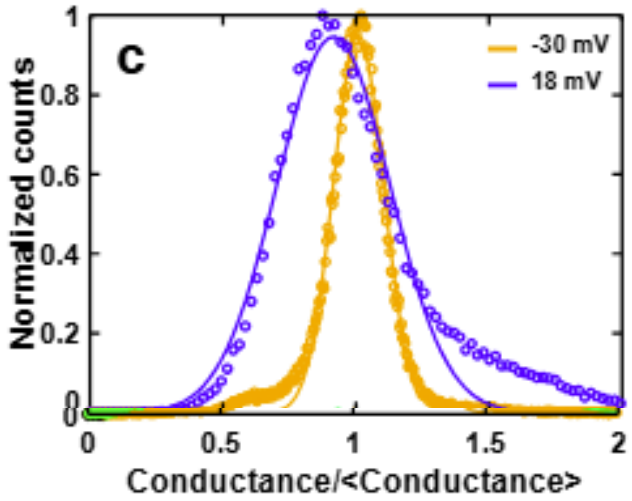
Disordered potential landscape









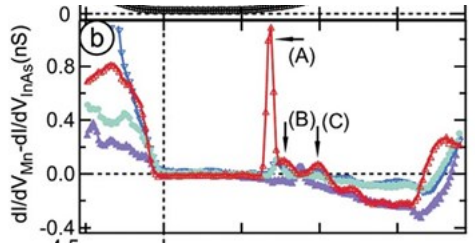


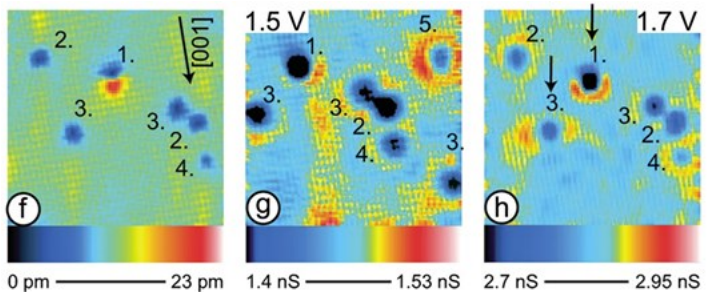
STM in semiconductors

PRL 99, 157202 (2007) PHYSICAL REVIEW LETTERS week ending 12 OCTOBER 2007

Local Electronic Structure near Mn Acceptors in InAs: Surface-Induced Symmetry Breaking and Coupling to Host States

F. Marczinowski,[1] J. Wiebe,[1,*] J.-M. Tang,[2,†] M. E. Flatté,[2] F. Meier,[1] M. Morgenstern,[3] and R. Wiesendanger[1]





Localized charge puddles at dopant's positions

Physica E 44 (2012) 1795–1814

Contents lists available at SciVerse ScienceDirect

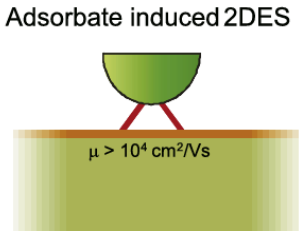
Physica E

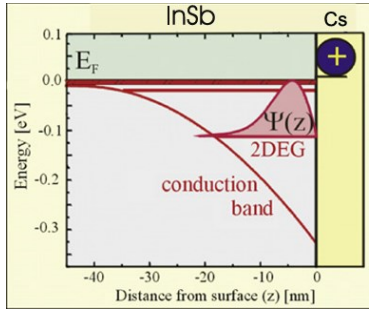
journal homepage: www.elsevier.com/locate/physe

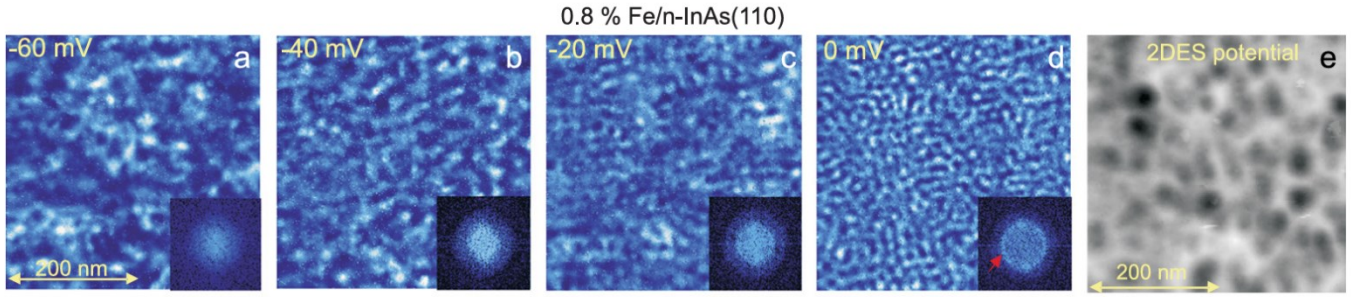
Invited review

Scanning tunneling microscopy of two-dimensional semiconductors: Spin properties and disorder

M. Morgenstern [a,*], A. Georgi [a], C. Straßer [b], C.R. Ast [b], S. Becker [a], M. Liebmann [a]

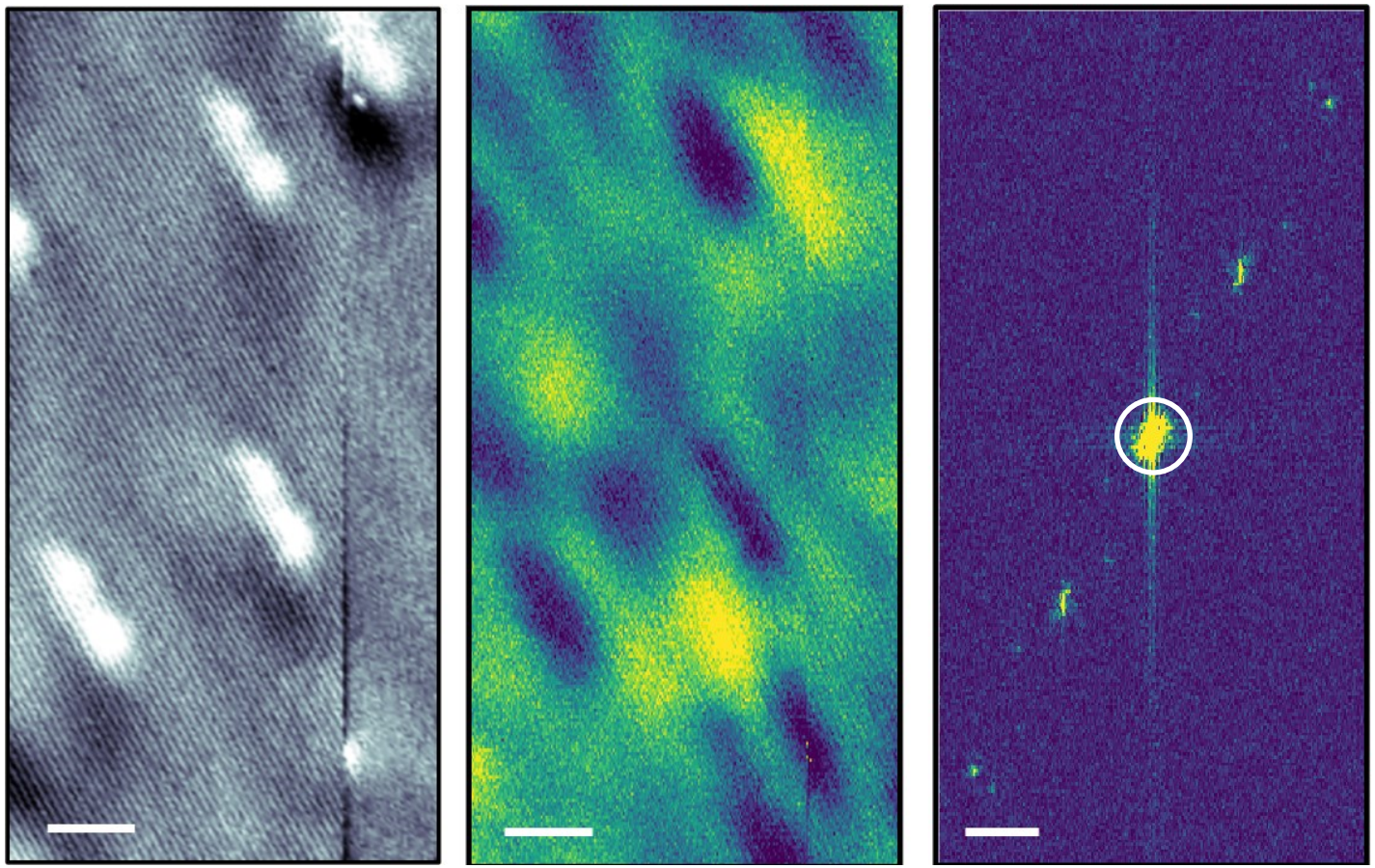


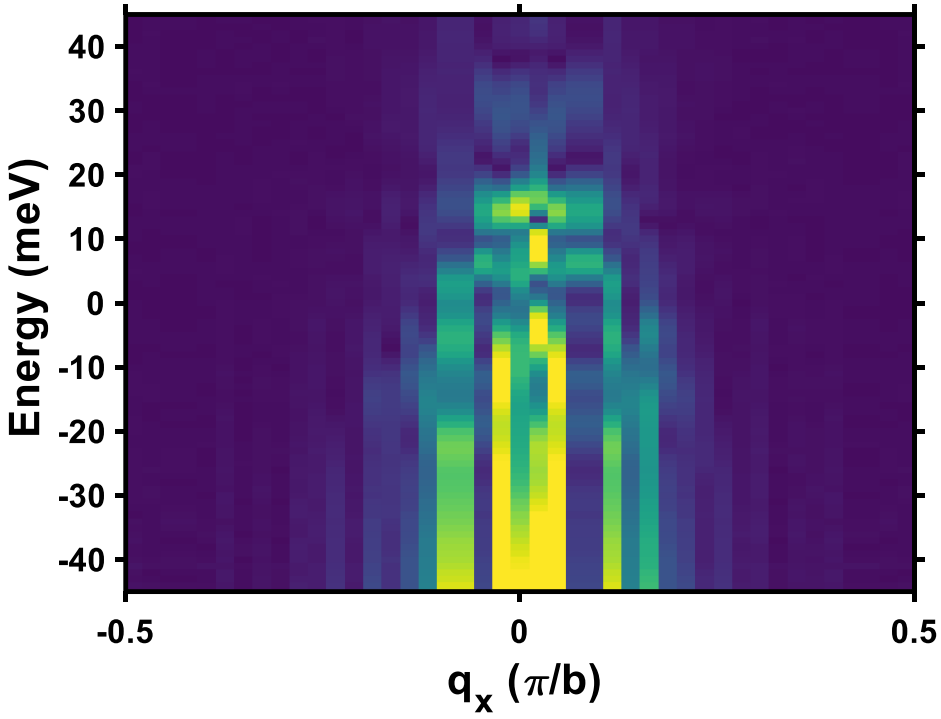




Disordered potential landscape

Eu interstitials on $EuCd_2As_2$: qpi

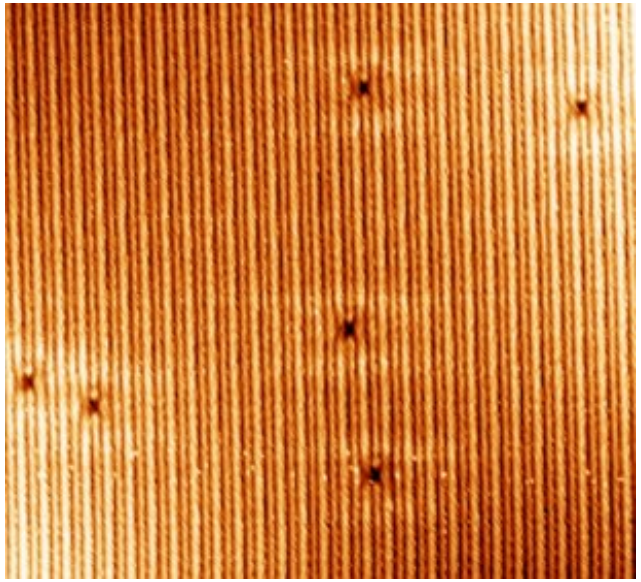


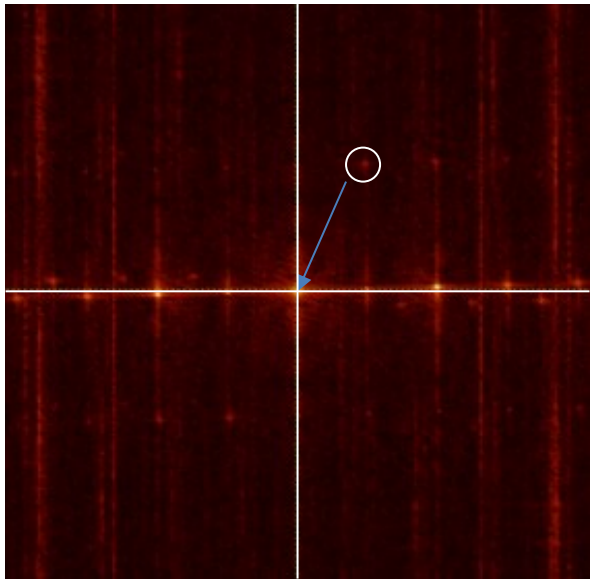


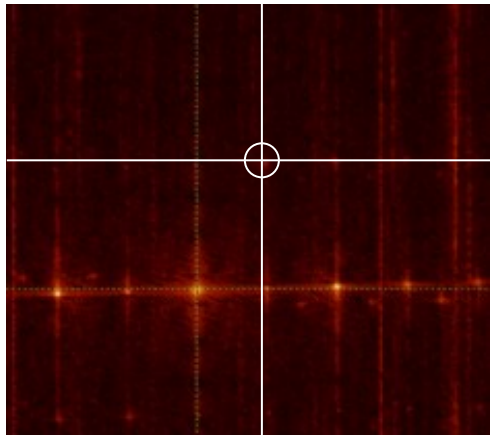
$$I(\mathrm{r}_0, V) \propto \int_{E_F}^{E_F+eV} dE\, N_{loc}(\mathbf{d}_0, E)$$

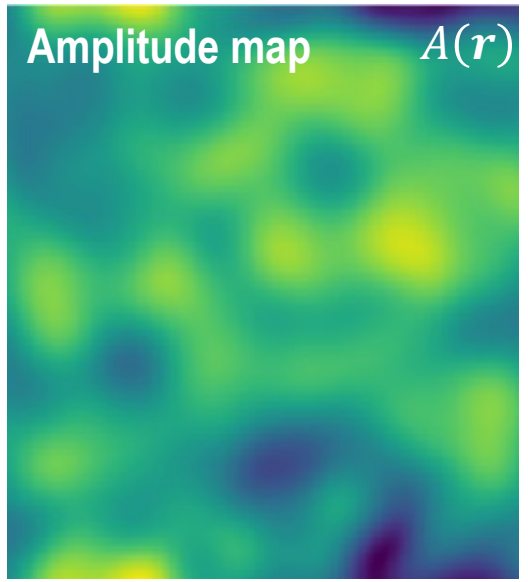
$$\frac{dI}{dV} \propto \int N_{loc}(E) \frac{\partial f(E-eV)}{\partial V} dE$$

Geometric phase analysis



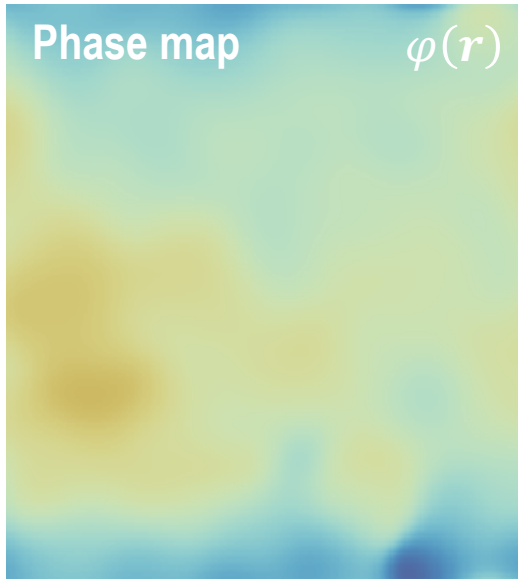






$$\rho(\boldsymbol{r}) \rightarrow \tilde{\rho}(\boldsymbol{k}) \rightarrow \tilde{\rho}_{Q_0}(\boldsymbol{k})$$

$$\tilde{\rho}(-\boldsymbol{k}) \neq \tilde{\rho}(\boldsymbol{k})$$
$$\rho(\boldsymbol{r}) \neq \rho(\boldsymbol{r})^*$$



$$\rho_{Q_0}(\boldsymbol{r}) = A(\boldsymbol{r})\cos\left(\boldsymbol{Q}_0 + \varphi(\boldsymbol{r})\right)$$

1D charge density wave in the hidden order state of URu_2Si_2

Edwin Herrera, Víctor Barrena, Isabel Guillamón, José Augusto Galvis, William J. Herrera, José Castilla, Dai Aoki, Jacques Flouquet & Hermann Suderow

Wave field reconstruction and phase imaging by electron diffractive imaging

Jun Yamasaki[1,2]

[1]Research Center for Ultra-High Voltage Electron Microscopy, Osaka University, 7-1 Mihogaoka, Ibaraki, Osaka, Japan and [2]Institute of Materials and Systems for Sustainability, Nagoya University, Nagoya, Aichi, Japan

Disentangling Coexisting Structural Order Through Phase Lock-In Analysis of Atomic-Resolution STEM Data Get access

Berit H Goodge, Ismail El Baggari, Seung Sae Hong, Zhe Wang, Darrell G Schlom, Harold Y Hwang, Lena F Kourkoutis

Microscopy and Microanalysis, Volume 28, Issue 2, 1 April 2022, Pages 404–411, https://doi.org/10.1017/S1431927622000125

Letter | Published: 15 July 2010

Intra-unit-cell electronic nematicity of the high-T_c copper-oxide pseudogap states

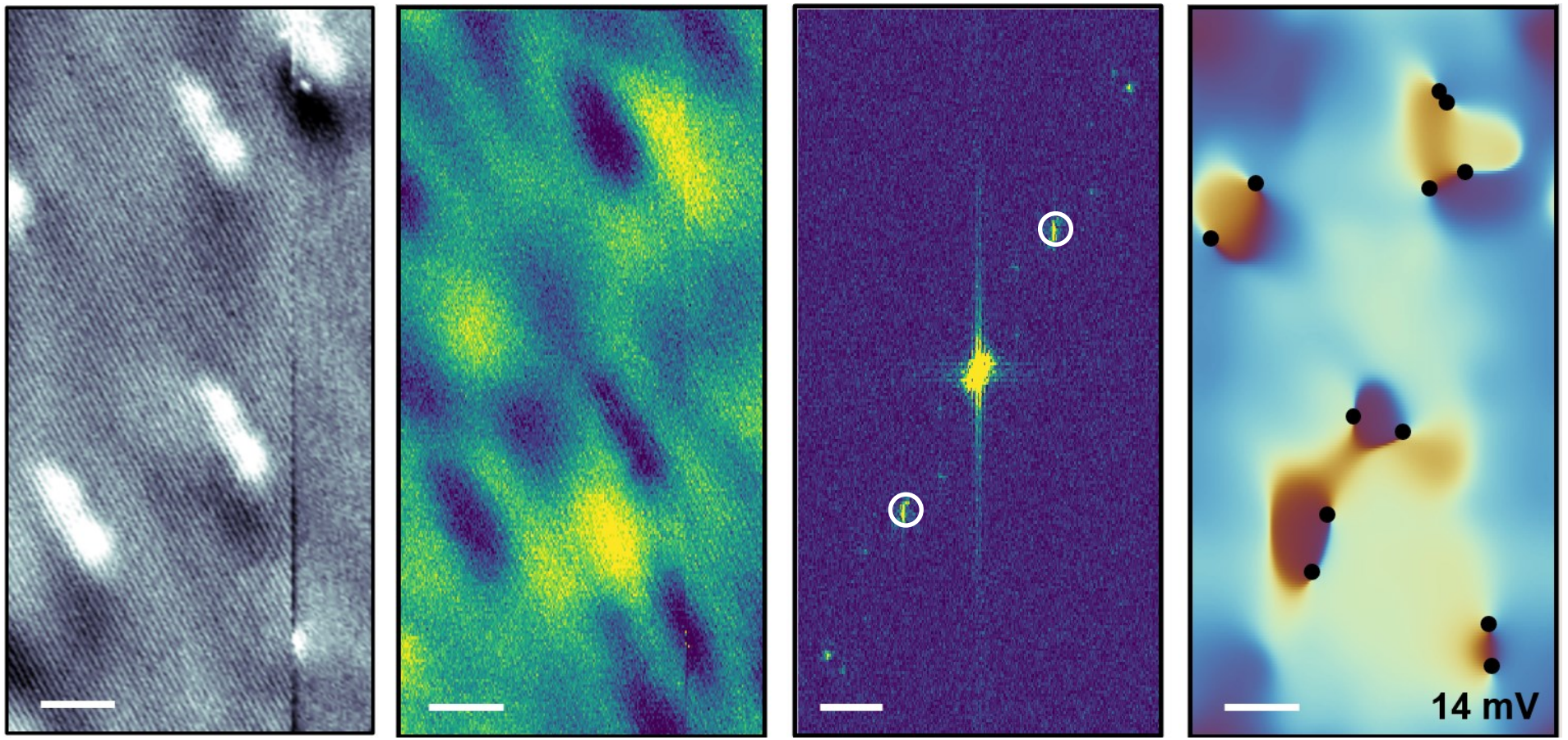
M. J. Lawler, K. Fujita, Jhinhwan Lee, A. R. Schmidt, Y. Kohsaka, Chung Koo Kim, H. Eisaki, S. Uchida, J. C. Davis, J. P. Sethna & Eun-Ah Kim

Nature **466**, 347–351 (2010) | Cite this article

Quantitative measurement of displacement and strain fields from HREM micrographs

M.J. Hÿtch a, E. Snoeck b, R. Kilaas c

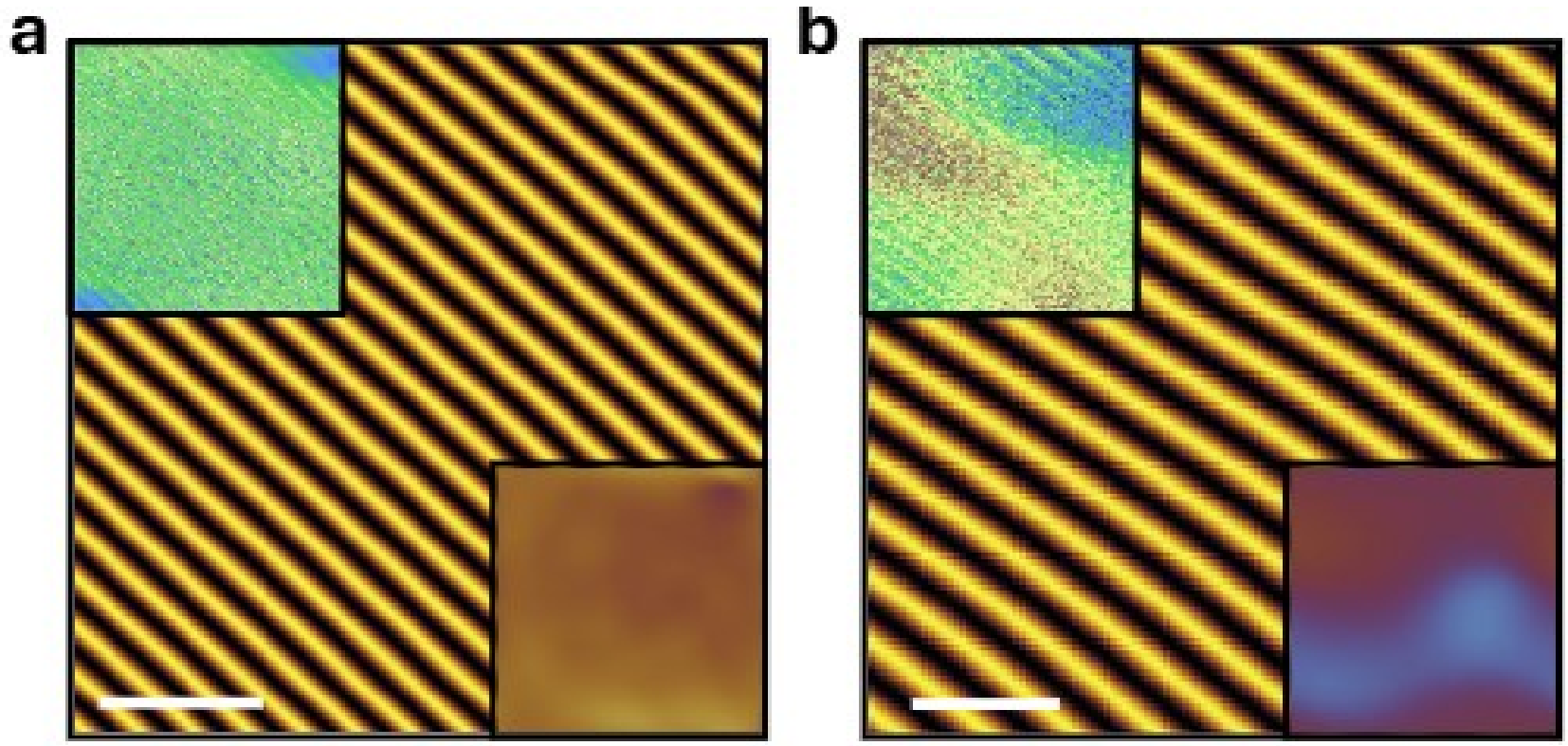
Eu interstitials on $EuCd_2As_2$: Geometric phase analysis



2π

$$\rho_{Q_0}(\boldsymbol{r}) = A(\boldsymbol{r})\cos\left(\boldsymbol{Q}_0 + \varphi(\boldsymbol{r})\right)$$

Geometric phase analysis: variations in the intensity do NOT create phase dislocations

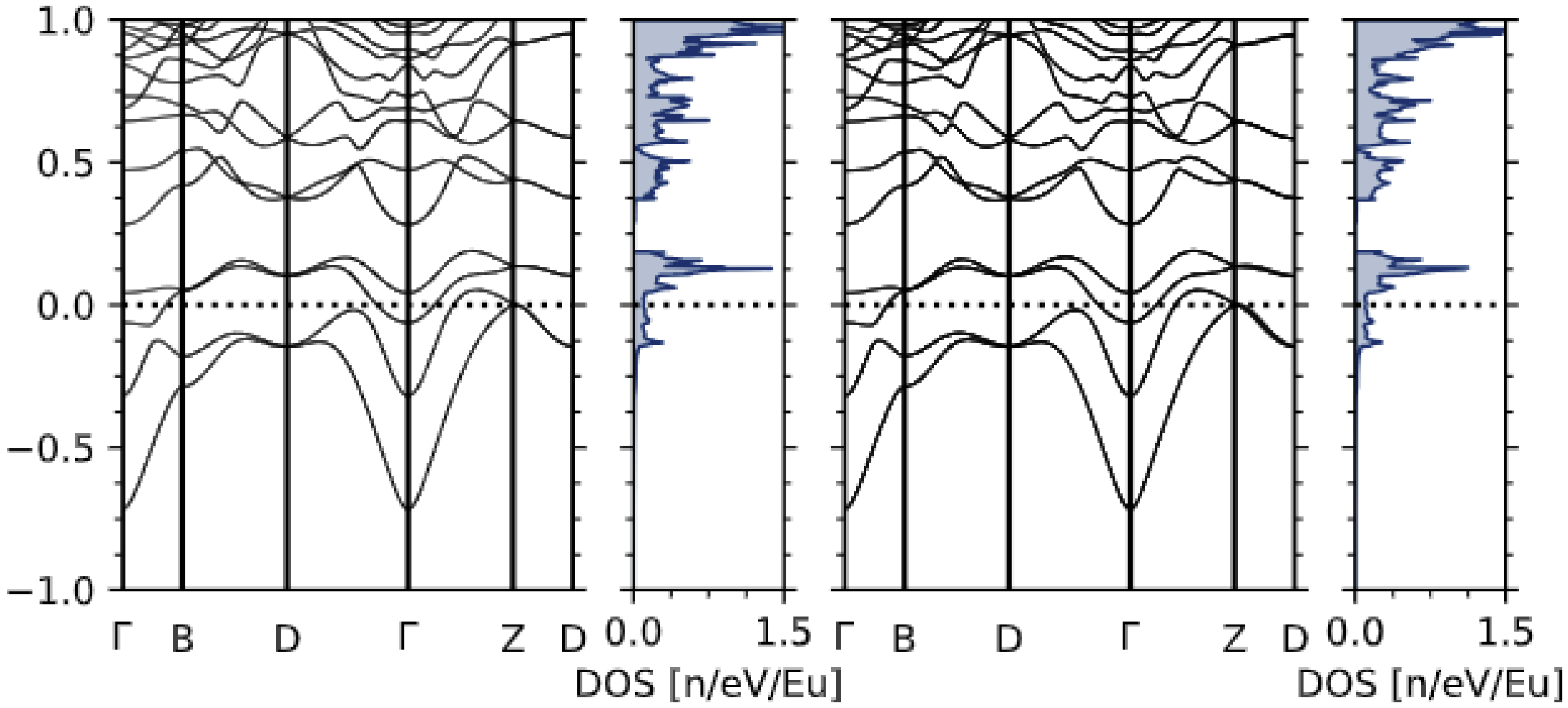


$$\rho_{Q_0}(\boldsymbol{r}) = A(\boldsymbol{r})\cos\left(\boldsymbol{Q}_0 + \varphi(\boldsymbol{r})\right)$$

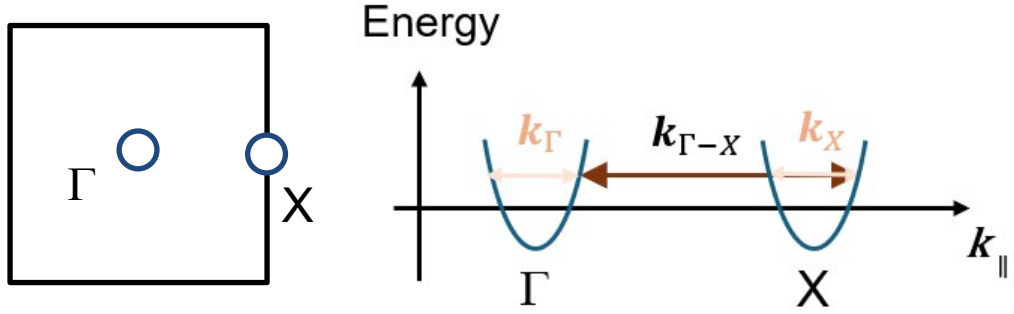
- No dislocations in the reconstruction or atomic arrangements (energy dependence)
- No Spinor in the bandstructure (Dirac, Weyl, SOC)
- Strong oscillations of the density
- Strong one-dimensional modulation

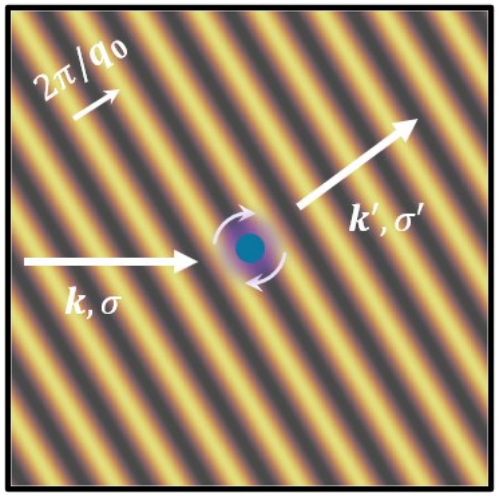
Scattering phase dislocations induced by SOC

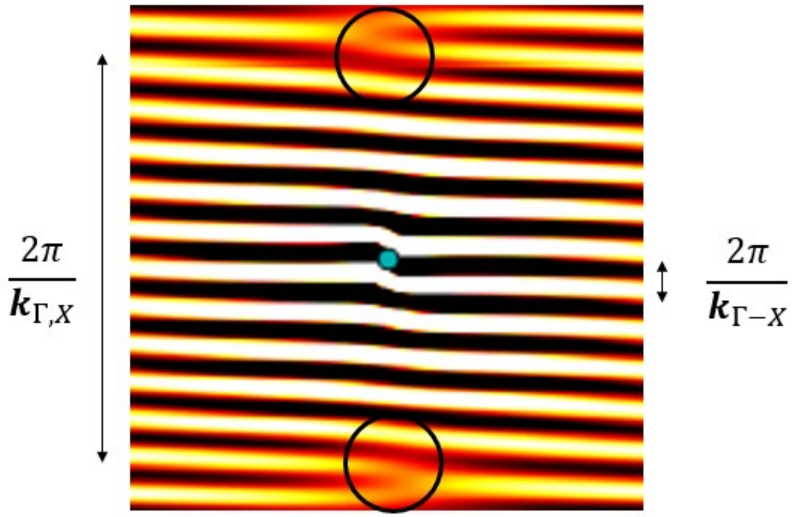
$$H_{SOC} = \frac{\hbar}{4m^2c^2}(\nabla V \times \boldsymbol{p}) \cdot \boldsymbol{\sigma}$$



Scattering phase dislocations induced by SOC





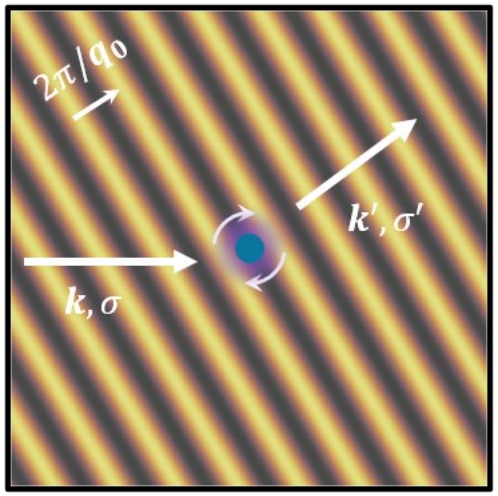


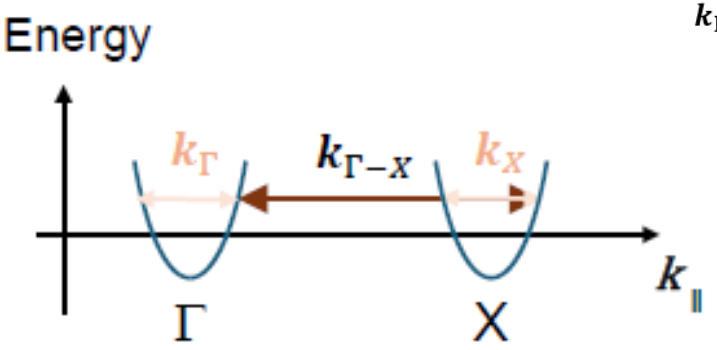
$$SOC = \frac{t_{SOC}}{t_0}$$

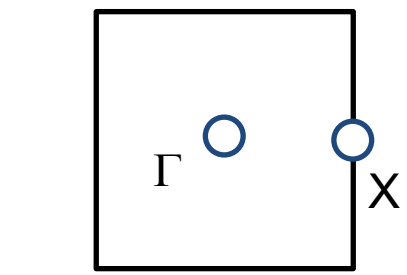
$$t_0^2 + t_{SOC}^2(\boldsymbol{k} \times \boldsymbol{k}') = t_0^2 + t_{SOC}^2(|k| \cdot |k'| \sin\theta)$$

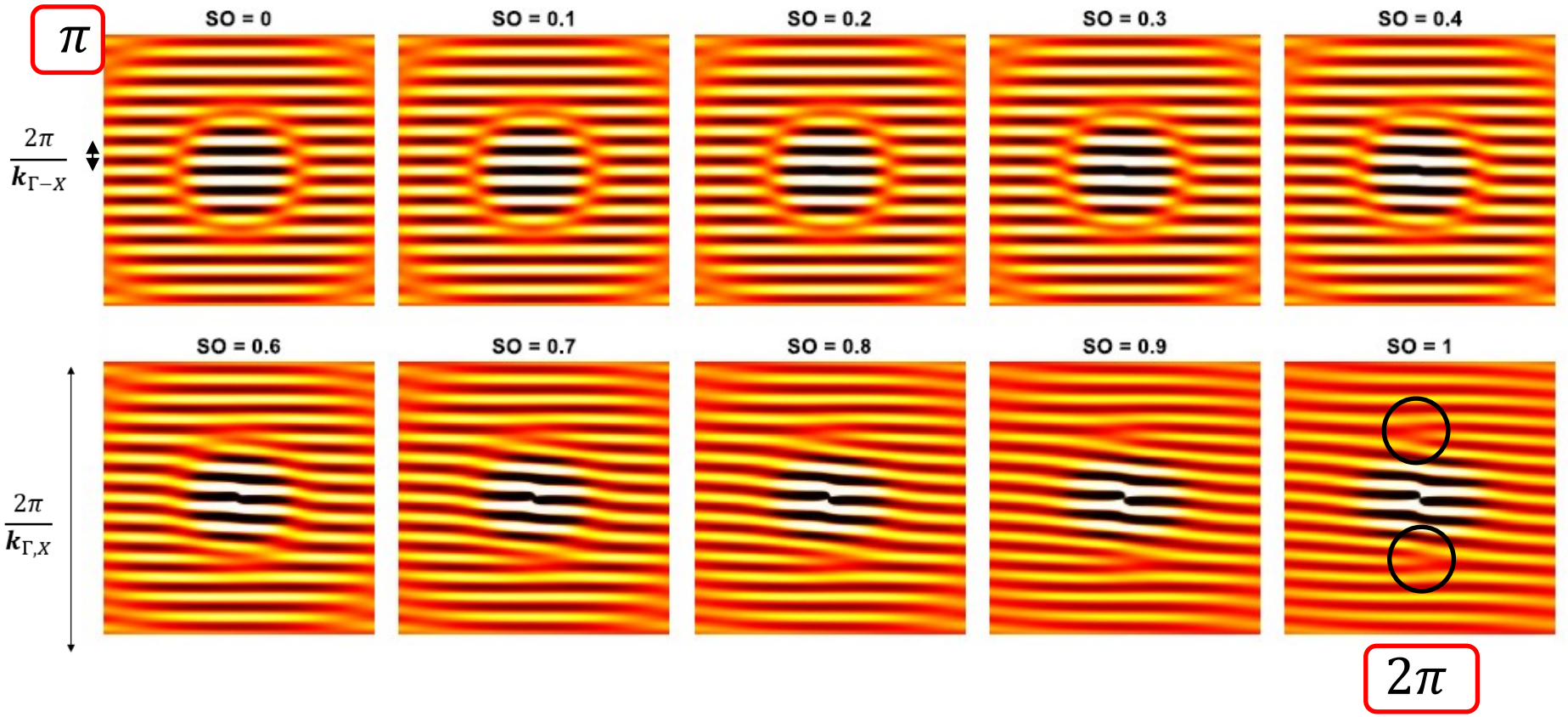
Calculations: Rafael Pineda, William Herrera (Bogotá) and Alfredo Levy Yeyati (Madrid)

Scattering phase dislocations induced by SOC





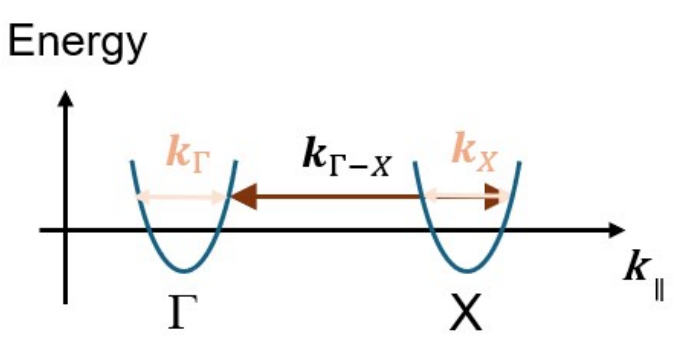


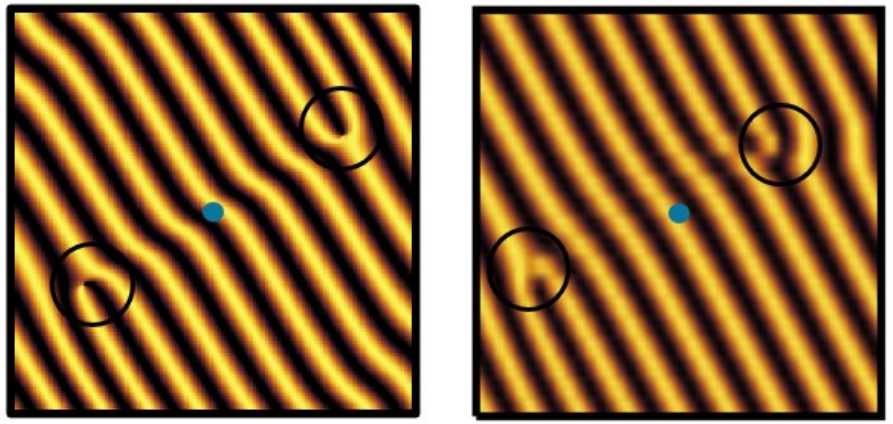


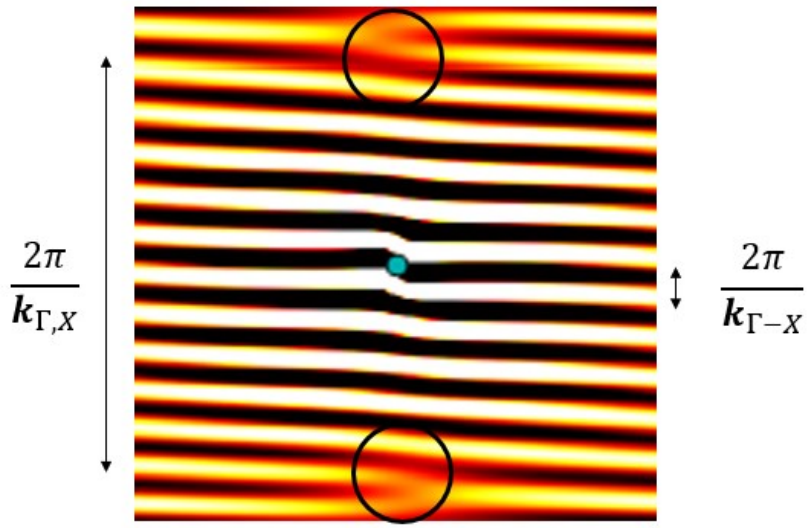
$$SOC = \frac{t_{SOC}}{t_0}$$

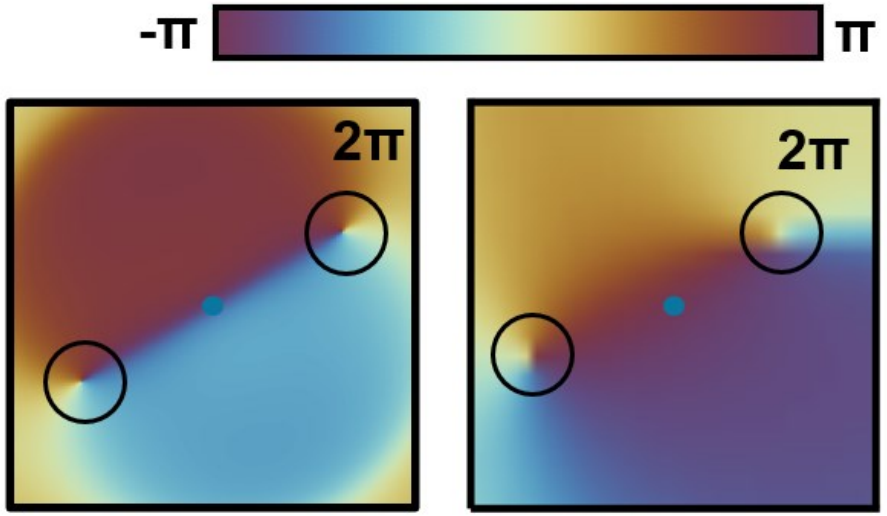
$$t_0^2 + t_{SOC}^2(\boldsymbol{k} \times \boldsymbol{k}') = t_0^2 + t_{SOC}^2(|k| \cdot |k'| \sin\theta)$$

Scattering phase dislocations induced by SOC



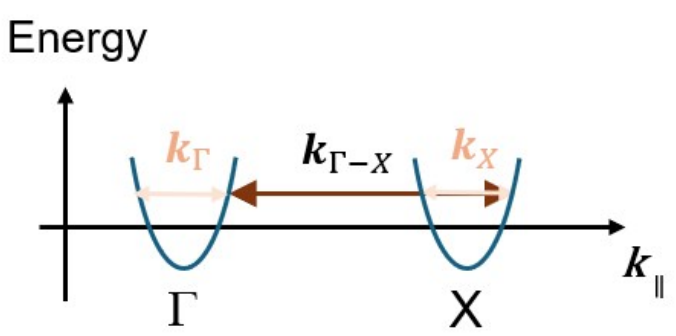


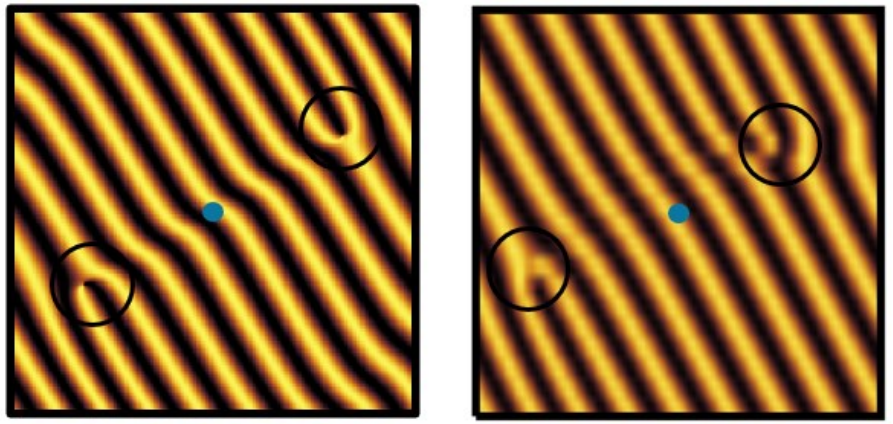


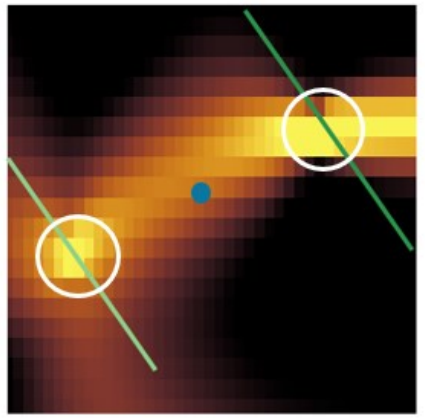


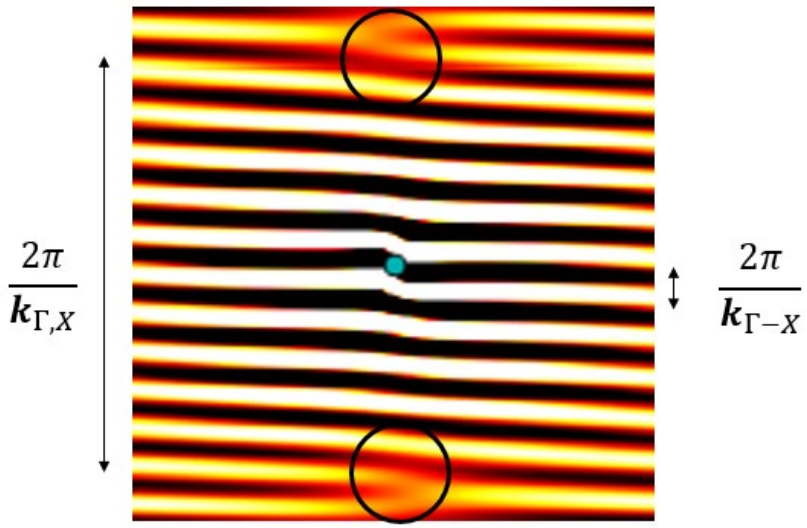
Calculations: Rafael Pineda, William Herrera (Bogotá) and Alfredo Levy Yeyati (Madrid)

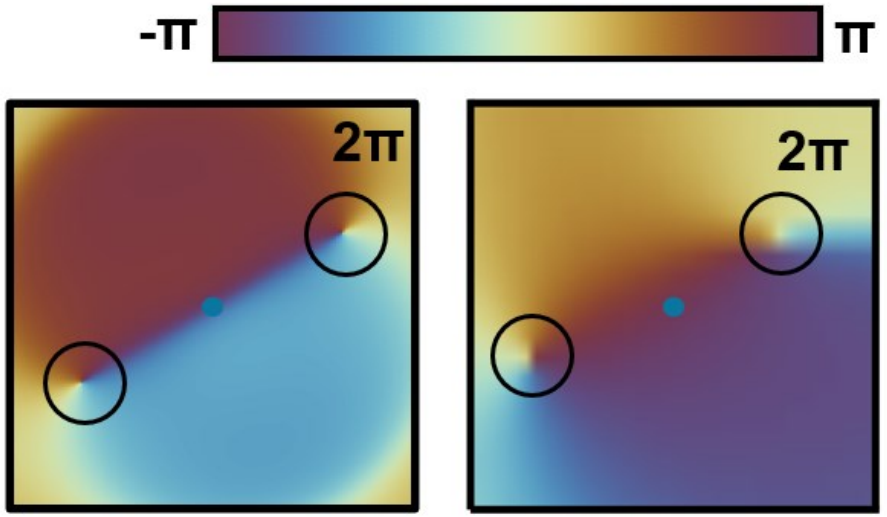
Scattering phase dislocations induced by SOC

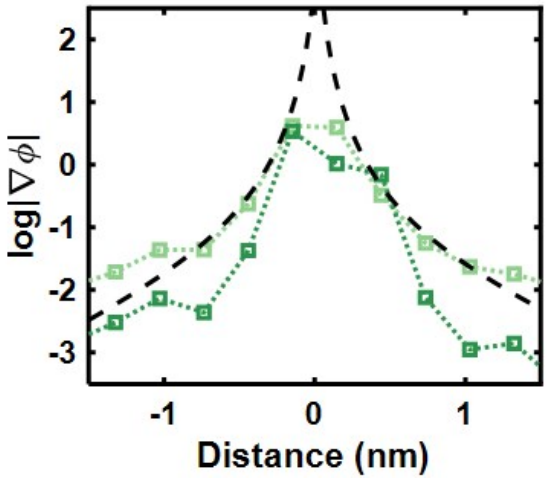






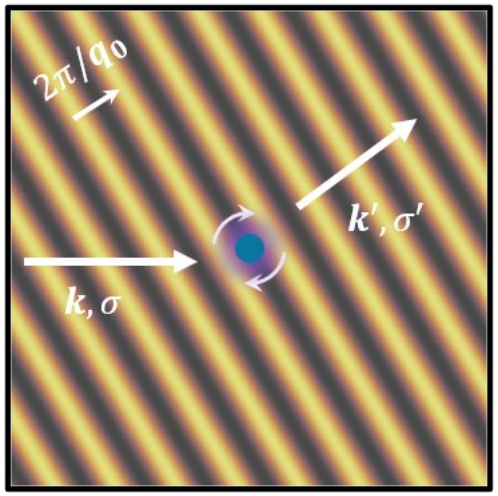


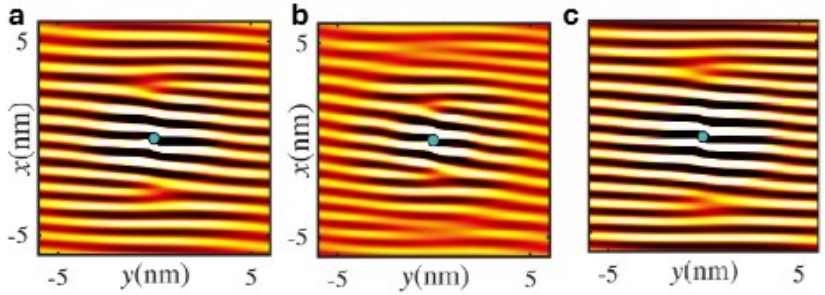


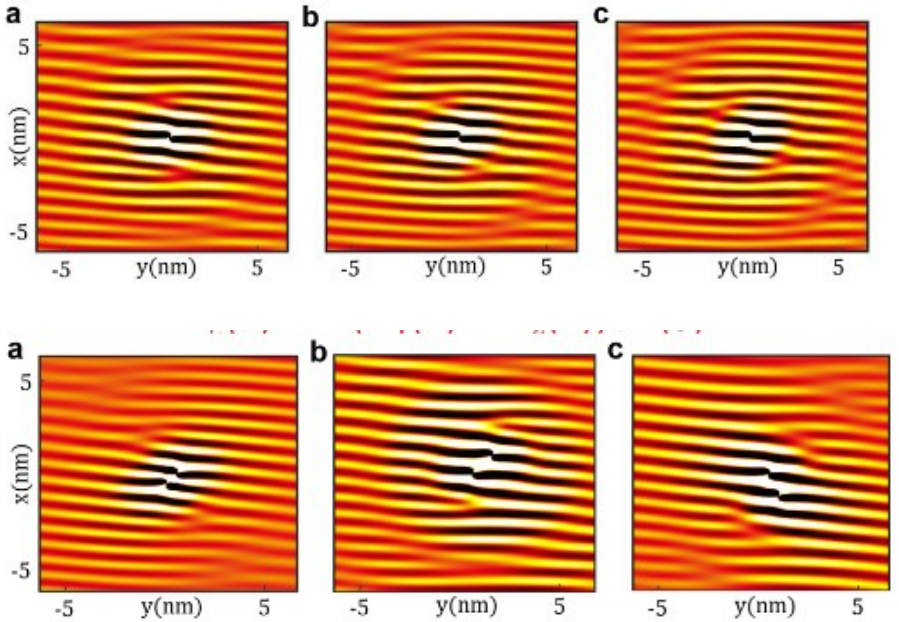


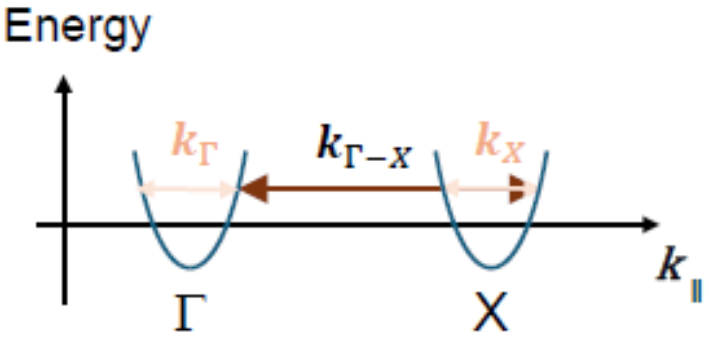
Calculations: Rafael Pineda, William Herrera (Bogotá) and Alfredo Levy Yeyati (Madrid)

Scattering phase dislocations induced by SOC







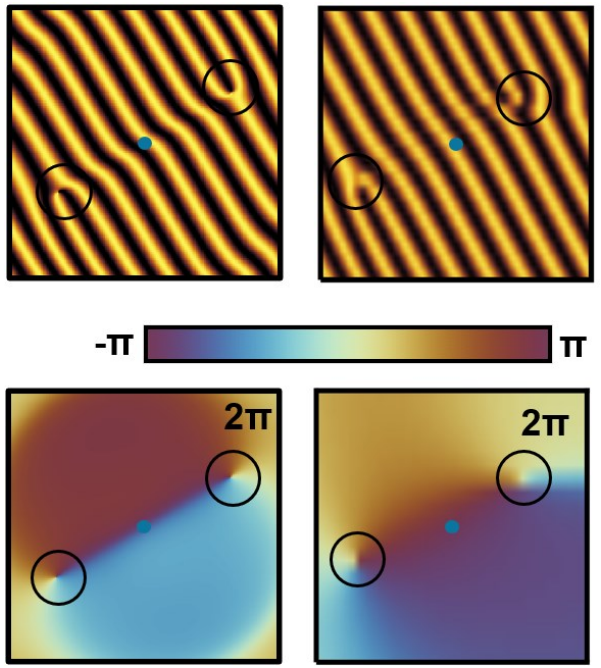


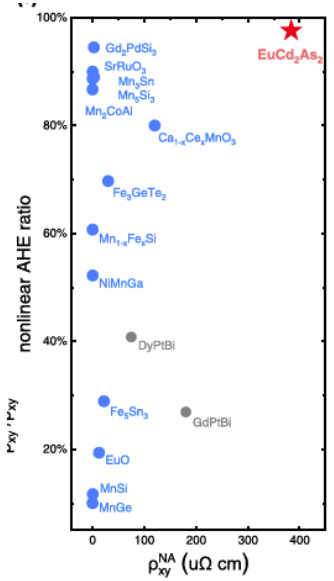
- Band structure (electrons, holes, effective mass)
- Spatial dependence (anisotropy in the scattering potential)
- Energy dependence

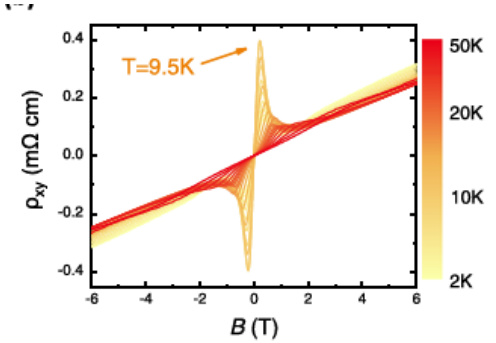
Real-space visualization of scattering phase dislocations in a magnetic semiconductor

- Discriminate between skew scattering and Berry phase
- Quantify SOC
- SOC scattering Eu interstitials as dopants in $EuCd_2As_2$

https://arxiv.org/abs/2609.13398







PHYSICAL REVIEW LETTERS **126,** 076602 (2021)

Unconventional Transverse Transport above and below the Magnetic Transition Temperature in Weyl Semimetal $EuCd_2As_2$

Y. Xu,[1,*] L. Das,[1] J. Z. Ma,[2,3] C. J. Yi,[4] S. M. Nie,[5] Y. G. Shi,[4,6] A. Tiwari,[1,7] S. S. Tsirkin,[1] T. Neupert,[1] M. Medarde,[8] M. Shi,[3] J. Chang,[1,†] and T. Shang[9,1,8,‡]

PHYSICAL REVIEW RESEARCH **4,** 023100 (2022)

Giant nonlinear anomalous Hall effect induced by spin-dependent band structure evolution

Xiangyu Cao,[1,*] Jie-Xiang Yu,[2,3,*] Pengliang Leng,[1,*] Changjiang Yi,[4,5,*] Xiaoyang Chen,[1,6] Yunkun Yang,[1] Shanshan Liu,[1] Lingyao Kong,[8] Zihan Li,[1] Xiang Dong,[1] Youguo Shi,[4] Manuel Bibes,[7] Rui Peng,[6,11] Jiadong Zang,[2,†] and Faxian Xiu[1,9,10,11,‡]

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Superconductor Science and Technology

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ROADMAP

Roadmap on nanoscale superconductivity for quantum technologies

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