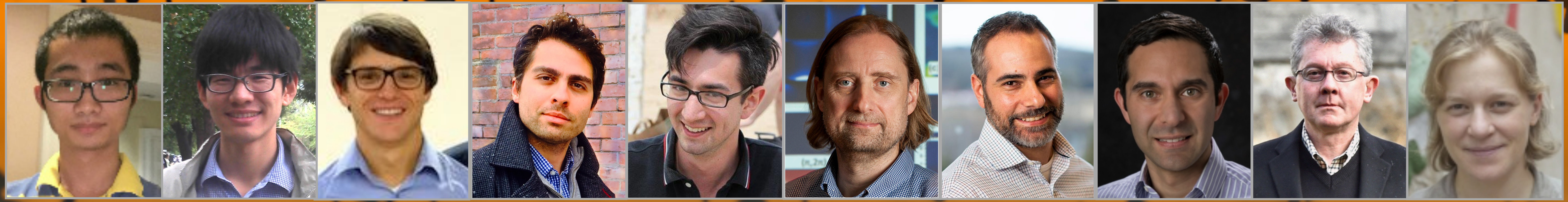
Visualizing the origin of bulk metallicity in SmB_6

Harris Pirie (Oxford)



GORDON AND BETTY MOORE FOUNDATION

Funded by the Horizon 2020 Framework Programme of the European Union

UNIVERSITY OF OXFORD

Samarium hexaboride (SmB_6) is controversial

SmB_6 timeline:

1955 - 2010 — Impurity states vs surface states

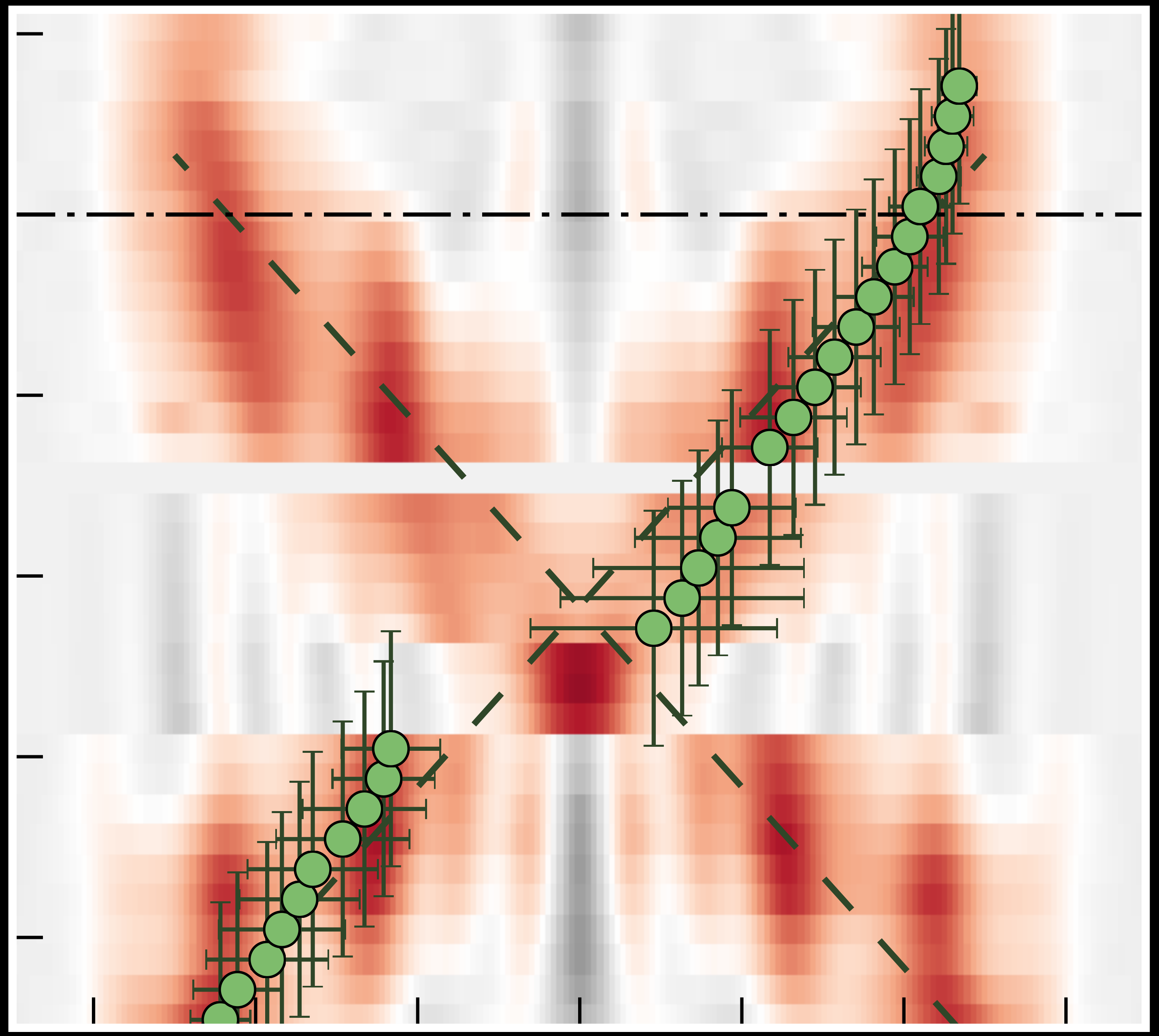
2010 - 2020 — Topological or not?

2015 - 2023 — Insulating or not?

Image credit: Quanta Magazine

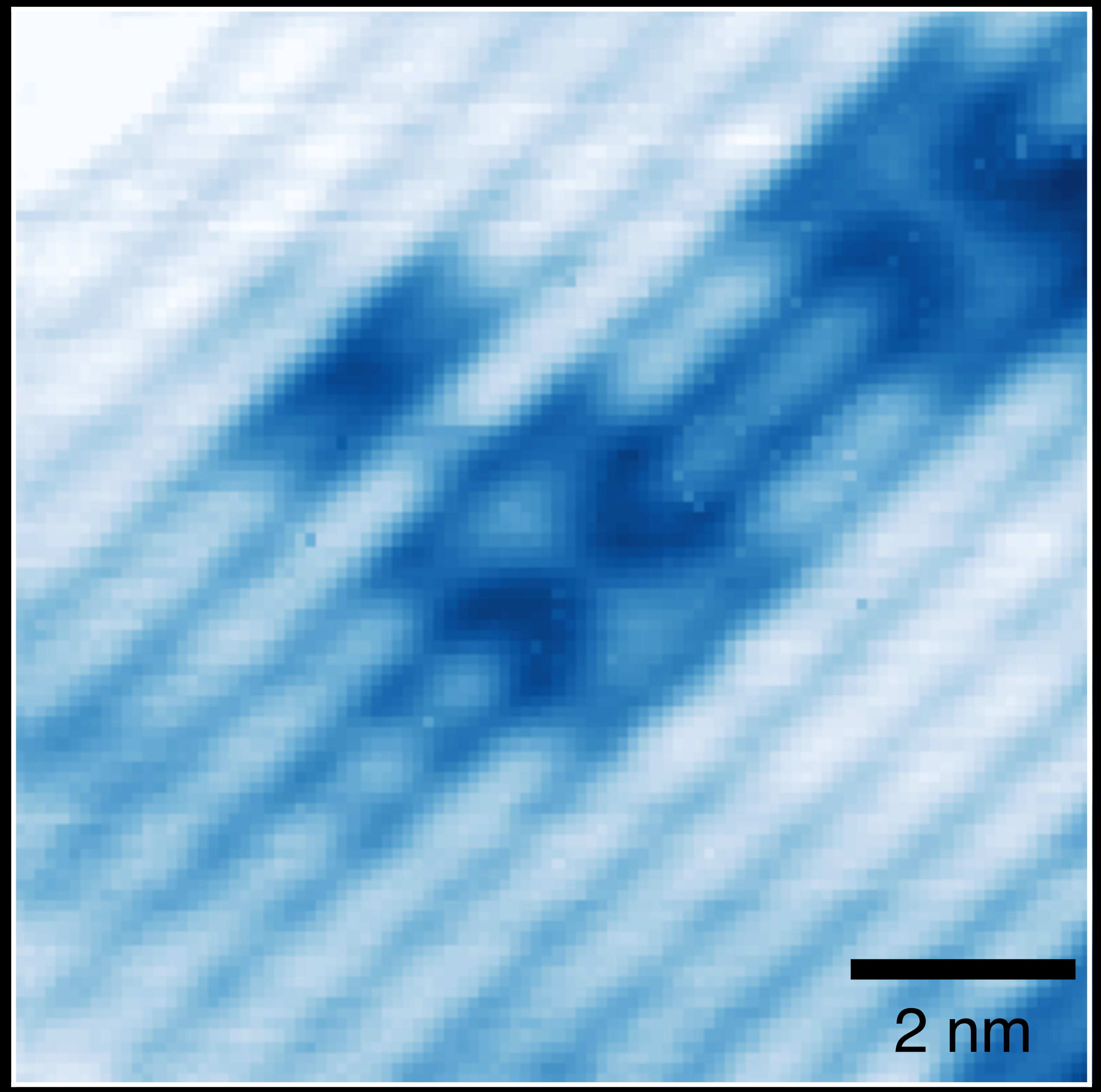
Outline

(1) Dirac fermions **410 times** heavier than a bare electron!



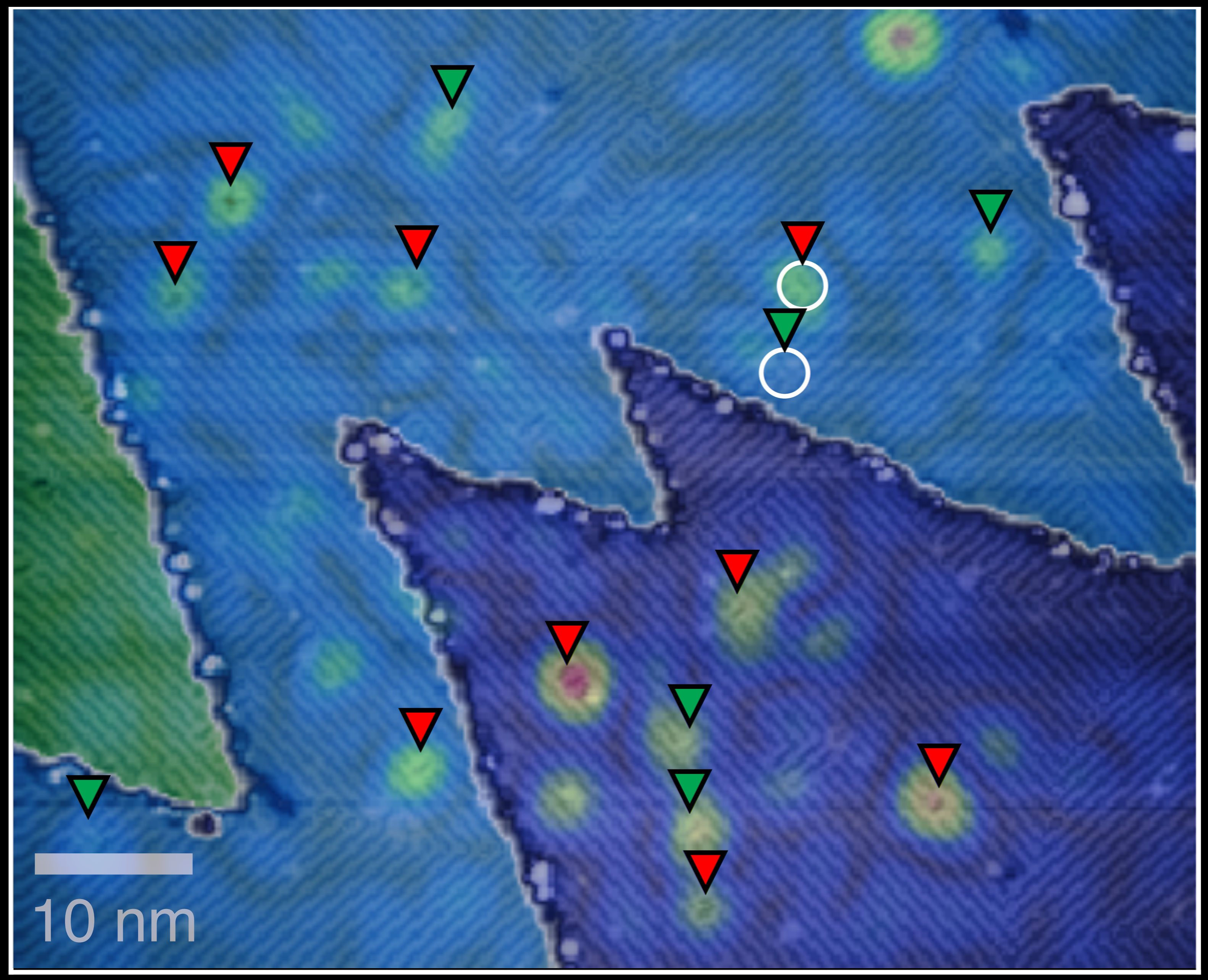
Pirie et al., *Nat. Phys.* **16**, 52 (2020)
Matt et al., *Phys. Rev. B* **101**, 085142 (2020)

(2) Metallicity in an **insulator**!



Pirie et al., *Science* **379**, 1214 (2023)

(3) Breakdown of **topological protection!**



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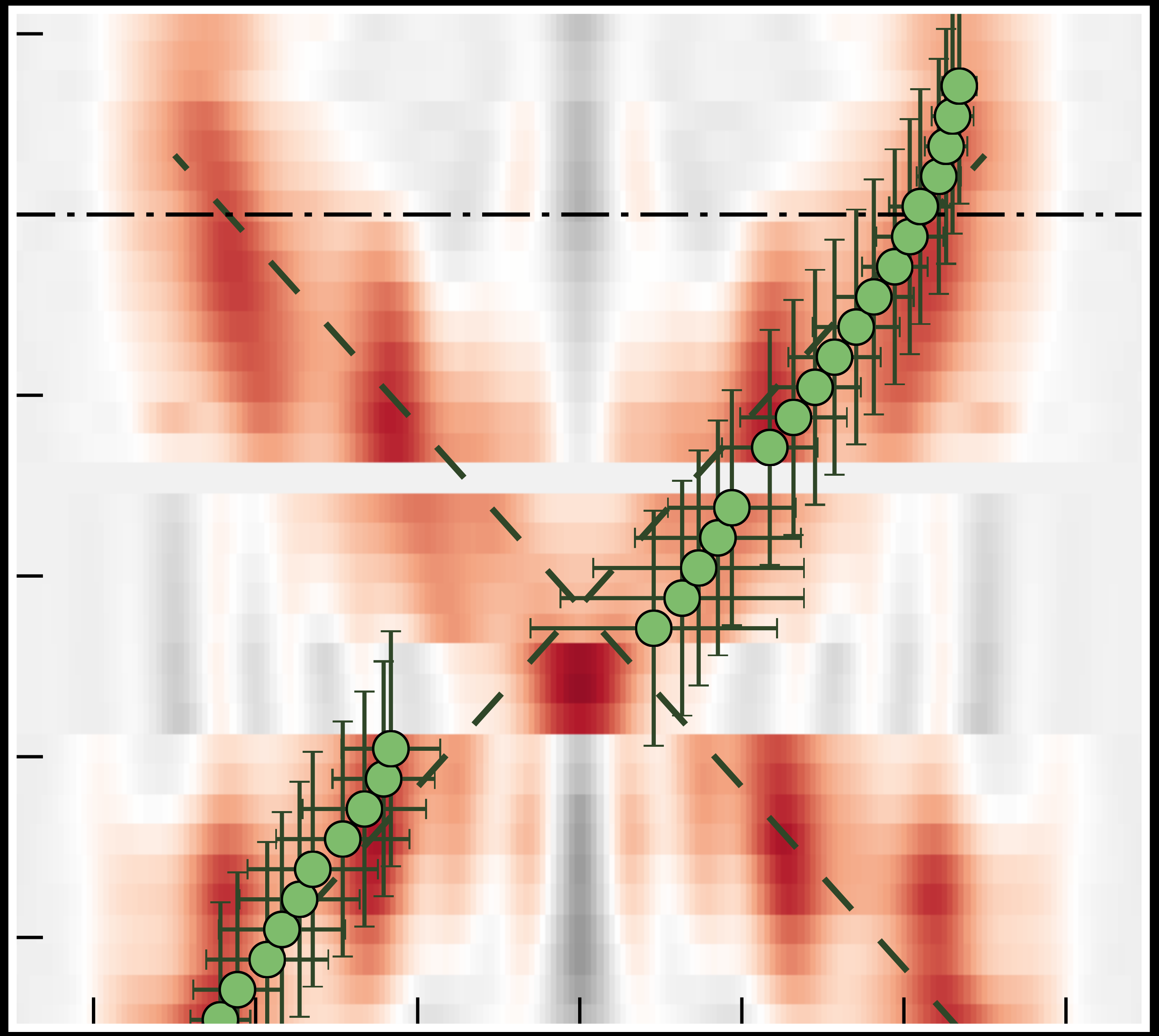

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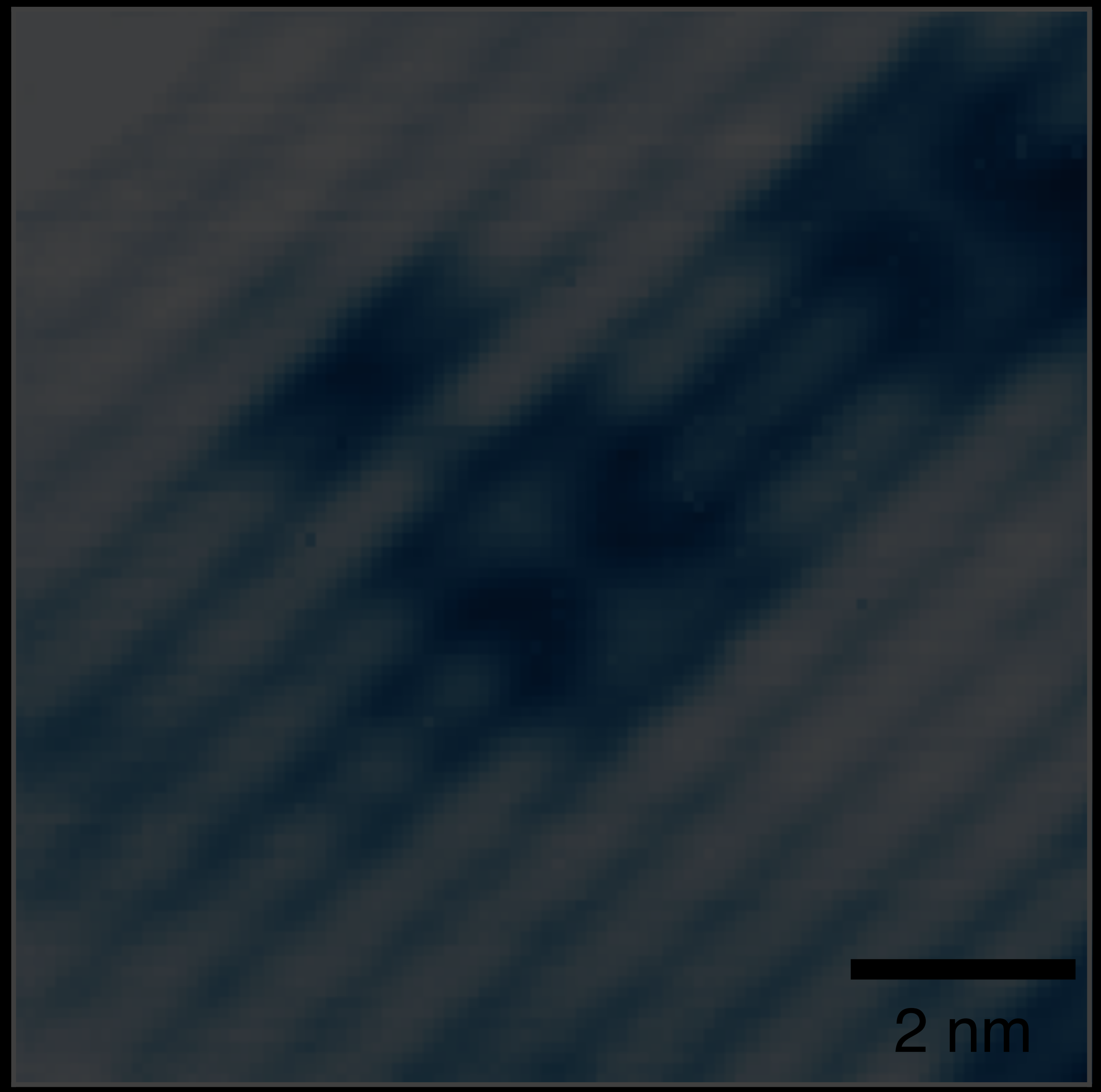

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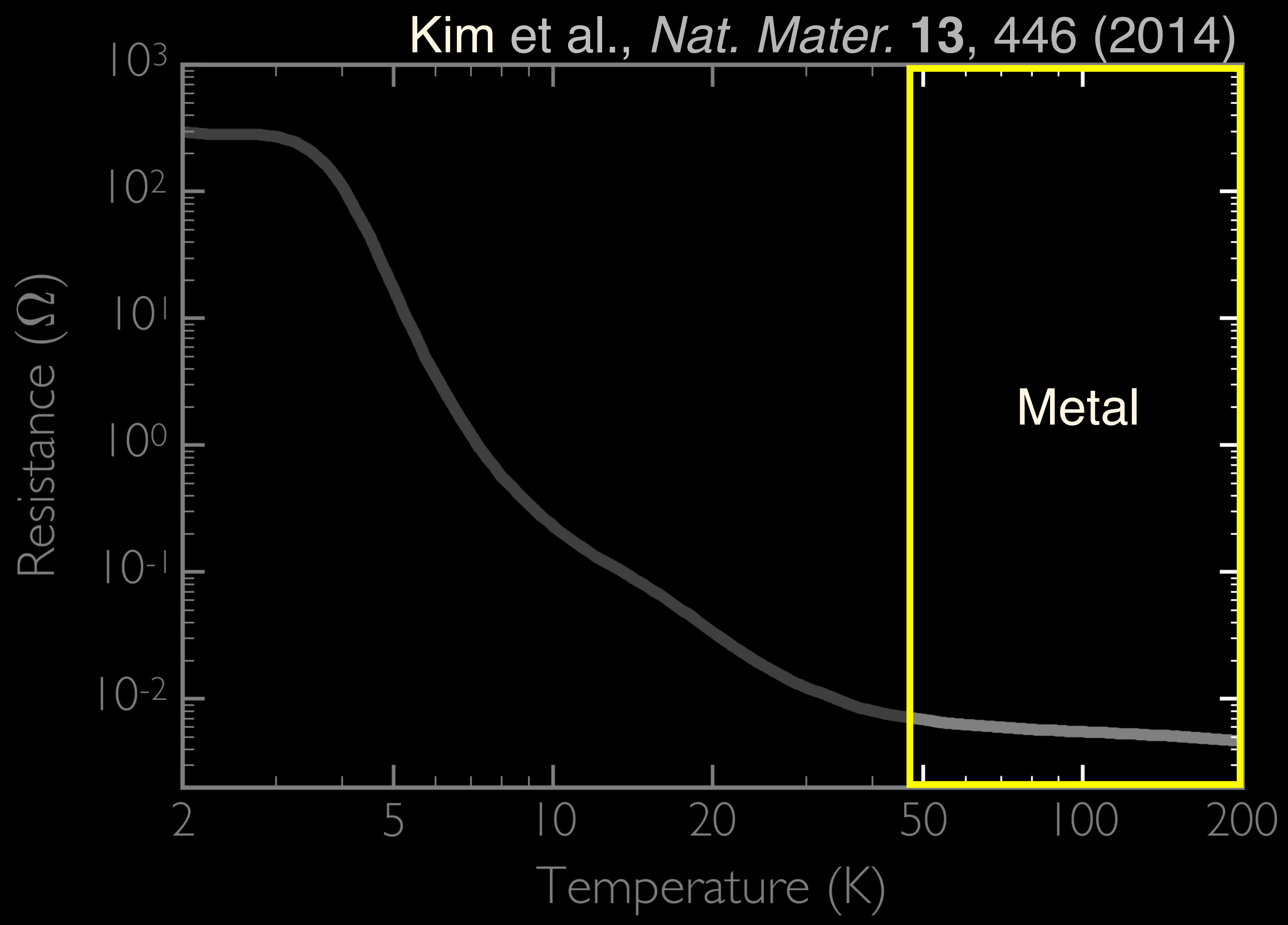
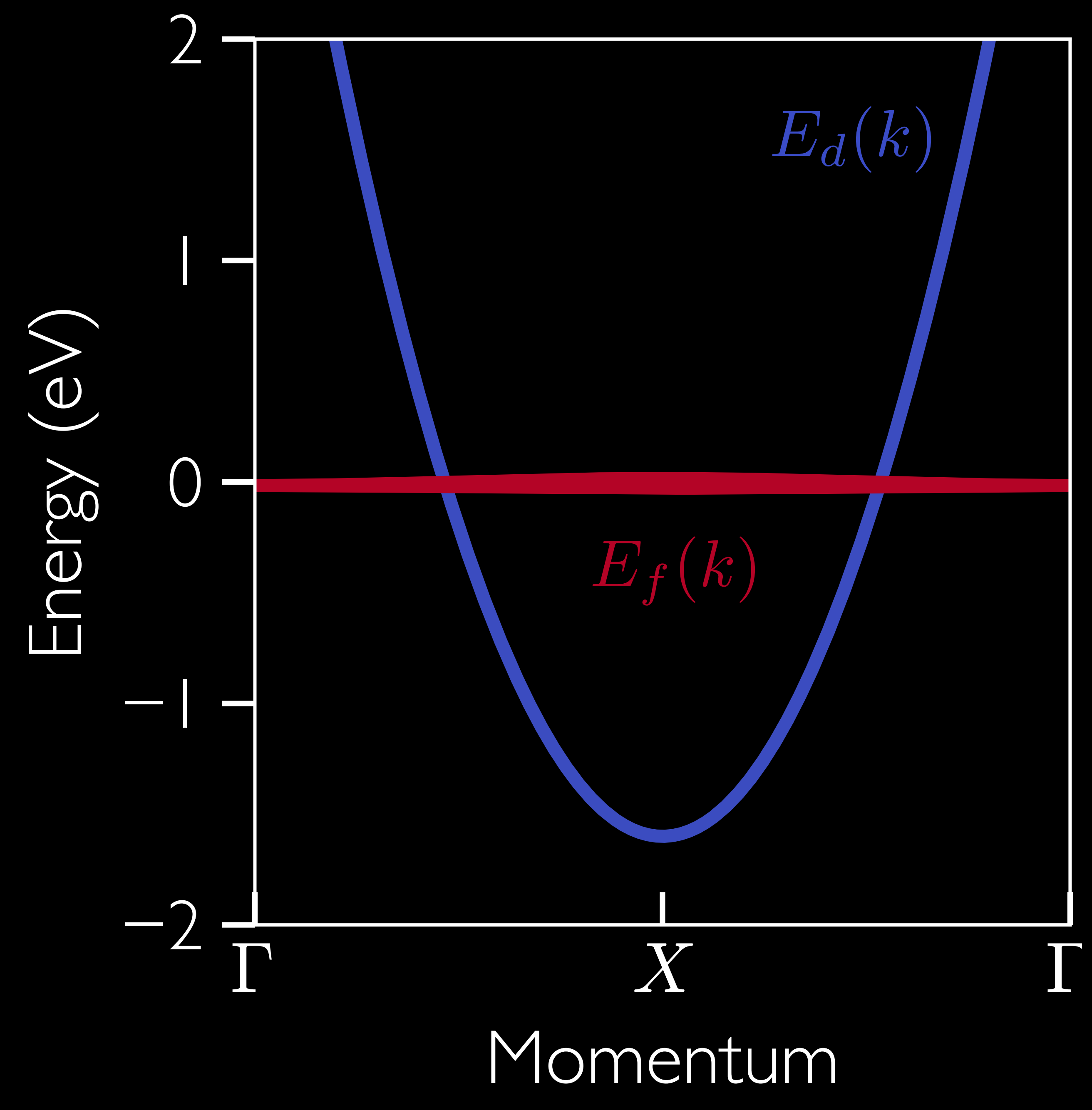
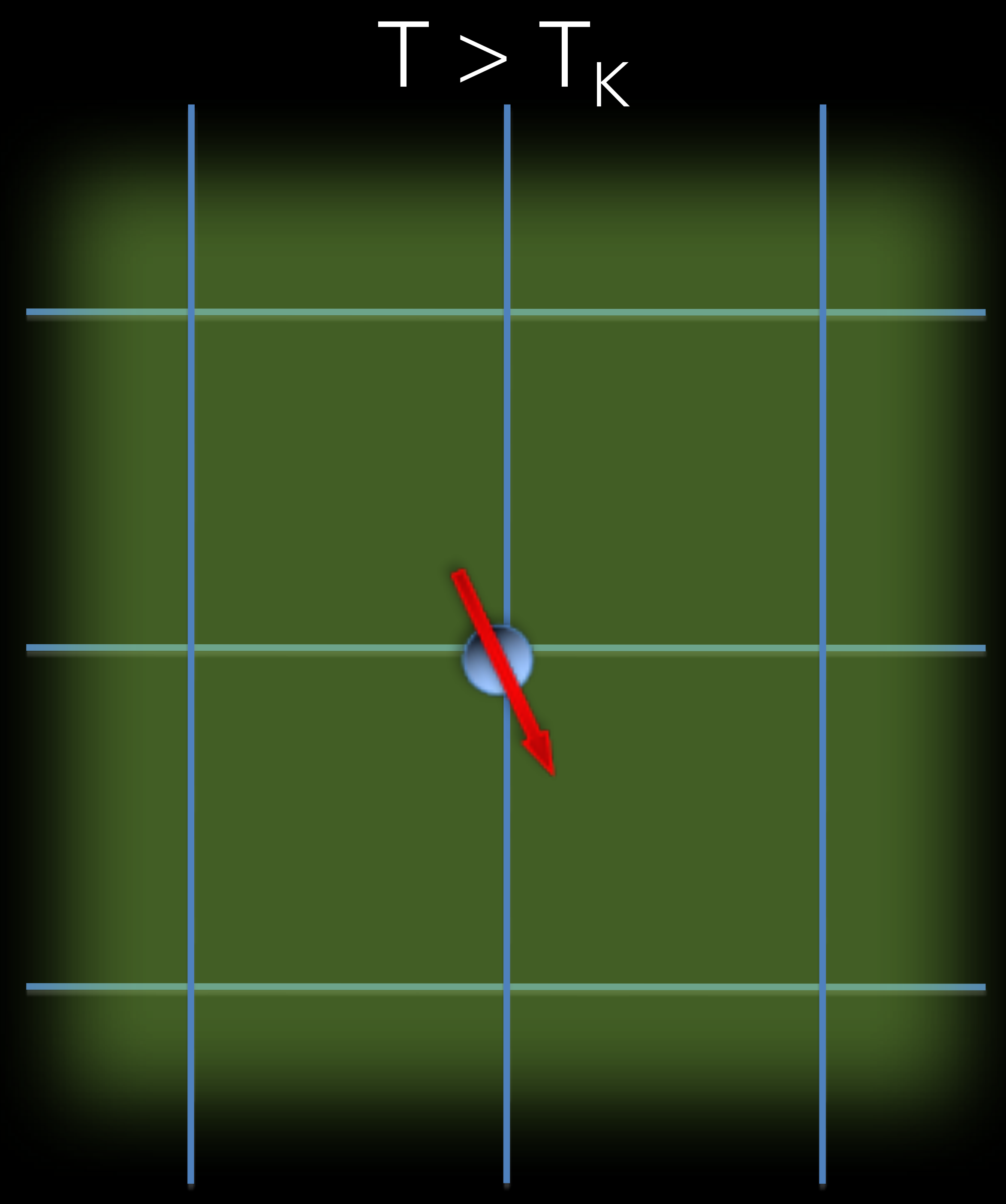
SmB_6 is a high-temperature metal







Local *4f* moments
\+ Itinerant *5d* electrons

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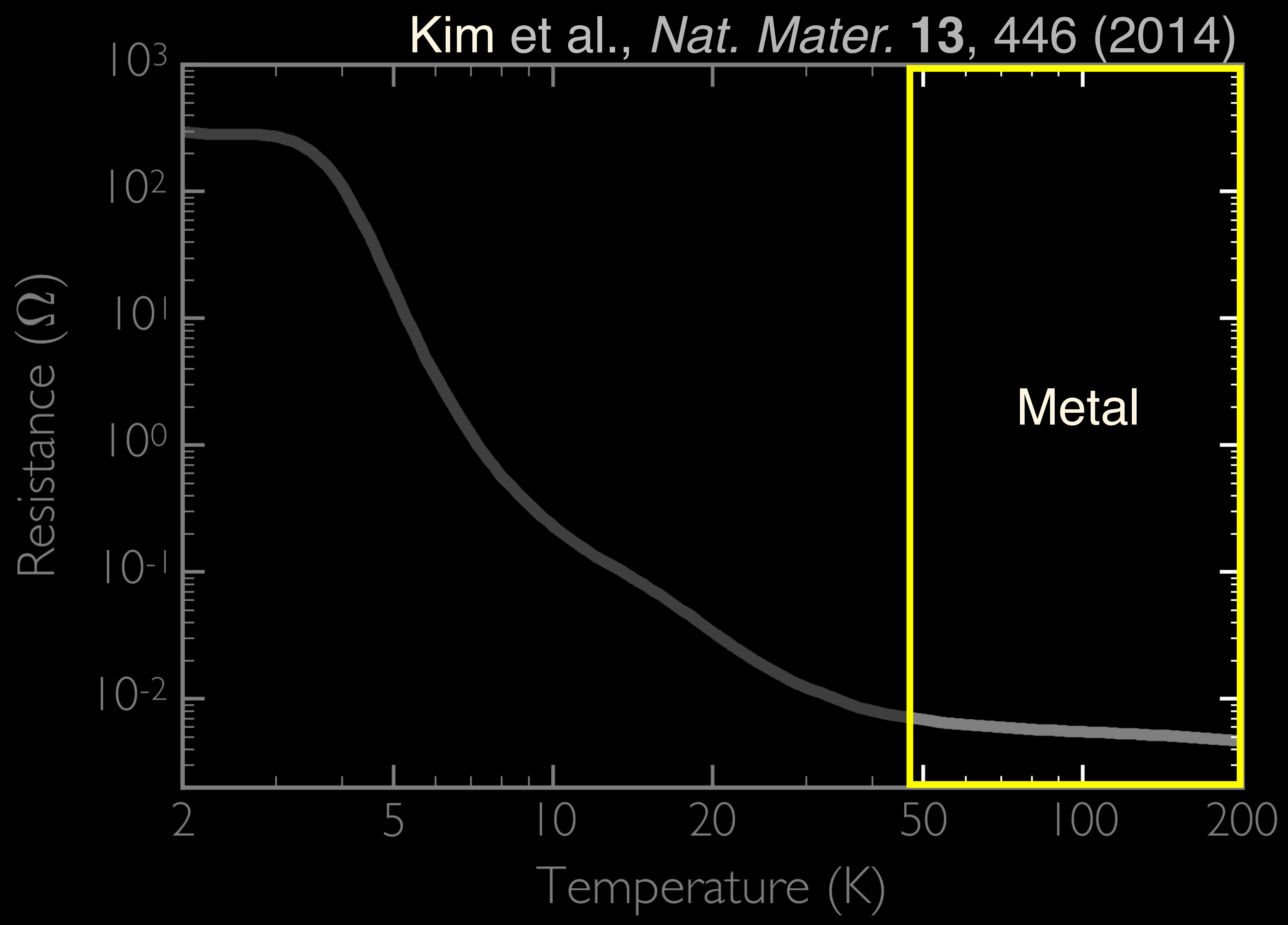

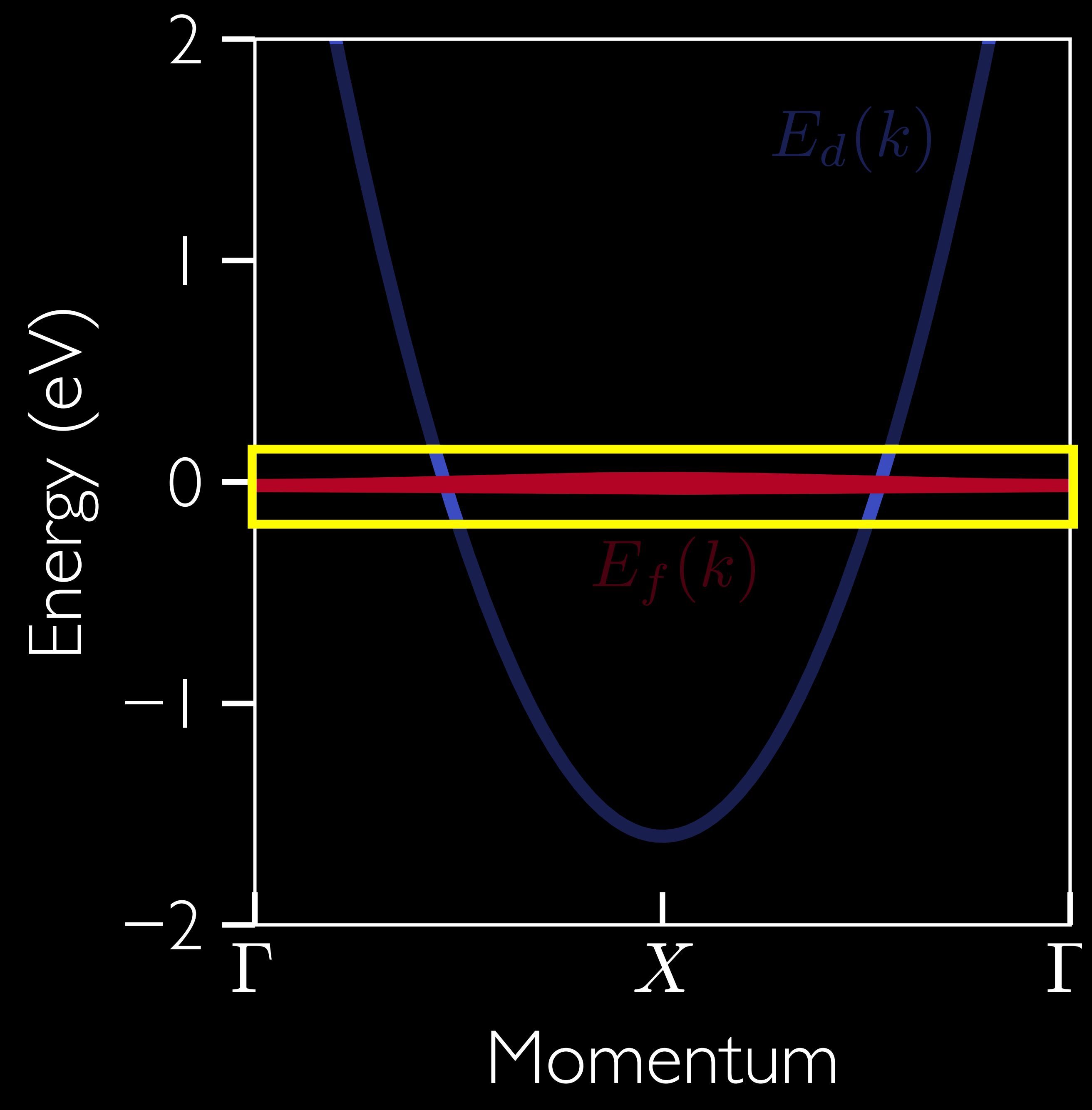

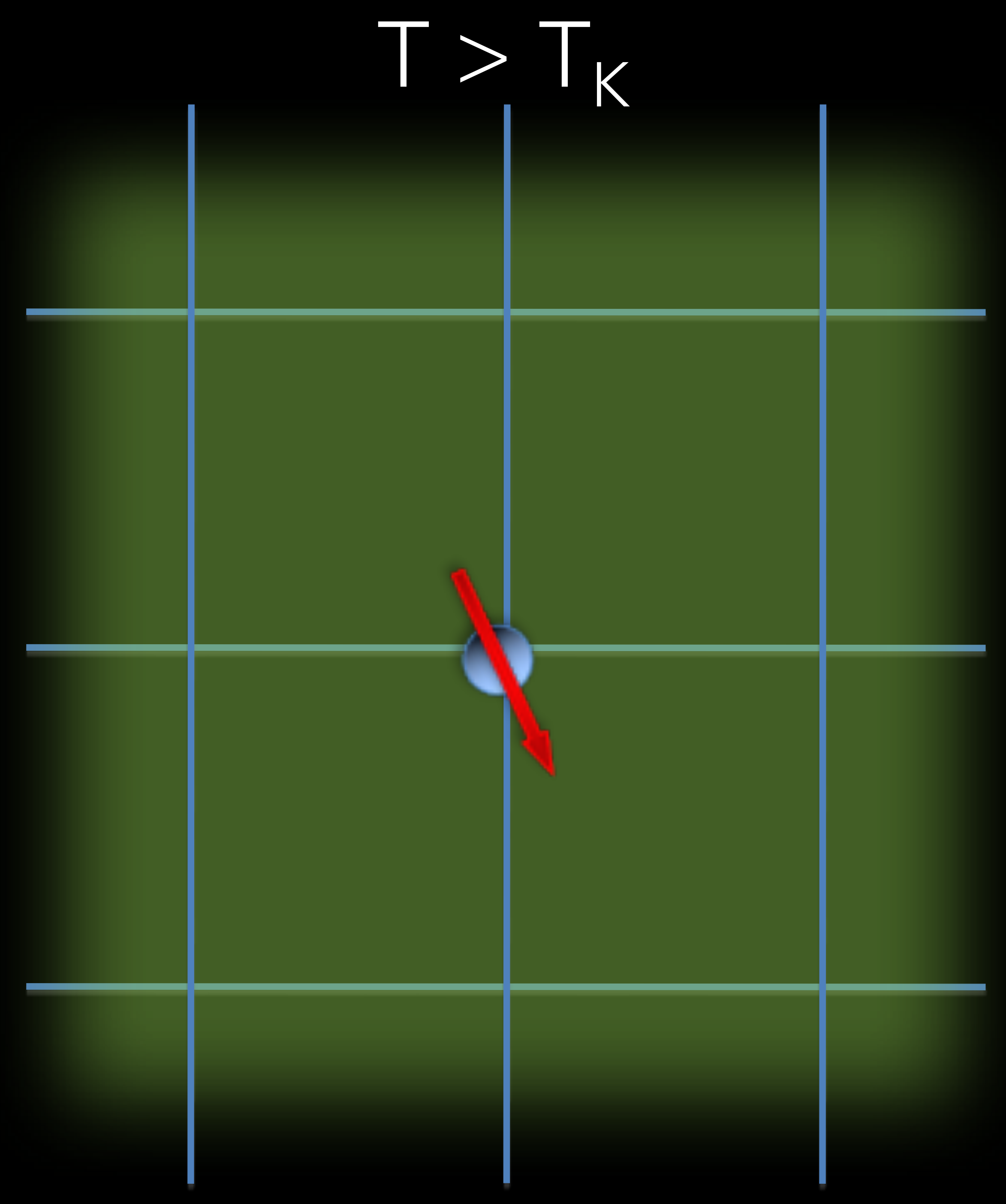

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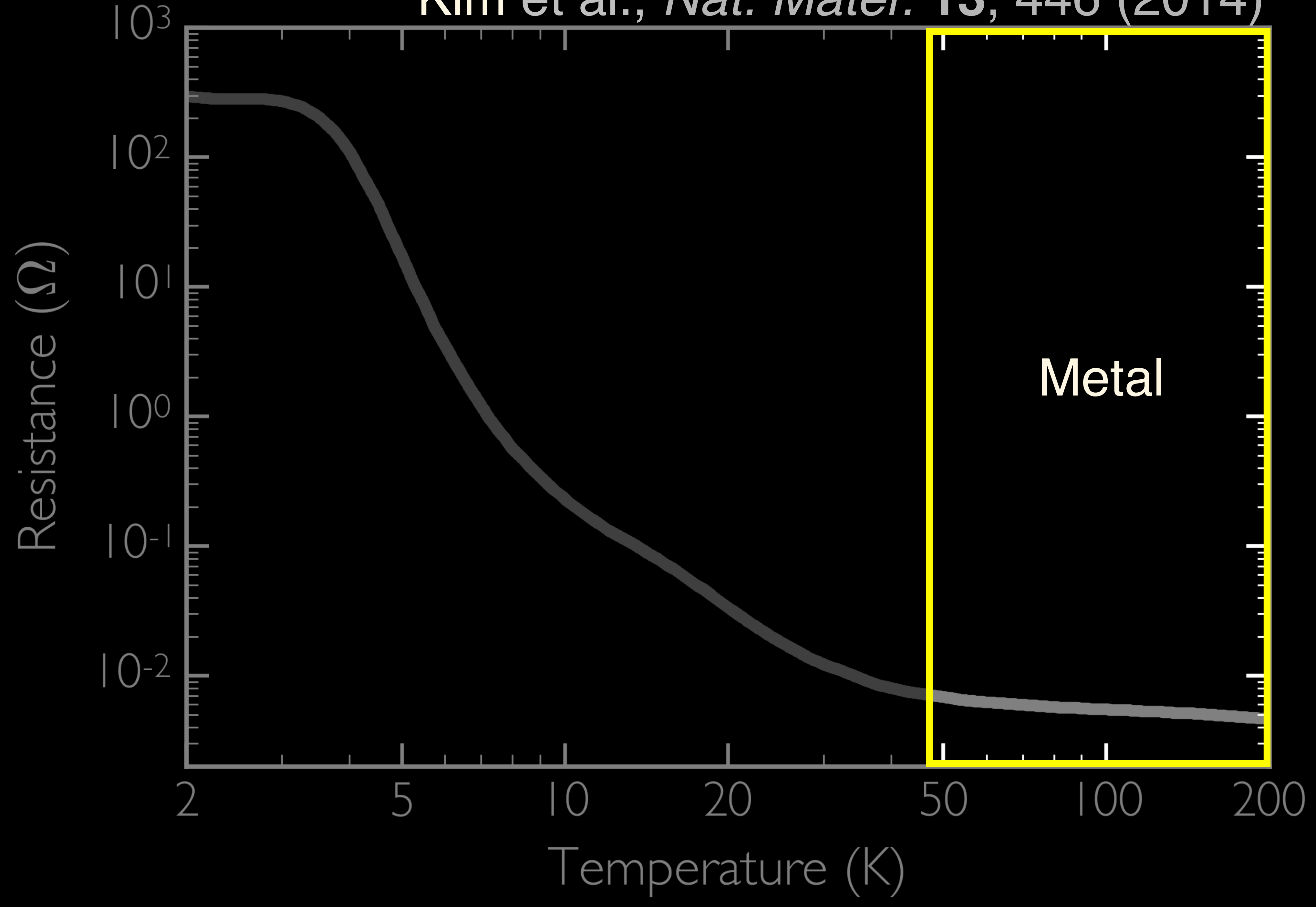
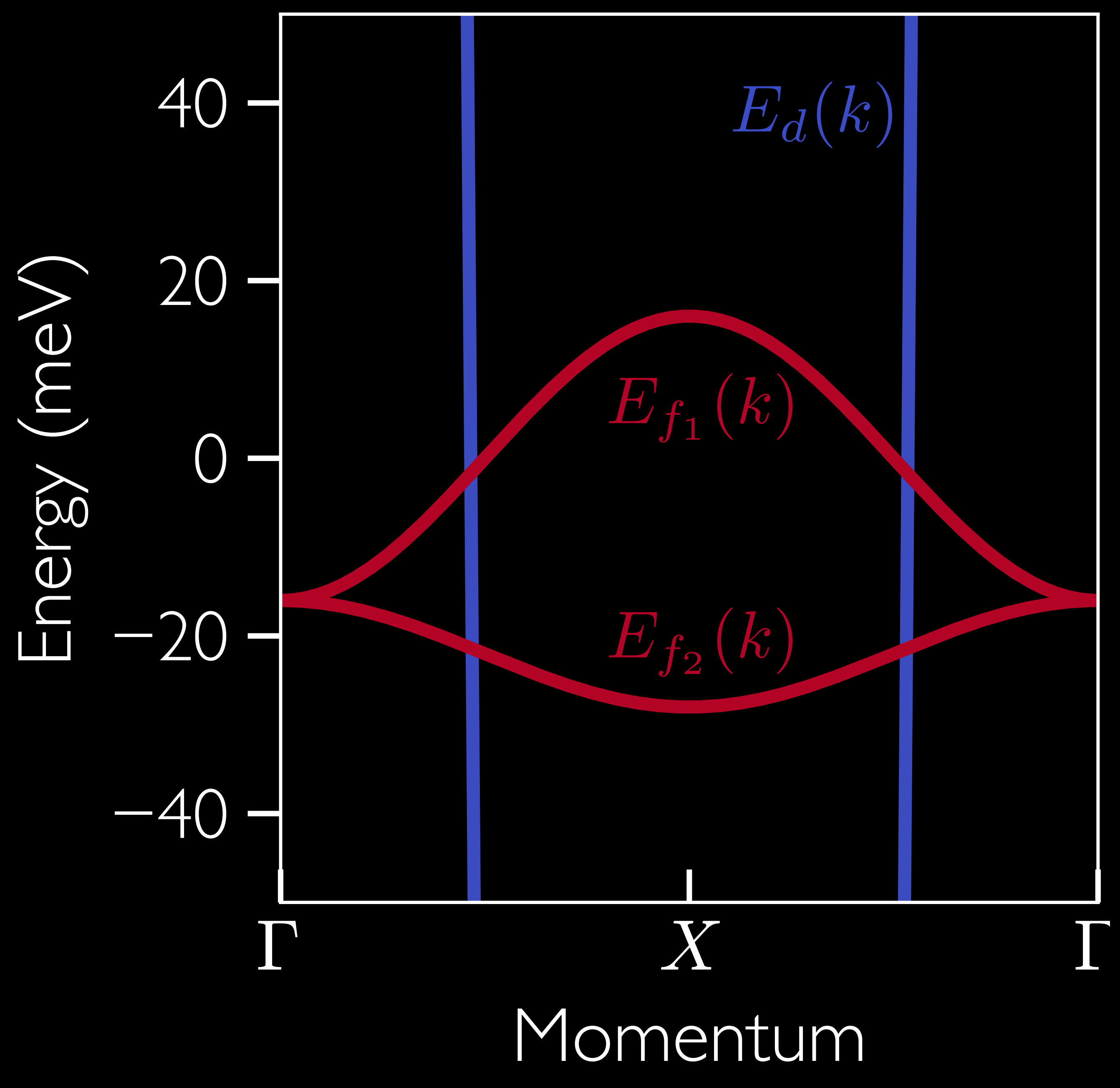
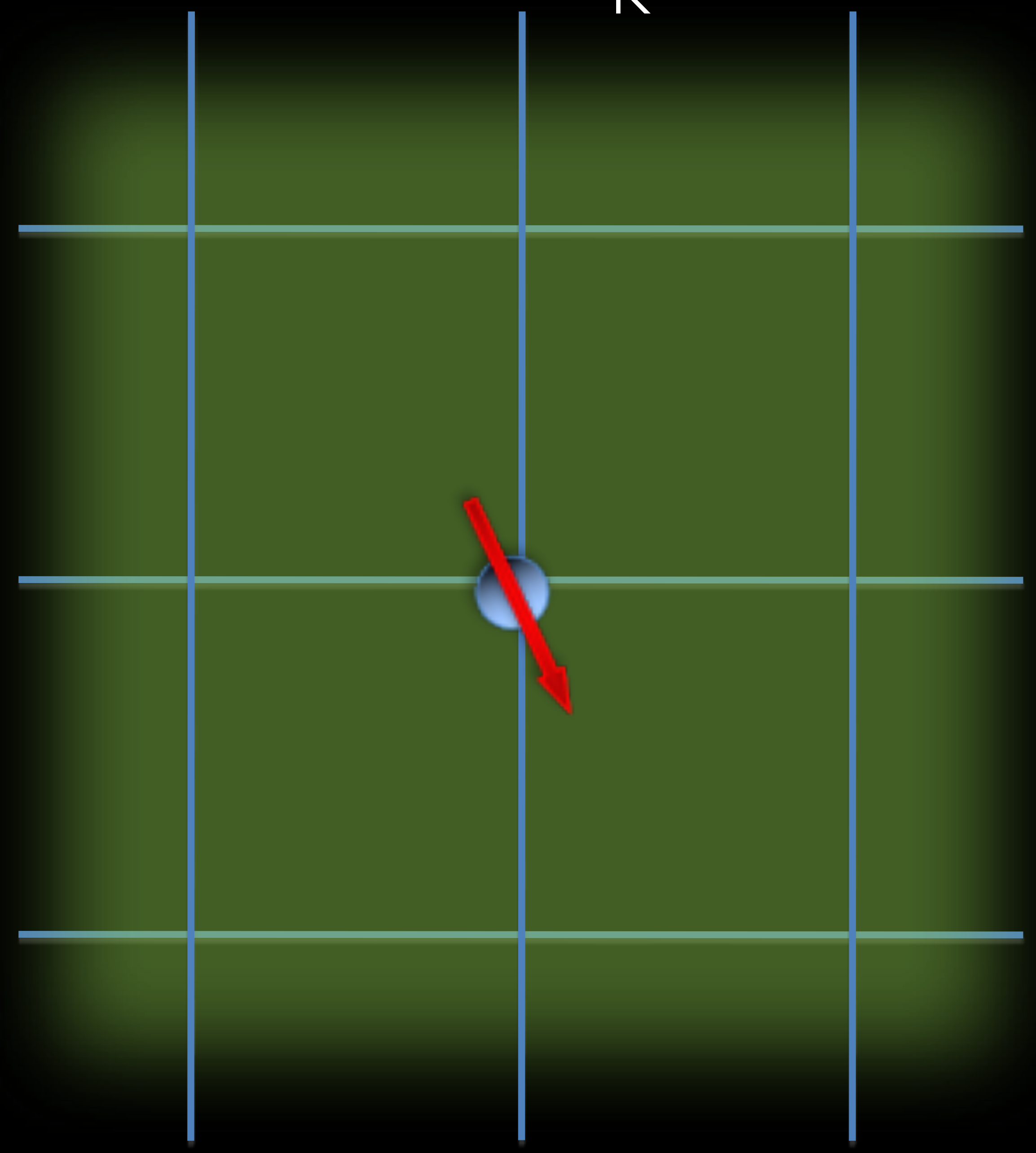
Kim et al., *Nat. Mater.* **13**, 446 (2014)





$T > T_K$



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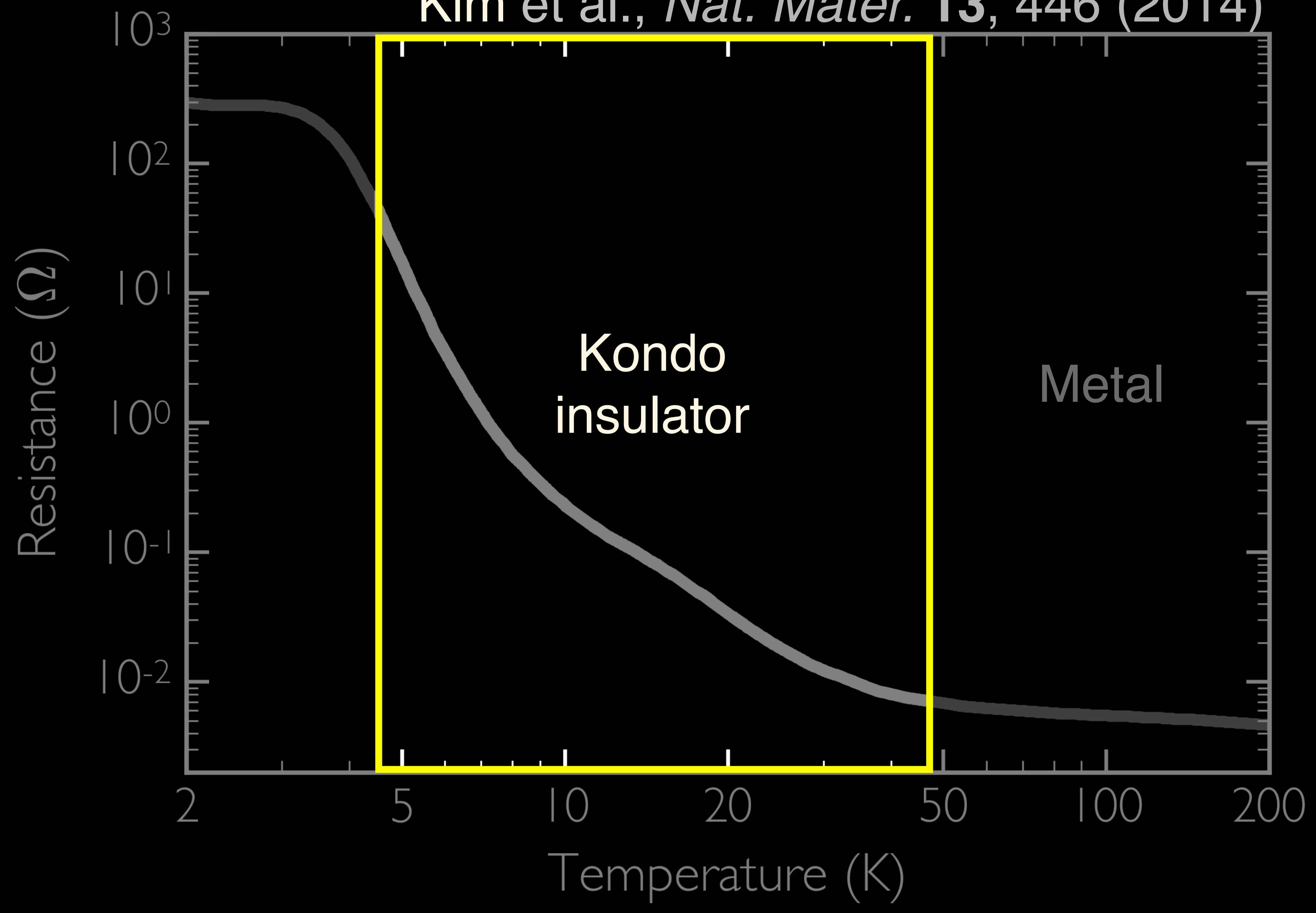
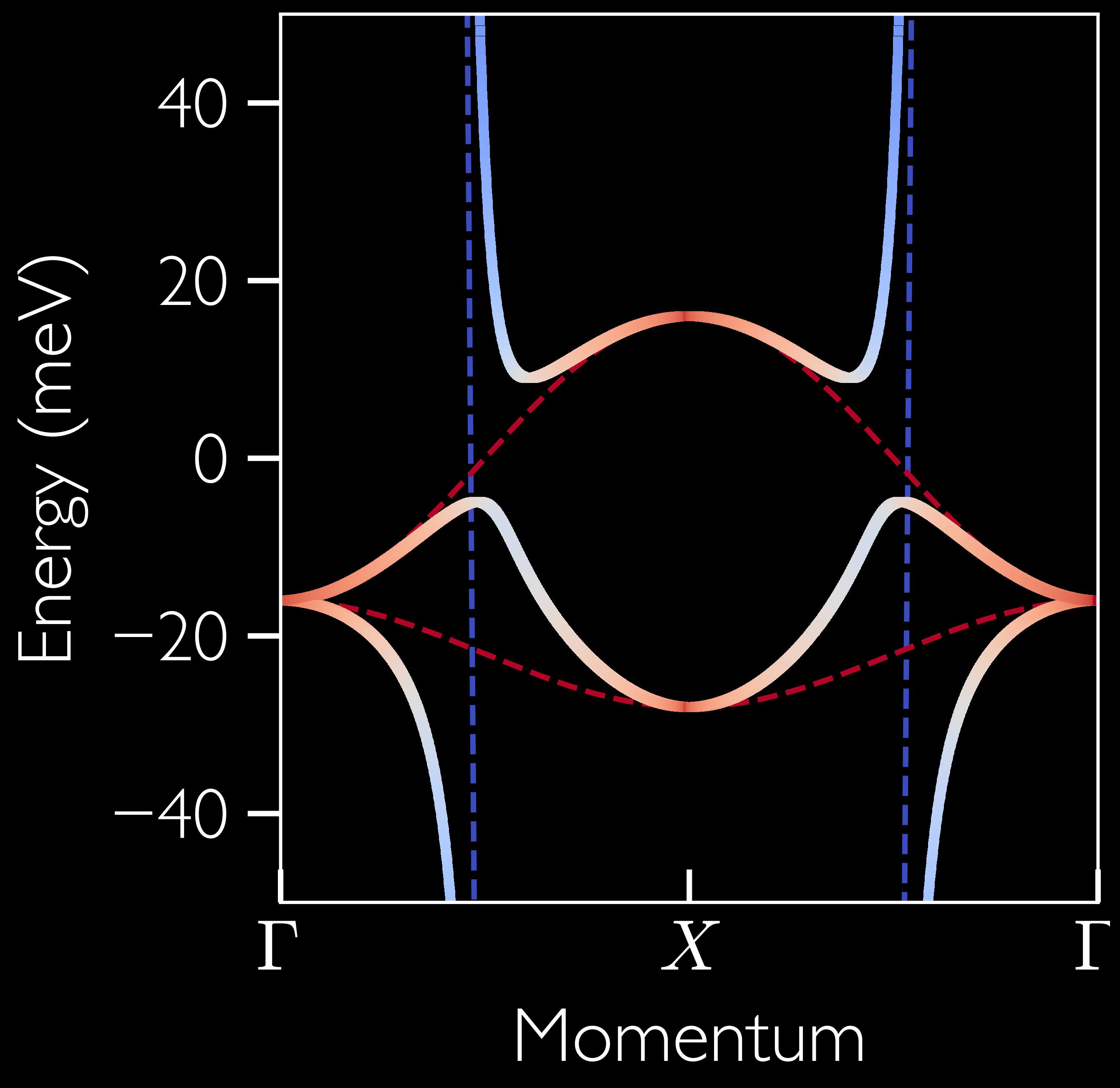
Kim et al., *Nat. Mater.* **13**, 446 (2014)





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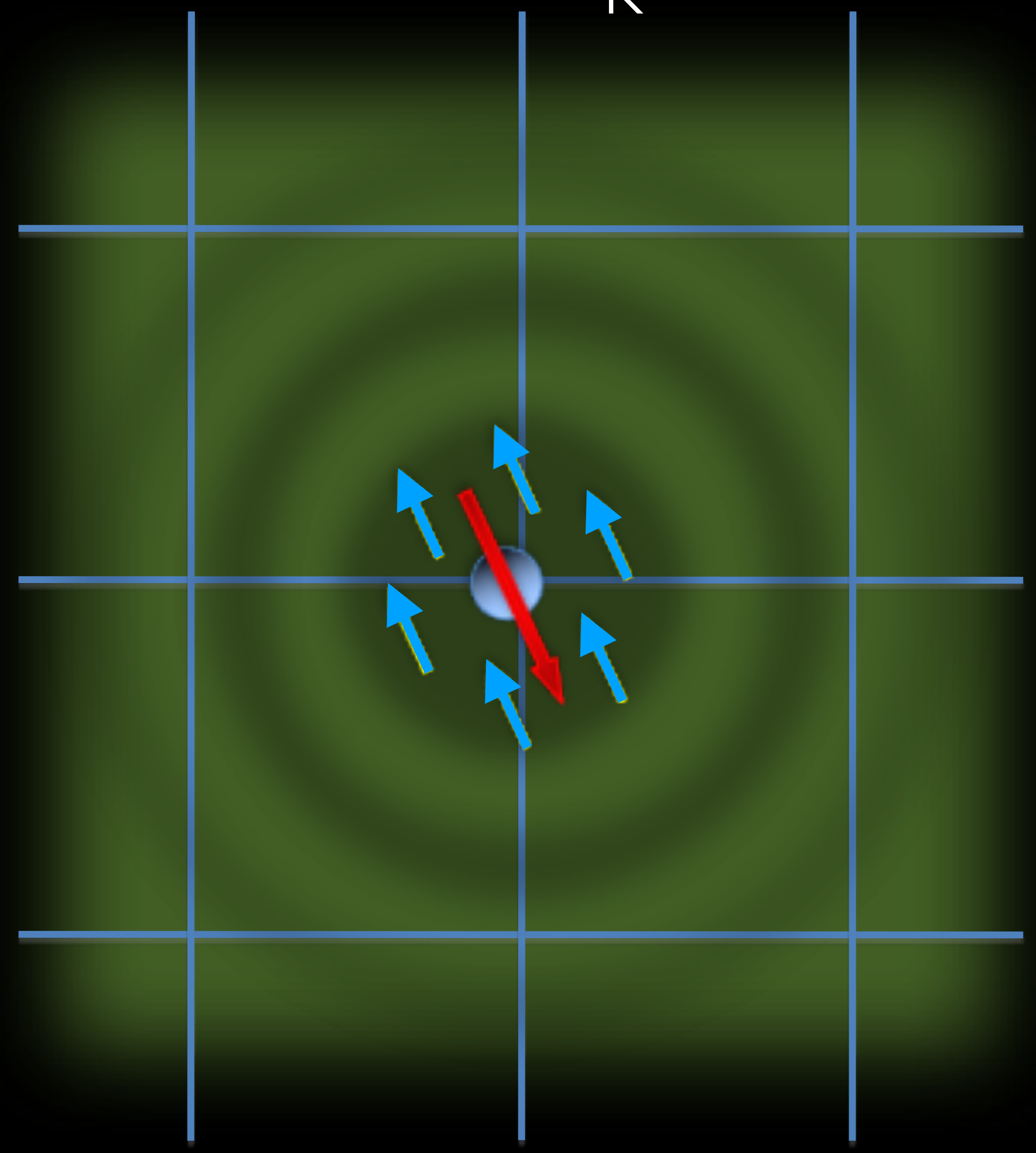

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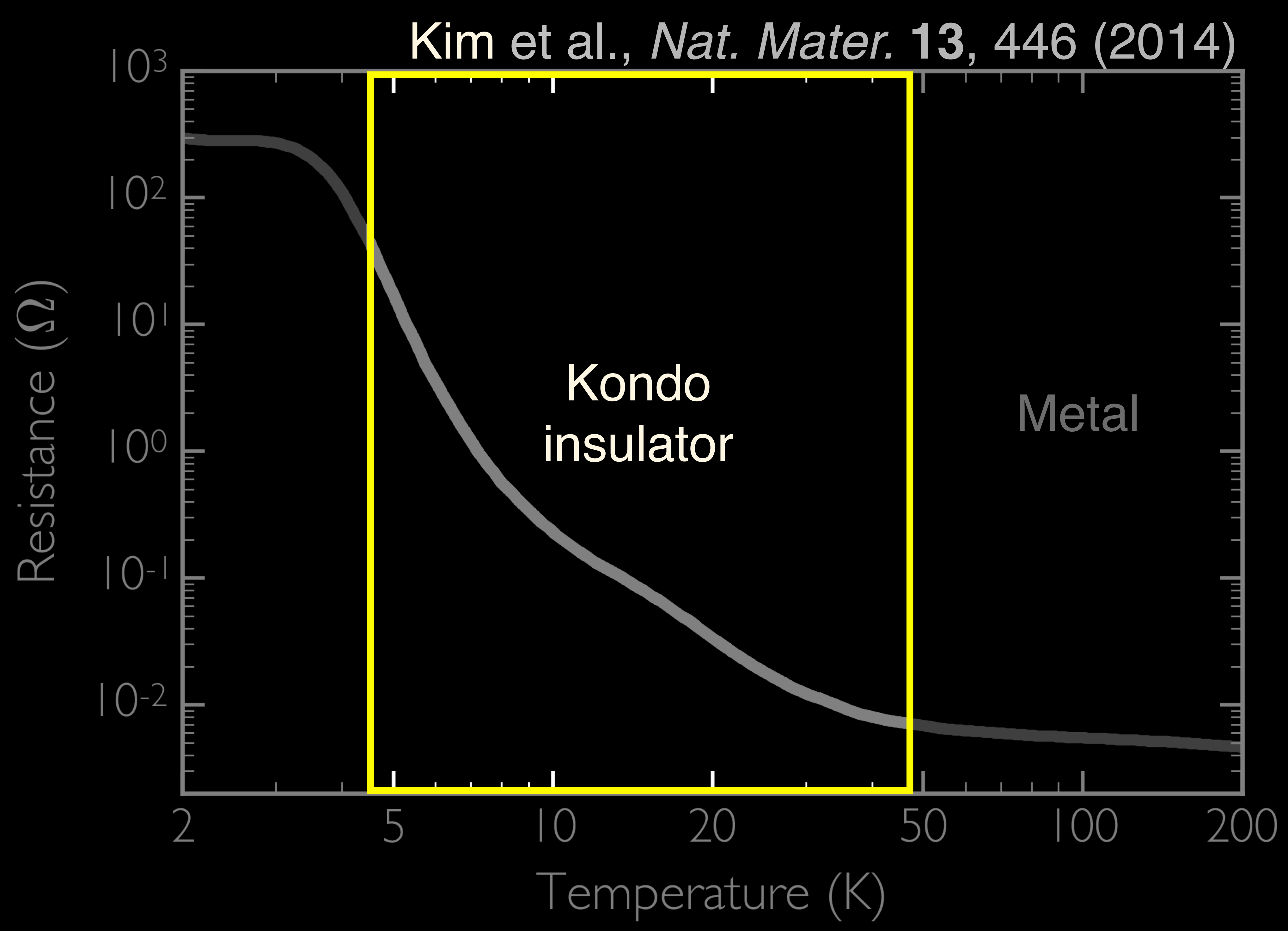

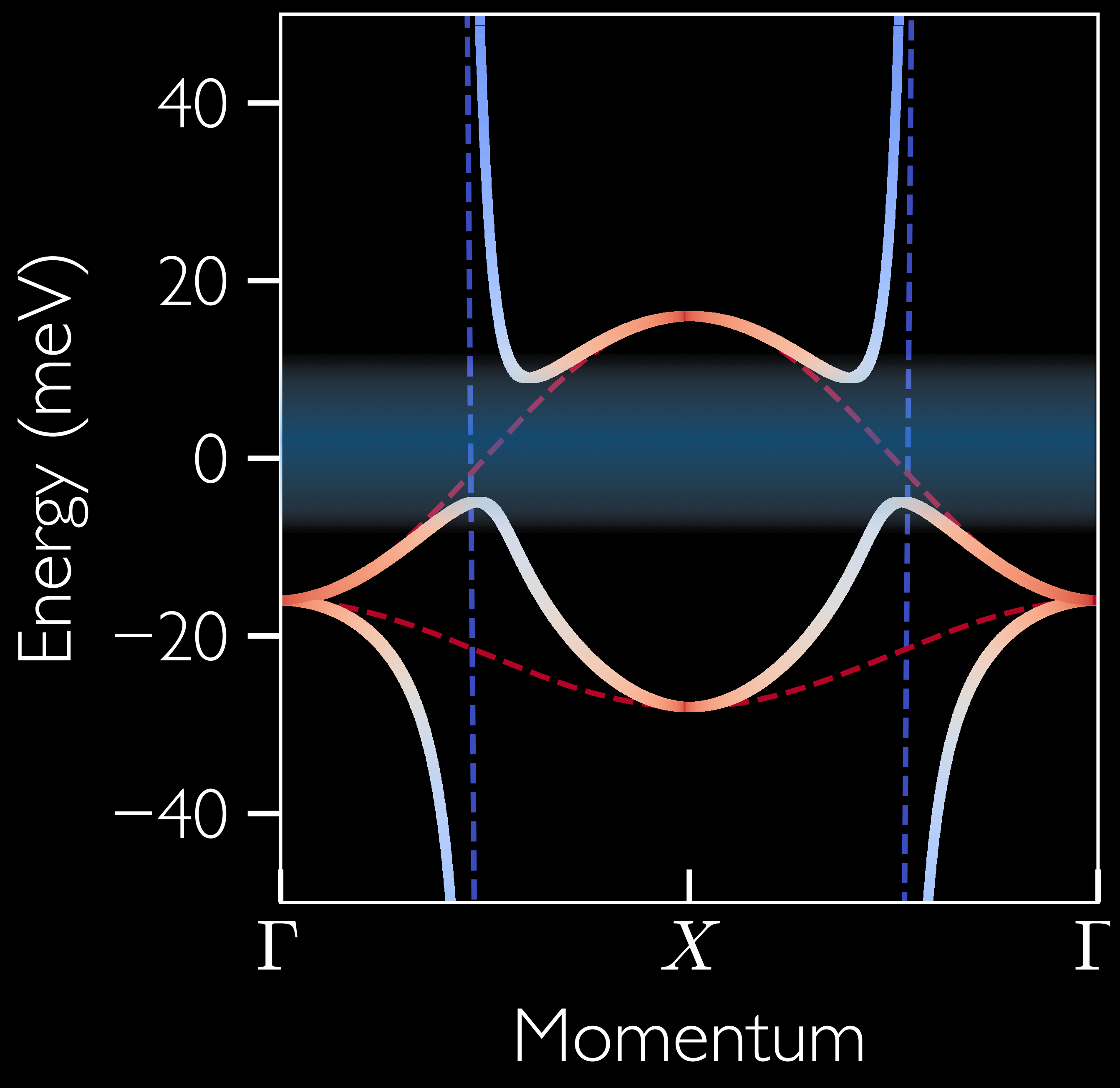

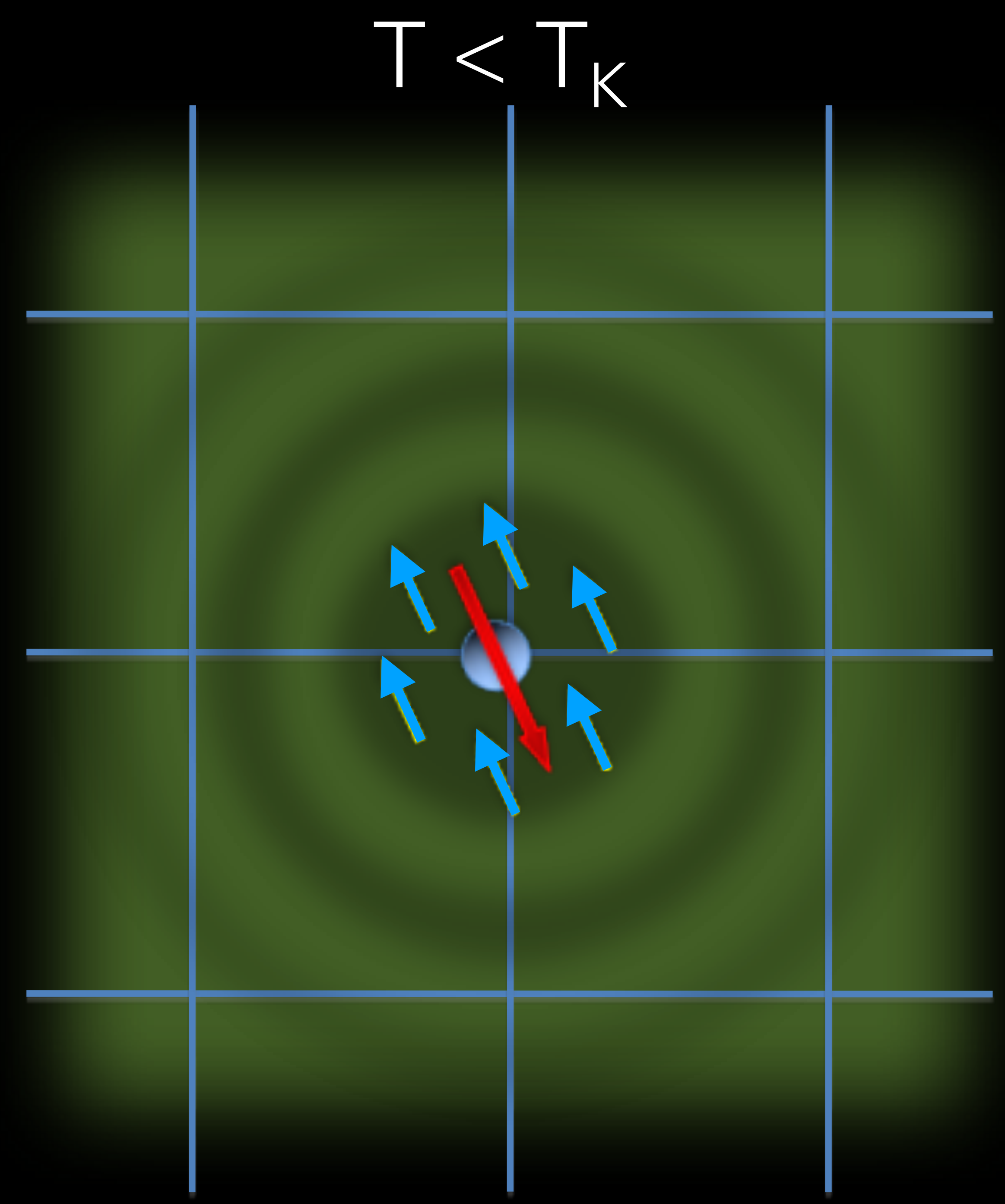

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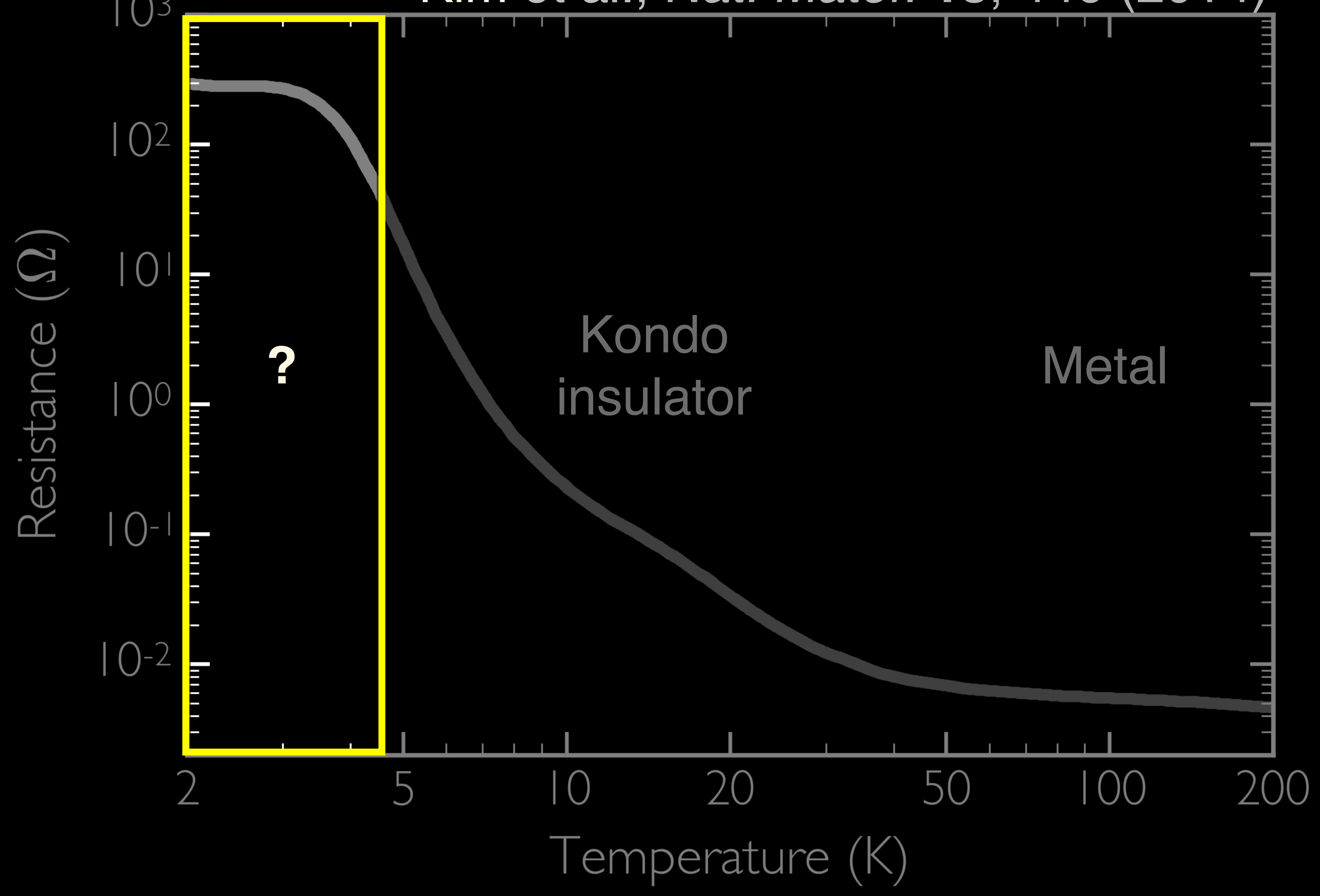
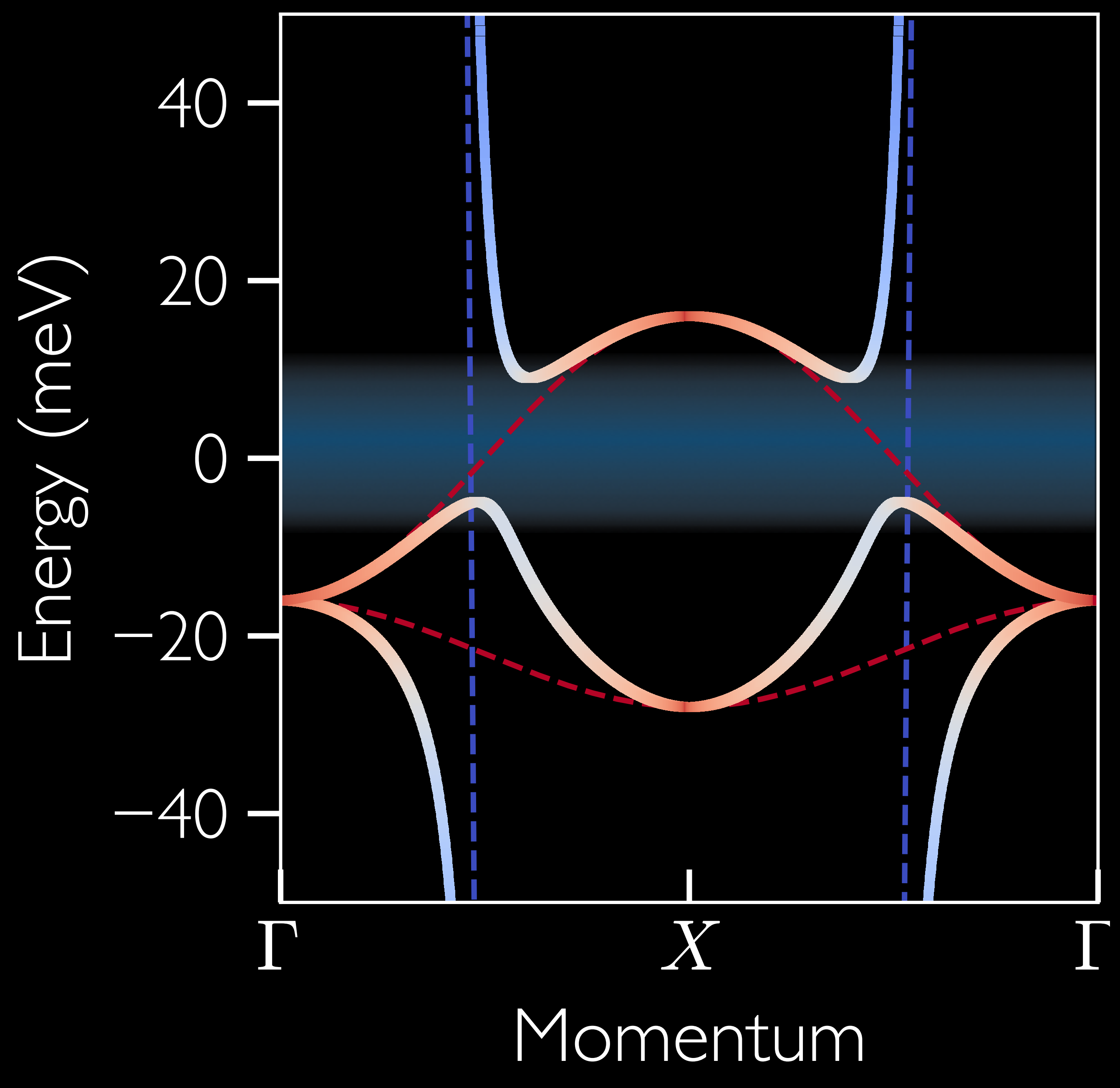
Low-*T* conductivity dominated by surface

Kim et al., *Nat. Mater.* **13**, 446 (2014)





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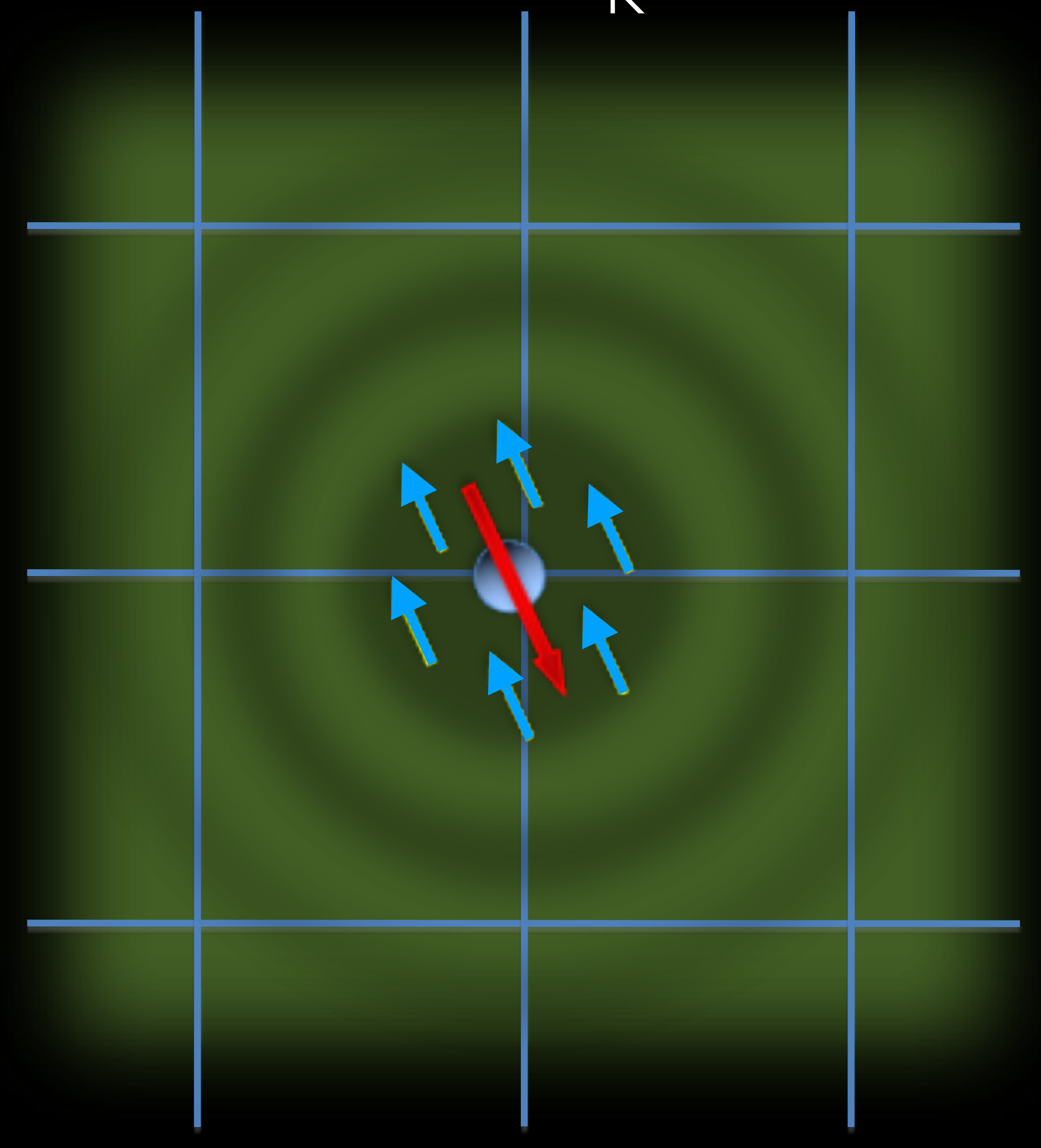

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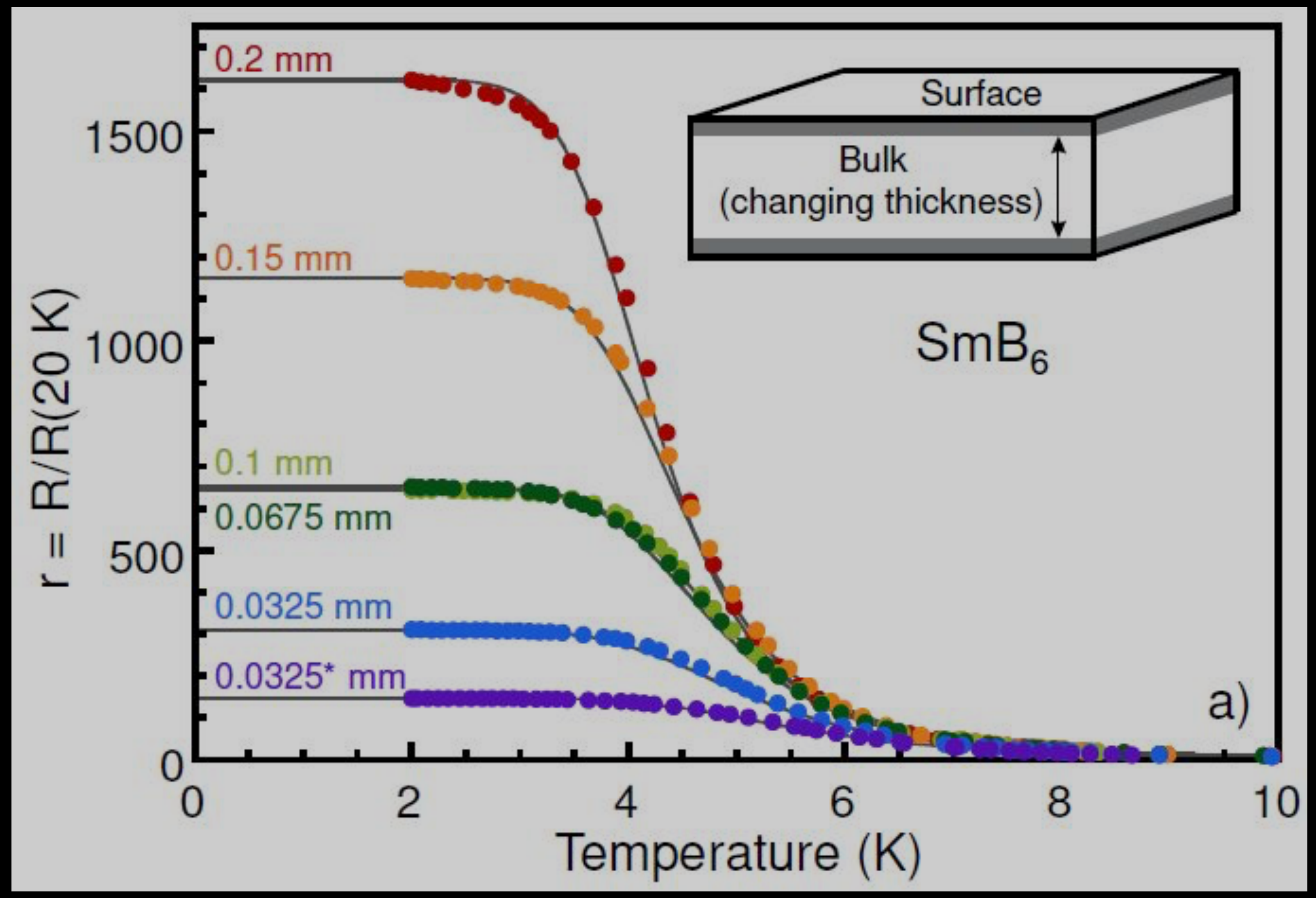

Syers et al., *Phys. Rev. Lett.* **114**, 096601 (2015)

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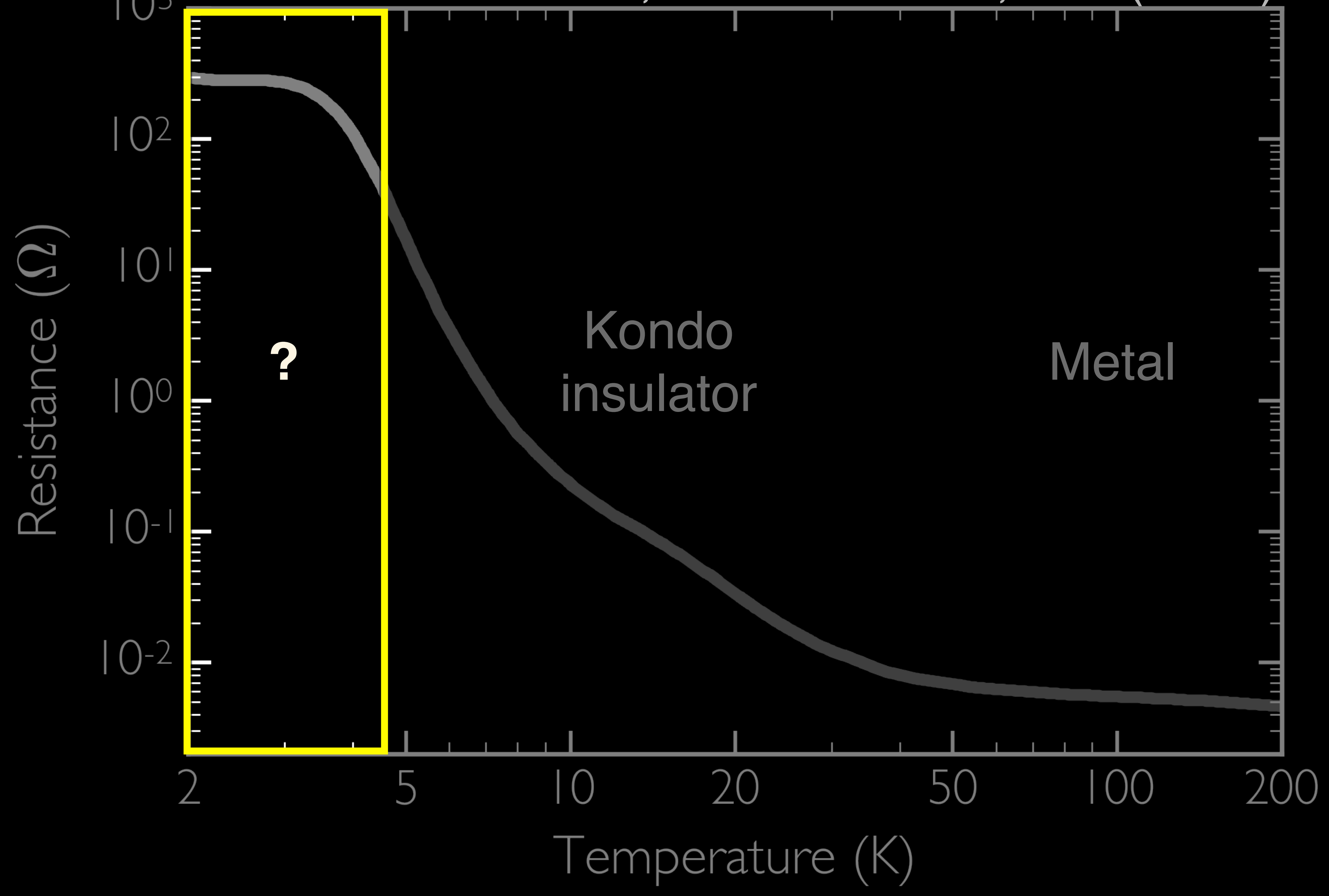

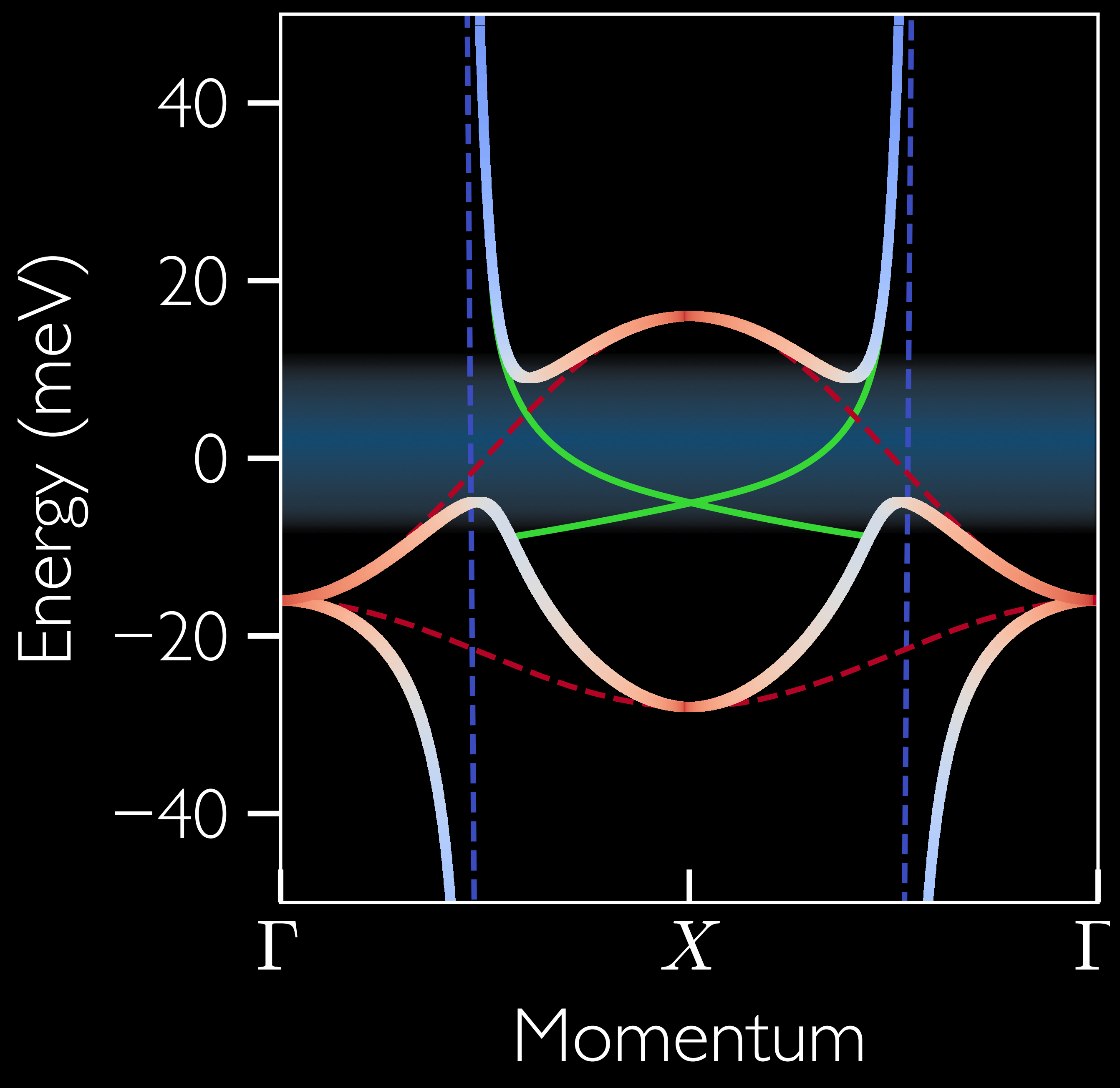

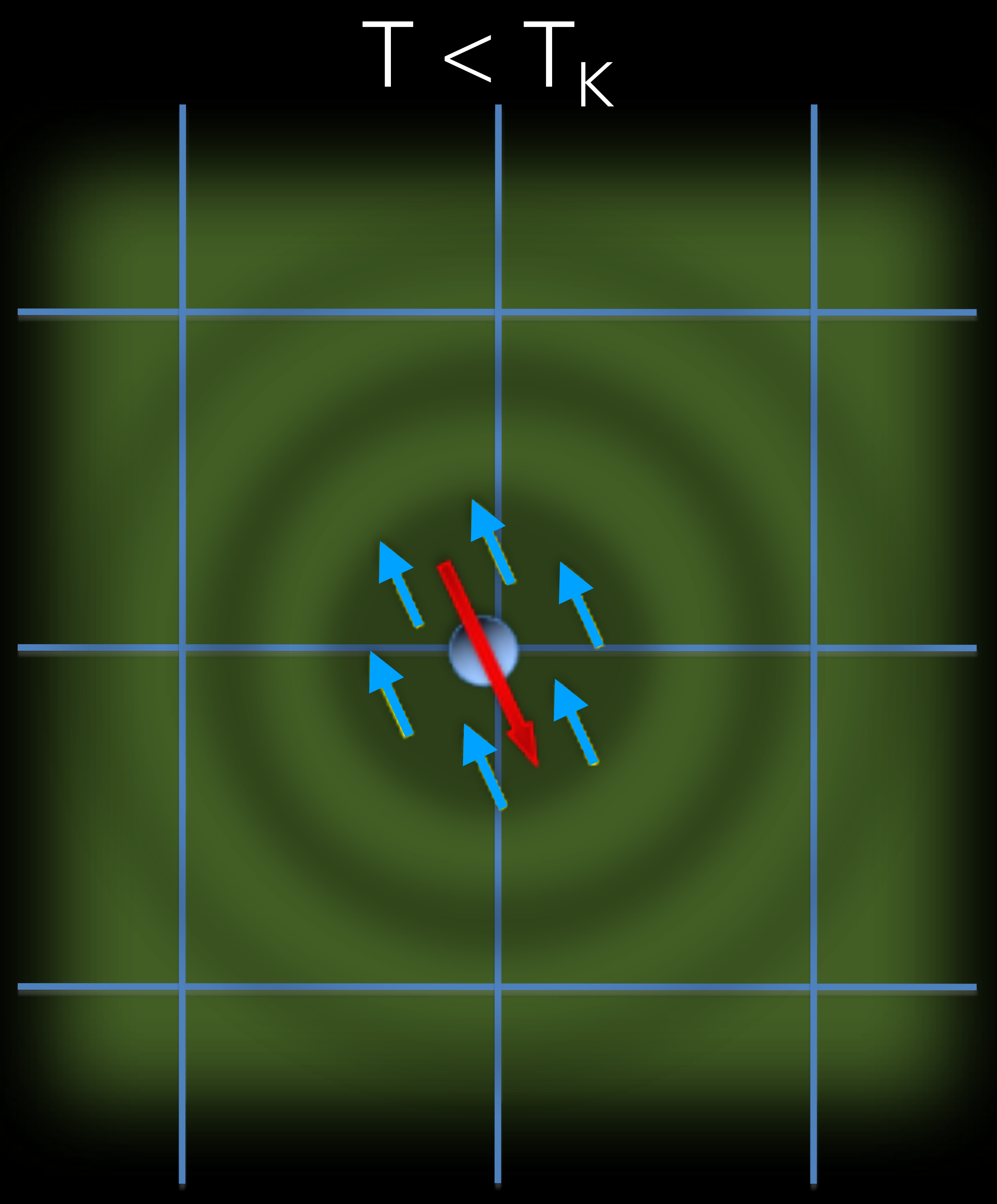

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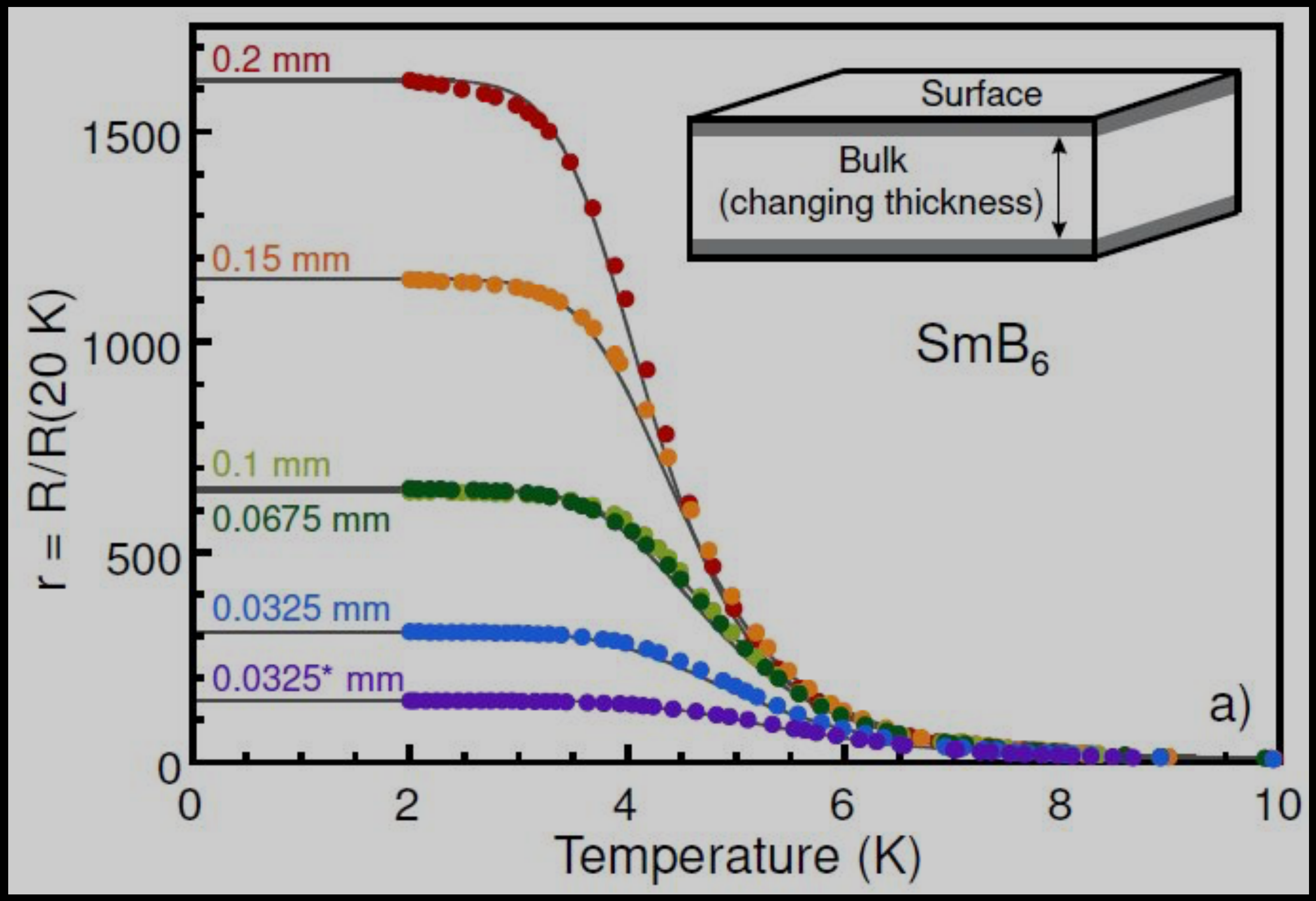

Prediction: Strong topological insulator

Dzero et al., *Phys. Rev. Lett.* (2010)
Takimoto et al., *JSPJ* (2011)
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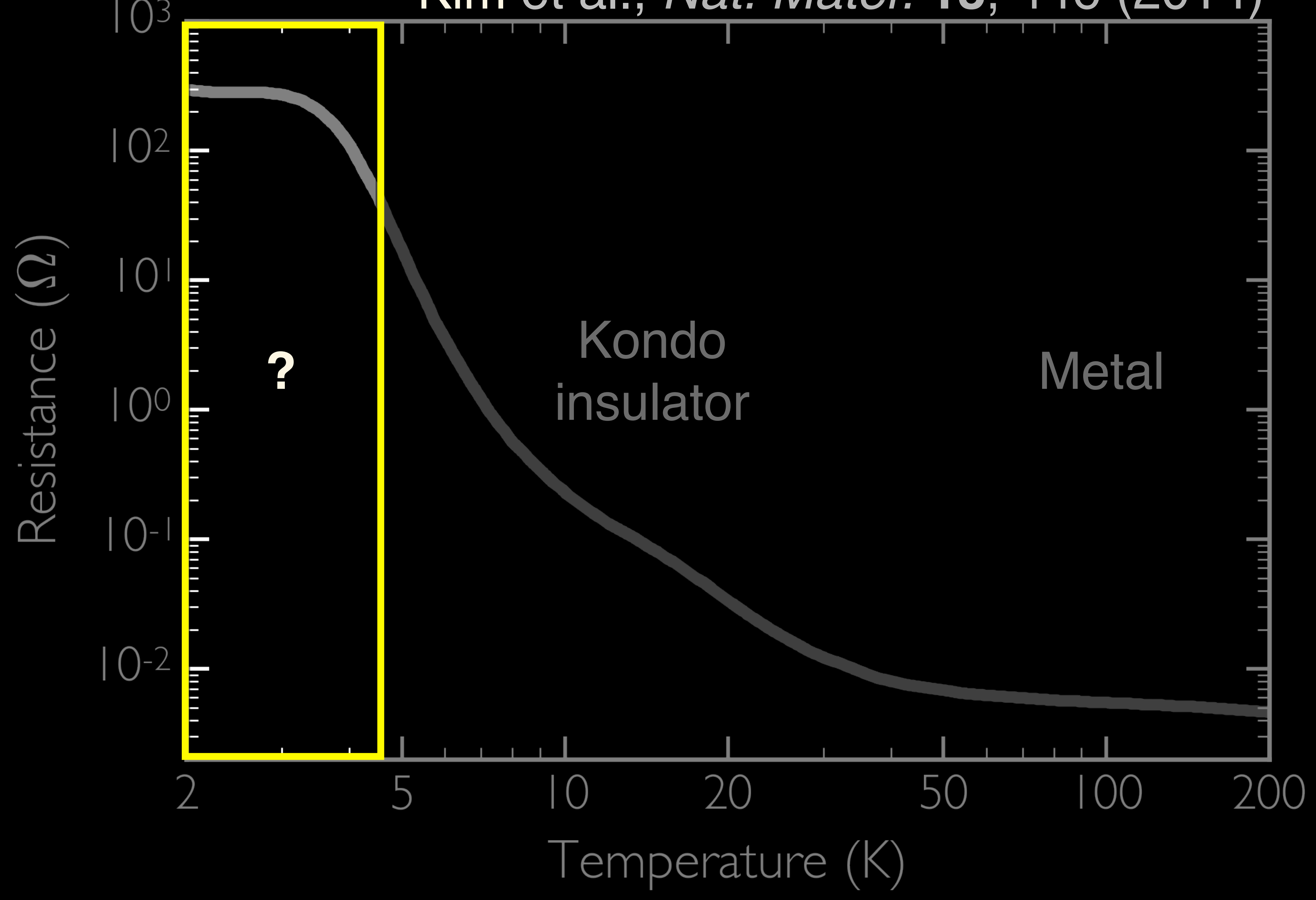

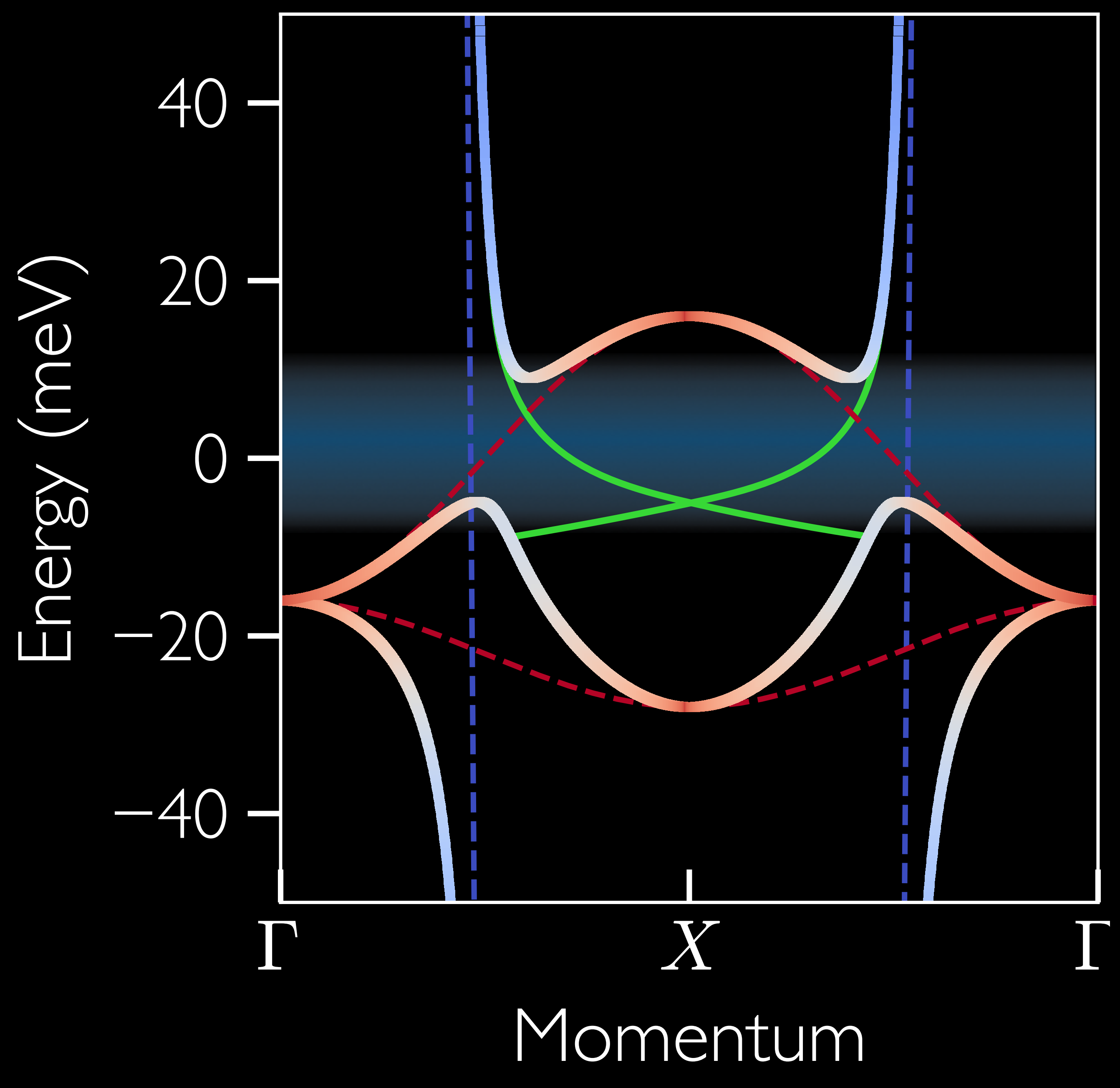

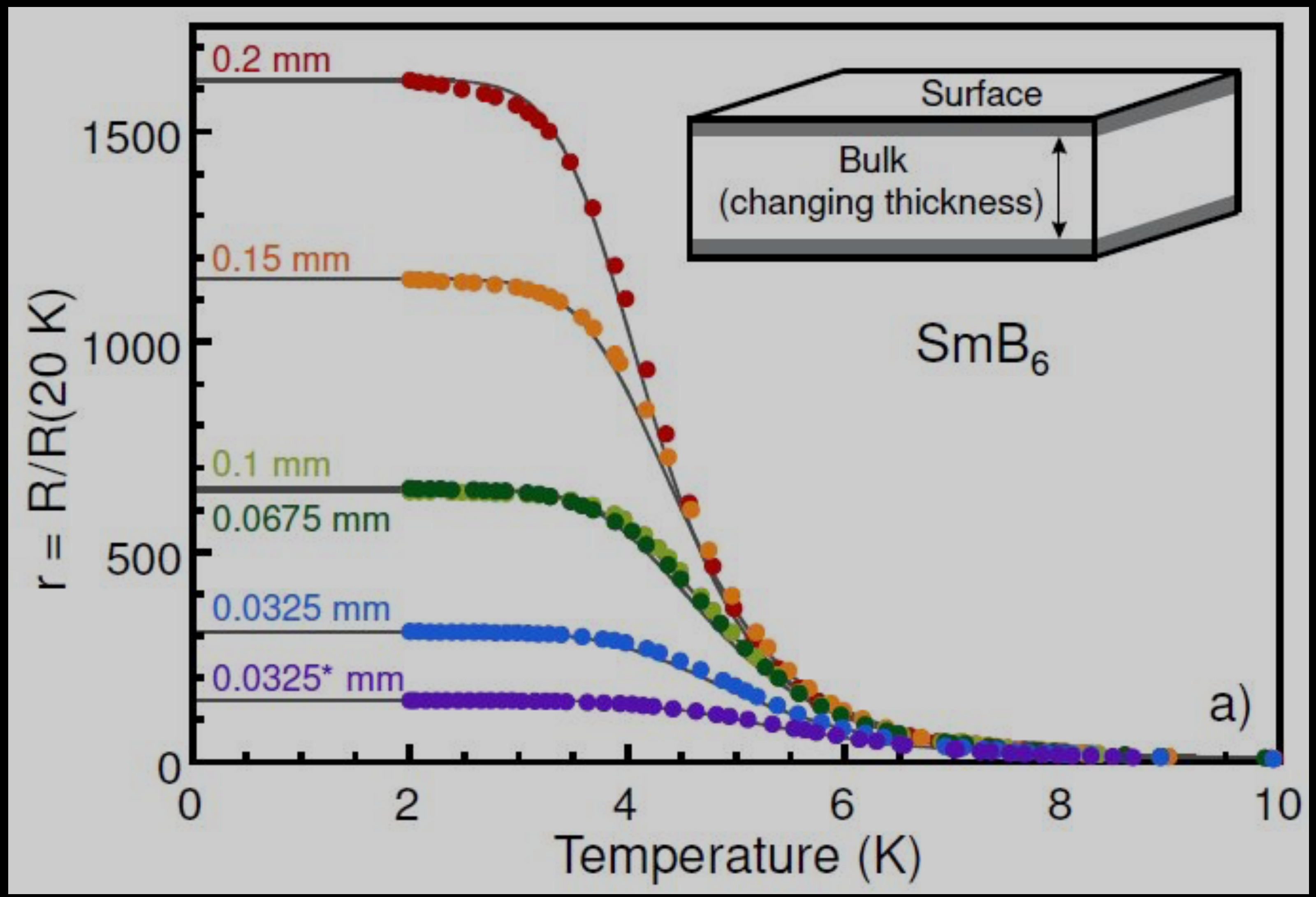

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Takimoto et al., *JSPJ* (2011)
Lu et al., *Phys. Rev. Lett.* (2013)

Transport—can't measure velocity!

Zhang *et al*, PRX 3, 011011 (2013)
Wolgast *et al*, PRB 88, 180405 (2013)
Kim *et al*, Nat Mat 13, 3913 (2014)
Luo *et al*, PRB 91, 075130 (2014)
Syers *et al*, PRL 114, 096601 (2015)
…

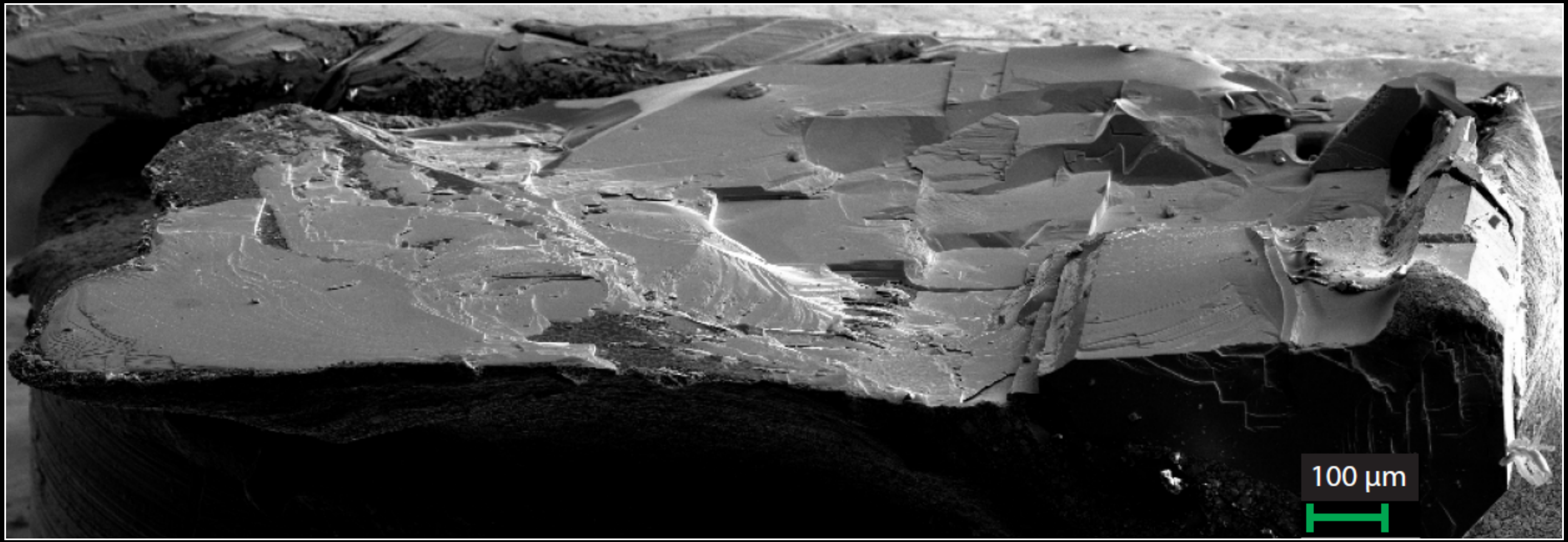
Photoemission (ARPES)—10x too fast!

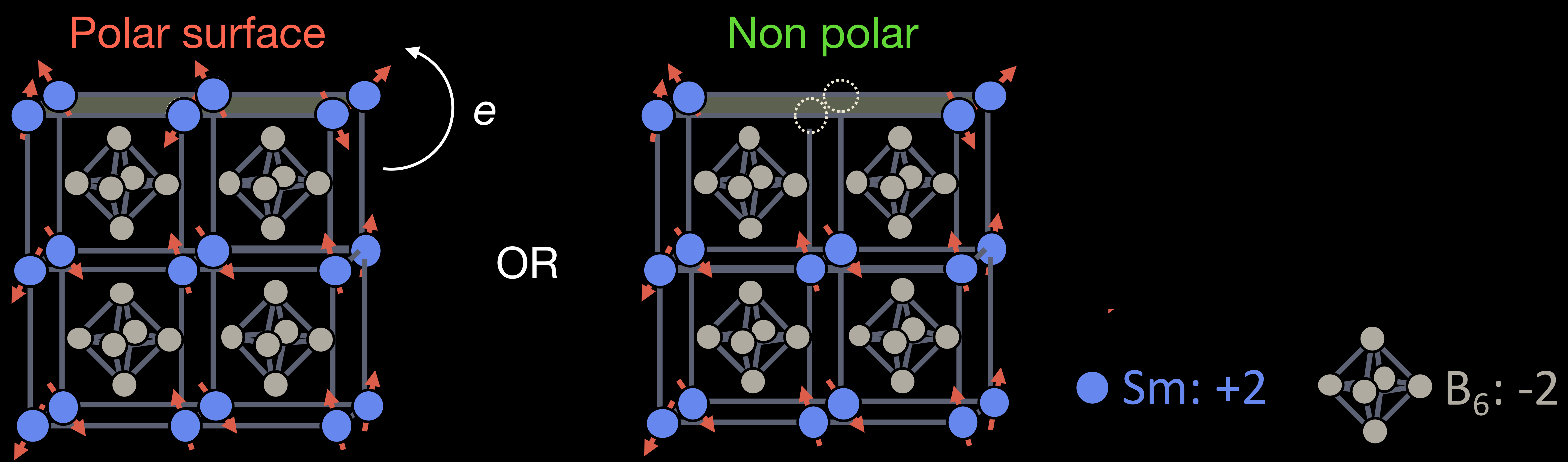
Miyazaki *et al*, PRB 86, 075105 (2012)
Xu *et al*, PRB 88, 121102 (2013)
Jiang *et al*, Nat Com 4, 3010 (2013)
Neupane *et al*, Nat Com 4, 2991 (2013)
Denlinger *et al*, arXiv:1312.6637 (2013)
Suga *et al*, JPSJ 83, 014705 (2014)
Xu *et al*, Nat Com 5, 5566 (2014)
…

Quantum oscillations (dHvA)—100x too fast!

Li *et al*, Science 346, 6214 (2014)

SmB_6 has polar and non-polar surfaces





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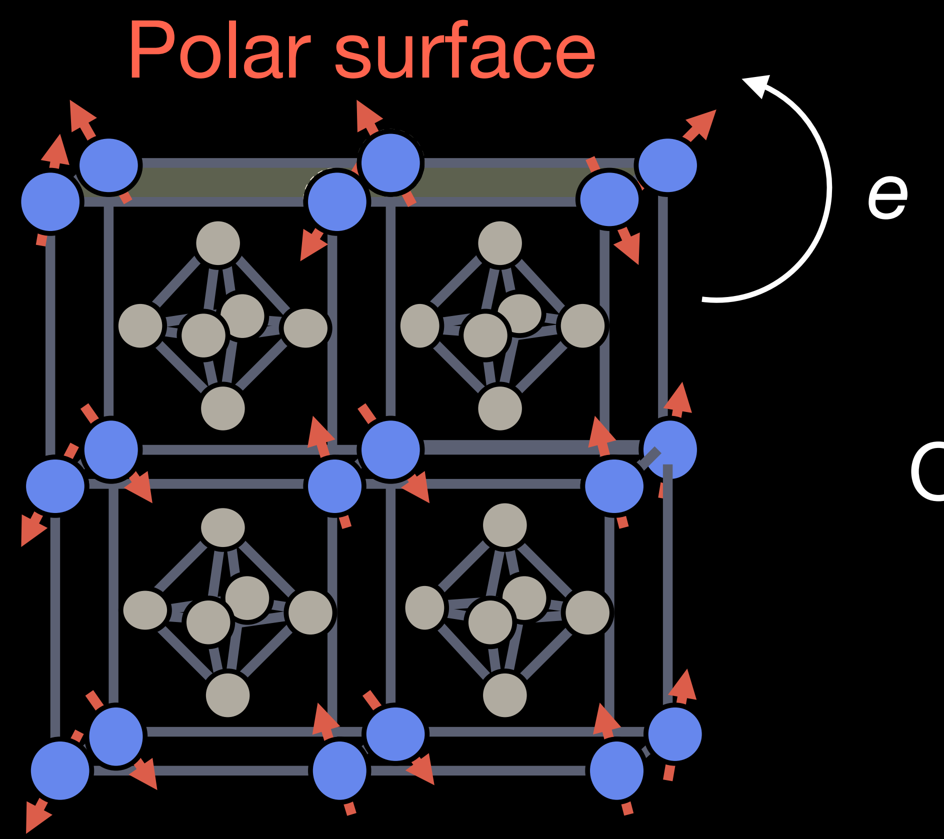

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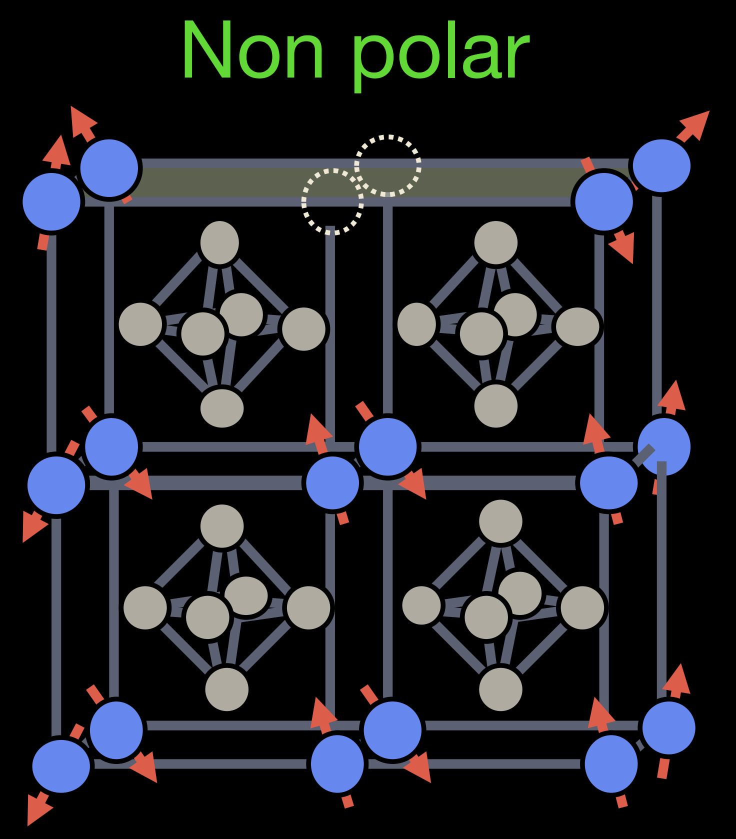
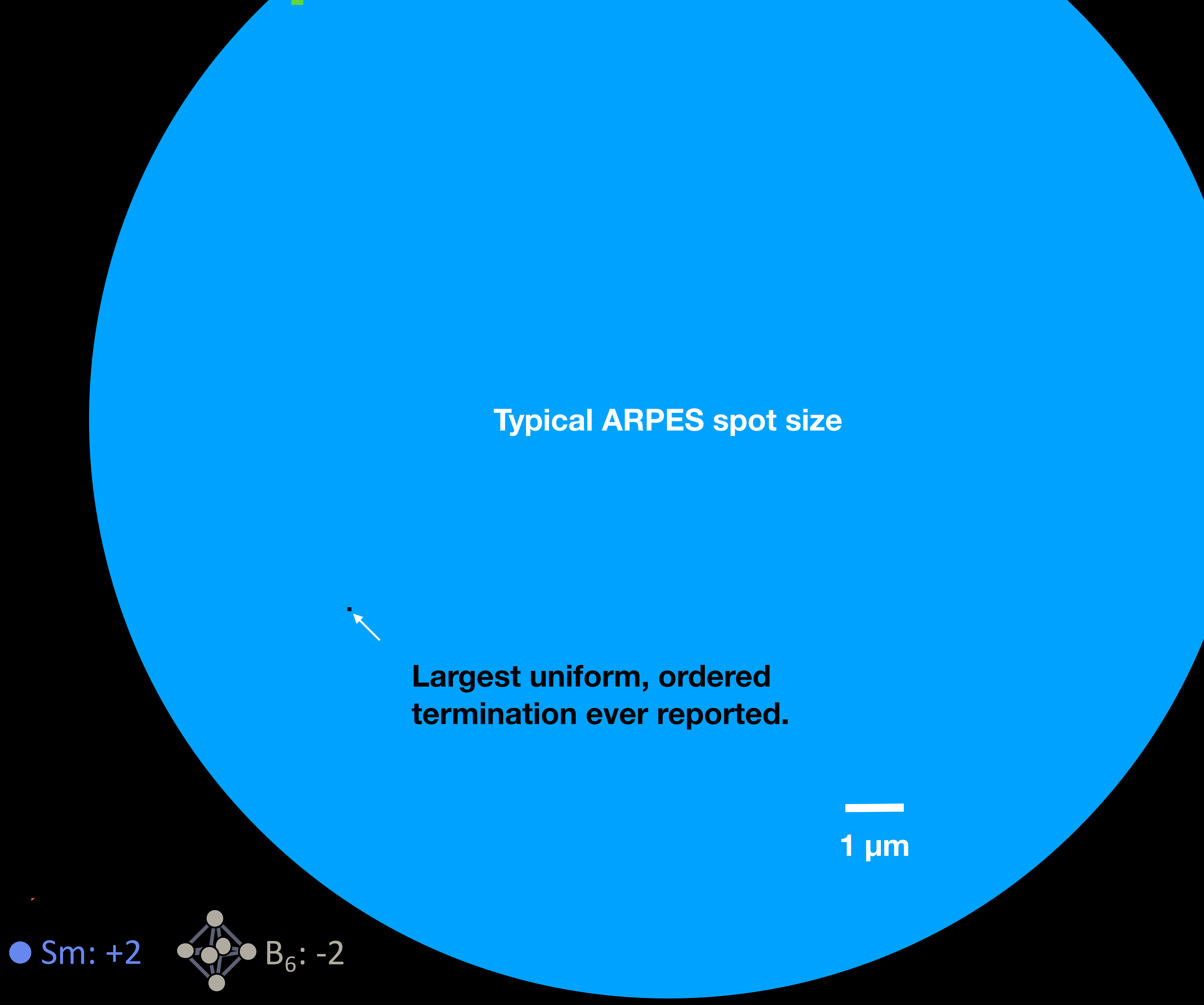
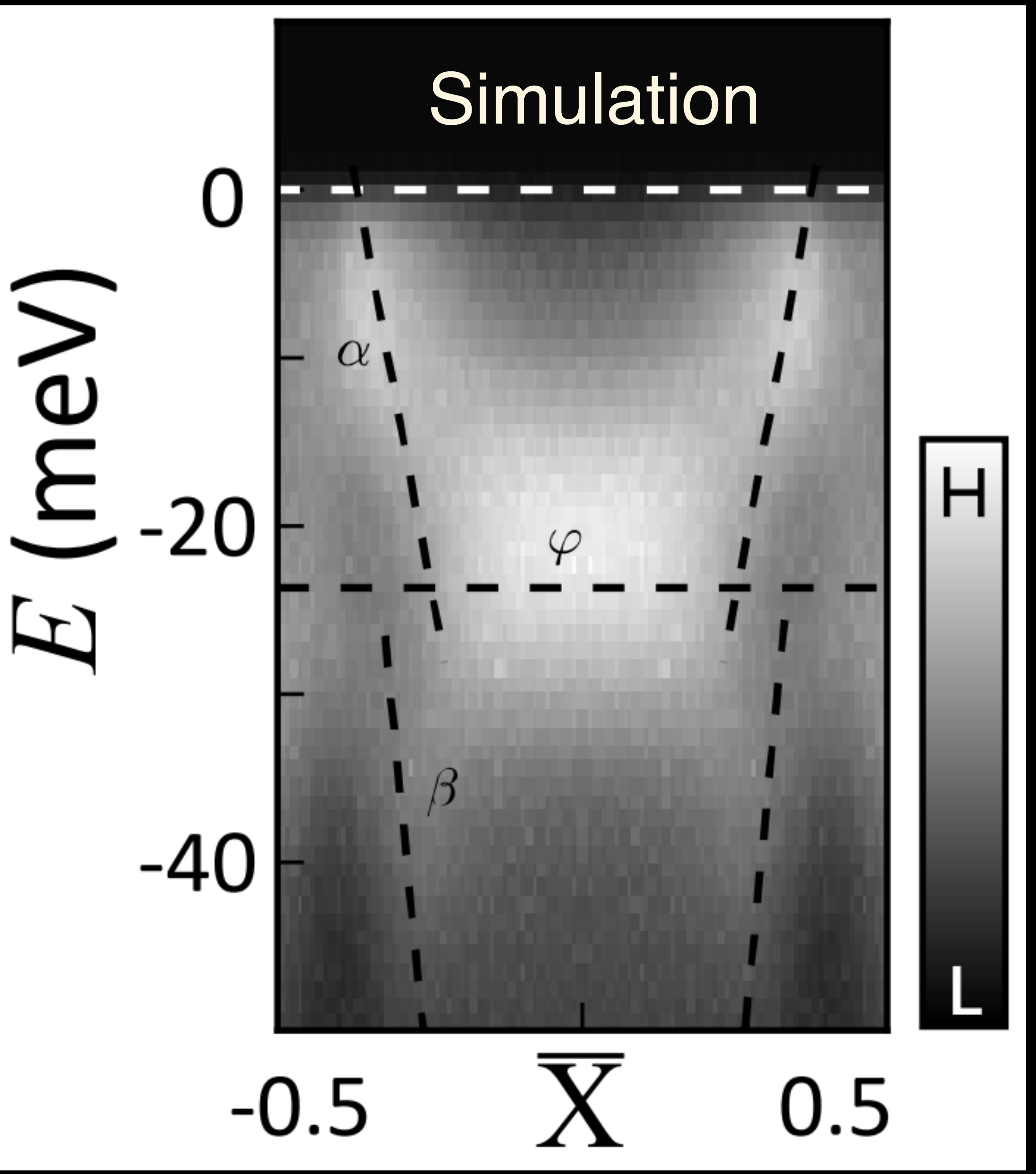
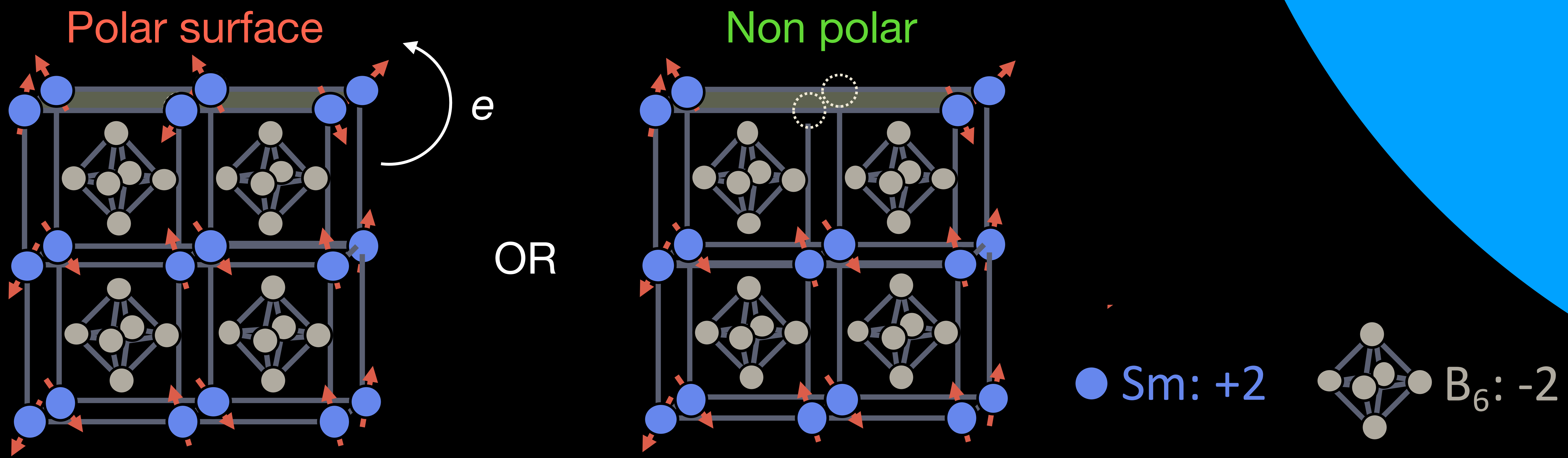


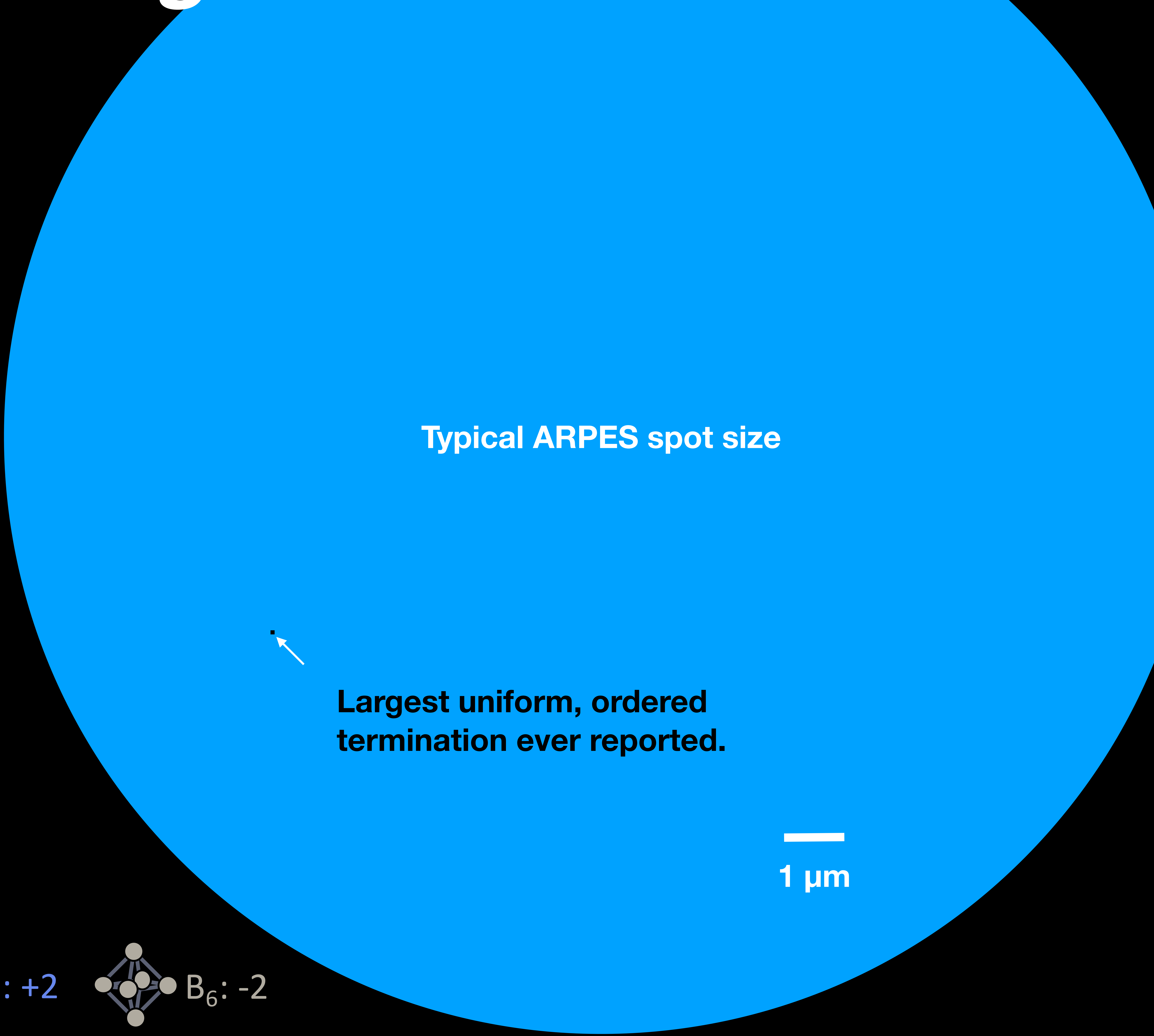


Simulated APRES has *light* surface states



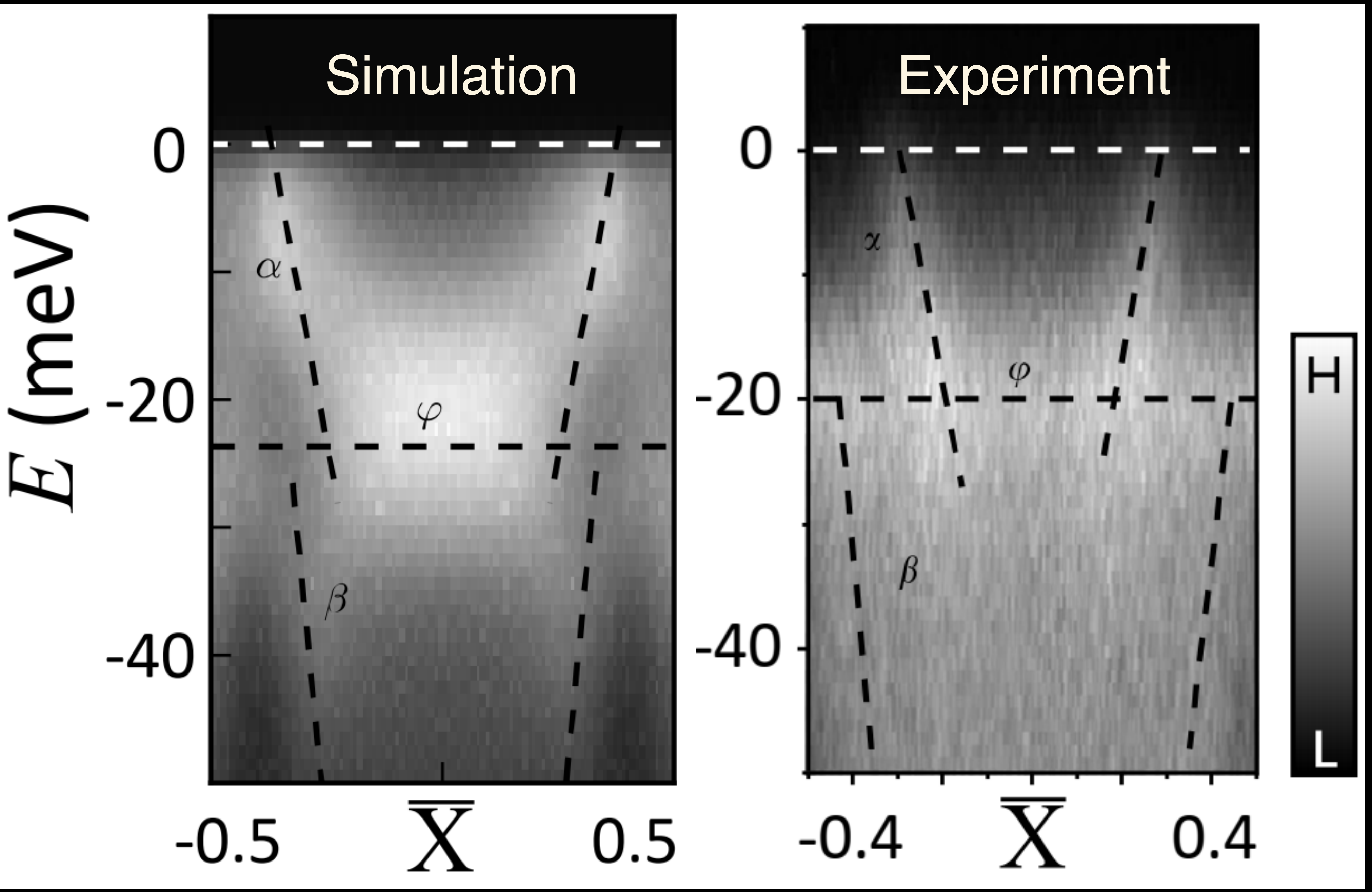
Matt et al., *Phys. Rev. B* **101**, 085142 (2020)





ARPES consistent with polar surfaces

Jiang et al., *Nat. Commun.* **4**, 3010 (2013)



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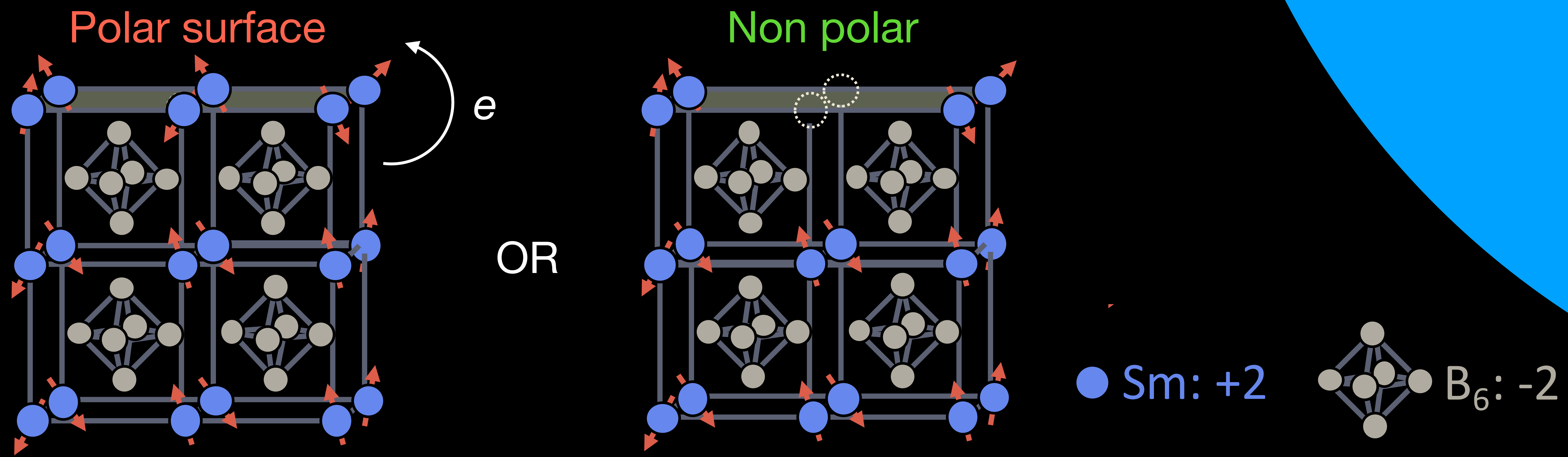
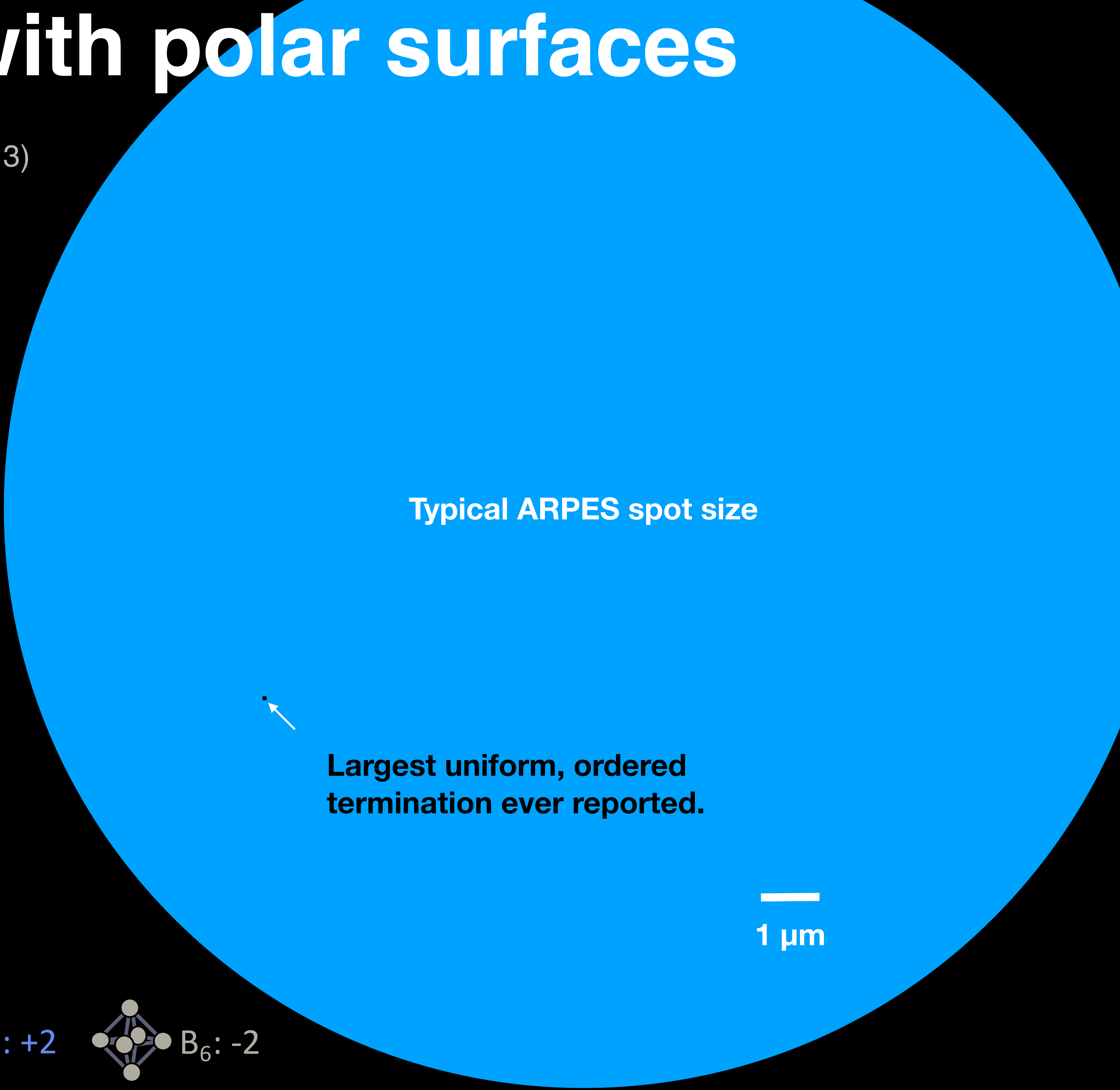




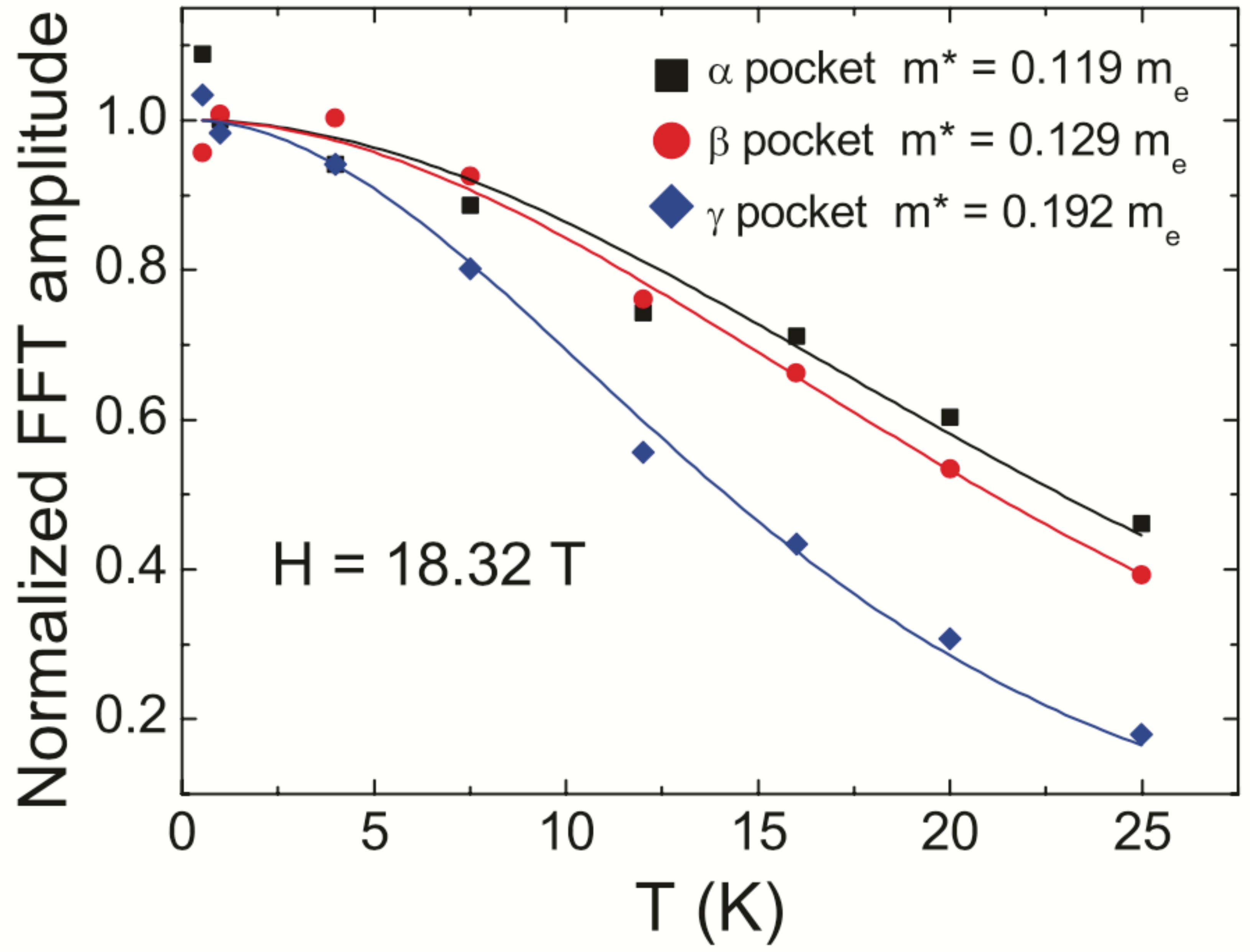
dHvA measures *light* Dirac fermions?

Li et al., *Science.* **346**, 1208 (2014)

HEAVY FERMIONS

Two-dimensional Fermi surfaces in Kondo insulator SmB_6

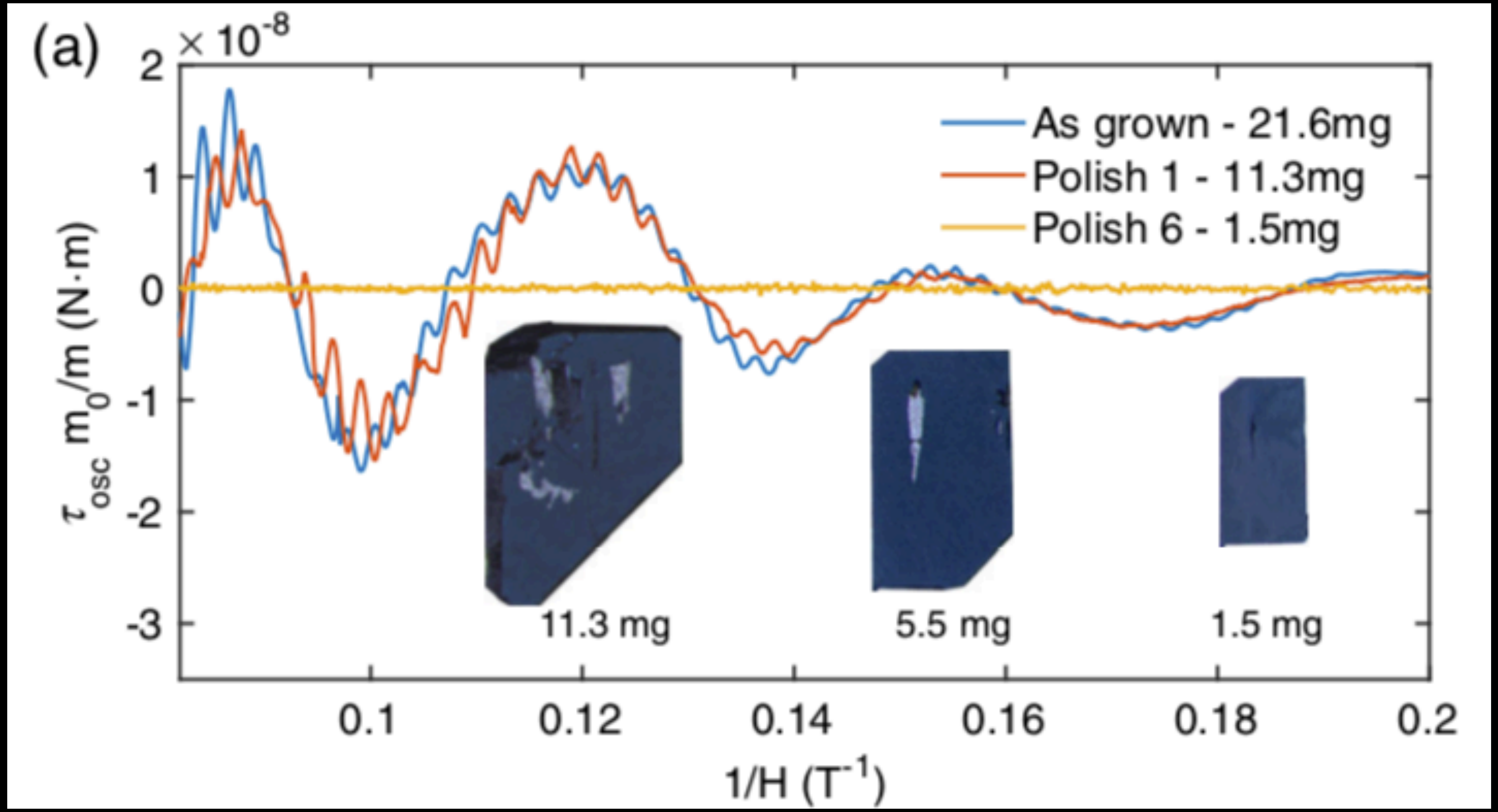
G. Li,[1] Z. Xiang,[1,2] F. Yu,[1] T. Asaba,[1] B. Lawson,[1] P. Cai,[1,3] C. Tinsman,[1] A. Berkley,[1] S. Wolgast,[1] Y. S. Eo,[1] Dae-Jeong Kim,[4] C. Kurdak,[1] J. W. Allen,[1] K. Sun,[1] X. H. Chen,[2] Y. Y. Wang,[3] Z. Fisk,[4] Lu Li[1]*



dHvA measures aluminum inclusions?

This SmB_6 is grown with **aluminum flux**

Thomas et al., *Phys. Rev. Lett.* **122**, 166401 (2019)



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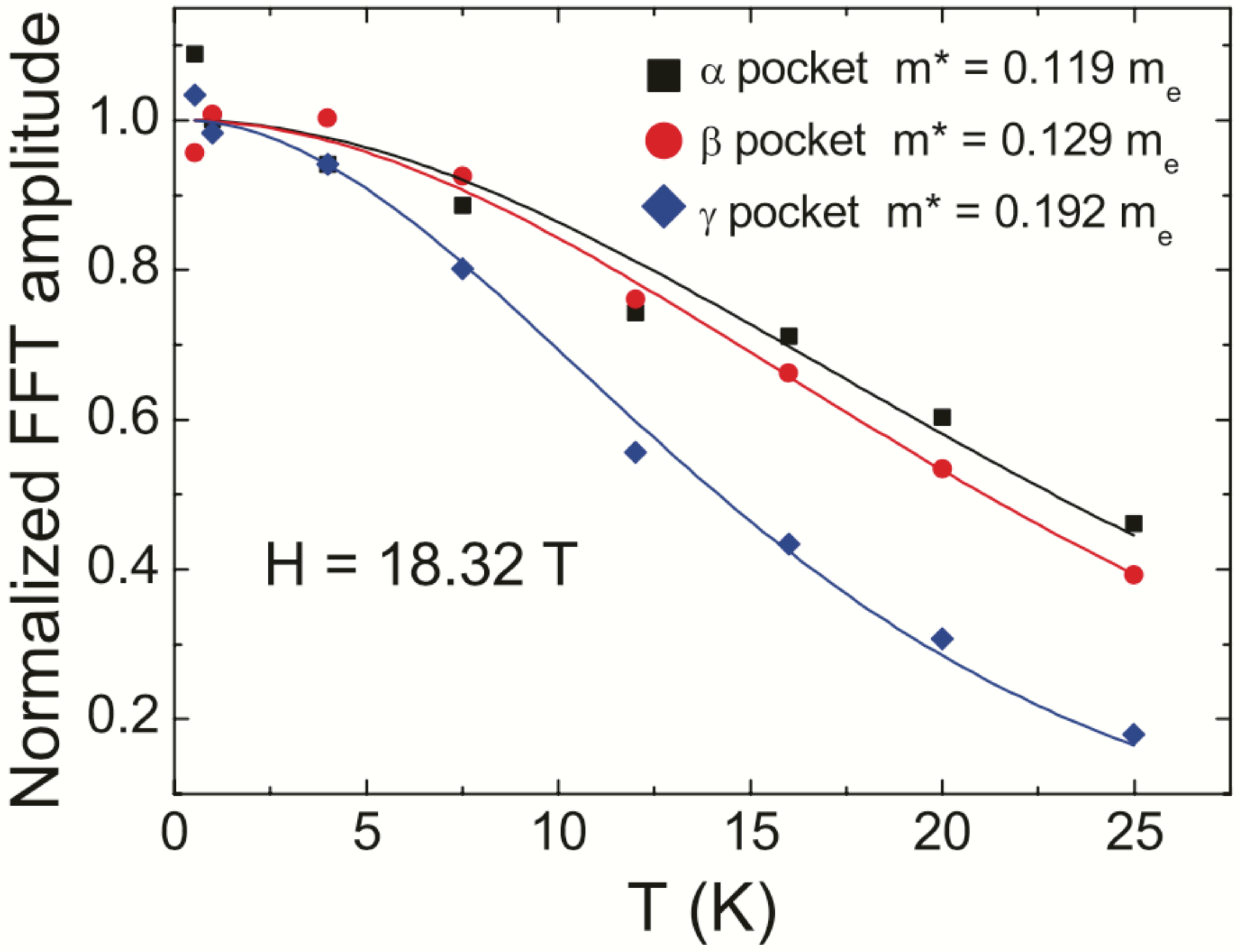
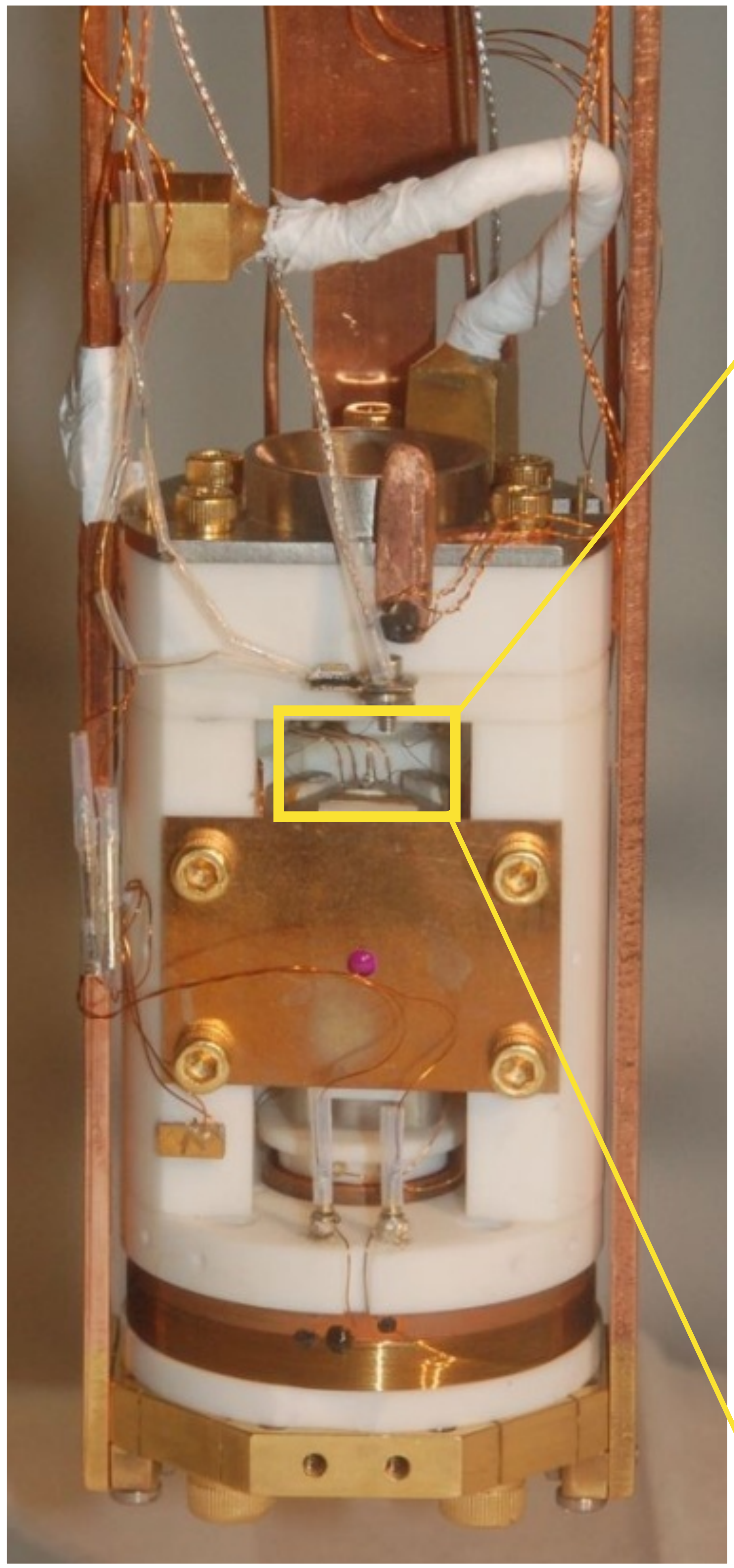
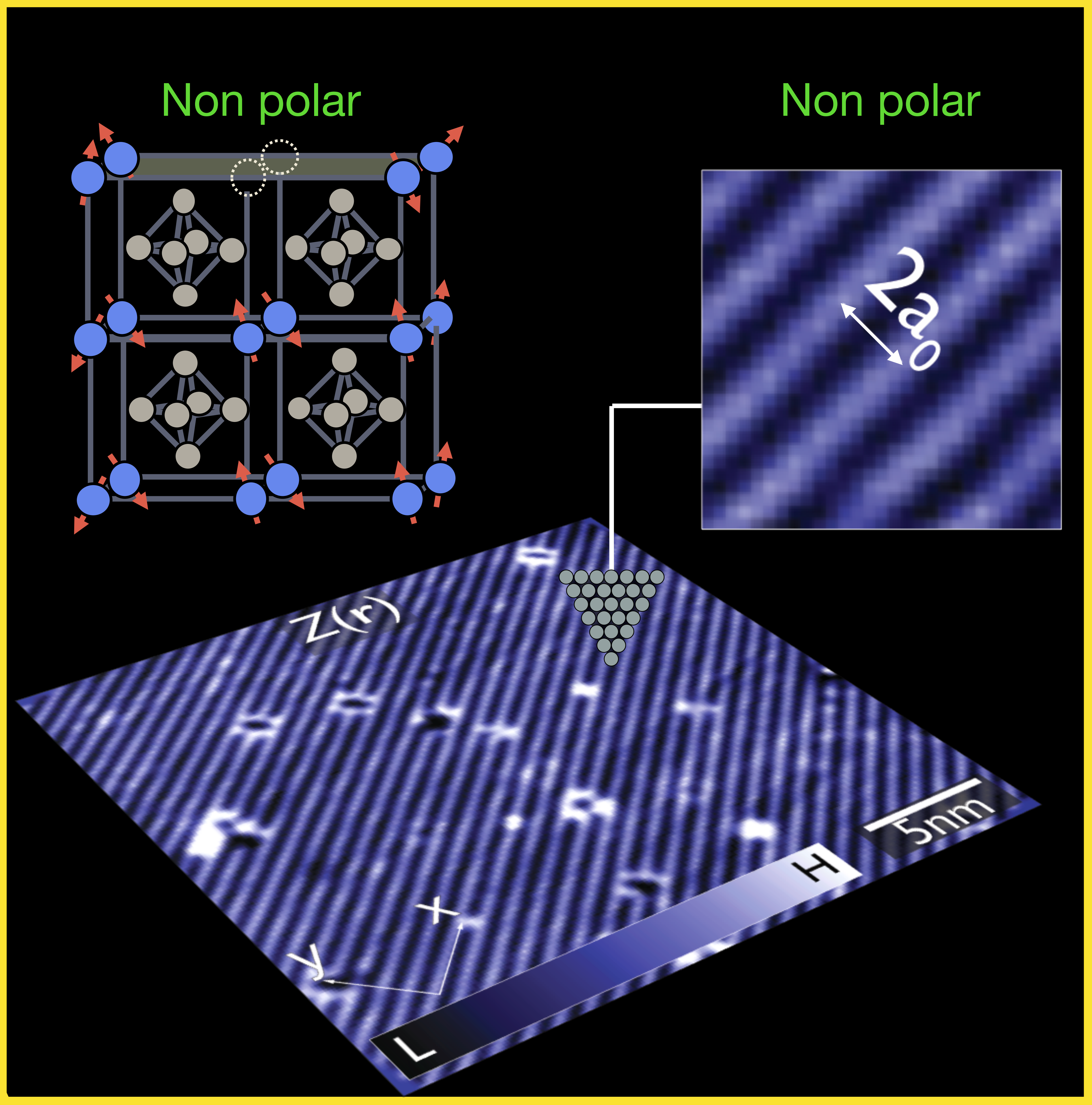


Requirements to image heavy Dirac states

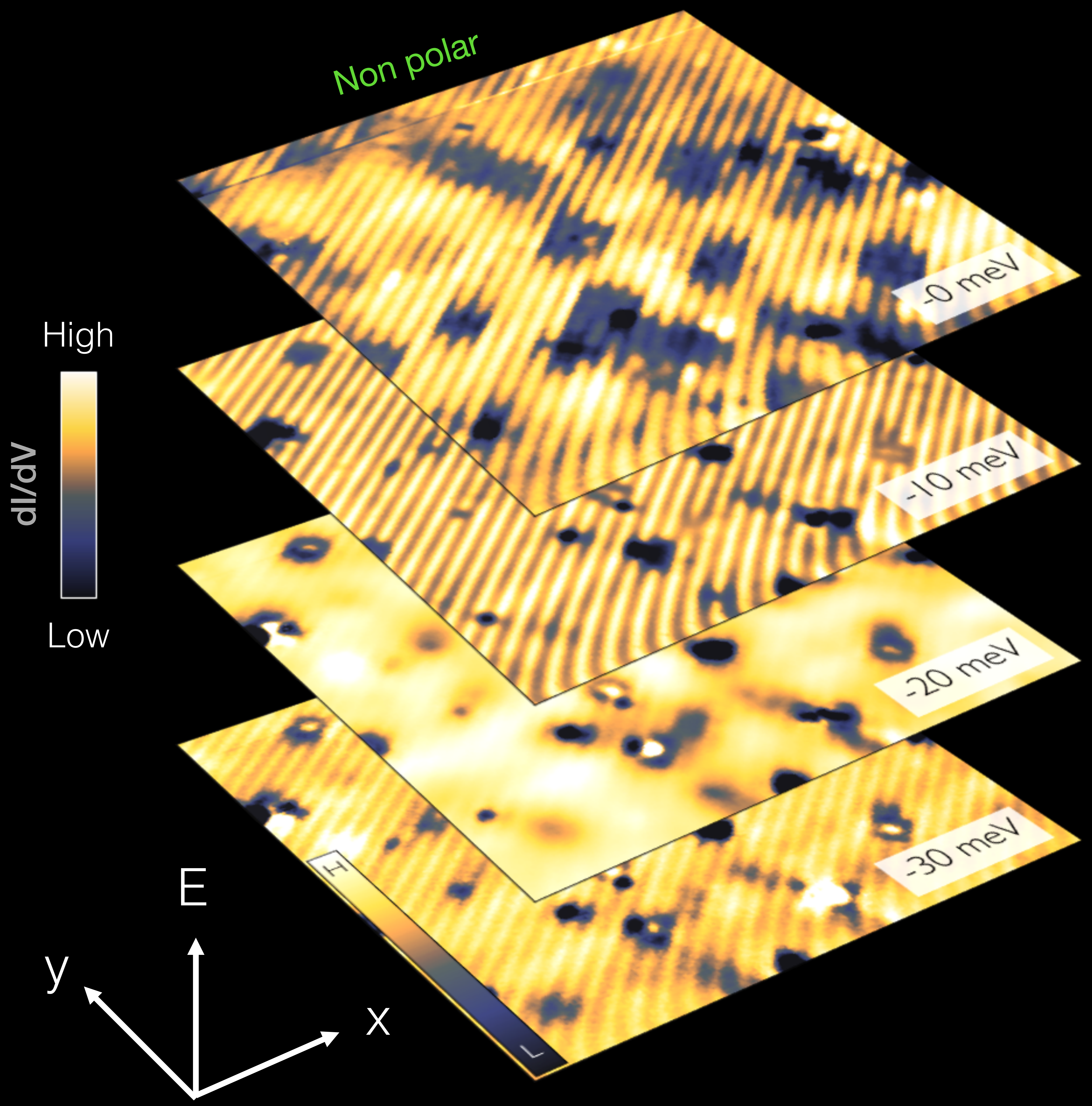
- Small polar and non-polar terminations
  → Need **nanometer** spatial resolution
- Gap and most of the surface state is above E_F
  → Need to access both **filled & empty** states
- Heavy fermion bands are extremely flat
  → Need **sub-meV** energy resolution
- Heavy fermions are deeply entangled
  → Need **real & momentum** space imaging

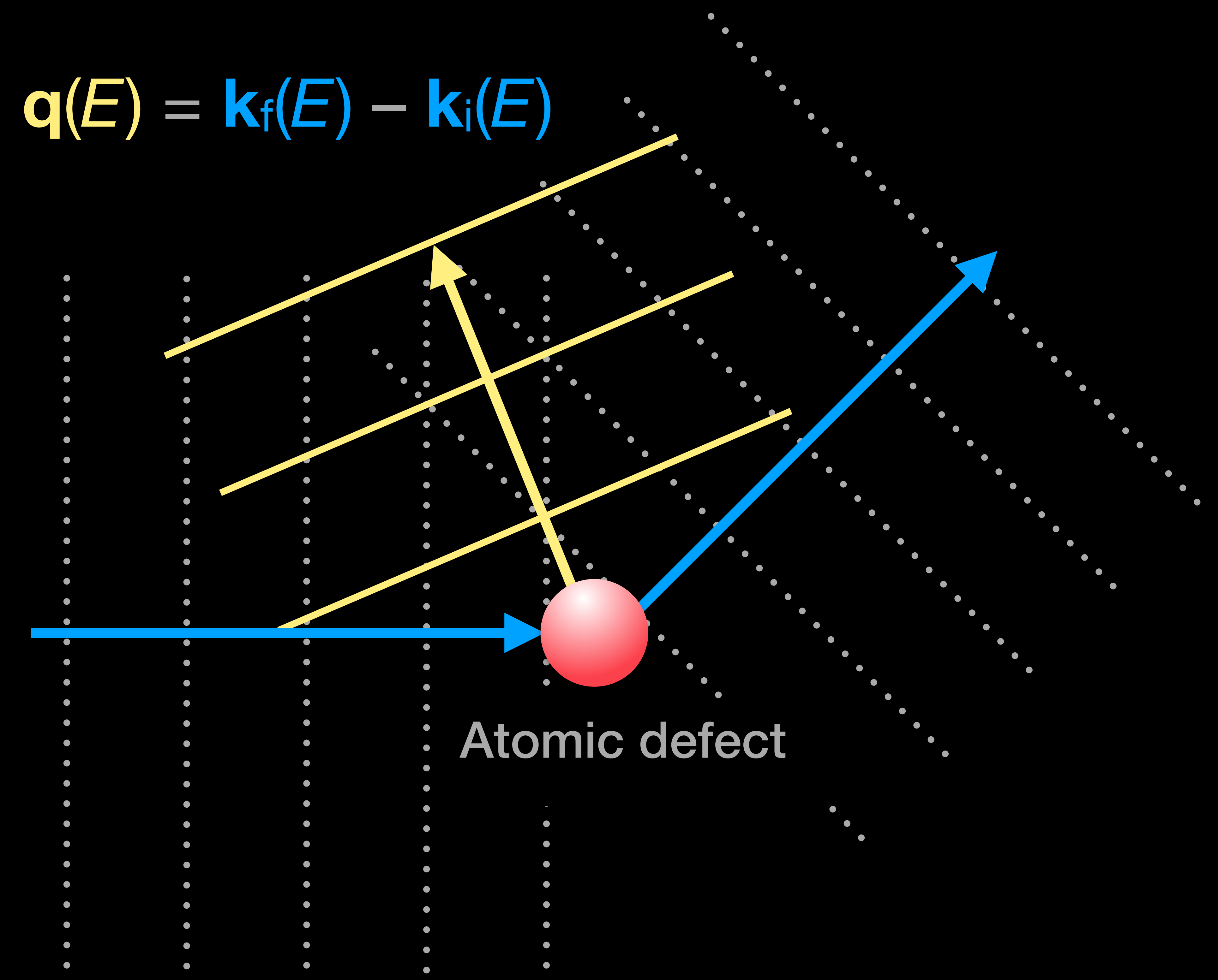


Scanning tunneling microscopy



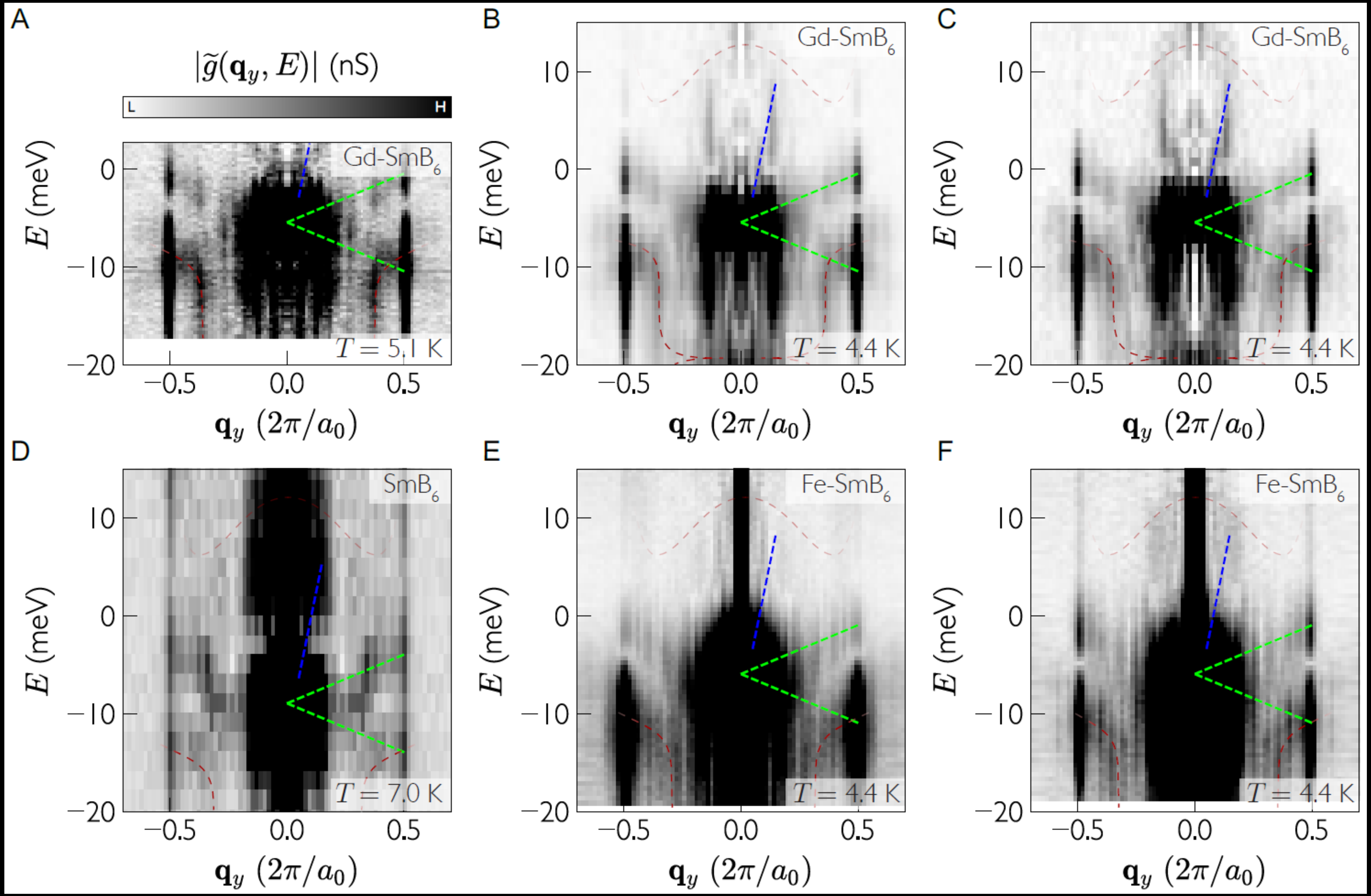
Quasiparticle interference reveals *E* (k)





Heavy Dirac states visible in raw data

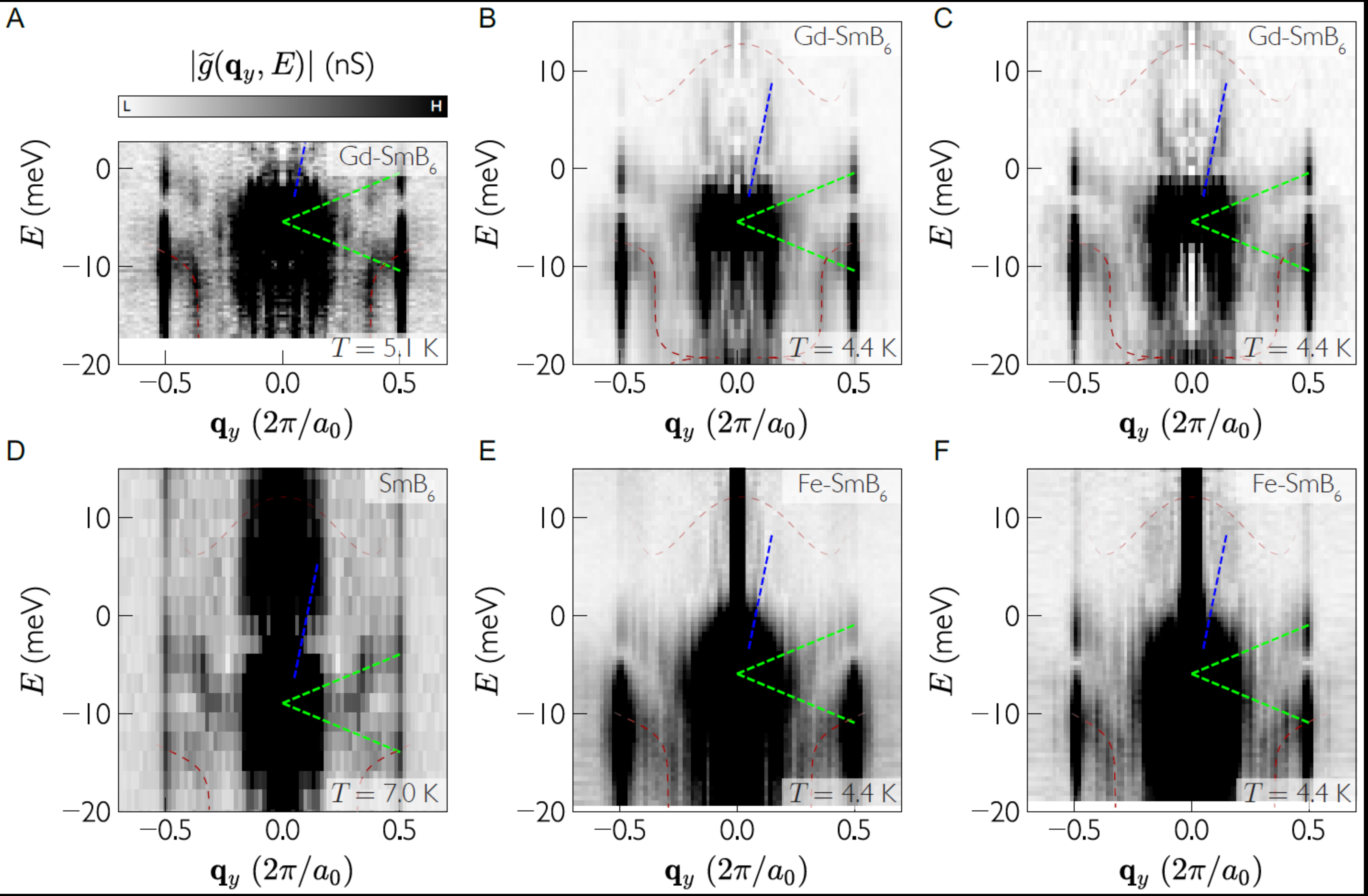
Pirie et al., *Nat. Phys.* **16**, 52 (2020)



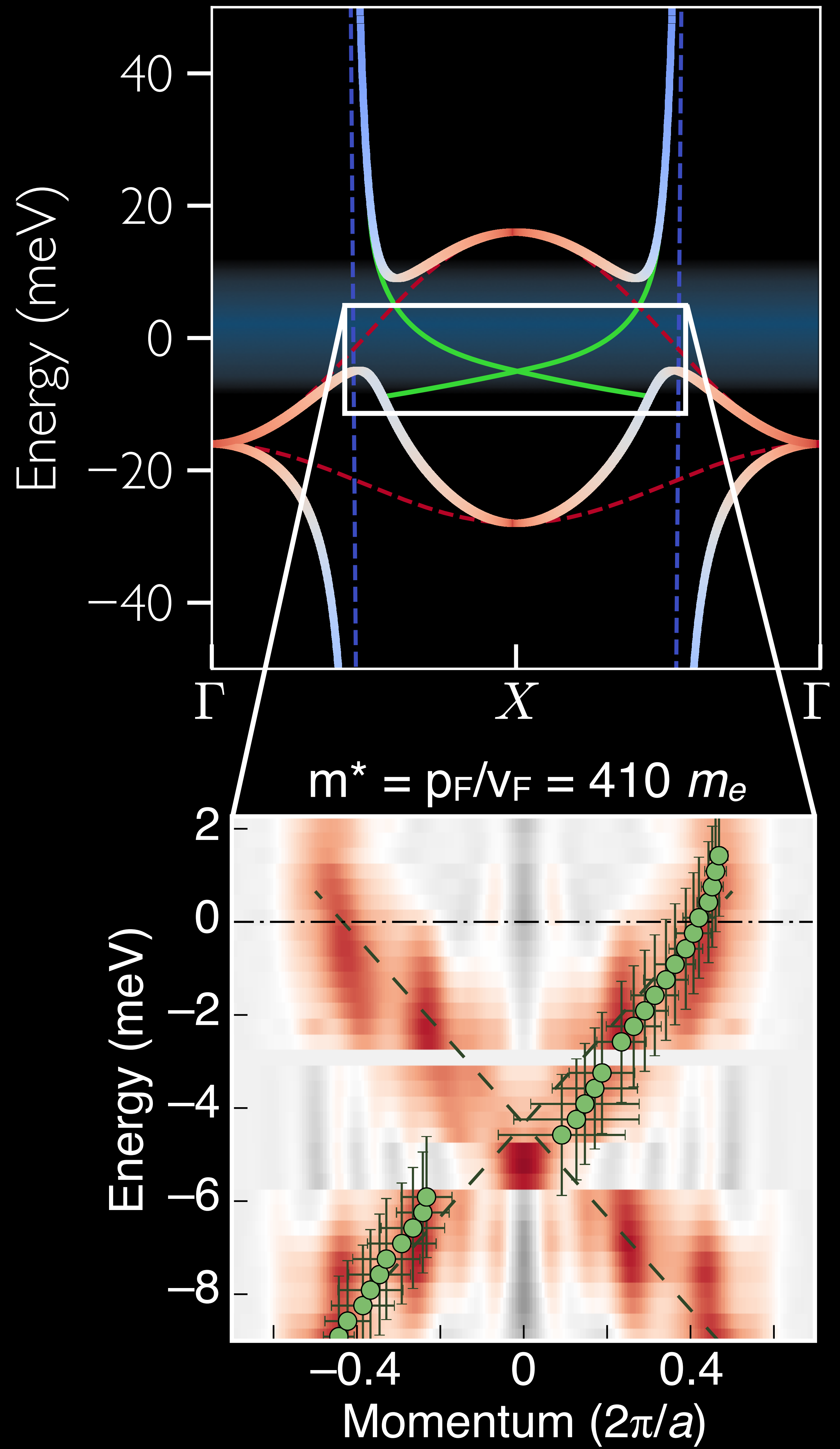
Heavy Dirac states visible in raw data

Pirie et al., *Nat. Phys.* **16**, 52 (2020)

Measured velocity: 7.6 ± 0.3 meV•Å



Predicted velocity: 16 meV•Å



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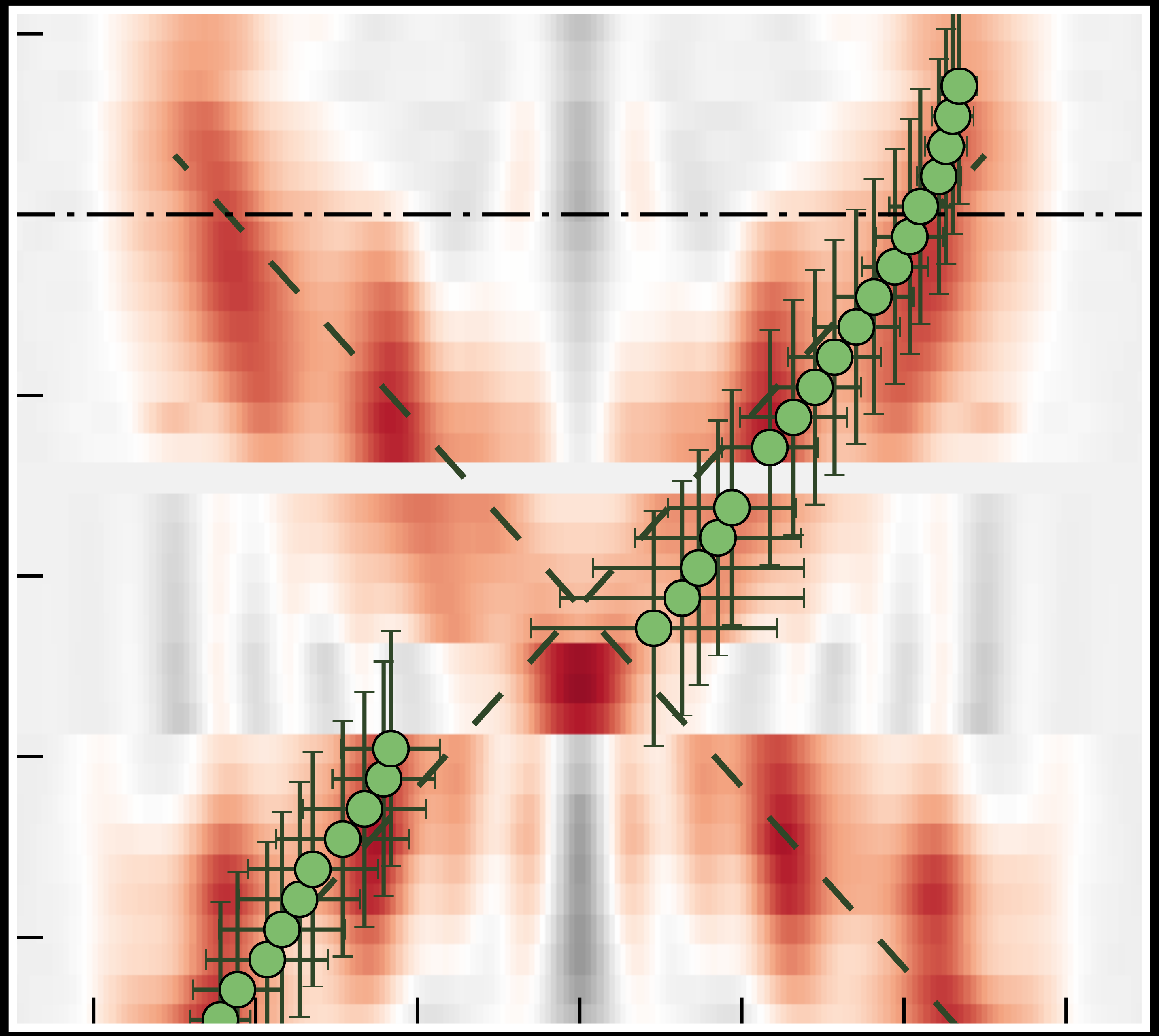
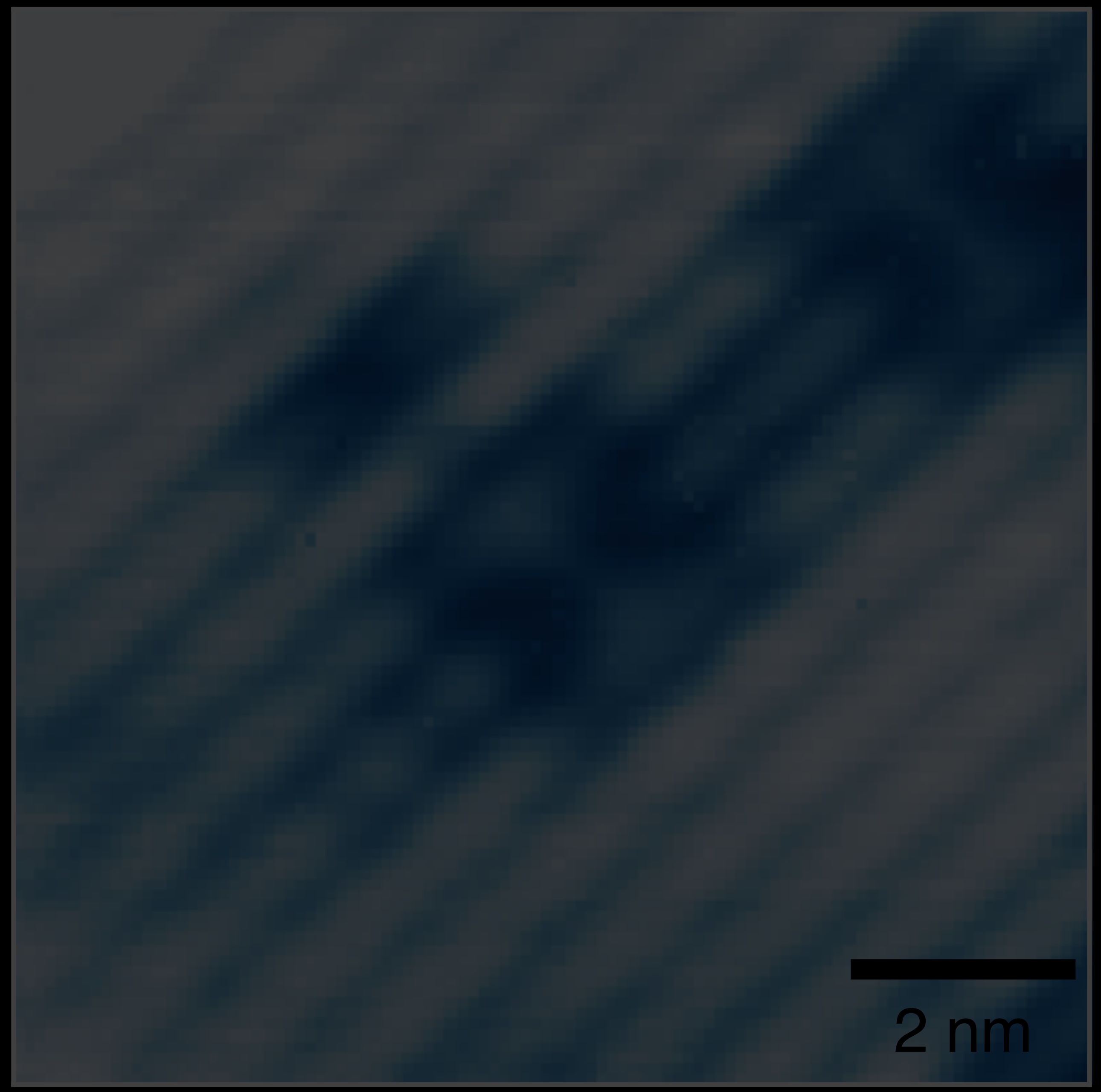


Pirie et al., *Nat. Phys.* **16**, 52 (2020)
Matt et al., *Phys. Rev. B* **101**, 085142 (2020)

(2) Metallicity in an **insulator**!



Pirie et al., *Science* **379**, 1214 (2023)

(3) Breakdown of **topological protection**!

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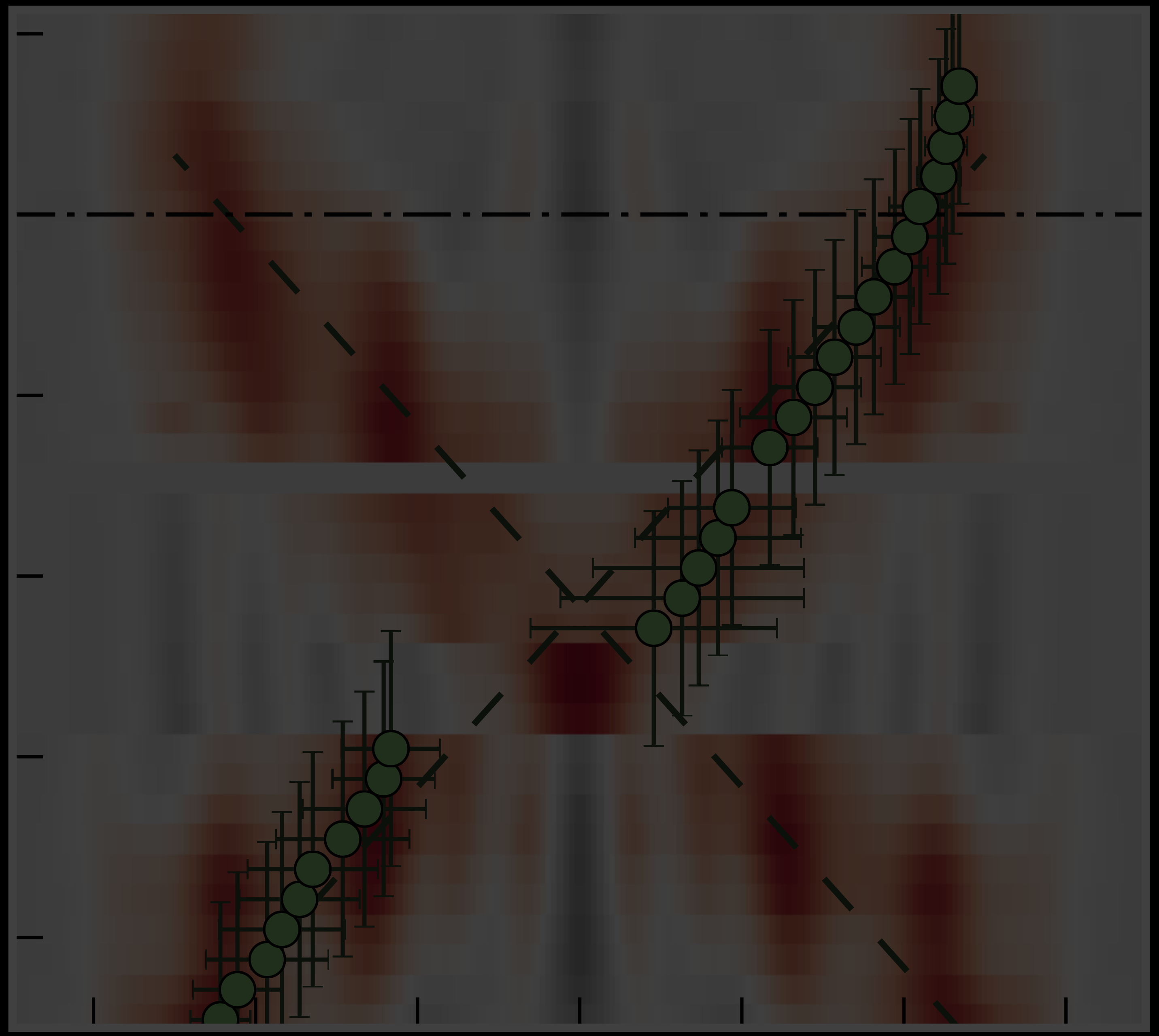

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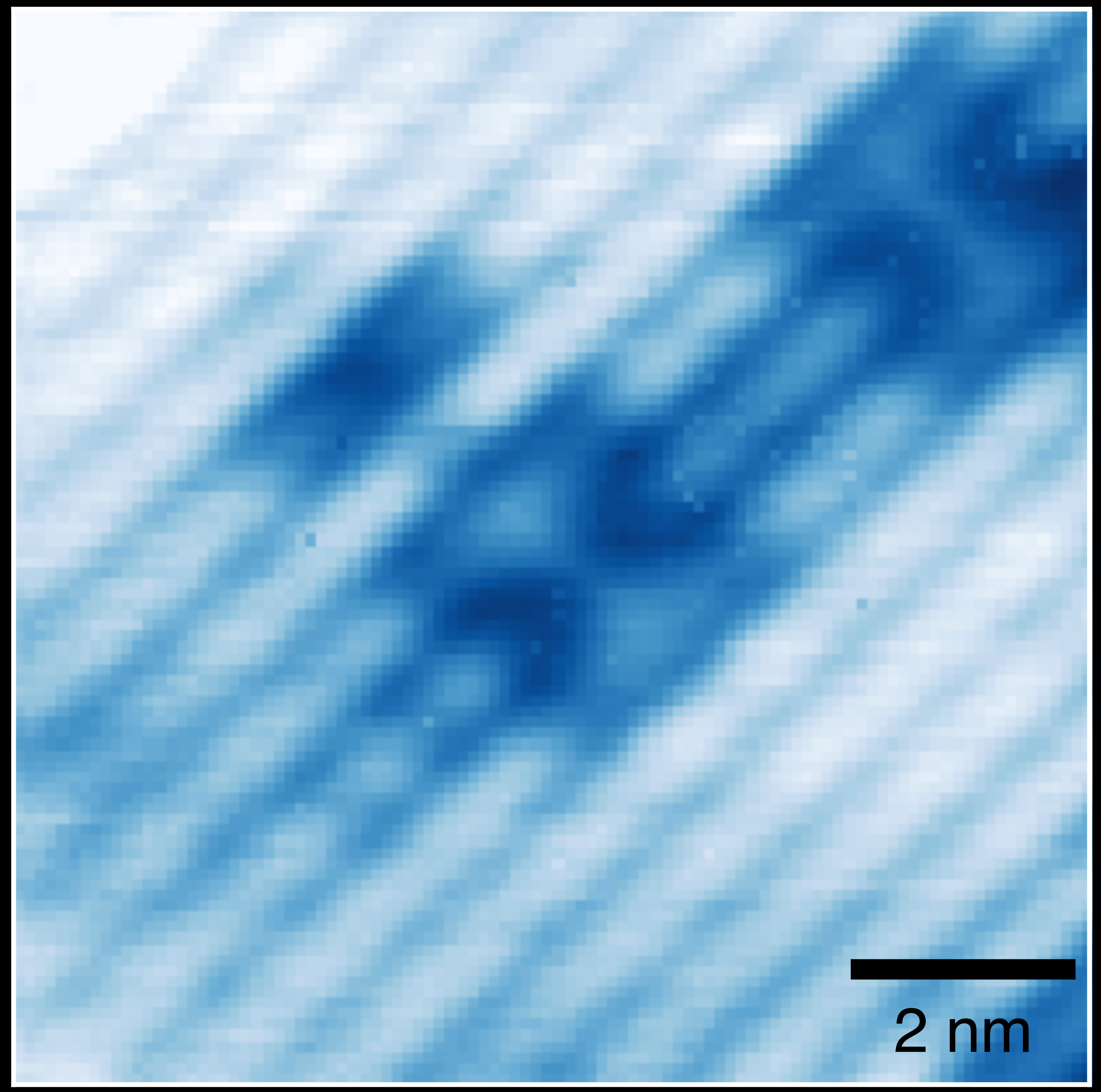

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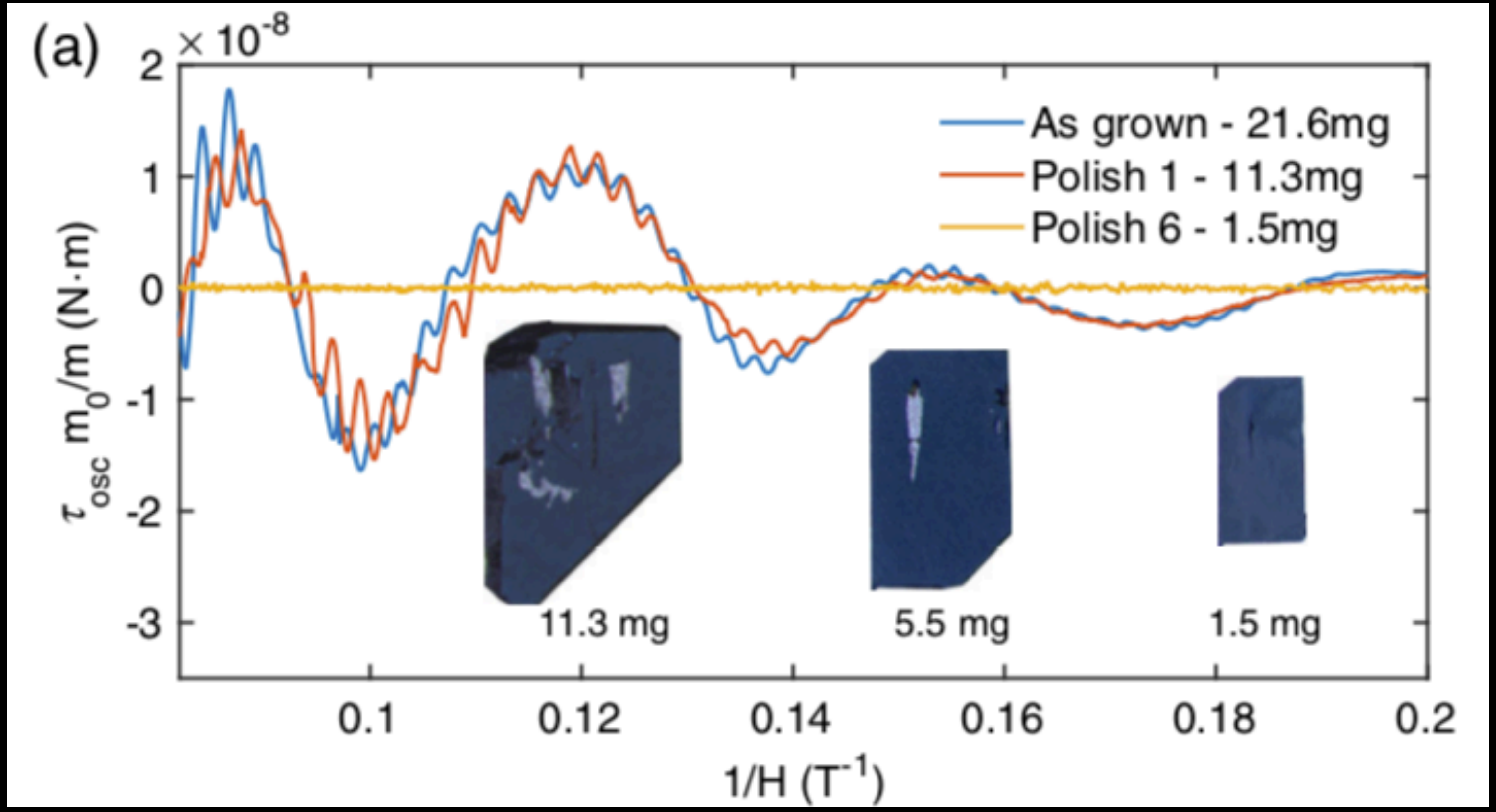
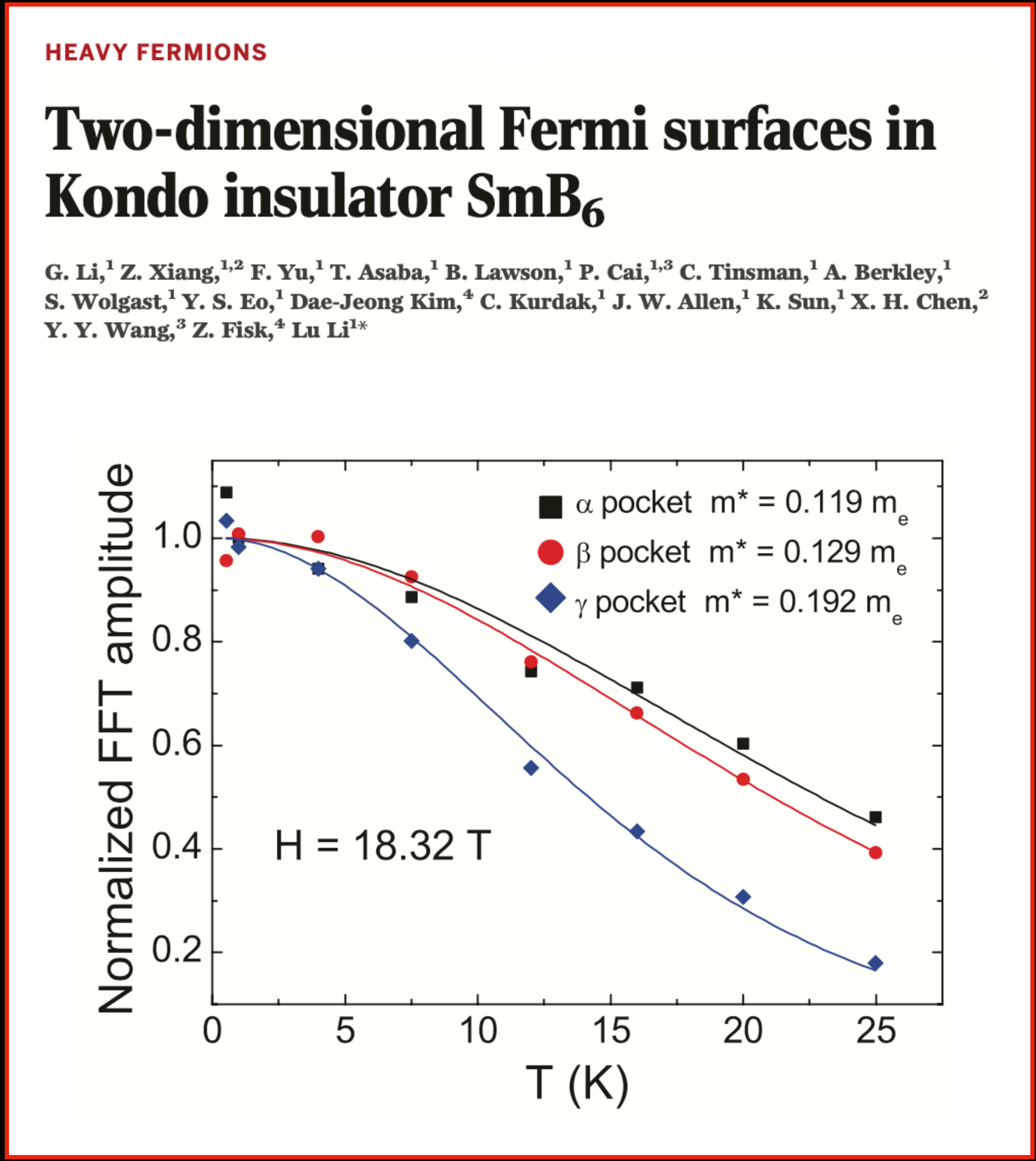


Li et al., *Science.* **346**, 1208 (2014)

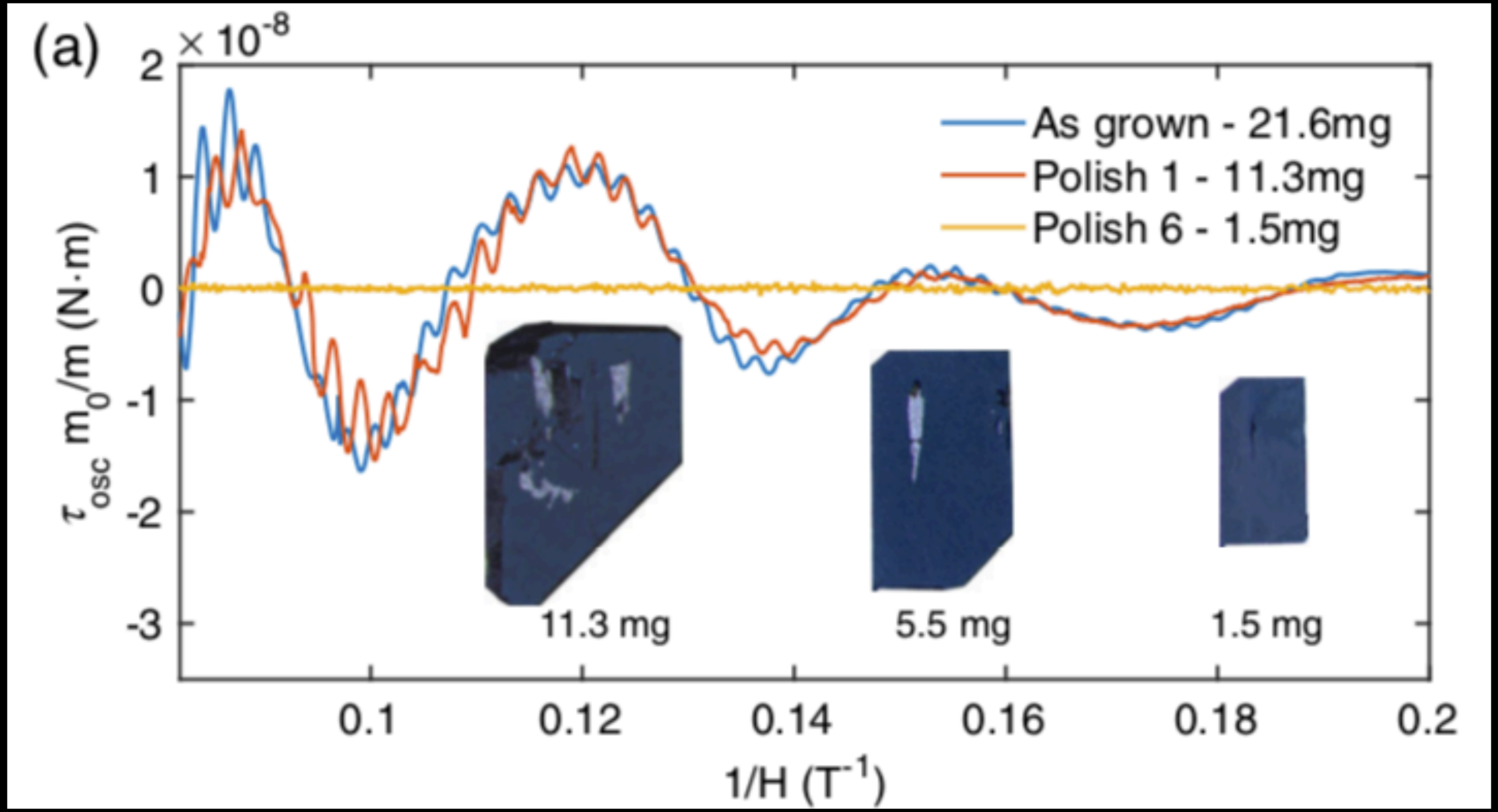


*This is only half of the story…

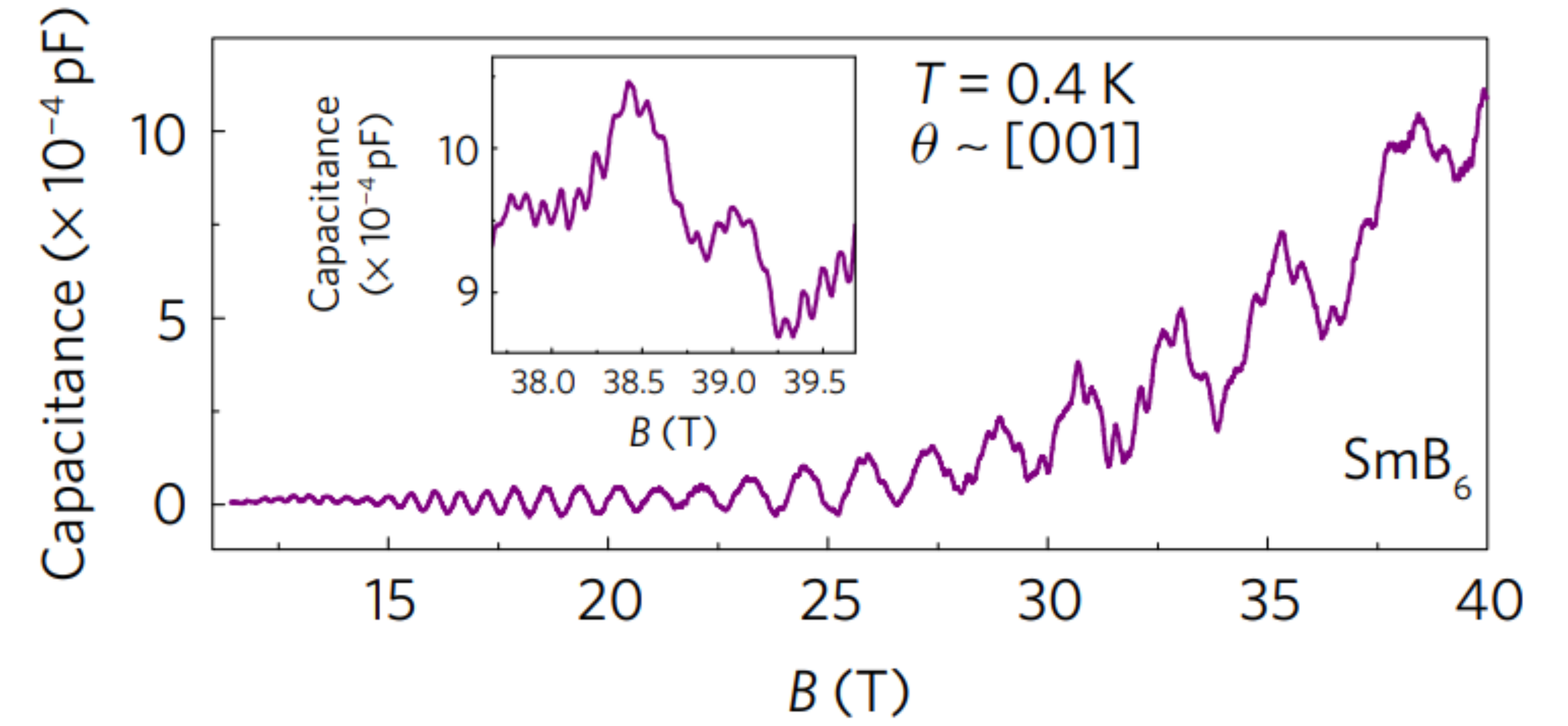
dHvA without aluminum inclusions!

Thomas et al., *Phys. Rev. Lett.* **122**, 166401 (2019)

This SmB_6 is grown with **aluminum flux**

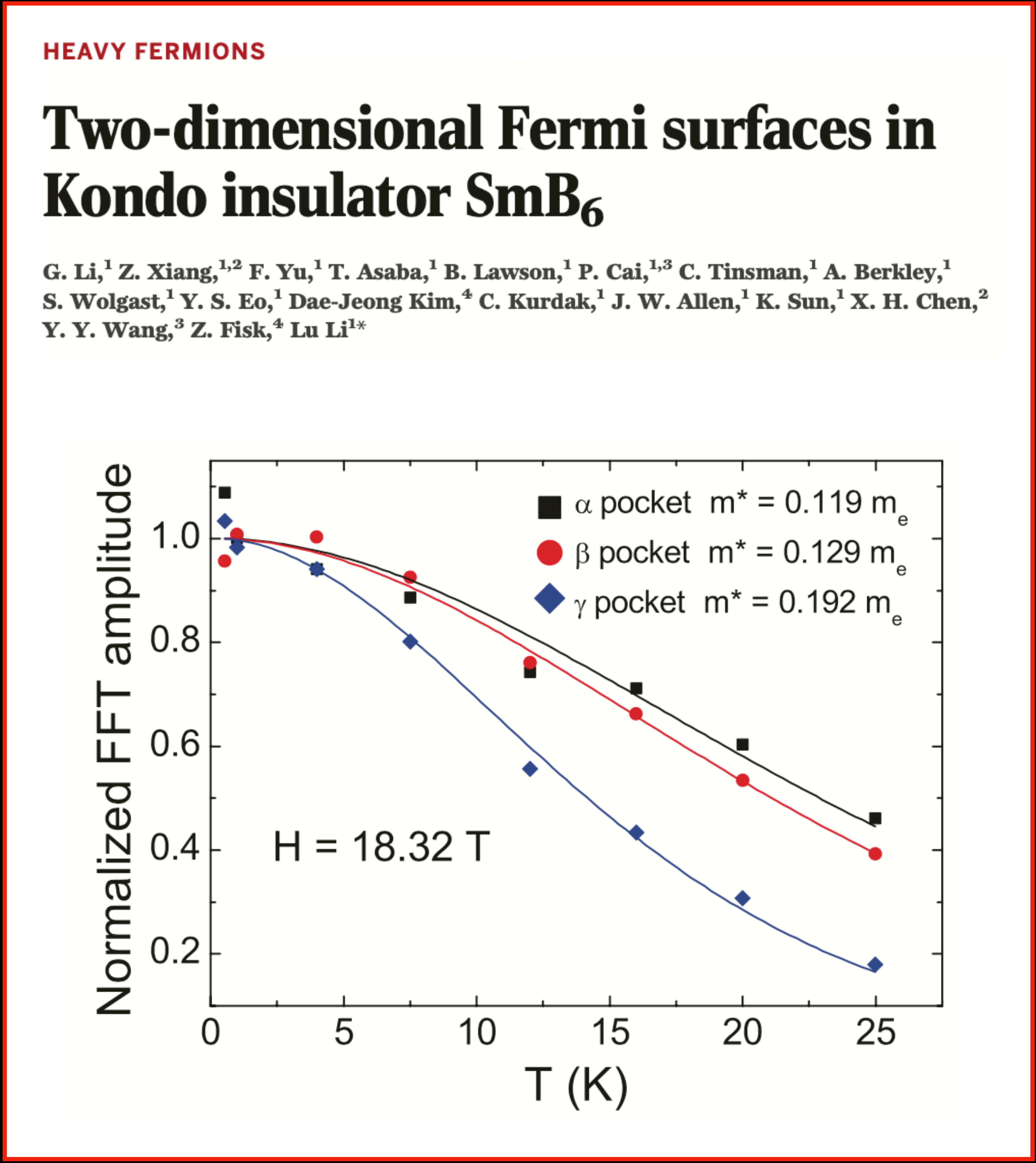


This SmB_6 is grown using **floating zone** technique (typically introduces ~0.1% Sm vacancies)



Tan et al., *Science* **349**, 287 (2015)   Hartstein et al., *Phys. Rev. Lett.* **14**, 166 (2018)

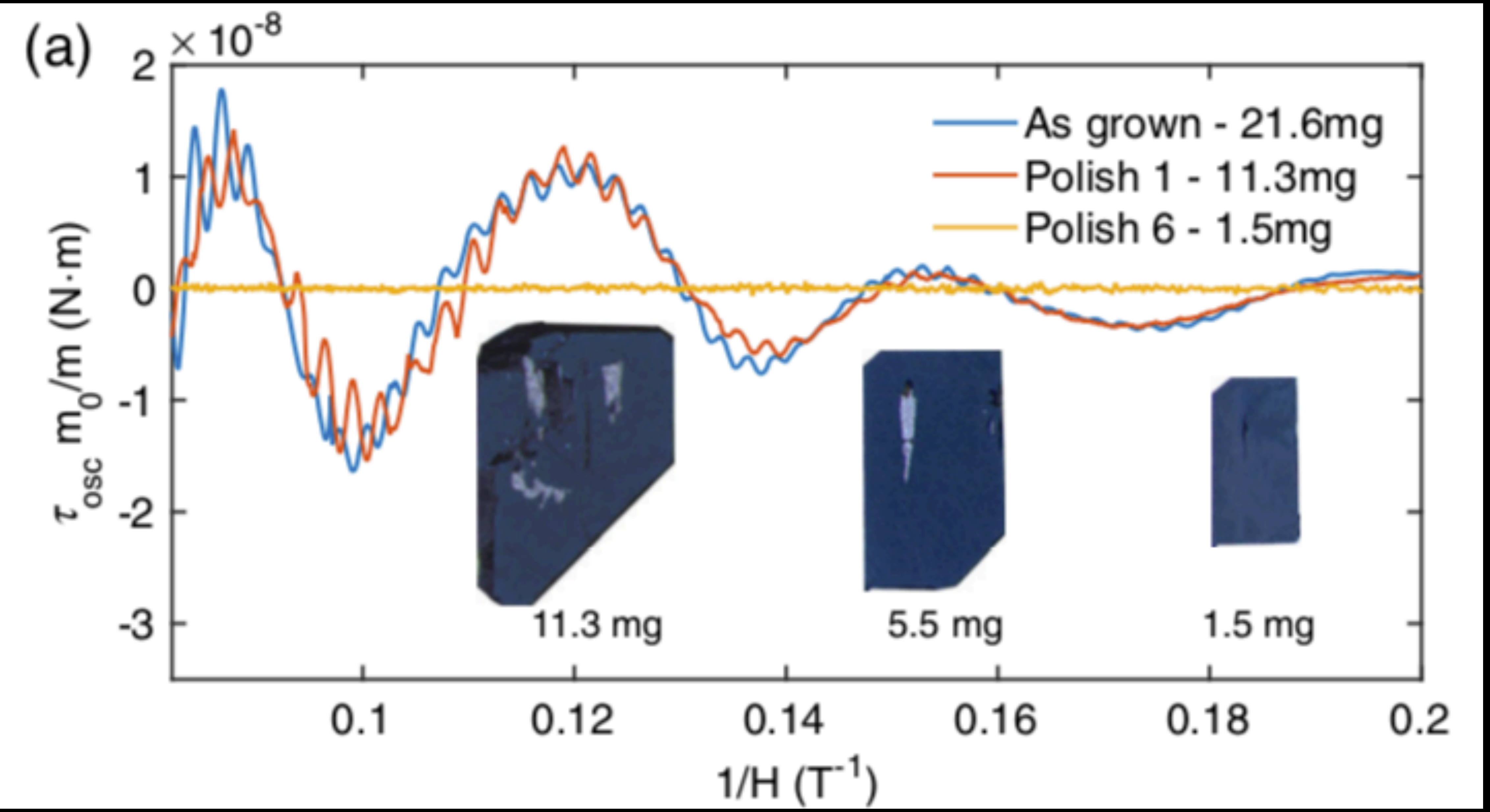
Li et al., *Science.* **346**, 1208 (2014)



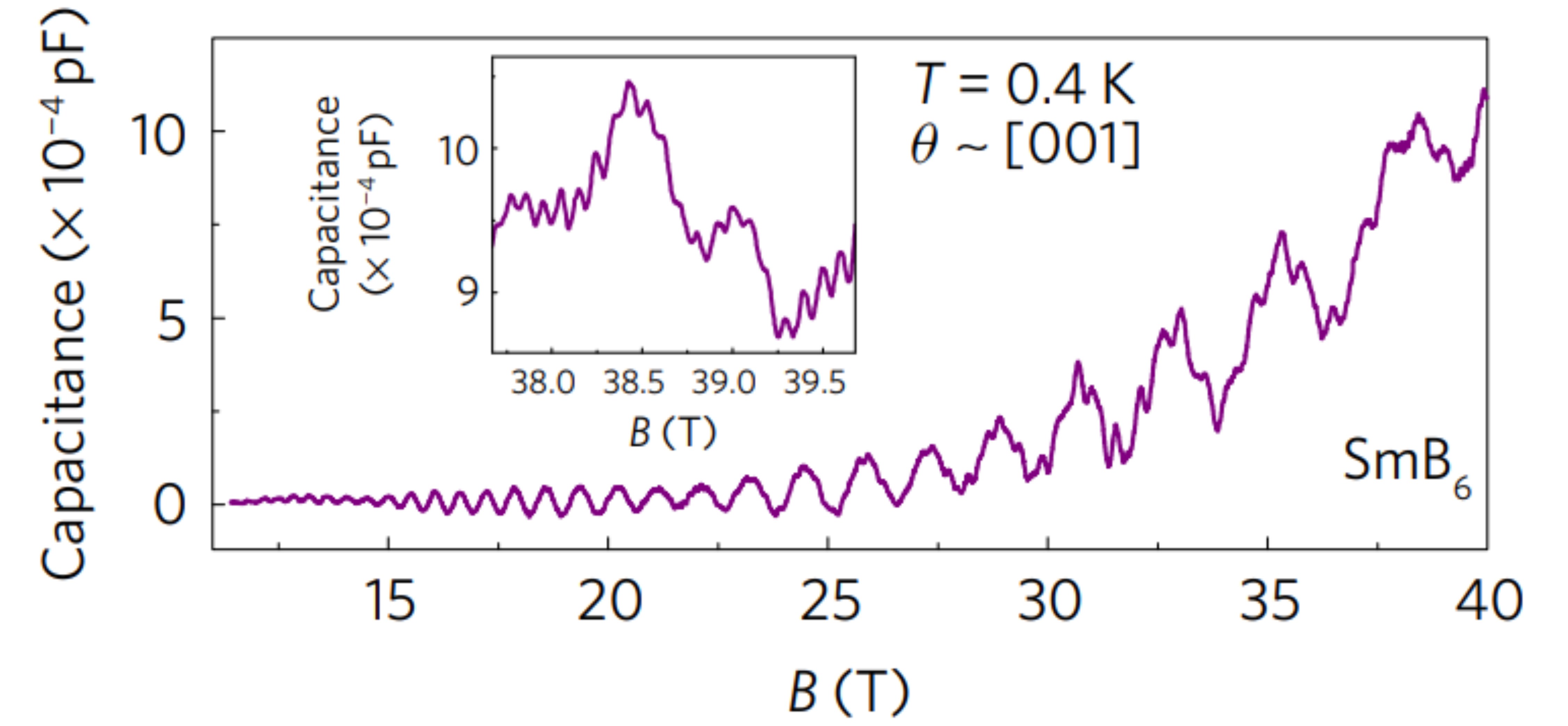
dHvA without aluminum inclusions!

Thomas et al., *Phys. Rev. Lett.* **122**, 166401 (2019)

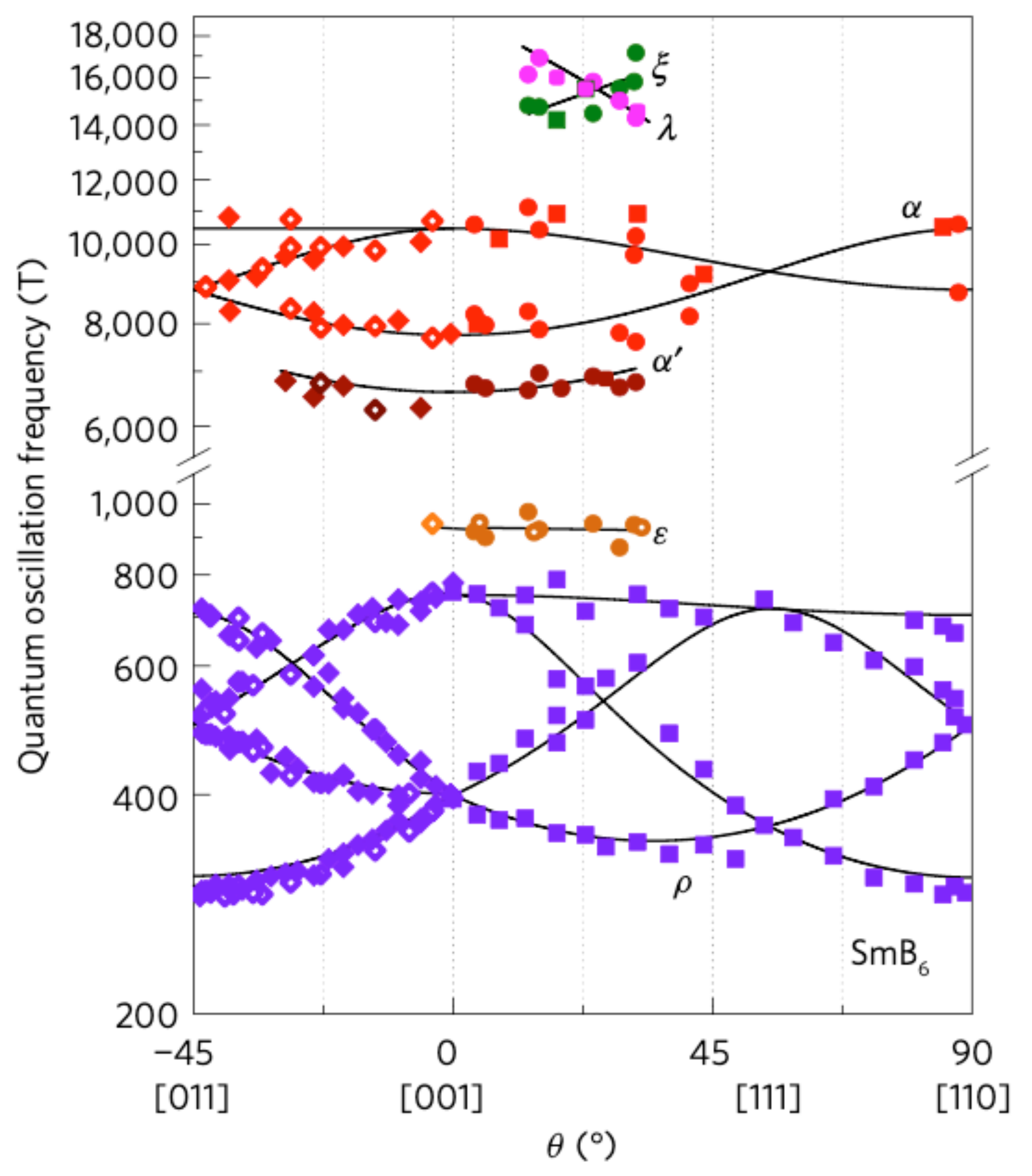
This SmB_6 is grown with **aluminum flux**



This SmB_6 is grown using **floating zone** technique (typically introduces ~0.1% Sm vacancies)



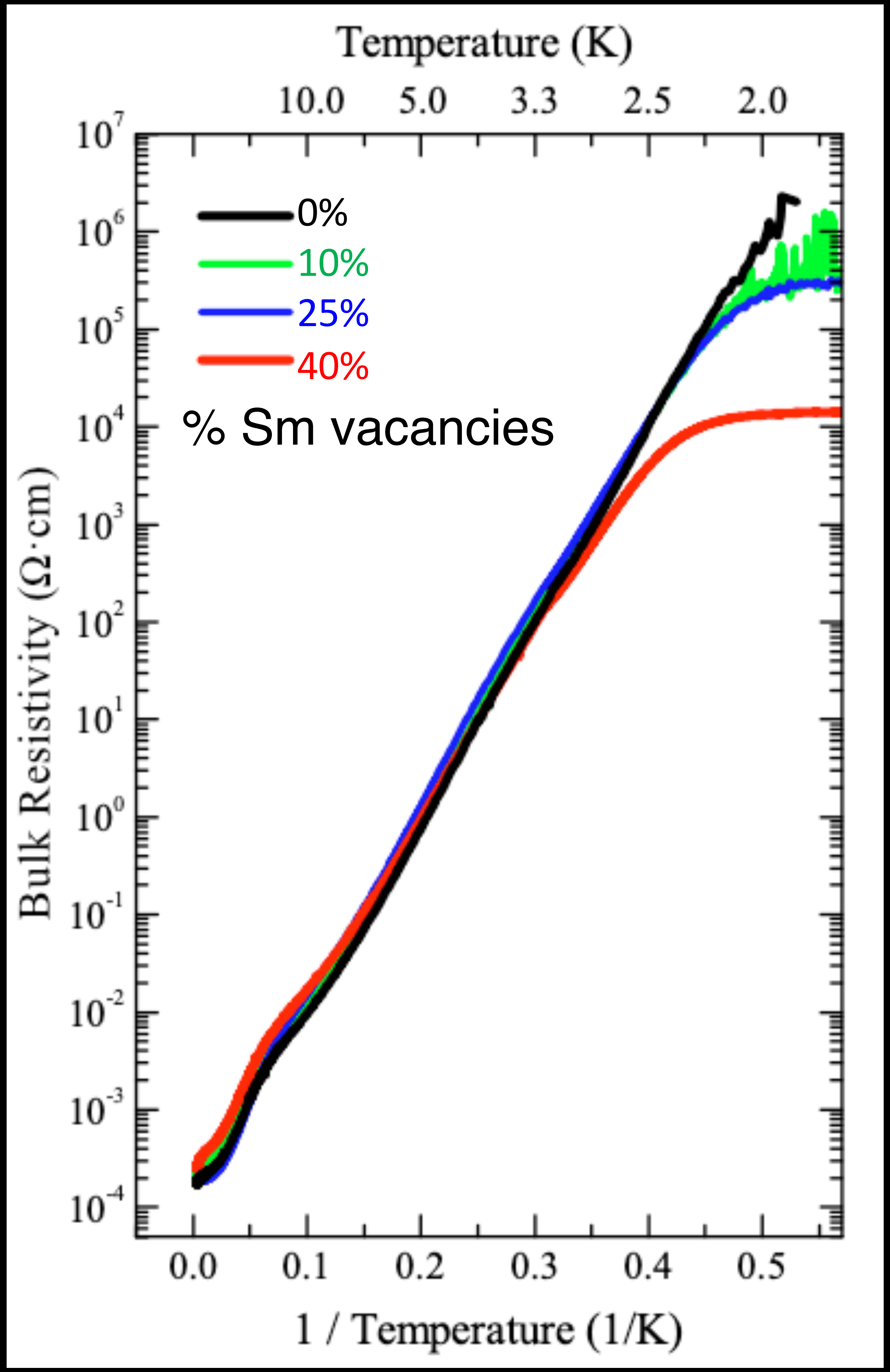
Angular dependence of dHvA implies a **3D Fermi surface**



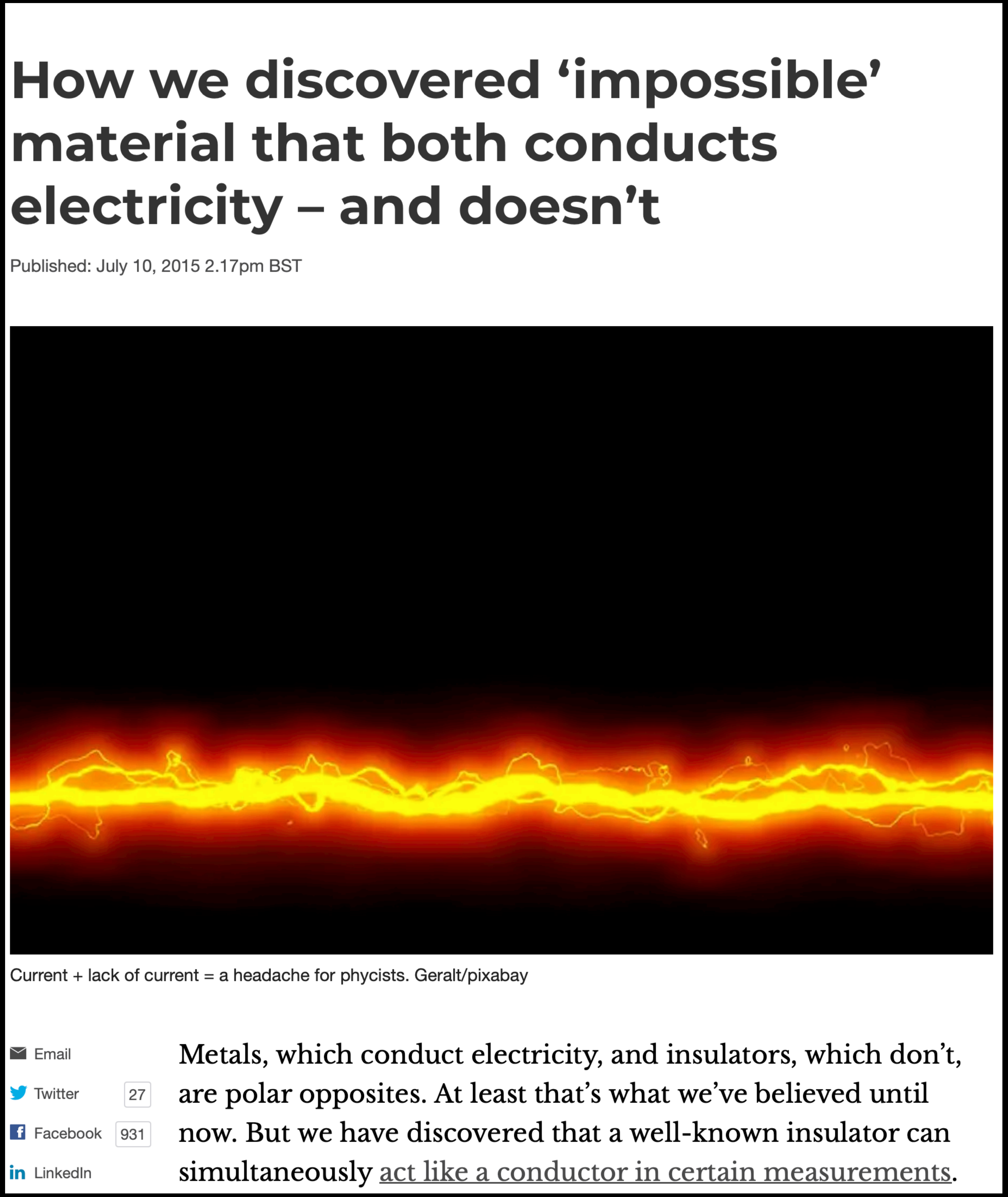
Tan et al., *Science* **349**, 287 (2015) Hartstein et al., *Phys. Rev. Lett.* **14**, 166 (2018)

But SmB_6 is an excellent insulator!

Inverted Corbino transport



Eo et al., *Proc. Nat. Acad. Sci.* **116**, 26 (2019)



How we discovered ‘impossible’ material that both conducts electricity – and doesn’t

Published: July 10, 2015 2.17pm BST

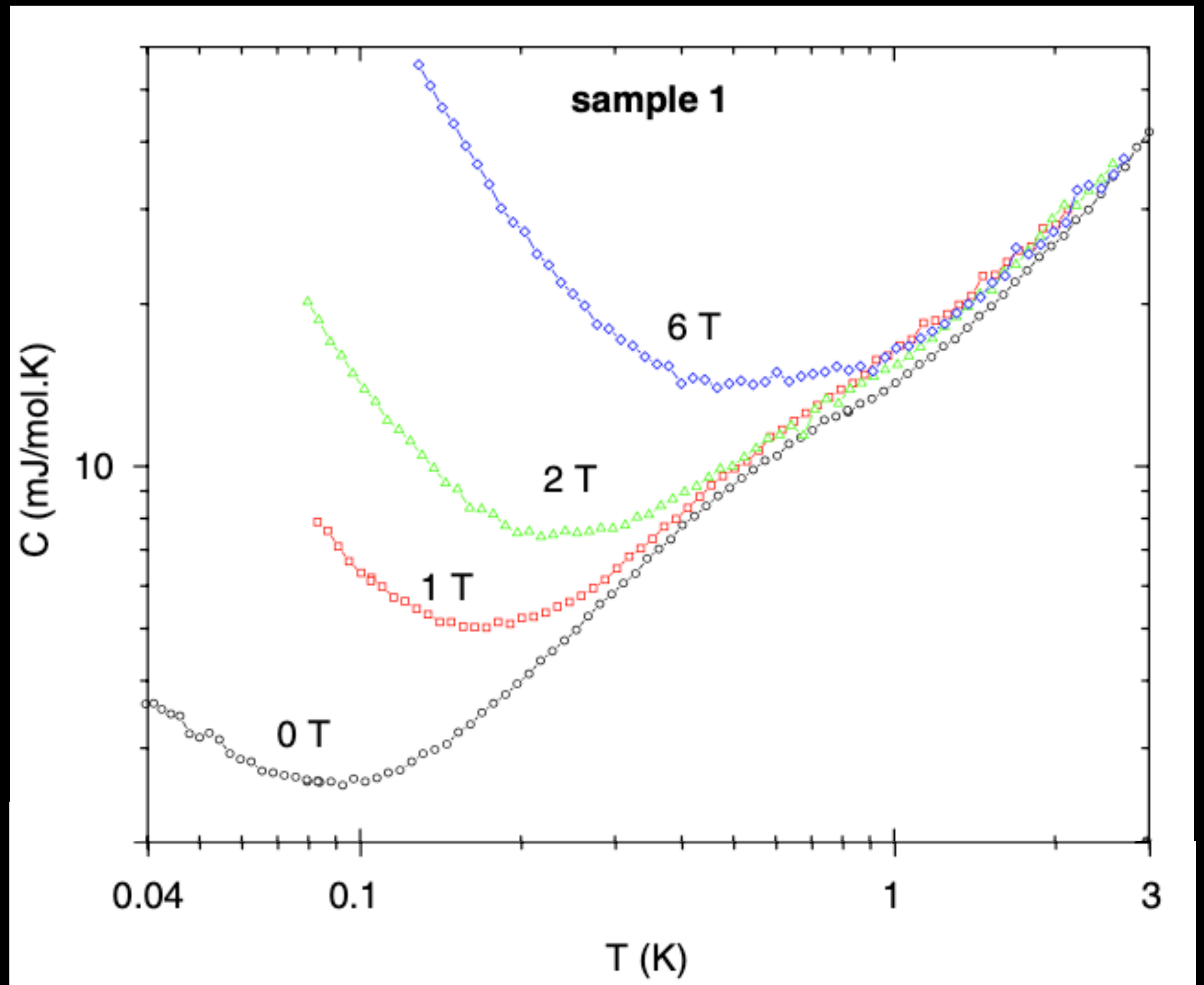
Current + lack of current = a headache for phycists. Geralt/pixabay

Email
Twitter 27
Facebook 931
LinkedIn

Metals, which conduct electricity, and insulators, which don’t, are polar opposites. At least that’s what we’ve believed until now. But we have discovered that a well-known insulator can simultaneously act like a conductor in certain measurements.

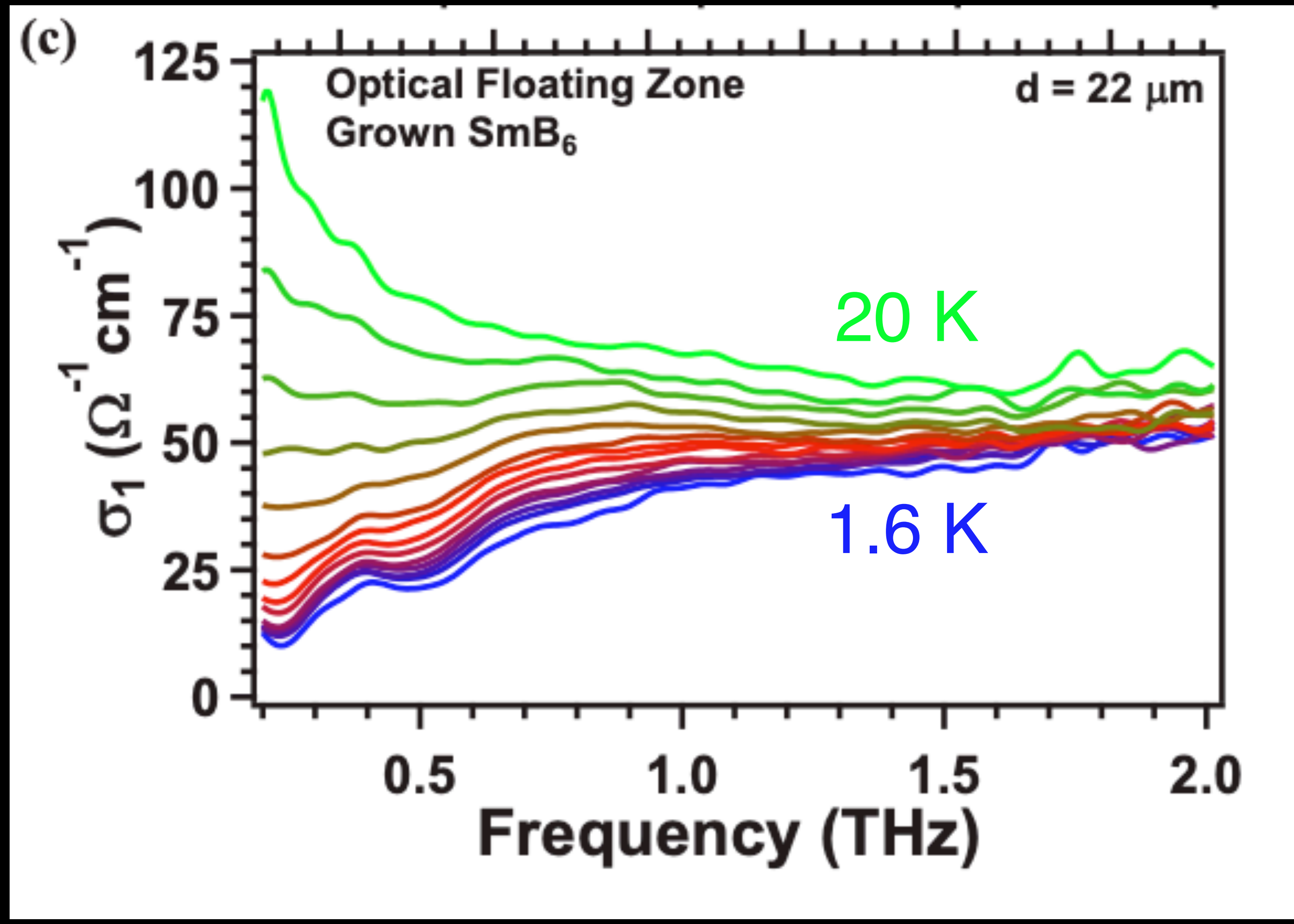
Remnant metallicity in floating-zone SmB_6

Low temperature specific heat



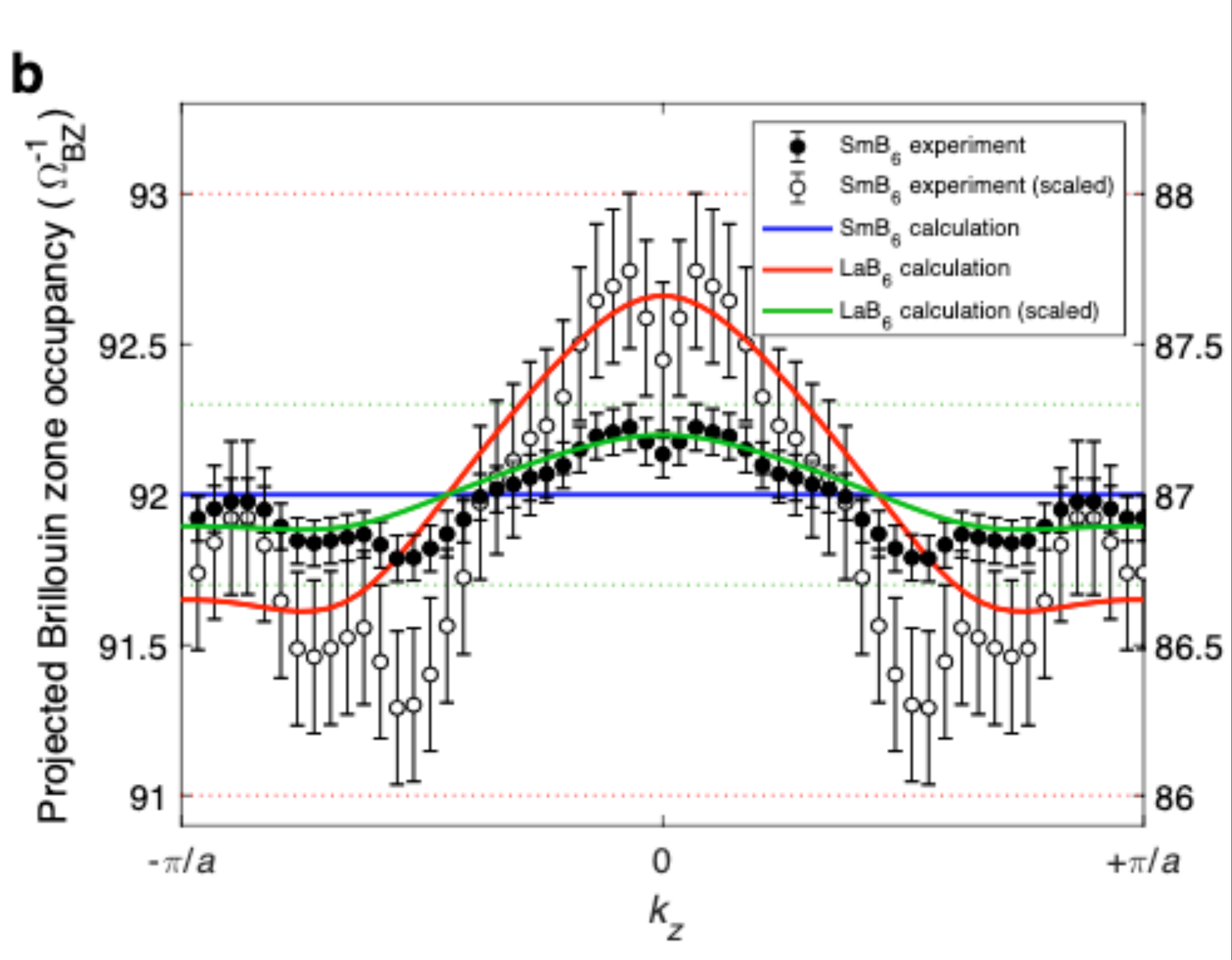
Flachbart et al., *Physica B.* **378**, 610 (2006)

AC optical conductivity



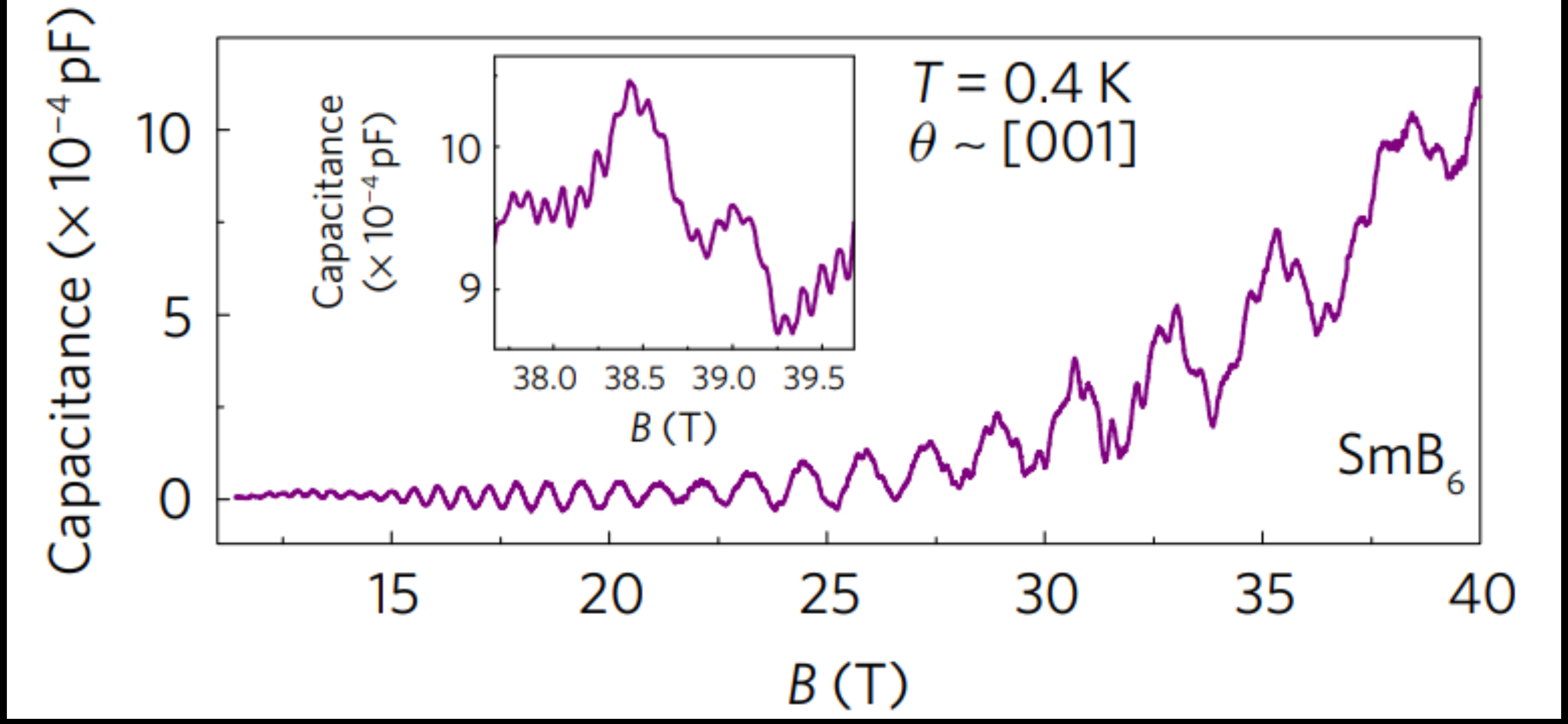
Laurita et al., *Phys. Rev. B* **122**, 165154 (2016)

Compton scattering



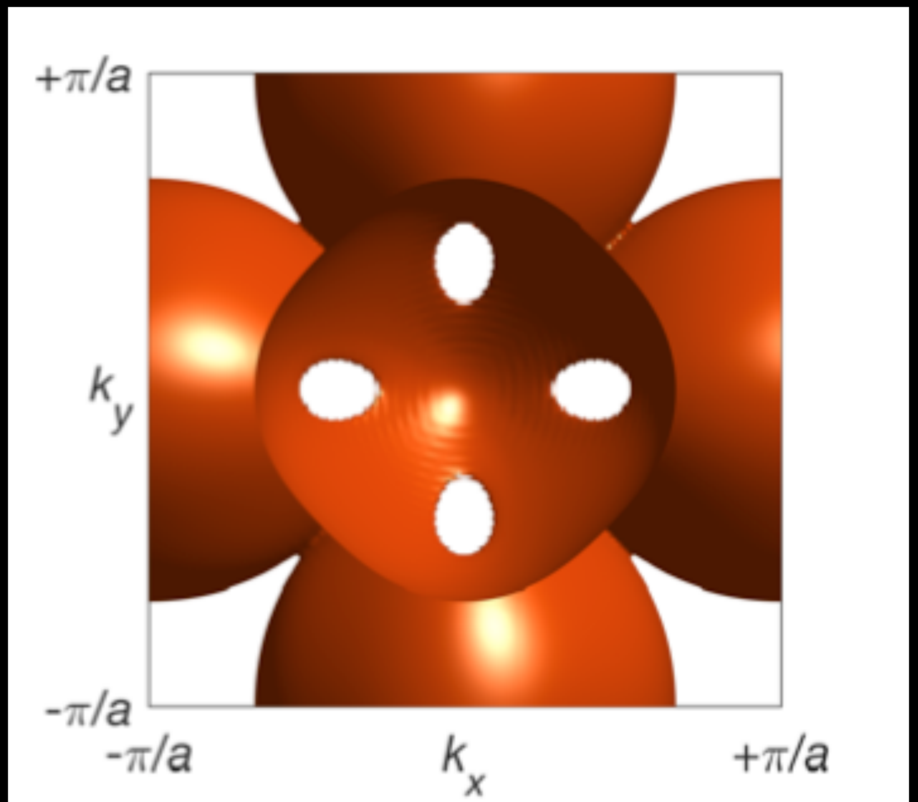
Millichamp et al., *arXiv 2011.07727* (2021)

This SmB_6 is grown using **floating zone** technique



Hartstein et al., *Phys. Rev. Lett.* **14**, 166 (2018)

Looks like SmB_6 at **high temperature**



Is the origin intrinsic or extrinsic?

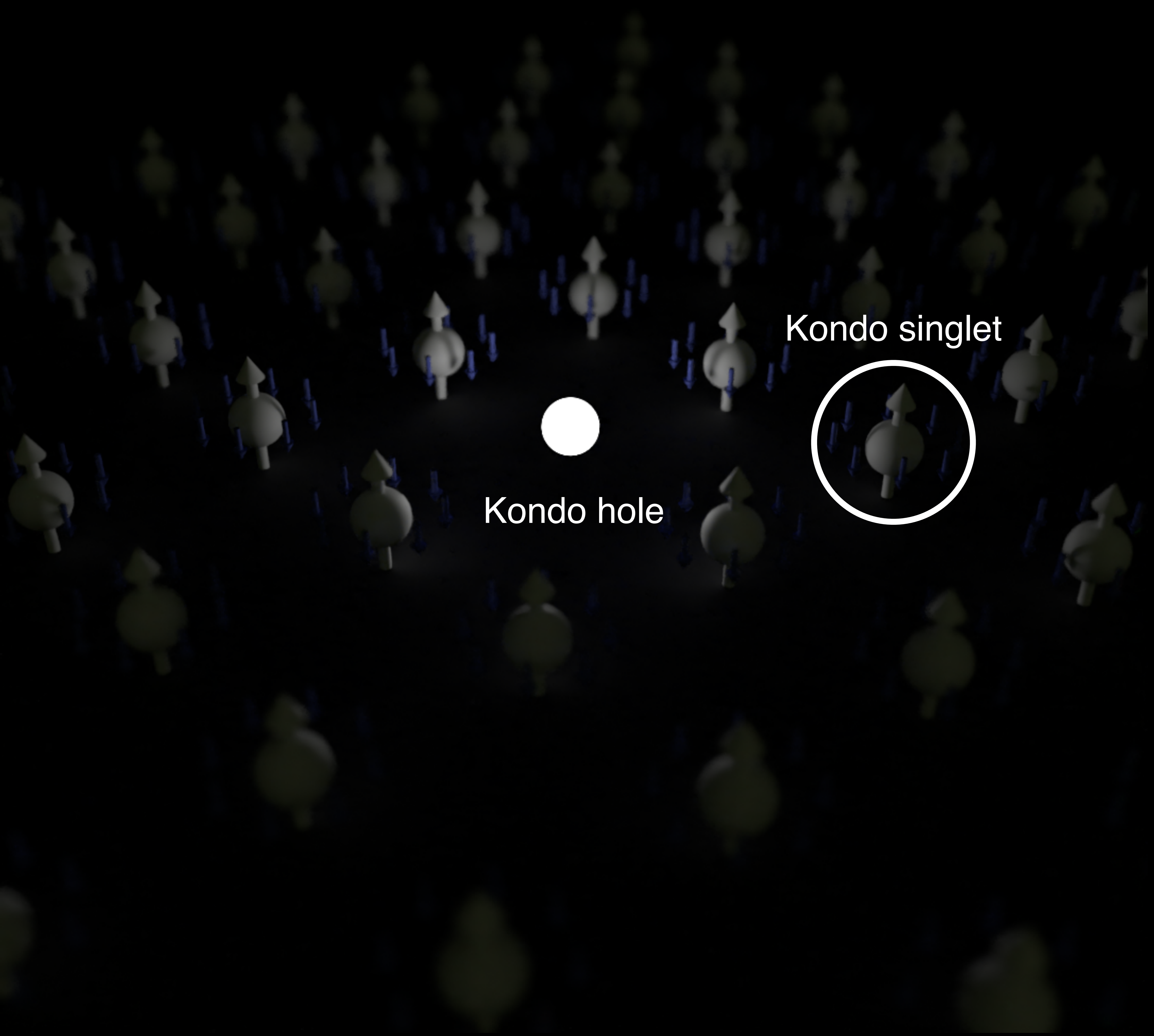
Time

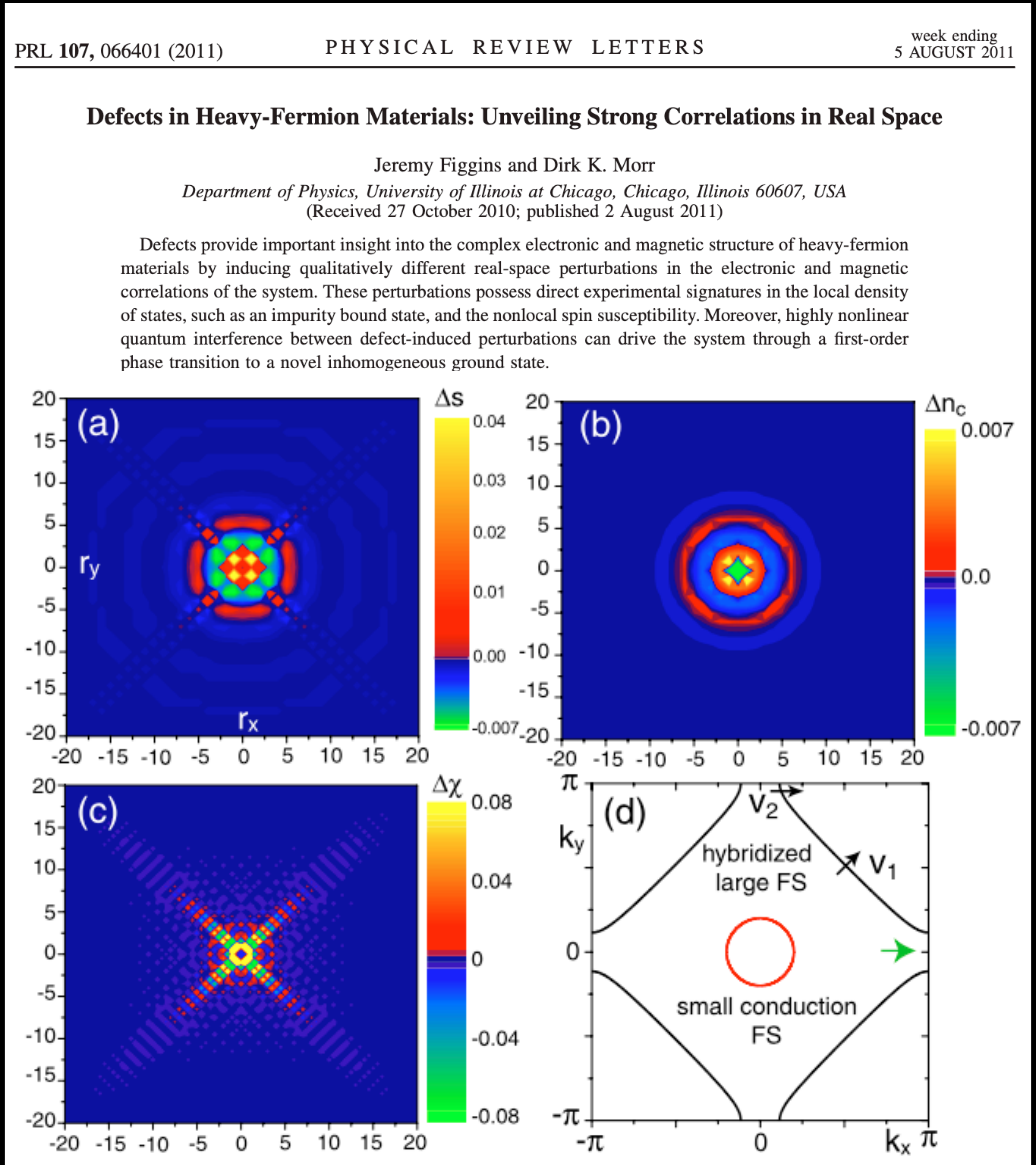
Is the origin intrinsic or extrinsic?

We will answer this question **experimentally:**

Question: Is there microscopic evidence of **light electrons?**

Are Kondo holes the culprit?





PRL 107, 066401 (2011) PHYSICAL REVIEW LETTERS week ending 5 AUGUST 2011

Defects in Heavy-Fermion Materials: Unveiling Strong Correlations in Real Space

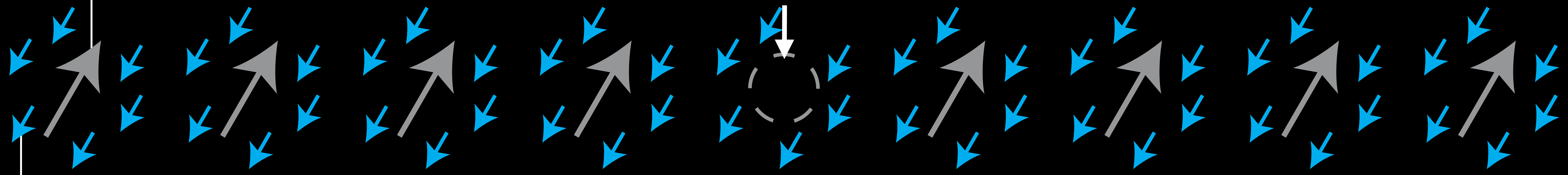
Jeremy Figgins and Dirk K. Morr

Department of Physics, University of Illinois at Chicago, Chicago, Illinois 60607, USA

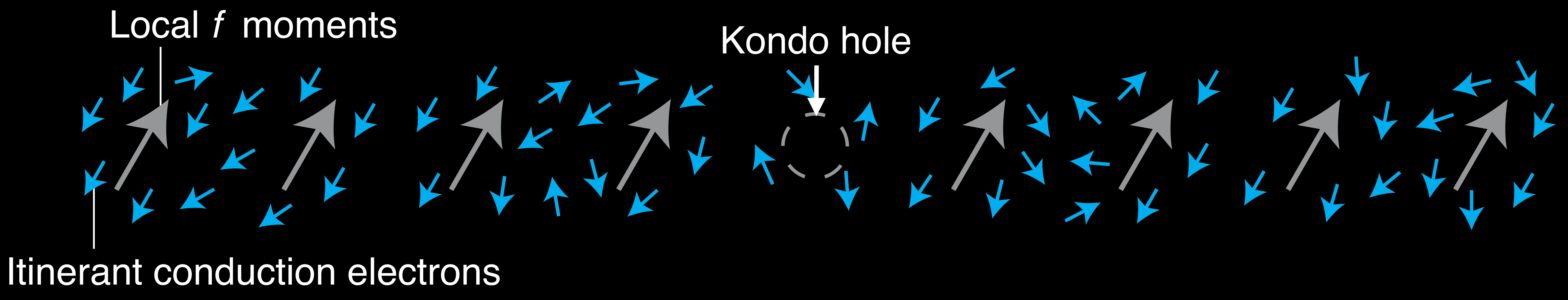
(Received 27 October 2010; published 2 August 2011)

Defects provide important insight into the complex electronic and magnetic structure of heavy-fermion materials by inducing qualitatively different real-space perturbations in the electronic and magnetic correlations of the system. These perturbations possess direct experimental signatures in the local density of states, such as an impurity bound state, and the nonlocal spin susceptibility. Moreover, highly nonlinear quantum interference between defect-induced perturbations can drive the system through a first-order phase transition to a novel inhomogeneous ground state.

Punching a hole in a Kondo lattice



Kondo holes redistribute the screening cloud



Kondo holes modulate the local charge density

Kondo holes modulate the interaction strength

Already observed in URu_2Si_2

PNAS

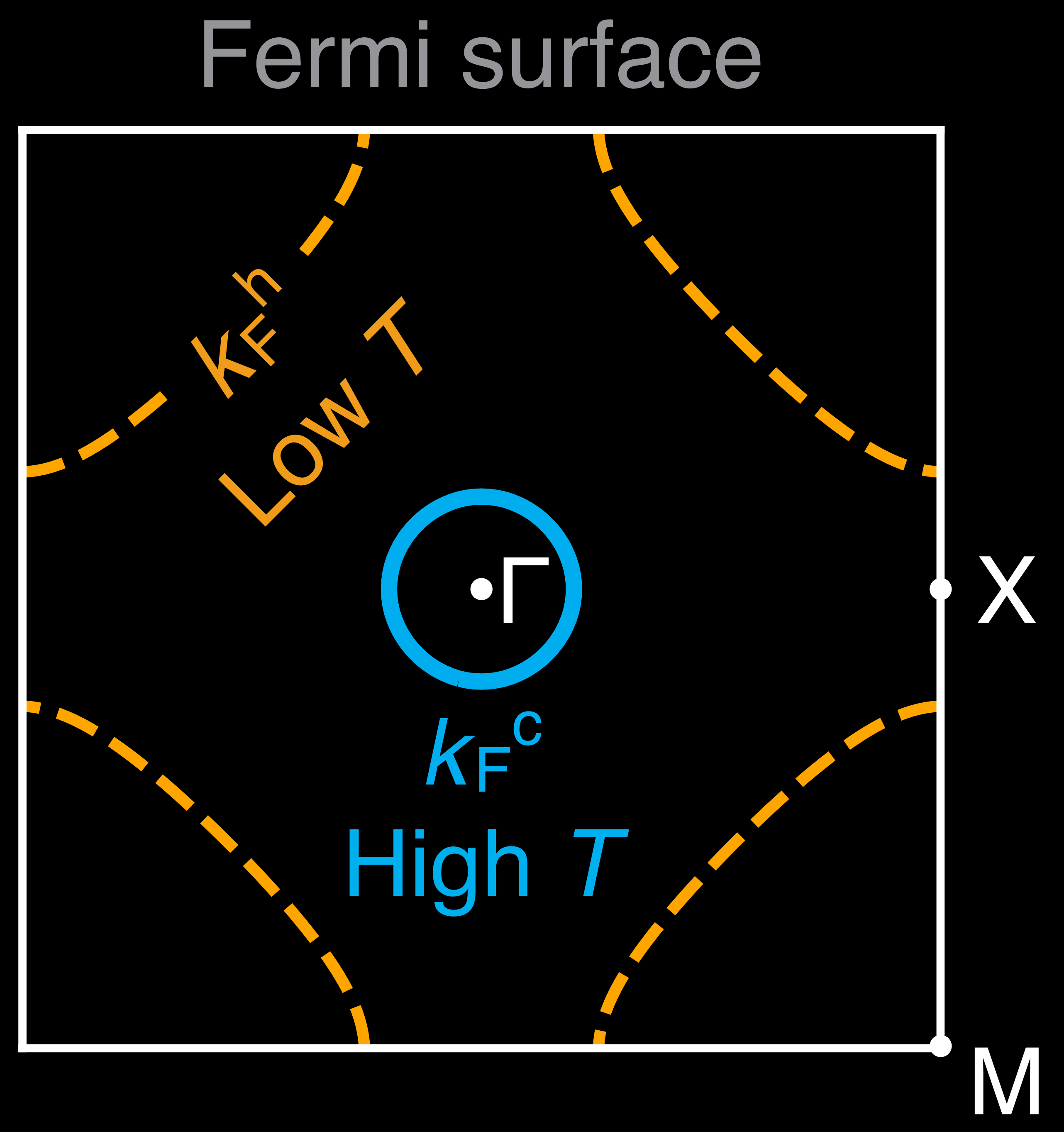
How Kondo-holes create intense nanoscale heavy-fermion hybridization disorder

Mohammad H. Hamidian[a,b,1], Andrew R. Schmidt[a,b,c,1], Inês A. Firmo[a,b], Milan P. Allan[a,d], Phelim Bradley[e], Jim D. Garrett[f], Travis J. Williams[g], Graeme M. Luke[g,h], Yonatan Dubi[i,j], Alexander V. Balatsky[i], and J. C. Davis[a,b,d,k,2]

Contributed by J.C. Séamus Davis, September 13, 2011 (sent for review July 27, 2011)

Kondo holes modulate magnetic susceptibility

Kondo holes reveal the itinerant electrons



How can we measure them?

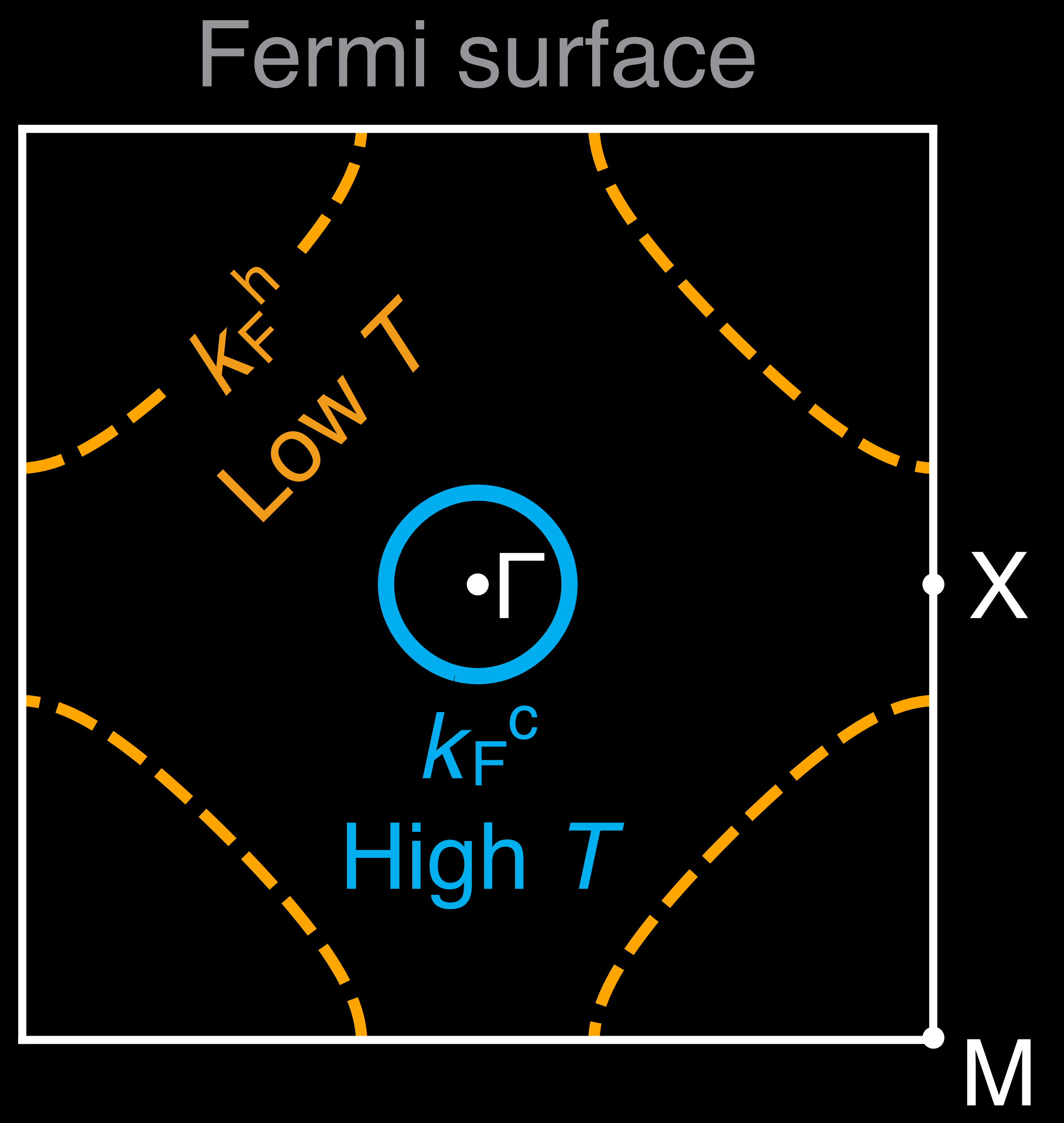
Experimental requirements:

< nm spatial resolution

< mV energy resolution

~ K temperature

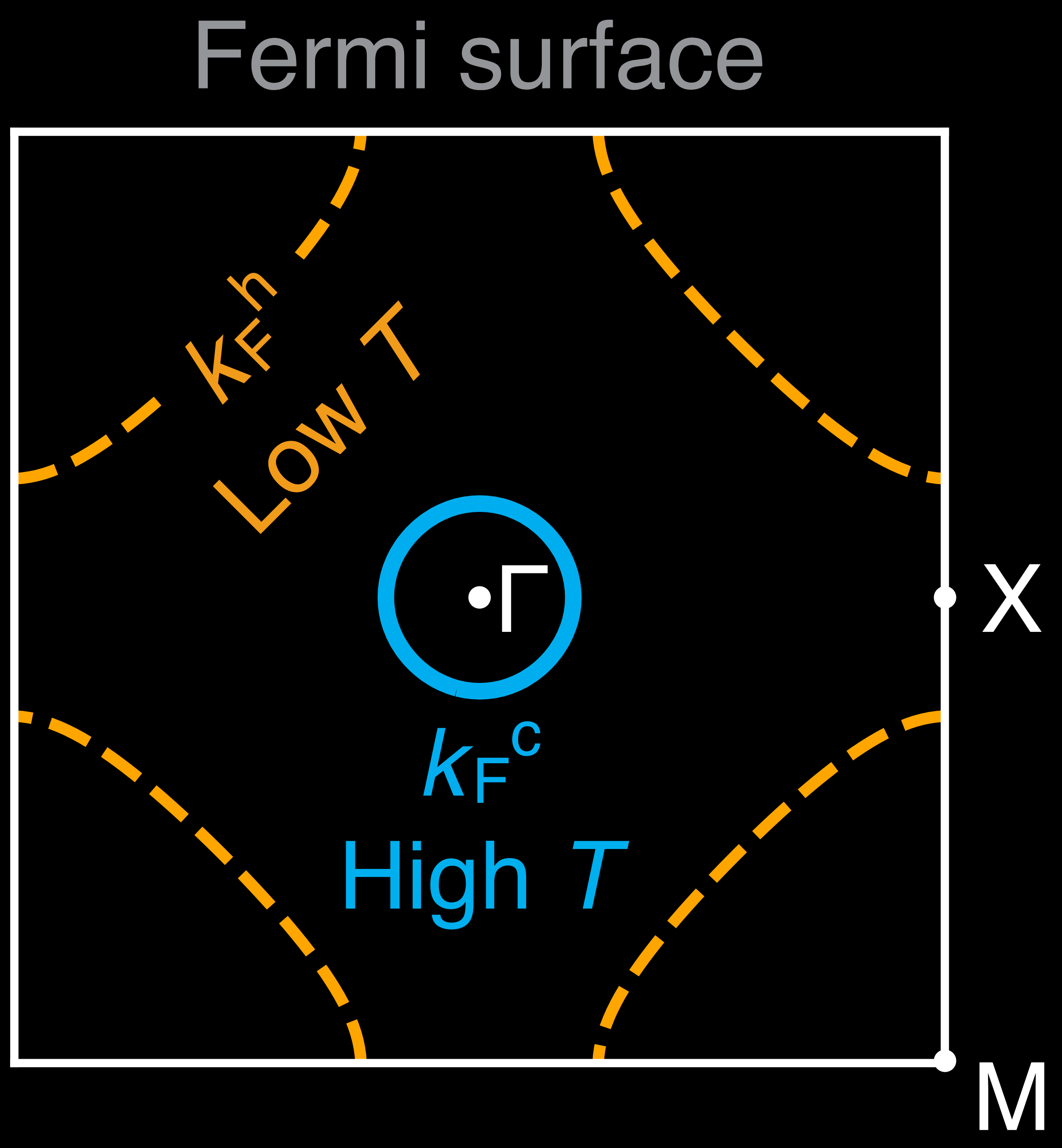
Charge probe



STM could work, but needs charge sensitivity

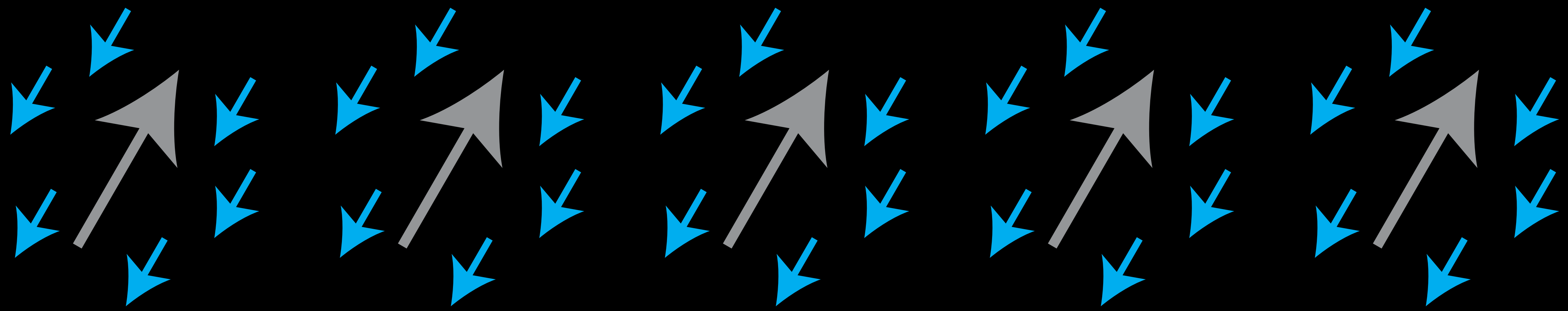
Scanning tunneling microscopy:

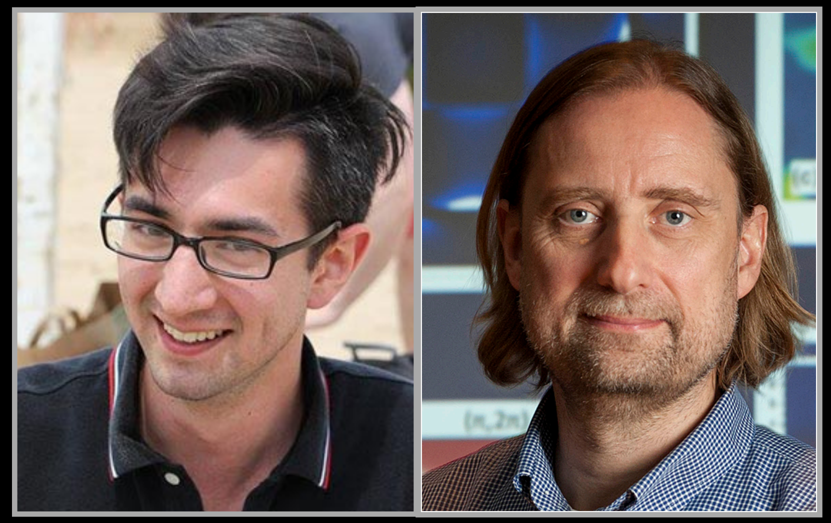
✅ < nm spatial resolution
✅ < mV energy resolution
✅ ~ K temperature
❌ Charge probe



What happens when we add charge?

Adding charge cannot change the number of *f* electrons, n_f



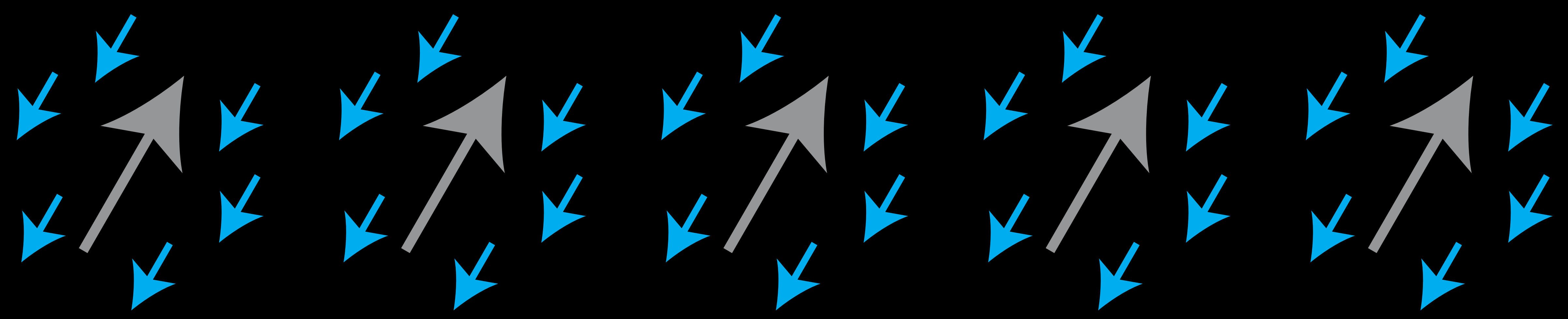


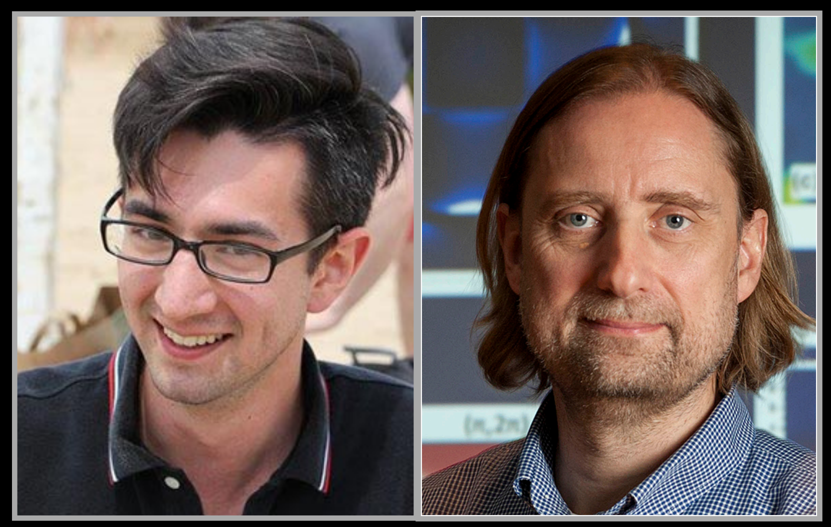
Eric Mascot

Dirk Morr

What happens when we add charge?

Adding charge cannot change the number of *f* electrons, n_f





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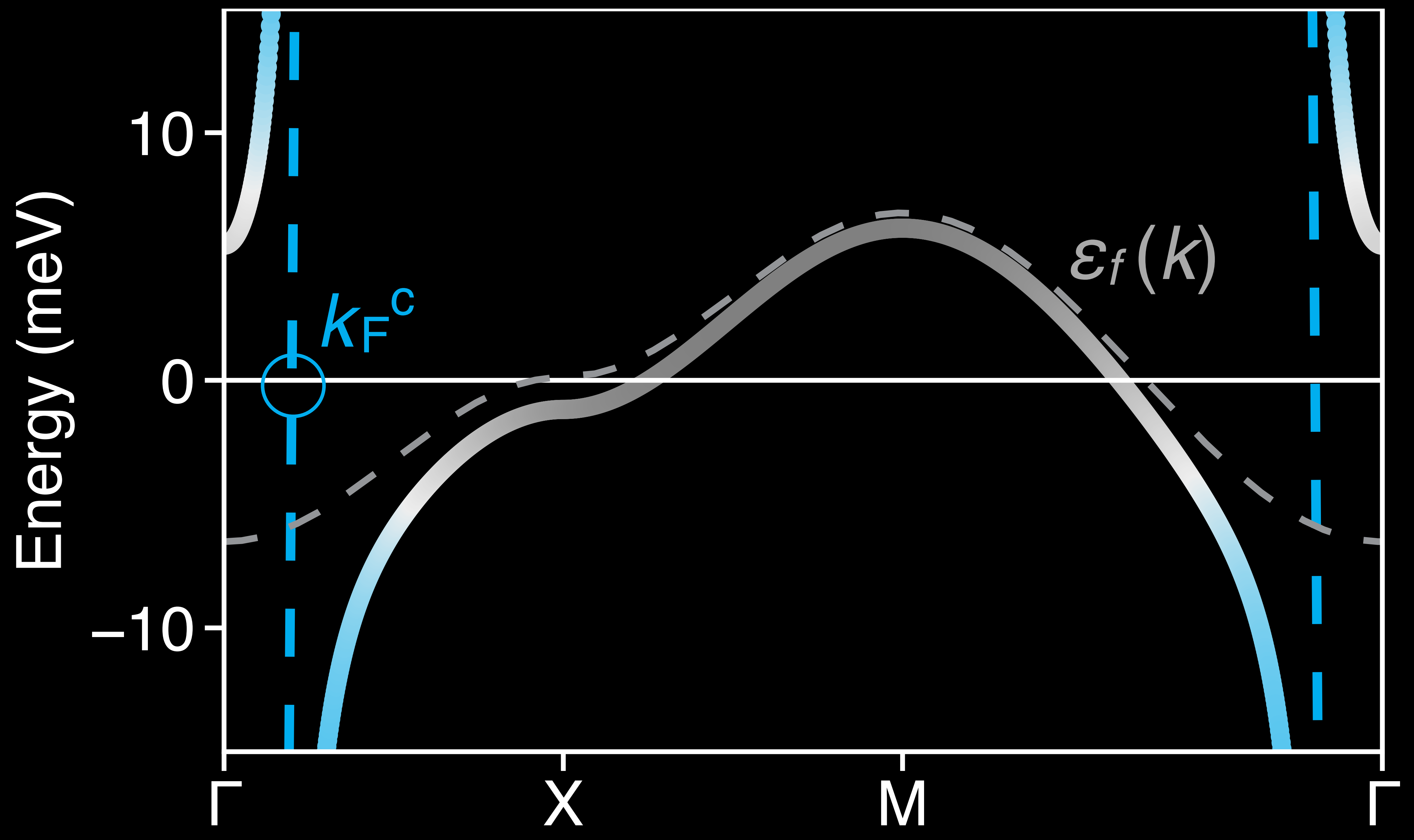
Dirk Morr

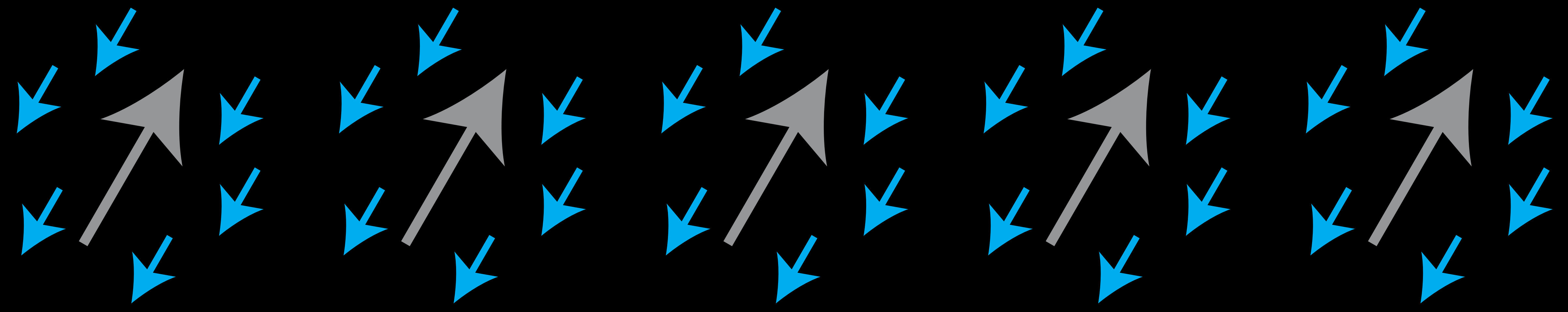
Heavy fermion band structure

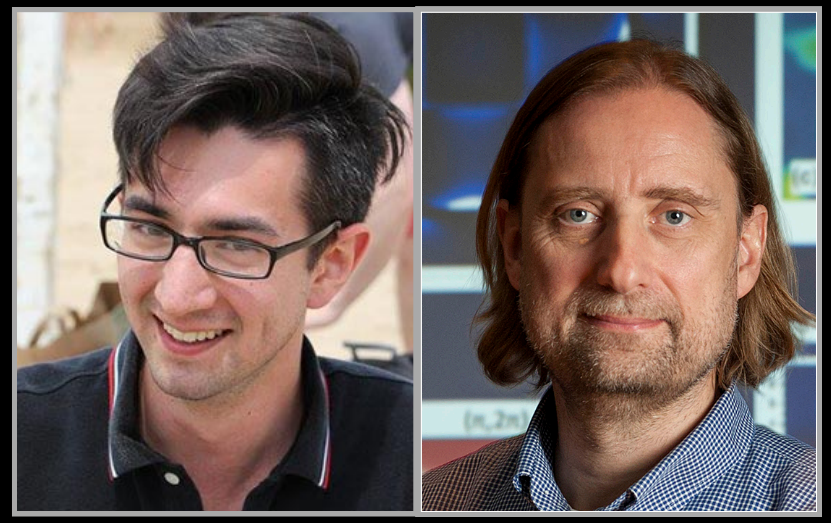


n_f = integrated *f* orbital character = 1

Adding charge adjusts the energy position of ε_f

Adding charge cannot change the number of *f* electrons, n_f

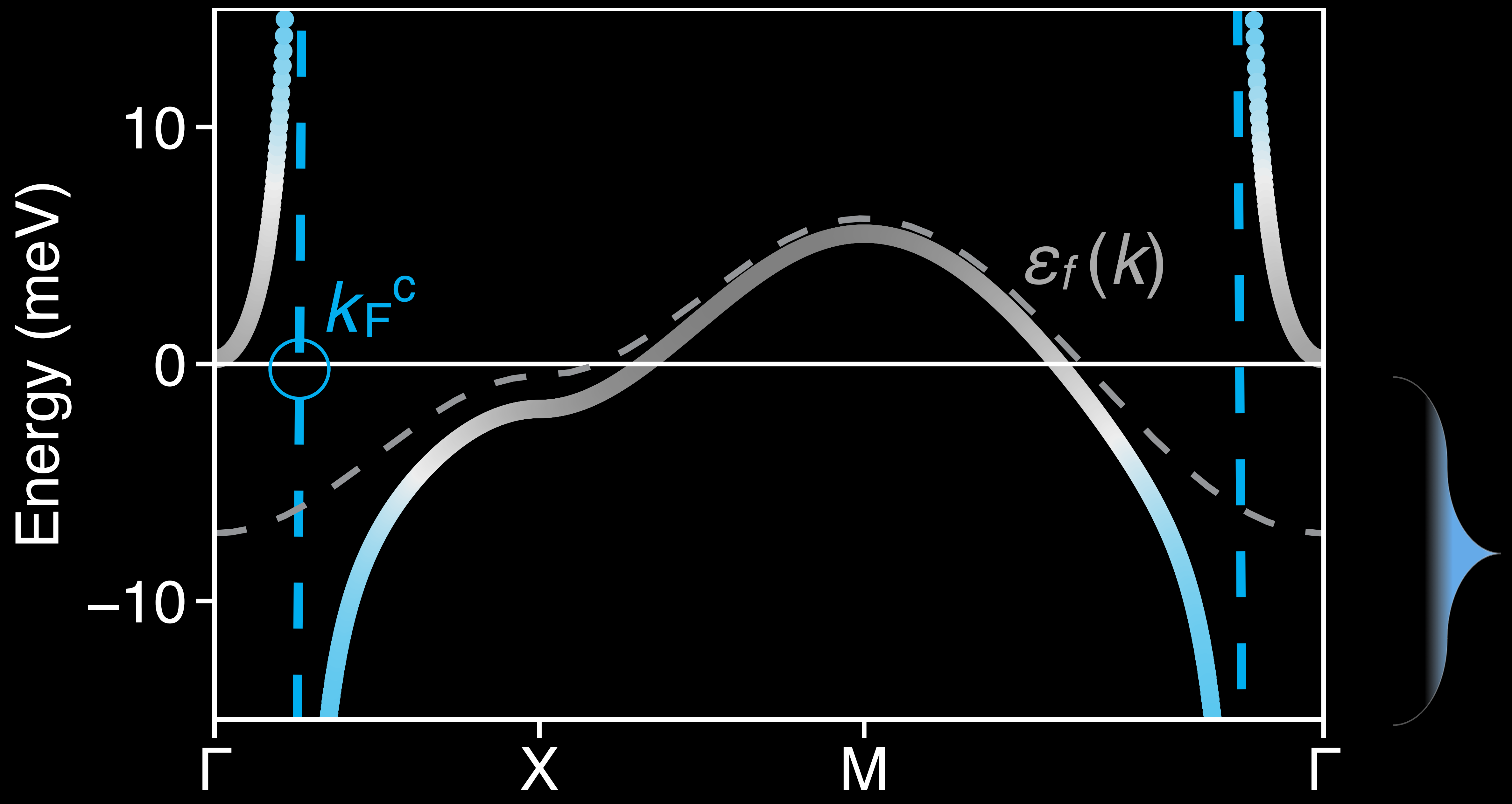




Eric Mascot

Dirk Morr

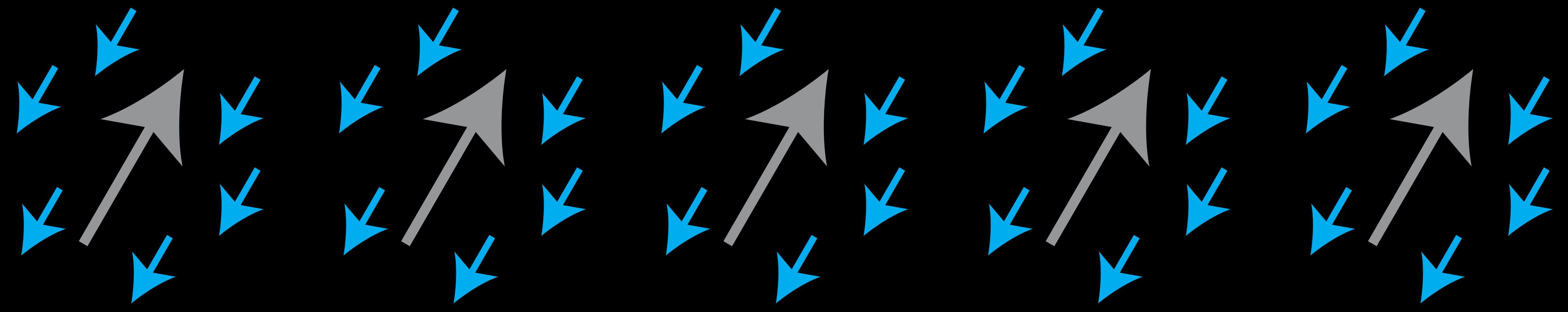
Heavy fermion band structure

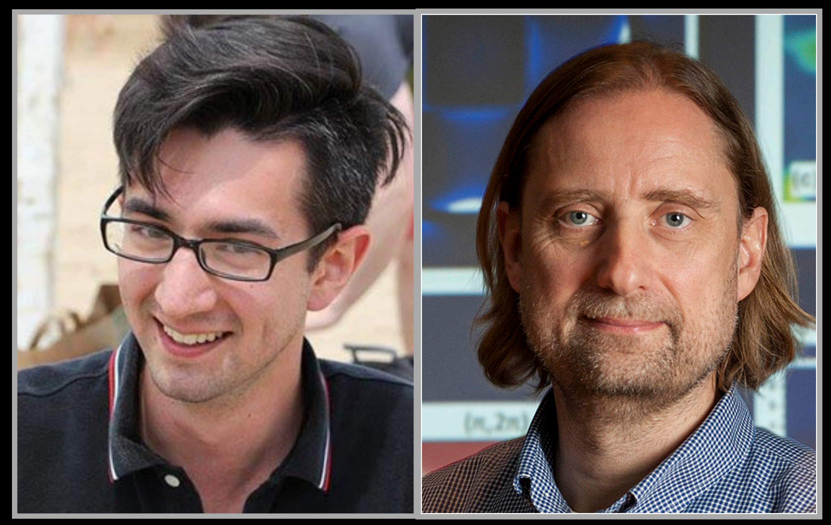


n_f = integrated *f* orbital character = 1

The Kondo resonance is a **charge** sensor

Adding charge cannot change the number of *f* electrons, n_f

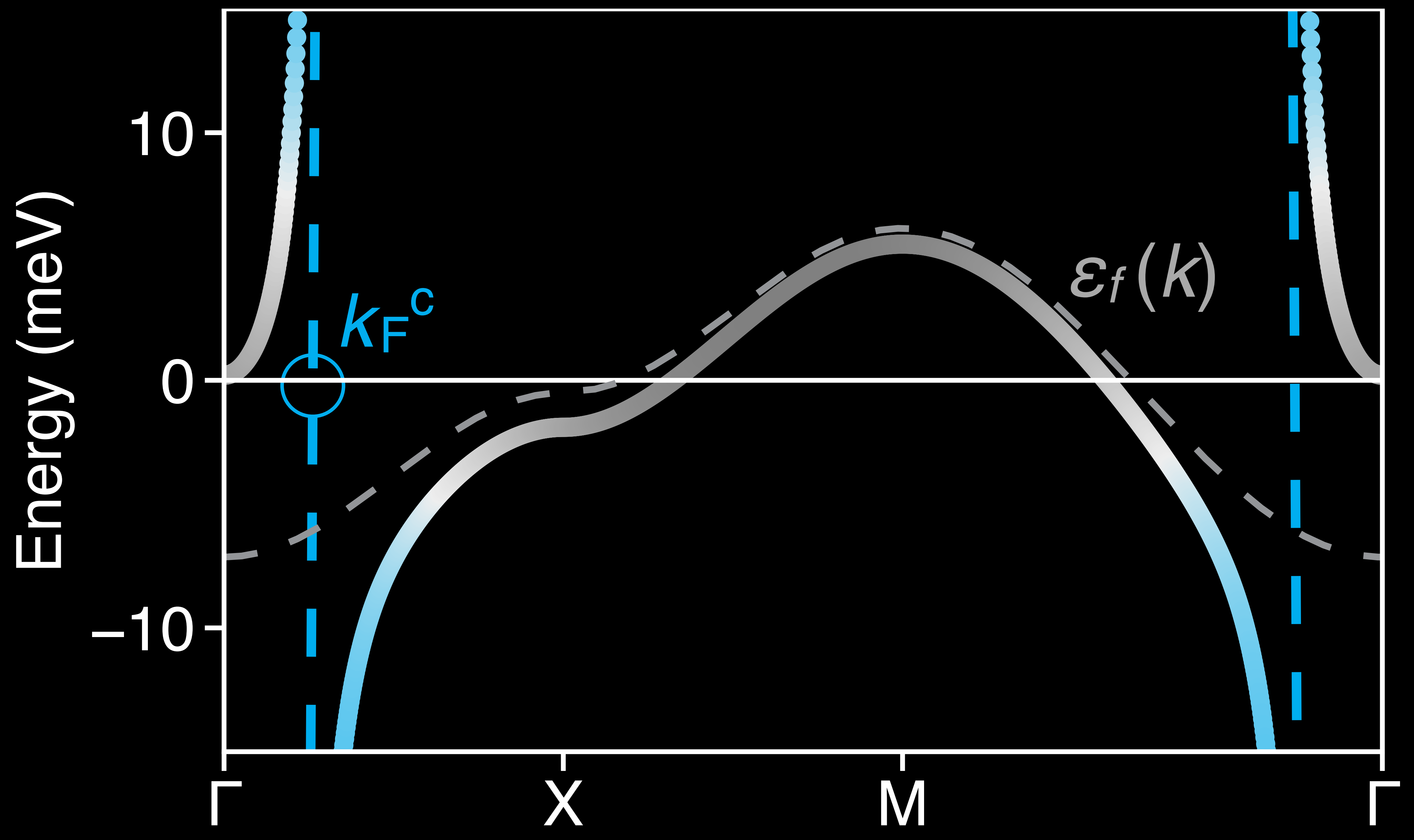




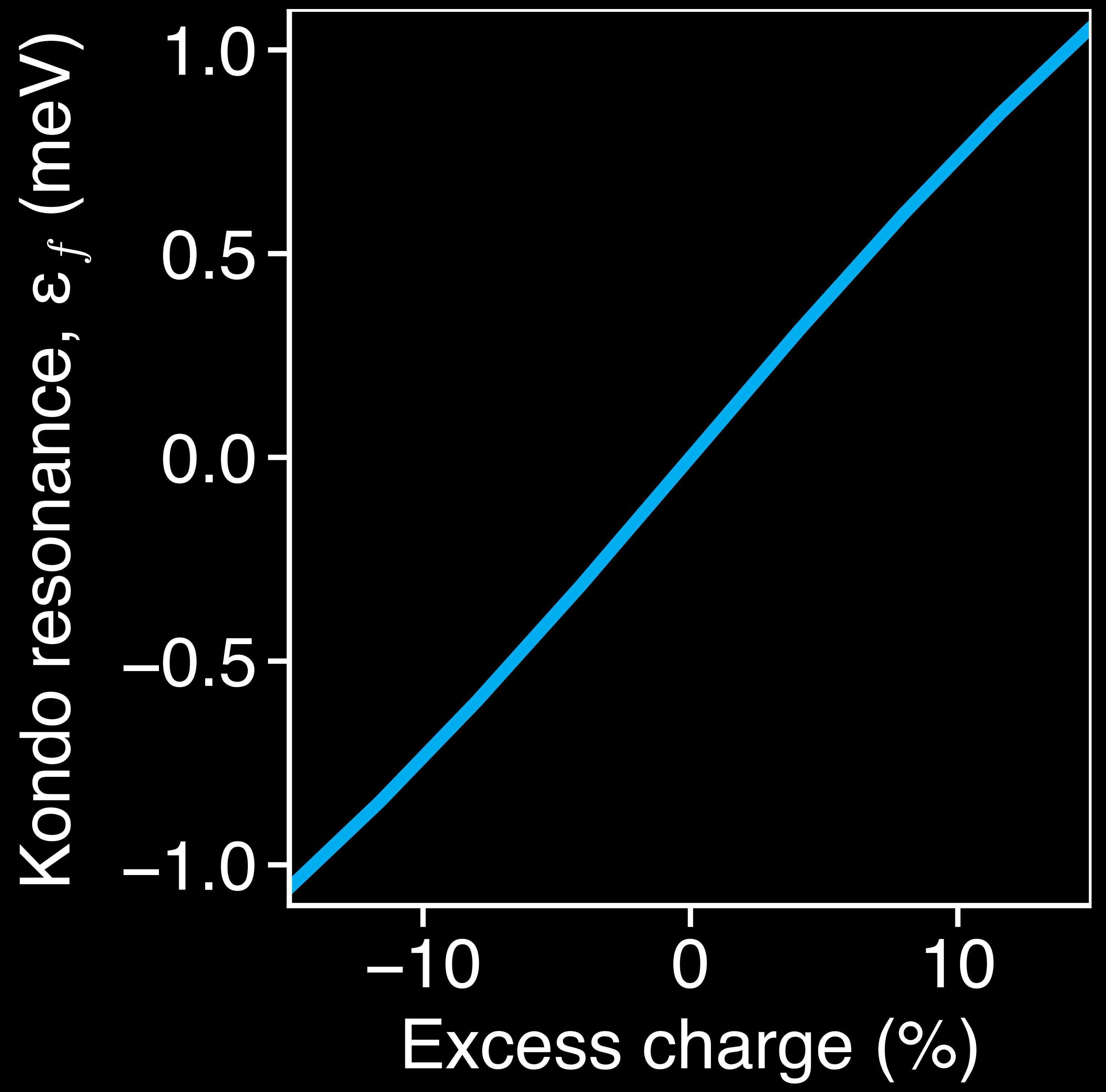
Eric Mascot

Dirk Morr

Heavy fermion band structure

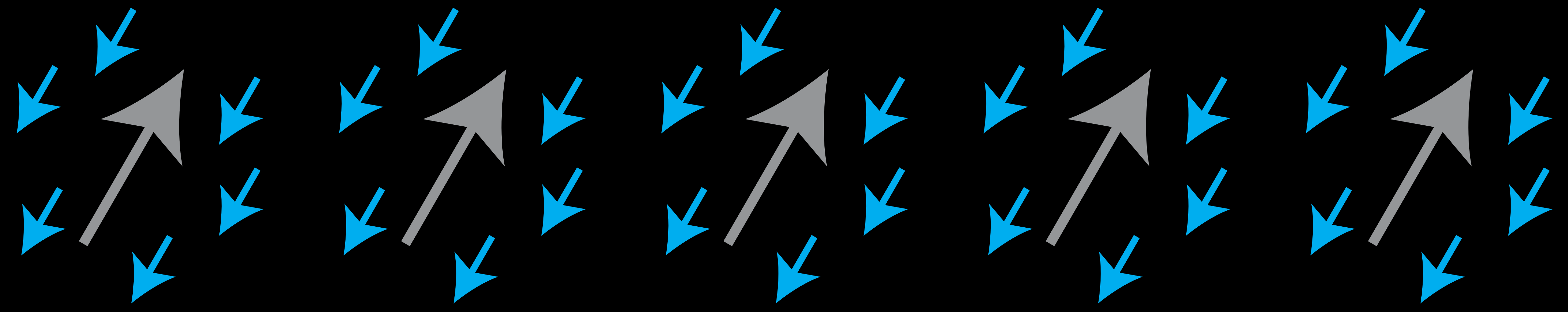


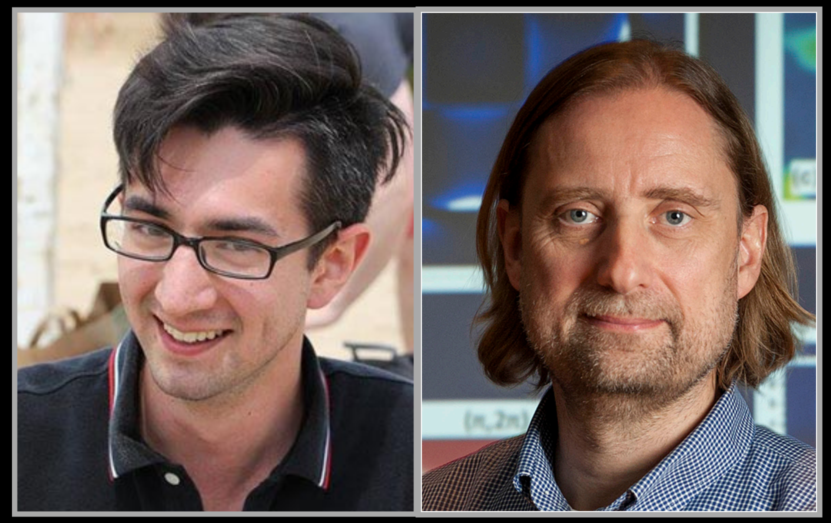
n_f = integrated *f* orbital character = 1



How to image the small $\Delta\varepsilon_f$ shifts?

Adding charge cannot change the number of *f* electrons, n_f

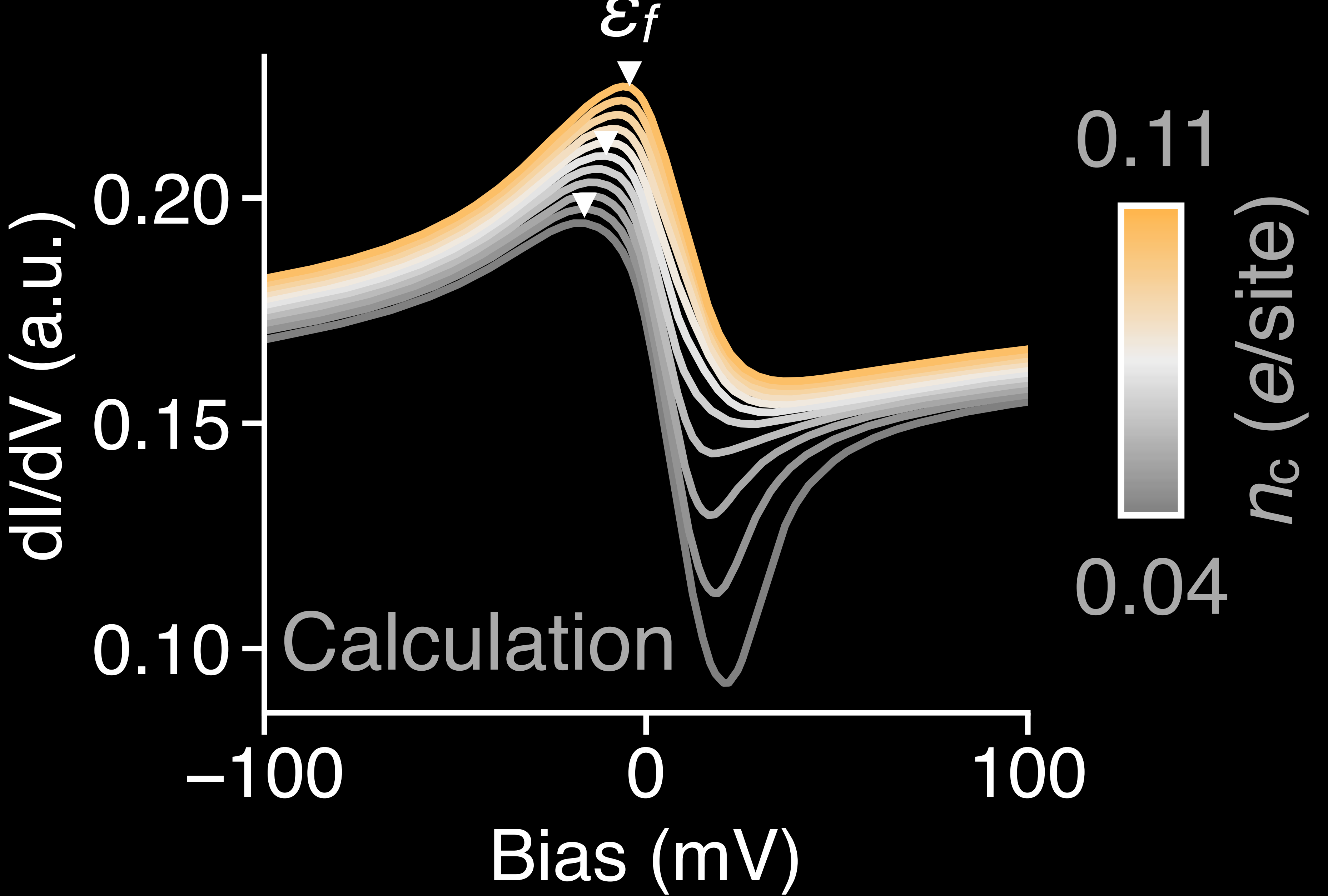




Eric Mascot

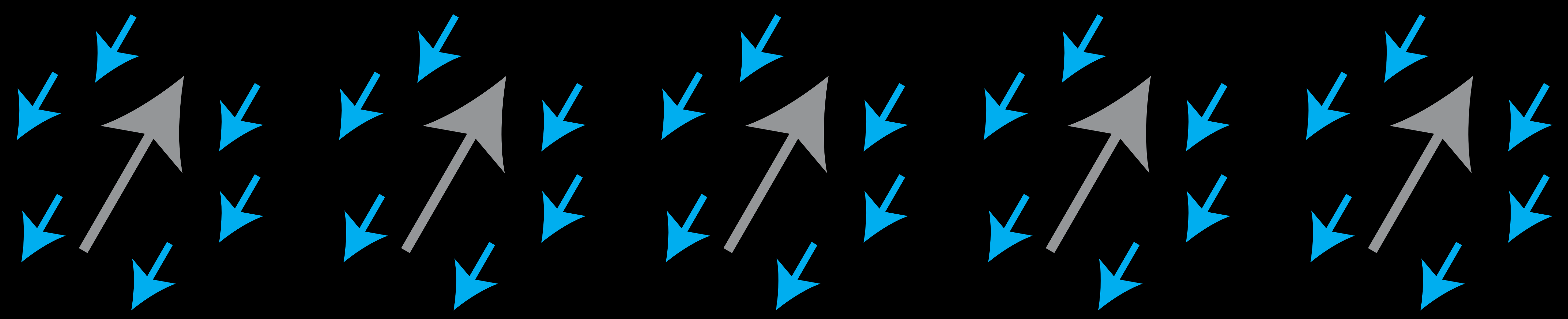
Dirk Morr

(1) $\Delta\varepsilon_f$ moves dI/dV peak position

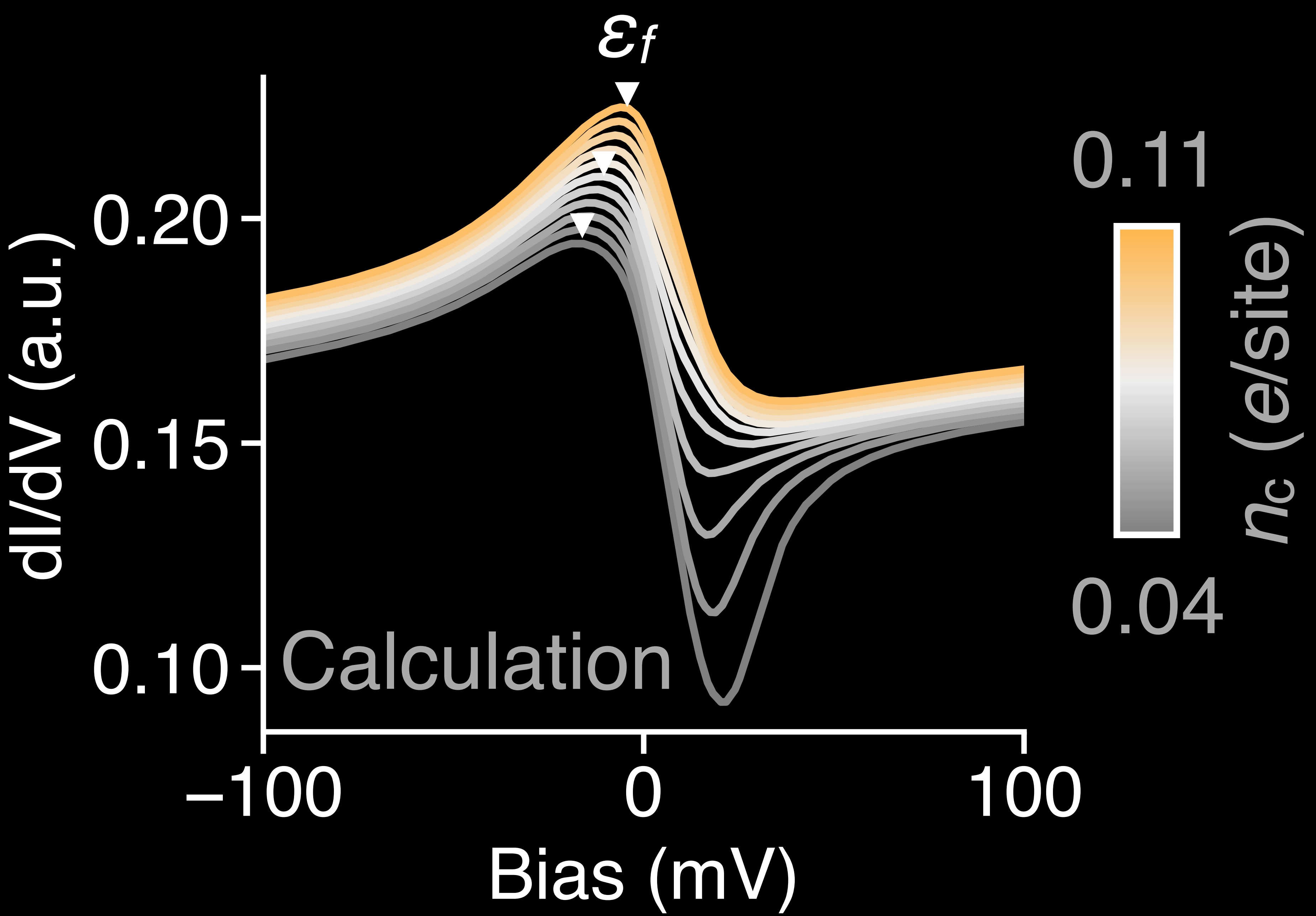


The $\Delta\varepsilon_f$ shifts are magnified in $R(\mathbf{r}, V)$

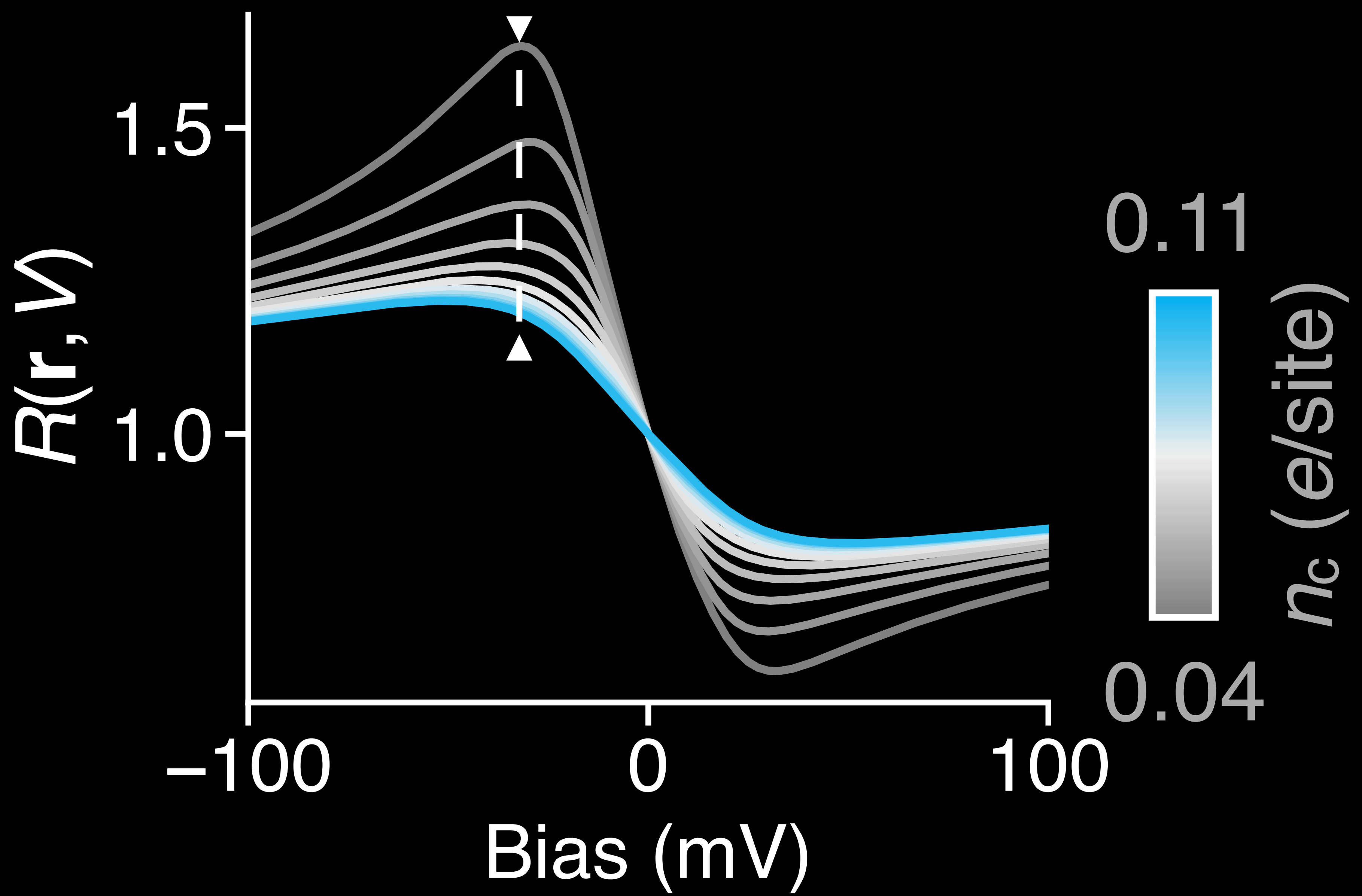
Adding charge cannot change the number of *f* electrons, n_f



(1) $\Delta\varepsilon_f$ moves dI/dV peak position



(2) Changes $I(+V)$ compared to $I(-V)$

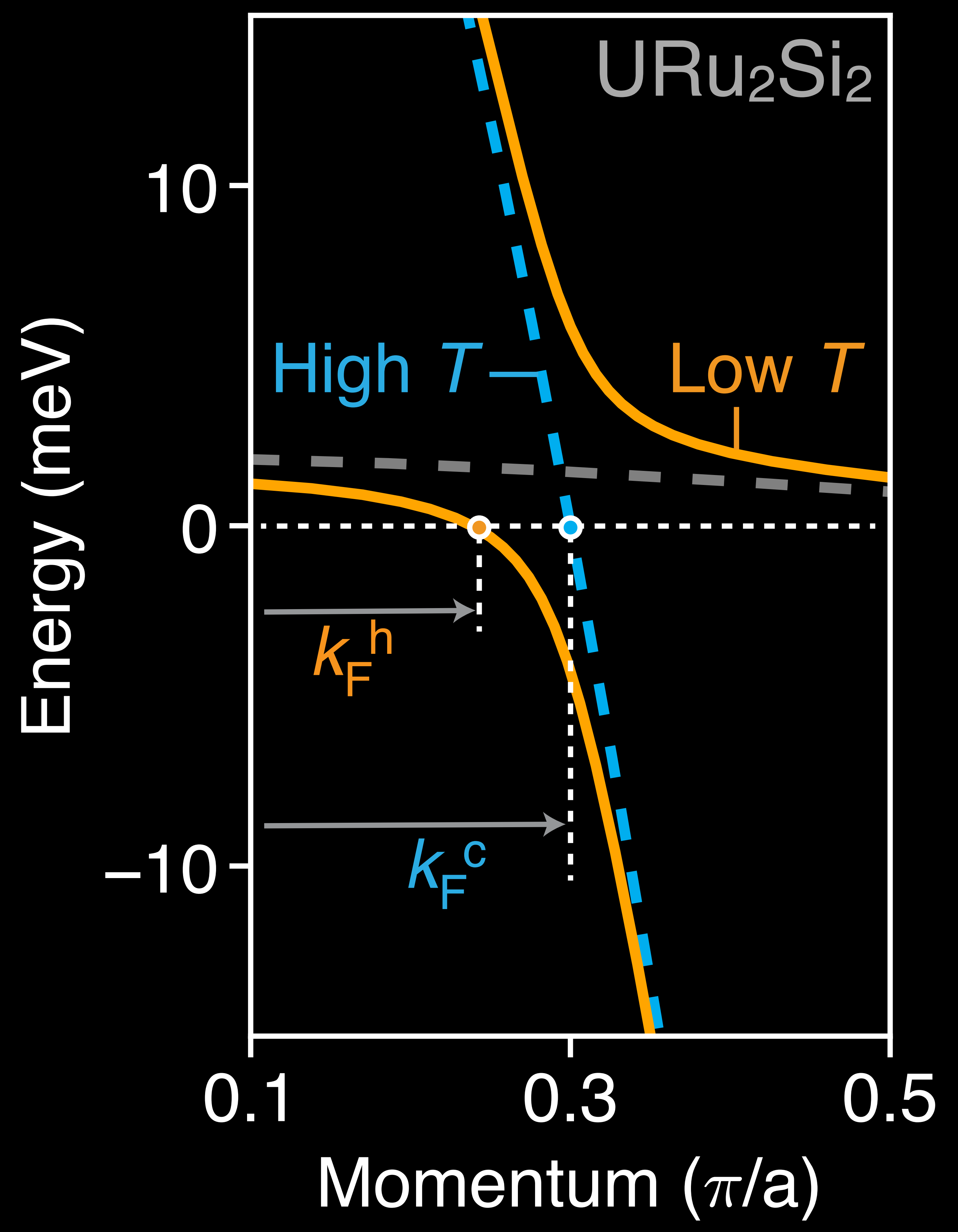


Rectification:

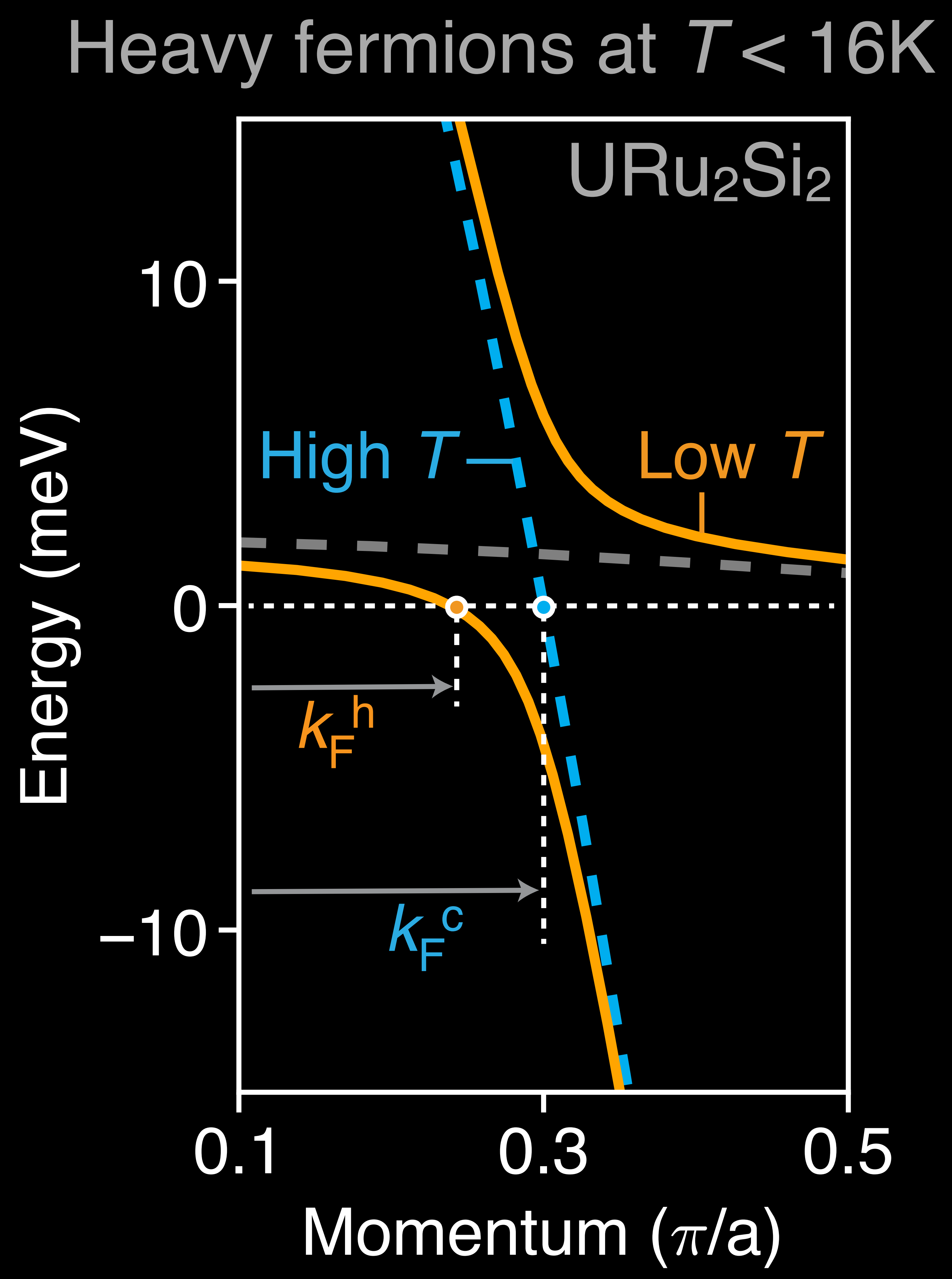
$$R(\mathbf{r}, V) = \frac{I(\mathbf{r},+V)}{I(\mathbf{r},-V)}$$

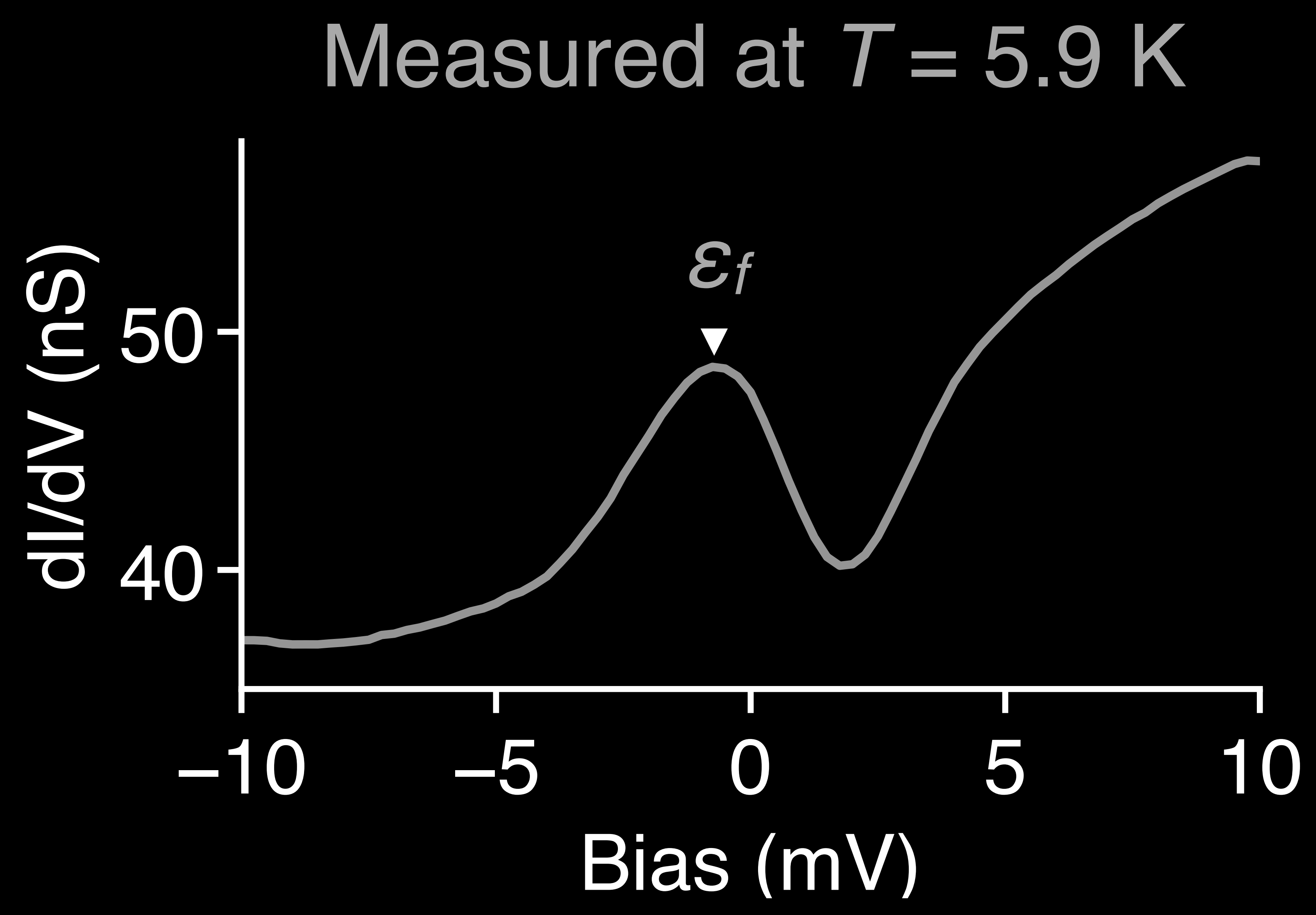
Test case: URu_2Si_2

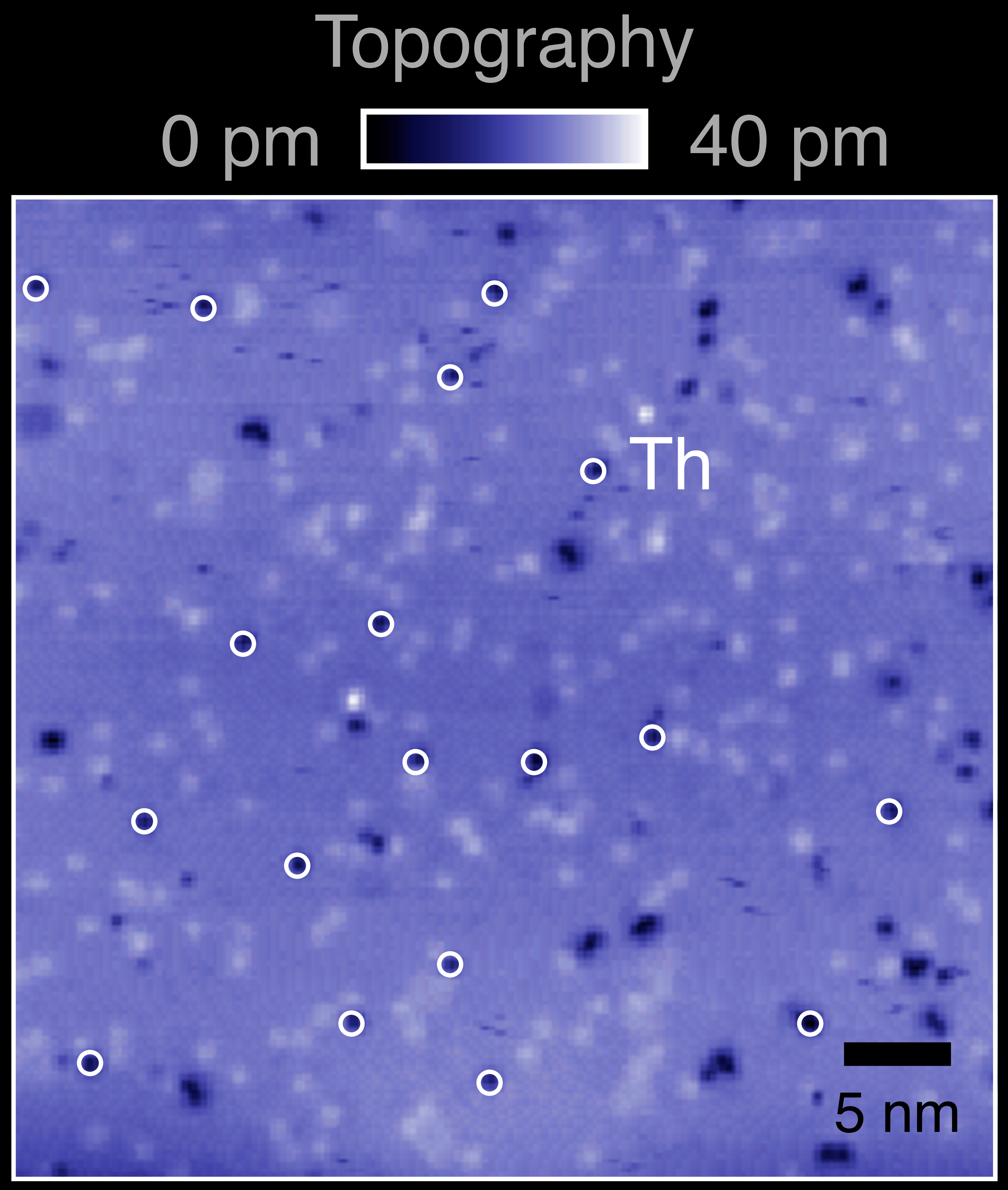
Heavy fermions at $T < 16K$



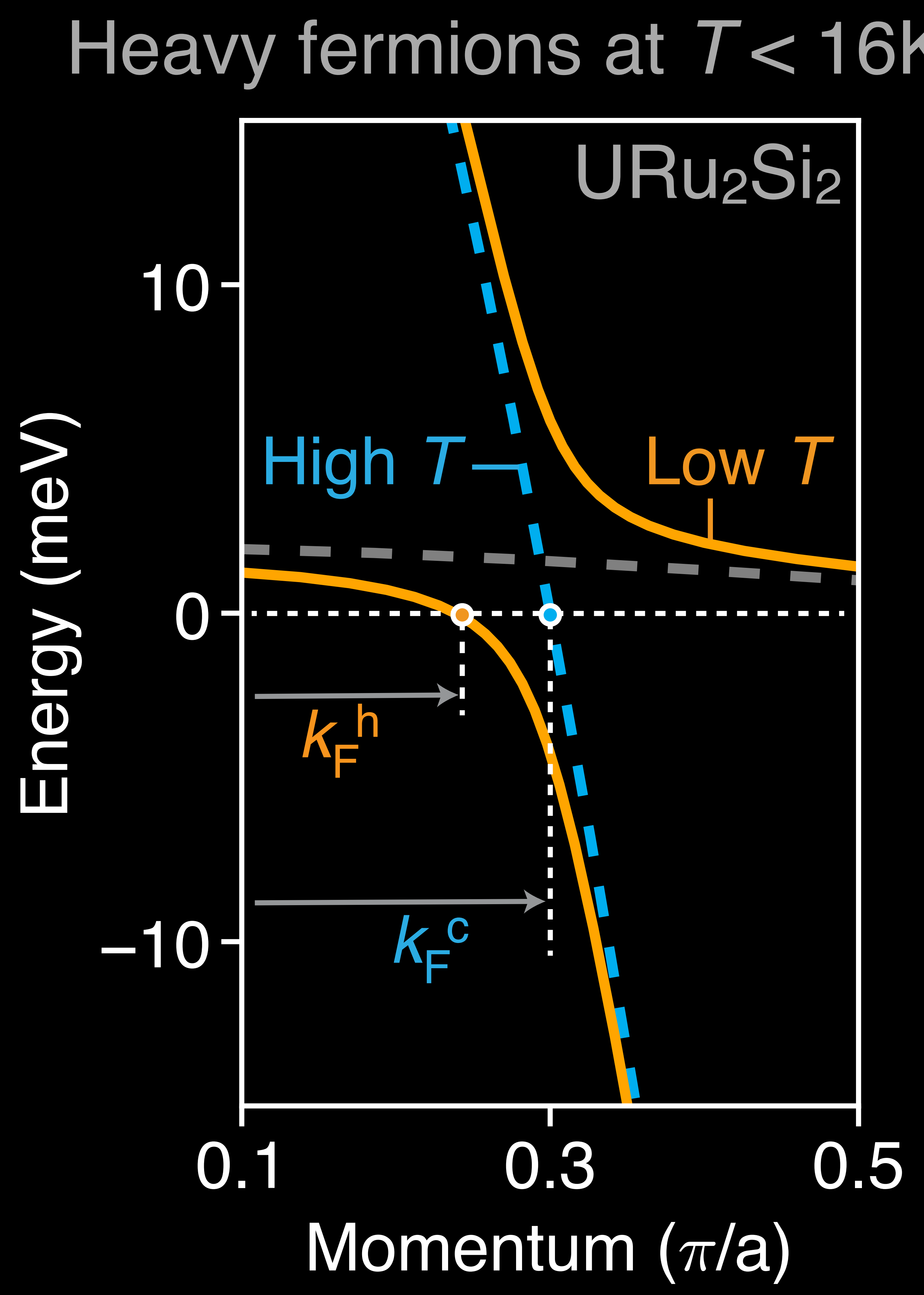
Kondo resonance appears as Fano-like dI/dV

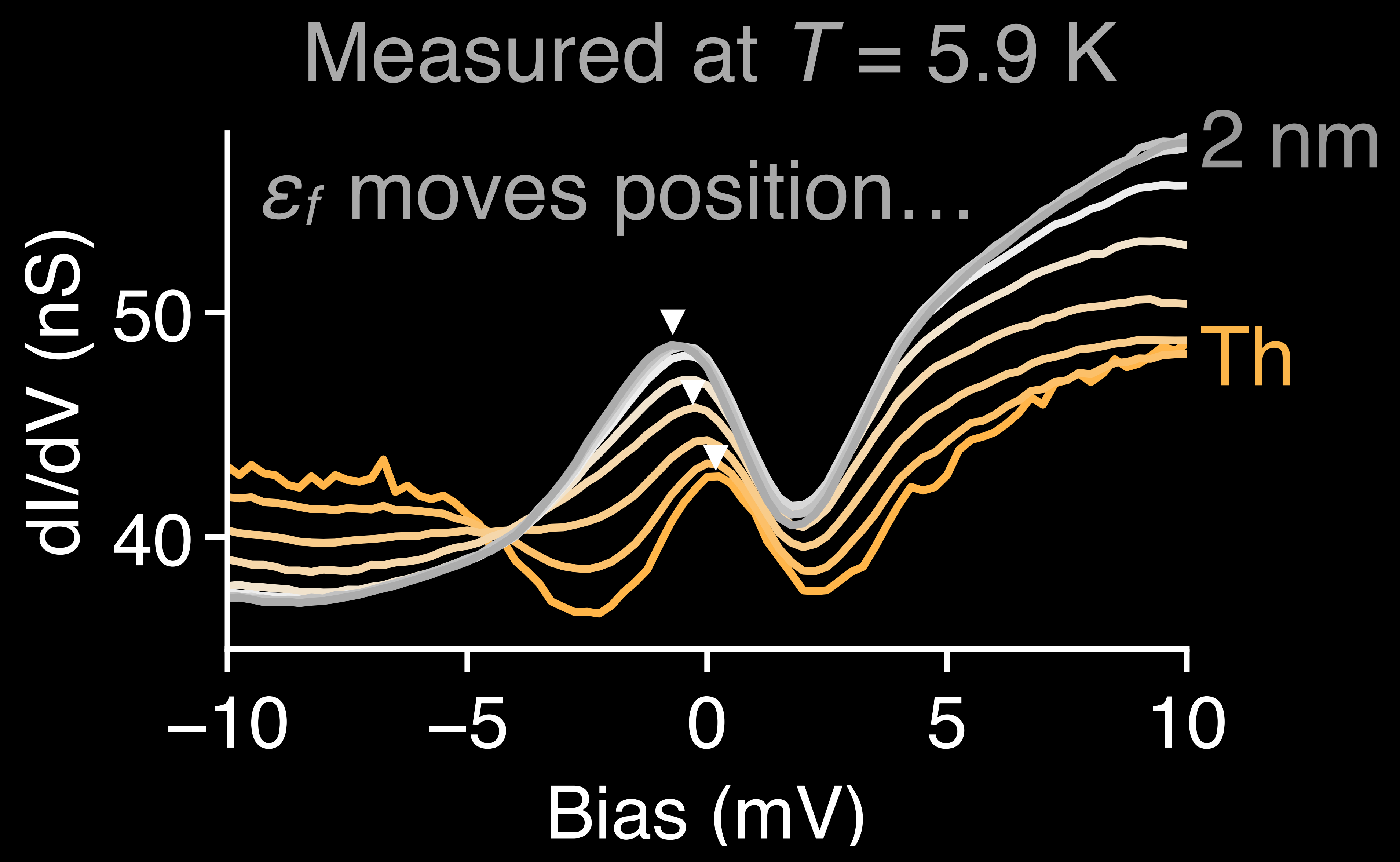


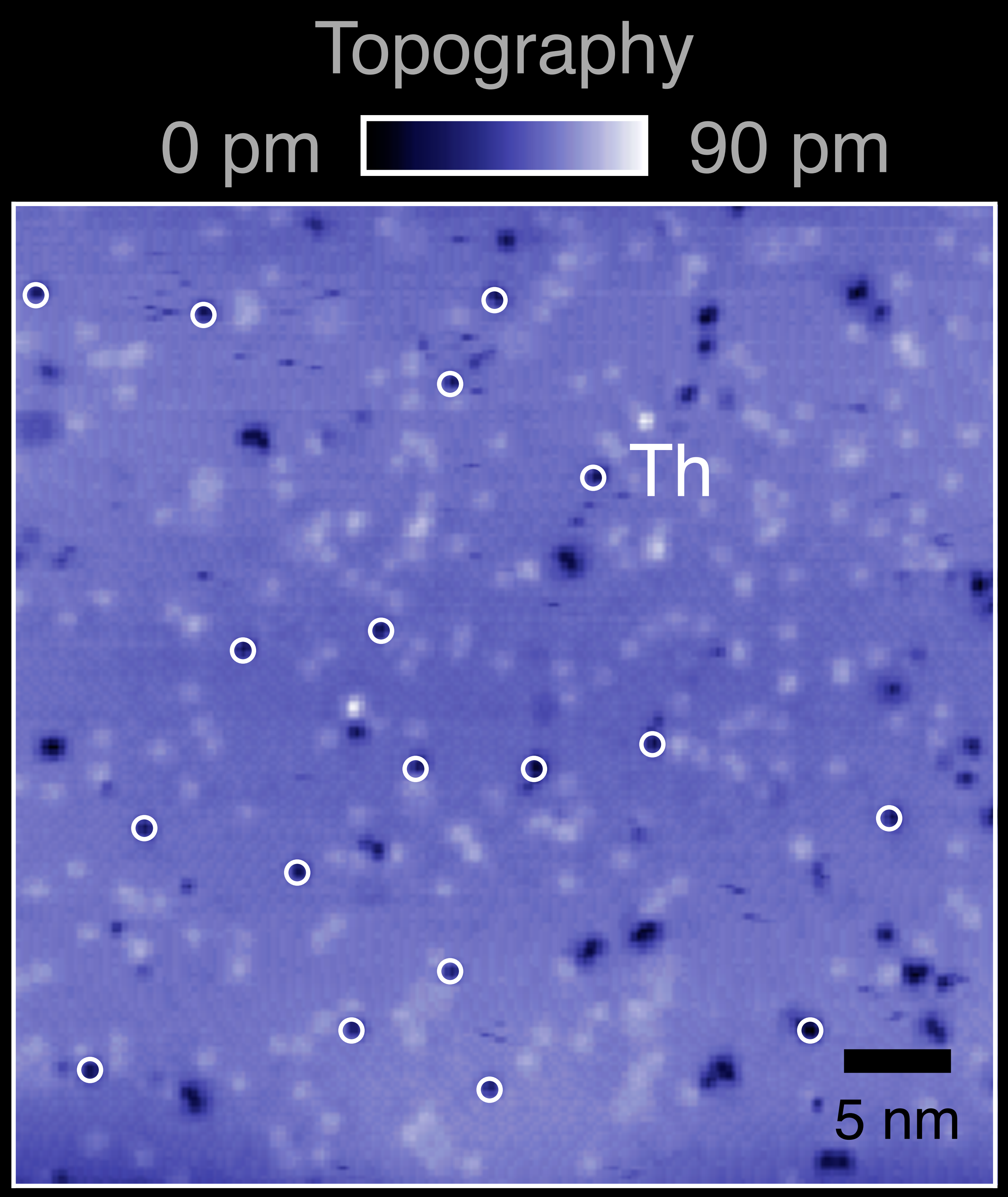




ε_f shifts energy position around Th dopants

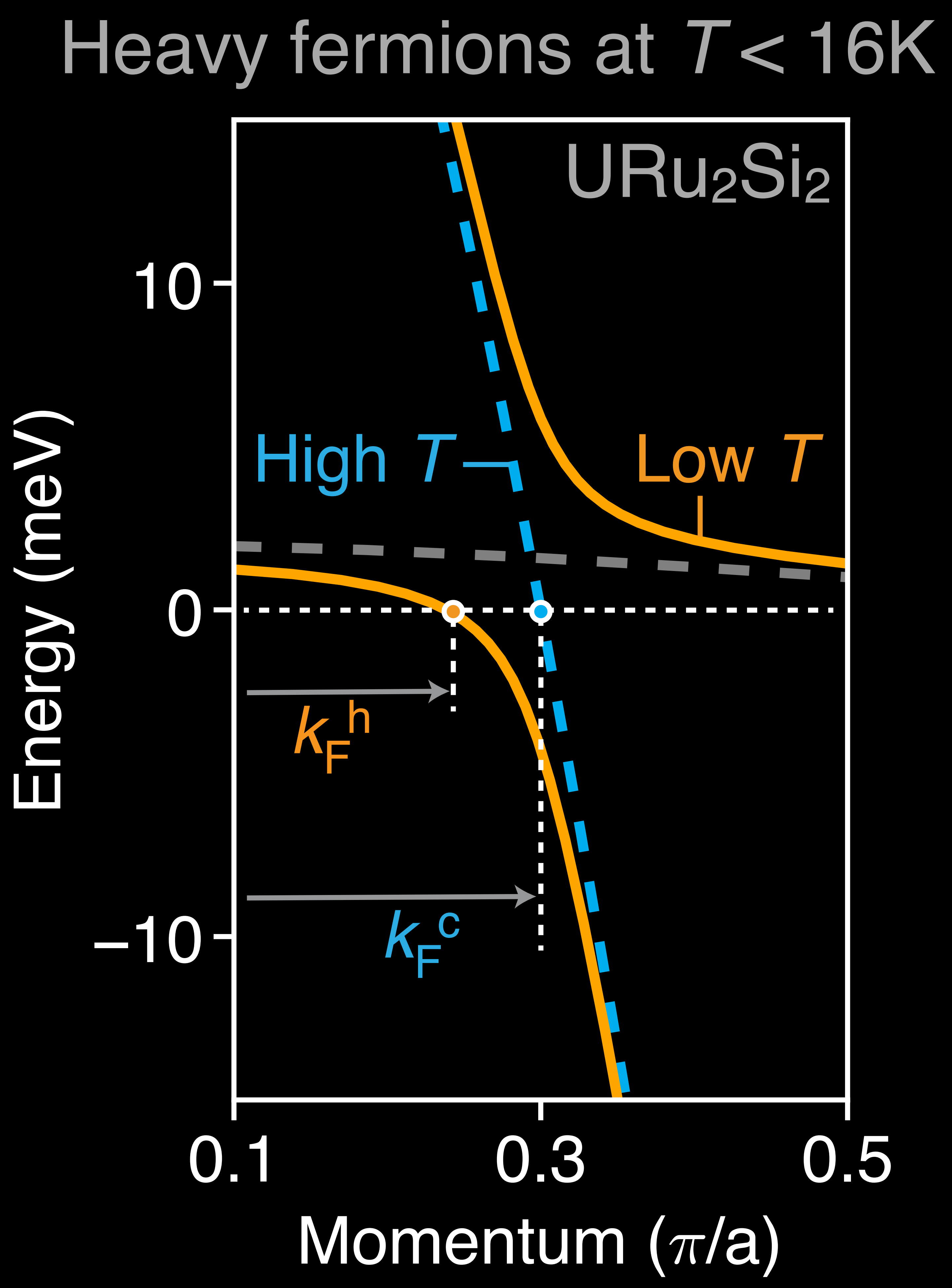


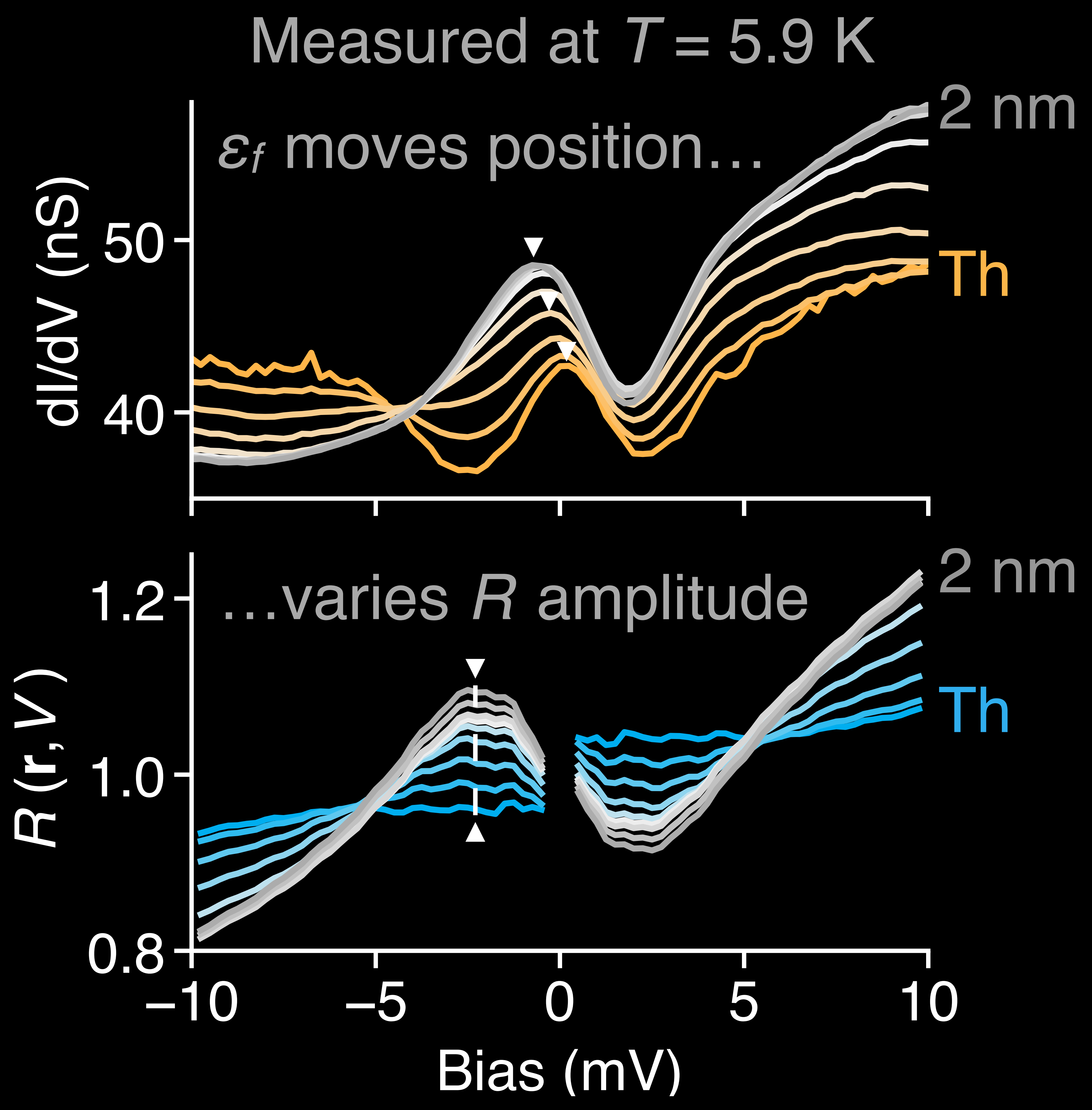


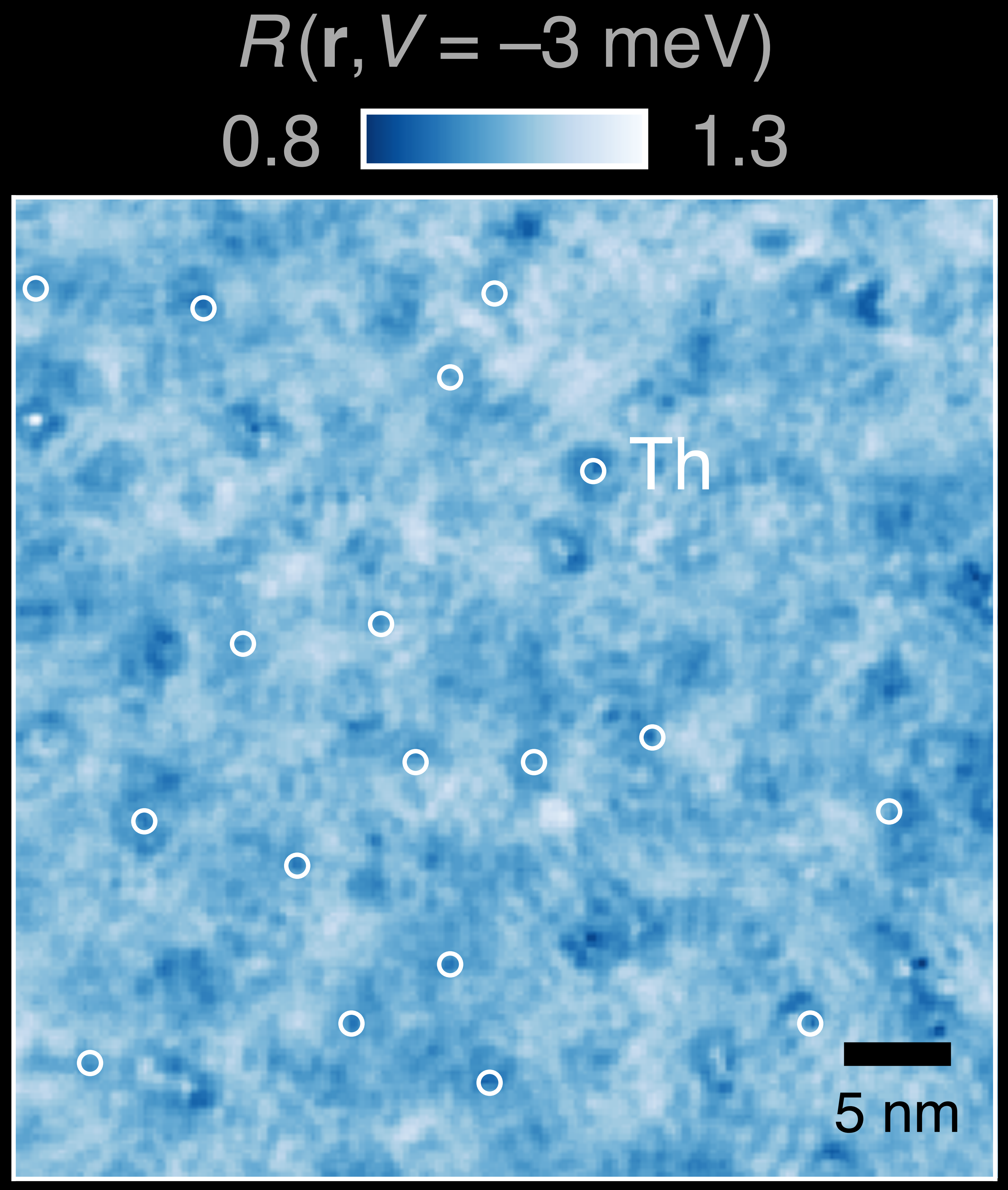


Measured at $T = 5.9$ K

These ε_f shifts are amplified in $R(\mathbf{r}, V)$

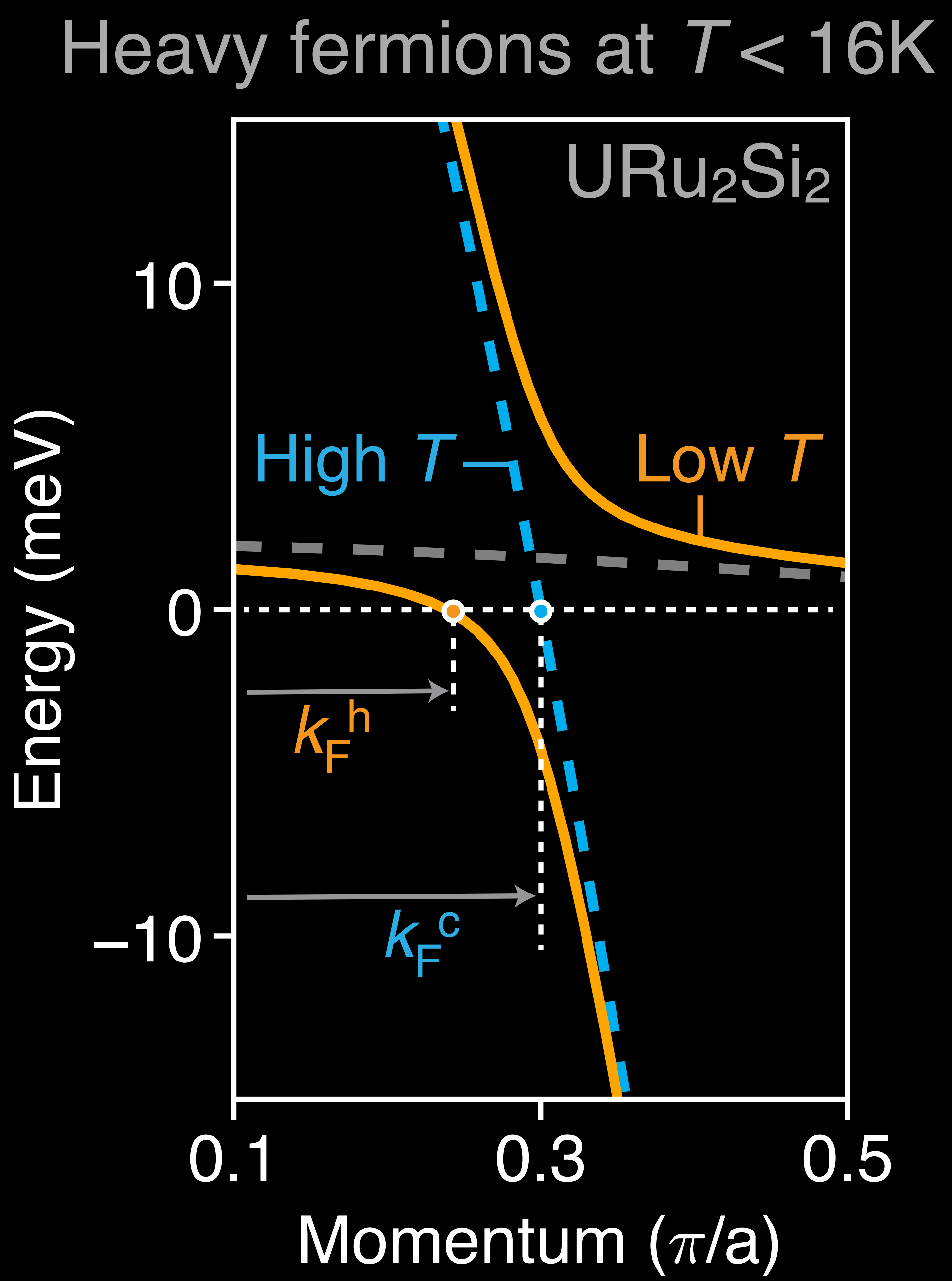


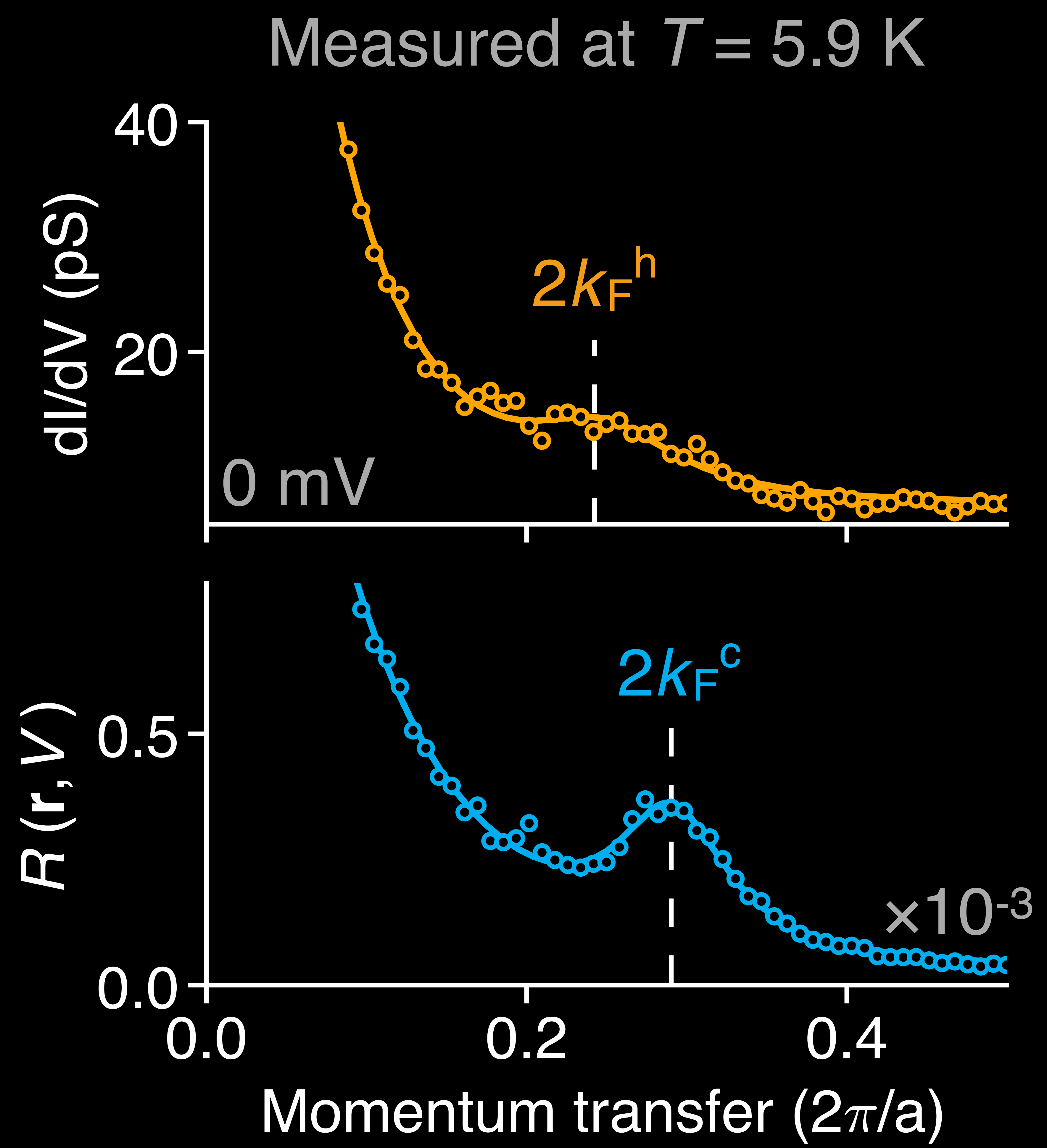


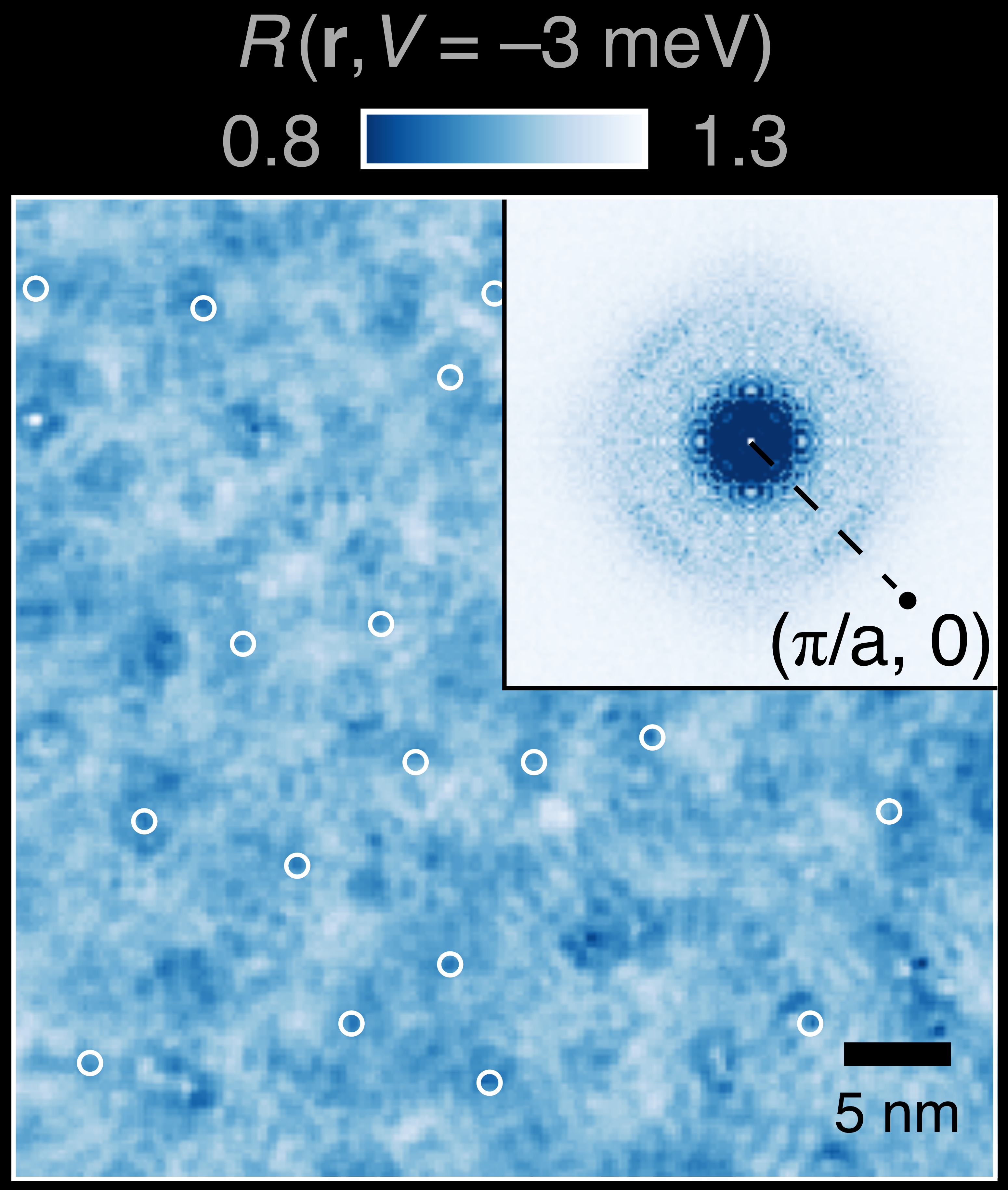


$$R(\mathbf{r}, V) = \frac{I(\mathbf{r}, +V)}{I(\mathbf{r}, -V)}$$

R(r, *V*) reveals itinerant charge



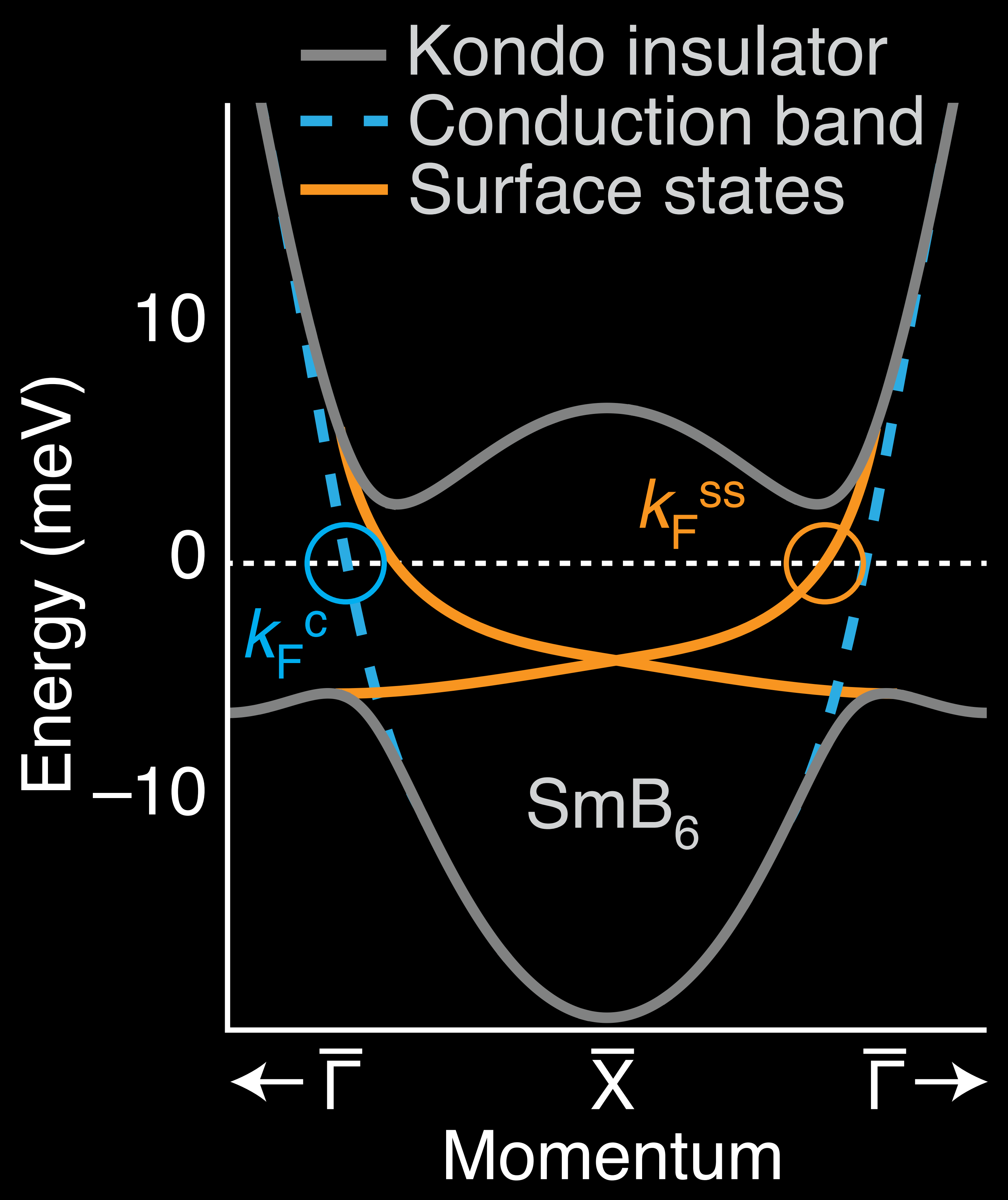




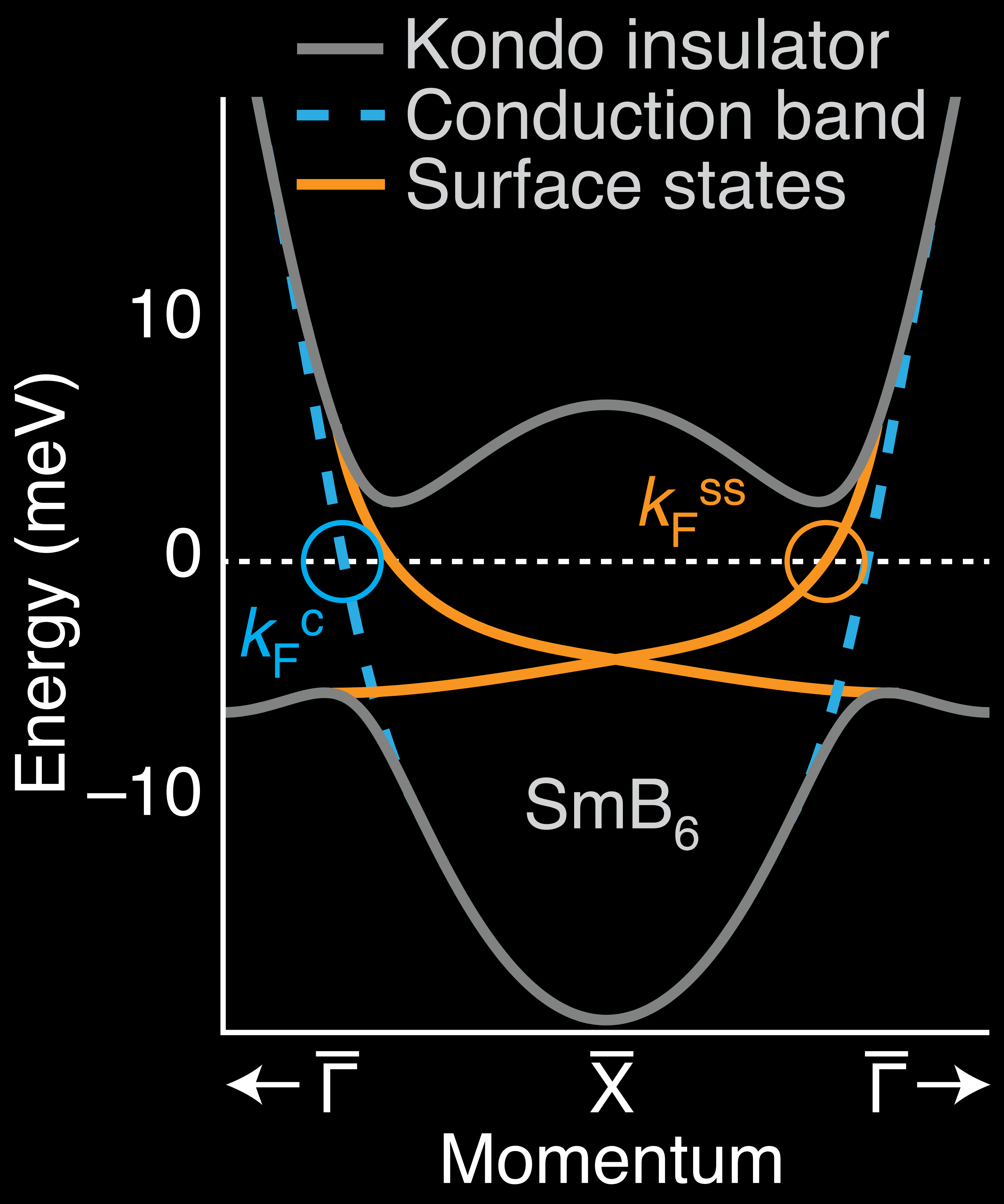
$$R(\mathbf{r}, V) = \frac{I(\mathbf{r}, +V)}{I(\mathbf{r}, -V)}$$

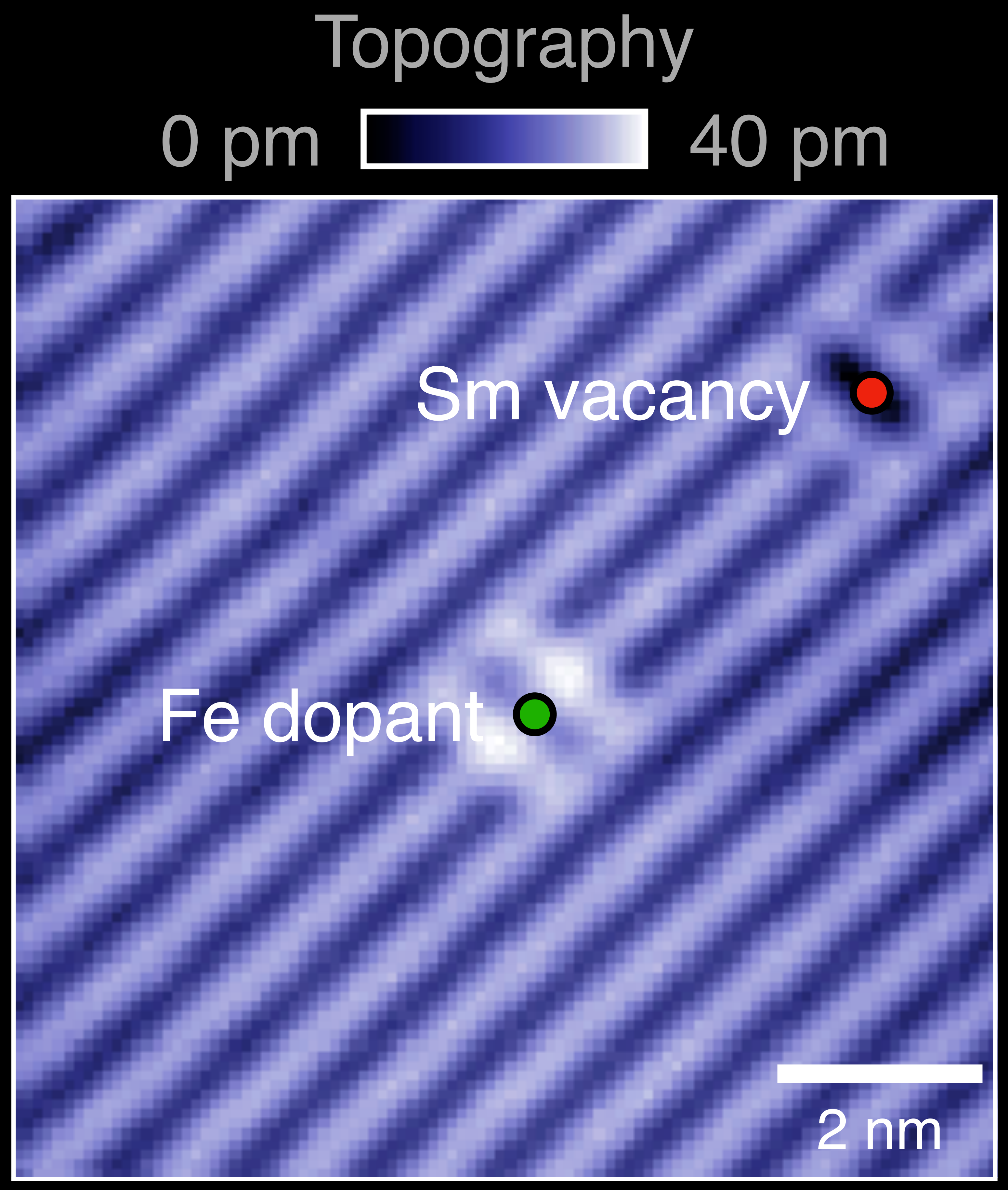
Does this work in SmB_6?

SmB_6 has heavy Dirac fermions on surface



Fe dopants and Sm vacancies replace *f* moments



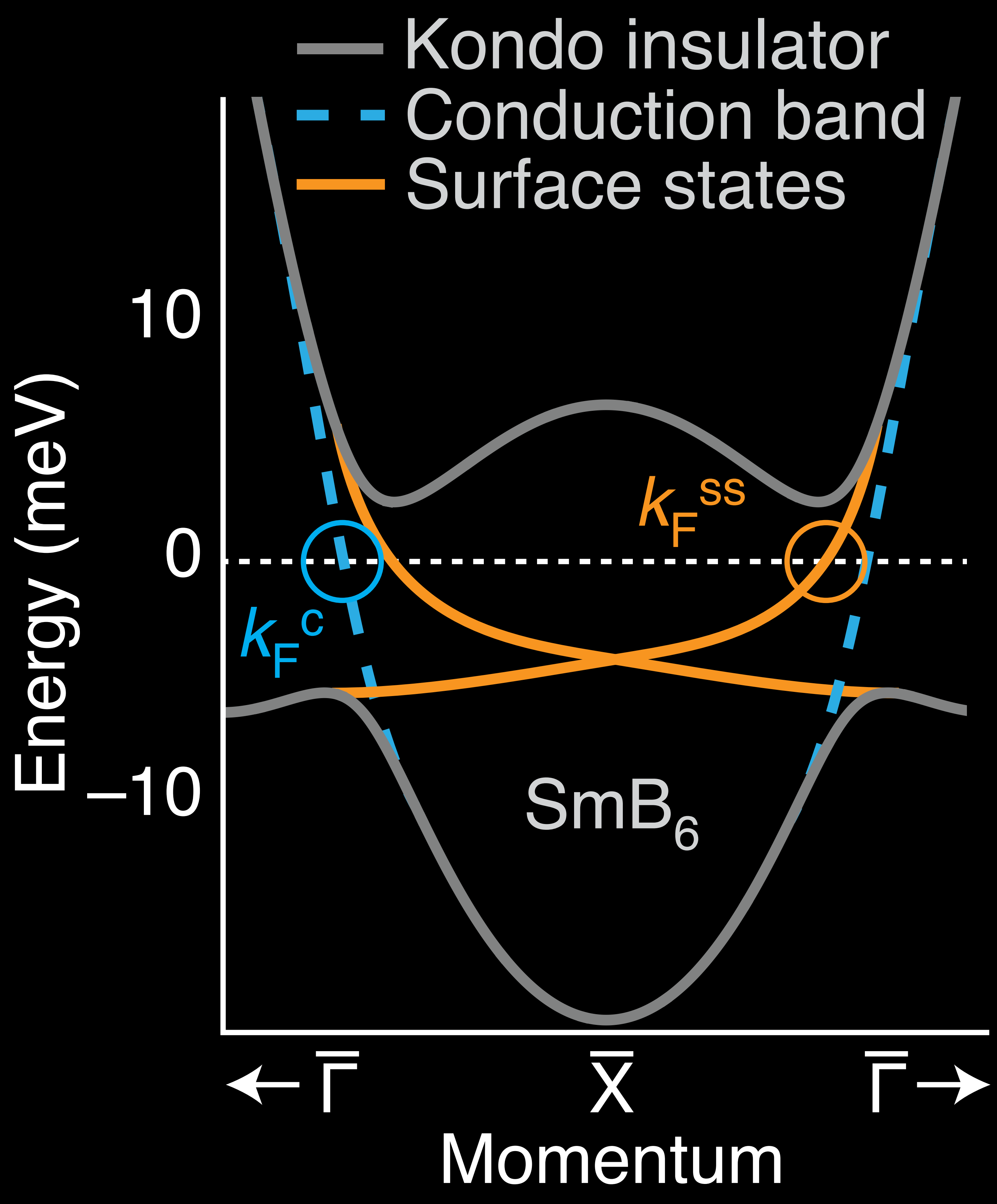


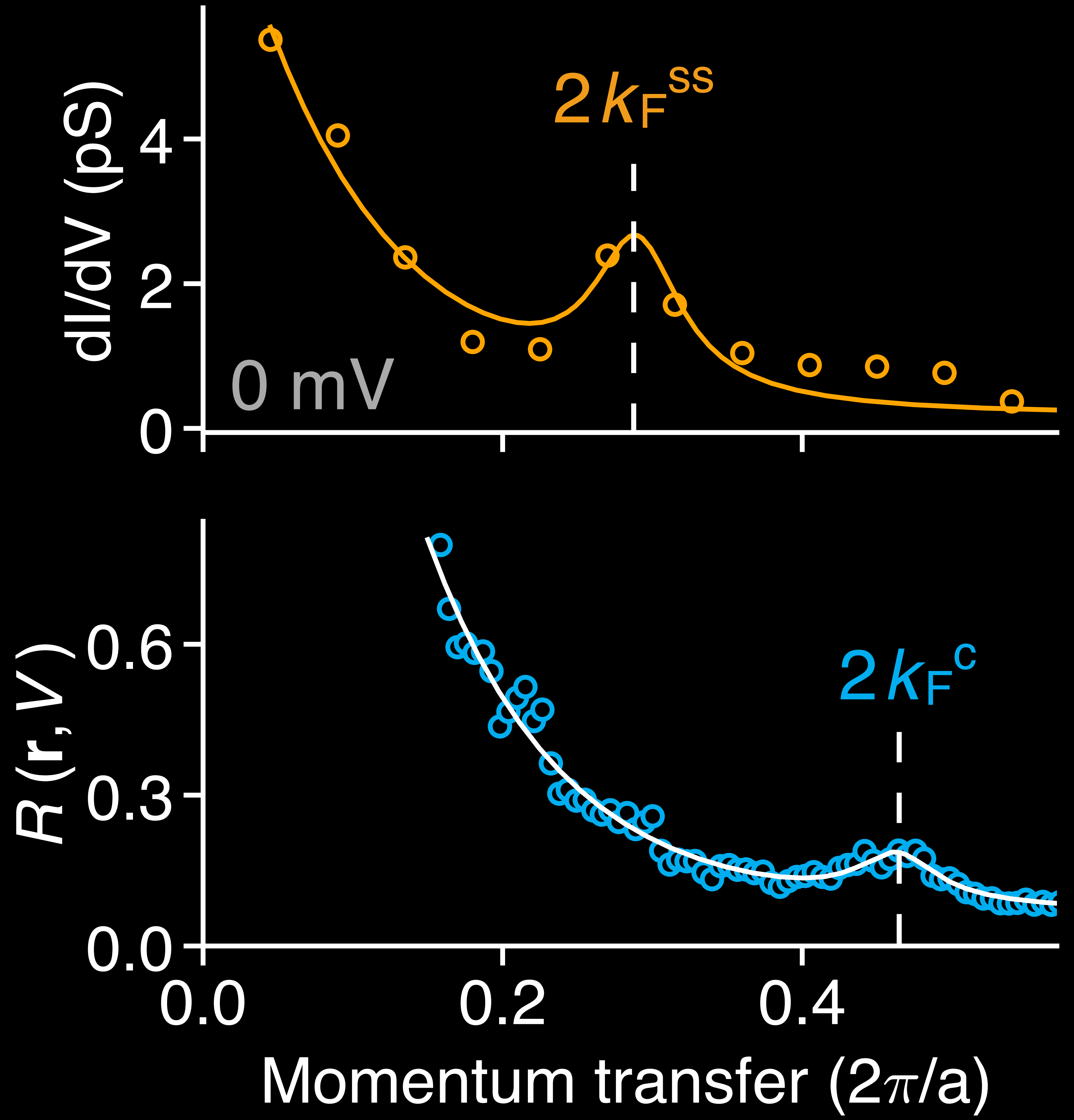
Measured ε_f around dopants

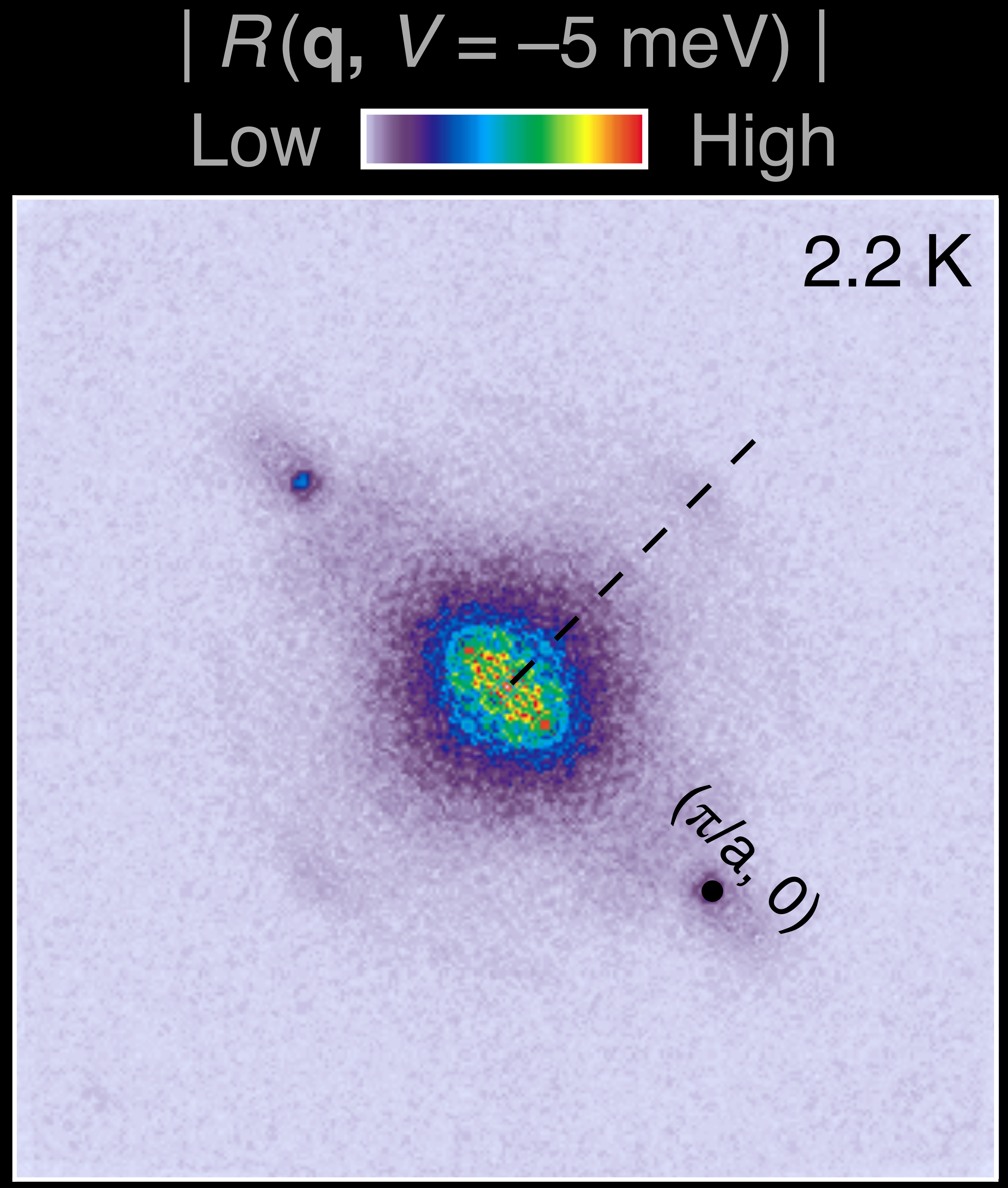
The ε_f shifts are amplified in $R(\mathbf{r}, V)$

$$R(\mathbf{r}, V) = \frac{I(\mathbf{r}, +V)}{I(\mathbf{r}, -V)}$$

Charge oscillations come from light electrons

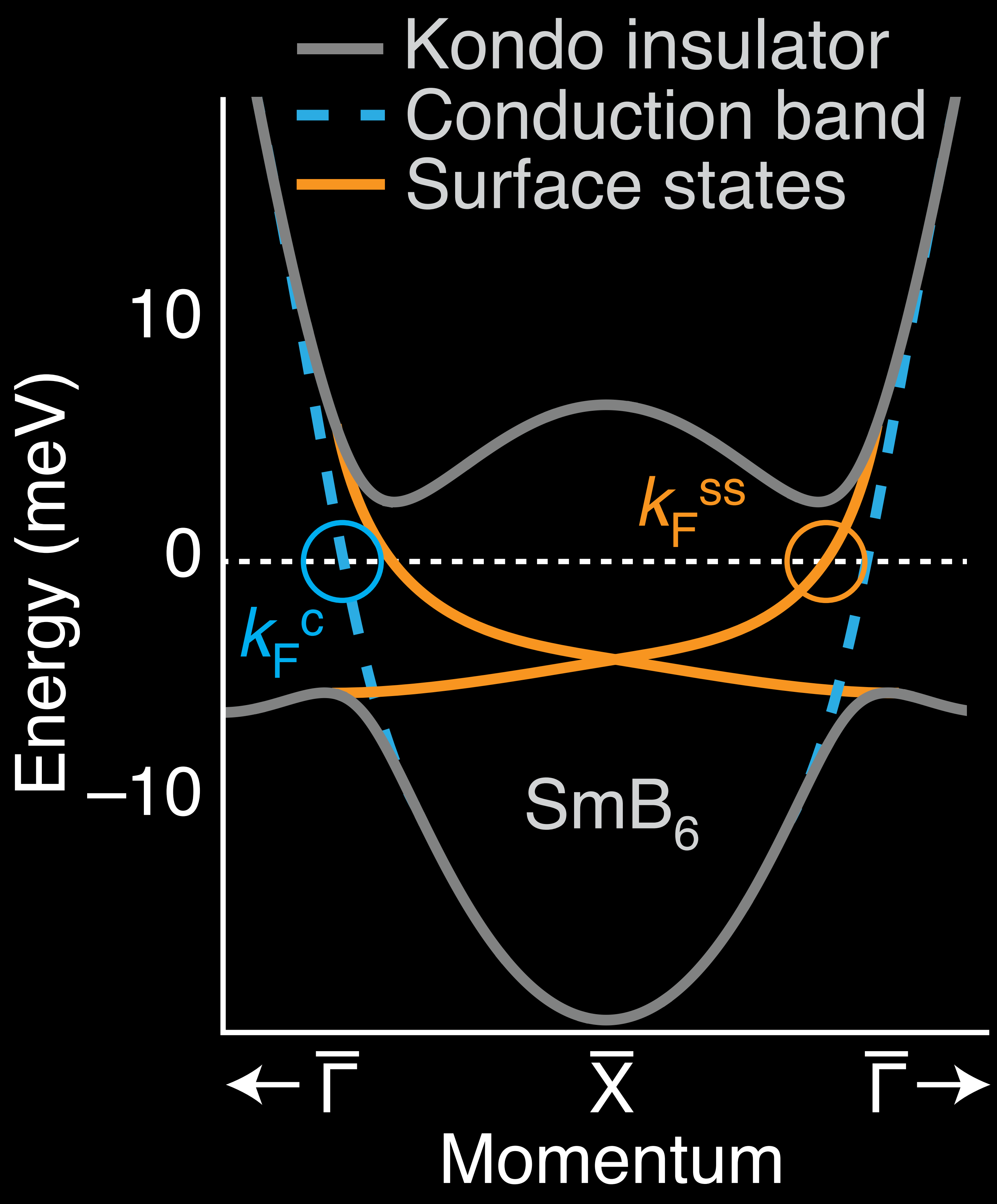


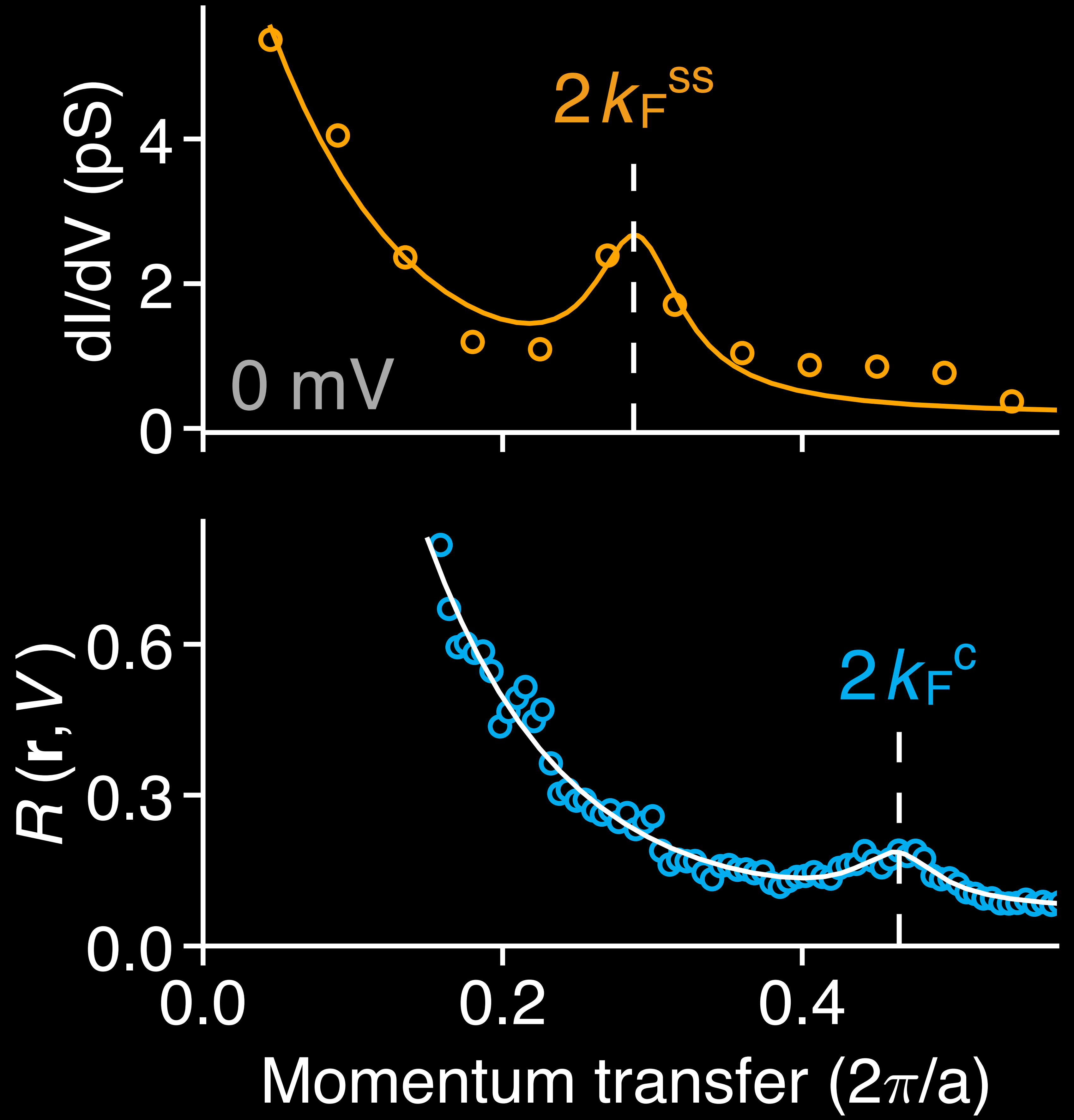


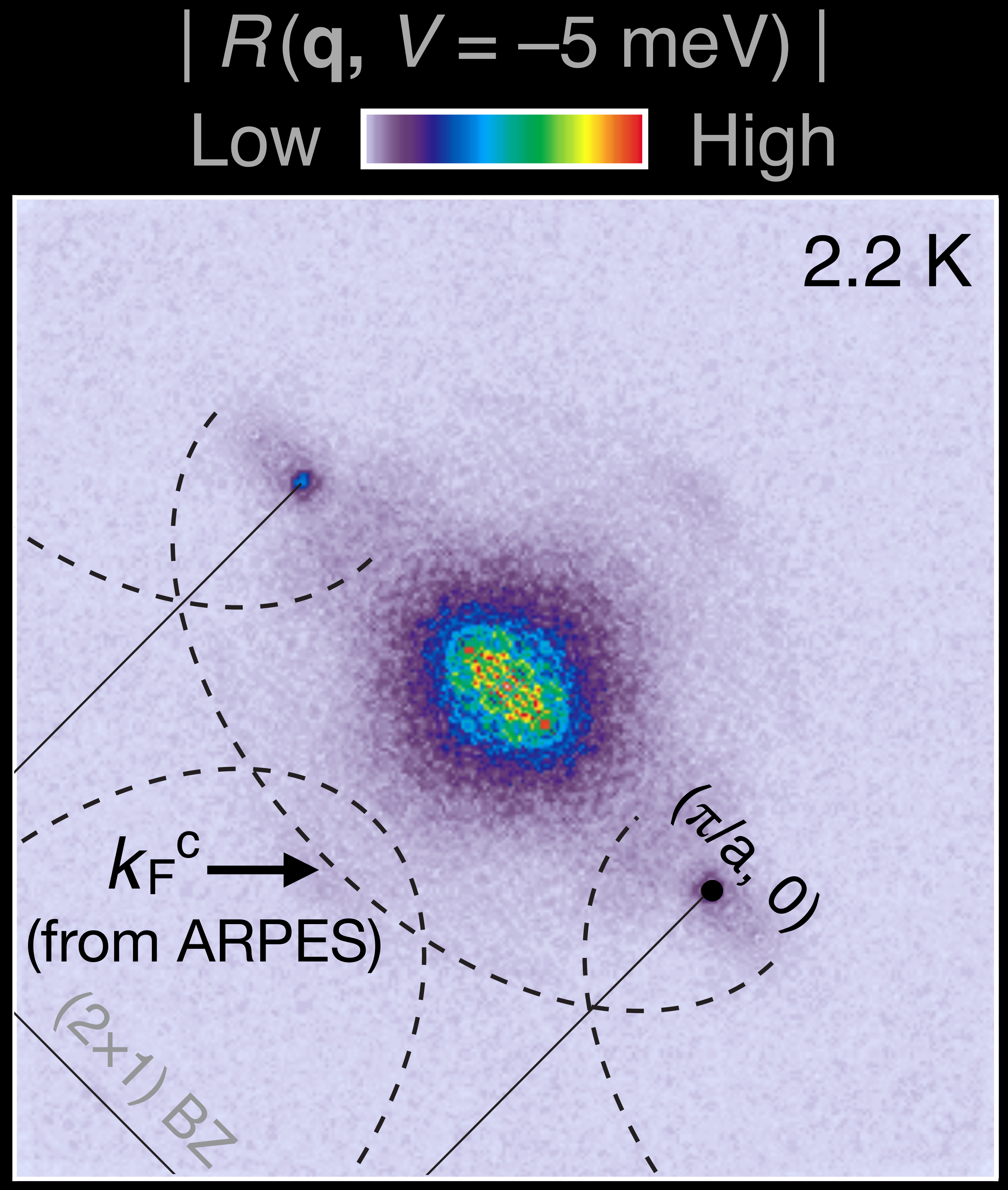


$$R(\mathbf{r}, V) = \frac{I(\mathbf{r}, +V)}{I(\mathbf{r}, -V)}$$

Charge oscillations come from light electrons







$$R(\mathbf{r}, V) = \frac{I(\mathbf{r}, +V)}{I(\mathbf{r}, -V)}$$

Is the origin intrinsic or extrinsic?

We will answer this question **experimentally:**

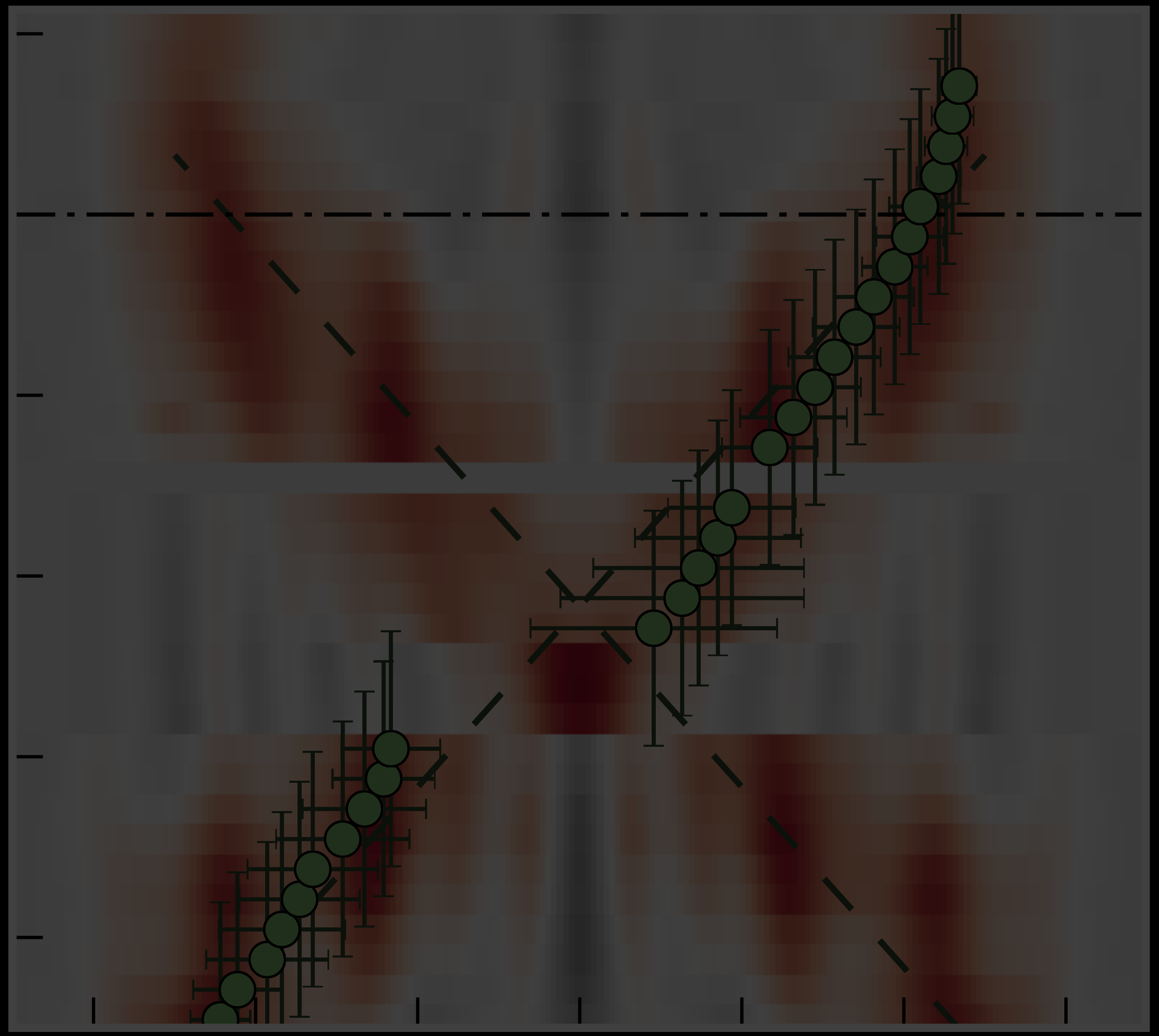
Question: Is there microscopic evidence of **light electrons?**

Answer: **Yes**, light electrons are released by Kondo holes

Time

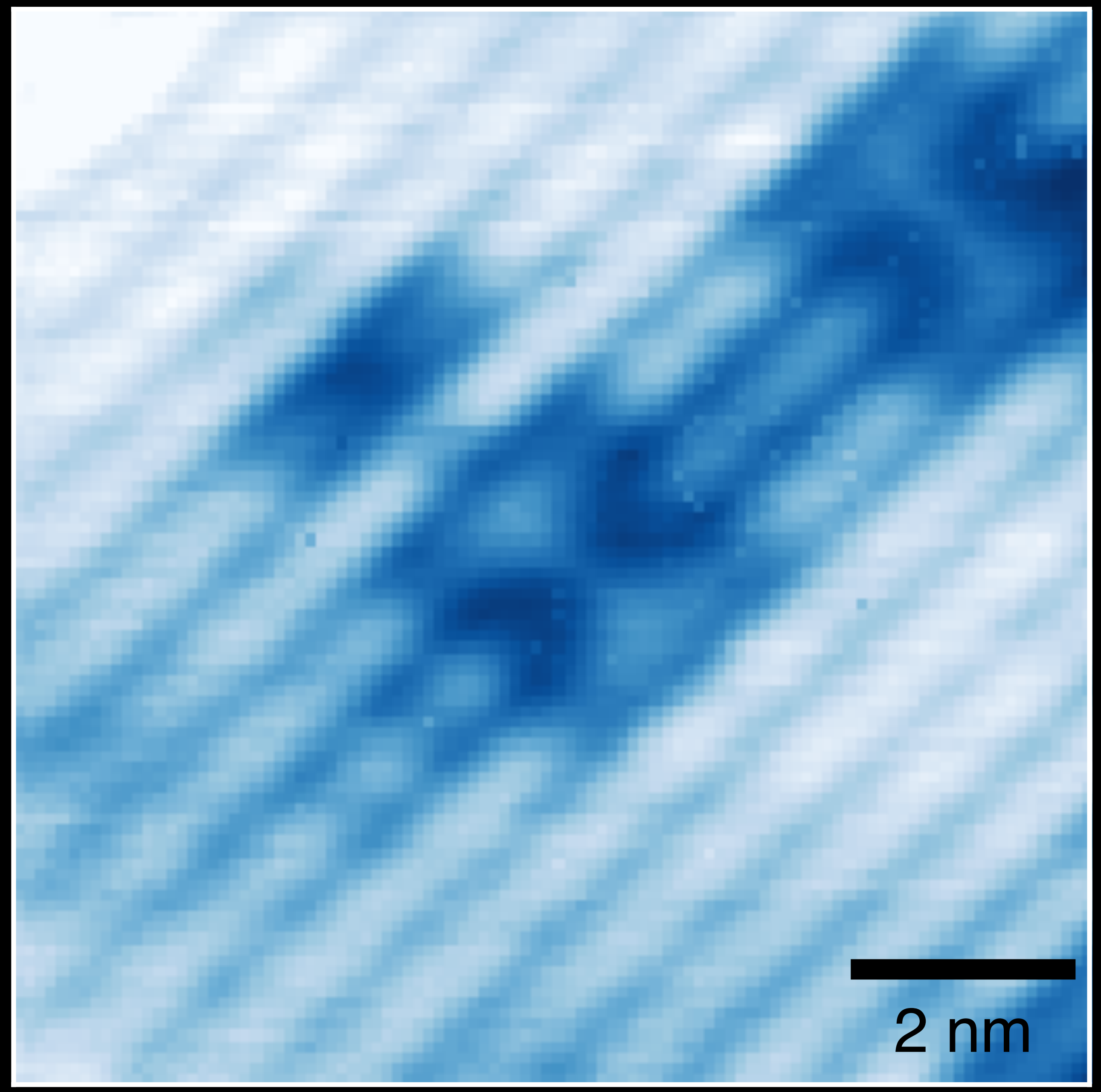
Outline

(1) Dirac fermions **410 times** heavier than a bare electron!



Pirie et al., *Nat. Phys.* **16**, 52 (2020)
Matt et al., *Phys. Rev. B* **101**, 085142 (2020)

(2) Metallicity in an **insulator**!

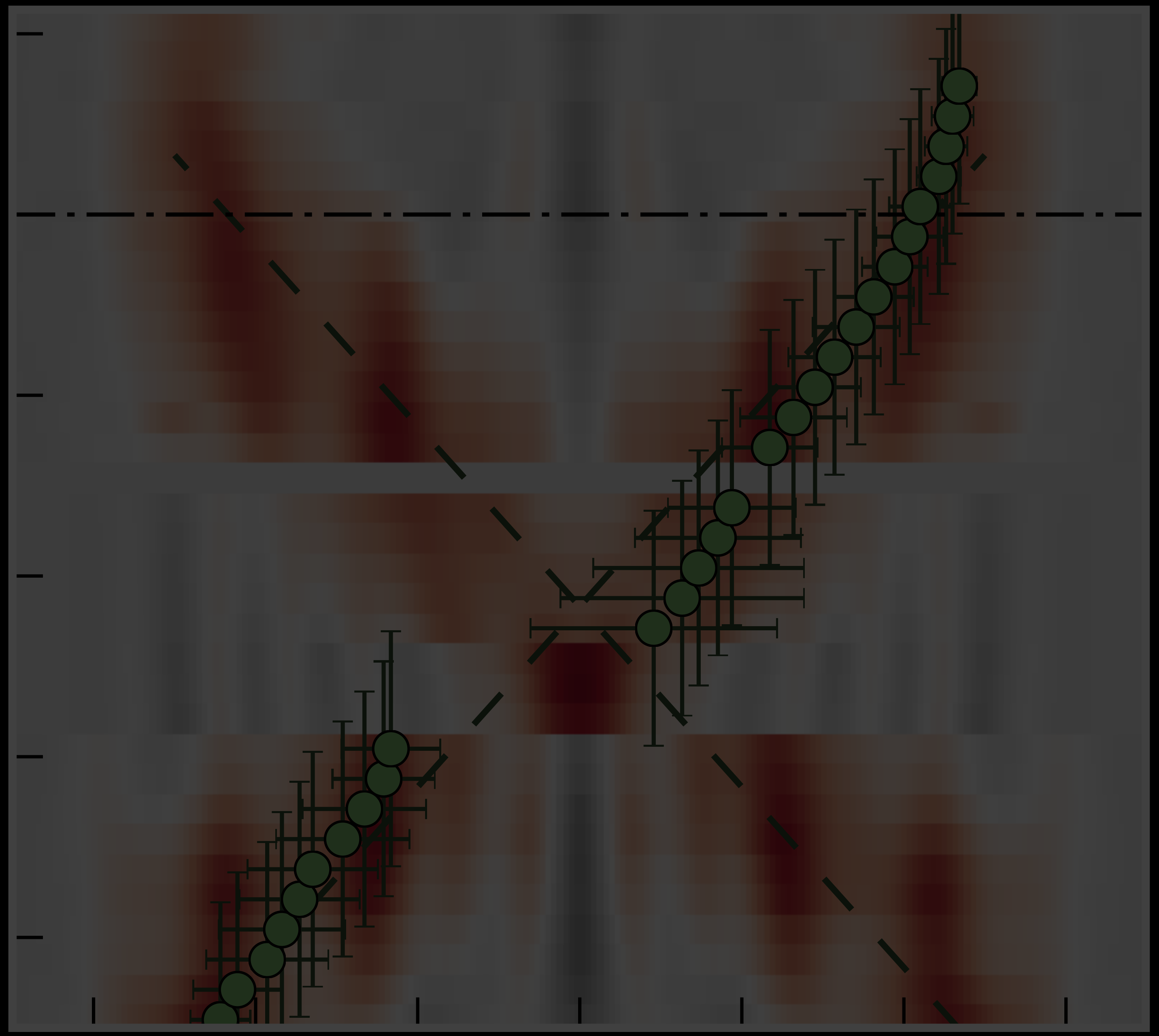


Pirie et al., *Science* **379**, 1214 (2023)

(3) Breakdown of **topological protection**!

Outline

(1) Dirac fermions **410 times** heavier than a bare electron!



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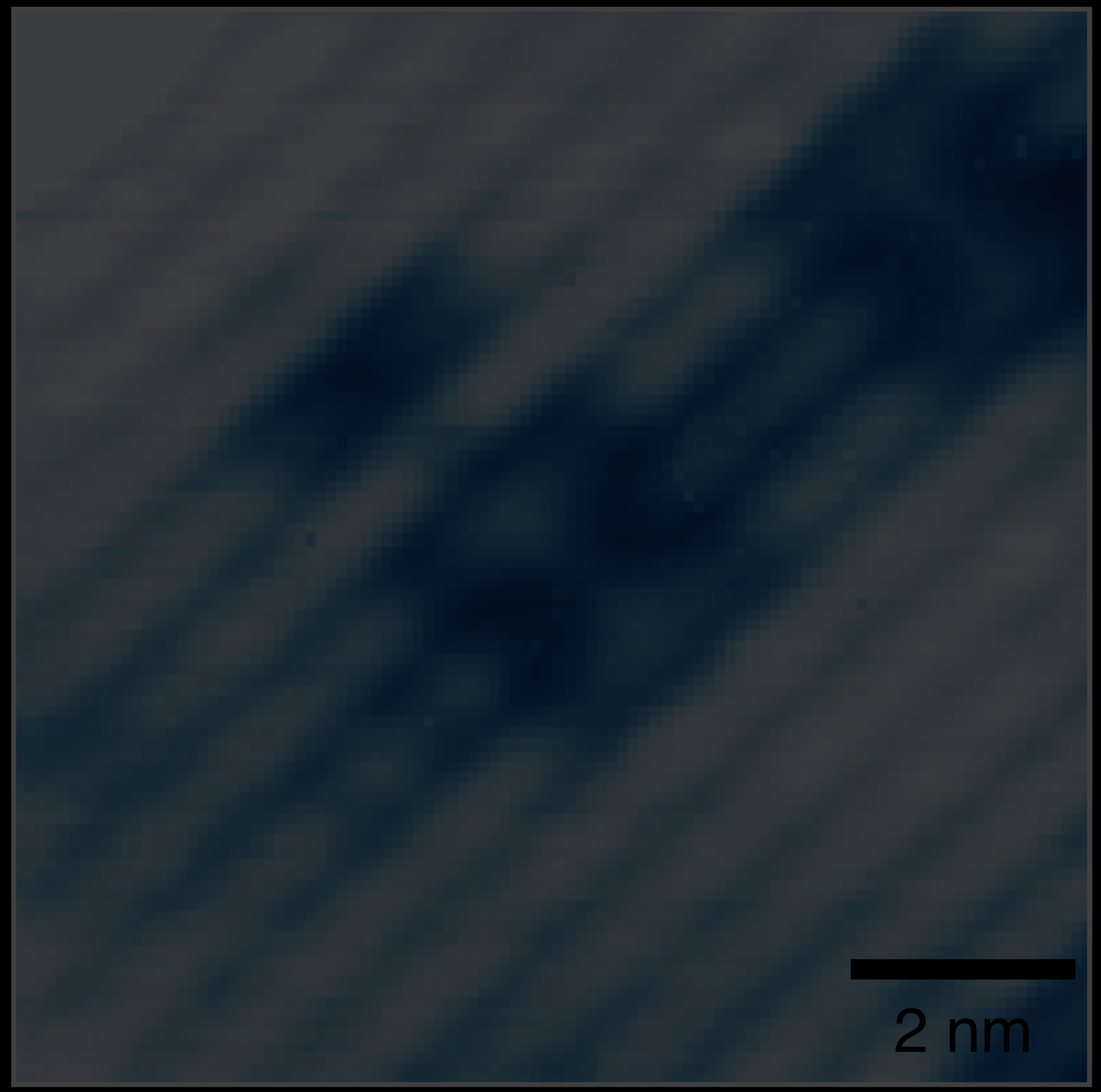

Pirie et al., *Science* **379**, 1214 (2023)

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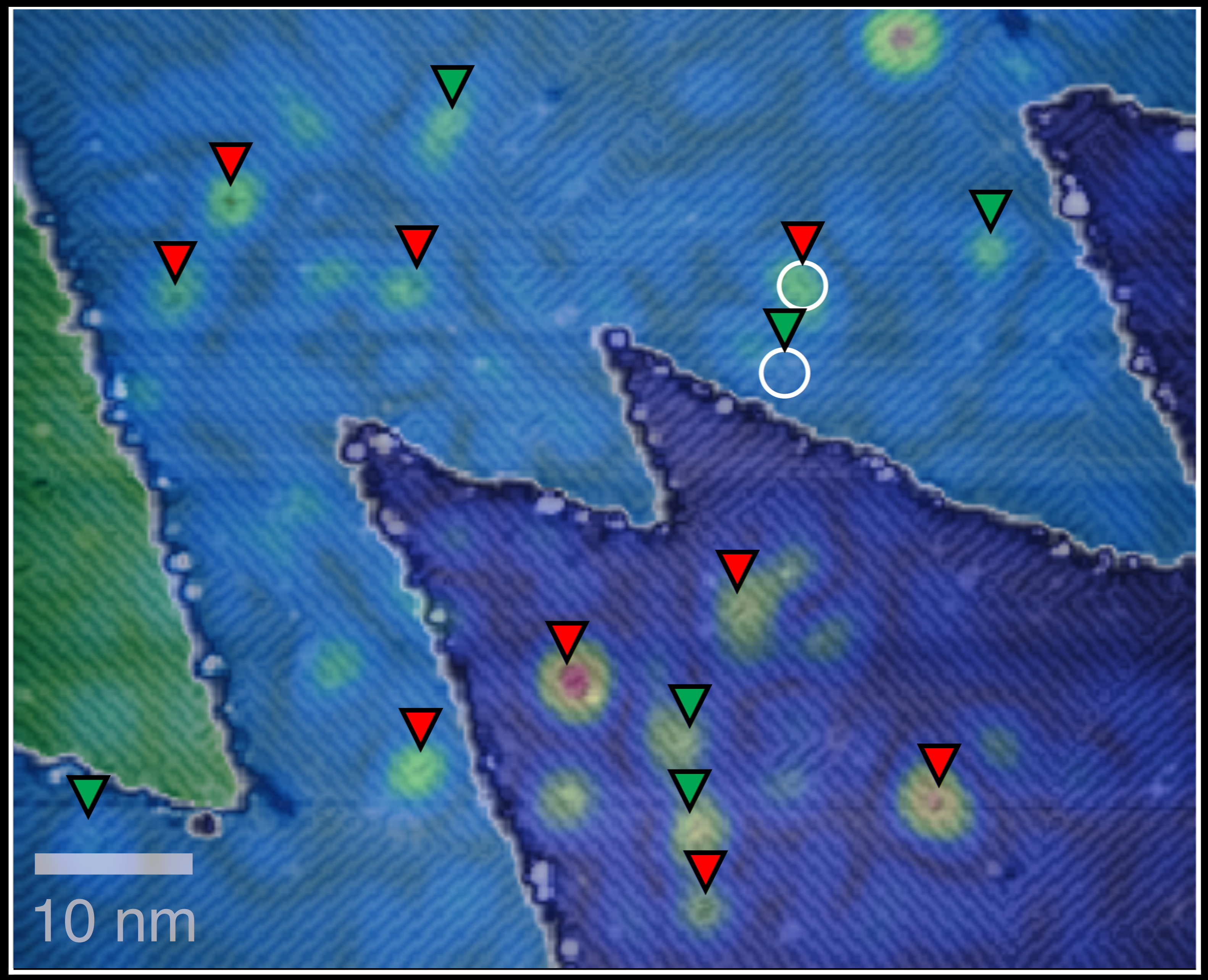

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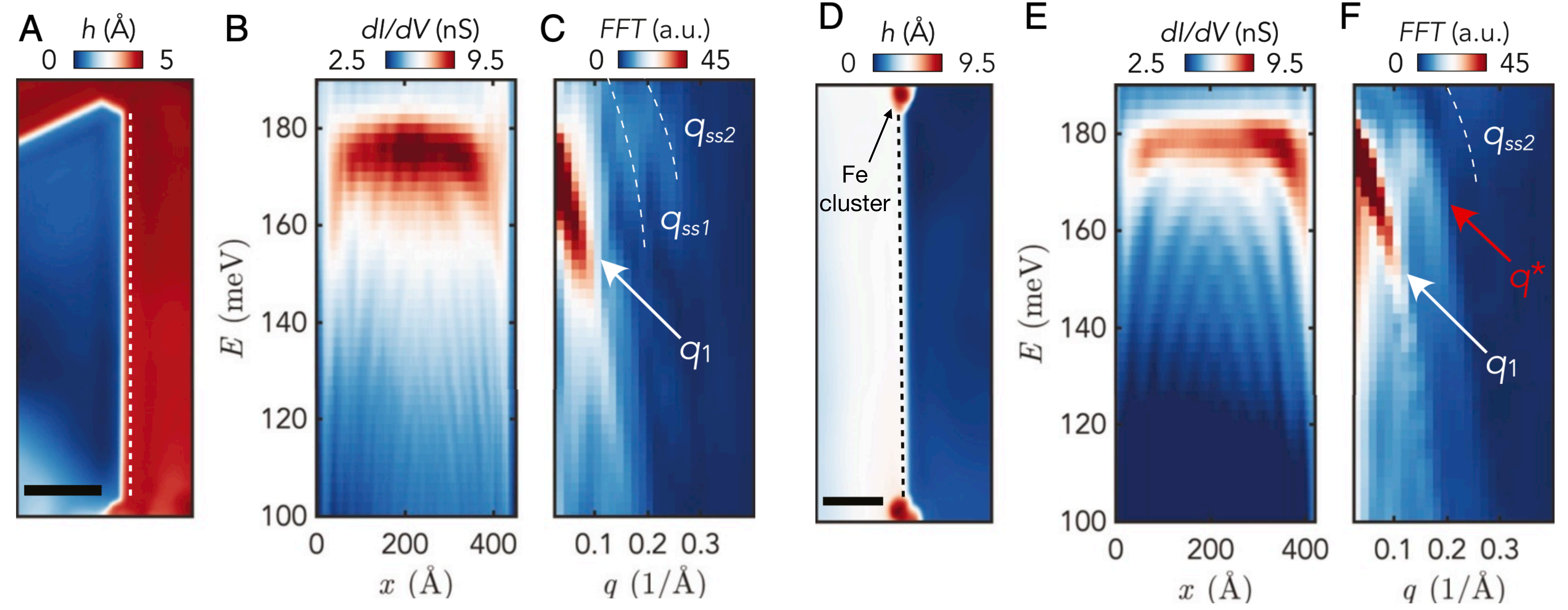
Question: Do the metallic puddles have a finite magnetic susceptibility?

Topological states are a magnetic probe

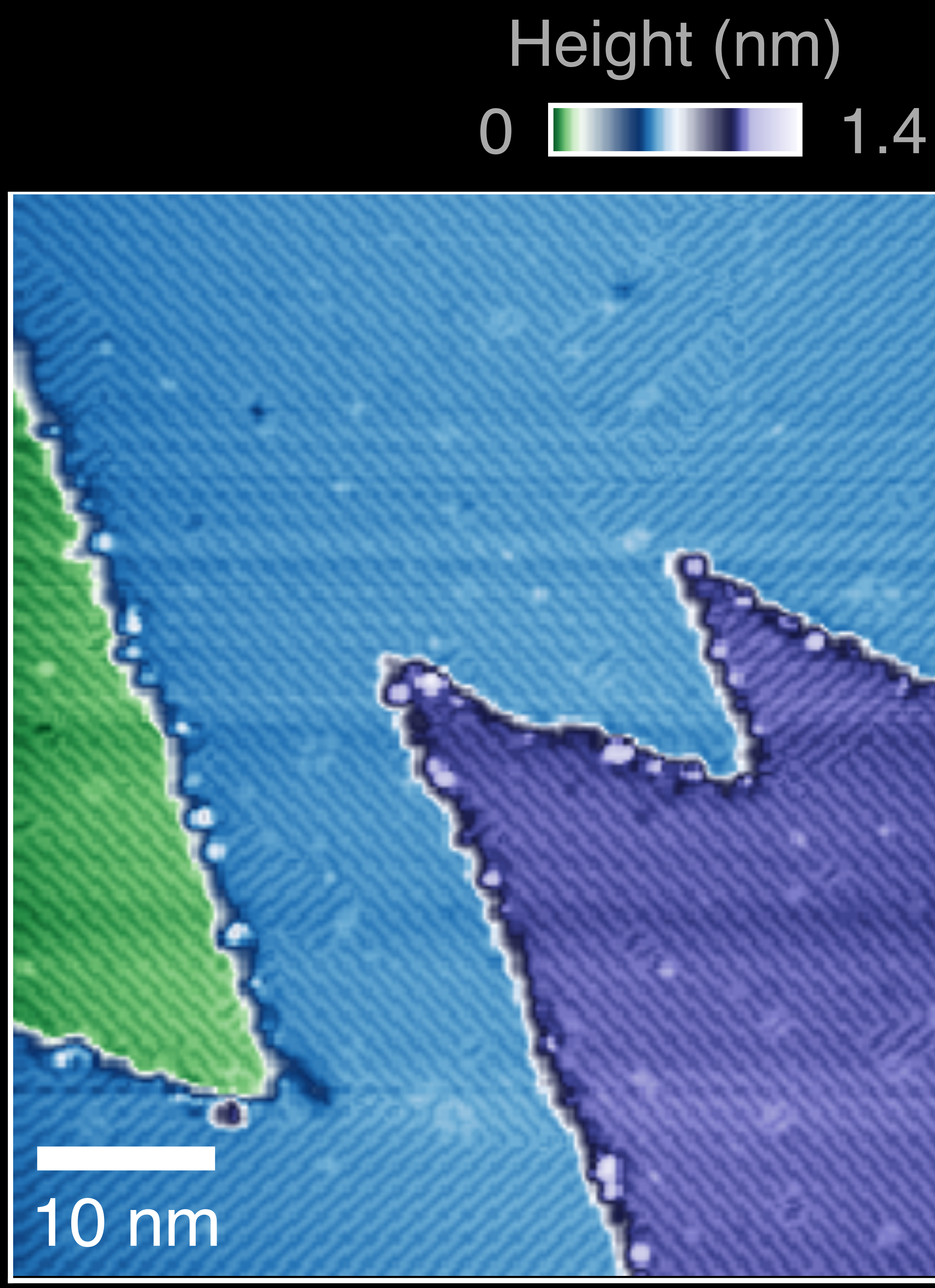
Observation of backscattering induced by magnetism in a topological edge state

Berthold Jäck[a,b], Yonglong Xie[a,b], B. Andrei Bernevig[a,b], and Ali Yazdani[a,b,1]

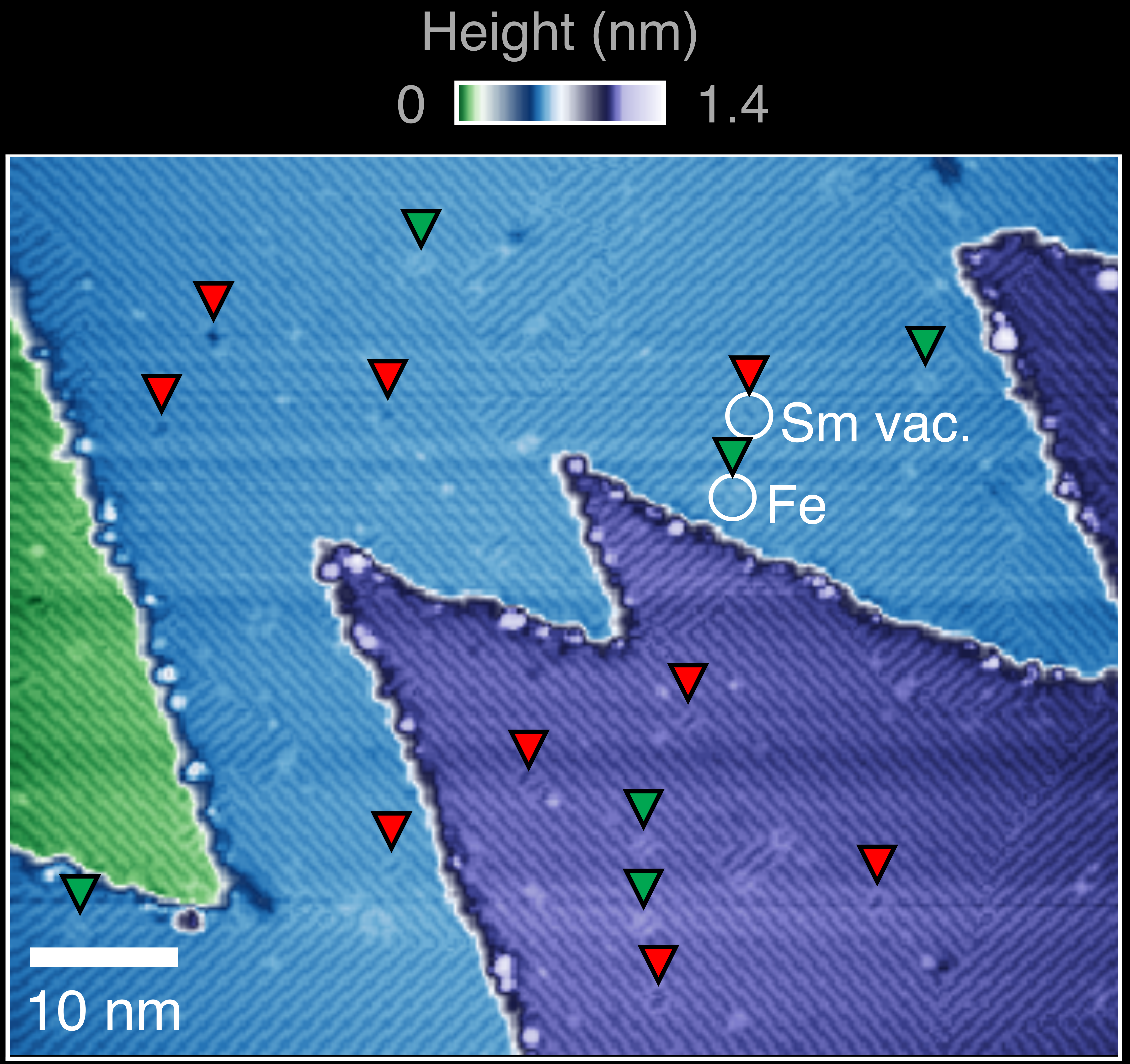


Jäck et al., *Proc. Natl. Acad. Sci. U.S.A.* **117**, 1621 (2020)

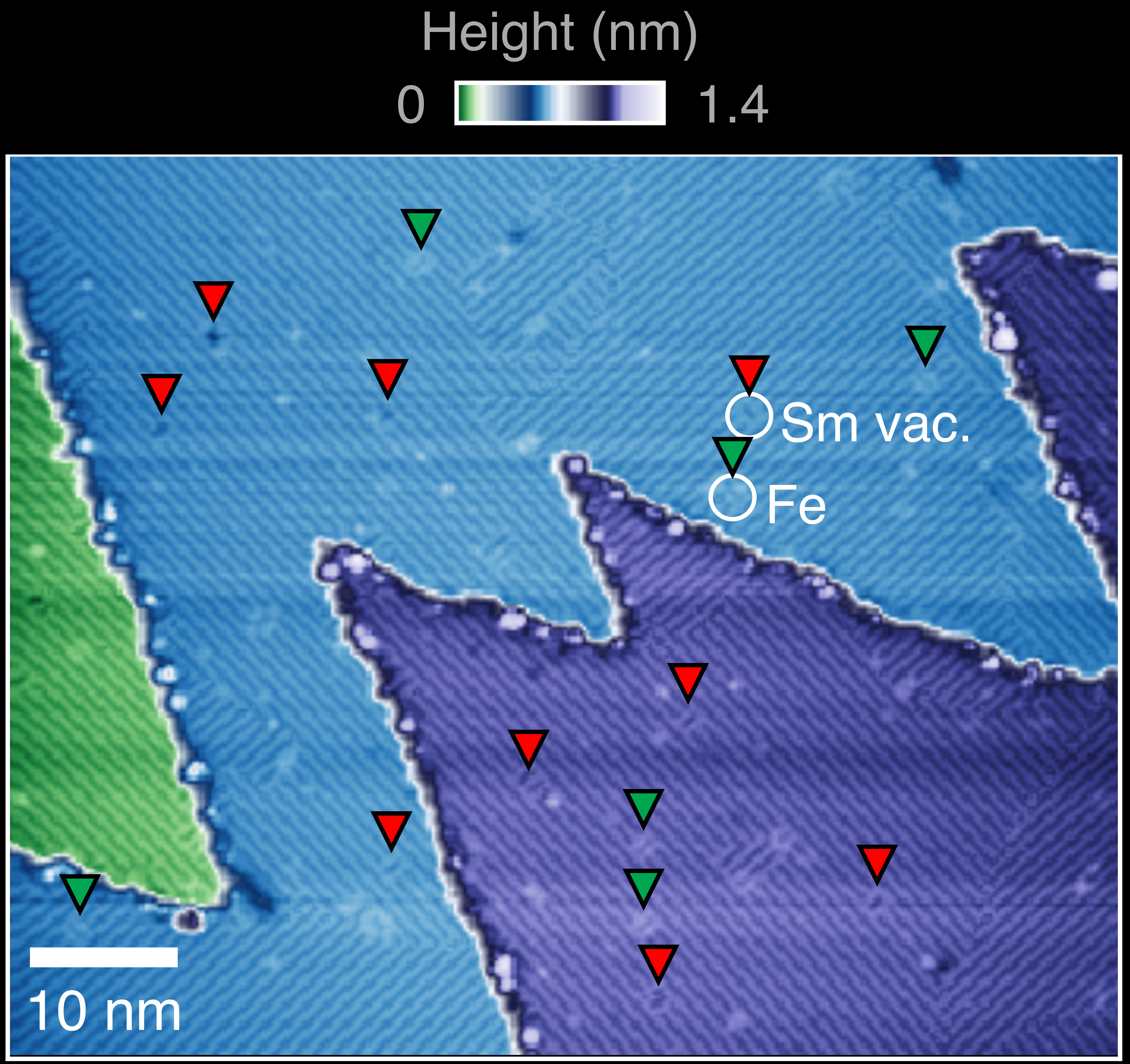
Which defects backscatter Dirac fermions?

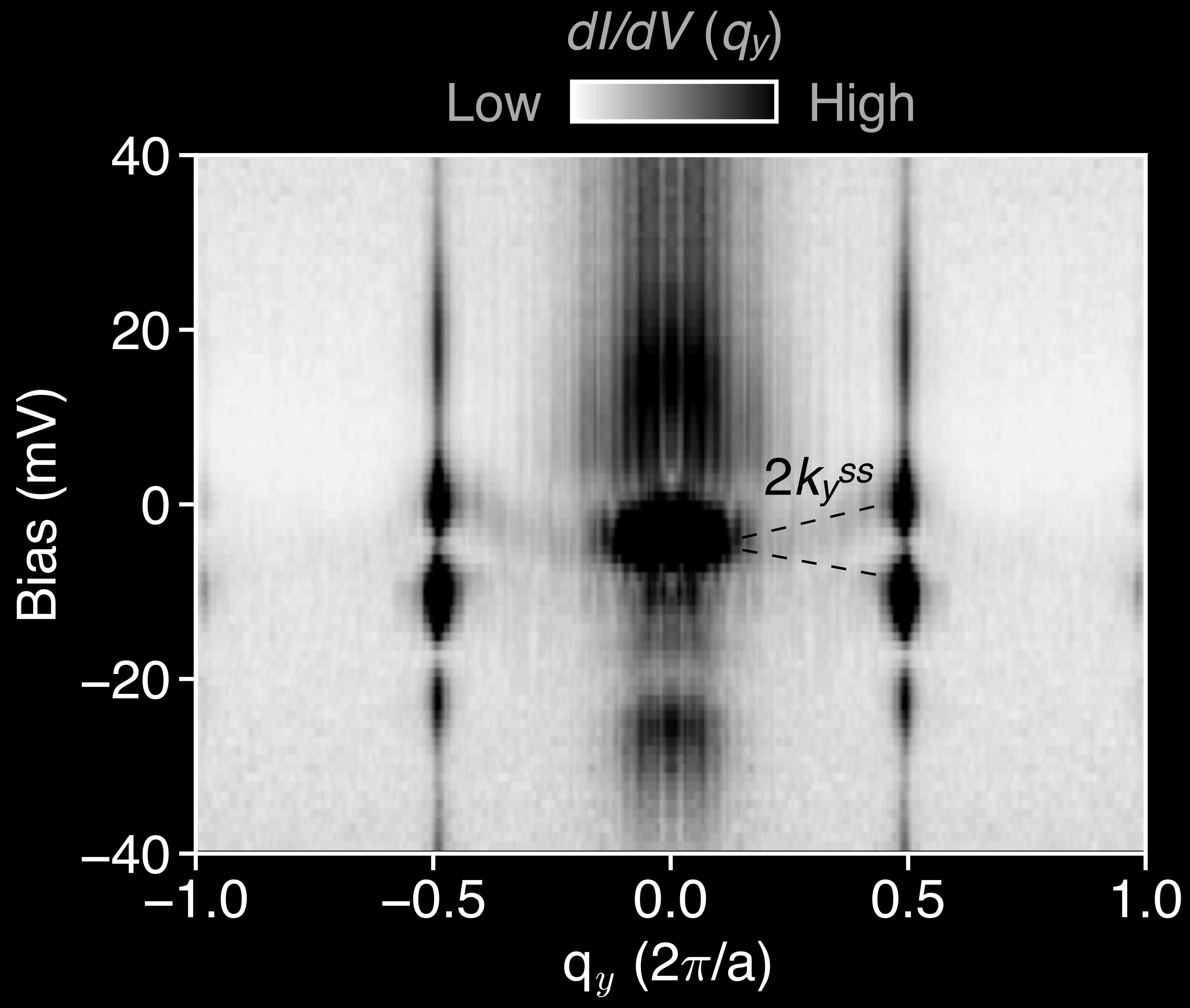


Which defects backscatter Dirac fermions?

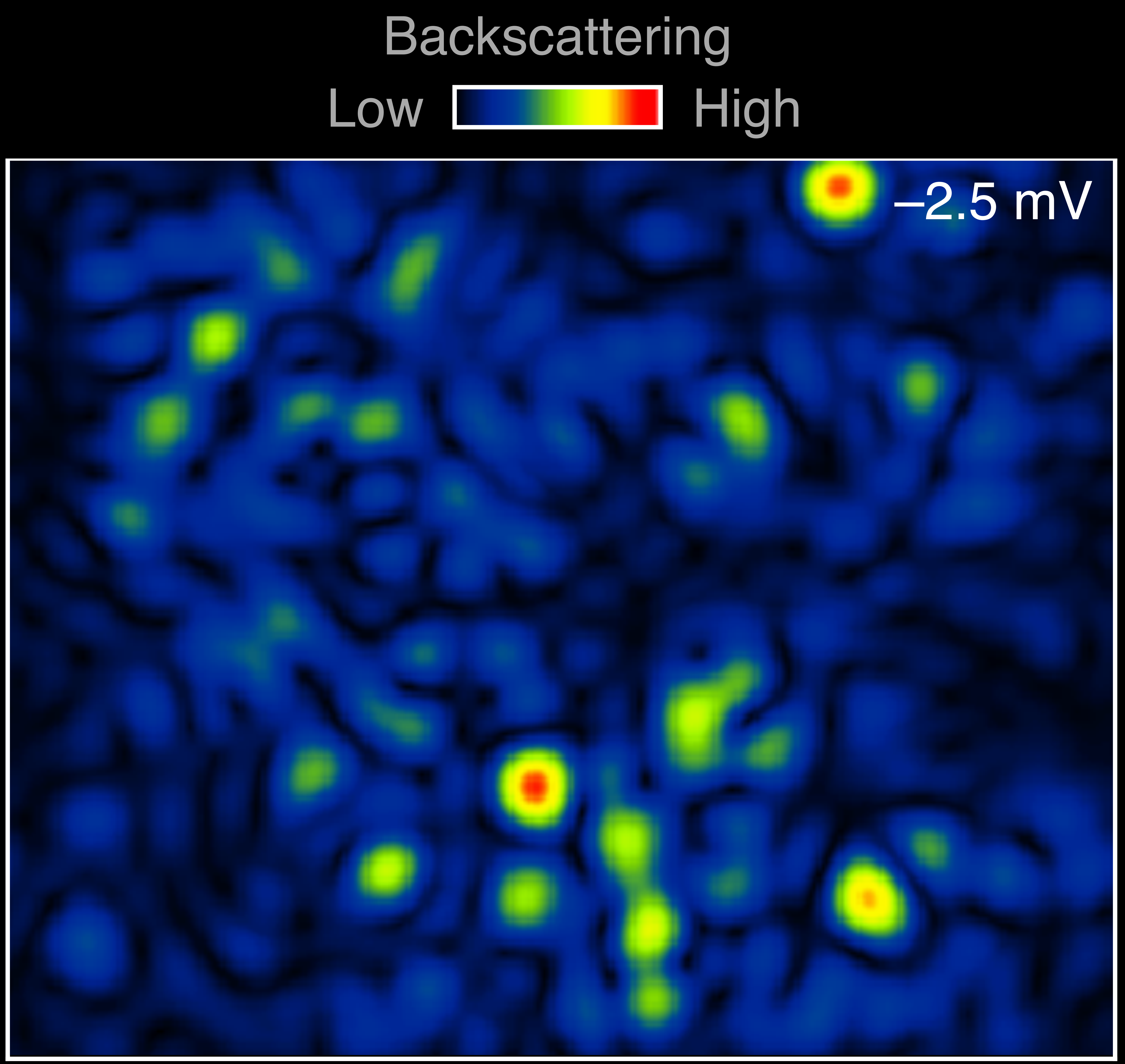


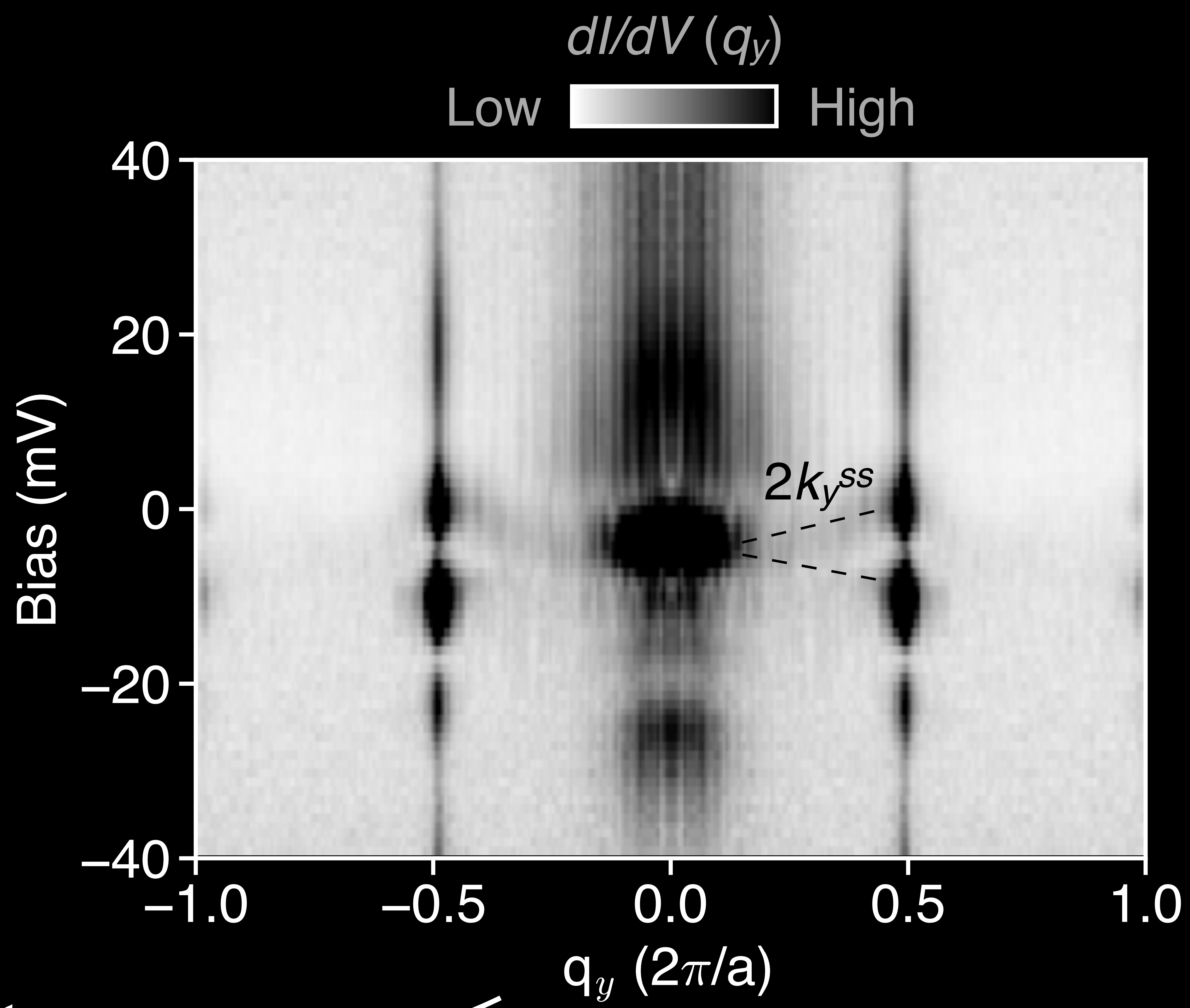
Heavy Dirac fermions are visible in raw *dI/dV*





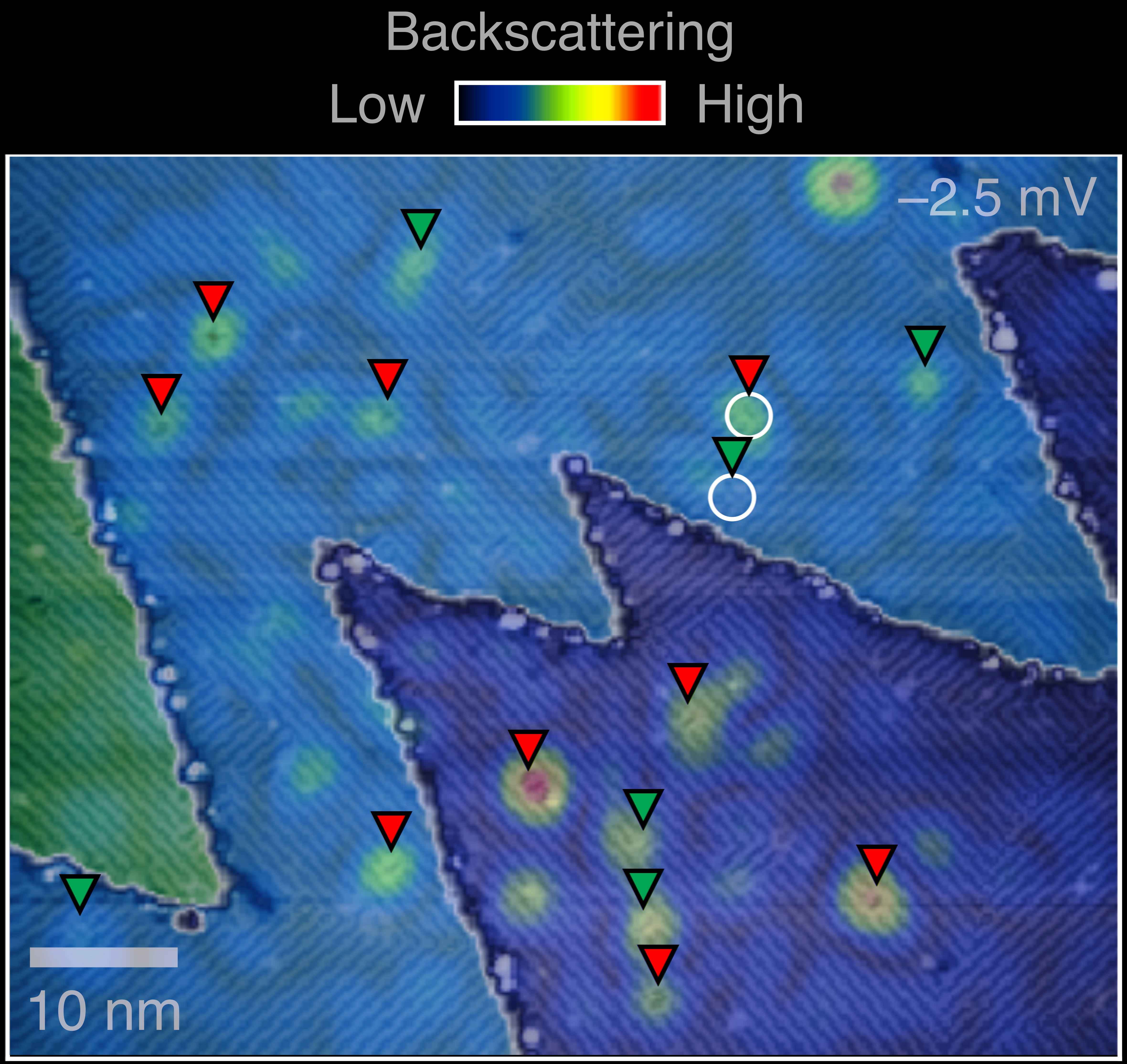
Imaging backscattering centres

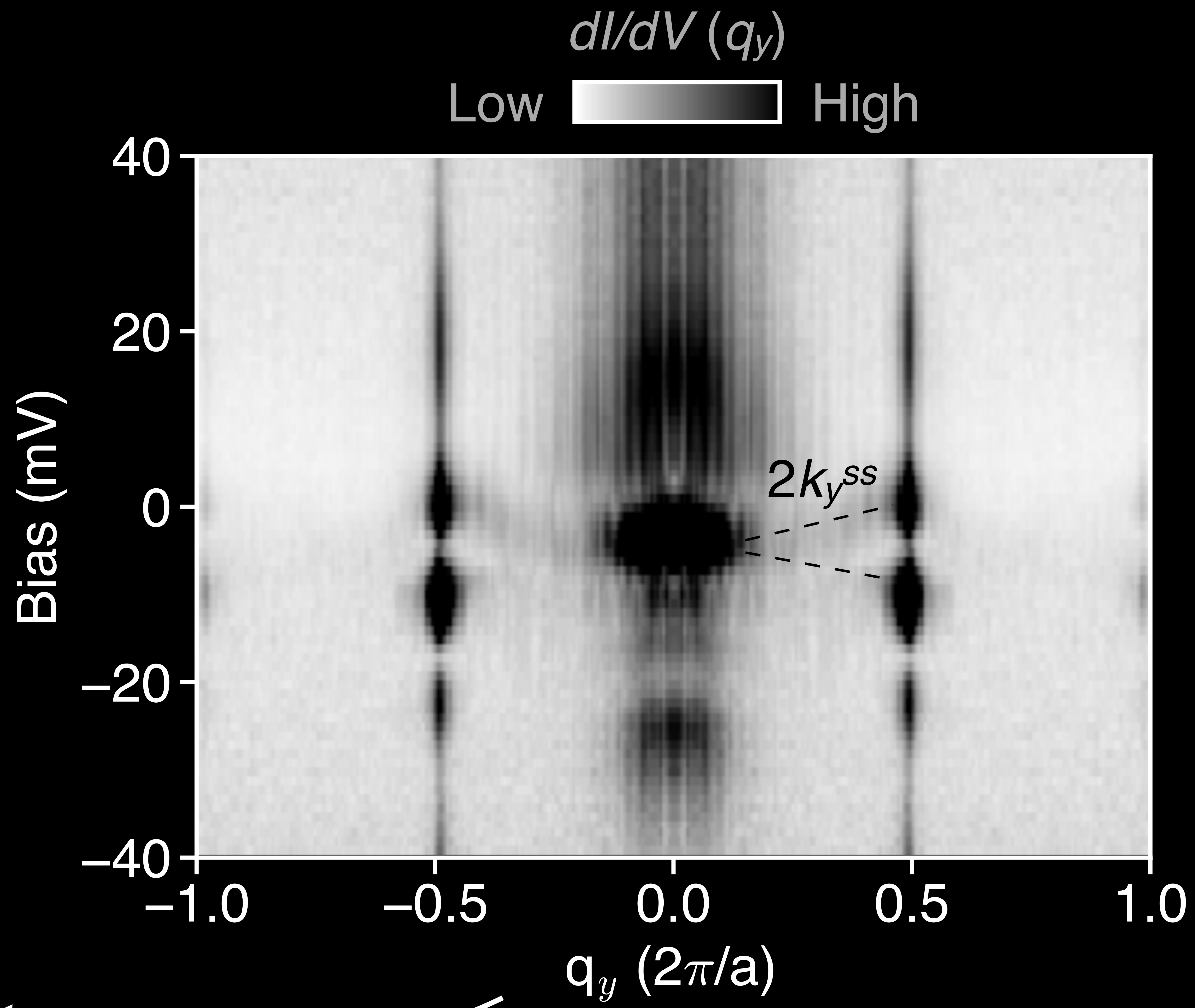




Inverse Fourier transform at $q = 2k_y^{ss}$

Kondo holes backscatter heavy Dirac fermions





Inverse Fourier transform at $q = 2k_y^{ss}$

Is the origin intrinsic or extrinsic?

We will answer this question **experimentally:**

Question: Is there microscopic evidence of **light electrons?**

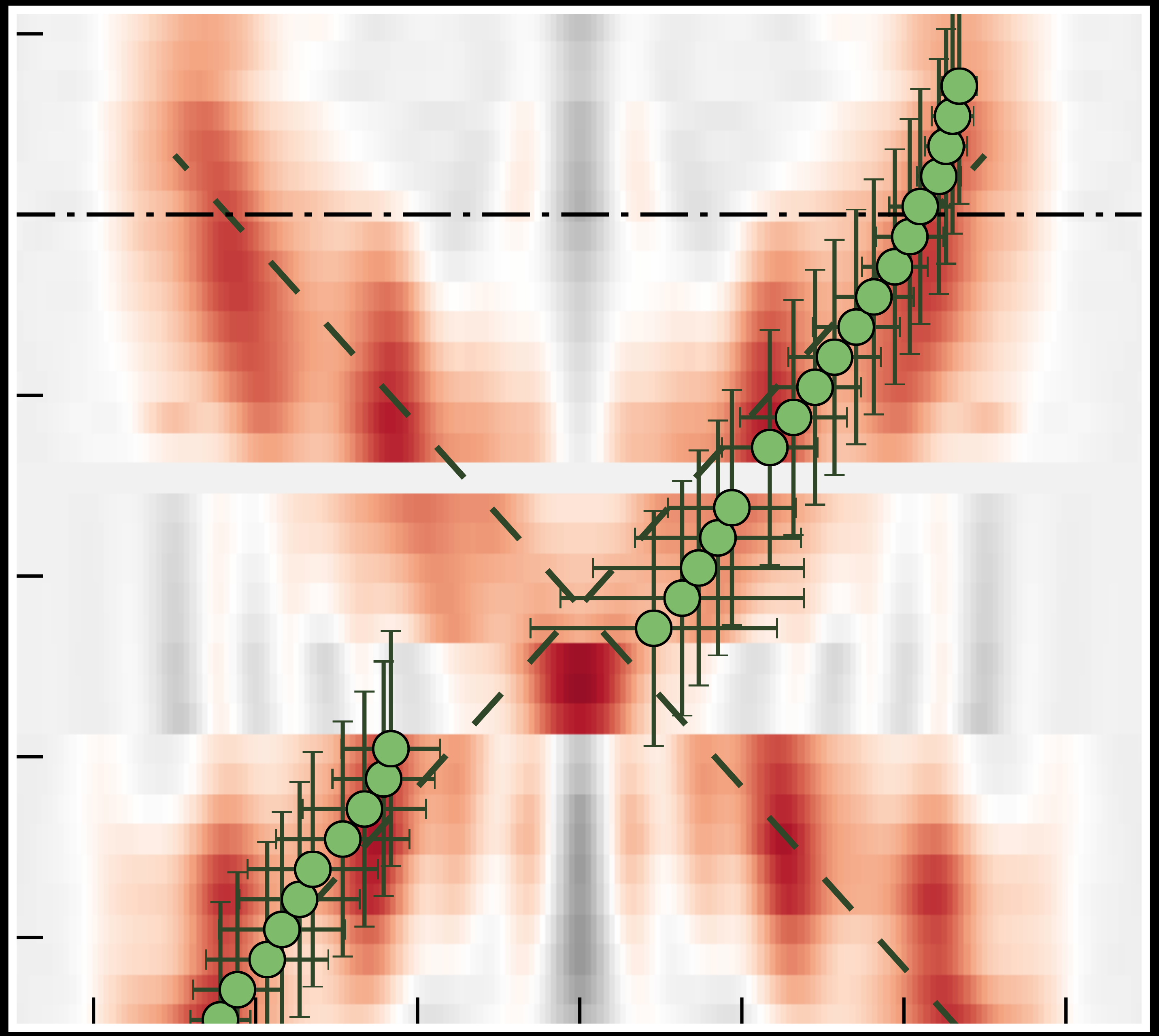
Answer: **Yes**, light electrons are released by Kondo holes

Question: Do the metallic puddles have a finite magnetic susceptibility?

Answer: **Yes**, Kondo holes magnetically scatter Dirac fermions

Conclusion

(1) Dirac fermions **410 times** heavier than a bare electron!



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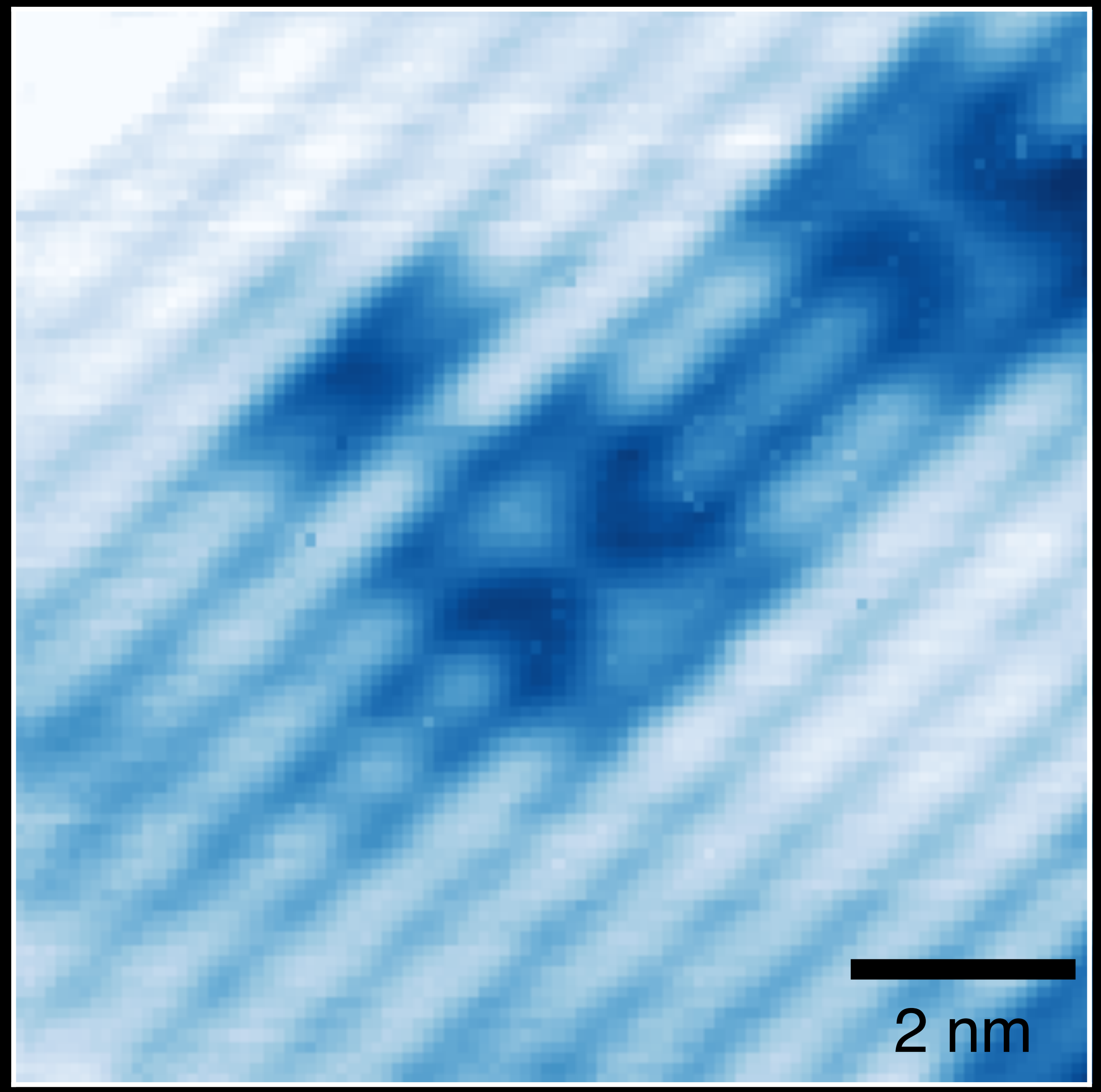

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