SAND2020-7646PE

Anomalous Shapiro steps in a Dirac semimetal Cd3As2-based SQUID

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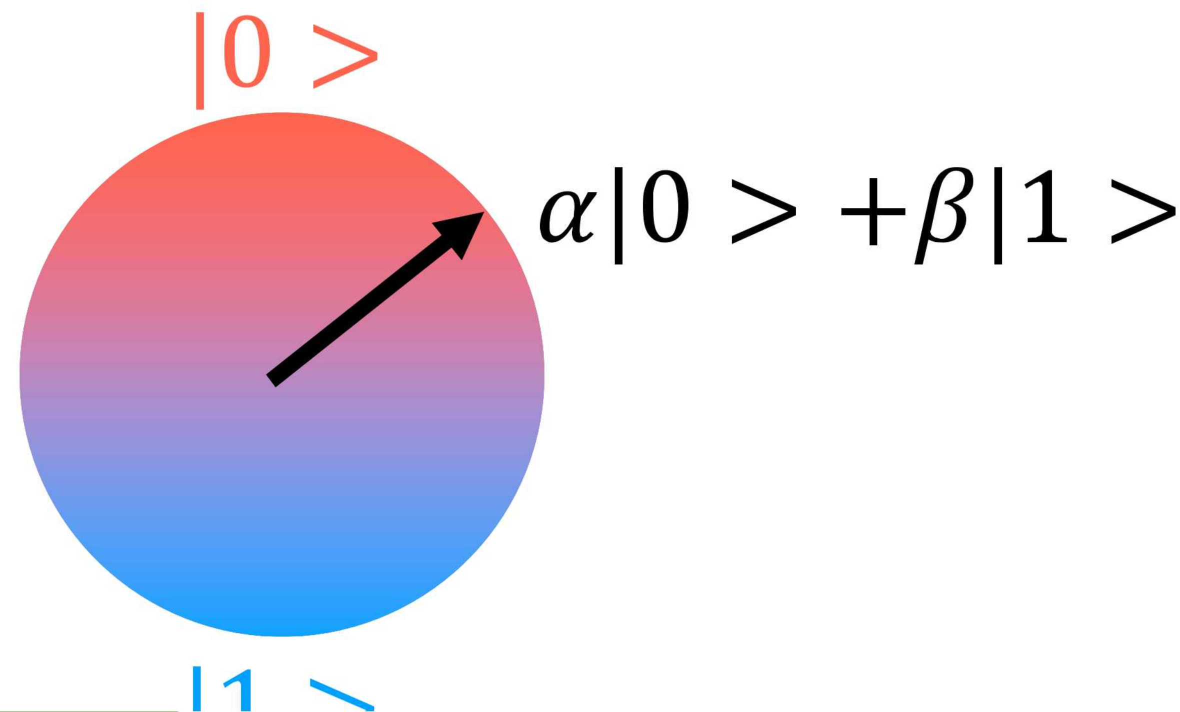
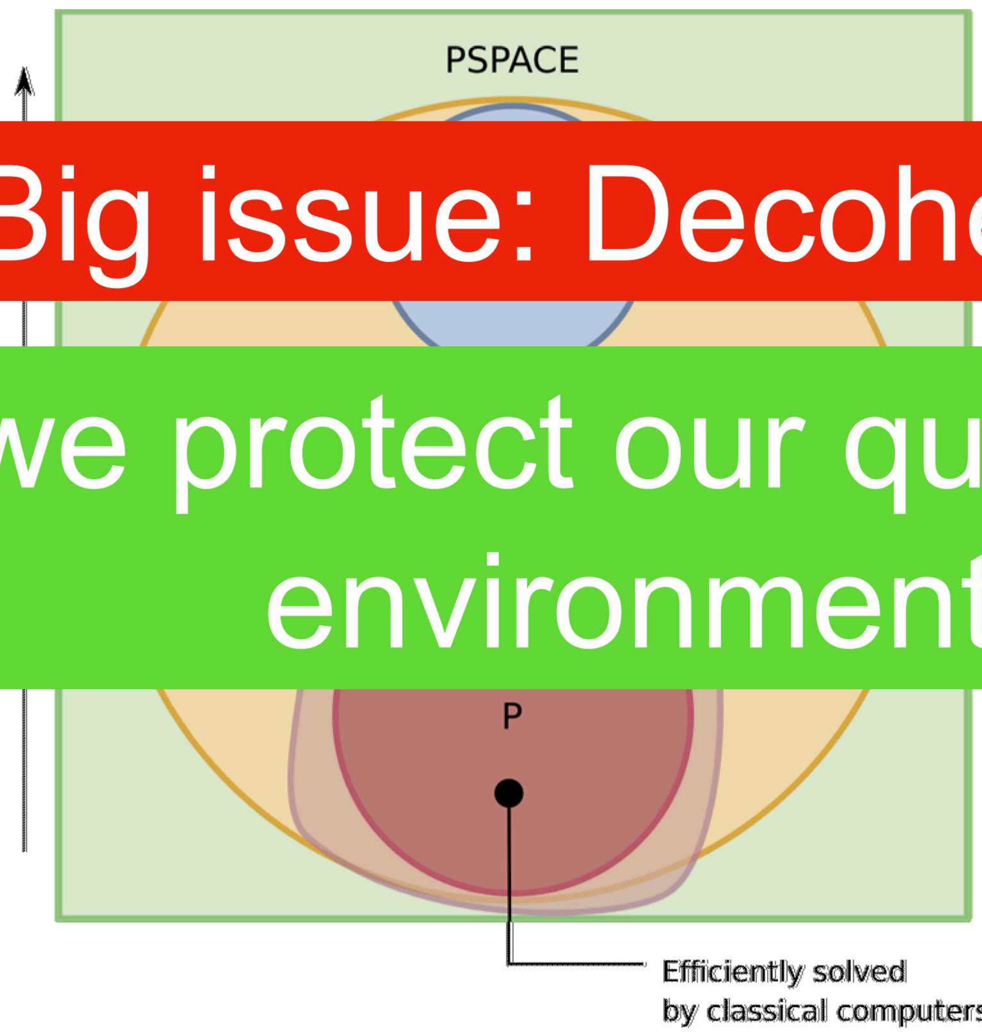
Quantum computing

Classical bit

Qubit





Big issue: Decoherence

Can we protect our qubit from the environment?

...ng
...reak
key cryptography
schemes!

Motivation

PHYSICAL REVIEW X **6,** 031016 (2016)

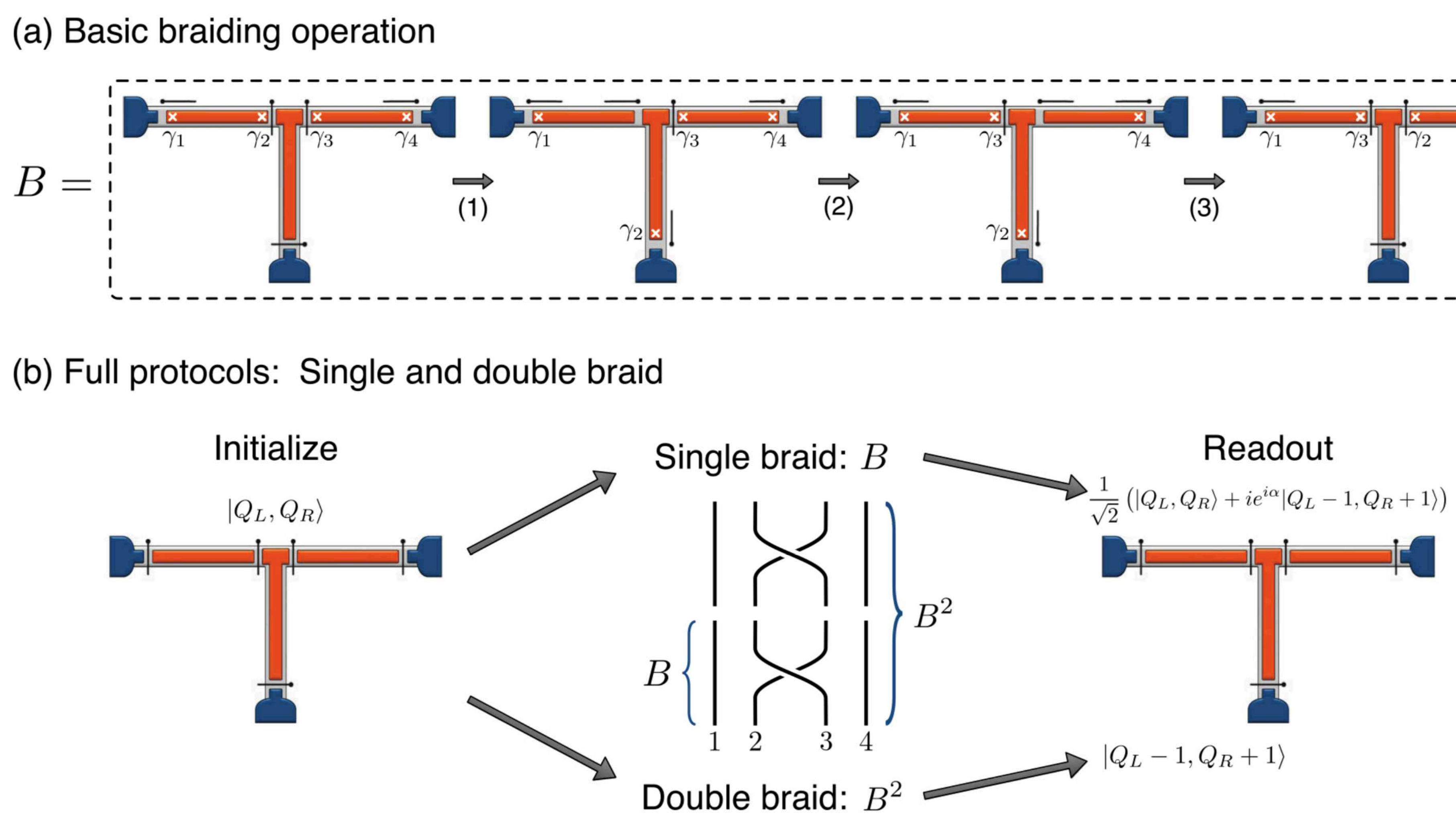
Milestones Toward Majorana-Based Quantum Computing

David Aasen,[1] Michael Hell,[2,3] Ryan V. Mishmash,[1,4] Andrew Higginbotham,[5,3] Jeroen Danon,[3,6] Martin Leijnse,[2,3] Thomas S. Jespersen,[3] Joshua A. Folk,[3,7,8] Charles M. Marcus,[3] Karsten Flensberg,[3] and Jason Alicea[1,4]

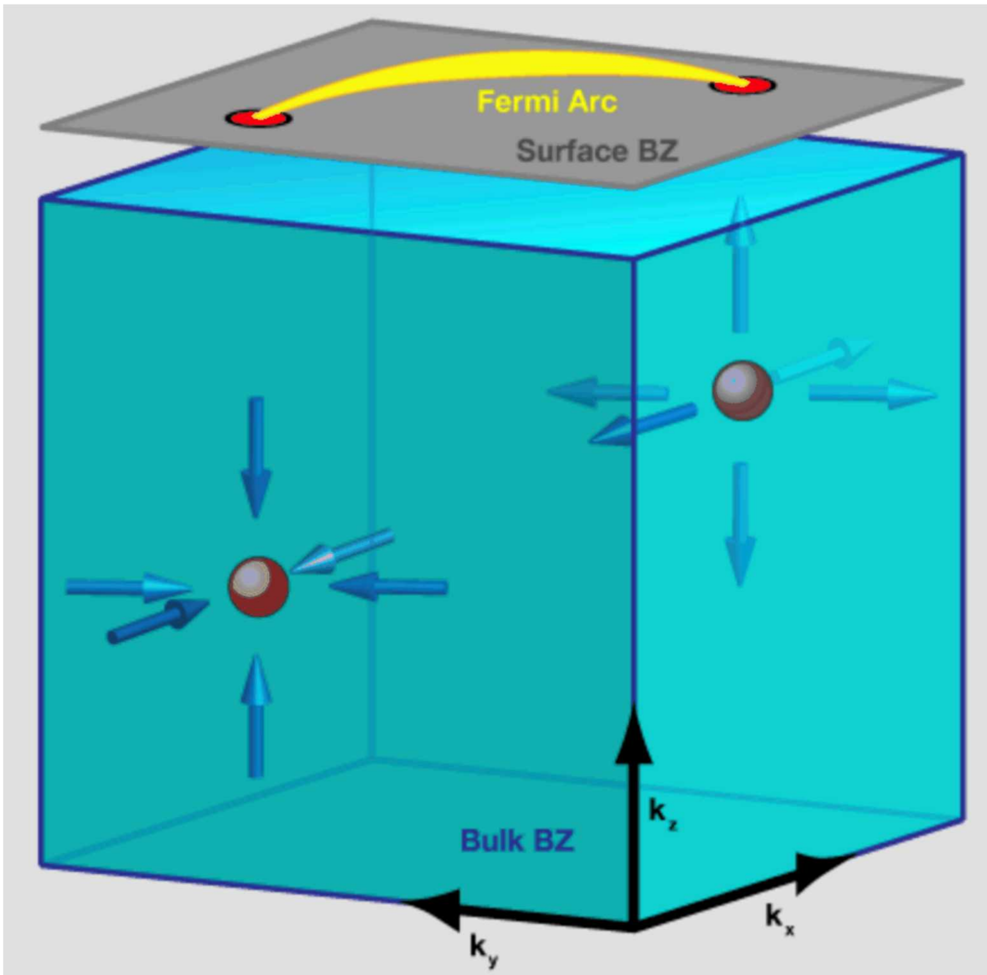
Non-Abelian anyons and topological quantum computation

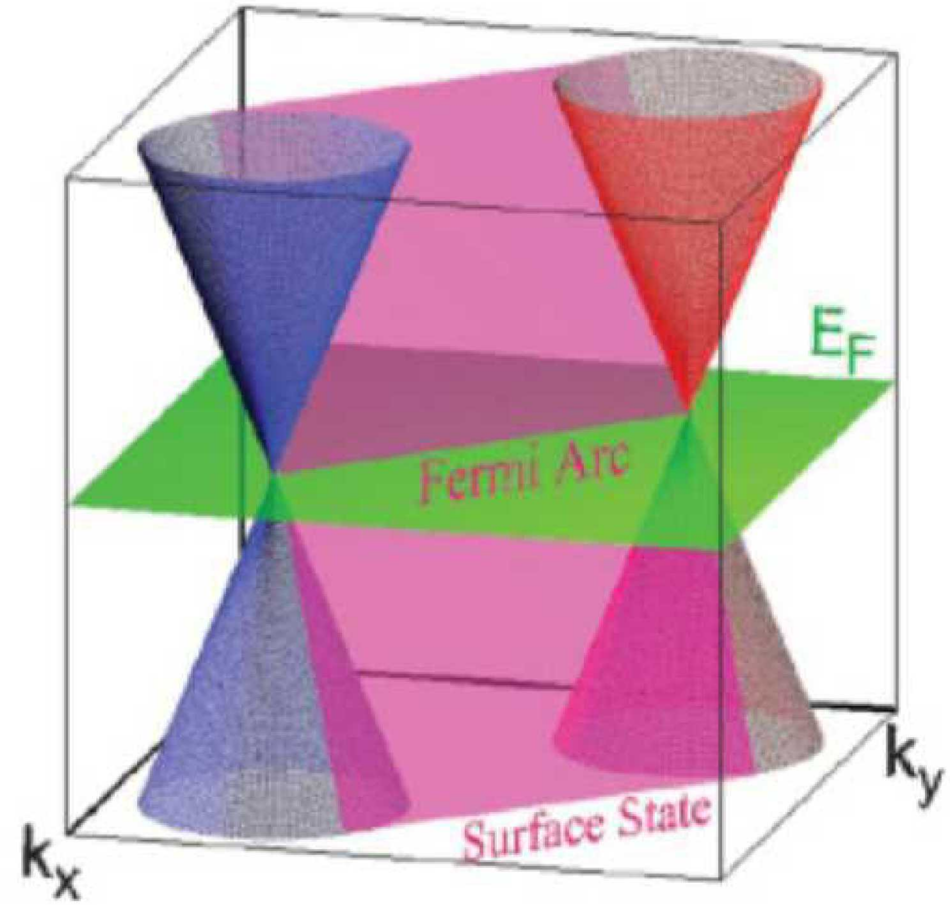
Chetan Nayak, Steven H. Simon, Ady Stern, Michael Freedman, and Sankar Das Sarma

Rev. Mod. Phys. **80**, 1083 – Published 12 September 2008



Dirac & Weyl Semimetals





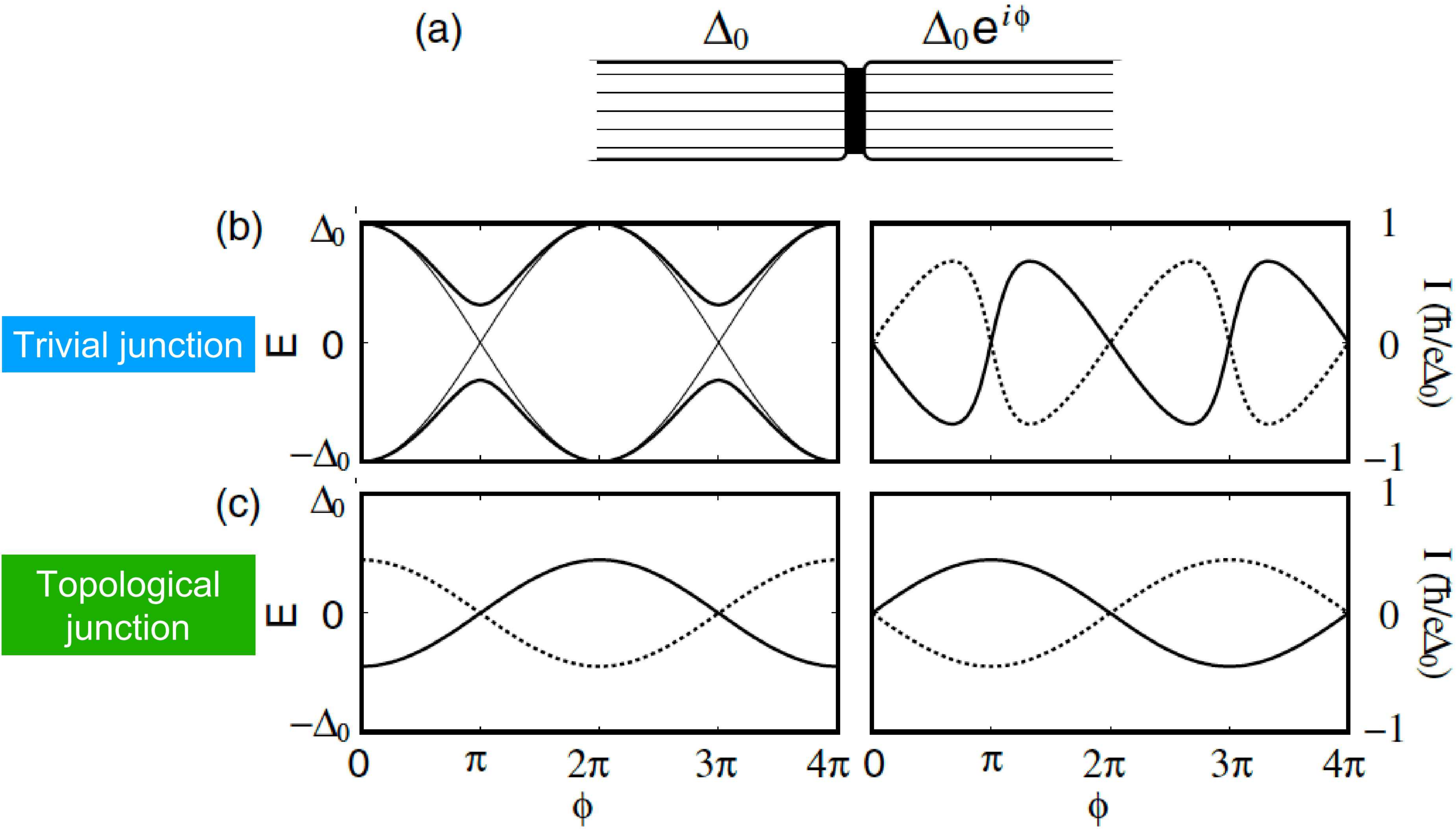
PHYSICAL REVIEW B **95**, 174505 (2017)

Josephson current signatures of Majorana flat bands on the surface of time-reversal-invariant Weyl and Dirac semimetals

Anffany Chen,[1,2] D. I. Pikulin,[1,2,3] and M. Franz[1,2]
[1]*Department of Physics and Astronomy, University of British Columbia, Vancouver, BC, Canada V6T 1Z1*
[2]*Quantum Matter Institute, University of British Columbia, Vancouver, BC, Canada V6T 1Z4*
[3]*Station Q, Microsoft Research, Santa Barbara, California 93106-6105, USA*
(Received 26 October 2016; revised manuscript received 13 March 2017; published 8 May 2017)

L. Balents, *Physics* **4**, 36 (2011)
X. Wan, A. M. Turner, A. Vishwanath, and S. Y. Savrasov, *Phys. Rev. B* **83**, 205101 (2011)

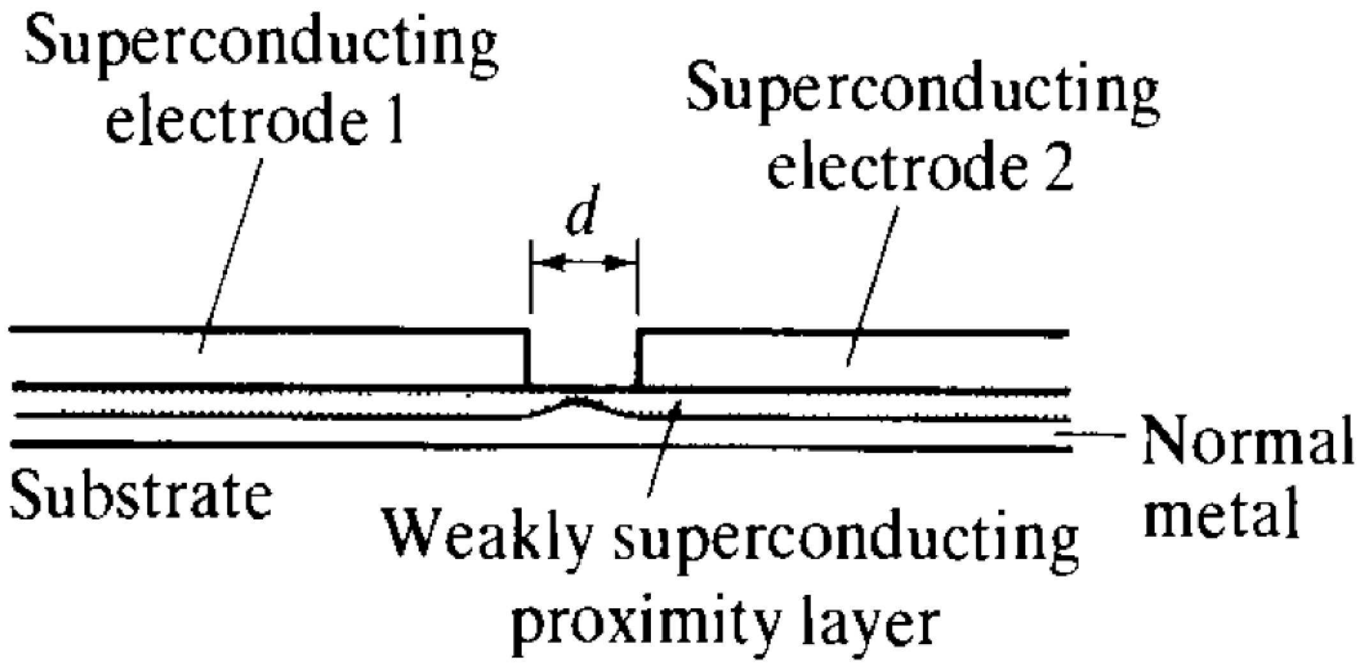
Josephson Effect

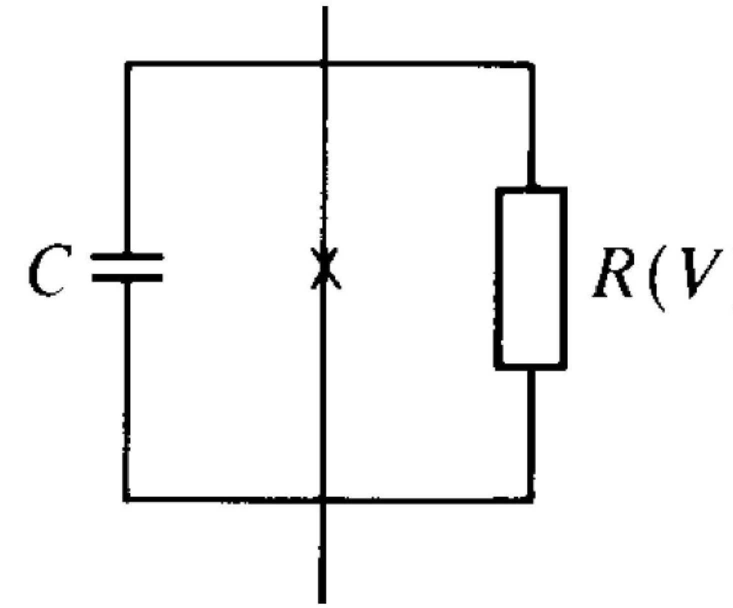


For a short junction and T=0: $$I = \frac{2e}{\hbar} \sum_{mid-gap E_n} \frac{\partial E_n}{\partial \phi}$$

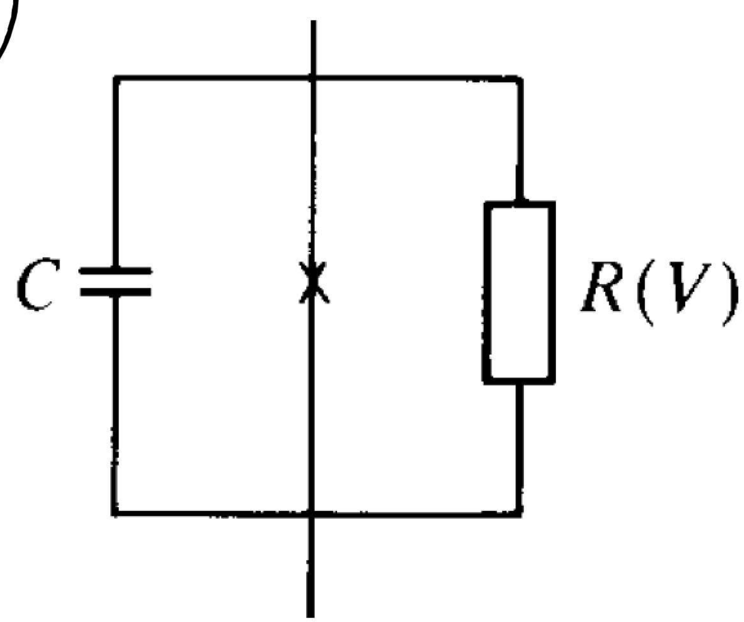
Tinkham, M. (2004). Introduction to Superconductivity. Dover Publications. ISBN: 0486435032
H.-J. Kwon, K. Sengupta, and V.M. Yakovenko ,Eur. Phys. J. B 37, 349–361 (2004)

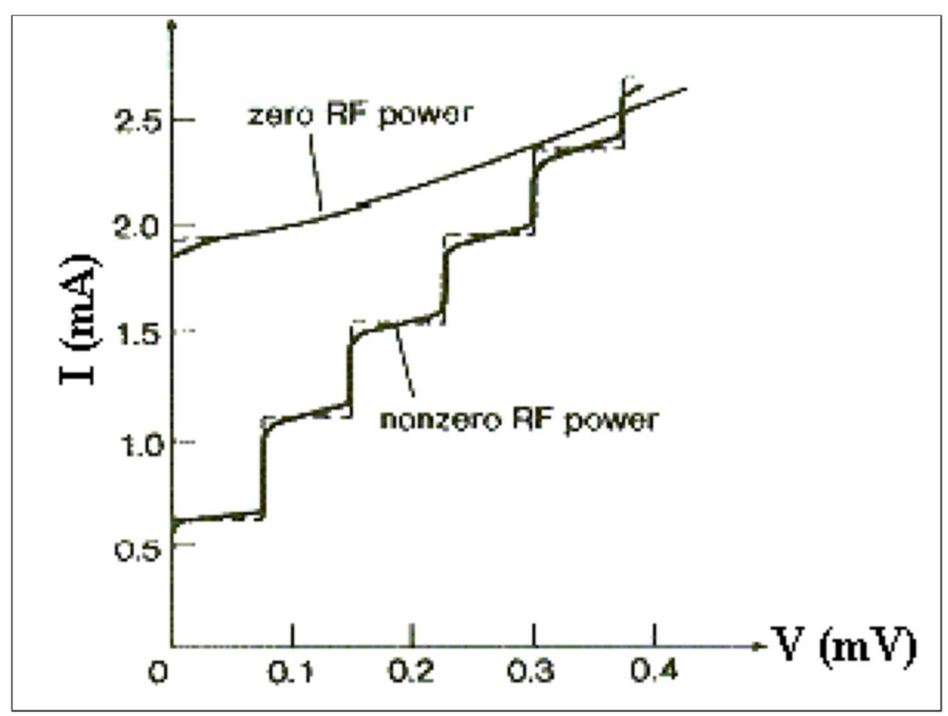
Shapiro Steps





$$I_{bias} = I_s + \frac{V}{R} + C\,\frac{dV}{dt}$$

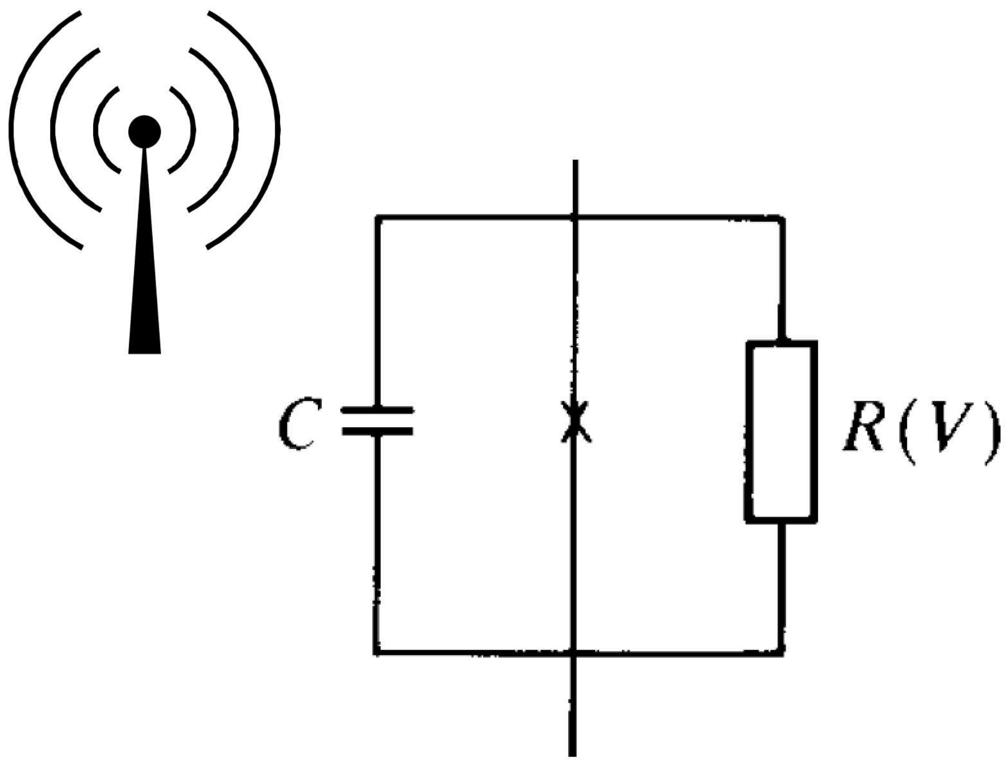


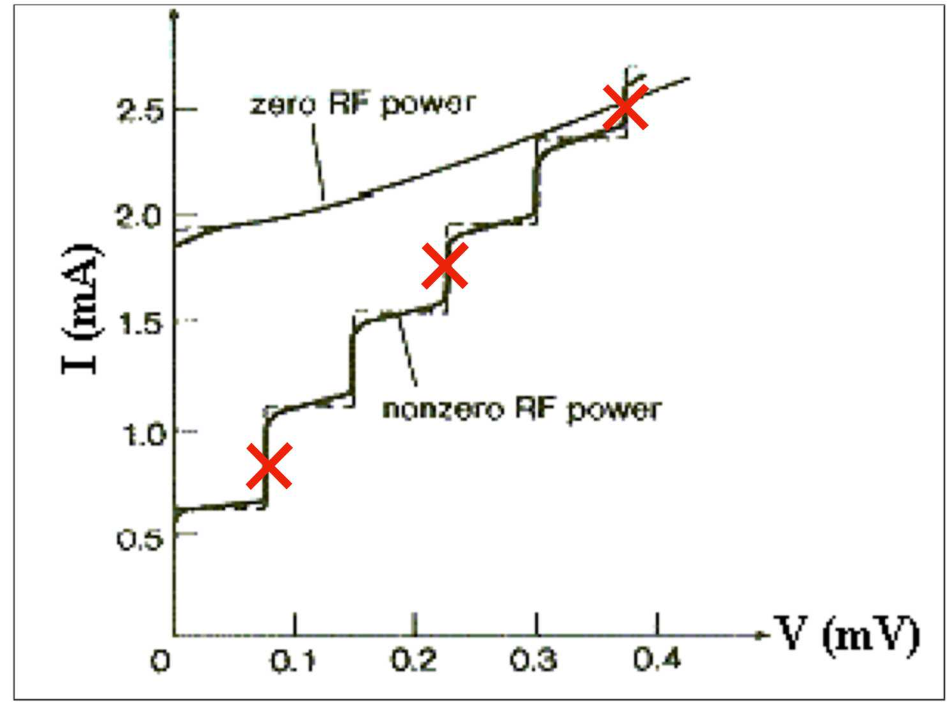


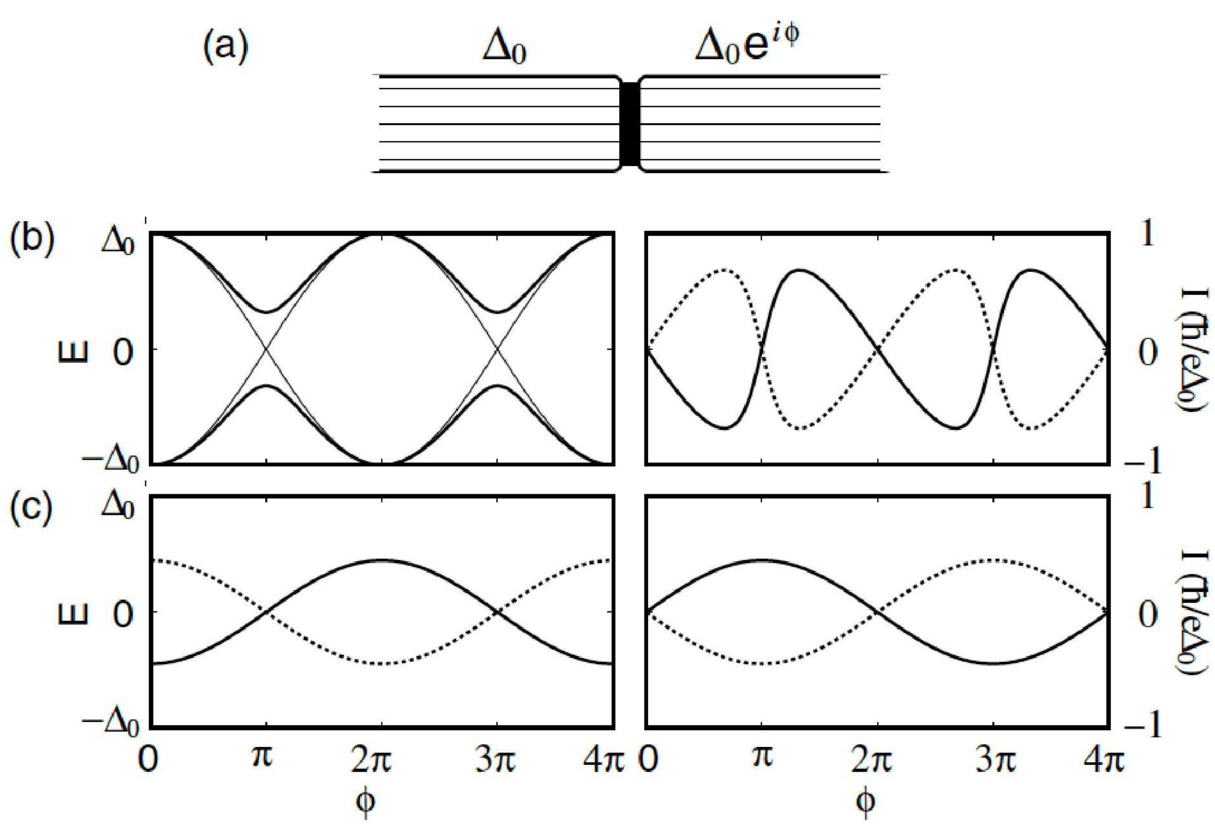
$$\boxed{V_n = n\,\frac{\hbar\omega}{2e}}$$

 Tinkham, M. (2004). Introduction to Superconductivity. Dover Publications. ISBN: 0486435032

Topological Superconductivity







Trivial junction

$$V_n = n\frac{\hbar\omega}{\boxed{2e}}$$

Supercurrent carried by a pair of electrons

Topological junction

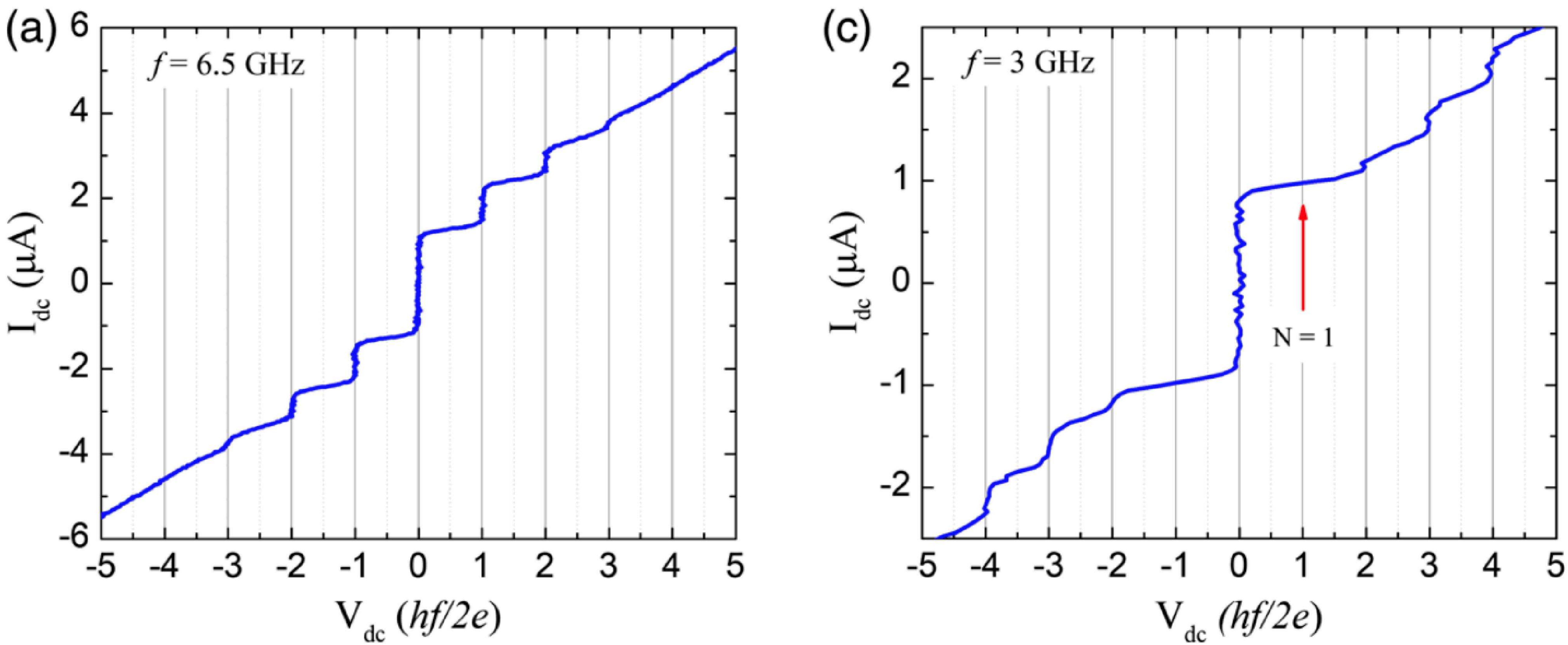
$$V_n = n\frac{\hbar\omega}{\boxed{e}} = (2n)\frac{\hbar\omega}{2e}$$

Supercurrent carried by single electrons

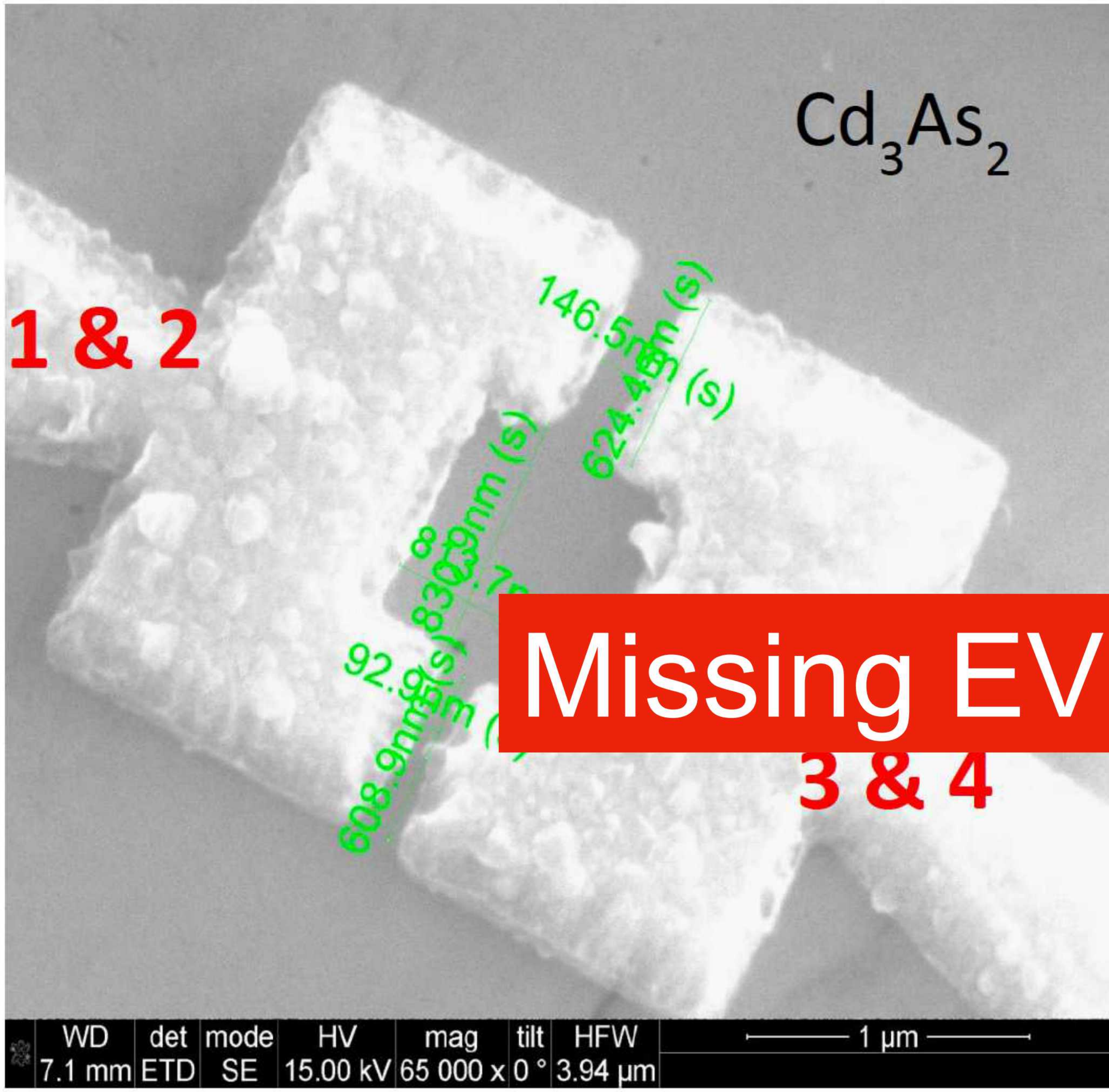
PHYSICAL REVIEW LETTERS **120,** 177704 (2018)

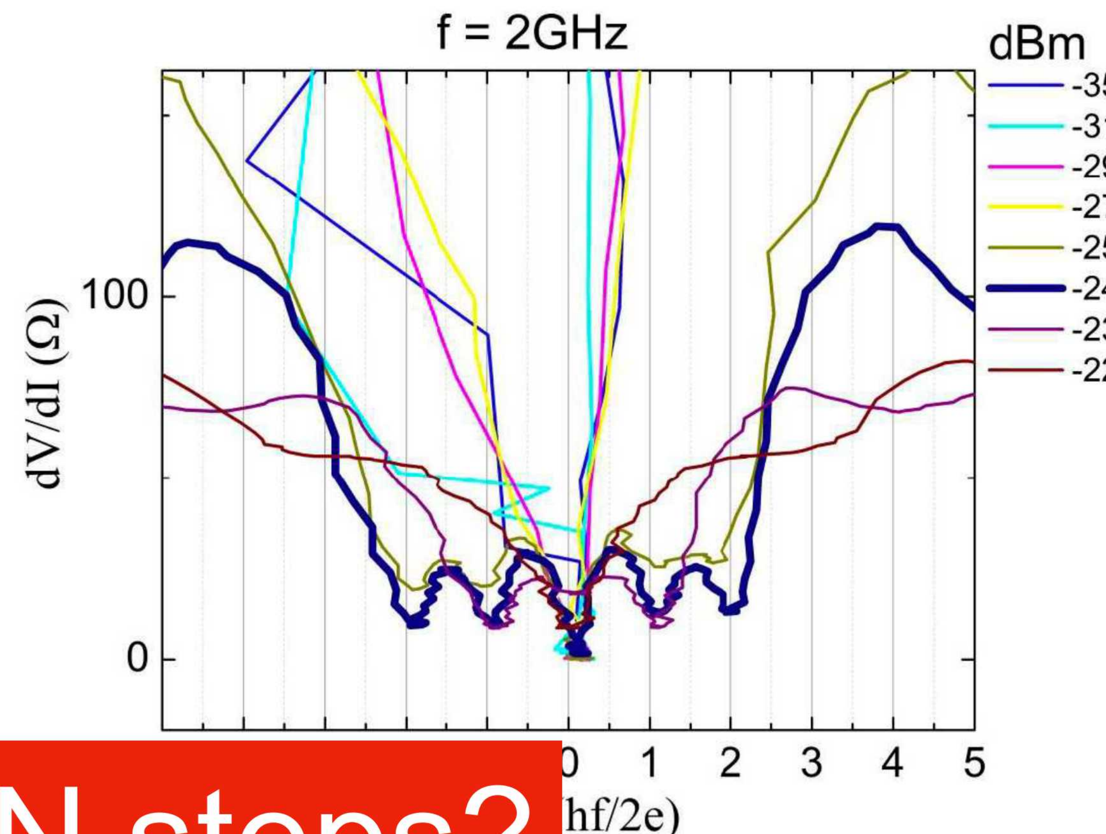
π and 4π Josephson Effects Mediated by a Dirac Semimetal

W. Yu,[1] W. Pan,[1] D. L. Medlin,[2] M. A. Rodriguez,[1] S. R. Lee,[1] Zhi-qiang Bao,[3] and F. Zhang[3]
[1]*Sandia National Laboratories, Albuquerque, New Mexico 87185, USA*
[2]*Sandia National Laboratories, Livermore, California 94551, USA*
[3]*Department of Physics, University of Texas at Dallas, Dallas, Texas 75080, USA*

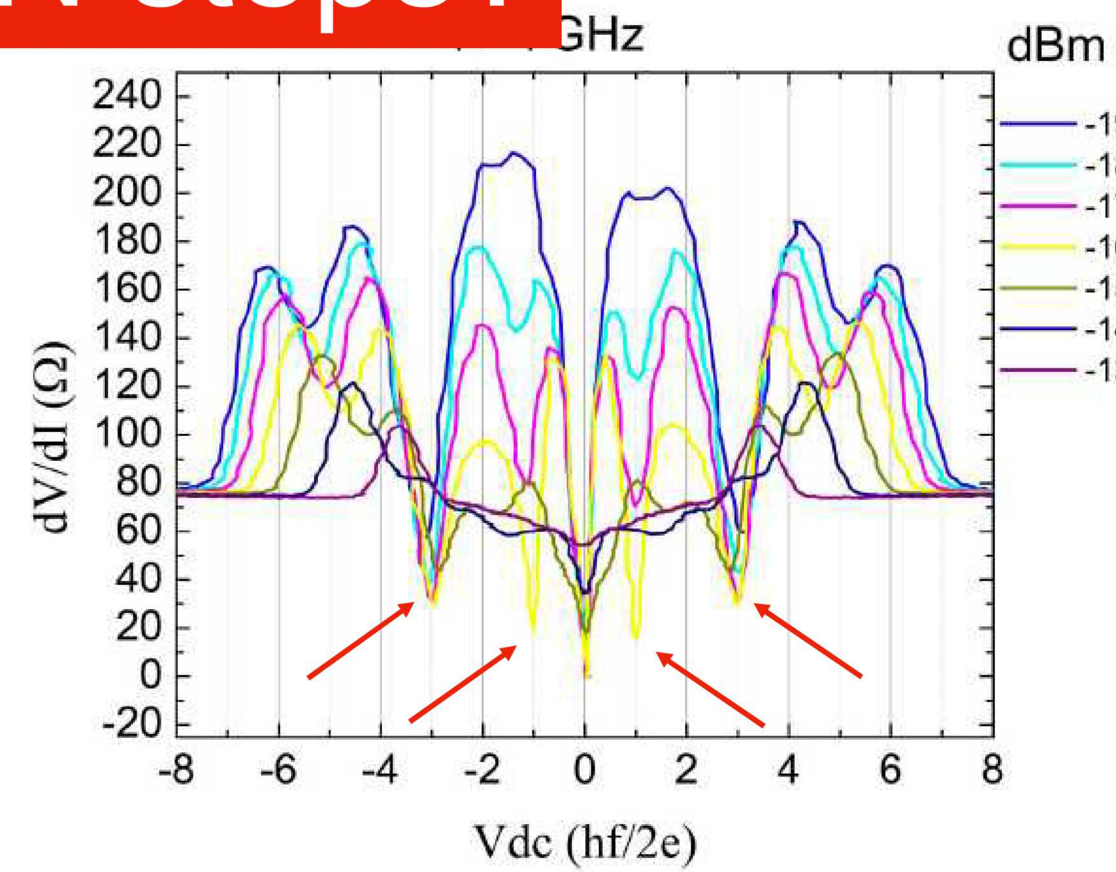


Anomalous Shapiro Steps



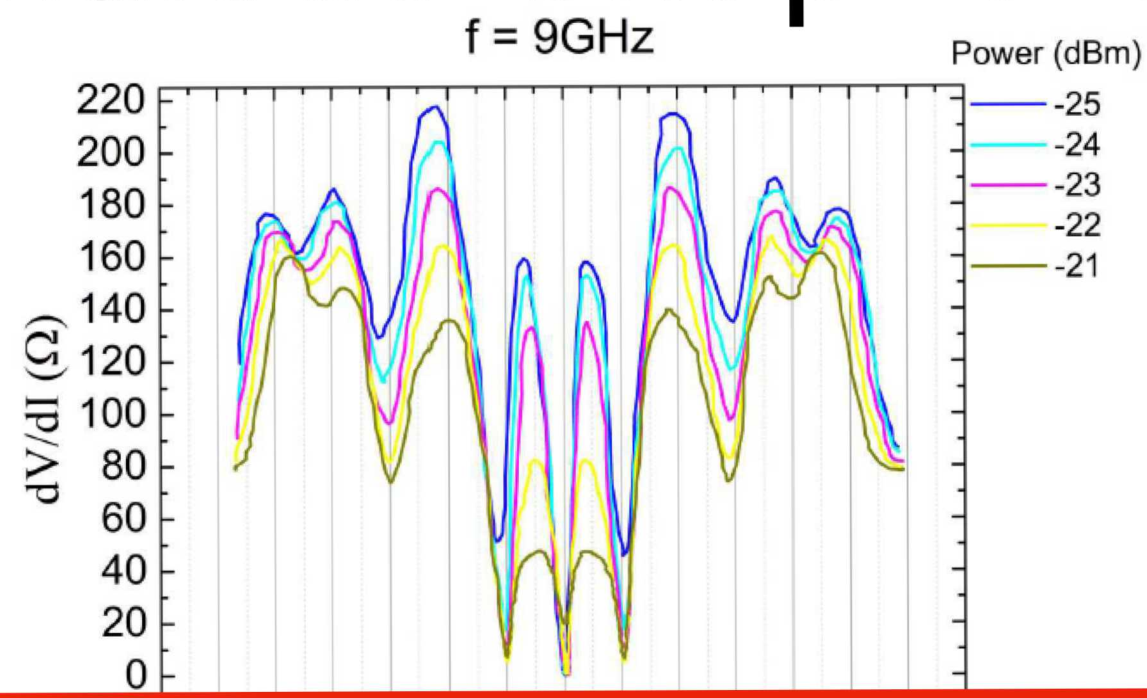


Missing EVEN steps?

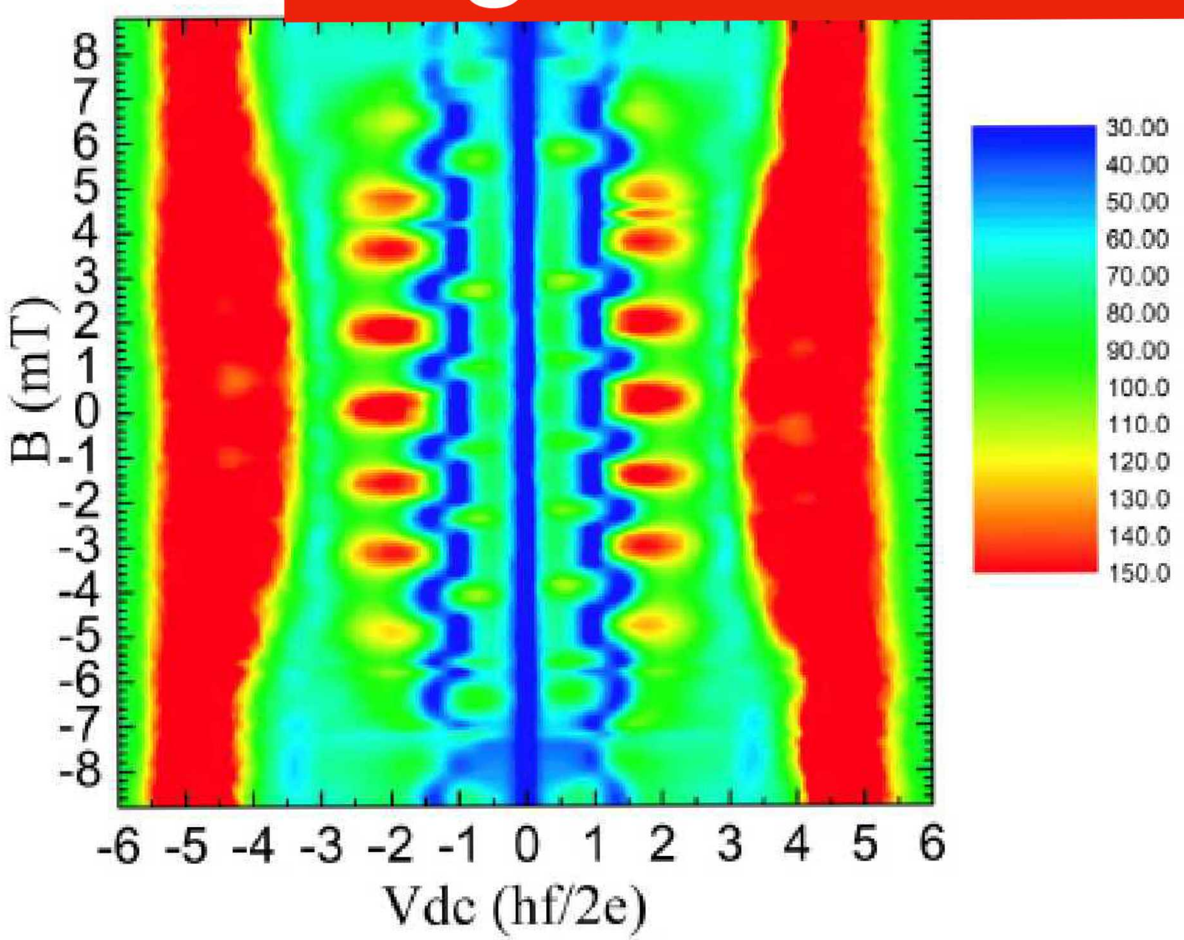


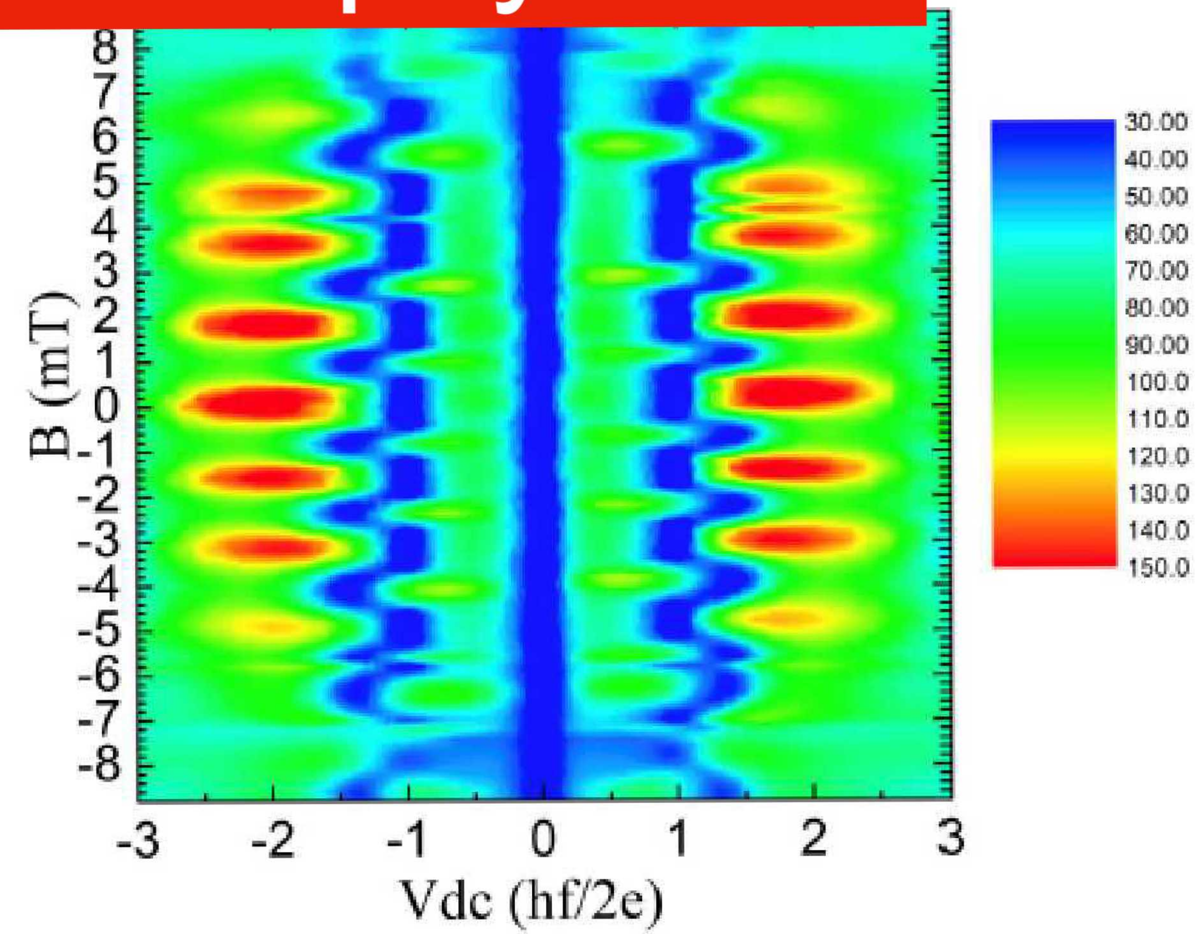
At a Shapiro step: $R = \dfrac{dV}{dI} = 0$

Anomalous Shapiro Steps



Signatures of Majorana physics?

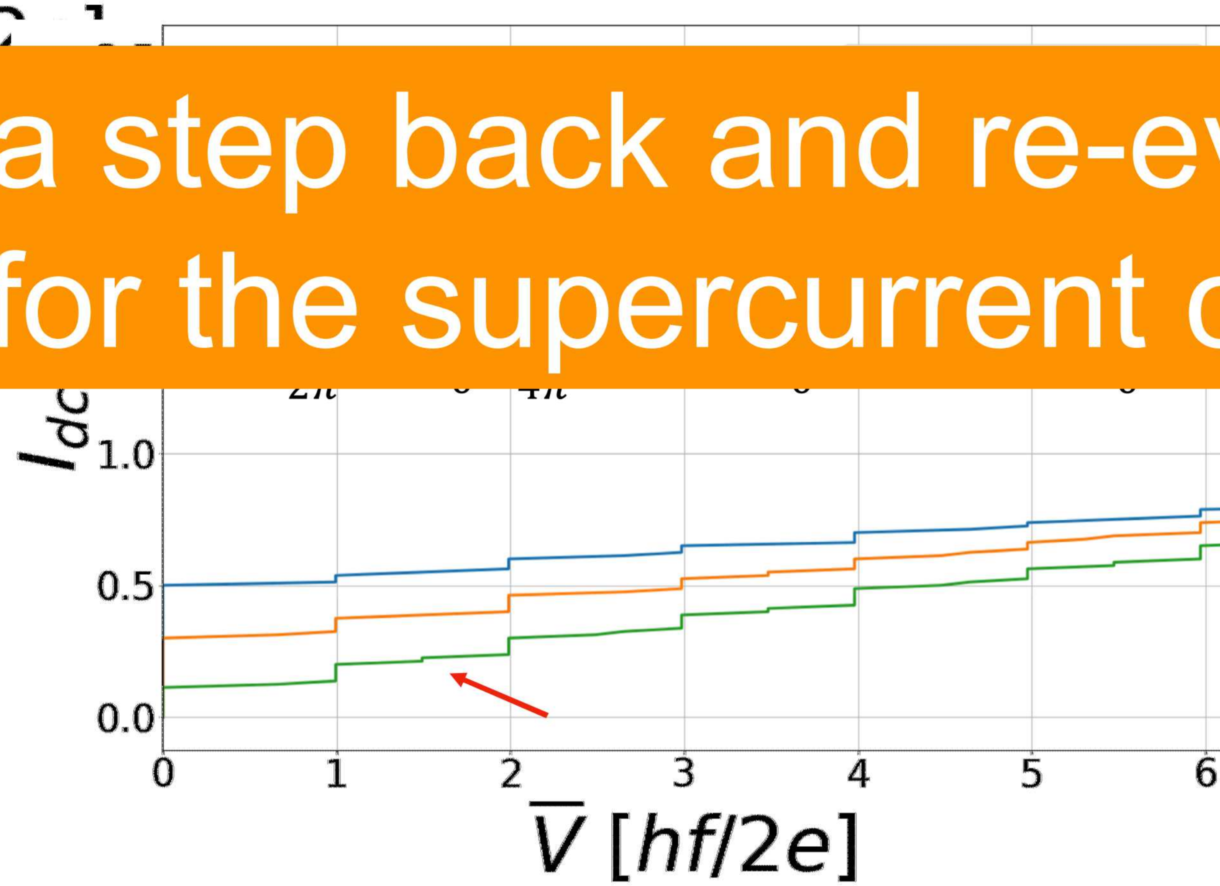




Shapiro Steps in Symmetric SQUID

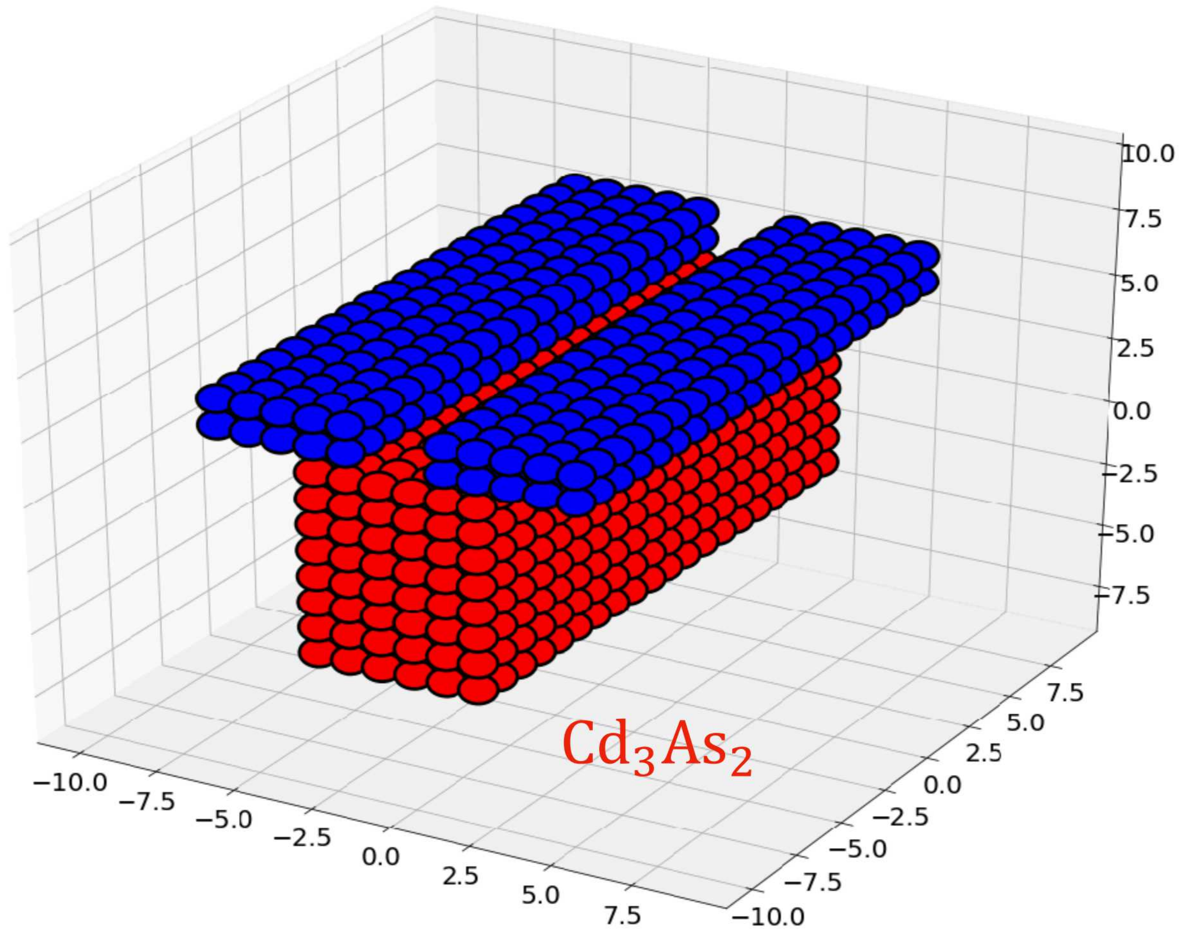
Fail to observe suppressed even steps with most basic description of supercurrent channels

Let's take a step back and re-evaluate the model for the supercurrent channel

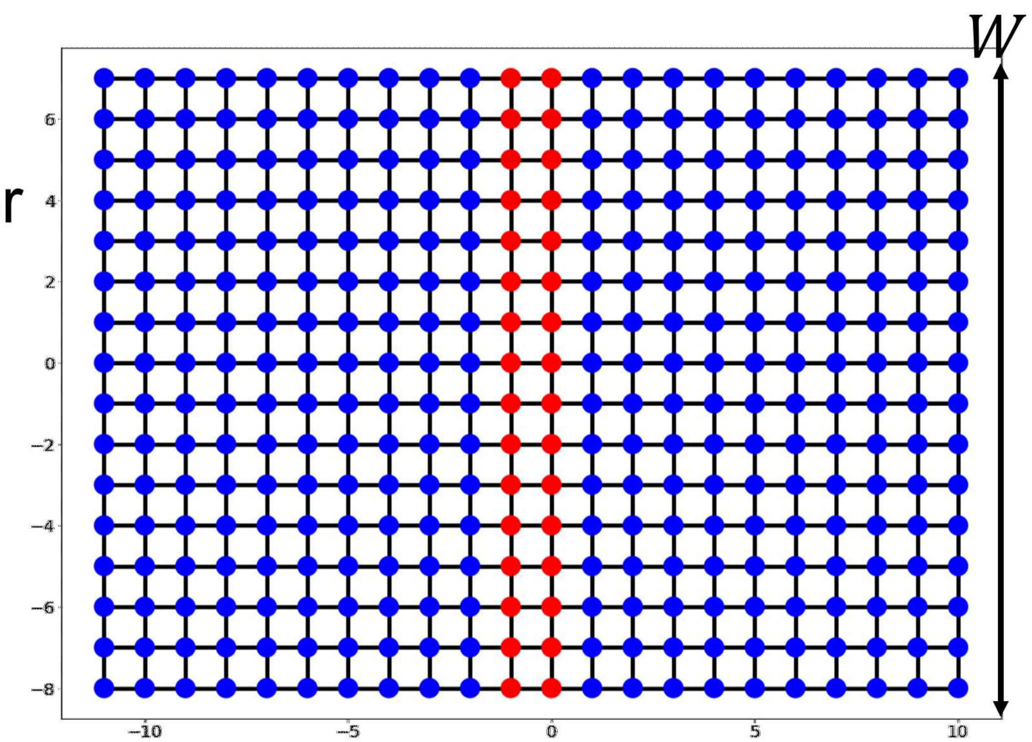


Observe 3/2 step and *suppressed* 1/2 step, as seen in experiment

Tight-binding Simulations



Reduce dimensionality for simplicity

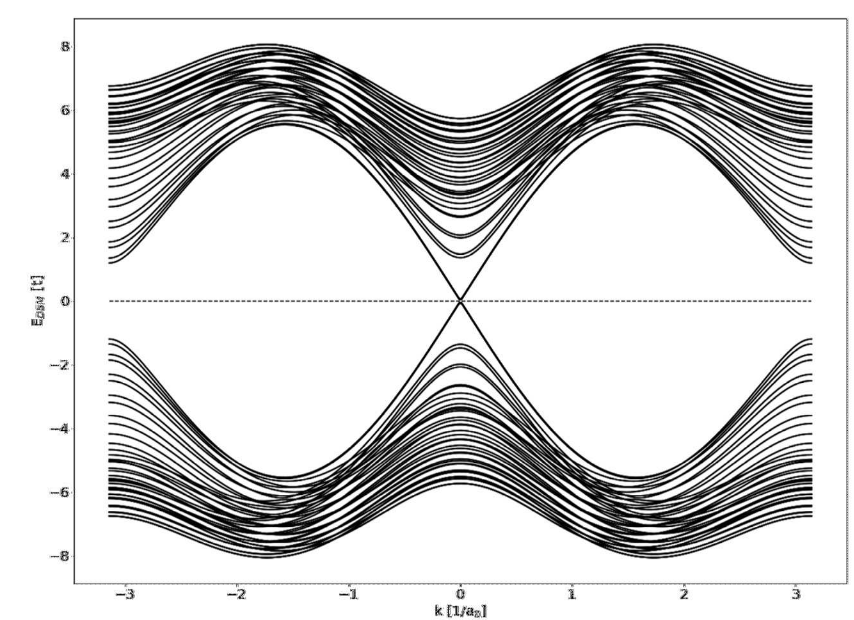


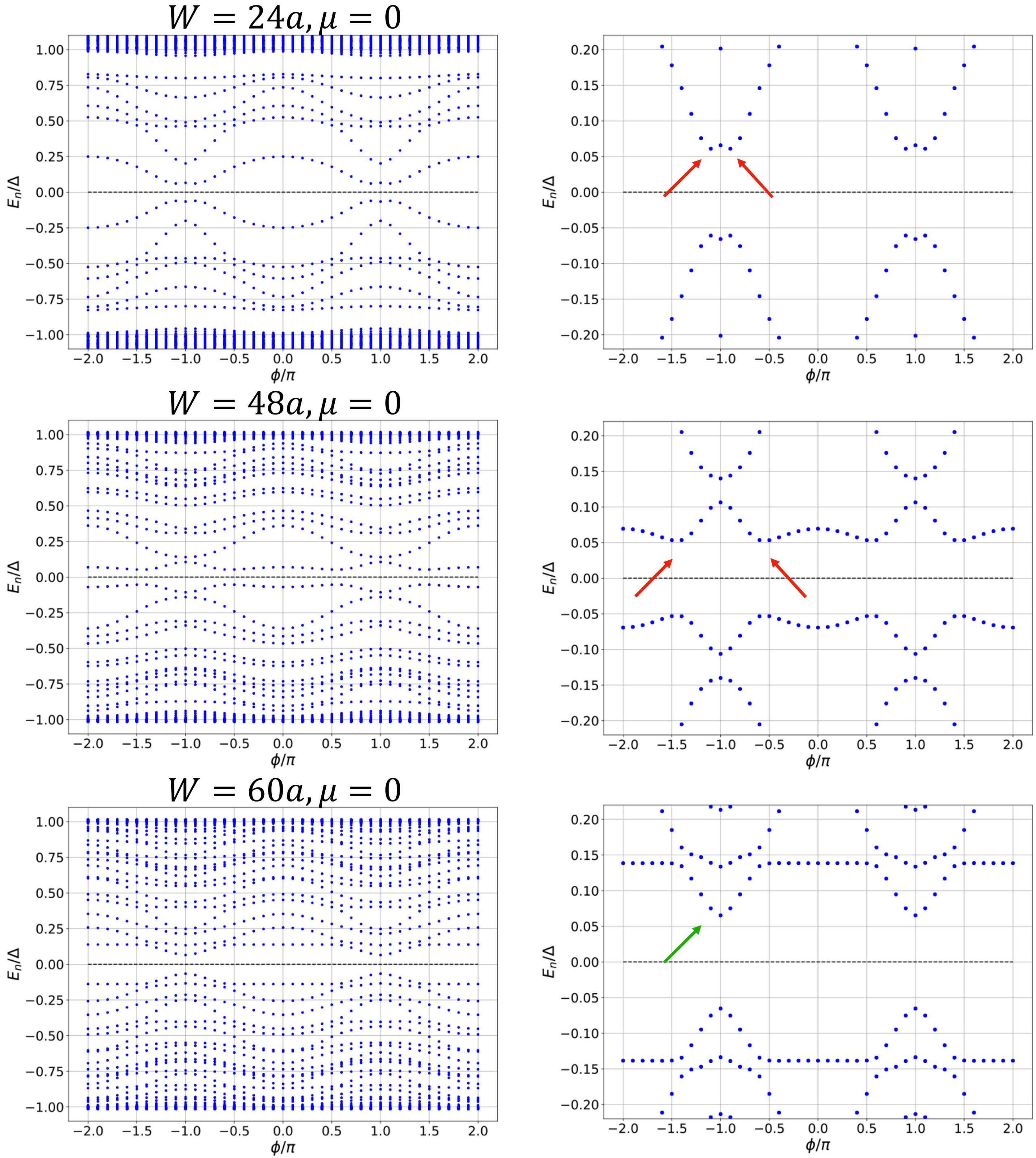
$$H_{dsm}(\vec{k}) = \epsilon(\vec{k}) s_0 \otimes \sigma_0 + M(\vec{k}) s_0 \otimes \sigma_z + A_0\left(k_x s_z \otimes \sigma_x - k_y s_0 \otimes \sigma_y\right)$$

$$\epsilon(\vec{k}) = C_0 - \mu + 2C_1 k_z^2 + 2C_2(k_x^2 + k_y^2)$$

$$M(\vec{k}) = M_0 - 2M_1 k_z^2 - 2M_2(k_x^2 + k_y^2)$$

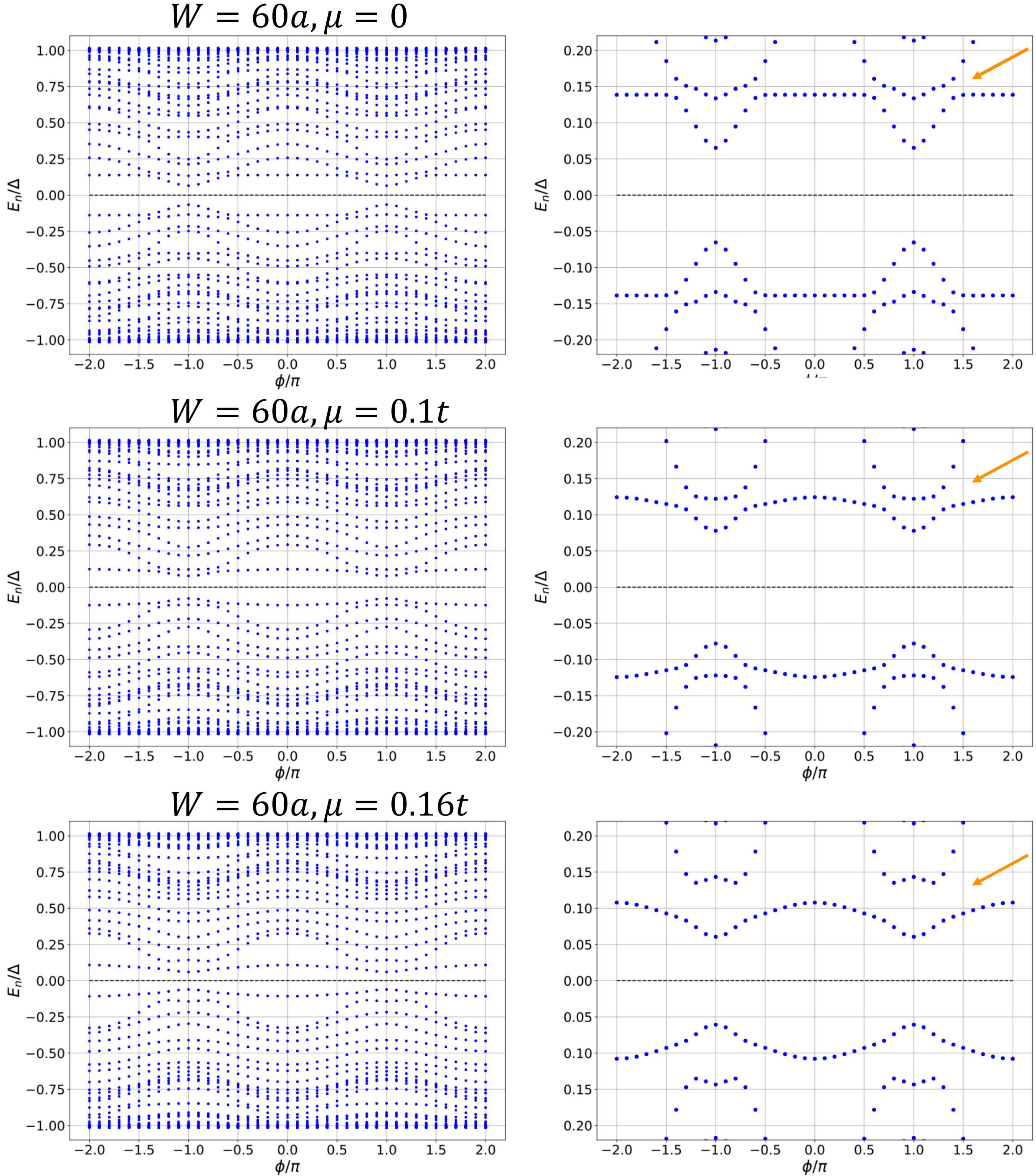
$$s_i \rightarrow \text{spin} \qquad \sigma_i \rightarrow \text{orbital}$$





Two minima in excited ABS split symmetrically about pi associated with spin-orbit coupling

Splitting is sensitive to junction geometry



Splitting is insensitive to small deviations of the chemical potential away from the DP, but leads to avoided crossings due to backscattering

Gap at pi: sensitive to chemical potential

Summary

- No trivial mechanism identified to explain anomalous Shapiro steps
- Simplest description of a topological SQUID fails to agree with experiment
- Strong SOC in Cd3As2 affects ABS spectrum (directly related to supercurrent) significantly, even in the *absence* of Zeeman splitting
- Outlook:
  - Developing more detailed analytic model of CPR for Cd3As2 with and without magnetic field
  - Experimental signatures - potentially less ambiguous demonstration of Fermi-arc topological superconductivity