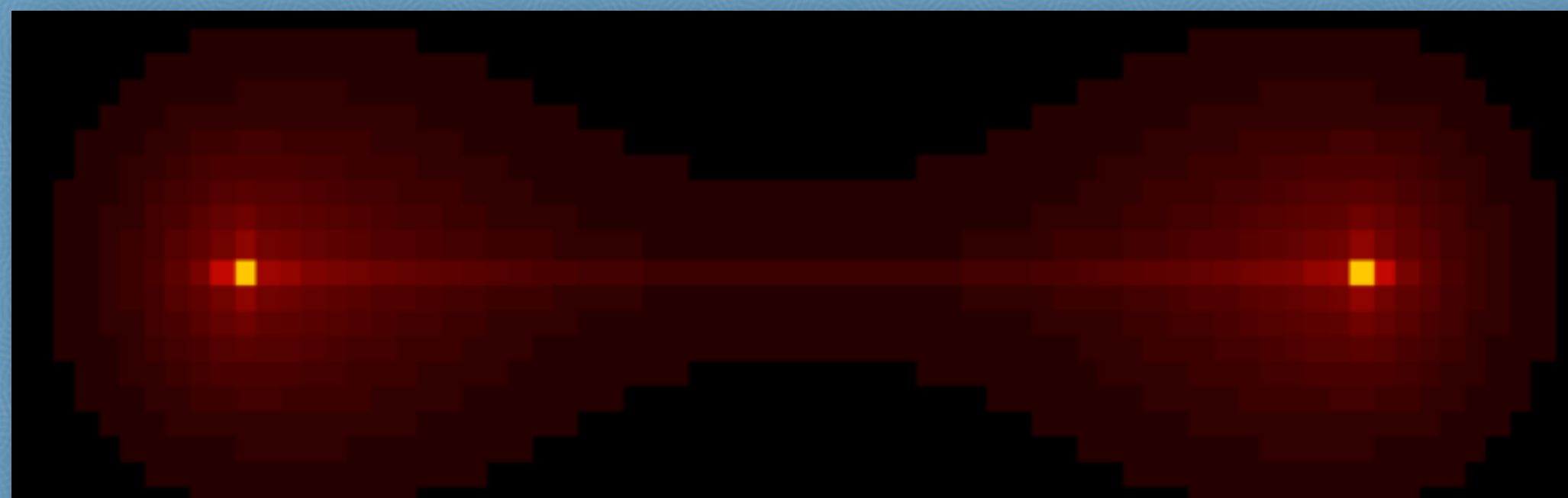# Topological quantum computing with Majorana fermions

in superconducting nanowires

RESEARCH WATCH

Majorana fermions – the answer to Life, the Universe, and Everything?

By Dario Borghino
April 27, 2012

8 Comments
7 Pictures

Bogoliubov quasiparticle

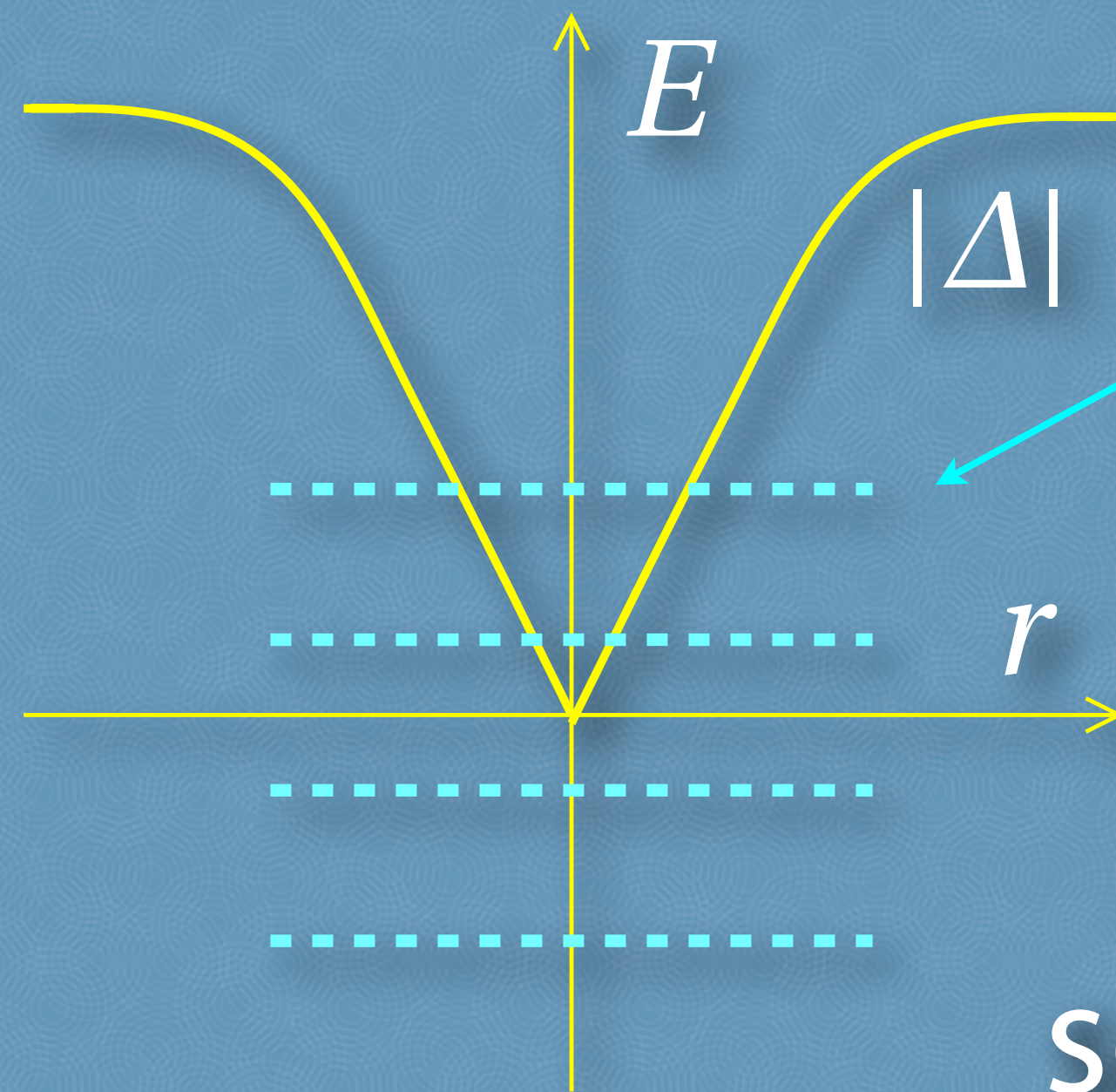$$\gamma_{k\uparrow} = u(E)c_{k\uparrow} + u^*(-E)c^\dagger_{-k,\downarrow}$$

superposition of electron and hole
excitations in a superconductor

spinless bound state at zero
energy is a Majorana fermion

$$\gamma = \gamma^\dagger \quad \text{particle = antiparticle}$$

obstacle: zero-point motion

bound states in a vortex core

$$E_n = E_0(n + 1/2)$$

electron-hole symmetry:

$$\gamma(-E) = \gamma^\dagger(E)$$

so Majorana fermion at E=0

however, zero-point motion prevents a bound state at E=0

Fu & Kane (2008): use Berry phase of massless electrons to eliminate the ½ phase shift

The breakthrough

Superconducting Proximity Effect and Majorana Fermions at the Surface of a Topological Insulator

Phys. Rev. Lett. **100**, 096407 – Published 6 March 2008

Liang Fu and C. L. Kane
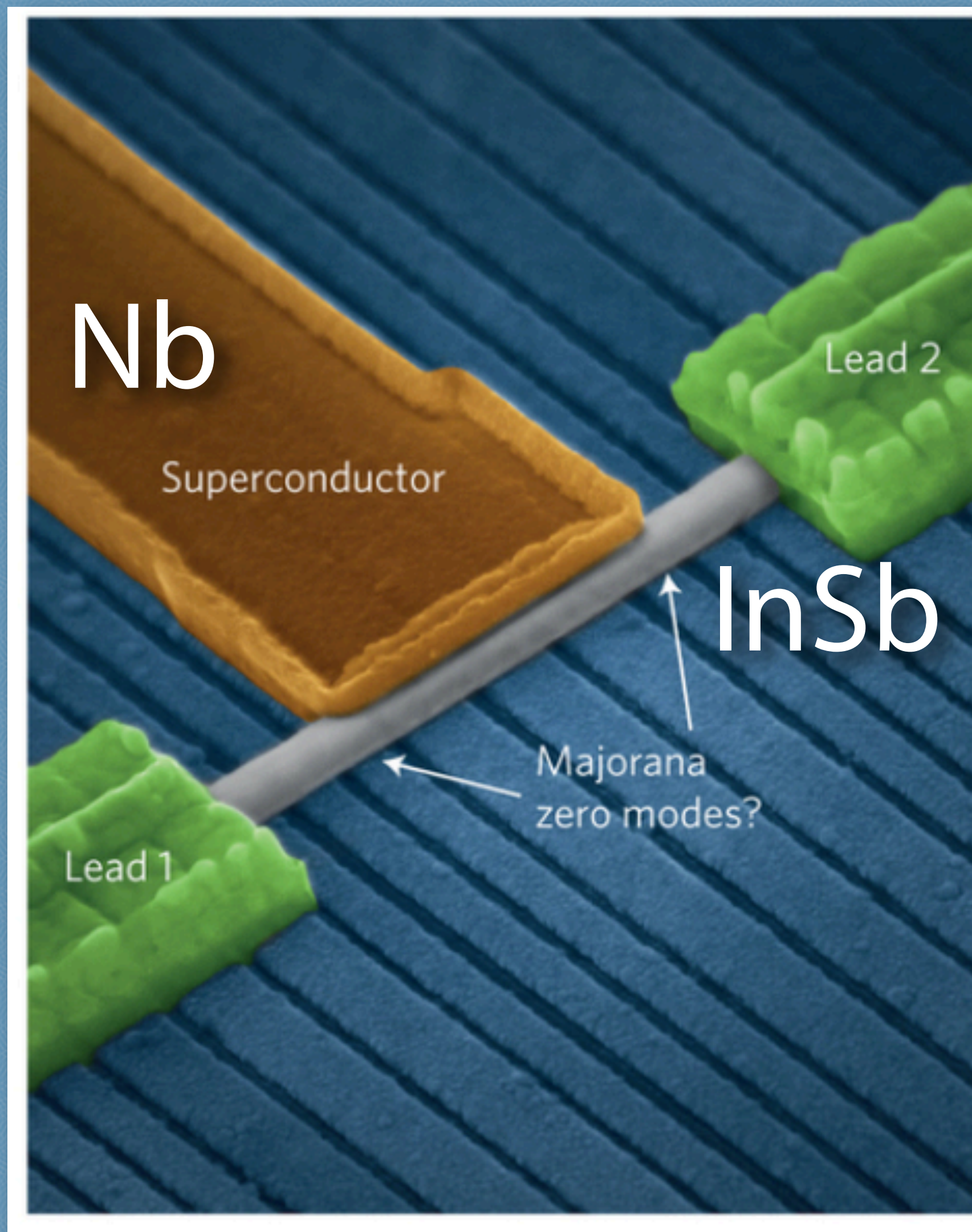
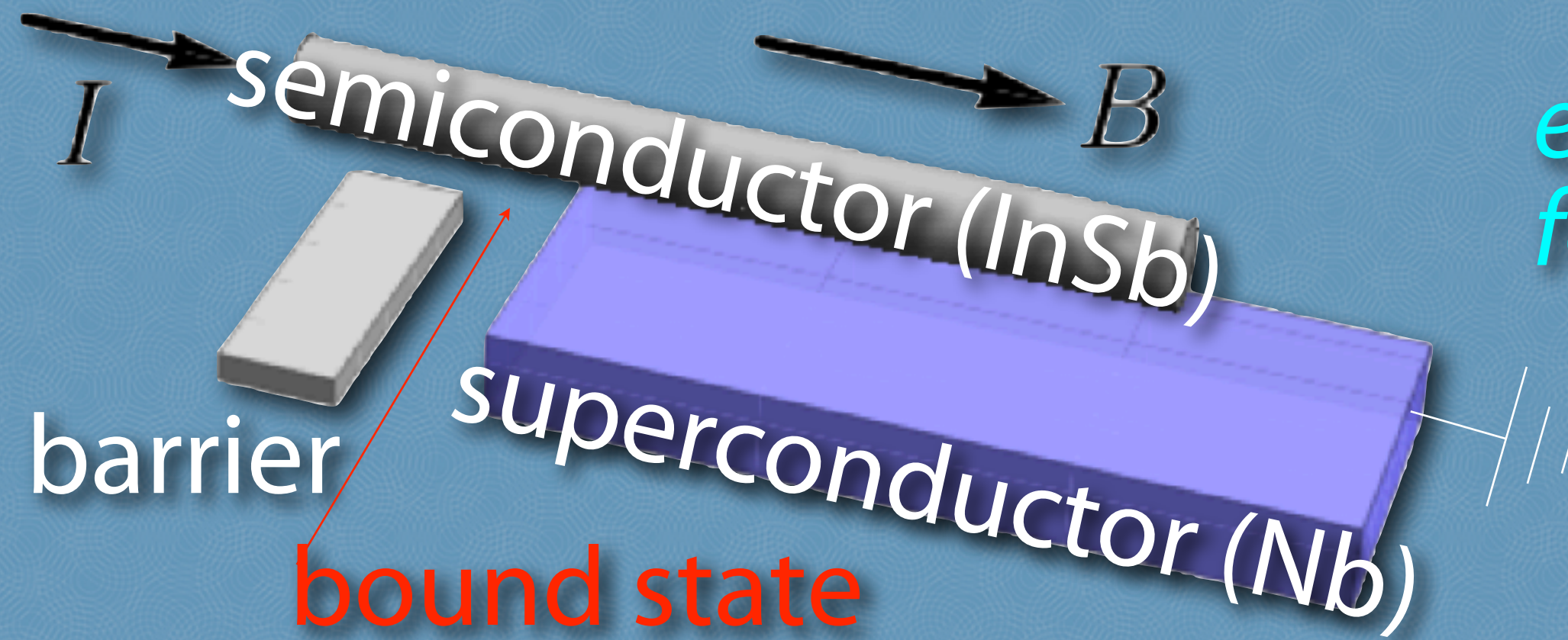| PDF | HTML | Export Citation | Citing Articles (1,100) | | f Like | 0 |

s-wave superconductivity
+ spin-orbit coupling

→ Majoranas bound to a defect
(vortex core, ends of nanowire)

no exotic superconductivity needed

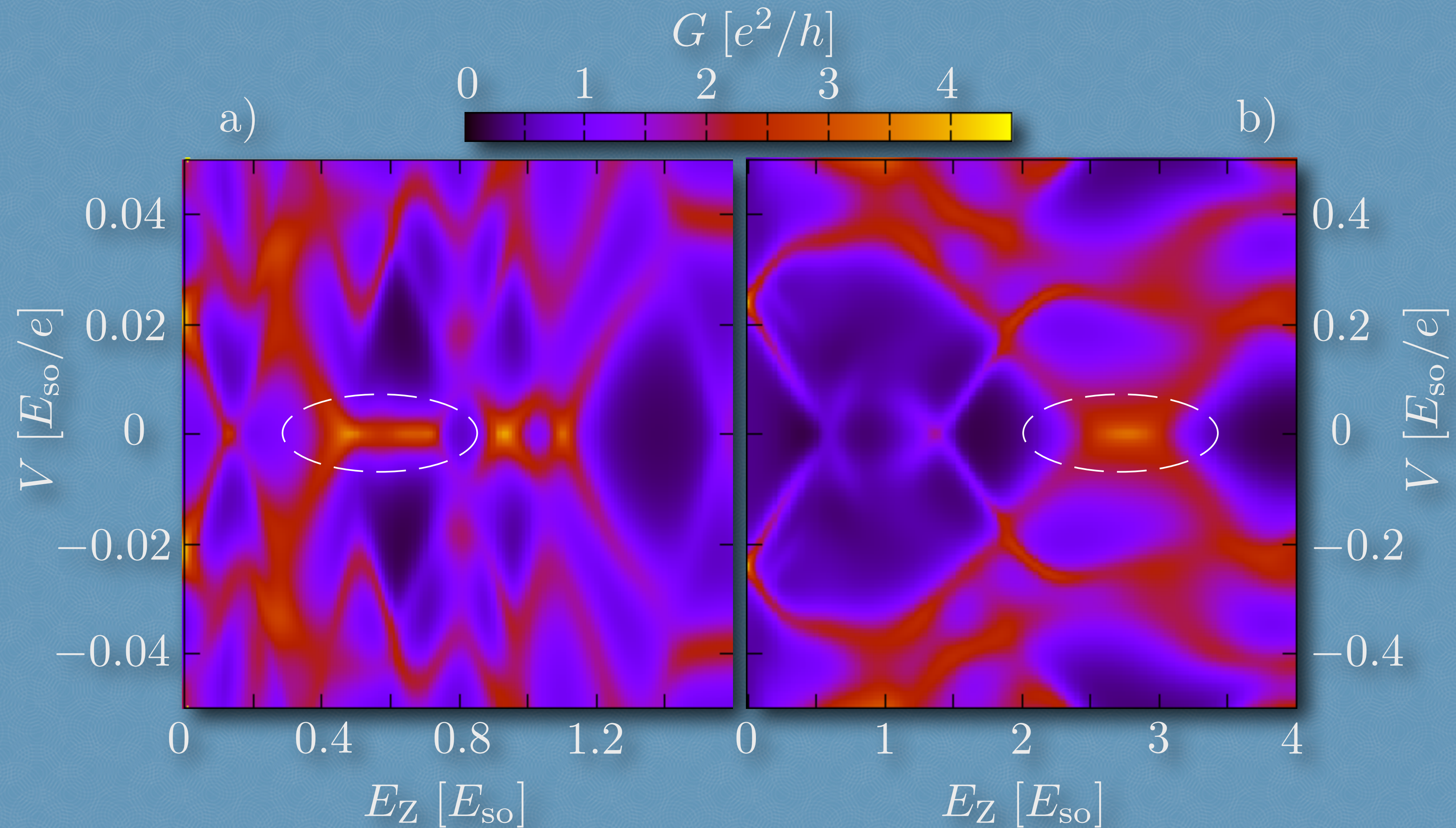2012 experiment by the Delft group, following theoretical proposals by Maryland & Berlin/Weizmann groups

I

semiconductor (InSb)

B

experiment @ Delft (2012)
followed by many more

barrier

superconductor (Nb)

bound state

X-shaped &
Y-shaped
resonance
profiles

not quite a
smoking
gun for
Majoranas

$(2e^2/h)$

V (μV)

B (T)

7
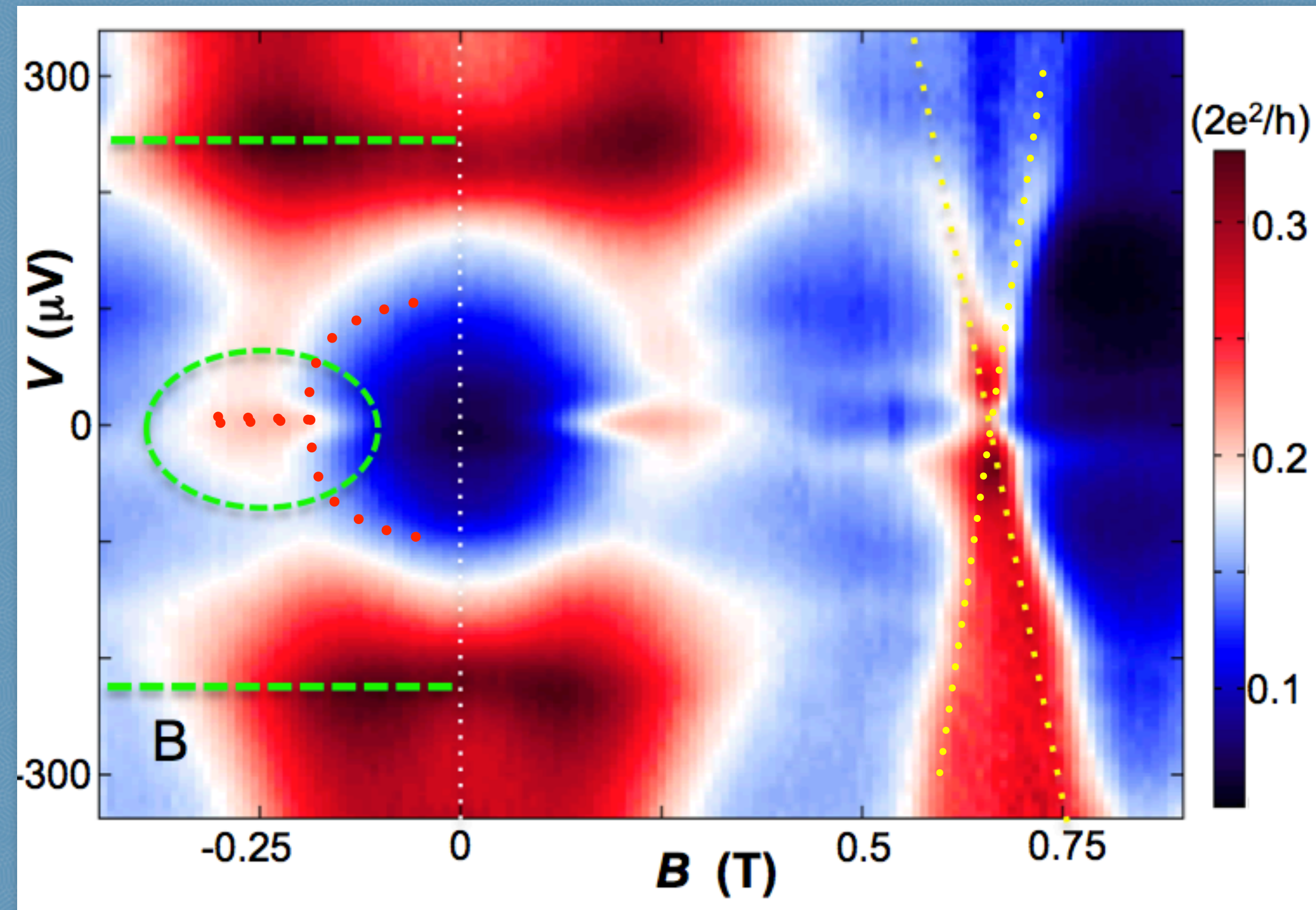
fake Majoranas
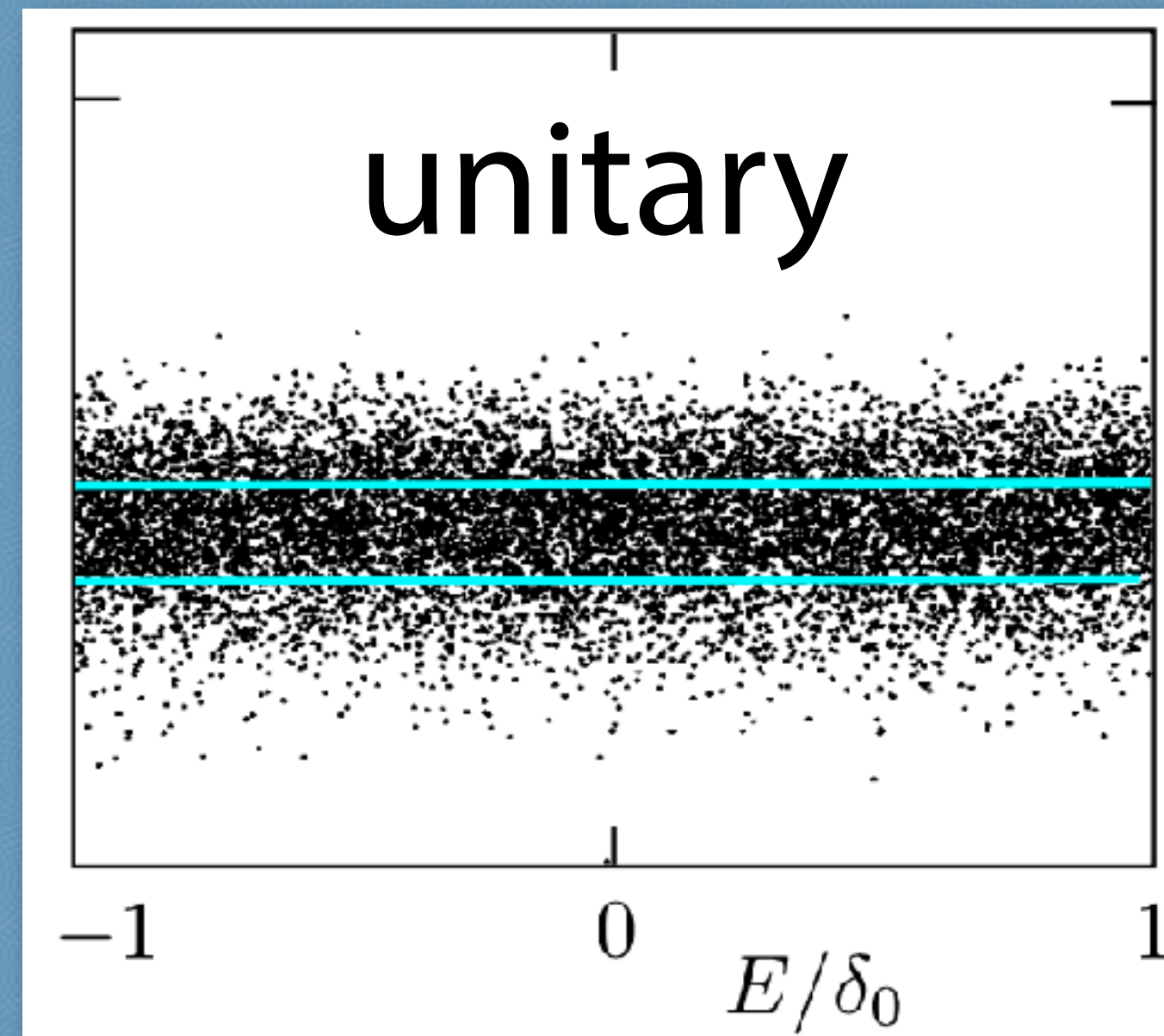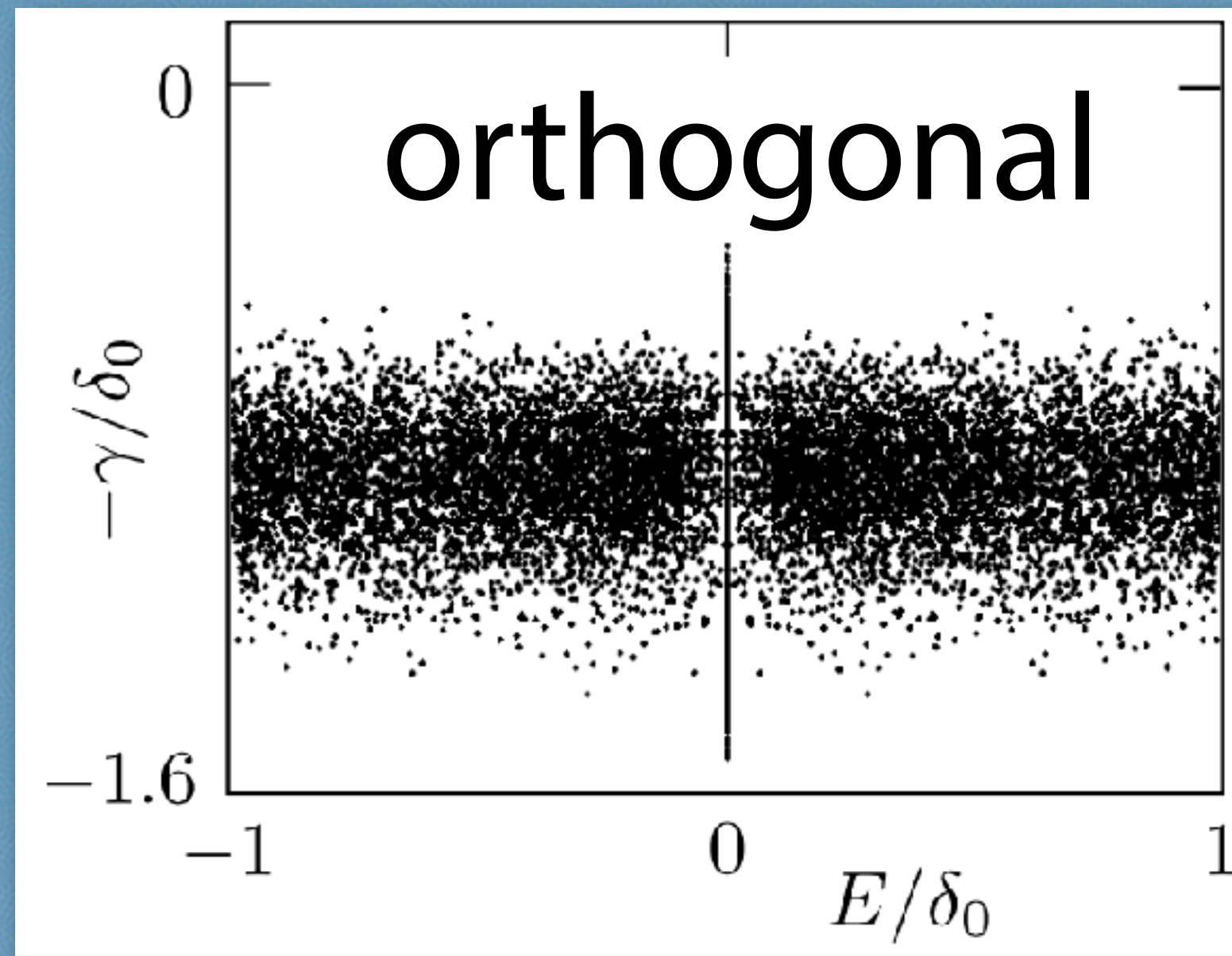
arXiv:1206.6687

*not all zero-voltage peaks in a magnetic field
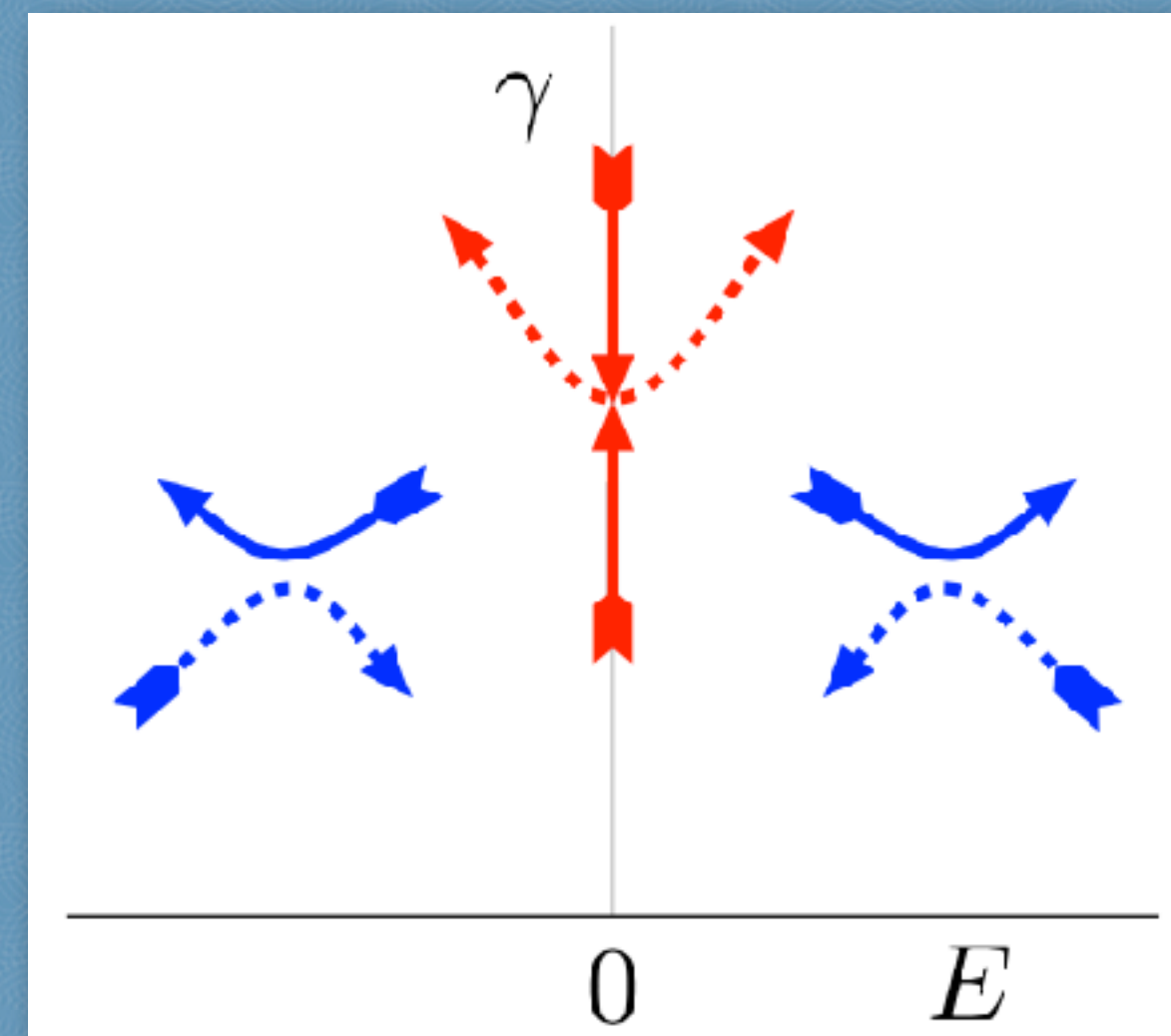are due to Majoranas…...*

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poles of the scattering matrix

orthogonal

unitary

$$S(E - i\gamma) = S^*(-E - i\gamma)$$

poles of orthogonal scattering
matrix are *pinned* to *E=0*

(Pikulin & Nazarov, 2011)

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InAs-Al Hybrid Devices Passing the Topological Gap Protocol

Morteza Aghaee, Arun Akkala, Zulfi Alam, Rizwan Ali, Alejandro Alcaraz Ramirez, Mariusz Andrzejczuk, Andrey E Antipov, Pavel Aseev, Mikhail Astafev, Bela Bauer, Jonathan Becker, Srini Boddapati, Frenk Boekhout, Jouri Bommer, Esben Bork Hansen, Tom Bosma, Leo Bourdet, Samuel Boutin, Philippe Caroff, Lucas Casparis, Maja Cassidy, Anna Wulf

arXiv:2207.02472
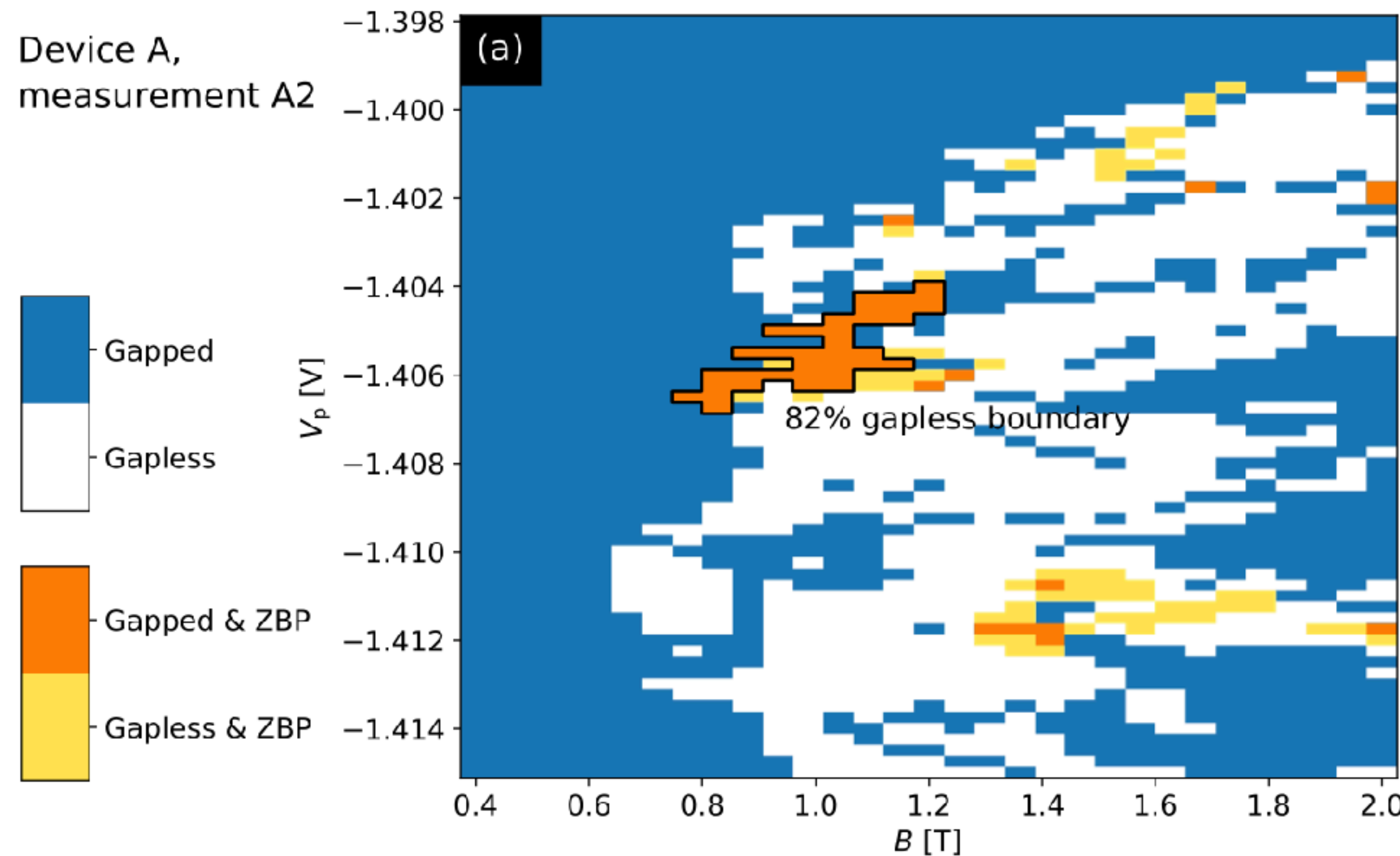
only a small portion of the phase diagram is topologically nontrivial

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the holy grail

Majorana braiding:

Read & Green (2000)

the pairwise exchange of Majorana zero-modes uniquely transforms the operators:

$$\gamma_1 \mapsto \pm\gamma_2 \qquad \gamma_2 \mapsto \mp\gamma_1$$

- no complex phase factors allowed
- fermion parity conserved

$$\gamma_1\gamma_2 \mapsto -\gamma_2\gamma_1 = \gamma_1\gamma_2$$

building block of a quantum computation

how can we move the Majoranas around?

we need a "handle"

Kitaev (2003)

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