PHYS596-Journal club presentation

Signatures of Majorana Fermions in Hybrid Superconductor-Semiconductor Nanowire Device

V. Mourik et al., Science **336,** 1003 (2012)

Team7: William McFaul, David Meldgin, William Morong, Moonjip Park

Main Result:

Strong evidence of Majorana fermions is found at the edges of a superconducting nanowire.

Question:

What is a Majorana fermion?

What can we do with this?

What is a Majorana fermion?(MF)

1. It is its own antiparticle

2. Interchanging MF twice does not return to original state(anyon)

Ettore Majorana(1906-1938?)

Majorana state found in this paper is not elementary particle, but quasiparticle state

Majorana fermion as anyon

Dirac fermion and boson have eigenvalues of under interchange of particle

$\Rightarrow$ One particle exchange shifts phase by

$\Rightarrow$ Two particle exchange will give original state

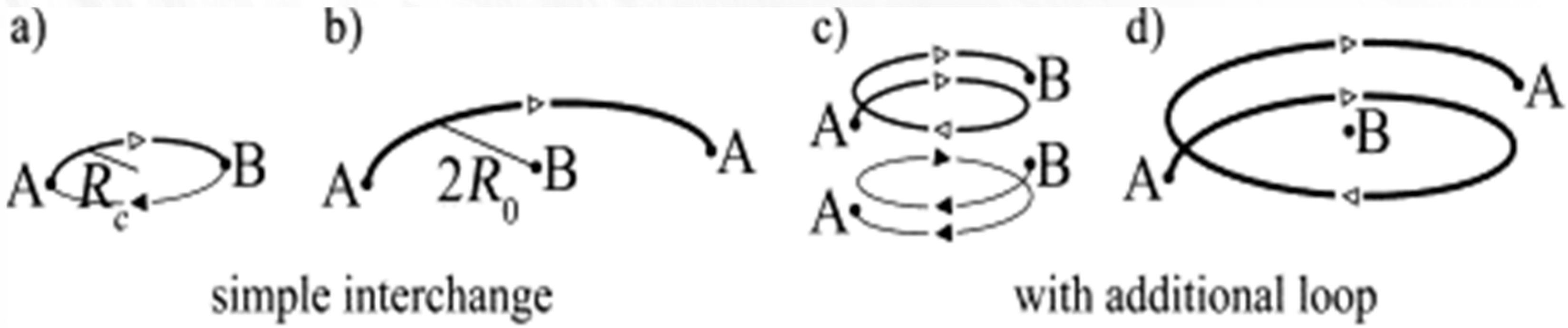
This is not the case for MF:
Exchange of MF returns matrix not phase shift(non-abelian statistics).

=>Important application in quantum computing

Majorana fermion as anyon(2)

Anyon exists only in <3+1D(Topology matters)

In 2dimensional space, winding point(particle) is well defined.



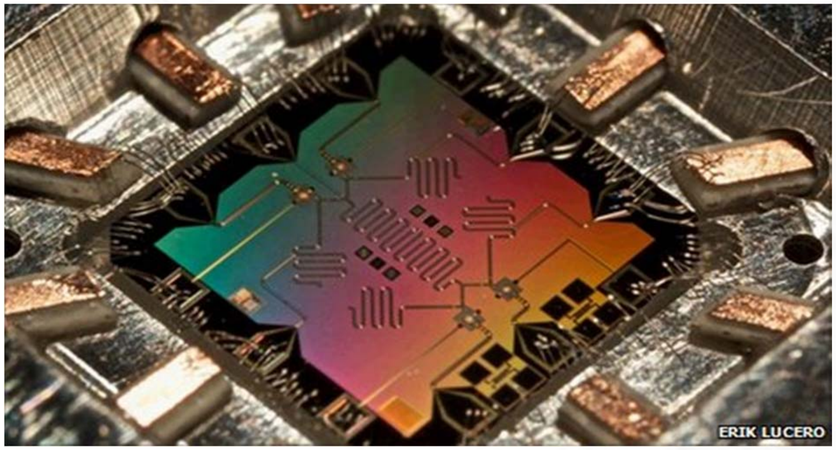
If a particle returns to the same position with the history of winding, the state does not have to return to the original.

Figure: J.jacak New implementation of composite
fermions in terms of subgroups of a braid group,
Physics letter A 374, 2 (2009)

The two (conflicting) requirements of qubits for quantum computation

Controllability

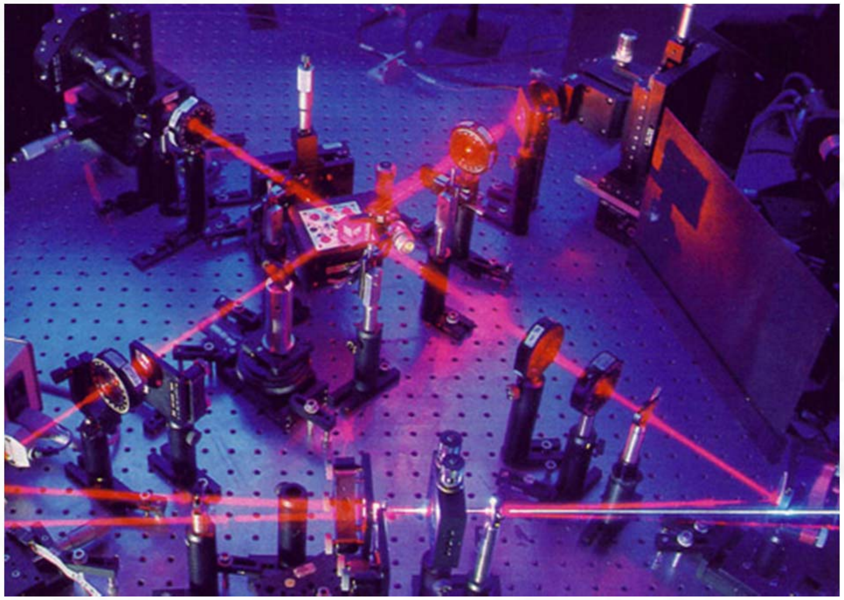
- Arbitrary rotation of one-qubit state
- Two- bit interaction
- Quick response/ readout



Superconducting Qubit- Martinis Group

Coherence

Qubit states remain isolated from environment


Quantum Teleportation- Zeilinger group

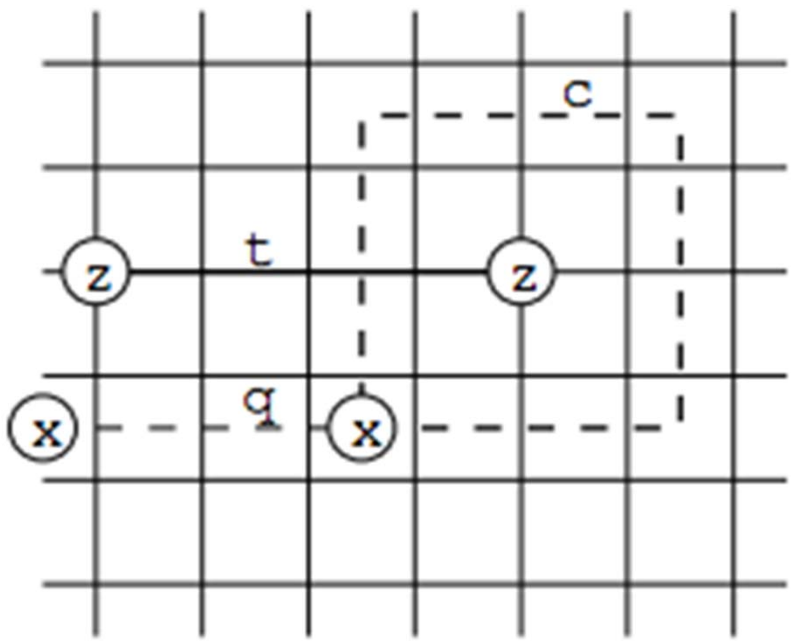
Global or topological qubits resist decoherence

- Interactions are local.
- Topological properties are invariant to small disturbances
- What protects Majorana fermions? Fermion number.

$$c_{2j} = a_j + a_j^\dagger$$

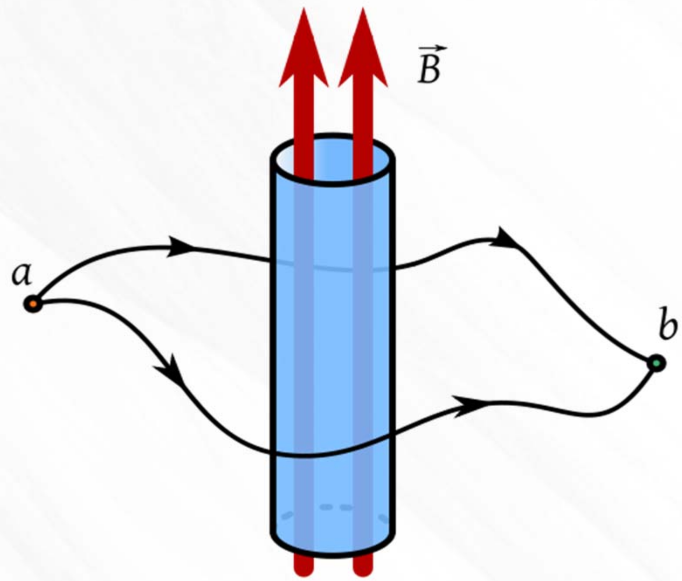
Anyon statistics can be used for quantum gates

- Single- qubit gates through 'braiding' Majorana fermions



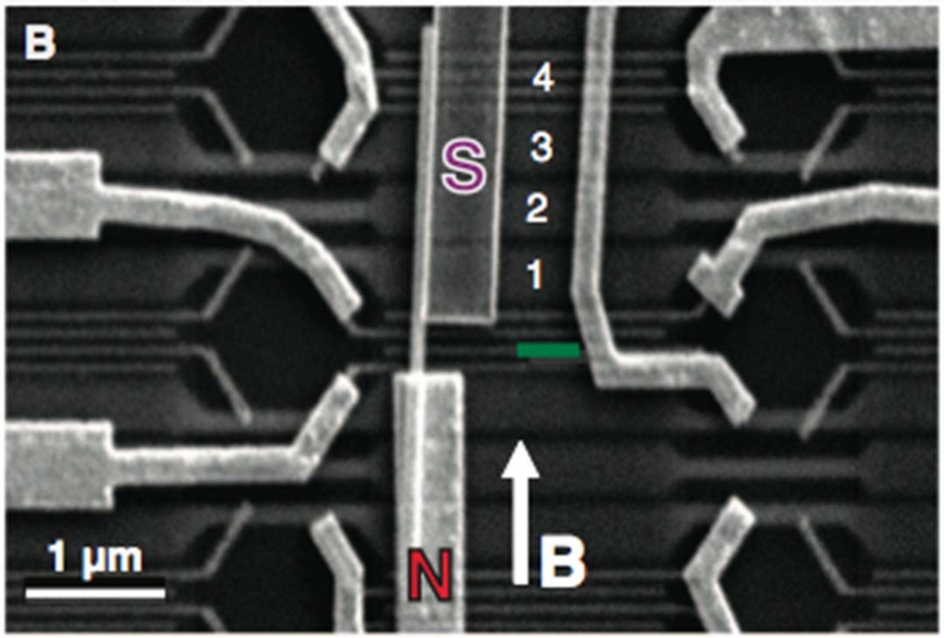
A. Yu. Kitaev, quant-ph/9707021

- This is analogous to the Aharonov-Bohm effect in QED.

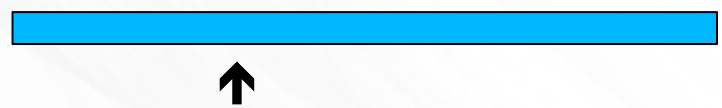


Kismalac, Wikimedia Commons

Drawn Diagram vs. Physical Device

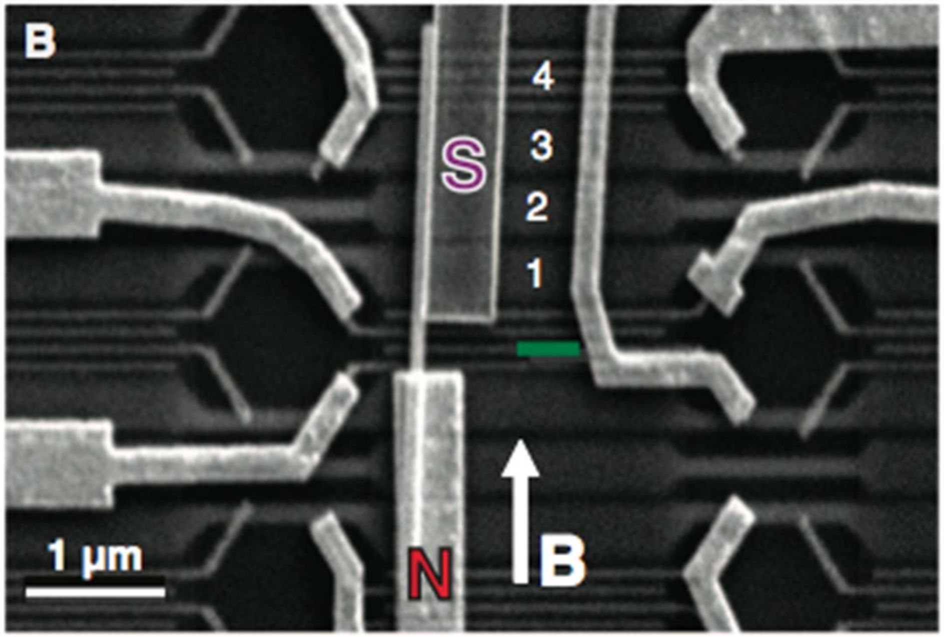


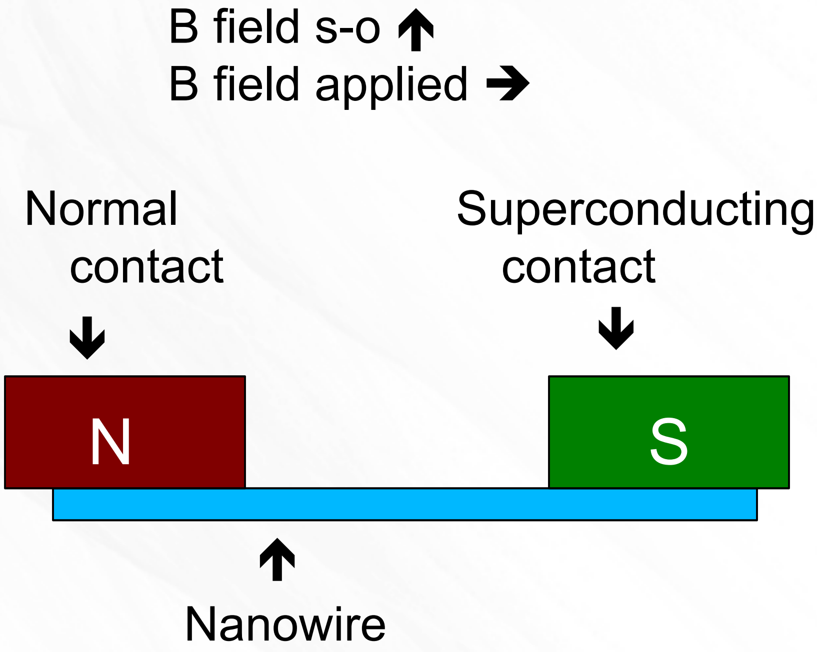
B field s-o ↑
B field applied →



Nanowire

Drawn Diagram vs. Physical Device





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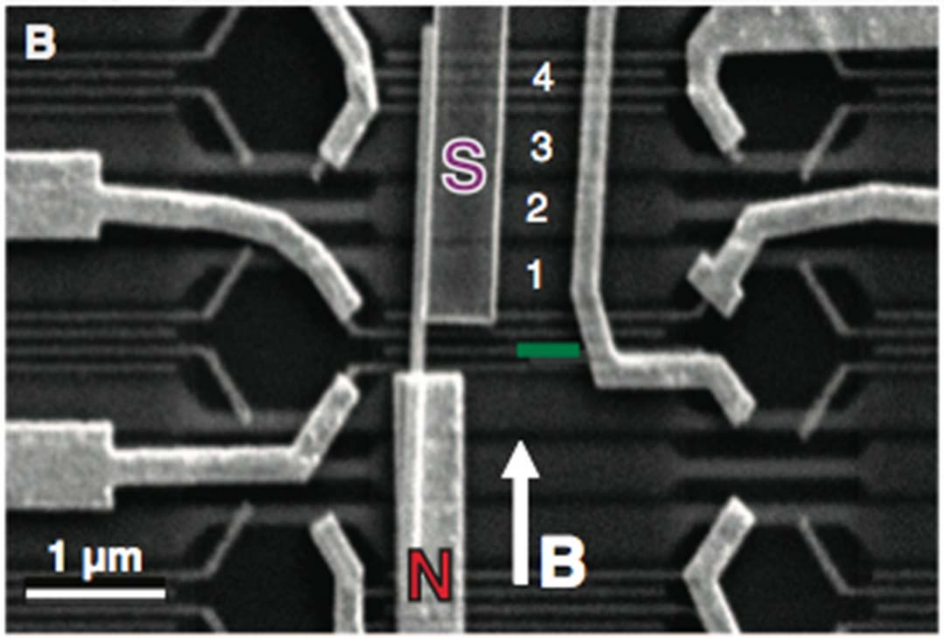
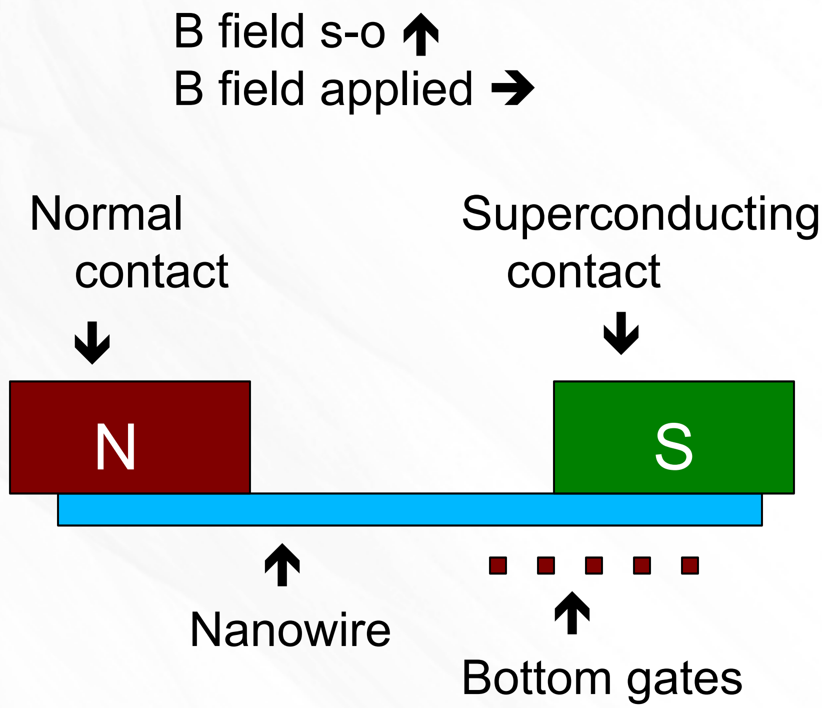
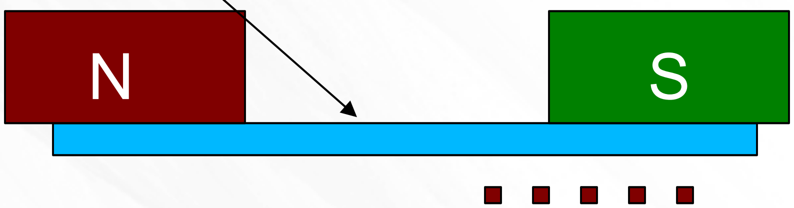




Forming a Majorana Bound State

InSb nanowires (NW):

- Magnetic field along NW axis
  creates Zeeman Ez = 1.5 meV/T.
- Chemical potential μ



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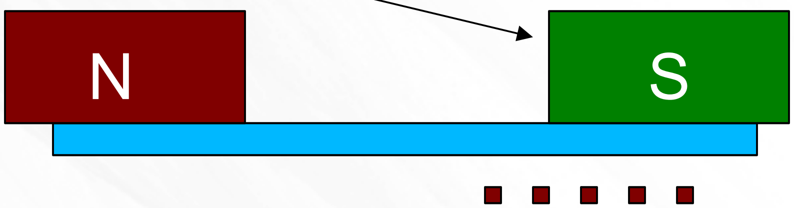

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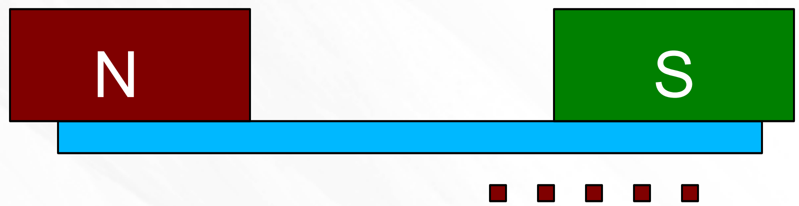
Topological state:
- A topologica $E_Z > (\Delta^2 + \mu^2)^{1/2}$ ne NW wherever
- A nontopological state exists elsewhere.



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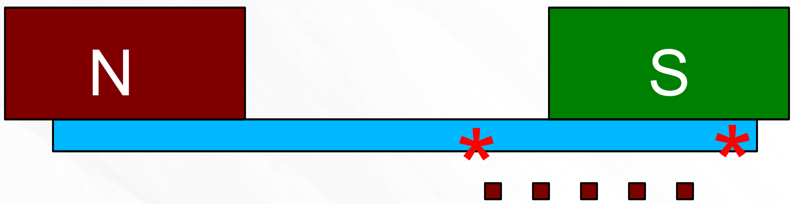
- A nontopological state exists
  elsewhere.
- A Majorana bound state exists in
  between the two phases.

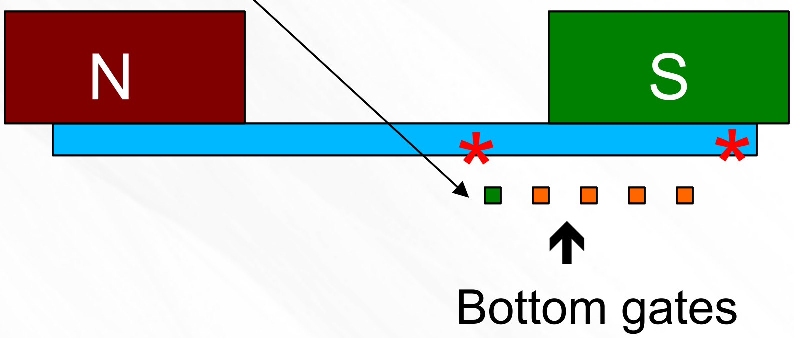
(*)



Probing the Majorana Bound State

Bottom gates:

- Green gate creates a tunnel barrier directly above in the NW.



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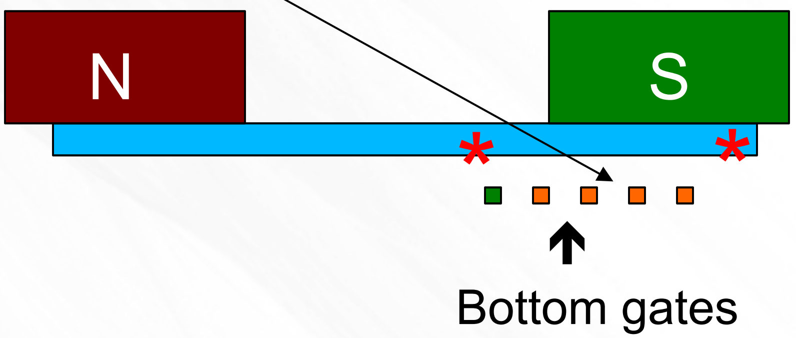

Probing the Majorana Bound State

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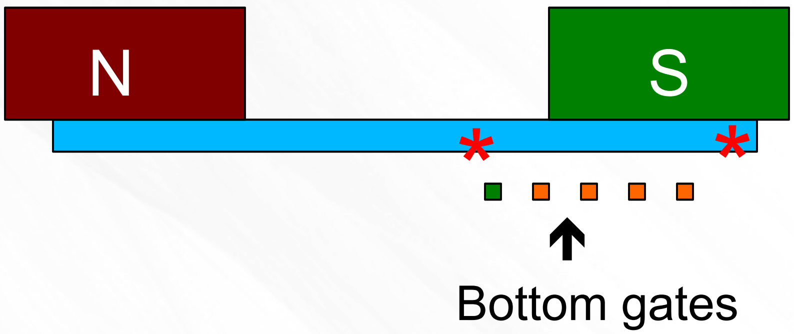
- Other gates tune the density of states in other sections of the NW.

N-NW-S circuit:

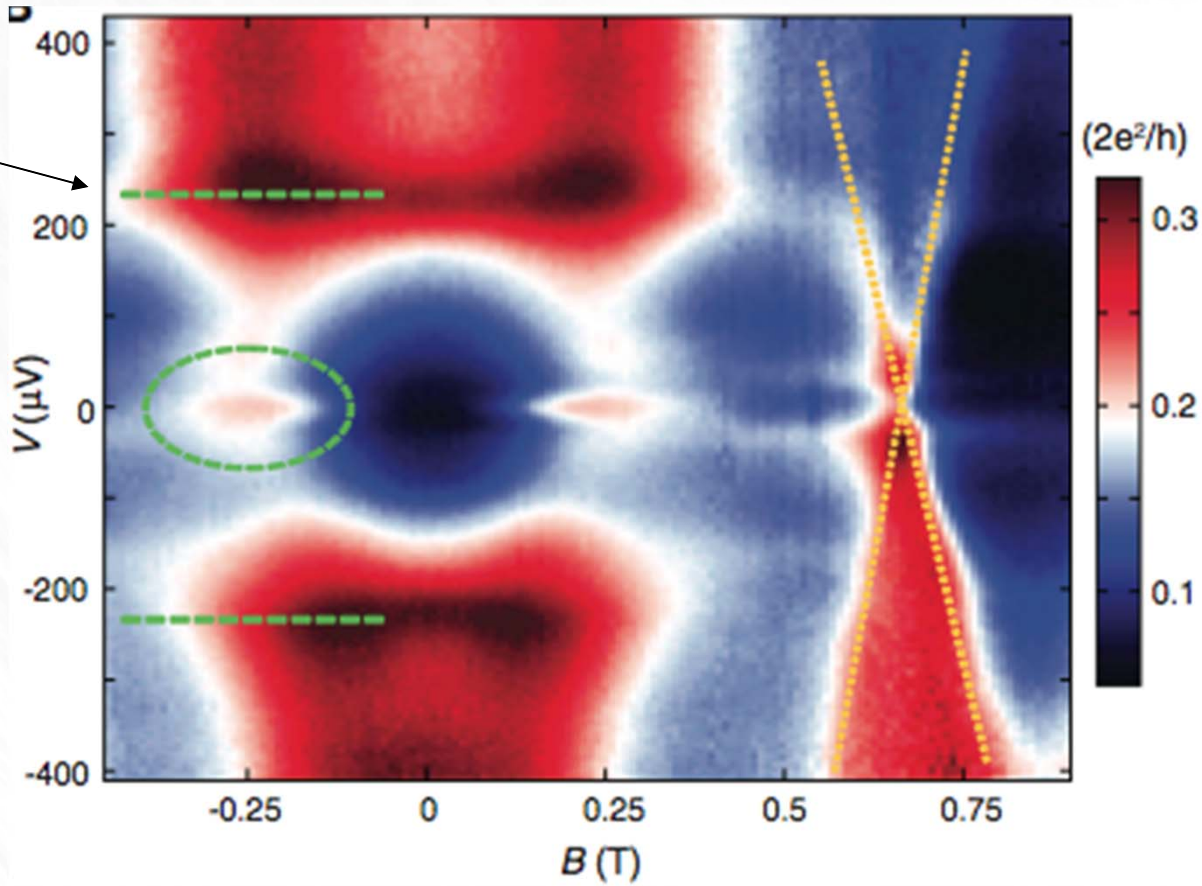
- The left MBS (*) is very close to the tunnel barrier.
- Expect to see zero-bias conductance peak when MBS is present, and no zero-bias peak when MBS is absent.



Conductance vs. Voltage and B Field

Main features

- Induced gap edges appear at 250 uV (green lines).



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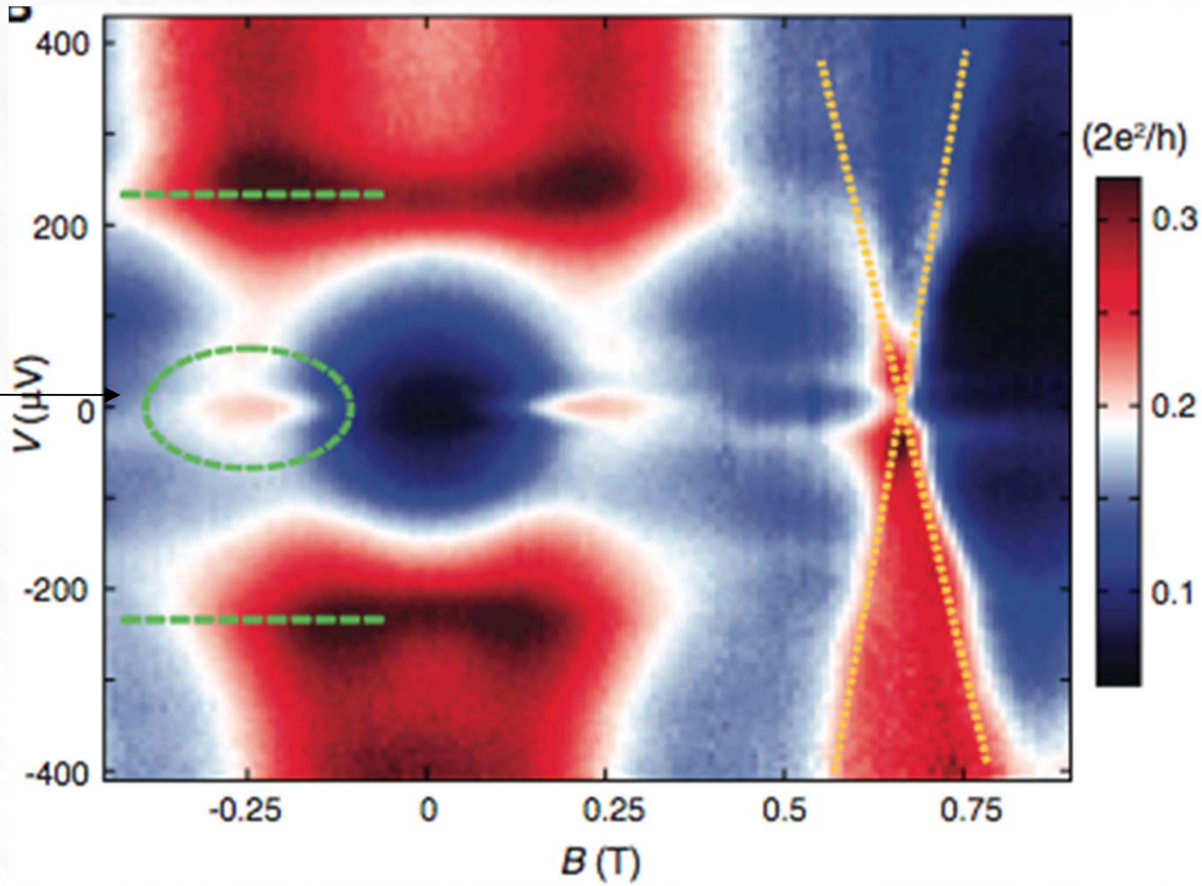
- Zero-bias peak (ZBP) appears at B>150 mT (green circle).



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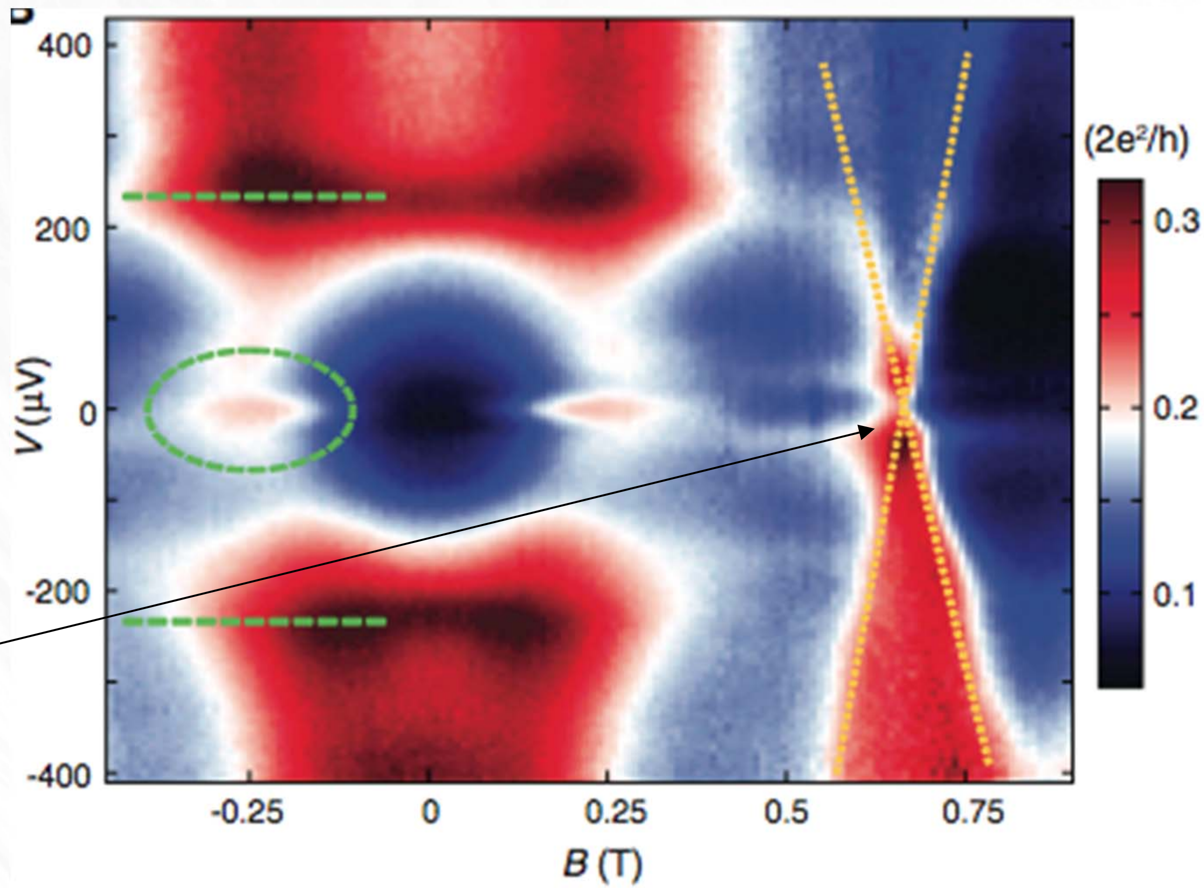
- Pair of Andreev resonances appear at B~600 mT (orange lines).



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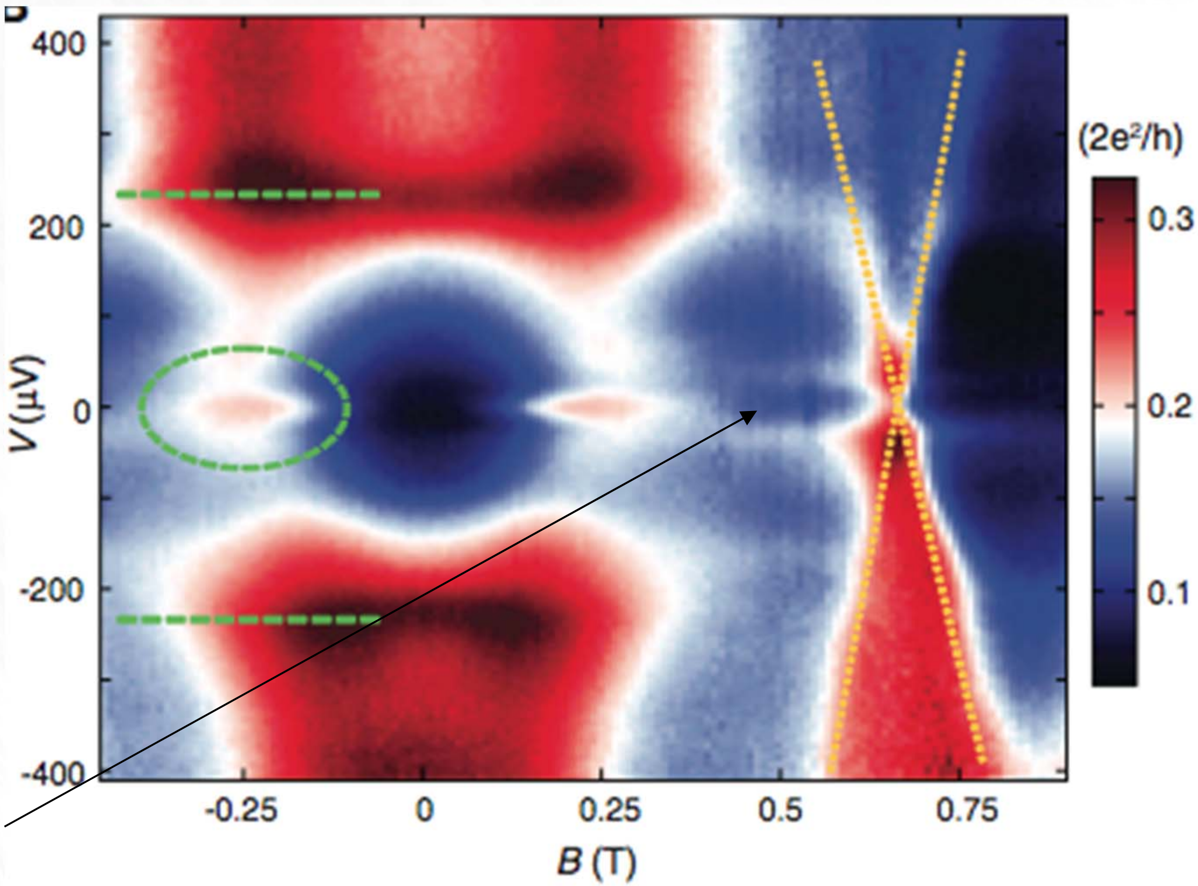
- ZBP splits into two peaks symmetric about zero bias at B~400 mT (strange!)



Stability of the Zero-Bias Peak (ZBP)

ZBP center is fixed

- As B_parallel is above
  150 mT, which we just saw.

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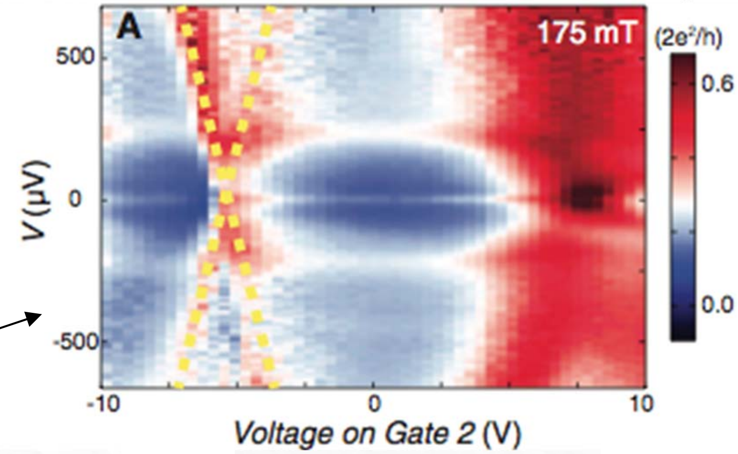
- With gate 2 voltage.



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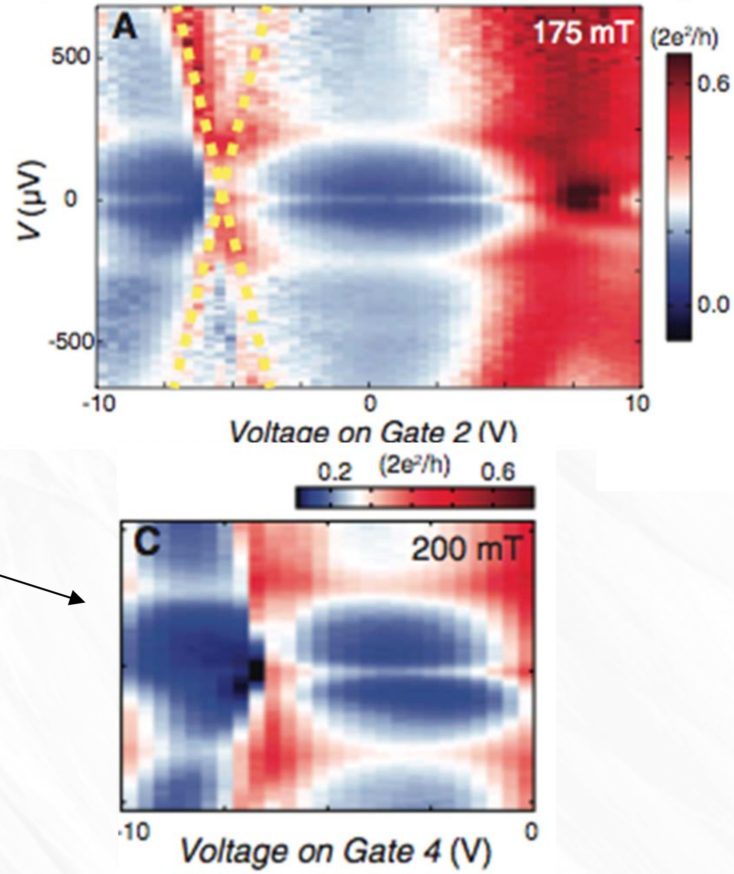
- With gate 4 voltage.



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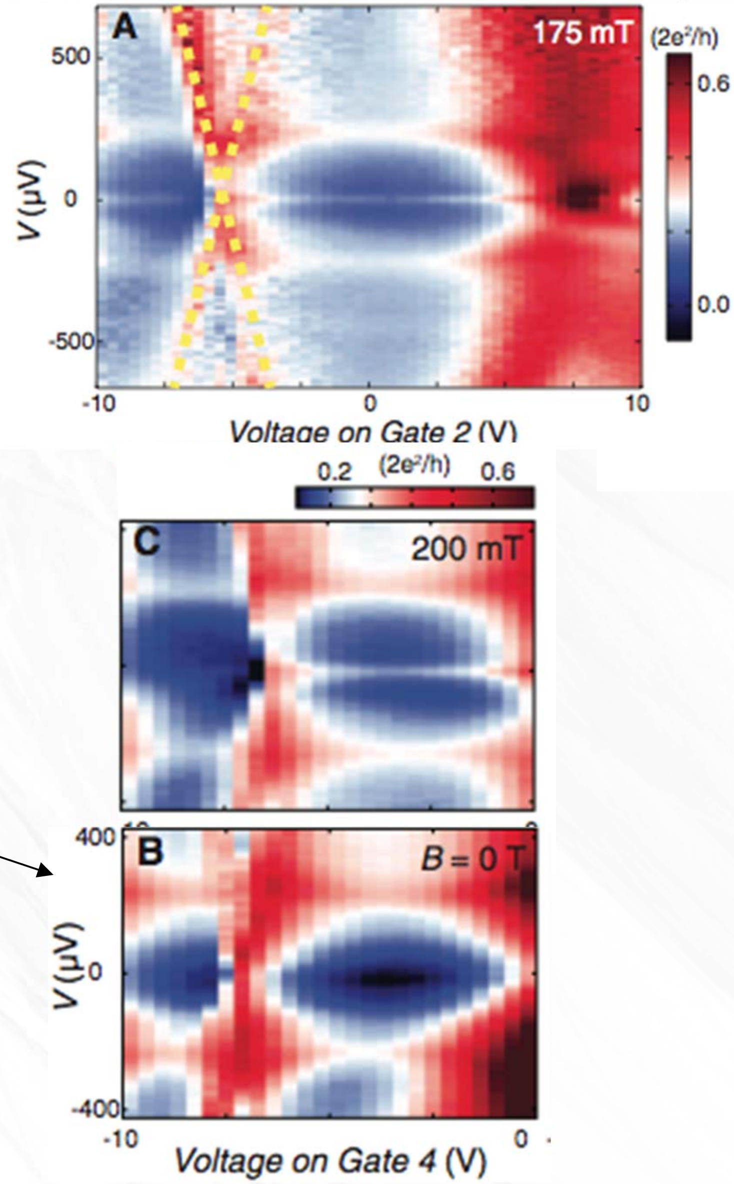
- With gate 2 voltage.

- With gate 4 voltage.

ZBP disappears

- As B_parallel dips below 150 mT.

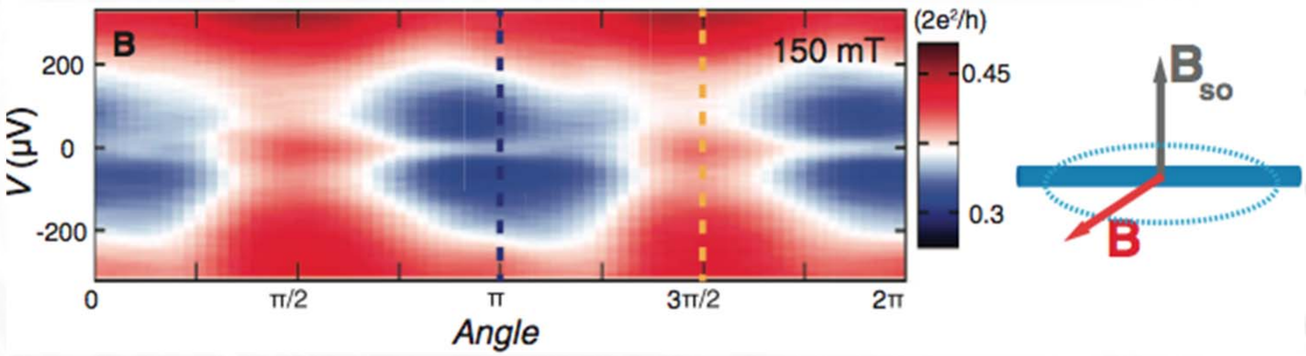
- T > 300 mK (not shown).



Stability of the Zero-Bias Peak (ZBP)

ZBP center is fixed

- As B is rotated perpendicular to B-SO.



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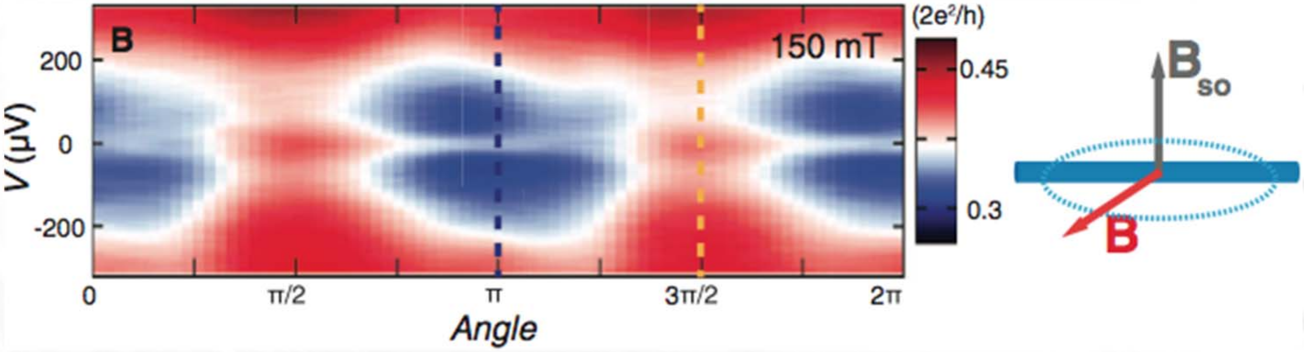
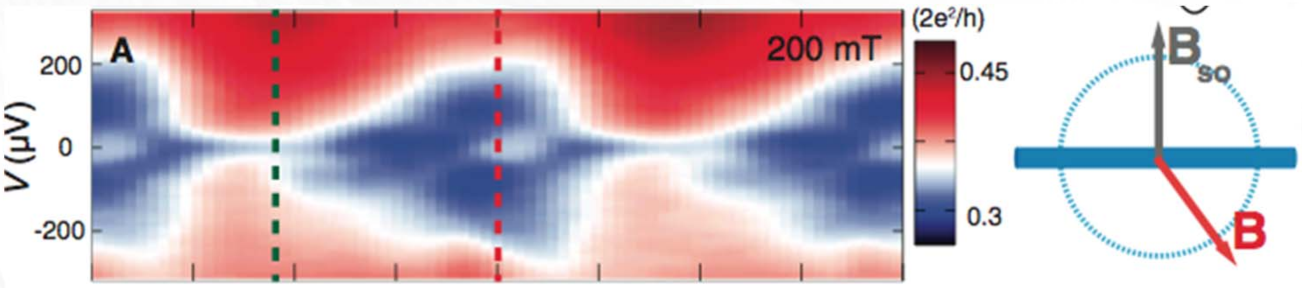


ZBP disappears

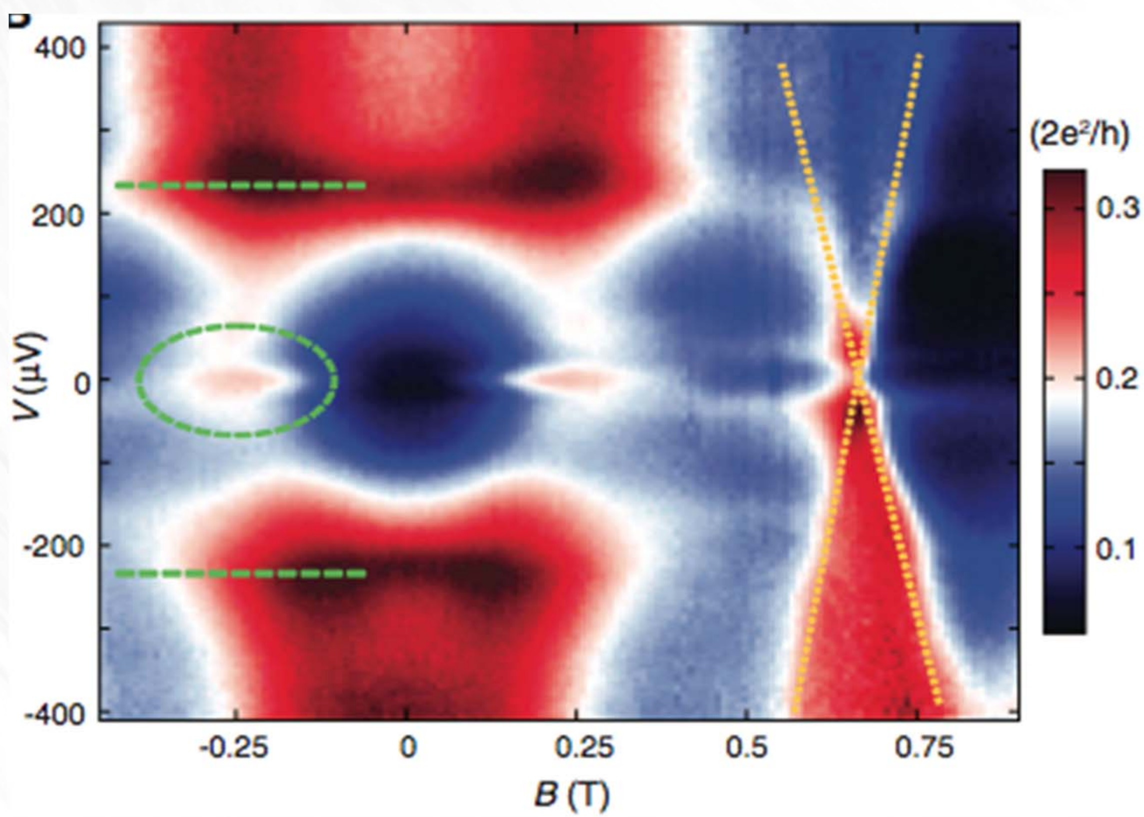
- As B is rotated parallel to B-SO.



The ZBP appears and disappears in accordance with an MBS hypothesis!

An Unexplained Splitting of Zero Bias Peak

Above 400 microTelsa the zero bias peak, the signal for the Majorana, splits in two.



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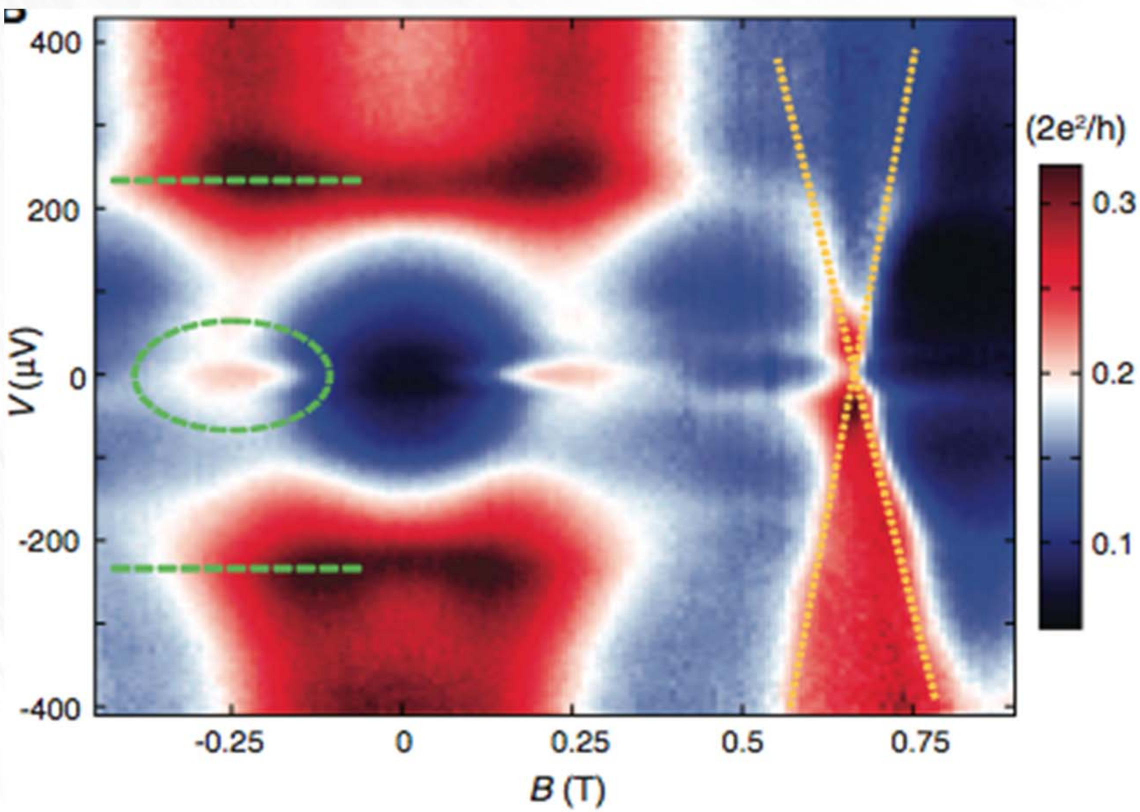
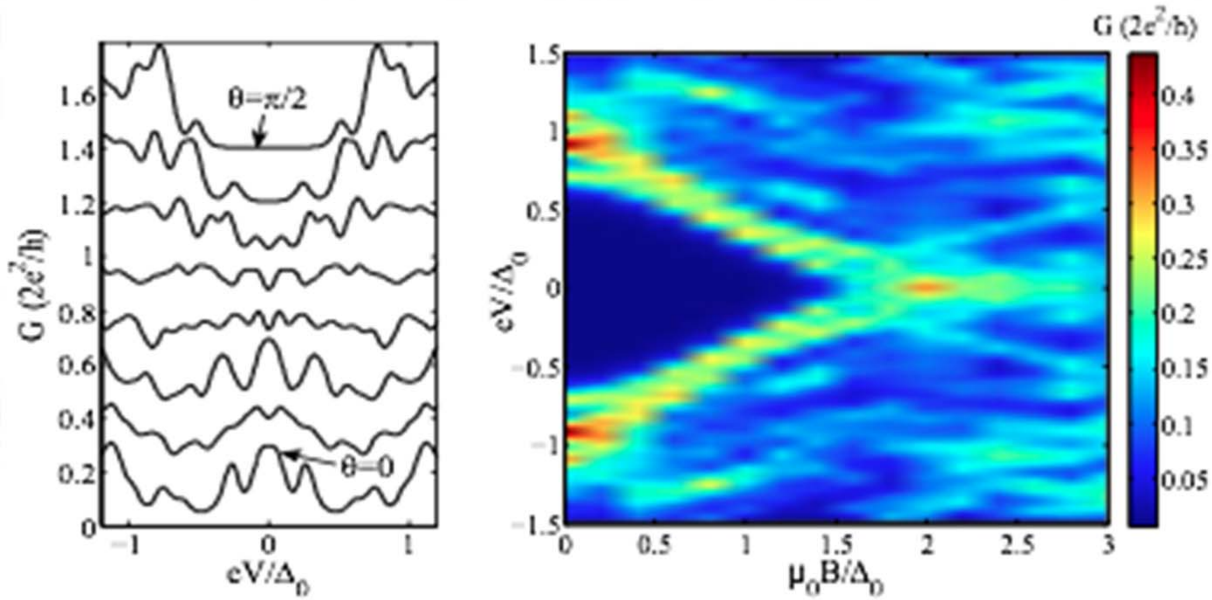
Result is Not Explained In Paper.

Not a direct prediction from Majorana theory.



Are they seeing Majorana Fermions or the effects of Disorder?

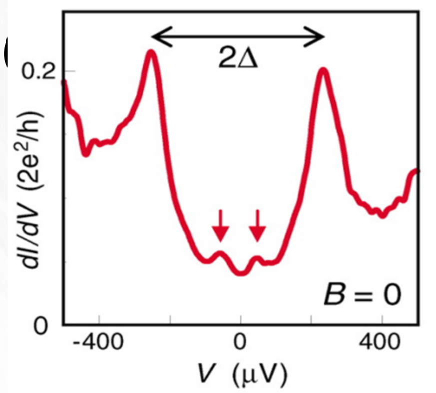
Liu et al. ran computer simulations and were able to produce the same Majorana signal by adding disorder to their nanowires.



To verify discovery of Majorana fermions, a higher resolution experiment would need to be done at colder temperature to reduce thermal noise.

Probable Discovery of Majorana Fermions.

A signal existed when a Majorana fermion was predicted to exist, and disappeared when no signal was expected.



This is the first evidence of Majorana fermions in a condensed matter system. If Majorana states can be made they might be used for quantum computing.

Acknowledgments.

The Discovery Paper.

V. Mourik, K. Zuo, S.M. Frolov, S.R. Plissard, E.P.A.M. Bakkers, and L.P. Kouwenhoven, Science 336, 1003 (2012)

J. Liu, A.C. Potter, K.T. Law, P.A. Lee arXiv 1206.1276v1 6 Jun 2012.

Assistance Provided by Lance Cooper.