# Majorana Fermion Experiments in Nanowires

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University of Pittsburgh

## Lecture 1

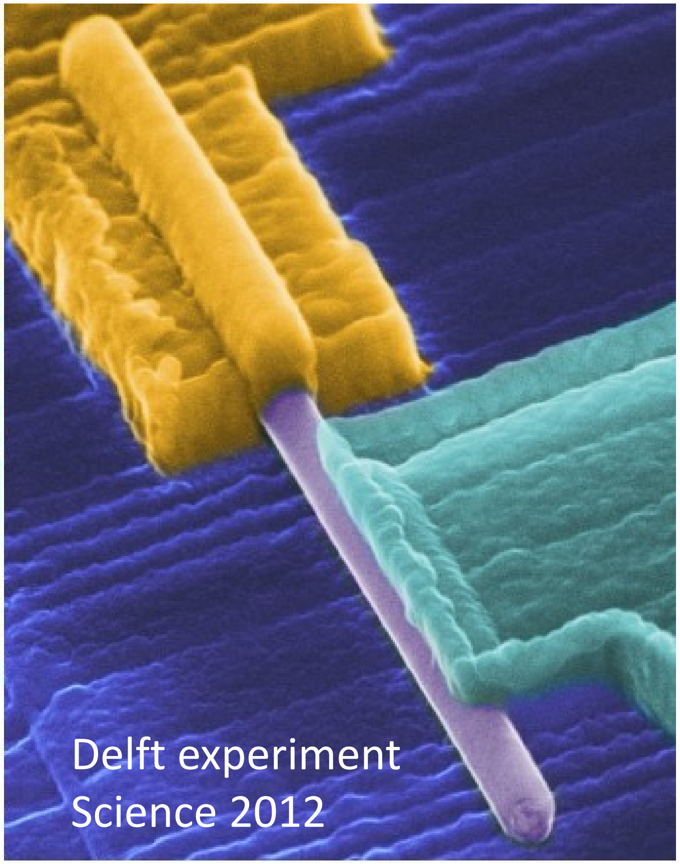
Kitaev Model mapped on to superconductor-semiconductor hybrids

Experimental signature: zero-bias peaks

## Lecture 2

Modern state of the field

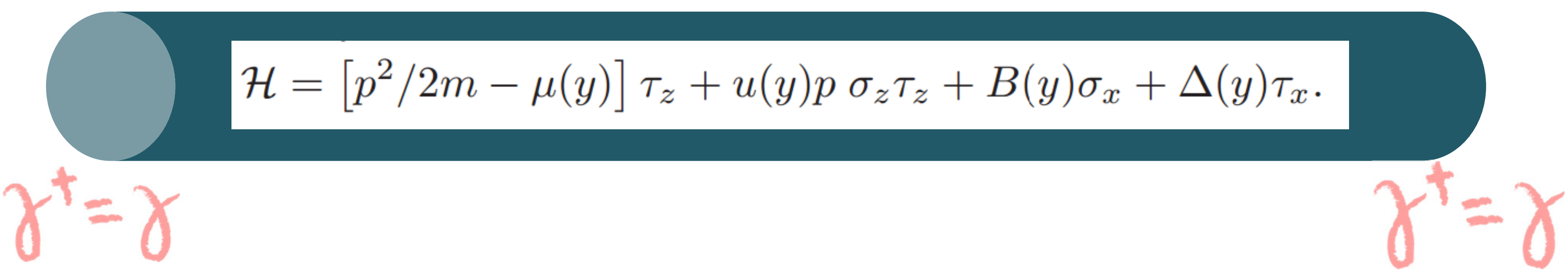
Andreev states in quantum dots



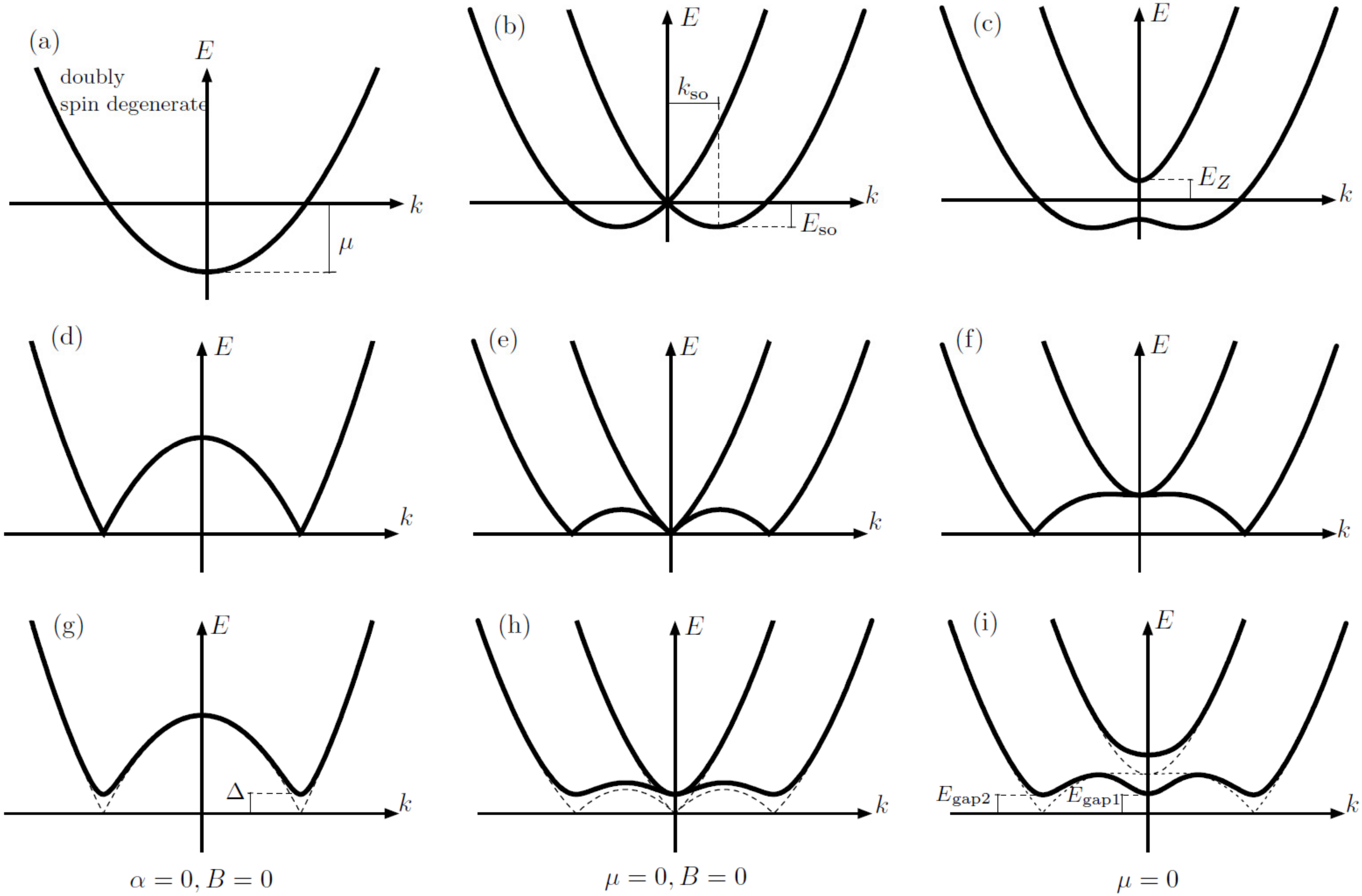

Boulder Summer School, 2016

# Majorana recipe for nanowires:

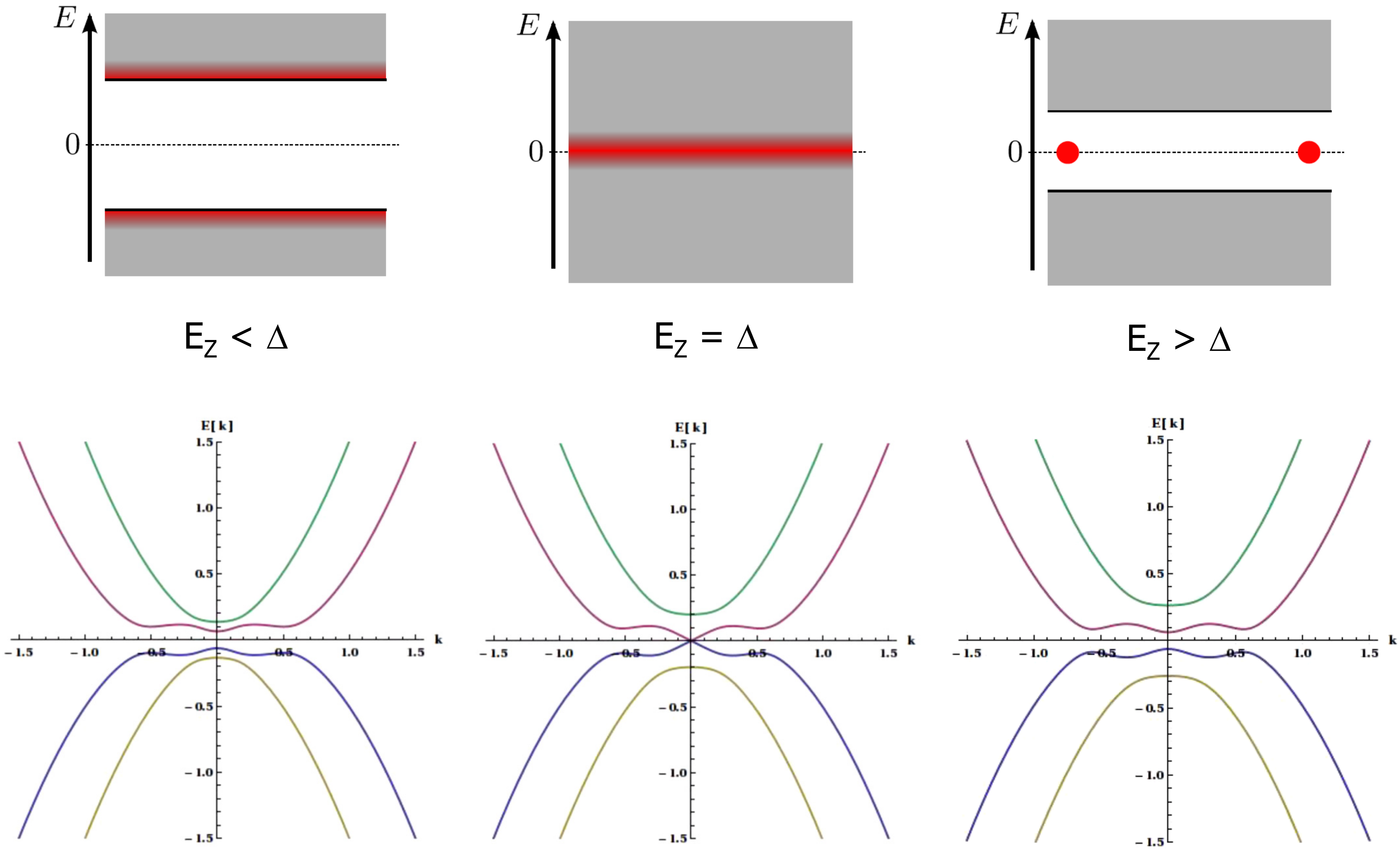
1. One-dimensional wire
2. Spin-orbit interaction
3. Superconductivity
4. Magnetic field




Lutchyn, Sau, Das Sarma, PRL 2010
Oreg, Refael, von Oppen, PRL 2010




Sim by Fabian Hassler

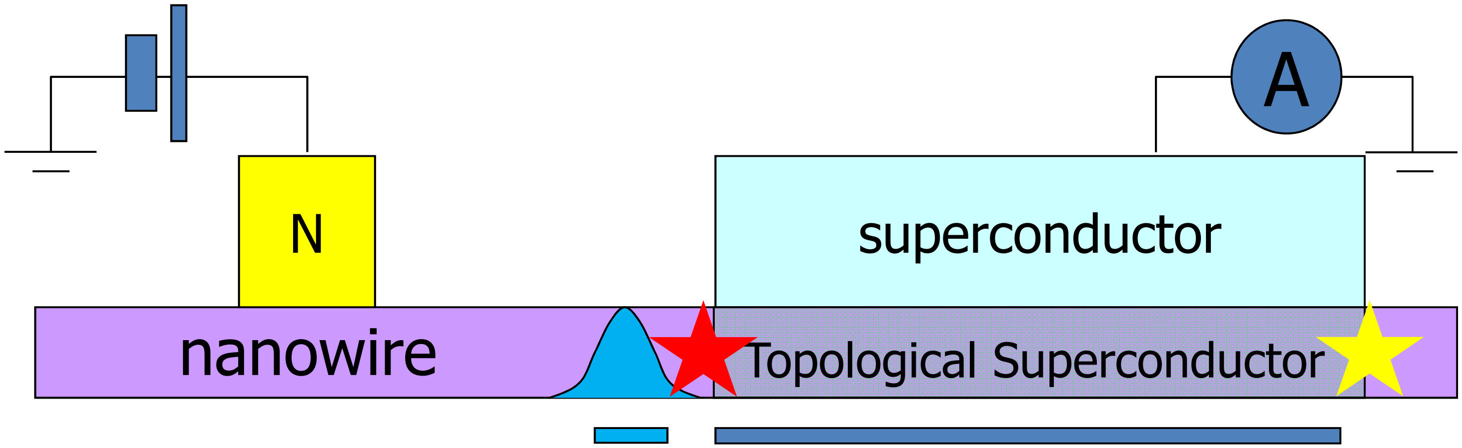



Trivial Superconductor
"positive gap"

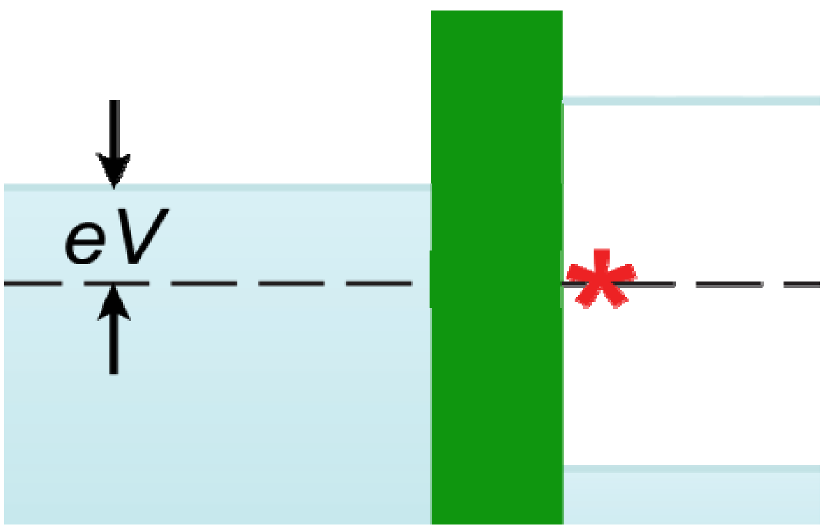
Majorana
"zero gap"

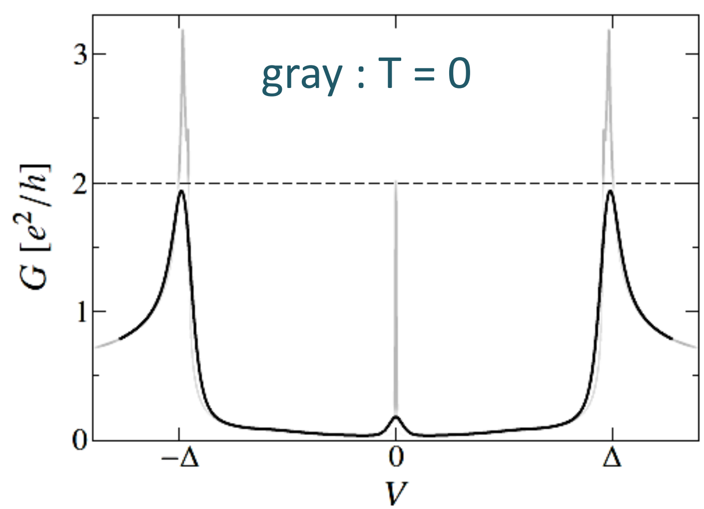
Topological Superconductor
"negative gap"

# Tunneling experiment




Tunneling into a Majorana bound state:
Resonant Andreev current!



# Which nanowire? Which superconductor?

Need:
- strong spin-orbit coupling
- large g-factor
- ballistic 1D transport

Need:
- large gap
- withstand high B-fields
- small work function mismatch

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InAs nanowires:

g = 6-10, lso=100 nm
Disorder is high (low mobility)

InSb nanowires:

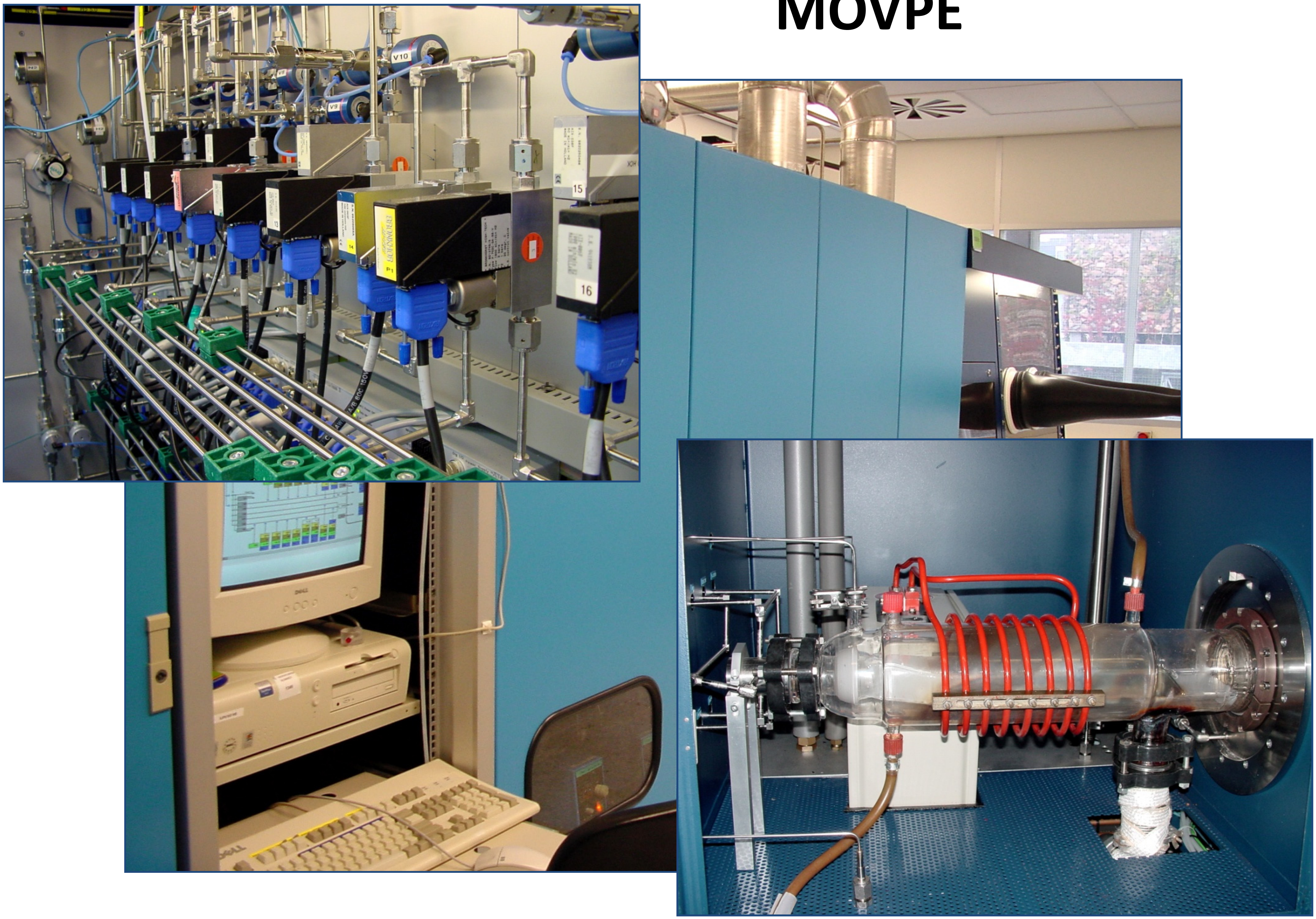
Larger g, similar lso, "cleaner"

Aluminum contacts:

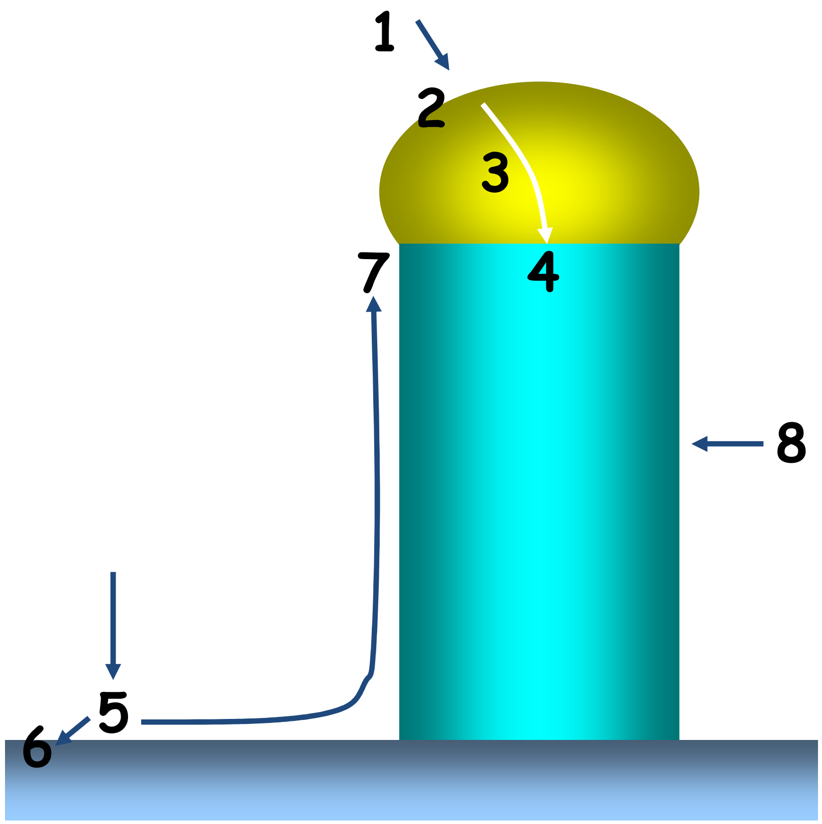
Gap ~ 100 ueV
Critical field ~100 mT

NbTiN contacts:
Gap ~ 3meV
Critical field > 10 T

# MOVPE



# Growth dynamics




1: Precursor transport

2: Precursor dissociation

3: Diffusion through Au

4: Crystal growth

5: Adsorption on substrate

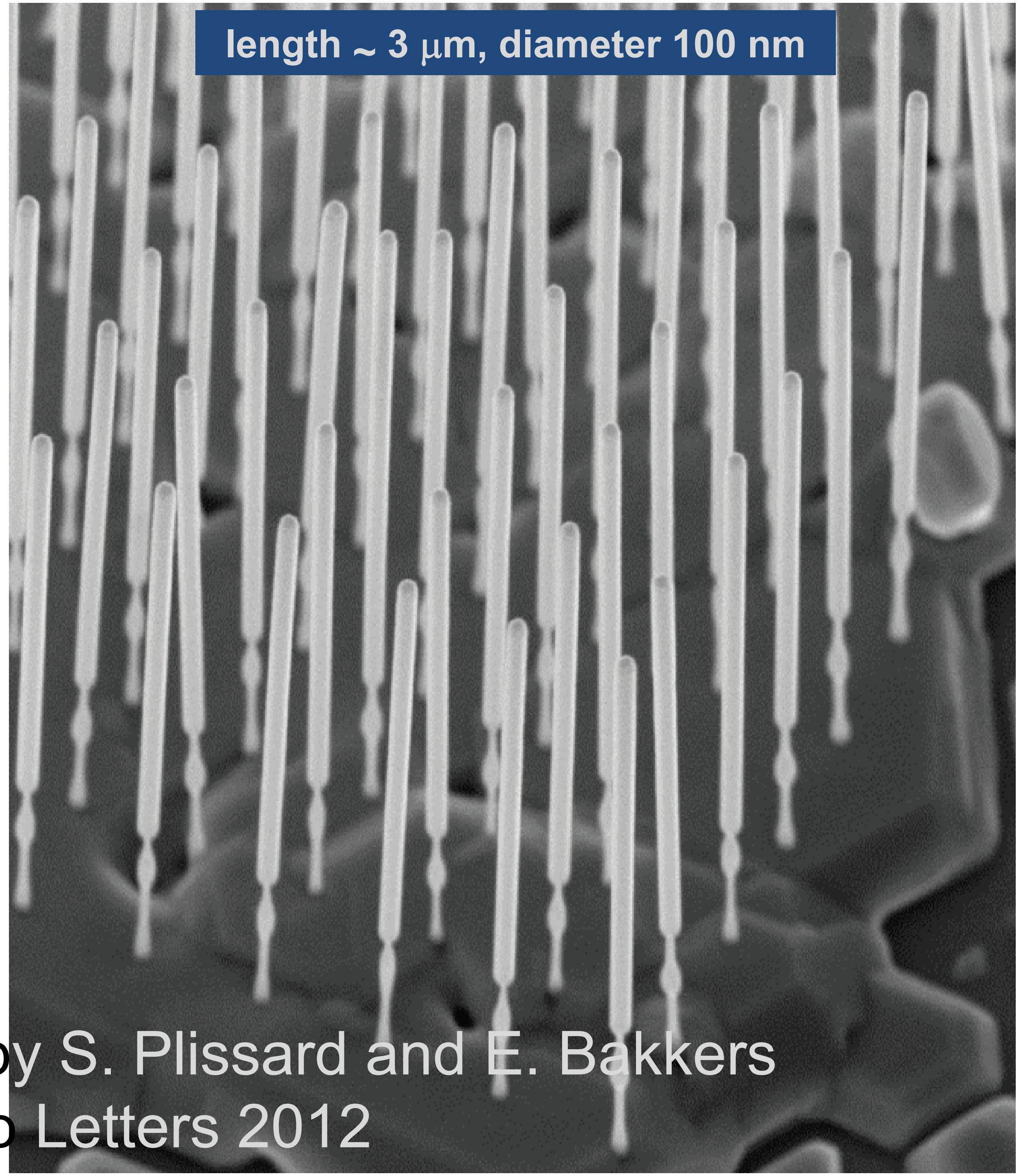
6: Film deposition on substrate

7: Surface diffusion

8: Film deposition on nanowire sides

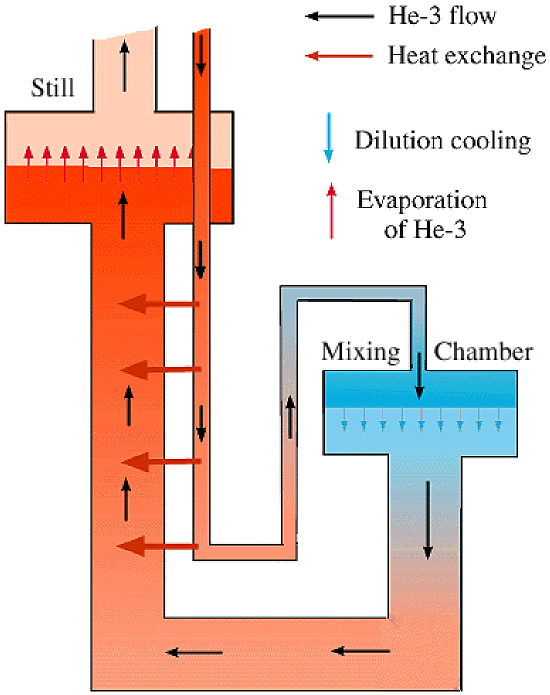
# Why InSb?

1) High mobility
2) Large spin-orbit
3) Large g-factor
4) Easy ohmic contact

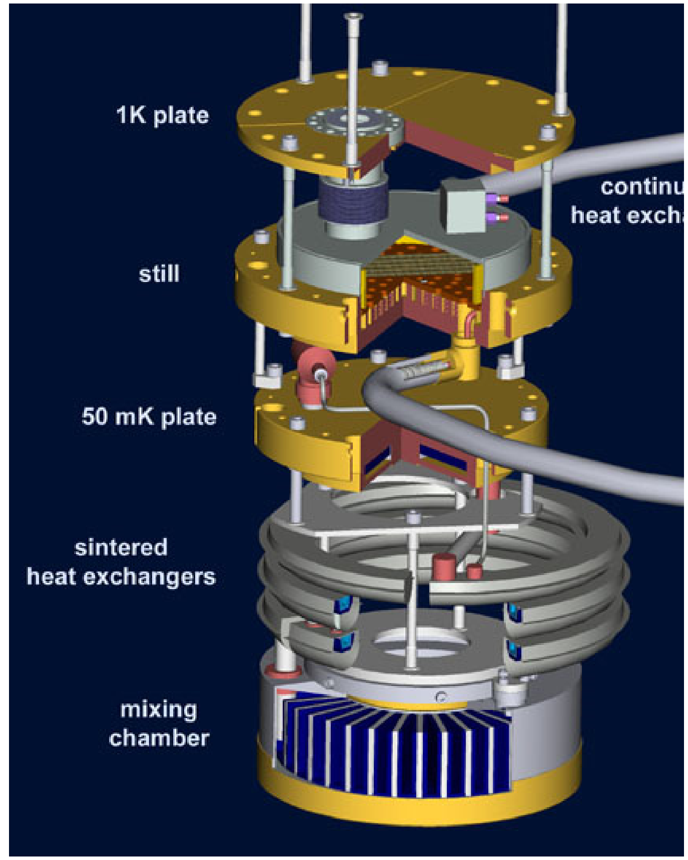


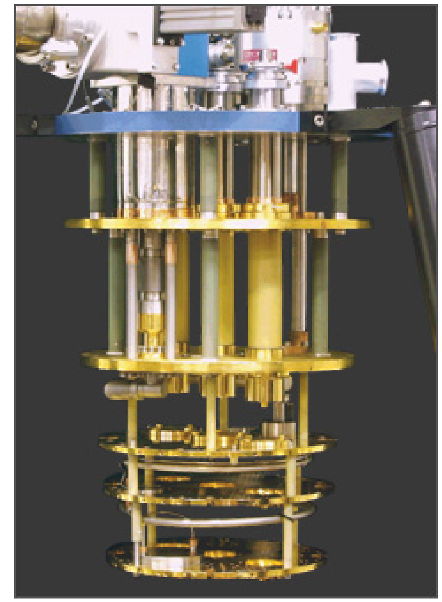

Nanowires grown by S. Plissard and E. Bakkers
Plissard et al, Nano Letters 2012

# Dilution refrigerator: 5-10 mK

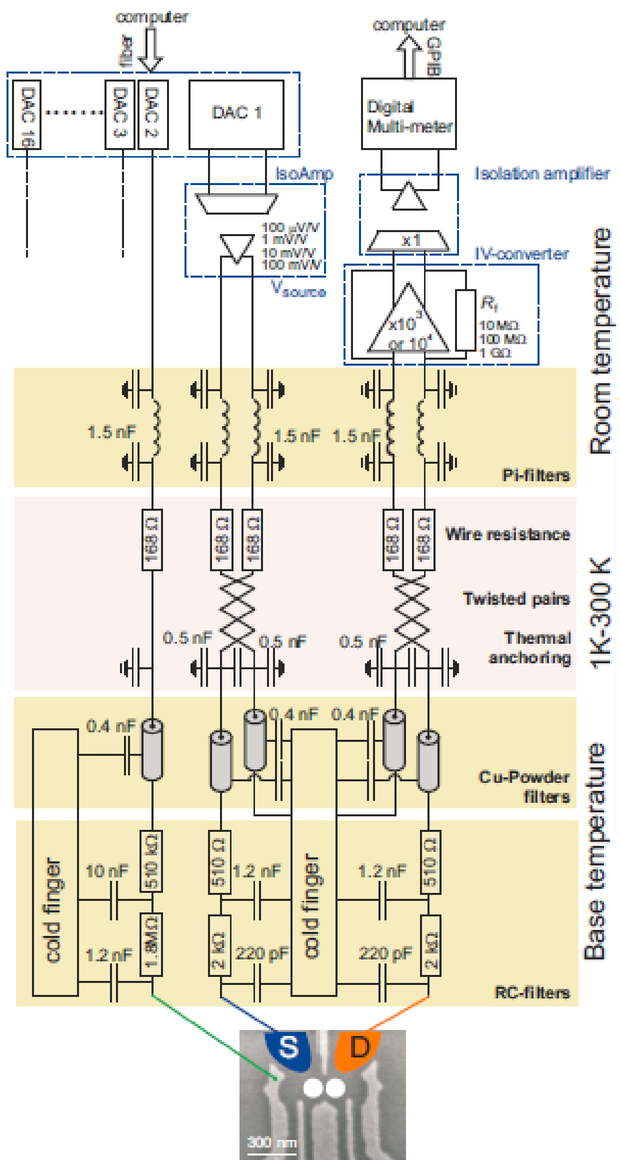



CF refrigerator and gas handling system



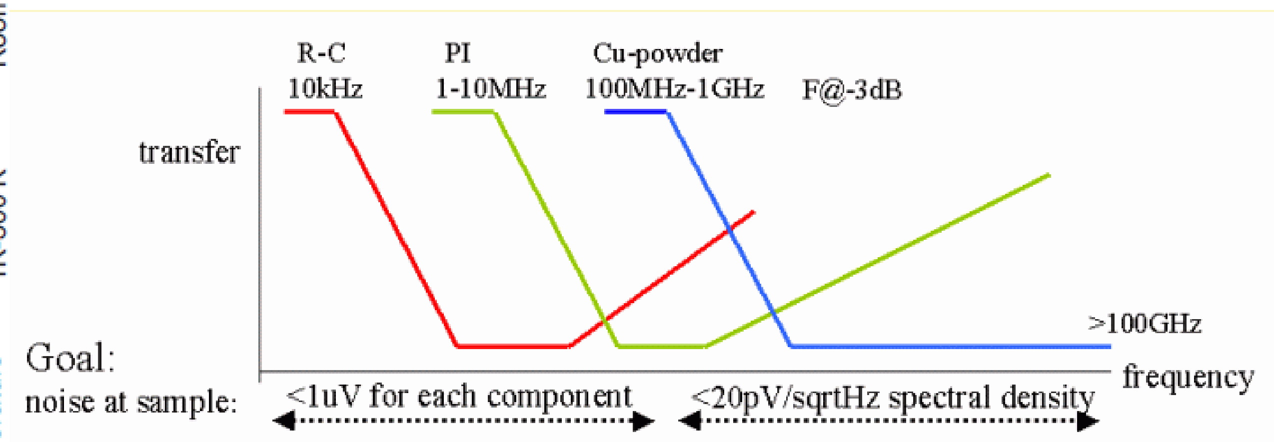



# Cooling electrons down

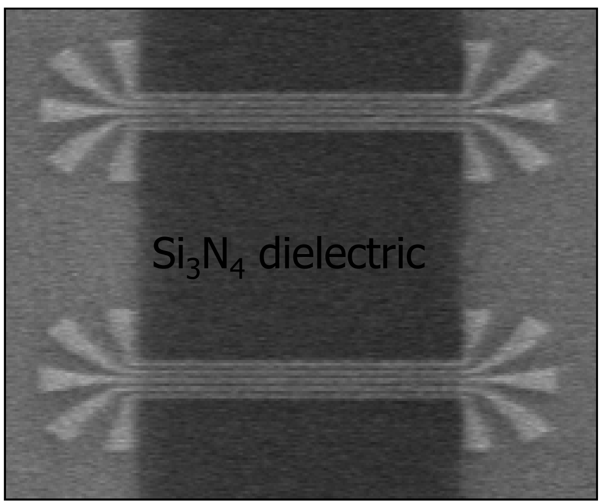


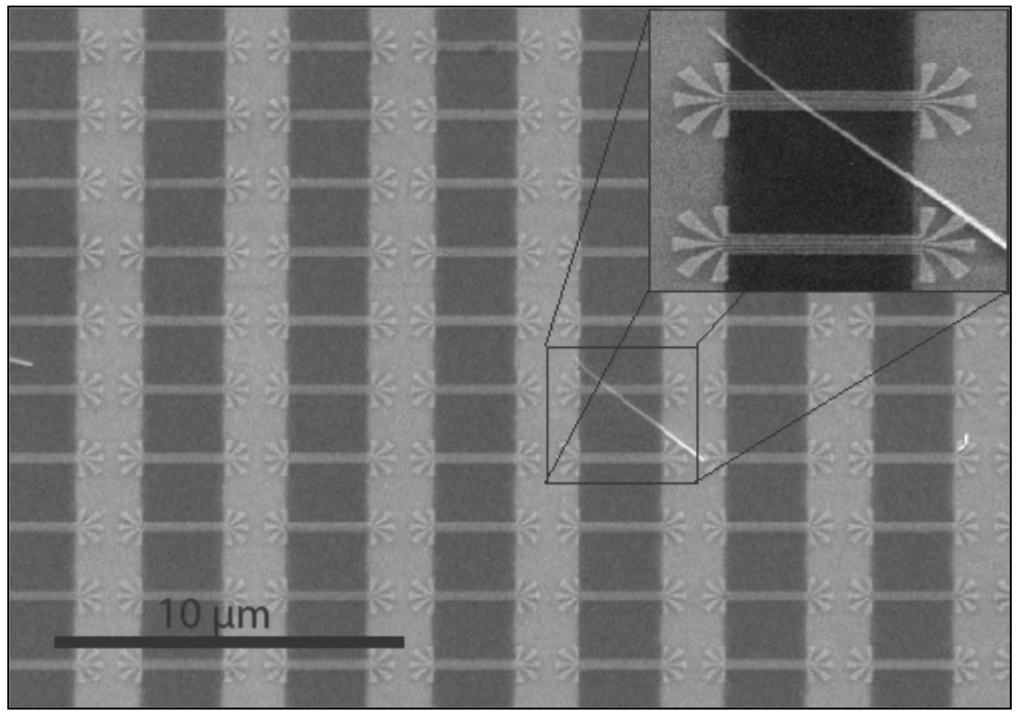

2.8: Electrical circuit for applying voltages to the gate electrodes, and for ng a voltage-biased current measurement

**Electron temperature ≠ Lattice T!**

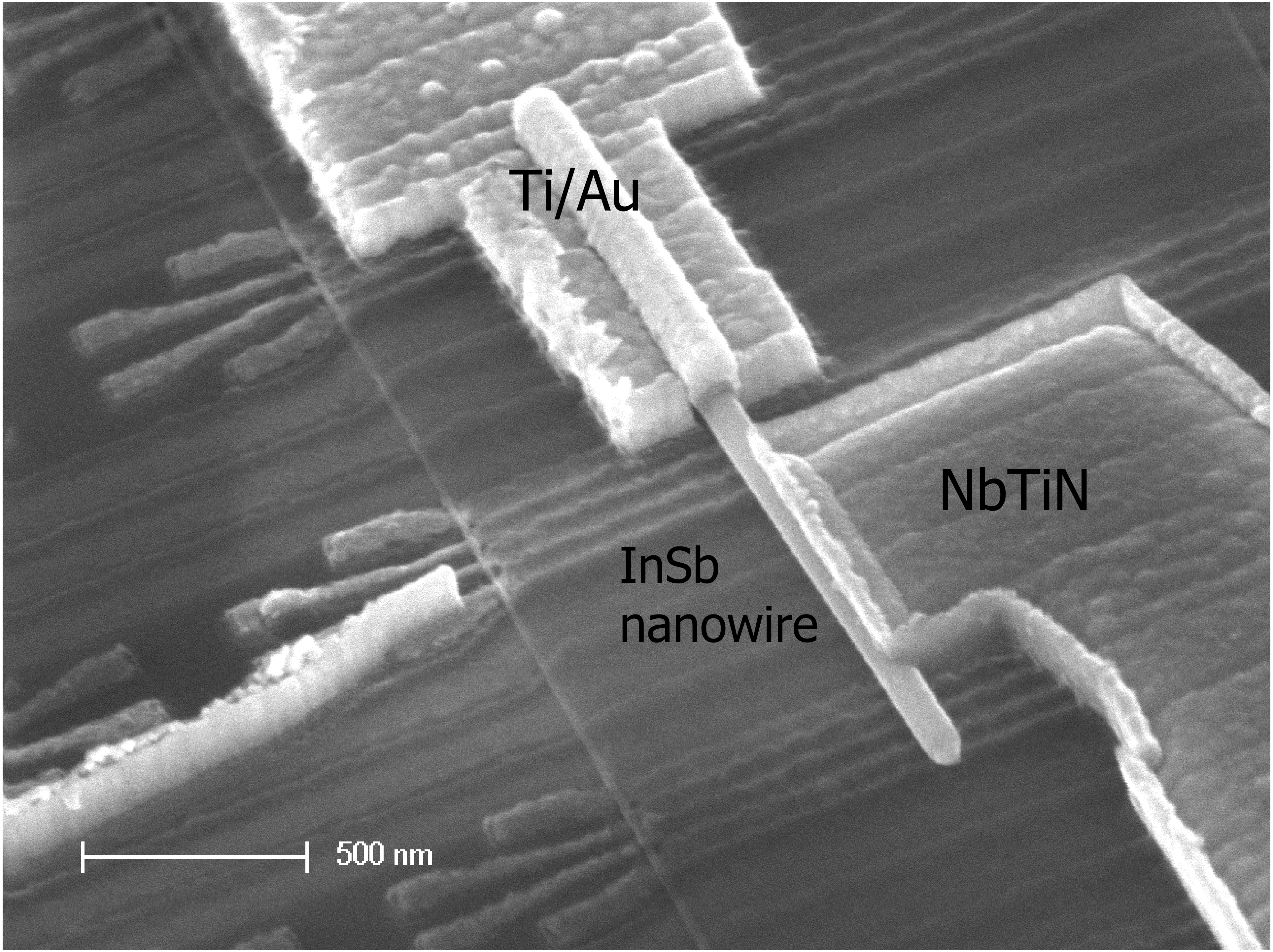


# Device Fabrication

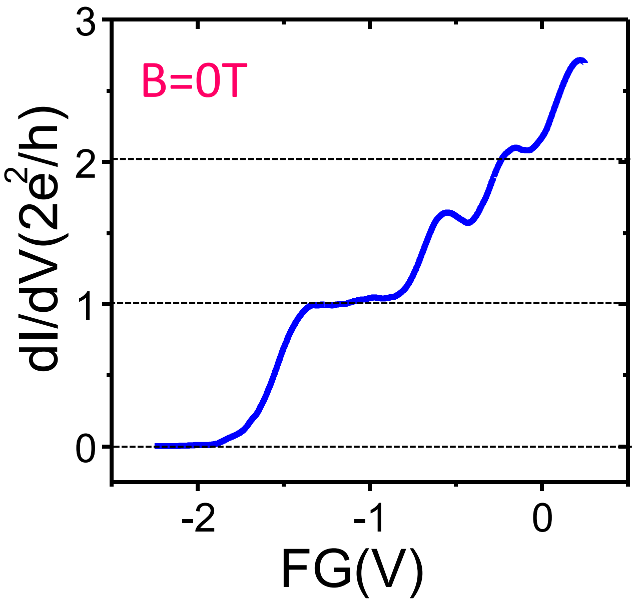


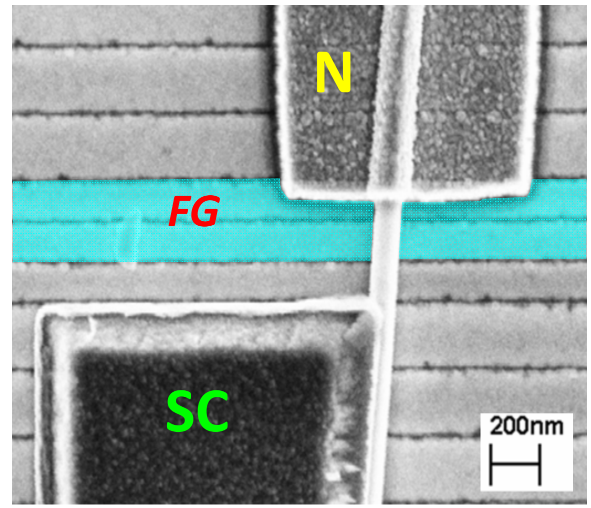



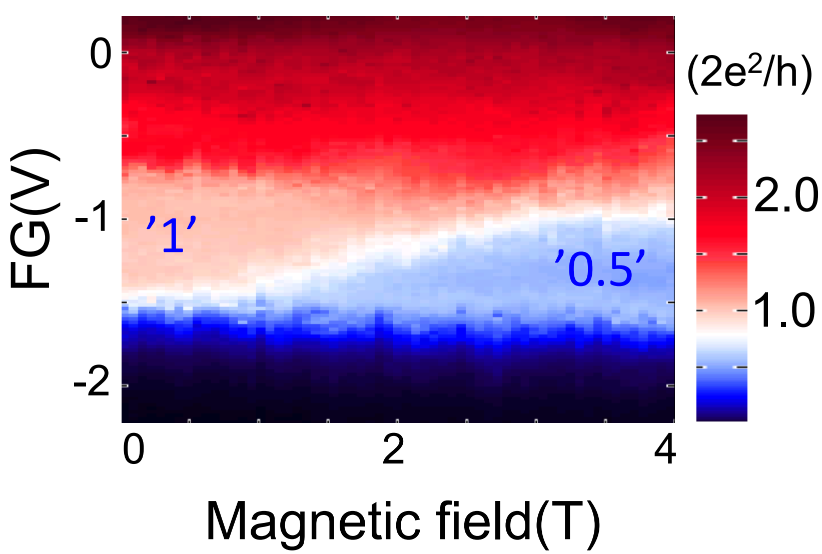

following e.g. Fasth PRL 07

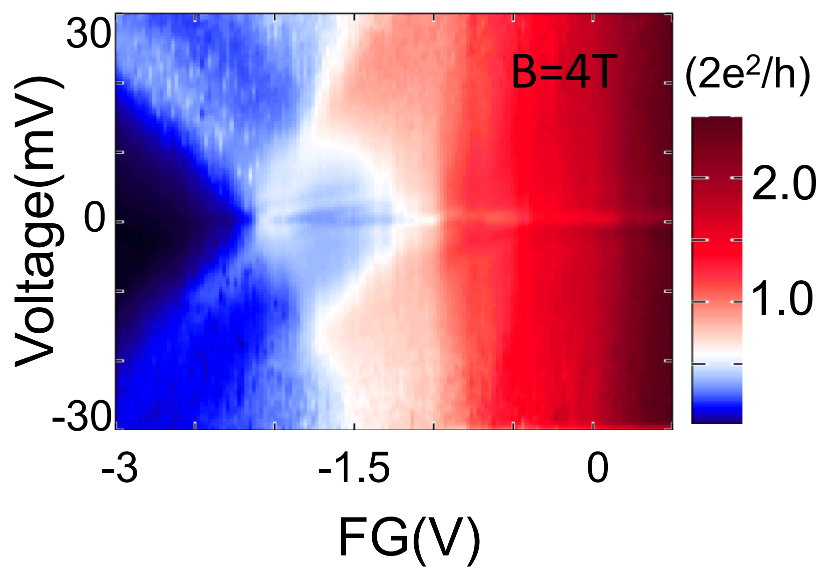

Ti/Au
NbTiN
InSb
nanowire
500 nm

# First Majorana ingredient: one-dimensional system



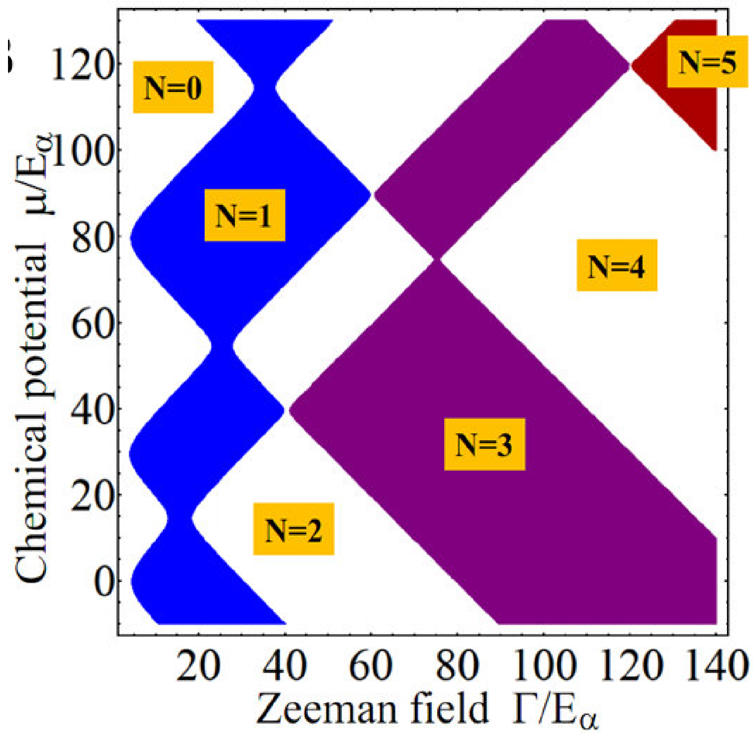




Data: Jun Chen, Peng Yu (Pitt)

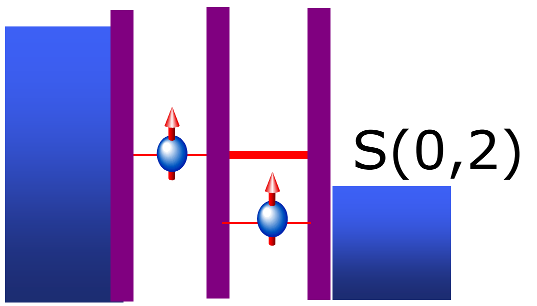
# Multi-subband topological superconductor

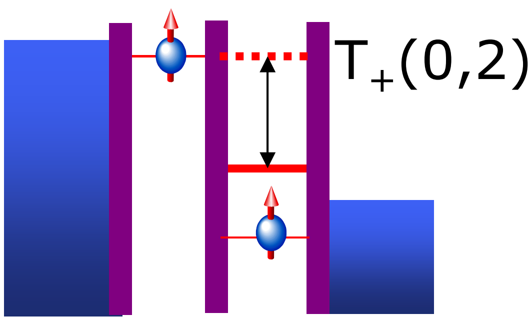
$$g\mu_B B(\theta) > \sqrt{\Delta^2_{k=0,N} + \mu^2(x)}$$



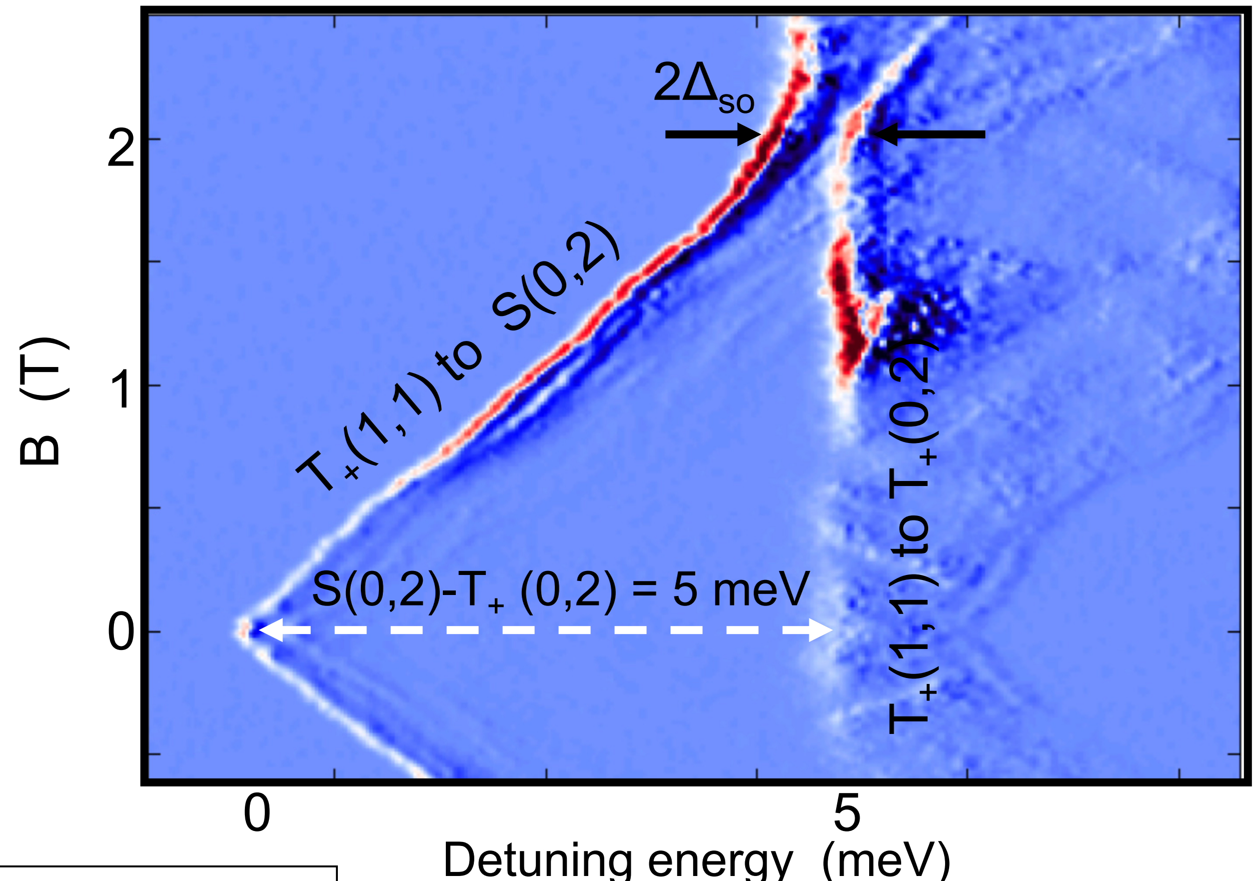

Stanescu, Lutchyn, Das Sarma; Phys Rev B 2011

# Spin-orbit strength in InSb nanowires




Nadj-Perge et al. PRL 2012




$\Delta_{so}$ = 0.3 meV

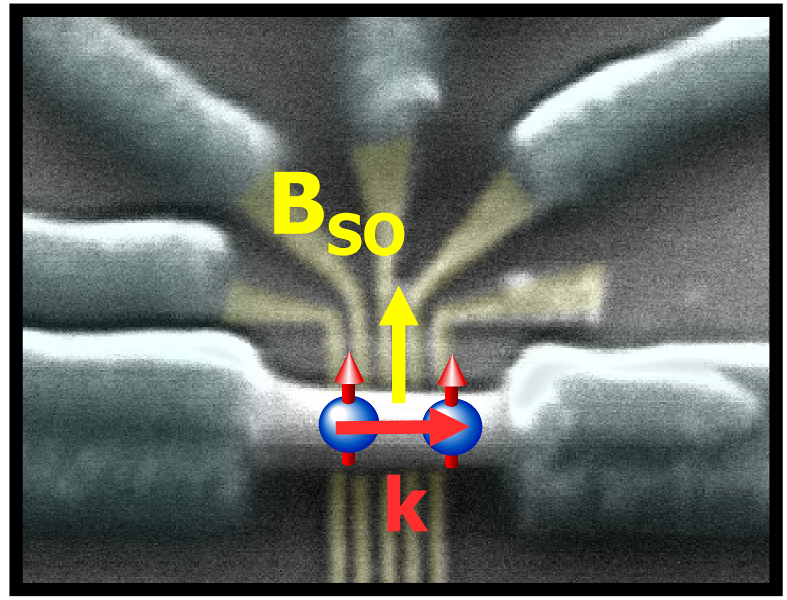
$\Delta_{so}/g\mu_B B$ = 0.06 and $g$ = 43

*lso* = 200 nm

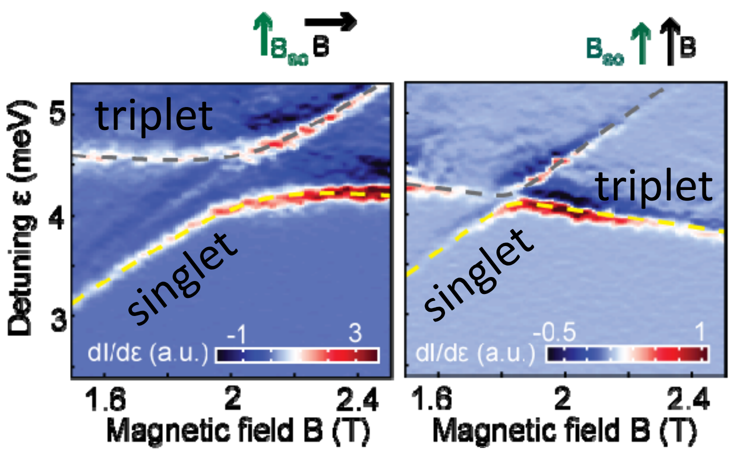
# Majorana recipe:

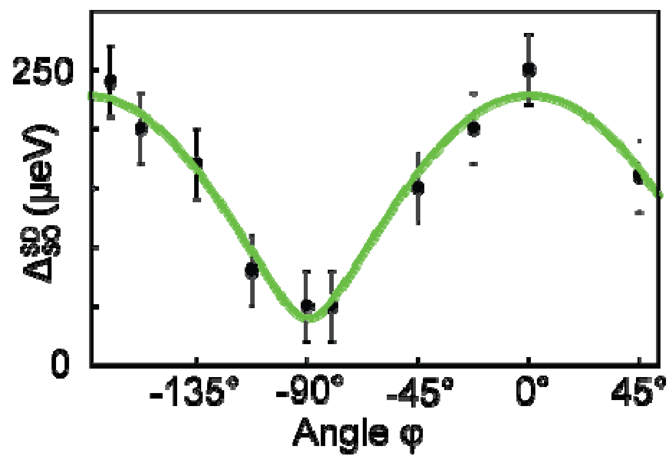
1. One-dimensional wire
2. Spin-orbit interaction
3. Superconductivity
4. Magnetic field

Nadj-Perge et al. PRL 2012



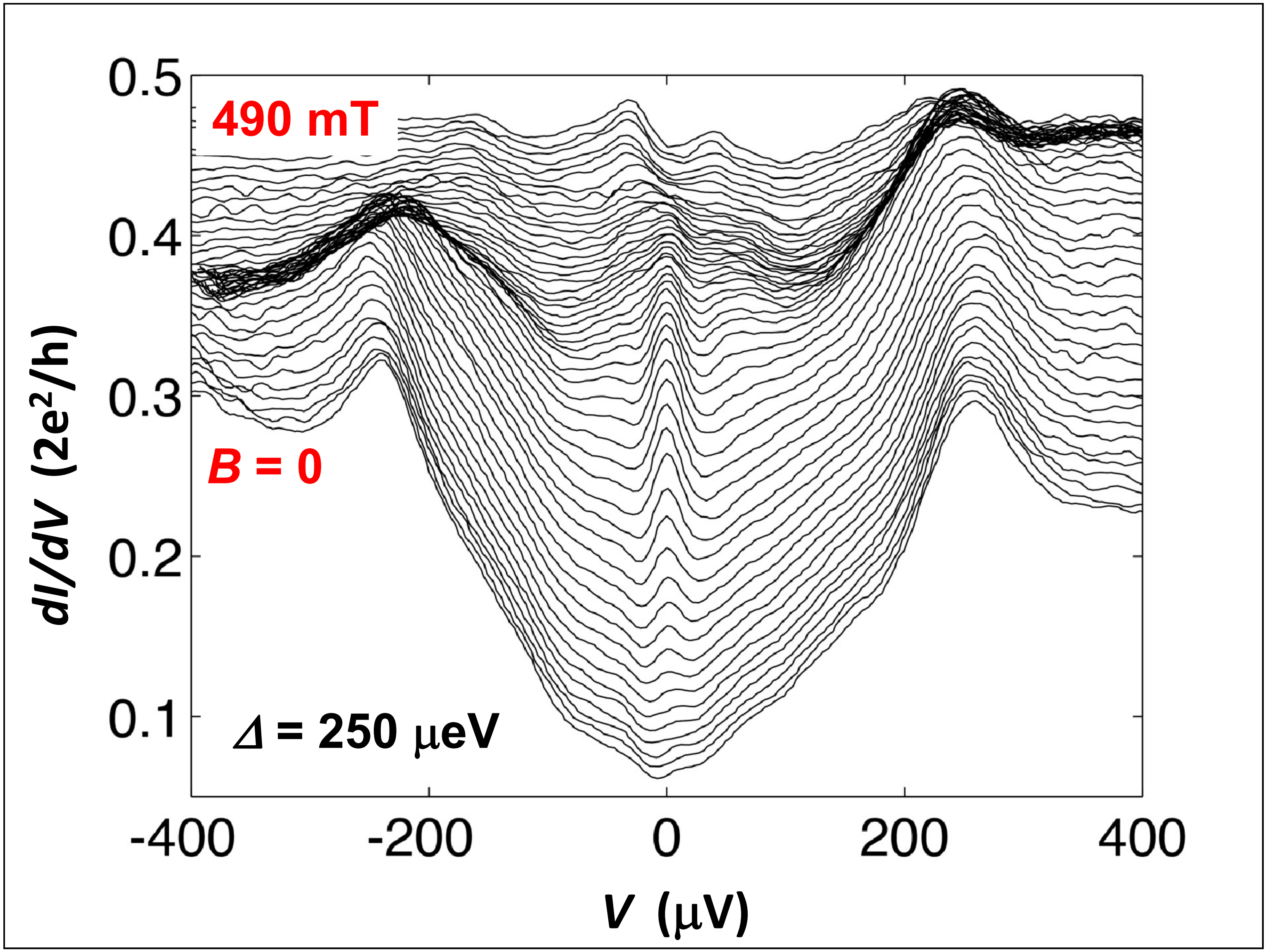

Not the subband spin-orbit splitting!



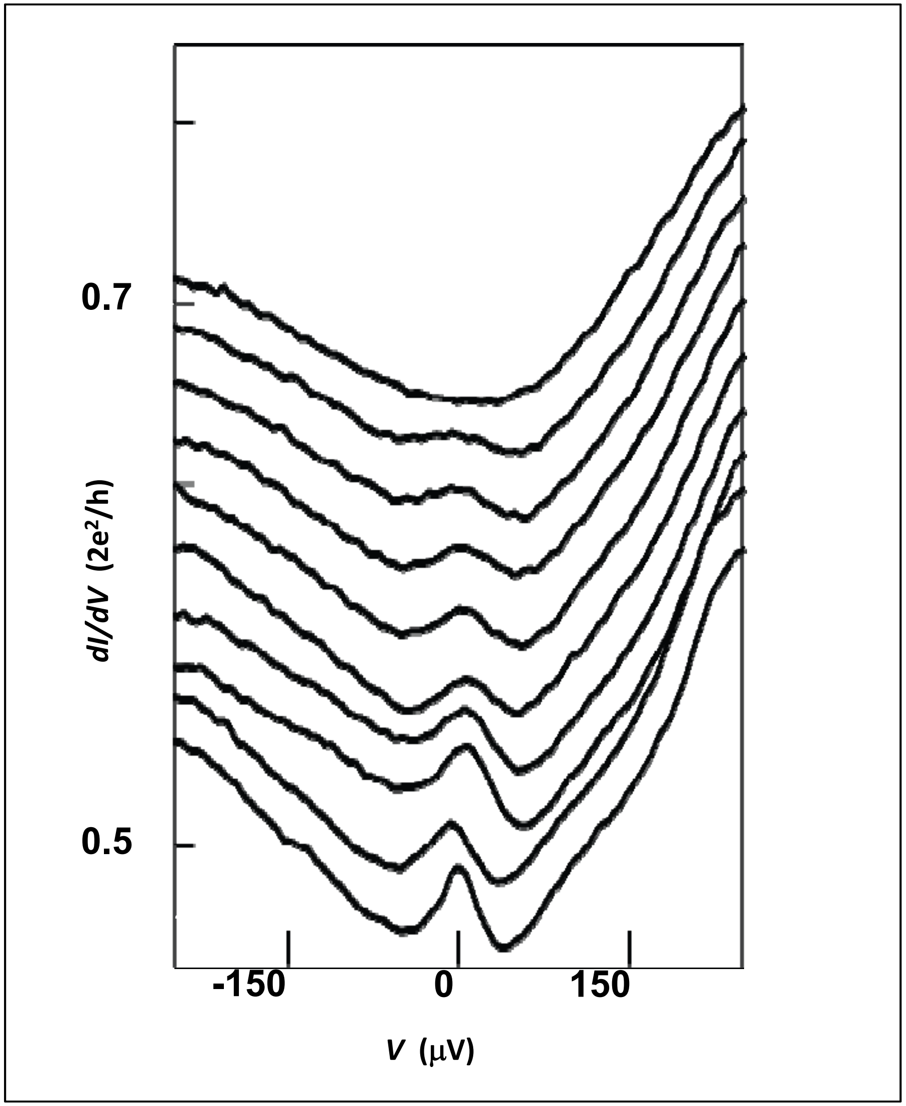

InAs NW, C. Fasth et. al, PRL 2007; Pfund, PRB 2007;
InSb NW, H. A. Nillson et. al, Nano Lett. 2010

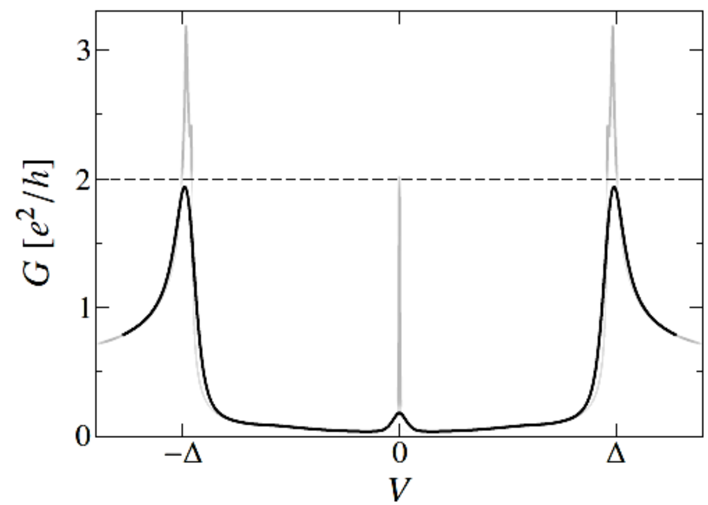
# Observation of zero bias peak




Data: Delft

## Temperature dependence

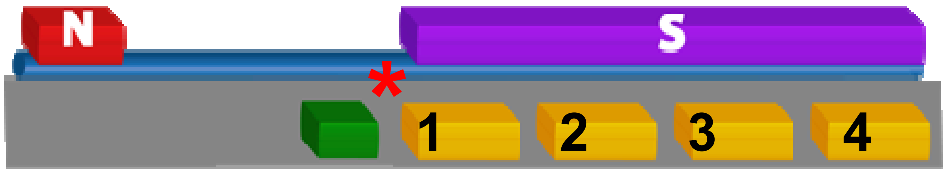


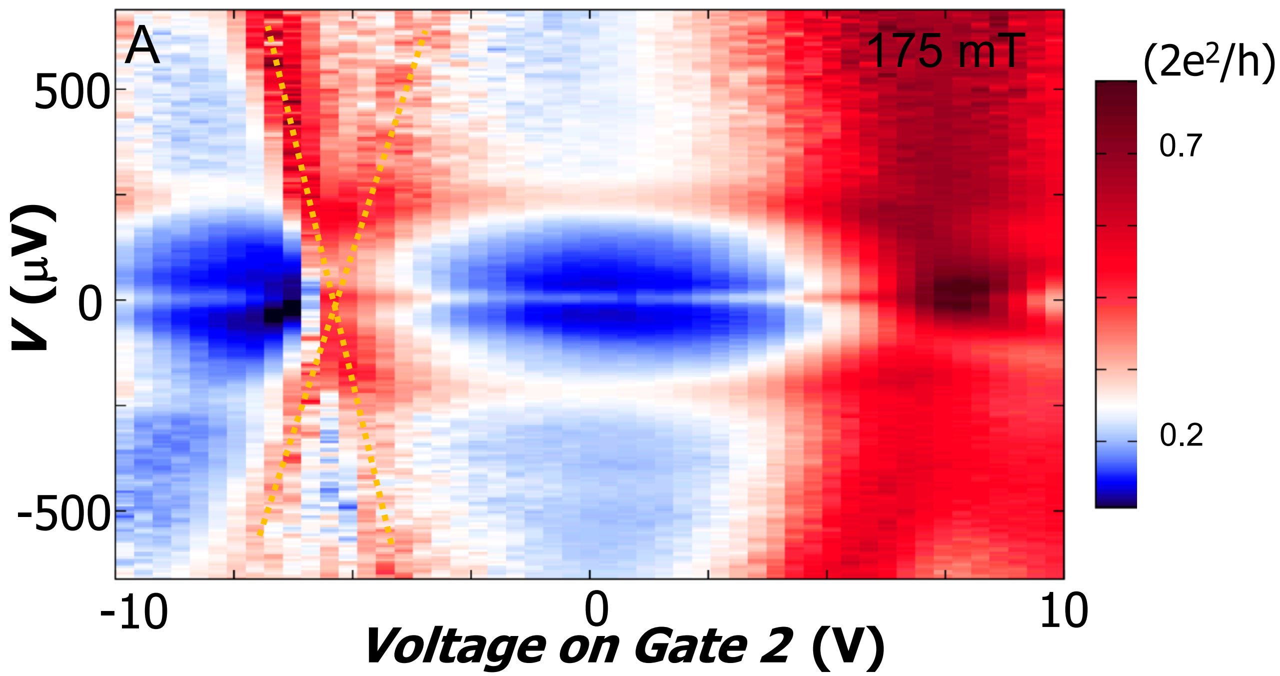




=> Temperature scale is 0.3-0.4 Kelvin

Data: Delft

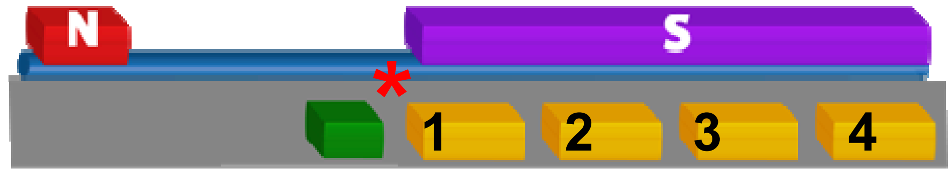
# Gate dependence: under the superconductor

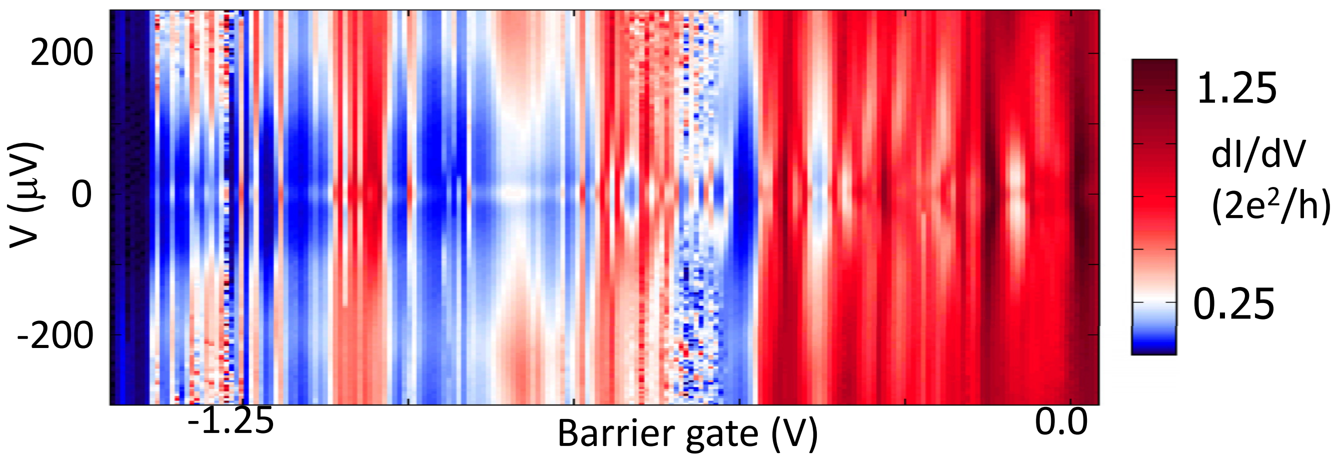


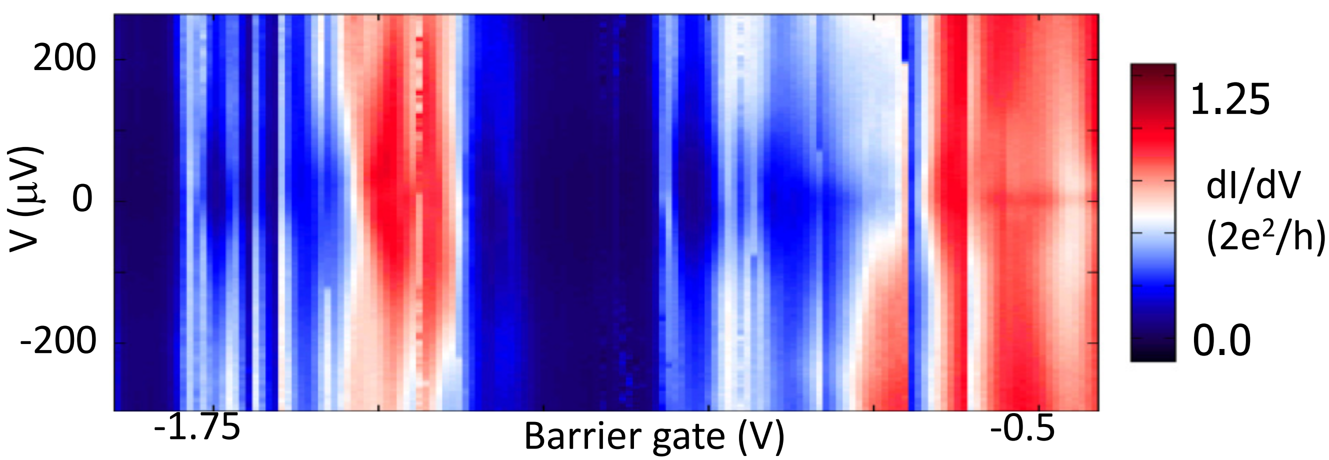




Data: Delft

# Gate dependence: barrier gate



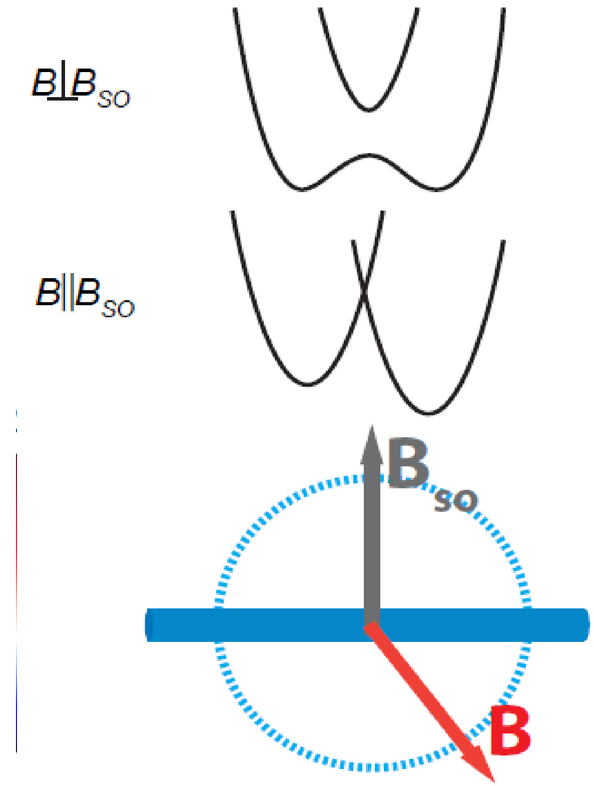



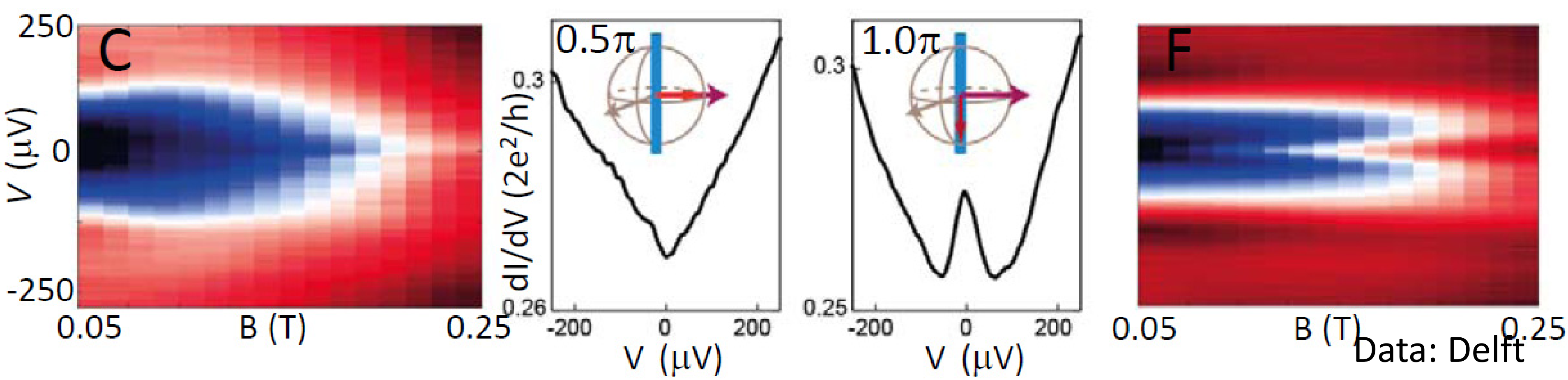




Data: Delft

# Majorana recipe:

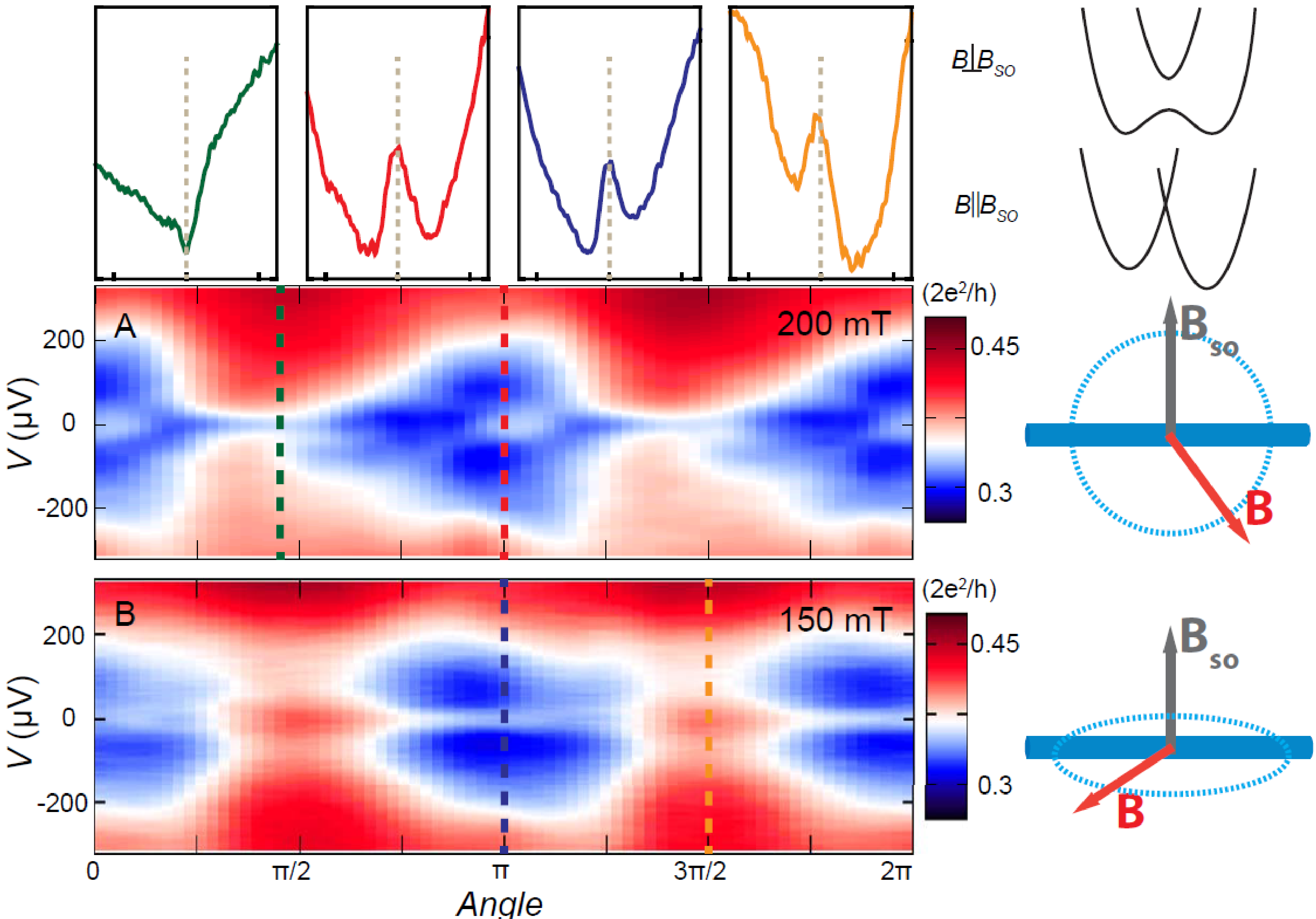
1. One-dimensional wire ✔
2. ~~Spin-orbit interaction~~
3. Superconductivity
4. Magnetic field ✔




Data: Delft

# Third device in a 3D vector magnet

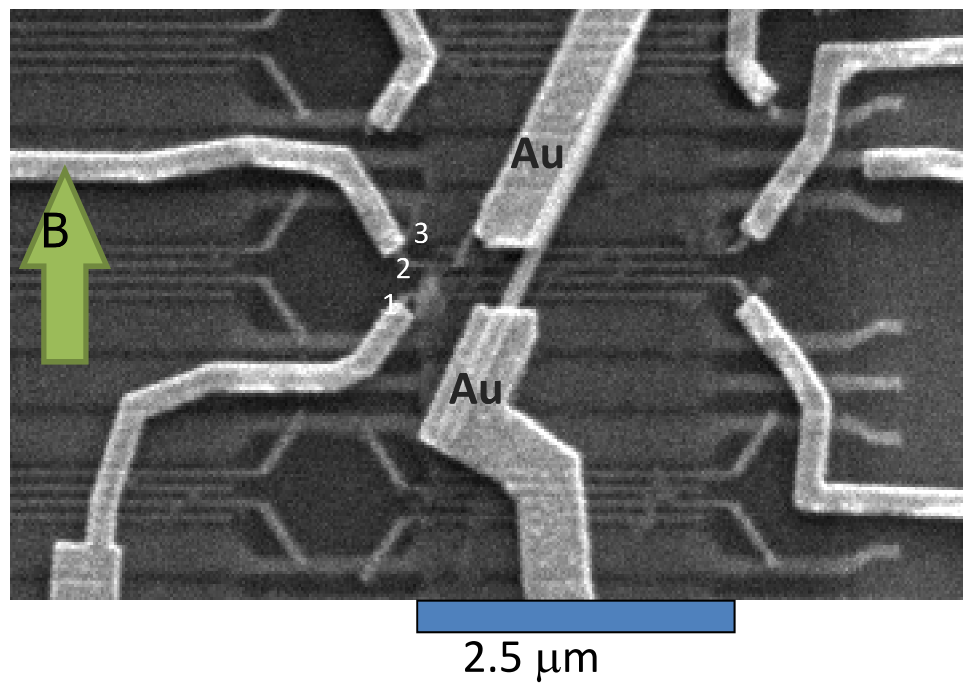



Data: Delft

# Majorana recipe:

1. One-dimensional wire ✔
2. Spin-orbit interaction ✔
3. ~~Superconductivity~~
4. Magnetic field ✔

No robust zero bias peaks observed



# Zero-bias Zoo

Disorder
(WAL, Reflectionless
tunneling)

Andreev
Bound
States

Majorana

Unknown effect

Kondo

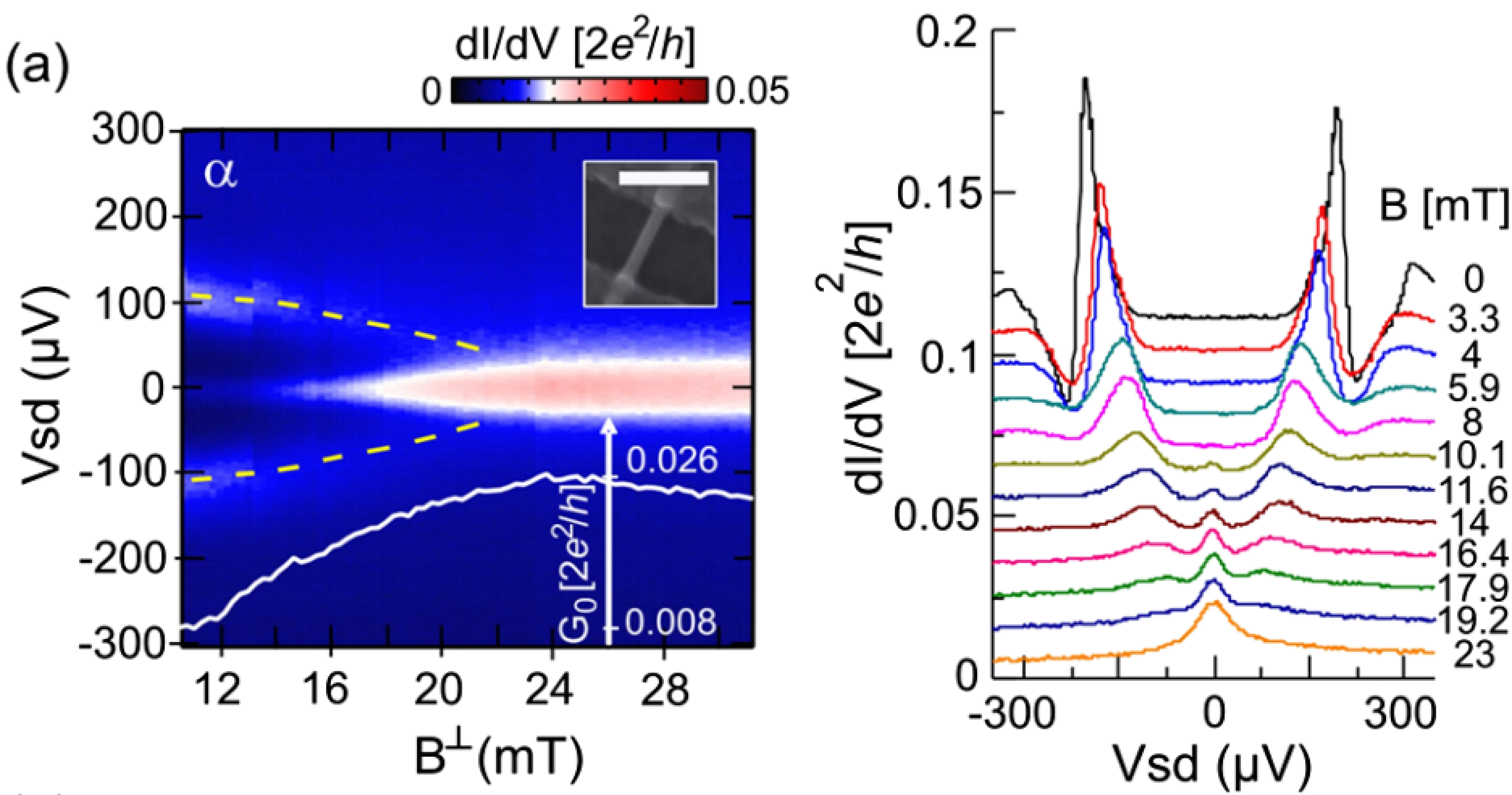
Josephson

Kondo

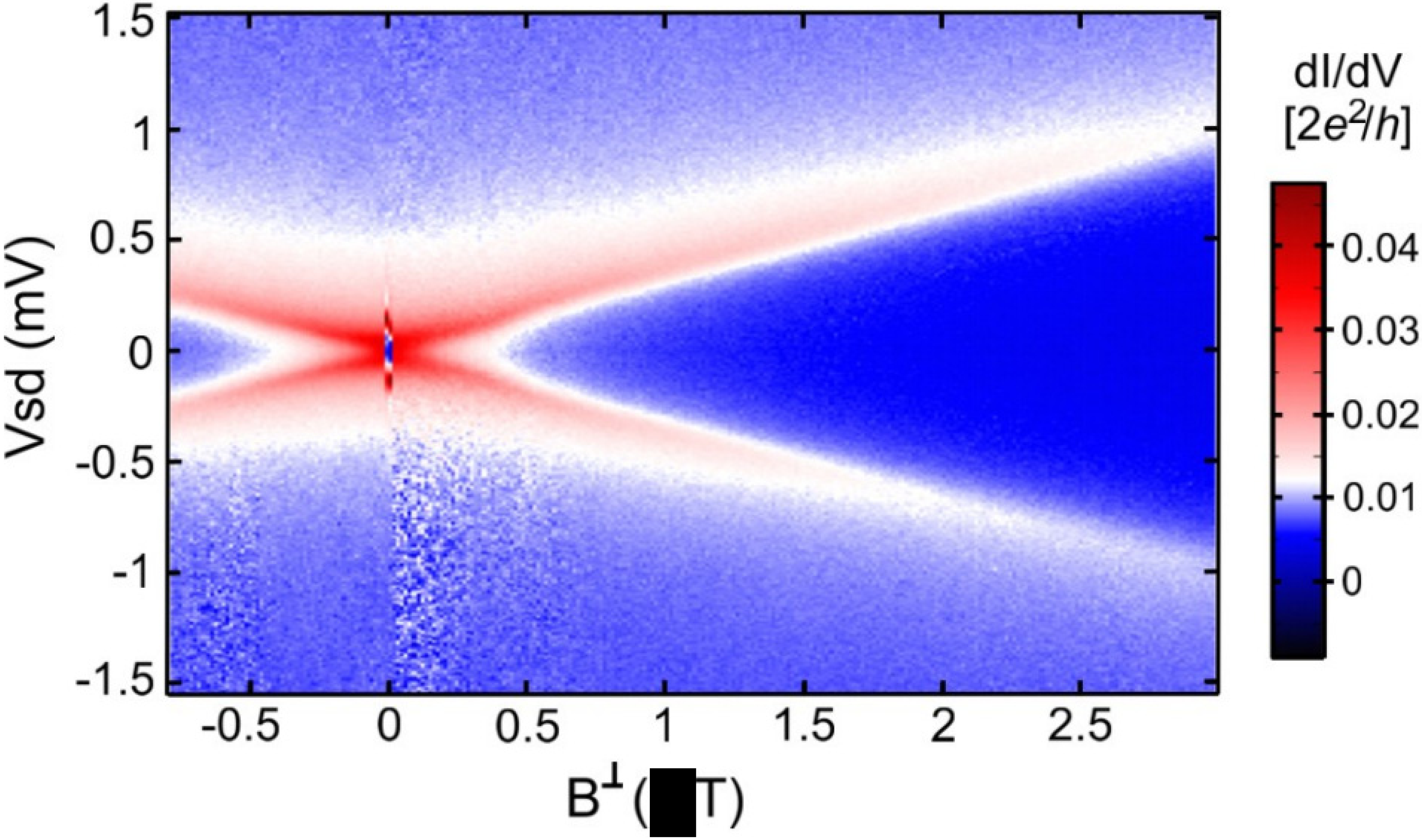
# $g^* > 50$

# in InSb

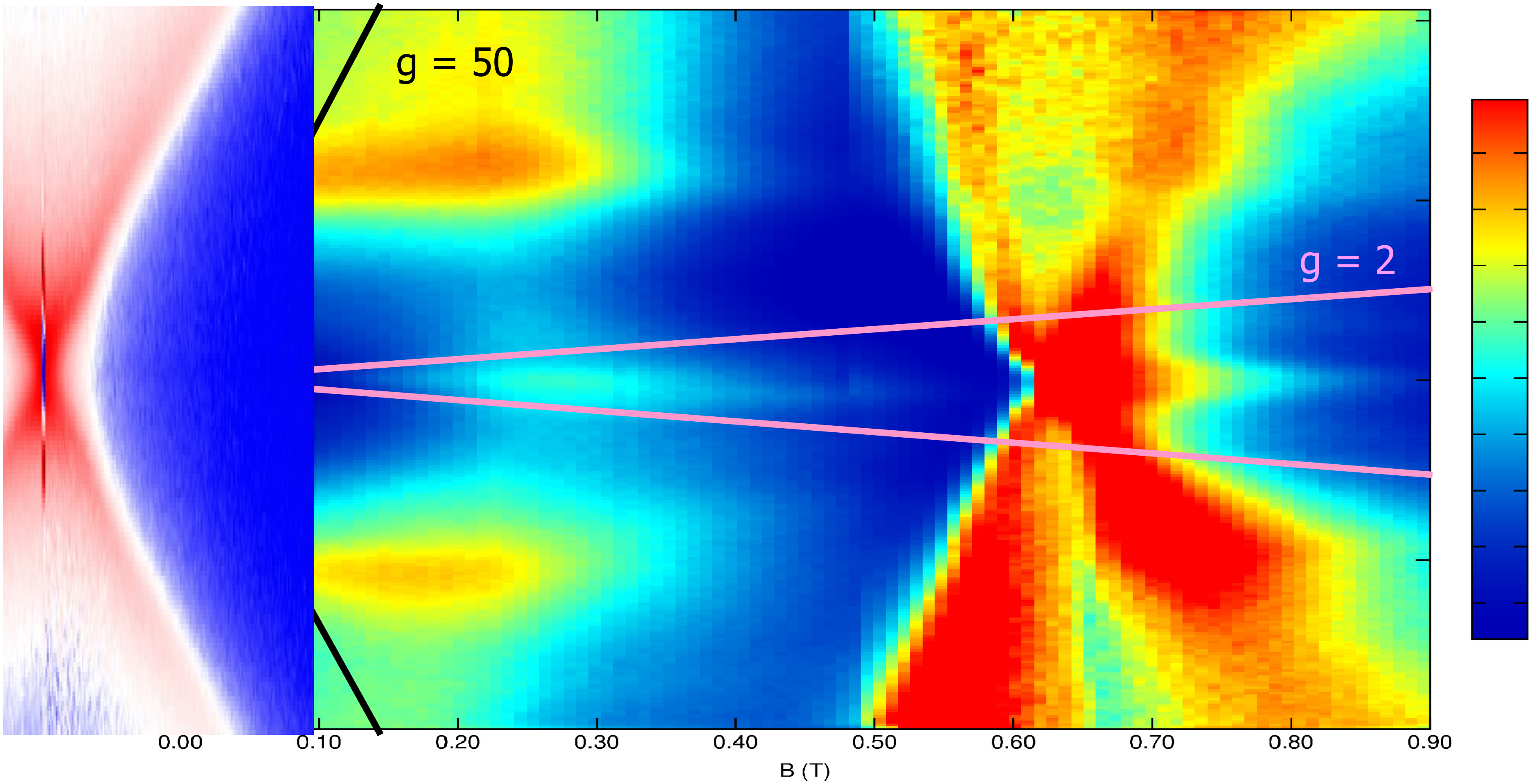
…so, 1 Tesla = 1.5 meV




**EJH Lee et al, PRL 2012**

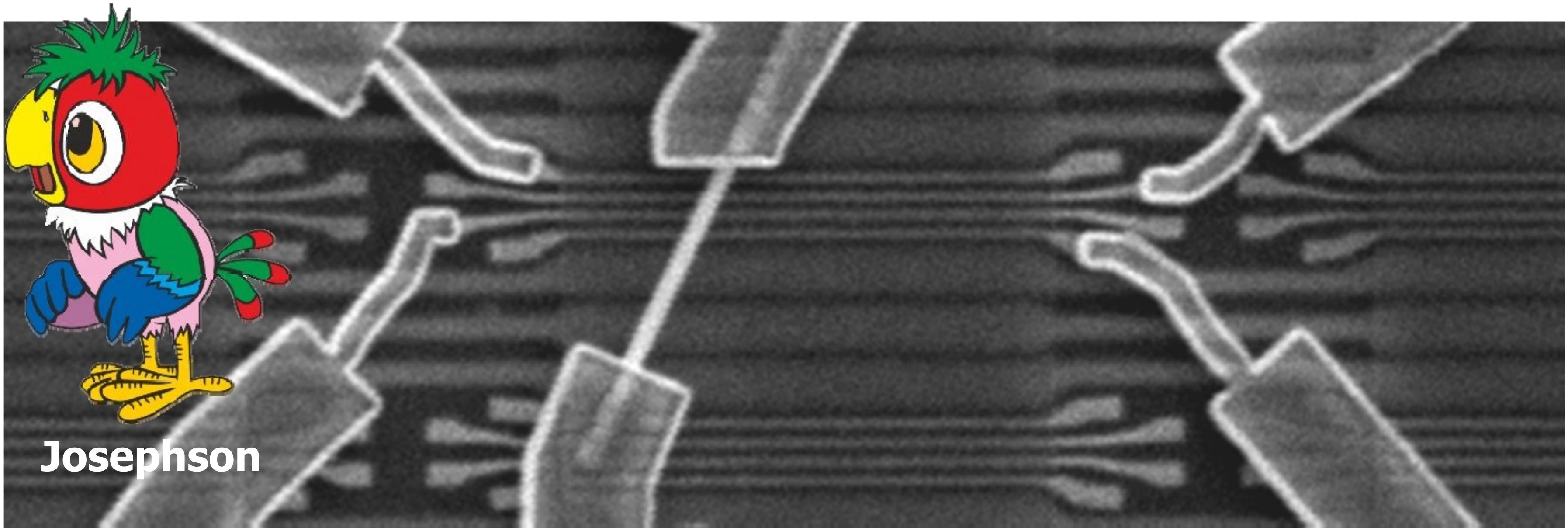

dI/dV
[2e²/h]
0.04
0.03
0.02
0.01
0
1.5
1
0.5
0
-0.5
-1
-1.5
Vsd (mV)
-0.5
0
0.5
1
1.5
2
2.5
B⊥ ([redacted]T)

# How would Kondo effect look?



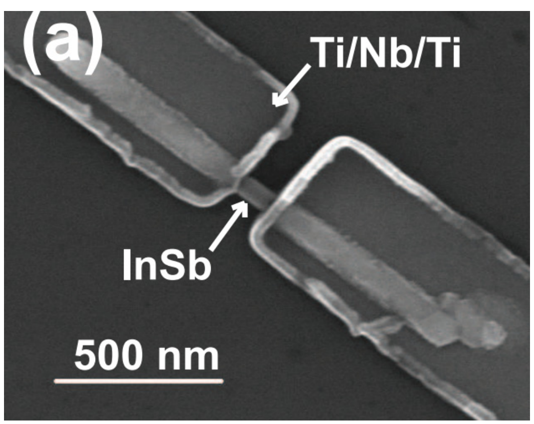

Data: Delft

# July 2011: Two Superconducting Contacts



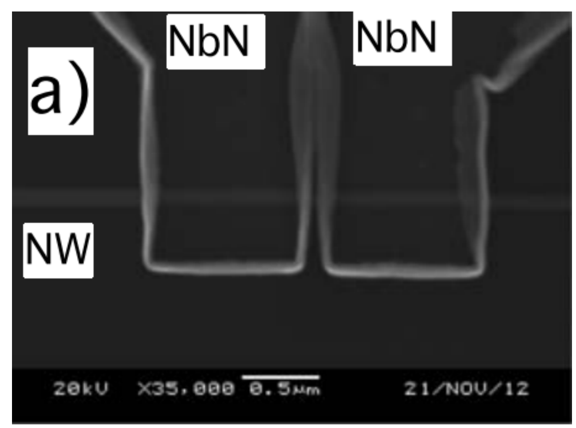

Deng et at, Nano Letters 2012

**“Observation of Majorana Fermions in a Nb-InSb Nanowire-Nb Hybrid Quantum Device”**



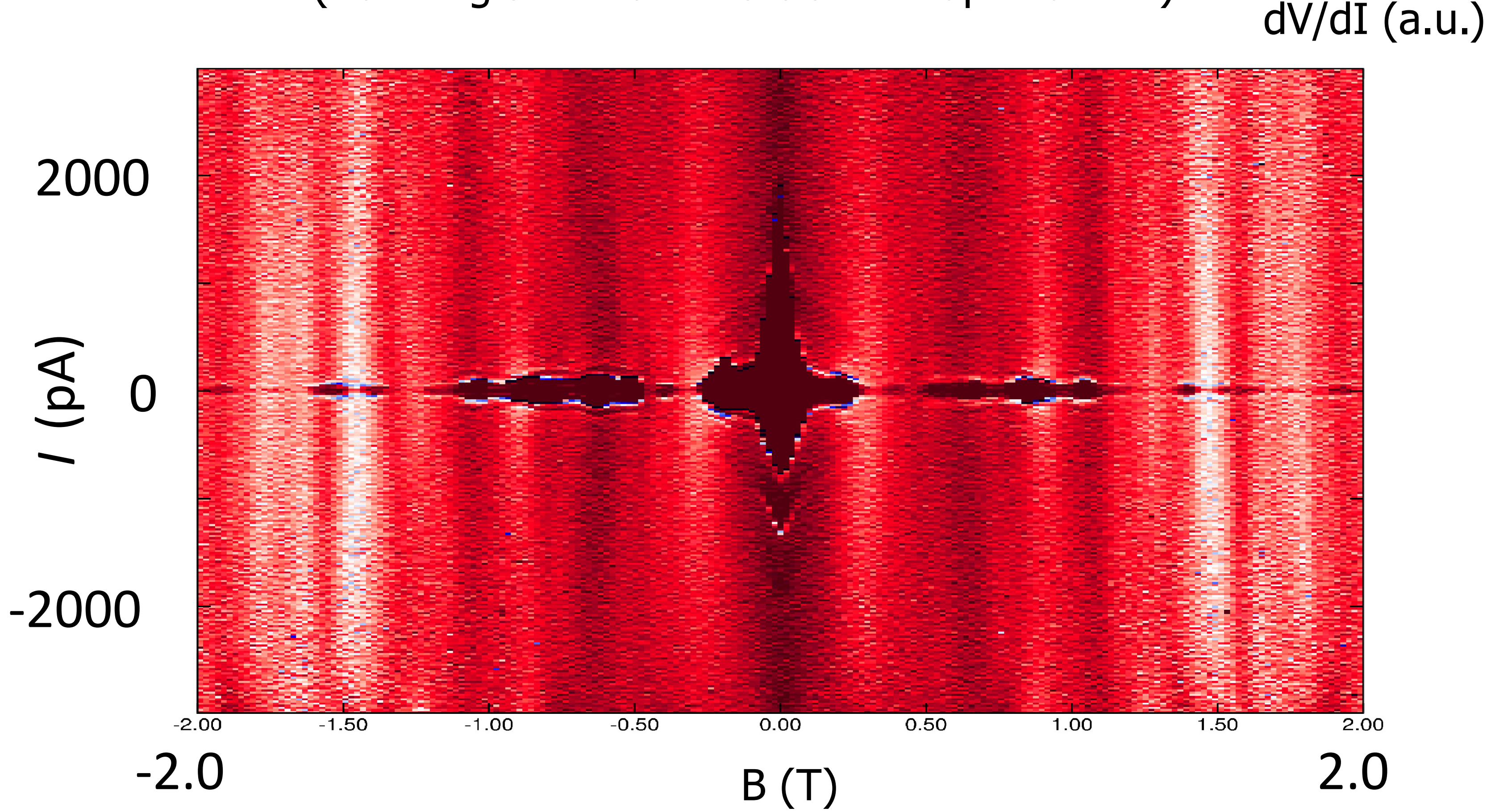

Finck et al, PRL 2012

**“…while considering more mundane explanations.”**



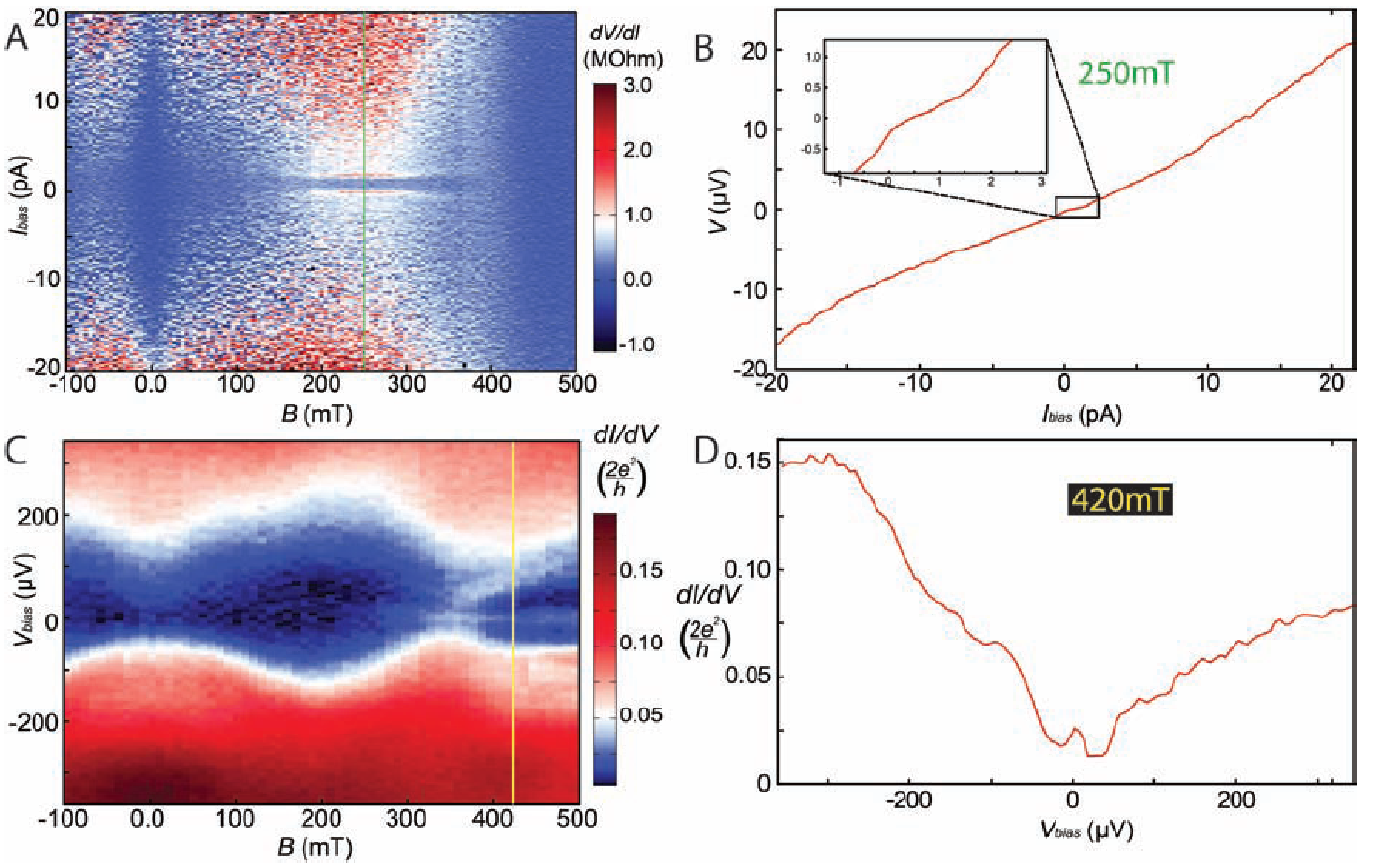
# Supercurrents surviving to 2 Tesla.
# Contact spacing = 900 nm

(Dark regions near zero bias = supercurrent)




Data: Delft

# Play with gates – make ZBP due to Josephson effect appear at finite field!



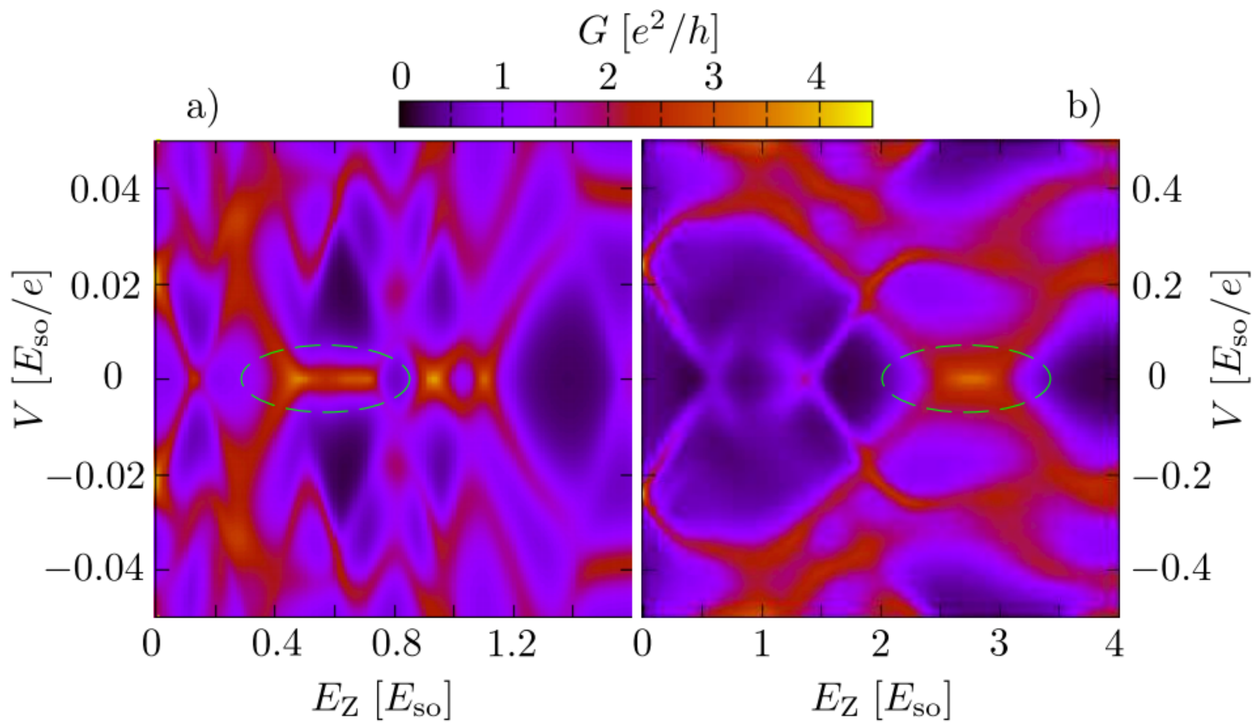

Data: Delft

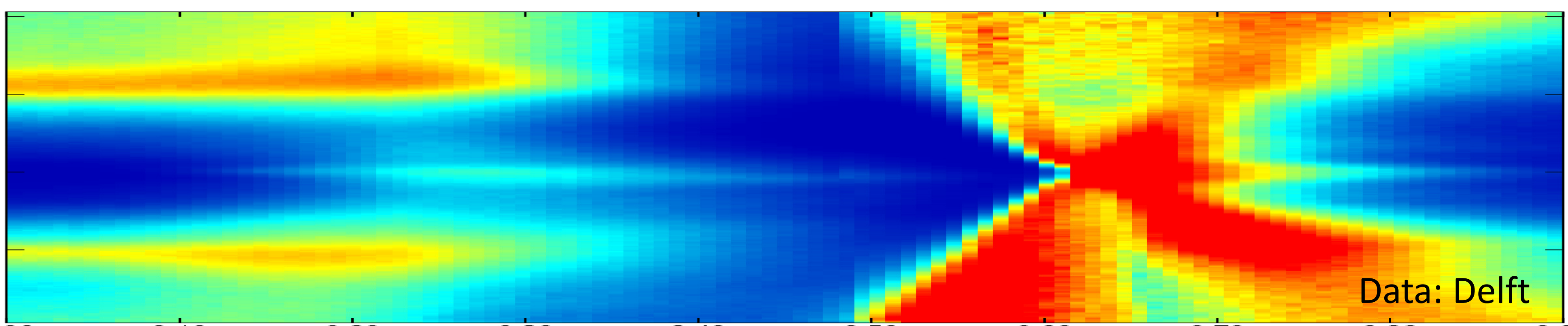
# Zero-voltage conductance peak from weak antilocalization in a Majorana nanowire

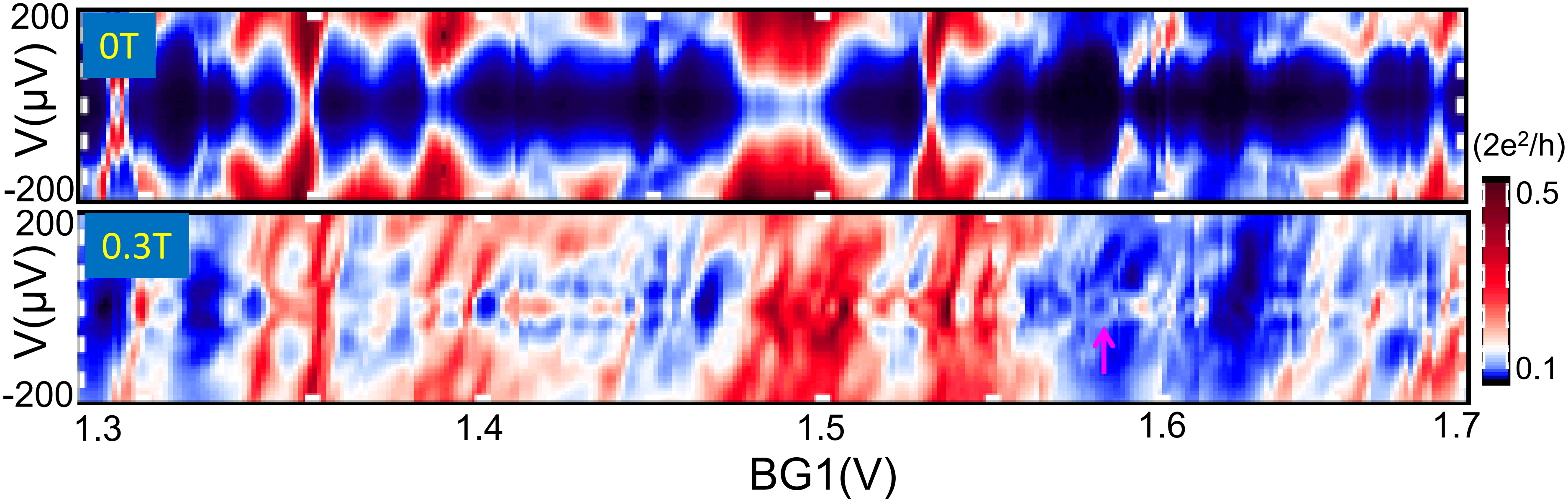
D. I. Pikulin,[1] J. P. Dahlhaus,[1] M. Wimmer,[1] H. Schomerus,[2] and C. W. J. Beenakker[1]

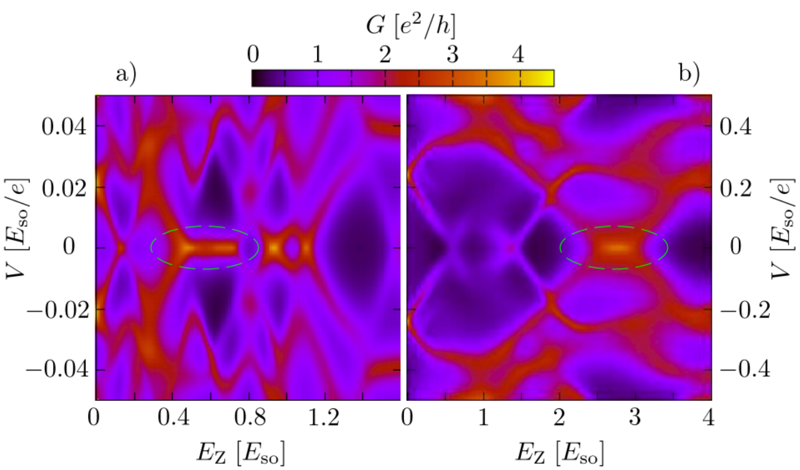
[1] *Instituut-Lorentz, Universiteit Leiden, P.O. Box 9506, 2300 RA Leiden, The Netherlands*
[2] *Department of Physics, Lancaster University, Lancaster, LA1 4YB, United Kingdom*

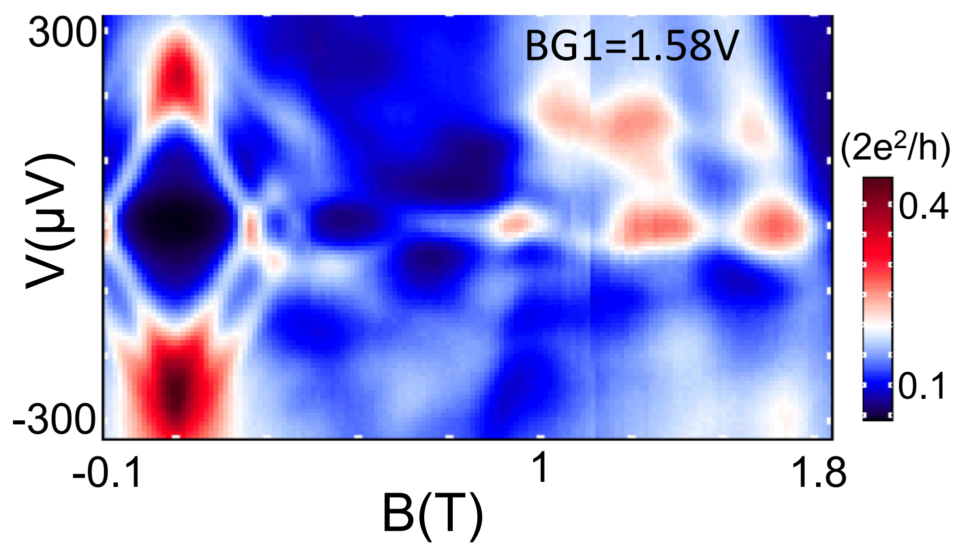
(Dated: August 2012)






Data: Jun Chen, Peng Yu (Piitsburgh)

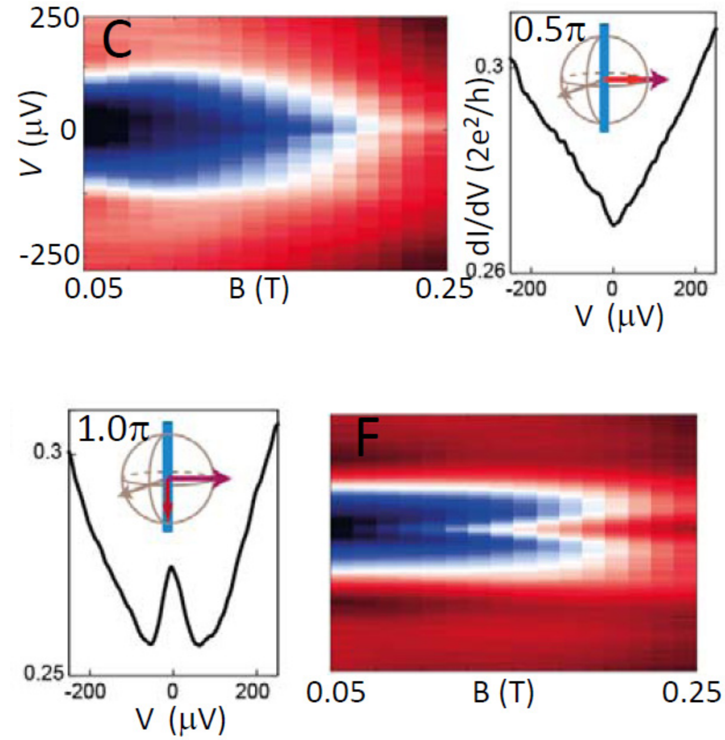
# 2012 signatures of Majorana

Zero bias peak (ZBP) onsets at B ~ 100 mT
$E_z \sim 150\ \mu eV$, so $E_z \sim \Delta$

ZBP remains stuck to zero bias over significant range of B
(peak width 30 ueV, $\Delta E_z \sim 0.5$-$1.5$ meV)

ZBP persist over large gate ranges for all gates, but gate tuning is required!

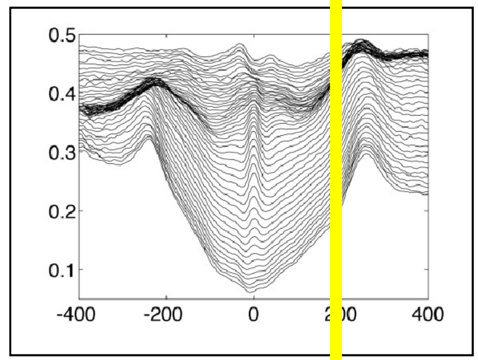
ZBP vanishes when B is aligned with $B_{SO}$)

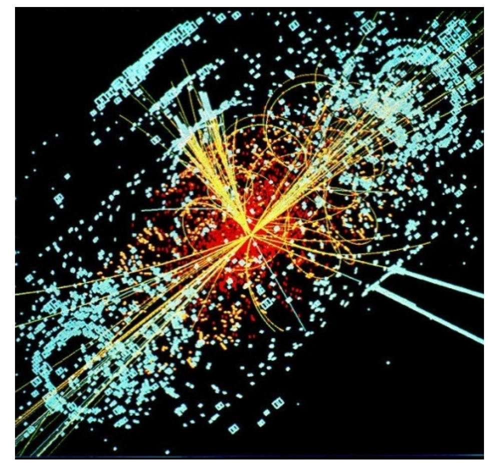



ZBP robust in both gate and magnetic field NOT OBSERVED in three N-NW-N devices (superconductivity is important)

Trivial alternative scenarios ruled out easily (Kondo, Josephson, WAL…)

# Where we are now

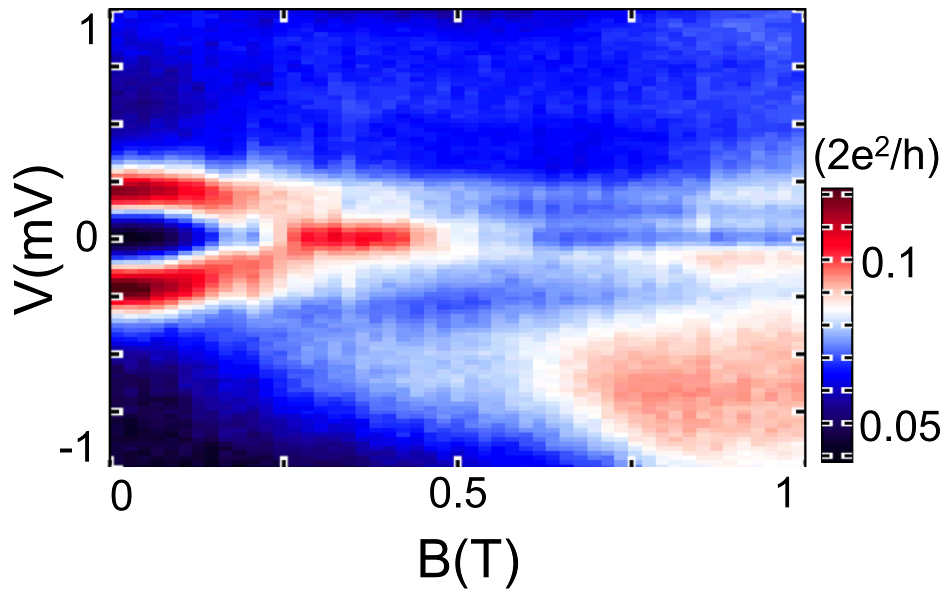



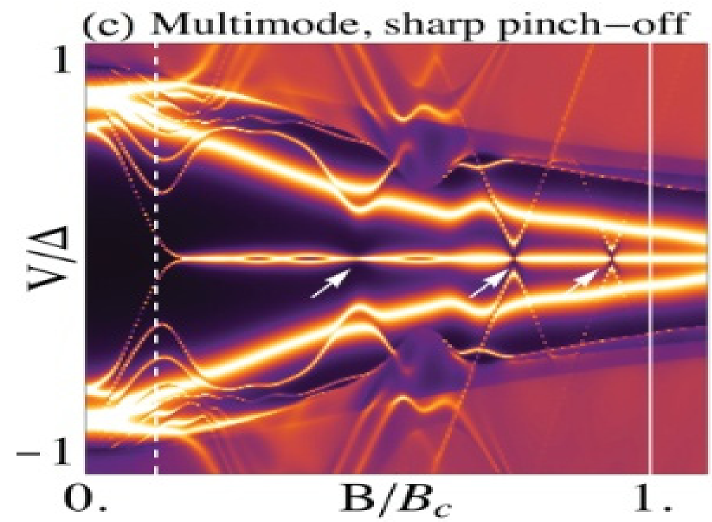
Is that a UFO???

Mourik Science 2012

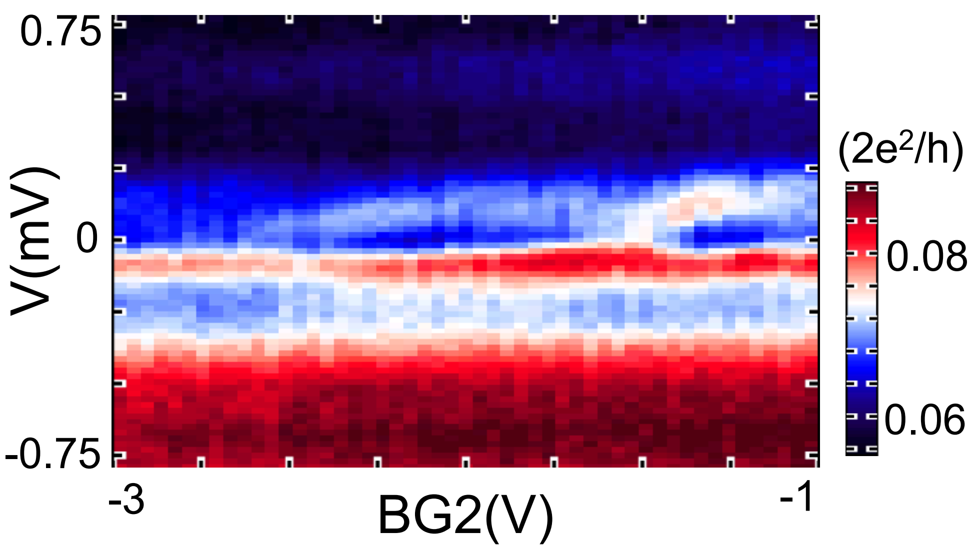
CERN $5\sigma$

# ZBP splitting: coupled Majoranas?



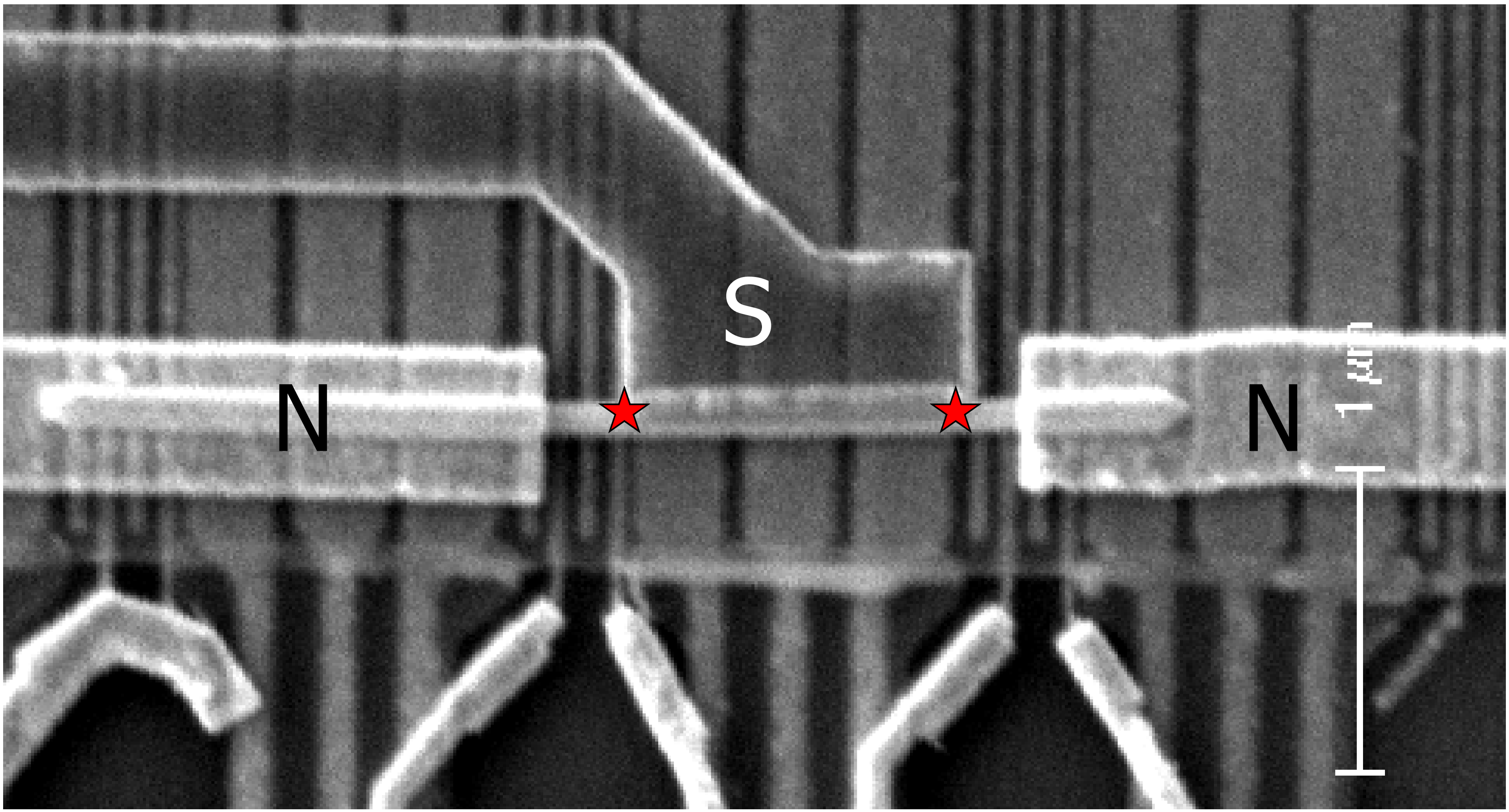



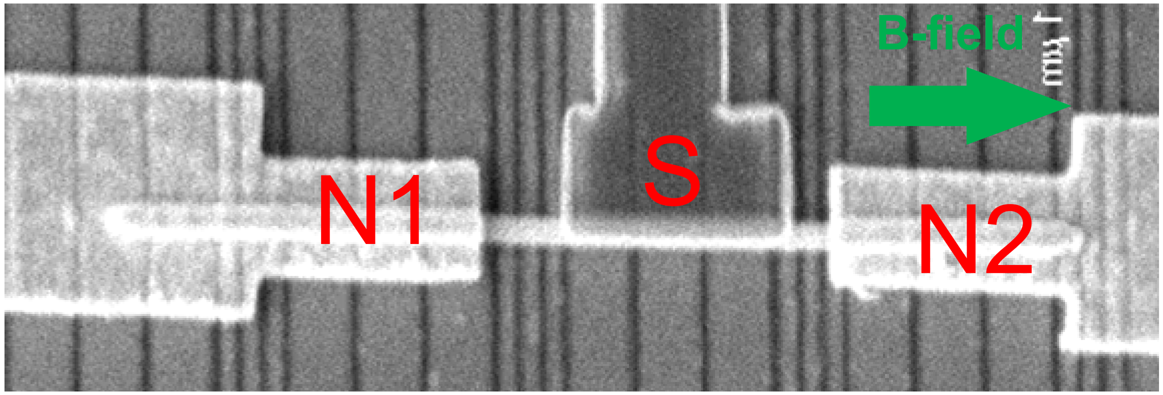

Sim: Aguado group

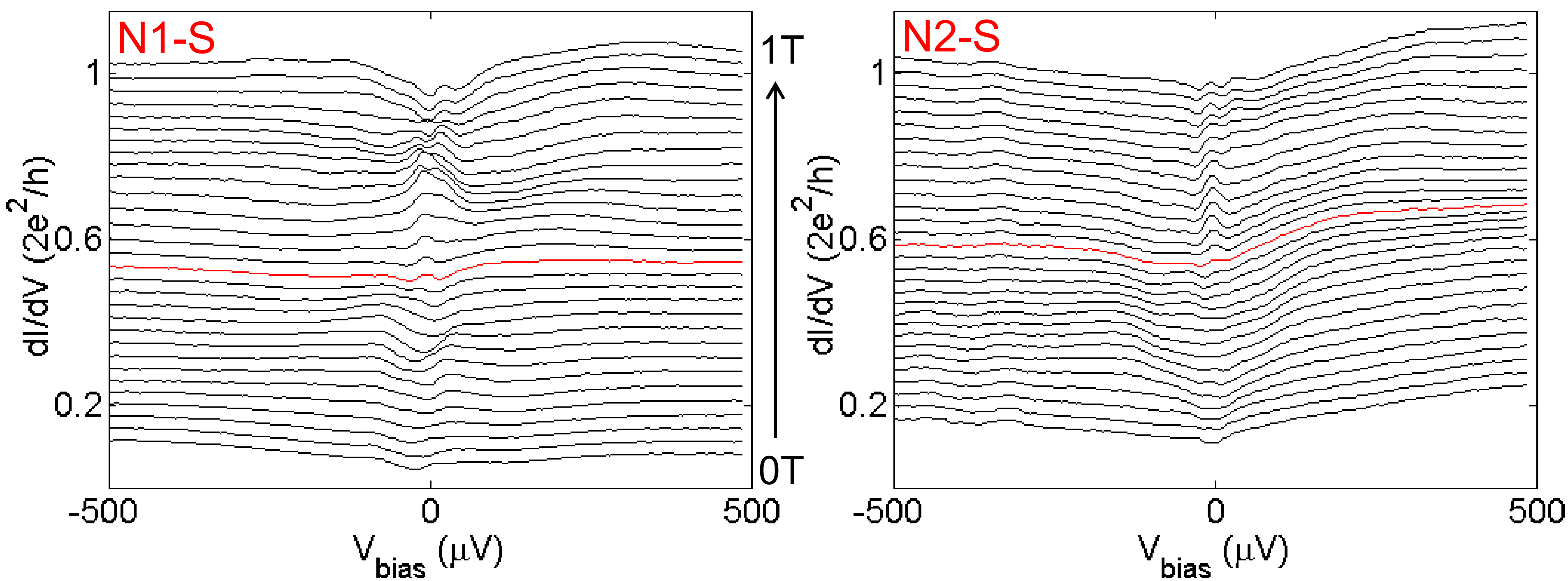



Data: Jun Chen, Peng Yu (Pittsburgh)

# Where is the second Majorana?



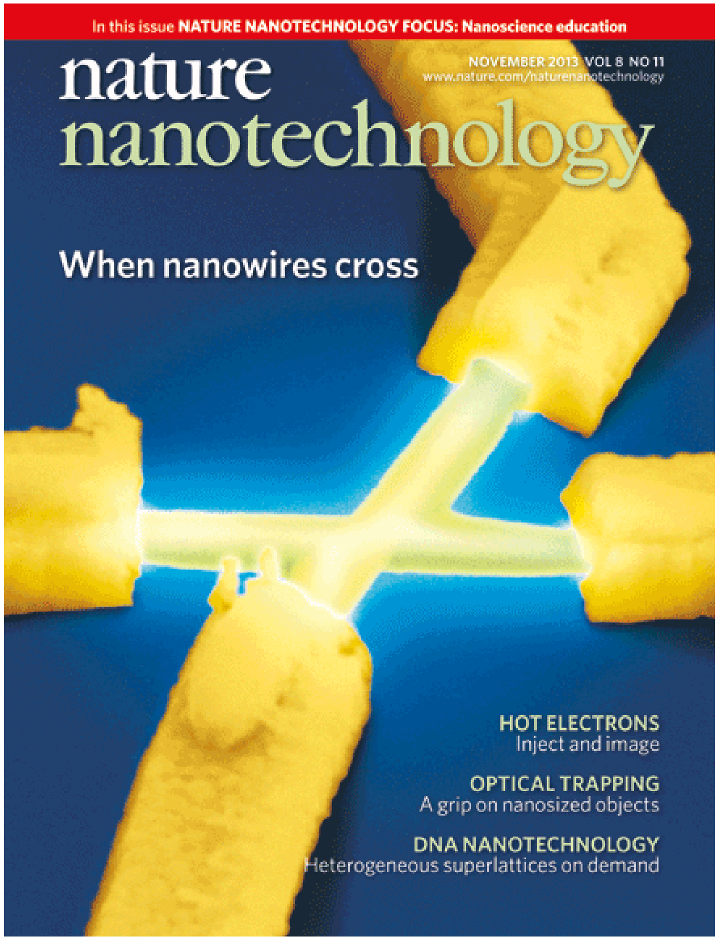



=> correlation in peak onset

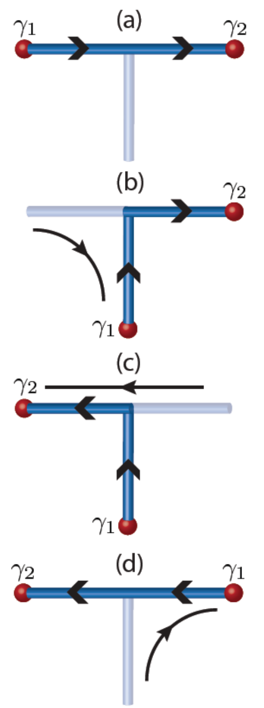
Data: Delft

# Nanowire networks for topological qubits



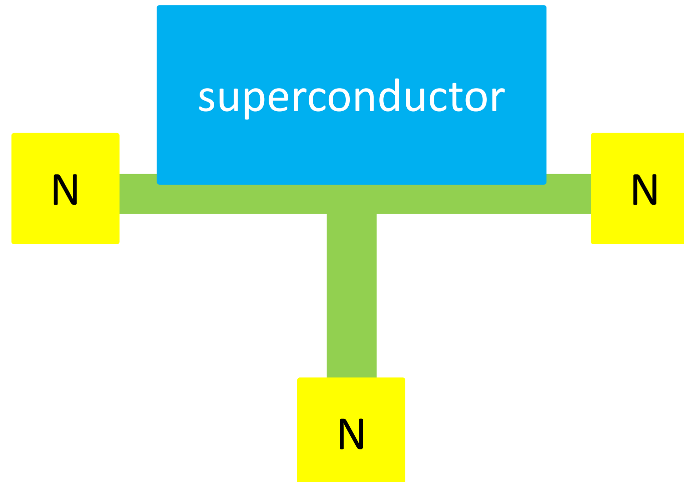

Plissard et al.
“Formation and electronic properties of InSb nanocrosses”
Nature Nanotechnology (2013)

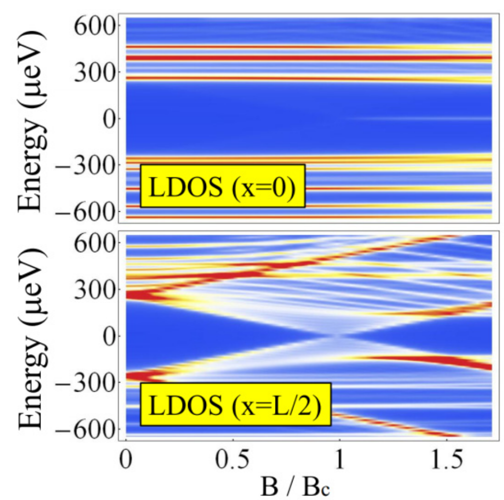
Braiding:




Alicea et al.
Nature Physics 2011

Advanced spectroscopy:




Stanescu et al, PRB 2012