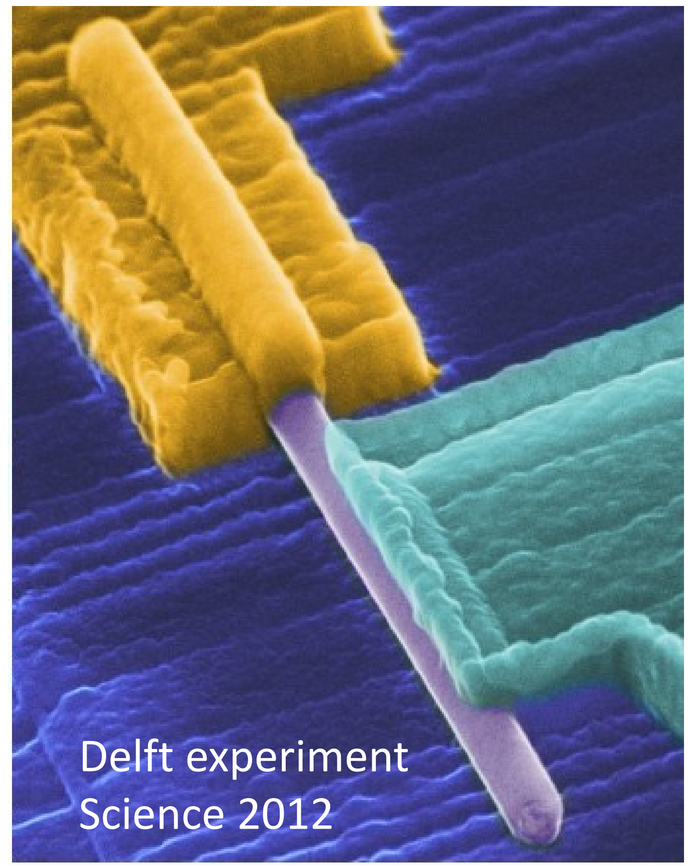
Majorana Fermion Experiments in Nanowires

Kitaev Model mapped on to superconductor-semiconductor hybrids

Experimental signature: zero-bias peaks

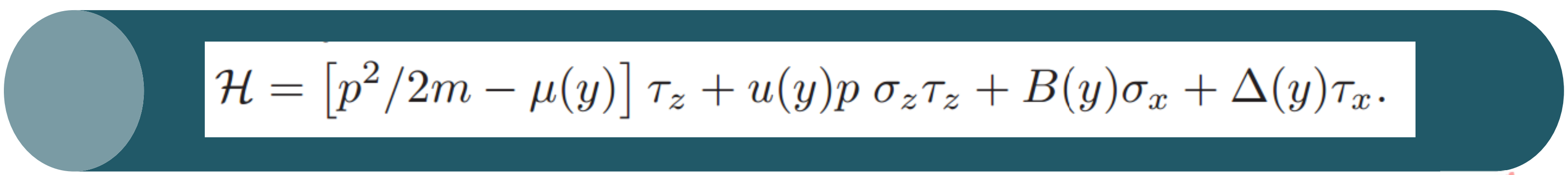
Modern state of the field

Andreev states in quantum dots



Majorana recipe for nanowires:

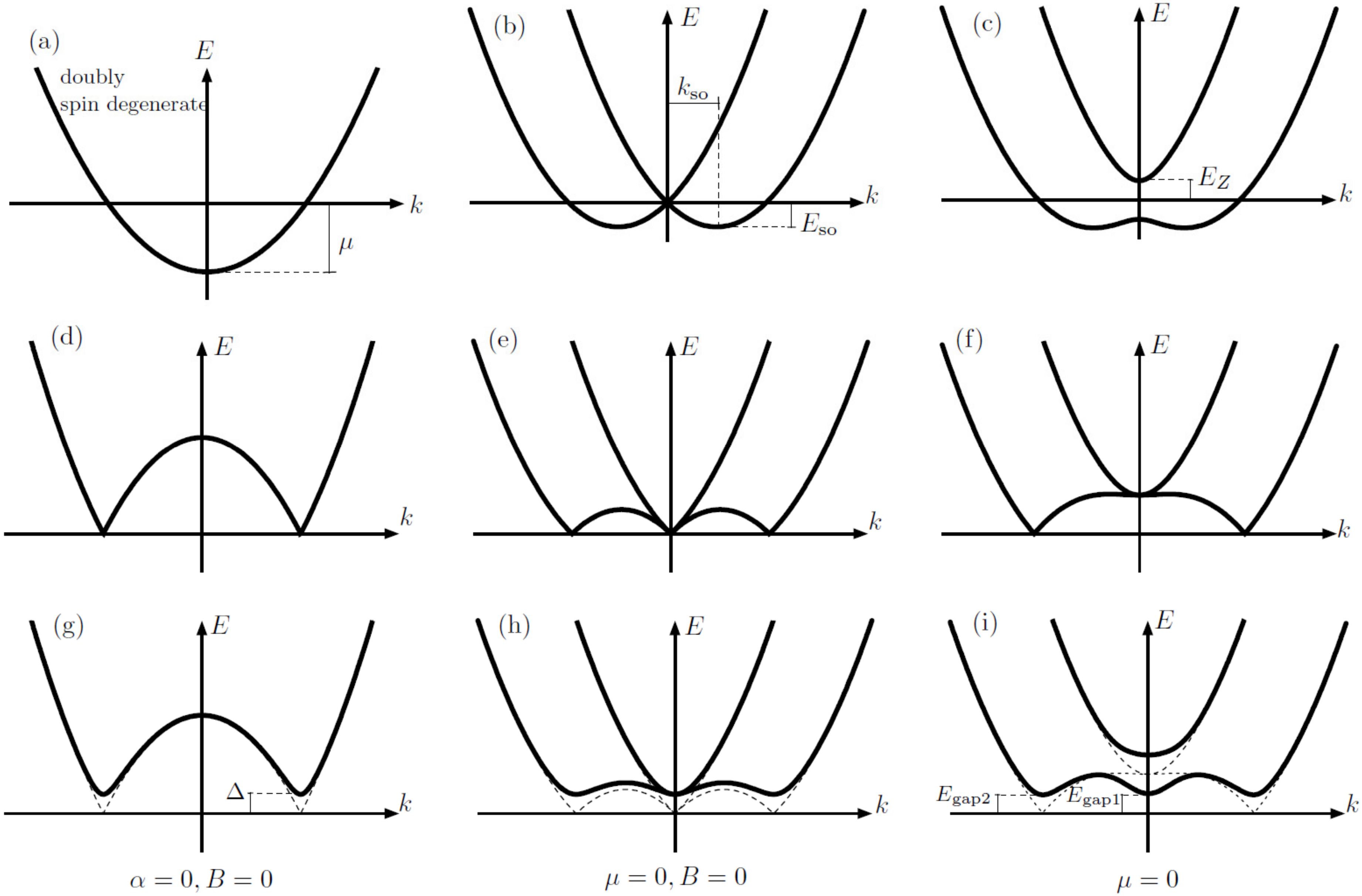
1. One-dimensional wire
2. Spin-orbit interaction
3. Superconductivity
4. Magnetic field



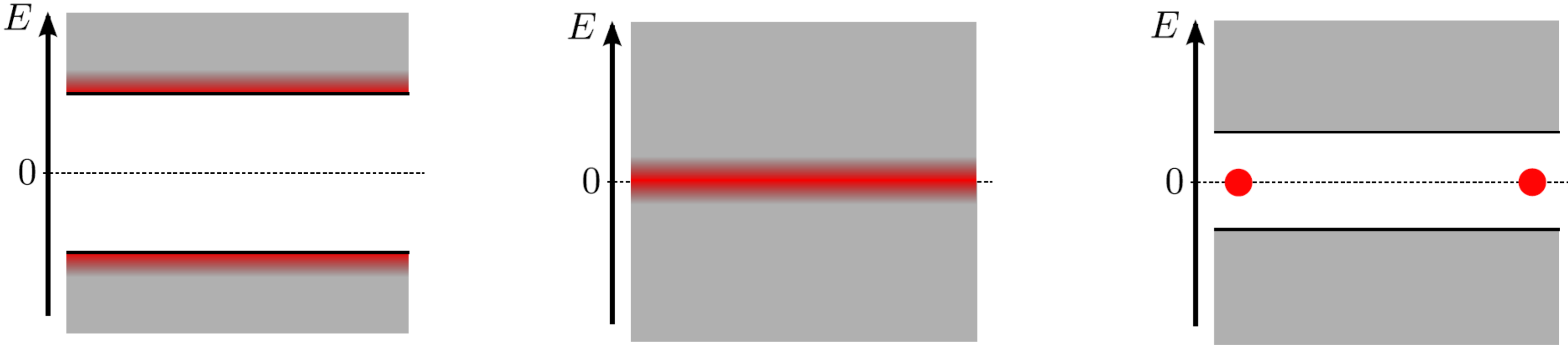
$$\mathcal{H} = \left[p^2/2m - \mu(y)\right]\tau_z + u(y)p\,\sigma_z\tau_z + B(y)\sigma_x + \Delta(y)\tau_x .$$

$\gamma^\dagger = \gamma$ $\qquad$ $\gamma^\dagger = \gamma$

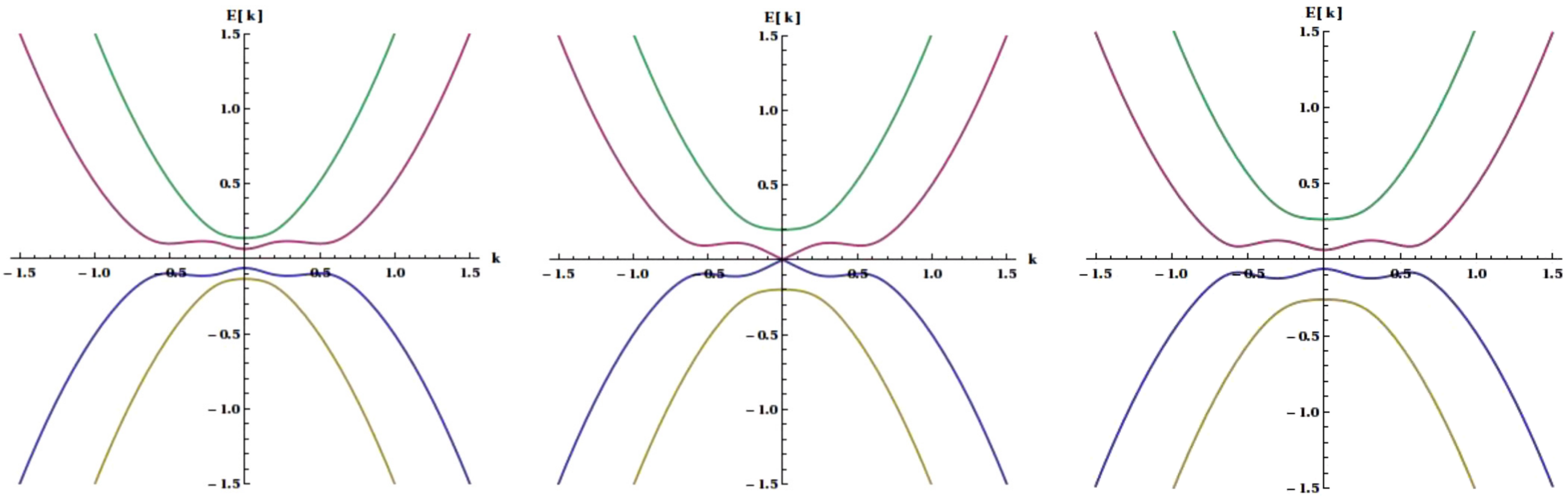
Lutchyn, Sau, Das Sarma, PRL 2010
Oreg, Refael, von Oppen, PRL 2010



Sim by Fabian Hassler



$E_Z < \Delta$ $\quad$ $E_Z = \Delta$ $\quad$ $E_Z > \Delta$

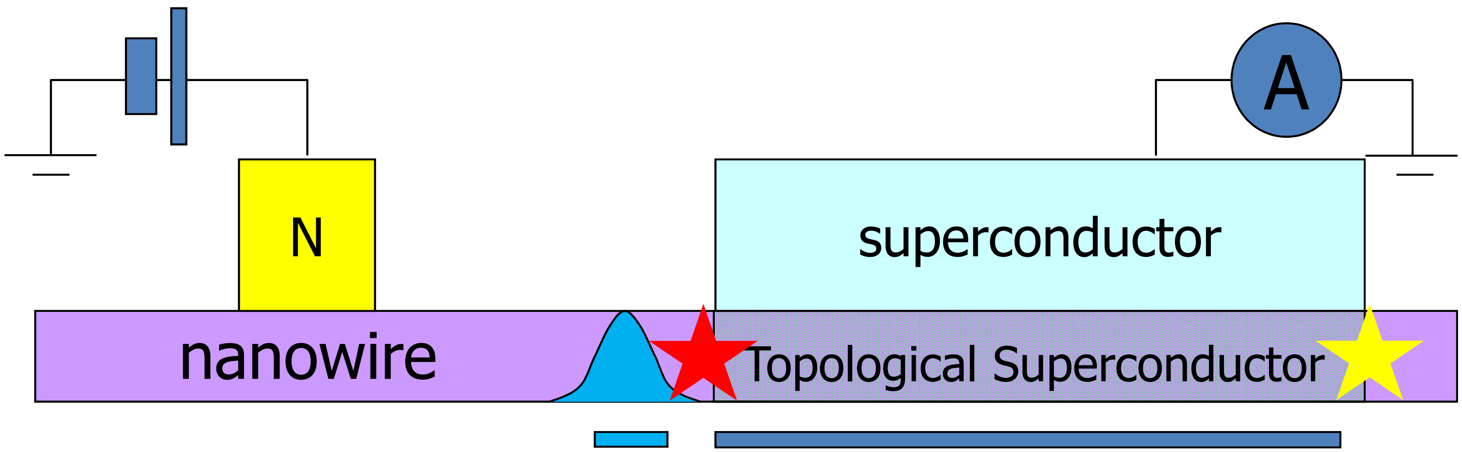


Trivial Superconductor
"positive gap"

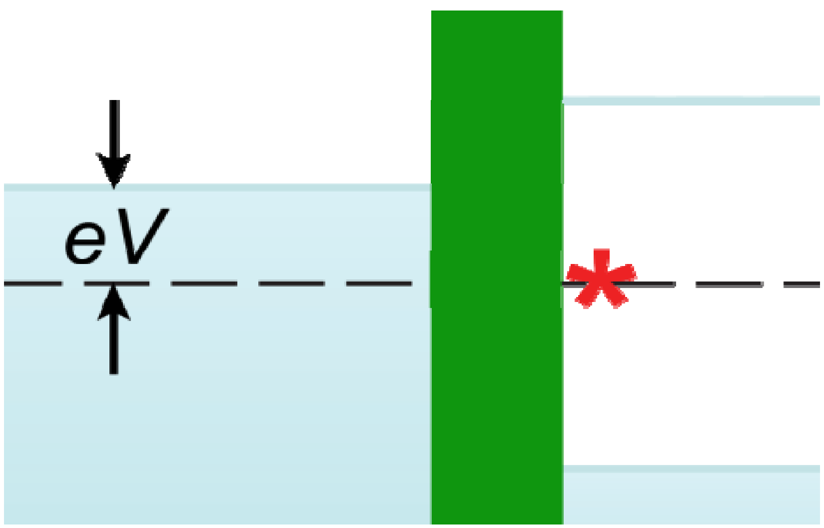
Majorana
"zero gap"

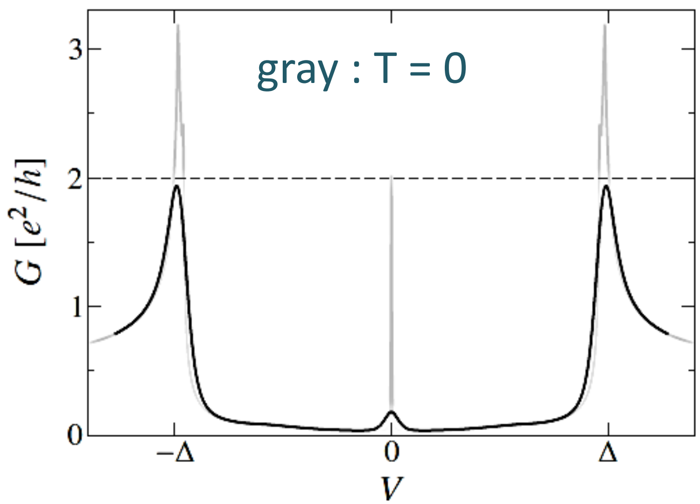
Topological Superconductor
"negative gap"

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

InAs nanowires:

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

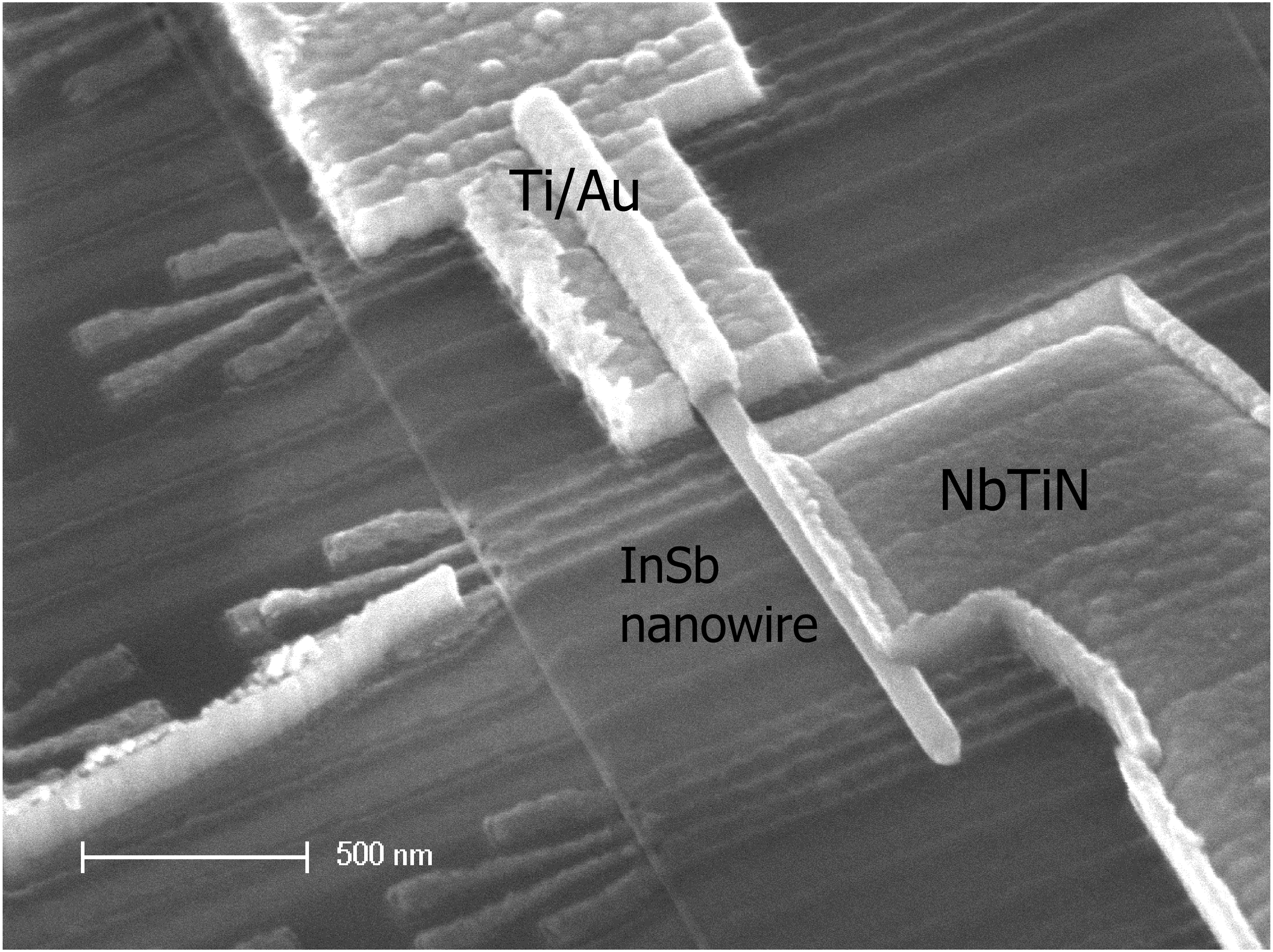
InSb nanowires:

Larger g, similar lso, “cleaner”

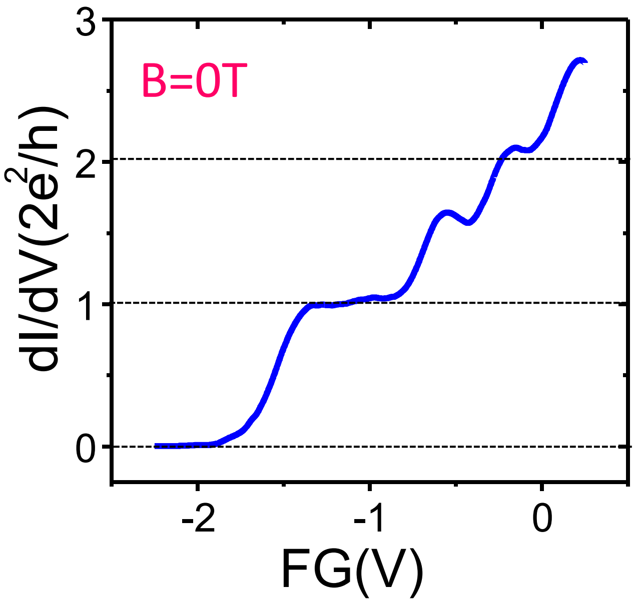
Aluminum contacts:

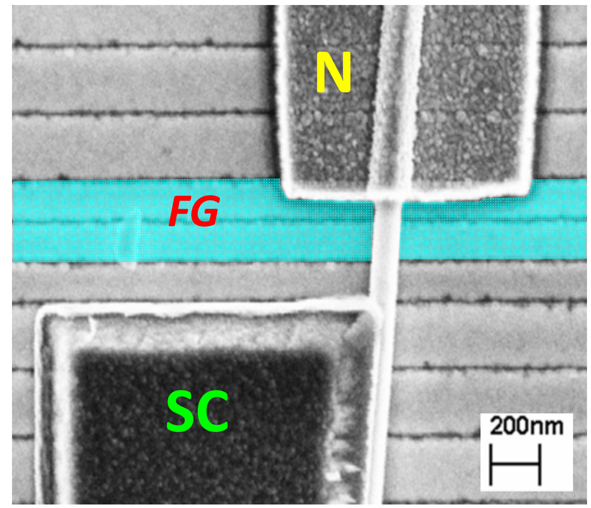
Gap ~ 100 ueV
Critical field ~100 mT

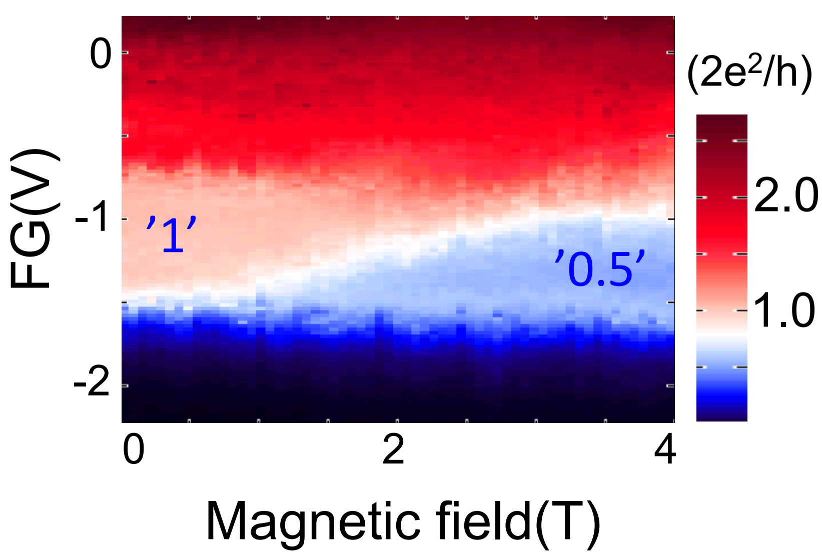
NbTiN contacts:
Gap ~ 3meV
Critical field > 10 T

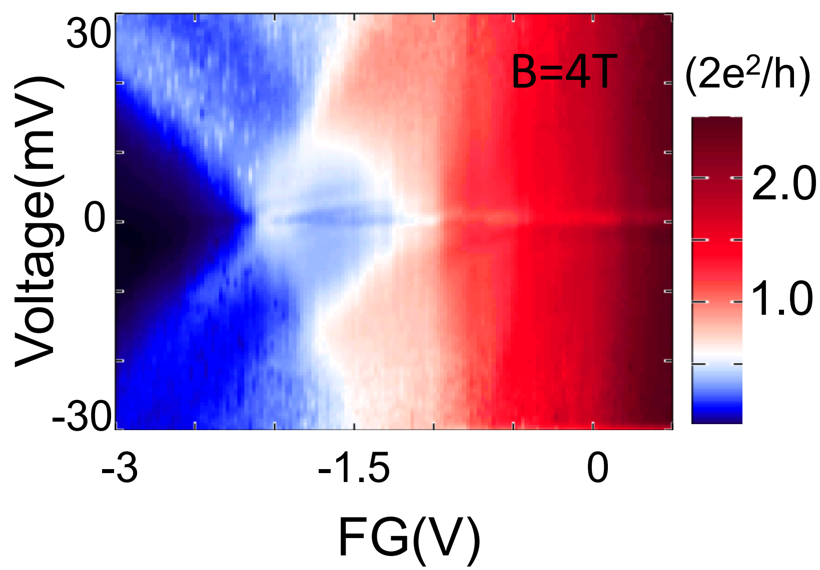

Ti/Au
NbTiN
InSb
nanowire
500 nm

First Majorana ingredient: one-dimensional system





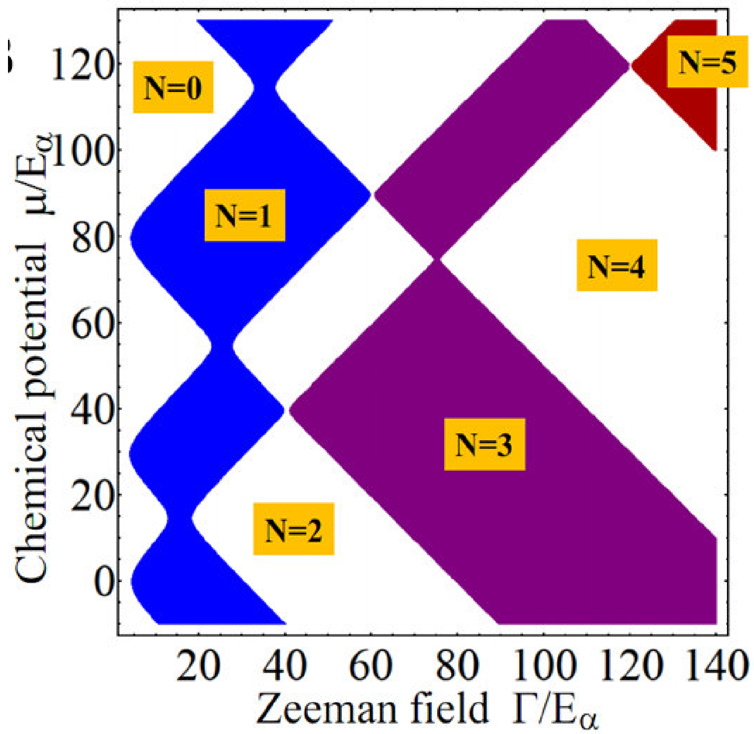




Data: Jun Chen, Peng Yu (Pitt)

Multi-subband topological superconductor

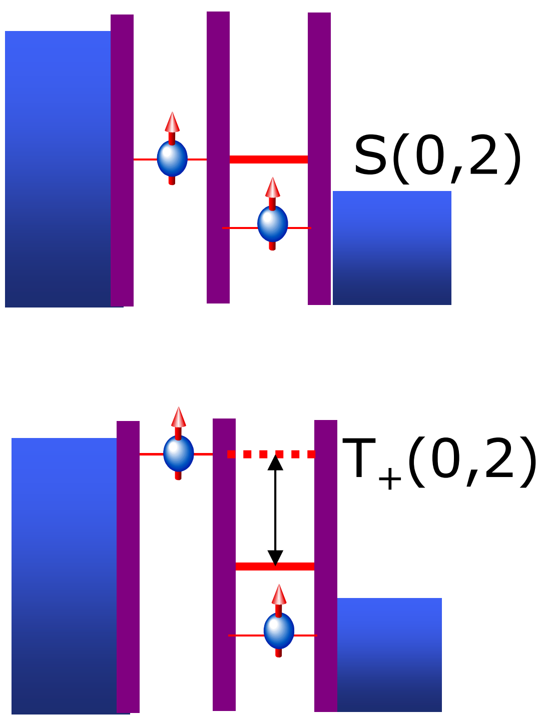
$$g\mu_B B(\theta) > \sqrt{\Delta^2_{k=0,N} + \mu^2(x)}$$

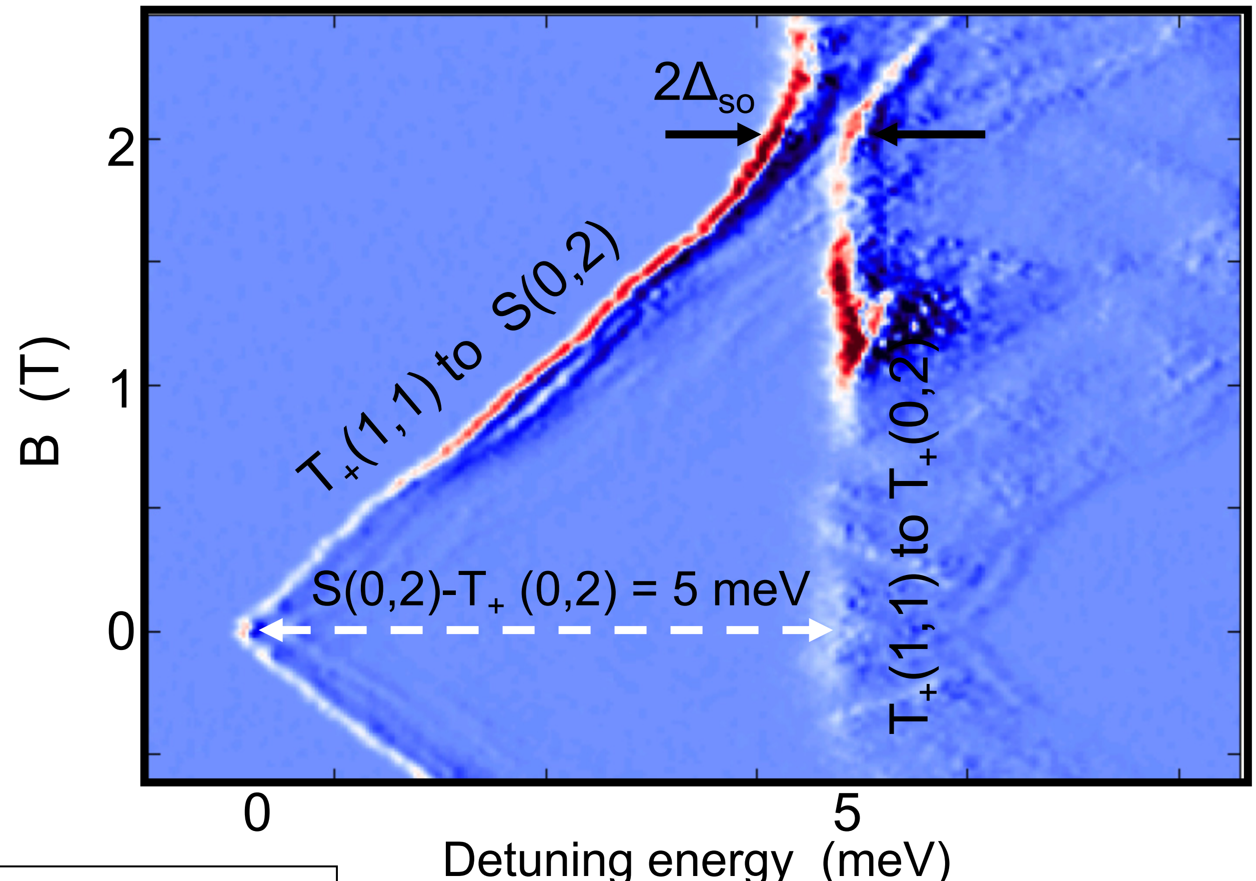


Stanescu, Lutchyn, Das Sarma; Phys Rev B 2011

Spin-orbit strength in InSb nanowires

Nadj-Perge et al. PRL 2012





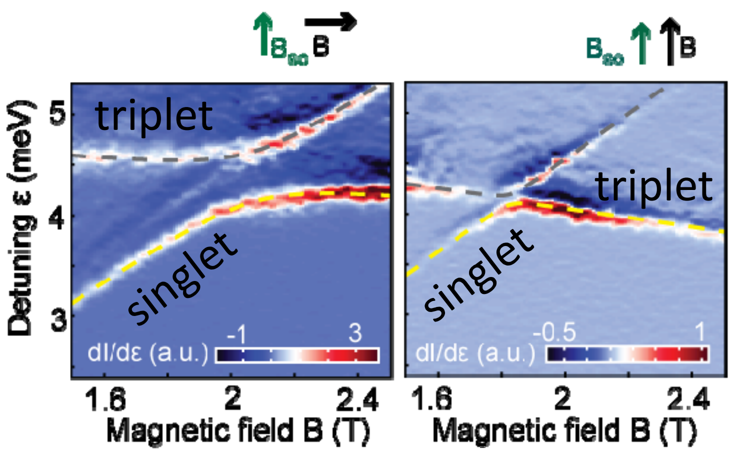
Δ_{so} = 0.3 meV

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

lso = 200 nm

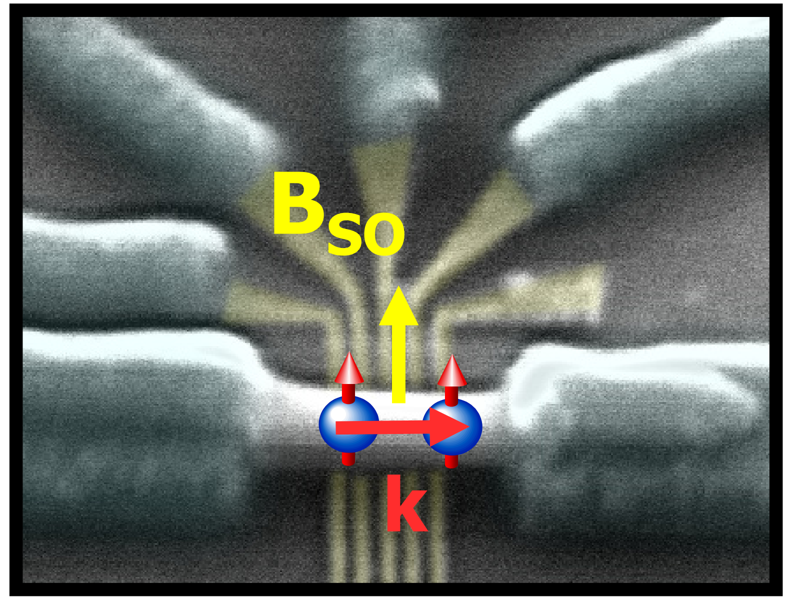
Majorana recipe:

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

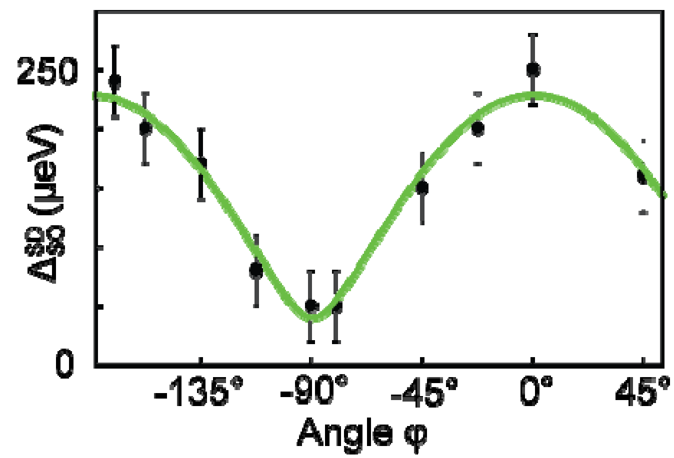


InAs NW, C. Fasth et. al, PRL 2007; Pfund, PRB 2007;
InSb NW, H. A. Nillson et. al, Nano Lett. 2010

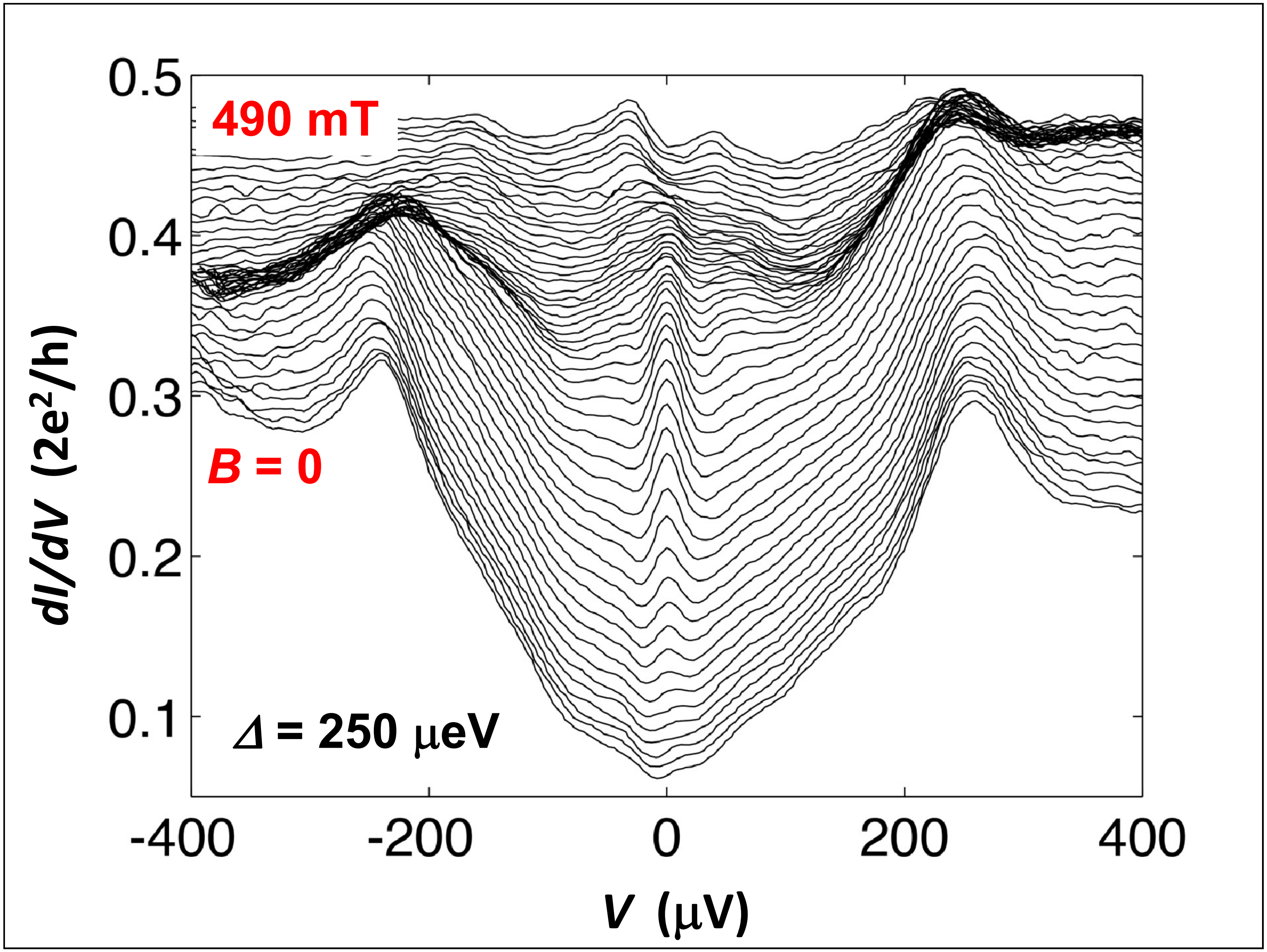
Nadj-Perge et al. PRL 2012



Not the subband spin-orbit splitting!

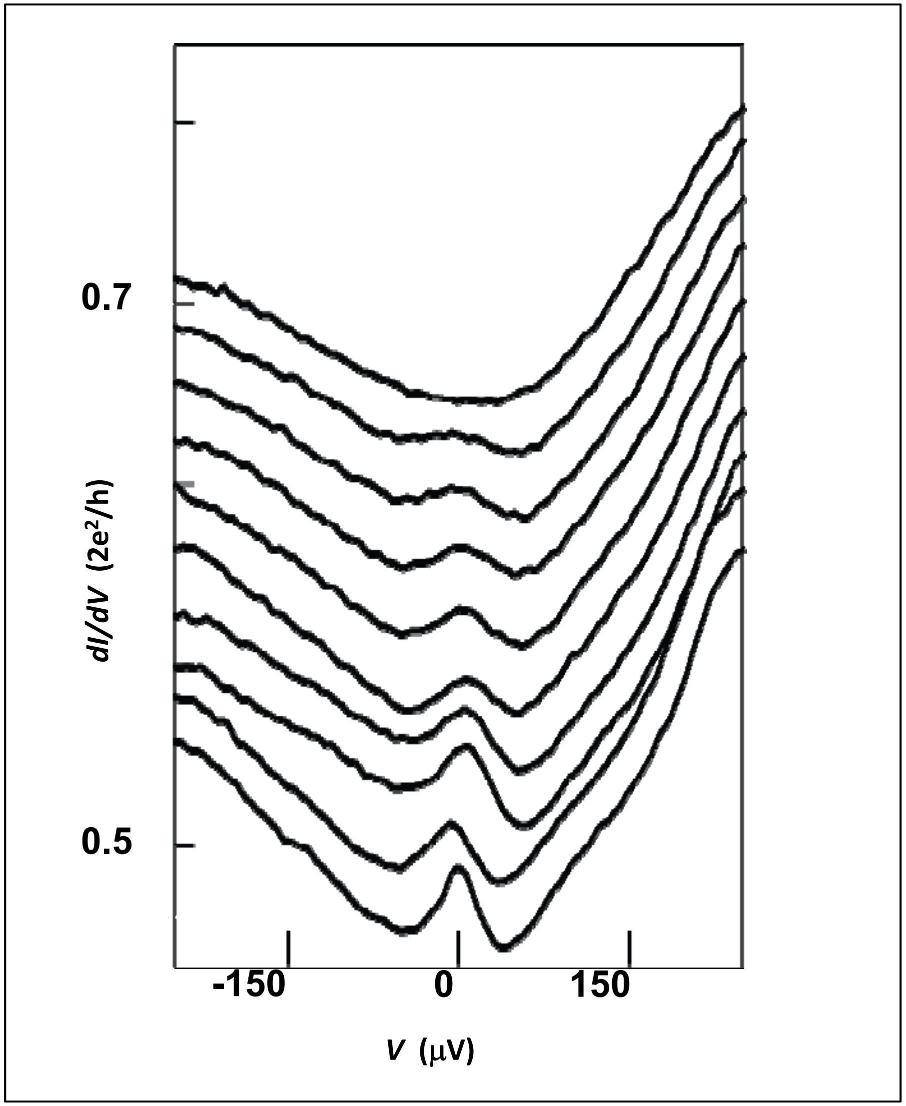


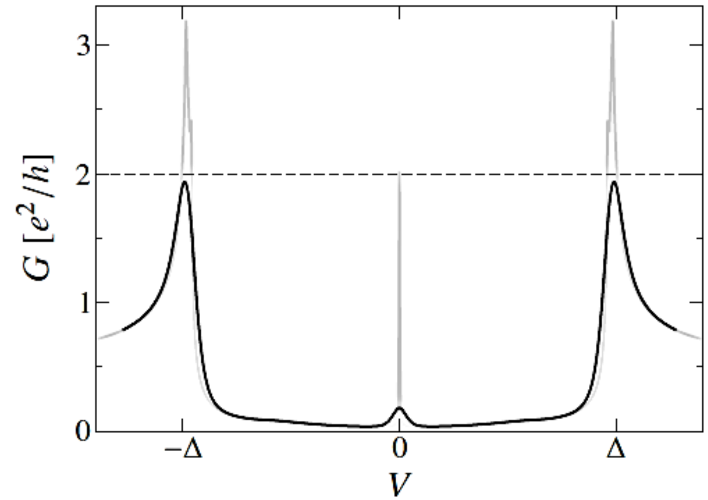
Observation of zero bias peak



Data: Delft

Temperature dependence

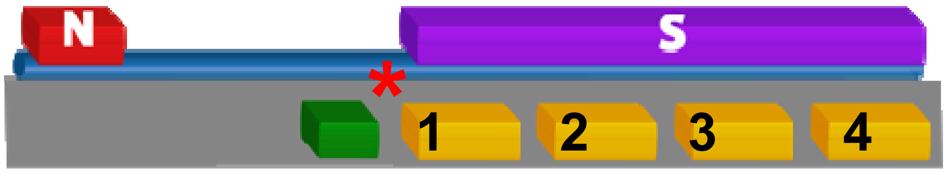


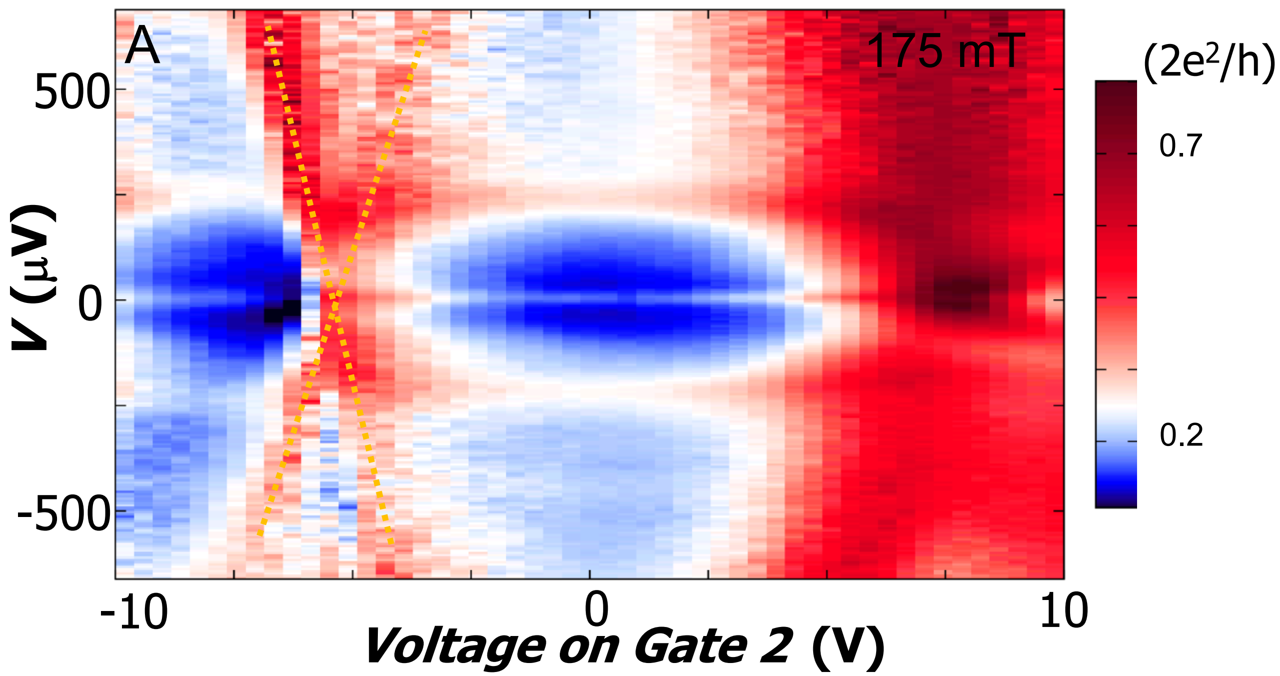


=> Temperature scale is 0.3-0.4 Kelvin

Data: Delft

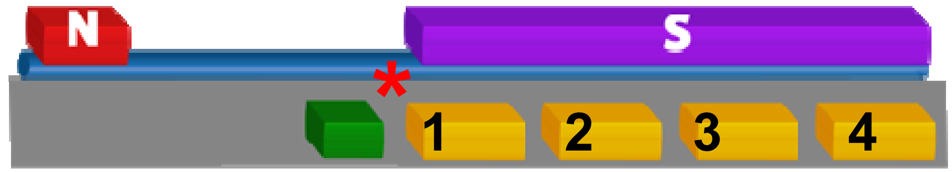
Gate dependence: under the superconductor

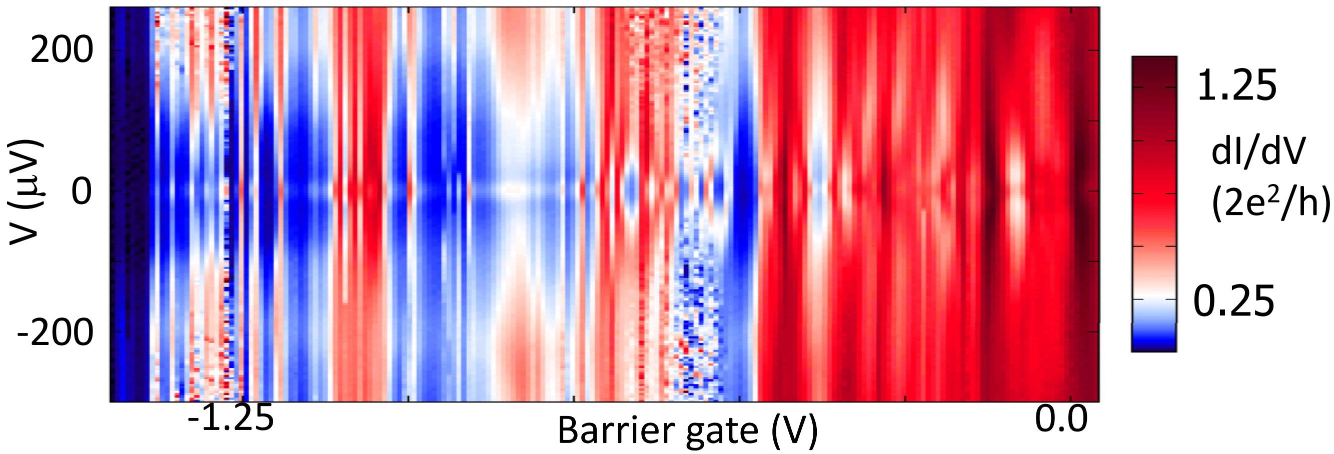


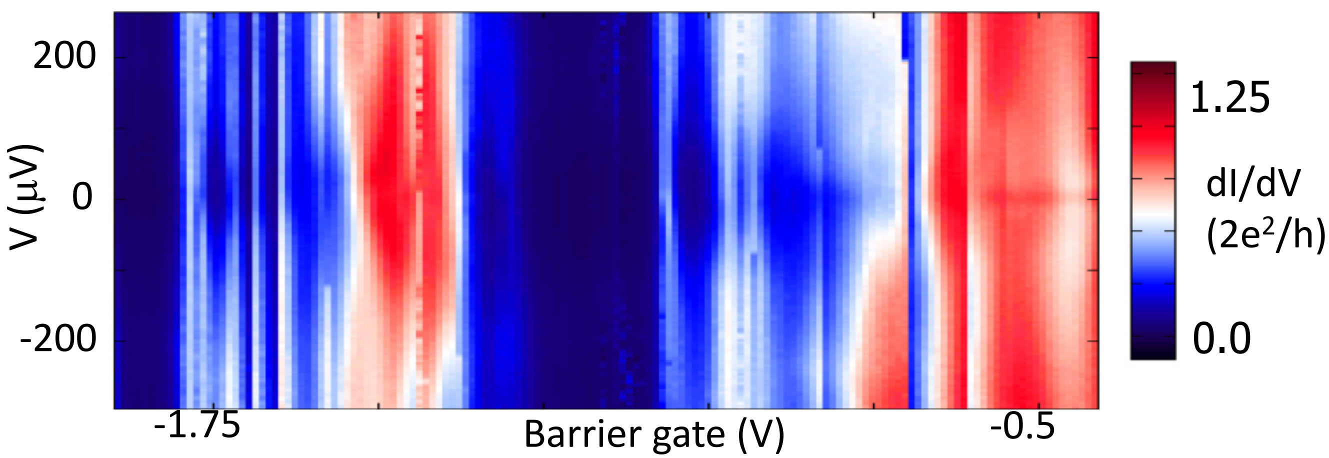


Data: Delft

Gate dependence: barrier gate



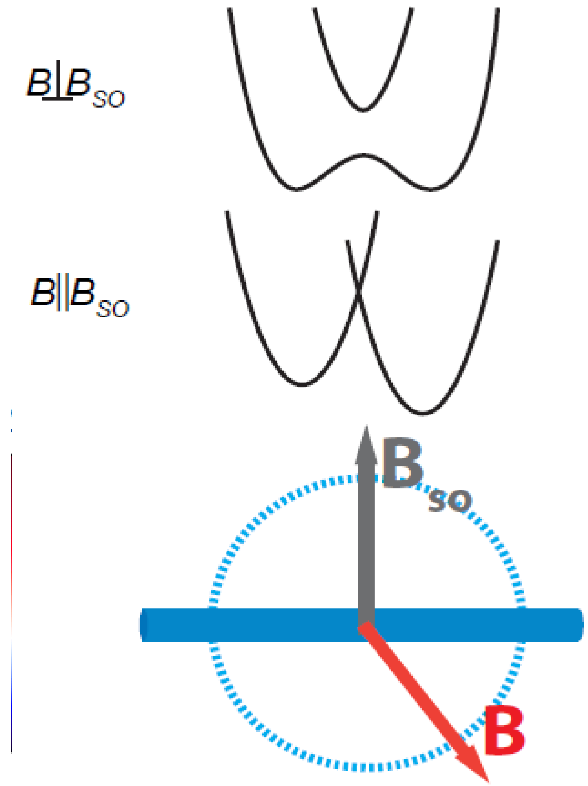


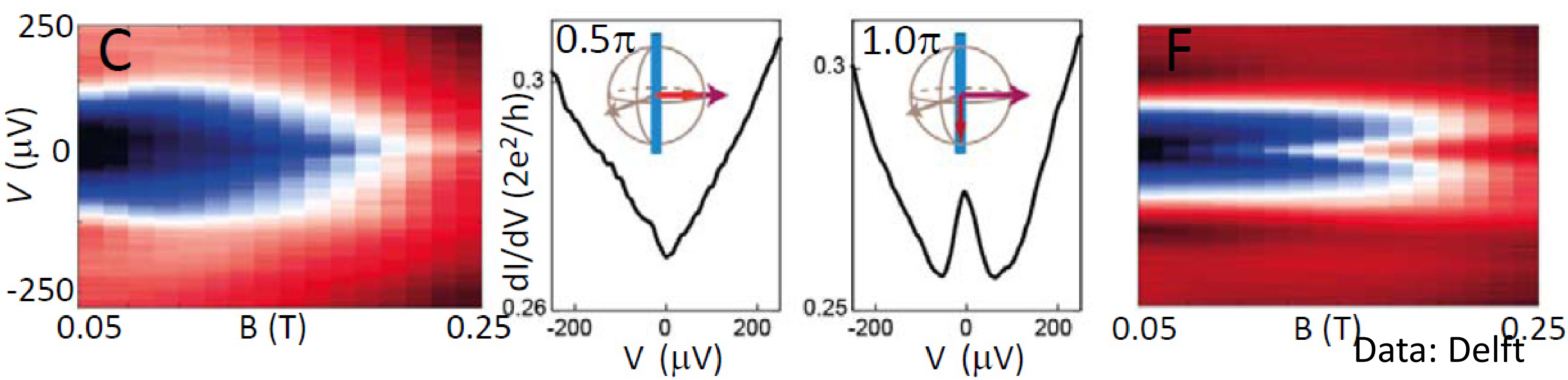


Data: Delft

Majorana recipe:

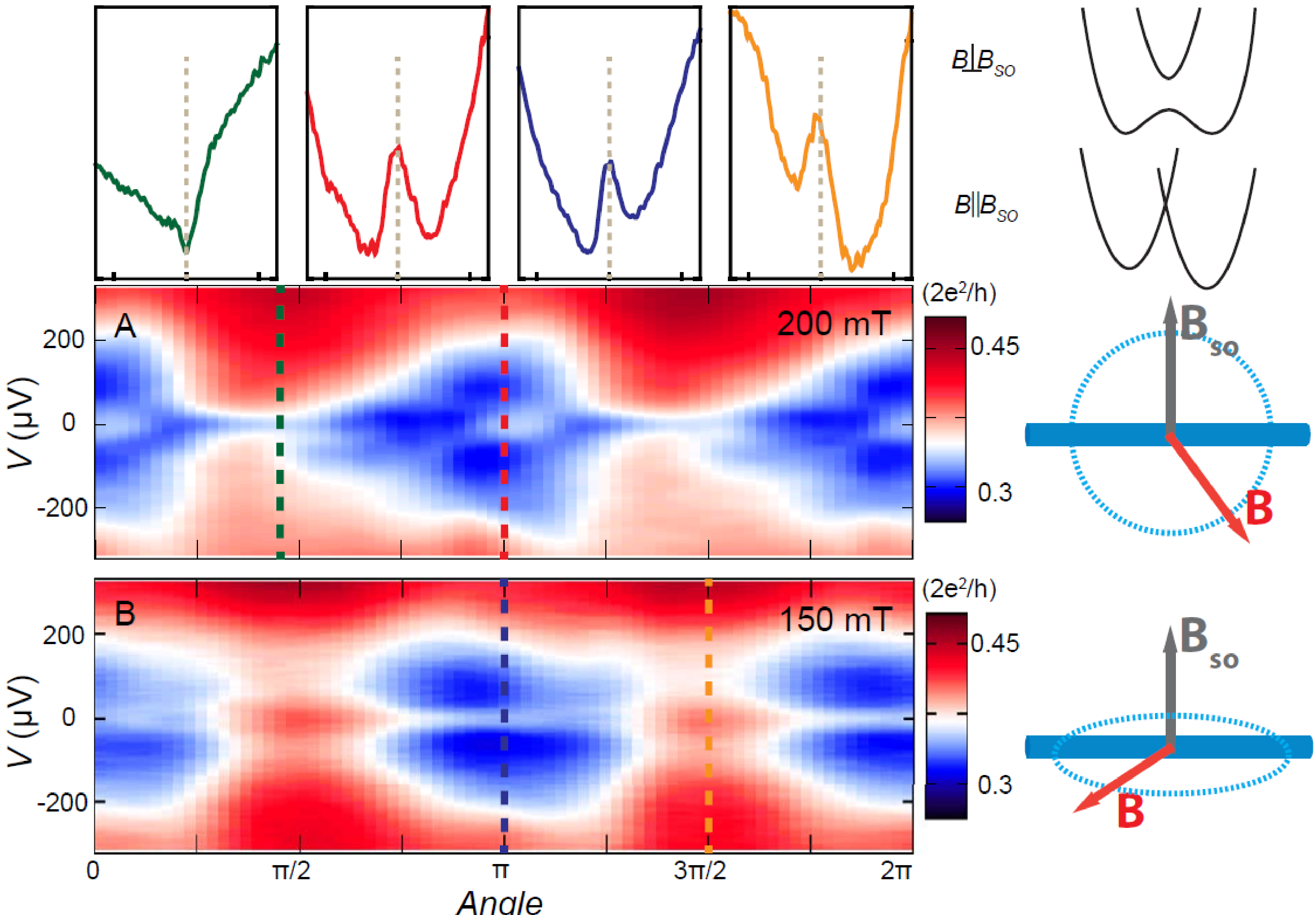
1. One-dimensional wire ✔
2. ~~Spin-orbit interaction~~
3. Superconductivity
4. Magnetic field ✔





Data: Delft

Third device in a 3D vector magnet

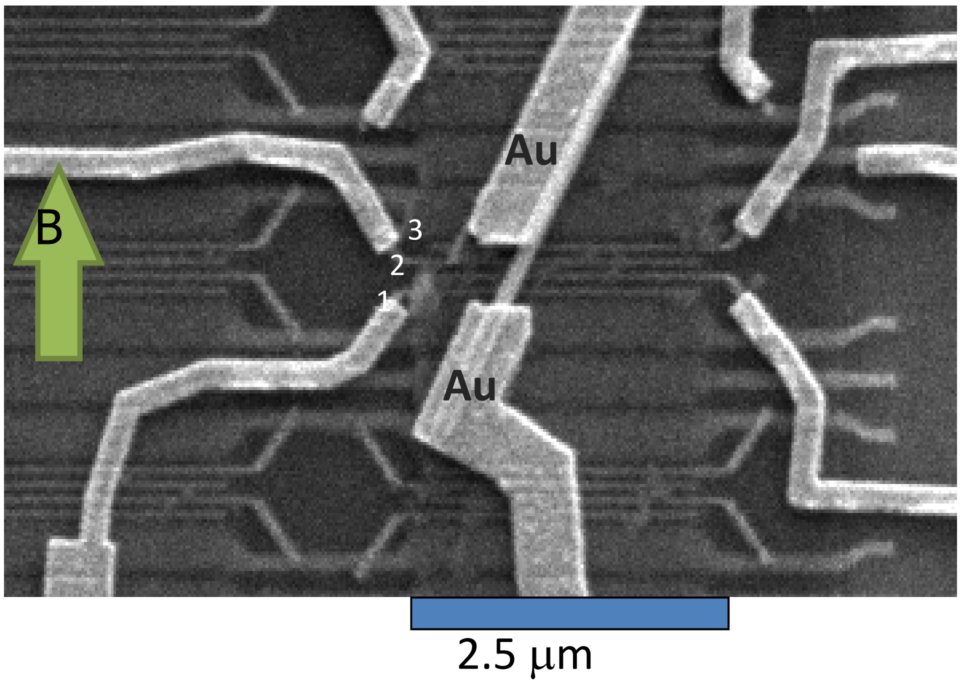


Data: Delft

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

Kondo

Josephson

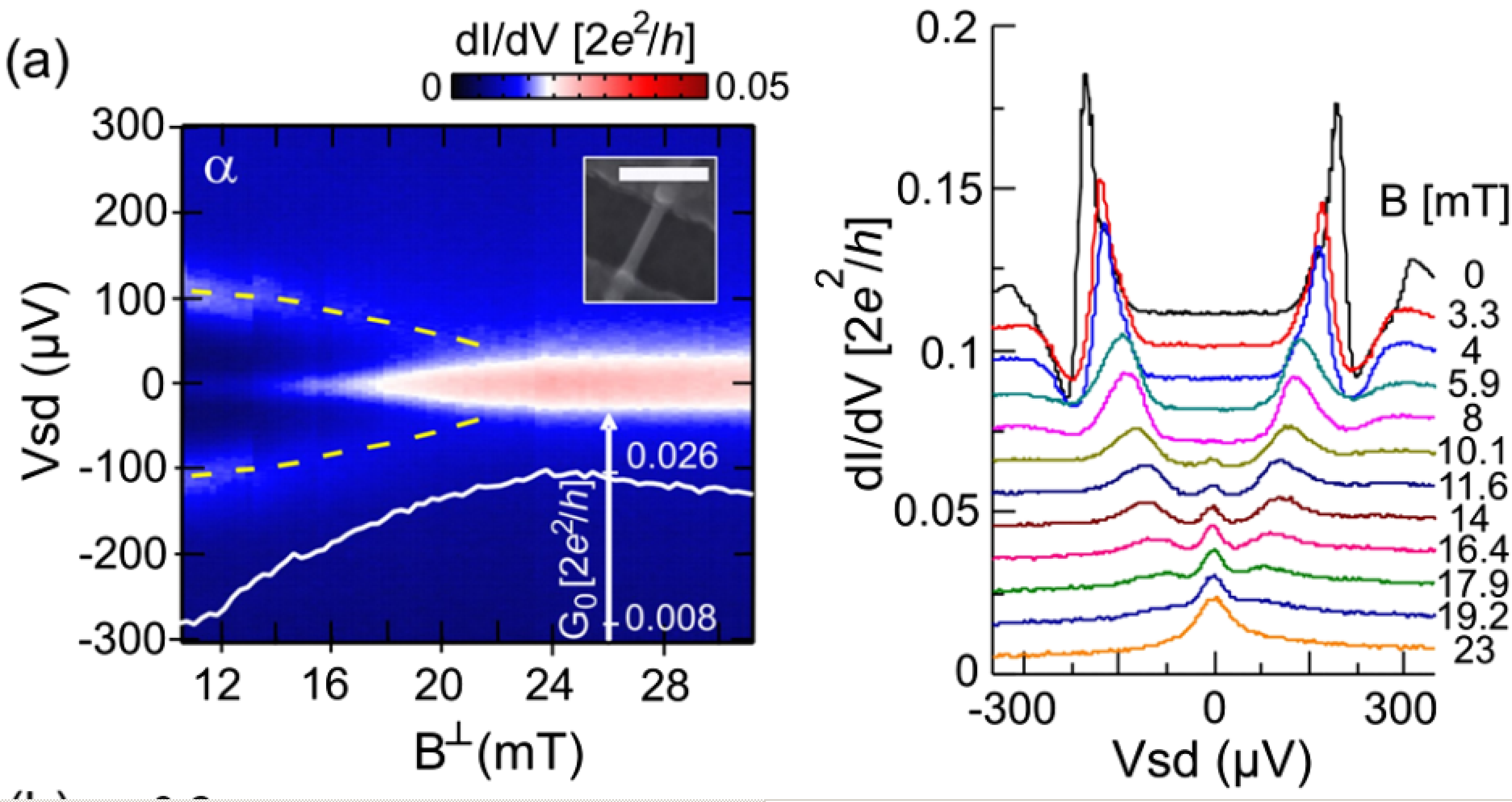
Unknown effect

Kondo

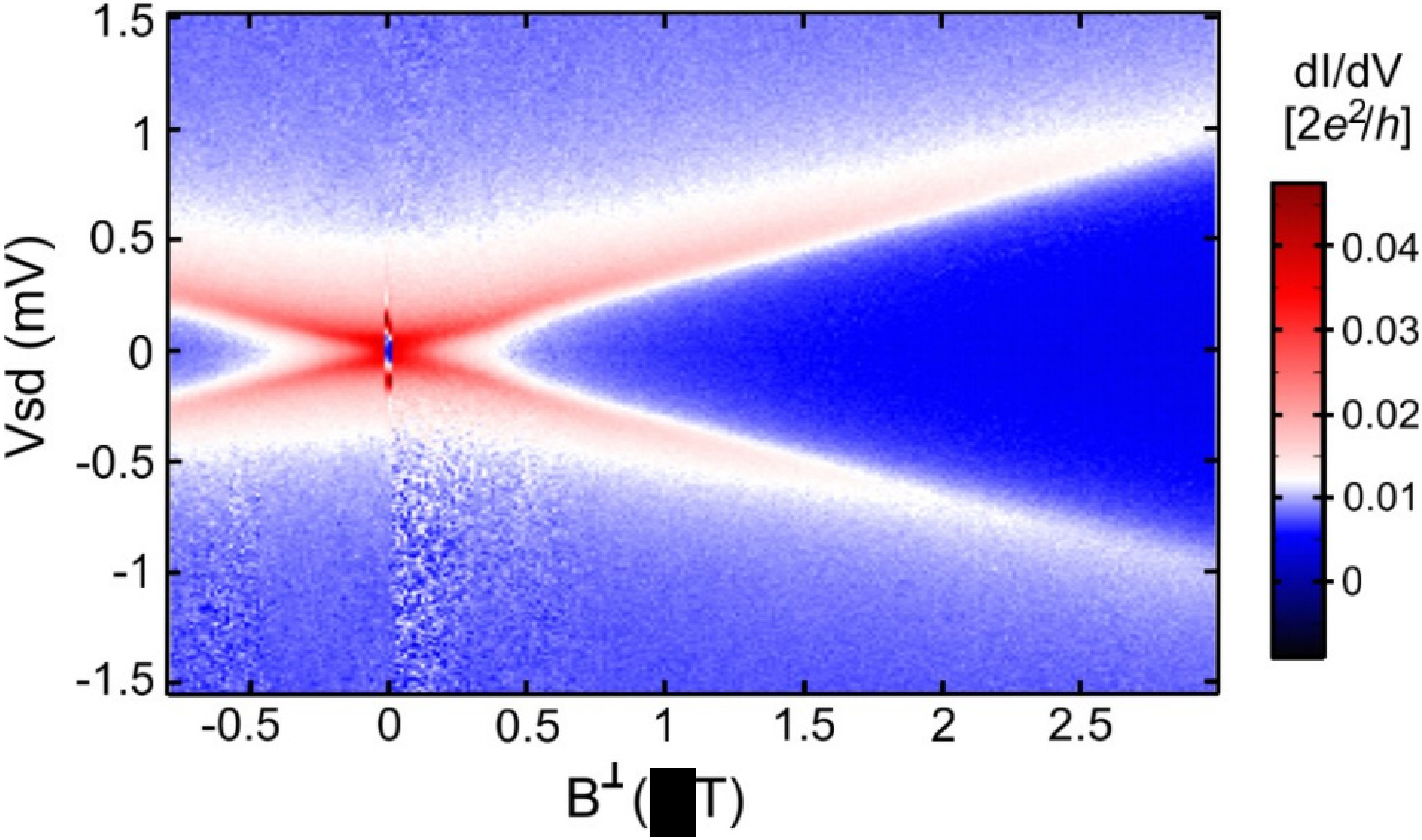
$g^* > 50$

in InSb

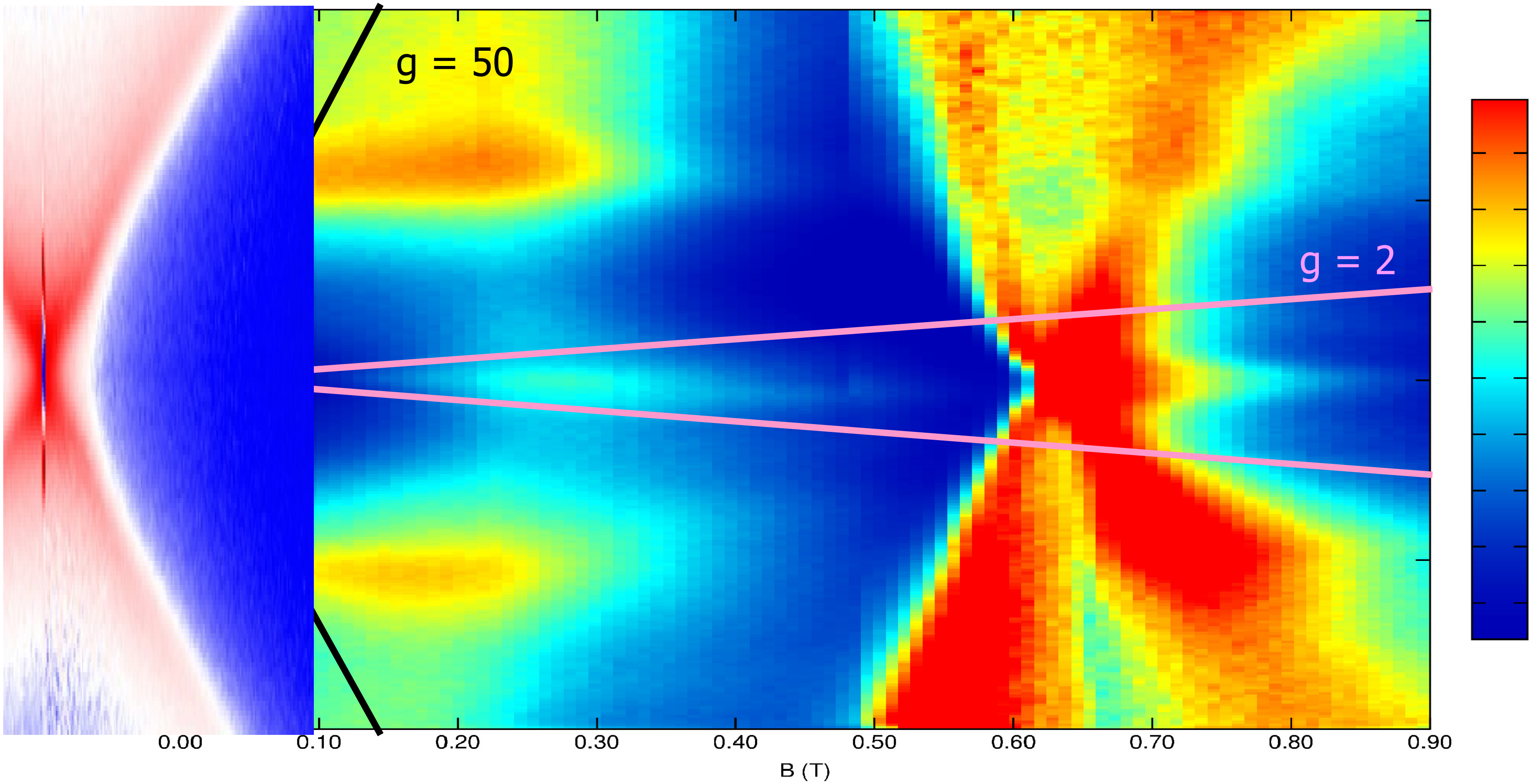
…so, 1 Tesla = 1.5 meV



EJH Lee et al, PRL 2012

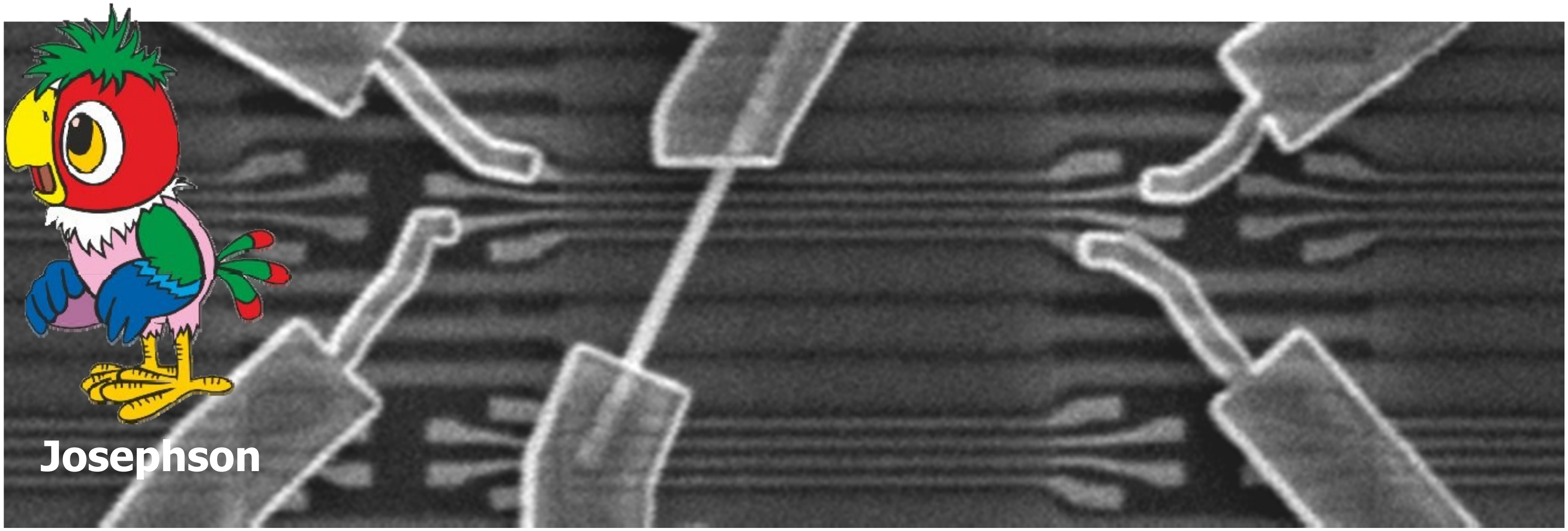

Vsd (mV)
1.5
1
0.5
0
-0.5
-1
-1.5
-0.5
0
0.5
1
1.5
2
2.5
B⊥ ([redacted]T)
dI/dV
[2e²/h]
0.04
0.03
0.02
0.01
0

How would Kondo effect look?



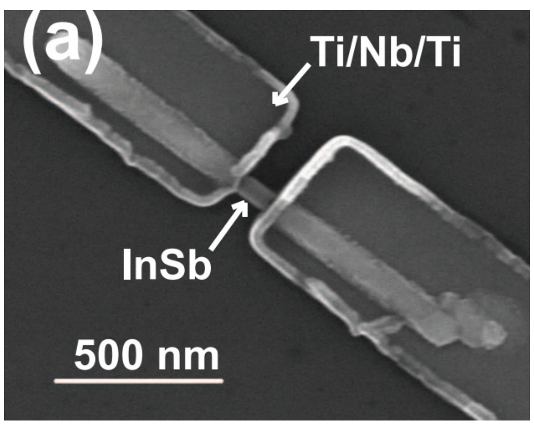
Data: Delft

July 2011: Two Superconducting Contacts



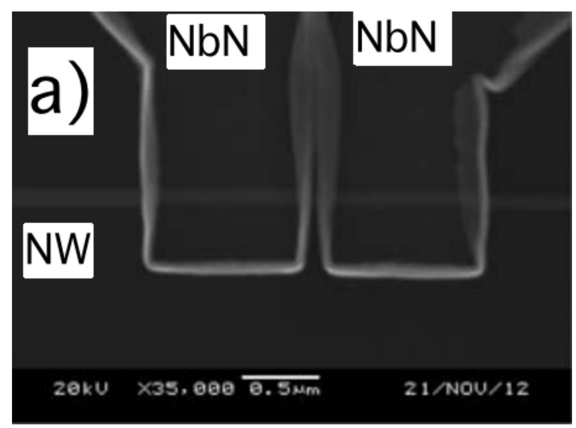
Deng et at, Nano Letters 2012

"Observation of Majorana Fermions in a Nb-InSb Nanowire-Nb Hybrid Quantum Device"



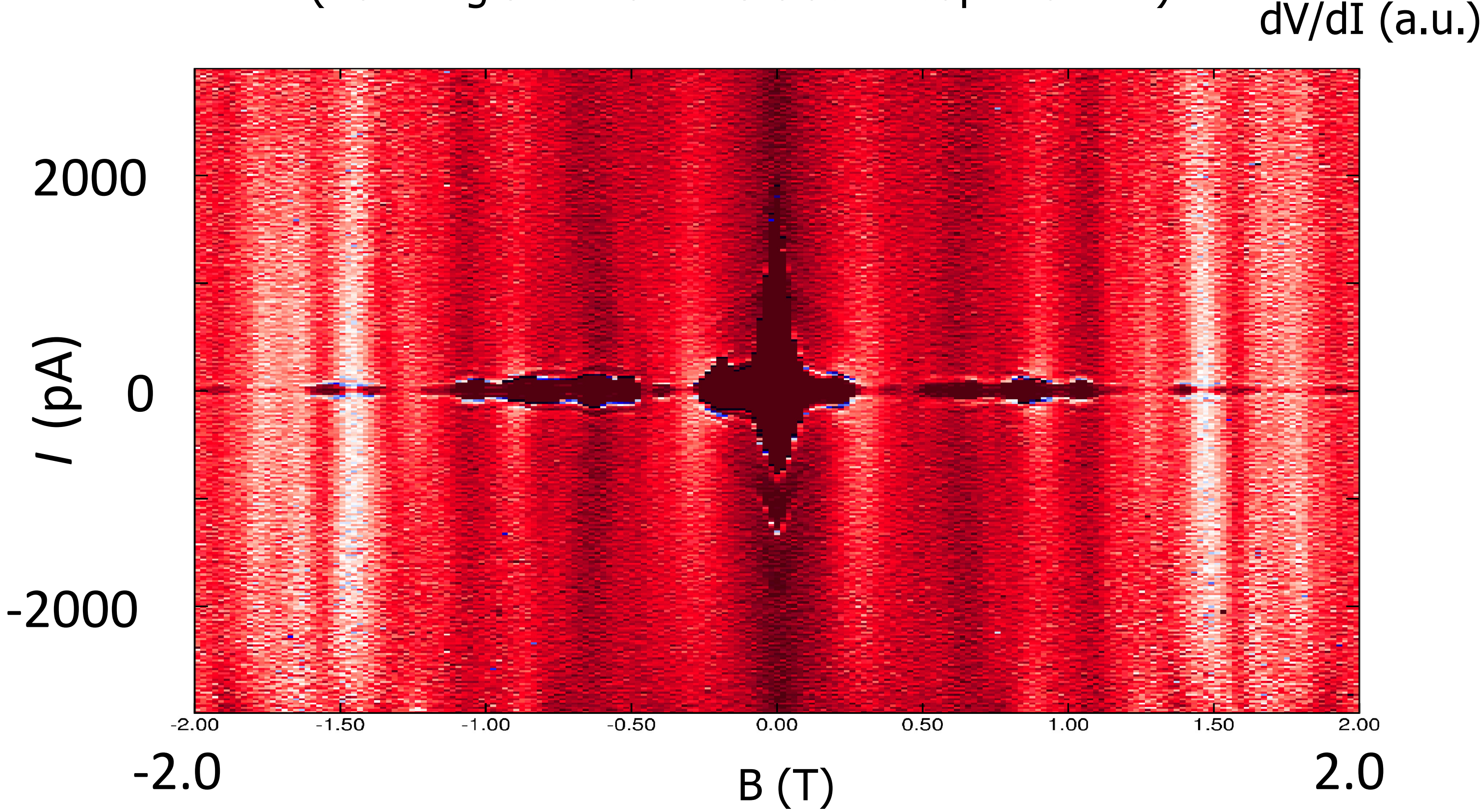
Finck et al, PRL 2012

"…while considering more mundane explanations."



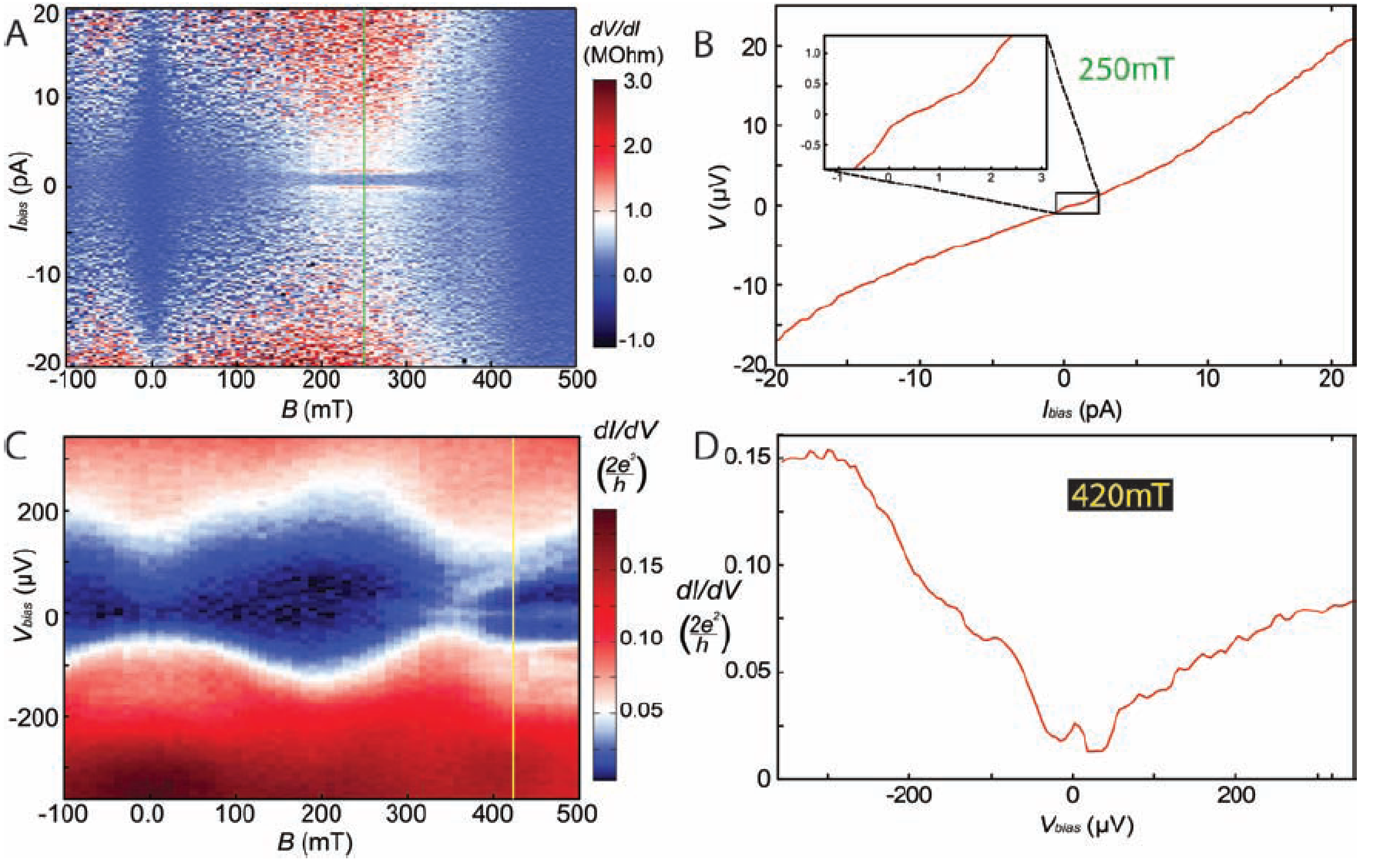
Supercurrents surviving to 2 Tesla.
Contact spacing = 900 nm

(Dark regions near zero bias = supercurrent)



Data: Delft

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



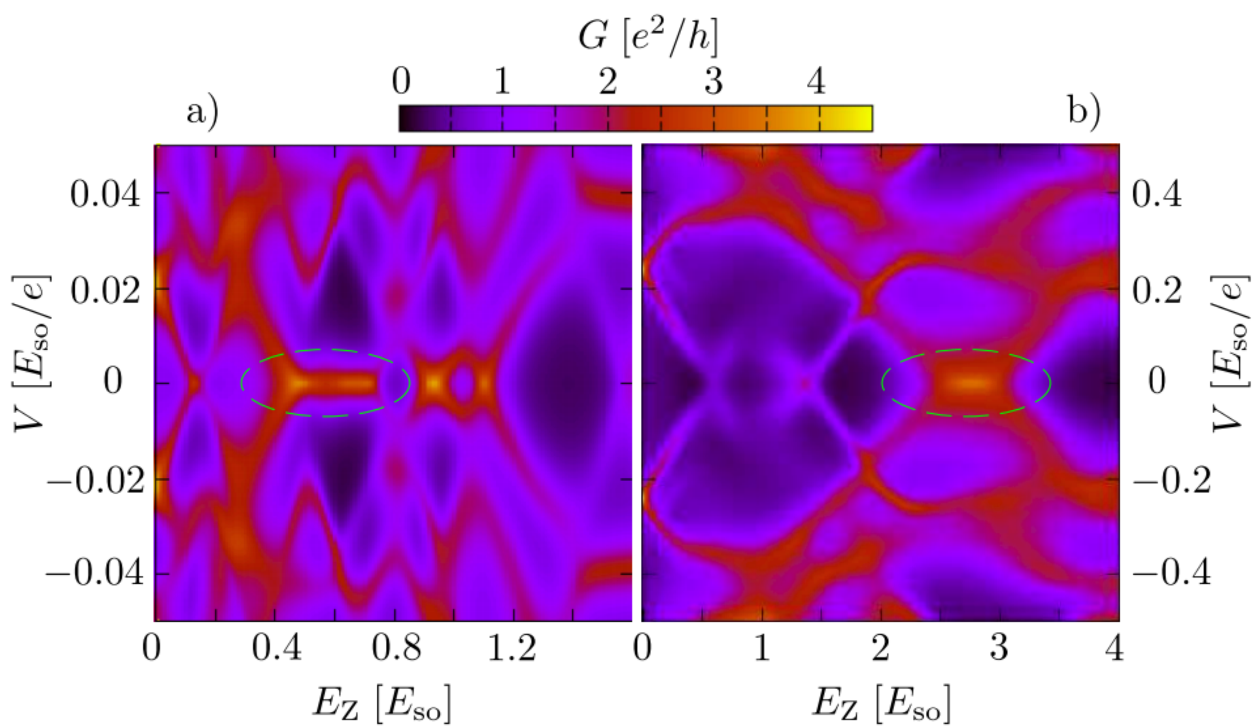
Data: Delft

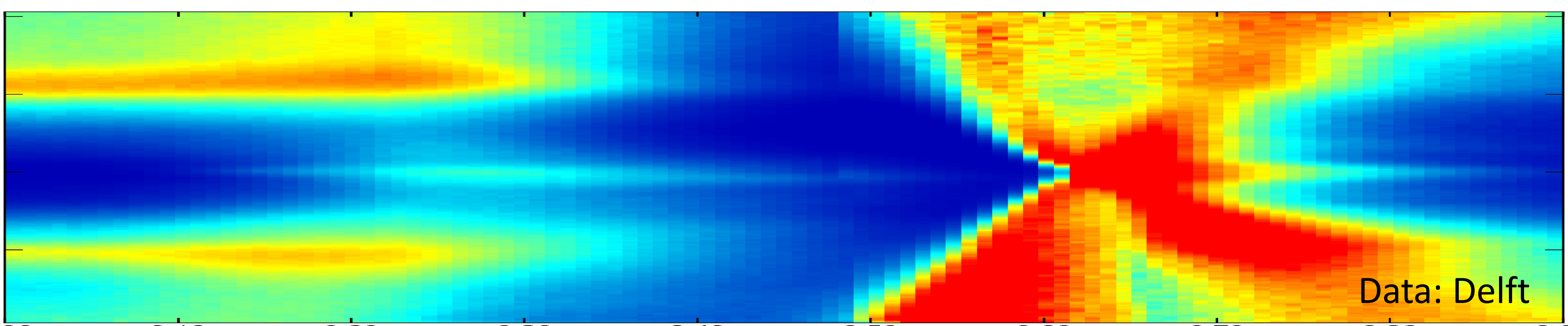
Zero-voltage conductance peak from weak antilocalization in a Majorana nanowire

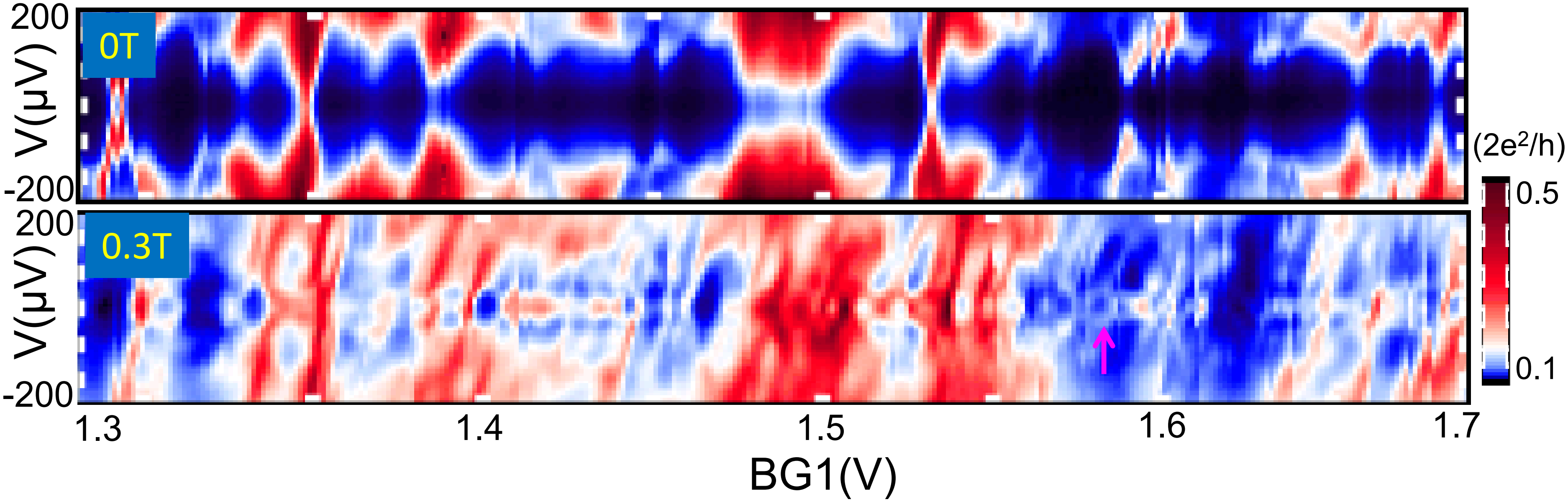
D. I. Pikulin,[1] J. P. Dahlhaus,[1] M. Wimmer,[1] H. Schomerus,[2] and C. W. J. Beenakker[1]

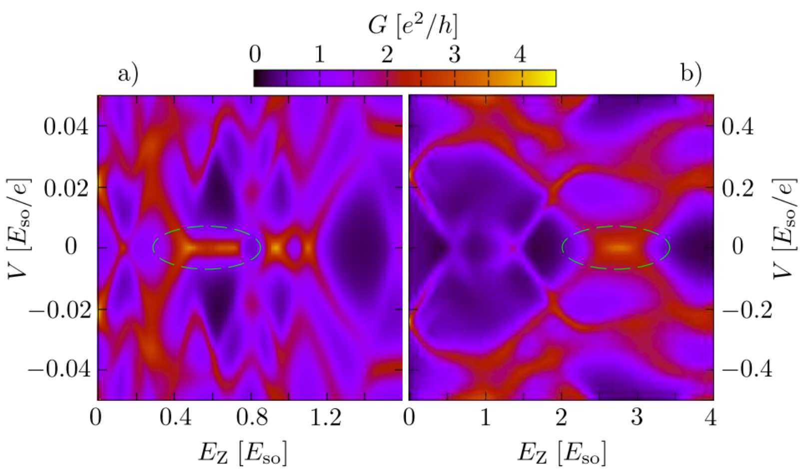
[1] *Instituut-Lorentz, Universiteit Leiden, P.O. Box 9506, 2300 RA Leiden, The Netherlands*
[2] *Department of Physics, Lancaster University, Lancaster, LA1 4YB, United Kingdom*

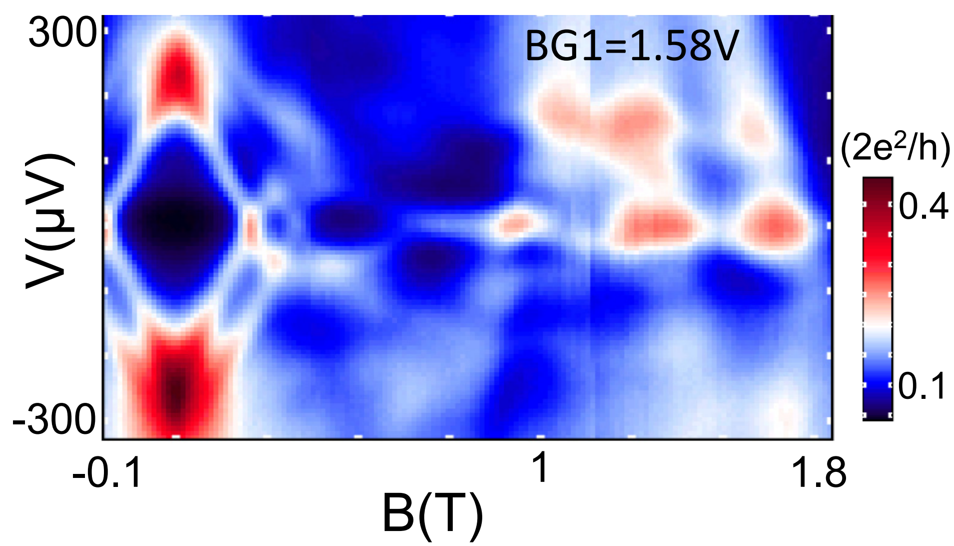
(Dated: August 2012)











Data: Jun Chen, Peng Yu (Piitsburgh)

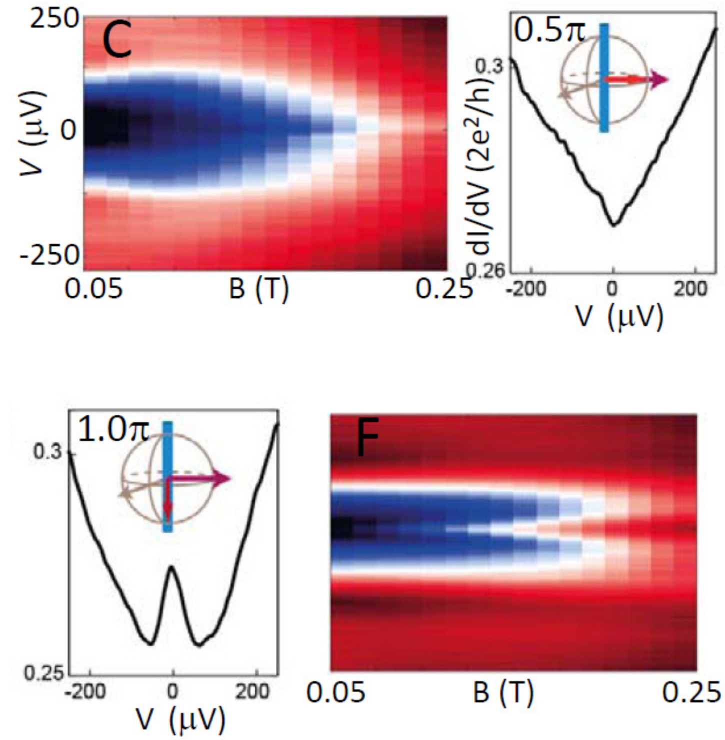
2012 signatures of Majorana

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, $\Delta E_z \sim 0.5\text{-}1.5$ meV)

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

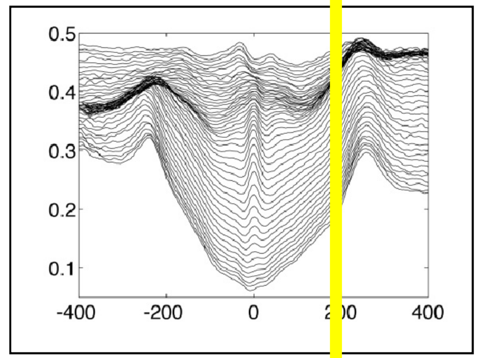
ZBP vanishes when B is aligned with B_{SO})

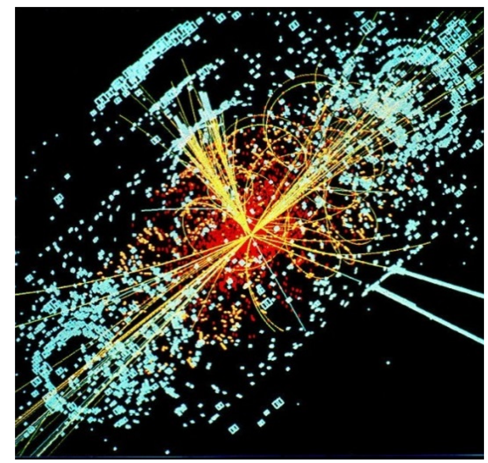


ZBP robust in both gate and magnetic field NOT OBSERVED in three N-NW-N devices (superconductivity is important)

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

Where we are now



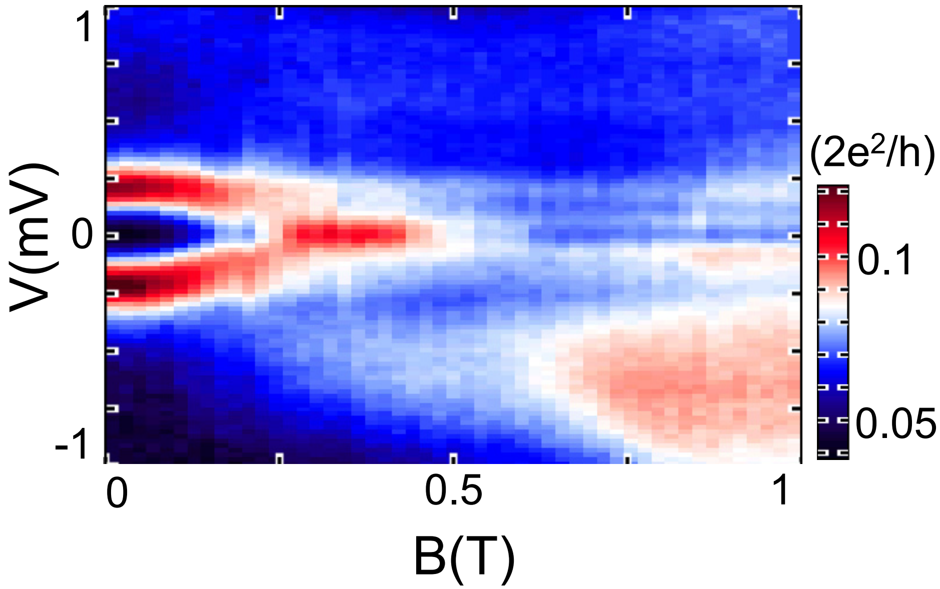


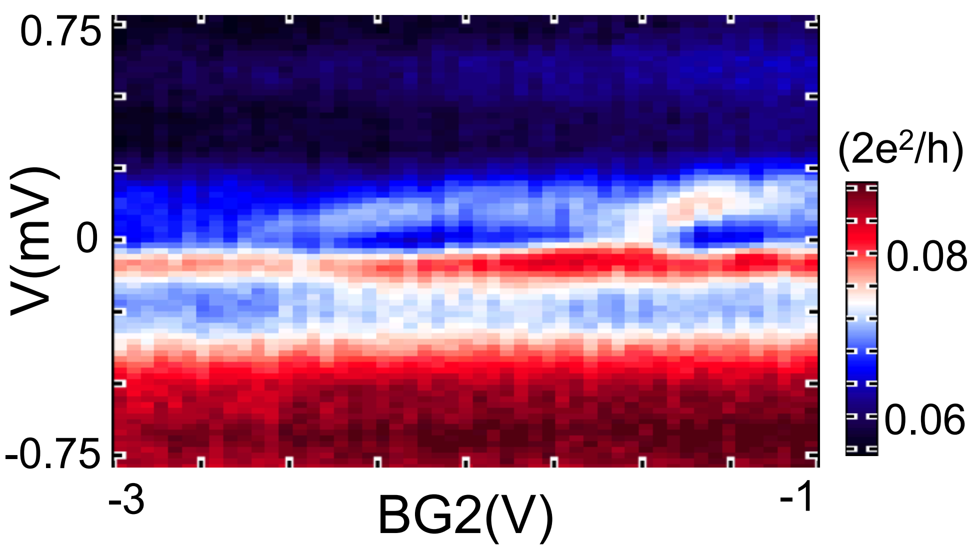
Is that a UFO???

Mourik Science 2012

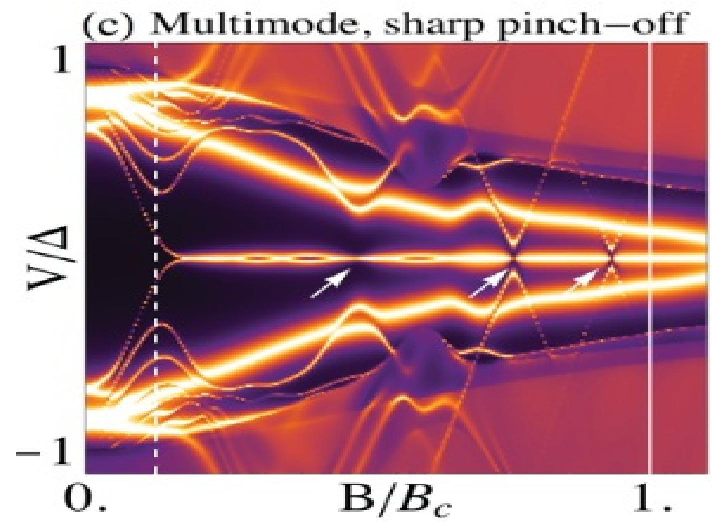
CERN 5σ

ZBP splitting: coupled Majoranas?



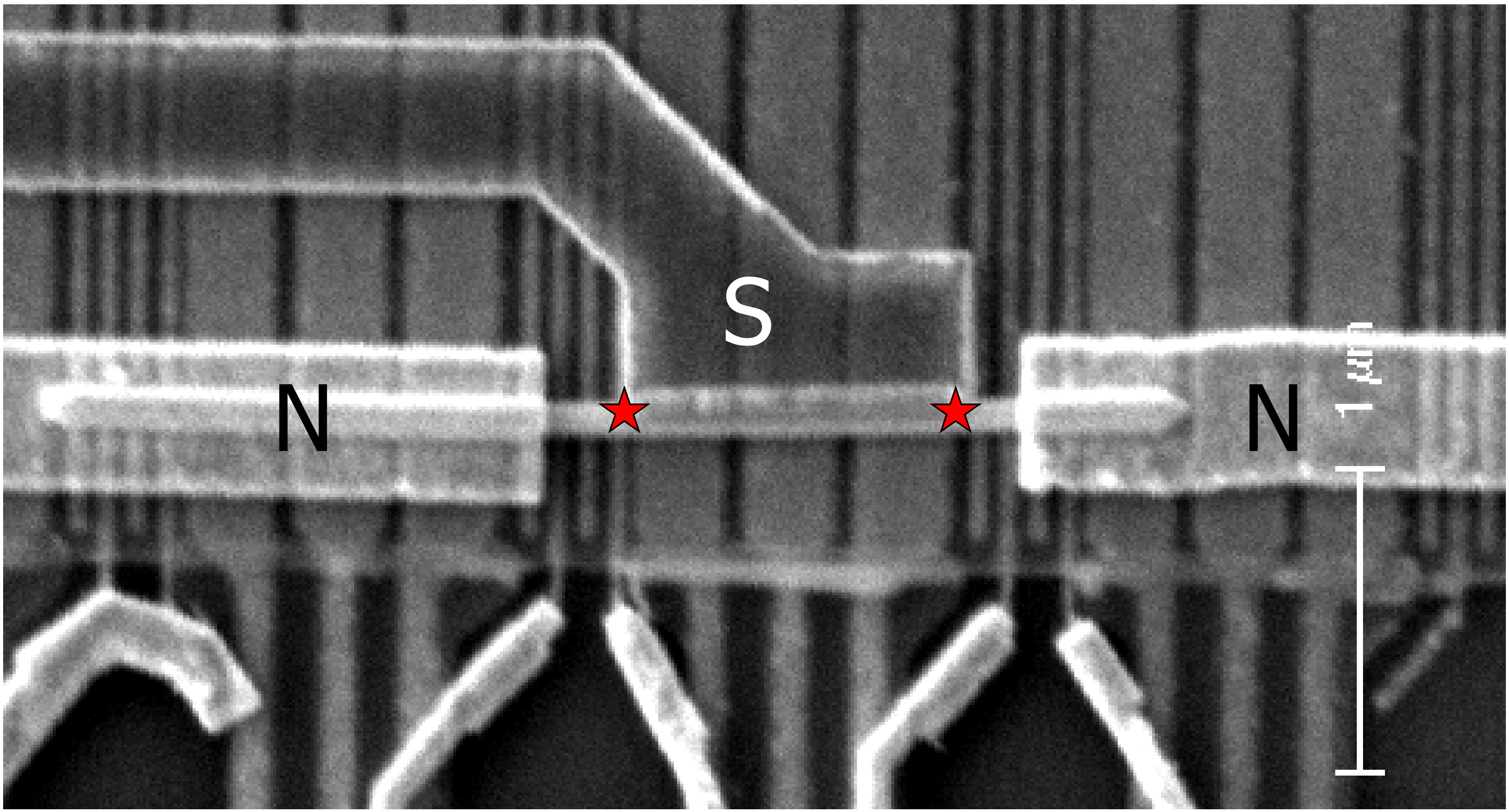


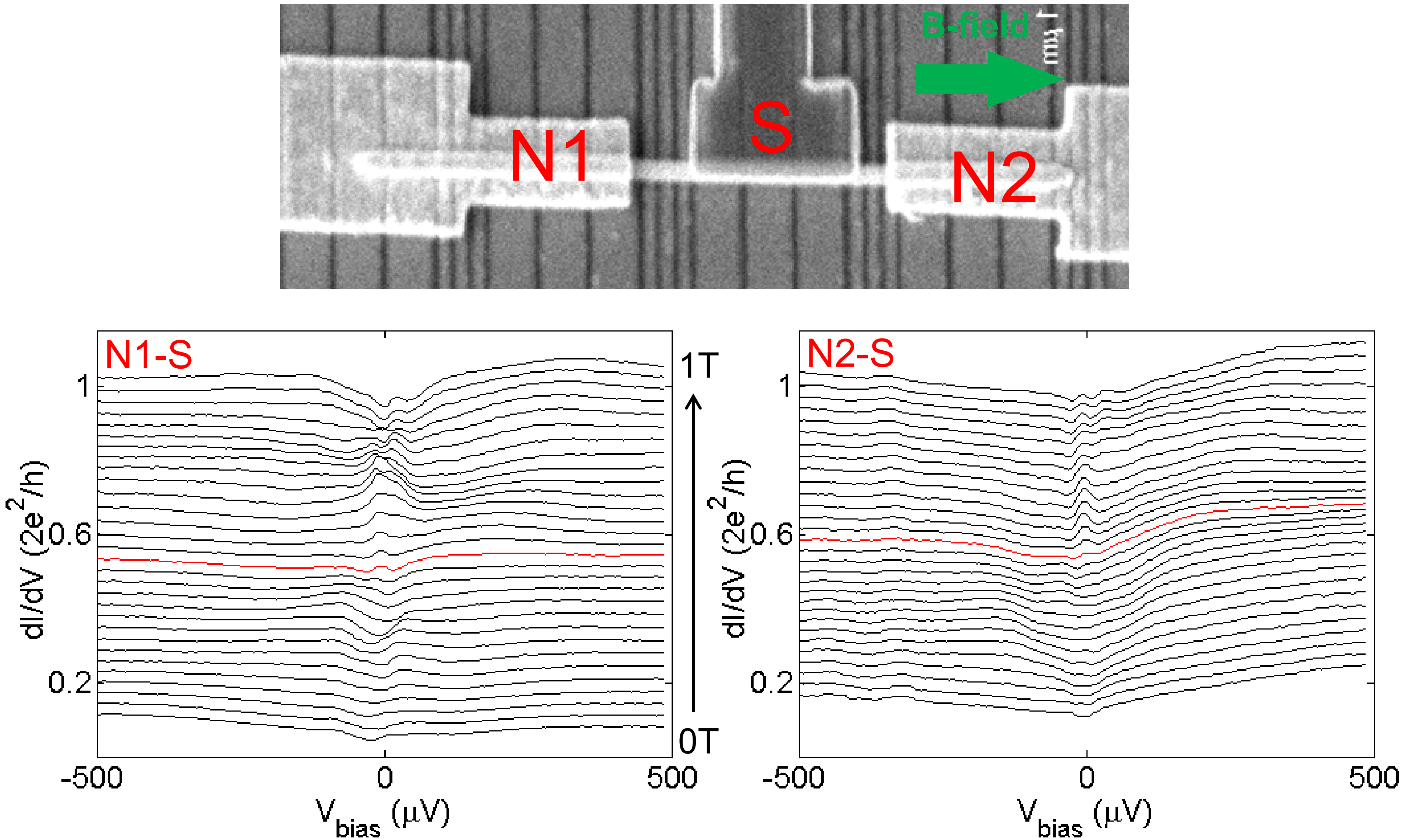
Data: Jun Chen, Peng Yu (Pittsburgh)



Sim: Aguado group

Where is the second Majorana?





=> correlation in peak onset

Data: Delft