Majoranas in semiconductor nanowires

Leo Kouwenhoven

Önder Gül, Hao Zhang, Michiel de Moor, Fokko de Vries, Jasper van Veen
David van Woerkom, Kun Zuo, Vincent Mourik, Srijit Goswami,
Maja Cassidy, Attila Geresdi

wires: Diana Car, Sebastien Plissard & Erik Bakkers

materials: S. Conesa Boj, M. Quintero-Perez, K. Watanabe, T. Taniguchi

theory: Michal Nowak, Michael Wimmer, Anton Akhmerov

Microsoft

TU Delft Delft University of Technology

QUTech

INTRO

Majorana Fermion

"a particle that is equal to its own anti-particle"

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

creating a Majorana is the same operation as annihilating it:

meaning zero energy, zero spin and zero charge.

okay for Bosons but not for Fermions (electron $\neq$ positron)

How to detect a particle with everything zero?

Chi l'ha visto?

Ettore Majorana, ordinario di fisica teorica all' Università di Napoli, è misteriosamente scomparso dagli ultimi di marzo. Di anni 31, alto metri 1,70, snello, con capelli neri, occhi scuri, una lunga cicatrice sul dorso di una mano. Chi ne sapesse qualcosa è pregato di scrivere al R. P. E. Marianecci, Viale Regina Margherita 66 - Roma.

1938

(Wilczek, *Majorana Returns,* Nature Physics, 2009
Wilczek, *Majorana modes materialize*, Nature, News&Views, 2012)

Consiglia Condividi 6,9mila Tweet

Etto
Rom
'59"

Il grande
ricerche s

6,9mila
Consiglia
Condividi
125
Tweet
79
+1
37
LinkedIn

ANSAen Science & Tecnology

General News | Politics | Business | Science&Technology | LifeStyle + | Sport

TRENDING > Renzi • Budget • Grillo euro exit • Pope Francis • Expo2015

ANSA.it • English • Science & Tecnology • 1938 disappearance physicist Majorana 'alive 1955-59'

1938 disappearance physicist Majorana 'alive 1955-59'

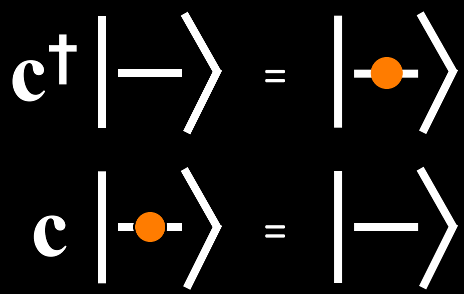
Rome prosecutors close case of mysterious disappearance

Redazione ANSA
ROME
04 February 2015
16:48
NEWS

Suggerisci
Facebook
Twitter
Google+
Altri
A+ A A-
Stampa

Particle superpositions

"equal superposition of an electron and a hole"



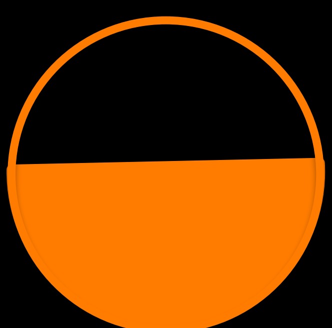
$c^\dagger = \gamma_1 + i\gamma_2$ creates an electron

$c \;= \gamma_1 - i\gamma_2$ creates a hole

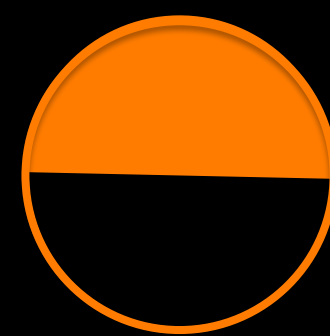
$\gamma_1 = ½\,(c^\dagger + c)$ is Majorana-1

$\gamma_2 = ½i\,(c^\dagger - c)$ is Majorana-2

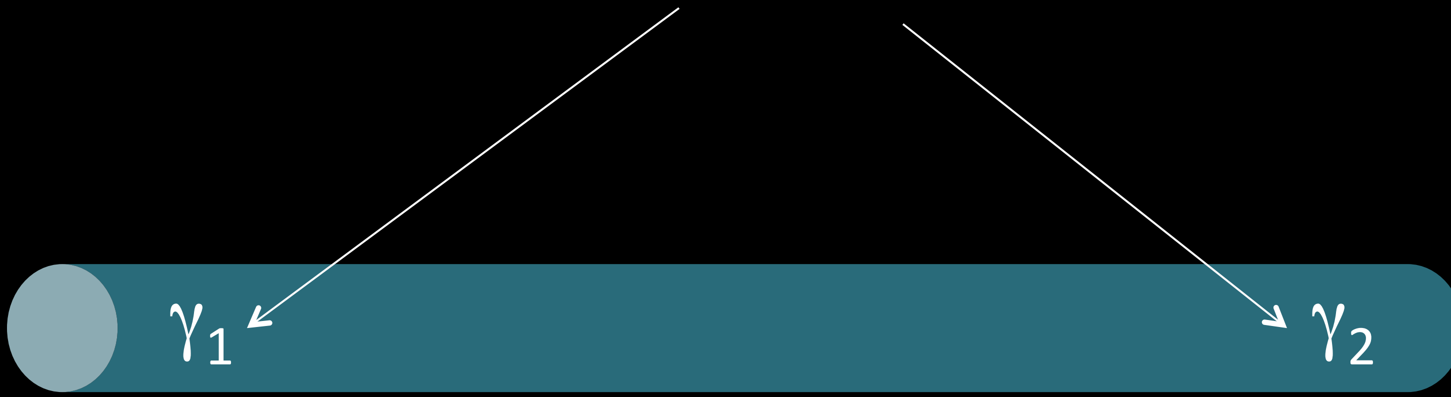
satisfying $\gamma_1{}^\dagger = \gamma_1$ and $\gamma_2{}^\dagger = \gamma_2$



One Majorana is "half" a Fermion

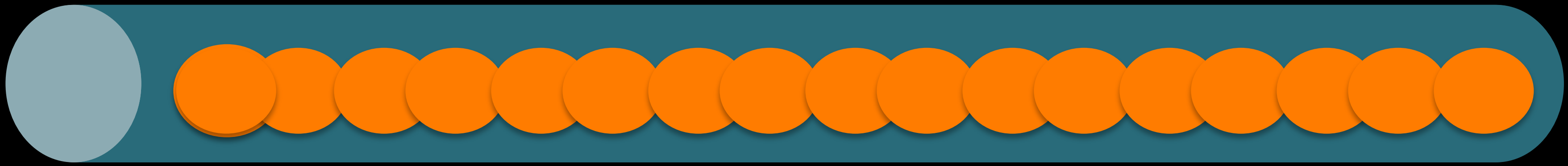


$$c^{\dagger} = \gamma_1 + i\gamma_2$$

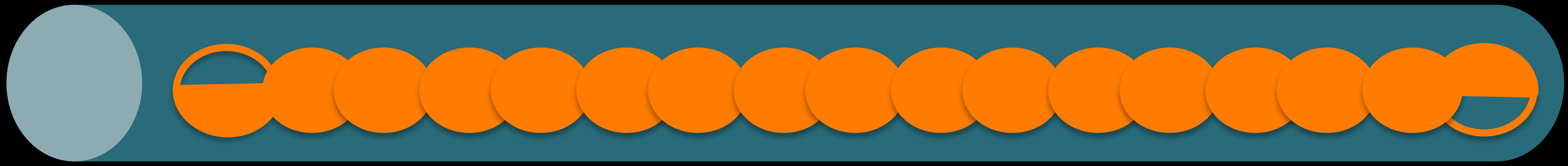


non-local separation provides topological protection

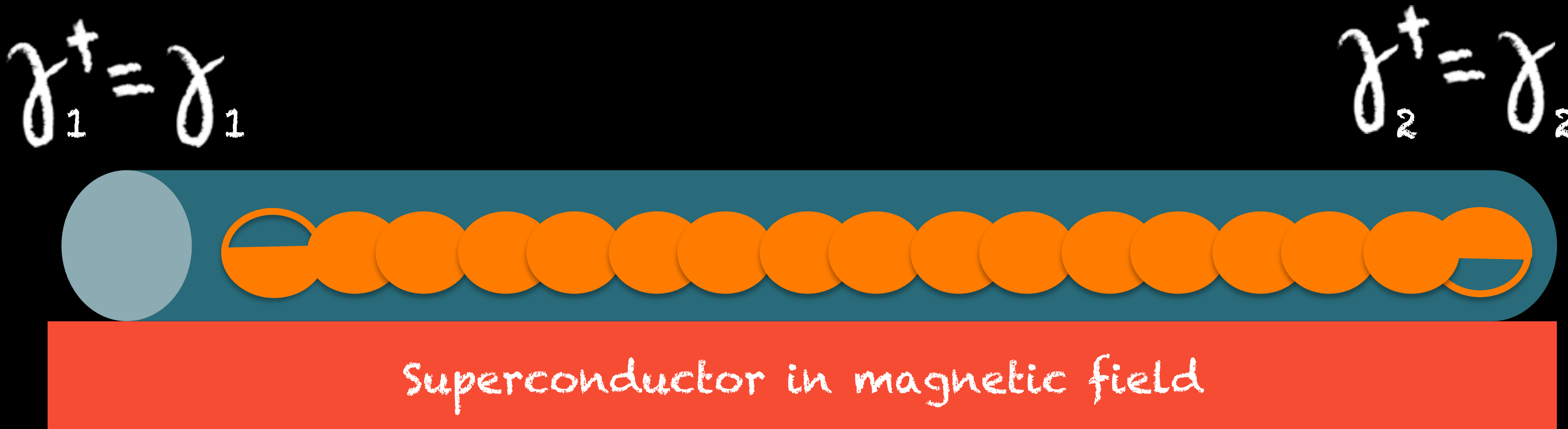
…,Kitaev, Read, Fu, Kane, Das Sarma, Beenakker, Alicea,….
(see review Nick Read, Physics Today July 2012.)



from spatial to particle superposition



from spatial to particle superposition



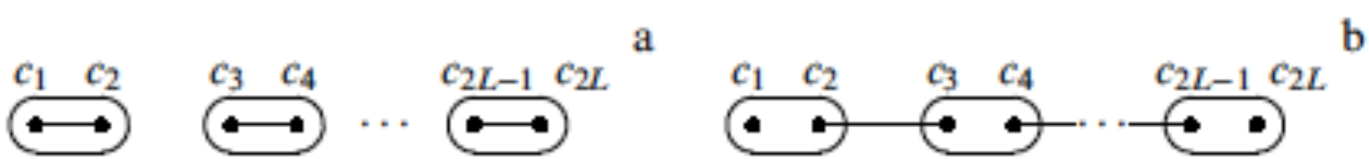


Figure 2. Two types of pairing.

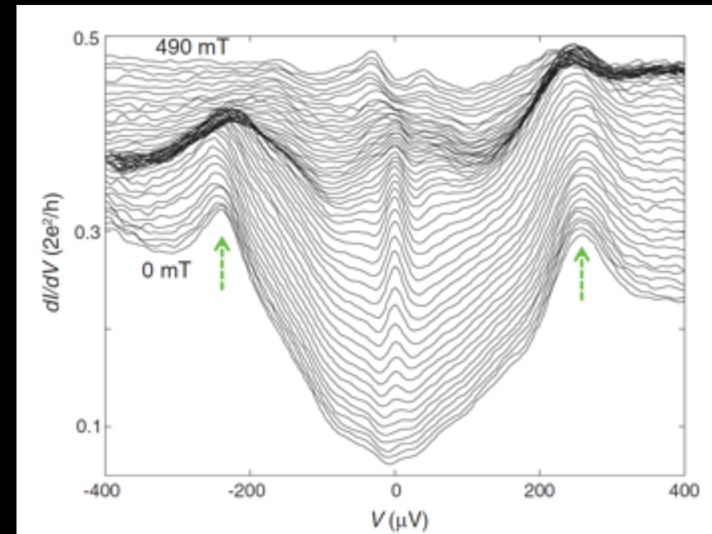
Kitaev 2001

INTRO-2

Majorana recipe

$\gamma_1^\dagger = \gamma_1$ $\gamma_2^\dagger = \gamma_2$

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



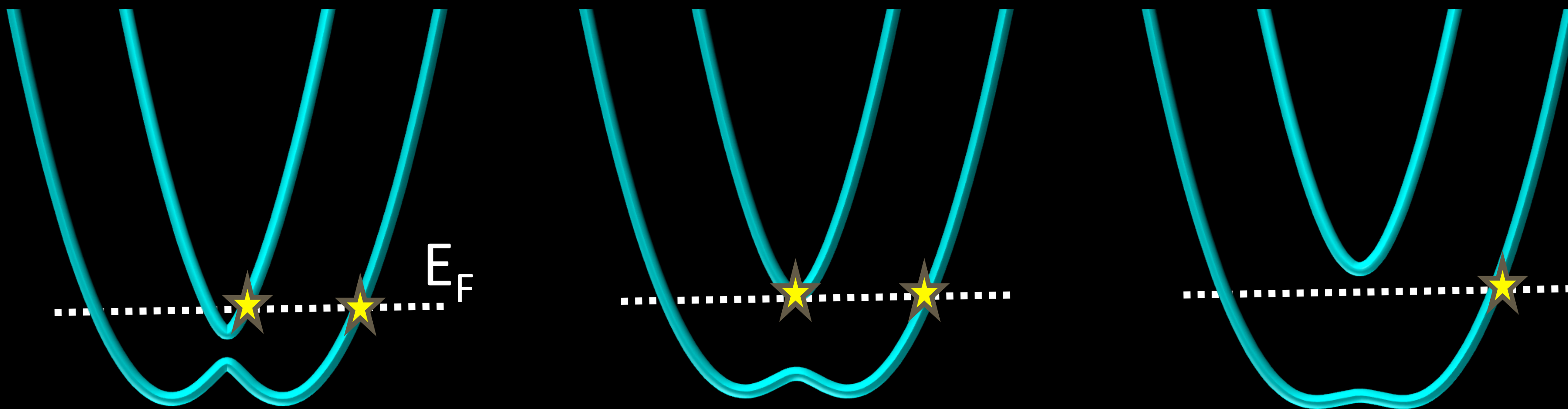
- one-dimensional quantum wire
- spin-orbit interaction →
- superconductivity
- tune μ & apply magnetic field

zero bias anomalies

Kouwenhoven, *Delft* (2012)
Xu, *Lund*
Heiblum, *Weizmann*
Harlingen, *Urbana-Champaign*
Marcus, *Copenhagen*

SOI + Magnetism

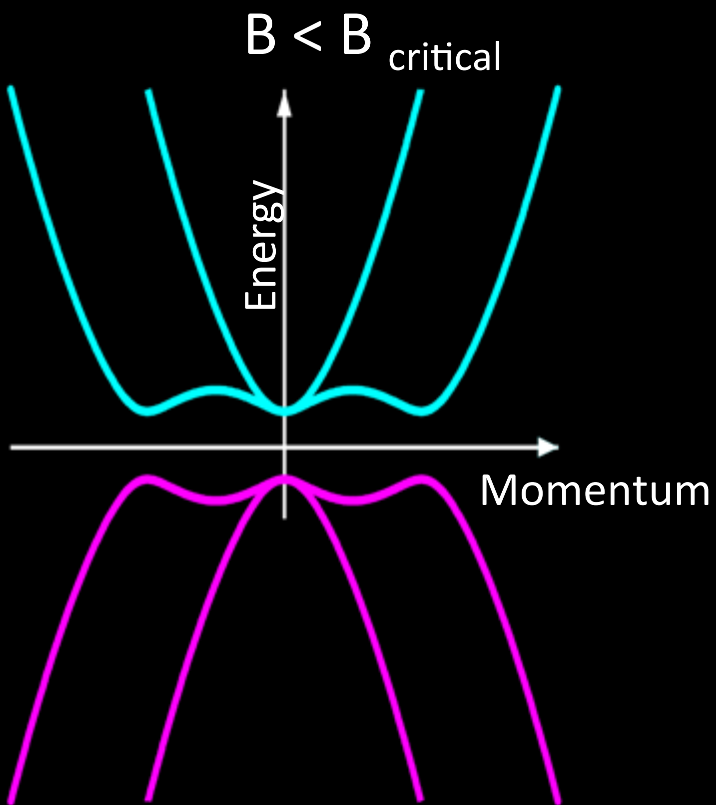
$B < B_{critical}$ $B = B_{critical}$ $B > B_{critical}$



TOPOLOGICALLY DISTINCT

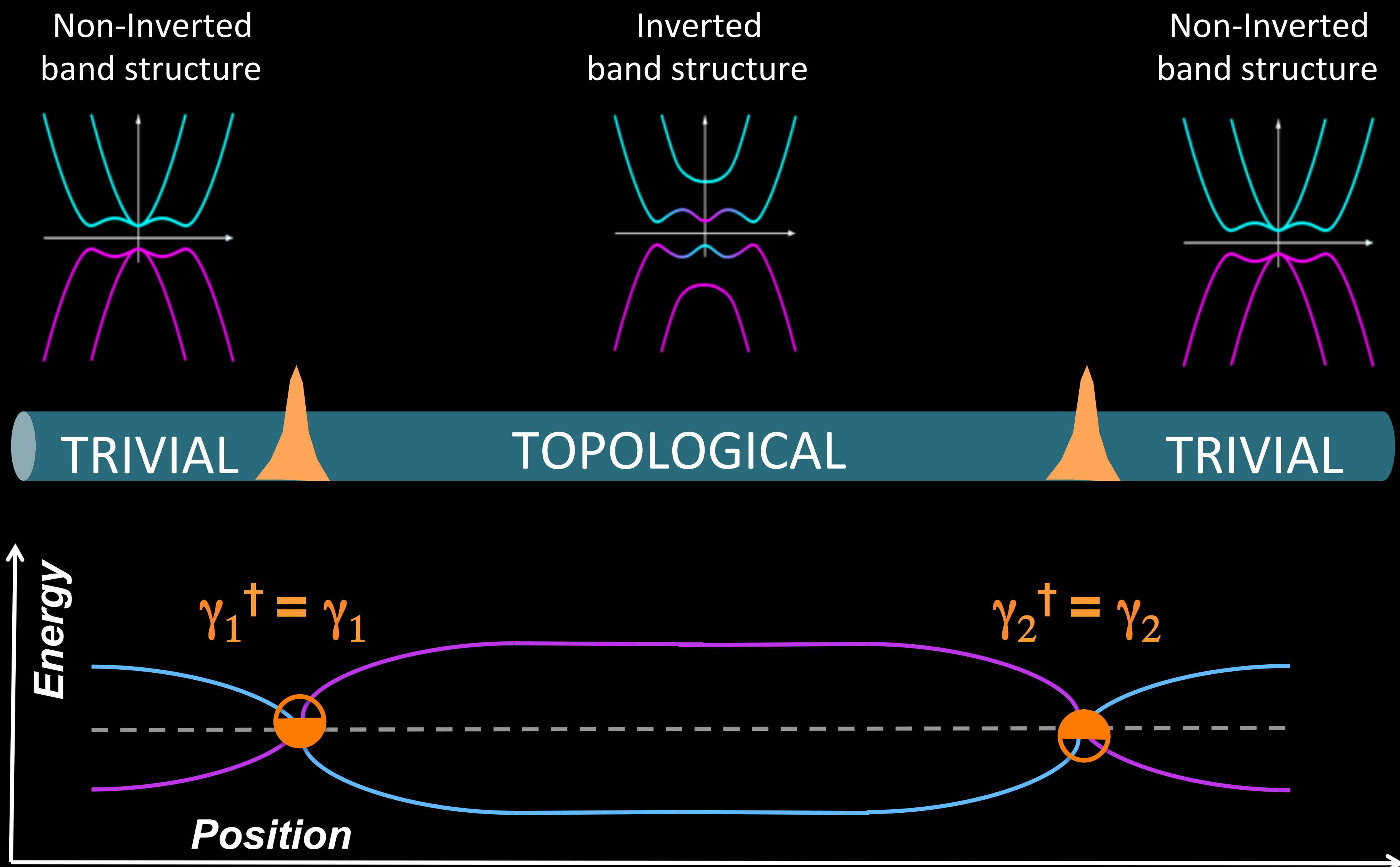
Number of crossing different in parity

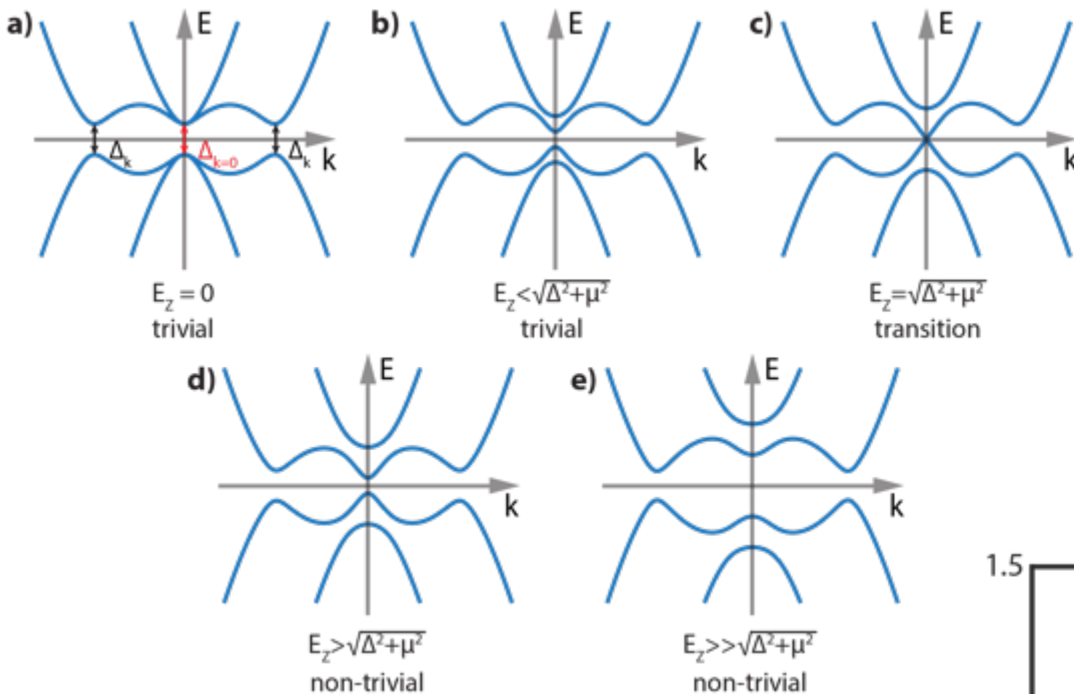
SOI + Magnetic field + superconductivity

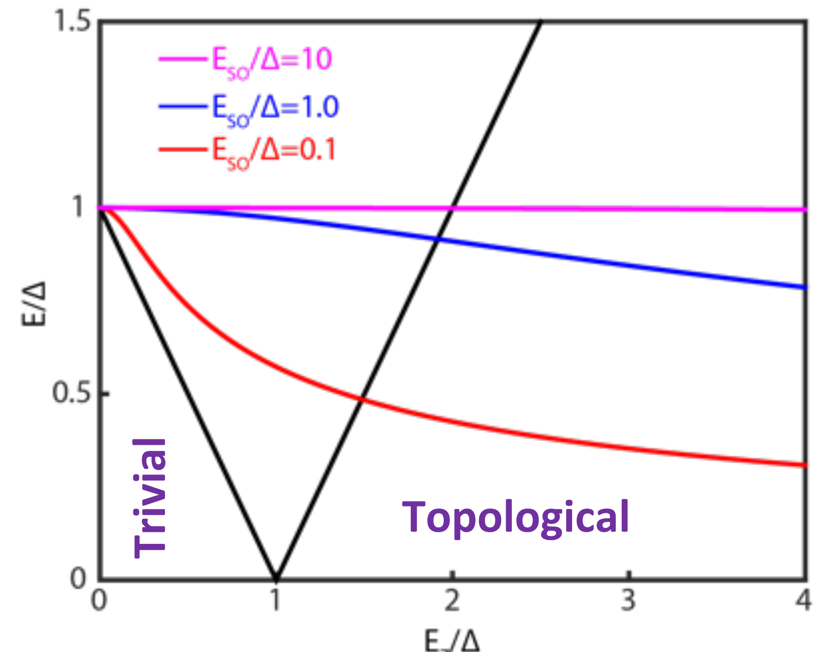


Y. Oreg et al. PRL(2010); R. M. Lutchyn et al PRL (2010);

Topology & bandstructure in 1D





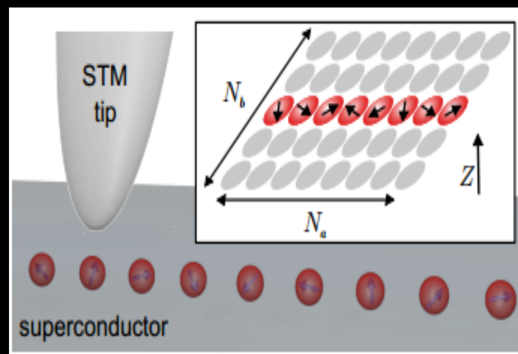


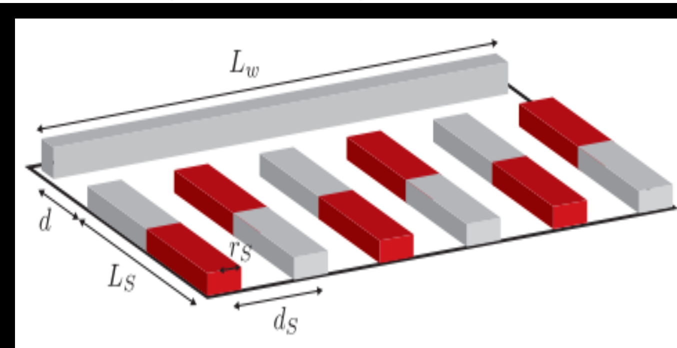
Thesis 2016, TUDelft repository
Kun Zuo & Vincent Mourik

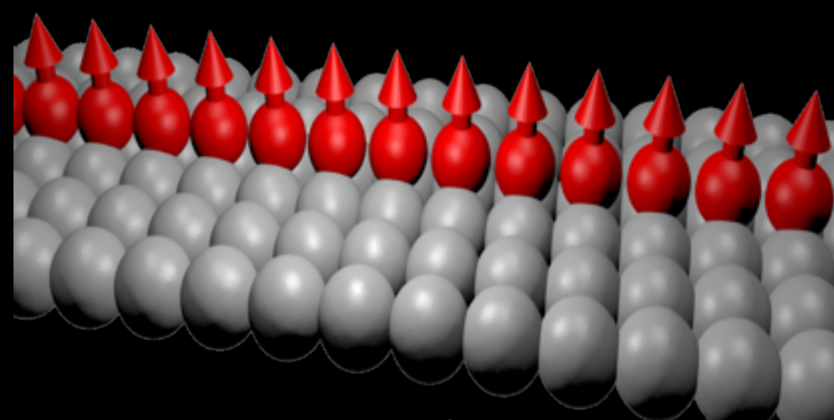
effective SOI from magnetic texture

Majorana fermions emerging from magnetic nanoparticles on a superconductor without spin-orbit coupling

T.-P. Choy, J. M. Edge, A. R. Akhmerov, and C. W. J. Beenakker
Instituut-Lorentz, Universiteit Leiden, P.O. Box 9506, 2300 RA Leiden, The Netherlands







Kjaergaard, Wölms, Flensberg (PRB 2012)

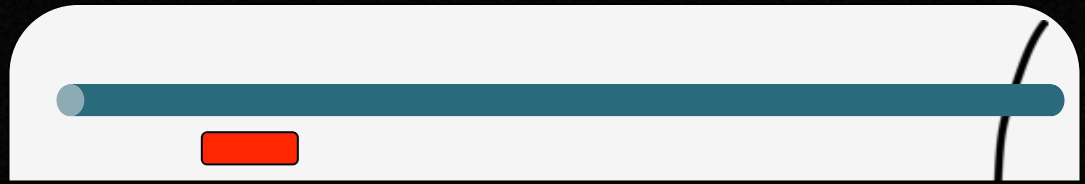
Klinovaja, Stano, Loss (PRL 2012)

Nakosai, Tanaka, Nagaosa (PRB 2013)

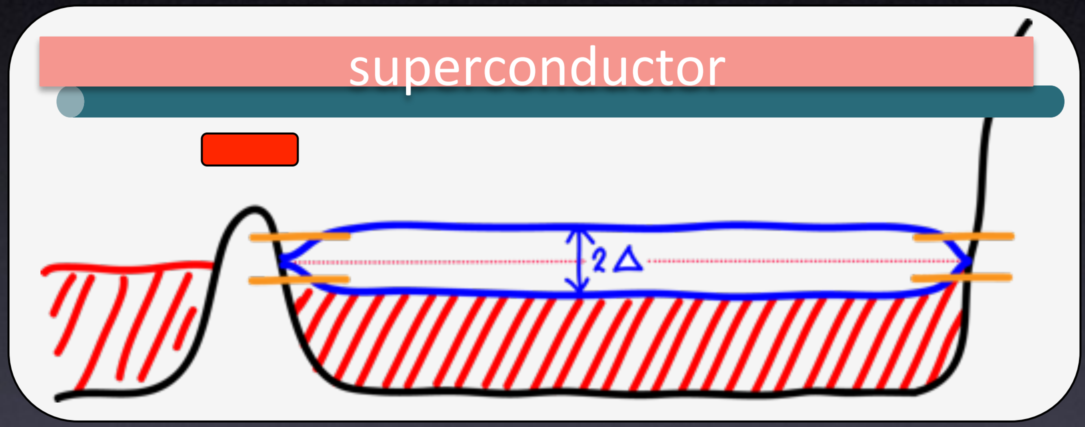
Martin and Morpurgo (PRB 2012)
Glazman (PRB 2013), and others ..

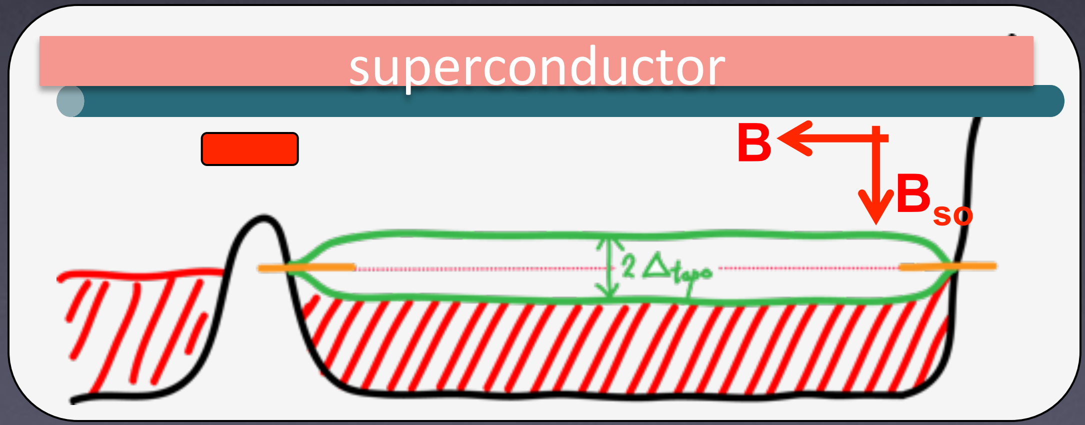
Nadj-Perge, Yazdani, et al. (2014)

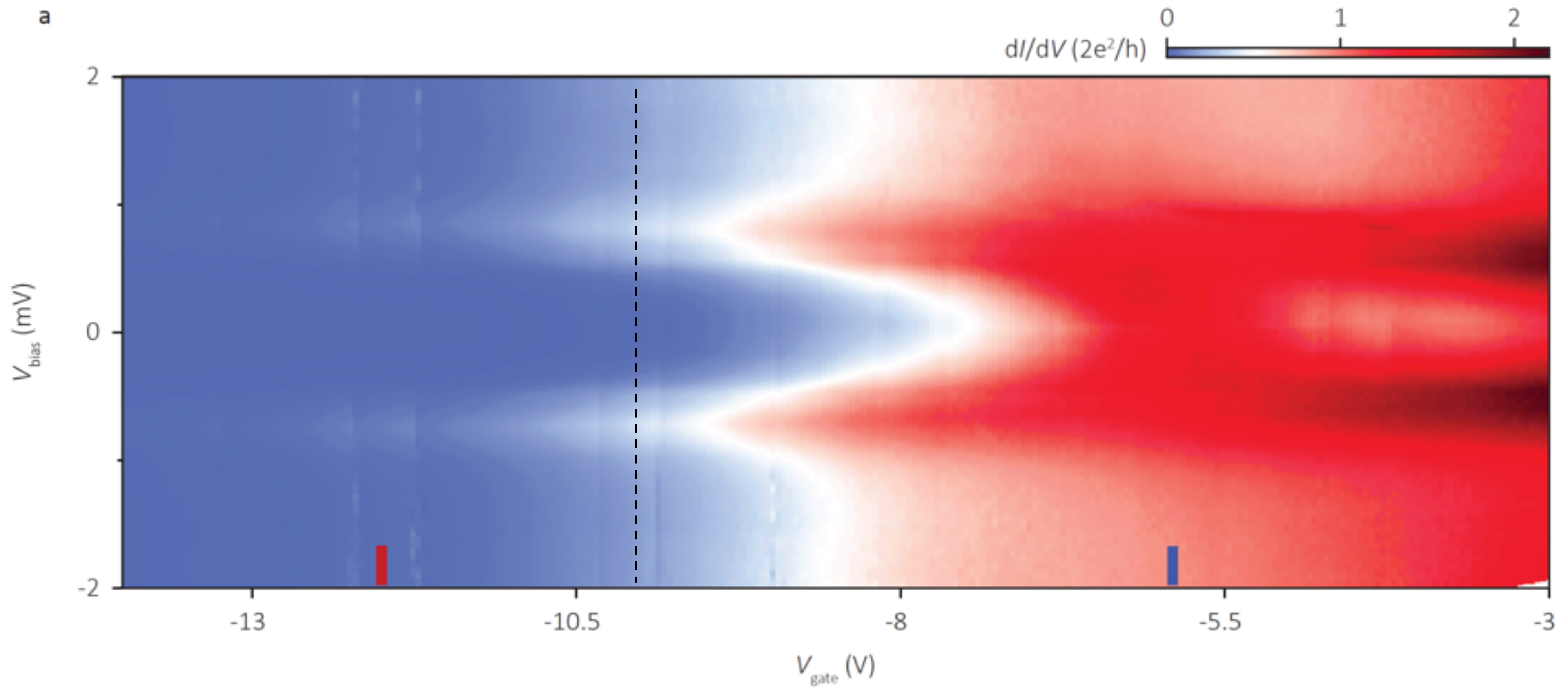
ZBP



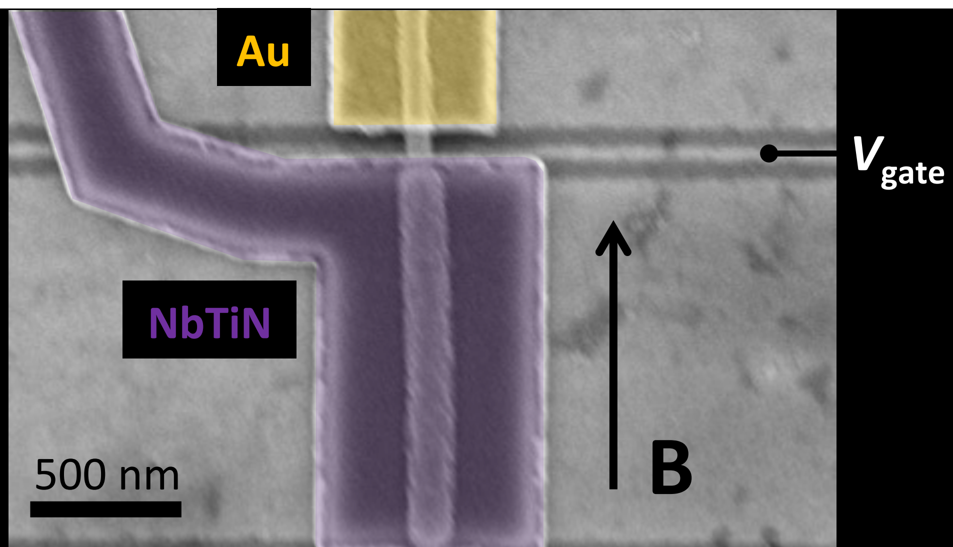
[redacted]



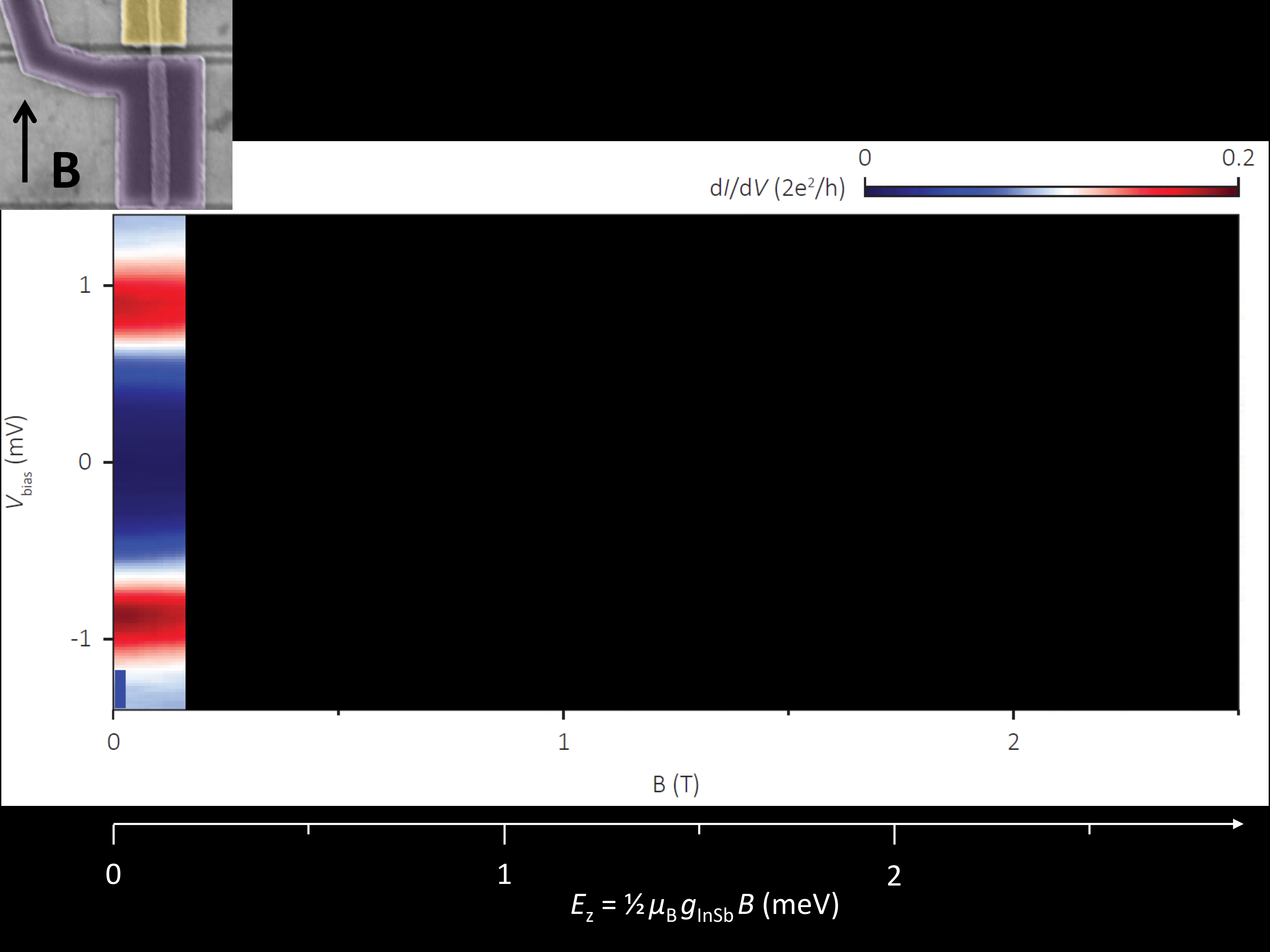


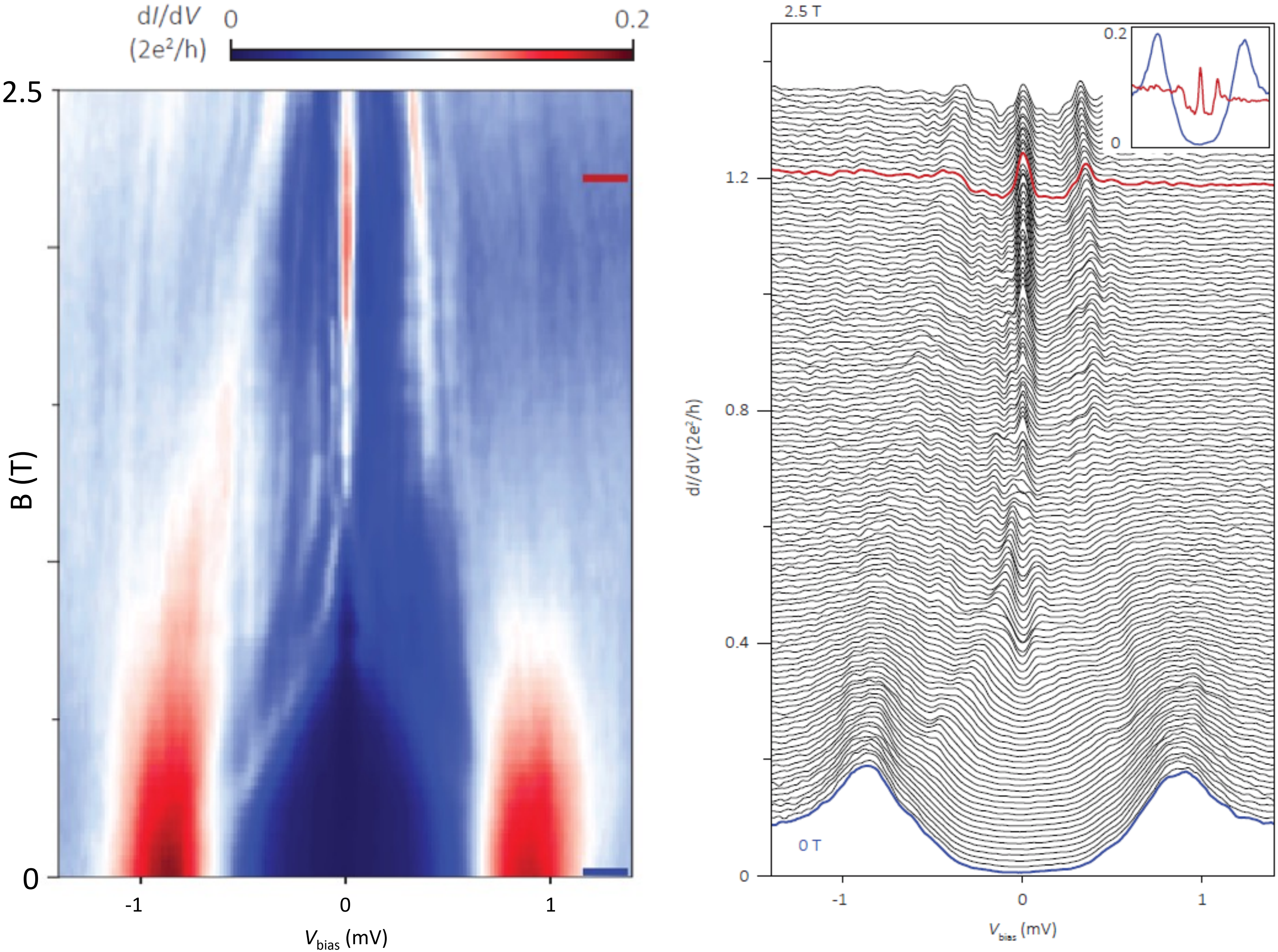


a
0
1
2
dI/dV (2e²/h)
2
0
-2
V_bias (mV)
-13
-10.5
-8
-5.5
-3
V_gate (V)

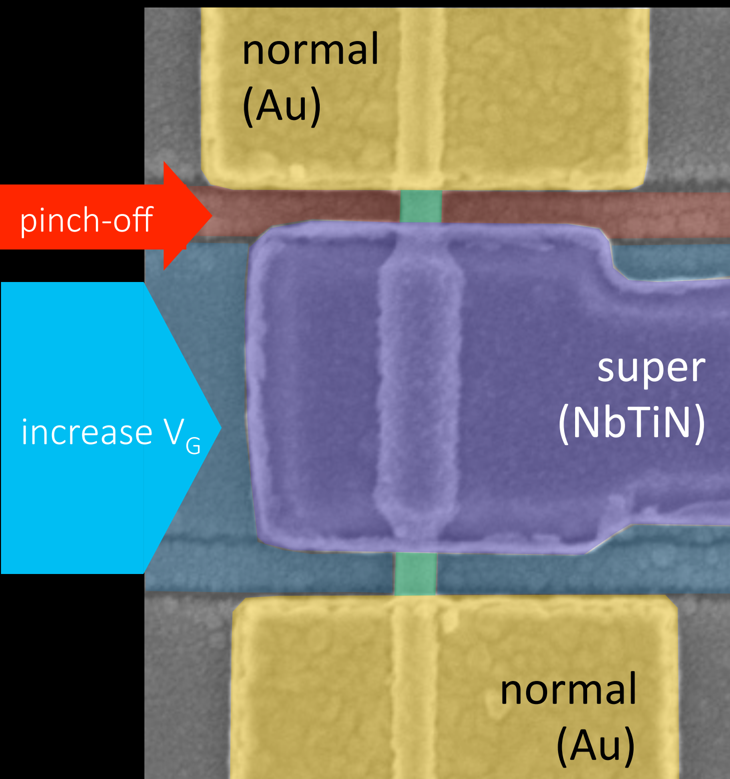


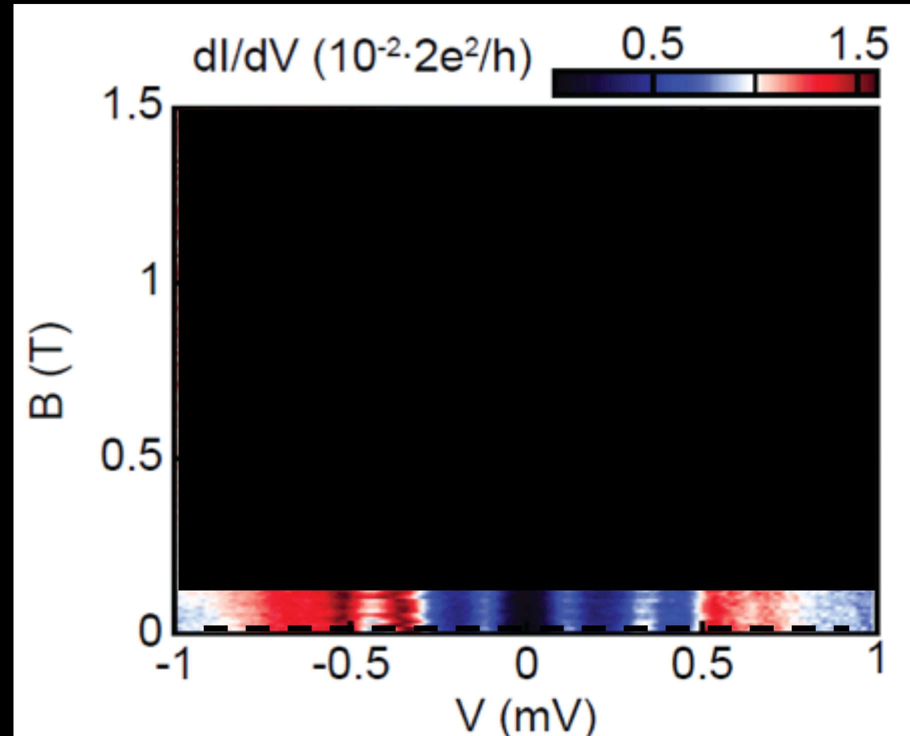
Au
NbTiN
V_gate
B
500 nm


B
0
0.2
dI/dV (2e²/h)
1
0
-1
V_bias (mV)
0
1
2
B (T)
0
1
2
E_z = ½ μ_B g_InSb B (meV)

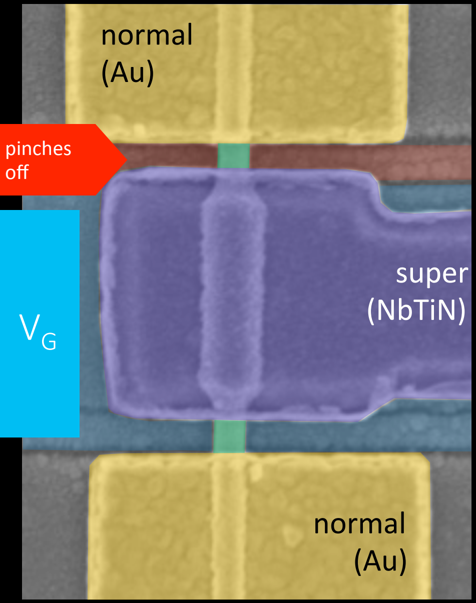


dI/dV (2e²/h)
0
0.2
2.5
0
B (T)
-1
0
1
V_bias (mV)
2.5 T
0 T
1.2
0.8
0.4
dI/dV (2e²/h)


normal
(Au)
pinch-off
increase V_G
super
(NbTiN)
normal
(Au)

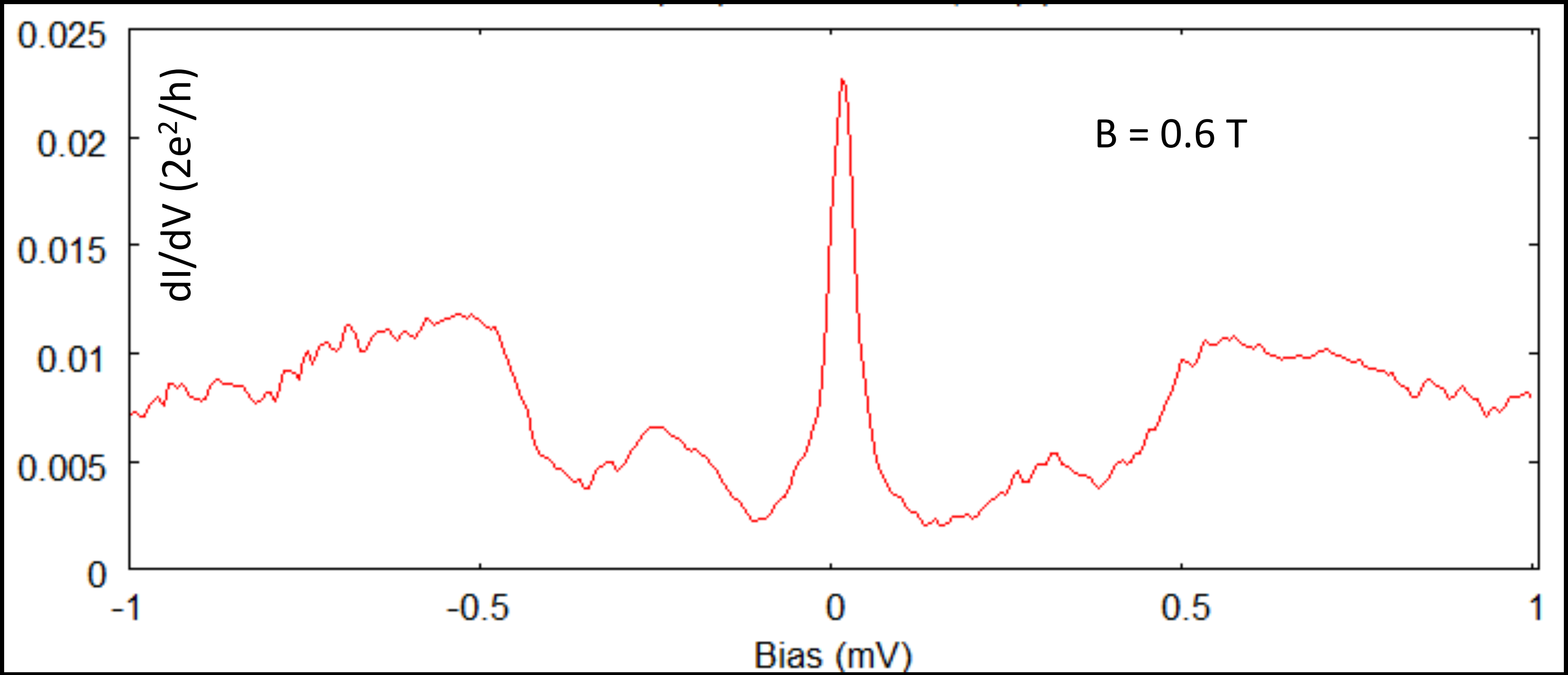

dI/dV ($10^{-2} \cdot 2e^2/h$)
0.5
1.5
1.5
1
0.5
0
B (T)
-1
-0.5
0
0.5
1
V (mV)

B // wire

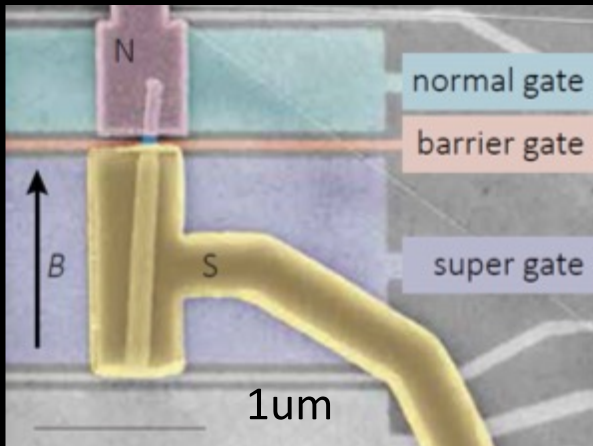


B // wire

ZBP exceeds normal state conductance

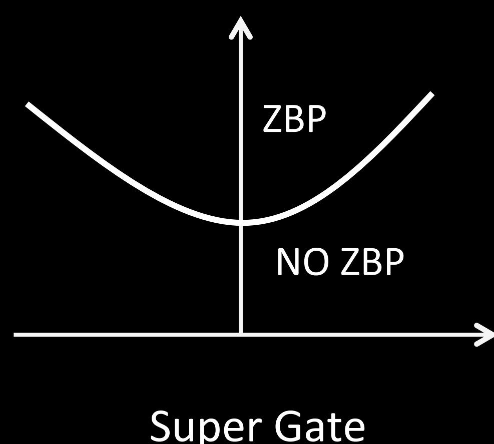


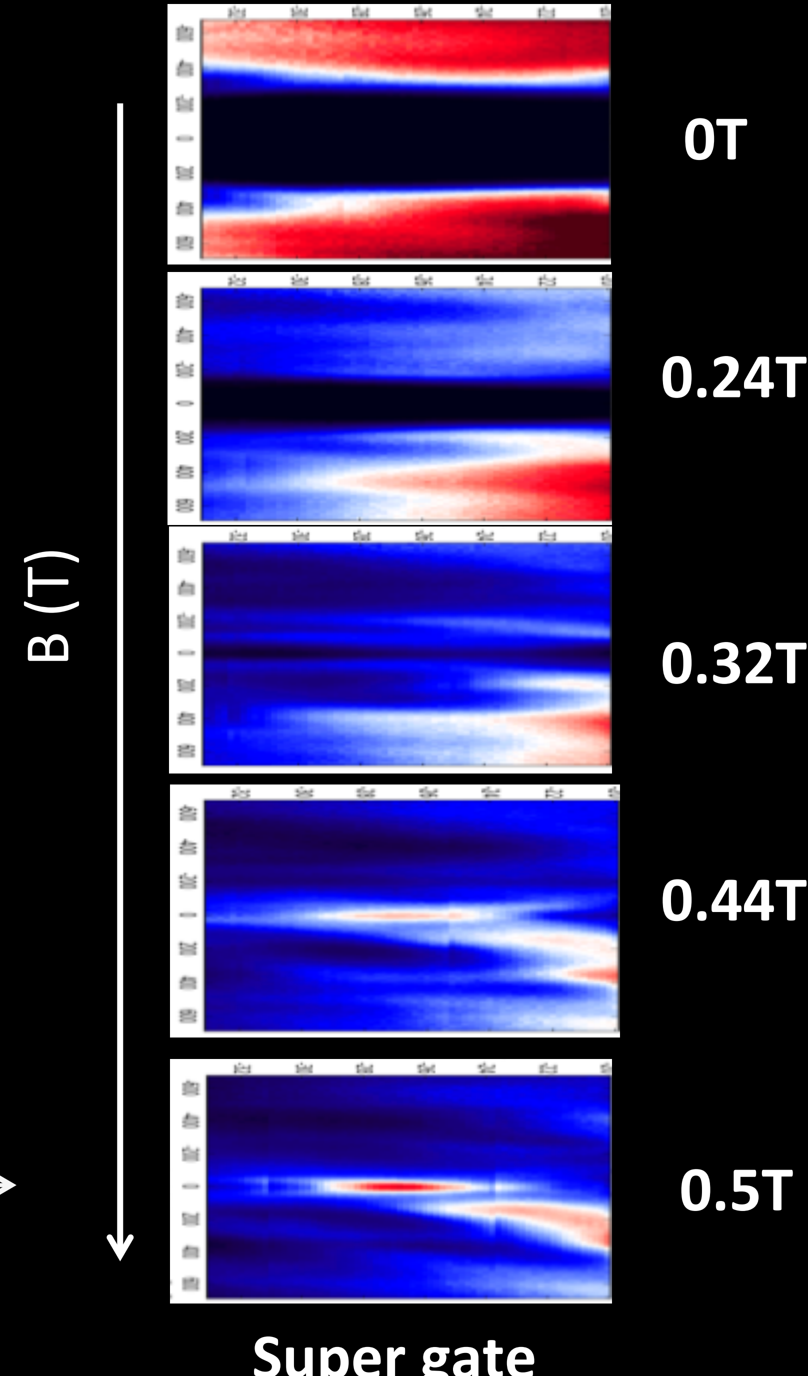
A typical Majorana Device:



Majorana condition (single sub-band regime)

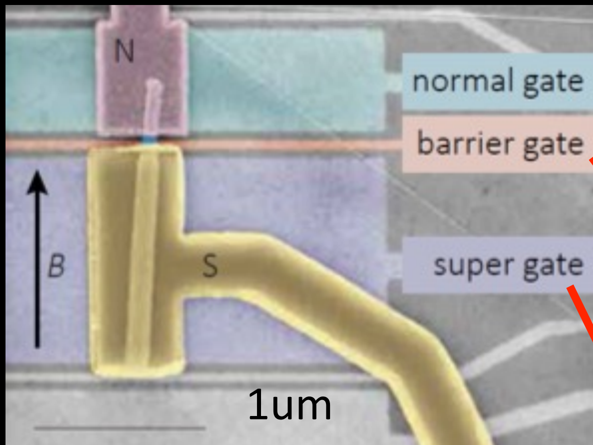
B ↓ Super gate ↓

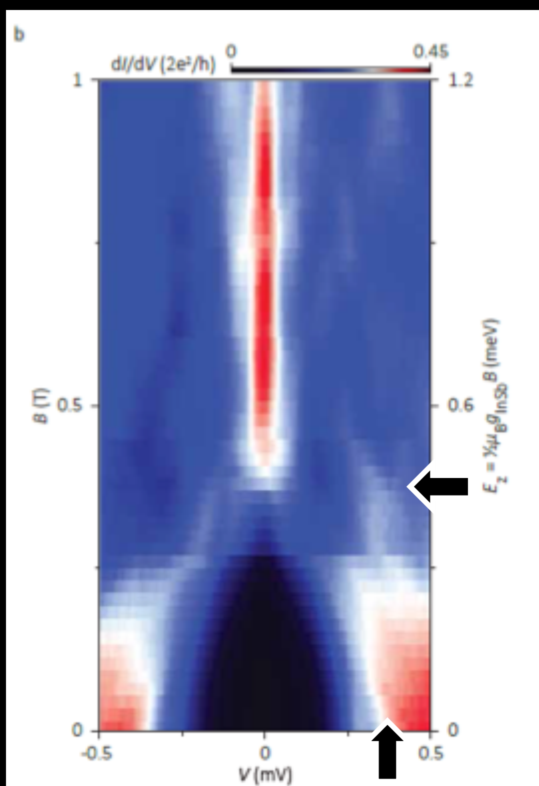


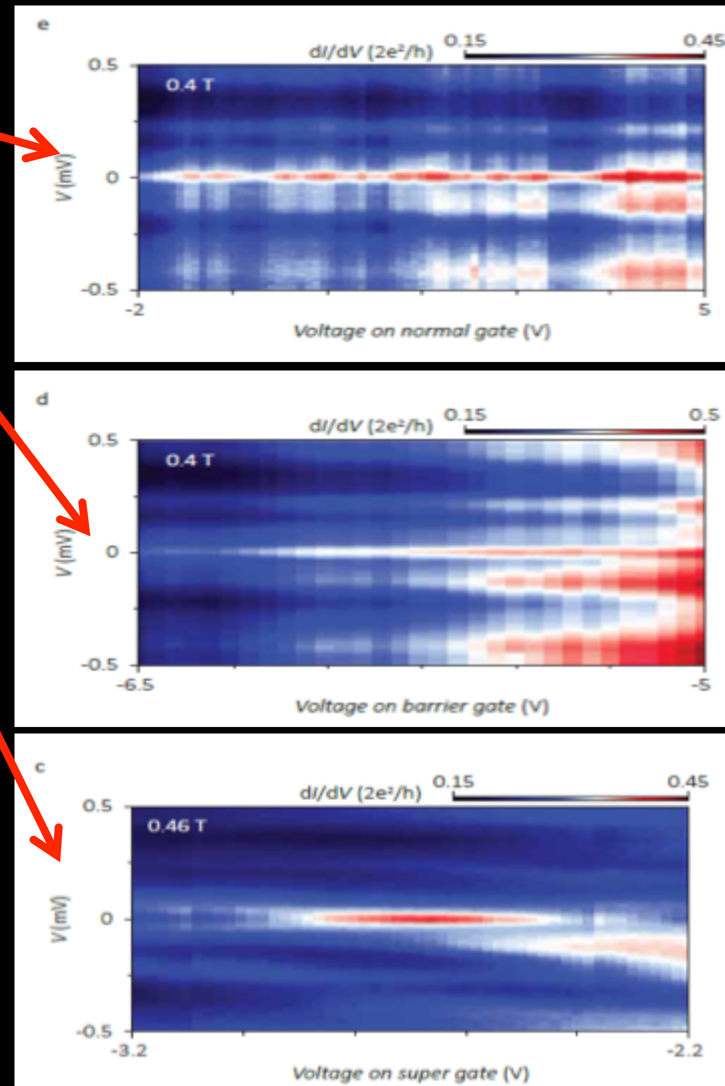


A typical Majorana Device:

Where does the ZBP live?

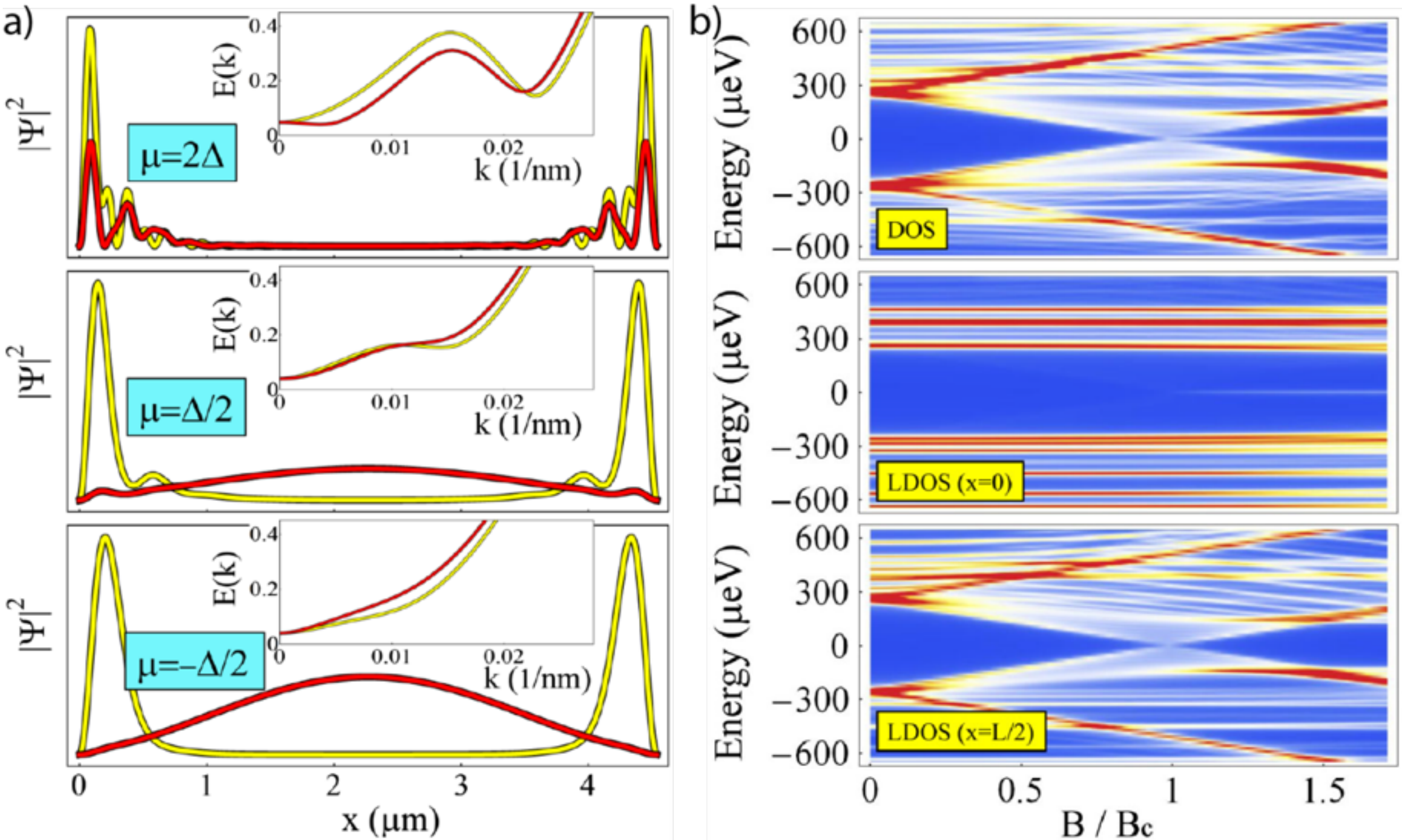




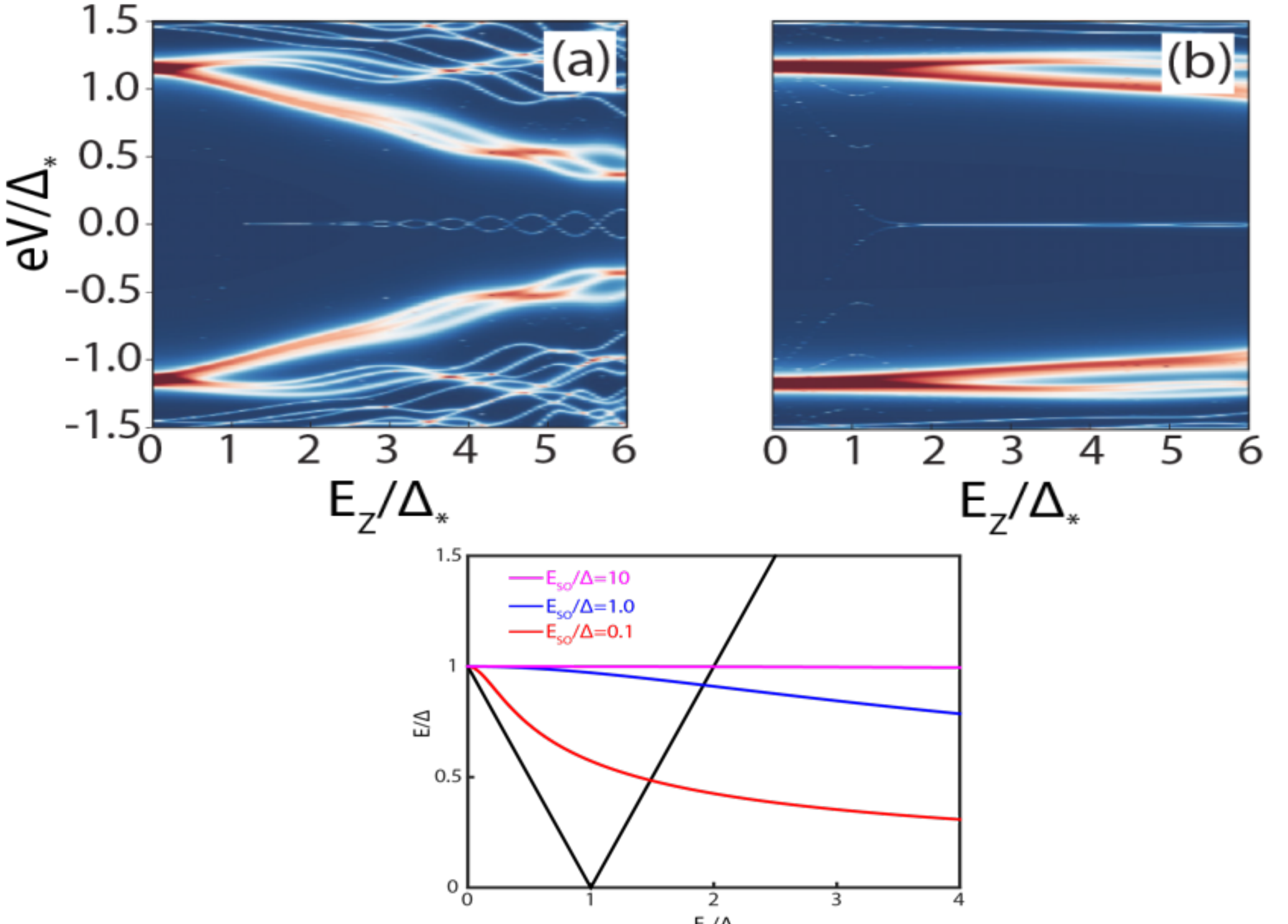


The ZBP lives underneath the superconductor

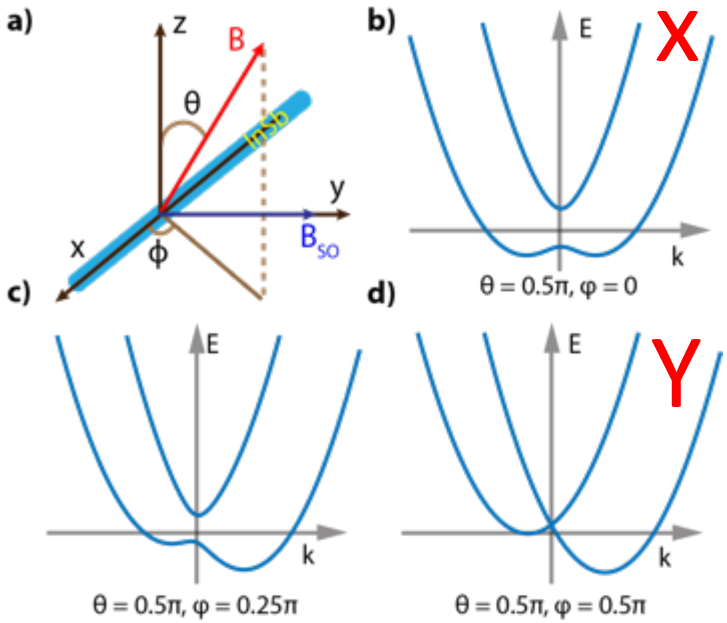
Numerics Stanescu, Tewari, Sau & Das Sarma

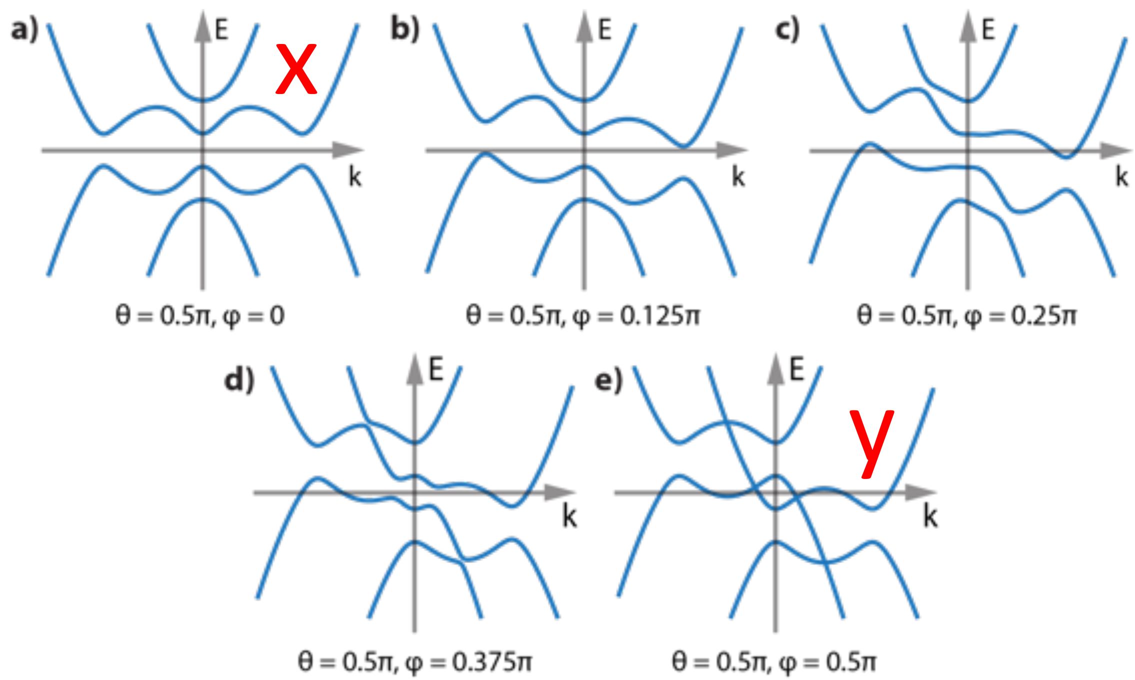


Numerics Rainis, Triffunovic, Klinovaja & Loss

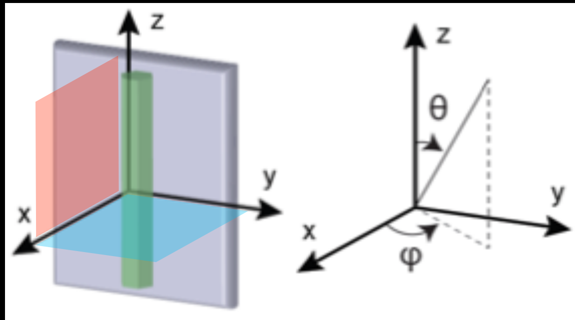


Angle


a)
z
B
θ
InSb
y
x
ϕ
B_{SO}
b)
E
X
k
θ = 0.5π, φ = 0
c)
E
k
θ = 0.5π, φ = 0.25π
d)
E
Y
k
θ = 0.5π, φ = 0.5π


a)
E
X
k
θ = 0.5π, φ = 0
b)
E
k
θ = 0.5π, φ = 0.125π
c)
E
k
θ = 0.5π, φ = 0.25π
d)
E
k
θ = 0.5π, φ = 0.375π
e)
E
y
k
θ = 0.5π, φ = 0.5π

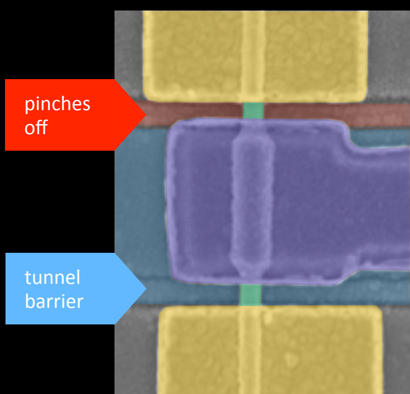
rotation of magnetic field

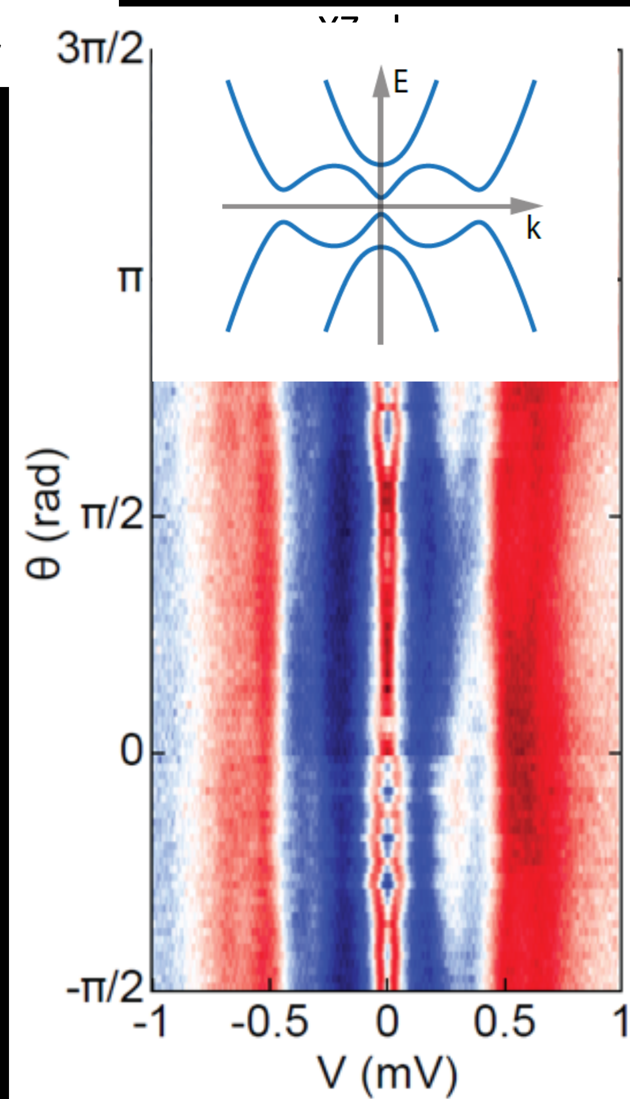


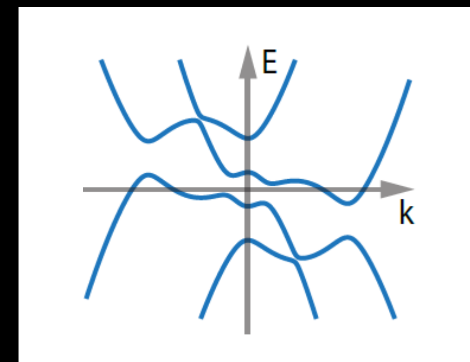
spin-orbit along y

XZ plane ⊥ spin-orbit

XY plane // spin-orbit



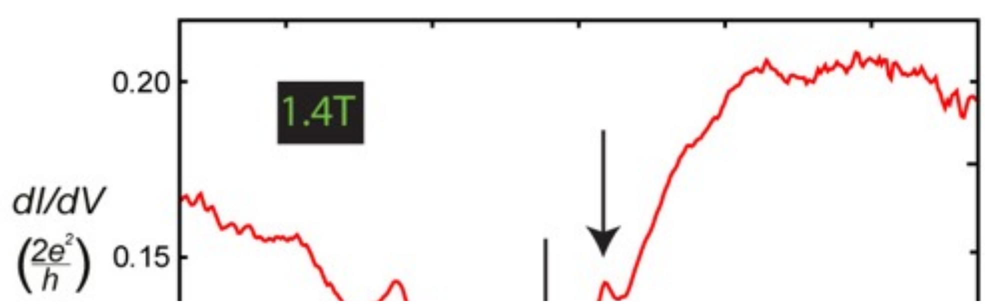


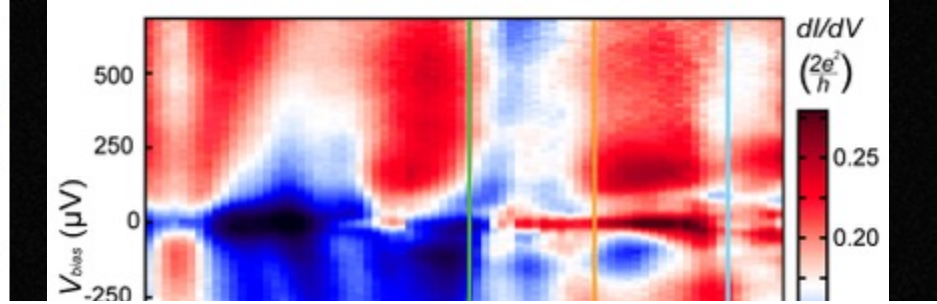


B = 0.42 T

ZBP

SPLITTING





A Majorana smoking gun for the superconductor-semiconductor hybrid topological system

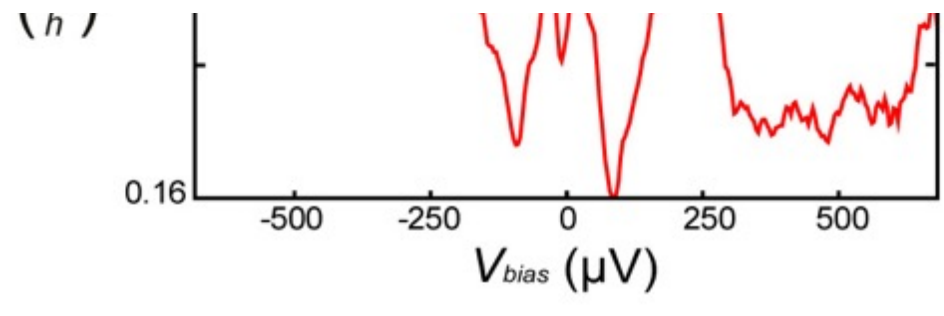
S. Das Sarma[1], Jay D. Sau[2], and Tudor D. Stanescu[3]

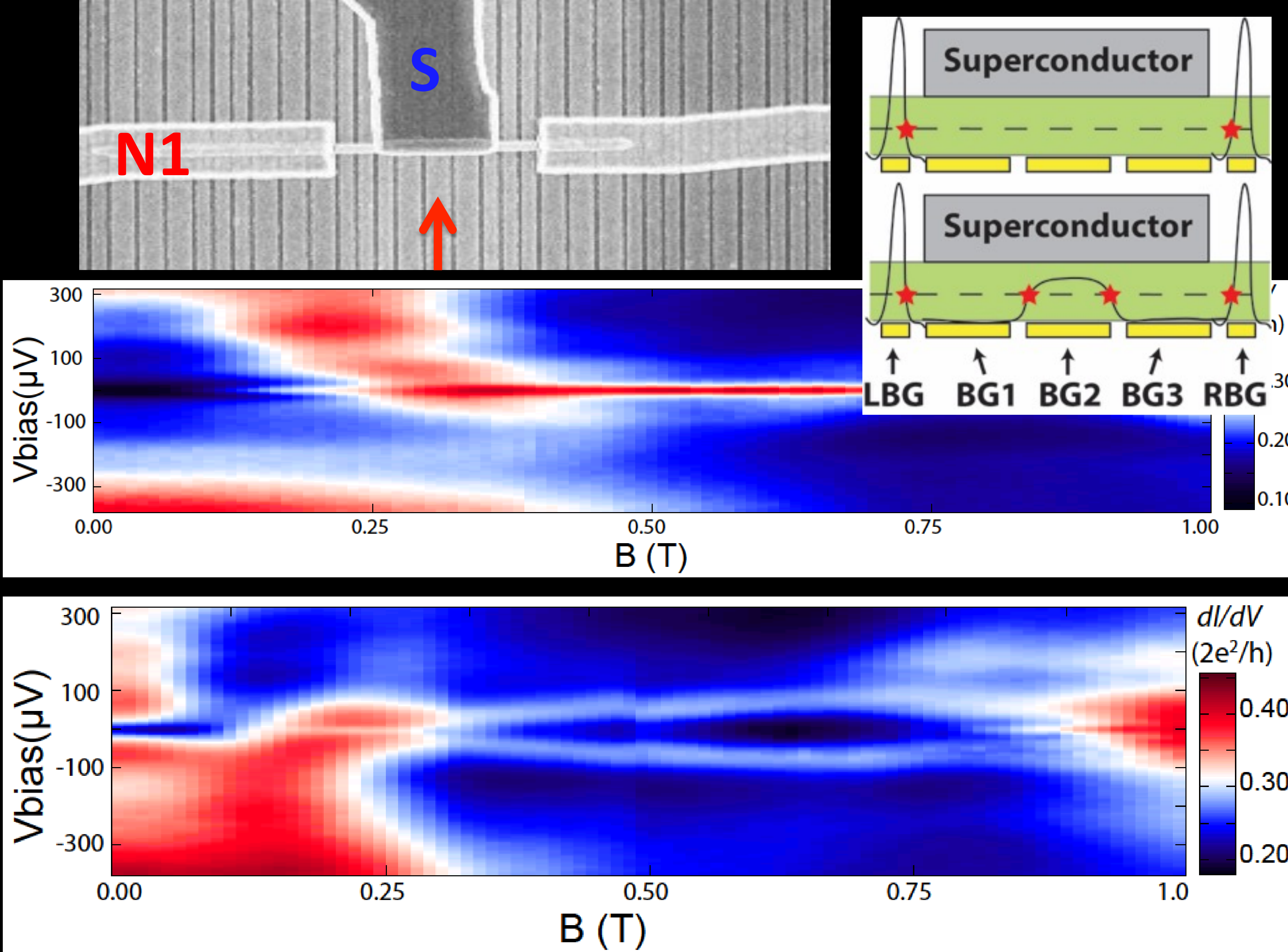
[1] *Condensed Matter Theory Center, Department of Physics, University of Maryland, College Park, Maryland 20742-4111, USA*

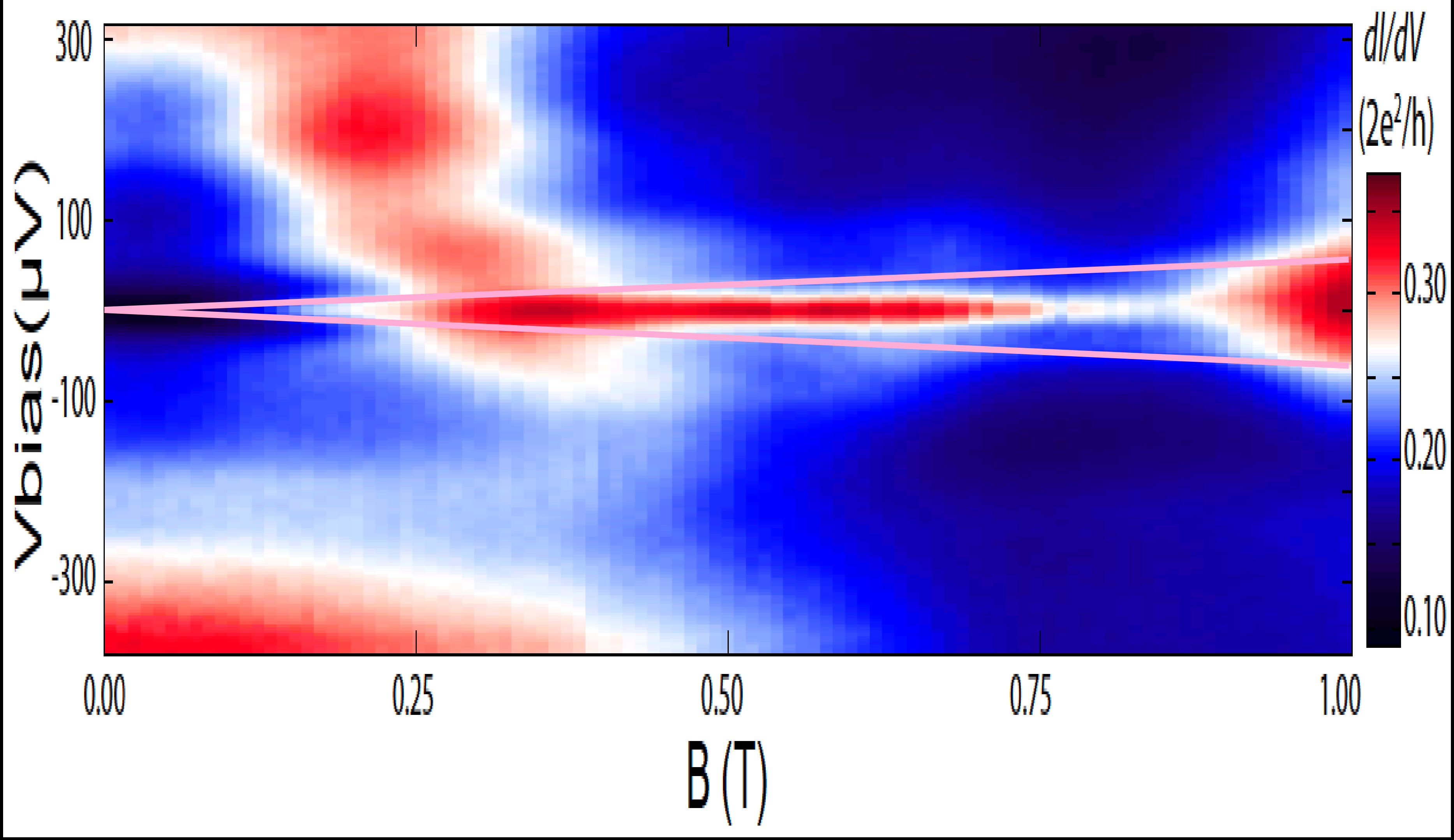
[2] *Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA*

[3] *Department of Physics, West Virginia University, Morgantown, WV 26506, USA*

Recent observations of a zero bias conductance peak in tunneling transport measurements in superconductor–semiconductor nanowire devices provide evidence for the predicted zero–energy Majorana modes, but not the conclusive proof for their existence. We establish that direct observation of a splitting of the zero bias conductance peak can serve as the smoking gun evidence for the existence of the Majorana mode. We show that the splitting has an oscillatory dependence on the Zeeman field (chemical potential) at fixed chemical potential (Zeeman field). By contrast, when the density is constant rather than the chemical potential – the likely situation in the current experimental set-ups – the splitting oscillations are generically suppressed. Our theory predicts the conditions under which the splitting oscillations can serve as the smoking gun for the experimental confirmation of the elusive Majorana mode.

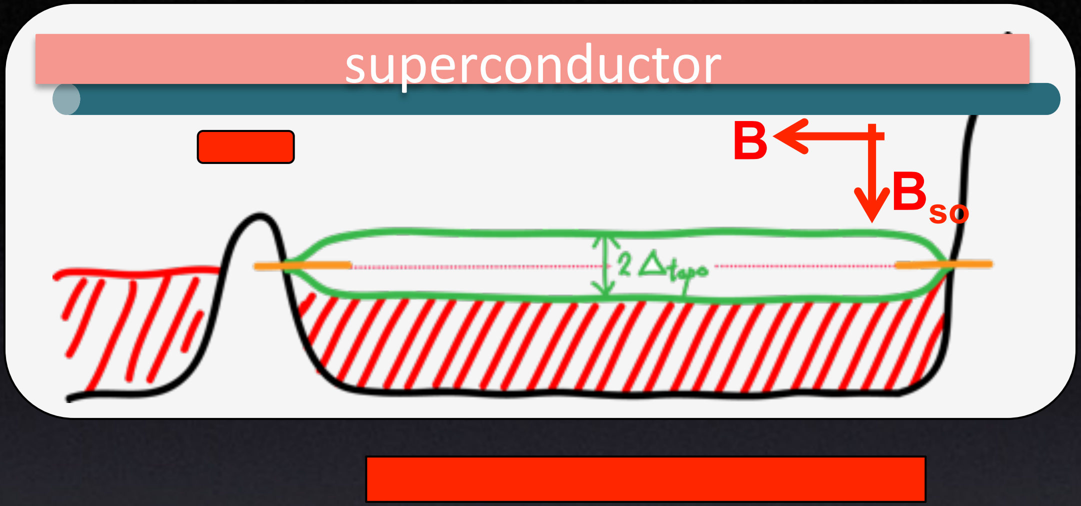



S
N1
Superconductor
Superconductor
LBG
BG1
BG2
BG3
RBG
300
100
-100
-300
Vbias(μV)
0.00
0.25
0.50
0.75
1.00
B (T)
0.20
0.10
300
100
-100
-300
Vbias(μV)
0.00
0.25
0.50
0.75
1.0
B (T)
dI/dV
(2e²/h)
0.40
0.30
0.20

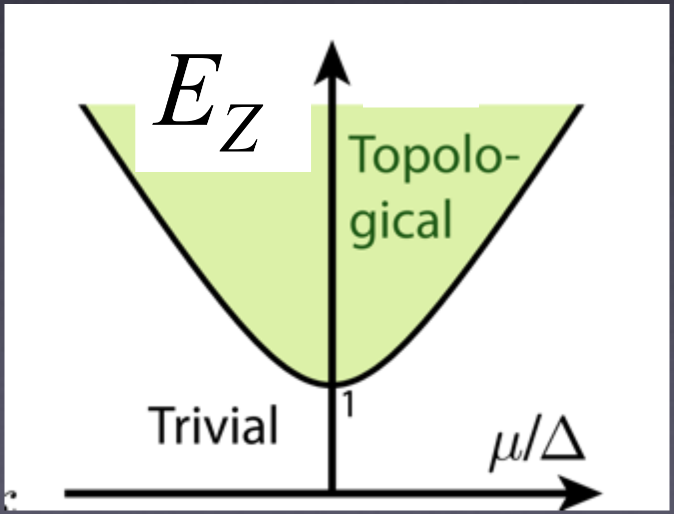


if Kondo-1/2, then $g\mu_B B$ < 60 μeV and thus g < 1 << g_{InSb}/50

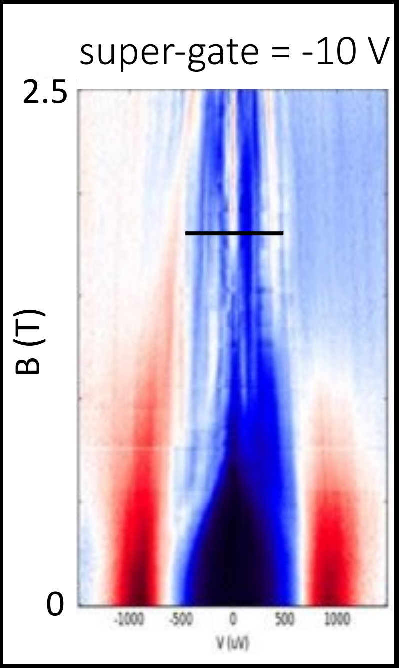
PHASE DIAGRAM

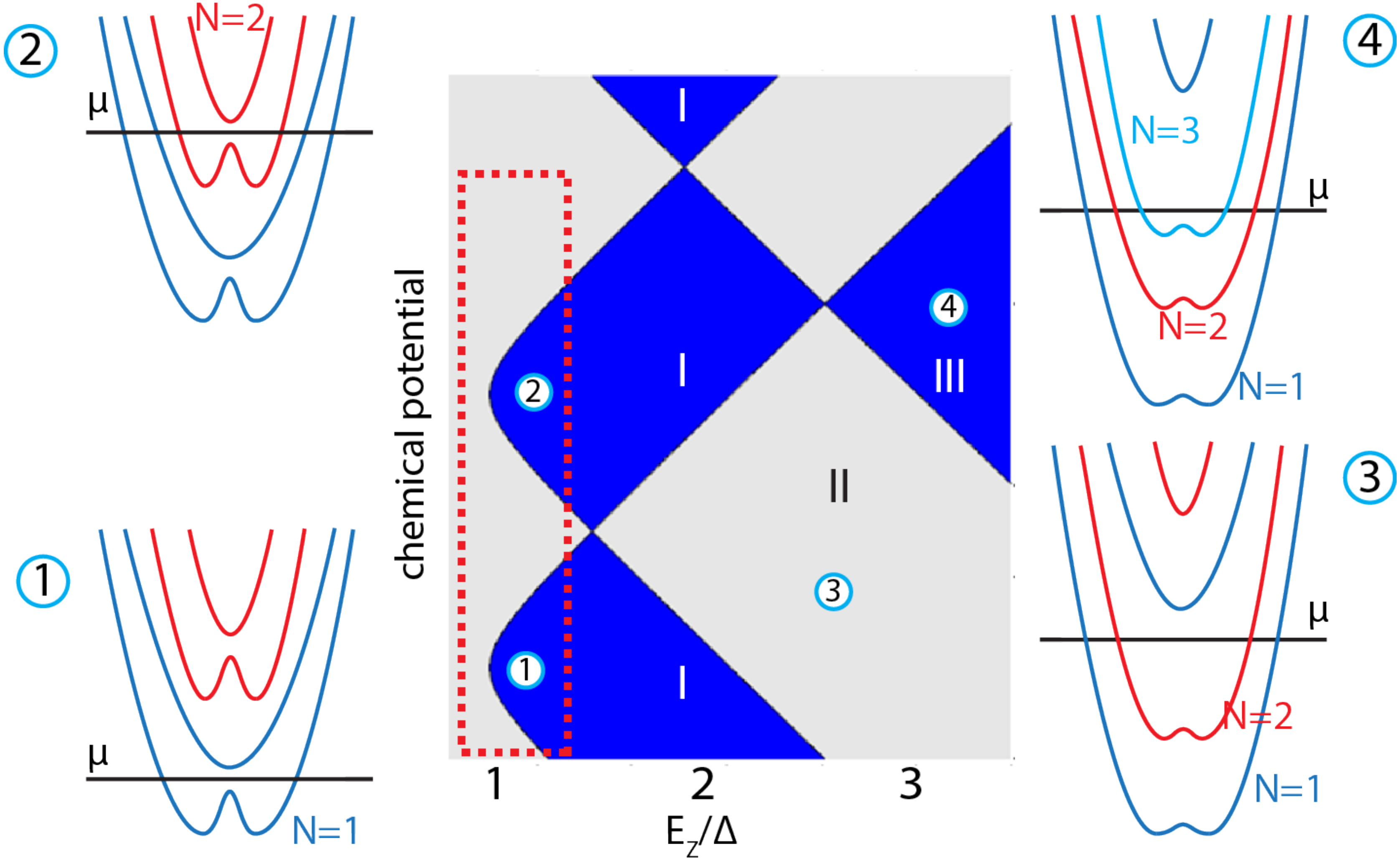


super-Vg



$$E_Z > \sqrt{\Delta^2 + \mu^2}$$


super-gate = -10 V
2.5
B (T)
0
-1000
-500
0
500
1000
V (uV)

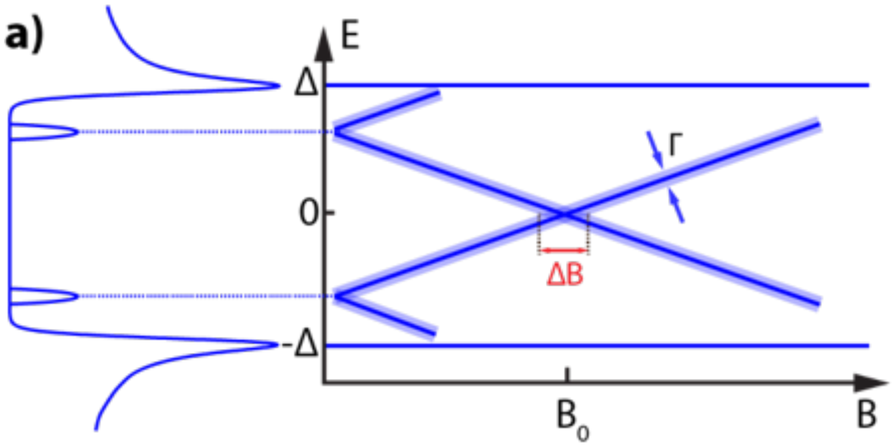


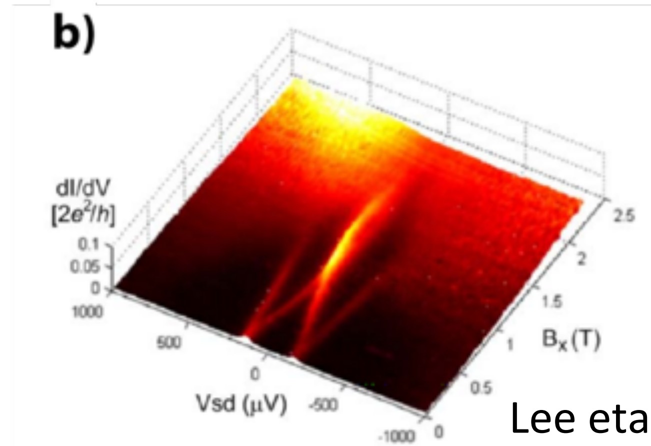
2
N=2
μ
1
μ
N=1
chemical potential
I
I
I
2
1
4
III
II
3
1
2
3
E_Z/Δ
4
N=3
μ
N=2
N=1
3
μ
N=2
N=1

Level-crossing

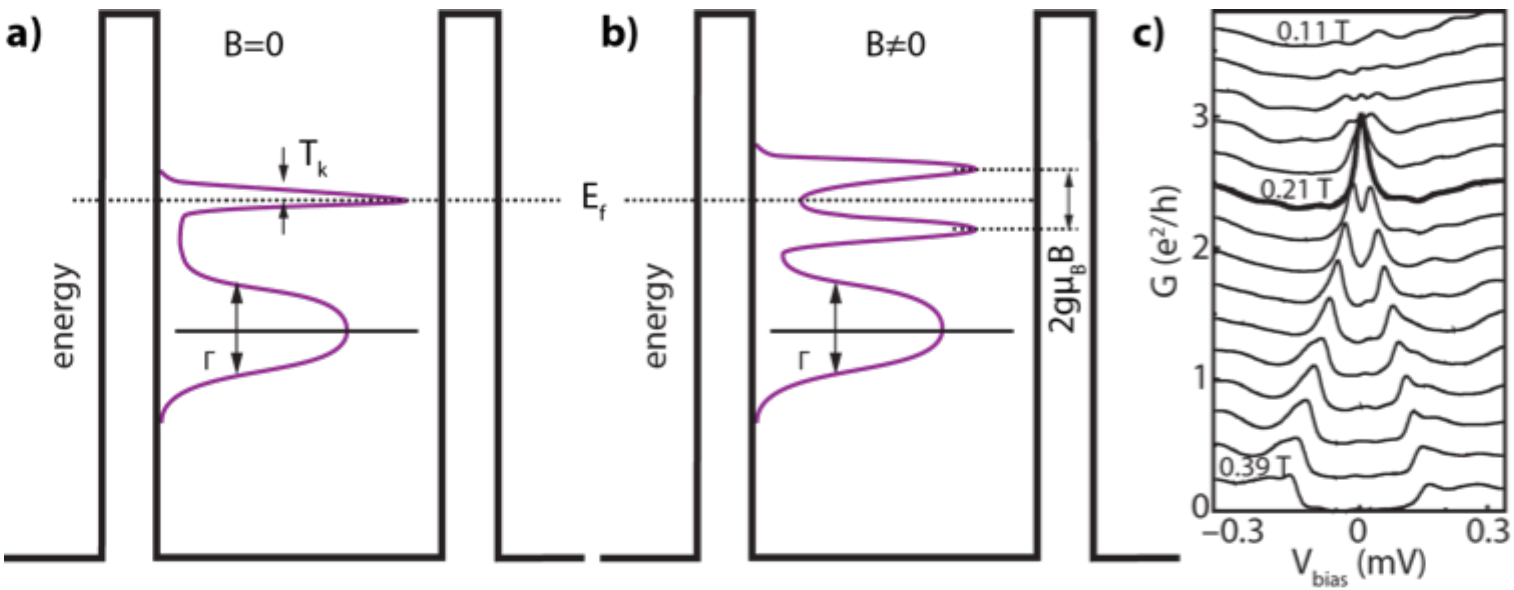
&

KONDO

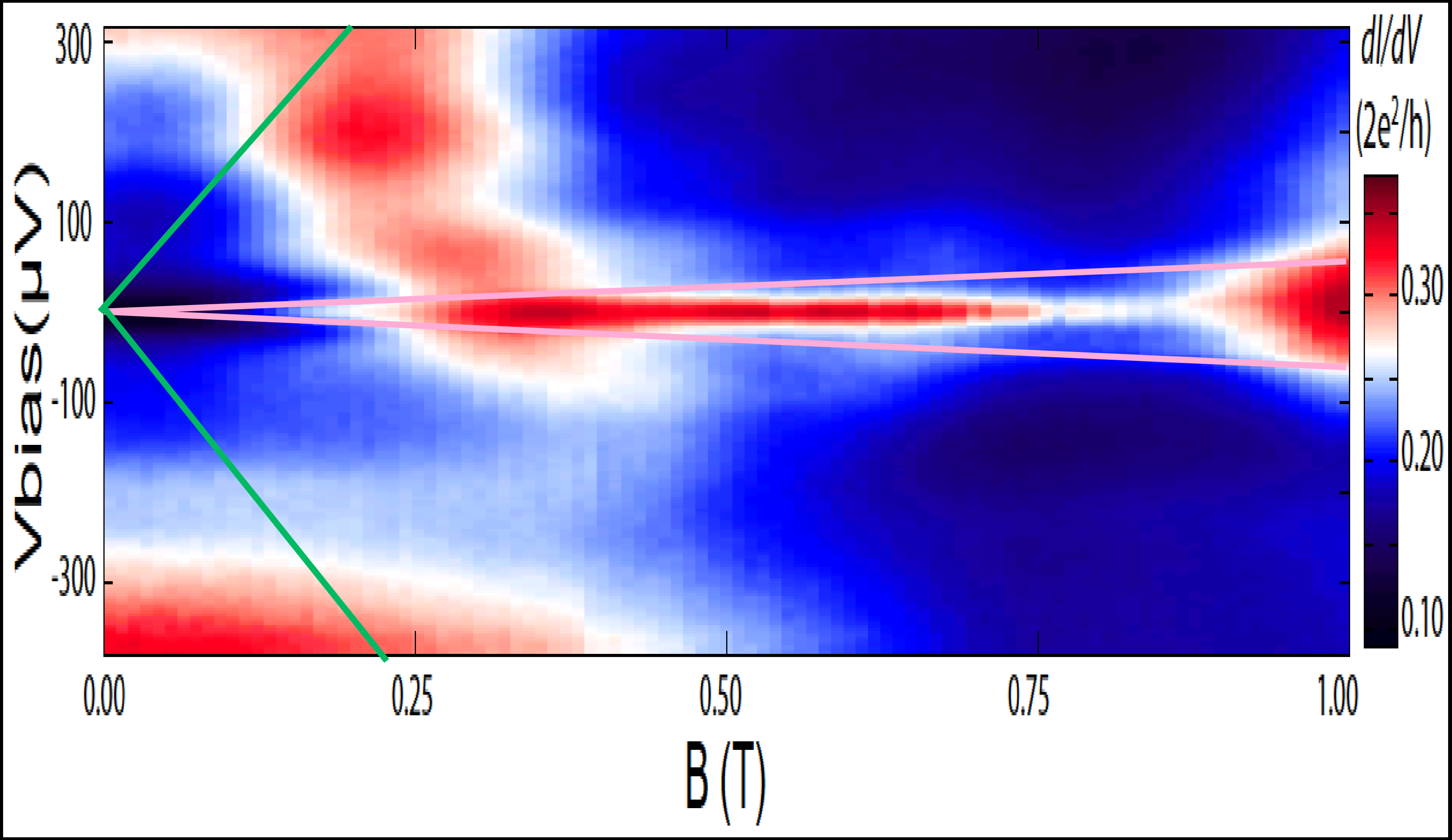




Lee etal.

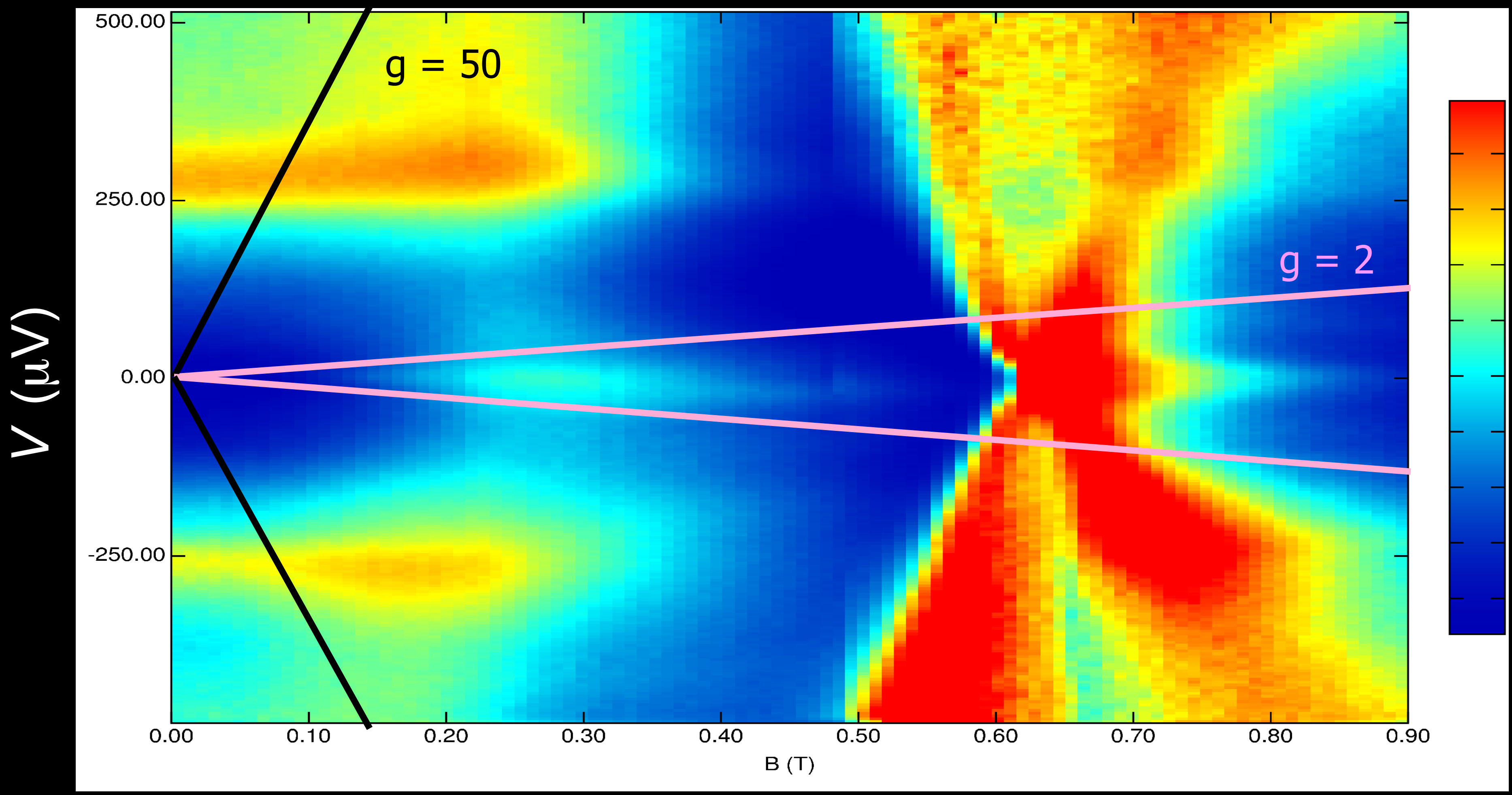


ST-Kondo, Sasaki etal.



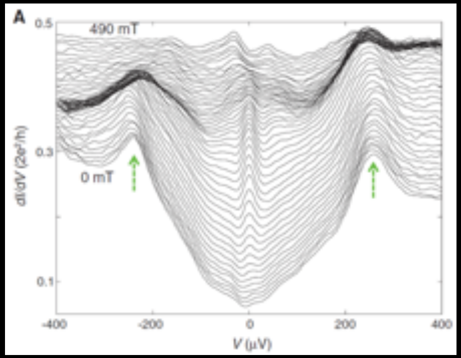
if Kondo-1/2, then $g\mu_B B$ < 60 μeV and thus g < 1 << g_{InSb}/50

how would spin ½ Kondo look?

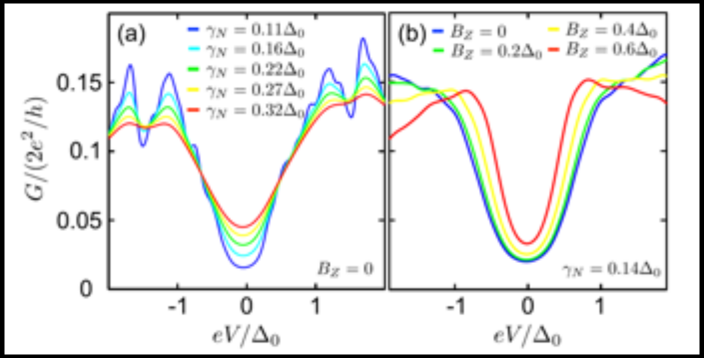


DISORDER

challenge: disorder

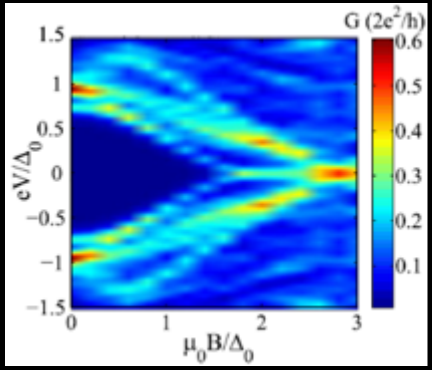


Mourik et al (2012)

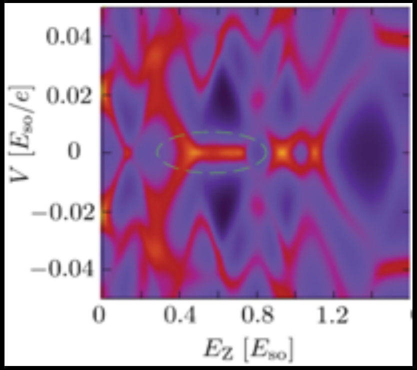


Takei et al. (2013), Chang et al (2015)

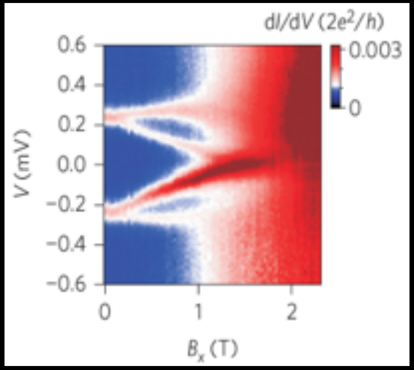
soft gap linked to disorder



Liu et al (2012)



Pikulin et al (2012)



Lee et al (2014)

Majorana signatures mimicked by disorder

Conclusions

Majorana recipe

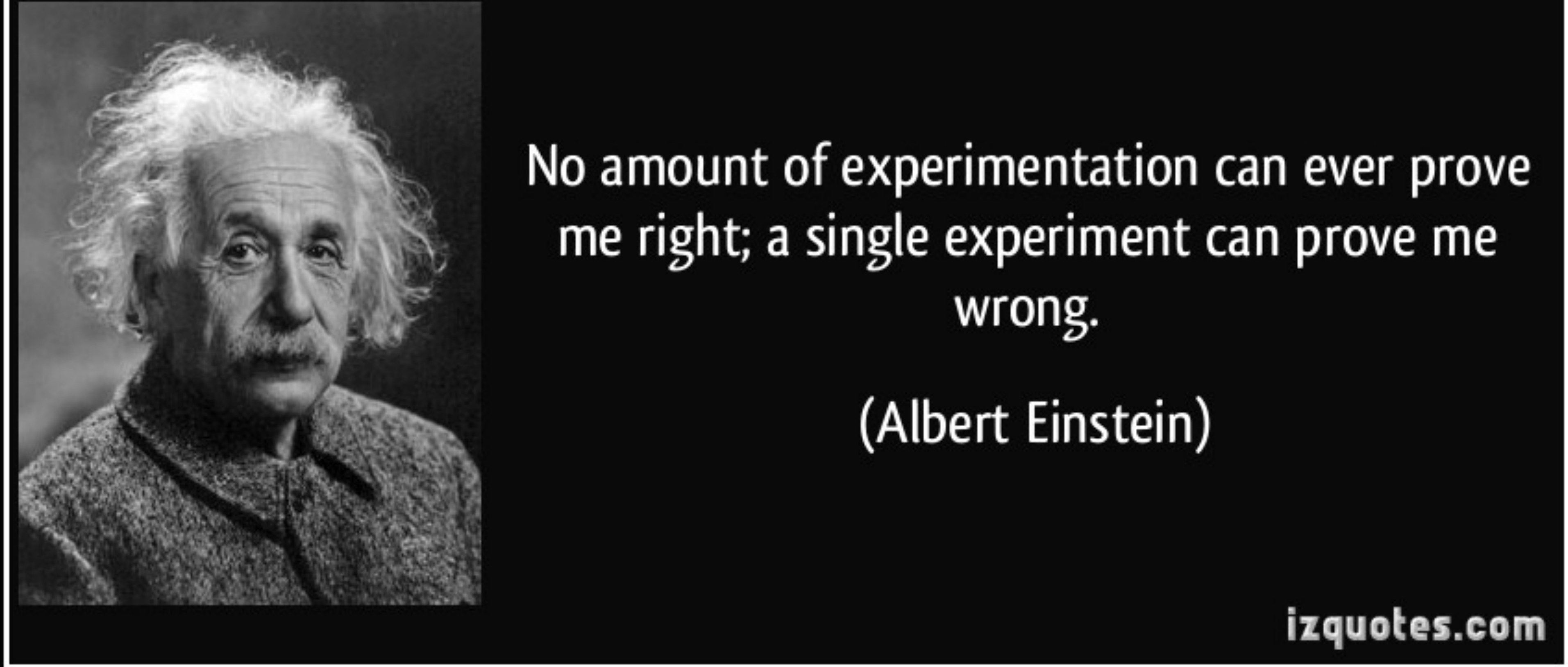
1. One-dimensional quantum wire
2. Spin-orbit interaction
3. Superconductivity
4. Apply magnetic field

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

Unique recipe for Majoranas.

Take one ingredient out and Majoranas are gone.

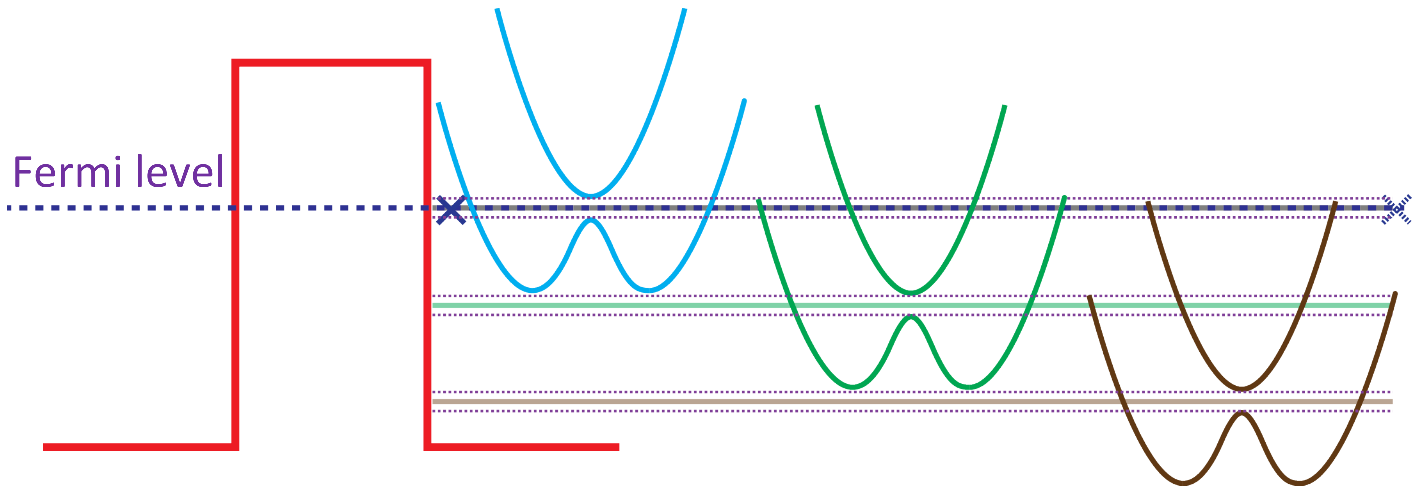
ZBP rigid over large ranges in *B* and *Vg.*



<u>Theories are excluded that are based on:</u>

- an efffect from the tunnel barrier
- *$T \sim 1$ => no Coulomb blockade*
- *ballistic wires => no localization effects*
- *Kondo only possible if $g < 0.5 = g_{InSb}/100$*

BARRIER

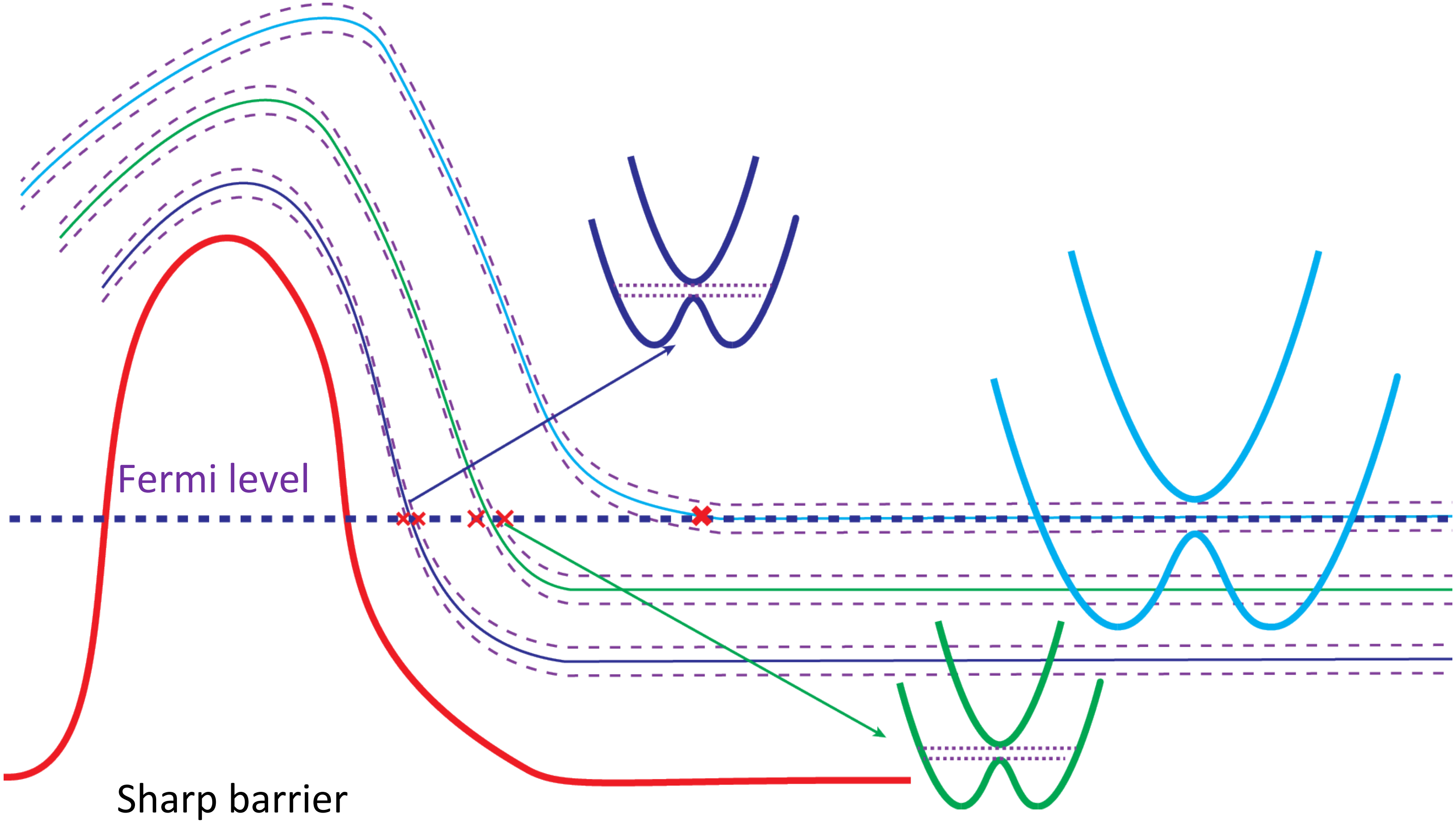


Sharp barrier

1. With a sharp tunnel barrier, only the top populated subband will be topological (holds Majorana's) and the other two bands as shown in the plot are all trivial.

2. As the tunnel barrier is sharp, the three bands have the same transmmision coefficient, therefore Majorana's as ZBP in the tunneling measurement will be clear.

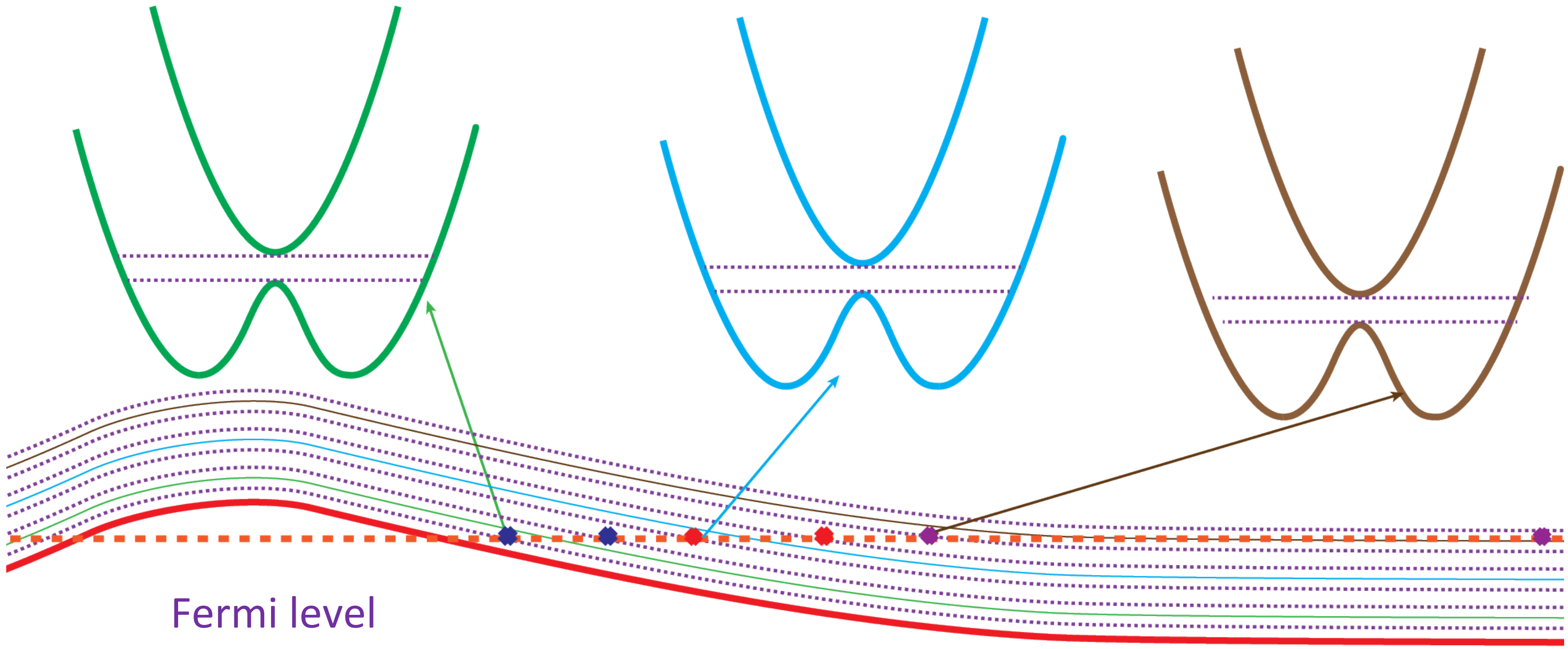
Dashed lines indicate the spin orbit gap



If we have a smooth barrier, the situation would be different

1. For smooth barrier, what is the relevant length scale?
2. What are the coherence length of Majorana's, could we have multiple Majorana's, like indicated in the figure.

Dashed lines indicate the spin orbit gap

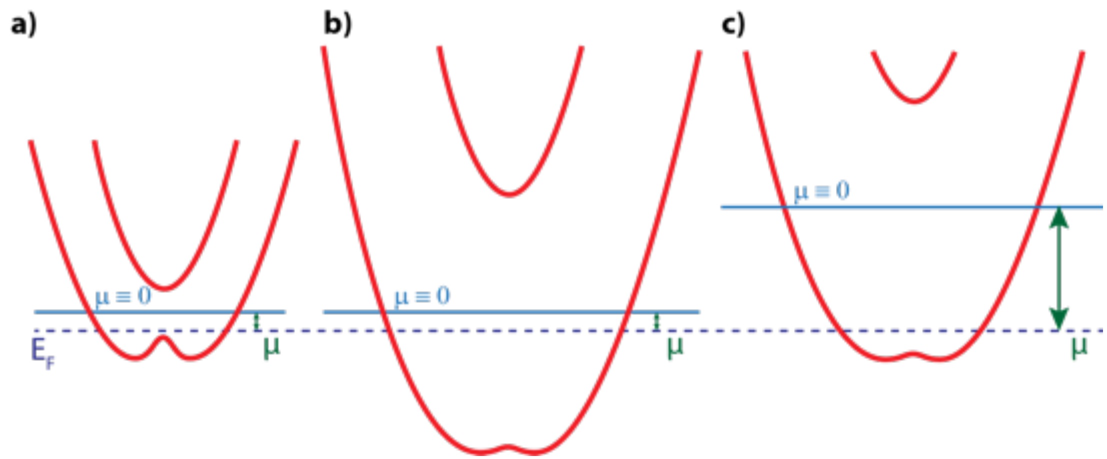


An more exaggerated case, tunnel barrier is very smooth, could be relevant for T. Stanescu's soft gap paper, the two more possible Majorana's pairs are well separated (still depend on the coherent length of Majorana's in the system):

1. Could we discriminate them?
2. What is the visibility difference in tunneling measurements of the Majorana's at the top subband vs. lower subbands?
3. How about the stability in B and chemical potential of these Majorana's at lower subbands compared to top subband Majorana's?

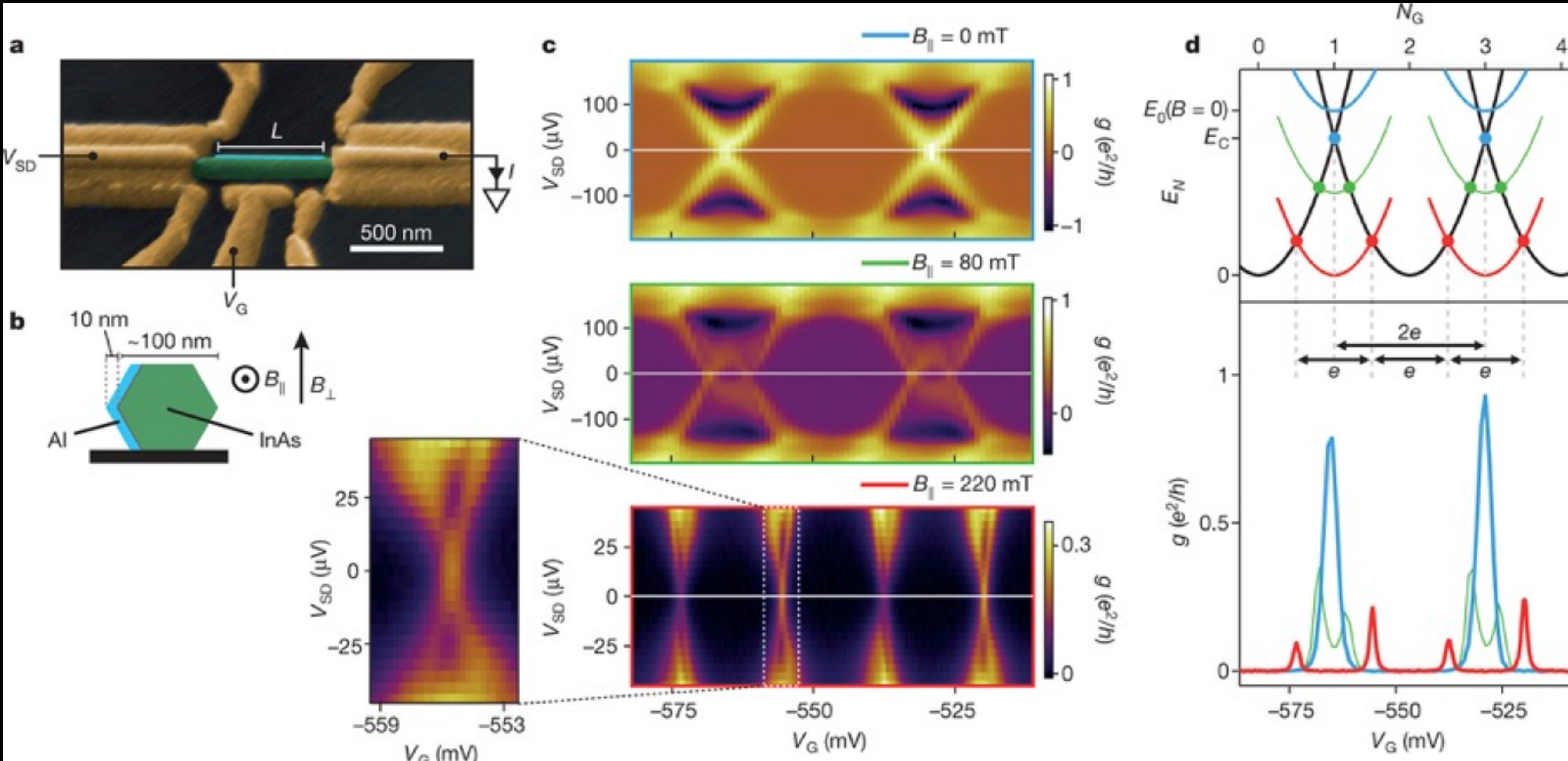
Dashed lines indicate the spin orbit gap

rest

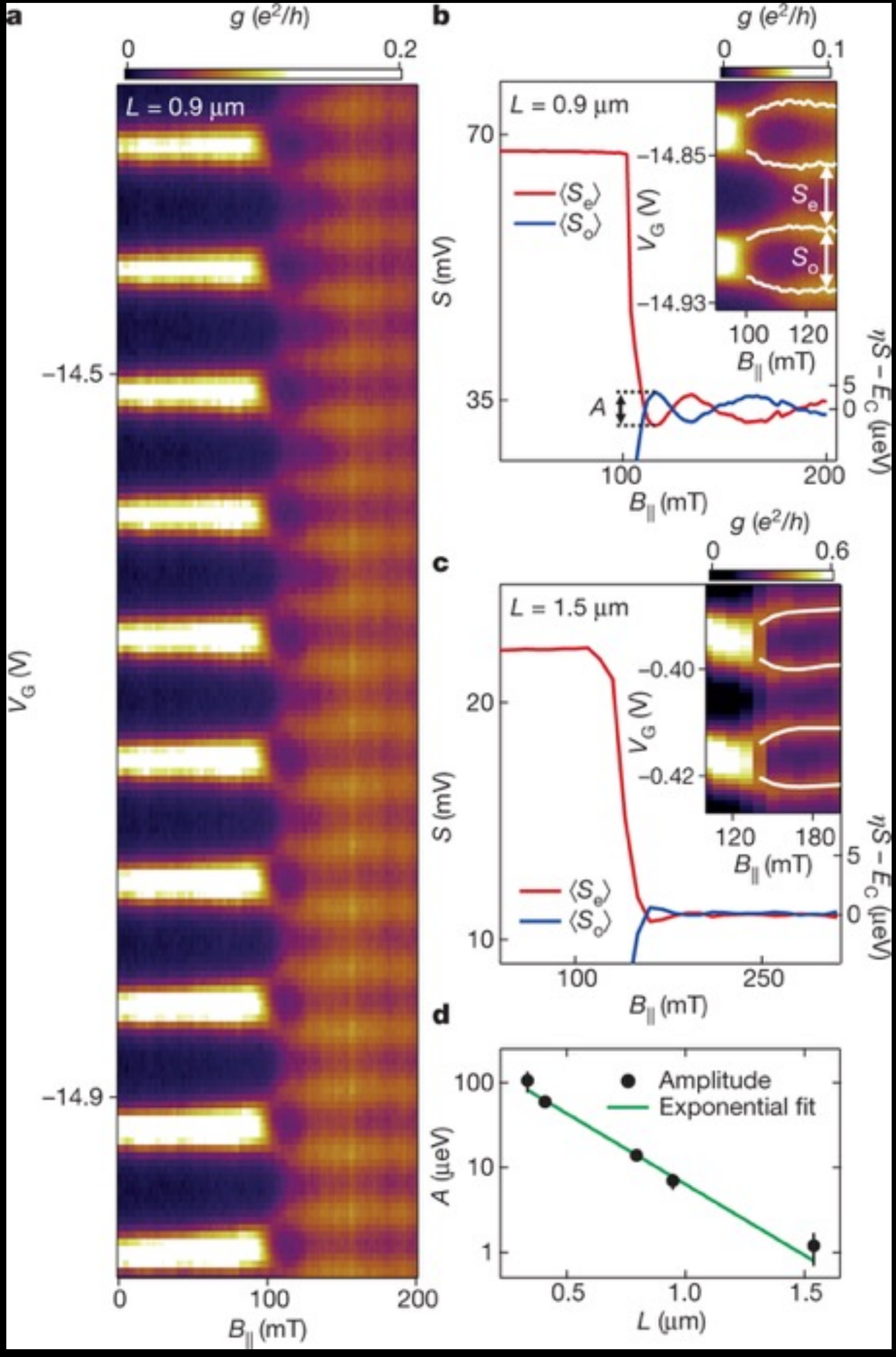


a)
b)
c)
μ ≡ 0
μ ≡ 0
μ ≡ 0
E_F
μ
μ
μ

Majorana island device



S M Albrecht *et al.* *Nature* **531**, 206–209 (2016) doi:10.1038/nature17162



a
g (e²/h)
0
0.2
L = 0.9 μm
−14.5
−14.9
V_G (V)
0
100
200
B_∥ (mT)
b
g (e²/h)
0
0.1
L = 0.9 μm
70
35
S (mV)
⟨S_e⟩
⟨S_o⟩
−14.85
−14.93
V_G (V)
S_e
S_o
100
120
B_∥ (mT)
A
5
0
S_o − E_C (μeV)
100
200
B_∥ (mT)
c
g (e²/h)
0
0.6
L = 1.5 μm
20
10
S (mV)
−0.40
−0.42
V_G (V)
120
180
B_∥ (mT)
⟨S_e⟩
⟨S_o⟩
5
0
S_o − E_C (μeV)
100
250
B_∥ (mT)
d
100
10
1
A (μeV)
Amplitude
Exponential fit
0.5
1.0
1.5
L (μm)