The Abdus Salam International Centre for Theoretical Physics

2451-7

Workshop on Interferometry and Interactions in Non-equilibrium Meso- and Nano-systems

8 - 12 April 2013

Zero-bias Oscillations and Magnetoconductance Crossover in Superconductor-Nanowire Devices

Hugh CHURCHILL

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Zero-bias Oscillations and Magnetoconductance Crossover in Superconductor-Nanowire Devices

+ N-dot-S

Hugh Churchill (Harvard, now MIT)
Valla Fatemi (MIT)
Kasper Grove-Rasmussen (NBI)
Charles Marcus (NBI)

wires: Mingtang Deng (Lund)
Philippe Caroffe (Lund)
Hongqi Xu (Lund)

arXiv:1303.2407

New directions in the pursuit of Majorana fermions in solid state systems

Jason Alicea[1]

[1] *Department of Physics and Astronomy, University of California, Irvine, California 92697*

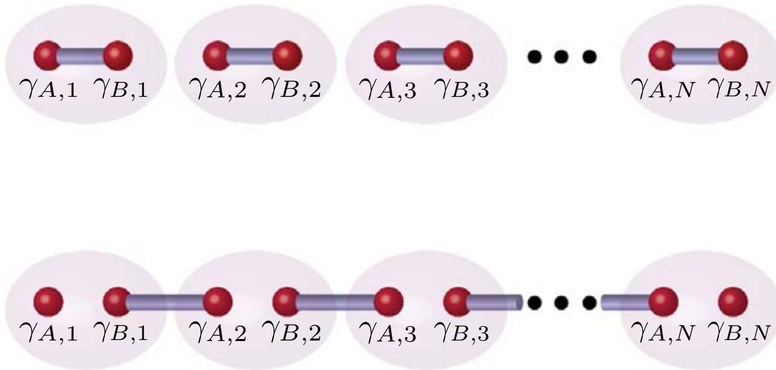
(Dated: February 8, 2012)

Rep. Prog. Phys. (2012)

idea: engineer a 'Kitaev chain' in a spin-orbit coupled nanowire

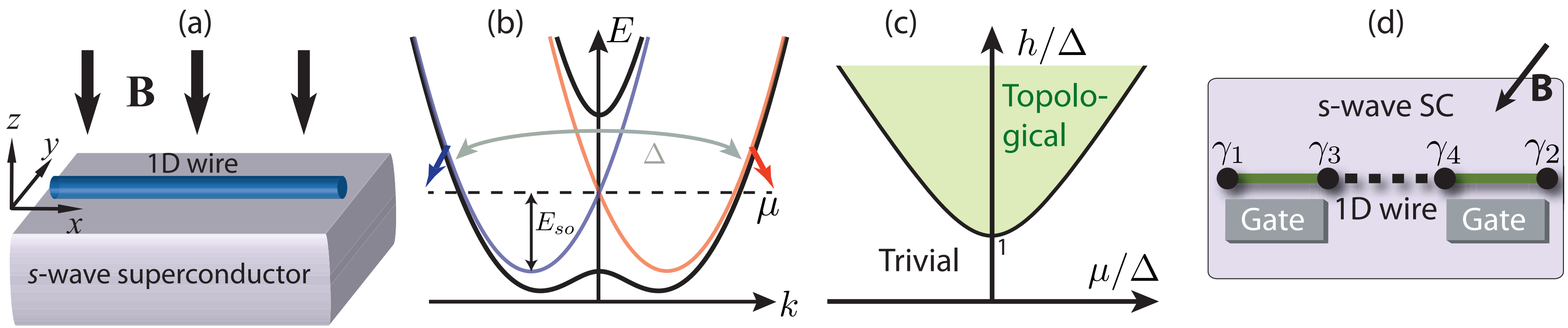
Oreg, Refael, von Oppen PRL (2010)

Lutchyn, Sau, Das Sarma PRL (2010)



$t = \Delta = 0$

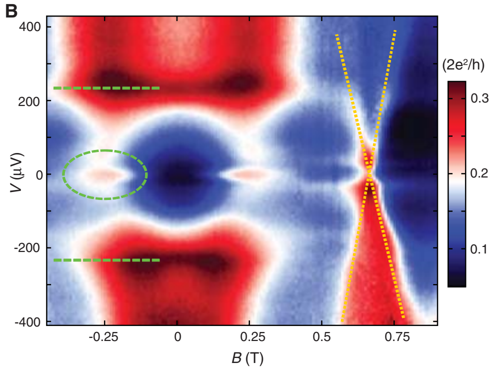
$t = \Delta \neq 0$



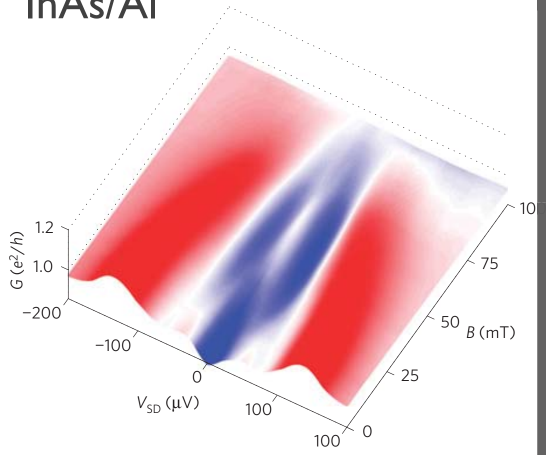
Recent experiments with nanowires and superconductors

Majorana

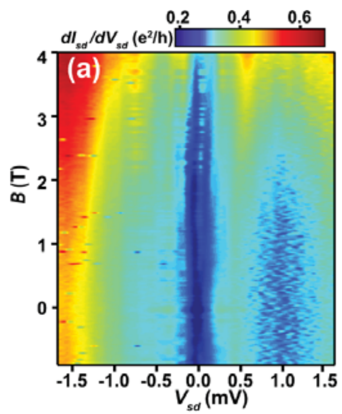
Mourik *et al.* (Delft)
InSb/NbTiN



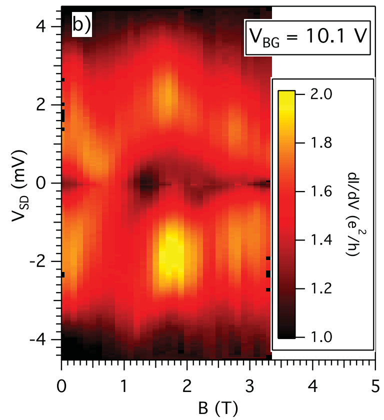
Das *et al.* (Weizmann)
InAs/Al



Deng *et al.* (Lund)
InSb/Nb



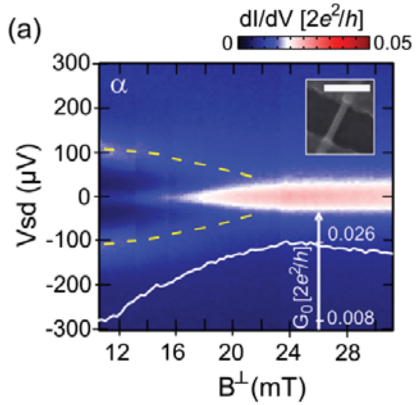
Finck *et al.* v1 (UIUC)
InAs/NbN



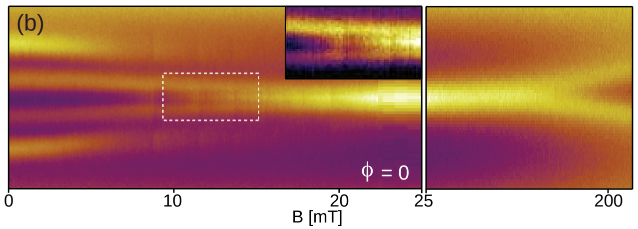
this talk (Harvard/NBI) InSb/NbTiN

Kondo

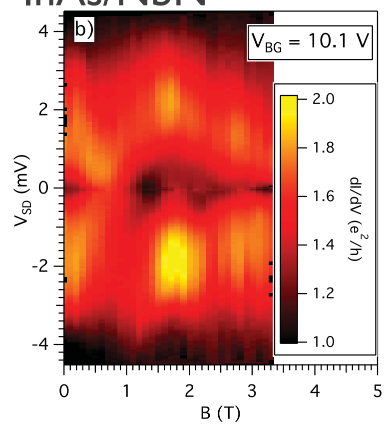
Lee *et al.* (Genoble) InAs/Al



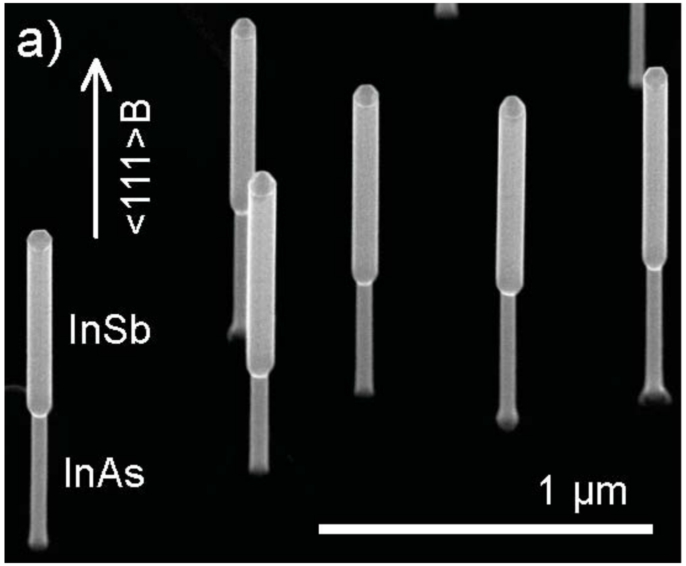
Chang *et al.* (Harvard/NBI) InAs/Al



Finck *et al.* v2 (UIUC)
InAs/NbN

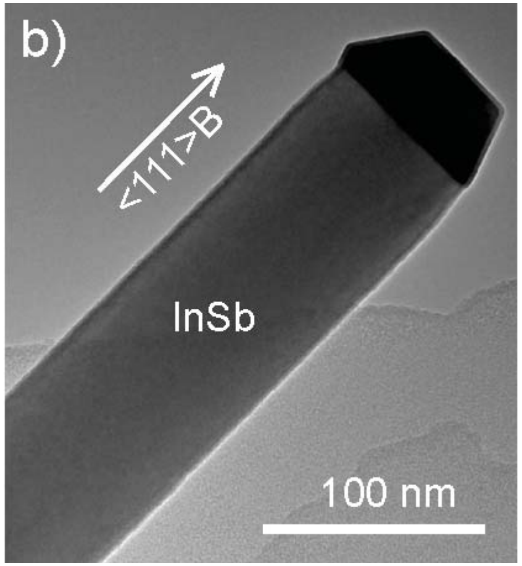


InSb nanowires with NbTiN contact



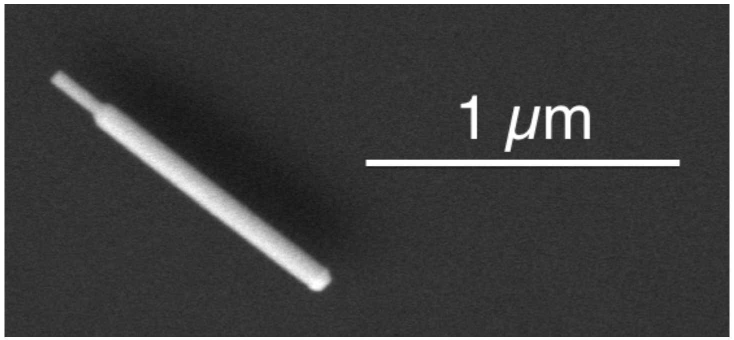
Nilsson *et al.* Nano Lett.

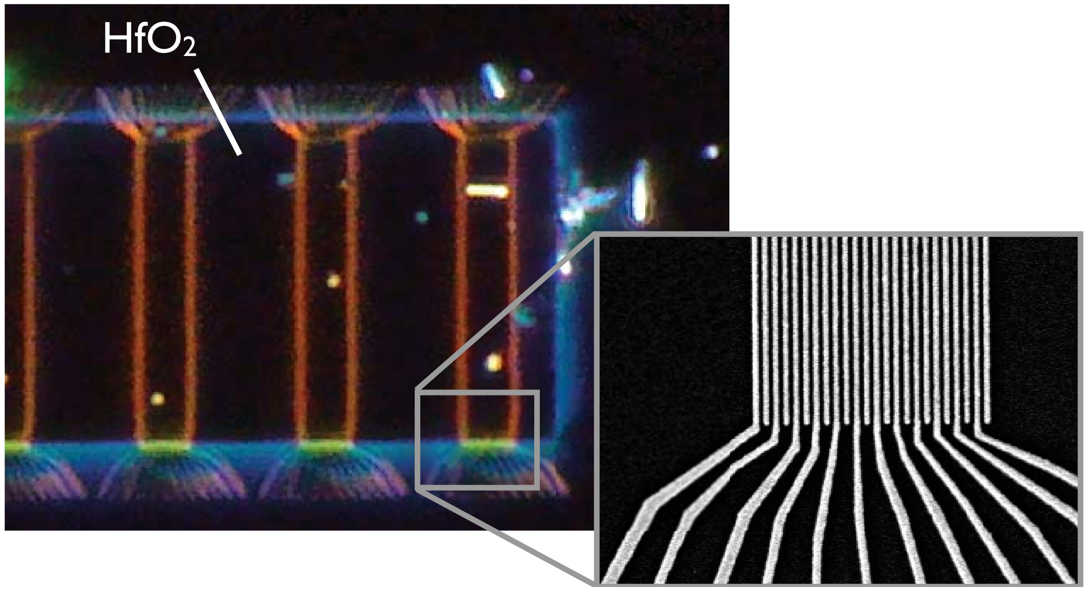
(2009)



H. Xu, Lund

Wires deposited on
bottom-gate substrates:





InSb nanowires with NbTiN contact

Device #1: two-sided (N-wire-S-wire-N)

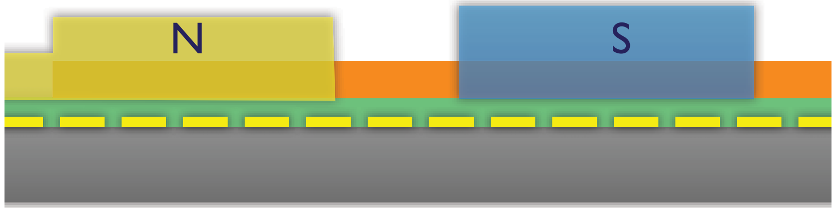
150 nm wide uncovered regions

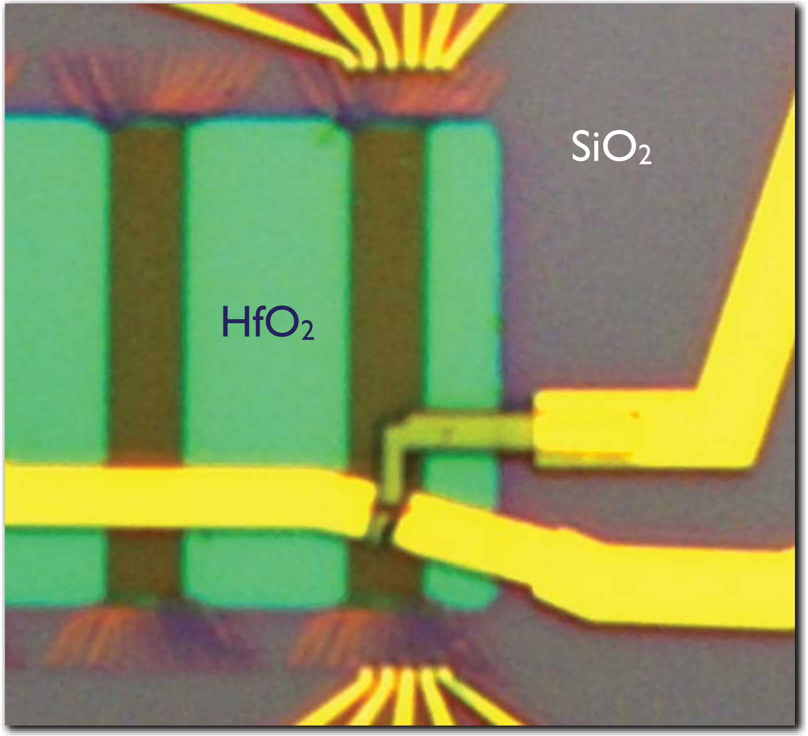
300 nm wide superconducting contacts

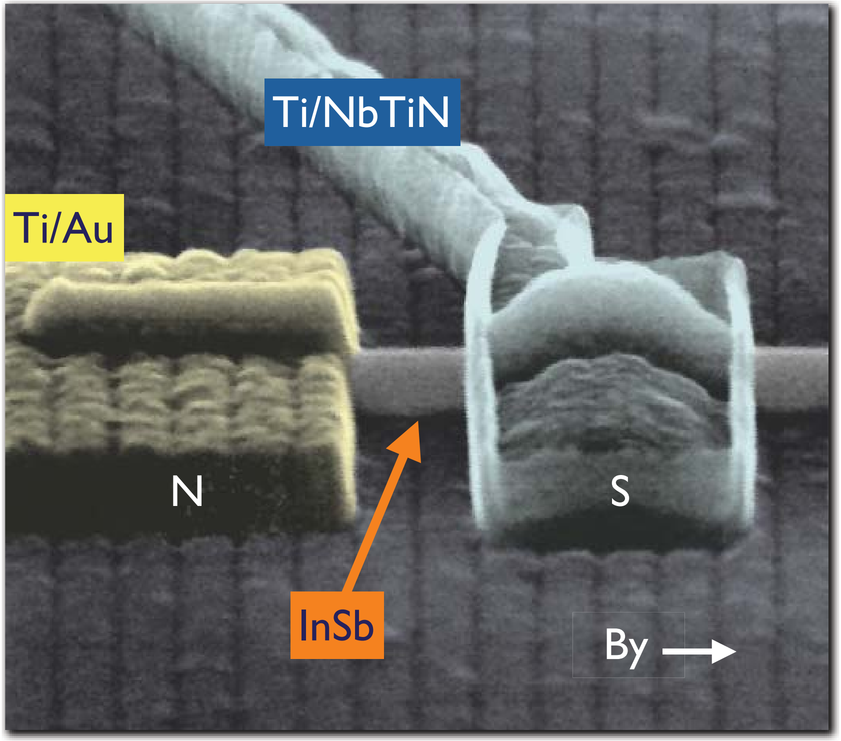
Device #2: one-sided (N-wire-S)

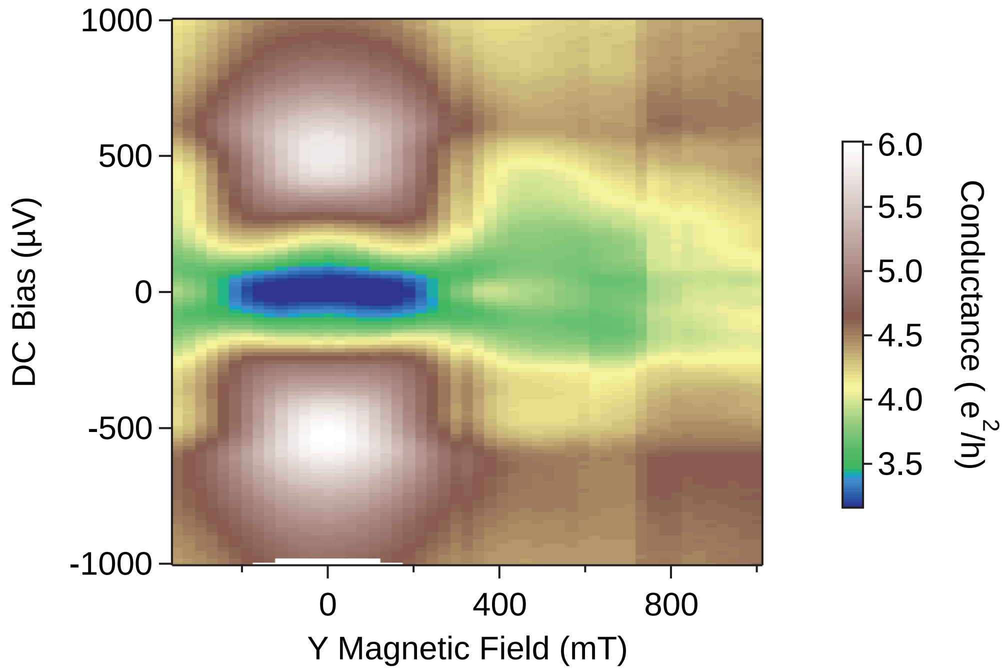
100 nm wide uncovered region

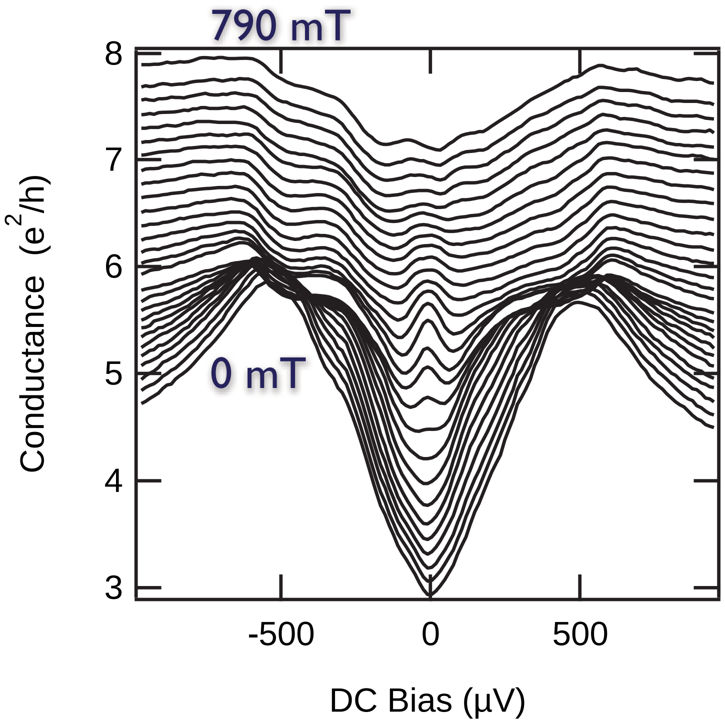
400 nm wide superconducting contact

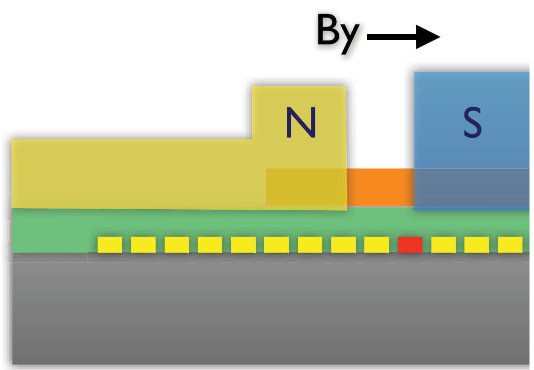


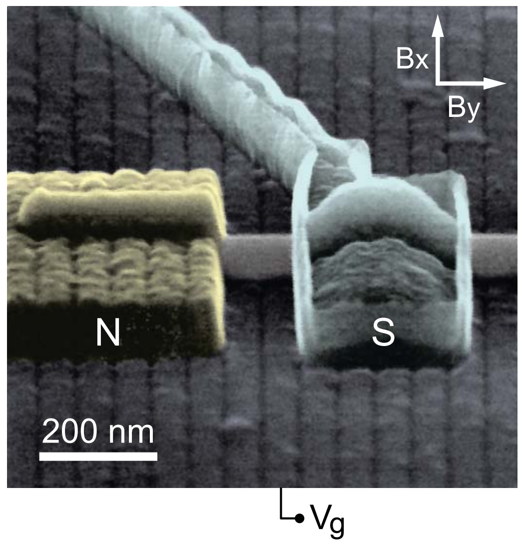


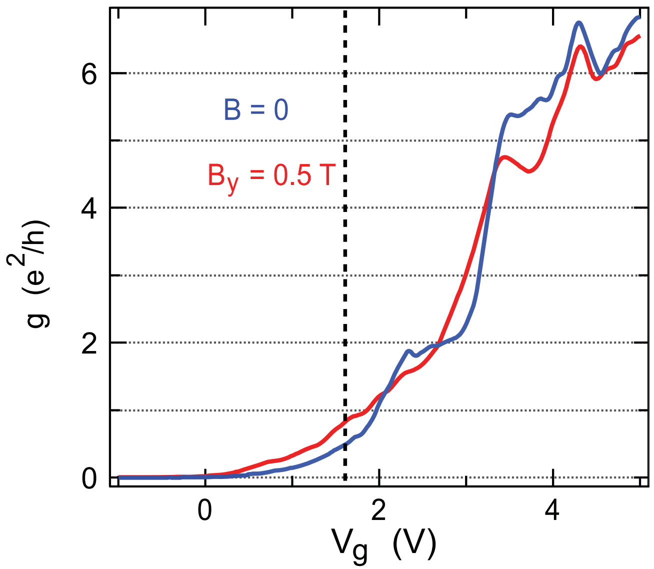


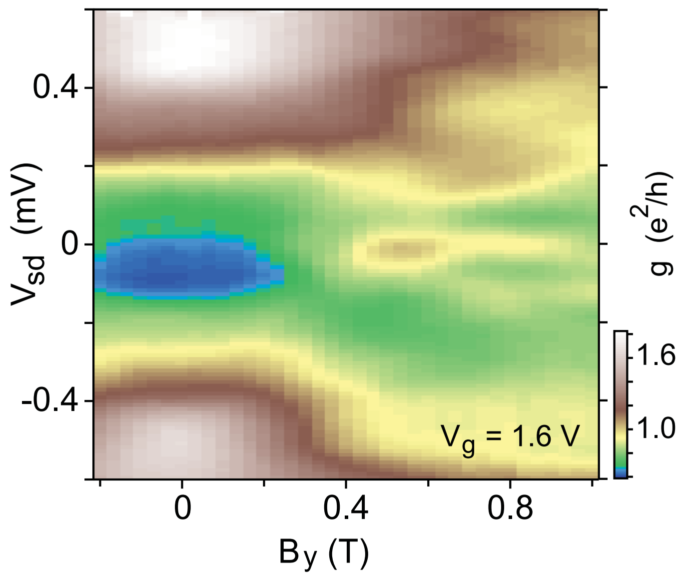

1000
500
0
-500
-1000
DC Bias (µV)
0
400
800
Y Magnetic Field (mT)
6.0
5.5
5.0
4.5
4.0
3.5
Conductance (e²/h)

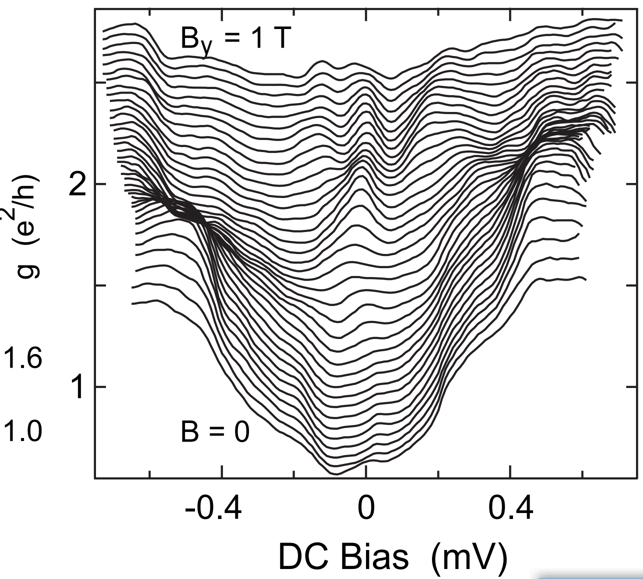

790 mT
0 mT
8
7
6
5
4
3
Conductance (e²/h)
-500
0
500
DC Bias (µV)


By
N
S

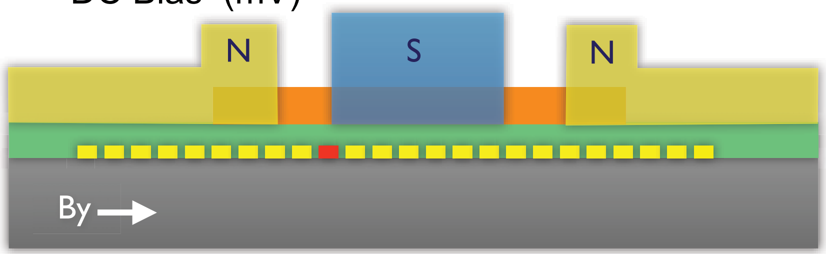


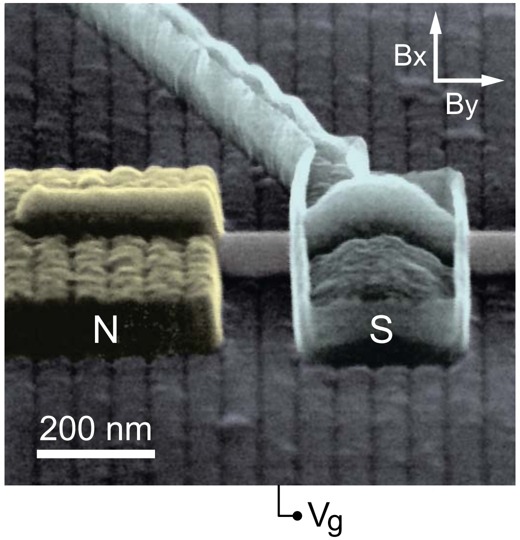


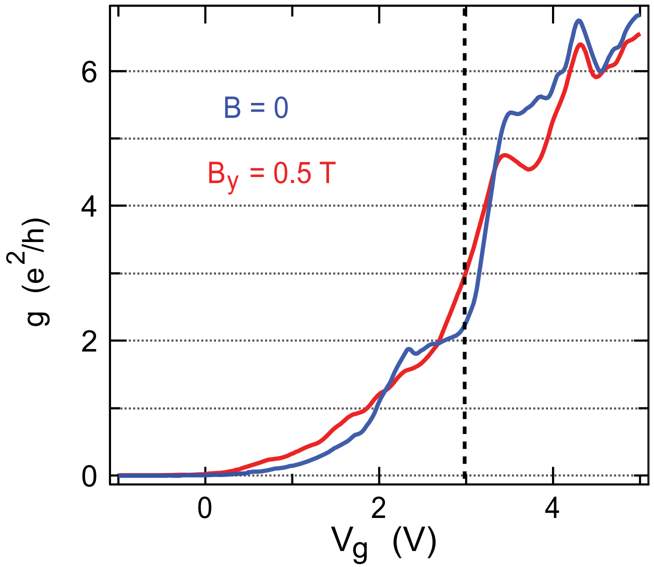


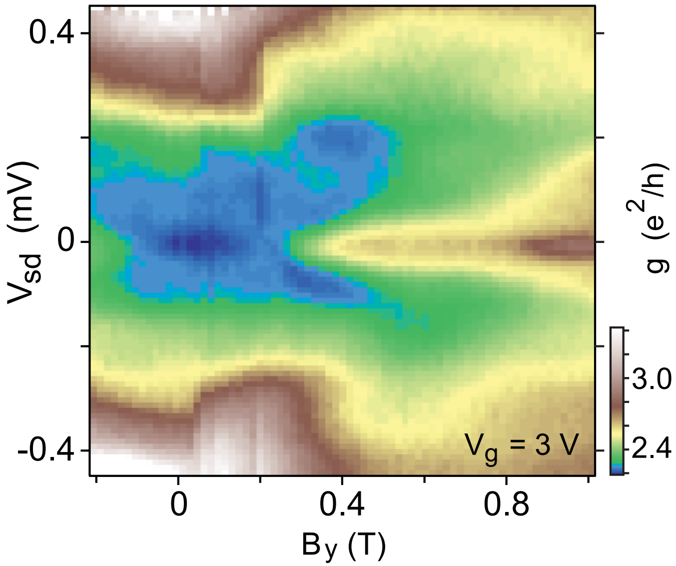


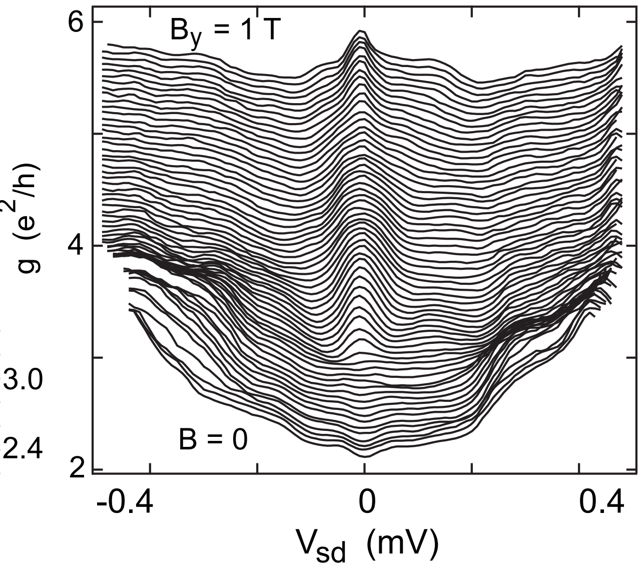
FWHM = 100 μV,
3x larger than thermal
broadening at 0.1 K



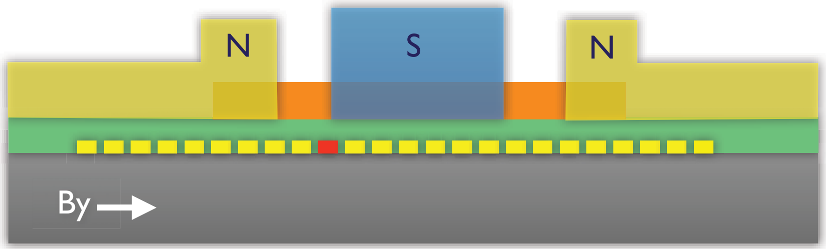




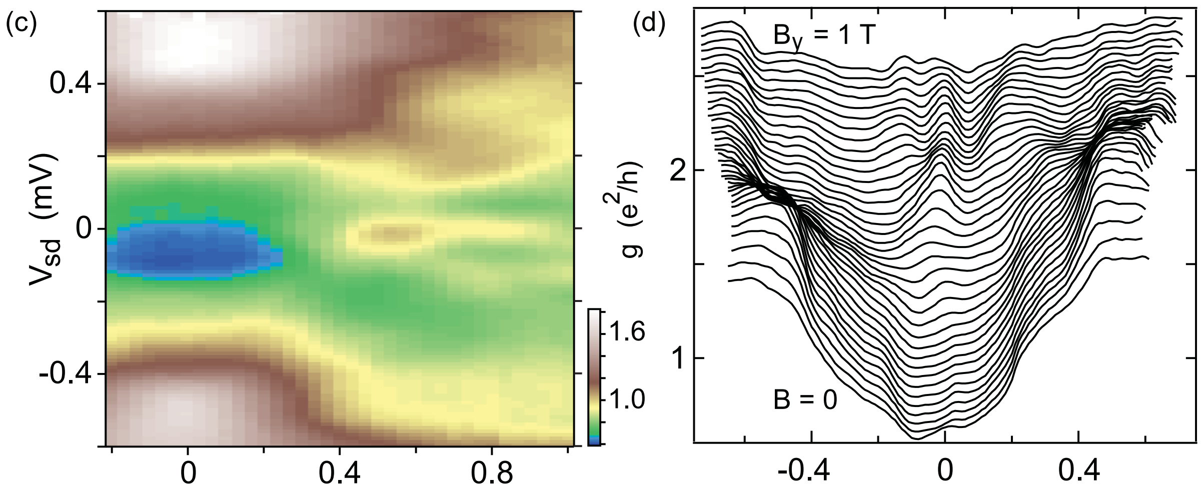


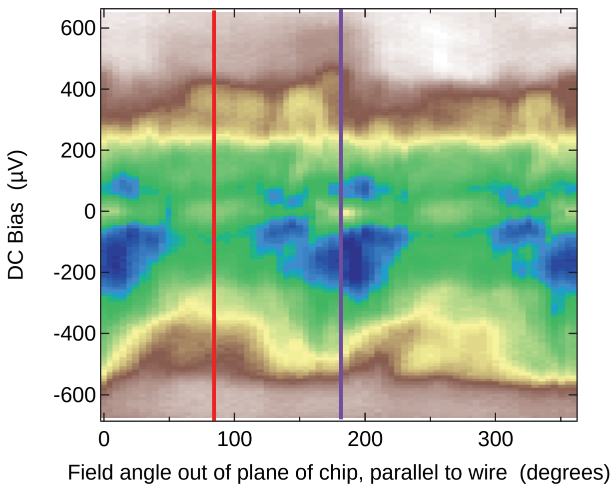


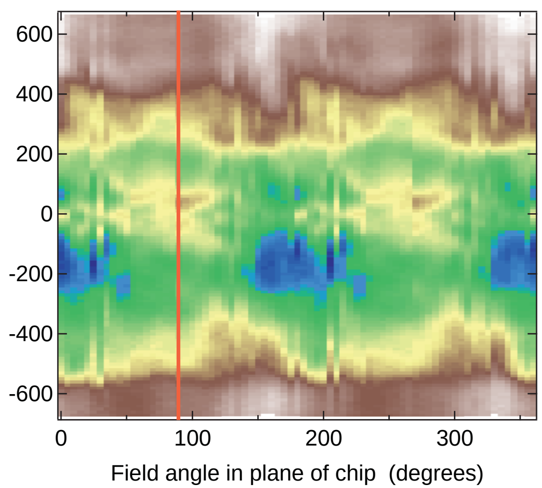
FWHM = 100 μV,
3x larger than thermal
broadening at 0.1 K

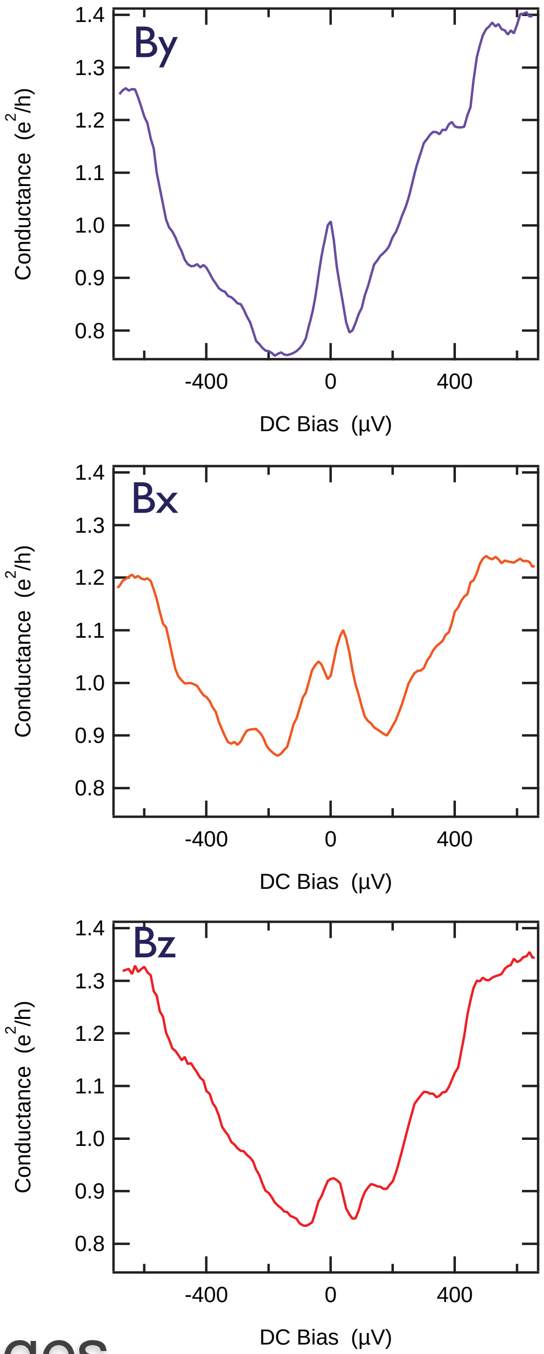


Field-angle dependence



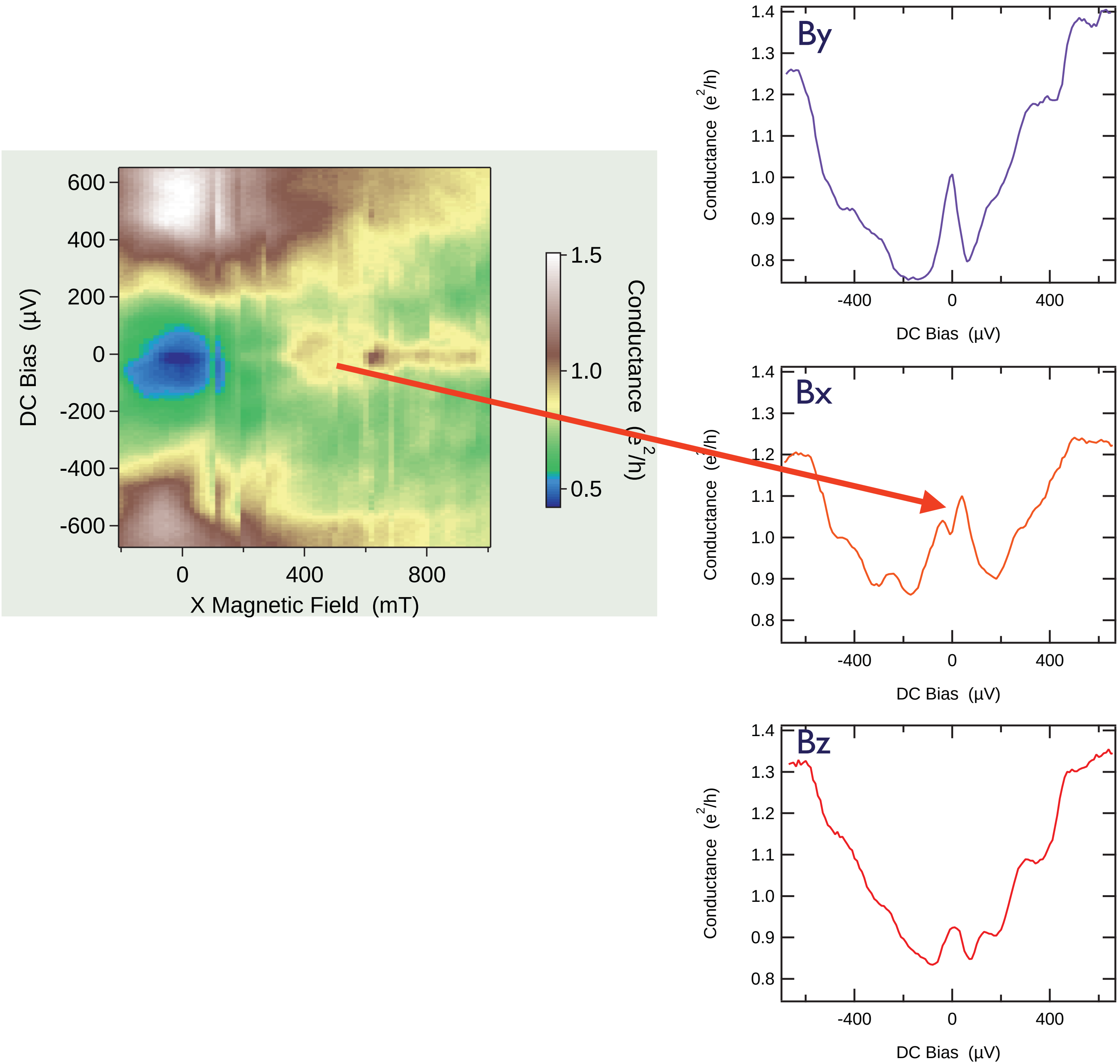






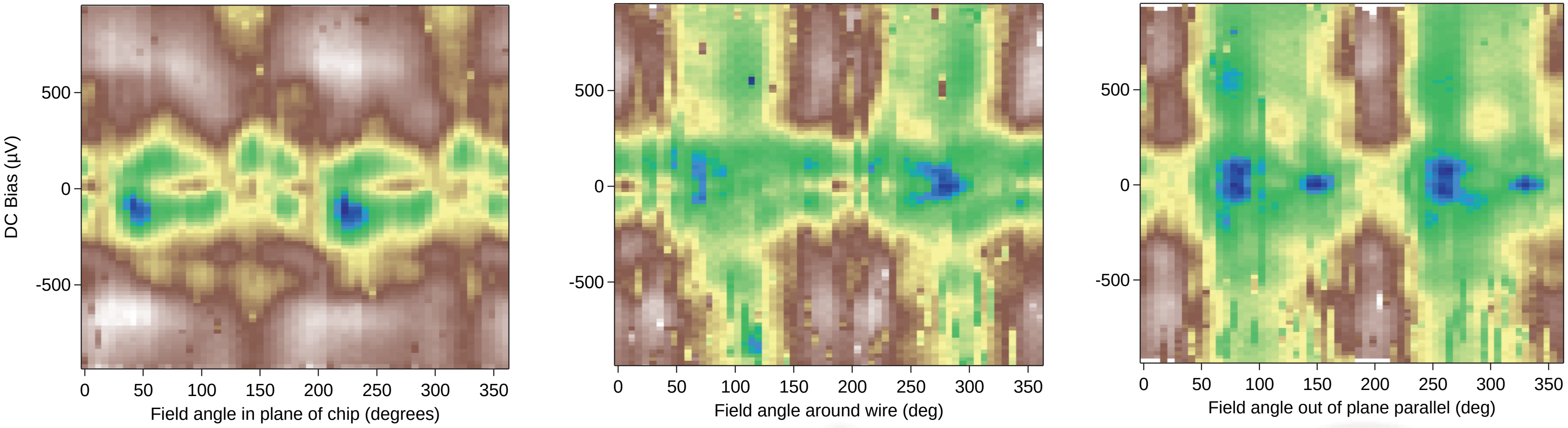
|B| = 500 mT

Zero-bias peaks persist over broad gate ranges

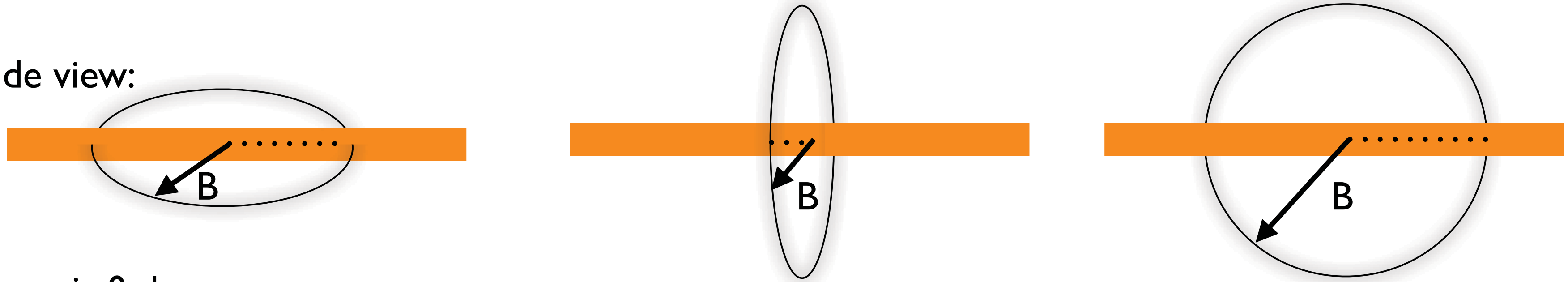

600
400
200
0
-200
-400
-600
DC Bias (µV)
0
400
800
X Magnetic Field (mT)
1.5
1.0
0.5
Conductance (e^2/h)
By
Bx
Bz
1.4
1.3
1.2
1.1
1.0
0.9
0.8
Conductance (e^2/h)
-400
0
400
DC Bias (µV)

Field-angle dependence

|B| = 500 mT



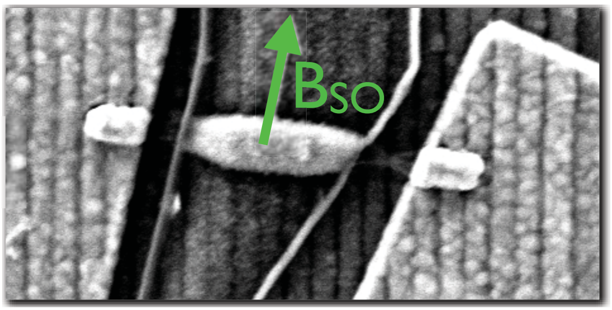
side view:



········ is 0 degrees

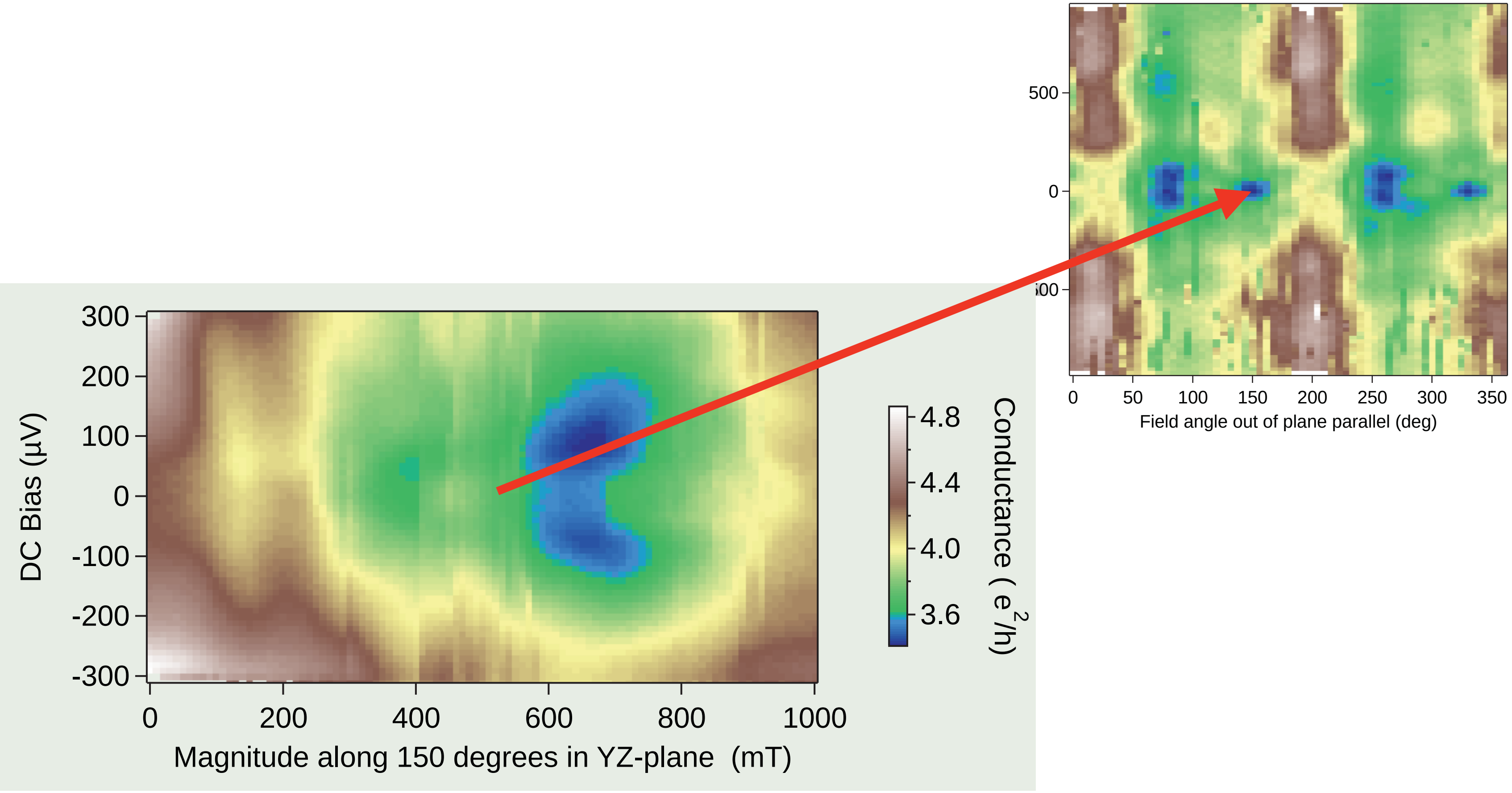
top view:

"expectation":

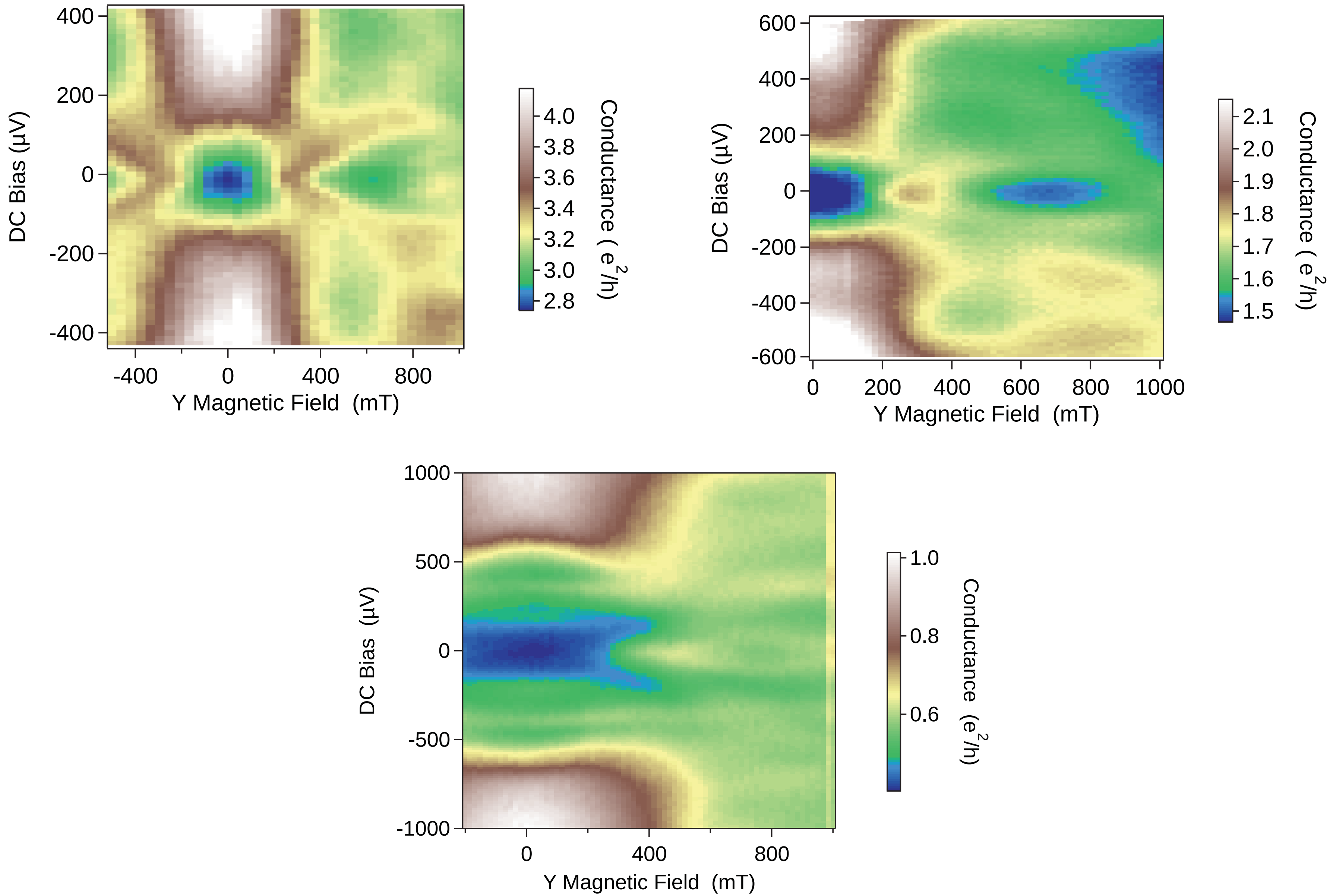


QPC, vary field angle

|B| = 500 mT



Splitting of Zero-bias Peaks

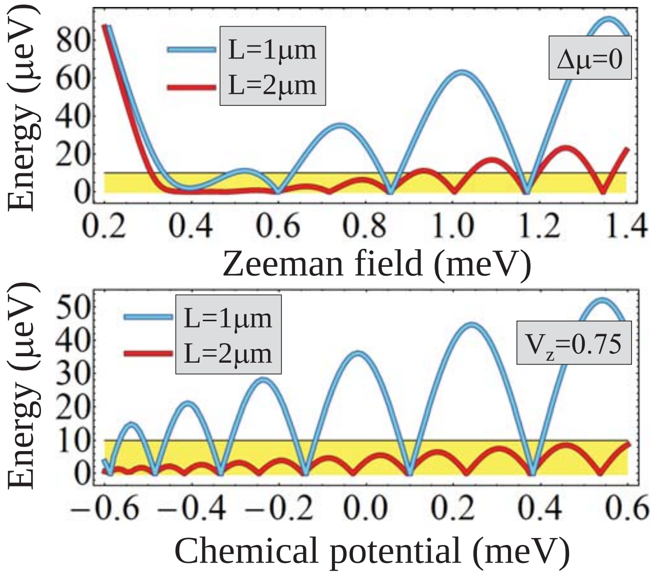


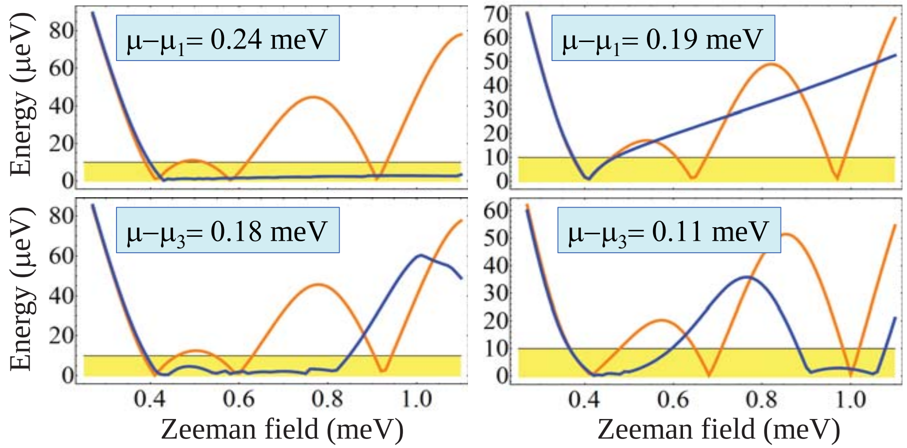
PHYSICAL REVIEW B **86**, 220506(R) (2012)

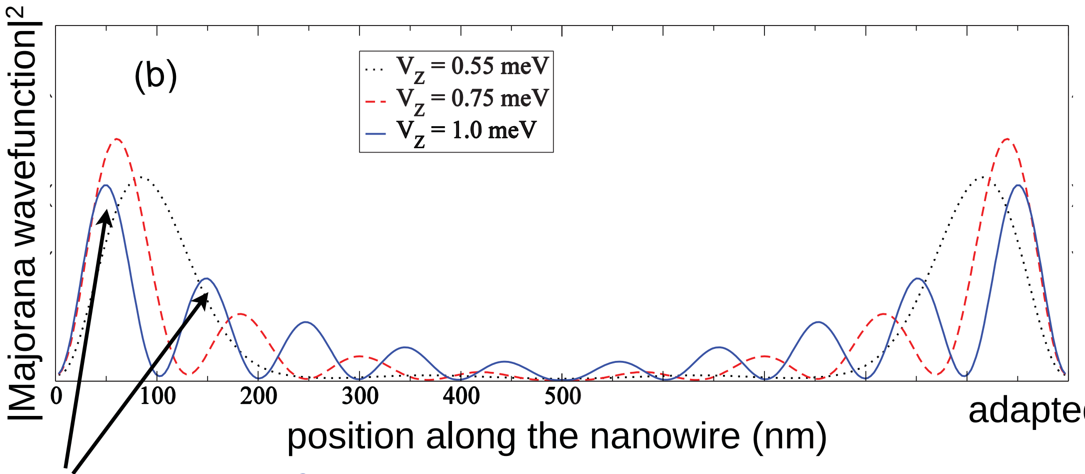
Splitting of the zero-bias conductance peak as smoking gun evidence for the existence of the Majorana mode in a superconductor-semiconductor nanowire

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

see also
Prada *et al.* PRB (2012)
Lin *et al.* PRB (2012)
Rainis *et al.* PRB (2013)







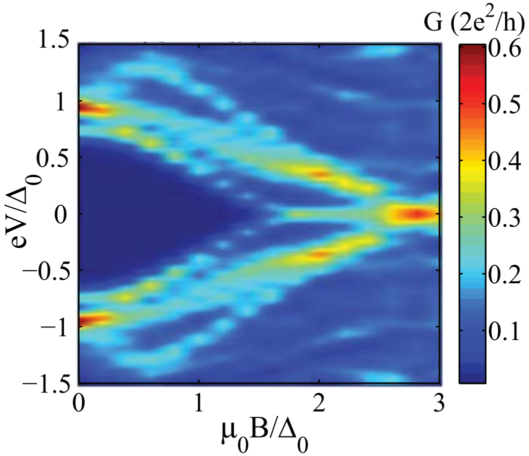
adapted from Sau *et al.* PRB (2010)

period set by λ_F, which depends on B and μ

Non-Majorana oscillations

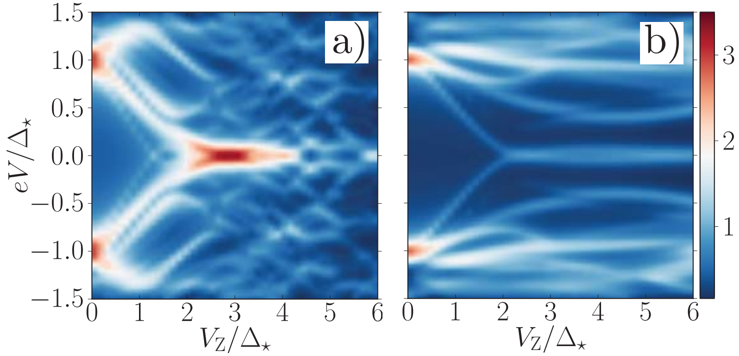
Zero-bias peaks in spin-orbit coupled superconducting wires with and without Majorana end-states

Jie Liu[1,*] Andrew C. Potter[2,*] K.T. Law[1], and Patrick A. Lee[2]
[1] *Department of Physics, Hong Kong University of Science and Technology, Clear Water Bay, Hong Kong, China and*
[2] *Massachusetts Institute of Technology 77 Massachusetts Ave. Cambridge, MA 02139*



Realistic transport modeling for a superconducting nanowire with Majorana fermions

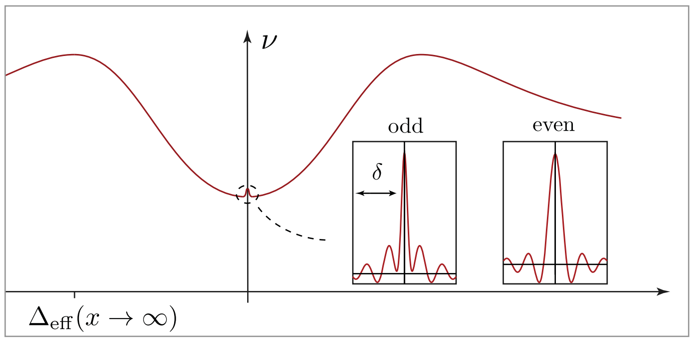
Diego Rainis, Luka Trifunovic, Jelena Klinovaja, and Daniel Loss
Department of Physics, University of Basel, Klingelbergstrasse 82, CH-4056 Basel, Switzerland
(Dated: July 26, 2012)



PRL **109,** 227005 (2012) PHYSICAL REVIEW LETTERS week ending 30 NOVEMBER 2012

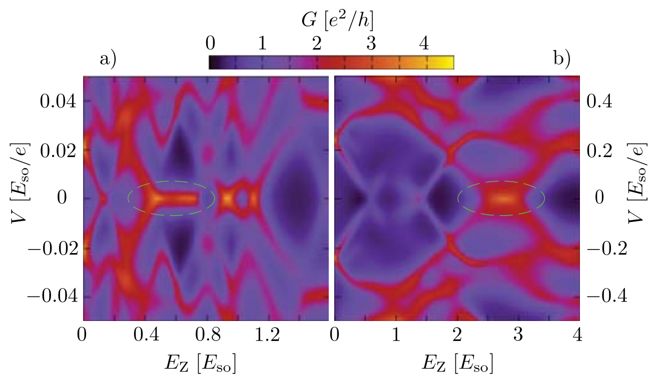
Class *D* Spectral Peak in Majorana Quantum Wires

Dmitry Bagrets and Alexander Altland
Institut für Theoretische Physik, Universität zu Köln, Köln 50937, Germany
(Received 4 June 2012; published 29 November 2012)

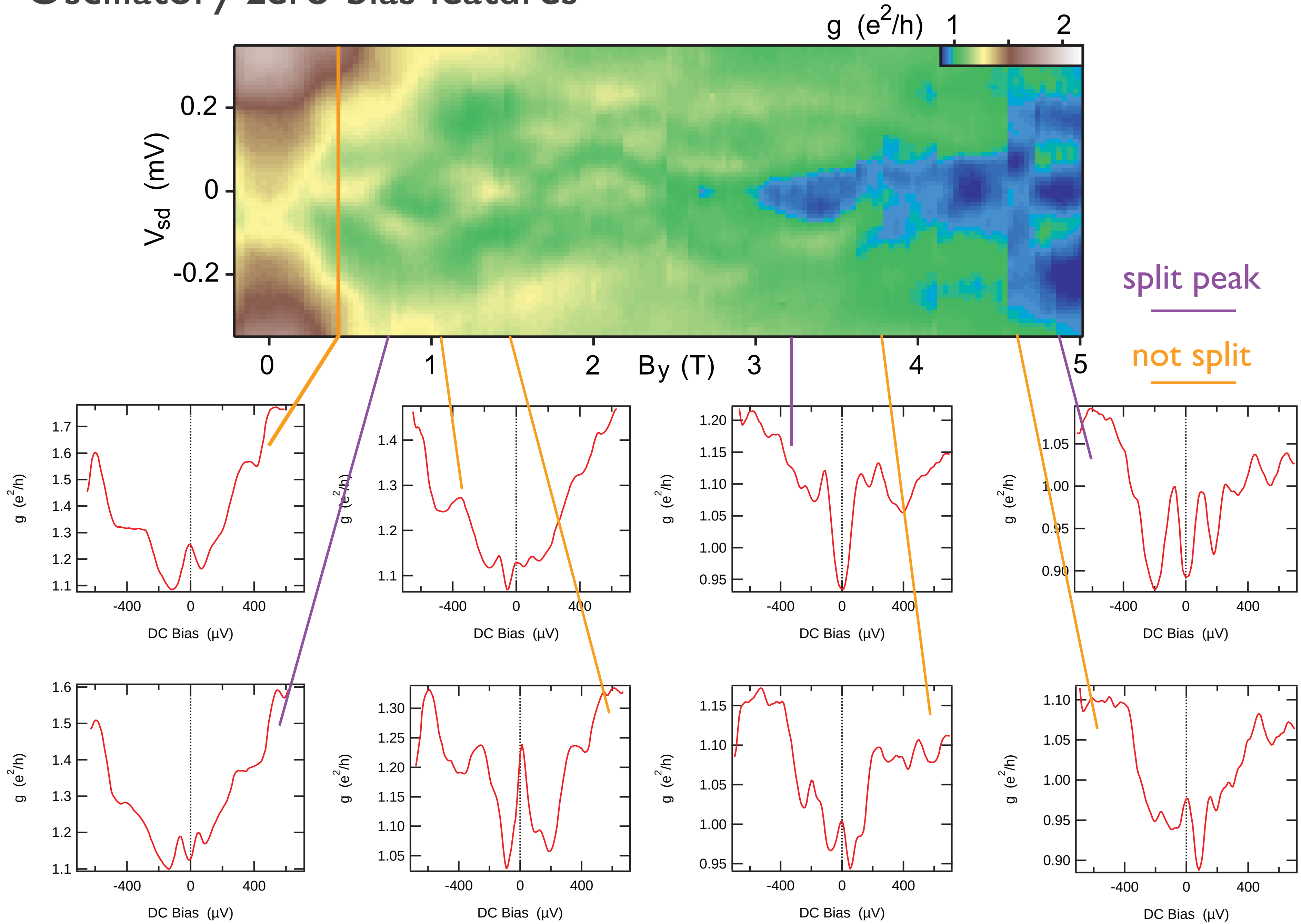


A zero-voltage conductance peak from weak antilocalization in a Majorana nanowire

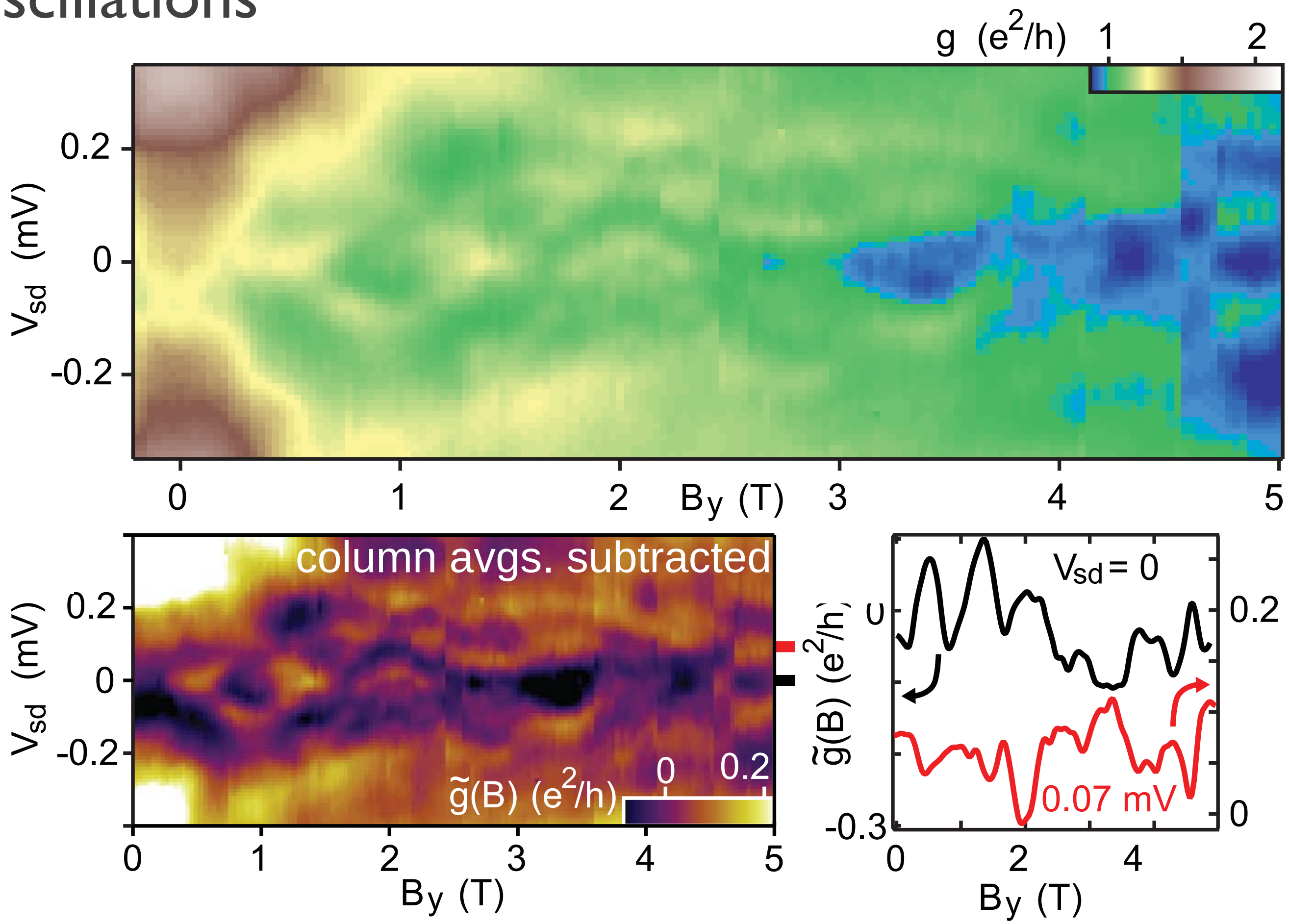
D I Pikulin[1,3], J P Dahlhaus[1], M Wimmer[1], H Schomerus[2] and C W J Beenakker[1]
[1] Instituut-Lorentz, Universiteit Leiden, PO Box 9506, 2300 RA Leiden, The Netherlands
[2] Department of Physics, Lancaster University, Lancaster, LA1 4YB, UK



Oscillatory zero-bias features



Oscillations



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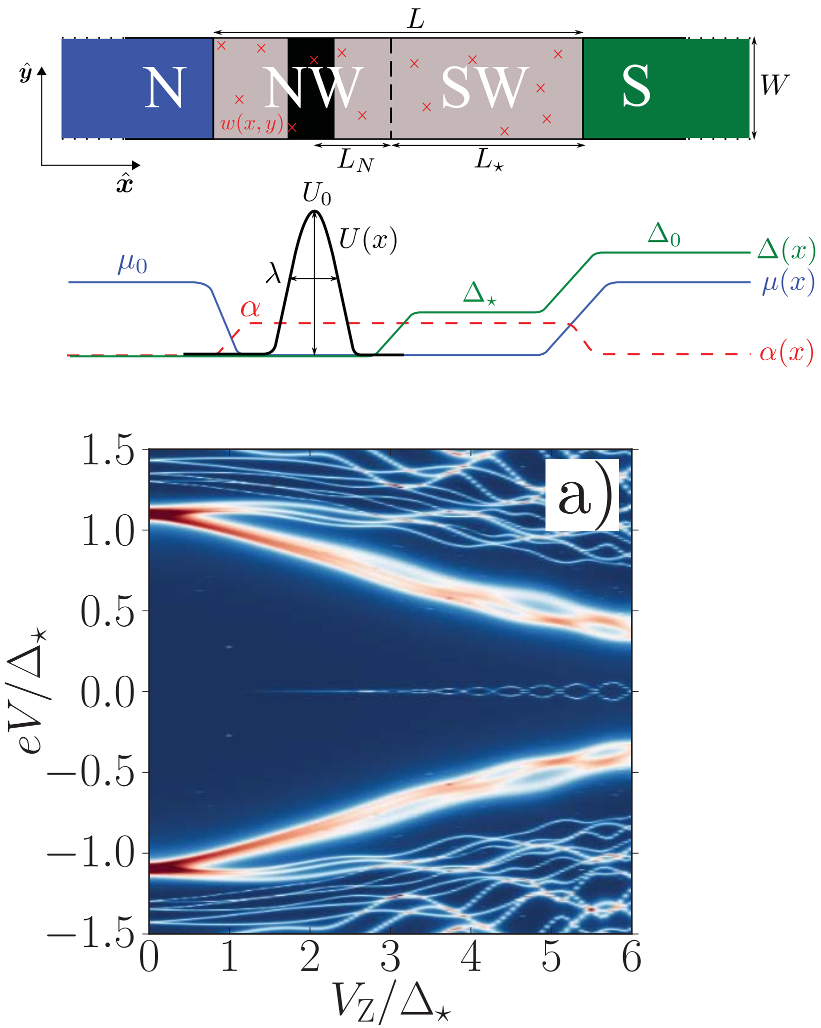


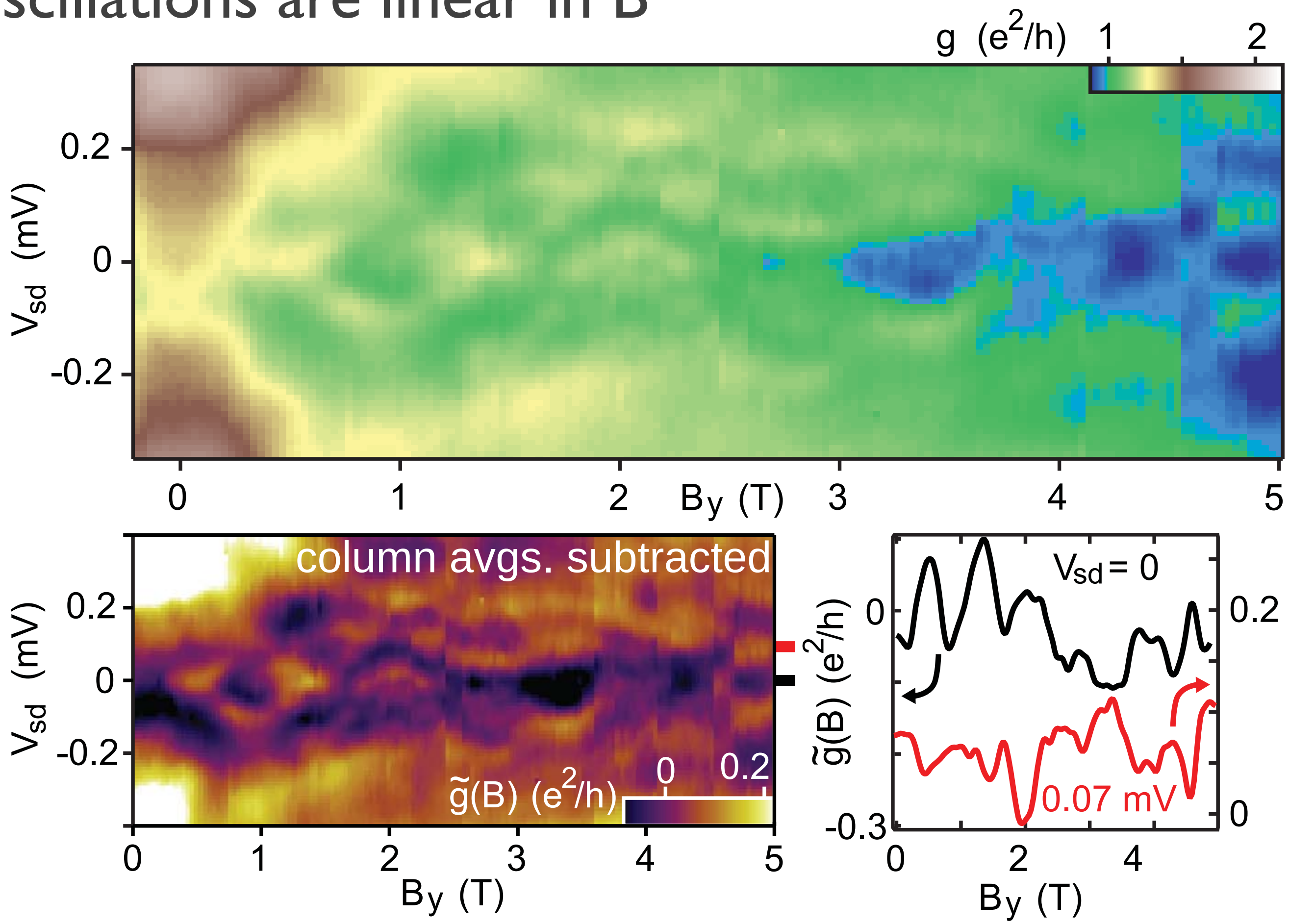
see also
Das Sarma *et al.* PRB (2012)
Prada *et al.* PRB (2012)
Lin *et al.* PRB (2012)

period of oscillations should grow with B:

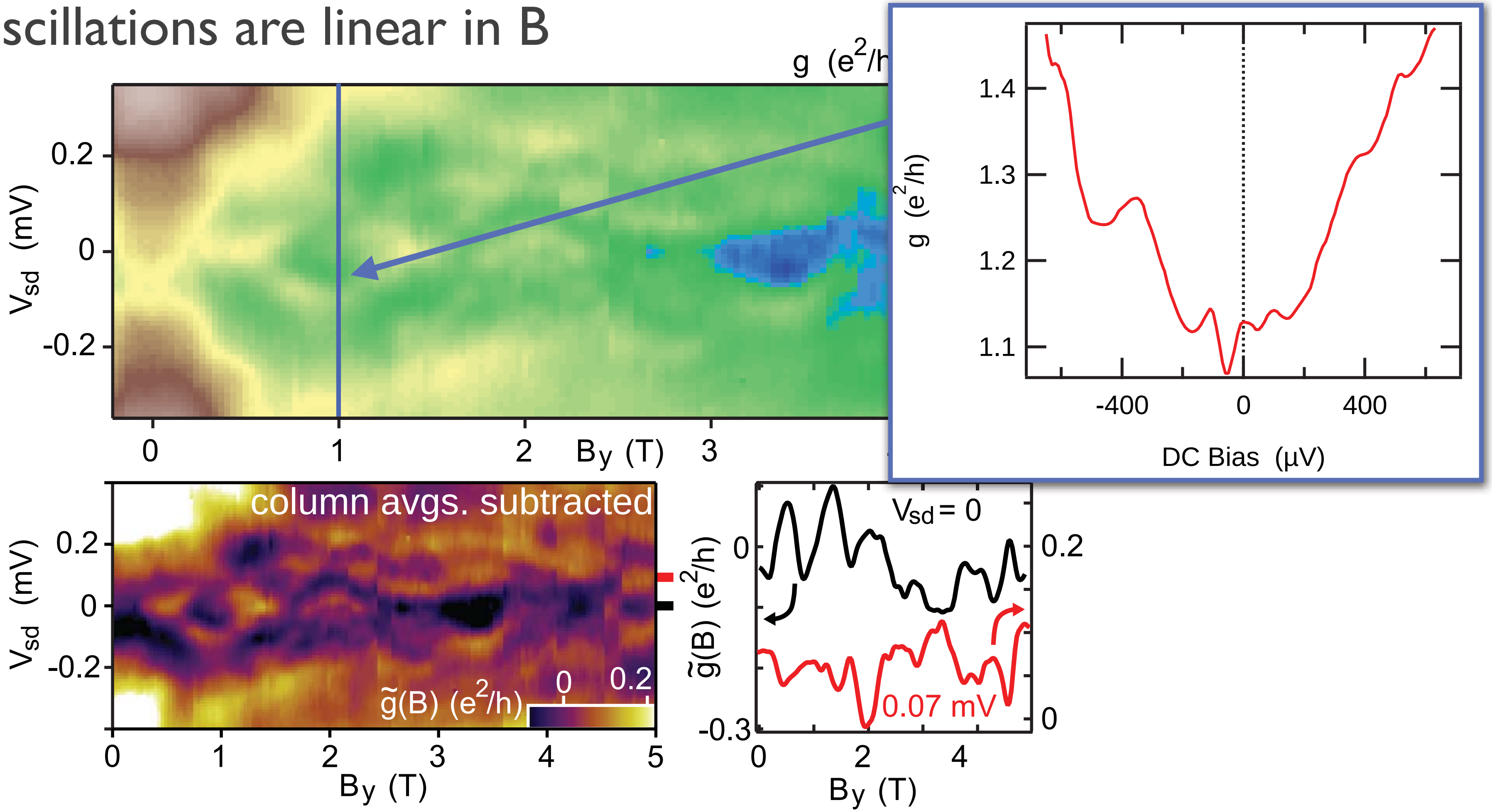
$$\delta(V_Z/\Delta_\star) = \frac{\pi\hbar}{L_\star\Delta_\star}\sqrt{\frac{2V_Z}{m}} = \frac{\pi a}{L_\star}\frac{\sqrt{tV_Z}}{\Delta_\star}$$

peak position $\propto B^2$

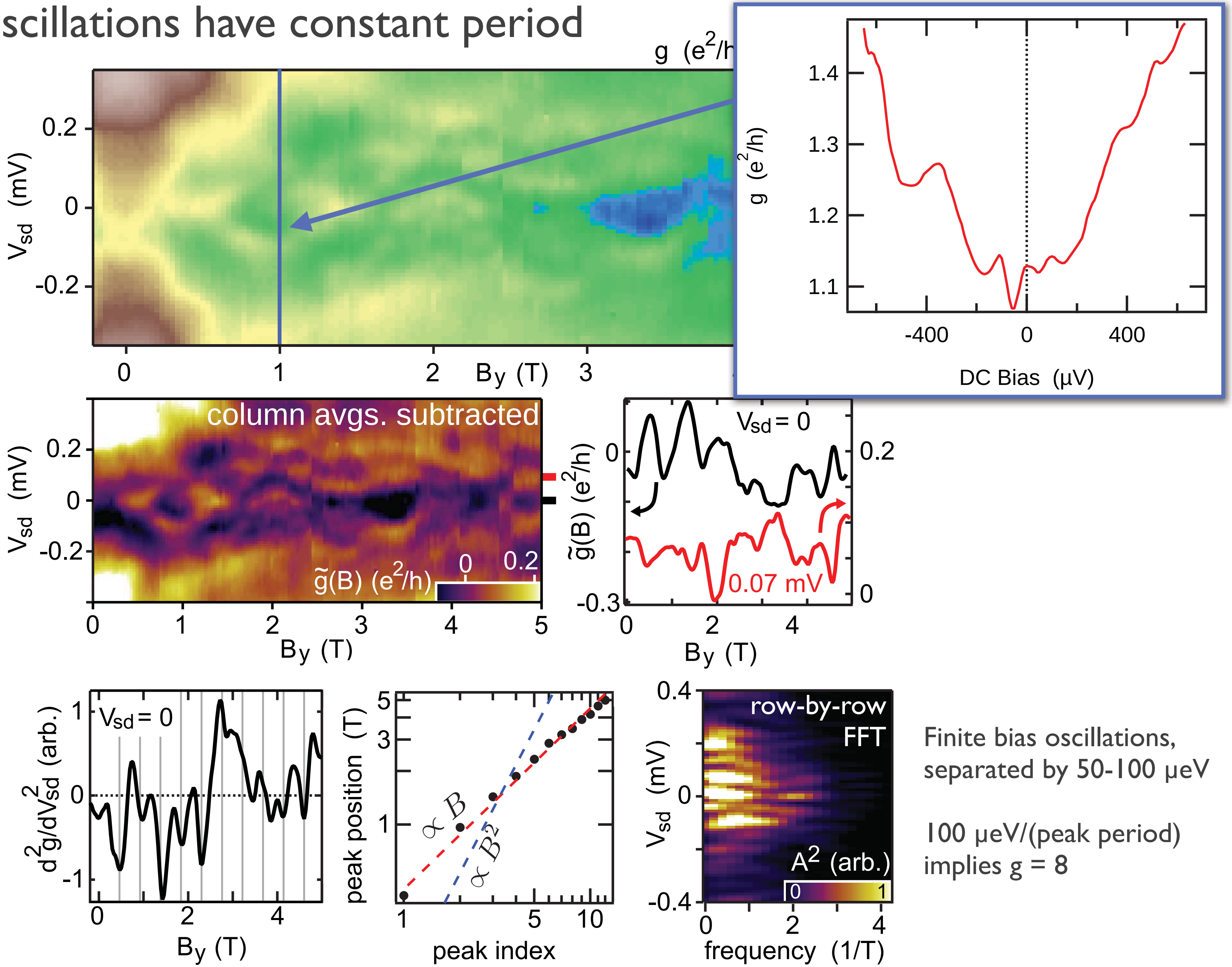
Oscillations are linear in B



Oscillations are linear in B



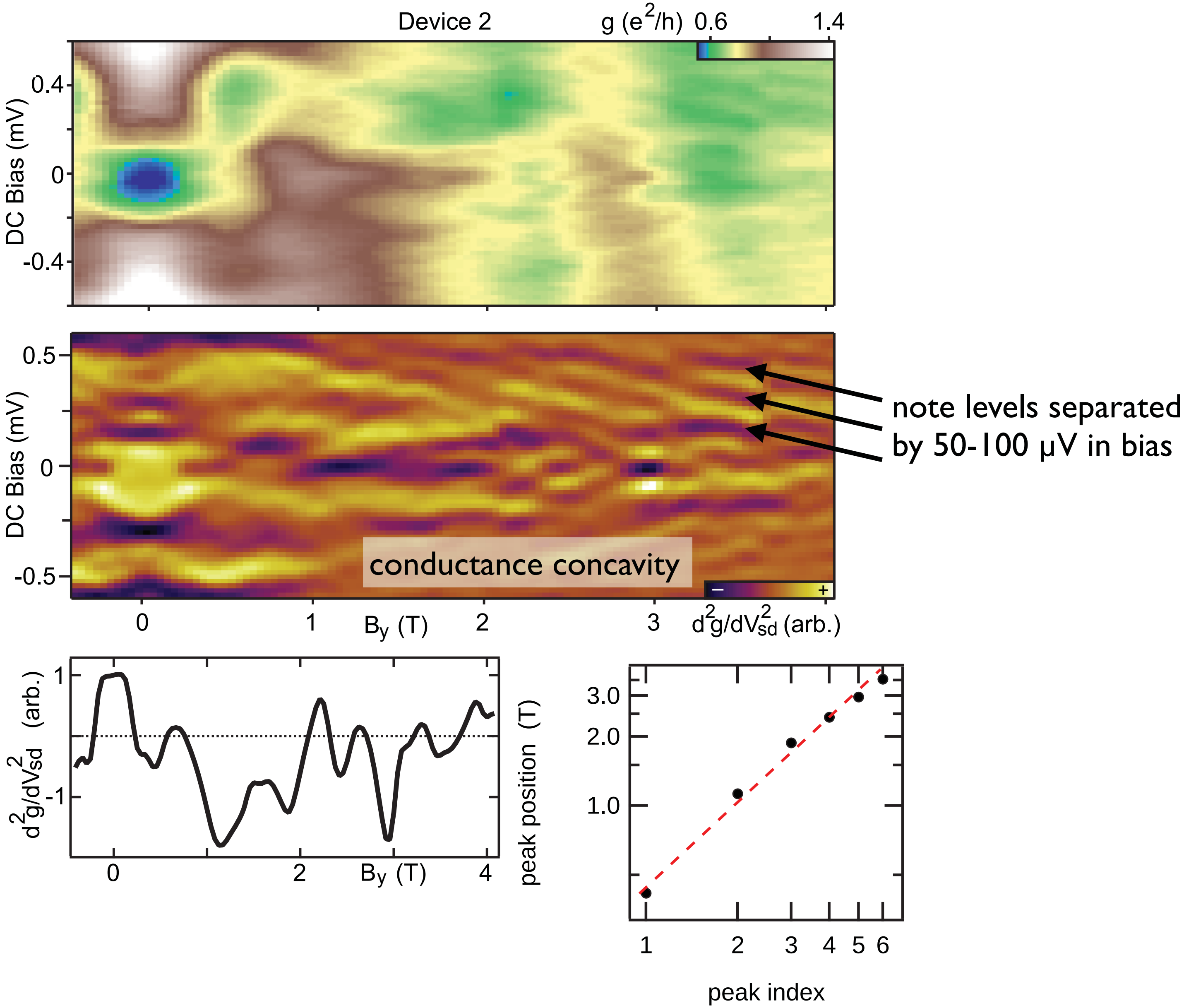
Oscillations have constant period



Finite bias oscillations, separated by 50-100 μeV

100 μeV/(peak period) implies g = 8

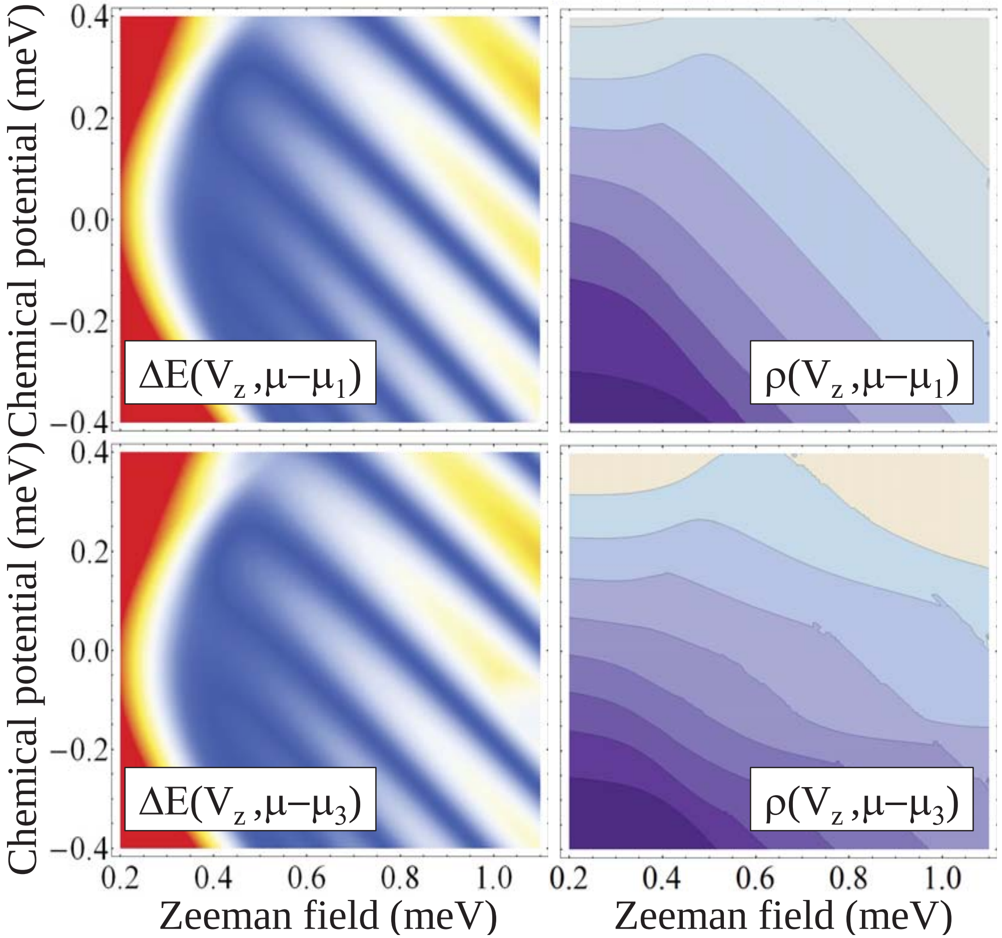
Second device, oscillations also linear in B



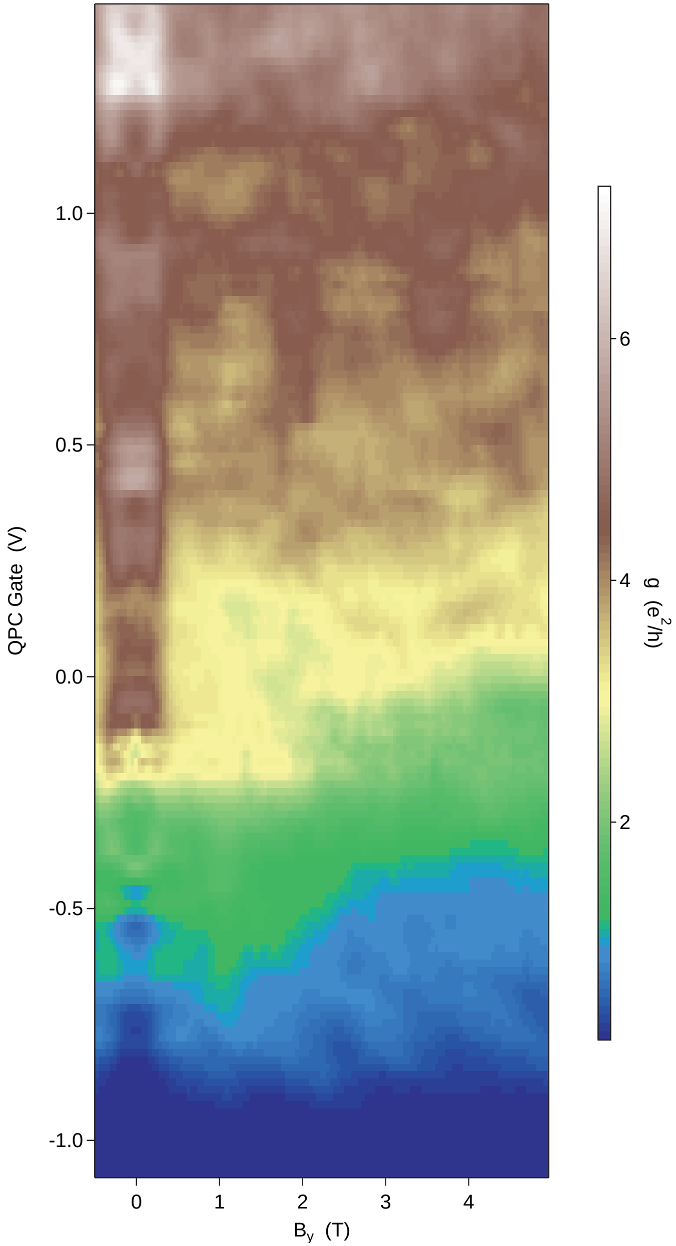
PHYSICAL REVIEW B **86**, 220506(R) (2012)

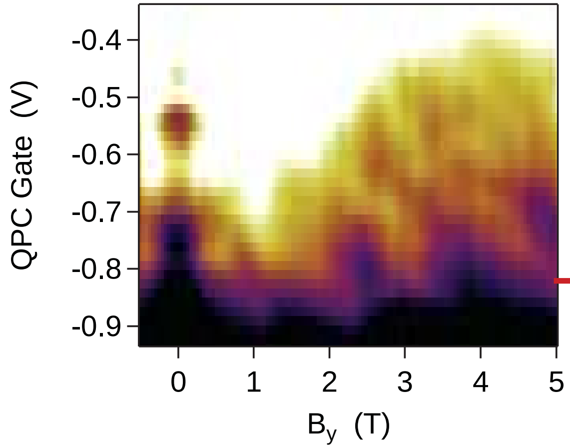
Splitting of the zero-bias conductance peak as smoking gun evidence for the existence of the Majorana mode in a superconductor-semiconductor nanowire

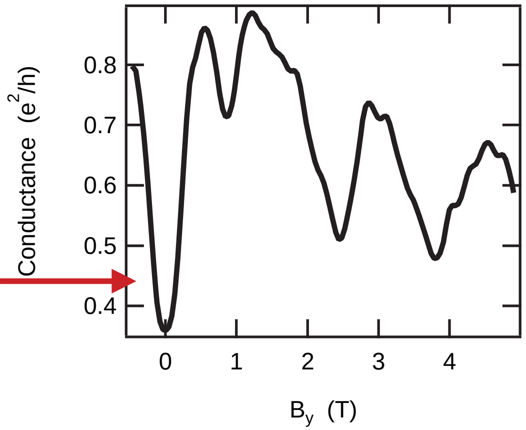
S. Das Sarma,[1] Jay D. Sau,[2] and Tudor D. Stanescu[3]

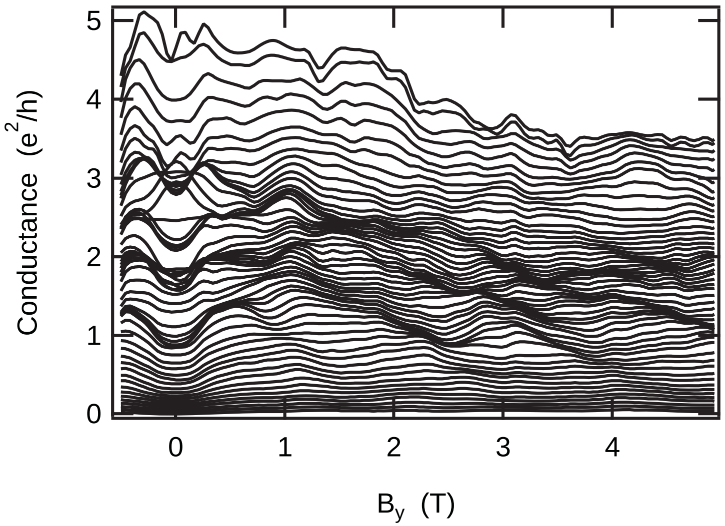


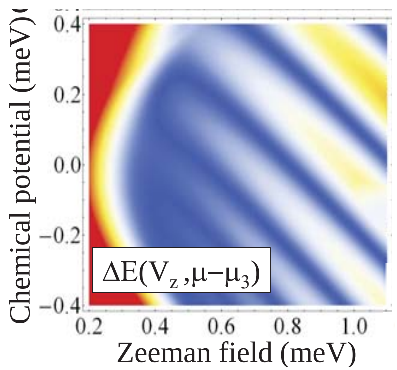
Oscillations vs. B and Vg





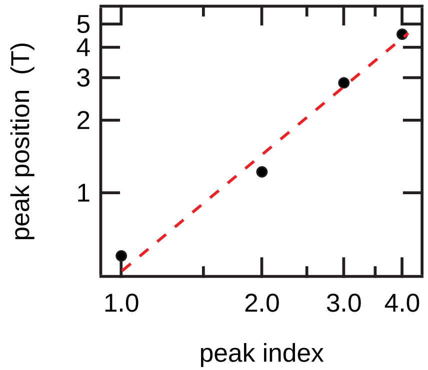






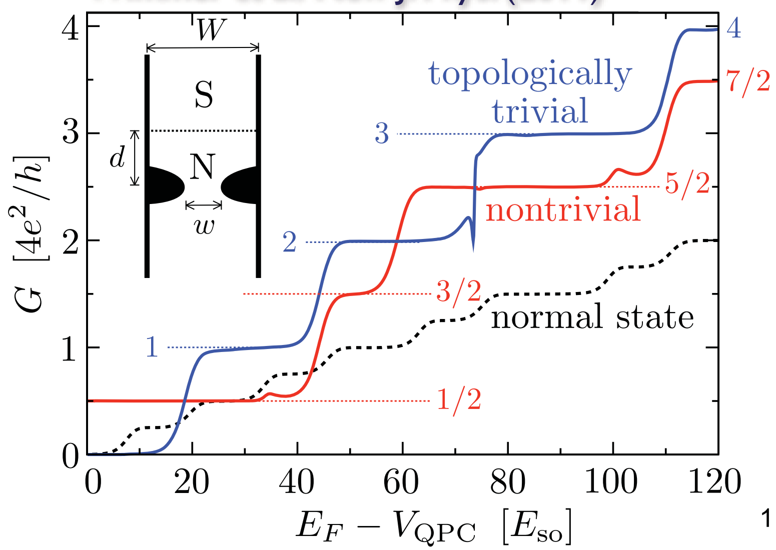
Das Sarma *et al.*
arXiv:1211.0539

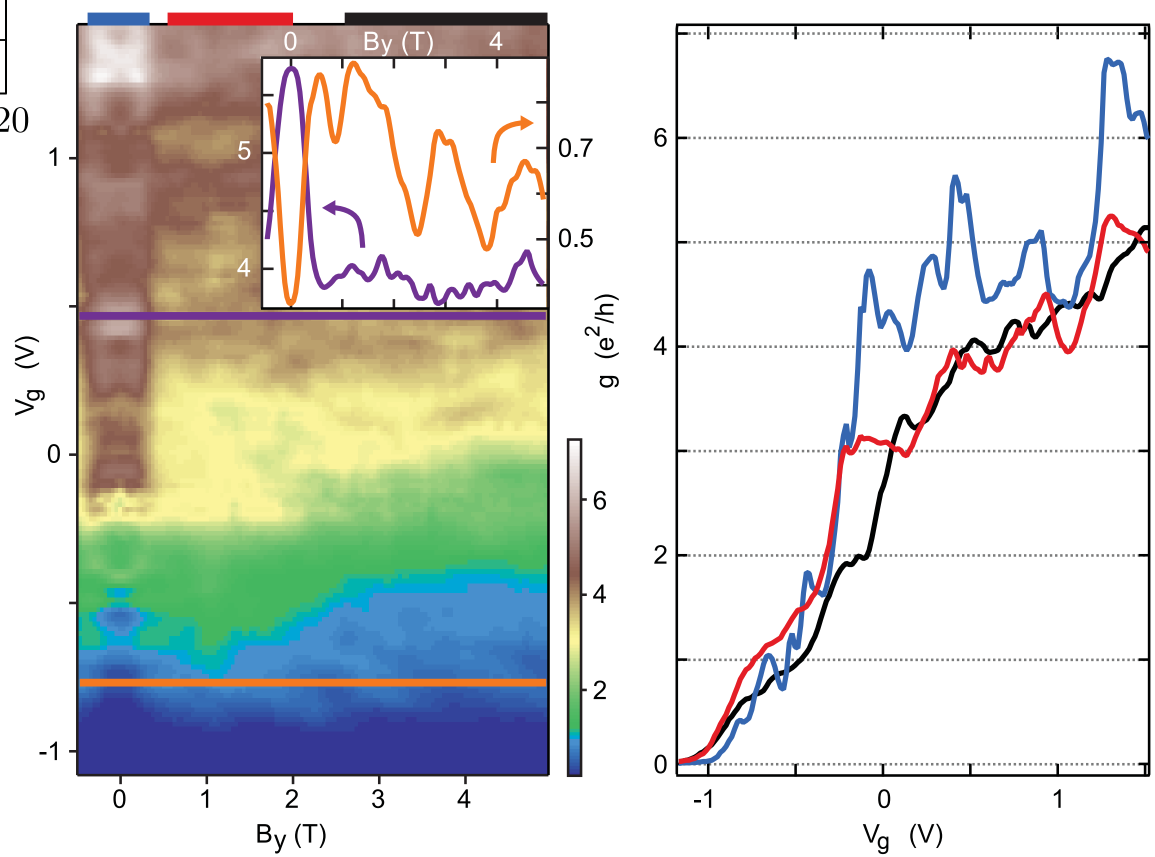
also approx. linear:



Magnetoconductance crossover

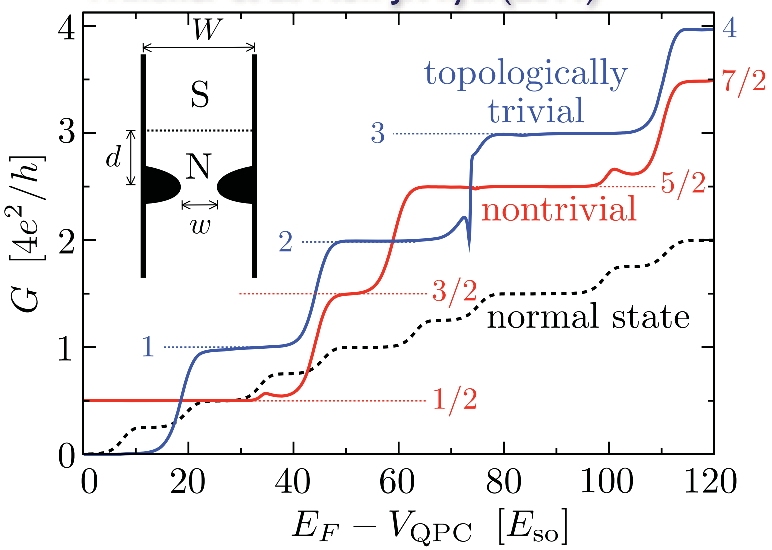
Wimmer *et al.* New J. Phys. (2011)

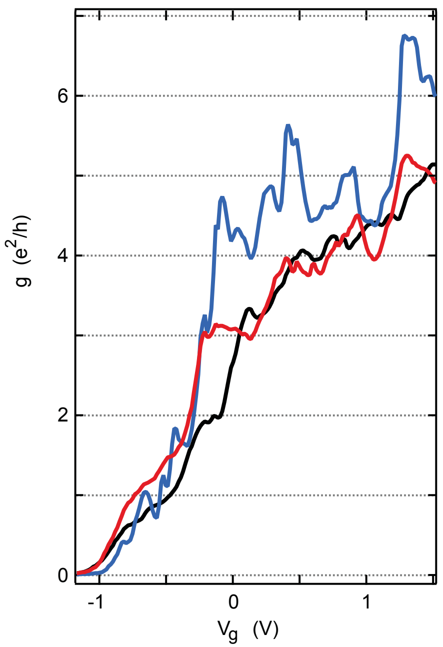




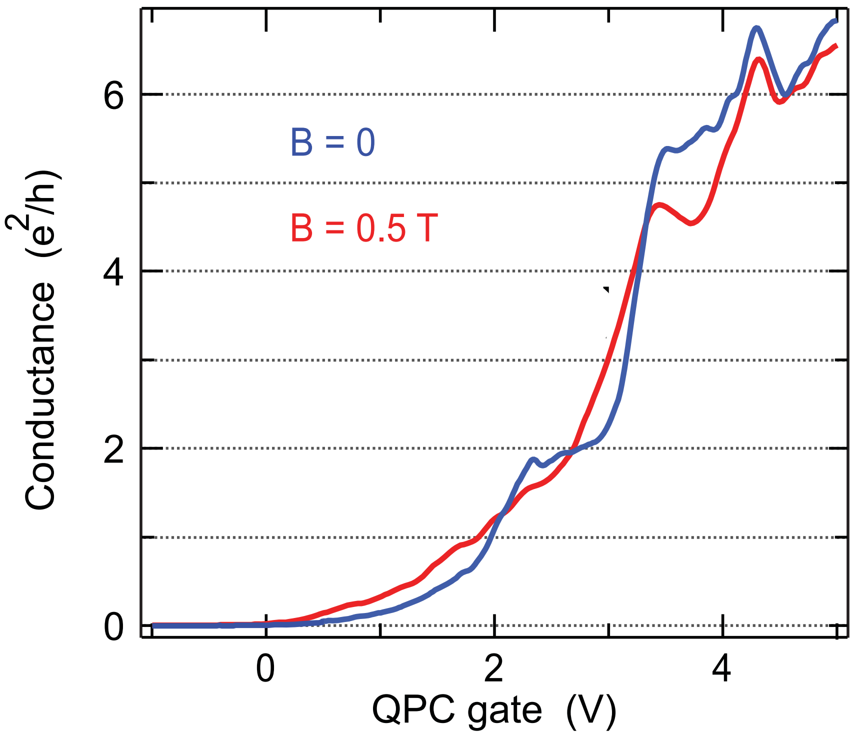
Magnetoconductance crossover

Wimmer *et al.* New J. Phys. (2011)

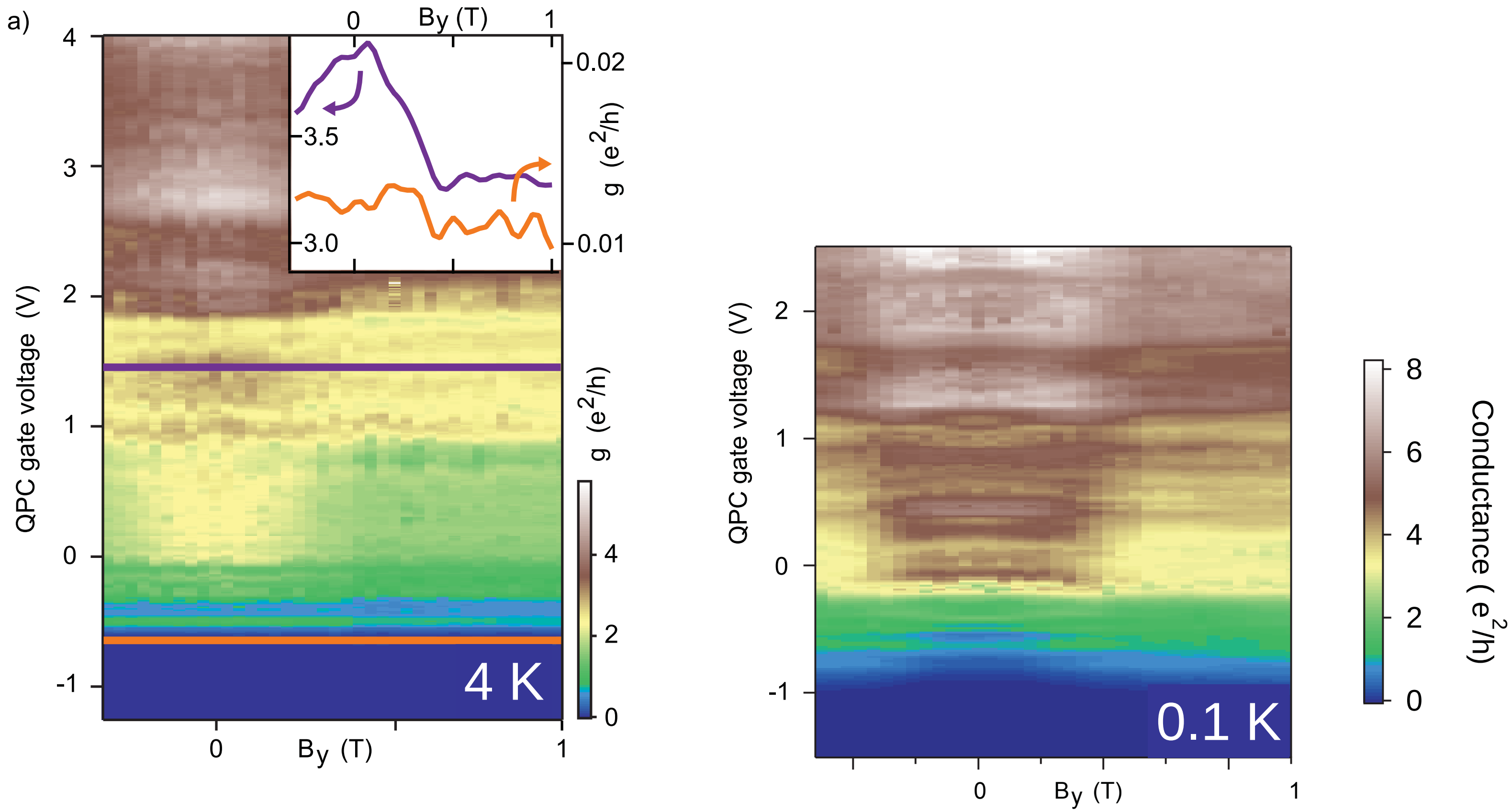




Other device, no field averaging:



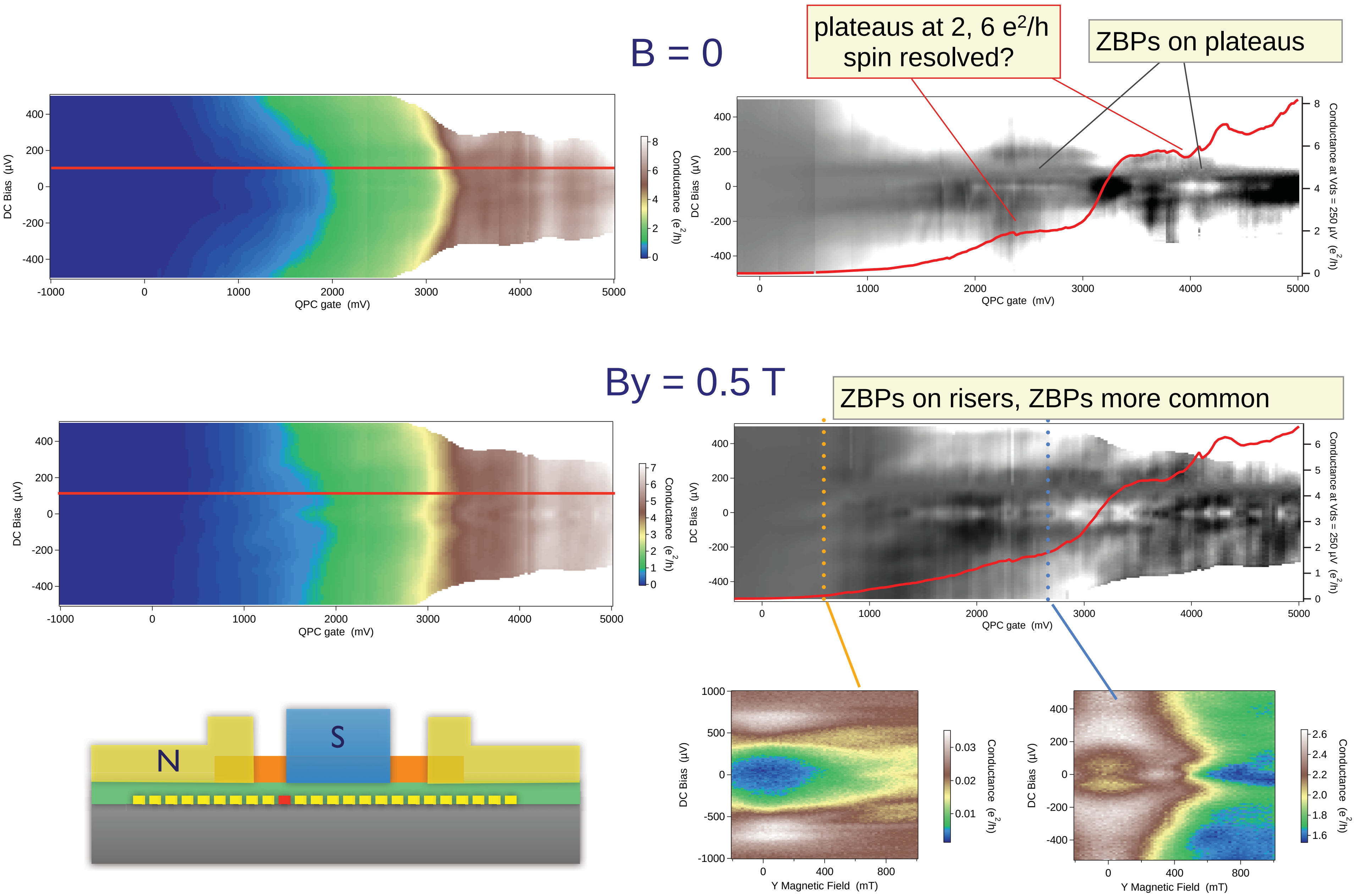
QPC field dependence at 4 K



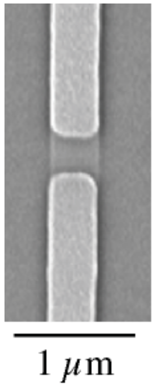
Crossover gone at 4 K:

Conductance increase near pinch-off is gone, but Andreev enhancement at higher conductance is still present

Zero-bias peaks at zero field and at finite field

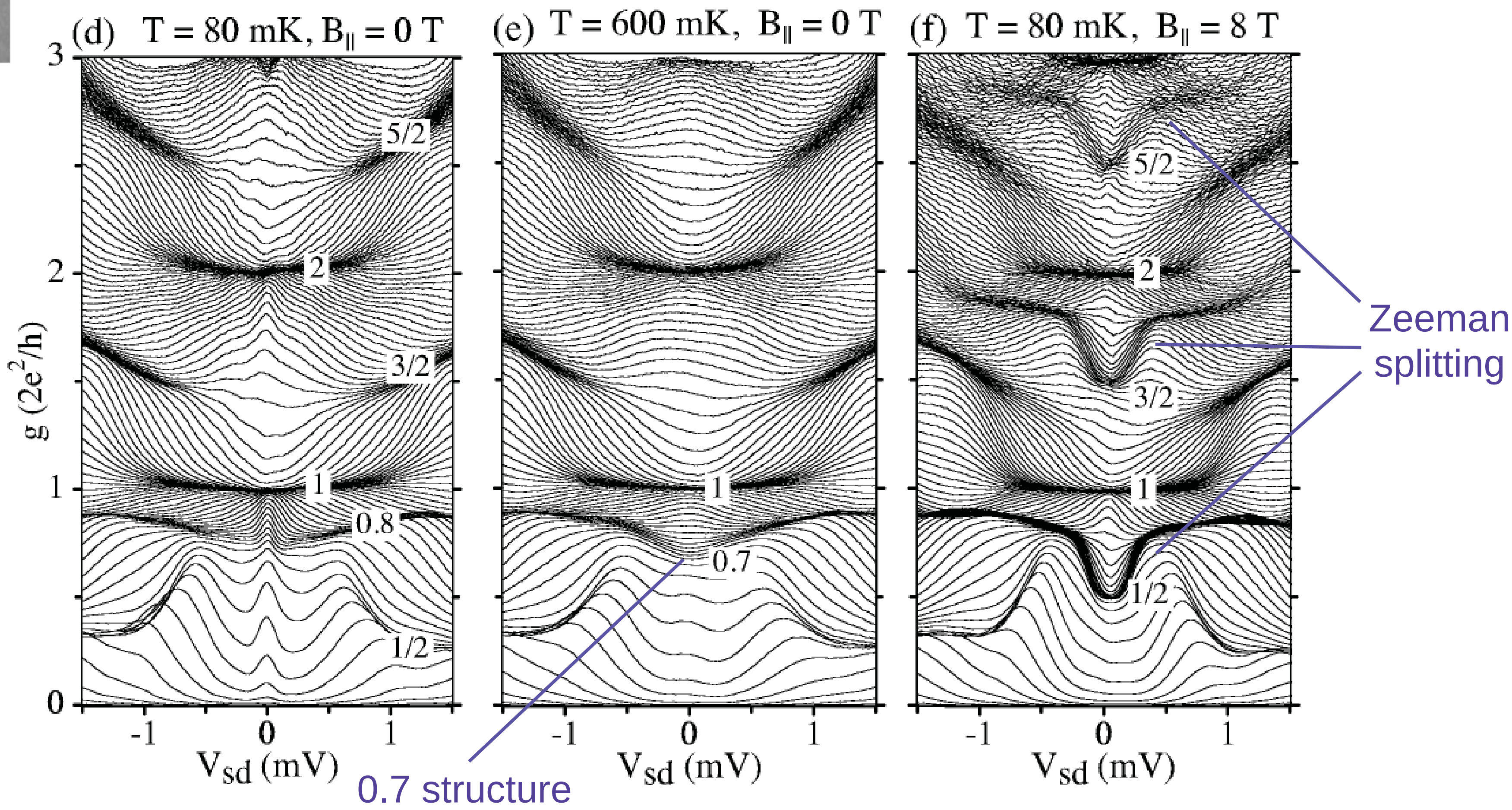


VOLUME 88, NUMBER 22 PHYSICAL REVIEW LETTERS 3 JUNE 2002

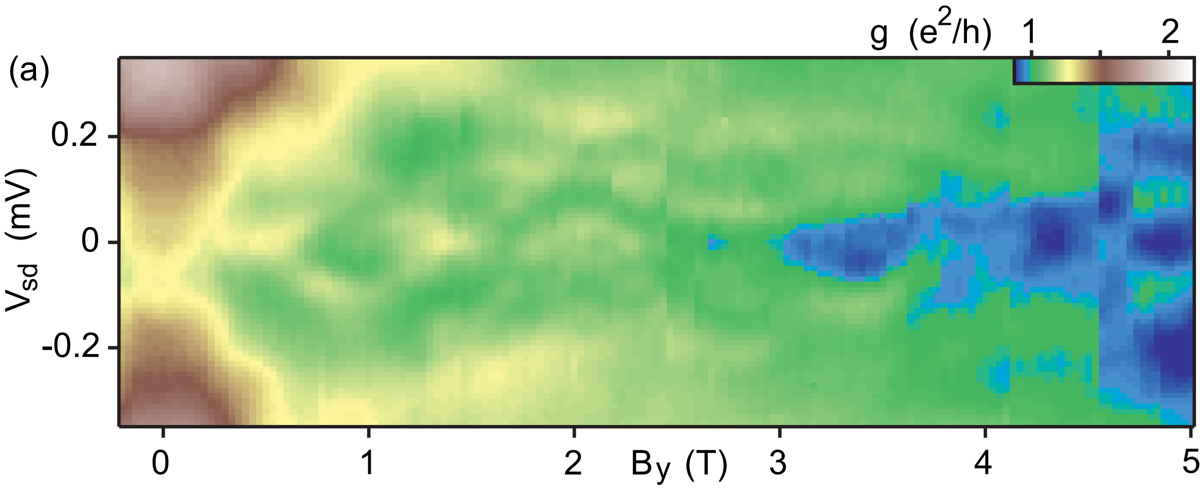


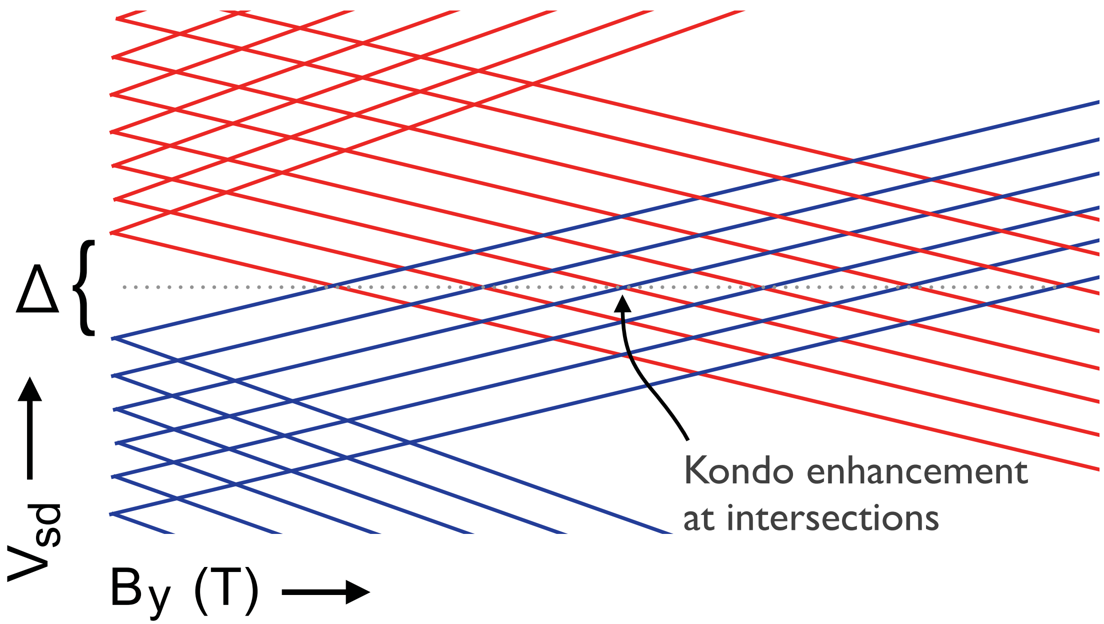
Low-Temperature Fate of the 0.7 Structure in a Point Contact: A Kondo-like Correlated State in an Open System

S. M. Cronenwett,[1,2] H. J. Lynch,[1] D. Goldhaber-Gordon,[1,2] L. P. Kouwenhoven,[1,3] C. M. Marcus,[1] K. Hirose,[4] N. S. Wingreen,[5] and V. Umansky[6]

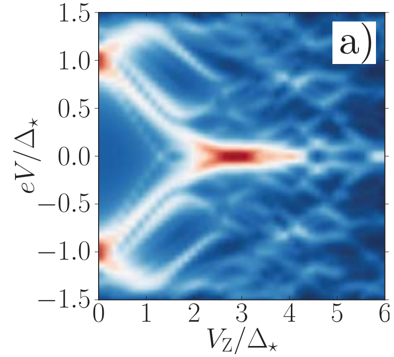


Disorder + Kondo/0.7 picture

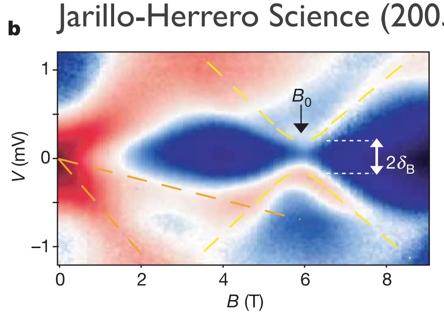




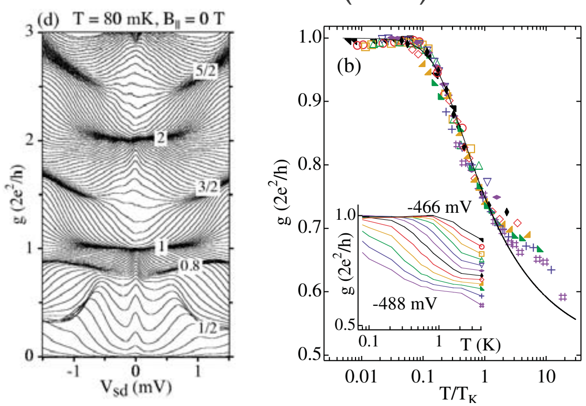
don't expect g = 50
for clustered, repelling levels
Rainis *et al.* arXiv:1207.5907



CNTs: Kondo with large g-factor (20)
and >2 states
Jarillo-Herrero Science (2005)

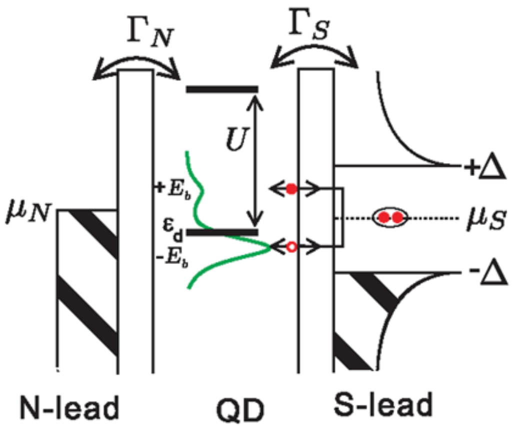


0.7: Kondo-like features in QPCs
Cronenwett *et al.* PRL (2002)

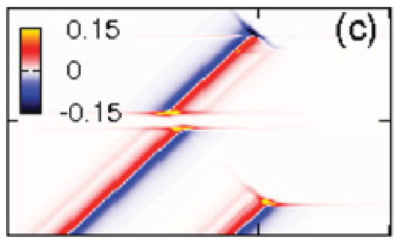


switch from N-QPC-S to N-dot-S

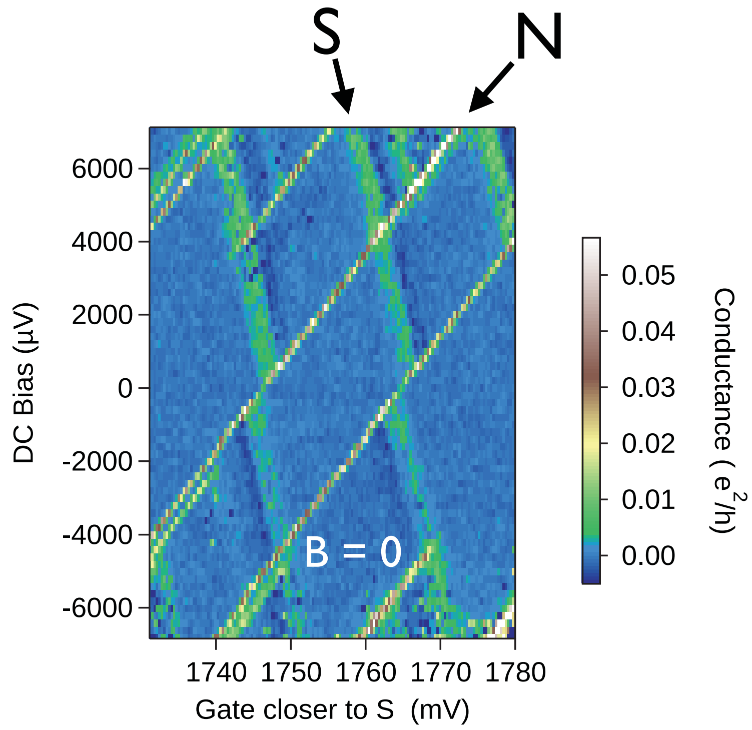
N-dot-S

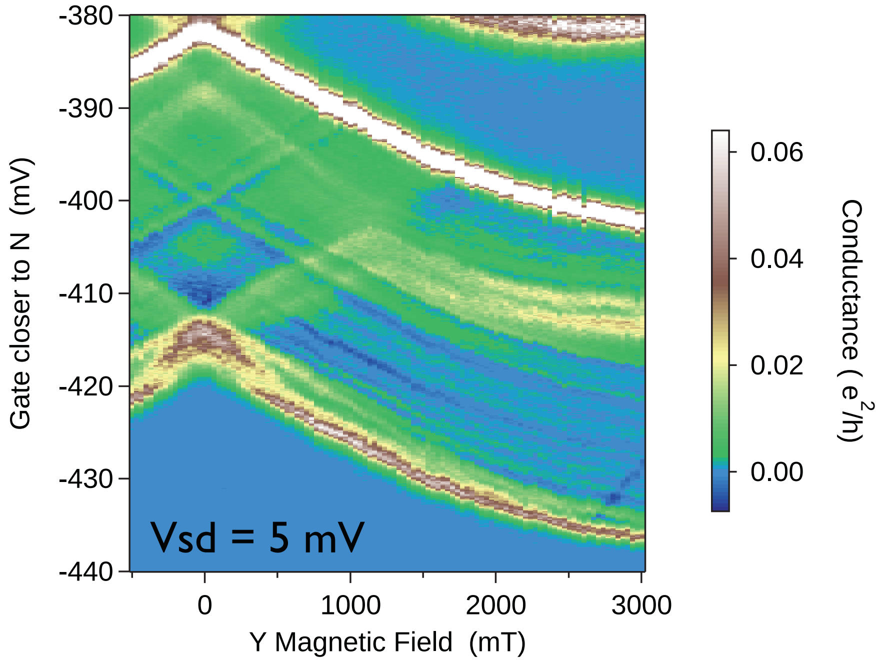


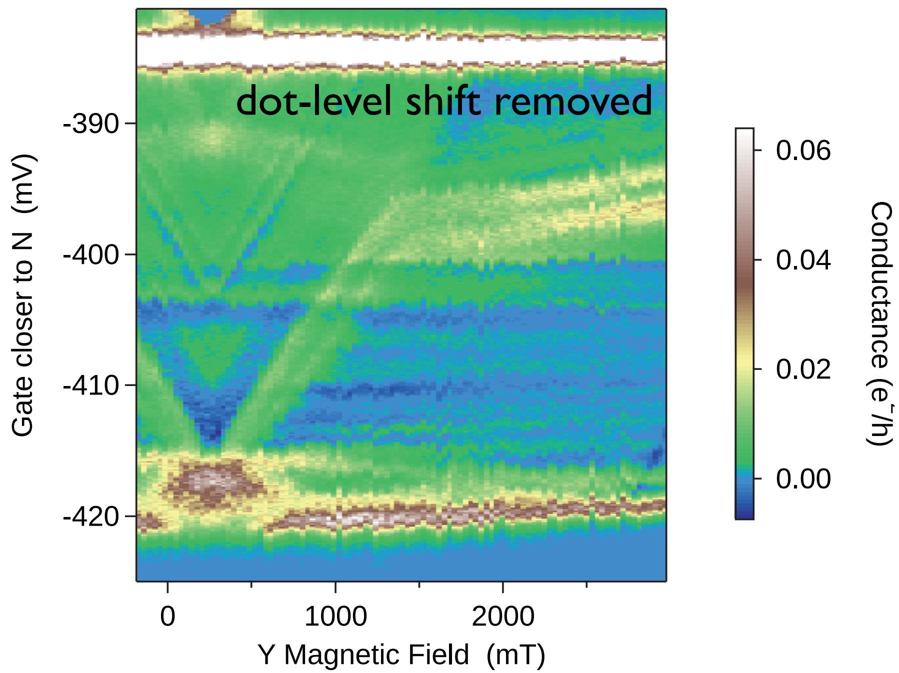
Deacon *et al.* PRL (2010)



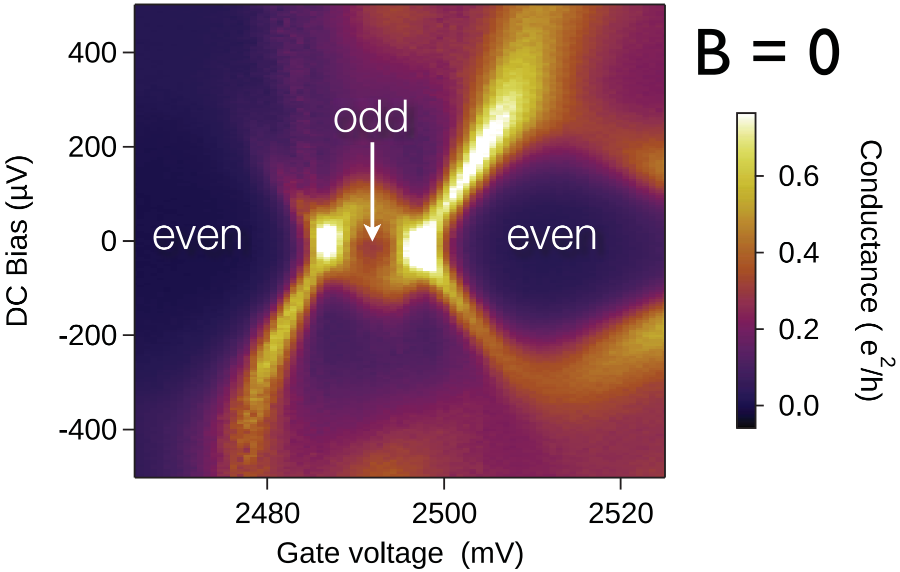
Leijnse and Flensberg PRB (2011)

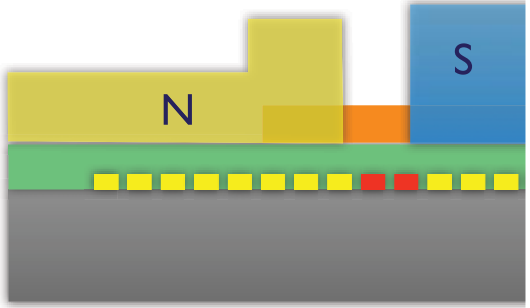




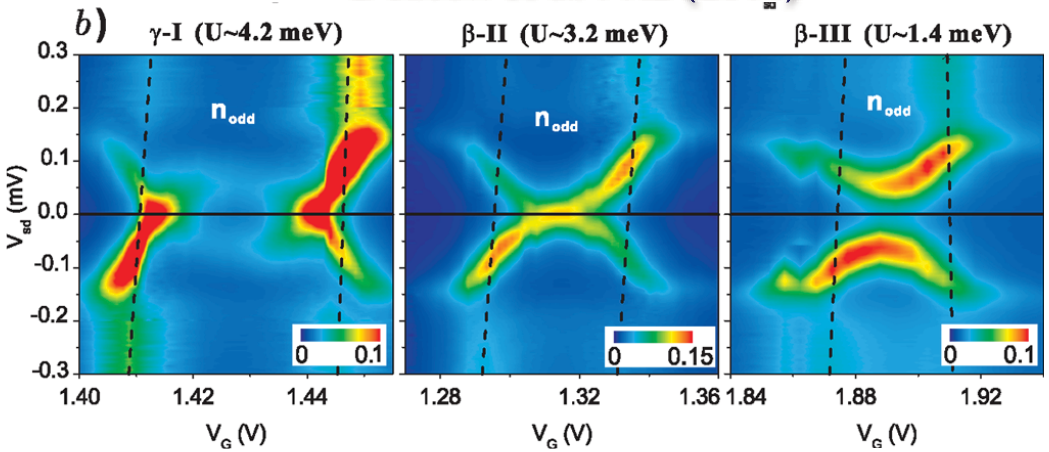


Andreev bound states, Zeeman splitting





Deacon *et al.* PRL (2010)

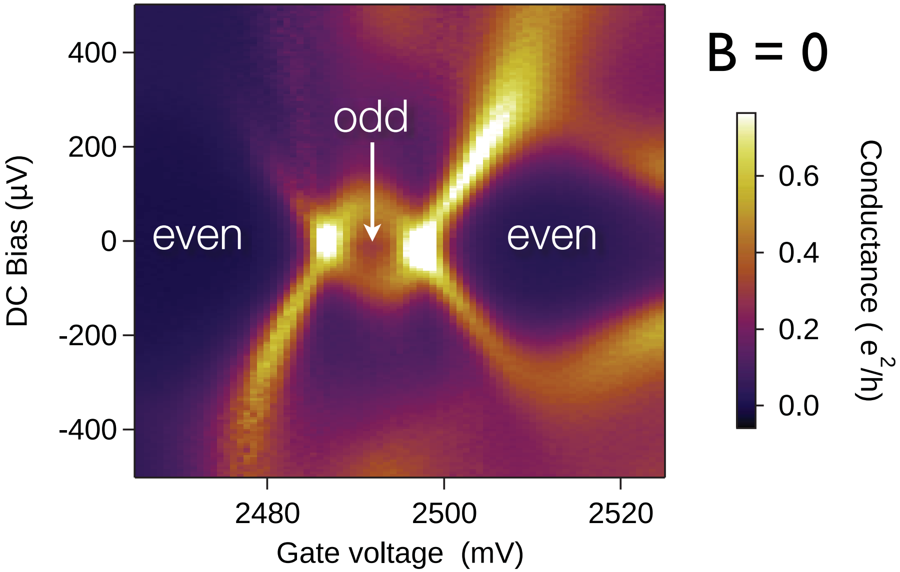


U wins - doublet GS

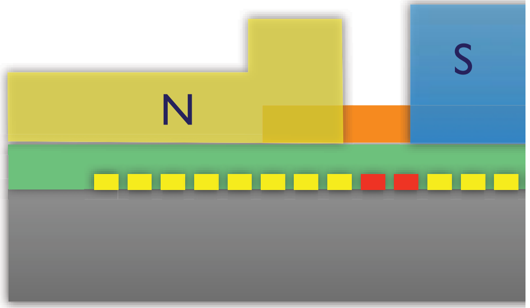
tie

Δ wins - singlet GS

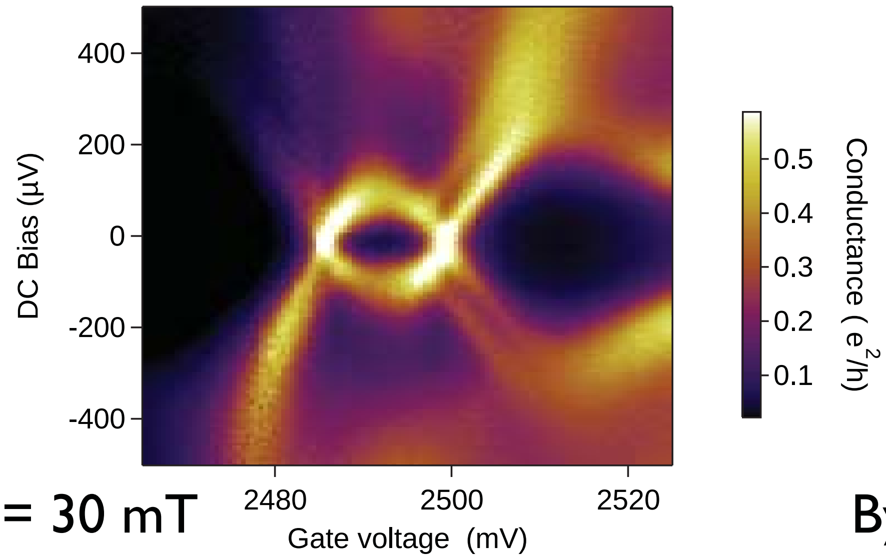
Andreev bound states, Zeeman splitting



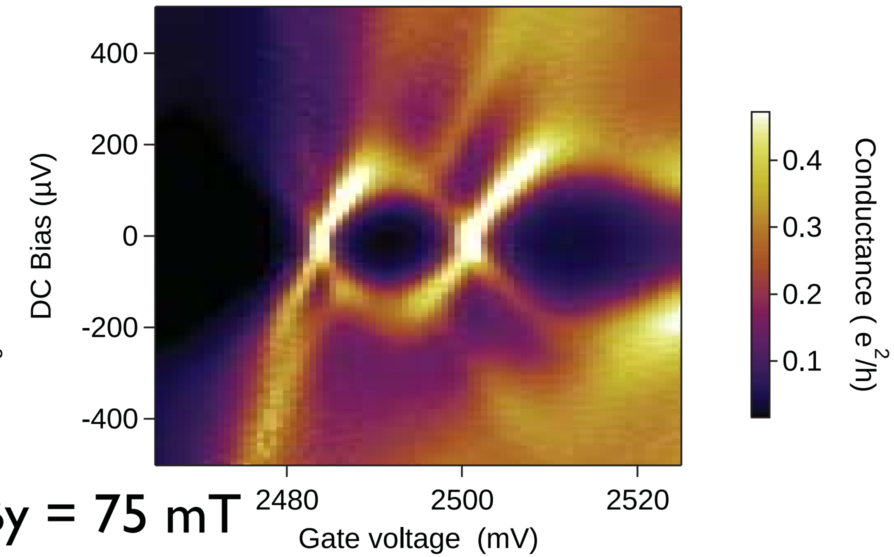
B = 0



see also Lee *et al.* arXiv:1302.2611

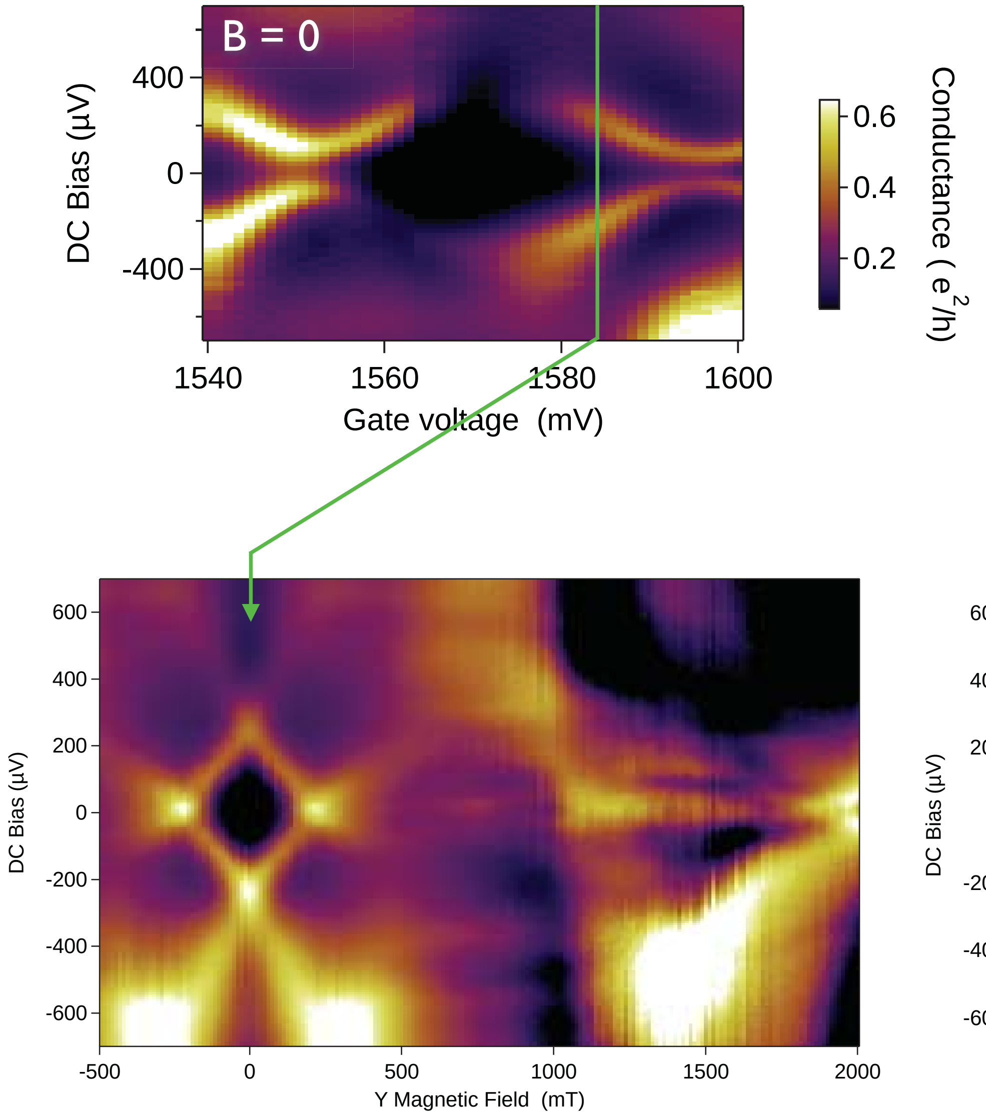


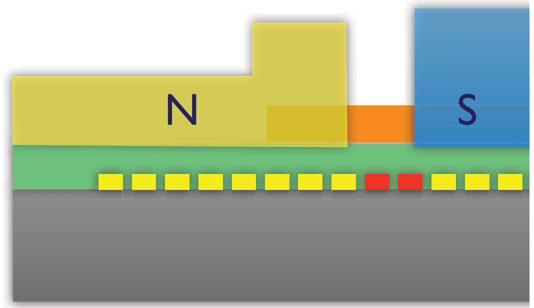
By = 30 mT



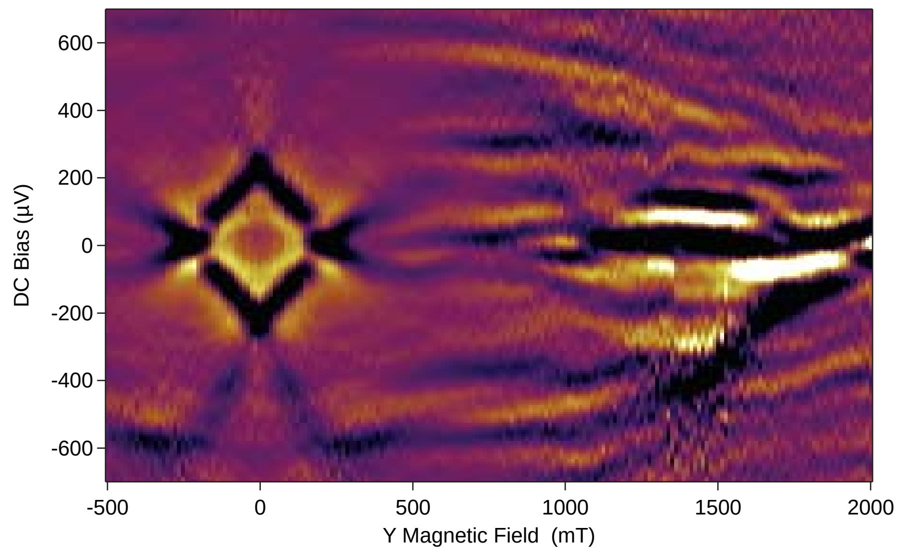
By = 75 mT

Andreev bound states, Zeeman splitting

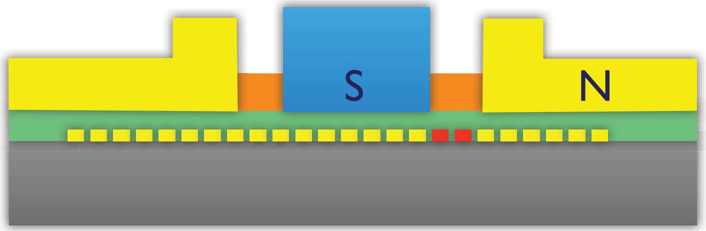




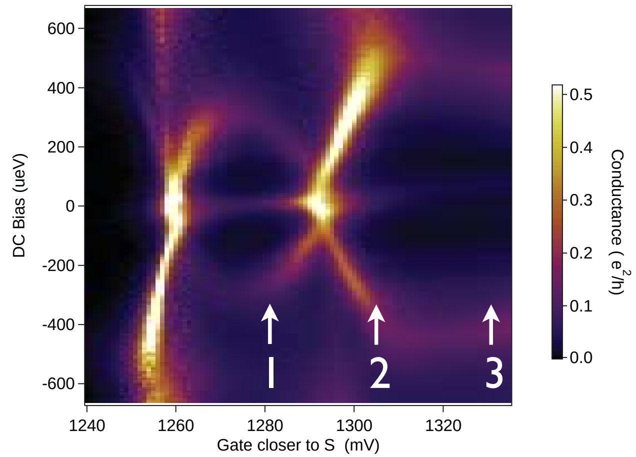
2nd derivative of conductance w.r.t. bias

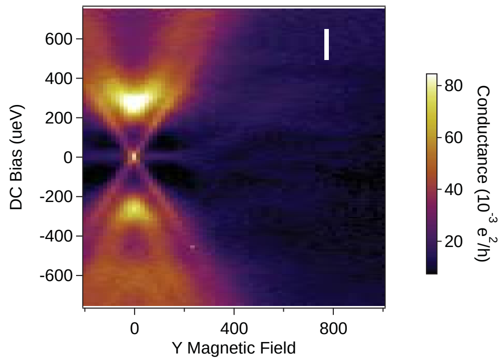


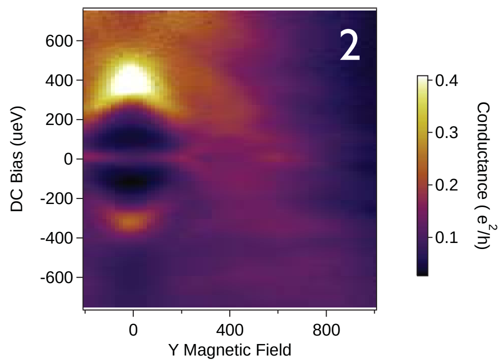
Andreev bound states, vary N and S coupling

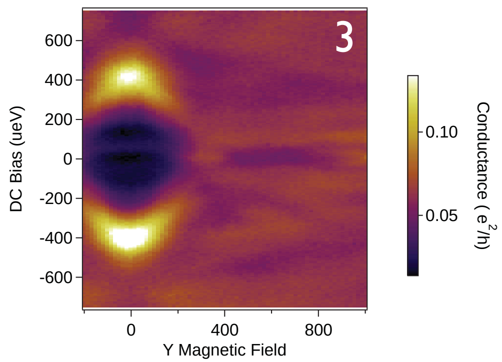


stronger N, weaker S

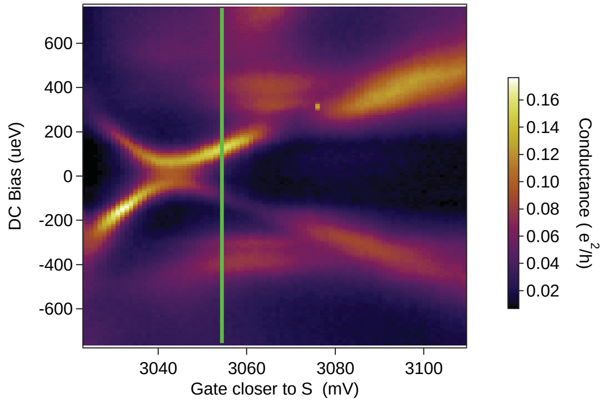


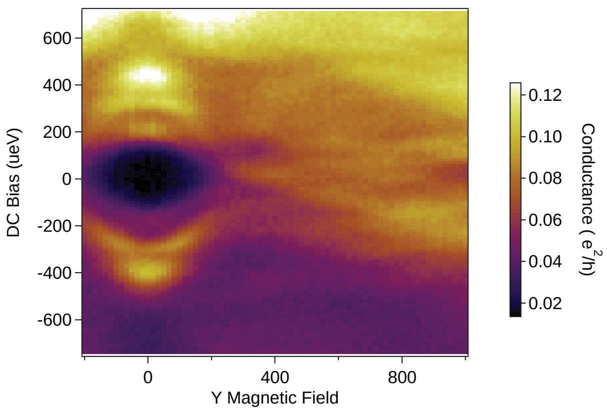




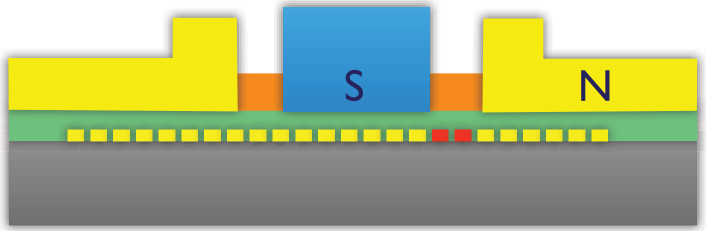


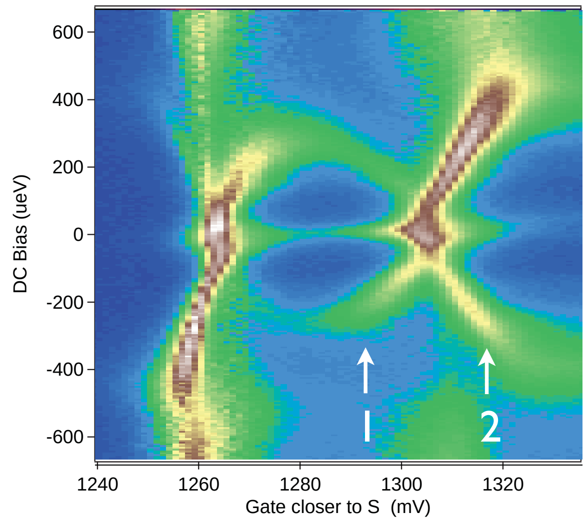
stronger S, weaker N

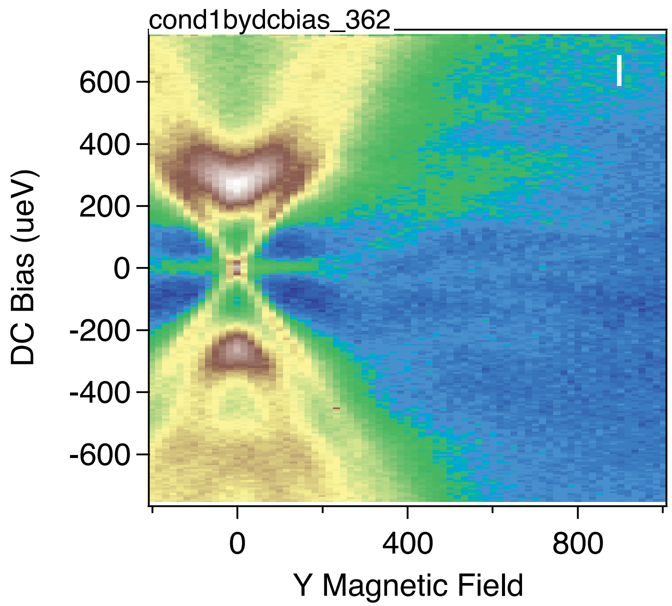


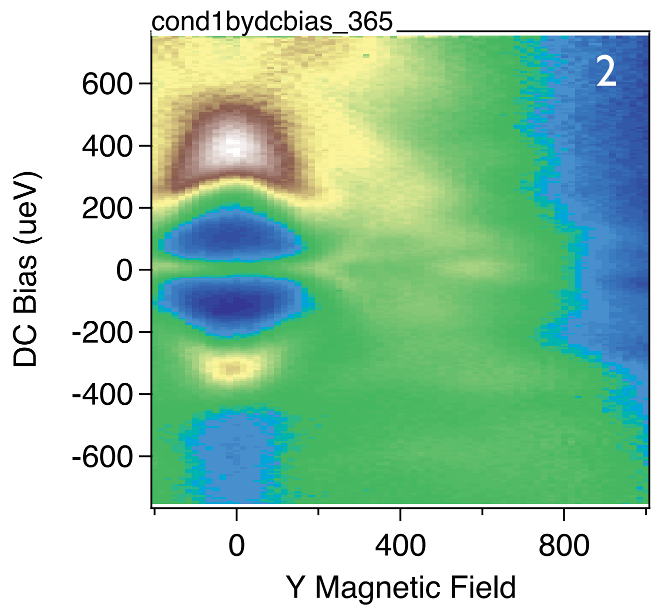


Andreev Bound States, vary N and S coupling

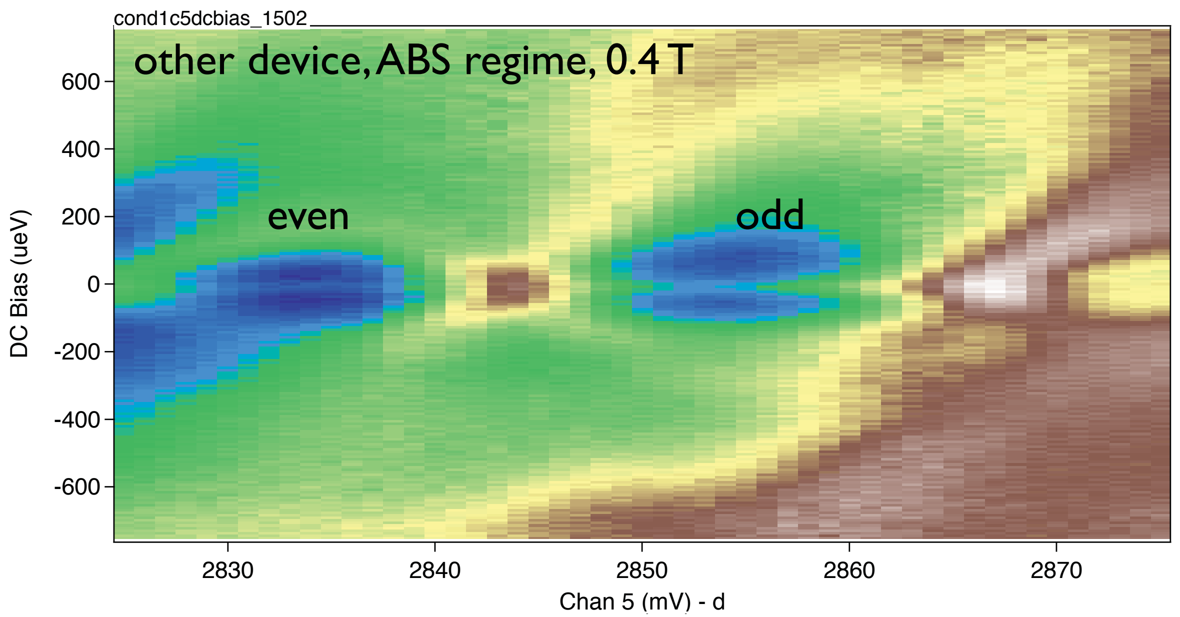








Andreev Bound States, vary N and S coupling



Conclusion

arXiv:1303.2407

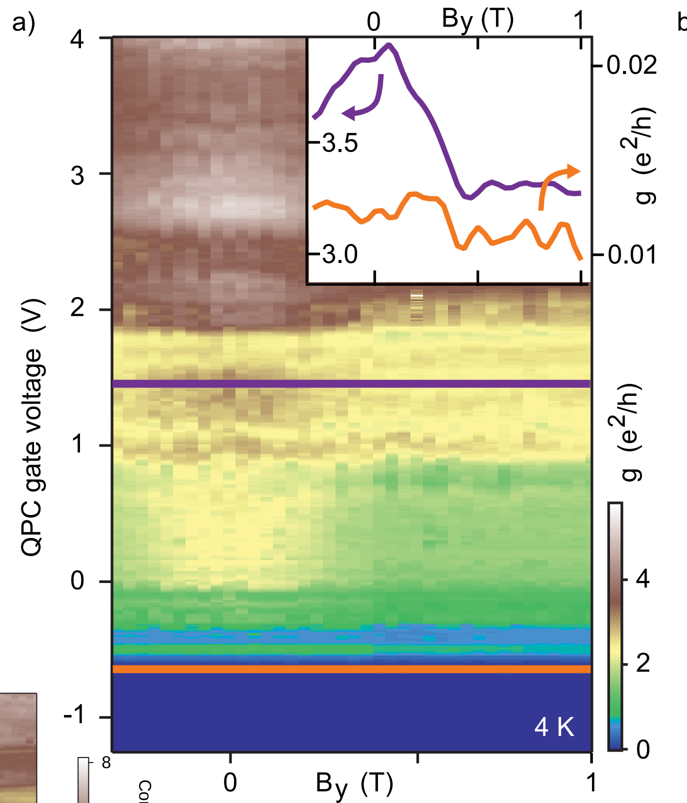
- QPC ZBPs consistent with some but not all Majorana predictions
- Soft gap, wide peak, and disorder obscure discrimination between Majorana and Kondo/0.7

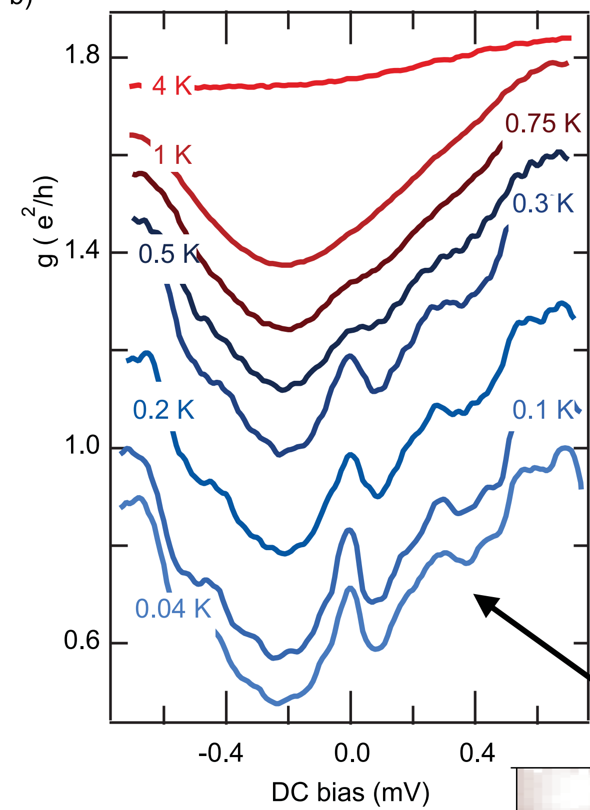
- N-dot-S allows spectroscopy of superconducting-wire DOS
- Zeeman-split Andreev bound states, anomalous ZBPs

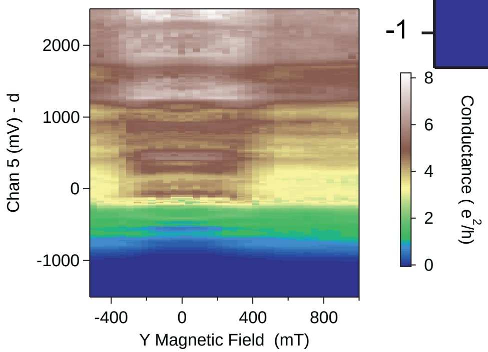
QPC field dependence at 4 K

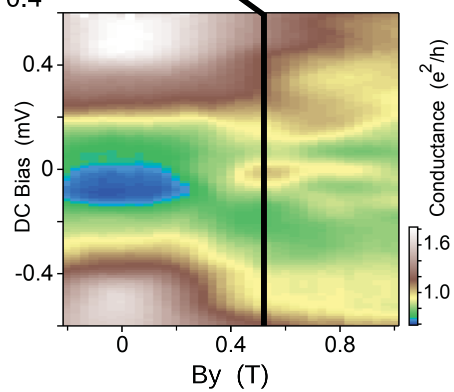
Zero-bias peak gone by 1 K,

temp. dependence doesn't discriminate





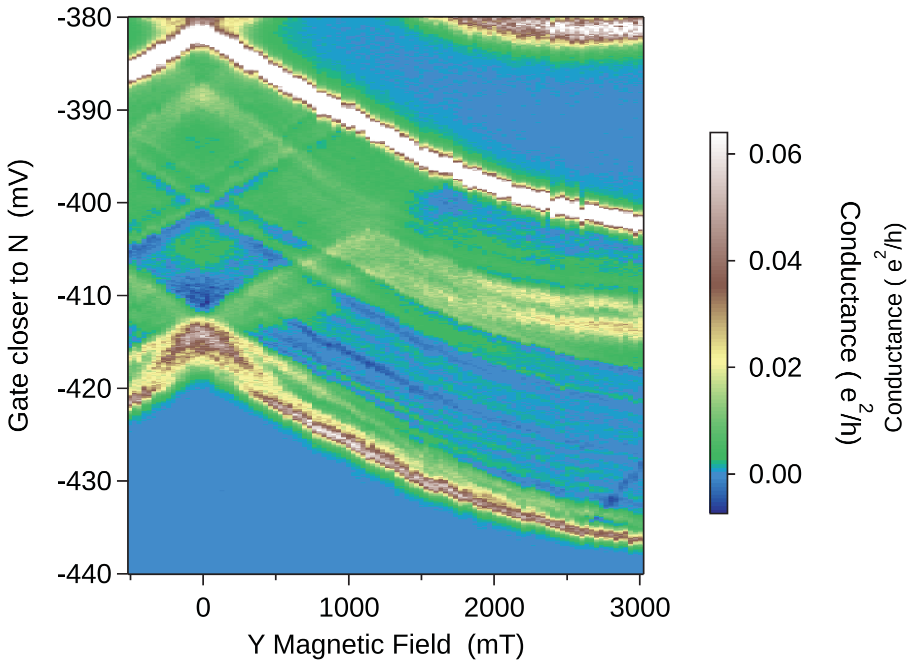


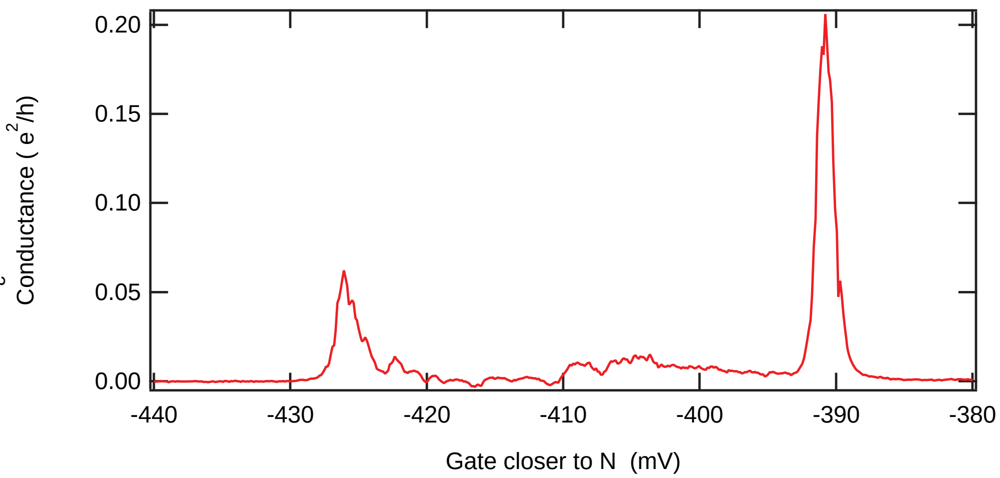


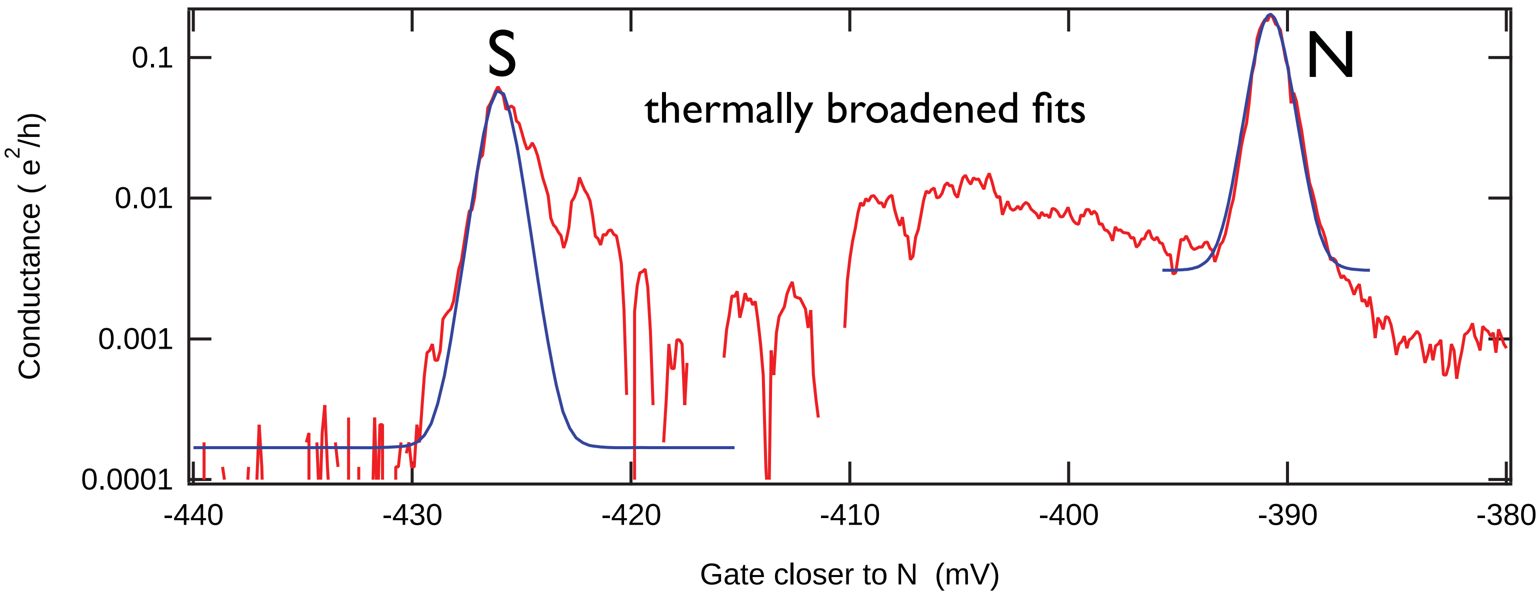
Conductance increase near pinch-off is gone by 4 K,

Andreev enhancement at higher conductance is still present

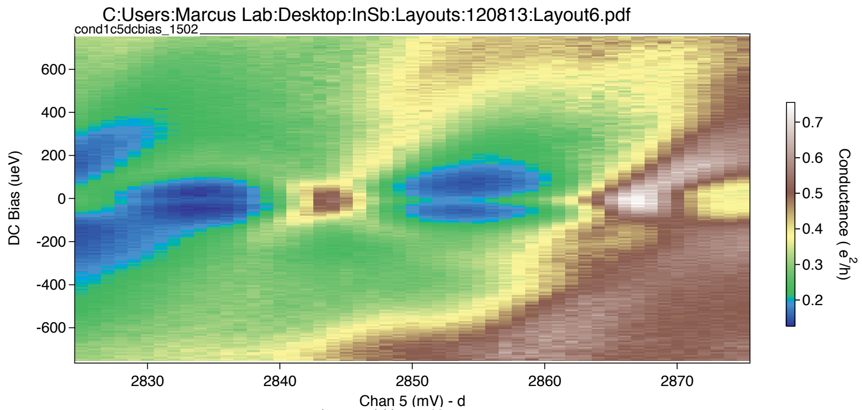
N-dot-S: lineshape at 1 T

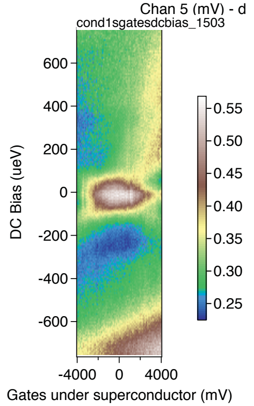


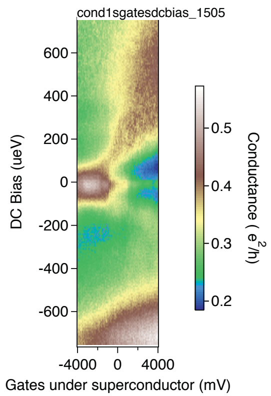




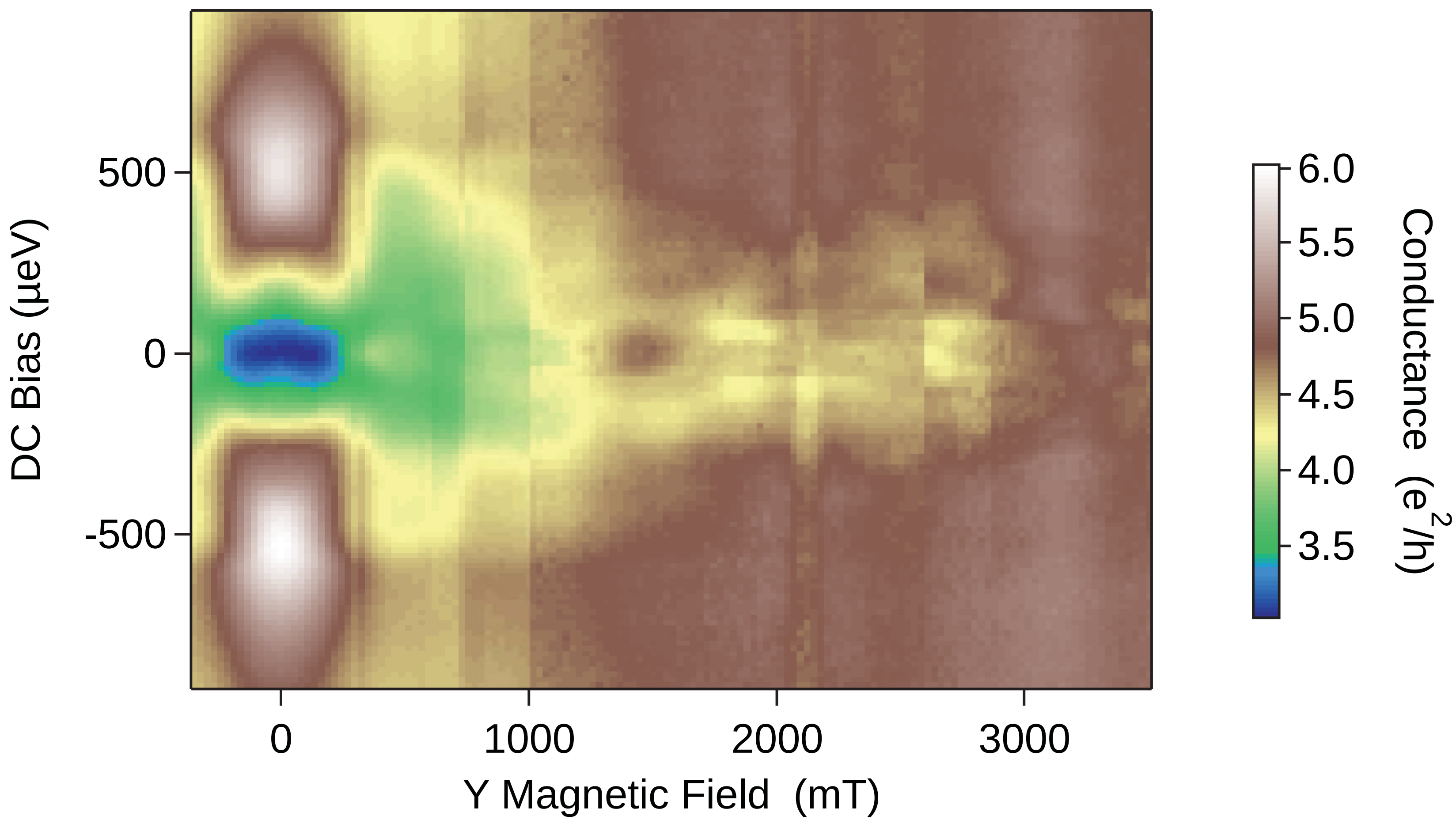
ABS: S gates gate uncovered part with 1000x smaller coupling







QPC


500
0
-500
DC Bias (μeV)
0
1000
2000
3000
Y Magnetic Field (mT)
6.0
5.5
5.0
4.5
4.0
3.5
Conductance (e²/h)