

# Majorana in nanowires

Lecture II (zero-bias peaks)

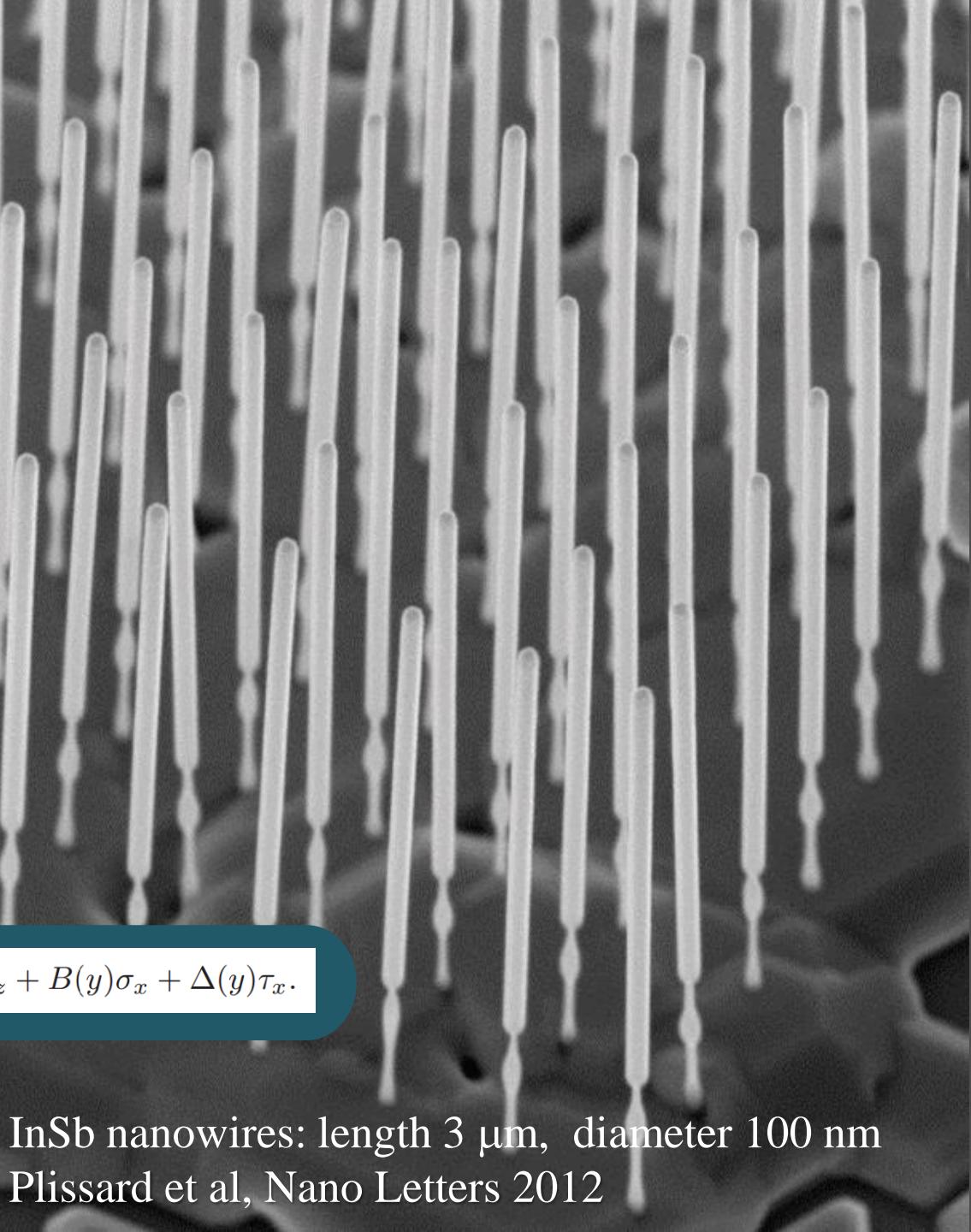
Sergey Frolov  
University of Pittsburgh

# Majorana recipe:

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

1. Nanowire
2. Spin-orbit interaction
3. Superconductivity
4. Magnetic field

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

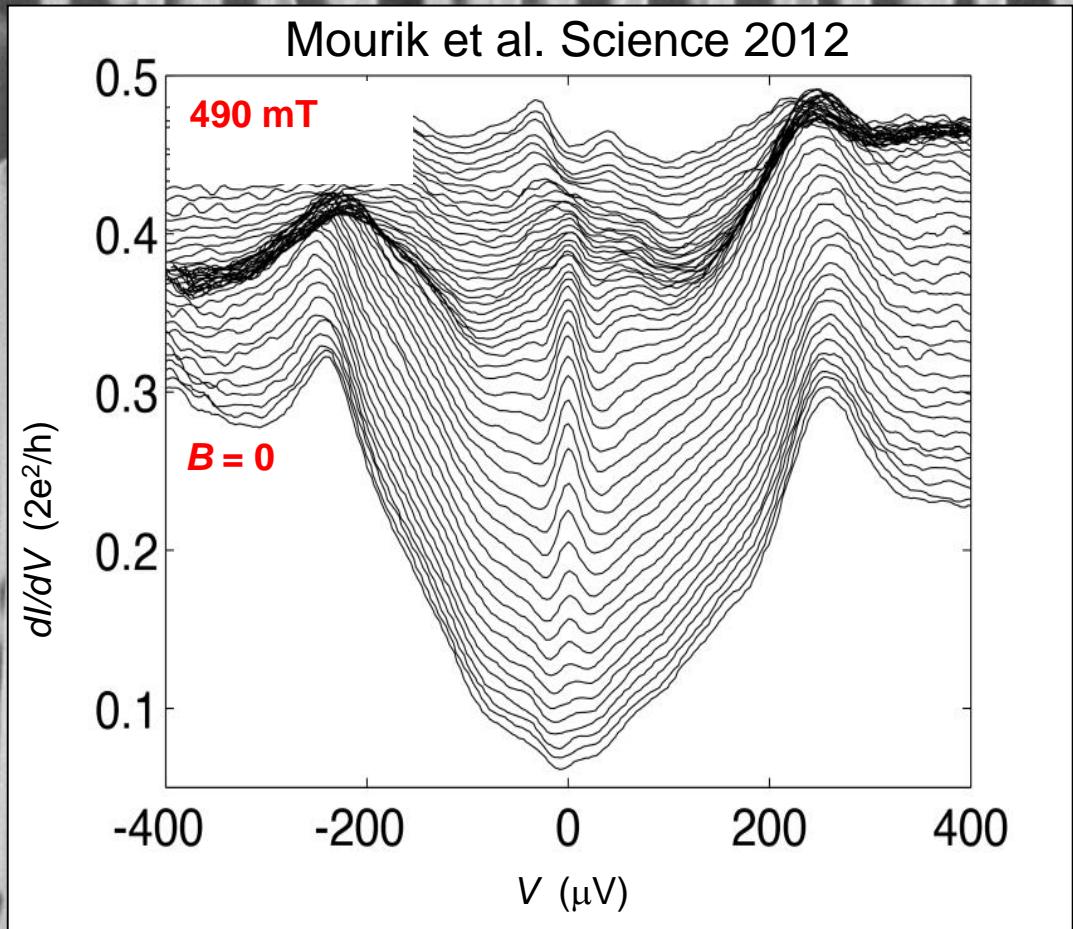


InSb nanowires: length 3  $\mu\text{m}$ , diameter 100 nm  
Plissard et al, Nano Letters 2012

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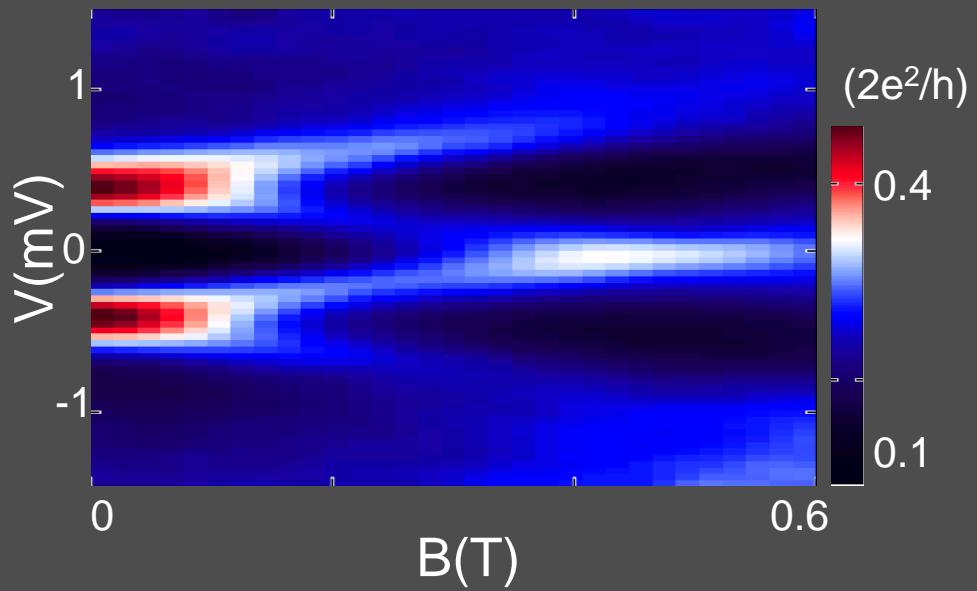
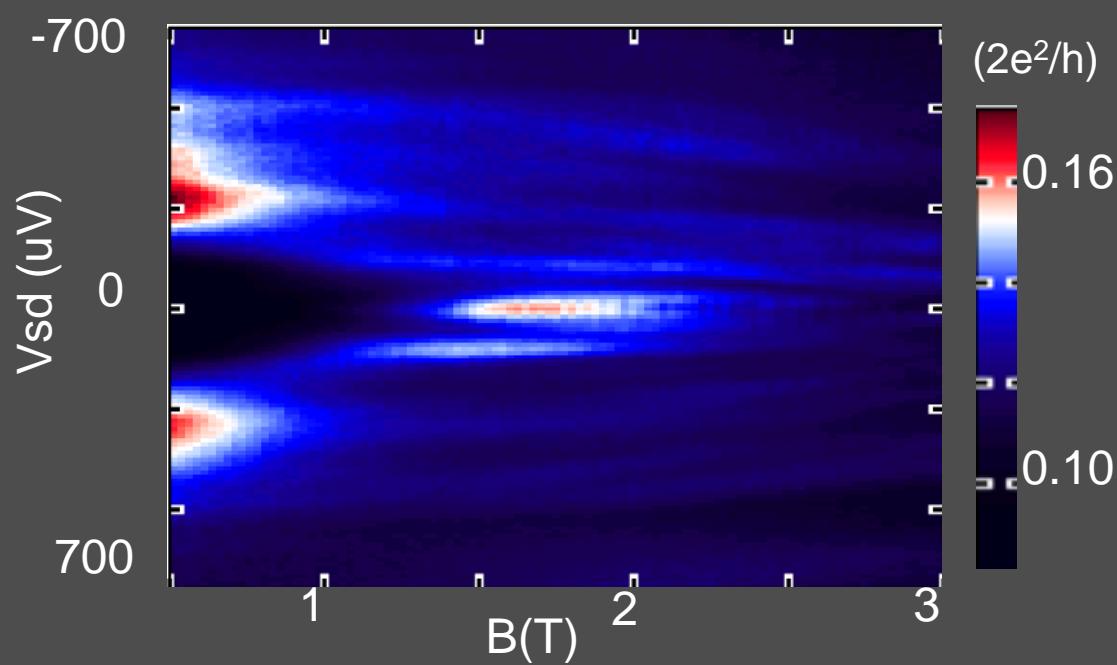
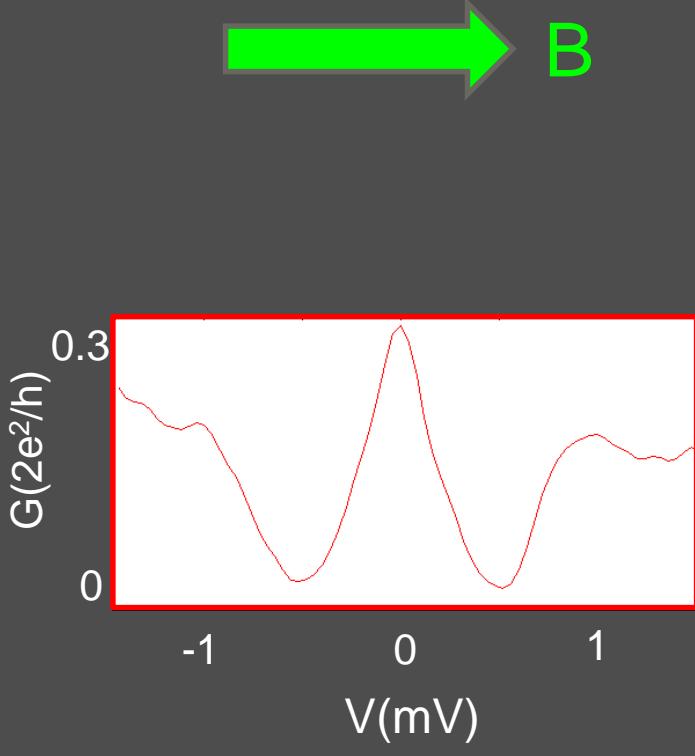
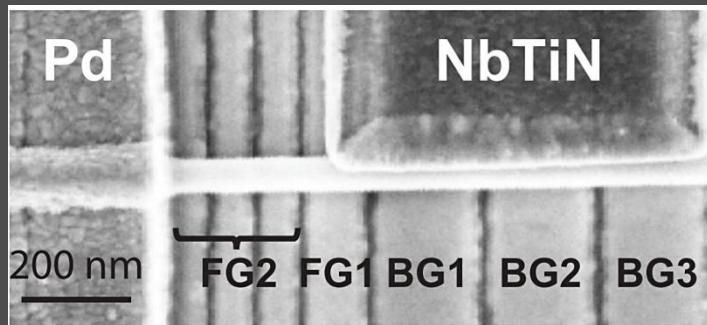
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3. Superconductivity
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Plissard et al, Nano Letters 2012

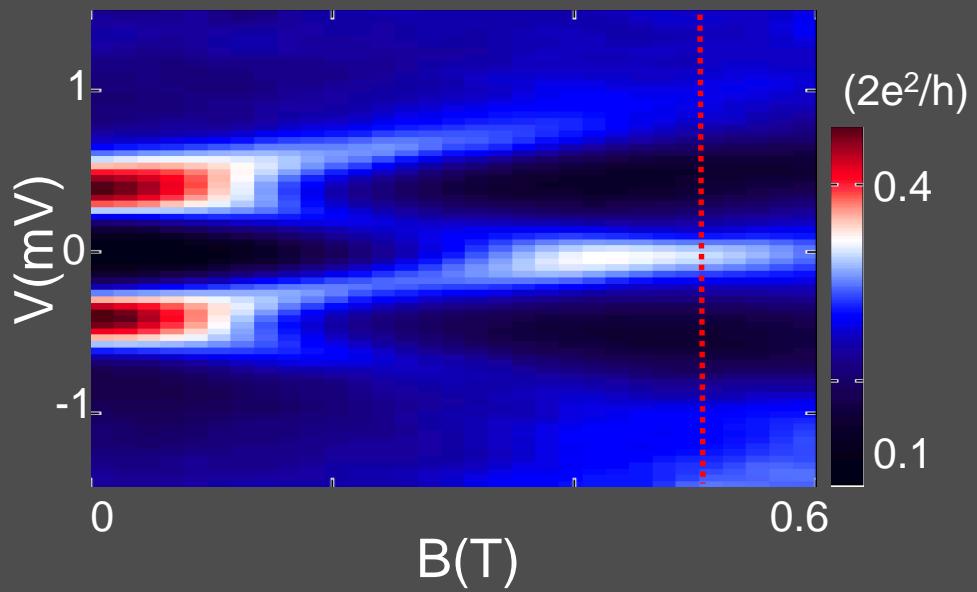
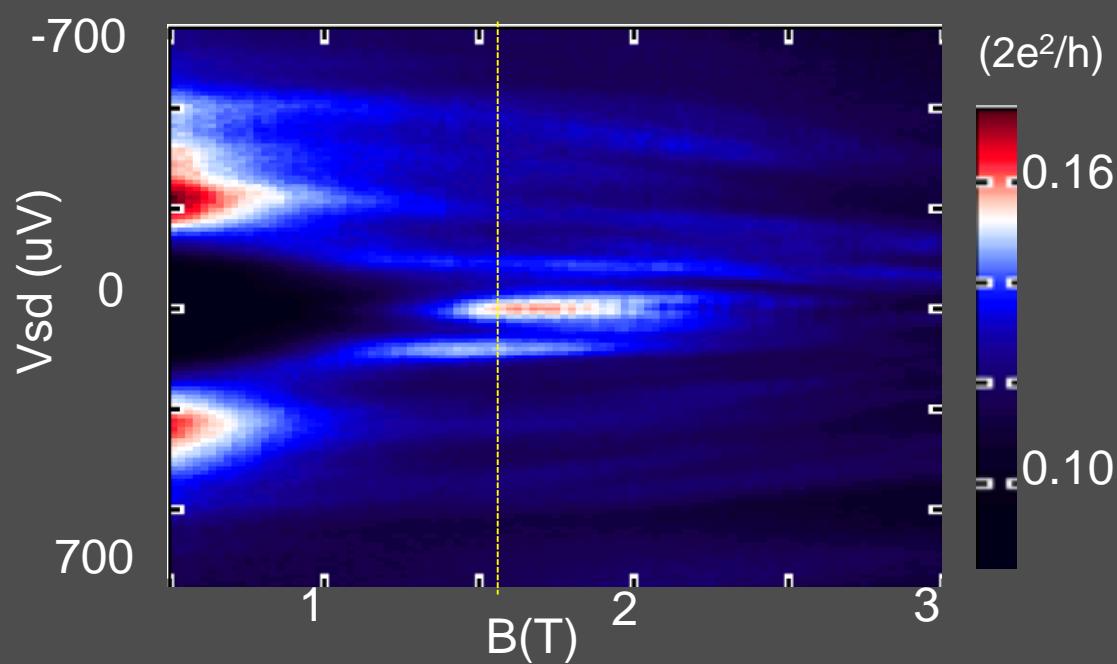
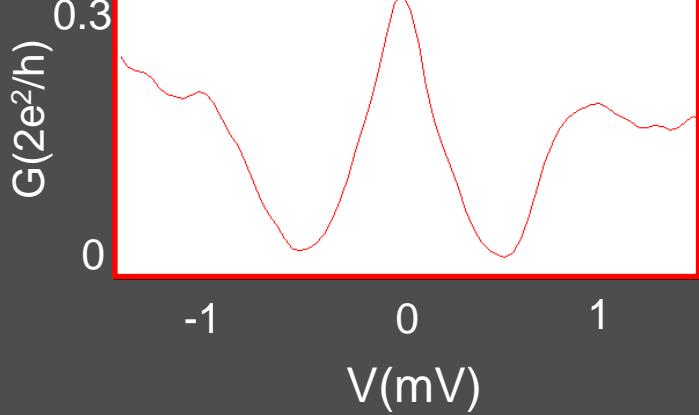
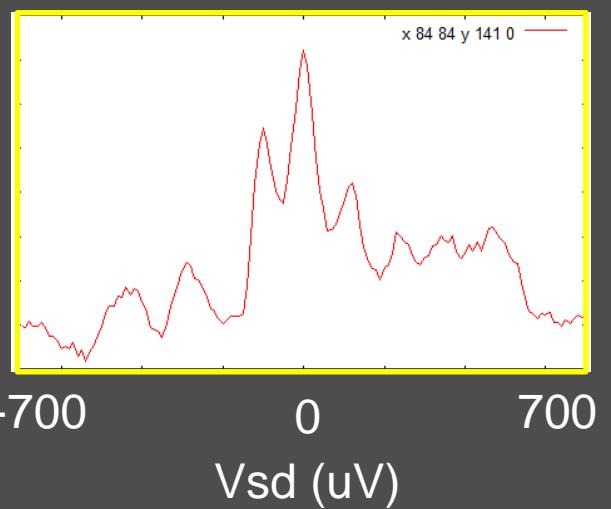
# Tunneling Spectroscopy: a powerful technique

Data: Peng Yu (unpublished)



# Tunneling Spectroscopy: a powerful technique

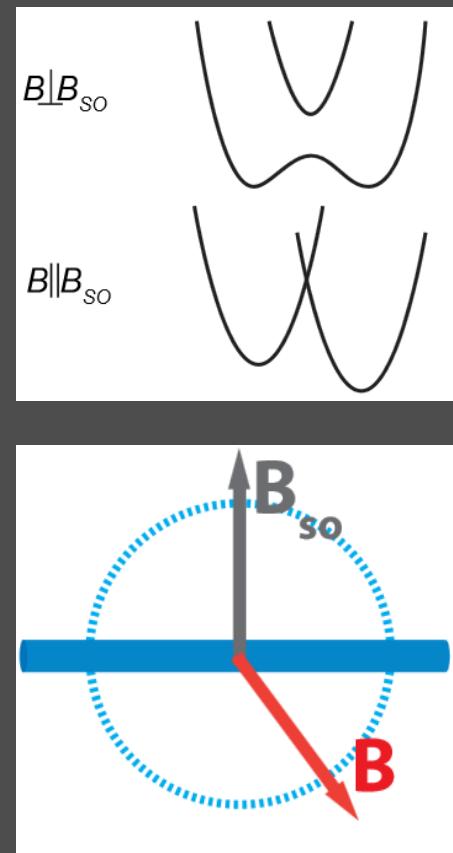
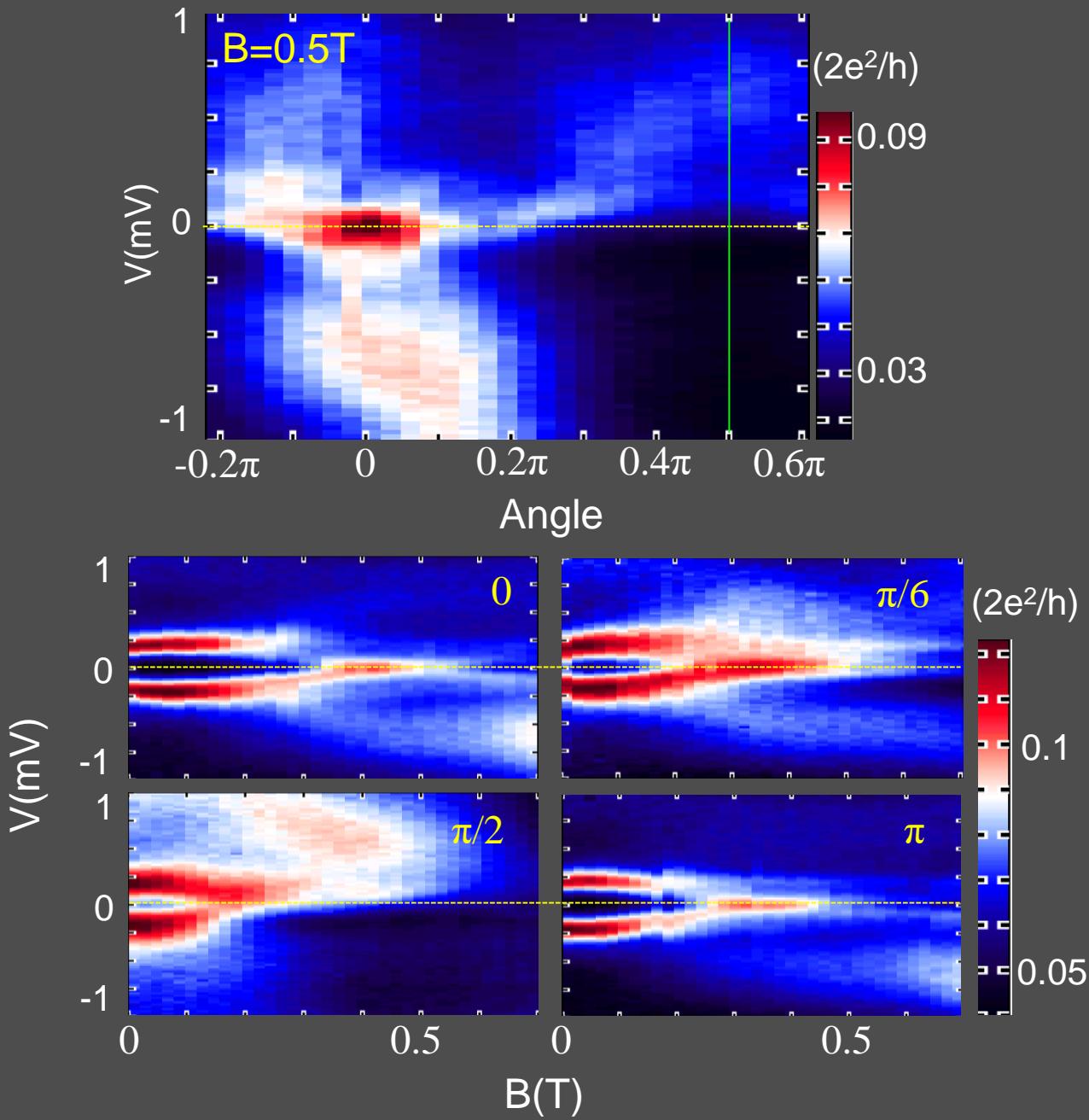
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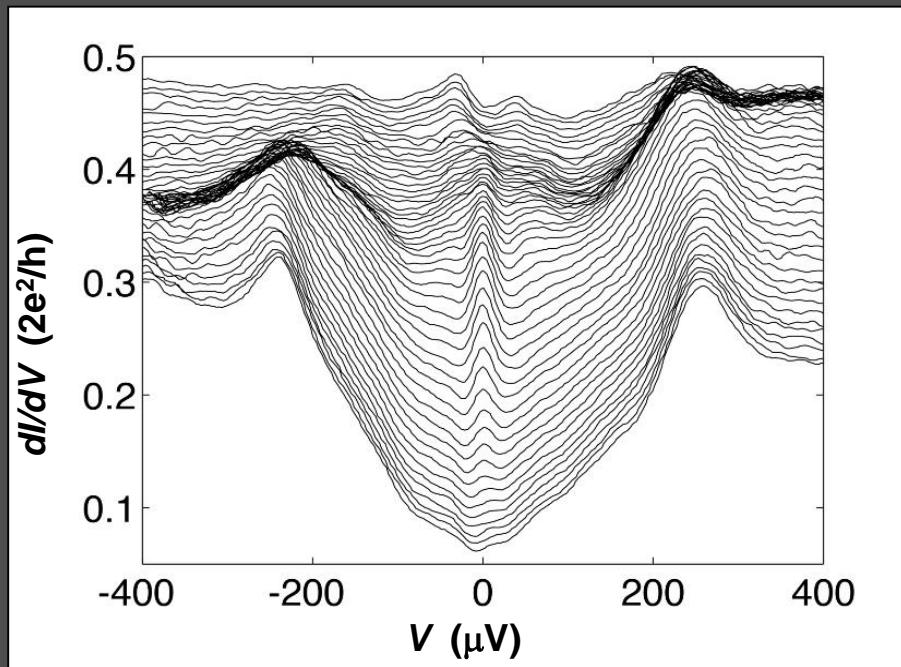
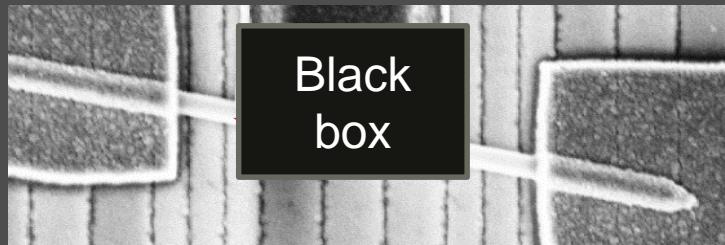
# What are the basic properties of Majorana Bound States?

- Pinned to (or near) zero energy
- Exist in a limited parameter space of  $\mu, E_z$
- Require spin-orbit interaction
- Come in pairs

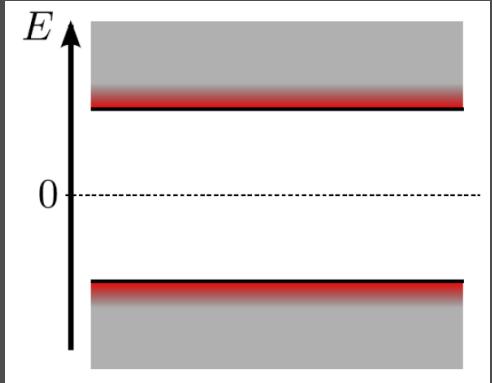
# Field orientation dependence



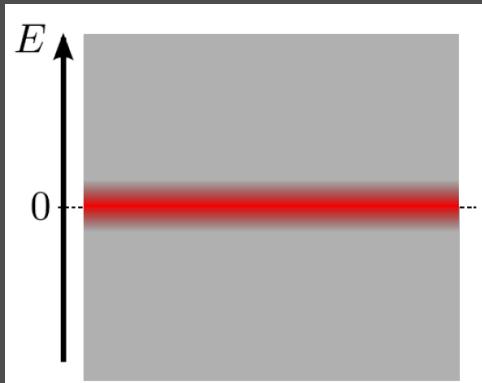
# How are we finding Majoranas, actually?



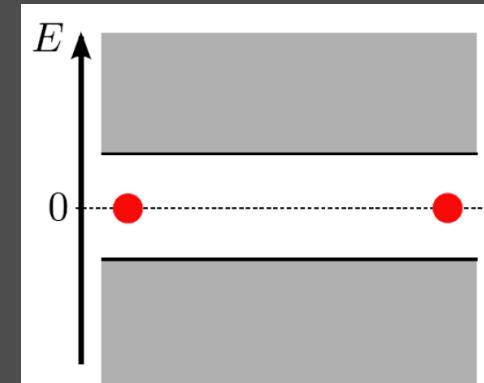
# Topological Transition



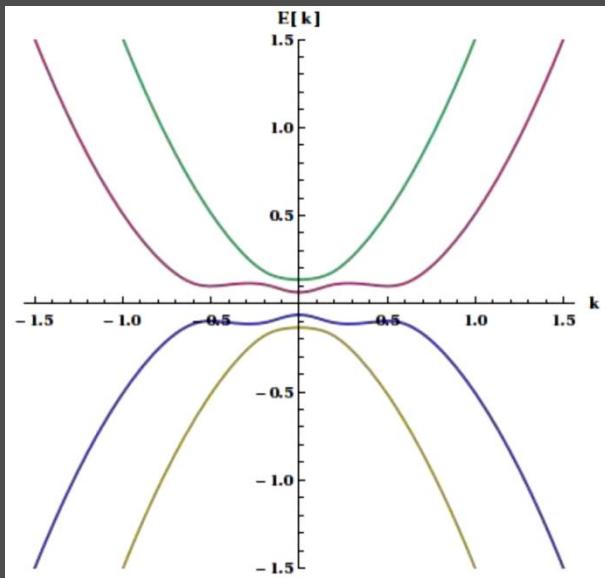
$$E_z < \Delta$$



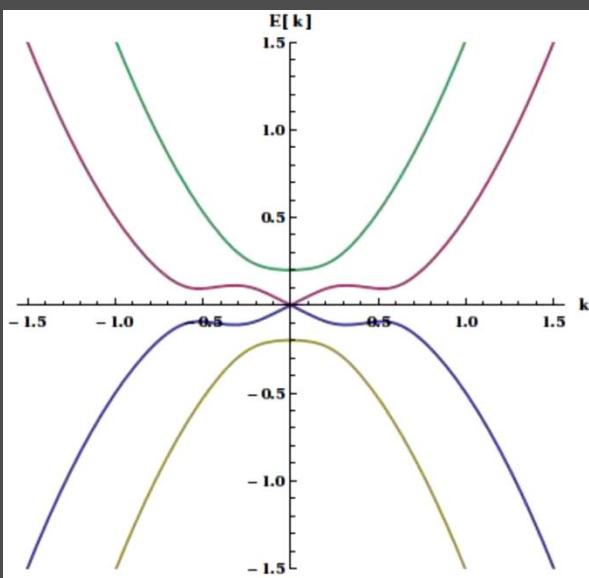
$$E_z = \Delta$$



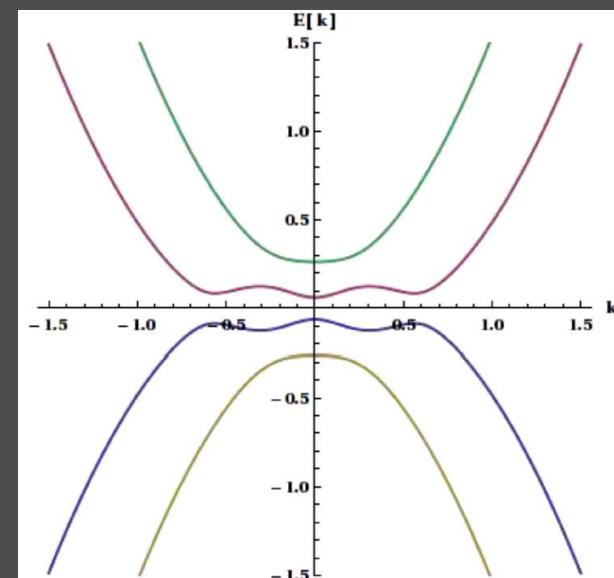
$$E_z > \Delta$$



Trivial Superconductor  
“positive gap”

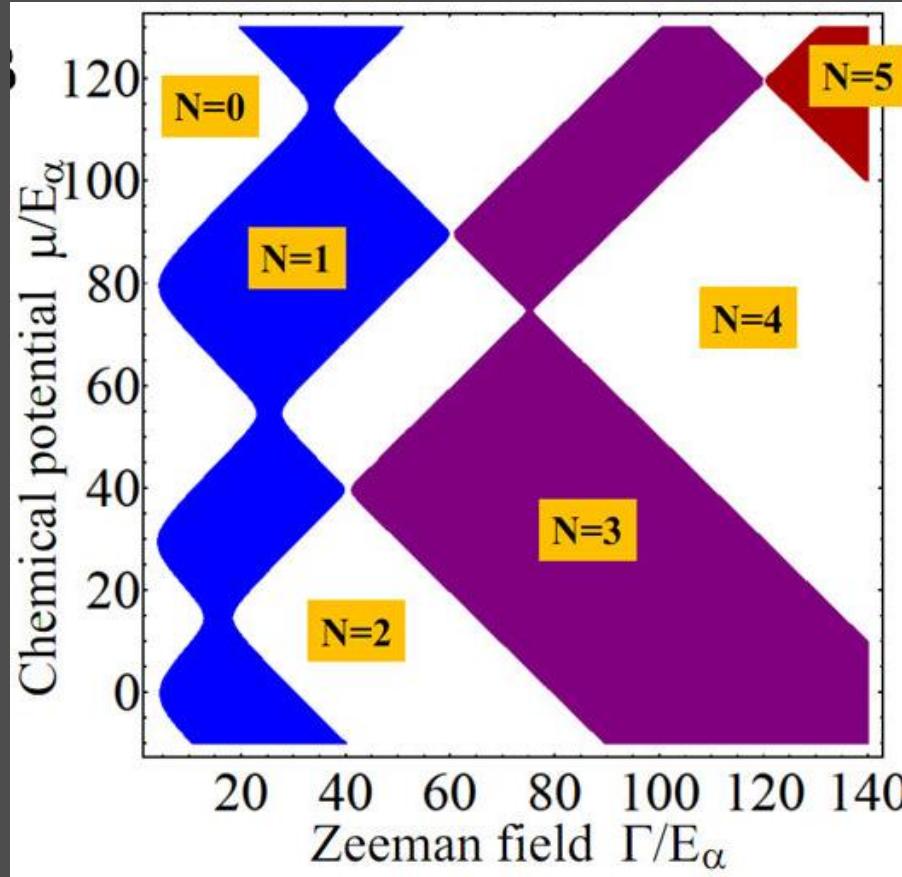


Majorana  
“zero gap”



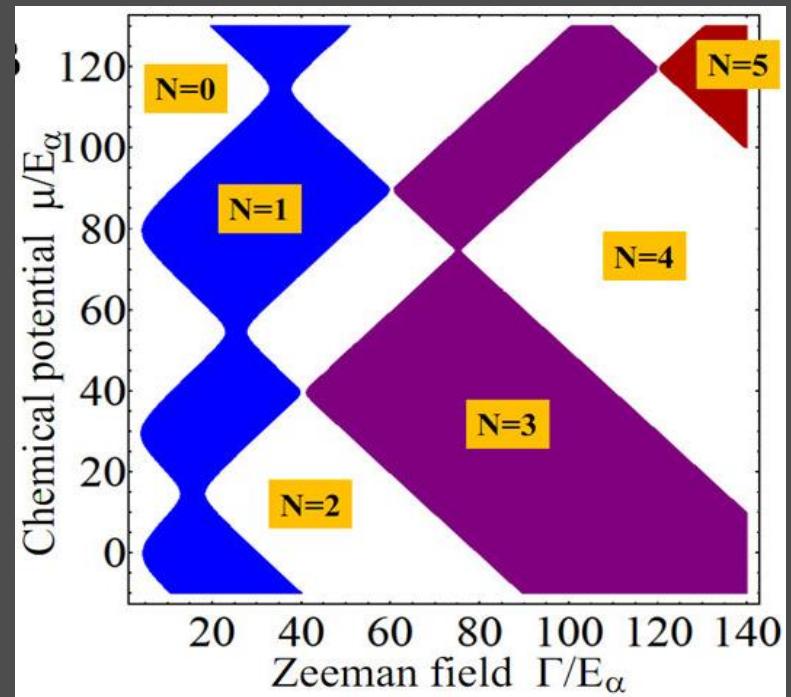
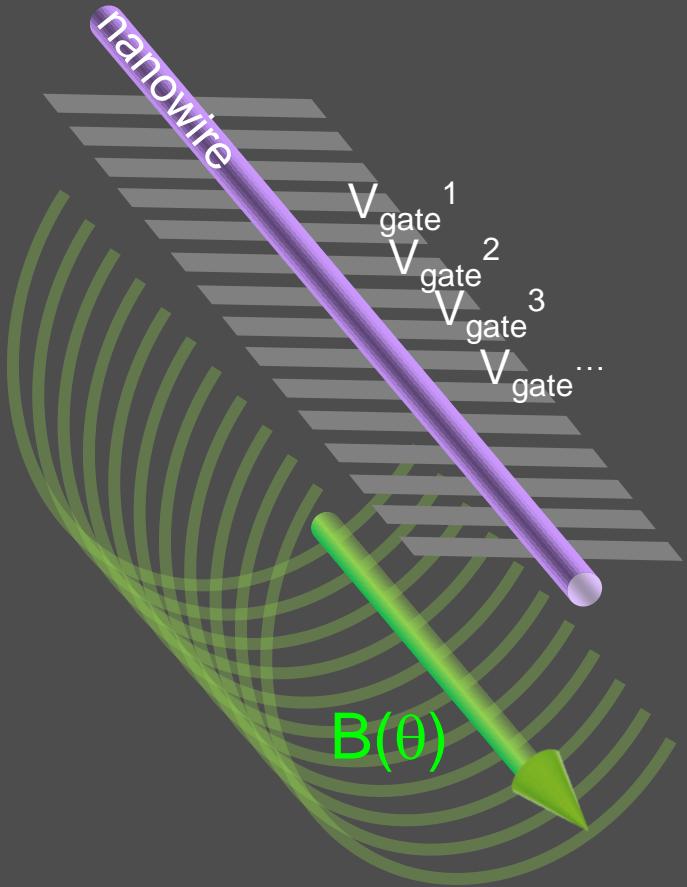
Topological Superconductor  
“negative gap”

$$E_Z > \sqrt{\Delta_{k=0}^2 + \mu^2}$$



Stanescu, Lutchyn, Das Sarma; Phys Rev B 2011

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

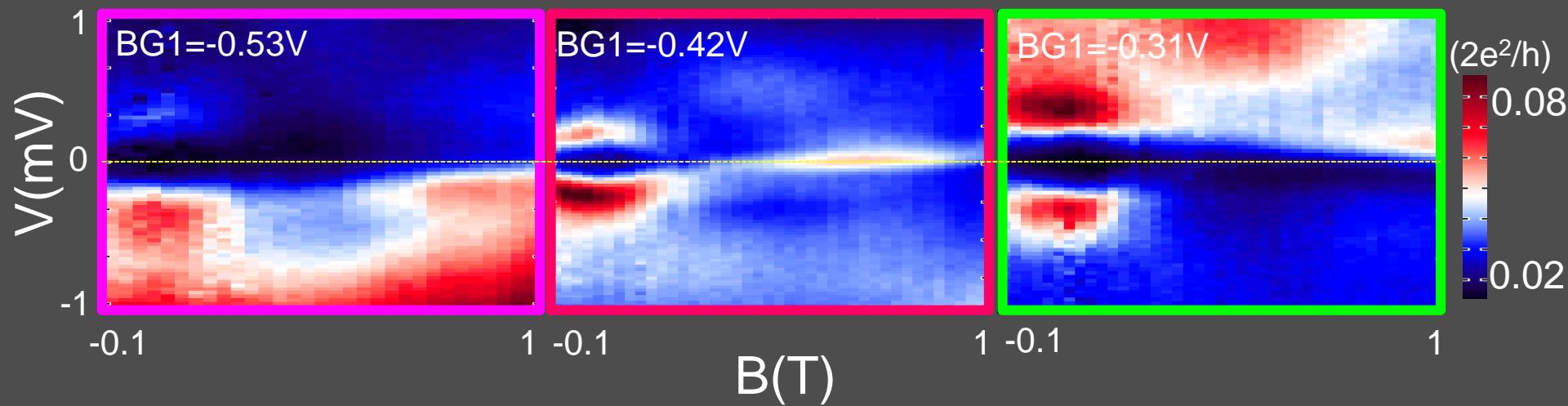
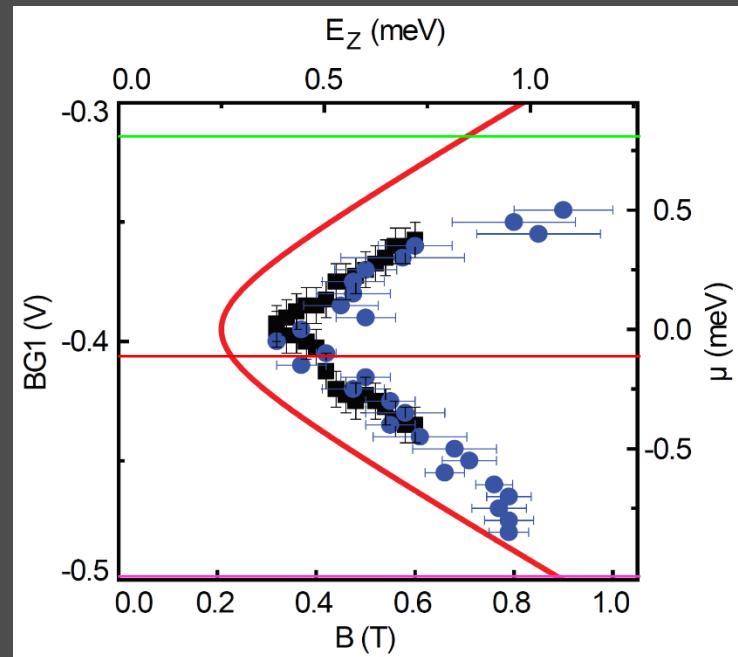
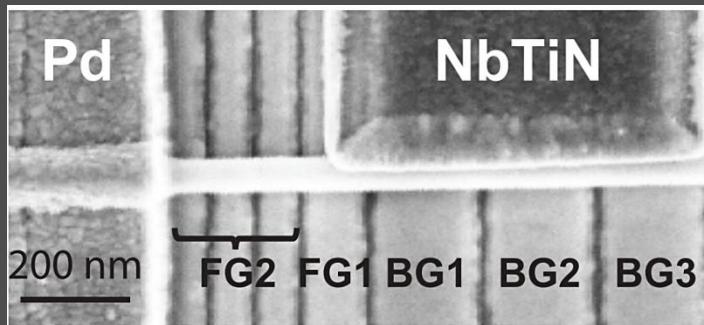


Stanescu, Lutchyn, Das Sarma; Phys Rev B 2011

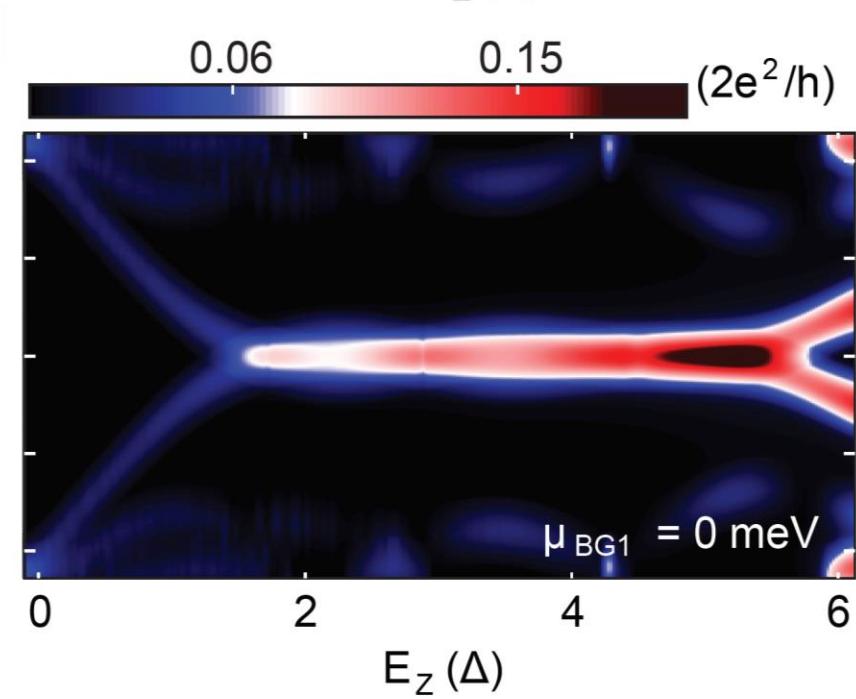
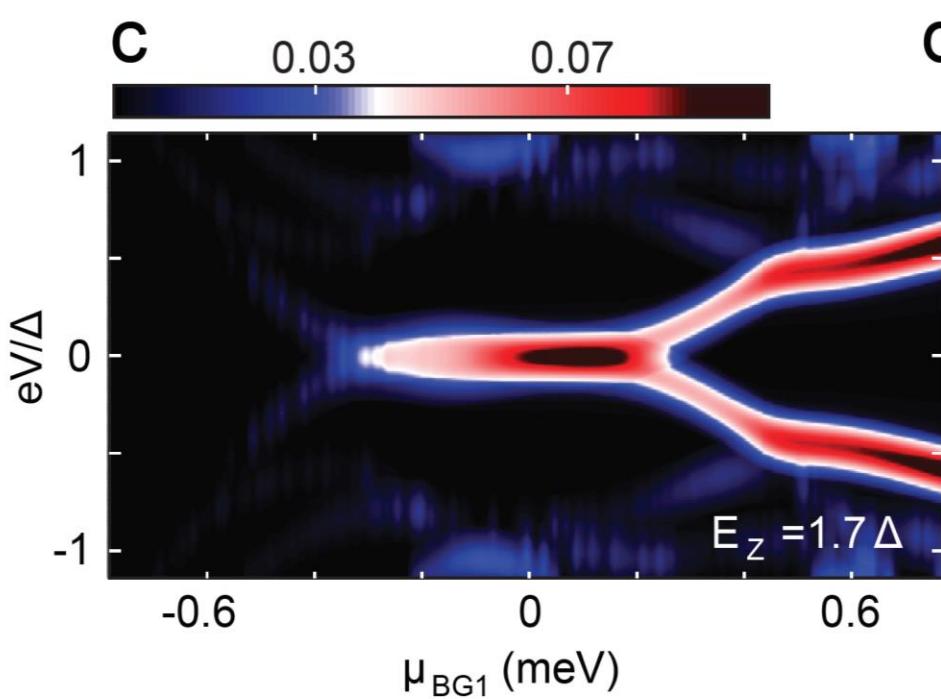
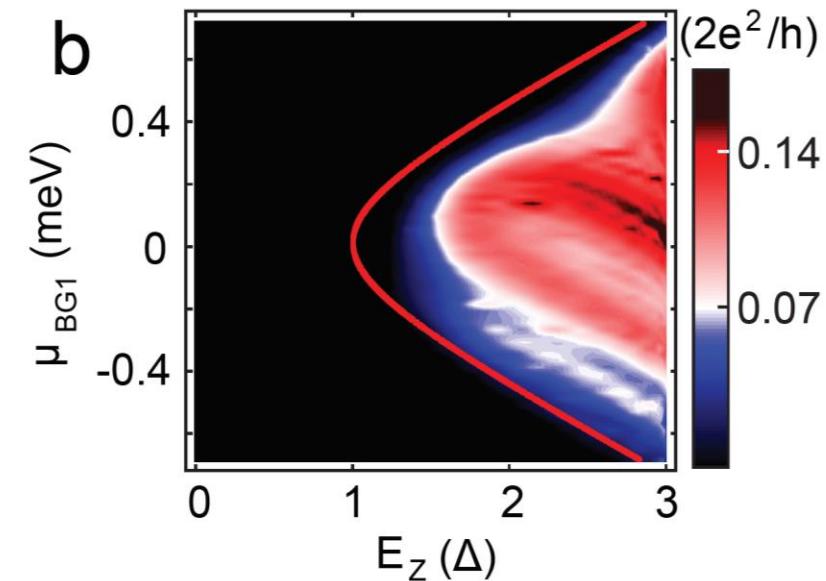
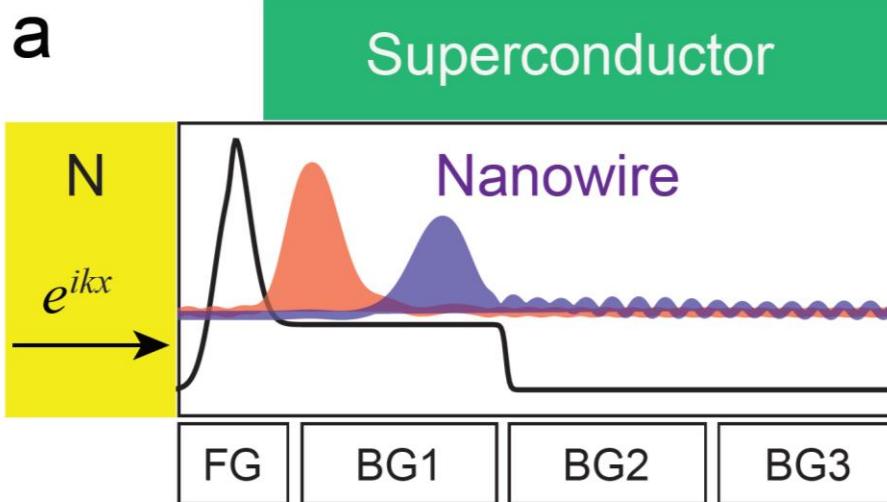
# Phase diagram of Zero Bias Peaks – Mapping out the Topological Condition

$$E_Z > (\Delta^2 + \mu^2)^{0.5}$$

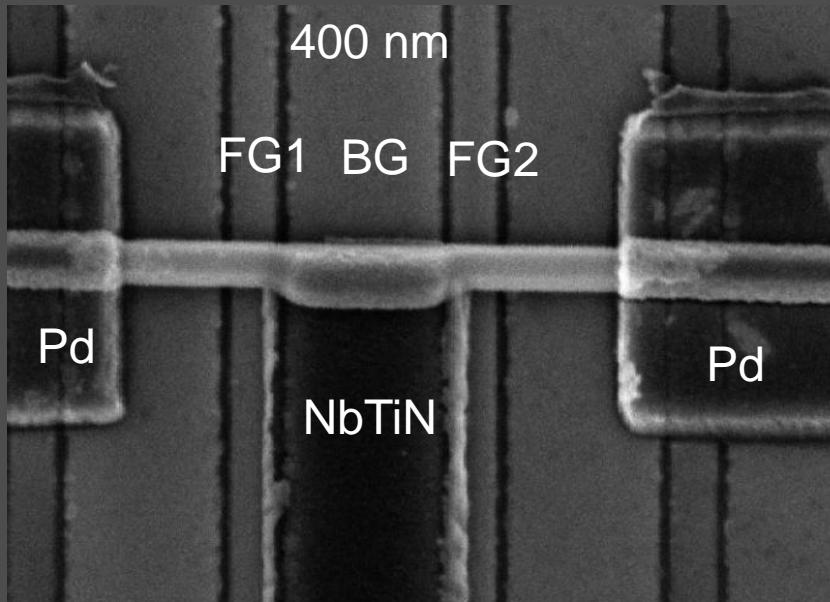
J. Chen et al, Science Advances (2017)



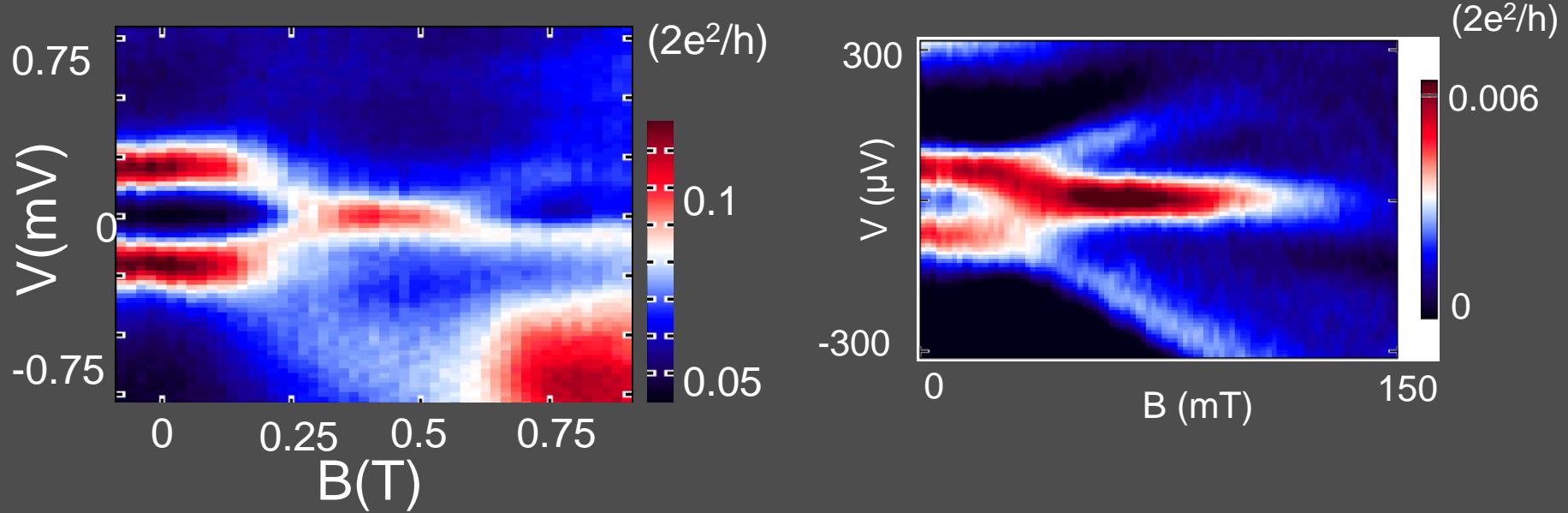
# Numerics : Stanescu Group



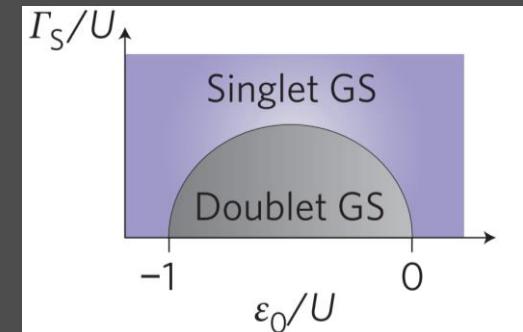
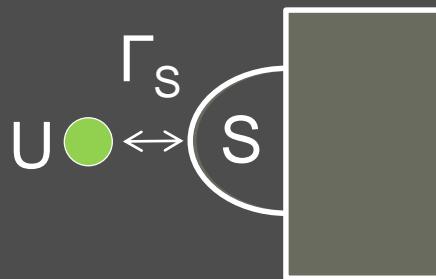
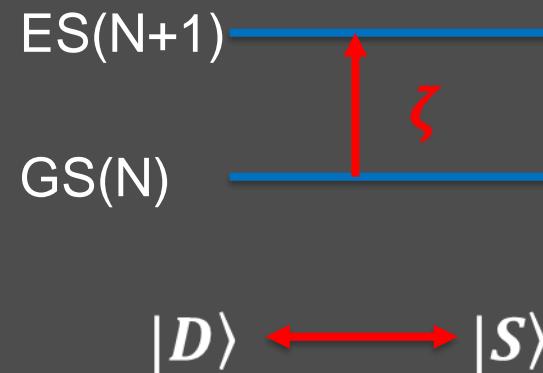
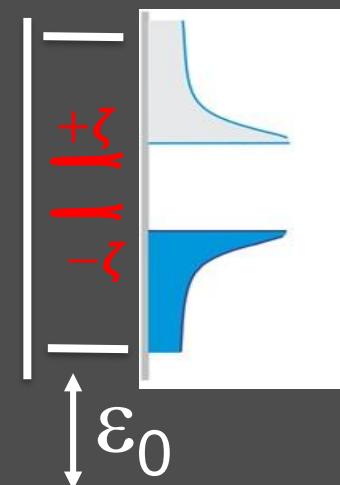
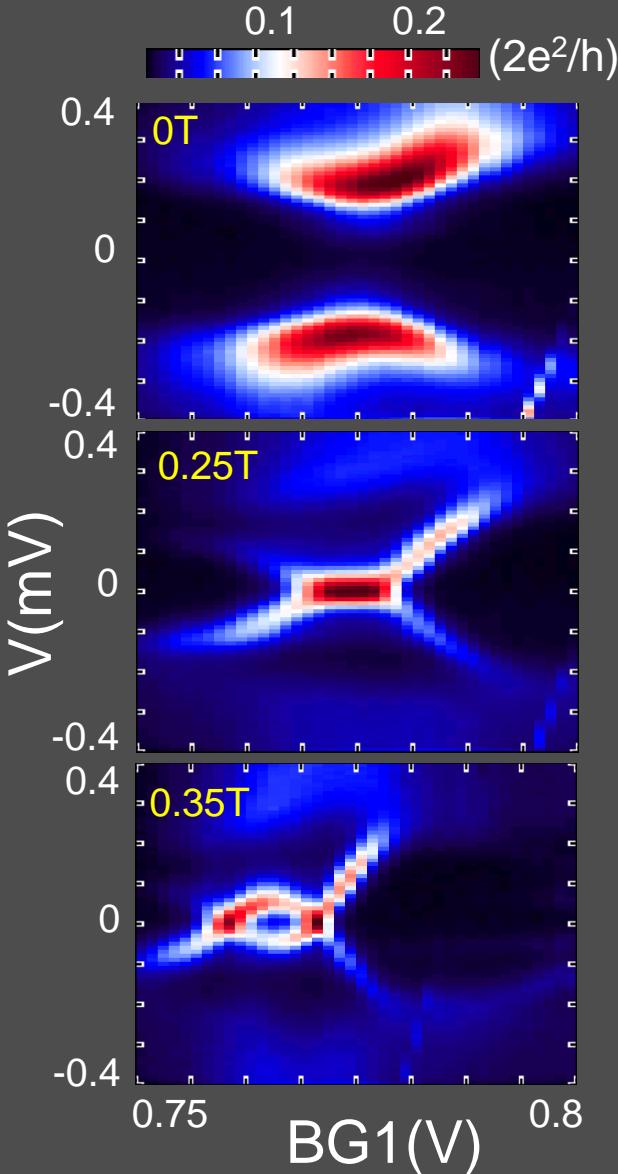
# Where is the second Majorana?



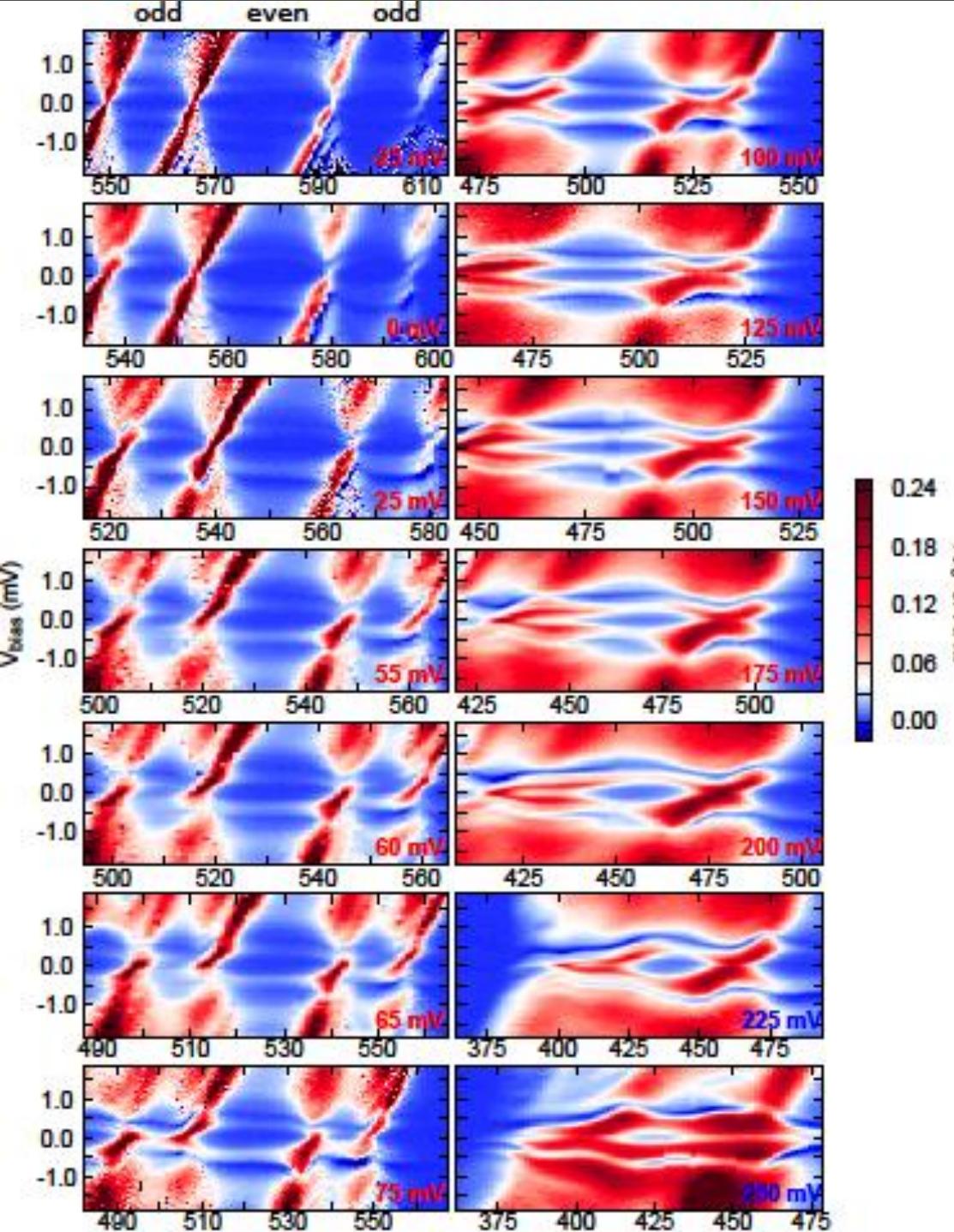
# Quiz



# Andreev Bound States in Single Quantum Dots

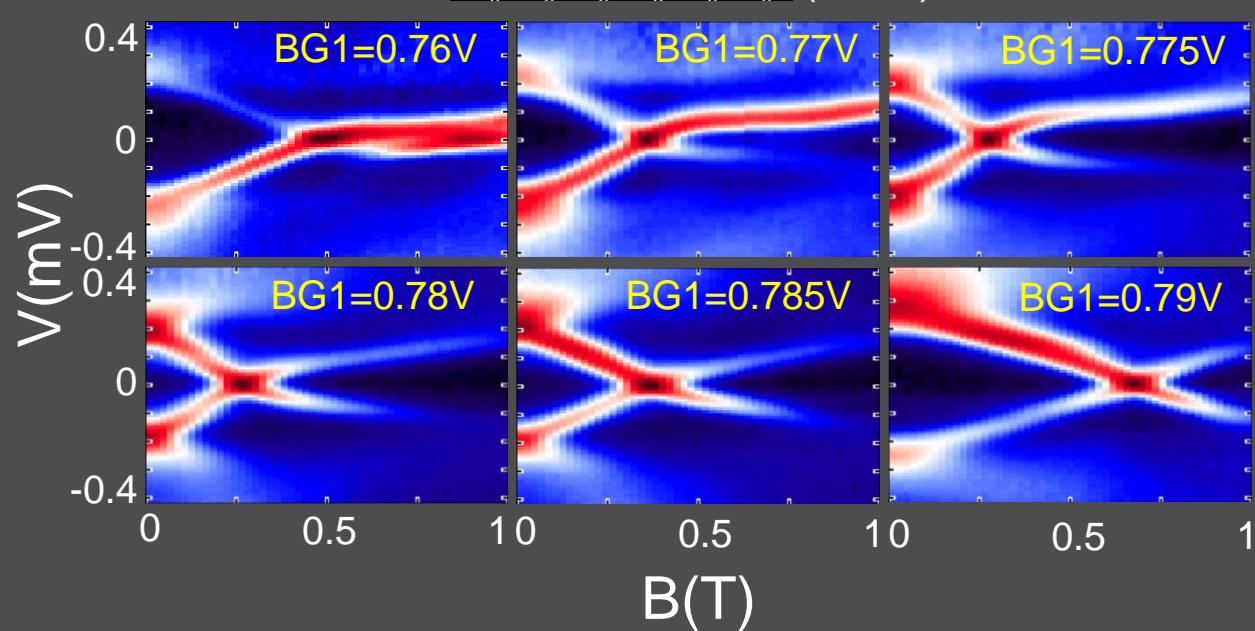
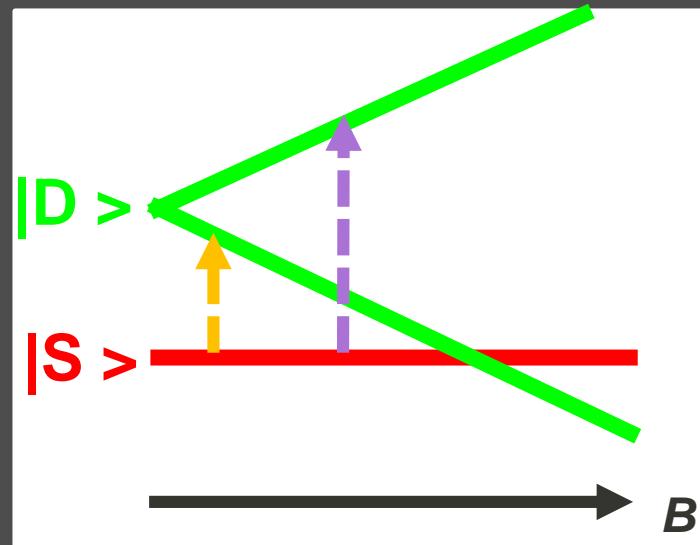
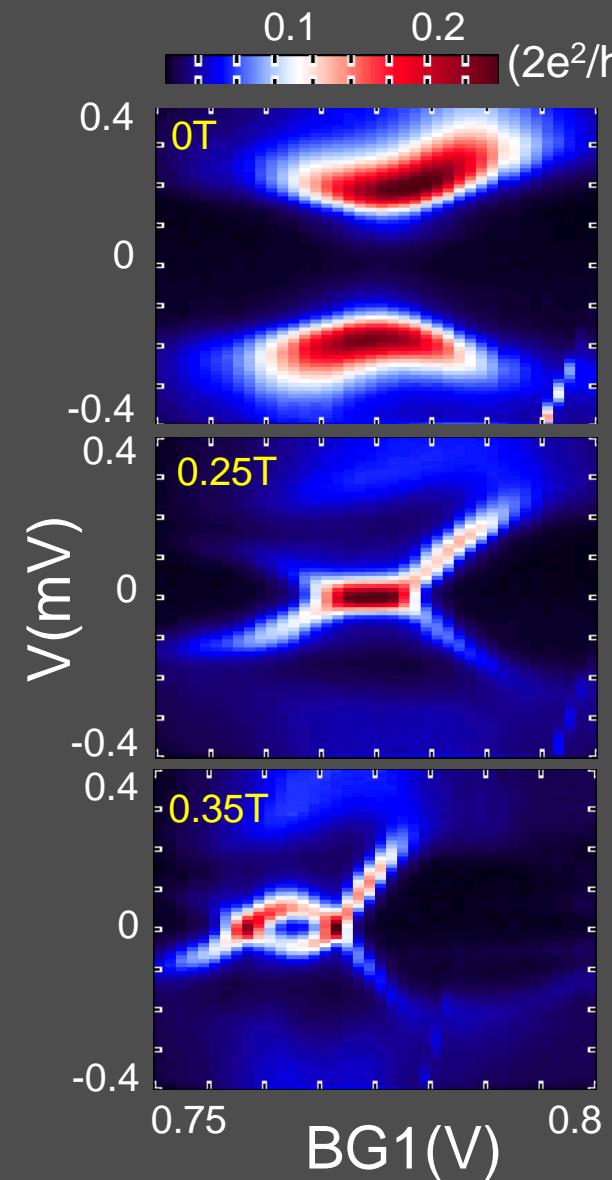


EJH Lee, NatNano 2014

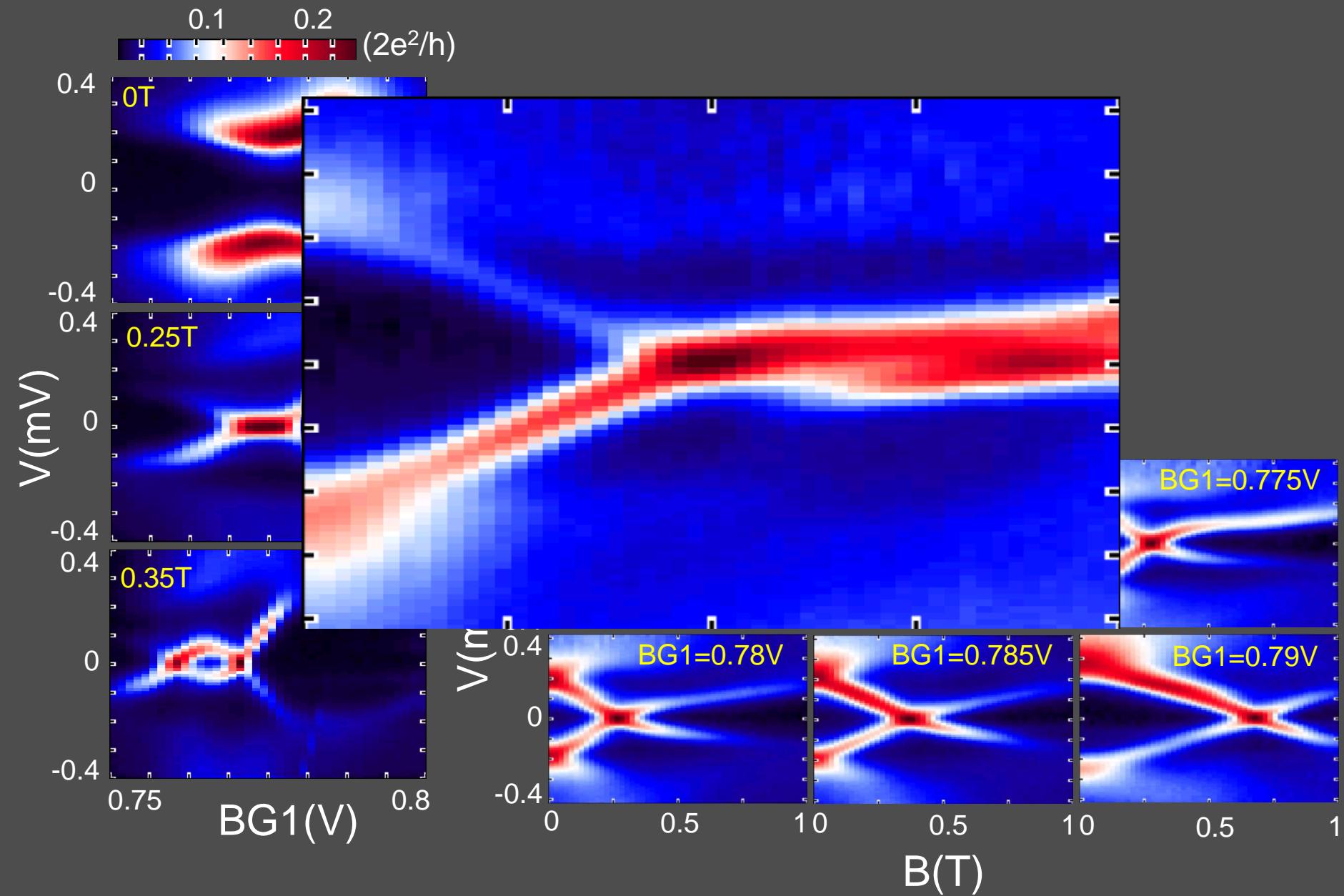


Su et al, arXiv:1904.05354  
2019

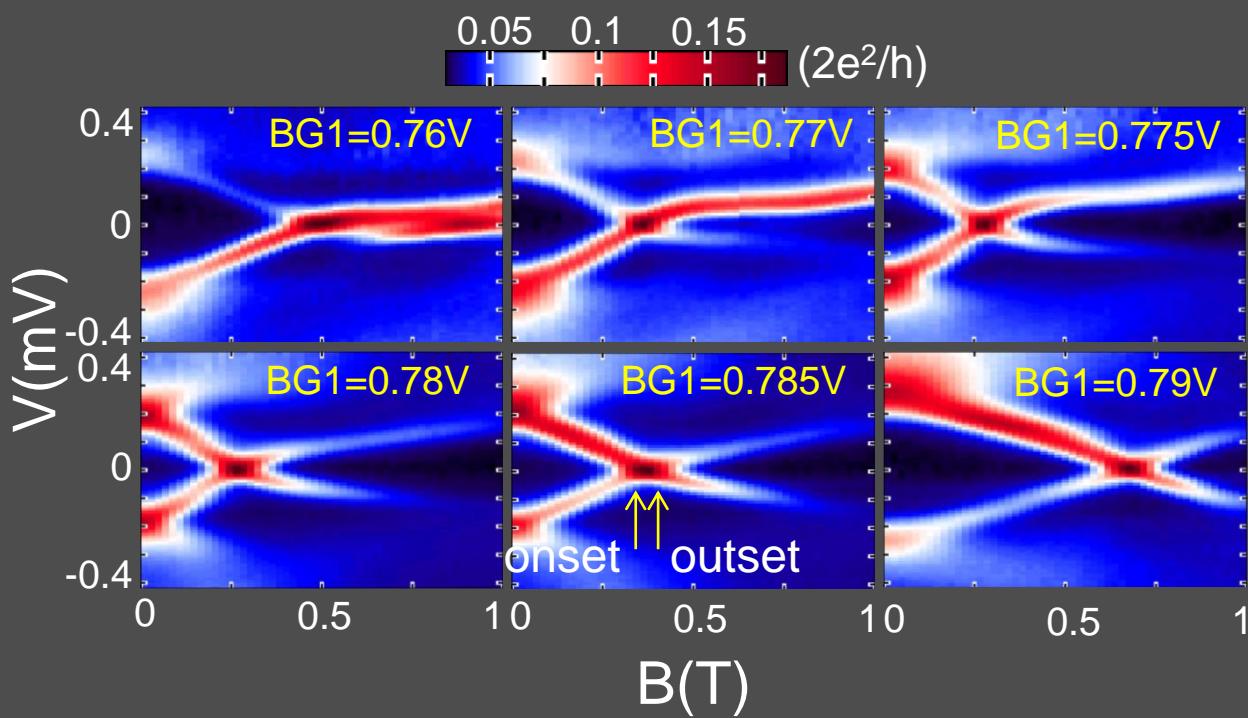
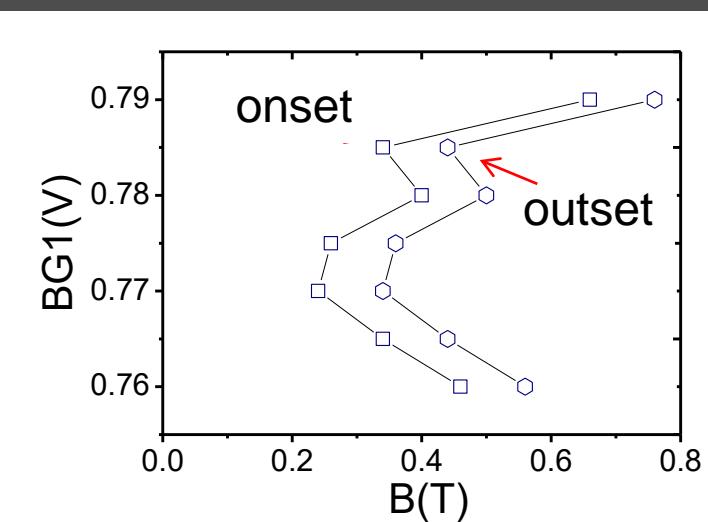
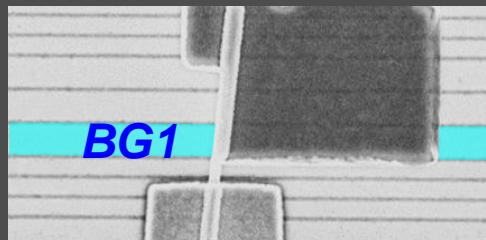
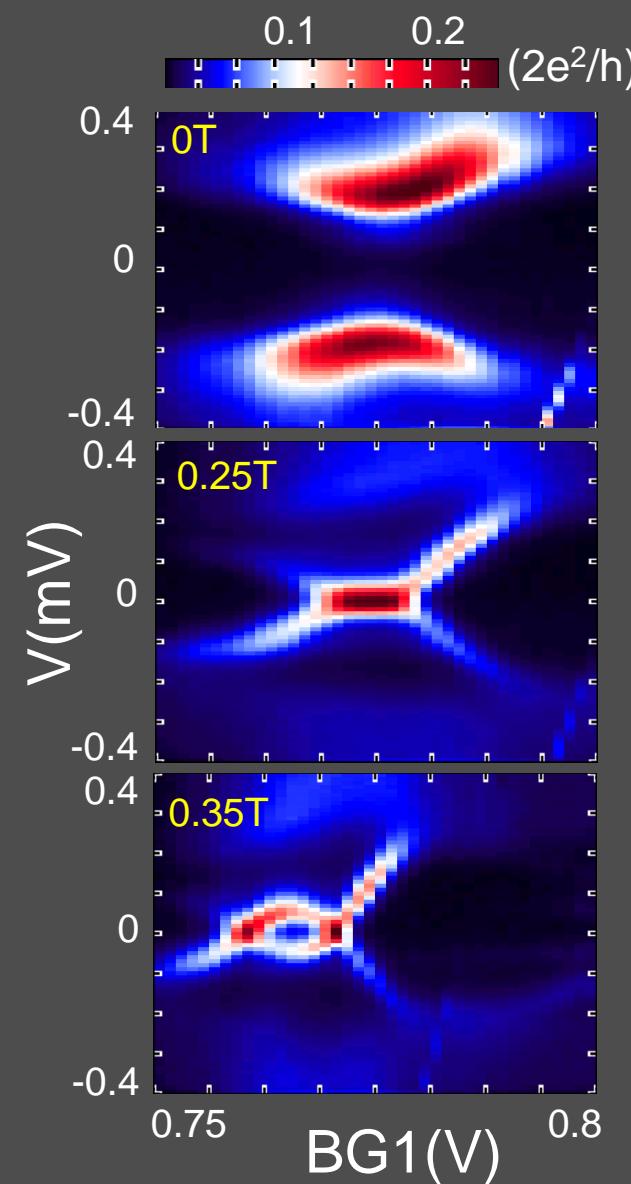
# Magnetic field evolution of Andreev bound states



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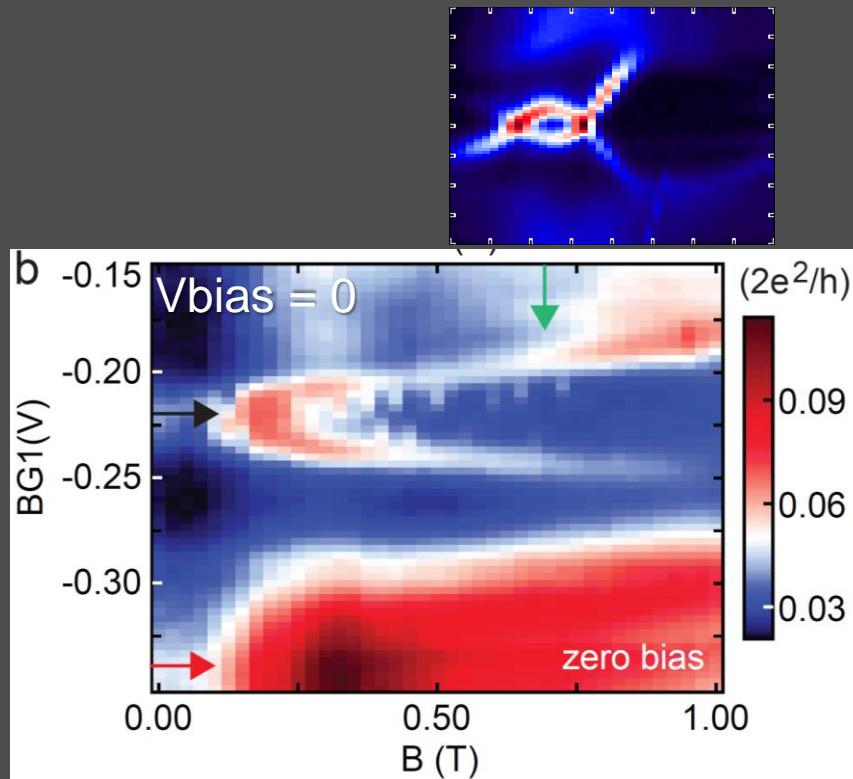


# Single dot: Andreev Bound States

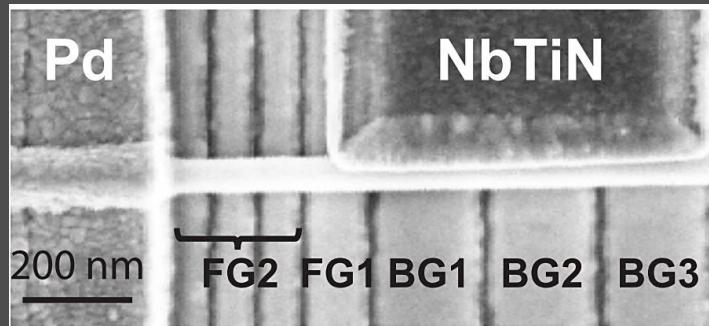
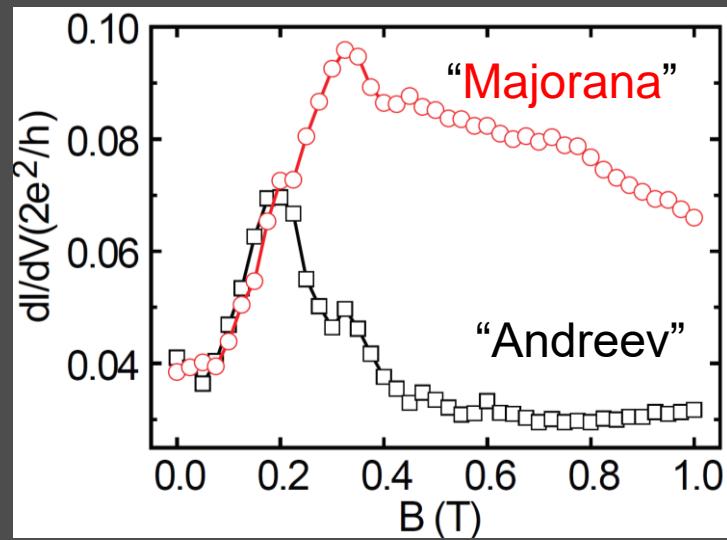


# Majorana vs. Andreev

Possible way to distinguish Majorana and Andreev: zero-bias conductance



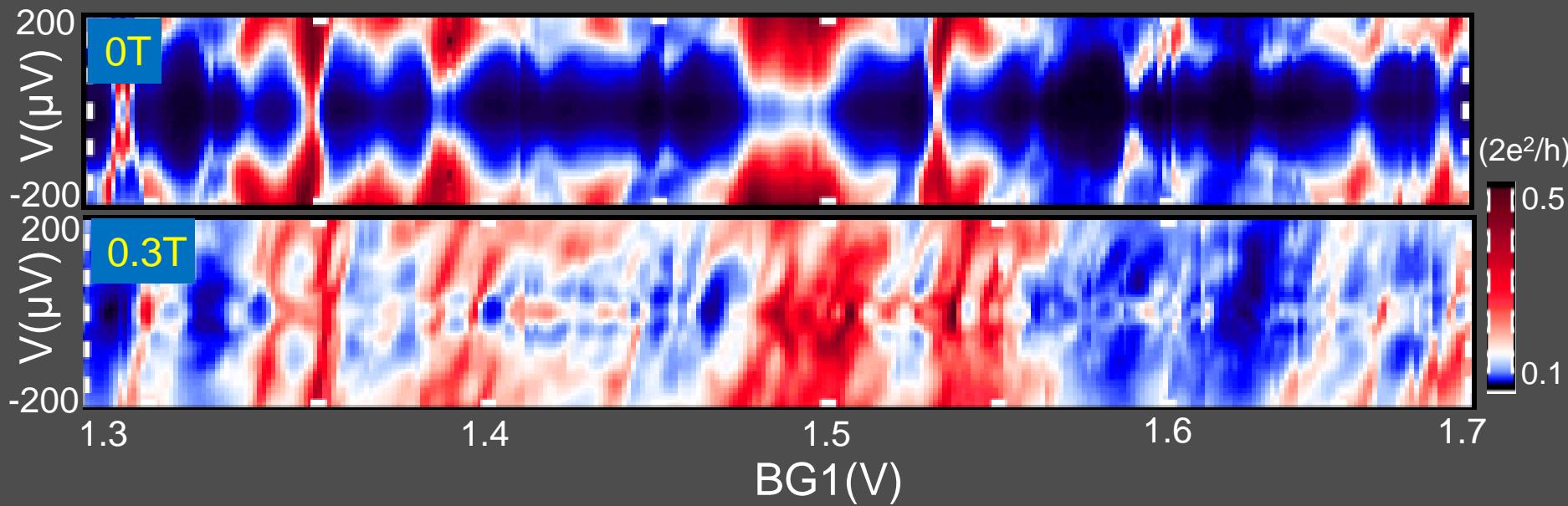
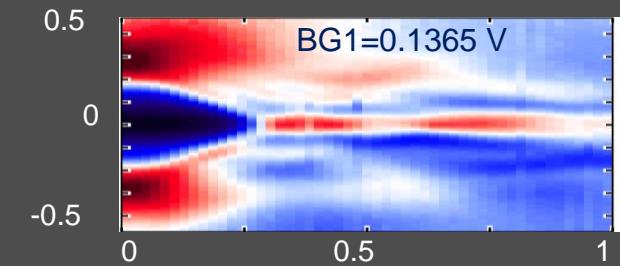
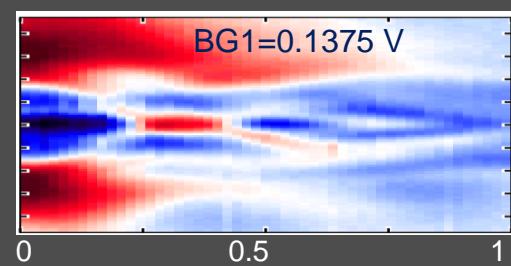
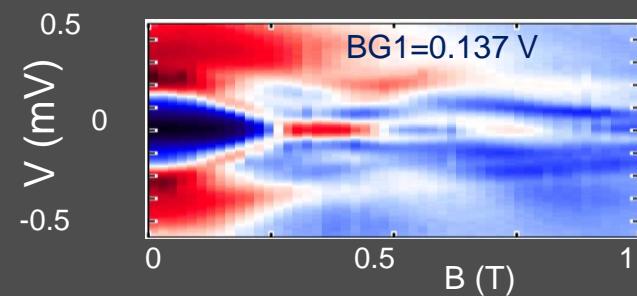
Phase diagram of ZBPs:  
J. Chen et al, arXiv:1611.00727



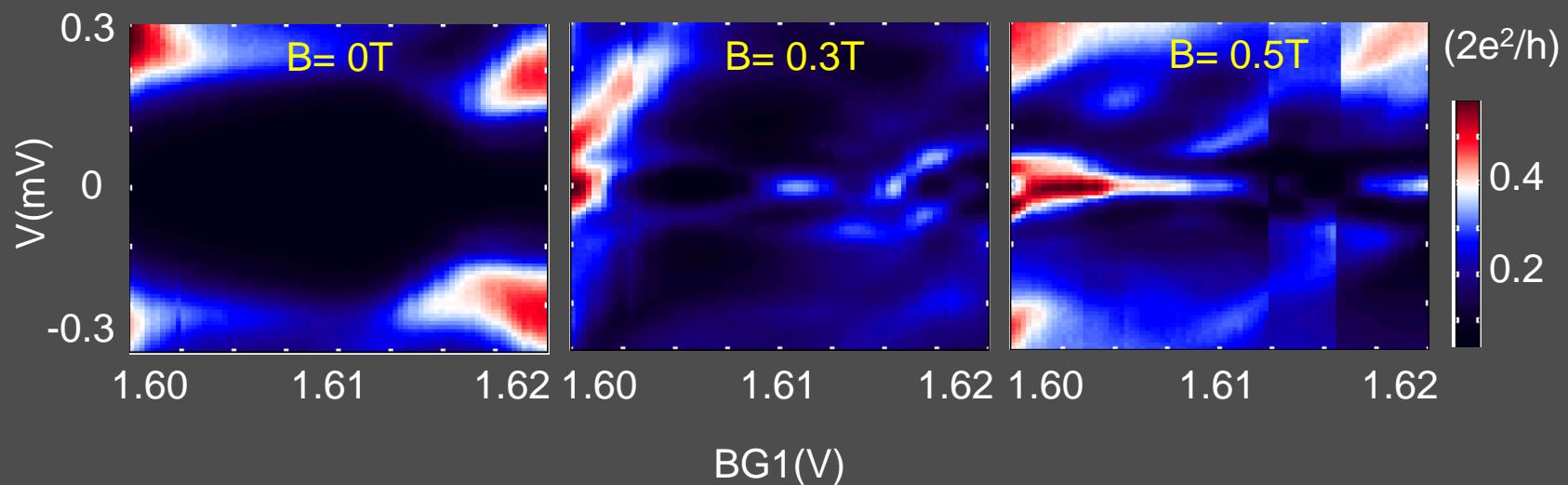
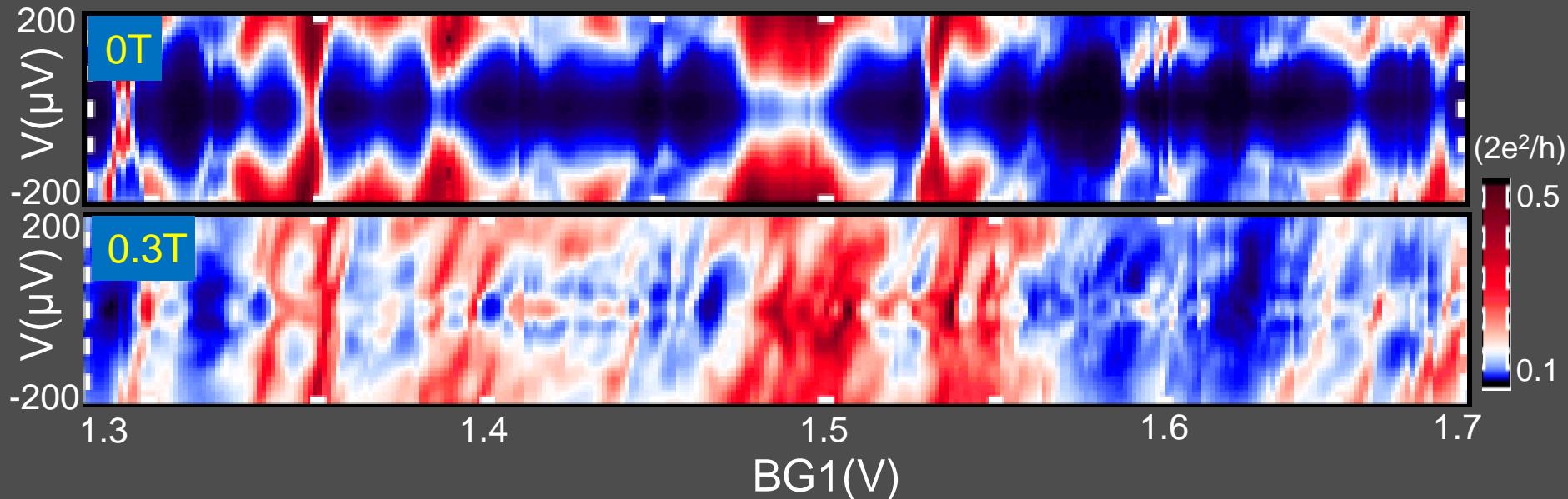
# Trivial (Non Topological) Andreev States



Ubiquitous non-Majorana zero-bias peaks:  
J. Chen et al, arXiv:1902.02773



# ZBP ubiquitous in gate space – at finite field



# Conclusions

- Theory is solid, so Majorana must be there
  - But! Zero bias peaks are way to easy to find
  - Trivial Andreev Bound States hard to distinguish from Majorana
- 
- Need to see MANY (ideally all) basic Majorana signatures in a single device!  
(otherwise fine-tuning must be assumed)

