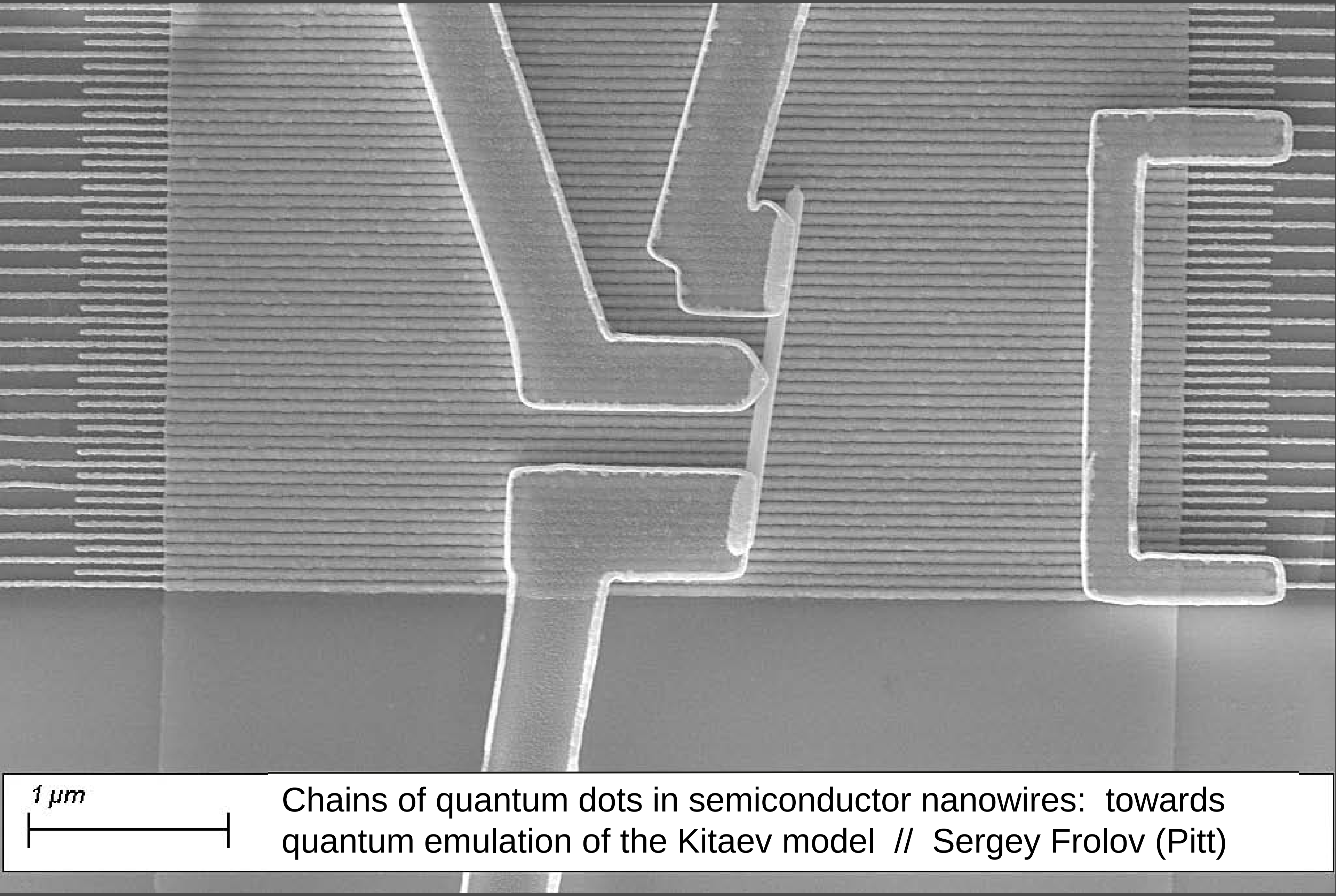


Chains of quantum dots in semiconductor nanowires: towards quantum emulation of the Kitaev model // Sergey Frolov (Pitt)

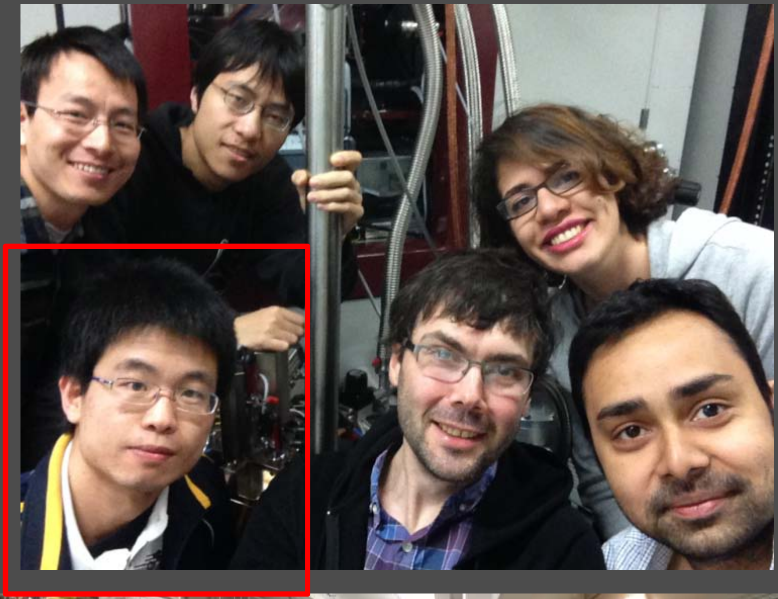
Frolov Lab, University of Pittsburgh

InSb nanowires:

Erik Bakkers
Diana Car
Sebastien Plissard
Sasa Gazibegovic
TU Eindhoven

<u>**Zhaoen Su**</u>
Hao Wu
Jun Chen
Peng Yu

Theory:
David Pekker
Andrew Daley
Alex Tacla

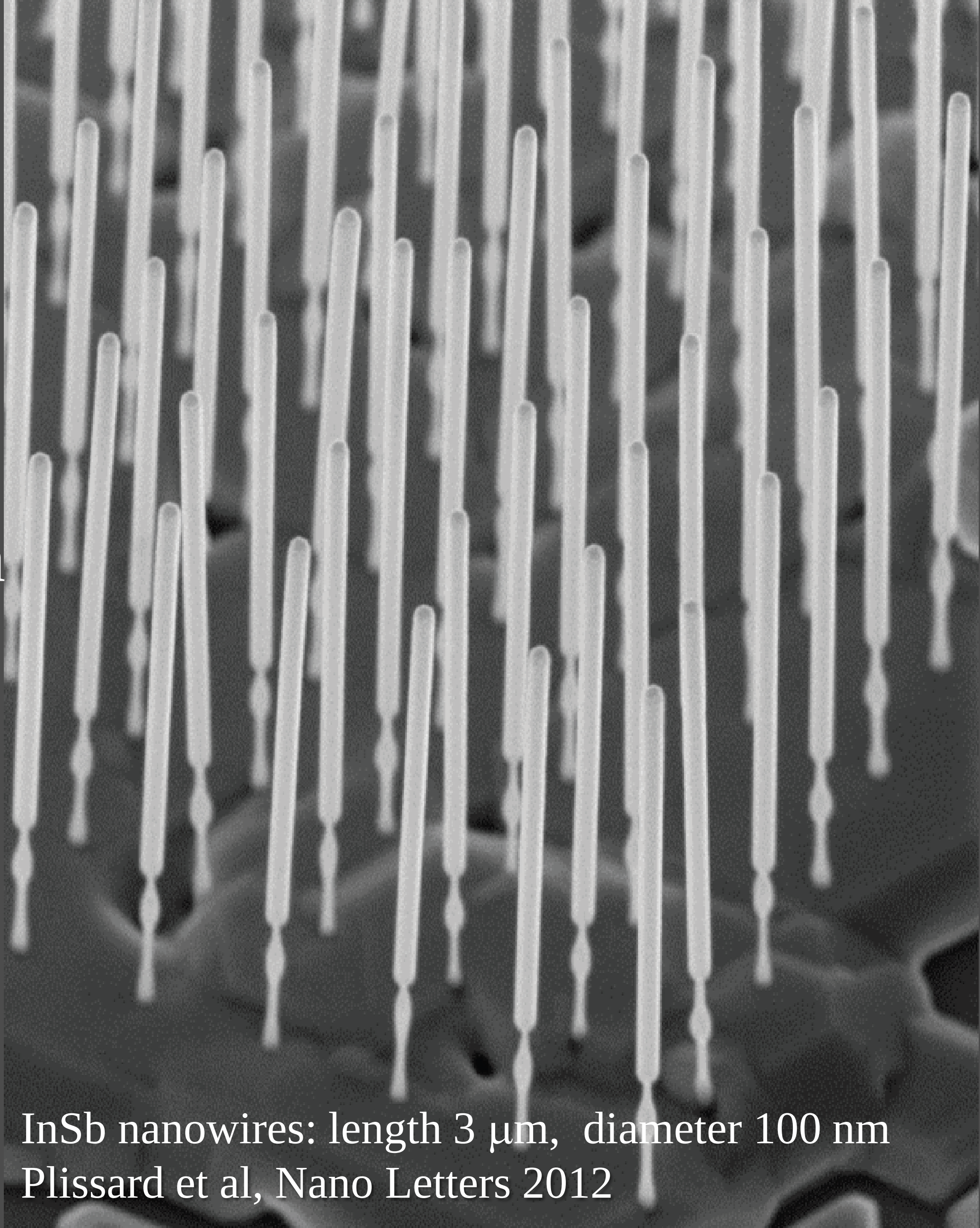


Support: NSF, ONR, Sloan, Kaufman, Cottrell, Nanoscience Foundation Grenoble, ANR

Majorana recipe:

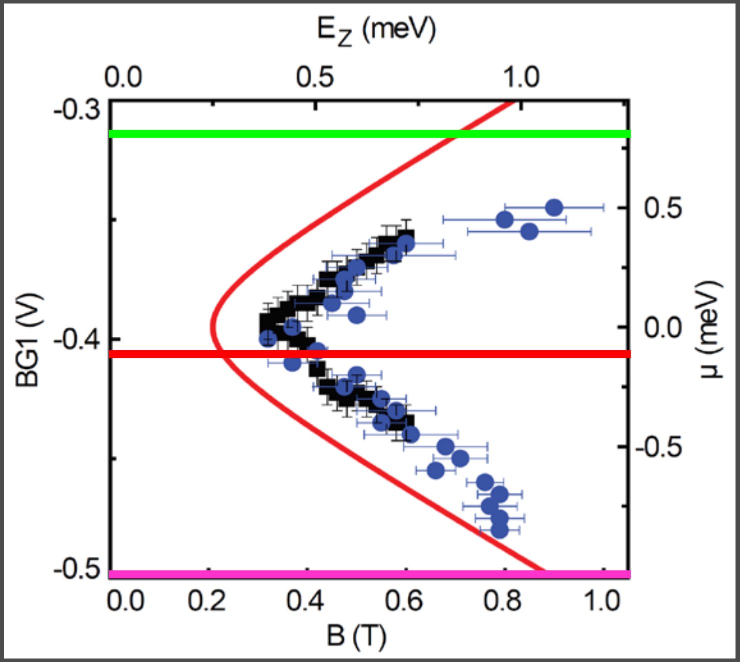
Lutchyn, Sau, Das Sarma, PRL 2010
Oreg, Refael, von Oppen, PRL 2010

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

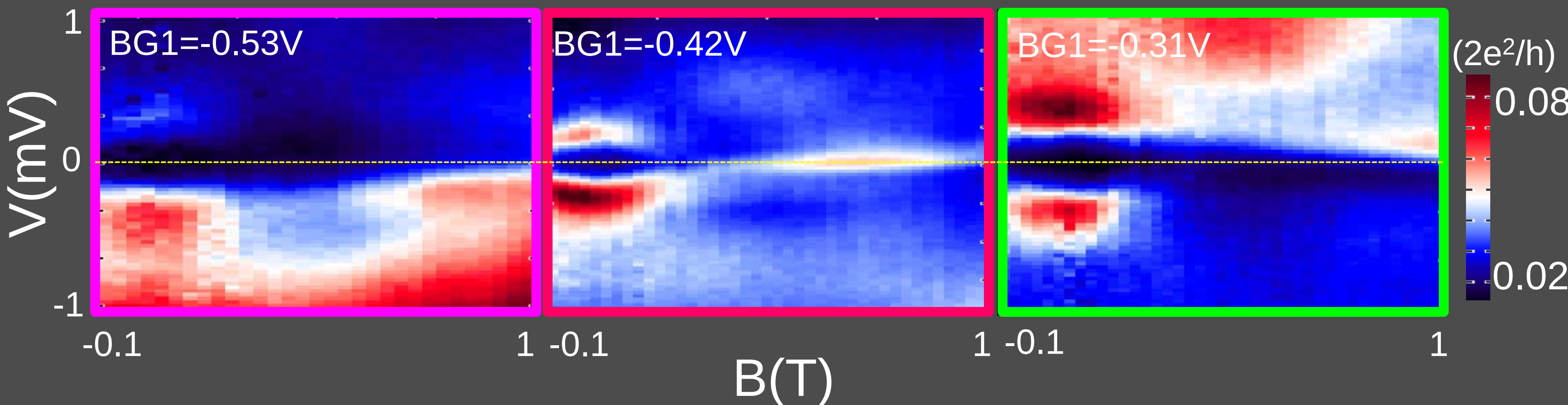


InSb nanowires: length 3 μm, diameter 100 nm
Plissard et al, Nano Letters 2012

Same nanowires and same superconductors as in Majorana experiments



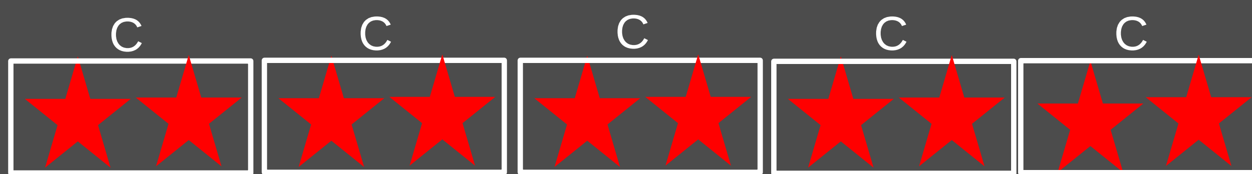
Topological condition: $E_Z > (\Delta^2+\mu^2)^{0.5}$



J. Chen et al, arXiv:1611.00727

single fermion:  $c = \gamma_1 + i\gamma_2$

chain of fermions:

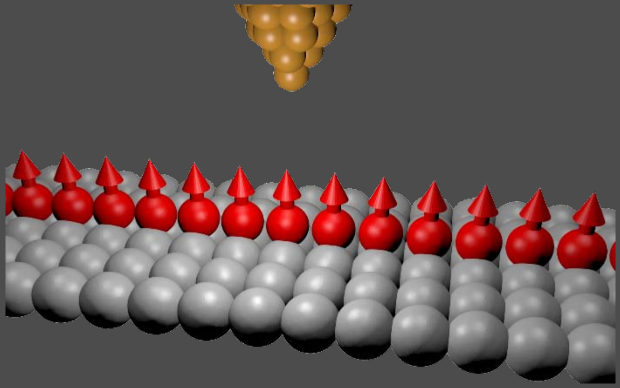


p-wave coupling:

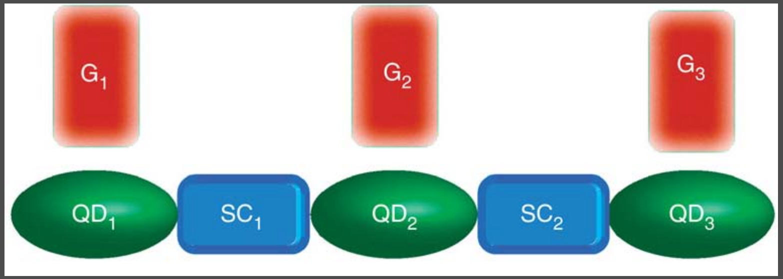
$\gamma_1^\dagger = \gamma_1$ $\gamma_2^\dagger = \gamma_2$

A.Yu. Kitaev, Unpaired Majorana fermions in Quantum Wires, Physics Uspekhi (2001)

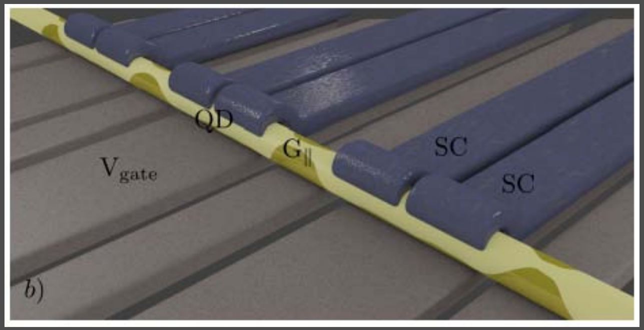
Can we build a *verbatim* Kitaev chain?



Nadj-Perge, Science 2014
(Yazdani Lab)



Sau and Das Sarma 2012

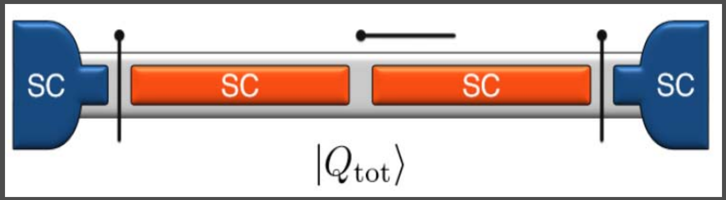


Fulga et al 2012

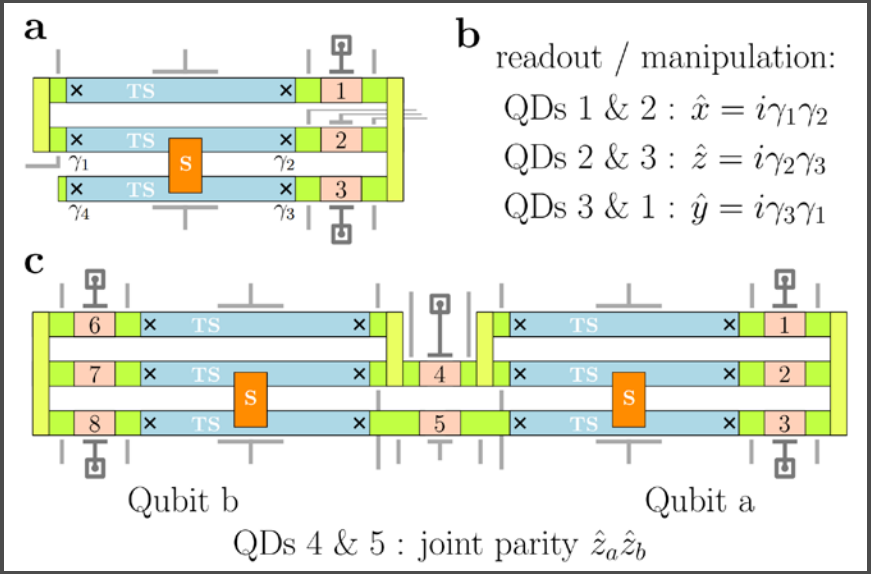
Hybrid Superconductor-Semiconductor Quantum Dots as Topological Qubits

Double Dot geometry: Majorana fusion

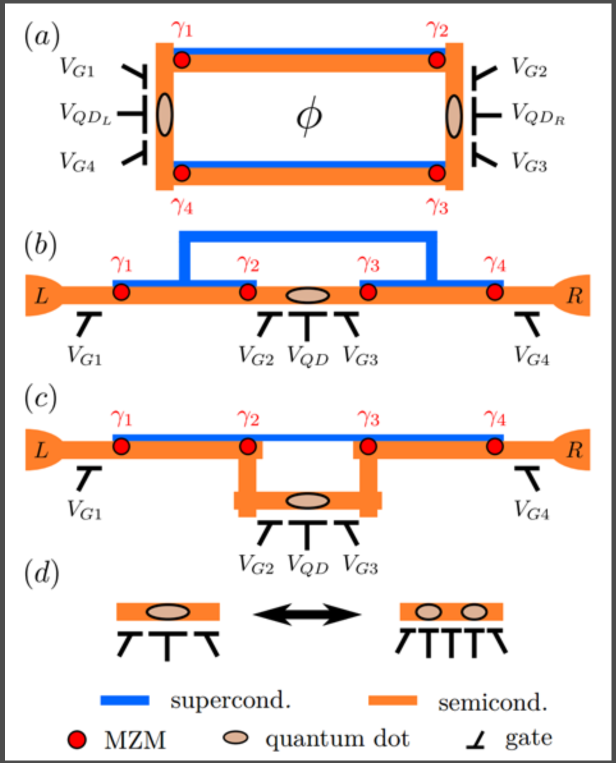
Aasen et al PRX 2015



Braiding mediated by dots:



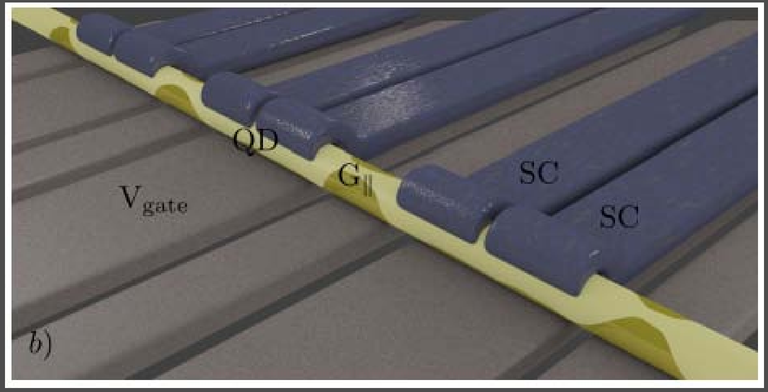
Plugge et al, arXiv:1609.01697



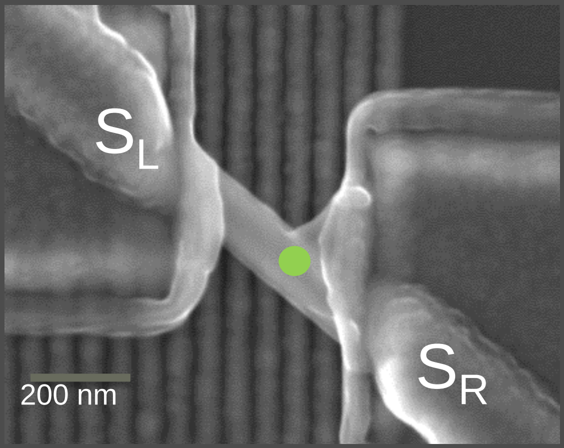
Karzig et al, arXiv:1610.05289

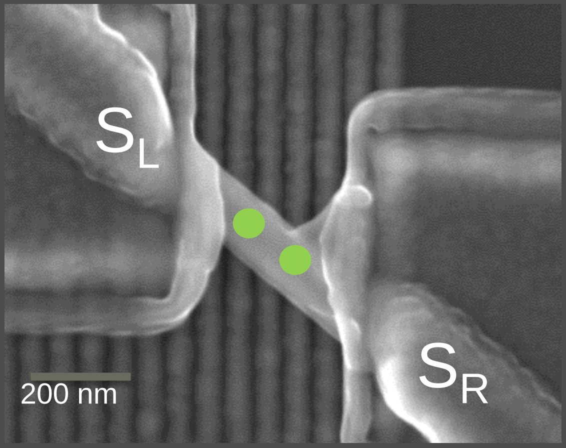
Outline

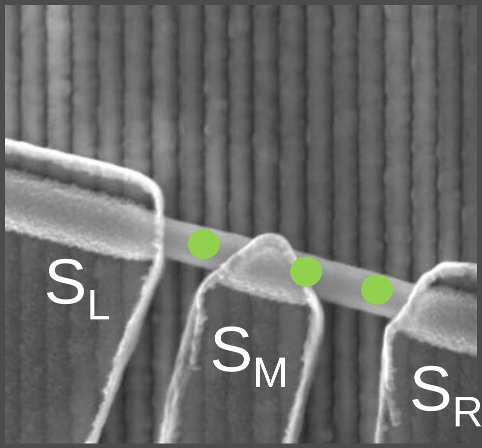
- One dot
- Two dots
- Three dots



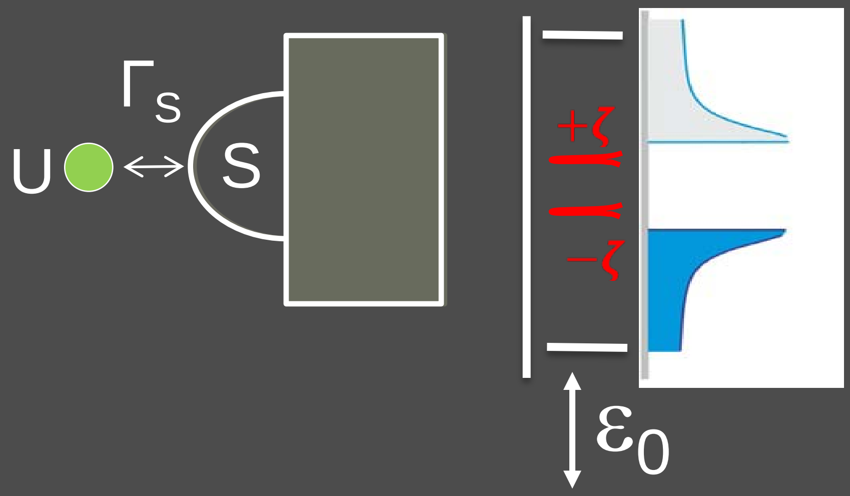
arXiv:1611.00727

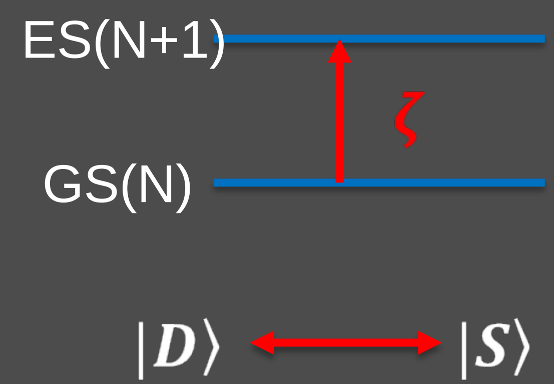


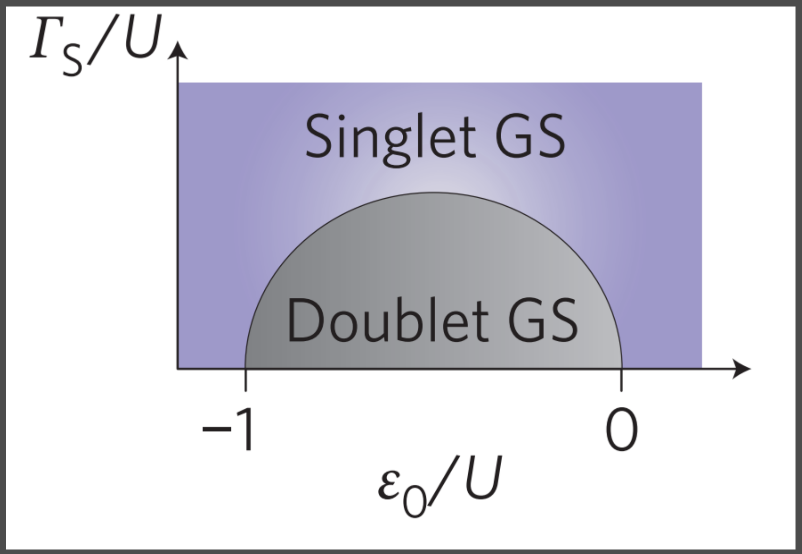




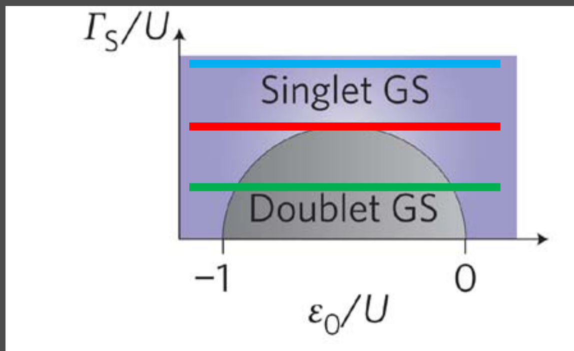
Andreev Bound States in <u>Single</u> Quantum Dots coupled to Superconductors



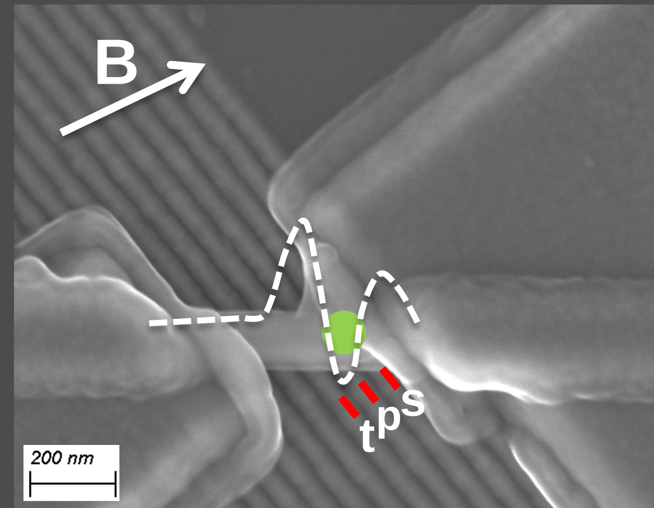




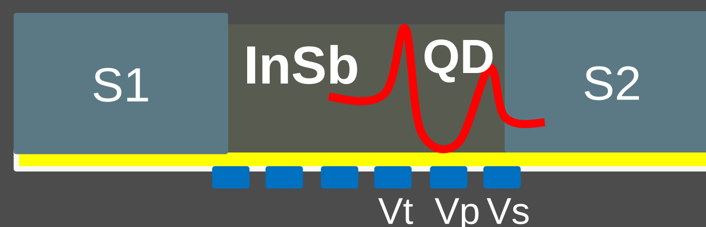
E.J.H. Lee Nature Nanotechnology 2013



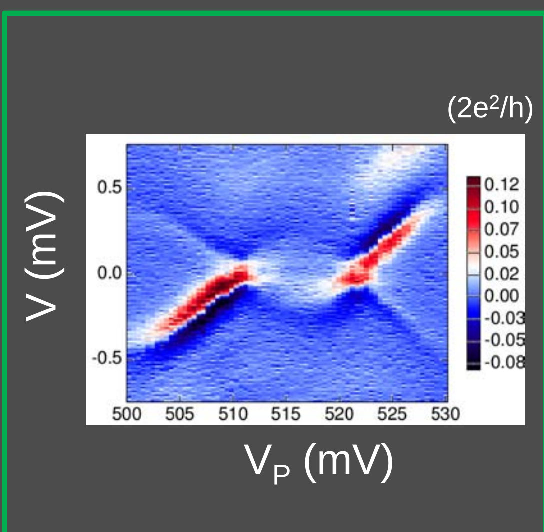
Γ_S/U
Singlet GS
Doublet GS
−1
0
ε_0/U



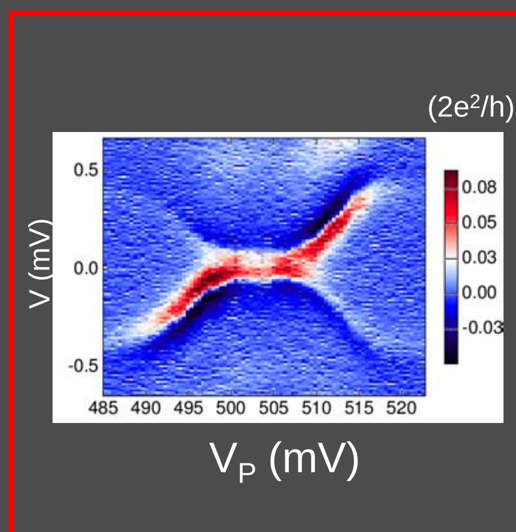
B
t
p
s
200 nm



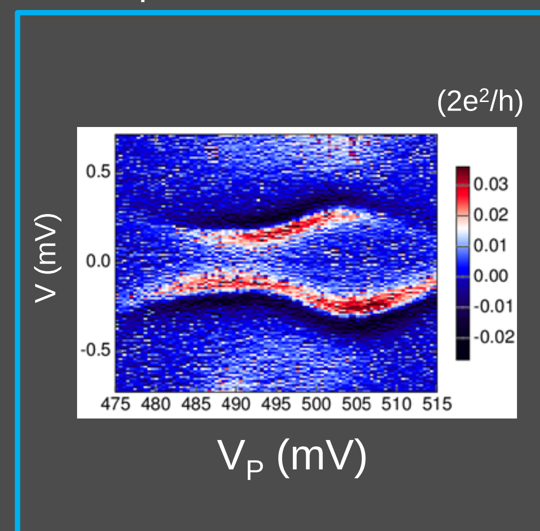
S1
InSb
QD
S2
Vt
Vp
Vs



(2e²/h)
V (mV)
0.5
0.0
-0.5
500 505 510 515 520 525 530
0.12 0.10 0.07 0.05 0.02 0.00 -0.03 -0.05 -0.08
V_P (mV)

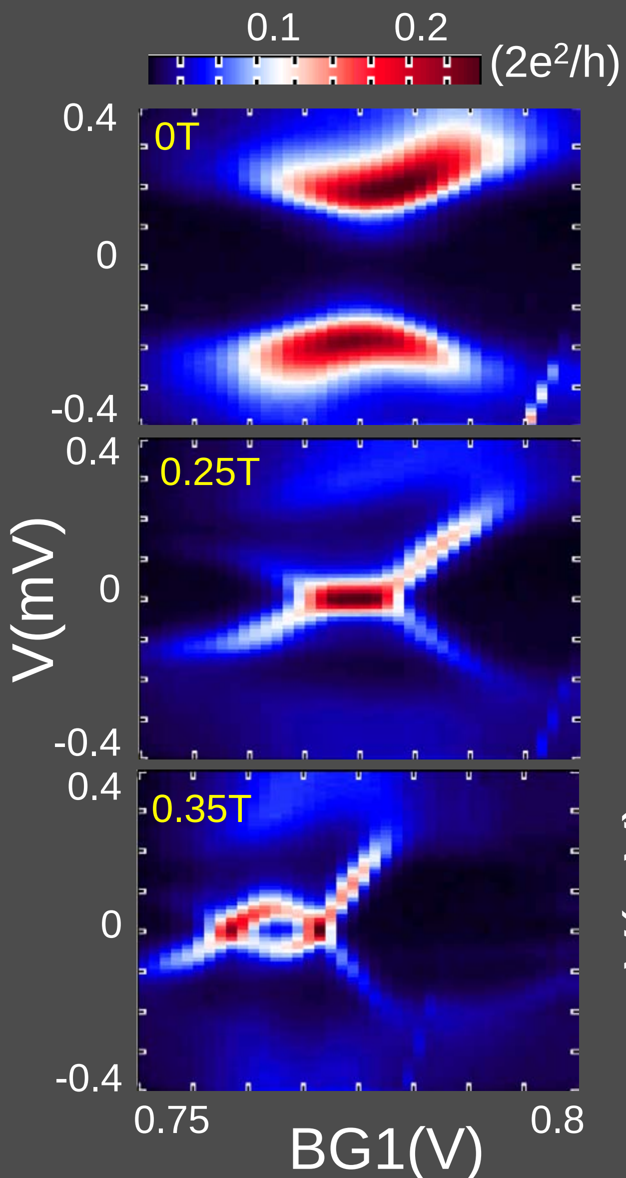


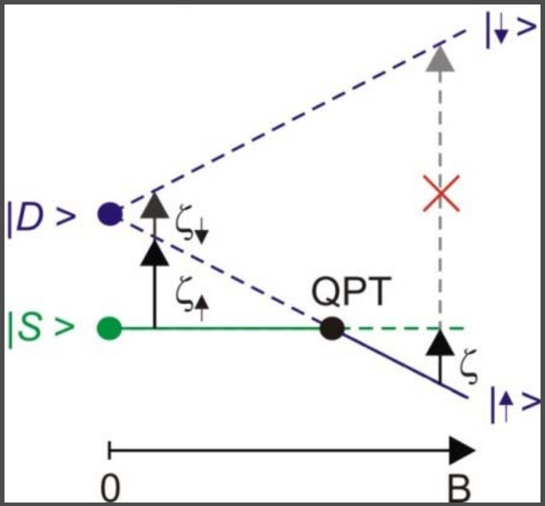
(2e²/h)
V (mV)
0.5
0.0
-0.5
485 490 495 500 505 510 515 520
0.08 0.05 0.03 0.00 -0.03
V_P (mV)

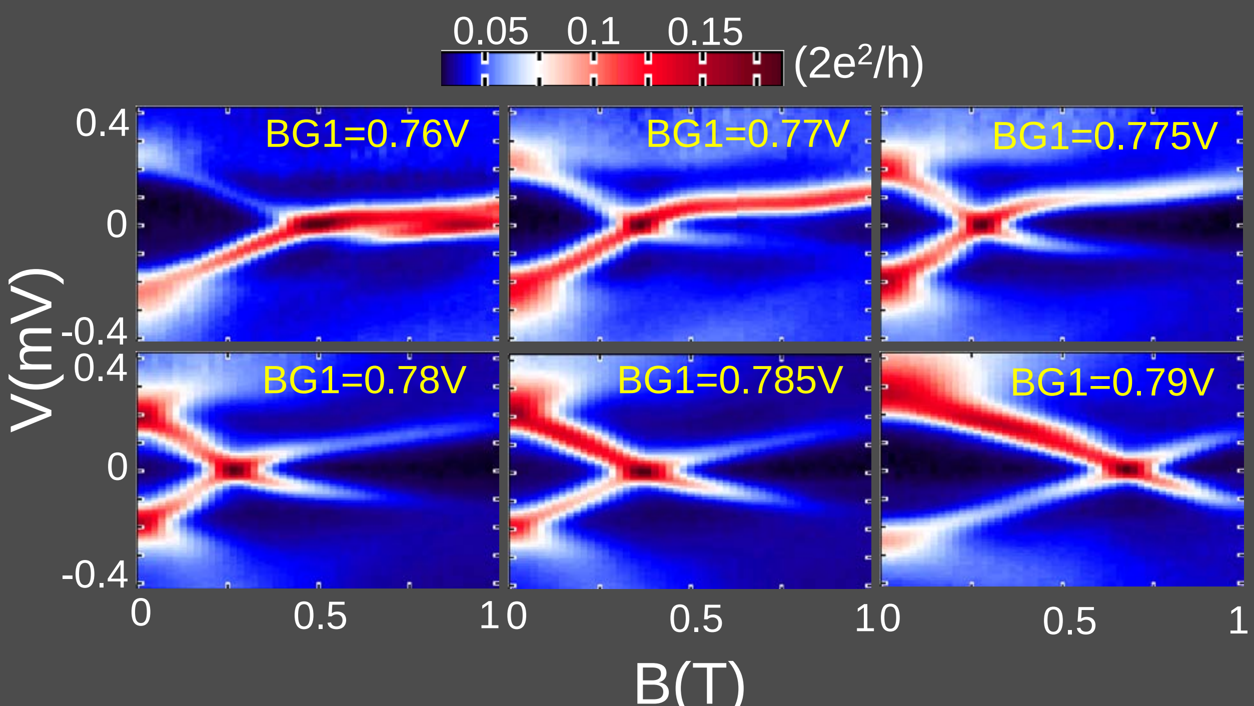


(2e²/h)
V (mV)
0.5
0.0
-0.5
475 480 485 490 495 500 505 510 515
0.03 0.02 0.01 0.00 -0.01 -0.02
V_P (mV)

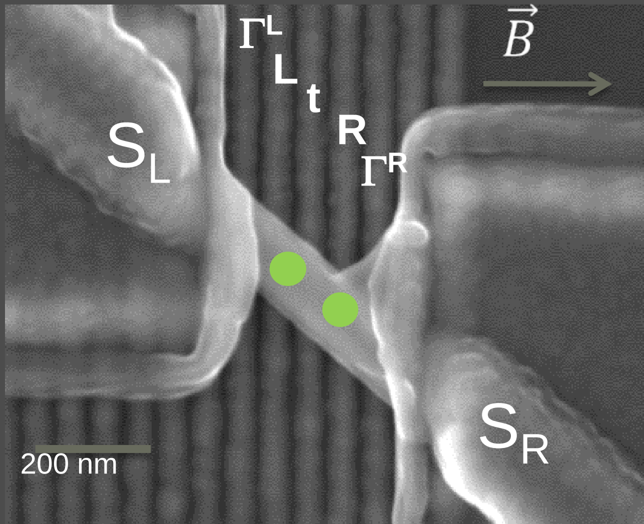
Magnetic field evolution of Andreev bound states



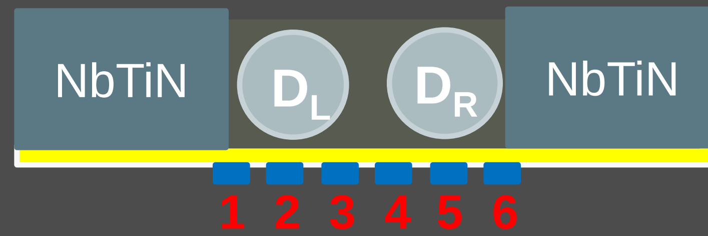


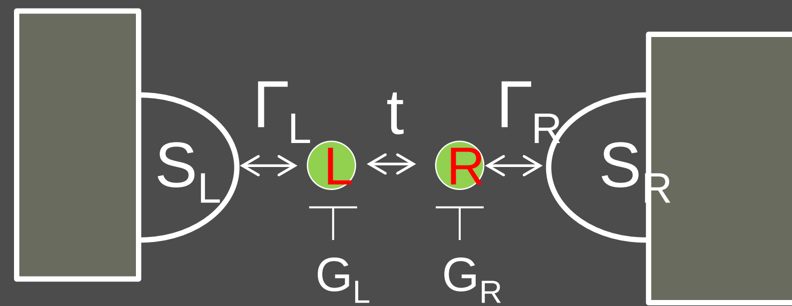


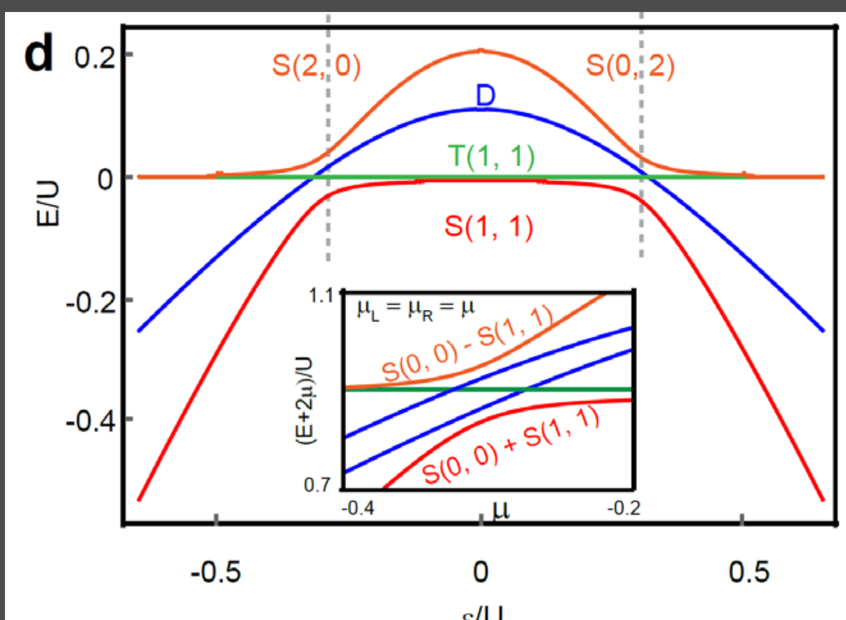
Double Dots: Andreev Molecules

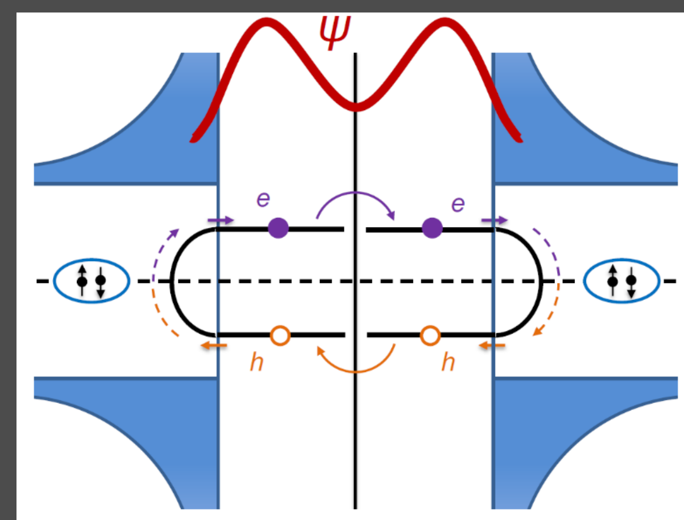


arXiv:1611.00727

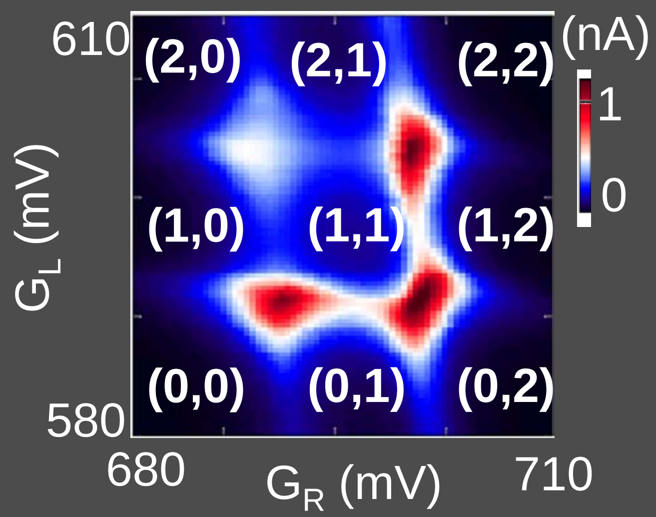


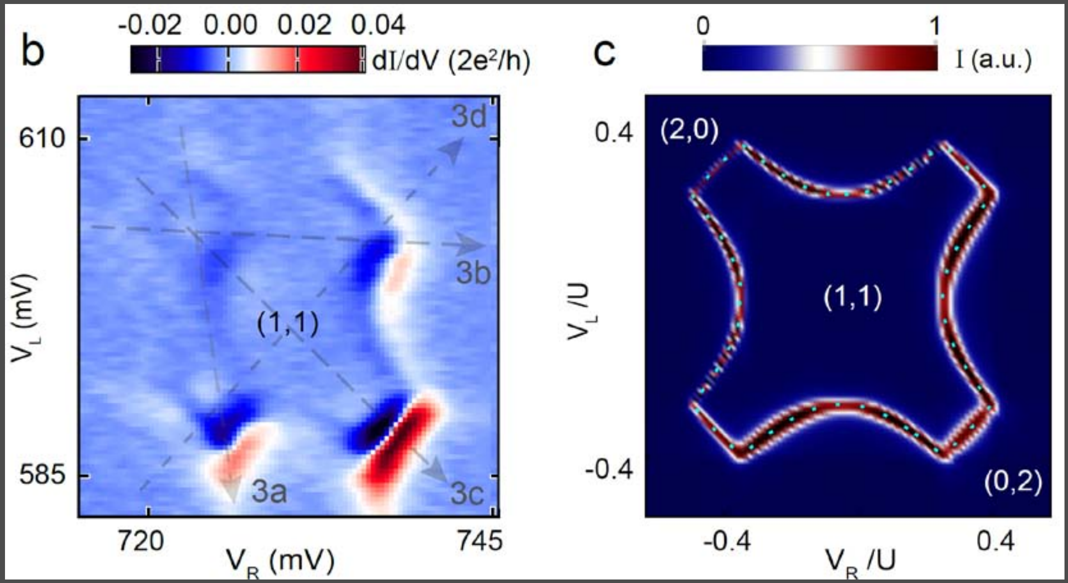






Double dot parity stability diagram



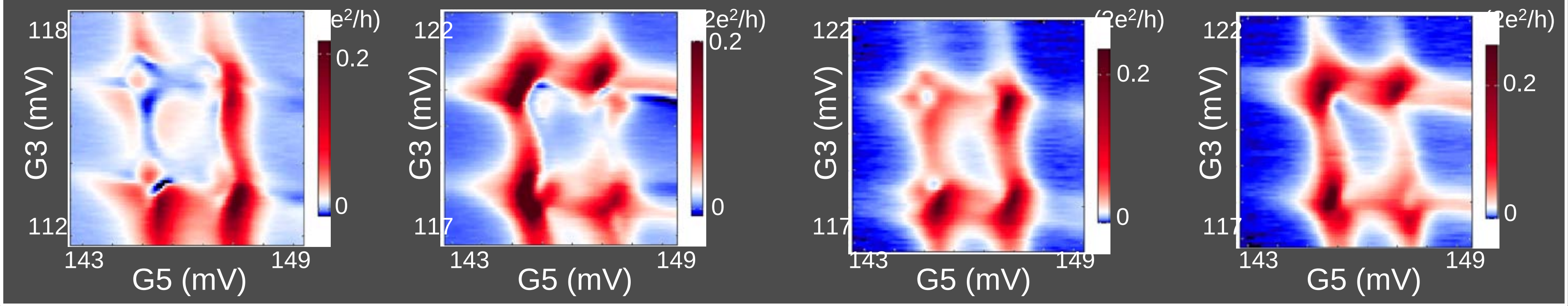


arXiv:1611.00727

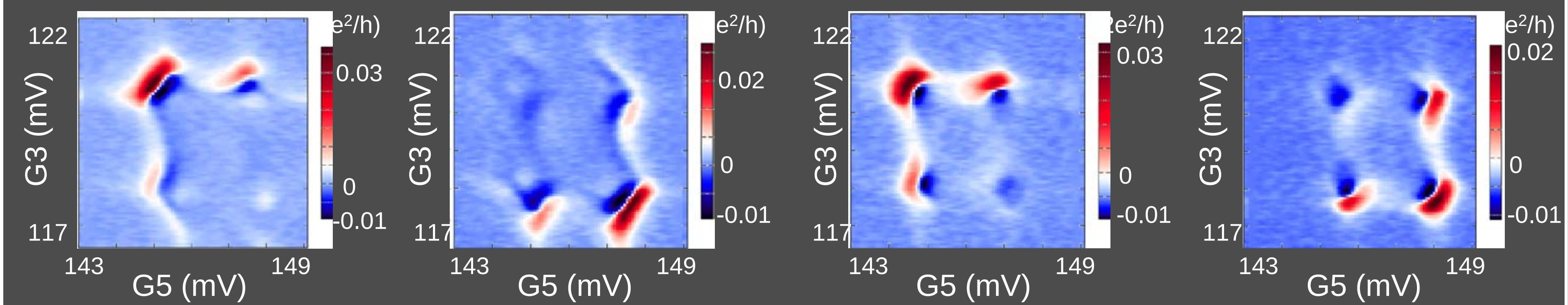
Differential conductance stability diagrams with strong and weak inter-dot coupling

Bias = -200 μV   Bias = 200 μV   Bias = -100 μV   Bias = 100 μV

Strong inter-dot coupling



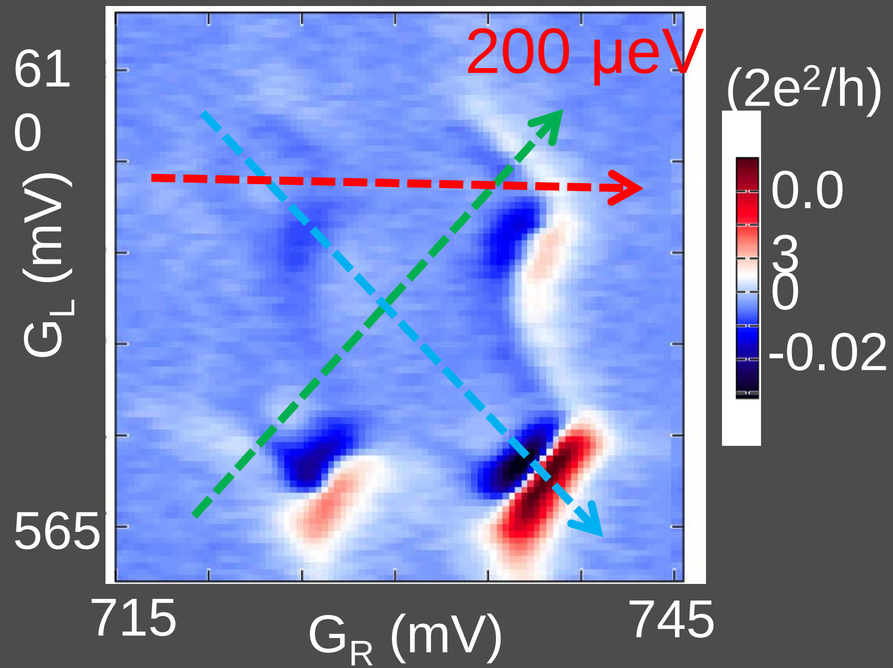
Weak inter-dot coupling

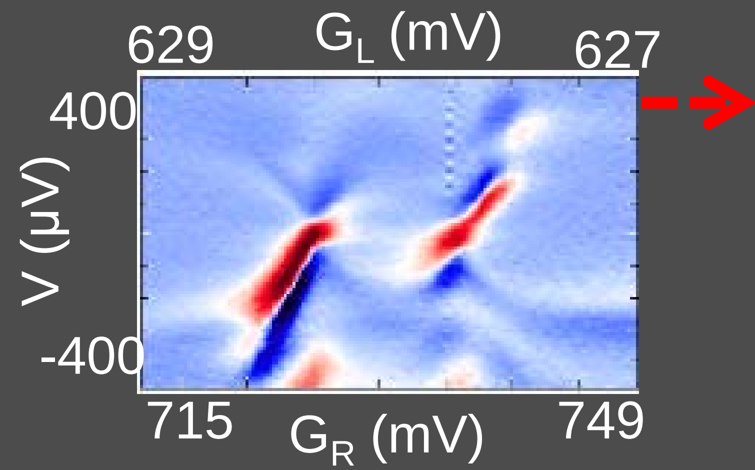


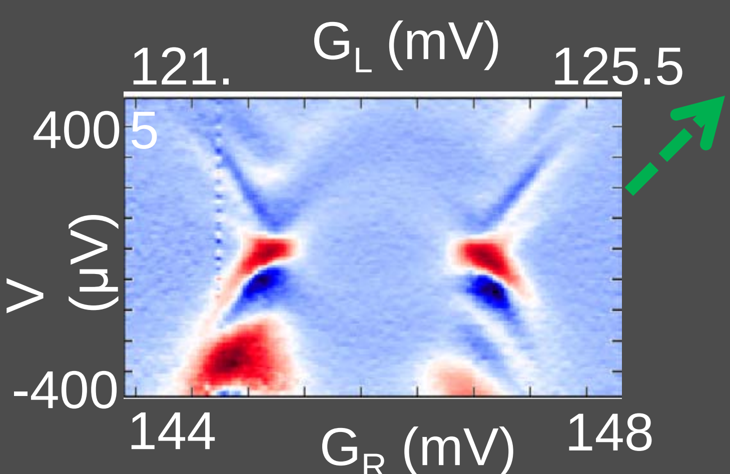
arXiv:1611.00727

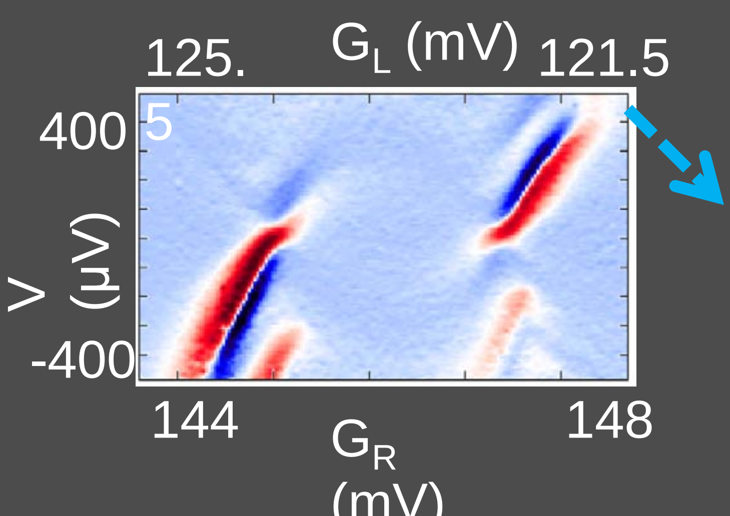
Molecular Andreev levels and the gate dependence

arXiv:1611.00727

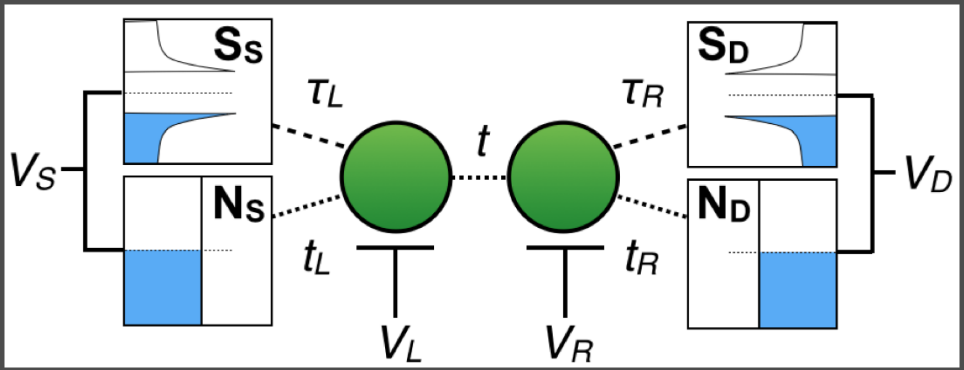


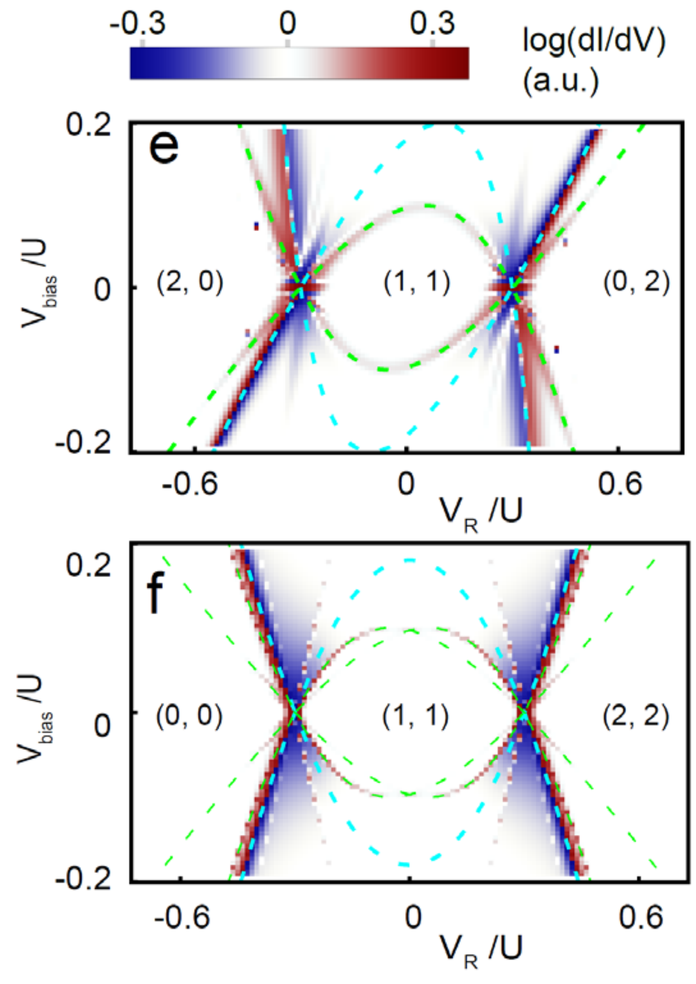




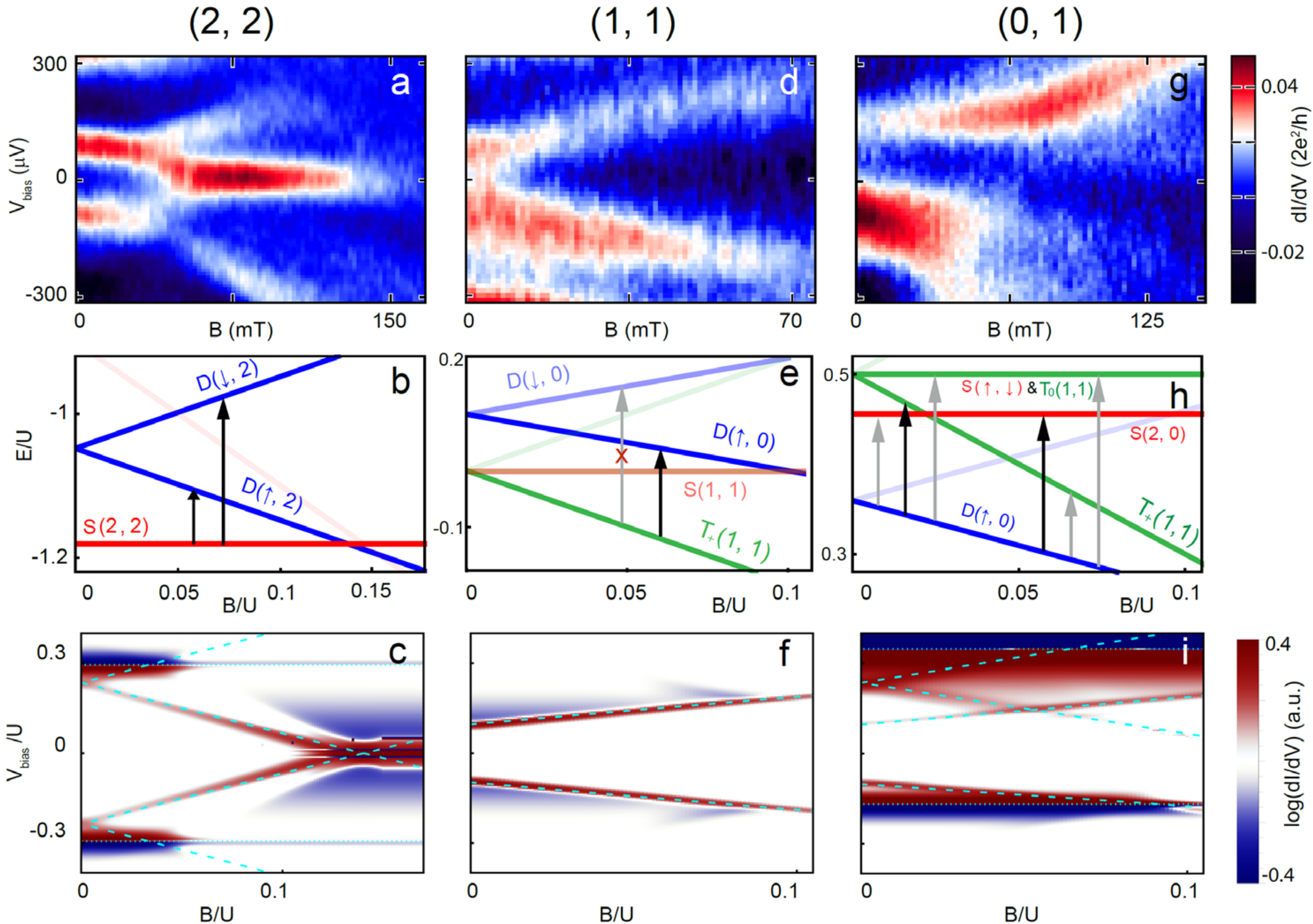


“Two-fluid” leads model (D. Pekker)





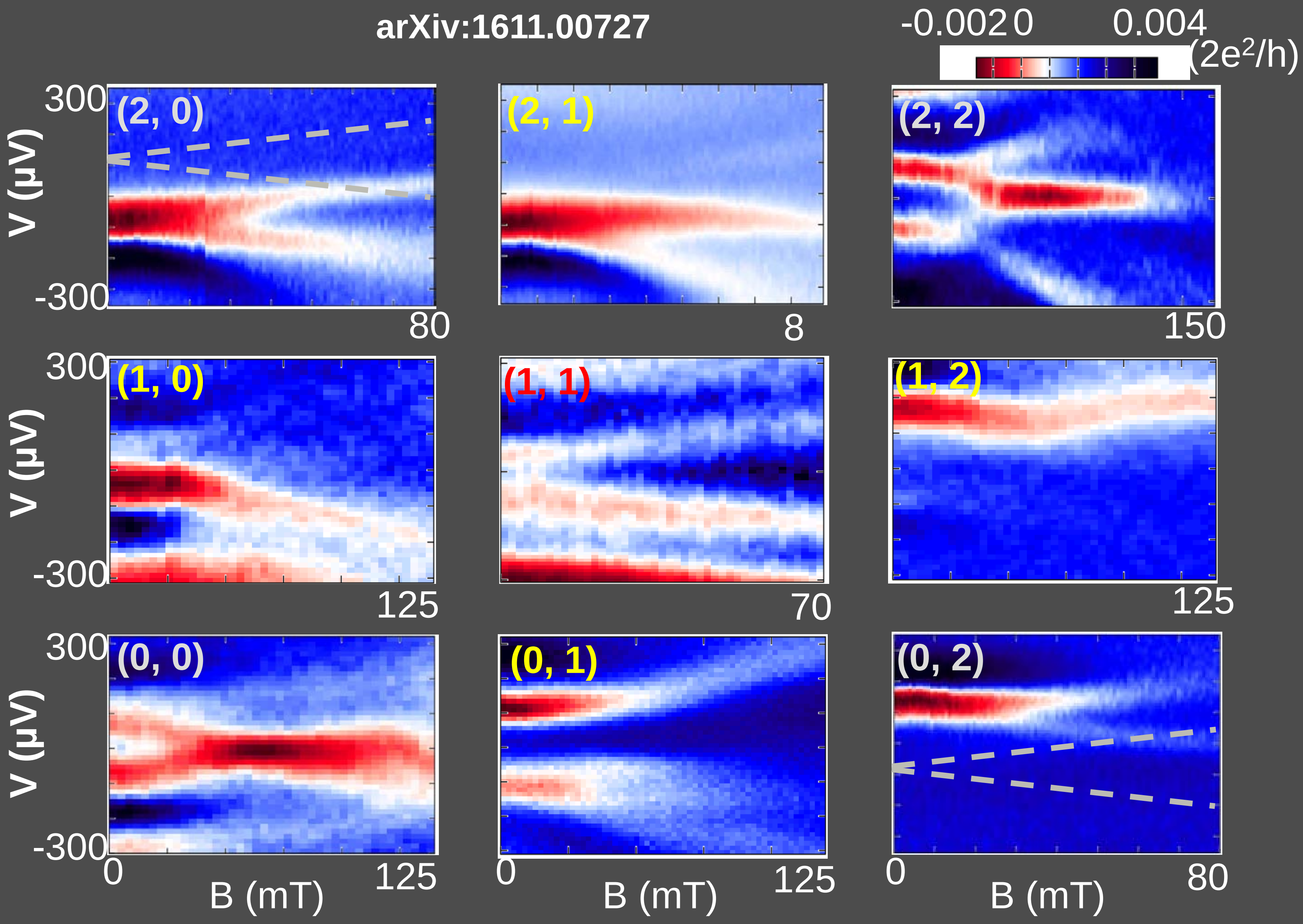
arXiv:1611.00727



(2, 2)
(1, 1)
(0, 1)
a
d
g
300
0
-300
V_{bias} (μV)
B (mT)
150
70
125
0.04
-0.02
dI/dV ($2e^2$/h)
b
e
h
E/U
-1
-1.2
0.2
-0.1
0.5
0.3
D(↓, 2)
D(↑, 2)
S(2, 2)
D(↓, 0)
D(↑, 0)
S(1, 1)
T_+(1, 1)
S(↑, ↓) & T_0(1,1)
S(2, 0)
D(↑, 0)
T_+(1, 1)
B/U
0.05
0.1
0.15
c
f
i
0.3
-0.3
V_{bias}/U
0.4
-0.4
log(dI/dV) (a.u.)

Spin table

arXiv:1611.00727



Summary

Andreev states in coupled multiple dots

Soft gap allows probing of Andreev spectra at zero bias

Triple dot: each dot strongly coupled to superconductor,
weak coupling between dots
(need both couplings same for Kitaev model)

Zero bias peaks abundant in 1,2,3 dots – this informs Majorana studies

Andreev molecules: Z. Su et al, arXiv:1611.00727

More to come…

D. Pekker

Z. Su