Andreev and Josephson Transport in InAs Nanowire-based Quantum Dots

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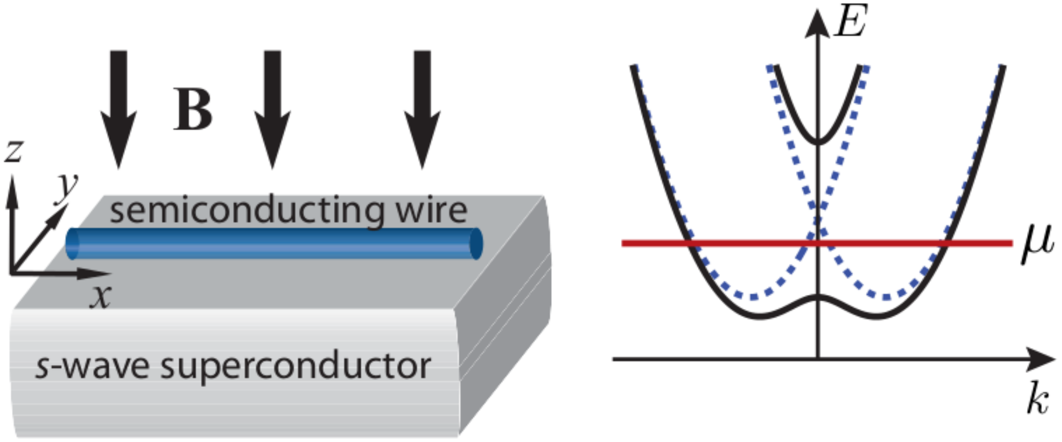
Motivation

- One-dimensional Topological Superconductors have seen recent attention because:

- They host a pair of Majorana Bound States (MBS) at the ends of a quantum wire, which are **chargeless**, **spinless**, and at **zero energy**.

- A recipe for MBS: a superconductor / semiconducting nanowire / superconductor proximity effect junction, in a strong magnetic field. [R. Lutchyn et al., PRL 105, 077001 (2010)]

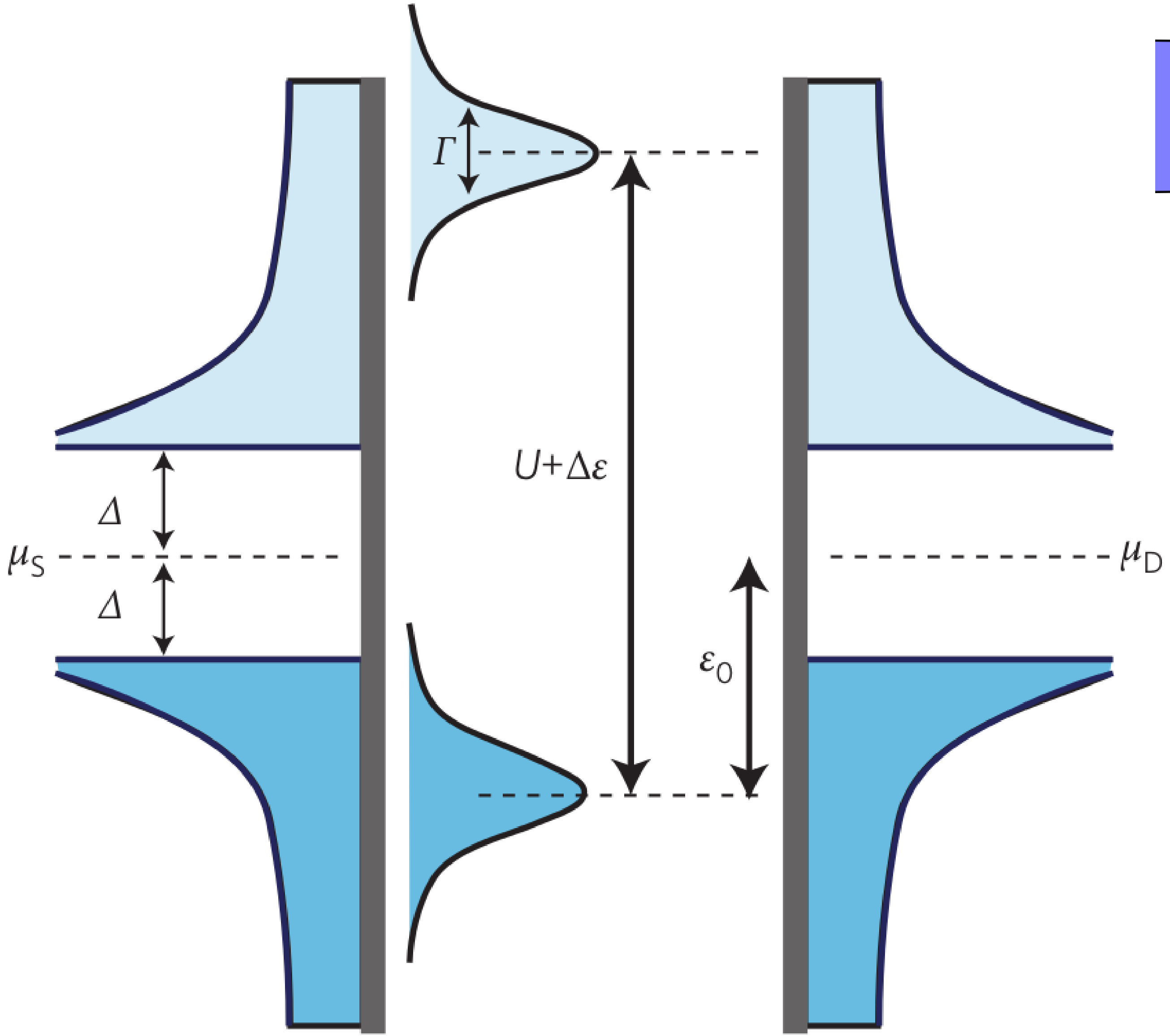
- InAs nanowires are suitable as the semiconductor (strong spin-orbit coupling), and Nb as the superconductor (high critical field).



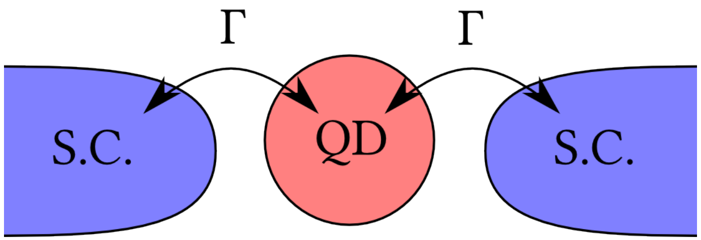
[J. Alicea et al., Nature Physics **7**, 412–417 (2011)]

- A quantum dot embedded in the semiconductor can be used to perform initialization and readout operations on the MBS. [K. Flensberg, PRL **106**, 090503 (2011)]

Proximity Effect in Quantum Dots Coupled to Superconductors



[S. Franceschi et al., Nat. Nanotech. **5**, 703–711(2010)]



Strong Coupling Regime:

$$\Gamma >> \Delta, U$$

- Cooper pairs tunnel across.

Weak Coupling Regime:

$$\Gamma << \Delta, U$$

- Sequential tunnelling of single charges.

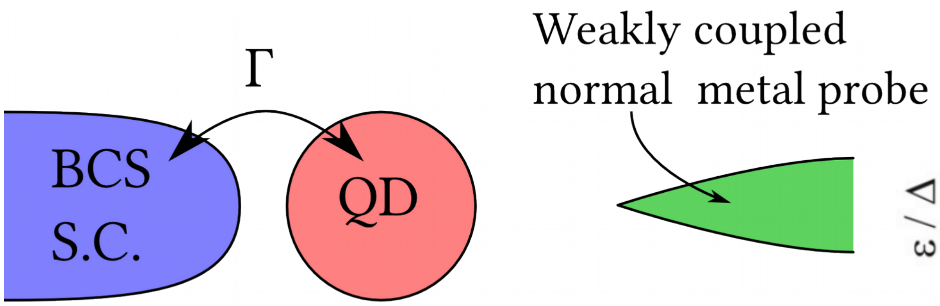
Intermediate Regime:

$$\Gamma \sim \Delta << U$$

- States on the Dot hybridize with quasiparticles in the S.C. leads, forming Andreev Bound States.

Anderson Impurity Model

- Minimal Model for a Quantum Dot connected to a S.C. bank.



Γ

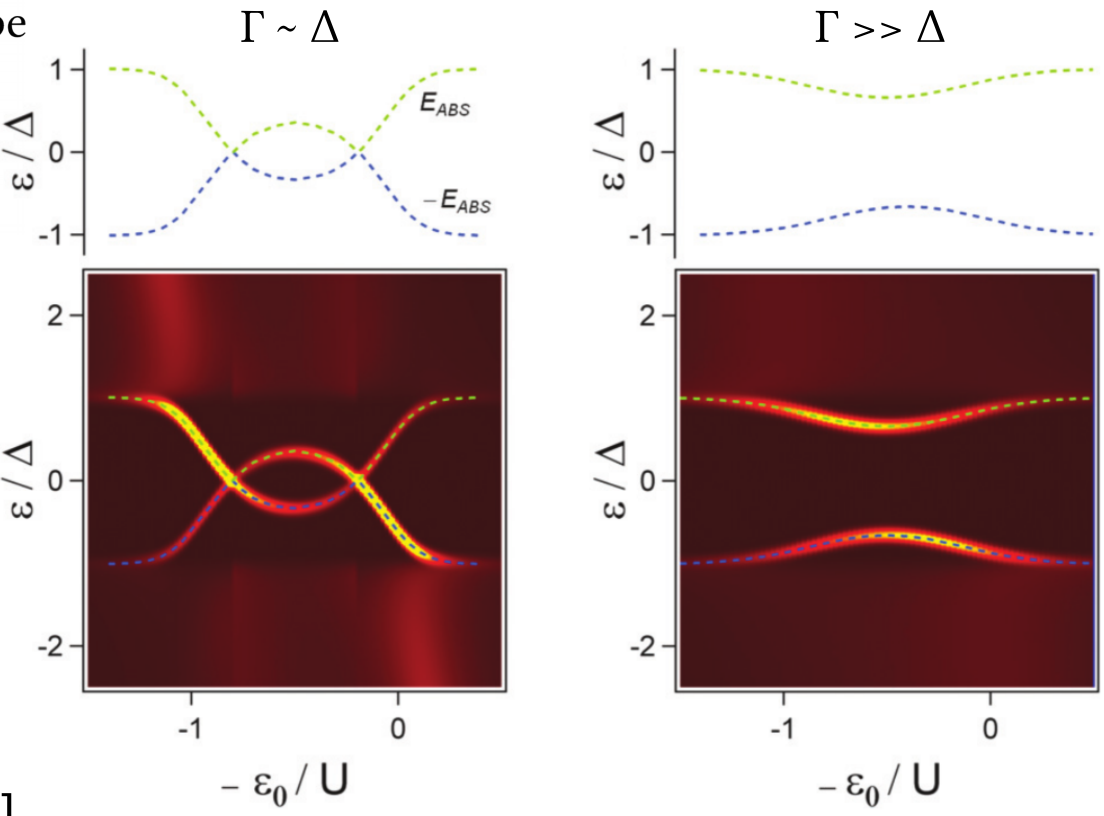
BCS S.C.

QD

Weakly coupled normal metal probe

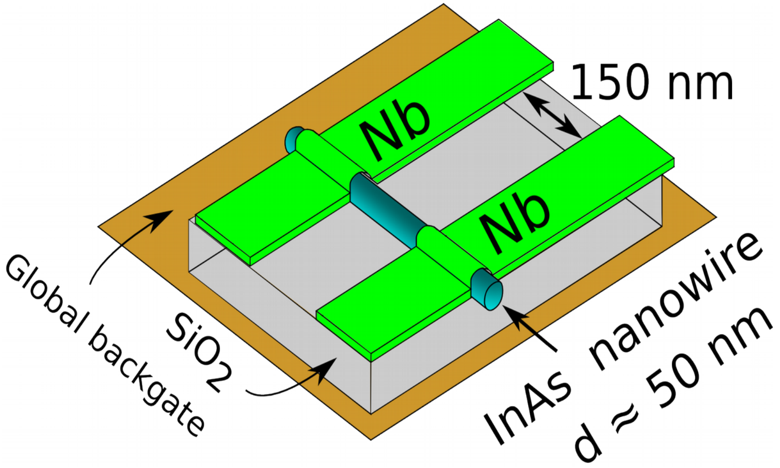
$$H_{\mathrm{QD}} = \varepsilon_0(n_\uparrow + n_\downarrow) + U\, n_\uparrow n_\downarrow$$

- A pair of Andreev Bound States (ABS) predicted, shown below for U >> Δ.
- The coupling strength Γ qualitatively changes the behaviour of ABS vs. dot energy.

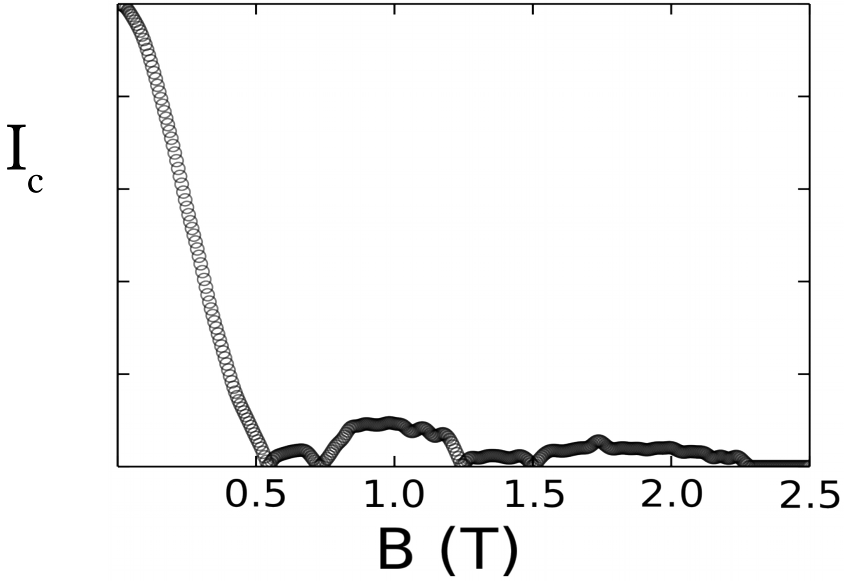


[J.-D. Pillet et al., PRB **88**, 045101 (2013)]

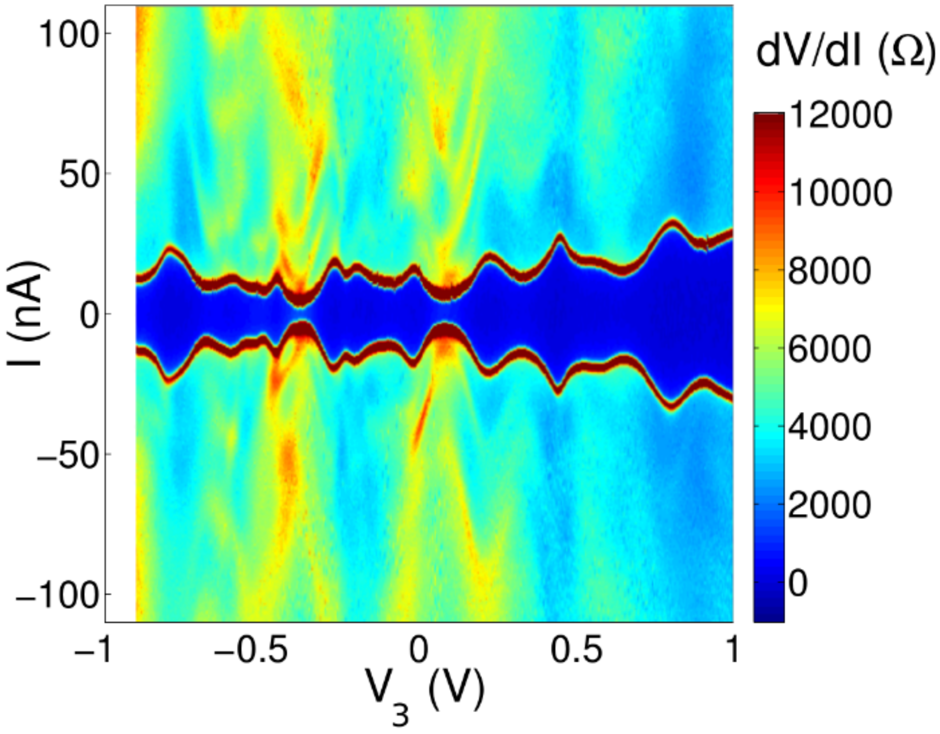
Nb-InAs nanowire-Nb Field Effect Transistor Devices



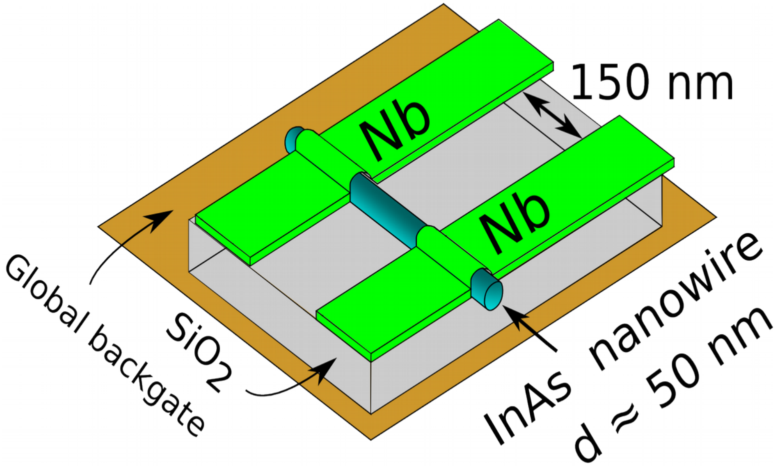
- Some devices can be tuned to the Josephson Transport regime.
- I_c up to 55 nA observed.
- Orbital Josephson Interference observed in an axial magnetic field.



- Theory: KG, J. Baugh arXiv:1411.3054
- Experiment: KG, G.W. Holloway, J. Baugh et al., arXiv:1405.7455

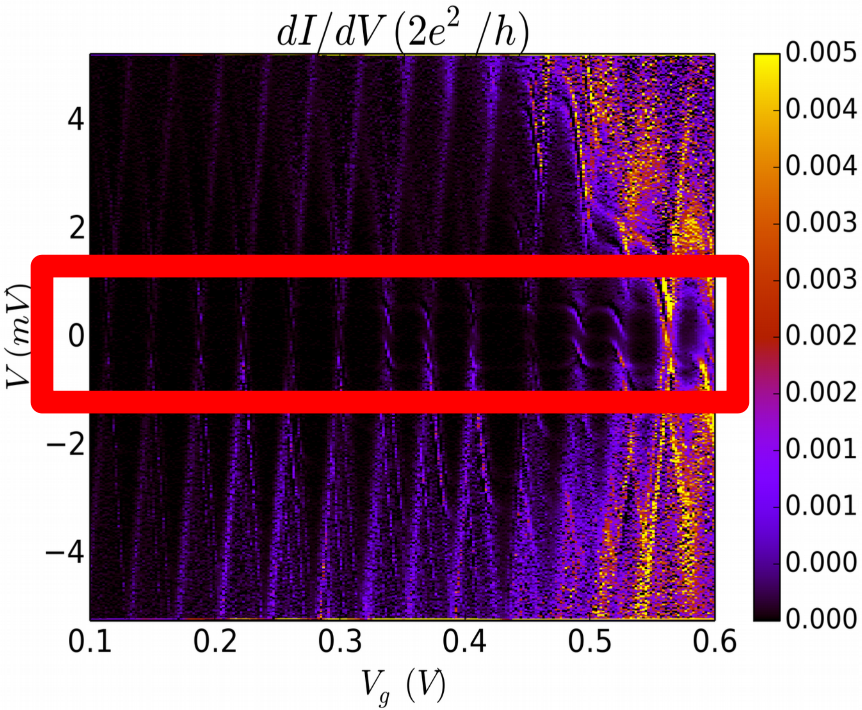


Nb-InAs naowire-Nb Field Effect Transistor Devices

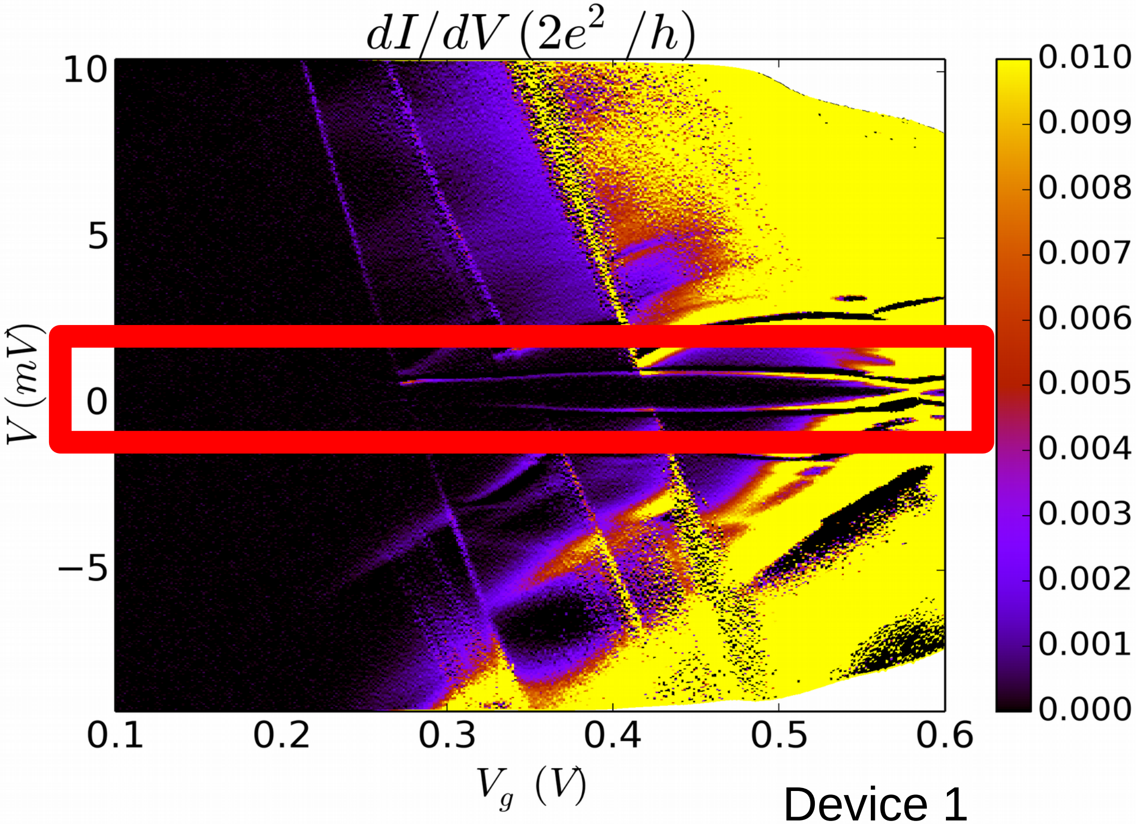


We concentrate on devices tuned to the quantum dot regime.

- Charging Energy U ~ 10 meV
- μ (20 K) $>$ 5000 cm^2/(V.s)
- Signatures of Andreev transport observed within the bias window $-\Delta/e$ to Δ/e.
- $\Delta = 1.1$ meV

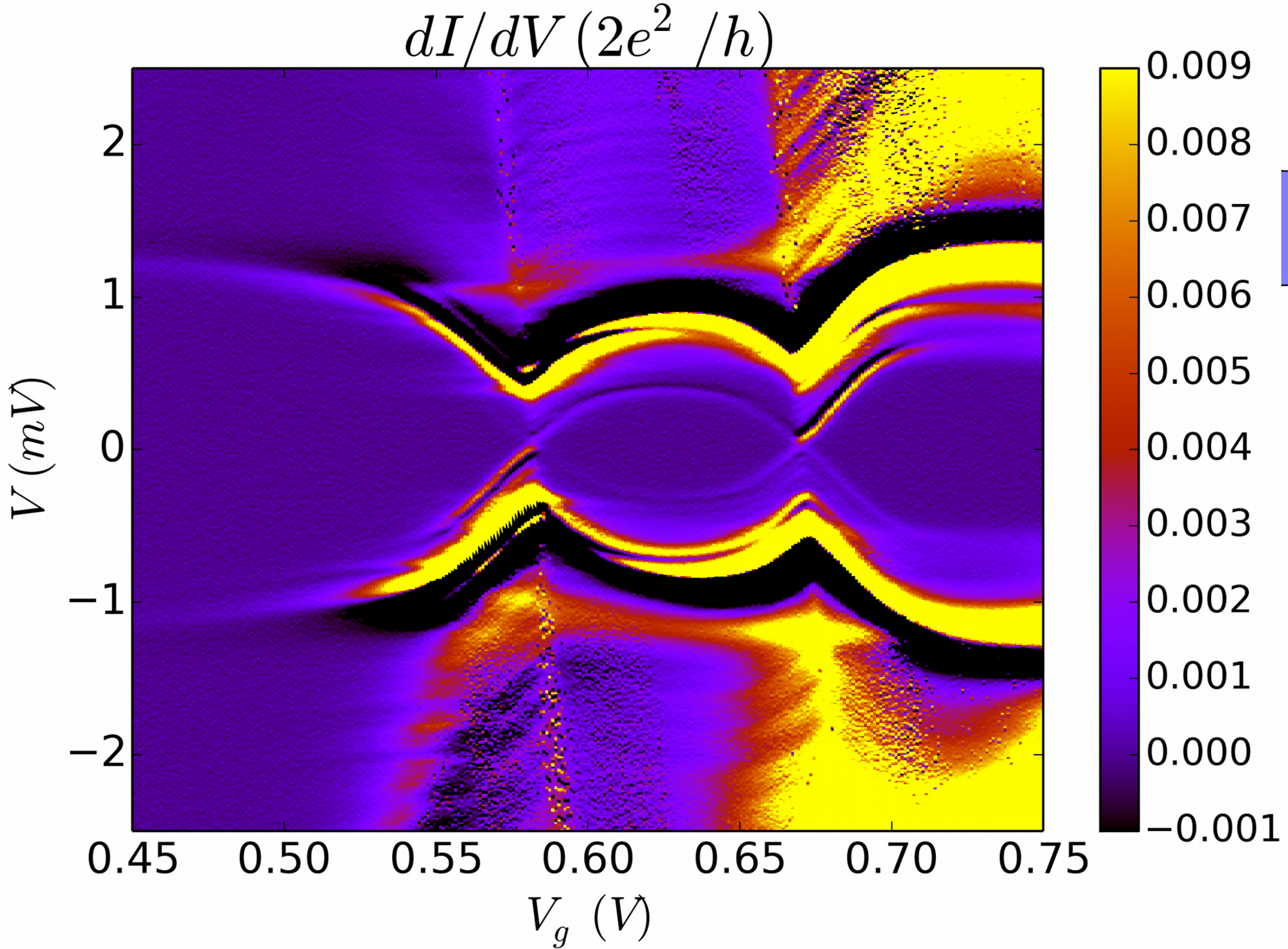


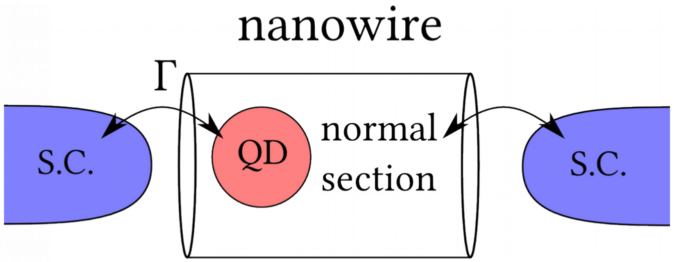
Device 2



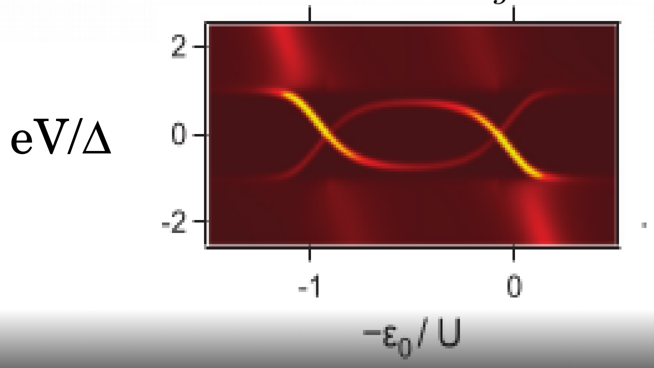
Device 1

Andreev Transport in Nb-InAs nanowire-Nb Devices





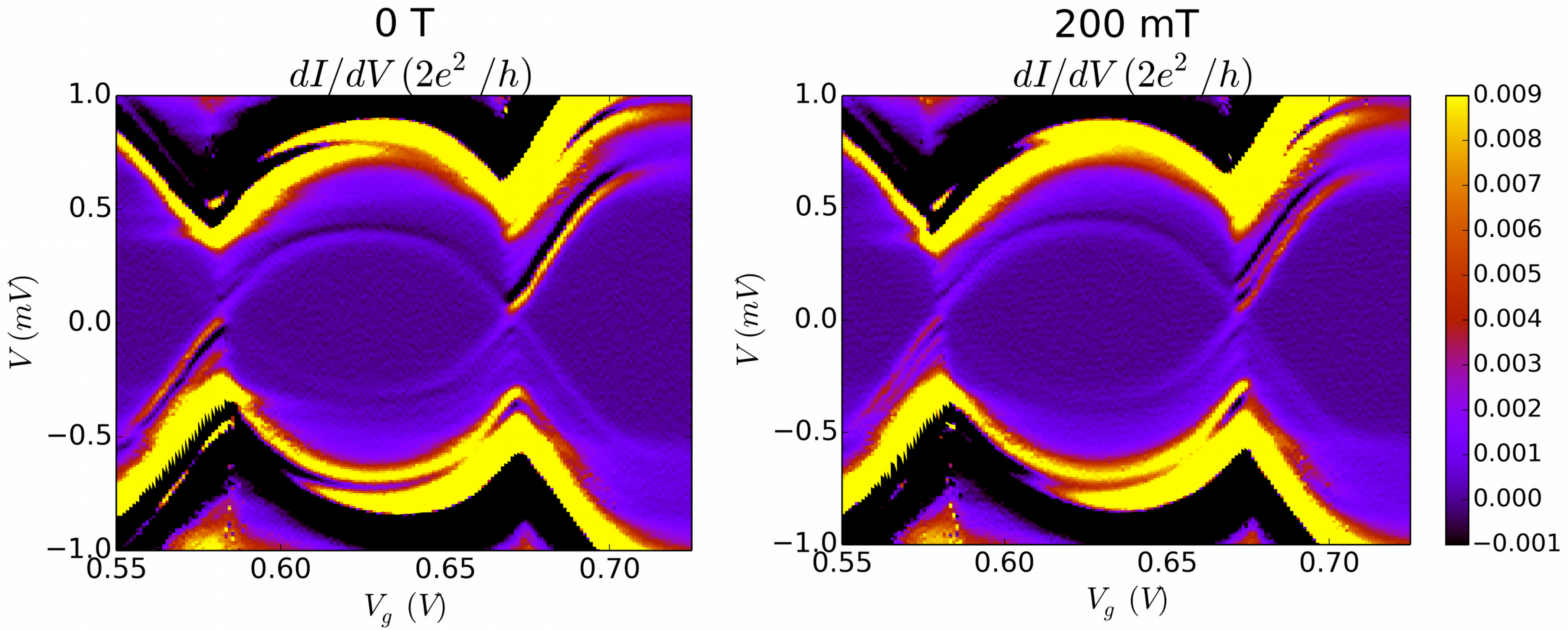
- Regions of negative dI/dV consistent with BCS-like DOS of the lead.
- Horizontal features at Δ = 1.1 meV indicate 1st order Andreev transport.



Features above and below the ABS might be:

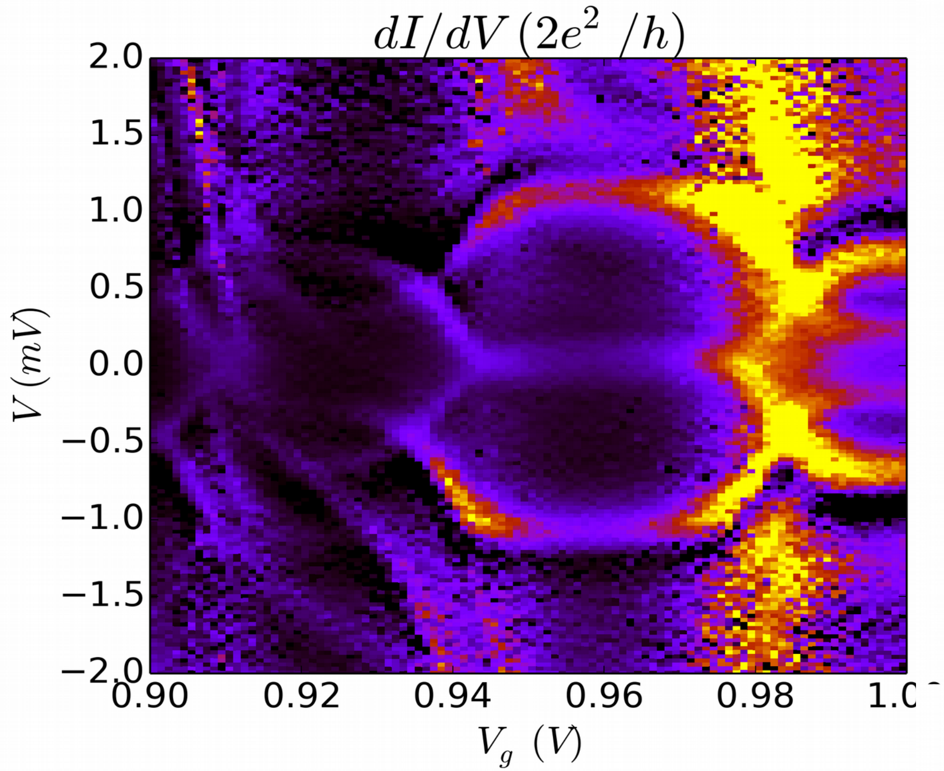
- Another pair of ABS, connected to the continuum levels.
- Signatures of Multiple Andreev Reflection, rounded near the charge degeneracy points.

Splitting in a Magnetic Field

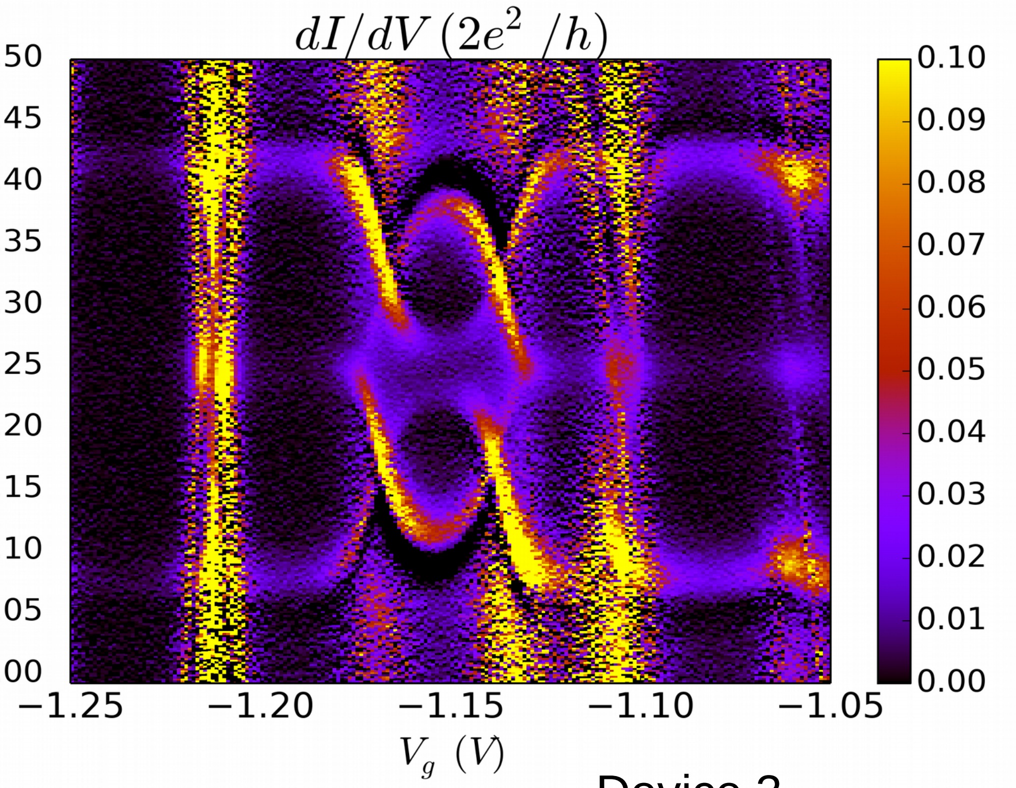


- The ABS are split in the presence of an axial magnetic field.
- A Landé factor of $g \approx 8$ is estimated from the maximum splitting.
- Splitting appears for every other charge state (even-odd effect), consistent with the Anderson model.
- The splitting closes as V_g moves away from the charge degeneracy point.
  - The nature of the ground-state is changing – why?

Other Andreev Bound States



Device 2



Device 3

- More complex features visible as the devices are tuned to more conductive regimes.
- ABS appear to be pinned to zero energy to form a zero-bias peak.

- Two pairs of ABS visible, which might indicate two dots in series.

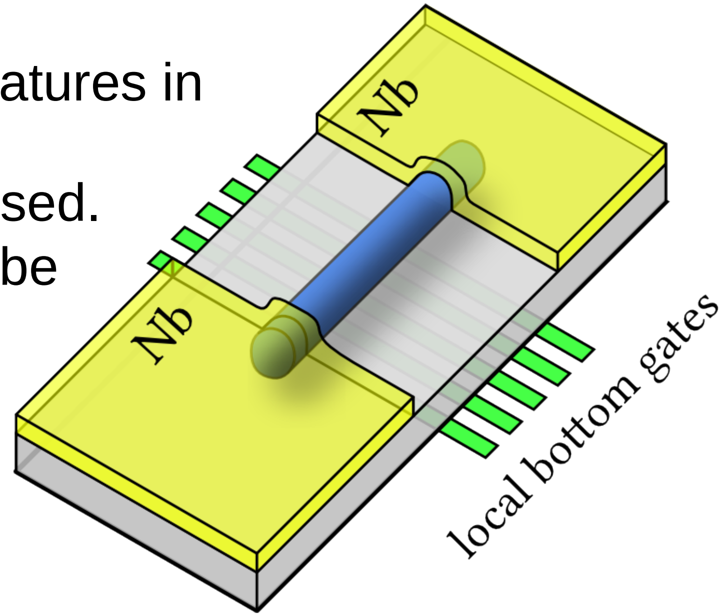
Conclusions

- Proximity superconductivity observed in Nb-InAs nanowire-Nb junction devices tuned to the Intermediate Coupling regime, with $\Gamma \sim \Delta << U$.

- Similar devices can be used to look for signatures of Majorana Bound States in Topological Superconductors.

- Rich and complex Andreev transport features go beyond the Anderson impurity model, especially when devices are tuned to more conductive regimes.

- Future work will look at Andreev transport features in different geometries, including:
  - SQUIDs, so the junction can be phase-biased.
  - Devices with local bottom gates, so Γ can be tuned.



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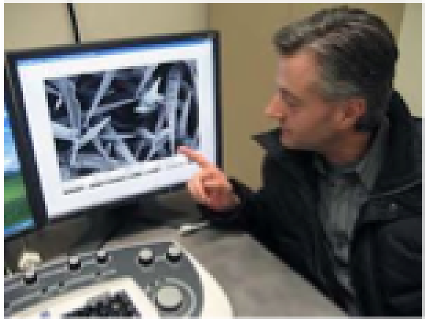

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