Andreev-reflection-enhanced conductance of semiconductor-superconductor hybrid nanodevices

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Experiment:

(QuTech, Delft):
H. Zhang, Ö. Gül, S. Conesa-Boj, K. Zuo, V. Mourik, F. K. de Vries, J. van Veen, D. J. van Woerkom, D. Car, S. Plissard, E. P. A. M. Bakkers, M. Quintero-Pérez, S. Goswami, K. Watanabe, T. Taniguchi, L. P. Kouwenhoven

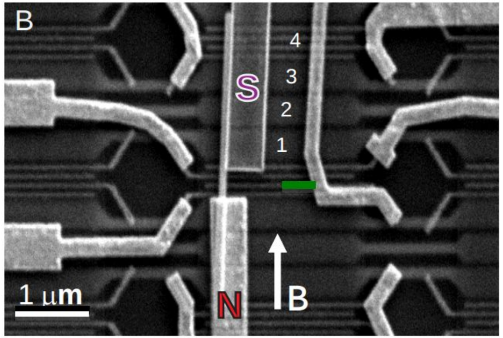
(Station Q, Copenhagen):
M. Kjaergaard, H. J. Suominen, J. Shabani, C. J. Palmstrøm, F. Nichele, C. M. Marcus

Outline

1. Motivation
2. How Andreev reflection modifies the conductance?
3. Conductance steps of a QPC in NS junction
4. Subgap features in conductance of SNS junction
5. Summary

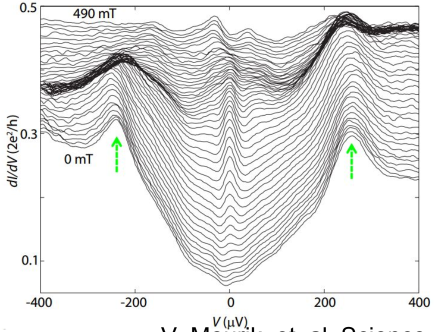
What is so exciting in physics of Normal (N) - Superconductor (S) hybrids?

Coupling normal material with superconductor allows to engineer nanostructures that inherit properties of both



Engineering of topological phases and exotic quasiparticles

Majorana fermion resolved by transport measurement



V. Mourik, et. al, Science (2012)

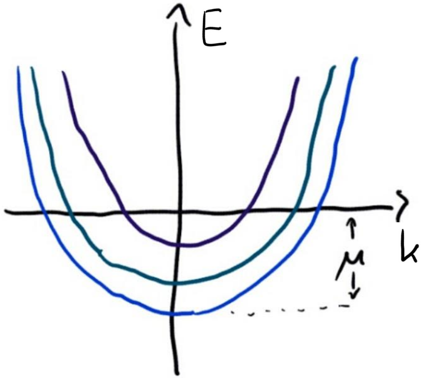
The promise of fault-tolerant quantum computation

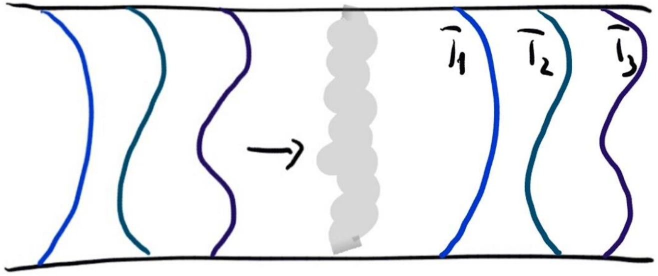
- Two Majorana bound states forming a qubit
- Braiding as a tool for quantum gates

But:

- The fabrication technology of hybrid nanostructures needs to be perfected
- The properties of actual experimental devices needs to be understood

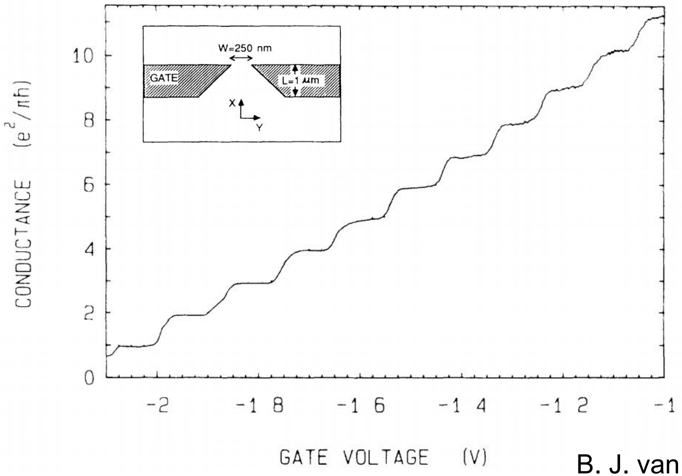
Conductance of a normal system





$$S = \begin{pmatrix} r_{12} & t_{12} \\ t_{21} & r_{21} \end{pmatrix}$$

$$t_{21} t_{21}^{*} \rightarrow T_1, T_2, T_3, \ldots$$

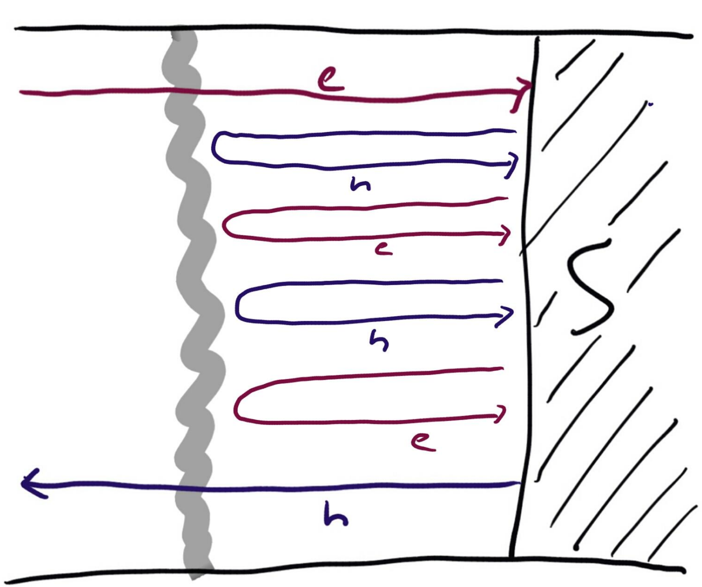


$$G_N = \frac{2e^2}{h} \sum_{n=1}^{N} T_n$$

B. J. van Wees, et al., PRL (1988)

How Andreev reflection modifies conductance of a NS hybrid?

$$G_{\mathrm{NS}} = \frac{2e^2}{h}\mathrm{Tr}\,(1 - s_{\mathrm{ee}}s_{\mathrm{ee}}^\dagger + s_{\mathrm{he}}s_{\mathrm{he}}^\dagger) = \frac{4e^2}{h}\mathrm{Tr}\, s_{\mathrm{he}}s_{\mathrm{he}}^\dagger$$

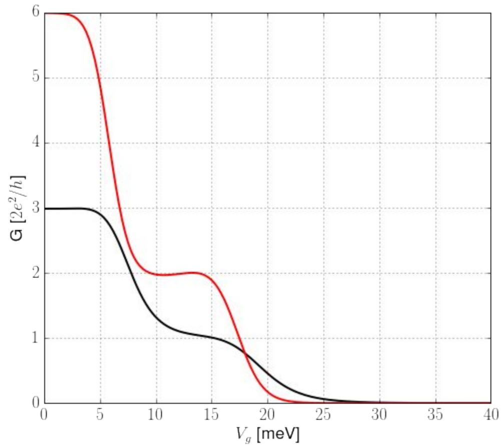


$$s_{he} \sim \alpha t^* t + \alpha t^* \alpha^2 r r^* t + \alpha t^* (\alpha^2 r r^*)^2 t +$$

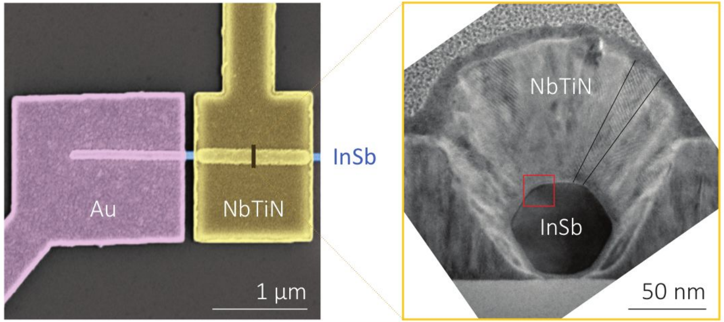
$$s_{he} = \alpha t^* \frac{1}{1-\alpha^2 r r^*} t$$

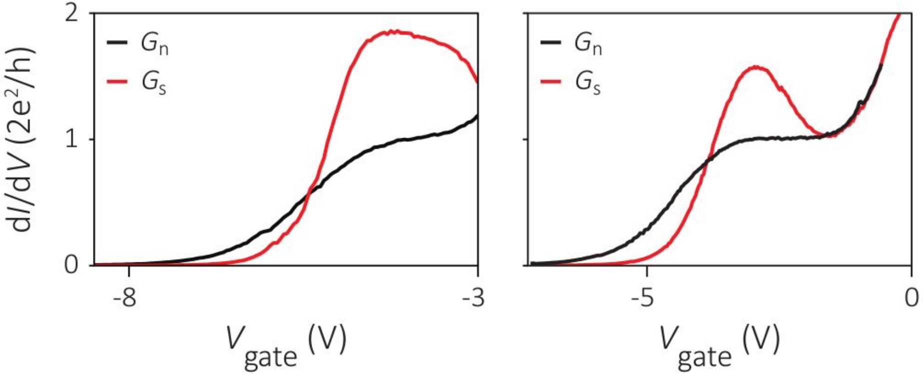
$$G_{NS} = \frac{4e^2}{h}\sum_{n=1}^{N}\frac{T_n^2}{(2-T_n)^2}$$

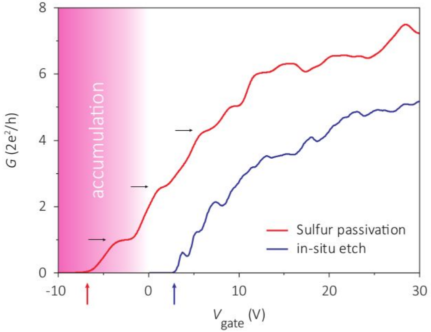
C. W. J. Beenakker, PRB (1992)



Measured QPC steps





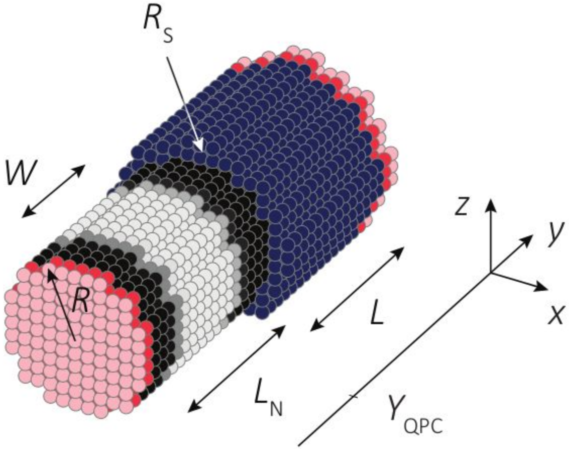


$$G_N = \frac{2e^2}{h} \sum_{n=1}^{N} T_n$$

$$G_{NS} = \frac{4e^2}{h} \sum_{n=1}^{N} \frac{T_n^2}{(2 - T_n)^2}$$

H. Zhang, et al., arXiv (2016)

Model system



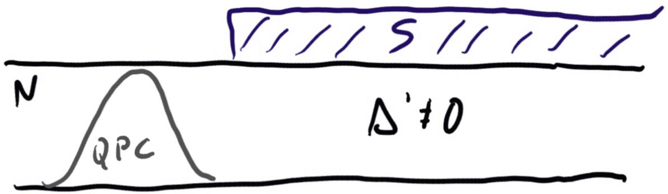
BdG Hamiltonian:

$$H = \left(\frac{\hbar^2\mathbf{k}^2}{2m^*} - \mu + V(x,y,z)\right)\tau_z + \Delta(x,y,z)\tau_x$$

$$V(x,y,z) = \tilde{V}_{qpc}(y) + V_D(x,y,z)$$

$$U_0 = \sqrt{3\pi/l_e m^{*2} a^3}$$

$$\tilde{V}_{qpc}(y) = -\frac{eV_{\mathrm{QPC}}}{2}\left[\tanh\frac{y - Y_{QPC} + W/2}{\lambda} - \tanh\frac{y - Y_{QPC} - W/2}{\lambda}\right]$$



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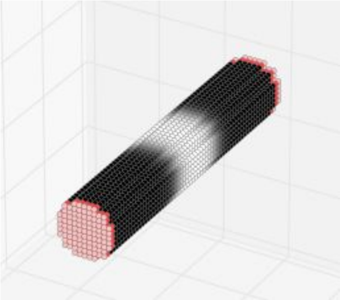
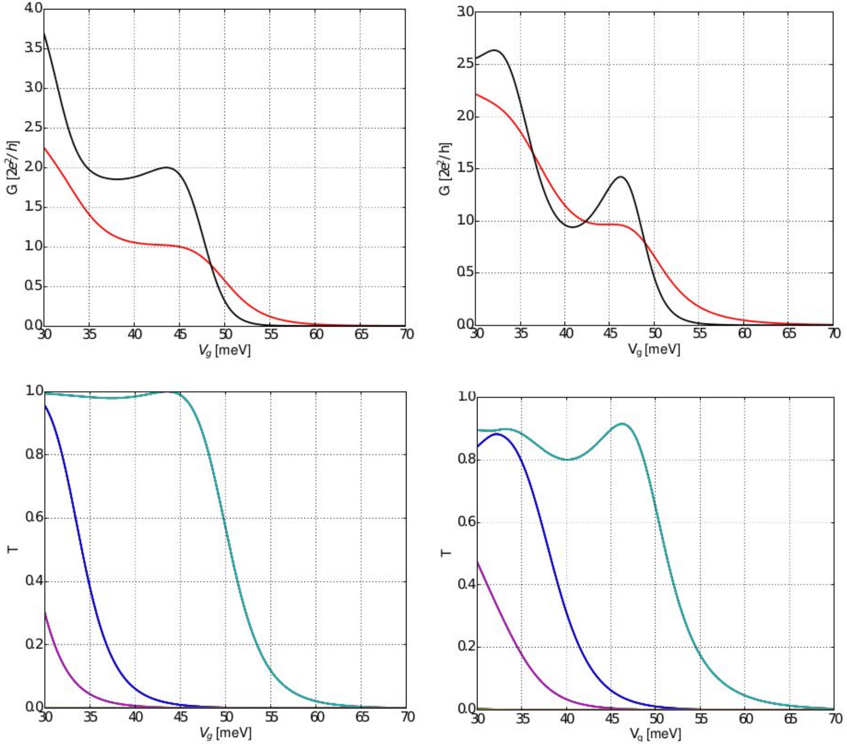
C. W. Groth, et al., NJP (2014)

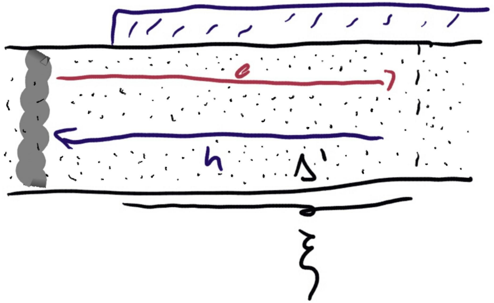
Mode mixing in a normal system



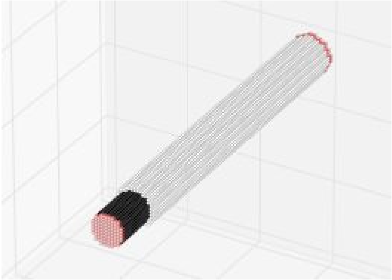
No disorder | Weak disorder

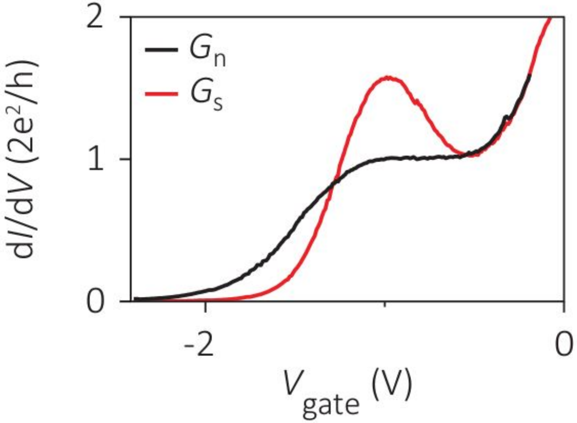


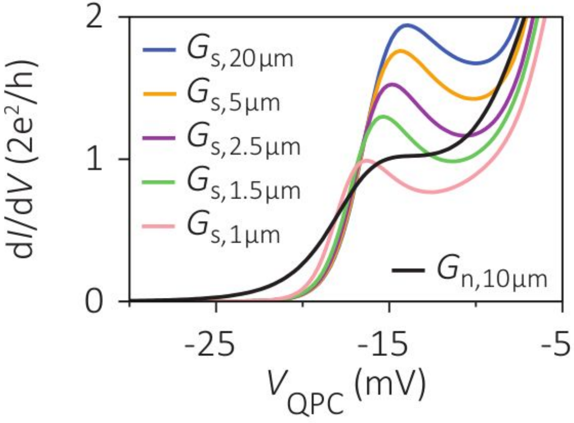
Andreev reflection and QPC as a magnifying glass for a residual disorder



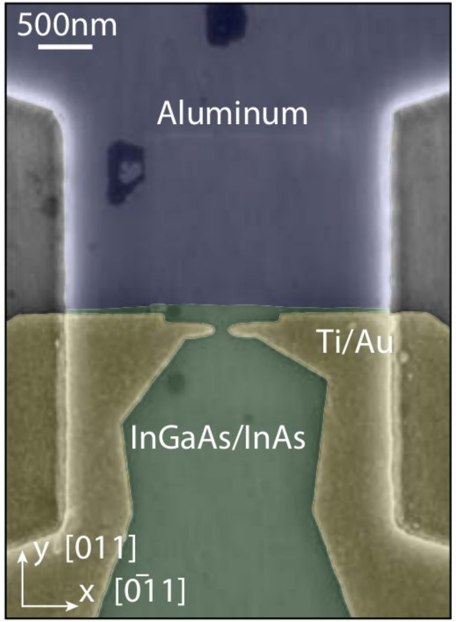
Coherence length $\xi = \hbar v_F / \Delta \sim 500$ nm.

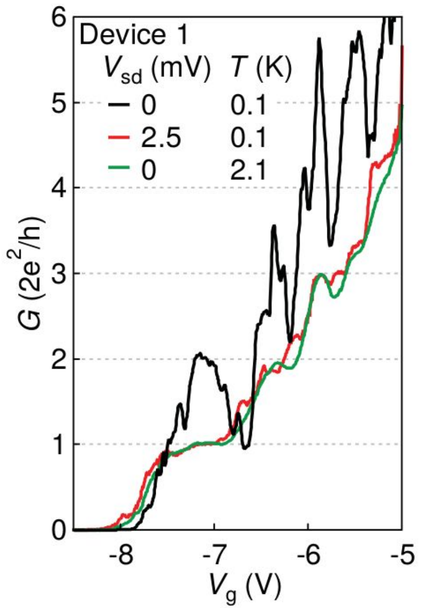






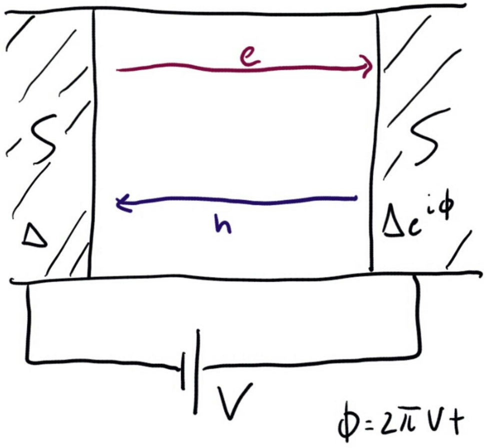
Is it a general feature?

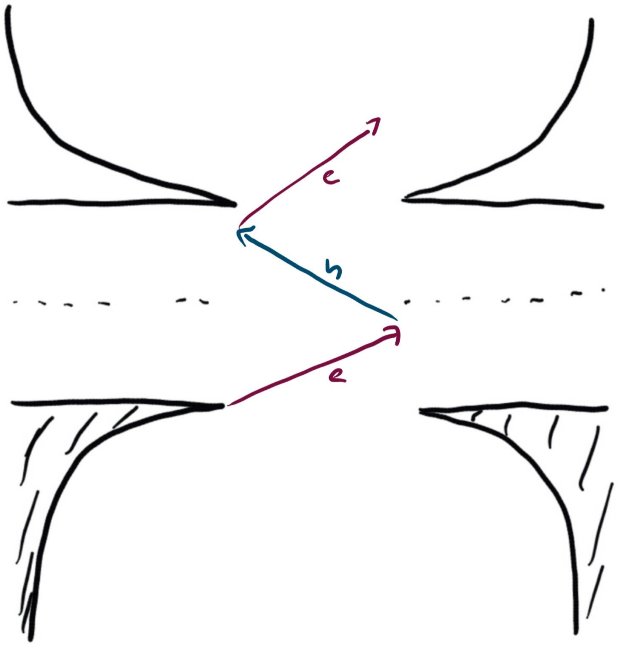




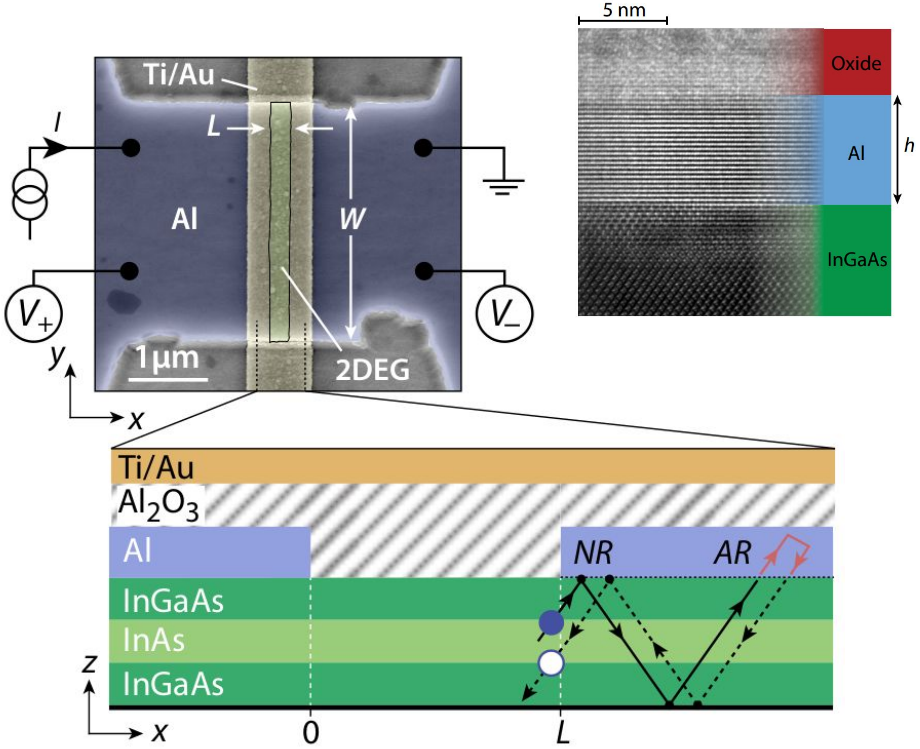
M. Kjaergaard, et al. (2016)

Biased SNS junction - multiple Andreev reflections

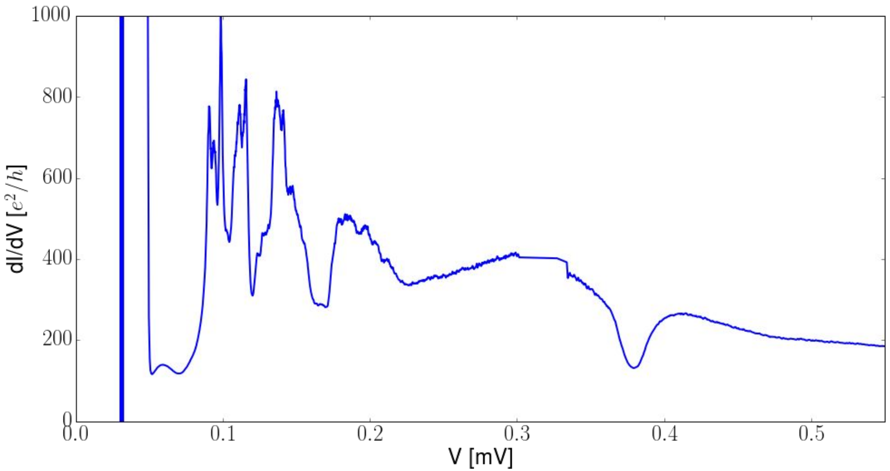




Measured signatures of multiple Andreev reflections

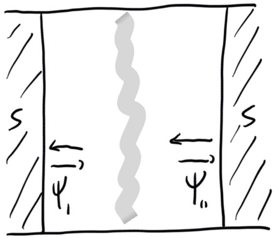


M. Kjaergaard, et al. Nat. Comm. (2016)



What story does it tell?

Model for MAR



$$a(E) = \frac{1}{\Delta}\begin{cases} E - \mathrm{sgn}(E)\sqrt{E^2-\Delta^2} & |E| > \Delta \\ E - i\sqrt{\Delta^2 - E^2} & |E| < \Delta \end{cases}$$

$$S_e = \begin{pmatrix} r & t \\ t & -r^* t/t^* \end{pmatrix}$$

$$\Psi_I = \sum_n \left[\begin{pmatrix} A_n^e + J\delta_{n0} \\ A_n^h \end{pmatrix} e^{ikx} + \begin{pmatrix} B_n^e \\ B_n^h \end{pmatrix} e^{-ikx} \right] e^{-i(E+2neV)t/\hbar},$$

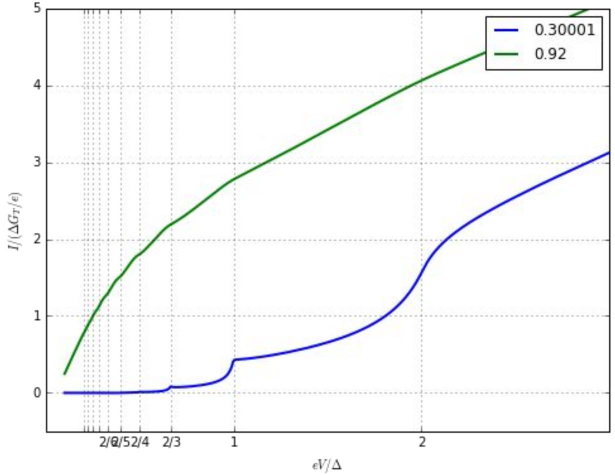
$$\Psi_{II} = \sum_n \left[\begin{pmatrix} C_n^e \\ C_n^h \end{pmatrix} e^{ikx} + \begin{pmatrix} D_n^e \\ D_n^h \end{pmatrix} e^{-ikx} \right] e^{-i[E+(2n+1)eV]t/\hbar}.$$

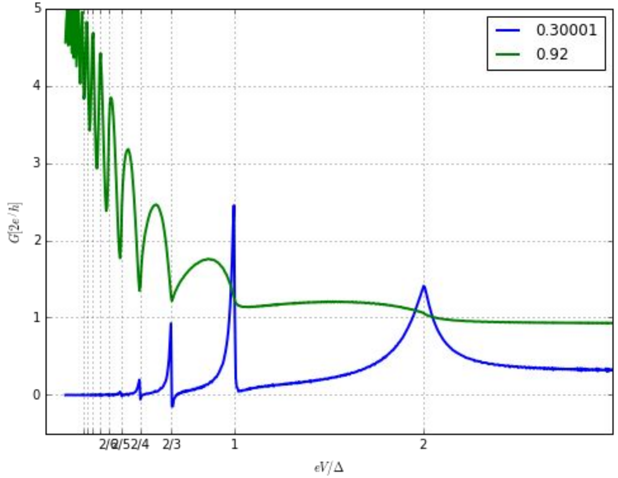
$$\begin{pmatrix} B_n^e \\ C_n^e \end{pmatrix} = S_e \begin{pmatrix} A_n^e + J\delta_{n0} \\ D_n^e \end{pmatrix}$$

$$\begin{pmatrix} A_n^e \\ B_n^h \end{pmatrix} = \begin{pmatrix} a_{2n} & 0 \\ 0 & a_{2n} \end{pmatrix} \begin{pmatrix} A_n^h \\ B_n^e \end{pmatrix}$$

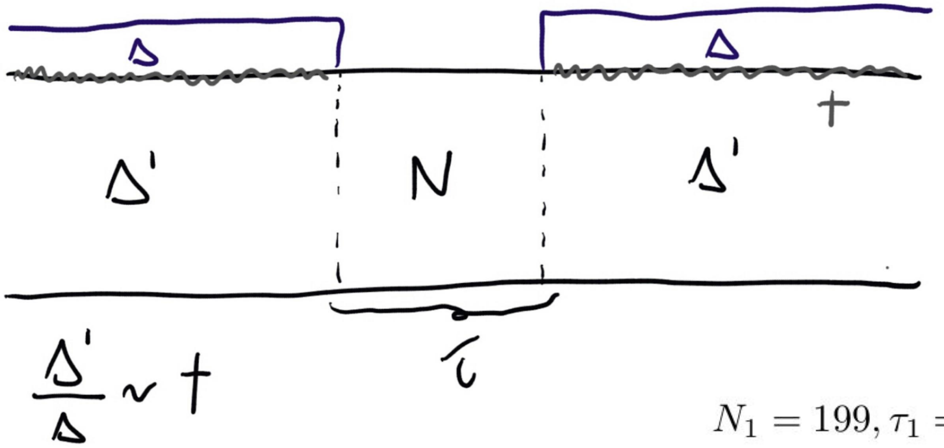
$$I = \sum_k I_k e^{2keiVt/\hbar} \qquad I_k = -\frac{e}{\hbar\pi}\int_{-E-V}^{E} dE \tanh\left(\frac{E}{2k_bT}\right) \sum_n (\mathbf{A}_{k+n}^* \mathbf{A}_n - \mathbf{B}_{k+n}^* \mathbf{B}_n)$$

D. Averin, et al., PRL (1995)





Fitting the conductance traces



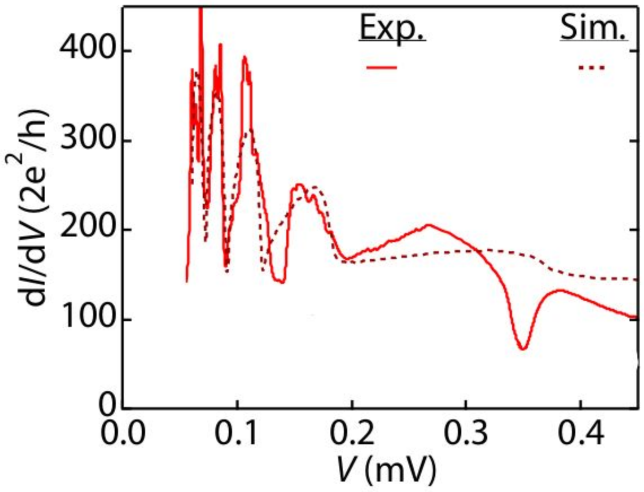
$$G(V) = \sum_i^M N_i G^{(\tau_i)}(V)$$

$$N_1 = 199, \tau_1 = 0.98$$

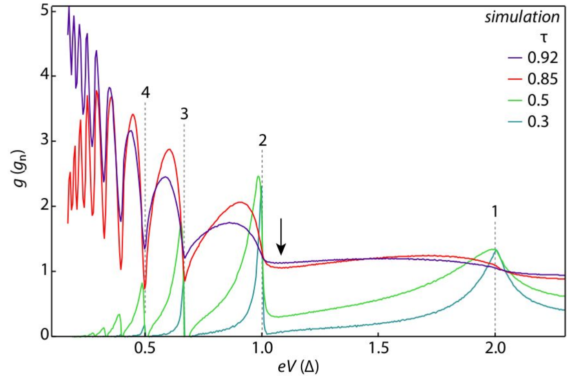
$$N_1 = 109, \tau_1 = 0.8$$

$$\Delta' = 182\ \mu\text{eV}$$

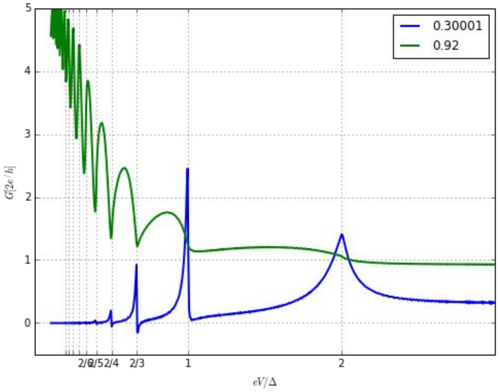
$$\Delta = 237\ \mu\text{eV}$$

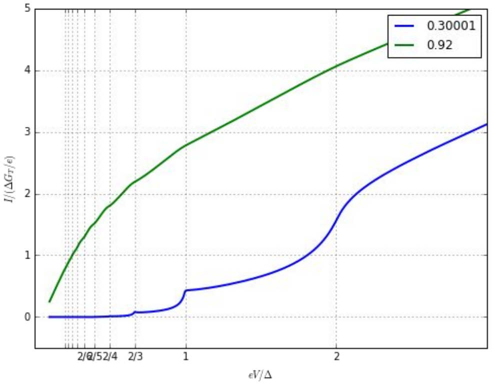


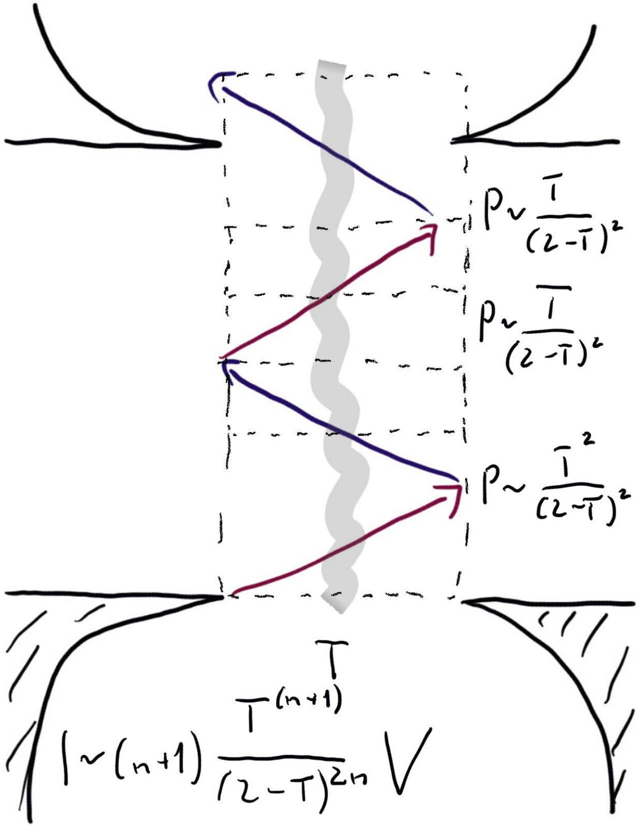
No subgap features as peaks of the conductance!

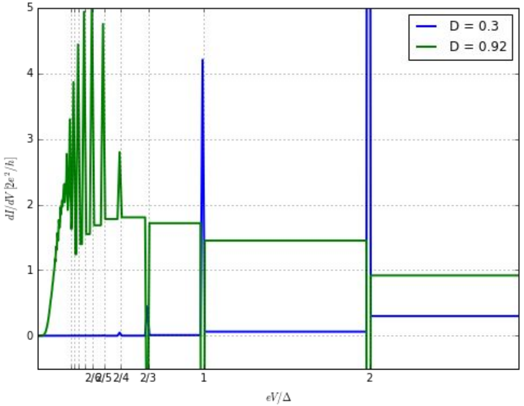


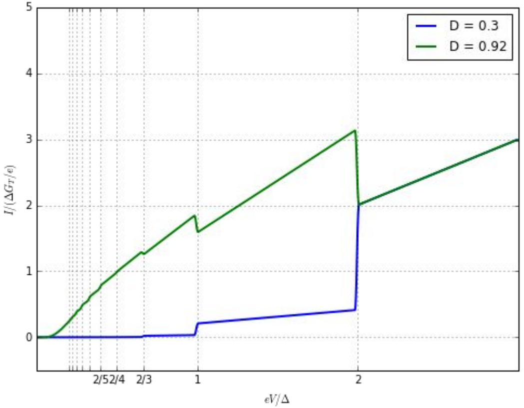
Can we understand qualitatively the conductance?











Take-home messages

1. Selective mode transport through a QPC combined with Andreev reflections provide a magnifying glass to probe the transparency of proximitized semiconductor
2. Residual disorder destroys perfect quantization of Andreev-enhanced QPC steps
3. Conductance trace of a SNS junction governed by multiple Andreev reflections qualitatively differs between a transparent and an opaque junction
4. Determining the superconducting gap by tracing peaks in the conductance is misleading for transparent junctions

Acknowledgments

Theory: Anton Akhmerov, Michael Wimmer

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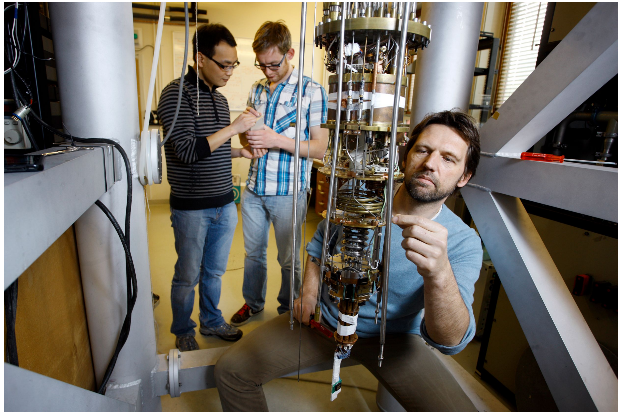

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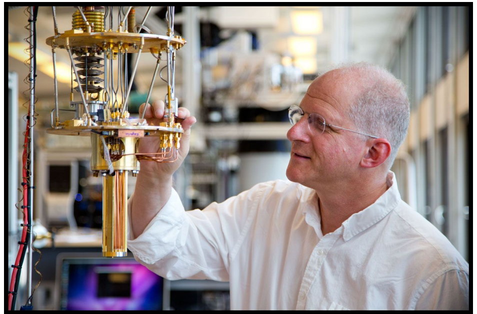

The End
Thank you!