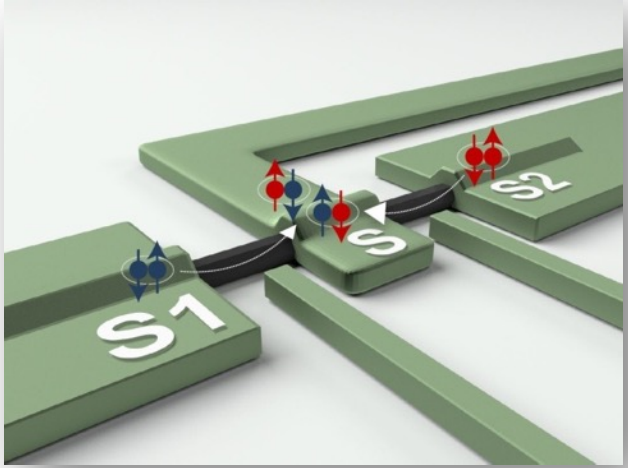
Semiconducting Nanowires with three superconducting contacts



Capri Spring School
11.04.2016

Christian Jünger

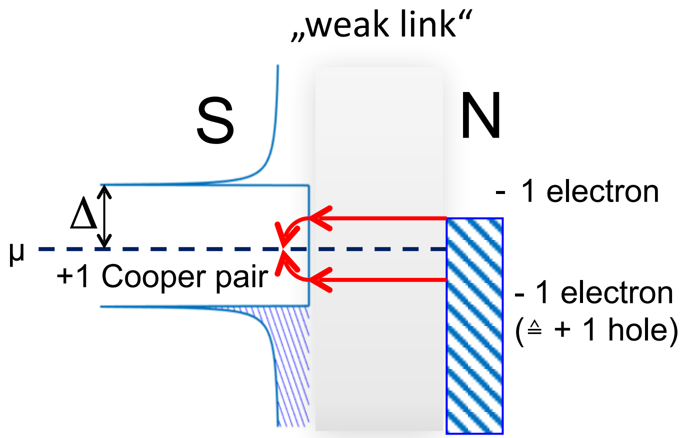
Outline

- Motivation: Two and three terminal devices
- Multipair transport - Quartets
- First measurements
- Summary

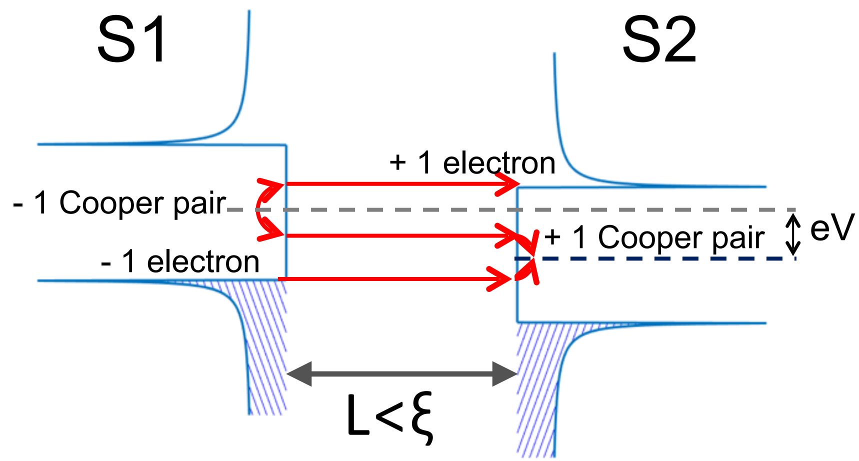
Two Terminal devices

- Possible transport mechanisms with Superconducting contacts
- Josephson Junctions

supercurrent for $V_{SD}=0$



Andreev **R**eflection (AR)



Multiple **A**ndreev **R**eflection (MAR)

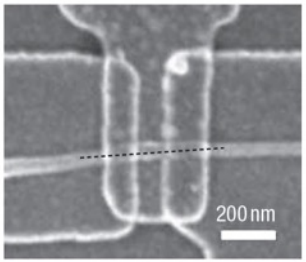
$eV_n=2\Delta/n$, n=1,2,...

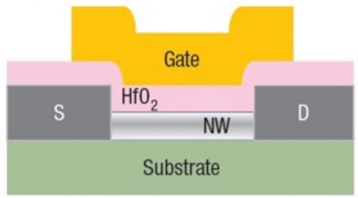
➢ coherent transport

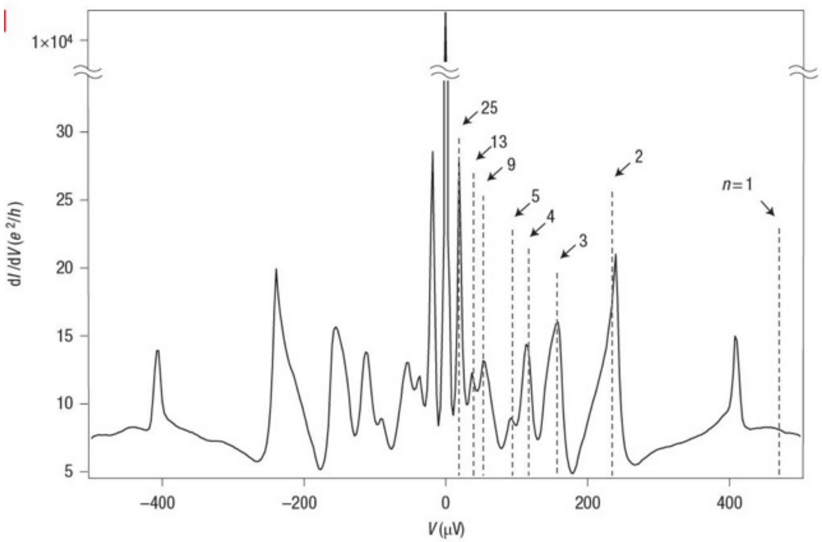
A. F. Andreev, Sov. Phys. JETP **19,** 1228 (1964)
G.E. Blonder et al., Phys. Rev. B **25,** 4515 (1982)
J. Gramich *et al.*, Phys. Rev. L. **115**, 216801 (2015)
M. Octavio *et al.*, Phys. Rev. B **27**, 6739 - 6746 (1983)

Two Terminal devices

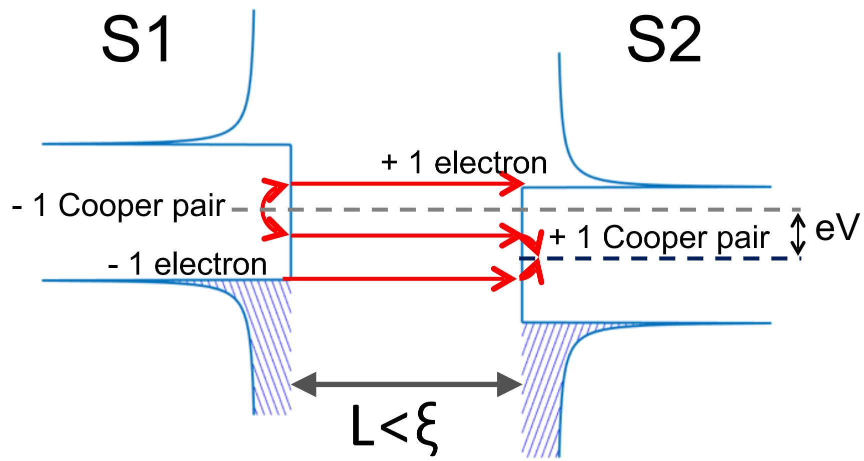
- Josephson Junctions with semiconducting Nanowire as weak link
- Si/Ge Nanowire with Aluminum contacts:







supercurrent for $V_{SD}=0$



Multiple **A**ndreev **R**eflection (MAR)

$eV_n=2\Delta/n$, n=1,2,...

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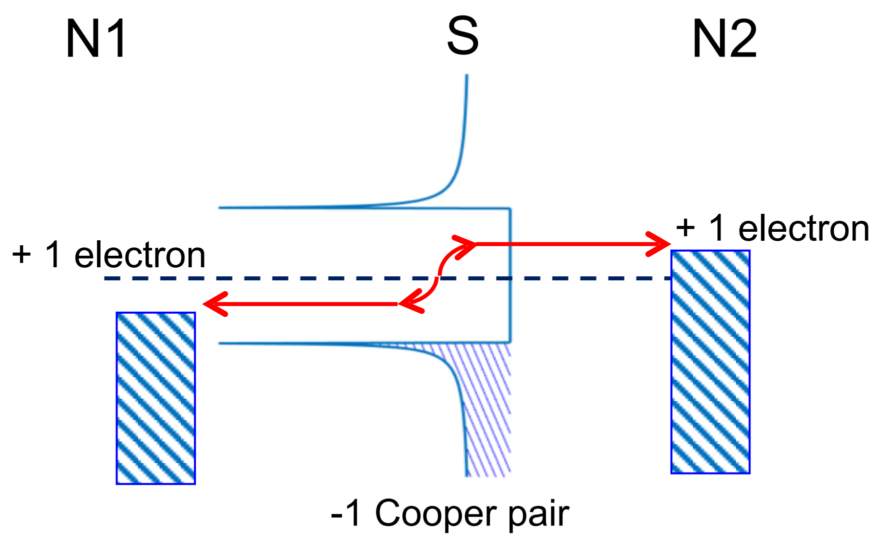
J. Xiang *et al.*, Nat. Nanotech. **1**, 208 - 213 (2006)

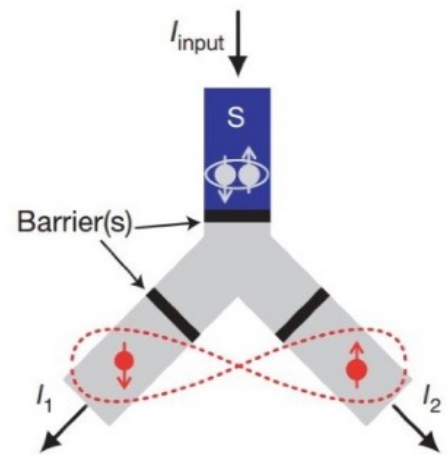
M. Octavio *et al.*, Phys. Rev. B **27**, 6739 - 6746 (1983)

Three terminal devices

- Possible non - local transport mechanism
- Cooper pair splitting: N - S – N



Crossed Andreev Reflection (CAR)

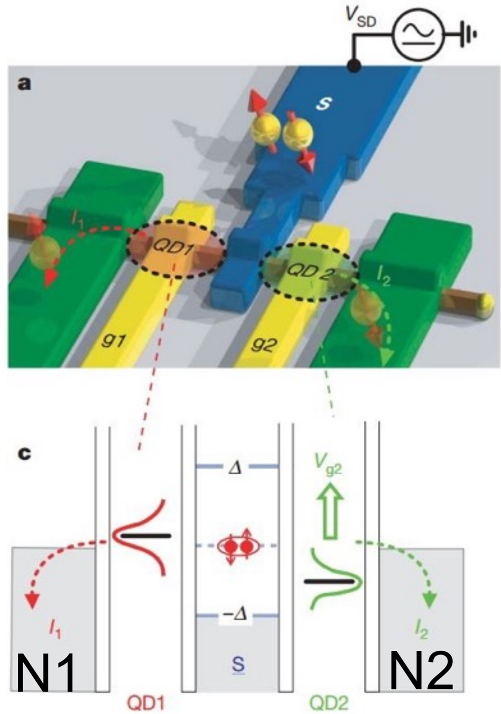


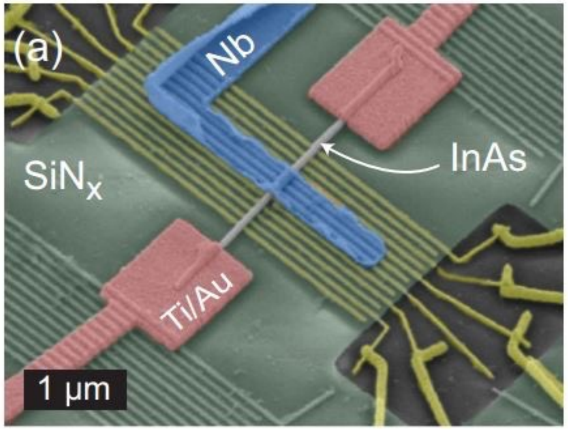
- Entanglement of two spatially separated single electrons

P. Recher et al., Phys. Rev. B **63**, 165314 (2001)
L. Hofstetter *et al.*, Nature **461**, 960 - 963 (2009)

Three terminal devices

- Possible non - local transport mechanism
- Cooper pair splitting: N - S – N



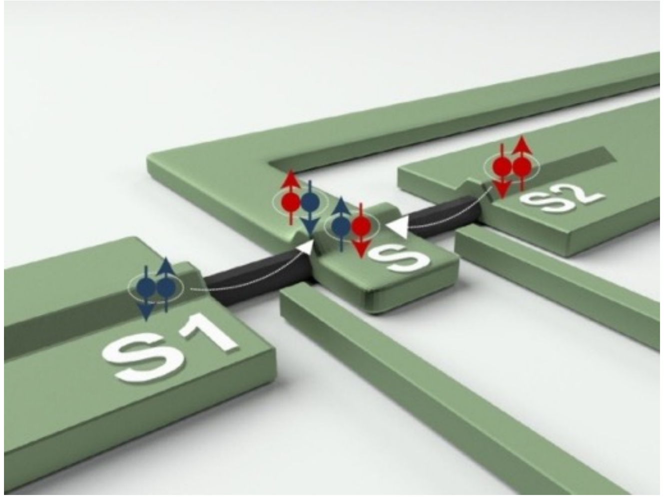


- Entanglement of two spatially separated <u>single</u> electrons

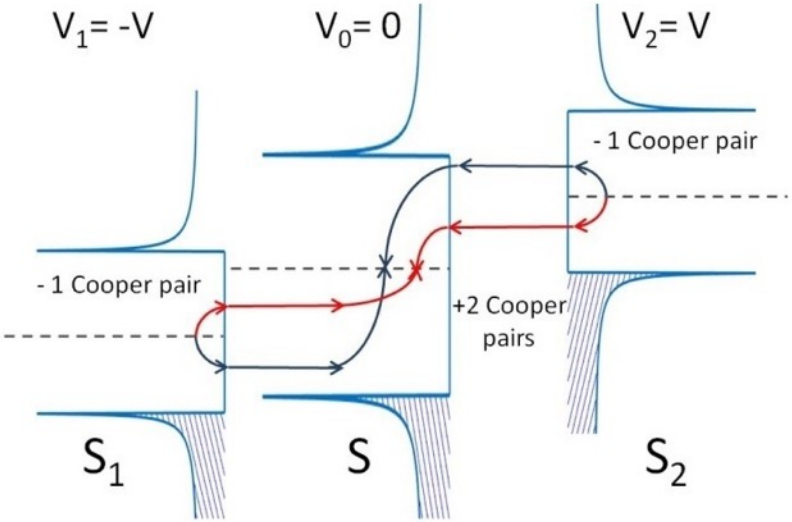
G. Fülüp *et al.*, Phys. Rev. B **90**, 235412 (2014)
G. Fülüp et al., Phys. Rev. Lett. **115**, 227003 (2015)
L. Hofstetter *et al.*, Phys. Rev. Lett. **107**, 136801 (2011)
L. Hofstetter *et al.*, Nature **461**, 960 - 963 (2009)

Multipair transport - Quartets

- All superconducting Bijunction: S–S–S
- Entanglement of two spatially separated <u>pairs</u> of electrons



double **C**rossed **A**ndreev **R**eflection (dCAR)



  - one realized experiment in metallic system
  - QD in NW: filter local effects

$$nV_1 + m\,V_2 = 0 \qquad n,m = 1,2,\ldots$$

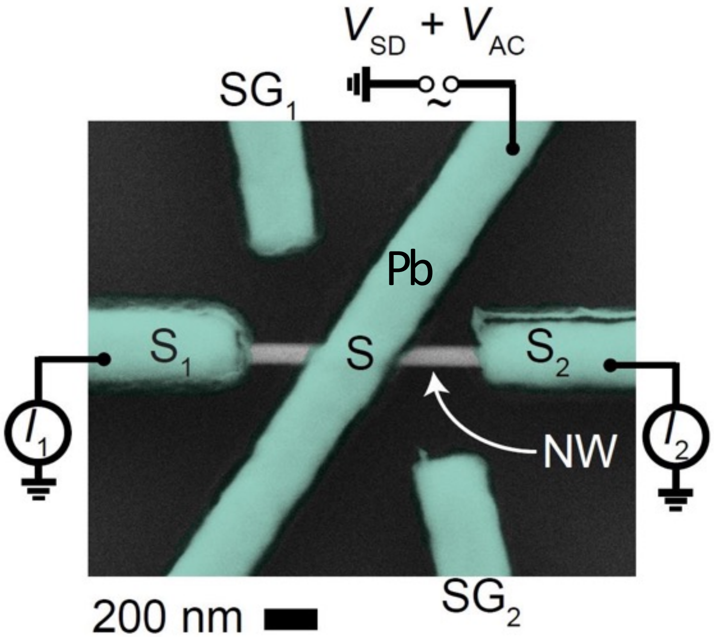
$\boxed{n = m = 1 \rightarrow \textbf{Quartets}}$

A. H. Pfeffer *et al*., Phys. Rev. B **90**, 075401 (2014)

T. Jonckheere *et al*., Phys. Rev. B **87**, 214501 (2013)
A. Freyn *et al*., Phys. Rev. Lett. **106**, 257005 (2011)

First devices

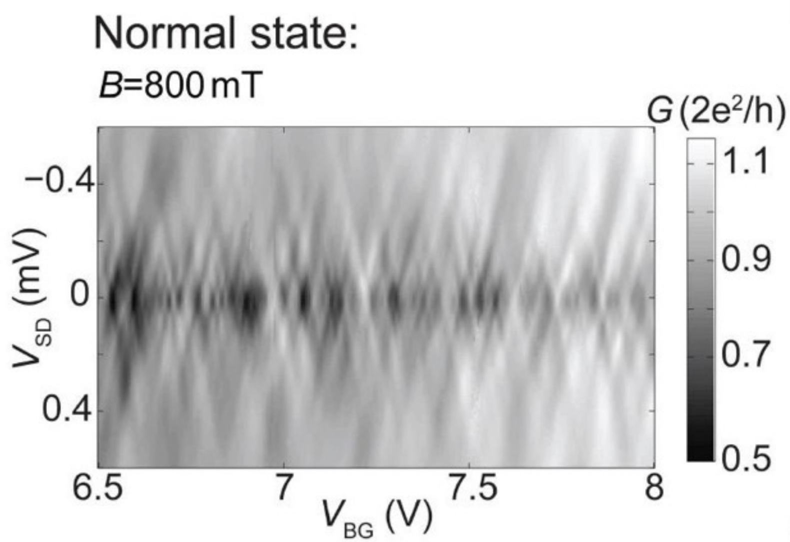
- **Fabrication:**
  - p-doped Si substrate , 400nm SiO_2 insulator (V_{BG})
  - InAs Nanowire:* 65nm diameter
  - Contacting method: Argon plasma etching / sulfur passivation
  - Superconducting contacts: Pd/Pb/In: 130nm;
  - material characteristics of Pb:
    - large energy gap $\Delta \approx$ 2.7 meV
    - critical temperature T_C = 7.2K
    - coherence length $\xi_{Pb} \approx$ 100 nm

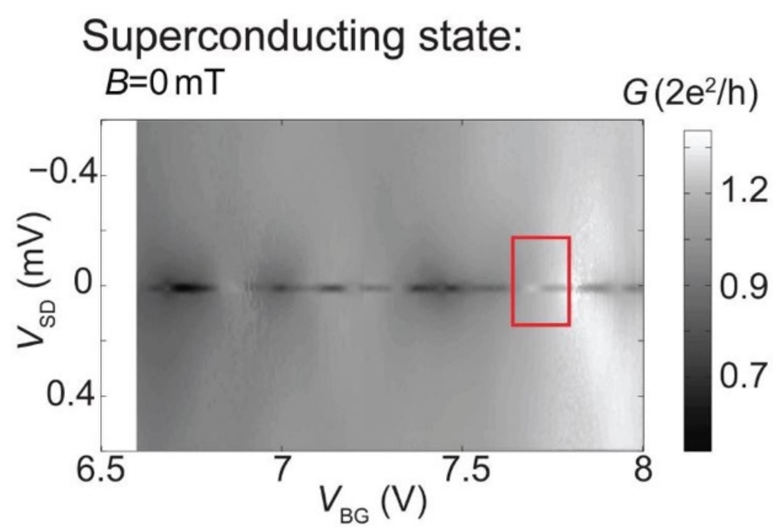


*grown by the group of J. Nygård from University of Copenhagen

First measurements

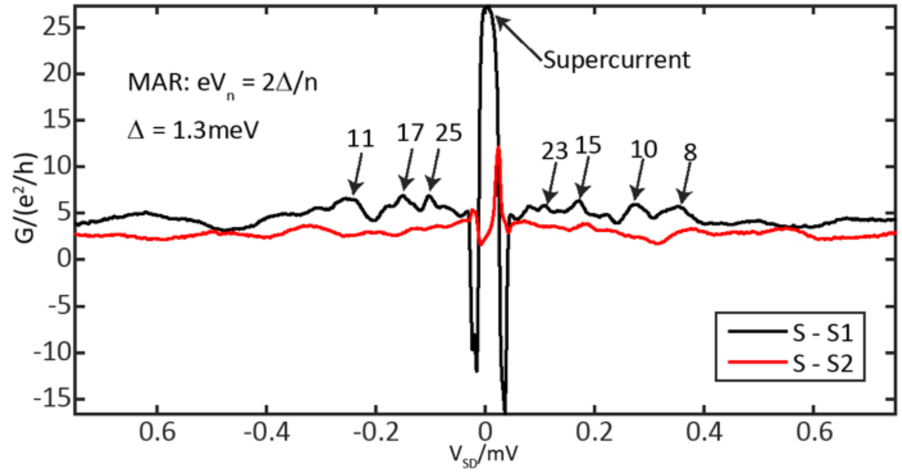
- Long–Junction: L>ξ_{Pb}
  - Normal state: Fabry-Perot like behavior
  - Superconducting state: Fabry-Perot pattern fully suppressed

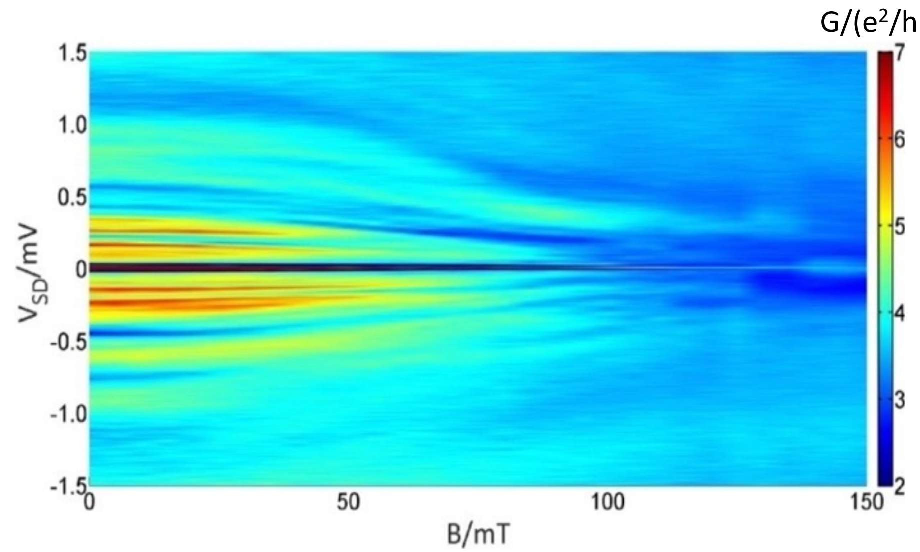




First measurements

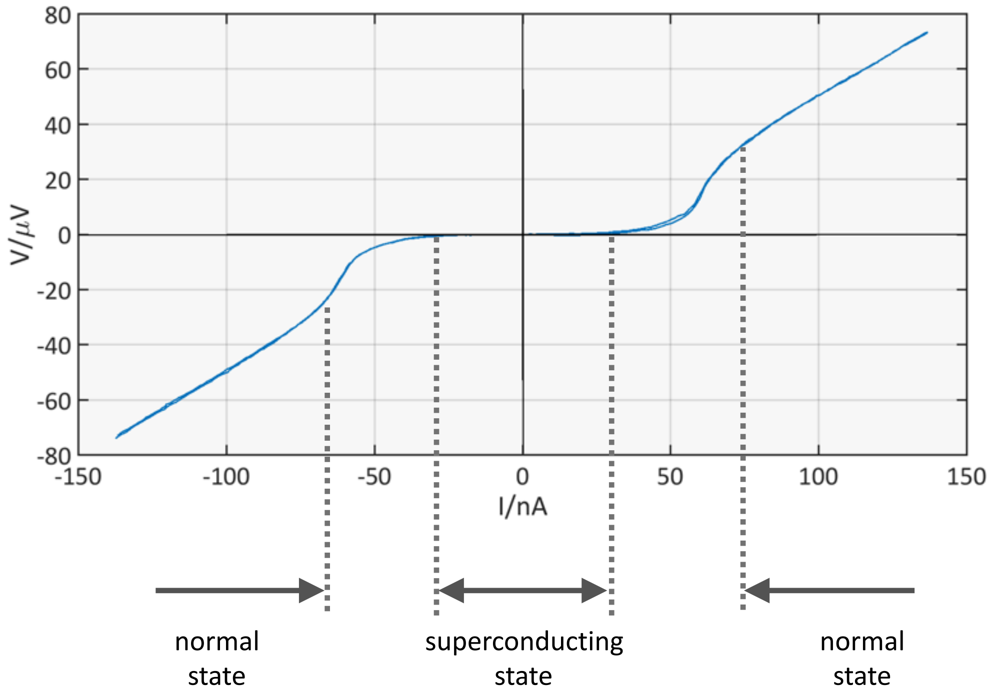
- Short junction: $L < \xi_{Pb}$
- Multiple Andreev Reflection:
  - supercurrent for $V_{SD} = 0$
  - high order MAR
- Magnetic field dependence
  - B_C: 150mT to 450mT
  - $\Delta \approx 1.3$meV
- coherent transport and <u>very high</u> transparency

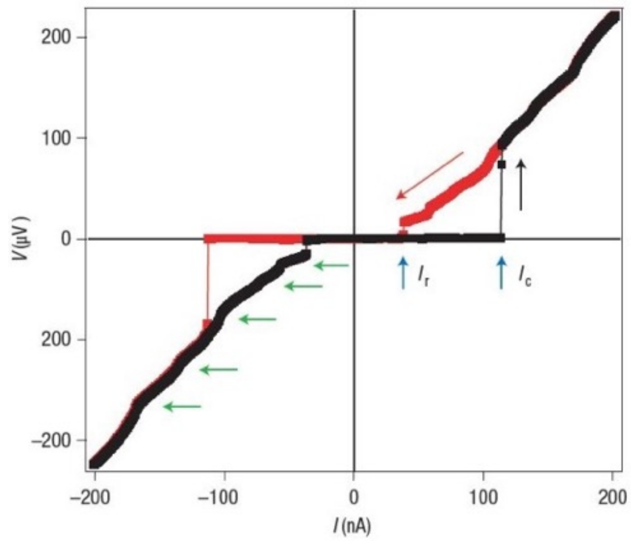




First measurements

- Four-probe measurement of supercurrent
  - switching between 30nA and 70nA

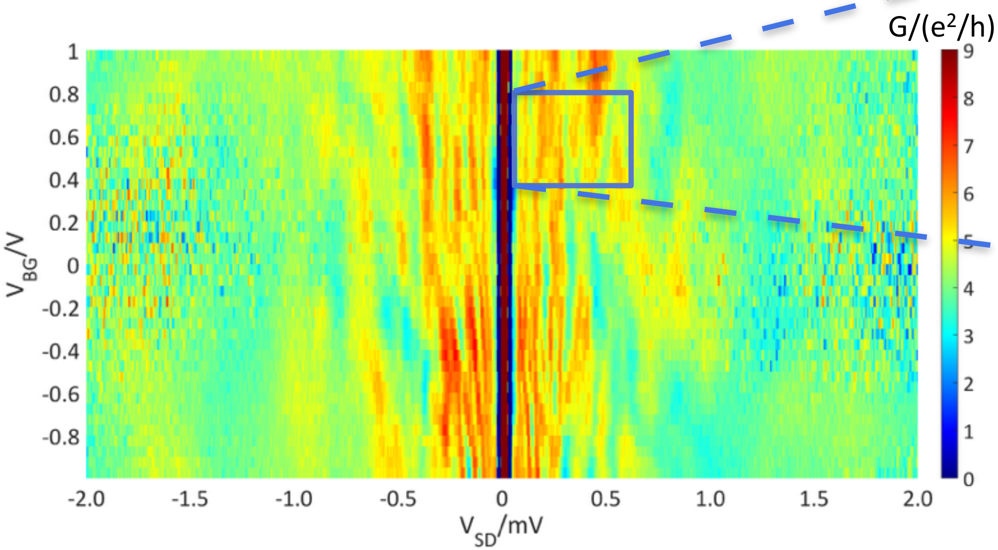


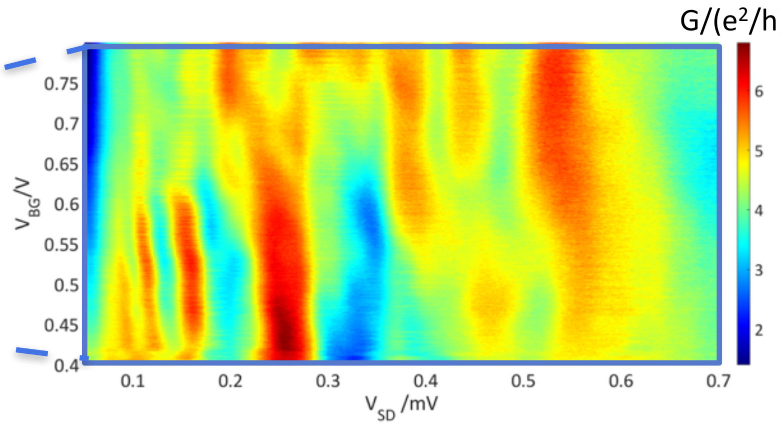


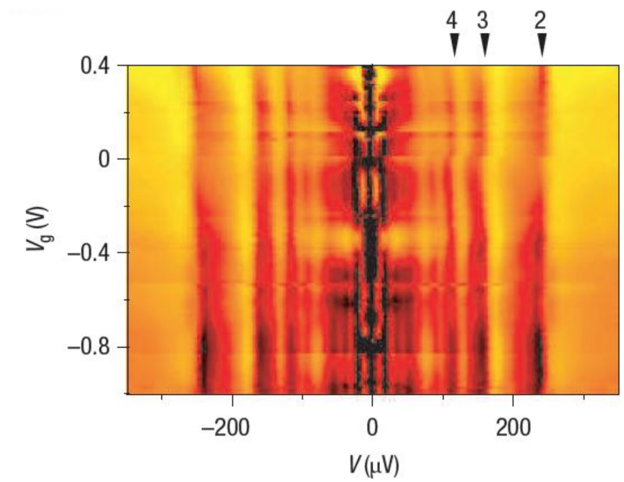
J. Xiang *et al.*, Nat. Nanotech. **1**, 208 - 213 (2006)

First measurements

- Backgate Voltage dependence





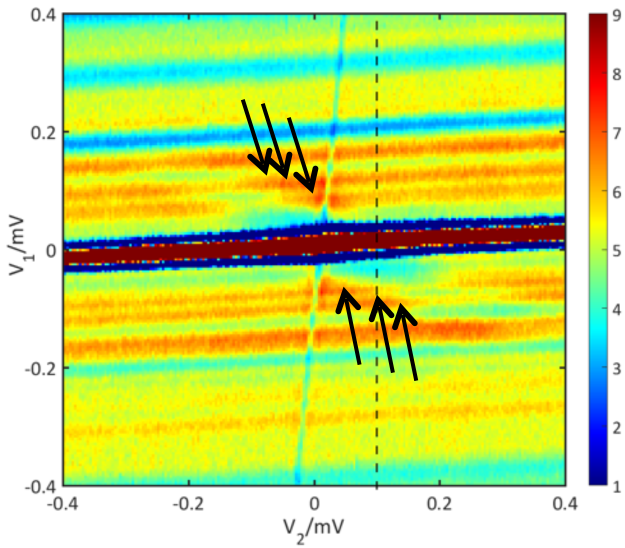


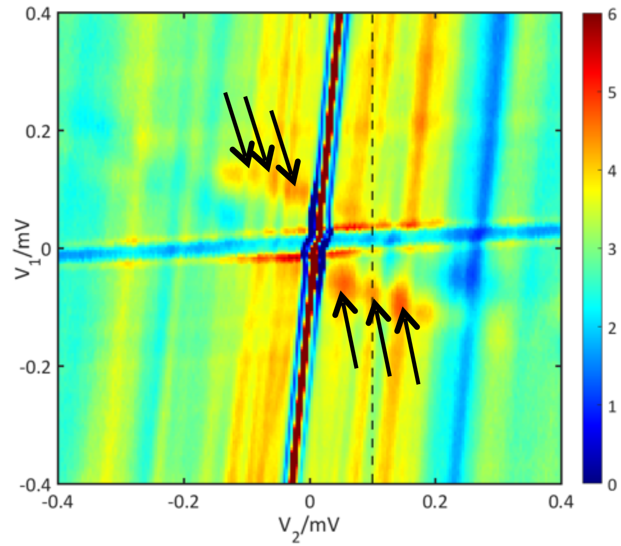
  - Tunable MAR, which is not expected
  - maybe related to variations in transmission T(E)

J. Xiang *et al.*, Nat. Nanotech. **1**, 208 - 213 (2006)

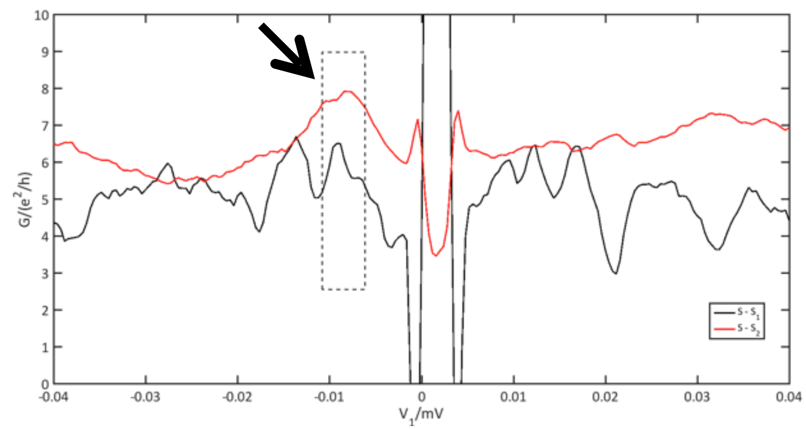
Three terminal measurement

- First hints of non-local signal





- positive correlated regions visible



Three terminal measurement

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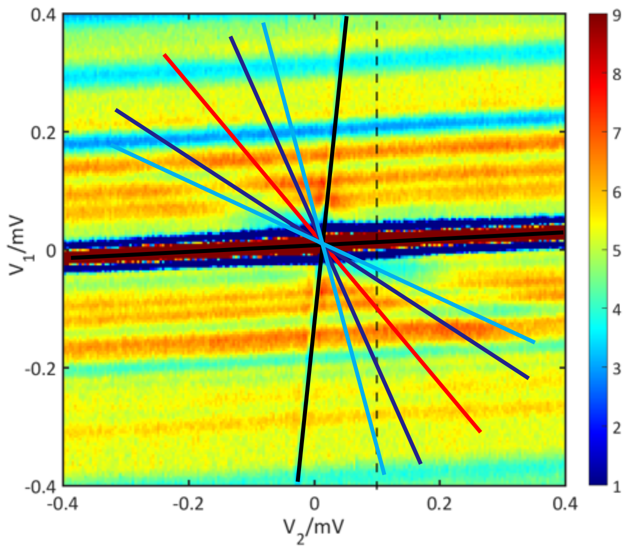

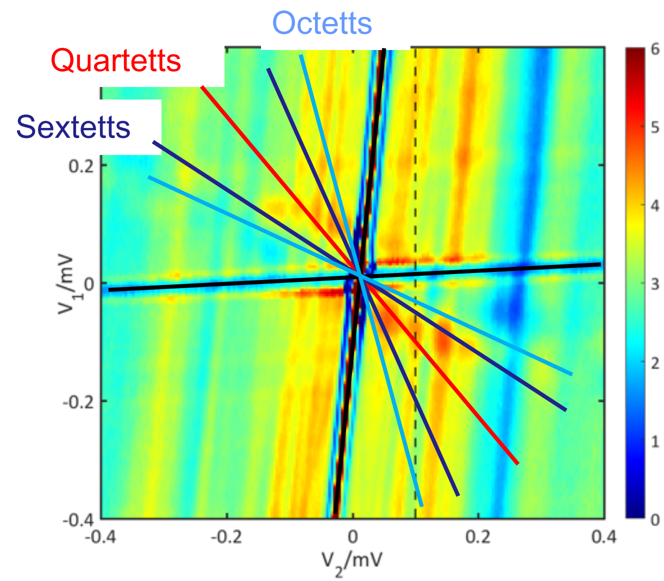

$$\mathrm{n}V_1 + \mathrm{m}\ V_2 = 0$$

Quartetts: n = m = 1

Sextetts: n =1,2; m = 2,1

Octetts: n =1,3; m = 3,1

- positive correlated regions visible
- not fully fitting with Quartet signature

T. Jonckheere *et al*., Phys. Rev. B **87**, 214501 (2013)

Summary

- Fabry – Perot behavior in long junctions
- Supercurrent and MAR in short junctions
  - ➢ coherent transport and very high transparency
- MAR dependent on applied gate voltage
  - ➢ tunability of MAR
- First hints of non - local signal
  - ➢ Further investigations are needed

➢ Required ingredients for Quartets measurement are available

Acknowledgements

- University of Basel:

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S. Baba

Thank you for your attention