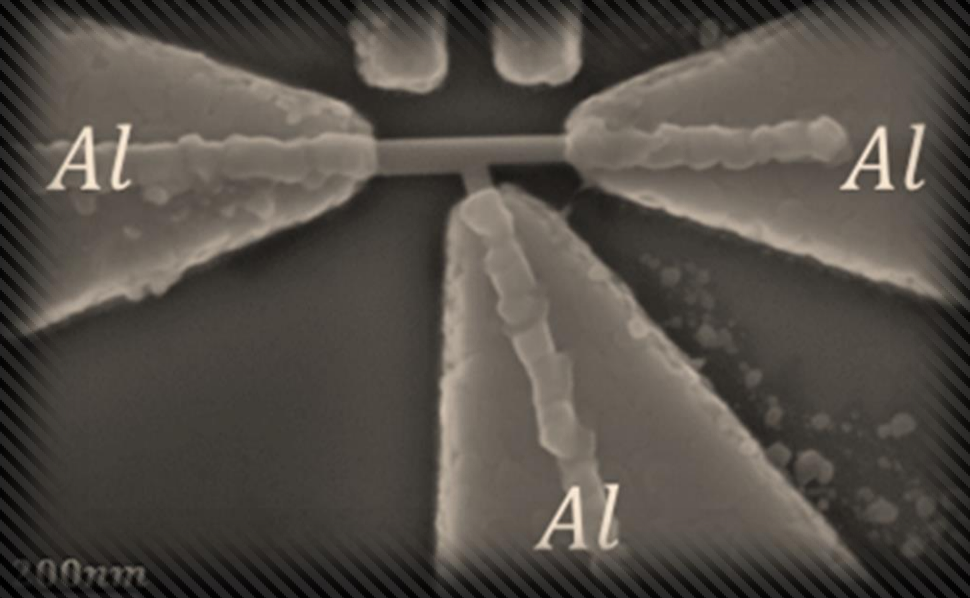


Non-local supercurrent of Quartets in a three-terminal Josephson junction

Yonatan Cohen

GDR physique mésoscopique, Aussois

Weizmann Institute of Science

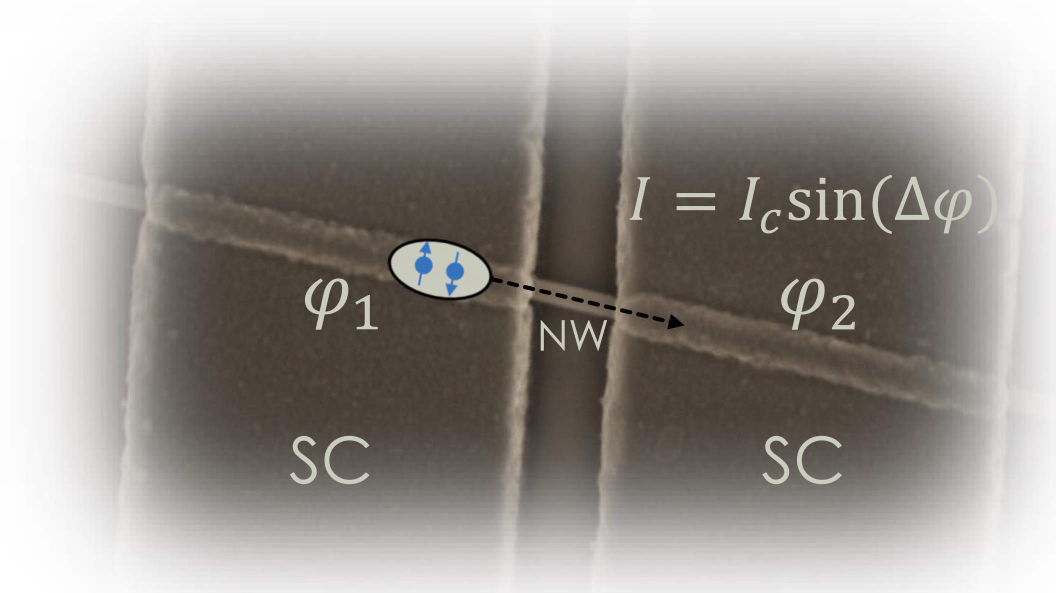
Josephson Junction

Volume 1, number 7 PHYSICS LETTERS 1 July 1962

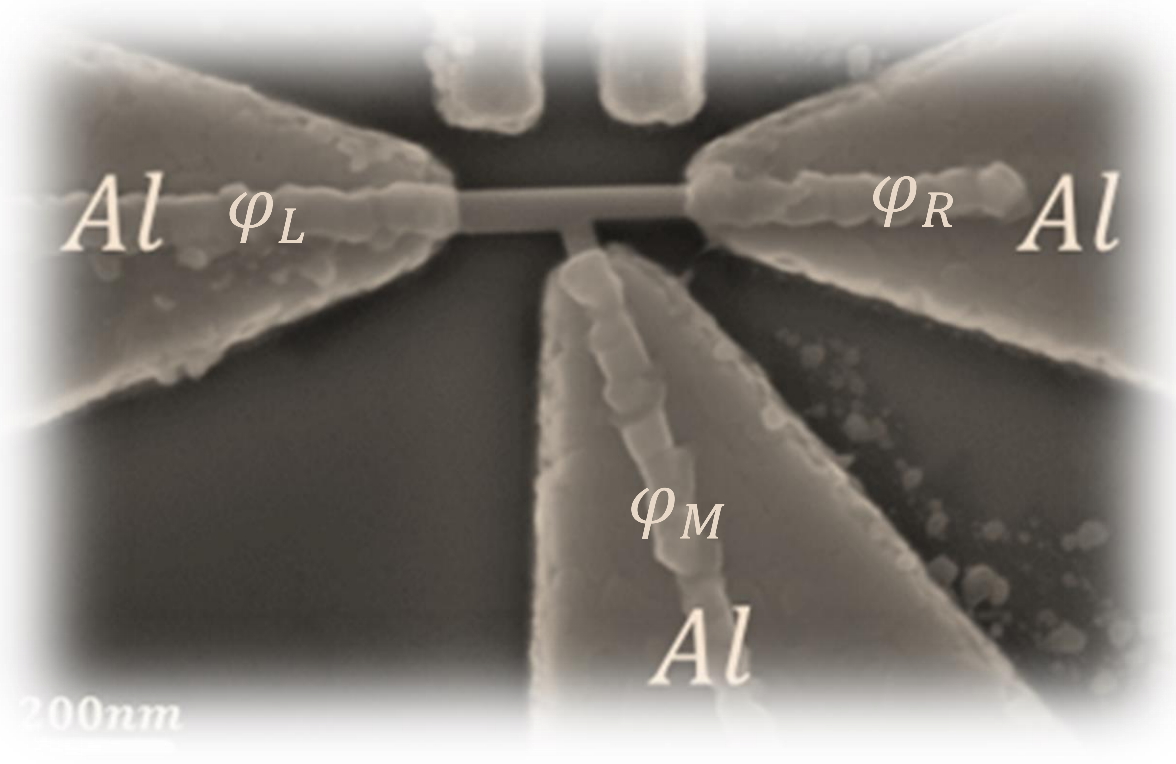
POSSIBLE NEW EFFECTS IN SUPERCONDUCTIVE TUNNELLING *

B. D. JOSEPHSON
Cavendish Laboratory, Cambridge, England

Received 8 June 1962

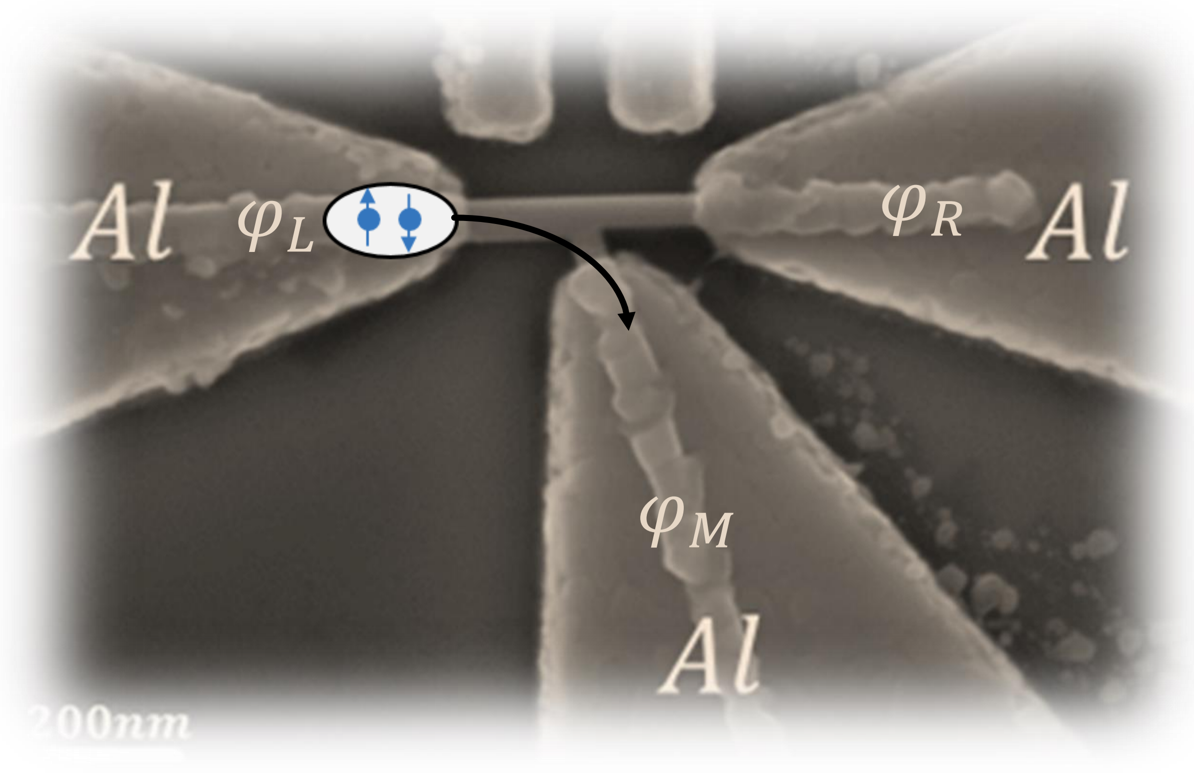


Three terminal Josephson Junction



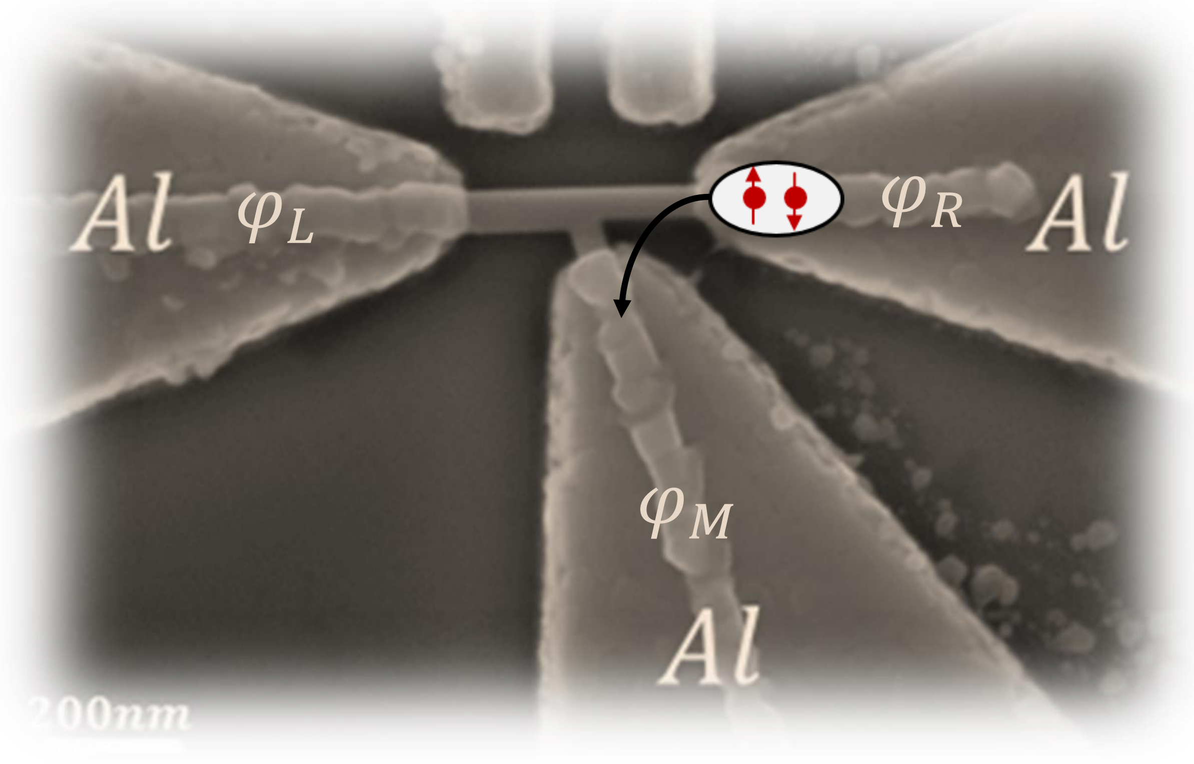
Weizmann Institute of Science

Three terminal Josephson Junction

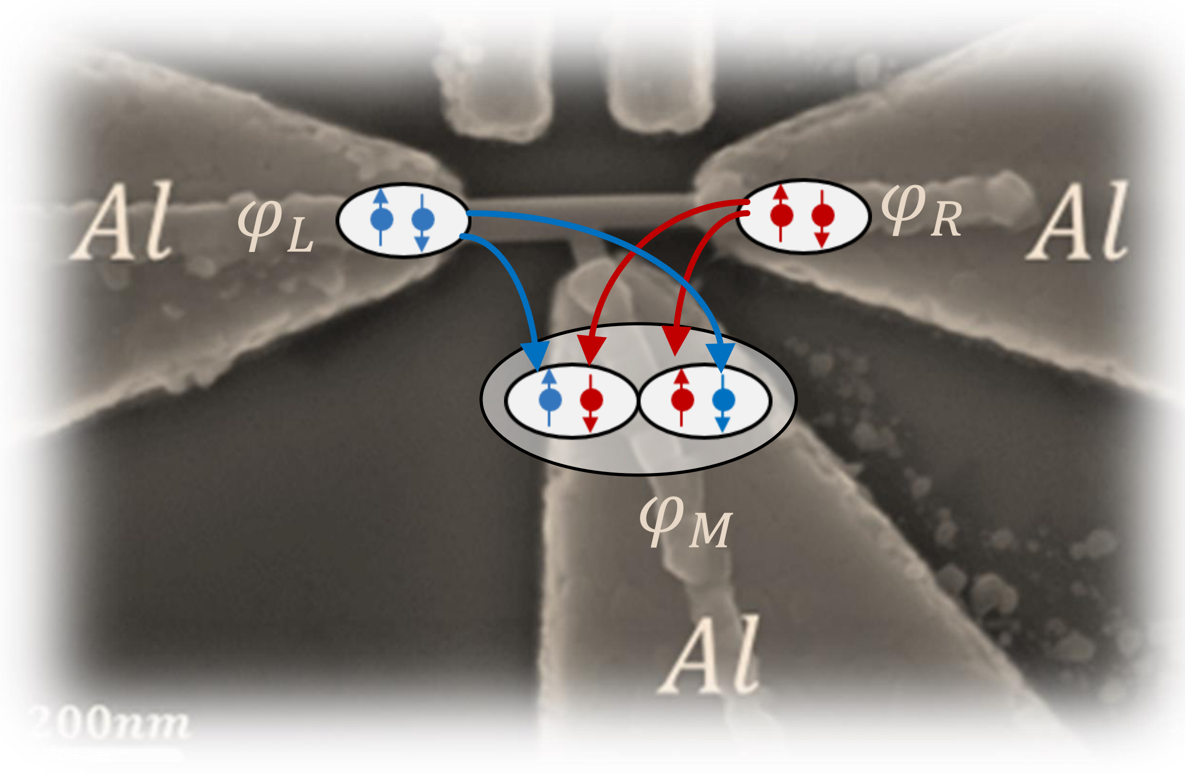


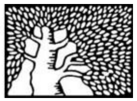
Weizmann Institute of Science

Three terminal Josephson Junction

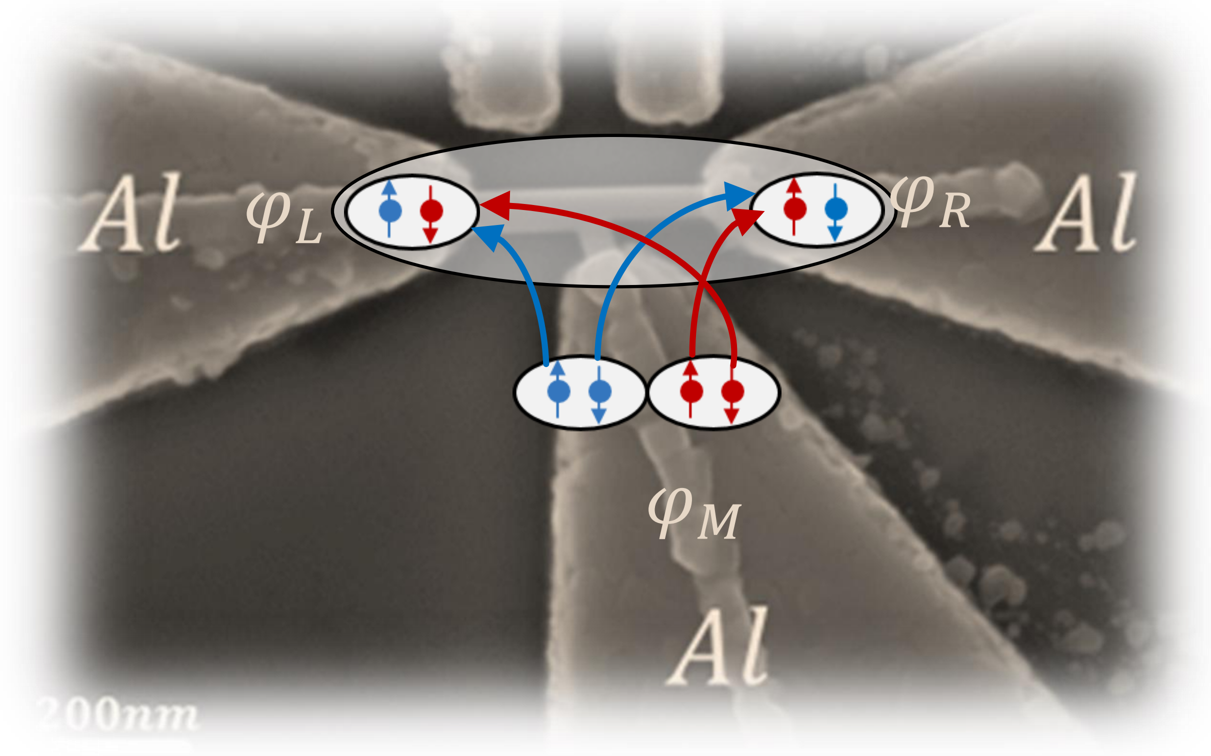


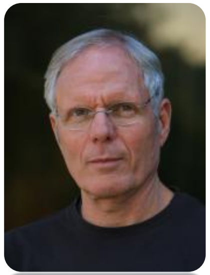
Three terminal Josephson Junction





Three terminal Josephson Junction





Moty
Heiblum

Yuval
Ronen

Yonatan
Cohen

Régis
Mélin

Denis
Feinberg

Jung-Hyun
Kang

Hadas
Shtrikman

Jérome
Rech

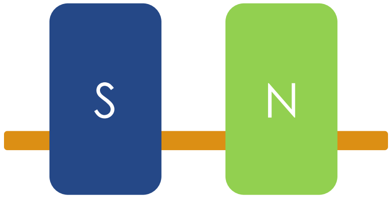
Thierry
Martin

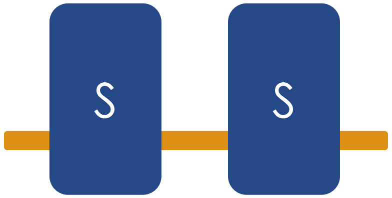
Thibaut
Jonckheere

Non-local supercurrent of Quartets in a three-terminal Josephson junction

Outline

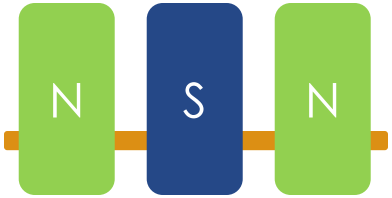
Andreev
reflection

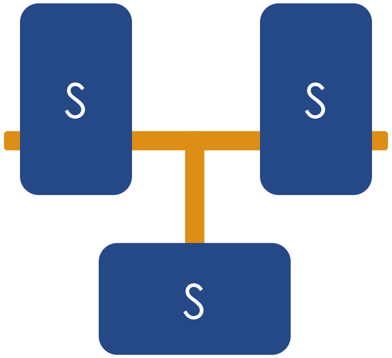




Andreev
bound state
Cooper pair
Supercurrent

Crossed Andreev
reflection
Cooper pair
splitting

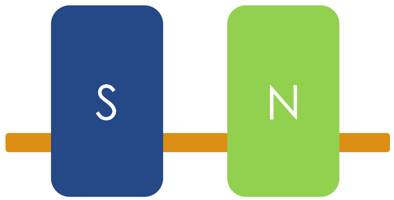




Quartet
bound state
Quartet
Supercurrent

Outline

Andreev reflection

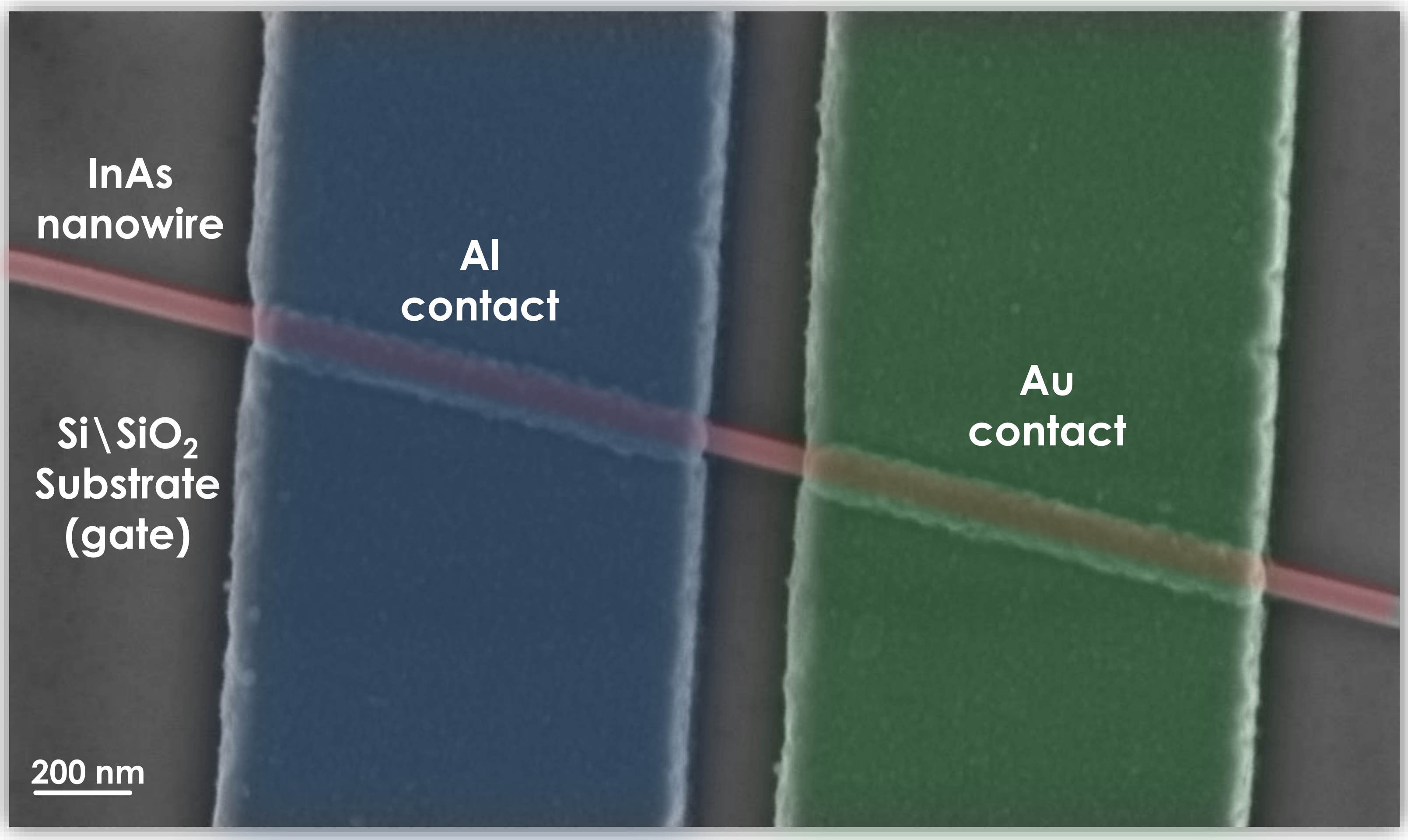


Andreev bound state
Cooper pair Supercurrent

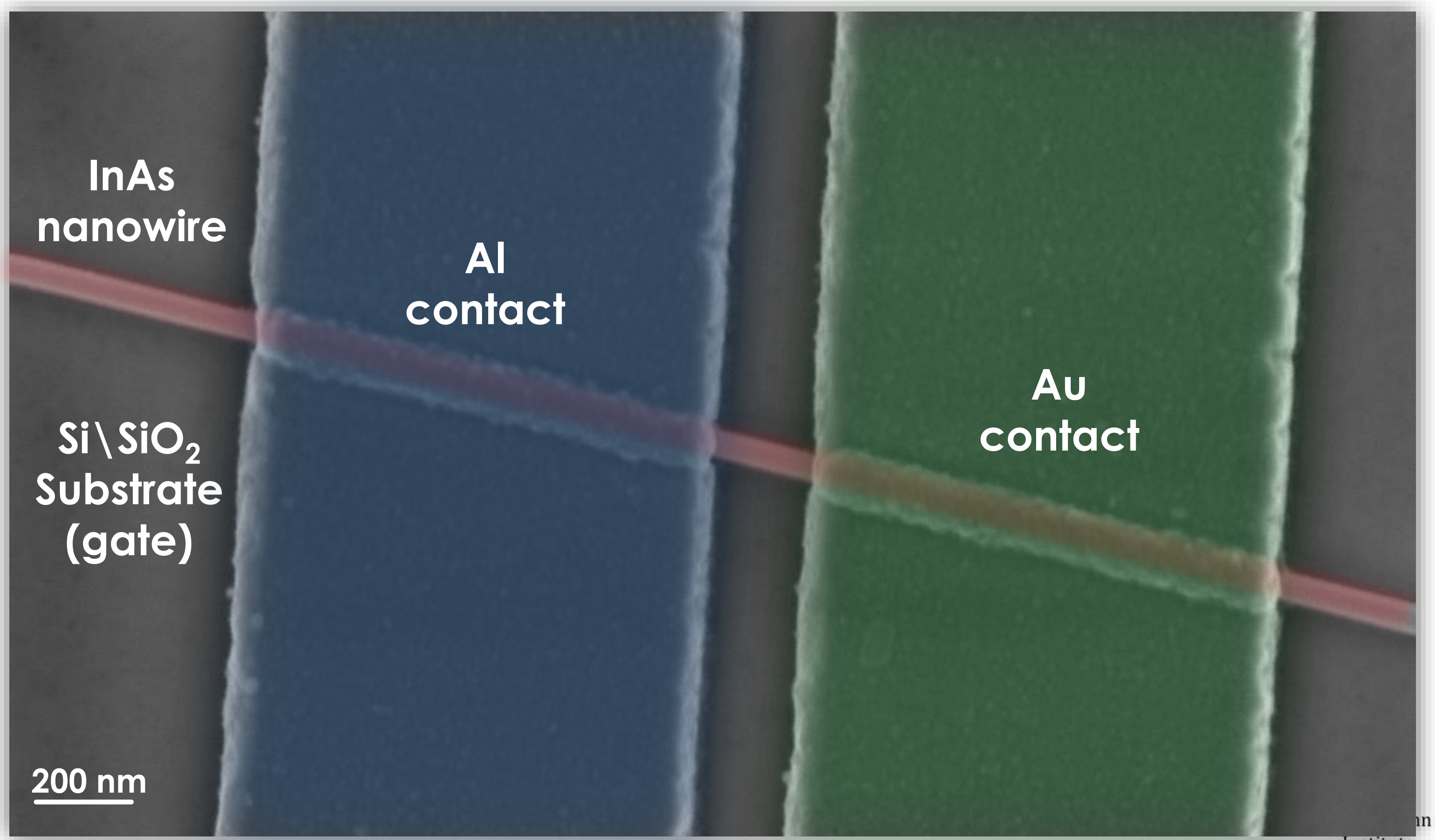
Crossed Andreev reflection
Cooper pair splitting

Quartet bound state
Quartet Supercurrent

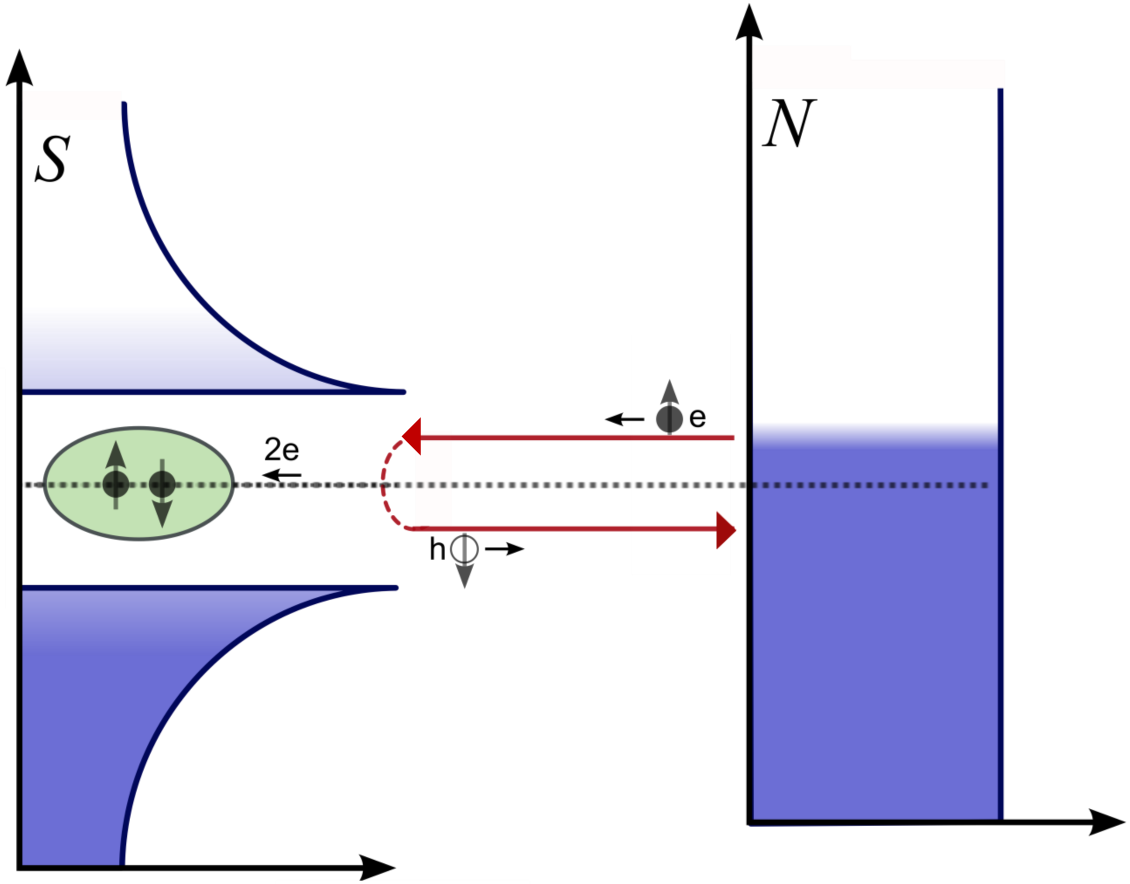
Realizing an SN junction



Transport in an SN junction?



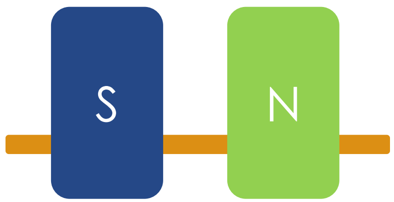
Andreev Reflection (AR)



Weizmann Institute of Science

Outline

Andreev reflection



Andreev bound state
Cooper pair Supercurrent

Crossed Andreev reflection
Cooper pair splitting

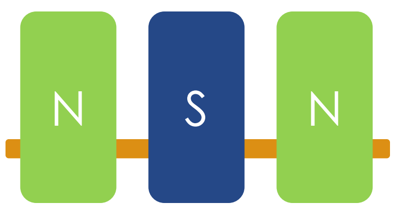
Quartet bound state
Quartet Supercurrent

Outline

Andreev
reflection

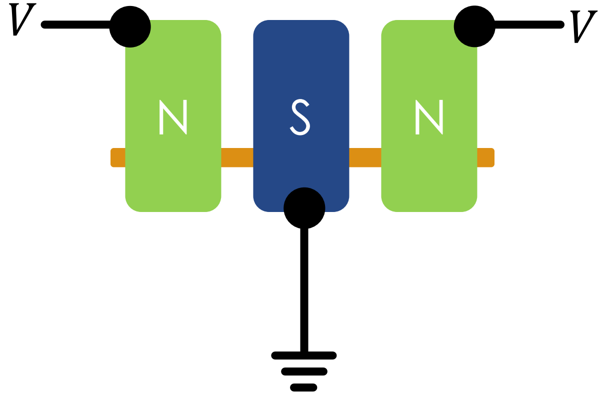
Andreev
bound state
Cooper pair
Supercurrent

Crossed Andreev
reflection
Cooper pair
splitting

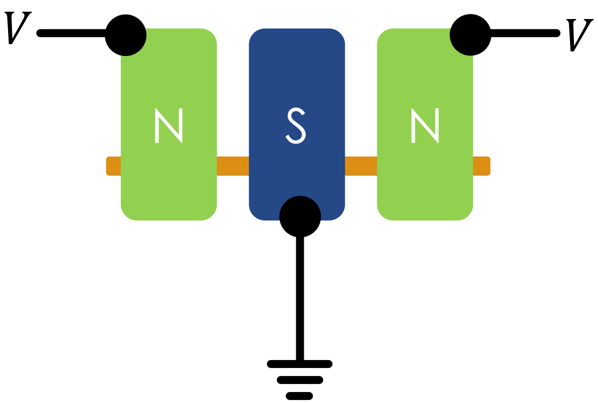


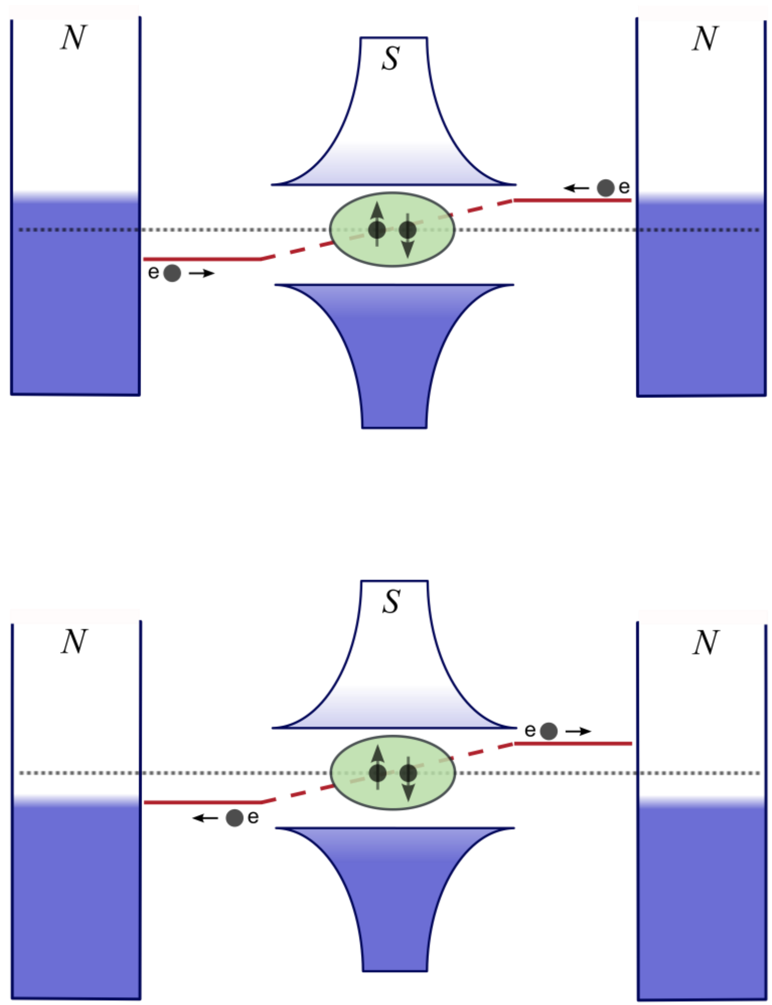
Quartet
bound state
Quartet
Supercurrent

Crossed Andreev Reflection (CAR)



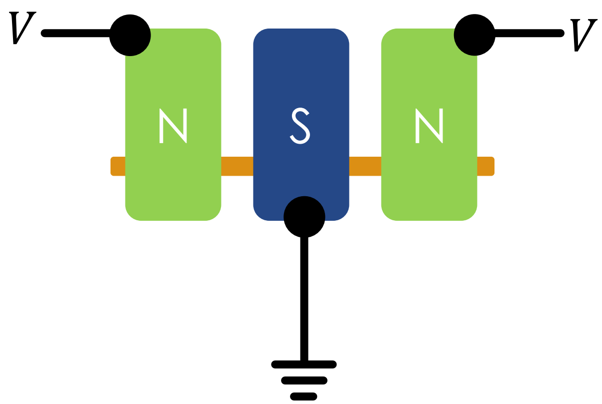
Crossed Andreev Reflection (CAR)

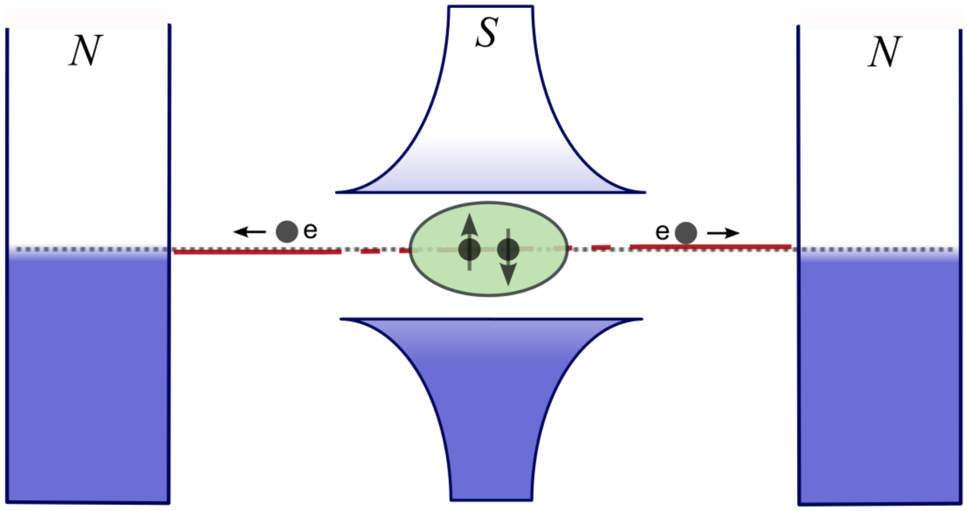




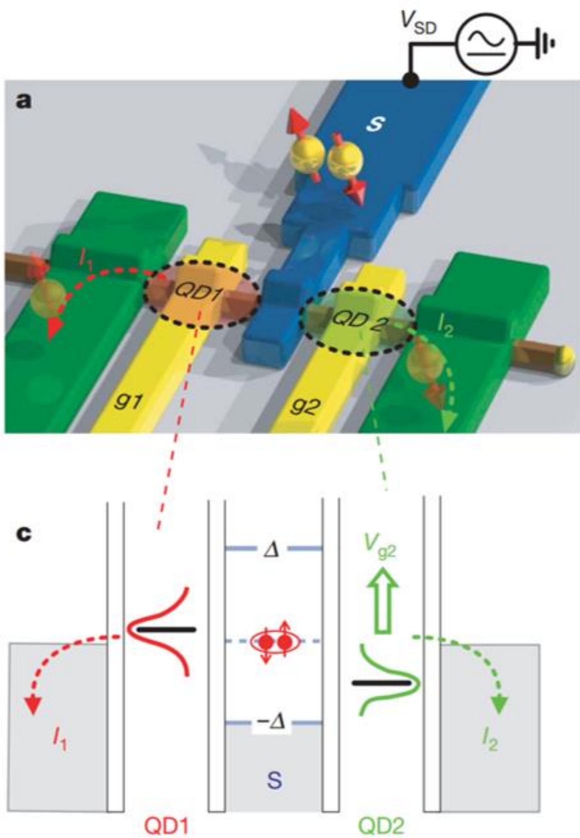
Crossed Andreev Reflection (CAR)

A source of
entangled electrons

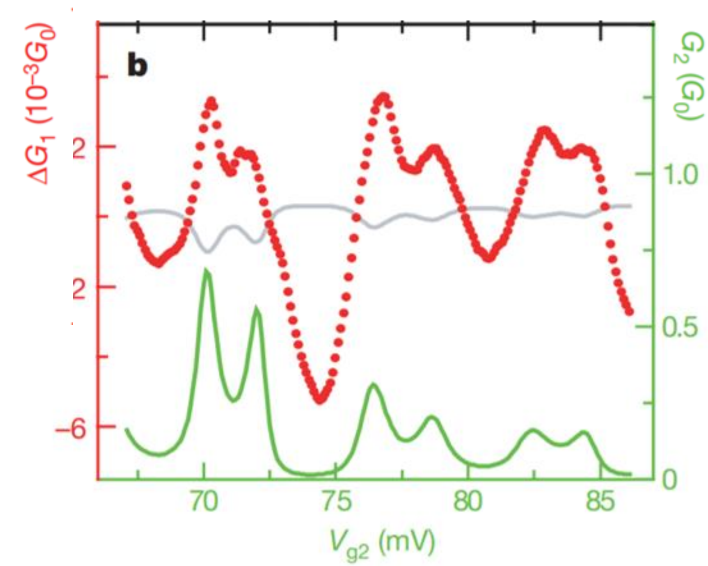




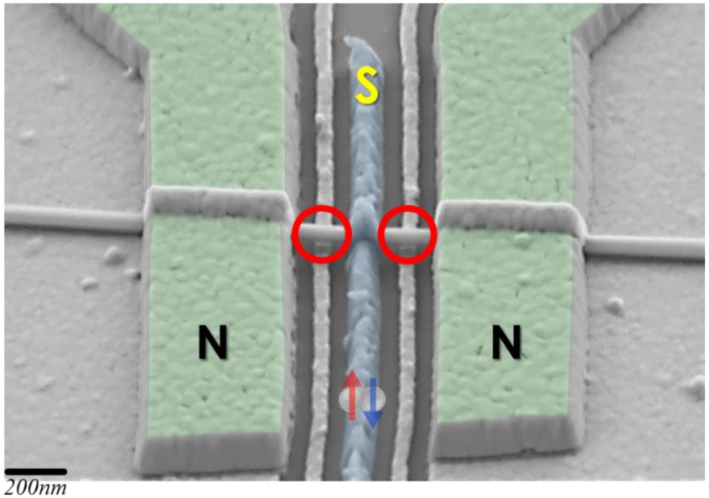
$$|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$$

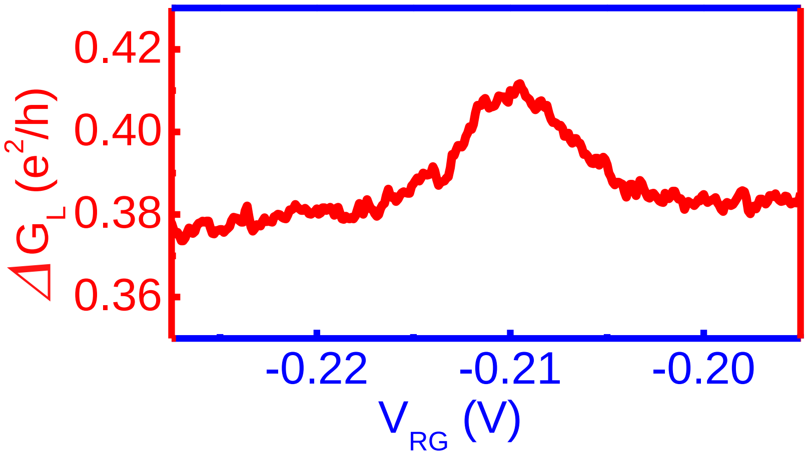


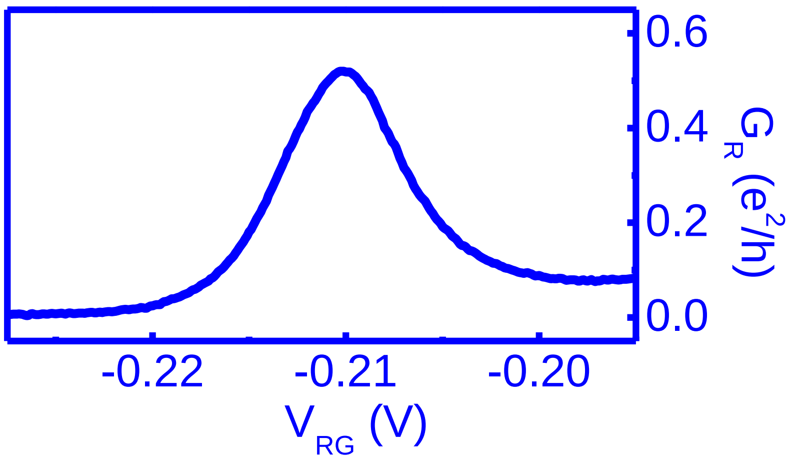
L. Hofstetter, S. Csonka, J. Nygard
& C. Schonenberger, *Nature* (2009)



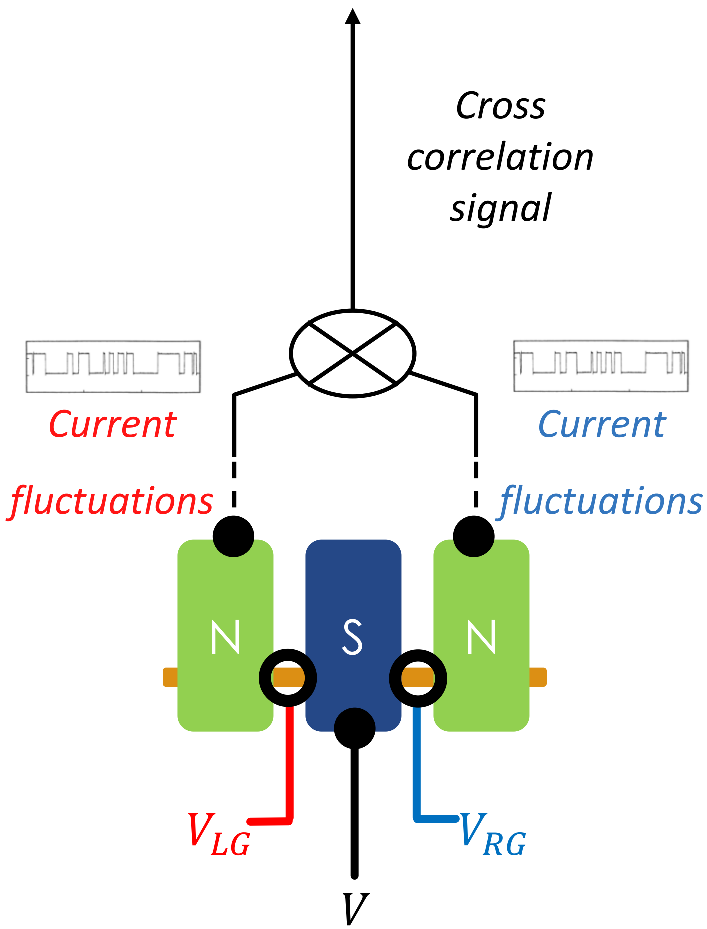
A. Das, Y.Ronen, M. Heiblum, D. Mahalu,
A. V. Kretinin & H. Shtrikman, *Nat. Comm.* (2012)



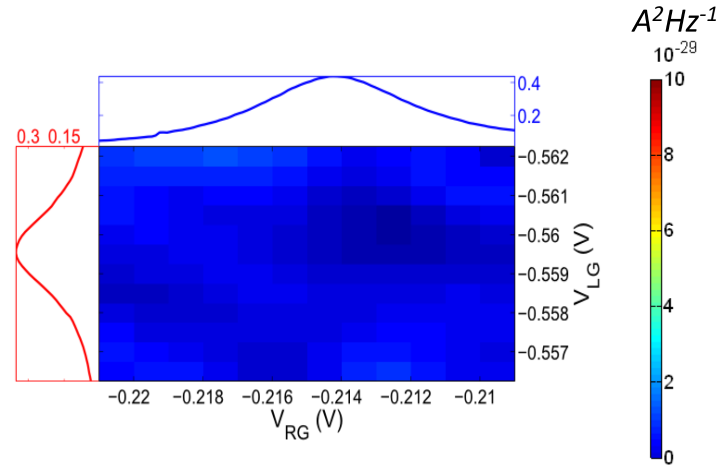




Positive Cross-Correlation



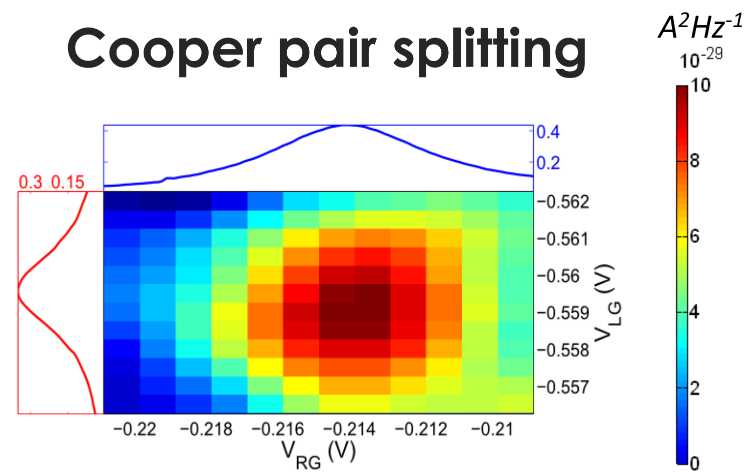
B=0.3T



Positive cross-correlation

Cooper pair splitting

B=0

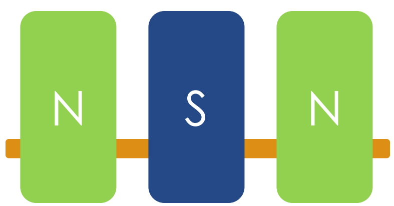


Outline

Andreev reflection

Andreev bound state
Cooper pair Supercurrent

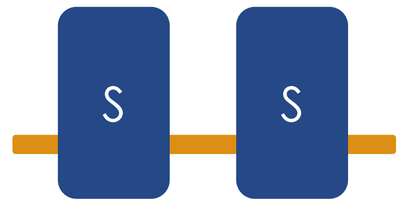
Crossed Andreev reflection
Cooper pair splitting



Quartet bound state
Quartet Supercurrent

Outline

Andreev reflection

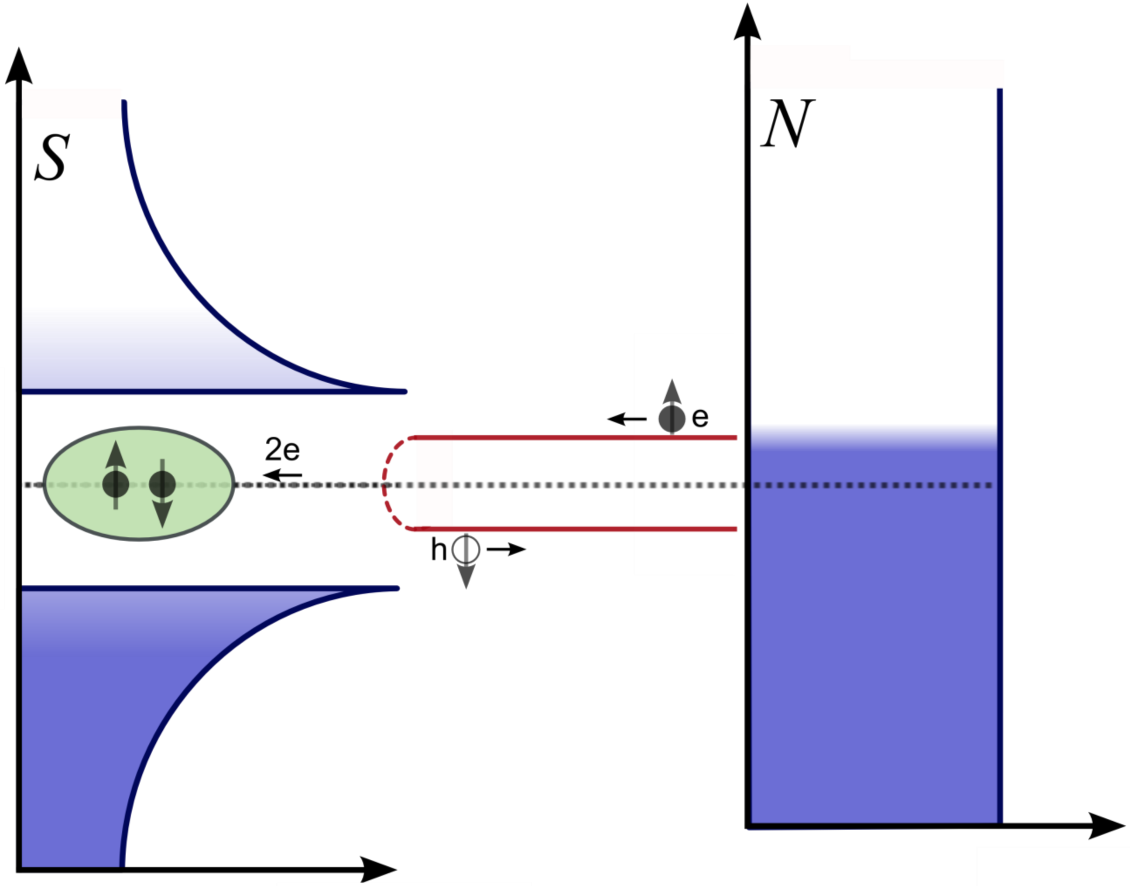


Andreev bound state
Cooper pair Supercurrent

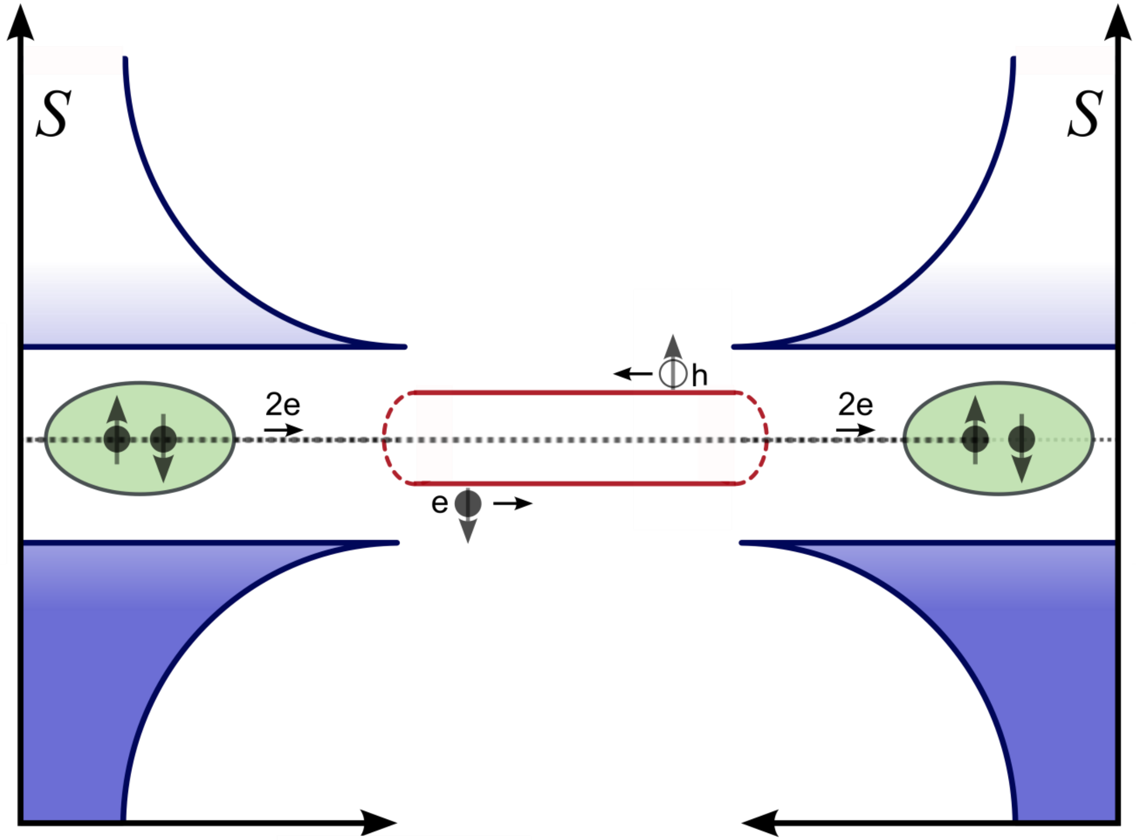
Crossed Andreev reflection
Cooper pair splitting

Quartet bound state
Quartet Supercurrent

Current flow in a Josephson junction

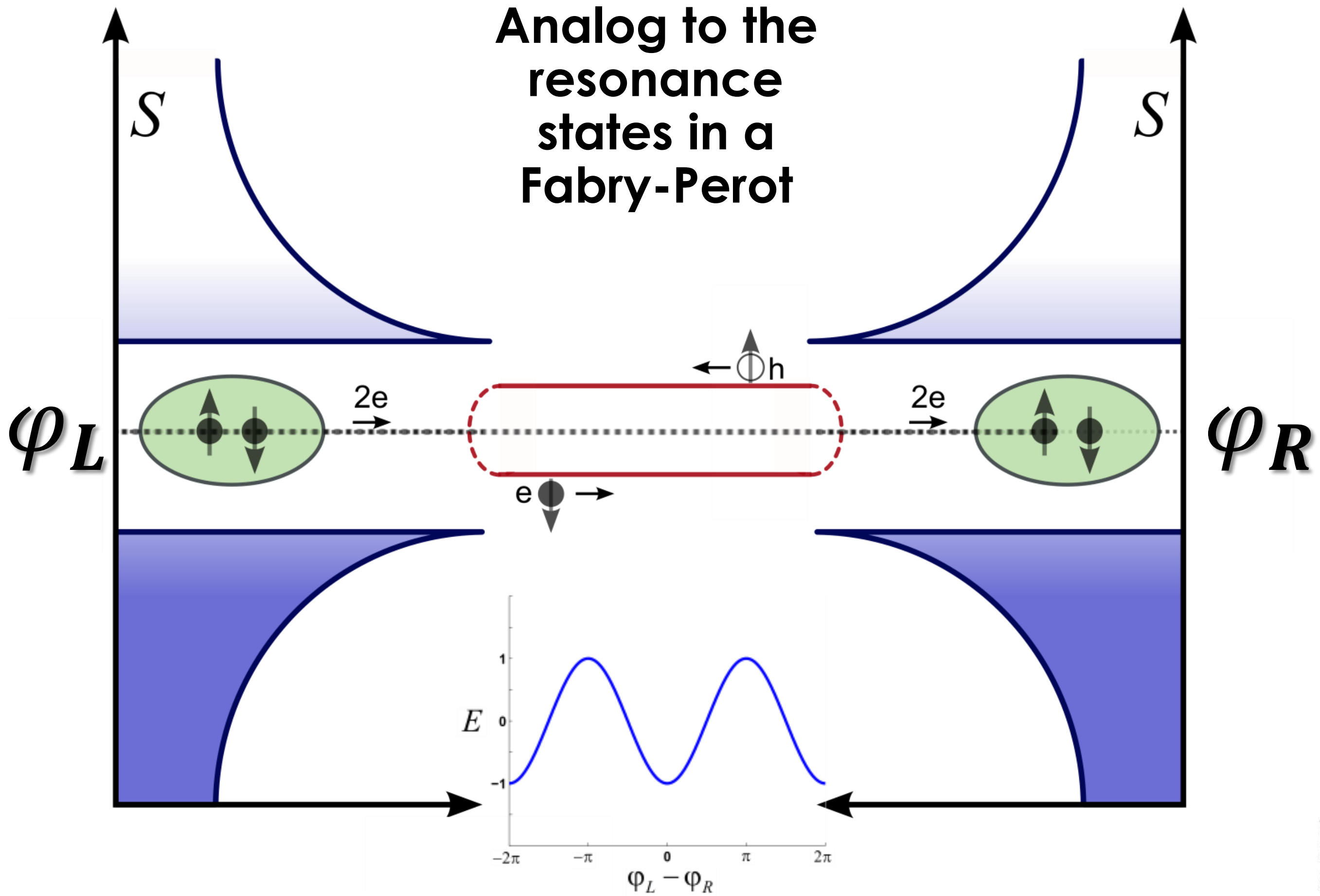


Current flow in a Josephson junction



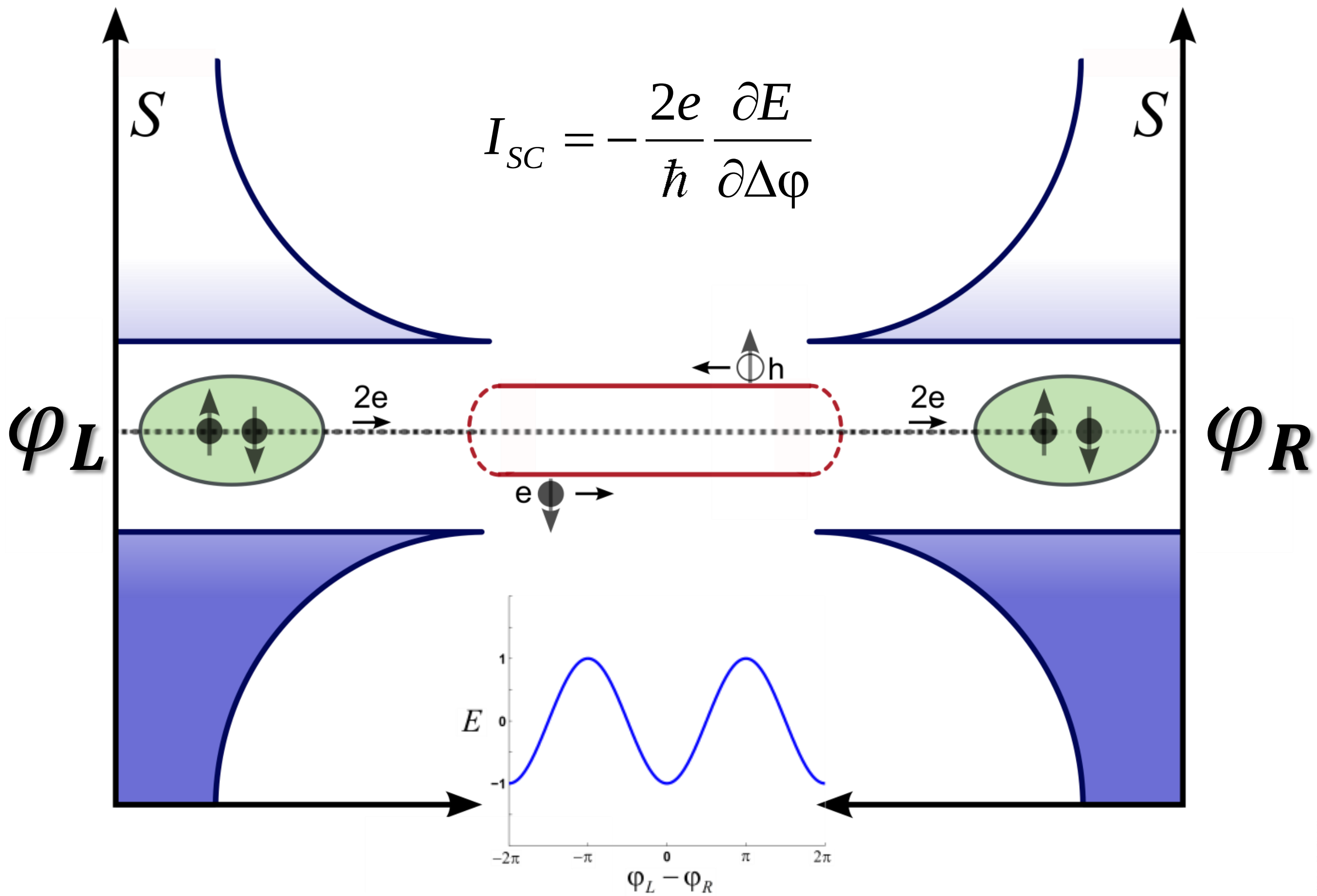
Weizmann Institute of Science

Current flow in a Josephson junction

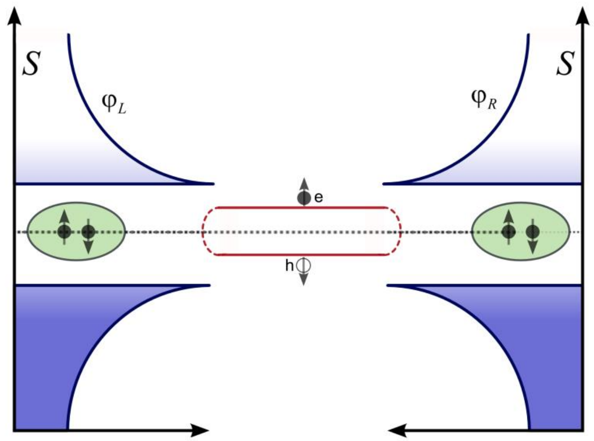


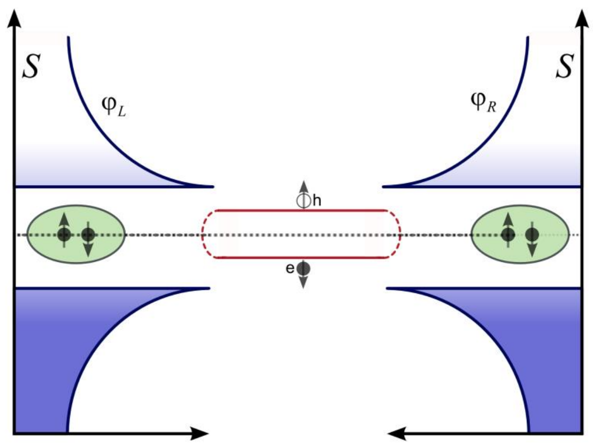
Weizmann Institute of Science

Current flow in a Josephson junction

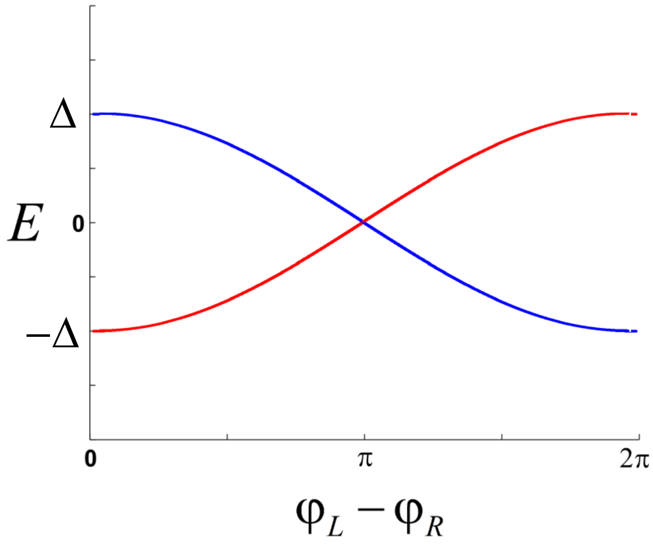


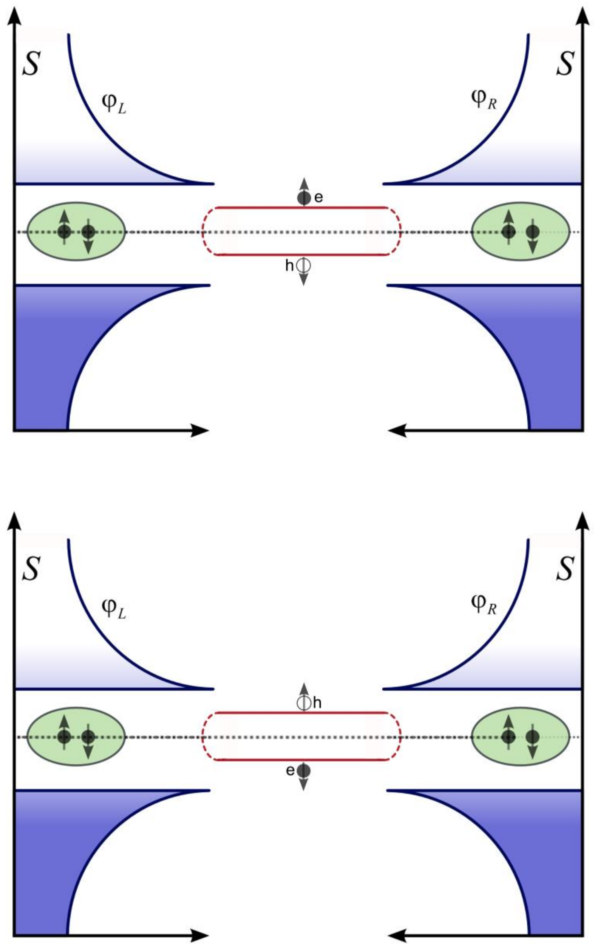
(Ballistic)
Andreev bound state



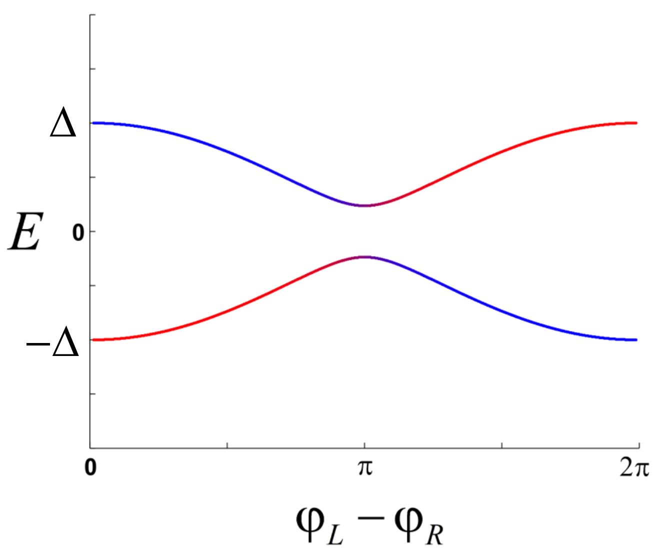


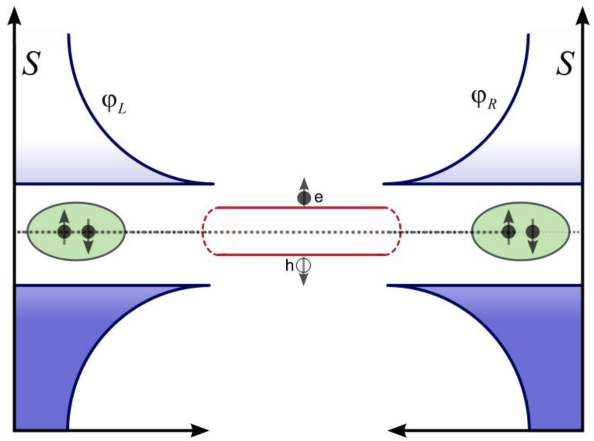
(Ballistic) Andreev bound state

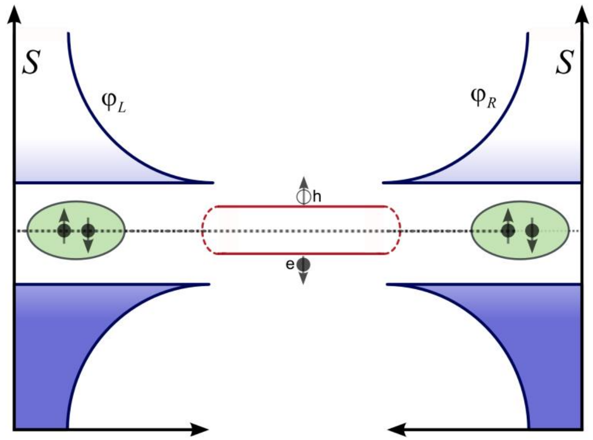




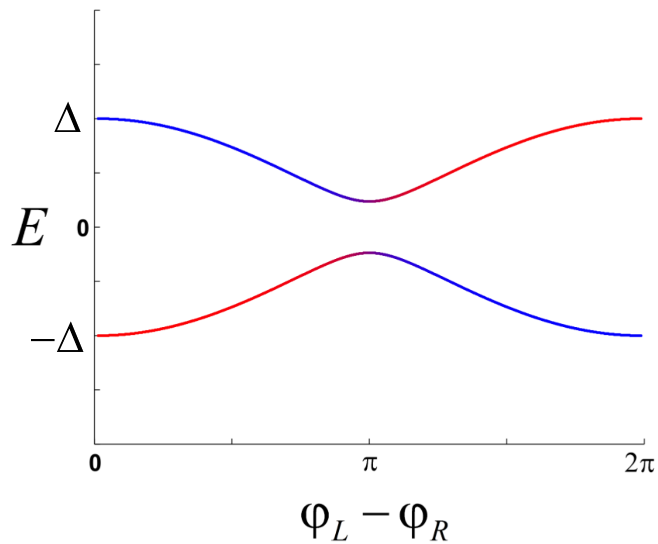
Andreev bound state

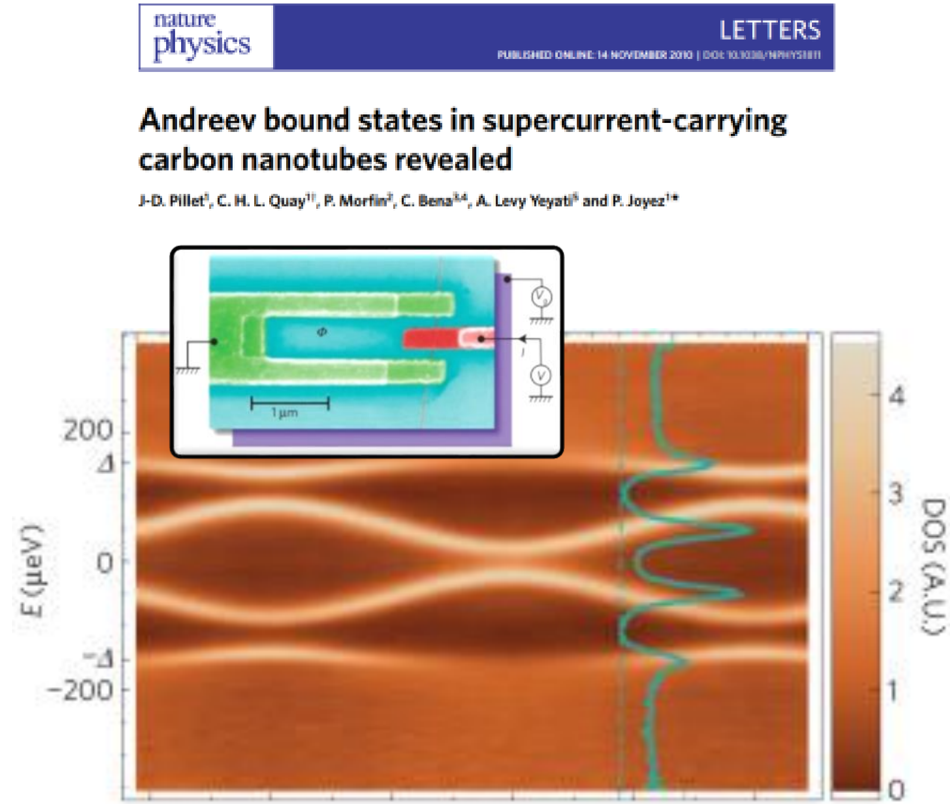






Andreev bound state

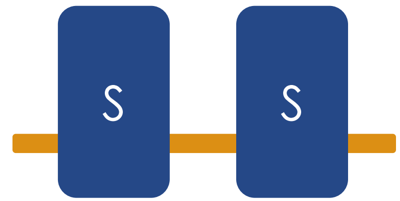




J-D. Pillet, C. H. L. Quay, P. Morfin, C. Bena, A. Levy Yeyati & P. Joyez, *Nat. Phys.* (2010)

Outline

Andreev
reflection



Andreev
bound state
Cooper pair
Supercurrent

Crossed Andreev
reflection
Cooper pair
splitting

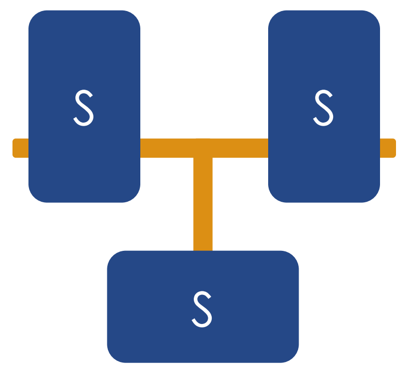
Quartet
bound state
Quartet
Supercurrent

Outline

Andreev
reflection

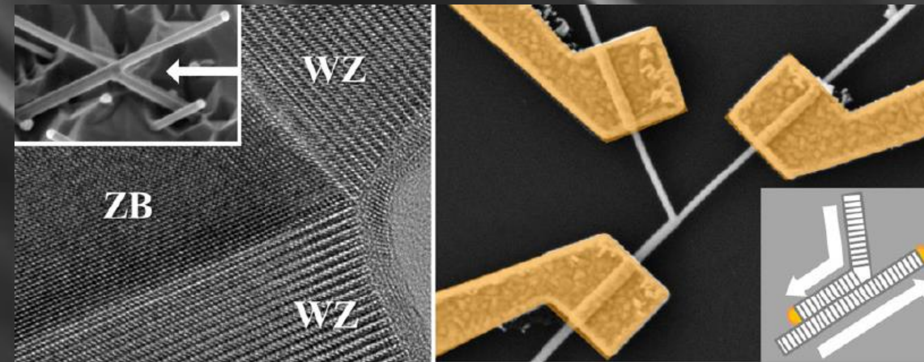
Andreev
bound state
Cooper pair
Supercurrent

Crossed Andreev
reflection
Cooper pair
splitting



Quartet
bound state
Quartet
Supercurrent

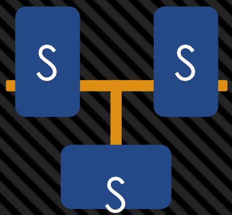
Growth on (100) InAs

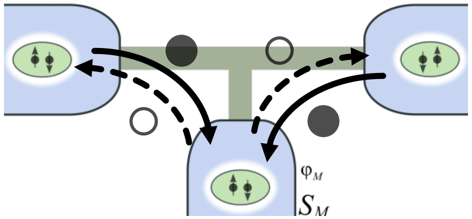


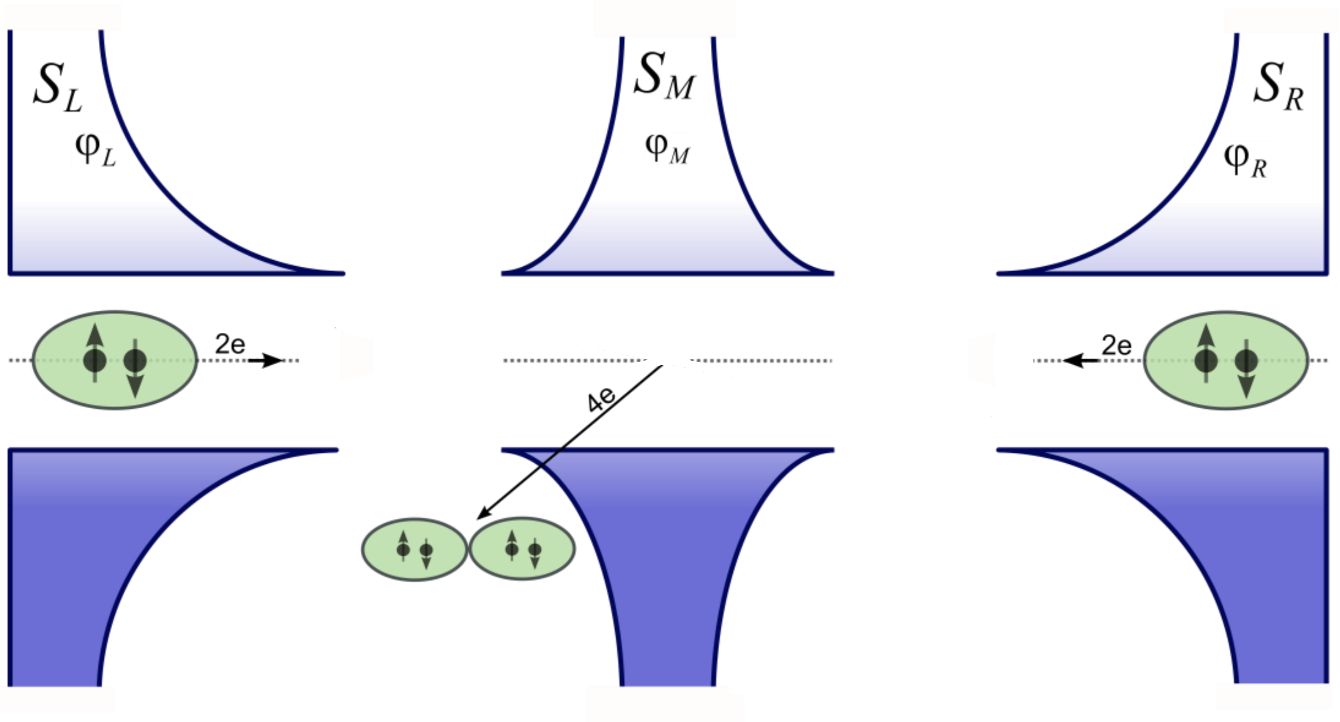
J.H.Kang, Y. Cohen, Y. Ronen, M. Heiblum, R. B., P. Kacman, R. Popovitz-Biro, Hadas Shtrikman, *Nano Lett.* (2013)

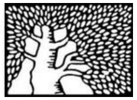
200nm

Quartet Andreev bound state

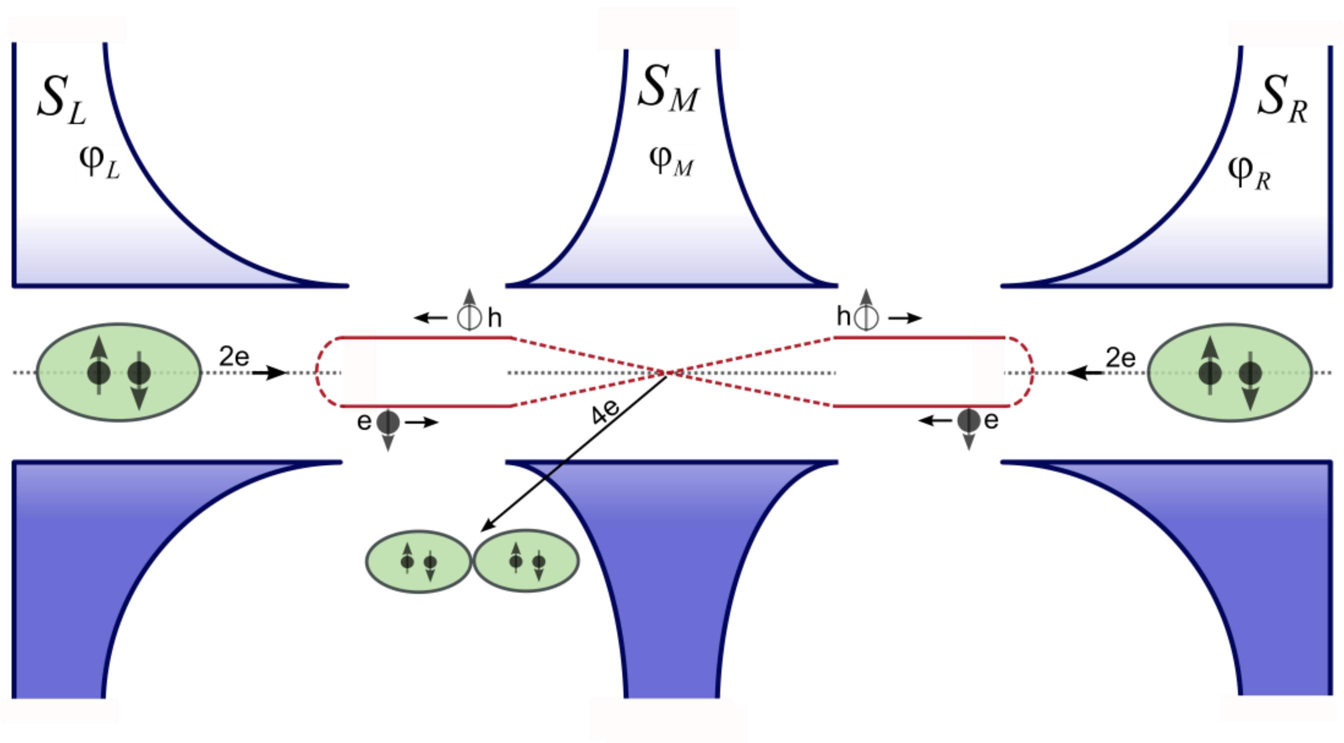




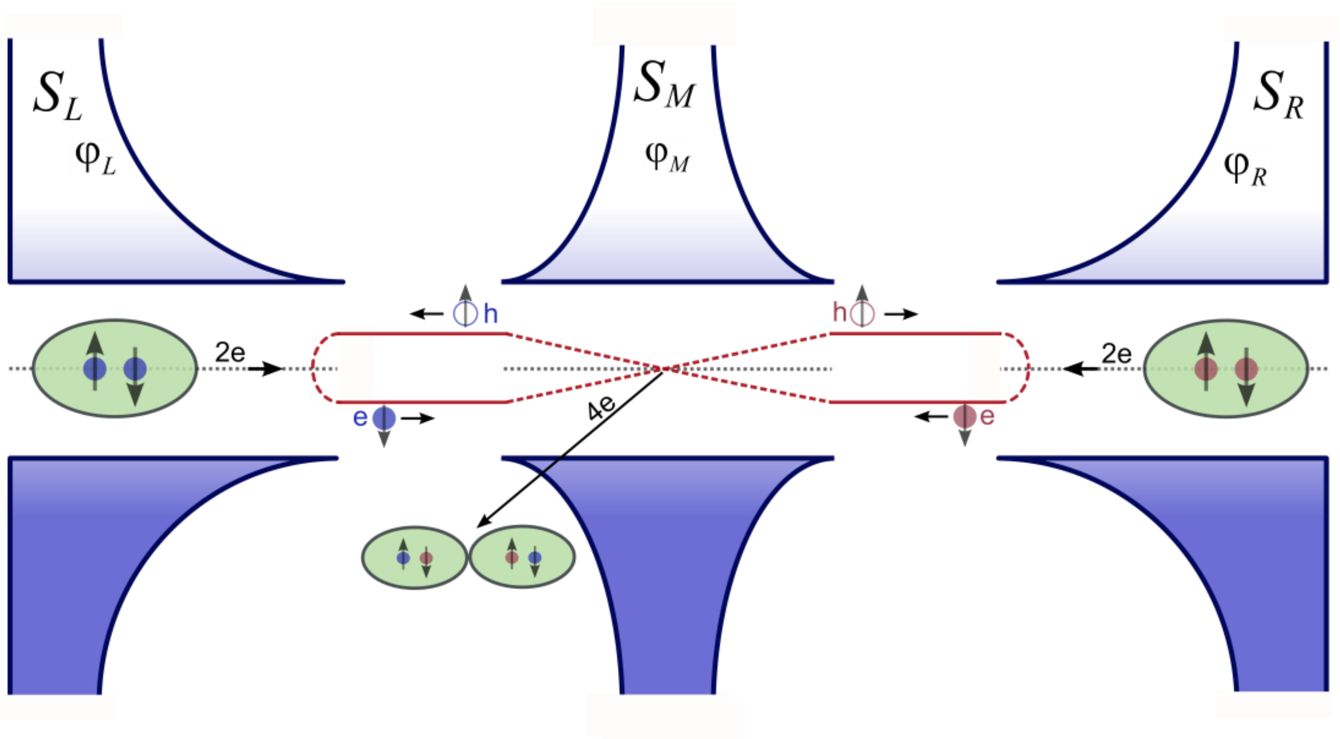




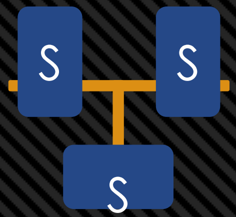
Quartet Andreev bound state

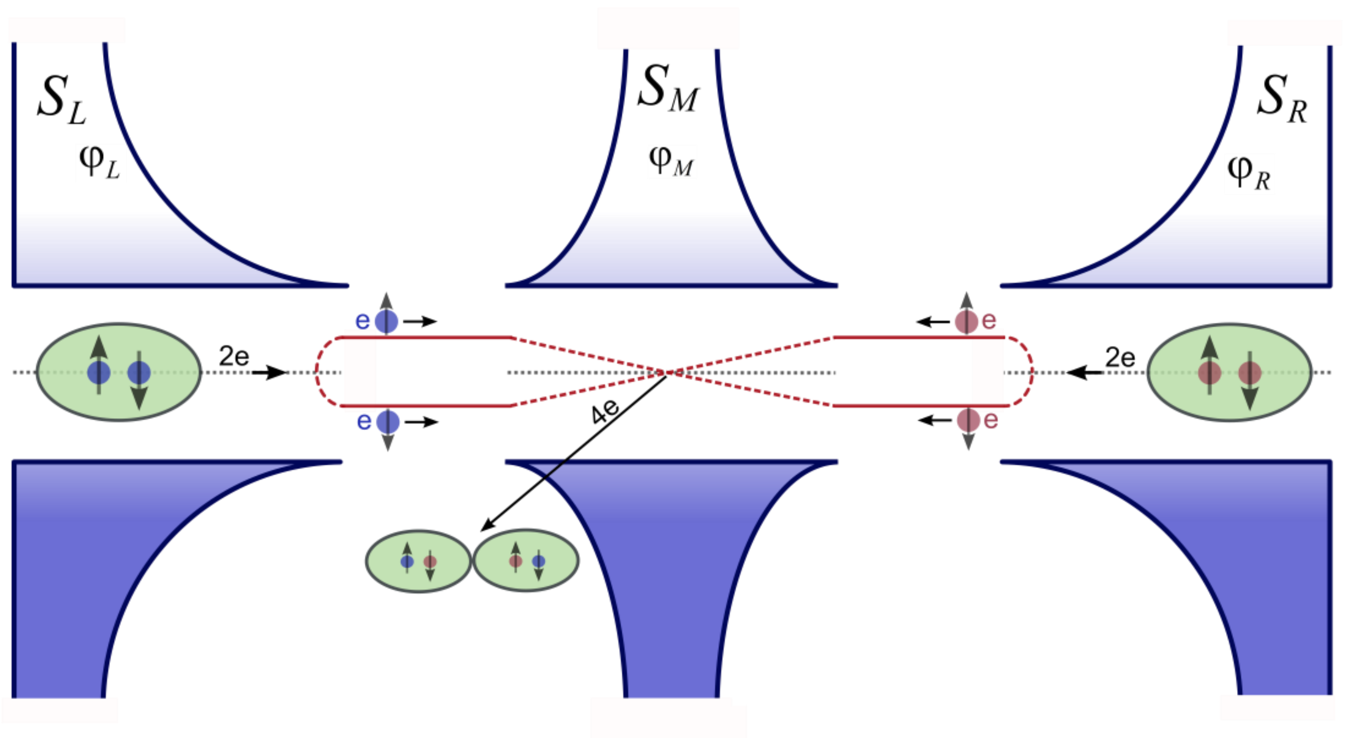


Quartet Andreev bound state

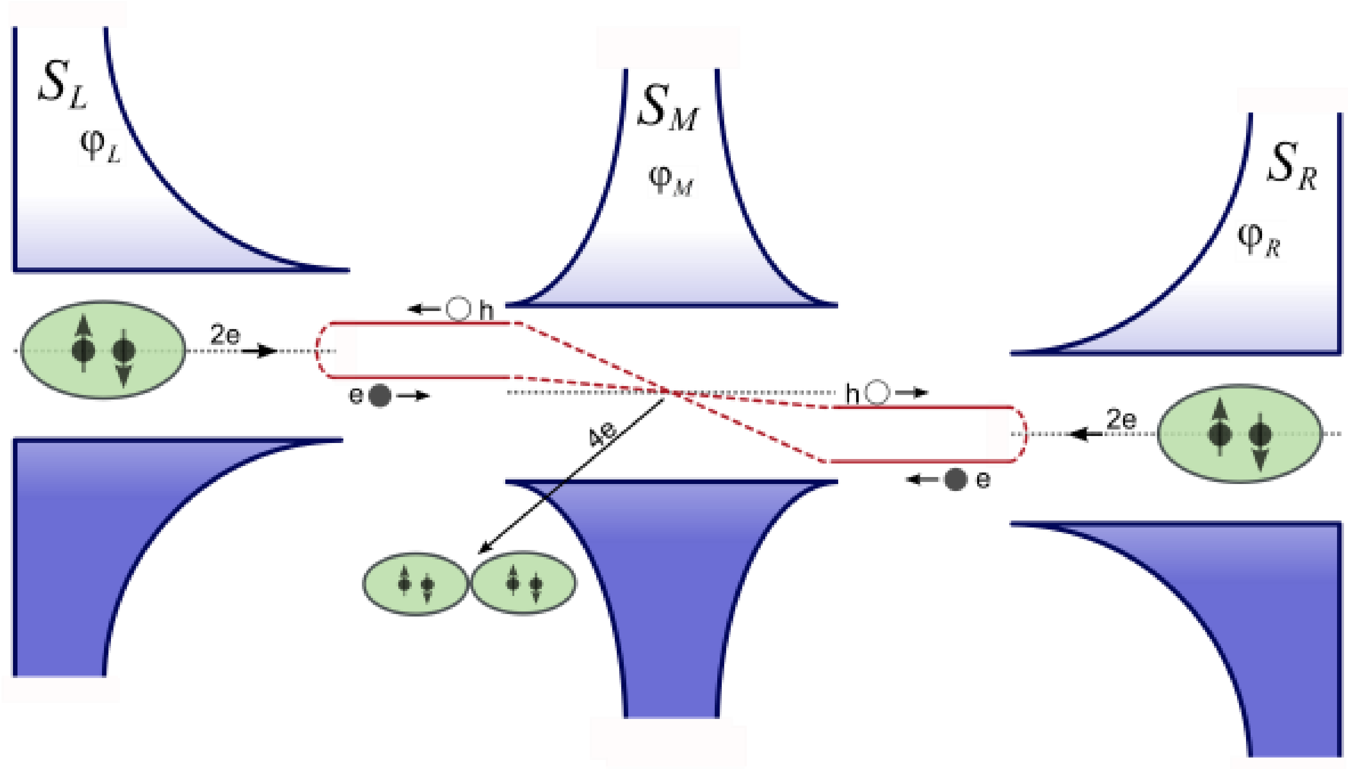


Quartet Andreev bound state

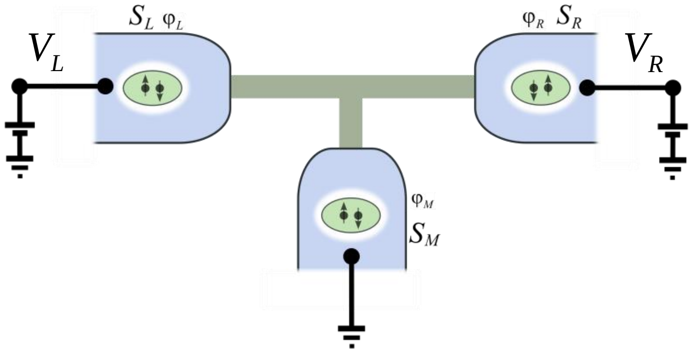


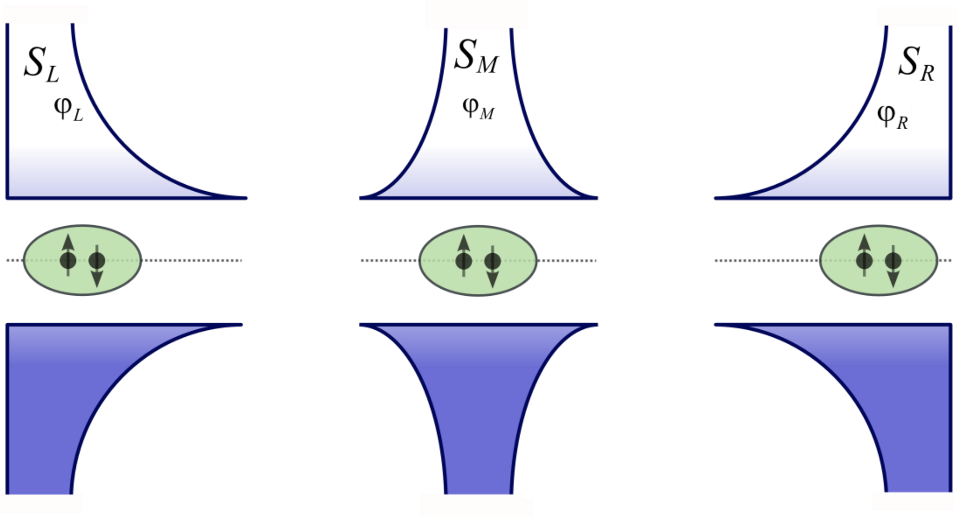


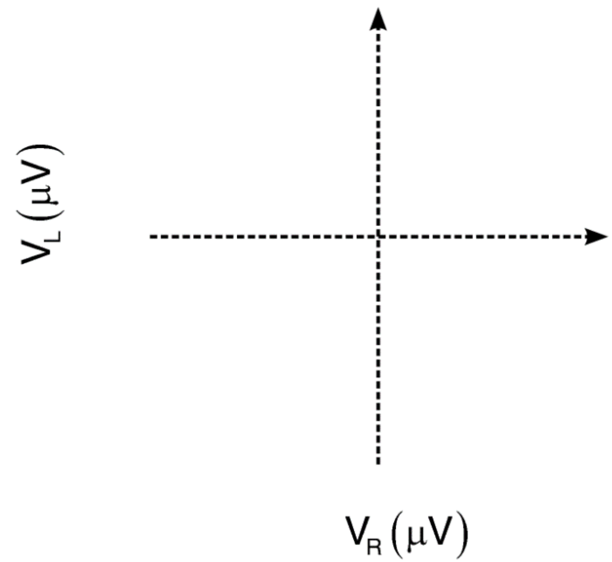
Quartet Andreev bound state



Supercurrents in the three-terminal Josephson junction

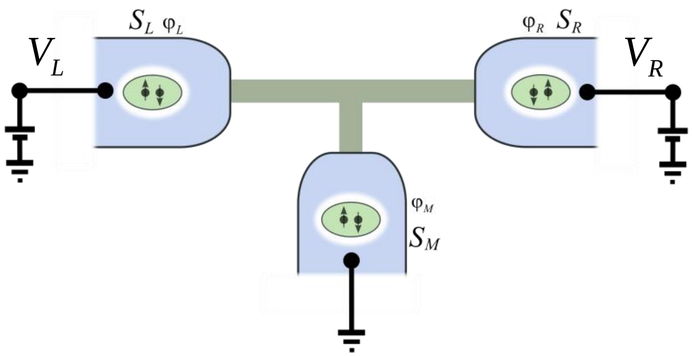


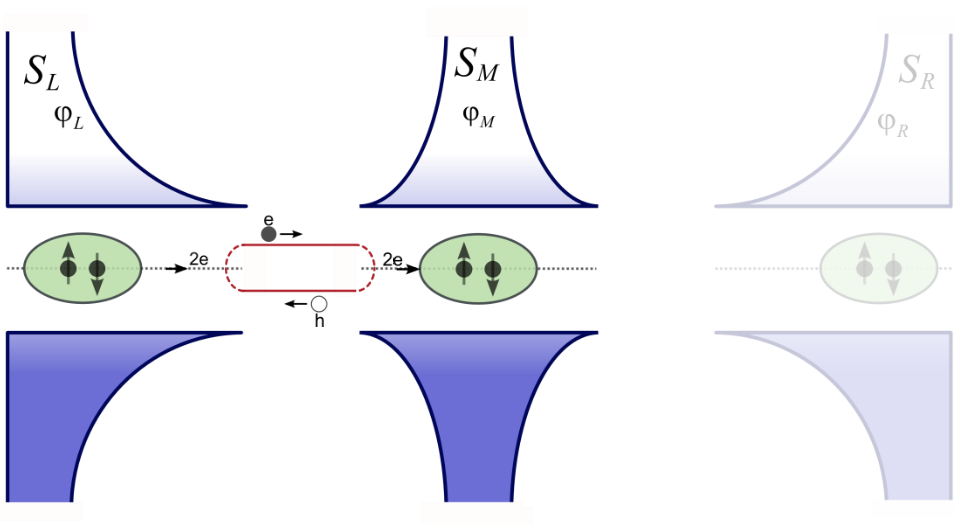


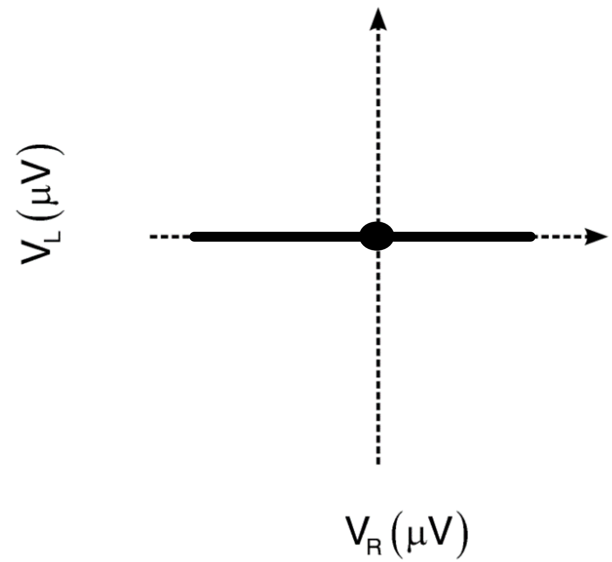


Weizmann Institute of Science

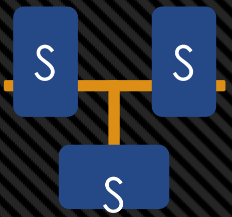
Supercurrents in the three-terminal Josephson junction

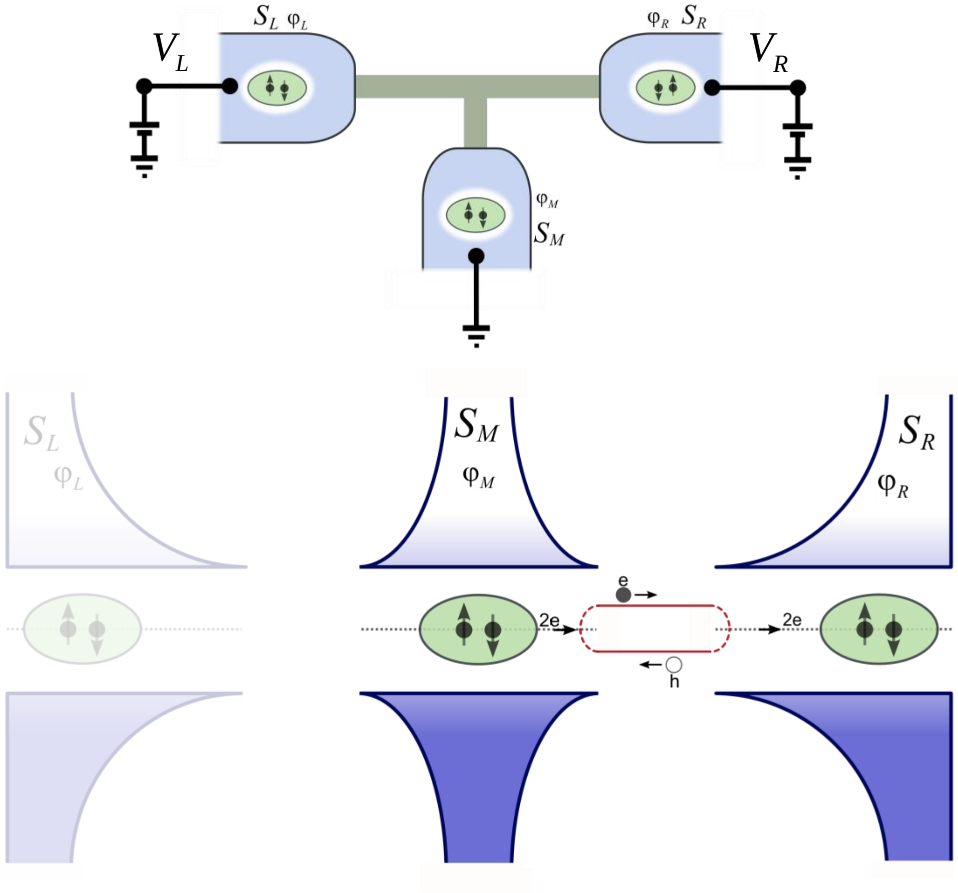


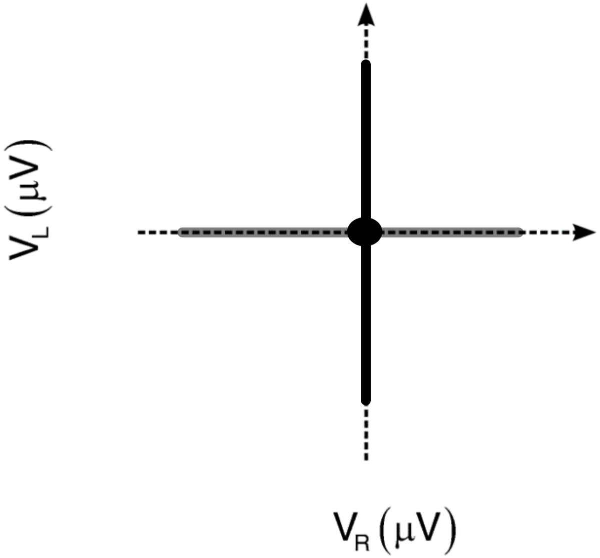




Supercurrents in the three-terminal Josephson junction

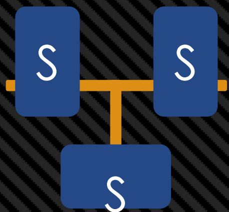


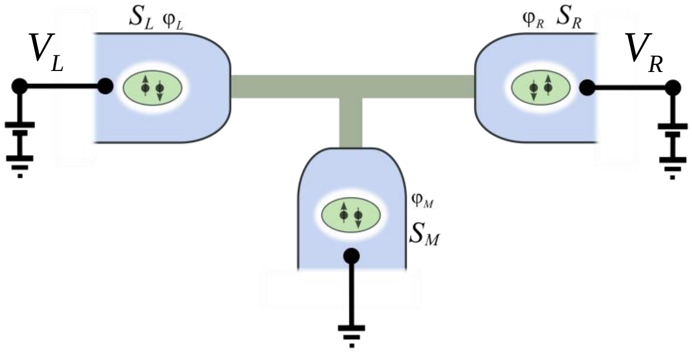


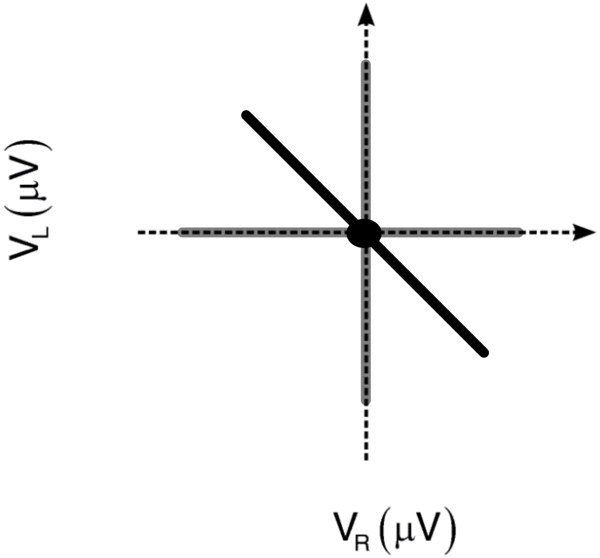


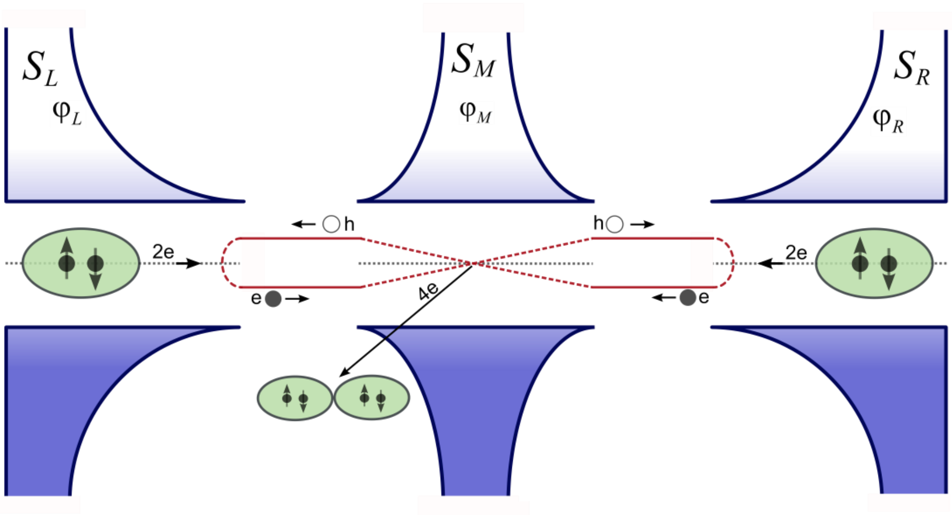
Weizmann Institute of Science

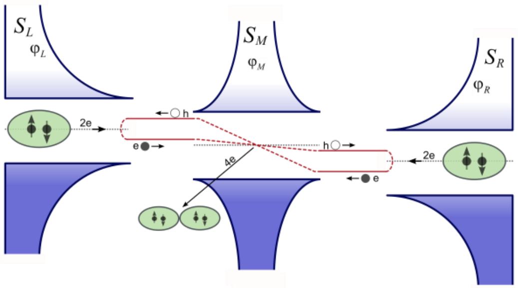
Supercurrents in the three-terminal Josephson junction







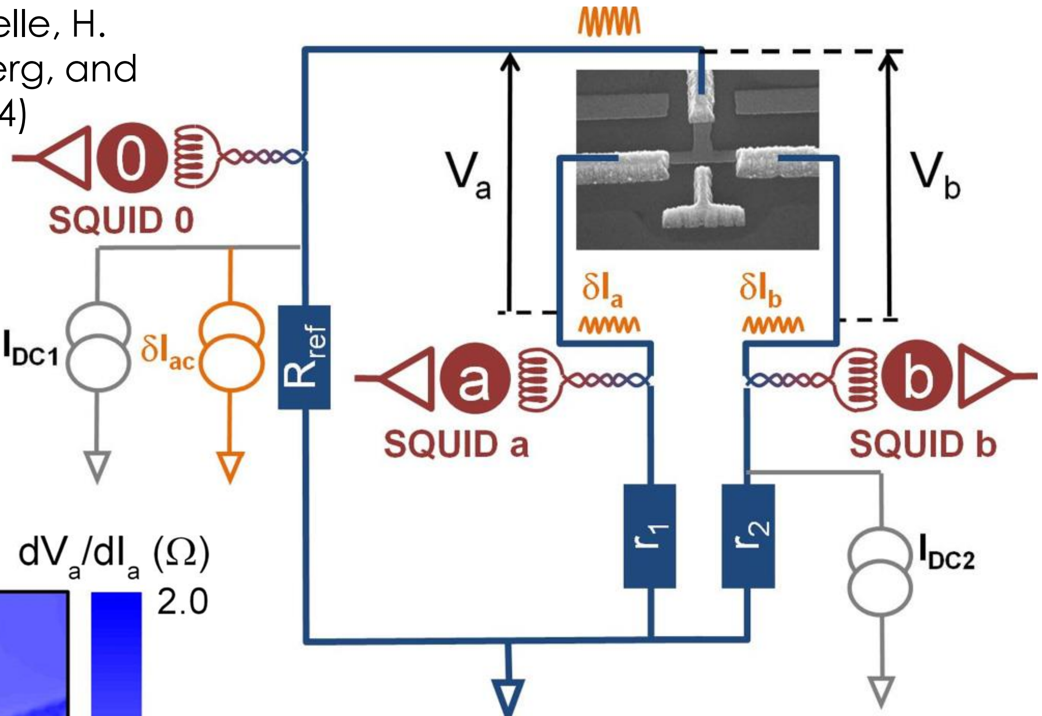


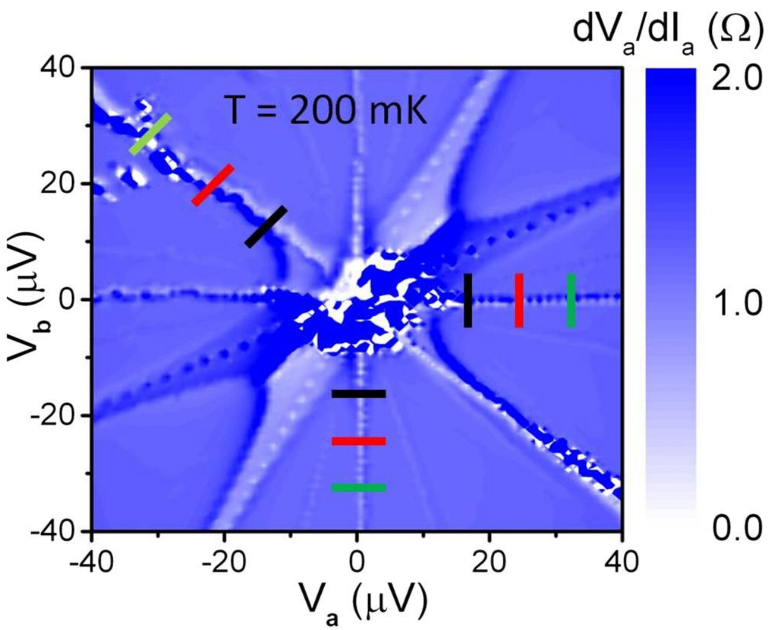


Weizmann Institute of Science

Experimental Results

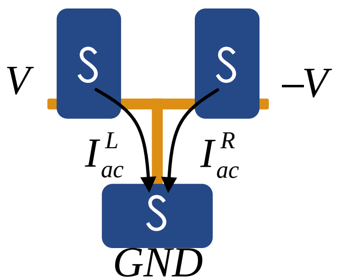
A. H. Pfeffer, J. E. Duvauchelle, H. Courtois, R. Mélin, D. Feinberg, and F. Lefloch. *Phys. Rev. B* (2014)

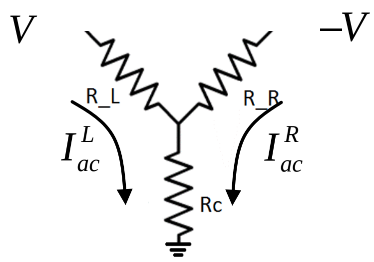




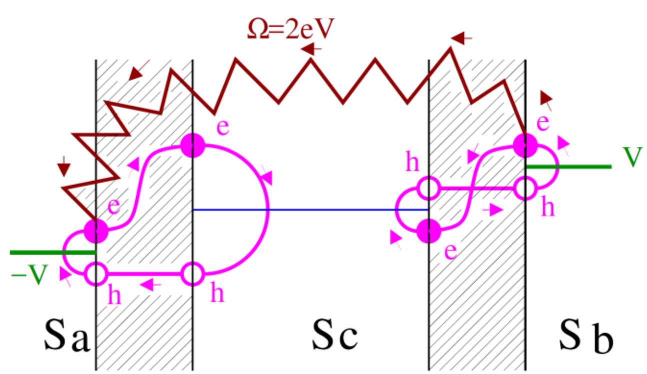
Alternative mechanisms

Down-mixing of two ac Josephson currents

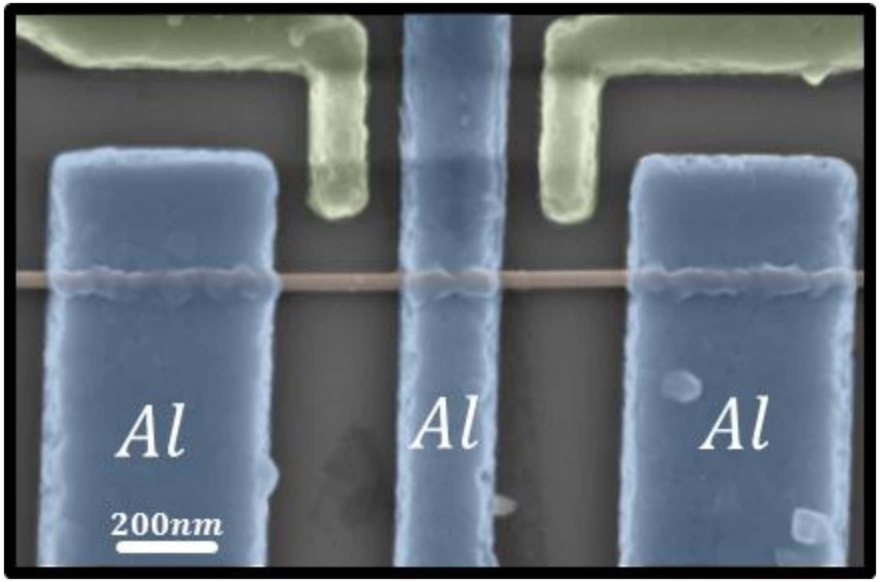




Synchronization of ac Josephson currents

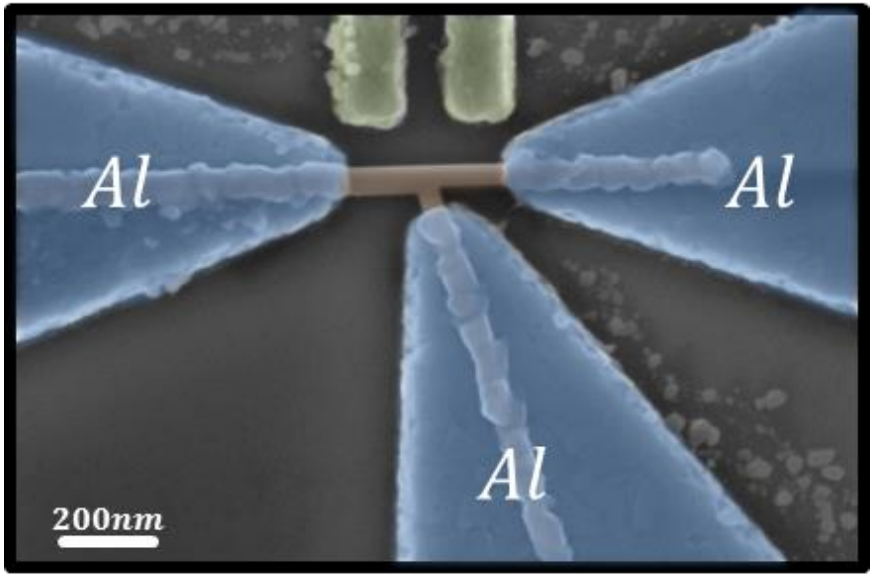


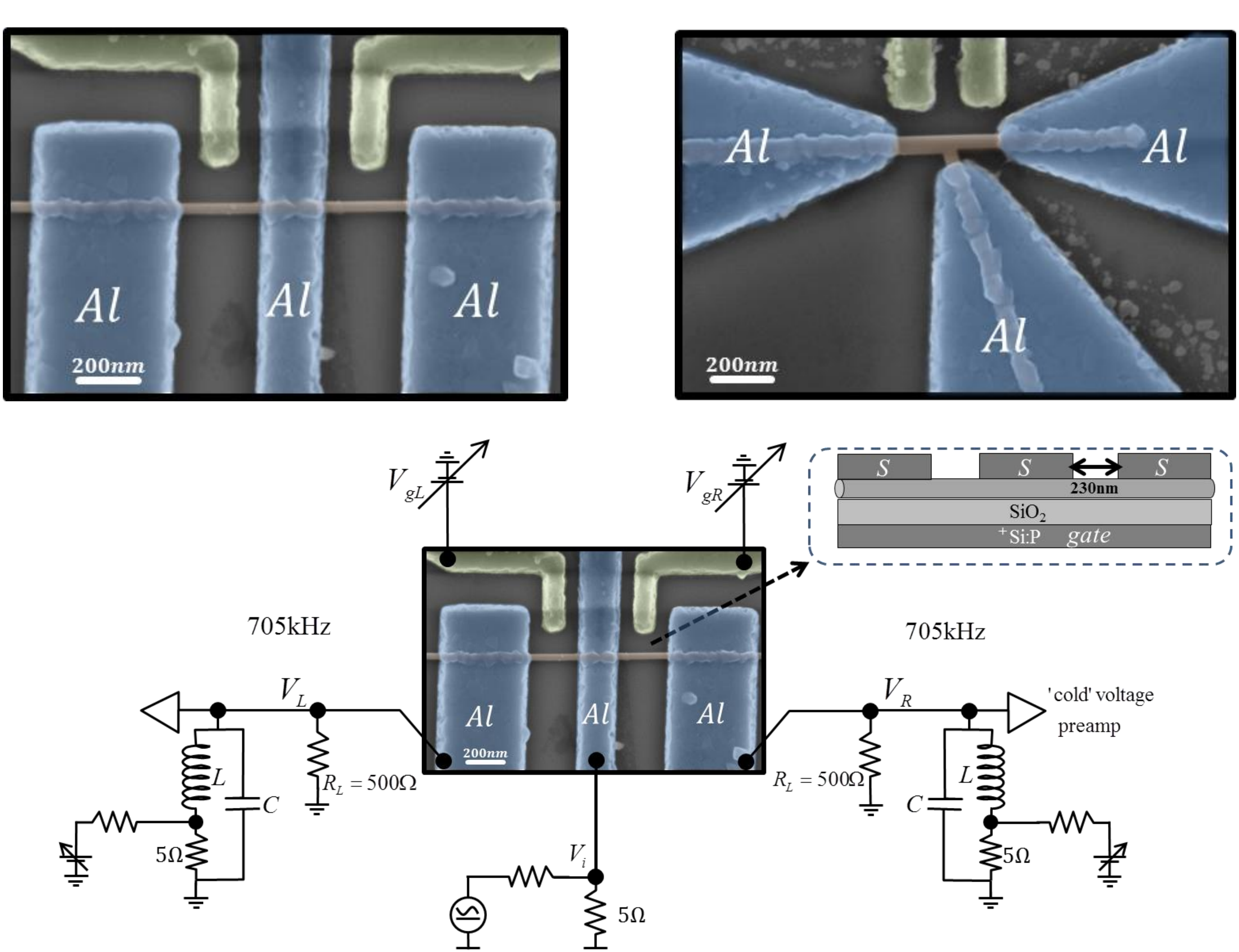
Can produce a coherent resonant state like the quartet state



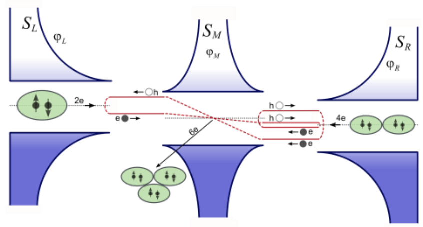
Device 1

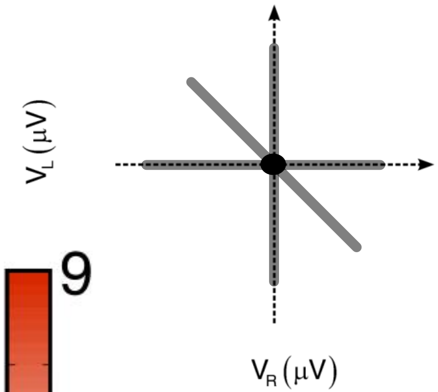
Device 2



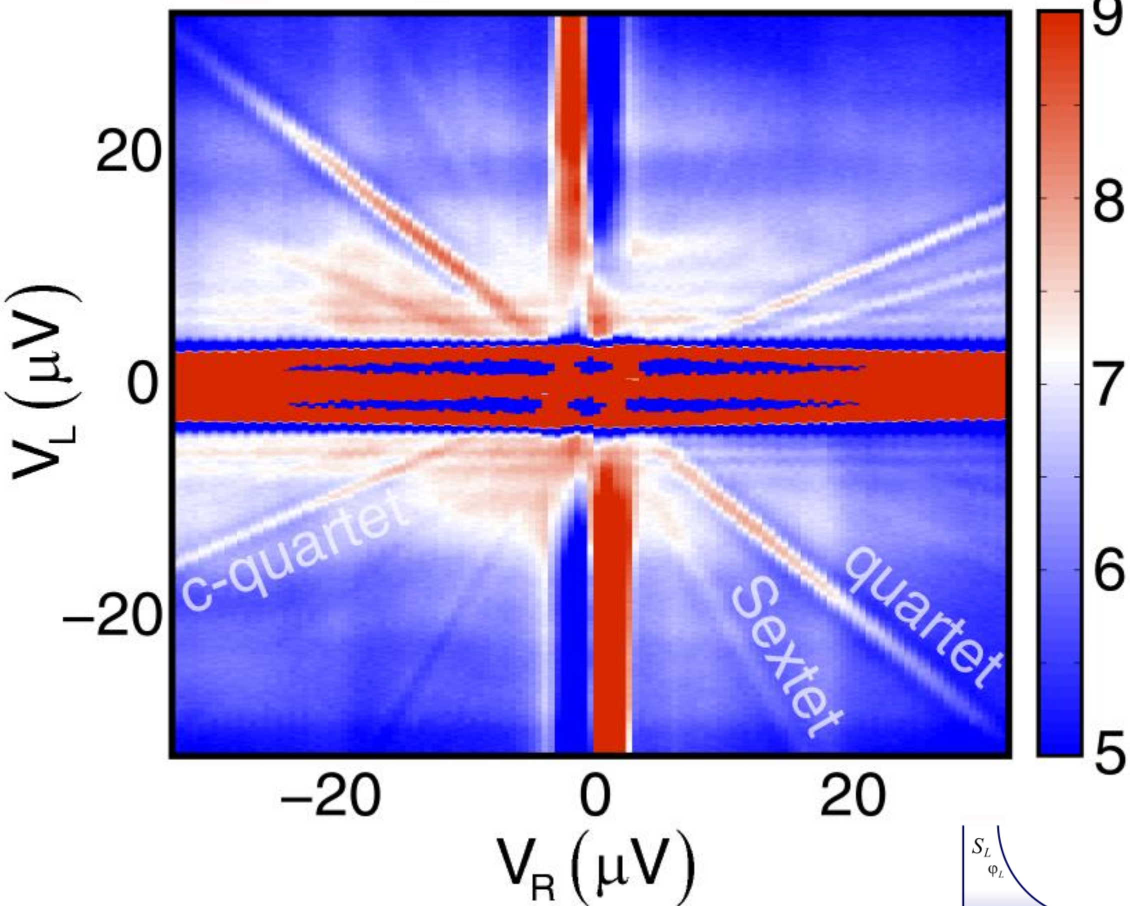


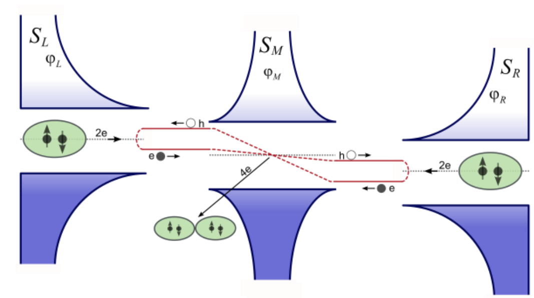
Al
Al
Al
200nm
Al
Al
Al
200nm
V_gL
V_gR
S
S
S
230nm
SiO2
+Si:P gate
705kHz
705kHz
V_L
V_R
'cold' voltage
preamp
Al
Al
Al
200nm
L
C
R_L = 500Ω
R_L = 500Ω
C
L
5Ω
5Ω
V_i
5Ω





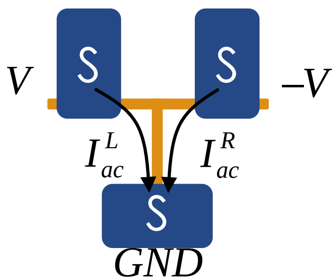
arXiv:1606.08436

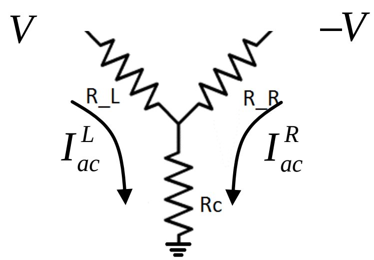


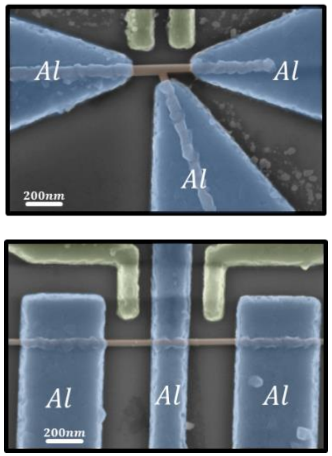


Alternative mechanisms

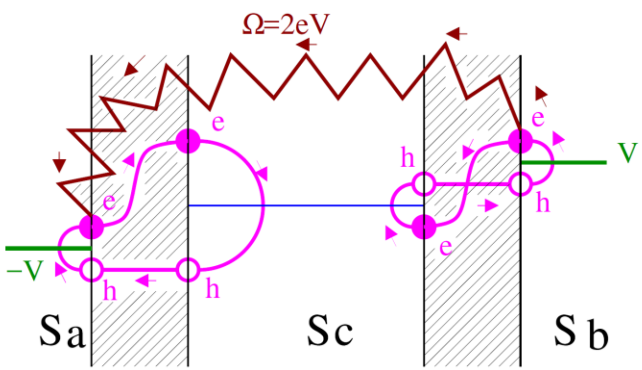
Down-mixing of two ac Josephson currents



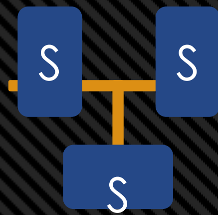




Synchronization of ac Josephson currents



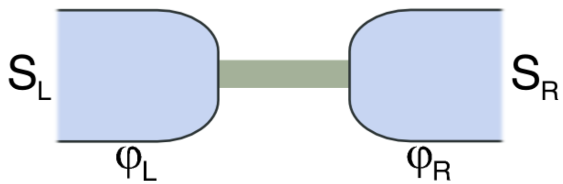
Can produce a coherent resonant state like the quartet state

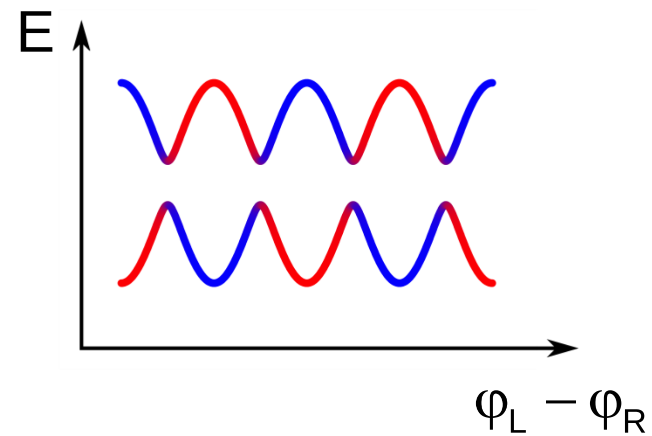


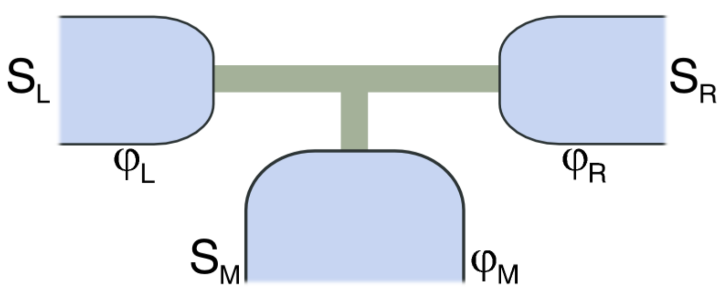
Cross correlation of current fluctuations

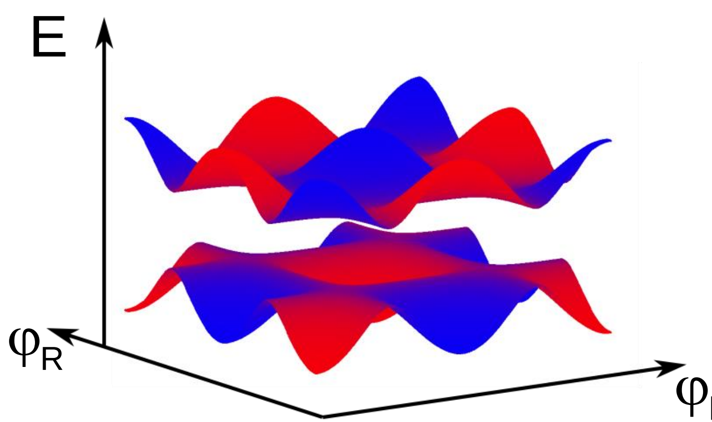
Can point to the existence of the quartet Andreev bound states

2D - Andreev bound state







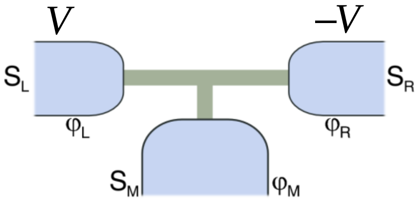


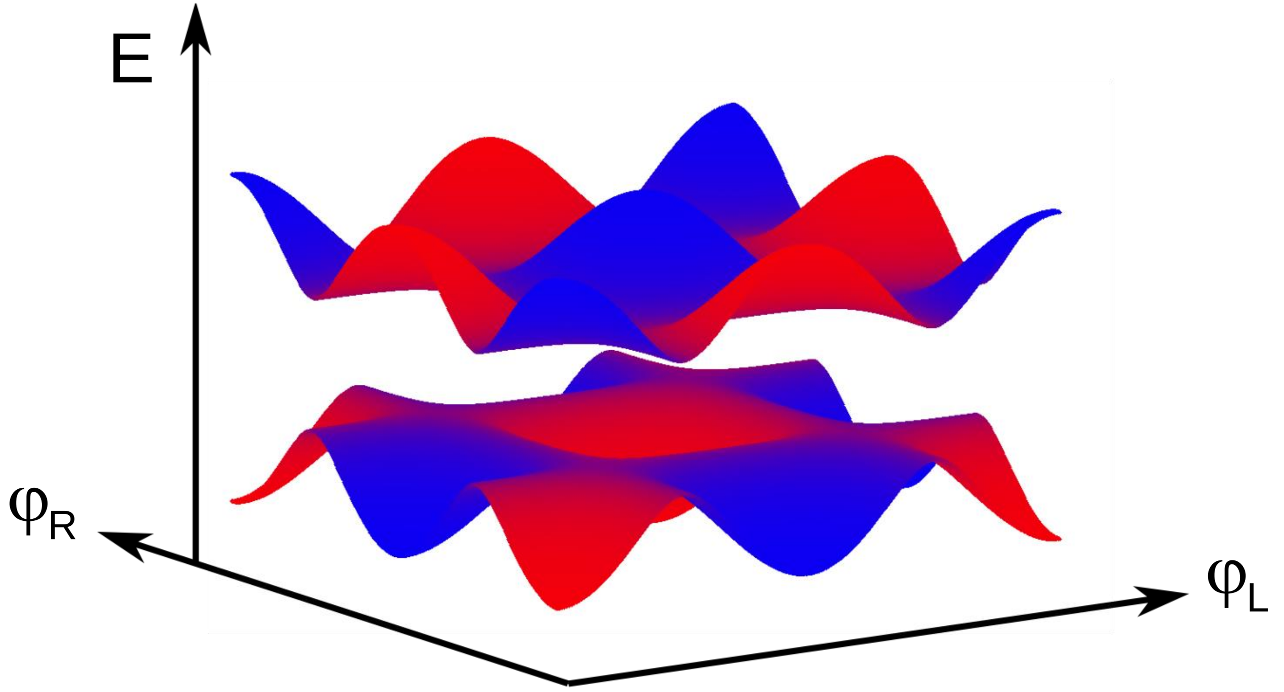
2D - Andreev bound state

$$\dot{\varphi}_L = +\frac{2e}{\hbar}V$$

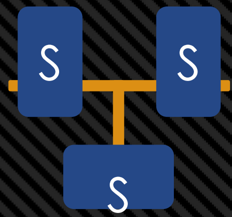
$$\dot{\varphi}_R = -\frac{2e}{\hbar}V$$

$$\begin{cases} \varphi_q = \varphi_L + \varphi_R \\ \tilde{\varphi}_q = \varphi_L - \varphi_R \end{cases}$$





2D - Andreev bound state



$$\dot{\varphi}_L = +\frac{2e}{\hbar}V$$

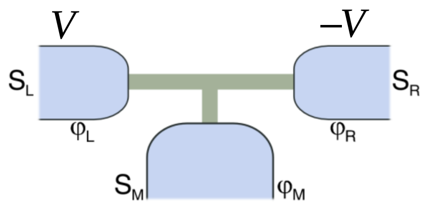
$$\dot{\varphi}_R = -\frac{2e}{\hbar}V$$

$$\begin{cases} \varphi_q = \varphi_L + \varphi_R \\ \tilde{\varphi}_q = \varphi_L - \varphi_R \end{cases}$$

$$\dot{\varphi}_q = 0 \qquad \dot{\tilde{\varphi}}_q = \frac{4e}{\hbar}V$$

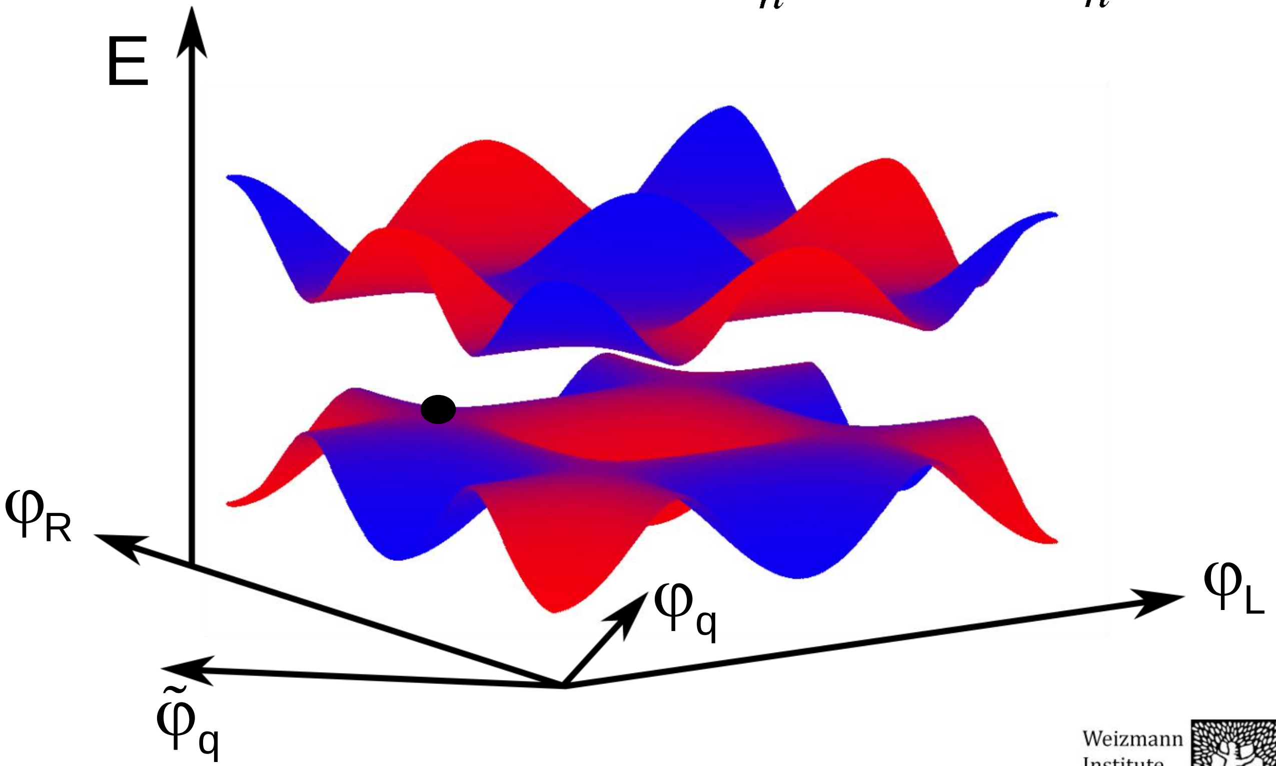
$$\boxed{\varphi_q = \text{const}}$$

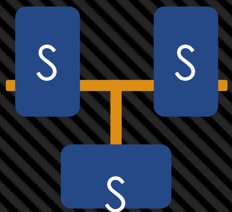
$$\tilde{\varphi}_q = \frac{4e}{\hbar}V \cdot t$$



$$\boxed{I_Q = -\frac{2e}{\hbar}\frac{\partial E}{\partial \varphi_q}}$$

Adiabatic limit





2D - Andreev bound state

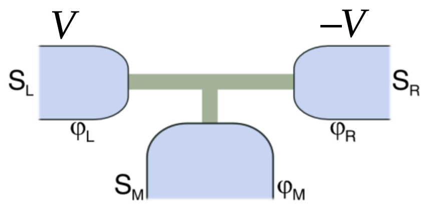
$$\dot{\varphi}_L = +\frac{2e}{\hbar}V$$

$$\dot{\varphi}_R = -\frac{2e}{\hbar}V$$

$$\begin{cases} \varphi_q = \varphi_L + \varphi_R \\ \tilde{\varphi}_q = \varphi_L - \varphi_R \end{cases}$$

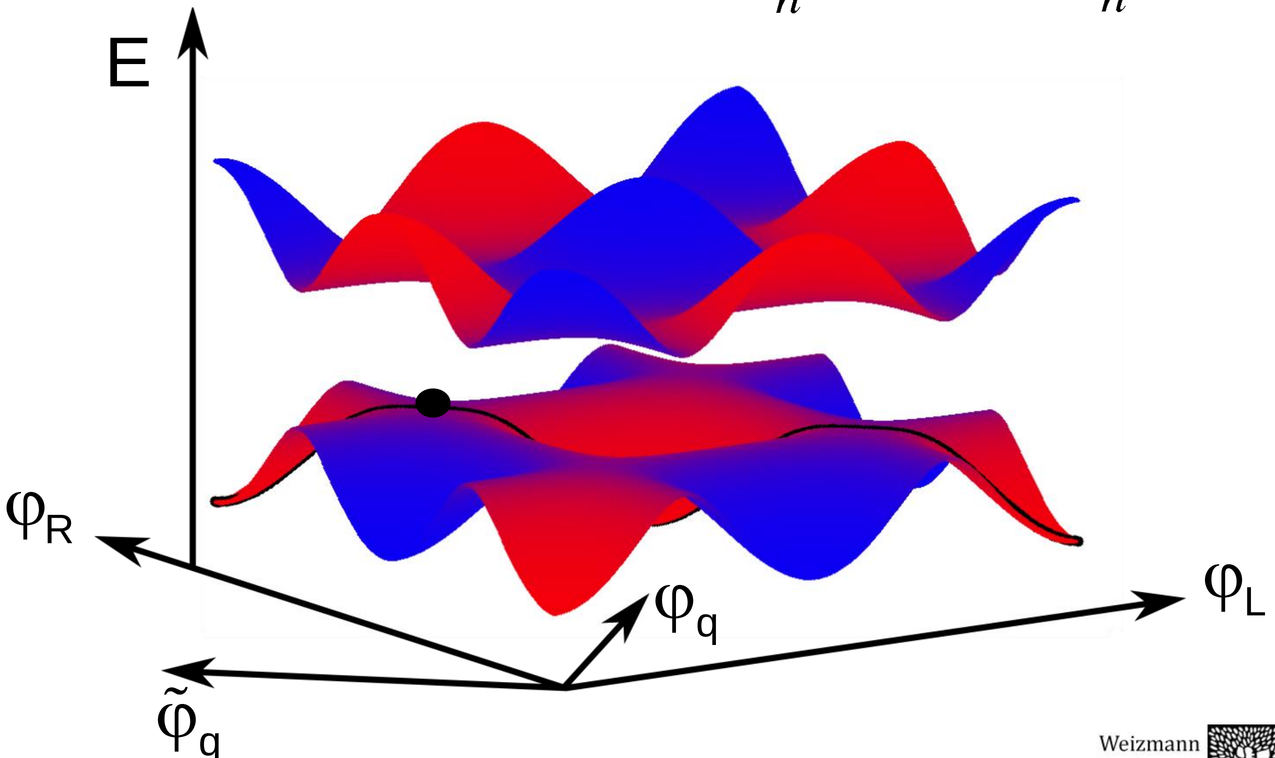
$$\dot{\varphi}_q = 0 \qquad \varphi_q = \text{const}$$

$$\dot{\tilde{\varphi}}_q = \frac{4e}{\hbar}V \qquad \tilde{\varphi}_q = \frac{4e}{\hbar}V \cdot t$$

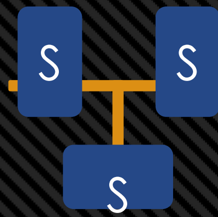


$$I_Q = -\frac{2e}{\hbar}\frac{\partial E}{\partial \varphi_q}$$

Adiabatic limit



Weizmann Institute of Science



2D - Andreev bound state

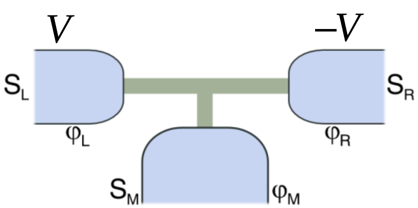
$$\dot{\varphi}_L = +\frac{2e}{\hbar}V$$

$$\dot{\varphi}_R = -\frac{2e}{\hbar}V$$

$$\begin{cases} \varphi_q = \varphi_L + \varphi_R \\ \tilde{\varphi}_q = \varphi_L - \varphi_R \end{cases}$$

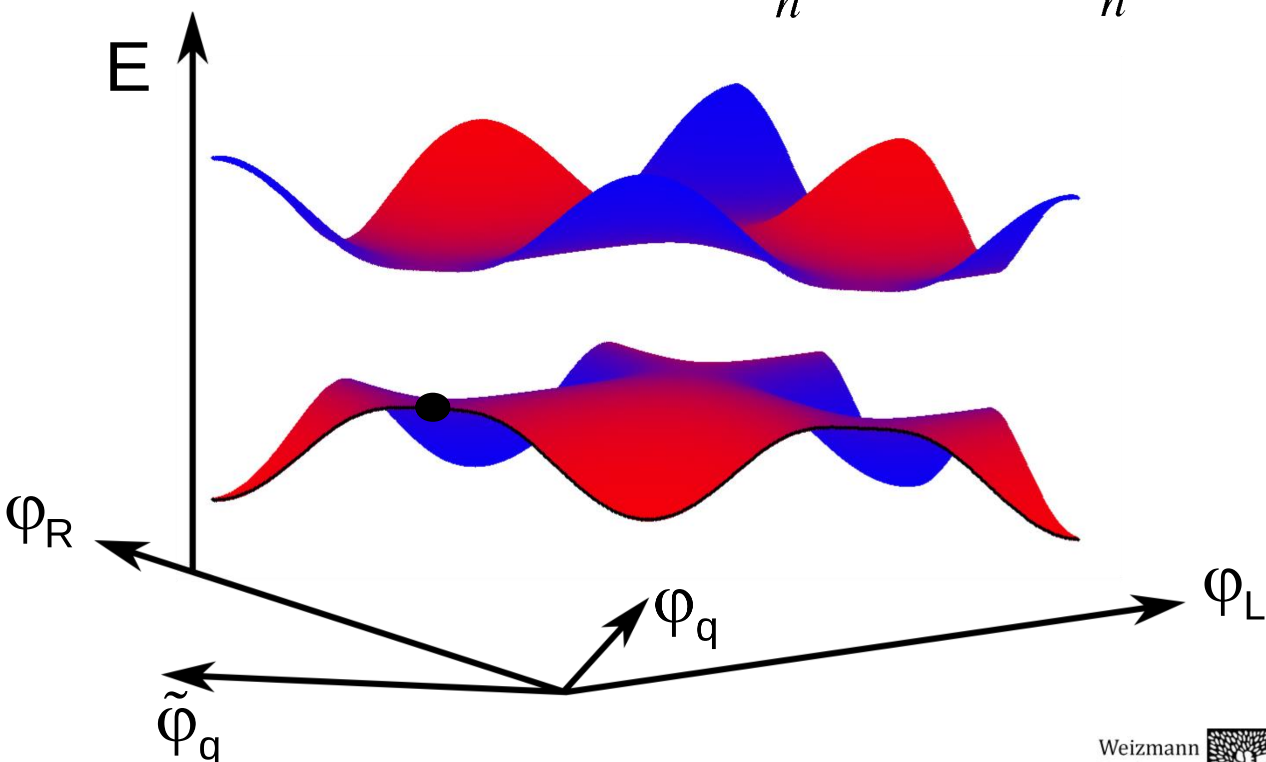
$$\dot{\varphi}_q = 0 \qquad \varphi_q = \text{const}$$

$$\dot{\tilde{\varphi}}_q = \frac{4e}{\hbar}V \qquad \tilde{\varphi}_q = \frac{4e}{\hbar}V \cdot t$$



$$I_Q = -\frac{2e}{\hbar}\frac{\partial E}{\partial \varphi_q}$$

Adiabatic limit



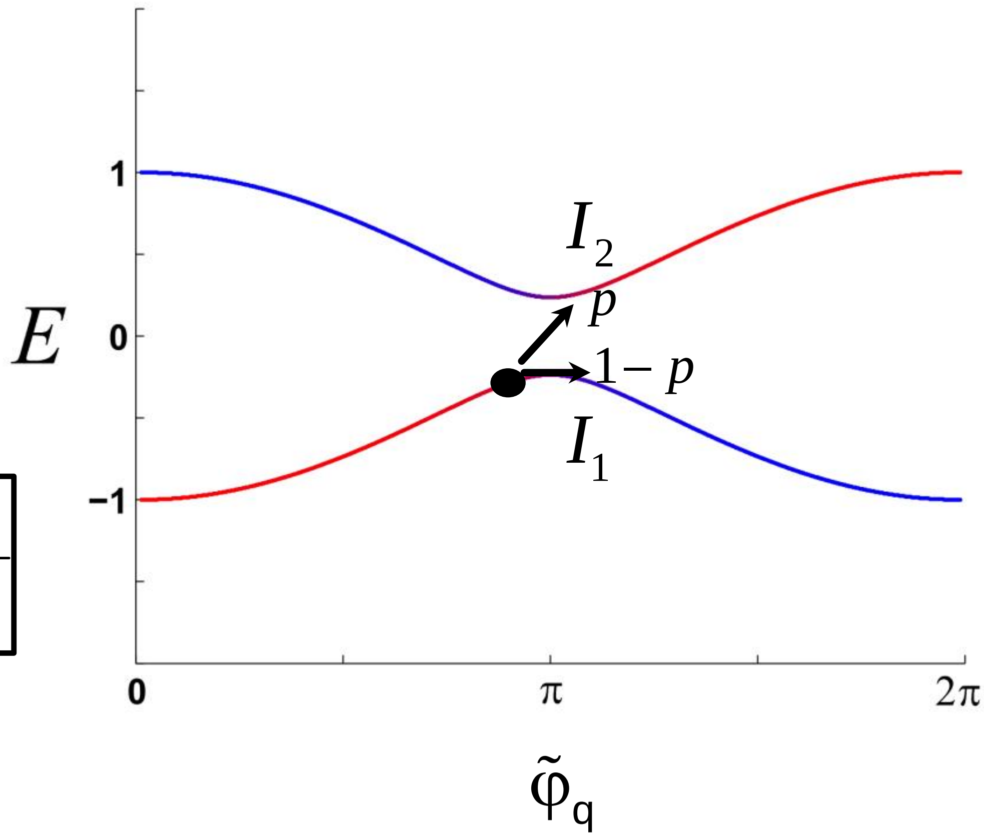
Weizmann Institute of Science

2D - Andreev bound state

$\varphi_q = \text{const}$

$\tilde{\varphi}_q = \frac{4e}{\hbar} V \cdot t$

$$I_Q = -\frac{2e}{\hbar}\frac{\partial E}{\partial \Delta\varphi_q}$$

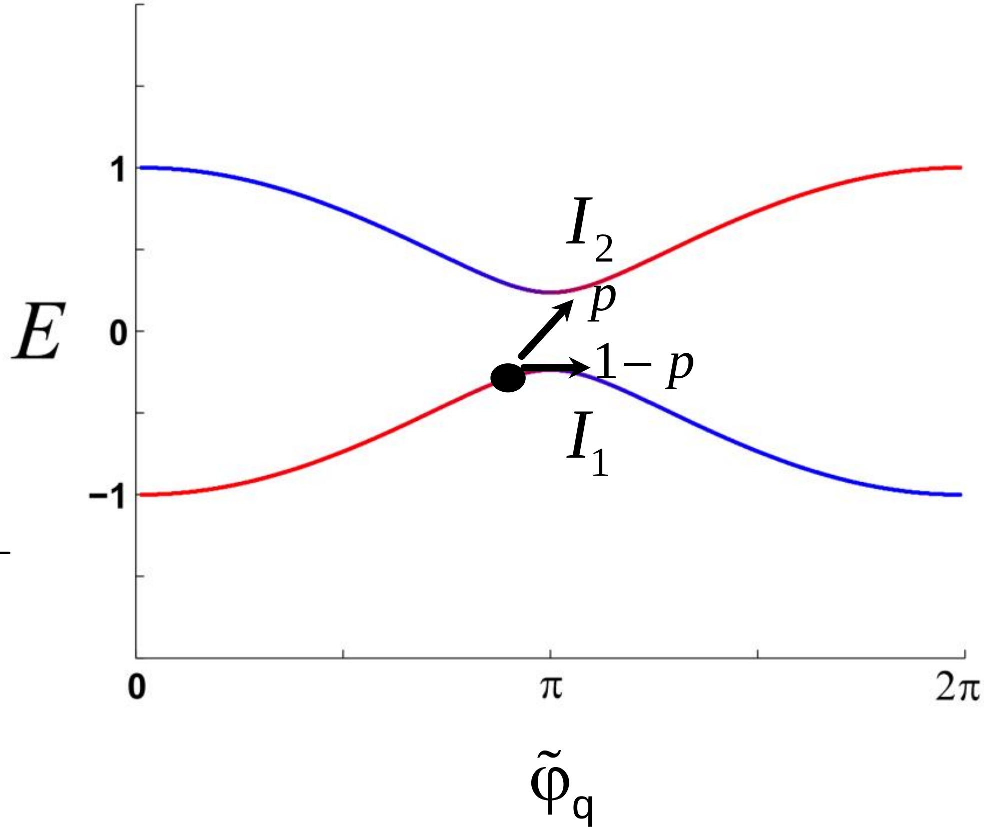


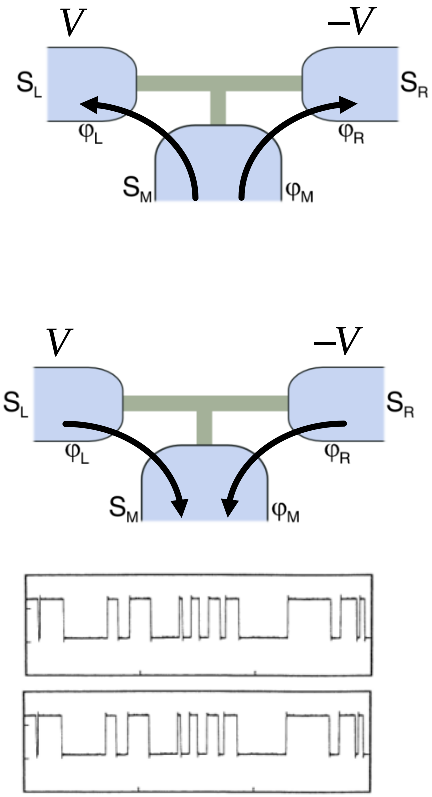
2D - Andreev bound state

$$\varphi_q = \text{const}$$

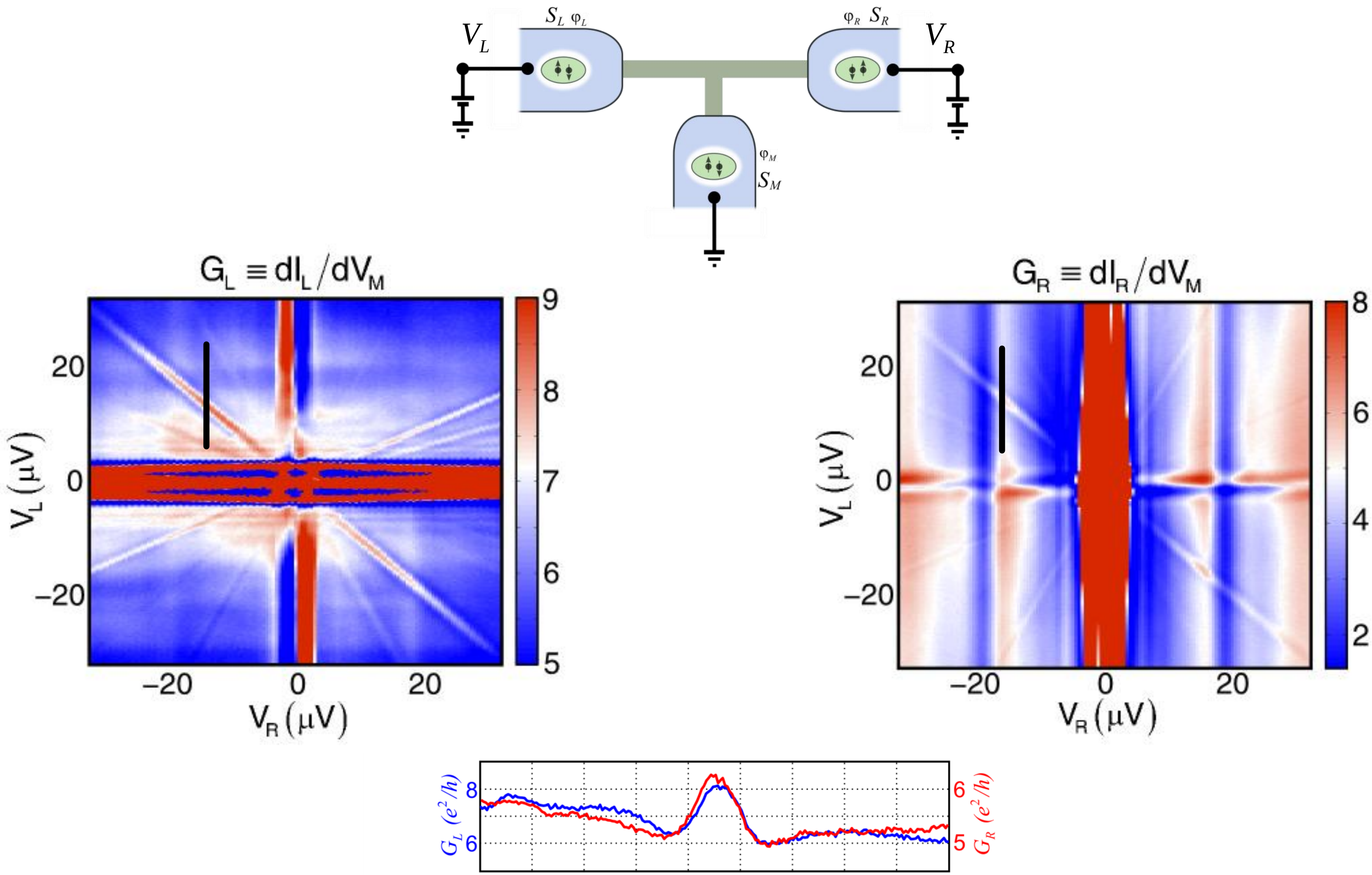
$$\tilde{\varphi}_q = \frac{4e}{\hbar} V \cdot t$$

$$I_Q = -\frac{2e}{\hbar} \frac{\partial E}{\partial \Delta\varphi_q}$$

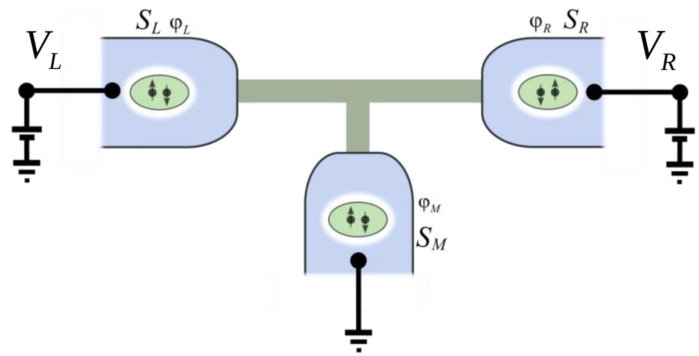


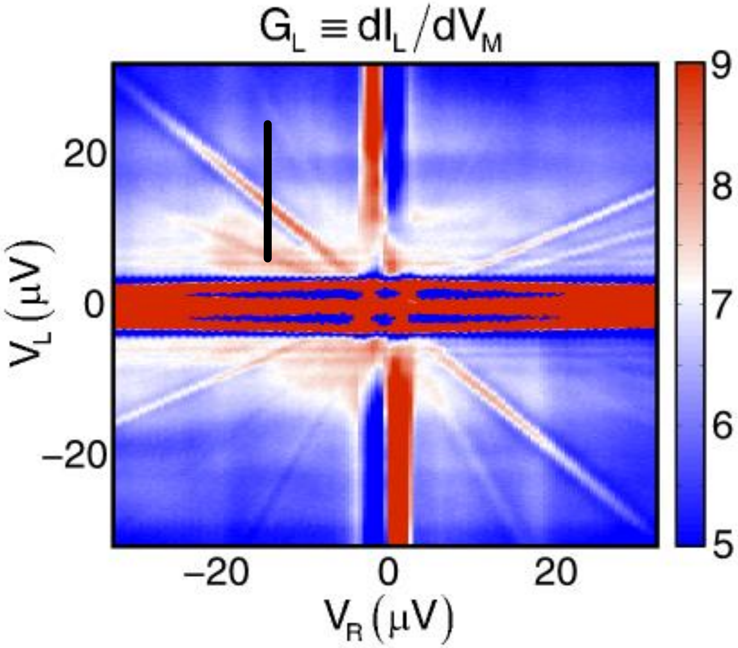


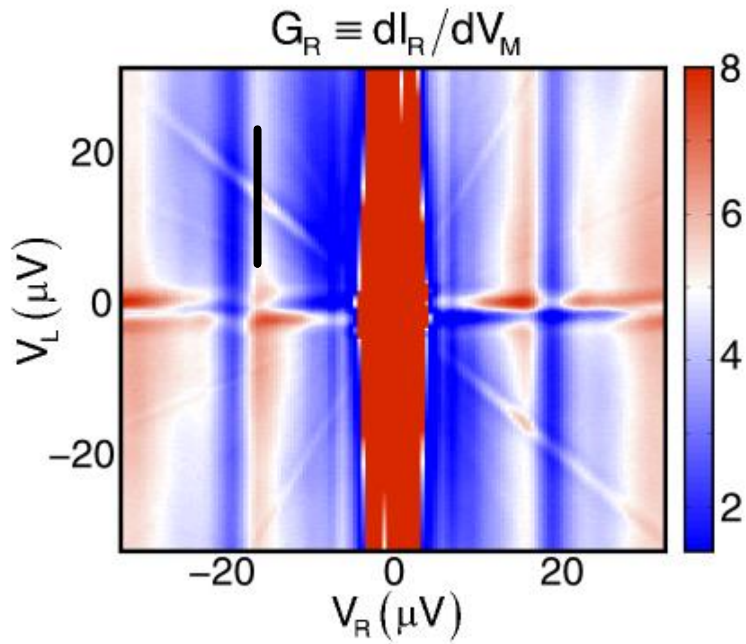
Positive cross-correlation

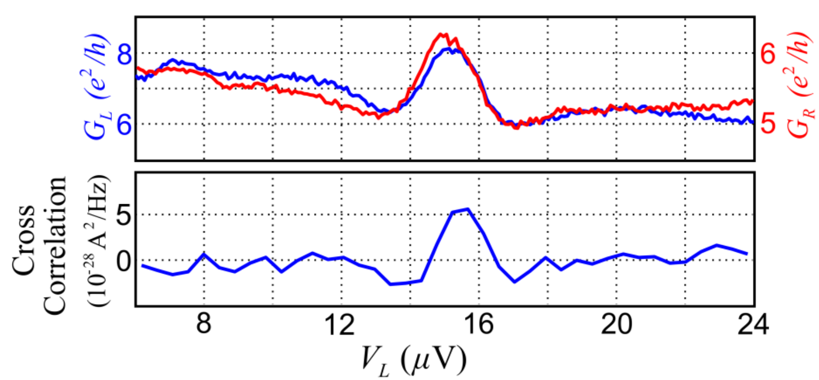


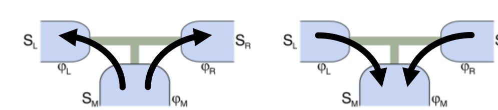
S_L φ_L
V_L
φ_R S_R
V_R
φ_M
S_M
G_L ≡ dI_L/dV_M
G_R ≡ dI_R/dV_M
V_L (μV)
V_R (μV)
−20
0
20
9
8
7
6
5
4
2
G_L (e²/h)
G_R (e²/h)



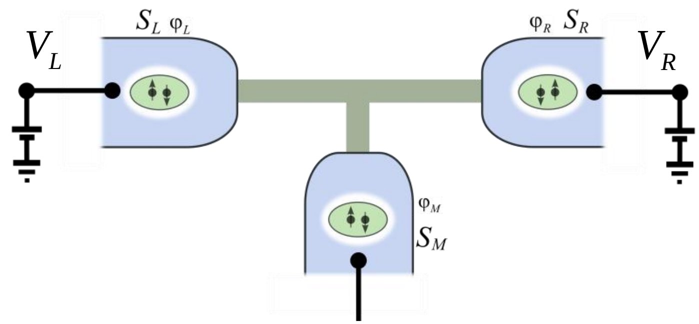


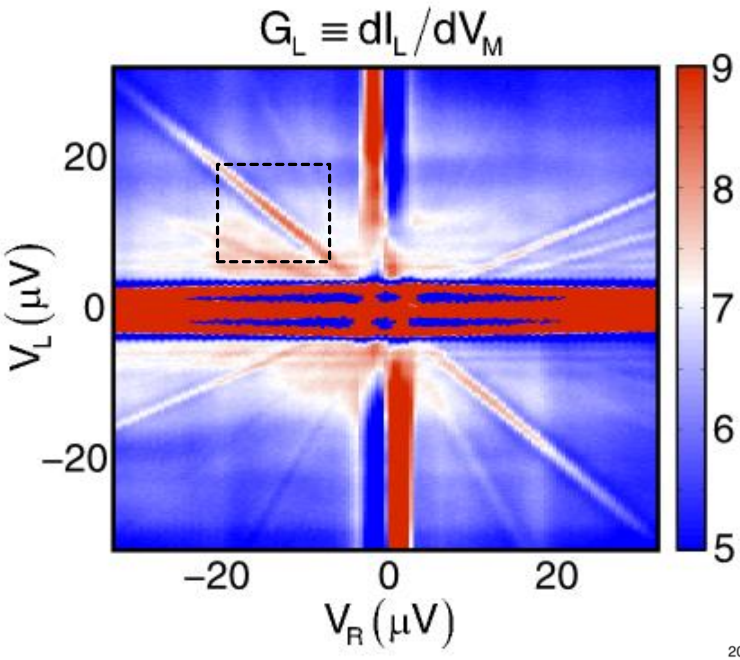


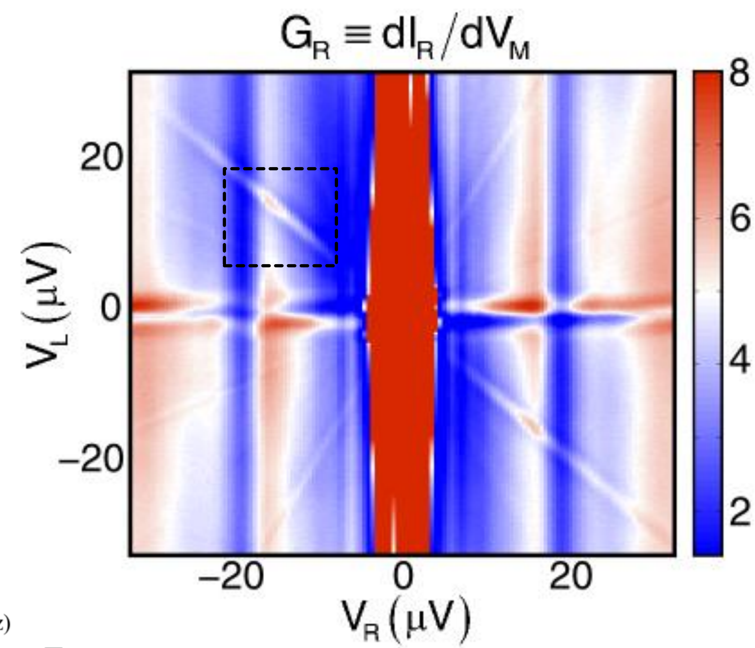


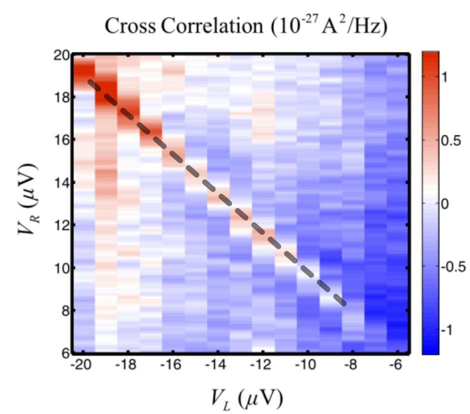


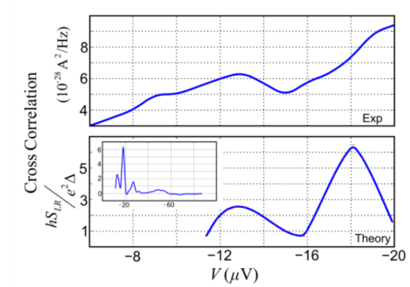
Positive cross-correlation







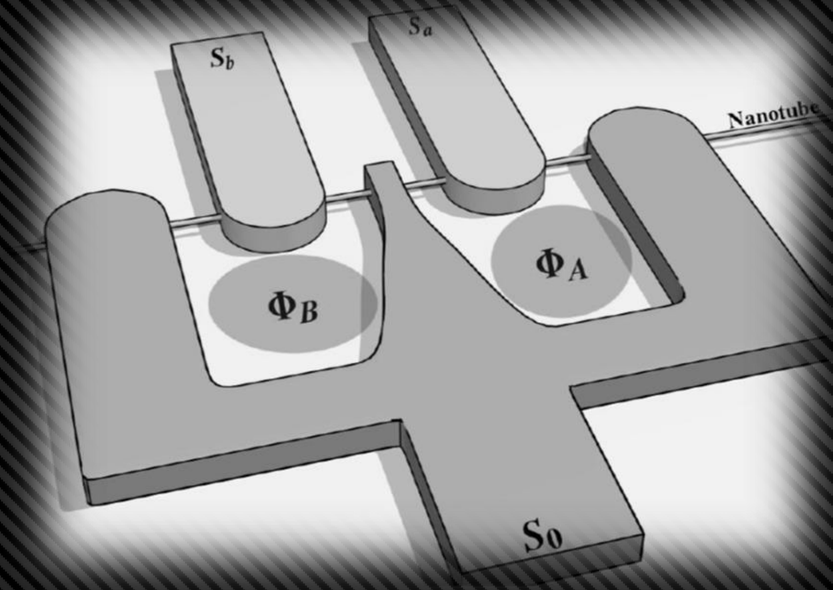




Non-monotonic behavior

Bi-SQUID

showing coherence



Phase dependence of the quartet current

Weizmann Institute of Science

Bi-Squid: show that the quartet current depends on phase

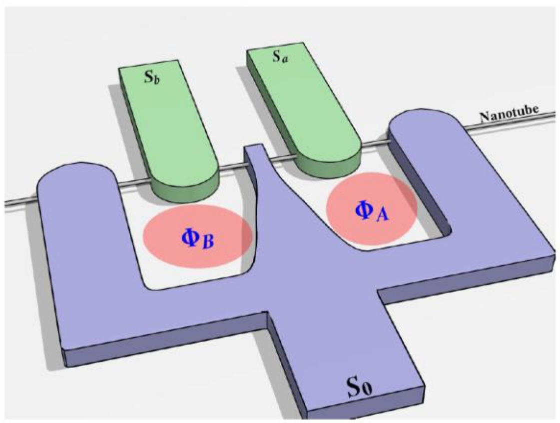
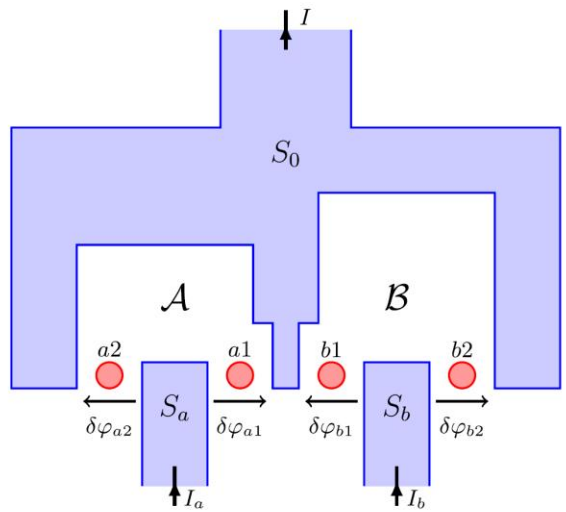


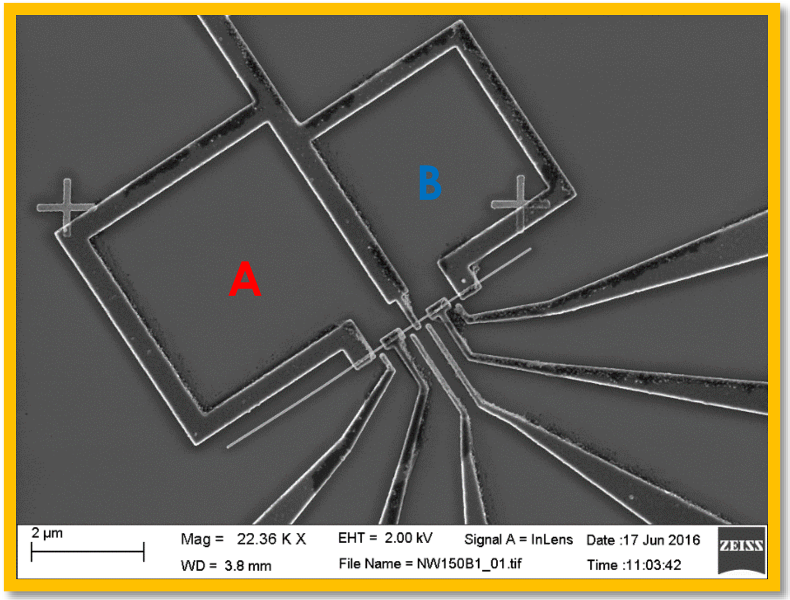
FIG. 1. (Color online) Artistic view of the biSQUID setup where a single nanotube or nanowire is contacted to three superconducting electrodes (all at the same potential), with magnetic field biasing.

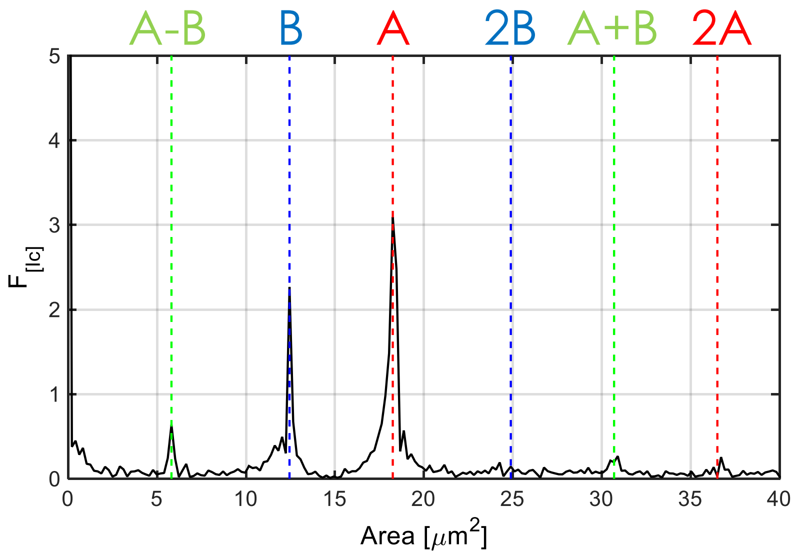


J. Rech, T. Jonckheere, T. Martin, B. Douc'ot, D. Feinberg, R. M´elin
PRB (2014)

$$
\begin{aligned}
I_c(\Phi_{\mathcal{A}}, \Phi_{\mathcal{B}}) = 2I_{\mathrm{J}}[&|\cos(\pi\tilde{\Phi}_{\mathcal{A}})| + |\cos(\pi\tilde{\Phi}_{\mathcal{B}})|] \\
&+ |I_{\mathrm{Q}}||\sin(\pi\tilde{\Phi}_{\mathcal{A}} - \pi\tilde{\Phi}_{\mathcal{B}})| \\
&+ |I_{\mathrm{PC}}||\sin(\pi\tilde{\Phi}_{\mathcal{A}} + \pi\tilde{\Phi}_{\mathcal{B}})|.
\end{aligned}
$$

Bi-Squid: show that the quartet current depends on phase





$$
\begin{aligned}
I_c(\Phi_{\mathcal{A}},\Phi_{\mathcal{B}}) = 2I_{\mathrm{J}}[|\cos(\pi\tilde{\Phi}_{\mathcal{A}})| + |\cos(\pi\tilde{\Phi}_{\mathcal{B}})|] \\
+ |I_{\mathrm{Q}}||\sin(\pi\tilde{\Phi}_{\mathcal{A}} - \pi\tilde{\Phi}_{\mathcal{B}})| \\
+ |I_{\mathrm{PC}}||\sin(\pi\tilde{\Phi}_{\mathcal{A}} + \pi\tilde{\Phi}_{\mathcal{B}})|.
\end{aligned}
$$

Thank You!

GDR physique mésoscopique, Aussois