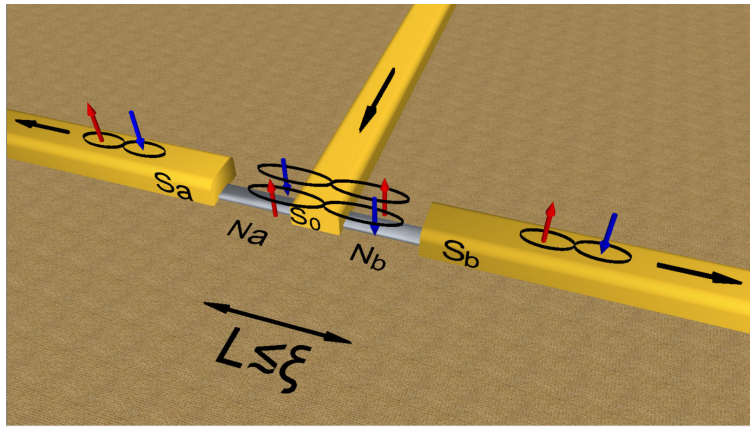
MULTI-CONDENSATE SUPERFLUID MOTION IN JOSEPHSON JUNCTIONS



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OUTLOOK

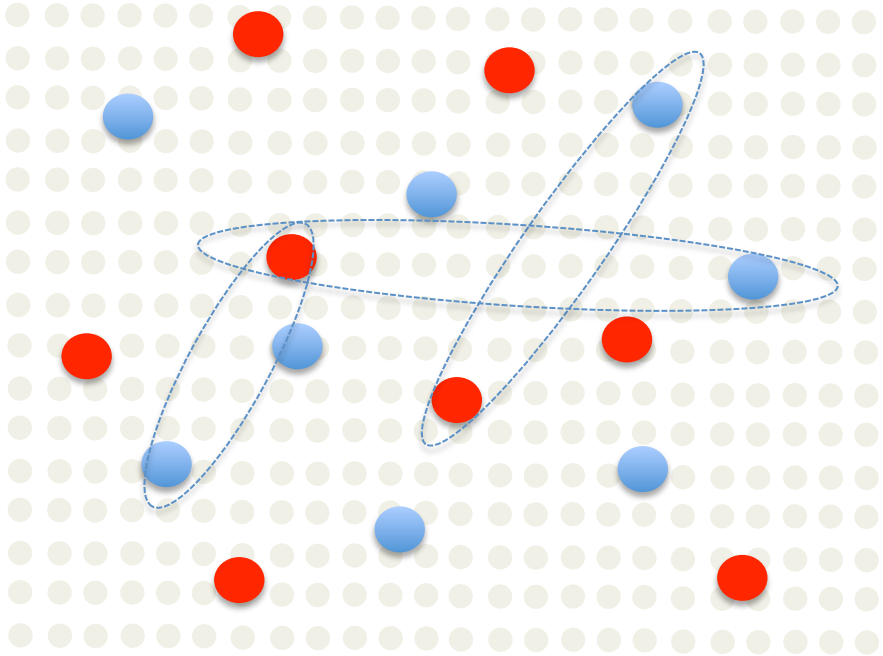
1. Basics of SIS and SNS Josephson junctions

2. Multiterminal junctions

- Equilibrium
- Commensurate biases : quartets and more

3. Towards BEC ?

BCS superconductors : large overlapping Cooper pairs

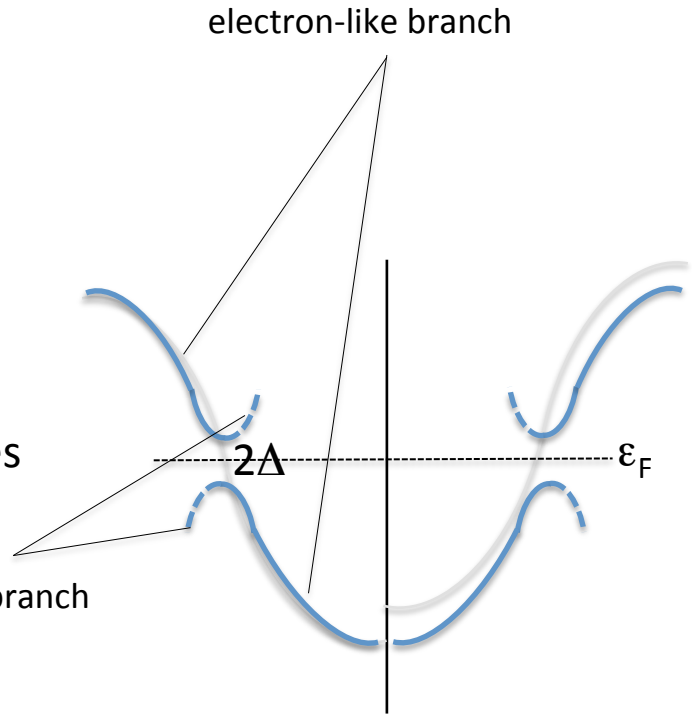


$\xi / a_{latt} >> 1$

Remaining interactions negligible (Fermi liquid)

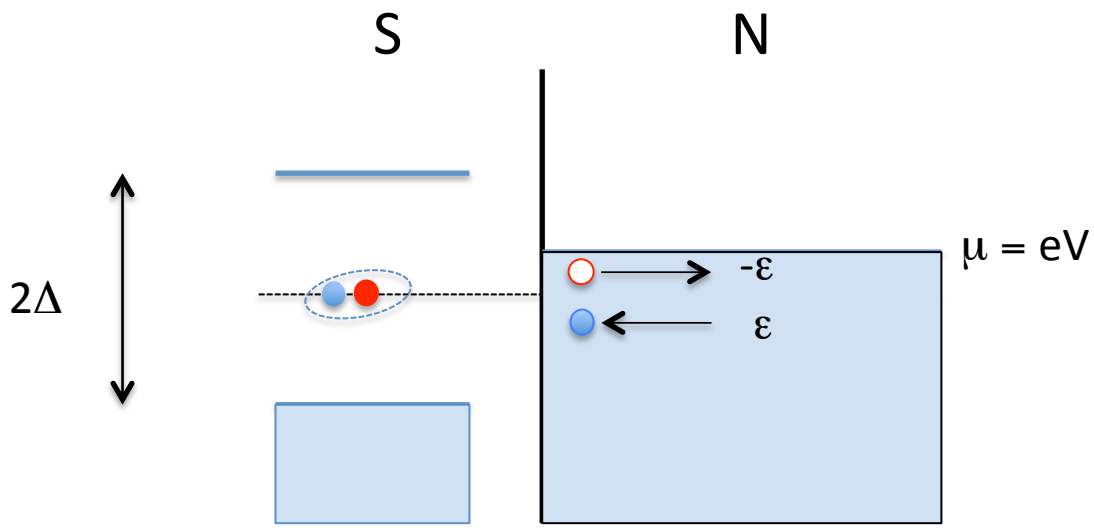
Excitation spectrum : Fermionic Bogoliubov quasiparticles

$$\gamma_{ks} = u_k\, c_{ks} + (-1)^s\, v_k\, c^{+}_{ks}$$



Transport at a Superconductor- Normal metal contact

Andreev reflection of spin-up electrons into spin-down holes



Josephson junction : tunnel barrier or metallic

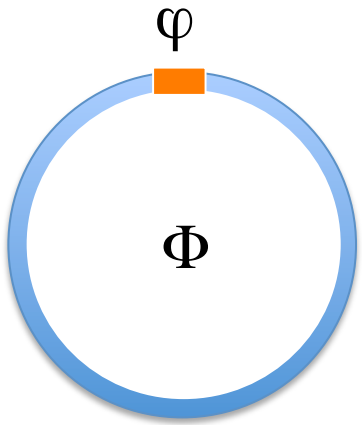
DC Josephson effect at equilibrium

$E = E_J (\varphi_1 - \varphi_2)$, period 2π

$I = (2e/\hbar)\,(dE/d\varphi)$, $\quad \varphi = \varphi_1 - \varphi_2$

if φ forced by a magnetic flux

Equilibrium state



$[\, N, \varphi \,] = i$

Voltage biased junction

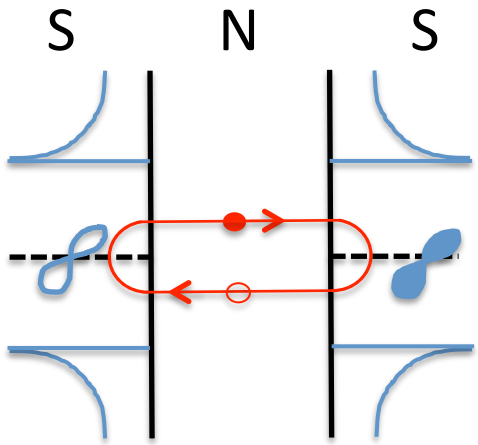
$d\varphi/dt = 2eV/\hbar \rightarrow \varphi(t) = \varphi_0 + \omega_J t$

adiabatic $\rightarrow I = I_c \sin(\varphi_0 + \omega_J t)$

S-N-S contact

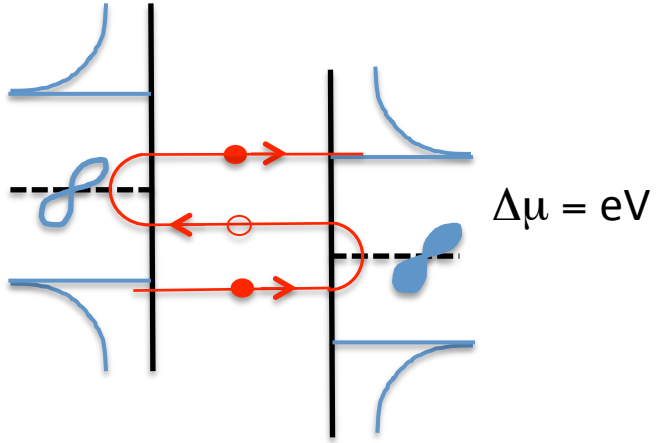
At equilibrium

Andreev bound states in the gap
(trapped Bogoliubov quasiparticles)

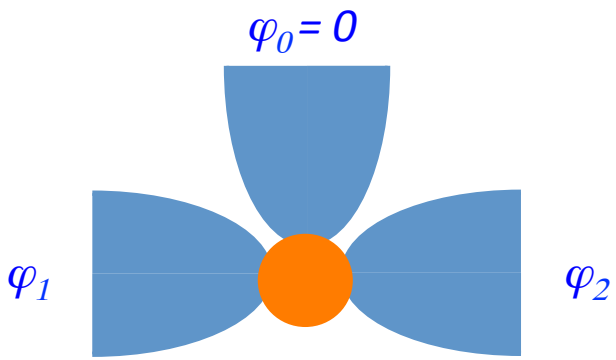


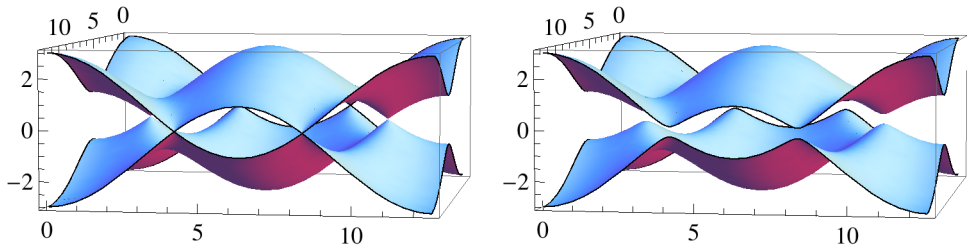
Voltage-biased junction

Multiple Andreev reflections :
subgap transport



N – terminal junctions : equilibrium





Andreev bound state dispersion
in two (phase) dimensions

one level in junction : gapped vs ungapped

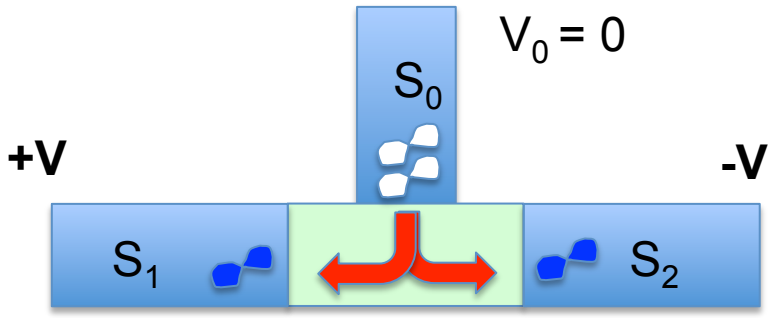
(Akhmerov et al., Padurariu et al.)

N > 3 terminals -> Topological properties *(Riwar, Meyer, Houzet, Nazarov 2016)*

A platform to simulate topological materials built in the Cooper pair number space $| N_i >$

$$[N_i , \varphi_i] = i$$

Biased 3-terminal junctions : quartets and multipair transport



$$\varphi_1(t) = \varphi_{10} + \omega_J t$$

$$\varphi_2(t) = \varphi_{20} - \omega_J t$$

$$\omega_J = 2eV/\hbar$$

$$\varphi_1(t) + \varphi_2(t) = \varphi_{10} + \varphi_{20} - 2\varphi_{00} = \varphi_Q$$

3 – body phase combination

Lowest harmonic, dc current $I_1 = I_2 = I_q \sin[\varphi_1(t) + \varphi_2(t)] = I_q \sin\varphi_Q$

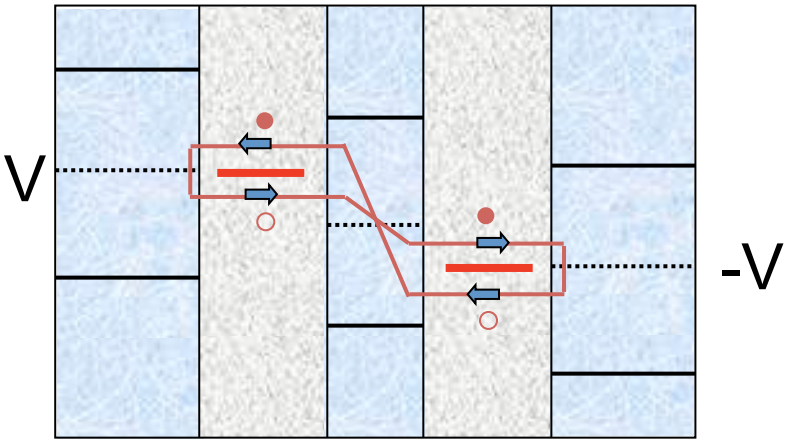
Quartet current made of 2 correlated pairs : energy-conserving process

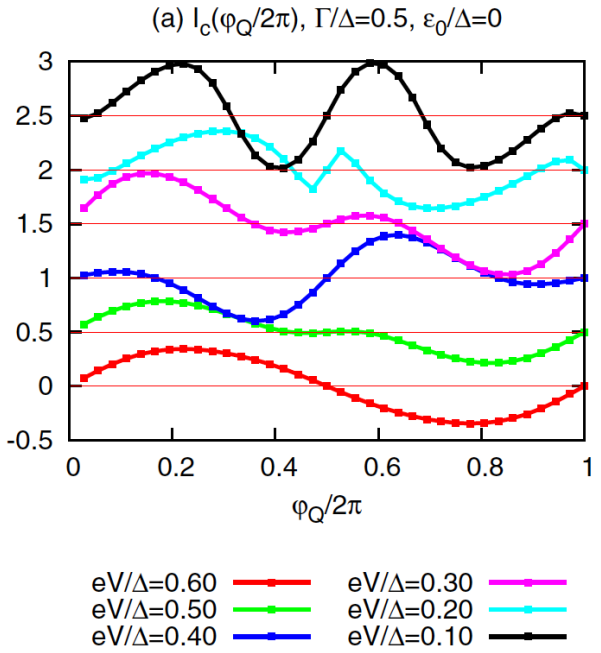
(Generalizes to higher order : $n V_1 + m V_2 = 0 \rightarrow$ **n+m pairs altogether)**

Tripartite number entanglement :

$$|\Psi\rangle = \sum A_n e^{in\varphi_Q} |N_0 - 2n\rangle_0 |N_1 + n\rangle_1 |N_2 + n\rangle_2$$

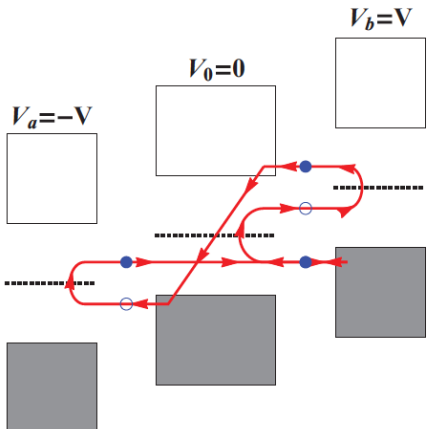
Quartet current



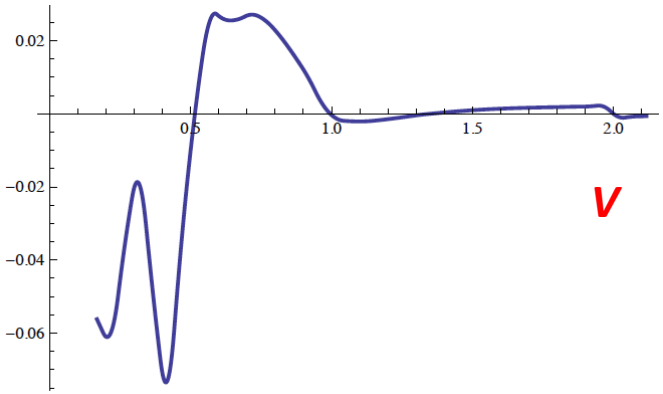


Four coherent Andreev reflections, 0-π transition with the voltage V

Phase-dependent multiple Andreev reflections (quasiparticle current)



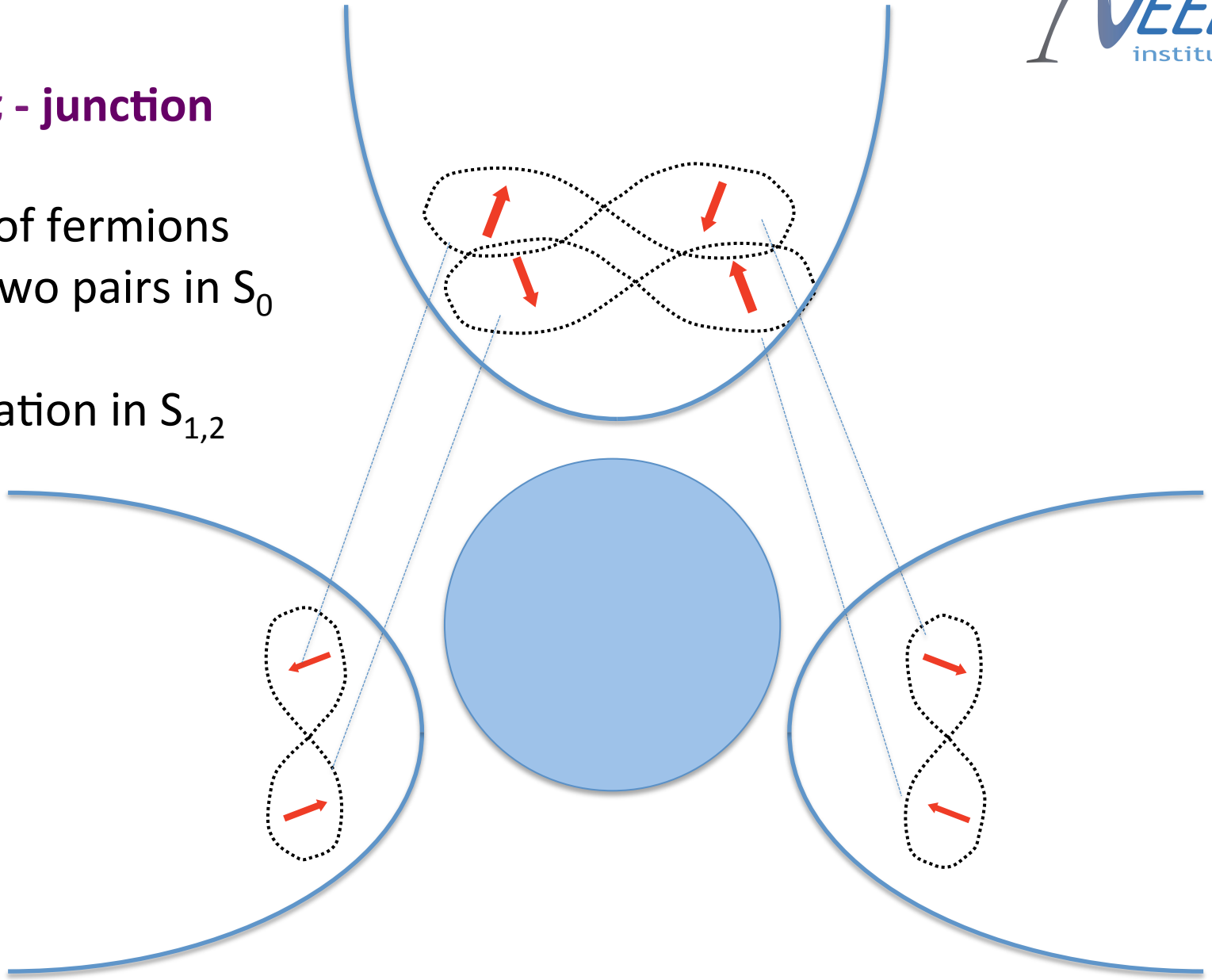
Quartet current (fixed φ_Q)



Quartet π - junction

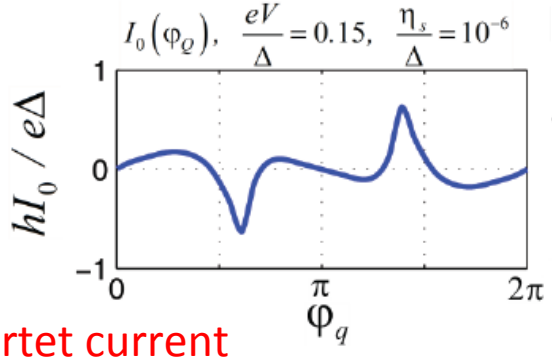
Exchange of fermions between two pairs in S_0

Recombination in $S_{1,2}$

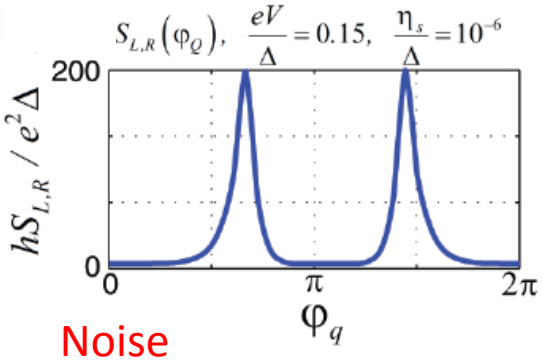


More theory : a double dot model (R. Mélin)

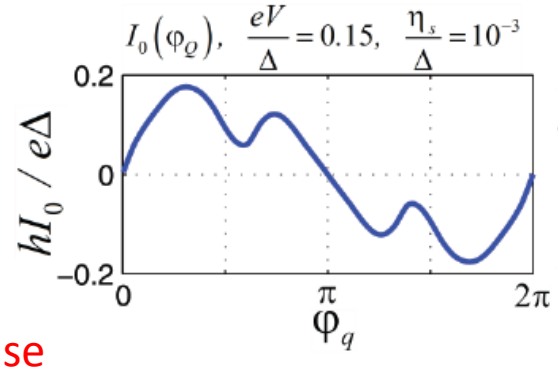
Quartet current



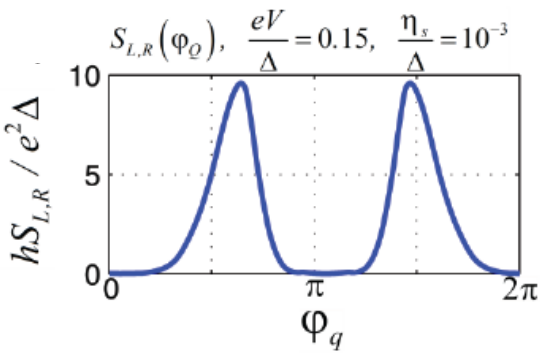
Noise



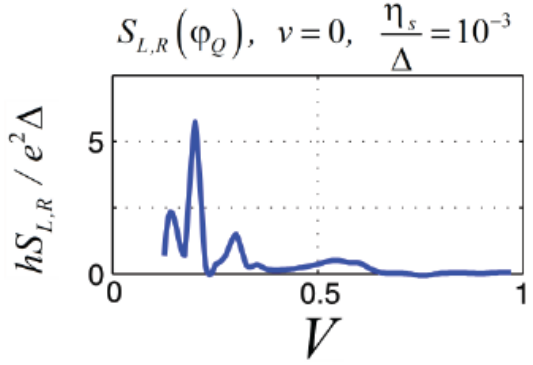
Quartet current



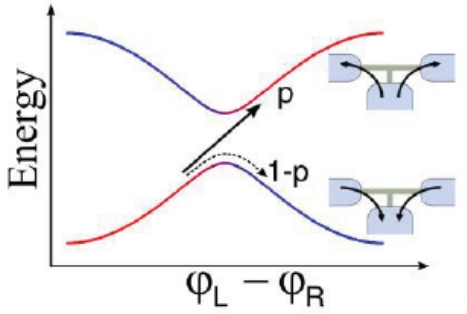
Noise



Noise



Strong dependence on the Dynes parameter !

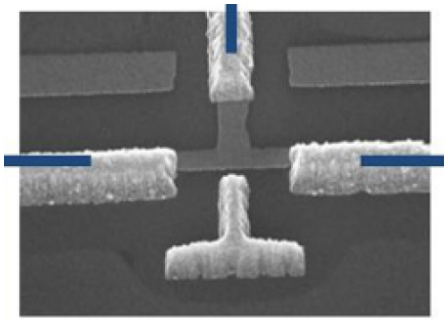


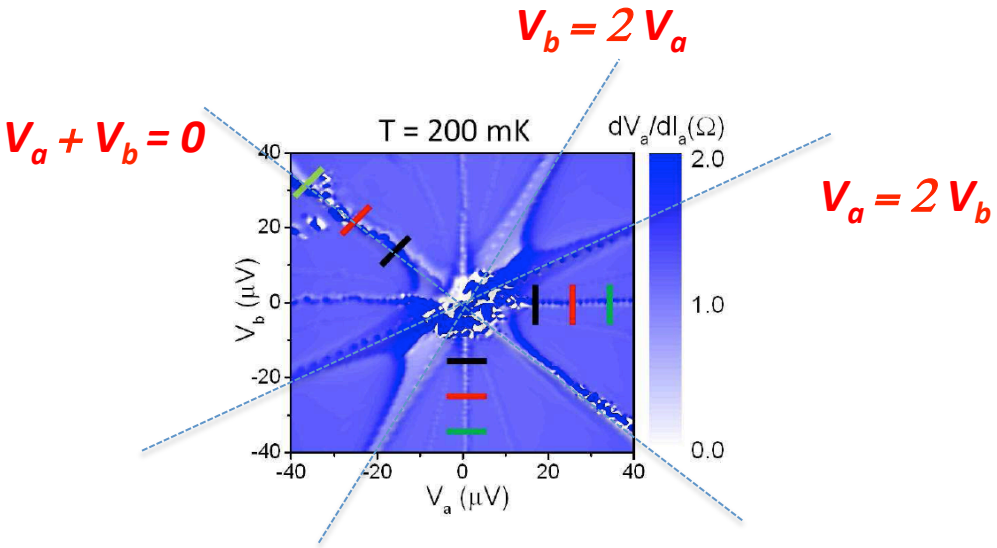
Nonadiabatic transitions
between Andreev quasi-bound states

EXPERIMENT 1 : *Pfeffer, Lefloch, Duvauchelle, Courtois, PRB 2014 (Grenoble)*

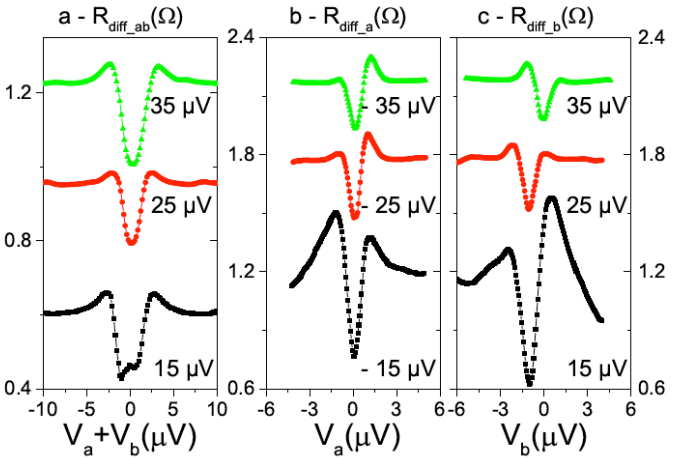
Al-Cu diffusive long junctions

$E_{Th} < eV << \Delta$



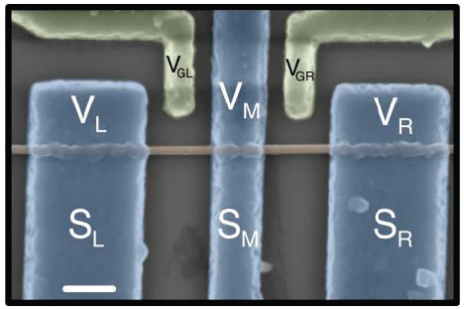


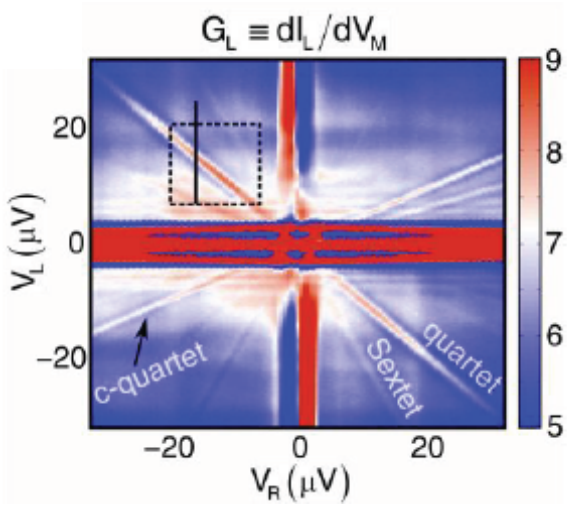
Quartet dc signatures



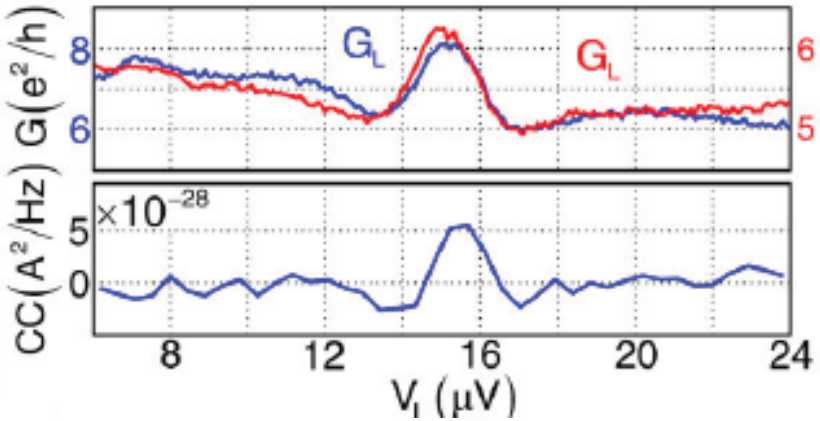
EXPERIMENT 2 : *Cohen, Ronen, Heiblum, Shtrikman 2016 (Weizmann)*

Al - InSb nanowires ***eV << Δ < E_{th}***

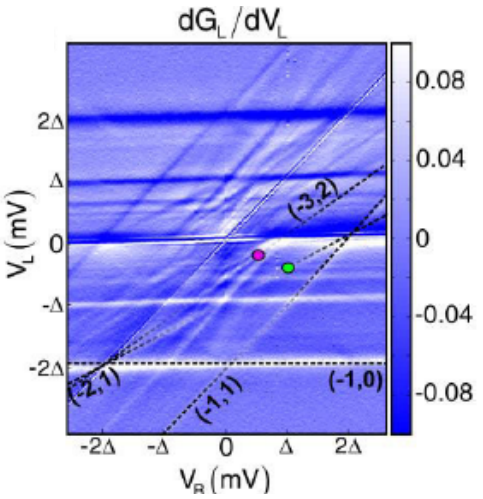




Large and positive cross-correlation noise



Nonlocal MAR

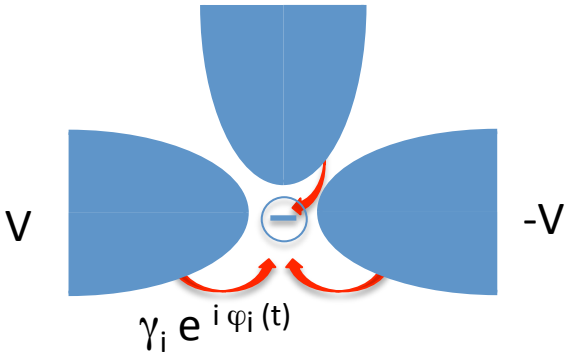


Towards BEC ... (prospective part)

An infinite gap model :

Single dot level, non-interacting
Equivalent to hard-core bosons

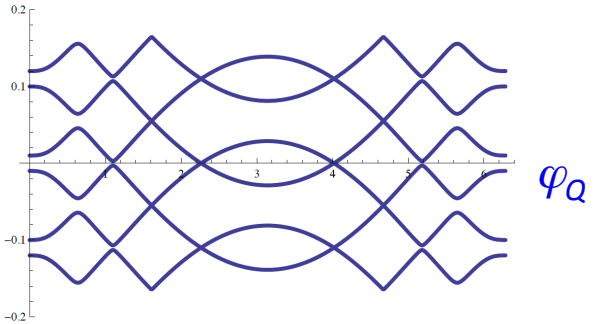
states | 0 >, | ↑↓ >



mean field, no interactions in the reservoirs

$$H = \varepsilon_0\, b^{+} b \;+ \sum_i \gamma_i\, e^{\,i\,\varphi_i\,(t)} \;+ \text{h. c.}$$

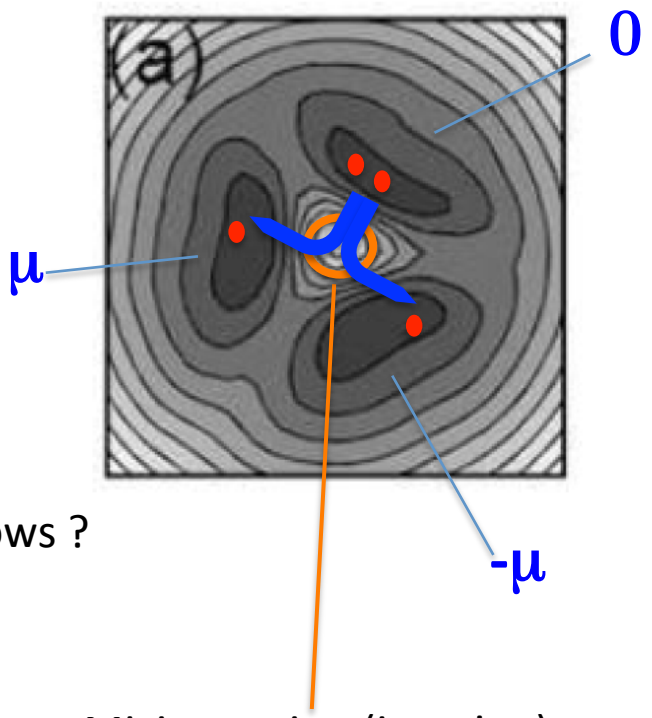
Floquet solution $E_{Fl,n\pm}(\varphi_Q)$



Current in state | 0, - > : generalization of the Josephson relation

$$< I > = (2e/\hbar)\, d\, E_{Fl} / d\, \varphi_Q$$

Multi-BEC condensates : some directions



- **Multi-boson superfluidity in tri-condensates**

  Fermionic BEC : analogous to BCS superconductors ?

  Bosonic BEC : what ingredient to correlate 2 bosonic flows ?

Role of interactions (in the reservoirs, in the junction..) ?

Detection of 3-body phase coherence

- **Simulation of topological lattices by multi-condensates**

  Realization of edge states ?

  Detection of topological transitions

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Yu. Ronen (Rehovot, Weizmann)
Y. Cohen (Rehovot, Weizmann)
M. Heiblum (Rehovot, Weizmann)
H. Shtrikman (Rehovot, Weizmann)
J-H. Kang (Rehovot, Weizmann)

Freyn et al. PRL 2011
Jonckheere et al. PRB 2013
Mélin et al. PRB 2016