Time-resolved Andreev states in superconducting hybrid structures

Tadeusz DOMAŃSKI

M. Curie-Skłodowska Univ.

IFM PAN Poznań **5 November 2021**

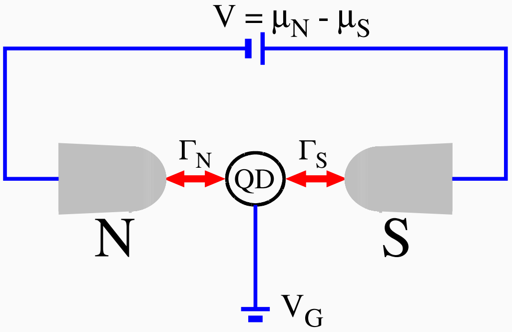
Superconducting nanostructures

Superconducting nanostructures

a few examples ...

1. ANDREEV-TYPE JUNCTION

Normal metal (N) - Quantum Dot (QD) - Superconductor (S)



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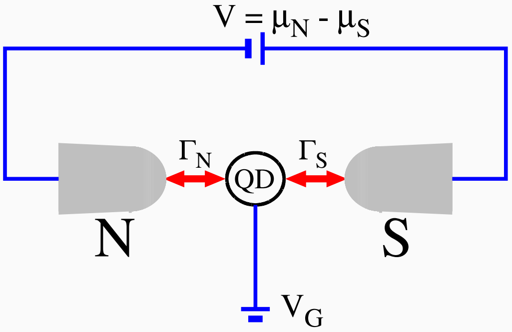
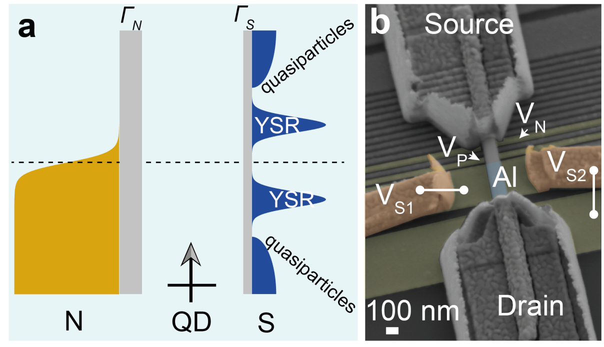


This is particular version of single-electron-transistor (SET) which operates on the Andreev (electron-to-hole) scattering mechanism.

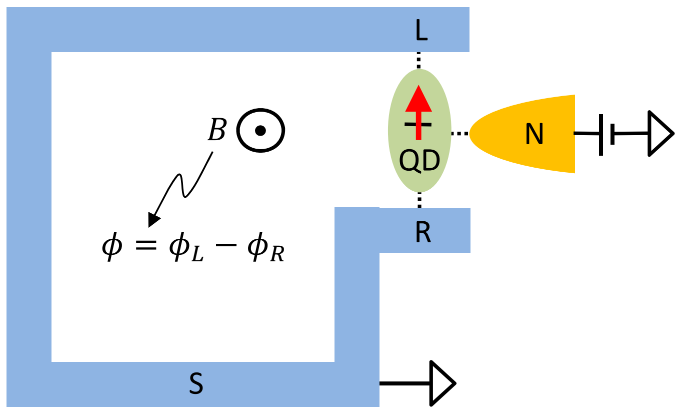
Example of the recent empirical realization



J. Estrada Saldaña, A. Vekris, V. Sosnovtseva, T. Kanne, P. Krogstrup, K. Grove-Rasmussen and J. Nygård, Commun. Phys. 3, 125 (2020).

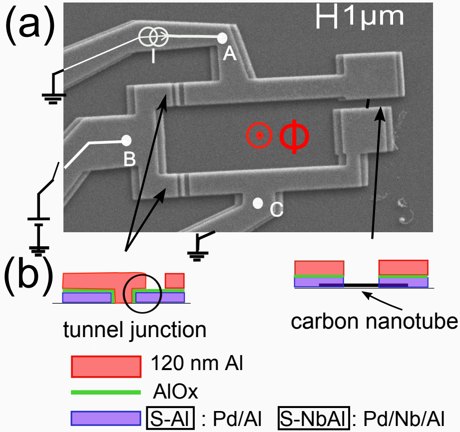
2. JOSEPHSON JUNCTION

Schematics of realistic S_L-QD-S_R (Josephson-type) junction



G. Kiršanskas, M. Goldstein, K. Flensberg, L.I. Glazman & J. Paaske, Phys. Rev. B 92, 235422 (2015)

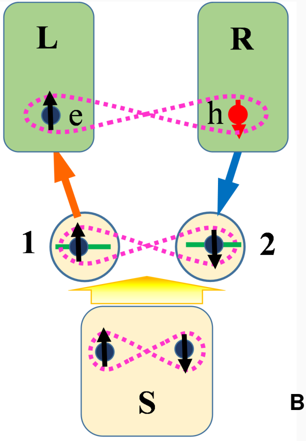
Selected example of experimental realization



R. Delagrange, R. Weil, A. Kasumov, M. Ferrier, H. Bouchiat, R. Deblock, Phys. Rev. B 93, 195437 (2016).

3. COOPER PAIR SPLITTER

Three-terminal geometry of the Cooper pair splitter with two quantum dots (1,2) coupled to the normal (L, R) electrodes and strongly coupled to the superconductor (S) as a reservoir of Cooper pairs.



B.R. Bułka, Phys. Rev. B 104, 155410 (2021)

SUPERCONDUCTING PROXIMITY EFFECT

- **Quantum dot (QD) coupled to bulk superconductor (SC) induces:**

$\Longrightarrow$ **on-dot pairing**

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- **This is spectroscopically manifested by formation of:**

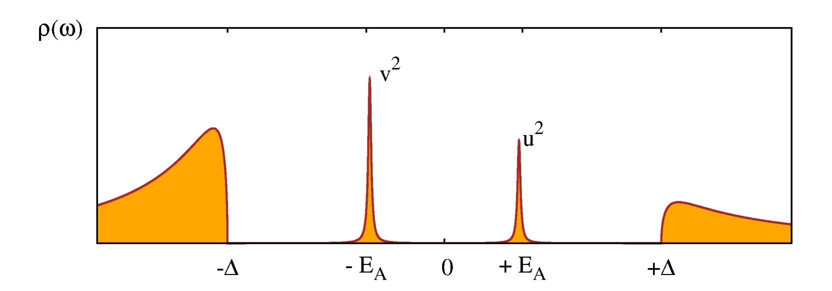
$\Longrightarrow$ **in-gap bound states**

- **Such in-gap states originate from:**

$\Longrightarrow$ **leakage of Cooper pairs on QD** **(Andreev)**

$\Longrightarrow$ **exchange int. of QD with SC** **(Yu-Shiba-Rusinov)**

Spectrum of a single impurity coupled to bulk superconductor:



Bound states appearing in the subgap region $-\Delta < \omega < \Delta$

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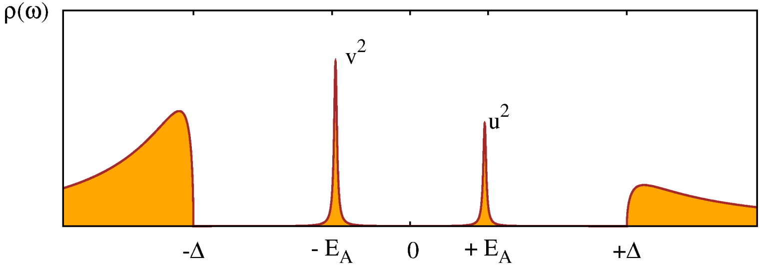

Bound states appearing in the subgap region $-\Delta < \omega < \Delta$

Yu-Shiba-Rusinov (Andreev) bound states

ISSUES TO BE ADDRESSED

I. Dynamics of Andreev bound states:

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$\Longrightarrow$ **transient phenomena**

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ISSUES TO BE ADDRESSED

I. Dynamics of Andreev bound states:

- $\Rightarrow$ **transient phenomena**
- $\Rightarrow$ **quantum quench**
- $\Rightarrow$ **periodic driving**

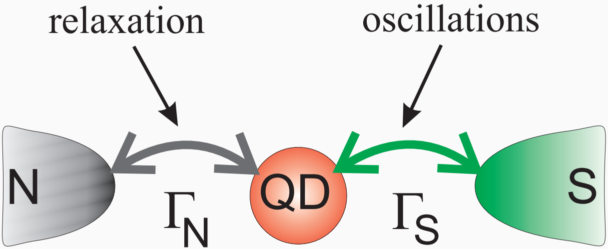
II. Phase transition in time-domain:

- $\Rightarrow$ **dynamical singlet-doublet transition**

Part I:

characteristic temporal scales of bound states

Consider a sudden coupling of QD to external leads



R. Taranko and T. Domański, Phys. Rev. B 98, 075420 (2018).

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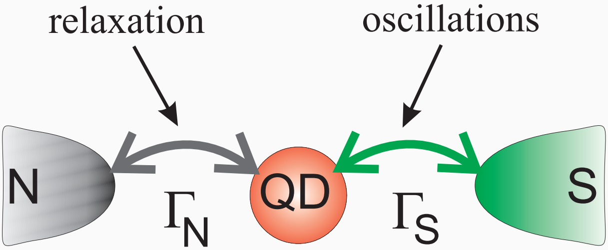
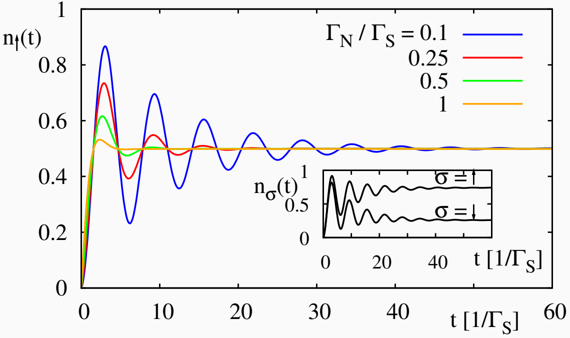


R. Taranko and T. Domański, Phys. Rev. B 98, 075420 (2018).

⇒ **how much time is needed to create in-gap states ?**

RELAXATION VS QUANTUM OSCILLATIONS

Time-dependent charge of an initially empty QD

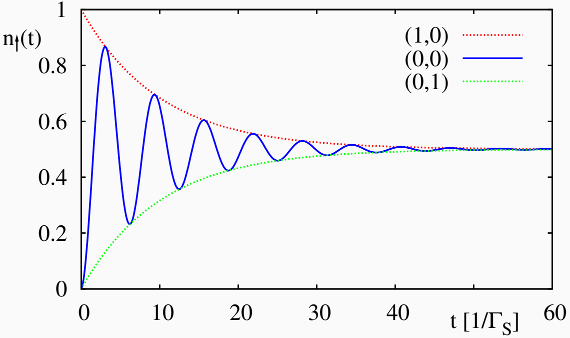


- **relaxation time is proportional to $1/\Gamma_N$**
- **oscillations depend on energies of in-gap states**

R. Taranko and T. Domański, Phys. Rev. B 98, 075420 (2018).

RELAXATION VS QUANTUM OSCILLATIONS

t-dependent charge for various initial fillings $(n_{\uparrow}, n_{\downarrow})$



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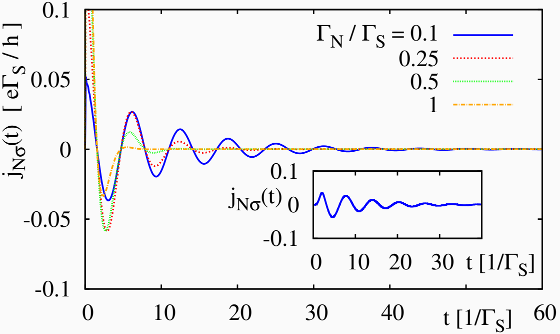
Time-dependent charge current of unbiased junction



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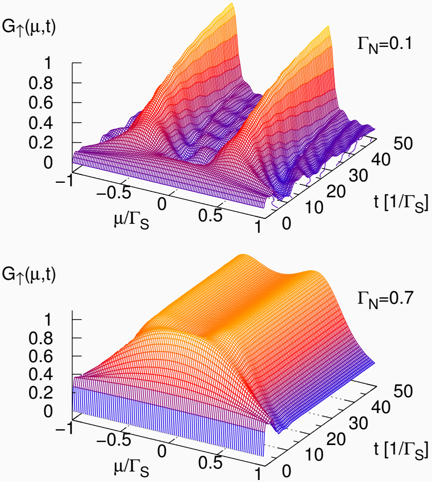
R. Taranko and T. Domański, Phys. Rev. B 98, 075420 (2018).

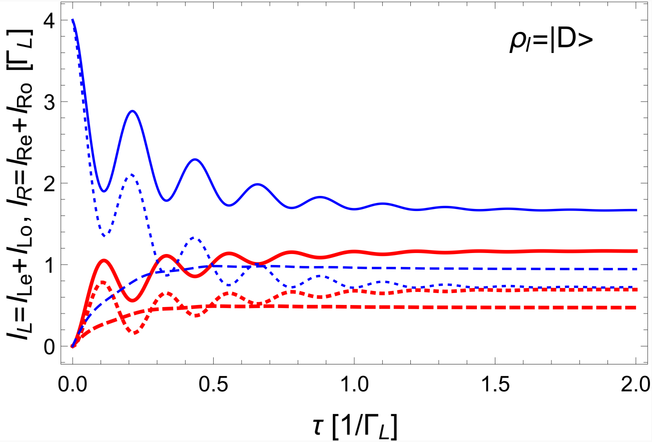
EXPERIMENTALLY ACCESSIBLE QUANTITIES

QD level $\varepsilon = 0$



Subgap tunneling conductance $G_\sigma = \frac{\partial I_\sigma}{\partial t}$ vs time (t) and voltage (μ)

STATISTICS OF TUNNELING EVENTS

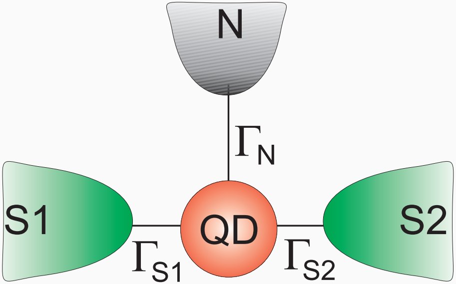


Transient currents from *'Waiting Time Distribution'* approach

G. Michałek, B. Bułka, T. Domański & K.I. Wysokiński, Acta Phys. Polon. A <u>133</u>, 391 (2018).

Josephson-type structures

PHASE-CONTROLLED TRANSIENT EFFECTS



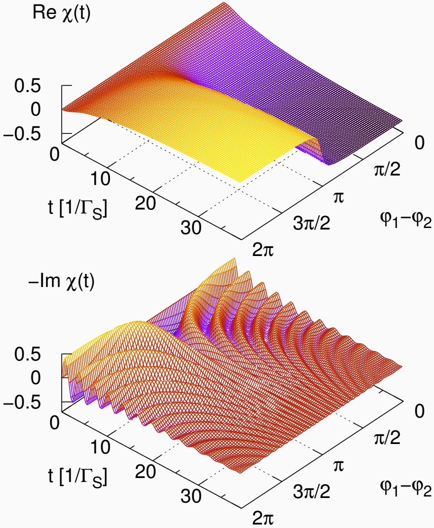
R. Taranko, T. Kwapiński & T. Domański, Phys. Rev. B 99, 165419 (2019).

Physical issue:

$\Rightarrow$ **phase tunable evolution of in-gap states**

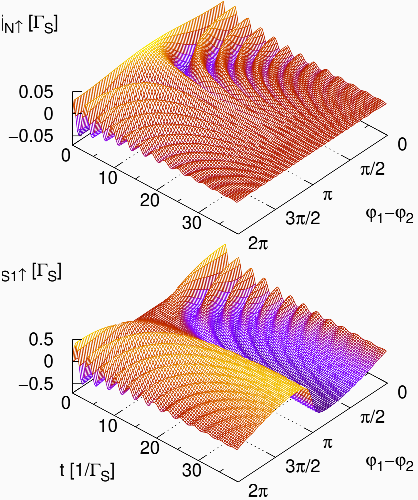
DEVELOPMENT OF ON-DOT PAIRING

Complex order parameter $\chi(t) = \langle \hat{d}_\downarrow \hat{d}_\uparrow \rangle$ induced by proximity effect



R. Taranko, T. Kwapiński & T. Domański, Phys. Rev. B 99, 165419 (2019).

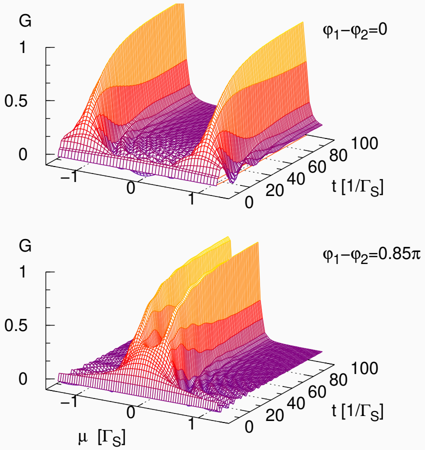
Time-dependent charge currents $j_N(t)$ and $j_{S1}(t)$.



R. Taranko, T. Kwapiński & T. Domański, Phys. Rev. B 99, 165419 (2019).

DYNAMICAL EFFECTS OF BIASED JUNCTION

Conductance of the Andreev current $j_N(t)$ versus voltage μ applied between the normal lead and superconductors.

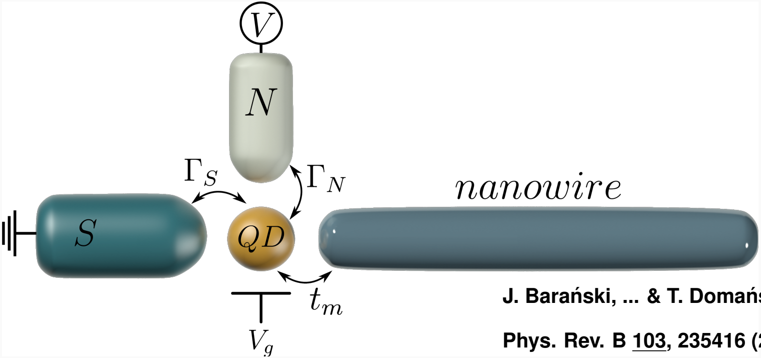


R. Taranko, T. Kwapiński & T. Domański, Phys. Rev. B 99, 165419 (2019).

Hybrid structure with topological superconductor

MAJORANA LEAKAGE ON QUANTUM DOT

N-QD-S circuit side-attached to topological superconductor



J. Barański, ... & T. Domański,

Phys. Rev. B 103, 235416 (2021).

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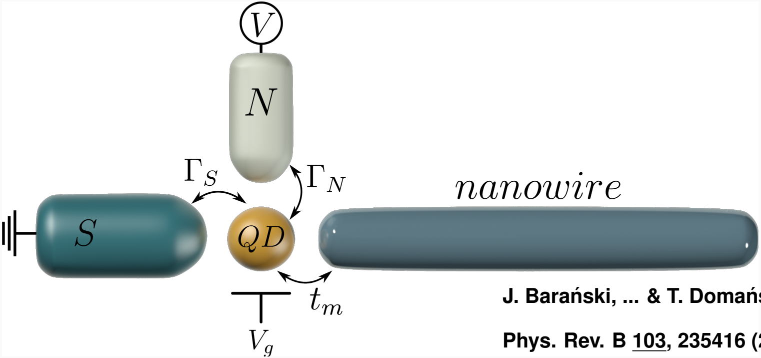

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$\Rightarrow$ **time-resolved transfer of Majorana mode on QD**

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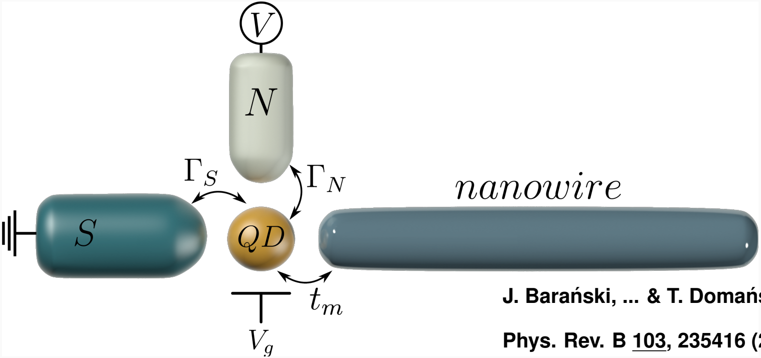

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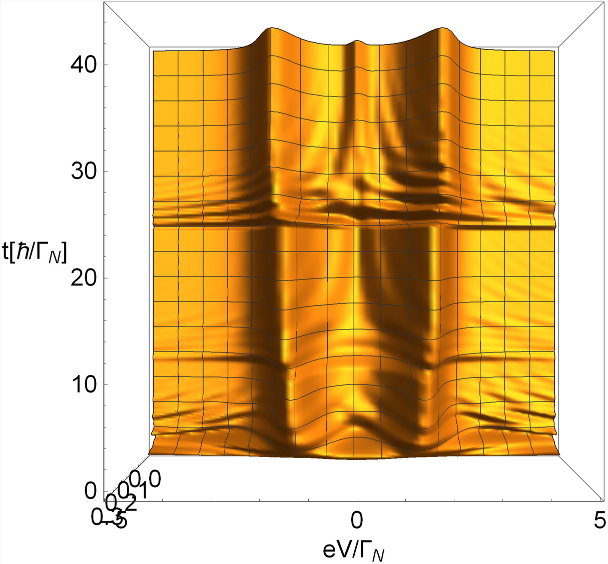
⇒ time-resolved transfer of Majorana mode on QD

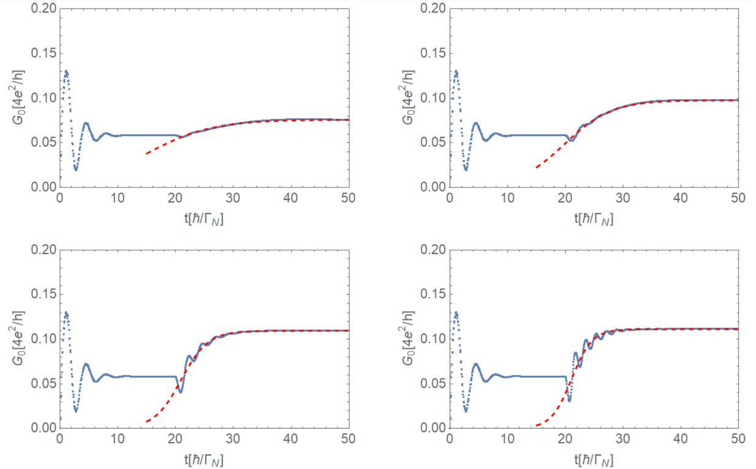
⇒ how does it show in the Andreev conductance

TIME-RESOLVED MAJORANA LEAKAGE



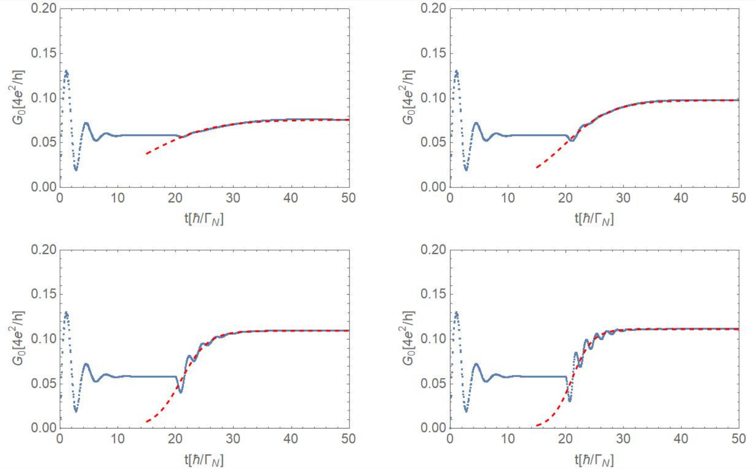
The differential Andreev conductance vs bias voltage V and time

TIME-RESOLVED ZERO BIAS CONDUCTANCE



The zero-bias differential conductivity obtained for $\Gamma_S = 3\Gamma_N$ and $\epsilon_d = \Gamma_N$, assuming: $t_m = 0.25$ (upper left), 0.5 (upper right), 1 (lower left), 1.5 (lower right) Γ_N. QD is abruptly connected to Majorana mode at time $t = 20\hbar/\Gamma_N$.

TIME-RESOLVED ZERO BIAS CONDUCTANCE



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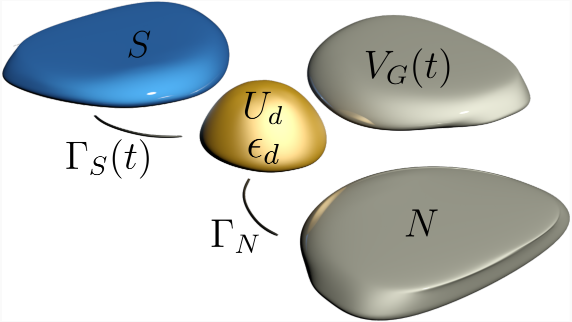
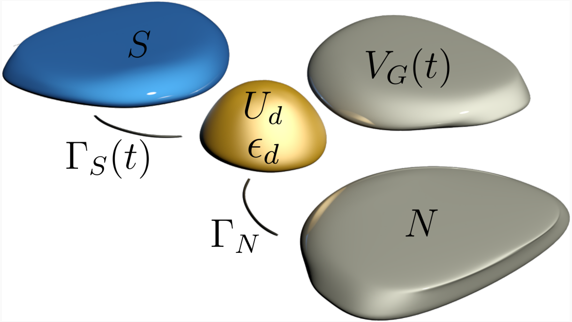
Typical values of the Majorana leakage time $\tau = 2 - 20$ nanoseconds.

Quench-induced dynamics



Quantum quench protocols:

QUENCH DRIVEN DYNAMICS



Quantum quench protocols:

$\Rightarrow$ **sudden change of the coupling** $\Gamma_S(t)$

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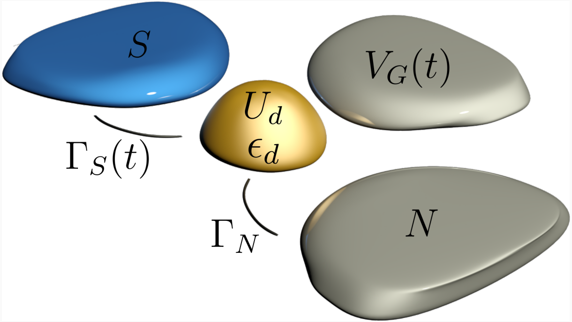


Quantum quench protocols:

$\Longrightarrow$ **sudden change of the coupling** $\Gamma_S(t)$

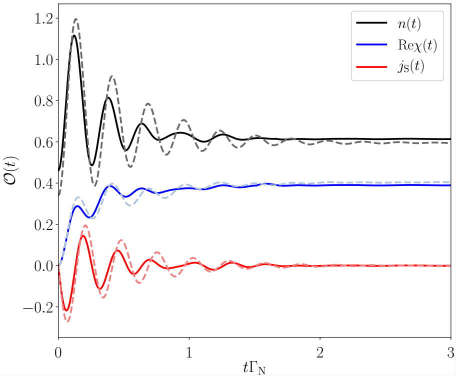
$\Longrightarrow$ **abrupt application of gate potential** $V_G(t)$

K. Wrześniewski, B. Baran, R. Taranko, T. Domański & I. Weymann, PRB 103, 155420 (2021).

QUENCH OF COUPLING Γ_S

Time-dependent observables driven by the quantum quench

$\Gamma_S = 0 \longrightarrow \Gamma_S = U$ **obtained for** $\varepsilon_d = 0$, $\Gamma_N = U/10$.



solid lines - time dependent NRG

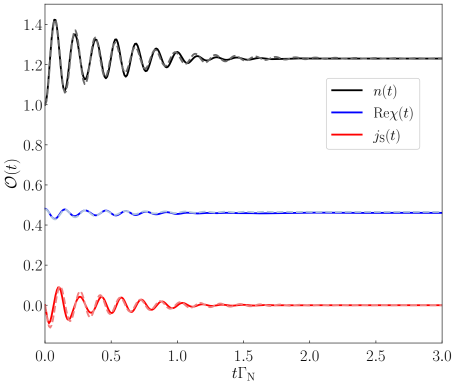
dashed lines - Hartree-Fock-Bogolubov

K. Wrześniewski, B. Baran, R. Taranko, T. Domański & I. Weymann, PRB 103, 155420 (2021).

QUENCH OF GATE POTENTIAL

Time-dependent observables driven by the quantum quench

$\varepsilon_d = -U/2 \longrightarrow \varepsilon_d = -U$ **obtained for** $\Gamma_S = 4U$, $\Gamma_N = U/10$.



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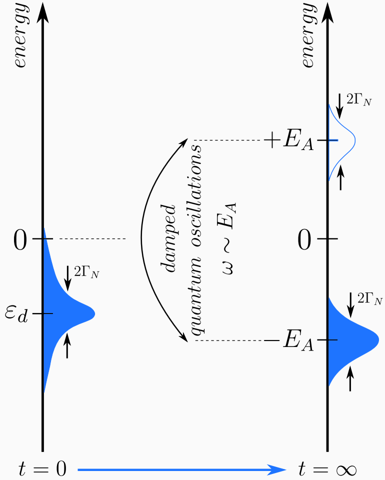
UNIVERSAL TENDENCY

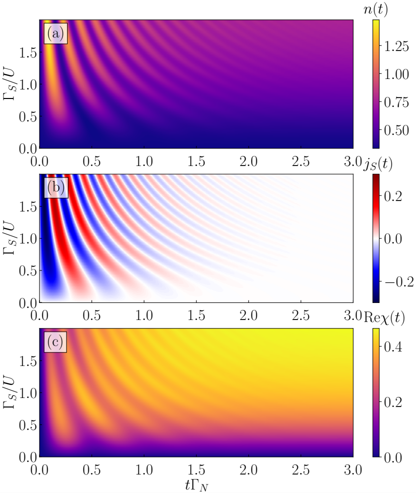
Rabbi-type oscillations observable in development of the in-gap states



K. Wrześniewski, B. Baran, R. Taranko, T. Domański & I. Weymann, PRB 103, 155420 (2021).

POST-QUENCH QUANTUM OSCILLATIONS

Rabi-type oscillations induced by the quench from $\Gamma_S = 0$ to Γ_S (as indicated).



K. Wrześniewski, B. Baran, R. Taranko, T. Domański & I. Weymann, PRB 103, 155420 (2021).

Part II: dynamical singlet-doublet transition

SINGLY OCCUPIED VS BCS-TYPE CONFIGURATIONS

The proximitized quantum dot can described by

$$\hat{H}_{QD} = \sum_{\sigma} \epsilon_d \, \hat{d}^{\dagger}_{\sigma} \, \hat{d}_{\sigma} \; + \; U_d \, \hat{n}_{d\uparrow} \hat{n}_{d\downarrow} - \left(\Delta_d \, \hat{d}^{\dagger}_{\uparrow} \hat{d}^{\dagger}_{\downarrow} + \text{h.c.} \right)$$

where $\Delta_d = \Gamma_S / 2$.

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where $\Delta_d = \Gamma_S/2$. True eigen-states are represented by:

$|\uparrow\rangle$ **and** $|\downarrow\rangle$ $\Leftarrow$ **doublet states (spin $\frac{1}{2}$)**

$$\left. \begin{array}{l} u\,|0\rangle - v\,|\uparrow\downarrow\rangle \\ v\,|0\rangle + u\,|\uparrow\downarrow\rangle \end{array} \right\} \Leftarrow$$ **singlet states (spin 0)**

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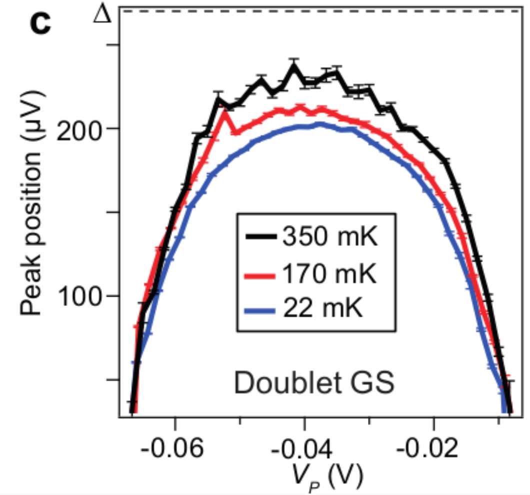
Upon varrying the parameters ε_d, U_d or Γ_S there can be induced quantum phase transition between these doublet/singlet states.

J. Bauer, A. Oguri & A.C. Hewson, J. Phys.: Condens. Matter 19, 486211 (2007).

QUANTUM PHASE TRANSITION: EXPERIMENT



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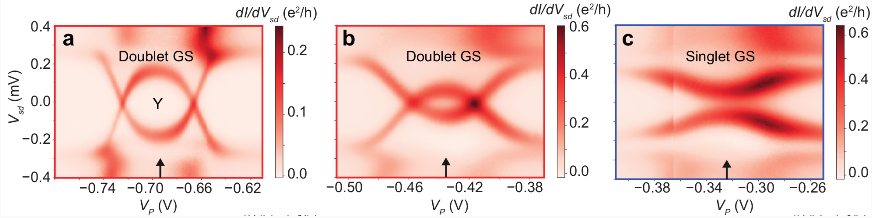
SINGLET VS DOUBLET: EXPERIMENT

Differential conductance vs source-drain bias V_{sd} (vertical axis) and gate potential V_p (horizontal axis) measured for various Γ_S/U

$U \gg \Gamma_s$ $\quad$ $U \geq \Gamma_s$ $\quad$ $U < \Gamma_s$



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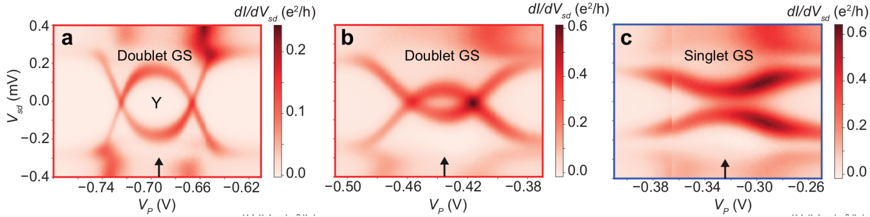

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Crossings of in-gap states correspond to the singlet-doublet QPT.

Outline of general concept

POST-QUENCH DYNAMICS

For $t < 0$ we assume the system $\hat{H}_0$ to be in its ground state:

$$\hat{H}_0 |\Psi_0\rangle = E_0 |\Psi_0\rangle$$

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$$\hat{H}_0 \longrightarrow \hat{H}$$

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Fidelity (similarity) of these states is:

$$\langle\Psi_0|\Psi(t)\rangle = \left\langle \Psi_0|e^{-it\hat{H}}|\Psi_0 \right\rangle$$

POST-QUENCH DYNAMICS

For $t < 0$ we assume the system $\hat{H}_0$ to be in its ground state:

$$\hat{H}_0 |\Psi_0\rangle = E_0 |\Psi_0\rangle$$

Next, at time $t = 0$, we impose an abrupt change (quench):

$$\hat{H}_0 \longrightarrow \hat{H}$$

For $t > 0$ Schrödinger equation $i\frac{d}{dt} |\Psi(t)\rangle = \hat{H} |\Psi(t)\rangle$ implies:

$$|\Psi(t)\rangle = e^{-it\hat{H}} |\Psi_0\rangle$$

Fidelity (similarity) of these states is:

$$\langle \Psi_0 | \Psi(t) \rangle = \left\langle \Psi_0 | e^{-it\hat{H}} | \Psi_0 \right\rangle$$

Loschmidt amplitude

STATIONARY VS DYNAMICAL PHASE TRANSITION

Idea: **M. Heyl, A. Polkovnikov, S. Kehrein, Phys. Rev. Lett. 110, 135704 (2013).**

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$$\mathcal{Z} = \left\langle e^{-\beta \hat{H}} \right\rangle$$

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nonanalytical $\lim_{T \to T_c} F(T)$

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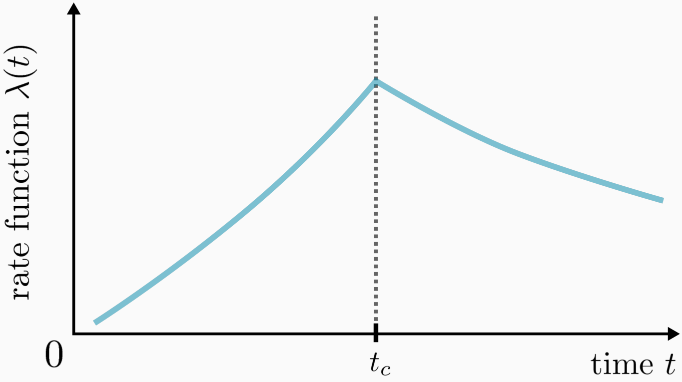
CRITICAL TIME

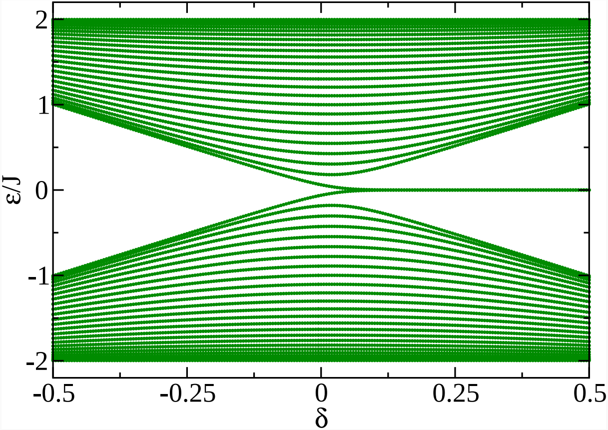


At critical time t_c the rate function $\lambda(t)$ of the Loschmidt echo $L(t) \equiv e^{-\lambda(t)}$ exhibits a nonanalytic kink.

Some examples ...

SU-SCHRIEFFER-HEEGER MODEL

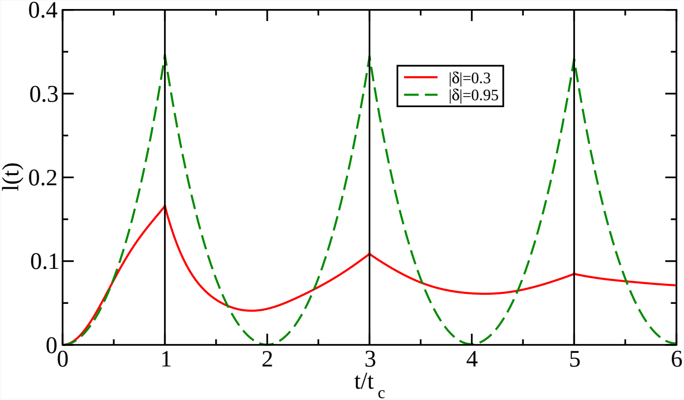
Quasiparticle spectrum of the SSH model under stationary conditions.



$$\hat{H} = -J \sum_j \left[\left(1 + \delta e^{i\pi j} \right) \hat{c}_j^\dagger \, \hat{c}_{j+1} \; + \; \text{h.c.} \right]$$

[N. Sedlmayr, Acta Phys. Polon. A 135, 1191 (2019)]

QUENCH DRIVEN TRANSITION



$$\hat{H} = -J \sum_j \left[\left(1 + \delta e^{i\pi j} \right) \hat{c}_j^\dagger \, \hat{c}_{j+1} \; + \; \text{h.c.} \right]$$

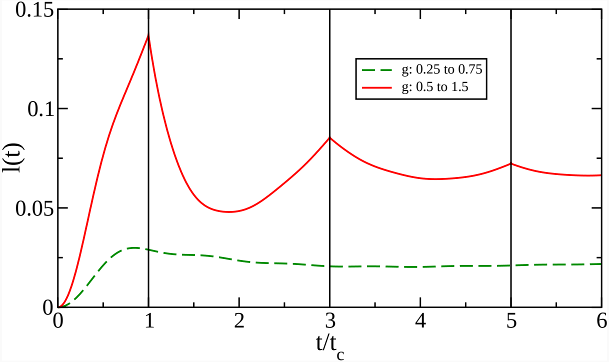
solid red line: $\delta = -0.3 \quad \longrightarrow \quad \delta = +0.3$

dashed green line: $\delta = 0.95 \quad \longrightarrow \quad \delta = -0.95$

[N. Sedlmayr, Acta Phys. Polon. A 135, 1191 (2019)]

QUENCH OF TRANSVERSE FIELD h

Post-quench return rate of the Ising model ($g \equiv h/J$)



$$\hat{H} = -\frac{J}{2}\sum_{j=1}^{N-1} \hat{\sigma}_j^z \ \hat{\sigma}_{j+1}^z \ + \ \frac{h}{2}\sum_{j=1}^{N} \hat{\sigma}_j^x$$

solid red line - across a phase transition ($g_c = 1$)

dashed green line - inside the same phase

A FEW REMARKS

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(however there are exceptions from this rule)

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$\Rrightarrow$ **upon crossing phase-boundaries**

(however there are exceptions from this rule)

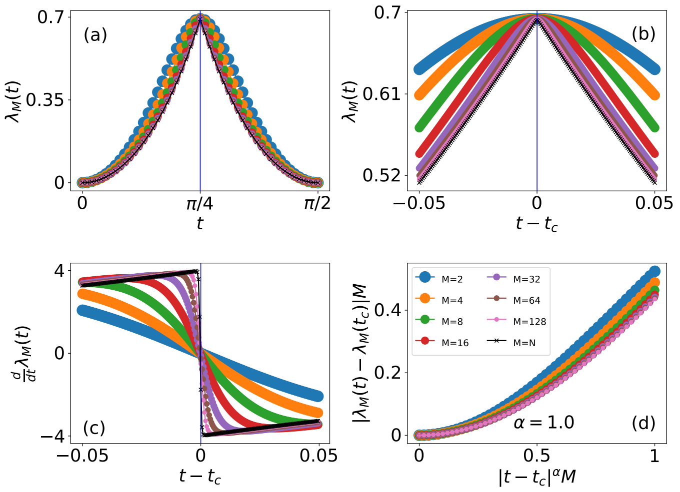
$\Rrightarrow$ **at equidistant critical times**

(in most cases, though not always)

$\Rrightarrow$ **at finite temperatures**

(but they are no longer sharp)

FINITE-SIZE EFFECTS

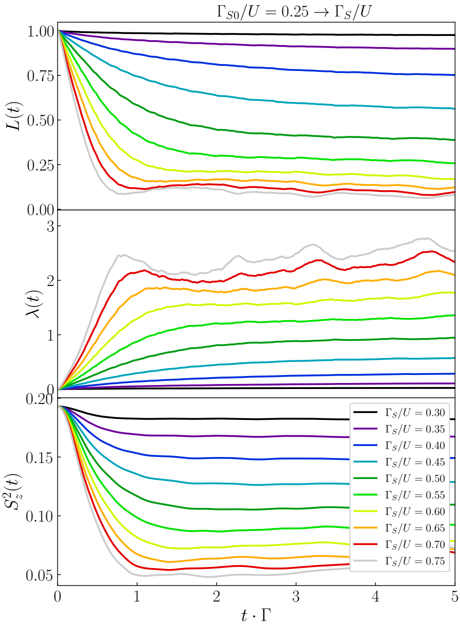


"Local measures of dynamical quantum phase transitions"

J.C. Halimeh, D. Trapin, M. Damme & M. Heyl, Phys. Rev. B 104, 075130 (2021).

Dynamical singlet-doublet transition

tNRG RESULTS: ABRUPT CHANGE OF Γ_S



Loschmidt echo

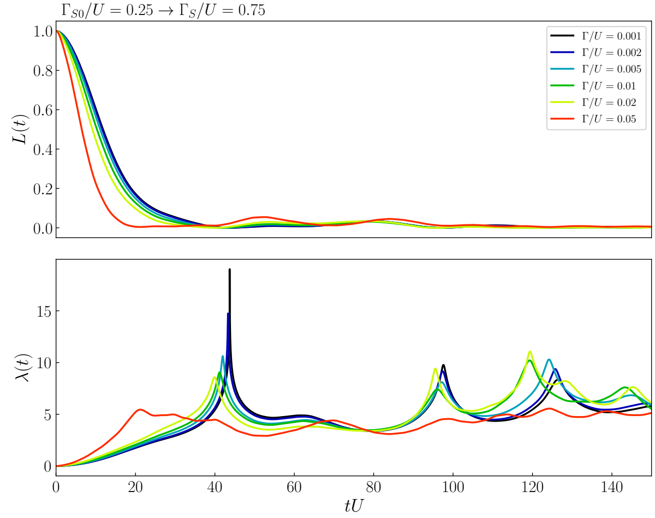
$$L(t) \equiv | \langle \Psi(0) | \Psi(t) \rangle |^2$$

Return rate

$$\lambda(t) \equiv - \ln \{L(t)\}$$

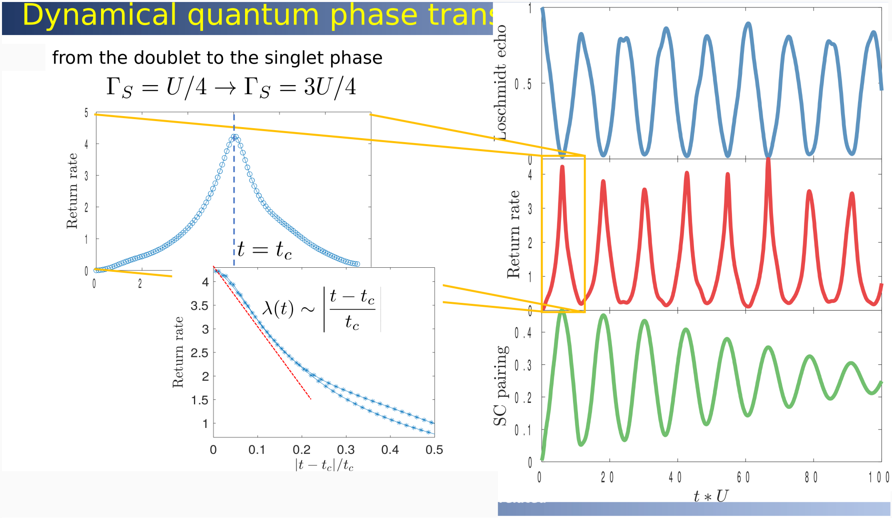
The squared magnetic moment $\langle S_z^2(t) \rangle$

tNRG RESULTS: $\Gamma_S = U/4 \longrightarrow \Gamma_S = 3U/4$



Loschmidt echo $L(t)$ and return rate $\lambda(t)$ obtained for various $\Gamma_N \equiv \Gamma$

tNRG RESULTS: $\Gamma_S = U/4 \longrightarrow \Gamma_S = 3U/4$



K. Wrześniewski, N. Sedlmayr, T. Domański & I. Weynmann, (2021)

CONCLUSIONS

Evolution of the Andreev in-gap states:

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- **activates Rabi-type oscillations** /due to particle-hole mixing/
- **depends on initial configuration** /proximity effect could be blocked/
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CONCLUSIONS

Evolution of the Andreev in-gap states:

- **activates Rabi-type oscillations** **/due to particle-hole mixing/**
- **depends on initial configuration** **/proximity effect could be blocked/**
- **may exhibit dynamical transition(s)** **/upon varying ground states/**

These phenomena are detectable in transport properties !

ACKNOWLEDGEMENTS

- **transient phenomena, Floquet formalism & machine-learning**

$\Longrightarrow$ **R. Taranko (Lublin), B. Baran (Lublin),**

- **statistical approach to Andreev transport**

$\Longrightarrow$ **B.R. Bułka & G. Michałek (Poznań), K.I. Wysokiński (Lublin),**

- **time-resolved leakage of Majorana mode**

$\Longrightarrow$ **J. Barański (Dęblin),**

- **dynamical singlet-doublet transition**

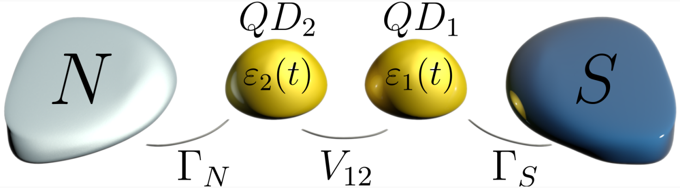
$\Longrightarrow$ **I. Weymann & K. Wrześniewski (Poznań),**

N. Sedlmayr (Lublin)

Andreev (triplet) blockade

DYNAMICAL EFFECTS IN DOUBLE QUANTUM DOT

Setup: let's consider two quantum dots ($QD_{1,2}$) placed between normal metal (N) and superconducting (S) electrodes

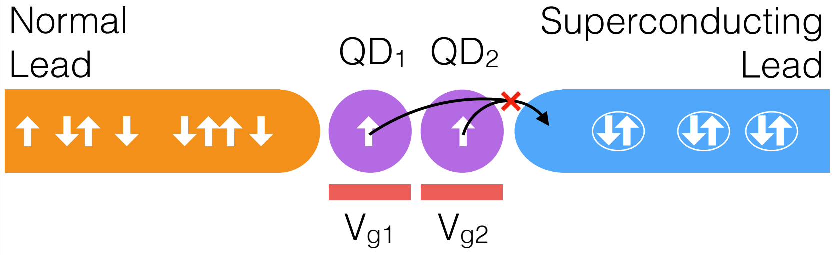


[1] R. Taranko, K. Wrześniewski, B. Baran, I. Weymann & T. Domański, Phys. Rev. B 103, 165430 (2021).

[2] B. Baran, R. Taranko & T. Domański, Sci. Rep. 11, 11148 (2021).

ANDREEV BLOCKADE

D. Pekker, P. Zhang & S.M. Frolov, SciPost Phys. 11, 081 (2021).



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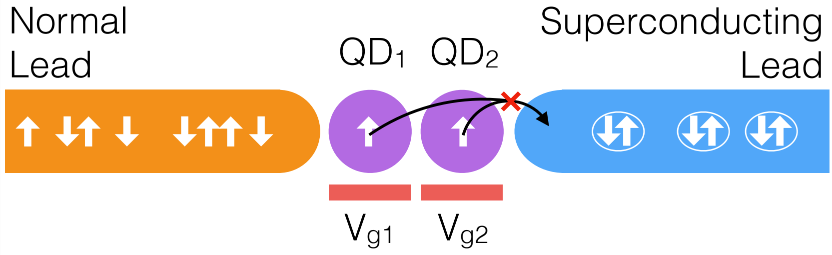
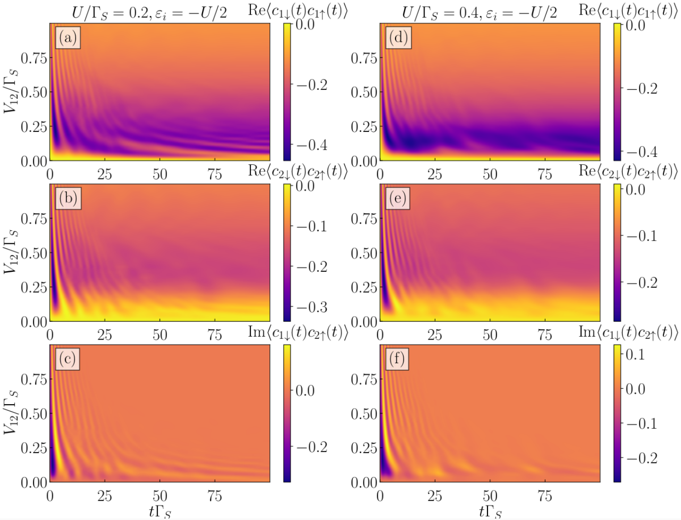


Problem: **initial triplet configuration does not allow for development of the superconducting proximity effect**

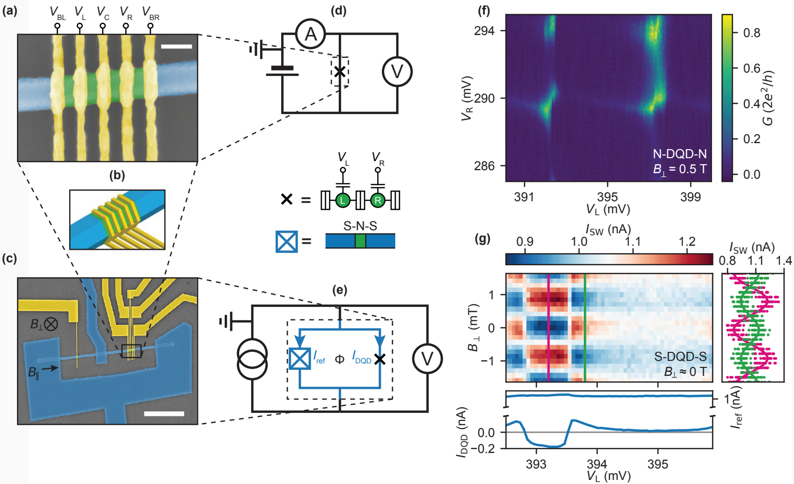
DYNAMICS OF ANDREEV BLOCKADE

Disappearance of Andreev blockade obtained for half-filled DQD.



R. Taranko, K. Wrześniewski, B. Baran, I. Weymann & T. Domański, PRB 103, 165430 (2021).

TRIPLET BLOCKADE IN JOSEPHSON JUNCTION

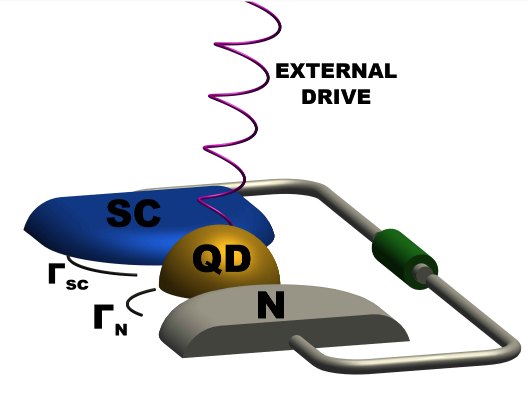


„Triplet-blockaded Josephson supercurrent in double quantum dots"

D. Bouman et al, Phys. Rev. B 102, 220505(R) (2020).

Periodically driven QD

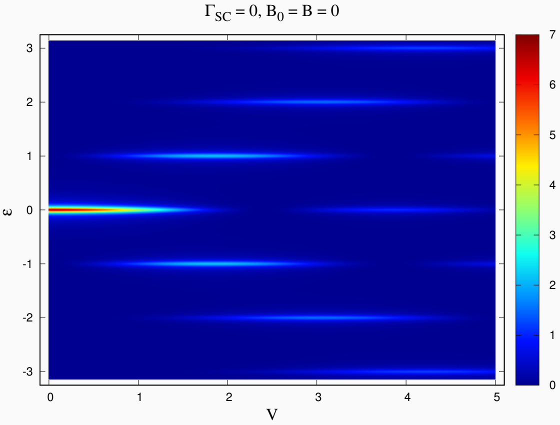
Quantum impurity with periodically oscillating energy level



$$\varepsilon(t) = \varepsilon_0 + V \times \cos(\omega t)$$

BOUND STATES OF A DRIVEN QUANTUM IMPURITY

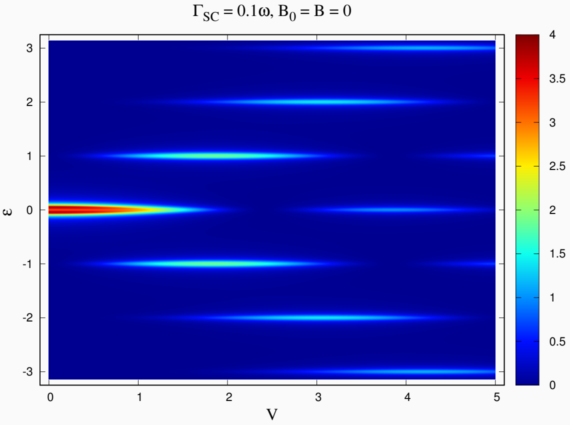
Floquet spectrum averaged over a period $T = 2\pi/\omega$



$\Gamma_S = 0.0$

B. Baran and T. Domański, Phys. Rev. B <u>100</u>, 085414 (2019).

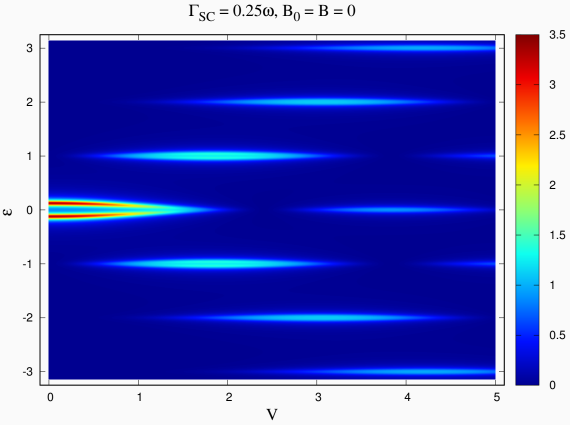
Floquet spectrum averaged over a period $T = 2\pi/\omega$



$\Gamma_S = 0.1\omega$

B. Baran and T. Domański, Phys. Rev. B 100, 085414 (2019).

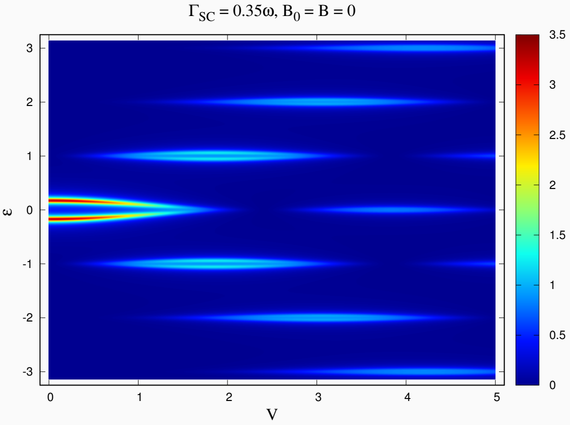
Floquet spectrum averaged over a period $T = 2\pi/\omega$



$\Gamma_S = 0.25\omega$

B. Baran and T. Domański, Phys. Rev. B 100, 085414 (2019).

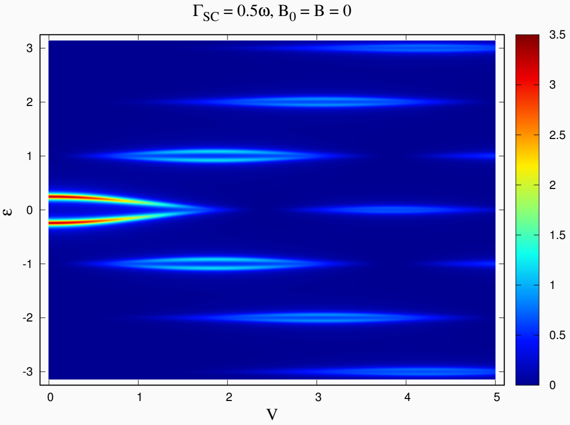
Floquet spectrum averaged over a period $T = 2\pi/\omega$



$\Gamma_S = 0.35\omega$

B. Baran and T. Domański, Phys. Rev. B 100, 085414 (2019).

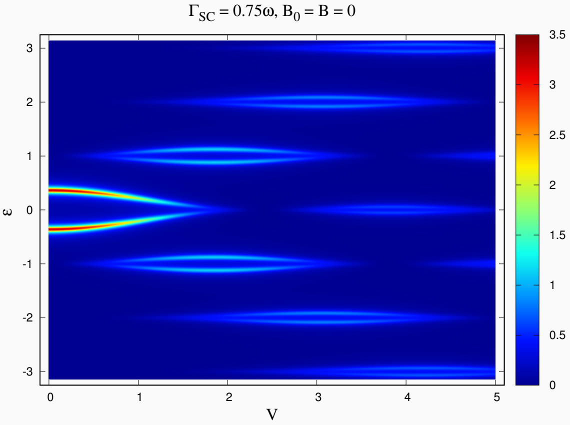
Floquet spectrum averaged over a period $T = 2\pi/\omega$



$\Gamma_S = 0.5\omega$

B. Baran and T. Domański, Phys. Rev. B <u>100</u>, 085414 (2019).

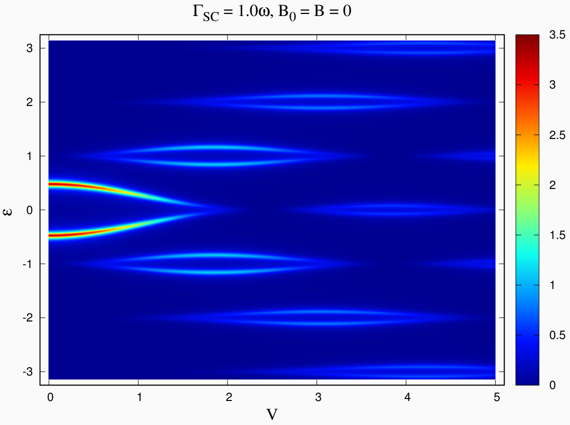
Floquet spectrum averaged over a period $T = 2\pi/\omega$



$\Gamma_S = 0.75\omega$

B. Baran and T. Domański, Phys. Rev. B 100, 085414 (2019).

Floquet spectrum averaged over a period $T = 2\pi/\omega$



$\Gamma_S = 1.0\omega$

B. Baran and T. Domański, Phys. Rev. B 100, 085414 (2019).