Dynamical effects in quantum dots coupled to superconductors

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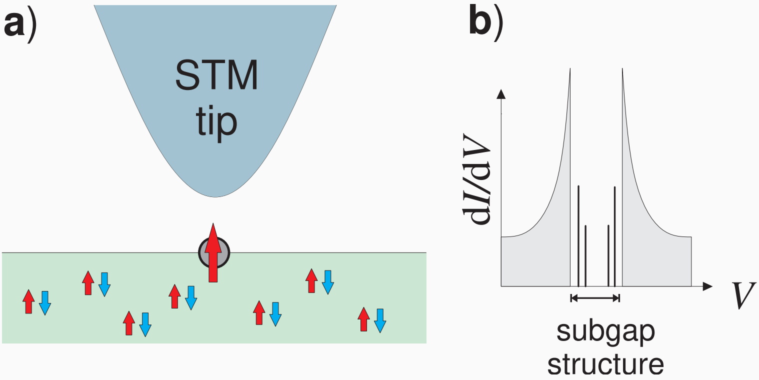
Praha **20 February 2025**

Superconducting nanostructures

NANOSTRUCTURES WITH SUPERCONDUCTOR(S)

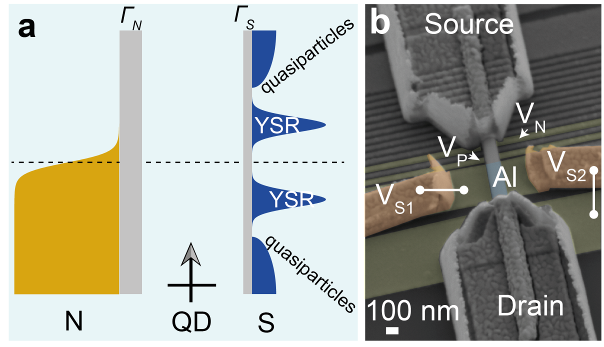
Quantum impurity on a surface of superconductor + STM tip



STM is a tool to probe the spectra of impurities

NANOSTRUCTURES WITH SUPERCONDUCTOR(S)

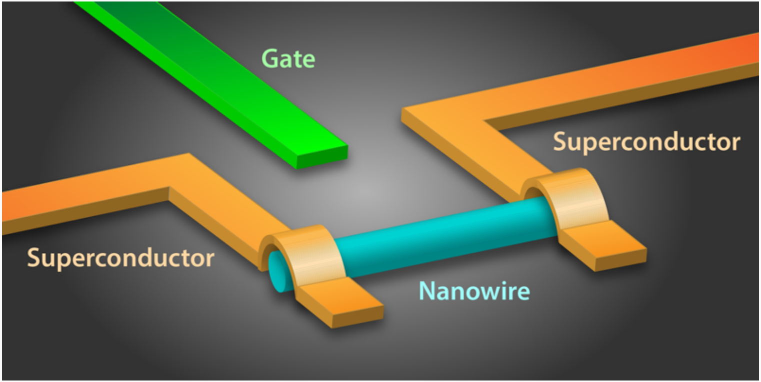
normal metal (N) - quantum dot (QD) - superconductor (S)



Tunneling by the electron-to-hole (Andreev) scattering.

NANOSTRUCTURES WITH SUPERCONDUCTOR(S)

superconductor (S) - quantum dot (QD) - superconductor (S)



Tunneling of Cooper pairs via bound states in Josephson junction.

SUPERCONDUCTING PROXIMITY EFFECT

- **Coupling of the localized (QD) to itinerant (SC) electrons induces:**

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

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- Coupling of the localized (QD) to itinerant (SC) electrons induces:

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

- manifested spectroscopically by:

$\Longrightarrow$ **bound states inside the gap of SC**

- originating from:

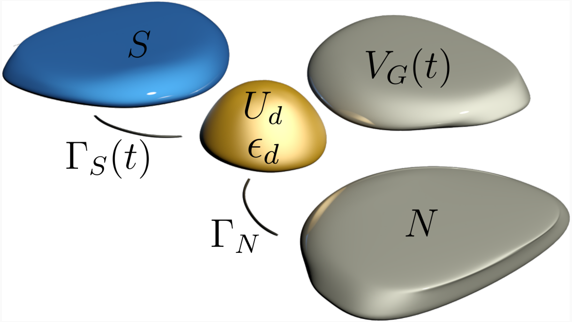
$\Longrightarrow$ **leakage of Cooper pairs on QD** **(Andreev)**

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

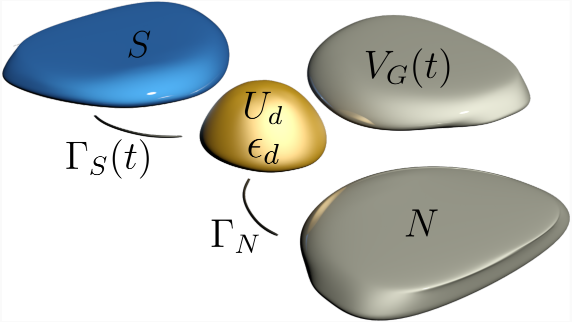
Characteristic time-scales

Characteristic time-scales

[emergence of in-gap states]



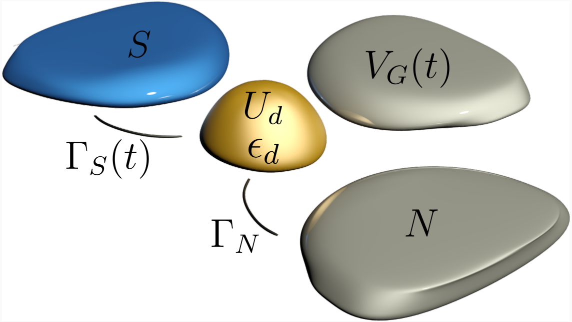
Protocols of non-equilibrium conditions:



Protocols of non-equilibrium conditions:

$\Rightarrow$ **variation of the coupling Γ_S to superconductor**

TIME-RESOLVED BOUND STATES

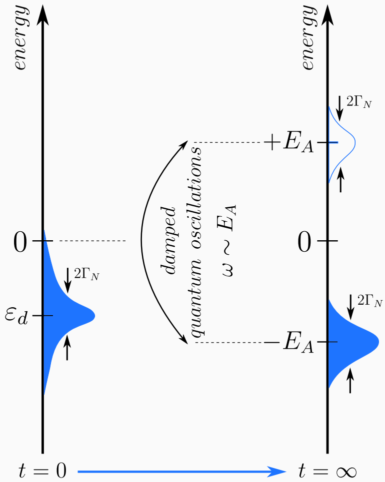


Protocols of non-equilibrium conditions:

$\Rightarrow$ **variation of the coupling Γ_S to superconductor**

$\Rightarrow$ **abrupt change of the gate potential V_G**

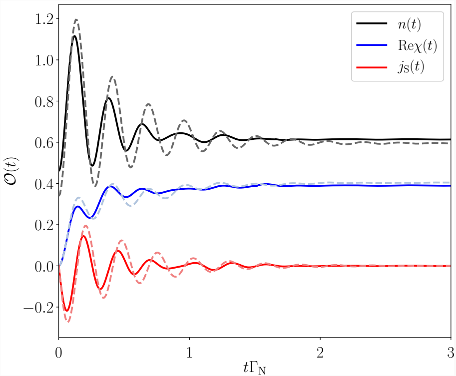
Emergence of Andreev states due to the sudden coupling $0 \to \Gamma_S$



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

BUILDUP OF IN-GAP STATES

Time-dependent observables driven by the quantum quench $0 \to \Gamma_S$



$n(t)$ **electron number**

$\chi(t) = \left\langle \hat{d}_\downarrow \hat{d}_\uparrow \right\rangle$ **on-dot pairing**

$j_S(t)$ **charge current**

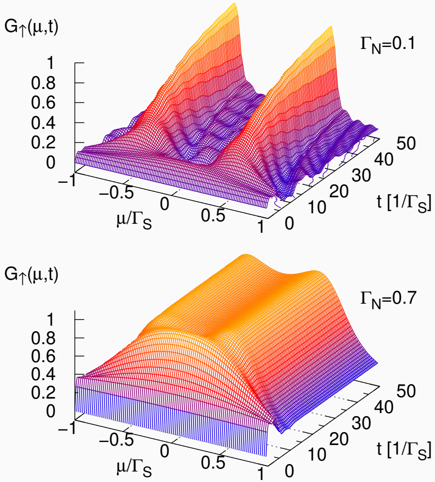
solid lines - time dependent NRG

dashed lines - Hartree-Fock-Bogolubov

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

TIME-DEPENDENT TUNNELING CONDUCTANCE

QD level $\varepsilon_d = 0$



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

BOUND STATES OF CLASSICAL IMPURITY

communications
physics

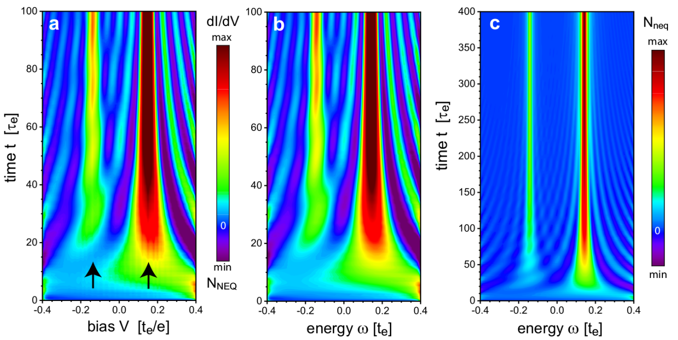
ARTICLE

https://doi.org/10.1038/s42005-022-01050-7 OPEN

Check for updates

Emergence and manipulation of non-equilibrium Yu-Shiba-Rusinov states

Jasmin Bedow [1], Eric Mascot [1,2] & Dirk K. Morr [1✉]



Correlation effects

Correlation effects

[Experts: T. Novotný, M. Žonda, V. Pokorny, P. Zalom]

SINGLY OCCUPIED VS BCS-TYPE CONFIGURATIONS

Quantum dot proximitized to superconductor can described by

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

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Eigen-states of this problem 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 ratio ε_d/U_d or Γ_S/U_d the doublet-singlet transition can be induced between these ground states.

Dynamical phase transition

Dynamical phase transition

[transition in time-domain]

GENERAL PROTOCOL

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

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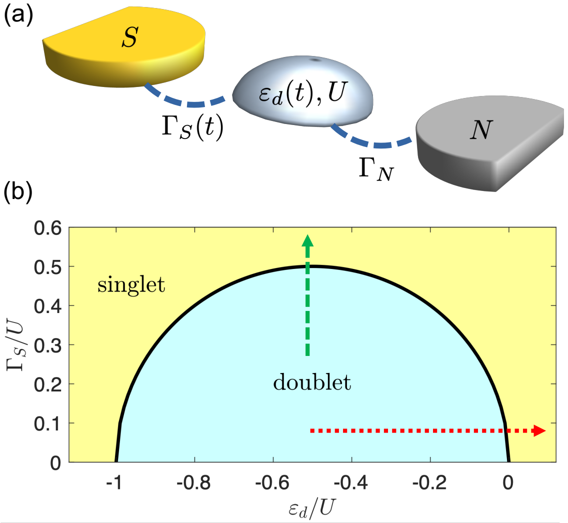
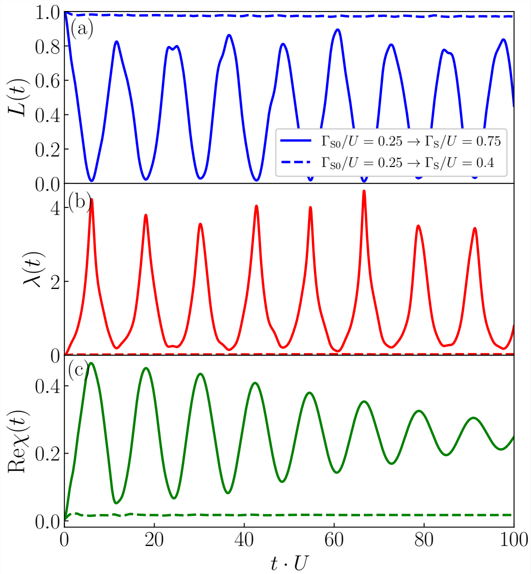
Loschmidt amplitude

QUENCH ACROSS STATIC QPT BOUNDARY



K. Wrześniewski, I. Weymann, N. Sedlmayr & T. Domański, Phys. Rev. B 105, 094514 (2022).

tNRG RESULTS: ABRUPT CHANGE OF Γ_S



$\varepsilon_d = -U/2$

$\Gamma_N = U/100$

K. Wrześniewski, I. Weymann, N. Sedlmayr & T. Domański, Phys. Rev. B 105, 094514 (2022).

CONCLUSIONS (PART 1)

Quantum impurity/dot embedded into bulk superconductor:

- **induces the Rabi-type oscillations**
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- **which can undergo dynamical transitions**

  (qualitative changeover of the ground states)

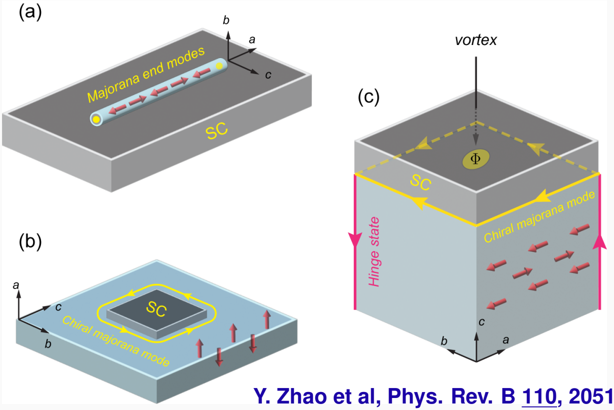
These phenomena could be detected by the charge transport and evidenced in time-resolved Andreev/Josephsnon conductance.

Part 2. topological superconductors

(Majorana-type quasiparticles)

MOTIVATION

The boundary modes (localized, chiral or Hinge states) of topological superconductors realized in different dimensions



Y. Zhao et al, Phys. Rev. B 110, 205111 (2024).

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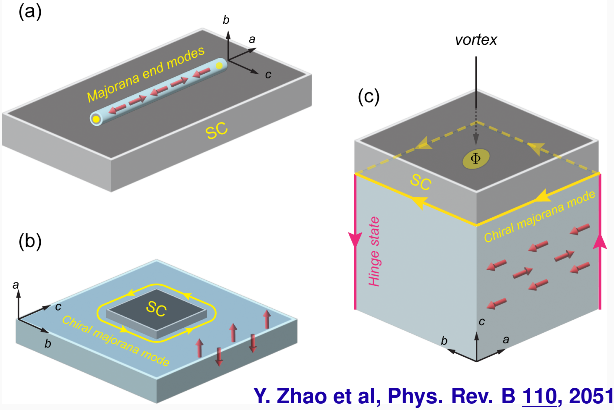

Y. Zhao et al, Phys. Rev. B 110, 205111 (2024).

can be detected, using the charge tunneling spectroscopies (with attachment of external electrodes) in nonequilibrium conditions.

HYBRID TOPOLOGICAL STRUCTURES

Topological superconductors can hybridize with other (topologically trivial) objects:

$\Longrightarrow$ **through some interface,**

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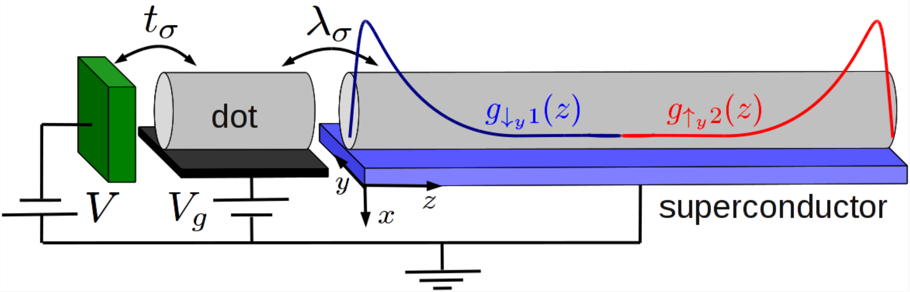
The simplest case:

$\Longrightarrow$ **single-level impurity + Majorana mode(s).**

LEAKAGE OF MAJORANA MODE ON QUANTUM DOT

Hybrid structure: quantum dot + topological superconductor

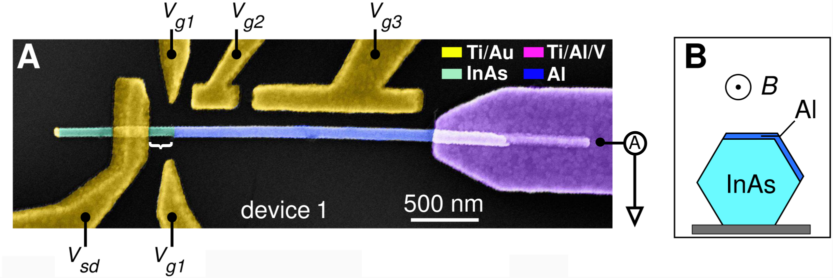


Idea: Majorana mode is partly transferred onto quantum dot where it can be detected by tunneling spectroscopy

M. Leijnse and K. Flensberg, Phys. Rev. B 84, 140501(R) (2011).

FIRST EXPERIMENTAL REALIZATION

Setup: **Epitaxial Al shell (blue) grown on two facets of the hexagonal InAs core (cyan), with a thickness of $\sim$ 10 nm.**



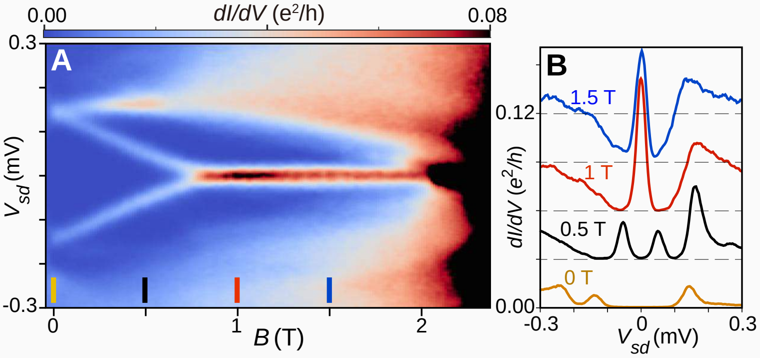
Data: **Transport measurements have been collected, varying the magnetic field oriented parallelly to the nanowire.**

M.T. Deng et al, Science 354, 1557 (2016).

EVIDENCE FOR MAJORANA LEAKAGE

Panel (A): **Tunneling spectrum for resonant dot-wire coupling obtained at $V_{bg} = -8.5$ V, $V_{g1} = 22$ V, and $V_{g2} = V_{g3} = -10$ V.**

Panel (B): **Differential conductance at various values of the magnetic field.**



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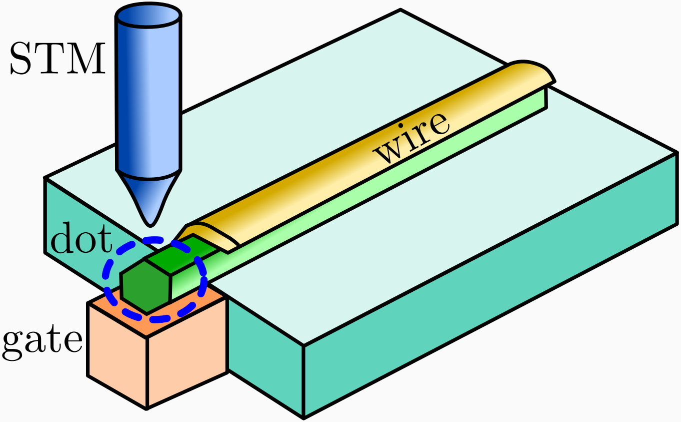
GATE-CONTROLLED BOUND STATES

Hybrid structure: **trivial + topological segments of nanowire**



Issue: **bound states of trivial segment attached to topological sc**

A. Ptok, A. Kobiałka, T. Domański, Phys. Rev. B 96, 195430 (2017).

GATE-CONTROLLED BOUND STATES

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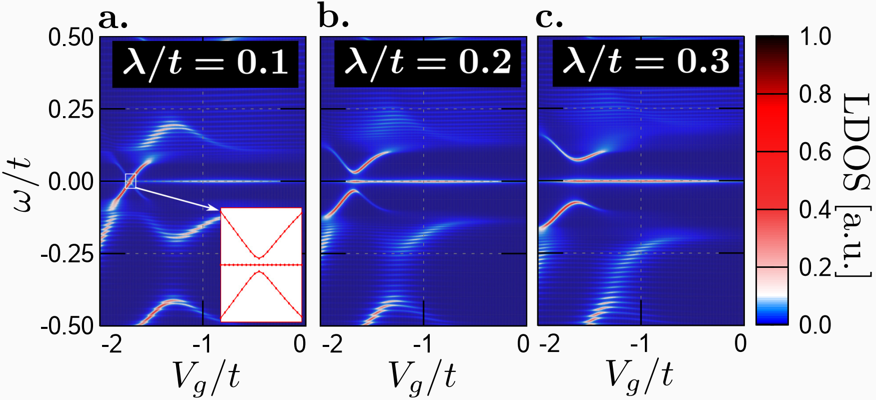


Variation the trivial (Andreev) & topological (Majorana) states vs the gate potential V_g for several spin-orbit couplings λ.

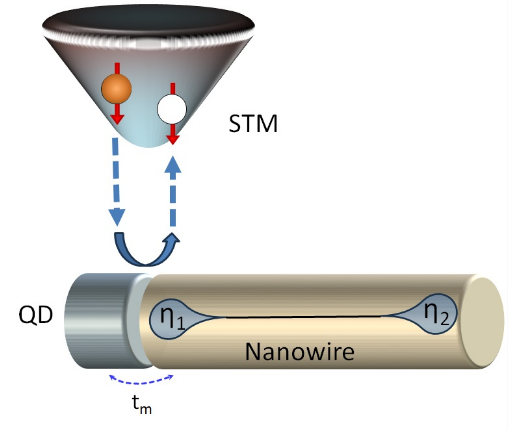
A. Ptok, A. Kobiałka, T. Domański, Phys. Rev. B 96, 195430 (2017).

What about correlations ?

/ induced by Coulomb repulsion /

CORRELATIONS VS LEAKAGE

Hybrid structure: Anderson impurity + topological superconductor



Question: Does the Coulomb repulsion affect the Majorana mode(s) leakage ?

CORRELATIONS VS LEAKAGE

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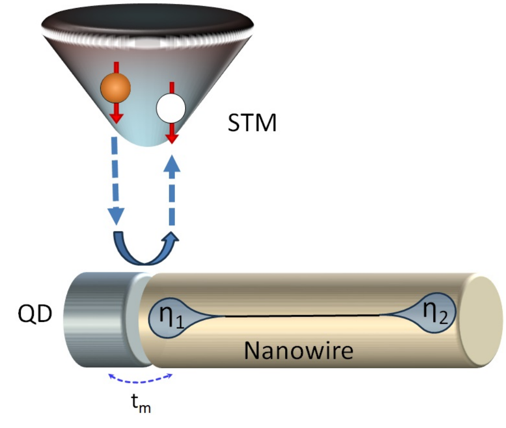

Question: Does the Coulomb repulsion affect the Majorana mode(s) leakage ? Is there any competition ?

J. Barański, M. Barańska, T. Zienkiewicz & T. Domański, J. Phys.: Cond. Matt. 37, 055302 (2025).

LOW ENERGY SCENARIO

For microscopic considerations we used the Anderson-type model

$$\hat{H} = \hat{H}_{QD} + \lambda(\hat{d}_{\downarrow}^{\dagger}\hat{\eta}_1 + \hat{\eta}_1\hat{d}_{\downarrow}) + i\epsilon_m\hat{\eta}_1\hat{\eta}_2$$

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recasting the Majorana operators in terms of conventional fermions

$$\hat{\eta}_1 = \frac{1}{\sqrt{2}}(\hat{f}^{\dagger} + \hat{f})$$

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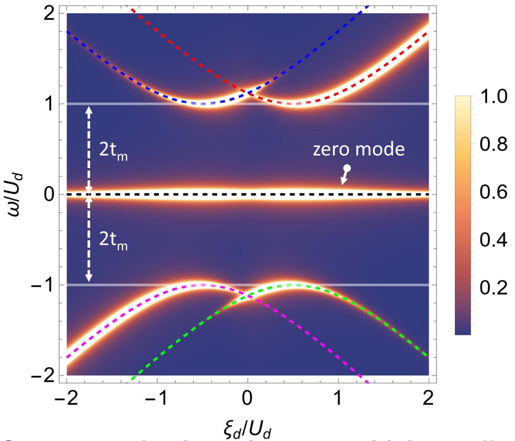
Quasiparticle states of the quantum dot can be determined analytically.

Hybrid structure: Anderson impurity + topological nanowire

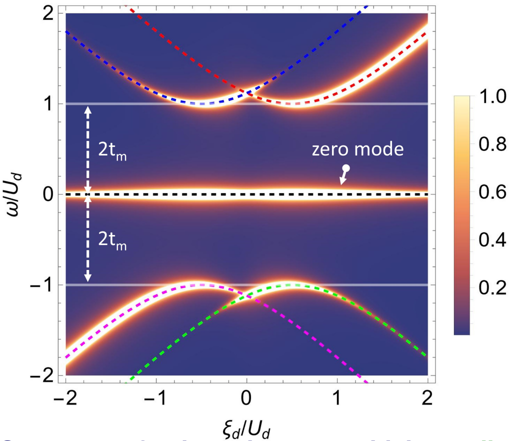


J. Barański et al, (2025).

Spectrum of spin-↓ electrons which are directly coupled to the Majorana mode.

SPIN-SENSITIVE LEAKAGE

Hybrid structure: Anderson impurity + topological nanowire



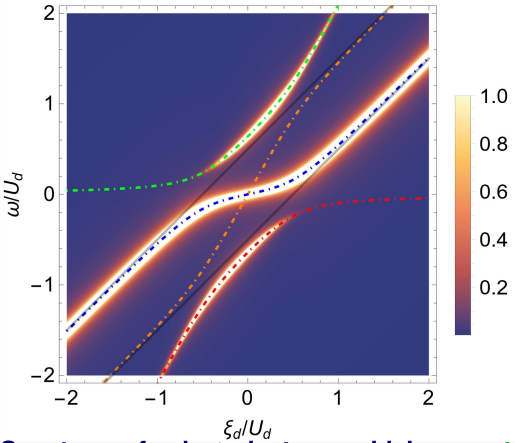
J. Barański et al, (2025).

Spectrum of spin-↓ electrons which are directly coupled to the Majorana mode. Zero-energy mode appears near ϵ_d and $\epsilon_d + U_d$.

Notation: $\xi_d \equiv \epsilon_d + U_d/2$.

SPIN-SENSITIVE LEAKAGE

Hybrid structure: Anderson impurity + topological nanowire

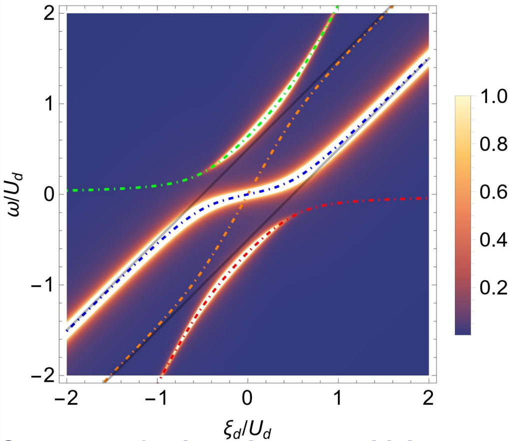


T. Barański et al, (2025).

Spectrum of spin-↑ electrons which are not directly coupled to the Majorana mode.

SPIN-SENSITIVE LEAKAGE

Hybrid structure: Anderson impurity + topological nanowire



T. Barański et al, (2025).

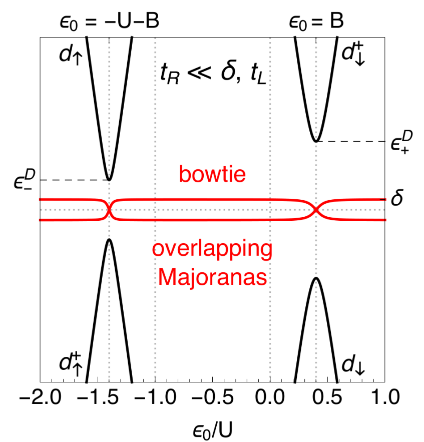
Spectrum of spin-↑ electrons which are not directly coupled to the Majorana mode. Majorana features are missing.

Short topological nanowire

/ overlapping Majorana modes /

OVERLAPPING MAJORANA MODES, $\epsilon_M \neq 0$

Hybrid structure: quantum impurity + short topological nanowire



E. Prada et al, PRB 96, 085418 (2017).

Quasiparticle spectrum of the quantum dot obtained for $\epsilon_M \neq 0$.

OVERLAPPING MAJORANA MODES, $\epsilon_M \neq 0$

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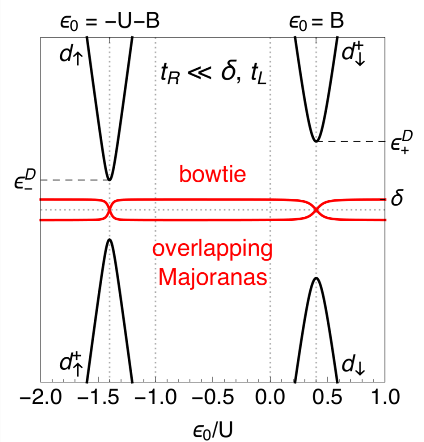

E. Prada et al, PRB 96, 085418 (2017).

Quasiparticle spectrum of the quantum dot obtained for $\epsilon_M \neq 0$.

Notice: bowtie features near the crossing points.

OVERLAPPING MAJORANA MODES, $\epsilon_M \neq 0$

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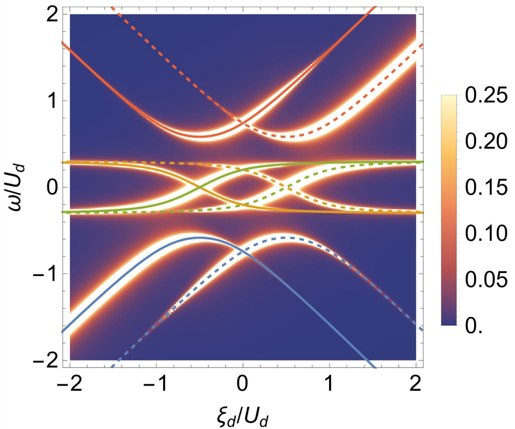
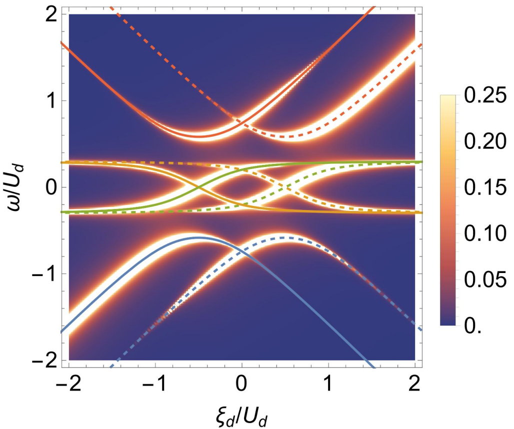


J. Barański et al, (2025).

Quasiparticle spectrum of spin-↓ electrons obtained for $\epsilon_M \neq 0$.

OVERLAPPING MAJORANA MODES, $\epsilon_M \neq 0$

Hybrid structure: Anderson impurity + short topological nanowire



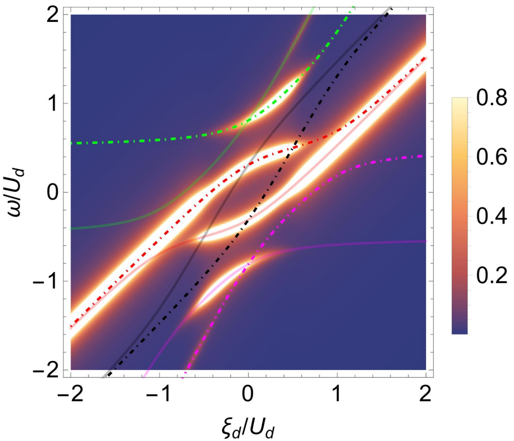
J. Barański et al, (2025).

Quasiparticle spectrum of spin-↓ electrons obtained for $\epsilon_M \neq 0$.

Appearance of two bowtie features inside the topological gap.

OVERLAPPING MAJORANA MODES, $\epsilon_M \neq 0$

Hybrid structure: Anderson impurity + short topological nanowire



J. Barański et al, (2025).

Quasiparticle spectrum of spin-↑ electrons obtained for $\epsilon_M \neq 0$.

OVERLAPPING MAJORANA MODES, $\epsilon_M \neq 0$

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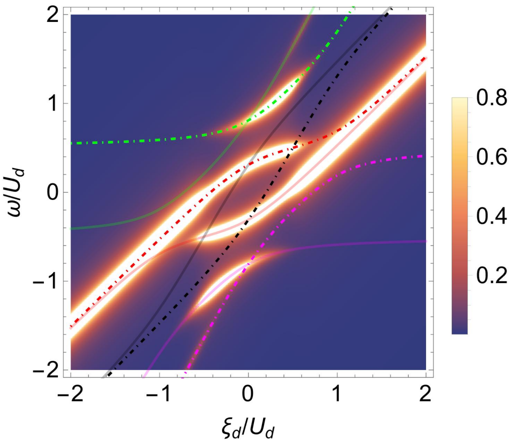


J. Barański et al, (2025).

Quasiparticle spectrum of spin-↑ electrons obtained for $\epsilon_M \neq 0$.

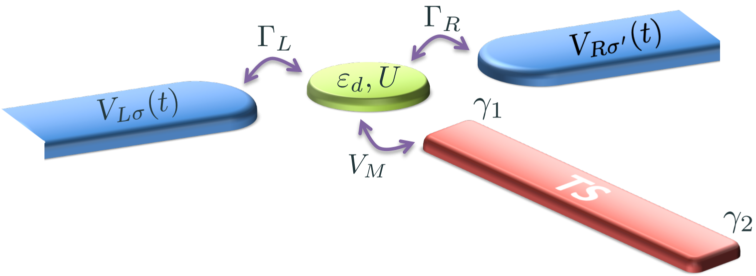
Majorana quasiparticles are completely absent.

Kondo vs Majorana

(means to distinguish them)

MAJORANA SIGNATURES IN AC-CONDUCTANCE

Quantum dot coupled to the topological nanowire under ac-voltage

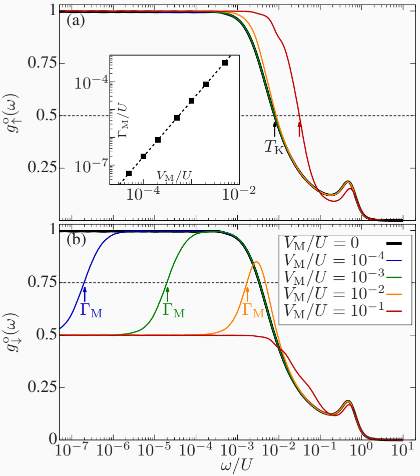


Question:

Can we resolve Majorana and Kondo states in ac-response ?

K.P. Wójcik, T. Domański, I. Weymann, Phys. Rev. B 109, 075432 (2024).

CONDUCTANCE OF *ac*-DRIVEN JUNCTION



Spin-resolved conductance: **Signatures of the Coulomb peak and the Kondo effect can be clearly distinguished at finite-frequencies.**

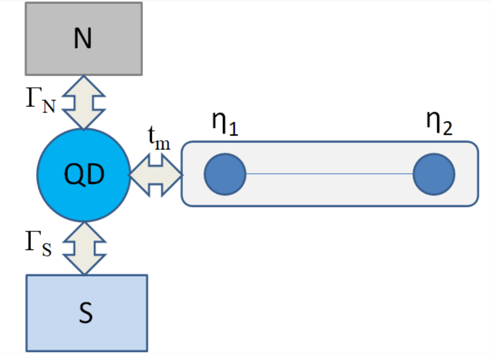
K.P. Wójcik, T. Domański, I. Weymann, Phys. Rev. B 109, 075432 (2024).

Time - resolved effects

(with Majorana modes)

TIME-RESOLVED LEAKAGE OF MAJORANA MODE

Hybrid structure: **quantum dot attached to topological nanowire**



Question:

How much time does it take to transfer the Majorana mode on QD ?

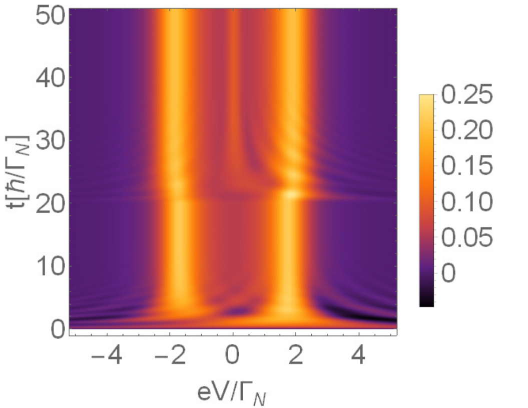
J. Barański, M. Barańska, T. Zienkiewicz, R. Taranko, T.Domański, PRB 103, 235416 (2021).

TIME-RESOLVED LEAKAGE OF MAJORANA MODE

Transient effects:

$\Rightarrow$ **at $t = 0$ QD is coupled to the external N and S electrodes,**

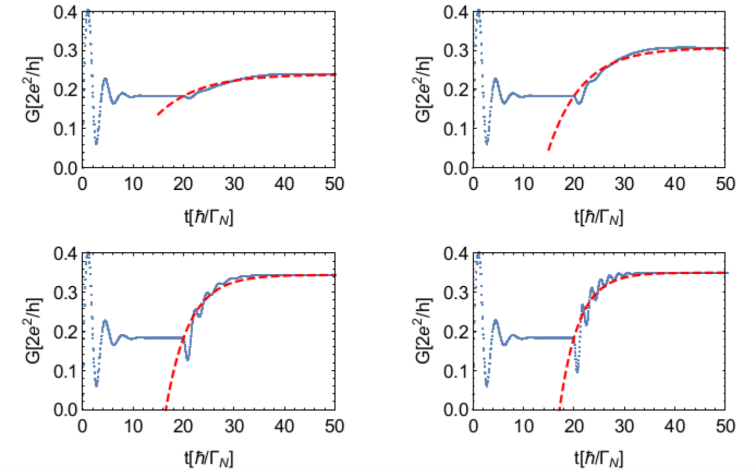
$\Rightarrow$ **at $t = 20$ topological nanowire is attached to N-QD-S setup.**



Gradual development of the trivial (Andreev) and topological (Majorana) states manifested in the differential conductance.

TIME-RESOLVED LEAKAGE OF MAJORANA MODE

Time-dependent zero-bias conductance



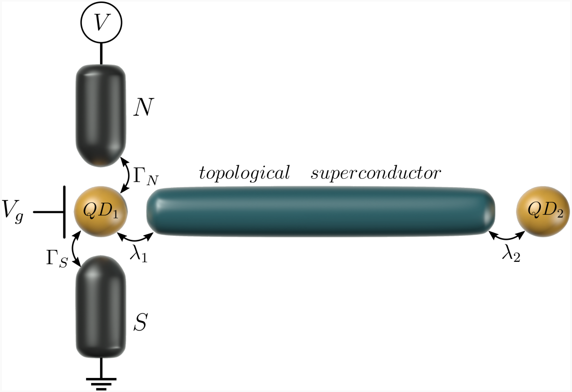
Majorana zero-bias feature establishes in about nanoseconds.

J. Barański, M. Barańska, T. Zienkiewicz, R. Taranko, T.Domański, PRB 103, 235416 (2021).

Distant cross-correlations

/ transmitted via Majorana modes /

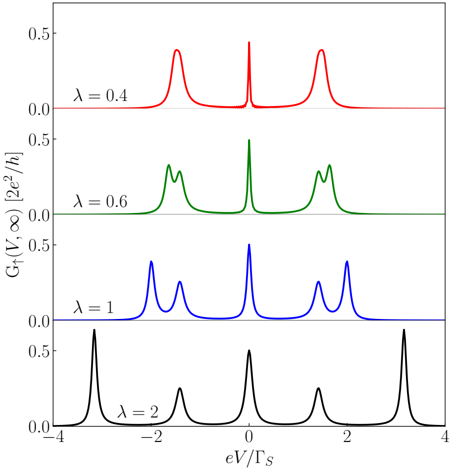
Two quantum dots interconnected via topological superconductor



Question: Is any nonlocal communication transmitted between QD_1 and QD_2 through the Majorana boundary modes ?

R. Taranko, K. Wrześniewski, I. Weymann, T. Domański, Phys. Rev. B 110, 035413 (2024).

STEADY-LIMIT CONDUCTANCE

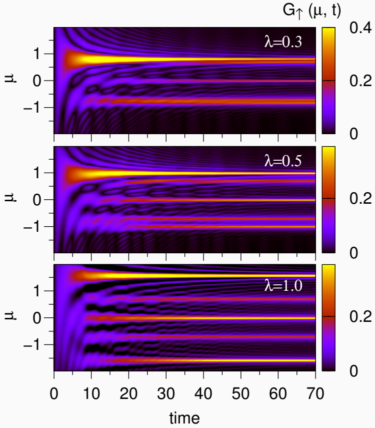


Differential conductance $G(V, t \rightarrow \infty)$ versus bias V for several couplings λ between $\mathrm{QD}_{1,2}$ and topological superconductor.

R. Taranko, K. Wrześniewski, I. Weymann, T. Domański, Phys. Rev. B 110, 035413 (2024).

TIME-RESOLVED CONDUCTANCE

Time-dependent conductance of the biased N-QD$_1$-S junction

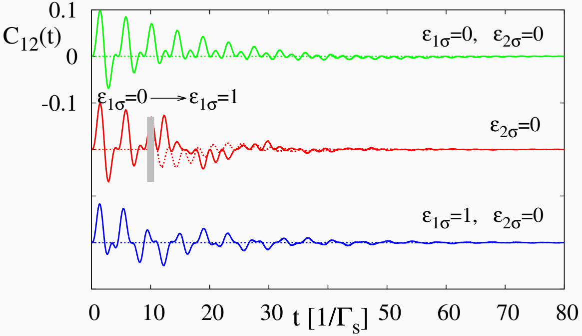


Signatures of the (trivial) molecular bound states and (topological) Majorana mode obtained for $\varepsilon_1 = 0$, $\varepsilon_2 = 2$.

R. Taranko, K. Wrześniewski, I. Weymann, T. Domański, Phys. Rev. B 110, 035413 (2024).

NONLOCAL CROSS-CORRELATIONS

Evolution of the interdot electron pairing $C_{12}(t) = \left\langle \hat{d}_{1\downarrow}\hat{d}_{2\uparrow} \right\rangle$



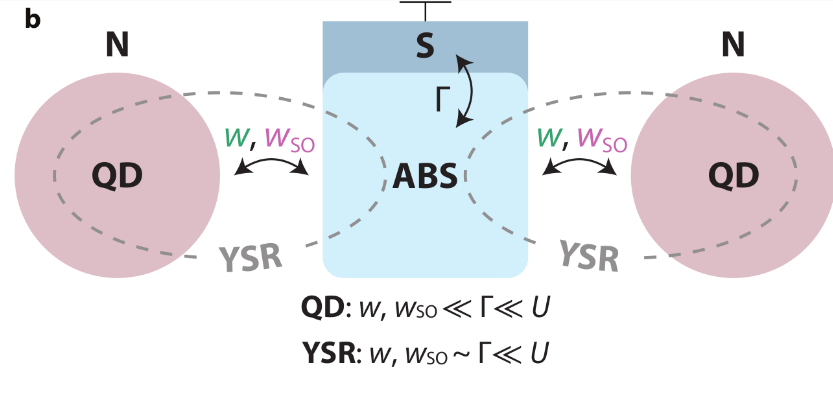
The nonlocal electron pairing persists only over a short transient time-scale. It could be detected by crossed Andreev refelections.

R. Taranko, K. Wrześniewski, I. Weymann, T. Domański, Phys. Rev. B 110, 035413 (2024).

Recent activities

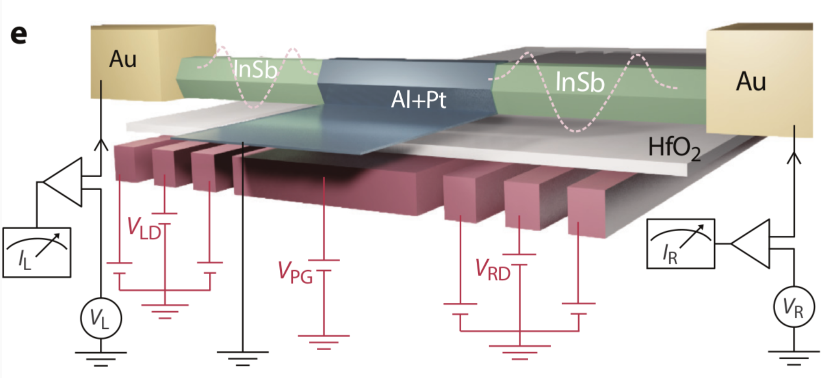
MINIMAL KITAEV CHAIN

Effective triplet pairing can be realized using two quantum dots interconnected by superconductor (Poor Man's Majorana states)



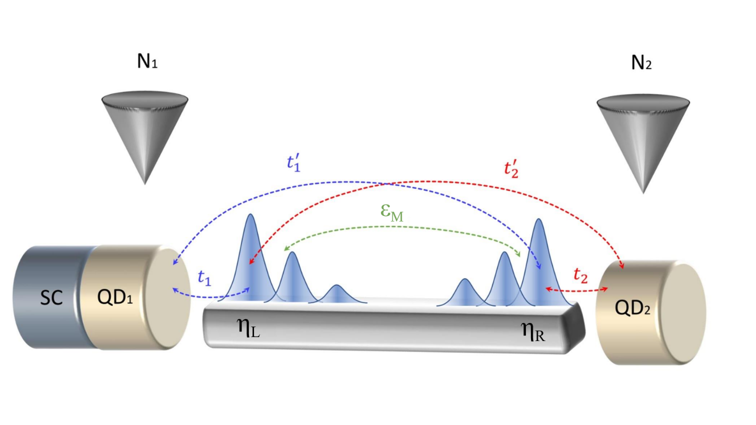
T. Dvir, ... & L.P. Kouwenhoven, Nature 614, 445 (2023).

Two spin-polarized quantum dots in an InSb nanowire strongly coupled by elastic co-tunneling and crossed Andreev reflection



T. Dvir, ... & L.P. Kouwenhoven, Nature 614, 445 (2023).

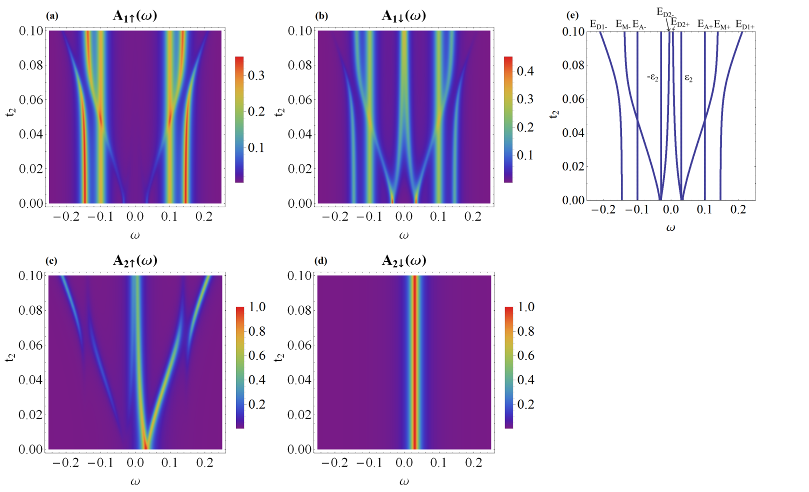
QUASIPARTICLE SPECTRUM OF QUANTUM DOTS



Issue: **Molecular quasiparticle spectrum of the quantum dots connected via the overlapping Majorana modes**

G. Górski, K.P. Wójcik, J. Barański, I. Weymann & T. Domański, Sci. Rep. 14, 13848 (2024).

QUASIPARTICLE SPECTRUM OF QUANTUM DOTS



Quasiparticles are shared by both quantum dots, however, appearing with different spectral weights.

G. Górski, K.P. Wójcik, J. Barański, I. Weymann & T. Domański, Sci. Rep. 14, 13848 (2024).

QUANTUM ENTANGLEMENT OF DOUBLE DOTS

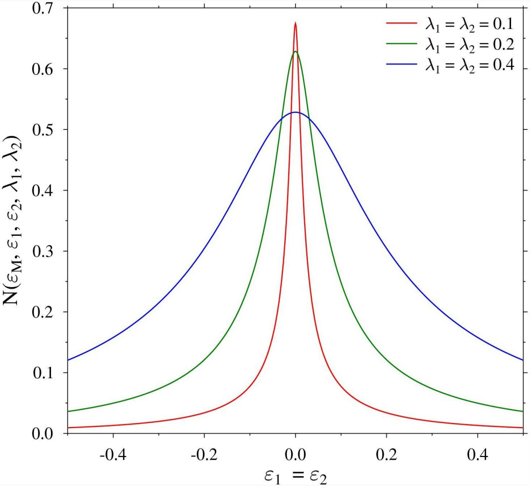
Setup: **Quantum dots interconnected via short topological nanowire**

Issue: **Quantum dots acquire entanglement via Majorana qps**

C. Jasiukiewicz, A. Sinner, I. Weymann, T. Domański & L. Chotorlishvili, Phys. Rev. B 111, 075415 (2025).

QUANTUM ENTANGLEMENT OF DOUBLE DOTS

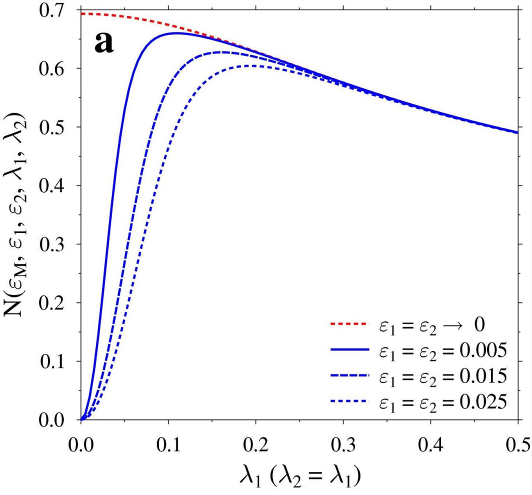
Setup: Quantum dots interconnected via short topological nanowire



Logarithmic negativity versus the energy levels QD's obtained for $\varepsilon_M \neq 0$.

QUANTUM ENTANGLEMENT OF DOUBLE DOTS

Setup: Quantum dots interconnected via short topological nanowire



Logarithmic negativity versus the coupling $\lambda_1 = \lambda_2$ obtained for $\varepsilon_M \neq 0$.

SUMMARY (PART 2)

Quantum dots attached to topological superconductors:

$\Longrightarrow$ **allow for leakage of Majorana mode(s)**

(no competition with on-site repulsion),

$\Longrightarrow$ **become nonlocally cross-correlated**

(but only under non-equilibrium conditions),

$\Longrightarrow$ **acquire quantum entanglement**

(solely via short topological superconductors).