DYNAMICAL QUANTUM PHASE TRANSITIONS IN SUPERCONDUCTING NANOSTRUCTURES

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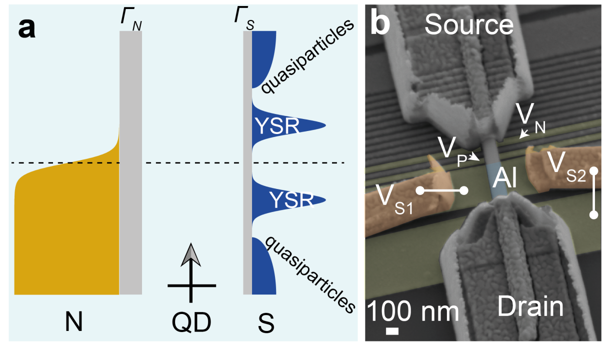
"Seminar on Coherence-Correlations-Complexity"

Wrocław, 13 Jan. 2021

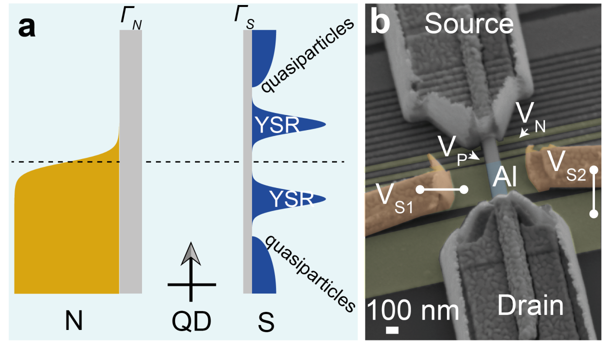
Superconducting nanostructures: examples

Small (nanoscopic) objects attached to bulk superconductor



HETEROSTRUCTURES WITH SUPERCONDUCTOR(S)

Small (nanoscopic) objects attached to bulk superconductor



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

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

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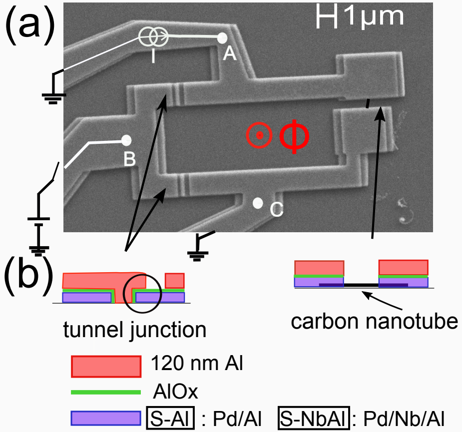
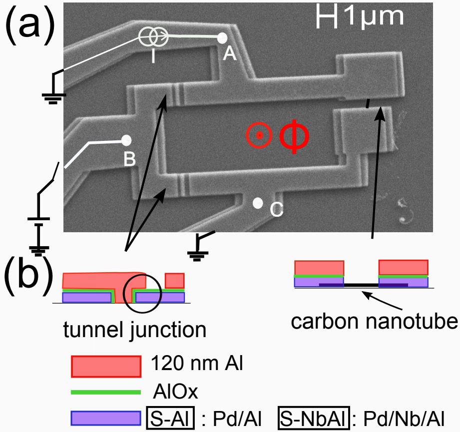


HETEROSTRUCTURES WITH SUPERCONDUCTOR(S)



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

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

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:**

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- **This is manifested spectroscopically by:**

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

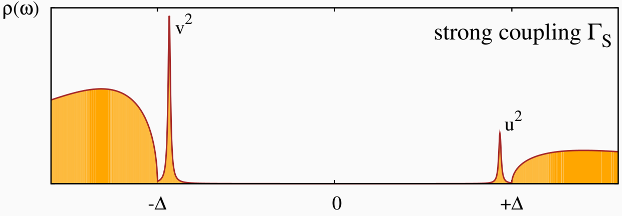
- **originating from:**

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

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

IN-GAP STATES

Spectrum of a single impurity coupled to bulk superconductor:



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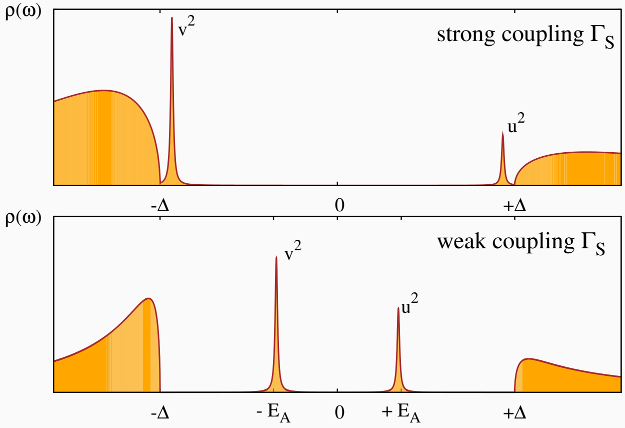
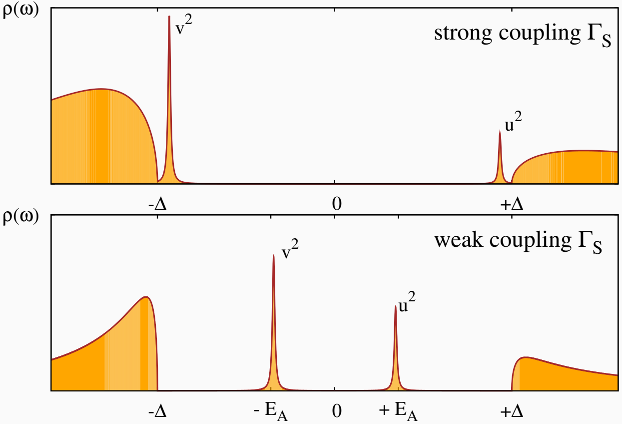


Bound states appearing in the subgap region $-\Delta < \omega < \Delta$.

Spectrum of a single impurity coupled to bulk superconductor:



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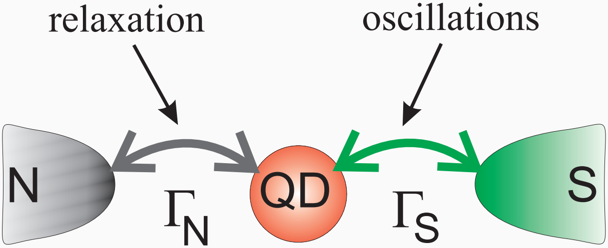
Yu-Shiba-Rusinov (Andreev) bound states

Characteristic temporal scales

Consider a sudden coupling of QD to external leads



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

TRANSIENT EFFECTS OF IN-GAP STATES

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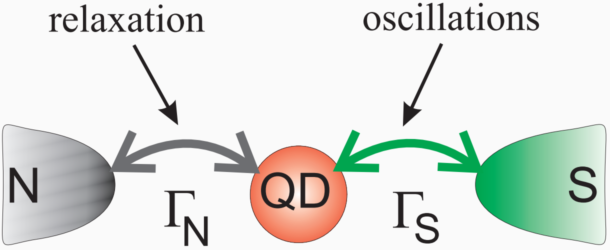

R. Taranko and T. Domański, Phys. Rev. B 98, 075420 (2018).

- **how much time does it take to create in-gap states?**

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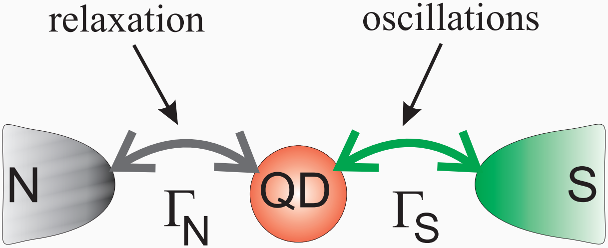
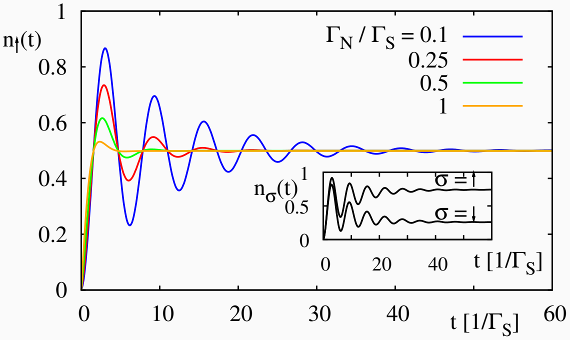


R. Taranko and T. Domański, Phys. Rev. B 98, 075420 (2018).

- how much time does it take to create in-gap states?
- are there any characteristic time-scales?

RELAXATION VS QUANTUM OSCILLATIONS

Time-dependent charge of an initially empty QD

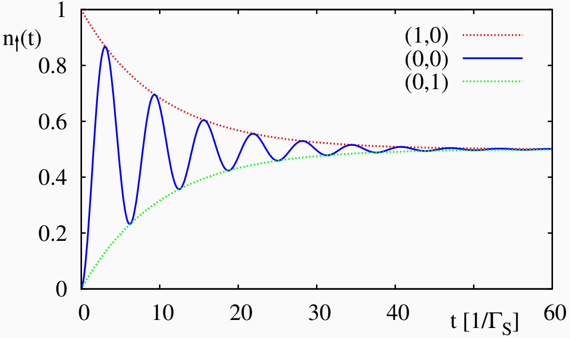


- **relaxation time is proportional to $1/\Gamma_N$**
- **oscillations depend on energies of in-gap states**

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

RELAXATION VS QUANTUM OSCILLATIONS

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



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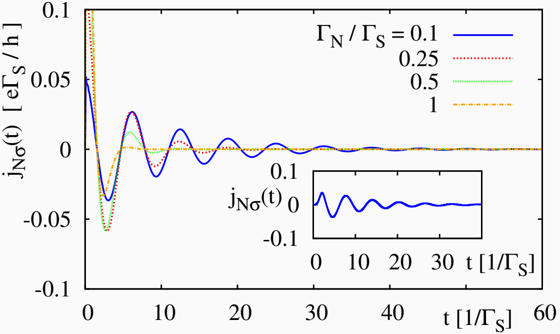
Time-dependent charge current of unbiased junction



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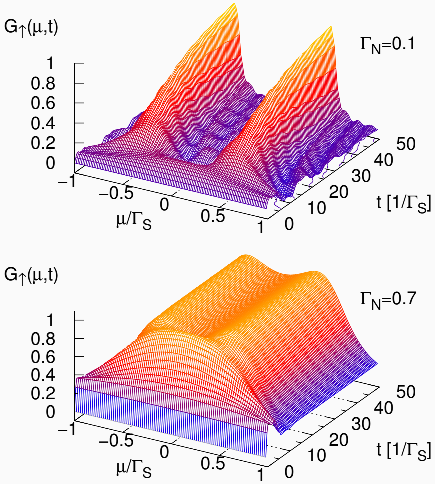
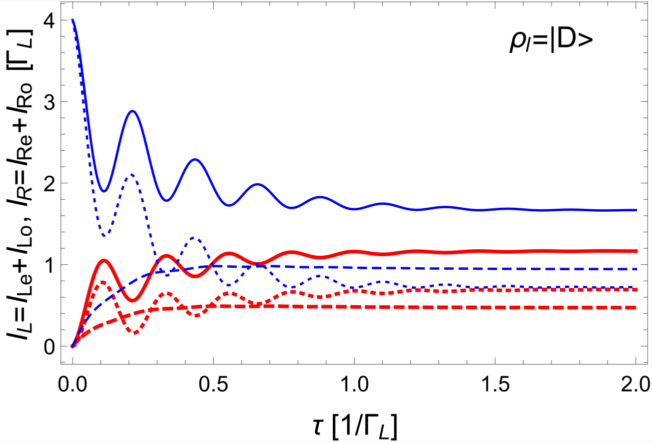
EXPERIMENTALLY ACCESSIBLE QUANTITIES

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

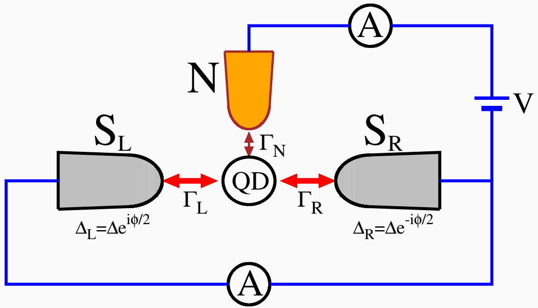


Transient currents from *'Waiting Time Distribution'* approach

G. Michałek, B. Bułka, T. Domański & K.I. Wysokiński, Phys. Rev. B 101, 235402 (2020).

Josephson-type structures

Quantum dot embedded into Josephson & Andreev circuits.

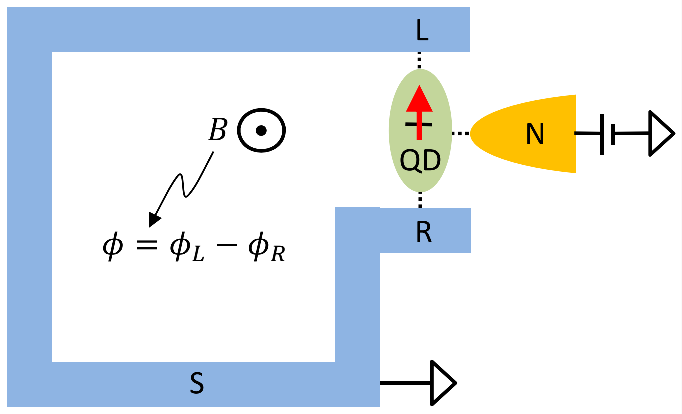


T. Domański ... V. Janiš & T. Novotný, Phys. Rev. B 95, 045104 (2017);

P. Zalom, V. Pokorný & T. Novotný, Phys. Rev. B 102, (2021) *to appear*

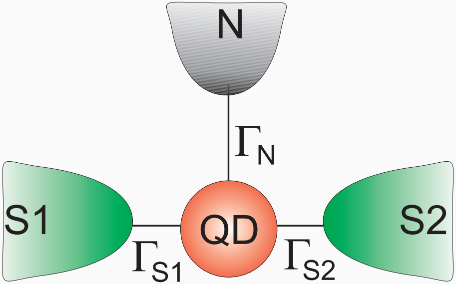
SCHEME FOR EMPIRICAL REALIZATION

Scheme for feasible realization of Josephson & Andreev circuits



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

PHASE-CONTROLLED TRANSIENT EFFECTS

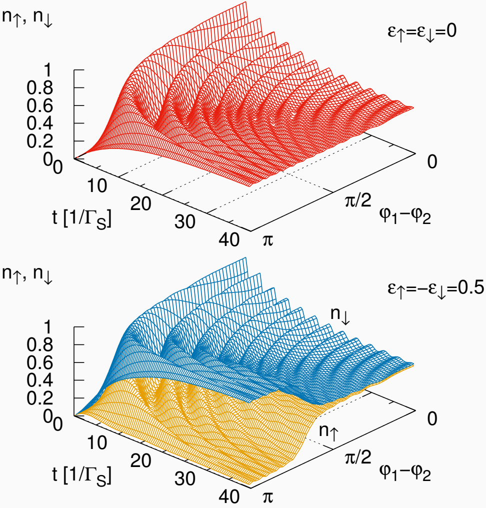


R. Taranko, T. Kwapiński & T. Domański, Phys. Rev. B 99, 165419 (2019).

Physical issue:

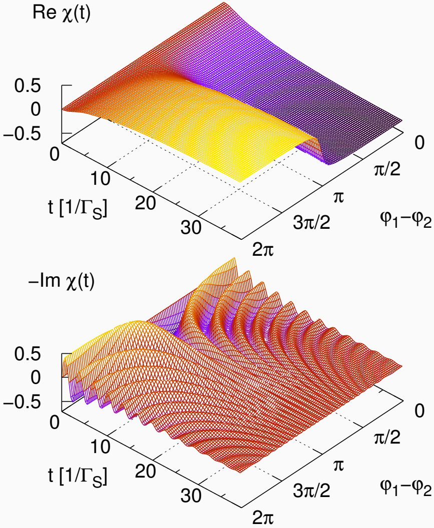
- **phase tunable evolution of in-gap states**

Phase & time dependent QD occupancy $n_\sigma(t)$



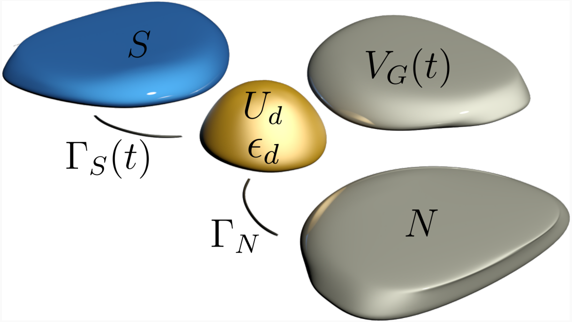
R. Taranko, T. Kwapiński & T. Domański, Phys. Rev. B 99, 165419 (2019).

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

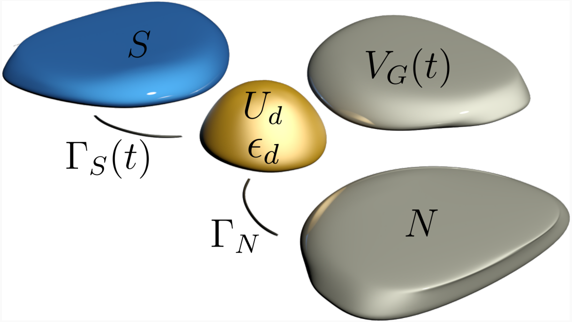


R. Taranko, T. Kwapiński & T. Domański, Phys. Rev. B 99, 165419 (2019).

Dynamics of correlated nanosuperconductors

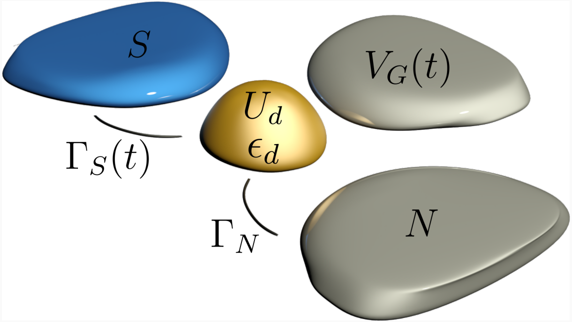


Quantum quench protocols:



Quantum quench protocols:

$\Rightarrow$ **sudden coupling to superconductor** $0 \to \Gamma_S$



Quantum quench protocols:

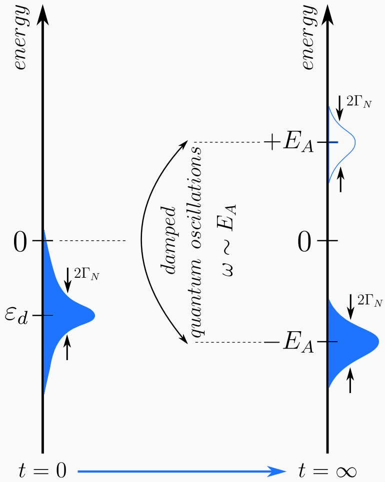
$\Rightarrow$ **sudden coupling to superconductor** $0 \to \Gamma_S$

$\Rightarrow$ **abrupt application of gate potential** $0 \to V_G$

K. Wrześniewski, B. Baran, R. Taranko, T. Domański & I. Weymann, arXiv:2007.10747 (2020).

A) BUILDUP OF IN-GAP STATES

Schematics of the Andreev states formation induced by quench $0 \to \Gamma_S$



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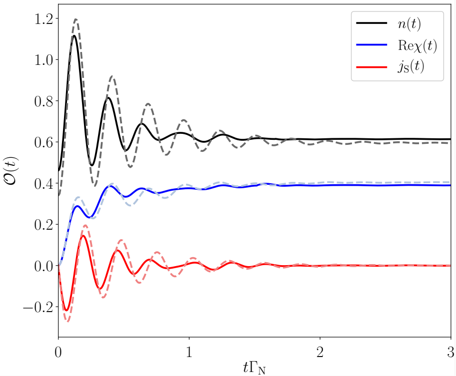
A) BUILDUP OF IN-GAP STATES

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

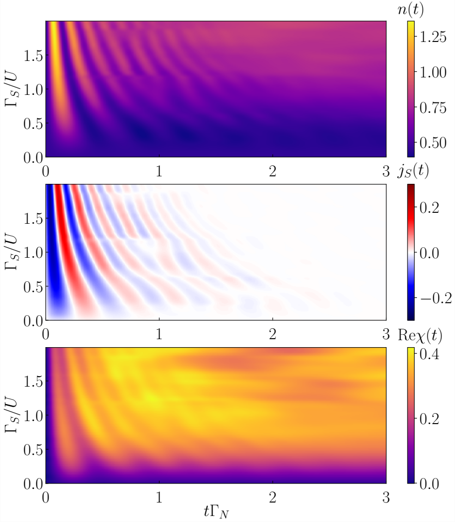


solid lines - time dependent NRG

dashed lines - Hartree-Fock-Bogolubov

K. Wrześniewski, B. Baran, R. Taranko, T. Domański & I. Weymann, arXiv:2007.10747 (2020).

tNRG results obtained for $\varepsilon_d = 0$



QD charge $n(t)$

charge current $j_S(t)$

from supercond. to QD

on-dot pairing

$\chi(t) \equiv \langle d_\downarrow d_\uparrow \rangle$

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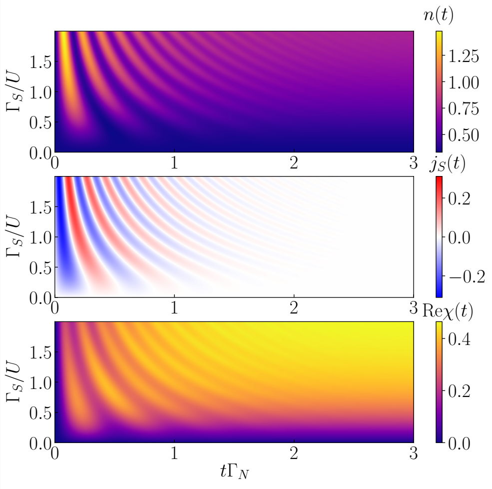
Hartree-Fock-Bogolubov results for $\varepsilon_d = 0$



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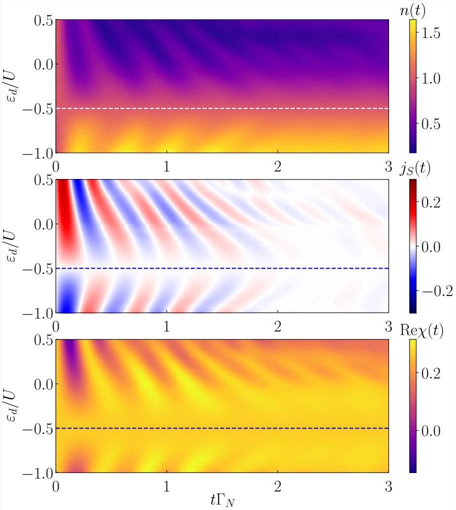

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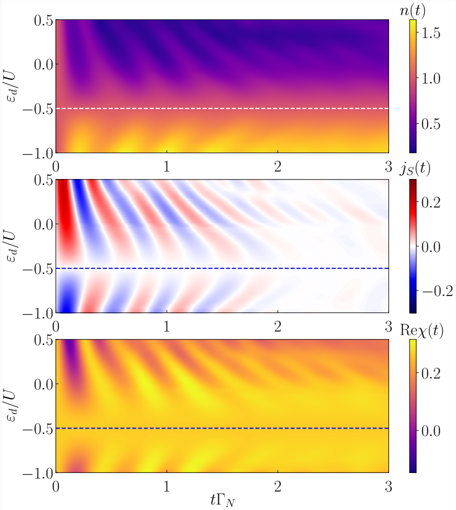

QD charge $n(t)$

Notice reversal of $j_S(t)$!

(dynamical 0-π transition)

on-dot pairing

$\chi(t) = \langle d_\downarrow d_\uparrow \rangle$

Quantum phase transition

SINGLY OCCUPIED VS BCS-TYPE CONFIGURATIONS

The proximitized quantum dot can described by

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

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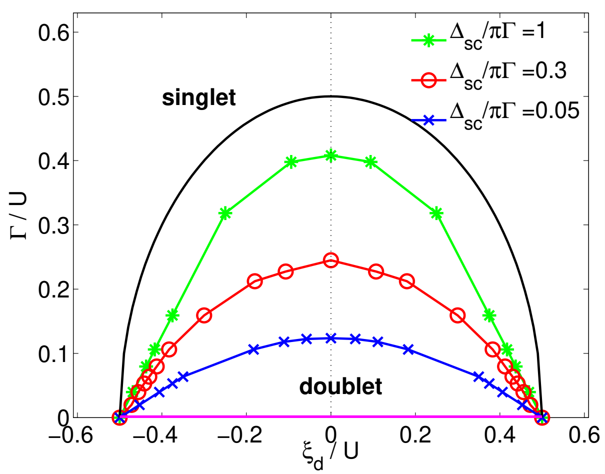
Upon varrying the parameters ε_d, U_d or Γ_S there can be induced quantum phase transition between these doublet/singlet states.

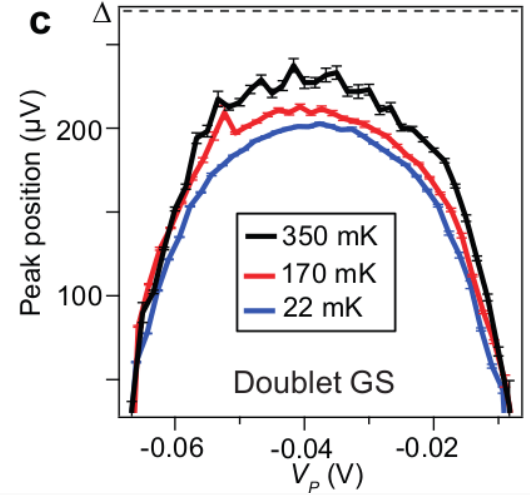
Singlet-doublet quantum phase transition: NRG results



$$\xi_d \equiv \varepsilon_d - U/2$$

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

QUANTUM PHASE TRANSITION: EXPERIMENT



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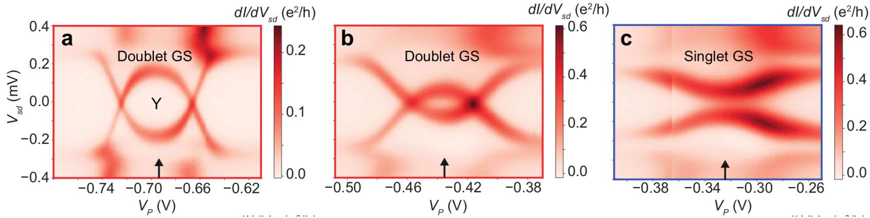
SINGLET VS DOUBLET: EXPERIMENT

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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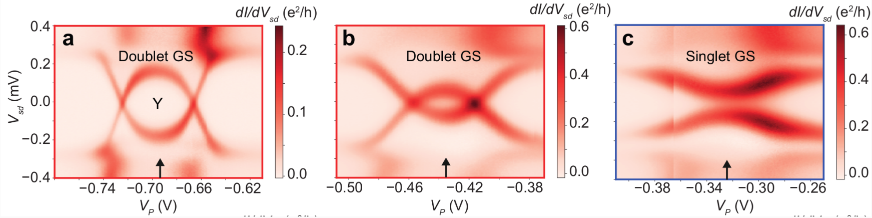

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Crossings of in-gap states correspond to the singlet-doublet QPT.

Dynamical quantum phase transition

QUENCH DYNAMICS

Initially, for $t < 0$:

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

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Loschmidt amplitude

STATIONARY VS DYNAMICAL PHASE TRANSITION

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

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Partition function

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

Loschmidt amplitude

$$\left\langle \Psi_0 \middle| e^{-it\hat{H}} \middle| \Psi_0 \right\rangle$$

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Loschmidt echo $L(t)$

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Free energy $F(T)$

$$\mathcal{Z} \equiv e^{-\beta F(T)}$$

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Return rate $\lambda(t)$

$$L(t) \equiv e^{-N\lambda(t)}$$

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

where

$$\beta = \frac{1}{k_B T} \longleftrightarrow it$$

Free energy $F(T)$

$$\mathcal{Z} \equiv e^{-\beta F(T)}$$

Critical temperature T_c

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

Loschmidt amplitude

$$\left\langle \Psi_0 \middle| e^{-it\hat{H}} \middle| \Psi_0 \right\rangle$$

Loschmidt echo $L(t)$

$$L(t) = \left| \left\langle \Psi_0 \middle| e^{-it\hat{H}} \middle| \Psi_0 \right\rangle \right|^2$$

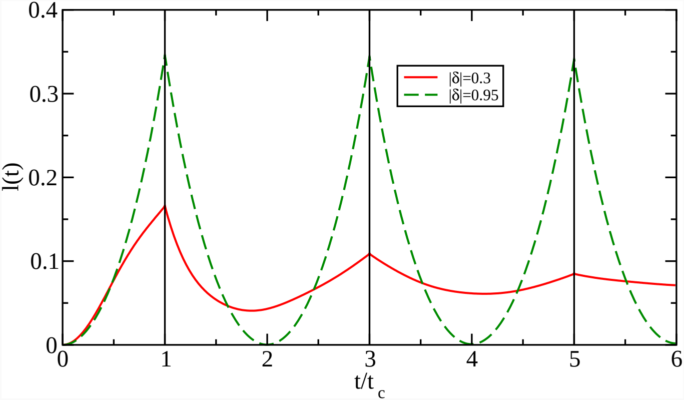
Return rate $\lambda(t)$

$$L(t) \equiv e^{-N\lambda(t)}$$

Critical time t_c

nonanalytical $\lim_{t \to t_c} \lambda(t)$

EXAMPLE 1: SSH (QUENCH: NONTOPO → TOPO)



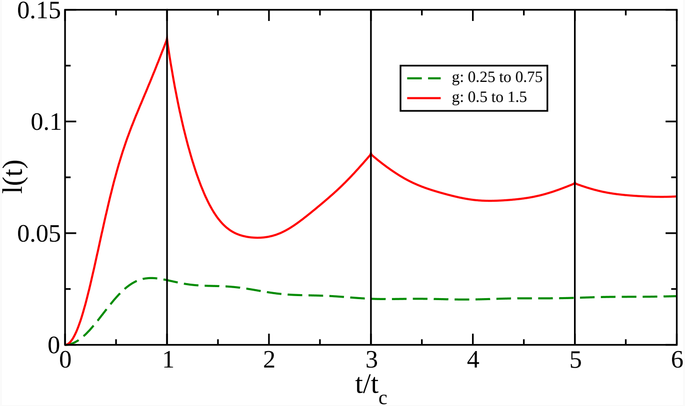
$$\hat{H} = -J \sum_j \left[\left(1 + \delta e^{i\pi j}\right) \hat{c}_j^\dagger \, \hat{c}_{j+1} \; + \; \text{h.c.} \right]$$

solid red line $|\delta| = 0.3$

dashed green line $|\delta| = 0.95$

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

EXAMPLE 2: ISING MODEL (TRANSITION FOR $g = 1$)

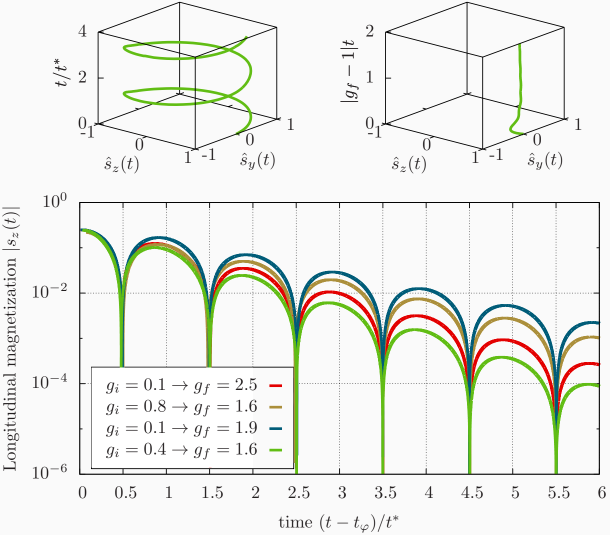


$$\hat{H} = -\frac{1}{2}\sum_{j=1}^{N-1} \hat{\sigma}_j^z\ \hat{\sigma}_{j+1}^z\ +\ \frac{g}{2}\sum_{j=1}^{N} \hat{\sigma}_j^x$$

solid red line - **across a phase transition**

dashed green line - **inside a phase transition**

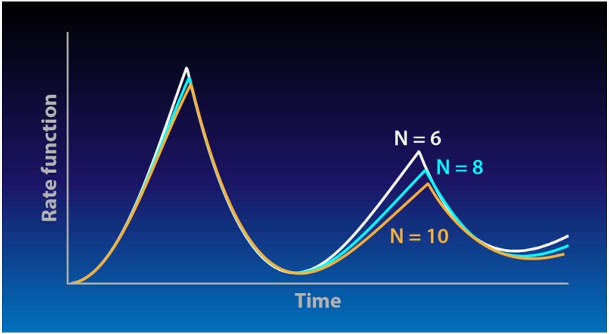
EXAMPLE 2: ISING MODEL (DYNAMICAL ORDER)



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

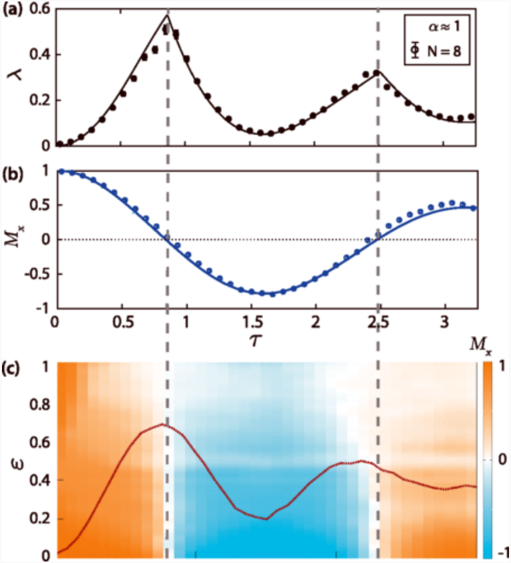
EXAMPLE 2: ISING MODEL (EXPERIMENT)

R. Blatt with coworkers [Austrian Acad. Sciences, Innsbruck] have observed dynamical quantum phase transitions in a linear string of N calcium-40 ions, with N up to 10. They measured the so-called rate function of the system as a function of time for N=6, N=8, and N=10. The singularities at two certain critical times that the measured function exhibited indicate that dynamical quantum phase transitions occurred at these times.



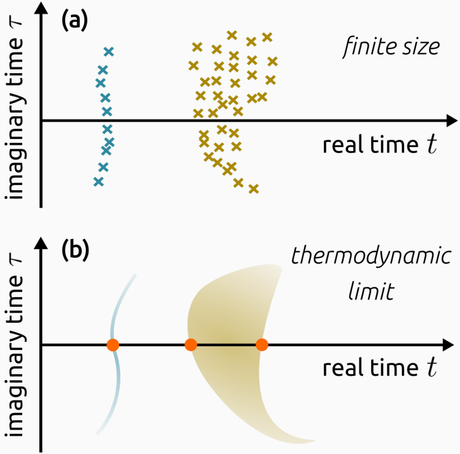
V. Gurarie, Physics 10, 95 (2017).

EXAMPLE 2: ISING MODEL (EXPERIMENT)



P. Jurcevic et al, Phys. Rev. Lett. 119, 080501 (2017).

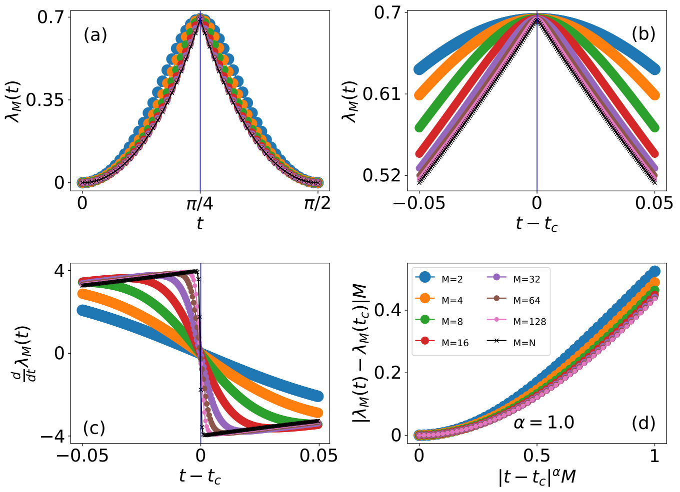
WHAT ABOUT FINITE-SIZE SYSTEMS ?



Schematic view of "Fisher zeros" obtained for the Loschmidt amplitude $\left\langle \Psi_0 | e^{-iz\hat{H}} | \Psi_0 \right\rangle$ in the complex plane $z = t + i\tau$.

Marcus Heyl, Rep. Prog. Phys. 81, 054001 (2018).

ISING MODEL: DQPT OF FINITE-SIZE SYSTEM

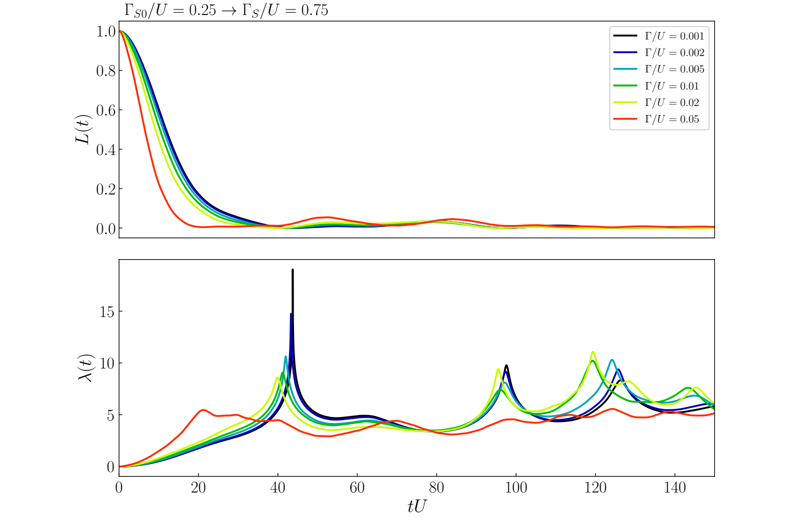


"Local measures of dynamical quantum phase transitions"

J.C. Halimeh, D. Trapin, M. Damme & M. Heyl, arXiv:2010.07307 (2020).

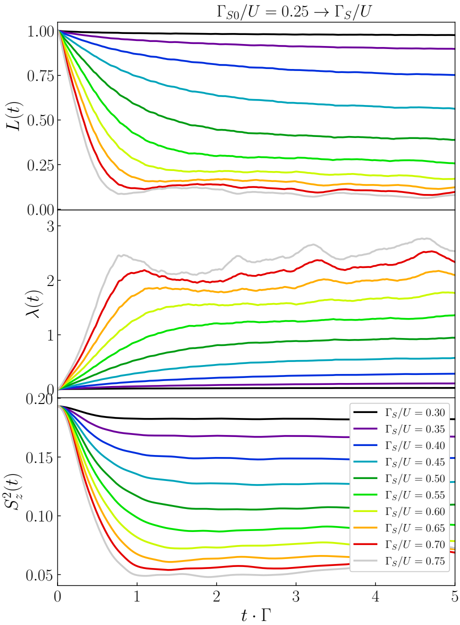
Singlet-doublet DQPT

tNRG RESULTS: ABRUPT CHANGE OF Γ_S



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

tNRG RESULTS: ABRUPT CHANGE OF Γ_S



Loschmidt echo

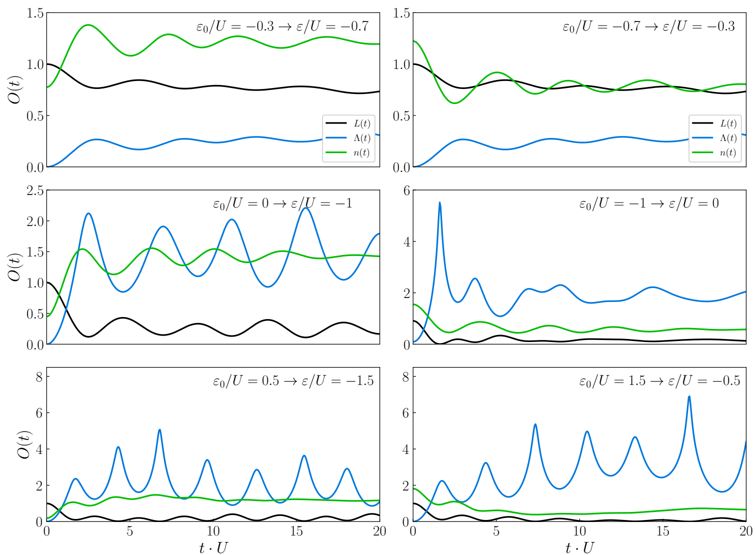
$L(t) \equiv |\langle \Psi(t)|\Psi(0)\rangle|^2$

Return rate

$|L(t)| \equiv e^{-N\lambda(t)}$

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

tNRG RESULTS: ABRUPT CHANGE OF ε_d



back **forth**

Issues to be clarified:

QUESTIONS (OF THIS ONGOING PROJECT)

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- what physical quantity does control t_c
- is critical time t_c really periodic ?
- is there any dynamical order ?
- empirical means to detect dynamical QPT ?

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- and ...
- **can anybody help us ?**

CONCLUSIONS

Quenching N-QD-S (and S_L-QD-S_R) nanostructures:

- **rescales/develops in-gap quasiparticles**

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Quenching N-QD-S (and S_L-QD-S_R) nanostructures:

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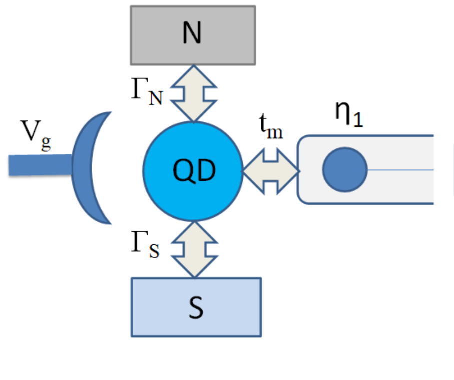
- **and may undergo dynamical QPT** **(upon varying ground states)**

$\Longrightarrow$ **These phenomena are manifested in transport properties.**

Other related topics

Abrupt coupling (t_m) of quantum dot to topological SC nanowire



J. Barański, ... & T. Domański,

arXiv:2012.03077 (2020).

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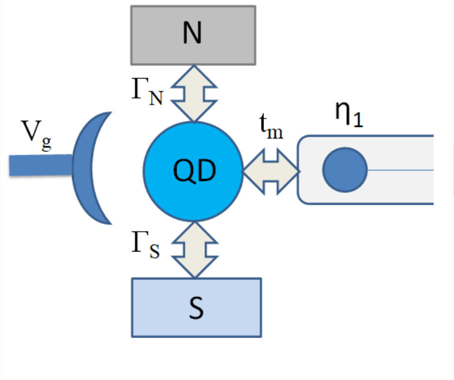

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- time needed for Majorana leakage on QD,

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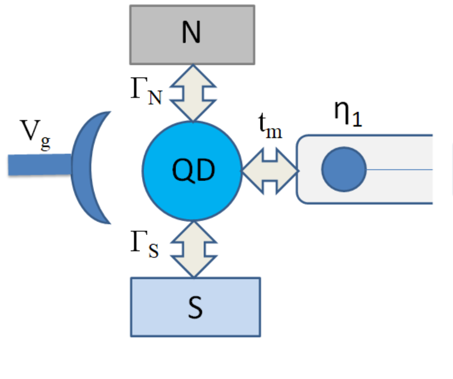
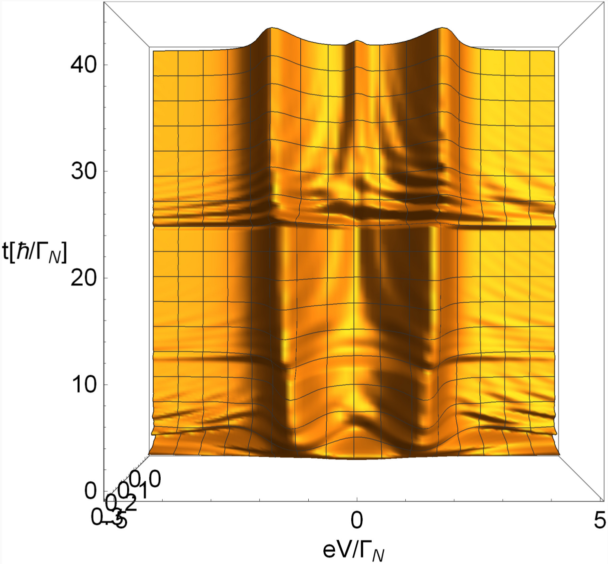


J. Barański, ... & T. Domański,

arXiv:2012.03077 (2020).

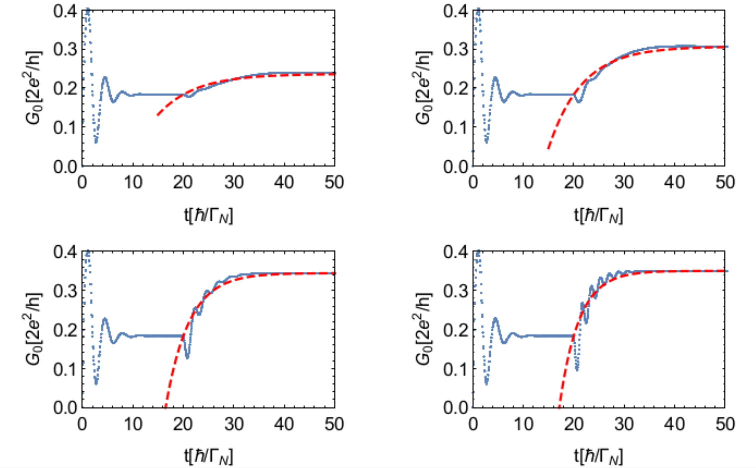
- time needed for Majorana leakage on QD,
- time-resoveld zero bias conductance.

TIME-RESOLVED MAJORANA LEAKAGE



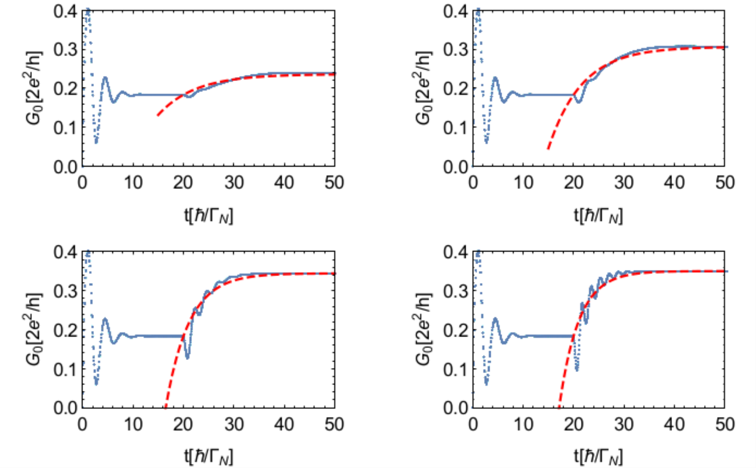
The differential Andreev conductance vs bias voltage V and time

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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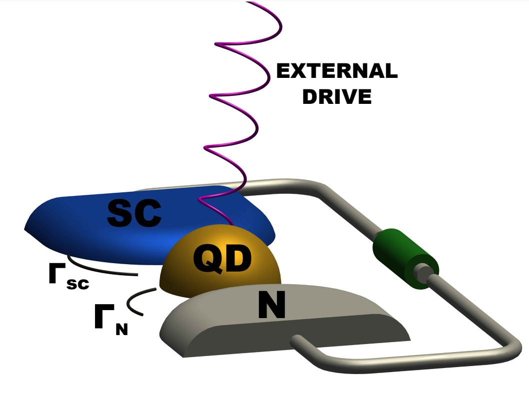
For realistic systems such leakage time takes 2-20 nanoseconds.

Floquet description of in-gap states

Quantum impurity with periodically oscillating energy level

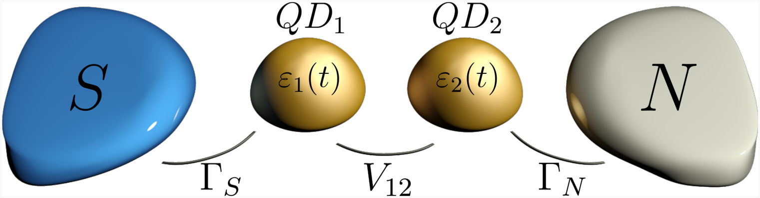


$$\varepsilon(t) = \varepsilon_0 + V \times \cos(\omega t)$$

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

Proximitized double QDs (qubits)

Quantum quench scenarios: gating, biasing & driving



Methods:

- Floquet approach,
- Keldysh technique,
- machine learning

ACKNOWLEDGEMENTS

- dynamics of in-gap states (transients, periodic driving, etc.)

⟹ R. Taranko (Lublin), B. Baran (Lublin),

- dynamical singlet-doublet phase transition

⟹ K. Wrześniewski (Poznań), I. Weymann (Poznań),

N. Sedlmayr (Lublin),

- time-dependent leakage of Majorana qps

⟹ J. Barański (Dęblin), M. Barańska (Dęblin),

- dynamical topological phase transitions

⟹ A. (Kobiałka), G. Wlazłowski (Warsaw).