Fluctuations in quasi-1-dimensional superconductors

Konstantin Arutyunov

Moscow Institute of Electronics and Mathematics HSE
и
Kapitza Institute for Physical Problems

Collaborators:
J. Lehtinen, T. Rantala (experiment)
A. Zaikin, A. Semenov, A. Radkevich (theory)

Ginzburg Centennial Conference, 31 May 2017, Moscow

Outline

1. Introduction

Fluctuations in superconductors

Quantum Phase Slip concept

2. Impact of phase slips

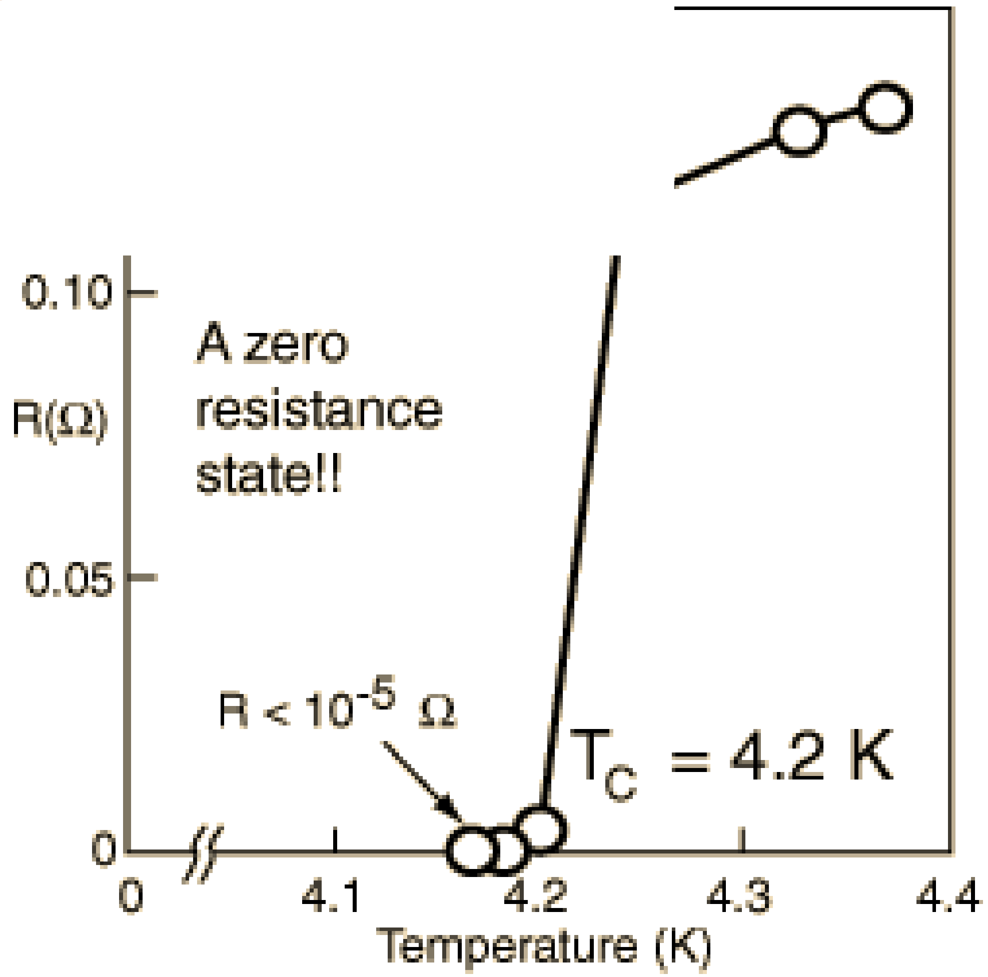
R(T)

Persistent currents

3. Impact of modulus (?) fluctuations

DOS and superconducting gap

R(T) transition



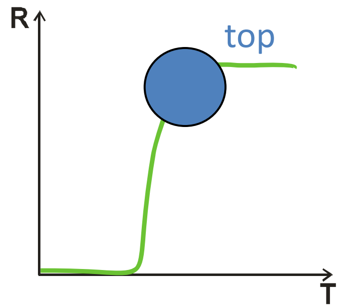
H. K. Onnes,
Commun. Phys. Lab.12,120, (1911)

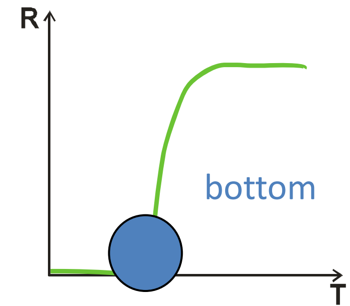
Fluctuations vs. system dimensionality

For a superconductor dimensionality is set by the temperature - dependent coherence length $\xi(T)$.

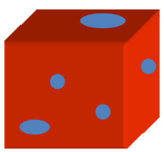
N normal metal

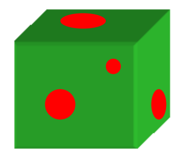
S superconductor



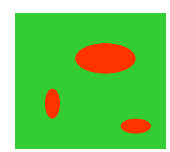


3D





2D



1D

S inclusions reduce the total system resistance →

rounded top

$\sigma_{FLUCT} \sim (T-T_c)^{-(2-D/2)}$

(Aslamazov – Larkin)

no contribution of N inclusions: normal current is shunted by supercurrent →

abrupt bottom

Topic of the talk

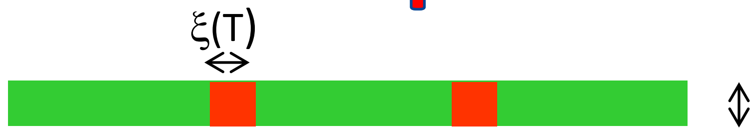
N inclusions block the supercurrent →

rounded bottom

(Langer – Ambegaokar)

Fluctuations in a 1D supercondcutor

Long 1D wire of cross section σ



$\sqrt{\sigma} < \xi(T) << L$

If the wire is infinitely long, there is always a finite probability that in some fragment(s) the magnitude of the order parameter instantly becomes zero and the phase changes by 2π

The minimum length the superconductivity can be destroyed is the coherence length $\xi(T)$

The minimum energy corresponds to destruction of superconductivity in a volume $\xi(T)\ \sigma$:
$\Delta F = B_c^2\ \xi(T)\ \sigma$, where $B_c(T)$ is the critical field

In the limit rare events the probability of the process $P(T) \sim \exp(-\Delta F / \mathcal{E})$

Thermal activation: $\mathcal{E} \sim k_B T$.

Important at $T \rightarrow T_c$.

Quantum: $\mathcal{E} \sim \Delta$.
Weak temperature dependence, exist even at $T \rightarrow 0$

In current state the particular manifestation of a quantum fluctuation when magnitude of the order parameter momentary nulls and phase changes by $\pm 2\pi$ is often called "phase slip"

Thermal activated phase slips

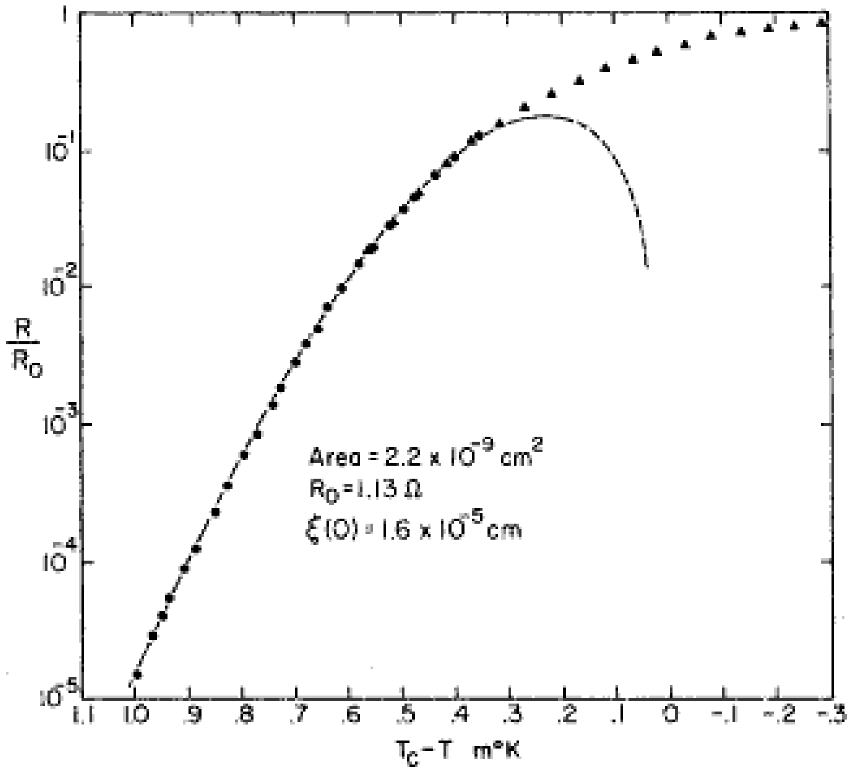
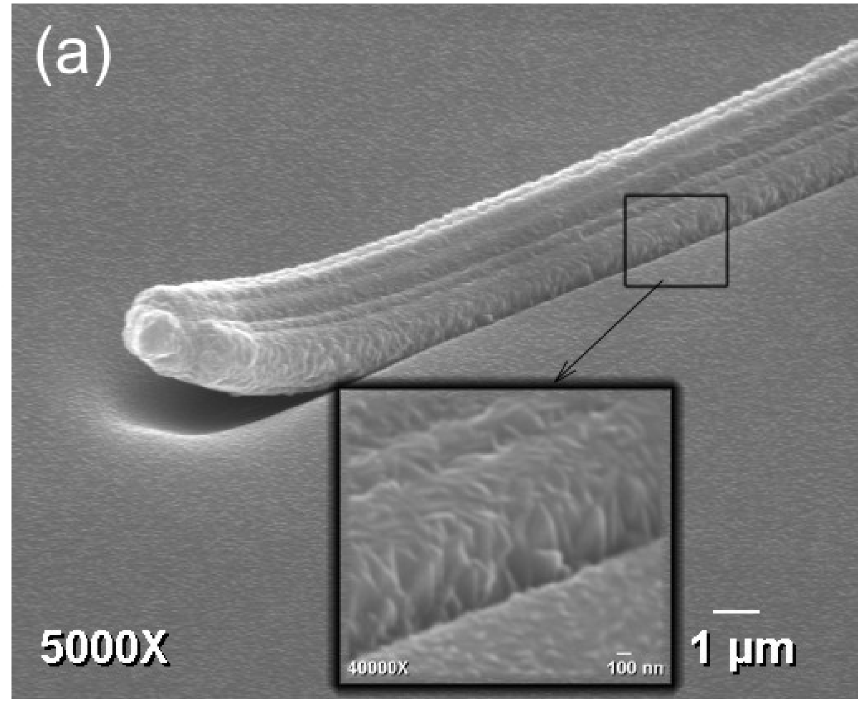


FIG. 3. Total resistance of tin crystal as a function of temperature. Closed circles, measured with superconducting femtovoltmeter; closed triangles, measured with nanovoltmeter. Line, two-parameter fit to M-H theory.



Tin whisker: $\sqrt{\sigma_{eff}} \sim 1\ \mu m$

Experiment:

J. E. Lukens, R.J. Warburton, W. W. Webb, Phys. Rev. Lett. ***25****, 1180 (1970)*

R. S. Newbower, M.R. Beasley, M. Tinkham, Phys. Rev. ***B 5****, 864, (1972)*

The results have been confirmed on multiple 'not too thin' samples

QPS contribution

Full model (G-Z) →

A. Zaikin, D. Golubev, A. van Otterlo, and G. T. Zimanyi, PRL **78**, 1552 (1997)
A. Zaikin, D. Golubev, A. van Otterlo, and G. T. Zimanyi, Uspexi Fiz. Nauk **168**, 244 (1998)
D. Golubev and A. Zaikin, Phys. Rev. **B 64**, 014504 (2001)

In the limit $R(T) \ll R_N$ QPSs are activated at a rate:
$\Gamma_{QPS} = E_{QPS}/h = \Delta_0[(R_Q L^2)/(R_N \xi^2)] \exp(-S_{QPS})$

$$R(T) = b\,\frac{\Delta_0(T) S_{QPS}^2 L}{\xi(T)} \exp\left\{-2S_{QPS}\right\}$$

where $S_{QPS} = A \cdot [(R_Q/\xi)/(R_N/L)]$, $R_Q = h/4e^2 = 6.45\ \mathrm{k}\Omega$, Δ = energy gap,

R_N = normal state resistance, L is wire length, $\xi = 0.85(\xi_0 l)^{1/2}$ is coherence length

$A \approx b \approx 1$ are numerical parameters.

Essentially, there is only one fitting parameter: $A \approx 1$.
For a dirty limit superconductor: $\Gamma_{QPS} \sim \exp(-A'\sigma T_c^{1/2}/\rho_N)$, where σ is the wire diameter and ρ_N is the normal state resitivity.
Materials with low T_c and high resitivity ρ_N are of advantage!

Existing experiments on QPS

J.M Graybeal, P. M. Mankiewich, R. C. Dynes, M. R. Beasley,

Phys. Rev. Lett. 59, 2697 (1987)

N. Giordano, et.al. PRL 61, 2137 (1988); Phys. Rev. Lett. 63, 2417 (1989); Phys. Rev. B 41, 6350 (1990); Phys. Rev. B 43, 160 (1991); Physica B 203, 460 (1994)

A. V. Herzog, P. Xiong, F. Sharifi, and R. C. Dynes

PRL, 76, 668 (1996)

A. Bezryadin, C. N. Lau and M. Tinkham, Nature 404, 971 (2000)

C. N. Lau, N. Markovic, M. Bockrath, A. Bezryadin, and M. Tinkham, Phys. Rev. Lett. 87, 217003 (2001)

MoGe nanowires

Nanowires of type-I superconductors

in situ grown granular metal wires

MoGe film on top of a carbon nanotube

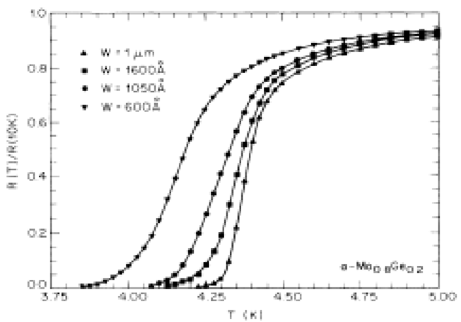


FIG. 1. Resistive transitions for a set of four wires with different widths w upon a single film of thickness 50 Å. Note the systematic decrease in T_c with decreasing sample width.

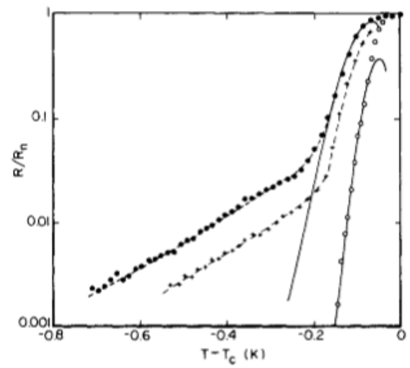


FIG. 1. Resistance, normalized by the normal stae value, as a function of temperature for three In wires; the sample diameters were 410 Å (●), 505 Å (+), and 720 Å (○). The solid curves are fits to the thermal activation theory (1), while the dashed curves are fits to (7). Where the solid and dashed curves overlap, only the former is shown for clarity. The samples had lengths of 80, 150, and 150 μm, and normal-state resistances of 5.7, 7.1, and 1.2 kΩ, where we list the values in order of sample size, with the value for the smallest sample first.

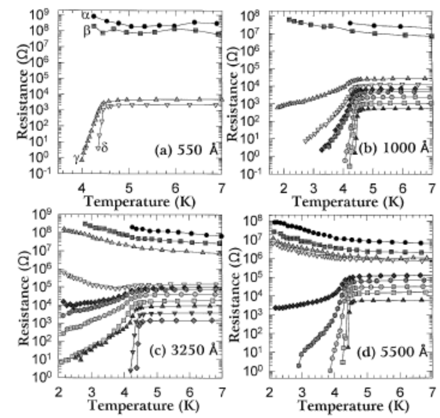


FIG. 1. The strong to weak localization transition for a series of Sn wires of increasing widths. Each set of data exhibits a gap in its resistance where no stable wire is obtained. (a) 550 Å wide: curve $\alpha \sim 78$ Å thick; $\beta \sim 81$ Å thick; γ approximately same thickness as curve β; $\delta \sim 107$ Å thick. (b) 1000 Å wide. (c) 3250 Å wide. (d) 5500 Å wide.

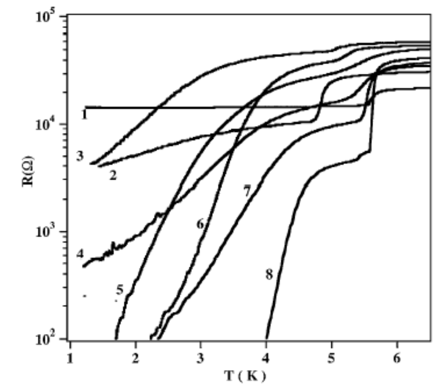


FIG. 1. Resistances as a function of temperature for eight different samples. The samples' normal state resistances and lengths are 1: 14.8 kΩ, 135 nm; 2: 10.7 kΩ, 135 nm; 3: 47 kΩ, 745 nm; 4: 17.3 kΩ, 310 nm; 5: 32 kΩ, 730 nm; 6: 40 kΩ, 1050 nm; 7: 10 kΩ, 310 nm; 8: 4.5 kΩ, 165 nm.

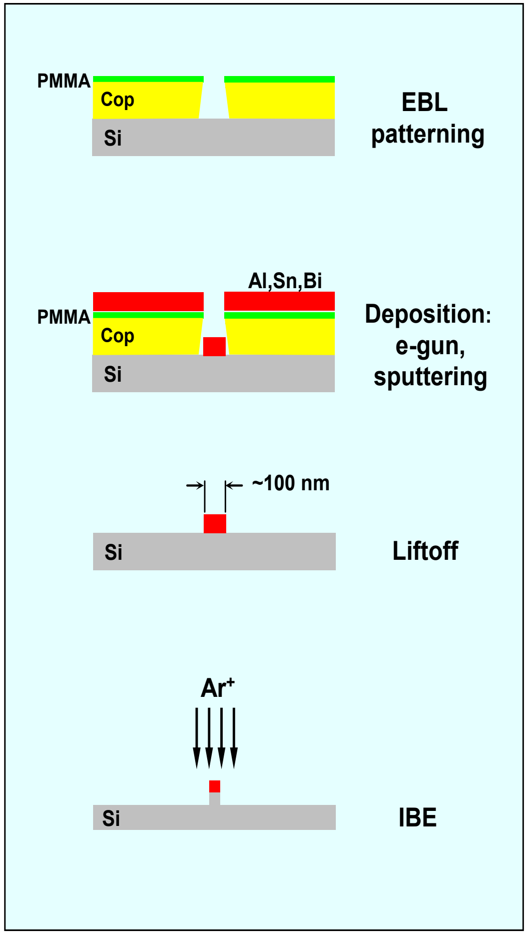
clean systems.[20] However, in this case one expects the resistance to fall off exponentially with temperature below T_c, which does not agree with the results of our

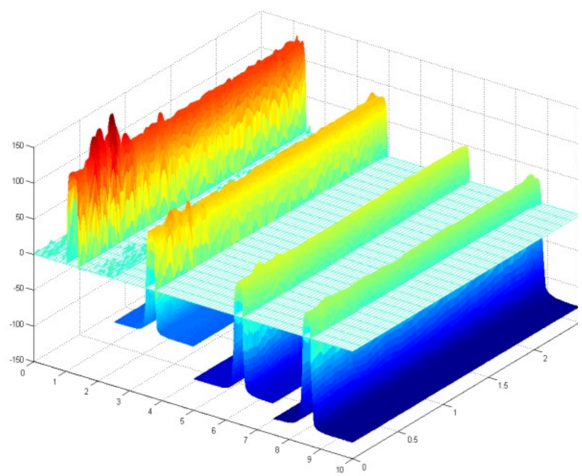
we may only conclude that the superconducting fluctuations are enhanced as the disordered 1D limit is approached.

More systematic study is required!

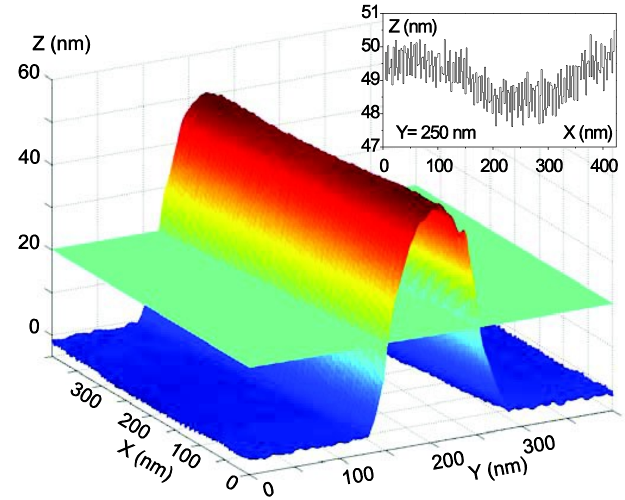
1D samples: fabrication & shape control

Objective: to enable measurements of the **same** nanowire with progressively reduced diameter





Evolution of Al nanowire after several sessions of ion milling.



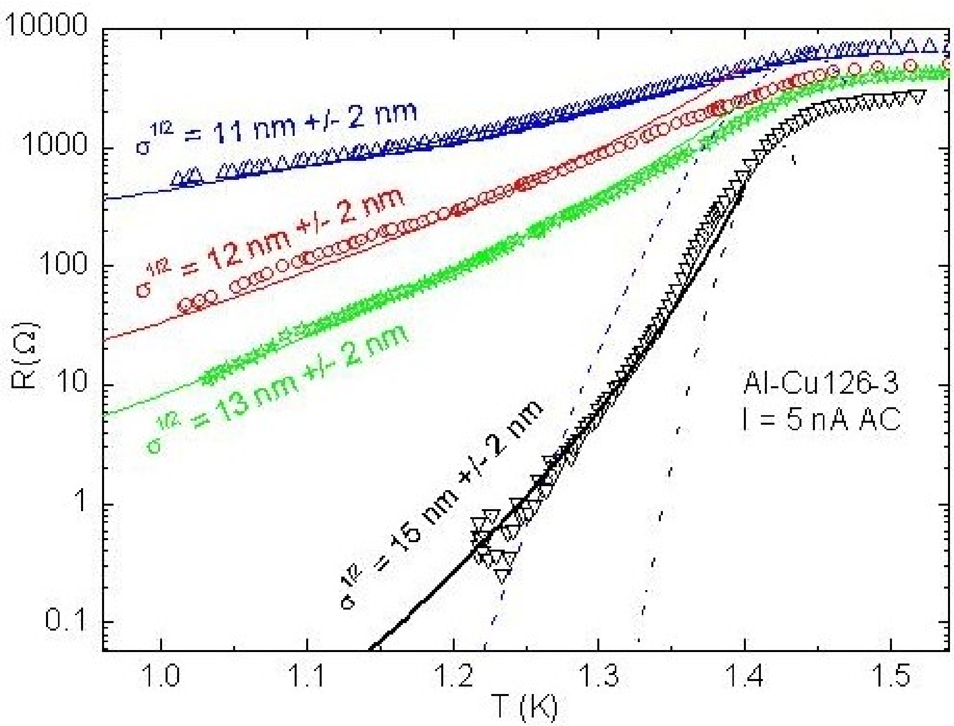
AFM image of a typical Ti nanowire. Inset shows the surface roughness ±1 nm.

Ion beam provides polishing and gradual reduction of the cross-section

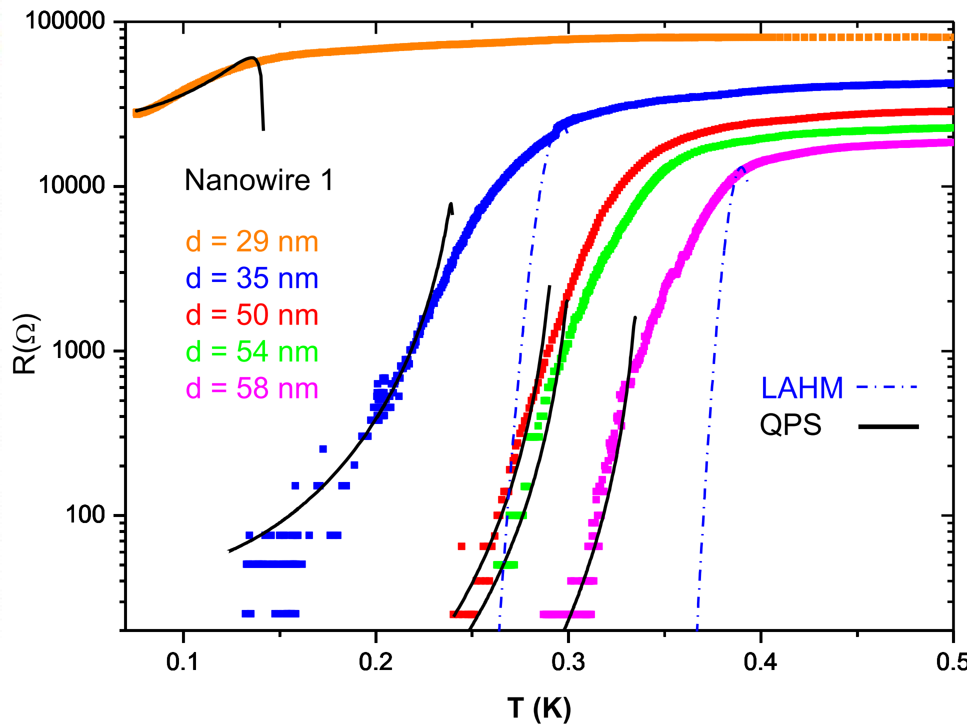
Penetration depth of 1 keV Ar^+ ions inside metal matrix < 2 nm

Manifestation of QPS: broadening of R(T) transition

Aluminium



Titanium



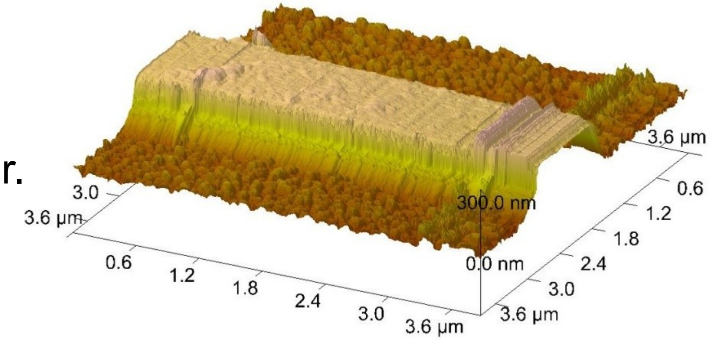
Dashed lines: thermally activated fluctuations (LAHM) at T ~Tc

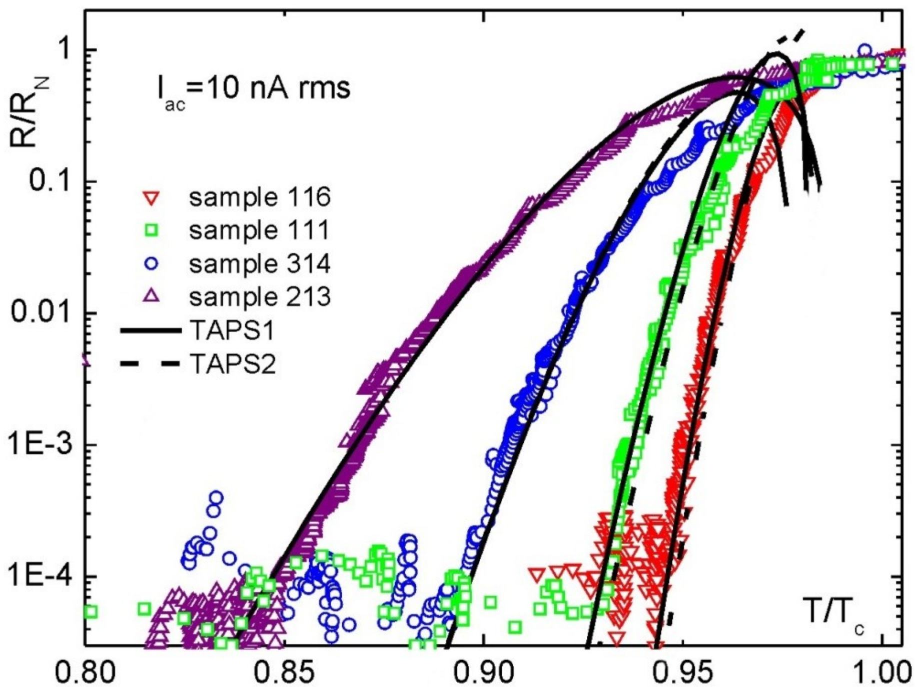
Solid lines: quantum fluctuations (Golubev – Zaikin) model at T << Tc

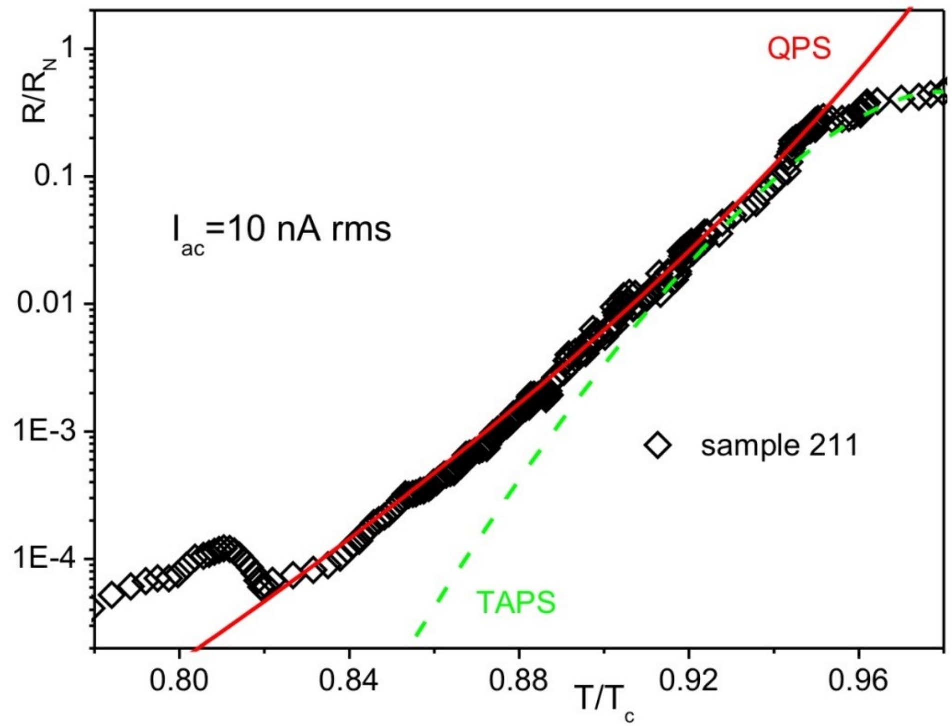
*M. Zgirski, K.-P. Riikonen, V. Touboltsev, and K. Arutyunov. // **Nano Letters** 5, 1029--1033 (2005).*
*M. Zgirski, K.-P. Riikonen, V. Touboltsev and K. Yu. Arutyunov.// **PRB** 77, 054508-1 -- 054508-6 (2008).*
*J. S. Lehtinen, T. Sajavara, K. Yu. Arutyunov, M. Yu. Presnjakov, and A. S. Vasiliev // **PRB** 85, 094508 (2012).*

NbN nanowires

NbN is a highly disordered (= highly resistive) superconductor. We studied more than 40 samples: 4 and 8 nm thick nanowires, width from 30 nm to 60 nm, length 5 um. $R_{\square}$ varied from 15 Ω to 100 Ω .



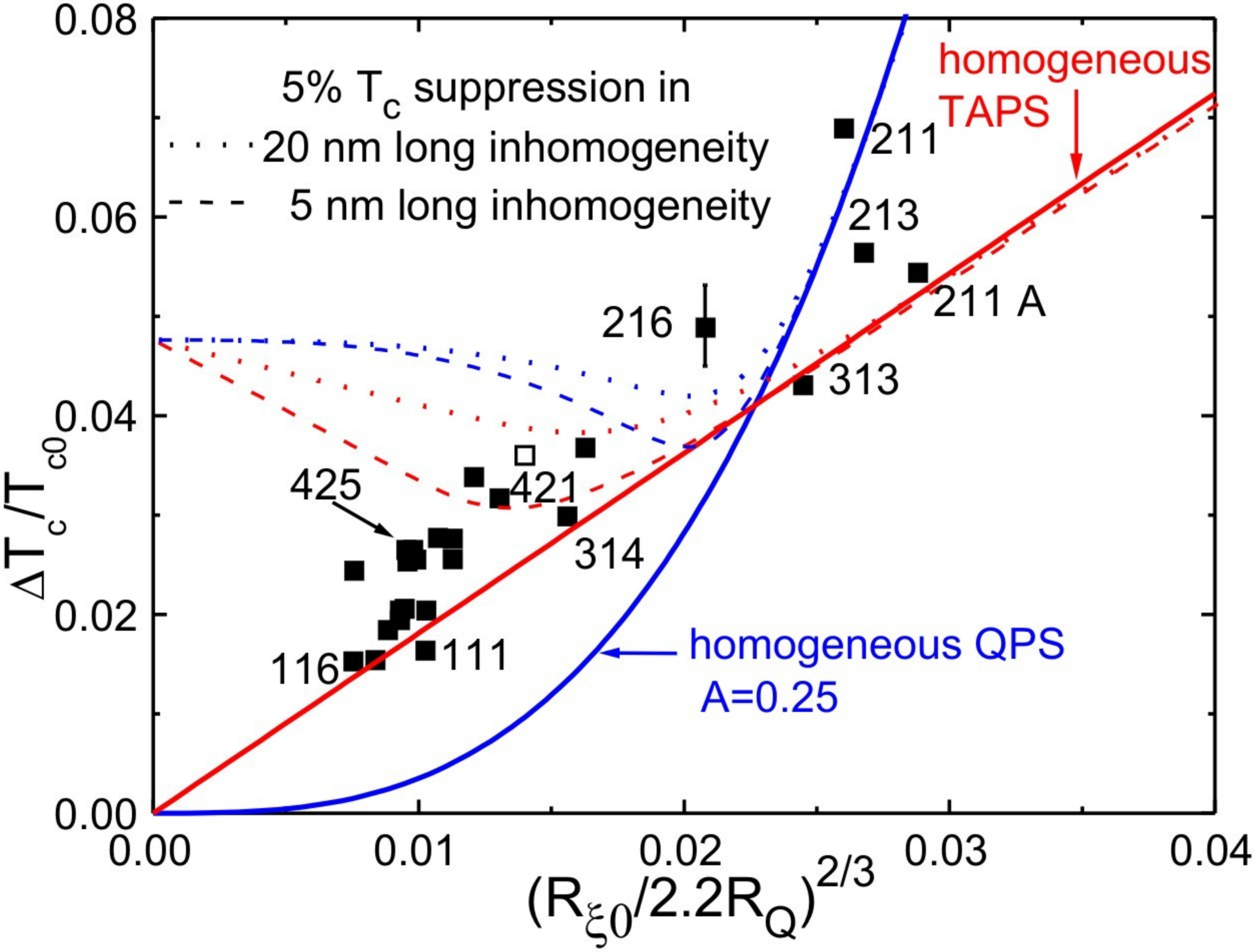




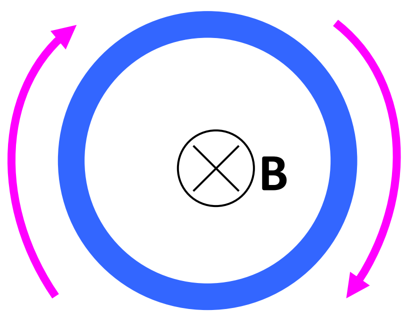
The experimental width of the R(T) transition correlates well with the resistance in normal state R_N. The shape of the majority of R(T) transitions can be nicely fit with TAPS model, while for the thinnest nanowires the best fit is provided with QPS.

K. Yu. A., Ramos-Álvarez, A. V. Semenov, Yu. P. Korneeva, P.P. An, A. A. Korneev, A. Murphy, A. Bezryadin, and G. N. Gol'tsman, ***Nanotechnology*** *27, 47LT02 (2016)*

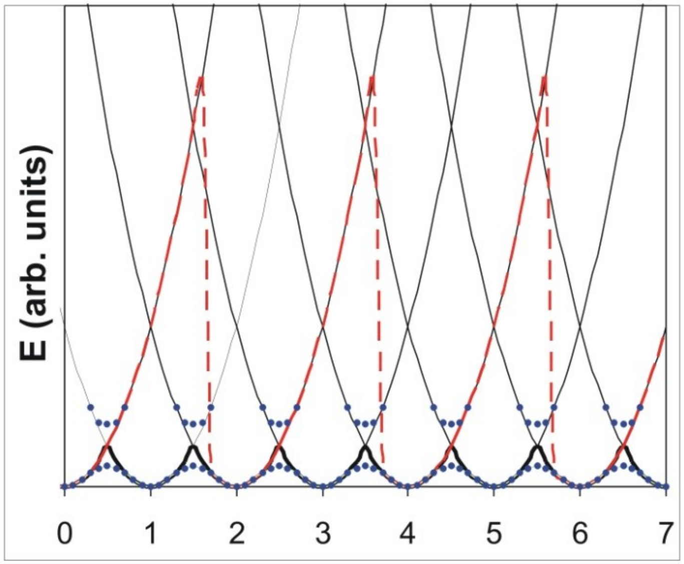
TAPS vs. QPS fits: role of inhomogeneities

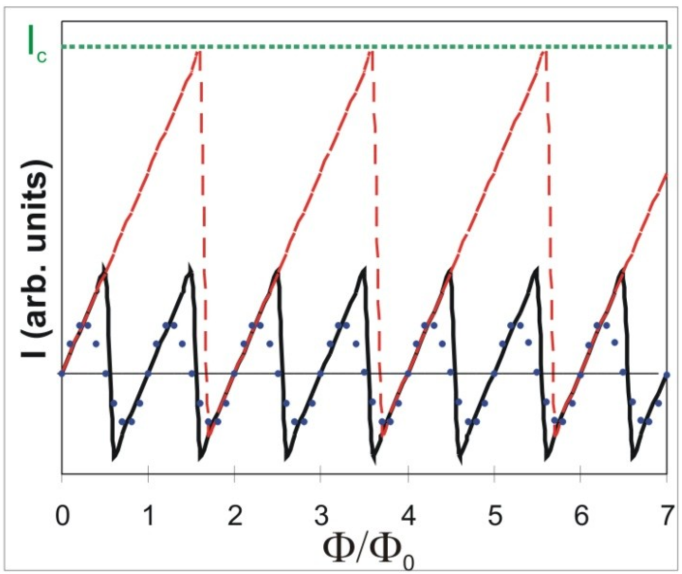


Persistent currents in nanorings



Persistent currents in a very narrow superconducting loop governed by quantum fluctuations





Quantum phase slips <u>open gap</u> in the energy spectrum of a very narrow superconducting loop: <u>coherent</u> superposition of +2π and -2π phase slips.

K. A. Matveev, A. I. Larkin, L. I. Glazman, PRL 89, 096802 (2002)
K.A., D. S. Golubev, A.D Zaikin, Phys. Rep. 464, 1 (2008)

For a loop of large and <u>fixed</u> circumference the reduction of the line width leads to QPS-governed regime which should result in:

1) Reduction of the magnitude of oscillations

2) Instead of saw-tooth → sine-type shape

+

3) Reduction of the <u>period</u> of oscillations

Oscillations of the persitent current→ oscillations of the tunnel current

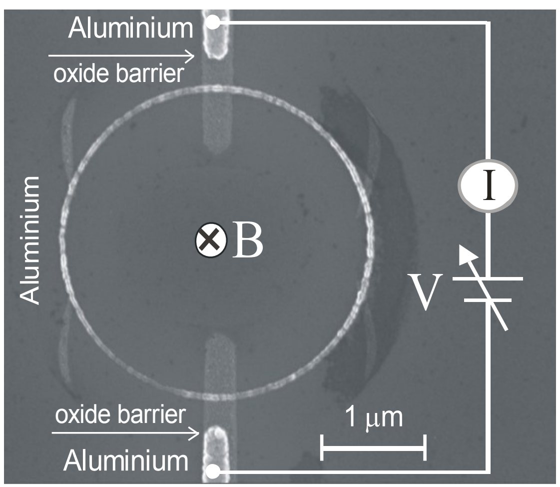
Experiment measuring DOS should probe the supercurrent I

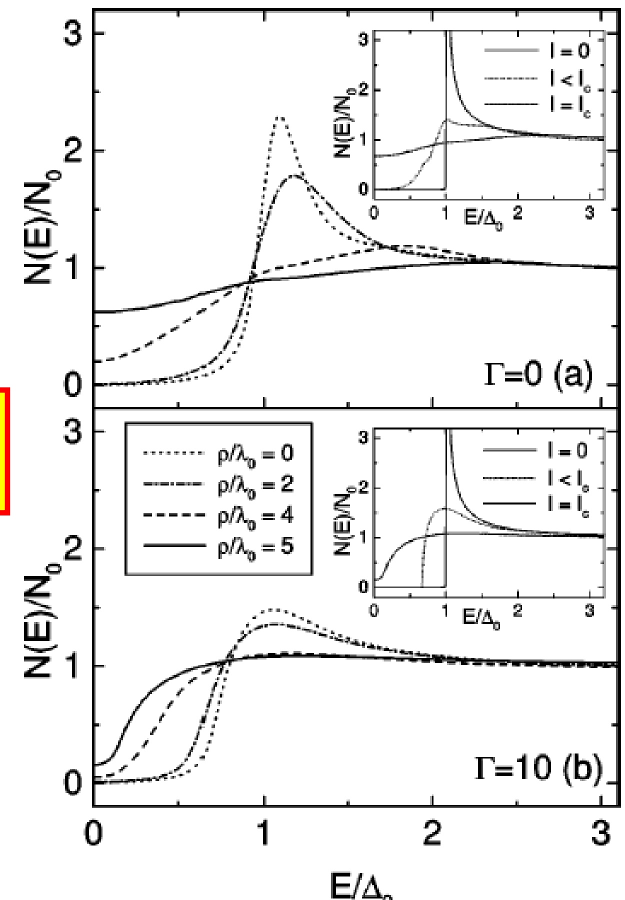
Tunnel current of NIS junction is:

$$I_T = \frac{1}{eR_T}\int_{-\infty}^{\infty}\frac{N_s(E,\Delta[\Gamma(I)])}{N(0)}[f(E)-f(E+eV)]dE$$

where $N_s(E,\Delta[\Gamma(I)]$ is non-equilibrium DOS

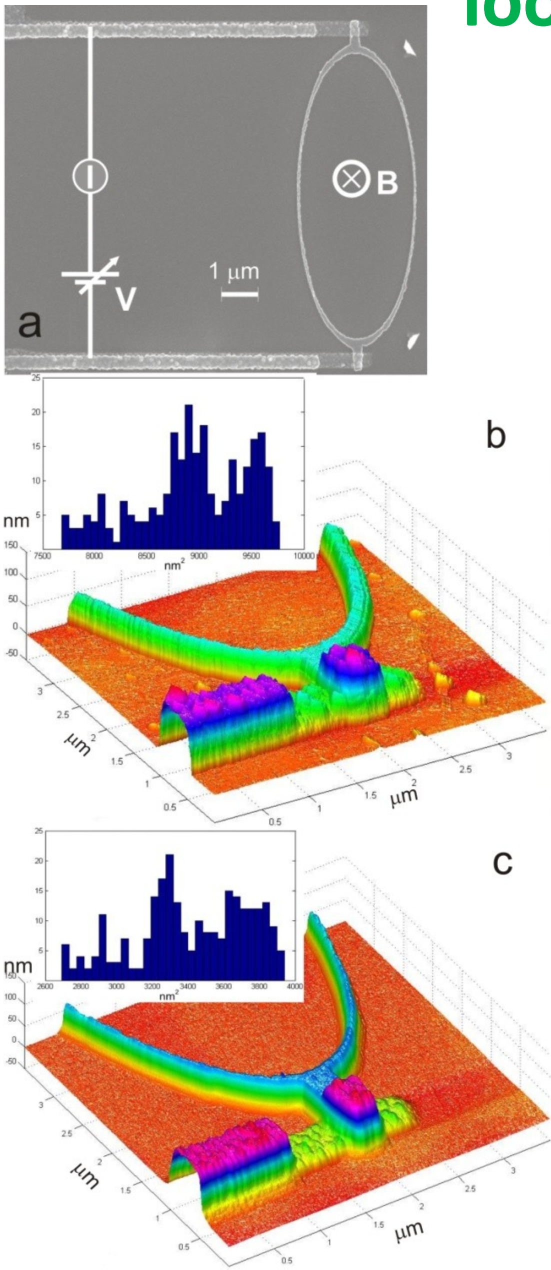
NIS (or SIS) tunnel experiment on a superconducting loop in magnetic field should probe the circulating persistent current





J. Sancez-Canizares, J. Ferrer and F. Sols, PRB 63, 134504 (2001)

Amplitude and period of oscillations as function of the loop linewidth (aluminium)



Wide wire: classic limit

110 nm x 75 nm wire,

T_{bath}=65±5 mK, $\sigma_{fit}^{1/2}$=90.8 nm

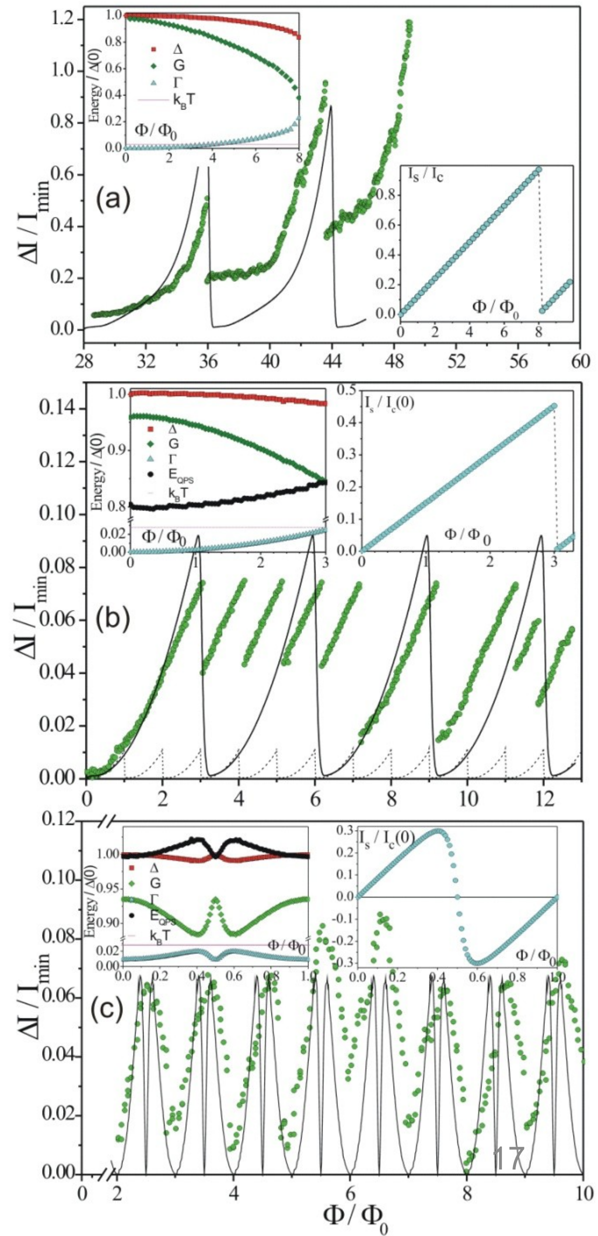
Intermediate regime:

T_{bath}=52±5mK. Solid line: $\sigma_{fit}^{1/2}$=12.49 nm and $\Delta\Phi/\Phi_0$=3 period, dashed line - calculated $\Delta\Phi/\Phi_0$=1 oscillations in a slightly narrower loop $\sigma_{fit}^{1/2}$=12.37 nm

QPS limit:

same sample as in (b) further gently sputtered at T_{bath}=54±5 mK Solid line - calculations in the QPS limit with $\sigma_{fit}^{1/2}$=12.15 nm

K. Yu. A, et. al. **NPG: Sci. Rep.** 2(293), (2012)



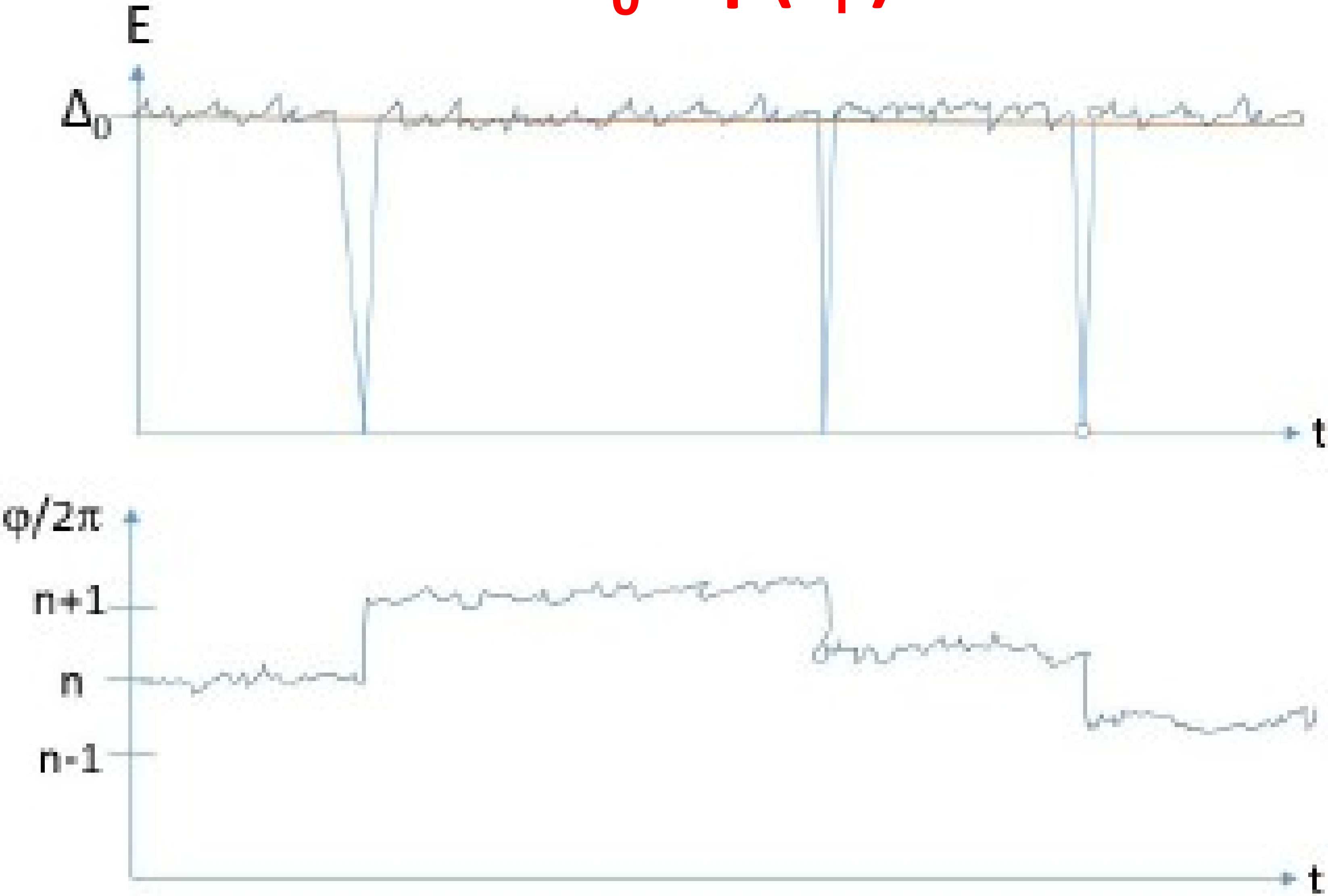
Conclusions on quantum phase slips

Quantum fluctuations of phase in narrow superconducting nanowires suppress all 'basic' attributes of superconductivity manifesting as:

- Broadening of the R(T) transition. In thinnest samples zero resistance is not reached even at T→0.
- Suppression of persistent currents in nanorings.

Fluctuations of the superconducting gap modulus

Fluctuations of the order parameter
$\Delta=\Delta_0\exp(i\varphi)$

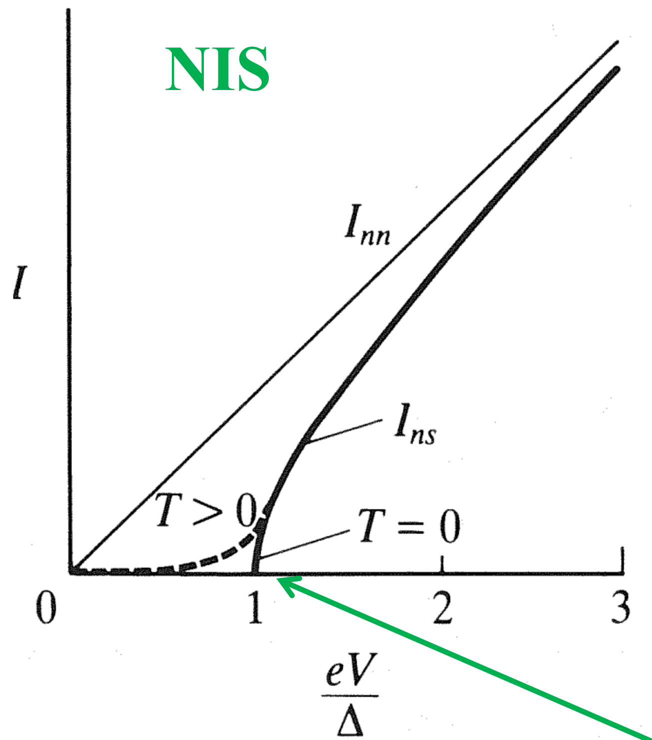


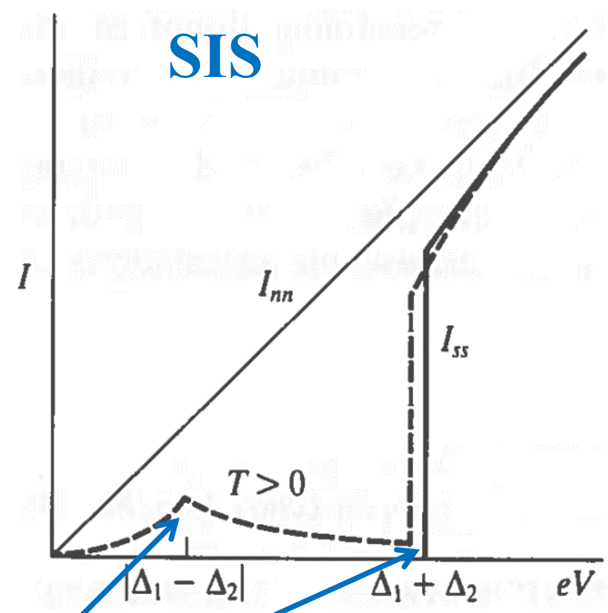
T. Rantala, MSc thesis, University of Jyvaskyla, 2013

Tunneling in NIS and SIS systems

Quantum fluctuations of Δ modulus should lead to extra (size dependent) broadening of the gap edge, which should affect the shape of I-V characteristic.

M. Tinkham, Introduction to supercondcutivity, Mc. Graw-Hill, 1996





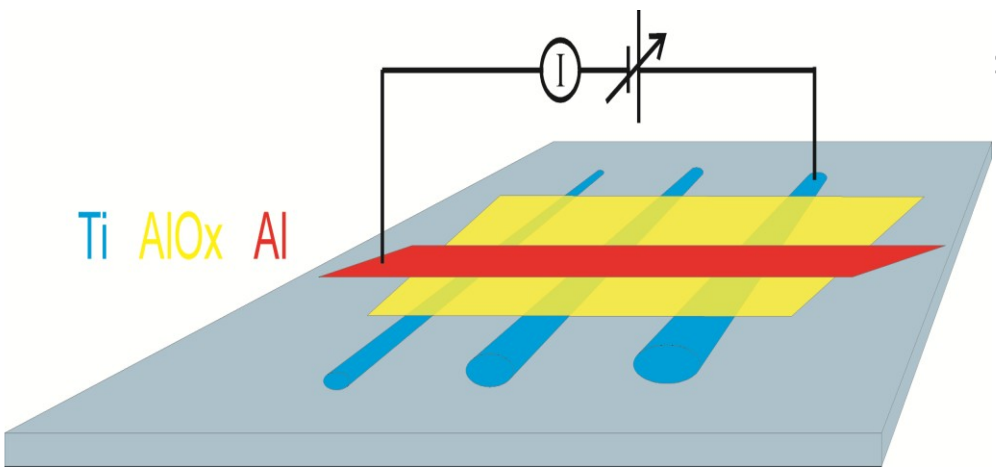
Note: for SIS junction <u>even at finite temperature</u> gap edge singularity is infinitely sharp!

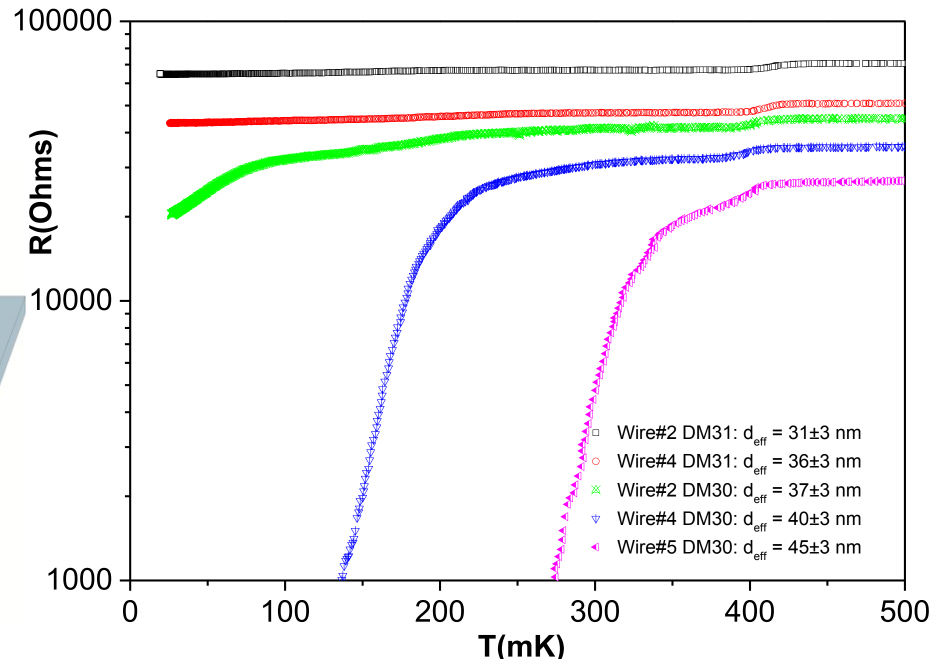
Typically finite broadening of DOS is characterized by phenomenologic Dynes parameter Γ:

$$N(E) \approx N(E_F)\,\mathrm{Re}\left(\frac{E + i\Gamma}{\sqrt{(E + i\Gamma)^2 - \Delta^2}}\right)$$

Experiment

Schematic of the experiment

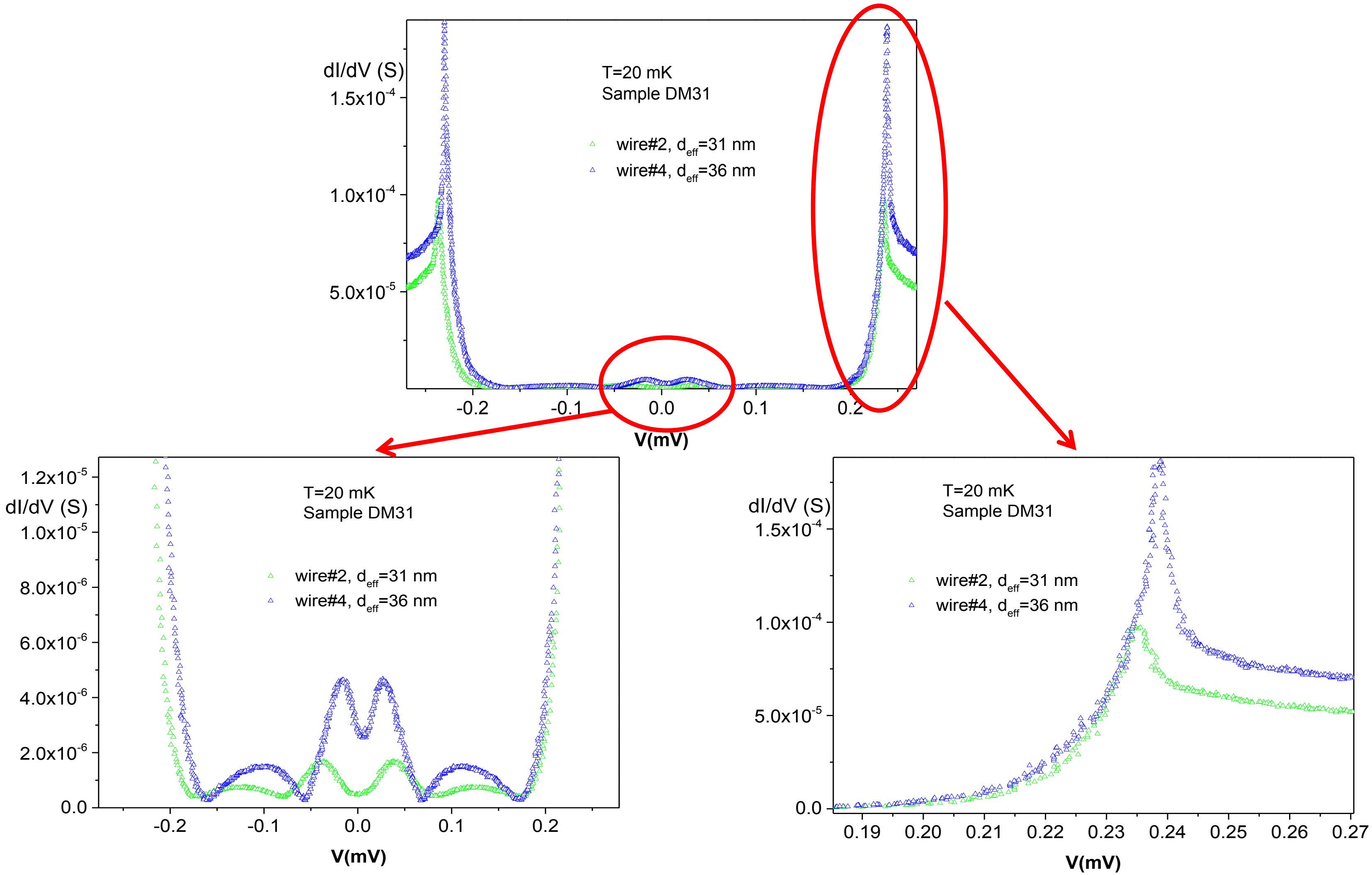




R(T) of each nanowire and I(V) chartacteristic between the nanowire and the aluminium electrode can be measured independently.

R(T) dependencies at these diameters are broad associated with QPS.

SIS I(V) at various diameters of nanowires



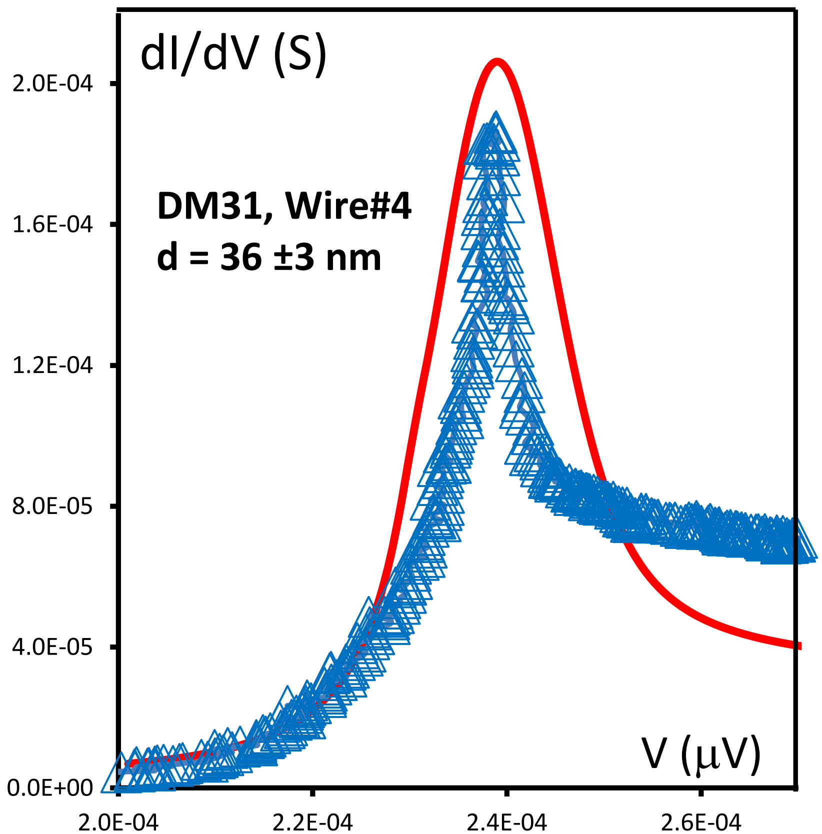
$\Delta 1 - \Delta 2$ features and
Coulomb blockade and/or Josephson current (?)

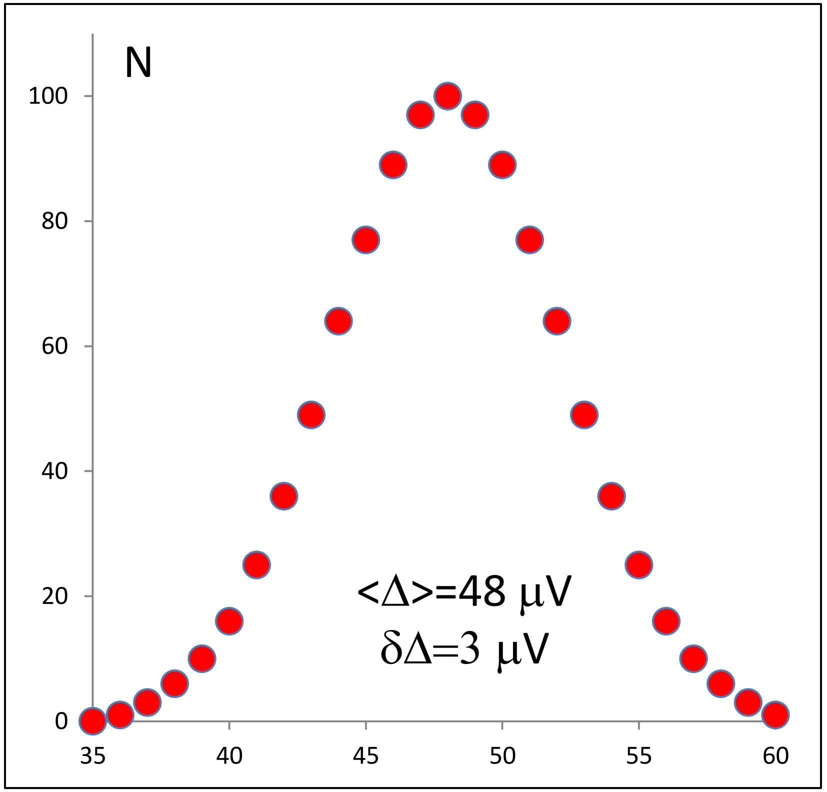
$\Delta 1 + \Delta 2$ features

The smaller the nanowire diameter (1) the smaller the average value <Δ> and (2) the larger the gap smearing $\delta\Delta$.

Simulations

We simulate I(V) dependencies assuming Gaussian distribution of the gap fluctuations centered at <Δ> with standard deviation δΔ.





Limitations & postulates:

- **Gaussian distribution of quantum fluctuation amplitude**
- **Cut-off $\Delta_{bulk}/2 < \Delta < \Delta_{bulk}$**
- **Finite magnitude of voltage modulation and finite lock-in integration time**

Other contributions

In 1-D superconductors QPSs, related to fluctuations of the phase φ, can excite 'soft' plasmonic mode (Mooij-Schoen mode). Electrons interact with these plasmonic excitations which cause re-distribution of electronic states. The process leads to broadening of DOS singularity at the gap edge Δ. At low temperatures $k_BT \ll \Delta$ such DOS singularity can be formally described by a parameter similar to the phenomenologic Dynes parameter Γ:

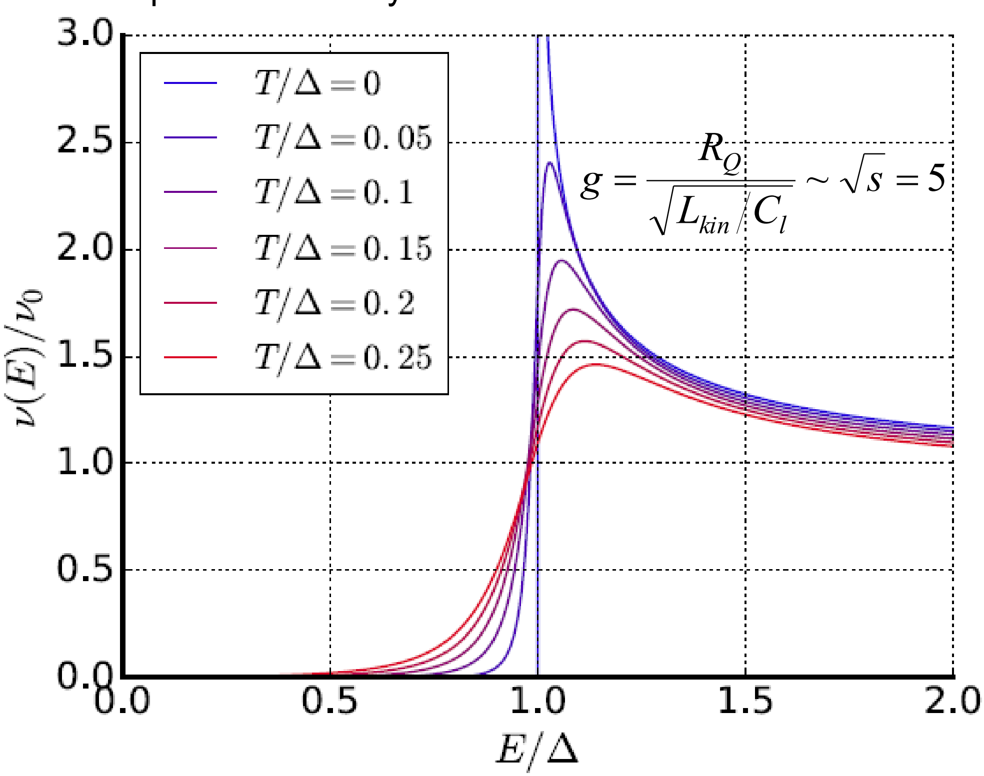
$$N_\varphi(E) = N_0(E_F)\,\mathrm{Re}\left\{\frac{E+i\Gamma}{\sqrt{(E+i\Gamma)^2-\Delta^2}}\right\} \sim \exp\left\{\frac{E-\Delta}{T}\right\}$$

, where $\alpha = \dfrac{e^2}{2\pi C_l v}$ – parameter, s - wire cross section,

C_l – wire capacitance per unit length, $v = \sqrt{\dfrac{\pi\Delta s\sigma_N}{C_l}}$ - plasmon velocity

DOS broadening depends on:
(1) nanowire cross section *s*,
(2) normal state resistivity σ_N ,
(3) temperature

$$\Gamma = (\alpha T)^{1-\alpha},\ \ \alpha \ll 1$$

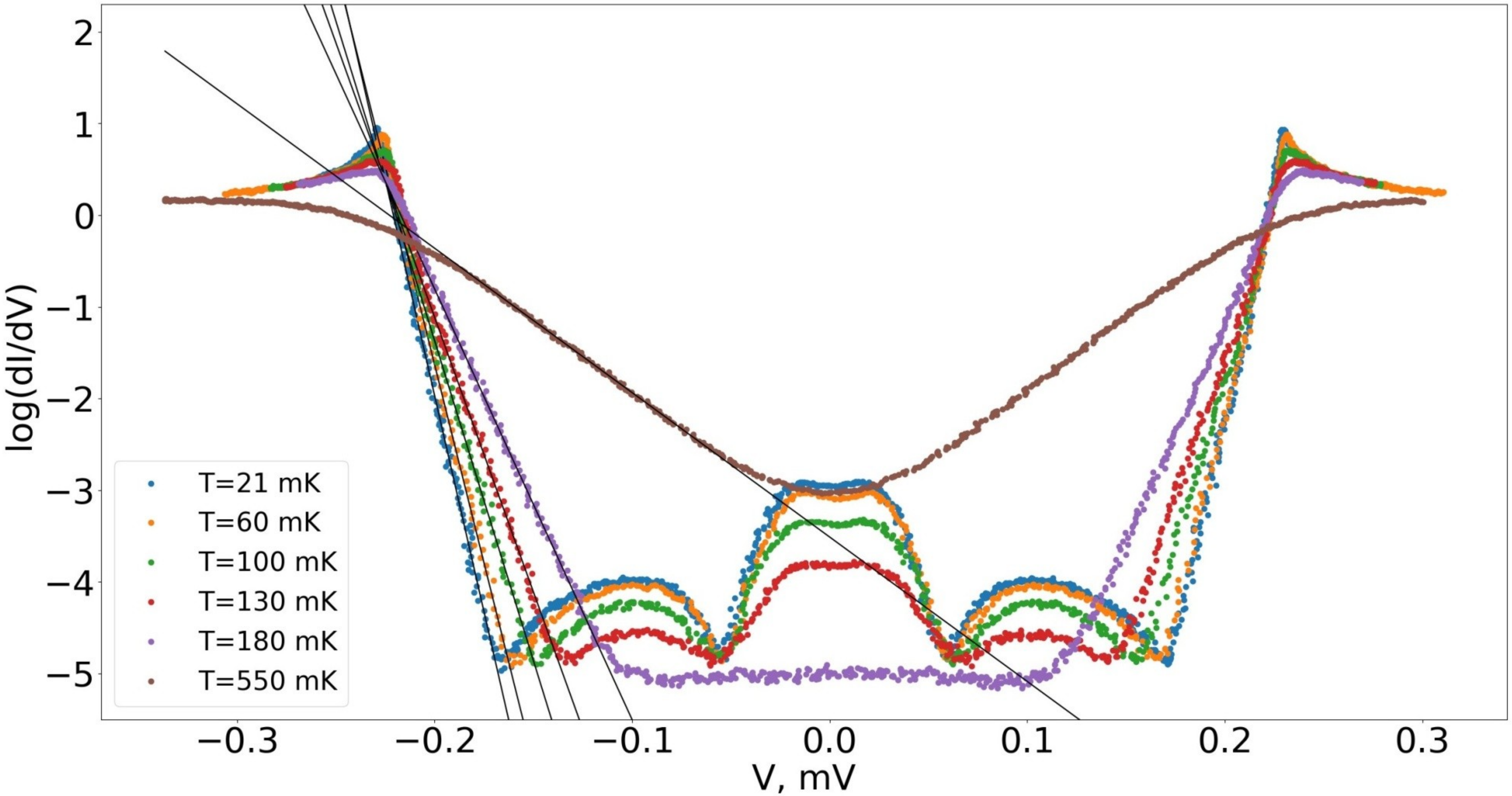


The model does NOT consider:
- fluctuations of the modulus |Δ| ;
- relaxation of Mooij-Schoen plasmons;
- finite length of the nanowire;
- dependence of Δ on cross section *s*.

A. Radkevich, A. G. Semenov and A. D. Zaikin, arXiv: 1704.08004 (2017)

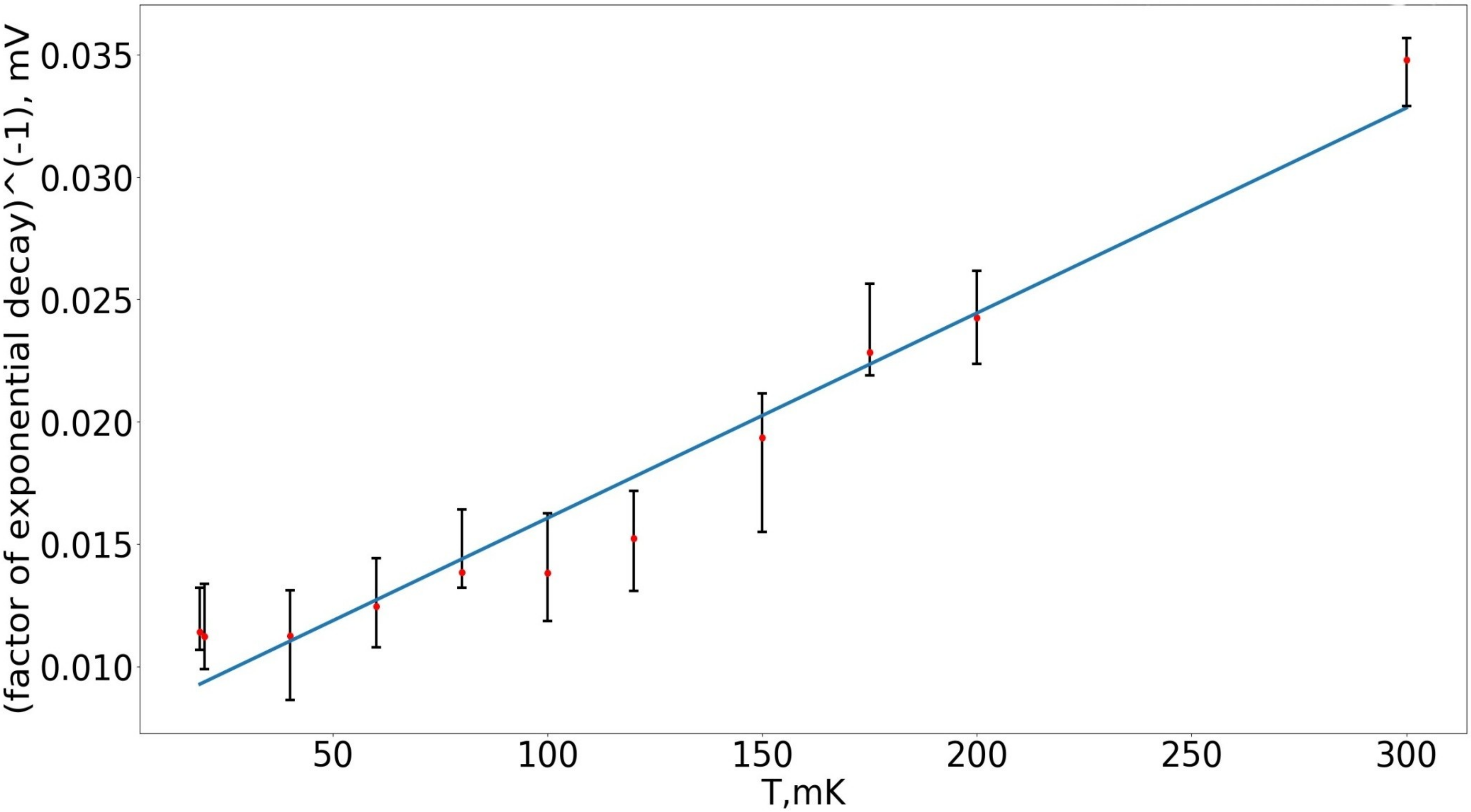
I(V) dependencies

In experiment we can measure both I(V) and dI/dV dependencies. According to the model, DOS (and hence the dI/dV) should exponentially 'leak' below the gap.



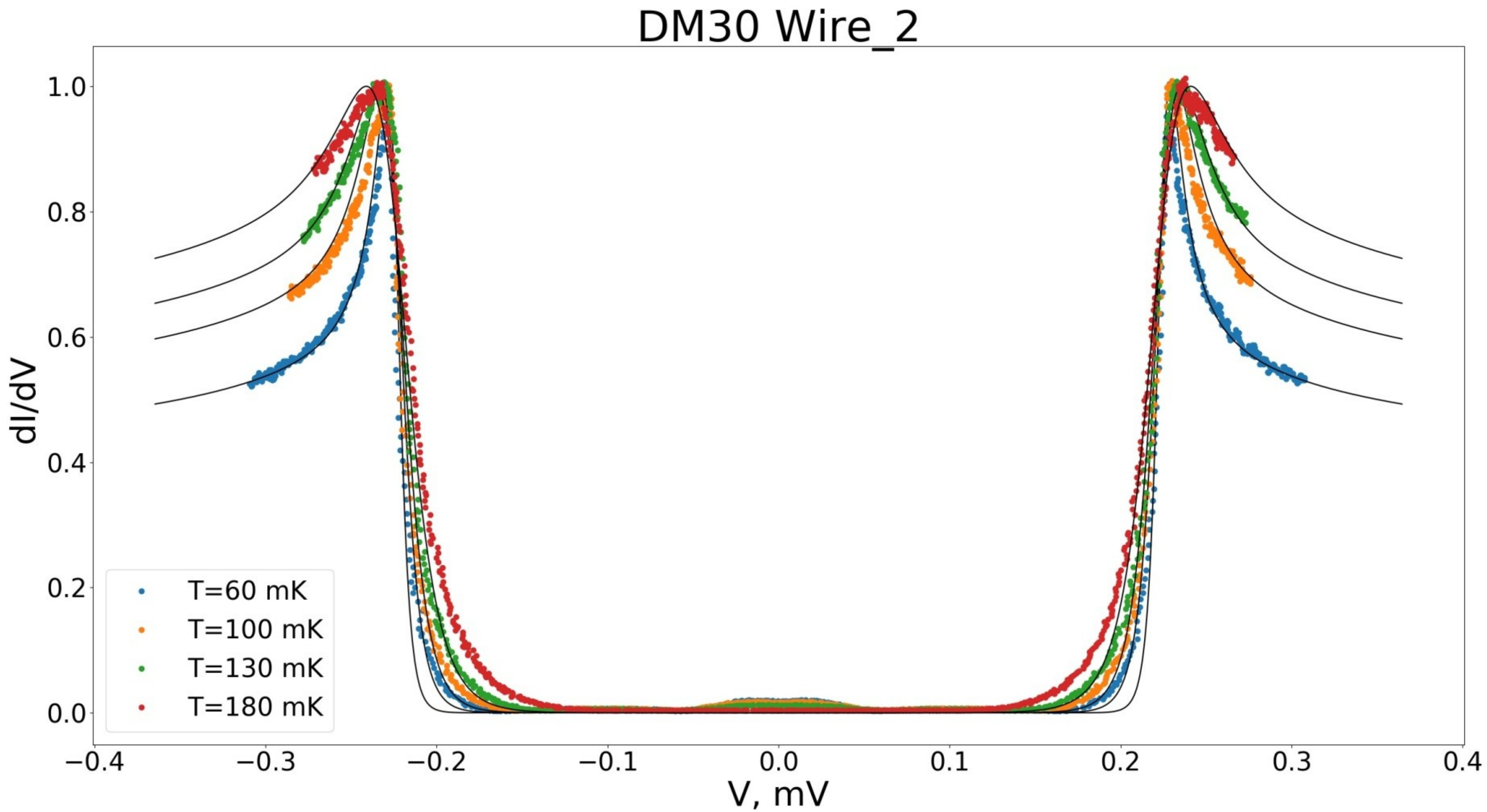
Theory predicts that under the exponent it should be ~(E-Δ/T): DOS subgap penetration depends on temperature.

Temperature dependence of DOS decay



At not-too-low temperatures experimentally measured DOS decay is about $8.4*10^{-5}$ V/K, which is in a reasonable agreement with theory prediction $k_B/e \approx 8.6*10^{-5}$ V/K.

Simulated dI/dV



Experimental dI/dV dependencies are fit with theory using parameter α=0.585, being normalized at maximum to 1. The agreement is acceptable, but not perfect. Presumably at such high constant of interaction α=0.585, one should take into consideration other contributions.

Conclusions on physics

Quantum fluctuations in narrow superconducting nanowires suppress all ‘basic’ attributes of superconductivity manifesting as:

- Broadening of R(T) transition. In thinnest samples zero resistance is not reached even at T→0.
- Suppression of persistent currents in nanorings.
- Smearing of DOS at energies ~Δ.

Open questions

- Mechanism of energy dissipation?
- How to separate smearing of DOS at energies ~Δ due to phase fluctuations, modulus fluctuations and the Mooij-Schoen plasmons?

Thank you!

Our key publications on QPS

• M. Zgirski, K.-P. Riikonen, V. Touboltsev, and K. Arutyunov. Size Dependent Breakdown of Superconductivity in Ultranarrow Nanowires // **Nano Letters** 5, 1029 (2005).

•K. Yu. Arutyunov, D. S. Golubev, and A. D. Zaikin. Superconductivity in one dimension // **Physics Reports** 464, 1-70 (2008).

•M. Zgirski, K.-P. Riikonen, V. Touboltsev and K. Yu. Arutyunov. Quantum fluctuations in ultranarrow superconducting nanowires // **Phys. Rev. B** 77, 054508 (2008).

•J. S. Lehtinen, T. Sajavara, K. Yu. Arutyunov, M. Yu. Presnjakov, and A. S. Vasiliev. Evidence of quantum phase slip effect in titanium nanowires // **Phys. Rev. B** 85, 094508 (2012).

•O. V. Astafiev, L. B. Ioffe, S. Kafanov, Yu. A. Pashkin, K. Yu. Arutyunov, D. Shahar, O. Cohen, and J. S. Tsai. Coherent quantum phase slip // **Nature** 484, 355 (2012).

•K. Yu. Arutyunov, T. T. Hongisto, J. S. Lehtinen, L. I. Leino, and A. S. Vasiliev. Quantum phase slip phenomenon in ultra-narrow superconducting nanorings // **Nature: Sci. Rep.** 2(293), (2012)

•J. S. Lehtinen, K. Zakharov, and K. Arutyunov, Coulomb blockade and Bloch oscillations in Superconducting Ti nanowires // **Phys. Rev. Lett**. 109, 187001 (2012).

•J. S. Lehtinen, T. Rantala and K. Yu. Arutyunov, Insulating State of a Quasi-1-Dimensional Superconductor // **arXiv.1311.3202** (2013).

•K. Yu. Arutyunov, J. S. Lehtinen, and T. Rantala, The Quantum Phase Slip Phenomenon in Superconducting Nanowires with High-Impedance Environment, ***J. Supercond. Nov. Magn***. 29, 569-572 (2016). DOI 10.1007/s10948-015-3298-9

•K. Yu. Arutyunov , J.S. Lehtinen , Junctionless Cooper pair transistor, ***Physica C*** (2016), DOI10.1016/j.physc.2016.02.010

•Arutyunov KY, Ramos-Álvarez A, Semenov AV, Korneeva YP, An PP, Korneev AA, Murphy A, Bezryadin A, Gol'tsman GN. Superconductivity in highly disordered NbN nanowires**, *Nanotechnology,*** *27*, 47LT02 (2016).