Institute for Physics of
Microstructures of RAS

Quantum Technology Center
Nizhny Novdorod State
Technical University n.a. R.E. Alexeev

НИЖЕГОРОДСКИЙ ГОСУДАРСТВЕННЫЙ
УНИВЕРСИТЕТ им. Н.И. ЛОБАЧЕВСКОГО
Национальный исследовательский университет

Noise-induced transitions in nonlinear systems

Andrey L. Pankratov

Laboratory of Superconducting Nanoelectronics

Triton 200: Heating of BB source, attached to 4 K plate, up to **58 K** at stabilized low plate temperature of **0.3K**

Obituary of L. S. Kuzmin, JLTP

L.S. Kuzmin's academic career began at the Department of Physics at the Moscow State University in 1964. He did his both undergraduate and doctoral studies under supervision by Professor Konstantin Likharev. He defended his PhD thesis in 1977, with the title “Nondegenerate single-frequency parametric amplification using Josephson junctions with selfpumping” and presented his post-doctoral research in 1997 on “Correlated Tunneling of Electrones and Cooper Pairs in Ultrasmall Tunnel Junctions”. During late 1980’s, Leonid gradually moved to Chalmers University of Technology. The first visit took place during a Gothenburg winter in 1989, and eventually continued all the way to a professorship at Chalmers in 2004.

During 1983, Likharev’s group has initiated investigations of the tunneling processes in small Josephson tunnel junctions. Leonid was devoted to the study and, together with K.K. Likharev, discovered the discrete correlated single-electron tunneling in a double junction structure published in JETP Lett. vol. 45, pp. 389-390, 1987. This effect was simultaneously observed at Bell Labs, by T. Fulton and G. Dolan and their manuscript was submitted for publication just on the same day, March 6, 1987. Later, detection of the so-called Bloch oscillations in arrays of Josephson junctions was a discovery that had a major impact.

https://link.springer.com/article/10.1007/s10909-022-02923-5

L. S. Kuzmin, and K. K. Likharev,
Direct experimental-observation of discrete correlated single-electron tunneling
JETP Letters, 45, 8, 495-497 (1987).

L. S. Kuzmin, P. Delsing, T. Claeson, and K. K. Likharev,
Single-electron charging effects in one-dimensional arrays of ultrasmall tunnel junctions,
Phys. Rev. Lett. 62, 2539 (1989).

P. Delsing, K. K. Likharev, **L. S. Kuzmin**, and T. Claeson,
Effect of high-frequency electrodynamic environment on the single-electron tunneling in ultrasmall junctions
Phys. Rev. Lett. 63, 1180 (1989).

P. Delsing, K. K. Likharev, **L. S. Kuzmin**, and T. Claeson,
Time-correlated single-electron tunneling in one-dimensional arrays of ultrasmall tunnel junctions,
Phys. Rev. Lett. 63, 1861 (1989).

L. S. Kuzmin and D. B. Haviland,
Observation of the Bloch oscillations in an ultrasmall Josephson junction
Phys. Rev. Lett. 67, 2890 (1991).

Professor **Yuri Pashkin**, Lancaster University,
is the most famous former PhD student of Professor **Leonid Kuzmin**

Y. Nakamura, **Yu. A. Pashkin** & J. S. Tsai
Coherent control of macroscopic quantum states in a single-Cooper-pair box
Nature 398, 786–788 (1999), 13k Accesses, 1944 Citations

New detectors with internal cooling of a nanoabsorber – the Cold-Electron Bolometer

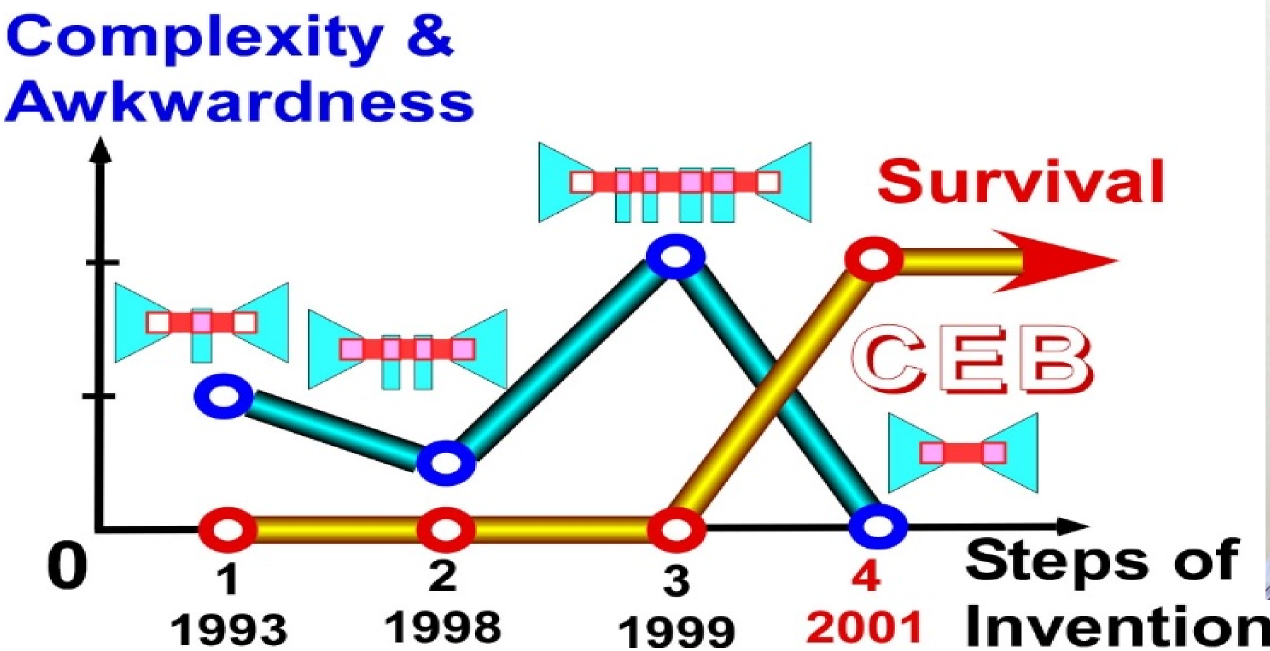
Leonid S.Kuzmin
On the concept of a hot-electron microbolometer with capacitive coupling to the antenna,
Physica B, 284–288, 2129-2130 (2000).

D.S. Golubev, **L.S. Kuzmin,**
Nonequilibrium theory of a hot-electron bolometer with normal metal-insulator-superconductor tunnel junction,
Journal of Applied Physics 89, 6464 (2001)

Ultimate cold-electron bolometer with strong electrothermal feedback
Leonid Kuzmin
SPIE Proceedings, V. 5498, Millimeter and Submillimeter Detectors for Astronomy II; (2004)
https://doi.org/10.1117/12.554317

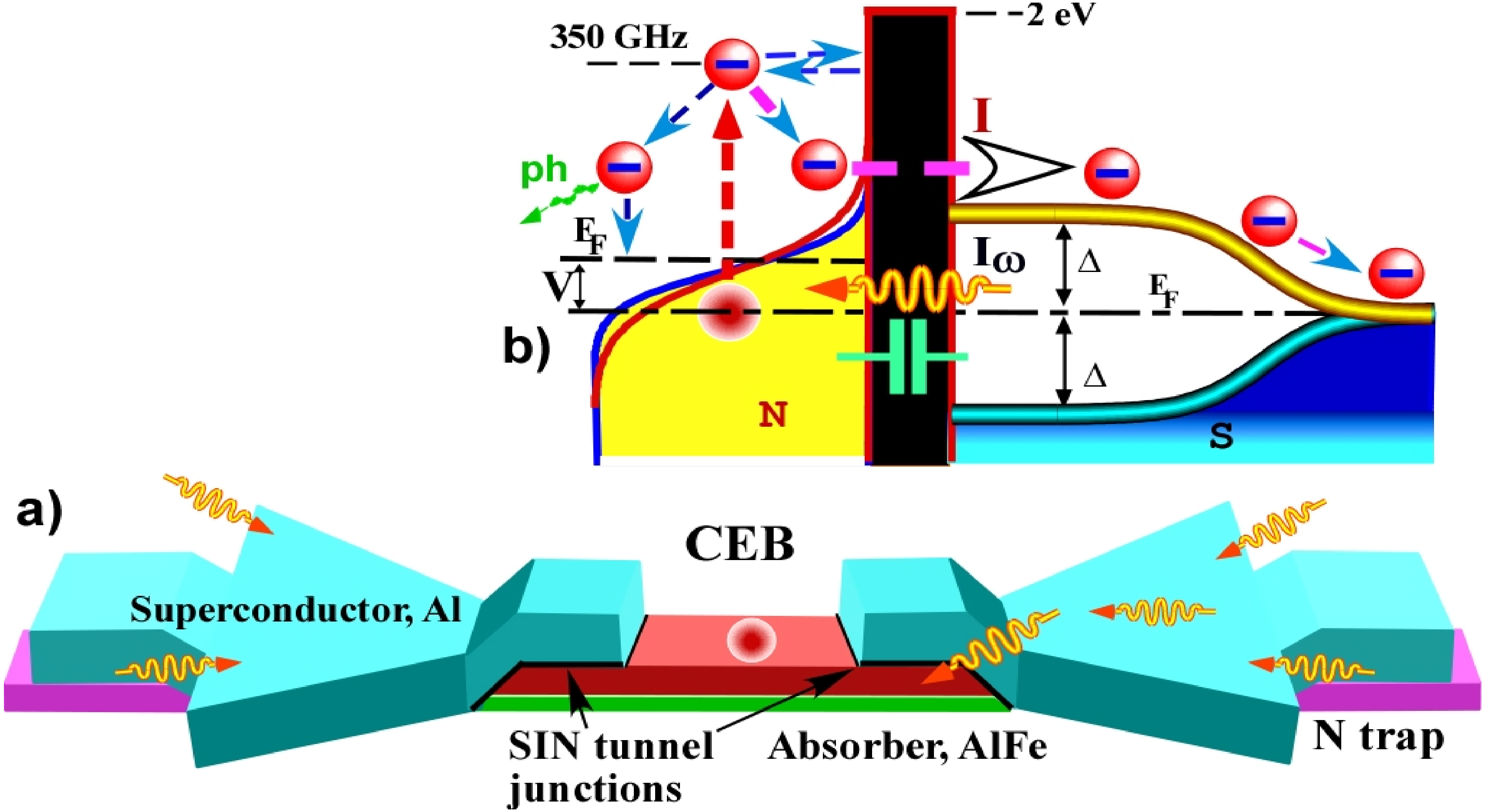
Comment in **Nature Research Communities blog** **BEHIND THE PAPER**
with CEB progress description
«Story of the Invention of a Cold-Electron Bolometer»

https://astronomycommunity.nature.com/channels/1490-behind-the-paper/posts/53529-story-of-the-invention-of-a-cold-electron-bolometer



4. Cold-Electron Bolometer (CEB) with SIN tunnel junctions as the thermometer, electron cooler, RF capacitive coupling and thermal isolation. L. Kuzmin (2002).

Cold-Electron Bolometers for Radio Astronomy



Tunnel SIN junctions perform 4 functions:

1) capacitive AC connection, 2) thermal isolation, 3) thermometry

4) electron cooling.

***Advantages*: background limited; record cosmic rays immunity.**

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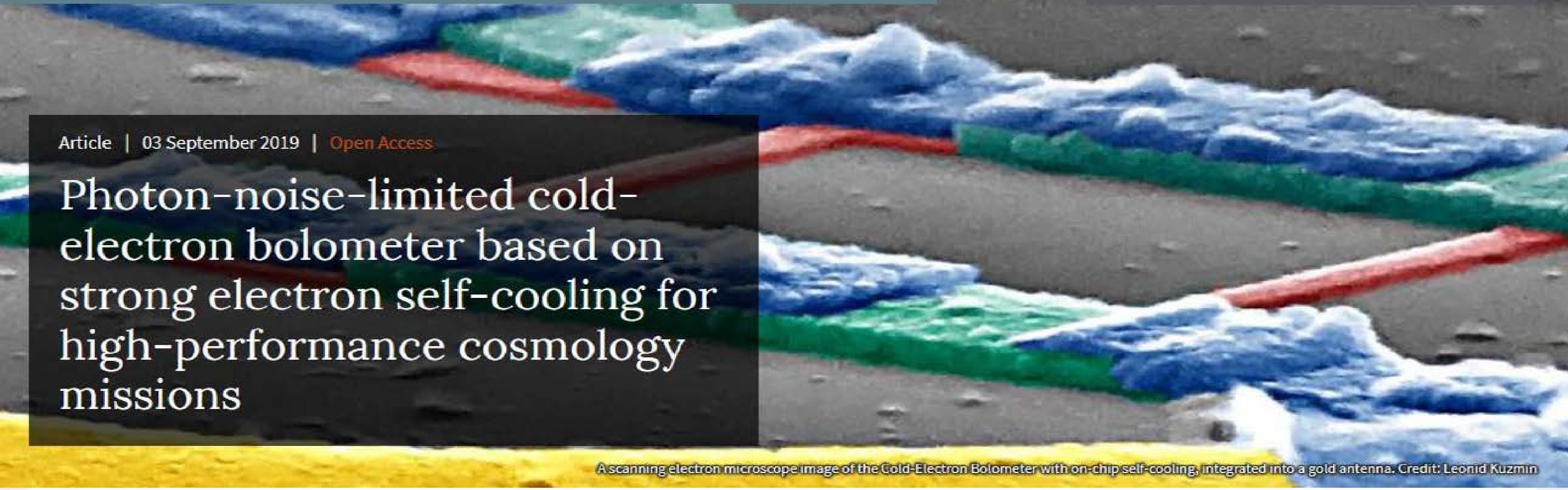


Article | 03 September 2019 | Open Access

Photon-noise-limited cold-electron bolometer based on strong electron self-cooling for high-performance cosmology missions

A scanning electron microscope image of the Cold-Electron Bolometer with on-chip self-cooling, integrated into a gold antenna. Credit: Leonid Kuzmin

Announcement

Travel Grant for Early Career Researchers

Early Careers and no funds to attend your dream conference? Applications are now open for grants to support travel in 2020.

Announcement

Dario Bercioux joins our Editorial Board

A warm welcome to our new Editorial Board Member Dario Bercioux. Dario will work with the journal editors in... show more

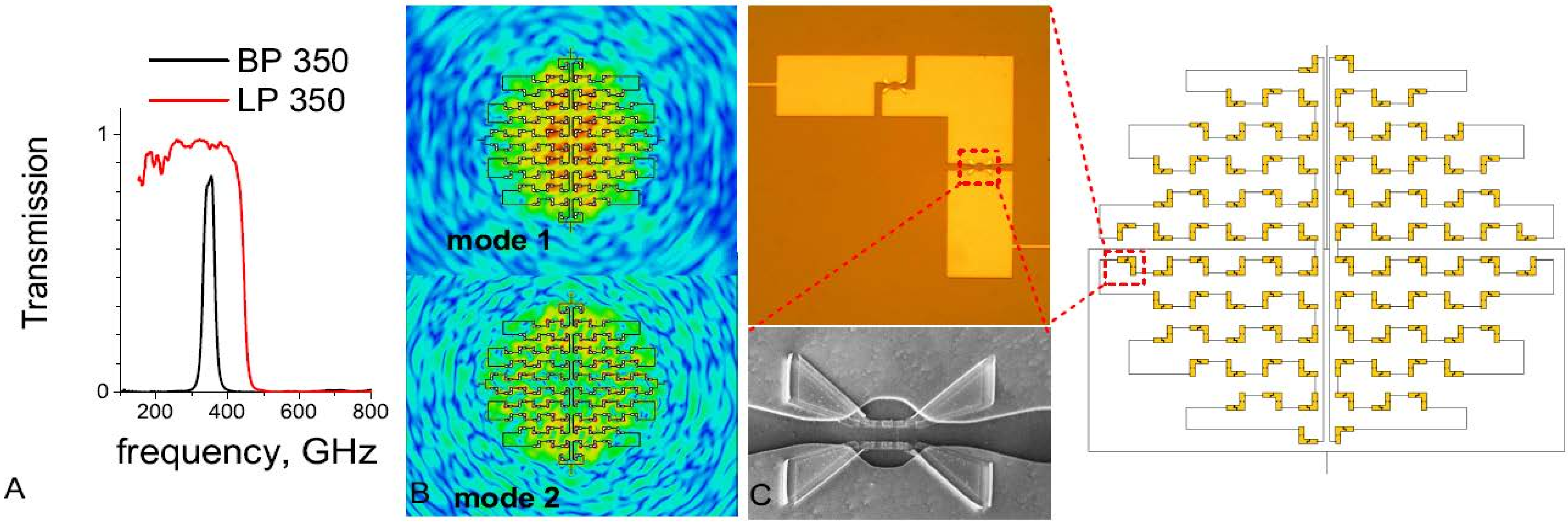
Announcement

Carl Ganter is our reviewer of the month

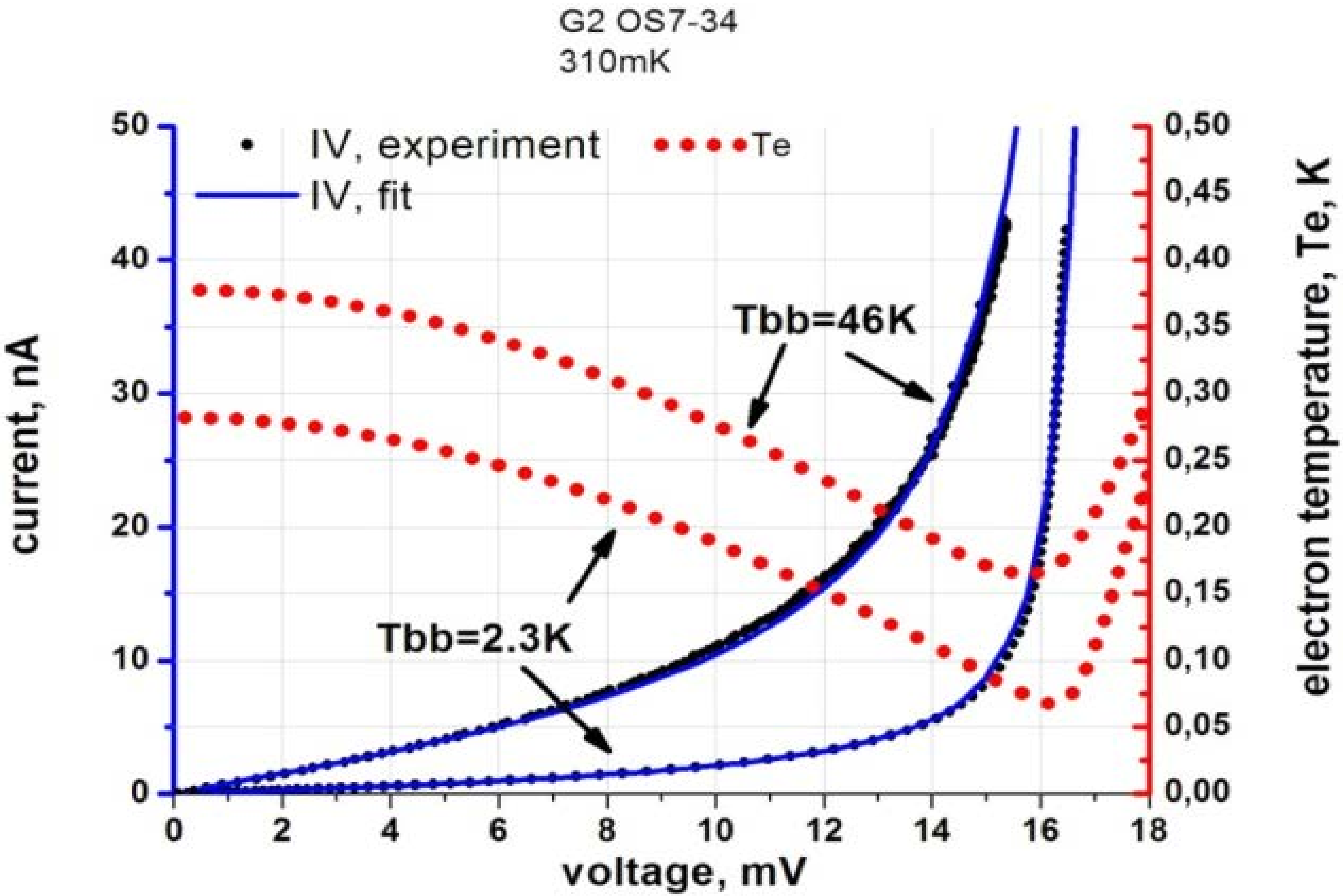
Carl Ganter provided an exceptionally thorough review, stretching to verify the calculations presented in the paper.

https://www.nature.com/articles/s42005-019-0206-9

Many antenna – many absorber receiving system for a high power load



L.S. Kuzmin, A.L. Pankratov, A.V. Gordeeva, V.O. Zbrozhek, V.A. Shamporov, L.S. Revin, A.V. Blagodatkin, S. Masi, P. de Bernardis, Photon-noise-limited cold-electron bolometer based on strong electron self-cooling for high-performance cosmology missions, **Comm. Phys.,** 2, 104 (2019).



Current-voltage characteristics of CEB at various black-body temperatures.

Ultimate sensitivity – backround limited operation: photon noise contribution is dominating

J Low Temp Phys (2016) 184:231–237 237

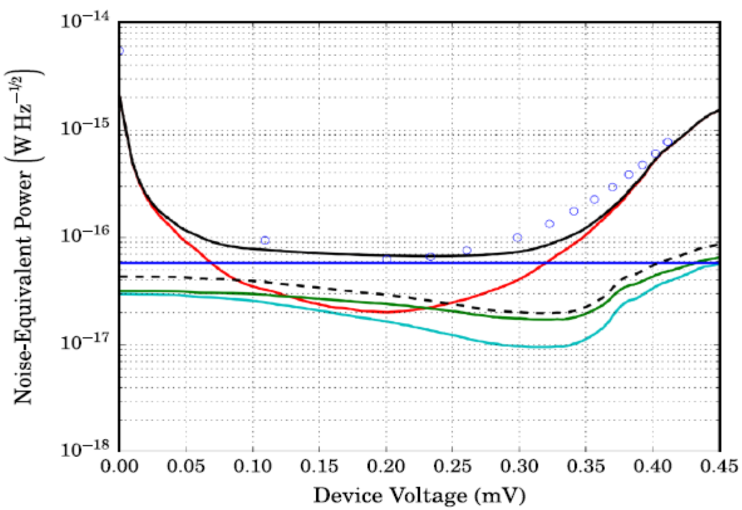
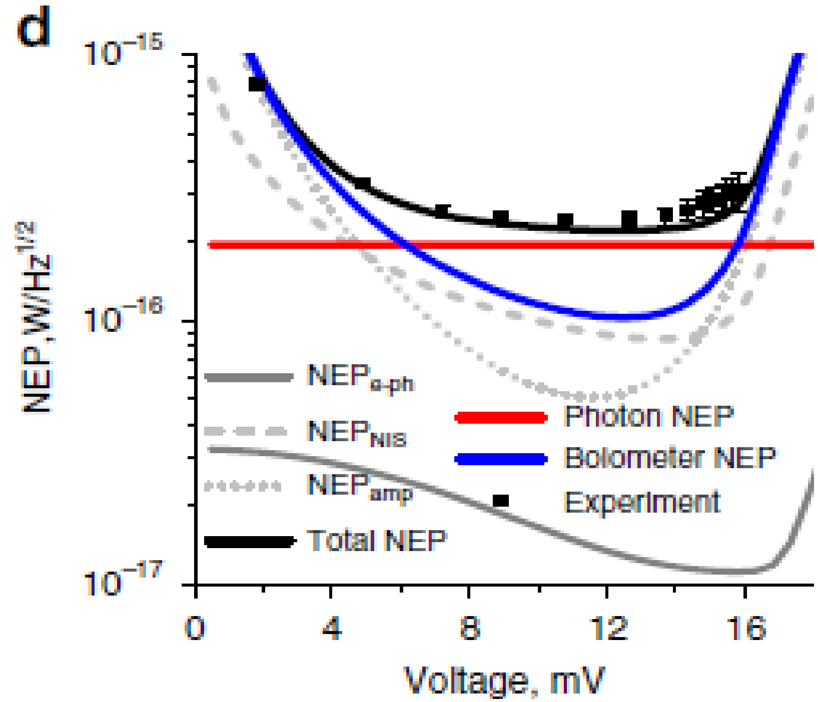


Fig. 4 Example of measured and modelled noise for the strained detector observing a 77-K source. Noise modelled using Eqs. 5 and 6. *Lines* modelled data, *red*—amplifier noise, *green*—tunnelling noise, *cyan*—e-ph noise, *blue*—photon noise, *dashed black*—total device noise (sum of tunnelling and e-ph noise), *black*—total modelled noise level. *Circles* measured data. Overall the model and data are in good agreement and show that the device is photon-noise limited from approximately 0.1–0.3 mV (Color figure online)

T.L.R. Brien, P.A.R. Ade, P.S. Barry, C.J. Dunscombe, D.R. Leadley, D.V. Morozov, M. Myronov, E.H.C. Parker, M.J. Prest, M. Prunnila, R.V. Sudiwala, T.E. Whall, P. D. Mauskopf, J. Low. Temp. Phys. 184, 231–237 (2016)

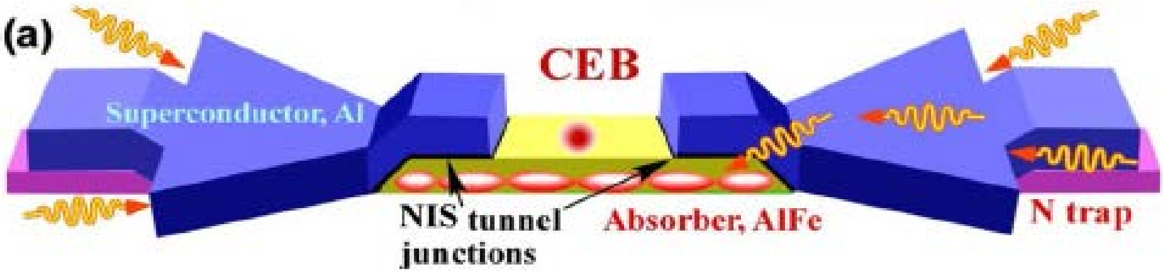


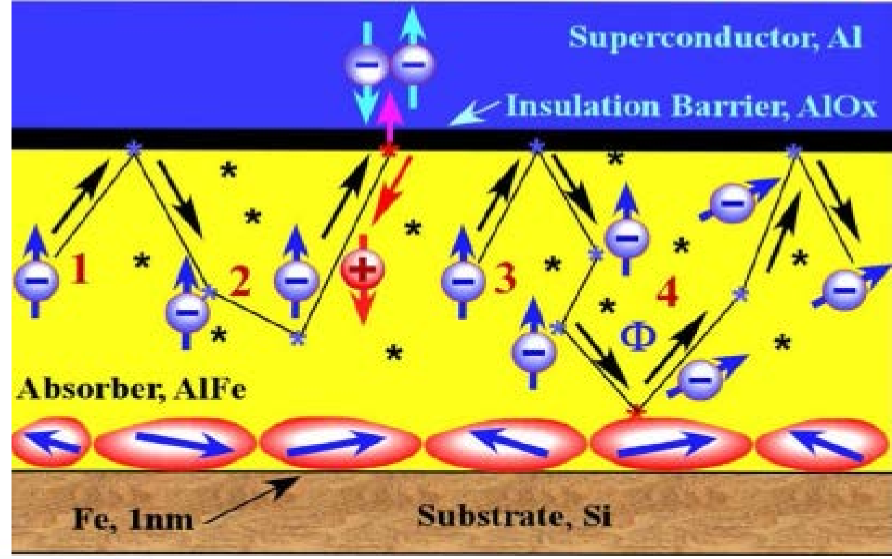
L.S. Kuzmin, A.L. Pankratov, A.V. Gordeeva, V.O. Zbrozhek, V.A. Shamporov, L.S. Revin, A.V. Blagodatkin, S. Masi, P. de Bernardis, Communications Physics, 2, 104 (2019).

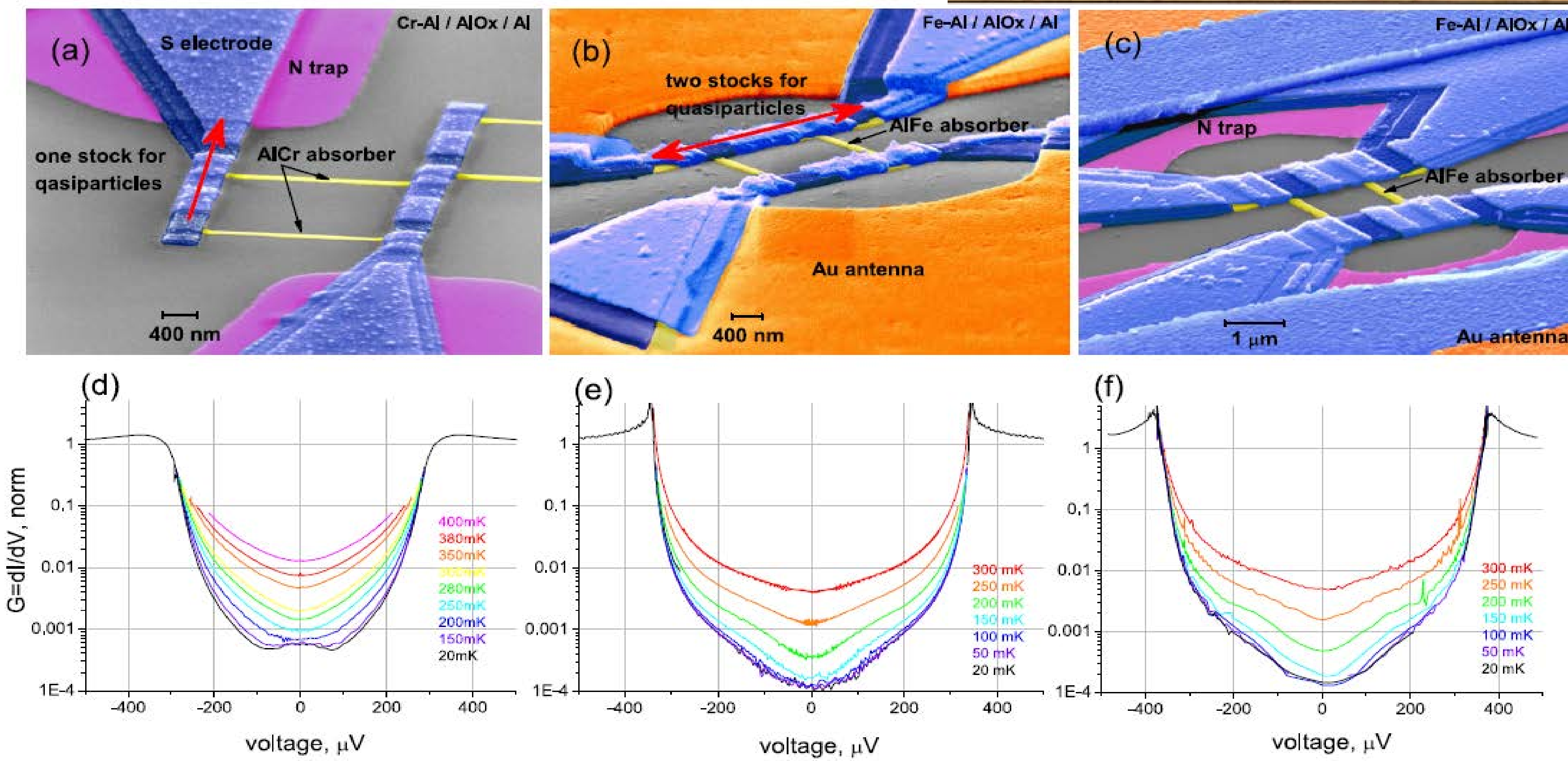
$$\mathrm{NEP_{ph}} = \sqrt{P_0 hf + P_0^2/\delta f}$$

with f=350 GHz, δf=33 GHz, P_0 – accepted power of a signal.

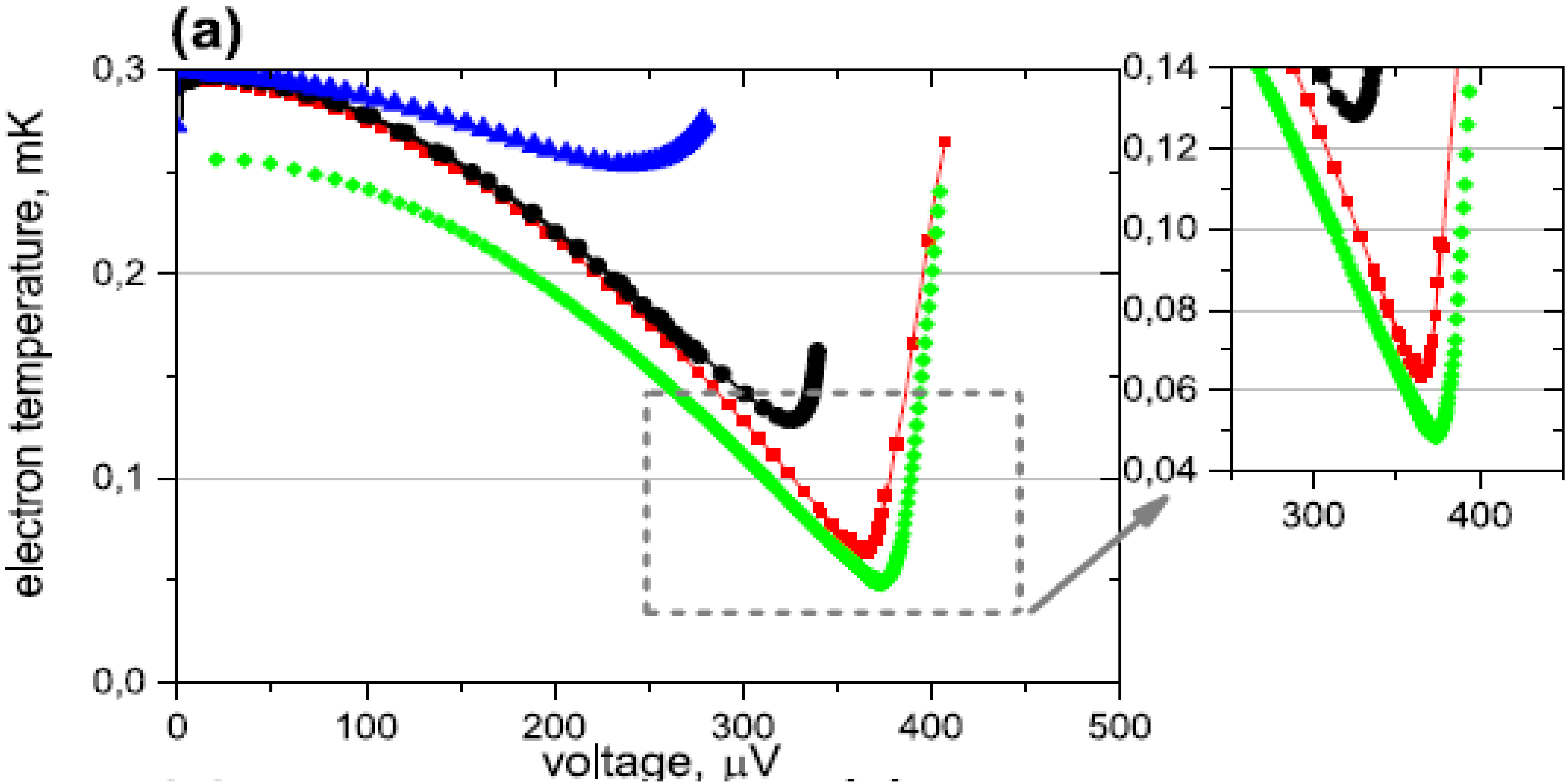
Suppression of Andreev heating current







Design 1 - Design 2 - Design 3

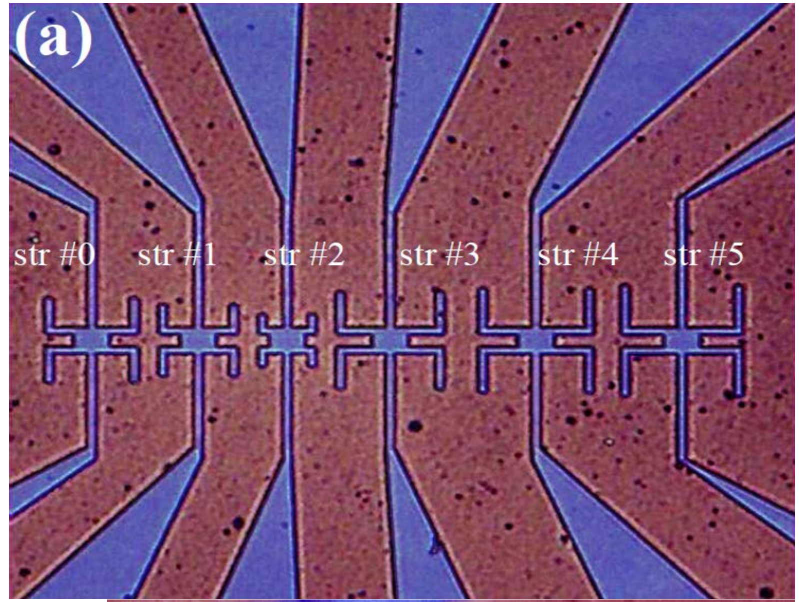


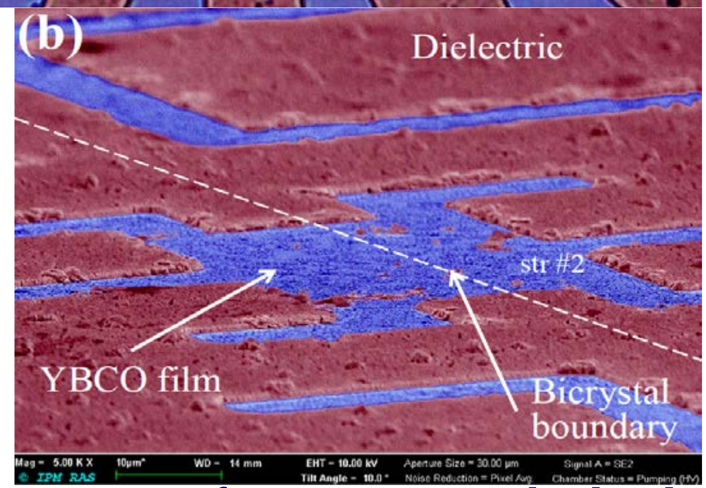
Record electron cooling from 300 to 65 mK!
And from 256 to 48 mK, by a factor of 5.3!

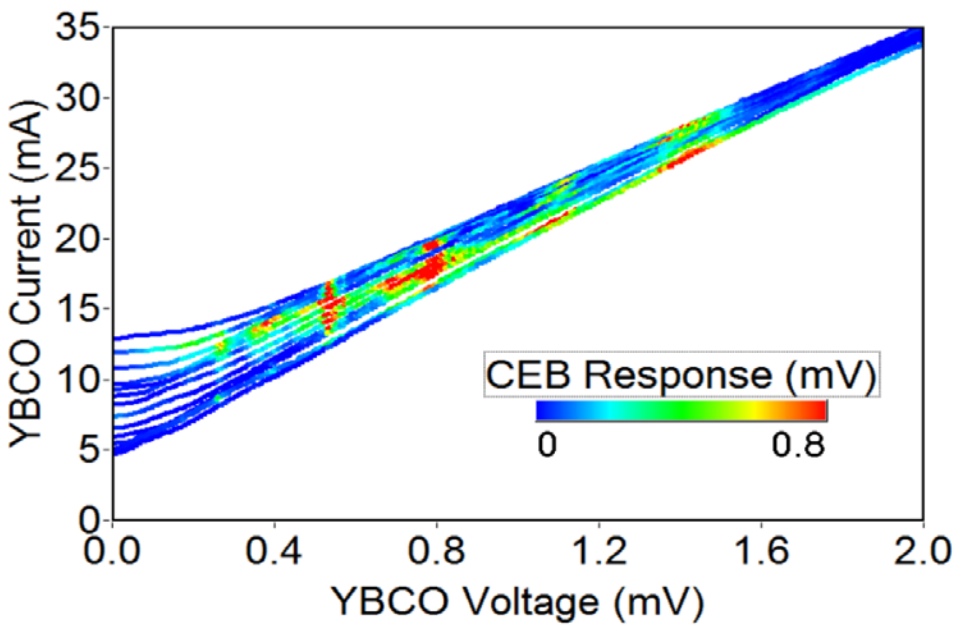
A.V. Gordeeva, A.L. Pankratov, et al, Scientific Reports, 10, 21961 (2020)
https://www.nature.com/articles/s41598-020-78869-z

Investigations of YBCO HTSC Josephson junctions

The preliminary mask technology has been developed for the formation of YBCO structures (patent No. 188983). The topology of the superconducting structure is formed at the stage of YBCO deposition into local windows of the preliminary mask - superconducting elements are formed in the mask windows, and insulating regions are formed between them. The operation of etching the YBCO film is eliminated. The number of defects is reduced. This technology makes it possible to carry out multiple cycles of YBCO deposition, increasing the film thickness.

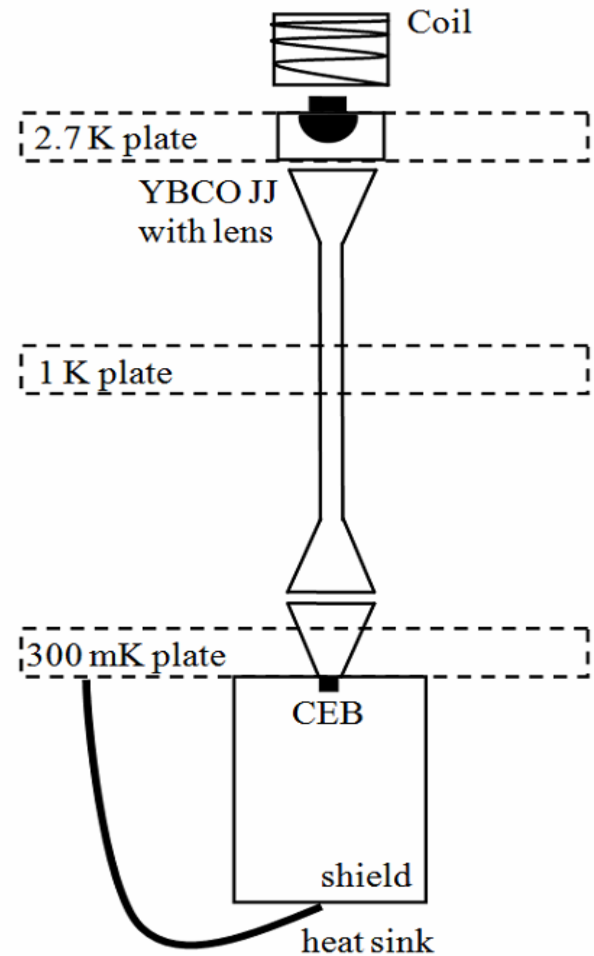






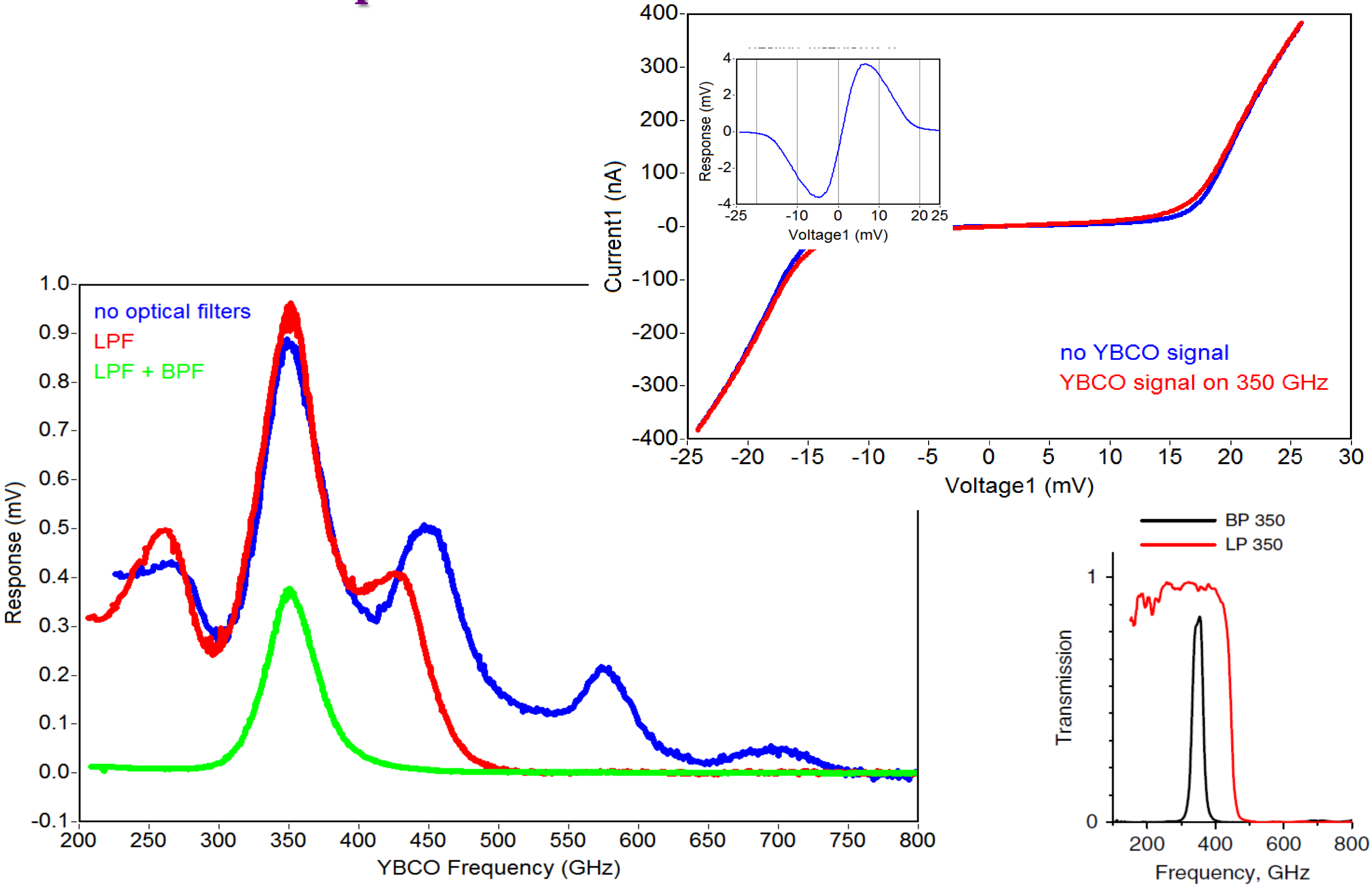
Above are SEM images of structures with dipole antennas. On the left, in blue – the family of current-voltage characteristics of the sample, in red – the signal power received by the bolometer.

Experimental setup

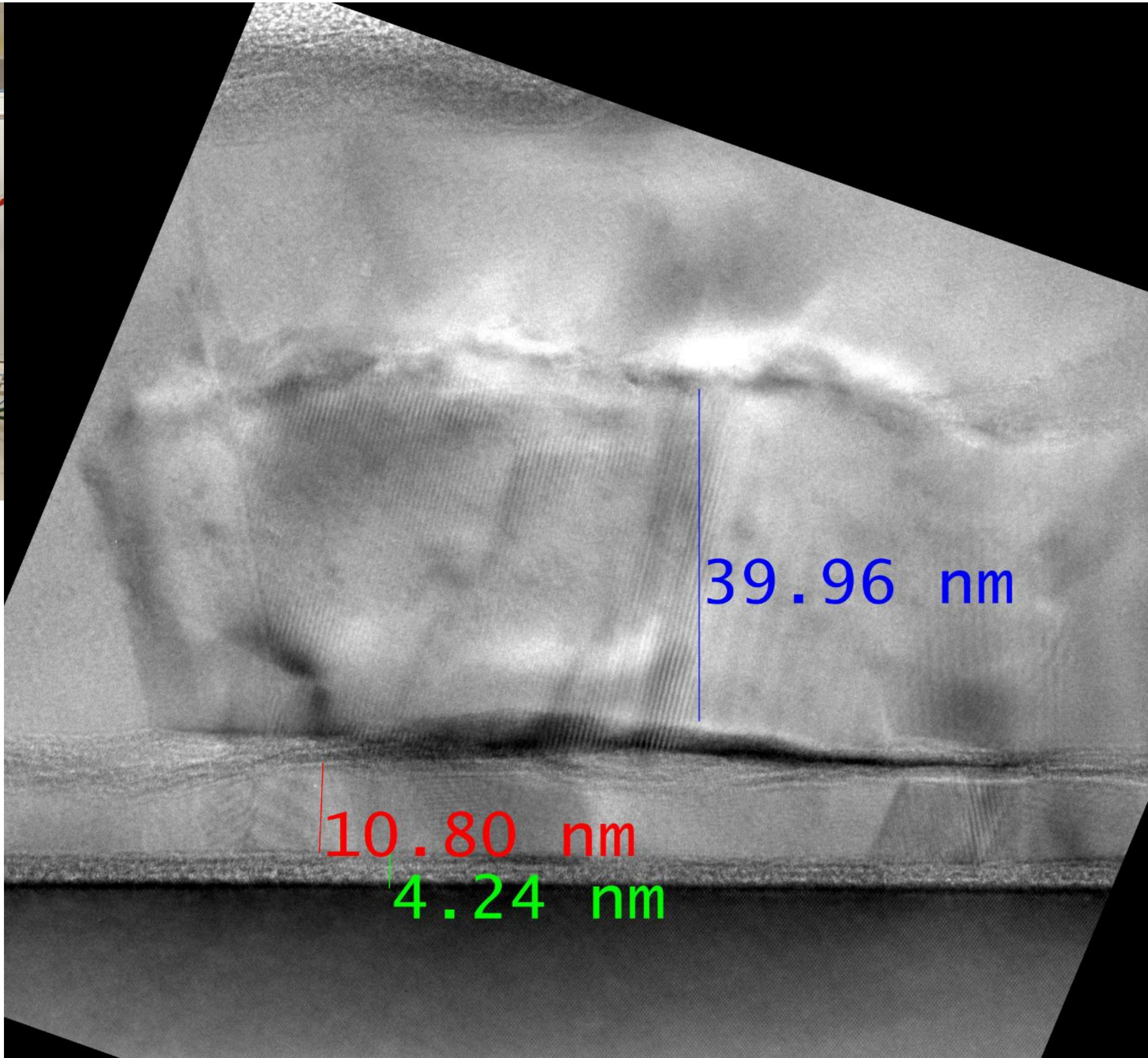


L. Revin, D. Masterov, A. Parafin, S. Pavlov, D. Pimanov, A. Chiginev, et al., A Bunch of YBCO Josephson Generators for the Analysis of Resonant Cold-Electron Bolometers, Applied Sciences 12, 11960 (2022).

Response of CEB to YBCO oscillator

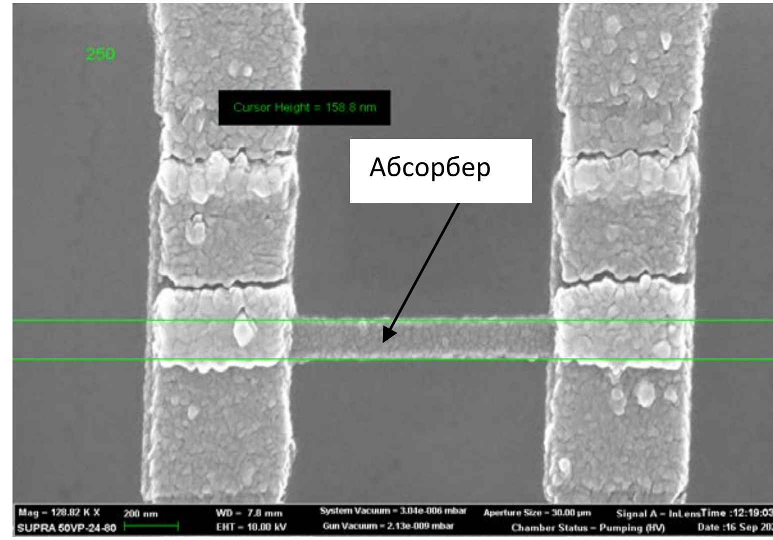


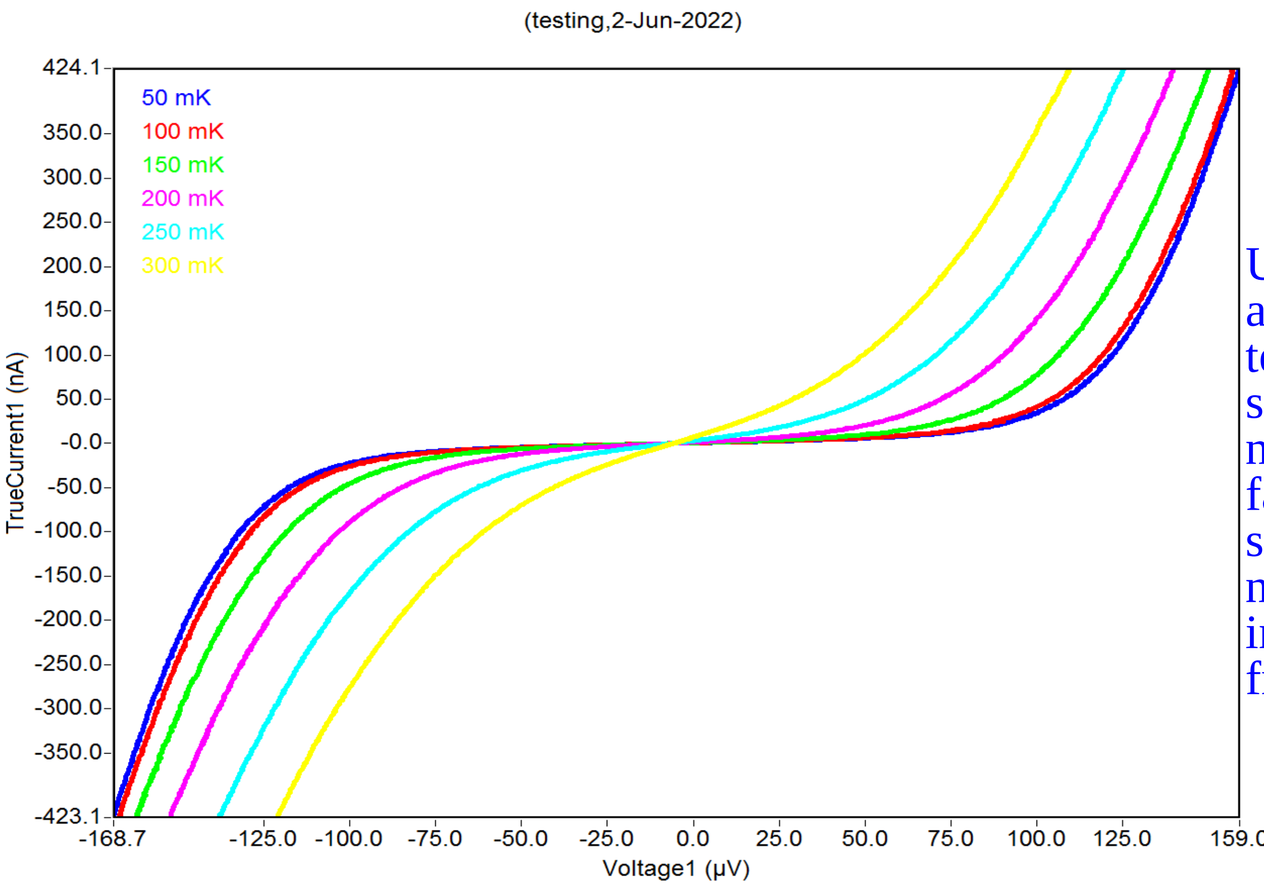
Transfer of technologies to Nizhny Novgorod



Transfer of technologies to Nizhny Novgorod

Transfer of technologies for creating superconducting tunnel junction nanostructures from Chalmers University of Technology is underway. Using the technological base of the Center for Collective Use of the IPM RAS and the Center for Quantum Technologies of the Nizhny Novgorod State Technical University, the first test structures of superconductor-insulator-normal metal contacts were fabricated.





Using electron- and photo- lithographies, as well as the shadow evaporation technique, the first Nizhny Novgorod structures with superconductor-insulator-normal metal tunnel junctions were fabricated. Top – SEM image of the structure with an absorber width of 150 nm, left – IVC of the structure measured in a dilution cryostat at temperatures from 50 to 300 mK.

Hierarchy of noise

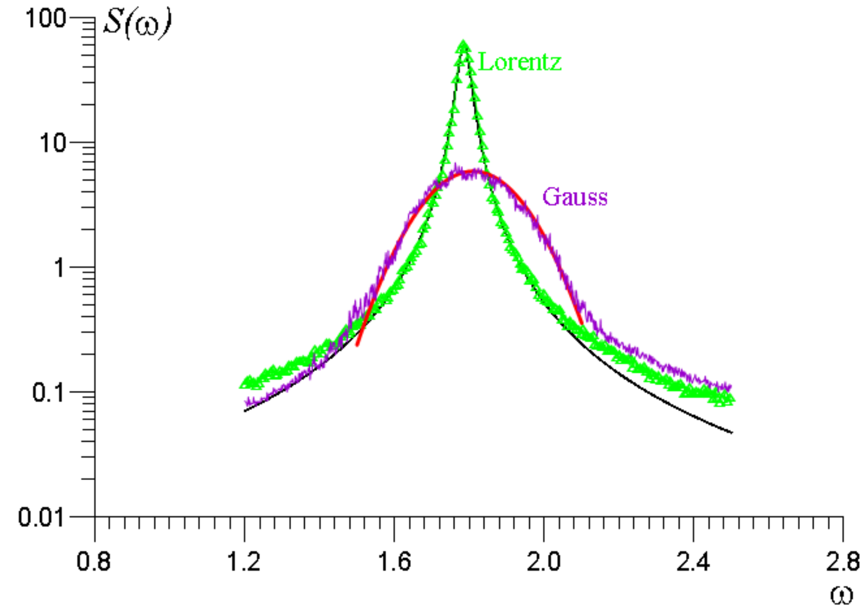
Technical noises (narrow band)

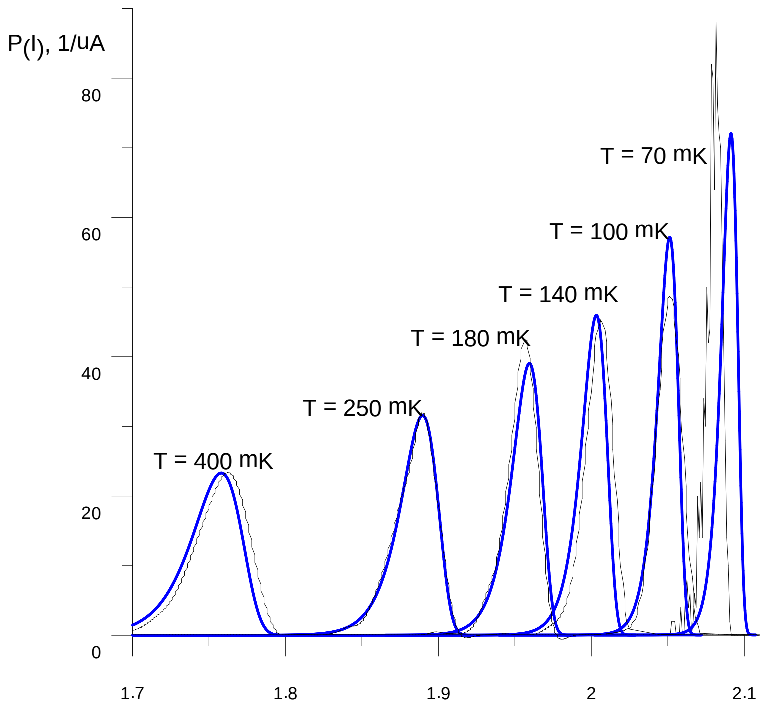
Natural noises (broad band):

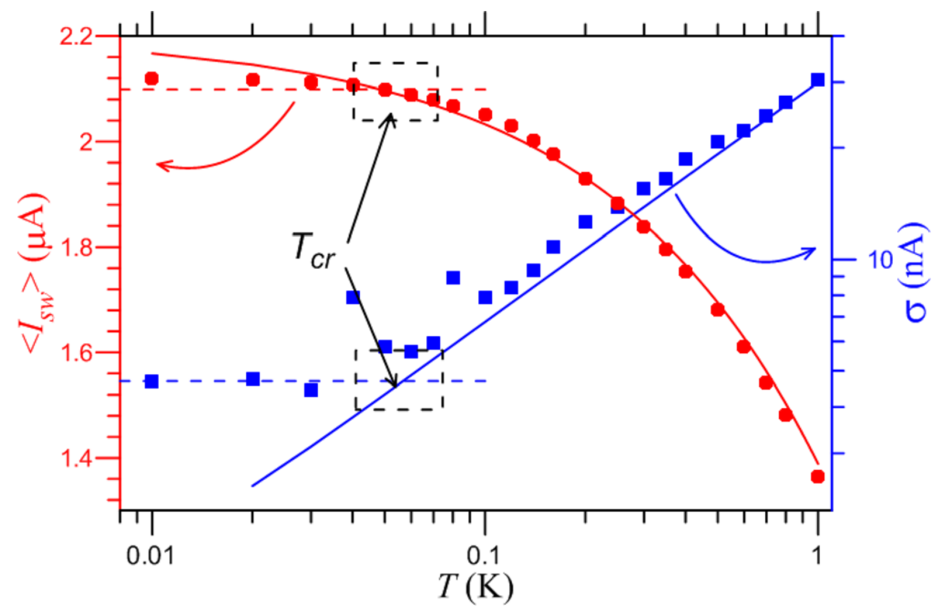
Thermal noise $S_I(\omega)\sim kT/R$

Shot noise $S_I(\omega)\sim eI/2$

Quantum noise $S_I(\omega)\sim h\omega/R$



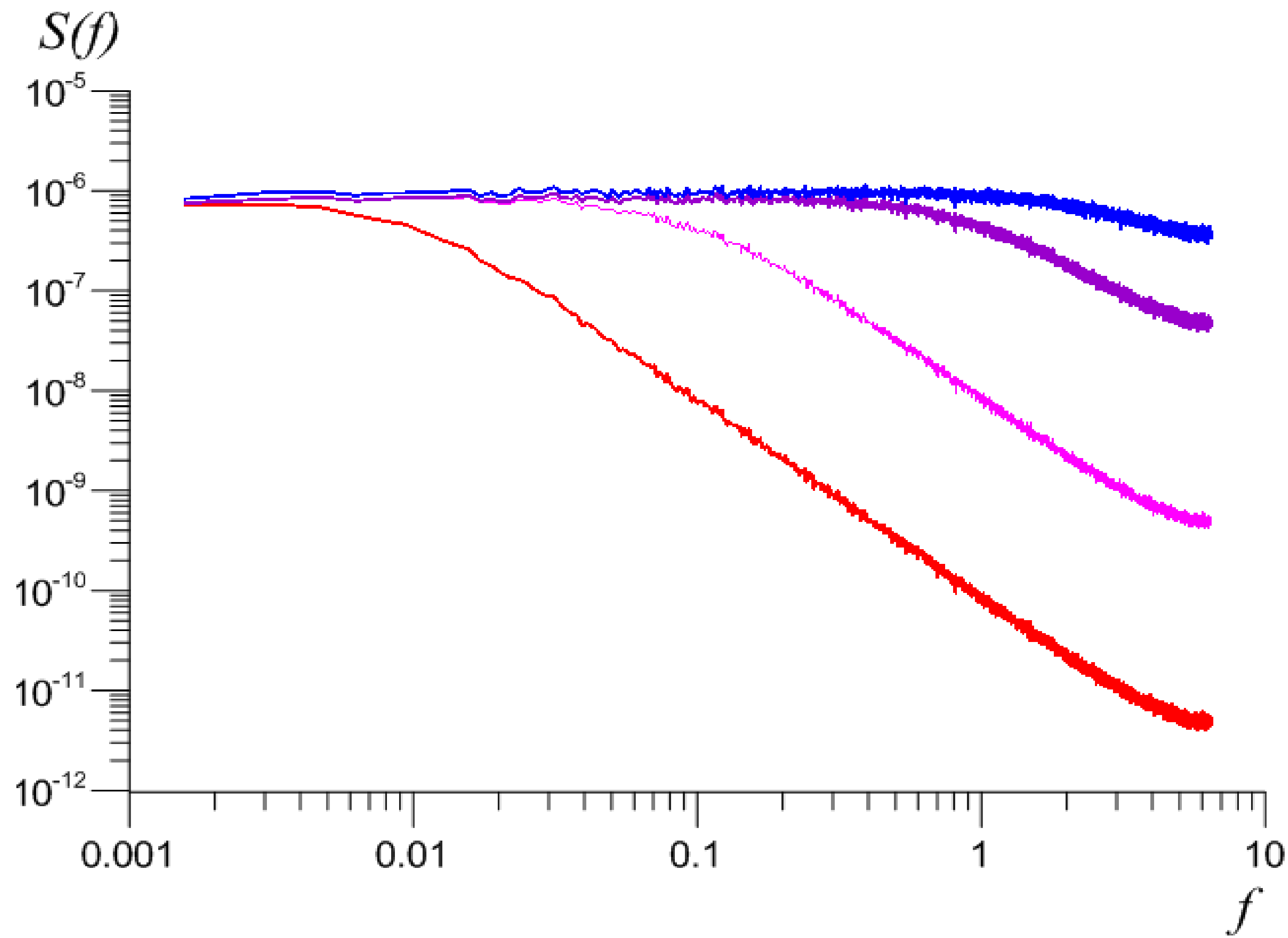




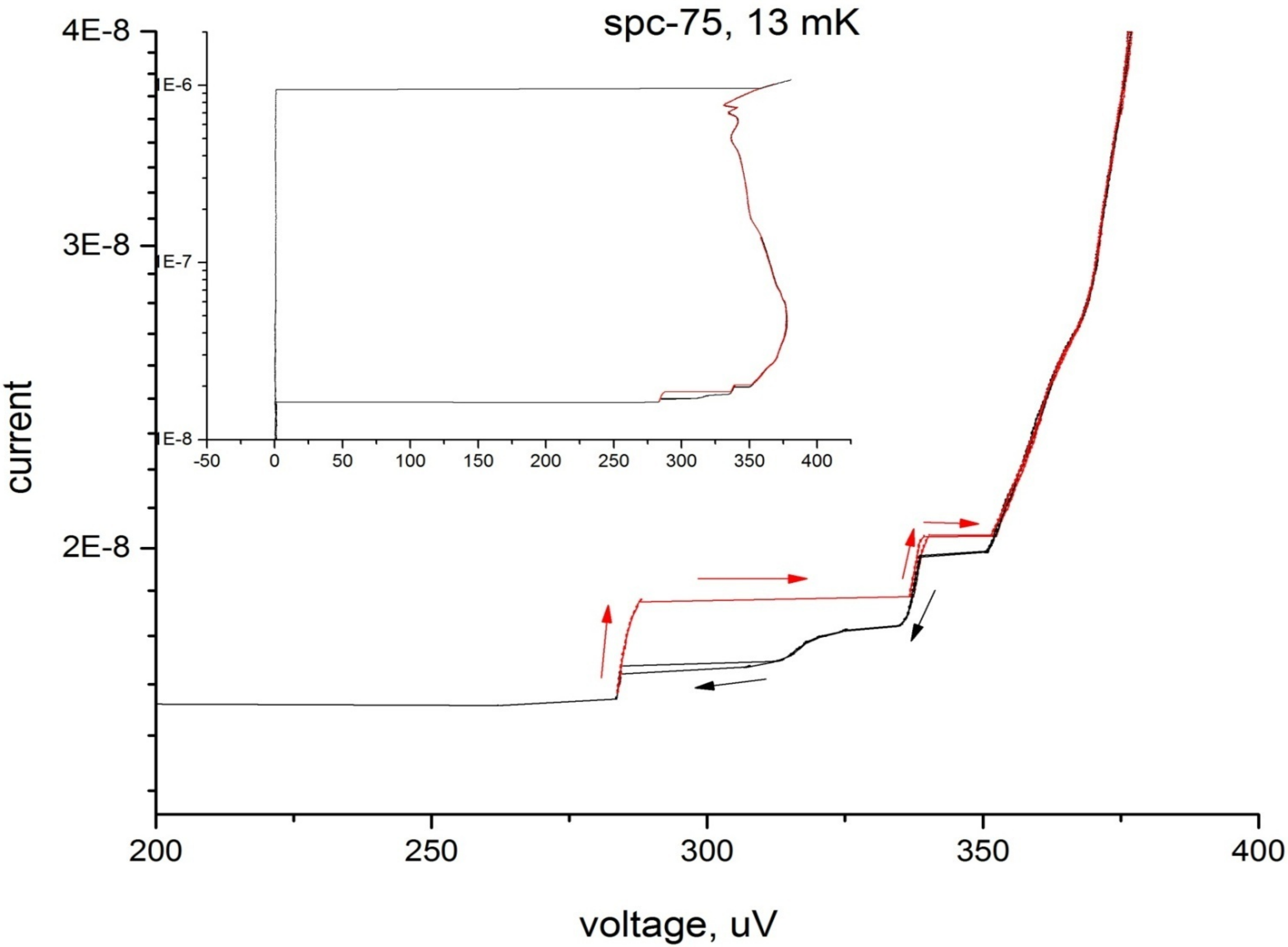
Oelsner G., Revin L.S., Ilichev E., Pankratov A.L., Meyer H.-G., Gronberg L., Hassel J., and Kuzmin L.S., Appl. Phys. Lett., 103, 142605 (2013).

Pink noise – realistic noise model

$$dx/dt=-ax+\xi(t),\ \langle\xi(t)\xi(t+\tau)\rangle=D\delta(\tau)$$



Current-voltage characteristics of SIS junction



Langevin and Fokker-Planck equations

$$\frac{dx(t)}{dt} = -\frac{1}{h}\frac{dU(x)}{dx} + \xi(t)$$

$$<\xi(t)>=0,\ <\xi(t)\xi(t+\tau)>=D\delta(\tau),\ D=2kT/h$$

$$\frac{\partial W(x,t)}{\partial t} = -\frac{\partial G(x,t)}{\partial x} = \frac{1}{B}\frac{\partial}{\partial x}\left[\frac{du(x)}{dx}W(x,t) + \frac{\partial}{\partial x}W(x,t)\right]$$

$$B=1/D,\ u(x)=U(x)/kT,\ W(c,t)=0,\ G(d,t)=0.$$

- Dimensionless FP equation

$$\frac{\partial W(x,t)}{\partial t} = D\frac{\partial}{\partial x}\left[\frac{du(x)}{dx}W(x,t) + \frac{\partial}{\partial x}W(x,t)\right]$$

- Change of variables:

$$W(x,t) = \Psi(x,t)e^{-\frac{u(x)}{2}}$$

- Change of time:

$$t = i\tau$$

- Dimensionless Schroedinger equation

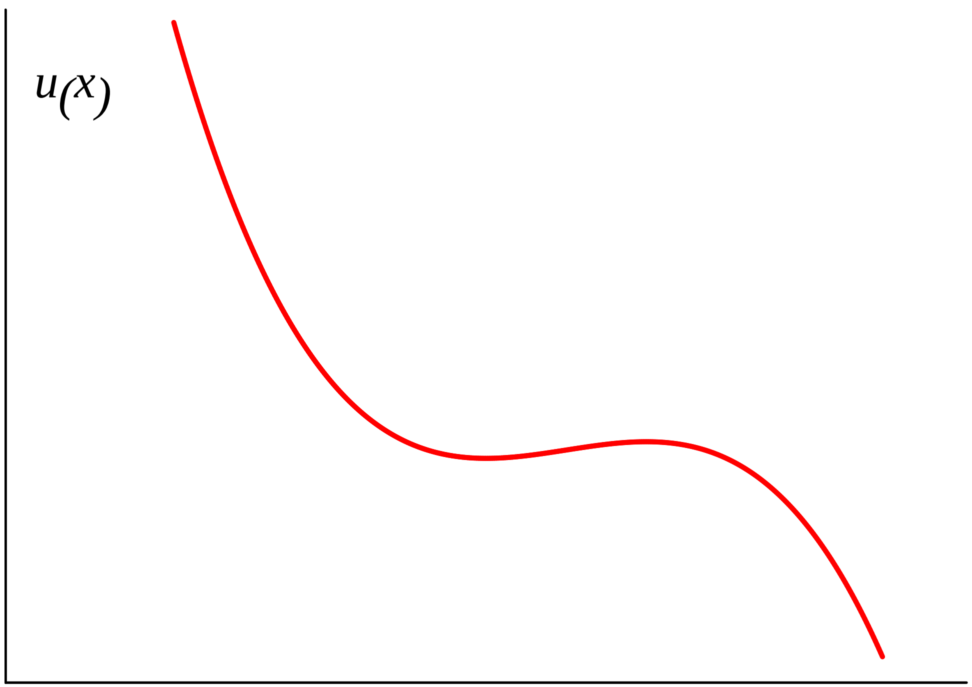
$$\frac{\partial\psi(x,\tau)}{\partial\tau} = iD\left[\frac{\partial^2\psi(x,\tau)}{\partial x^2} - V(x)\psi(x,\tau)\right]$$

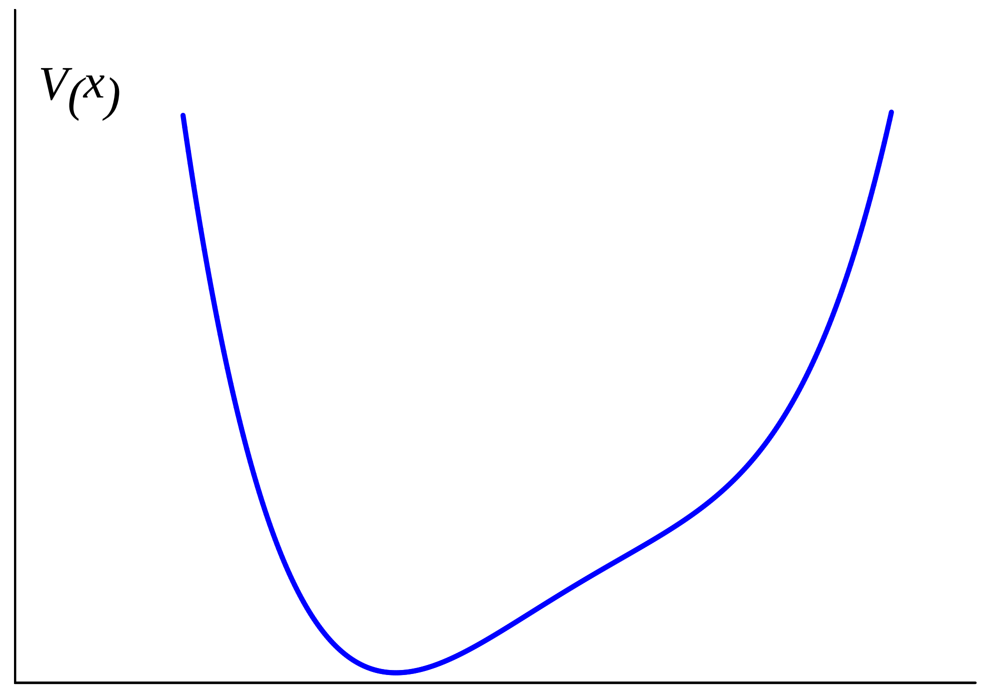
- Connection between potentials in FP and Schroedinger equations

$$V(x) = -\frac{1}{2}\frac{d^2u(x)}{dx^2} + \left(\frac{1}{2}\frac{du(x)}{dx}\right)^2$$

M. Bernstein and L.S. Brown, Supersymmetry and the Bistable Fokker-Planck Equation, Phys. Rev. Lett., **52**, 1933 (1984).

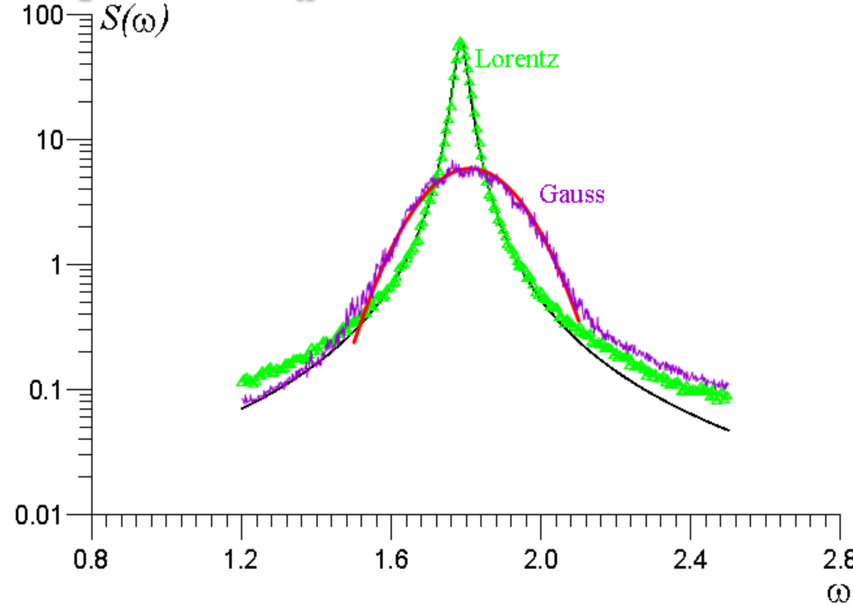
$$\frac{\partial W(x,t)}{\partial t} = D\frac{\partial}{\partial x}\left[\frac{du(x)}{dx}W(x,t)+\frac{\partial}{\partial x}W(x,t)\right] \qquad \frac{\partial \psi(x,\tau)}{\partial \tau} = iD\left[\frac{\partial^2\psi(x,\tau)}{\partial x^2} - V(x)\psi(x,\tau)\right]$$

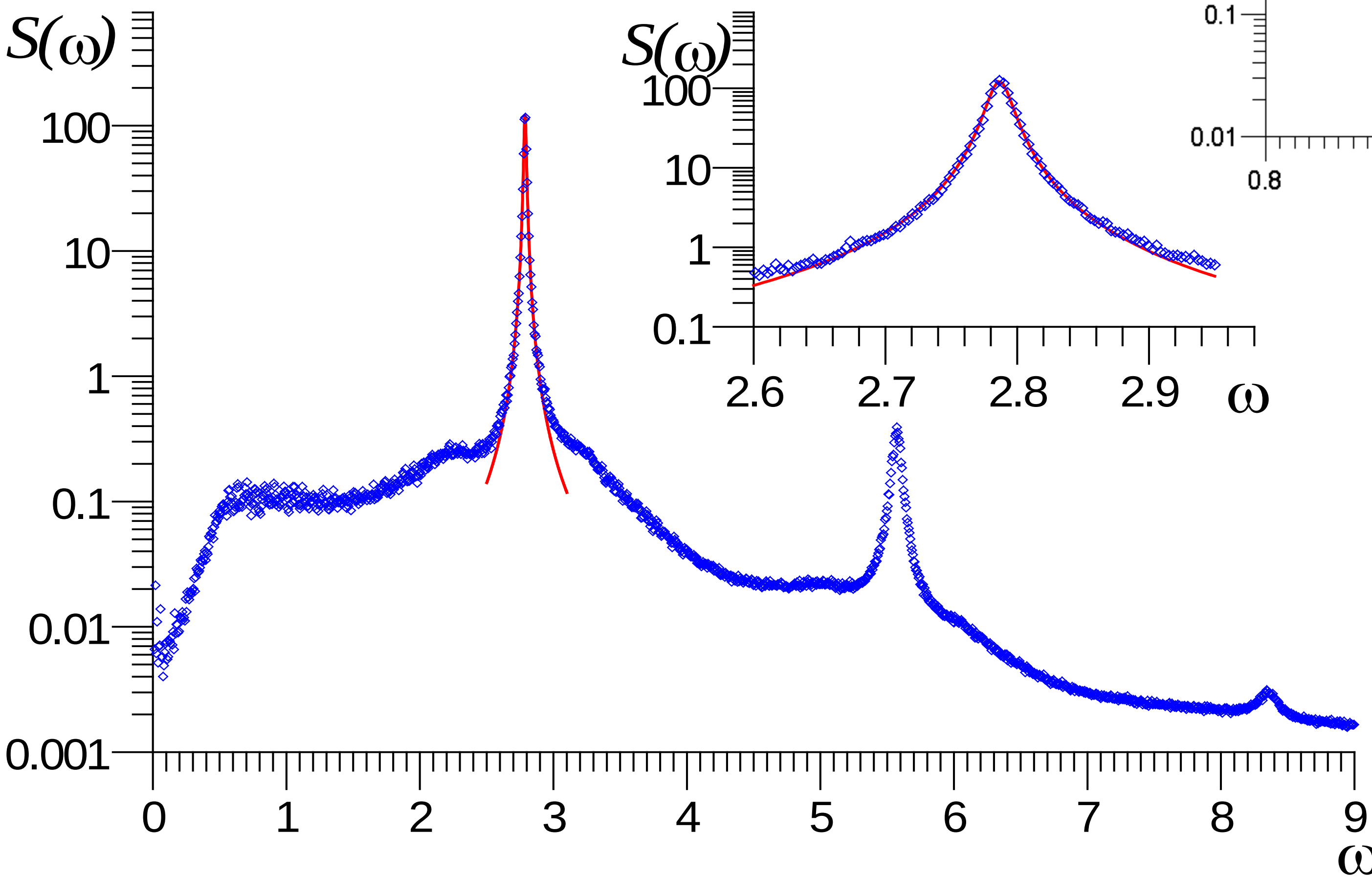




$u(x)=x^2-x^3$ $\qquad$ $V(x)=(3x^2/2-x)^2+3x-1$

Radiation linewidth of a Josephson junction





VOLTAGE DUE TO THERMAL NOISE IN THE dc JOSEPHSON EFFECT

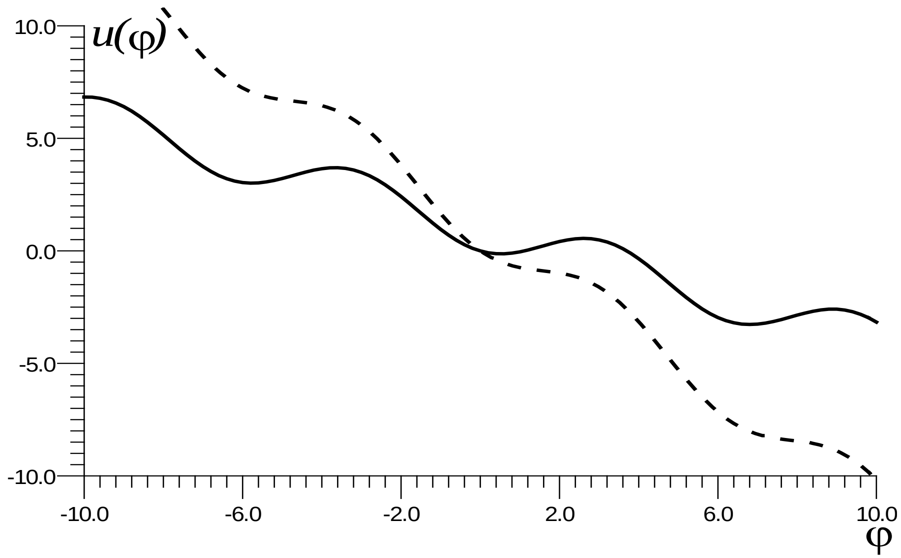
Vinay Ambegaokar*
Laboratory of Atomic and Solid State Physics, Cornell University, Ithaca, New York 14850

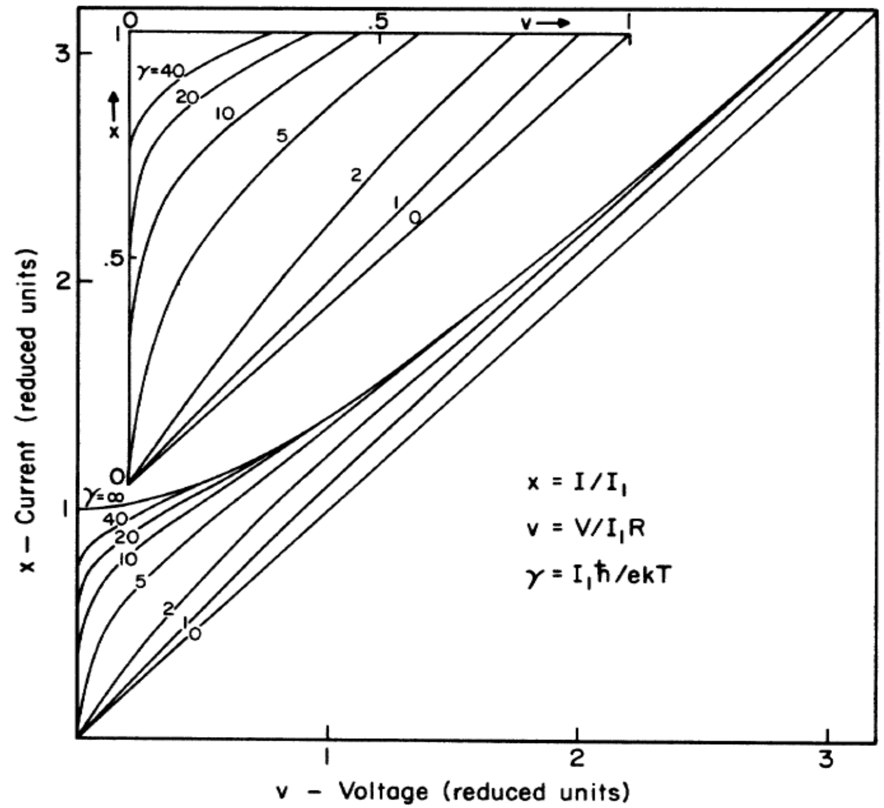
and

B. I. Halperin
Bell Telephone Laboratories, Murray Hill, New Jersey 07974

(Received 25 April 1969)

$$\frac{\partial W(\varphi,t)}{\partial t}=\frac{1}{B}\frac{\partial}{\partial\varphi}\left[\frac{du(\varphi)}{d\varphi}W(\varphi,t)+\frac{\partial}{\partial\varphi}W(\varphi,t)\right]$$





R. L. Stratonovich, “Topics in the Theory of Random Noise”, Gordon and Breach, New York, 1963.

Method of reduced phase

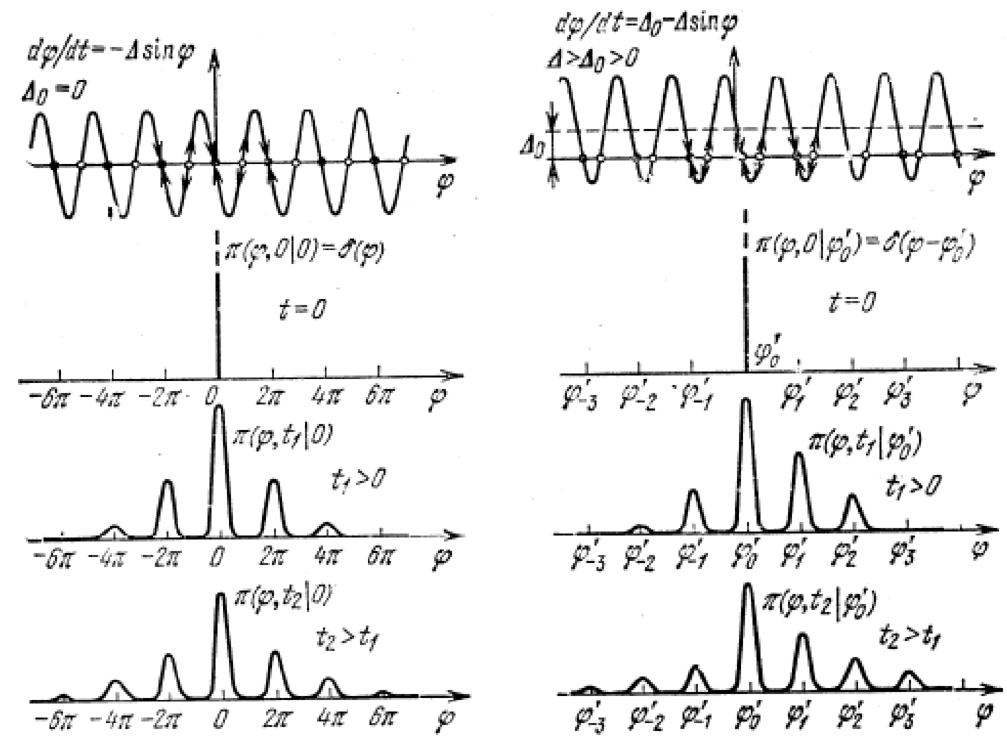


Рис. 22.3. Качественный характер изменения плотности вероятности полной фазы во времени при $\Delta_0=0$ и $\Delta>\Delta_0>0$.

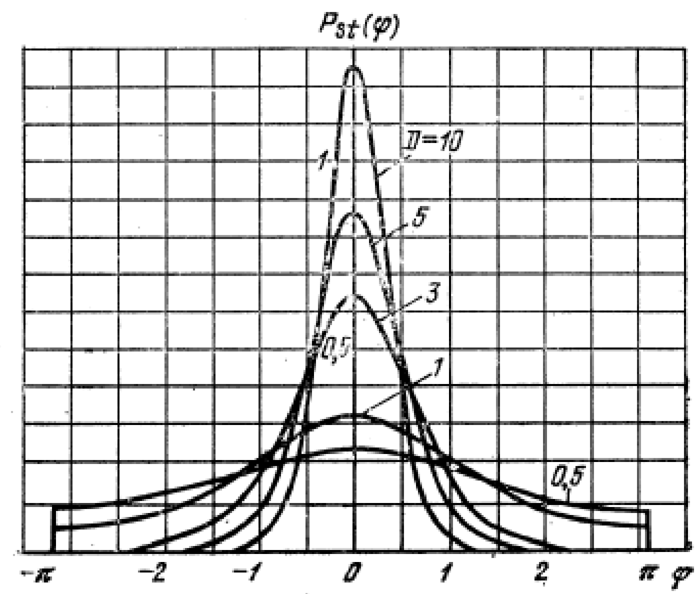


Рис. 22.4. Стационарные плотности вероятности приведенной разности фаз в отсутствие начальной расстройки ($\Delta_0=0$).

V.I. Tikhonov, M.A. Mironov, “Markovian processes” Moscow, Science, 1977.

Radiation linewidth of a short Josephson junction

VOLUME 22, NUMBER 26 PHYSICAL REVIEW LETTERS 30 JUNE 1969

LINEWIDTH OF THE RADIATION EMITTED BY A JOSEPHSON JUNCTION*

A. J. Dahm,† A. Denenstein,‡ D. N. Langenberg, W. H. Parker,§ D. Rogovin, and D. J. Scalapino
Department of Physics and Laboratory for Research on the Structure of Matter,
University of Pennsylvania, Philadelphia, Pennsylvania
(Received 18 April 1969)

backward junction currents. For the low-frequency region of interest, it follows from an analysis of the Josephson-Maxwell equations[6] (and it is clear on physical grounds) that the junction impedance is simply the dynamic resistance $R_D = (dI/dV)^{-1}$, so that

$$\langle \delta V^2 \rangle = R_D^{\,2} \int_0^\infty P_{Iqp}(\omega)\, d\omega. \tag{7}$$

Using Eq. (1), Eq. (3), and standard frequency-modulation noise theory,[7] we obtain for the quasiparticle contribution to the linewidth

$$\Delta\omega_{qp} = (2e/\hbar)^2 R_D^{\,2} e I_{qp}(V_0) \coth(\tfrac{1}{2}\beta V_0). \tag{8}$$

$$\Delta\nu = \Delta\omega/2\pi = (4\pi R_D^{\,2} kT/V_0)(2e/h)^2 (I_{qp} + I_p).$$

ing Eq. (9) arises because pairs of electrons are coherently transferred. The expression for the linewidth including both the quasiparticle and the pair contributions is[9]

$$S_I \sim kT/R_N \qquad\qquad S_I \sim kT(I_{qp} + I_p)/V = kTI/V = kT/R_S$$

Radiation linewidth of a short Josephson junction

$$I = I_c \sin\varphi + VG_N + C\frac{dV}{dt} + I_F(t).$$

$$\dot\varphi = \frac{2e}{\hbar}V,\ \omega_p = \sqrt{\frac{2eI_c}{\hbar C}},\quad \omega_c = \frac{2eR_N I_c}{\hbar}.$$

$$V = \bar V + \tilde V,\ \ \varphi = \omega_j t + \tilde\varphi,\ \ \tilde\varphi = \frac{2e}{\hbar}\int \tilde V dt$$

$$\omega_j = 2e\bar V/\hbar = 2\pi \bar V/\Phi_0$$

$$V(t) = \bar V + \mathrm{Im}\sum_{k>0} V_k \exp(jk\theta),\ \ \dot\theta = \omega_j = \overline{\dot\varphi}$$

Small fluctuations: $\Delta f << \omega_j$

Large damping:

$\beta = (\omega_c/\omega_p)^2 = 2e/\hbar I_c R_N^2 C << 1$

$$S_I(\omega) = {}^{kT}\!/_{\pi R_N} = const$$

$$\frac{1}{\omega_c}\frac{d\varphi}{dt} = i - \sin\varphi + i_F(t)$$

$$\langle i_F(t)\rangle = 0, \qquad \langle i_F(t) i_F(t+\tau)\rangle = 2\gamma\delta(\tau)$$

$$\gamma \equiv \frac{2ekT}{\hbar I_C} = \frac{I_T}{I_C}$$

$\tilde\varphi$ - small phase increments

φ_0 – solution in the absence of fluctuations

$$\omega_c^{-1}\dot\varphi + \sin\varphi = i,$$

$$\varphi_0 = 2Arctg\left\{\left[v/(i+1)\right] tg\frac{\theta}{2}\right\} - \pi/2,$$

$$\omega_c^{-1}\dot{\tilde\varphi} + \cos\varphi_0 \tilde\varphi = \tilde i, \quad \tilde i = i_F = I_F/I_c$$

$$S_V(0) = R_d^2 S_I^{'}(0);$$

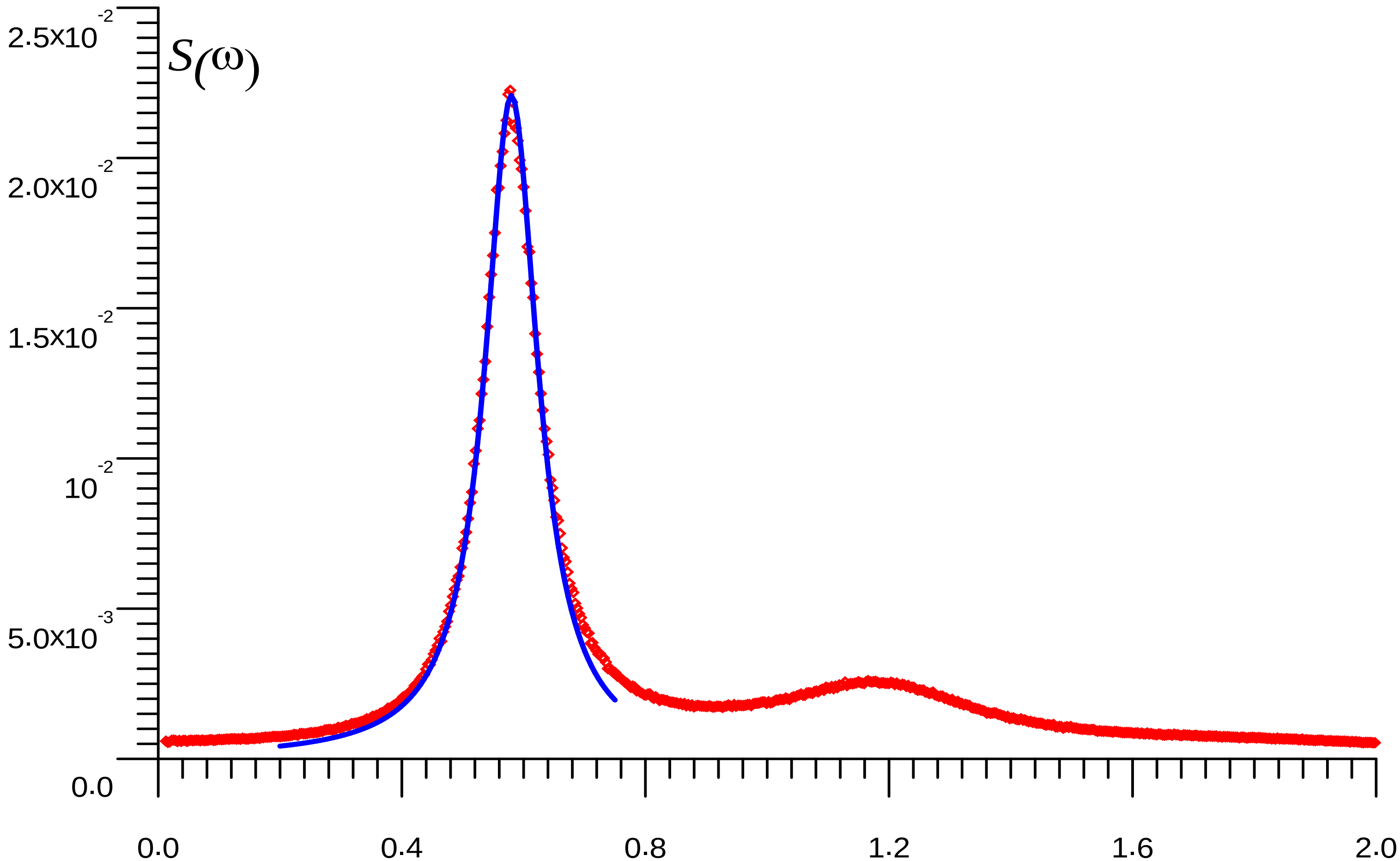
$$S_I^{'}(0) = S_I(0) + (I_c^2/2I^2) S_I(\omega_j)$$

$$\Delta f = \pi r_d^2 \gamma\left(1 + \frac{1}{2i^2}\right) \qquad r_d = \frac{dv}{di} = \frac{i}{\sqrt{i^2 - 1}}$$

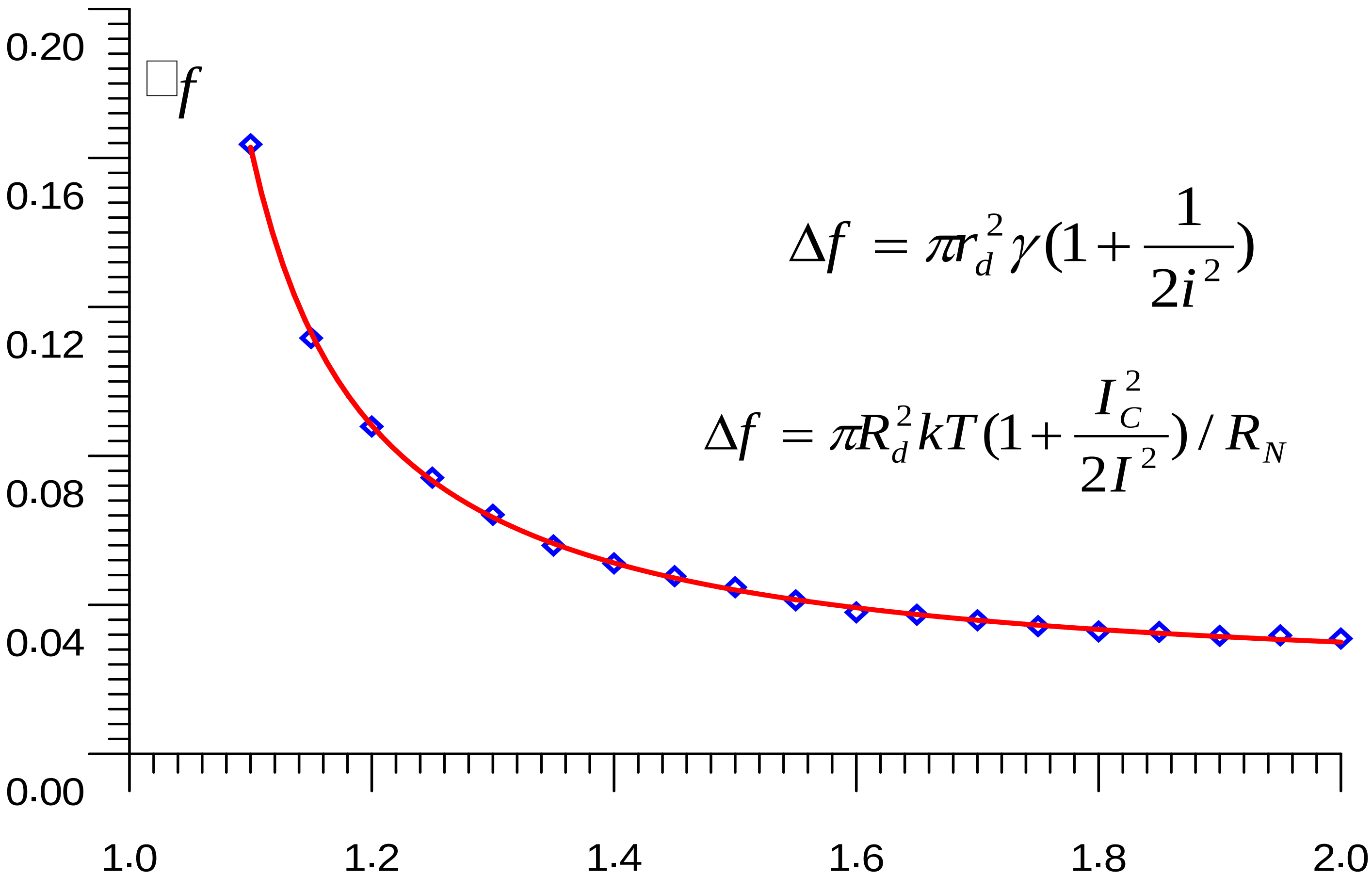
$$\Delta f = \pi R_d^2 kT\left(1 + \frac{I_C^2}{2I^2}\right)/R_N$$

[1] Likharev K.K. Dynamics of Josephson junctions and circuits. – NY: G&B, 1986.

Radiation linewidth of a short Josephson junction



Radiation linewidth of a short Josephson junction



Shamporov V.A., Myasnikov A.S., Pankratova E.V., Pankratov A.L. (2017): Spectral linewidth of parallel Josephson junction array with intermediate-to-large damping, Physical Review B, 96, 064522.

Radiation linewidth of a long Josephson junction

$$\frac{\partial^2\varphi}{\partial t^2}+\alpha\frac{\partial\varphi}{\partial t}-\frac{\partial^2\varphi}{\partial x^2}=\eta-\sin(\varphi);$$

$$\frac{\partial\varphi(0,t)}{\partial x}=\frac{\partial\varphi(L,t)}{\partial x}=H$$

$$\frac{\partial^2\varphi}{\partial\tau^2}+\beta\frac{\partial\varphi}{\partial\tau}-\frac{\partial^2\varphi}{\partial z^2}=\beta-\varepsilon\sin(\varphi);$$

$$\tau=\left(\eta/\alpha\right)t$$

$$\varepsilon=\left(\alpha/\eta\right)^2<<1$$

$$\frac{\partial^2\varphi_0}{\partial\tau^2}+\beta\frac{\partial\varphi_0}{\partial\tau}-\frac{\partial^2\varphi_0}{\partial z^2}=\beta;$$

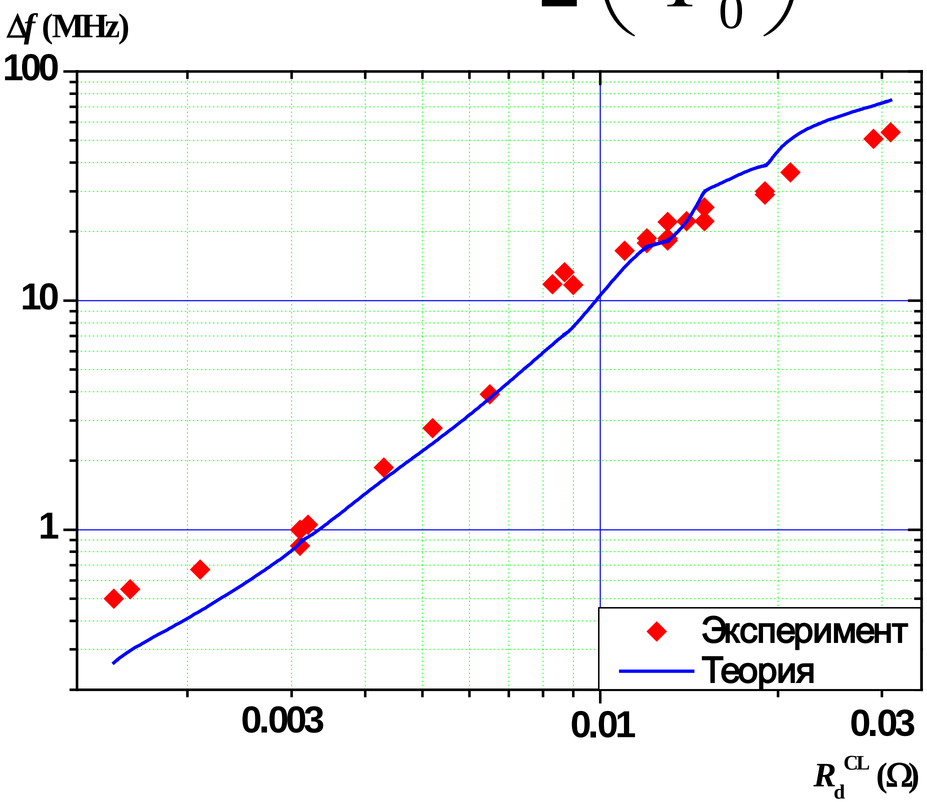
$$\frac{\partial^2\varphi_1}{\partial\tau^2}+\beta\frac{\partial\varphi_1}{\partial\tau}-\frac{\partial^2\varphi_1}{\partial z^2}=-\sin(\omega_J\tau+hz);$$

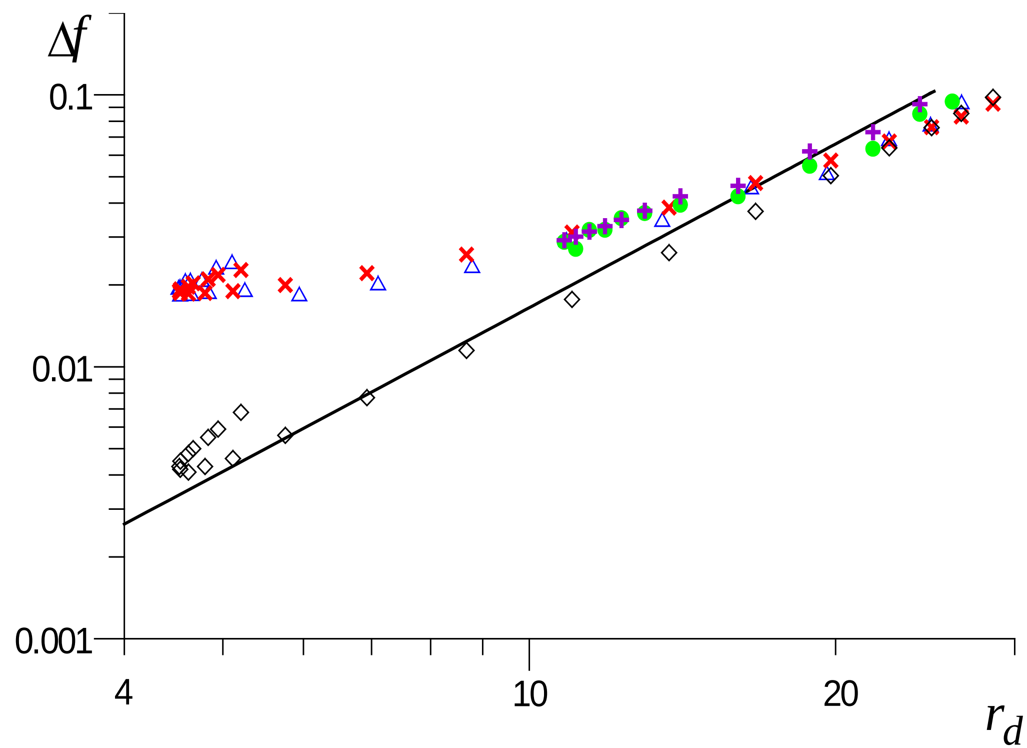
$$\frac{\partial^2\varphi_2}{\partial\tau^2}+\beta\frac{\partial\varphi_2}{\partial\tau}-\frac{\partial^2\varphi_2}{\partial z^2}=-\varphi_{1p}(\tau)\cos(\omega_J\tau+hz).$$

Radiation linewidth of a long Josephson junction

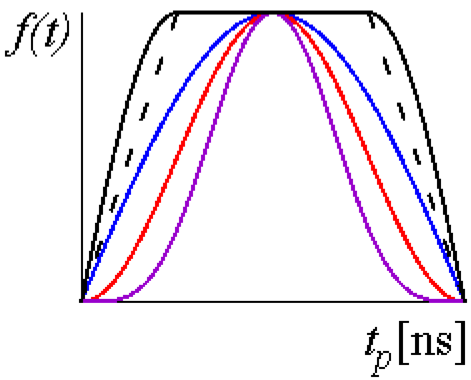
A.L. Pankratov, Phys. Rev. B 65, 054504 (2002).
A.L. Pankratov, Appl. Phys. Lett. 92, 082504 (2008).
A.L. Pankratov, Phys. Rev. B 78, 024515 (2008).

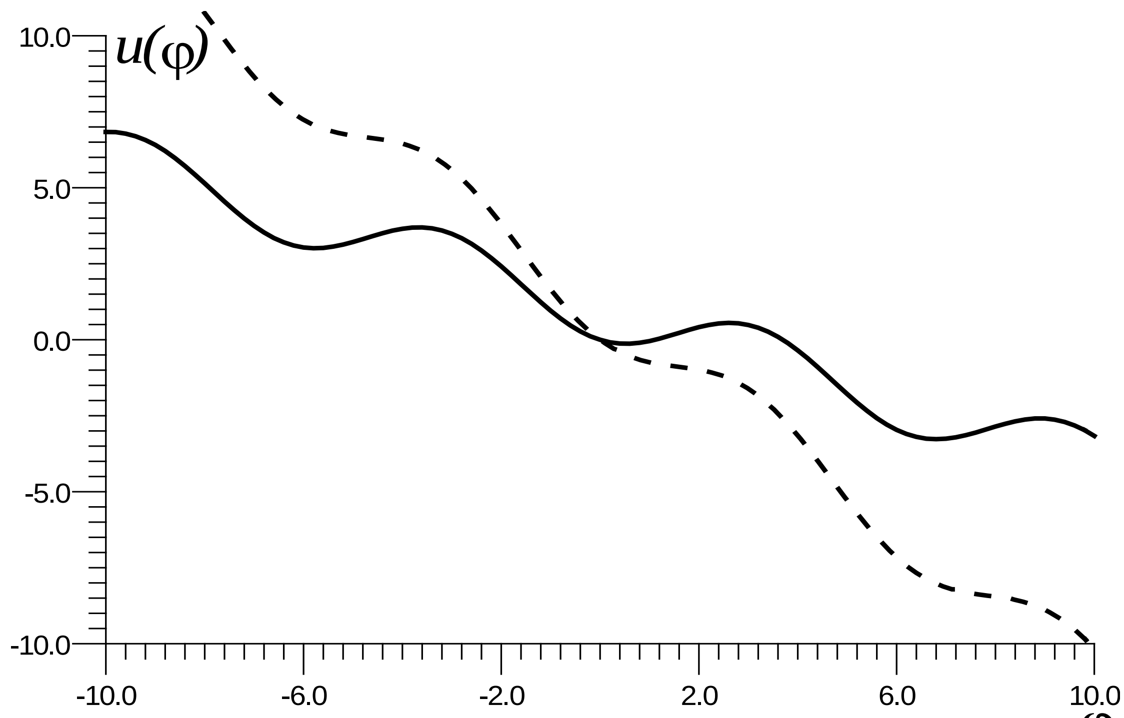
$$\Delta f_{FFO} = \frac{1}{2}\left(\frac{2\pi}{\Phi_0}\right)^2 \left(R_d + K R_d^{CL}\right)^2 \frac{kT}{R_N}\left(1 + H_0\right)$$



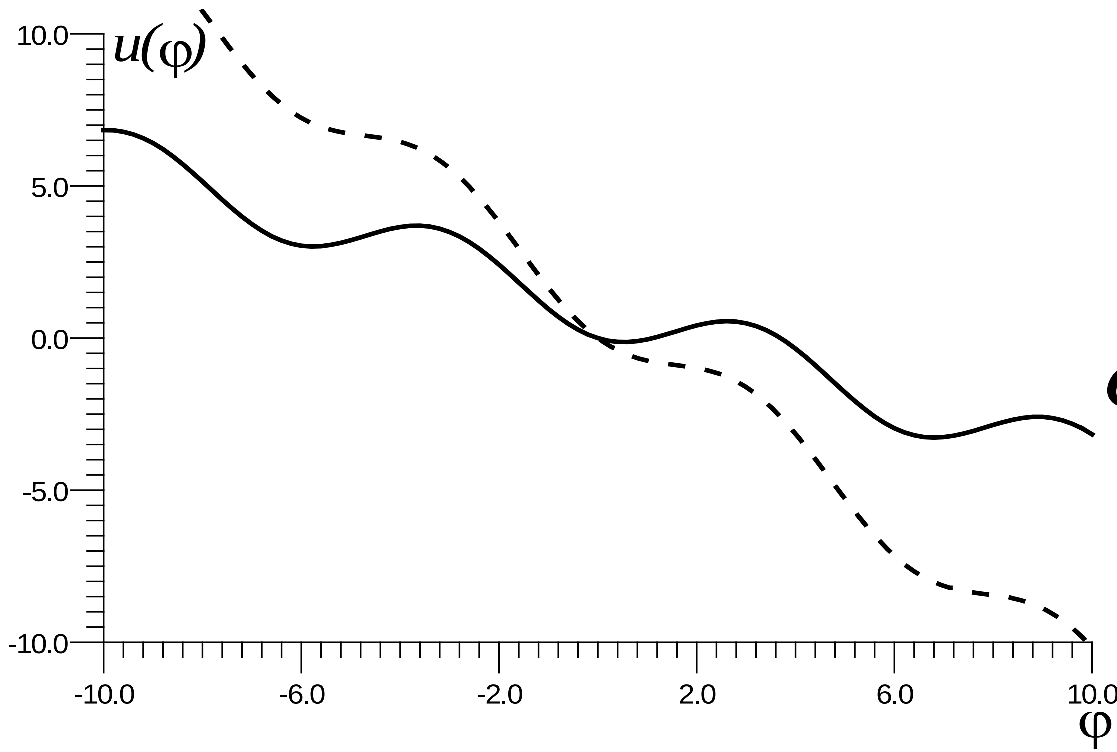


What do we mean under switching?





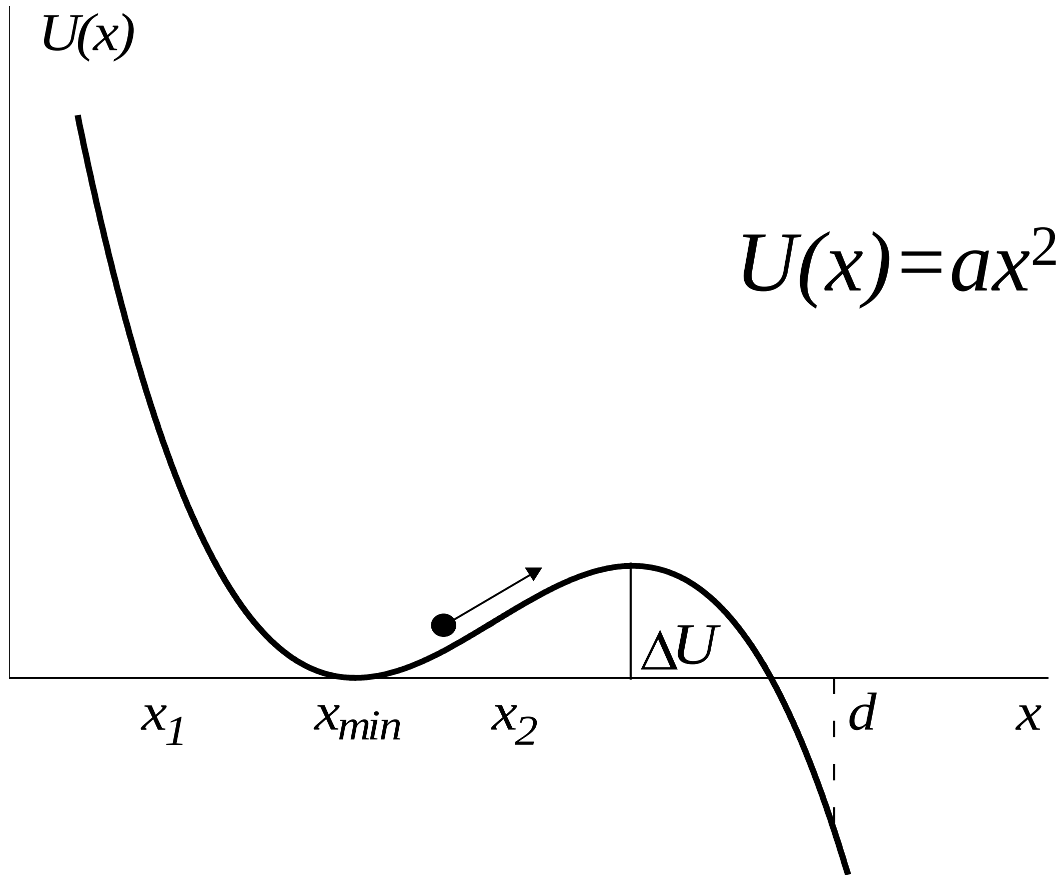
What do we mean under minimization of noise?



$$\sigma \sim e^{\Delta U / kT}$$

$$\sigma \sim \sqrt{kT}$$

Kramers' problem



$$U(x)=ax^2-bx^3$$

H.Kramers, Physica 7, 284 (1940).
P. Hanggi, P. Talkner, M. Borkovec, Reaction-rate theory: fifty years after Kramers, Rev. Mod. Phys. 62, 251-341 (1990).
V.I. Melnikov, The Kramers problem: Fifty years of development, Phys. Rep. 209, 1-71 (1991).
A.N. Malakhov, A.L. Pankratov, Evolution times of probability distributions and averages - Exact solutions of the Kramers' problem, Adv. in Chem. Phys., 121, 357-438 (2002).

Temporal characteristics

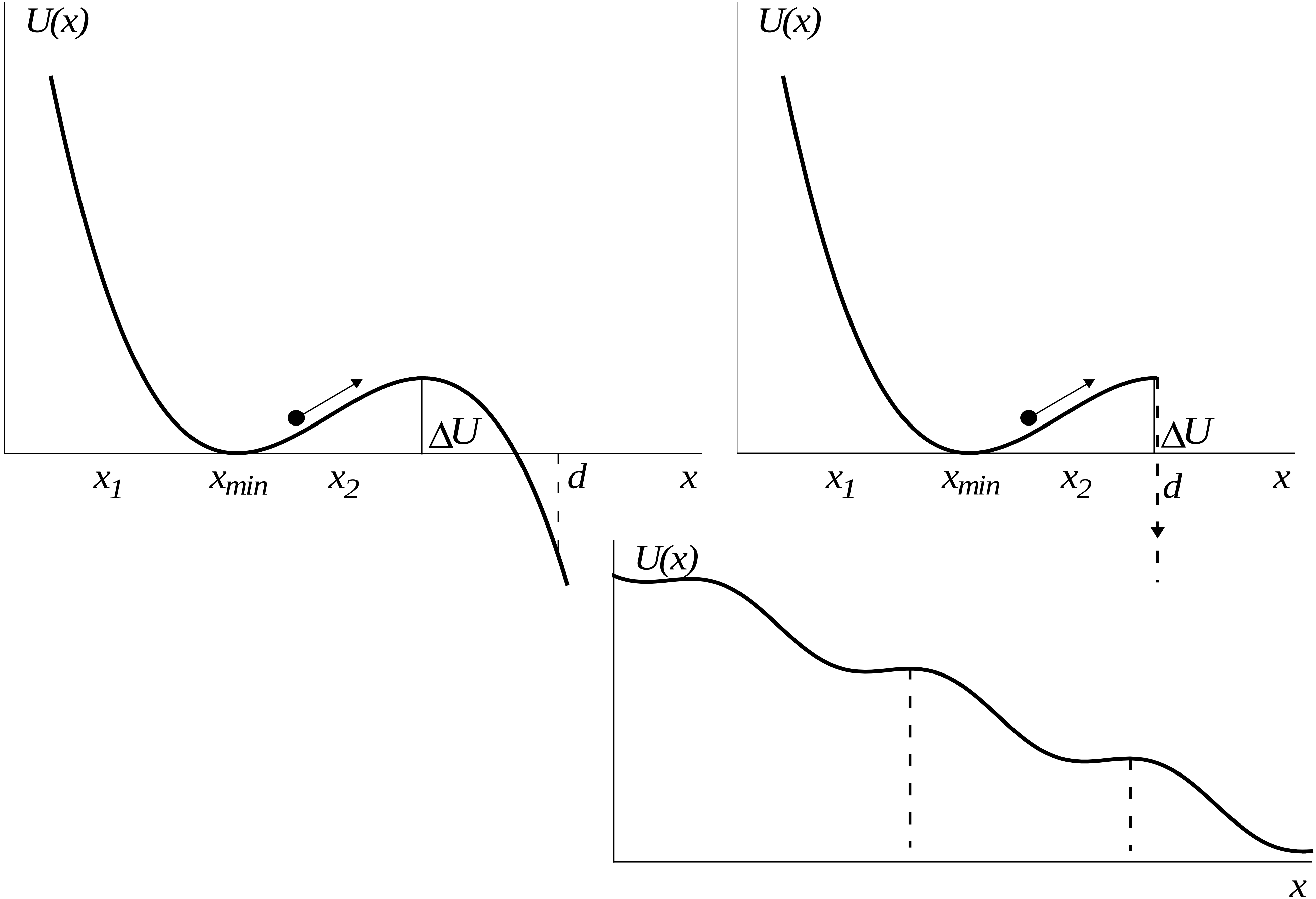
1. The moments of First Passage Time (Pontryagin, Andronov, Vitt, JETP, 1933)
2. Kramers' method: θ~exp($\Delta U/kT$), Physica, 1940
3. Effective eigenvalue (Risken, Yung, Garanin)
4. Generalized moment expansion (Nadler, Schulten)
5. Integral relaxation time (Coffey, Kalmykov, Titov)

$$\theta = \frac{\int\limits_0^\infty [P(t) - P(\infty)]dt}{P(0) - P(\infty)}$$

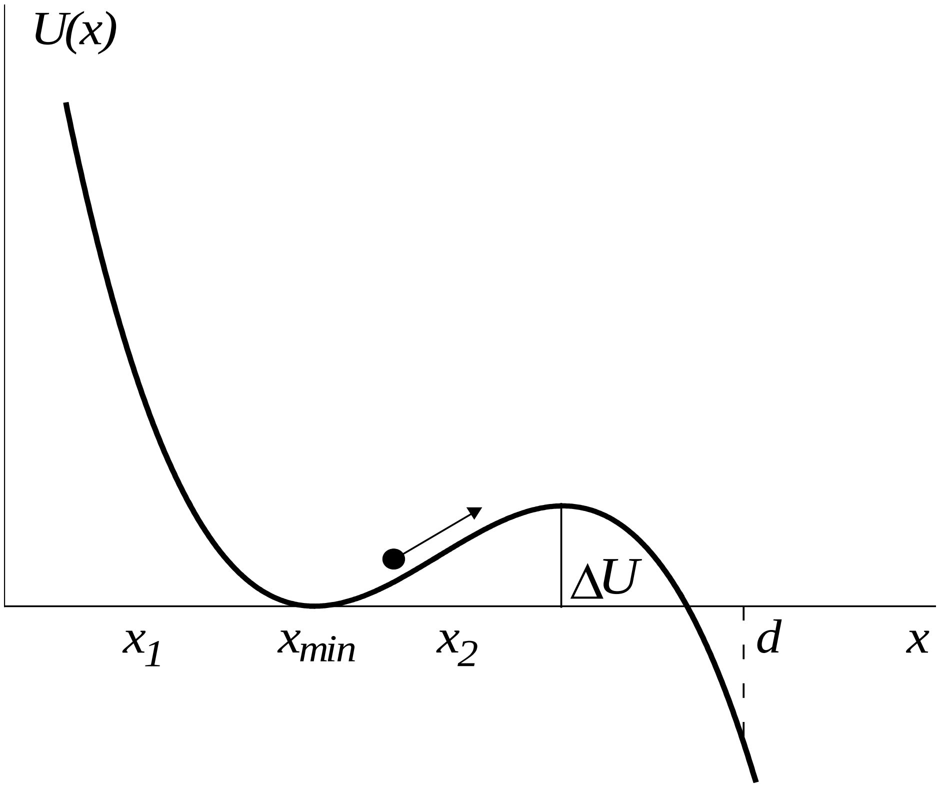
$$< t^n >= \int\limits_0^\infty t^n w(t)dt$$

$$P(t) = \int\limits_c^d W(x,t)dx$$

probability to find a particle in the area (c,d)


U(x)
ΔU
x1
xmin
x2
d
x
U(x)
ΔU
x1
xmin
x2
d
x
U(x)
x

Kramers' time



$$\tau = \tau_0(kT)e^{\Delta U/kT}$$

$\tau_0(kT) \sim$		$U_t(x) \sim$					
		$\lvert x\rvert^{\frac{1}{2}}$	$\lvert x\rvert^{\frac{2}{3}}$	$\lvert x\rvert$	x^2	x^4	x^∞
$U_b(x) \sim$	$\lvert x\rvert^{\frac{1}{2}}$	$(kT)^3$	$(kT)^{\frac{5}{2}}$	$(kT)^2$	$(kT)^{\frac{3}{2}}$	$(kT)^{\frac{5}{4}}$	$(kT)^1$
	$\lvert x\rvert^{\frac{2}{3}}$	$(kT)^{\frac{5}{2}}$	$(kT)^2$	$(kT)^{\frac{3}{2}}$	$(kT)^1$	$(kT)^{\frac{3}{4}}$	$(kT)^{\frac{1}{2}}$
	$\lvert x\rvert$	$(kT)^2$	$(kT)^{\frac{3}{2}}$	$(kT)^1$	$(kT)^{\frac{1}{2}}$	$(kT)^{\frac{1}{4}}$	$(kT)^0$
	x^2	$(kT)^{\frac{3}{2}}$	$(kT)^1$	$(kT)^{\frac{1}{2}}$	$(kT)^0$	$(kT)^{-\frac{1}{4}}$	$(kT)^{-\frac{1}{2}}$
	x^4	$(kT)^{\frac{5}{4}}$	$(kT)^{\frac{3}{4}}$	$(kT)^{\frac{1}{4}}$	$(kT)^{-\frac{1}{4}}$	$(kT)^{-\frac{1}{2}}$	$(kT)^{-\frac{3}{4}}$
	$\lvert x\rvert^\infty$	$(kT)^1$	$(kT)^{\frac{1}{2}}$	$(kT)^0$	$(kT)^{-\frac{1}{2}}$	$(kT)^{-\frac{3}{4}}$	$(kT)^{-1}$

Laplace transform method

$$\frac{d^2Y(x,s)}{dx^2}+\frac{d}{dx}\left[\frac{du(x)}{dx}Y(x,s)\right]-sBY(x,s)=-B\delta(x-x_0)$$

$$Y(x,s)=\int_0^\infty W(x,t)e^{-st}dt$$

$$G(x,s)=\int_0^\infty G(x,t)e^{-st}dt$$

$$\theta=\frac{\int_0^\infty [P(t)-P(\infty)]dt}{P(0)-P(\infty)}$$

$$\theta=\lim_{s\to 0}\frac{s\hat{P}(s)-P(\infty)}{s[P(0)-P(\infty)]}$$

$$s\hat{P}(s)-P(\infty)=G(c,s)-G(d,s)$$

$$H(x,s) = sG(x,s) = H_0(x) + sH_1(x) + s^2 H_2(x) + \ldots$$

$$\tau_1(c, x_0, d) = -(H_2(d) - H_2(c));$$

$$\tau_2(c, x_0, d) = 2(H_3(d) - H_3(c));$$

$$\tau_n(c, x_0, d) = (-1)^n n!(H_{n+1}(d) - H_{n+1}(c)).$$

$$\tau_1 = B\left\{ \int_{x_0}^{d} e^{u(x)} \int_{c}^{x} e^{-u(y)} dy dx + \int_{c}^{d} e^{-u(y)} dy \cdot \int_{d}^{\infty} e^{u(x)} dx \right\}$$

$$\tau_2 = 2\tau_1^2 + F, \qquad \tau_1 = \frac{2\pi}{\omega_c \sqrt{1-i^2}} \exp(\Delta u), \;\; \Delta u >> 1$$

A.N. Malakhov, A.L. Pankratov, Physica C **269**, 46-54 (1996).

A.N. Malakhov, Chaos **7,** 488 (1997).

A.L. Pankratov, Physics Letters A **234**, 329-335 (1997).

A.L. Pankratov, B. Spagnolo, Physical Review Letters **93**, 177001 (2004).

A.N. Malakhov, A.L. Pankratov, Adv. Chem. Phys. 121, 357-438 (2002).

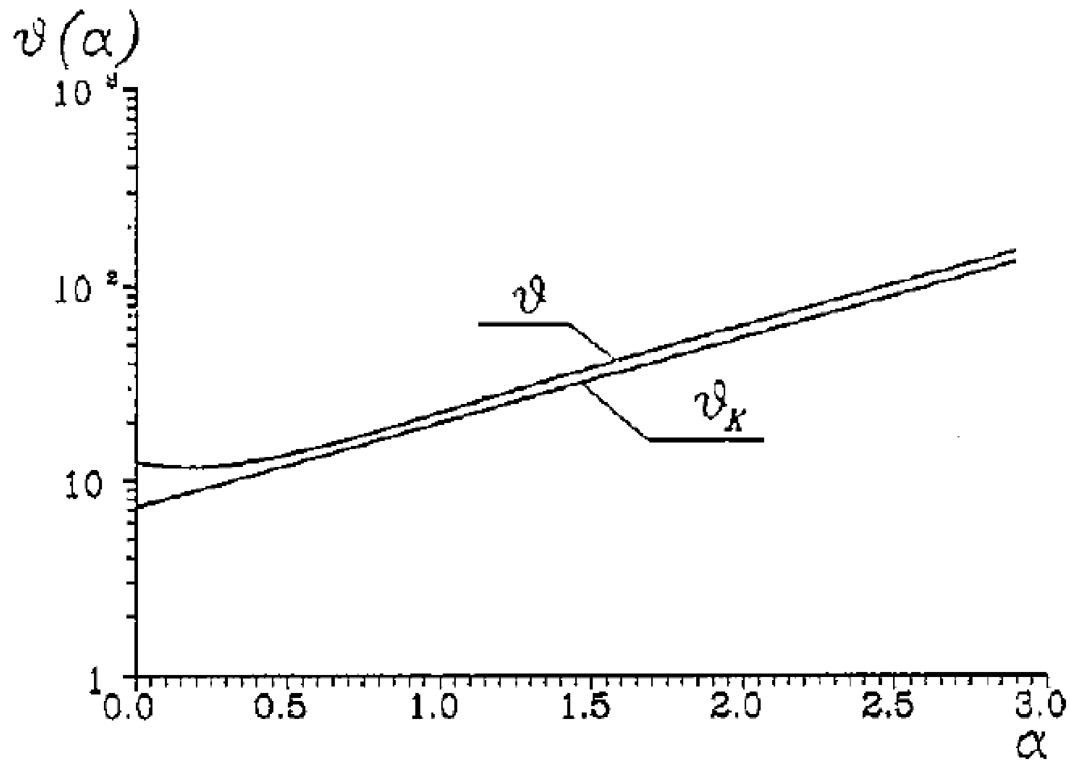
Kramers' formula

$$\tau = \frac{f(\alpha)\exp(\Delta u/\gamma)}{\sqrt{1-i^2}}$$

$$\frac{d^2\varphi}{dt^2} + \alpha\frac{d\varphi}{dt} = \eta - \sin\varphi + \xi(t)$$

$\gamma = I_T/I_C \quad I_T\,[\mu\text{A}] = 0.042T\,[\text{K}]$

M. Büttiker, E. P. Harris, R. Landauer,
Phys. Rev. B 28, 1268 (1983).

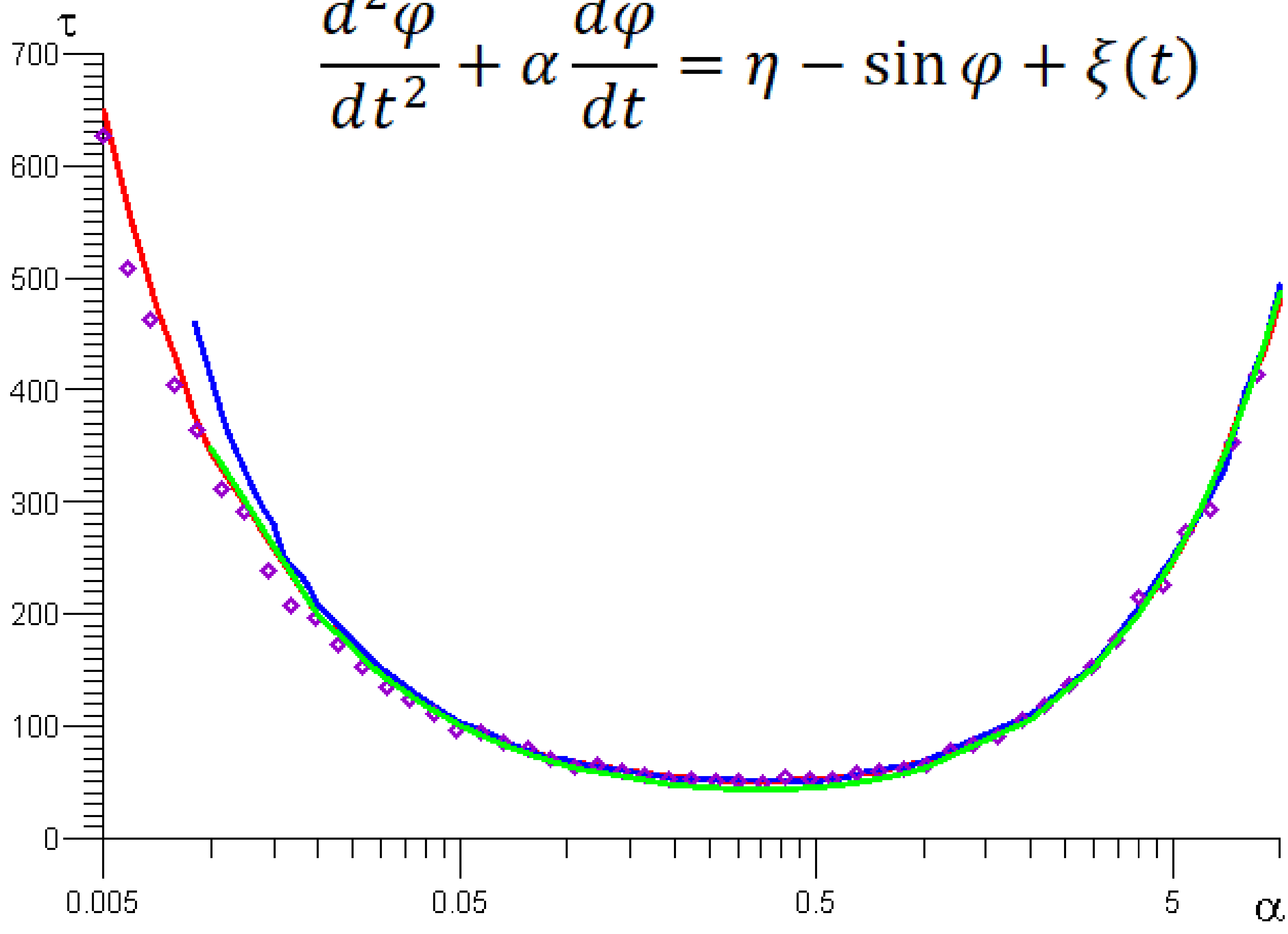


$$\tau_K = \frac{2\pi}{\omega_c\sqrt{1-i^2}}e^{\alpha},$$

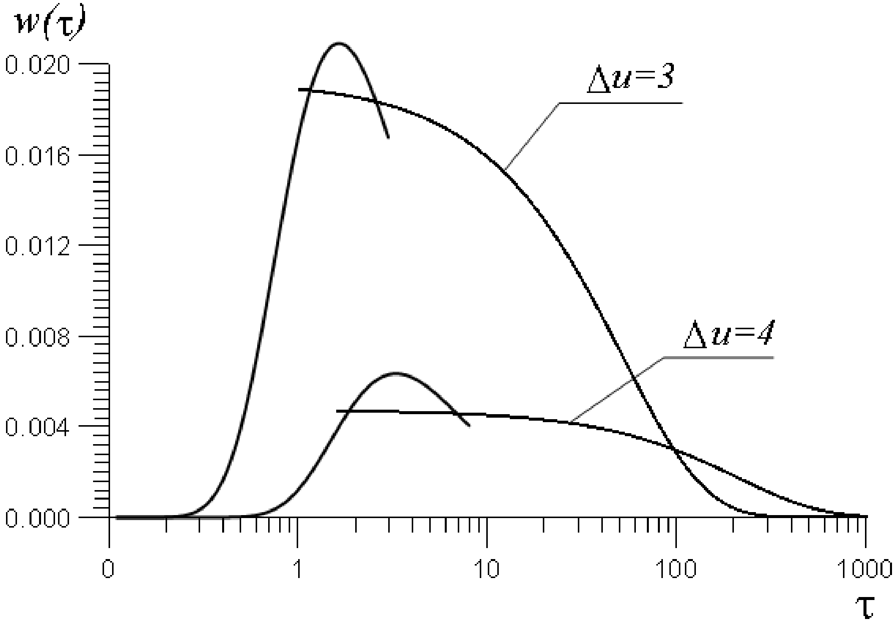
where $\alpha = \Delta u/\gamma = (2\sqrt{1-i^2} + 2i(\arcsin i - \pi/2))/\gamma$

Escape time for arbitrary damping α

$$\frac{d^2\varphi}{dt^2} + \alpha\frac{d\varphi}{dt} = \eta - \sin\varphi + \xi(t)$$

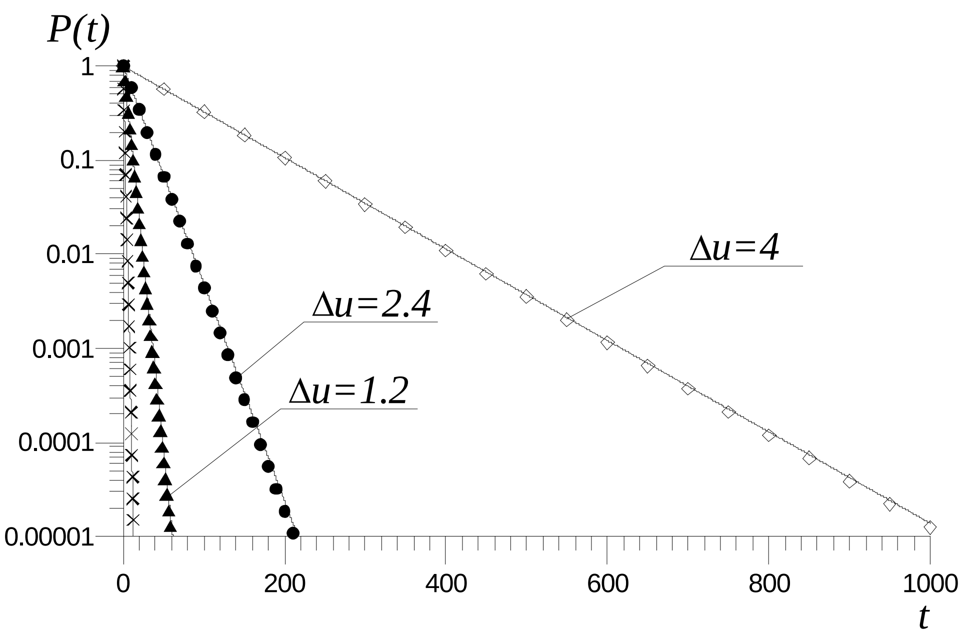


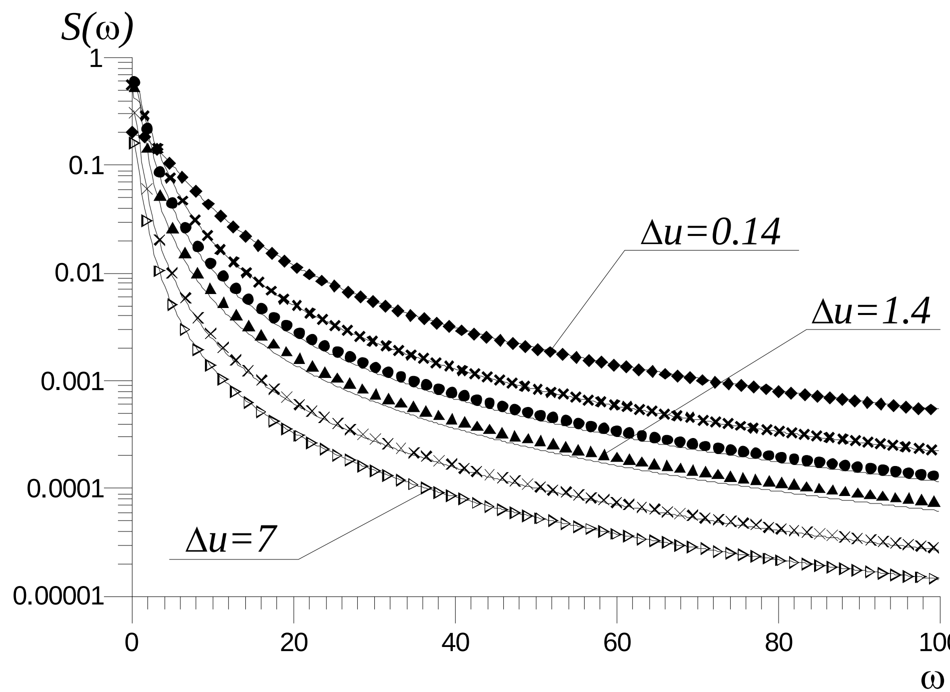
Time evolution of averages



$$\tau_n \approx n!\tau_1^n$$

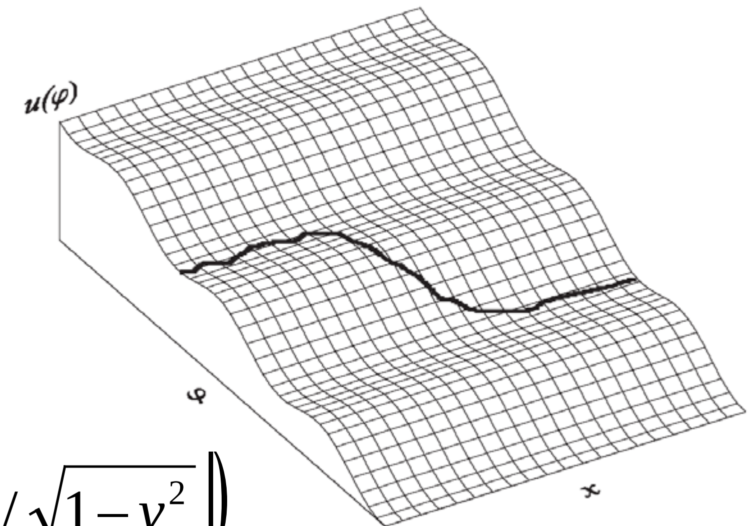
$$F(t) = F_0 \exp(-t/\tau)$$





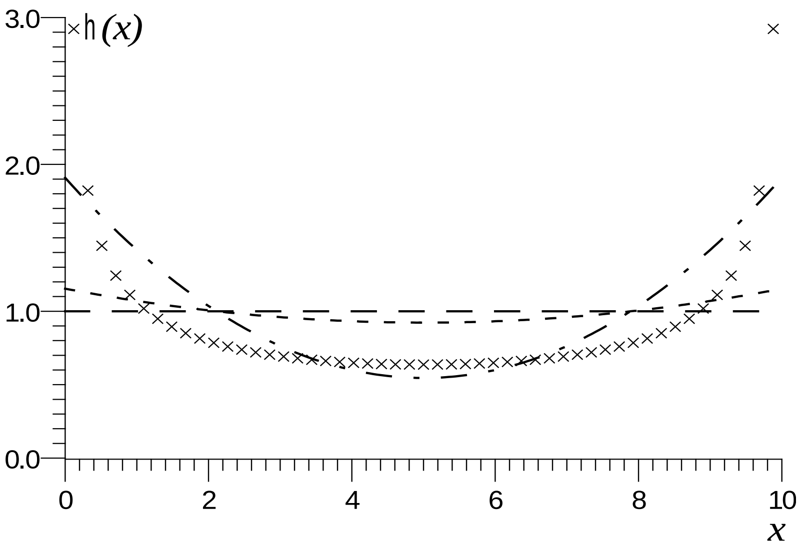
Lifetime in spatially extended systems

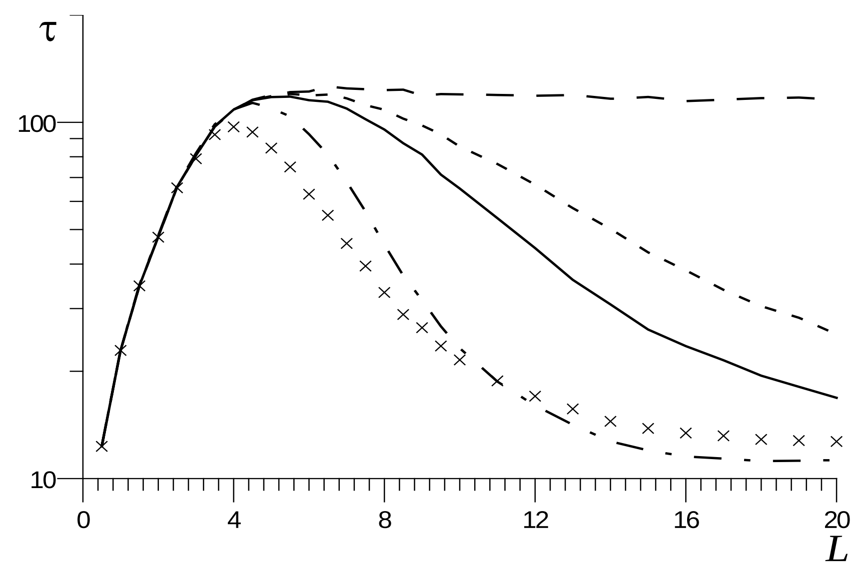
$$\frac{\partial^2 \varphi}{\partial t^2} + \alpha \frac{\partial \varphi}{\partial t} - \frac{\partial^2 \varphi}{\partial x^2} = \eta(x) - \sin(\varphi)$$

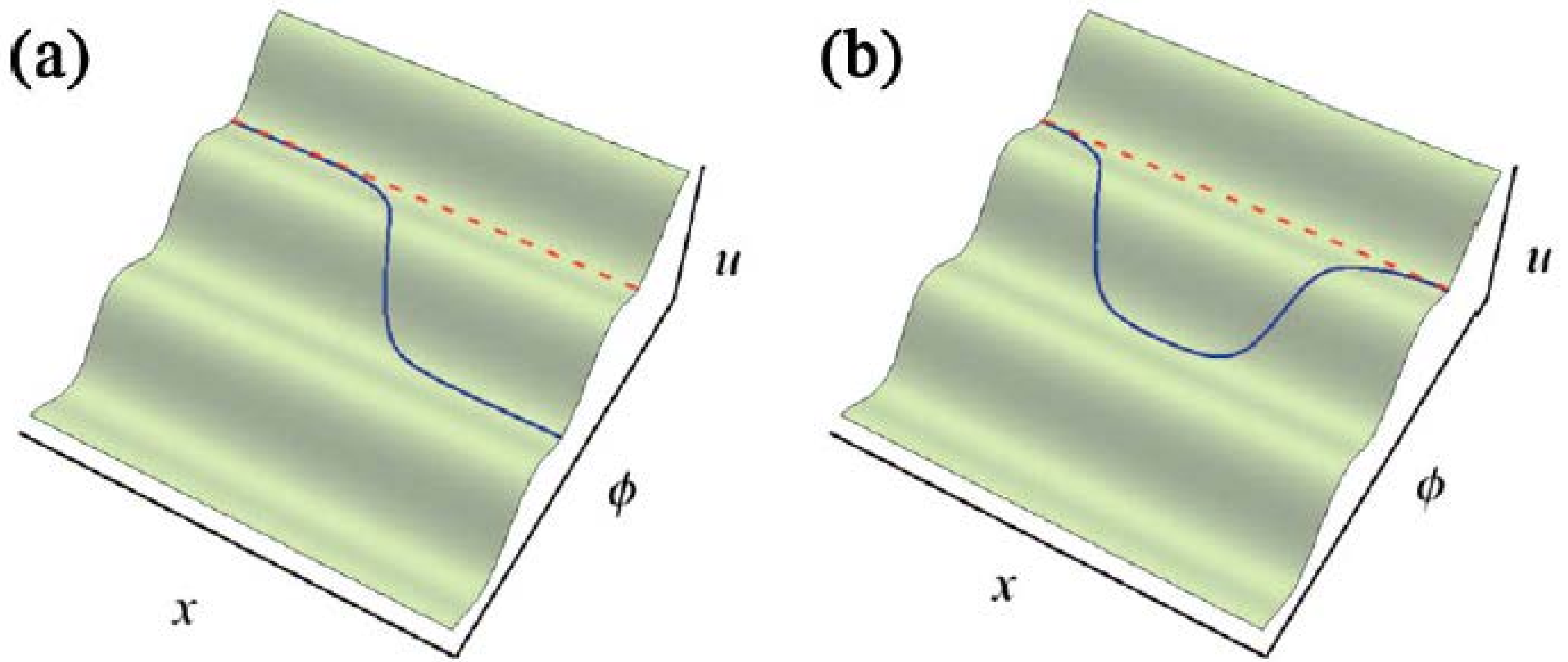


$$\frac{\partial \varphi(0,t)}{\partial x} = \frac{\partial \varphi(L,t)}{\partial x} = H$$

$$\varphi(x,t) = arctg\left(\exp\left[(x - vt)/\sqrt{1-v^2}\right]\right)$$

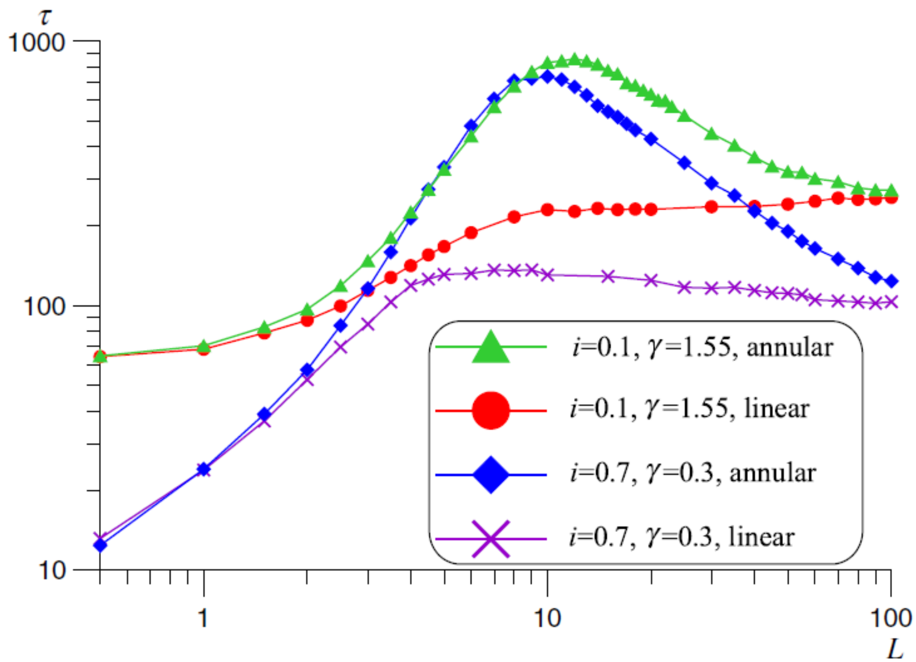


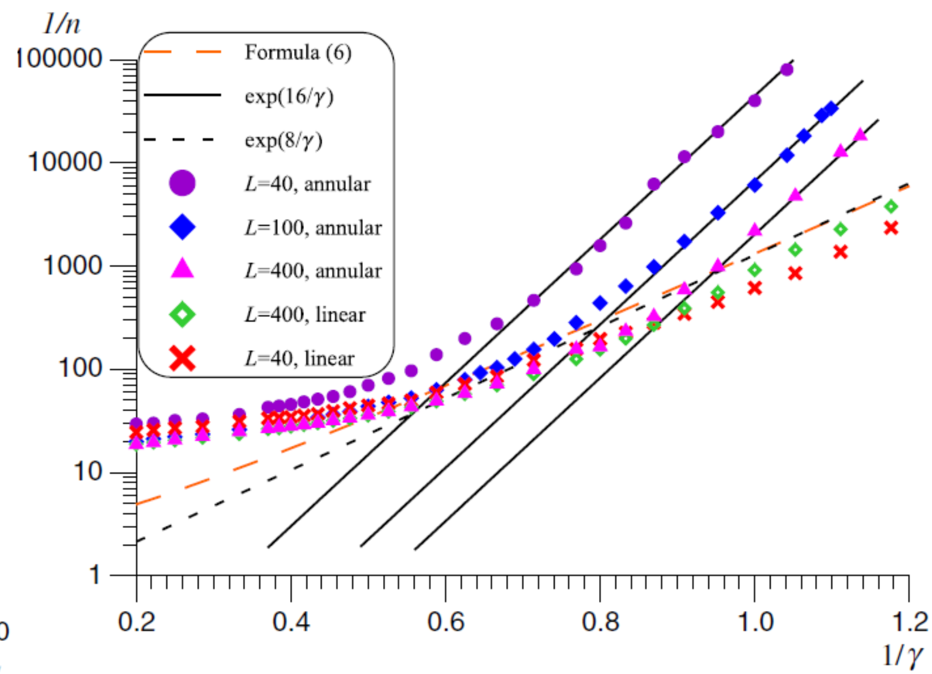




K.G. Fedorov, and A.L. Pankratov, Phys. Rev. Lett., 103, 260601 (2009).

Lifetime in spatially extended systems





$$n = \sqrt{2E_k/\pi\gamma}\,\exp(-E_k/\gamma), \qquad (6)$$

M. Buttiker, and R. Landauer, Phys. Rev. A, 23, 1397 (1981).
M. Buttiker, and T. Christen, Phys. Rev. Lett. 75, 1895 (1995).

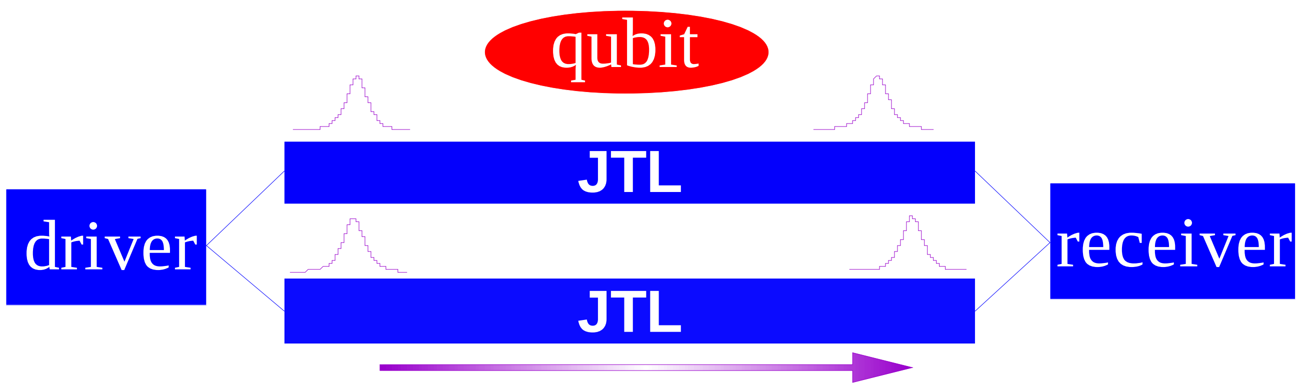
Sine-Gordon equation

$$\frac{\partial^2\phi}{\partial t^2}+\alpha\frac{\partial\phi}{\partial t}-\frac{\partial^2\phi}{\partial x^2}=i-\sin(\phi)+i_F(x,t)$$

$$\phi(0,t)_x+r_Lc_L\phi(0,t)_{xt}-c_L\phi(0,t)_{tt}=\Gamma$$

$$\phi(L,t)_x+r_Rc_R\phi(L,t)_{xt}+c_R\phi(L,t)_{tt}=\Gamma$$

and ballistic readout of qubits



Jitter in long Josephson junctions

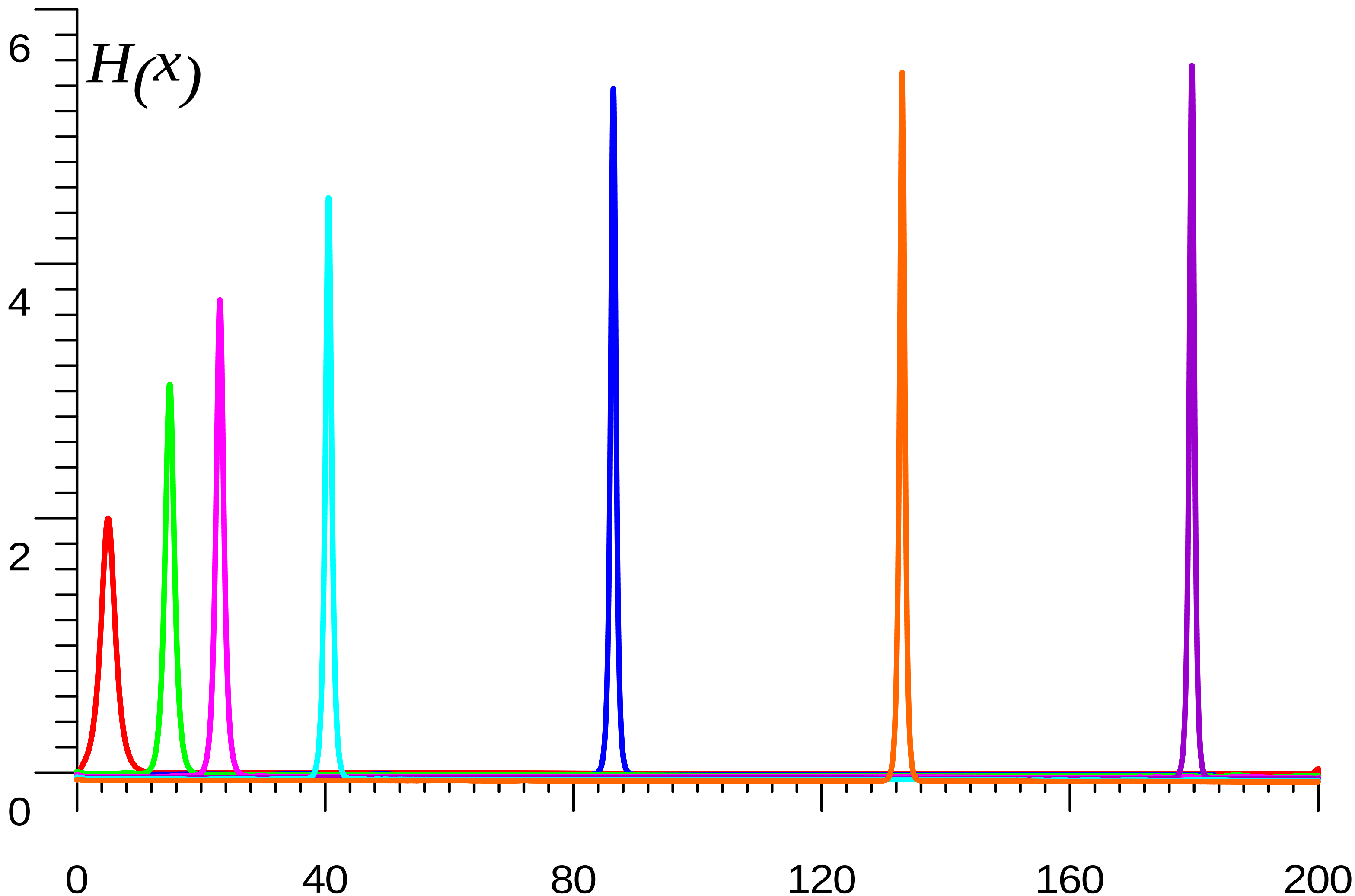
σ~sqrt(L) for a long junction, α<<1

Arkady Fedorov, Alexander Shnirman, Gerd Schön and Anna Kidiyarova-Shevchenko, Phys. Rev. B, 75, 224504 (2007).

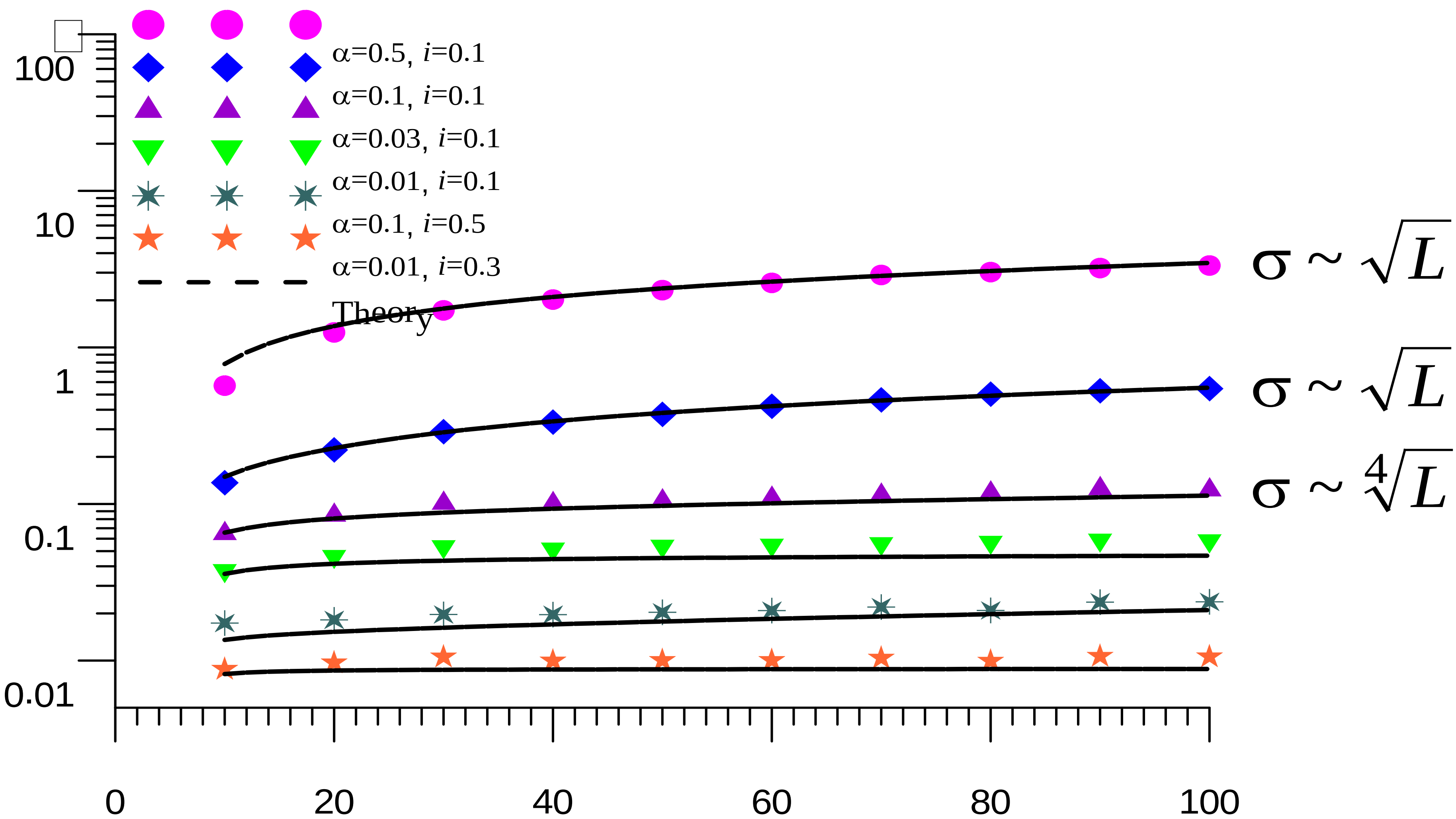
σ~sqrt(N) for a chain of N junctions, α>1

1. H. Terai, Z. Wang, Y. Hishimoto, S. Yorozu, A. Fujimaki, and N. Yoshikawa, Appl. Phys. Lett. 84, 2133 (2004).
2. H. Terai et al. IEEE Trans. Appl. Supercond., 15, 364 (2005).

Soliton dynamics, α=0.03

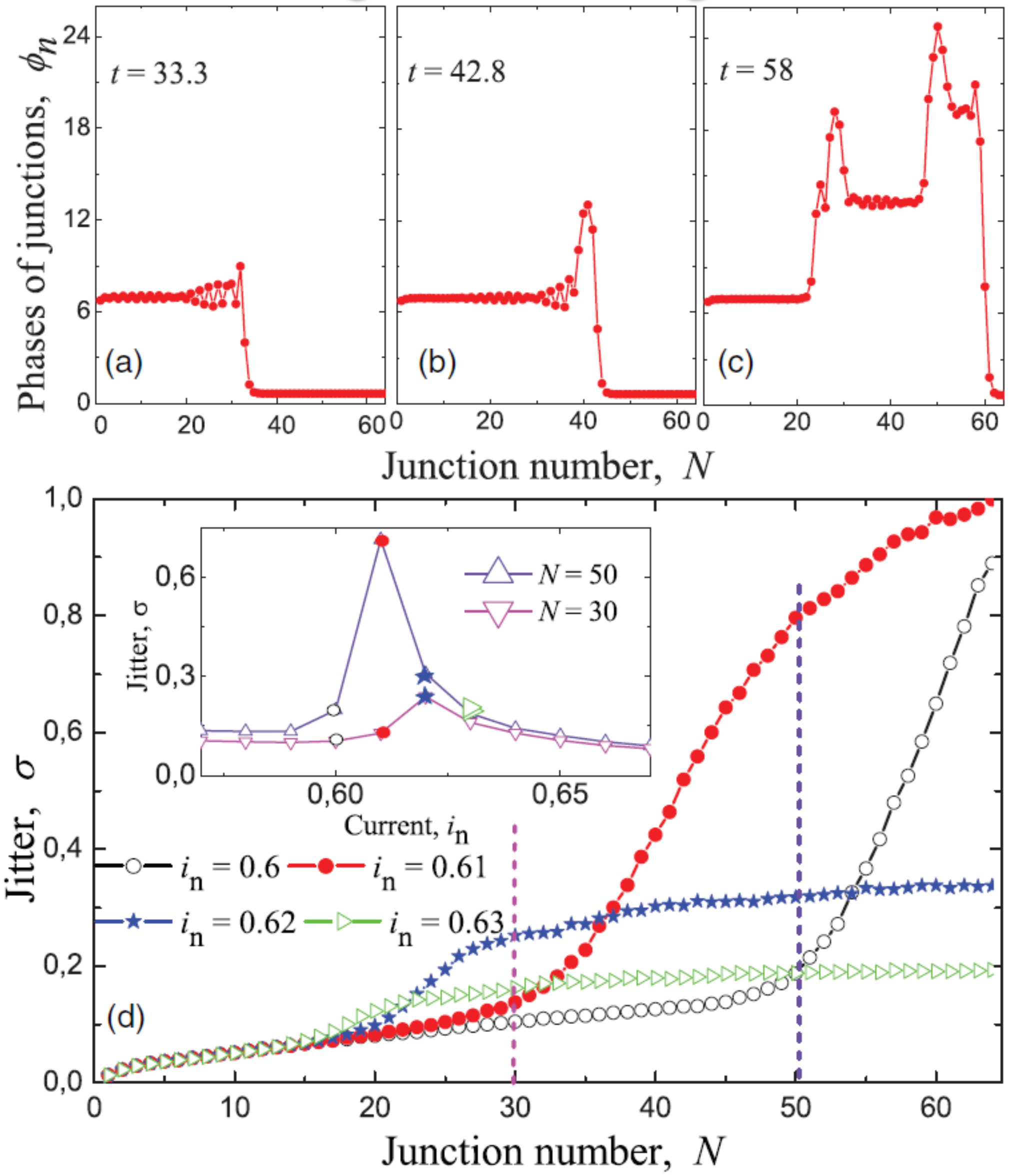


Dependence of jitter vs junction length



A. L. Pankratov, A. Gordeeva, L. S. Kuzmin, Phys. Rev. Lett. 109, 087003 (2012)

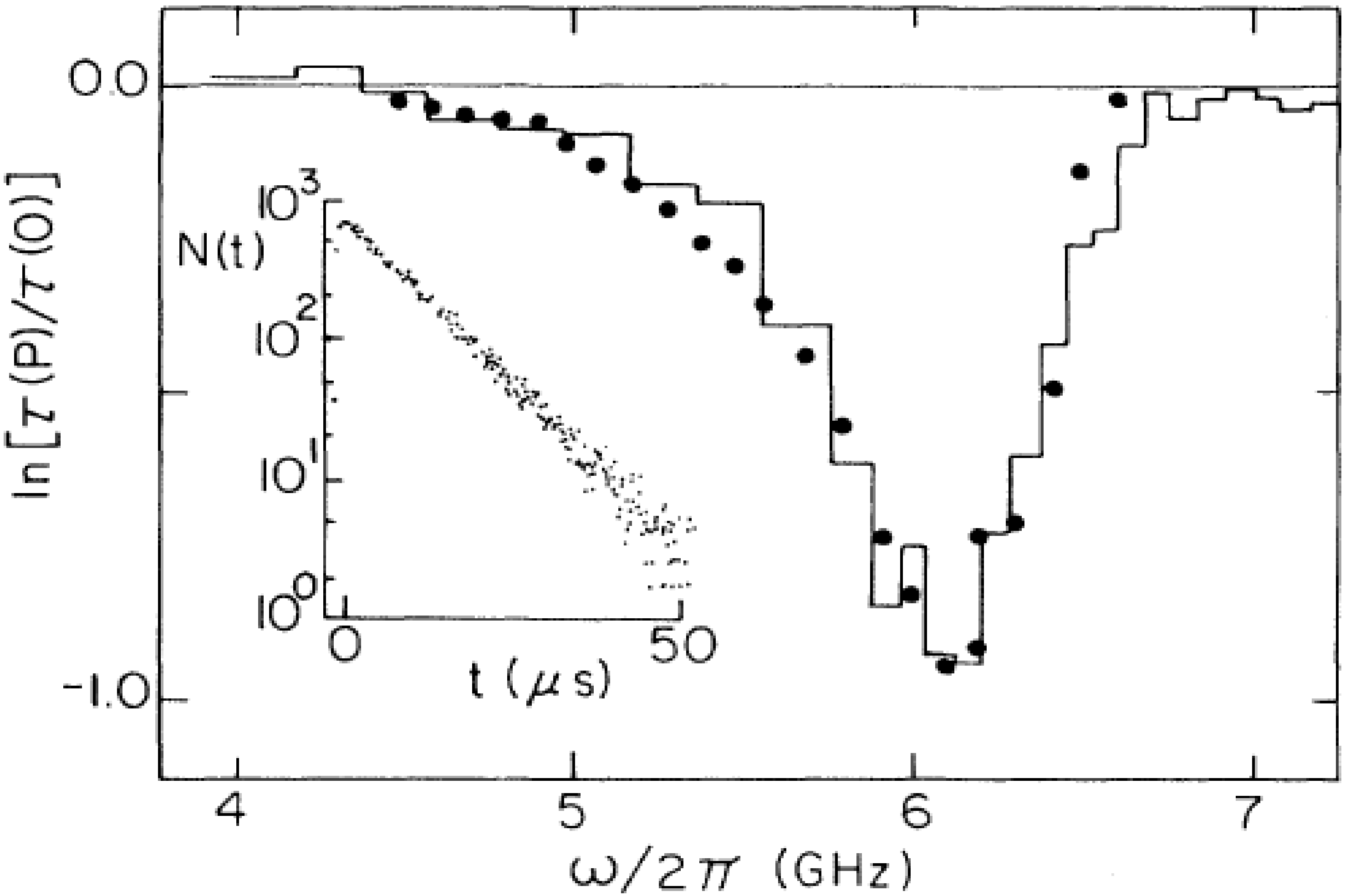
Dependence of jitter vs junction length



I. I. Soloviev, N. V. Klenov, A. L. Pankratov, E. Il'ichev, L. S. Kuzmin, Phys. Rev. E 87, 060901(R) (2013)

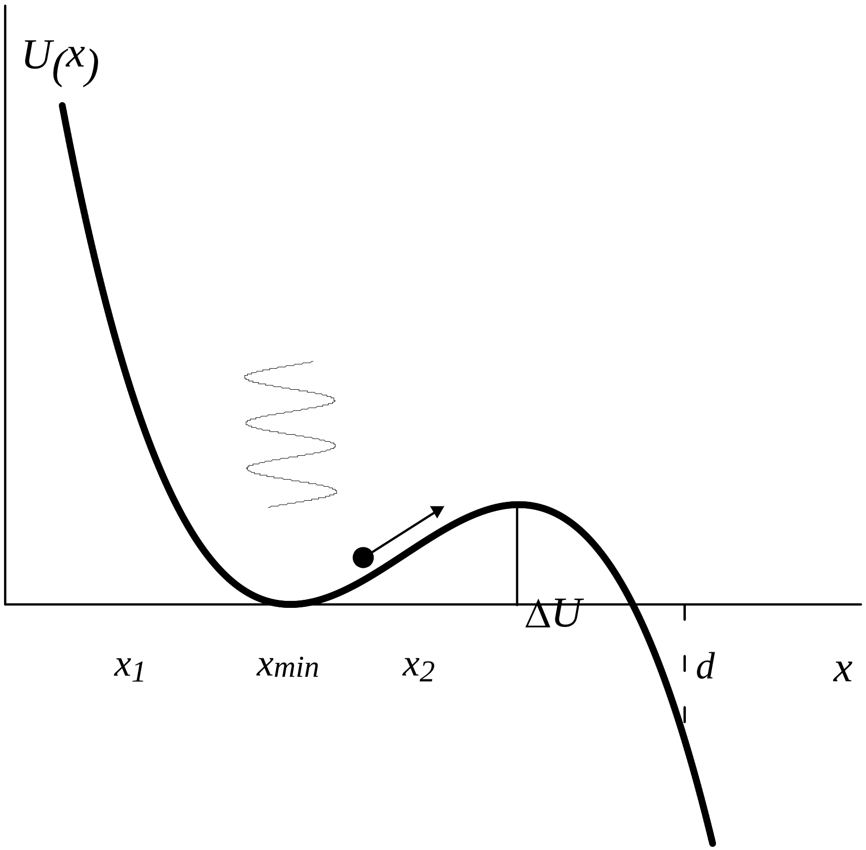
Resonant Activation from the Zero-Voltage State of a Current-Biased Josephson Junction

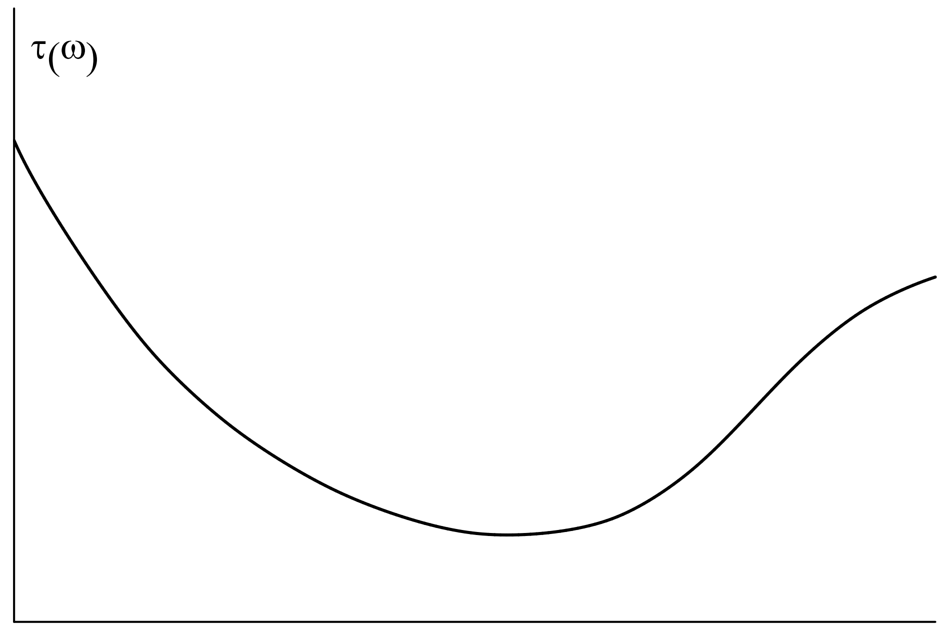
Michel H. Devoret,[a] John M. Martinis, Daniel Esteve,[a] and John Clarke
Department of Physics, University of California, Berkeley, California 94720, and Materials and Molecular Research Division, Lawrence Berkeley Laboratory, Berkeley, California 94720



Resonant activation

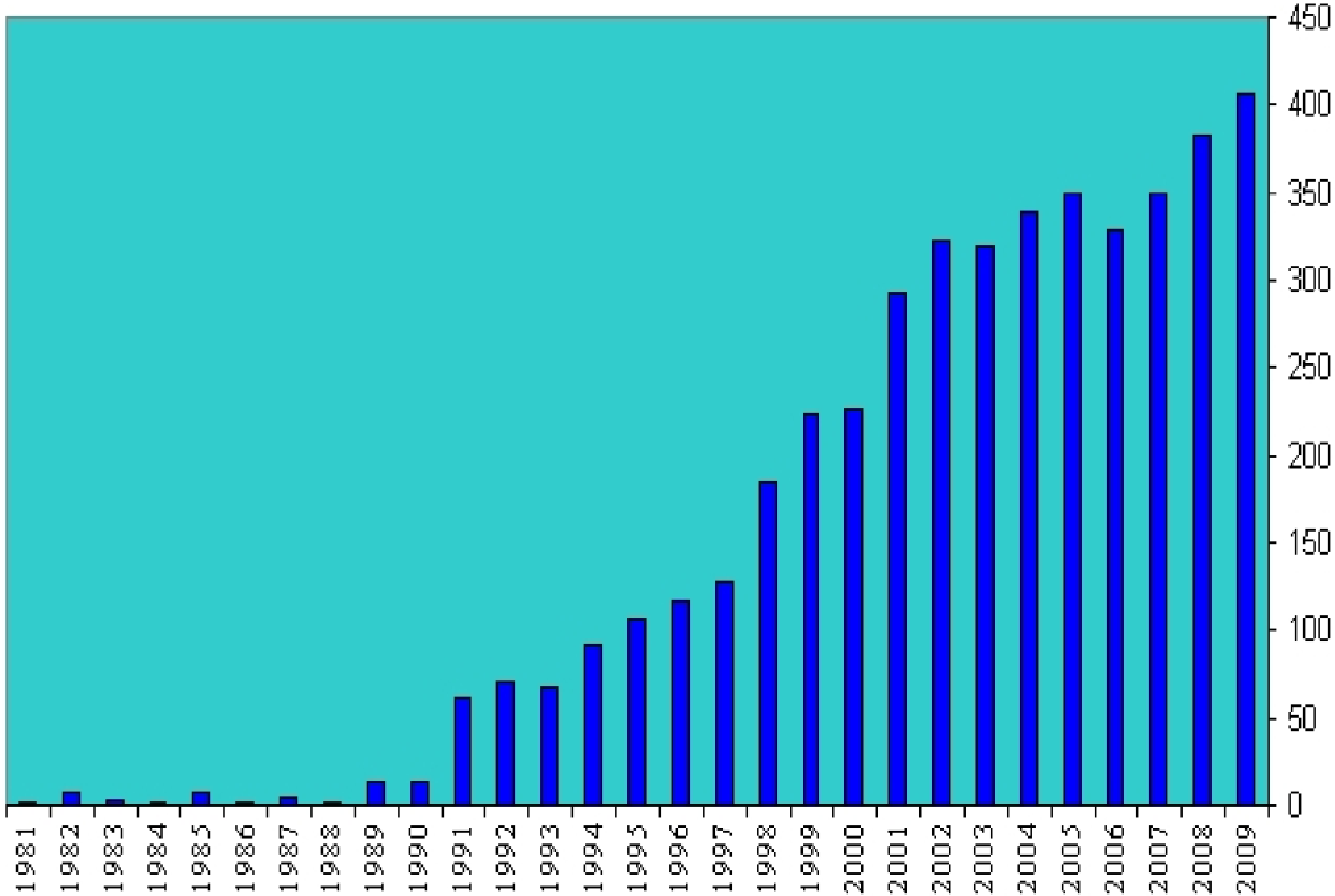
$$\frac{m}{h}\frac{d^2x(t)}{dt^2}+\frac{dx(t)}{dt}=-\frac{1}{h}\left(\frac{dU(x)}{dx}+A\sin(\omega t)\right)+\xi(t)$$





P. Jung, Physics Reports **234**, 175-295 (1993).

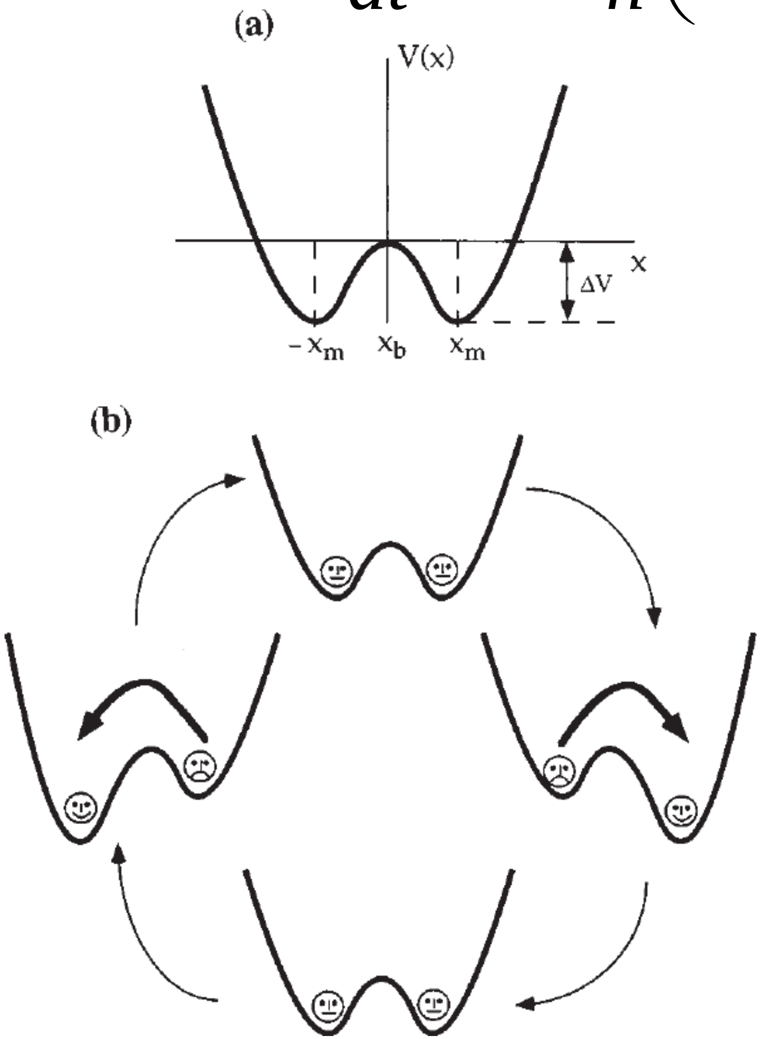
Stochastic resonance

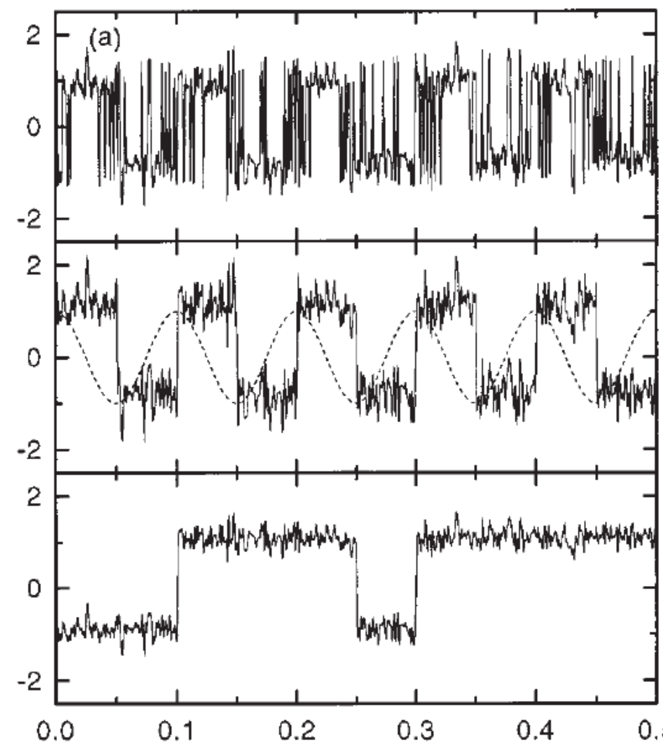


L. Gammaitoni, P. Hänggi, P. Jung and F. Marchesoni, Rev. Mod. Phys. 70, 223-287 (1998).
В.С. Анищенко, А.Б. Нейман, Ф. Мосс, Л. Шиманский-Гайер, УФН, 169, №1, 7 (1999).
Th. Wellens, Y. Shatokhin and A. Buchleitner, Rep. Progr. Phys. 67, 45-105 (2004).

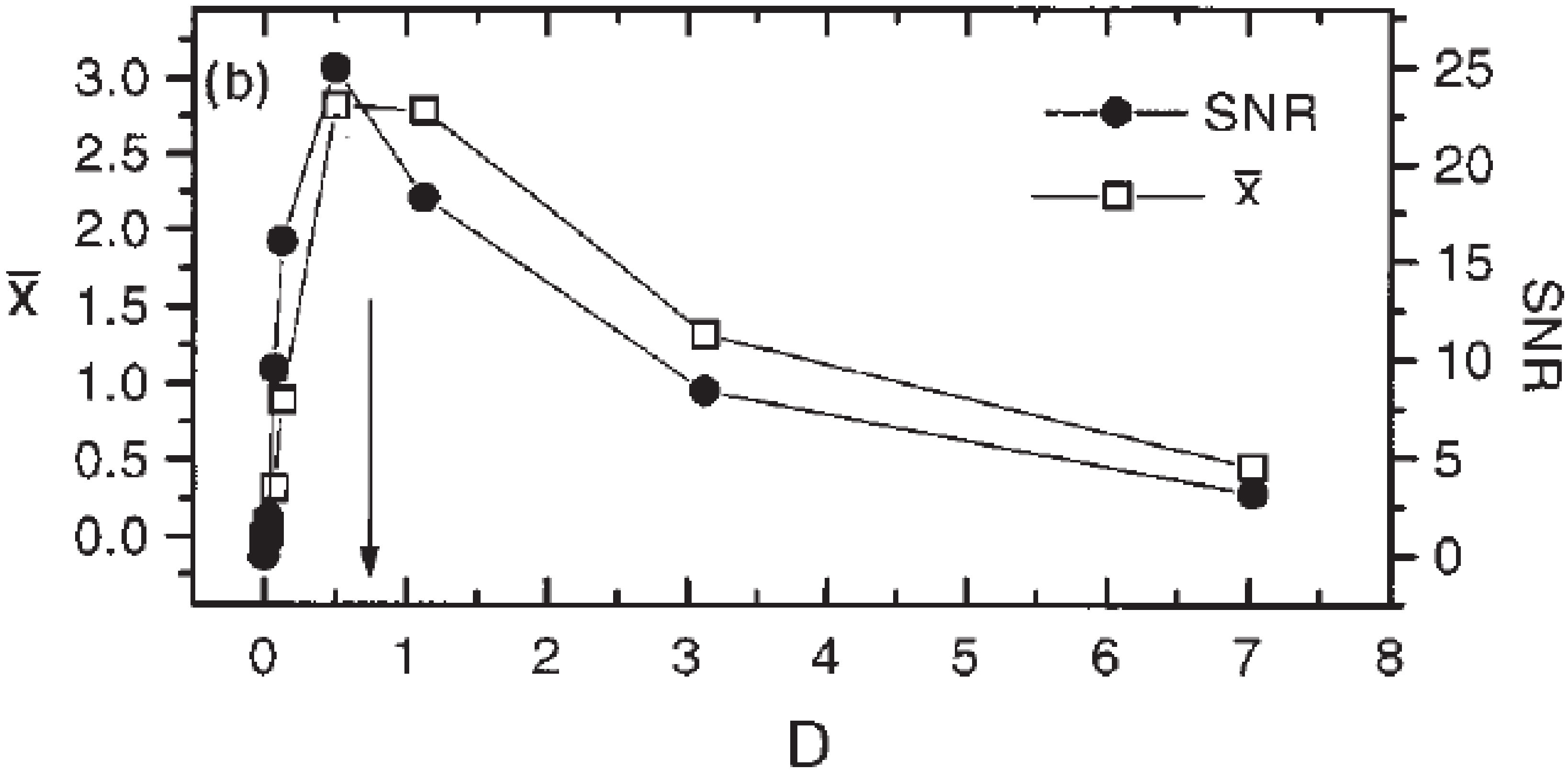
Stochastic resonance

$$\frac{dx(t)}{dt} = -\frac{1}{h}\left(\frac{dU(x)}{dx} + A\sin(\omega t)\right) + \xi(t)$$





Stochastic resonance



It is important to note that the variation of the angular frequency ω at a fixed value of the noise intensity *D* does not yield a resonance-like behavior of the response amplitude. This behavior is immediately evident from Eq. (2.7a) and also from numerical studies (for those who don't trust the theory).

L. Gammaitoni, P. Hänggi, P. Jung and F. Marchesoni, Rev. Mod. Phys. 70, 223-287 (1998).

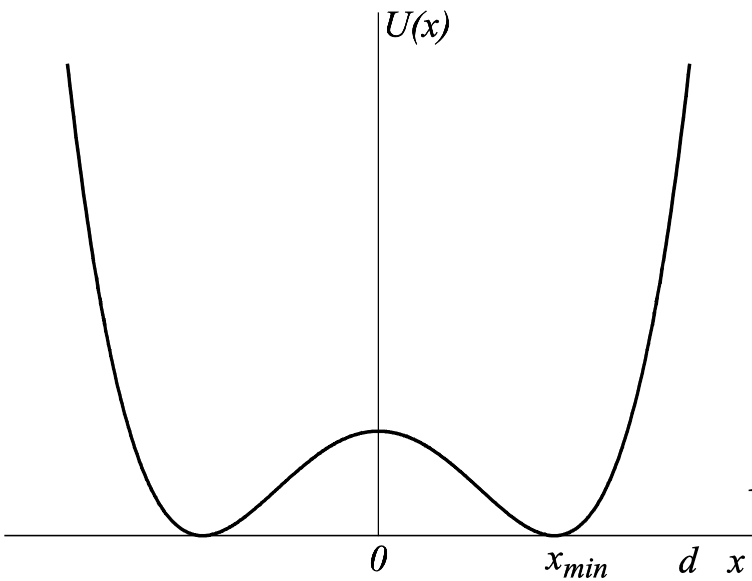
Adiabatic approximation

$$P(x_0,t)=\exp\left\{-\int_0^t \frac{1}{\tau_K(t')}dt'\right\}$$

$$P(x_0,t)=\frac{\exp\left\{-\int_0^t [1/\tau_p(t')]dt'\right\}+1}{2}$$

Standard adiabatic approximation

$$\tau_K = \tau_0(kT)e^{\Delta U/kT}$$



Modified adiabatic approximation

$$\tau_p(x_0)=T(x_0,0)=B\int_{x_0}^{0} e^{\varphi(y)}\int_{-\infty}^{y} e^{-\varphi(x)}dxdy$$

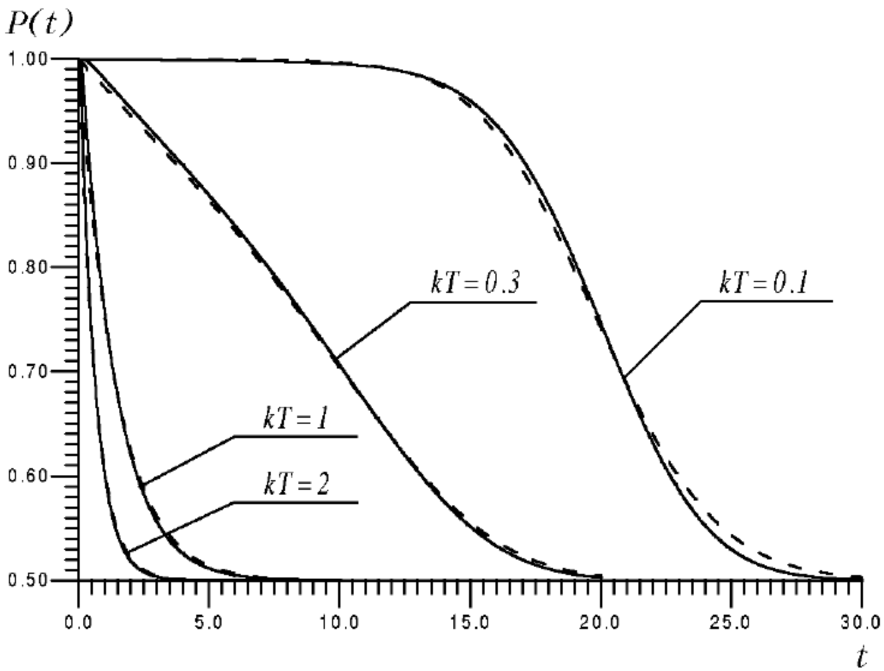
A.L. Pankratov, Physics Letters A **234**, 329 (1997).

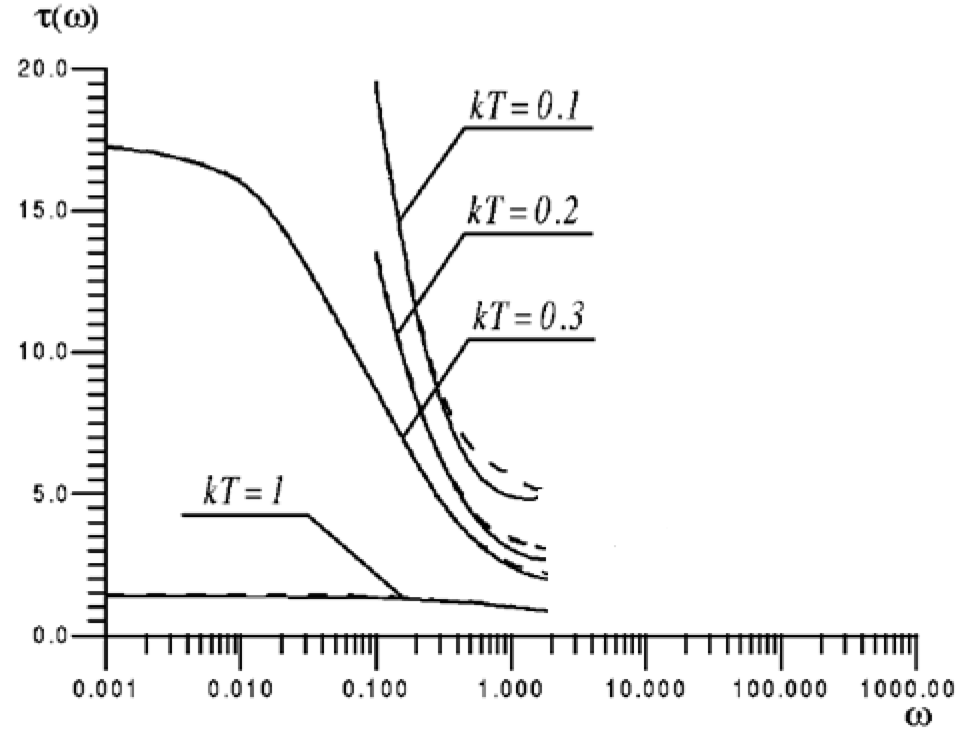
$$\tau_p = B\left\{\int_{x_0}^{d} e^{u(x)}\int_{c}^{x} e^{-u(y)}dydx+\int_{c}^{d} e^{-u(y)}dy\cdot\int_{d}^{\infty} e^{u(x)}dx\right\}$$

$$U(x)=bx^4-a(t)x^2,\ \ a(t)=1+\cos(\omega t)$$

A.L. Pankratov, M. Salerno, Phys. Rev. E **61**, 1206 (2000).

Parametric stochastic resonance





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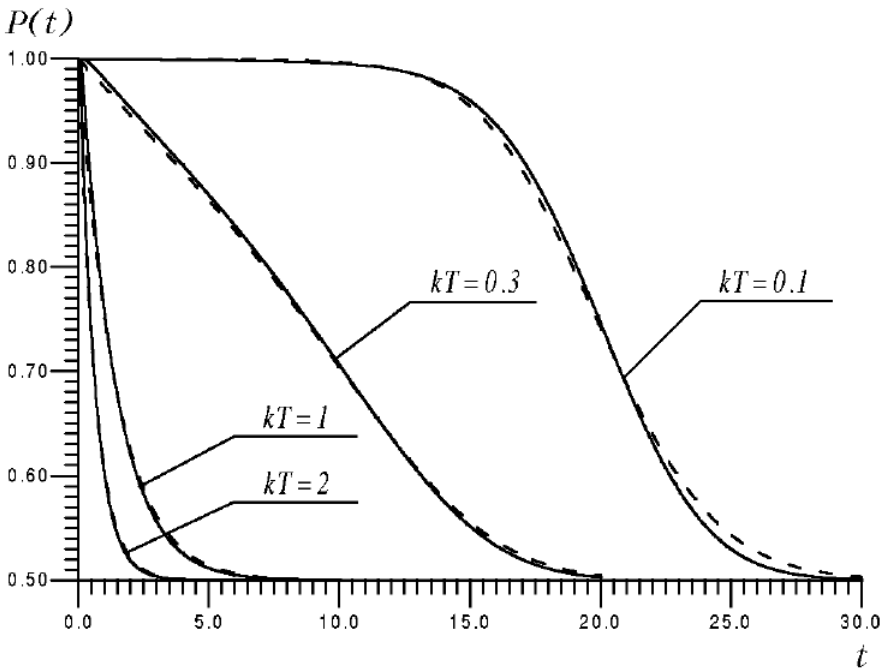
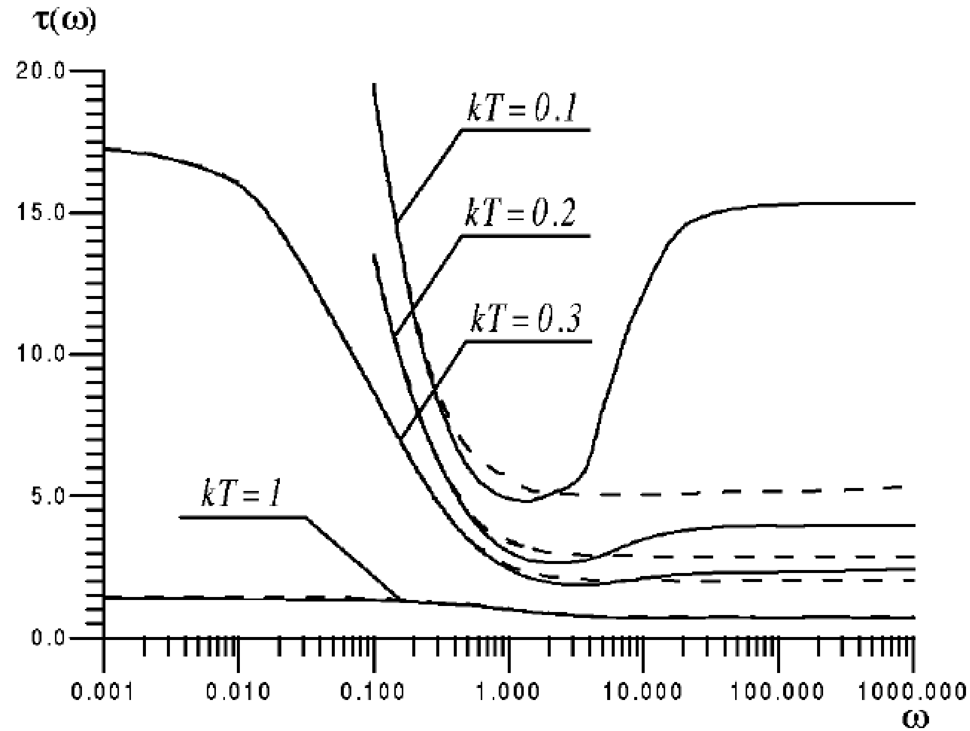
Parametric stochastic resonance



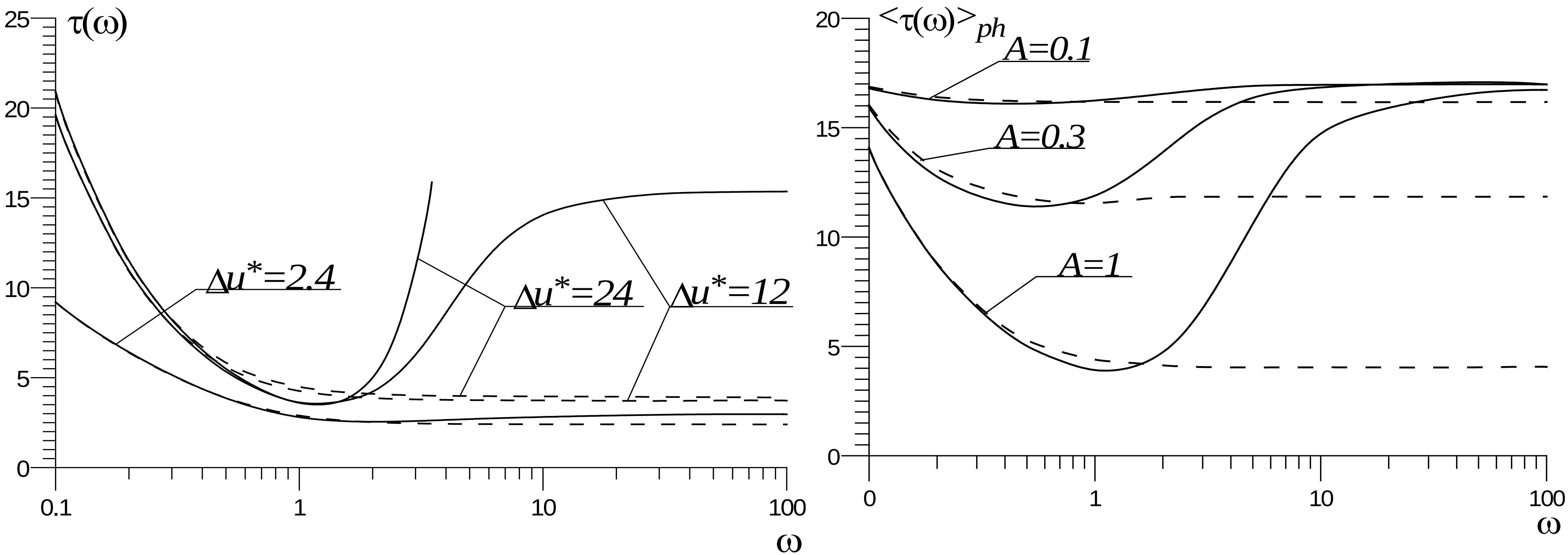


~~It is important to note that the variation of the angular frequency ω at a fixed value of the noise intensity *D* does not yield a resonance-like behavior of the response amplitude. This behavior is immediately evident from Eq. (2.7a) and also from numerical studies (for those who don't trust the theory).~~

A.L. Pankratov, M. Salerno, Phys. Rev. E **61**, 1206 (2000).

Resonant activation?

$$\frac{dx(t)}{dt} = -\frac{1}{h}\left(\frac{dU(x)}{dx} + A\sin(\omega t)\right) + \xi(t)$$

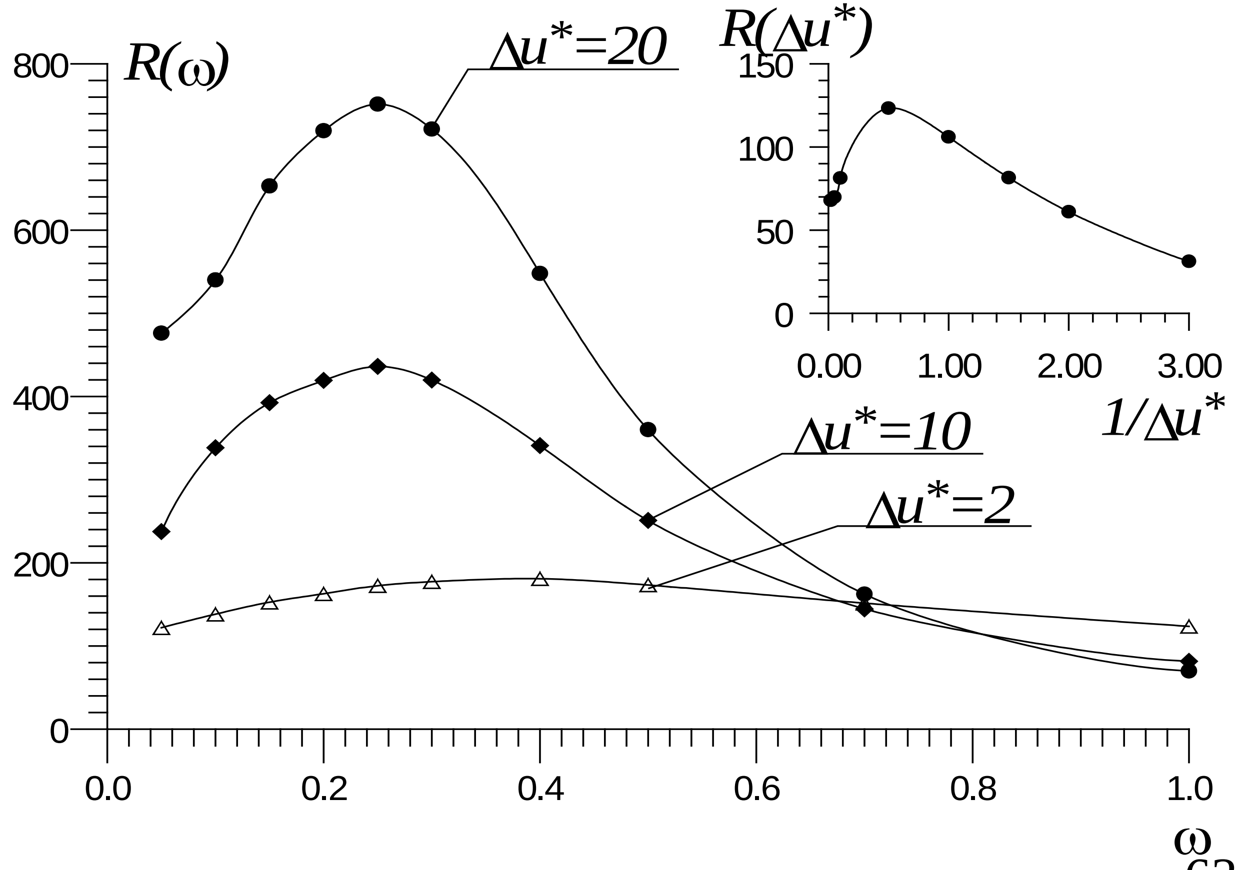


A.L. Pankratov, M. Salerno, Physics Letters A **273**, 162-166 (2000).

Suppression of noise by driving

$$\dot{x} = x - x^3 + A\sin(\omega t + \psi) + \xi(t)$$

$$R(\omega) = \frac{1}{S_N(\omega)} \lim_{\Delta\Omega \to 0} \int_{\omega-\Delta\Omega}^{\omega+\Delta\Omega} S(\omega) d\omega$$



Suppression of noise by driving

A.L. Pankratov, B. Spagnolo, Physical Review Letters **93**, 177001 (2004).

$$\frac{d\varphi}{dt} = \sin(\varphi) - i(t) + i_F(t)$$

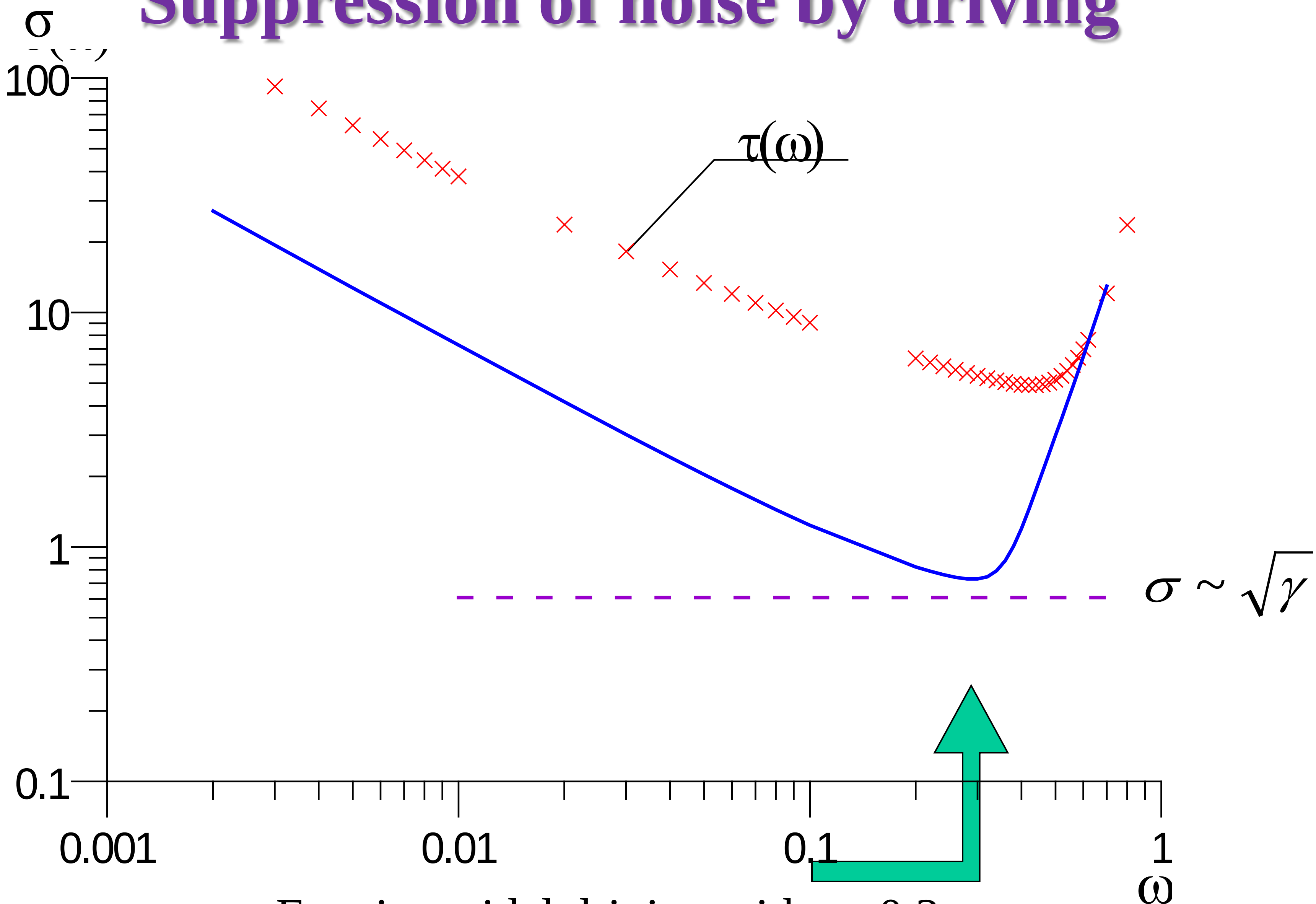
$$\tau = \langle t \rangle = \int_0^\infty t w(t) dt, \qquad \sigma = \sqrt{\langle t^2 \rangle - \langle t \rangle^2}$$

$$\tau = \frac{1}{\omega_C} \left\{ \frac{2}{\sqrt{i^2 - 1}} \arctan\left(\frac{i \tan(y/2) - 1}{\sqrt{i^2 - 1}} \right) \Bigg|_{y=x_0}^{y=d} + \right.$$

$$+ \gamma \left[\frac{1}{2(i - \sin d)^2} + \frac{1}{2(i - \sin x_0)^2} \right] +$$

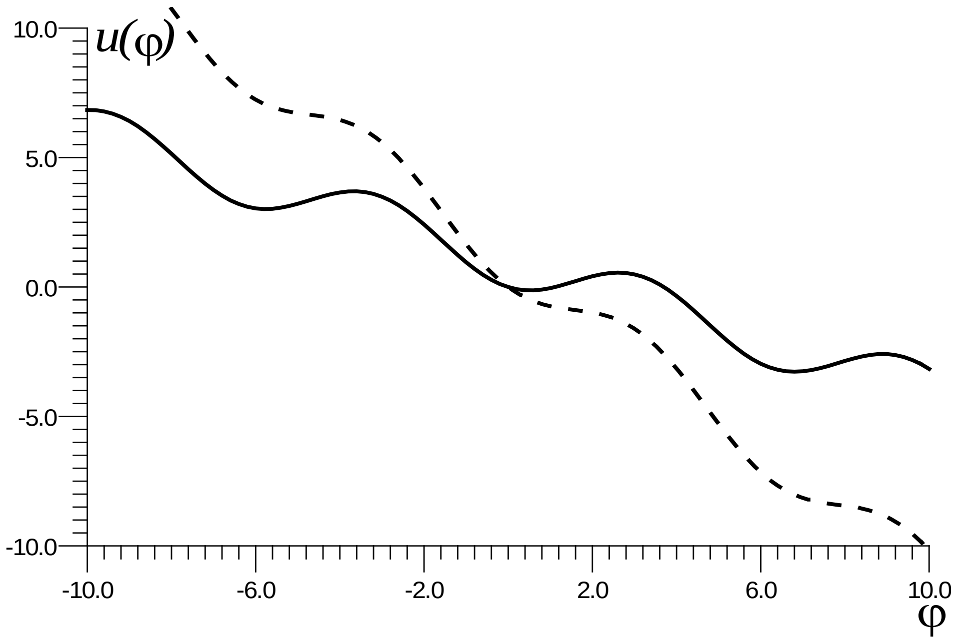
$$\left. + \gamma^2 \int_{x_0}^{d} \left[\frac{3\cos^2 y}{(i - \sin y)^5} - \frac{\sin y}{(i - \sin y)^4} \right] dy + \ldots \right\}$$

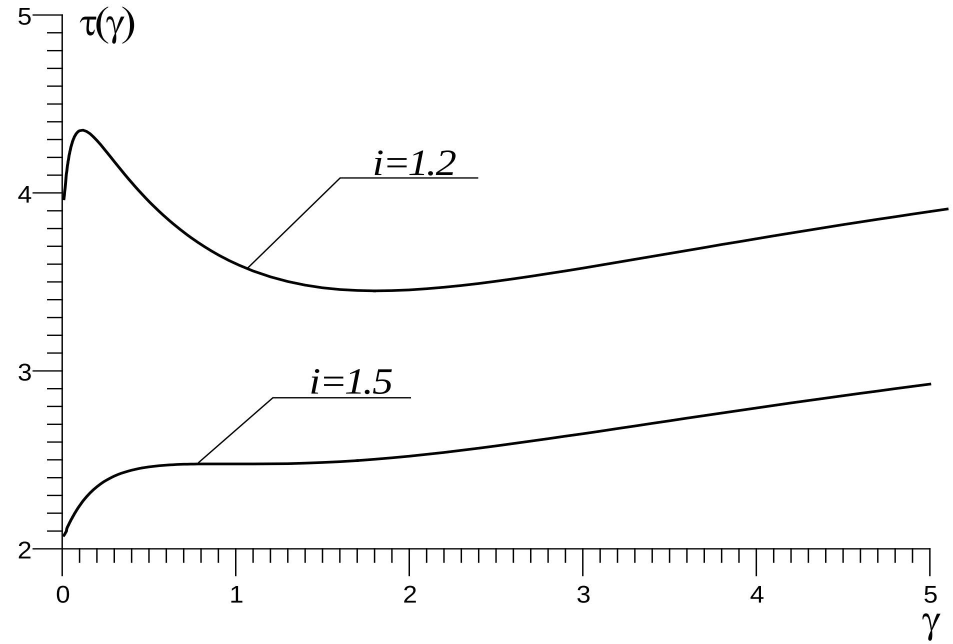
Suppression of noise by driving



For sinusoidal driving with ω~0.3
SD for meander driving is nearly reached

Noise delayed switching





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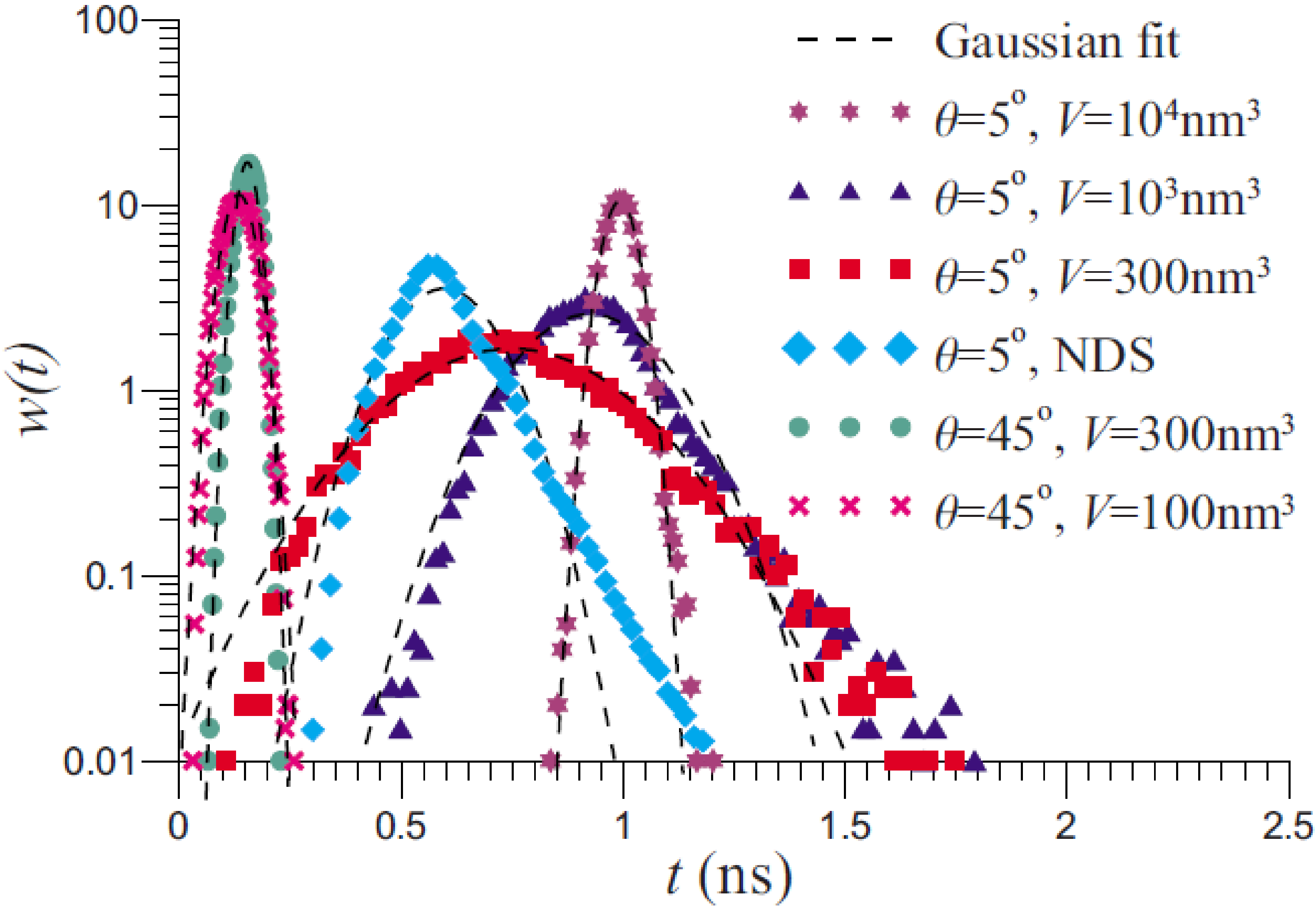

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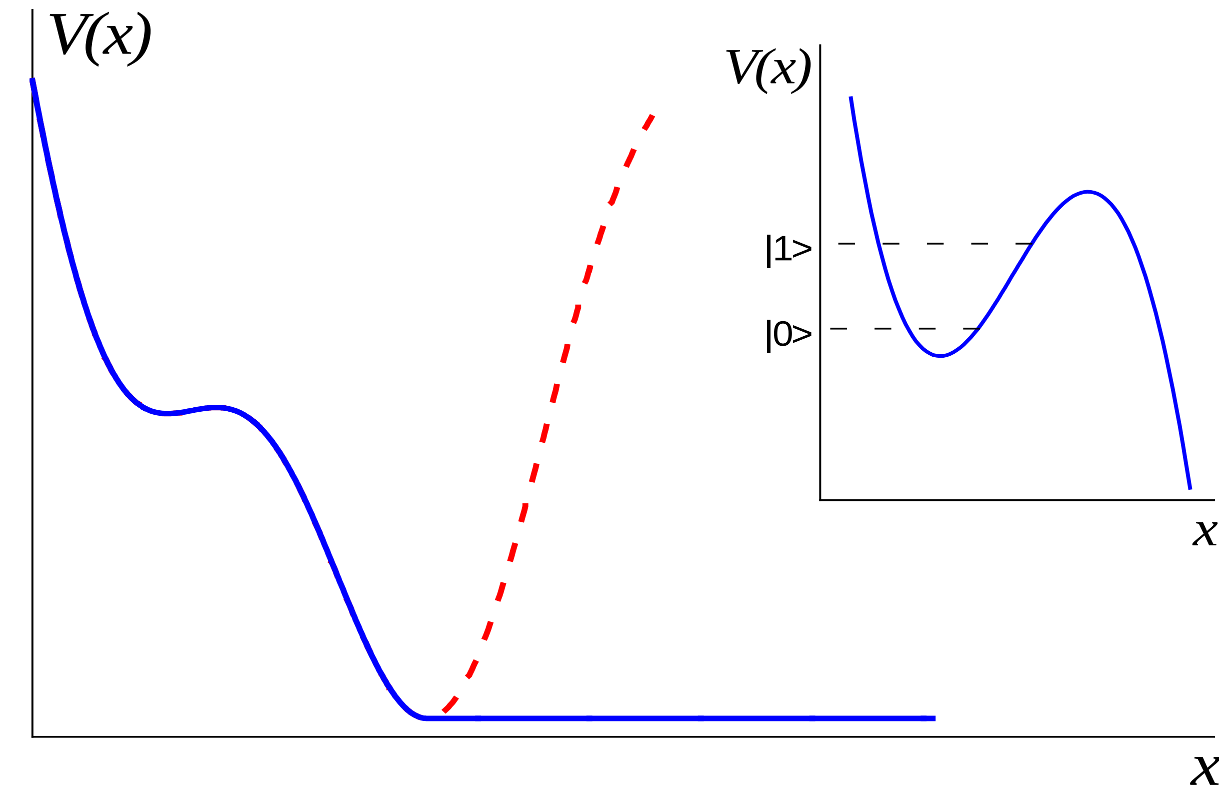
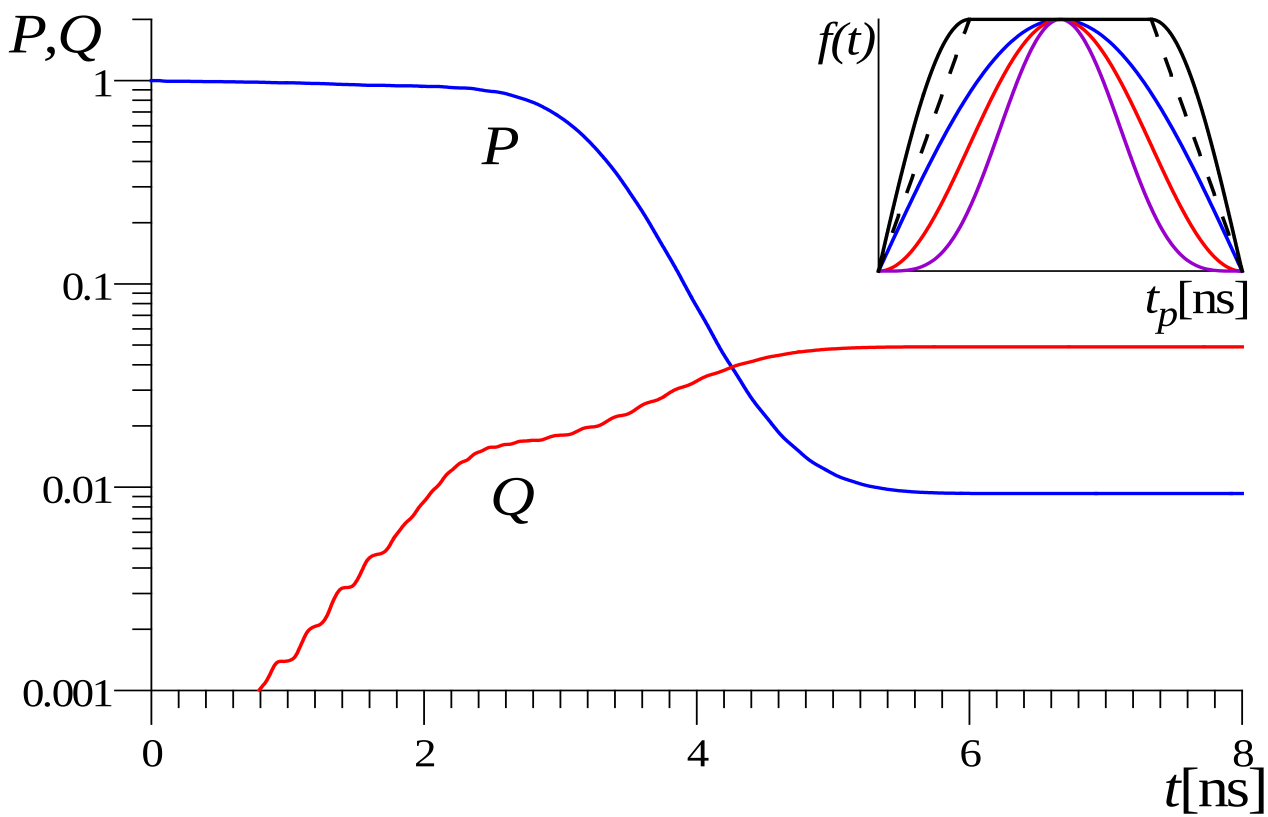
Optimal fast single pulse readout of qubits

$$i\frac{\partial\Psi(x,t)}{\partial t}=-\frac{2e^2}{hC}\frac{\partial^2\Psi(x,t)}{\partial x^2}+\frac{V(x,t)}{h}\Psi(x,t)$$



Probability evolution

$$N = P(t_p) + Q(t_p) = P_{10} + P_{01}, \qquad F = 1 - N$$



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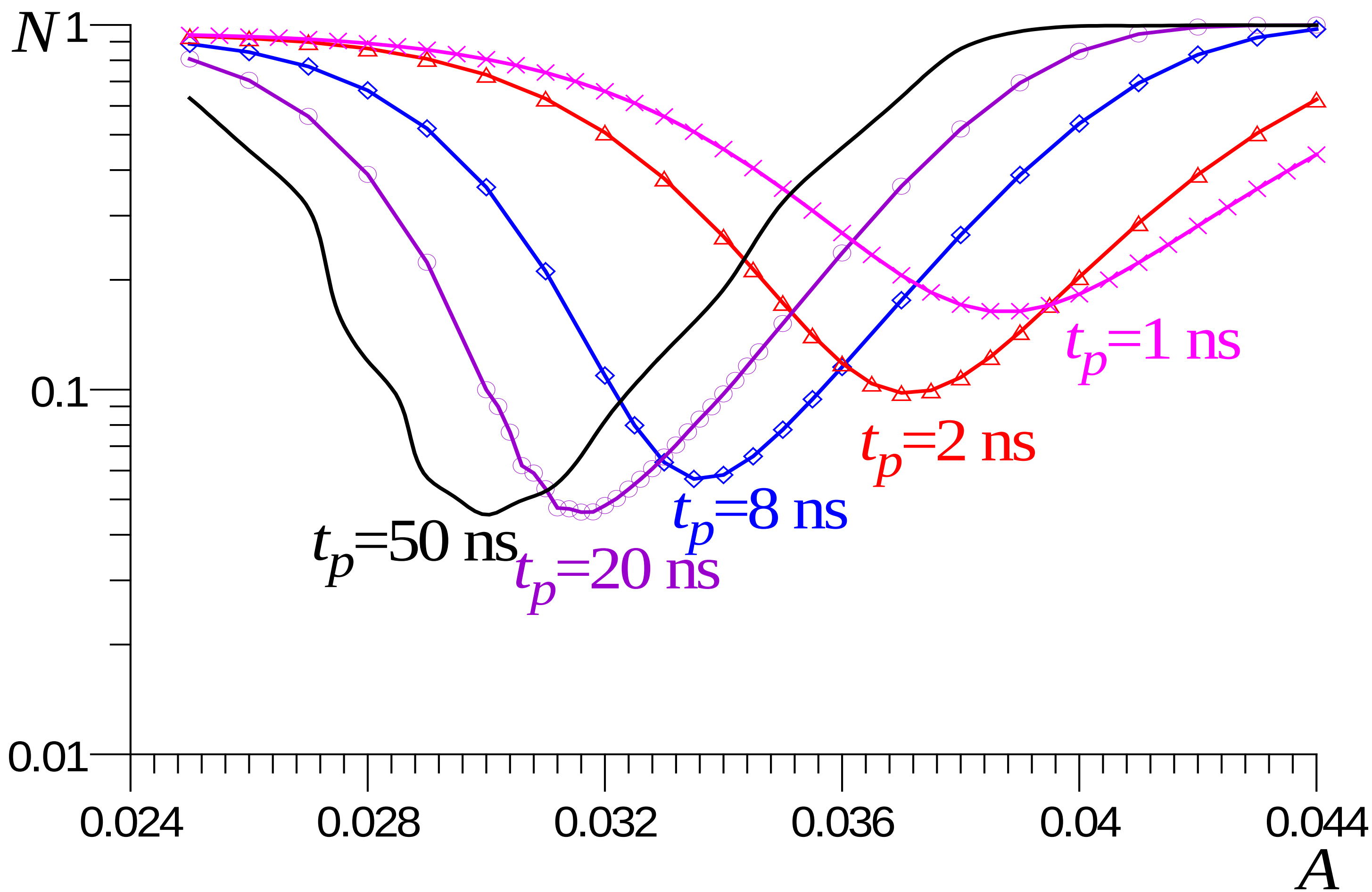
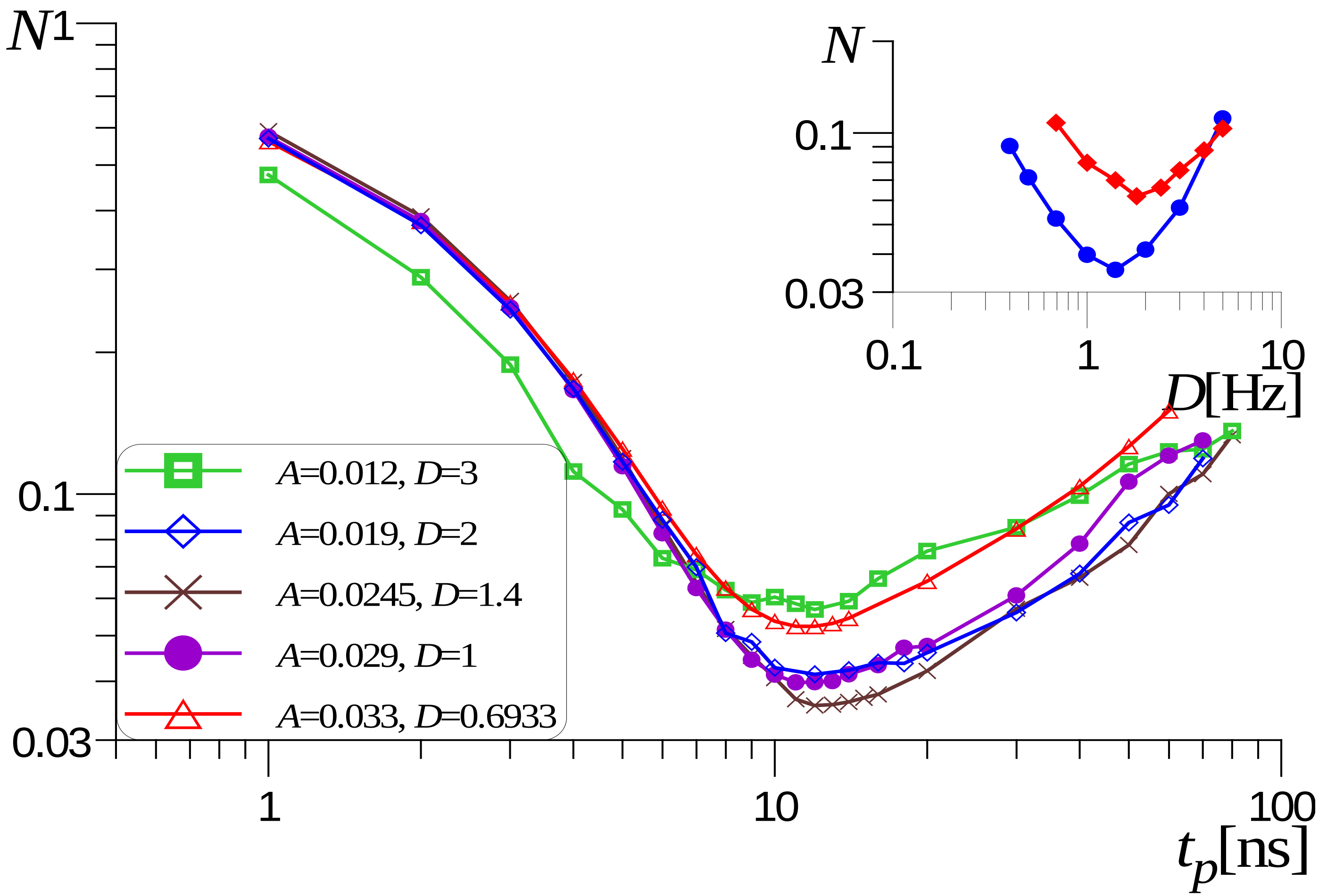
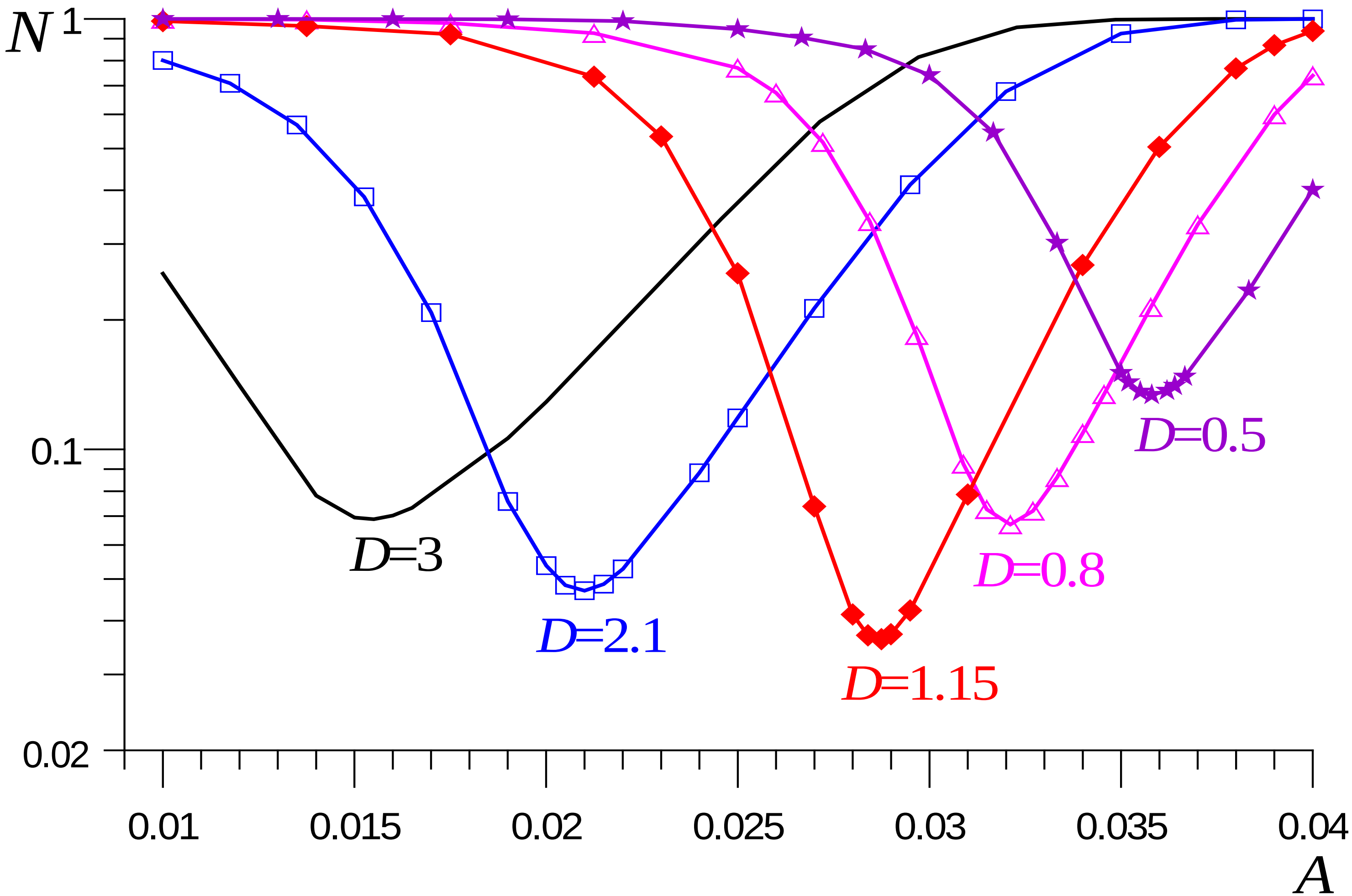
Readout error vs pulse amplitude



Readout error vs pulse duration



Readout error vs well depth



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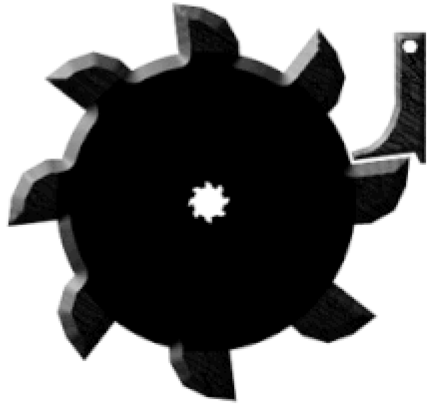
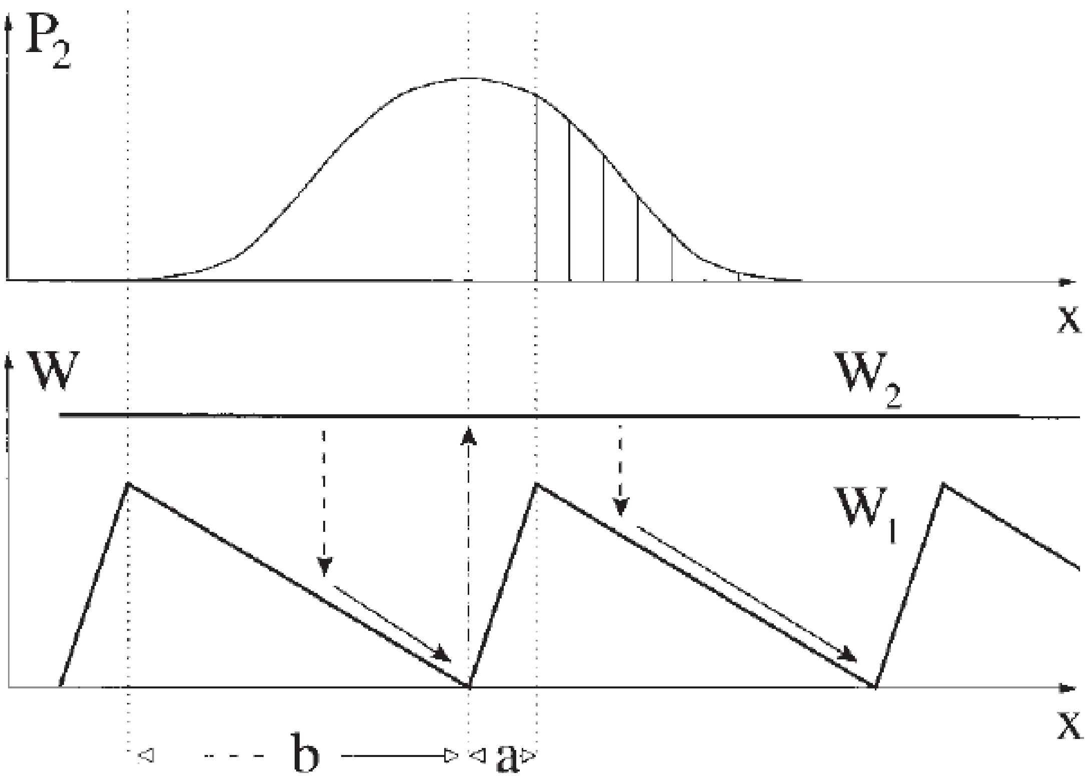
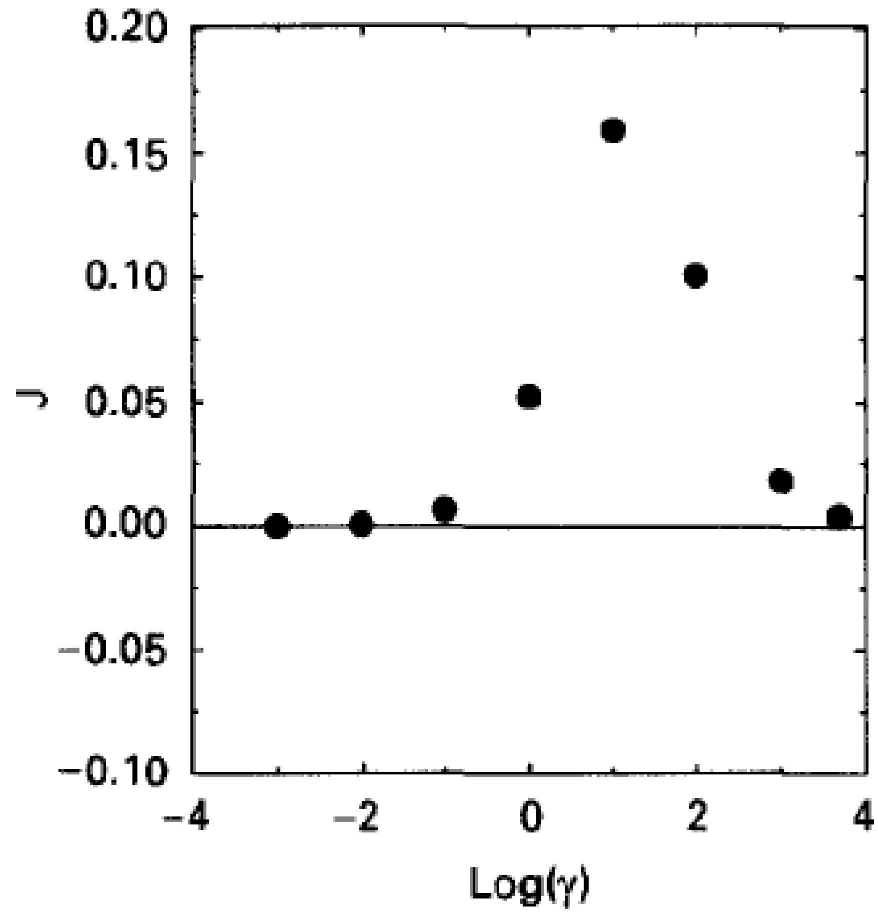
Ratchet effect







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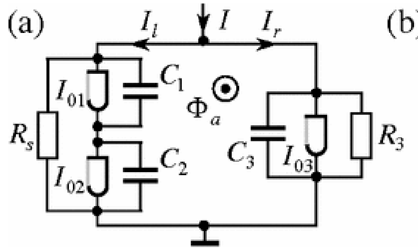
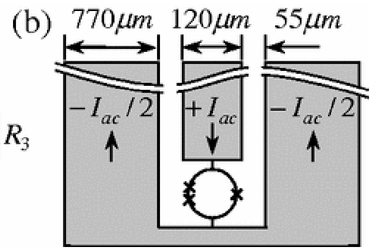
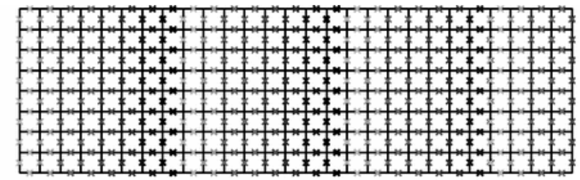
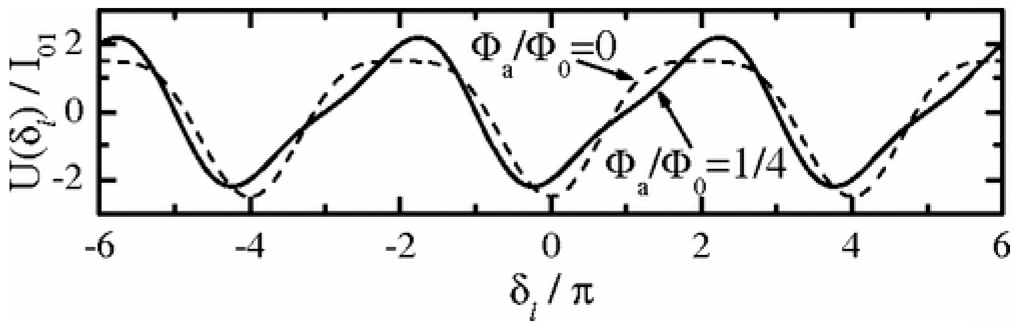
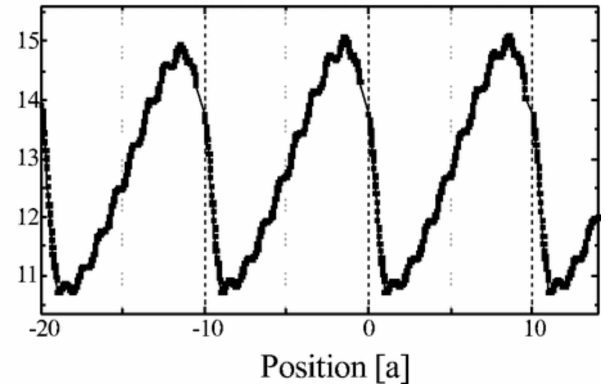




Ratchet effect







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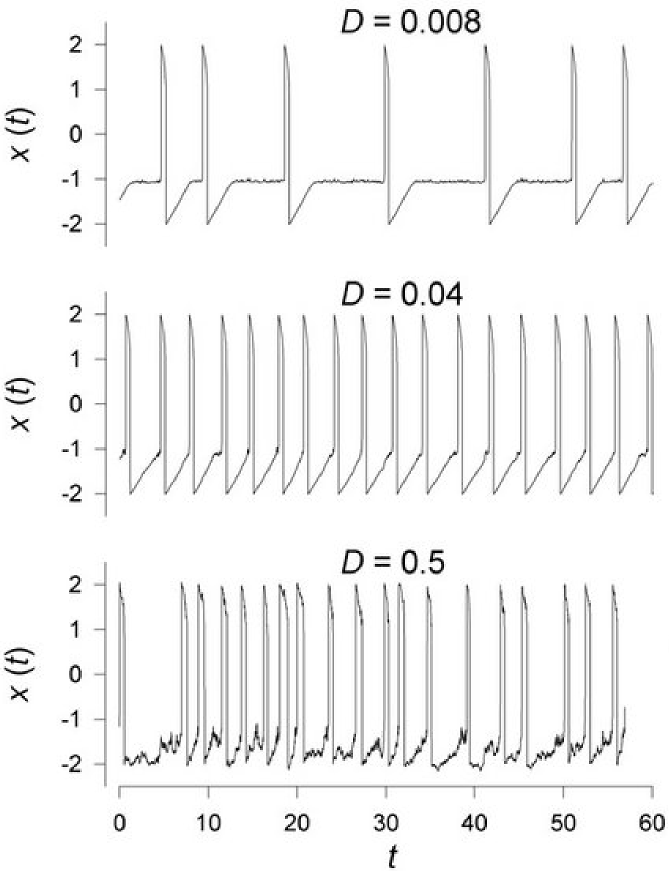
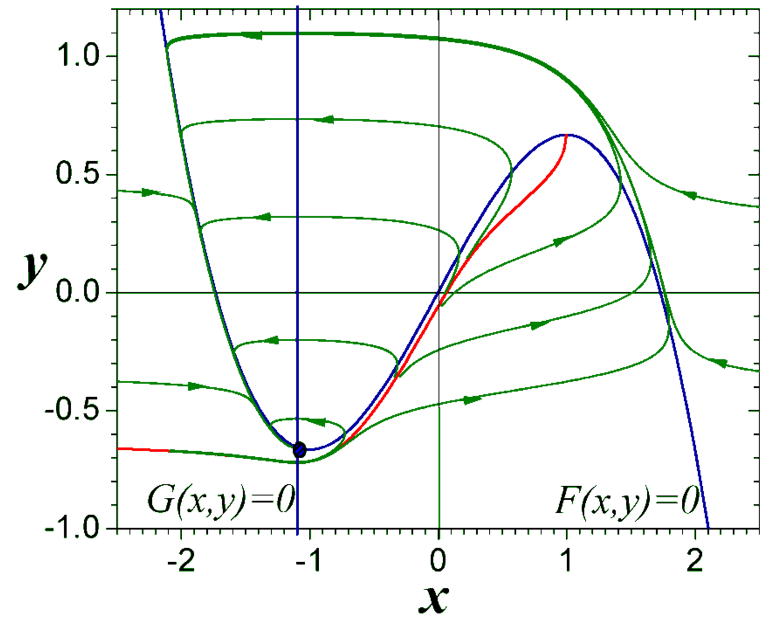
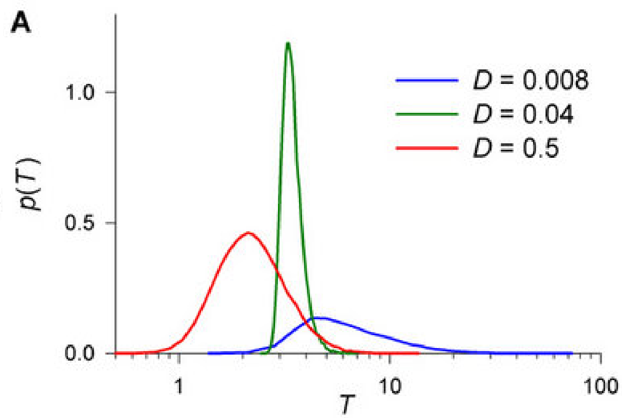
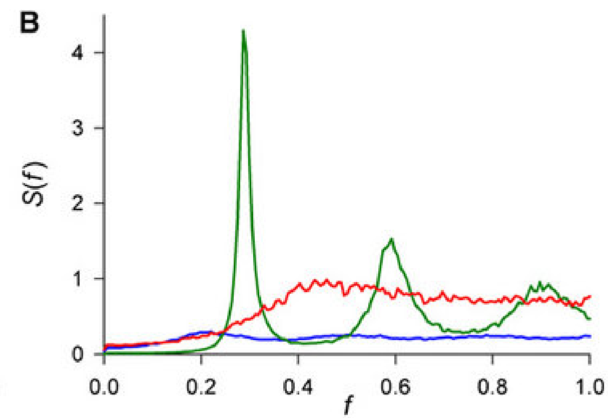
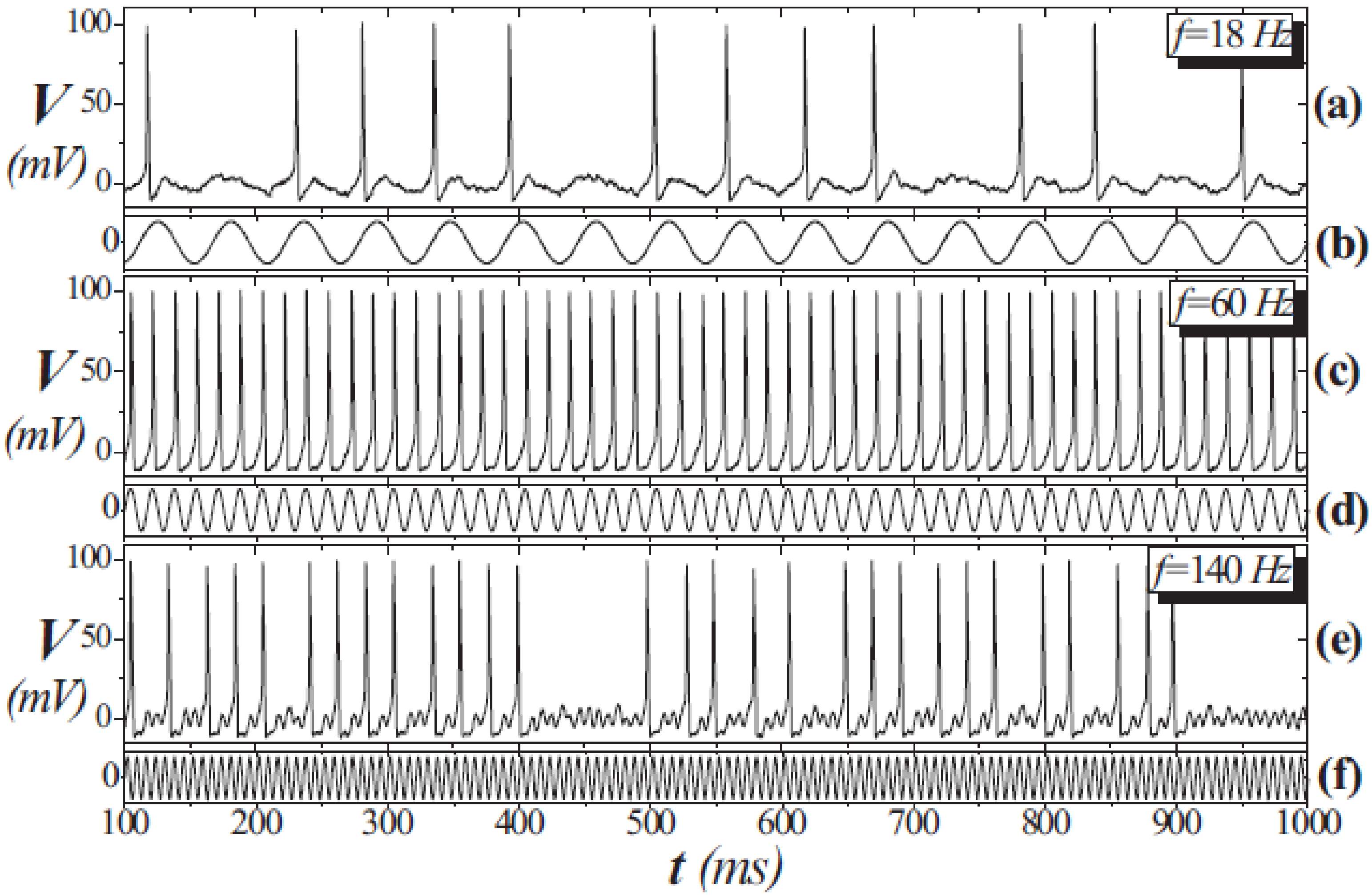




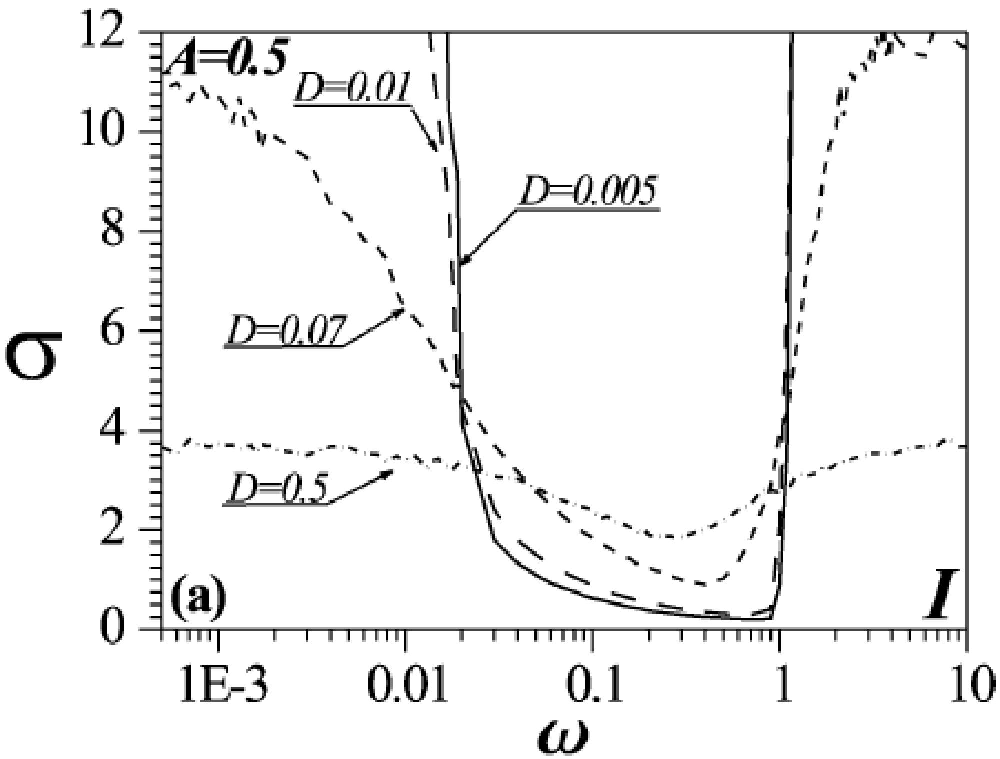


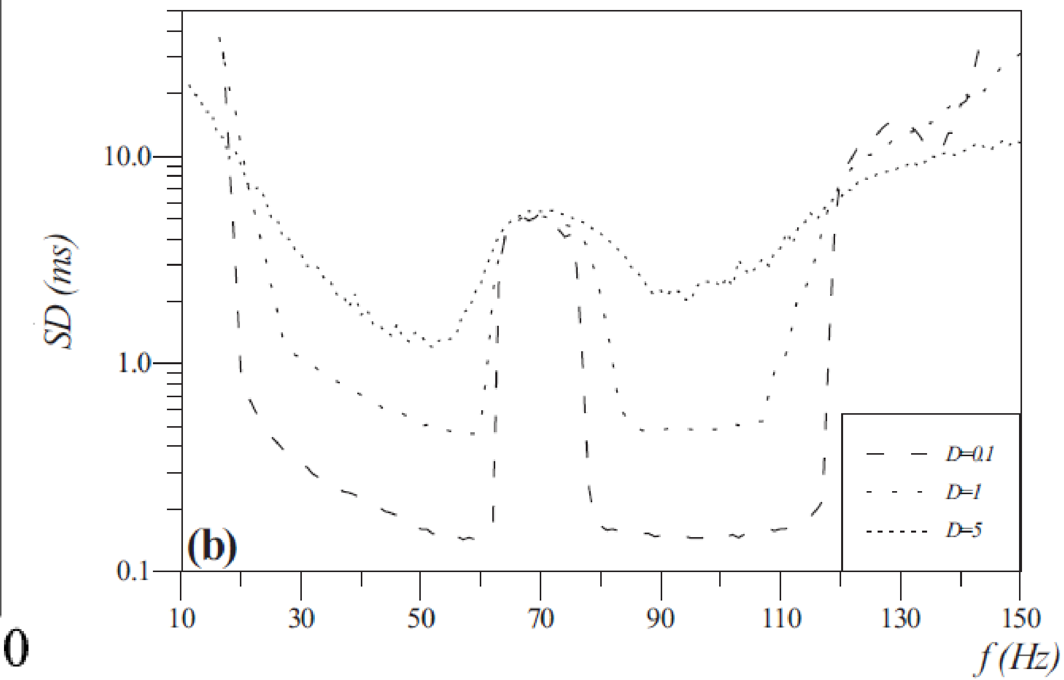


Suppression of noise in neuronal models



Suppression of noise in neuronal models





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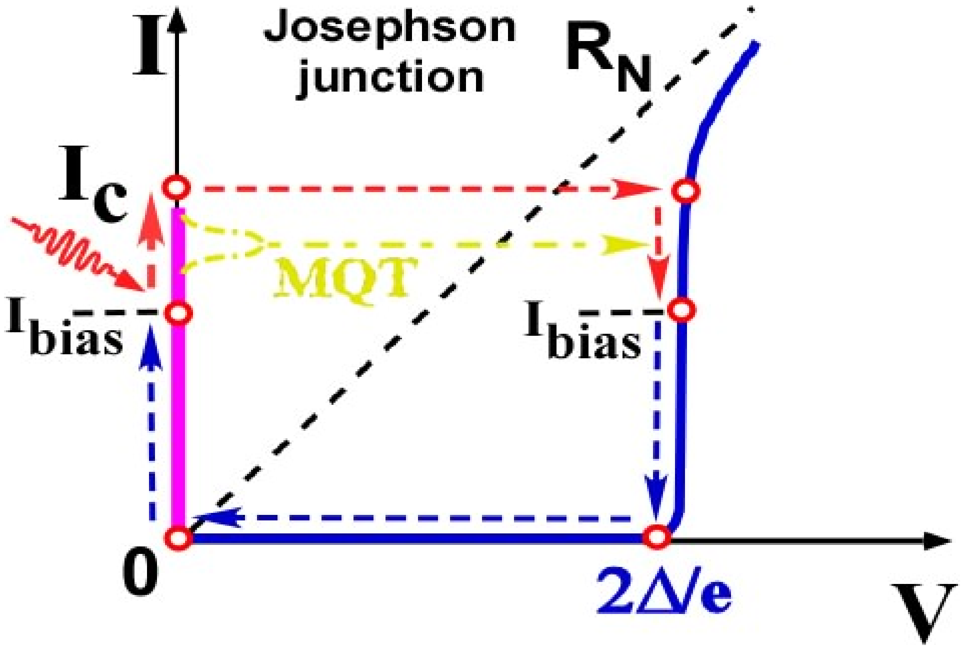
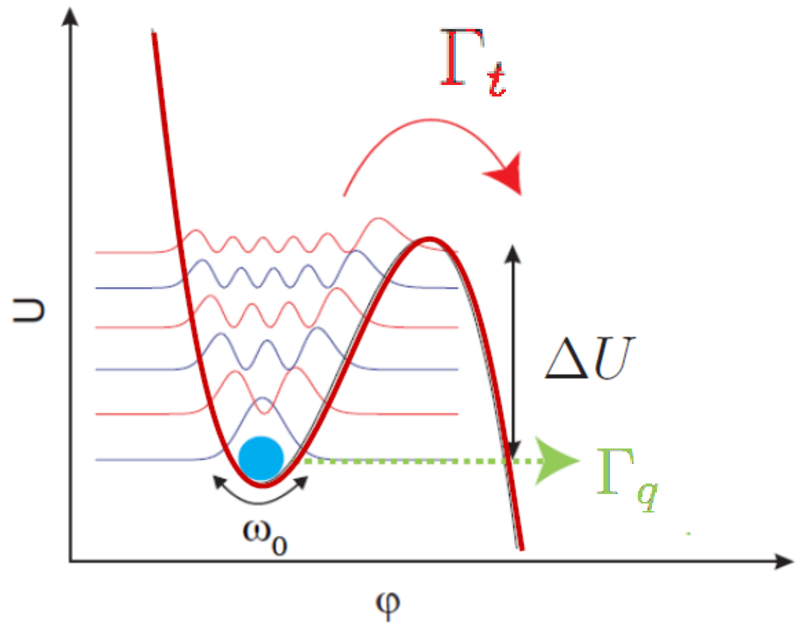
Al SIS junction as single photon counter for 14 GHz





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Search for axions – dark matter particles

Giovanni Carugno **Frank Wilczek** **Yannis Semertzidis**

Searching for galactic axions through magnetized media: The QUAX proposal

R.Barbieri a,b) C.Braggio c, G.Carugno c, C.S.Gallo c, A.Lombardi d, A.Ortolan d, R.Pengo d, G.Ruoso d,*,C.C.Speake e

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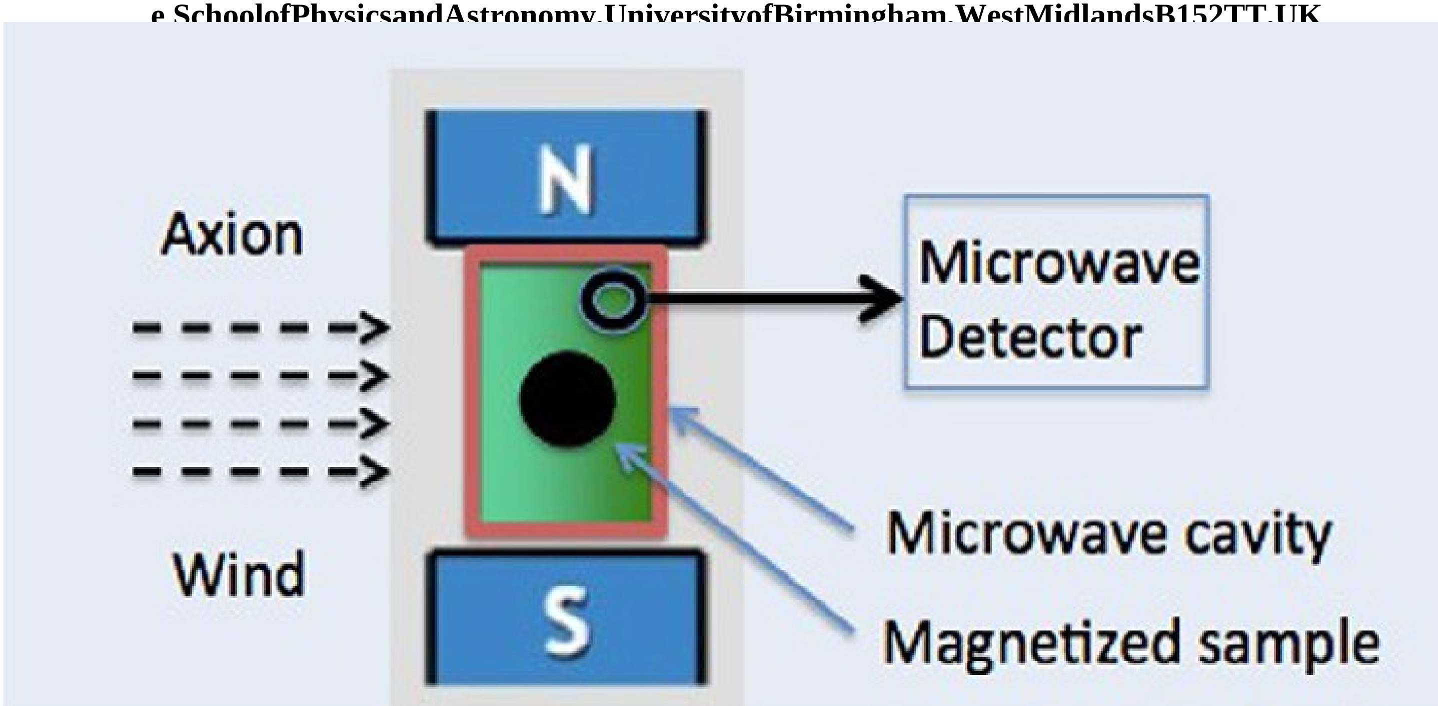
d INFN,LaboratoriNazionalidiLegnaro,Vialedell'Università2,35020Legnaro,Italy

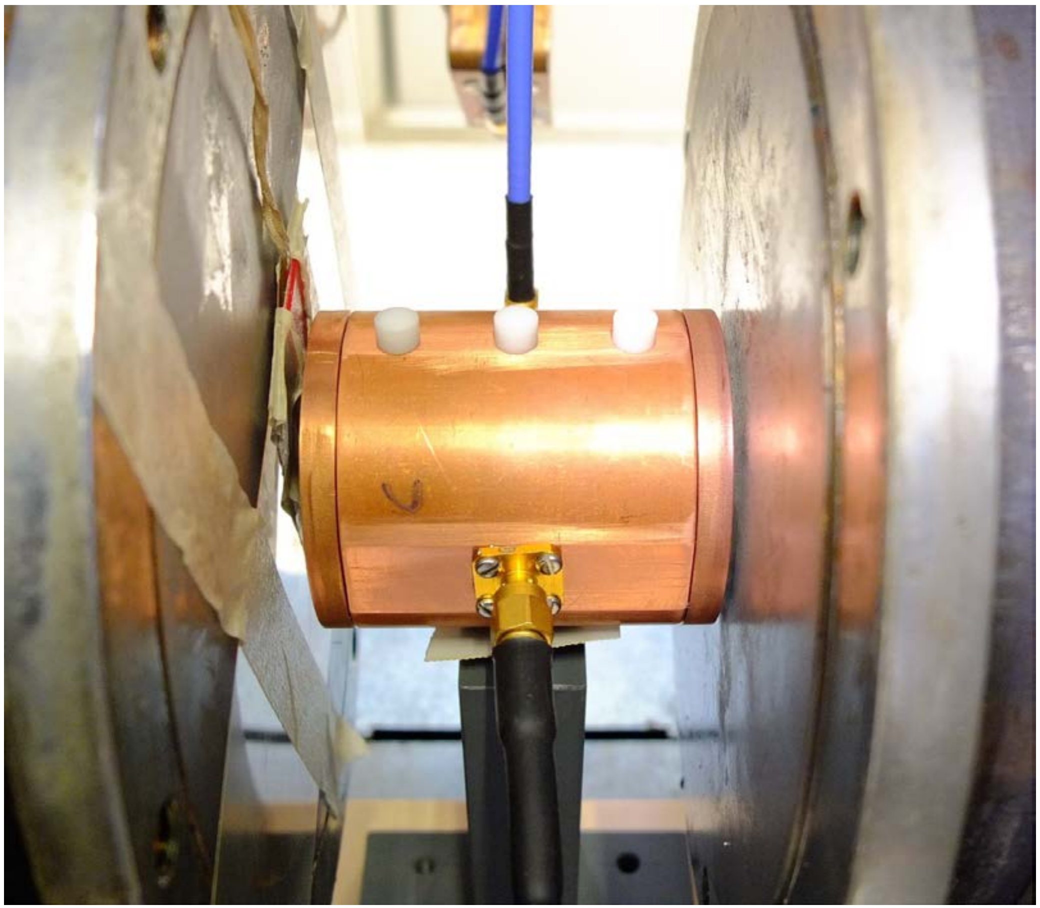
e SchoolofPhysicsandAstronomy,UniversityofBirmingham,WestMidlandsB152TT,UK



Principle scheme of the axion haloscope

Cavity

Half of a 14 GHz resonant cavity with conical endcaps used for the Quax R&D.



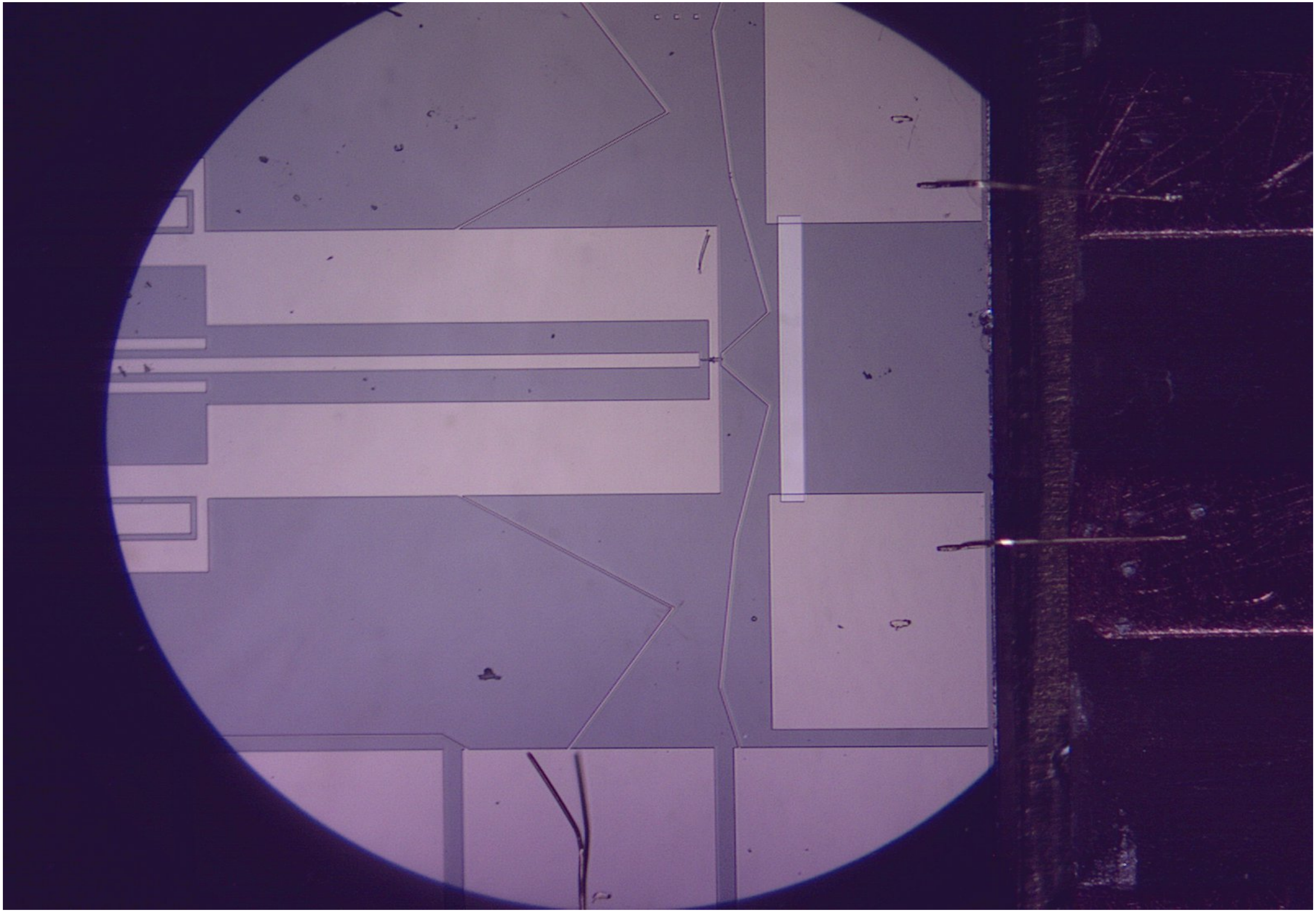
A cylindrical cavity with magnetized samples inserted from the top side during a test for the Quax R&D in magnetic field at room temperature.

Q quality factor = 50 000

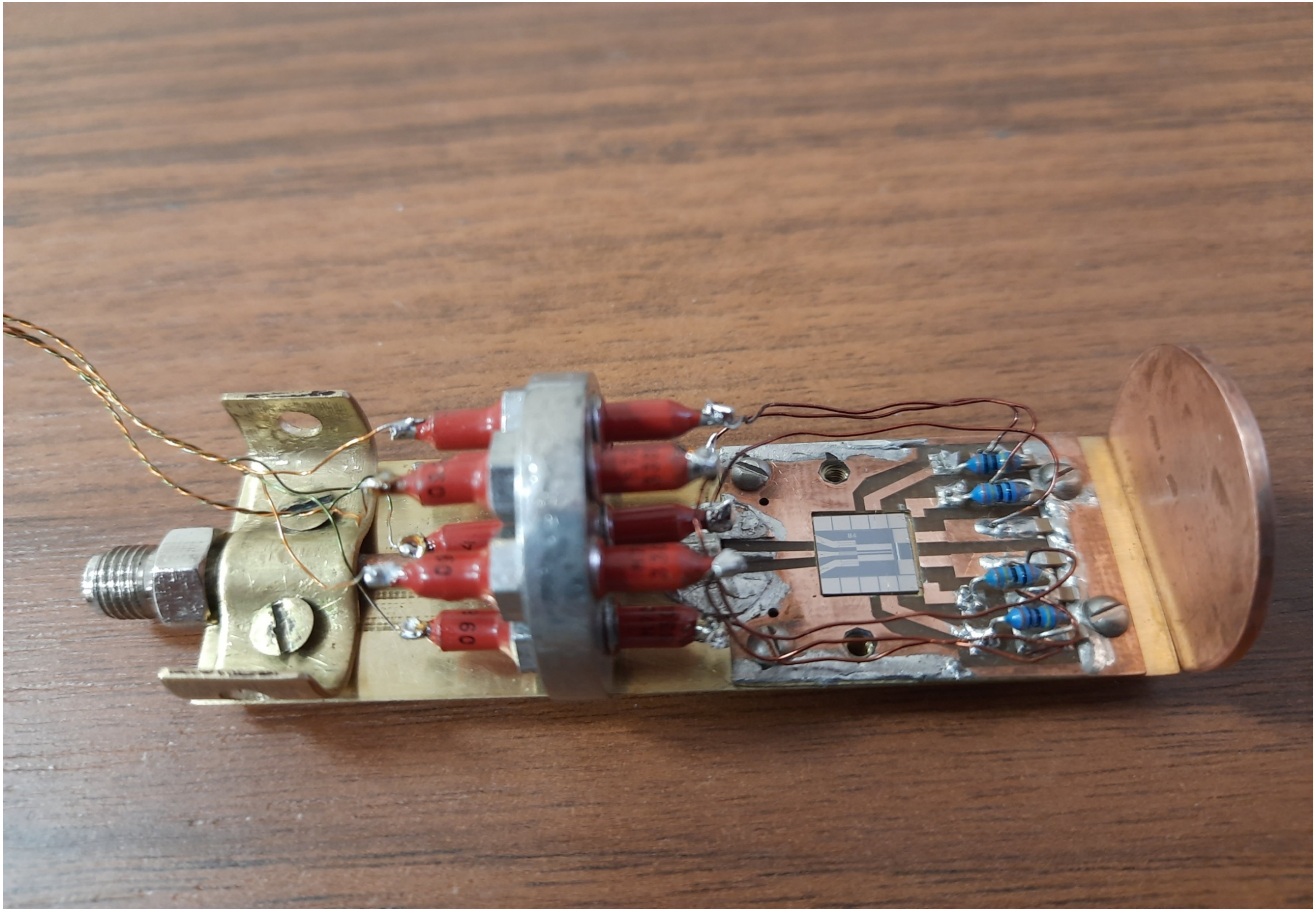
Resonant search of axions is performed tuning the cavity frequency by means of metallic tuning rods.

The frequency is shifted in a range ±10% corresponding to ±1.4 GHz.

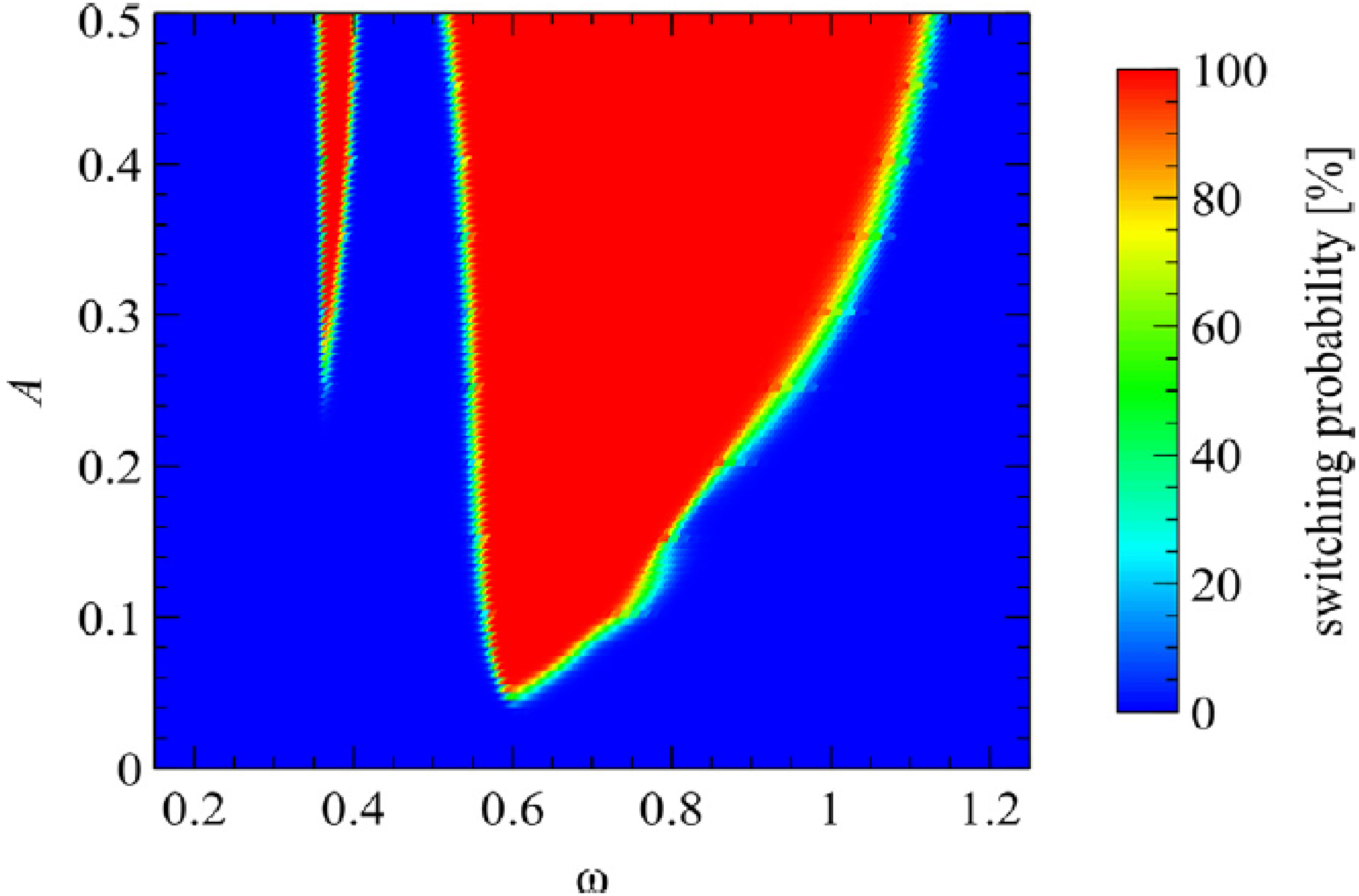
Sample photo



Sample photo



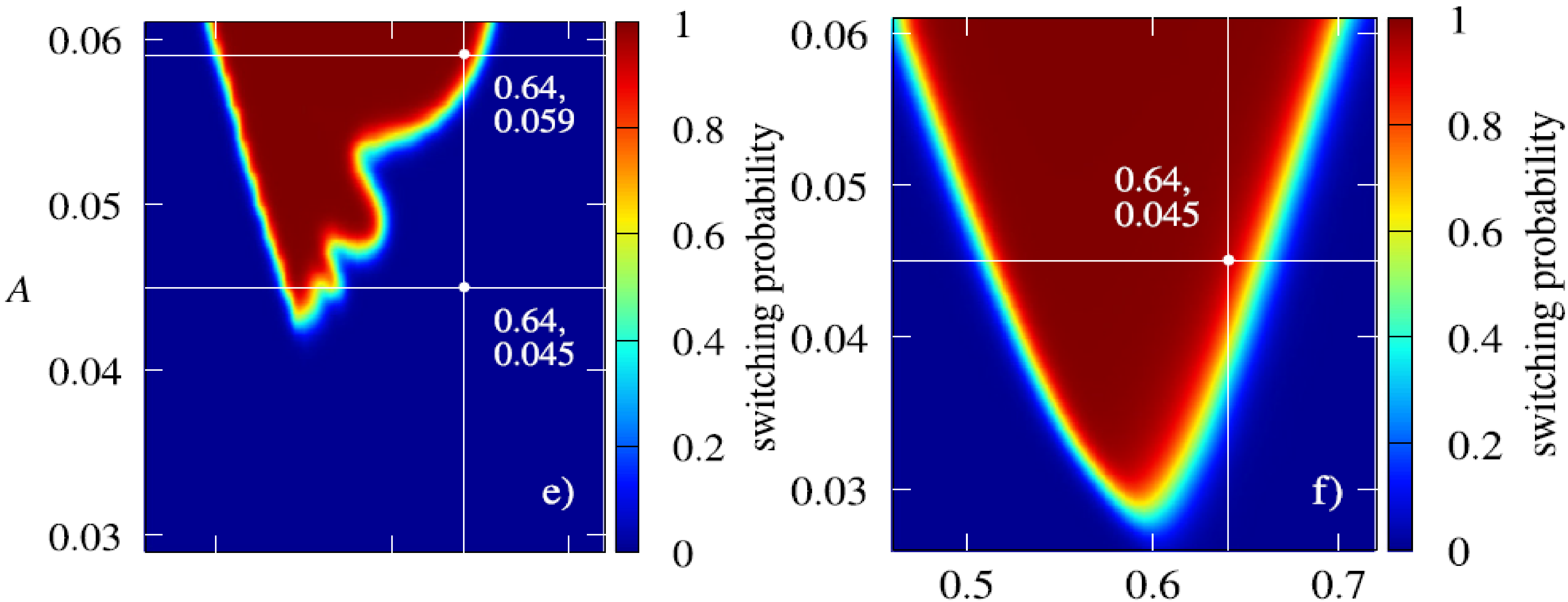
Resonant response drives sensitivity



Resonant response drives sensitivity of Josephson Escape Detector

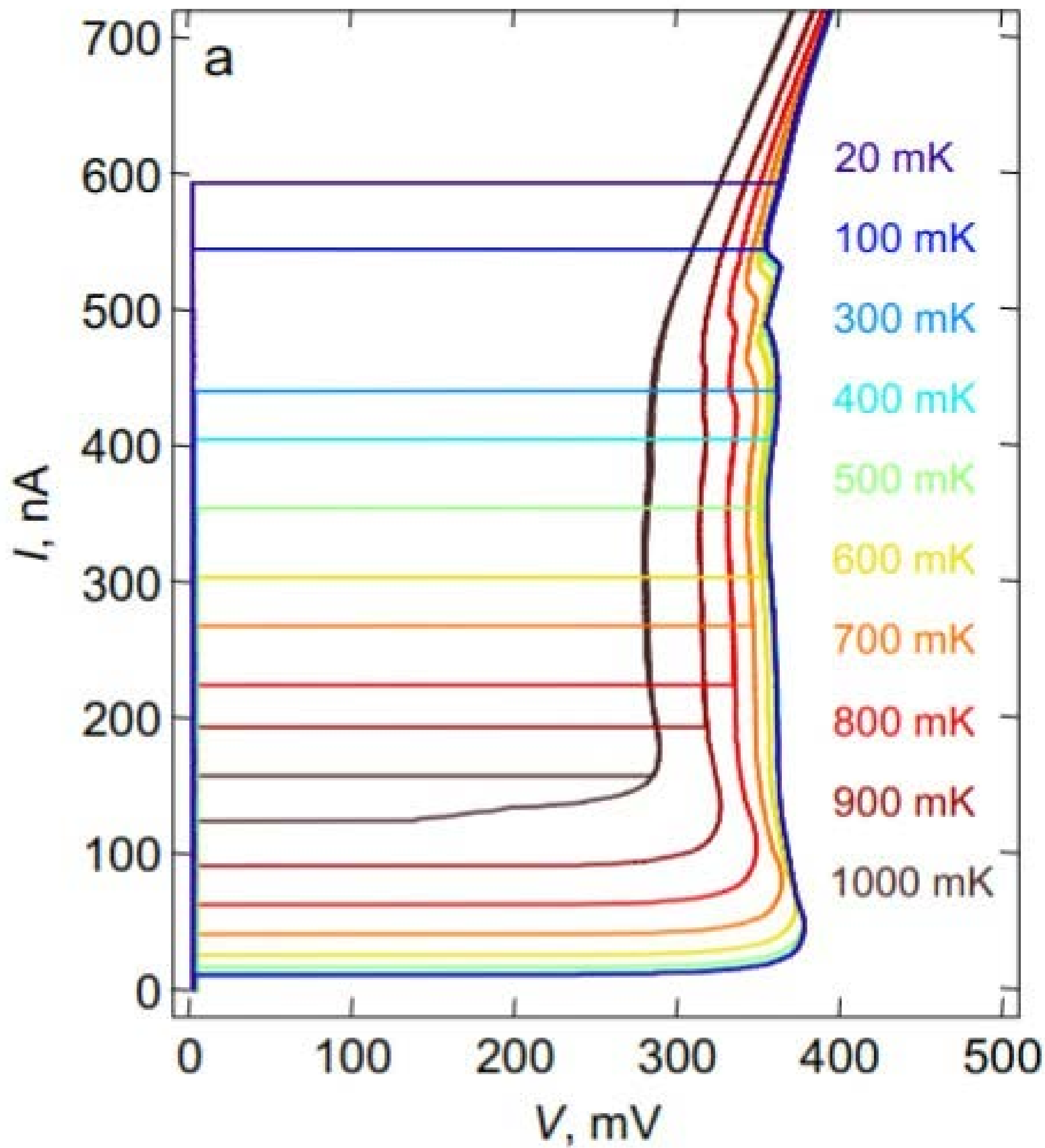
A.A. Yablokov, E.I. Glushkov, A.L. Pankratov, A.V. Gordeeva, L.S. Kuzmin, E.V. Il'ichev, Chaos, Solitons & Fractals 148, 111058 (2021)

Weak heating drives sensitivity



Stochastic versus dynamic resonant activation to enhance threshold detector sensitivity

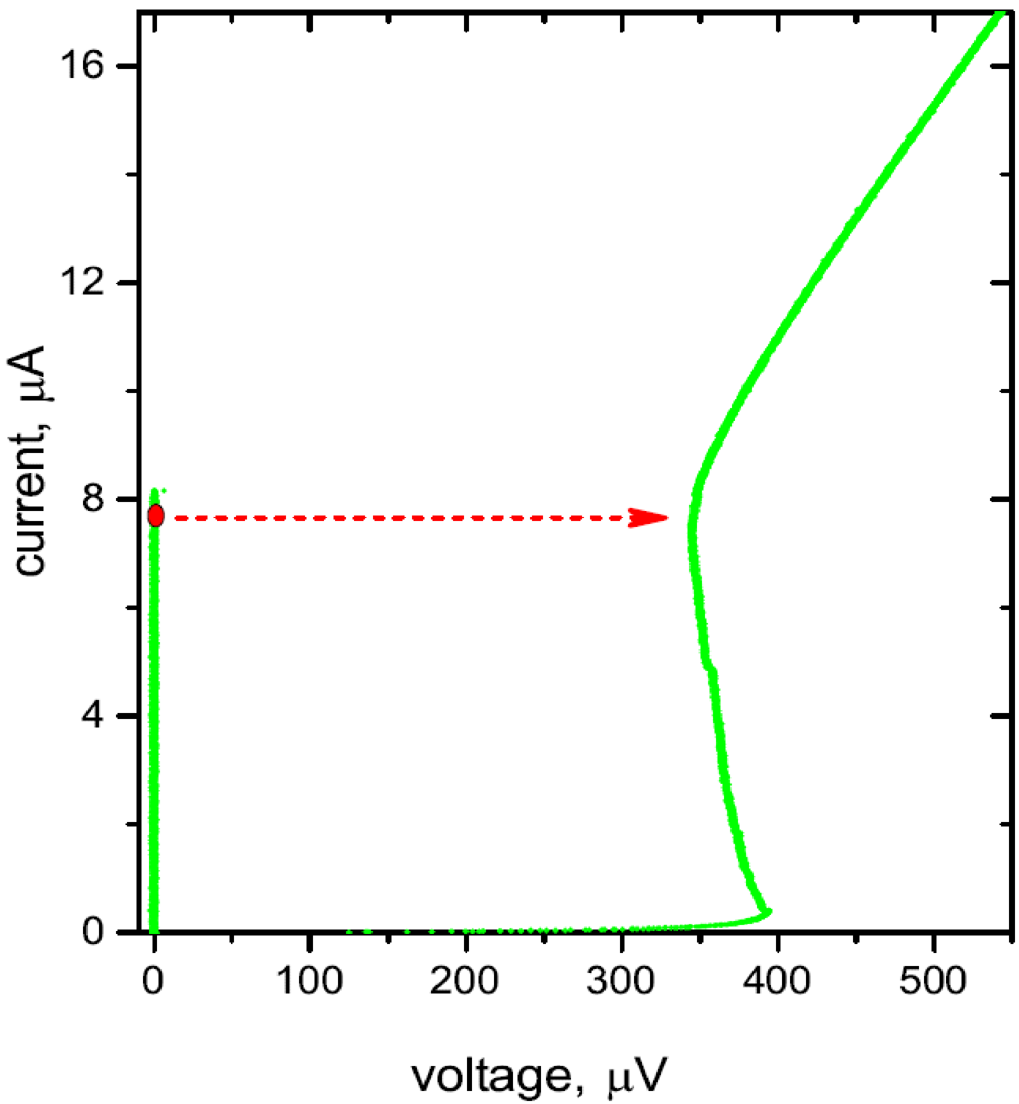
D.A. Ladeynov, E.G. Egorov, A.L. Pankratov, Chaos, Solitons & Fractals 171, 113506 (2023)

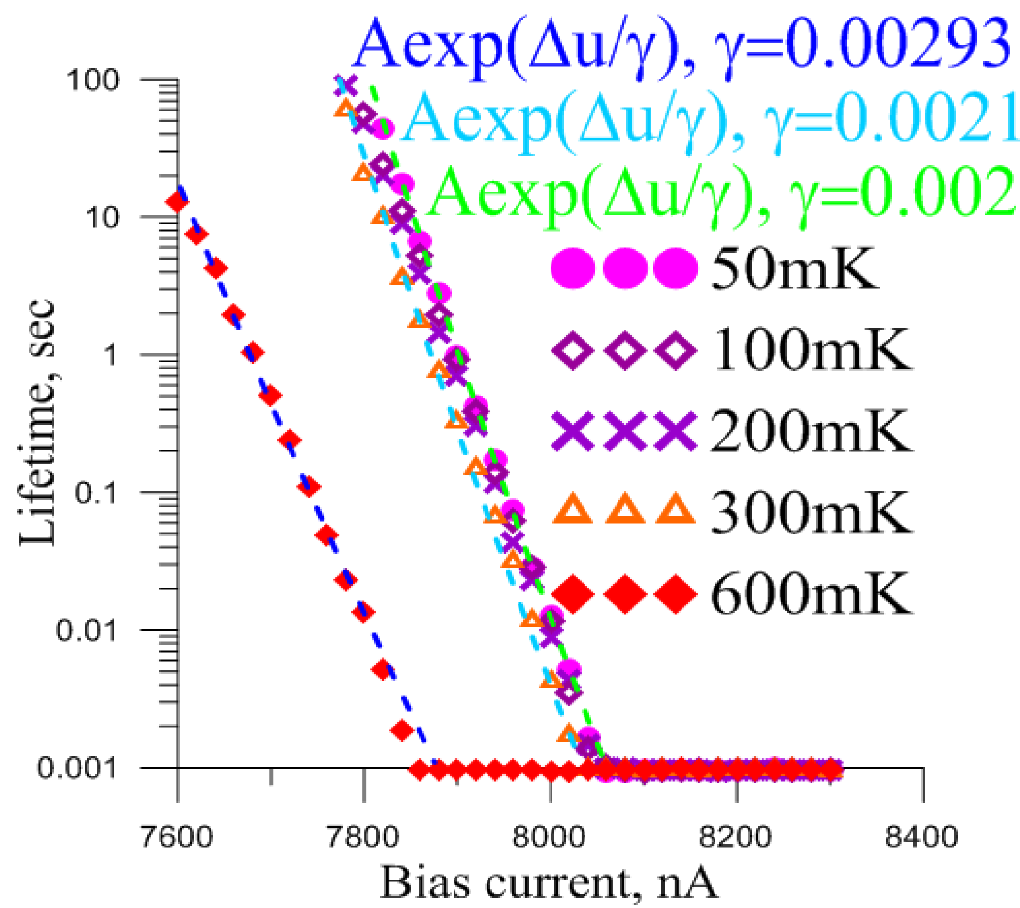

a
700
600
500
400
300
200
100
0
I, nA
0
100
200
300
400
500
V, mV
20 mK
100 mK
300 mK
400 mK
500 mK
600 mK
700 mK
800 mK
900 mK
1000 mK

Lifetime of a large SIS junction

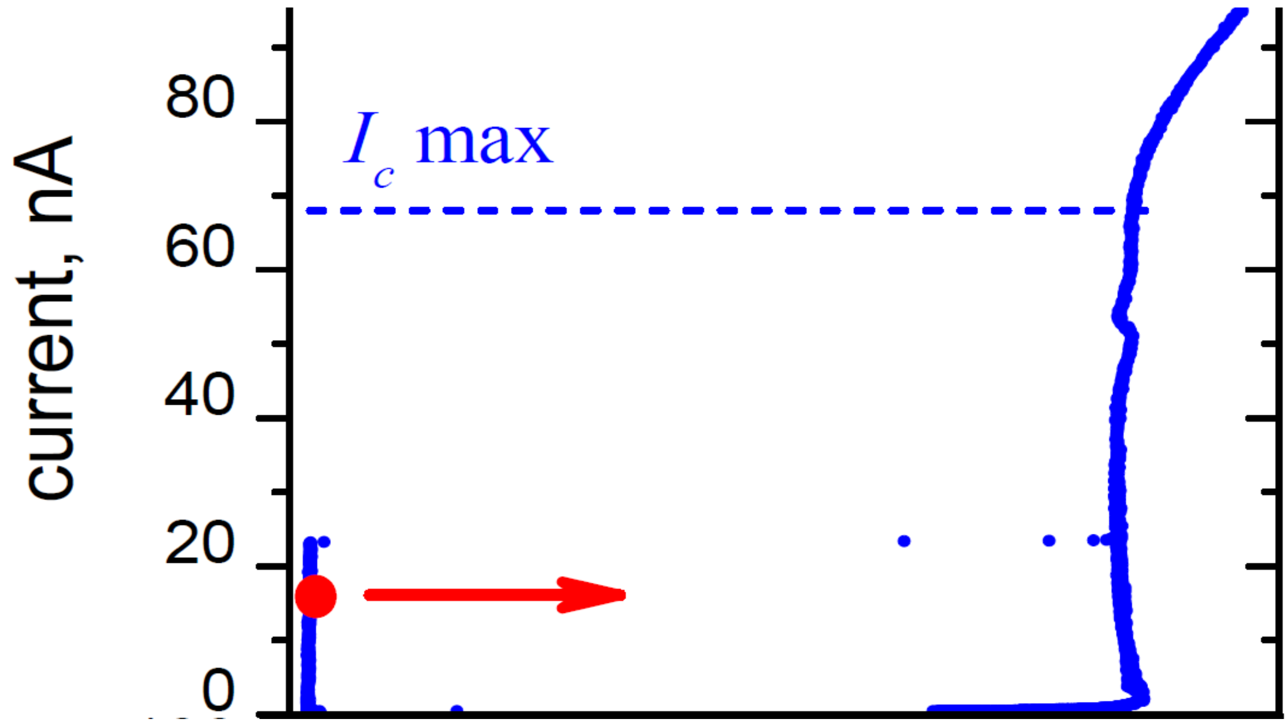
$\gamma = I_T / I_C \qquad I_T\ [\mu\text{A}] = 0.042T\ [\text{K}]$

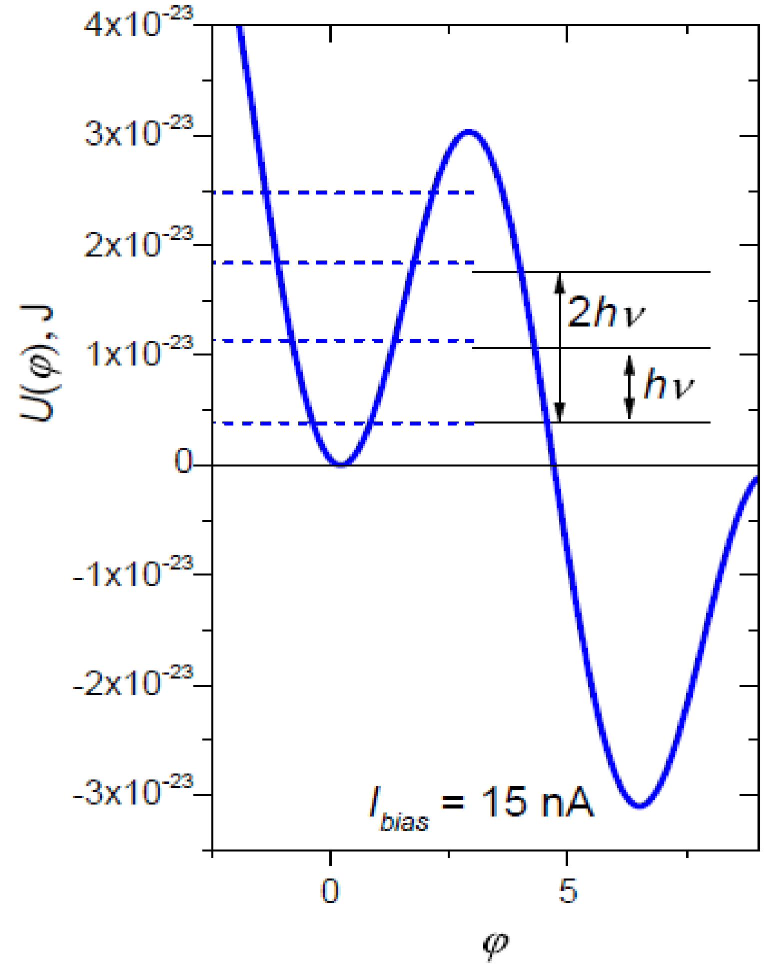
$$\tau = \frac{f(\alpha)\exp(\Delta u/\gamma)}{\sqrt{1-i^2}}$$





Lifetime of a small SIS junction

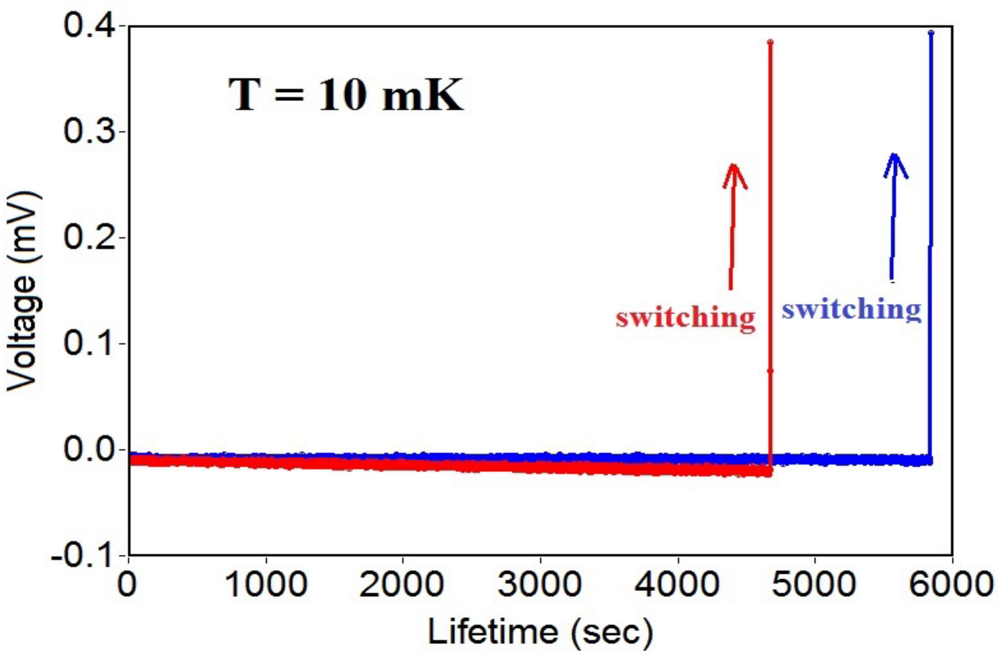


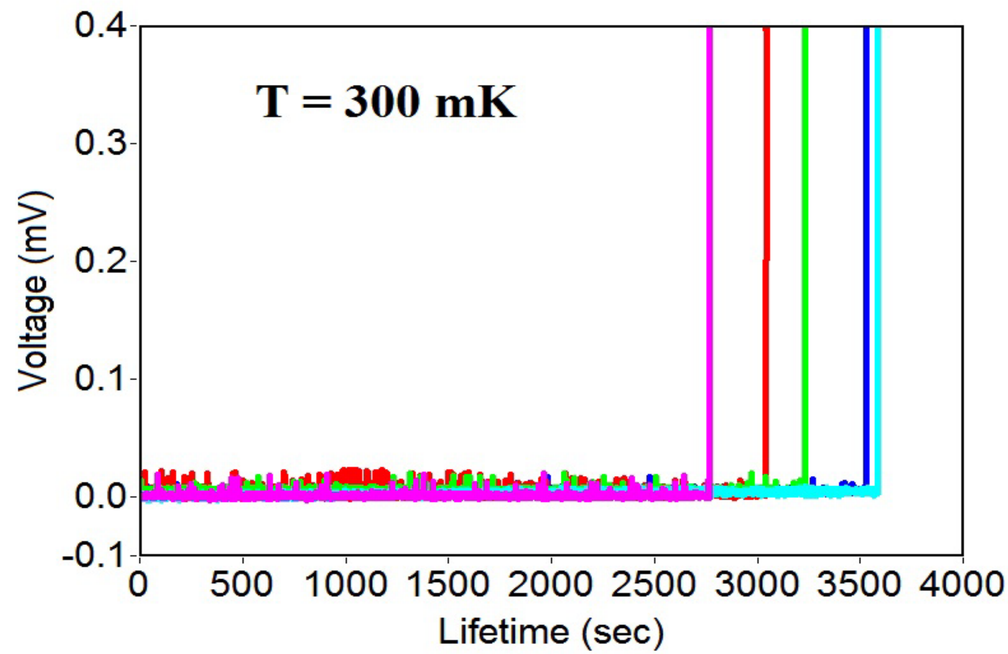


For small junctions the critical current is suppressed due to MQT.

D.S. Golubev, E.V. Il'ichev, & L.S. Kuzmin, Phys. Rev. Appl., 16, 014025 (2021).

Lifetime of a small SIS junction

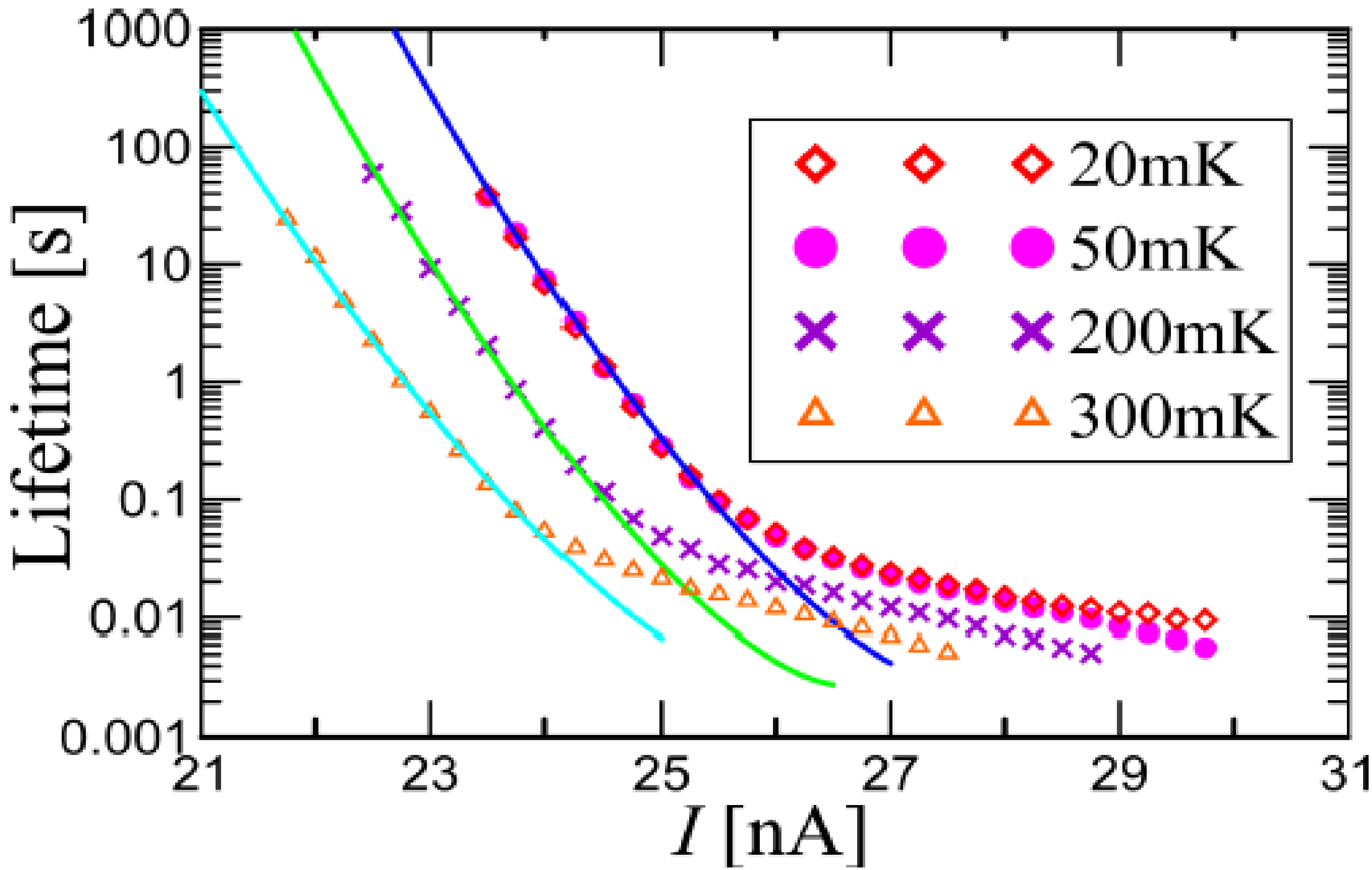




Does Kramers' formula $\tau \sim \exp(\Delta u/\gamma)$ still work ???
Lifetime can be increased by orders of magnitude
due to the phase diffusion regime

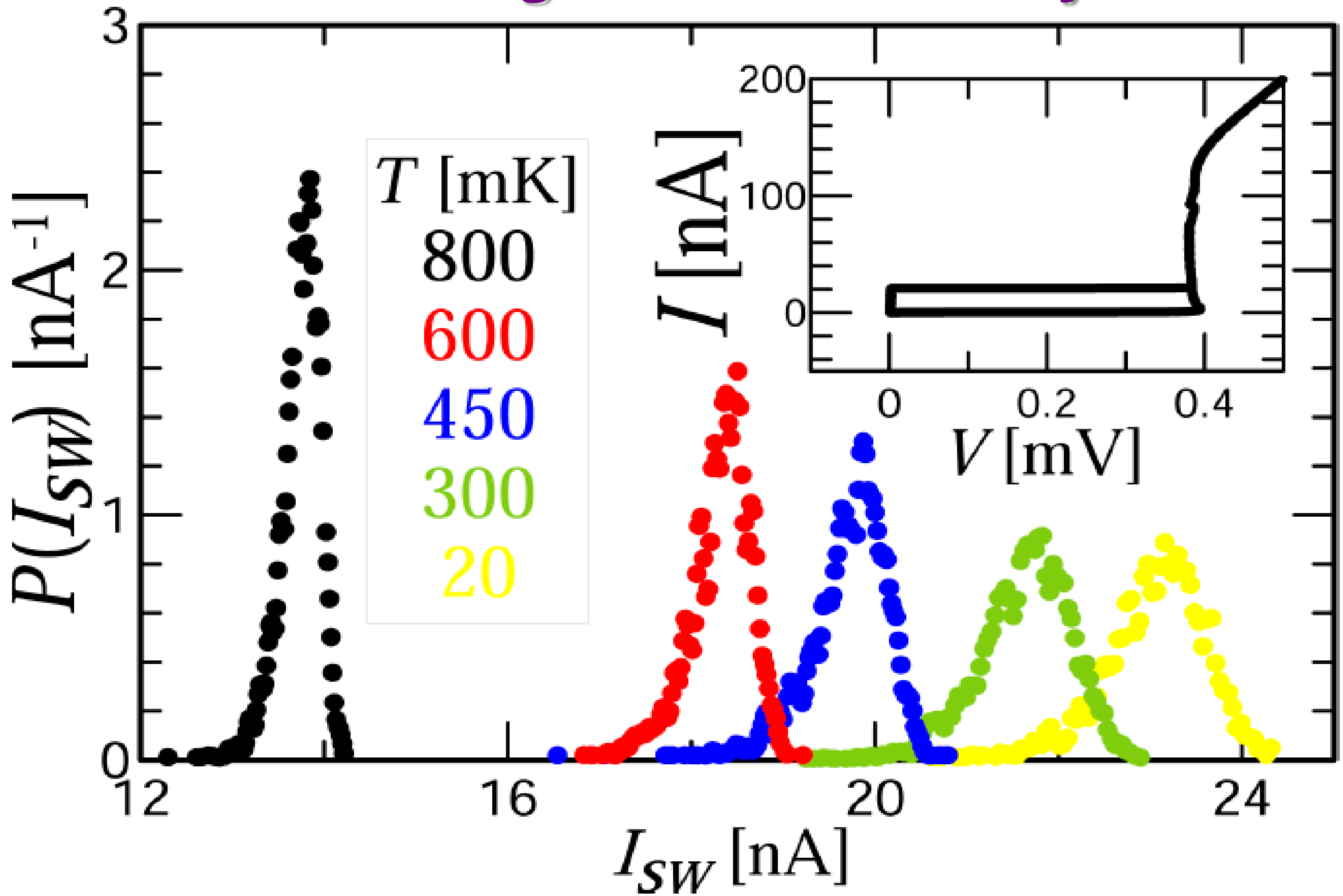
L.S. Revin, A.L. Pankratov, A.V. Gordeeva, A.A. Yablokov, I.V. Rakut, V.O. Zbrozhek, L.S. Kuzmin, Beilstein J. Nanotechnol. **11,** 960 (2020).

Lifetime of a small SIS junction



Kramers' formula $\tau \sim \exp(\Delta u/\gamma_{eff})$, but $\gamma_{eff} << \gamma$
Lifetime can be increased by orders of magnitude due to the phase diffusion regime

Phase diffusion regime in a small SIS junction



L.S. Revin, A.L. Pankratov, A.V. Gordeeva, A.A. Yablokov, I.V. Rakut, V.O. Zbrozhek, L.S. Kuzmin, Beilstein J. Nanotechnol. **11,** 960 (2020).

Phase diffusion regime

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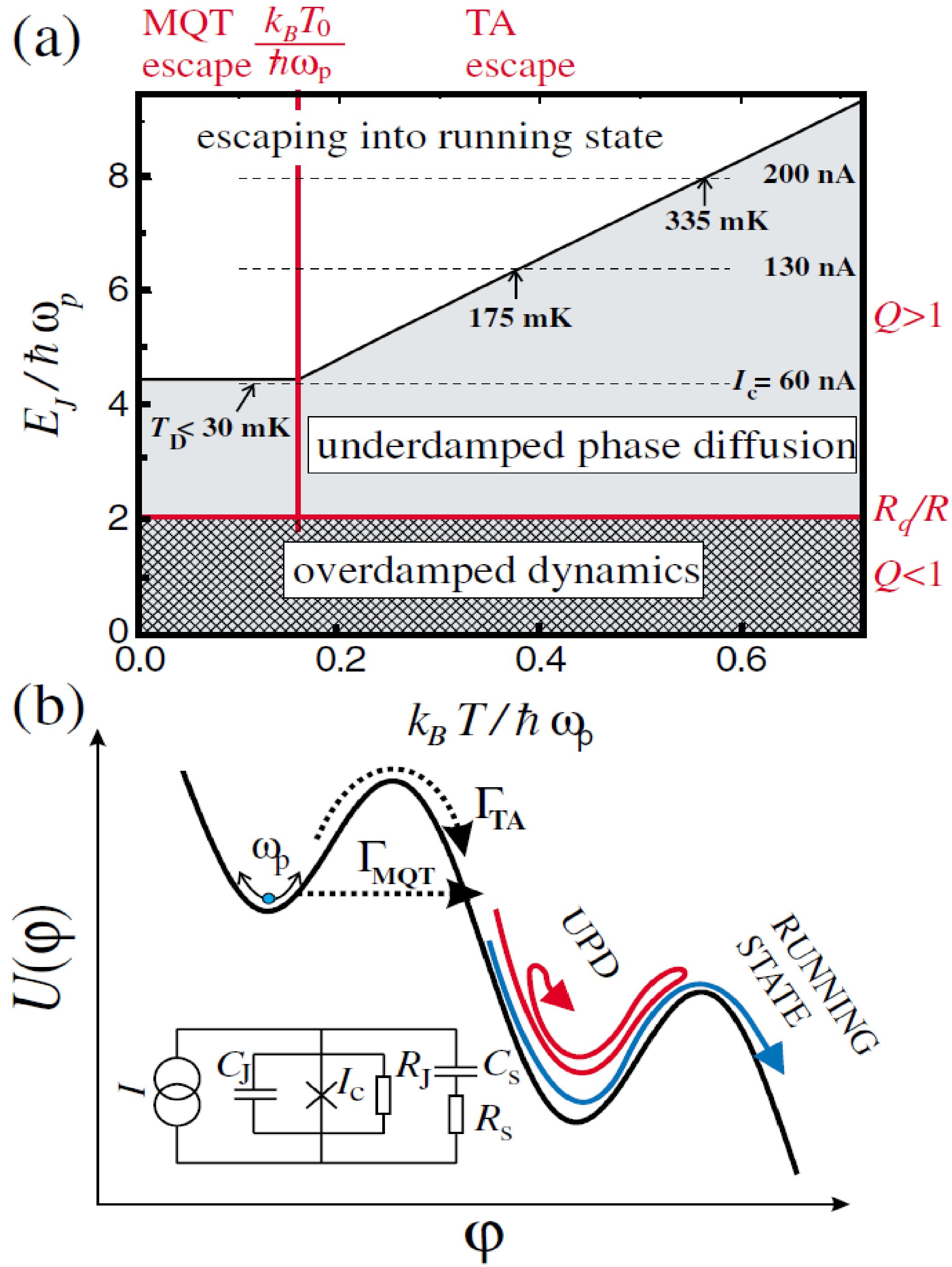
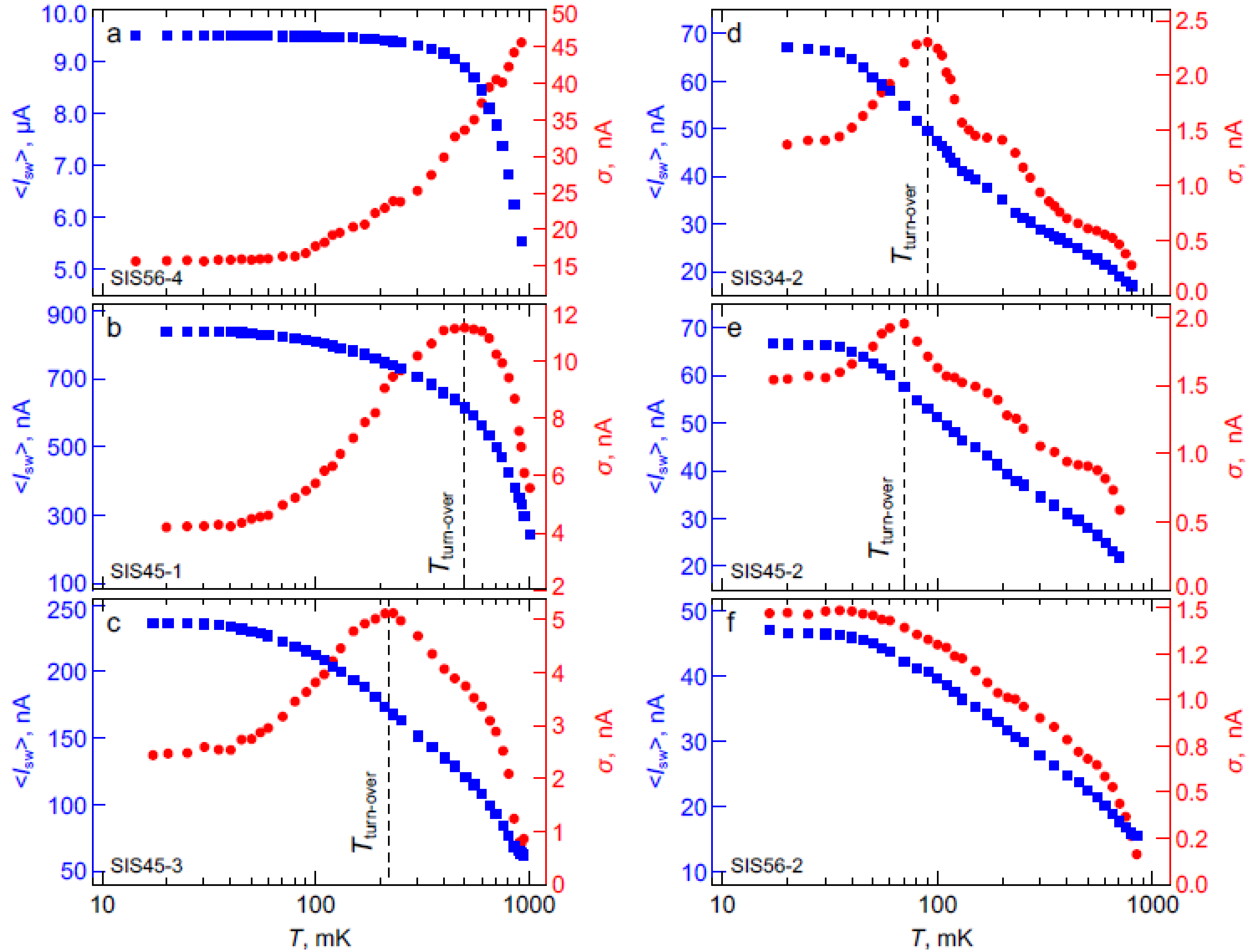
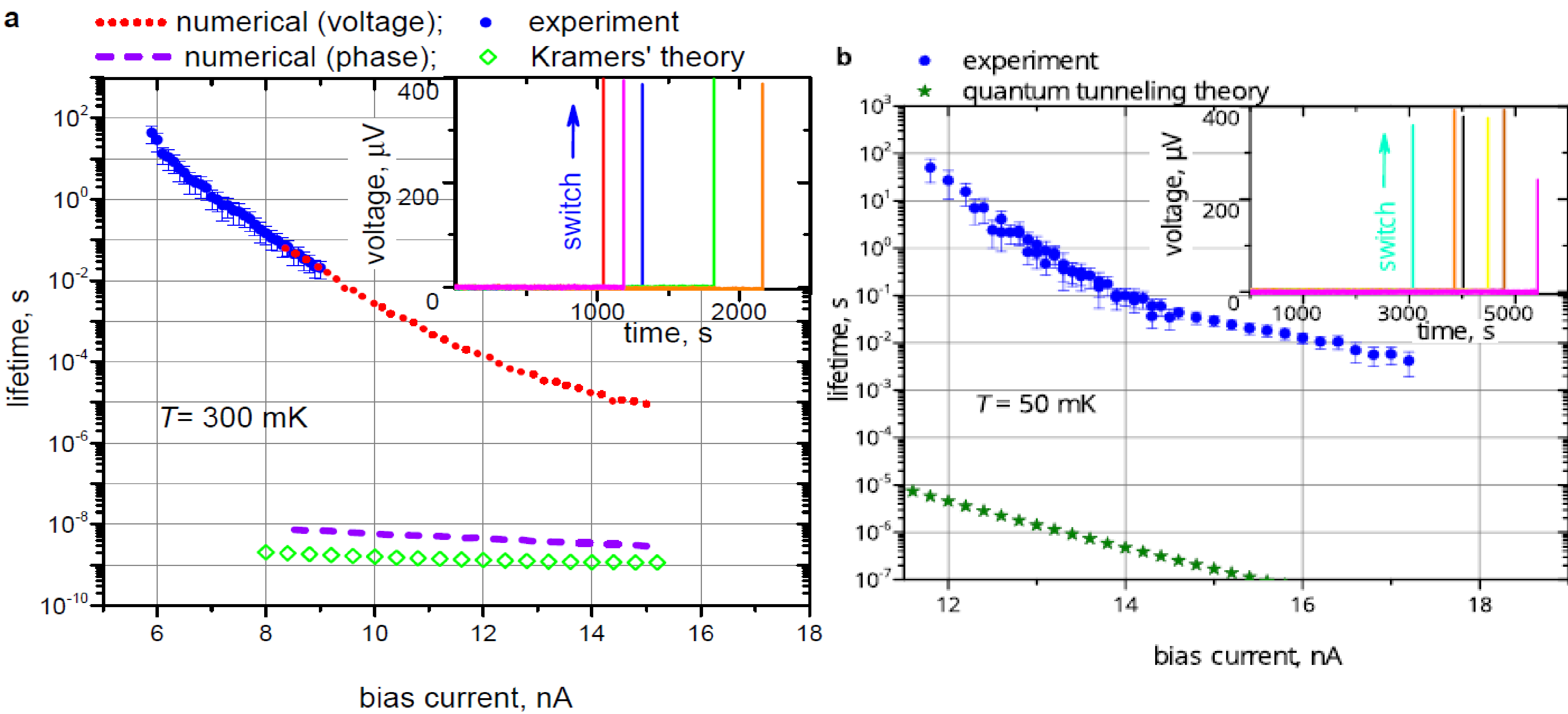


Switching current distributions

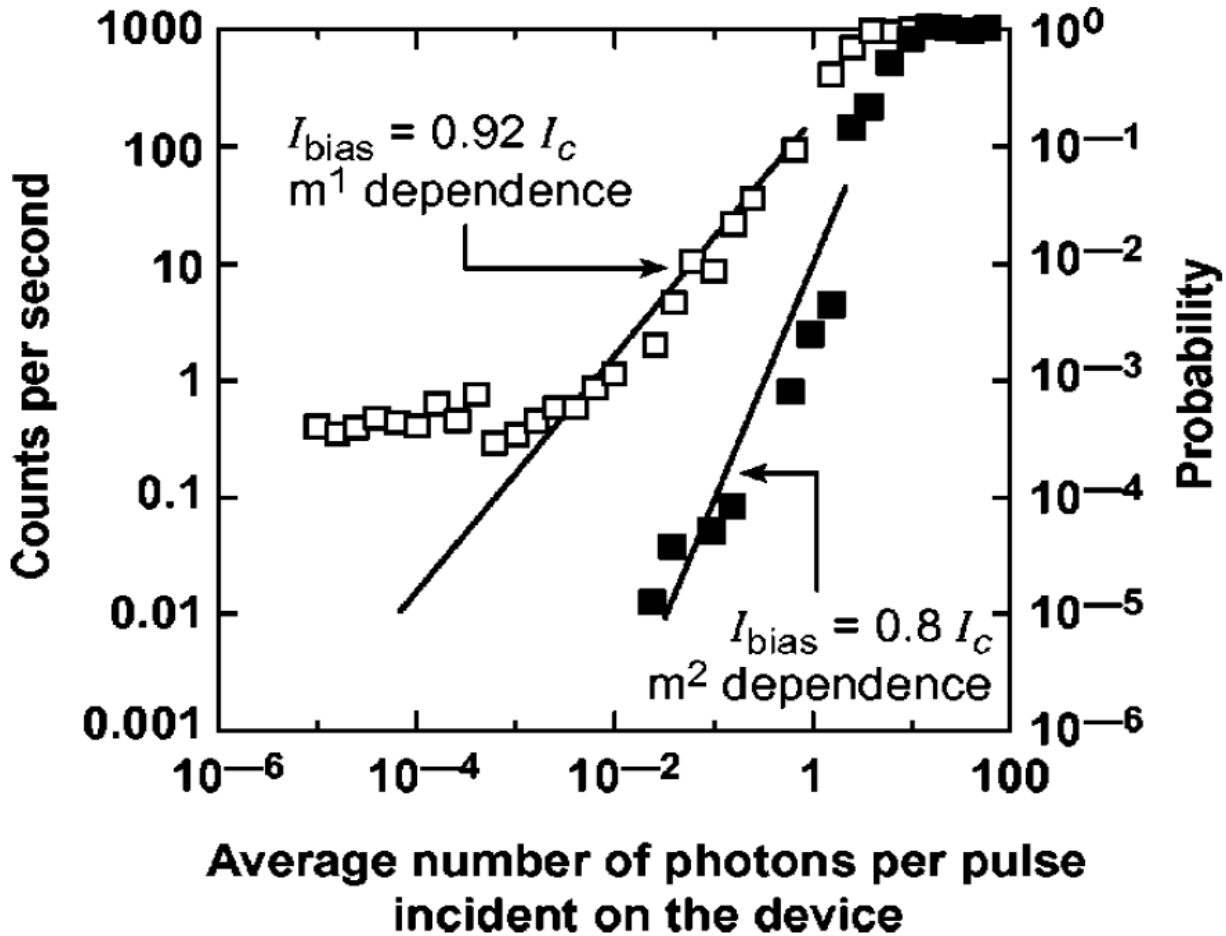


Lifetime of a small SIS junction



A. L. Pankratov, L. S. Revin, A. V. Gordeeva, A. A. Yablokov, L. S. Kuzmin & E. Il'ichev
Towards a microwave single-photon counter for searching axions,
npj Quantum Information, 8, 61 (2022)
https://www.nature.com/articles/s41534-022-00569-5

Counting of IR photons by statistics



Detection of IR photons at 4K

G. N. Gol’tsman, O. Okunev, G. Chulkova, A. Lipatov, A. Semenov, K. Smirnov, B. Voronov, and A. Dzardanov, Appl. Phys. Lett., **79**, 705 (2001).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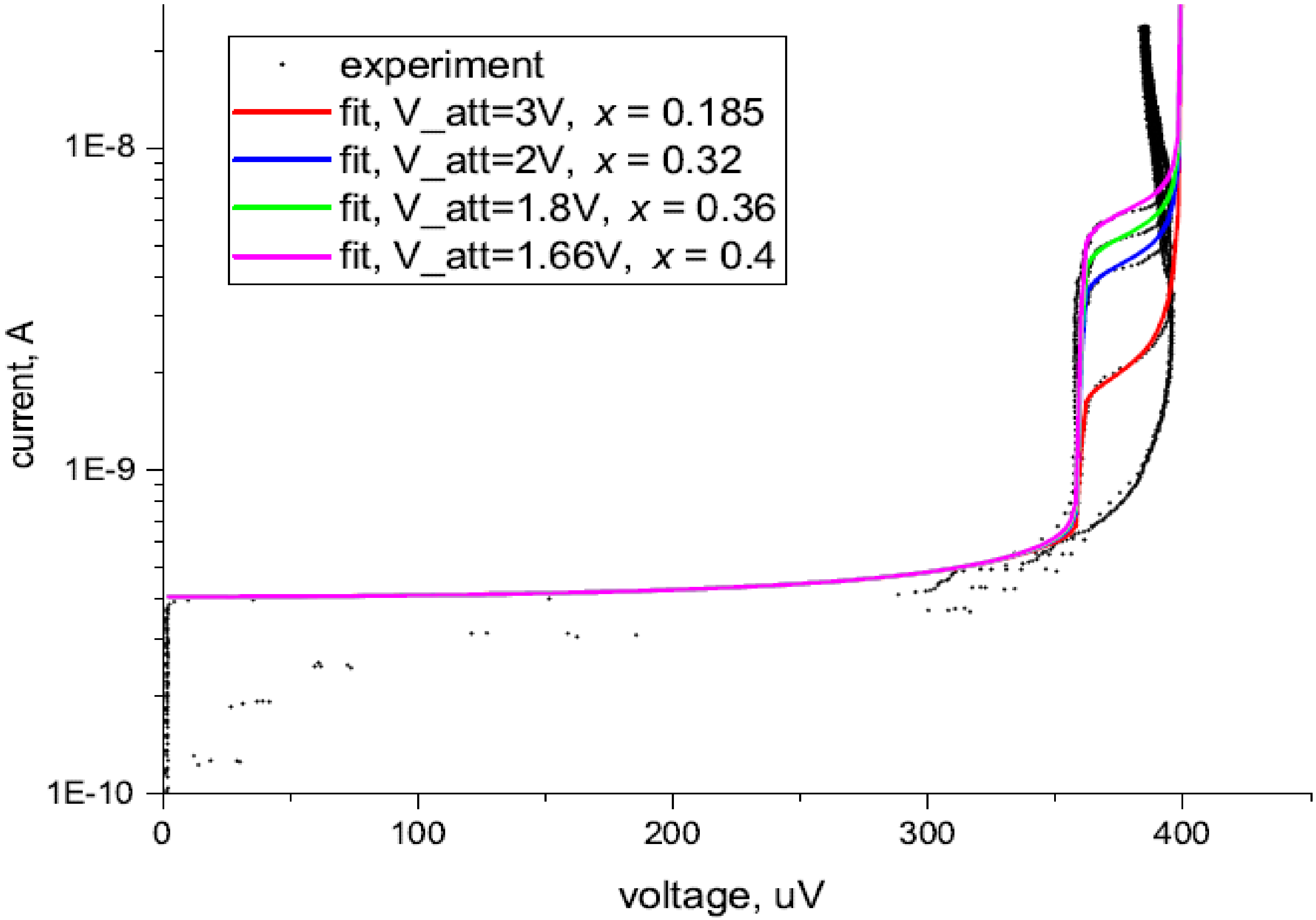
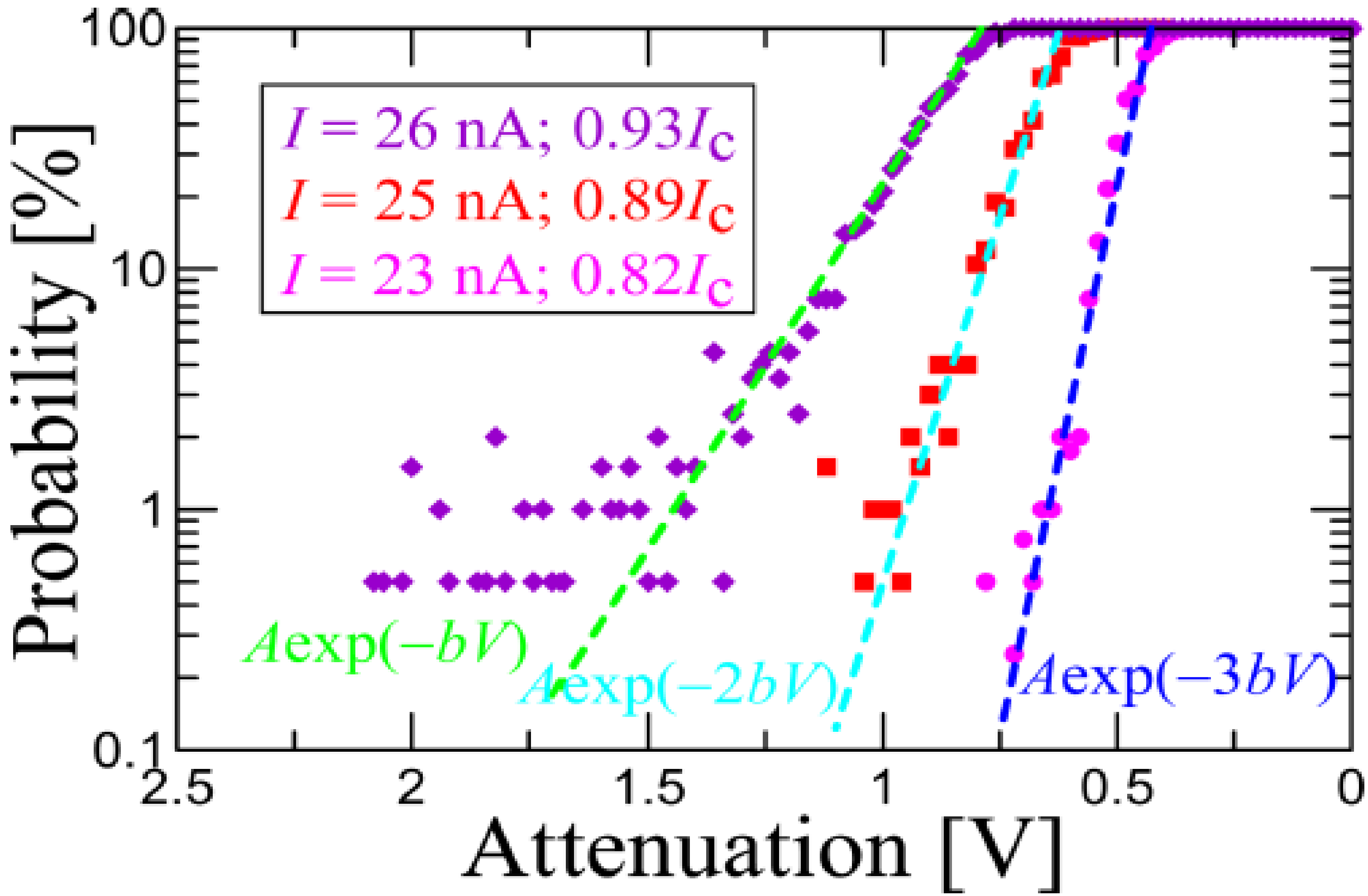
Signal power calibration by PAT steps



John R. Tucker and Marc J. Feldman, Rev. Mod. Phys. 57, 1055 (1985).

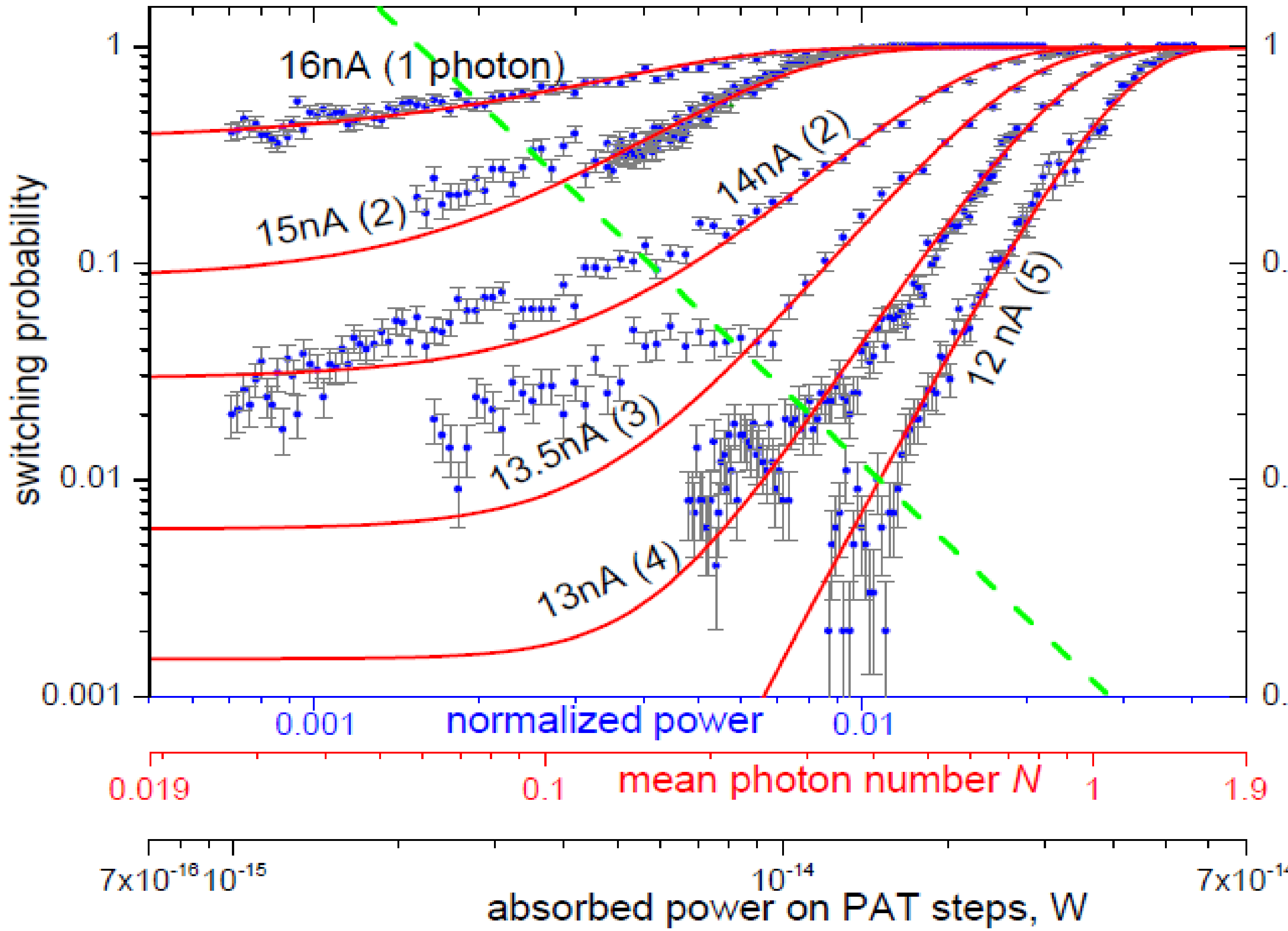
N-photon response for 9 GHz signal at 50 mK

Supply of a significantly attenuated harmonic signal, which decays into a stream of photons with a Poissonian distribution.



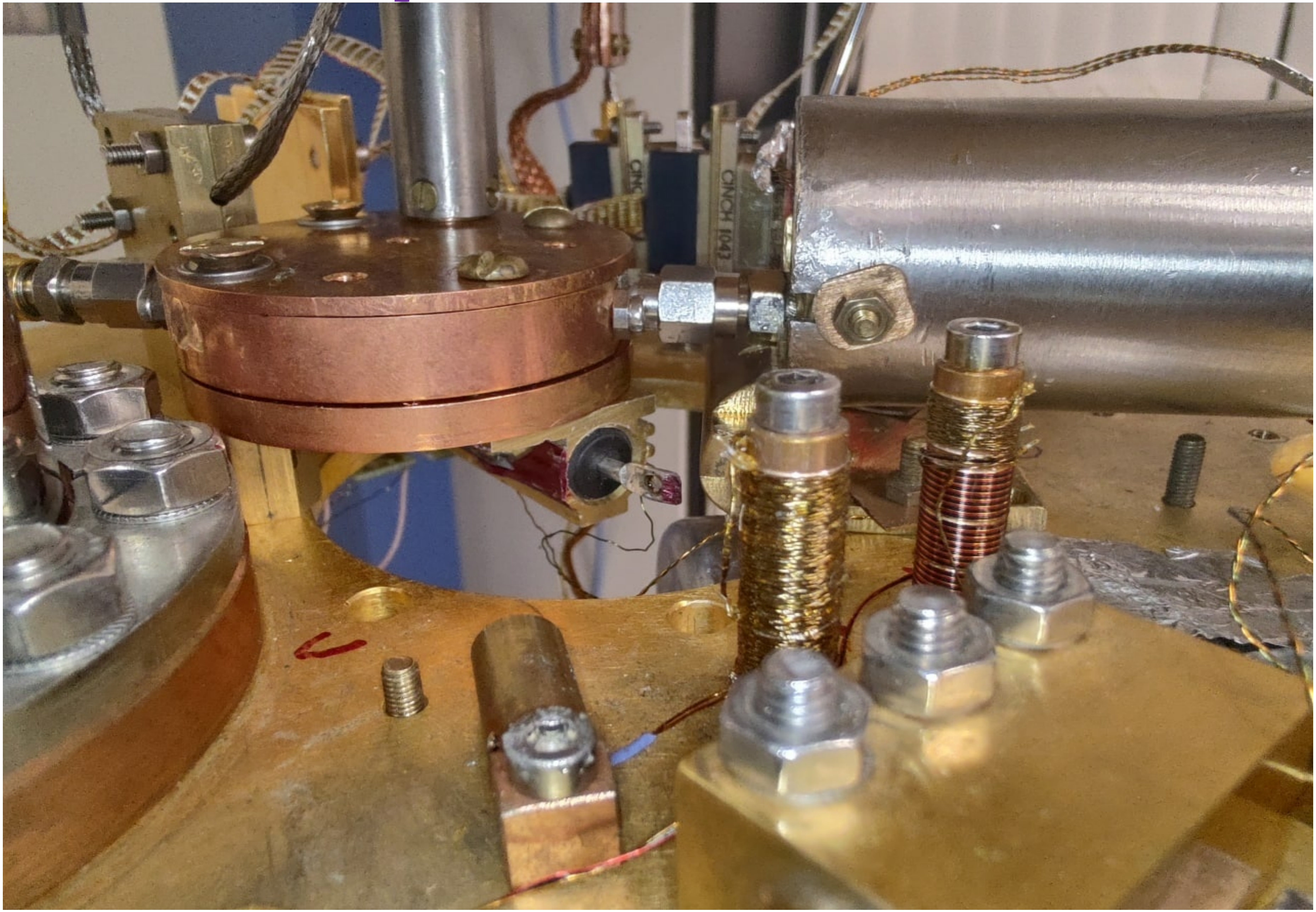
L.S. Revin, A.L. Pankratov, A.V. Gordeeva, A.A. Yablokov, I.V. Rakut, V.O. Zbrozhek, L.S. Kuzmin, Beilstein J. Nanotechnol. **11,** 960 (2020).

N-photon response for 10 GHz signal at 50 mK

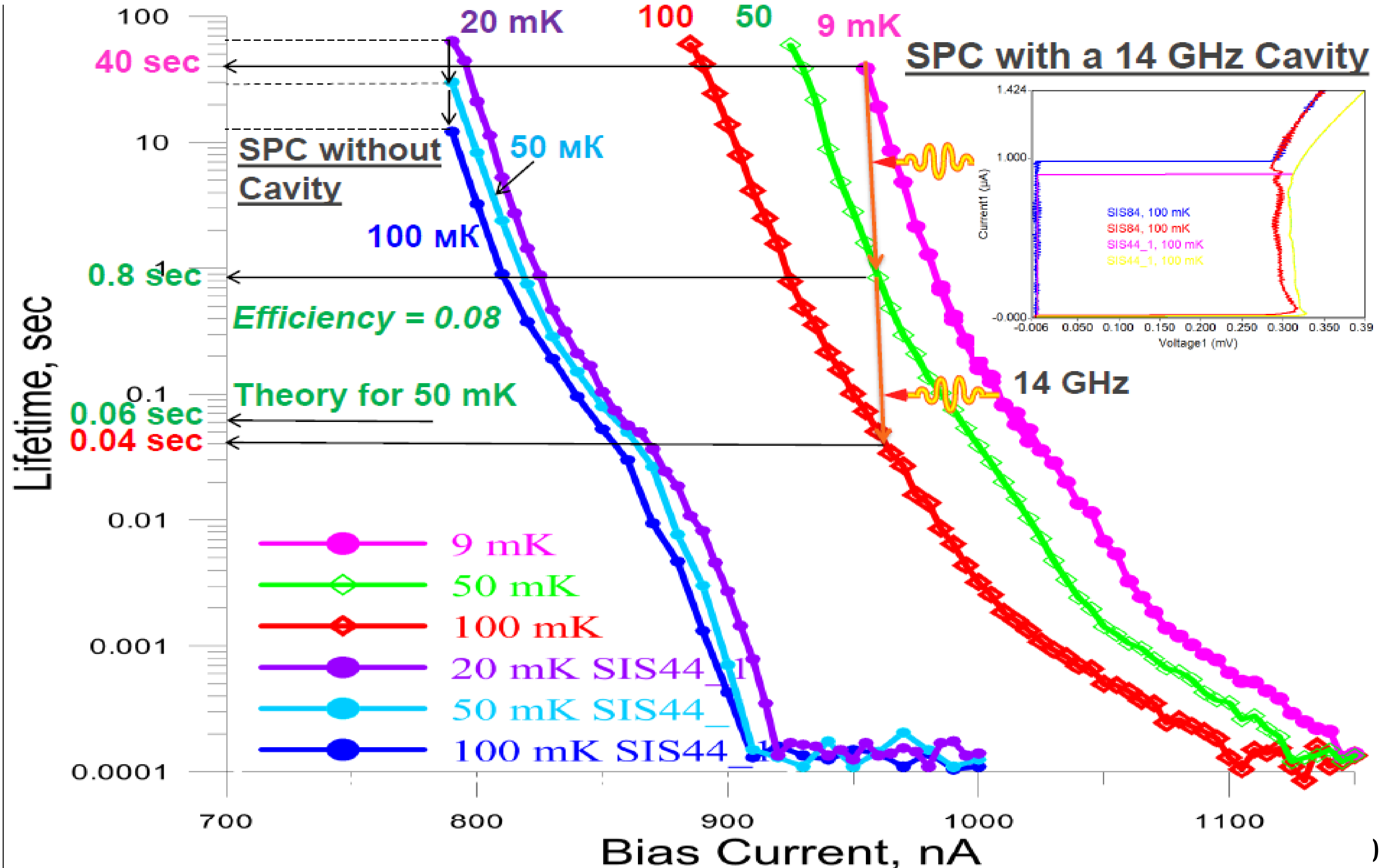


A. L. Pankratov, L. S. Revin, A. V. Gordeeva, A. A. Yablokov, L. S. Kuzmin & E. Il'ichev
Towards a microwave single-photon counter for searching axions, npj Quantum Information, 8, 61 (2022) https://www.nature.com/articles/s41534-022-00569-5

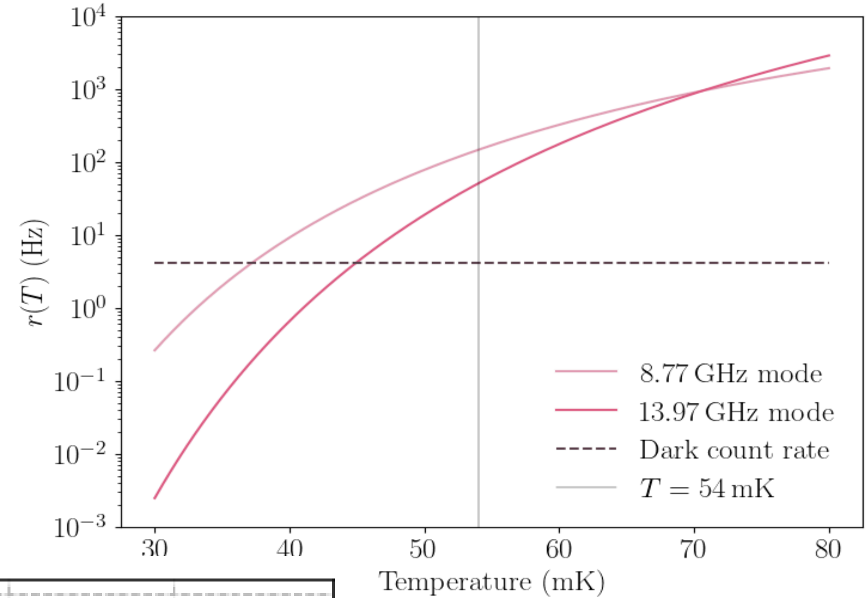
Thermal photons from 14 GHz resonator

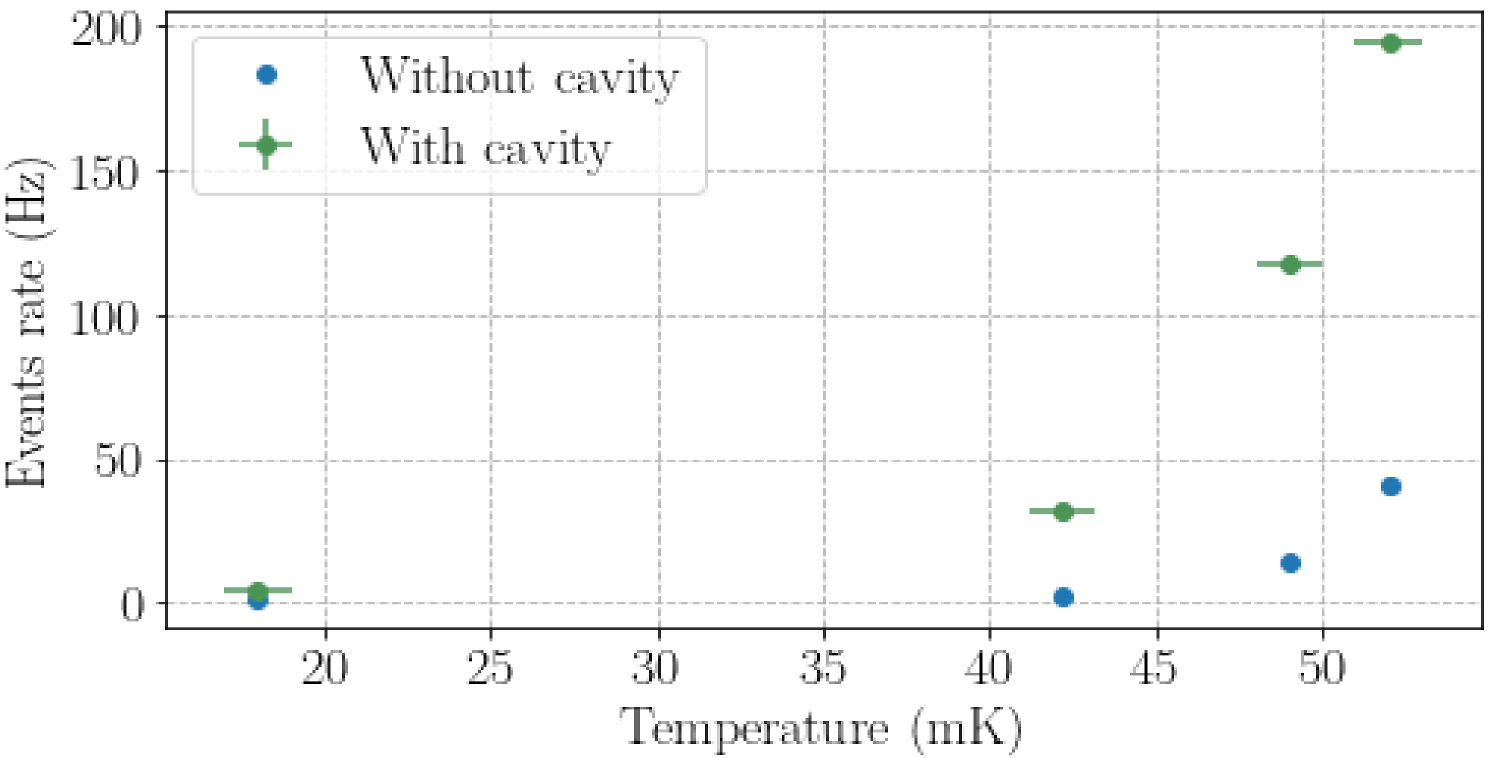


Thermal photons from 14 GHz resonator

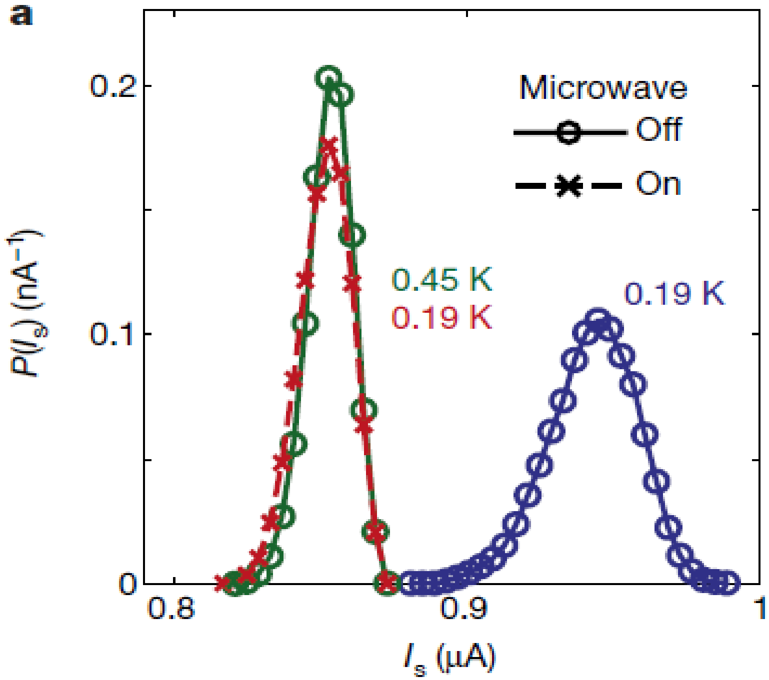


Thermal photons from 14 GHz resonator

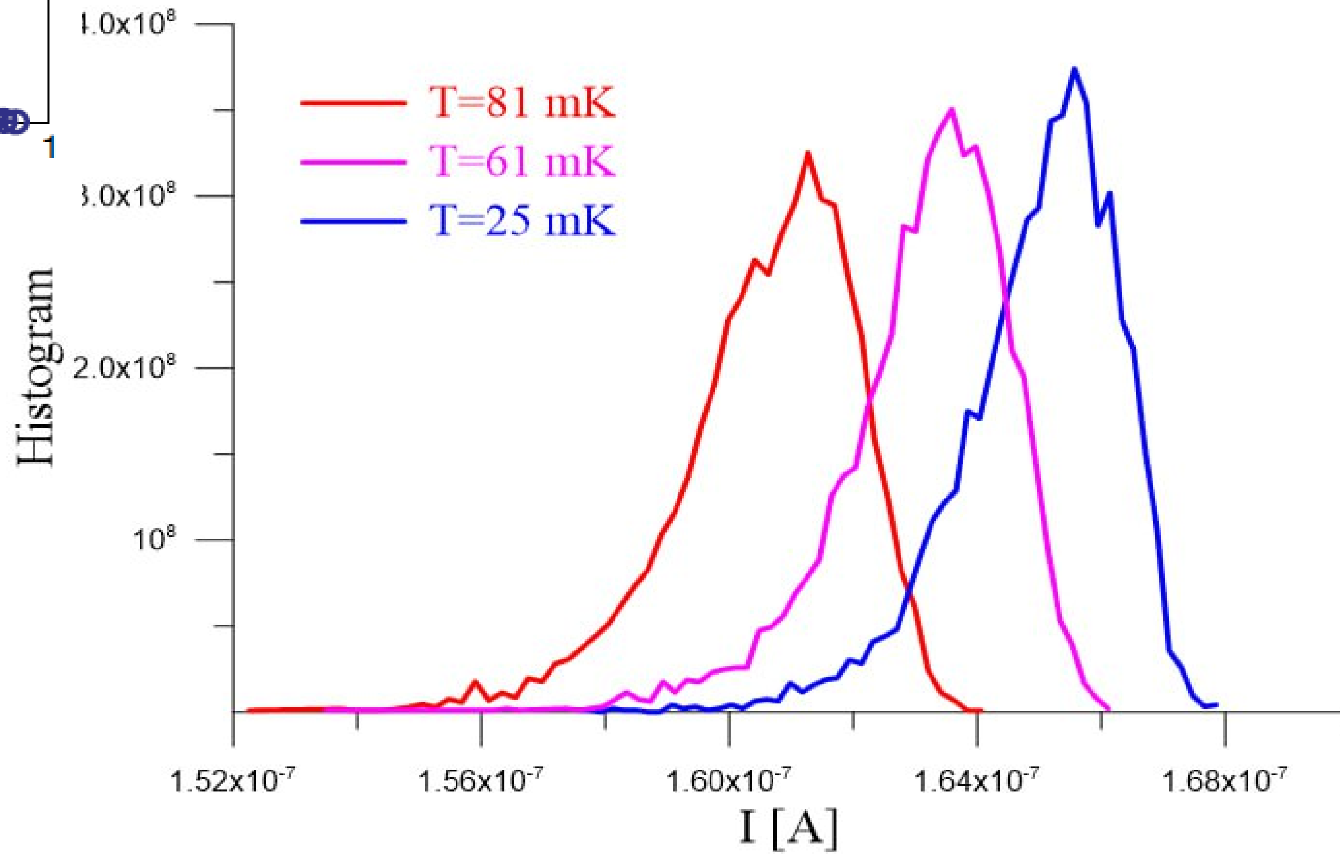




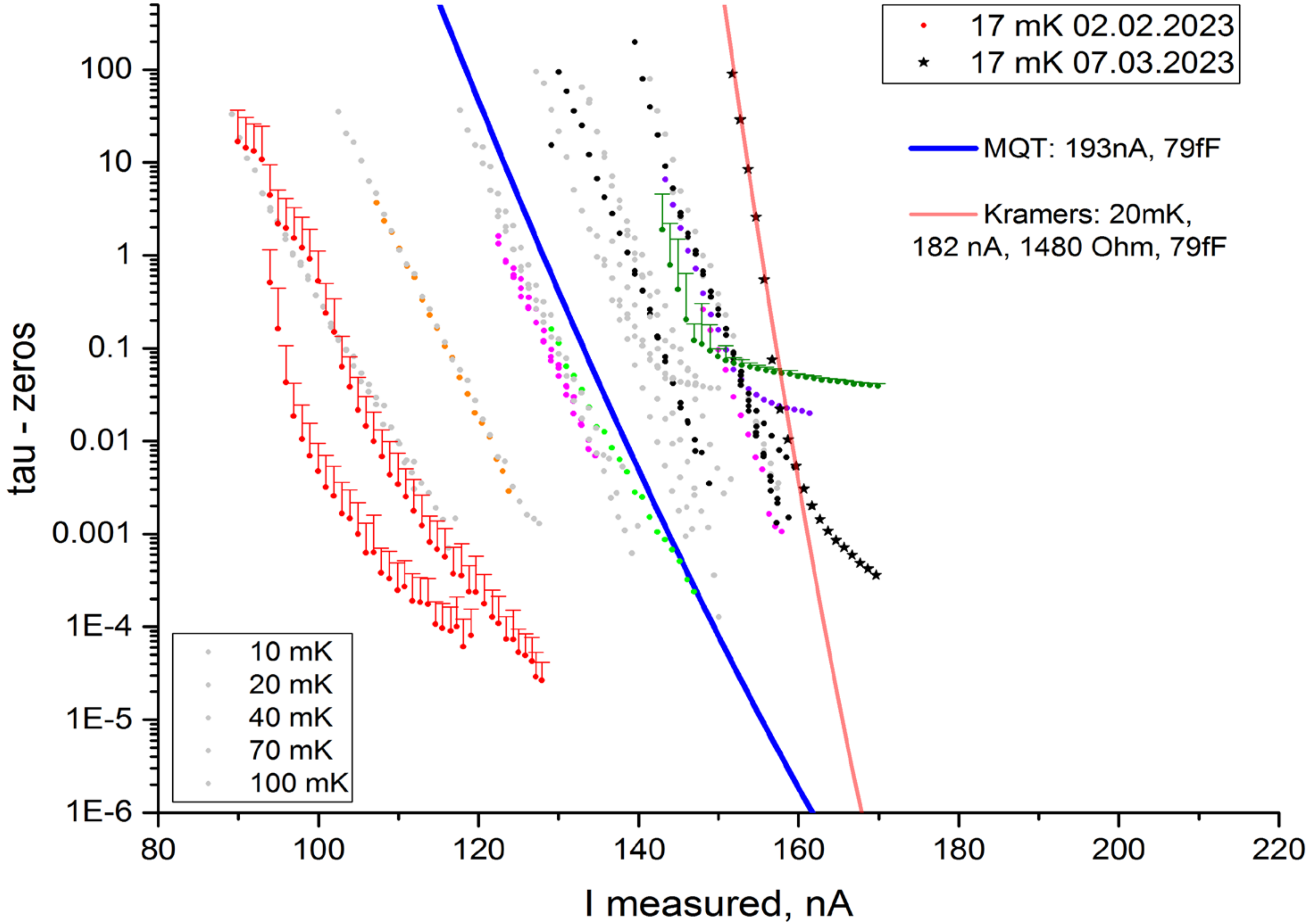
Thermal photons from 14 GHz resonator



Lee, G.-H. et al. Graphene-based Josephson junction microwave bolometer.
Nature **586**, 42–46 (2020).



Improvement of the lifetime – exceeding theoretical limit



Thank you
for attention!