Center for Quantum Technologies of NNSTU

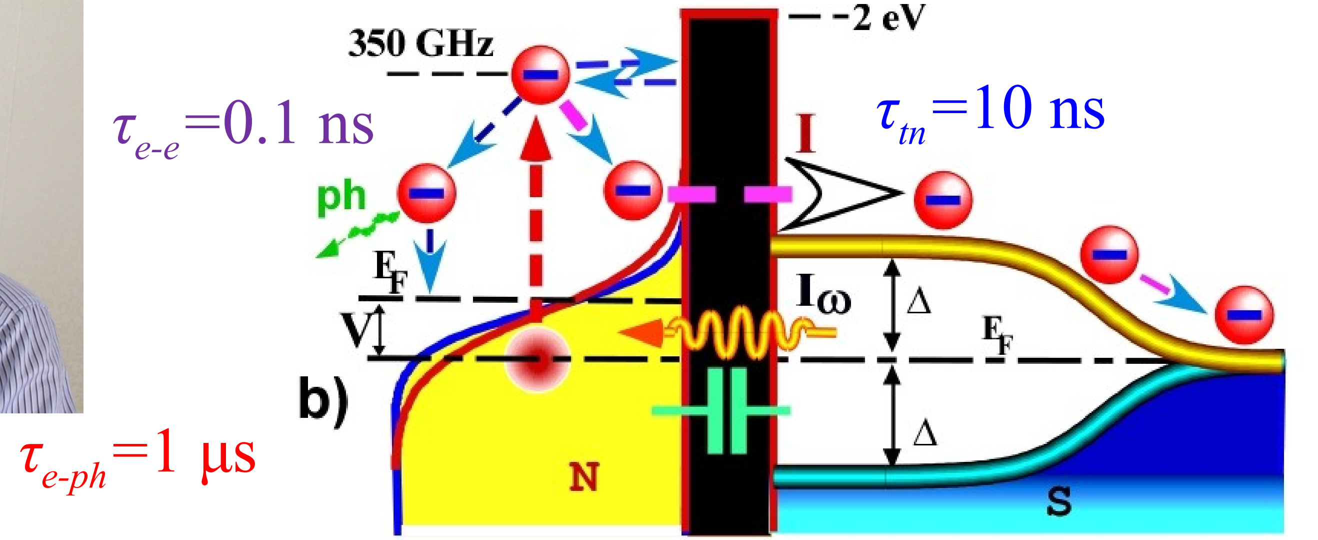
Institute for Physics of Microstructures of RAS

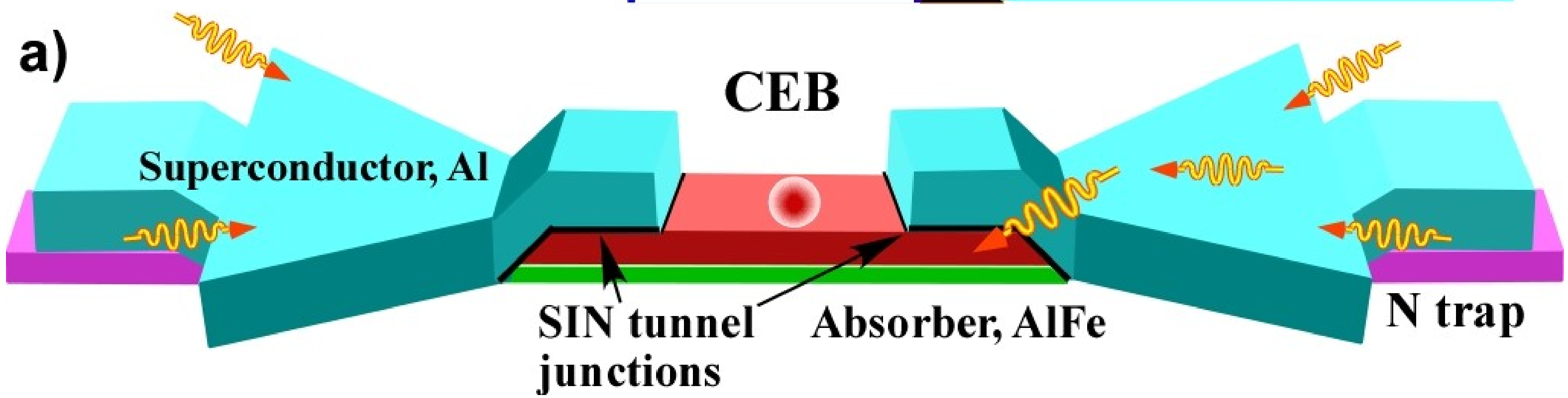
# Studying photon statistics with cold-electron bolometers and Josephson junctions

A.L. Pankratov, L.S. Revin, D.A. Pimanov,
A.V. Gordeeva, A.V. Chiginev, A.V. Blagodatkin

Moscow,
2025

# Cold-Electron Bolometers for Radio Astronomy




*Tunnel SIN junctions perform 4 functions:*

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

**4) electron cooling (instead of artificial heating for TES).**

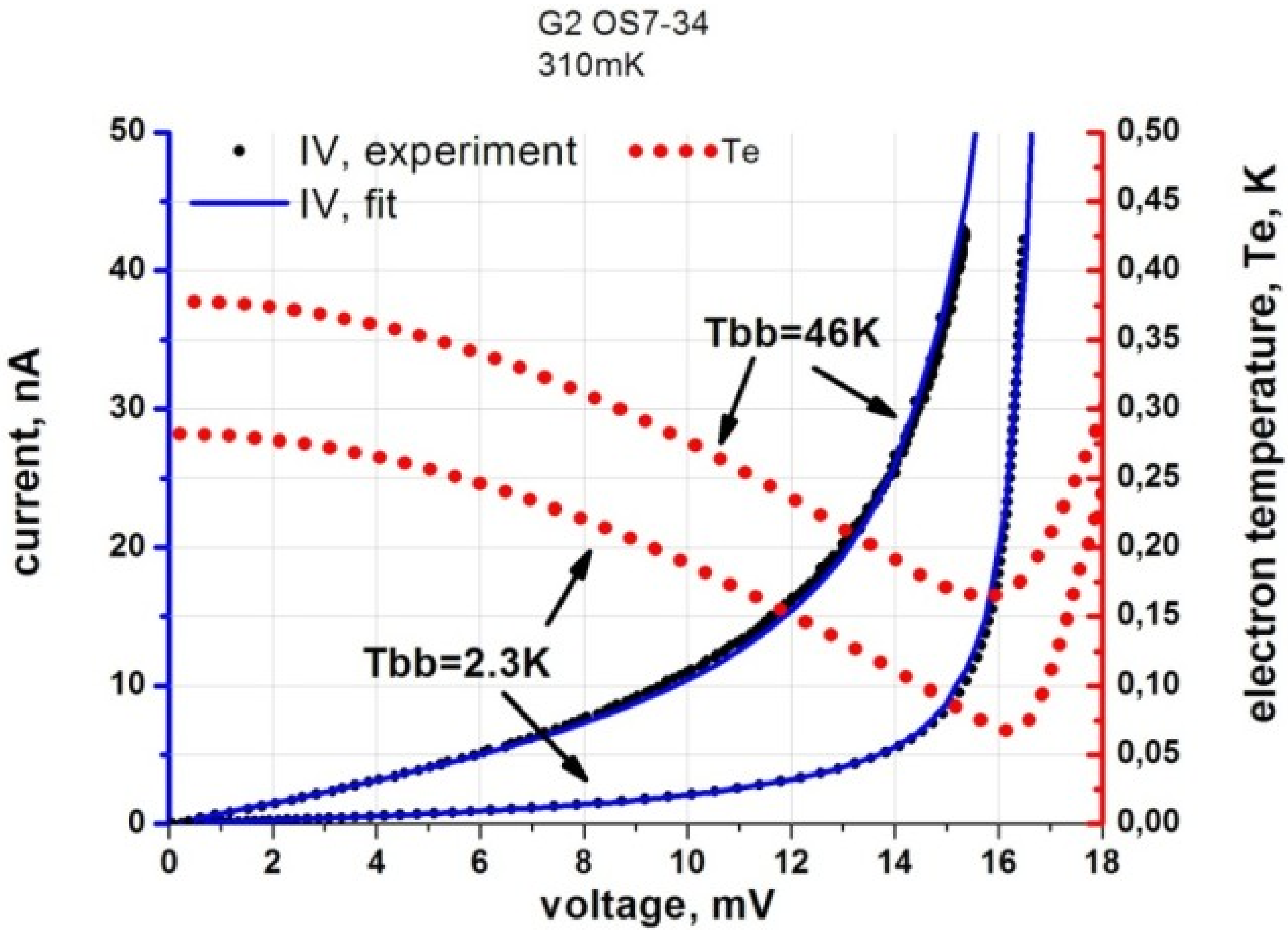
*Advantages*: **background limited; record cosmic rays immunity.**

# Quantum electronics for fundamental physics

**S. Withington**

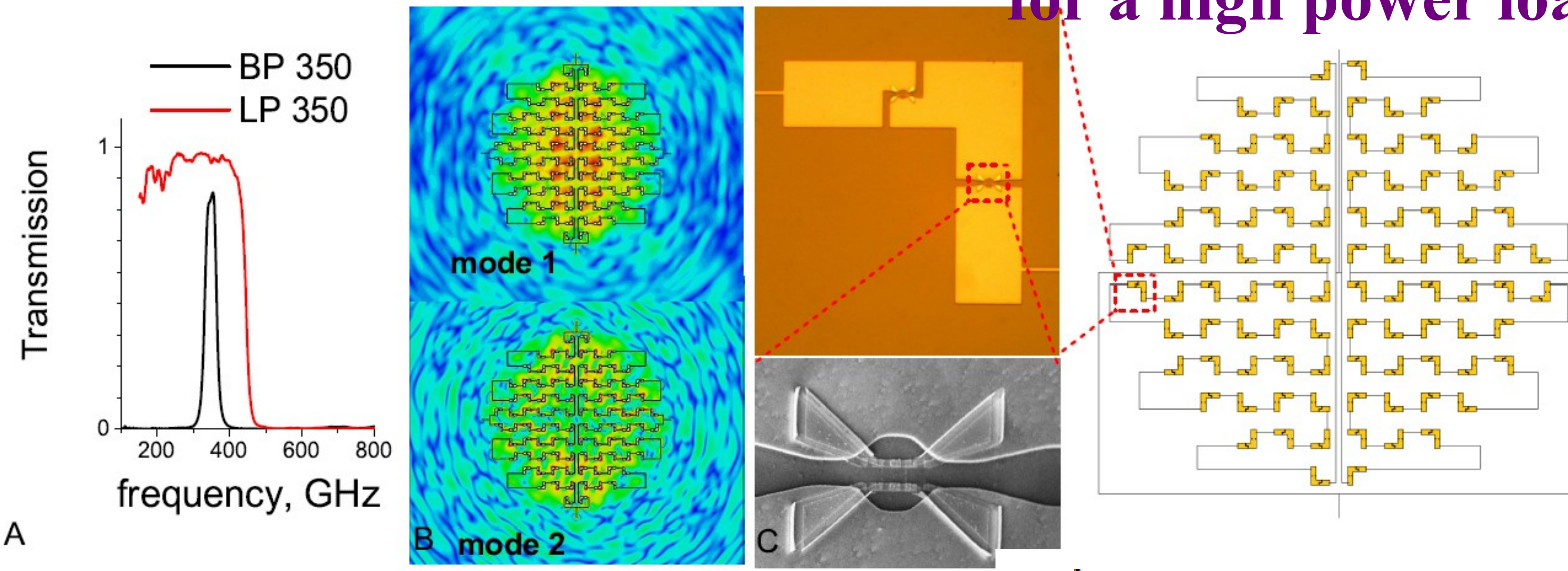
**To cite this article:** S. Withington (2022) Quantum electronics for fundamental physics, Contemporary Physics, 63:2, 116-137, DOI: 10.1080/00107514.2023.2180179

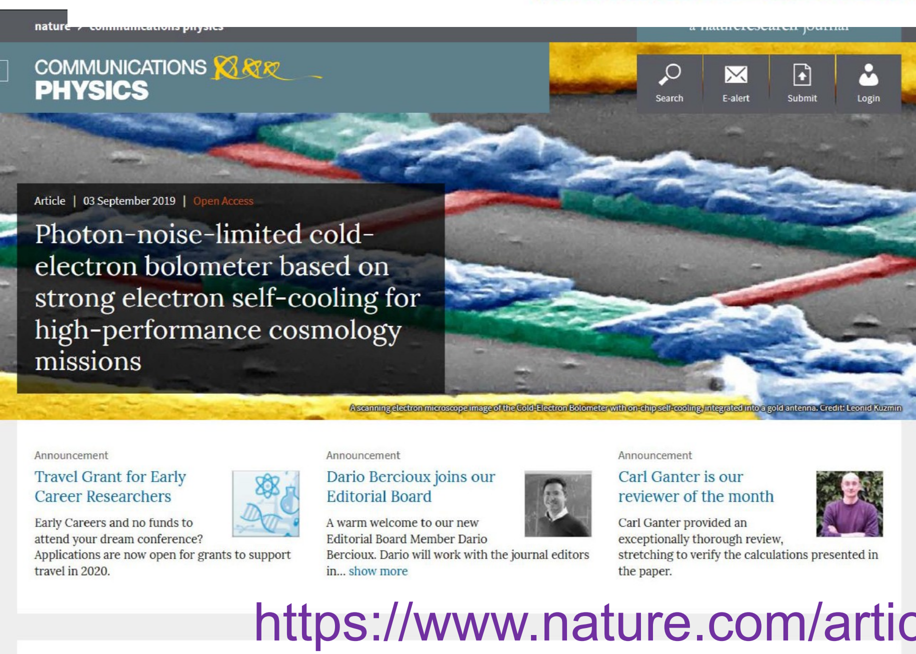
The above list of devices is certainly not exhaustive. TESs operate at $T_c$, which is usually chosen to be twice the bath temperature $T_b$, and although $T_b$ is typically in the range 50–300 mK, the active part of the device is not as cold as it might be, leading to noise. The Cold Electron Bolometer (CEB) is an ingenious device that overcomes this problem [33], enabling NEP's of $10^{-21}$ $\mathrm{WHz}^{-1/2}$ to be achieved. Also, Superconductor




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

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





COMMUNICATIONS PHYSICS

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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

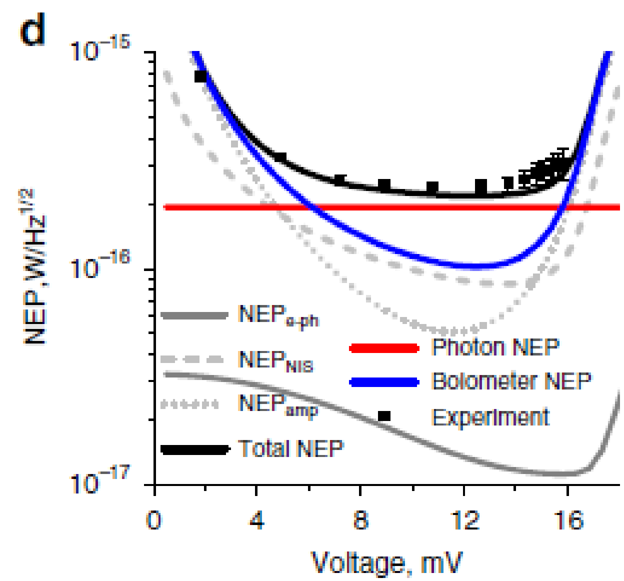
Dario Bercioux joins our Editorial Board

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

# Ultimate sensitivity – background limited operation: photon noise contribution is dominating

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

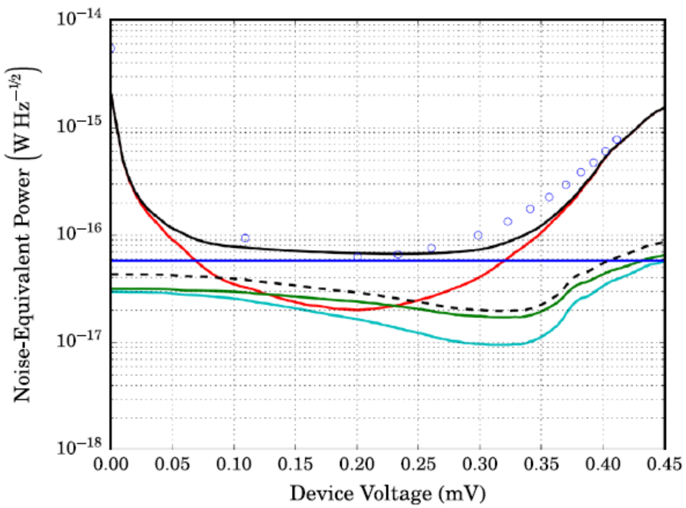
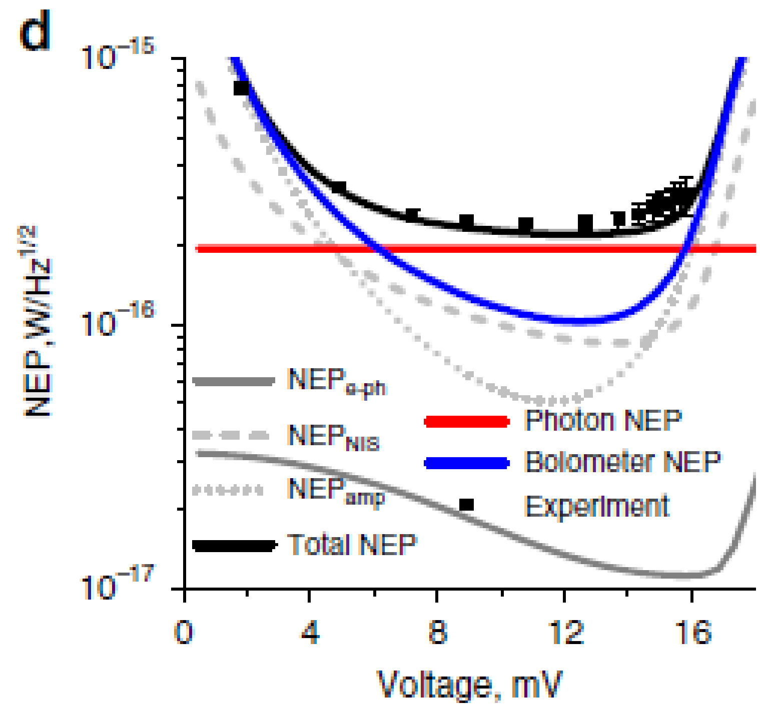



**Fig. 4** Example of measured and modelled noise for the strained detector observing a 77-K source. Noise modelled using Eqs. 5 and 6. *Lines* modelled data, *red*—amplifier noise, *green*—tunnelling noise, *cyan*—e-ph noise, *blue*—photon noise, *dashed black*—total device noise (sum of tunnelling 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)

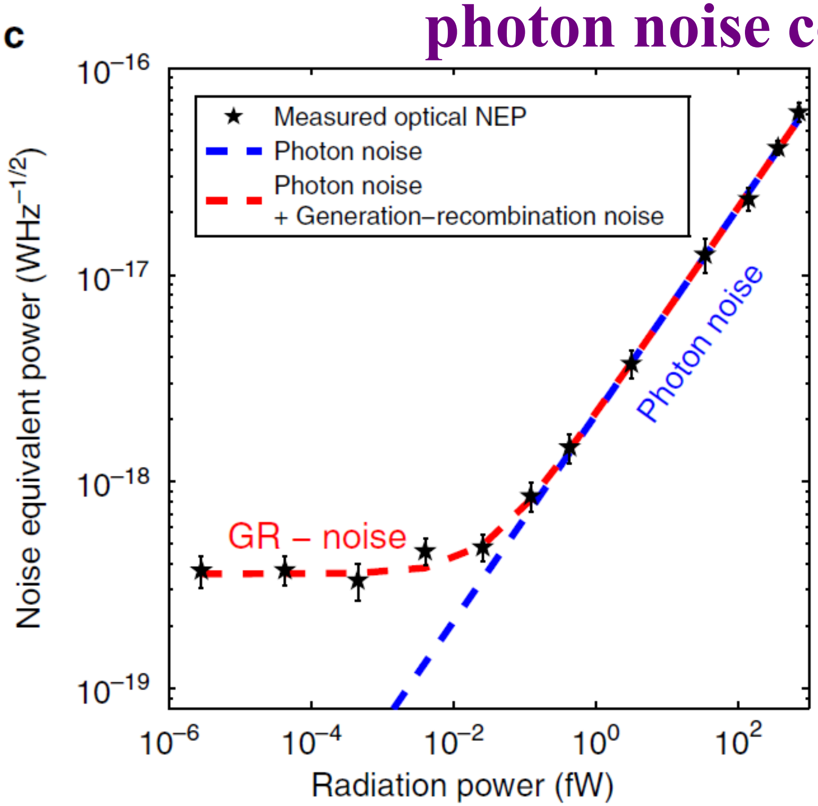


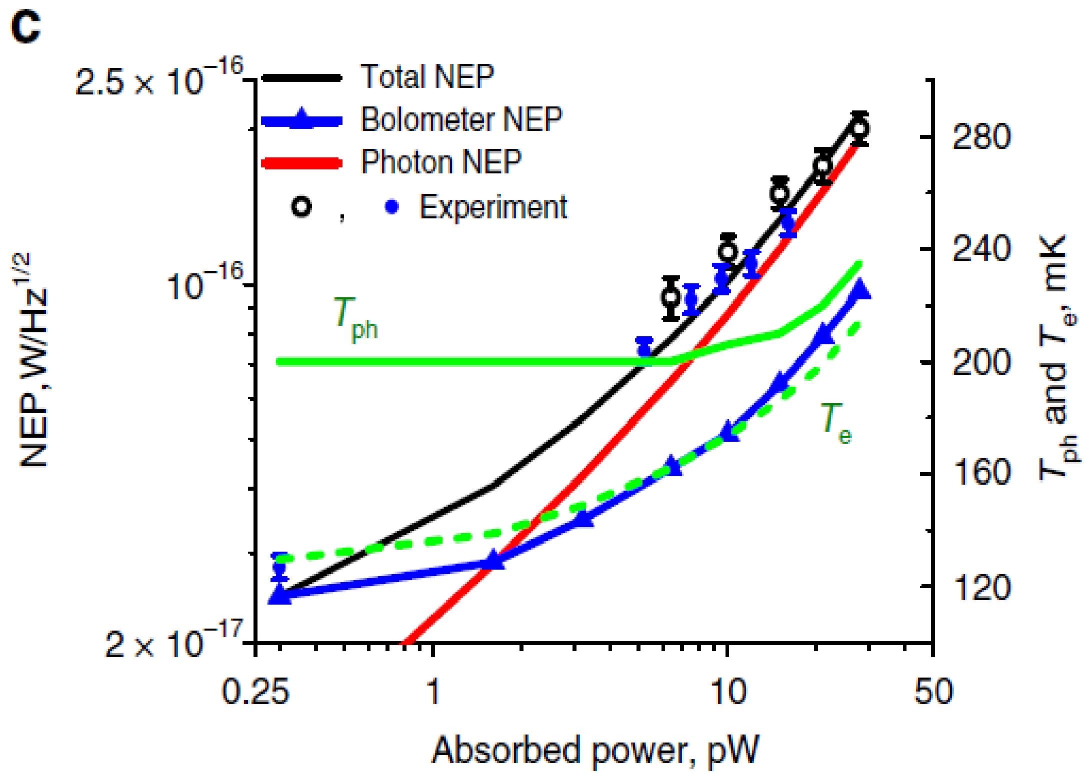

L.S. Kuzmin, A.L. Pankratov, A.V. Gordeeva, V.O. Zbrozhek, V.A. Shamporov, L.S. Revin, A.V. Blagodatkin, S. Masi, P. de Bernardis, Communications Physics, 2, 104 (2019).

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

- with $f$=350 GHz, $\delta f$=33 GHz, $P_0$ – accepted power of a signal.

# Ultimate sensitivity – background limited operation: photon noise contribution is dominating




P.J. de Visser, J.J.A Baselmans, J. Bueno, N. Llombart & T.M. Klapwijk,
DOI: 10.1038/ncomms4130

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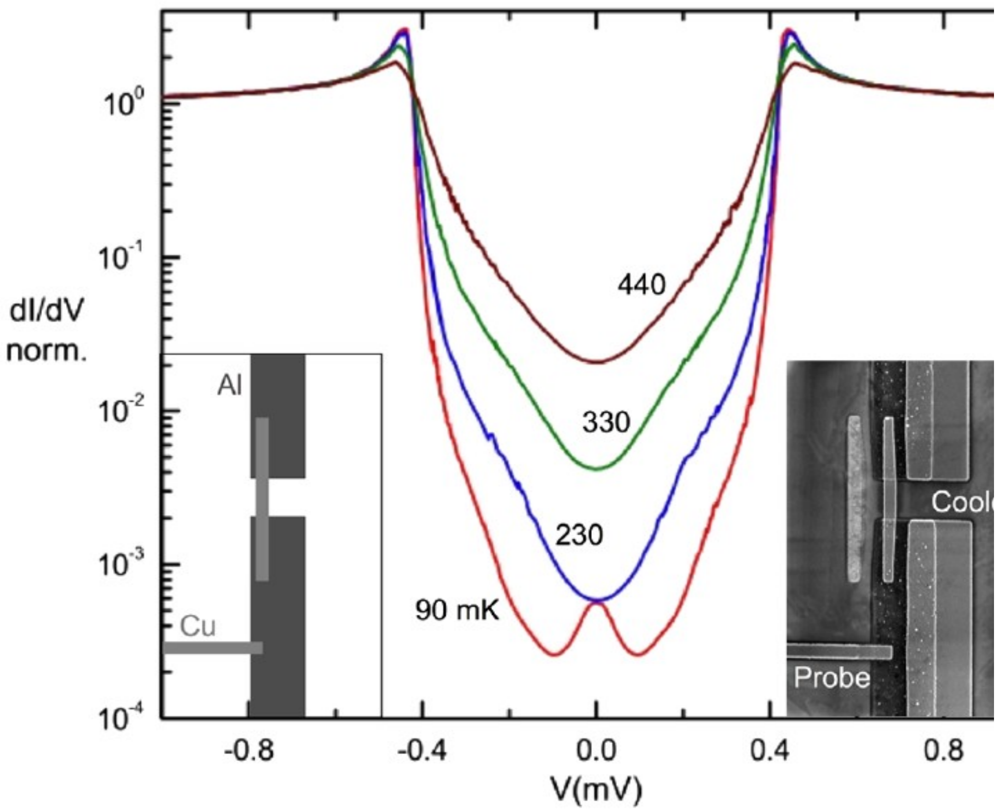
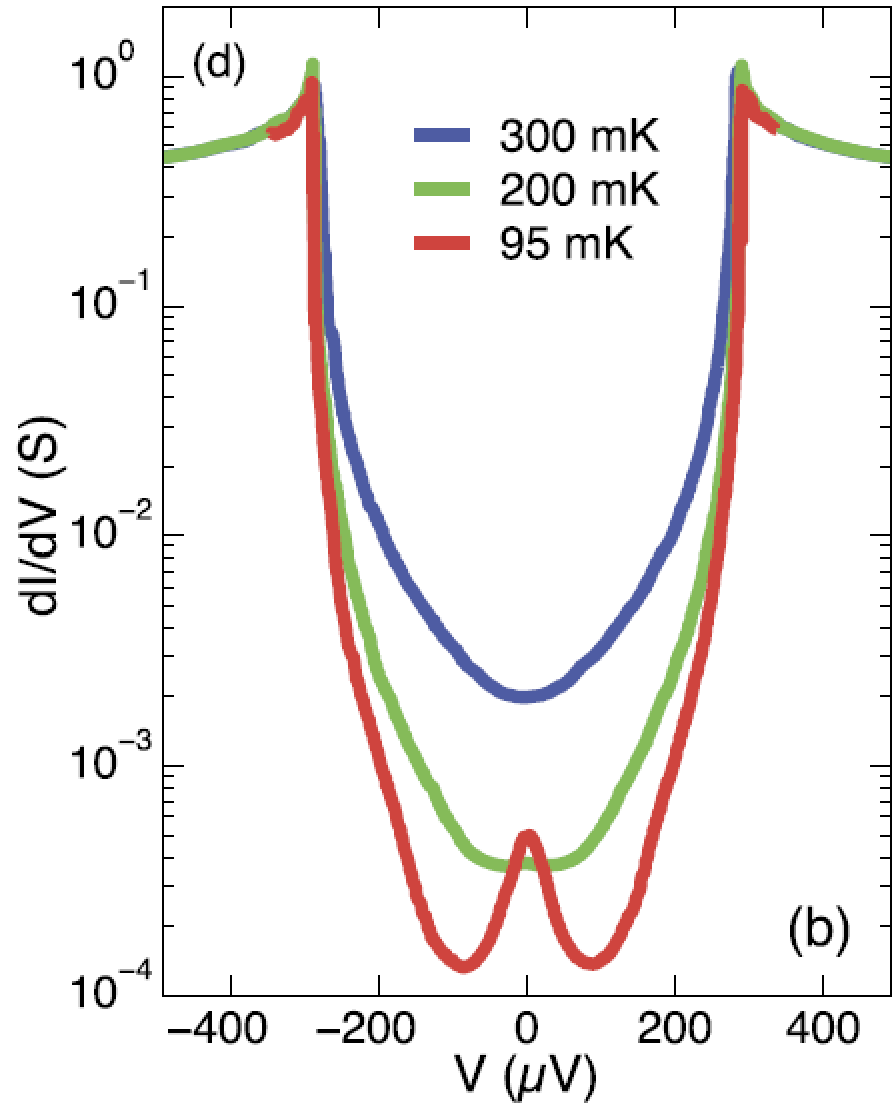
- with $f$=350 GHz, $\delta f$=33 GHz, $P_0$ – accepted power of a signal.

# Effect of Andreev current (overheating)

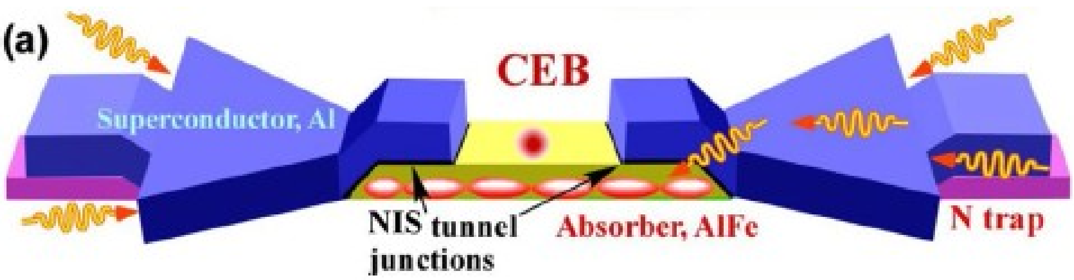
B. J. van Wees, P. de Vries, P. Magnee, T. M. Klapwijk, Phys. Rev. Lett., 69, 510 (1992).

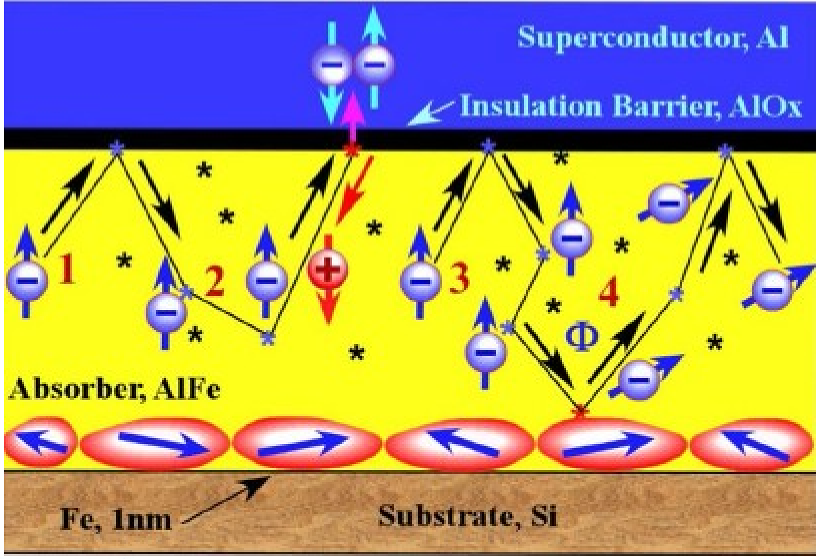
H. Courtois, H. Q. Nguyen, C. B. Winkelmann, J. P. Pekola, Comp. Ren. Phys. 17, 1139 (2016).

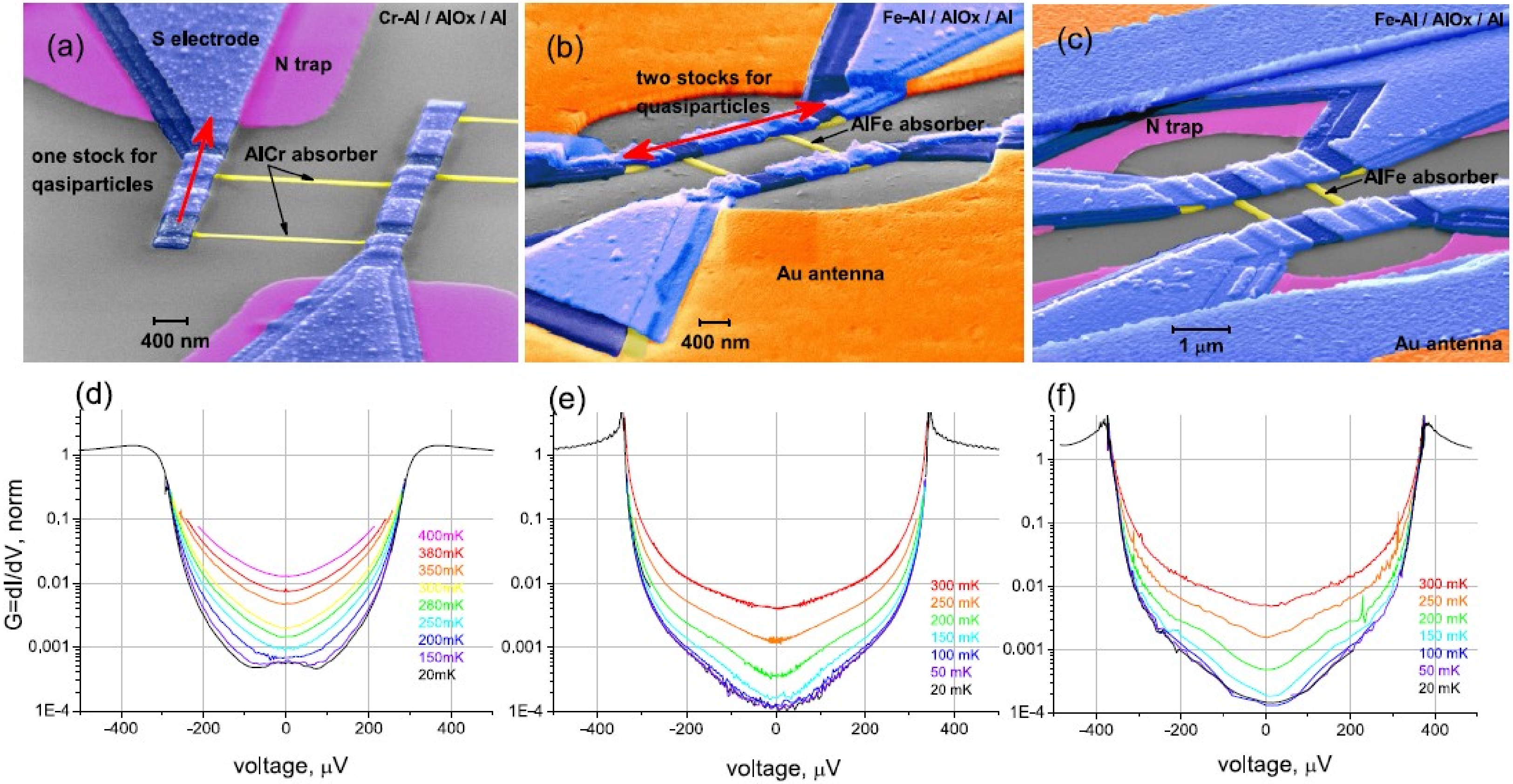


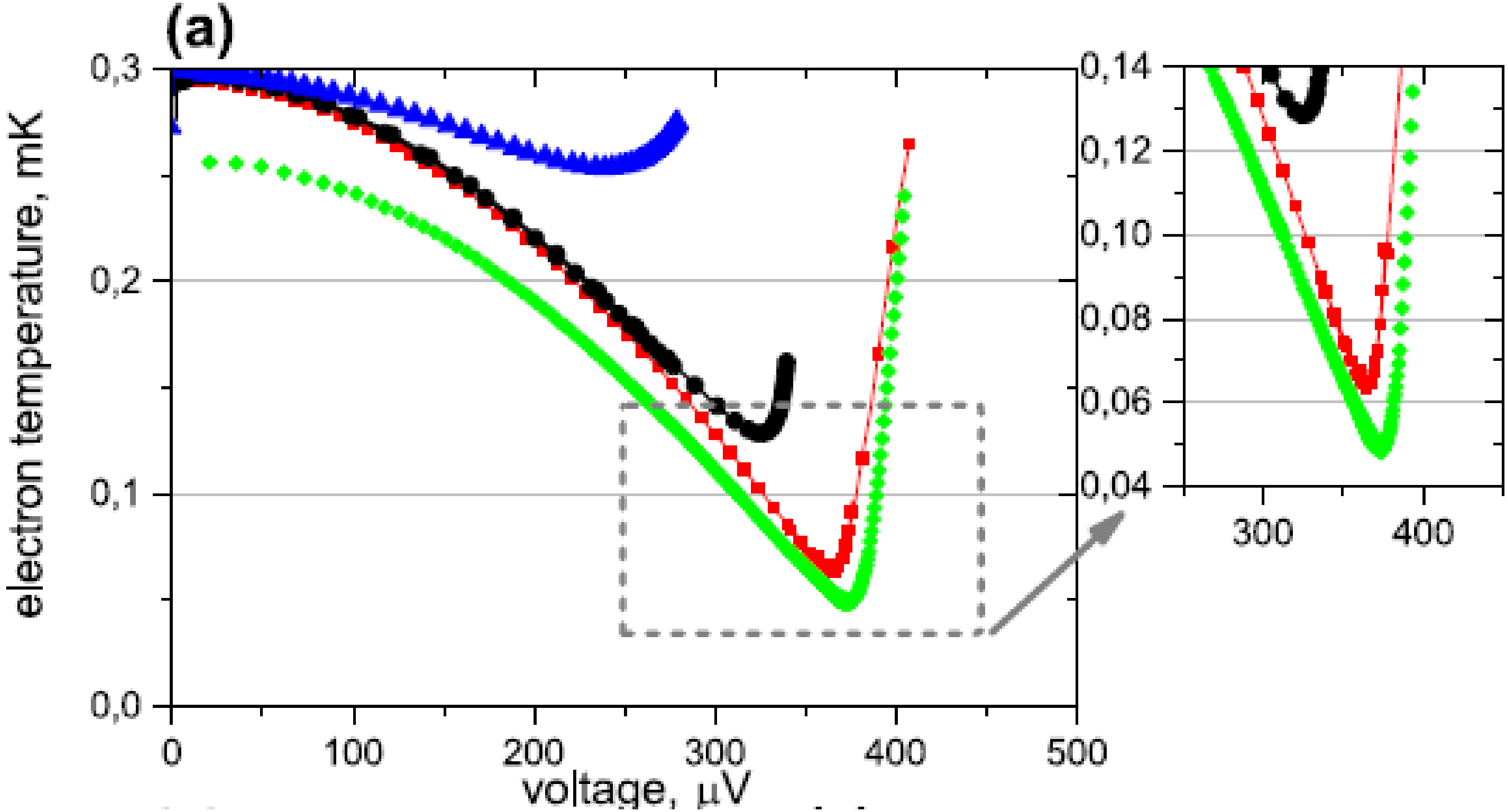
# Suppression of Andreev current



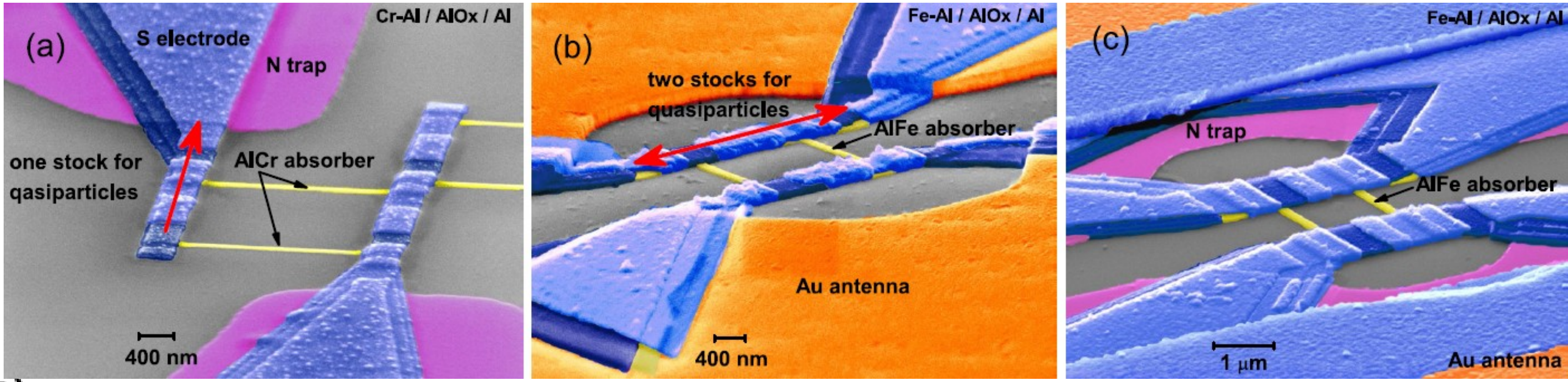
# Design 1 - Design 2 - Design 3

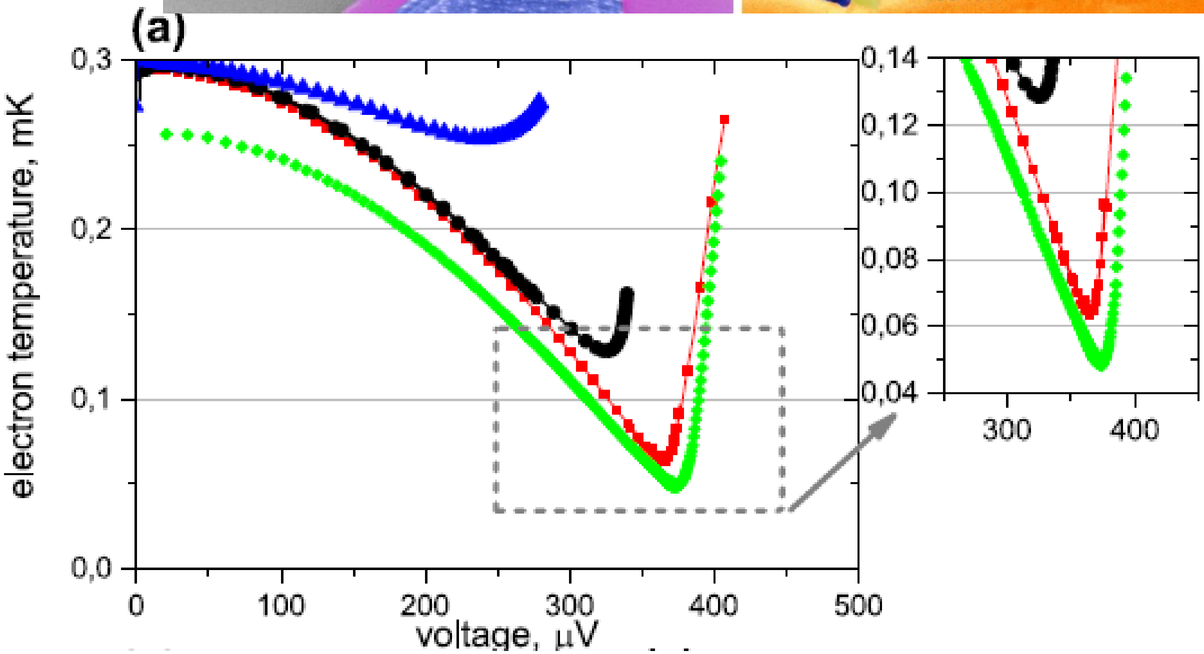



**Record electron cooling from 300 to 65 mK!**
**And from 256 to 48 mK, by a factor of 5.3!**

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

# Record electron cooling to improve sensitivity

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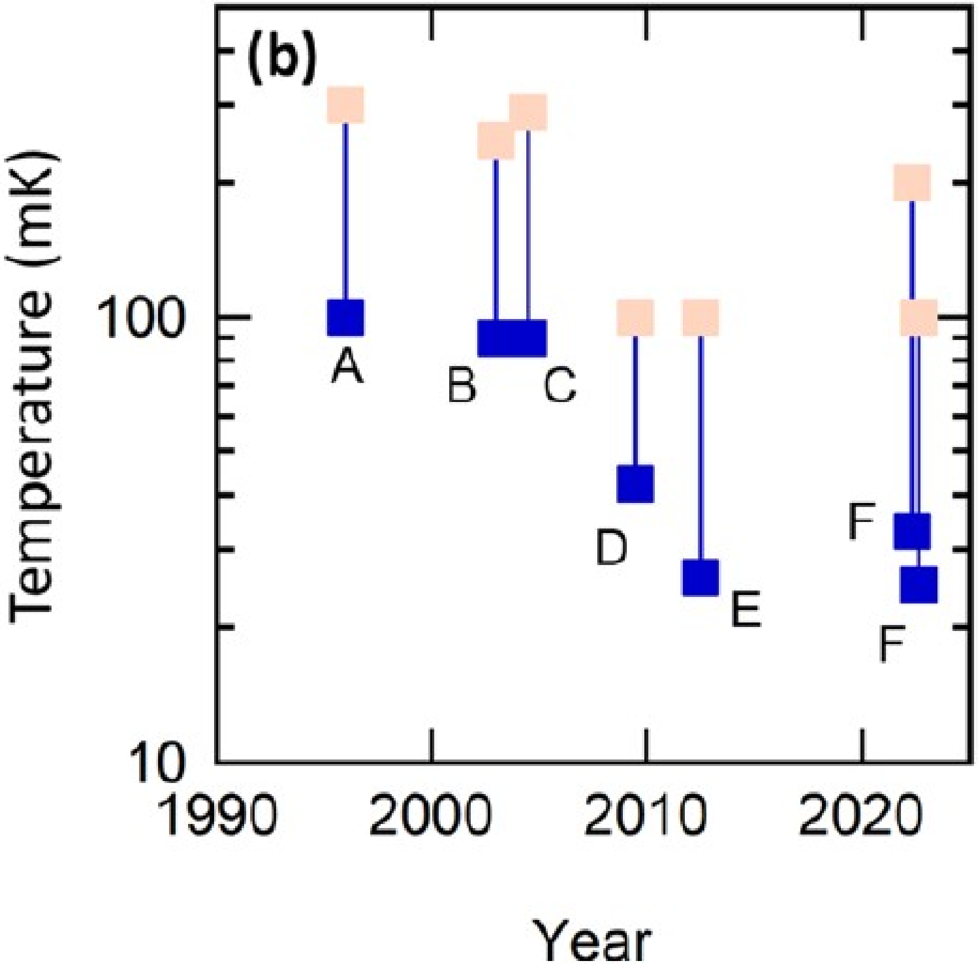



S. A. Lemziakov, B. Karimi, S. Nakamura, D. S. Lvov, R. Upadhyay, C. D. Satrya, Z.-Y. Chen, D. Subero, Y.-C. Chang, L. B. Wang, J. P. Pekola, Journal of Low Temperature Physics 217, 54–81 (2024).

Fig. 4 Advances in the cooling power (a) and the lowest temperature (b) in the electron cooling with NIS junctions. …
F — Pimanov et al. [42]

[42] D.A. Pimanov, V.A. Frost, A.V. Blagodatkin, A.V. Gordeeva, A.L. Pankratov, L.S. Kuzmin, Beilstein J. Nanotechnol. **13,** 896–901 (2022).

**Record electron cooling by a factor of 6, from 200 to 33 mK!**

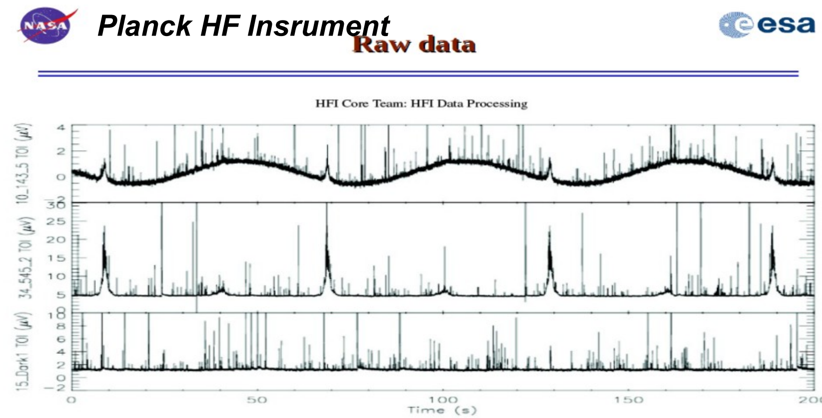
# Cosmic rays – dramatic problem!

M. Salatino, P. de Bernardis, L. Kuzmin, S. Mahashabde, S. Masi, J. of Low Temperature Physics (2014).

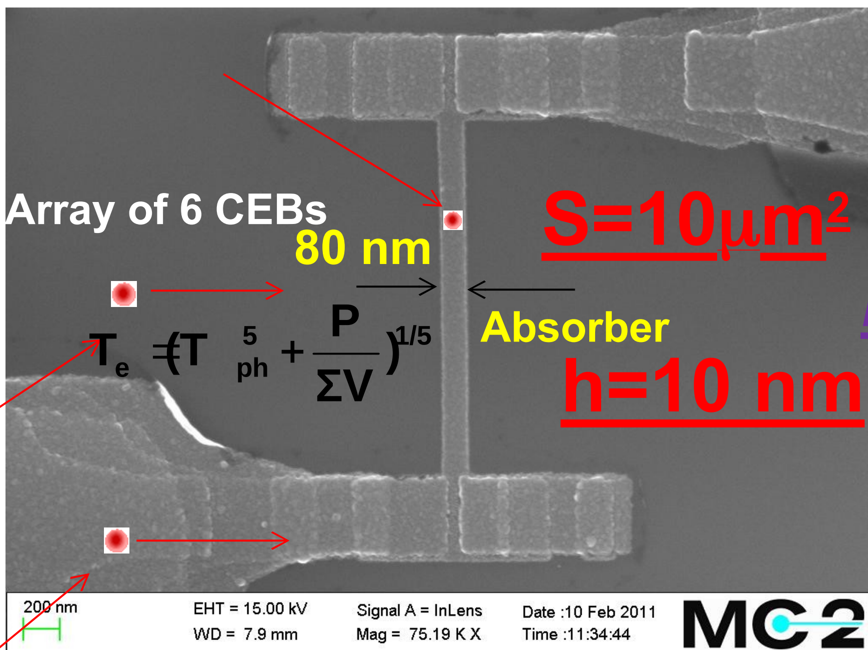
- 137Cs source (660 keV photons)
- in front of the window
- No single glitch was detected!

***Expectation time for a single glitch – 40 days!***

Double protection against Cosmic Rays by extremly smalll volume of absorber and decoupling of electron and phonon systems!




## CEB for LSPE




## Spider-web with TES for LSPE

*Gain*

*in Area*

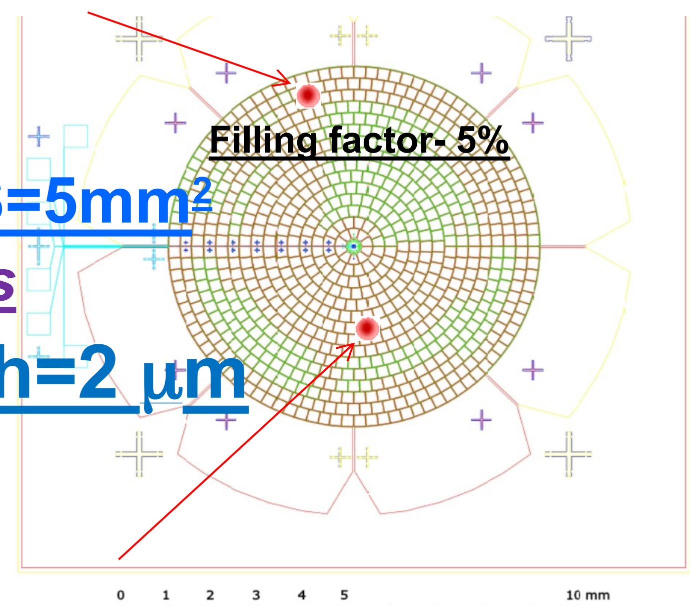
:1000

*in thickness*

:100

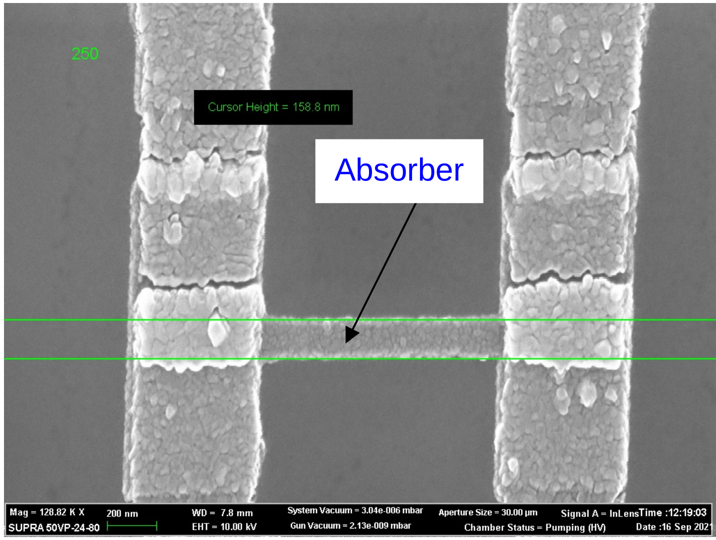
*in volume*

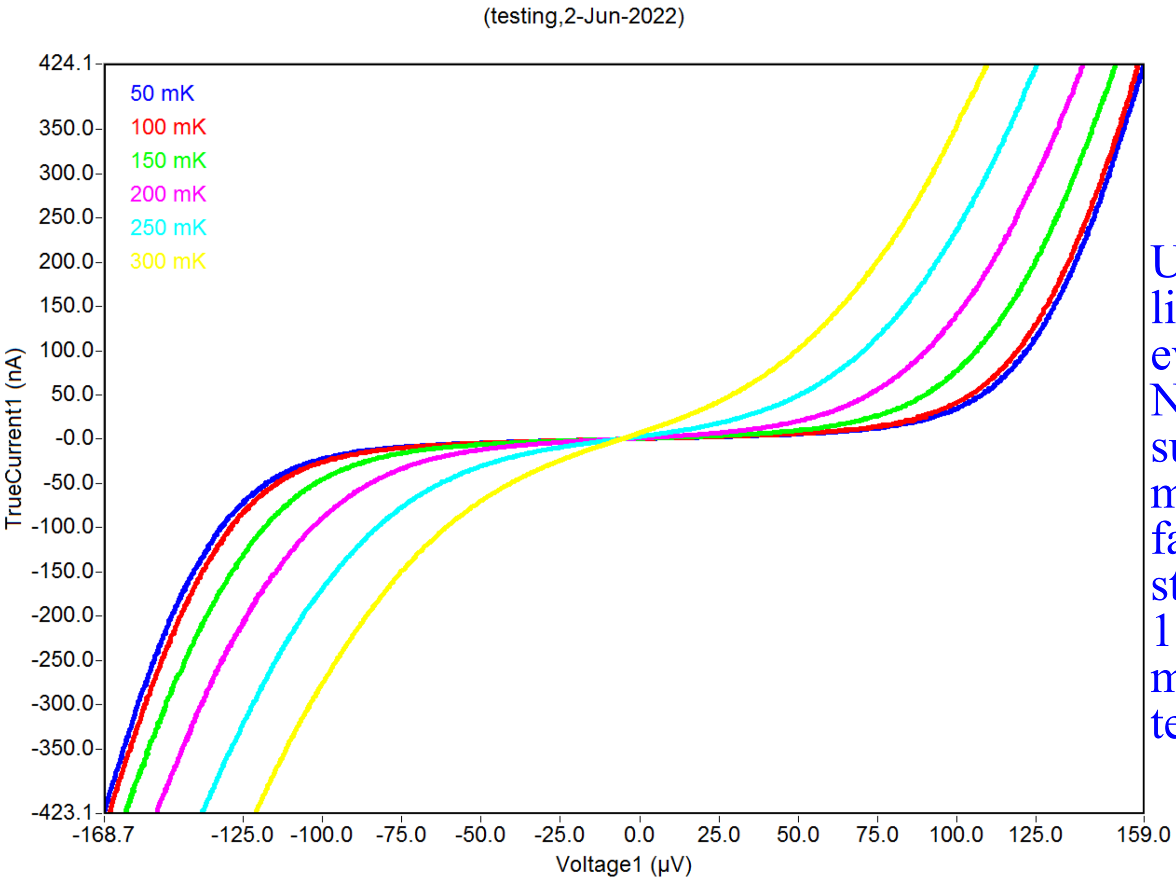
:$10^5$



# Transfer of technologies to Nizhny Novgorod

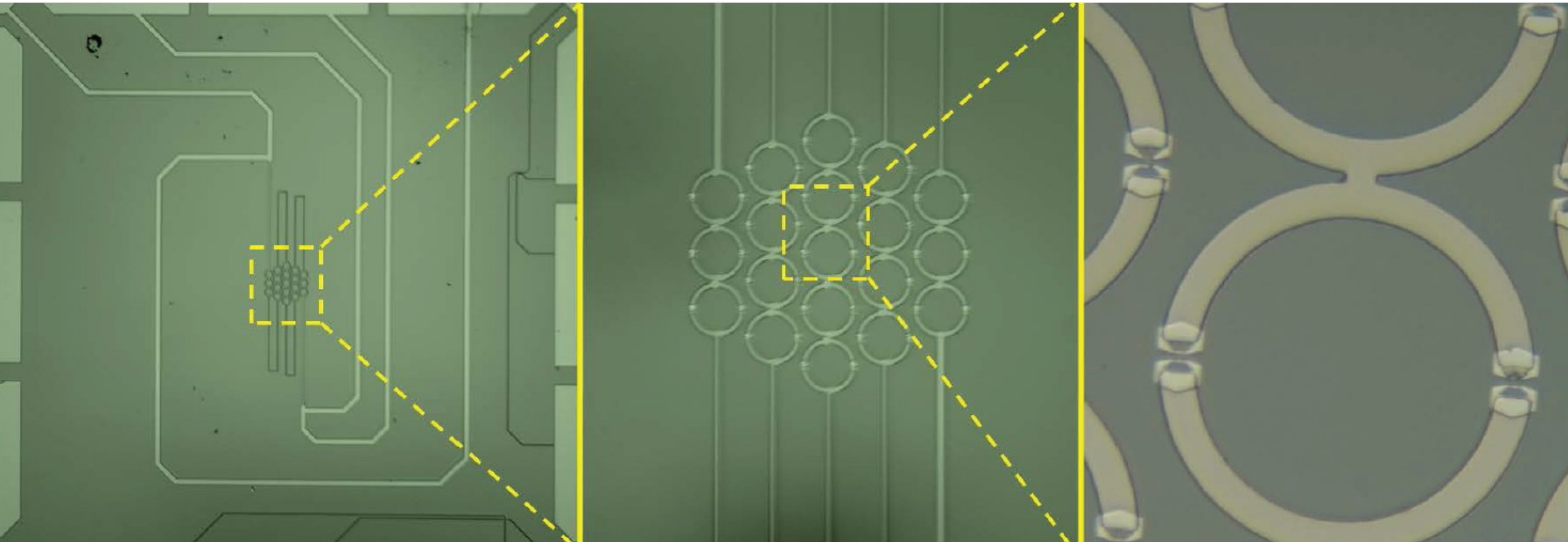
Transfer of technologies for creating superconducting tunnel junction nanostructures from Chalmers University of Technology is underway. Using the technological base of the Center for Collective Use of the IPM RAS and the Center for Quantum Technologies of the Nizhny Novgorod State Technical University,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

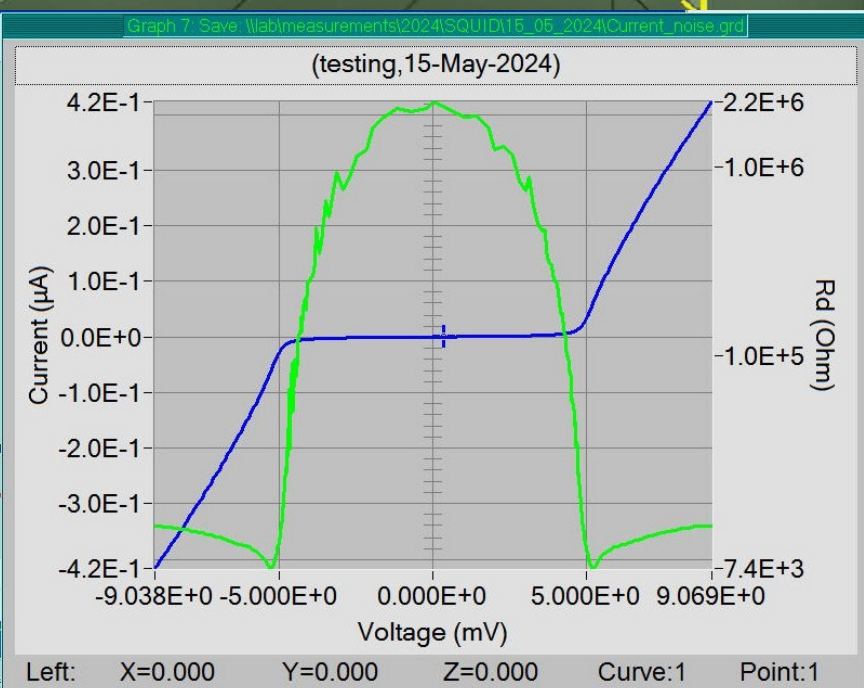


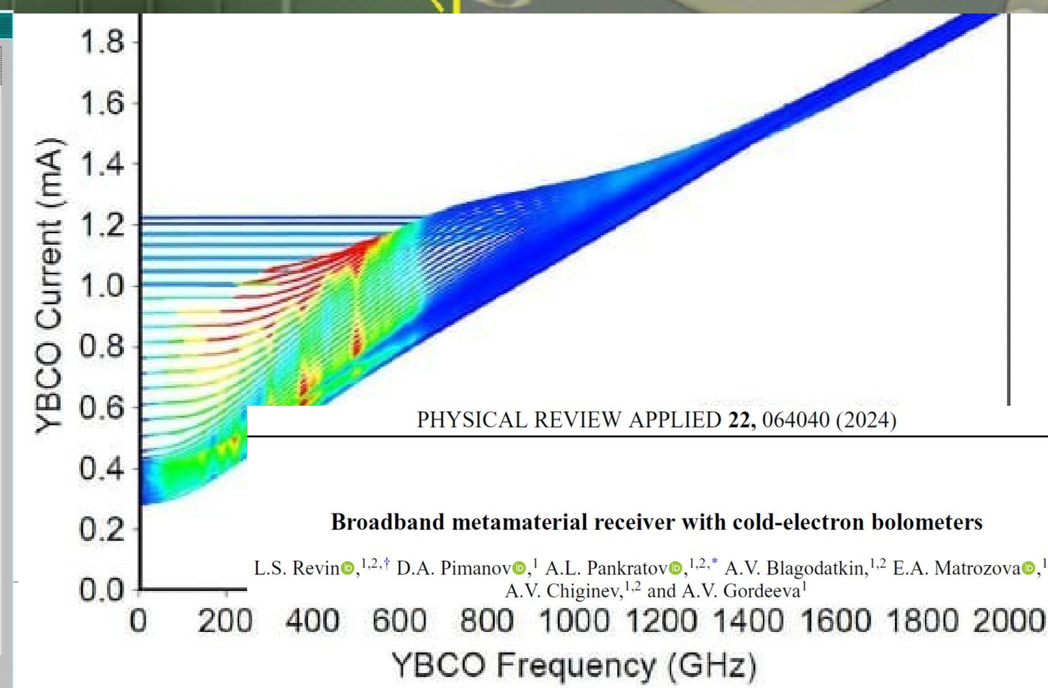




Using electron- and photo-lithographies, as well as the shadow evaporation technique, the first Nizhny Novgorod structures with superconductor-insulator-normal metal tunnel junctions were fabricated. Top – SEM image of the structure with an absorber width of 150 nm, left – IVC of the structure measured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

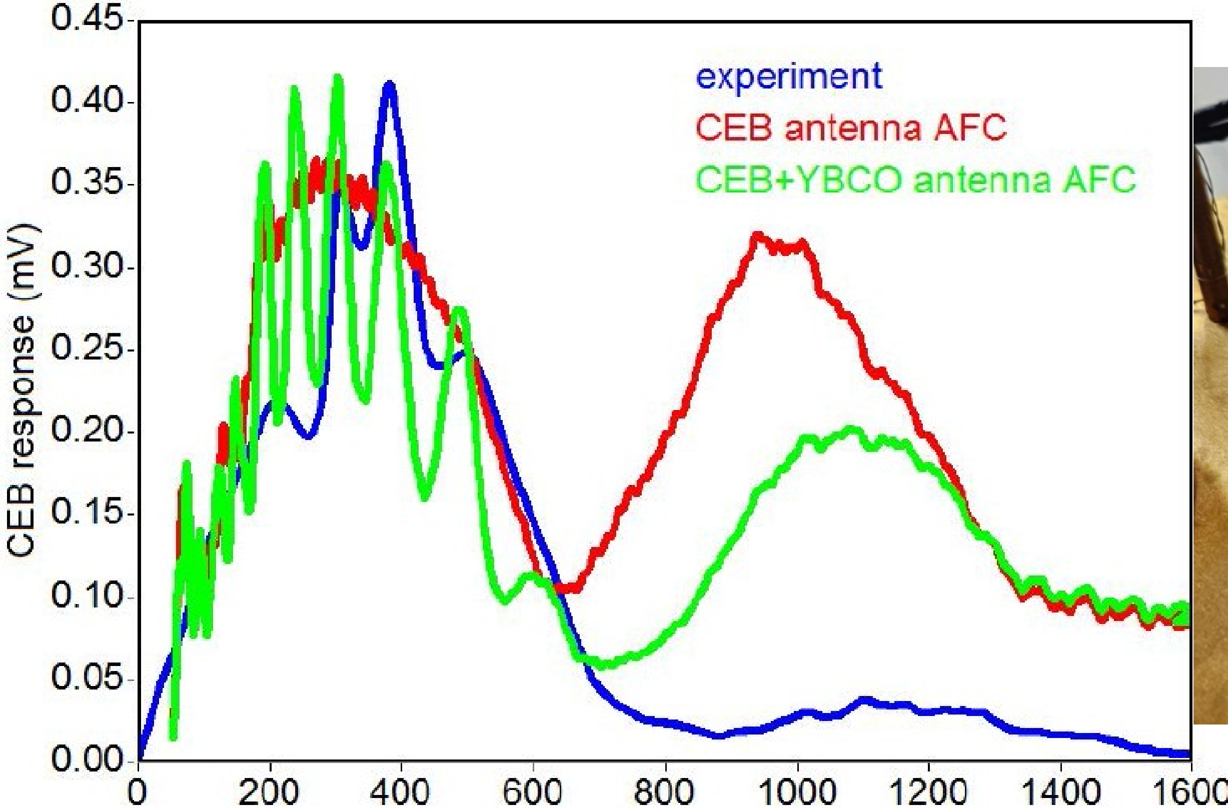
# Broadband metamaterial receiver for 150-450 GHz

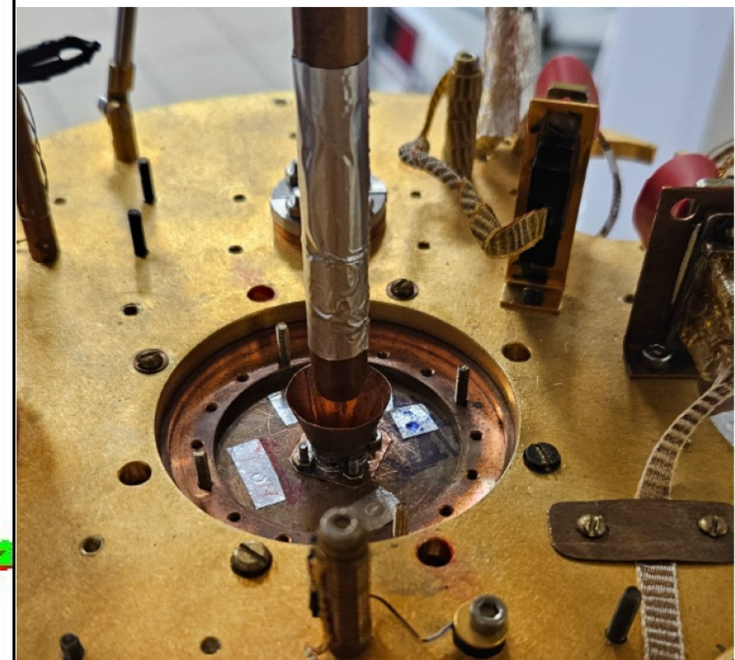


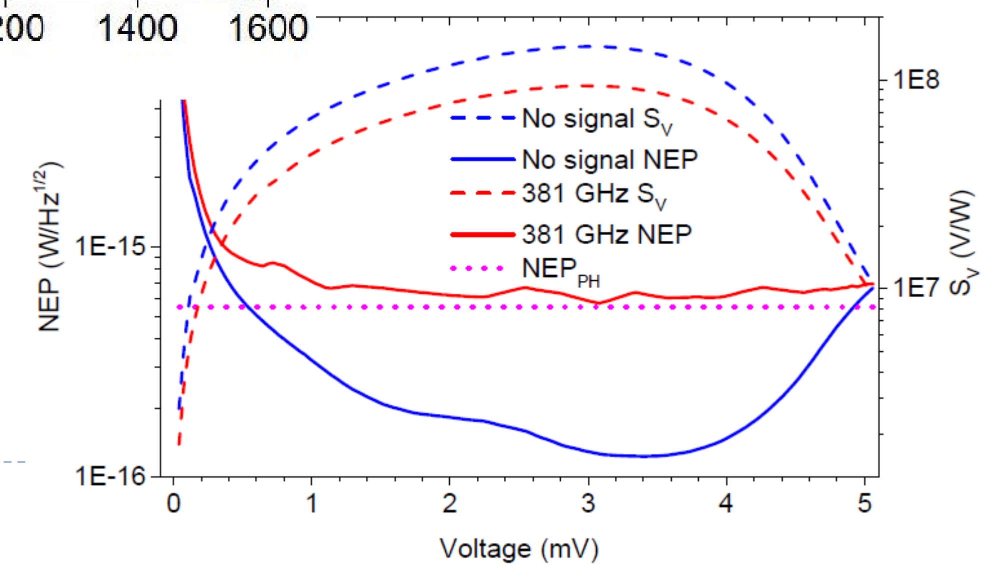


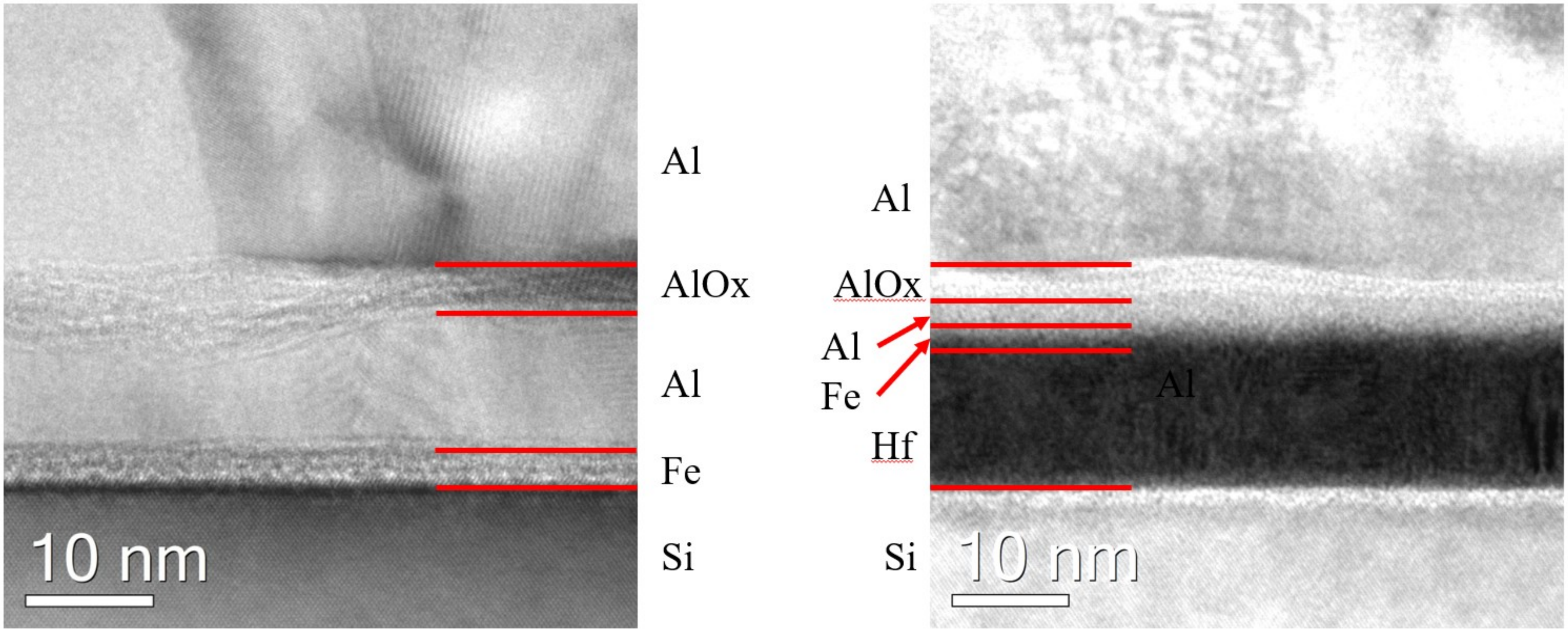
# Broadband metamaterial receiver for 150-450 GHz



# Using Hf sub-layer for electrons and phonons decoupling




IOP Publishing

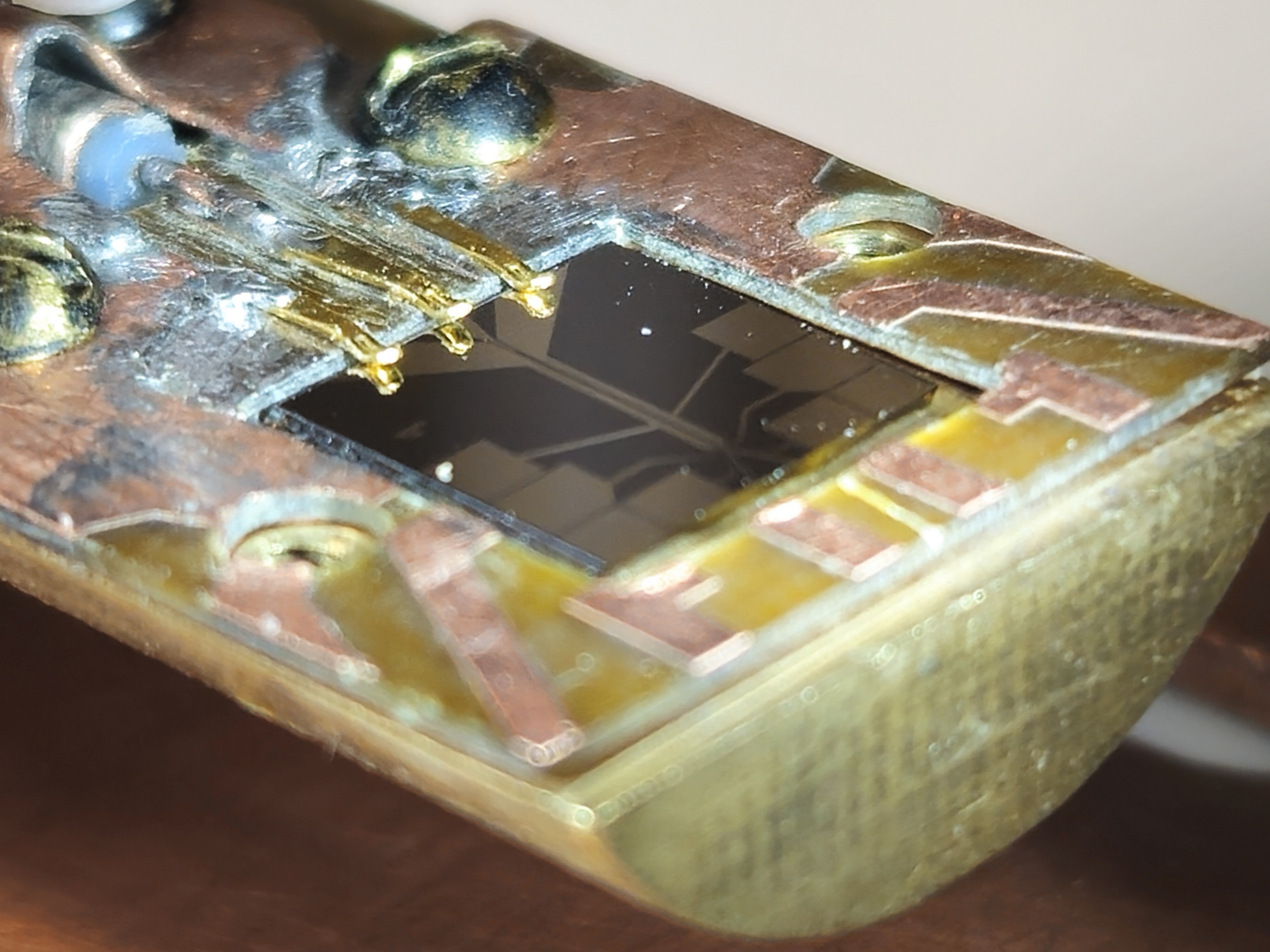
Superconductor Science and Technology

Supercond. Sci. Technol. **38** (2025) 035026 (6pp)

https://doi.org/10.1088/1361-6668/adb942

# Response of a cold-electron bolometer in a coplanar antenna system

D A Pimanov[1], A L Pankratov[1,2,*], A V Gordeeva[1], A V Chiginev[1,2], A V Blagodatkin[1,2], L S Revin[1,2], S A Razov[1], V Yu Safonova[1,2], I A Fedotov[2], E V Skorokhodov[2], A N Orlova[2], D A Tatarsky[2], N S Gusev[2], I V Trofimov[3], A M Mumlyakov[3] and M A Tarkhov[3]



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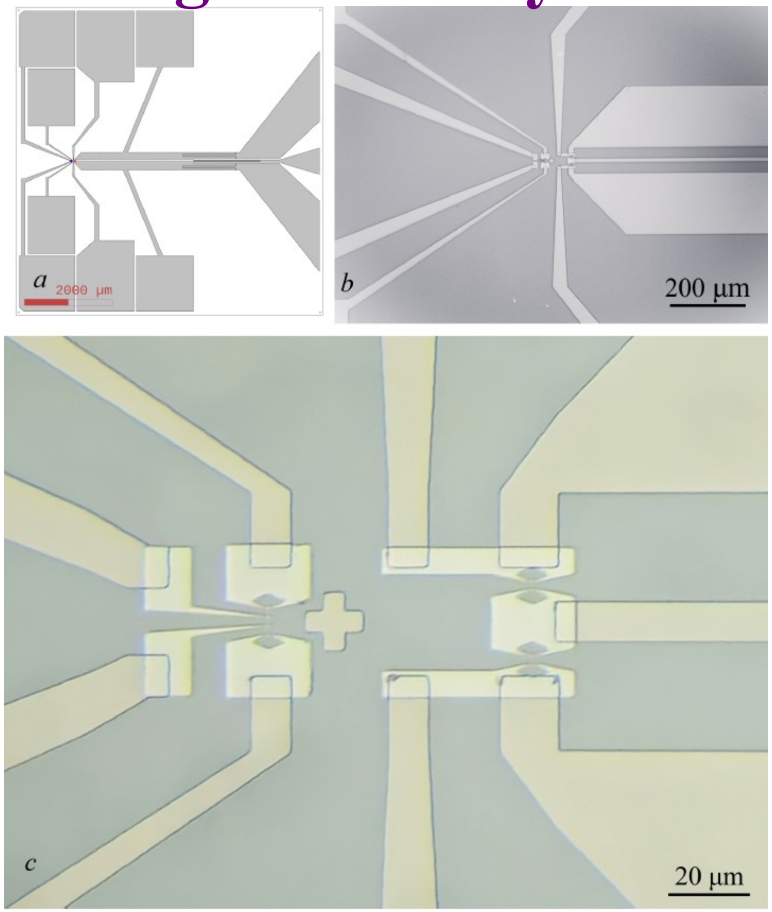
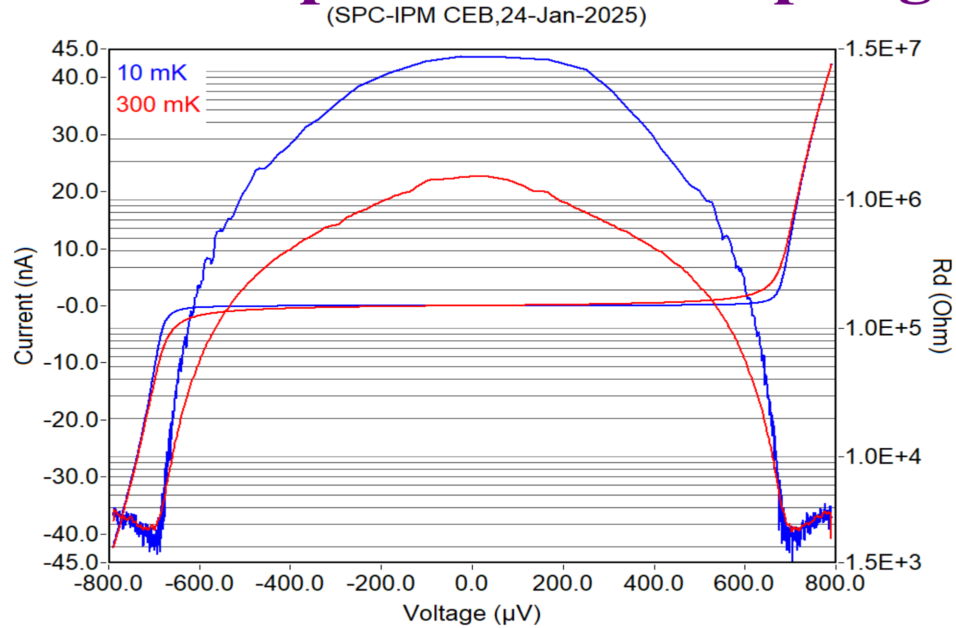
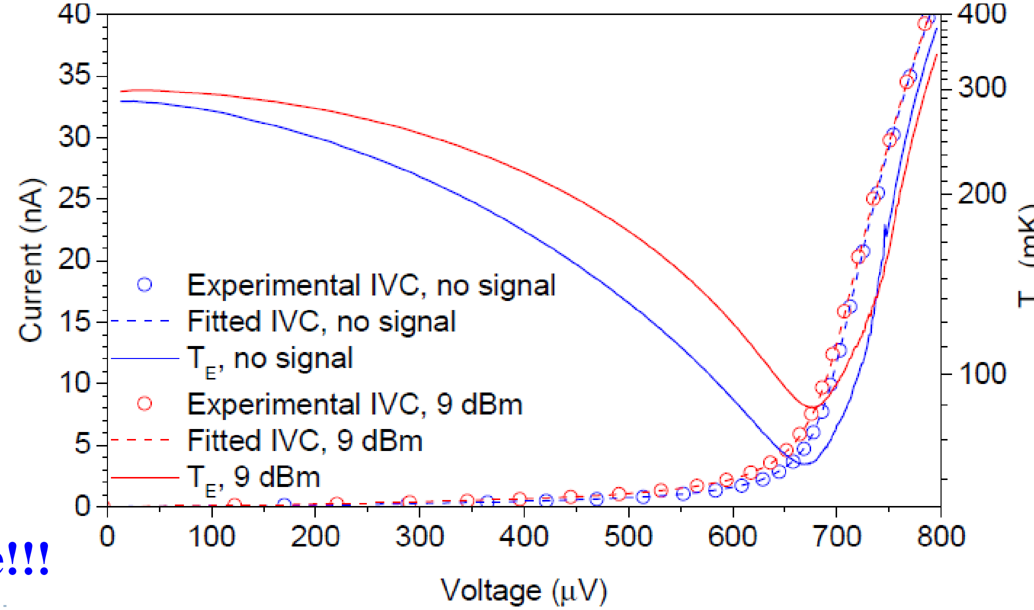


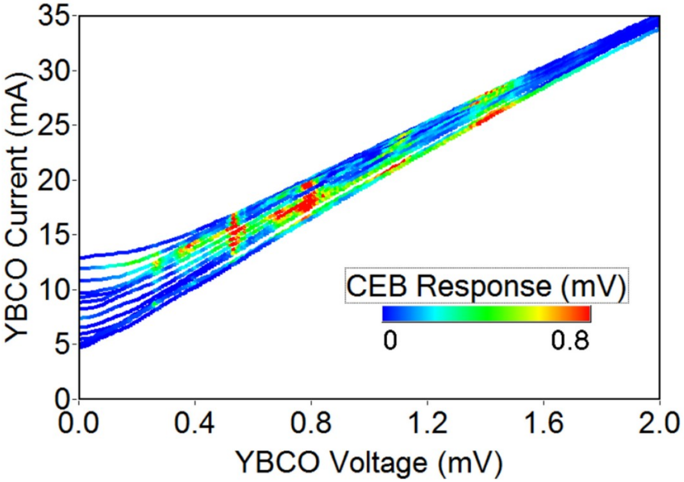

**High sensitivity of a bolometer due to electron cooling and low leakage current due to Hf sub-layer.**

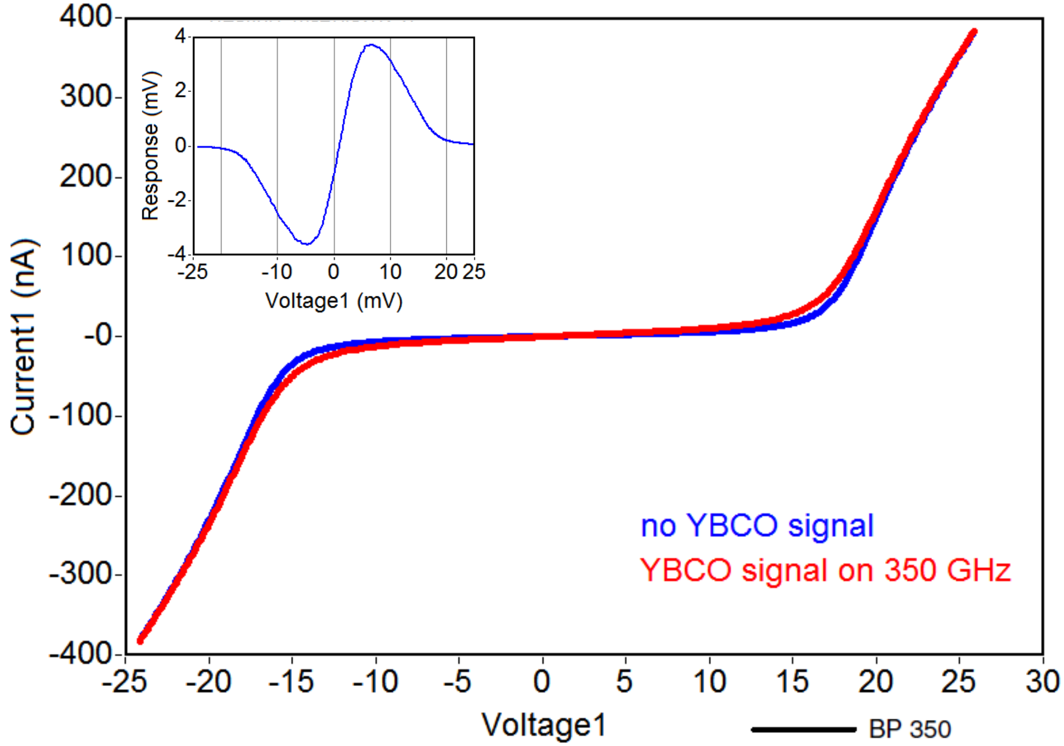
**Sensitivity is restricted by amplifier noise!!!**

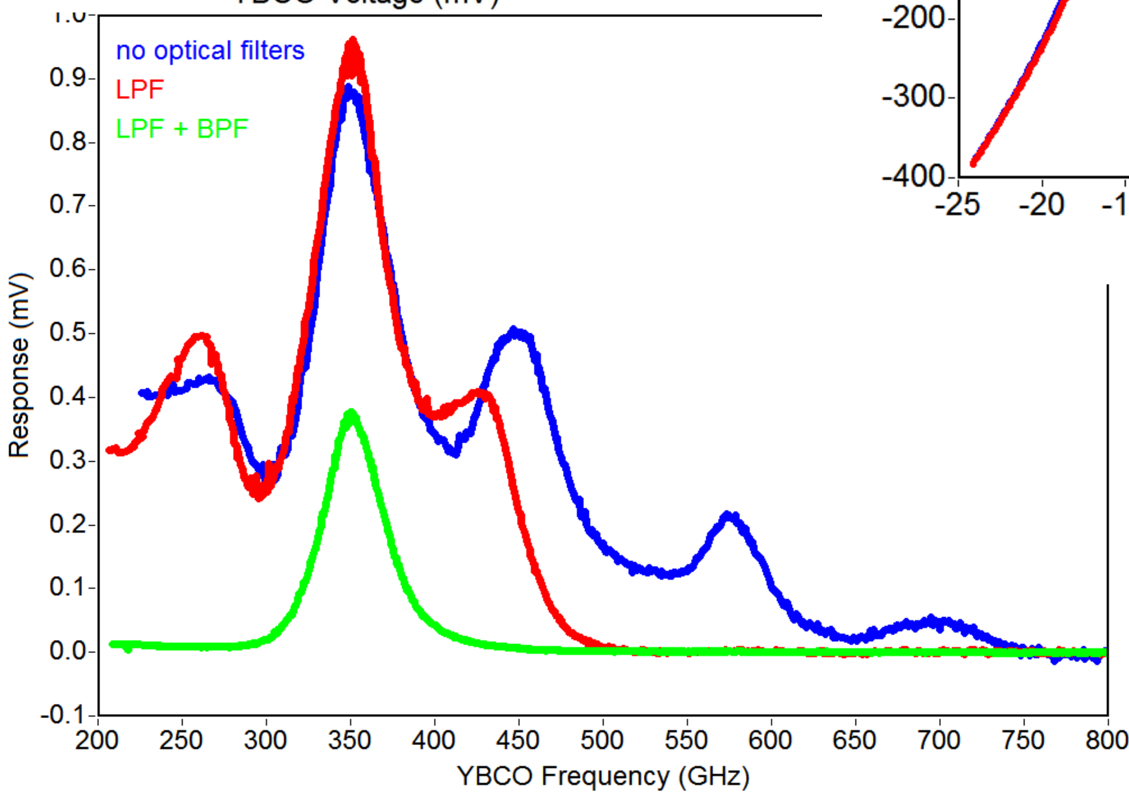
**SUST, 2025**

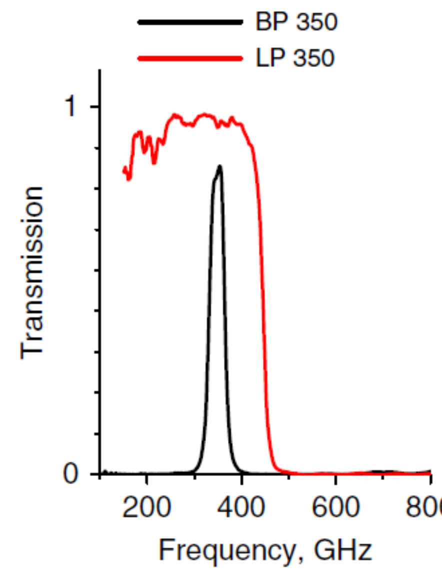
CEB NEP ~ $6\,\mathrm{aW}/\sqrt{\mathrm{Hz}}$ at 300 mK

# Using YBCO Josephson oscillators for bolometer characterization

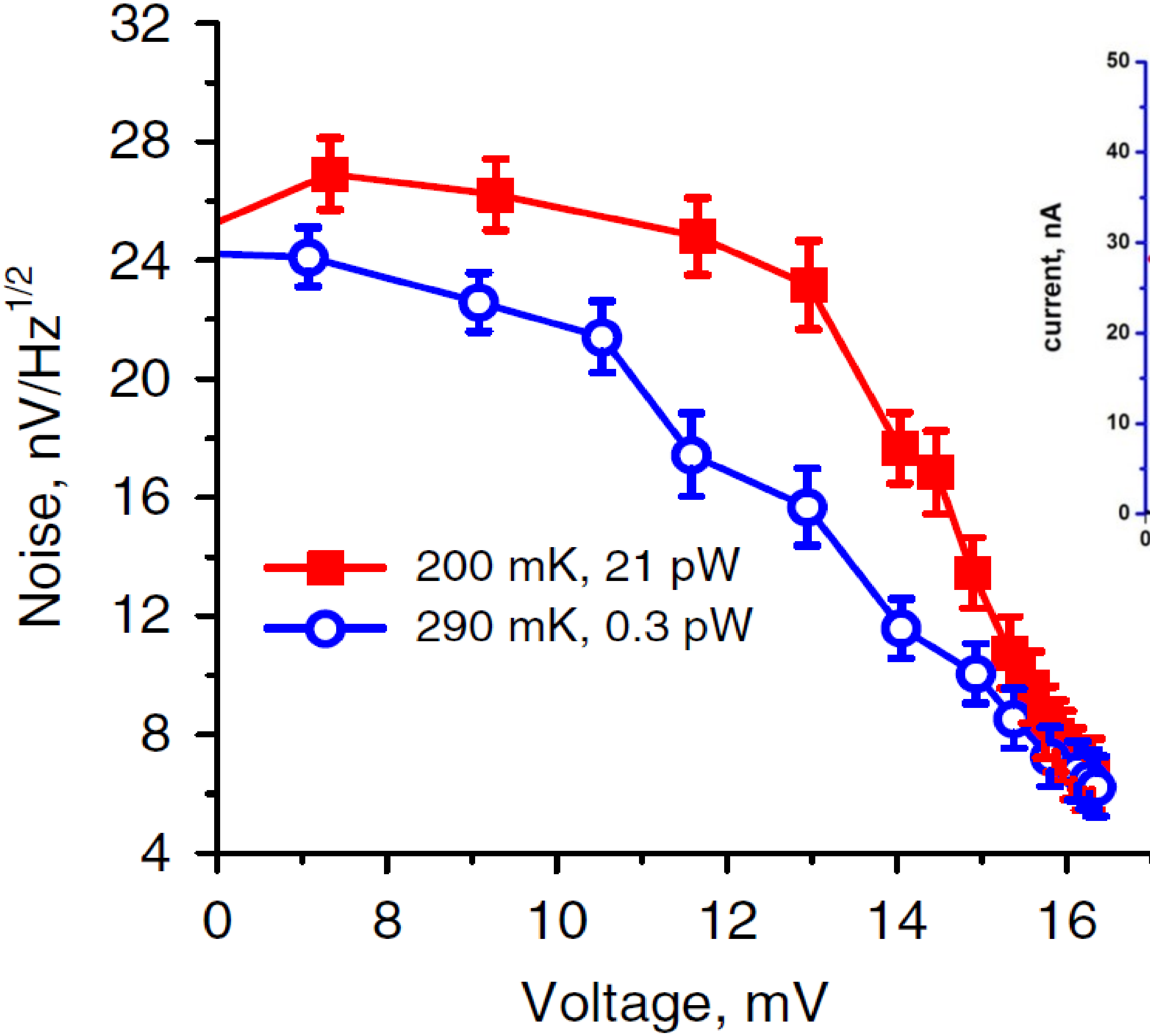


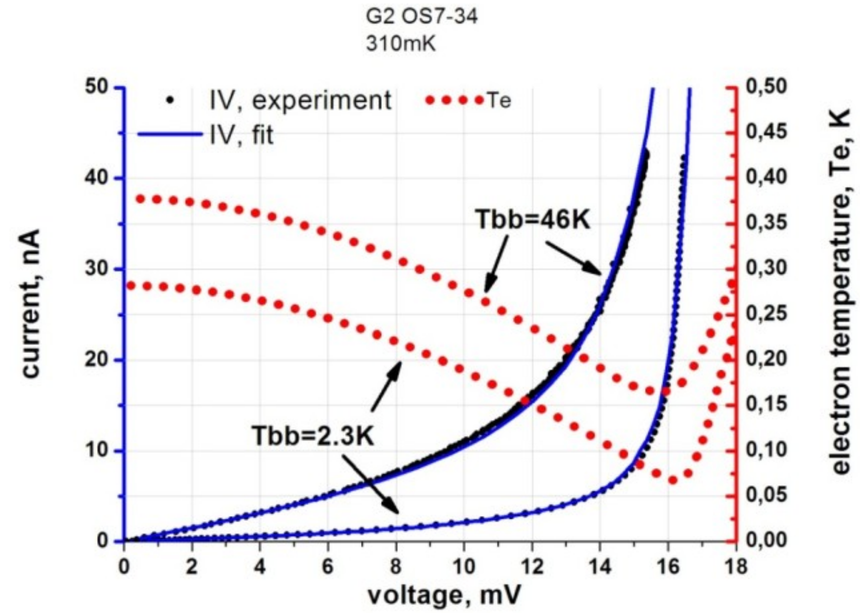



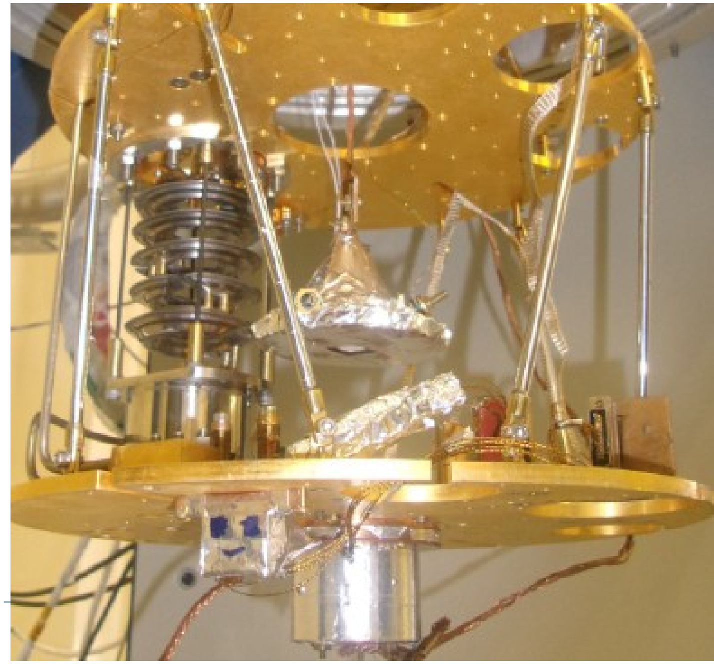



# Photon noise from black body source

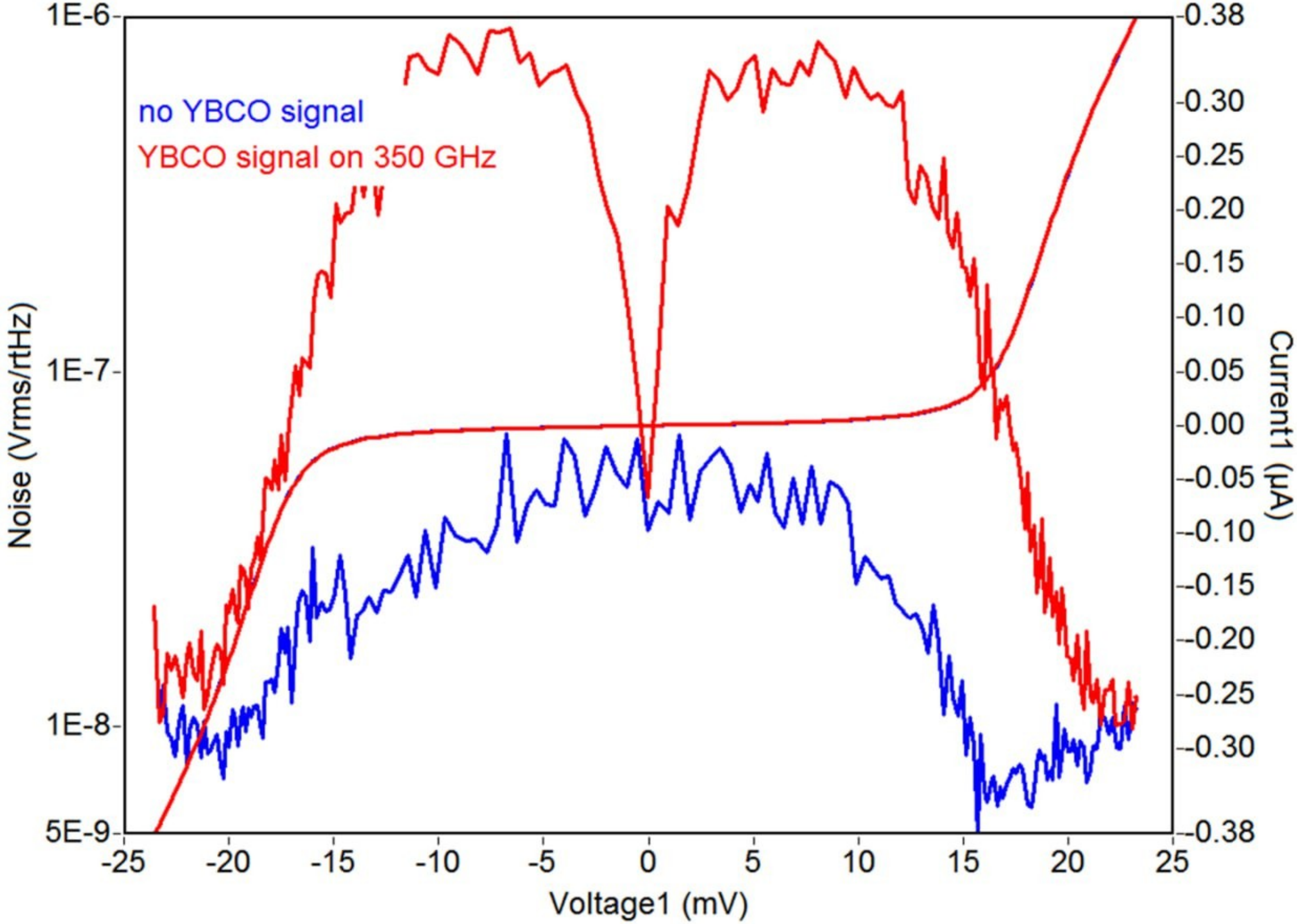


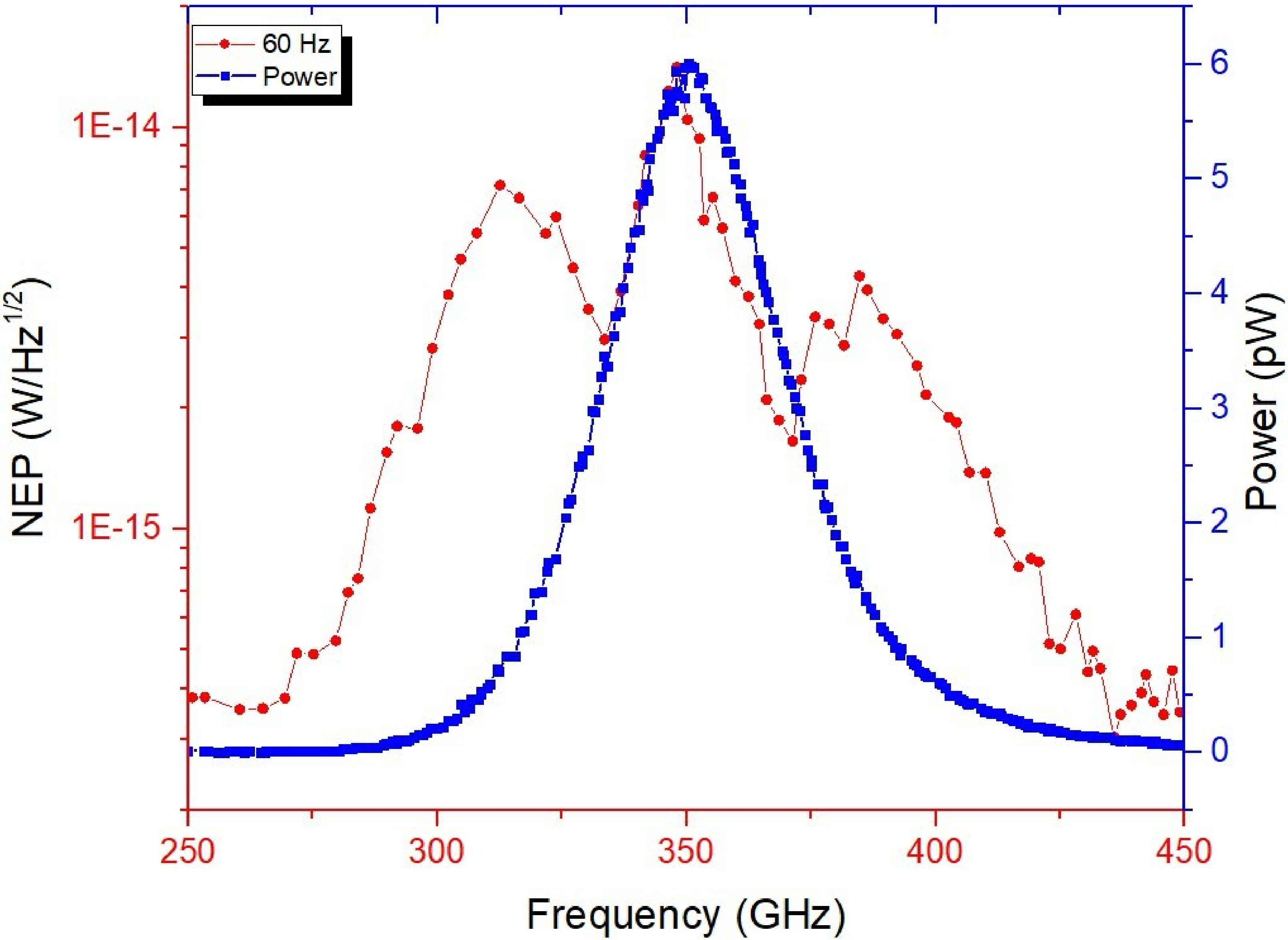
$$\mathrm{NEP_{ph}} = \sqrt{P_0 hf + P_0^2/\delta f}$$

# Giant photon noise from YBCO oscillator



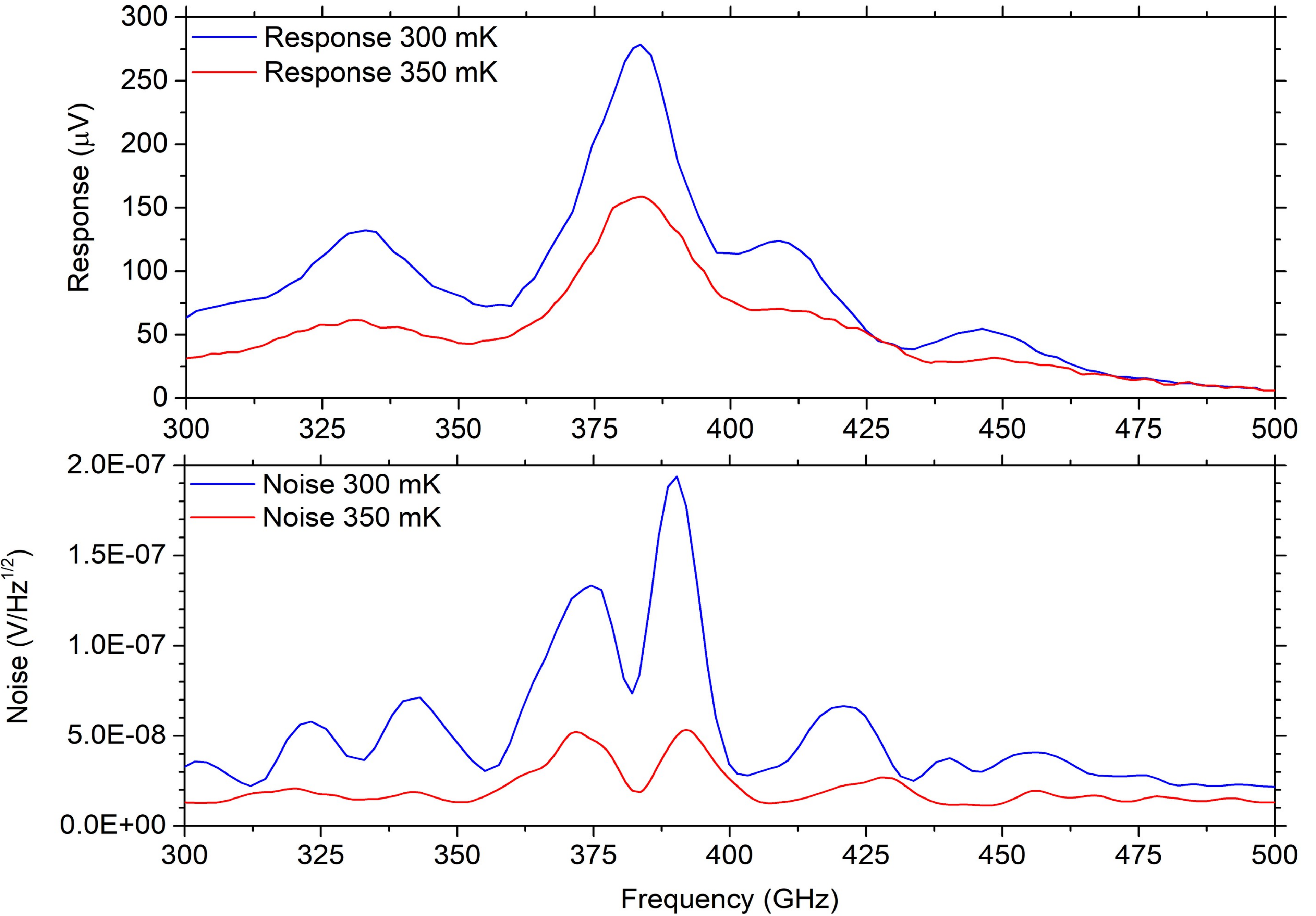

$$\mathrm{NEP_{ph}} = \sqrt{P_0 hf + P_0^2/\delta f}$$

# Giant photon noise from YBCO oscillator



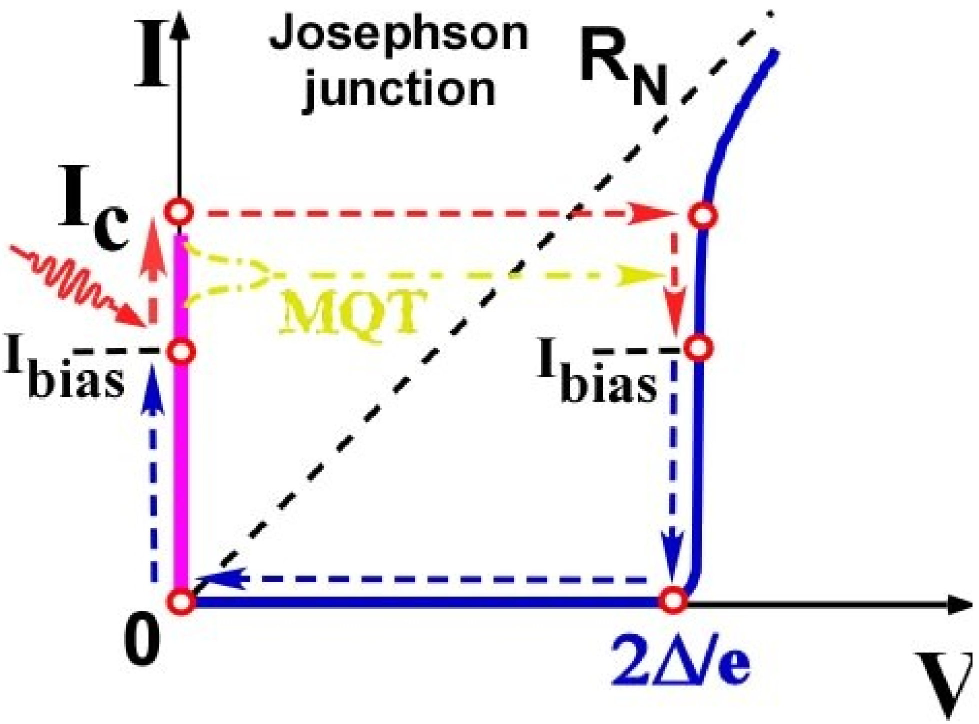

$$\mathrm{NEP_{ph}} = \sqrt{P_0 hf + P_0^2/\delta f}$$ ???

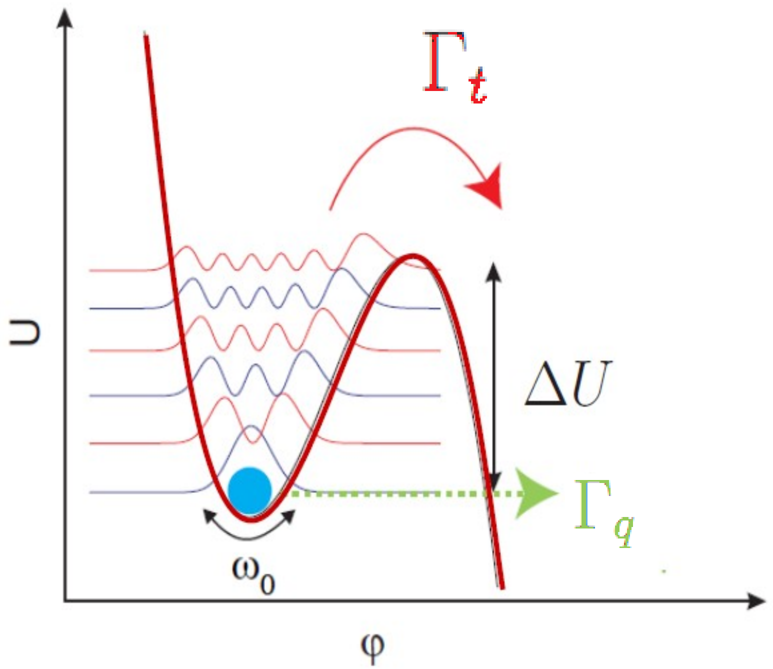
# Giant photon noise from YBCO oscillator

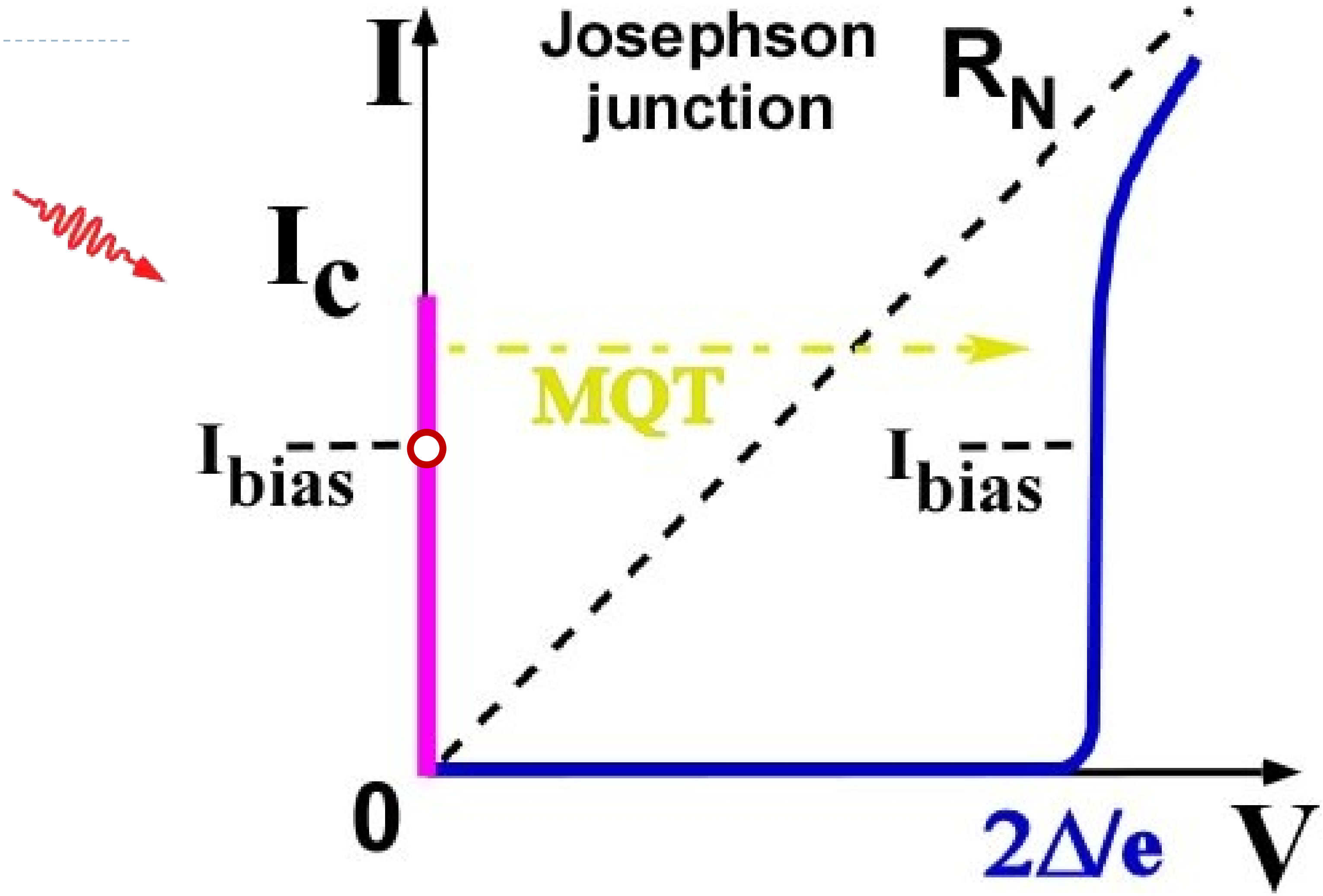


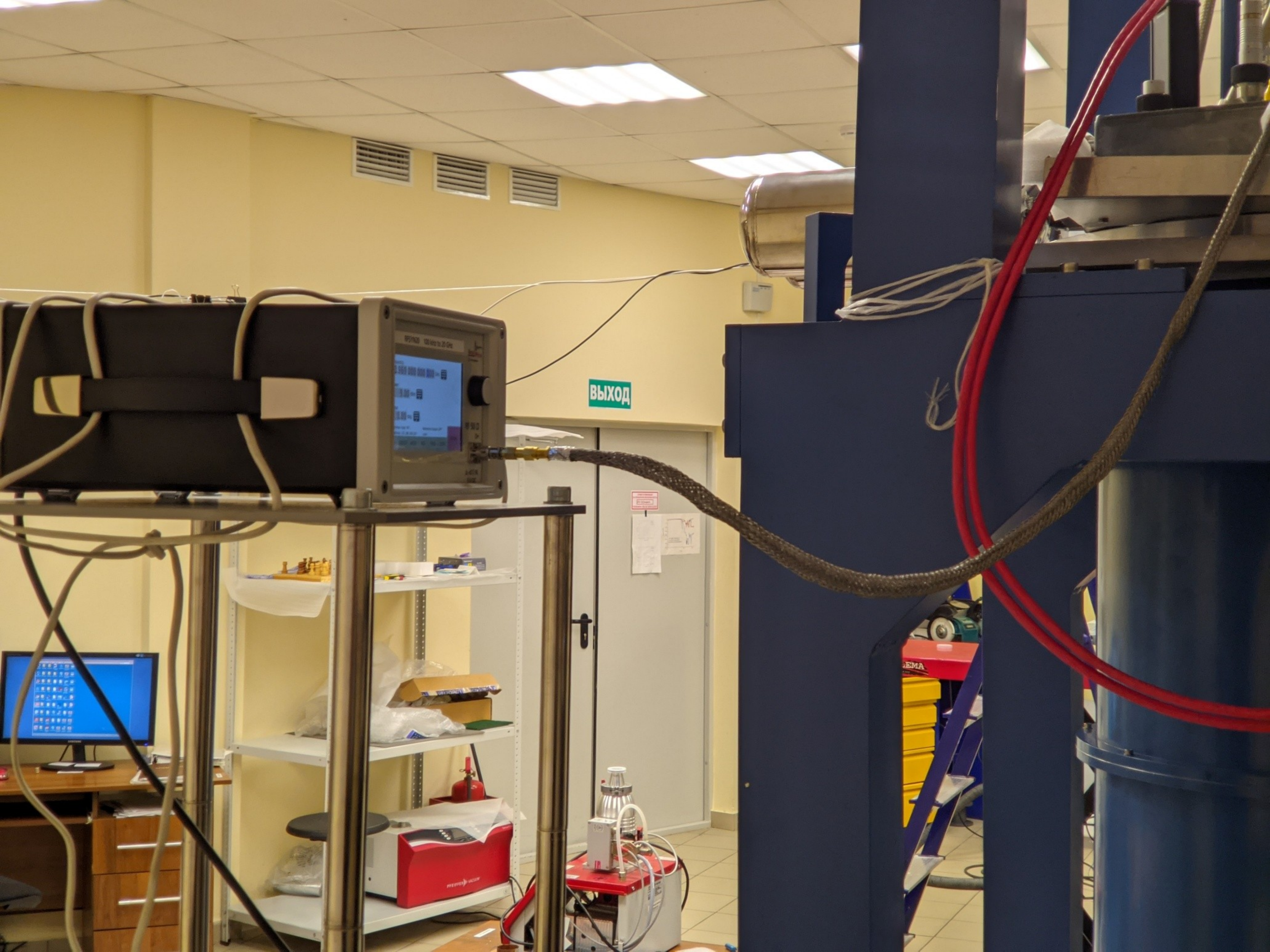
# Principle of operation of SIS SPD for axion search

**SIS tunnel junction is a type of Josephson junction with low damping, having hysteretic current-voltage characteristic. It is used as threshold detector – the single photon counter**

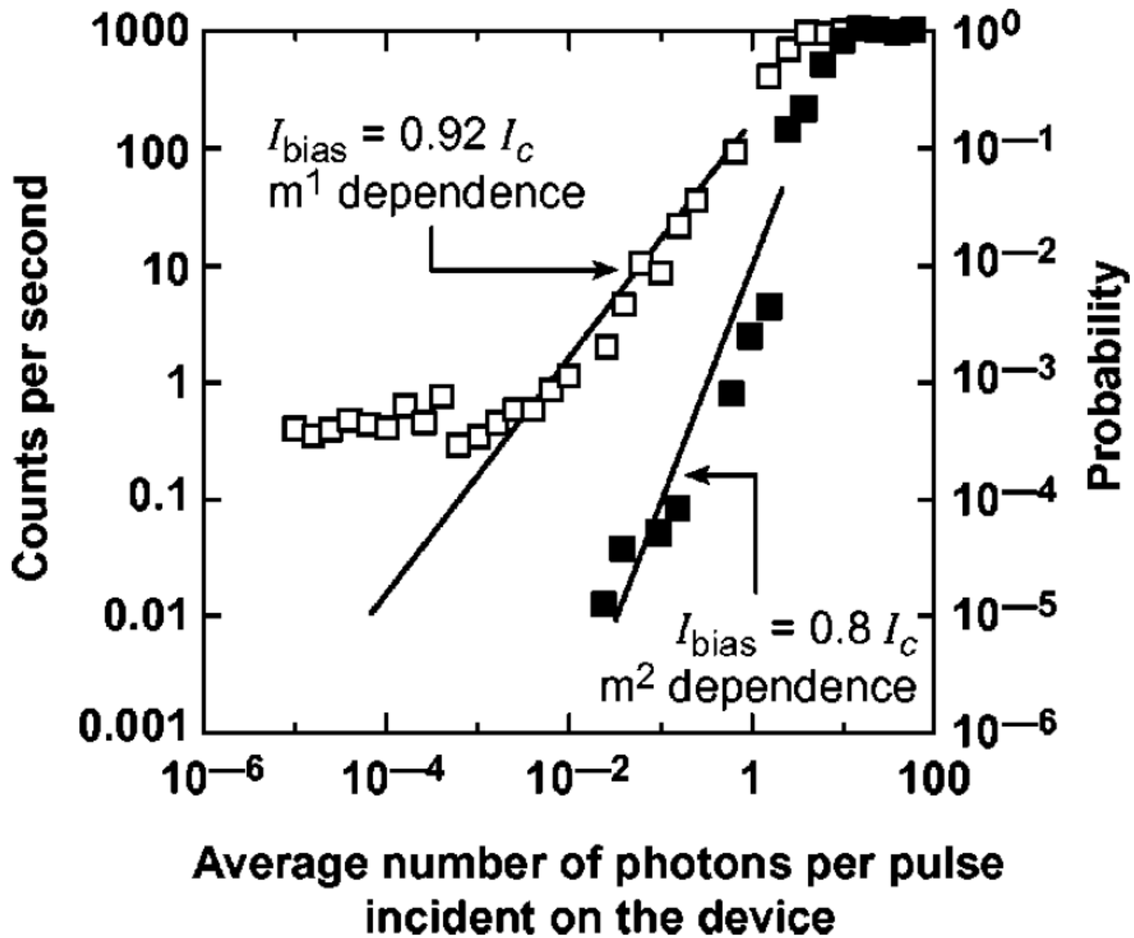



I
Josephson
junction
$R_N$
$I_c$
MQT
$I_{bias}$
$I_{bias}$
0
2Δ/e
V


ВЫХОД

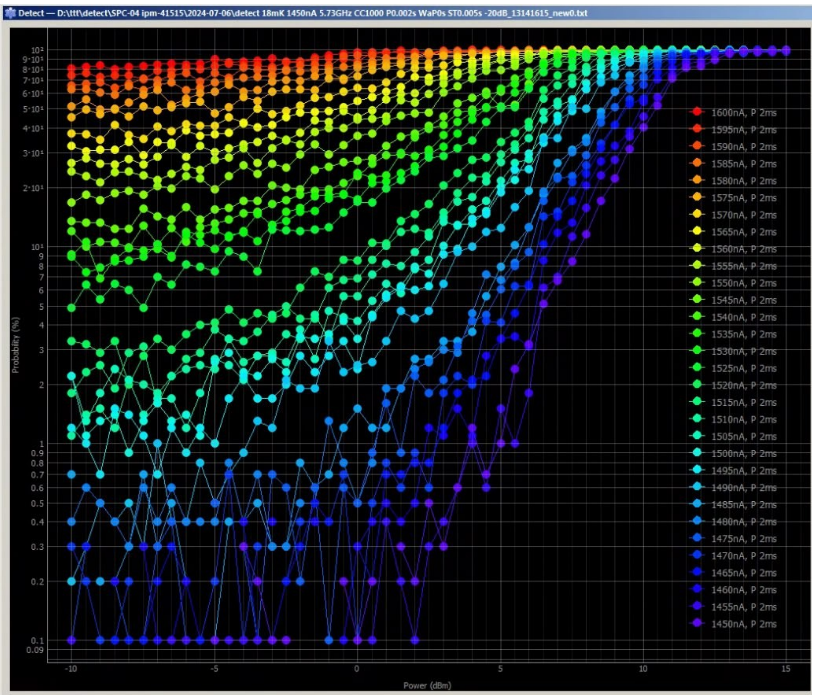
# Counting photons by large statistics in IR range

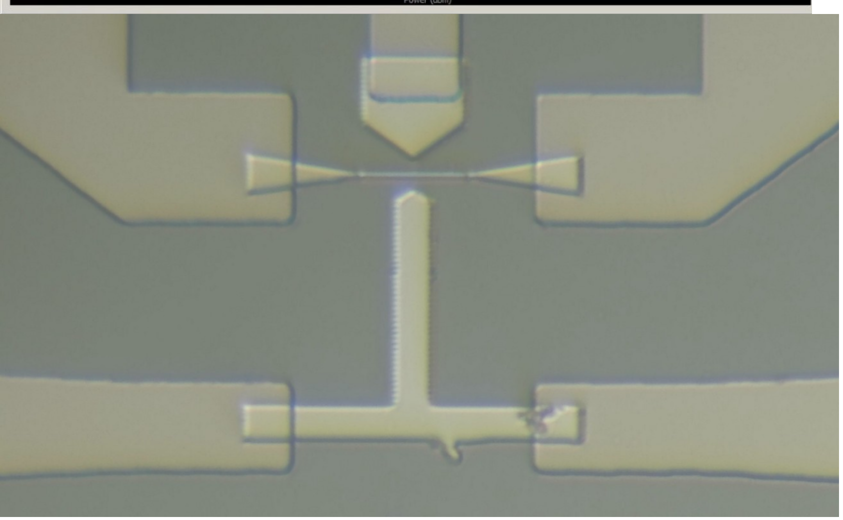


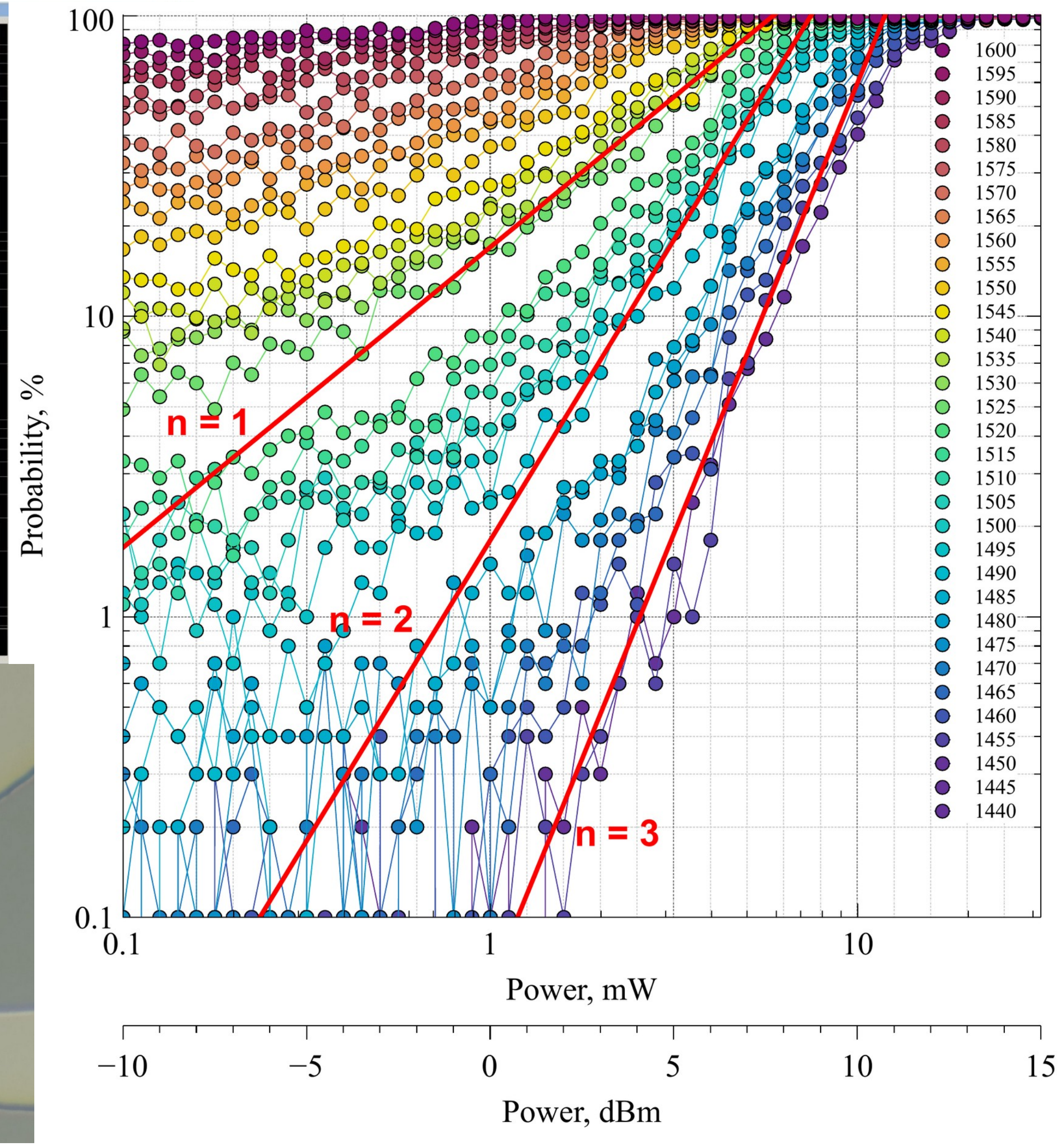

## Detection of 140 THz photons at 4 K

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).

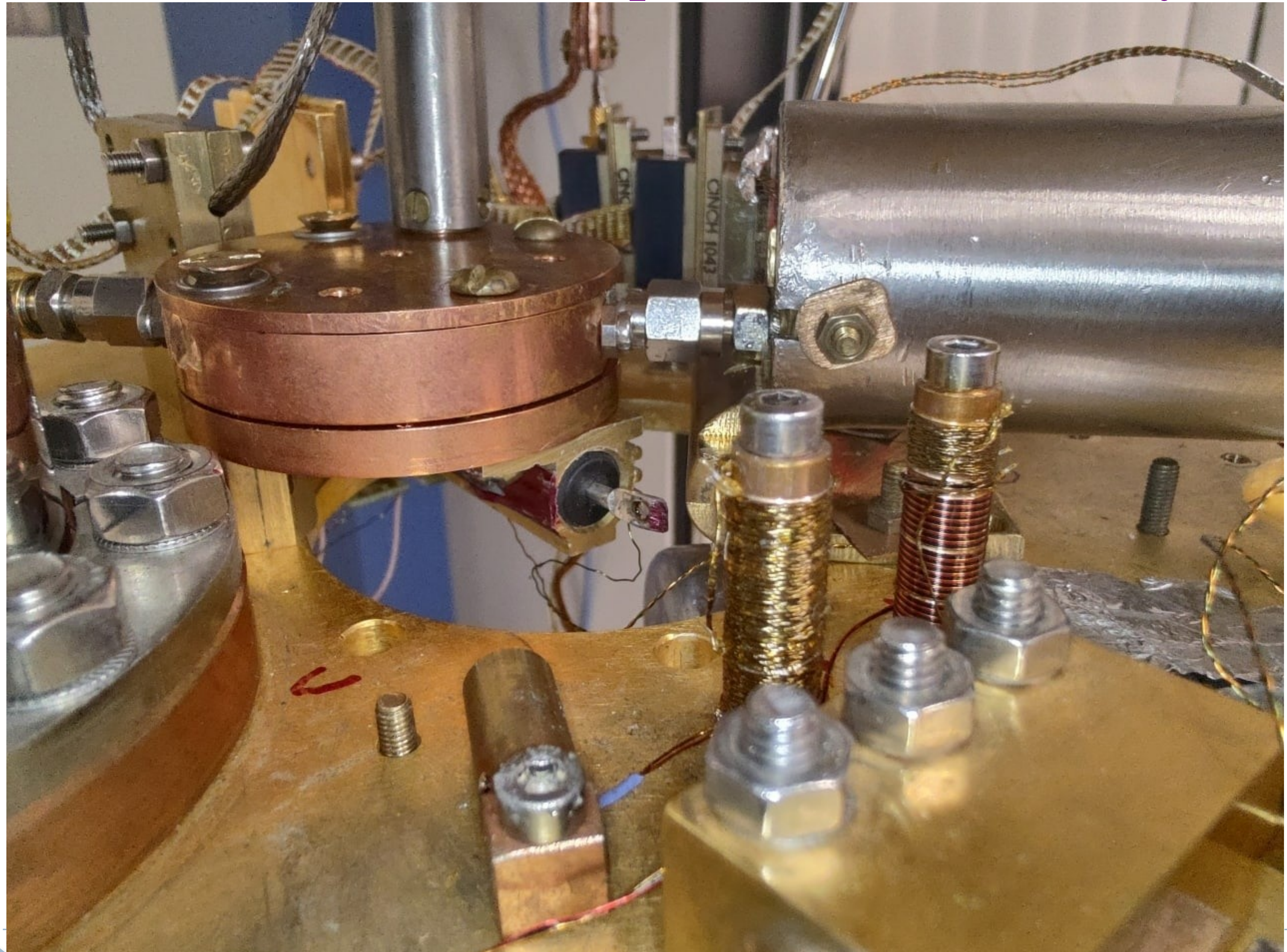
# Quantization of switching probability using 1st sample, fabricated in Nizhny Novgorod



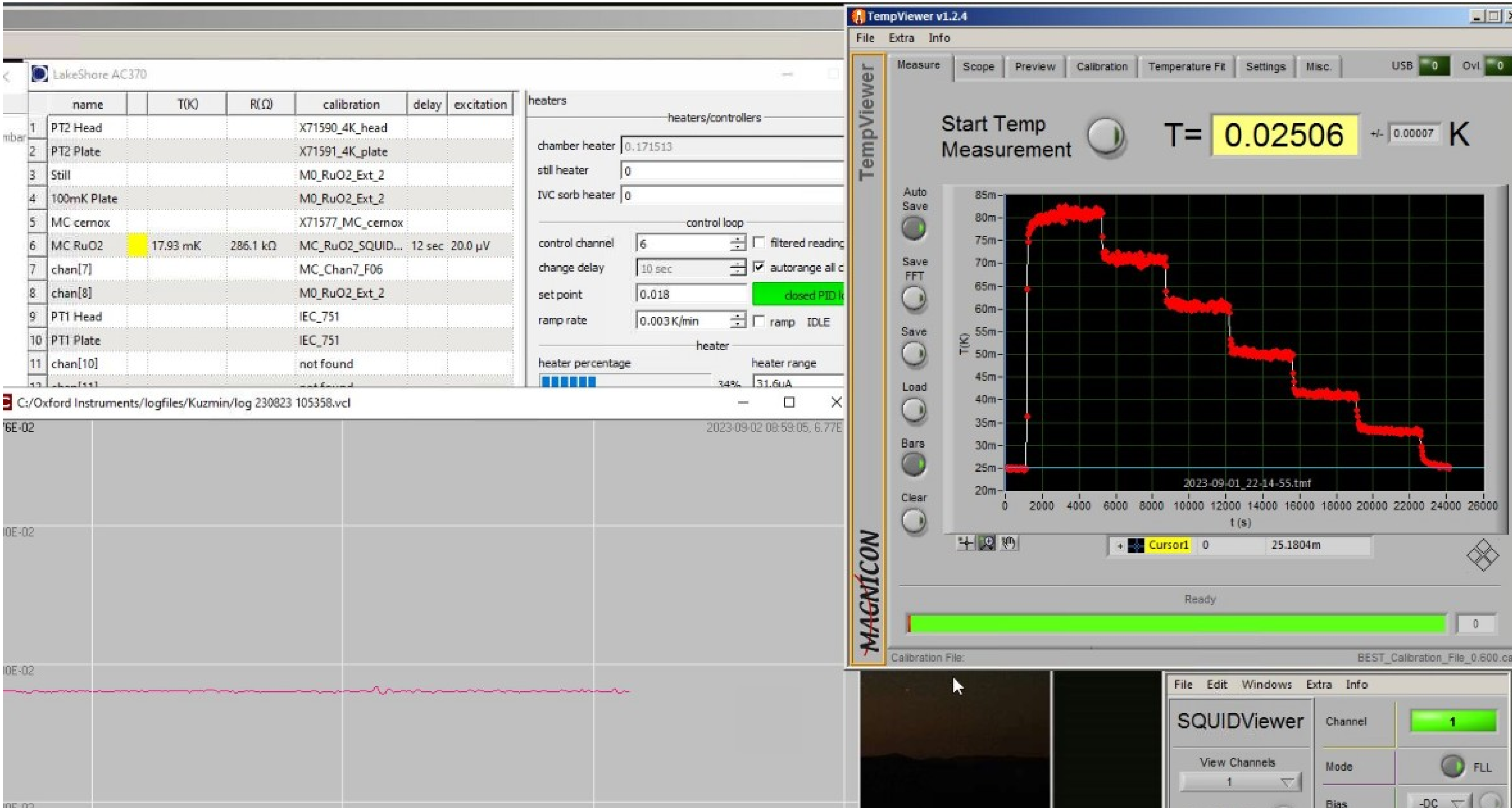


# Detection of thermal photons from a cavity

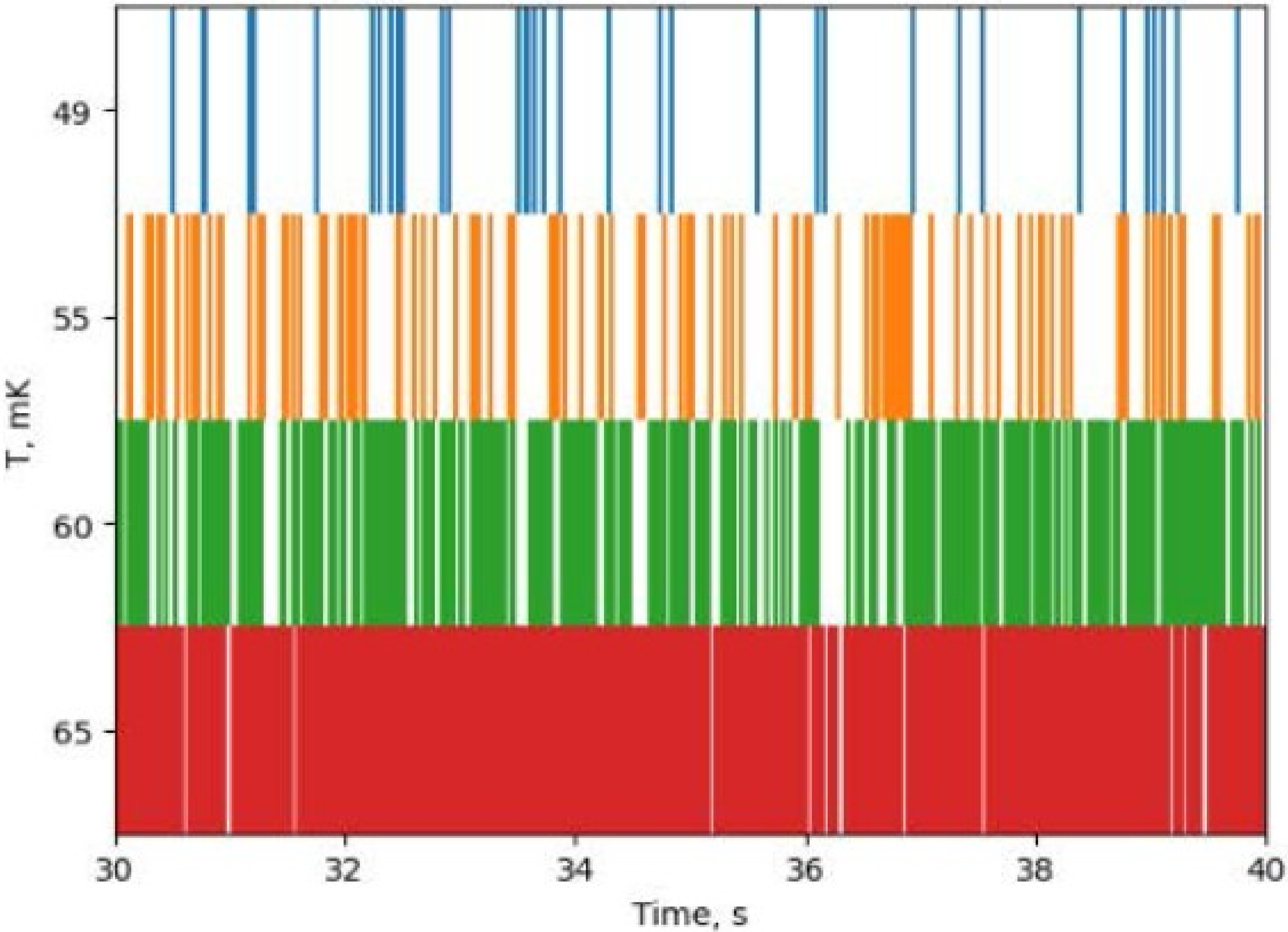



https://www.nature.com/articles/s41467-025-56040-4

# Calibration of cavity temperature by SQUID



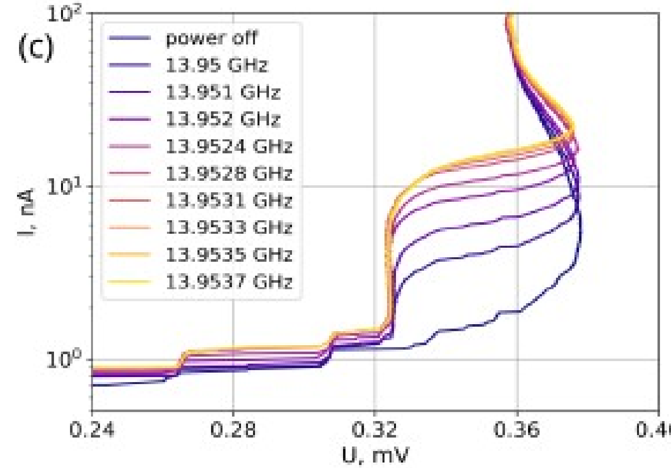
# Time intervals between switches + cavity

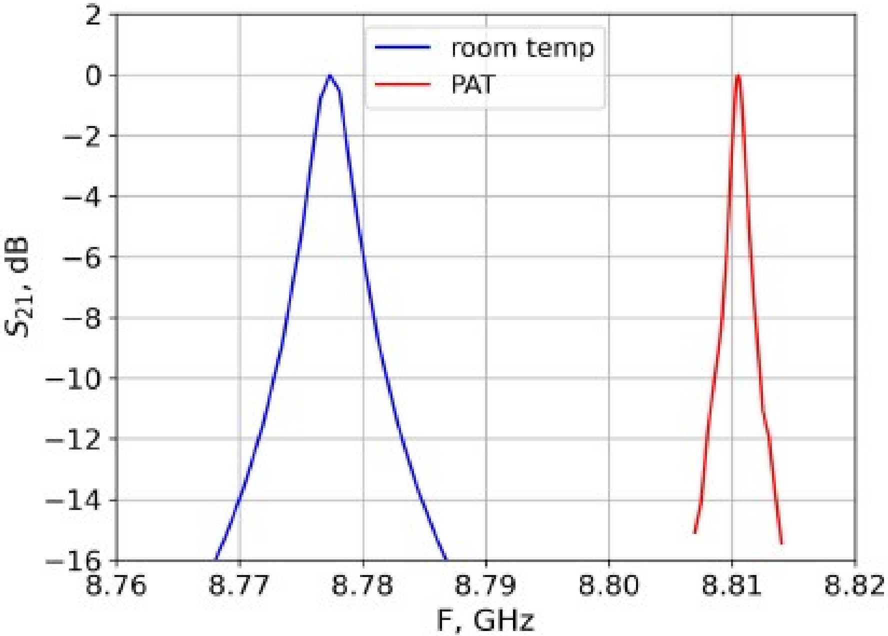


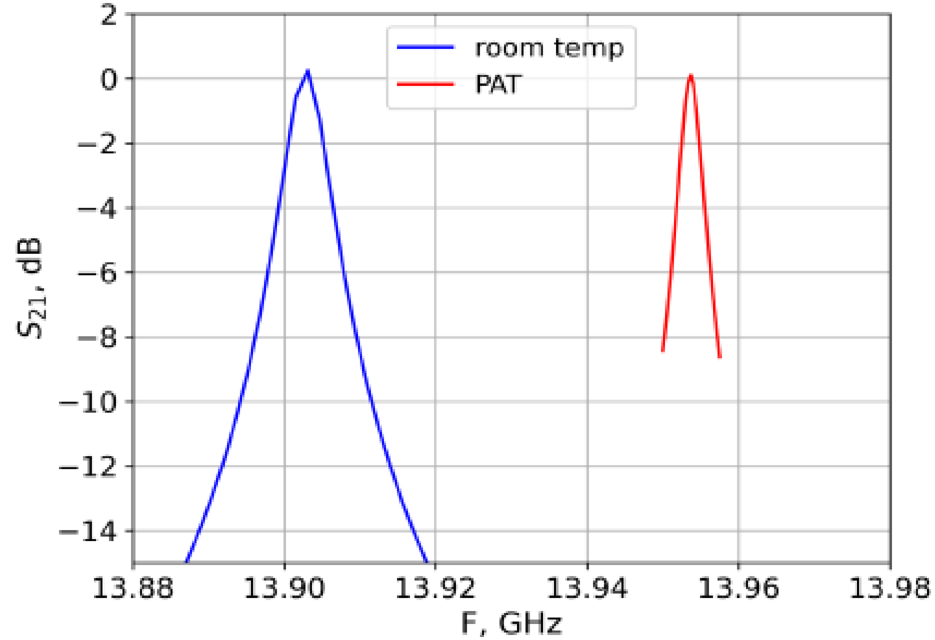
# Determining detection efficiency

$$r_c(T) = \sum_{i=1}^{n} \frac{\eta_i}{\tau_i} \frac{1}{e^{hf_i/k_B T} - 1}$$

$$\tau_i = Q_i/(2\pi f_i)$$



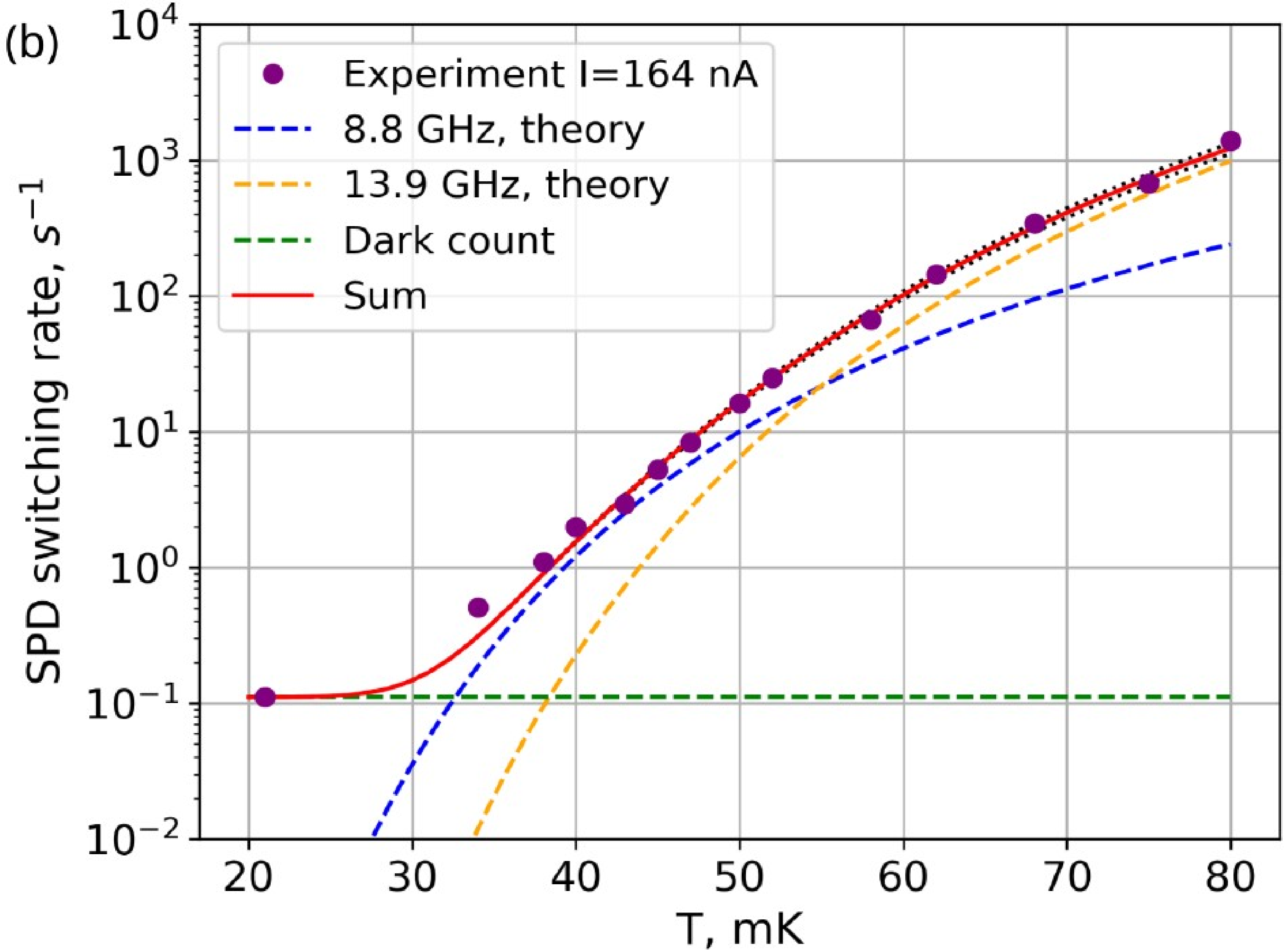






https://www.nature.com/articles/s41467-025-56040-4

# Determining detection efficiency

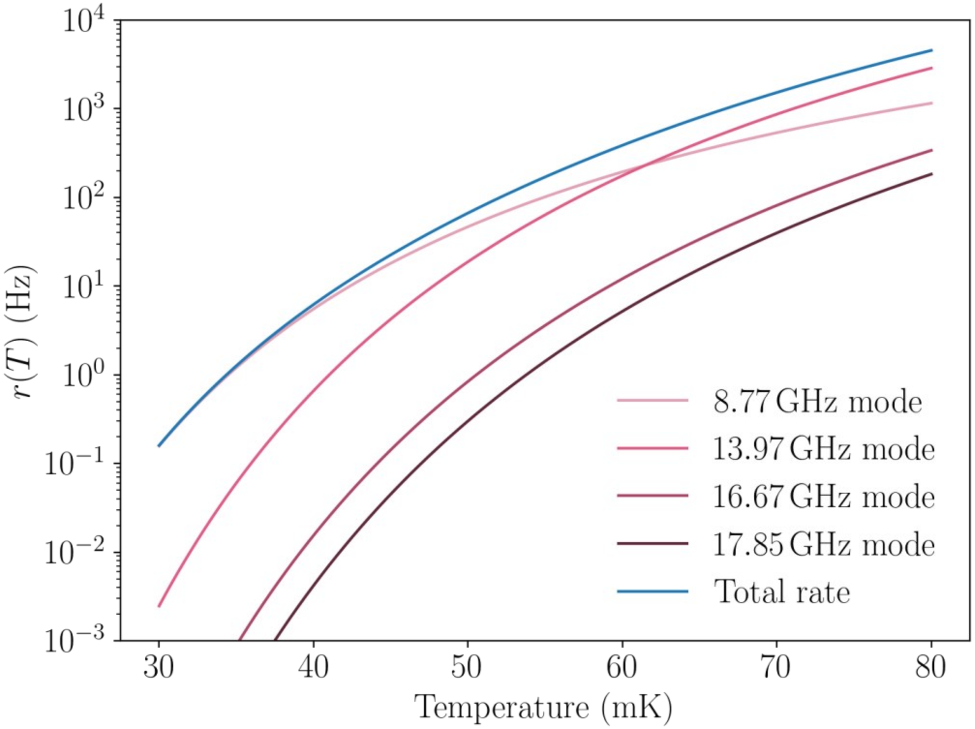



**Detection efficiency reaches 45 % - enough for axion search!**



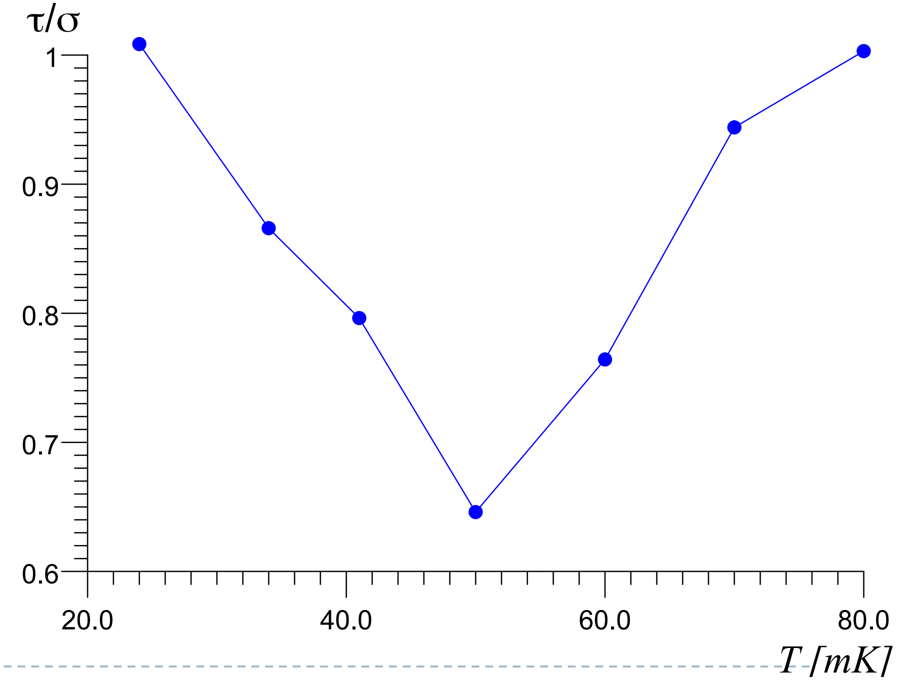
https://www.nature.com/articles/s41467-025-56040-4

# Change of Poisson statistics




**Calculating the ratio of the mean τ to the standard deviation σ – basic test of Poisson statistics**

**τ/σ<1 – super-Poisson distribution.**




**Change of Poisson statistics**

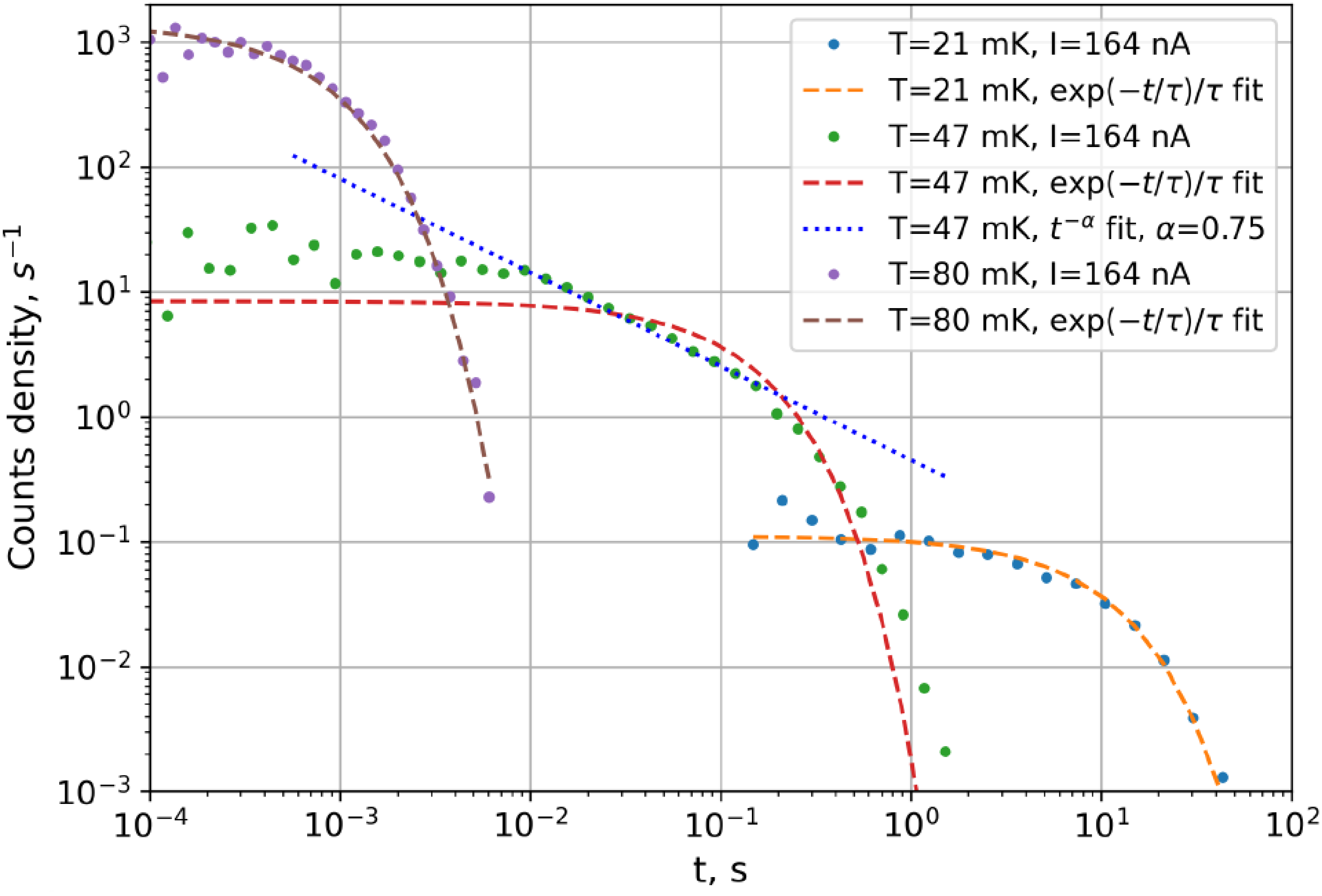
**– confirmation of thermal photons!**

M. Fox, **Quantum Optics: An Introduction**
Vol. 15 of Oxford Master Series in Physics
(Oxford University Press, 2006)

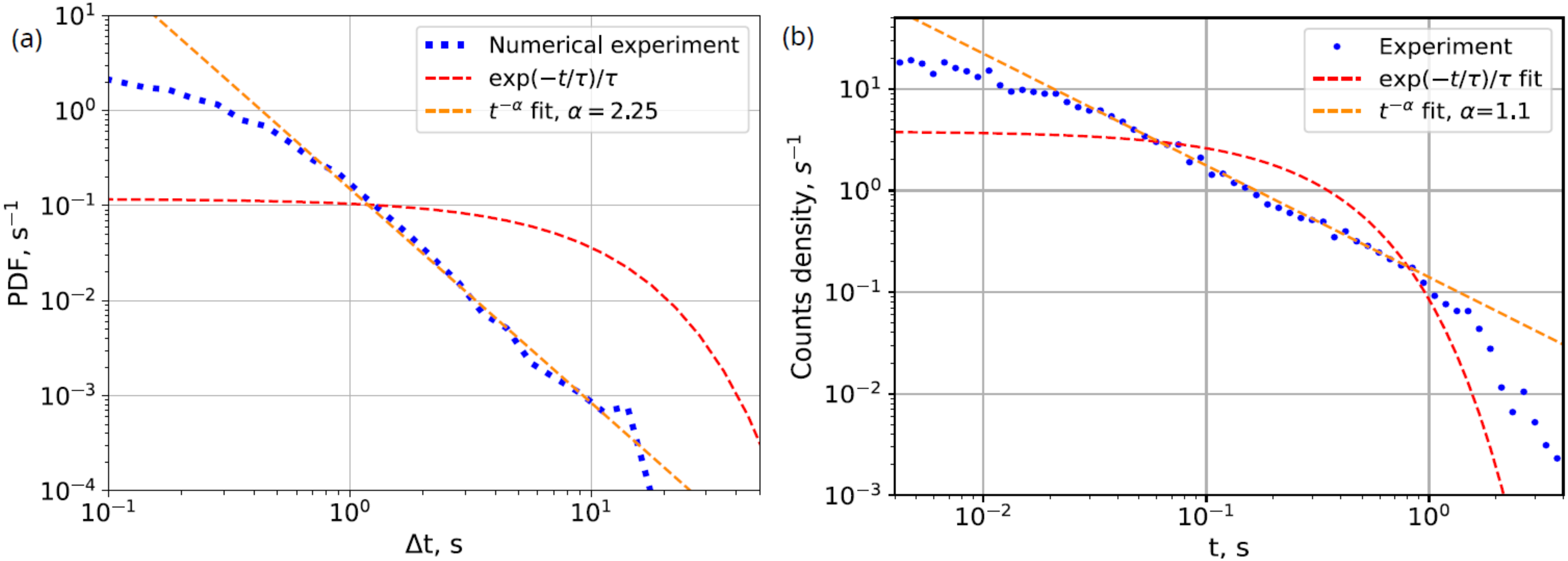


https://www.nature.com/articles/s41467-025-56040-4

# Change of Poisson statistics



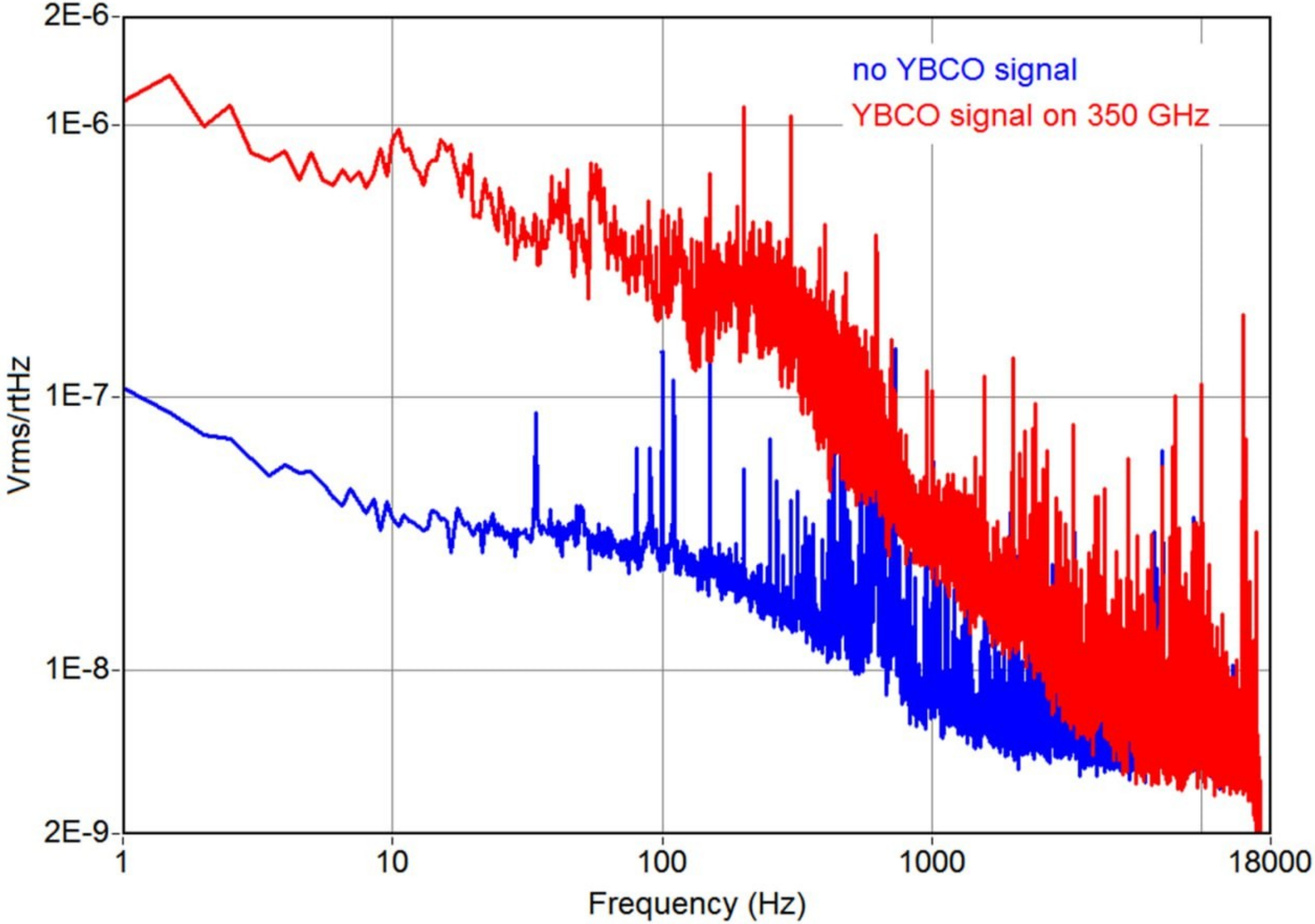
# Change of Poisson statistics




a) Numerically computed distributions according to [47]. b) Measured switching time distribution (blue dots) of thermal photons from a cavity representing super-Poissonian distribution, fitted with exponent (red dashed curve) and $t^{\alpha}$ dependence.

[47] I. I. Yusipov, O. S. Vershinina, S. V. Denisov, M. V. Ivanchenko, Chaos 30, 023107 (2020).

# Thank you for attention!



no YBCO signal
YBCO signal on 350 GHz
Vrms/rtHz
2E-6
1E-6
1E-7
1E-8
2E-9
1
10
100
1000
18000
Frequency (Hz)