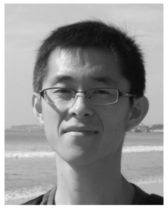
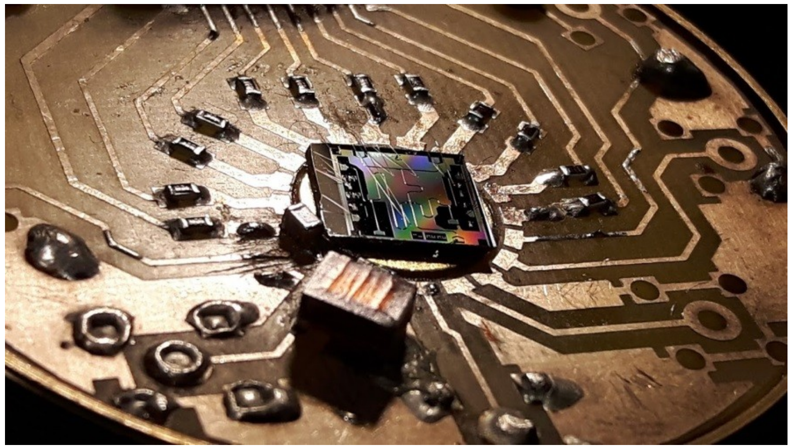
Thermometry and nano-calorimetry at very low temperatures

Jukka Pekola, Aalto University, Helsinki, Finland

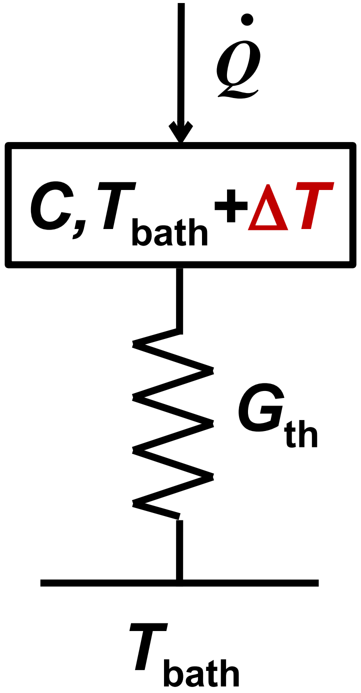
1. **Heat** in circuits
2. **Thermometry**
3. **Nano-calorimetry** limited by temperature fluctuations

Main collaborators:
Bayan Karimi
Libin Wang
Klaara Viisanen
Olli-Pentti Saira

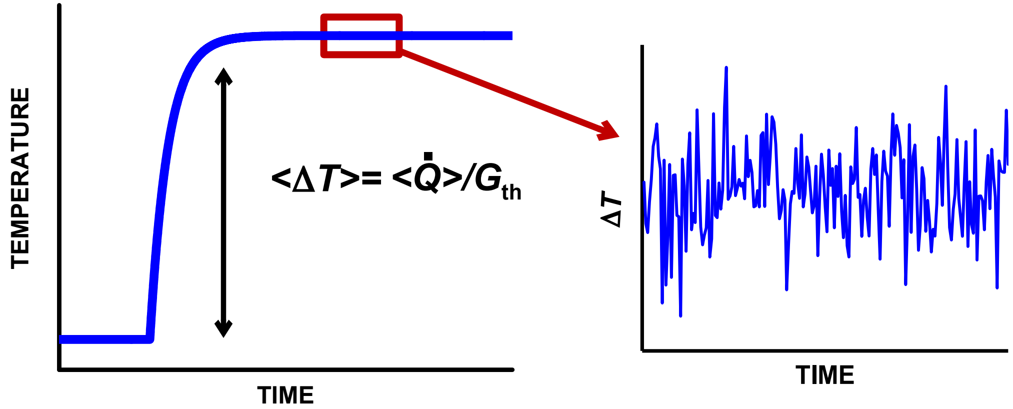




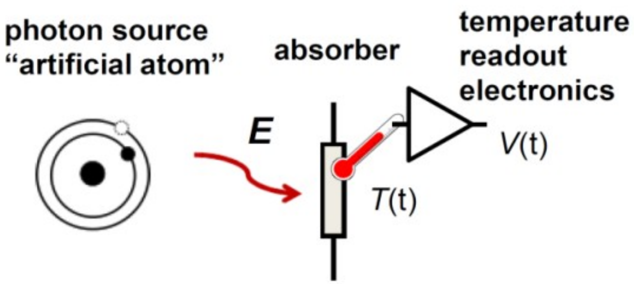
Measuring heat and radiation quanta by thermometry

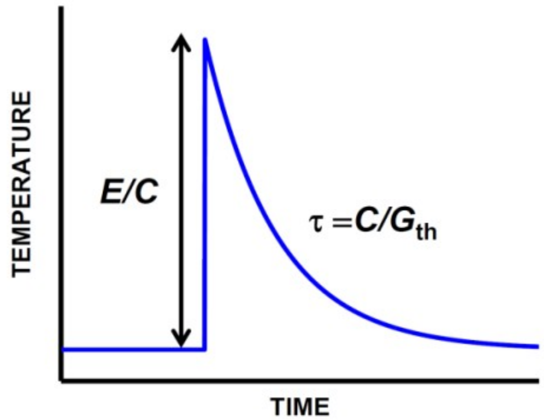


Measurement of temperature and its noise by a fast thermometer



Single quantum detection (calorimetry): electrons, photons

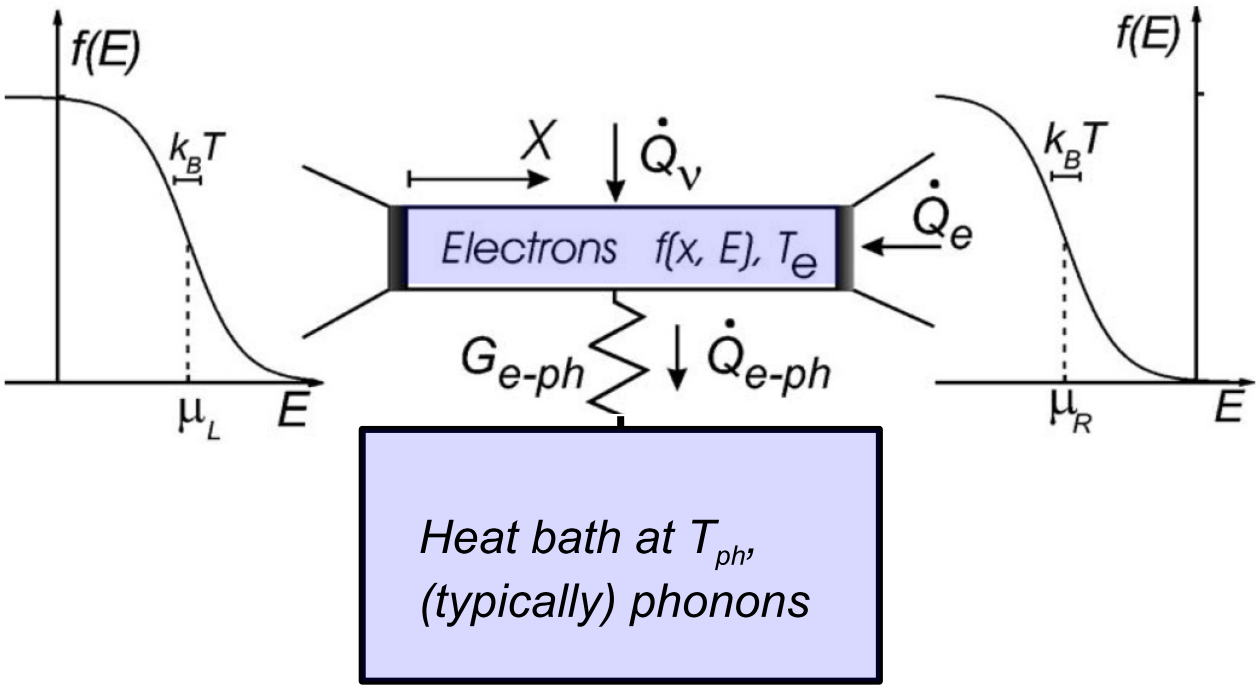




Energy resolution:

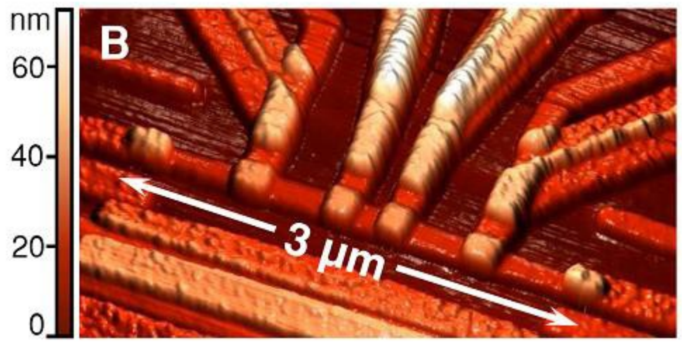
$$\delta E = \sqrt{C G_{\mathrm{th}} S_T} \quad \text{ideally} \quad \delta E = \sqrt{k_B C}\, T$$

Generic thermal model of an electronic conductor



Temperature of the (electron) system given by the distribution:

$$f(E) = \frac{1}{1 + e^{(E-\mu)/k_BT}}$$

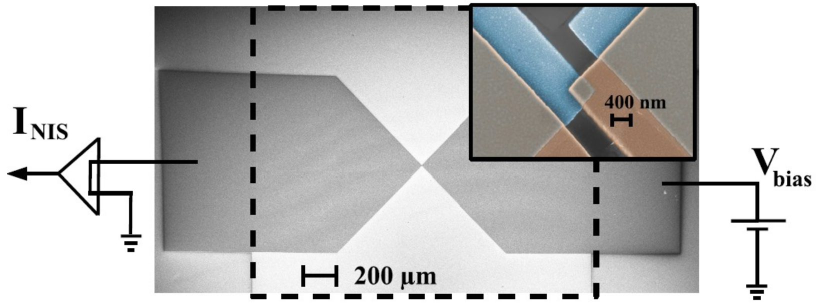


Separation of time scales: $\tau_{ee} < 10^{-9}$ s, $\tau_{ep} > 10^{-6}$ s

NIS-thermometry

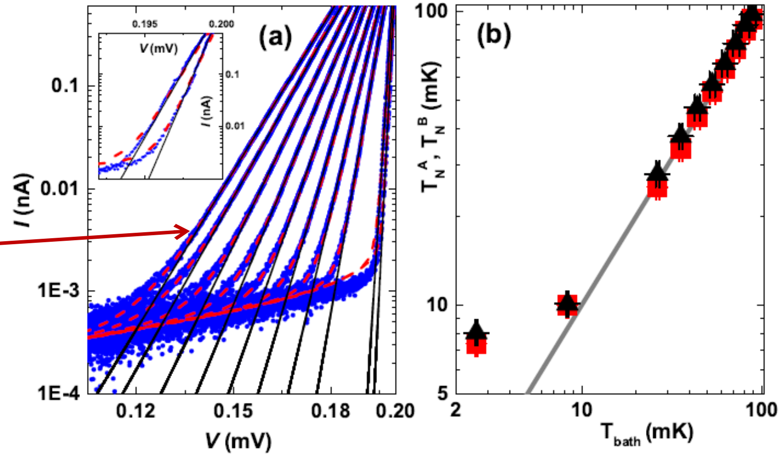
$$I = \frac{1}{2eR_T}\int n_S(E)[f_N(E-eV) - f_N(E+eV)]dE$$

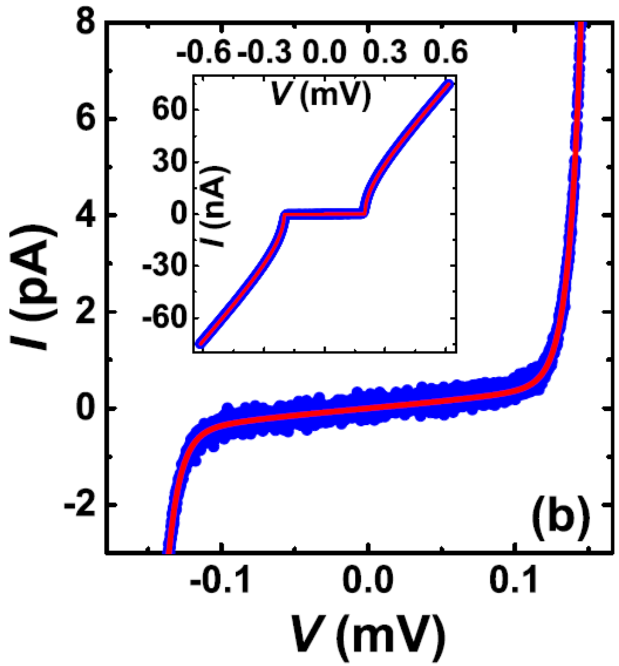
Probes electron temperature of N electrode (and not of S!)



$$I \approx I_0 e^{-(\Delta - eV)/k_B T}$$

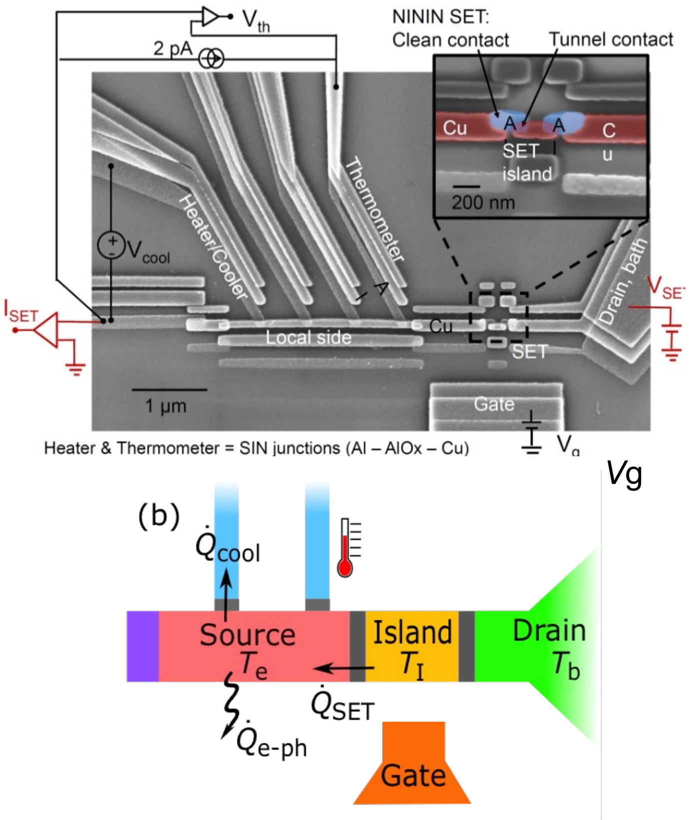
$$\frac{\mathrm{d}\ln(I/I_0)}{\mathrm{d}V} \approx \frac{e}{k_B T}$$

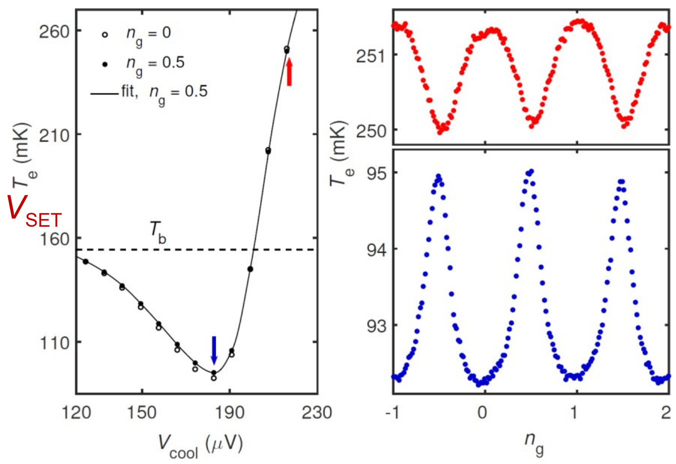




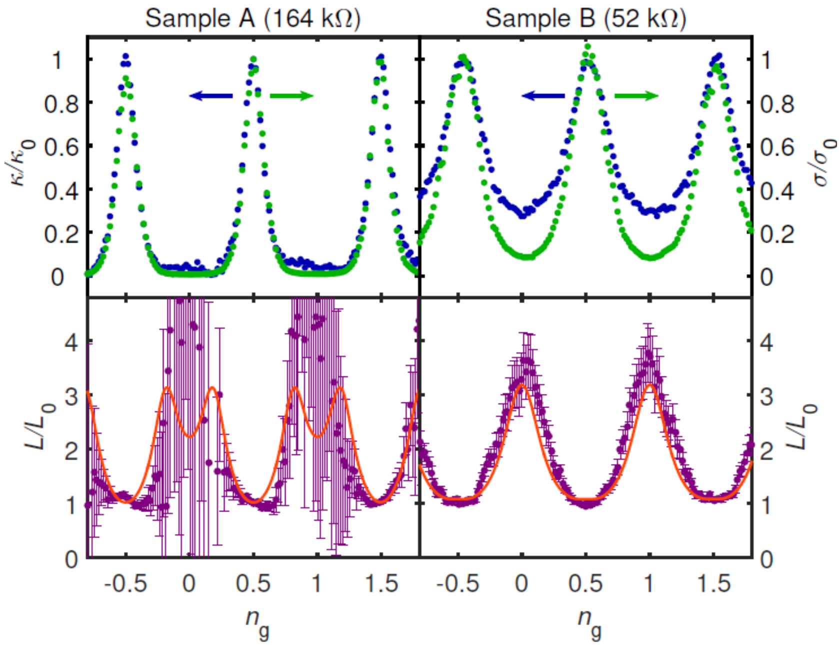
Phys. Rev. Appl. 4, 034001 (2015).

Heat through a single-electron transistor – deviation from Wiedemann-Franz law

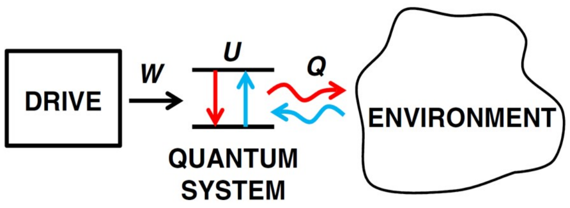


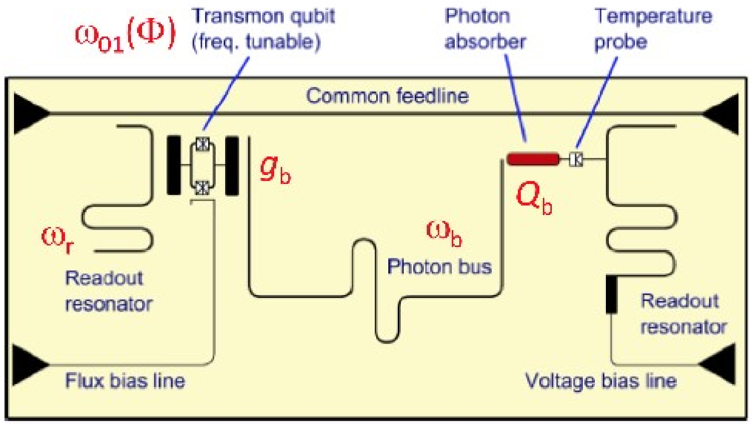


B. Dutta et al., PRL **119**, 077701 (2017)



Quantum thermodynamics with superconducting qubits and resonators (cQTD)

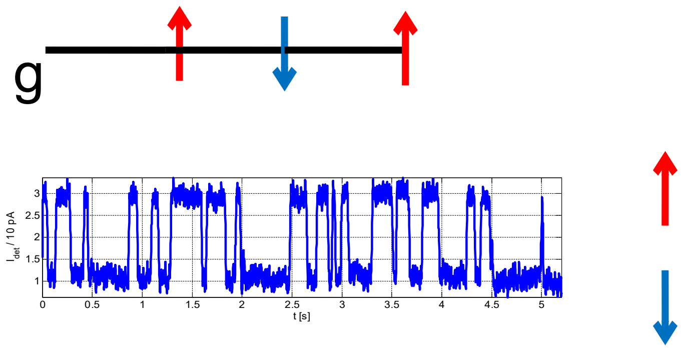




Stochastic thermodynamics of a driven qubit
Quantum jumps/trajectories

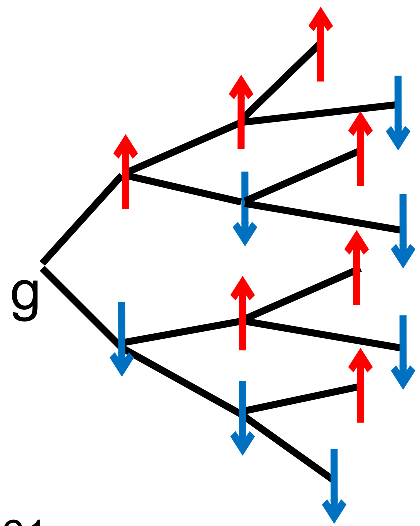
Hekking and JP, PRL 111, 093602 (2013);
Horowitz and Parrondo, NJP 15, 085028 (2013)

Classical evolution



TIME

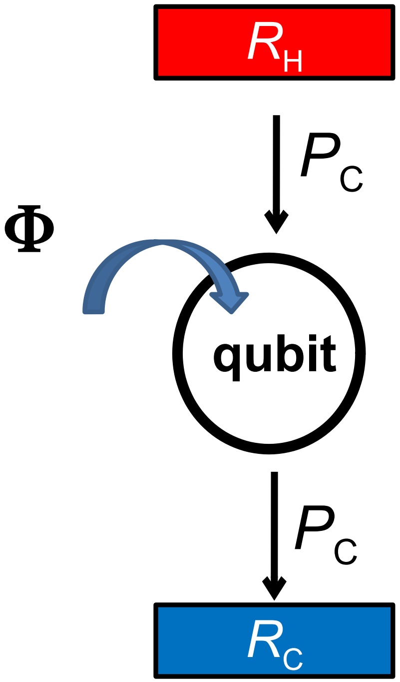
Quantum evolution

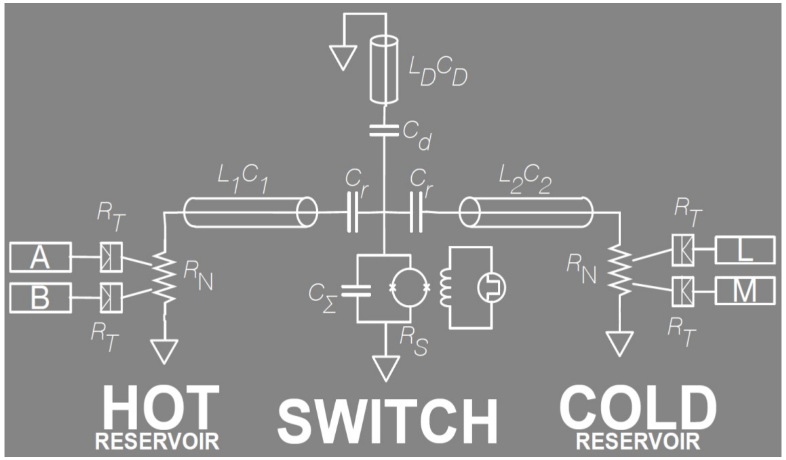


Direct dispersive measurements of a qubit: N. Cottet,..., B. Huard, arXiv:1702.05161

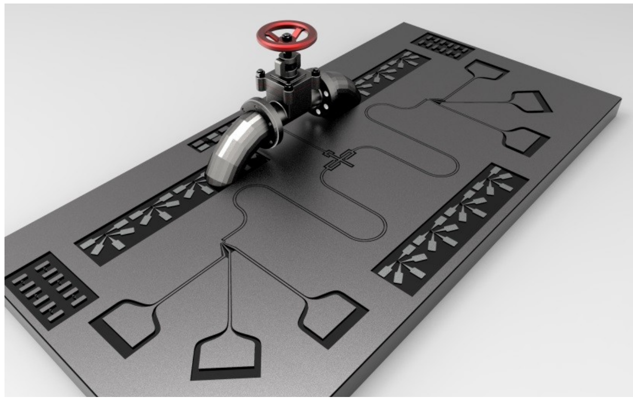
Quantum heat valve

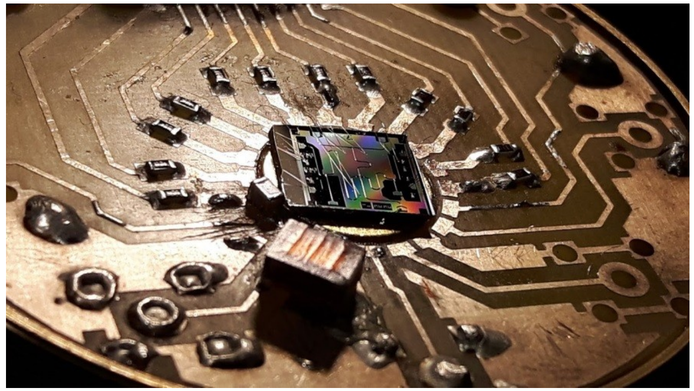
Alberto Ronzani, Bayan Karimi, Jorden Senior, Yu-Cheng Chang, ChiiDong Chen, Joonas T. Peltonen, and JP, Nature Physics **14, 991** ***(2018).***



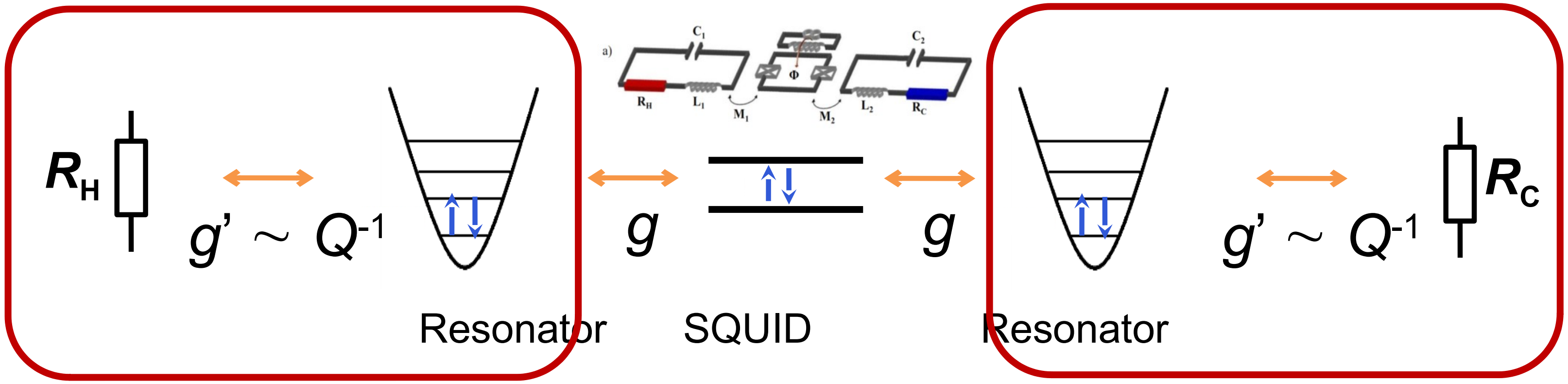


B. Karimi, J. Pekola, M. Campisi, and R. Fazio, Quantum Science and Technology **2**, 044007 (2017).



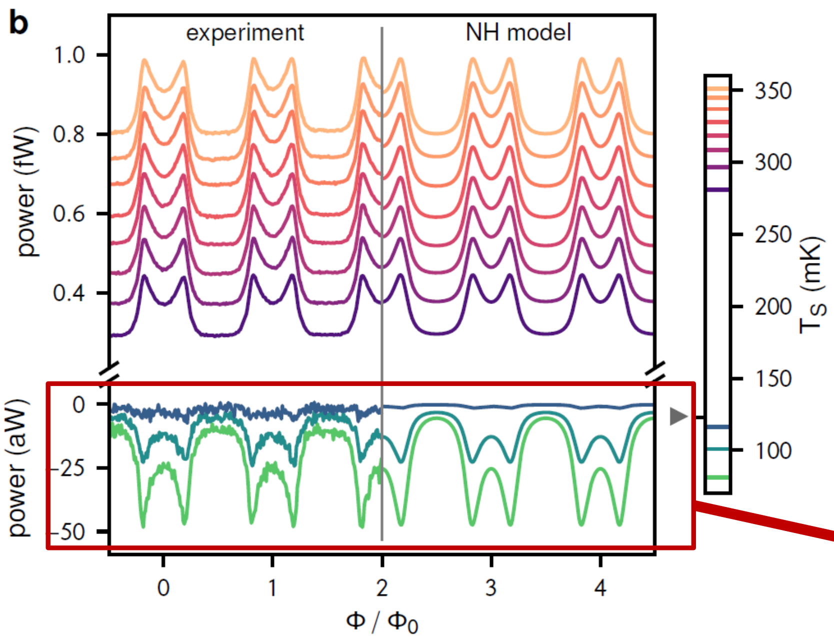


Theory vs experiment: low-Q regime

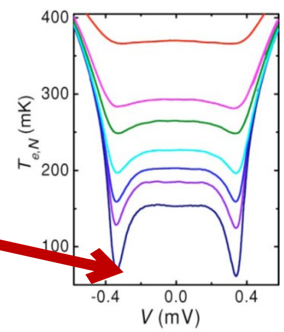


$gQ << 1$, ”non-Hamiltonian” model works

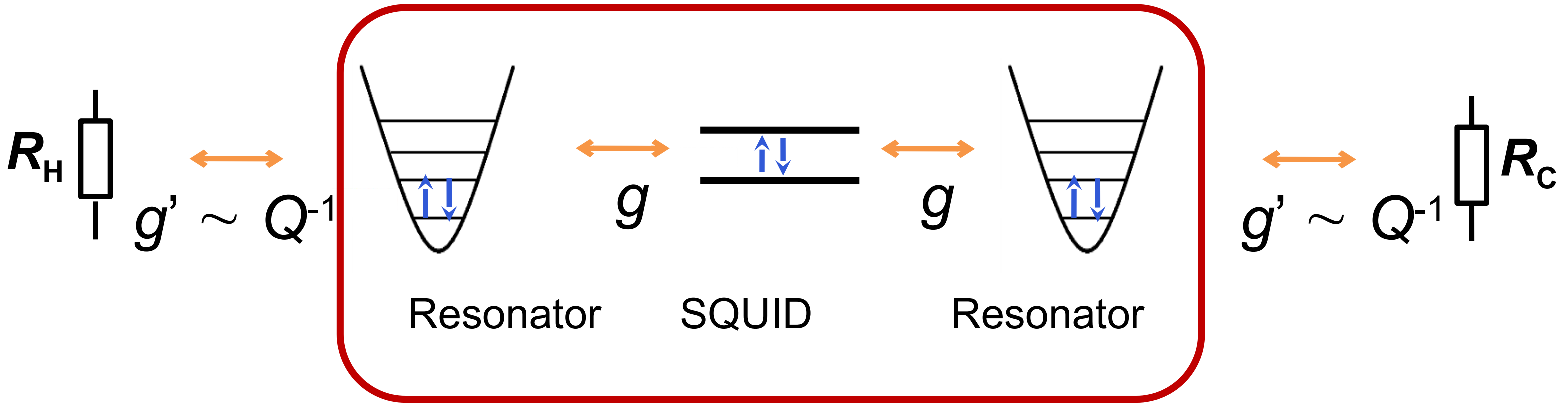
$Q = 3$



Cooling at distance of 4 mm by mw photons

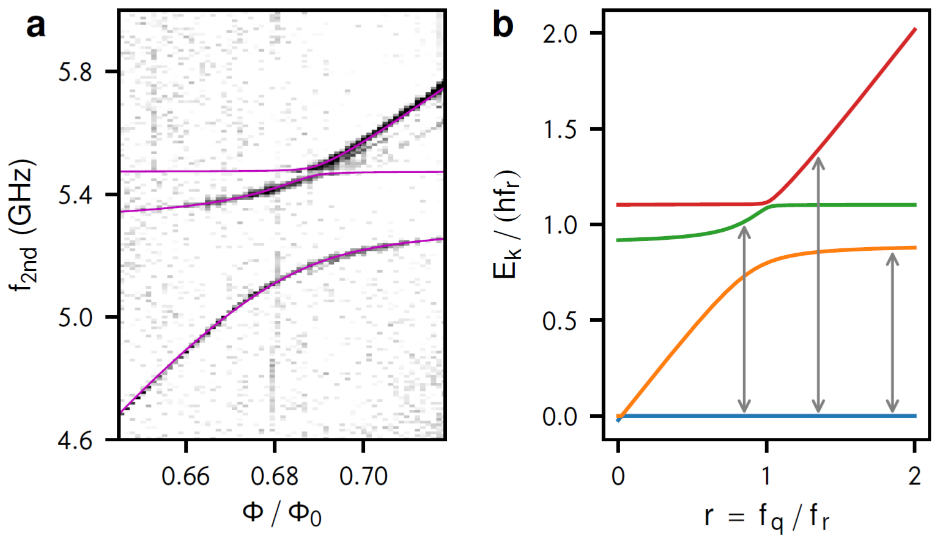


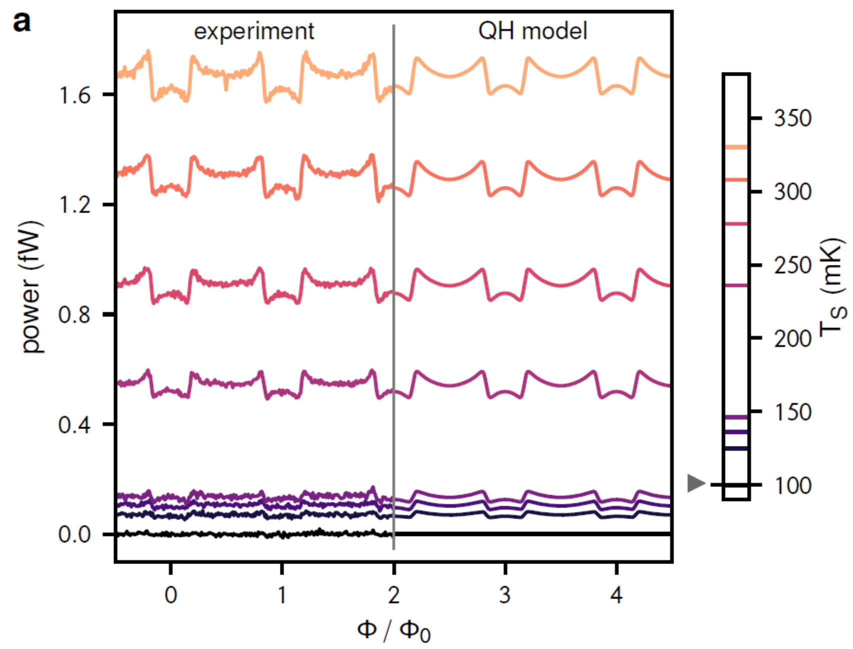
Theory vs experiment: intermediate-Q regime



$Q = 20$

$gQ \sim 1$, ”quasi-Hamiltonian” model works



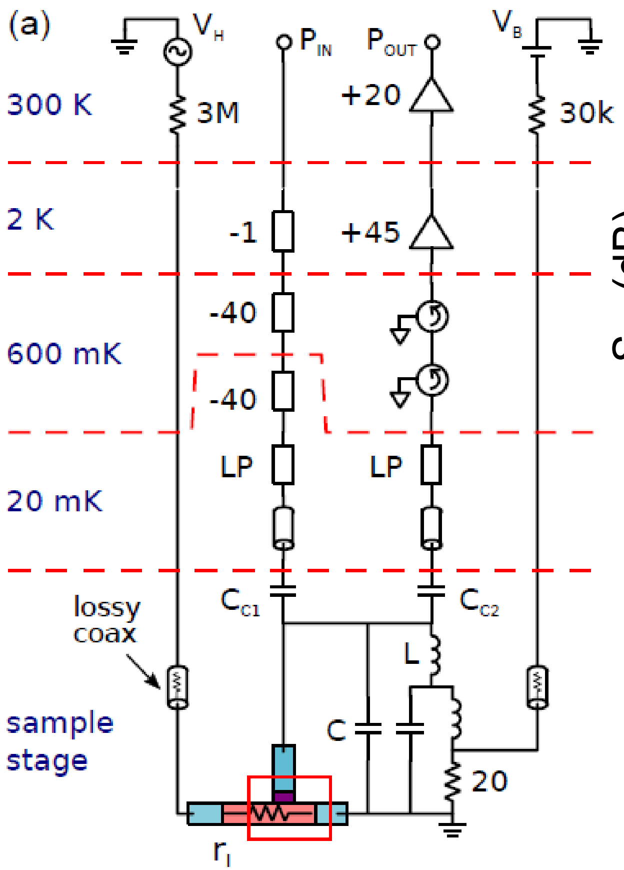


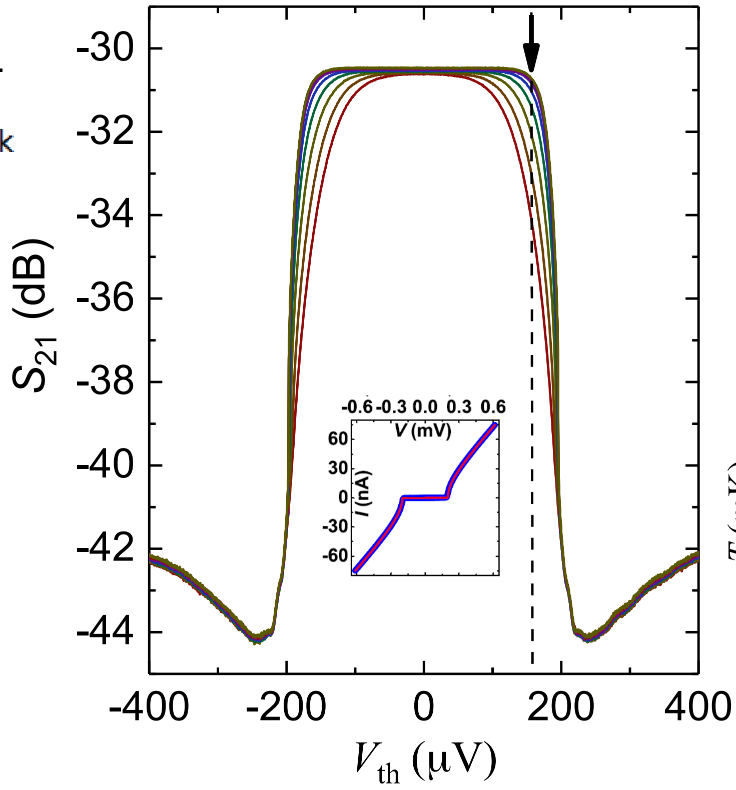
Fast NIS thermometry on electrons

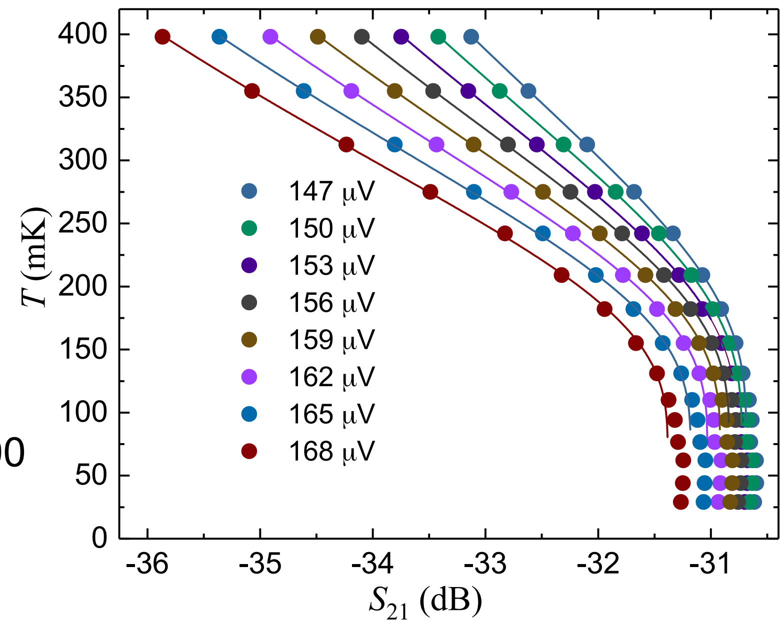
Read-out at 600 MHz of a NIS junction, 10 MHz bandwidth

S. Gasparinetti et al.,
Phys. Rev. Applied 3, 014007 (2015).

Proof of concept: D. Schmidt et al.,
Appl. Phys. Lett. 83, 1002 (2003).



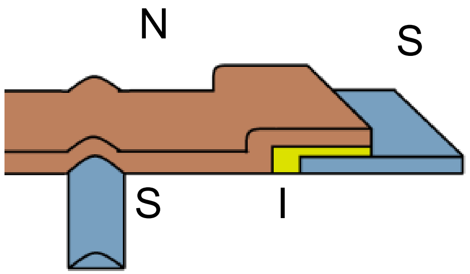




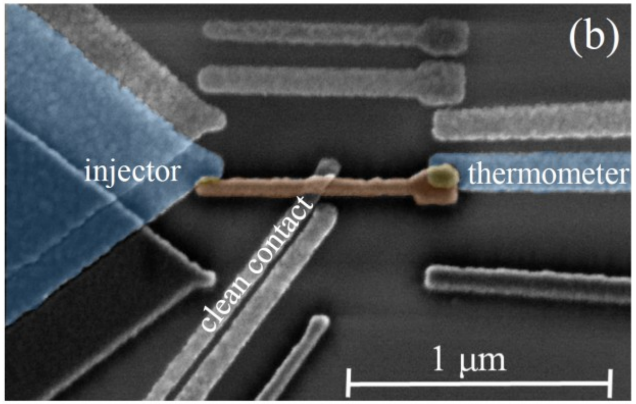
ZBA based thermometry

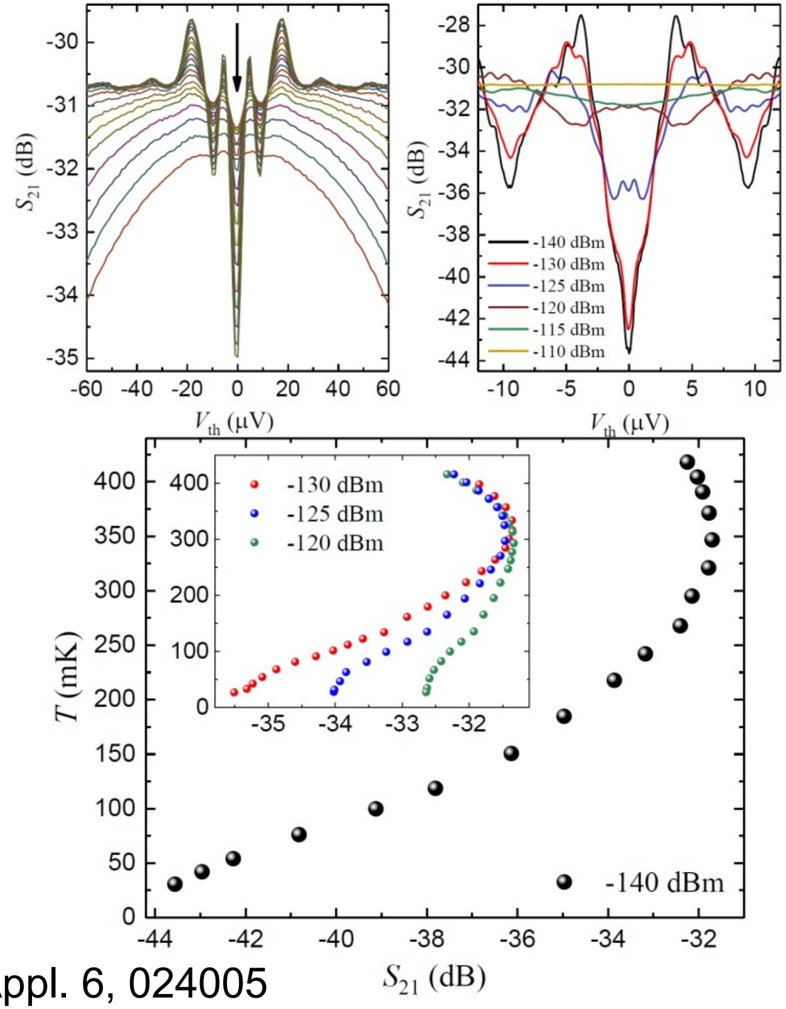
non-invasive, operates at low temperature

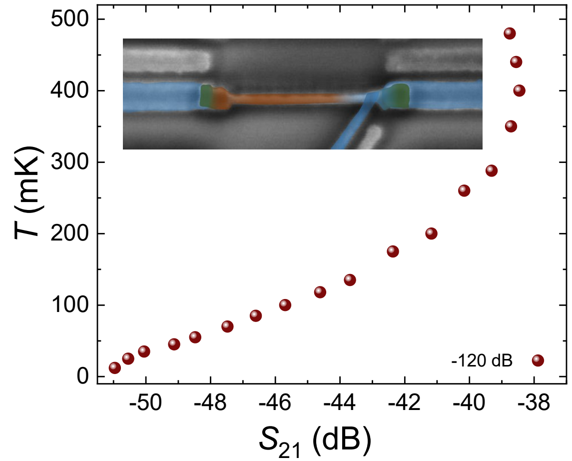
B. Karimi and JP, Phys. Rev. Applied **10**, 054048 (2018)

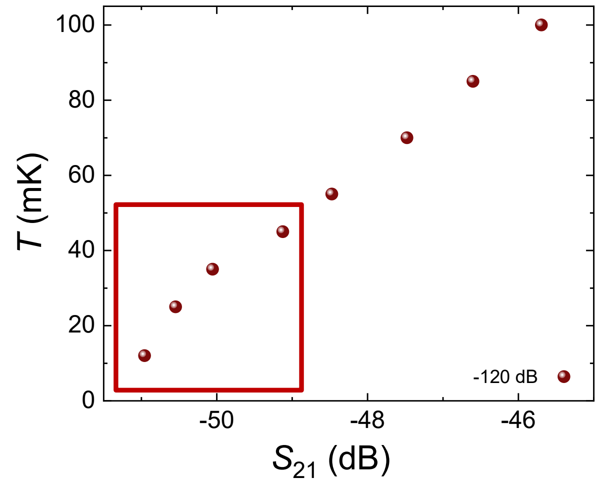


Proximity NIS junction



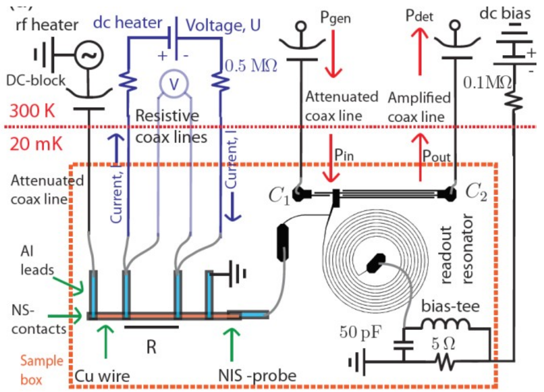


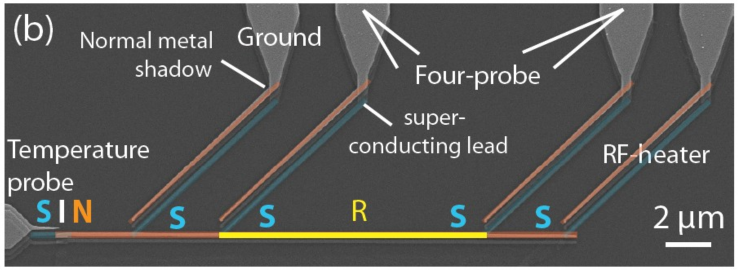




See also, O.-P. Saira et al., Phys. Rev. Appl. 6, 024005 (2016); J. Govenius et al., PRL 117, 030802 (2016)

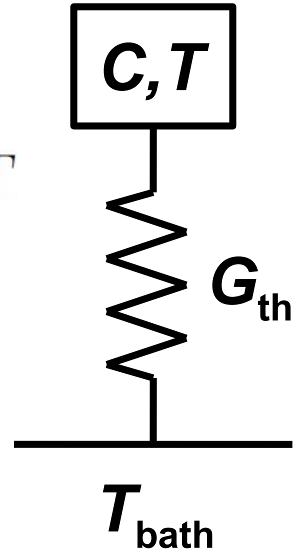
Time-resolved measurements by fast thermometer

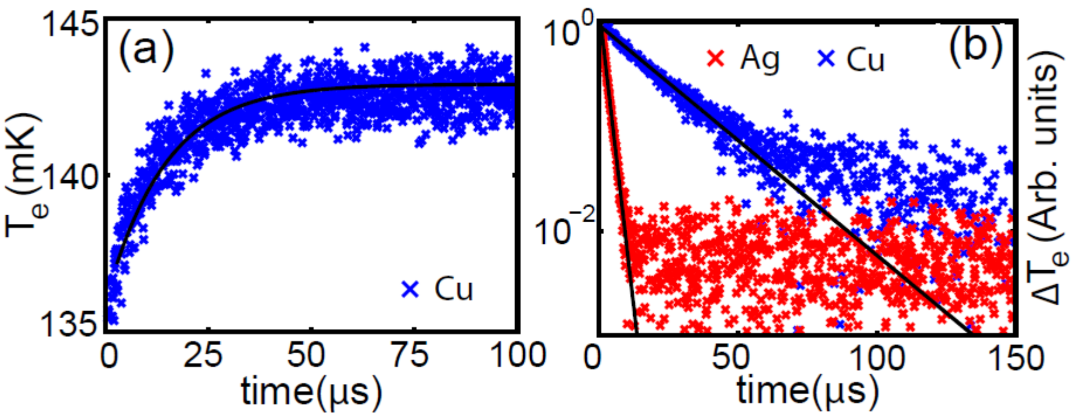


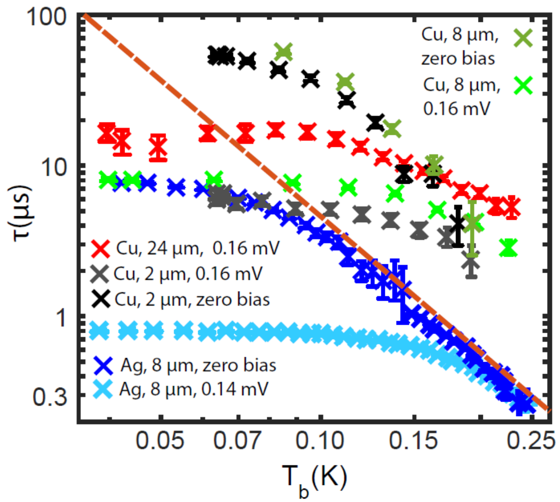


$$\mathcal{C}\frac{d\delta T}{dt} = -G_{\mathrm{th}}\delta T$$

$$\tau = \mathcal{C}/G_{\mathrm{th}}$$







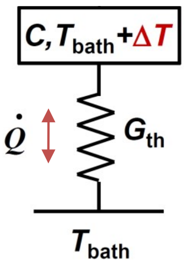
K. Viisanen and JP, PRB 97, 115422 (2018)

Noise of heat current and equilibrium temperature fluctuations

Noise of electrical curre $S_I(0) = 2k_BTG$ .e. Johnson-Nyquist noise $\langle \delta I^2 \rangle = 4k_BTG\Delta f$

Fluctuation-dissipation theorem for heat current

Low frequency noise:



$$S_{\dot{Q}}(0) = 2k_BT^2G_{\rm th}$$

$$\delta\dot{Q} = G_{\rm th}\delta T$$

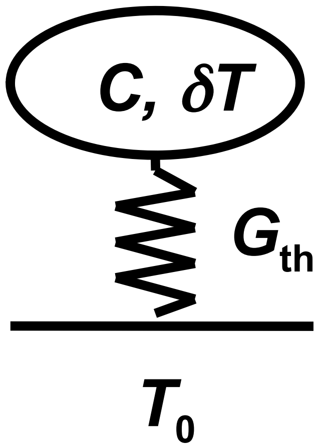
$$S_T(0) = 2k_BT^2/G_{\rm th}$$

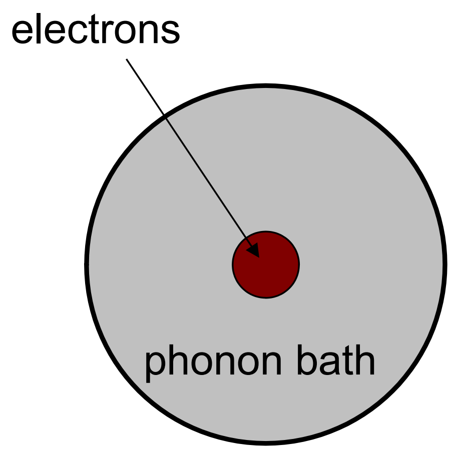
Finite frequencies (classical):

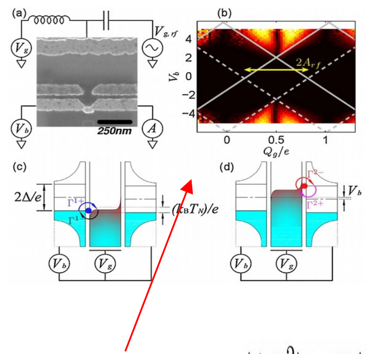
$$S_T(\omega) = \frac{S_T(0)}{1+(\omega/\omega_c)^2} \qquad \omega_c = G_{\rm th}/C$$

$$\langle \delta T^2 \rangle = \int \frac{d\omega}{2\pi} S_T(\omega) = k_BT^2/C$$

Temperature fluctuations







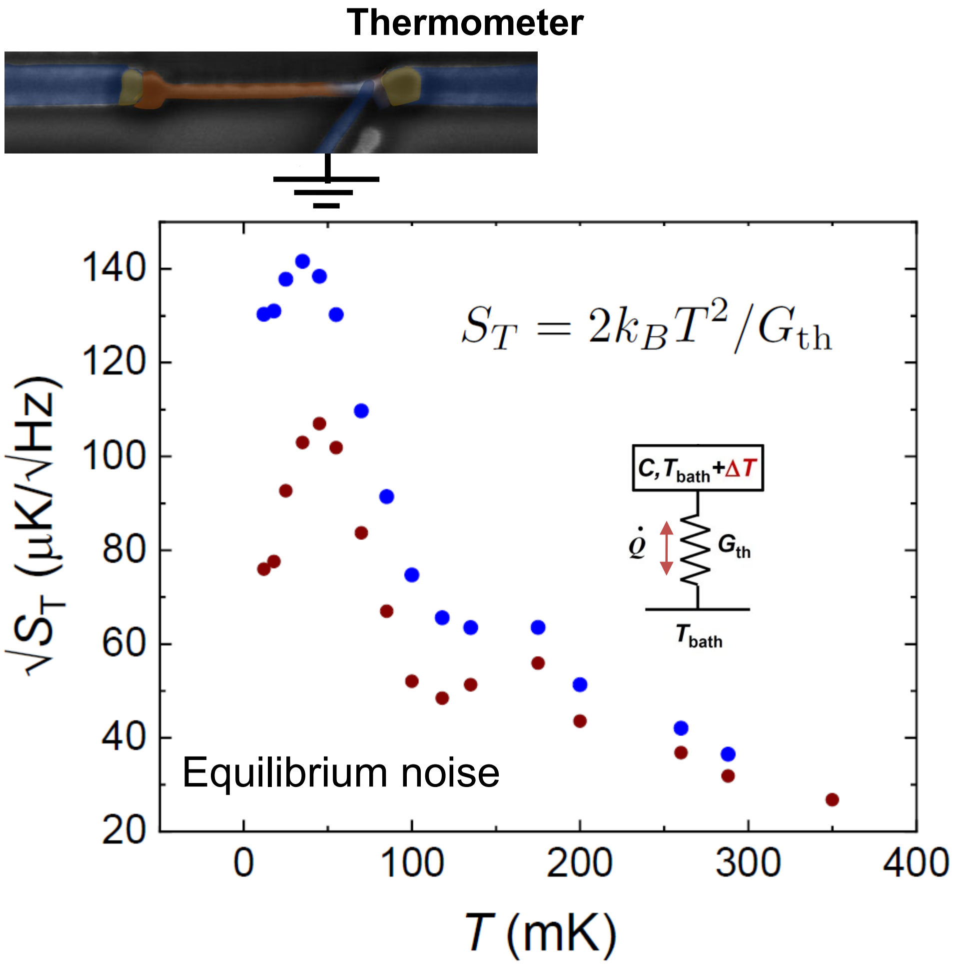
In this grain, $\langle \Delta T^2 \rangle \propto T/V$ is expected to be of the order of 1 mK at 100 mK, f_C = 10 kHz.

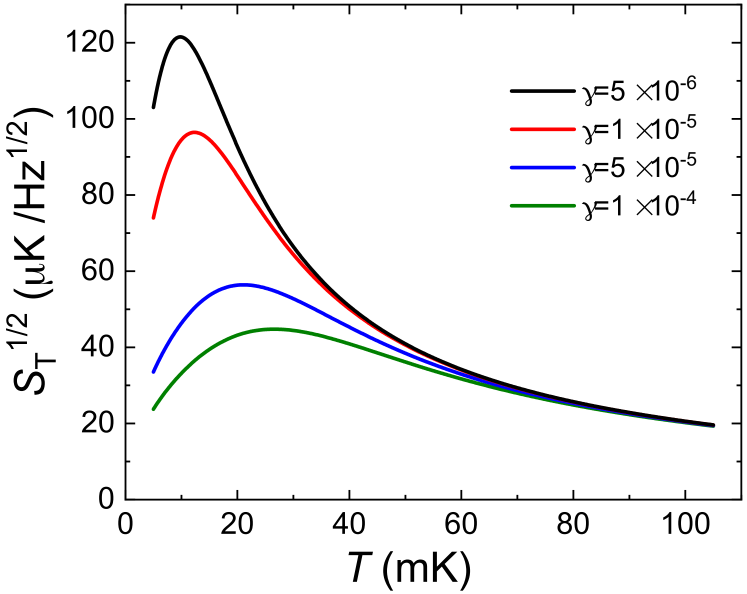
$$S_T(\omega) = \frac{2k_B T^2}{G_{\rm th}} \frac{1}{1+\omega^2 C^2/G_{\rm th}^2}$$

$$\langle \delta T^2 \rangle = k_B T^2/C$$

$$2\pi f_C = G_{\rm th}/C$$

Preliminary results on temperature fluctuations





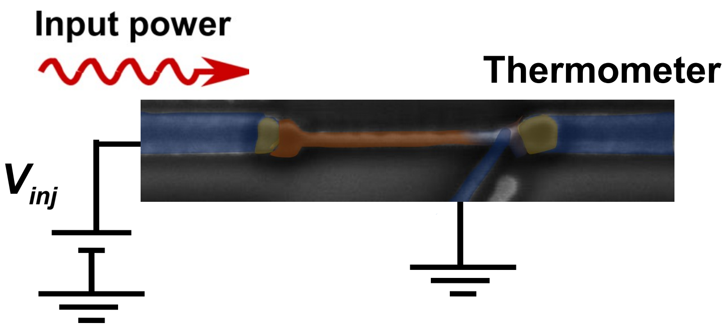
$$S_{\dot{Q}} = 2k_{\rm B}T^2 G_{th}$$

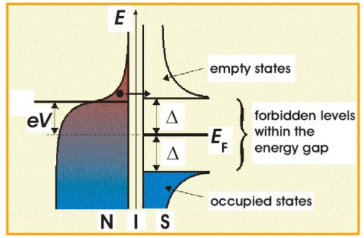
$$G_{th} = G_{th}^{ep} + G_{th}^{t} = 5\Sigma\mathcal{V}T^4 + \mathcal{L}_0\frac{\gamma}{R_T}T$$

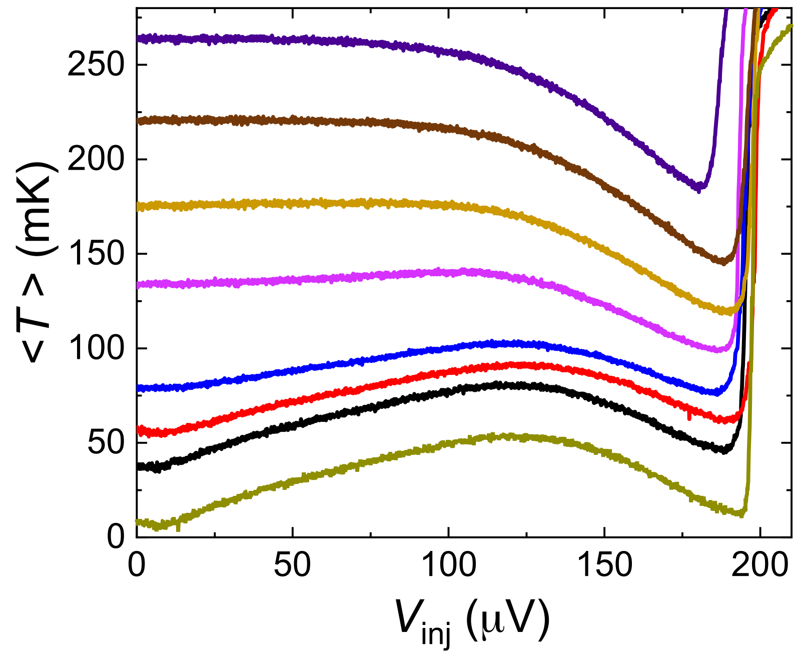
$$S_T = \frac{S_{\dot{Q}}}{G_{th}^2} = \frac{2k_{\rm B}T^2}{G_{th}}$$

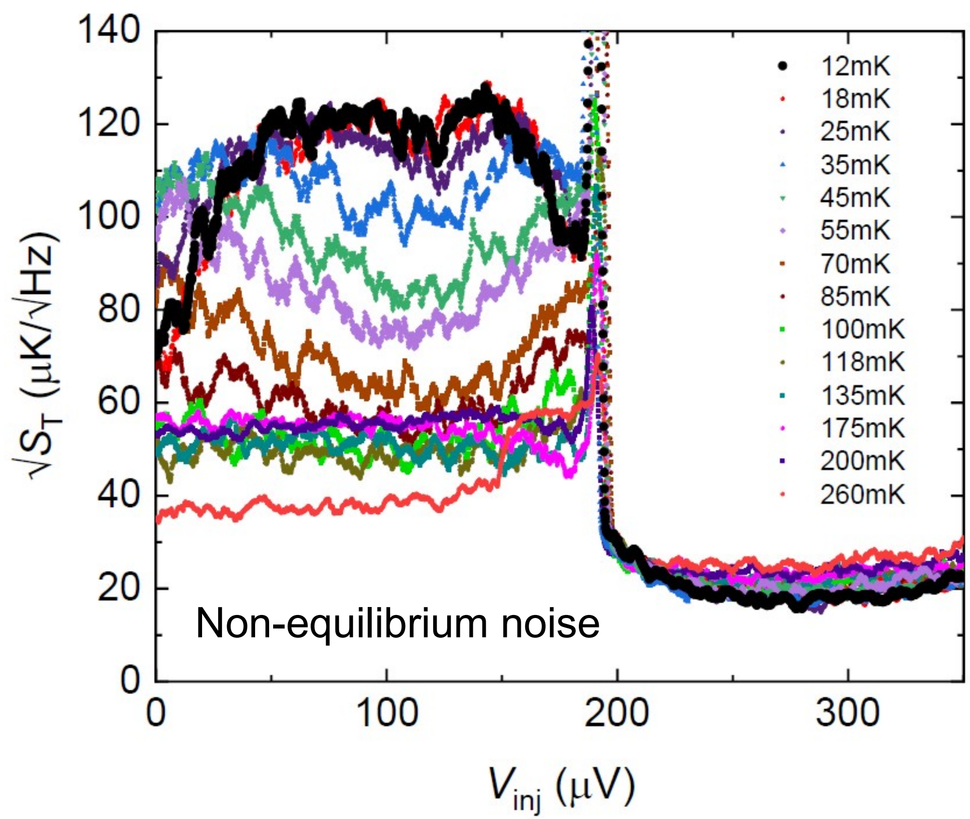
B. Karimi et al., in preparation

Non-equilirium temperature noise





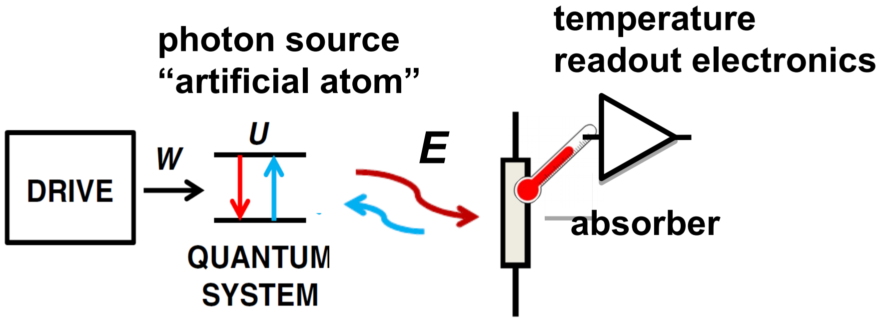




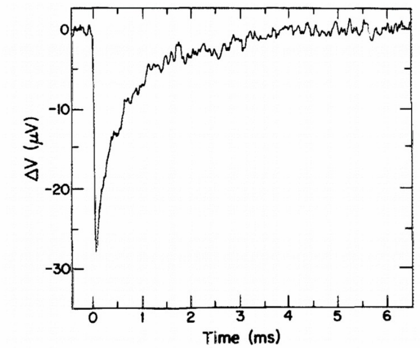
B. Karimi et al., in preparation

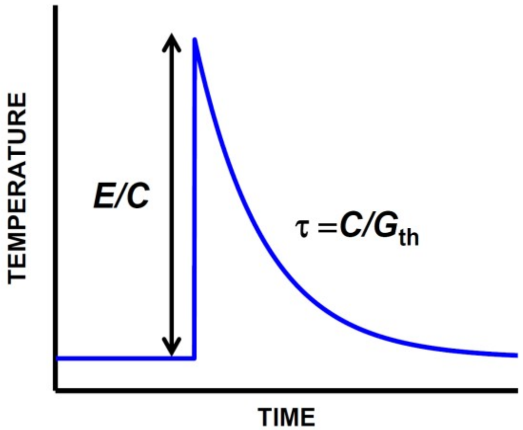
Theory: F. Brange, P. Samuelsson, B. Karimi, and JP, PRB **98**, 205414 (2018)

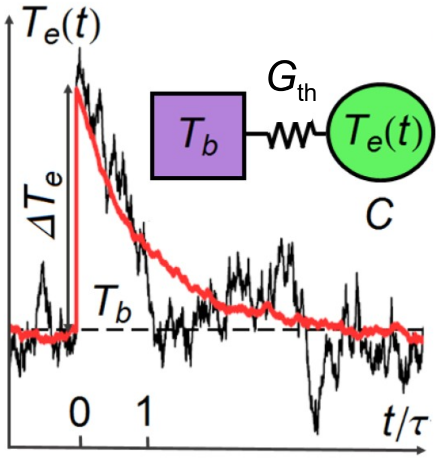
Towards calorimetry for measuring mw photons



D. McCammon et al., 1984 Single x-ray photon detection E = 6 keV







Typical parameters

Operating temperature:
T = 0.03...0.1 K
Photon energy:
E/k_B = 0.3...1 K
Heat capacity of absorber:
C = 300...1000k_B

ΔT ~ 1...3 mK. τ ~ 0.01...1 ms

Ideally $$\delta E = \sqrt{k_B C\,T}$$

Note: Energy resolution needs to be about 10^8 better than for typical X-ray calorimeters

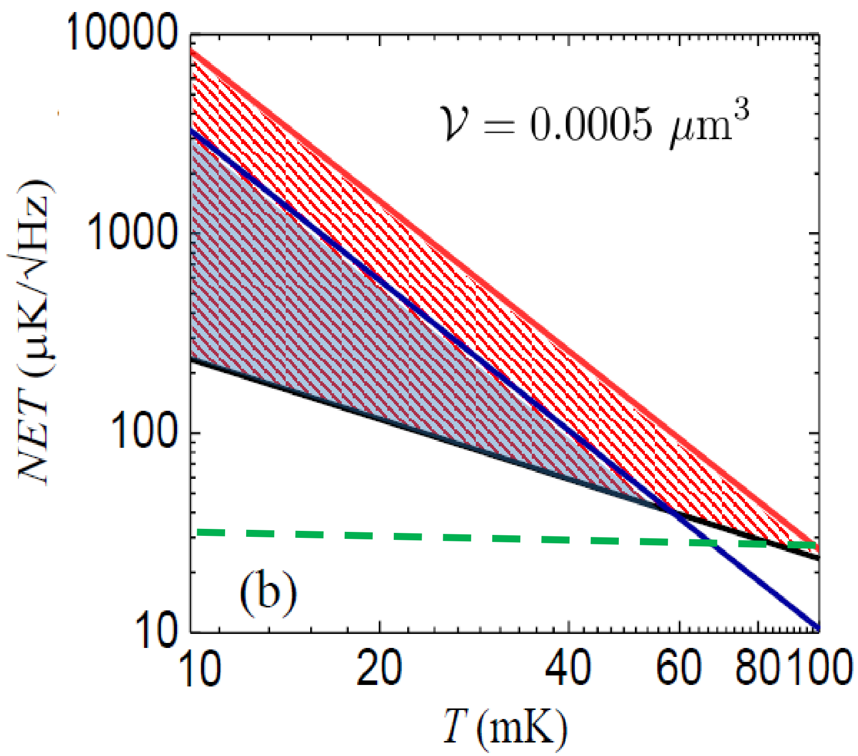
Requirements for single microwave photon detection

Detector noise bounded from below by effective temperature fluctuations of the absorber coupled to the bath.

$$\langle \delta T^2 \rangle = \int_{-\infty}^{\infty} \frac{d\omega}{2\pi} S_T(\omega) = k_B T^2 / C$$

Noise-equivalent temperature, NET

$$\mathrm{NET} \equiv S_T(0)^{1/2} = (2 k_B T^2 / G_{\mathrm{th}})^{1/2}$$



Standard copper absorber

Lines:

Green dashed one: current amplifier limited noise
Black: fundamental temperature fluctuations
Blue: threshold for detecting a single 1 K (100 μeV) microwave photon
Red: threshold for detecting a single 2.5 K quantum

B. Karimi and JP, Phys. Rev. Applied **10**, 054048 (2018)

Summary

Discussed:

Thermometry and calorimetry on low-T nanostructures

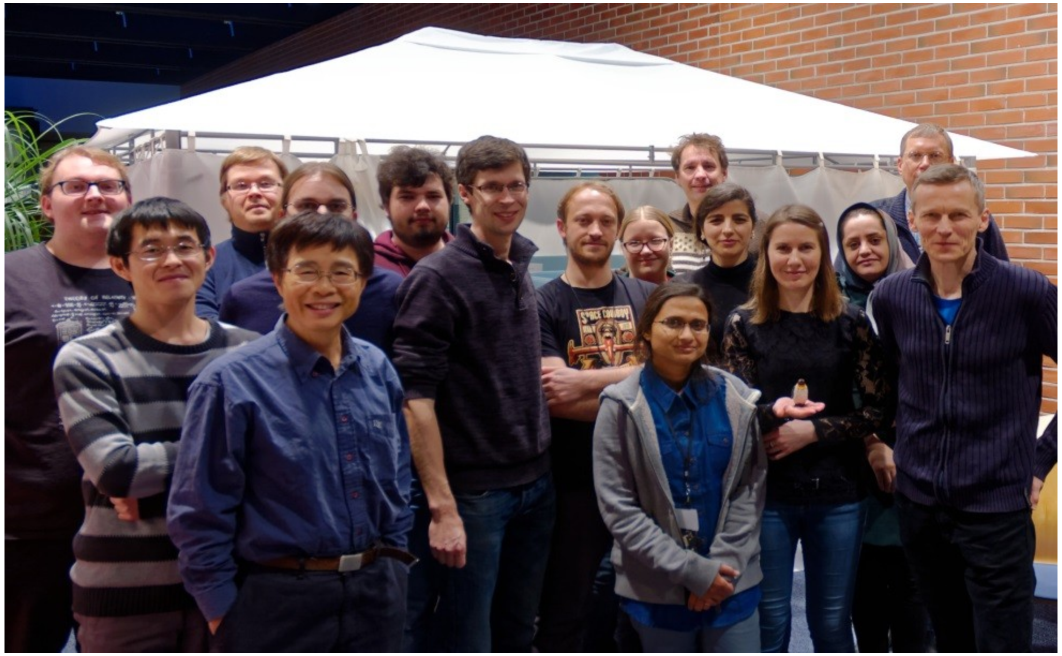
Potential for detecting < 10 GHz quanta

ACADEMY OF FINLAND

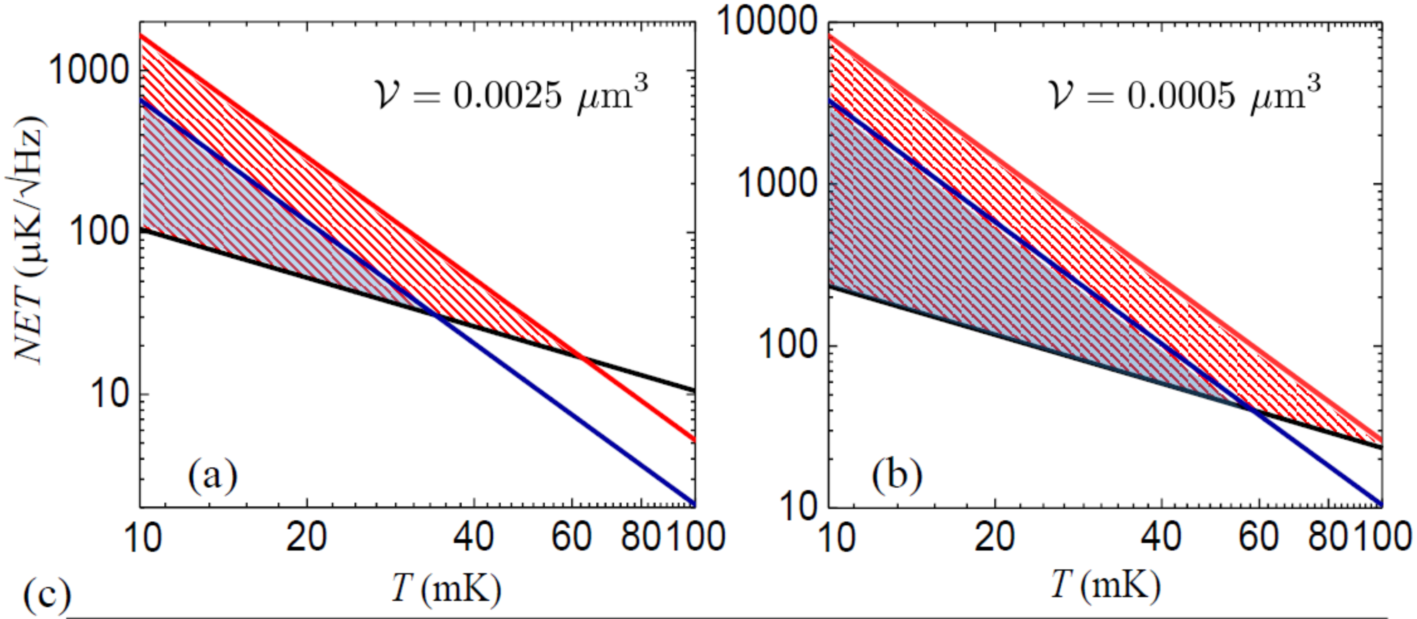
erc
European Research Council
Established by the European Commission

MARIE CURIE ACTIONS

nano SCIENCES
FOUNDATION
under the auspices of the
Université Grenoble Alpes Foundation



Requirements for single microwave photon detection



Standard copper absorber

(c)

Sample	T (mK)	$\mathcal{V}$ (μm^3)	$\mathbb{NET}_0$	$\mathbb{NET}^{e}_{req}$ ($\mu K/\sqrt{Hz}$)	$\mathbb{NET}^{ph}_{req}$	$(\mathbb{S}/\mathbb{N})_e$	$(\mathbb{S}/\mathbb{N})_{ph}$
B	130	0.005	5.7	1.4	0.5	0.2	0.1
A	50	0.0025	21	30	12	1.4	0.6
A	25	0.0025	42	170	67	4.0	1.6
Opt	10	0.0005	235	8250	3300	35	14