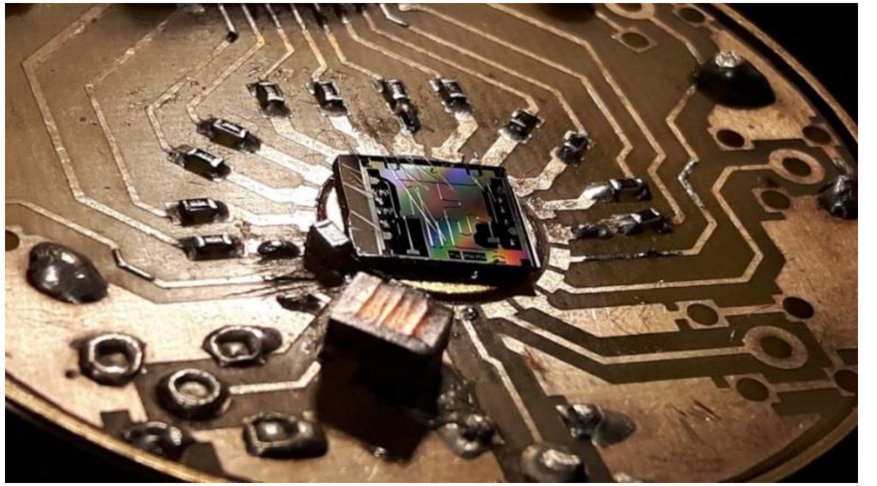
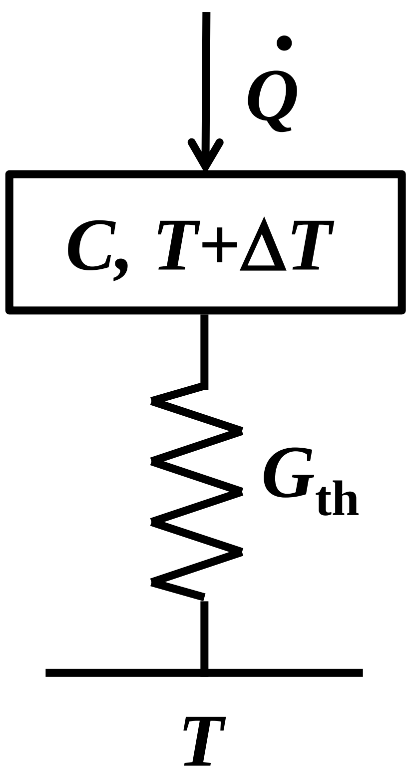
Experiments on quantum heat transport through a superconducting qubit and a single-electron transistor

Jukka Pekola, Aalto University, Helsinki, Finland

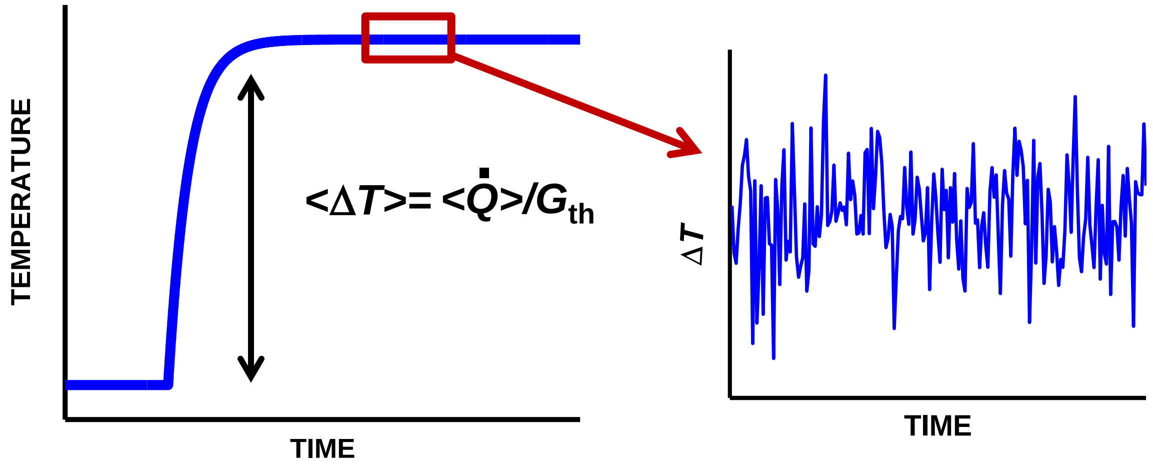
1. Heat in circuits: measurement and control
2. Thermometry
3. Single-electron transistor: heat transport and thermopower
4. Circuit quantum thermodynamics (cQTD): quantum of heat conductance, quantum heat valve, local and global picture, rectification of heat current
5. Fast thermometry, calorimetry



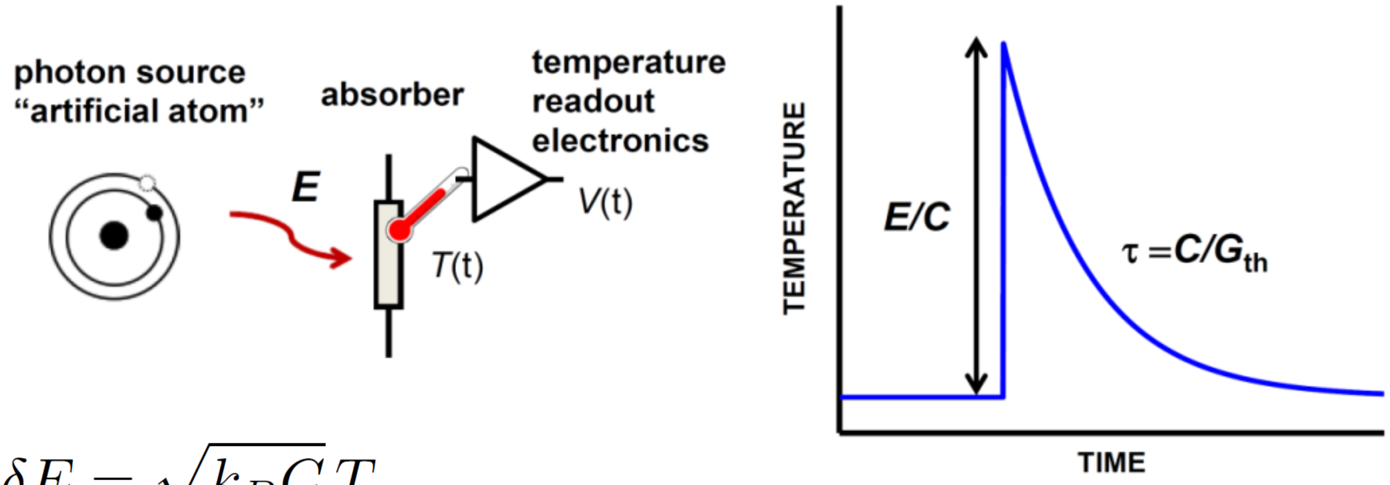
Measuring heat currents



Measurement of temperature by a (fast) thermometer

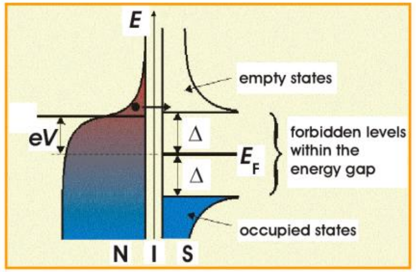


Single quantum detection (calorimetry

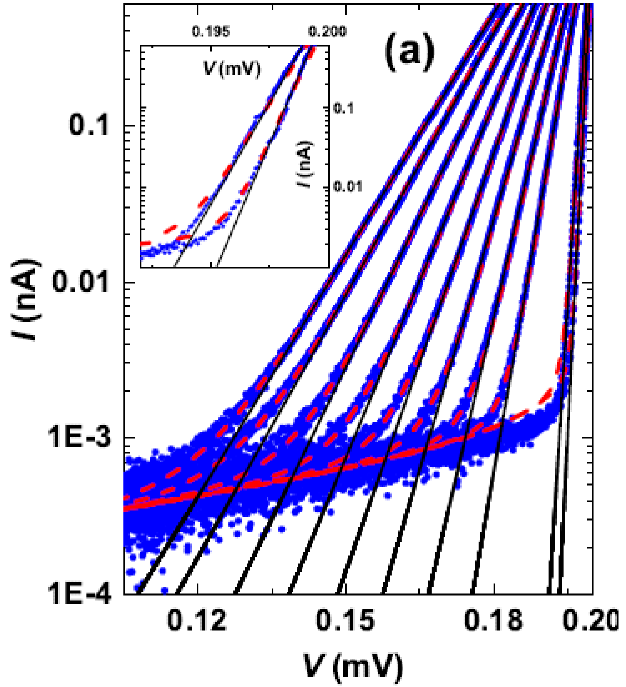


Energy resolution:

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

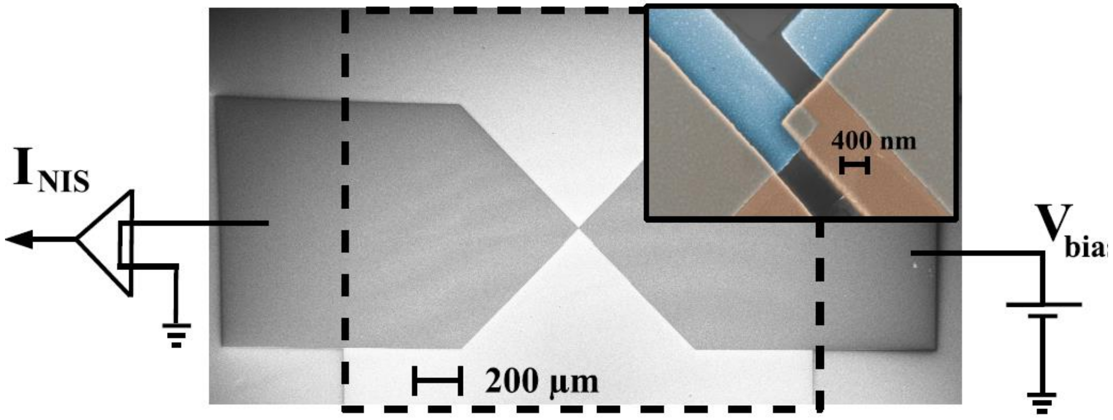


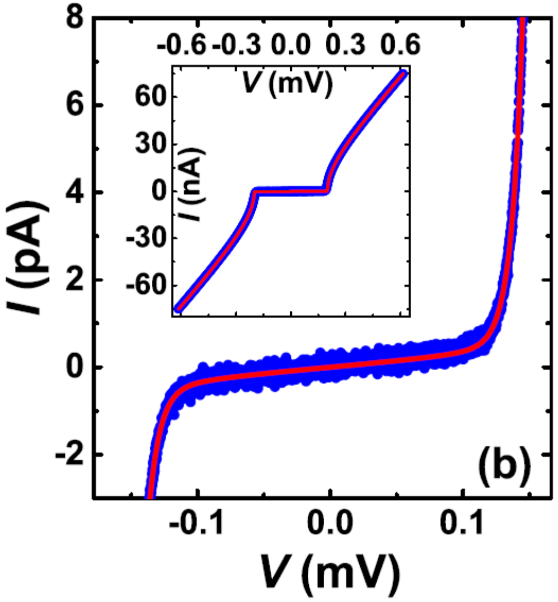
NIS-thermometry

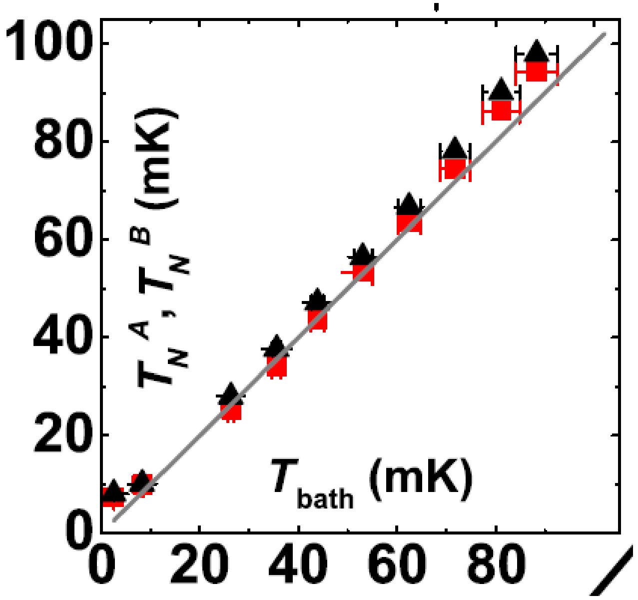


$$I = \frac{1}{2eR_T} \int n_S(E)[f_N(E - eV) - f_N(E + eV)]dE$$

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

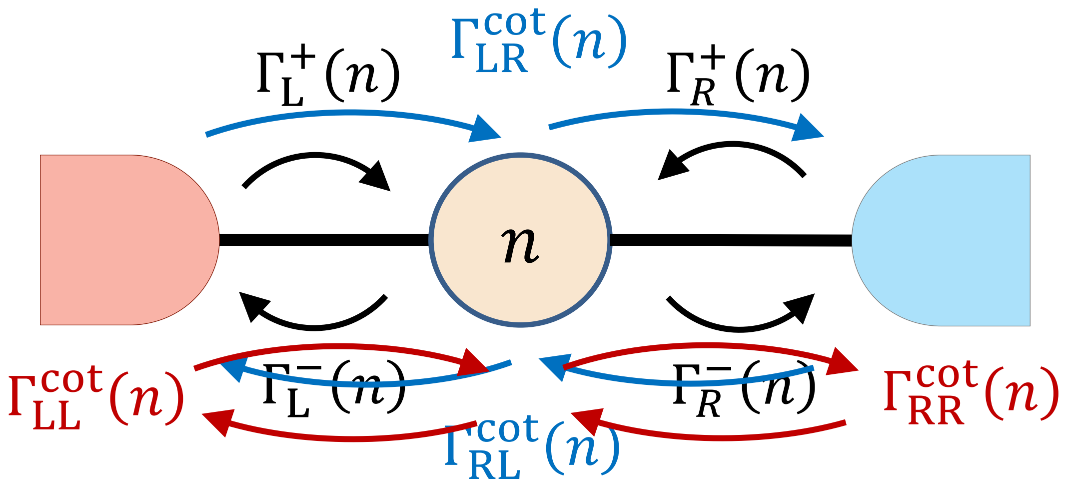






Phys. Rev. Appl. 4, 034001 (2015).

Single-electron transistor



Master equation:

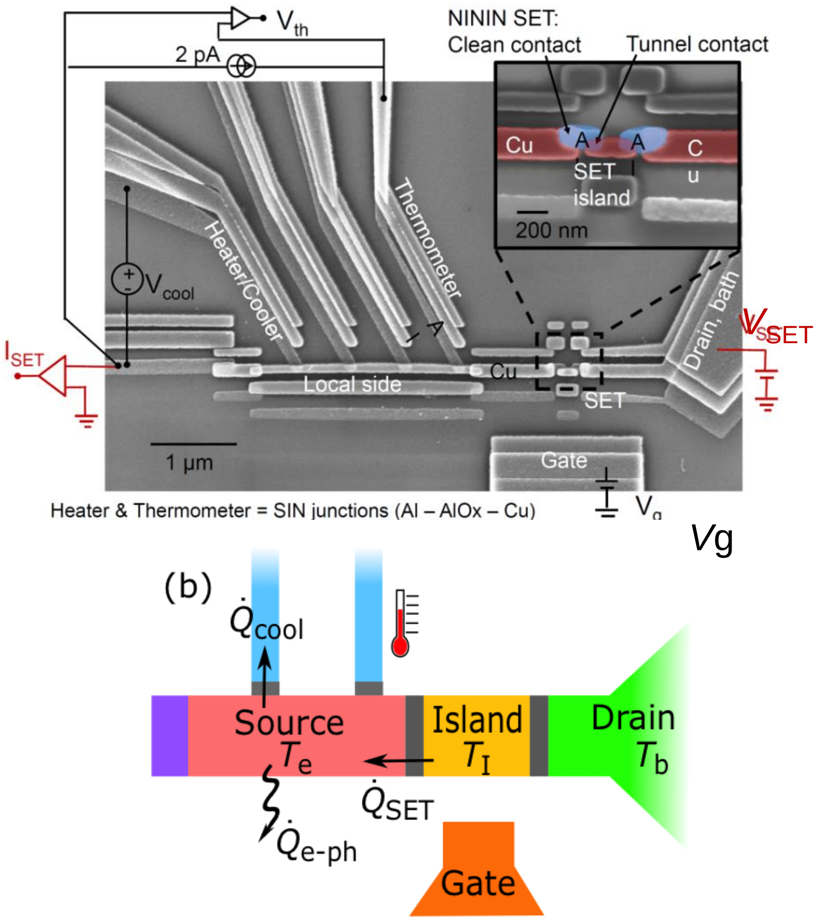
- Probabilities: $P(n)$
- Sequential Tunneling: $\Gamma^+(n)$, $\Gamma^-(n)$
- Co-tunneling: $\Gamma^{cot}(n)$

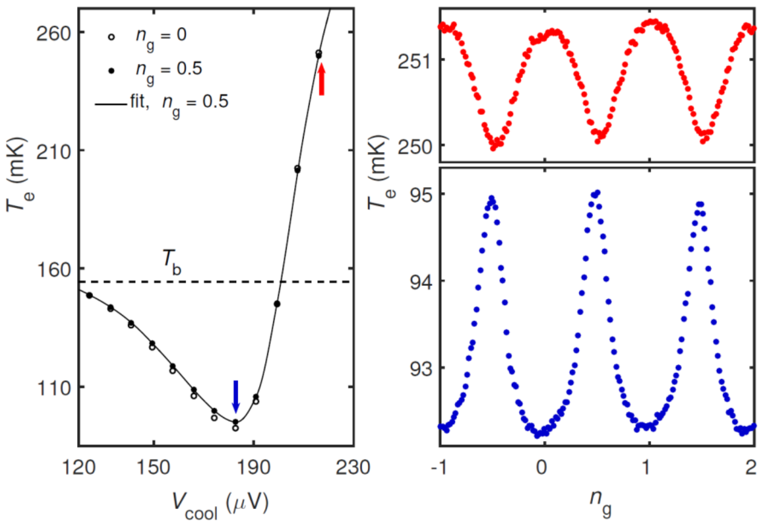
- $\frac{\partial P(n)}{\partial t} =$

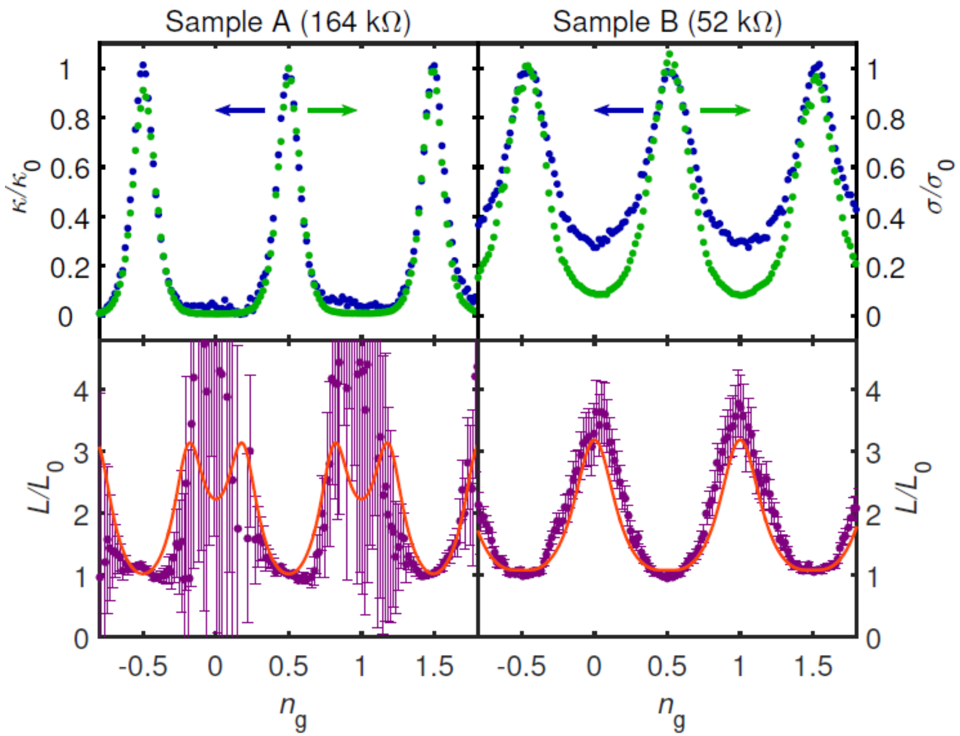
$$-P(n)\,[\Gamma^+(n) + \Gamma^-(n)]$$
$$+\,P(n-1)\,\Gamma^+(n-1)$$
$$+P(n+1)\,\Gamma^-(n+1).$$

$$\mathrm{I} = \ \mathrm{e}\sum P(n)[\Gamma_L^+(n) - \Gamma_L^-(n)]$$
$$+\,\mathrm{e}\sum P(n)[\Gamma_{LR}^{cot}(n) - \Gamma_{RL}^{cot}(n)].$$

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



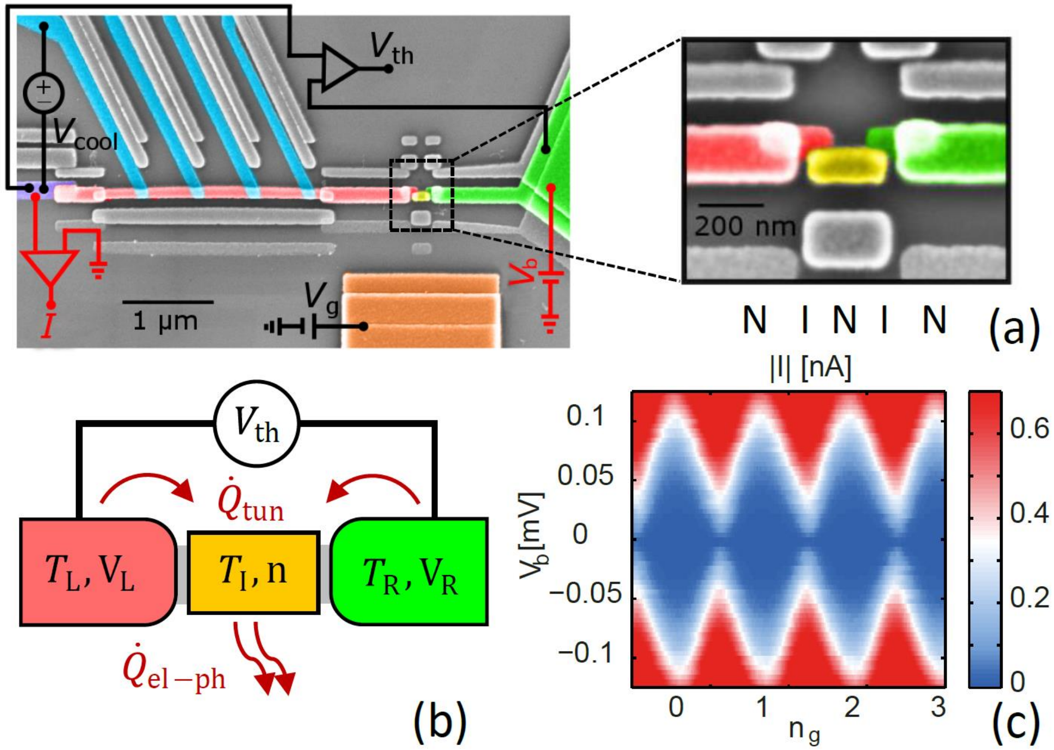




B. Dutta, J. Peltonen et al., PRL **119**, 077701 (2017)

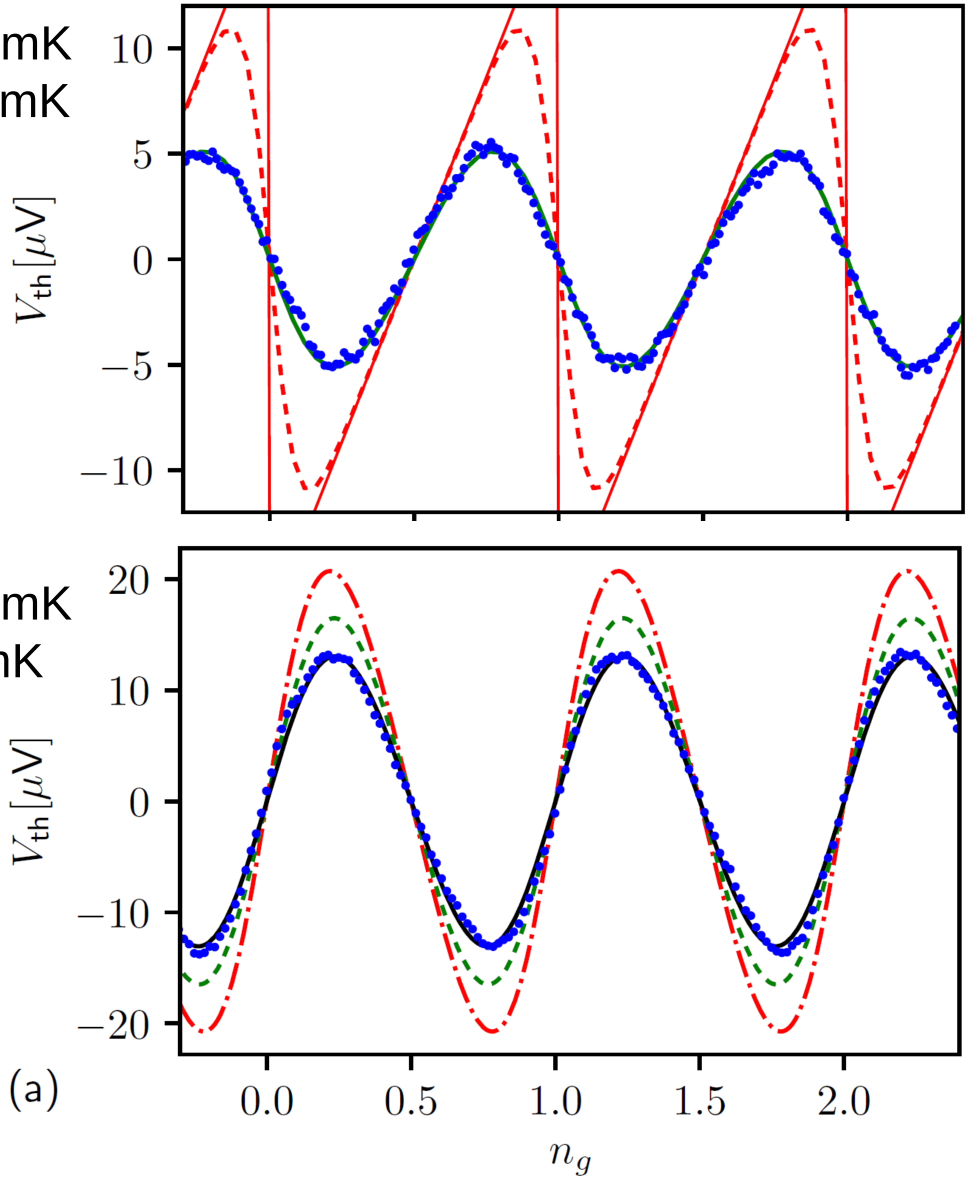
Thermopower in a single-electron transistor

No free parameters in model: red sawtooth – 2-state sequential, black – includes cotunneling



T_H = 190 mK
T_L = 134 mK

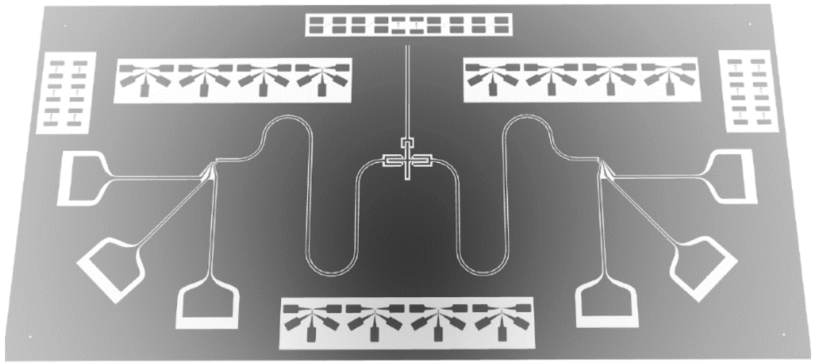
T_H = 342 mK
T_L = 63 mK



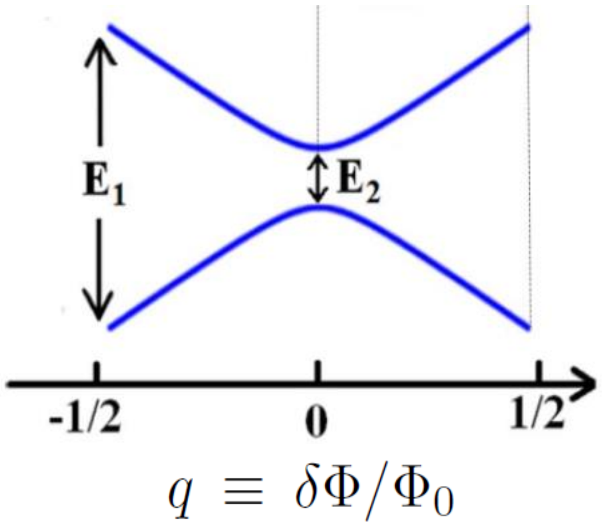
P. Erdman et al, arXiv:1812.06514

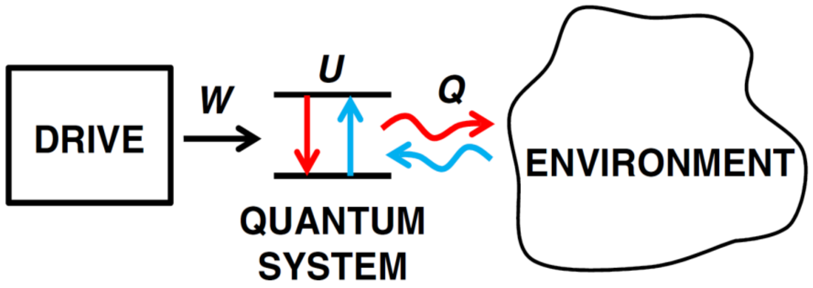
Qubit as an open quantum system

Superconducting qubits



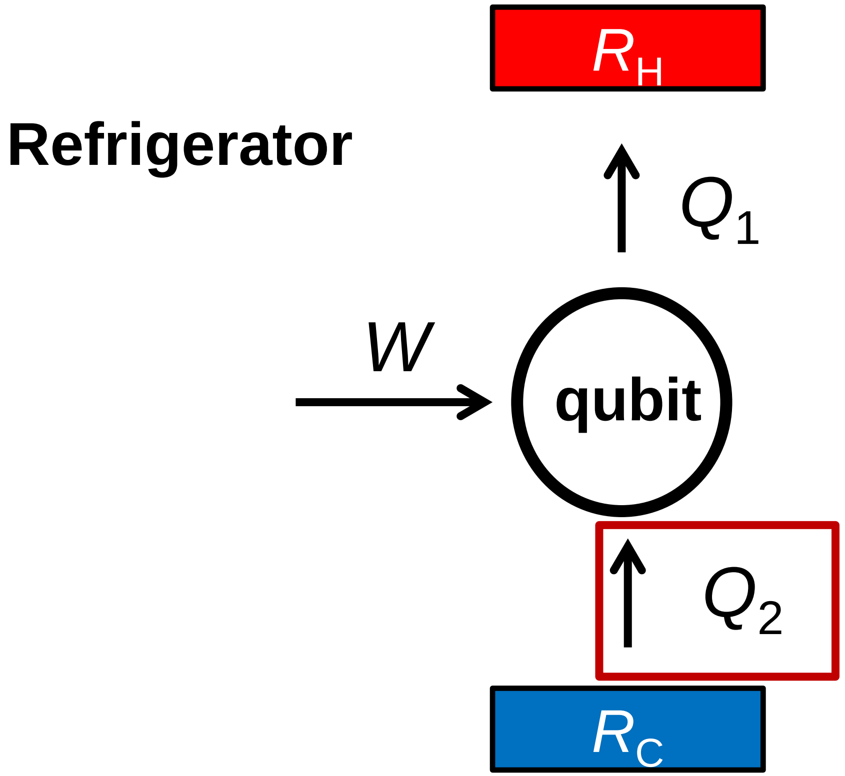
$$H_\mathrm{Q} = -E_0(\Delta\sigma_x + q\sigma_z)$$

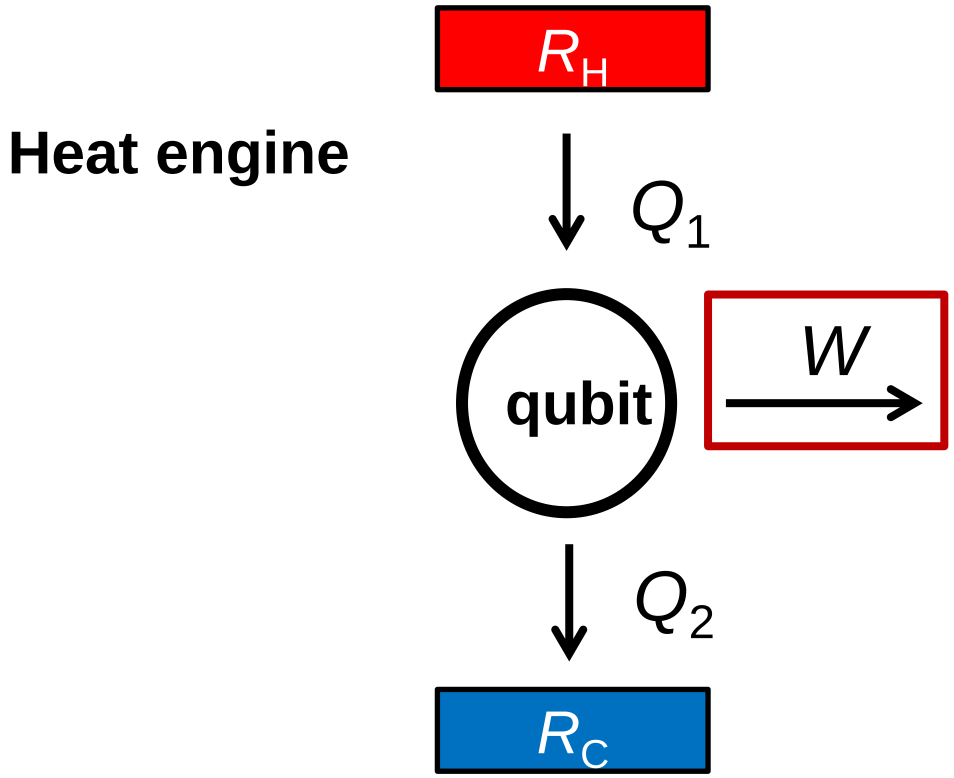




$$H = H_\mathrm{Q} + V + H_\mathrm{E}$$

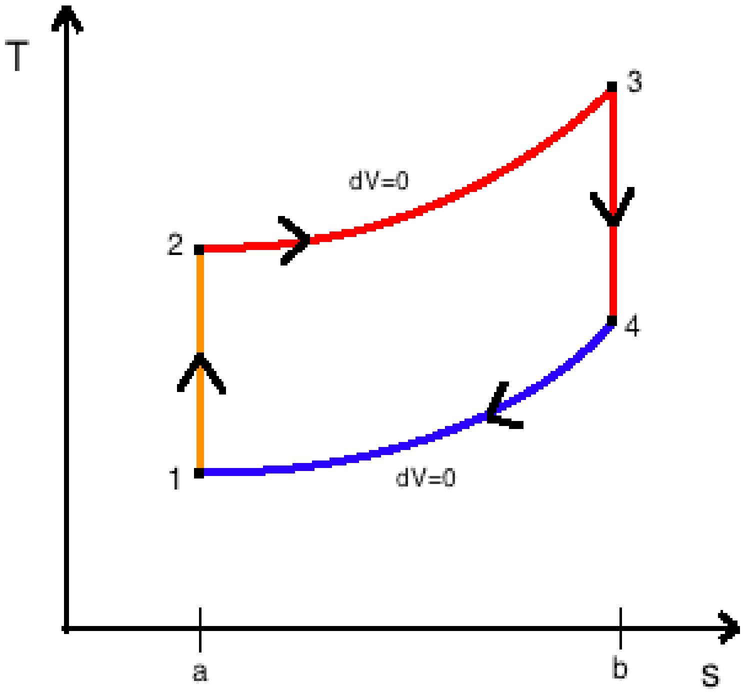
Refrigerator and heat engine

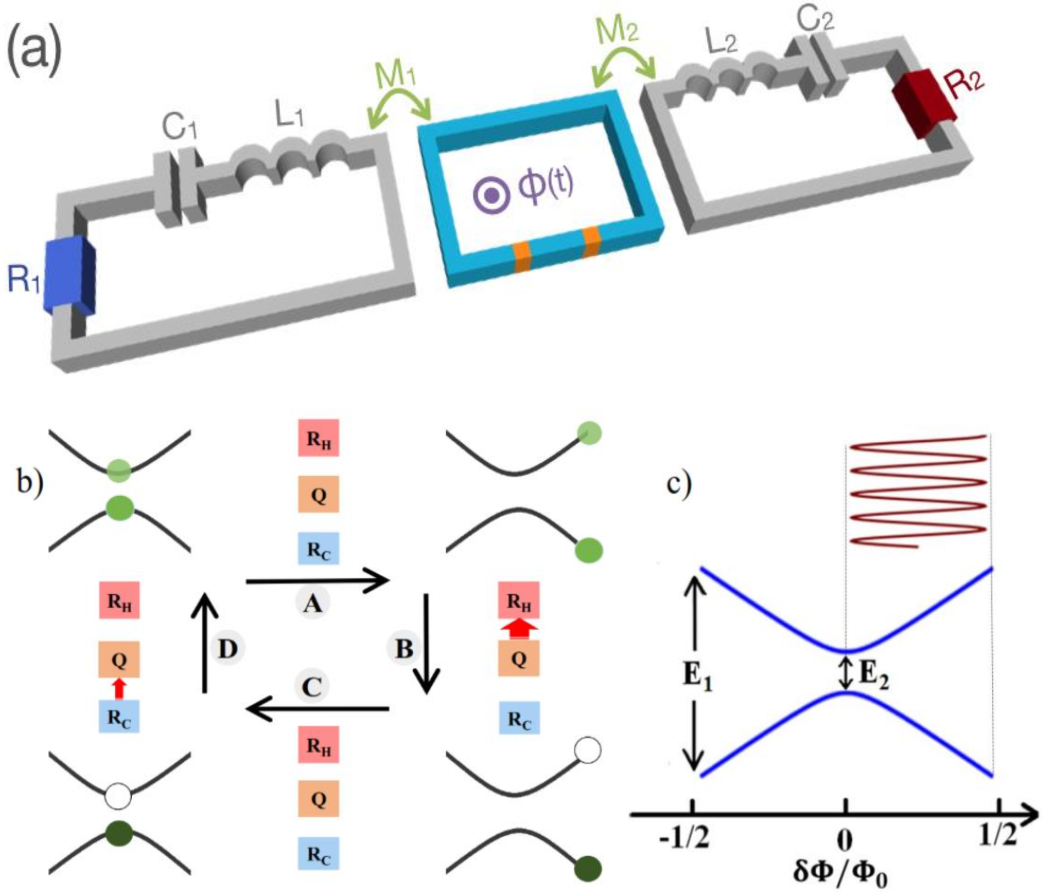




Quantum Otto refrigerator

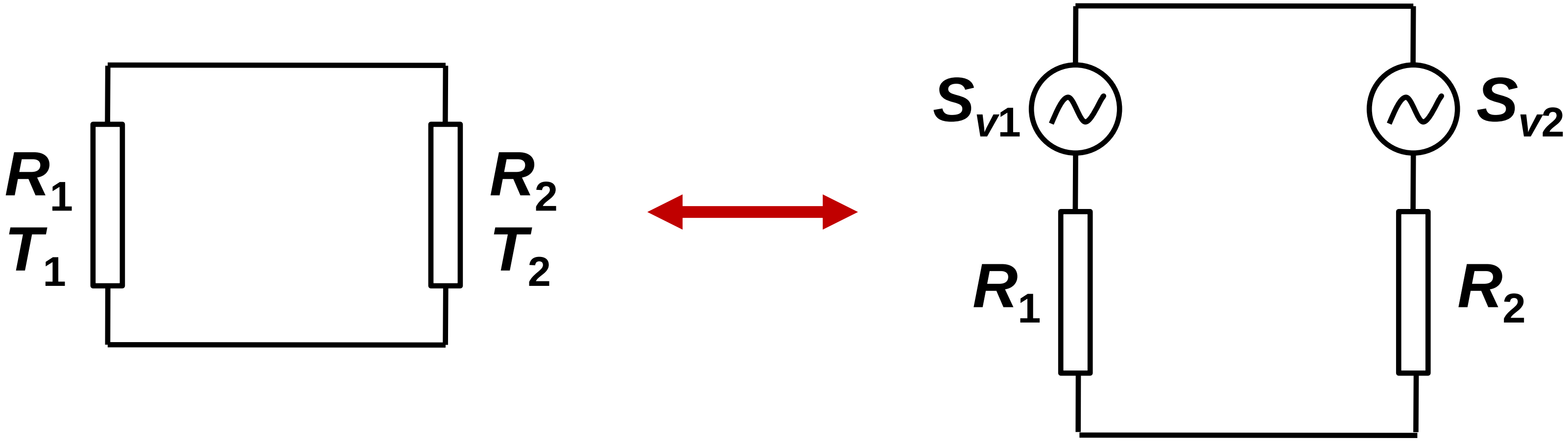
Otto cycle





Niskanen, Nakamura, Pekola, PRB 76, 174523 (2007);
B. Karimi and JP, Phys. Rev. B **94**, 184503 (2016).

Heat transported between two resistors



$$P = r\frac{\pi k_B^2}{12\hbar}(T_1^2 - T_2^2)$$

$$r \equiv \frac{4R_1 R_2}{(R_1 + R_2)^2}$$

For small temperature difference $\Delta T = T_1 - T_2$:

$$P = rG_Q \Delta T$$

$$G_Q = \frac{\pi k_B^2}{6\hbar}T$$

Johnson, Nyquist 1928

Photons

Schmidt et al., PRL 93, 045901 (2004)

Meschke et al., Nature 444, 187 (2006)

Timofeev et al., PRL 102, 200801 (2009)

Partanen et al., Nature Physics 12, 460 (2016)

Phonons

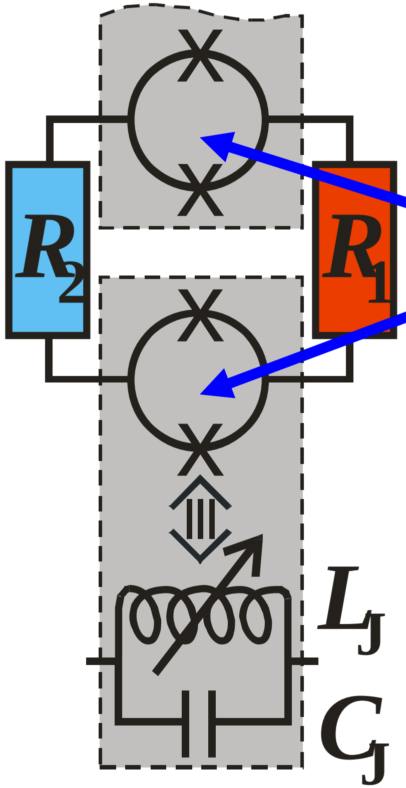
K. Schwab et al., Nature 404, 974 (2000)

Electrons

Jezouin et al., Science 342, 601 (2013)

Banerjee et al., Nature 545, 75 (2017)

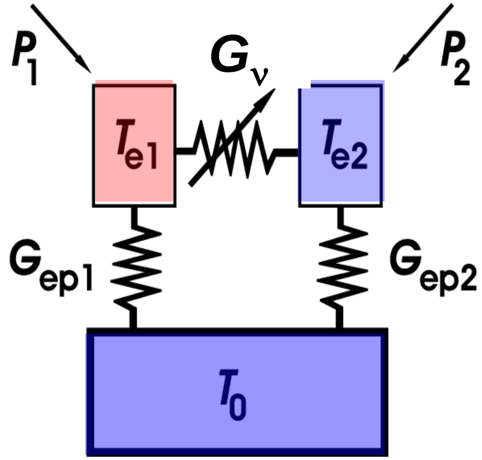
Experimental realization of photonic heat transport

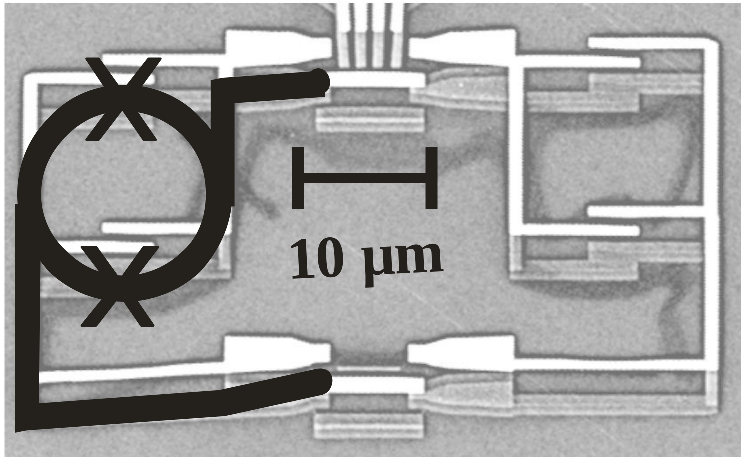


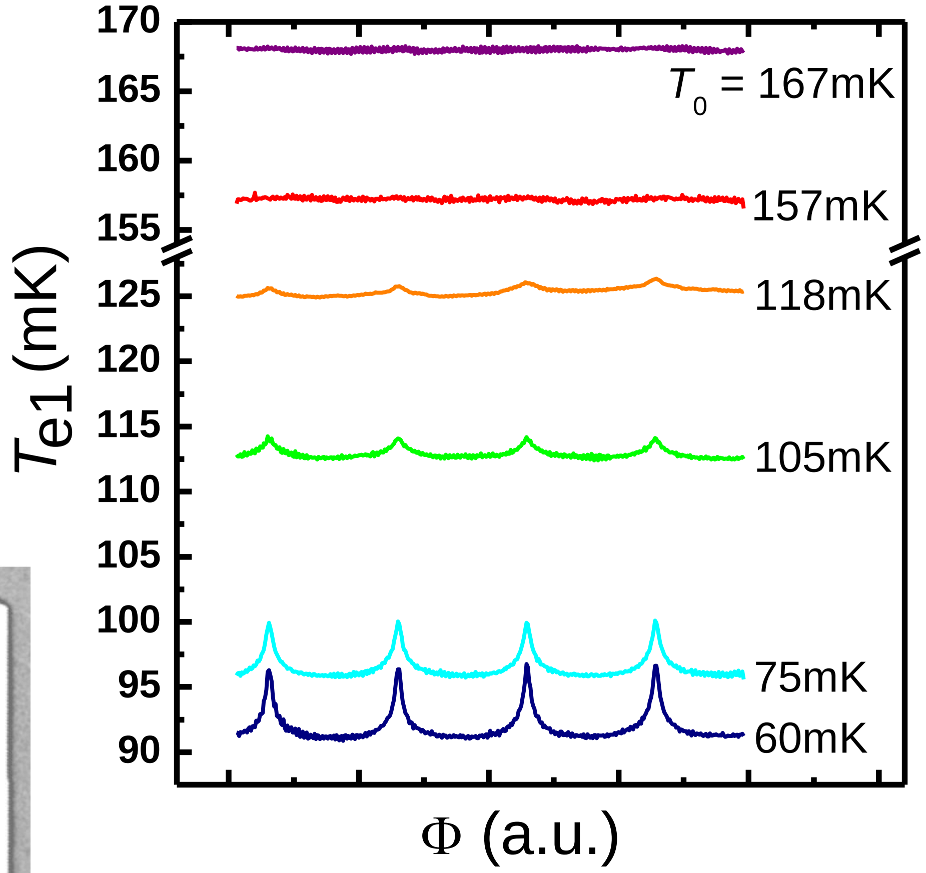
Tunable coupling using SQUIDs

$$L_J = \frac{\hbar}{2eI_{C,0}|\cos(\pi\Phi/\Phi_0)|}$$

Thermal model



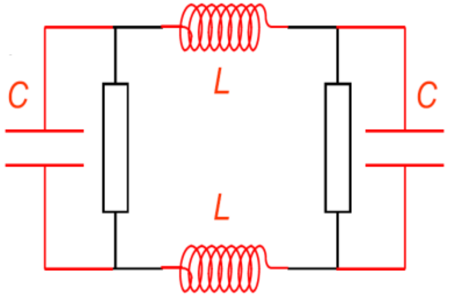




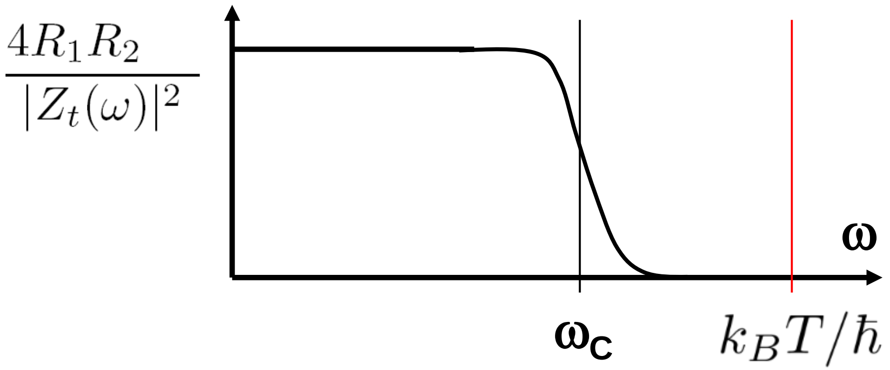
Meschke, Guichard and JP (2006)

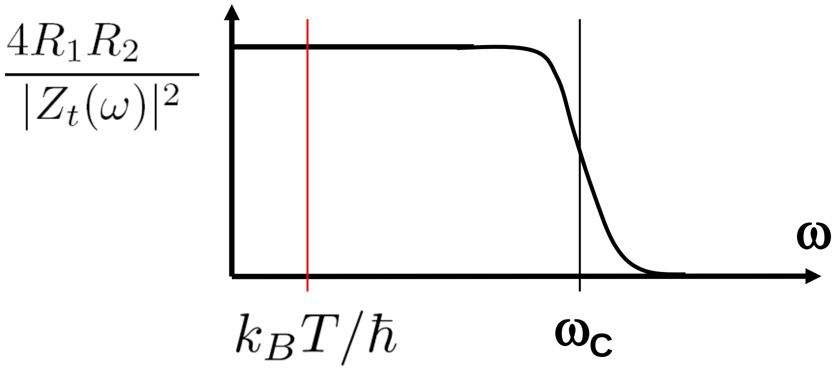
Classical or quantum heat transport?

$$P_\nu = \int_0^\infty \frac{d\omega}{2\pi} \frac{4R_1R_2\hbar\omega}{|Z_t(\omega)|^2}\left(\frac{1}{e^{\hbar\omega/k_BT_1}-1} - \frac{1}{e^{\hbar\omega/k_BT_2}-1}\right)$$



$$C \sim \epsilon\ell$$
$$L \sim \mu\ell$$





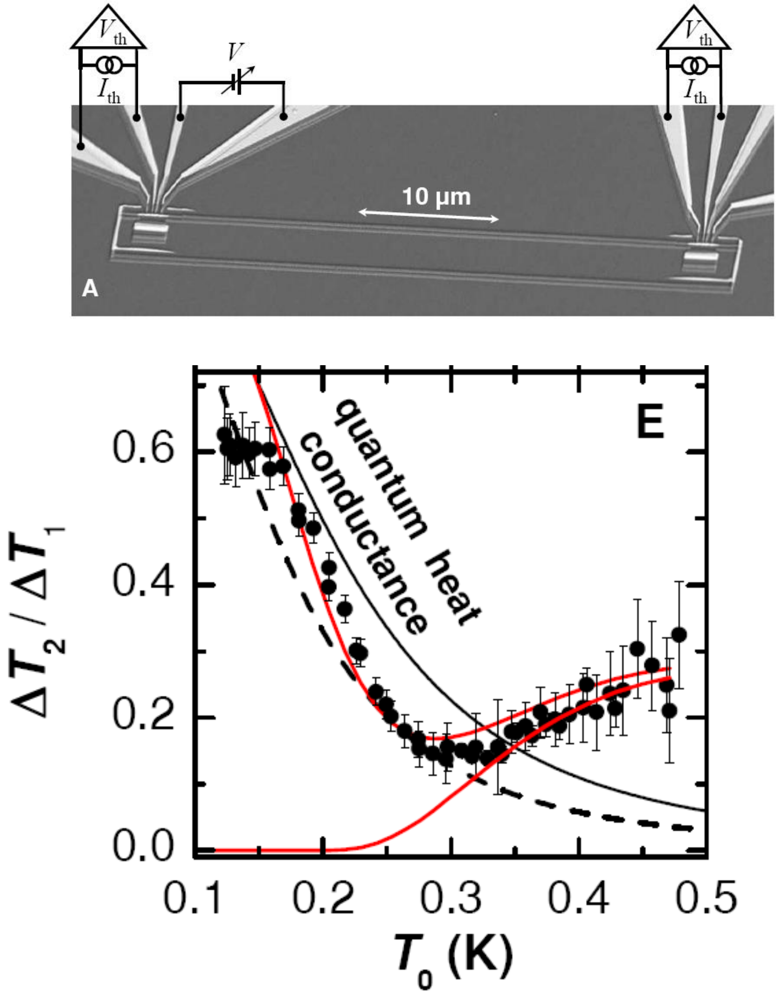
”Classical”
high T, macroscopic circuit
300 K, centimetres

$$G_\nu \sim rk_B\omega_C$$

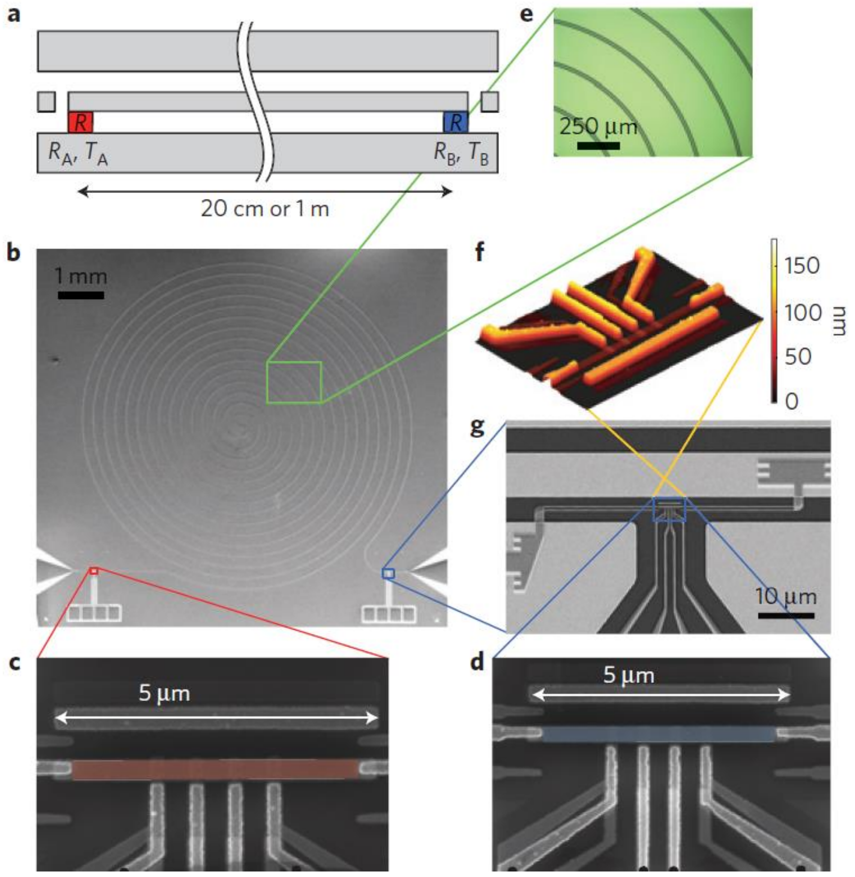
”Quantum”
low T, small circuit
50 mK, micrometres

$$G_\nu = rG_Q$$

Measurements of quantum of heat conductance by photons



...via a 1 m long transmission line

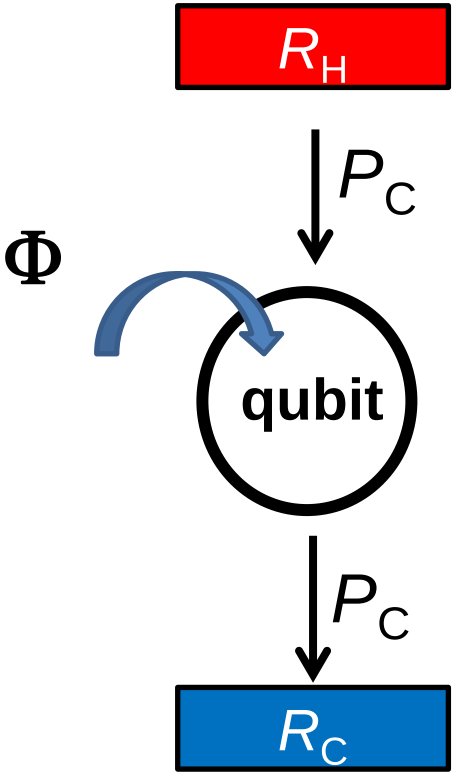


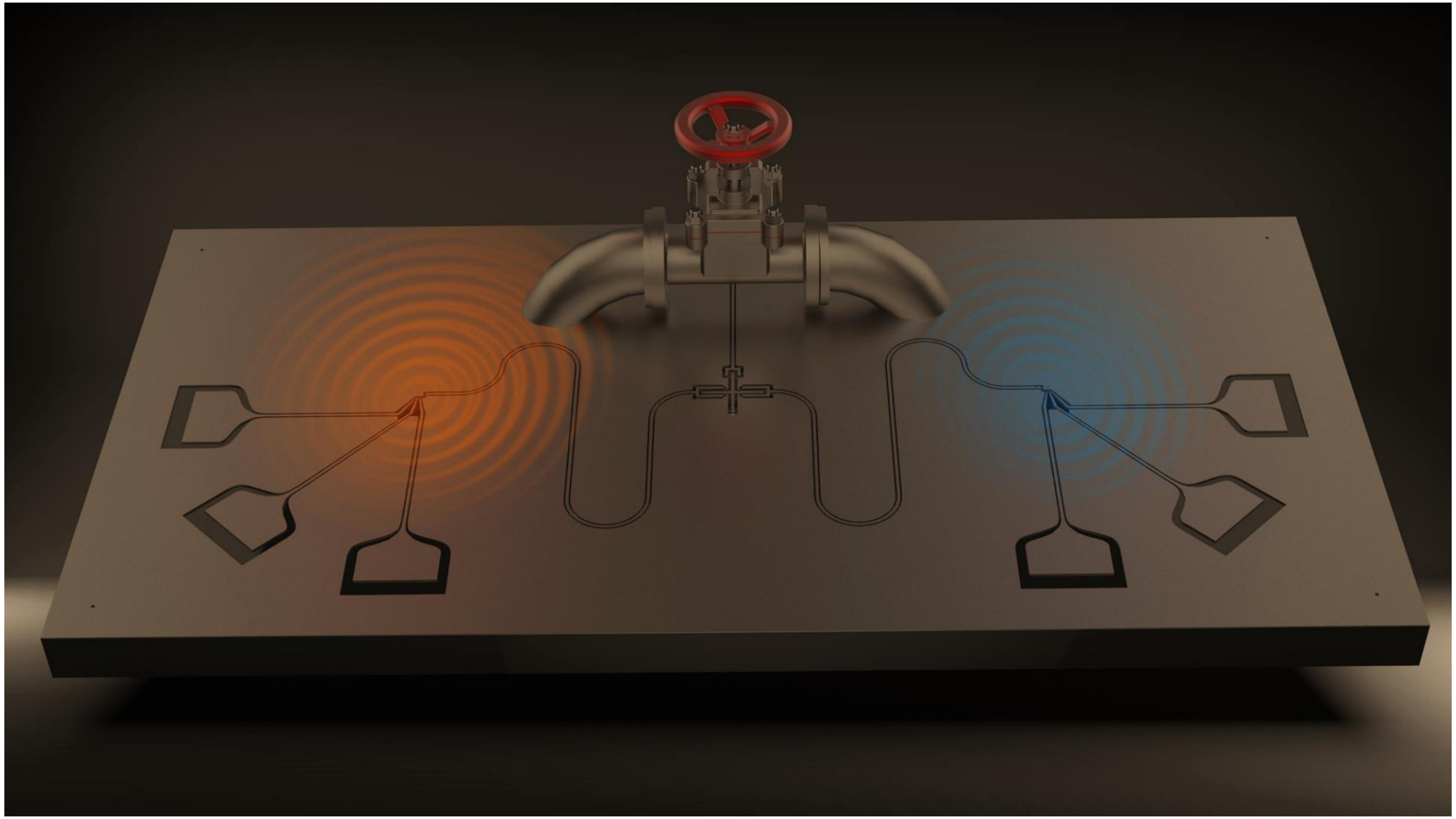
Timofeev et al., PRL 102, 200801 (2009)

Partanen et al., Nature Phys. 12, 460 (2016)

Quantum heat valve

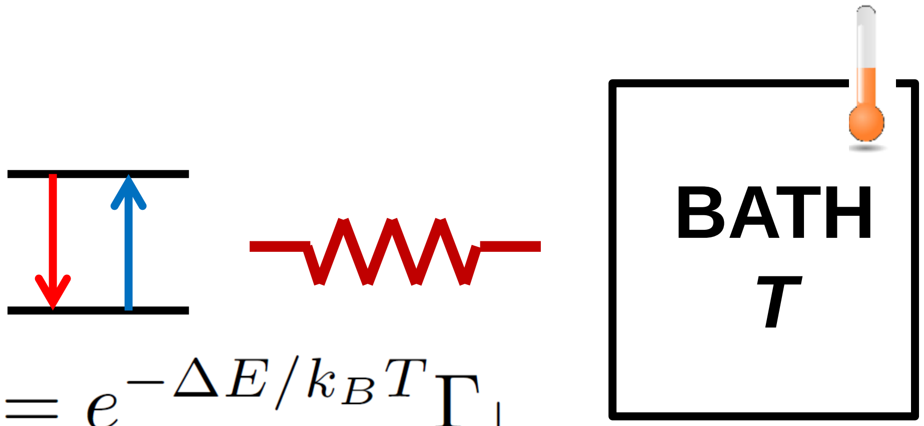
A. Ronzani, B. Karimi, J. Senior, Y.-C. Chang, J. Peltonen, C. D. Chen, and JP, Nature Physics 14, 991 (2018).





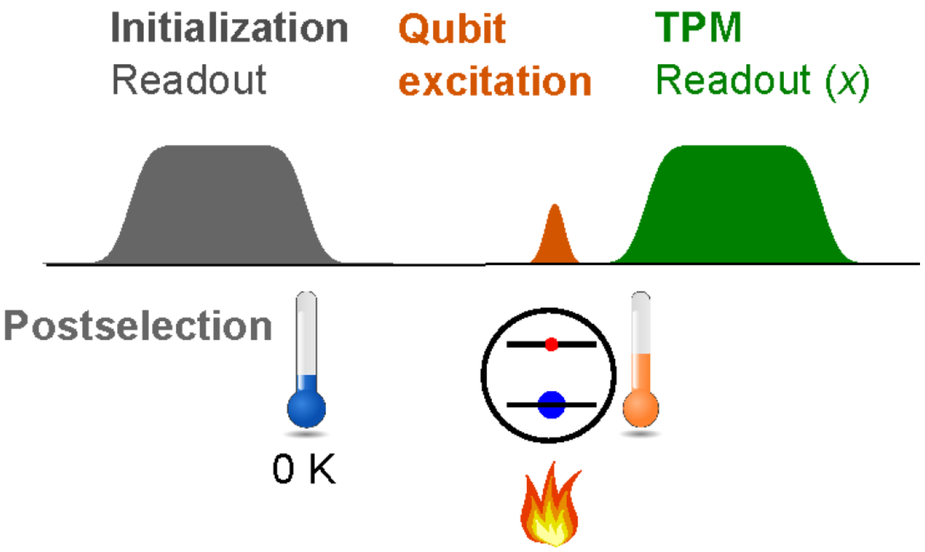
B. Karimi, J. Pekola, M. Campisi, and R. Fazio, Quantum Science and Technology **2**, 044007 (2017).

Temperature of a qubit?



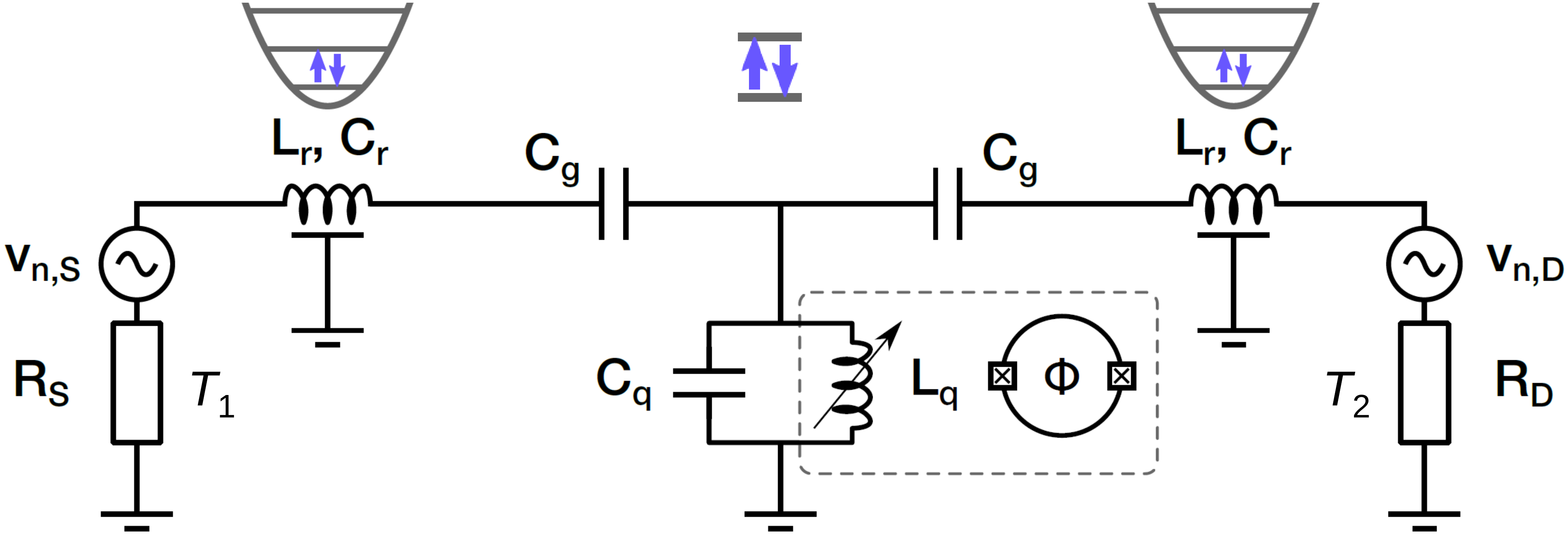
$$\Gamma_\uparrow = e^{-\Delta E/k_B T}\Gamma_\downarrow$$

Couple the qubit to a true thermal bath



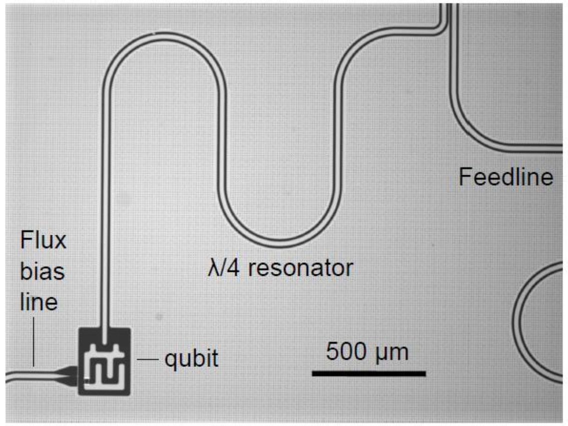
Alternative approach to initialize a qubit to a given ”temperature”: Y. Masuyama et al., Nature Comm. 9, 1291 (2018)

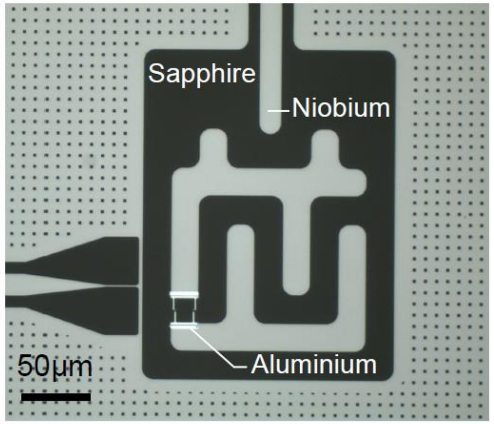
Idea of the experiment



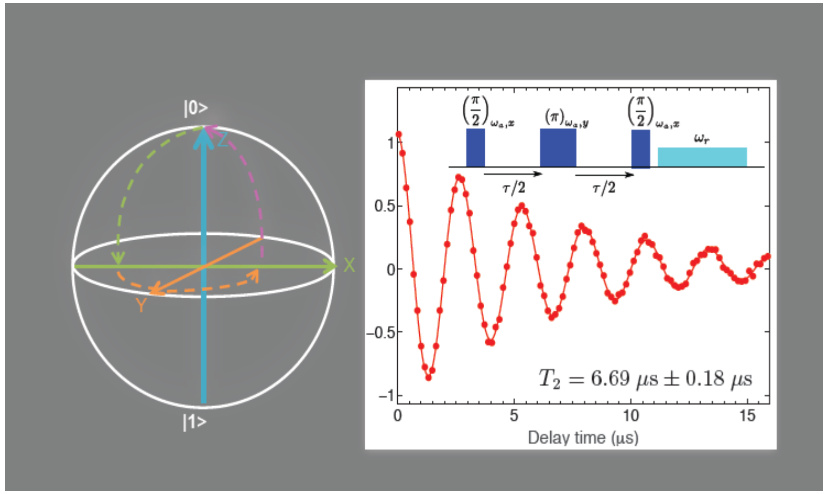
Power to each bath (in steady-state): $P_i = \hbar\omega_0(\rho_e\Gamma_{\downarrow}^{(i)} - \rho_g\Gamma_{\uparrow}^{(i)})$

Experimental realization of the heat valve

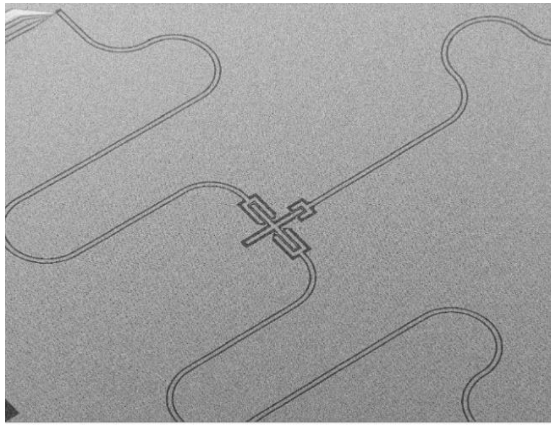




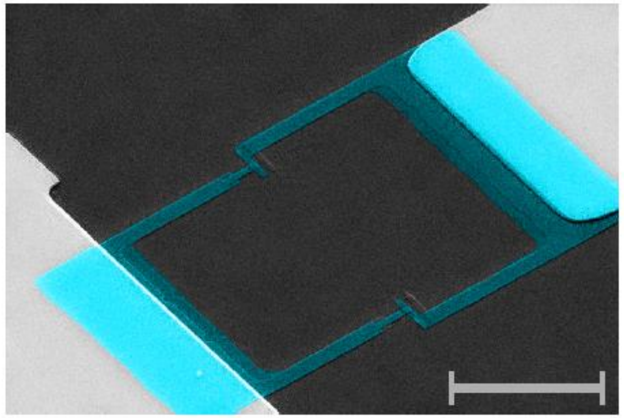
George et al. (2017)



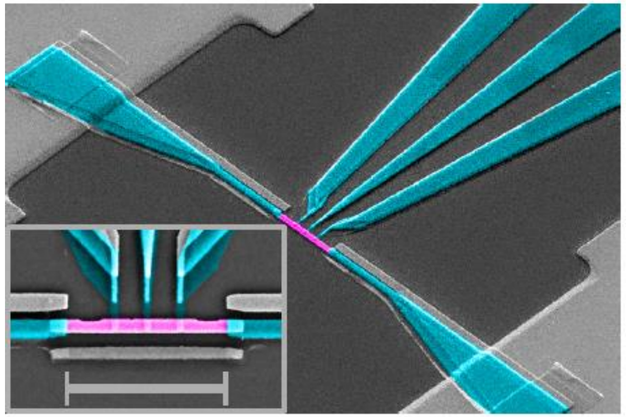
QUBIT WITHOUT ABSORBERS



1 mm



10 μm

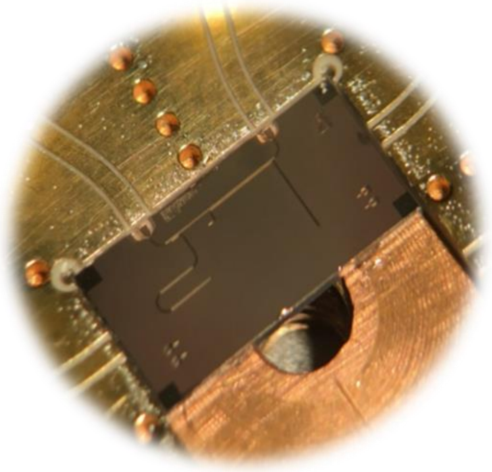


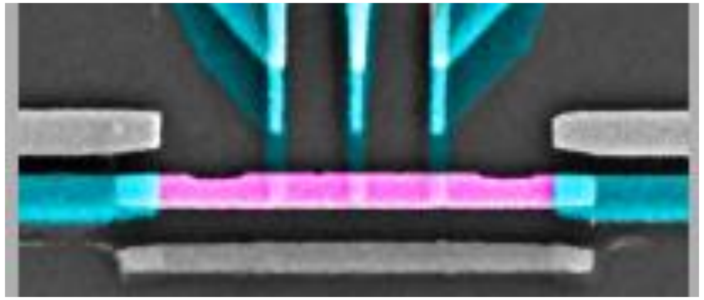
3 μm

TRANSMON QUBIT

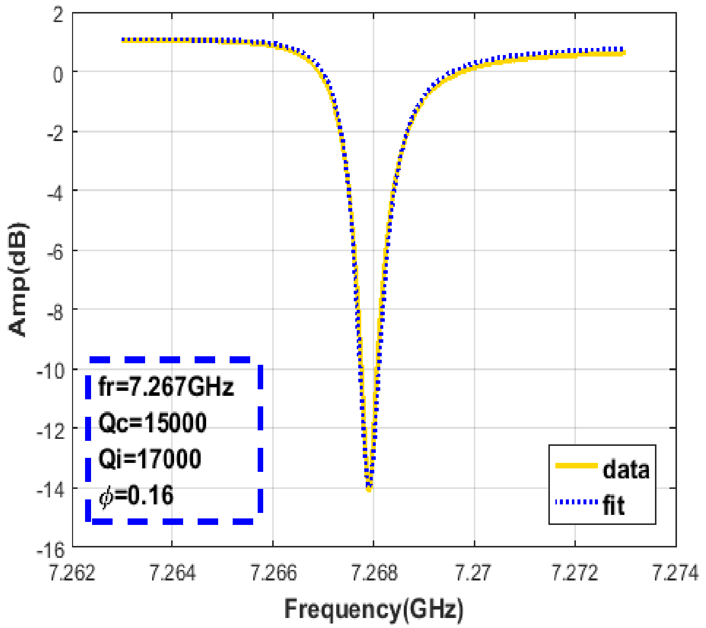
RESERVOIR AND THERMOMETERS

λ / 4 resonators terminated by heat bath *R*

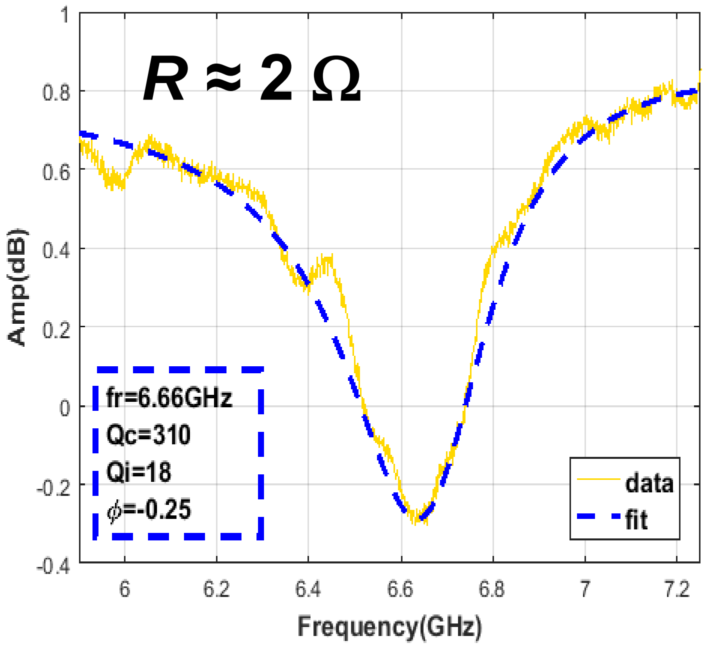




$Q = \pi Z_0 / 4R$



Superconducting shunt, Q = 17 000



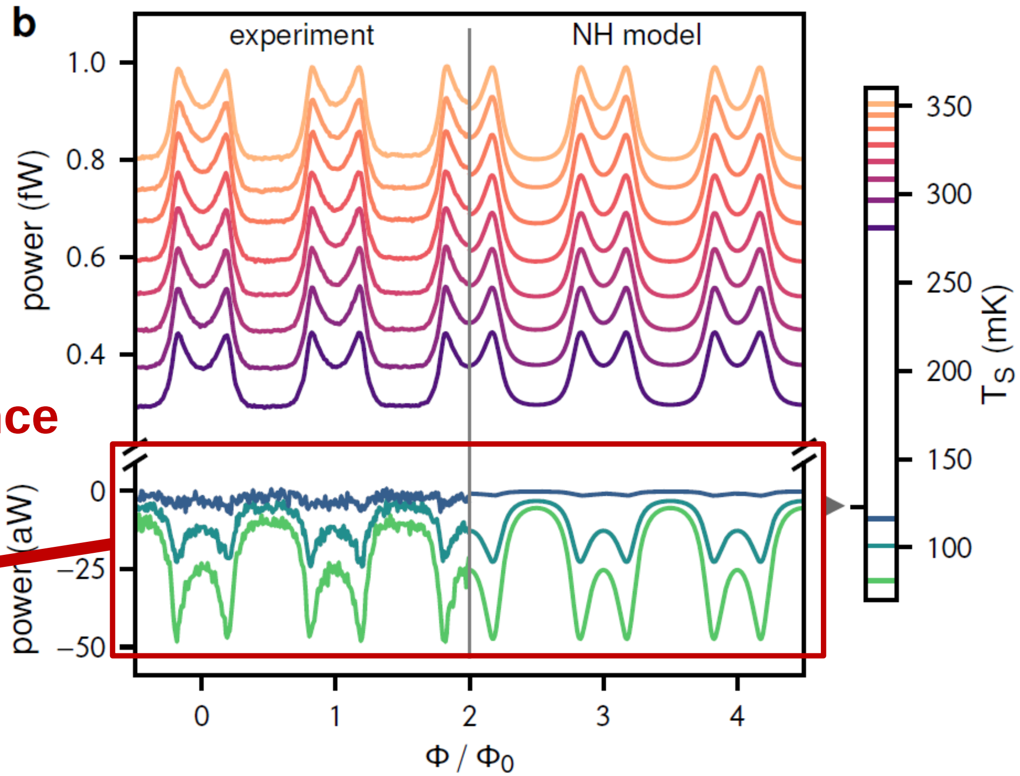
Normal (copper) shunt, Q = 18

Yu-Cheng Chang et al., in preparation

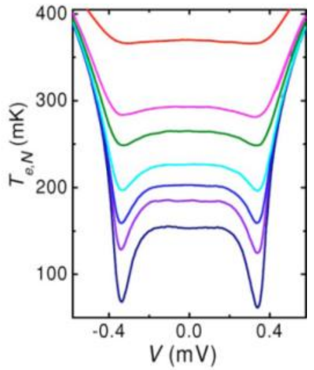
See also:
M. Partanen et al., Nat. Phys. **12**, 160 (2016); arXiv:1712.10256

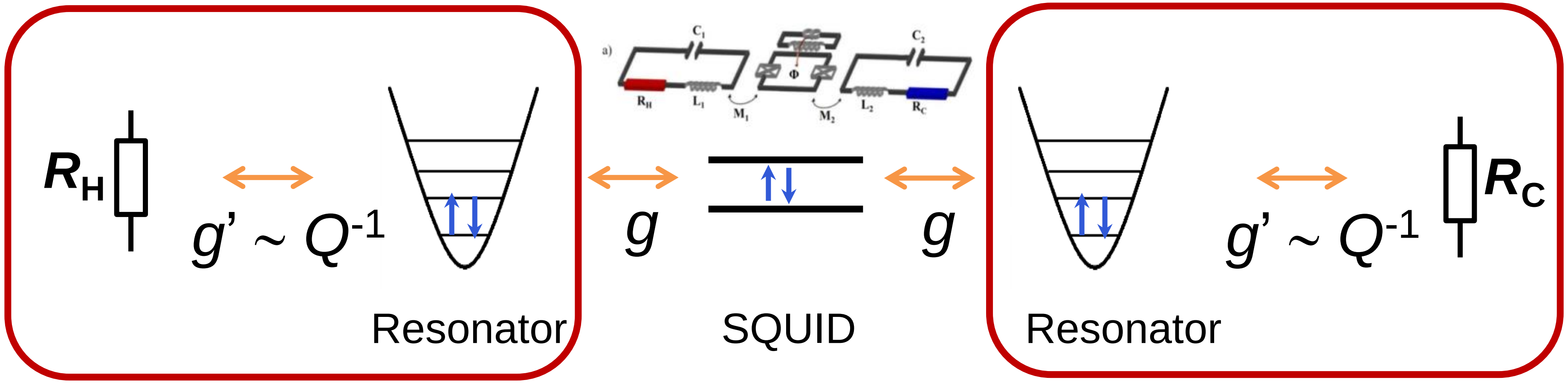
Low-Q regime

$Q = 3$



Cooling at distance of 4 mm by mw photons

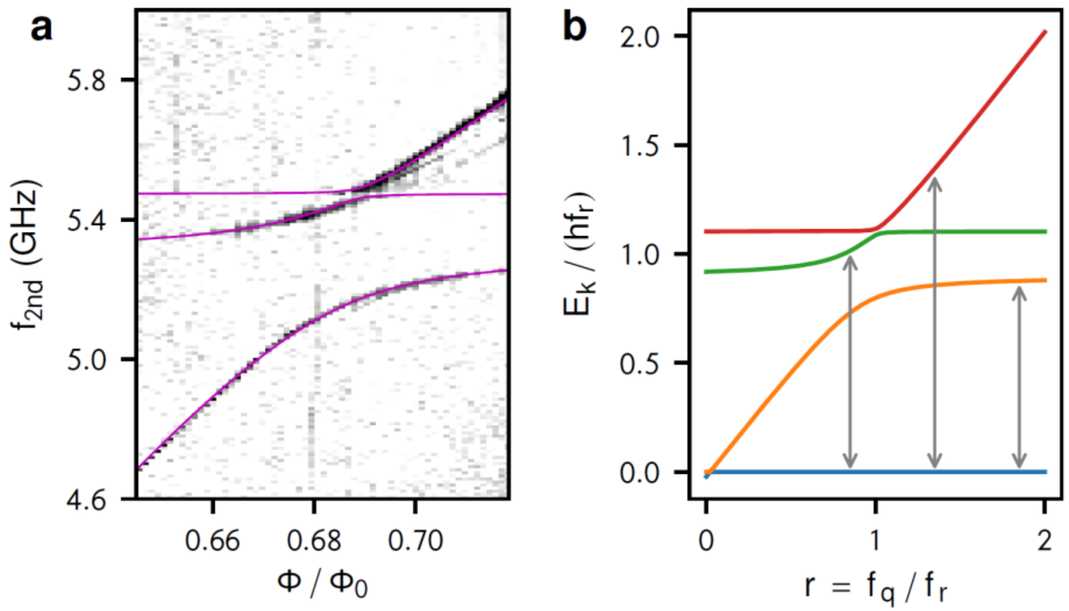


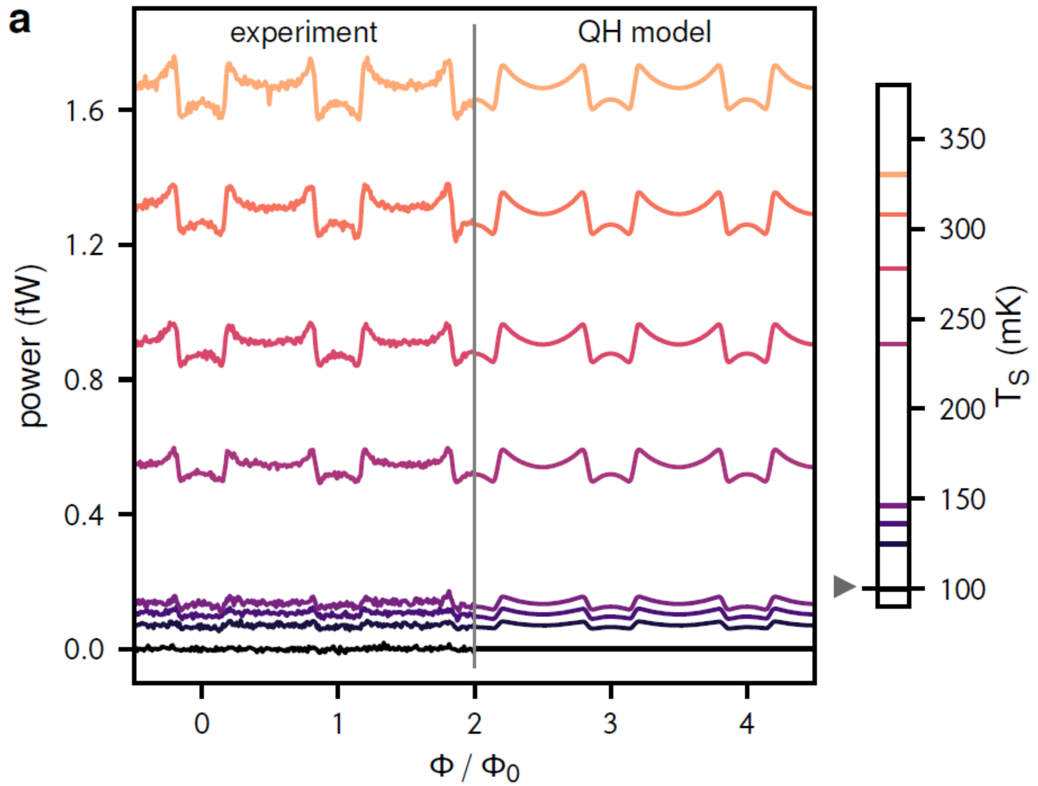


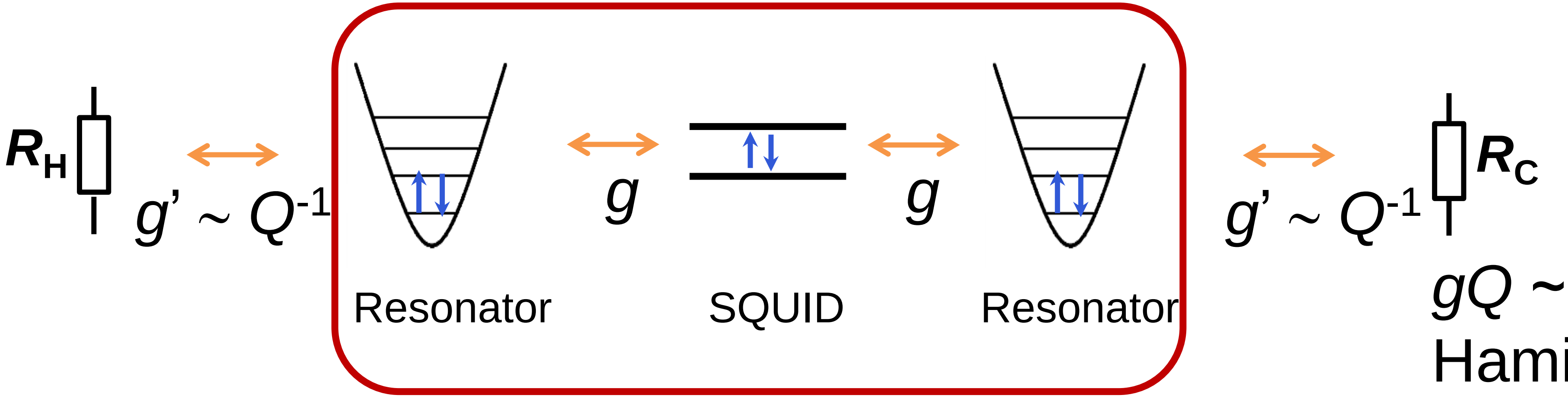
$gQ << 1$, ”non-Hamiltonian” model works

Intermediate-Q regime

$Q = 20$

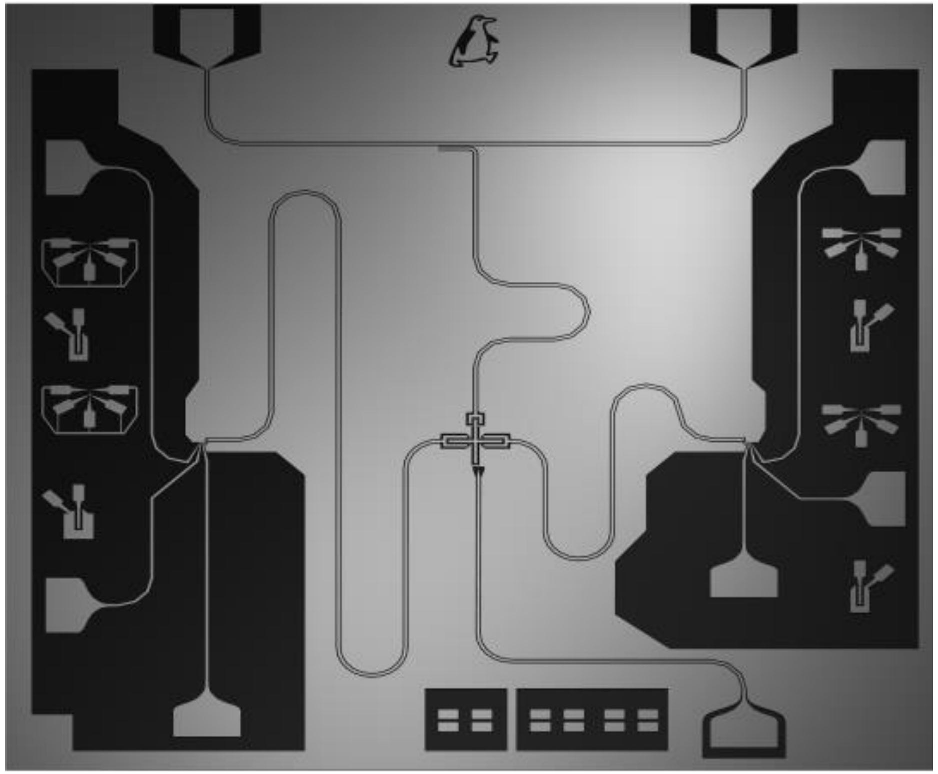




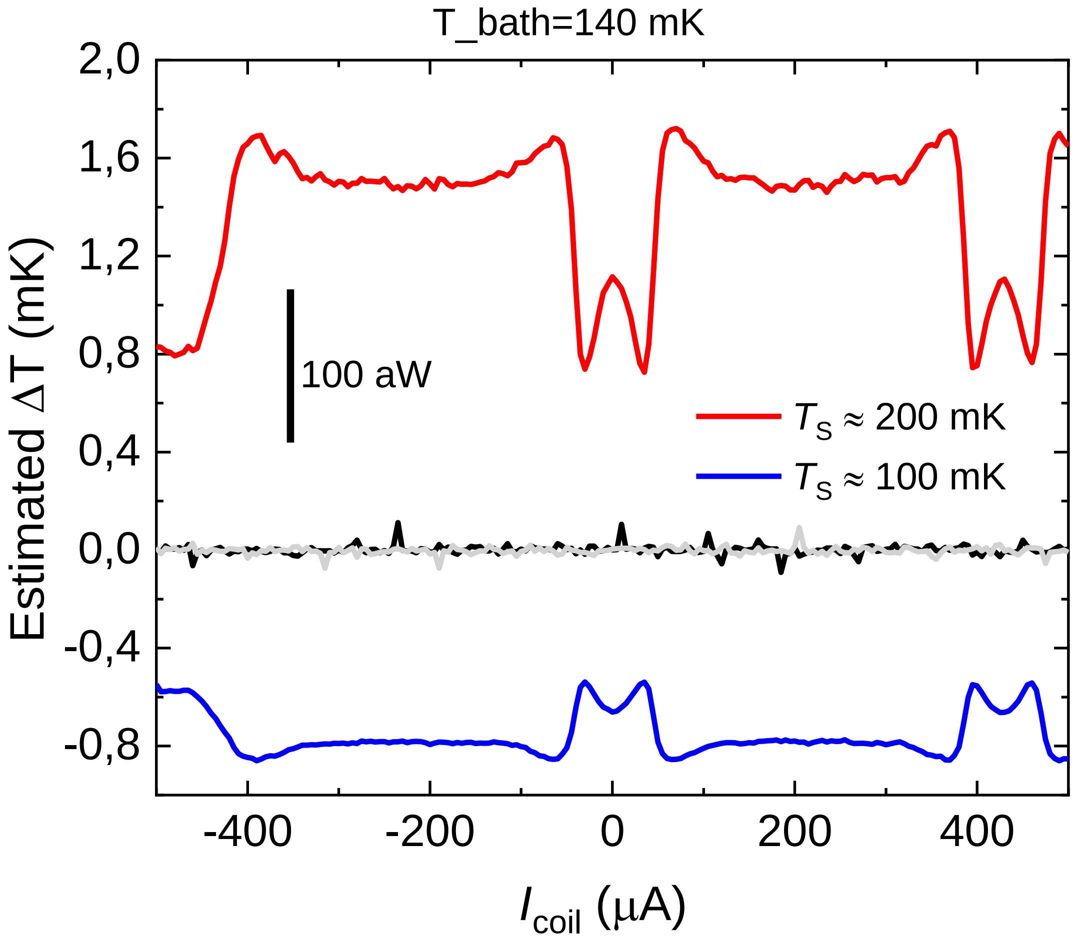


$gQ \sim 1$, "quasi-Hamiltonian" model works

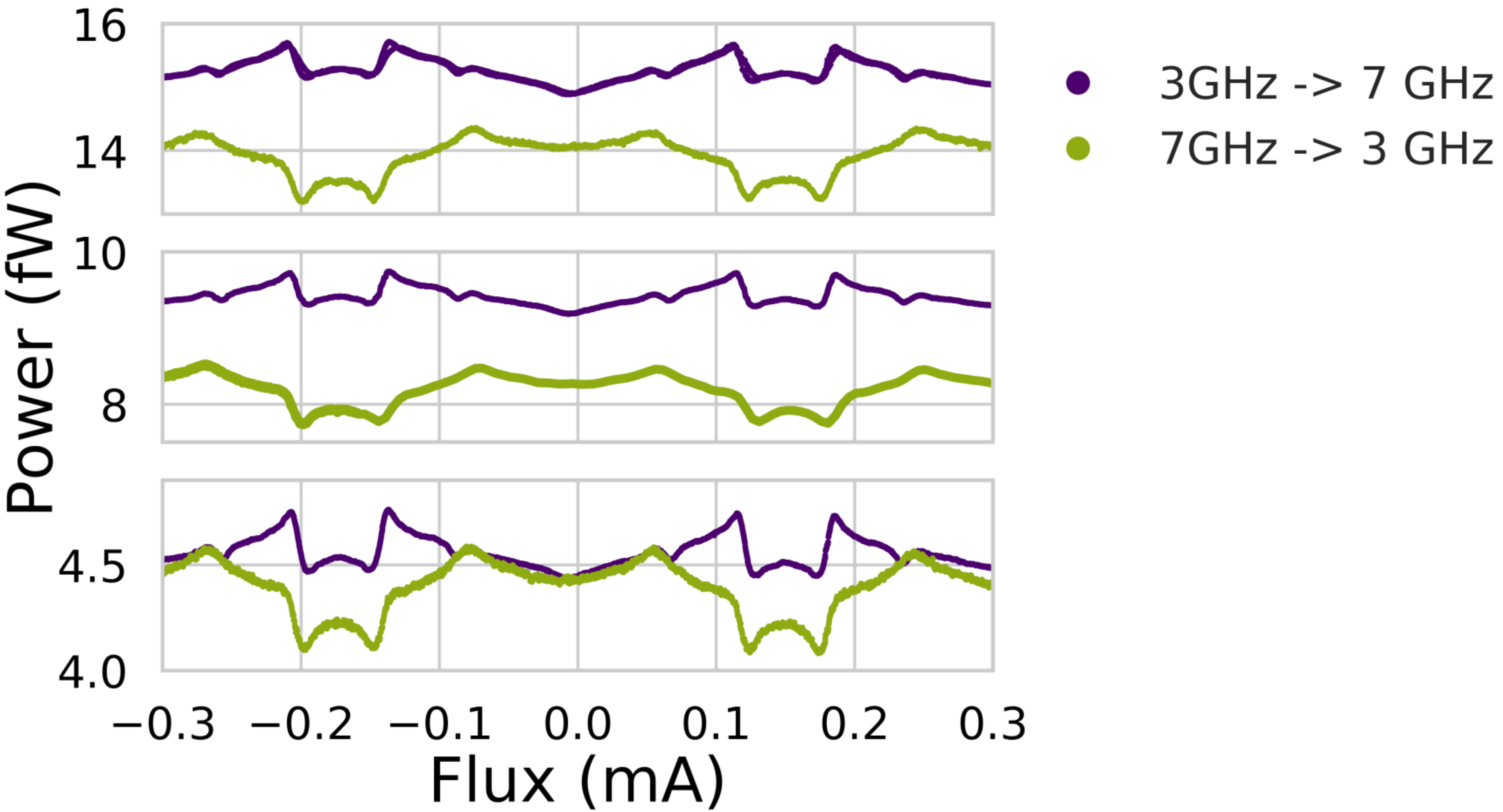
Current experiment: asymmetric device



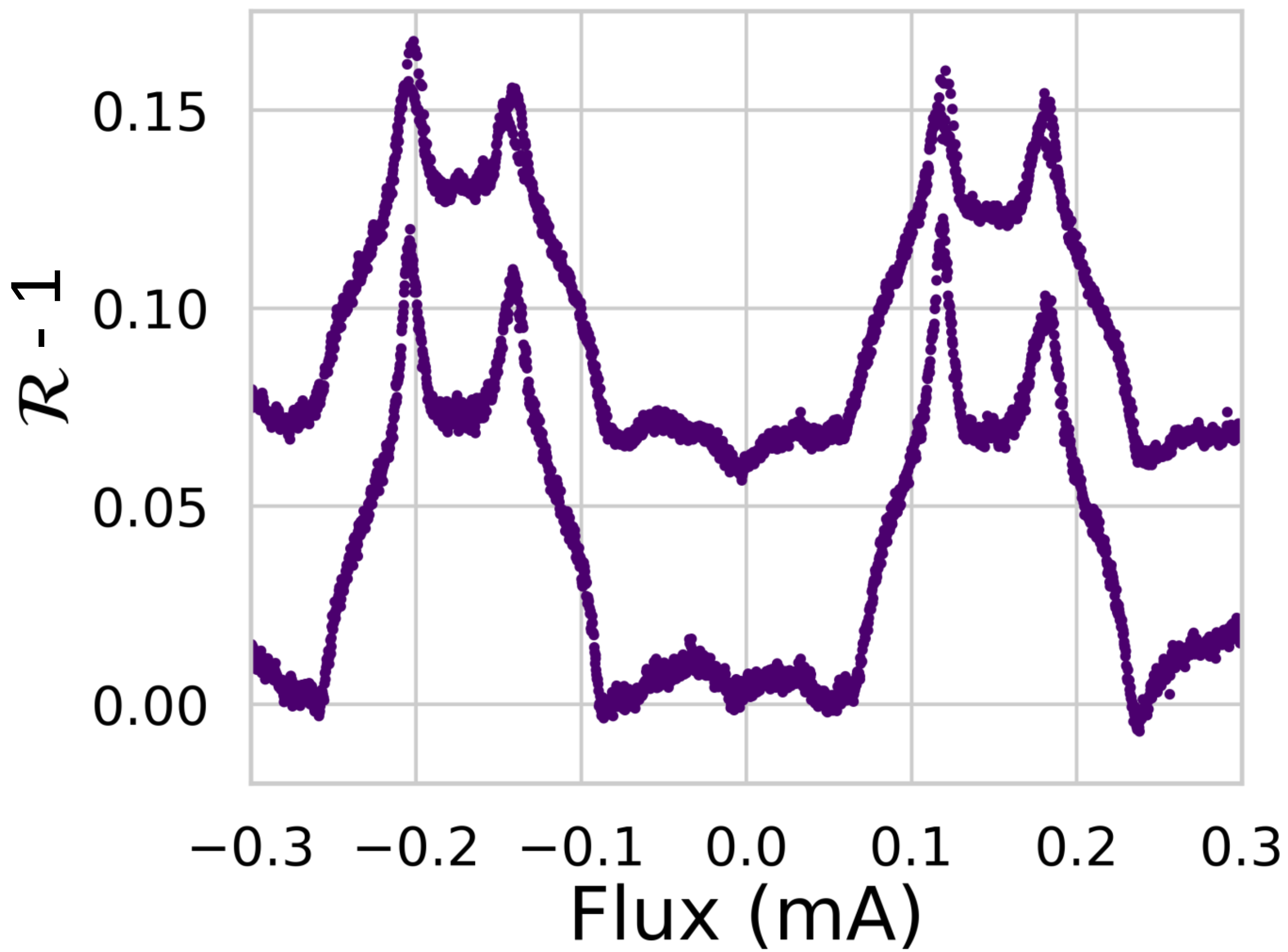
3 GHz 7 GHz



Forward and reverse powers



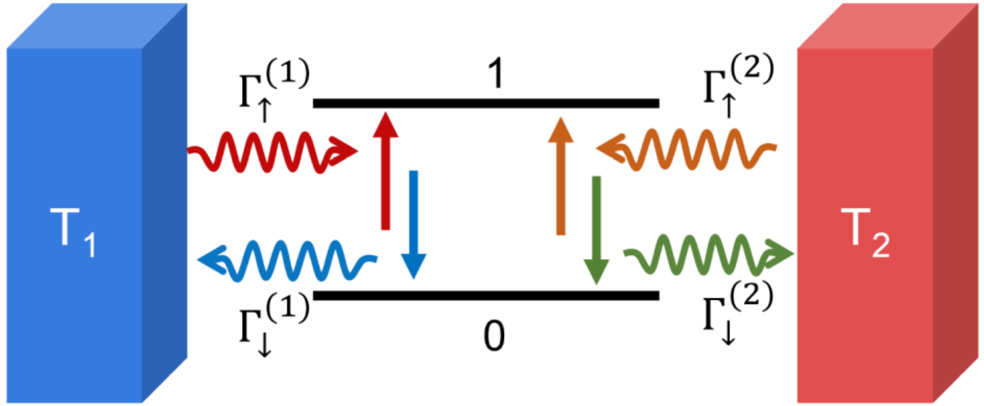
Rectification ratio from measurement



$$\mathcal{R} = |\frac{P_i^+}{P_i^-}|$$

Theory: Rectification of heat in spin-boson model, D. Segal and A. Nitzan, PRL 2005

Rectification of photonic heat current by a qubit



$$\Gamma_\uparrow^{(1)} = g_1 \frac{\omega_0}{e^{\beta_1 \hbar\omega_0} - 1}, \qquad \Gamma_\uparrow^{(2)} = g_2 \frac{\omega_0}{e^{\beta_2 \hbar\omega_0} - 1}$$

$$\Gamma_\downarrow^{(1)} = g_1 \frac{\omega_0}{1 - e^{-\beta_1 \hbar\omega_0}}, \qquad \Gamma_\downarrow^{(2)} = g_2 \frac{\omega_0}{1 - e^{-\beta_2 \hbar\omega_0}}$$

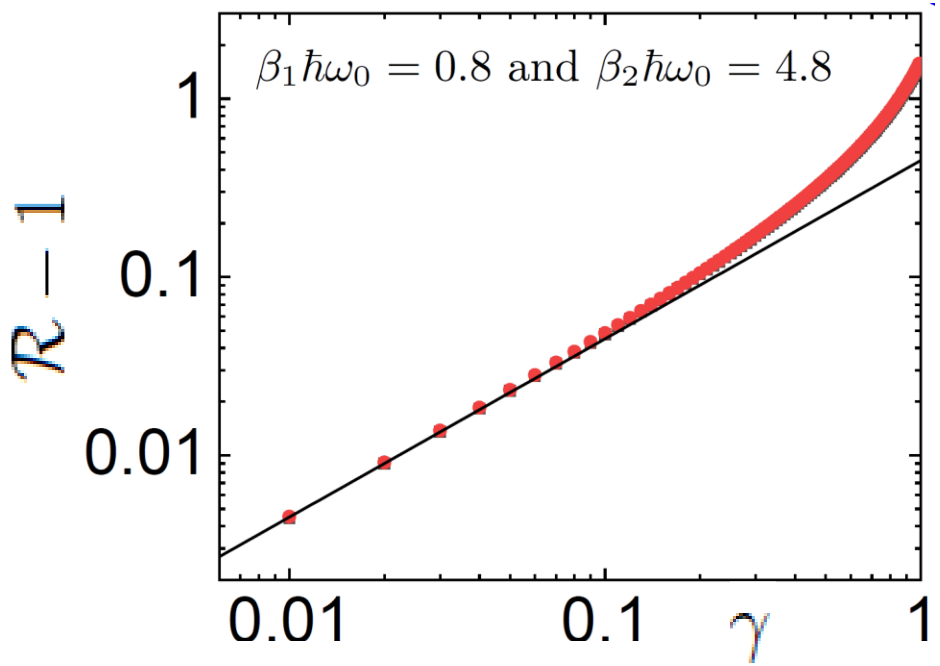
$$\rho_e = \frac{\Gamma_\uparrow}{\Gamma_\uparrow + \Gamma_\downarrow} \qquad \Gamma_{\uparrow,\downarrow} = \Gamma_{\uparrow,\downarrow}^{(1)} + \Gamma_{\uparrow,\downarrow}^{(2)}$$

$$P_i = \hbar\omega_0(\rho_e \Gamma_\downarrow^{(i)} - \rho_g \Gamma_\uparrow^{(i)})$$

$$\mathcal{R} = \left|\frac{P_i^+}{P_i^-}\right| \qquad \mathcal{R} = \frac{g_2 \coth(\frac{\beta\hbar\omega_0}{2}) + g_1}{g_1 \coth(\frac{\beta\hbar\omega_0}{2}) + g_2}$$

For small asymmetry: $\gamma = 1 - g_1/g_2$

$$\mathcal{R} - 1 = e^{-\beta\hbar\omega_0}\gamma$$

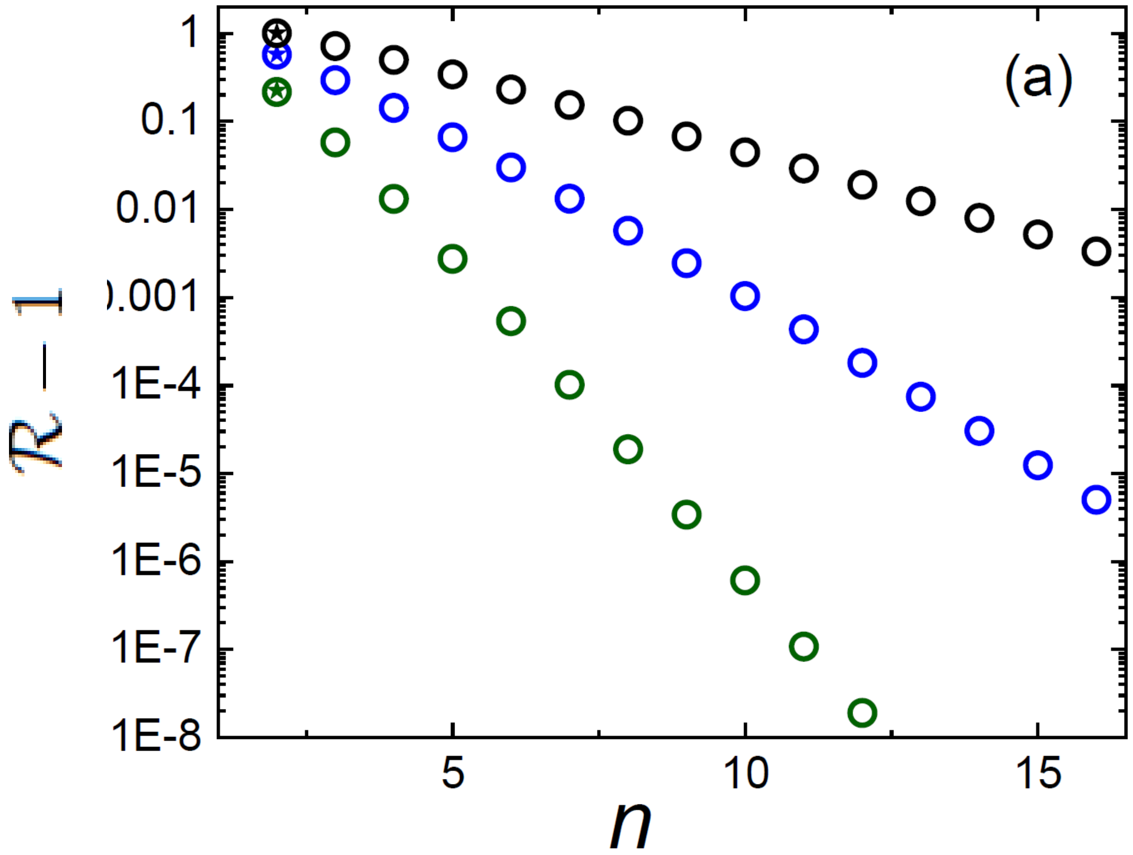


n-level system

Equidistant levels

$\beta_1 \hbar\omega_0 =$ 0.4, 0.8, 1.6

$\beta_2 \hbar\omega_0 = 4.8$

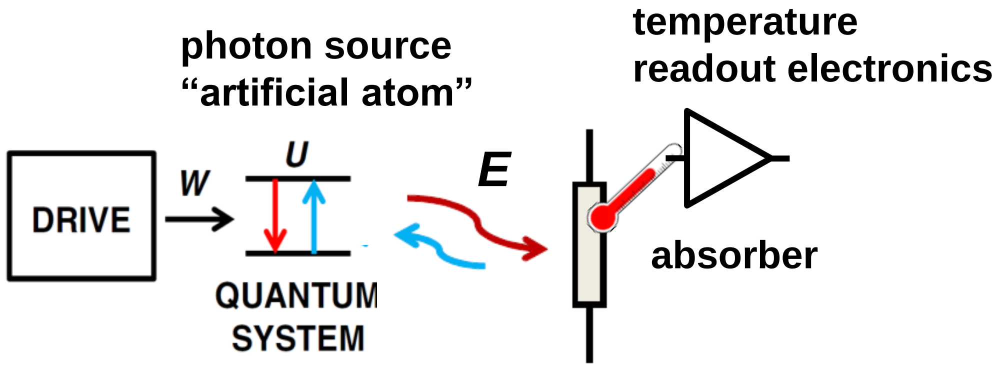


Rectification vanishes in a linear system (harmonic oscillator) even when couplings are unequal.

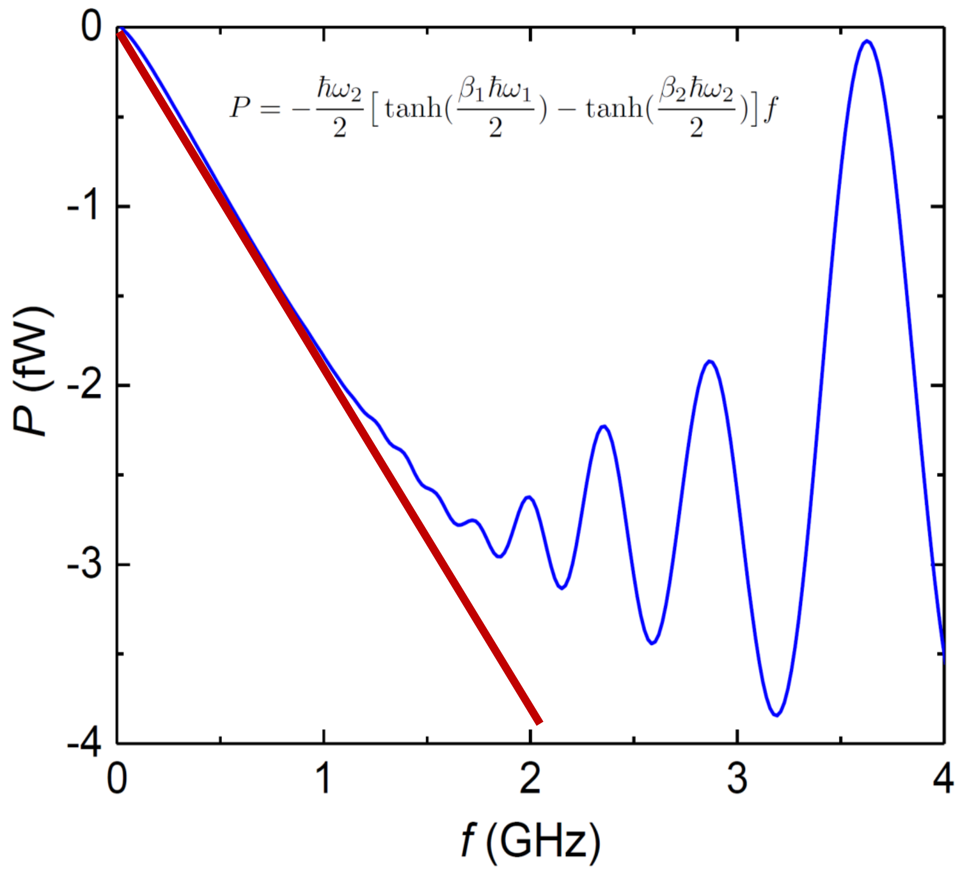
What next?

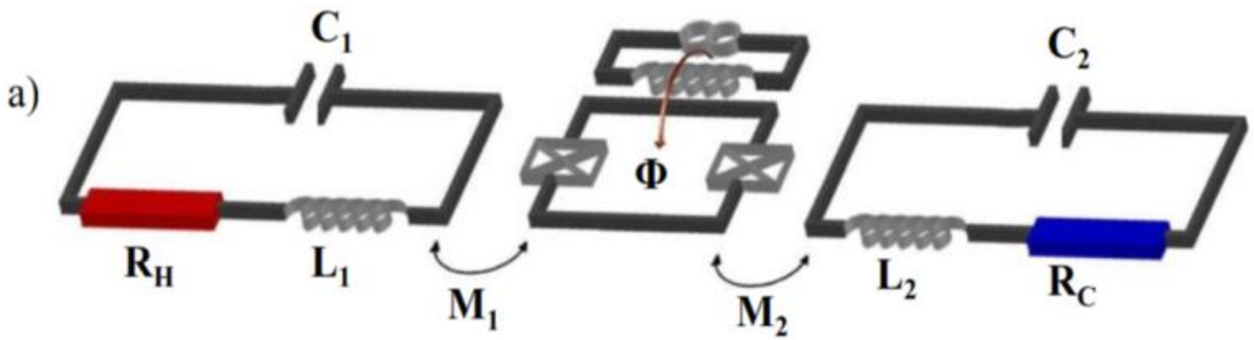
Quantum Otto refrigerator

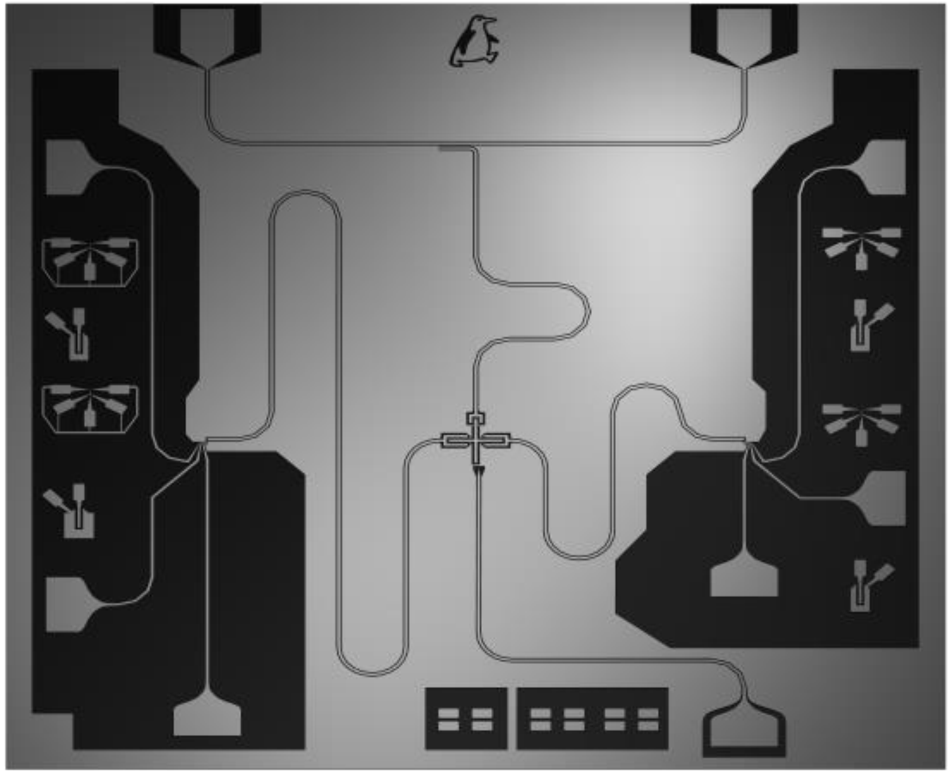
Time-domain measurements of temperature:
temperature fluctuations, single microwave photon detection



Quantum Otto refrigerator







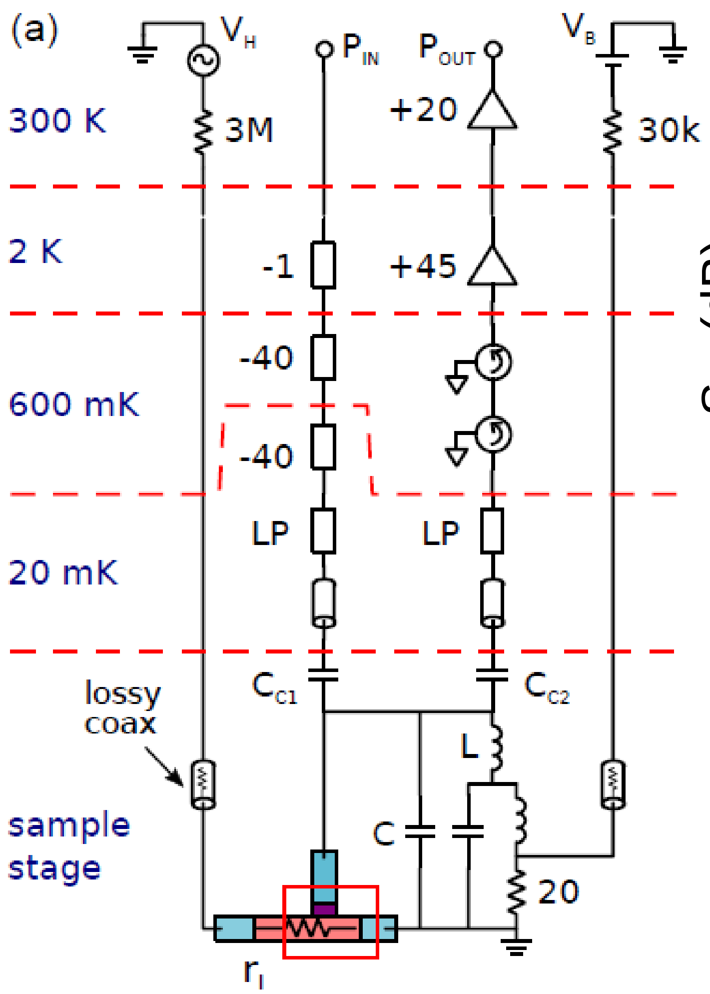
Expect about 1 fW cooling power at 1 GHz driving frequency

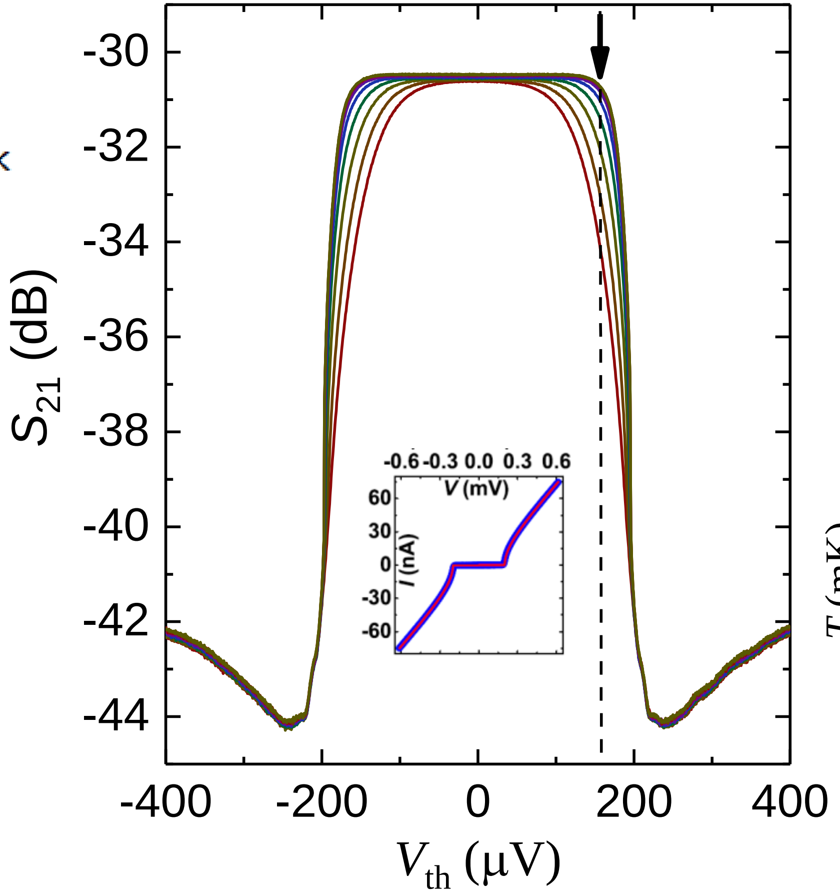
Fast NIS thermometry on electrons

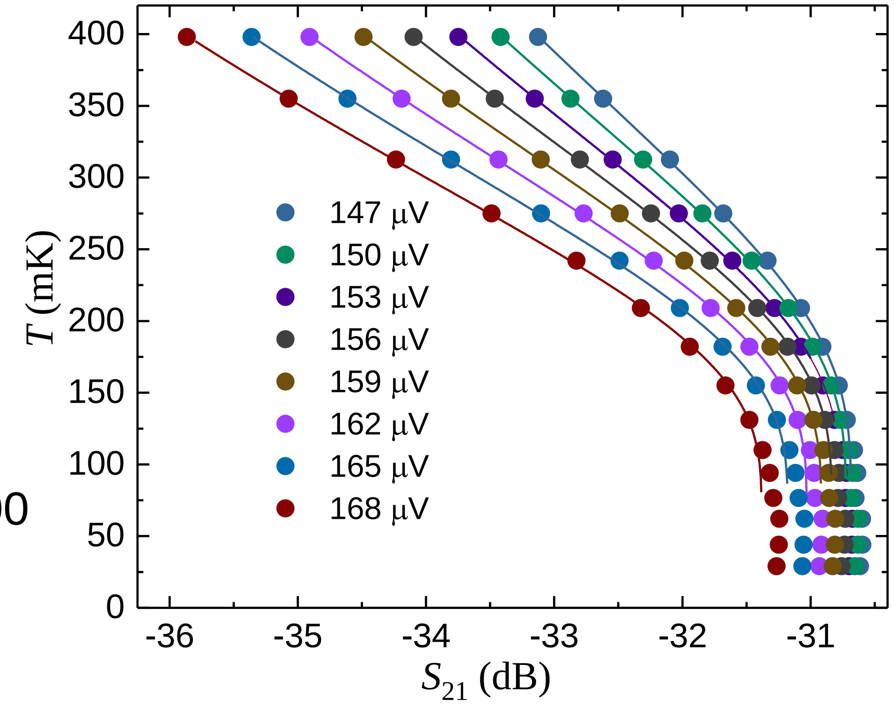
Read-out at 600 MHz of a NIS junction, 10 MHz bandwidth

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

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



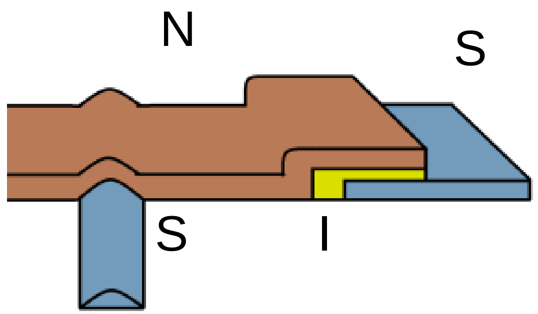




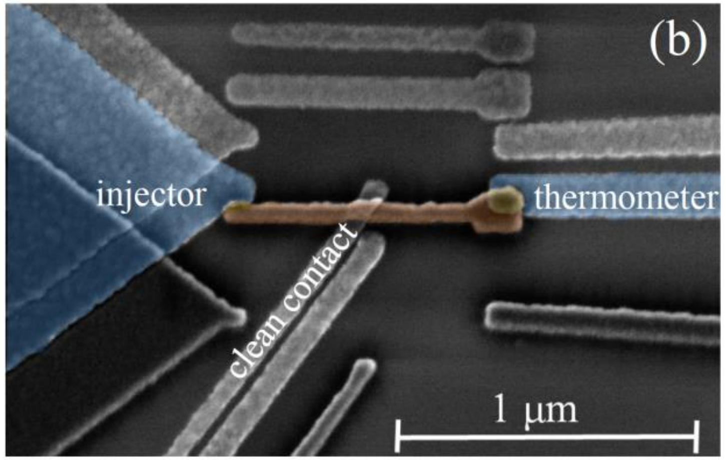
ZBA based thermometry

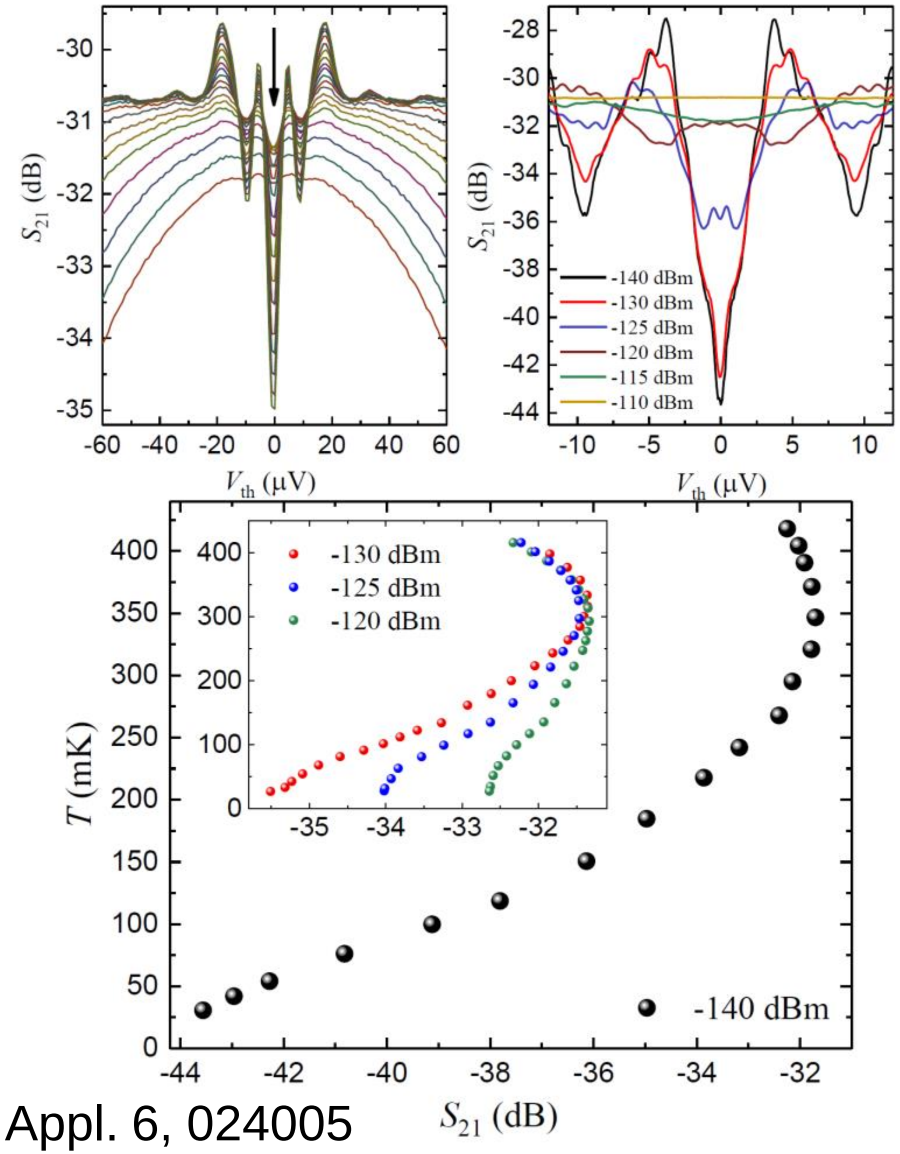
non-invasive, operates at low temperature

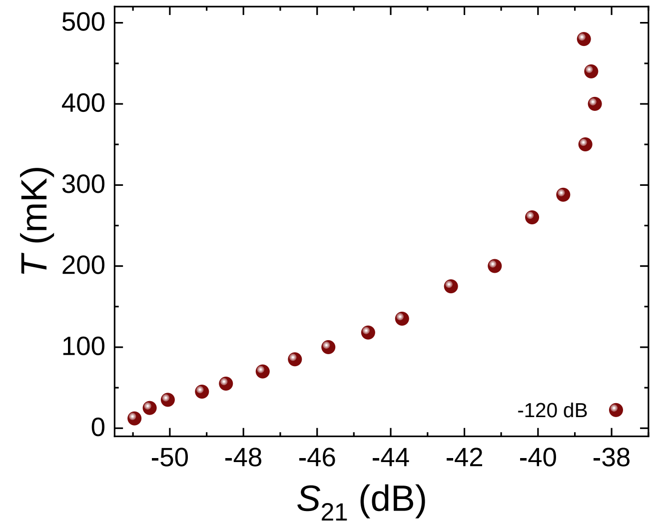
B. Karimi and JP, Phys. Rev. Applied 10, 054048 (2018)

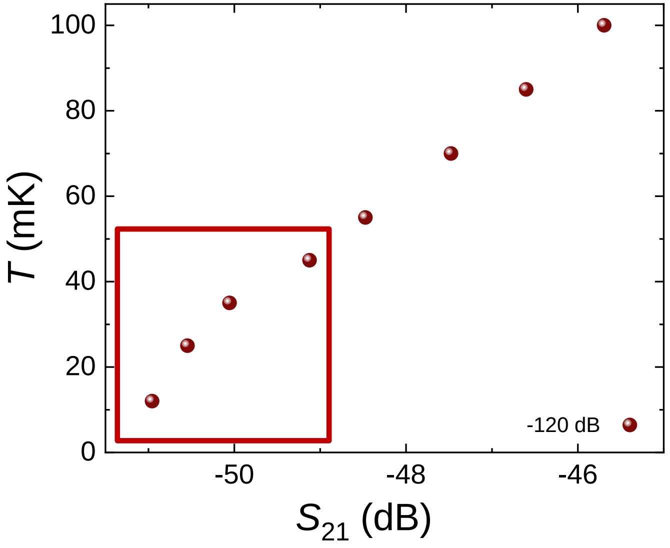


Proximity NIS junction



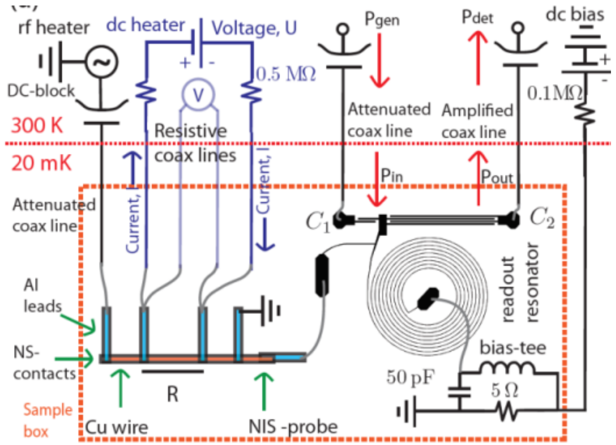


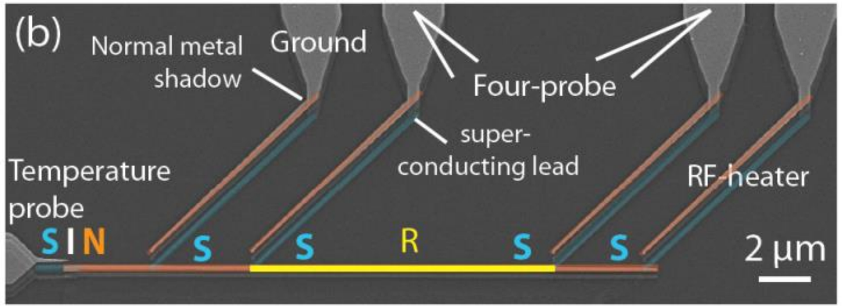




See also, O.-P. Saira et al., Phys. Rev. Appl. 6, 024005 (2016); J. Govenius et al., PRL 117, 030802 (2016)

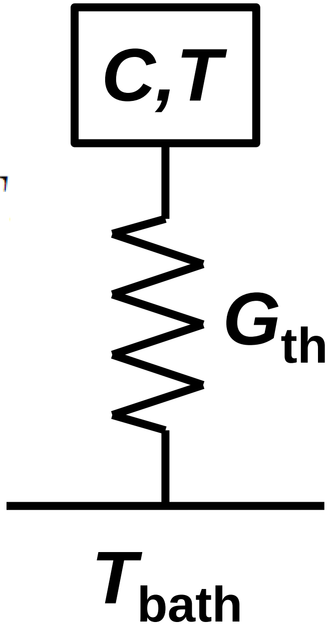
Time-resolved measurements by fast thermometer

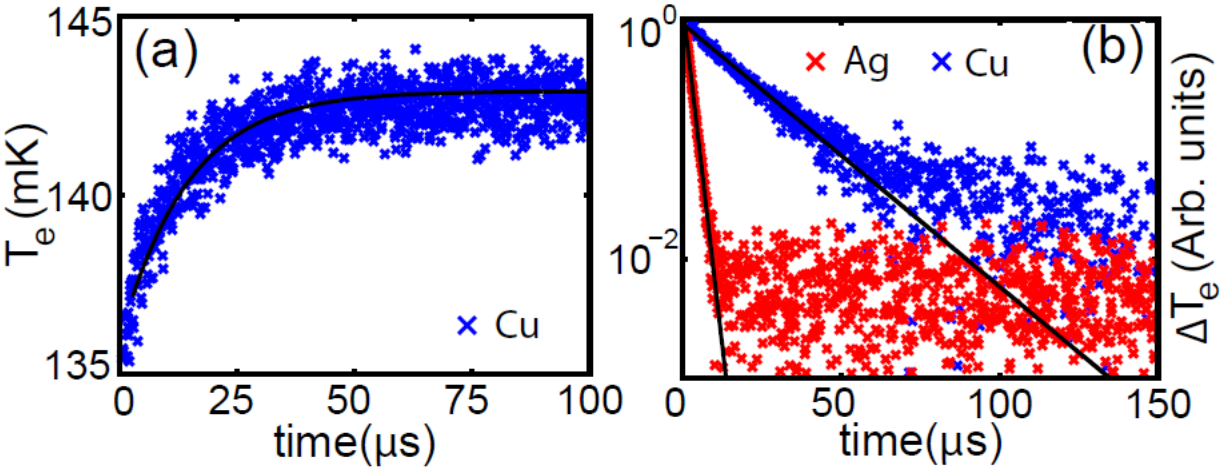


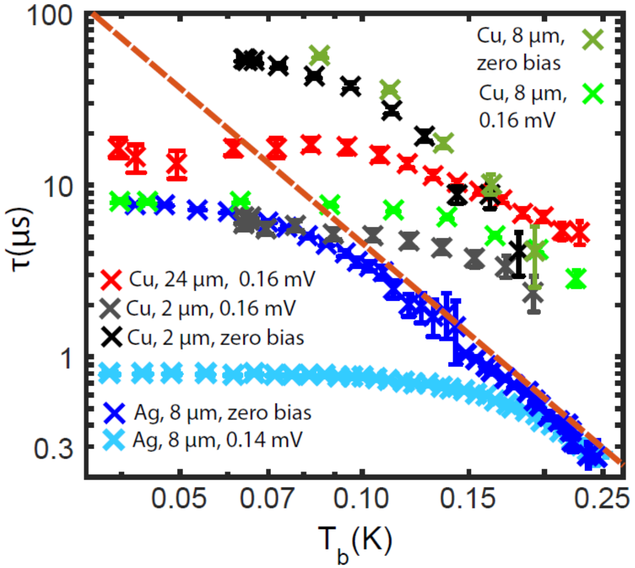


$$\mathcal{C}\frac{d\delta T}{dt} = -G_{\mathrm{th}}\delta T$$

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







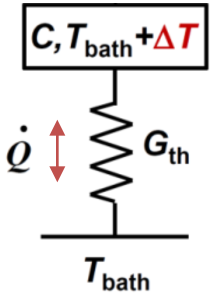
K. Viisanen and JP, PRB 97, 115422 (2018)

Noise of heat current and equilibrium temperature fluctuations

Noise of electrical current $S_I(0) = 2k_B TG$, i.e. Johnson-Nyquist noise $\langle \delta I^2 \rangle = 4k_B TG\Delta f$

Fluctuation-dissipation theorem for heat current

Low frequency noise:



$$S_{\dot{Q}}(0) = 2k_B T^2 G_{\mathrm{th}}$$

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

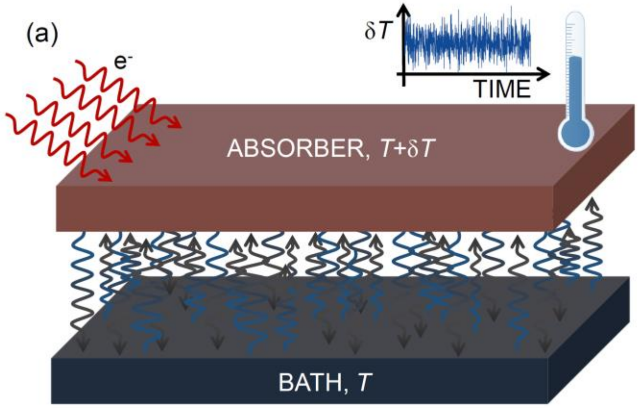
$$S_T(0) = 2k_B T^2 / G_{\mathrm{th}}$$

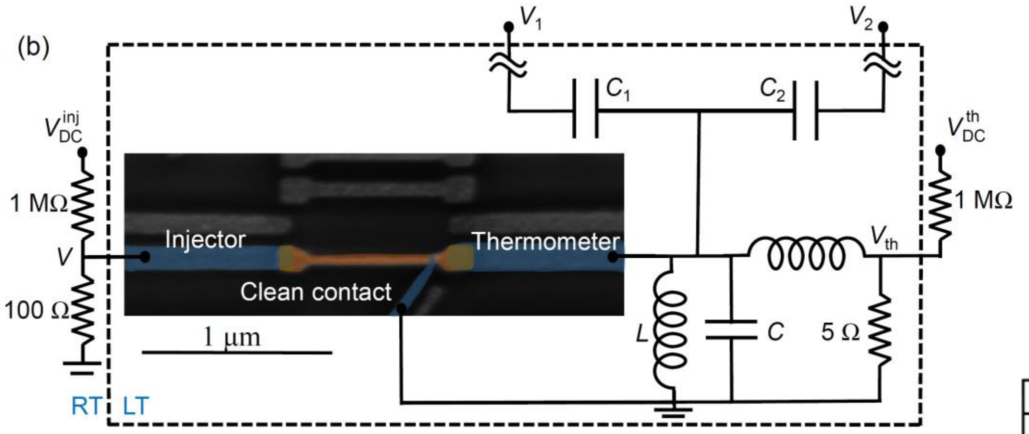
Finite frequencies (classical):

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

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

Preliminary results on temperature fluctuations





B. Karimi et al., in preparation

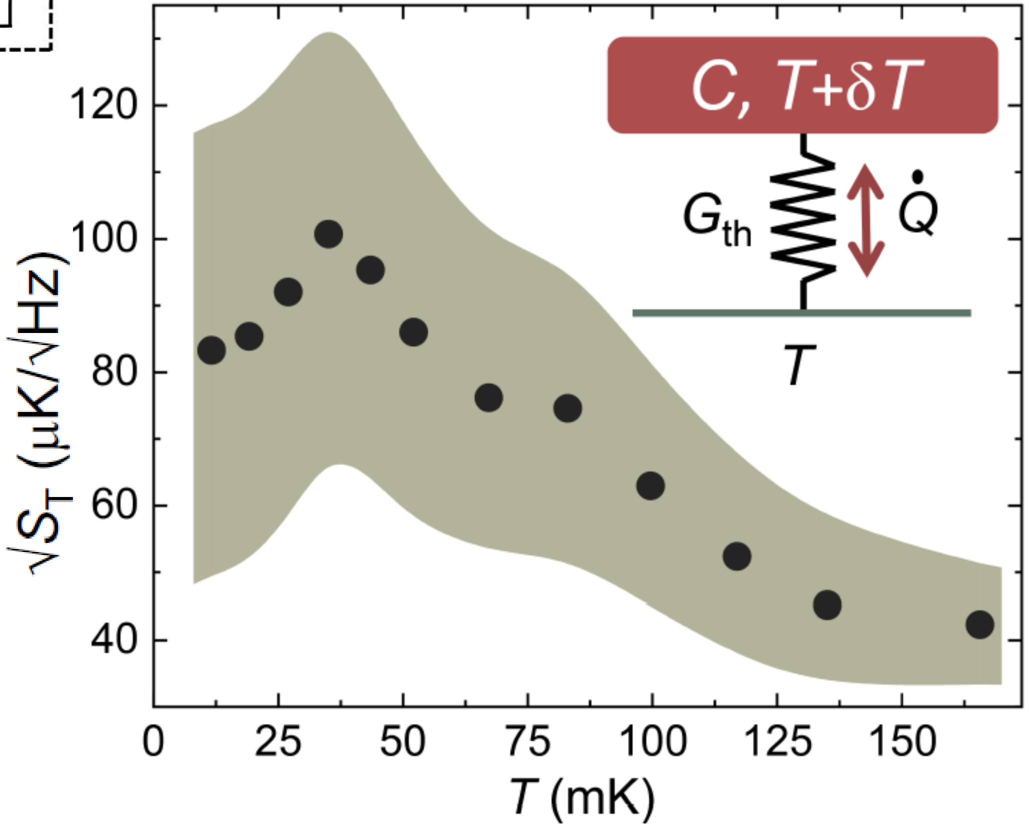
Equilibrium noise: $S_T = 2k_B T^2/G_{\rm th}$

$$G_{th} = 5\Sigma\mathcal{V}T^4 + \alpha g T$$

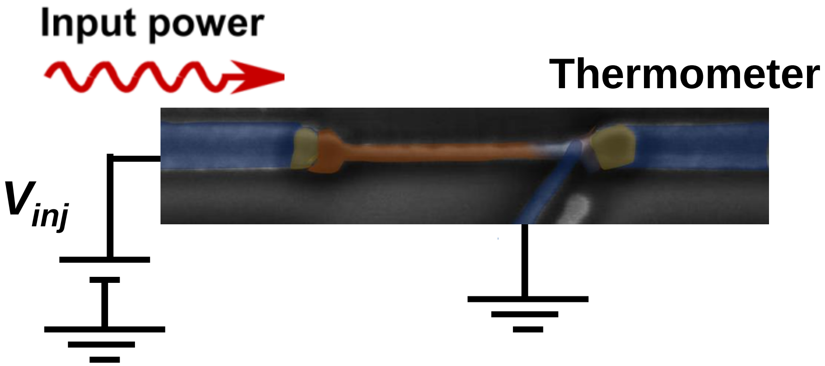
phonons — photons, tunneling

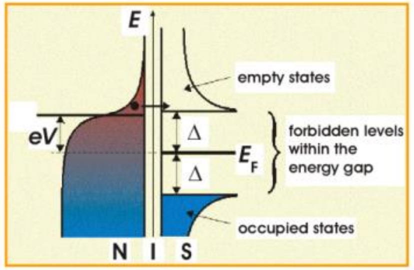
$$\sqrt{S_T} = \sqrt{\frac{2k_{\rm B}}{5\Sigma\mathcal{V}}}T^{-1} \quad (\text{high } T)$$

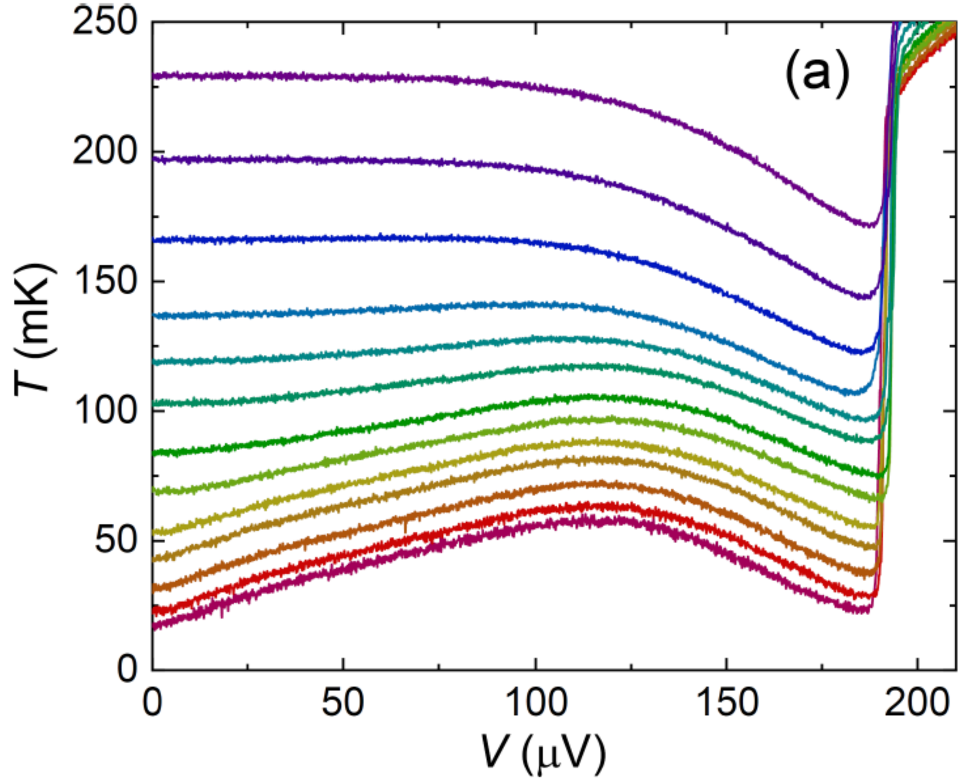
$$\sqrt{S_T} = \sqrt{\frac{2k_{\rm B}}{\alpha G_Q}}T^{1/2} \quad (\text{low } T)$$

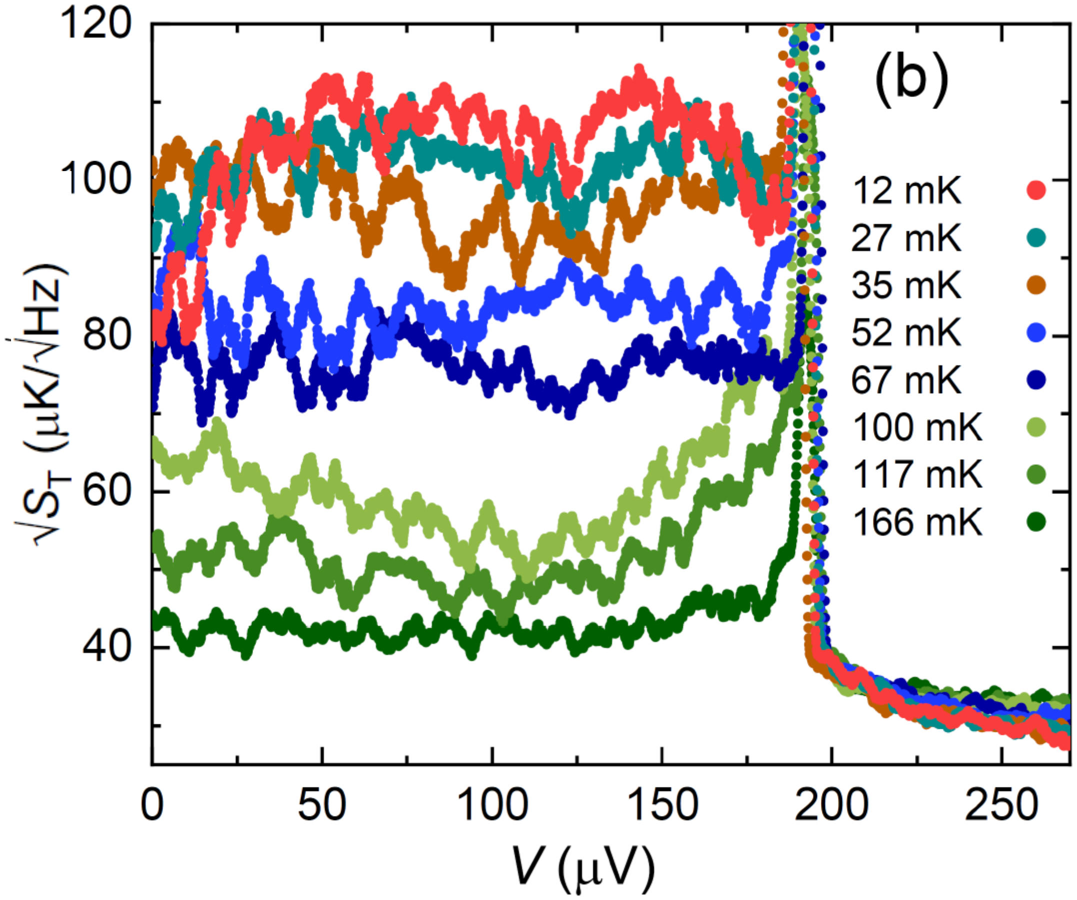


Non-equilirium temperature noise









B. Karimi et al., in preparation

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

Requirements for single microwave photon detection

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

Noise-equivalent temperature, NET

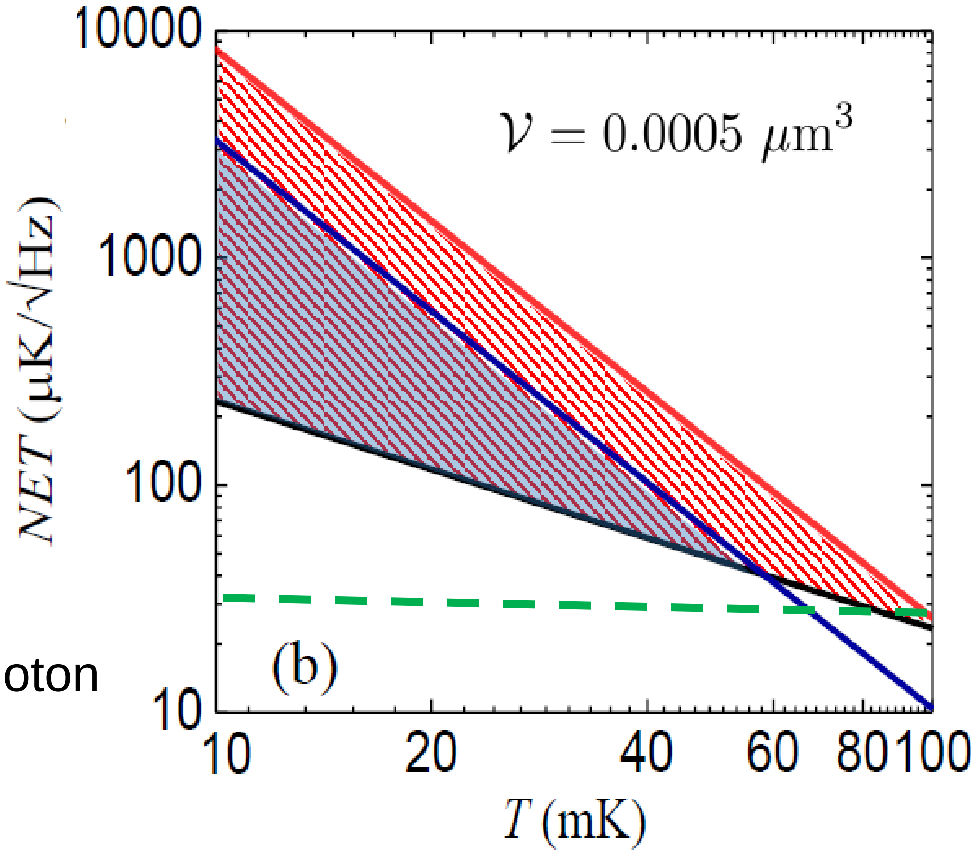
$$\mathrm{NET} \equiv S_T(0)^{1/2} = (2k_B T^2/G_{\mathrm{th}})^{1/2}$$

Required $\mathrm{NET} = E/(G_{\mathrm{th}}C)^{1/2}$

Lines:

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

Standard copper absorber



Summary

Discussed:

measurement of heat in circuits, thermometry

Heat transport and thermo-electricity of a single-electron transistor

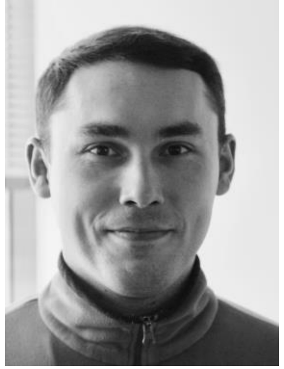
open quantum systems based on superconducting qubits

photonic heat transport, quantum of heat conductance

quantum heat valve, local and global picture, rectification of heat current

calorimetry, temperature fluctuations

Main collaborators

Bayan Karimi, Alberto Ronzani, Jorden Senior, Azat Gubaydullin, Yu-Cheng Chang, Joonas Peltonen

Bivas Dutta, Clemens Winkelmannn, Herve Courtois (CNRS Grenoble)
Paolo Erdman, Fabio Taddei (Pisa), Rosario Fazio (ICTP Trieste)
Hans He, Samuel Lara Avila, Sergey Kubatkin (Chalmers, graphene calorimeter)