# Quantum heat transport in superconducting circuits

Jukka Pekola
Aalto University

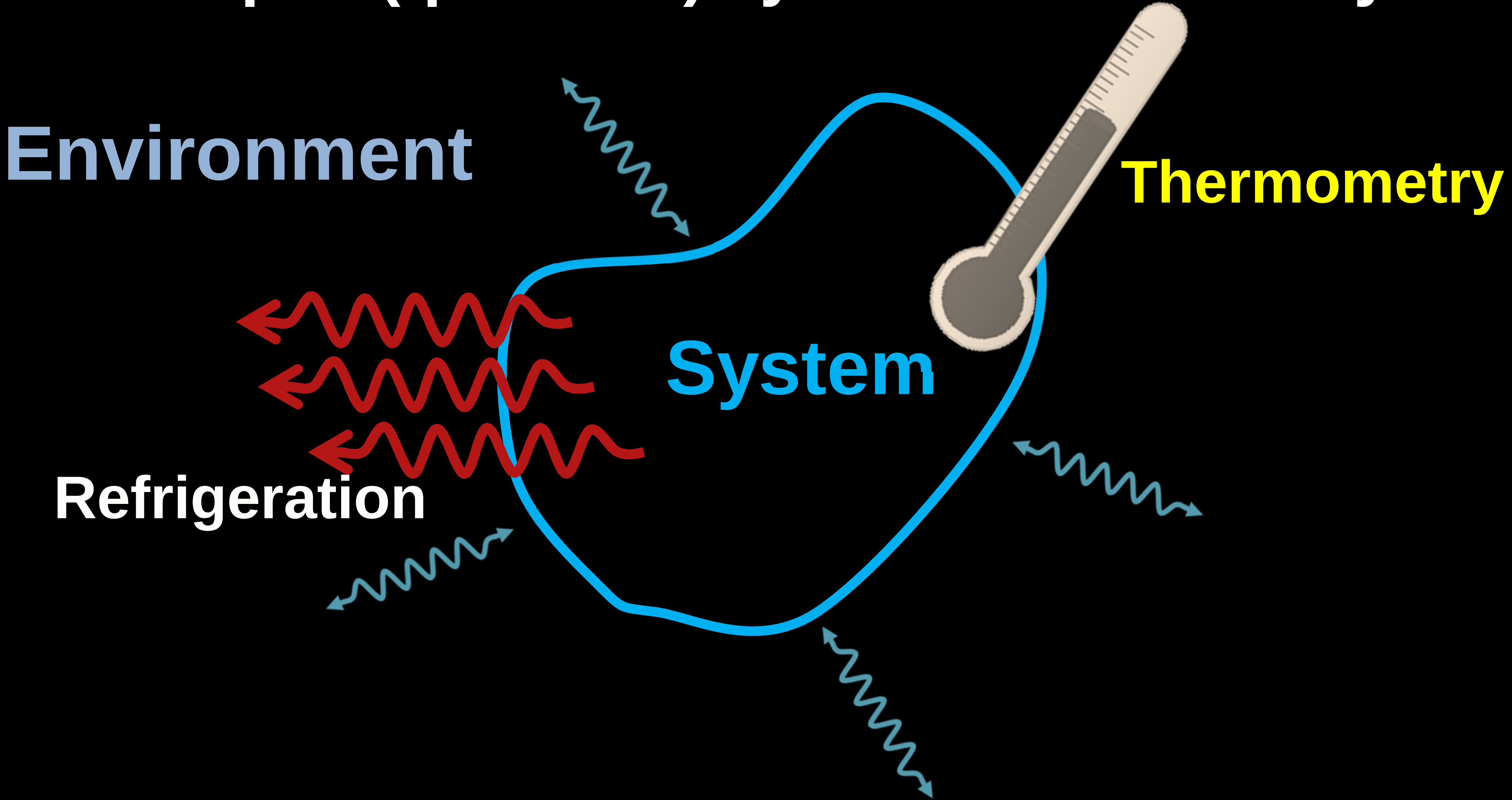
# *Matti 80*

*Warm congratulations to you Matti*

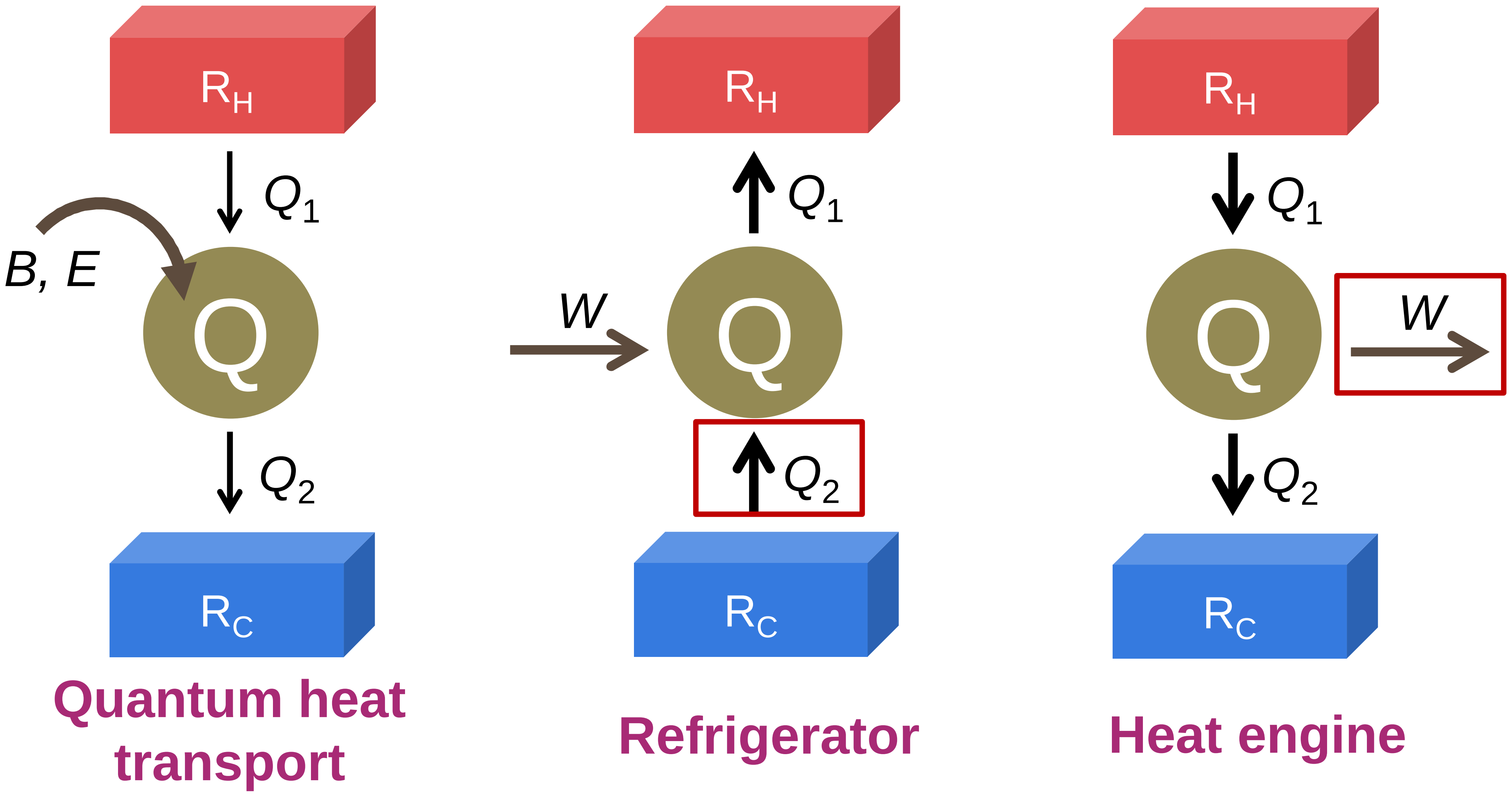
*– you have been the elder brother for me when becoming an experimental scientist, and a highly respected colleague thereafter*

*HYVÄÄ SYNTYMÄPÄIVÄÄ!*

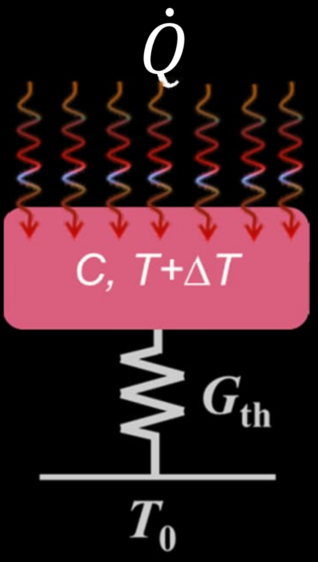
# Open (quantum) systems under study



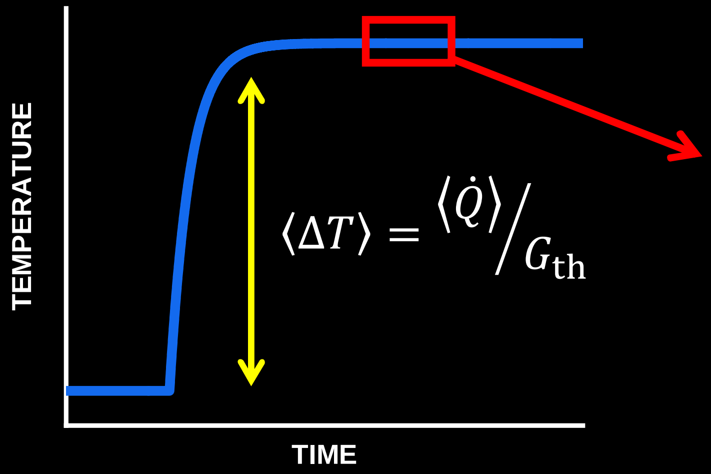
# Thermodynamics in quantum circuits

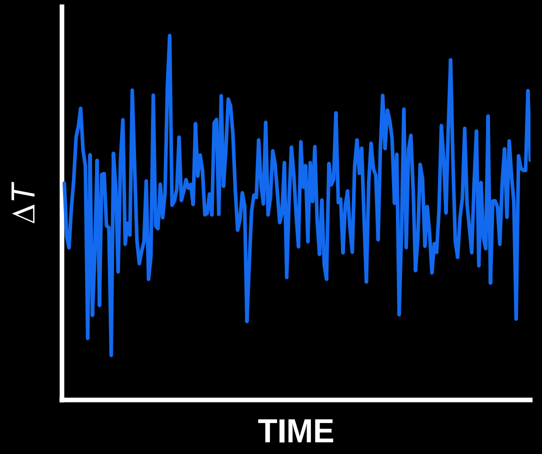


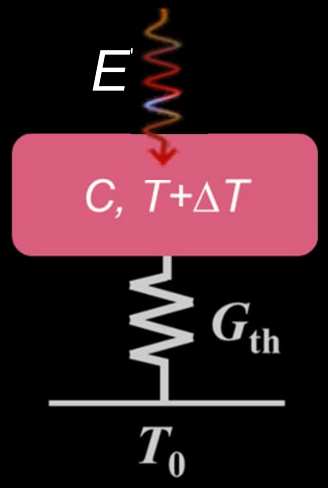
# Bolometry and calorimetry

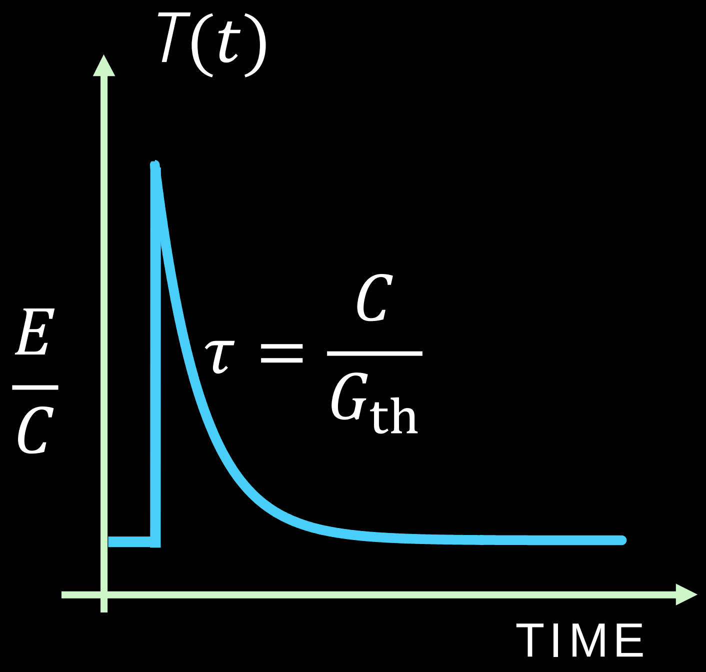


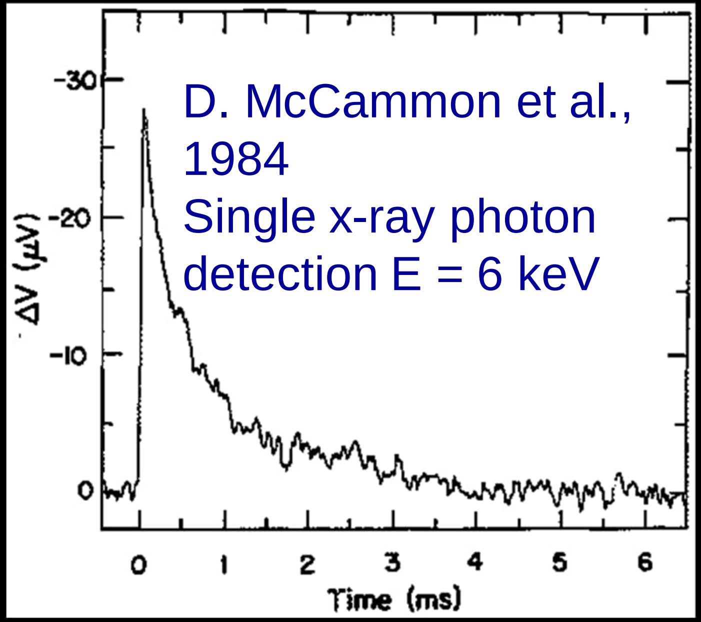

Measurement of temperature by a (fast) thermometer



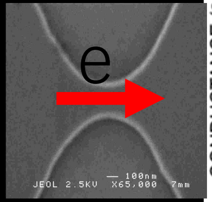

**Our goal**:
Single microwave photon detection $E$ = 100 μeV ($10^8$ times smaller energy!)

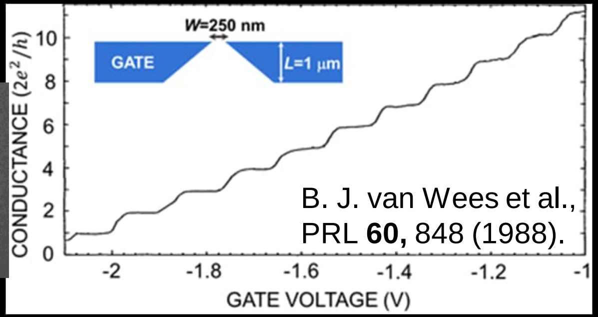
Energy resolution:

$$\delta E = \sqrt{C G_{th} S_T}$$

M. Roukes, Physica 263B-264B, 1 (1999).

# Thermal conductance in quantum limit




**Electrical conductance in a ballistic contact:**

$$G = N\frac{e^2}{h}$$

**Thermal conductance:**

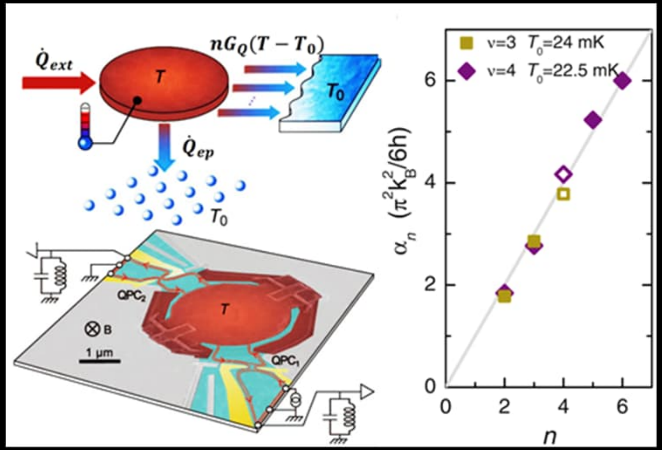
$$G_{th} = N\frac{\pi^2 k_B^2}{3h}T$$

Pendry 1983, Greiner et al. (1997).
Rego and Kirczenow (1999).
Blencowe and Vitelli (1999).

## Examples from experiments:

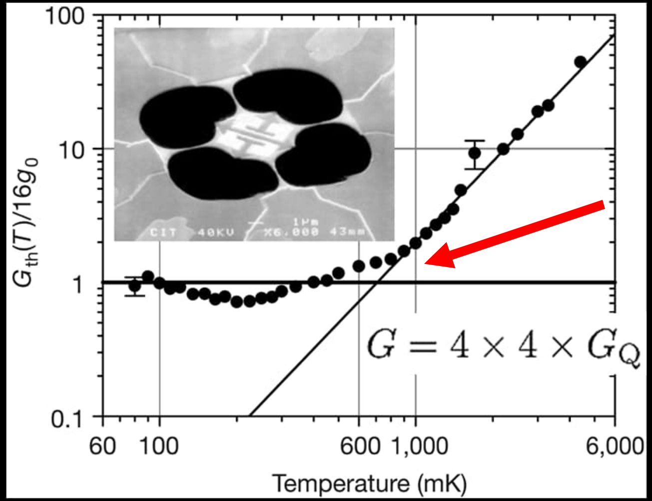
**Electrons:**

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




**Phonons:**

K. Schwab et al., Nature 404, 974 (2000).
C. Yung et al., Appl. Phys. Lett. 81 31 (2002).

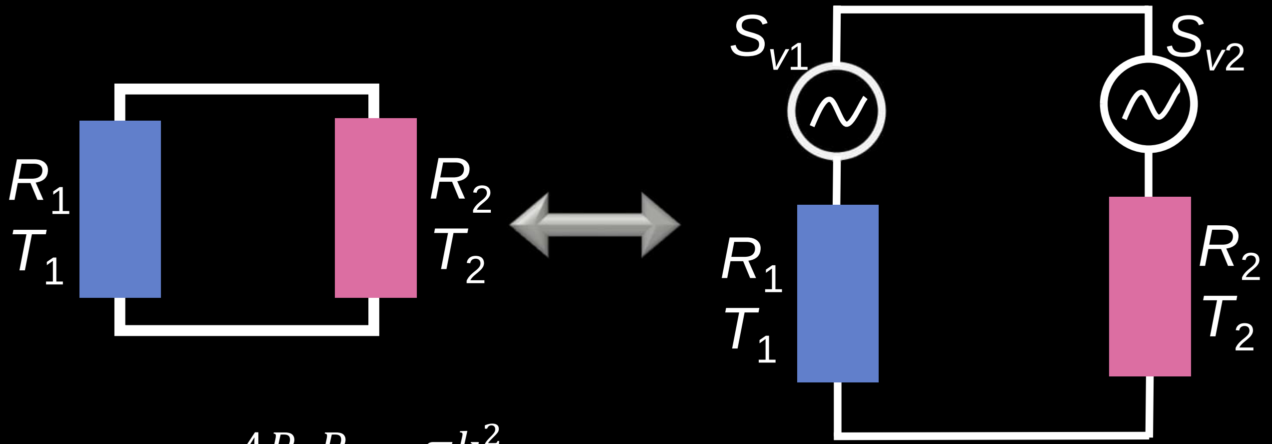



**Anyons:**

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

JP and Bayan Karimi, Rev. Mod. Phys. 93, 041001 (2021).

# Measurements of quantum of heat conductance by photons

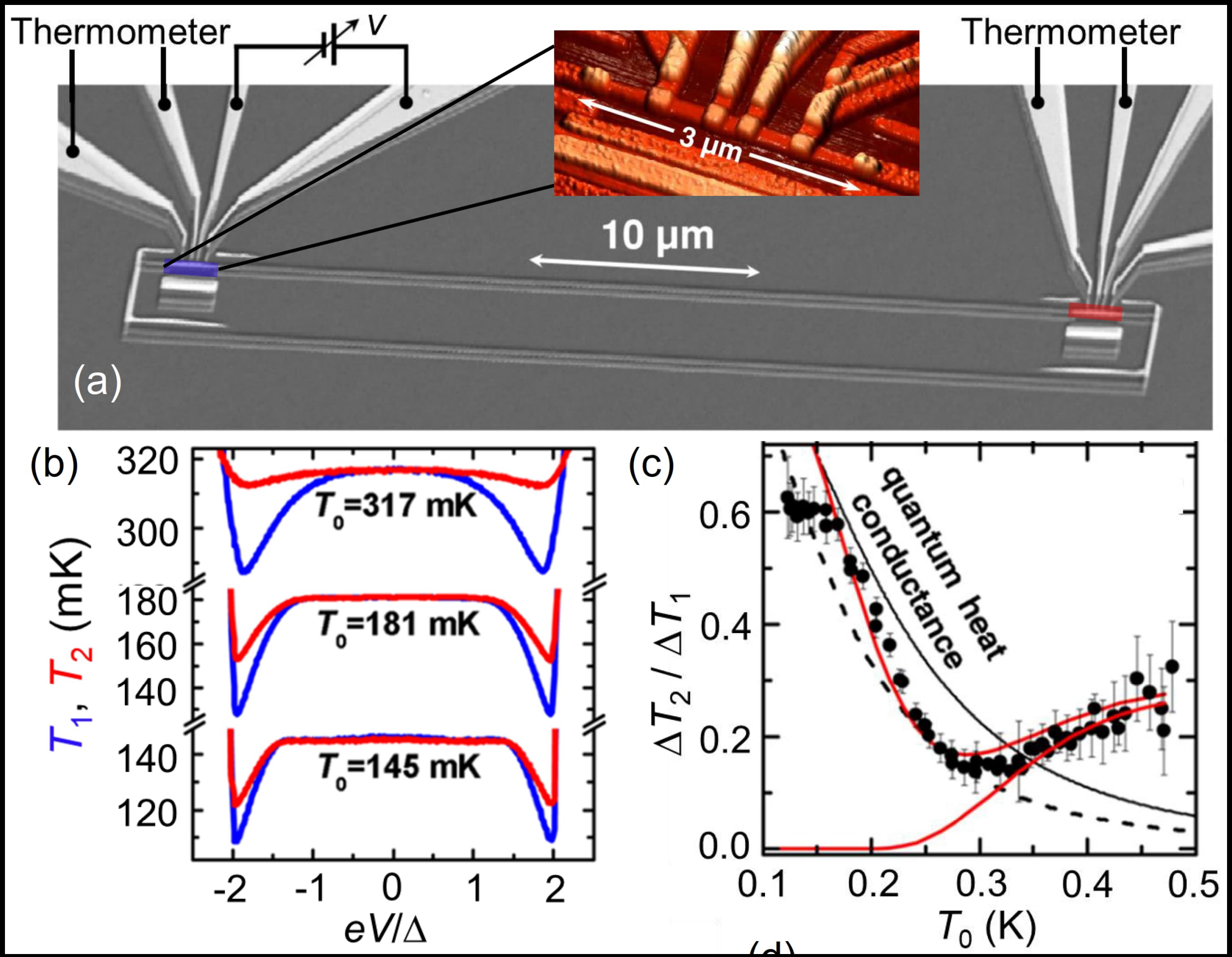



$$P = \frac{4R_1R_2}{(R_1+R_2)^2}\frac{\pi k_B^2}{12\hbar}(T_1^2 - T_2^2)$$

$$G_\nu = \frac{4R_1R_2}{(R_1+R_2)^2}\frac{\pi k_B^2}{6\hbar}T$$

$$r \equiv \frac{4R_1R_2}{(R_1+R_2)^2}$$

$$G_\nu = G_Q$$

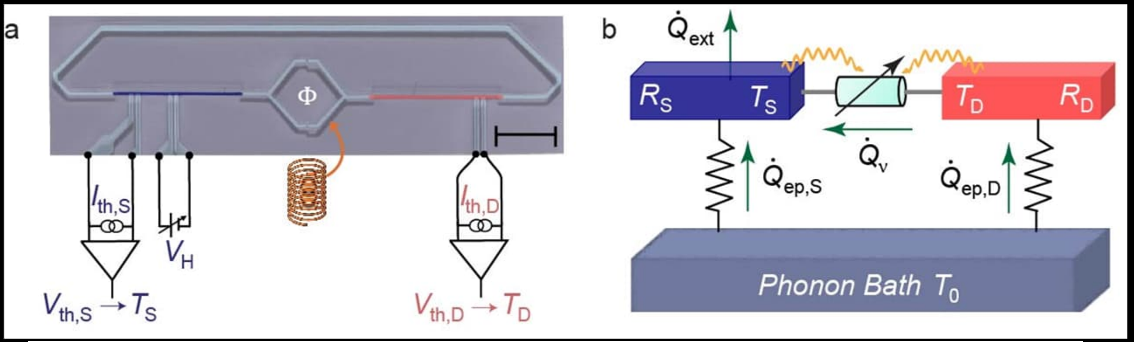


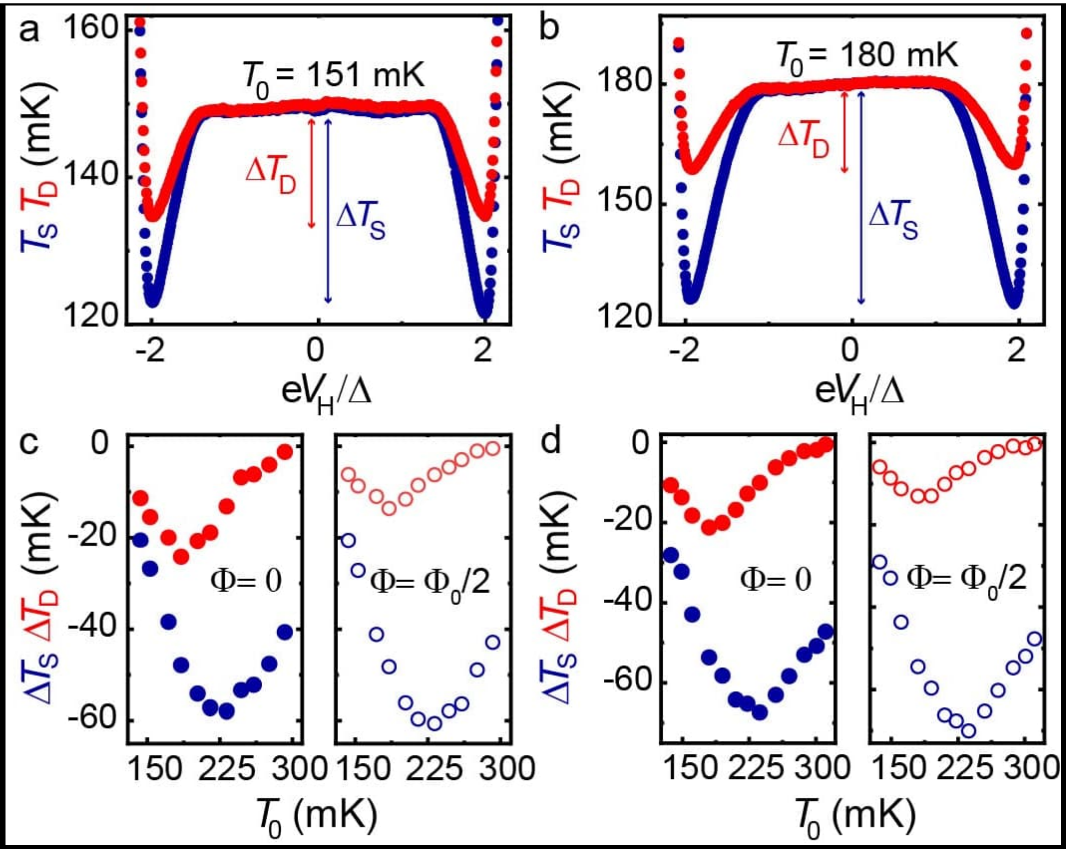

D. Schmidt et al., PRL 93, 045901 (2004).
M. Meschke et al., Nature 444, 187 (2006).

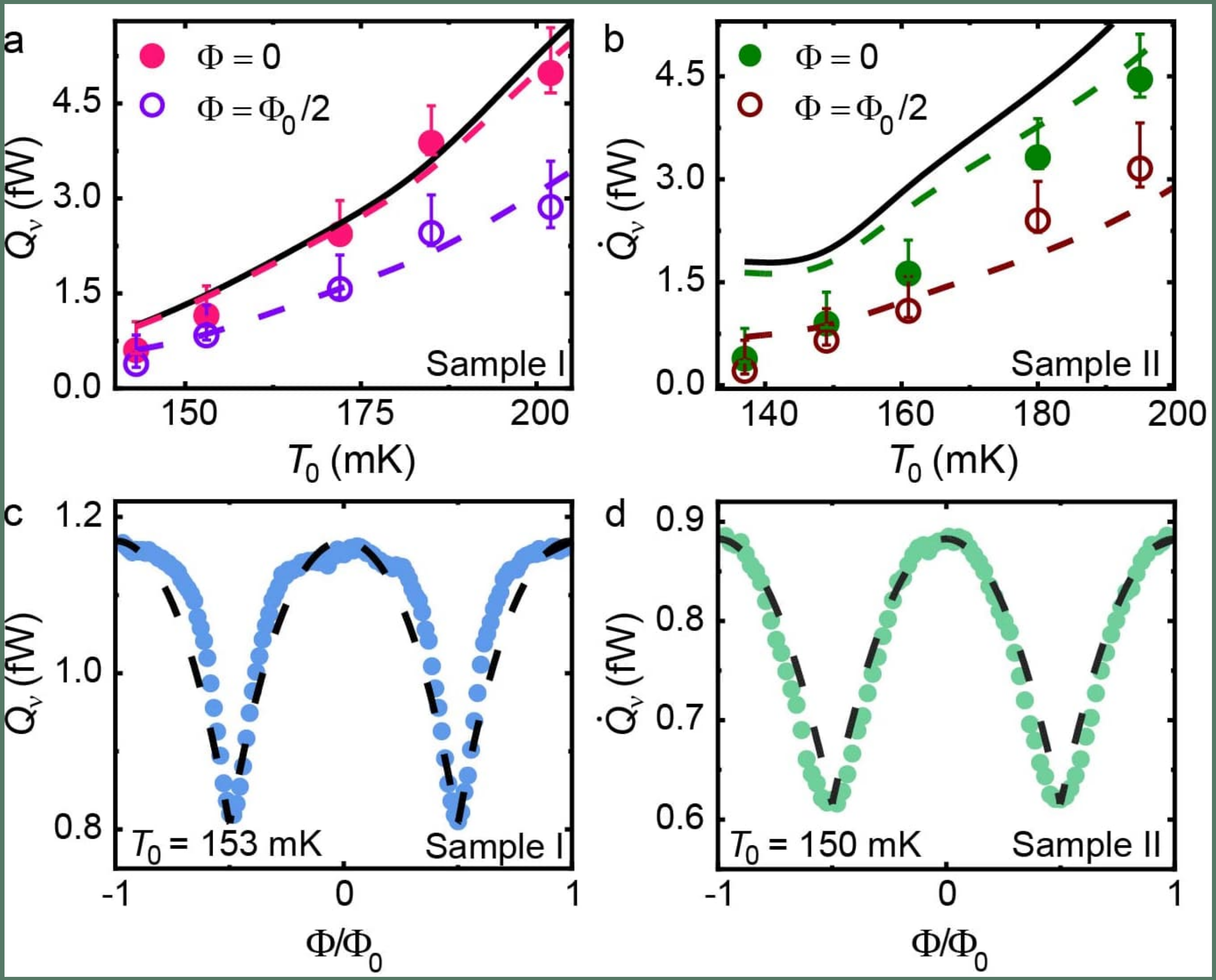
A. Timofeev et al., PRL 102, 200801 (2009).
M. Partanen et al., Nature Phys. 12, 460 (2016).

# Bolometric detection of coherent Josephson junction coupling in highly dissipative environment

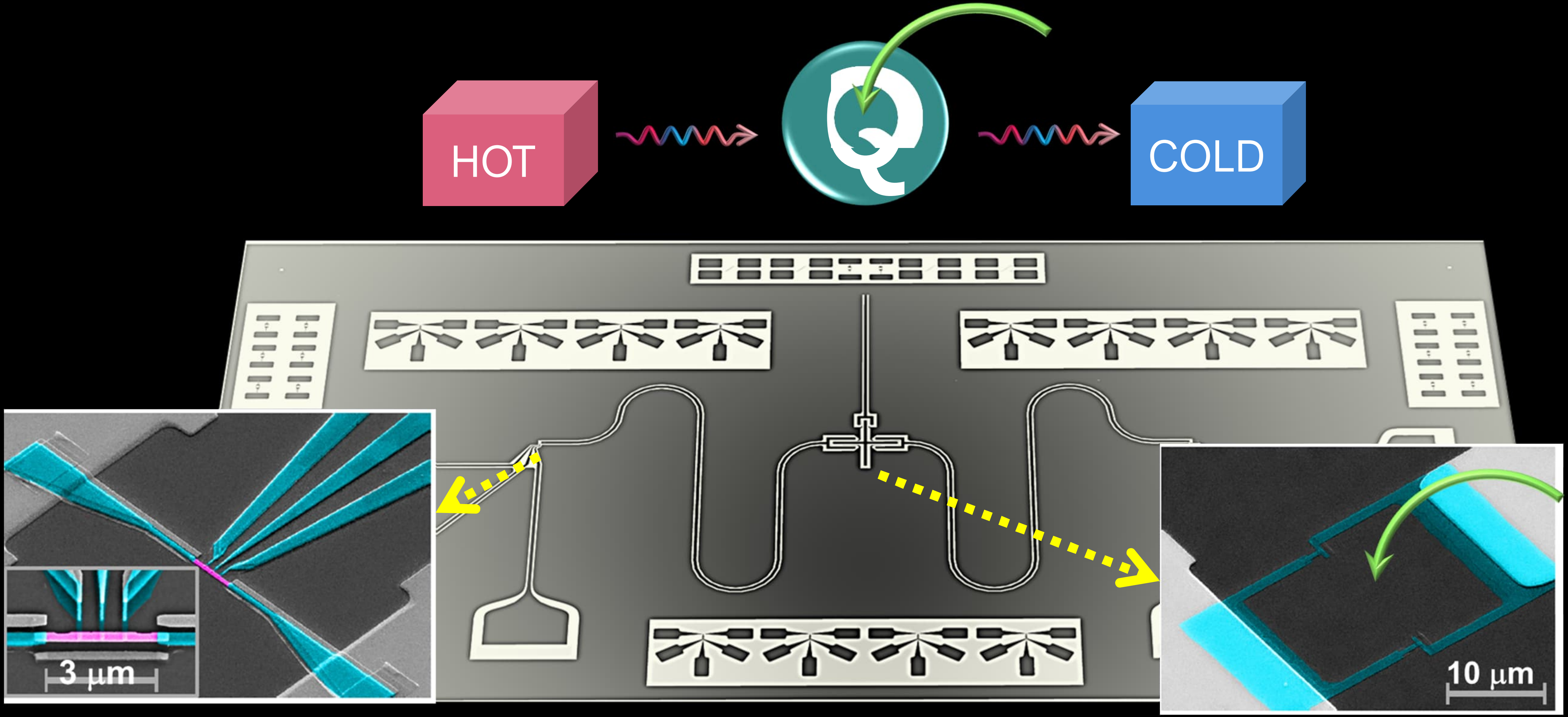
D. Subero et al., arXiv.2210.14953



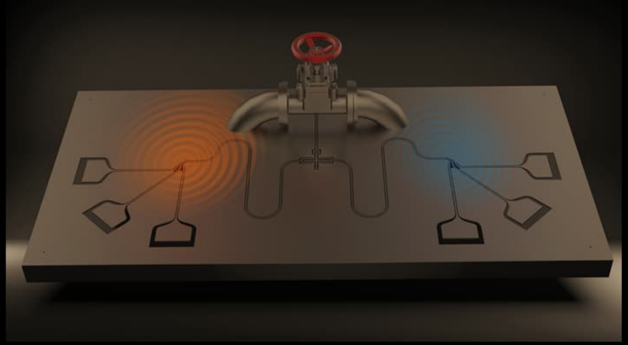



# Quantum heat valve

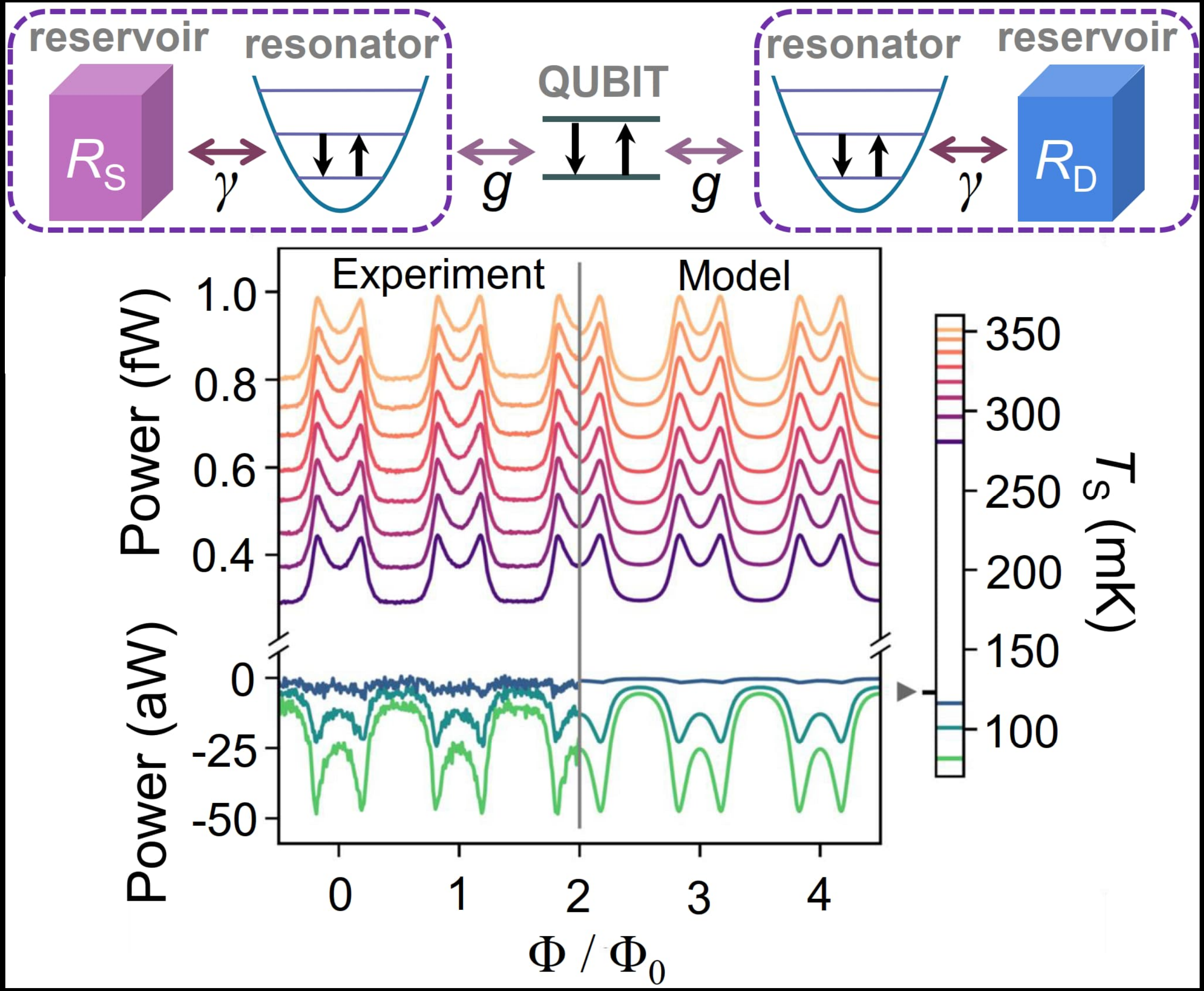



A. Ronzani, B. Karimi, J. Senior, Y.-C. Chang, J. Peltonen, C. D. Chen, and JP,
Nature Physics 14, 991 (2018).

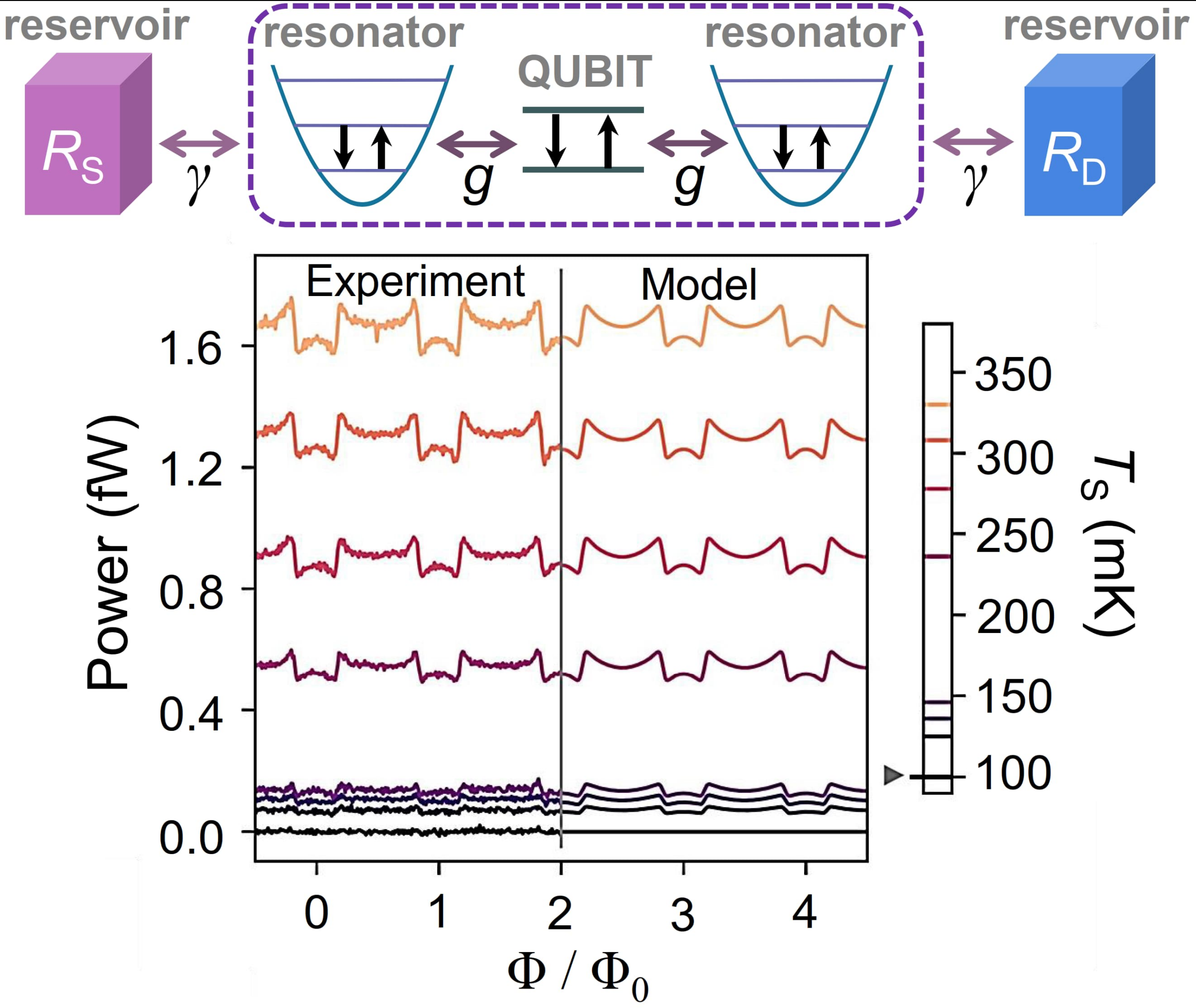
# Quantum heat valve



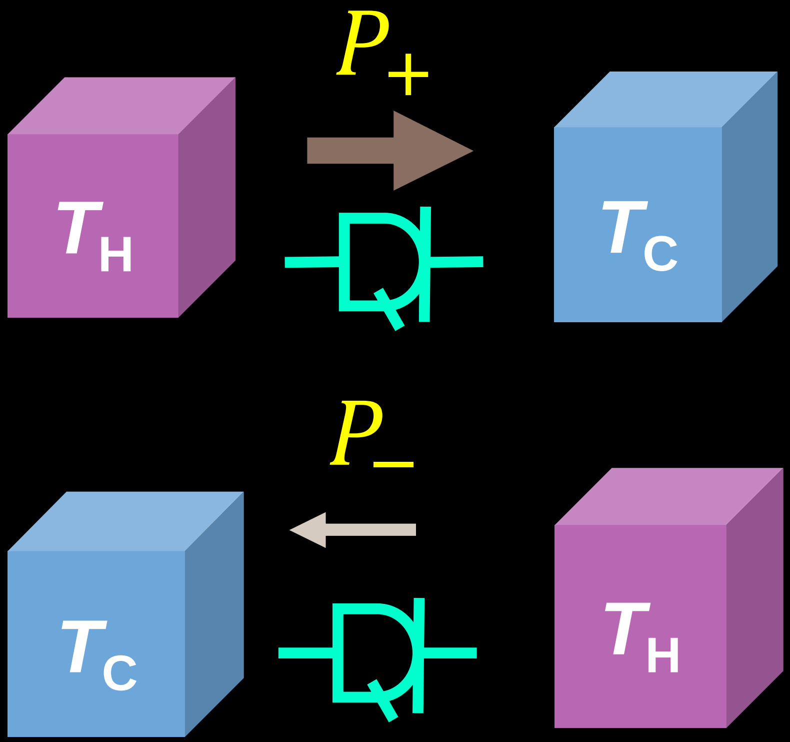
## LOCAL



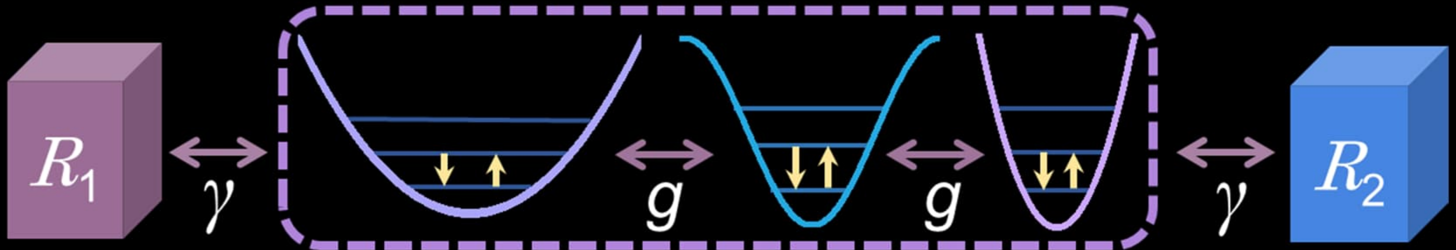

## GLOBAL



# Heat rectification




$$R = \left| \frac{P_+}{P_-} \right|$$



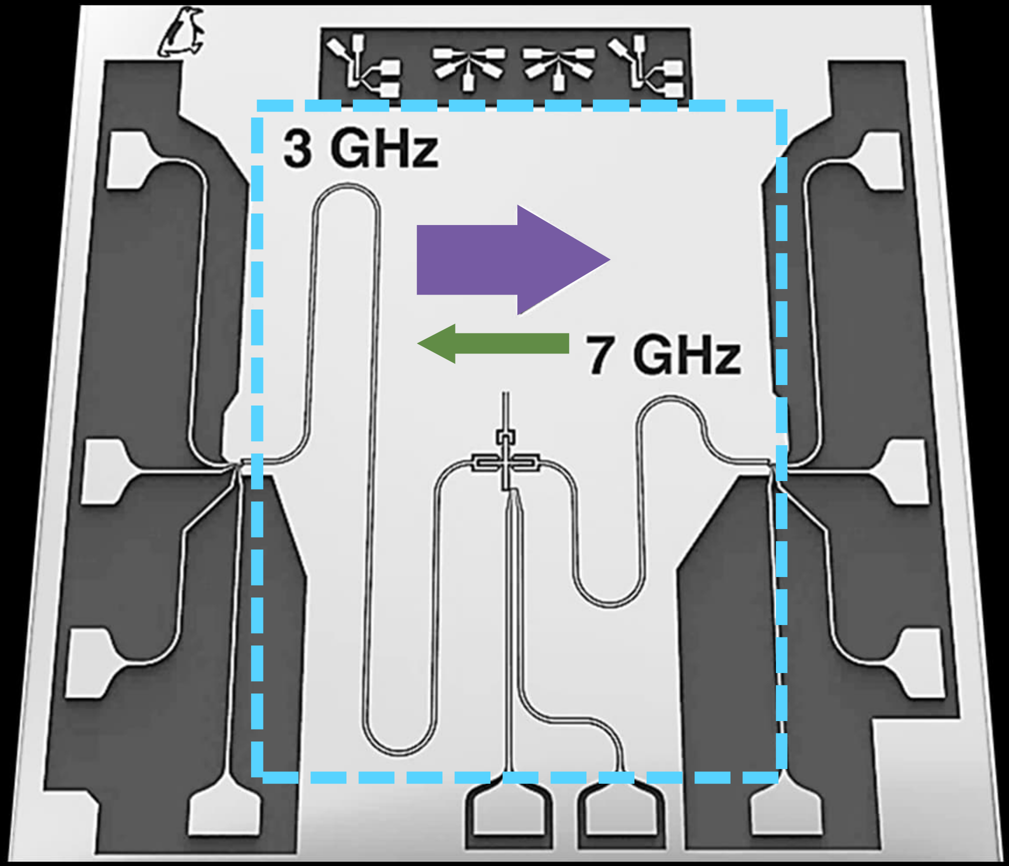

**Experiments:**

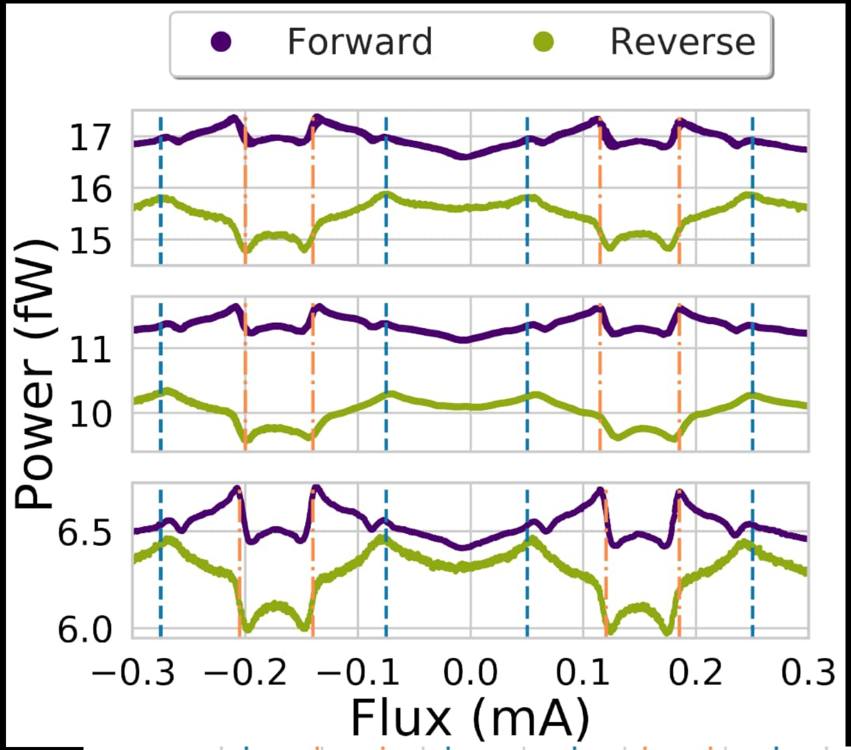
Carbon nanotubes: Chang et. al., Science 314, 5802 (2006).
Quantum dots: Scheibner et. al., NJP 10, 083016 (2008).
Suspended graphene: Wang et. al., Nature Comm. 8, 15843 (2017).

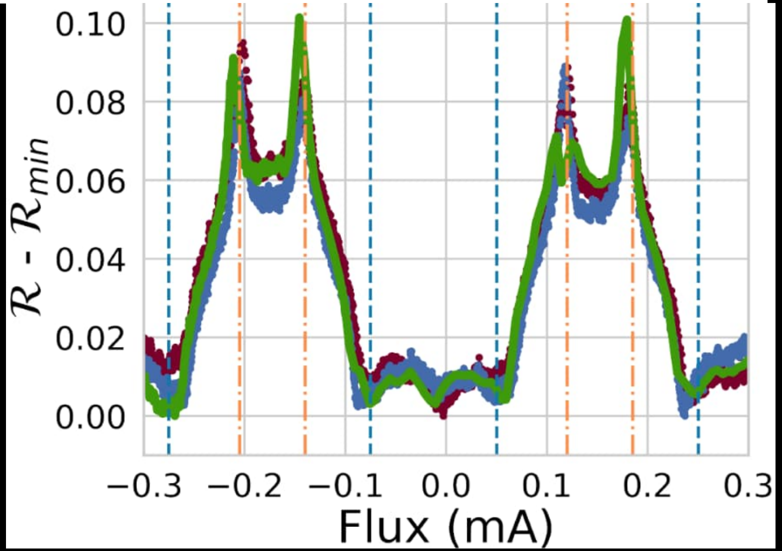
**Theories for (wireless) quantum rectifiers:**

Spin-Boson model: D. Segal and A. Nitzan, PRL 94, 034301 (2005).
Non-linear circuit: T. Ruokola, T. Ojanen, and A.-P. Jauho, Phys. Rev. B 79, 144306 (2009) .
Quantum chains: T. Motz et al., NJP 20, 113020 (2018).
Dynamic effects: A. Riera-Campeny et al., Phys. Rev. E 99, 032126 (2019).
Two-atom system: C. Kargi et al., Phys. Rev. E 99, 042121 (2019)
Palafox et al., arXiv:2204.07060.

# Heat rectifier experiment

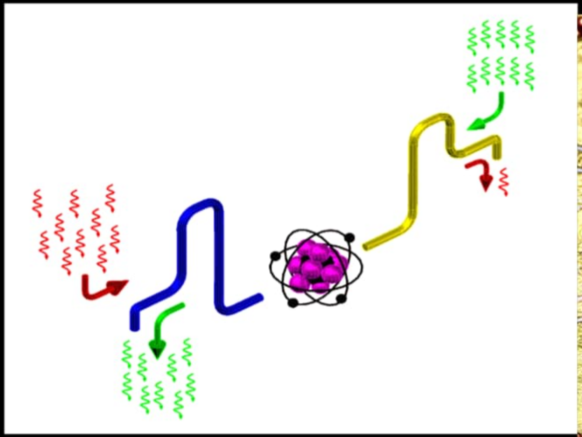



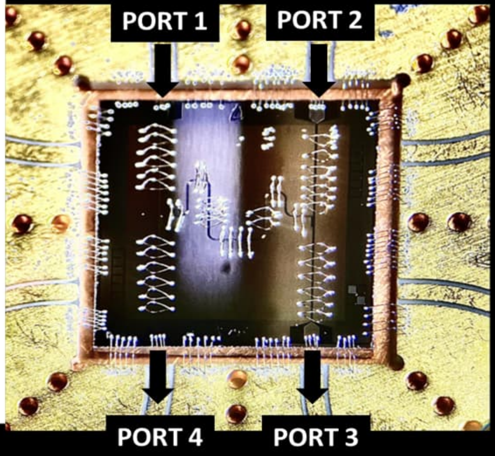

J. Senior et al., Commun. Phys. 3, 40 (2020).

# Flux tunable on-chip microwave diode

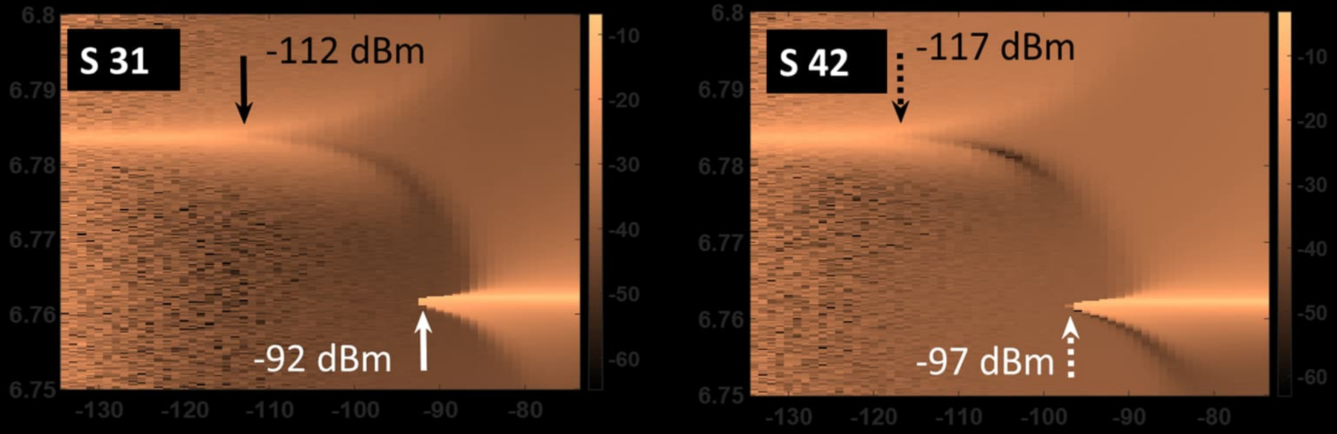
## Conceptual representation



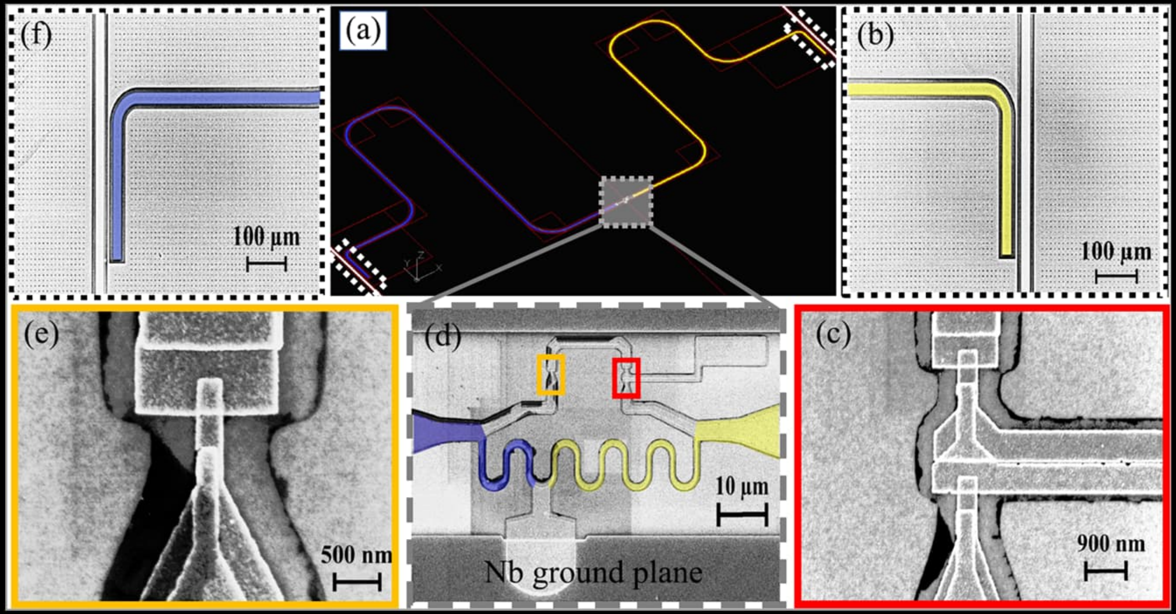
## Measured device



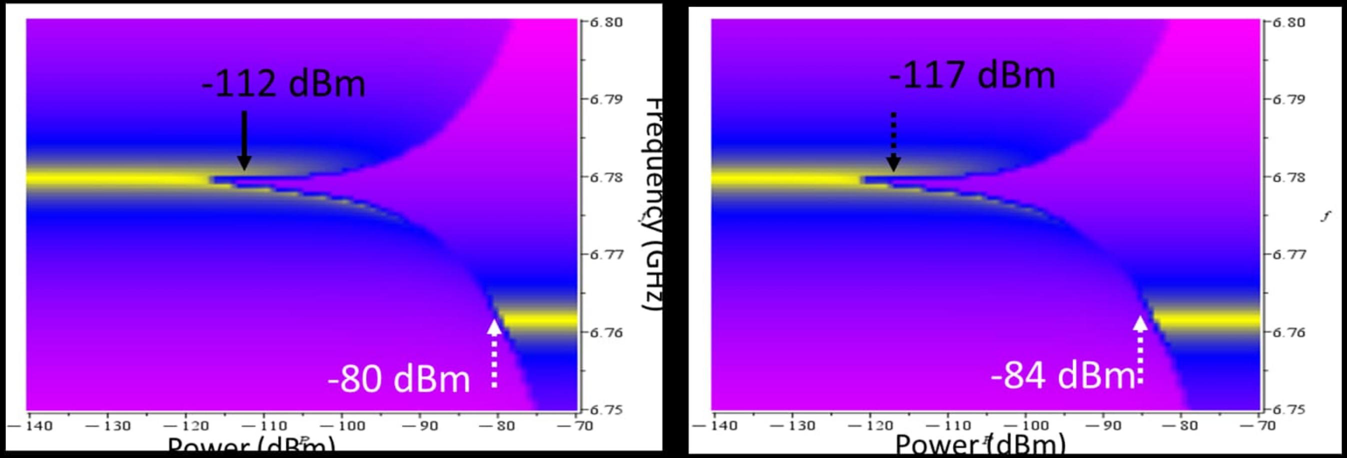

## Experimental observation




## Micrograph of the device



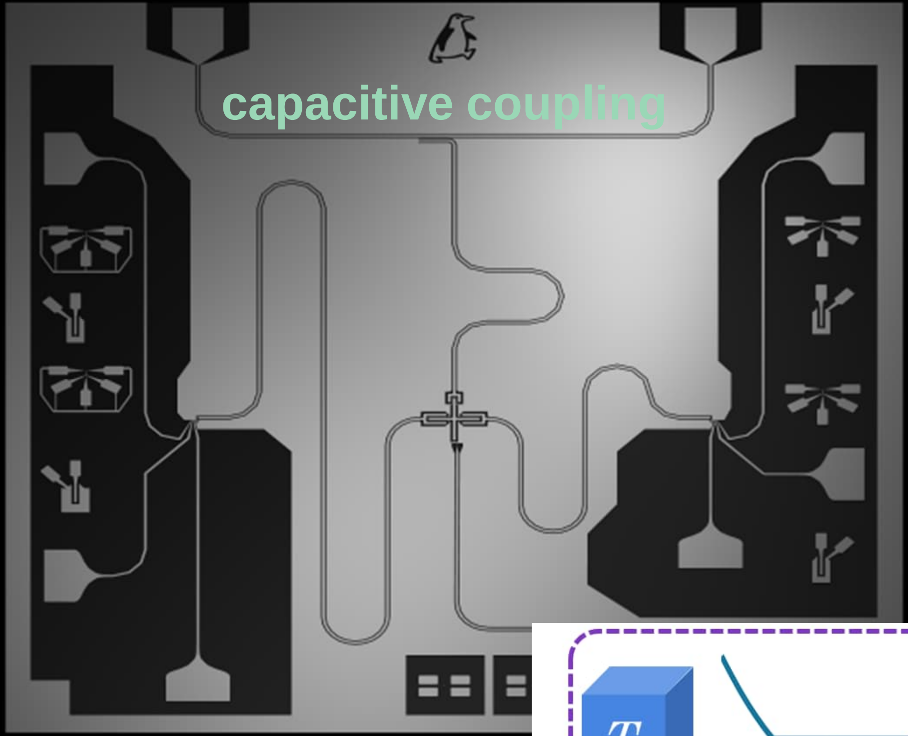

## Theory



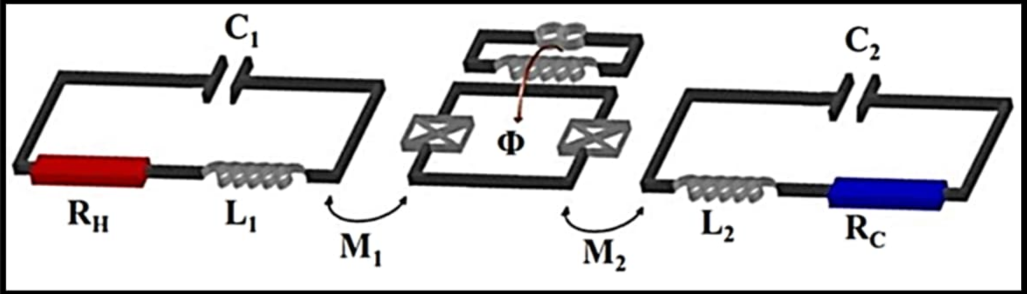

Rishabh Upadhyay et al., in preparation

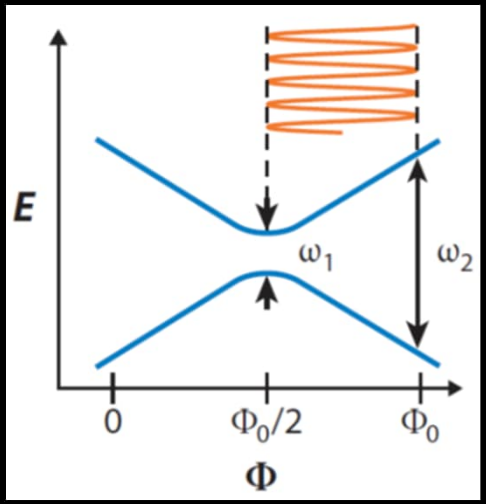
# Quantum Otto refrigerator

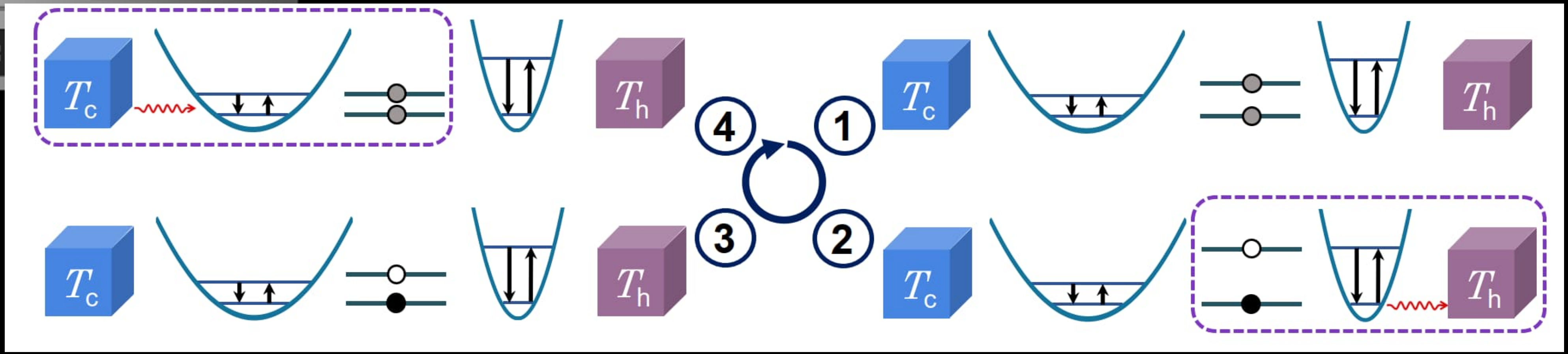
capacitive coupling



inductive coupling



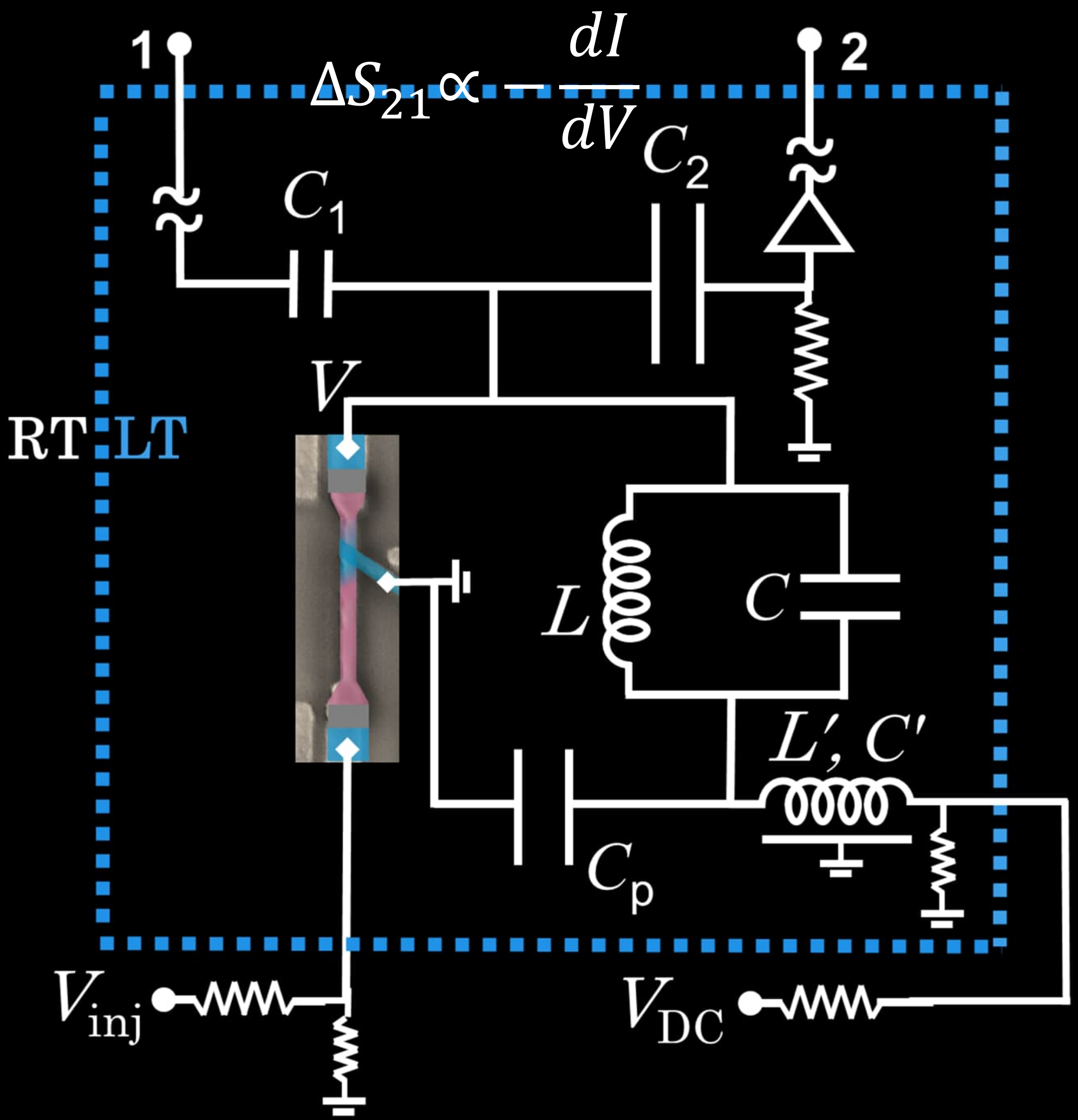




B. Karimi and JP, Phys. Rev. B 94, 184503 (2016).
Bayan Karimi, Thesis Aalto University, (2022).
JP and I. Khaymovich, Annu. Rev. Condens. Matter Phys. 10, 193 (2019).

**On-going experiments:**
C. Satrya et al. and R. Upadhyay et al.

# RF thermometry



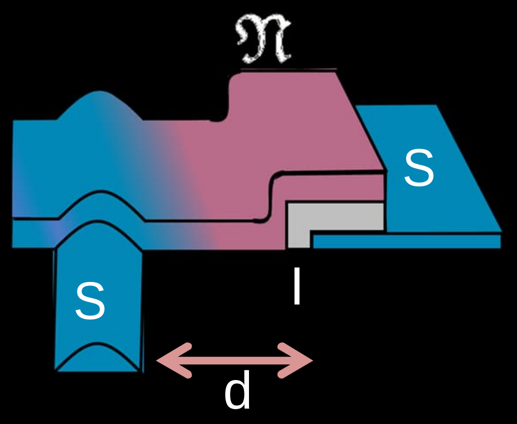

D. Schmidt et al., Appl. Phys. Lett. 83, 1002 (2003).
S. Gasparinetti, K. L. Viisanen et al., Phys. Rev. Applied 3, 014007 (2015).
B. Karimi and JP, Phys.Rev. Applied, 10, 054048 (2018).
K.L.Viisanen and JP, Phys. Rev. B, 97, 115422 (2018).

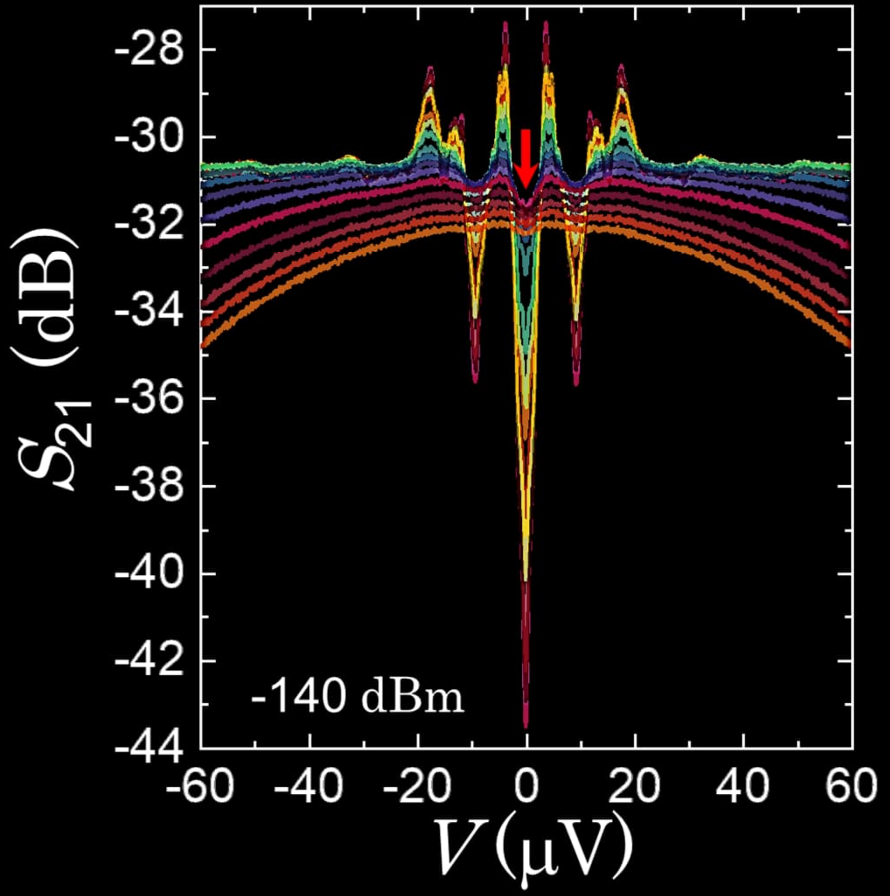
# ZBA thermometry

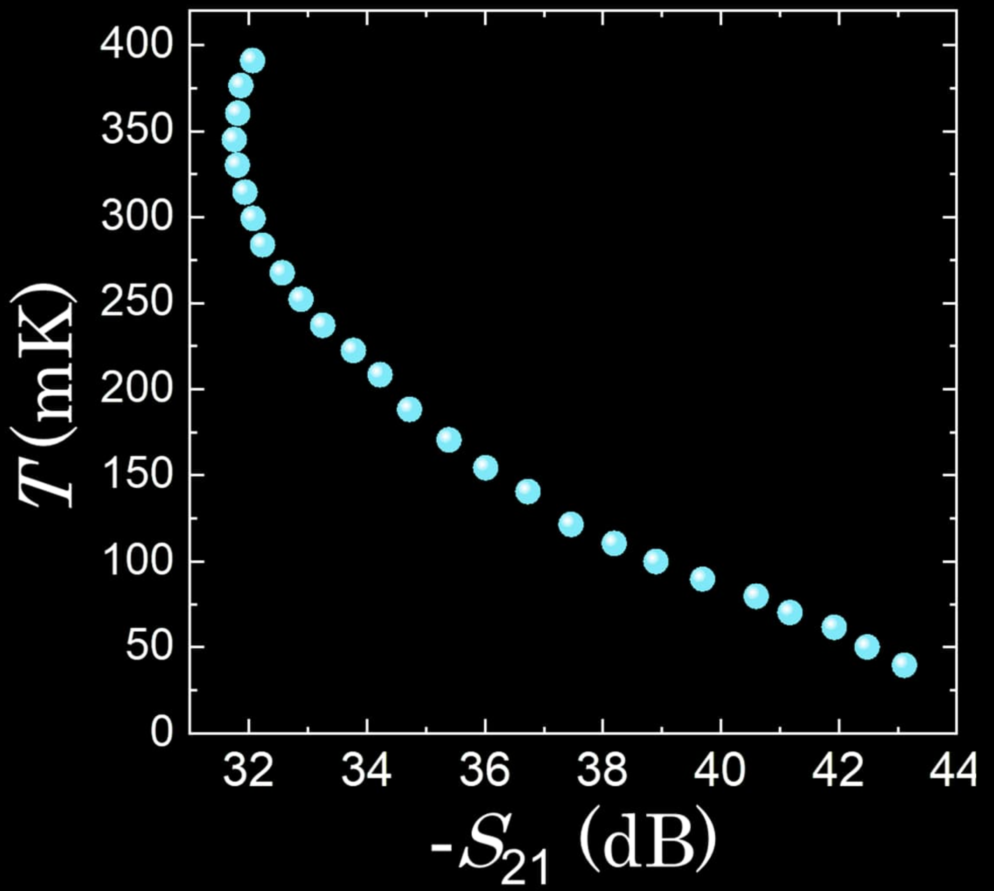
## RF measurement

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

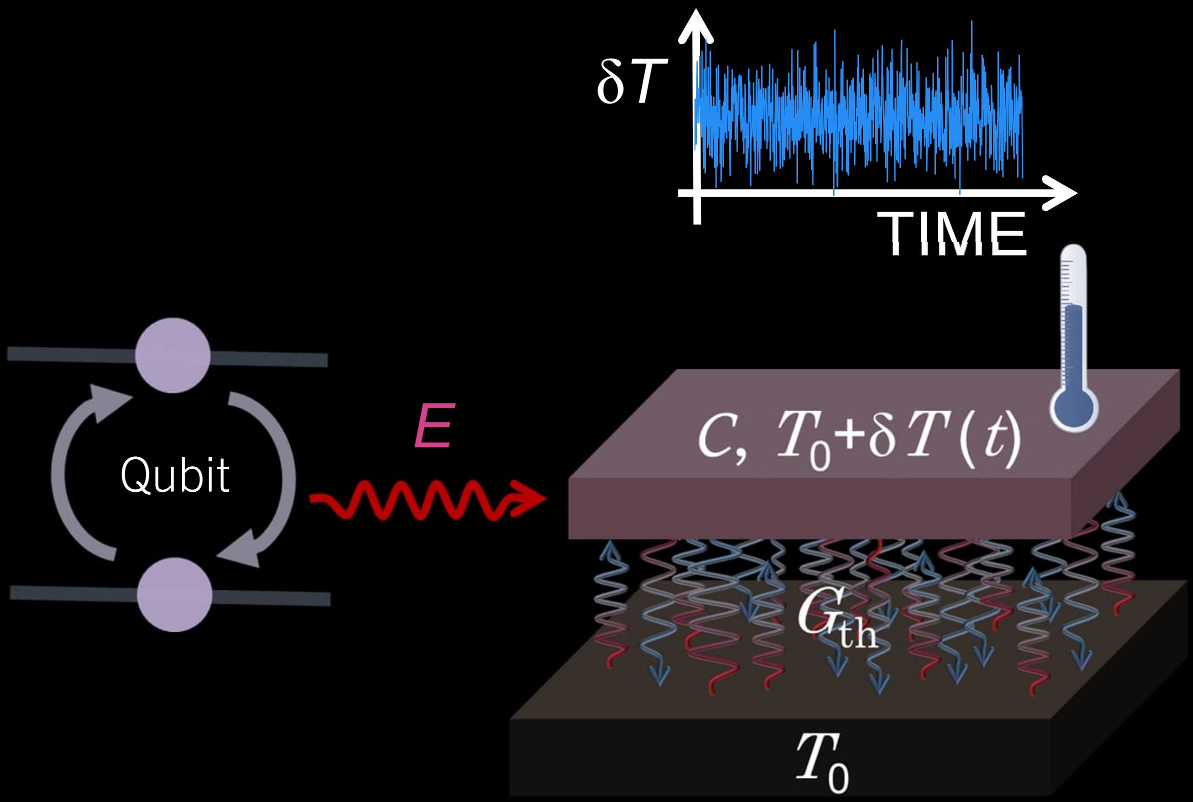
Proximity NIS junction

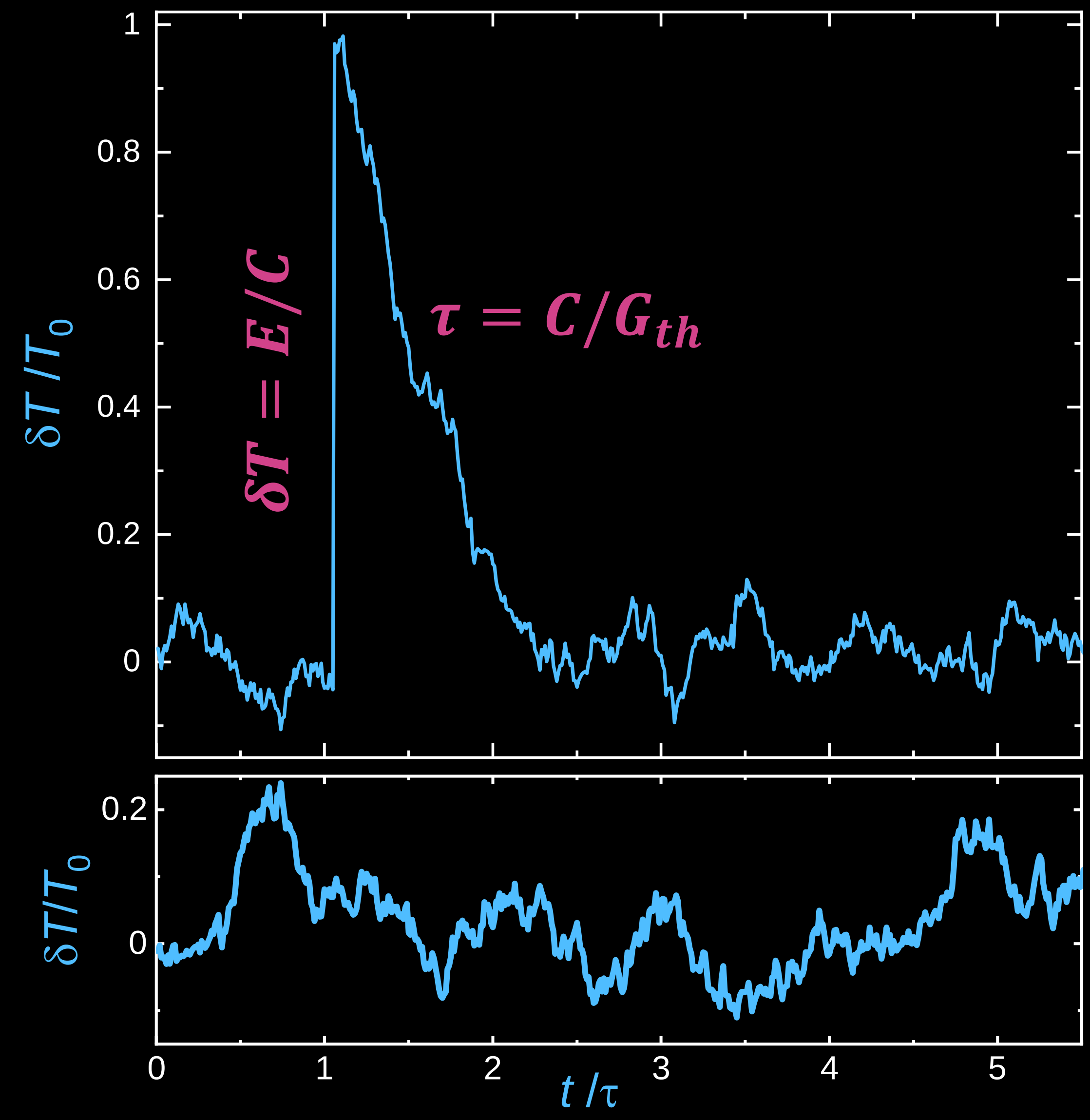


# Objective – Thermal single quantum detection

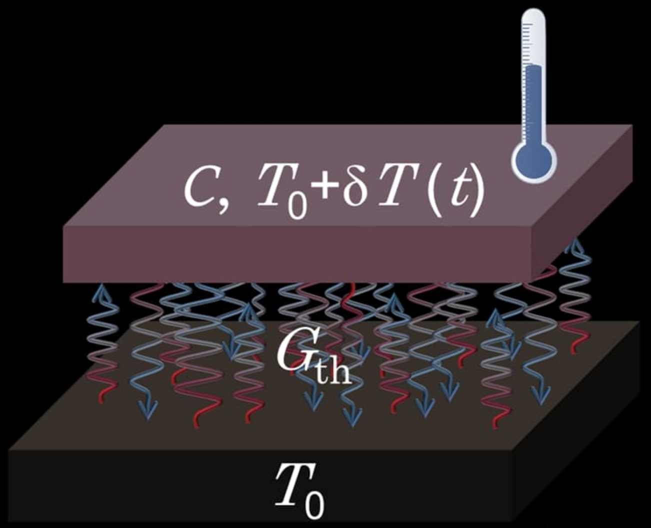



B. Karimi and JP, Phys. Rev. Lett. 124, 170601 (2020).

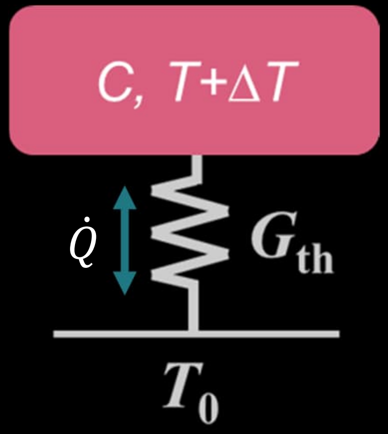
JP and Bayan Karimi, Rev. Mod. Phys. 93, 041001 (2021).

# Noise of heat current and equilibrium temperature fluctuations




Fluctuation-dissipation theorem for heat current

Low frequency noise:




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

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

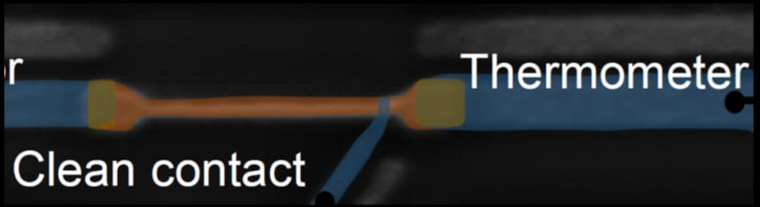
$$S_T(0) = \frac{2k_B T^2}{G_{th}}$$

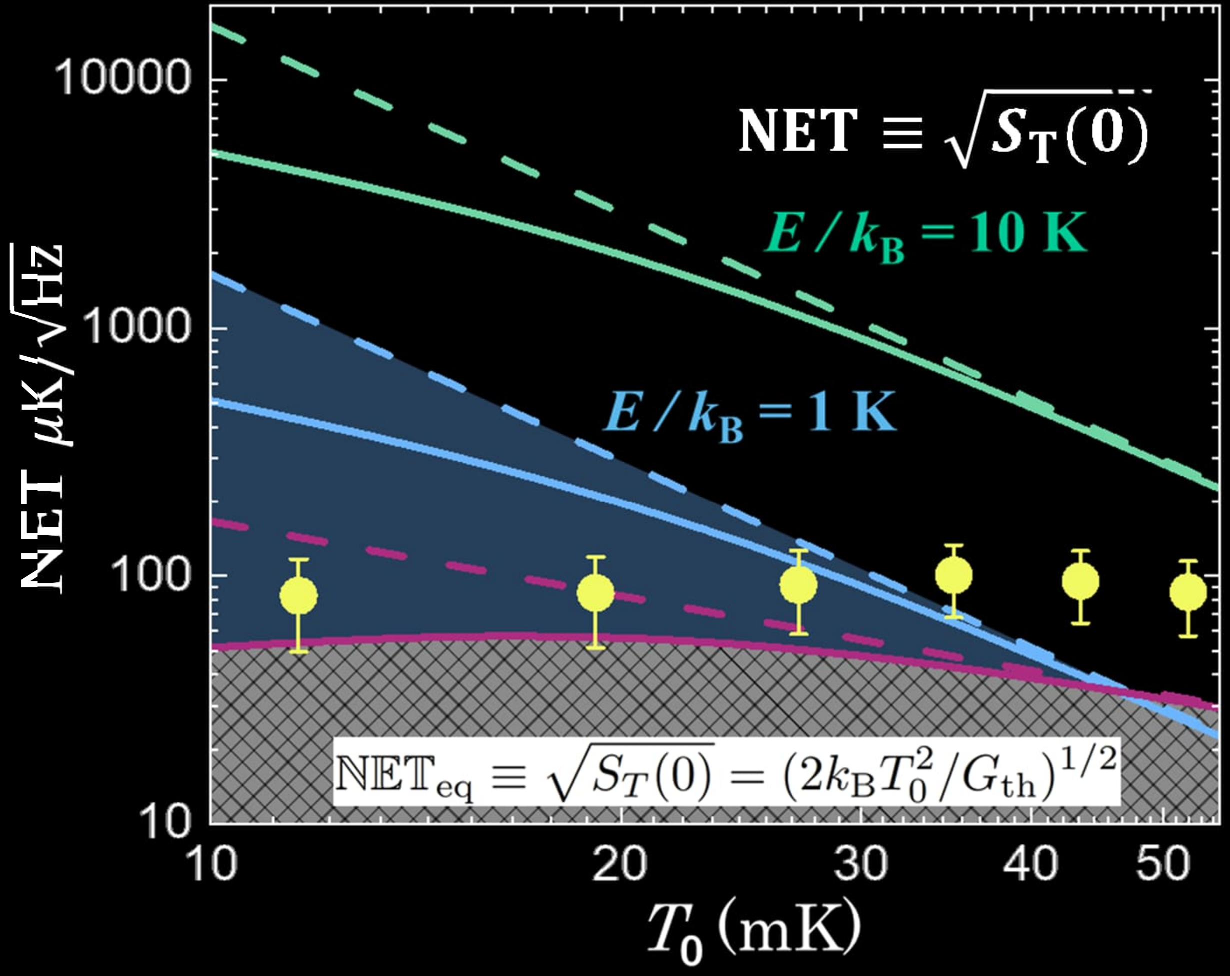
Non-zero frequencies (classical):

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

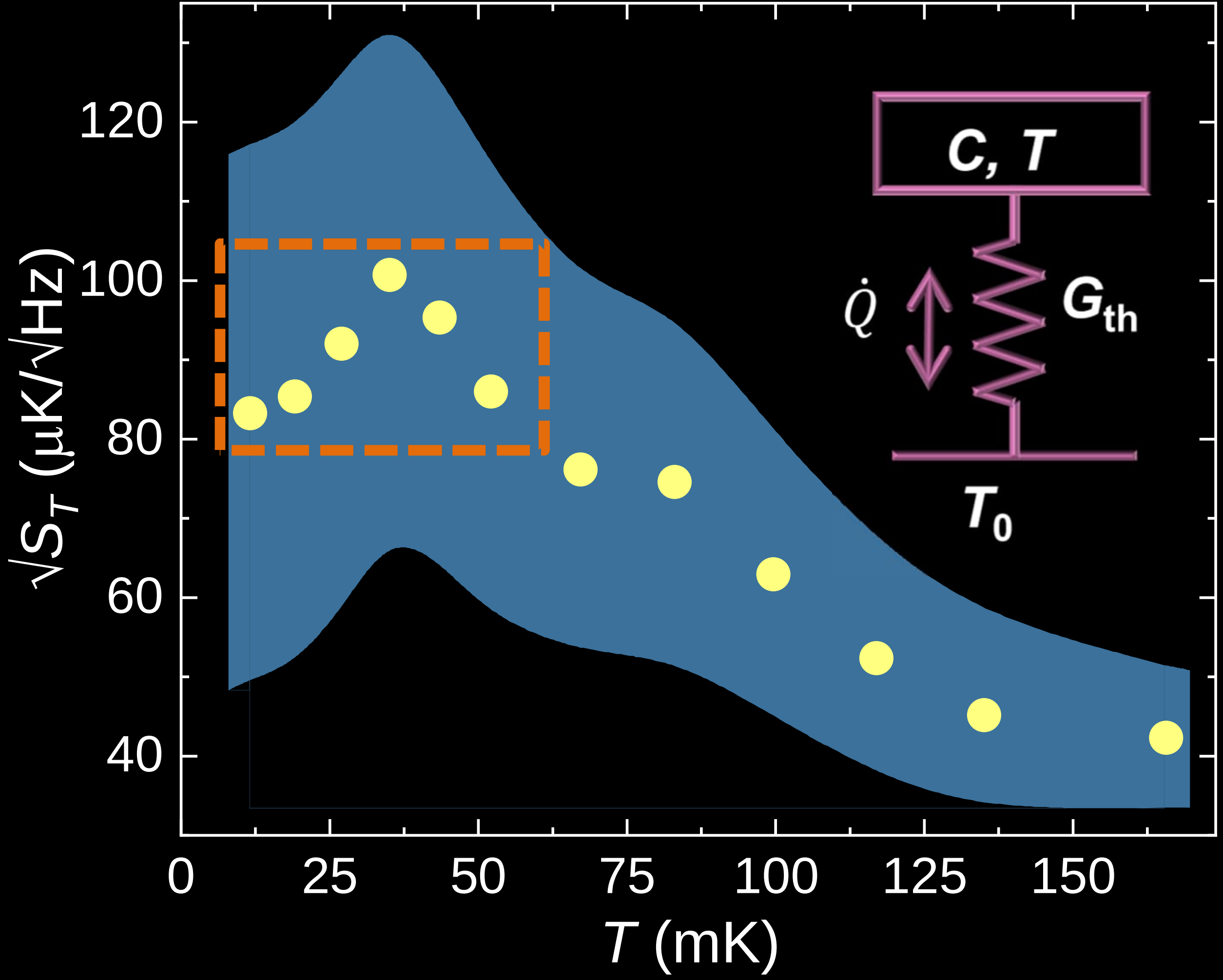
$$\langle\delta T^2\rangle = \int \frac{d\omega}{2\pi} S_T(\omega) = \frac{k_B T^2}{C}$$

# Noise of the calorimeter



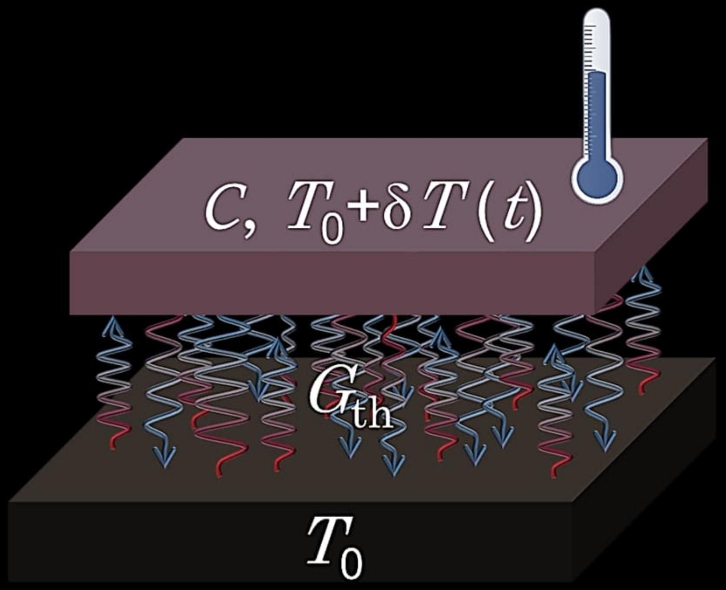




Bayan Karimi et al., Nat. Commun. 11, 367 (2020).



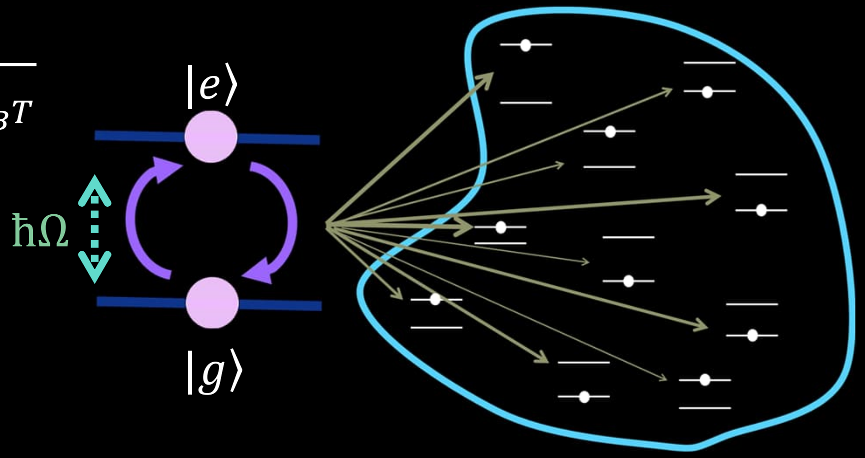

**Detector noise bounded from below by effective temperature fluctuations of the absorber coupled to the bath.**

# Does temperature fluctuate in a canonical system?




The most basic (but realistic) example: Qubit coupled to a heat bath

$$\rho_{ee} = \frac{1}{1 + e^{\hbar\Omega / k_B T}}$$




We convert energy fluctuations to (effective) temperature fluctuations, which are measurable by a thermometer.

Qubit does not have temperature, but bath has constant *T*.

We may write $\rho_{ee} = \frac{1}{1 + e^{\hbar\Omega / k_B T_{eff}}}$ . Due to energy fluctuations, $\rho_{ee}$ fluctuates and $T_{eff}$ fluctuates accordingly, but $T$ is constant.

Chui et al., PRL 69, 3005 (1992); Kittel, Phys. Today 41, 93 (1988); Mandelbrot, Phys. Today 42, 71 (1989).

# Pico group

Main contributors to this work: Bayan Karimi, Yu-Cheng Chang, Jorden Senior, Alberto Ronzani, Joonas Peltonen, Kuan-Hsun Chiang, Diego Subero, Christoforus Satrya, Rishabh Upadhyay, Dmitry Golubev, George Thomas, Dmitry Lvov, Sergei Lemziakov, Klaara Viisanen, Olivier Maillet