Thermal effects in quantum circuits

Clemens Winkelmann

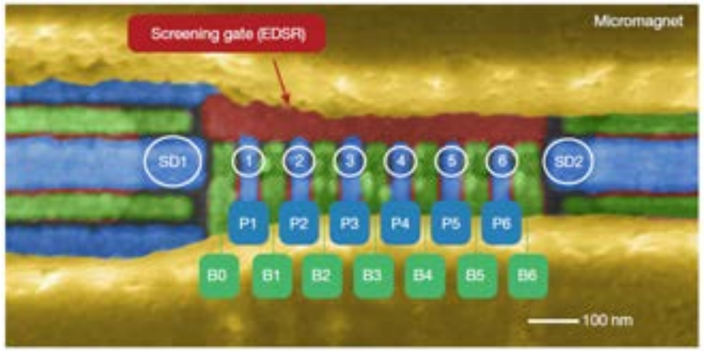
PHELIQS

Université Grenoble Alpes & CEA

The heat problem in quantum circuits

From quantum technologies … to quantum thermodynamics

6 qubit device with electron spin in Si/SiGe

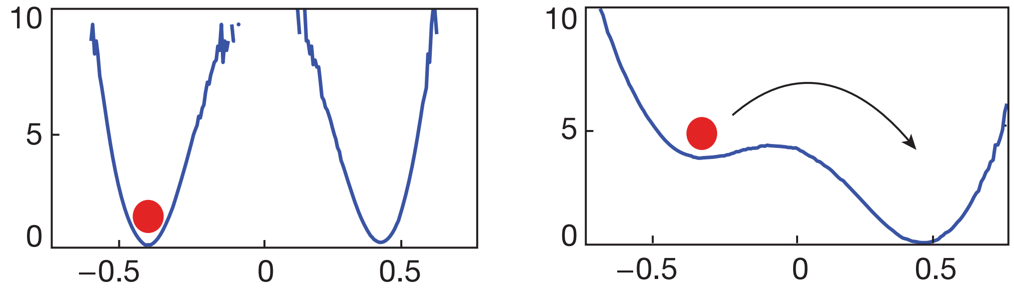


Phillips et al., Nature (2022)

« Future work must focus on **understanding and mitigating heating effects** leading to frequency shifts and reduced dephasing times, as we find this to be the limiting factor in executing complicated quantum circuits on many qubits. »

- Landauer principle (1961)

Bérut et al., Nature (2012)



- Maxwell demon
- Thermal engines

Outline

I. Temperature and heat balance in quantum circuits

II. Heat conductance in quantum devices

III. Temperature fluctuations and calorimeters

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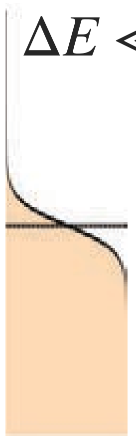
Where is temperature experimentally meaningful?

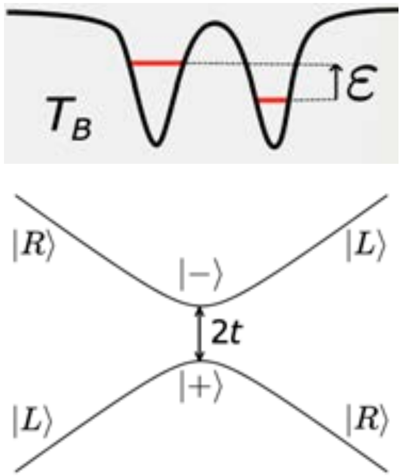
Metal

$\Delta E \ll 1\,K$



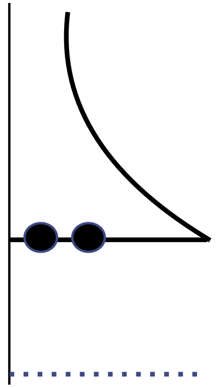
Must not be Fermi-Dirac
if out-of-equilibrium!
Pothier et al., PRL (1997)

Qubit



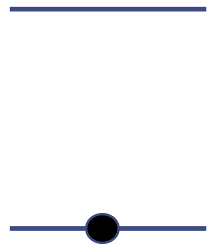
$\Delta E < 1\,K$

Superconductor



$\Delta E \sim 1\,K$

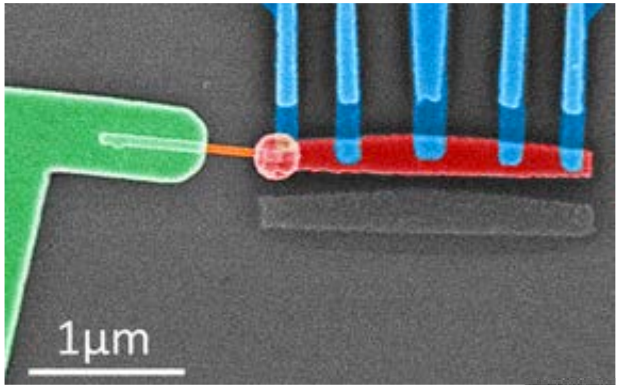
Quantum dot



$\Delta E \sim 10\,K$

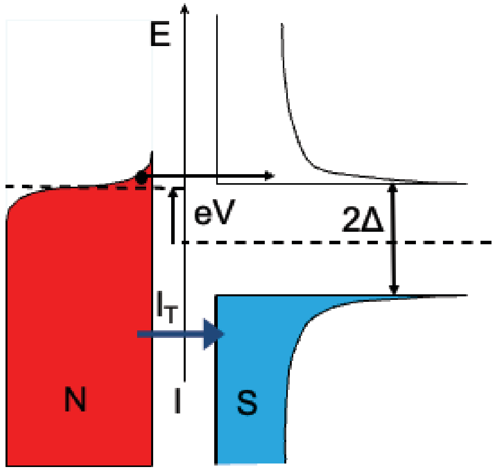
Superconducting Electron Thermometry

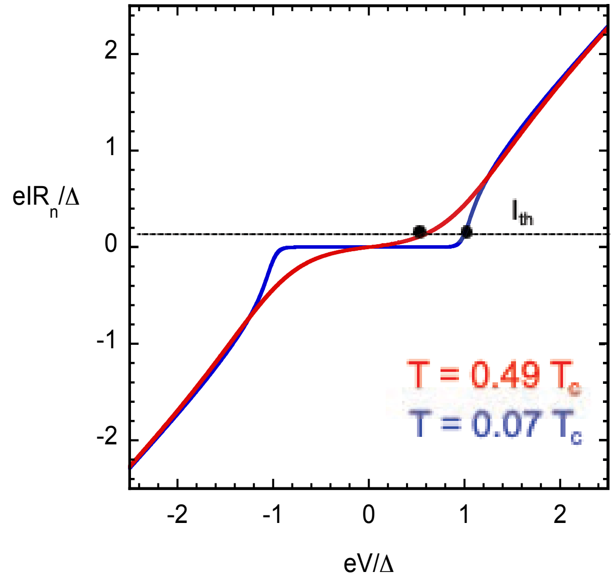
Electron thermometry with superconducting hybrid junctions

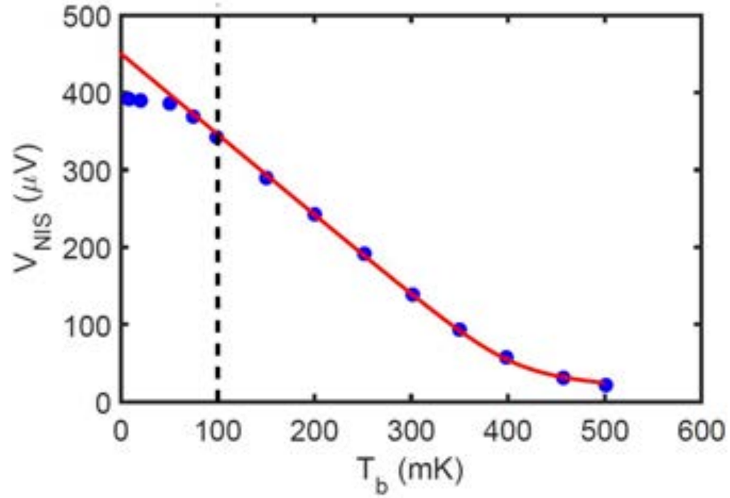


Superconductor

Normal metal







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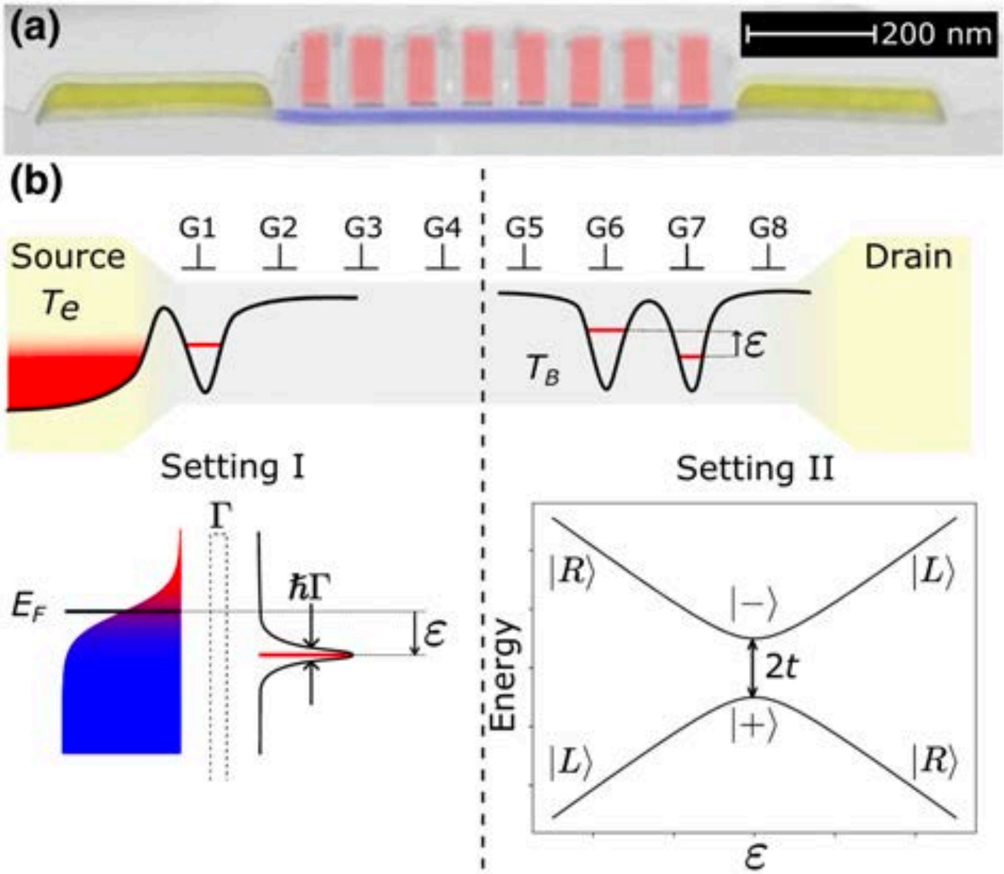
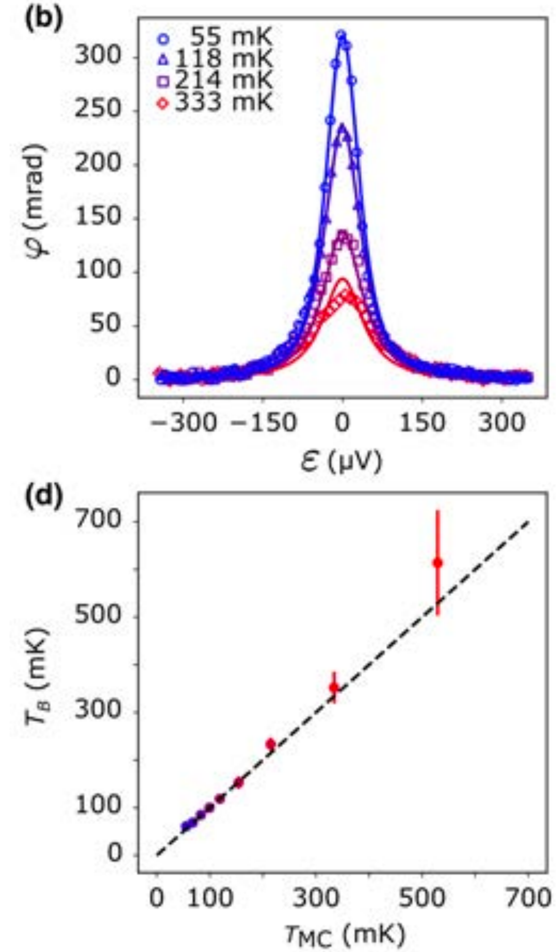
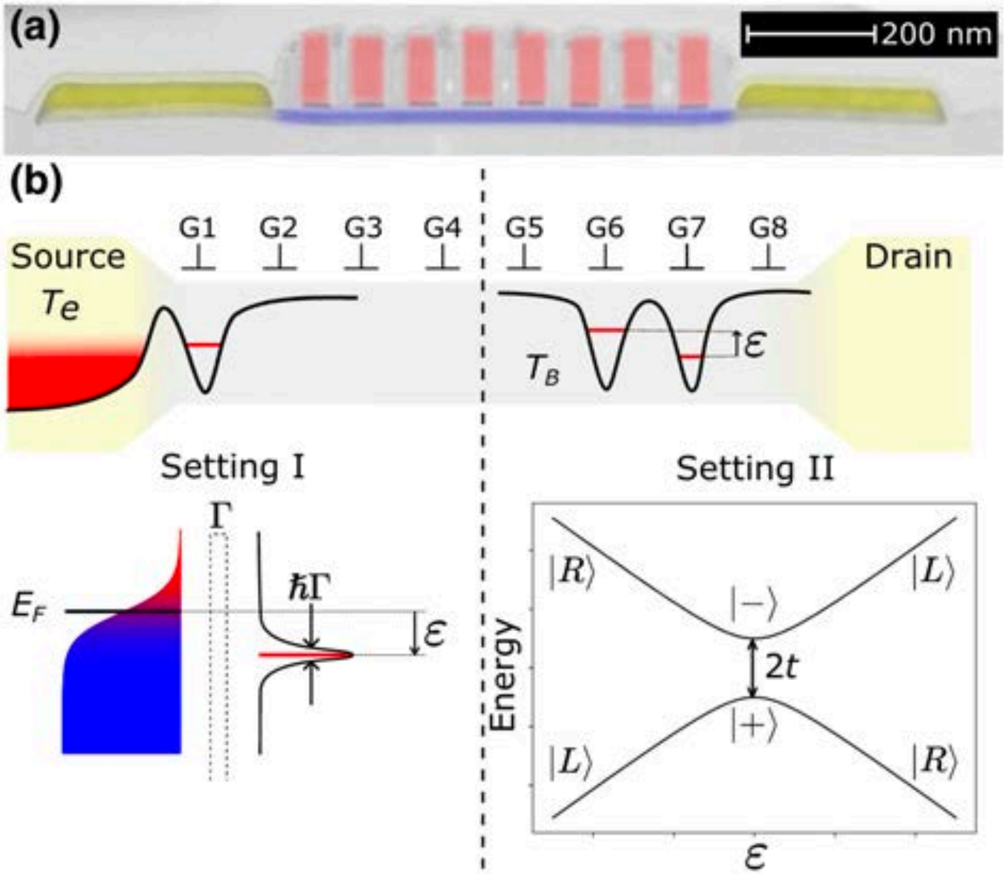
Quantum Dot Thermometry



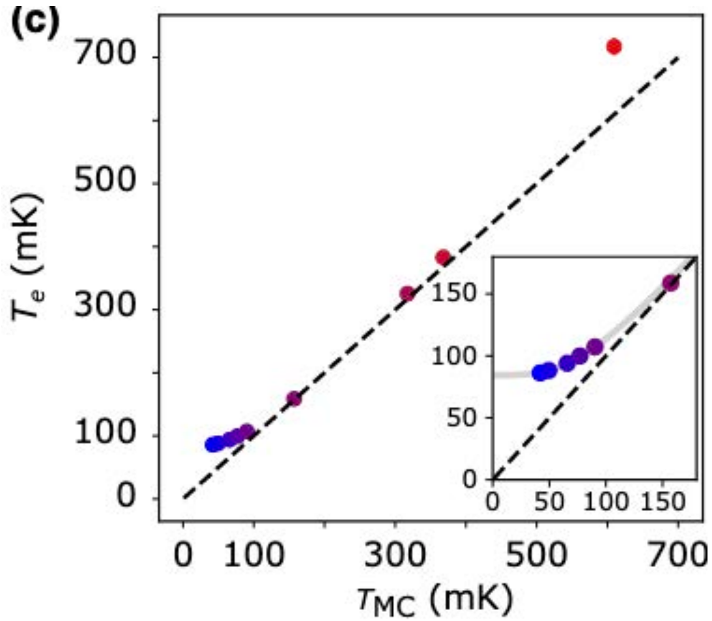


$$C_q(\varepsilon) = \alpha^2 e^2 \frac{2t^2}{\left((\alpha e \varepsilon)^2 + 4t^2\right)^{3/2}} \tanh\left(\frac{\left((\alpha e \varepsilon)^2 + 4t^2\right)^{1/2}}{2k_B T_B}\right)$$

Quantum Dot Thermometry



Champain et al., Phys. Rev. Appl. (2024)



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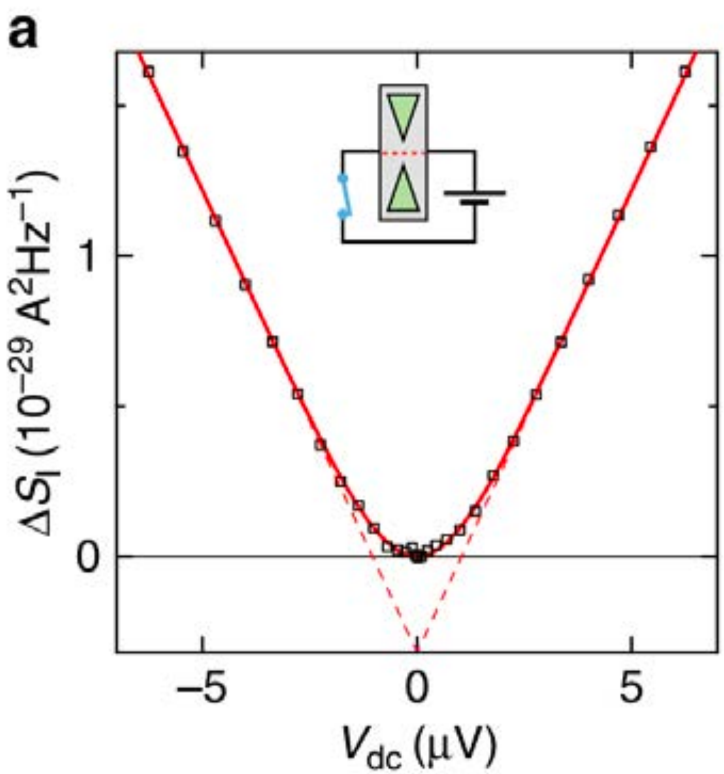
Electron noise thermometry

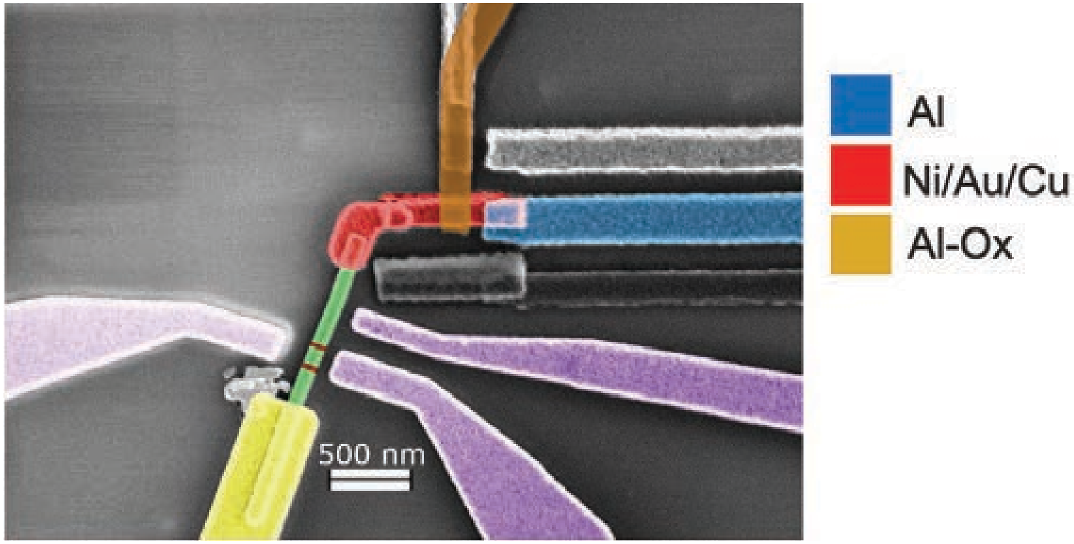


E. Sivré, PhD thesis (2019)
F. Pierre group at C2N

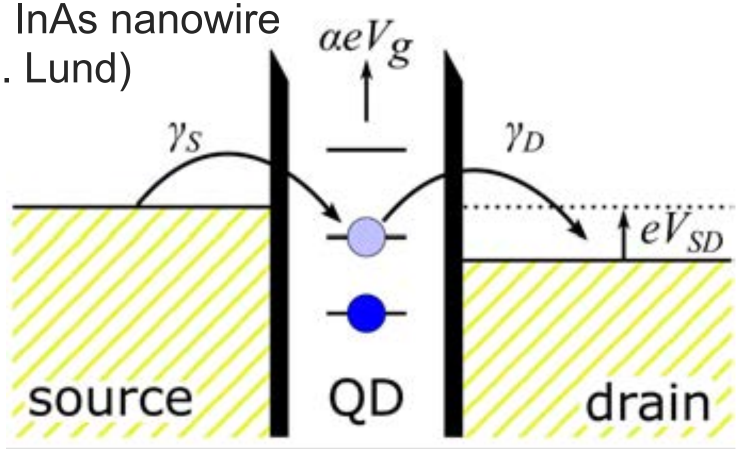
Thermal + shot noise

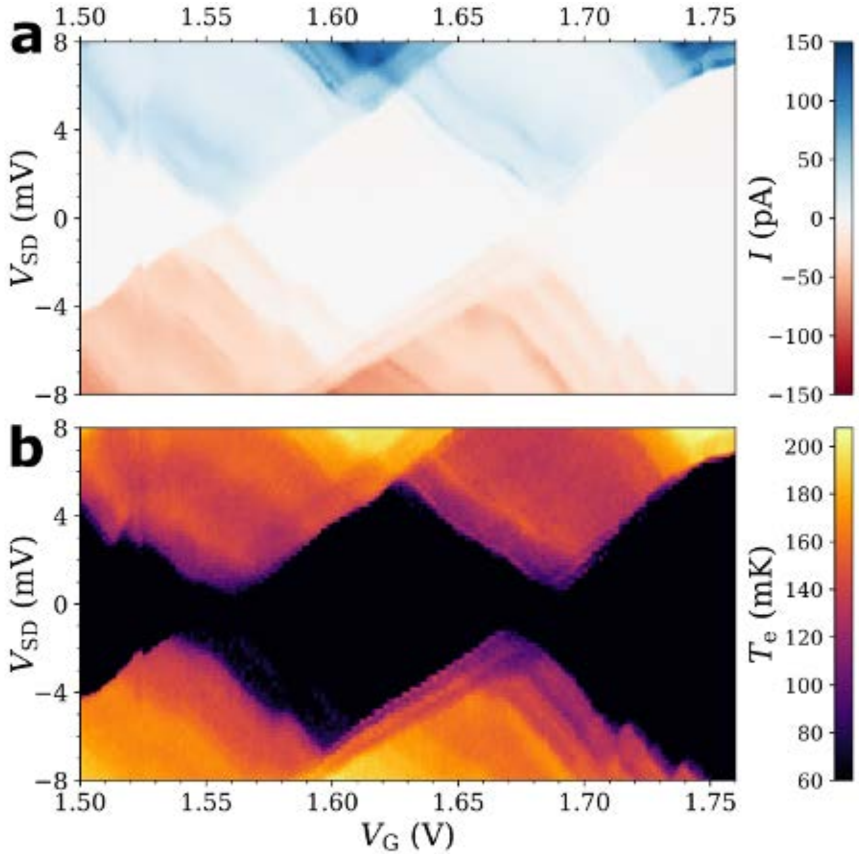
$$S = 4k_B T \sum_n \tau_n / R_K + \frac{2eV}{R_K} \sum_n \tau_n (1 - \tau_n) (\coth\left(\frac{eV}{2k_B T}\right) - \frac{2k_B T}{eV})$$

Heat detectors



Quantum dot in an InAs nanowire
Collab. V. Maisi (U. Lund)





Dutta et al., Phys. Rev. Lett. (2020)
Höfer et al., in preparation

Outline

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II. Heat conductance in quantum devices

III. Temperature fluctuations and calorimeters

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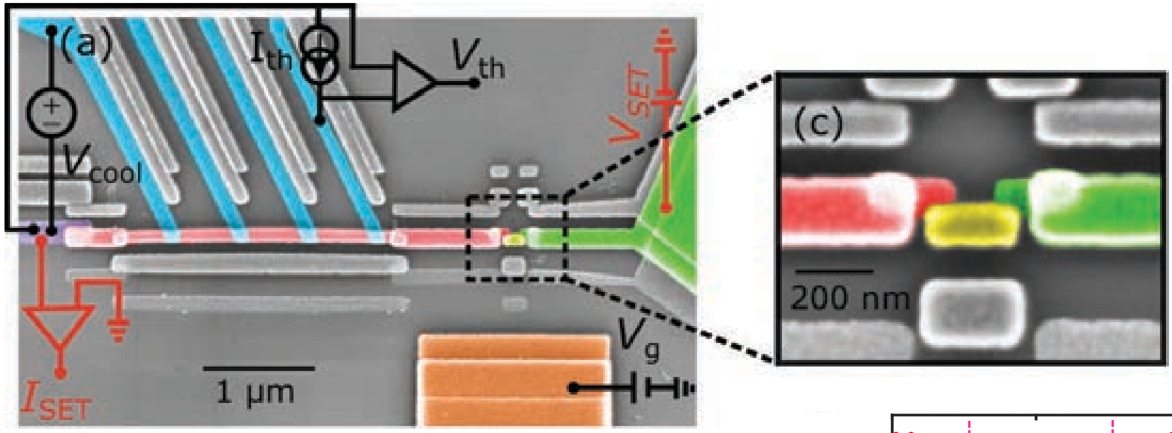
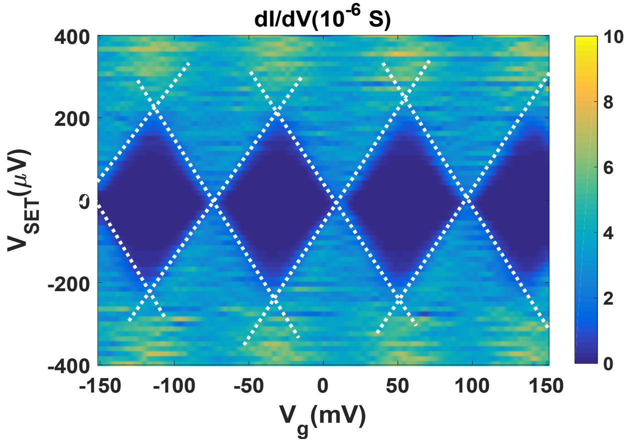
Heat detectors: heat transport

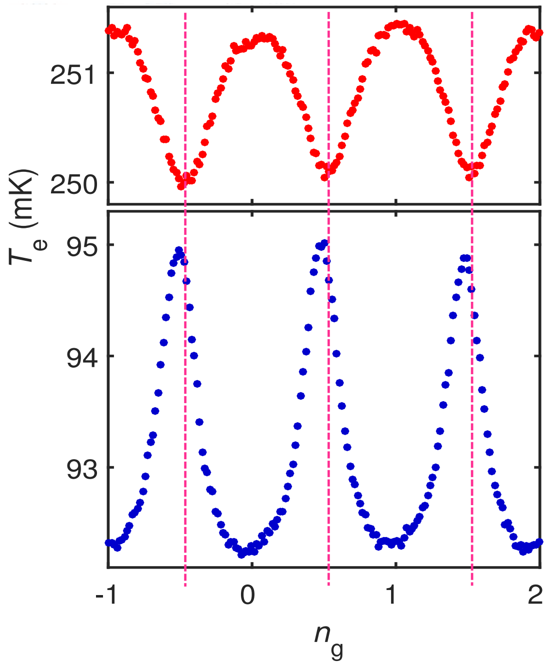




Collab. Aalto

Gate-modulated heat balance in bolometer island

deduce heat flow across single-electron transistor



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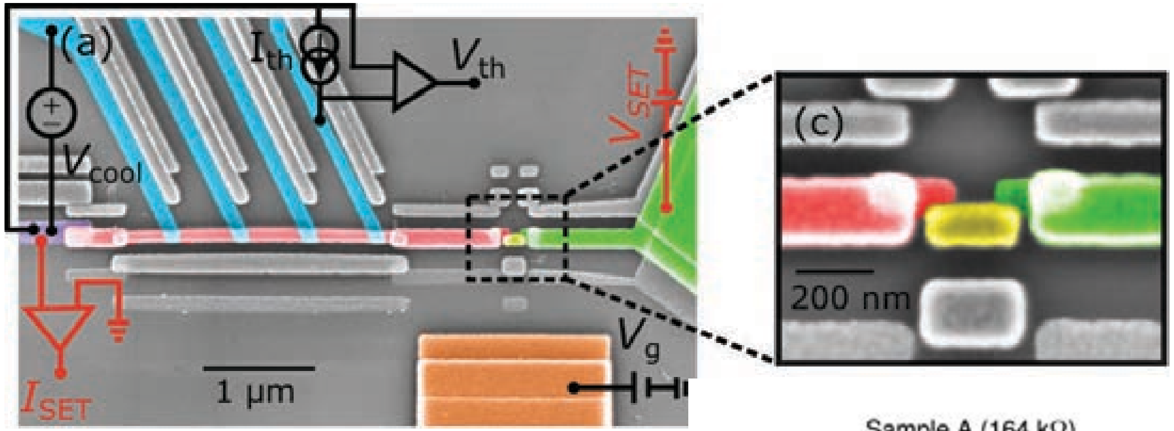
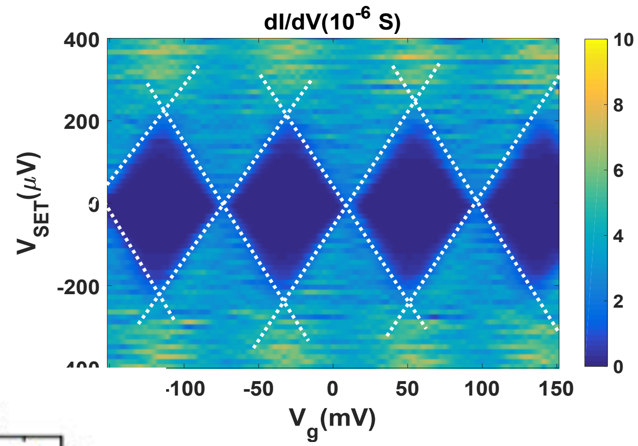
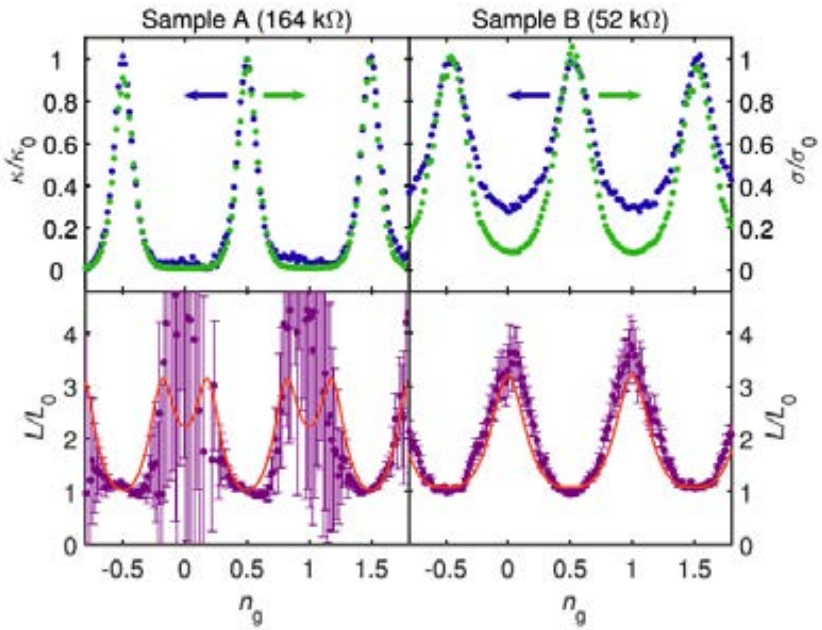
Heat conductance of a single-electron transistor







$$\frac{\kappa}{\sigma T} = \frac{L}{L_0}$$

Strong deviations from Wiedemann-Franz law away from charge degeneracy

Dutta et al.,
Phys. Rev. Lett. (2017).

***Theory**:*
Kubala et al., Phys. Rev. Lett. 2008
Zianni, Phys. Rev. B 2007

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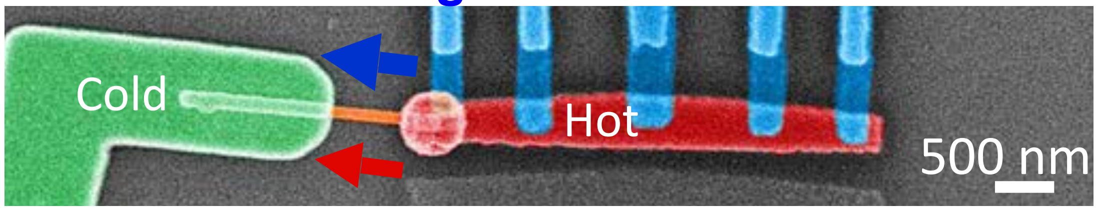
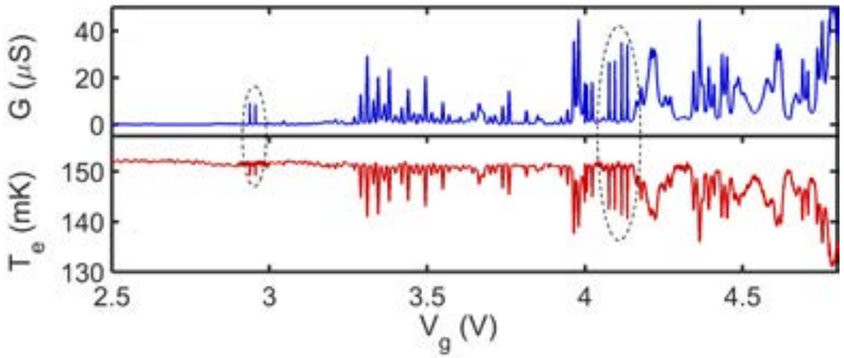
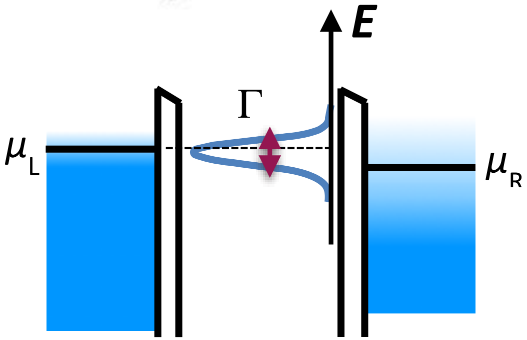
Heat conductance of a single quantum level



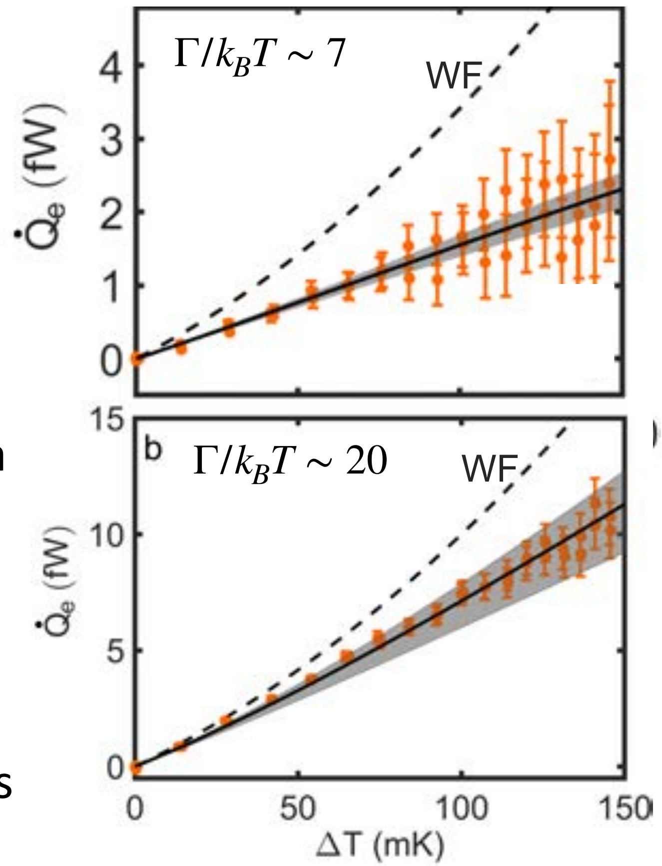
Collab.
Lund

Quantum dot in InAs nanowire





- Quantum dot heat valve
- Deviations from WF law for a single resonant quantum level
- Good agreement with scattering theory calculations



Majidi et al., Nano Lett. (2022)

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III. **Temperature fluctuations and calorimeters**

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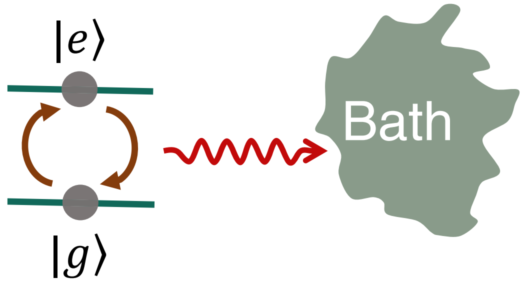
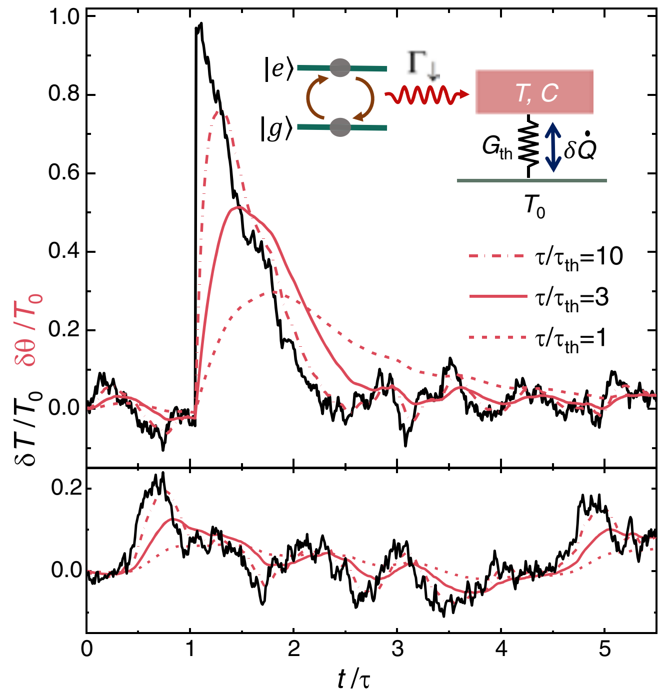
Real time thermometry of transients
Measuring quantum thermodynamic fluctuations



Calorimetric detection of energy quanta

- microwave photons emitted by a qubit
- single (hot) tunnelling electrons
- tunnelling of single fluxons across a Josephson junction

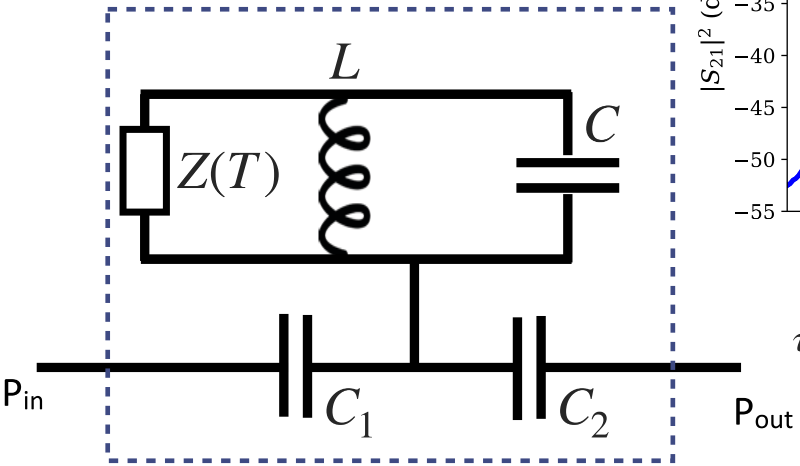
Karimi et al., Phys. Rev. Lett. (2020) & Phys. Rev. X (2022)

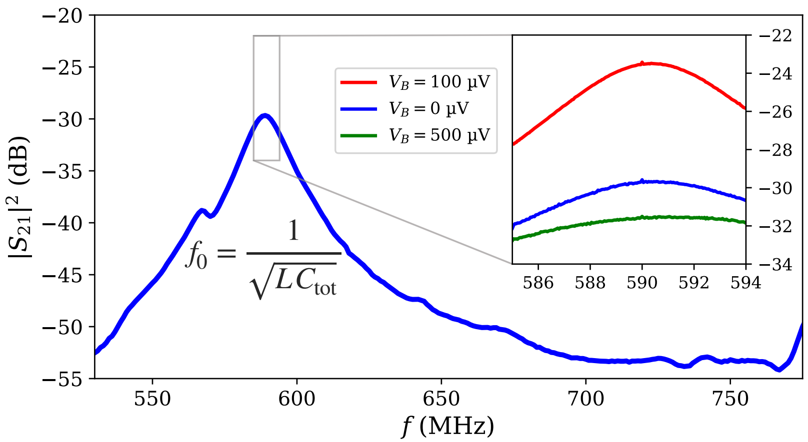


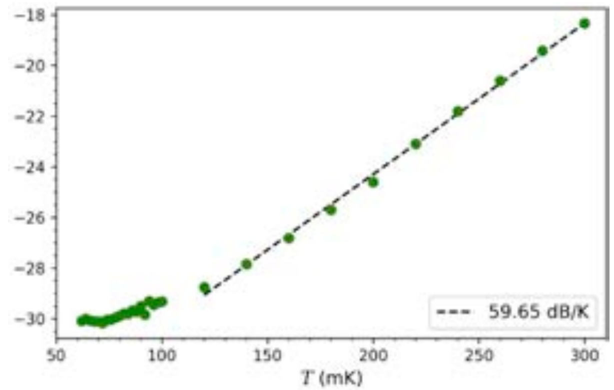
$$\tau_{th} = C/G_{th}$$

Real-time thermometry: RF readout

Collab. Aalto

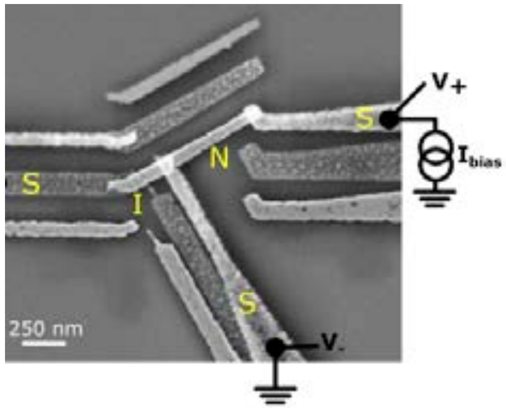


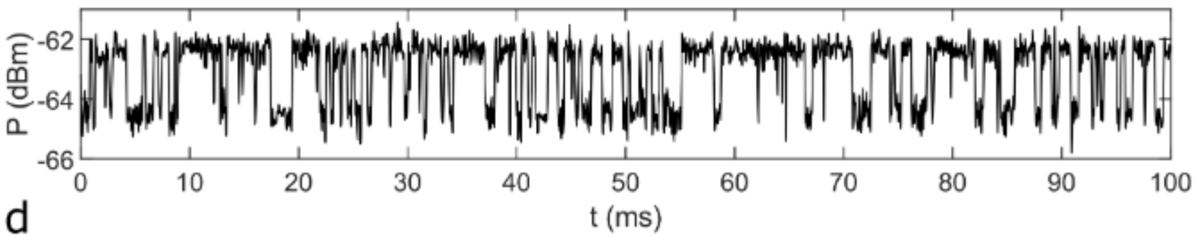




$$\tau = \frac{1}{\pi \Delta f}$$

Stochastic switching of a critically biased Josephson junction between hot and cold states





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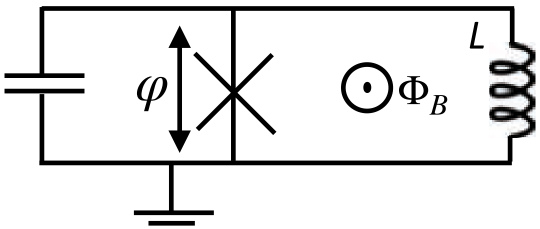
Dissipation from a phase slip in a Josephson junction

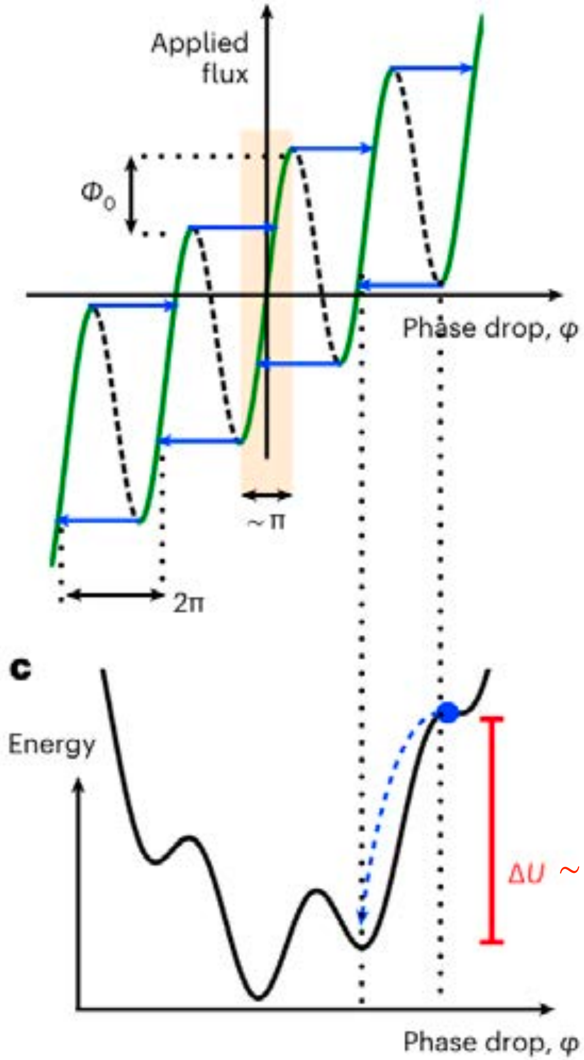


$$H = 4E_c\hat{n}^2 - E_J\cos\hat{\varphi} + \frac{E_L}{2}\left(\hat{\varphi} - 2\pi\frac{\Phi_B}{\Phi_0}\right)^2$$

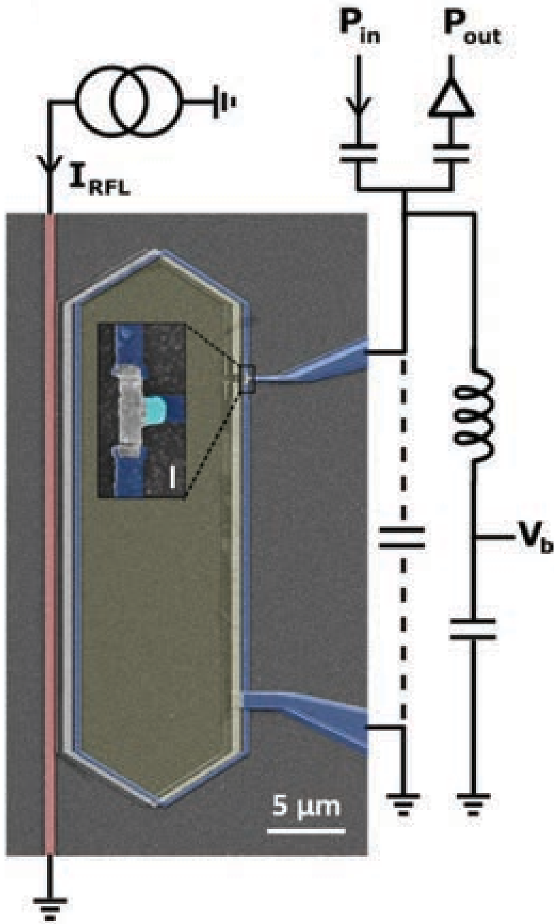
$$[\hat{\varphi}, \hat{n}] = i$$

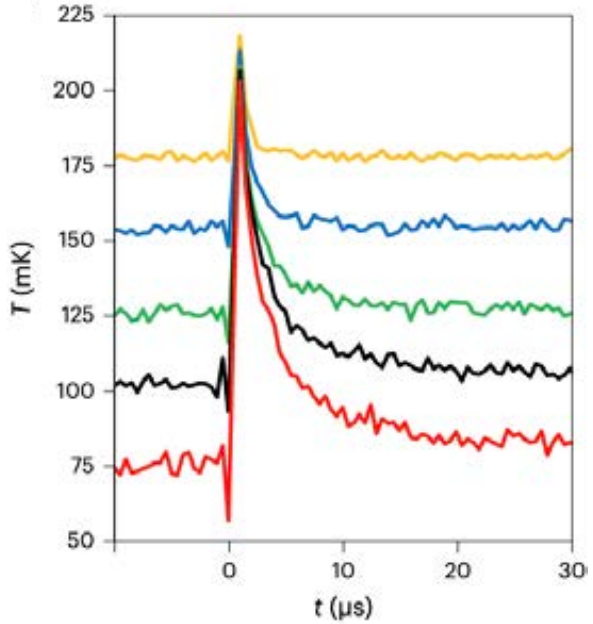
Hysteretic
RF SQUID

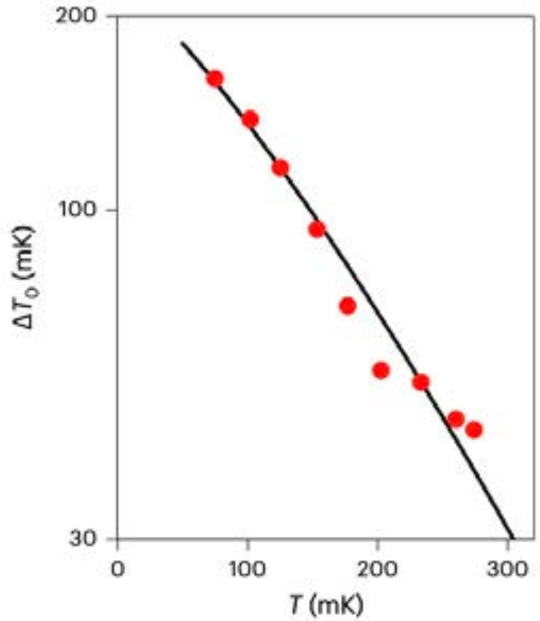
$$\beta = \frac{2\pi L I_0}{\Phi_0} > 1$$



Dissipation from a phase slip in a Josephson junction







P_{in} = -110 dBm, 70 ns pulses, 2 MHz sampling rate, 2 kHz repetition rate, 10^5 repetitions

- Heating beyond linear regime at low temperature
- µs-scale thermal relaxation times
- Quantitative understanding of calorimetric response

Calorimetry of a phase slip in a Josephson junction
Gümüs et al., Nat. Phys. 19, 196 (2023).

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