Electrons in a Box: Realization of Szilard Engine and Autonomous Maxwell Demon

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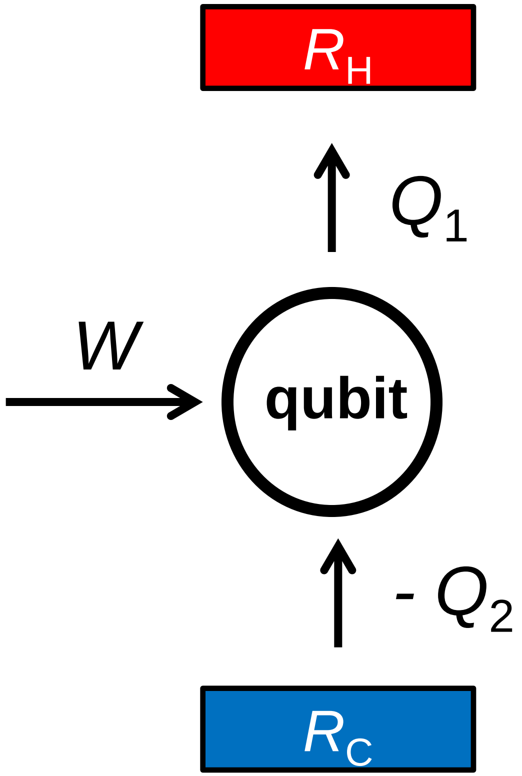
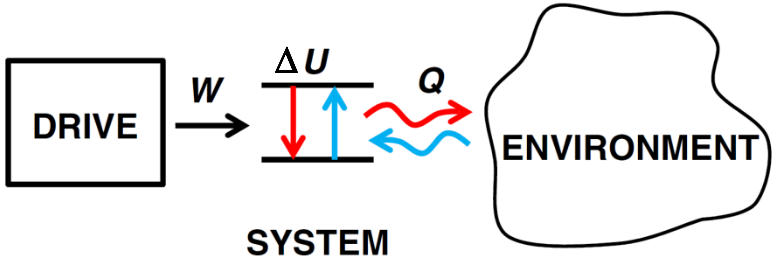
1. Heat in circuits: measurement and control
2. Single-electron box
3. Stochastic thermodynamics and fluctuation relations
4. Szilard engine
5. Thermometry
6. Autonomous Maxwell demon
7. Quantum thermodynamics with superconducting qubits and resonators
8. Quantum Otto refrigerator
9. Quantum heat valve
10. Calorimetry towards single micro wave photon detection

Thermodynamics experiments in circuits

Heat engines and refrigerators



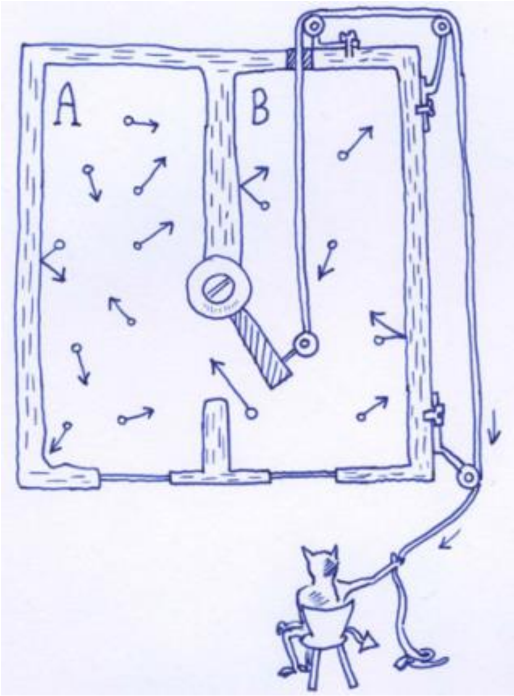
Testing and establishing fundamental laws of TD in small systems



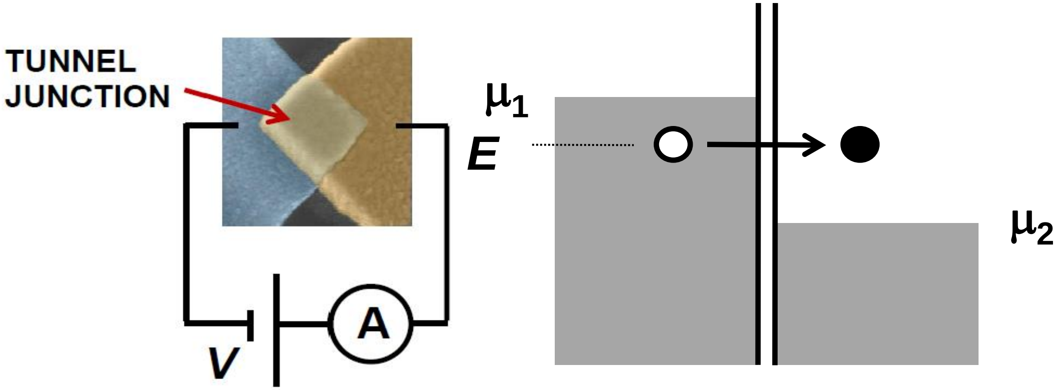
$$W = \Delta U + Q \qquad \langle \Delta S \rangle \geq 0$$

$$P(\Delta S)/P(-\Delta S) = e^{\Delta S/k_B}$$

Curiosity experiments, e.g. Maxwell's Demon



Dissipation in transport through a barrier



Dissipation generated by a tunneling event in a junction biased at voltage *V*

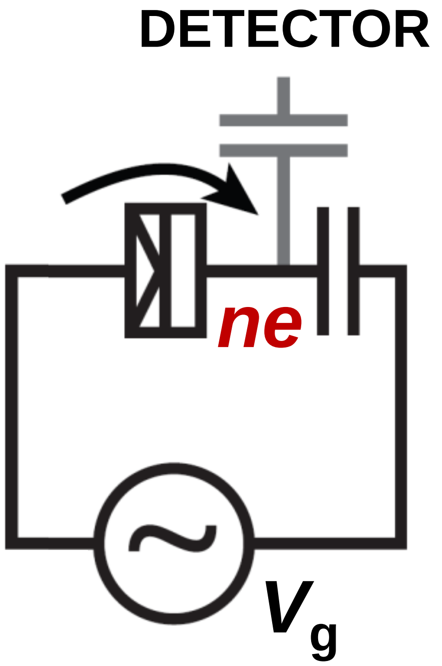
$$\Delta Q = (\mu_1 - E) + (E - \mu_2) = \mu_1 - \mu_2 = eV$$

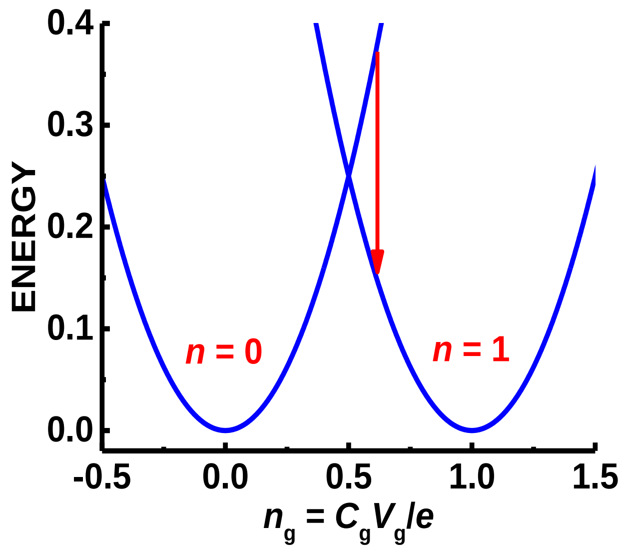
$\Delta Q = T\Delta S$ is first distributed to the electron system, then typically to the lattice by electron-phonon scattering

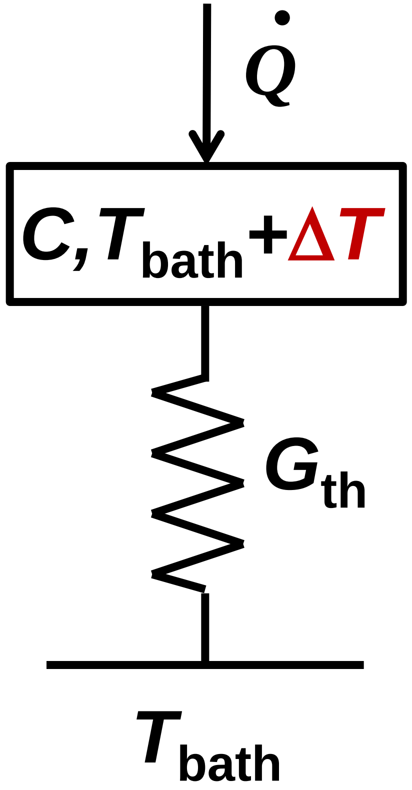
For average current *I* through the junction, the total average power dissipated is naturally

$$P = (I/e)\Delta Q = IV$$

Indirect and direct measurement of heat







$E = E_C(n - n_g)^2$

$Q = E_C(2n_g - 1)$

Indirect measurement of heat (and work) by counting electrons

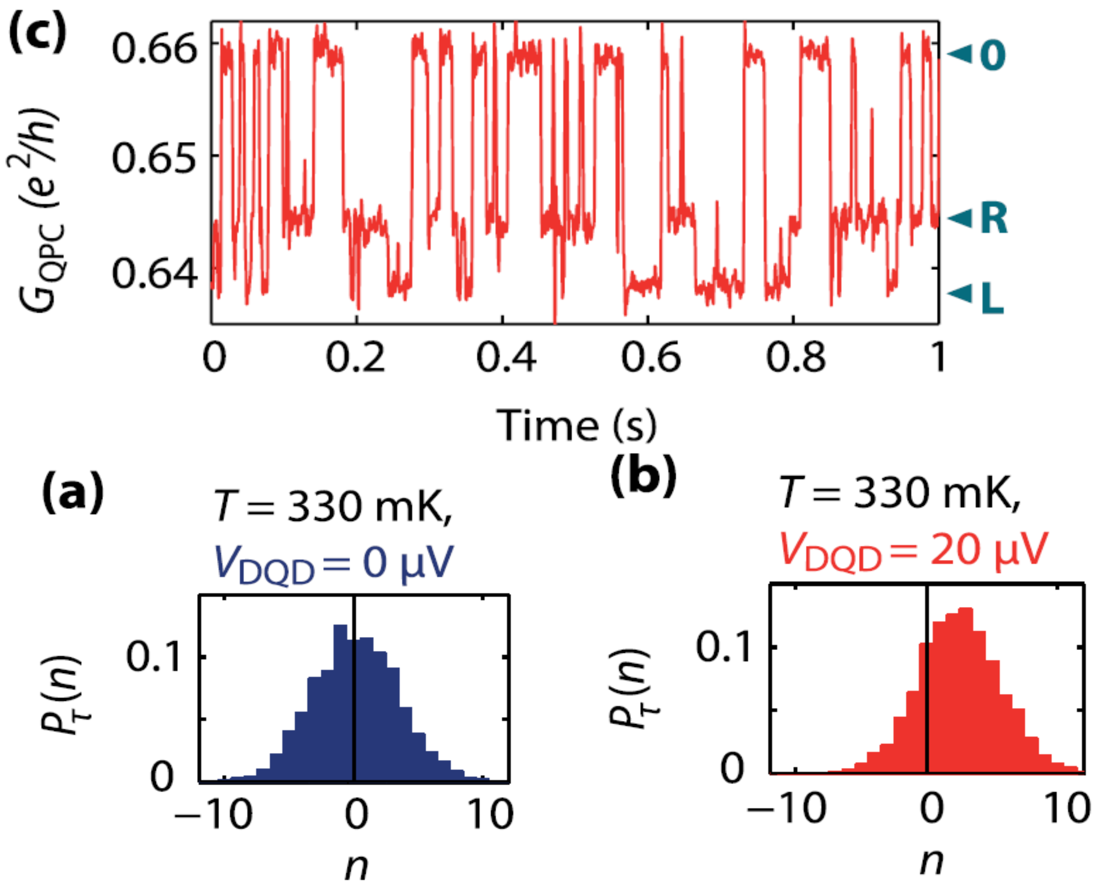
Direct measurement of heat by thermometry

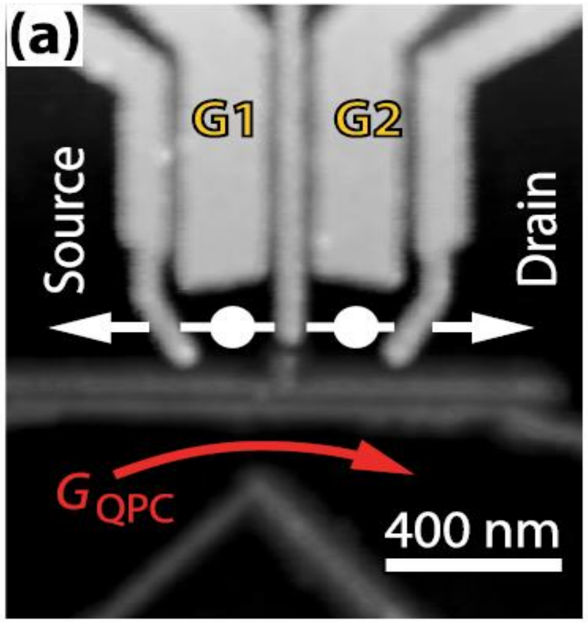
Fluctuation relations in a circuit

$$\frac{P_\tau(\Delta S)}{P_\tau(-\Delta S)} = e^{\Delta S/k_\mathrm{B}}$$

U. Seifert, Rep. Prog. Phys. **75**, 126001 (2012)

$$\langle e^{-\Delta S/k_B} \rangle = 1$$

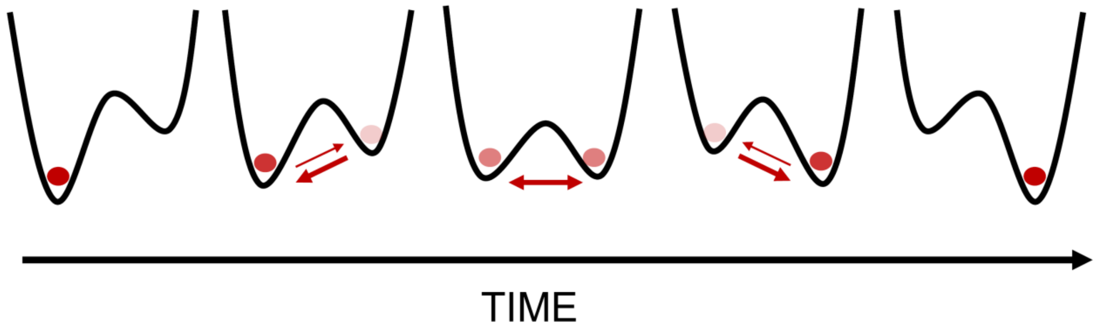


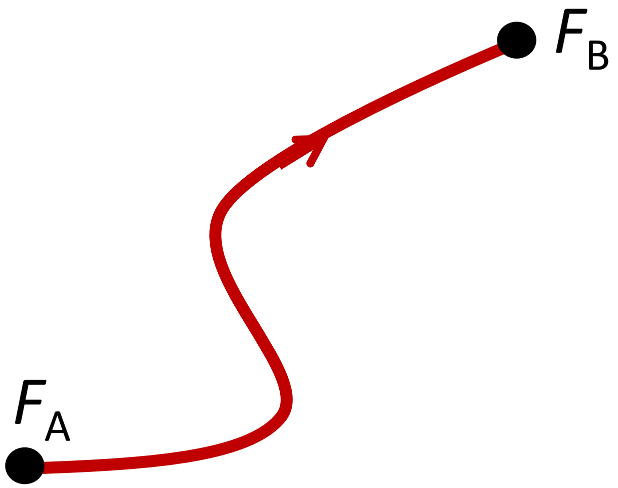


Experiment on a double quantum dot
Y. Utsumi et al. PRB 81, 125331 (2010), B. Kung et al. PRX 2, 011001 (2012).

$$\frac{P_\tau(n)}{P_\tau(-n)} = e^{neV_\mathrm{DQD}/k_\mathrm{B}T}$$

Work and dissipation in driven systems





Systems **driven** by control parameter(s), starting in equilibrium

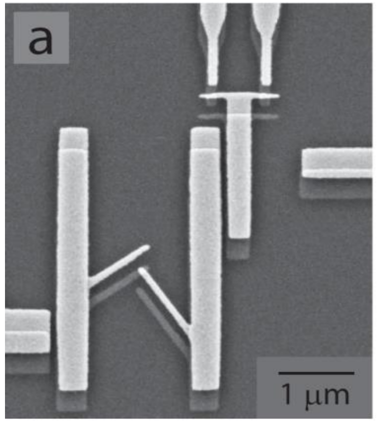
$$W_d = W - \Delta F$$ "dissipated work"

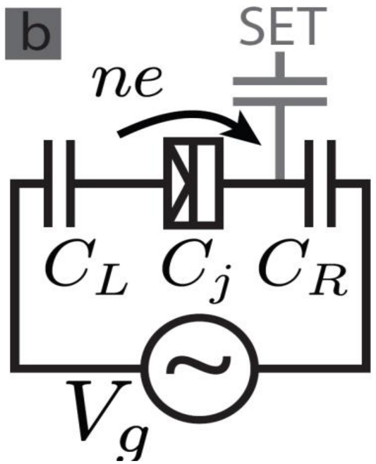
C. Jarzynski 1997 $$\langle e^{-\beta W_d} \rangle = 1$$ $$\langle W \rangle \geq \Delta F$$

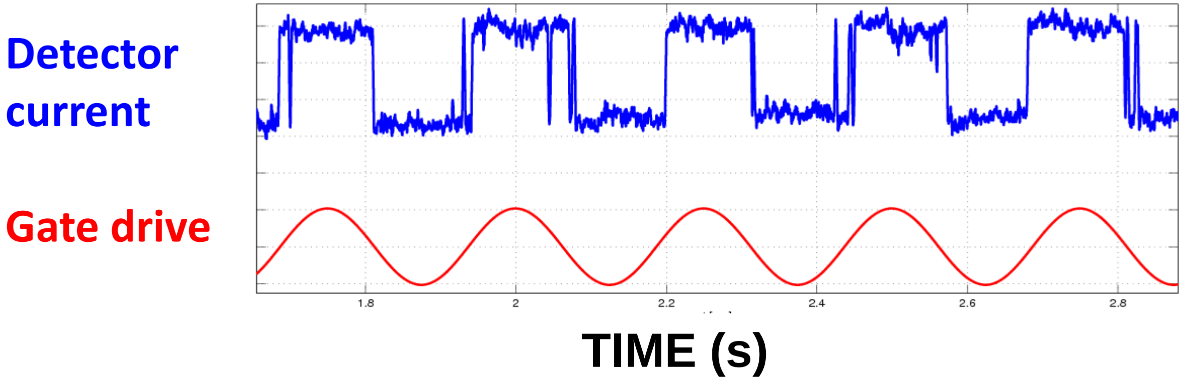
G. Crooks 1999 $$p_F(W_d)/p_R(-W_d) = e^{\beta W_d}$$

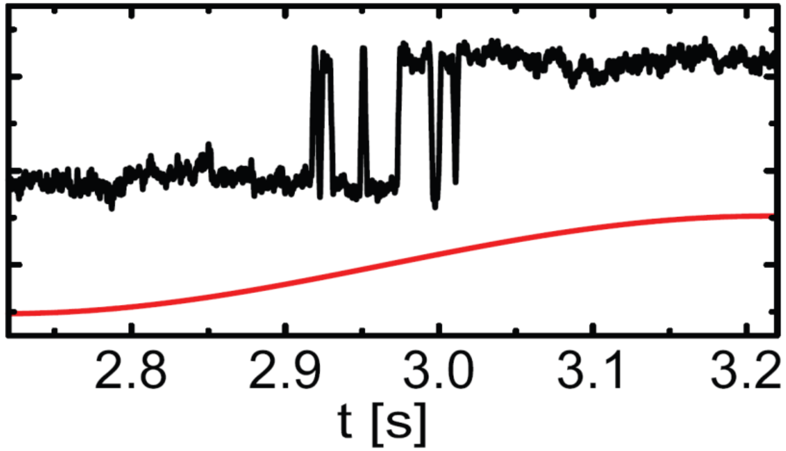
Experiment on a single-electron box

Saira et al., PRL 109, 180601 (2012); Koski et al, Nature Physics 9, 644 (2013)



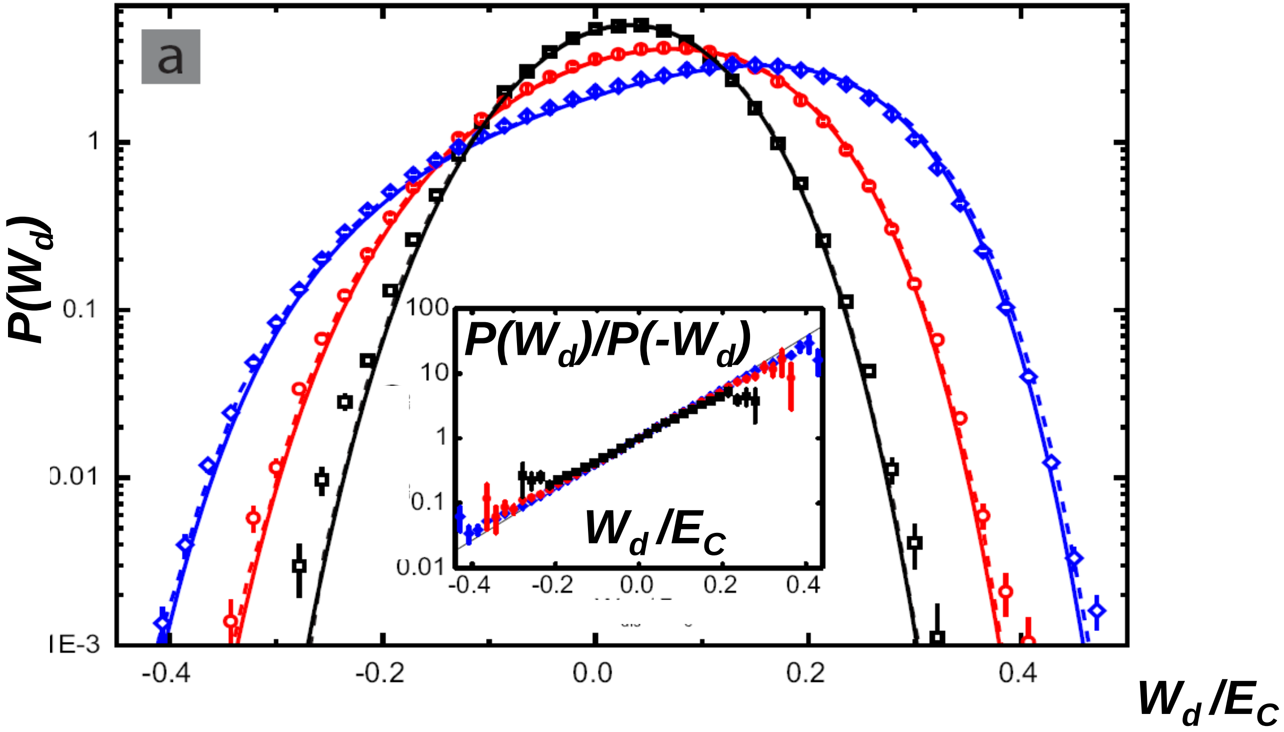




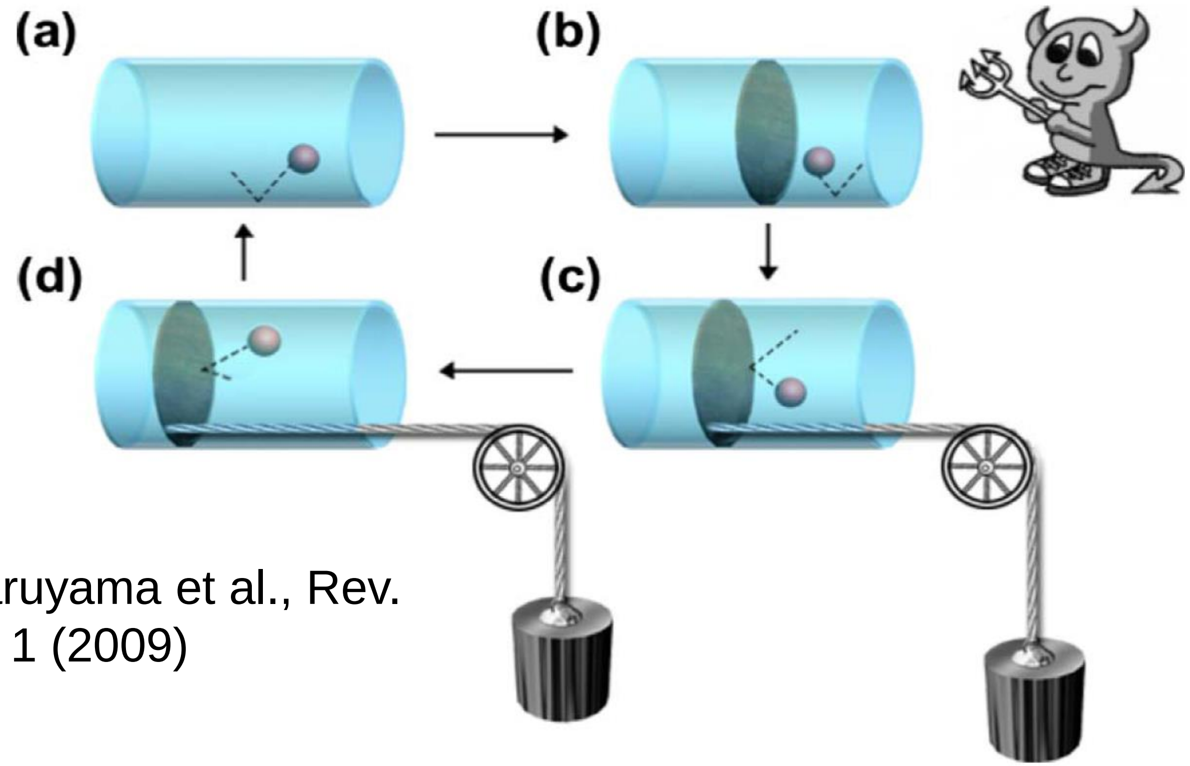


The distributions satisfy Jarzynski equality:

$$\langle e^{-\beta(W-\Delta F)} \rangle = 1.03 \pm 0.03$$



Information-powered cooling: Szilard engine



(L. Szilard 1929)

Figure from Maruyama et al., Rev. Mod. Phys. 81, 1 (2009)

Isothermal expansion of the "single-molecule gas" does work against the load

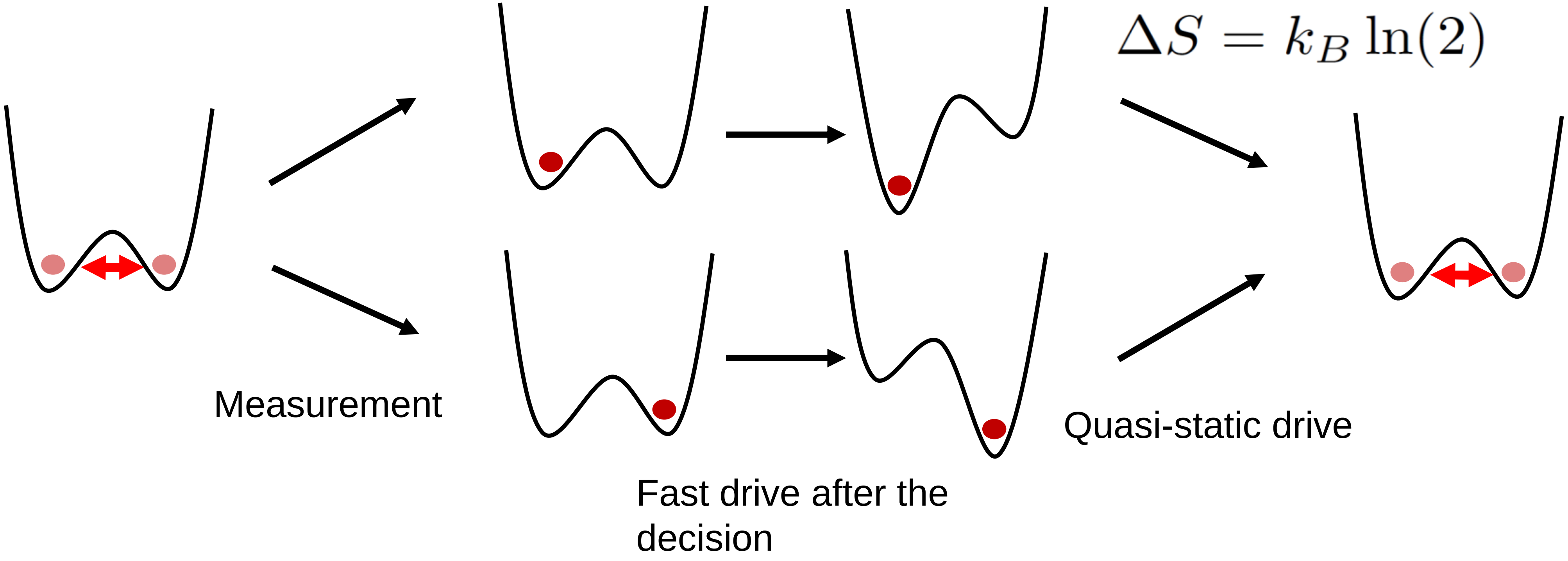
$$W = Q = \int_{V/2}^{V} p dV = \int_{V/2}^{V} \frac{k_B T}{V} dV = k_B T \ln 2$$

Szilard engine for single electrons

J. V. Koski et al., PNAS 111, 13786 (2014), PRL 113, 030601 (2014)

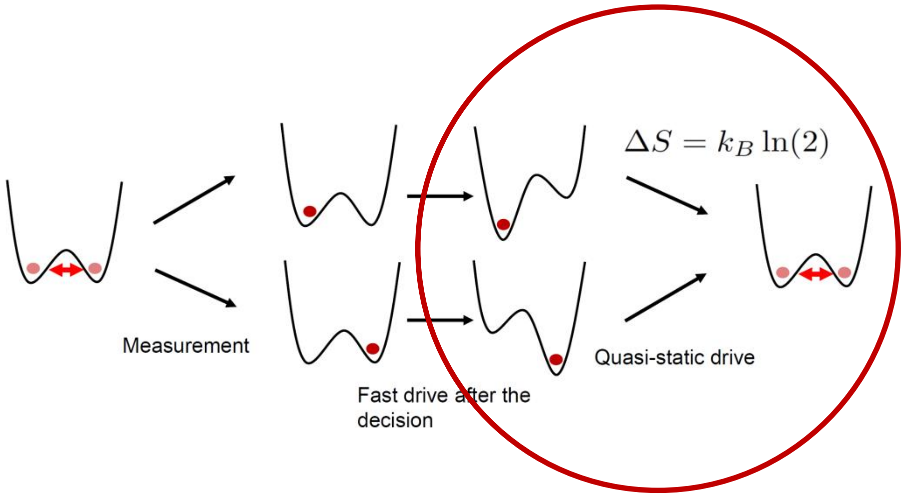
Entropy of the charge states: $$S = -k_B \sum_{i=0,1} p(i) \ln[p(i)]$$

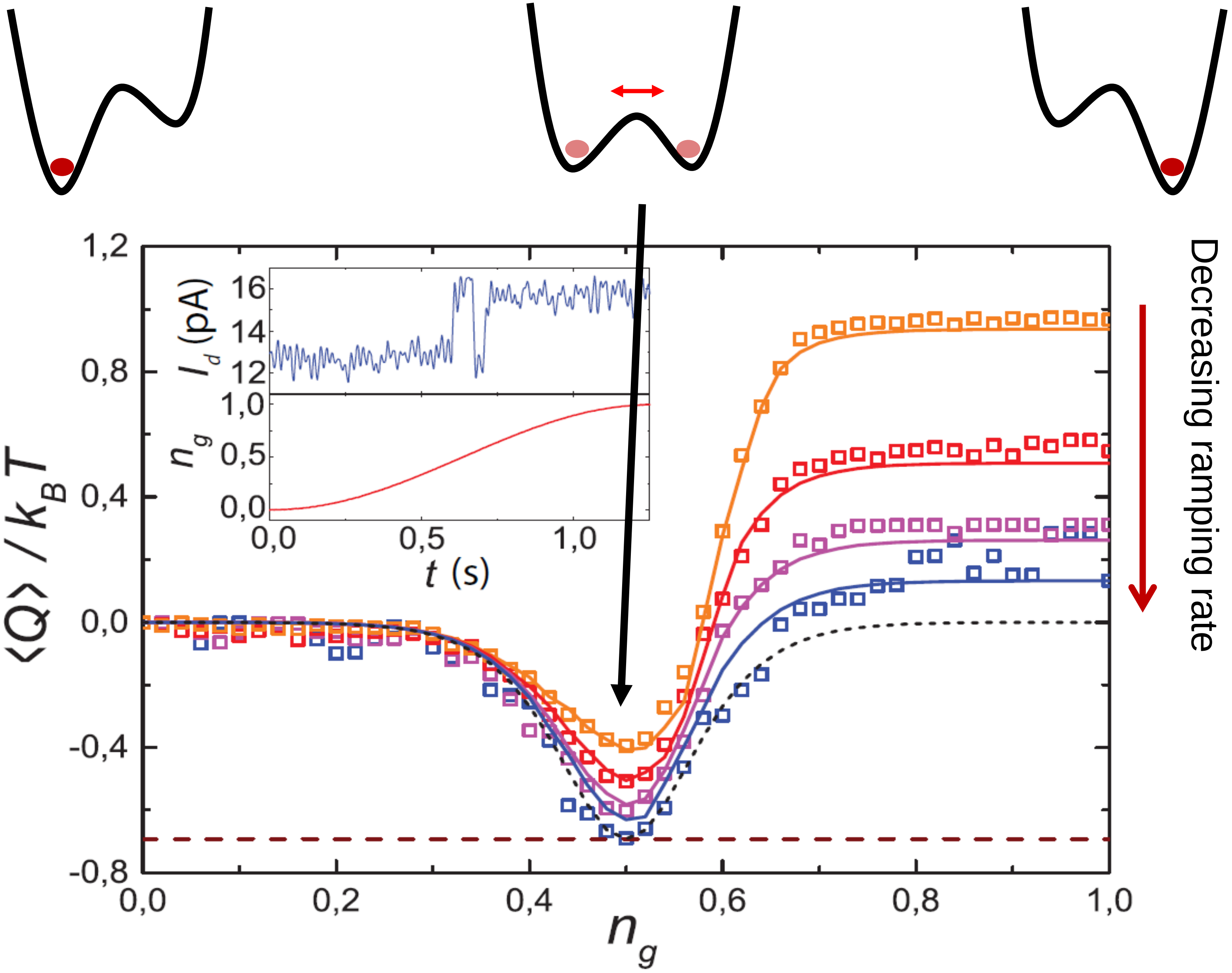
$$\Delta S = k_B \ln(2)$$



In the full cycle (ideally): $$Q = W = -k_B T \ln(2)$$

Extracting heat from the bath in quasi-static drive





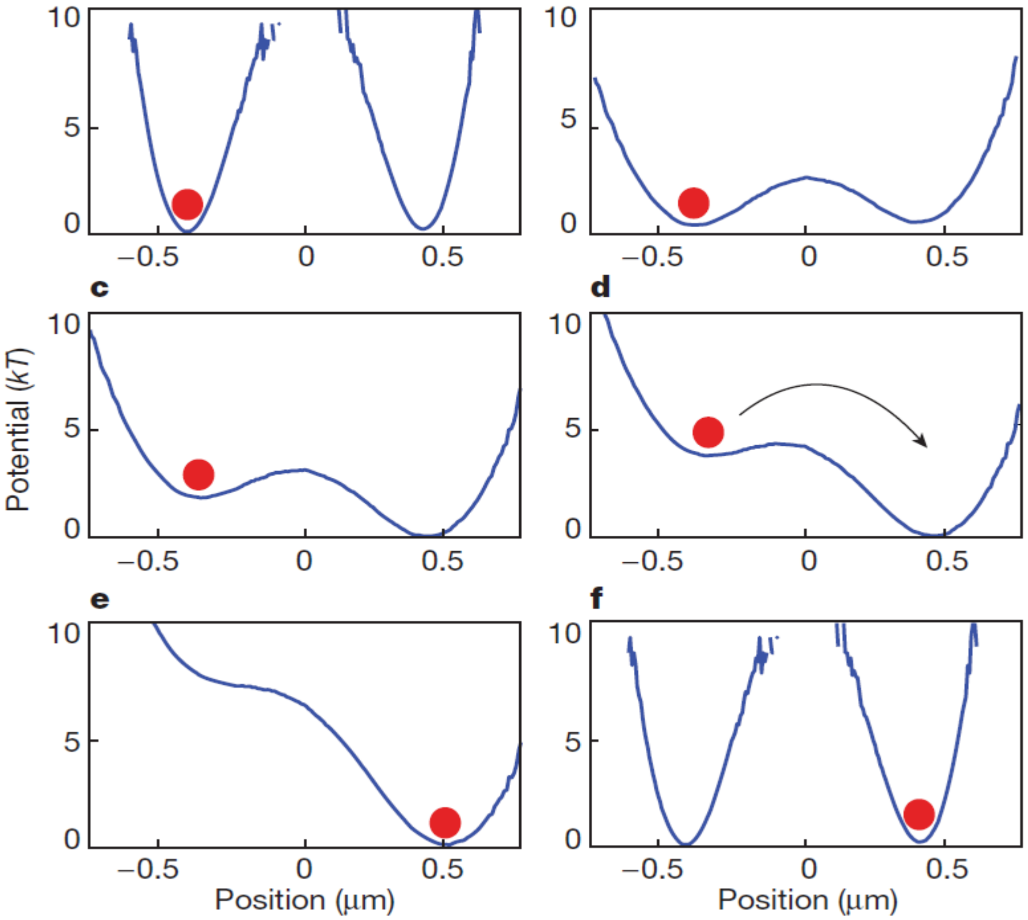
$-\ k_B T \ln(2)$

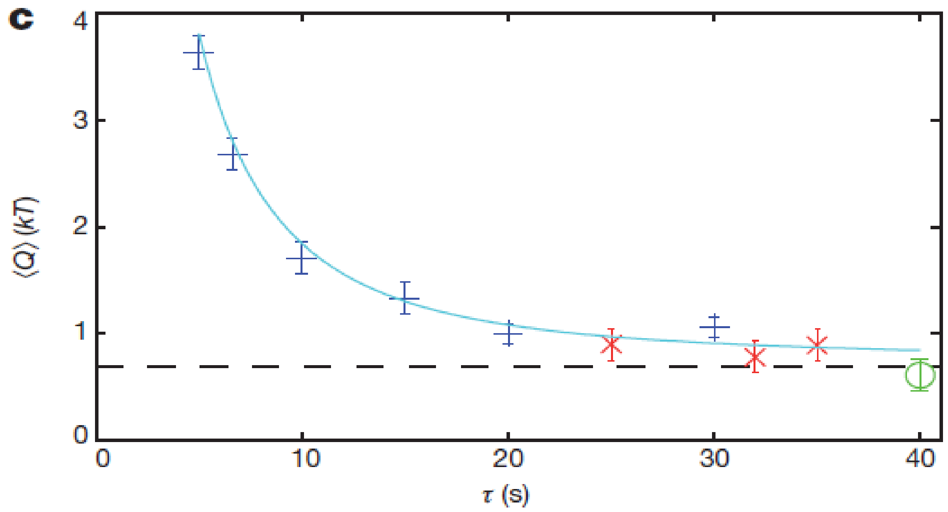
Erasure of a bit

A. Berut et al., Nature 2012

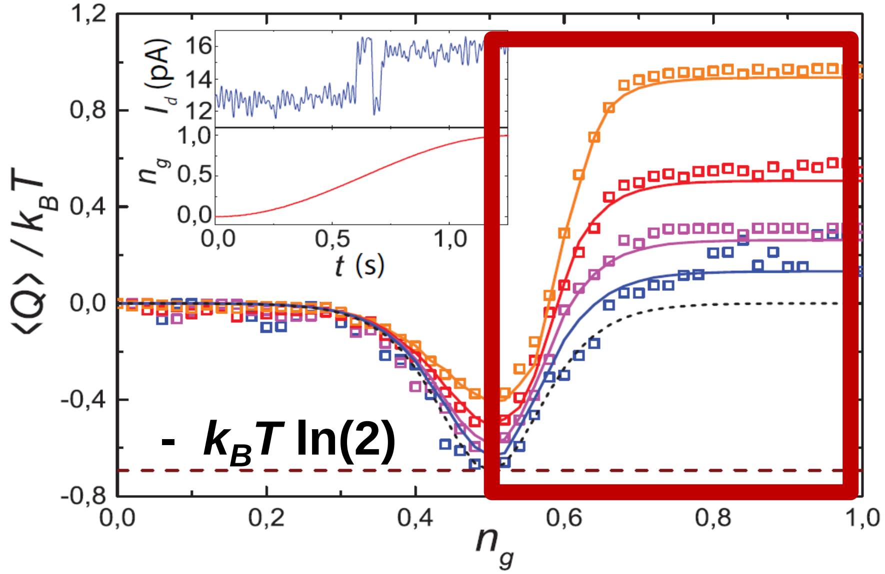
Landauer principle: erasing a single bit costs energy of at least $k_B T \ln(2)$

Experiment on a colloidal particle:



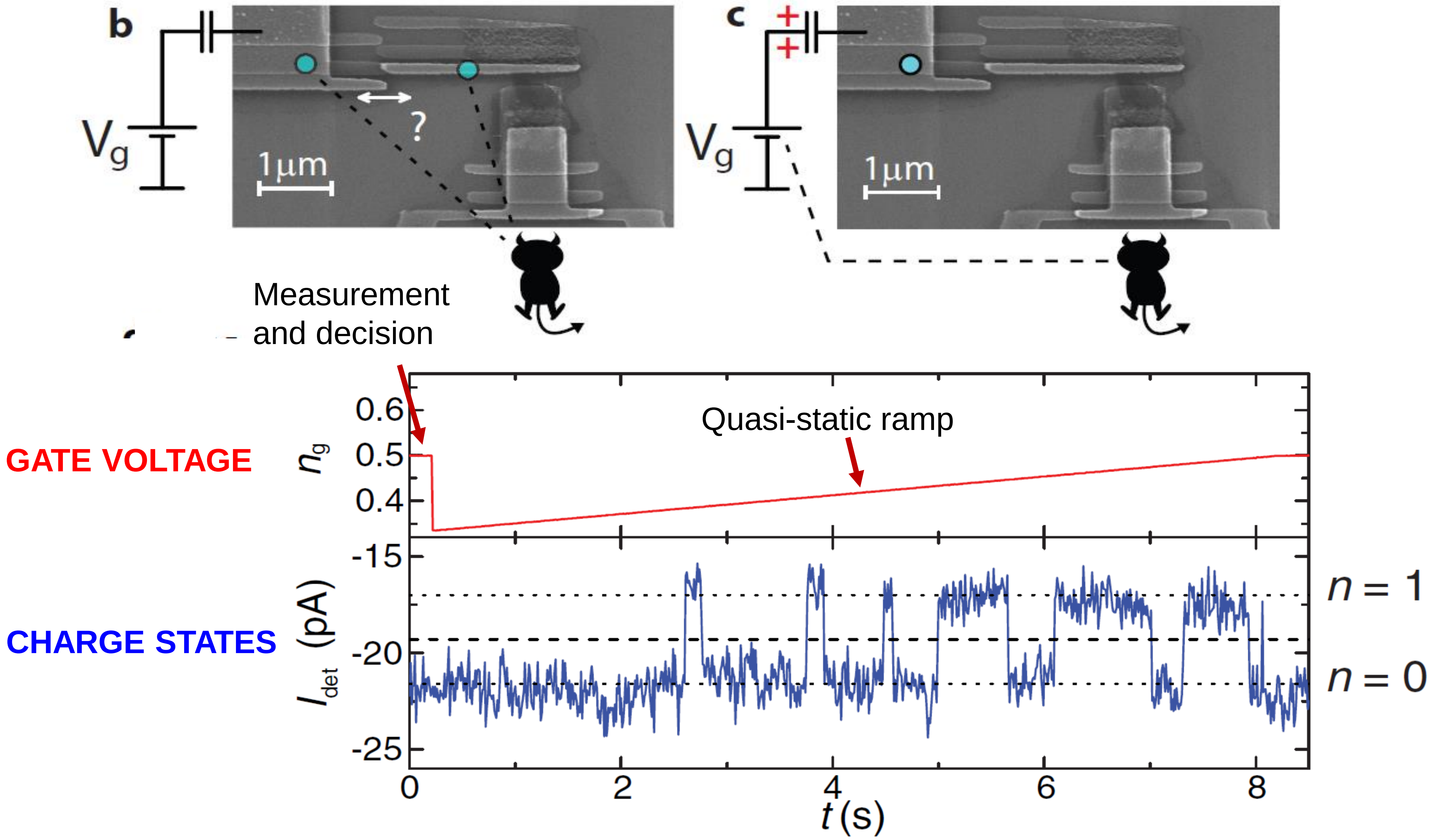


Corresponds to our experiment:

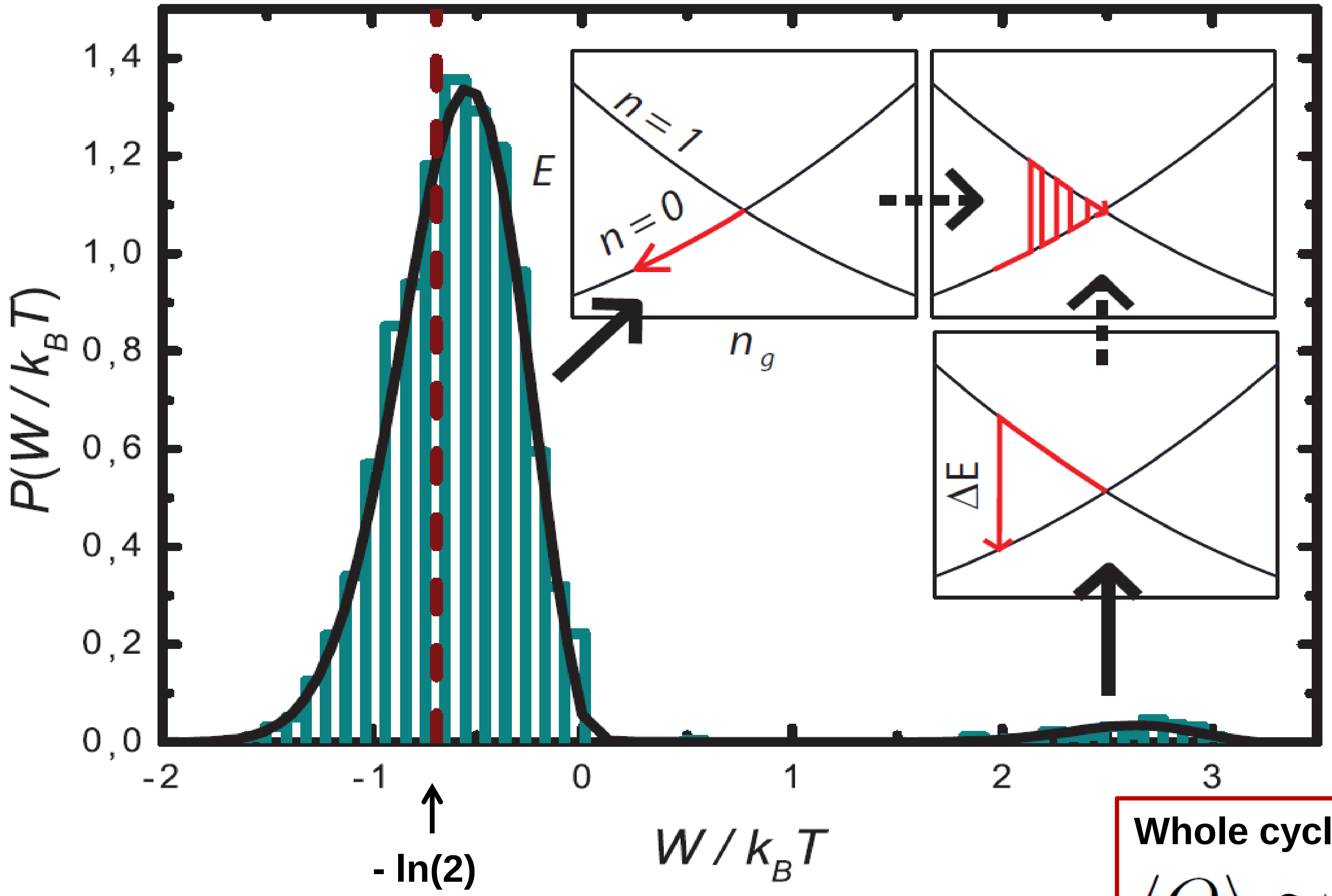


A quantum version: L. Yan et al., Phys. Rev. Lett. 120, 210601 (2018)

Realization of the Szilard engine with an electron



Experimental work distributions



Jonne Koski

J. V. Koski et al., PNAS 111, 13786 (2014), PRL 113, 030601 (2014)

Whole cycle with ca. 3000 repetitions:

$$\langle Q \rangle \approx -0.75\, k_B T \ln(2)$$

Sagawa-Ueda relation

$$\langle e^{-(W-\Delta F)/k_BT - I} \rangle = 1 \qquad I(m,n) = \ln\left(\frac{P(n|m)}{P(n)}\right)$$

T. Sagawa and M. Ueda, PRL 104, 090602 (2010)

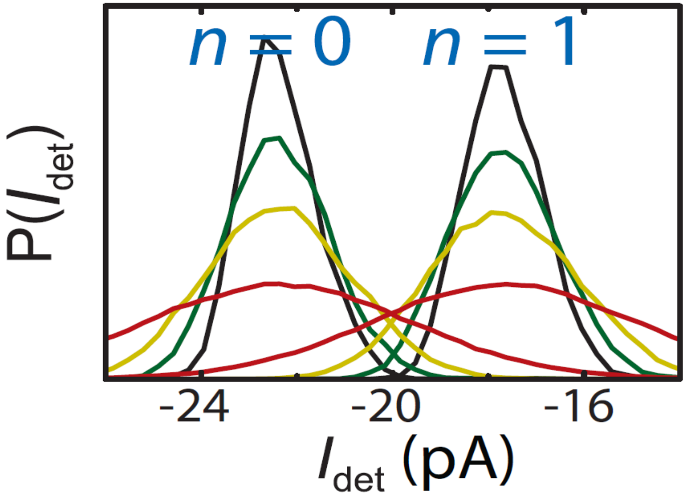
For a symmetric two-state system:

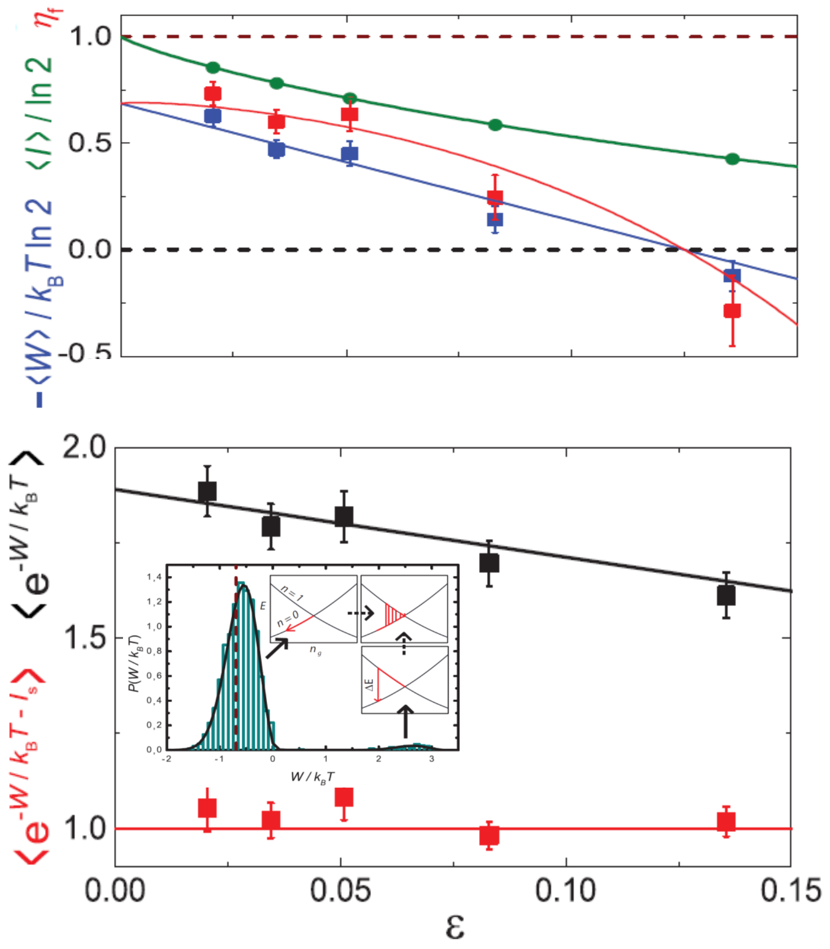
$$I(n = m) = \ln(2(1-\epsilon))$$

$$I(n \neq m) = \ln(2\epsilon)$$

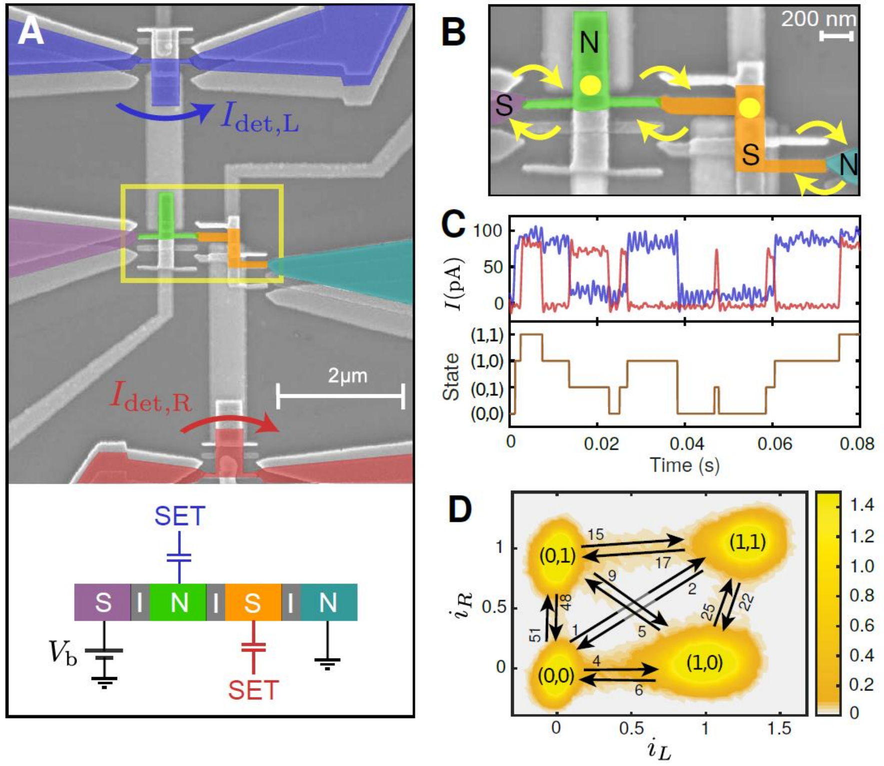
J. V. Koski et al., PRL 113, 030601 (2014)

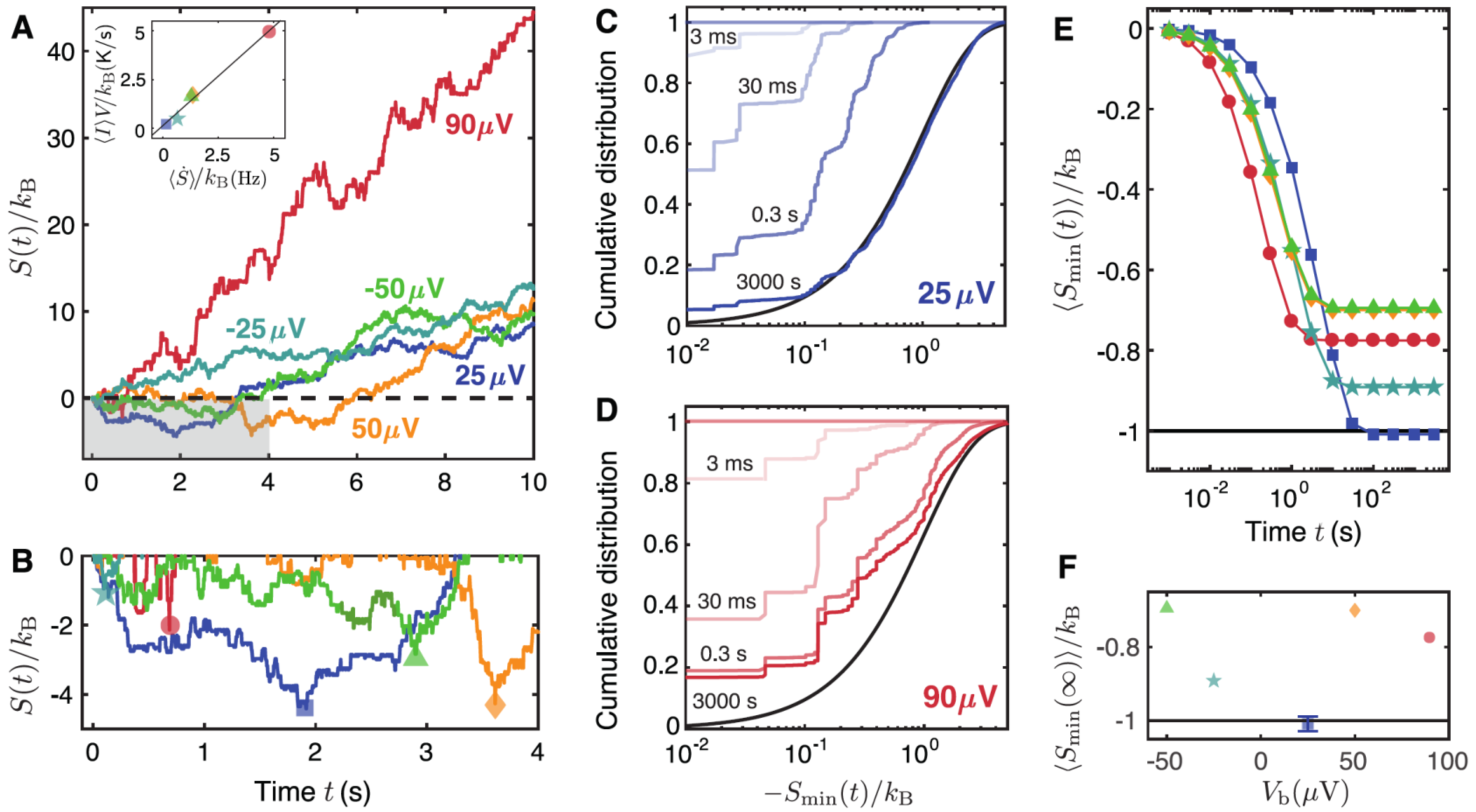
Measurements of *n* at different detector bandwidths





Entropy minimum in a double dot





$$\frac{S(t)}{k_B} = \log \frac{P^{\rm st}(n_0)}{P^{\rm st}(n_{\mathcal{N}(t)})} + \log \prod_{j=1}^{\mathcal{N}(t)} \frac{\Gamma(n_{j-1} \to n_j)}{\Gamma(n_j \to n_{j-1})}$$

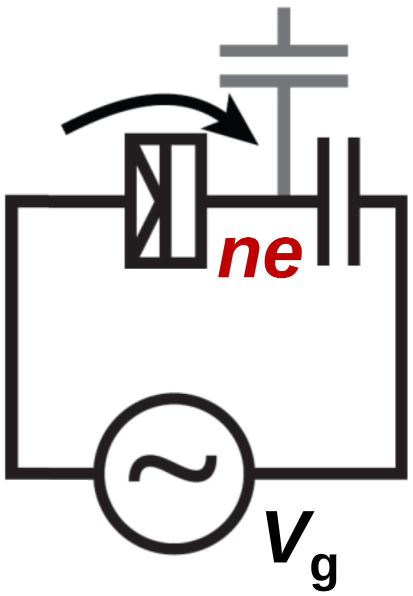
$$\Pr\left(S_{\rm min}(t) \geq -s\right) \geq 1 - e^{-s/k_B}, \quad s \geq 0$$

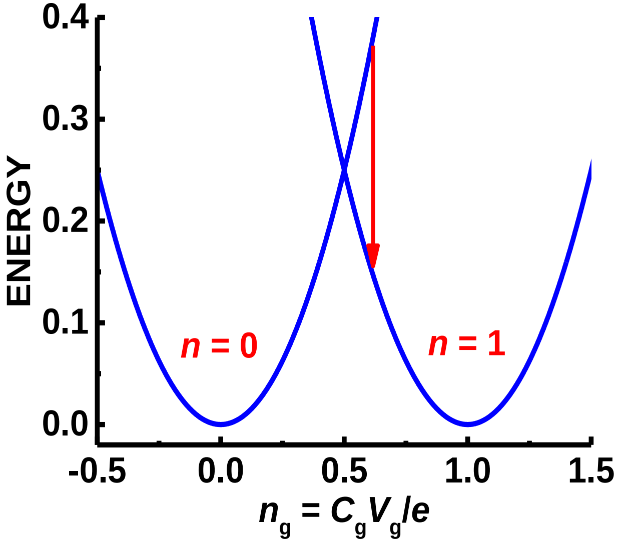
$$\langle S_{\rm min}(t) \rangle \geq -k_B$$

S. Singh, E. Roldan et al., arXiv:1712.

Indirect and direct measurement of heat

DETECTOR

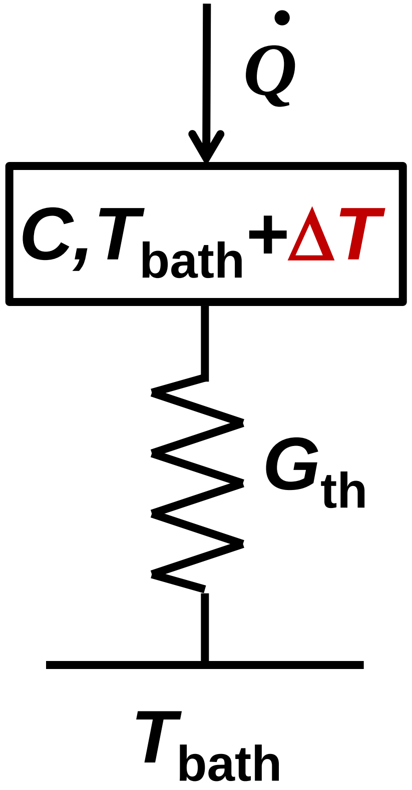




$$E = E_C(n - n_g)^2$$

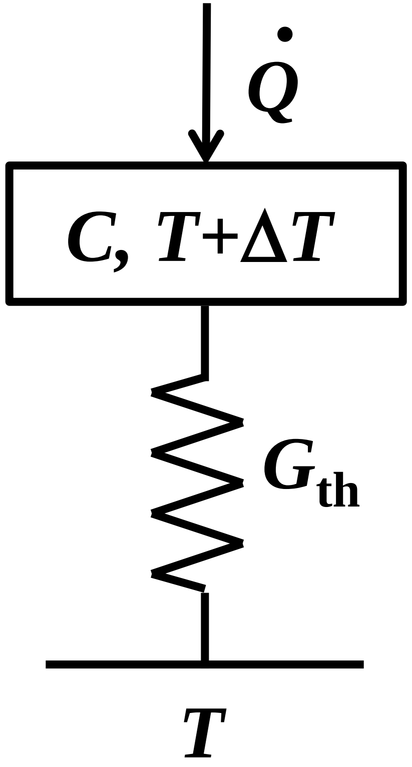
$$Q = E_C(2n_g - 1)$$

Indirect measurement of heat (and work) by counting electrons

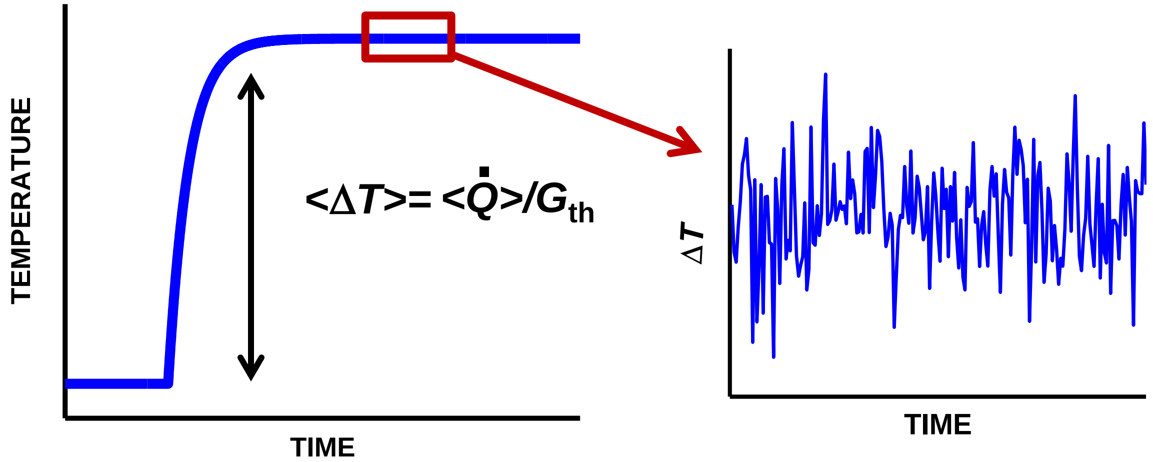


Direct measurement of heat by thermometry

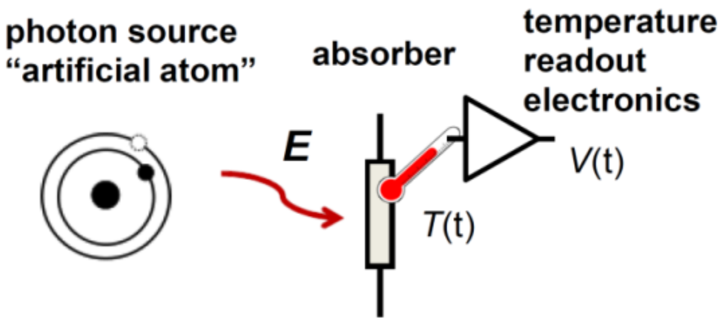
Measuring heat currents by thermometry

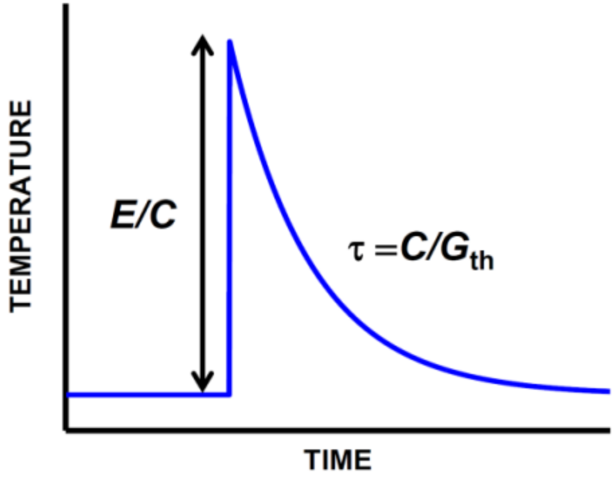


Measurement of temperature by a fast thermometer



Single quantum detection (calorimetry): electrons, photons

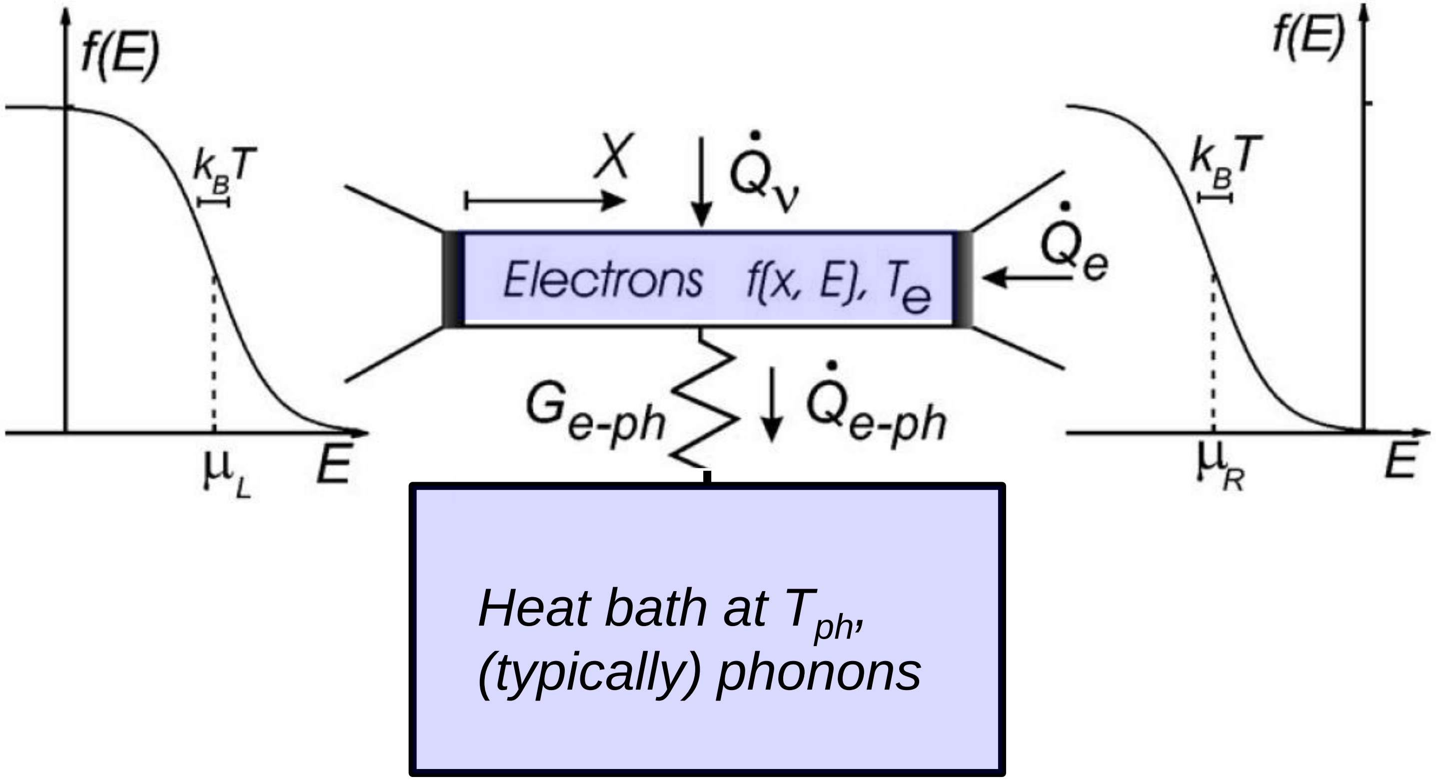




Energy resolution:

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

Generic thermal model of an electronic conductor



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

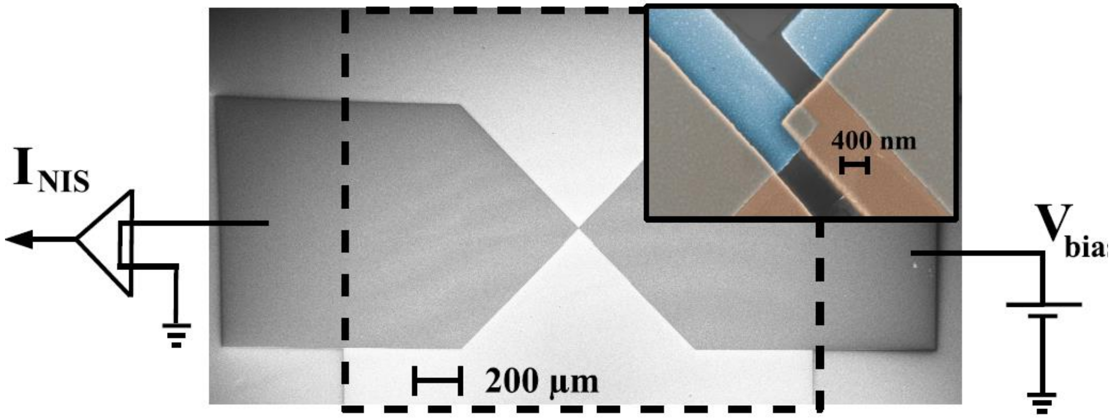
$$f(E) = \frac{1}{1 + e^{(E-\mu)/k_B T}}$$

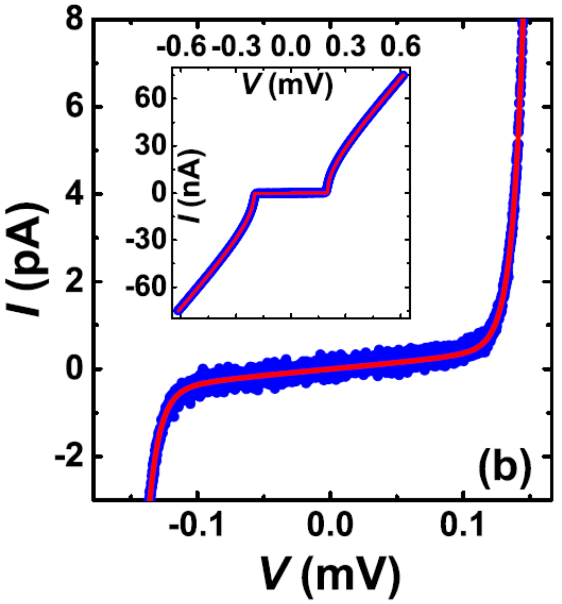
Separation of time scales: $\tau_{ee} < 10^{-9}$ s, $\tau_{ep} > 10^{-6}$ s

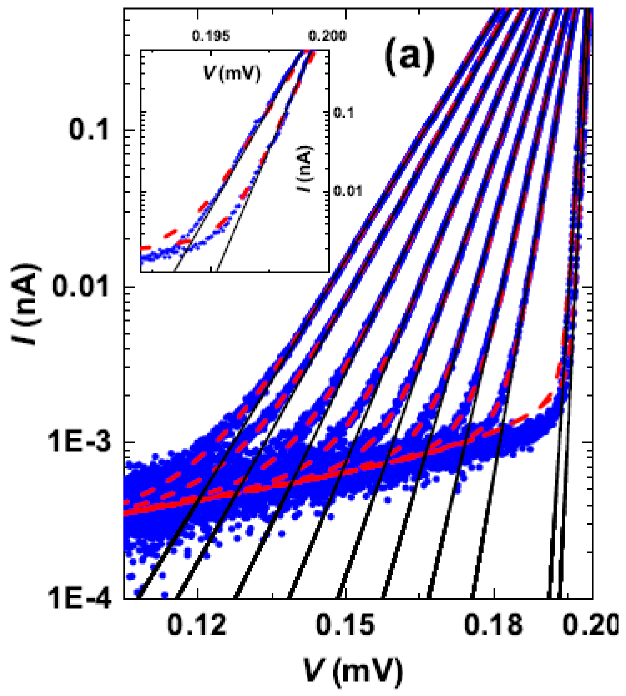
NIS-thermometry

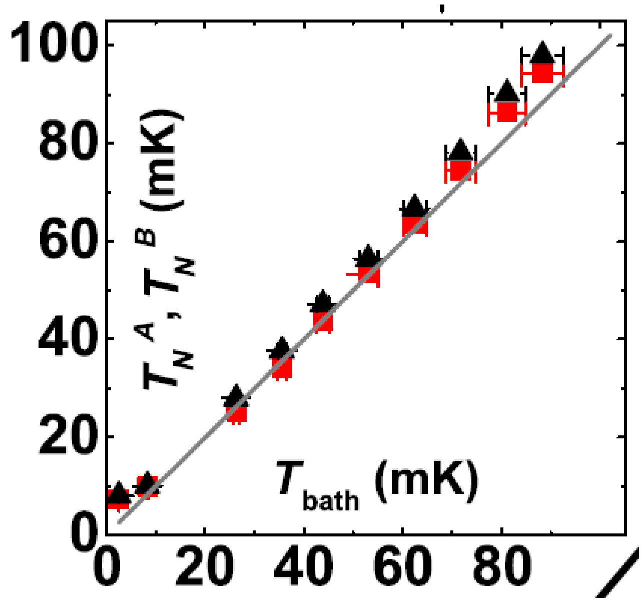
$$I = \frac{1}{2eR_T}\int n_S(E)[f_N(E-eV)-f_N(E+eV)]dE$$

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



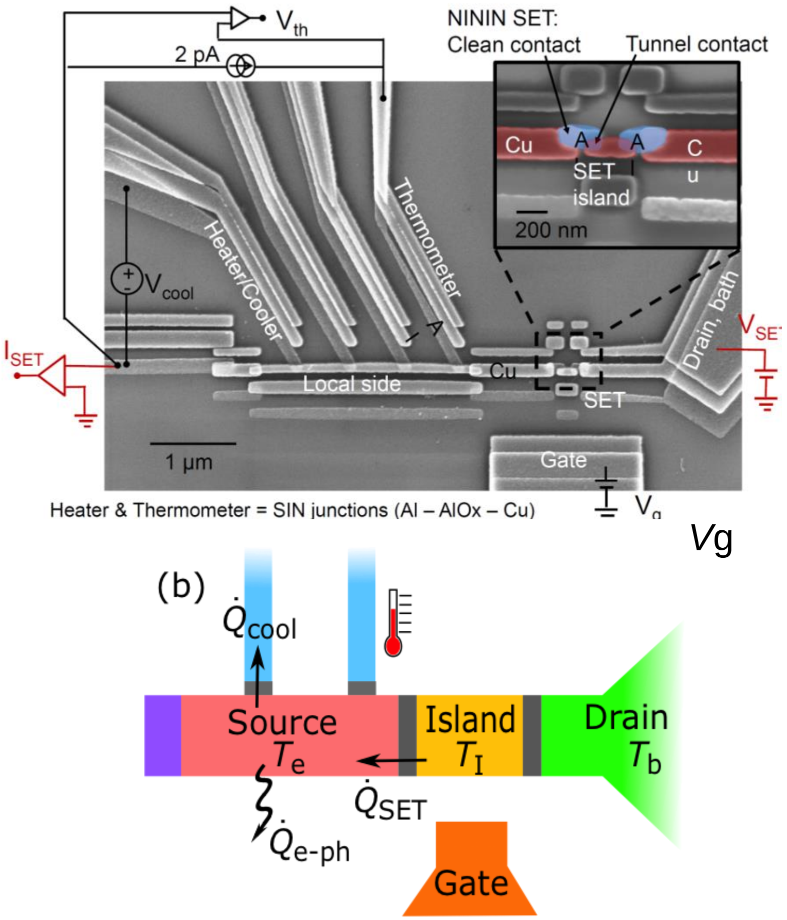


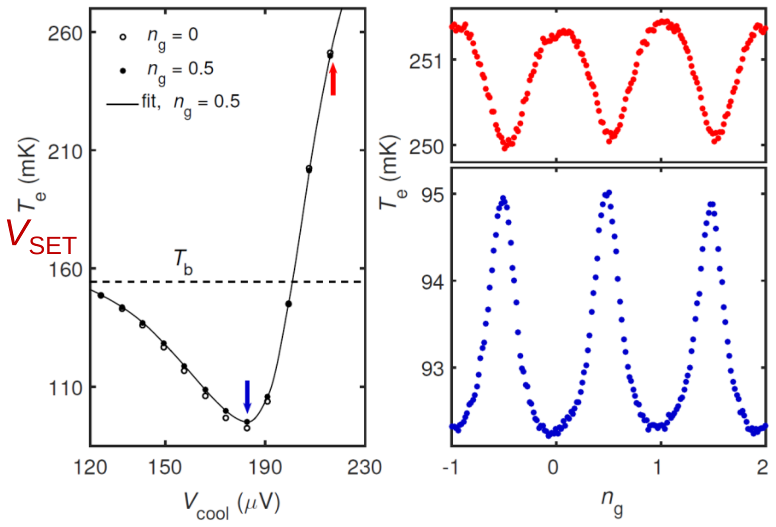


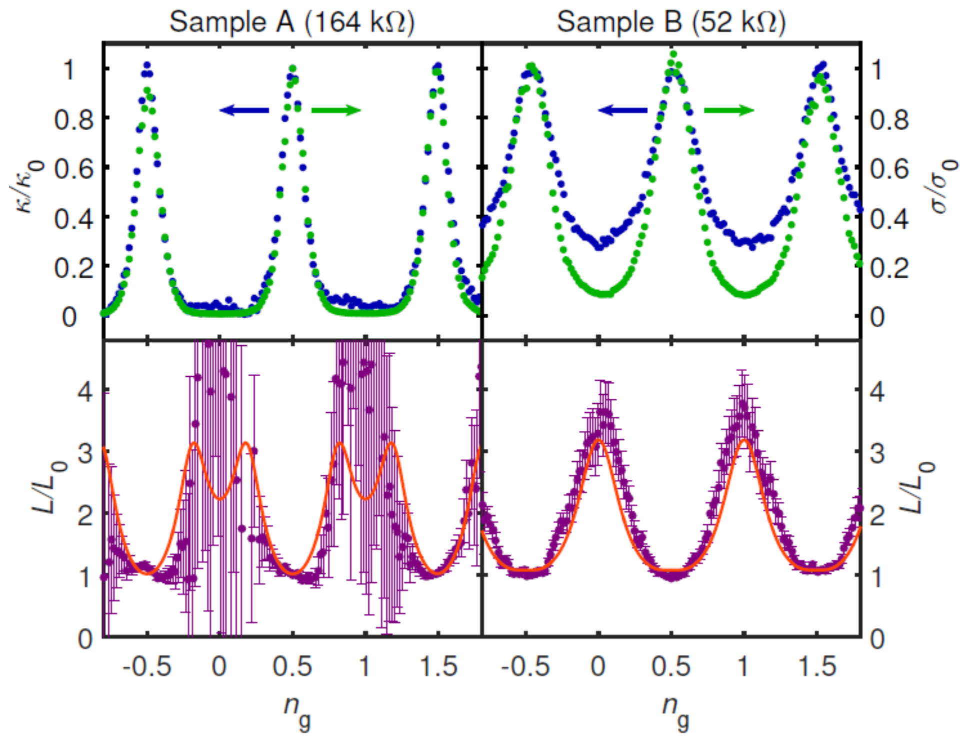


Phys. Rev. Appl. 4, 034001 (2015).

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







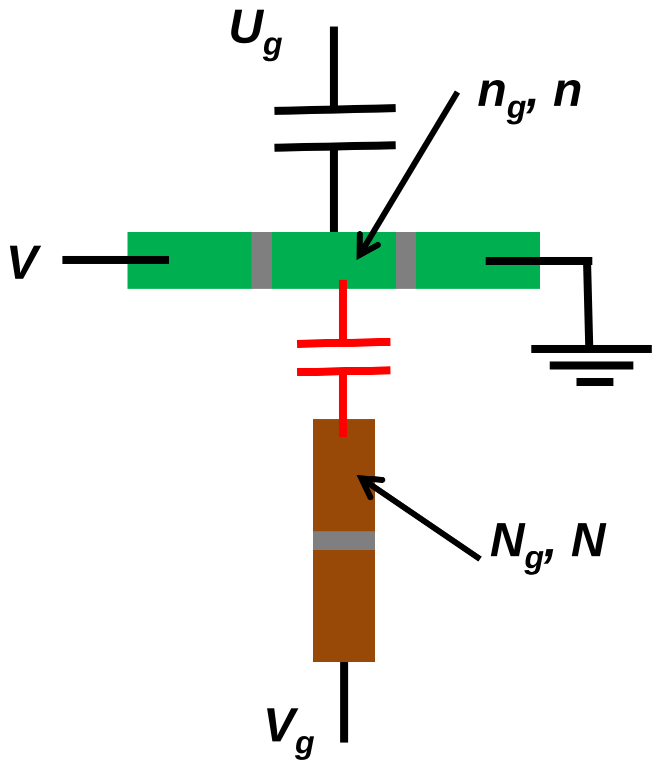
B. Dutta et al., PRL **119**, 077701 (2017)

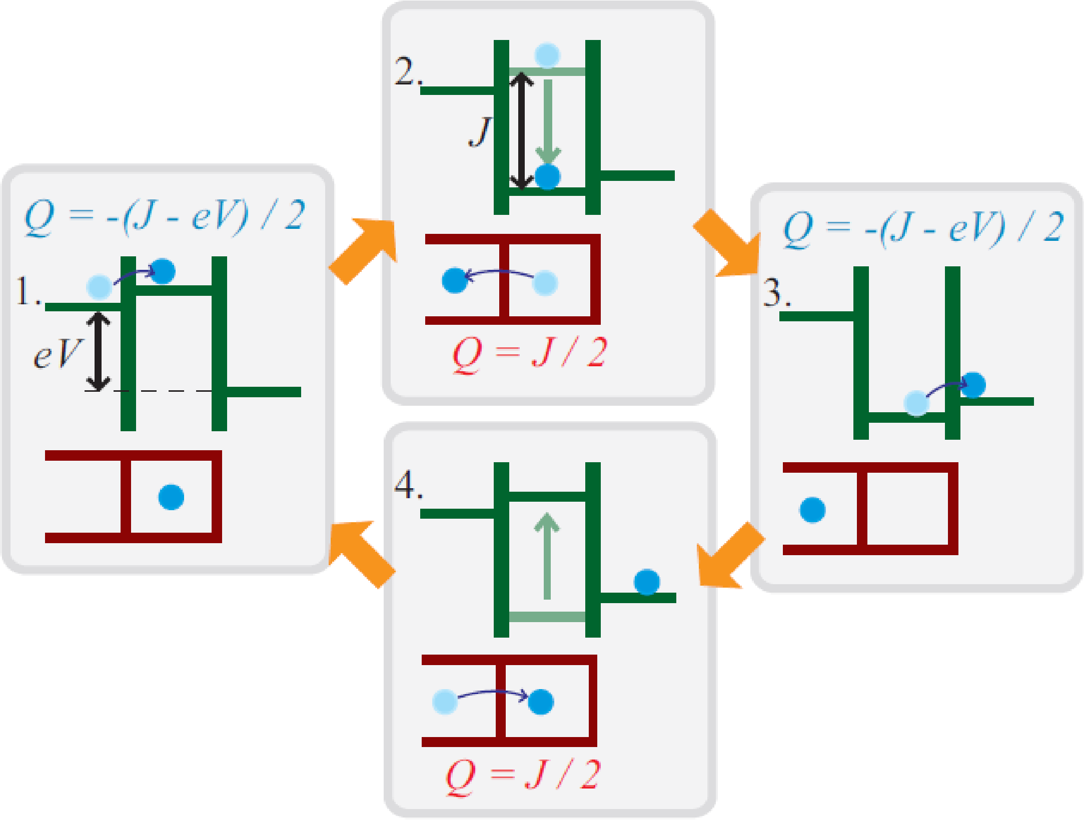
Autonomous Maxwell demon

System and Demon: all in one

Realization in a circuit:

$$H(n,N) = E_{\rm s}(n-n_g)^2 + E_{\rm d}(N-N_g)^2 + 2J(n-n_g)(N-N_g)$$





J. V. Koski et al., PRL 115, 260602 (2015).
Similar idea: P. Strasberg, ..., M. Esposito, PRL 110, 040601 (2013).

Autonomous Maxwell demon – information-powered refrigerator

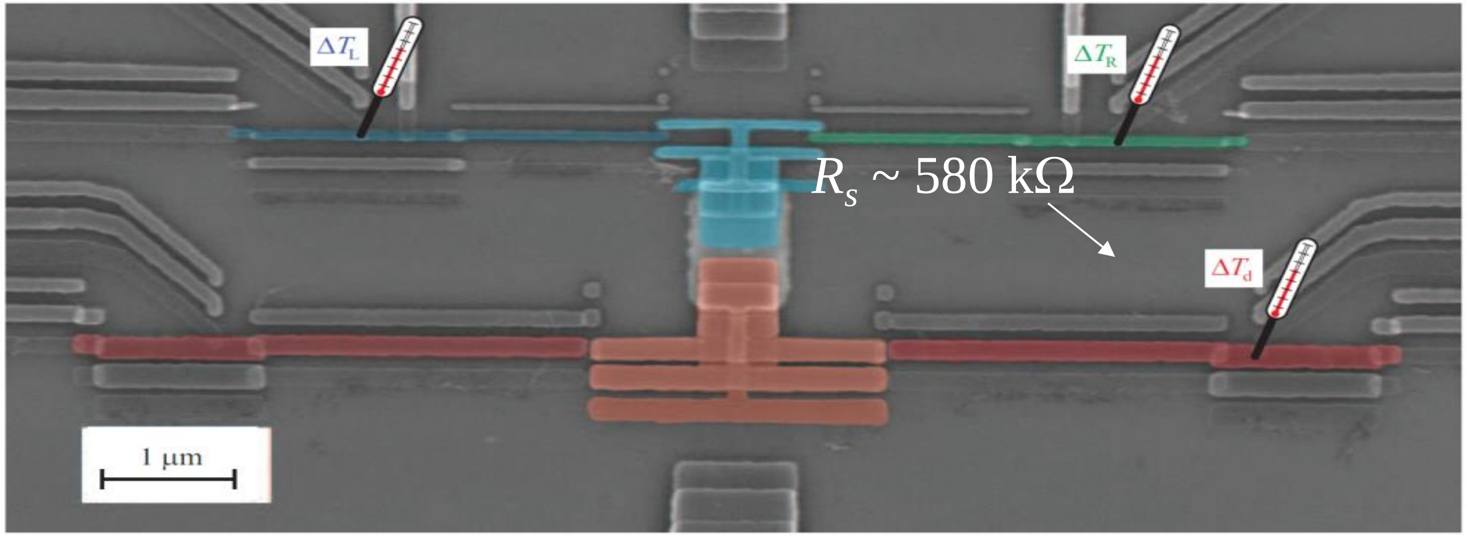
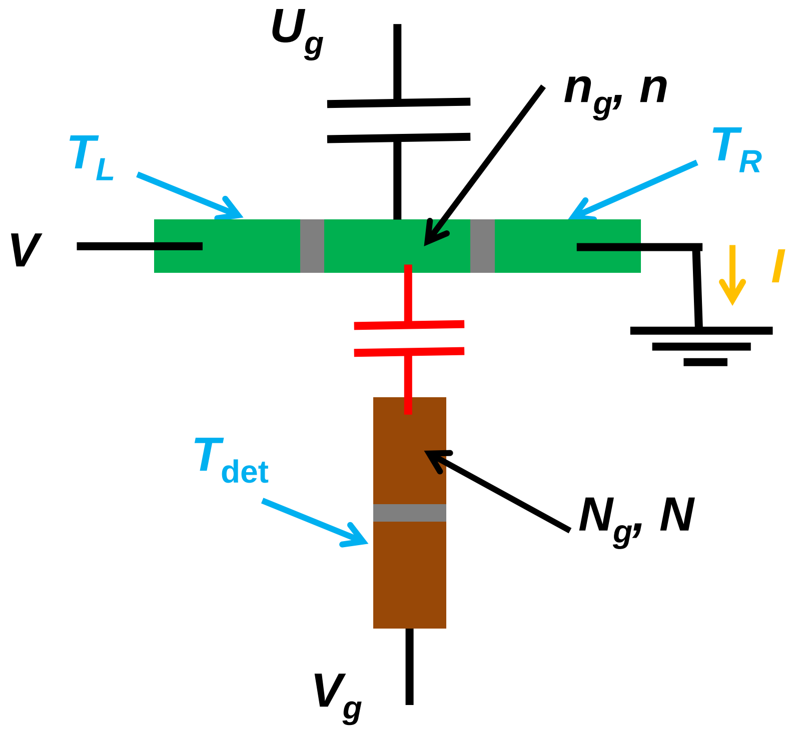
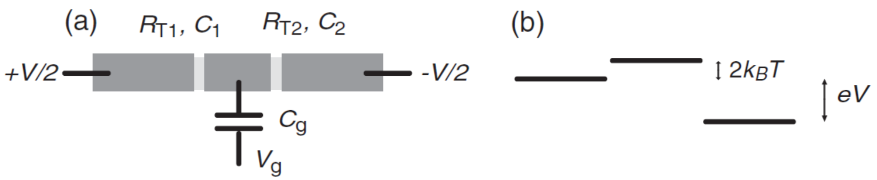


Image of the actual device



$N_g = 0$: No feedback control ("SET-cooler")

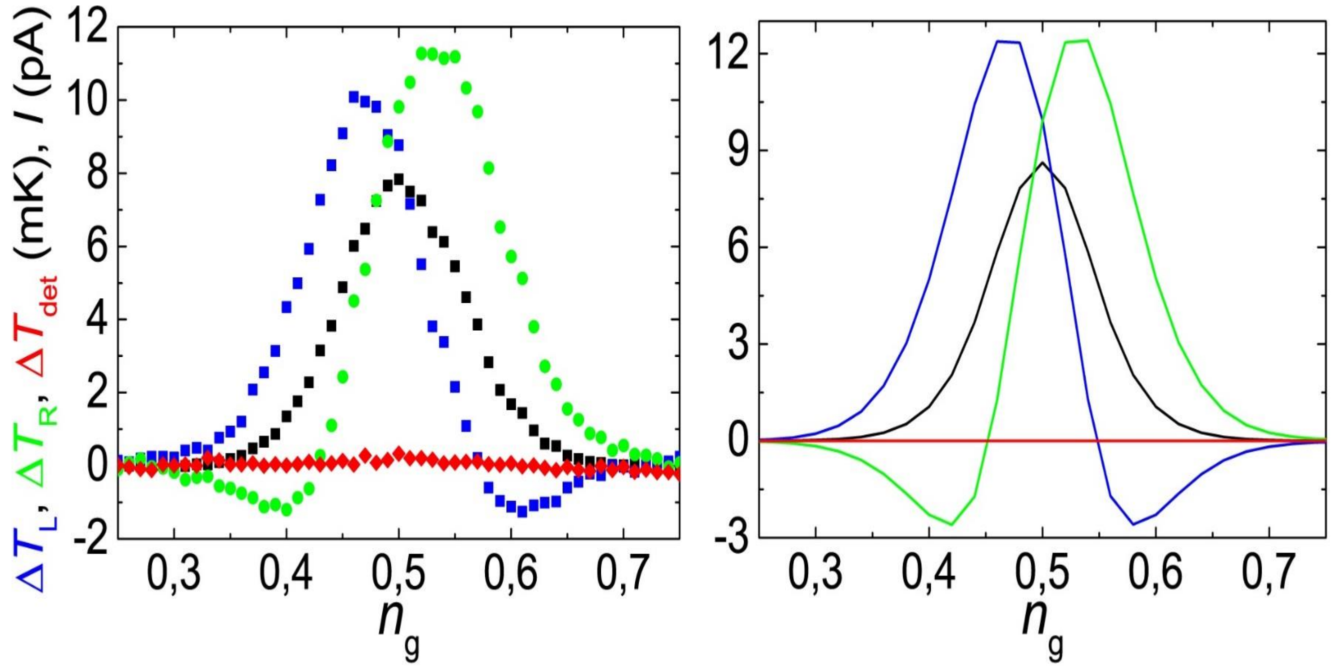
$$H(n,N) = E_s(n-n_g)^2 + E_d(N-N_g)^2 + 2J(n-n_g)(N-N_g)$$

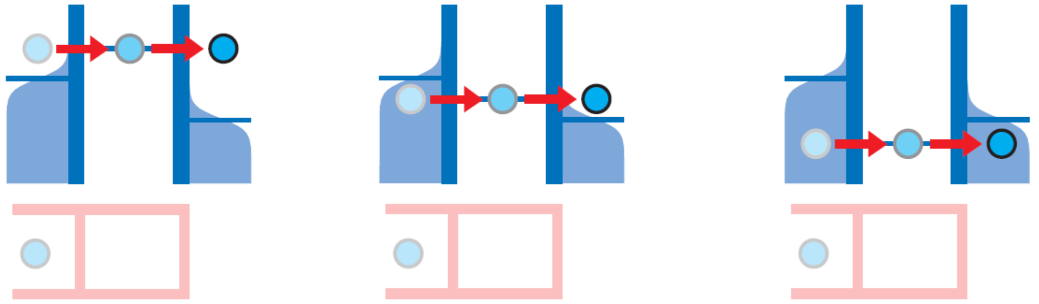


$N_g = 0$ freezes $N = 0$

$E = E_s(n-n_g)^2$

Behaves like in the absence of Demon





JP, J. V. Koski, and D. V. Averin, PRB **89**, 081309 (2014)
A. V. Feshchenko, J. V. Koski, and JP, PRB **90**, 201407(R) (2014)

N_g = 0.5: feedback control (Demon)

$$H(n,N) = E_s(n-n_g)^2 + E_d(N-N_g)^2 + 2J(n-n_g)(N-N_g)$$

$N_g = 0.5$, N adjusts to minimize Coulomb repulsion

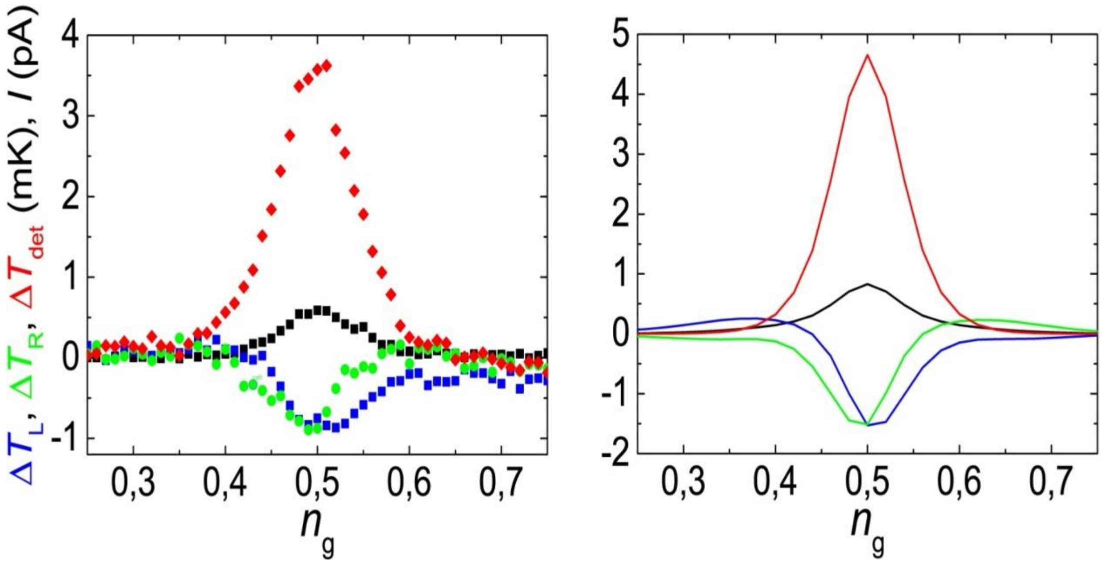
In particular at $n_g = 0.5$

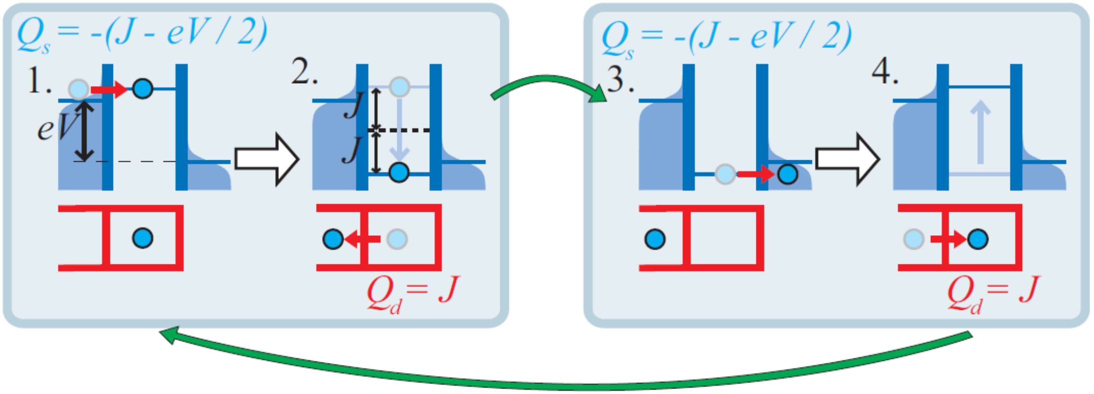
$E = 2J(n-n_g)(N-N_g)$

$n \to 1$, $N \to 0$

$n \to 0$, $N \to 1$

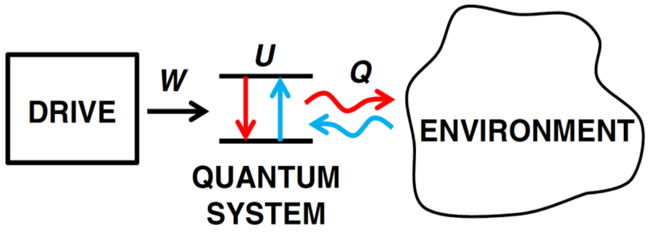
The lower box acts as a Demon on the top System

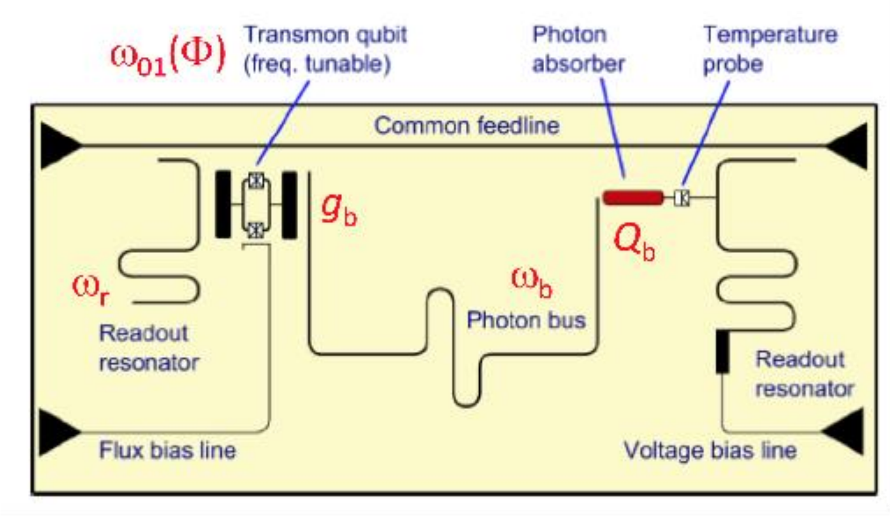




Both T_L and T_R drop: entropy of the System decreases; T_{det} increases: entropy of the Demon increases

Quantum thermodynamics with superconducting qubits and resonators

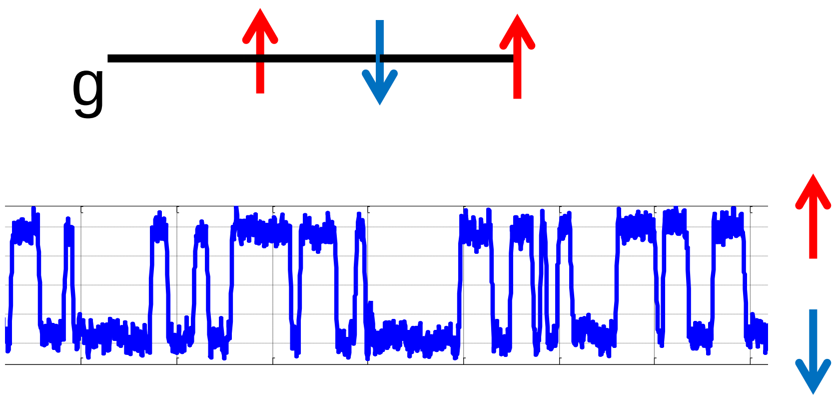




Stochastic thermodynamics of a driven qubit
Quantum jumps/trajectories

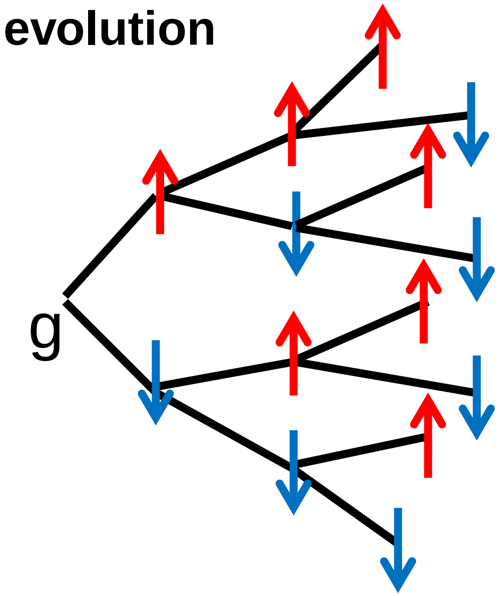
Hekking and JP, PRL 111, 093602 (2013);
Horowitz and Parrondo, NJP 15, 085028 (2013)

Classical evolution



TIME

Quantum evolution

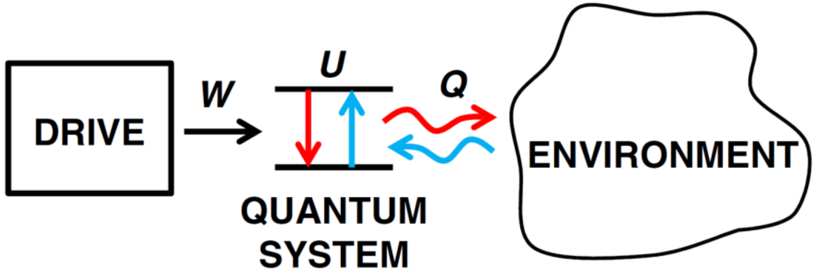


Quantum trajectories

Objective: **unravel into single realizations** ("single experiments") instead of averages (the latter ones come naturally from the density matrix)

Construct the Monte Carlo wave function (MCWF) for the system
Dalibard, Castin and Mölmer 1992
Plenio and Knight 1998

$$|\psi(t)\rangle = a(t)|g\rangle + b(t)|e\rangle$$



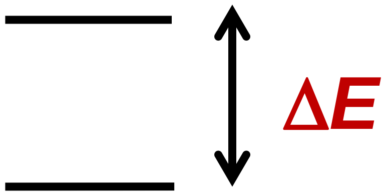
At $t = t + \Delta t$, we have three possibilities:

1. Relaxation $|\psi(t+\Delta t)\rangle_\downarrow = |g\rangle$ with probability $\Delta p_\downarrow = \Gamma_\downarrow |b(t)|^2 \Delta t$ **Q = +ΔE**

2. Excitation $|\psi(t+\Delta t)\rangle_\uparrow = |e\rangle$ with probability $\Delta p_\uparrow = \Gamma_\uparrow |a(t)|^2 \Delta t$ **Q = -ΔE**

3. Evolution without photon absorption/emission

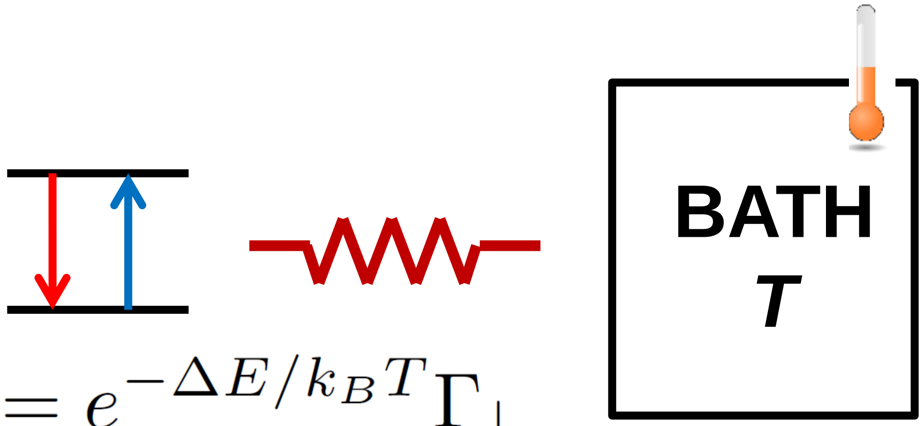
$$|\psi^{(0)}(t+\Delta(t))\rangle = \mu[1 - \frac{i}{\hbar}\Delta t\, H]|\psi(t)\rangle, \quad \mu = (1 - \Delta p_\downarrow - \Delta p_\uparrow)^{-1/2}$$



Here the Hamiltonian is non-hermitian (to preserve the norm)

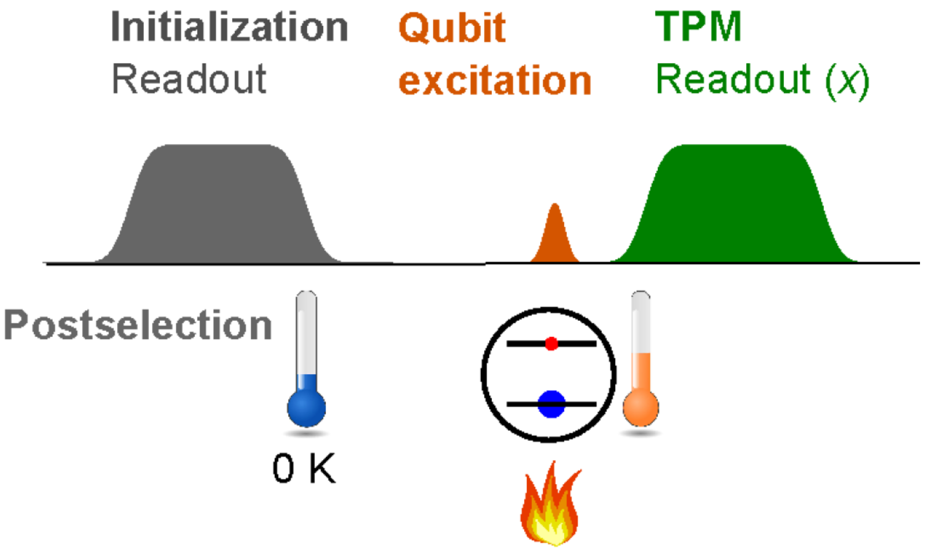
$$H = H_S - i\hbar\Gamma_\downarrow |e\rangle\langle e|/2 - i\hbar\Gamma_\uparrow |g\rangle\langle g|/2$$

Temperature of a qubit?



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

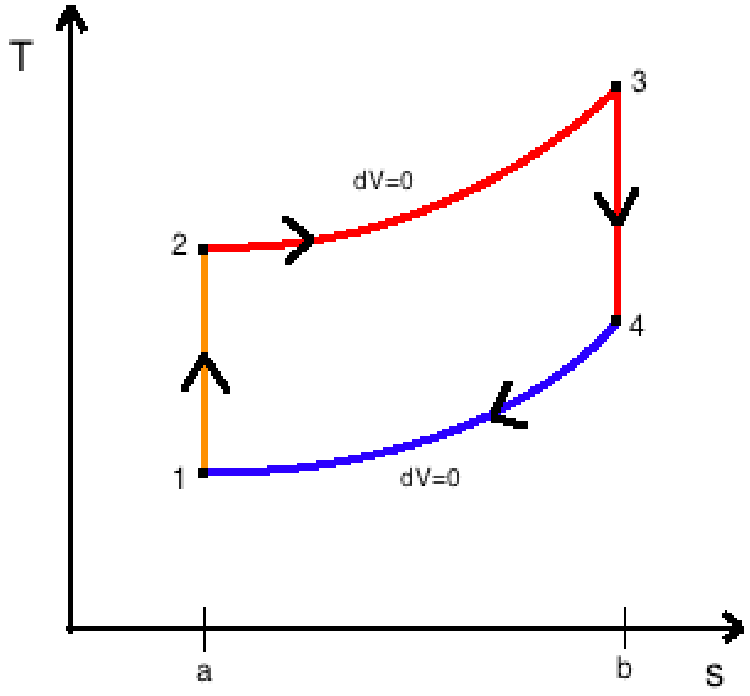
Couple the qubit to a true thermal bath

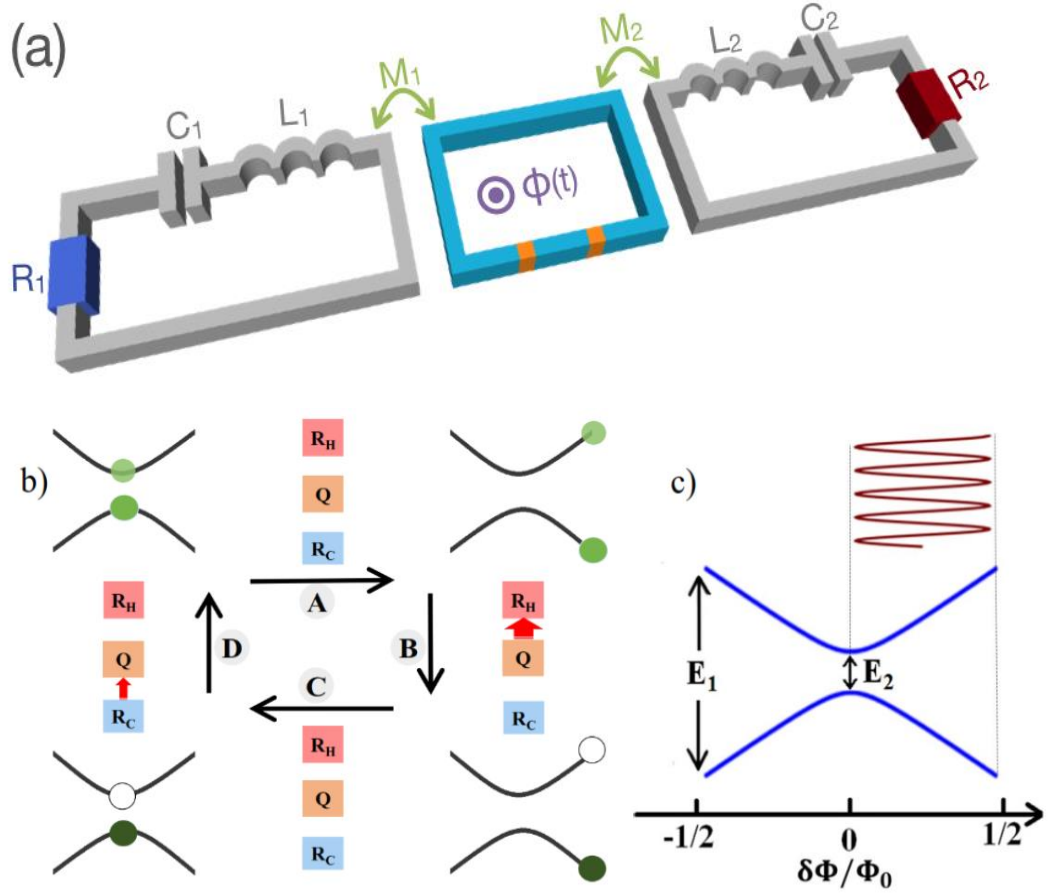


Alternative approach to initialize a qubit to a given ”temperature”:
Y. Masuyama et al., Nature Comm. 9, 1291 (2018).

Quantum Otto refrigerator

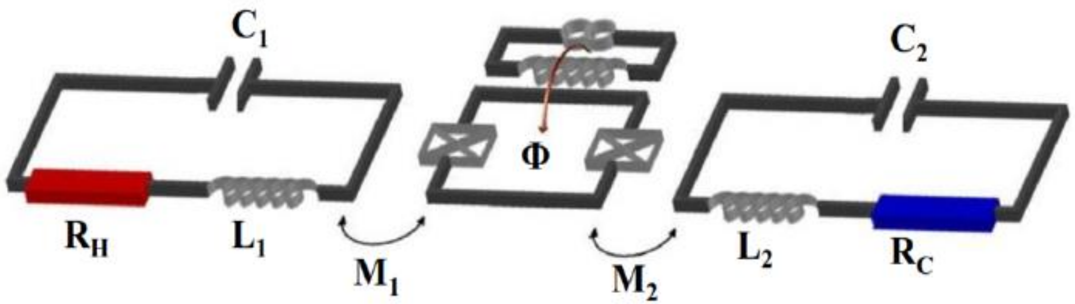
Otto cycle





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

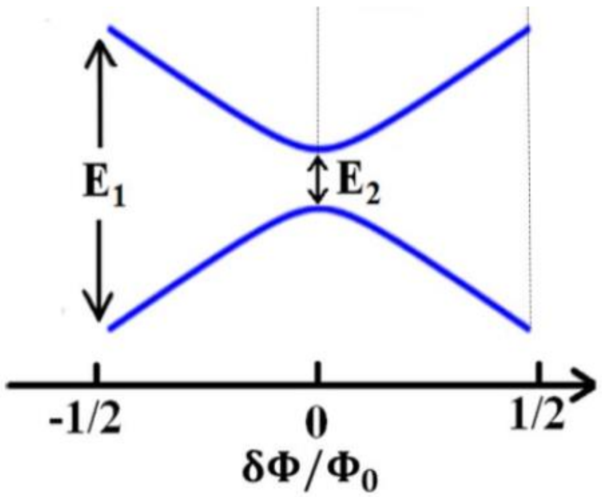
System and Hamiltonian



$$H = H_{R_\mathrm{H}} + H_{R_\mathrm{C}} + H_{\mathrm{cH}} + H_{\mathrm{cC}} + H_\mathrm{Q}$$

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

$$\Delta = E_2/(2E_0)$$
$$q \equiv \delta\Phi/\Phi_0$$



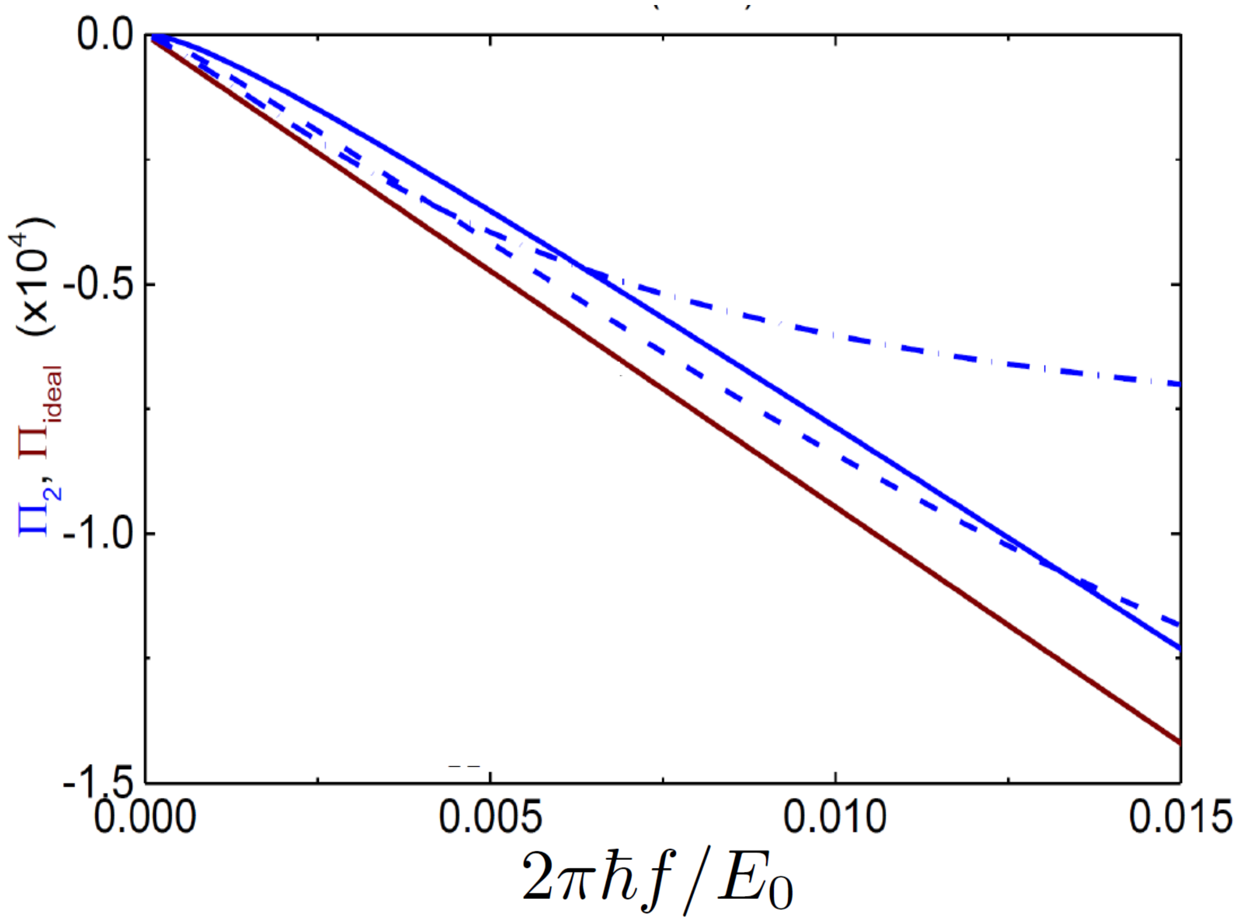
$$\dot{\rho}_{gg} = -\frac{\Delta}{q^2+\Delta^2}\dot{q}\,\mathrm{Re}[\rho_{ge}e^{i\phi(t)}] - \Gamma_\Sigma\rho_{gg} + \Gamma_\downarrow$$

$$\dot{\rho}_{ge} = \frac{\Delta}{q^2+\Delta^2}\dot{q}(\rho_{gg} - 1/2)e^{-i\phi(t)} - \frac{1}{2}\Gamma_\Sigma\rho_{ge}$$

$$\Gamma_{\downarrow,\uparrow,j} = \frac{E_0^2 M_j^2}{\hbar^2\Phi_0^2}\frac{\Delta^2}{q^2+\Delta^2}S_{I,j}(\pm E/\hbar)$$

$$P_j = E(t)(\rho_{ee}\Gamma_{\downarrow,j} - \rho_{gg}\Gamma_{\uparrow,j})$$

Nearly ideal refrigerator (at intermediate pumping frequencies)



Ideal Otto cycle: brown line

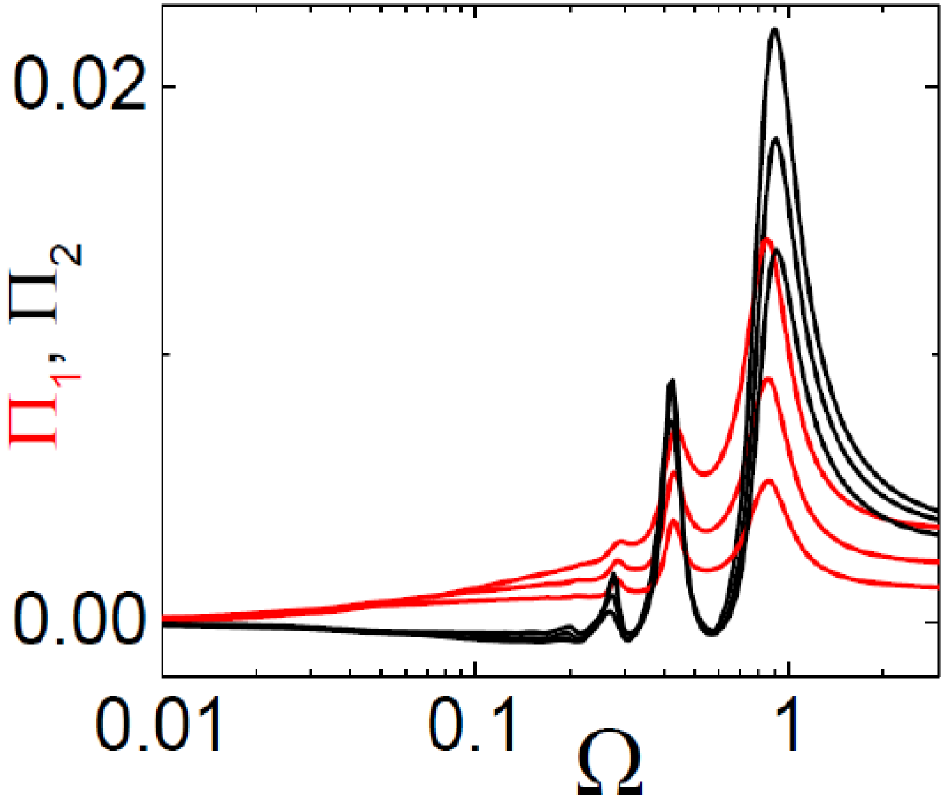
Different coupling to the baths: blue lines

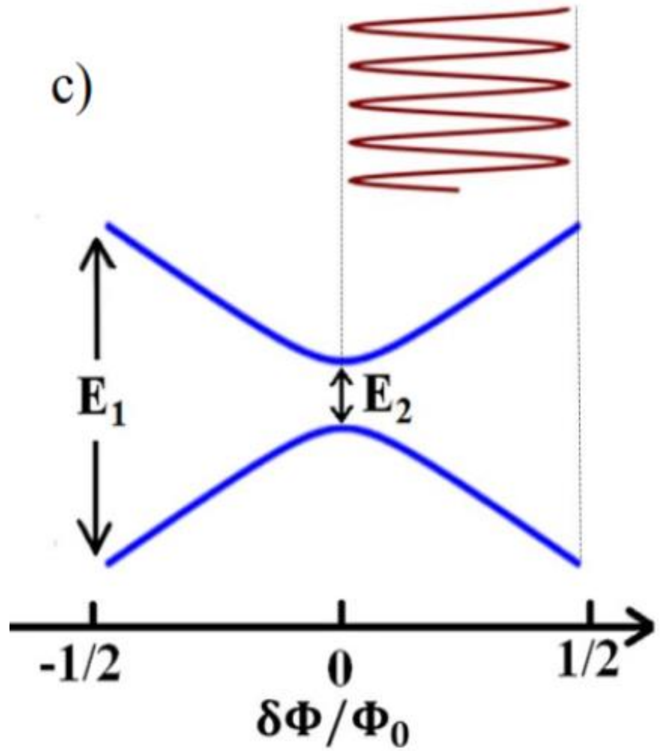
$$P_1 = +\frac{\hbar\omega_1}{2}[\tanh(\frac{\beta_1\hbar\omega_1}{2}) - \tanh(\frac{\beta_2\hbar\omega_2}{2})]f,$$

$$P_2 = -\frac{\hbar\omega_2}{2}[\tanh(\frac{\beta_1\hbar\omega_1}{2}) - \tanh(\frac{\beta_2\hbar\omega_2}{2})]f.$$

$$\Pi_j \equiv P_j/(E_0^2/\hbar)$$

Coherent oscillations of heat current at high frequencies

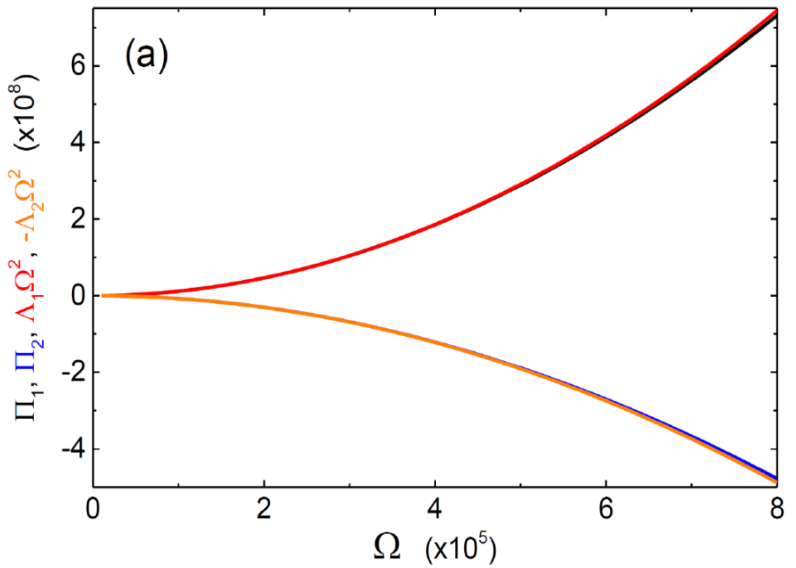




$\Omega = 2\pi\hbar f / E_0$

E_2 E_1

Nearly adiabatic regime (at very low frequencies)



Dimensionless power to reservoir j, $\Pi_j \equiv P_j/(E_0^2/\hbar)$ as a function of dimensionless frequency $\Omega = 2\pi\hbar f/E_0$

$$\Pi_j^{(2)} = \Lambda_j \Omega^2$$

1. Classical rate equation: $\dot{\rho}_{gg} = -\Gamma_\Sigma \rho_{gg} + \Gamma_\downarrow$

$$\Lambda_{j,\mathrm{CL}} = -\frac{1}{\pi}\int_0^{2\pi} du\sqrt{q^2+\Delta^2}\left(\frac{\frac{d^2\rho_{\mathrm{eq},gg}}{du^2}}{\xi_\Sigma^2} - \frac{\left(\frac{d\rho_{\mathrm{eq},gg}}{du}\right)\left(\frac{d\xi_\Sigma}{du}\right)}{\xi_\Sigma^3}\right)\xi_{\Sigma,j}$$

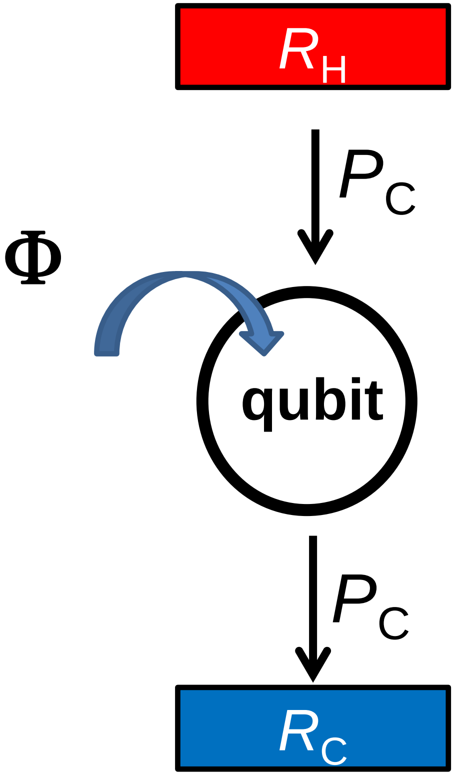
2. Full (quantum) master equation: $\Lambda_j = \Lambda_{j,\mathrm{CL}} + \delta\Lambda_{j,\mathrm{Q}}$

$$\delta\Lambda_{j,\mathrm{Q}} = \frac{1}{\pi}\int_0^{2\pi} du \frac{\Delta^2}{(q^2+\Delta^2)^{3/2}}\left(\frac{dq}{du}\right)^2 \frac{(\xi_\downarrow - \xi_\uparrow)\xi_{\Sigma,j}}{\xi_\Sigma[\xi_\Sigma^2 + 16(q^2+\Delta^2)]} > 0$$

Quantum coherence degrades the performance of the refrigerator

Quantum heat valve

A. Ronzani et al., Nature Physics, to be published (2018).



Alberto Ronzani

Bayan Karimi

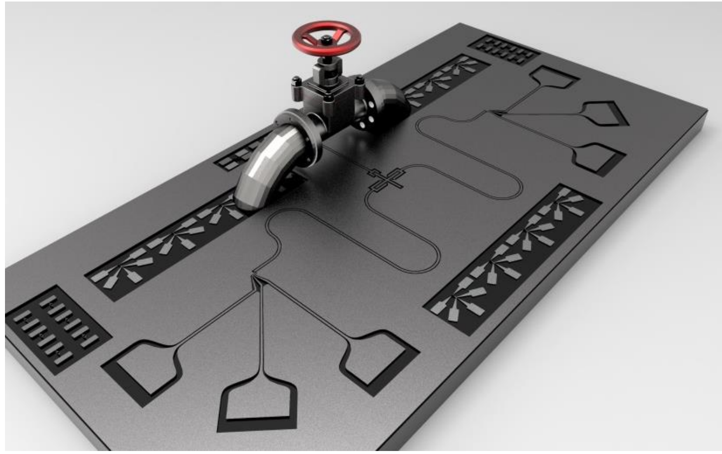
Jorden Senior

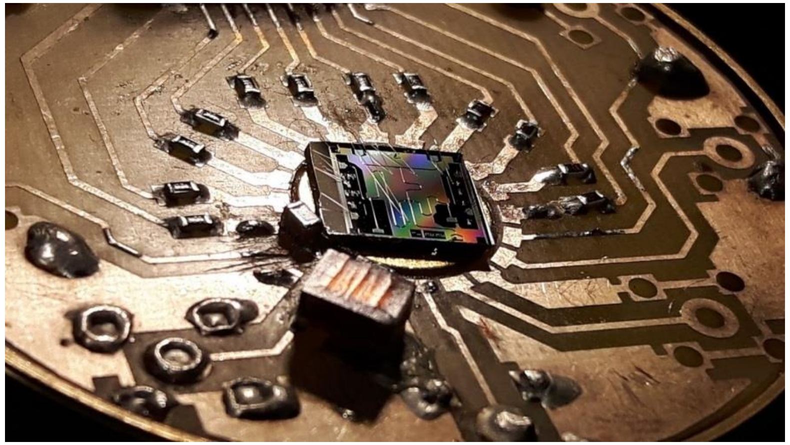
Yu-Cheng Chang

ChiiDong Chen

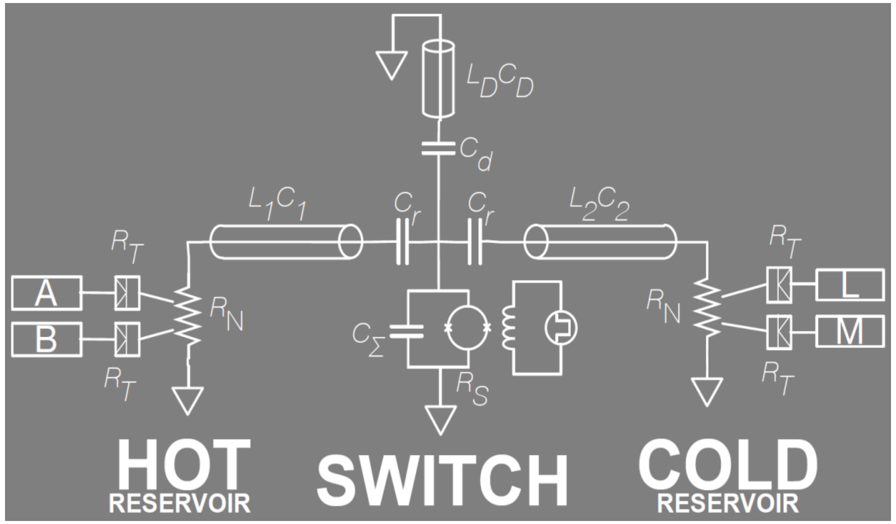
Joonas Peltonen

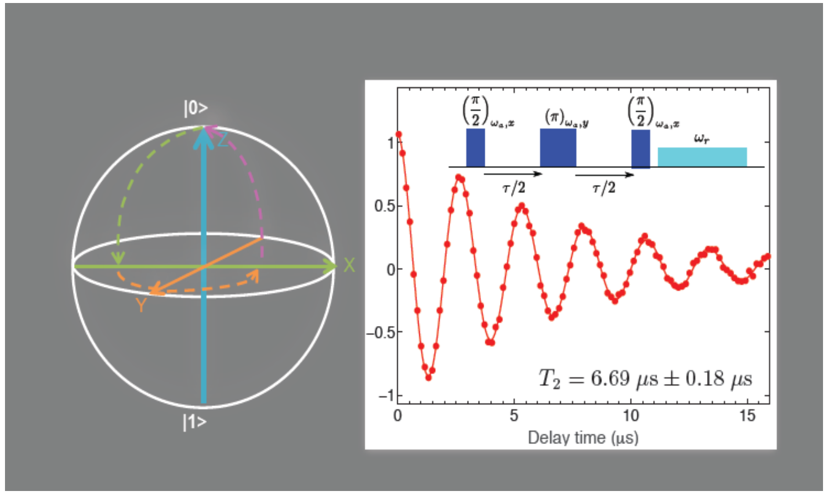
B. Karimi, J. Pekola, M. Campisi, and R. Fazio, Quantum Science and Technology **2**, 044007 (2017).



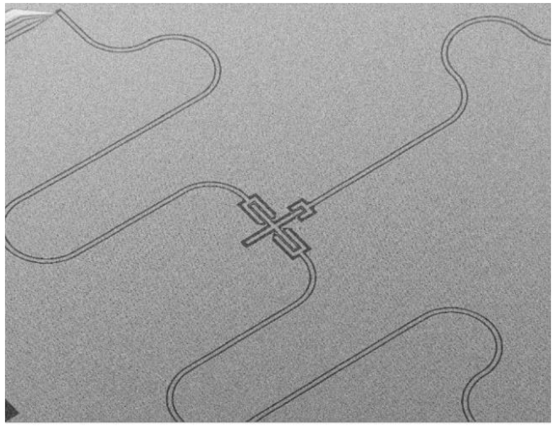


Experimental realization

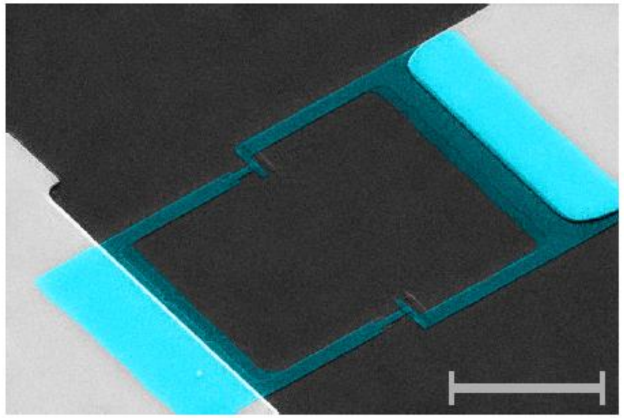




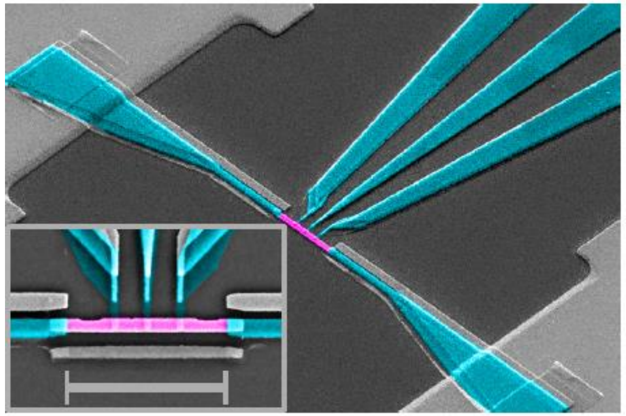
QUBIT WITHOUT ABSORBERS



1 mm



10 μm

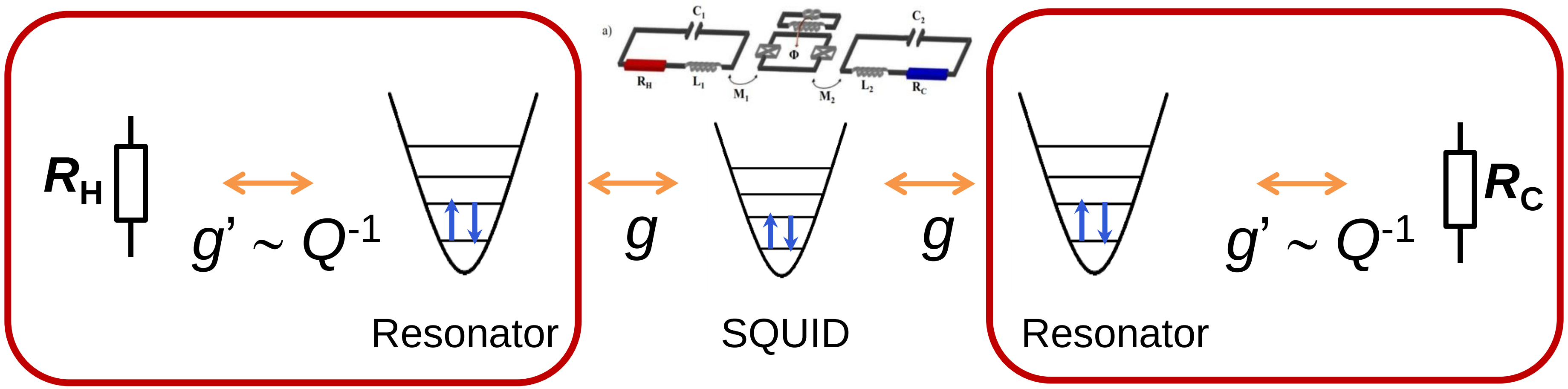


3 μm

TRANSMON QUBIT

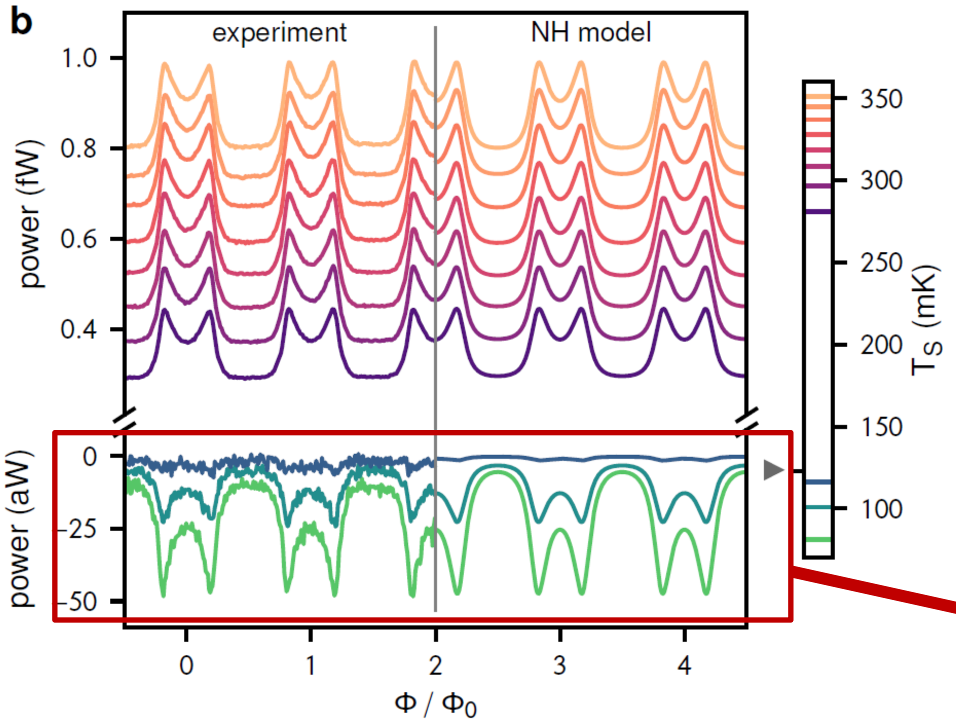
RESERVOIR AND THERMOMETERS

Theory vs experiment: low-Q regime

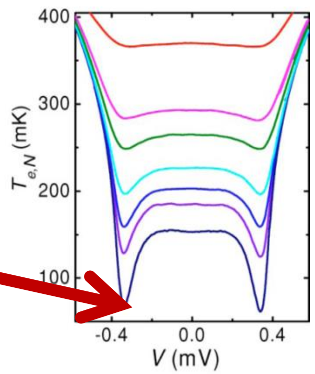


$gQ \ll 1$, ”non-Hamiltonian” model works

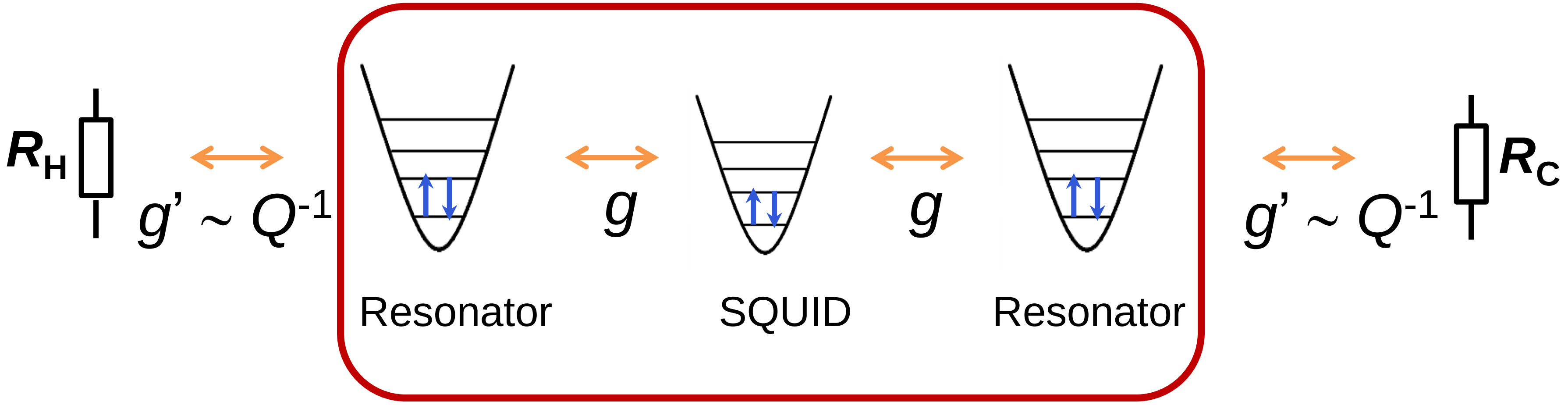
$Q = 3$



Cooling at distance of 4 mm by mw photons

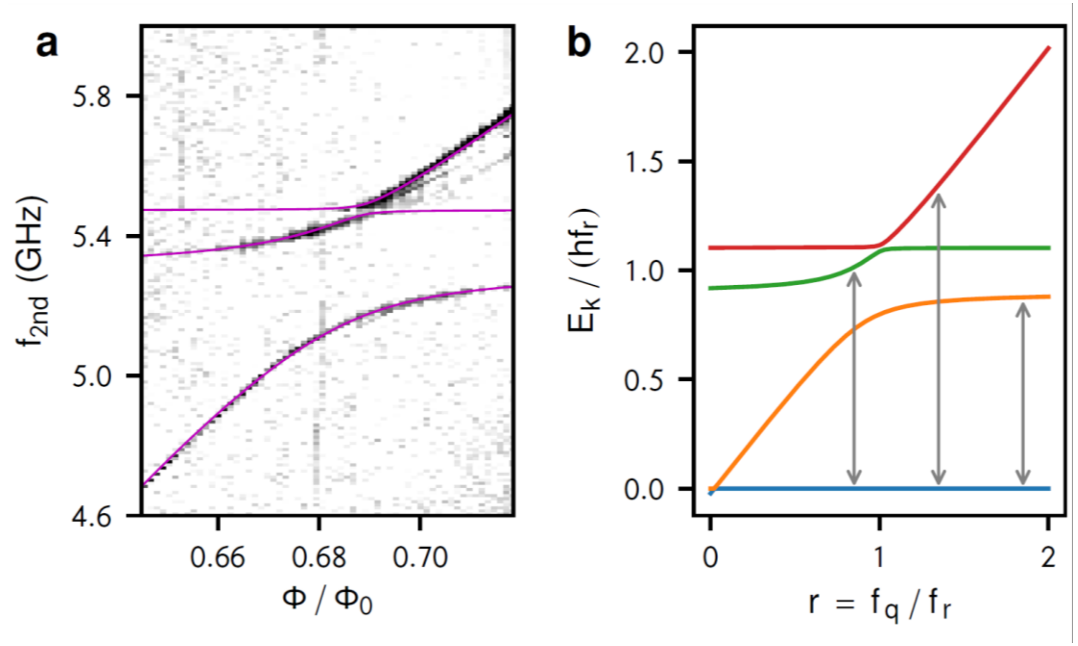


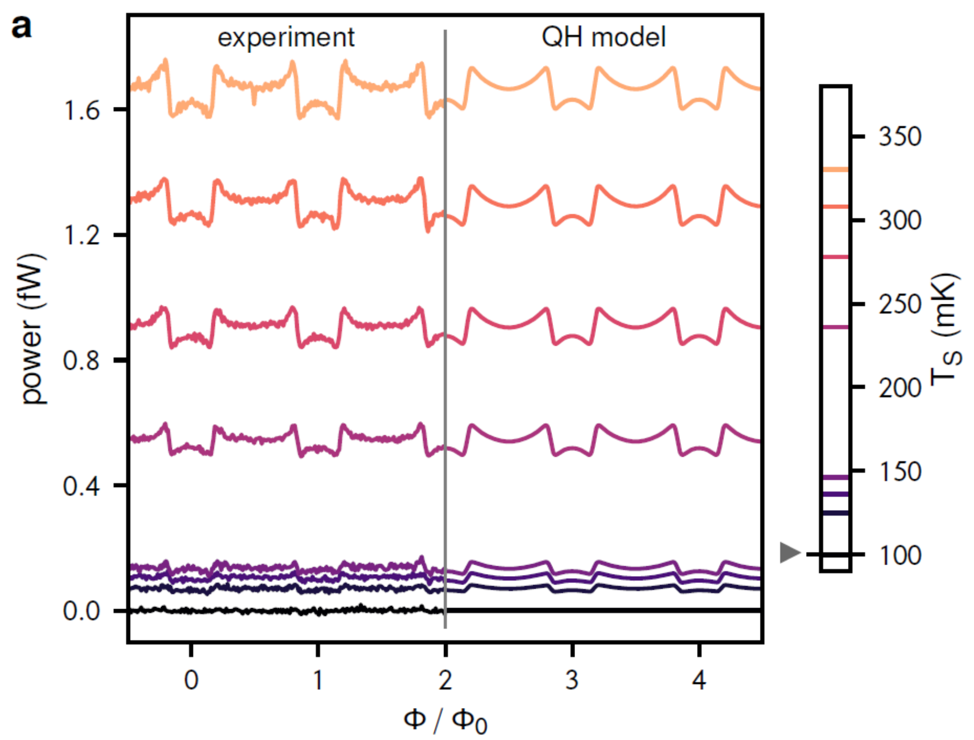
Theory vs experiment: intermediate-Q regime



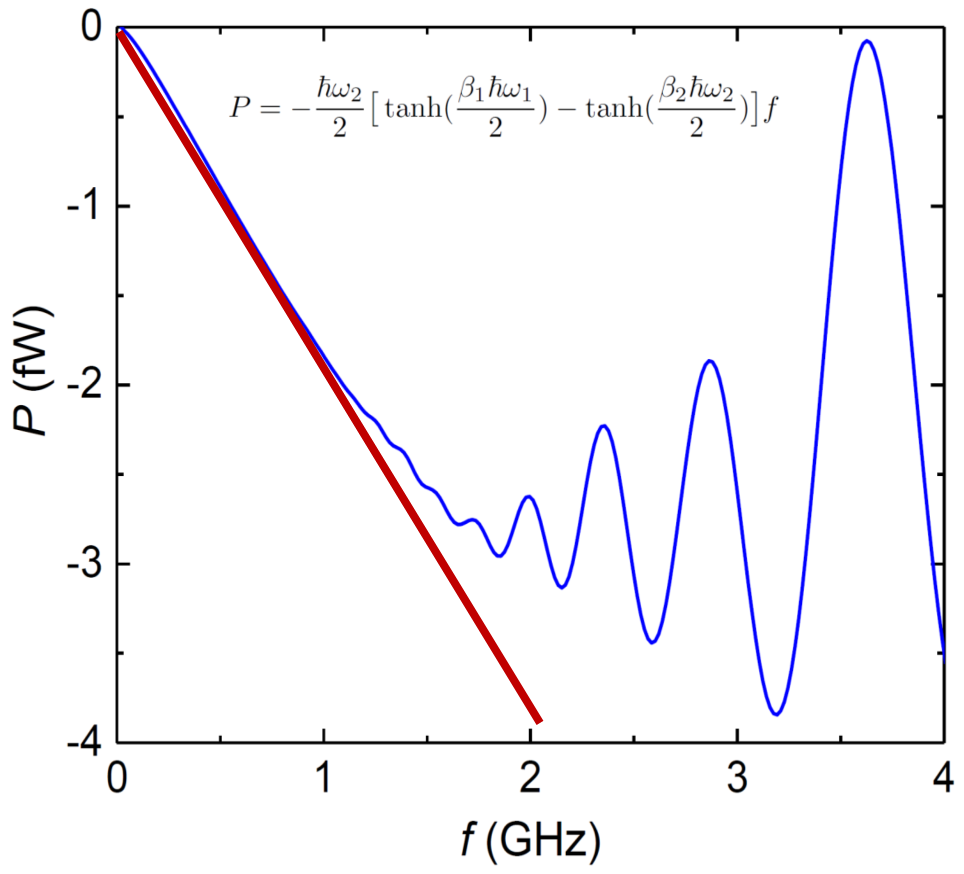
$Q = 20$

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

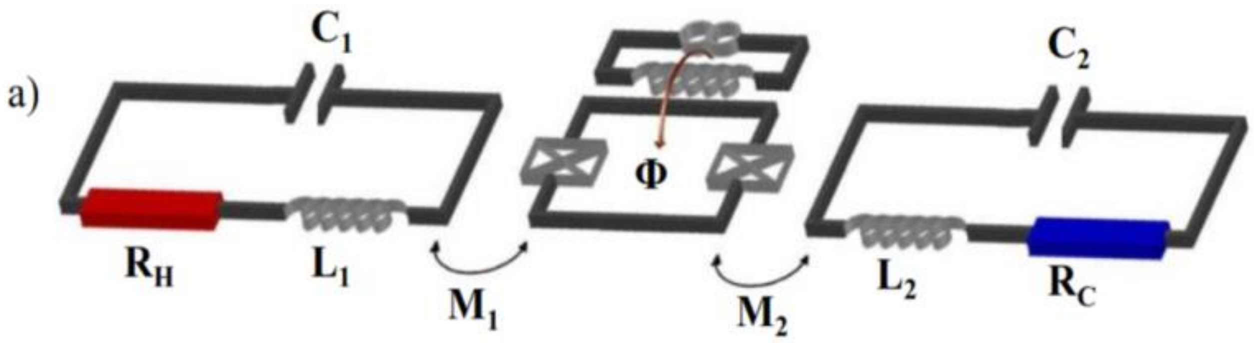


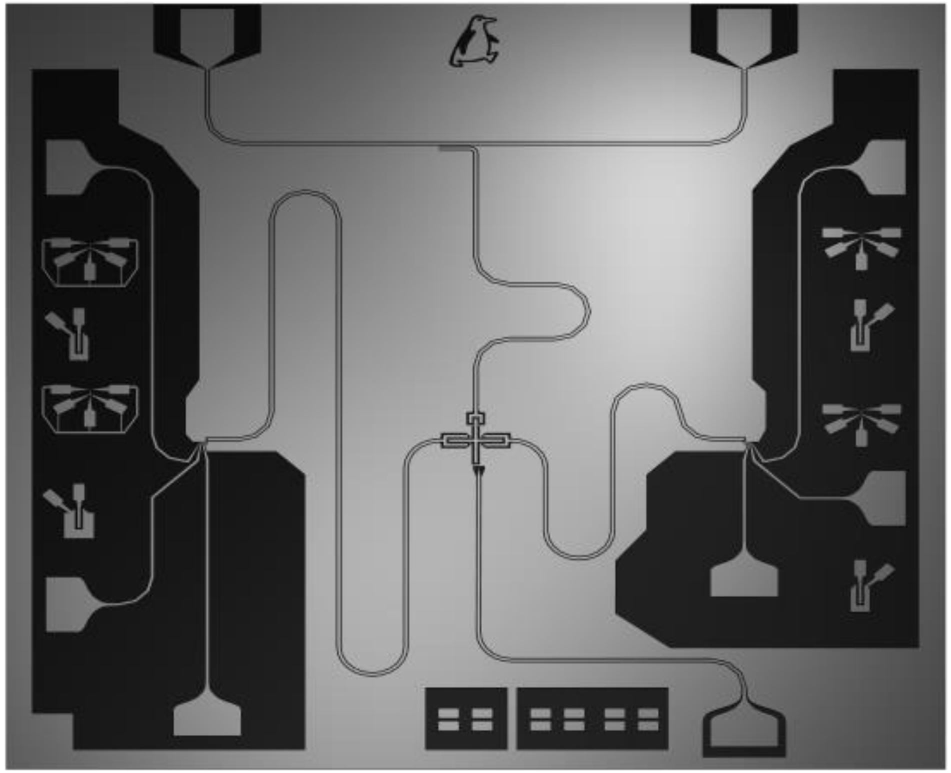


Quantum Otto refrigerator



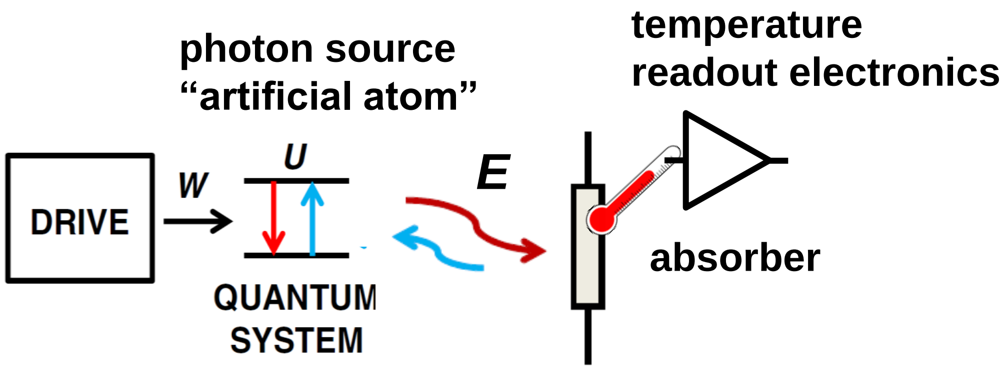
$$P = -\frac{\hbar\omega_2}{2}\left[\tanh\left(\frac{\beta_1\hbar\omega_1}{2}\right) - \tanh\left(\frac{\beta_2\hbar\omega_2}{2}\right)\right] f$$

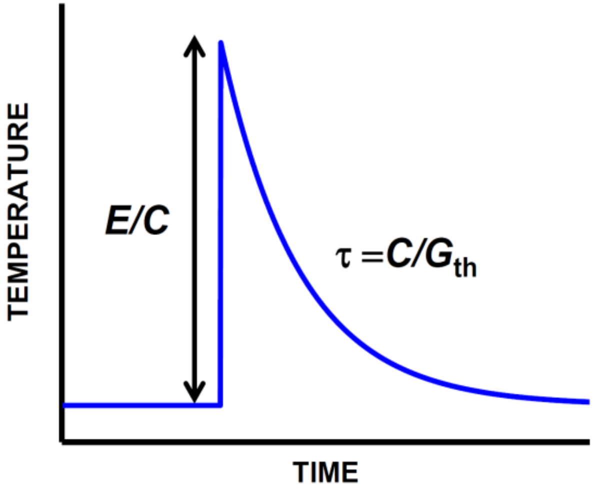


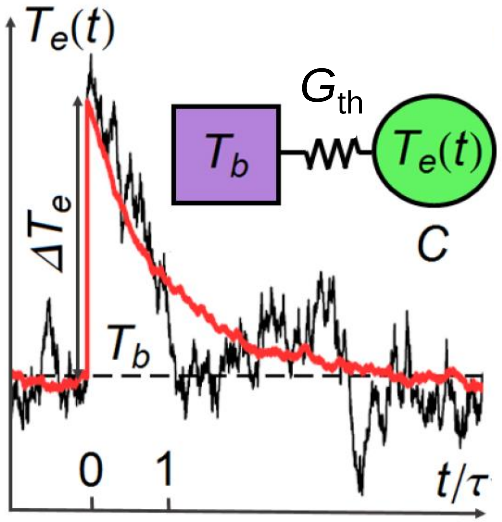


Expect about 1 fW cooling power at 1 GHz driving frequency

Calorimetry for measuring mw photons







Typical parameters

Operating temperature
T = 0.03...0.1 K

E/k_B = 0.3...1 K, C = 300...1000k_B

ΔT ~ 1...3 mK, τ ~ 0.01...1 ms

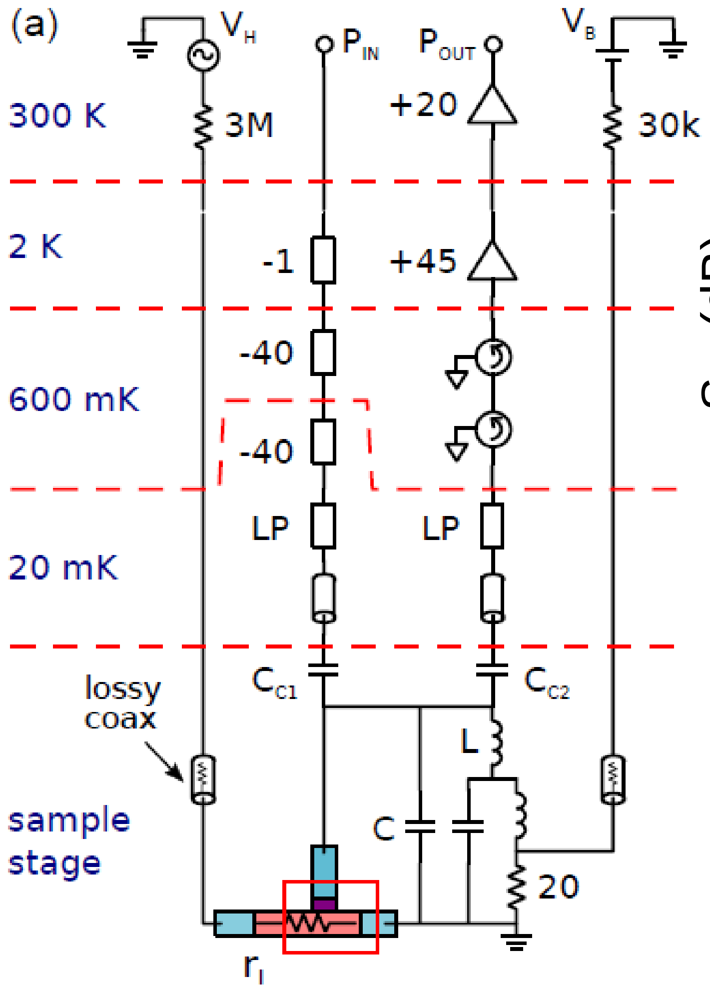
Ideally $\delta E = \sqrt{k_B C}\, T$

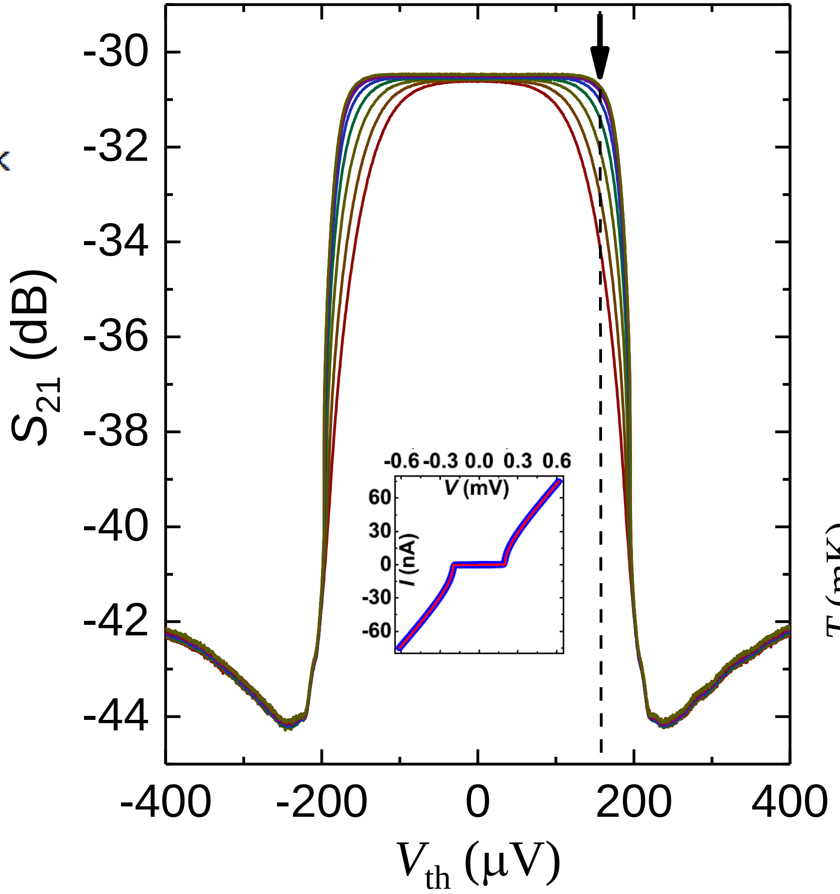
Fast NIS thermometry on electrons

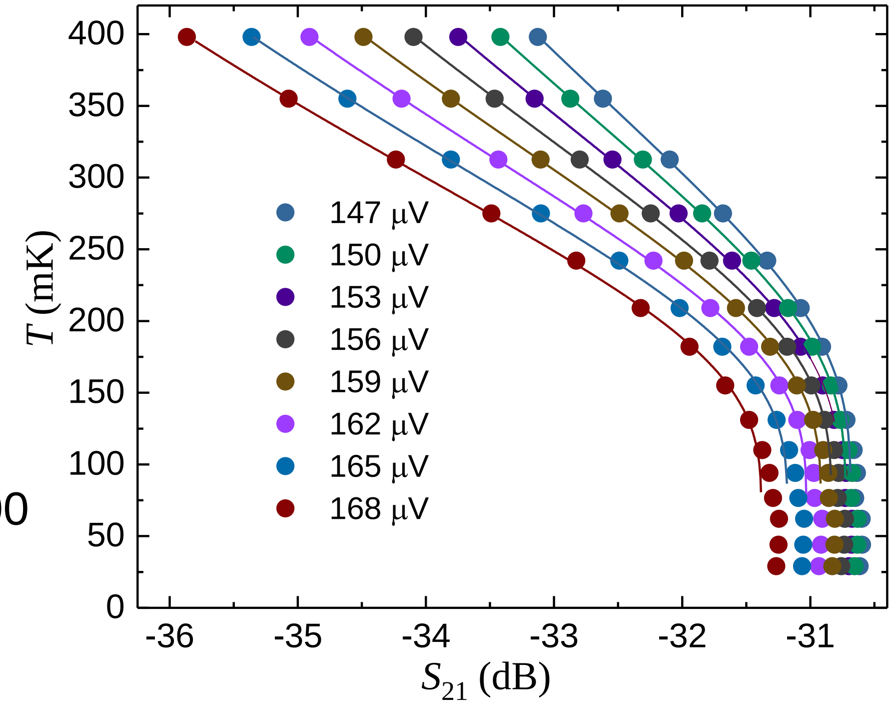
Read-out at 600 MHz of a NIS junction, 10 MHz bandwidth

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

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

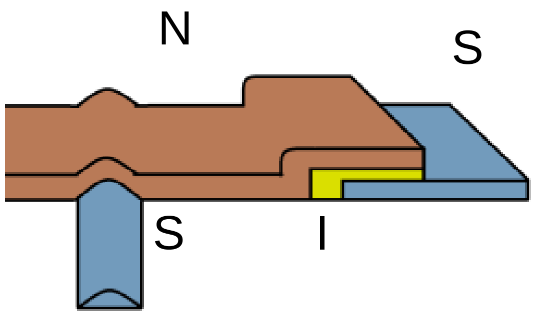




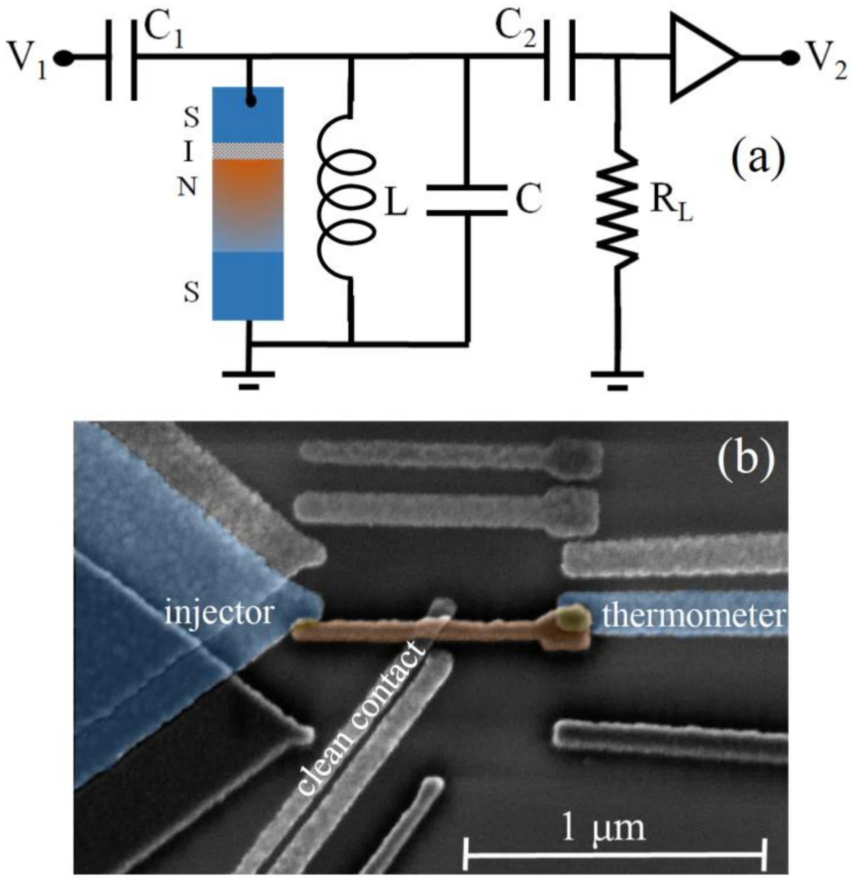


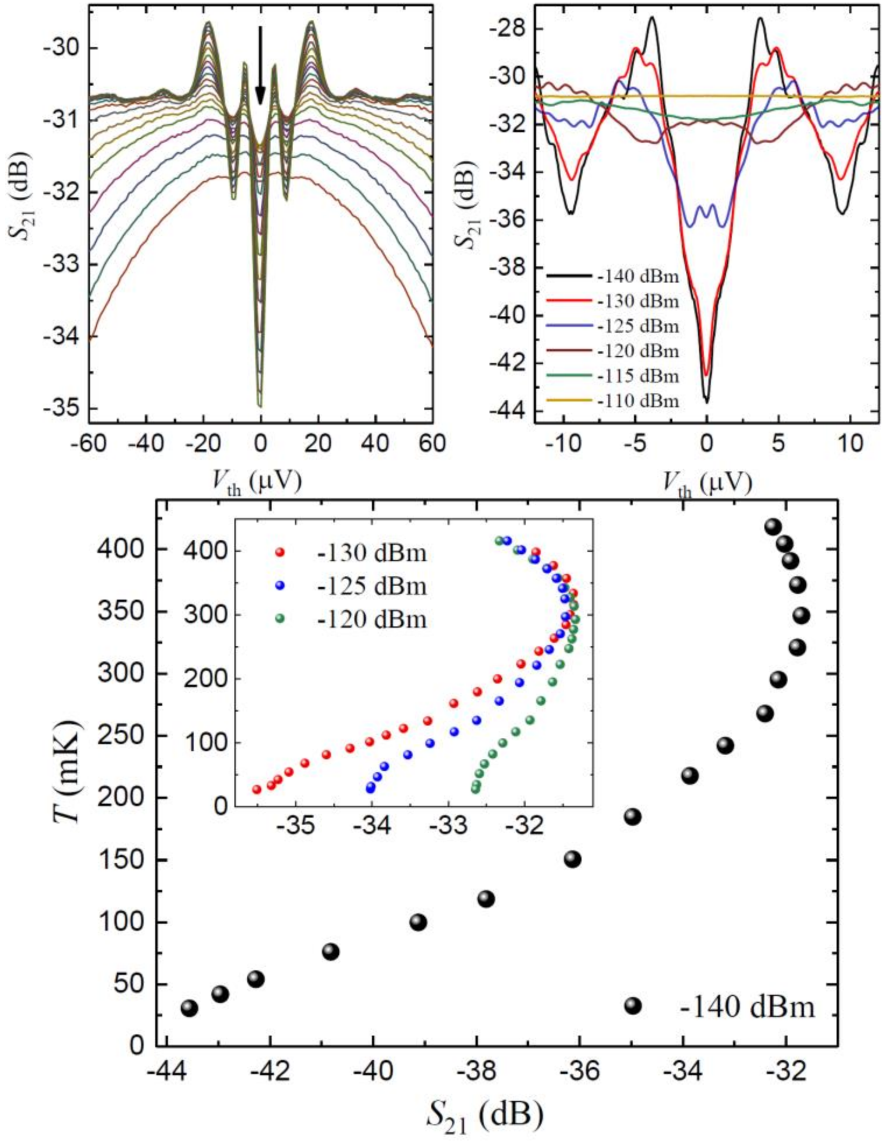
ZBA based thermometry

B. Karimi and JP, in preparation



Proximity NIS junction

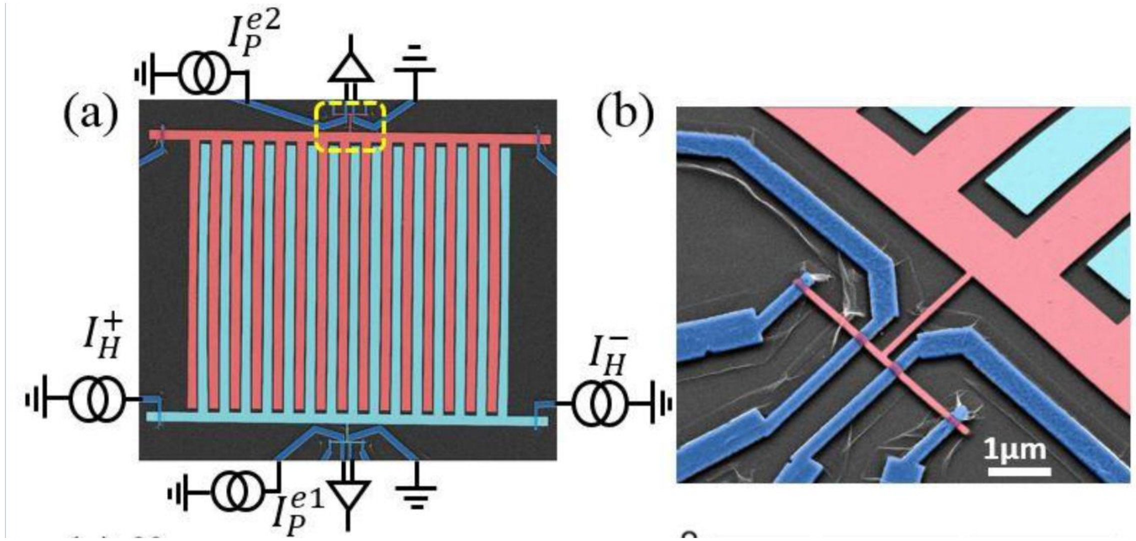


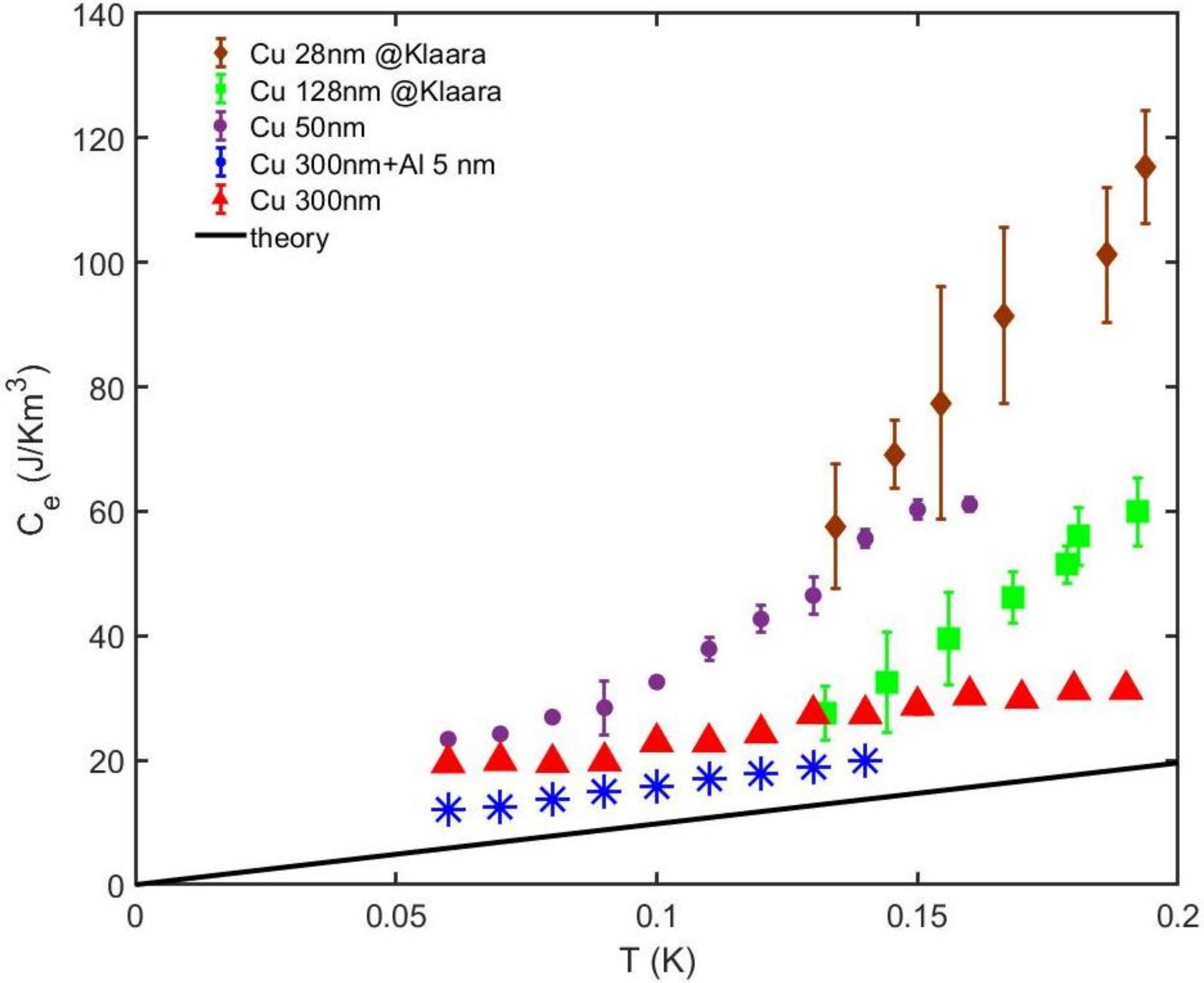


- non-invasive
- operates at low temperature

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

Heat capacity of copper films





Measurement by time-resolved SNS and NIS thermometry

Libin Wang, Klaara Viisanen, O.-P. Saira

Requirements for single microwave photon detection

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

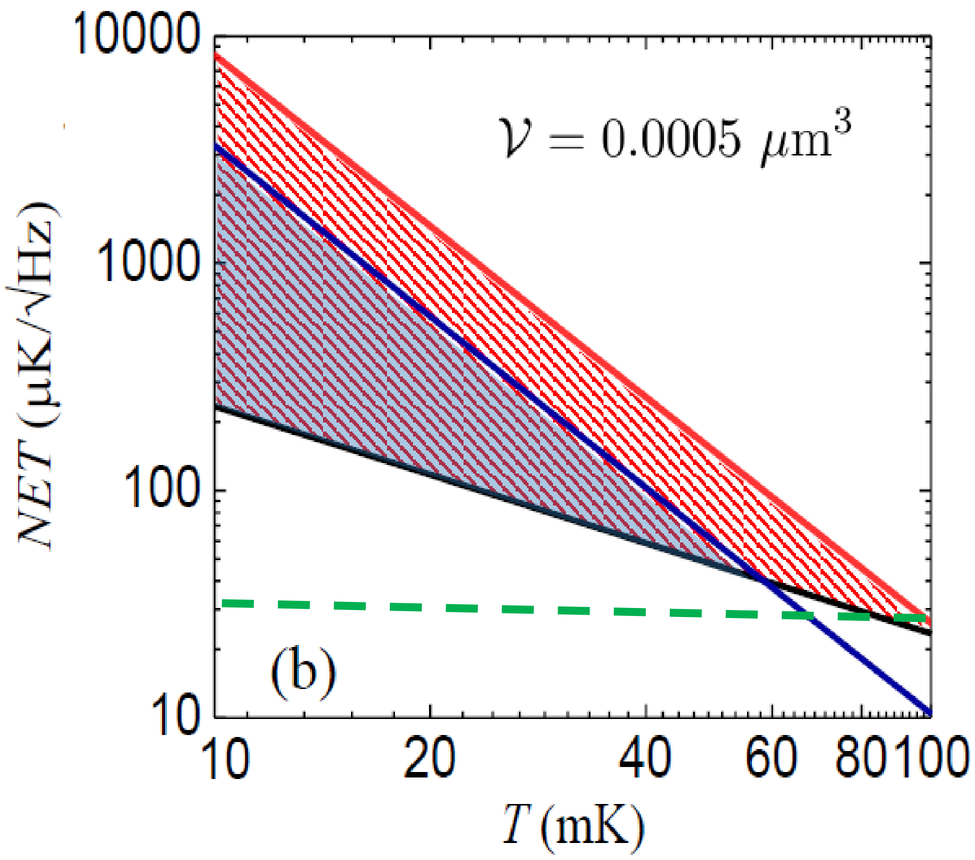
$$\langle \delta T^2 \rangle = \int_{-\infty}^{\infty} \frac{d\omega}{2\pi} S_T(\omega) = k_B T^2 / C$$

Noise-equivalent temperature, NET

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

Lines:

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



Standard copper absorber

Summary

Discussed:

stochastic thermodynamics in single-electron circuits
open quantum systems based on superconducting qubits
thermometry
quantum heat switch based on a superconducting qubit
plans for quantum heat engines and single-photon detection

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Université Grenoble Alpes Foundation

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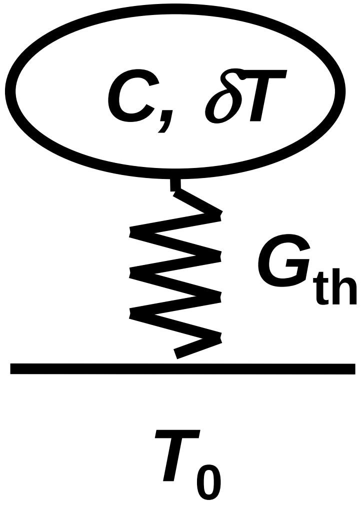
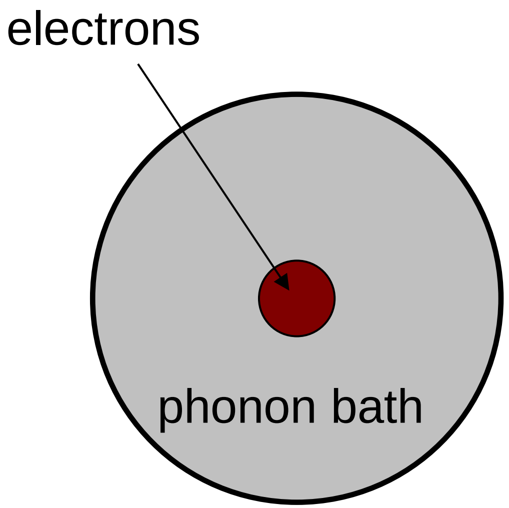
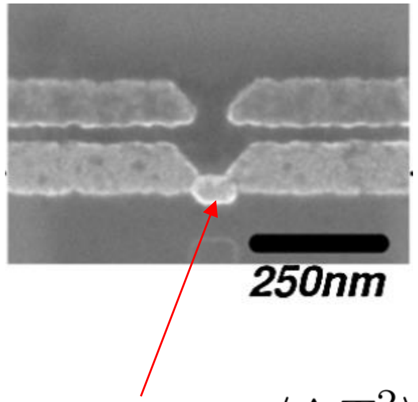
Temperature fluctuations







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

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

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

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

Heat transported between two resistors

Radiative contribution to net heat flow between electrons of 1 and 2:

$$P_\nu = \int_0^\infty \frac{d\omega}{2\pi}\left[S_{P12}(\omega) - S_{P21}(\omega)\right] = r\frac{\pi k_B^2}{12\hbar}(T_1^2 - T_2^2)$$

Coupling constant:

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

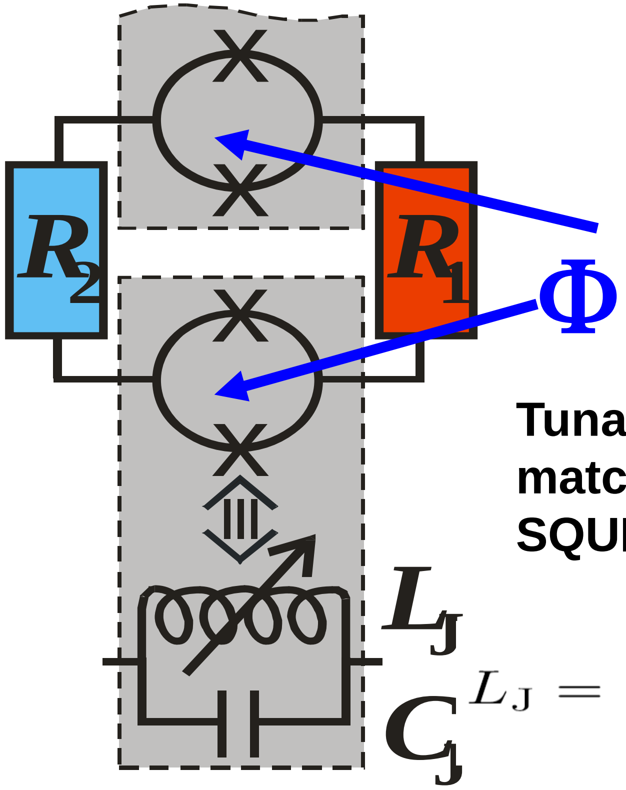
Linearized expression for small temperature difference $\Delta T = T_1 - T_2$:

$$P_\nu = rG_Q\Delta T$$

$$G_\nu = rG_Q$$

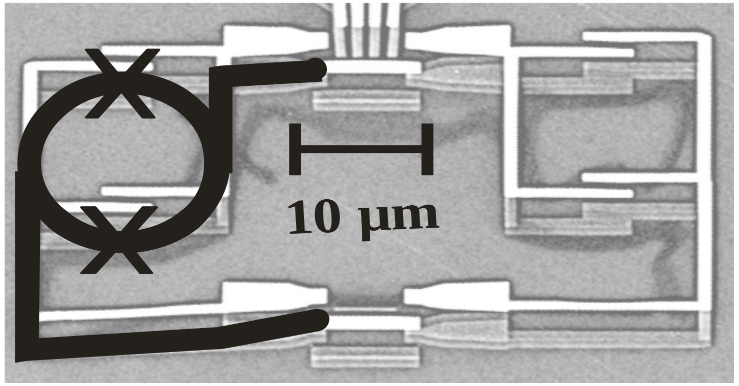
$$G_Q = \frac{\pi k_B^2}{6\hbar}T$$

Photonic heat transport

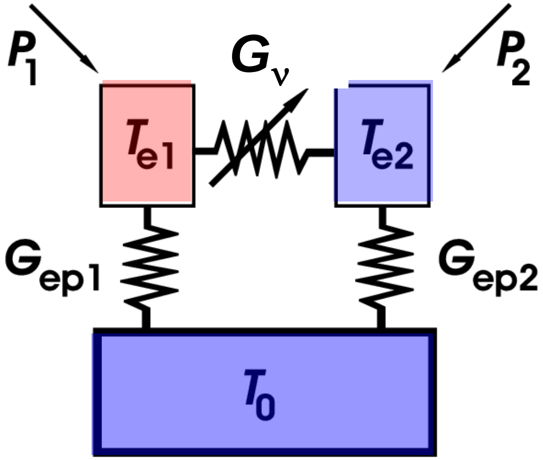


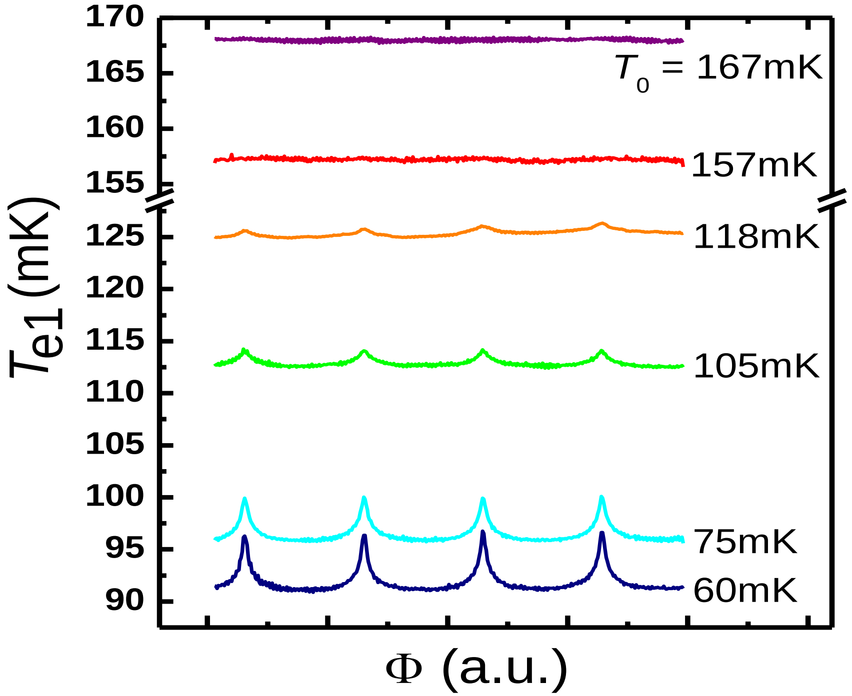
Tunable impedance matching using DC-SQUIDs

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



Thermal model





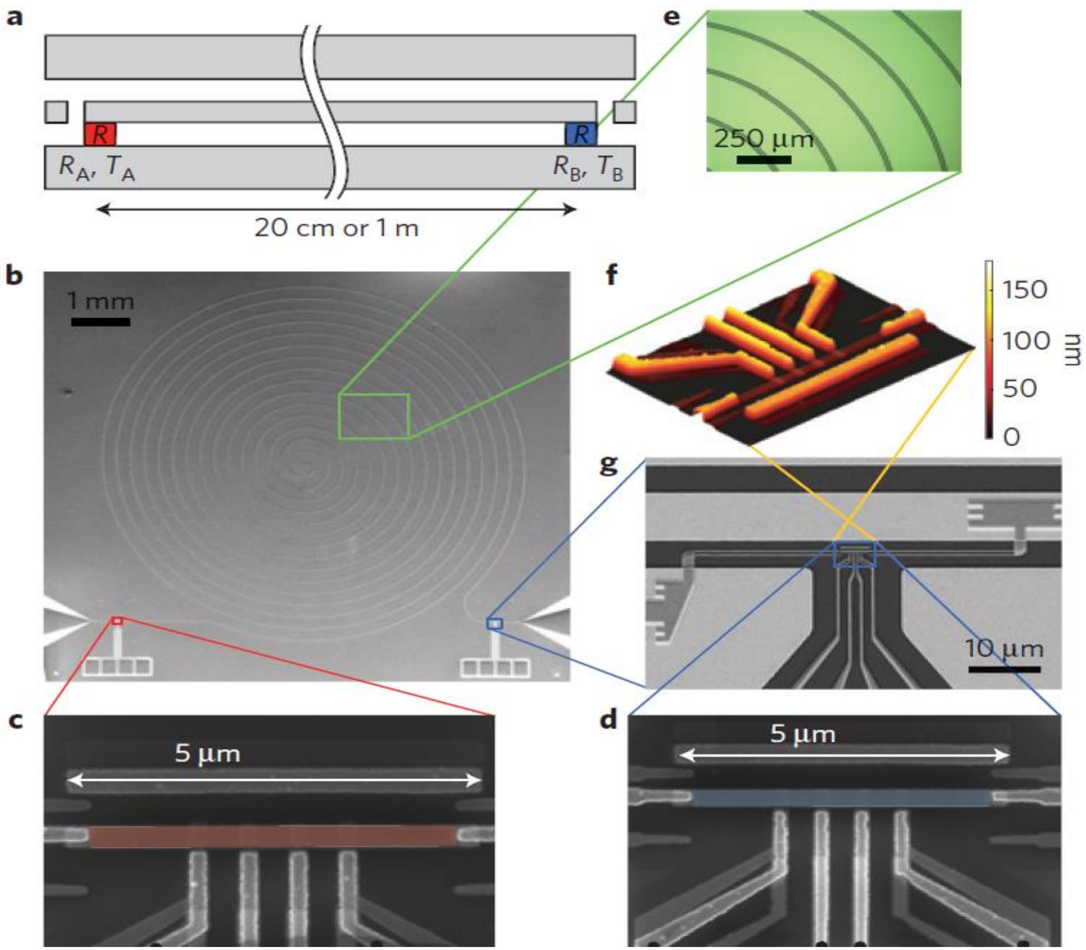
M. Meschke, W. Guichard and JP, Nature 444, 187 (2006)

”Quantum” of heat transport

$$G_{\mathrm{Q}} = \frac{\pi k_{\mathrm{B}}^2}{6\hbar} T$$

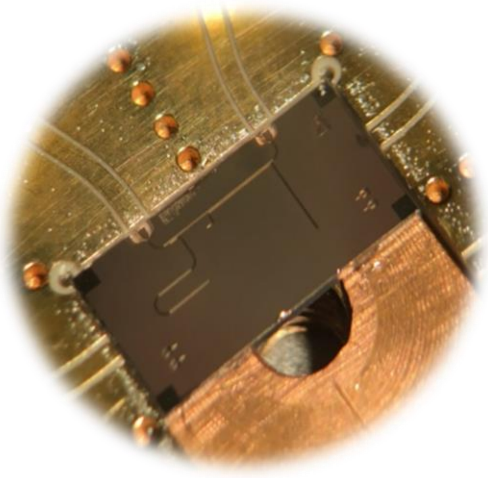
Schmidt et al., PRL 93, 045901 (2004)

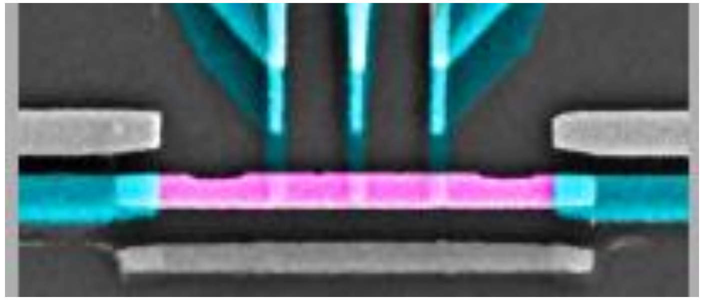
Timofeev et al., PRL 102, 200801 (2009)



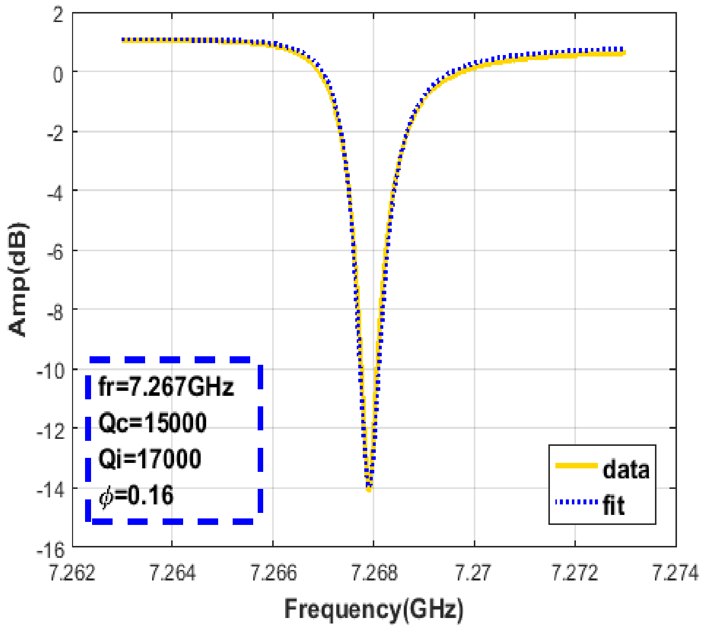
M. Partanen et al., Nature Physics 12, 460 (2016).

Shunted λ / 4 resonators, measurement of *Q*

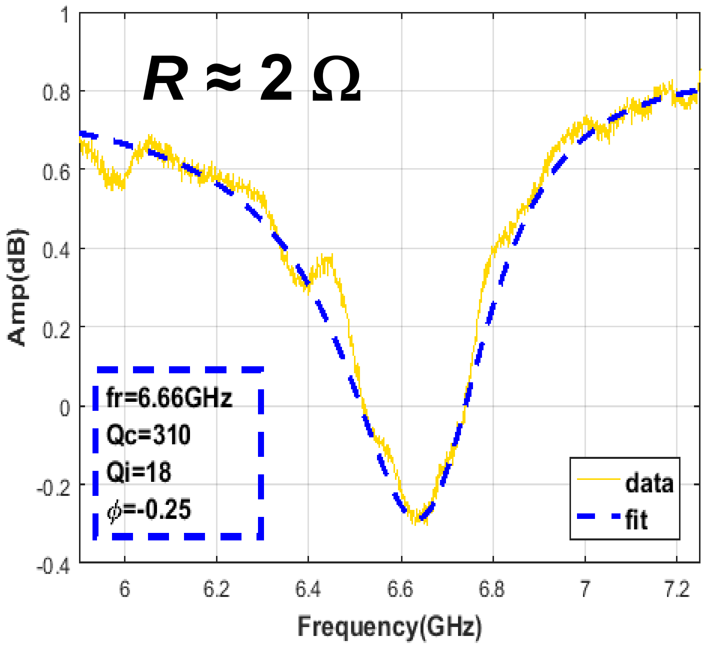




$$Q = \pi Z_0 / 4R$$



Superconducting shunt, Q = 17 000

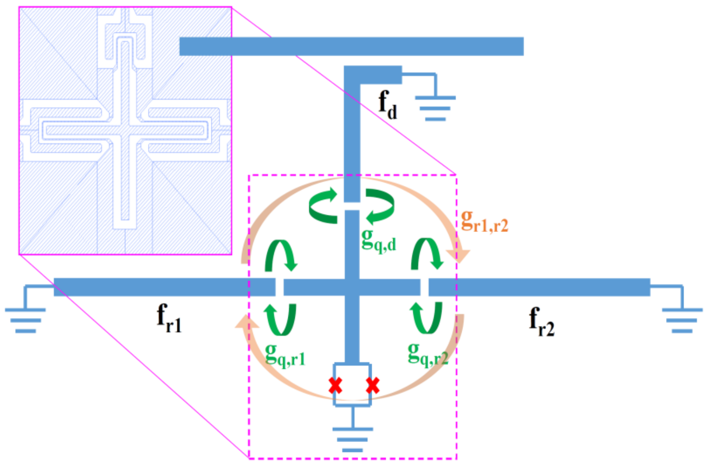


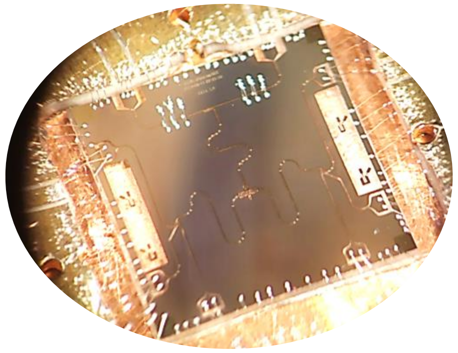
Normal (copper) shunt, Q = 18

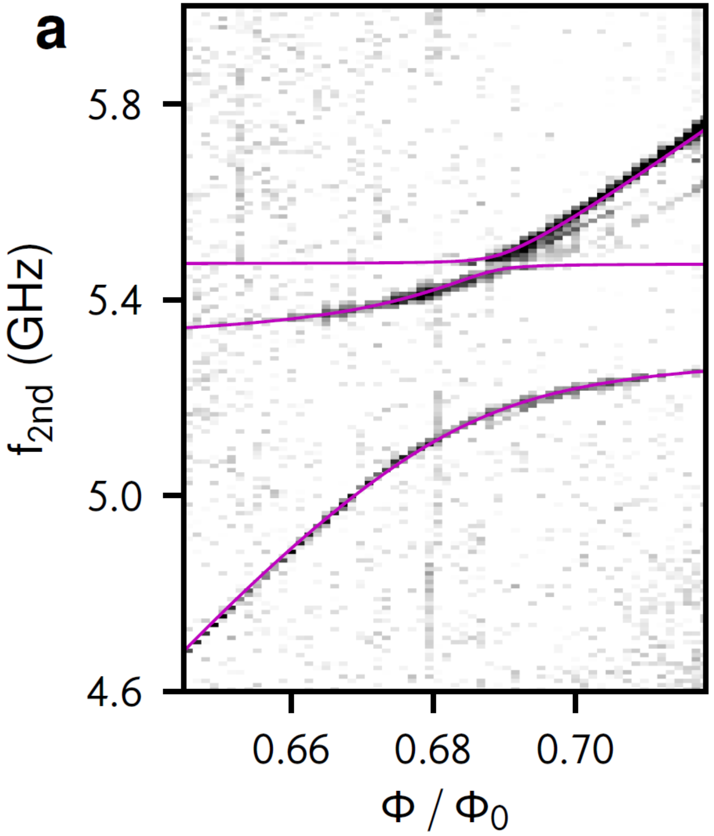
Yu-Cheng Chang et al., in preparation

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

Spectroscopy to determine circuit parameters







Two tone spectroscopy

$$\hat{H} = h f_r \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 + a/2 & g & \tilde{g} \\ 0 & g & r & g \\ 0 & \tilde{g} & g & 1 - a/2 \end{pmatrix}$$

$r = f_{qubit}/f_r$

f_r = 5.39 GHz

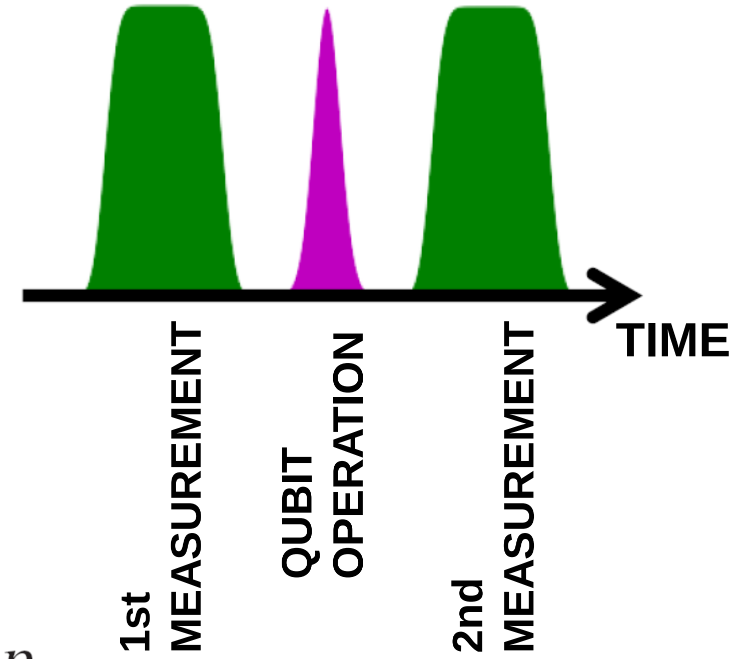
g = 0.020

$\tilde{g}$ = - 0.015

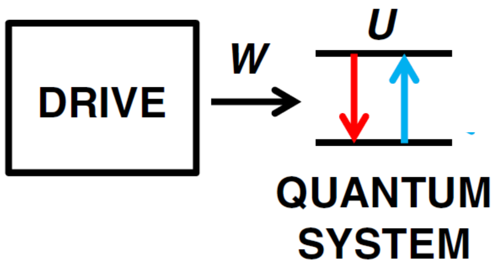
a = 0.008

Work measurement in a quantum system

Two-measurement protocol (TMP):



$W = E_f - E_i$



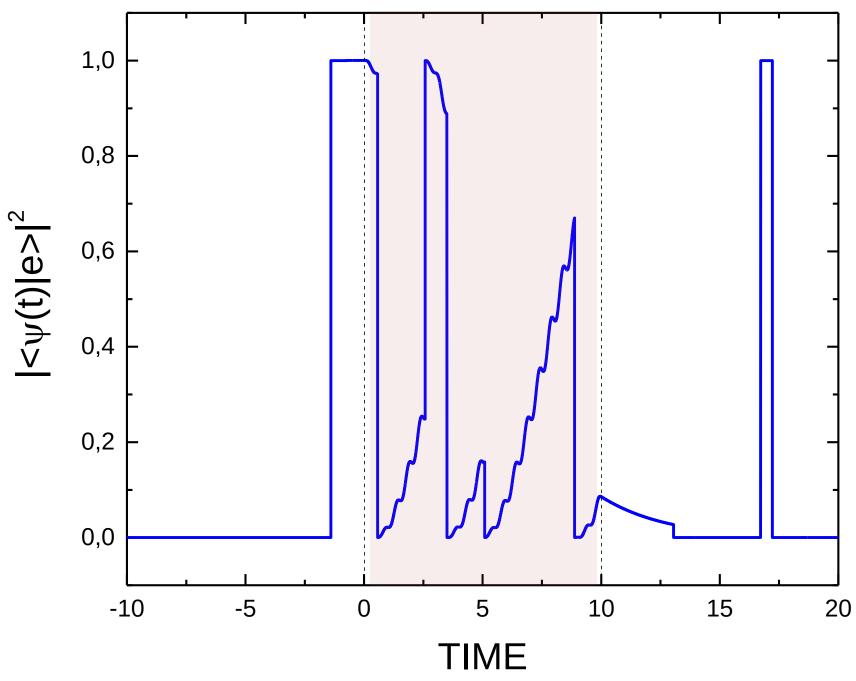
$$p(w) = \sum_{n,m} \delta(w - [e_m(t_f) - e_n(0)])p(m, t_f|n)p_n$$

Kurchan 2000, Talkner et al. 2007

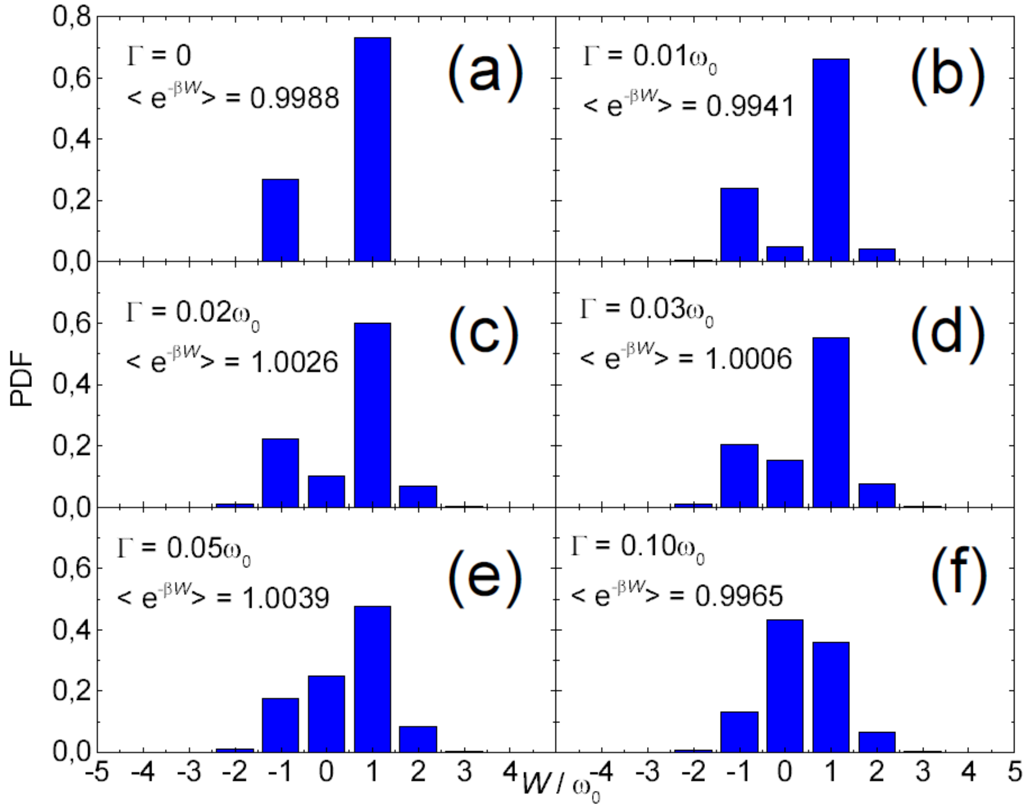
Since $W = \Delta U + Q$, and $\Delta U = E_f - E_i$, this measurement works only for a closed system

Quantum jump approach for analyzing distribution of dissipation

We apply the jump method to a driven qubit



π pulse with dissipation

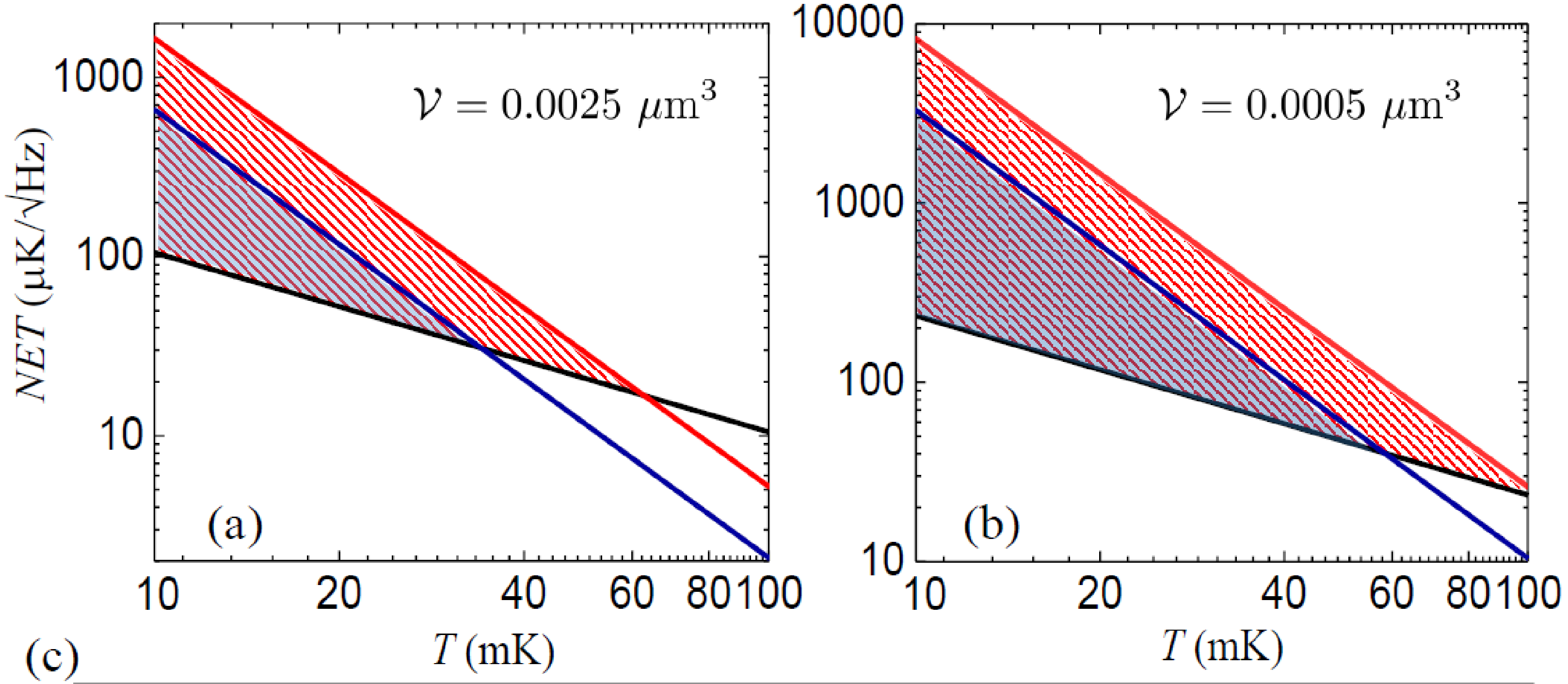


F. Hekking and JP, PRL 111, 093602 (2013).

Common fluctuation relations (Crooks, Jarzynski) are satisfied

$$p_F(W_d)/p_R(-W_d) = e^{\beta W_d} \qquad \langle e^{-\beta W_d} \rangle = 1$$

Requirements for single microwave photon detection



Standard copper absorber

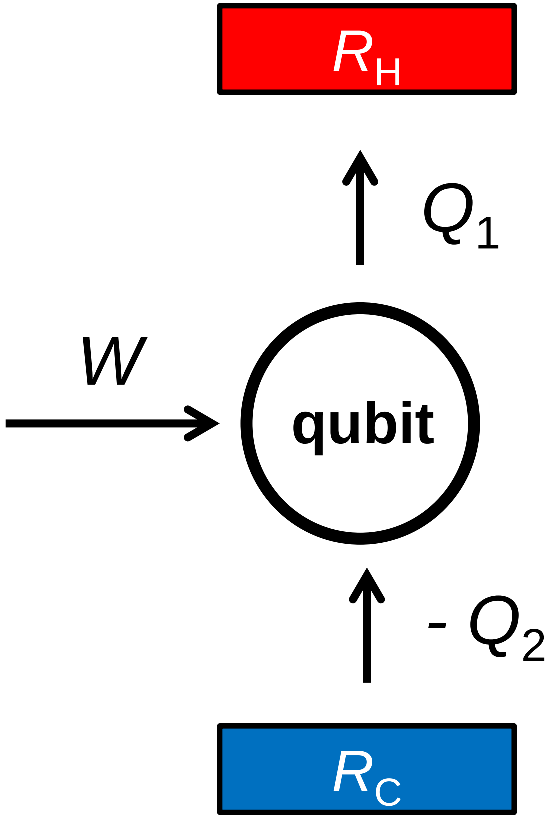
(c)

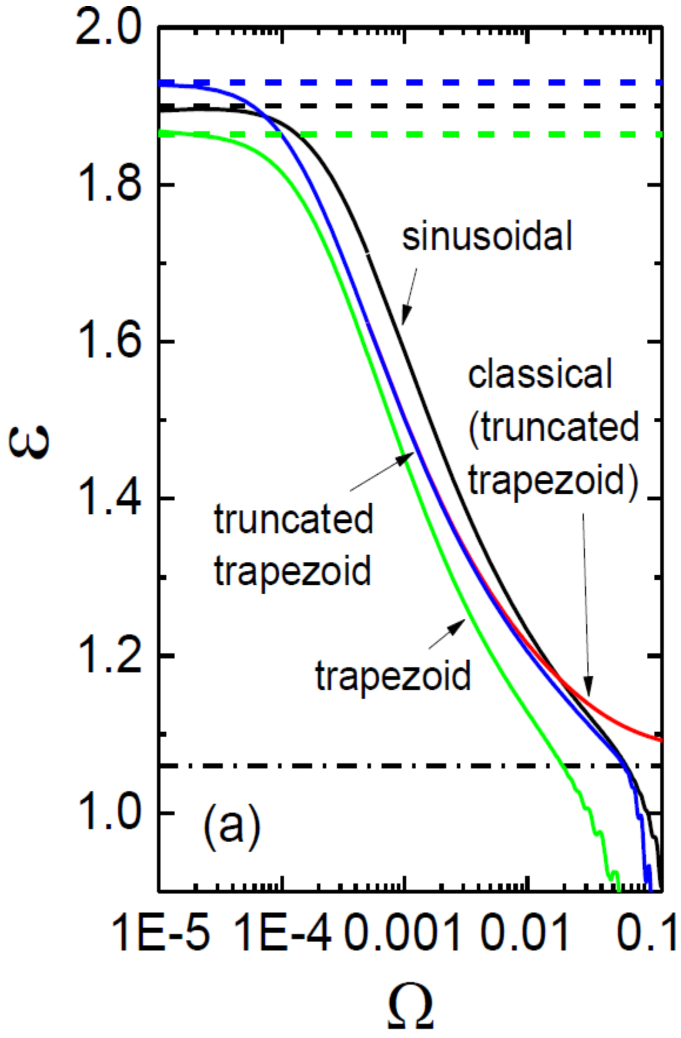
Sample	T (mK)	$\mathcal{V}$ (μm^3)	$\mathbb{NET}_0$	$\mathbb{NET}^{e}_{req}$ (μK/$\sqrt{\text{Hz}}$)	$\mathbb{NET}^{ph}_{req}$	$(\mathbb{S}/\mathbb{N})_e$	$(\mathbb{S}/\mathbb{N})_{ph}$
B	130	0.005	5.7	1.4	0.5	0.2	0.1
A	50	0.0025	21	30	12	1.4	0.6
A	25	0.0025	42	170	67	4.0	1.6
Opt	10	0.0005	235	8250	3300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

Efficiency (COP) of the quantum Otto refrigerator

$$\epsilon = -Q_2/W \;= -Q_2/(Q_1+Q_2)$$

$$\epsilon_C = 1/(T_H/T_C - 1)$$





$$\epsilon_p = \frac{1}{\Lambda_1/|\Lambda_2| - 1}$$

$$\epsilon_{\rm ideal} = \frac{1}{\omega_1/\omega_2 - 1}$$