Autonomous Maxwell's demon in a cavity QED system

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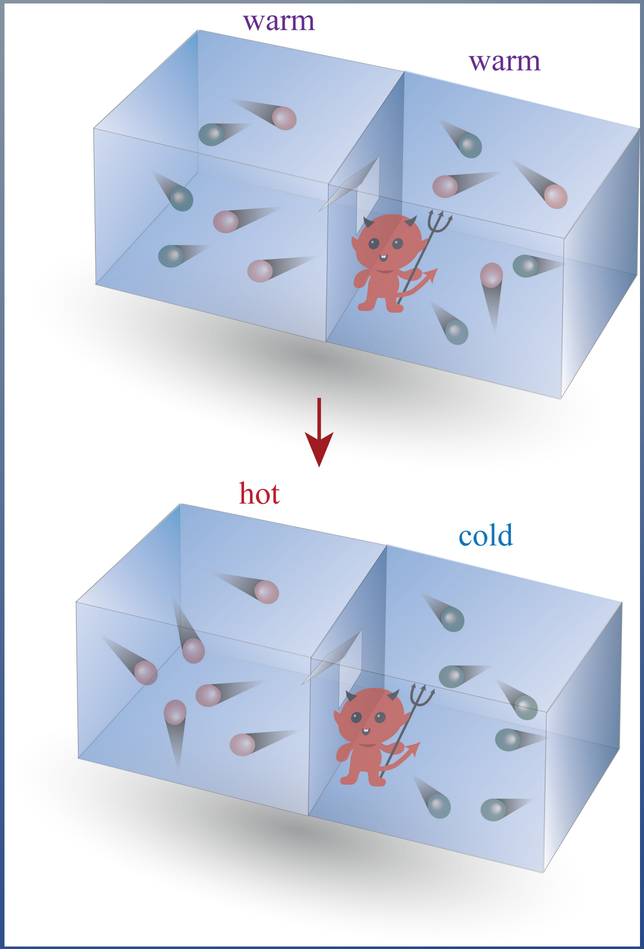
Maxwell's Demon



J. C. Maxwell, Theory of Heat 4th edition, London: Longmans, Green, and Co. (1875).

Statistical character of the second law

To the left: molecules faster than a threshold

To the right: molecules slower than a threshold

Sufficient control would “violate” the second law

Modern standpoint:

Information acquisition = Measurement

Feedback control = Conditional evolution

Experimental Implementations

On-Chip Maxwell's Demon as an Information-Powered Refrigerator

J. V. Koski,[1] A. Kutvonen,[2] I. M. Khaymovich,[1,3] T. Ala-Nissila,[2,4] and J. P. Pekola[1]

SEB (2015)

Experimental Rectification of Entropy Production by Maxwell's Demon in a Quantum System

Patrice A. Camati,[1] John P. S. Peterson,[2] Tiago B. Batalhão,[1] Kaonan Micadei,[1] Alexandre M. Souza,[2] Roberto S. Sarthour,[2] Ivan S. Oliveira,[2] and Roberto M. Serra[1,3,*]

NMR (2016)

Photonic Maxwell's Demon

Mihai D. Vidrighin,[1,2] Oscar Dahlsten,[2,3,*] Marco Barbieri,[4,2] M. S. Kim,[1] Vlatko Vedral,[2,5] and Ian A. Walmsley[2]

Optical (2016)

Observing a quantum Maxwell demon at work

Nathanaël Cottet[a,1], Sébastien Jezouin[a,1], Landry Bretheau[a], Philippe Campagne-Ibarcq[a], Quentin Ficheux[a], Janet Anders[b], Alexia Auffèves[c], Rémi Azouit[d,e], Pierre Rouchon[d,e], and Benjamin Huard[a,f,2]

CQED (2017)

Information-to-work conversion by Maxwell's demon in a superconducting circuit quantum electrodynamical system

Y. Masuyama[1], K. Funo[2], Y. Murashita[3], A. Noguchi[1], S. Kono[1], Y. Tabuchi[1], R. Yamazaki[1], M. Ueda[3,4] & Y. Nakamura[1,4]

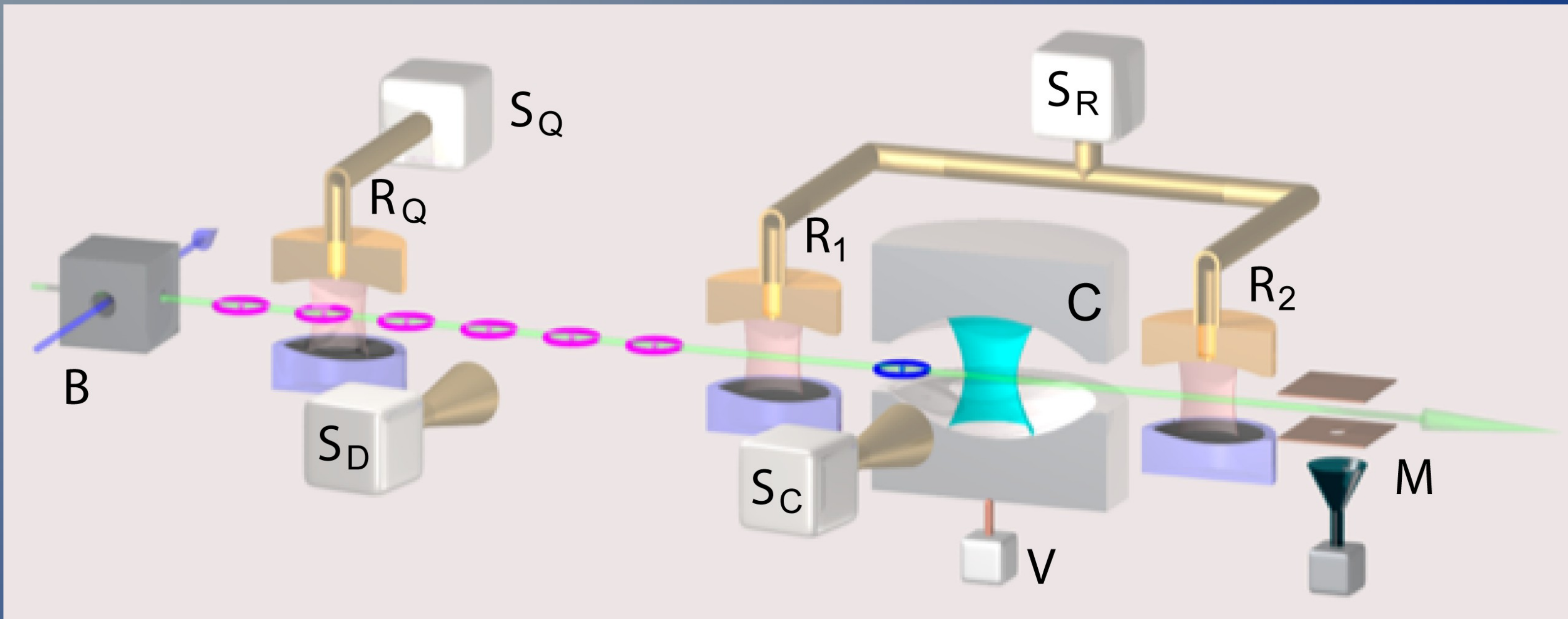
CQED (2018)

Information Gain and Loss for a Quantum Maxwell's Demon

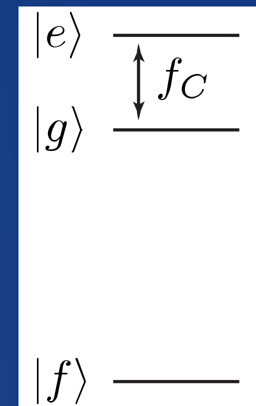
M. Naghiloo,[1] J. J. Alonso,[2] A. Romito,[3] E. Lutz,[2,4] and K. W. Murch[1,5,*]

CQED (2018)

Cavity QED setup (2020)



Structure Rydberg atoms



Average photon number

$\overline{n}_{th} = 0.63 \pm 0.04$

Resonance frequency

$f_C = 51 \text{ GHz}$

Atomic relaxation time

$\Gamma_a^{-1} \approx 30 \text{ ms}$

Thermal field temperature

$T_C = 2.6 \pm 0.1 \text{ K}$

Rabi frequency

$\Omega_0 = 2\pi \times 77 \text{ kHz}$

Total travel time

$\tau \approx 100\ \mu\text{s}$

Protocol without demon

The qubit and the cavity exchange energy through the interaction map

$$H^{QC}(t) = -\frac{\hbar\omega}{2}\sigma_z + \hbar\omega a^\dagger a + V(t)$$

Interaction map U^{QC}

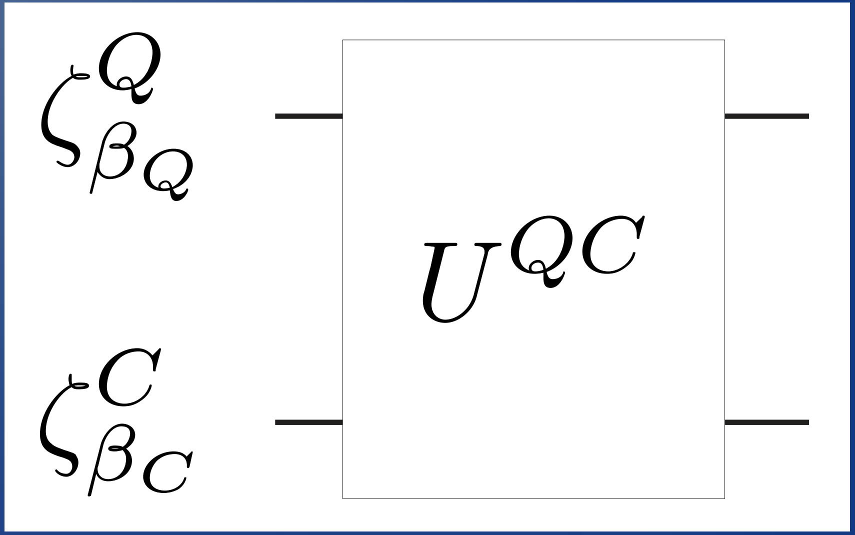
$$|1, n\rangle \longrightarrow |0, n+1\rangle$$

$$|0, n+1\rangle \longrightarrow |1, n\rangle$$

$$|0, 0\rangle \longrightarrow |0, 0\rangle$$

Single-energy quanta exchange

The protocol is



Features without demon

Entropy production (average)

$$\langle \Sigma \rangle = \beta_Q \mathcal{Q}_Q + \beta_C \mathcal{Q}_C$$

$$\Delta\beta = \beta_C - \beta_Q$$

Energy conservation

$$\mathcal{Q}_C = -\mathcal{Q}_Q$$

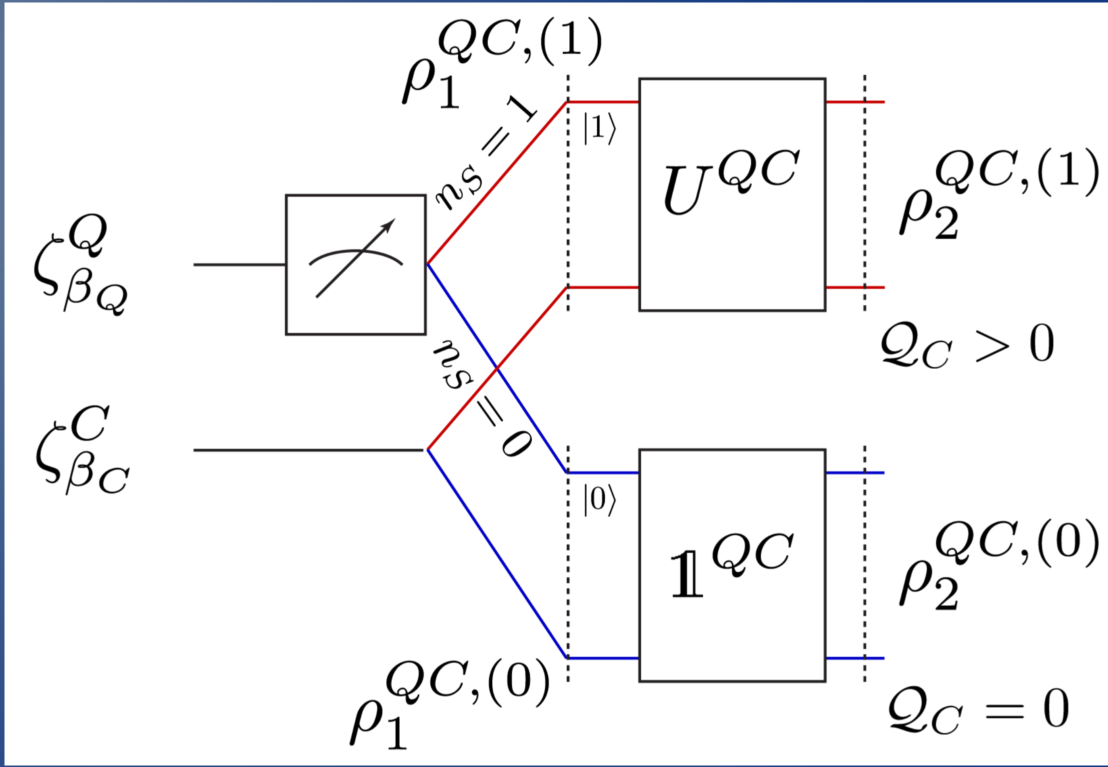
Second law

$$\langle \Sigma \rangle = \Delta\beta \mathcal{Q}_C \geq 0$$

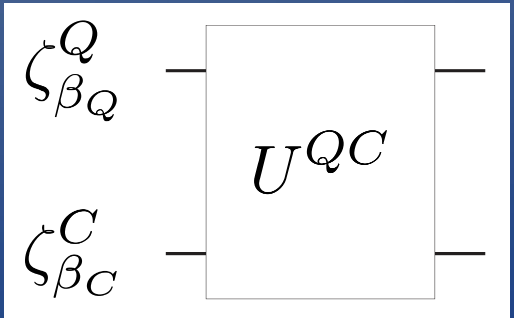
The hotter system always give off heat to the colder one

Exchange of energy controlled by a Maxwell's demon

Protocol with the demon



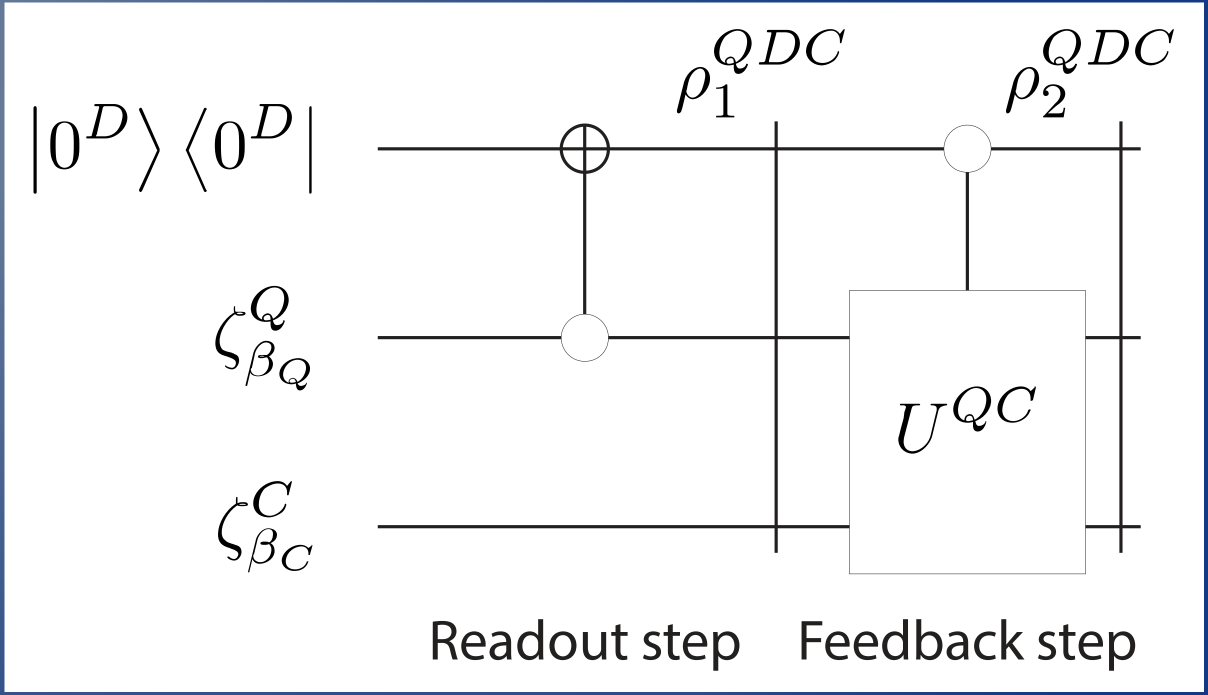
No demon



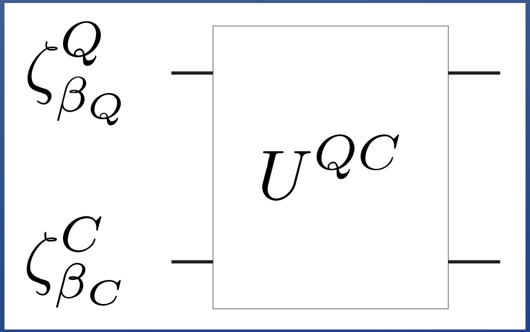
The feedback step is build so that heat from the cavity to the qubit is blocked

Exchange of energy controlled by a Maxwell's demon

Autonomous implementation

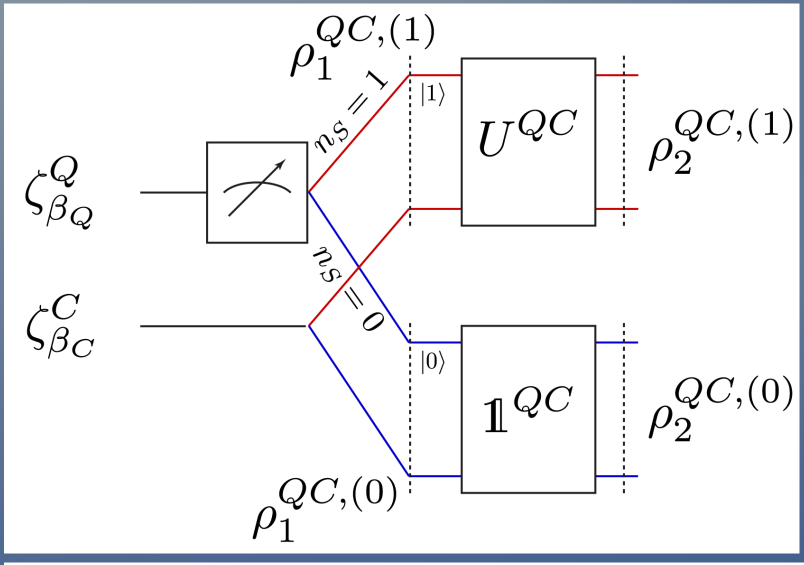


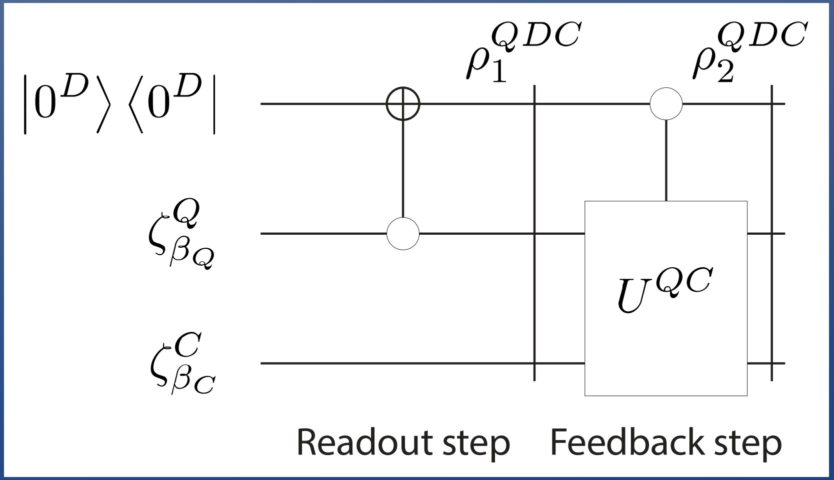
No demon



The measurement + feedback are performed dynamically (autonomous performance)

Relation between them



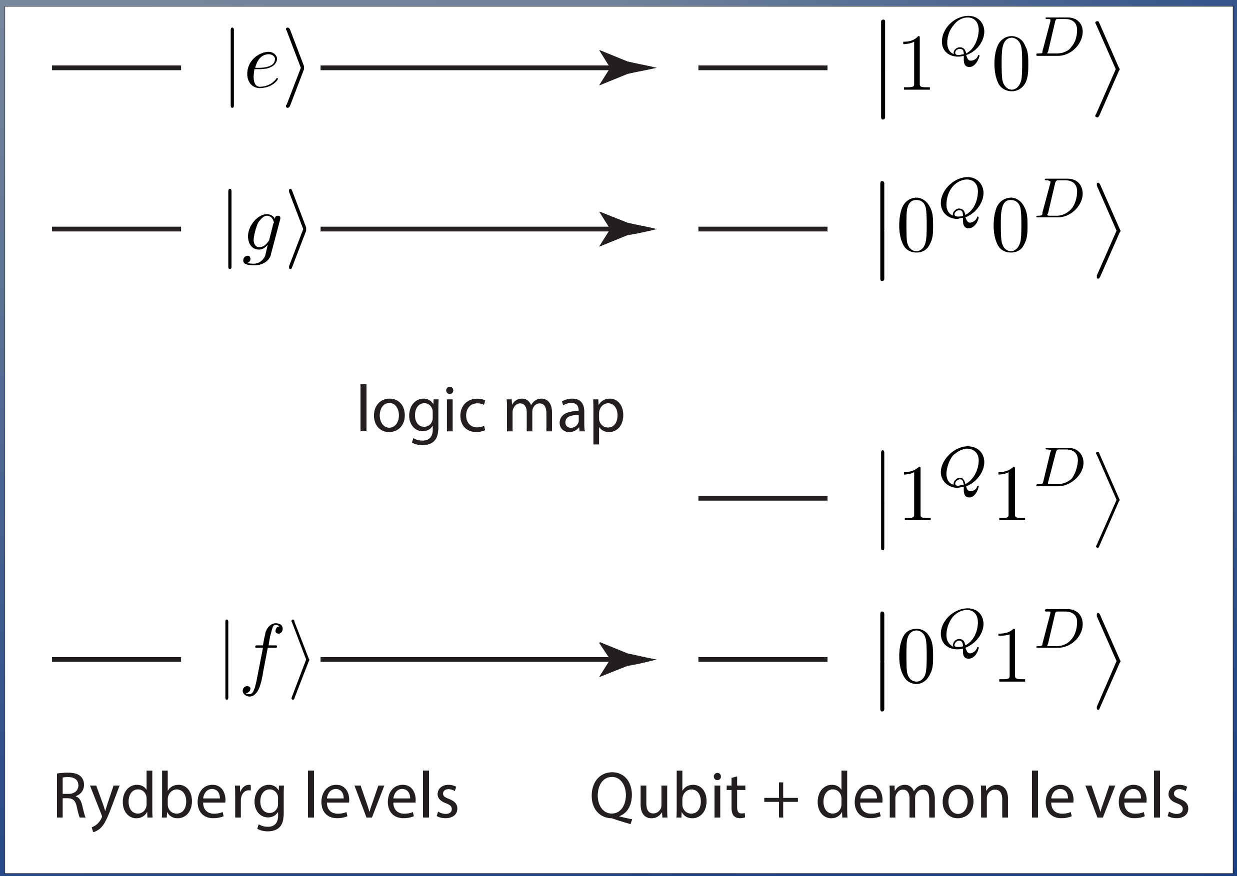


$p(k)$ is the probability of measuring the outcome k

$$\rho_1^{QC} = \sum_k p(k)\, \rho_1^{QC,(k)}$$

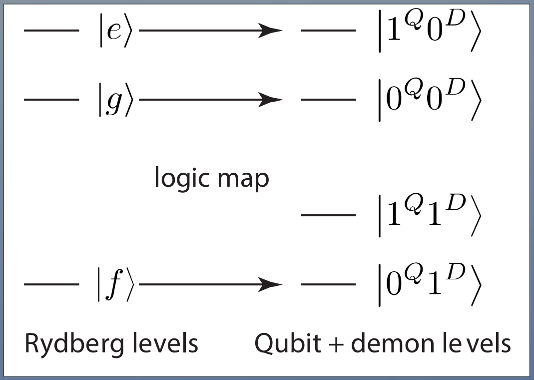
$$\rho_2^{QC} = \sum_k p(k)\, \rho_2^{QC,(k)}$$

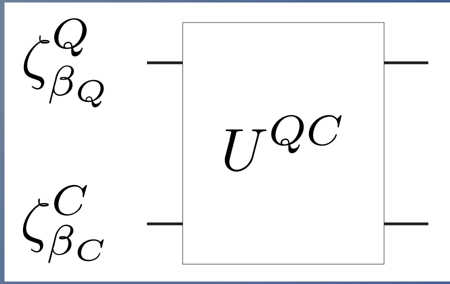
The logic map

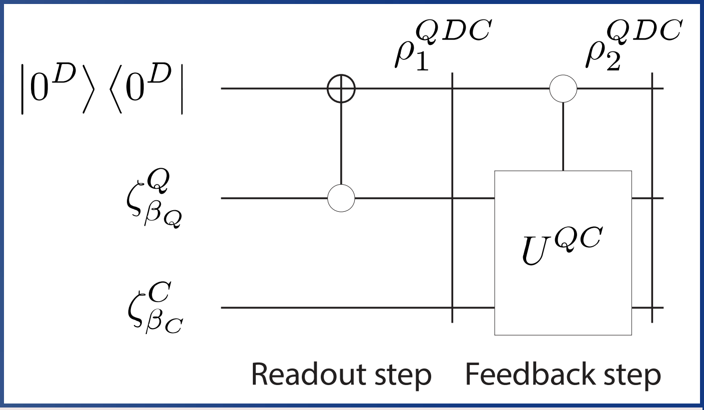


The Rydberg atom energy levels are related to the qubit + demon levels through the logic map

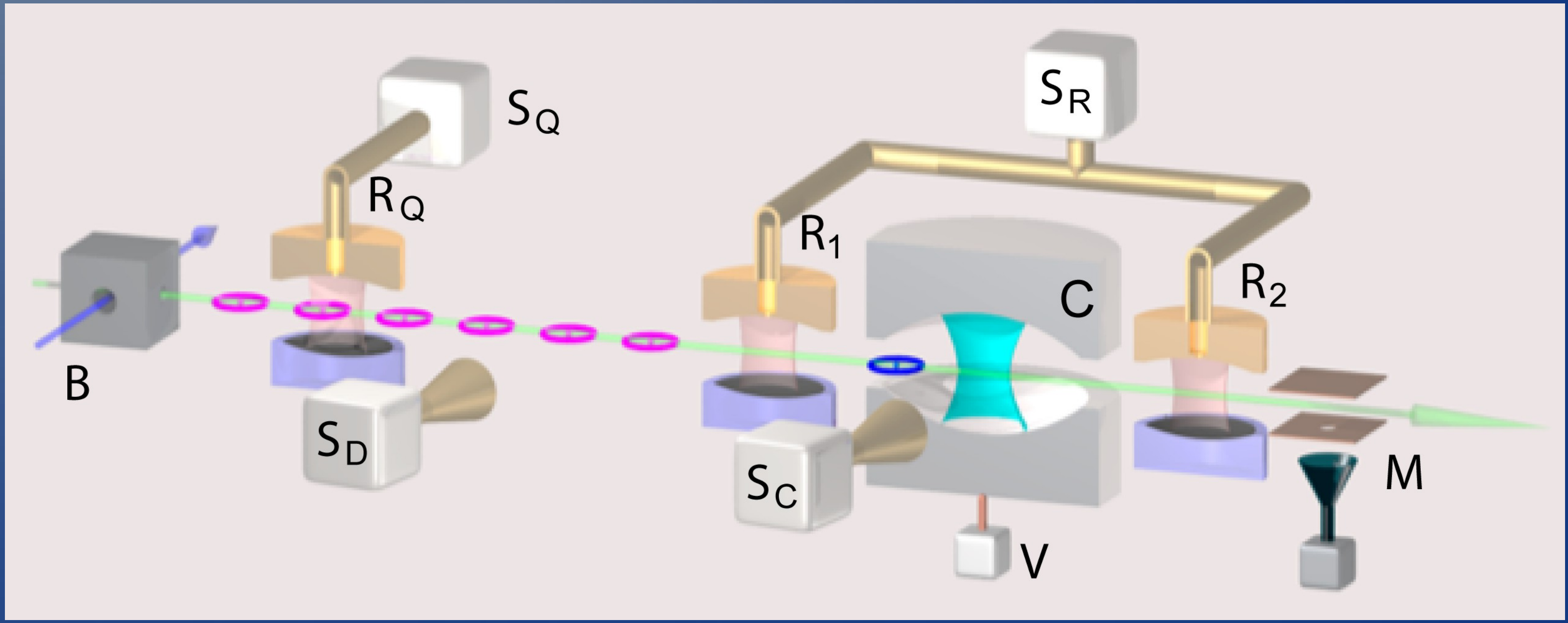
Setup (revisited)







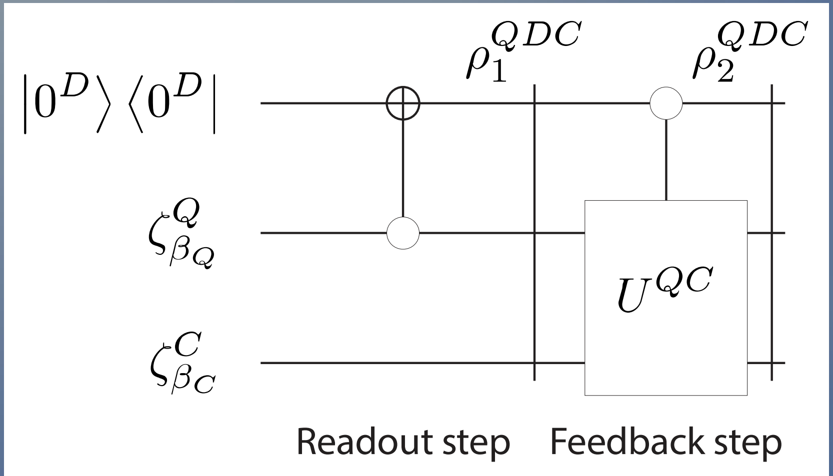
In light of the logic map both circuits can be implemented by turning the source SD on and off



Demon on-off

(Controlled) gate

Thermodynamic Relation



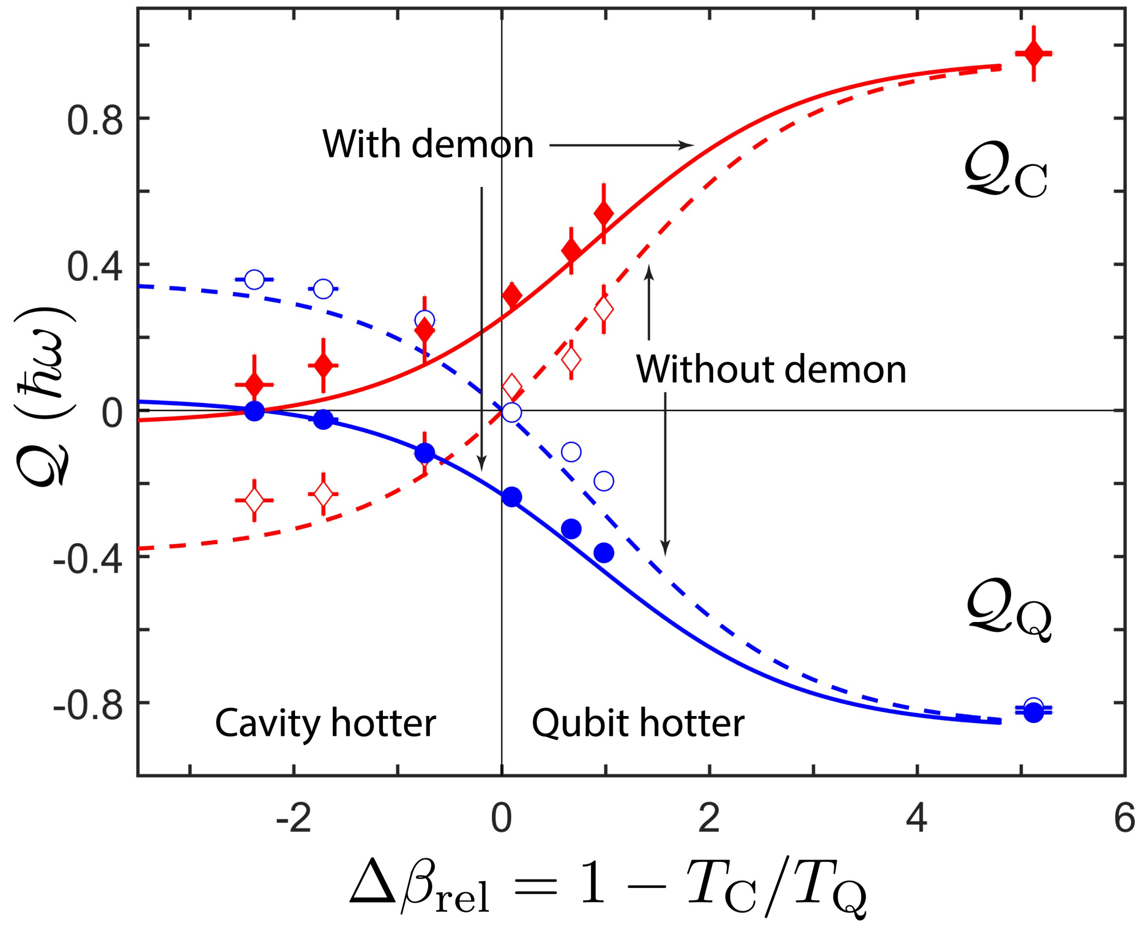
From the conservation of entropy in the global system we can show that

$$\Delta\beta\mathcal{Q}_C = D\left(\rho_2^{QC}||\zeta_{\beta_Q}^Q \otimes \zeta_{\beta_C}^C\right) + \Delta\mathcal{I}^{QC:D}$$

Relative entropy

Mutual information change during the feedback step

Heat transference

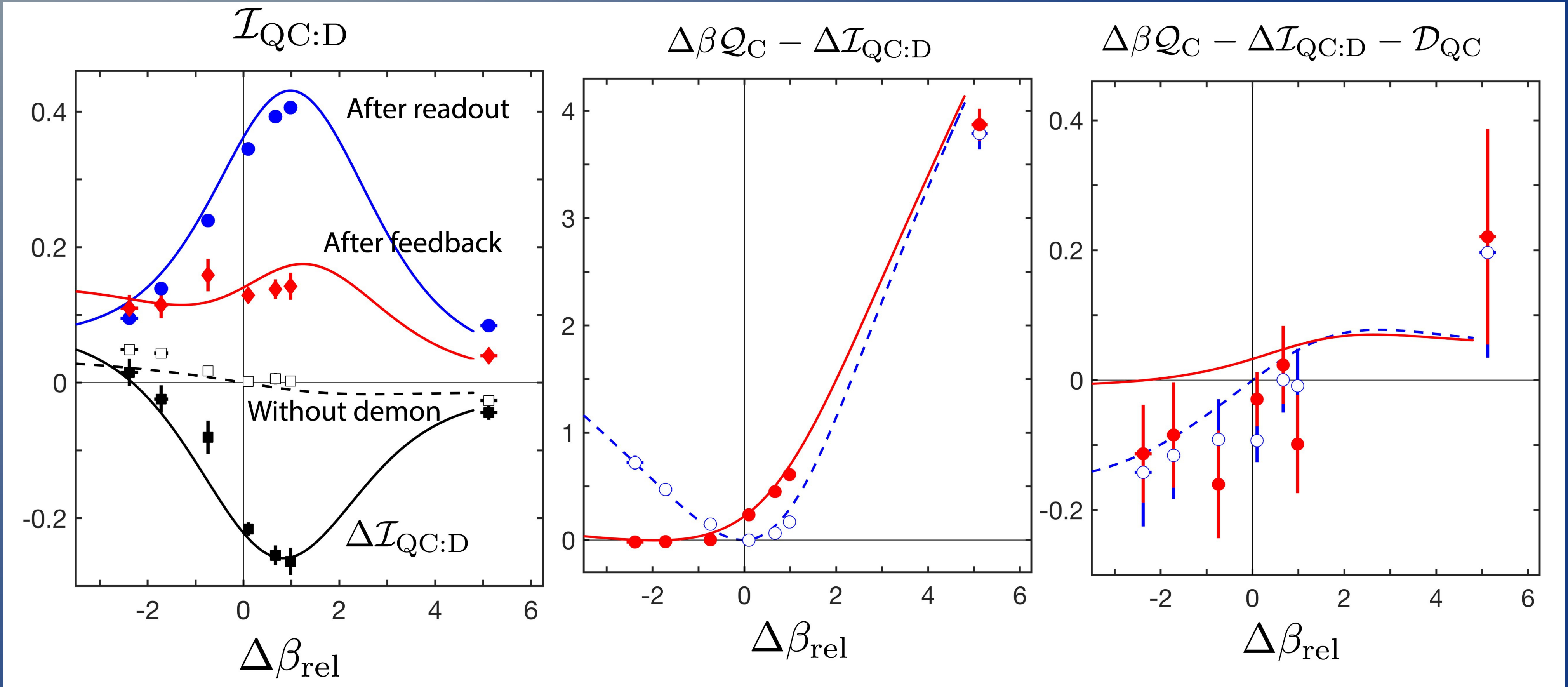


Without the demon, the heat flows in the “expected” direction

With the demon, the heat flows in the “inverse” direction

$$\Delta\beta\mathcal{Q}_C = D\left(\rho_2^{QC} || \zeta^Q_{\beta_Q} \otimes \zeta^C_{\beta_C}\right) + \Delta\mathcal{I}^{QC:D}$$

Entropic quantities



Generalized second law   Entropy conservation

K. Micadei, *et al.* Nat. Commn. **10**, 2456 (2019)

Wrapping up

- By employing a logic map we experimentally implemented an autonomous Maxwell's demon in a cavity QED setup.
- From the fact that our tripartite system (qubit + demon + cavity) is closed we obtained a thermodynamic relation between the qubit-cavity heat exchanged and the mutual information between the demon and the qubit-cavity system.
- The presence of the demon allows the inversion of heat flow at the expense of consuming the correlations created by the demon during the readout.

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Thank you!