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Qubit reset based on a quantum absorption refrigerator

Simone Gasparinetti

16th European Conference on Applied Superconductivity
Bologna, Italy
September 4, 2023

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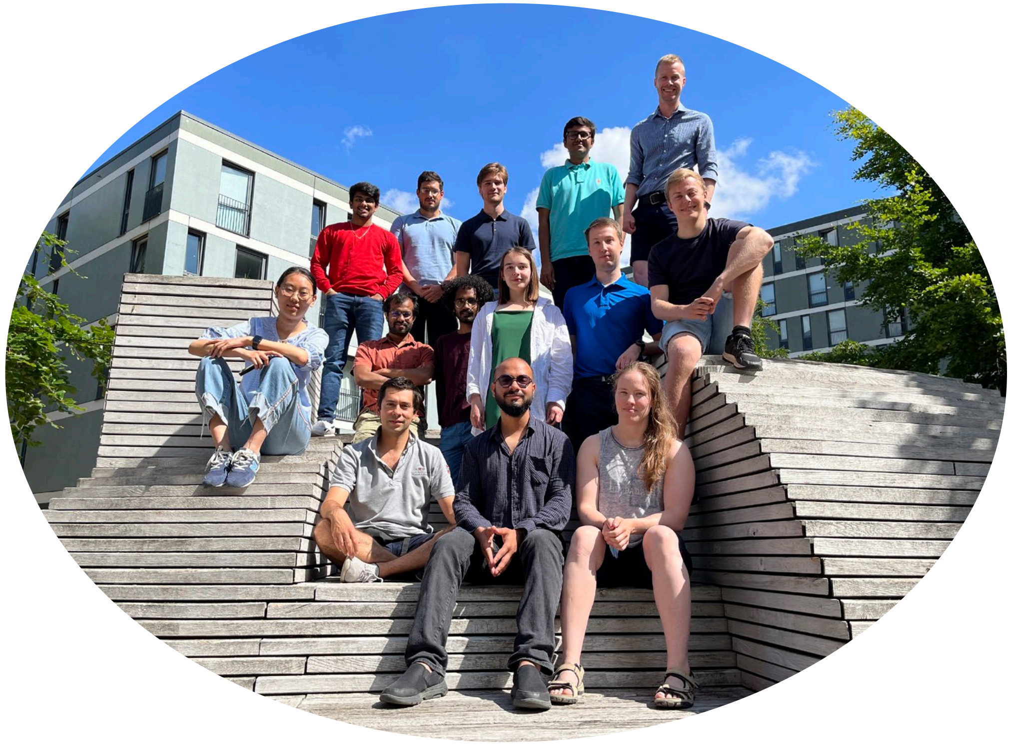

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Thermally driven quantum refrigerator autonomously resets superconducting qubit

Mohammed Ali Aamir,[1,*] Paul Jamet Suria,[1] José Antonio Marín Guzmán,[2] Claudia Castillo-Moreno,[1] Jeffrey M. Epstein,[2,3] Nicole Yunger Halpern,[2,3,†] and Simone Gasparinetti[1,‡]

arXiv:2305.16710

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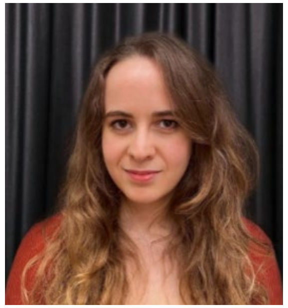
Aamir

Paul

Claudia



Simone

José Antonio

Jeffrey

Nicole

Quantum thermodynamics

(Classical) Thermodynamics → Stochastic Thermodynamics → Quantum Thermodynamics

small systems
large fluctuations

”genuinely quantum” effects
(Quantum 2.0)

Heat engines

Individual moleules
Colloidal particles
Single-electron devices

Cold atoms
Trapped ions
Superconducting circuits
…

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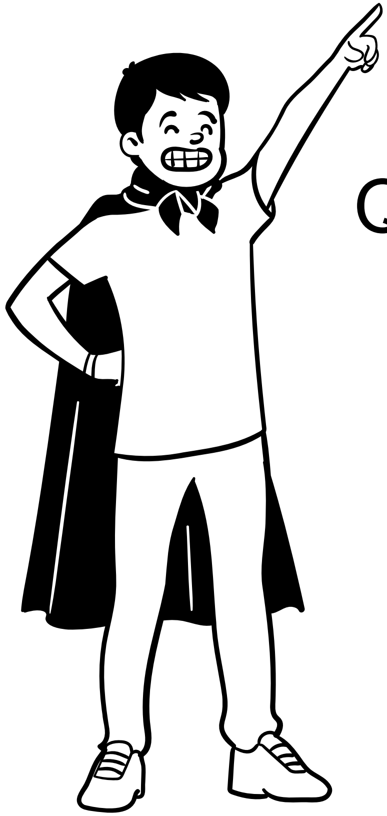
Quantum thermodynamics should be more useful...



Quantum advantages

Beat *any* classical machine at …
- power output
- charging speed
- precision

(Are we making a fair comparison?)

Practical applications

Deploy quantum thermal machines in useful settings, to do useful things

Example: Qubit reset

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Qubit reset

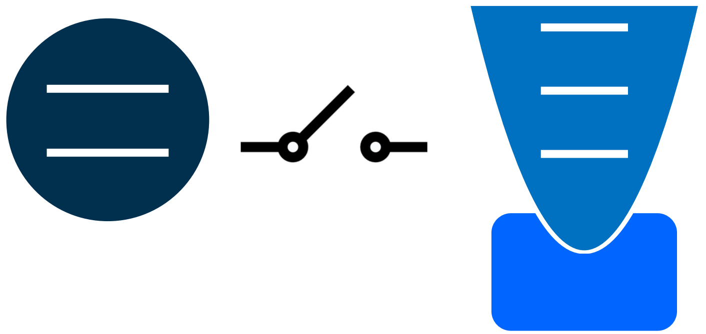
- Necessary primitive for computing
- Speed and fidelity are key metrics
- Passive thermalization may be too slow and/or too unfaithful
- Resetting ancillary qubits is key in quantum error correction

ACTIVE RESET

Measure qubit, then flip if needed

UNCONDITIONAL RESET

Couple qubit to thermalized cold mode



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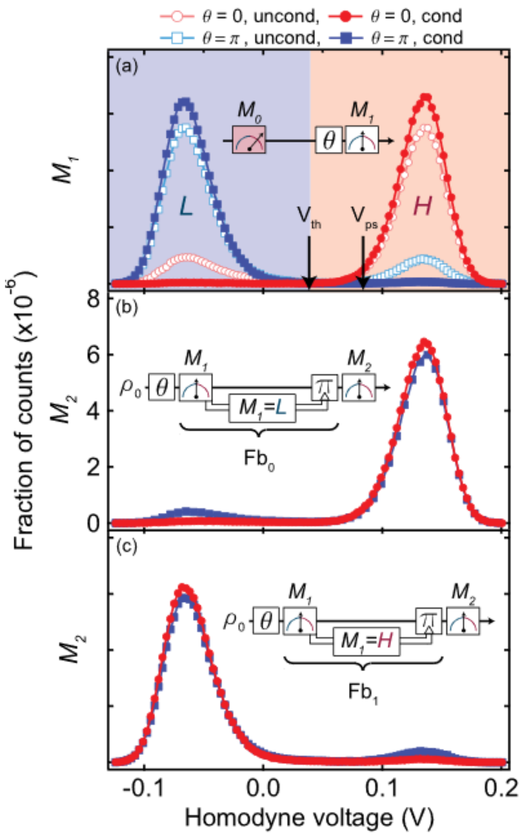
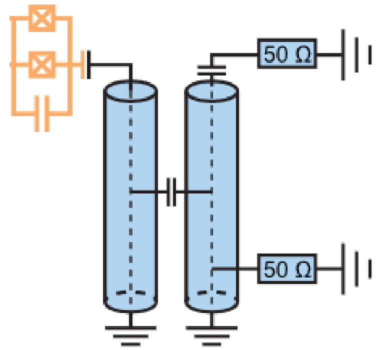
Qubit reset in superconducting circuits

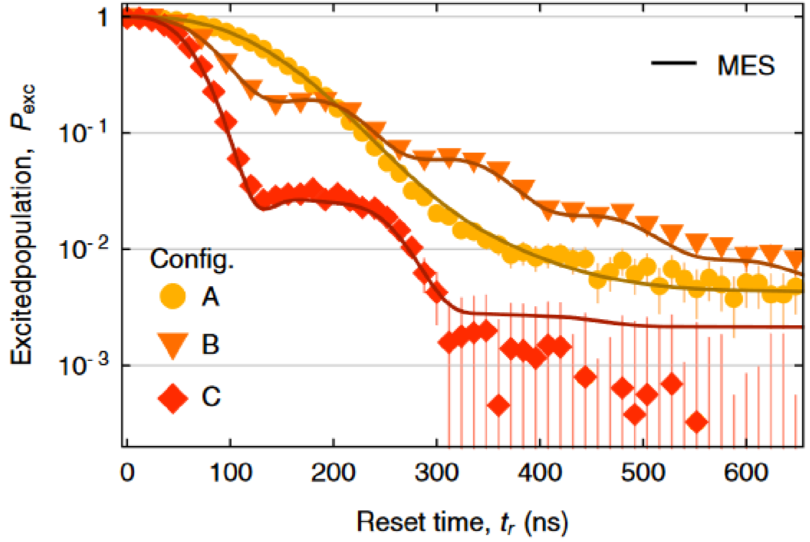
ACTIVE

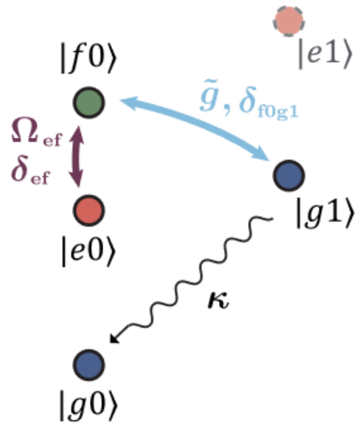


Ristè et int DiCarlo, PRL 109, 240502 (2012)

UNCONDITIONAL



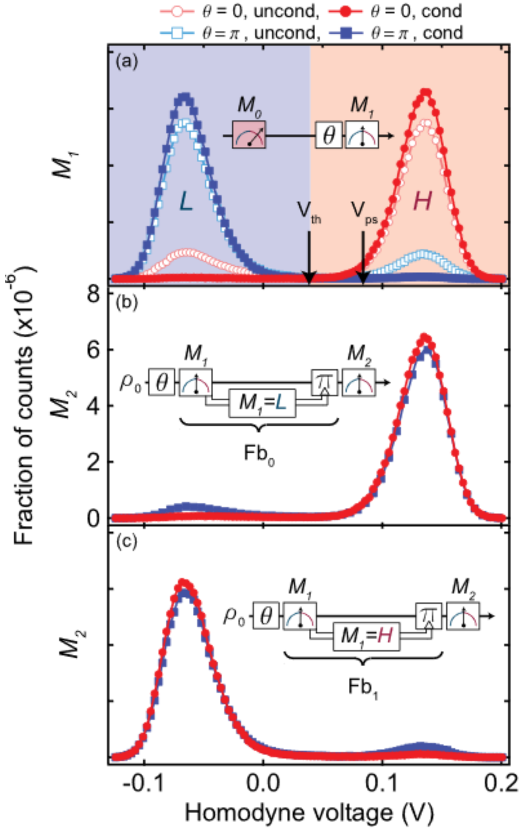




Magnard, …, SG, …, Wallraff, PRL 121, 060502 (2018)
See also: 1. Zhou et al, Nat Commun 12, 5924 (2021)

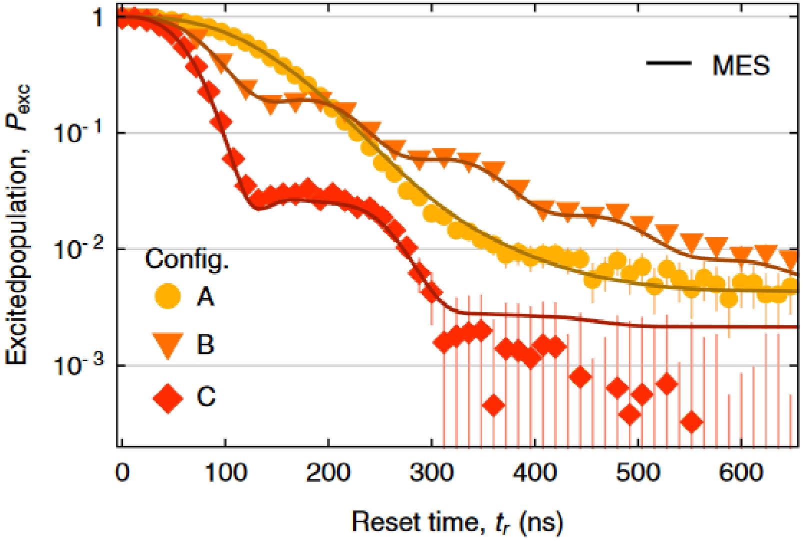
Qubit reset in superconducting circuits

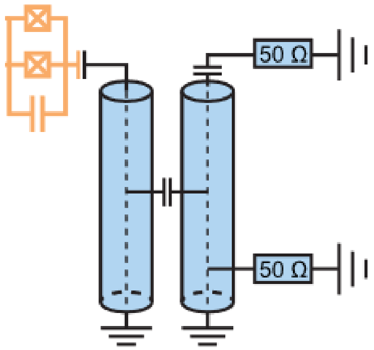
ACTIVE

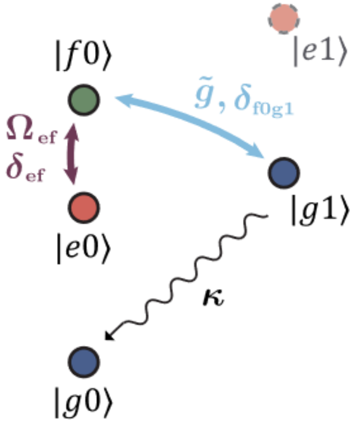


Ristè et int DiCarlo, PRL 109, 240502 (2012)

UNCONDITIONAL







Unconditional ≠ autonomous: need coherent drives.
Can we do the job with minimal thermodynamic resources?

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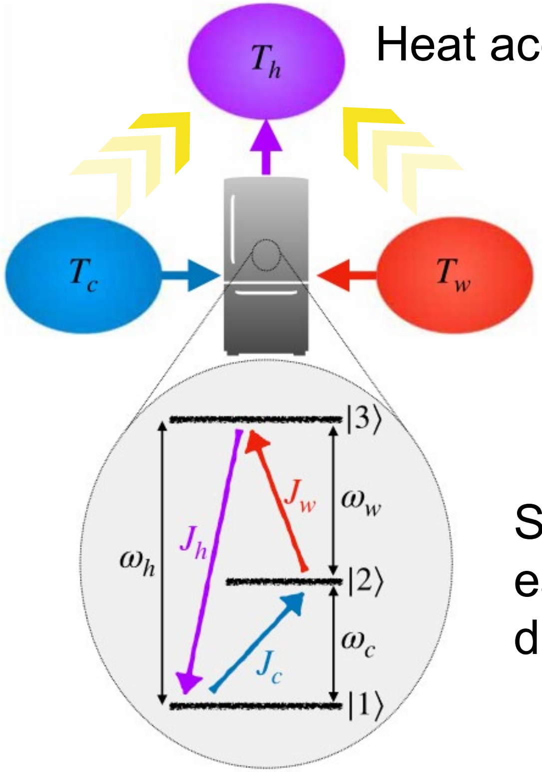
Quantum absorption refrigerator

Heat acceptor

Reservoir to be cooled

Work reservoir (ideally $T_w \to \infty$)



Simplest realization: 3 levels, each transition coupled to a different reservoir

Early theory work:
Palao, Kosloff & Gordon, PRE 64, 056130-8 (2001)
Linden et al, PRL 105, 130401 (2010)
Levy & Kosloff, PRL108, 070604 (2012)

Proposal with SC circuits Hofer et al, PRB 94, 235420 (2016)
Realization w trapped ions Maslennikov et al, Nat Commun 10, 202 (2019)
Reviews Mitchison, Contemp Phys 60, 164 (2019) (image credit)
Mitchison & Potts, in: *Thermodynamics in the Quantum Regime…(2018)*

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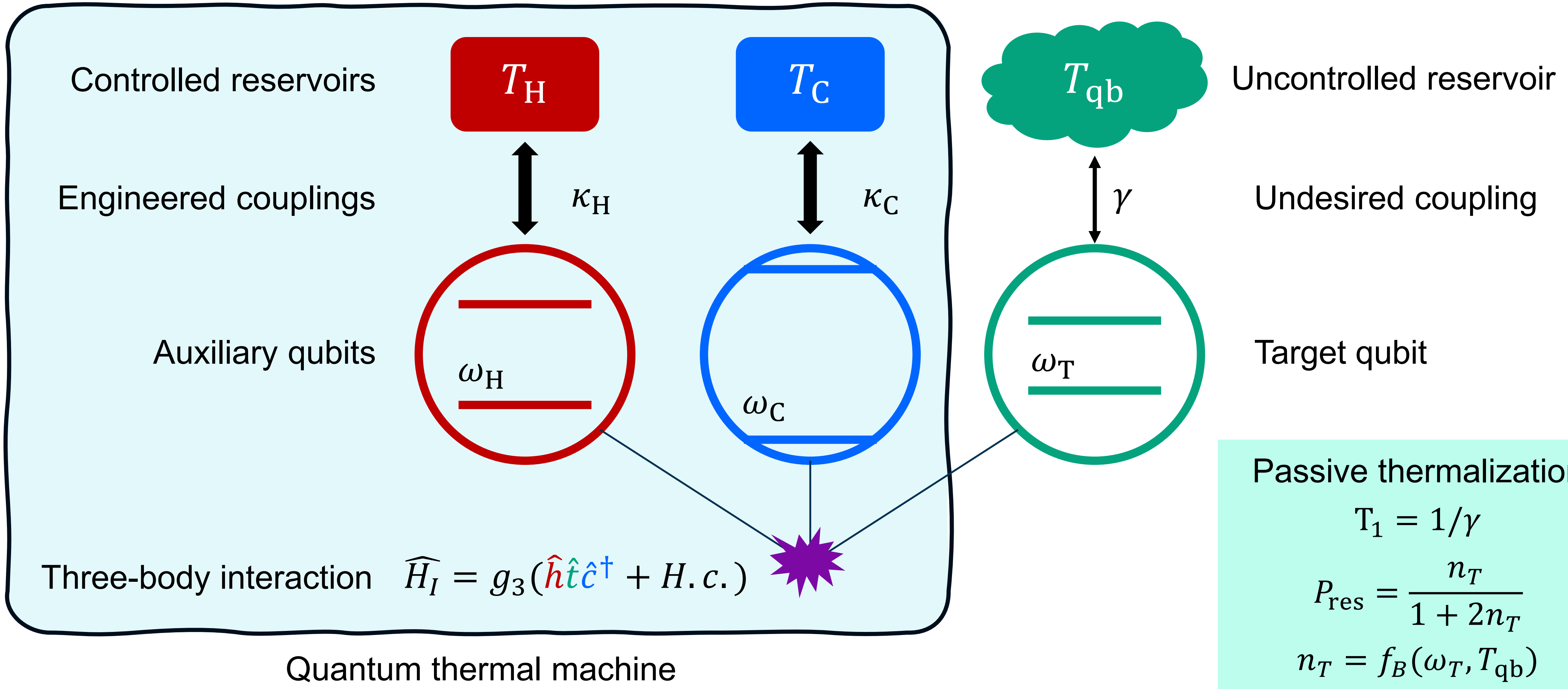
Resetting a qubit with a quantum absorption refrigerator



Passive thermalization

$$T_1 = 1/\gamma$$

$$P_{res} = \frac{n_T}{1 + 2n_T}$$

$$n_T = f_B(\omega_T, T_{qb})$$

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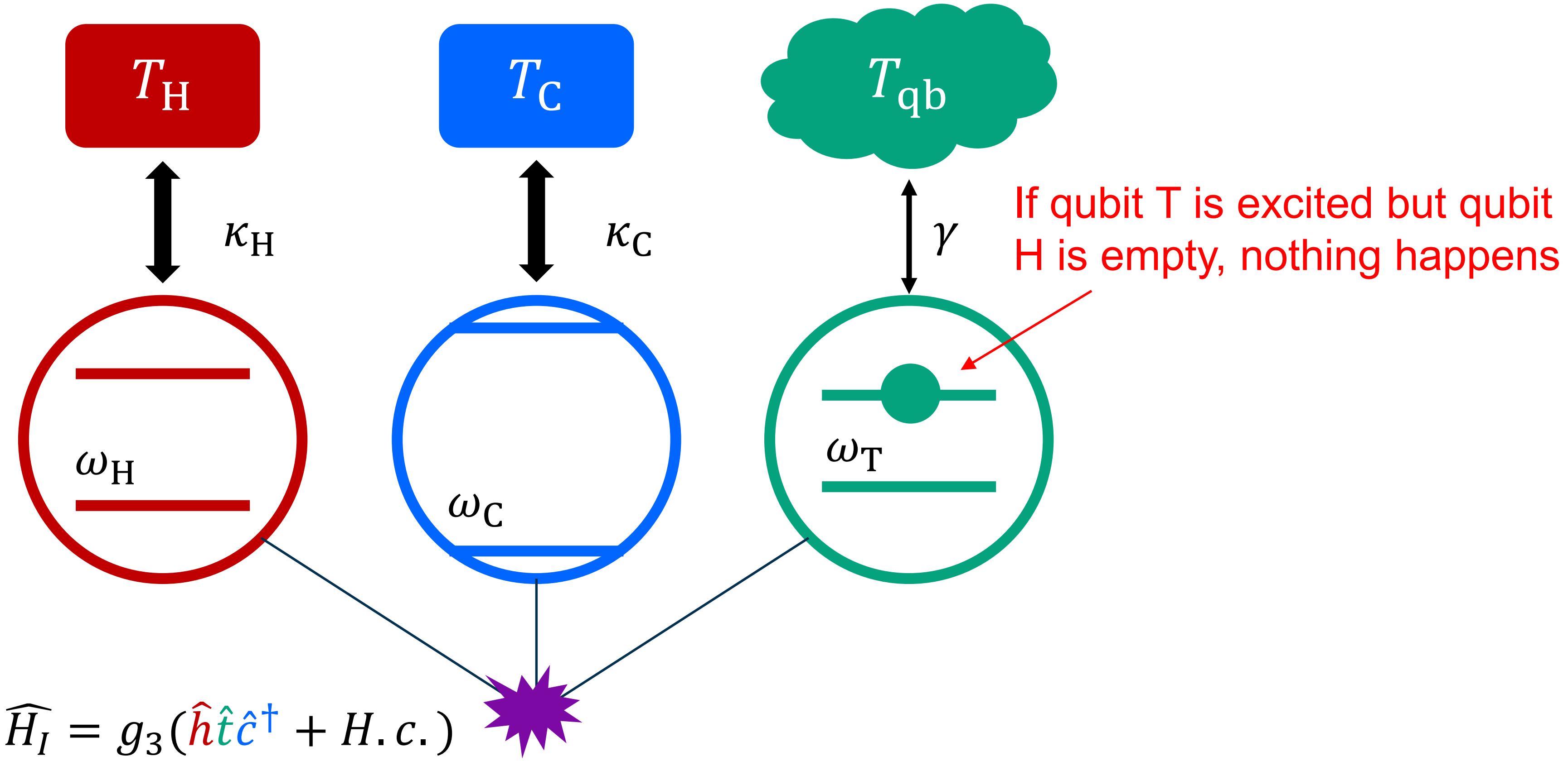

$$\widehat{H_I} = g_3(\hat{h}\hat{t}\hat{c}^\dagger + H.c.)$$

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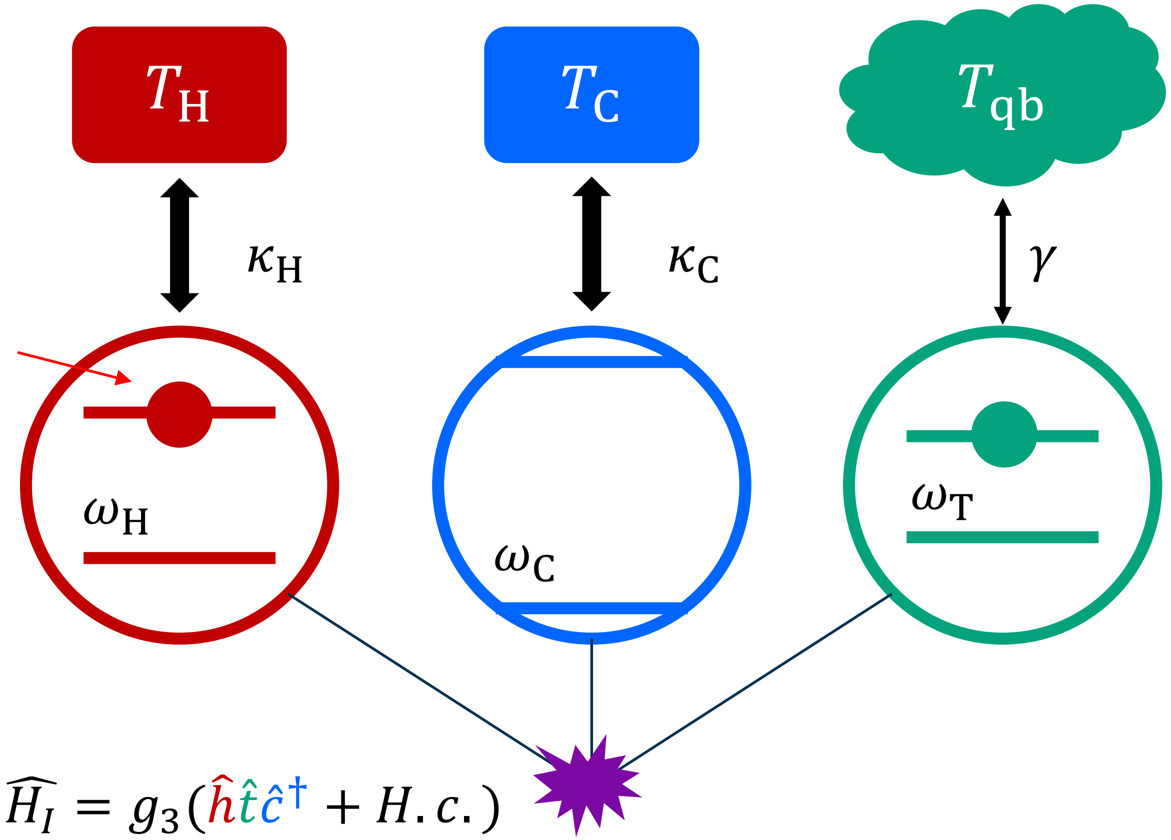
If also qubit H is excited, and the resonance condition $\omega_C = \omega_T + \omega_H$ is met, then both excitations are transferred to qubit C, then evacuated



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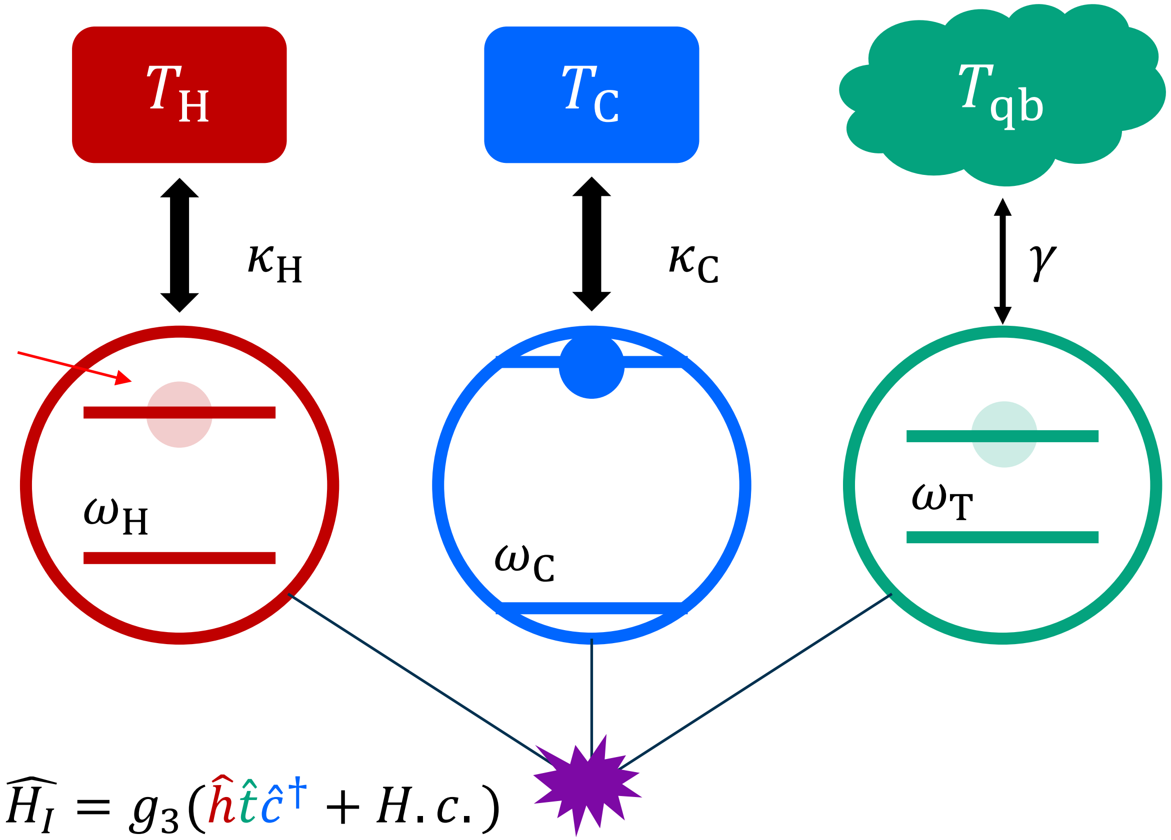

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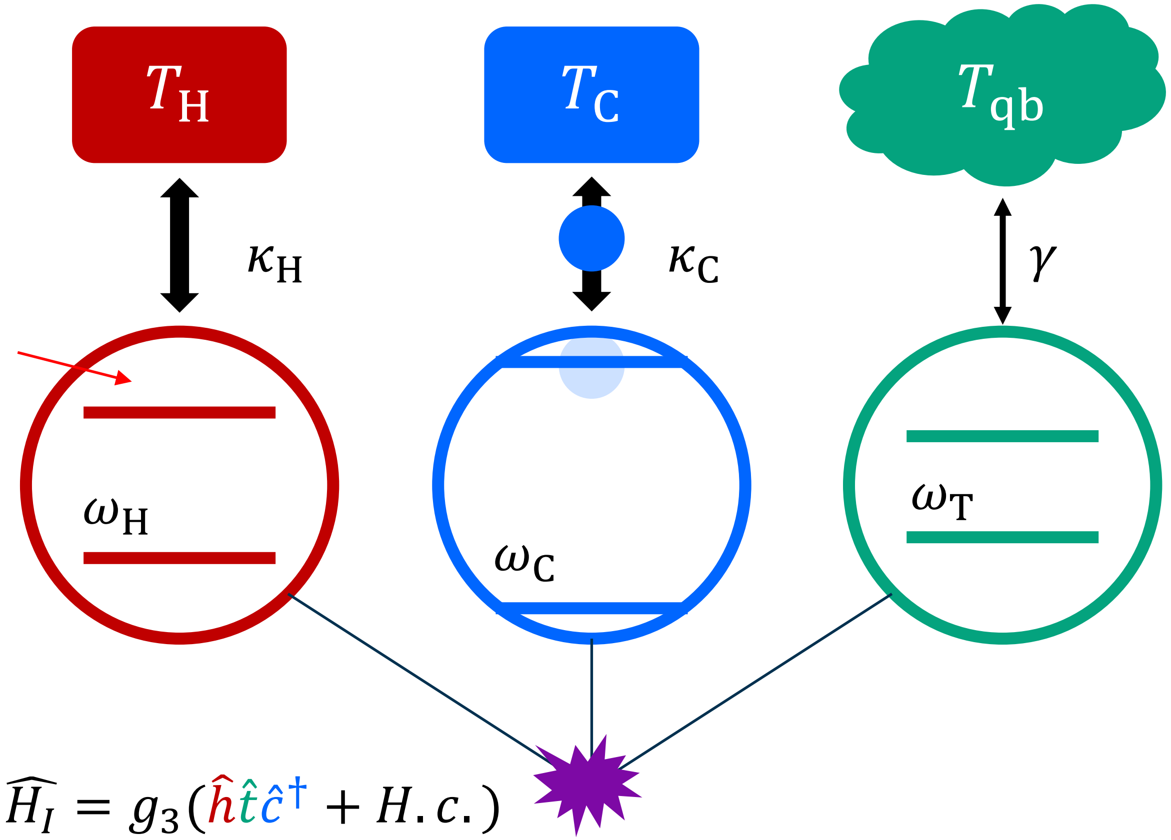

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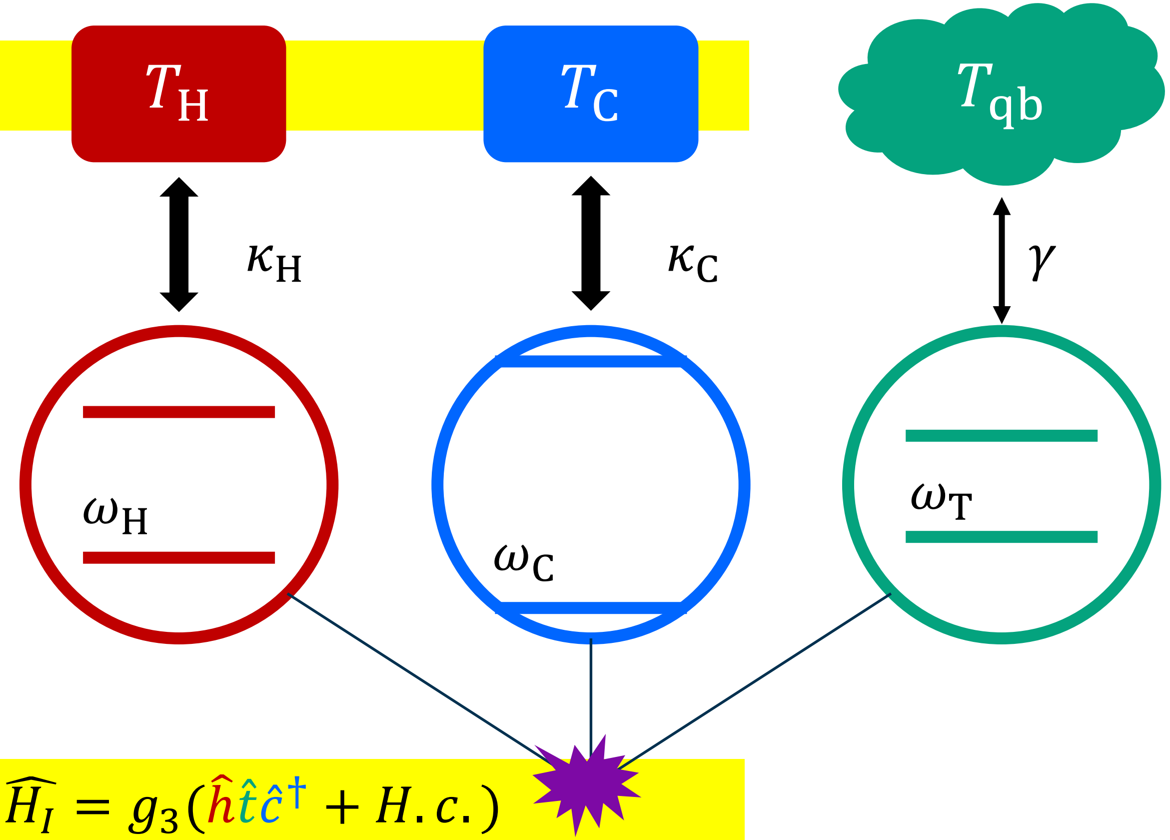
To build the machine, we need two key ingredients!

1) Controlled baths



2) Three-body interaction $\widehat{H_I} = g_3(\hat{h}\hat{t}\hat{c}^{\dagger} + H.c.)$

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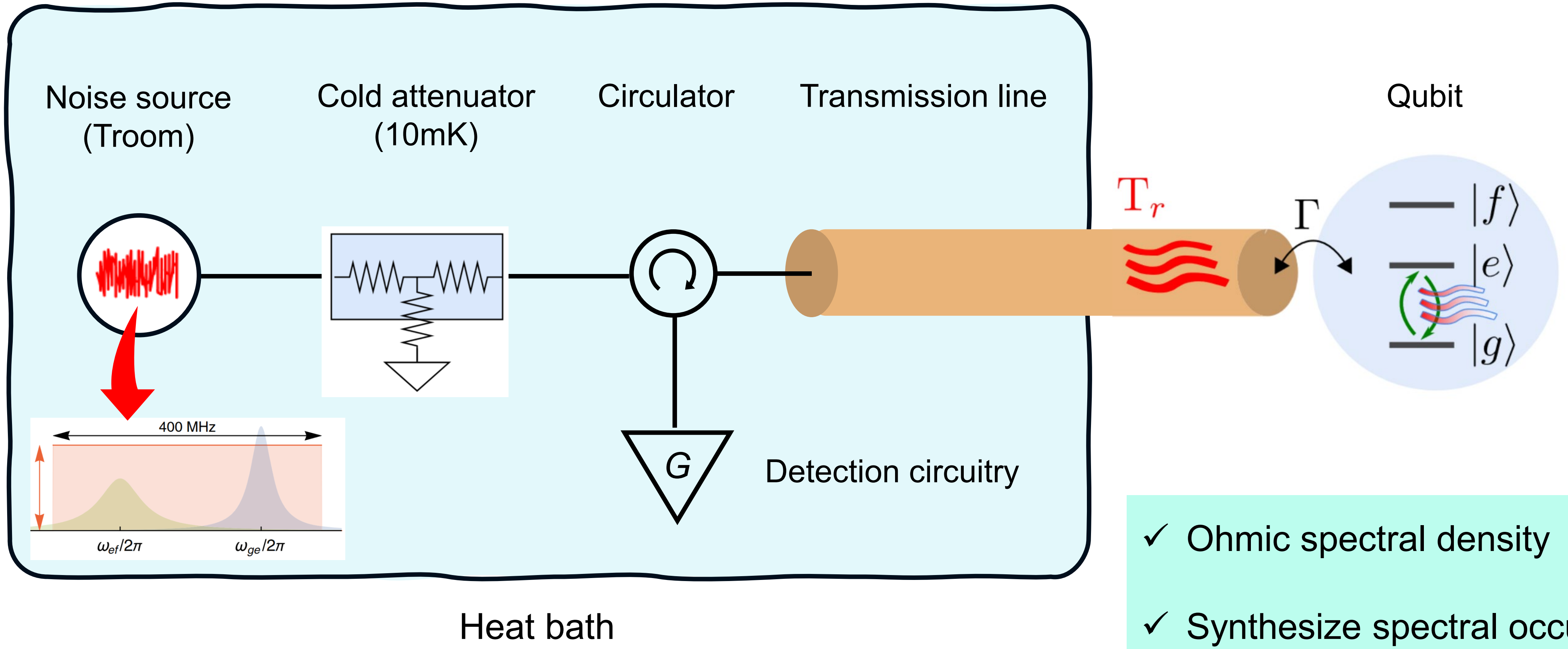
1) Microwave waveguides as heat baths



- ✓ Ohmic spectral density
- ✓ Synthesize spectral occupation
- ✓ Analyze scattered radiation

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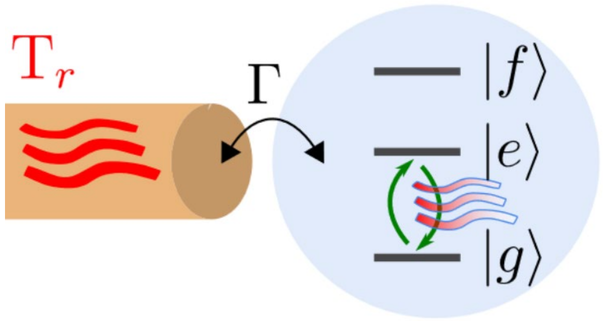
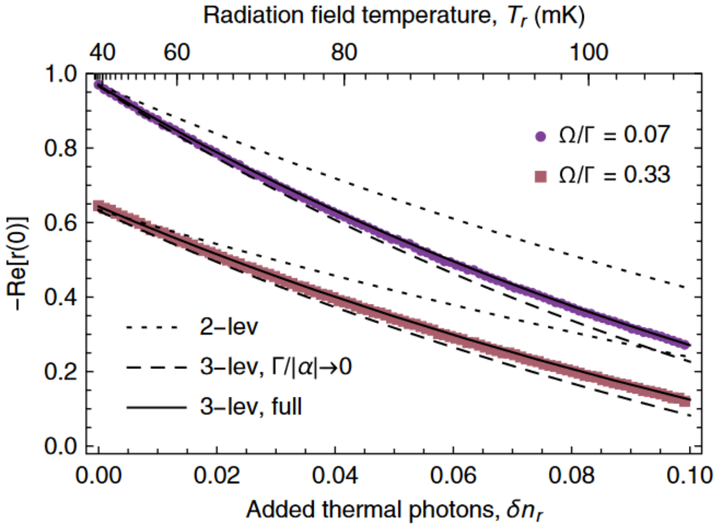
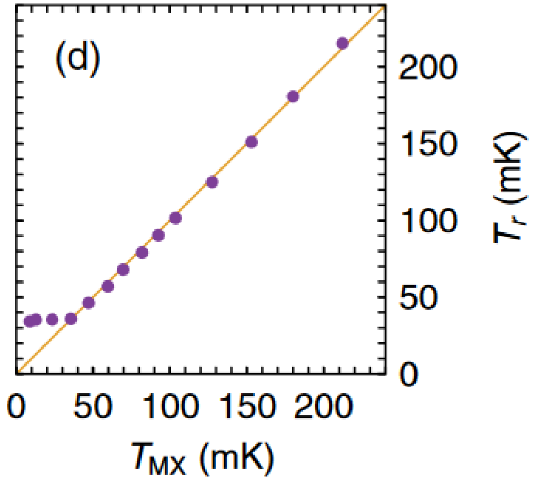
1) Microwave waveguides as heat baths

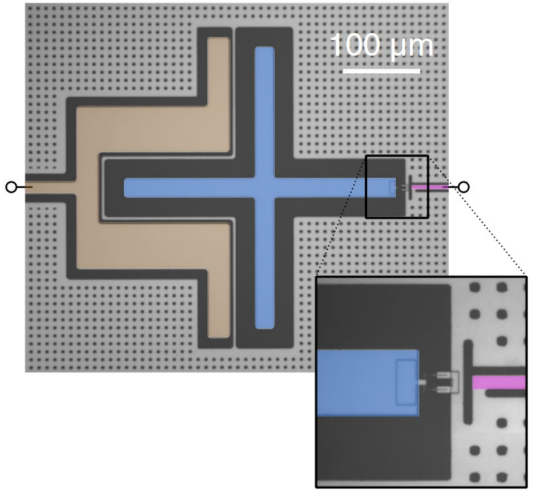
Previous work:

- Primary thermometry of synthesized thermal radiation
- Agreement bw synthesized and physical temperatures









Scigliuzzo et int SG, PRX 10, 041054 (2020)
Related work: Fink et al, PRL 105, 163601 (2010); Goetz et al, PRL 118, 103602 (2017); Wang et al, PRL 126, 180501 (2021)

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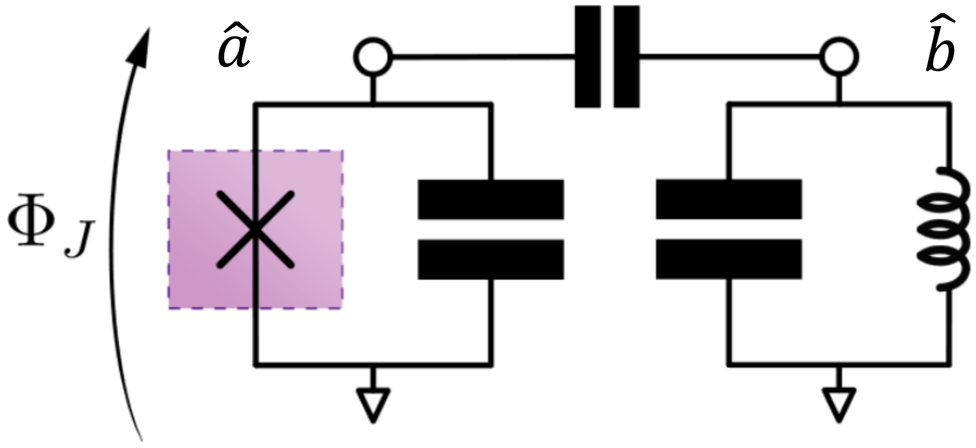
2) Josephson junction as a quantum mixer

- Josephson energy: $E_J(1-\cos\hat{\varphi}_J)$
- Expand around $\hat{\varphi}_J = 0$
- Quadratic term → linear eigenmodes $\hat{a}$, $\hat{b}$
- Write phase difference across junction as $\hat{\varphi}_J = \phi_a(\hat{a}+\hat{a}^\dagger) + \phi_b(\hat{b}+b^\dagger)$
- Expansion of cosine potential generates mixing products, for example

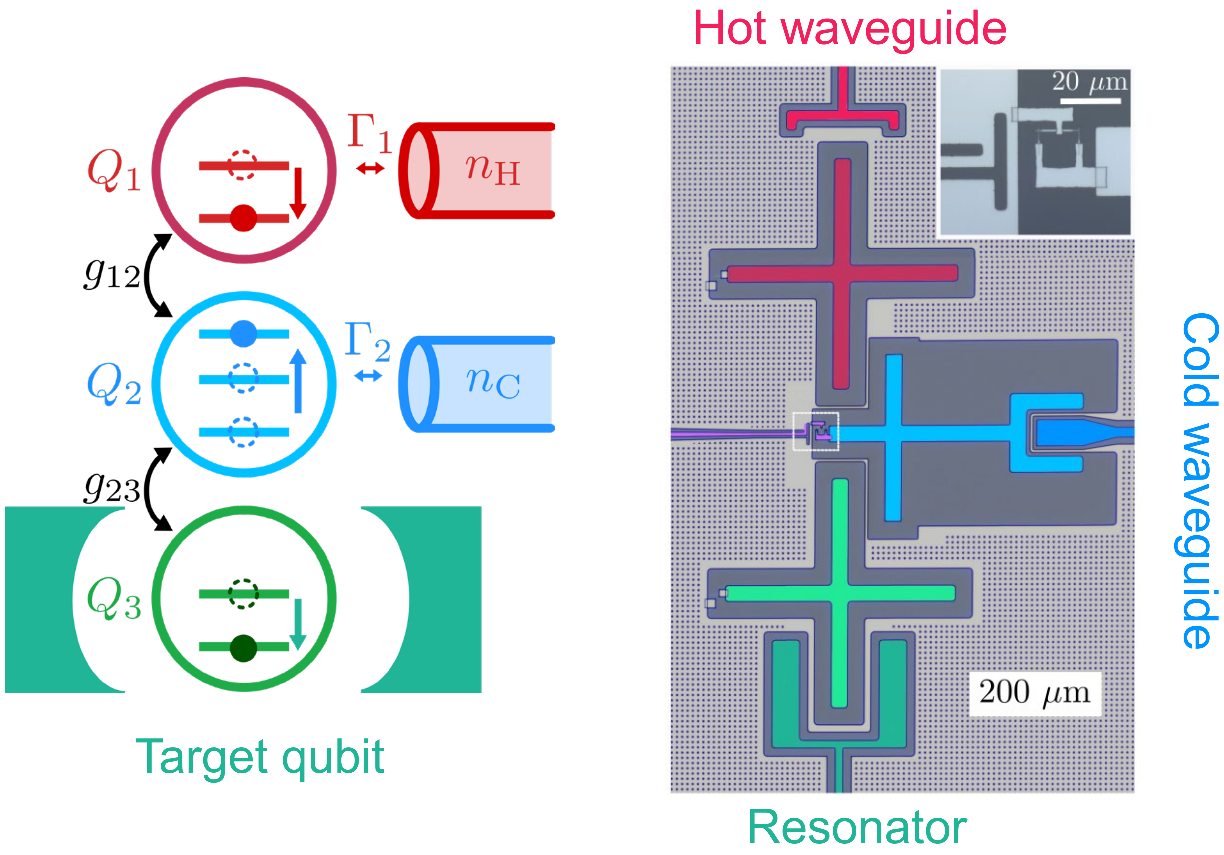
$$\frac{E_J}{4!}\left(\phi_a(\hat{a}+\hat{a}^\dagger)+\phi_b(\hat{b}+\hat{b}^\dagger)\right)^4$$



A simple quantum circuit with two modes.
Adapted from Minev et al, cit.

Black-box quantization Nigg et al, PRL 108, 240502 (2012)
Energy-participation quantization: Minev et al, npj Q Inf 7, 131 (2021)
Josephson junction as a mixer: P Reinhold, PhD thesis, Yale (2019)
(for the experts) 3-wave mixing with SNAIL: Frattini et al, APL 110, 222603 (2017)

Our quantum absorption refrigerator



- Three transmon qubits *Q1 Q2 Q3*
- Two waveguides
- Readout resonator for *Q3*
- *Q2* is used as a qudit
- 3-body interaction $a_1\hat{a}_2^\dagger\hat{a}_2^\dagger\hat{a}_3 + h.c.$
- Resonance when $\omega_1 + \omega_3 = 2\omega_2 + \alpha_2$
- *Q2* is frequency-tunable

QAR w superconducting circuits: Hofer et al, PRB 94, 235420 (2016)
This 3-body interaction: Ren et al, PRL 125, 133601 (2020)

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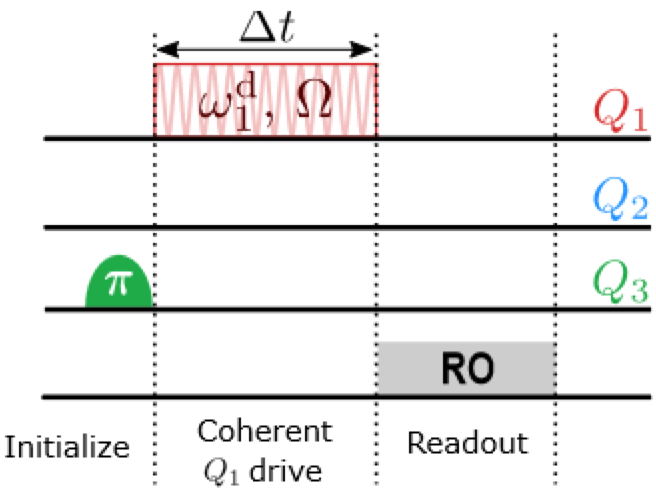
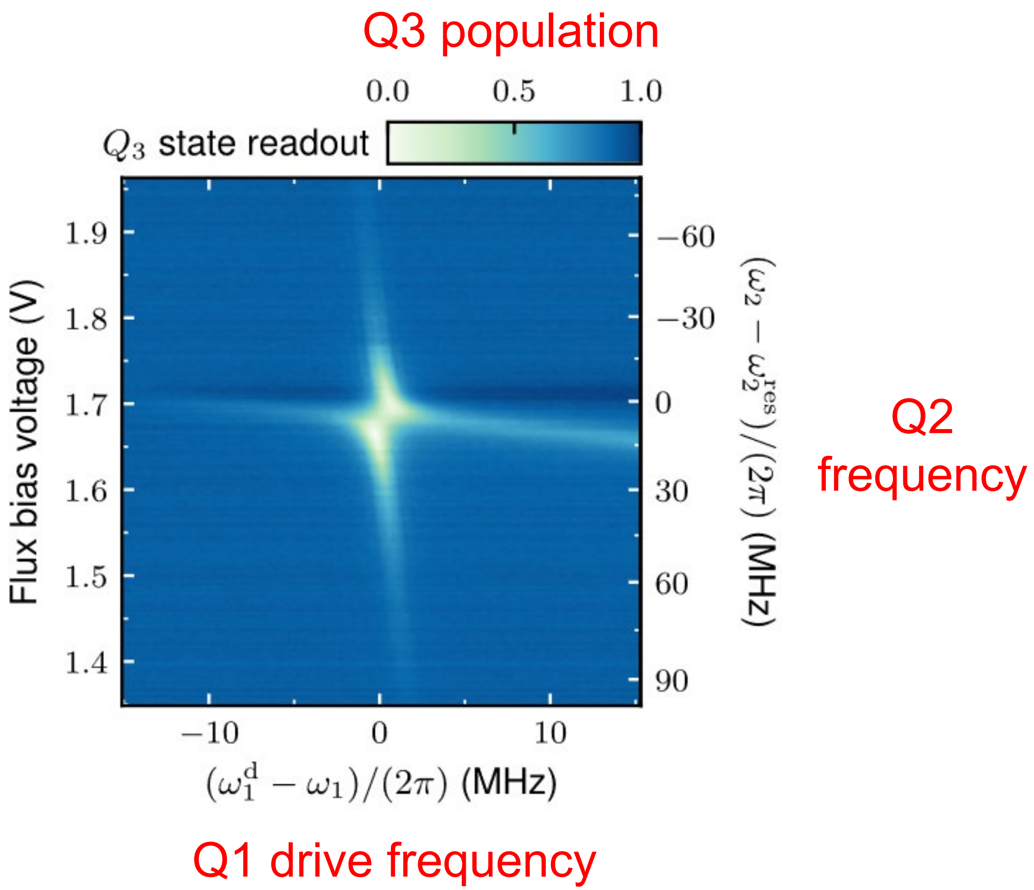
Demonstrating the three-body interaction



- Excite Q3, resonantly drive Q1, measure Q3
- Repeat for varying frequency of Q2
- Q3 pop is drastically reduced when resonance condition is met



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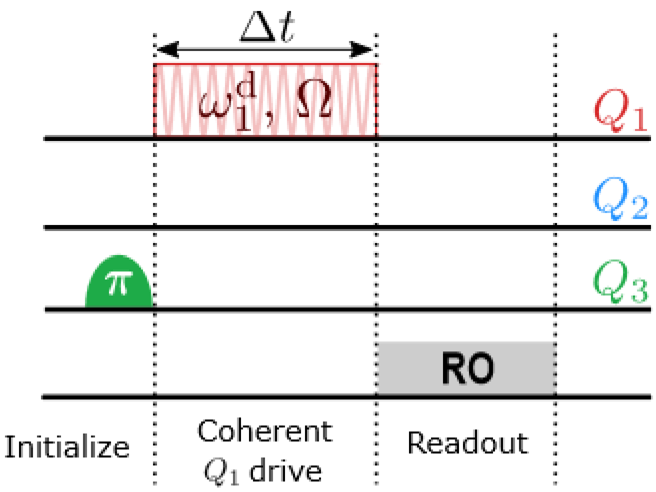

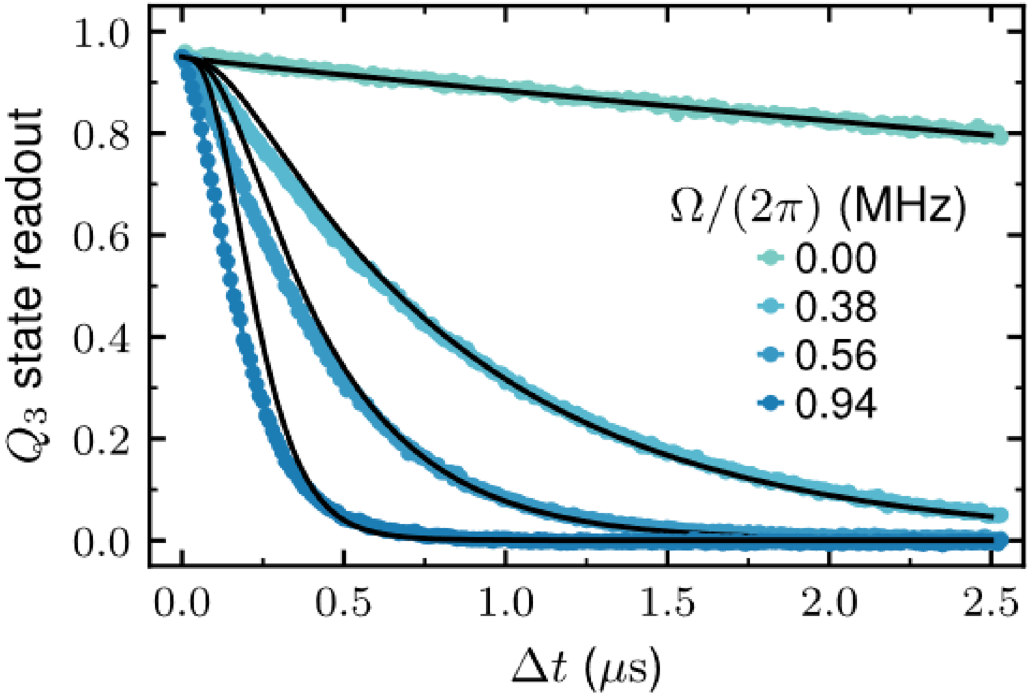

- Excite Q3, resonantly drive Q1, measure Q3
- Increasing the strength of Q1 drive results in faster decay of Q3 population

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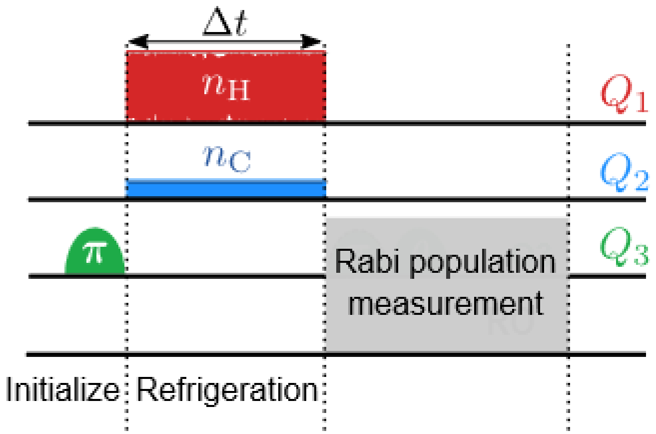
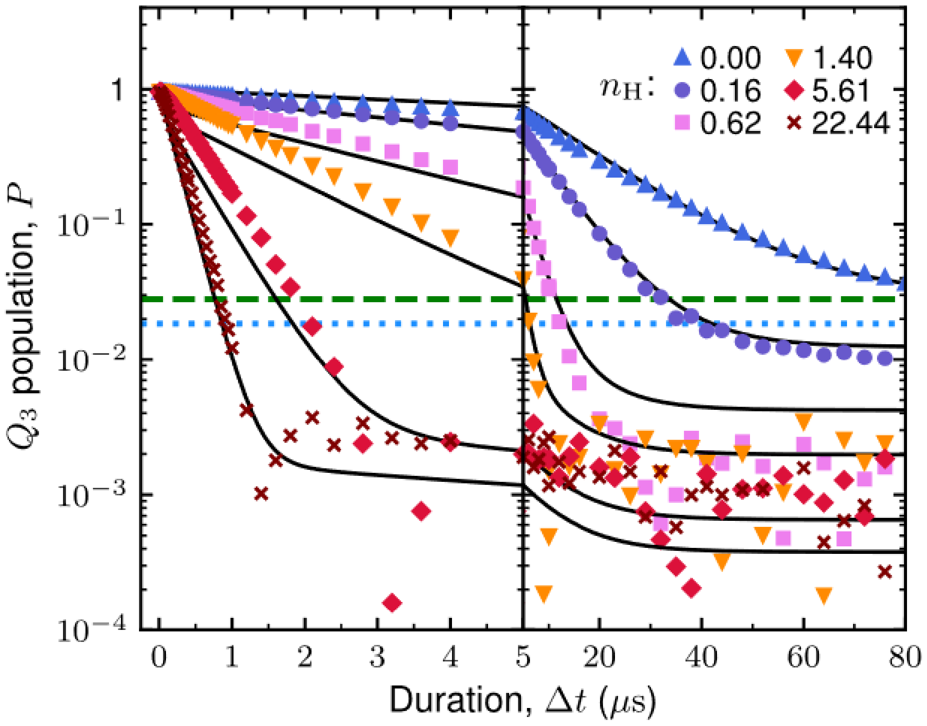
Temperature-controlled, autonomous qubit reset



- Excite Q3, then elevate temperature of hot bath and measure Q3 pop vs time
- Relaxation time of Q3 drops by a factor 60 by heating the bath coupled to Q1!
- Steady-state population is lower than
  - (i) passive thermalization to qubit bath! – –
  - (ii) Passive thermalization to coldest bath! · · · ·



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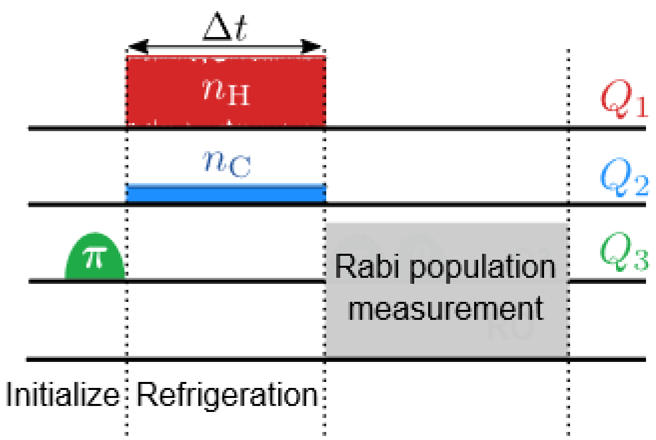

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- Steady-state population is lower than
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  - (ii) Passive thermalization to coldest bath!

Some numbers:

Lowest steady-state population: 5×10^{-4}
(Effective temperature: 23.5 mK)

Reset time (1%): 970 ns

For comparison:

Passive thermalization gives 2.8% (50 mK)

(Hypothetical) direct thermalization to cold waveguide would give 2.0% (45 mK)

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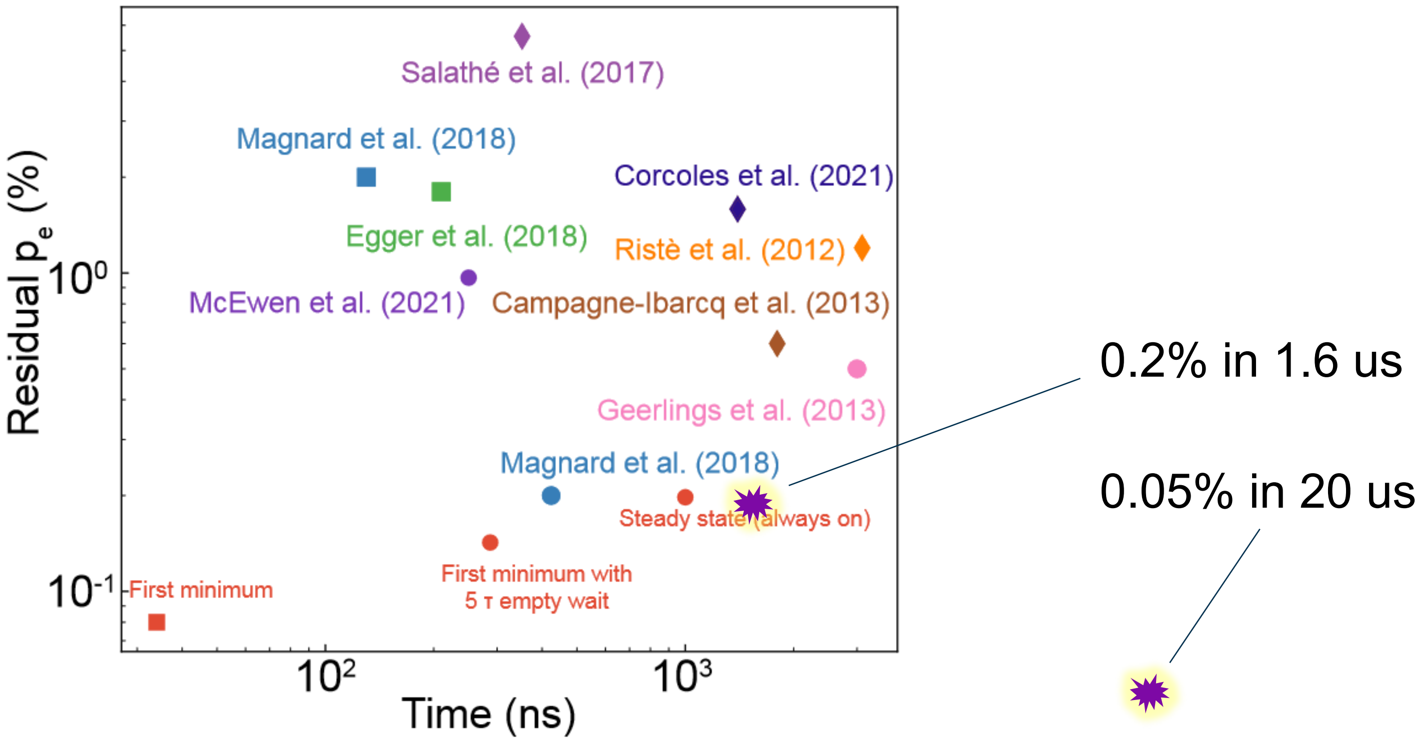
Comparing to the state of the art in qubit reset



Adapted from Zhou et al, Nat Commun 12, 5924 (2021), Suppl Mat

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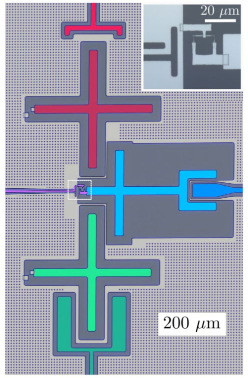
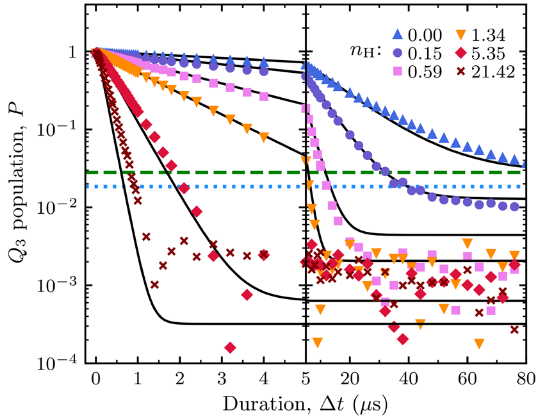
Summary and outlook





Here Quantum Thermodynamics

- Demonstrated useful, fully autonomous quantum thermal machine
- Performance competitive with state of the art
- Resource-efficient approach to a quantum computing task
- What other tasks could be executed autonomously?

Here circuit QED

- Circuit QED + thermal waveguides = comprehensive platform for experiments in qthermo
- Build one-of-a-kind quantum thermal machines to leverage native interactions
- Measure scattered thermal radiation: average power, fluctuations, correlations

This work: arXiv:2305.16710

More questions? simoneg@chalmers.se
Visit our website 202q-lab.se

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