

On-chip engineered heat baths for quantum devices

Mikko Möttönen

QCD Labs

Aalto University

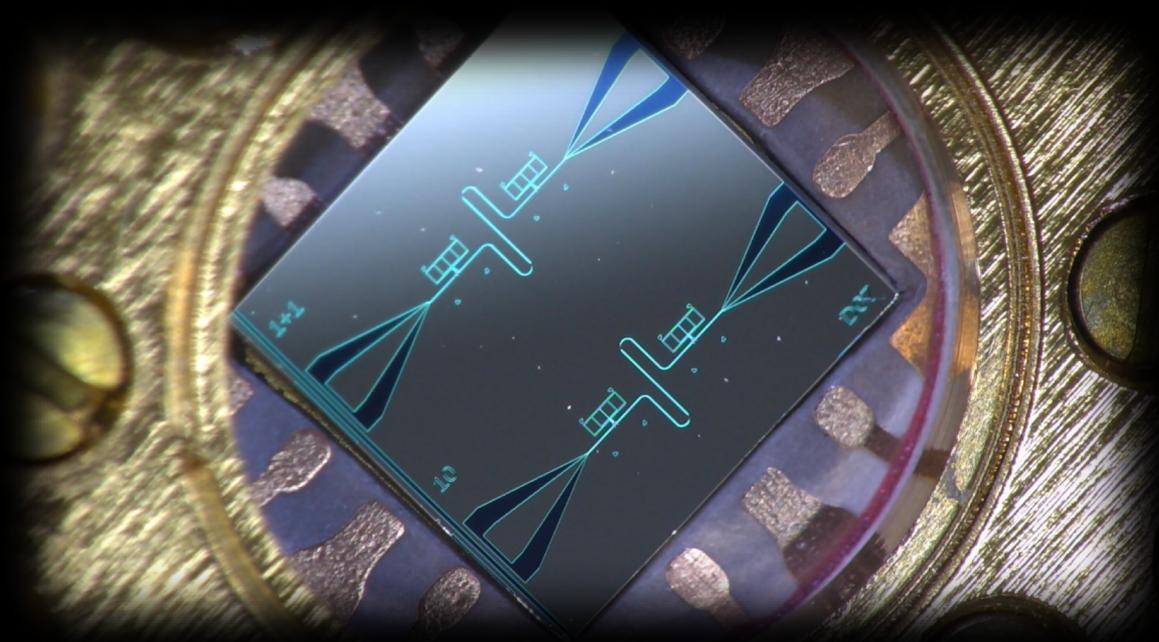


Figure credit: Kuan Yen Tan

On-chip engineered heat baths for quantum devices



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WHY?

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QUANTUM
COMPUTING

PHYSICS

QUANTUM
ANNEALING

[P. Magnard et al., arXiv:1801.07689 (2018)] [K. Geerlings et al., PRL **110**, 120501 (2013)]
[S. O. Valenzuela et al., Science **314**, 1589 (2006)] [D. J. Egger et al., arXiv:1802.08980 (2018)]
[M. Grajcar, et al. Nat. Phys. **4**, 612 (2008)] [D. Ristè et al., PRL **109**, 240502 (2012)]
[M. D. Reed et al., APL **96**, 203110 (2010)] [M. Mariatoni et al., Science **334**, 61 (2011)]
[J. E. Johson et al., PRL **109**, 050506 (2012)] [P. Campagne-Ibarcq et al., PRX **3**, 021008 (2013)]

WHY?

QUANTUM
COMPUTING

PHYSICS

QUANTUM
ANNEALING

ON-CHIP ENVIRONMENT

[P. Magnard et al., arXiv:1801.07689 (2018)] [K. Geerlings et al., PRL **110**, 120501 (2013)]
[S. O. Valenzuela et al., Science **314**, 1589 (2006)] [D. J. Egger et al., arXiv:1802.08980 (2018)]
[M. Grajcar, et al. Nat. Phys. **4**, 612 (2008)] [D. Ristè et al., PRL **109**, 240502 (2012)]
[M. D. Reed et al., APL **96**, 203110 (2010)] [M. Mariatoni et al., Science **334**, 61 (2011)]
[J. E. Johson et al., PRL **109**, 050506 (2012)] [P. Campagne-Ibarcq et al., PRX **3**, 021008 (2013)]

Quantum-limited heat conduction

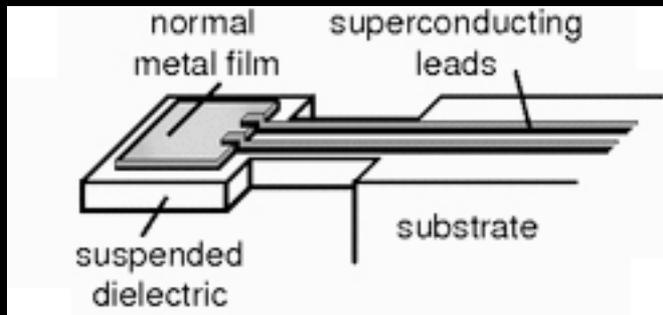
PICO

Theory for microwaves

- No distance limit
- Quantum limit for heat conductance

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

[D. R. Schmidt et al., PRL **93**, 045901 (2004)]

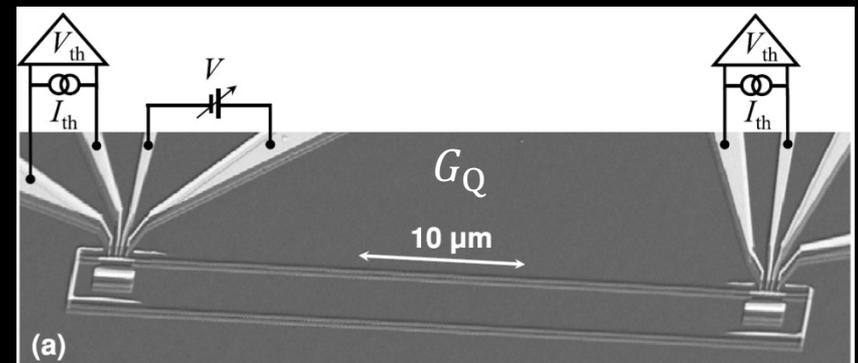


Subwavelength experiments

[M. Meschke et al., Nature **444**, 187 (2006)]

[A. Timofeev et al., PRL **102**, 200801 (2009)]

- Distance $\sim 50 \mu\text{m}$
- No impedance matching with transmission line

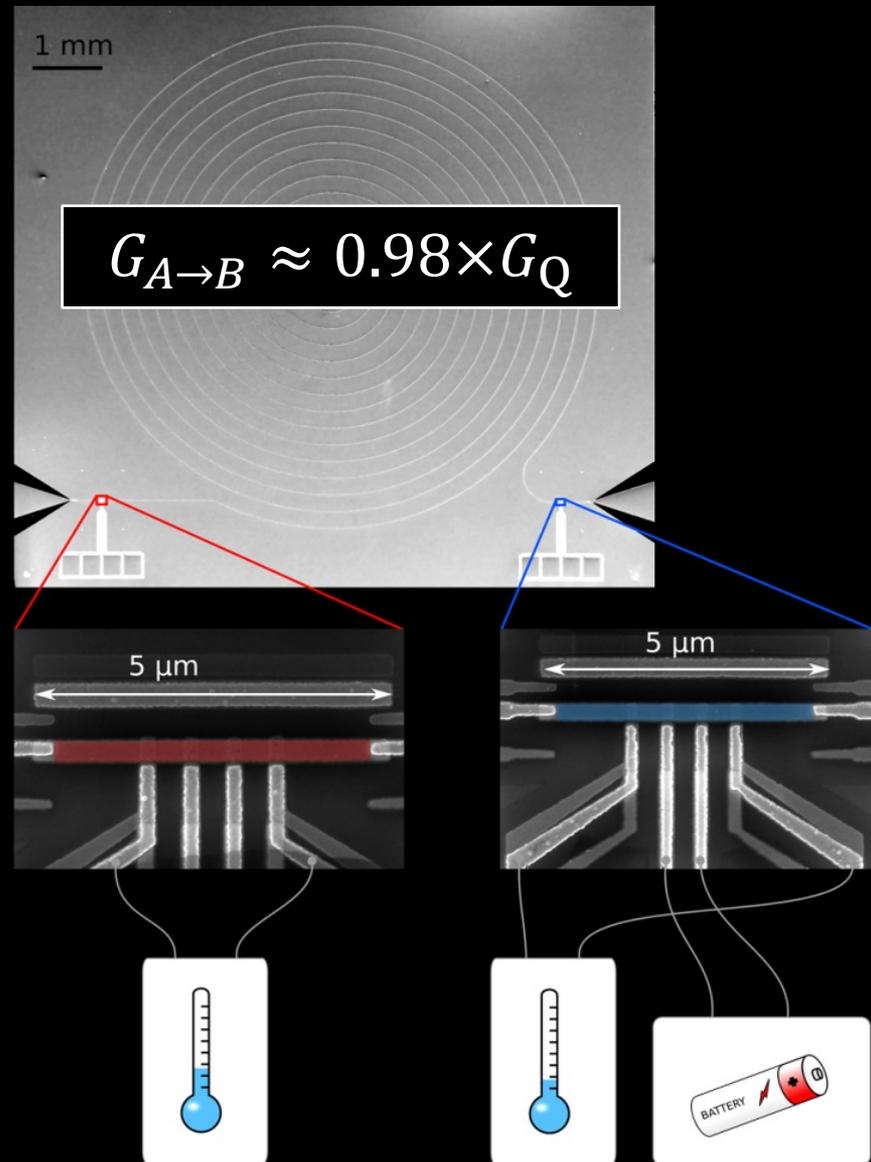
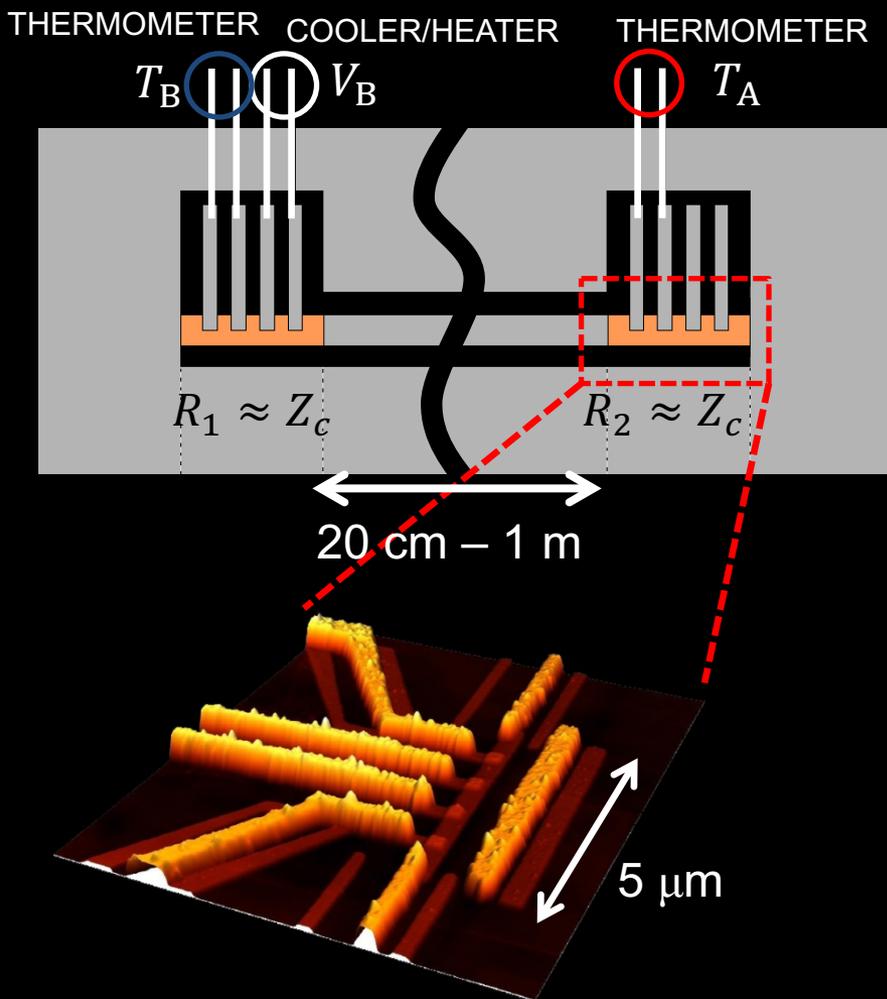


[General theory: J. Pendry, J. Phys. A **16**, 2161 (1983)]

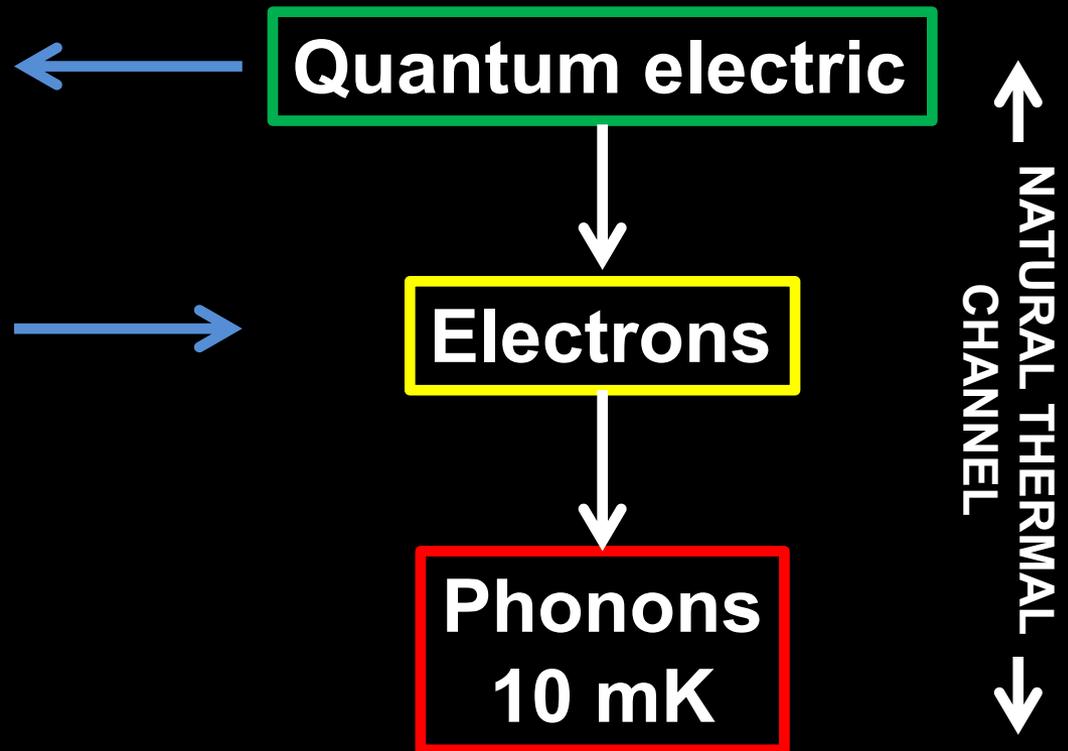
[Experiments: K. Schwab et al., Nature **404**, 974 (2000); S. Jezouin et al., Science **342**, 601 (2013)]

Far-away environment

[M. Partanen et al., Nature Phys. 12, 460 (2016)]

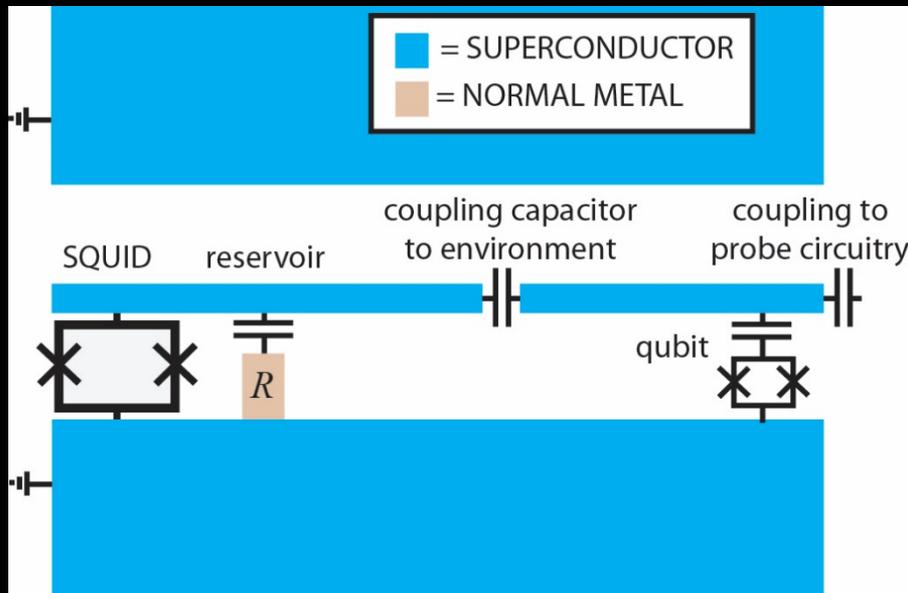


Quantum fridge



Tunable-Environment Qubit

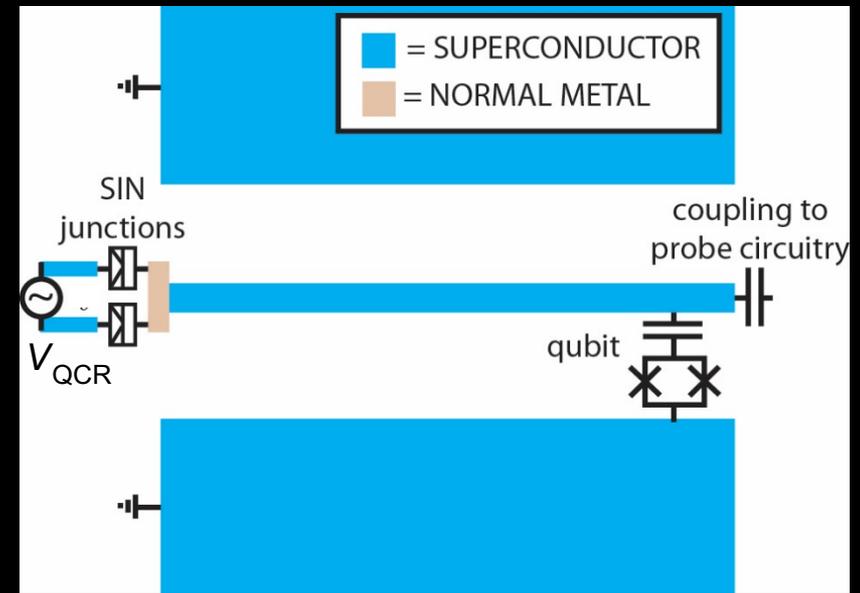
TUNABLE HEAT SINK



[J. Tuorila et al., npj Quant. Inf. **3**, 27 (2017)]

[M. Partanen et al., Sci. Rep. **8**, 6325 (2018)]

QUANTUM-CIRCUIT REFRIGERATOR



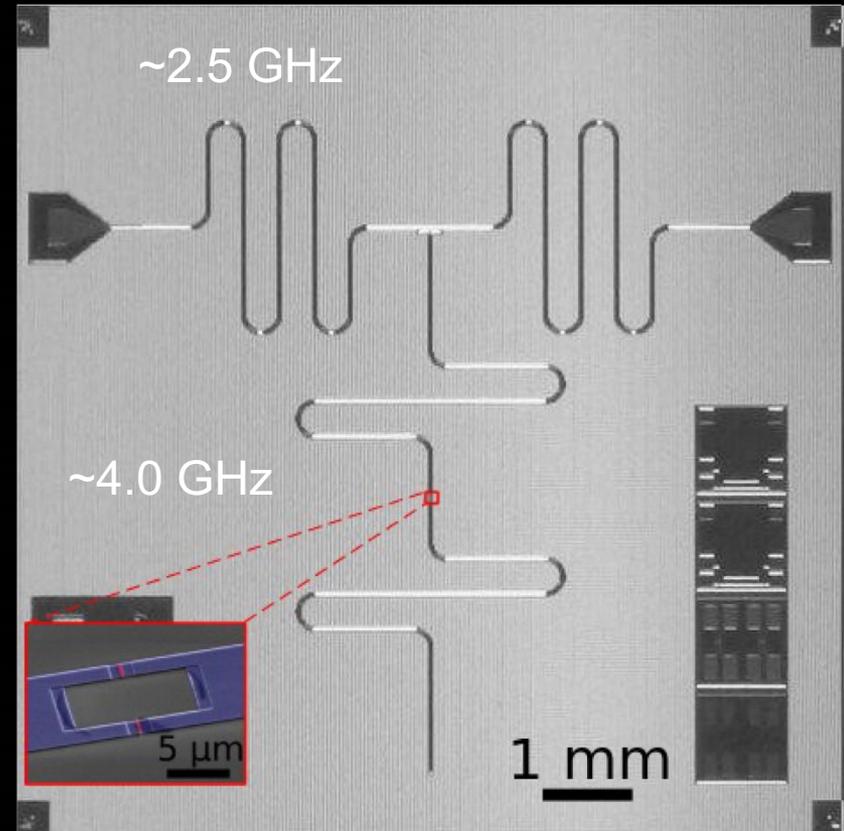
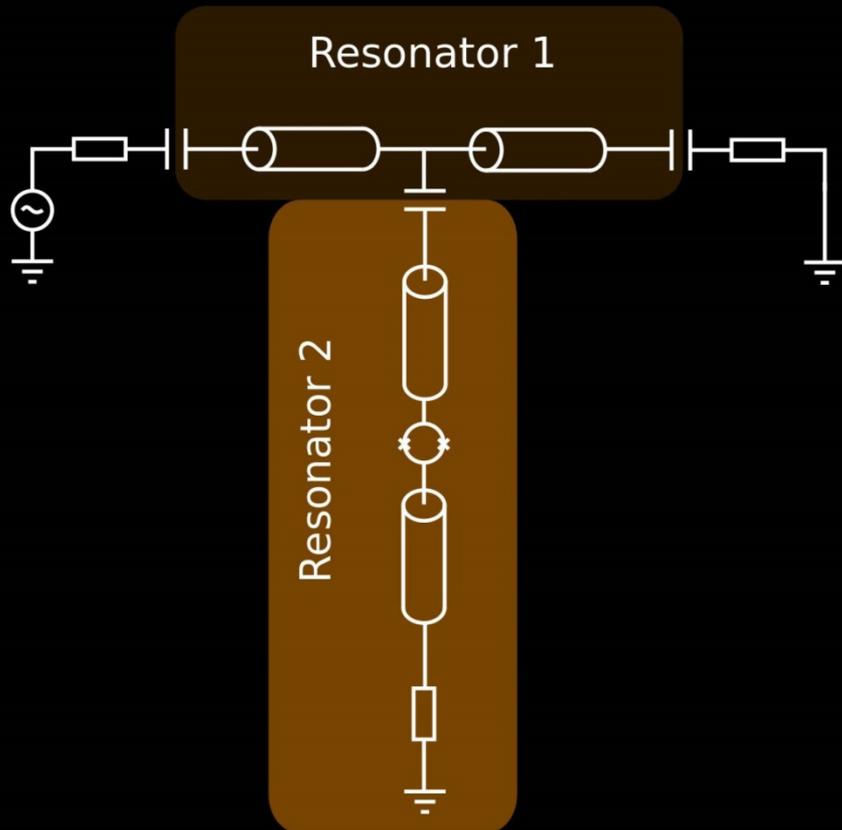
[K. Y. Tan et al., Nat. Commun. **8**, 15189 (2017)]

[M. Silveri et al. Phys. Rev. B **96**, 094524 (2017)]

[S. Masuda et al. Sci. Rep. **8**, 3966 (2018)]

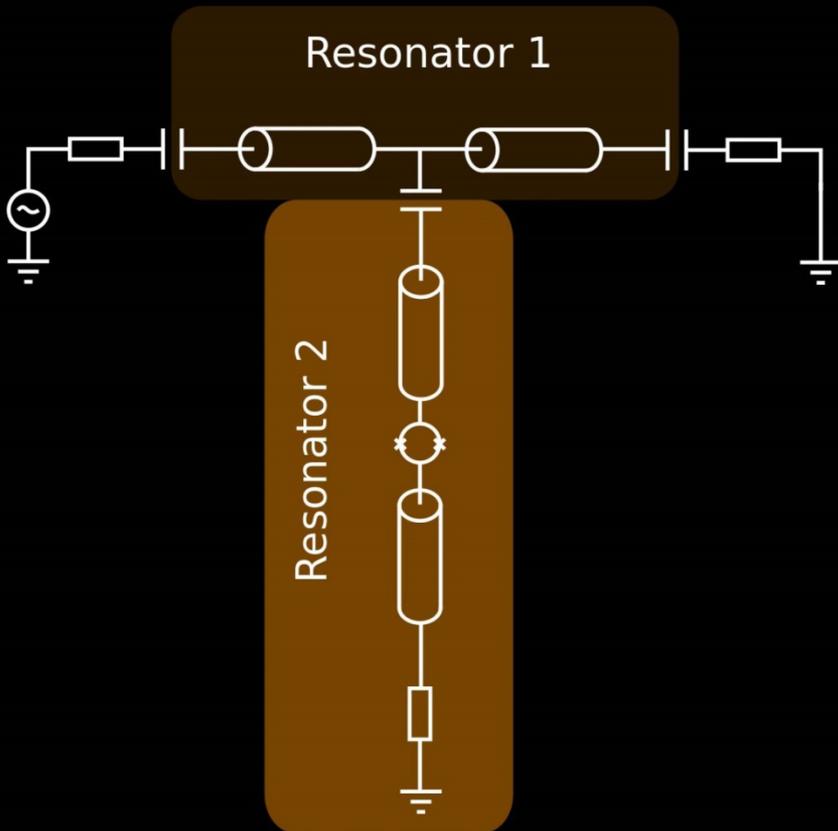
Tunable heat sink experiments

[M. Partanen et al., Sci. Rep. 8, 6325 (2018)]

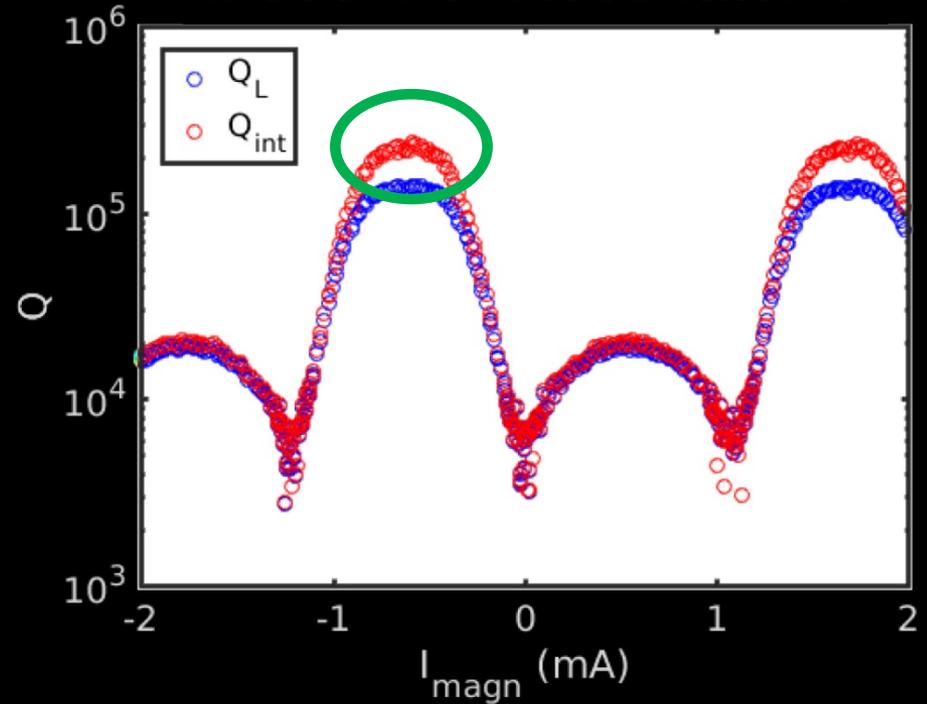


Tunable heat sink experiments

[M. Partanen et al., Sci. Rep. 8, 6325 (2018)]

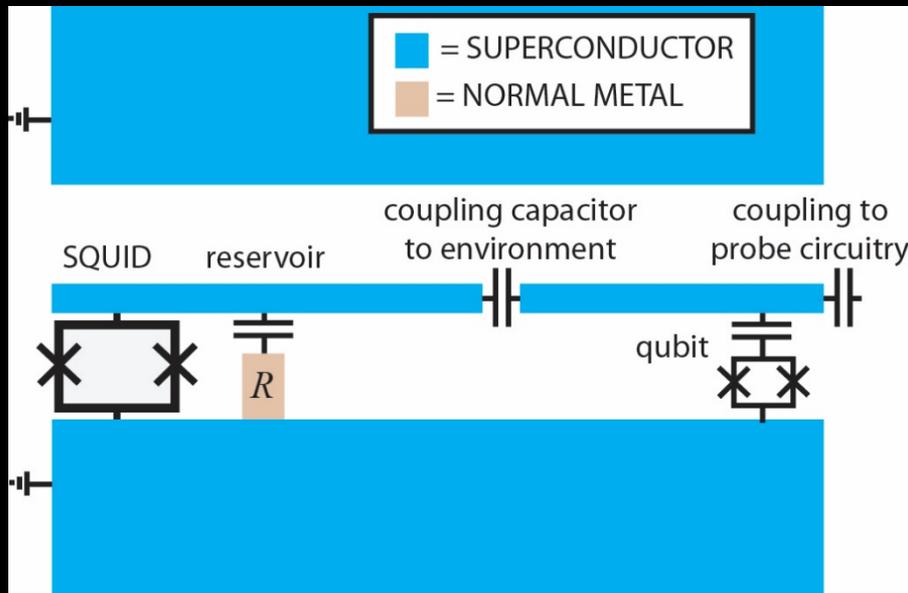


Mode 4 of Resonator 1



Tunable-Environment Qubit

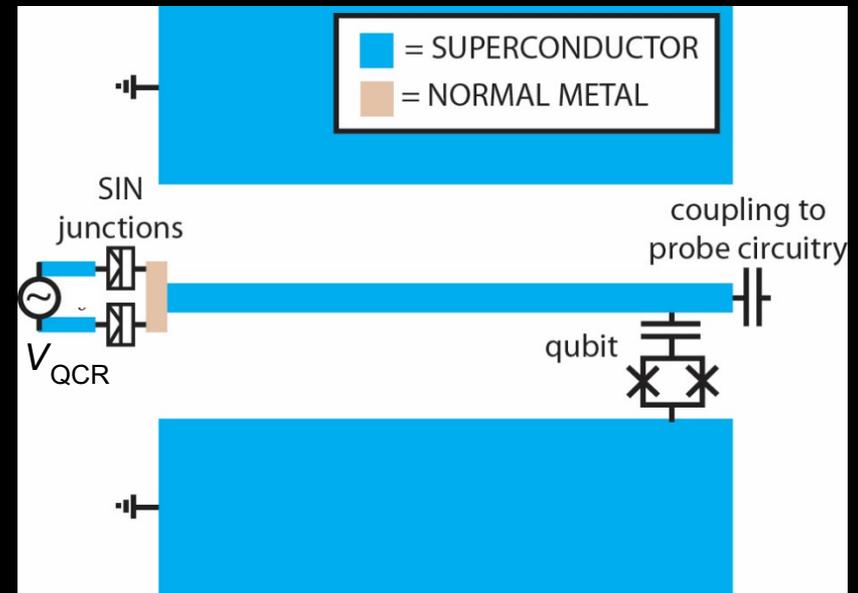
TUNABLE HEAT SINK



[J. Tuorila et al., npj Quant. Inf. **3**, 27 (2017)]

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QUANTUM-CIRCUIT REFRIGERATOR



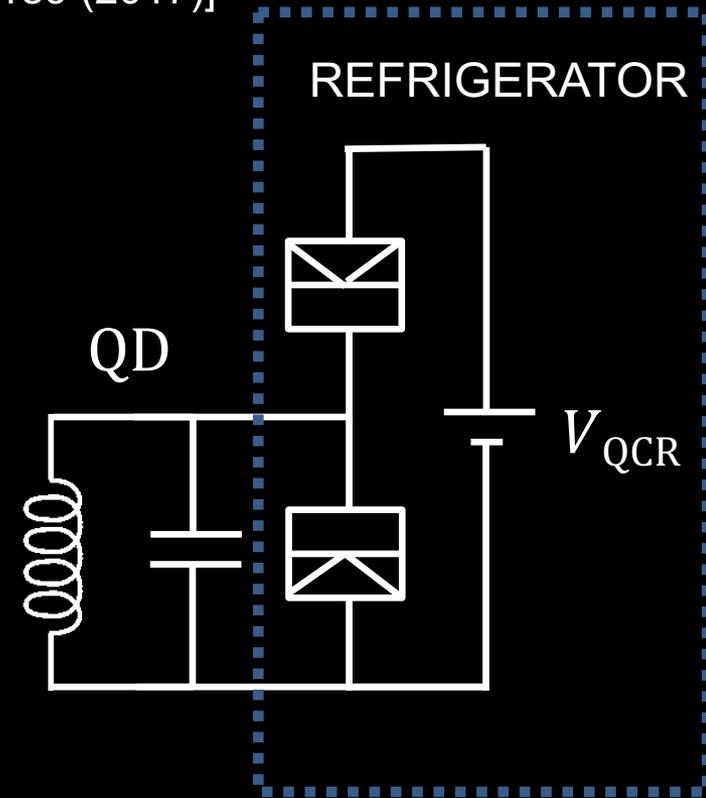
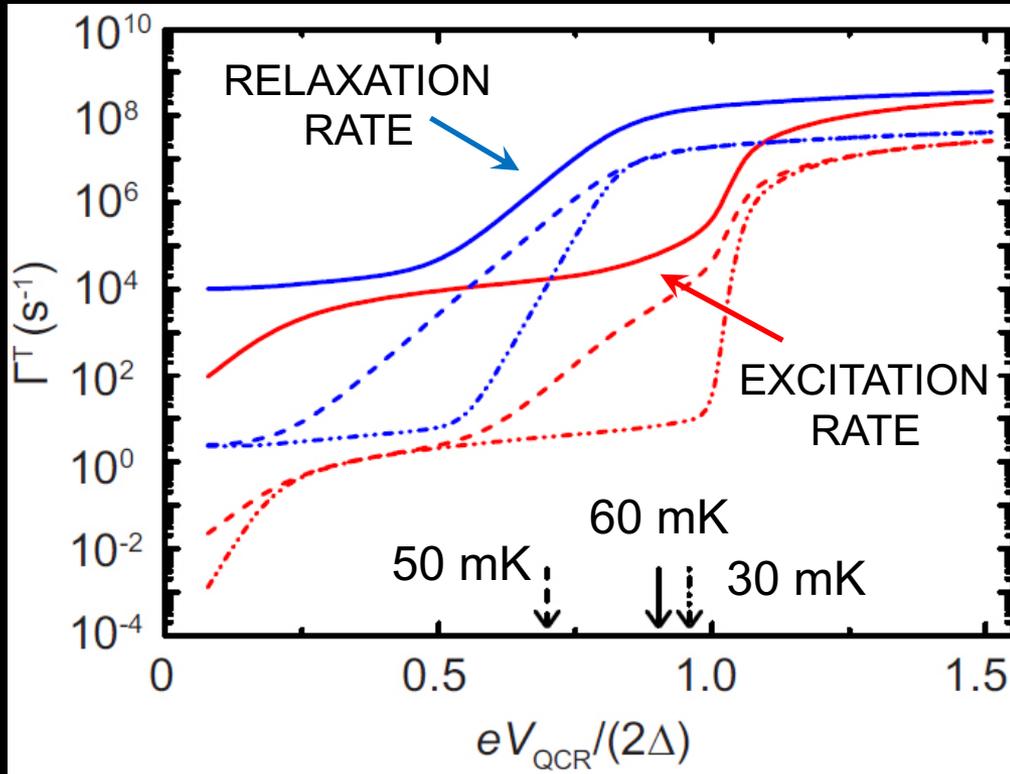
[K. Y. Tan et al., Nat. Commun. **8**, 15189 (2017)]

[M. Silveri et al. Phys. Rev. B **96**, 094524 (2017)]

[S. Masuda et al. Sci. Rep. **8**, 3966 (2018)]

$P(E)$ theory for the QCR

[K. Y. Tan et al., Nat. Commun. 8, 15189 (2017)]



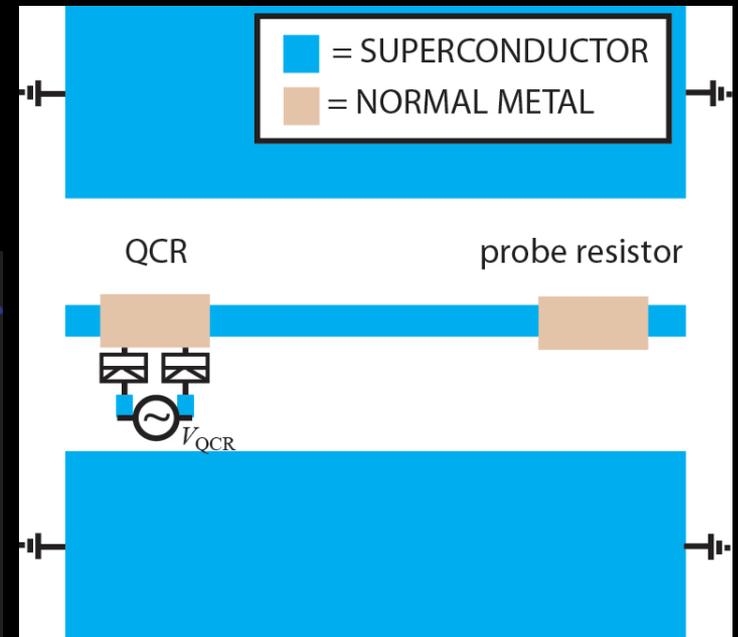
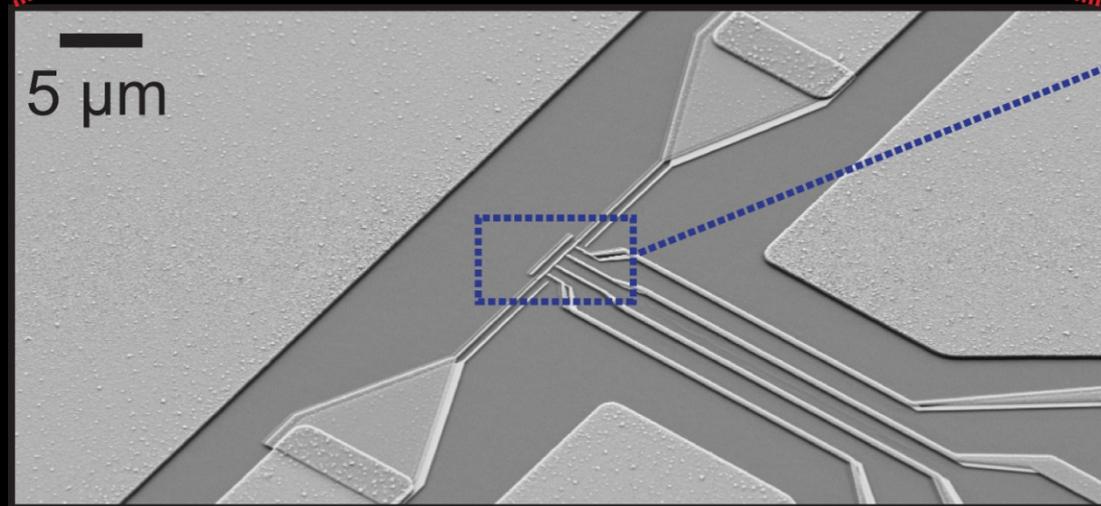
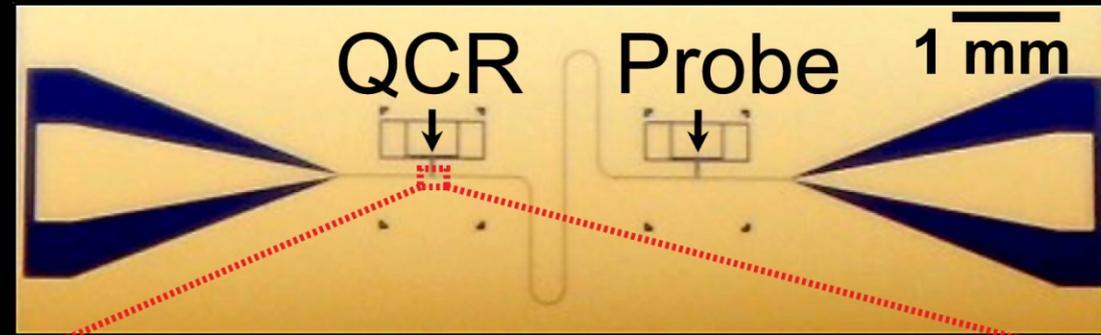
Transition rate theory: [M. Silveri et al. Phys. Rev. B 96, 094524 (2017)]

WORKS ALSO FOR QUBITS!

Quantum-Circuit Refrigerator

[K. Y. Tan et al., Nat. Commun. 8, 15189 (2017)]

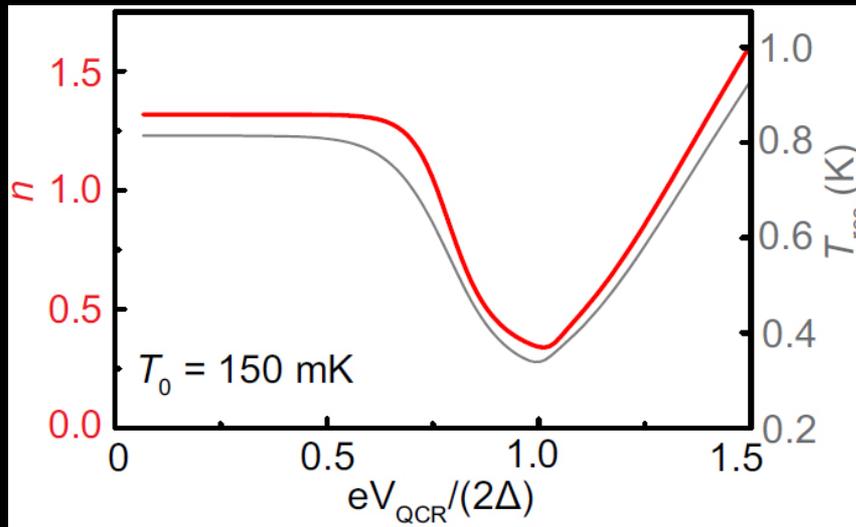
DEVICE



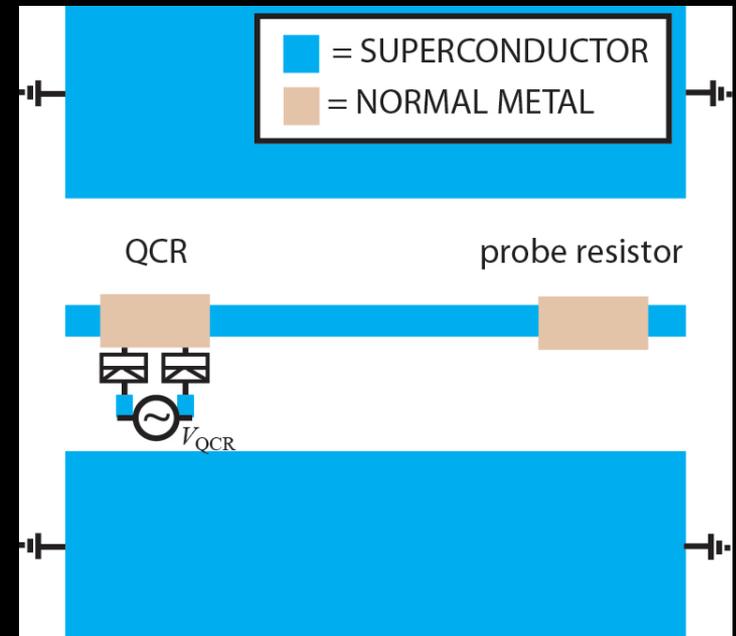
Quantum-Circuit Refrigerator

[K. Y. Tan et al., Nat. Commun. 8, 15189 (2017)]

REFRIGERATION



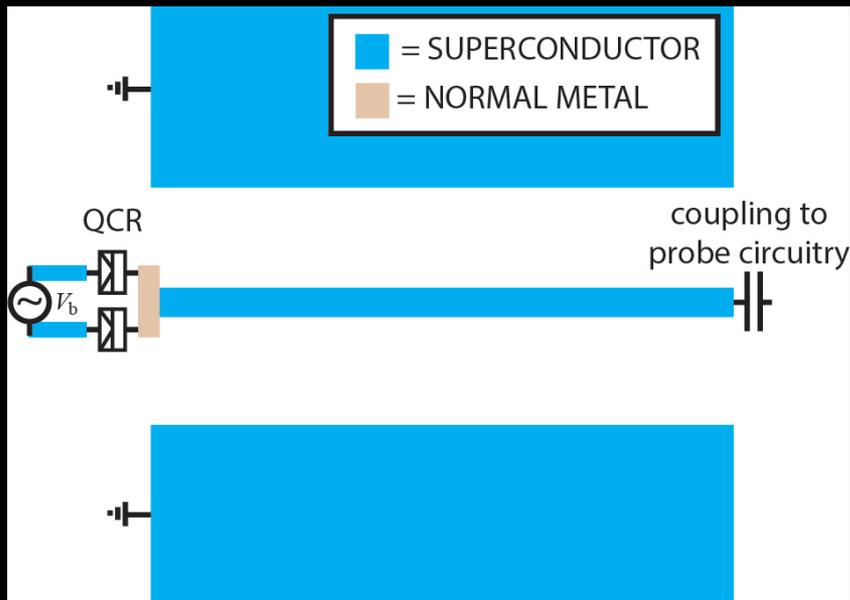
DEVICE



Emission Spectrum

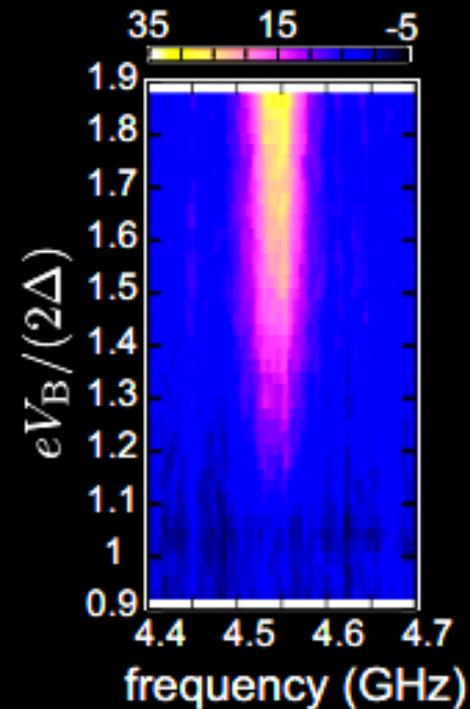
[S. Masuda et al. Sci. Rep. 8, 3966 (2018)]

DEVICE



RESULTS

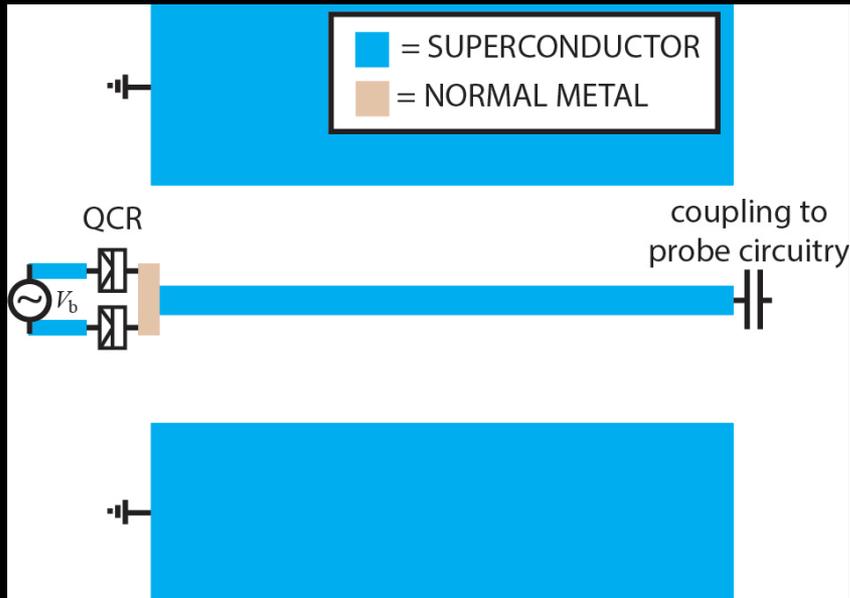
Power spectral density (fW/Hz)



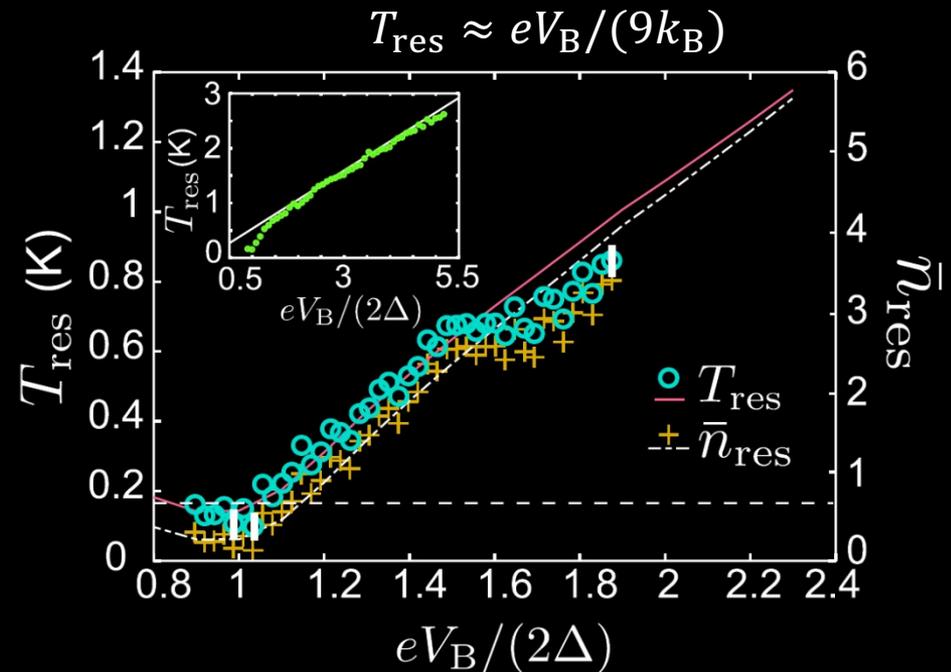
Emission Spectrum

[S. Masuda et al. Sci. Rep. 8, 3966 (2018)]

DEVICE



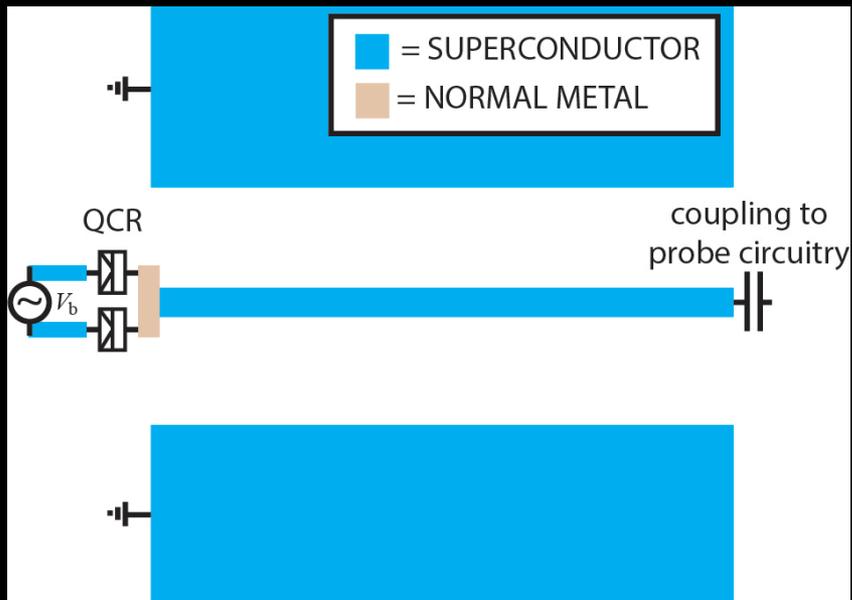
RESULTS



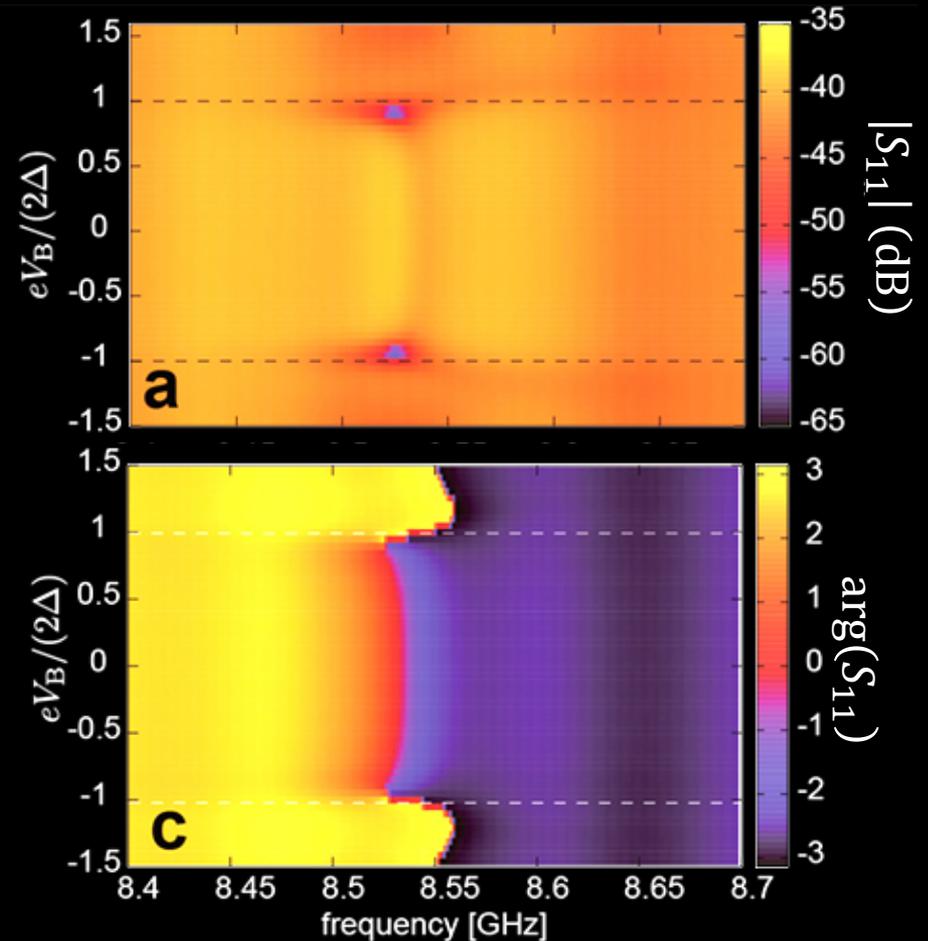
Reflection experiments

[M. Silveri et al. arXiv:1809.00822]

DEVICE



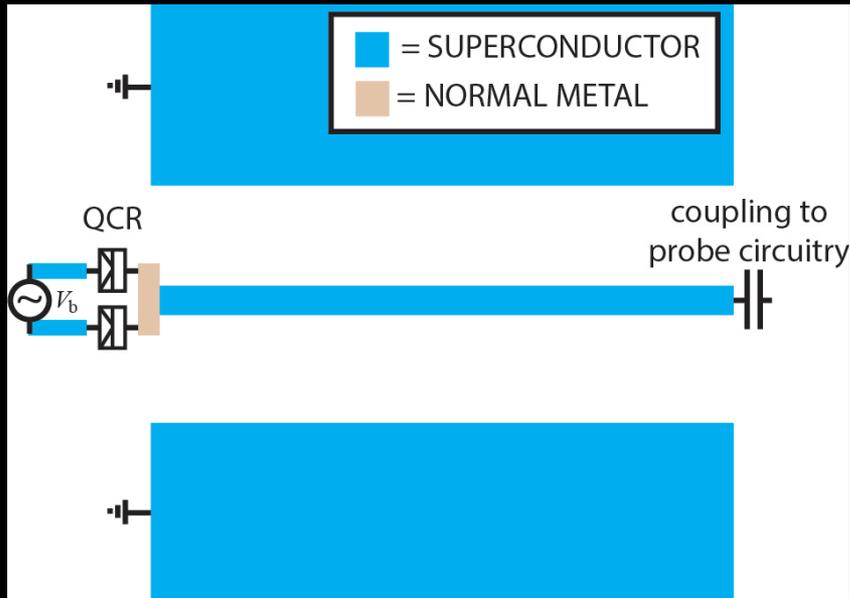
RESULTS



Reflection experiments

[M. Silveri et al. arXiv:1809.00822]

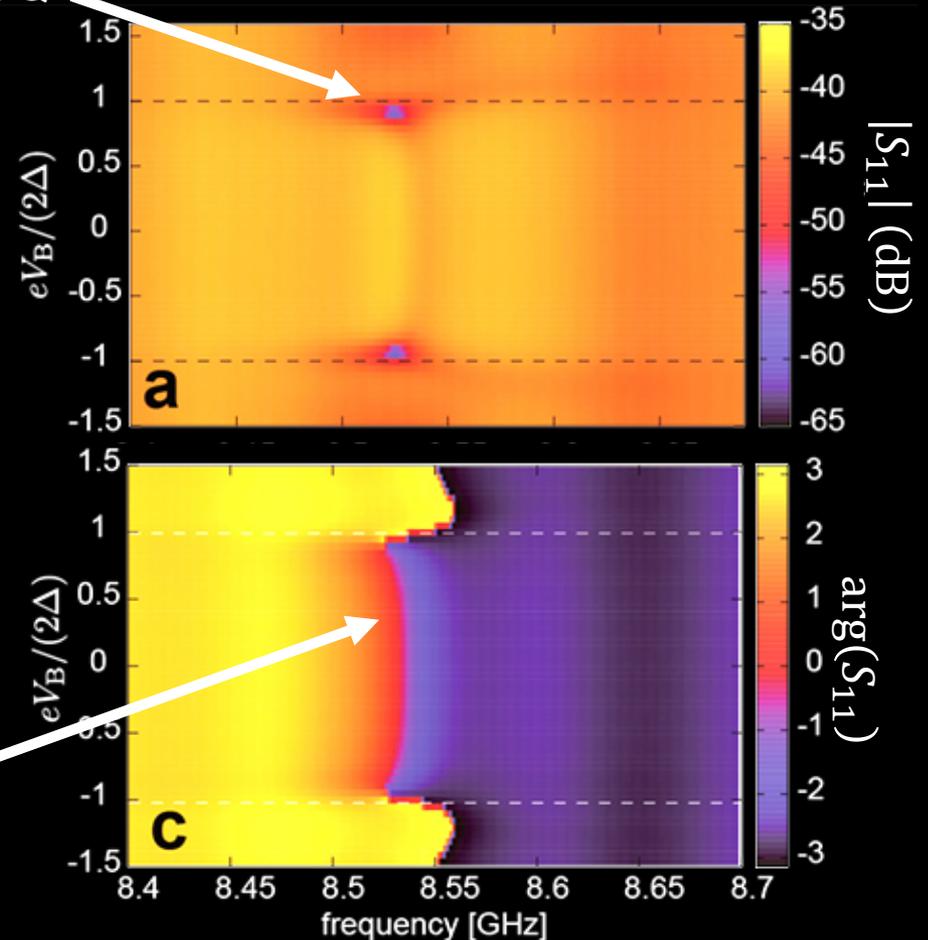
DEVICE



NOTICEABLE BENDING
→ LAMB SHIFT

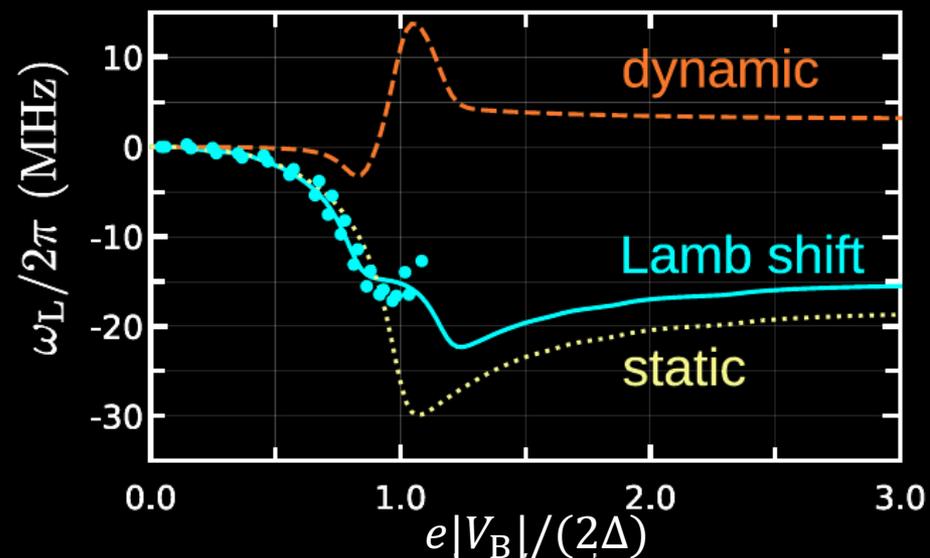
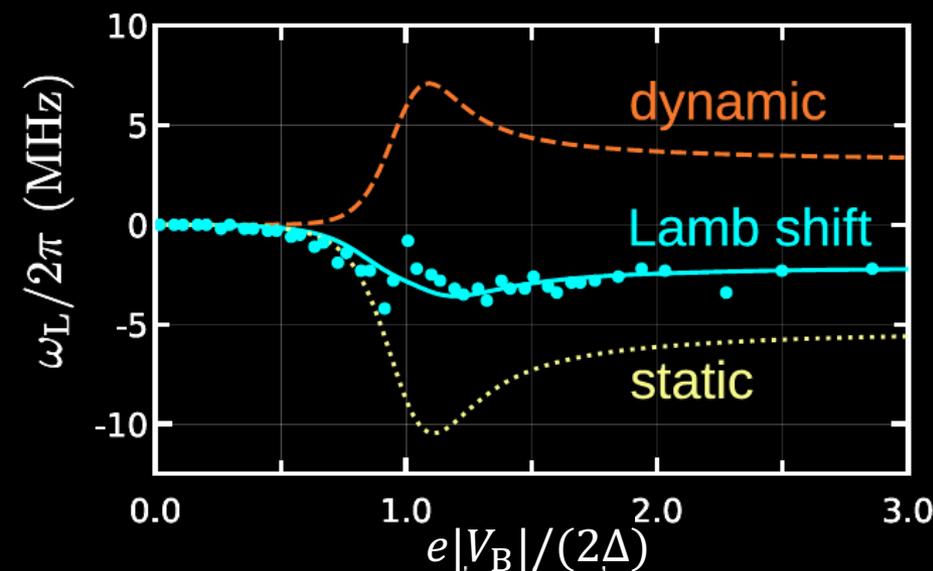
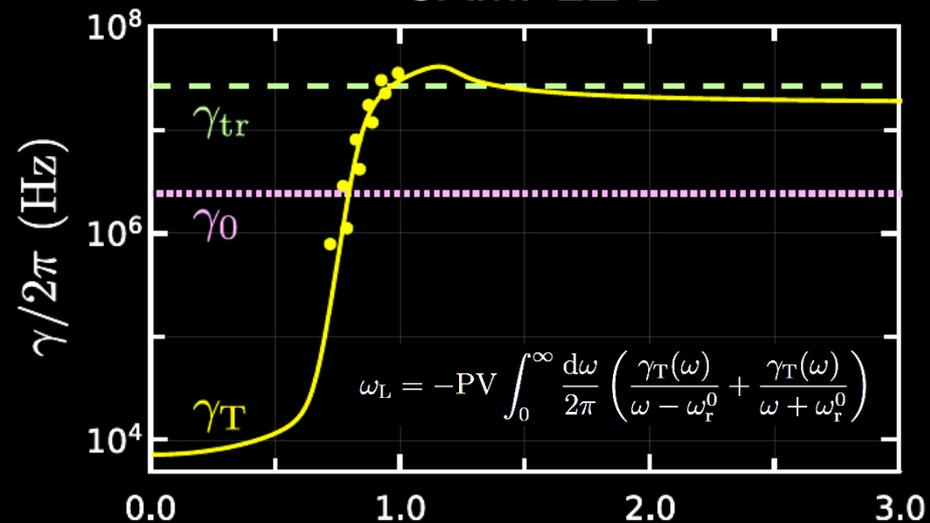
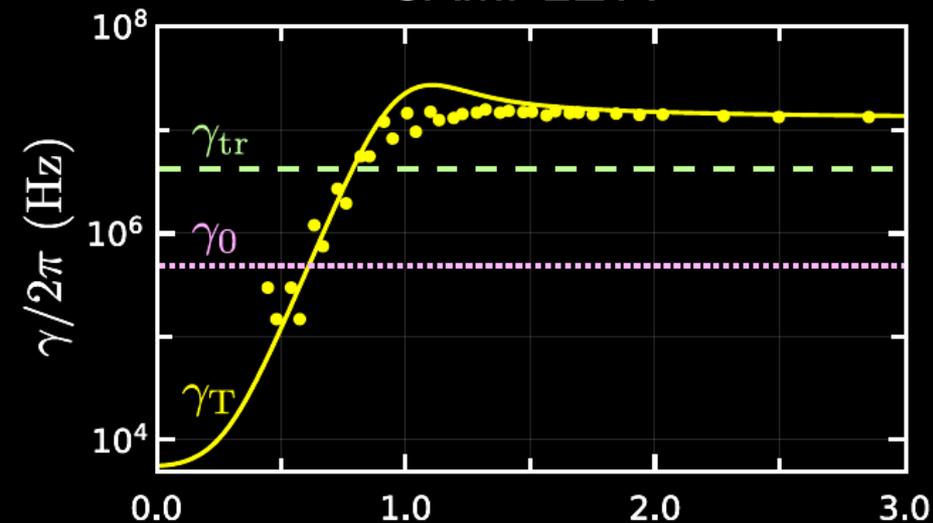
CRITICAL COUPLING
→ TUNABLE Q

RESULTS



Reflection experiments

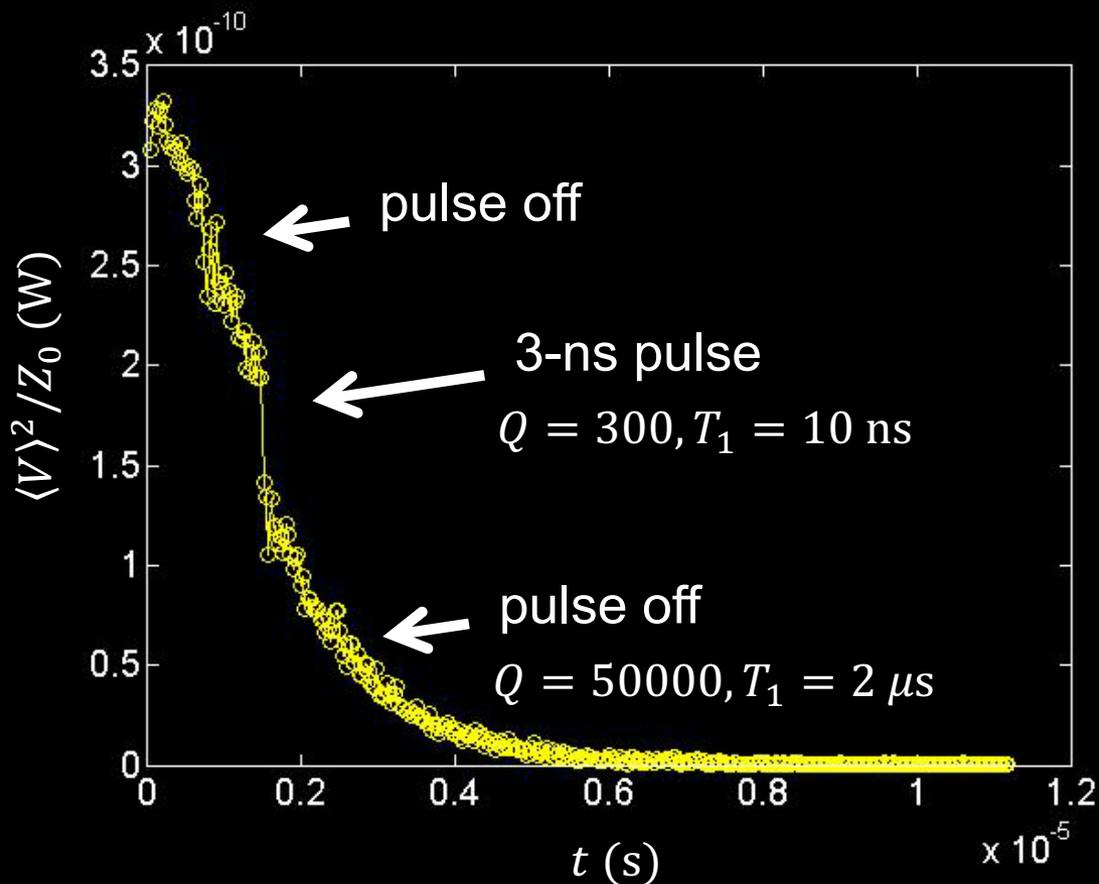
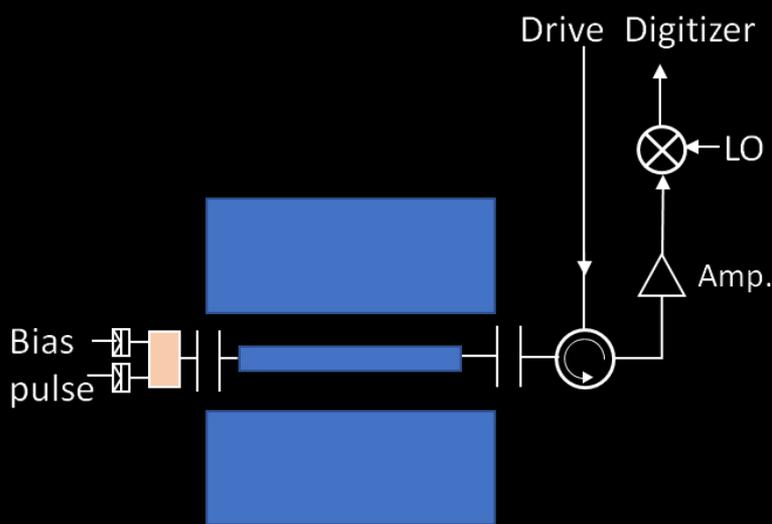
SAMPLE A [M. Silveri et al. arXiv:1809.00822] SAMPLE B



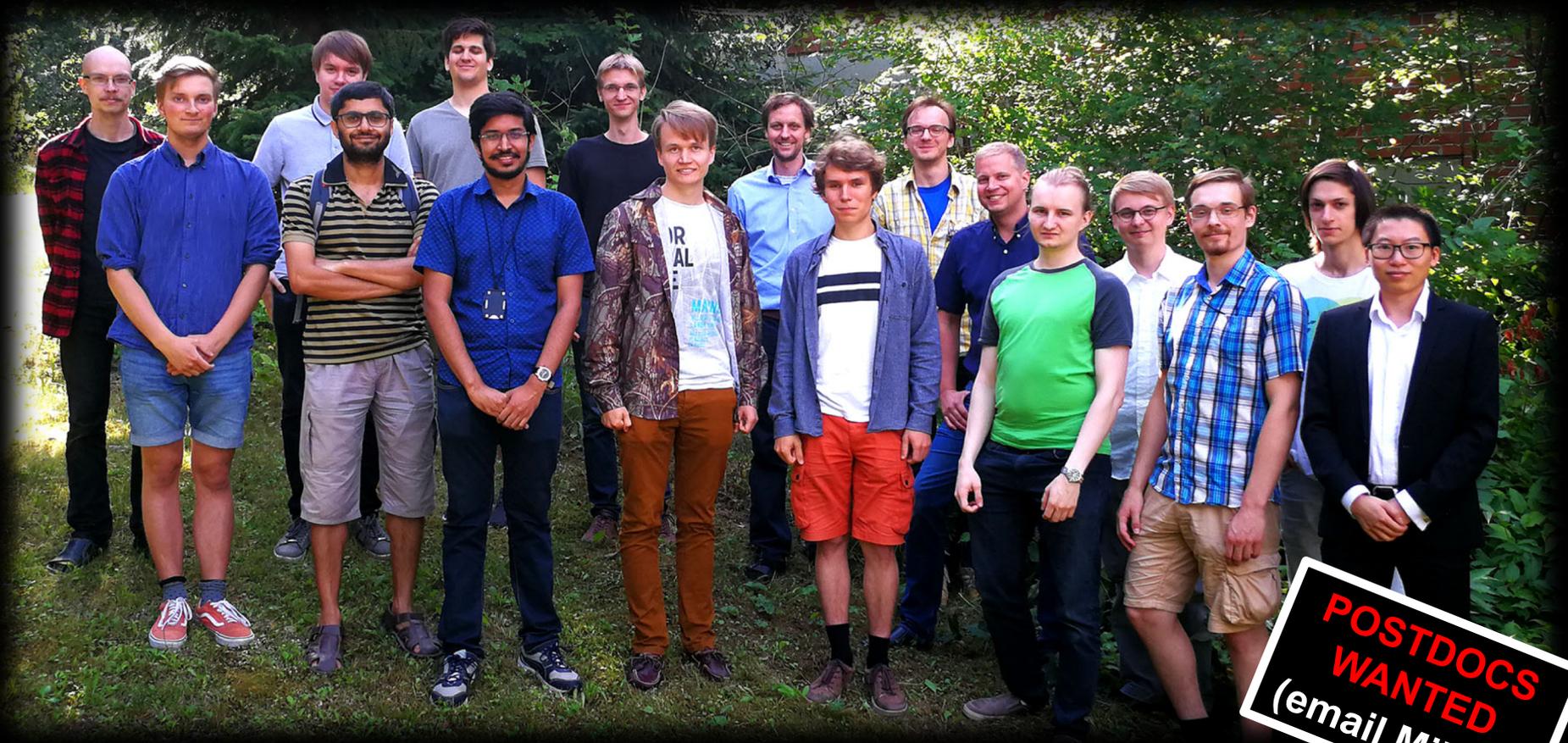
Fast on/off switch of QCR

[K. Y. Tan et al. unpublished]

1. Stop resonator drive and measure output voltage
2. Pulse V_b

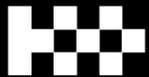


Quantum Computing and Devices (QCD)



**POSTDOCS
WANTED**
(email Mikko)

J&AE JANE JA AATOS
ERKON SÄÄTIÖ

 Teknologiateollisuuden
100-vuotissaatiö

A! Aalto University
School of Science

 **erc**

European Research Council


**SUOMEN
AKATEMIA**

Selected collaborators:
**H. Grabert, R. E. Lake, T. Ala-Nissilä,
J. Hassel, L. Grönberg, M. Prunnila,
S. Maniscalco, S. Masuda, J
Ankerhold, J. Pekola**

Summary and next steps

- Demonstrated the following:
 - Quantum-limited heat conduction across a meter
 - Quantum-circuit refrigerator
 - Microwave source based on NIS junctions
 - Tunable- Q resonators
 - Tunable Lamb shift
 - Fast on/off switching
- In the future:
 - Qubit initialization
 - Lower temperatures
 - Physics



JANE JA AATOS
ERKON SÄÄTIÖ

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Turun yliopisto
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Thanks!

