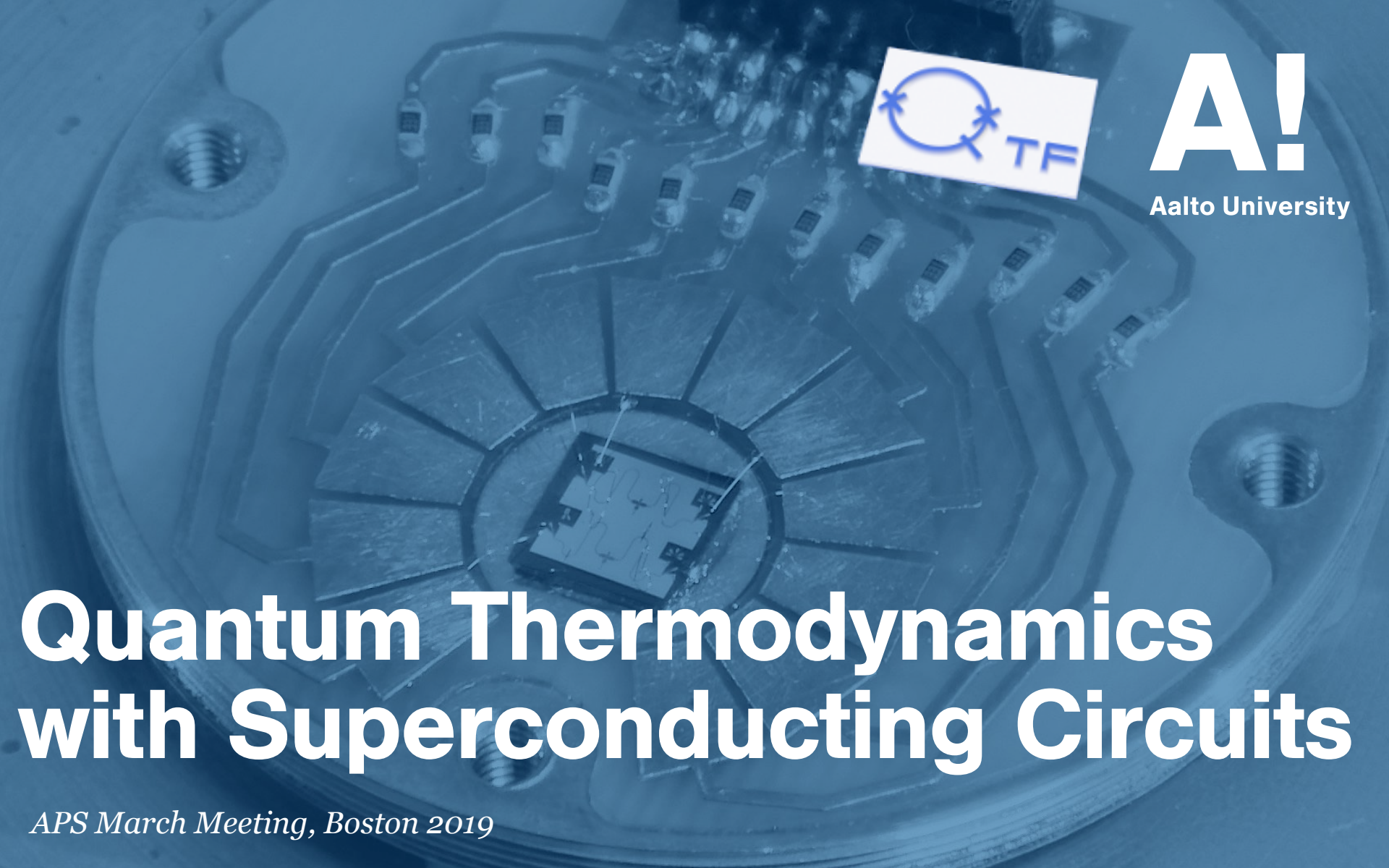
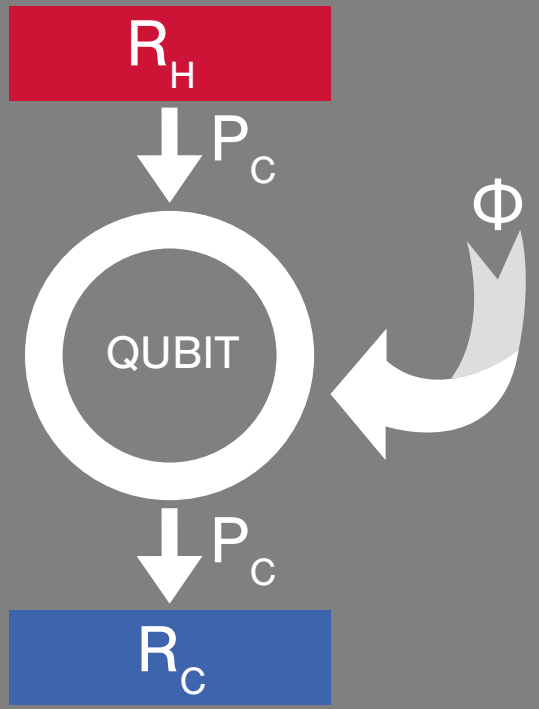


A!
Aalto University

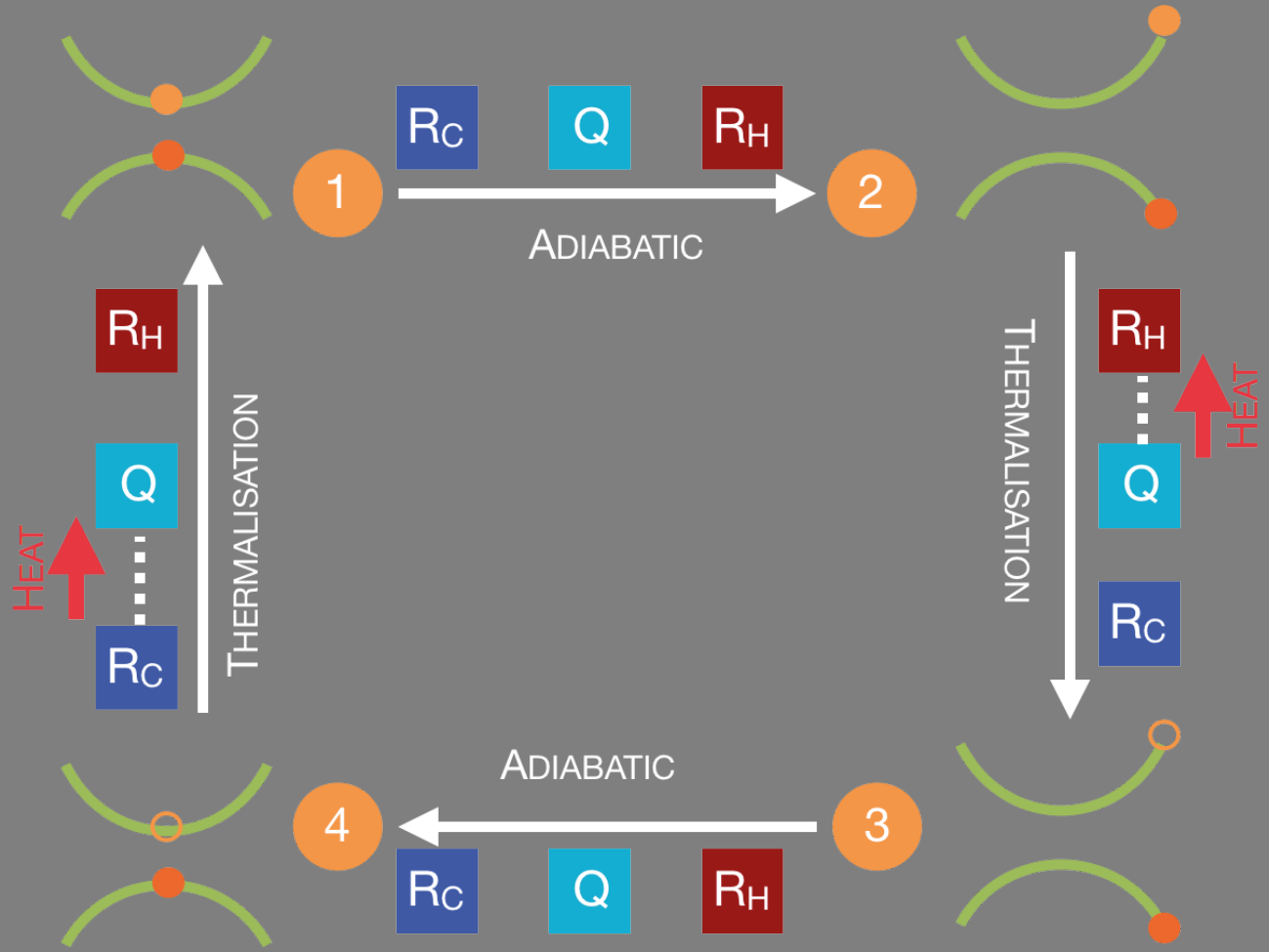
Quantum Thermodynamics with Superconducting Circuits

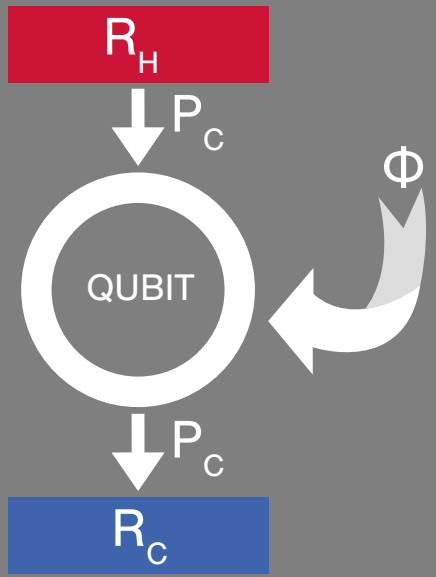
APS March Meeting, Boston 2019

Towards a Quantum Heat Engine



Jorden Senior





A. Niskanen, Y. Nakamura, J. Pekola, PRB 76, 174523 (2007)
B. Karimi and J. Pekola, PRB **94**, 184503 (2016)

Quantum heat engine (quantum Otto refrigerator)

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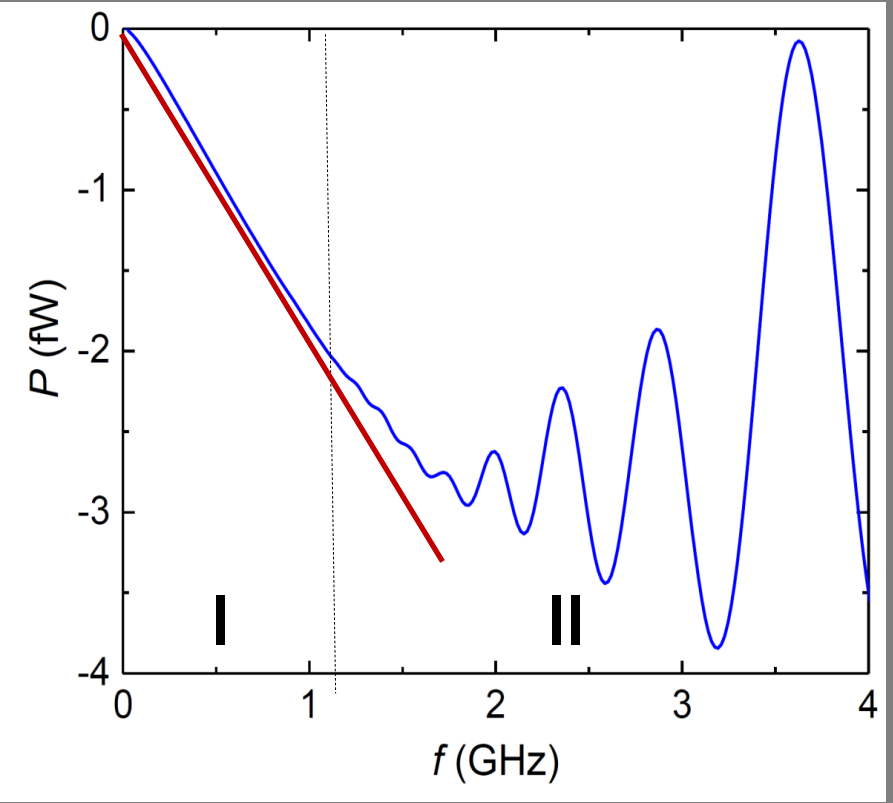
Different operation regimes:

I. Ideal Otto cycle
II. Coherent oscillations at high frequencies



A. Niskanen, Y. Nakamura, J. Pekola, PRB 76, 174523 (2007)
B. Karimi and J. Pekola, PRB **94**, 184503 (2016)

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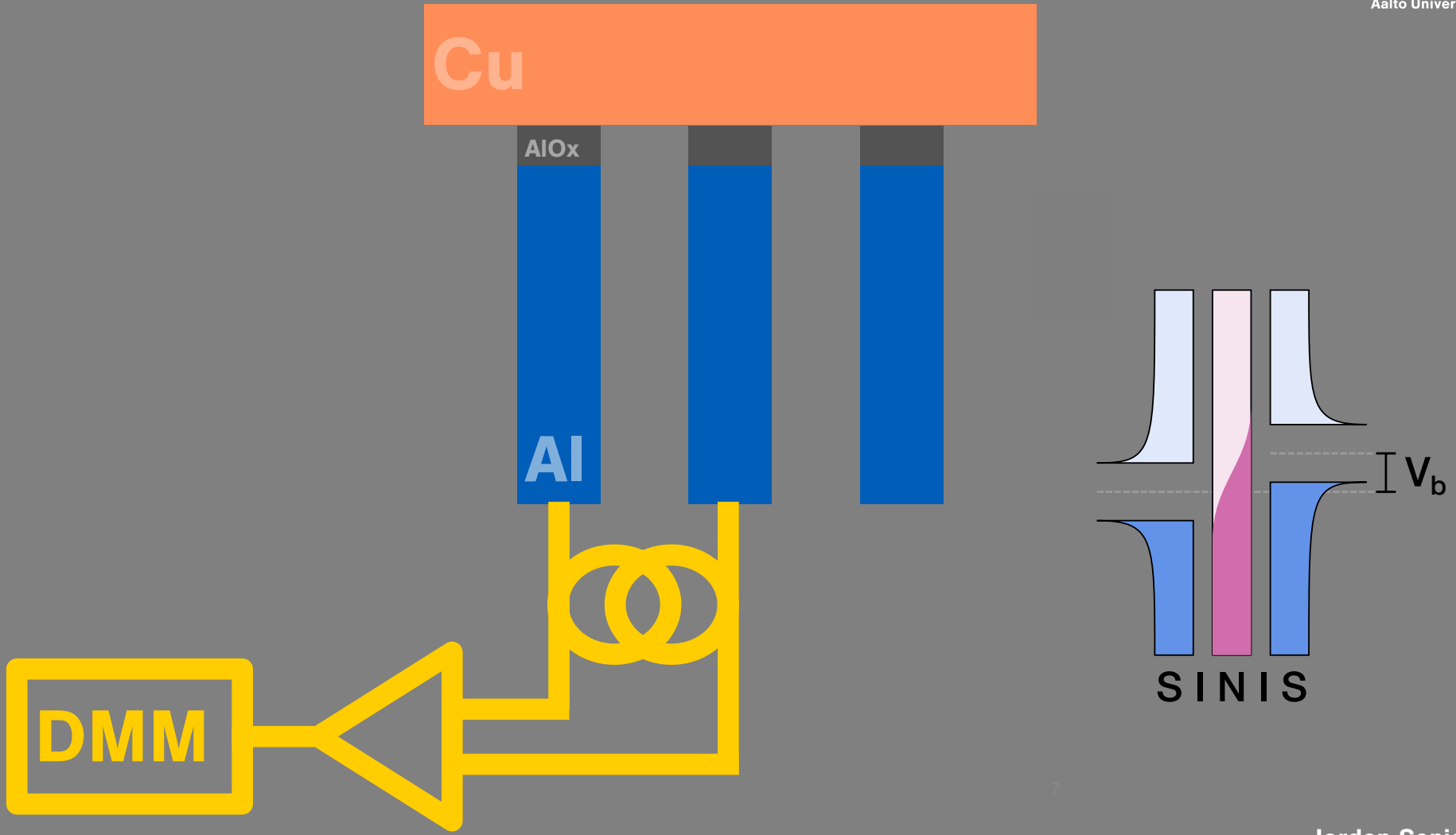
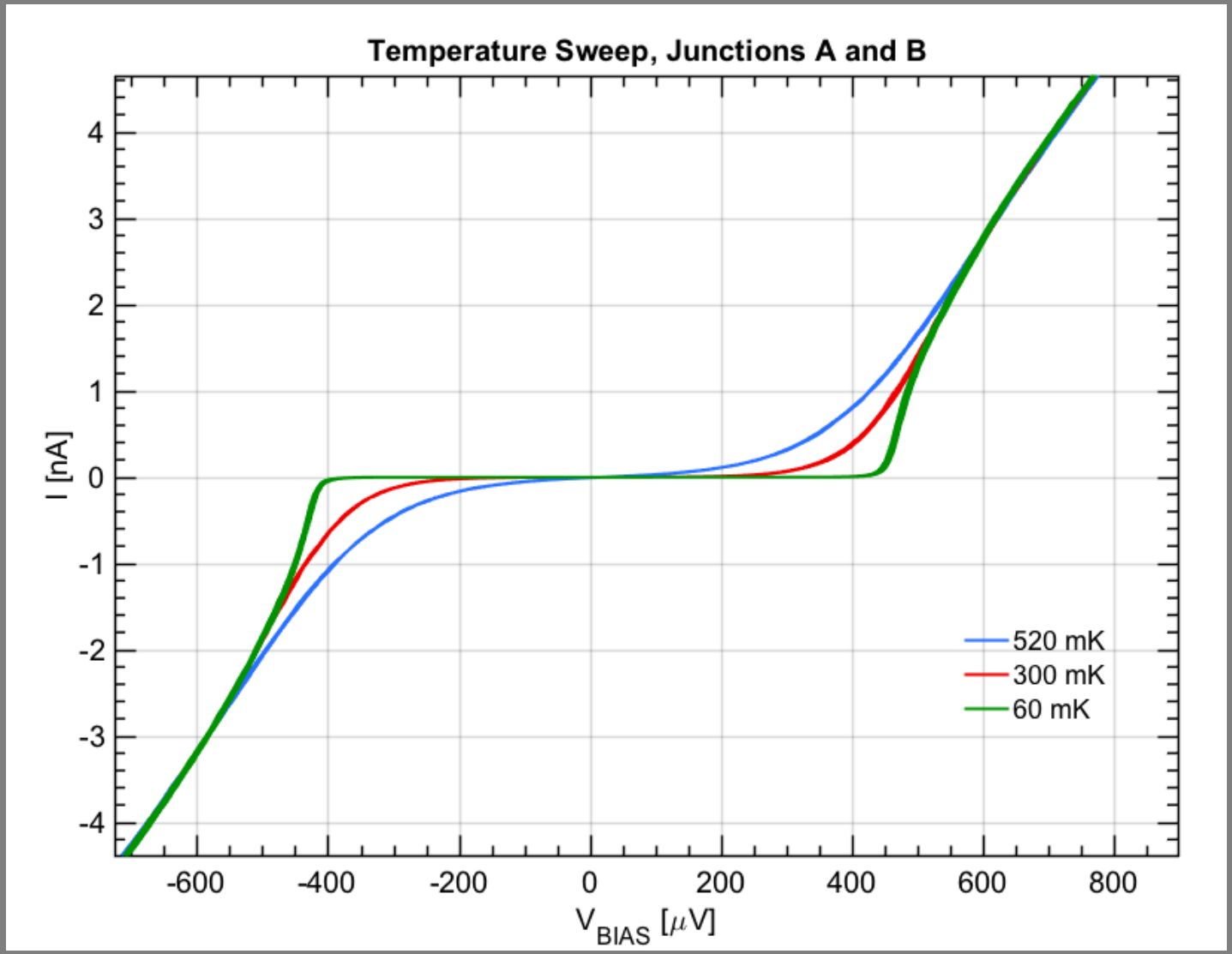
Let’s build our circuit…

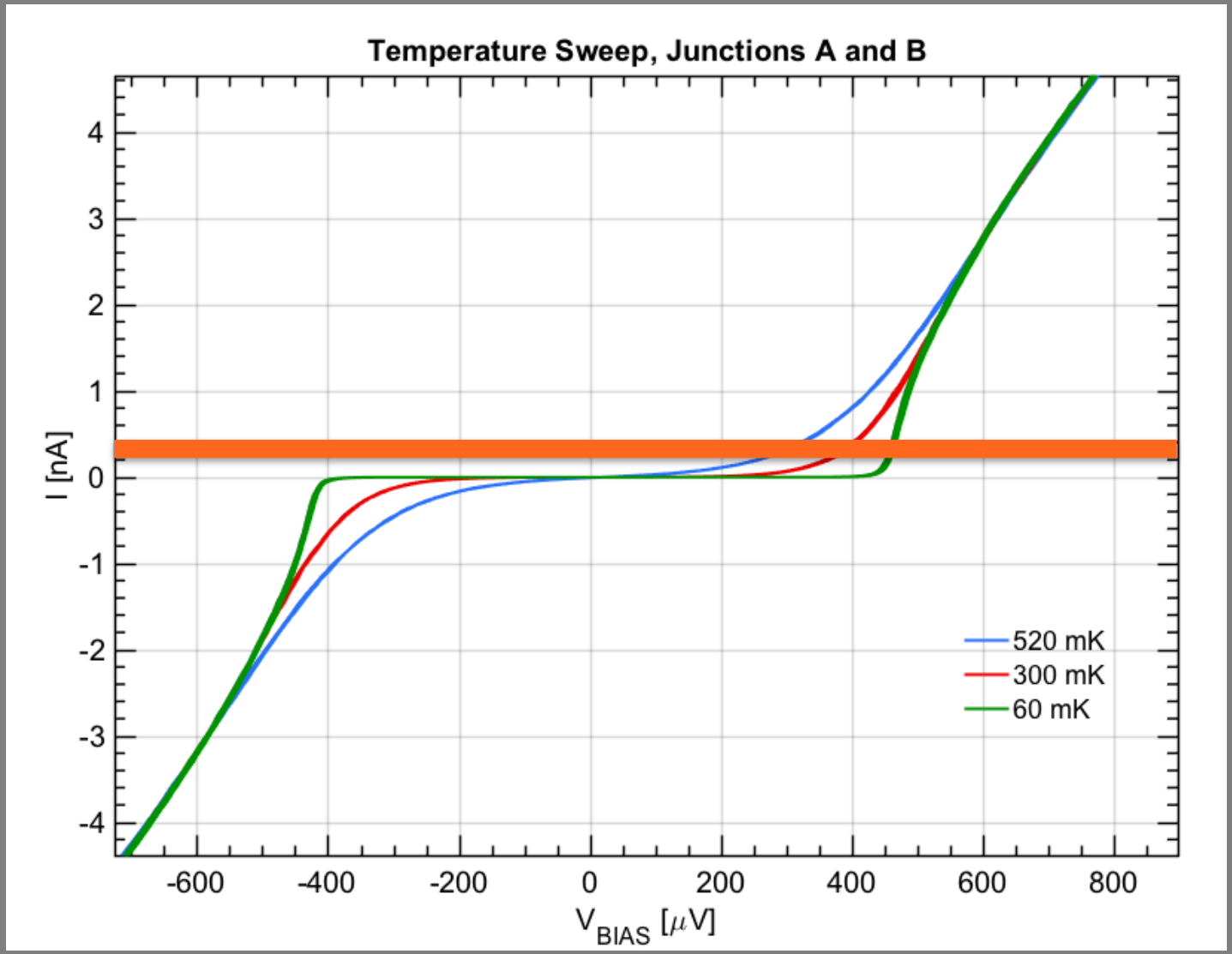
Aalto University

Cu

Jorden Senior


Cu
AlOx
Al
DMM
V_b
SINIS


Temperature Sweep, Junctions A and B
I [nA]
4
3
2
1
0
-1
-2
-3
-4
-600
-400
-200
0
200
400
600
800
V_{BIAS} [μV]
520 mK
300 mK
60 mK


Temperature Sweep, Junctions A and B
I [nA]
4
3
2
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0
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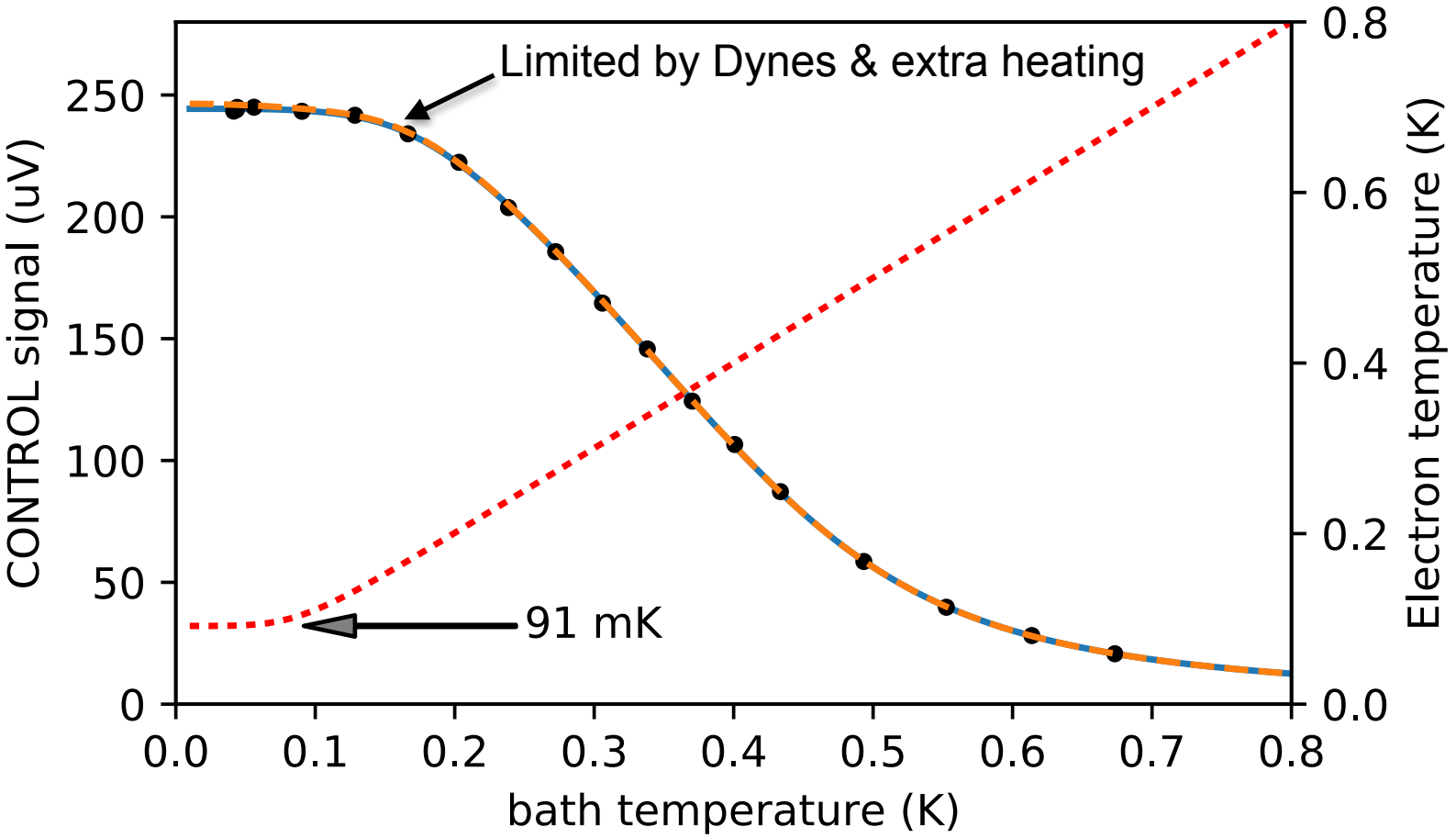
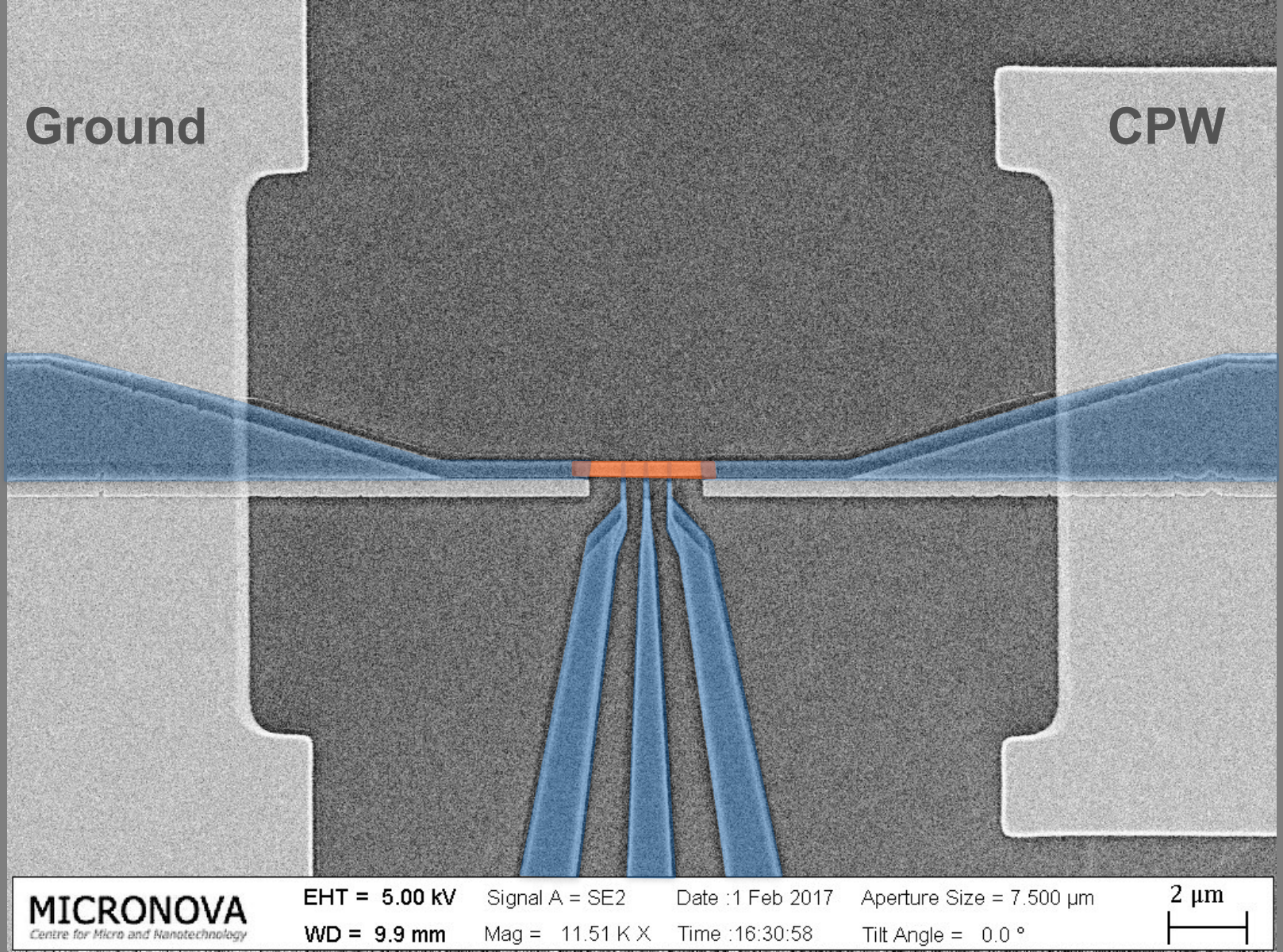
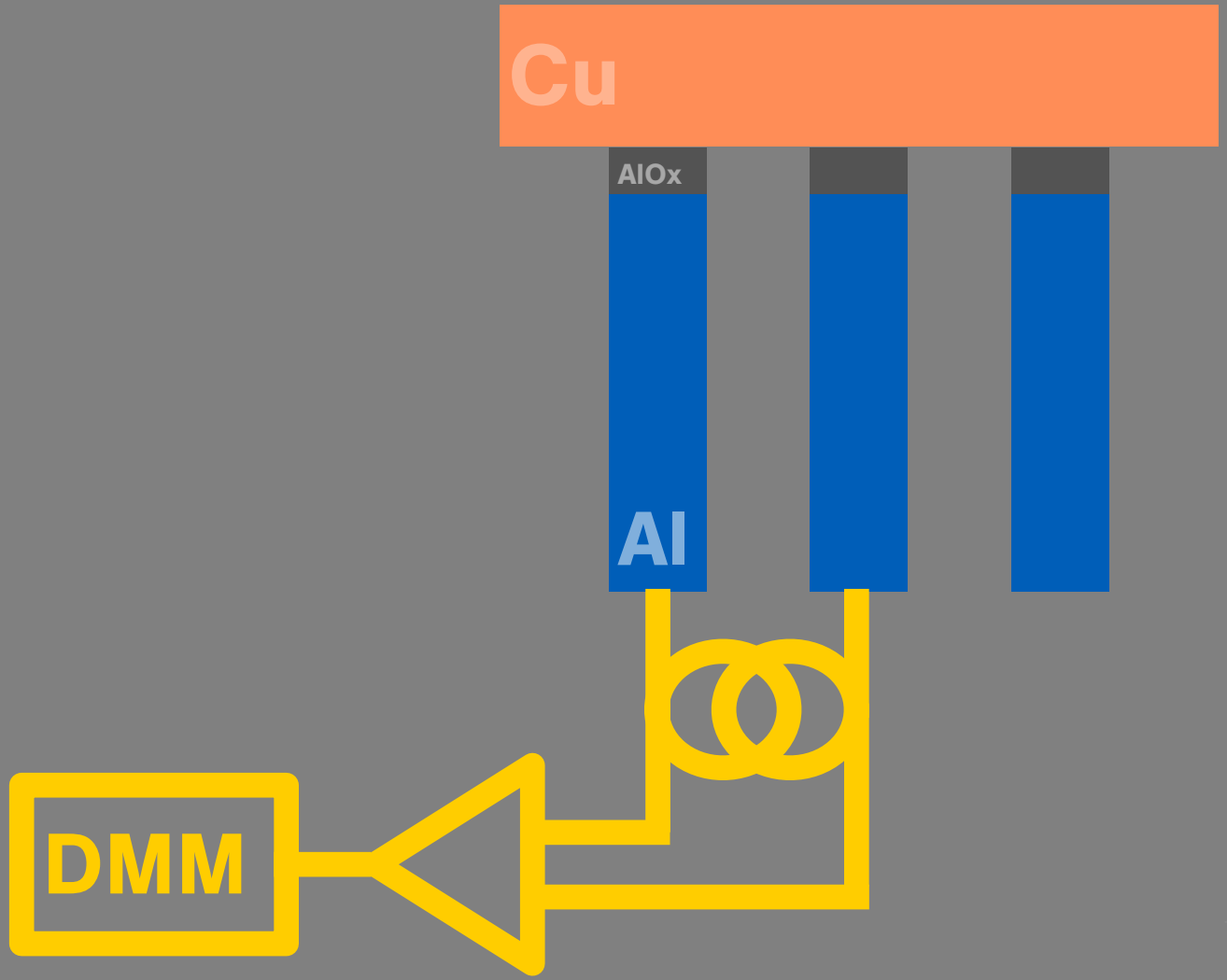
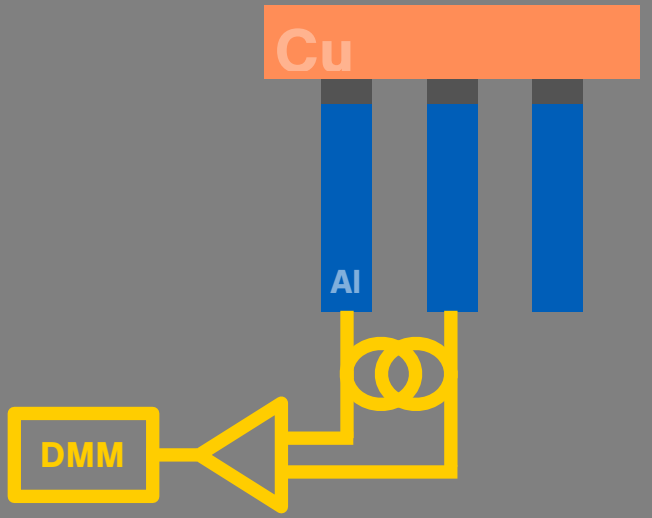
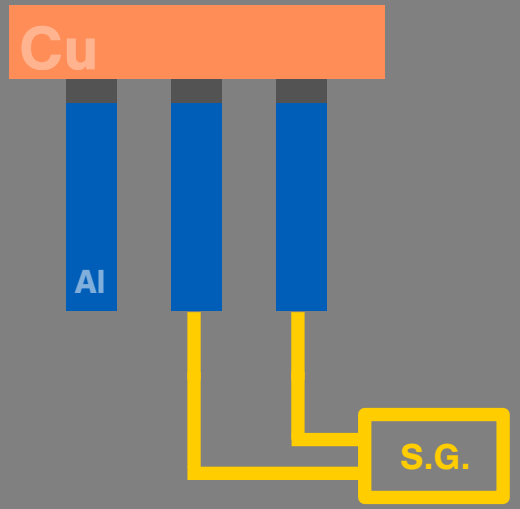
-3
-4
-600
-400
-200
0
200
400
600
800
V_{BIAS} [μV]
520 mK
300 mK
60 mK


Limited by Dynes & extra heating
91 mK
CONTROL signal (uV)
Electron temperature (K)
bath temperature (K)
0
50
100
150
200
250
0.0
0.2
0.4
0.6
0.8
0.1
0.3
0.5
0.7


Ground
CPW
MICRONOVA
Centre for Micro and Nanotechnology
EHT = 5.00 kV
WD = 9.9 mm
Signal A = SE2
Mag = 11.51 K X
Date :1 Feb 2017
Time :16:30:58
Aperture Size = 7.500 µm
Tilt Angle = 0.0 °
2 µm


Cu
AlOx
Al
DMM


Cu
Al
DMM


Cu
Al
S.G.

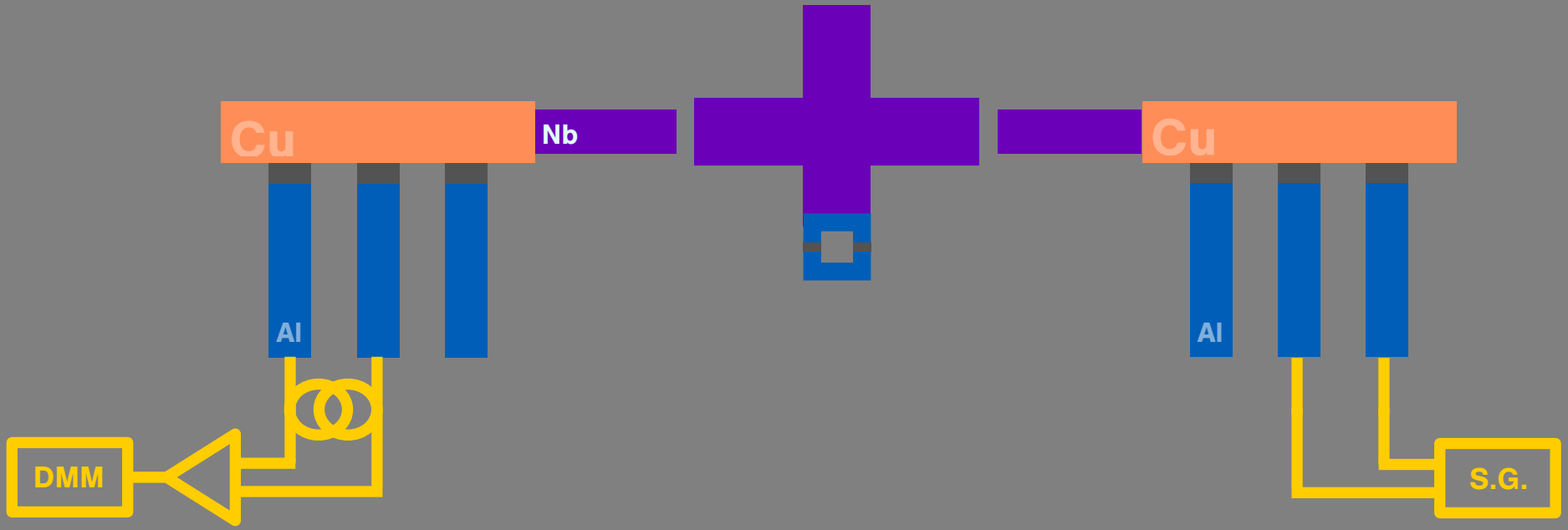
Schmidt et al., PRL 93, 045901 (2004)
Timofeev et al., PRL 102, 200801 (2009)

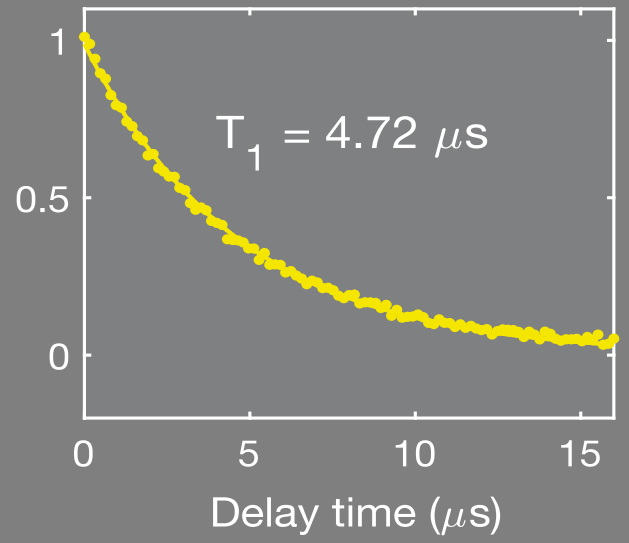
Photonic Heat Transport:

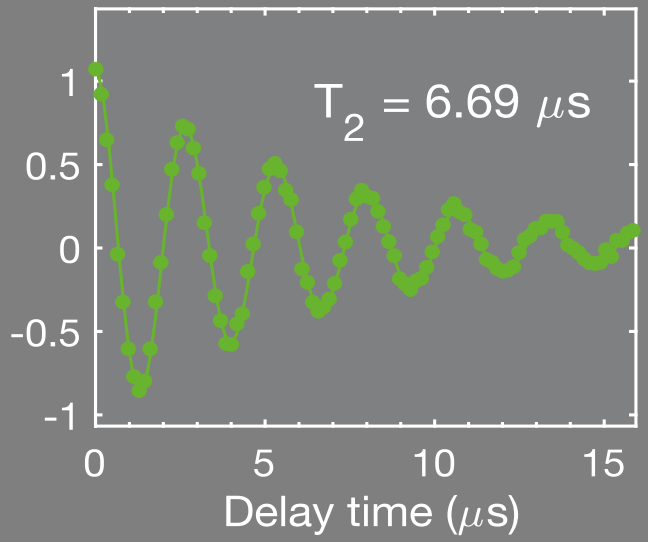
M. Meschke, W. Guichard and J. Pekola, Nature 444, 187 (2006)

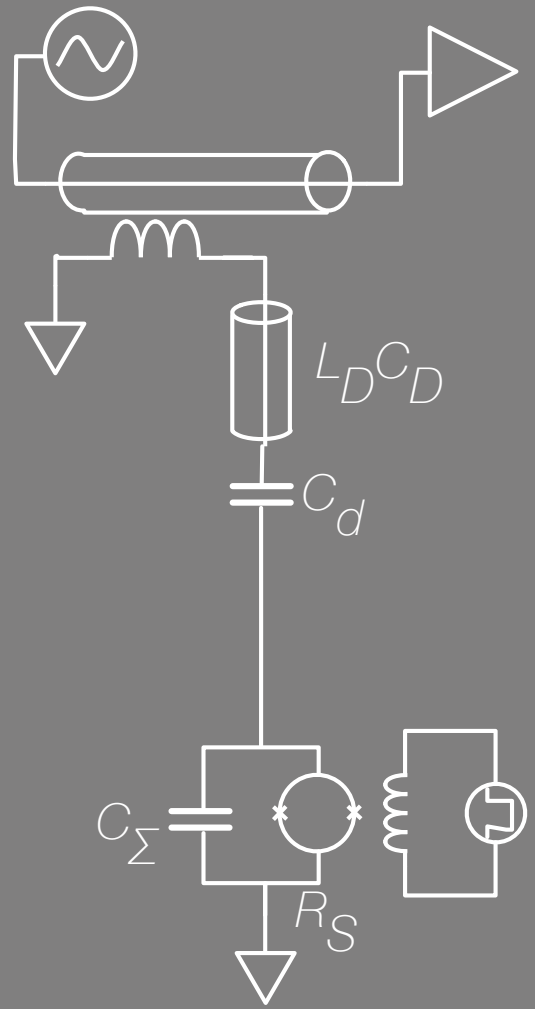
'Quantum' of Heat Transport

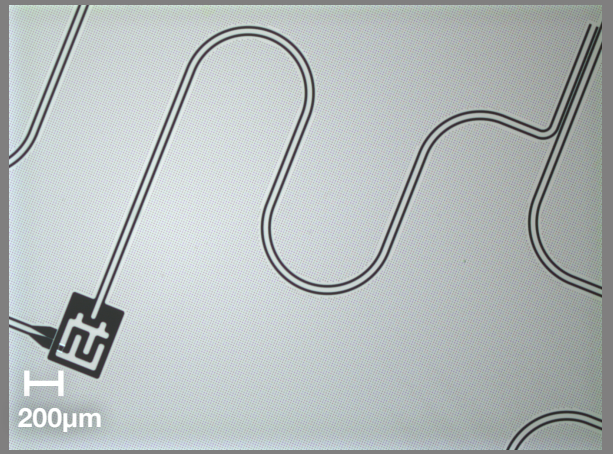
M. Partanen et al., Nature Physics 12, 460 (2016)

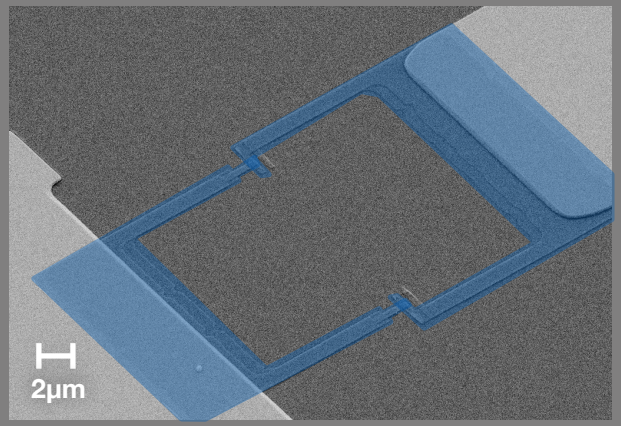

Cu
Nb
Cu
Al
Al
DMM
S.G.







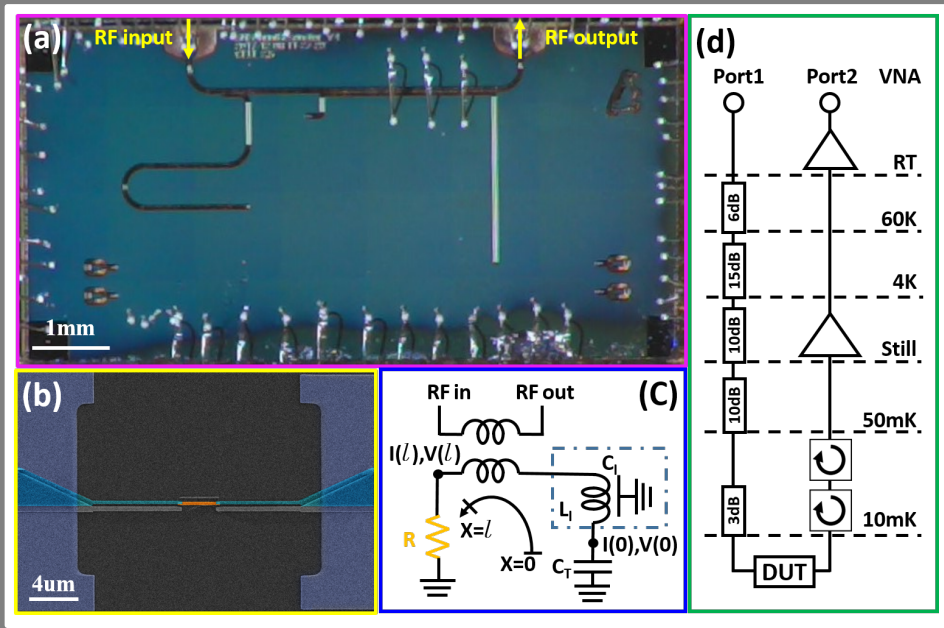


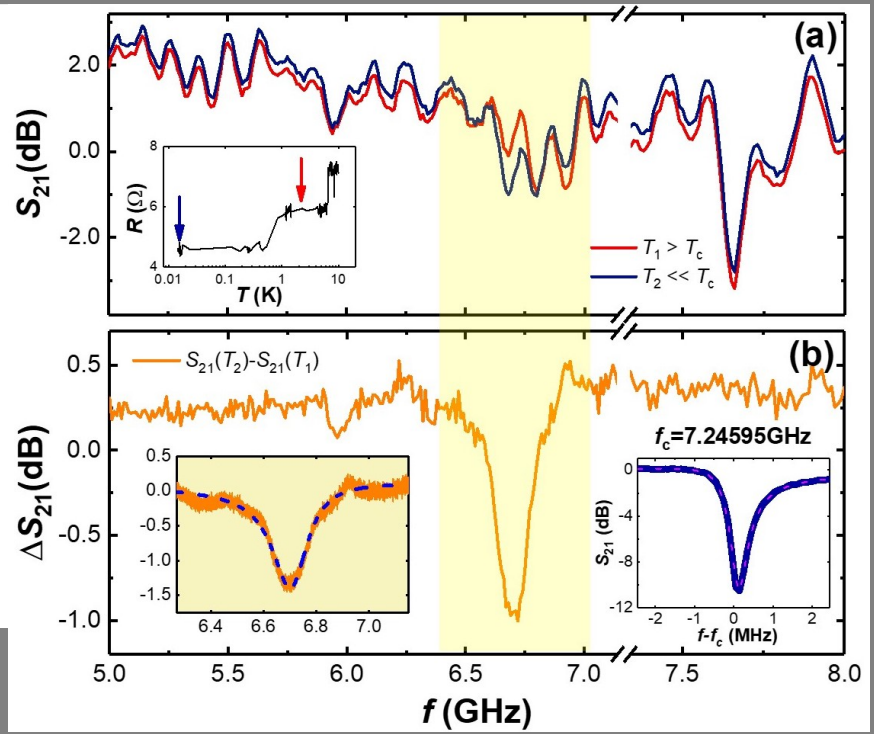


R. George, JS, et al, JLTP (2017)

Jorden Senior

What happens to Q of the resistively shunted resonators?





Q ≈ 4 - 20

Y-C.Chang, JS, B Karimi, et al, *under preparation*

Aalto University

Half-way summary:

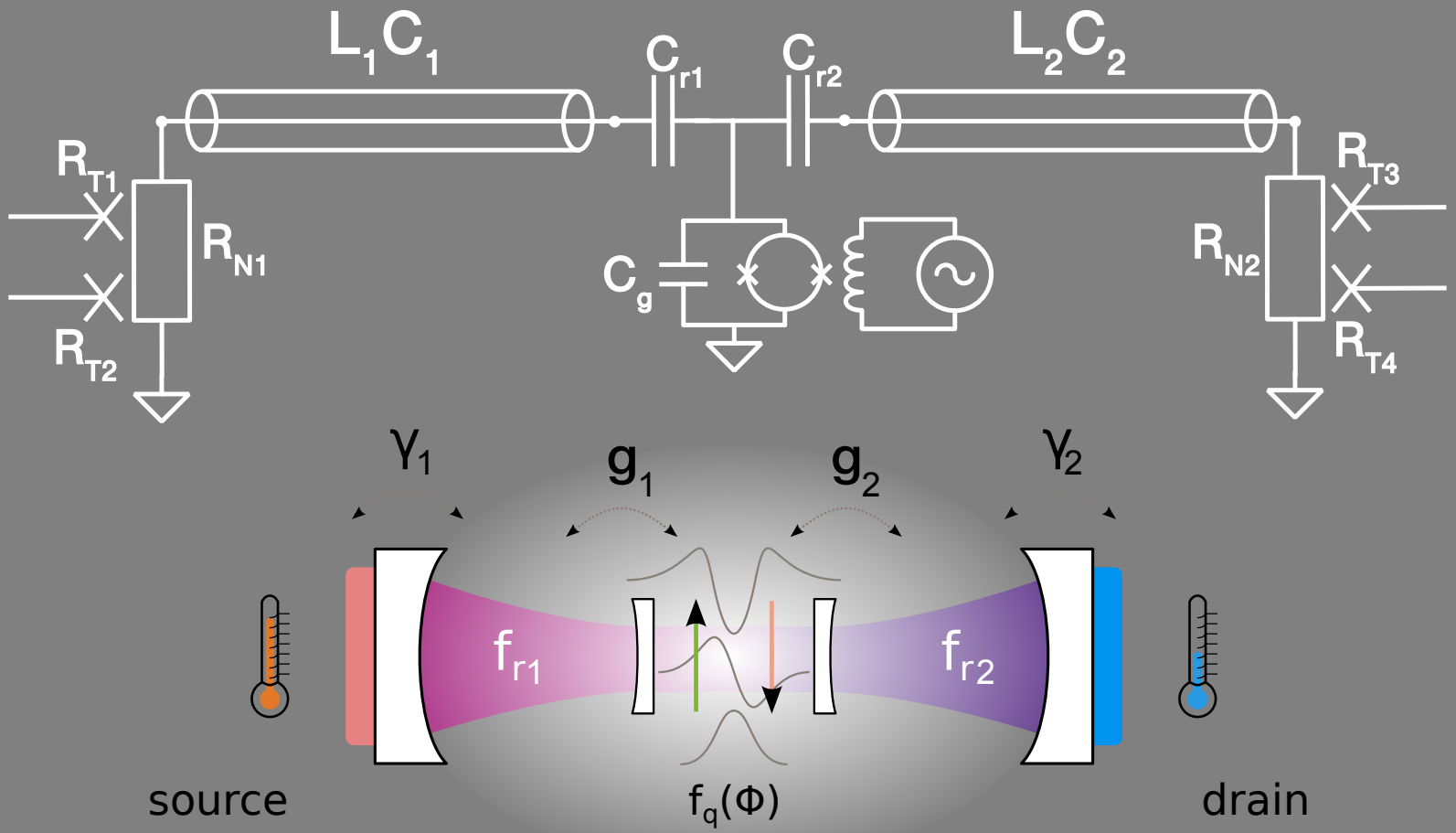
The goal is to develop a platform for looking at thermodynamics in an open quantum system (Otto engine)

We have our components:

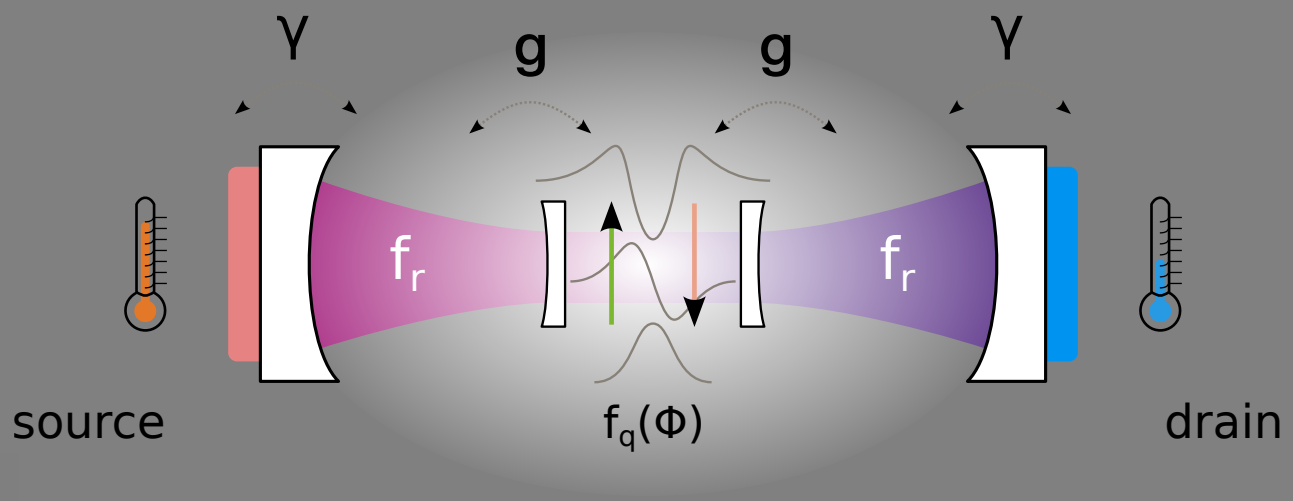
- **Ultra-sensitive thermal control and detection**
- **Artificial atom (superconducting transmon)**
- **Engineered microwave environment**

In Part II, let's put them all together to make a

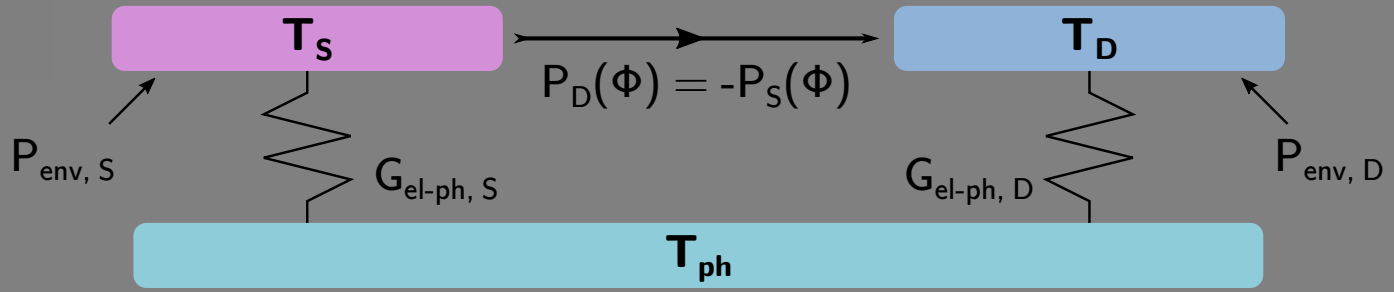
Quantum Heat Valve



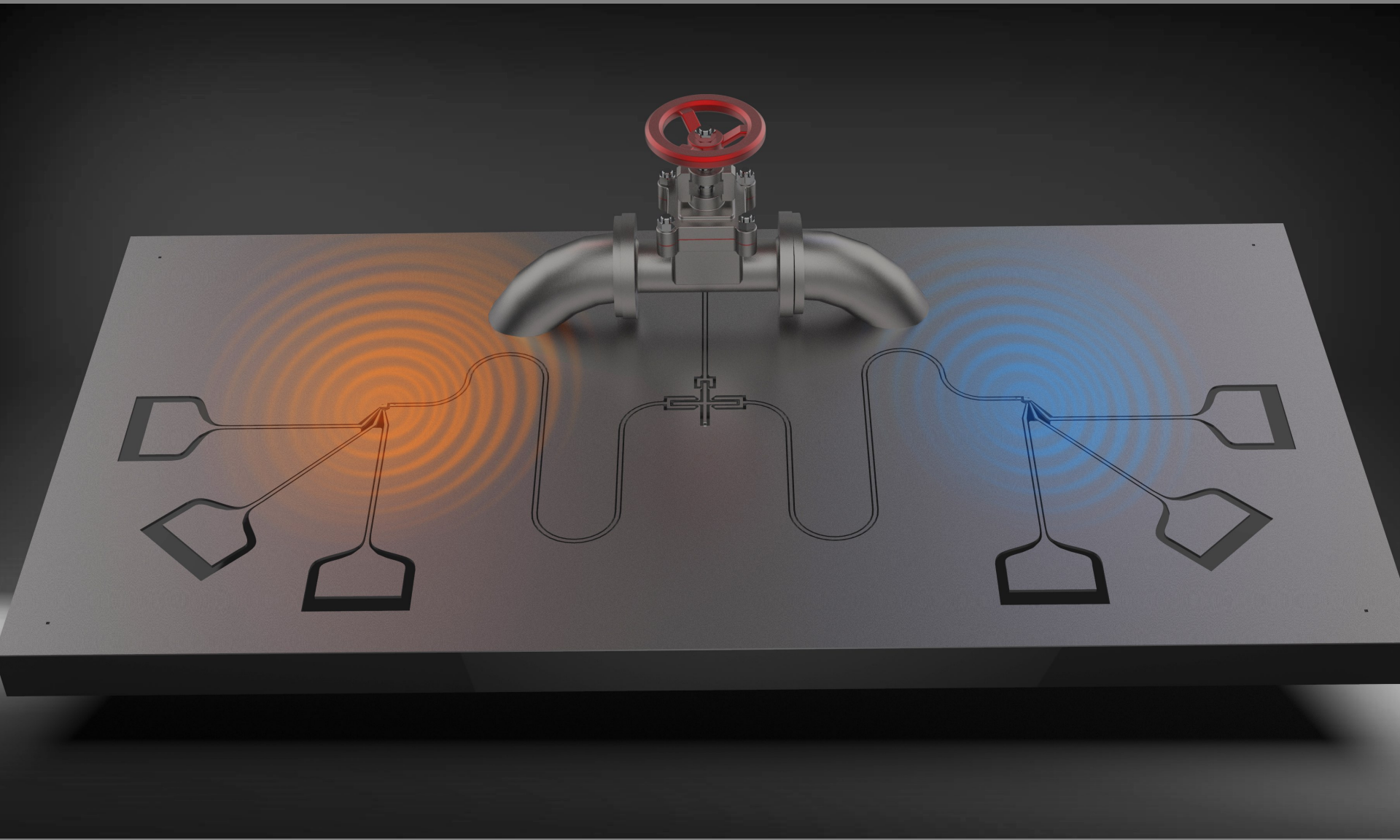
Large parameter space!



$$f_{r1} = f_{r2}$$

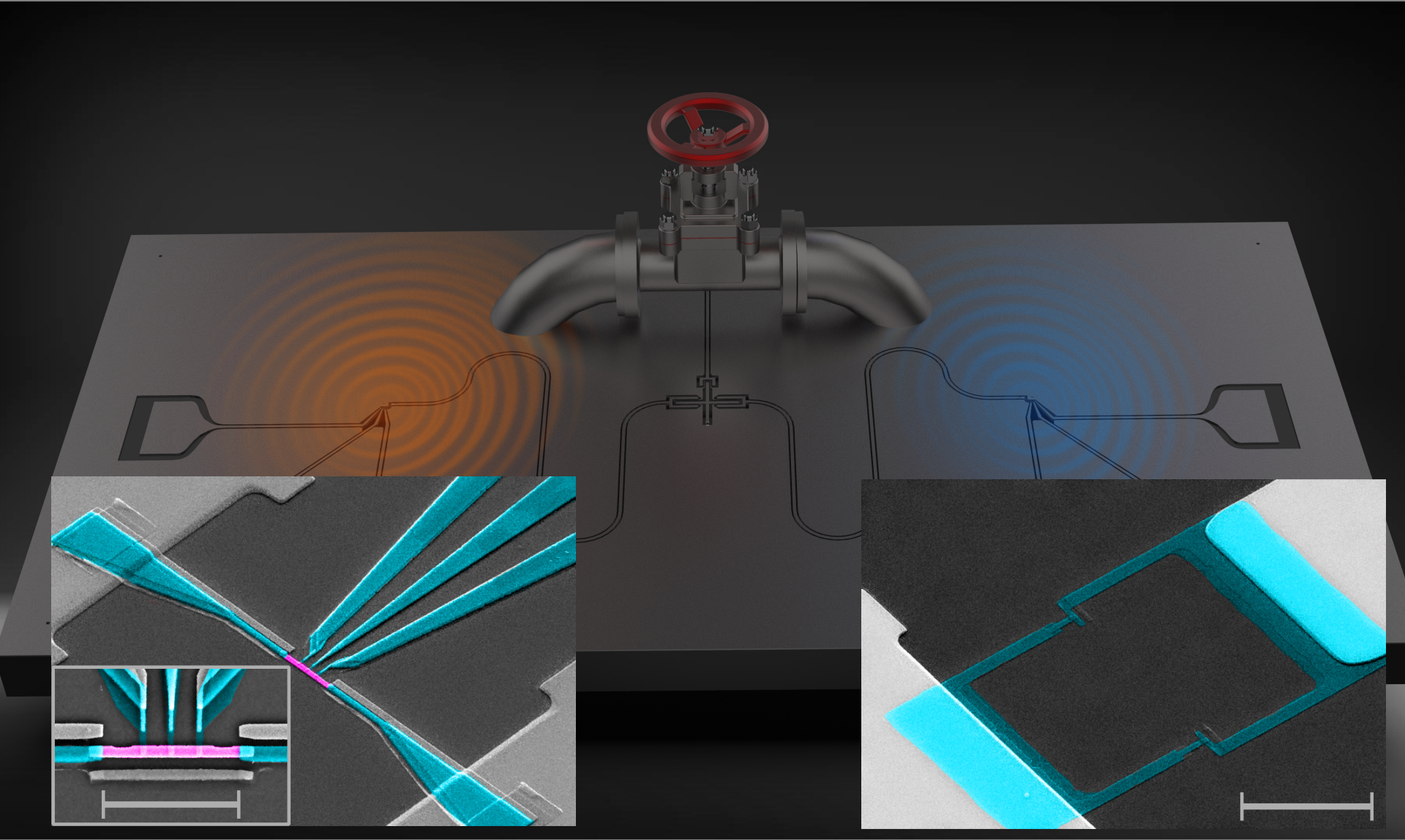


A Ronzani, JS, B Karimi, et al, *Nature Physics* **14** ,991–995 (2018)



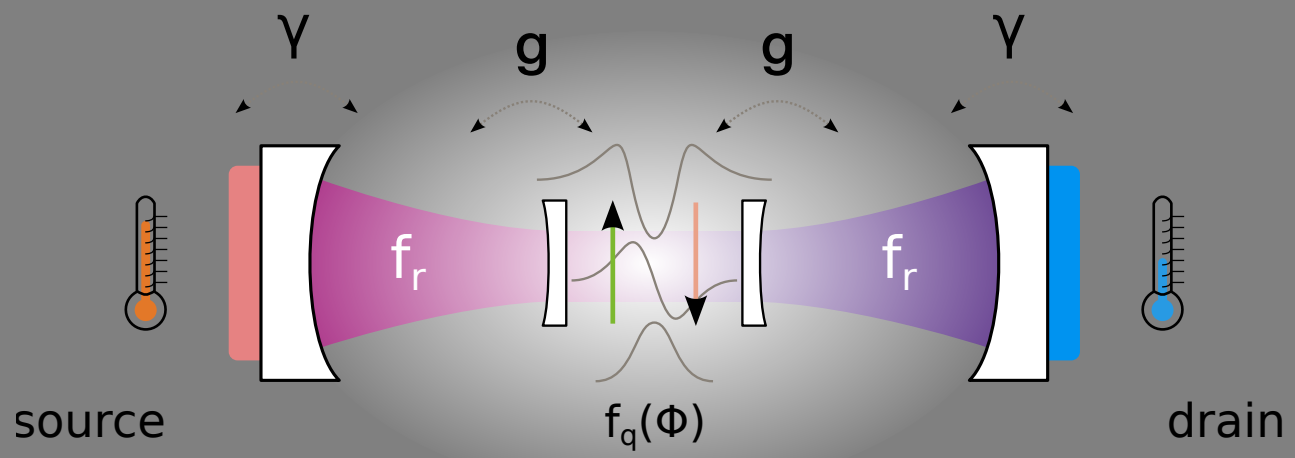
A Ronzani, JS, B Karimi, et al, *Nature Physics* **14** ,*991–995 (2018)*

Jorden Senior



A Ronzani, JS, B Karimi, et al, *Nature Physics* **14** ,991–995 (2018)

Jorden Senior



$g/\gamma = 0.05$

Q = 3

LOCAL

$g/\gamma = 0.4$

Q = 20

GLOBAL

A Ronzani, JS, B Karimi, et al, *Nature Physics* **14** ,991–995 (2018)

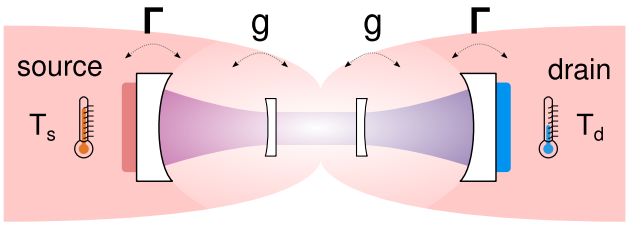
$g/\gamma = 0.05$

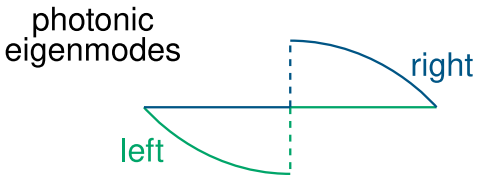
Q = 3

LOCAL

NEP ~5 aW

'wireless' cooling (4mm) of 50aW



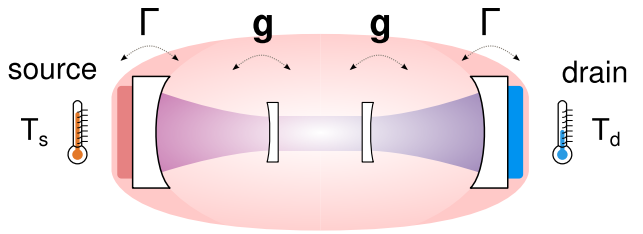


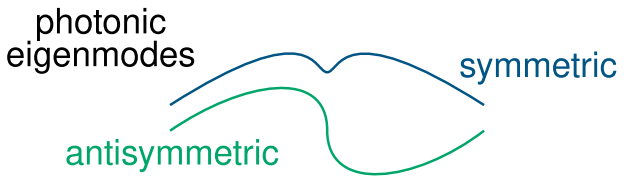
A Ronzani, JS, B Karimi, et al, *Nature Physics* **14** ,991–995 (2018)

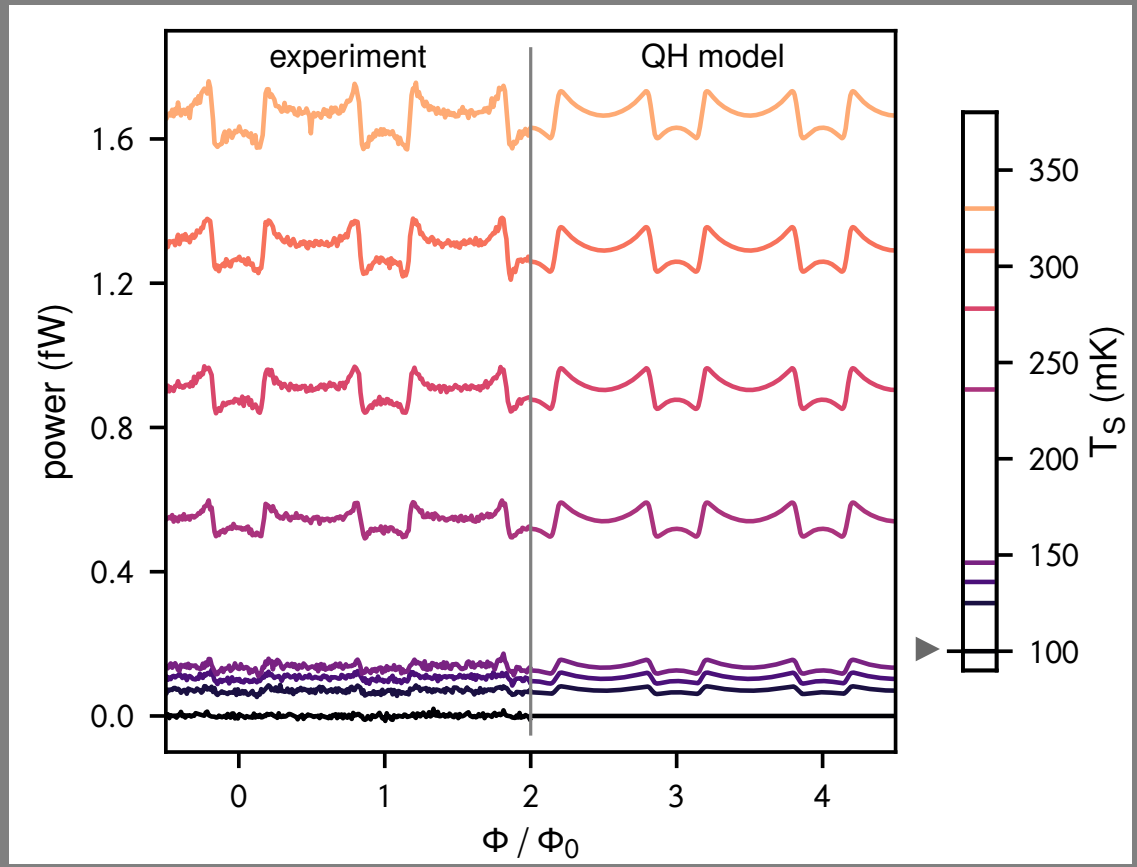
$g/\gamma = 0.4$

Q = 20

GLOBAL





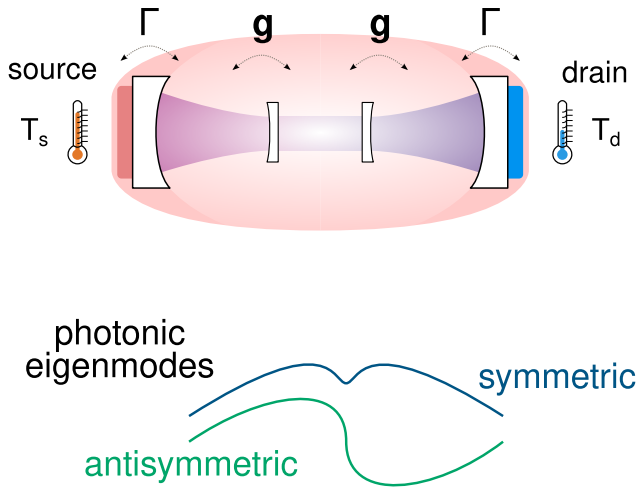


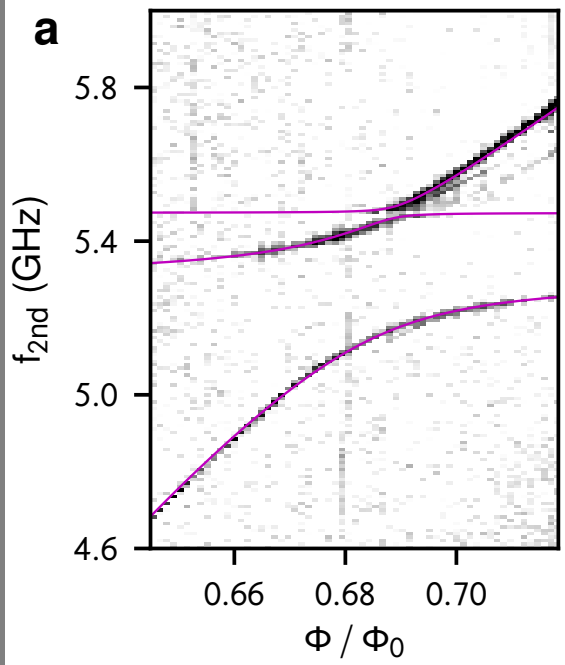
A Ronzani, JS, B Karimi, et al, *Nature Physics* **14** ,991–995 (2018)

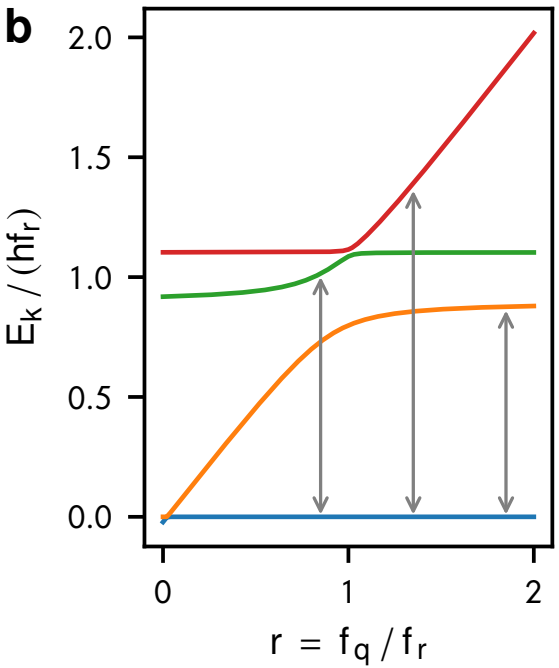
$g/\gamma = 0.4$

Q = 20

GLOBAL



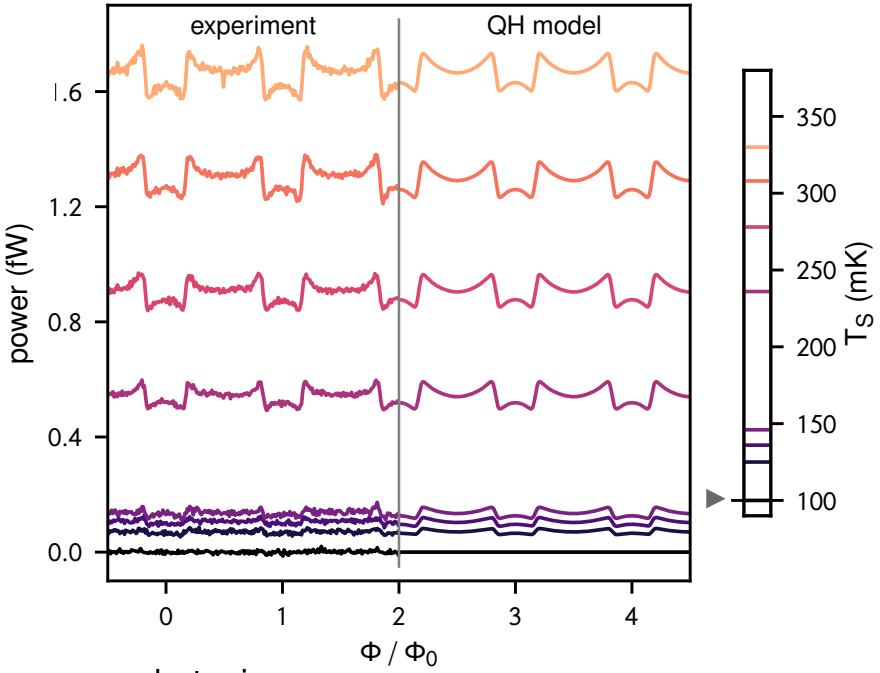


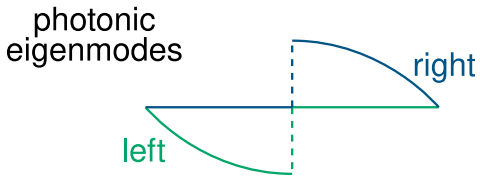


A Ronzani, JS, B Karimi, et al, *Nature Physics* **14** ,991–995 (2018)

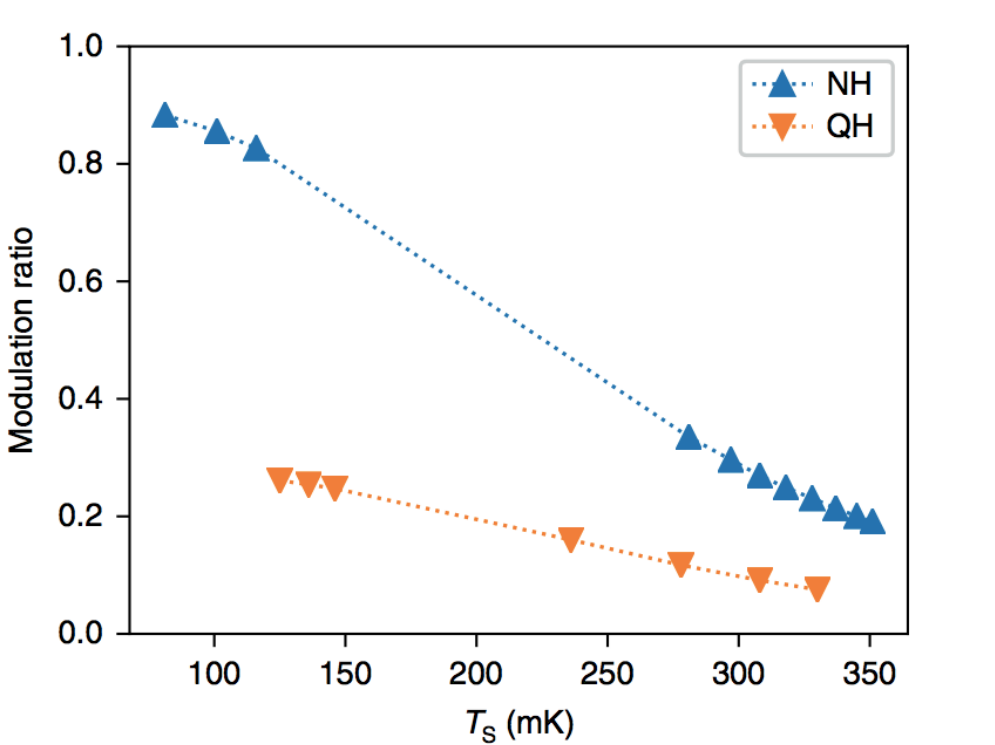
$g/\gamma = 0.05$

$g/\gamma = 0.4$





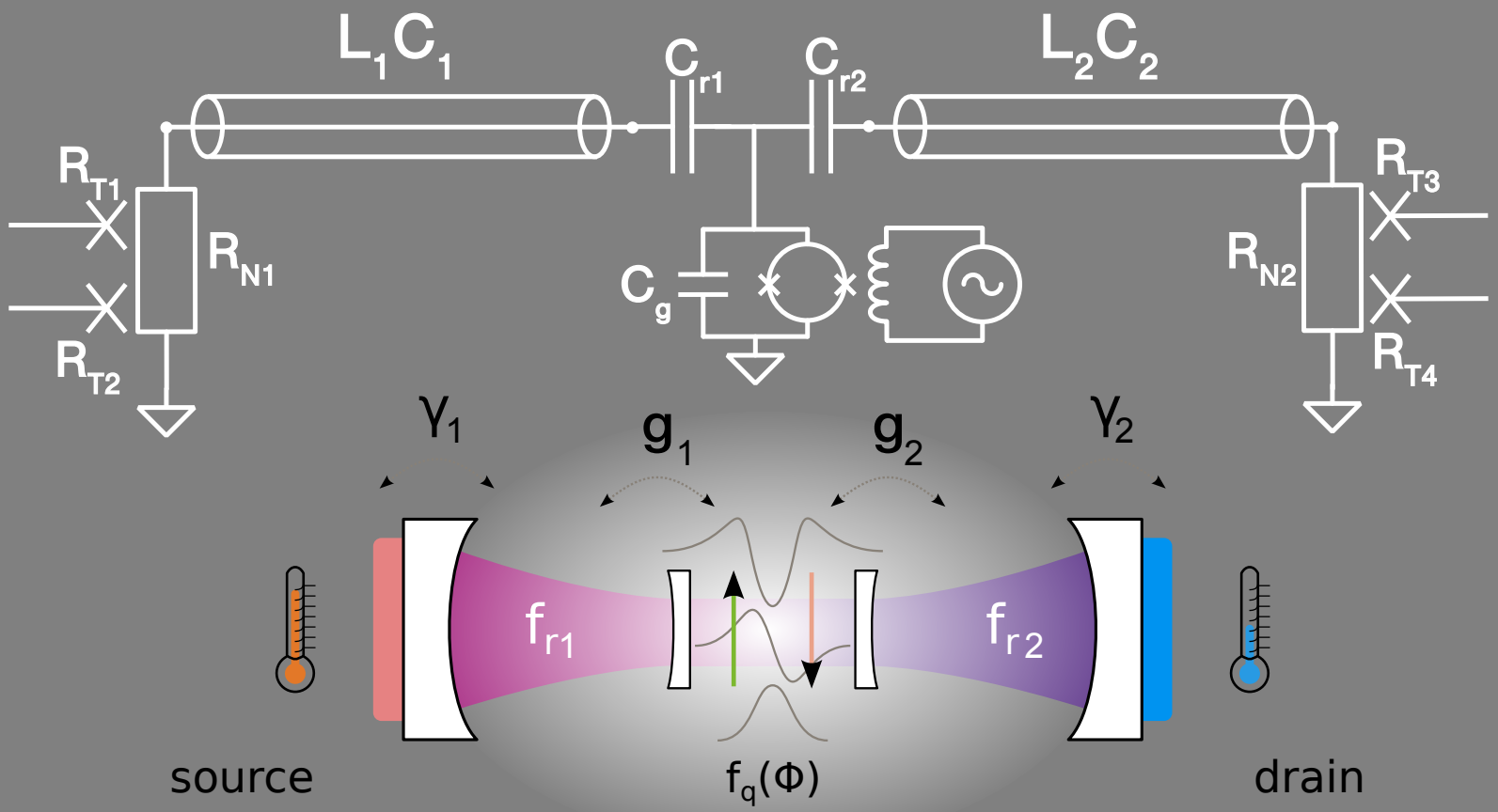
A Ronzani, JS, B Karimi, et al, *Nature Physics* **14** ,991–995 (2018)



$g/\gamma = 0.05$

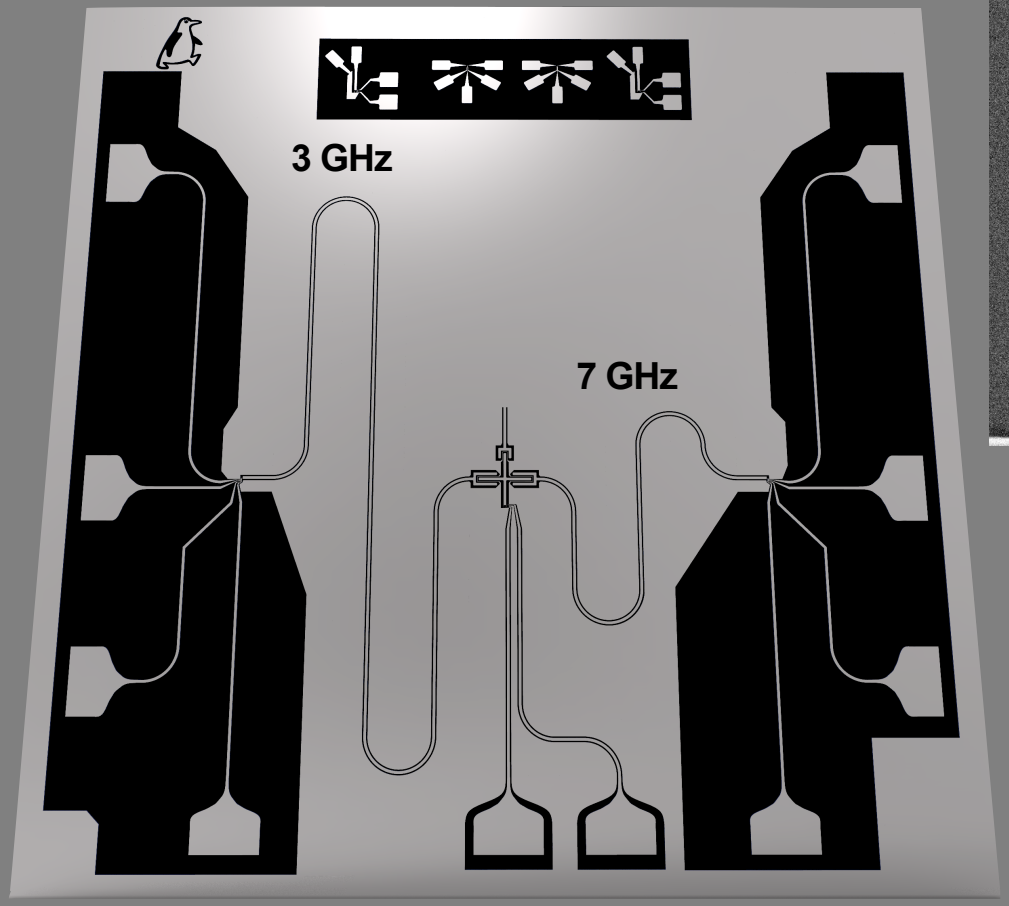
$g/\gamma = 0.4$

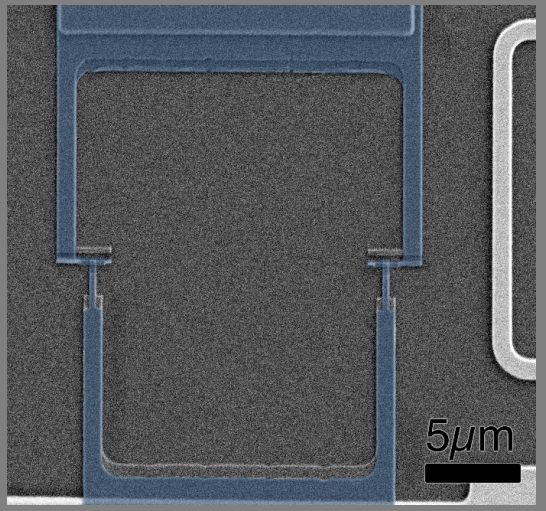
A Ronzani, JS, B Karimi, et al, *Nature Physics* **14** ,991–995 (2018)

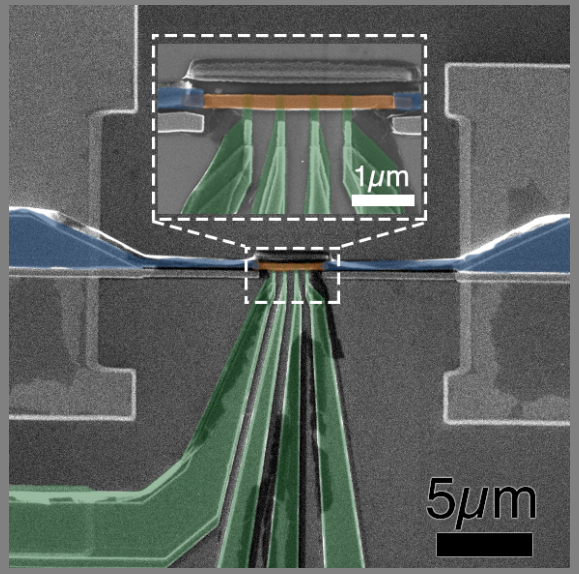


Artificial atom tunably coupled to two frequencies: wireless thermal rectification

Jorden Senior

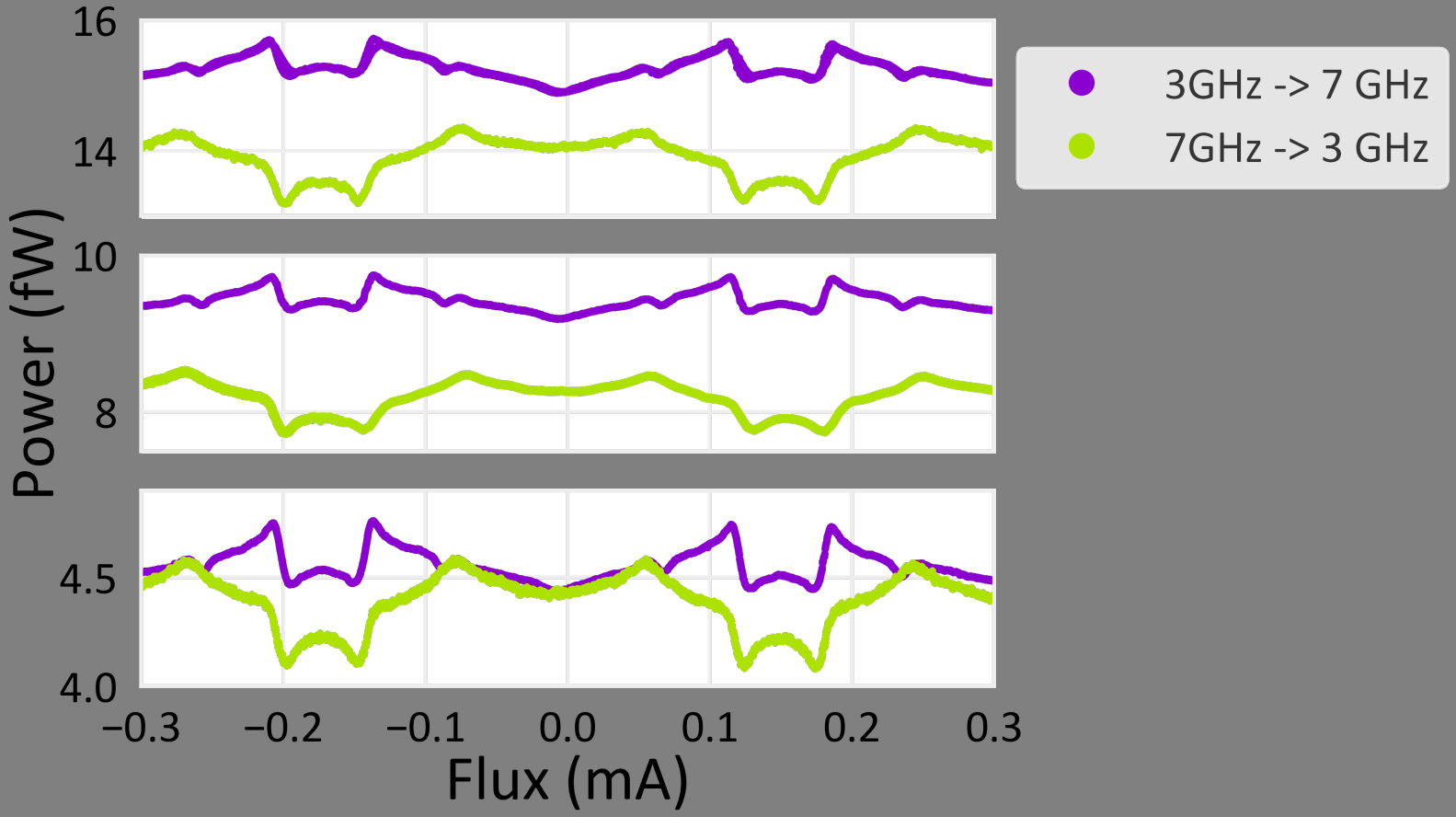




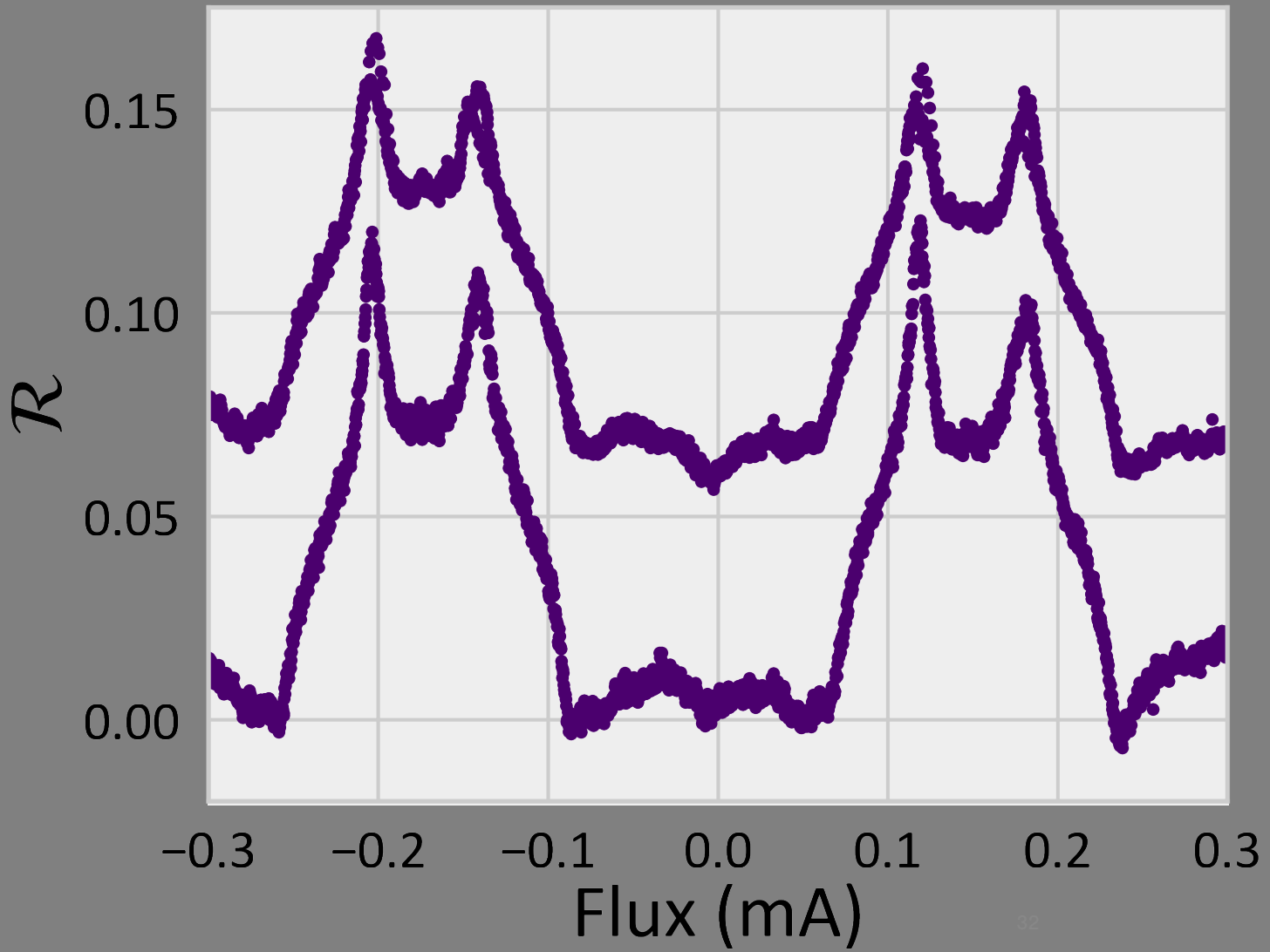


JS, A Gubaydullin, B Karimi, et al, *under preparation*

Jorden Senior



JS, A Gubaydullin, B Karimi, et al, *under preparation*



JS, A Gubaydullin, B Karimi, et al, *under preparation*

Key Messages:

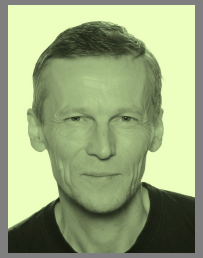
Superconducting circuits are a fertile ground for investigating Quantum Thermodynamics (cQTD)

Coupling is important: (Heisenberg cut)	$g/\gamma \ll 1$	$g/\gamma \approx 1$
	Local	Global

Wireless cooling is possible via a superconducting qubit coupled to two symmetric resonators

Wireless thermal rectification is achievable through a superconducting qubit coupled to two asymmetric resonators

Senior



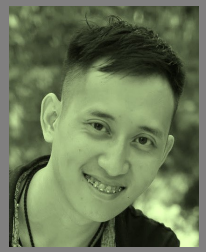
Jukka Pekola

Dmitri Golubev

Joonas Peltonen

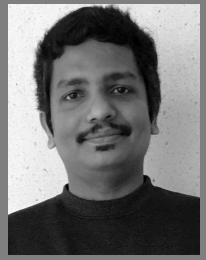
PostDocs

Azat Gubaydullin

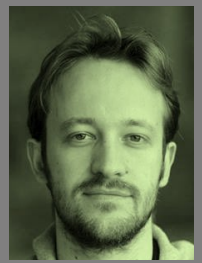


Yu-Cheng Chang

Olivier Maillet



George Thomas



Alberto Ronzani
(VTT)

Olli-Pentti Saira
(Brookhaven)

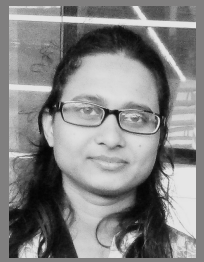
PhD Students

Jorden Senior

Bayan Karimi

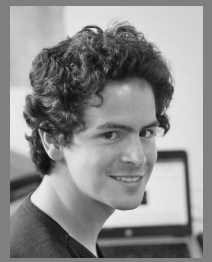
Brecht Donvil
(University of Helsinki)

Diego Subero



Shilpi Singh

Elsa Mannila



Marco Marín
Suárez

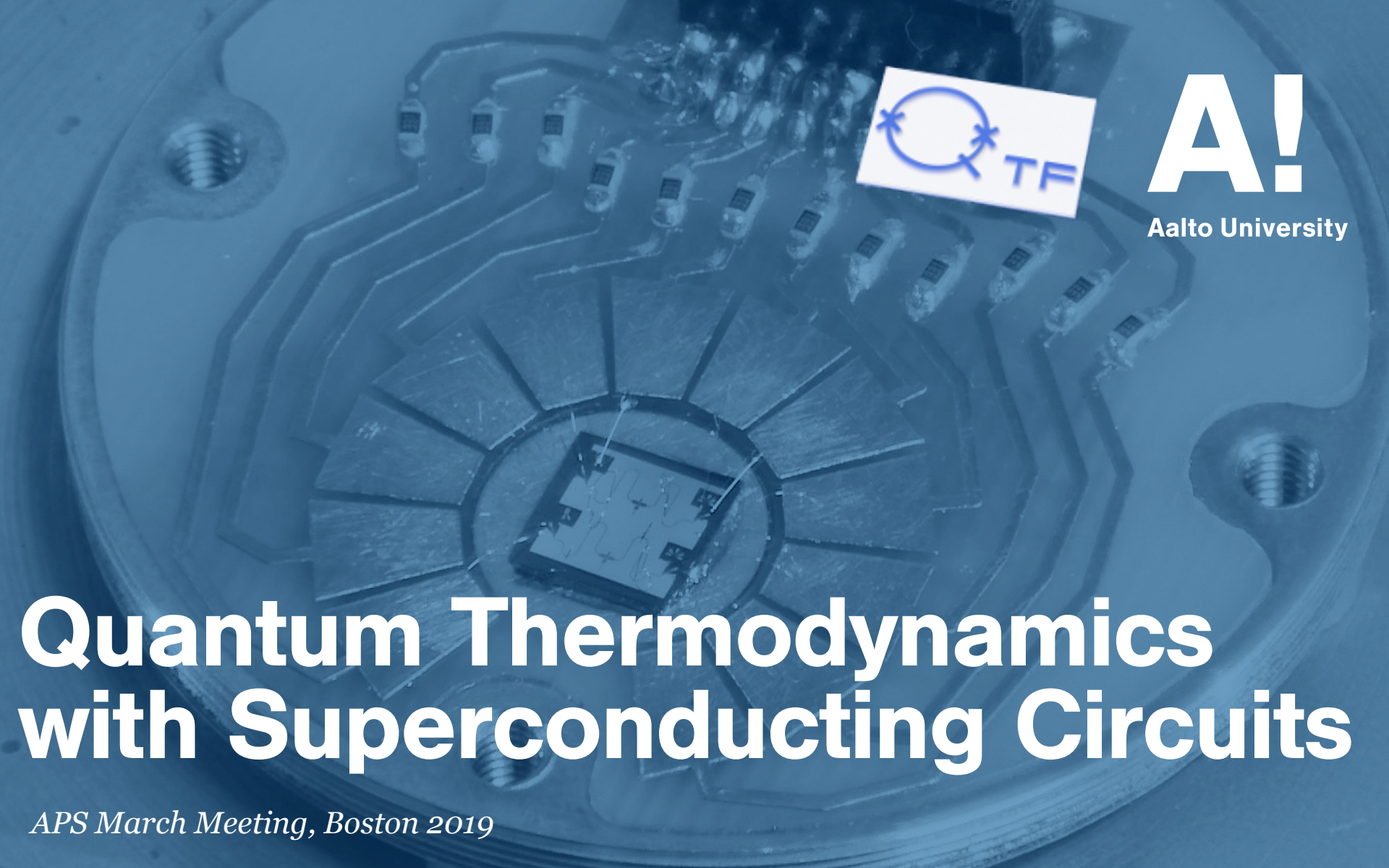
Klaara Viisanen

Libin Wang

Rishabh Upadhyay

Aalto University

Jorden Senior



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Aalto University

Quantum Thermodynamics with Superconducting Circuits

APS March Meeting, Boston 2019