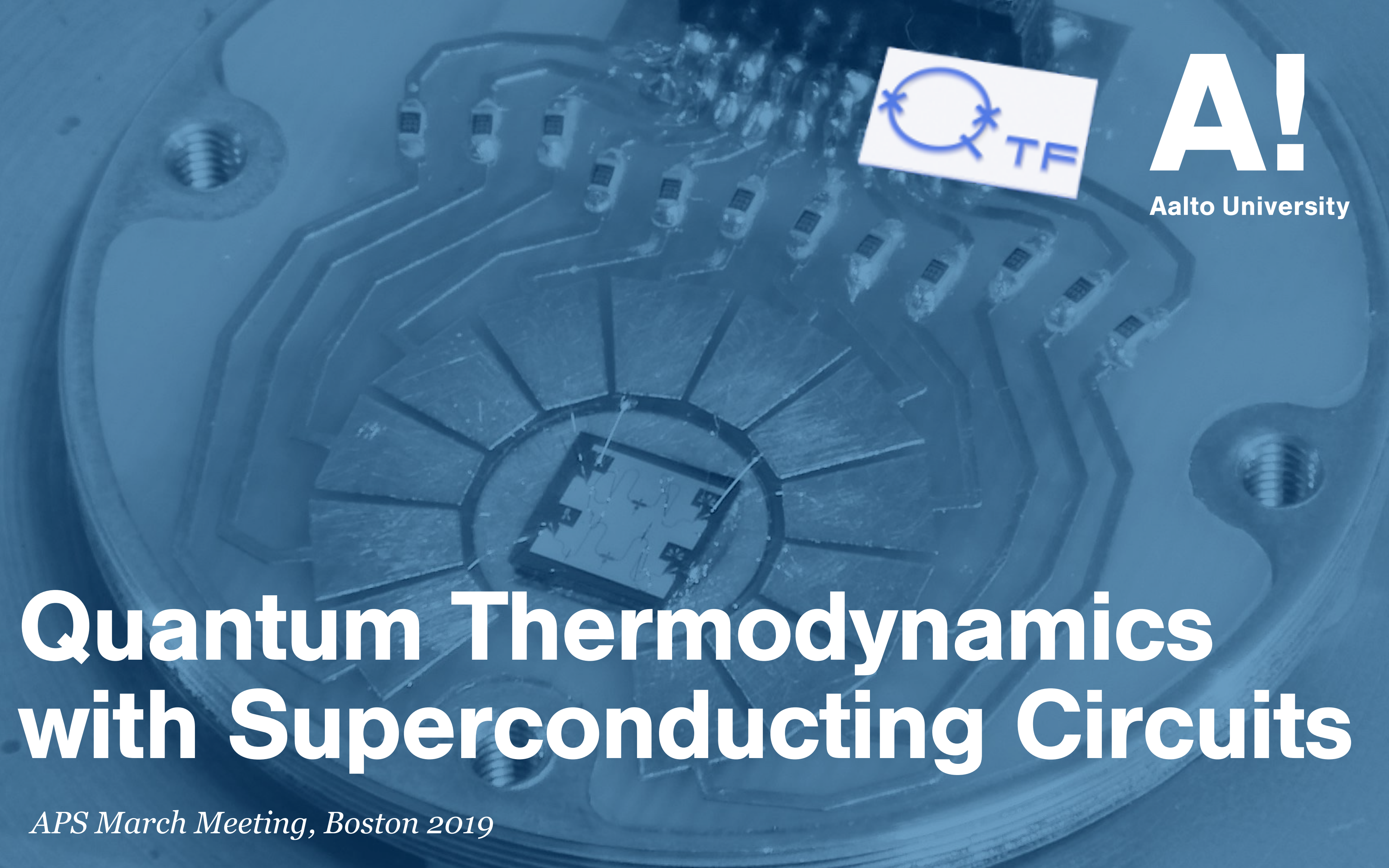
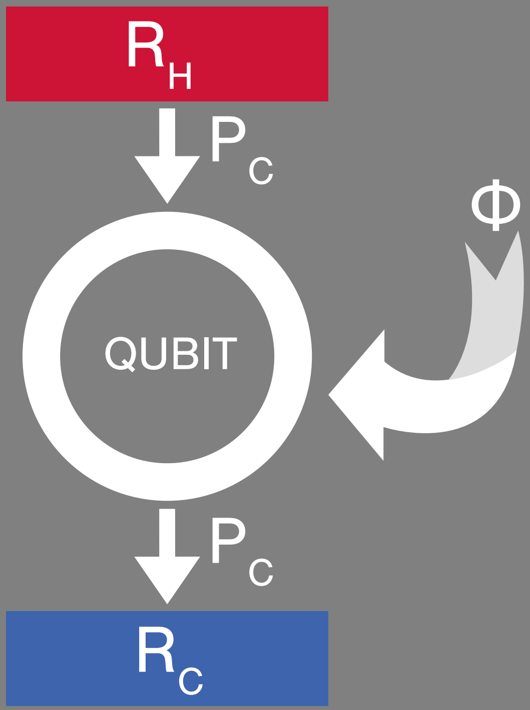


Aalto University

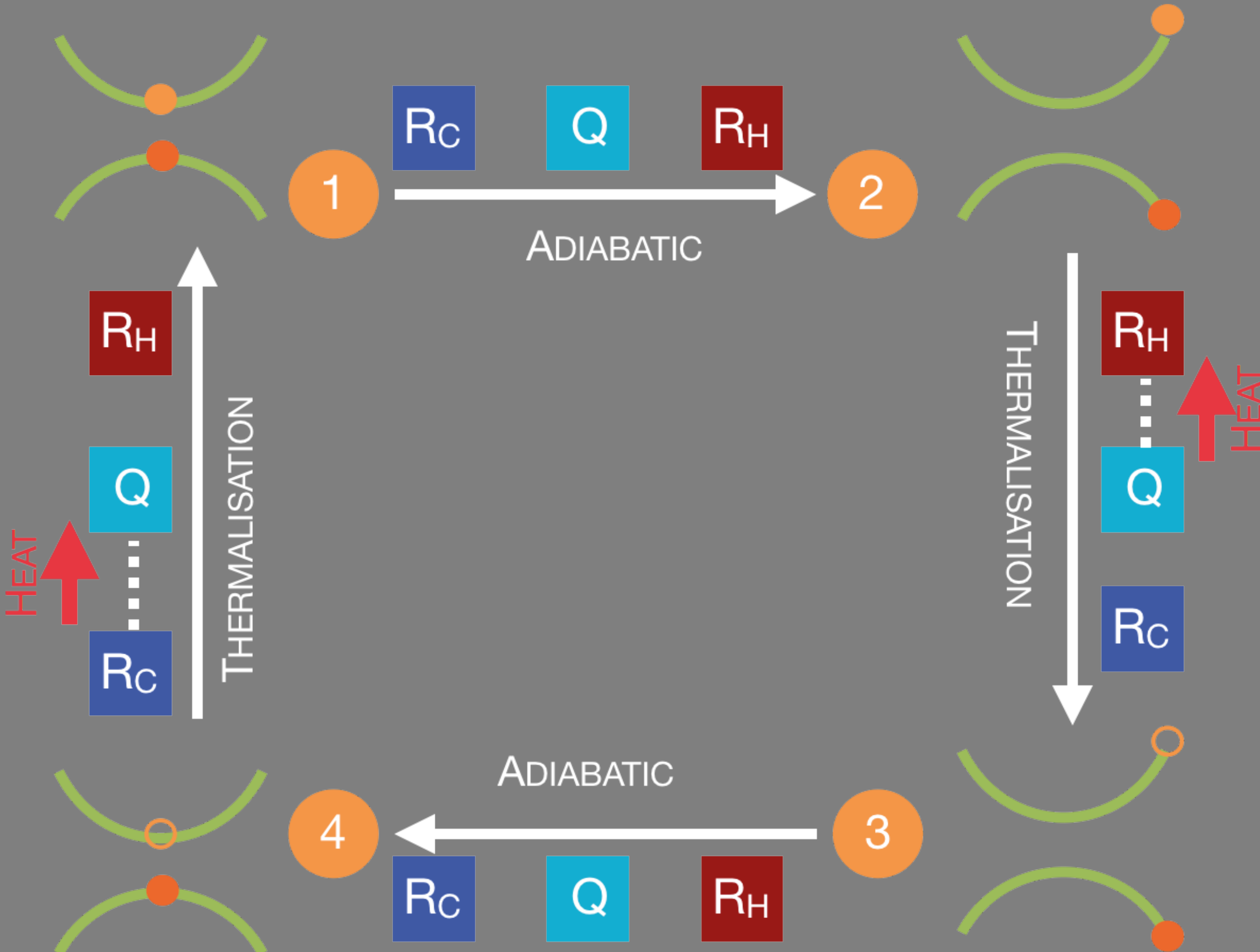
Quantum Thermodynamics with Superconducting Circuits

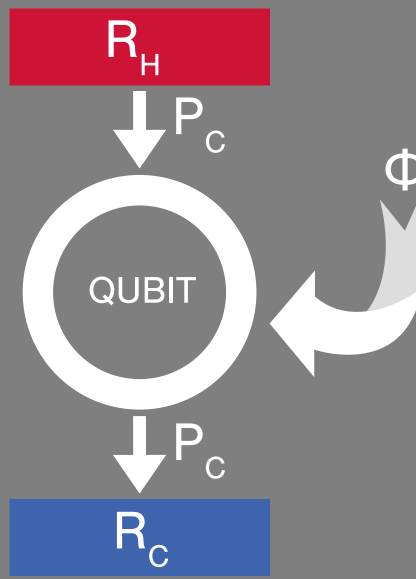
APS March Meeting, Boston 2019

Towards a Quantum Heat Engine



Jorden Senior





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

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Quantum heat engine (quantum Otto refrigerator)

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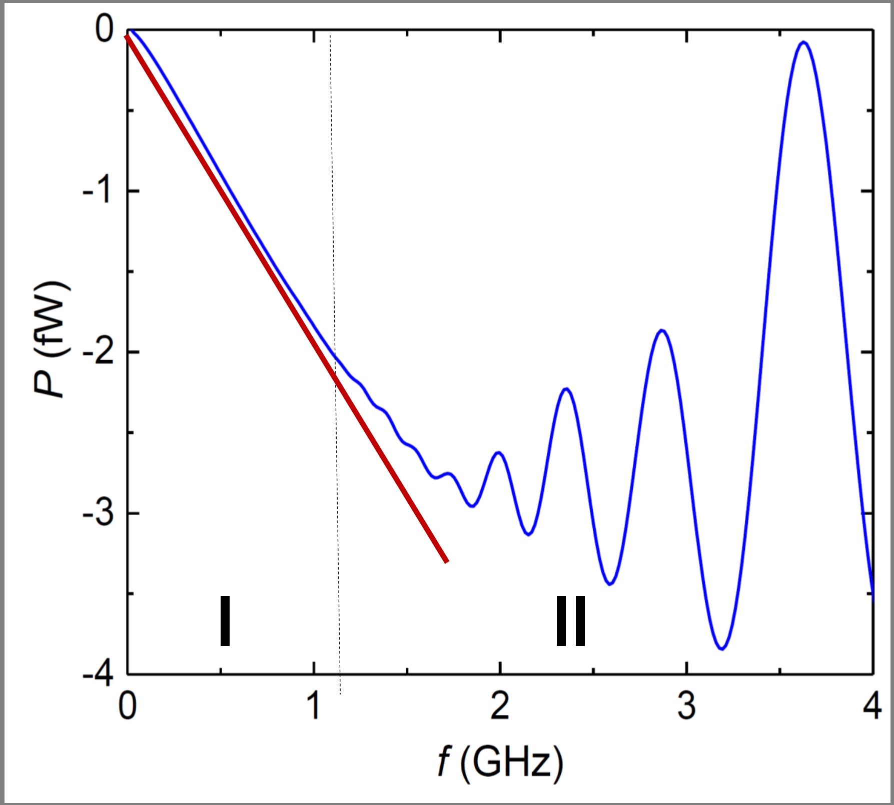
Different operation regimes:

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)

Let's build our circuit…

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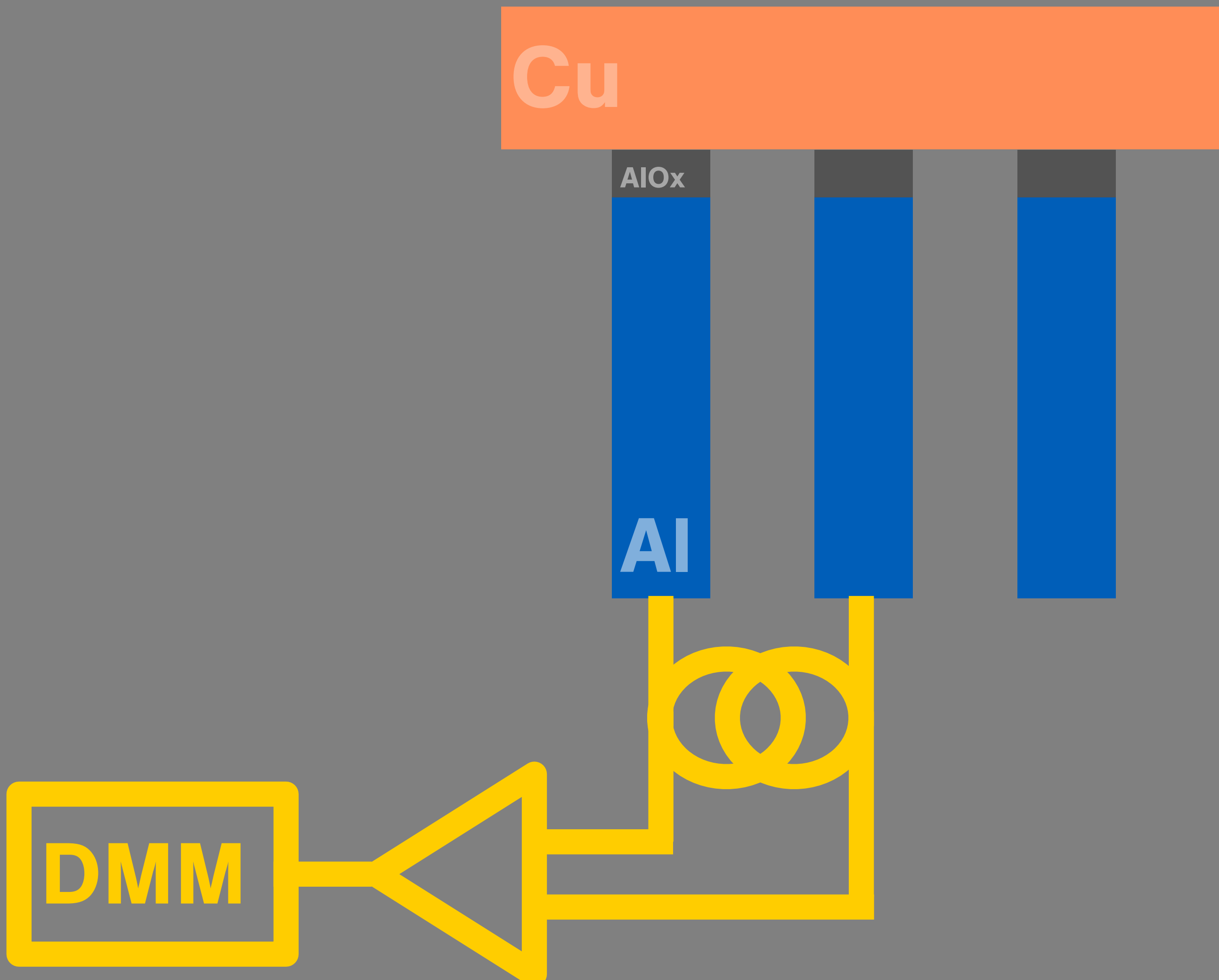
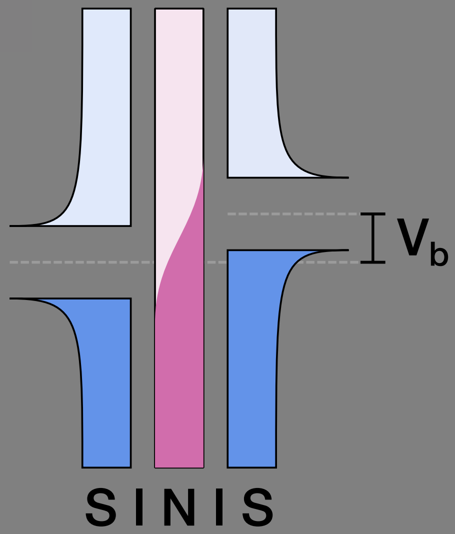
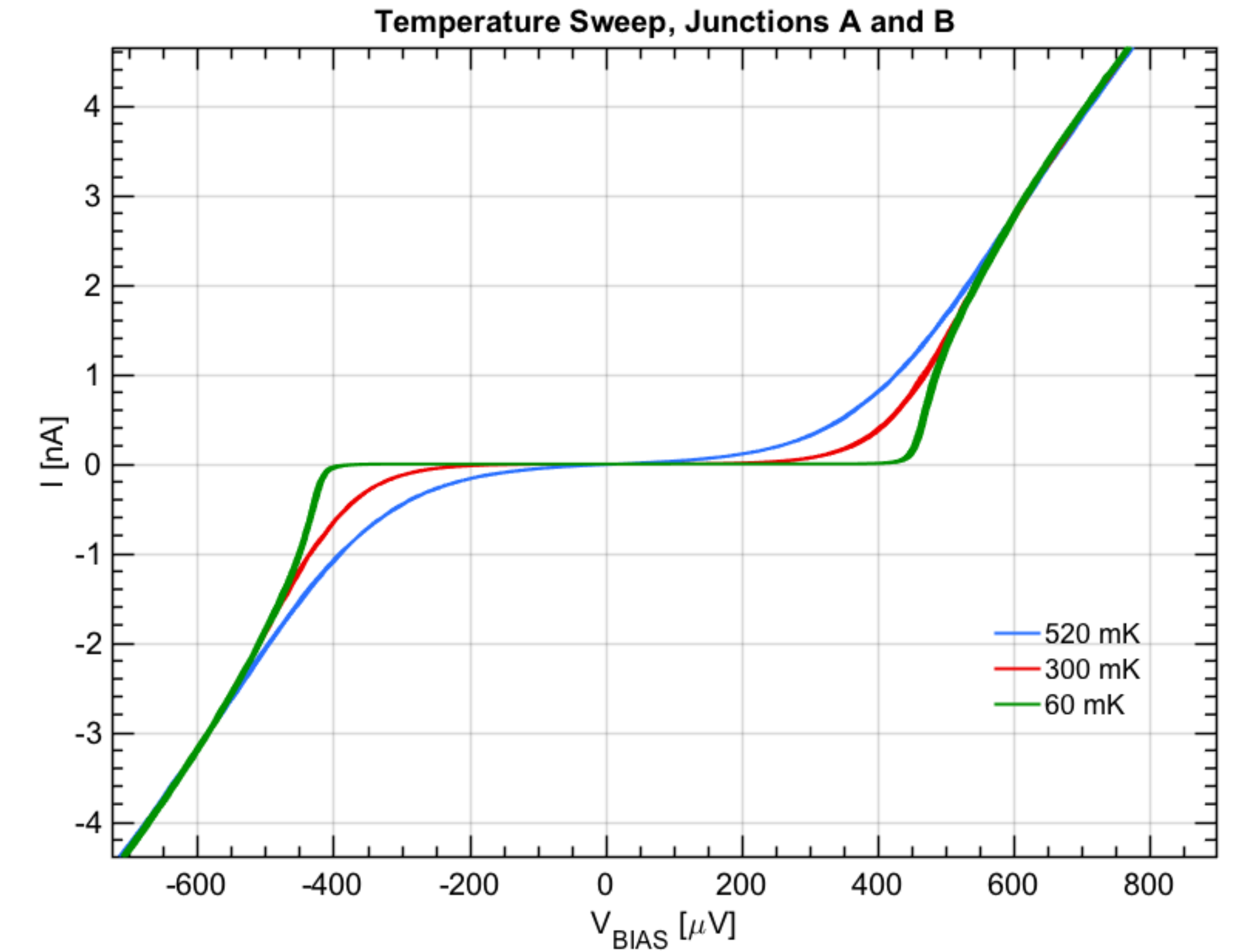
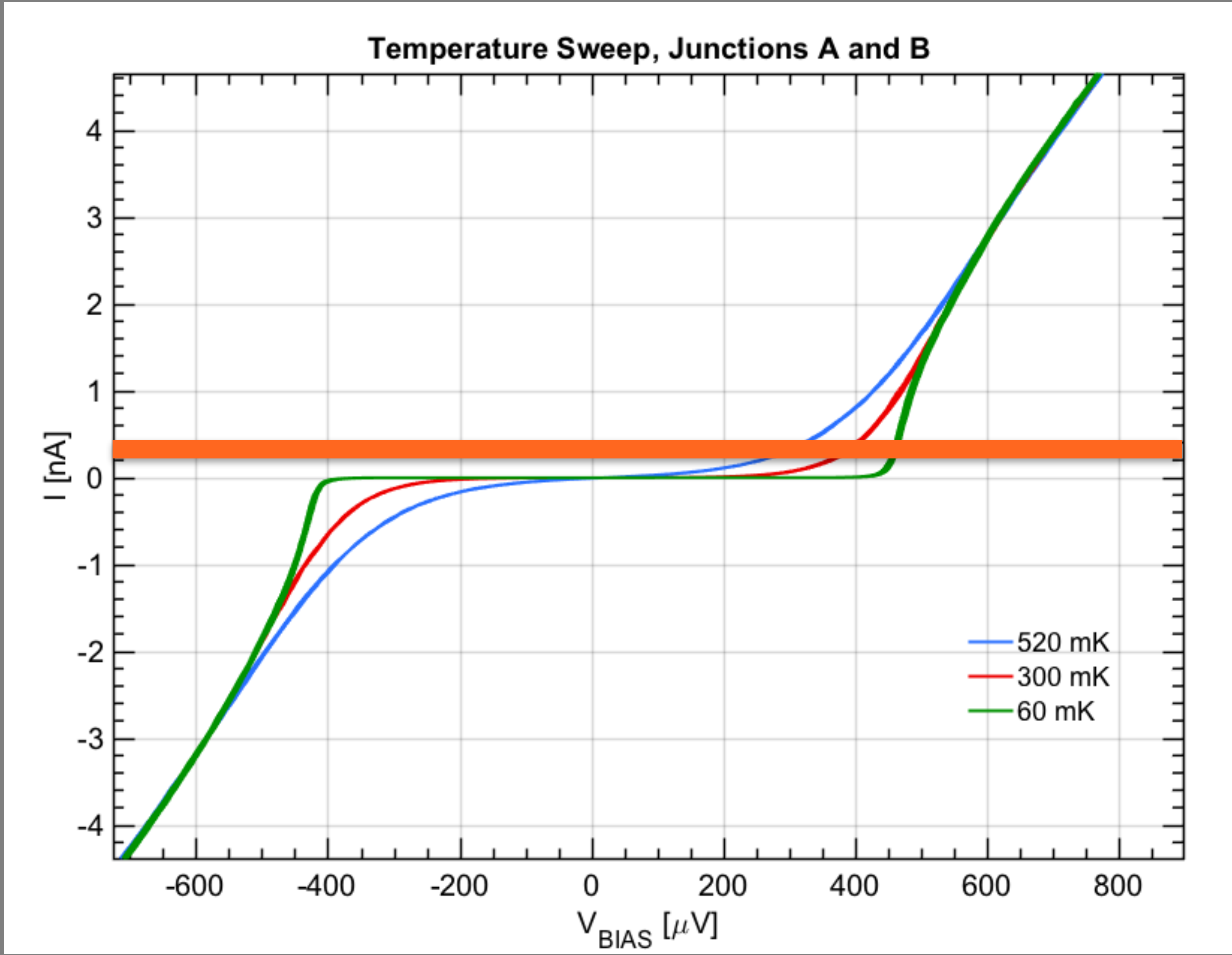
Cu


Cu
AlOx
Al
DMM

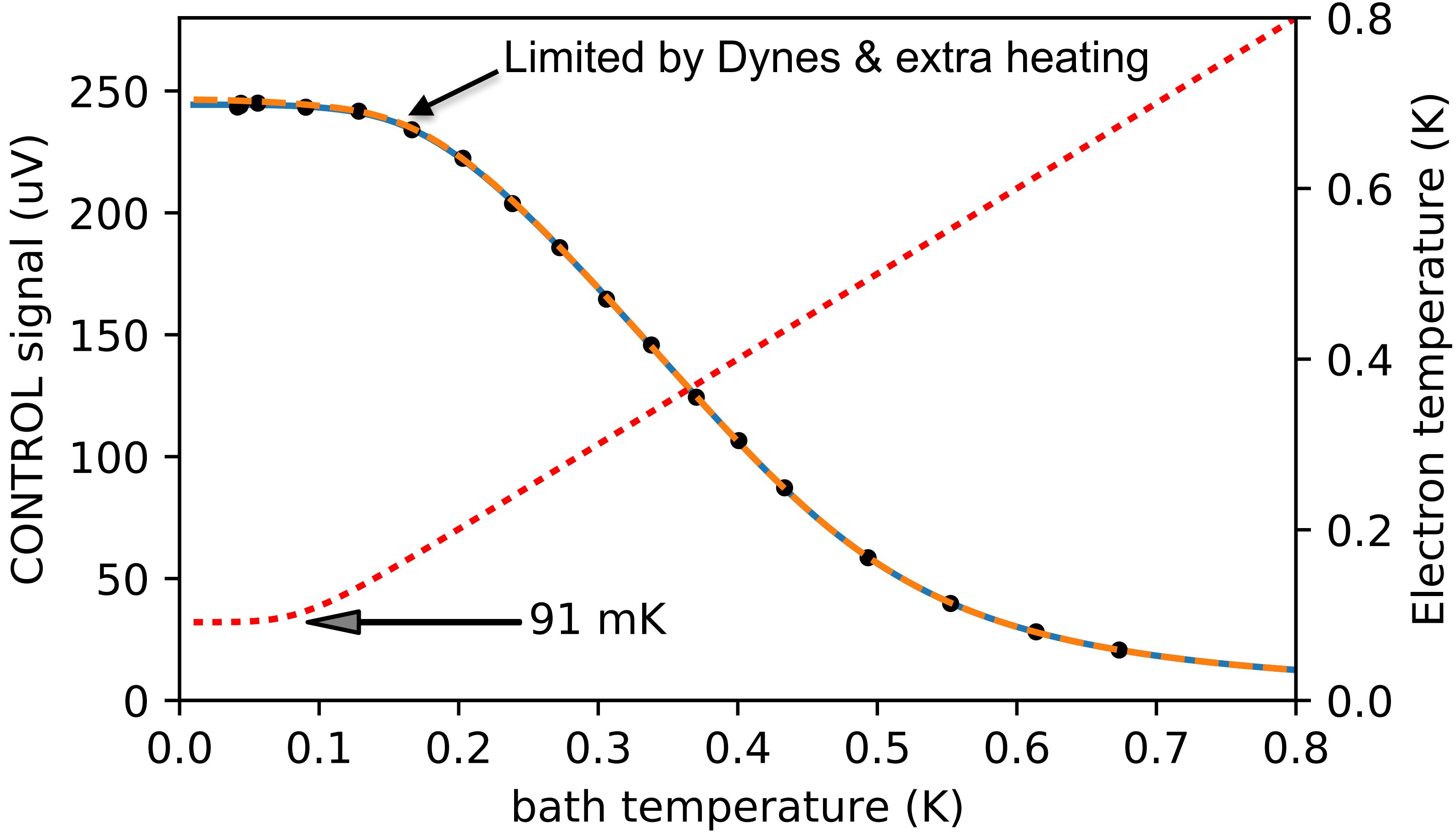

V_b
S I N I S

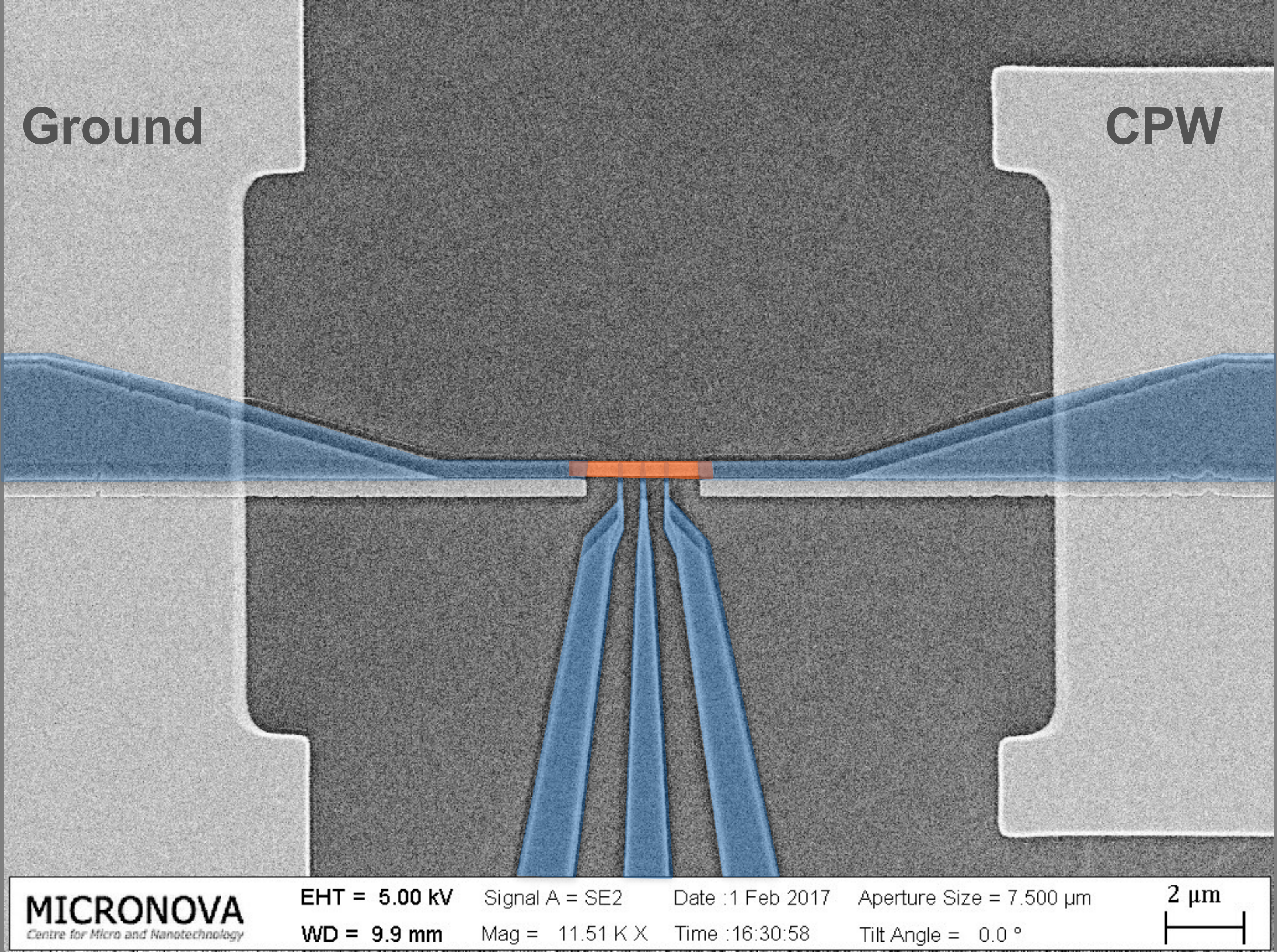


Temperature Sweep, Junctions A and B
I [nA]
4
3
2
1
0
-1
-2
-3
-4
-600
-400
-200
0
200
400
600
800
V_BIAS [μV]
520 mK
300 mK
60 mK

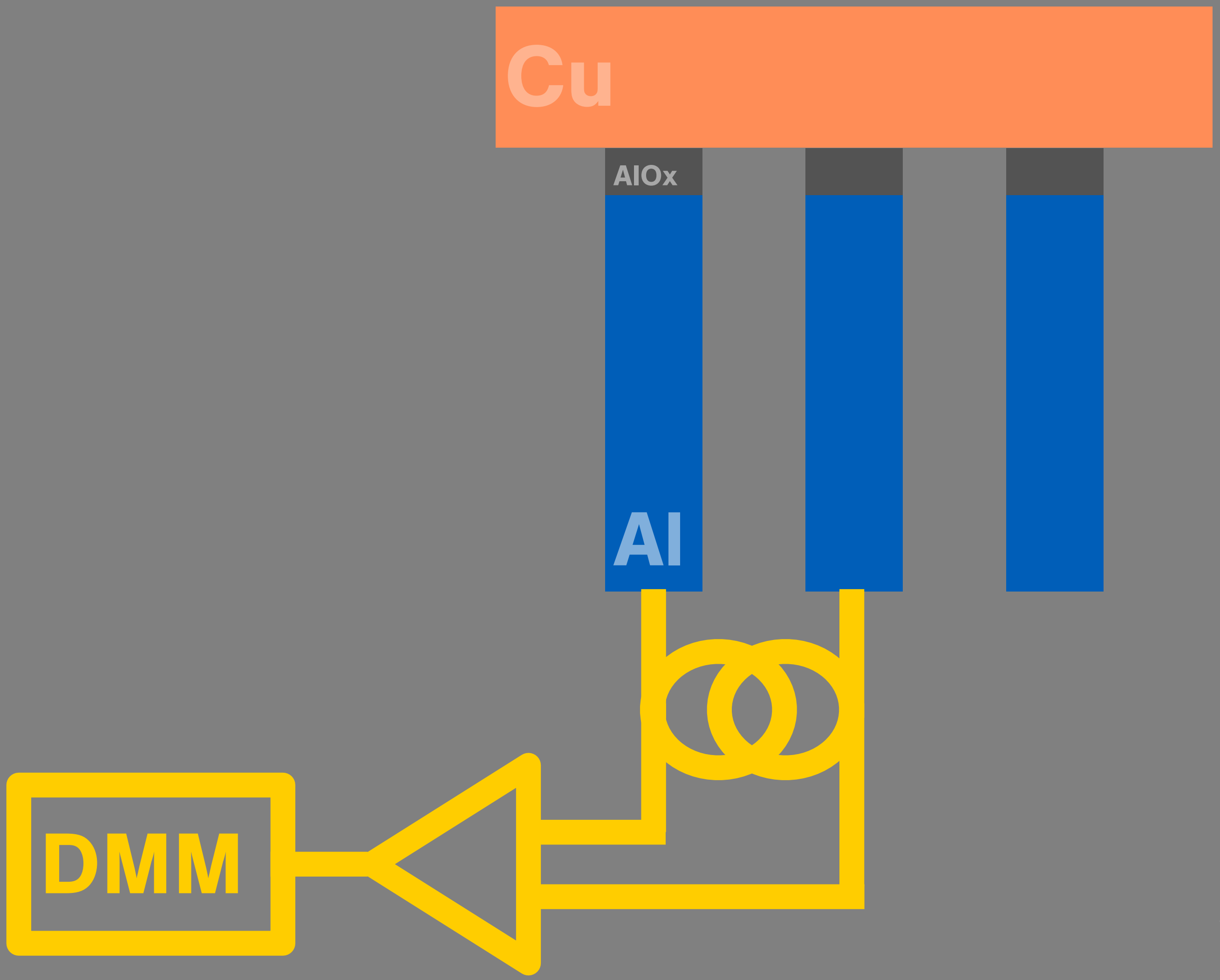


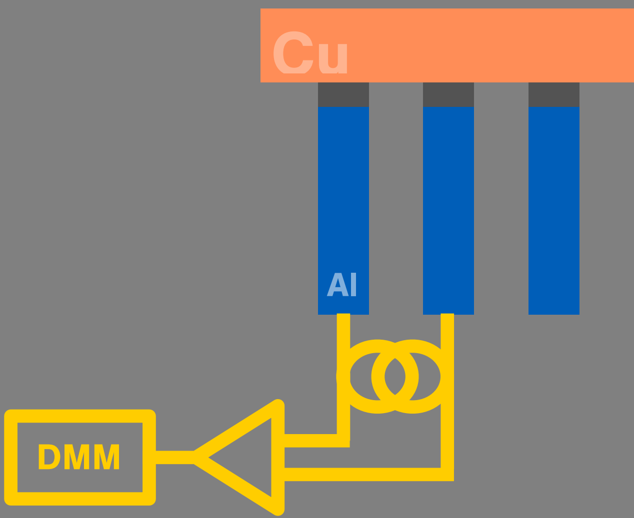
Temperature Sweep, Junctions A and B
I [nA]
4
3
2
1
0
-1
-2
-3
-4
-600
-400
-200
0
200
400
600
800
V_BIAS [μV]
520 mK
300 mK
60 mK

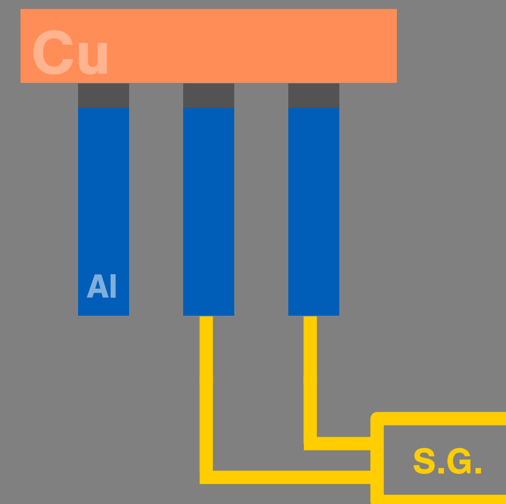

Limited by Dynes & extra heating
91 mK
CONTROL signal (uV)
Electron temperature (K)
bath temperature (K)
0
50
100
150
200
250
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.0
0.2
0.4
0.6
0.8



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.

Aalto University

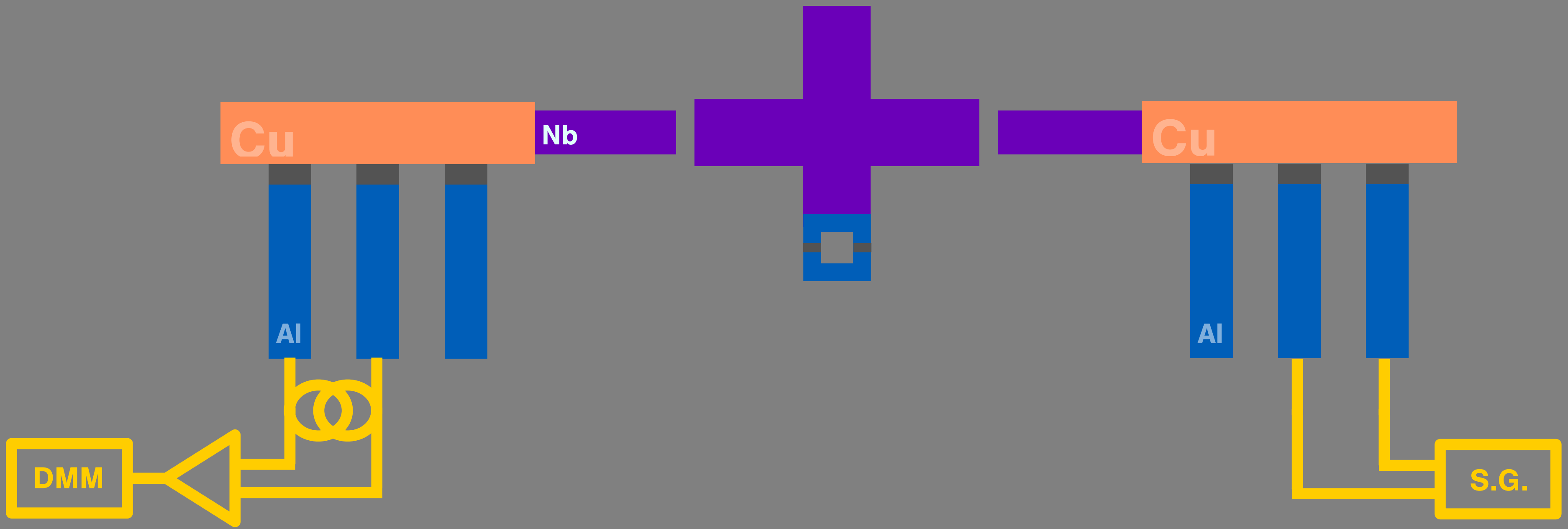
Schmidt et al., PRL 93, 045901 (2004)
Timofeev et al., PRL 102, 200801 (2009)

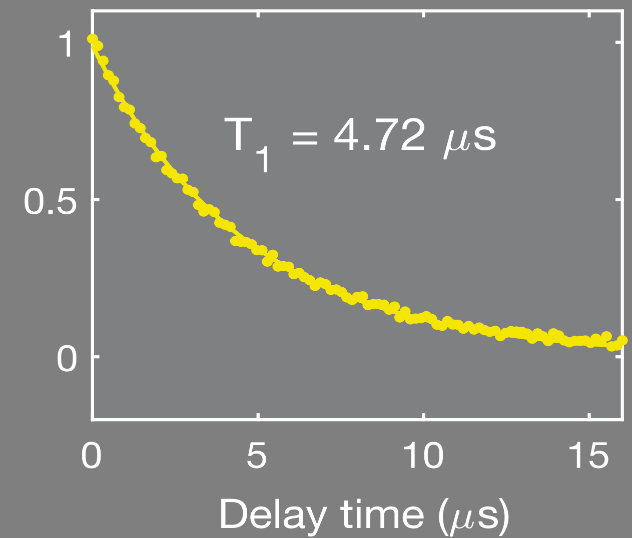
Photonic Heat Transport:

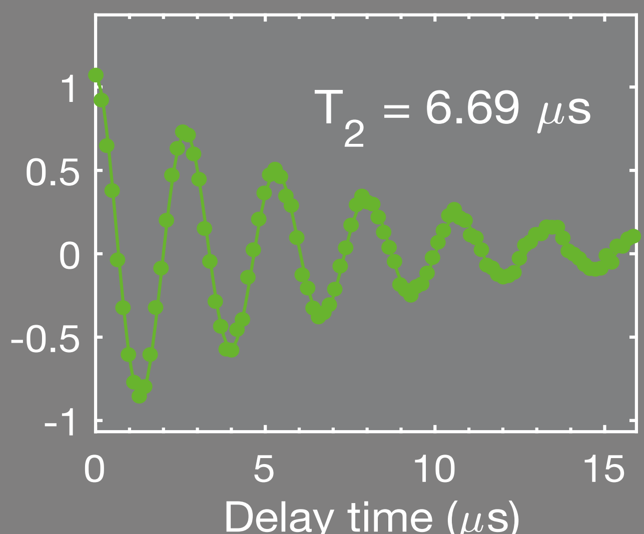
M. Meschke, W. Guichard and J. Pekola, Nature 444, 187 (2006)

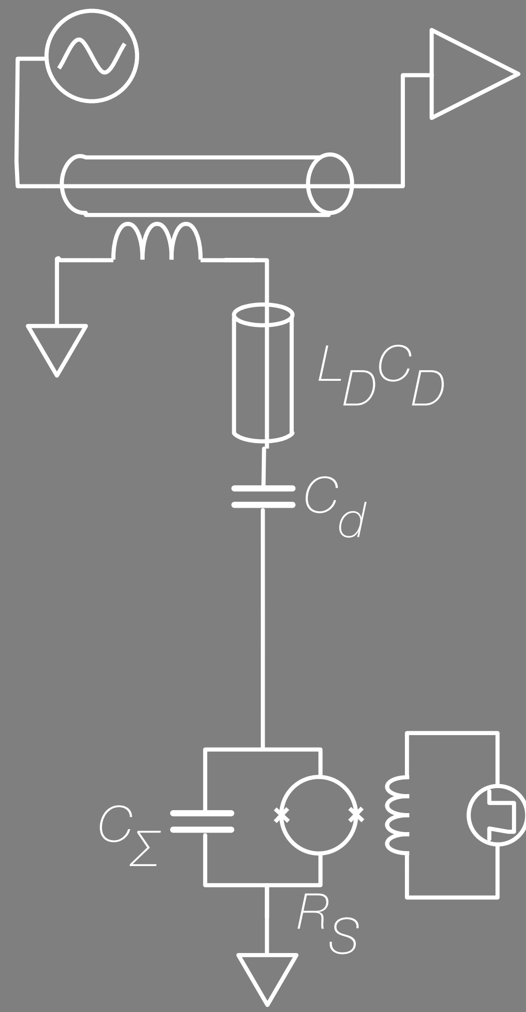
‘Quantum’ of Heat Transport

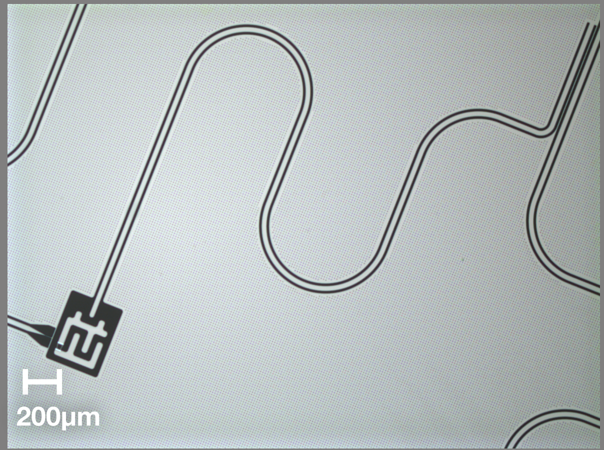
M. Partanen et al., Nature Physics 12, 460 (2016)

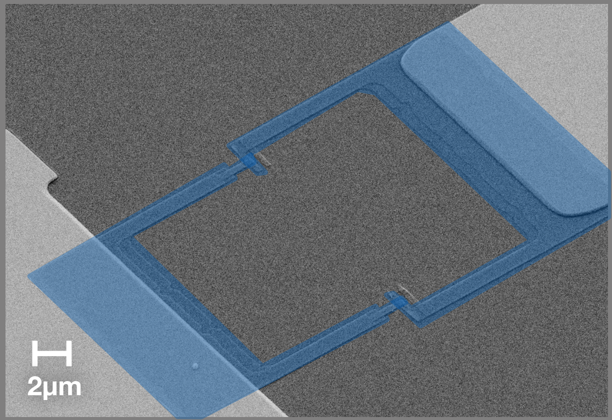

Cu
Nb
Cu
Al
Al
DMM
S.G.





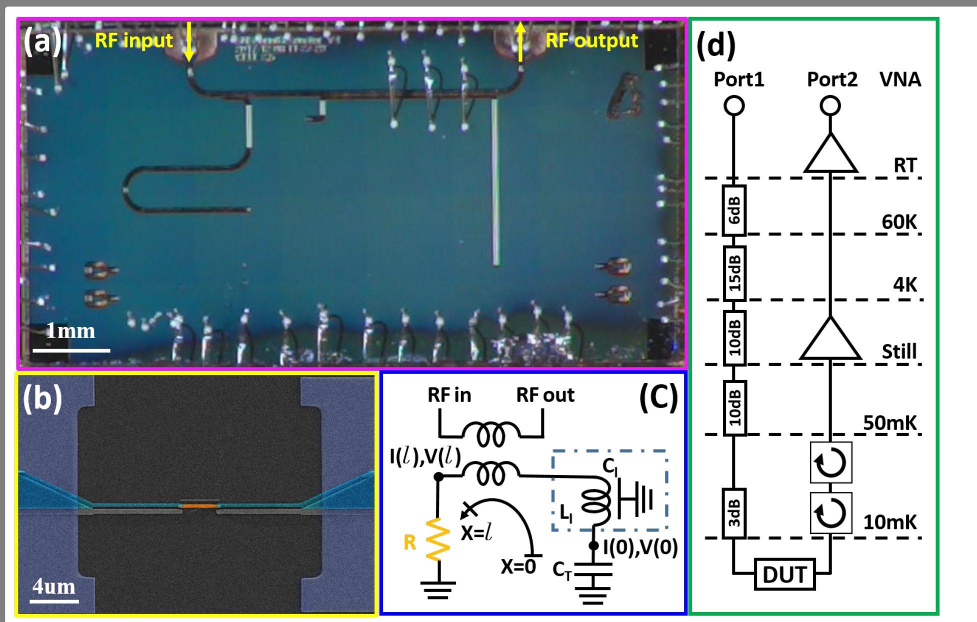


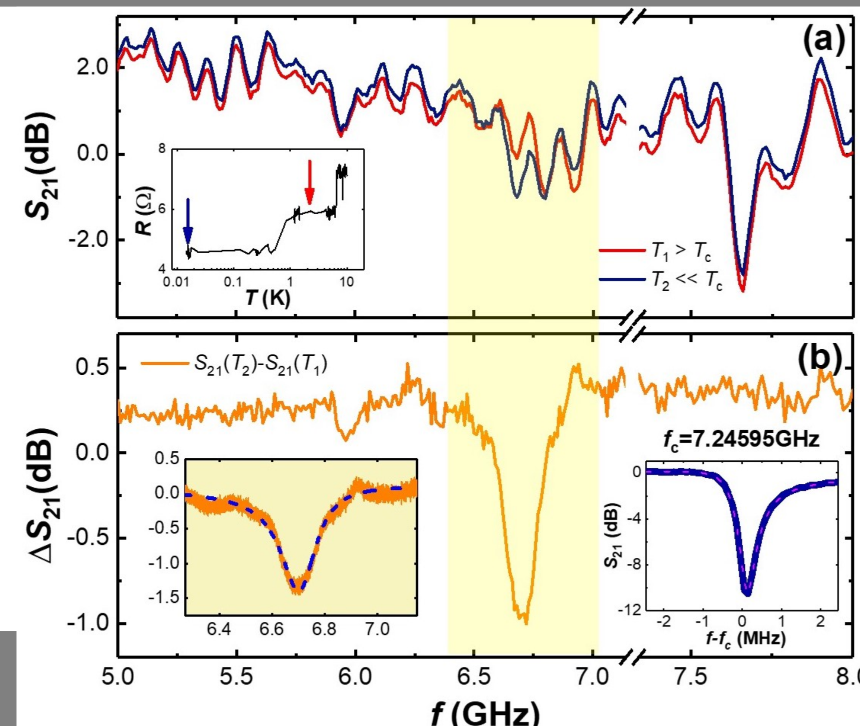




R. George, JS, et al, JLTP (2017)

What happens to Q of the resistively shunted resonators?





Q ≈ 4 - 20

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

Half-way summary:

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

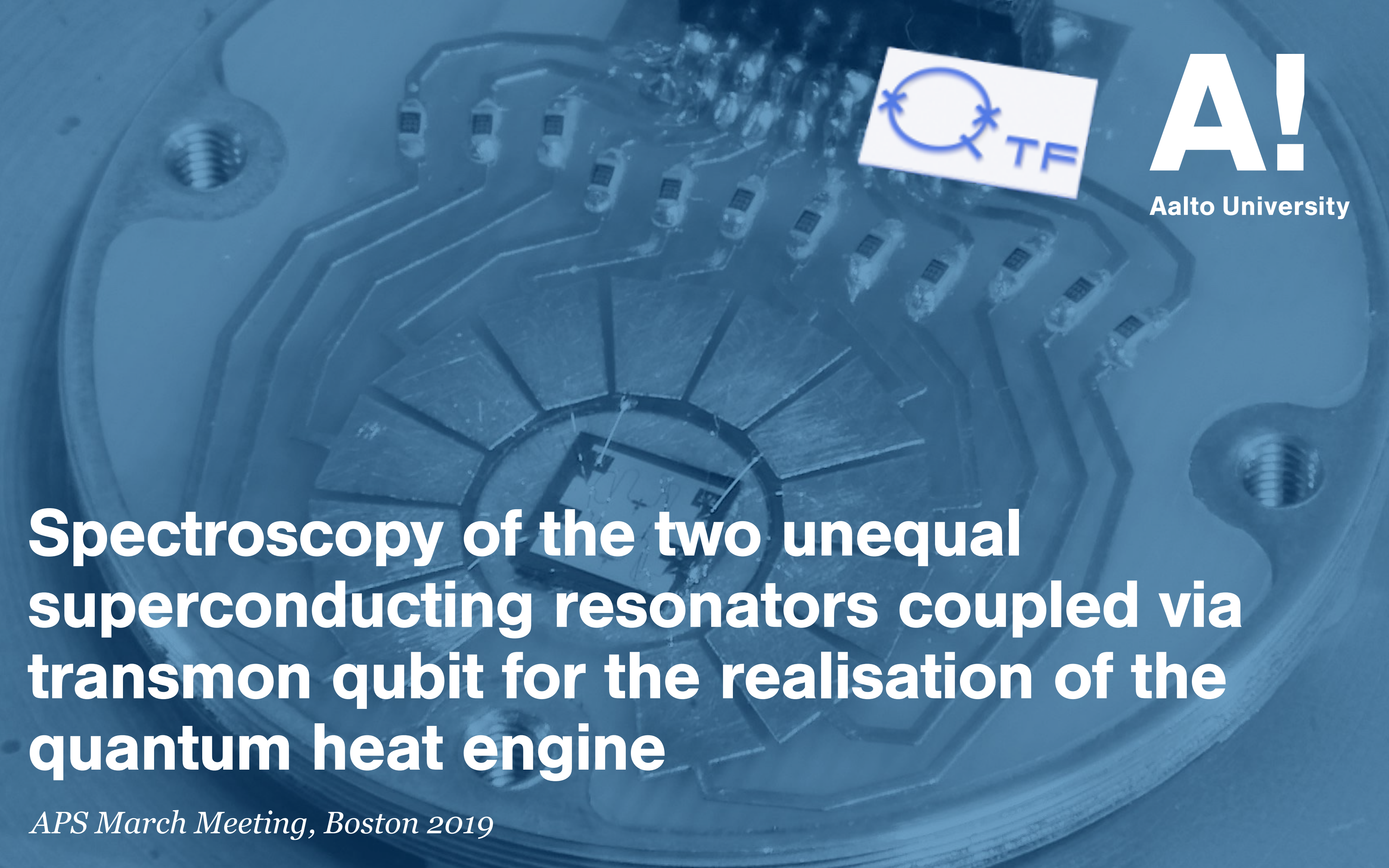
We have our components:

- 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

Jorden Senior



Spectroscopy of the two unequal superconducting resonators coupled via transmon qubit for the realisation of the quantum heat engine

APS March Meeting, Boston 2019

Aalto University

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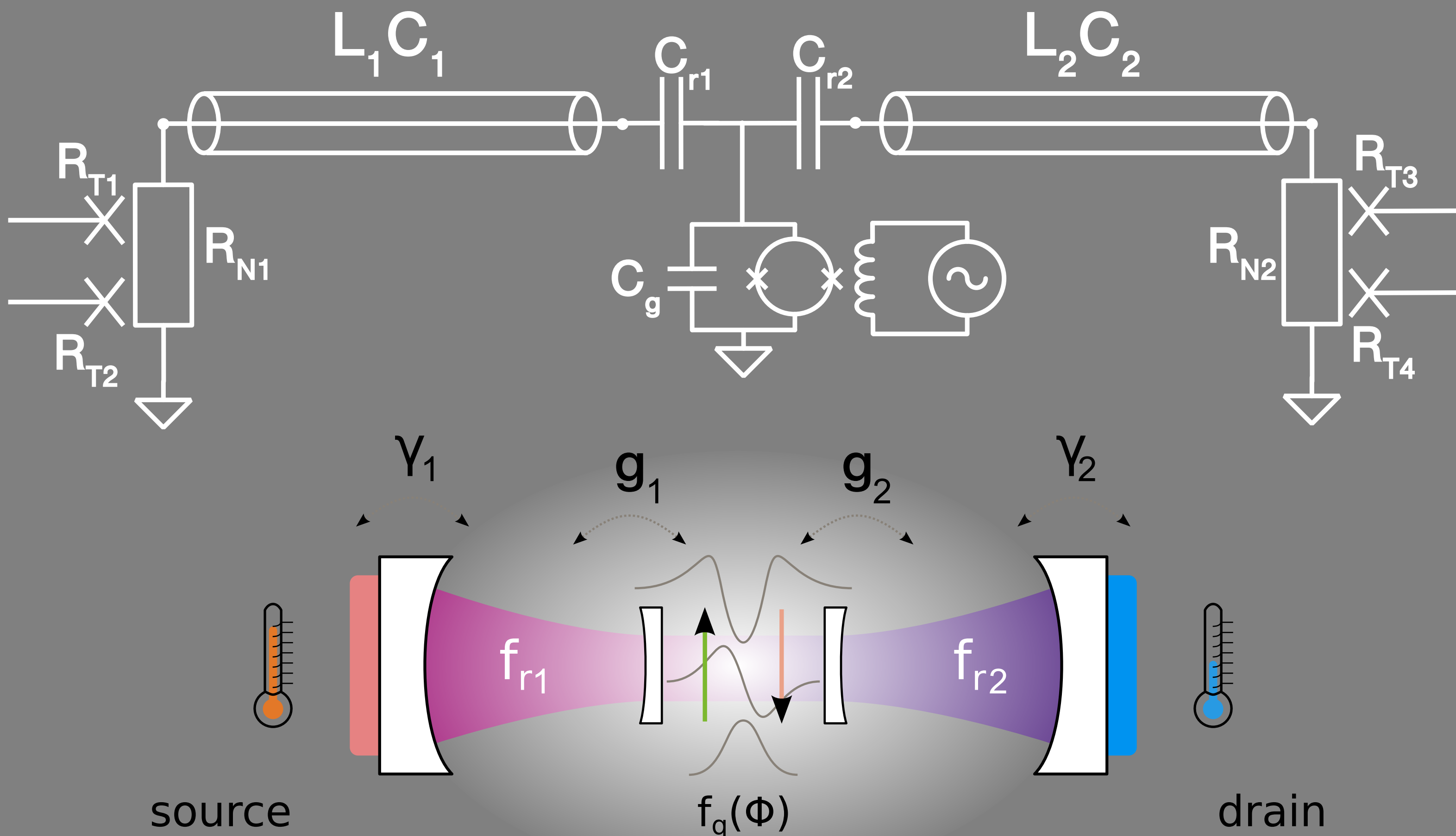
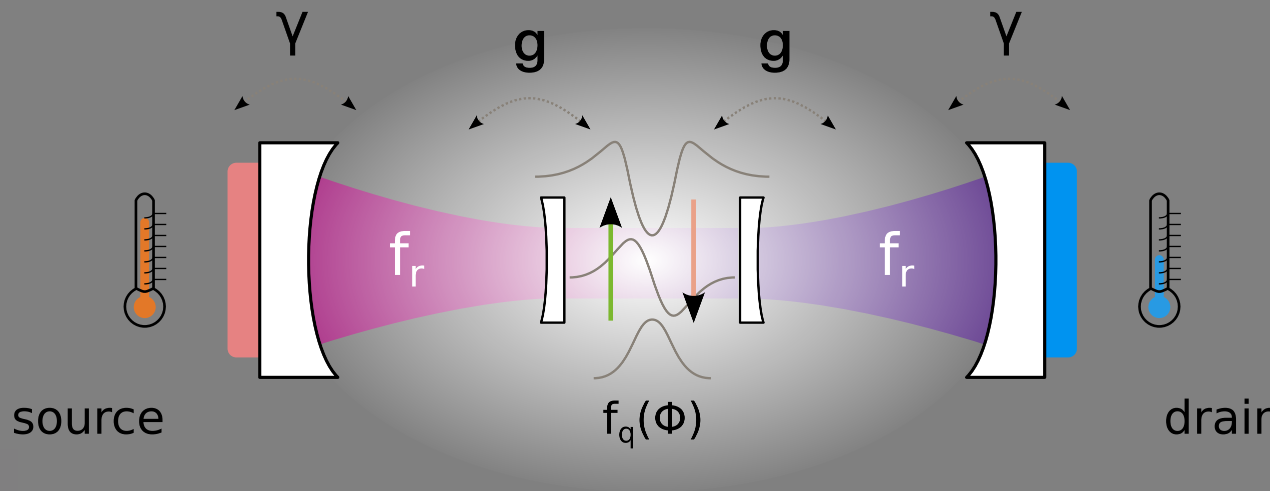
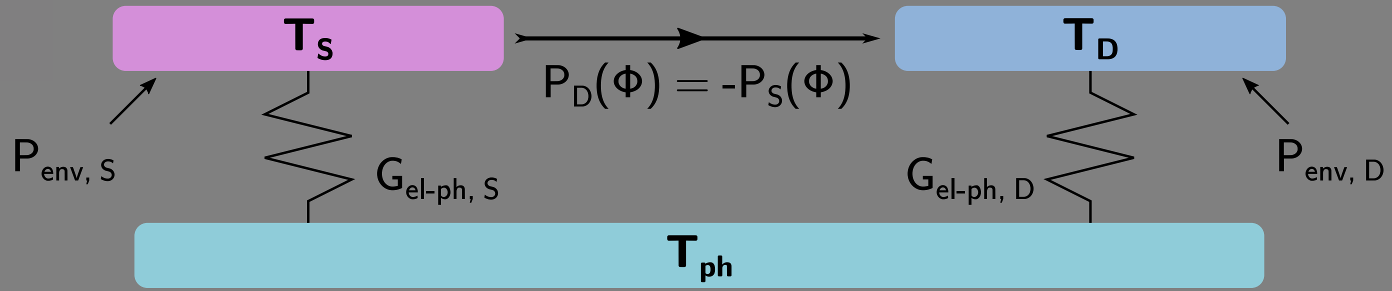


Large parameter space!

Jorden Senior

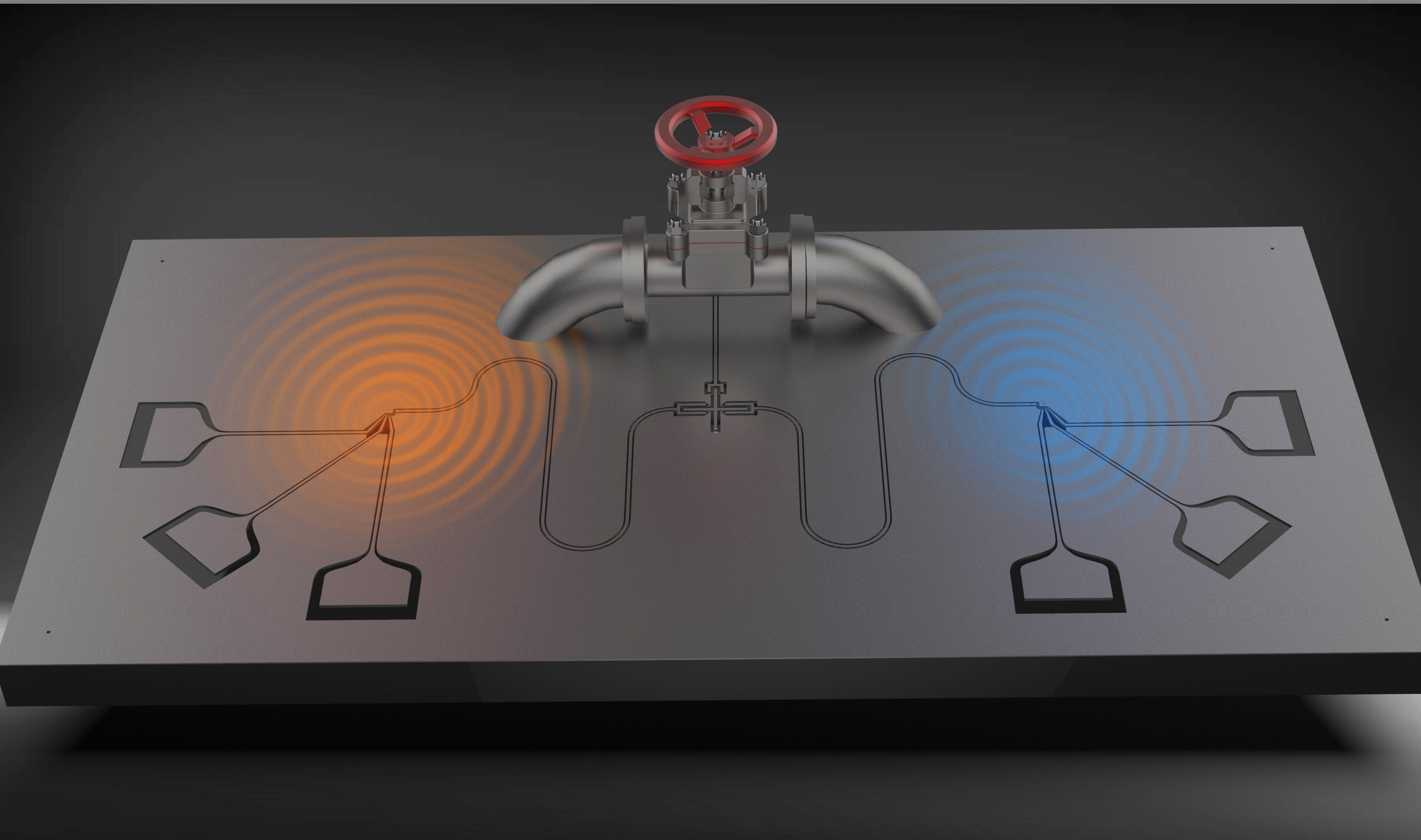


$$f_{r1} = f_{r2}$$



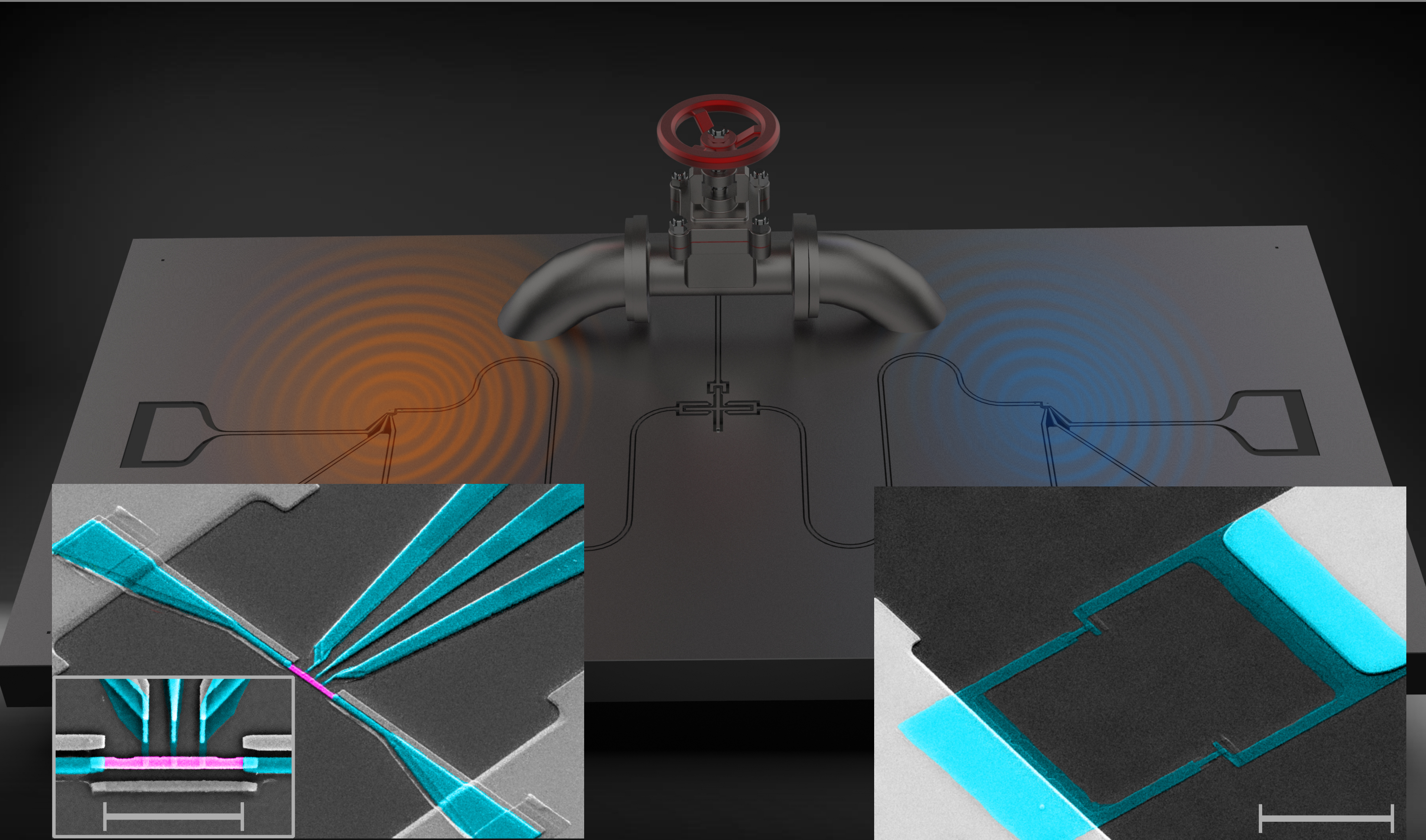
Ronzani, JS, et al, *Nature Physics* **14** ,*991–995 (2018)*

Jorden Senior



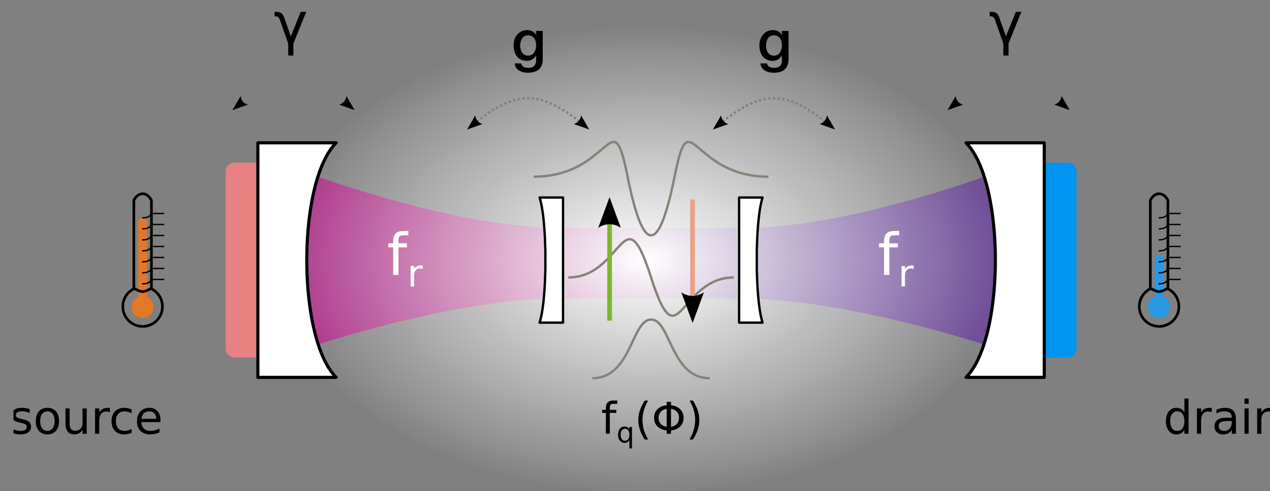
Ronzani, JS, et al, *Nature Physics* **14** ,*991–995 (2018)*

Jorden Senior



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

Jorden Senior



$g/\gamma = 0.05$
Q = 3
LOCAL

$g/\gamma = 0.4$
Q = 20
GLOBAL

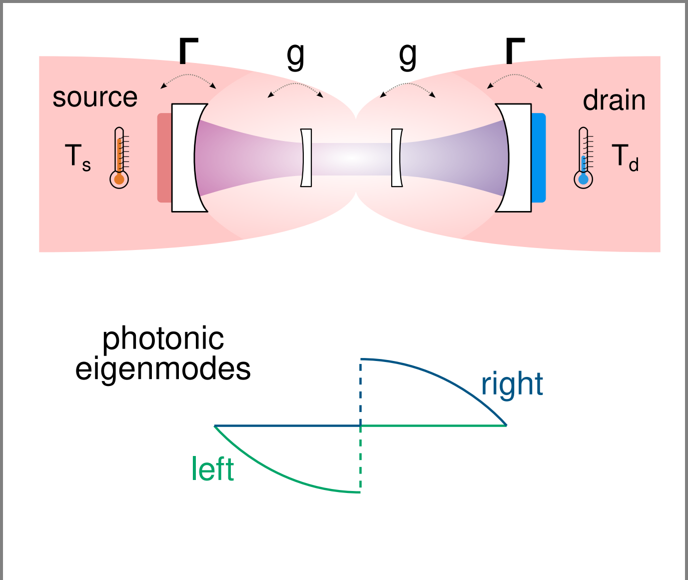
Ronzani, JS, et al, *Nature Physics* **14** ,*991–995 (2018)*

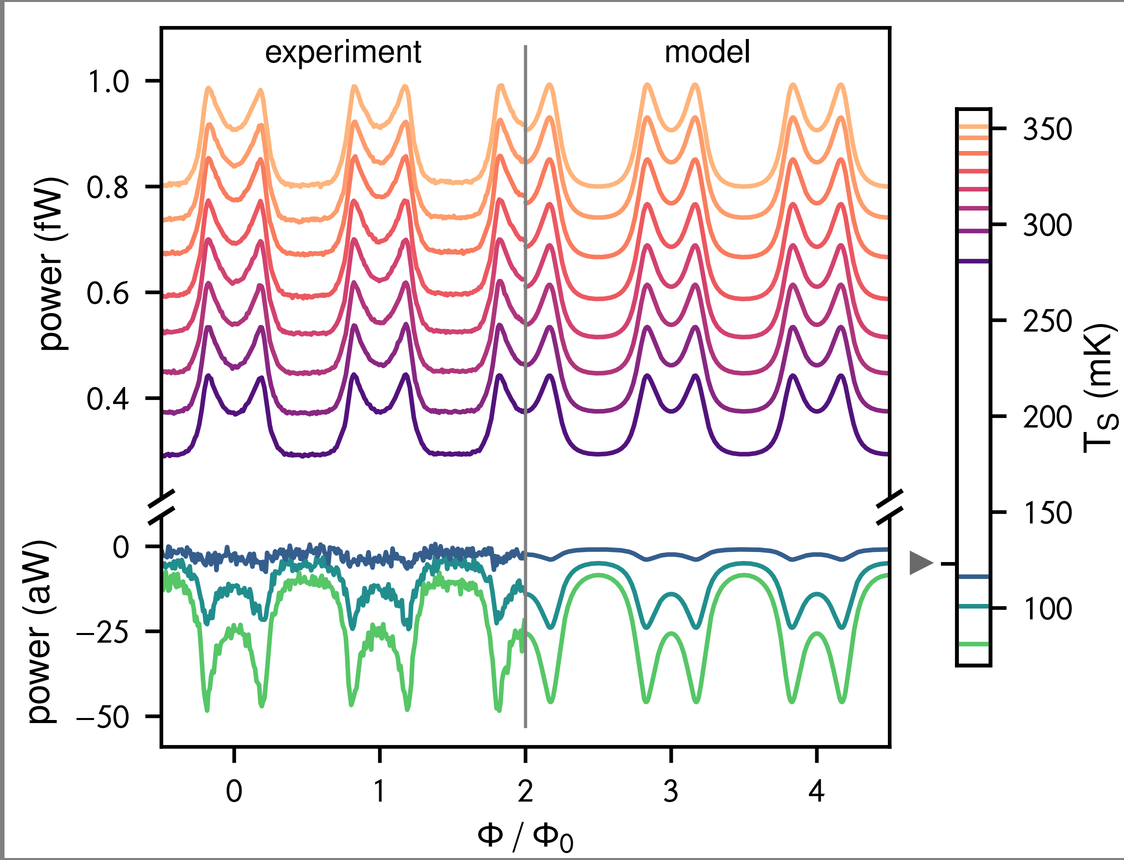
g/γ = 0.05

Q = 3

LOCAL

NEP ~5 aW
‘wireless’ cooling (4mm) of 50aW





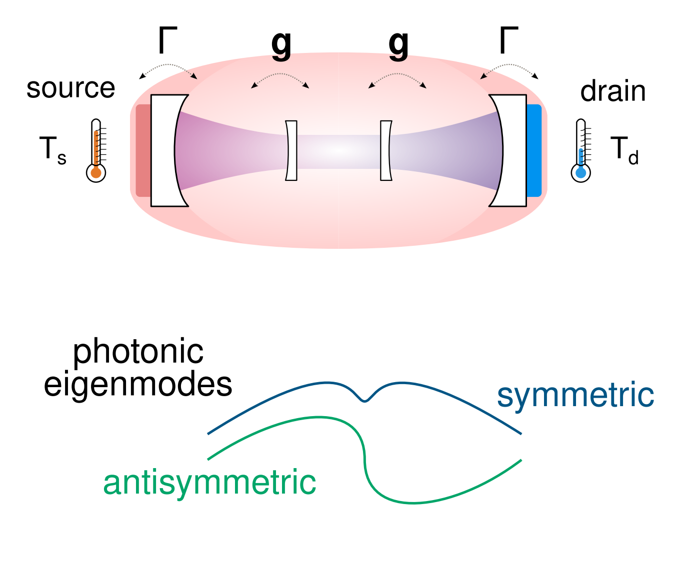
Ronzani, JS, et al, *Nature Physics* **14** *,991–995 (2018)*

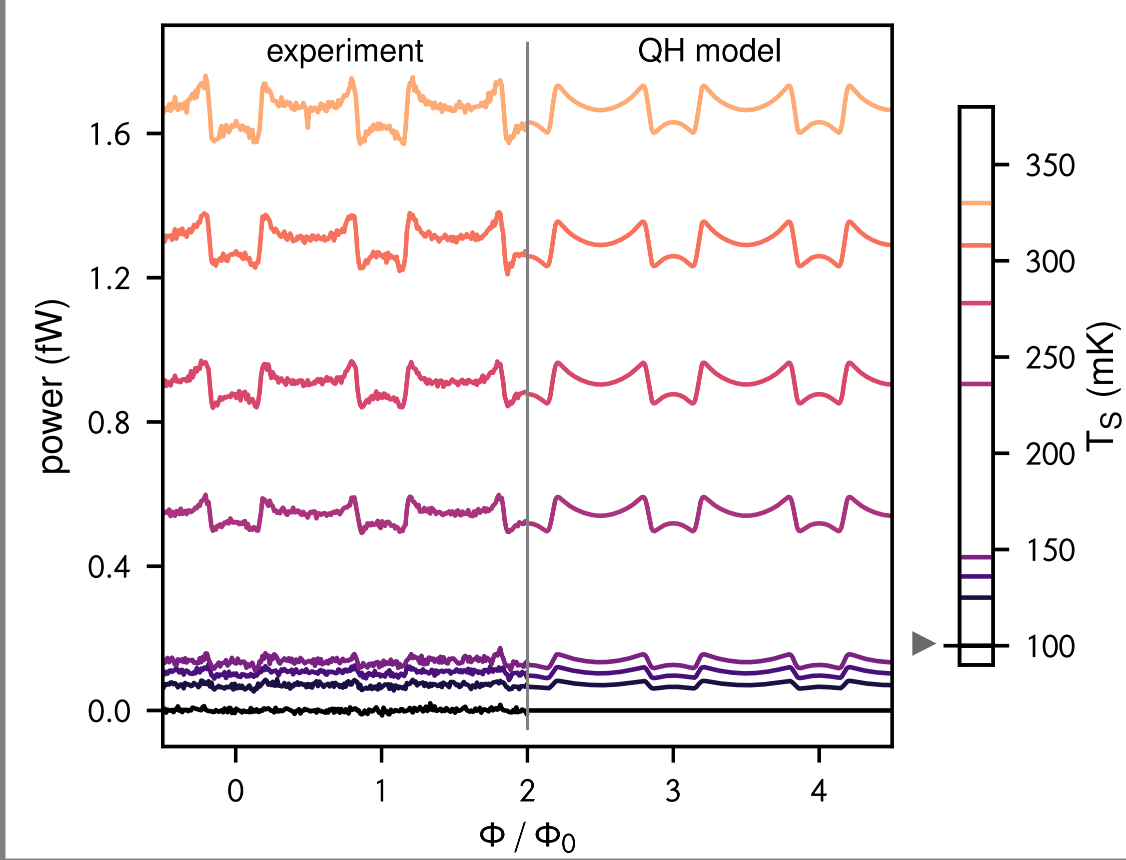
Jorden Senior

g/γ = 0.4

Q = 20

GLOBAL



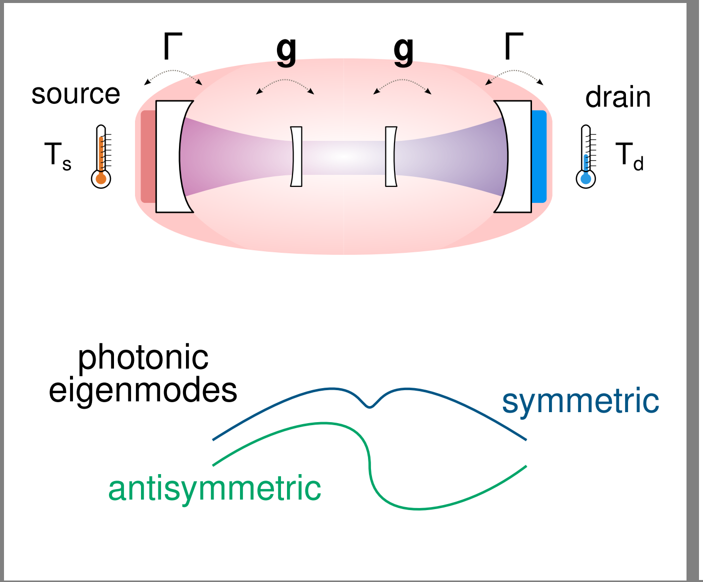


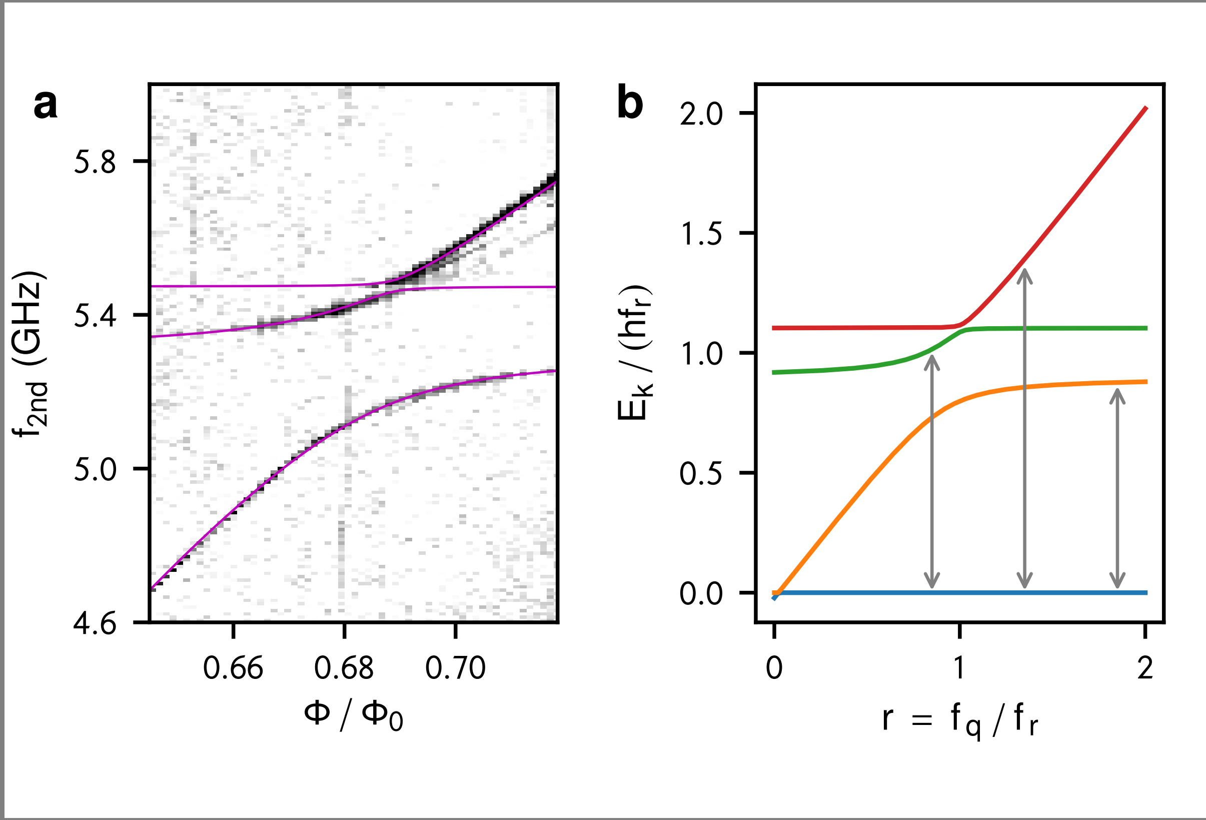
Ronzani, JS, et al, *Nature Physics* **14** *,991–995 (2018)*

$g/\gamma = 0.4$

Q = 20

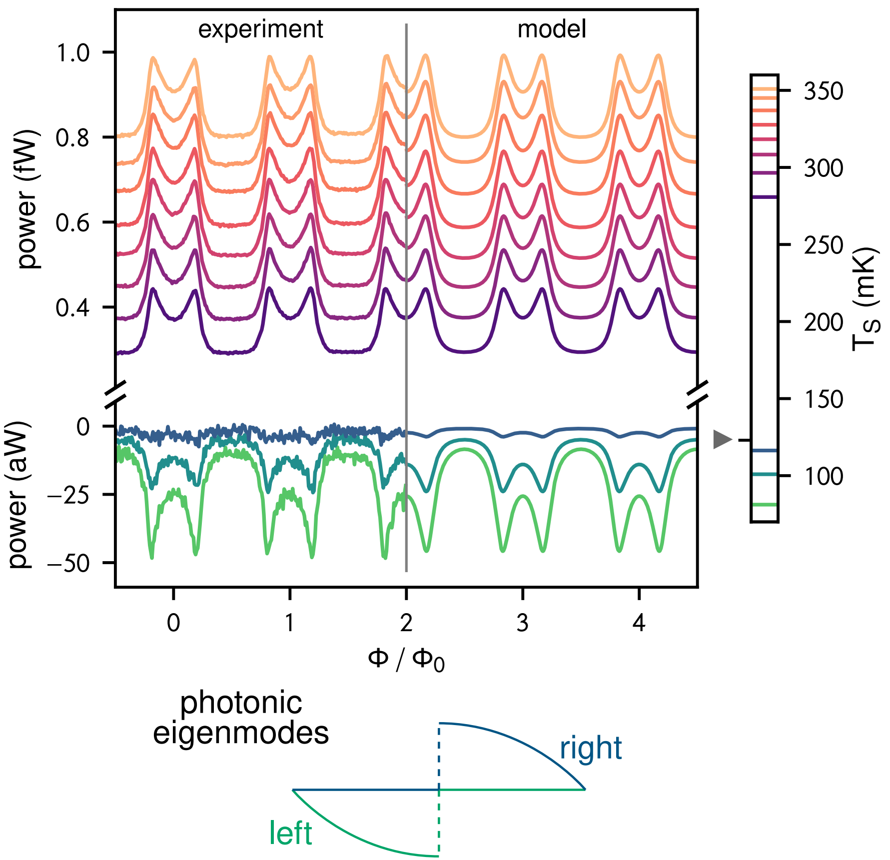
GLOBAL



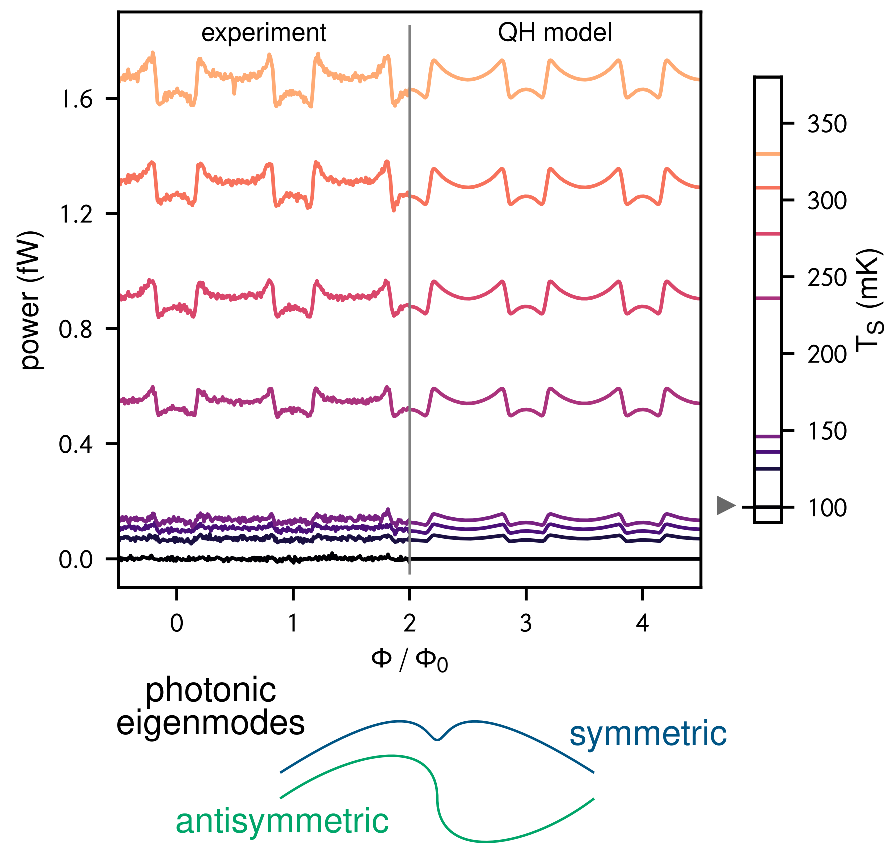


Ronzani, JS, et al, *Nature Physics* **14** *,991–995 (2018)*

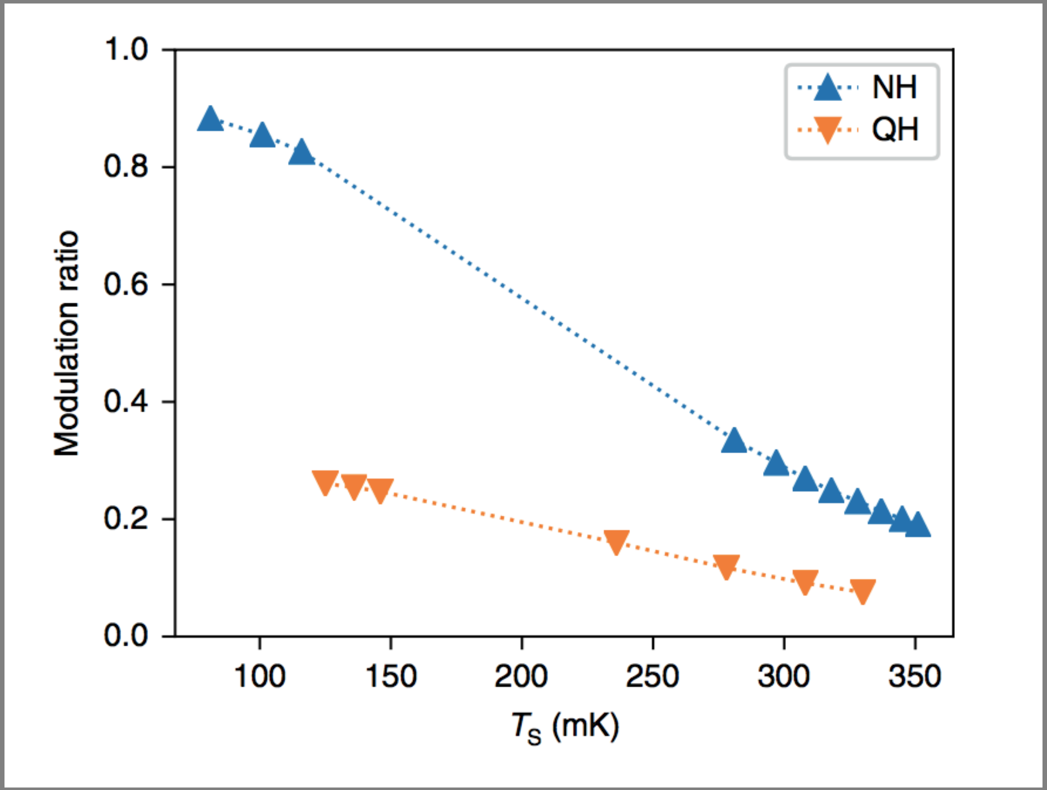
g/γ = 0.05



g/γ = 0.4



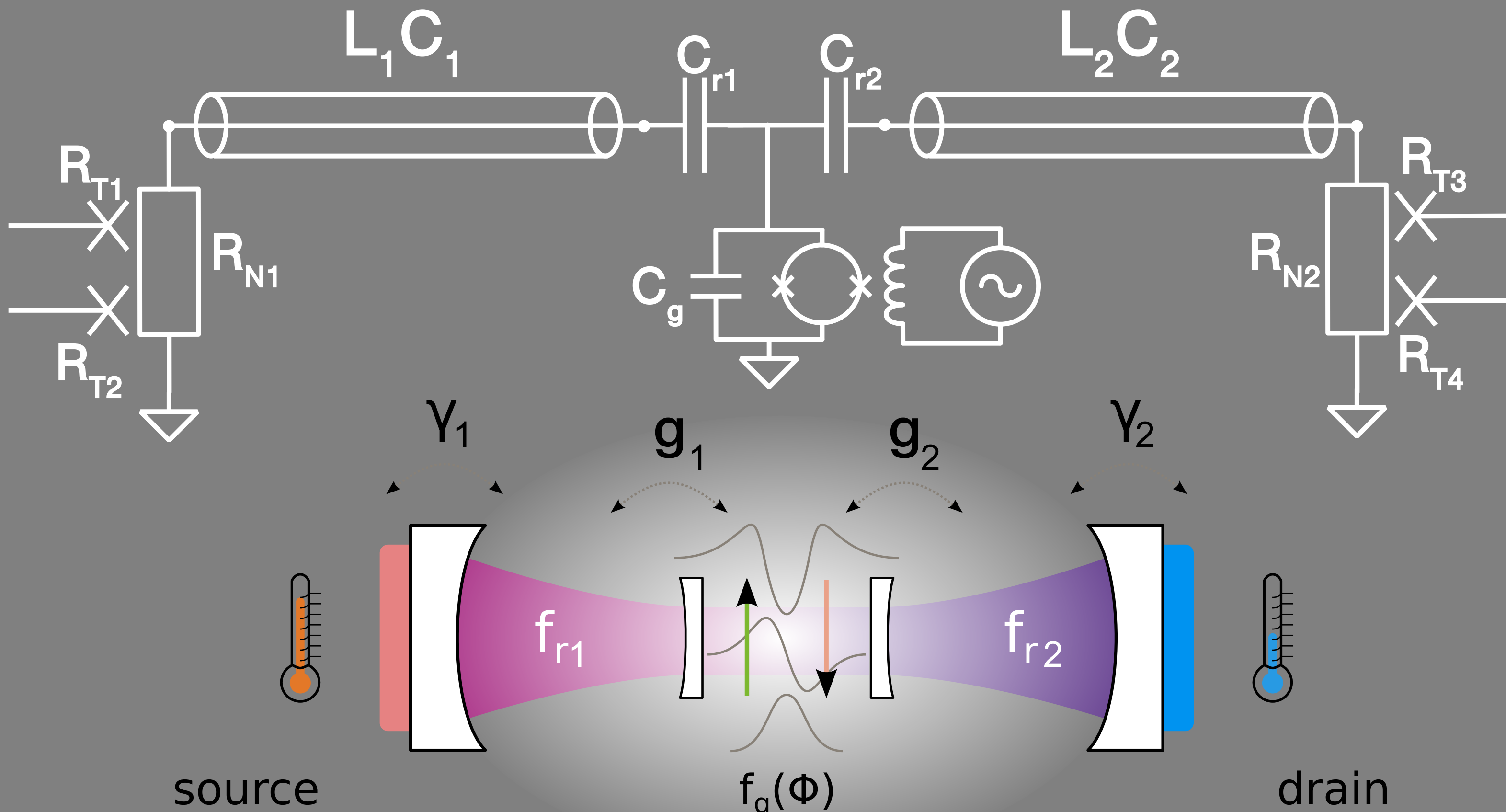
Ronzani, JS, et al, *Nature Physics* **14** ,*991–995 (2018)*



$g/\gamma = 0.05$

$g/\gamma = 0.4$

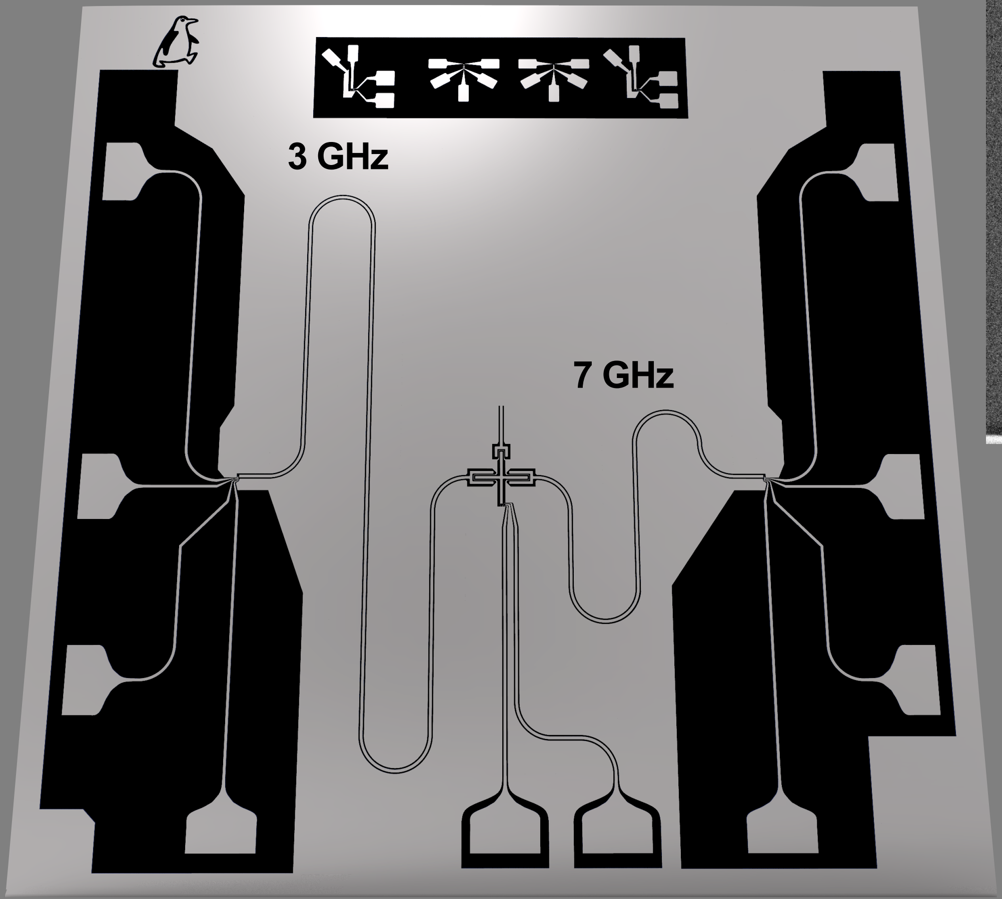
Ronzani, JS, et al, *Nature Physics* **14** ,*991–995 (2018)*

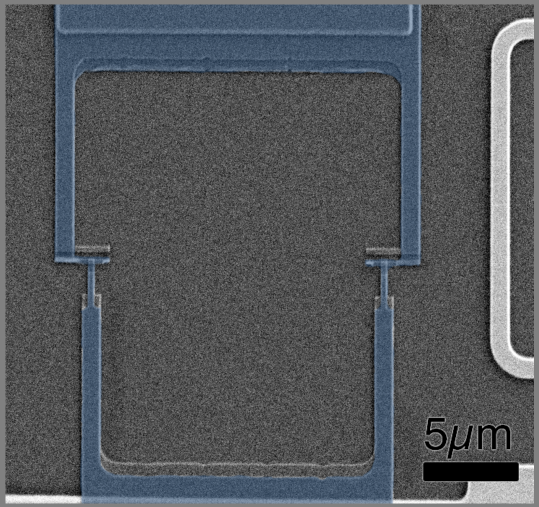


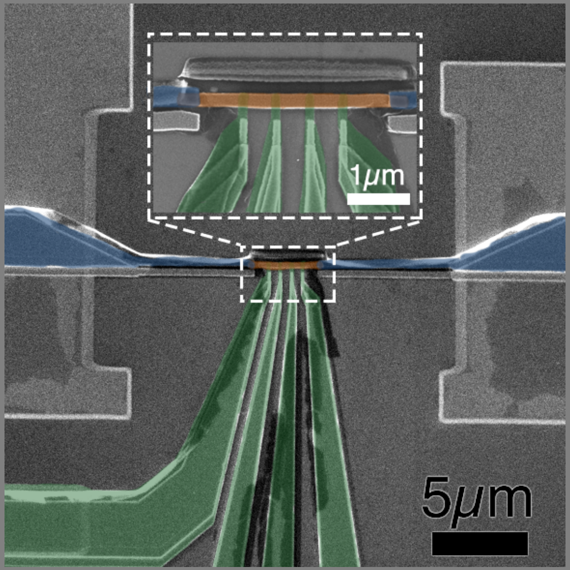
Aalto University

Artificial atom tunably coupled to two frequencies: wireless thermal rectification

Jorden Senior

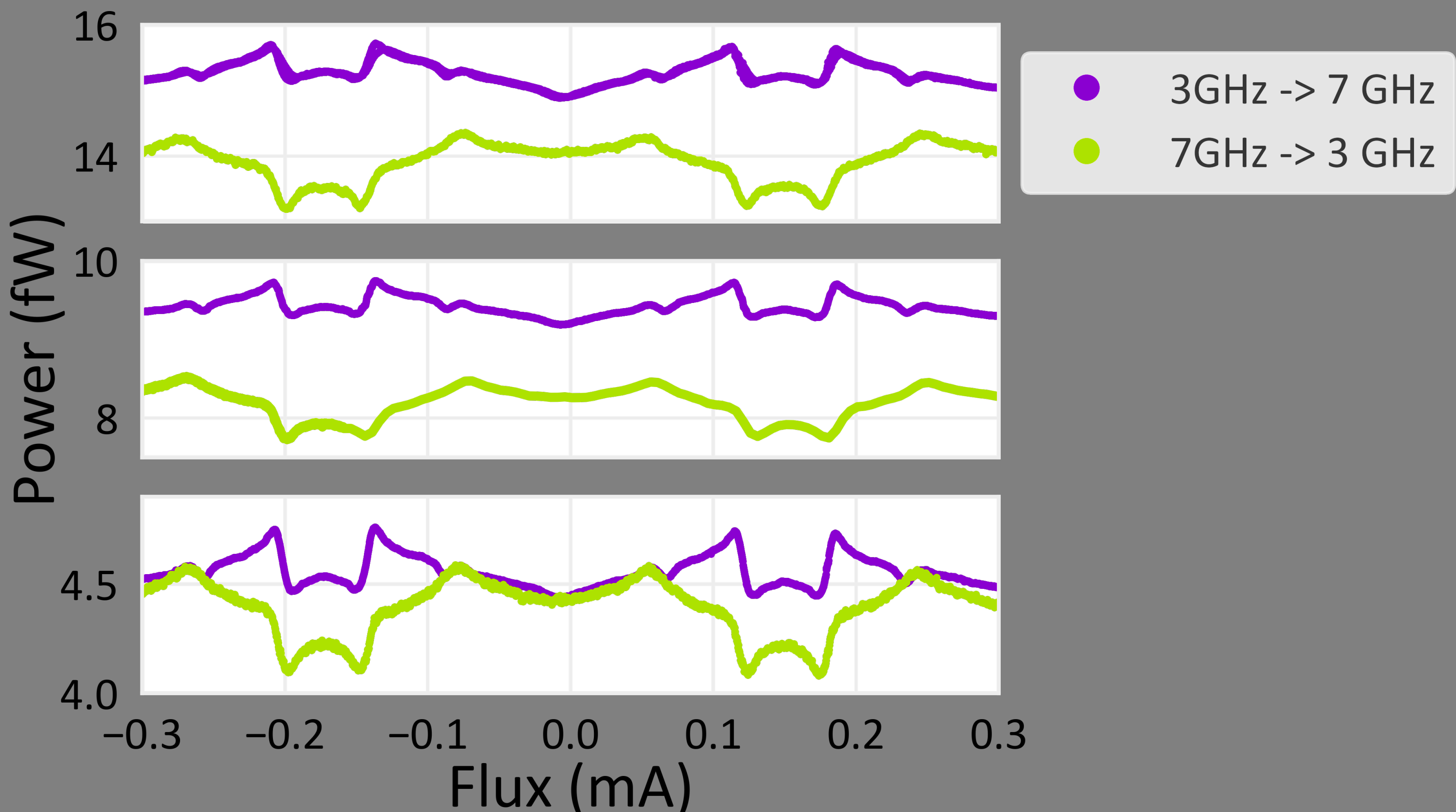




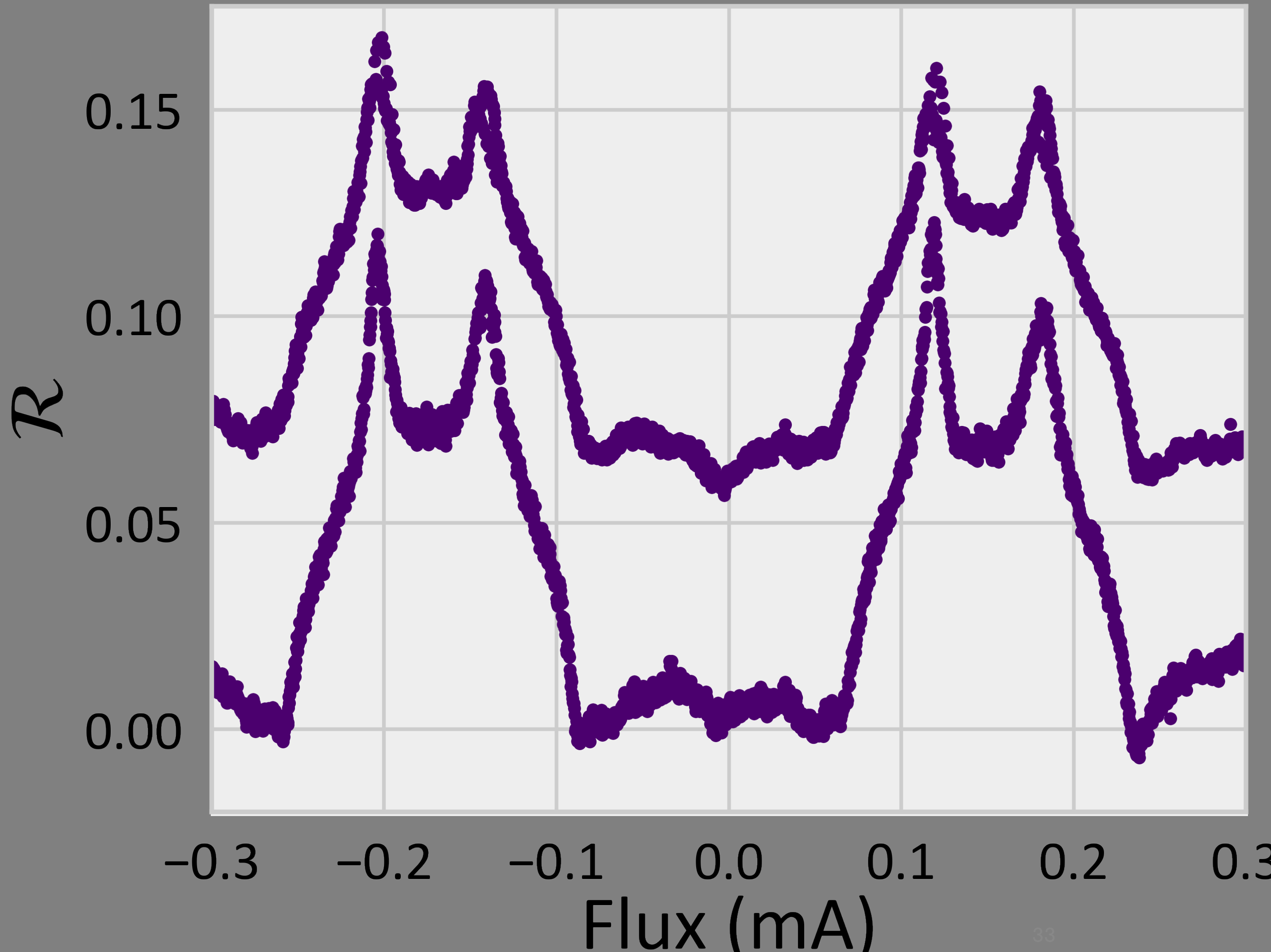


JS et al, *under preparation*

Jorden Senior



JS et al, *under preparation*



JS et al, *under preparation*

Key Messages:

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

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

Aalto University

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

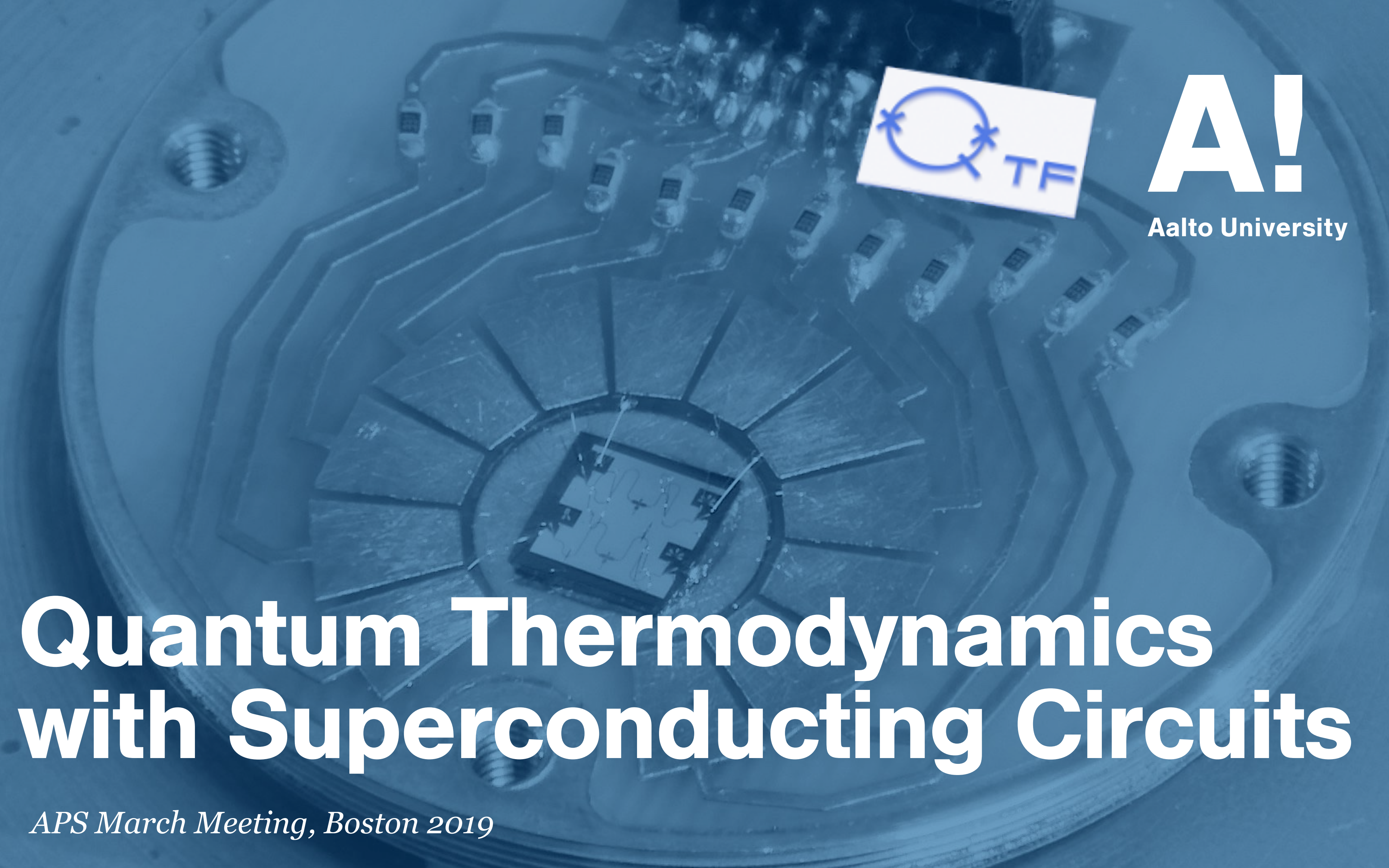

Elsa Mannila


Marco Marín Suárez


Klaara Viisanen


Libin Wang


Rishabh Upadhyay

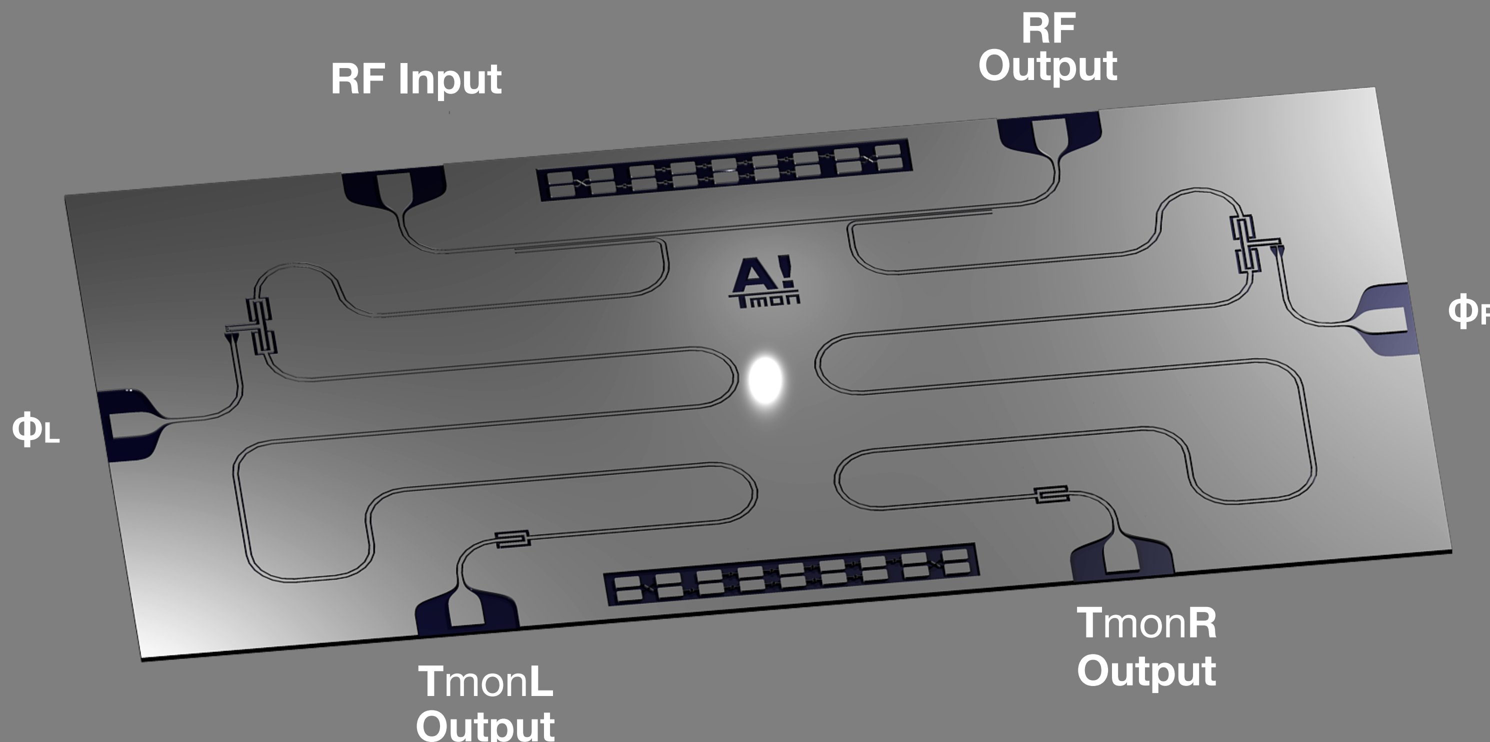


Aalto University

Quantum Thermodynamics with Superconducting Circuits

APS March Meeting, Boston 2019

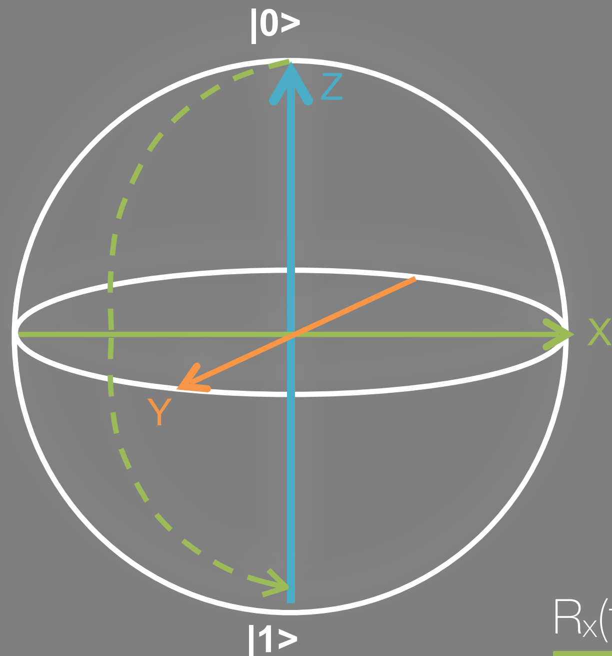
(8mm x 4mm)

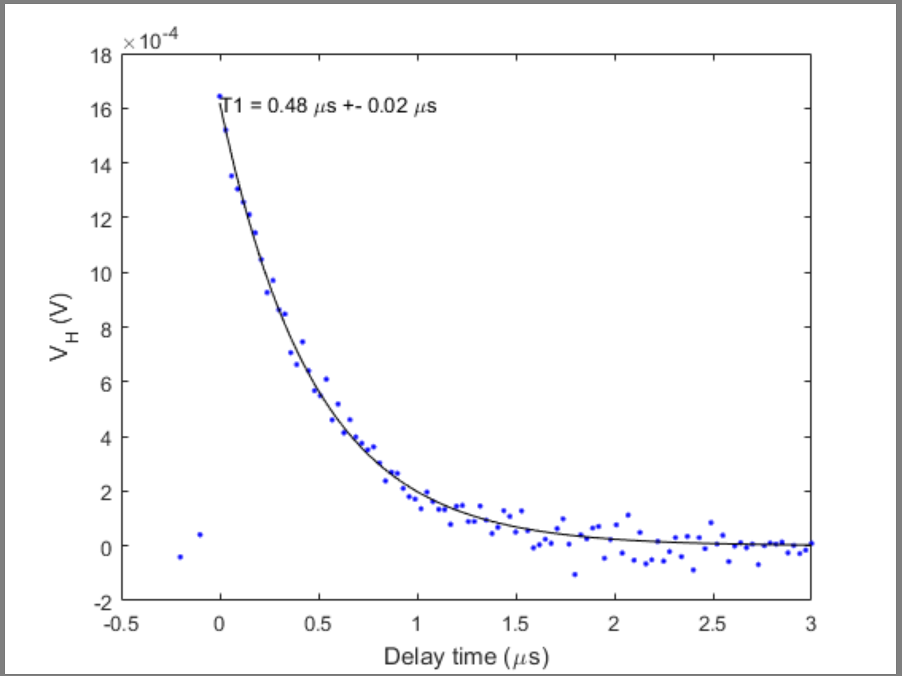


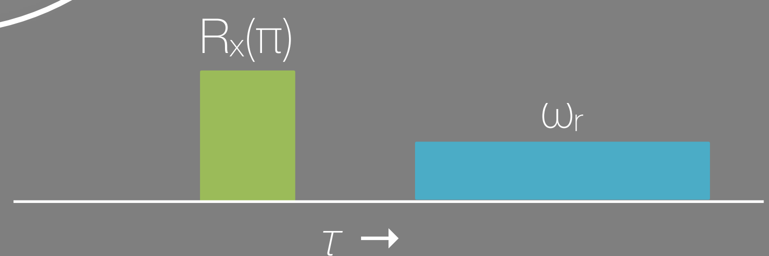
The chip:

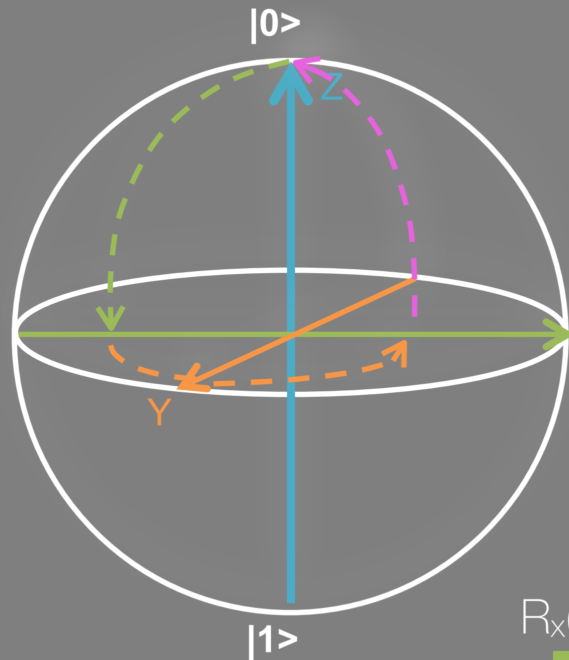
Substrate: HiRes Si

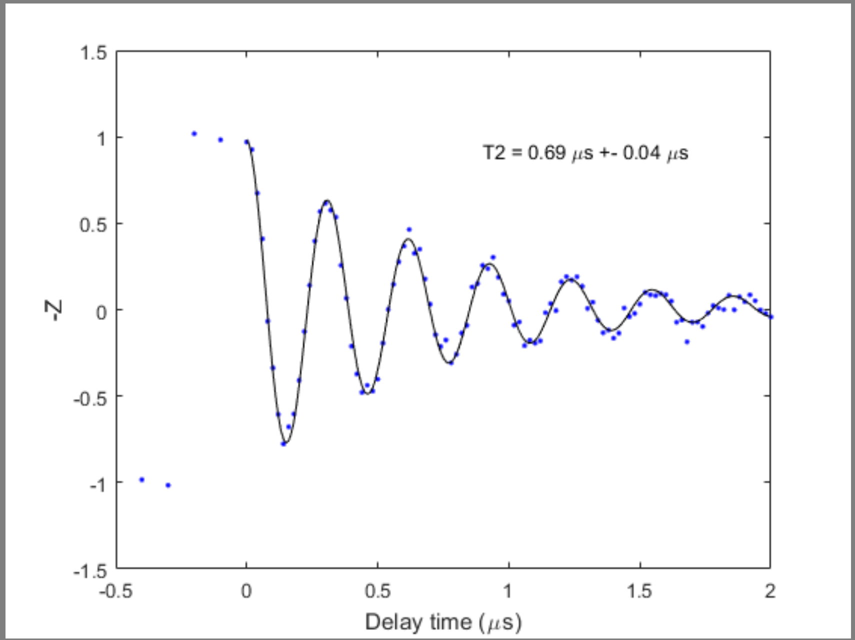
Materials: NbN (Al JJ's)

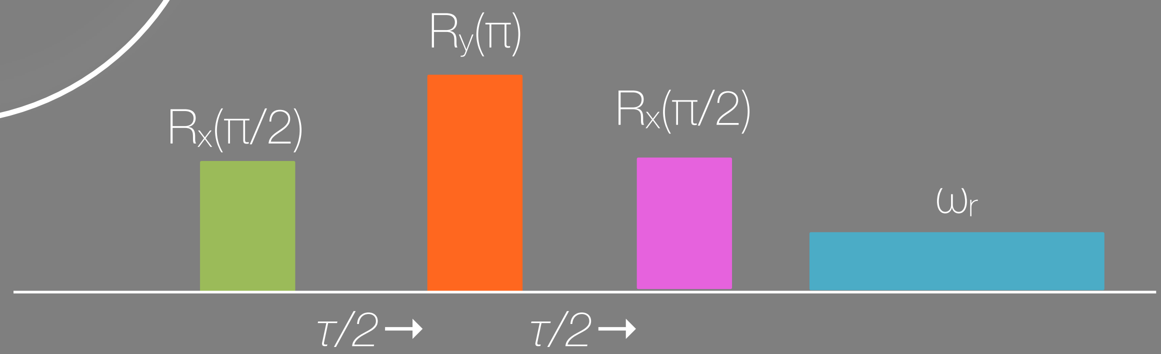

|0>
Z
X
Y
|1>

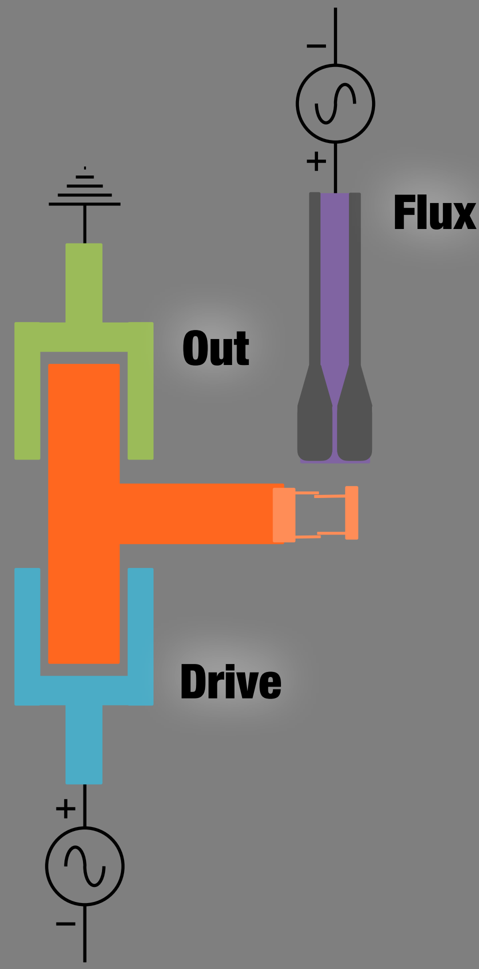

×10^-4
18
16
14
12
10
8
6
4
2
0
-2
T1 = 0.48 µs +- 0.02 µs
V_H (V)
-0.5
0
0.5
1
1.5
2
2.5
3
Delay time (µs)


Rx(π)
ωr
τ →


|0>
Z
Y
|1>


T2 = 0.69 μs +- 0.04 μs
-Z
Delay time (μs)
1.5
1
0.5
0
-0.5
-1
-1.5
-0.5
0
0.5
1
1.5
2


$R_x(\pi/2)$
$R_y(\pi)$
$R_x(\pi/2)$
ω_r
$\tau/2 \rightarrow$
$\tau/2 \rightarrow$



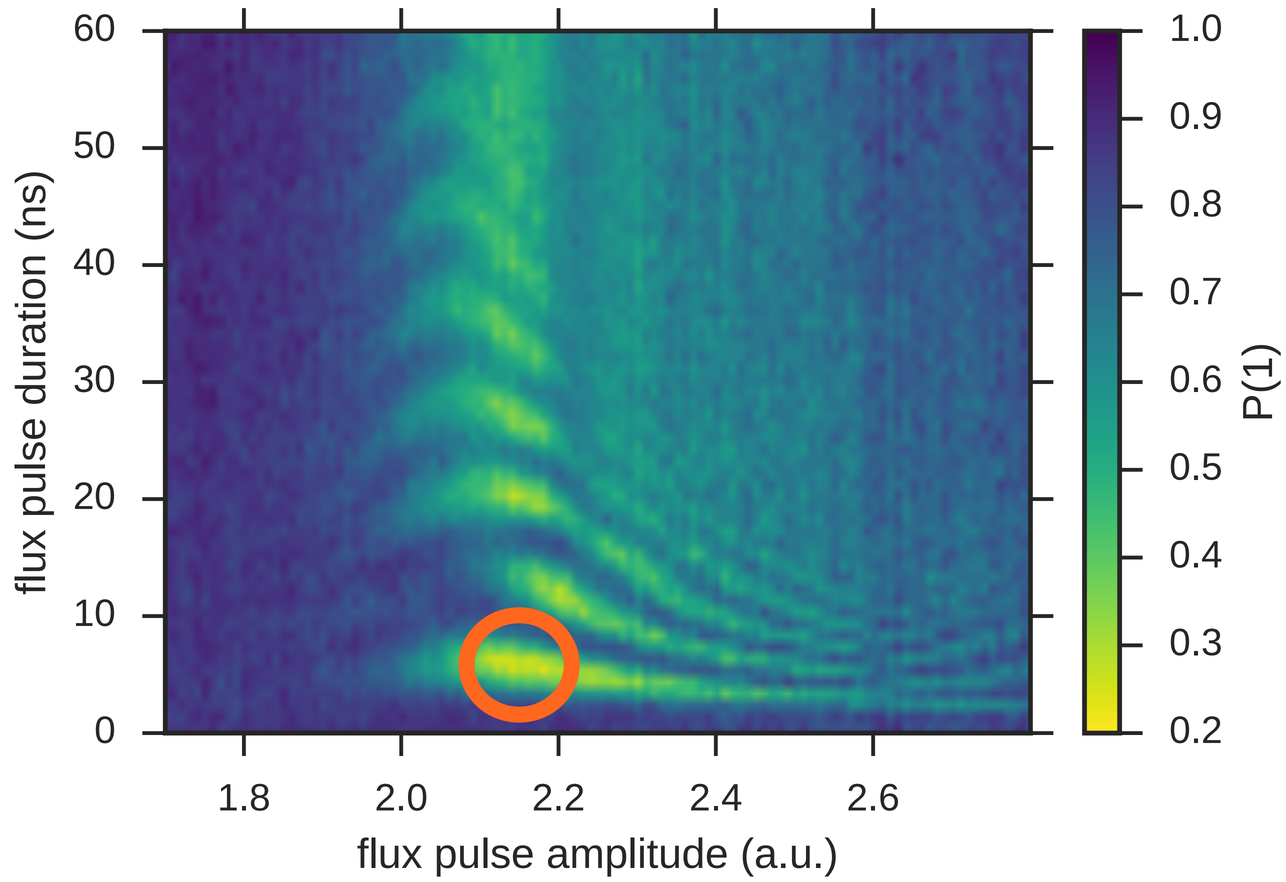
Protocol:

1. Initialise the qubit to $\mathbf{f_{01}}$ ground state

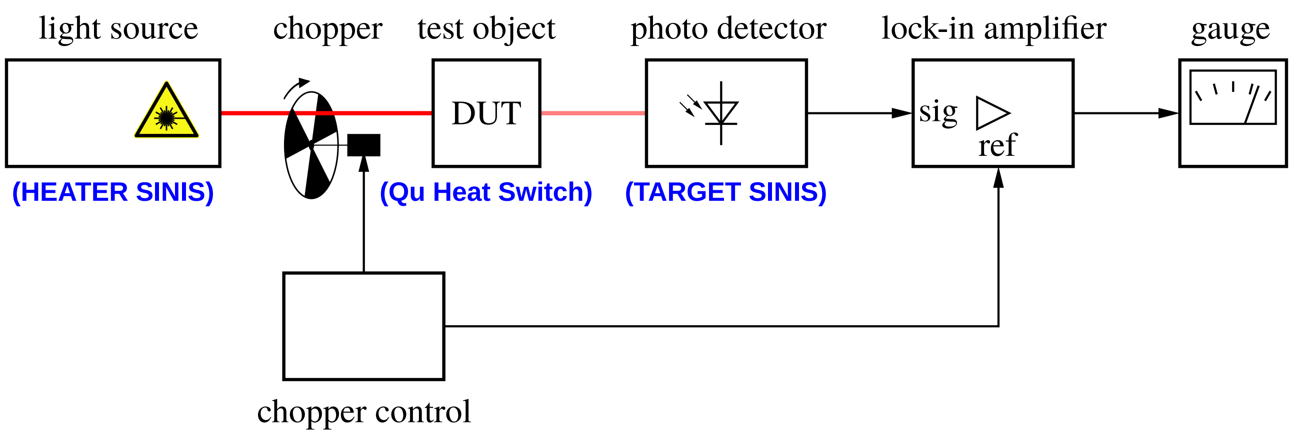
2. Apply $\mathbf{R_x(\pi)}$ pulse at **Drive** to excite qubit

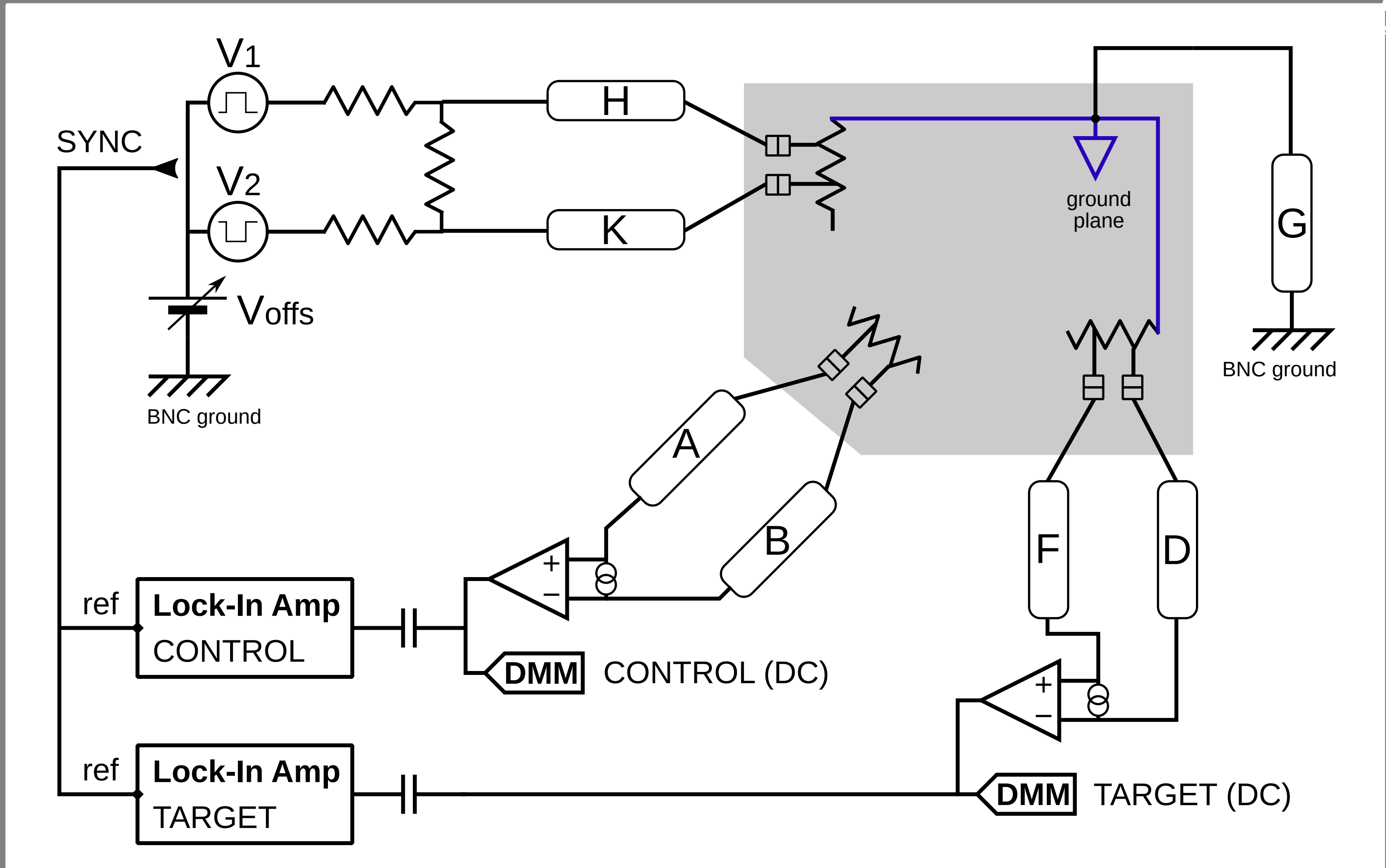
3. Apply pulse at **Flux** with variable amplitude and duration to bring qubit into resonance with **Out** and back

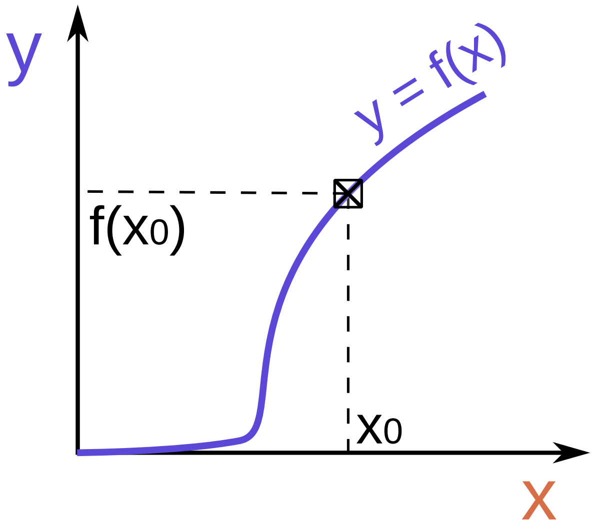
4. Perform readout operation at **Drive**

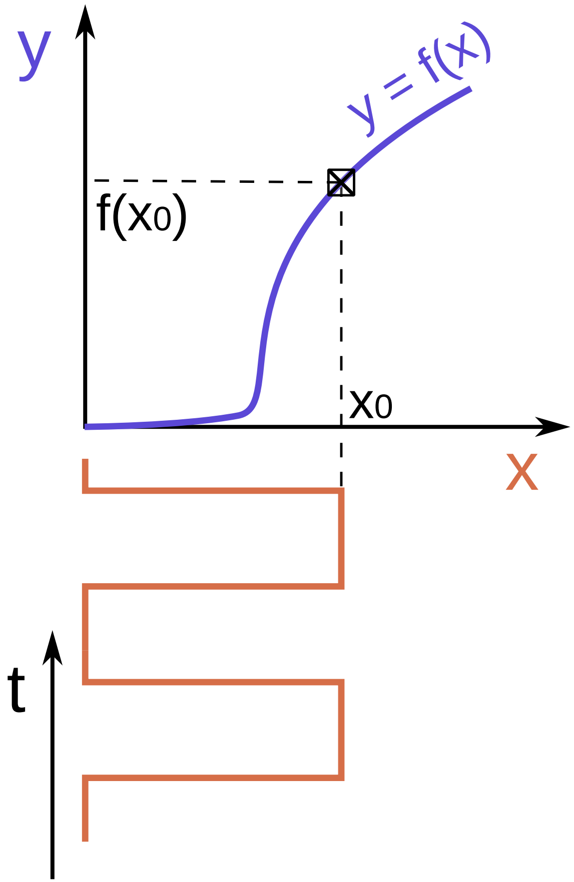


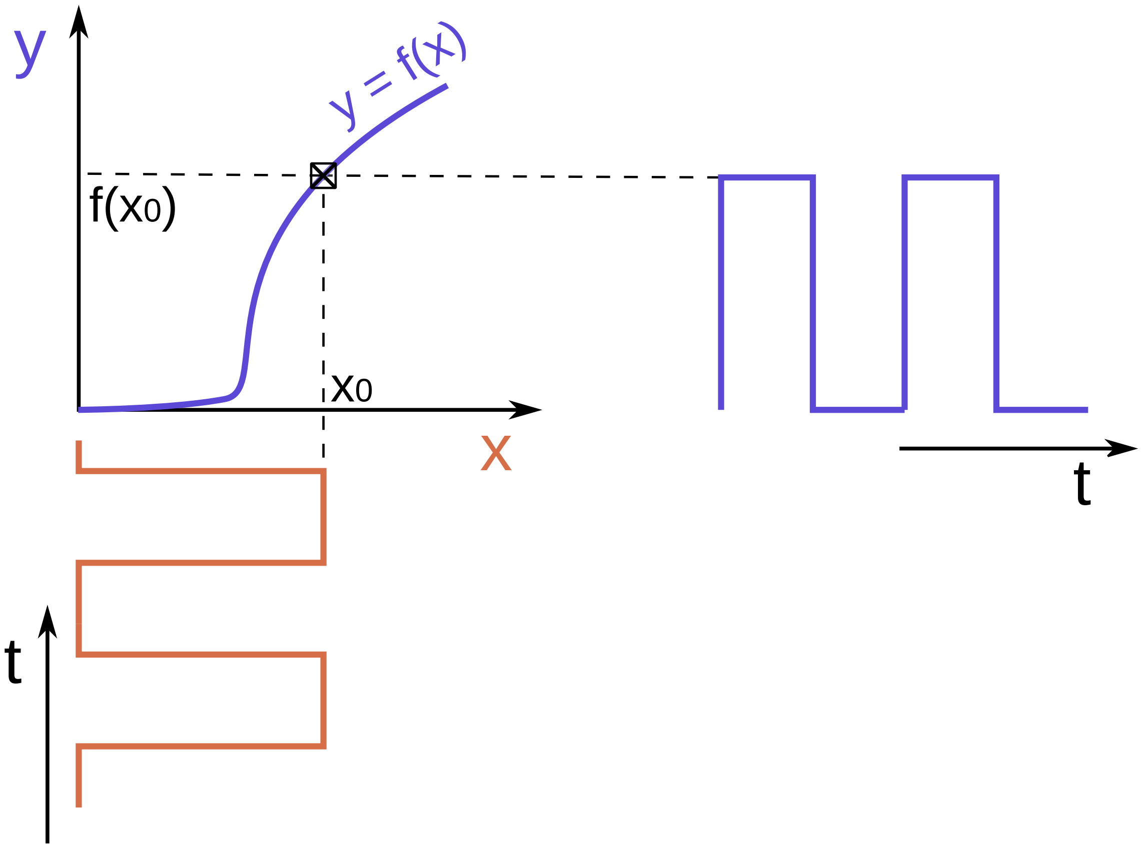
flux pulse duration (ns)
60
50
40
30
20
10
0
1.8
2.0
2.2
2.4
2.6
flux pulse amplitude (a.u.)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
P(1)


light source
chopper
test object
photo detector
lock-in amplifier
gauge
DUT
sig
ref
(HEATER SINIS)
(Qu Heat Switch)
(TARGET SINIS)
chopper control

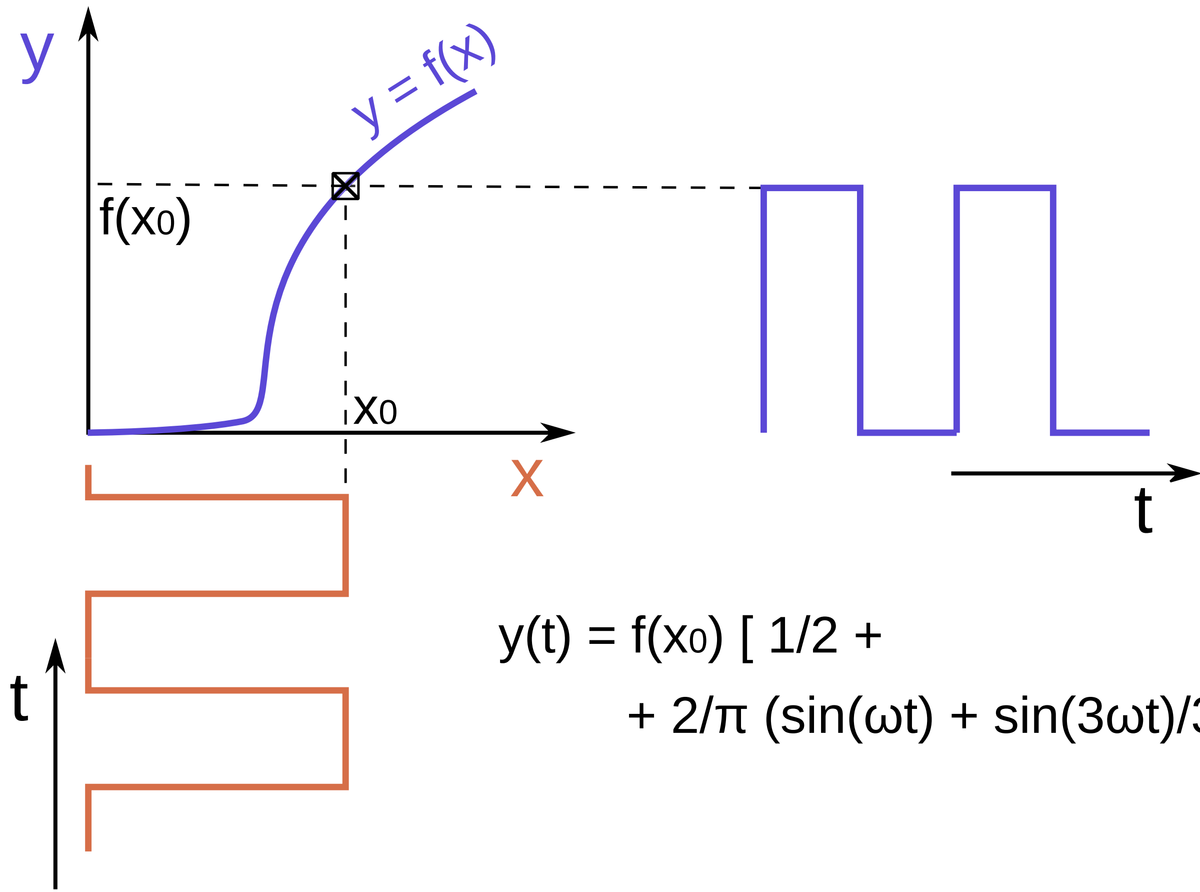

V1
V2
SYNC
Voffs
BNC ground
H
K
ground plane
G
BNC ground
A
B
F
D
ref
Lock-In Amp
CONTROL
DMM
CONTROL (DC)
ref
Lock-In Amp
TARGET
DMM
TARGET (DC)


y
y = f(x)
f(x0)
x0
x

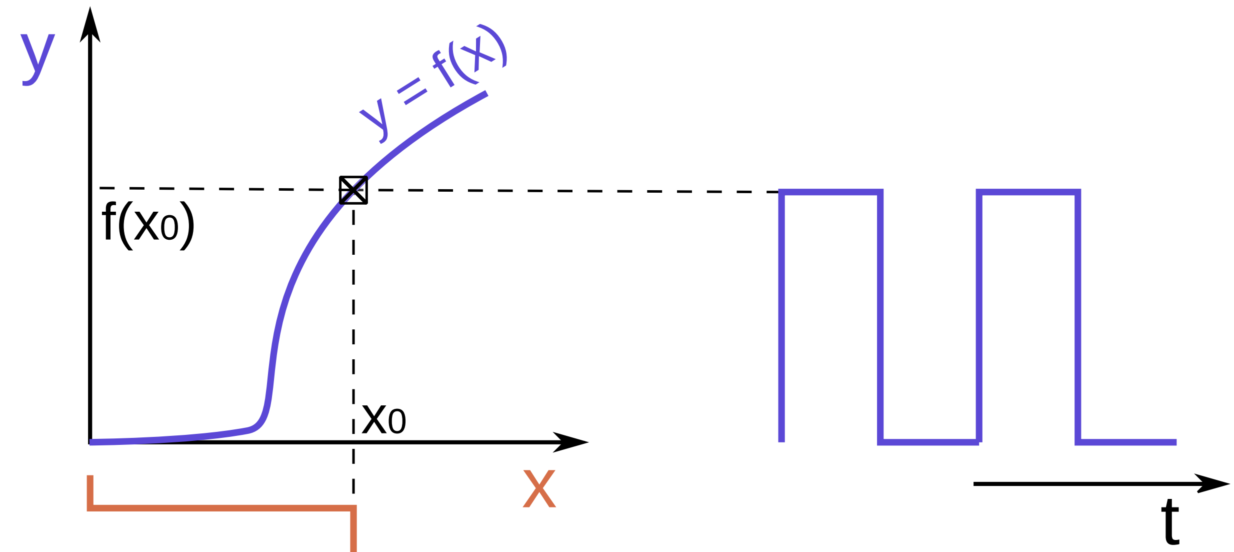

y
y = f(x)
f(x0)
x0
x
t

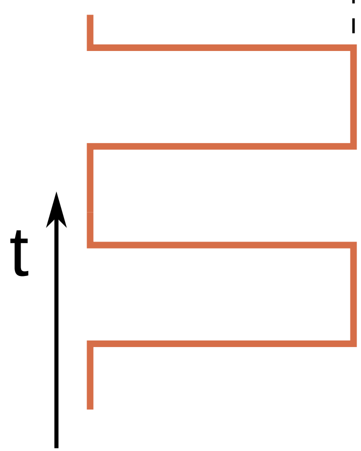


y
y = f(x)
f(x0)
x0
x
t
t

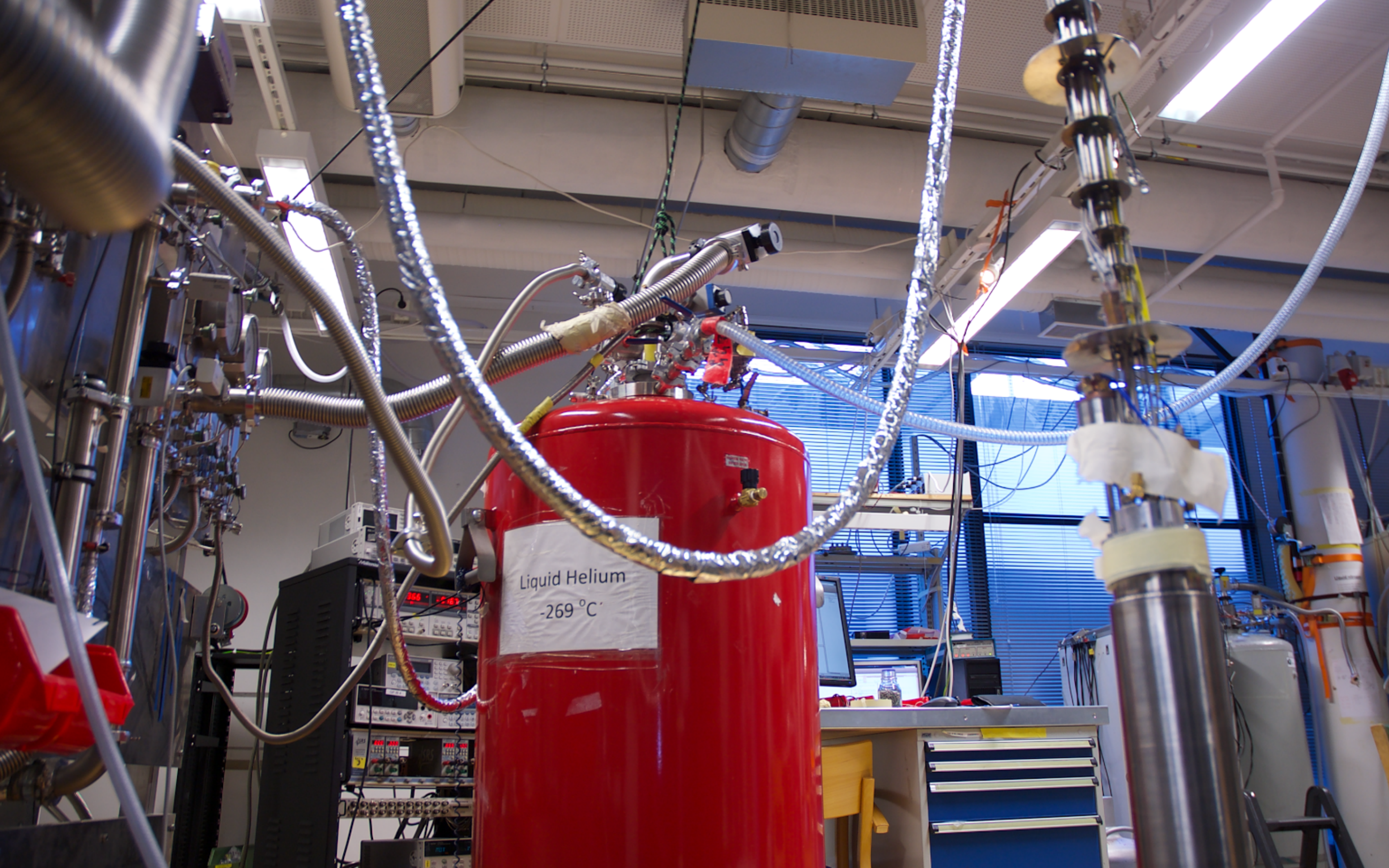


$$y(t) = f(x_0)\ [\ 1/2 + $$
$$+\ 2/\pi\ (\sin(\omega t) + \sin(3\omega t)/3 + \ldots)\ ]$$





$$y(t) = f(x_0)\ [\ 1/2 + $$
$$+\ 2/\pi\ (\sin(\omega t) + \sin(3\omega t)/3 + \ldots)\ ]$$


Liquid Helium
-269 °C

A! Aalto University

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Dmitri Golubev


Joonas Peltonen

PostDocs


Azat Gubaydullin


Yu-Cheng Chang


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Rishabh Upadhyay