Superconducting Quantum Circuits

Juan José García Ripoll, Spanish National Research Council

The OSA Quantum Computing and Communication Technical Group Welcomes You!

OSA Quantum Computing and Communication Technical Group

Technical Group Leadership 2020

Roberto de J. León-Montiel
Chair
UNAM, Mexico

Vito Giovanni Lucivero
ICFO, Spain

Veronica Vicuña-Hernandez
University of Naples “Federico II”

Ricardo Tellez-Limon
CICESE, Mexico

Jorge L. Domínguez-Juárez
UNAM, Mexico

Technical Group at a Glance

- Focus
  - Theoretical and experimental aspects of quantum computing
  - Quantum communication systems - Cryptography
  - Generation, detection and applications of non-classical light
  - Quantum measurement and quantum control

- Mission
  - To maximize the exchange of information and the creation of networking opportunities for our community
  - Webinars, technical events (workshops, tutorials, poster sessions), outreach activities
  - Interested in presenting your research? Have ideas for TG events? Contact us at TGactivities@osa.org.

- Find us here
  - Website: www.osa.org/OC
  - Facebook: https://www.facebook.com/groups/OSAQuantumCC/

Today's Webinar

Superconducting Quantum Circuits

Dr. Juan José García-Ripoll

Leader of the Quantum Information and Foundations Group at CSIC

jj.garcia.ripoll@csic.es

Speaker's Short Bio:

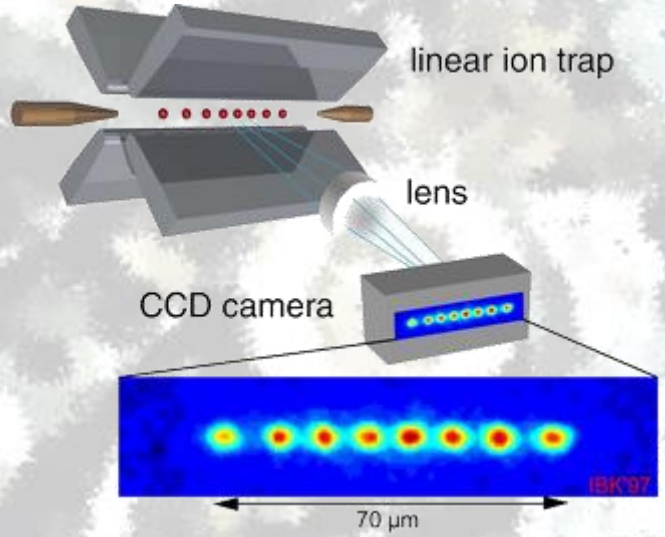
Juan José García Ripoll finished his PhD in Optics at Univ. Complutense de Madrid, while working at Univ. Castilla La Mancha on Bose-Einstein condensates and nonlinear Optics. He then moved to Munich with Ignacio Cirac, where he developed key contributions in the fields of trapped-ion quantum computing and helped starting the field of quantum simulation with ultracold atoms. He is the coordinator of the CSIC Platform on Quantum Technologies and the Spanish Network of Quantum Information and Quantum Technologies.

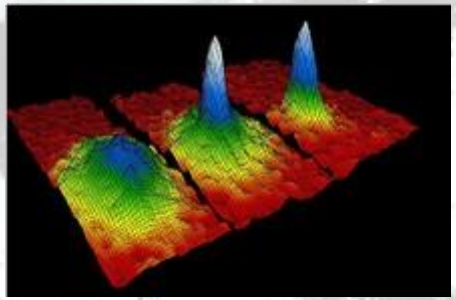
OSA Quantum Computing and Communication Technical Group

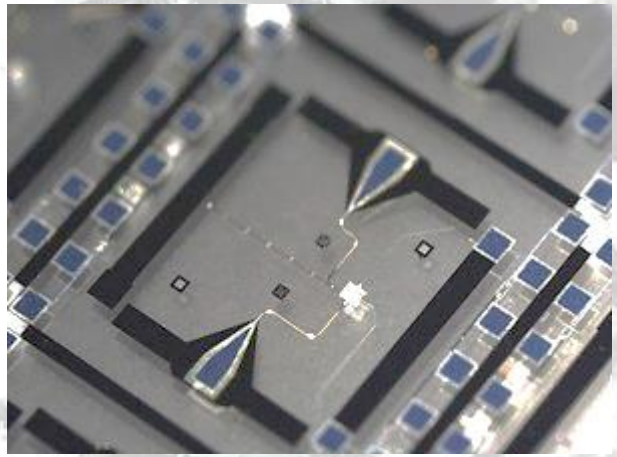
Juan José García Ripoll

Institute of Fundamental Physics

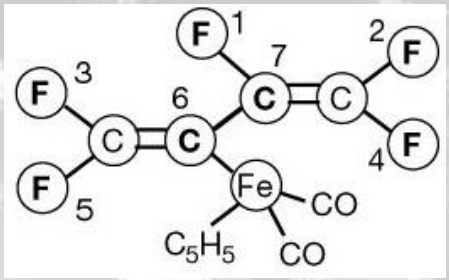
Superconducting Quantum Circuits

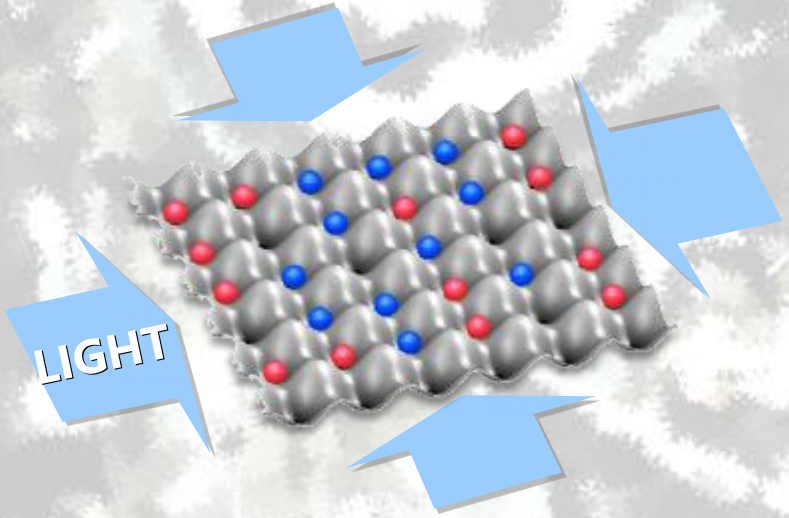


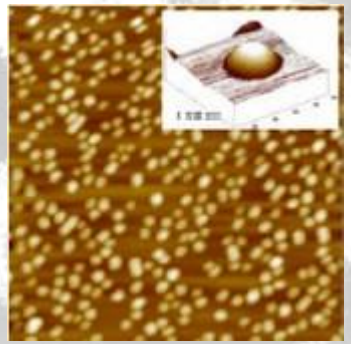




1	10	100	1000	10^4	10^5	10^{25}

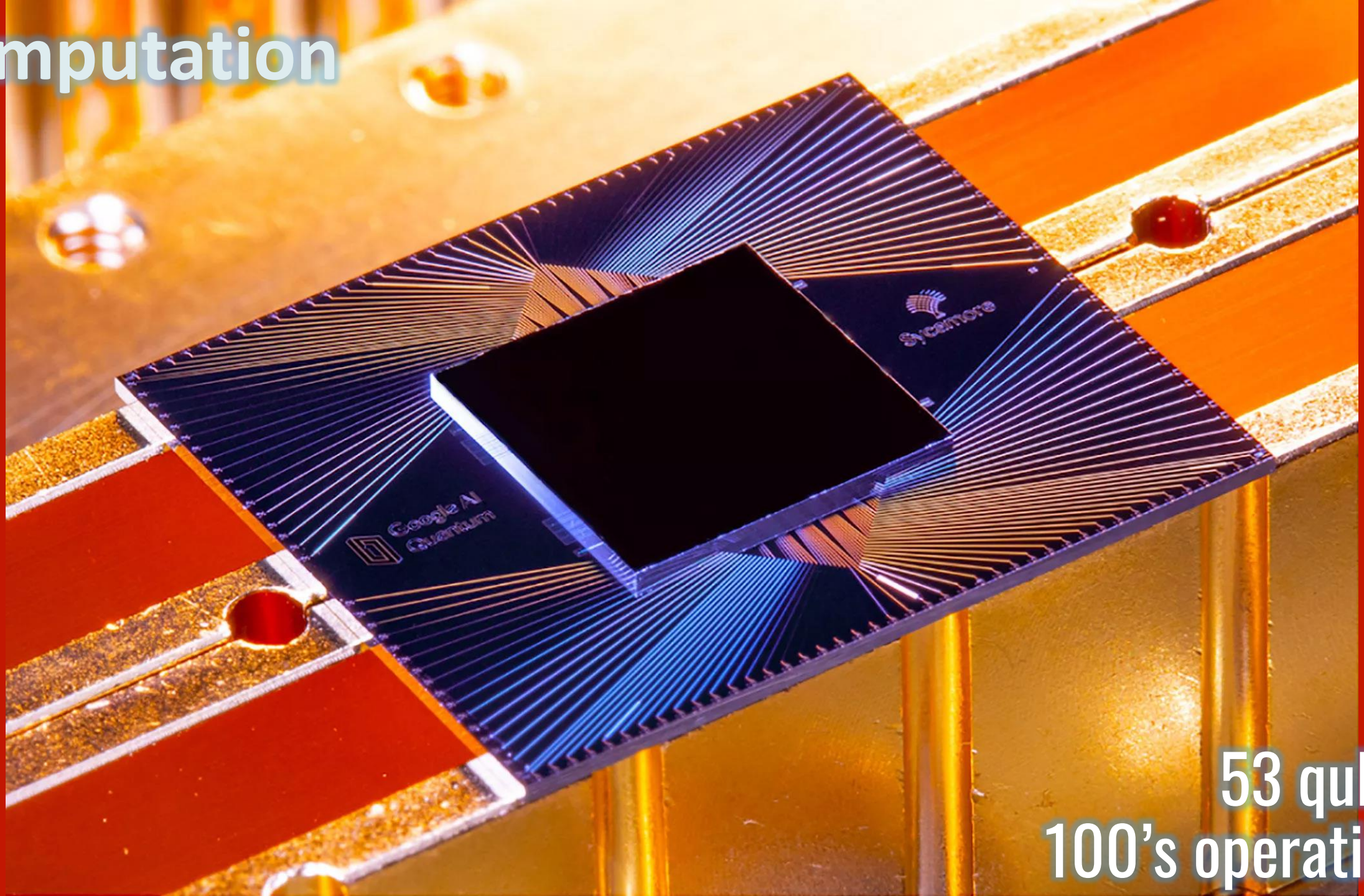




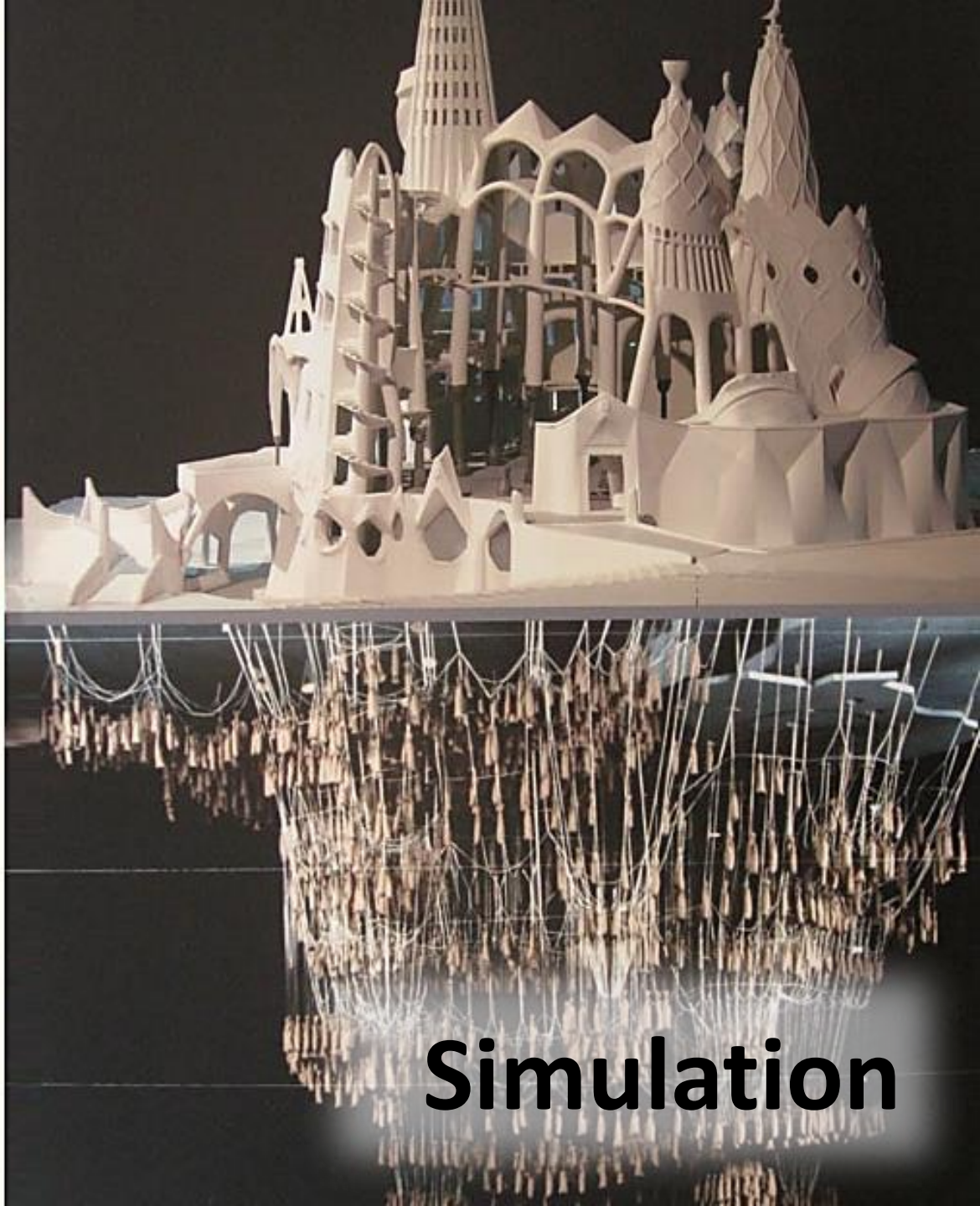


Why?

Computation

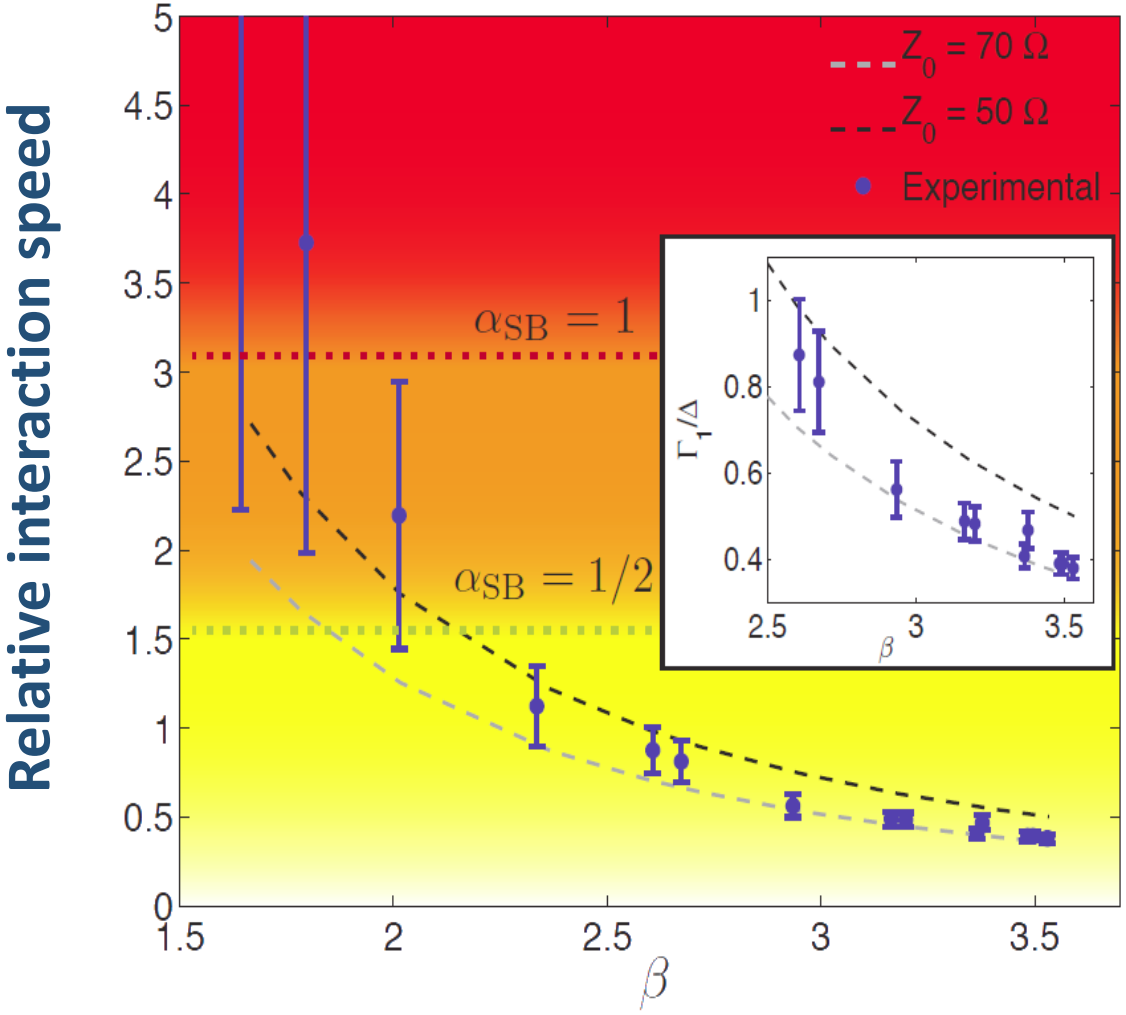


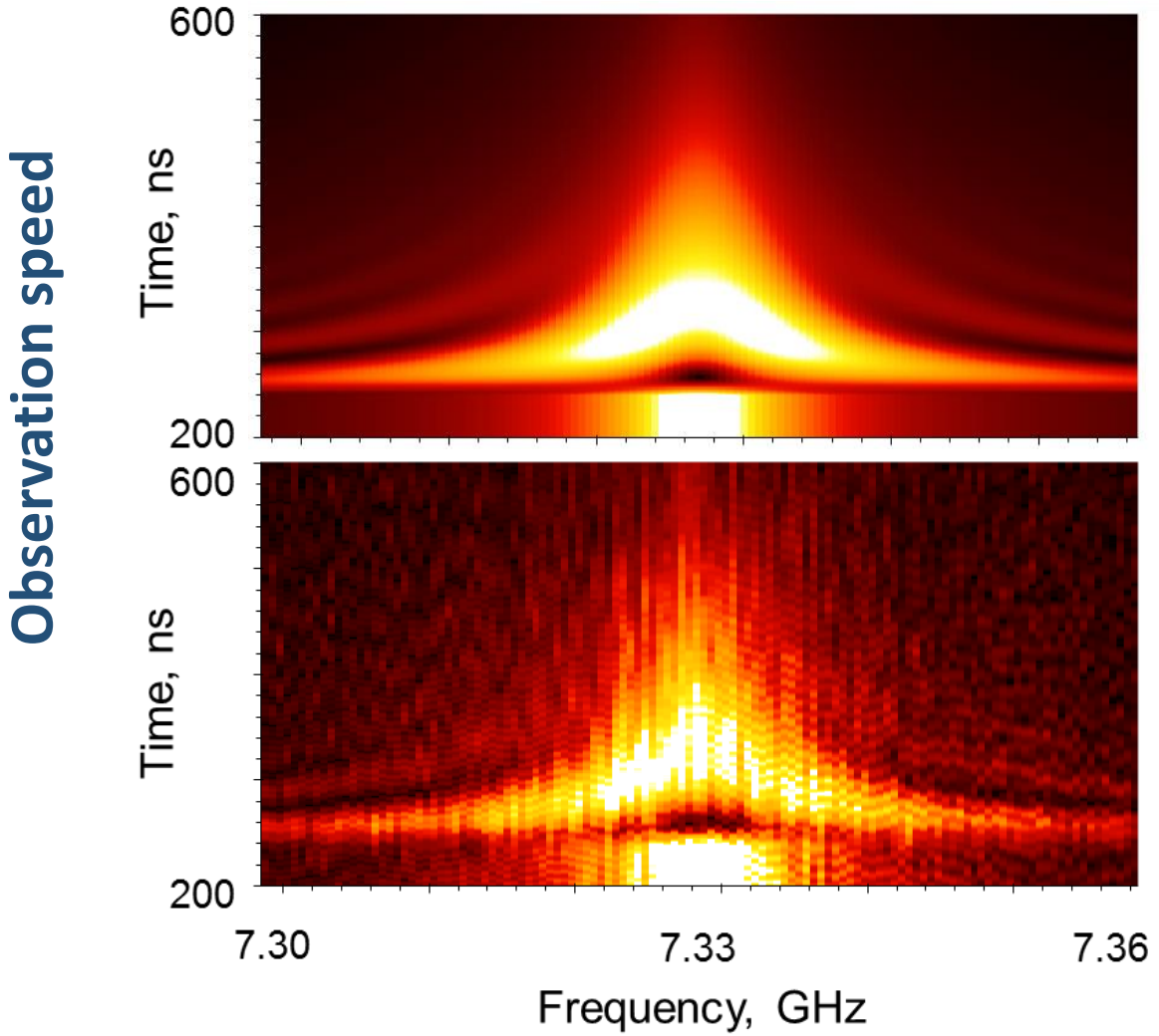
53 qubits
100's operations



Simulation

New physical possibilities

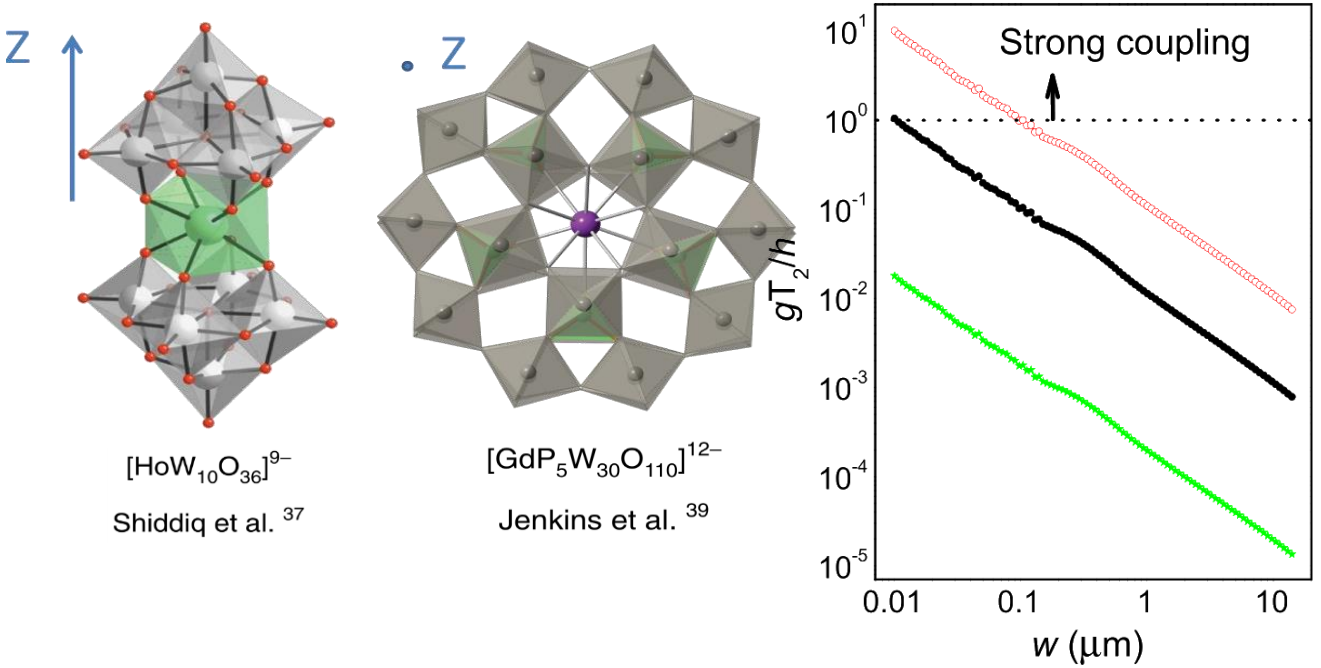




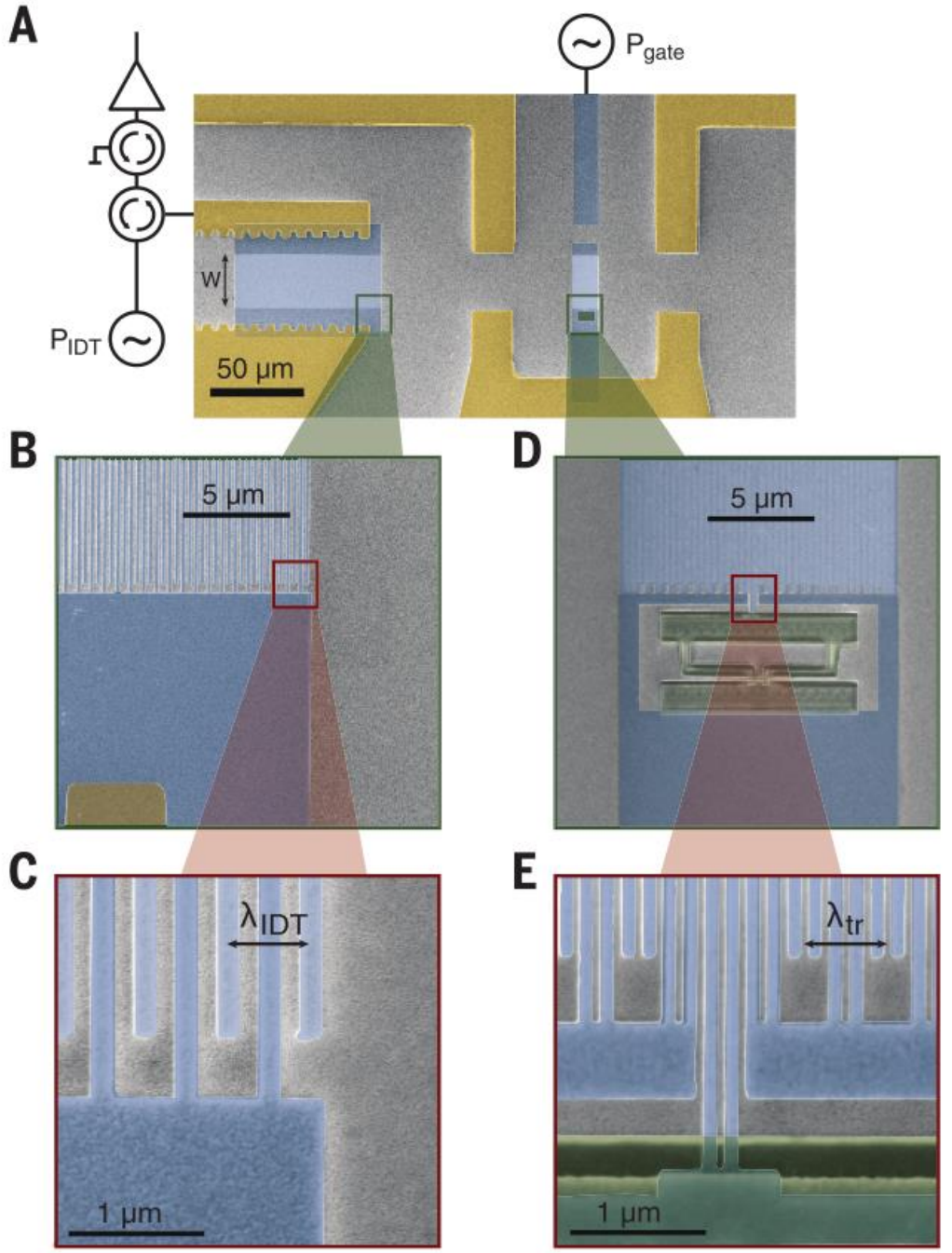
P. Forn Díaz et al, Nat. Phys. 13, 39 (2017)

A. Sharafiev et al, arXiv:2001.09737

Interfaces

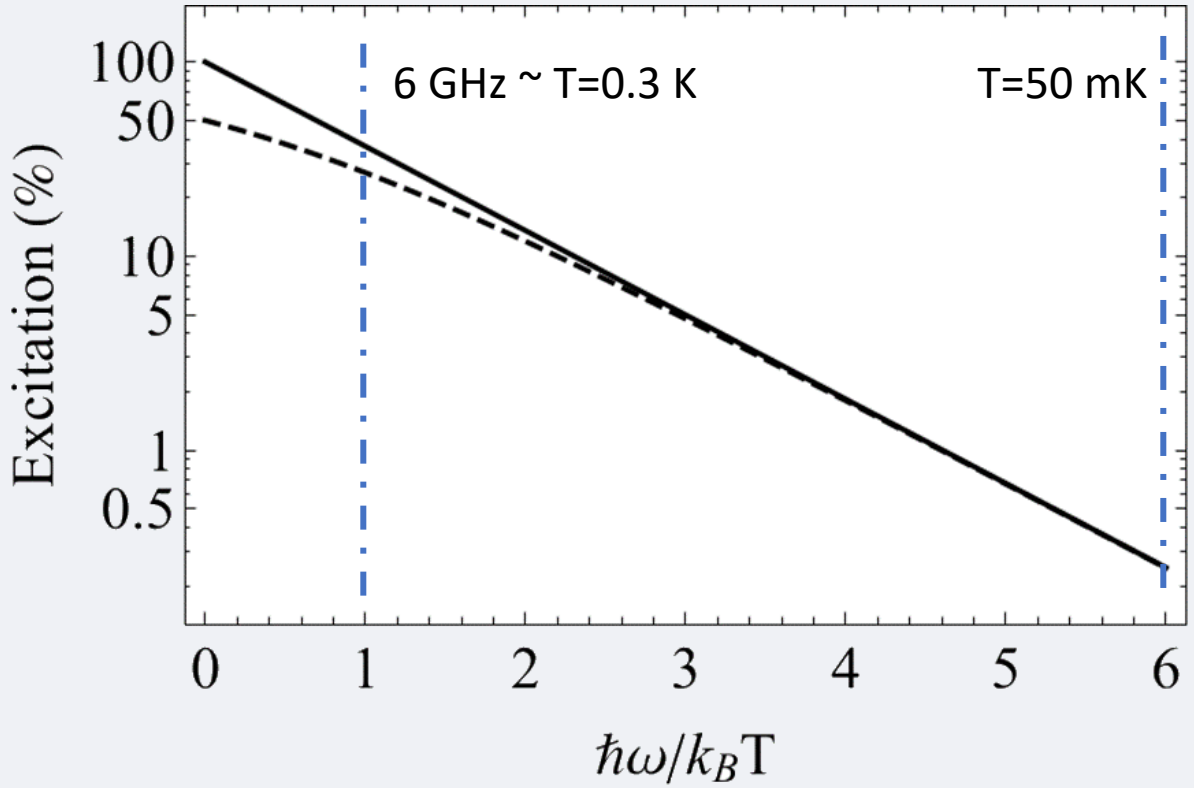


A. Gaita-Ariño et al, Nat. Chem. (2019)
M.D. Jenkins et al Dalton Trans. (2016)



Martin V. Gustafsson et al, Science (2014)

Frequency	Temperature	Range
10^{15} Hz	50.000 K	Ultraviolet
300 THz	15.000 K	Near infrarred
1 THz	50 K	High-energy microwaves
1-20 GHz	50 mK – 1 K	Microwaves



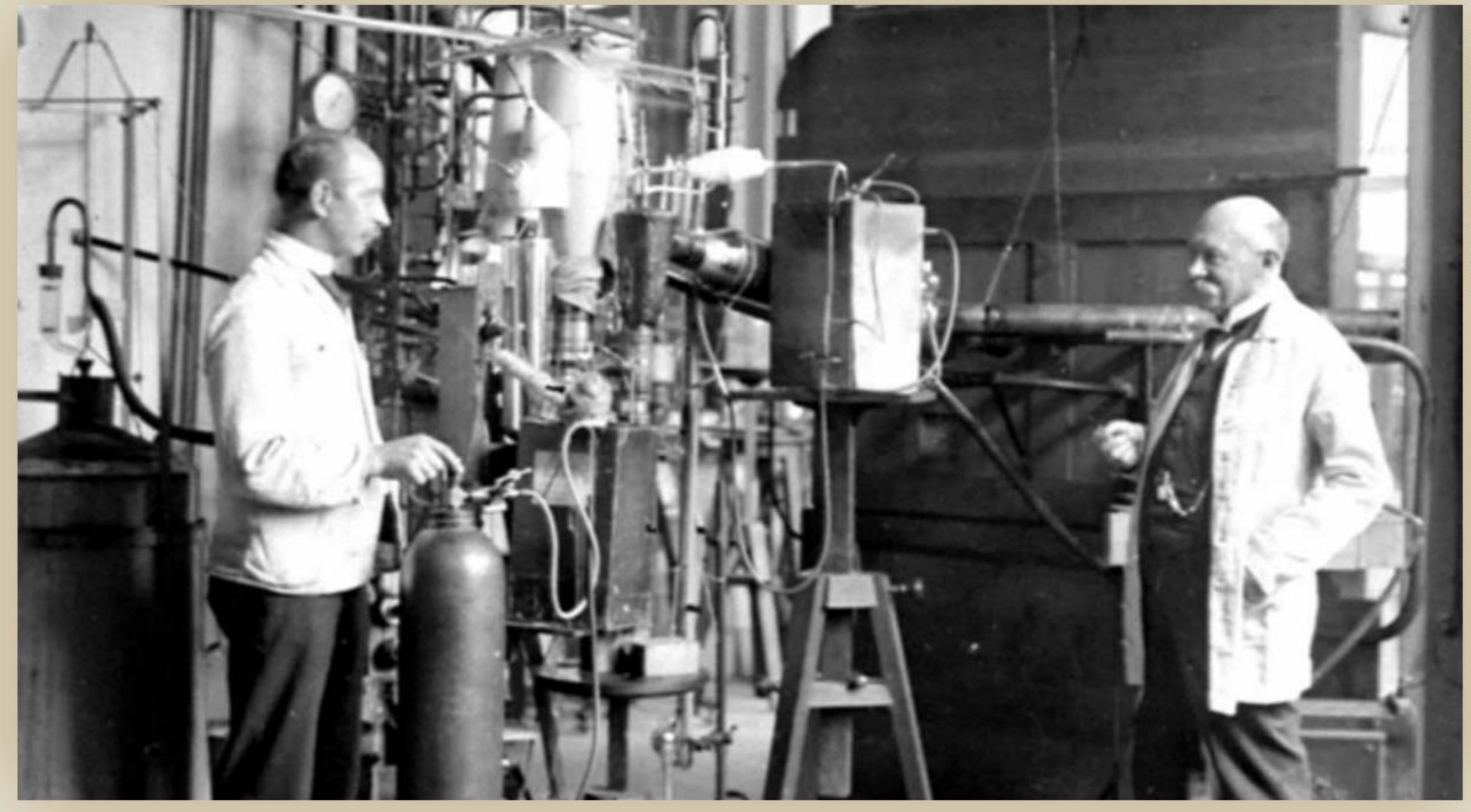


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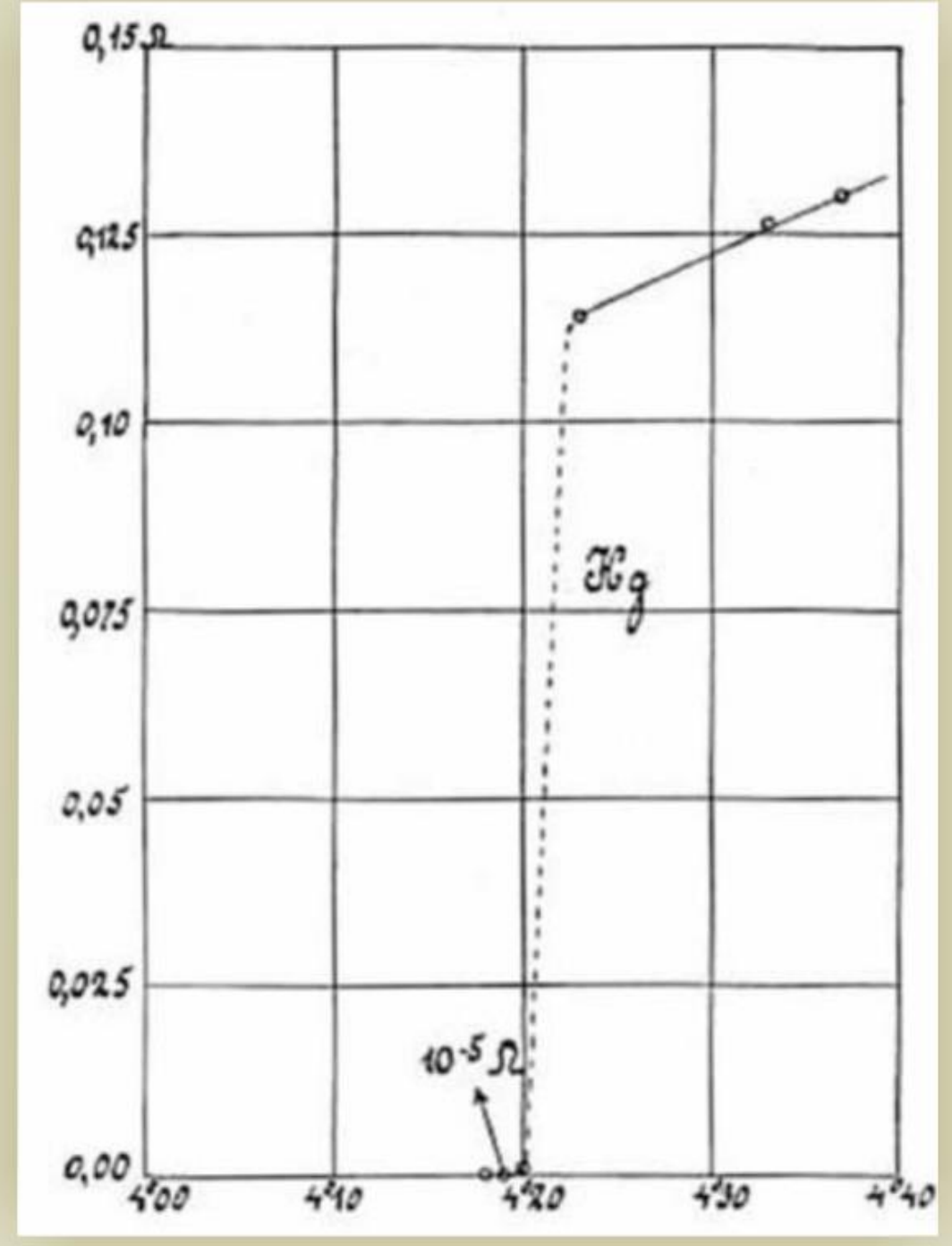
Figure 1. Heike Kamerlingh Onnes (right) and Gerrit Flim, his chief technician, at the helium liquefier in Kamerlingh Onnes's Leiden laboratory, circa 1911.



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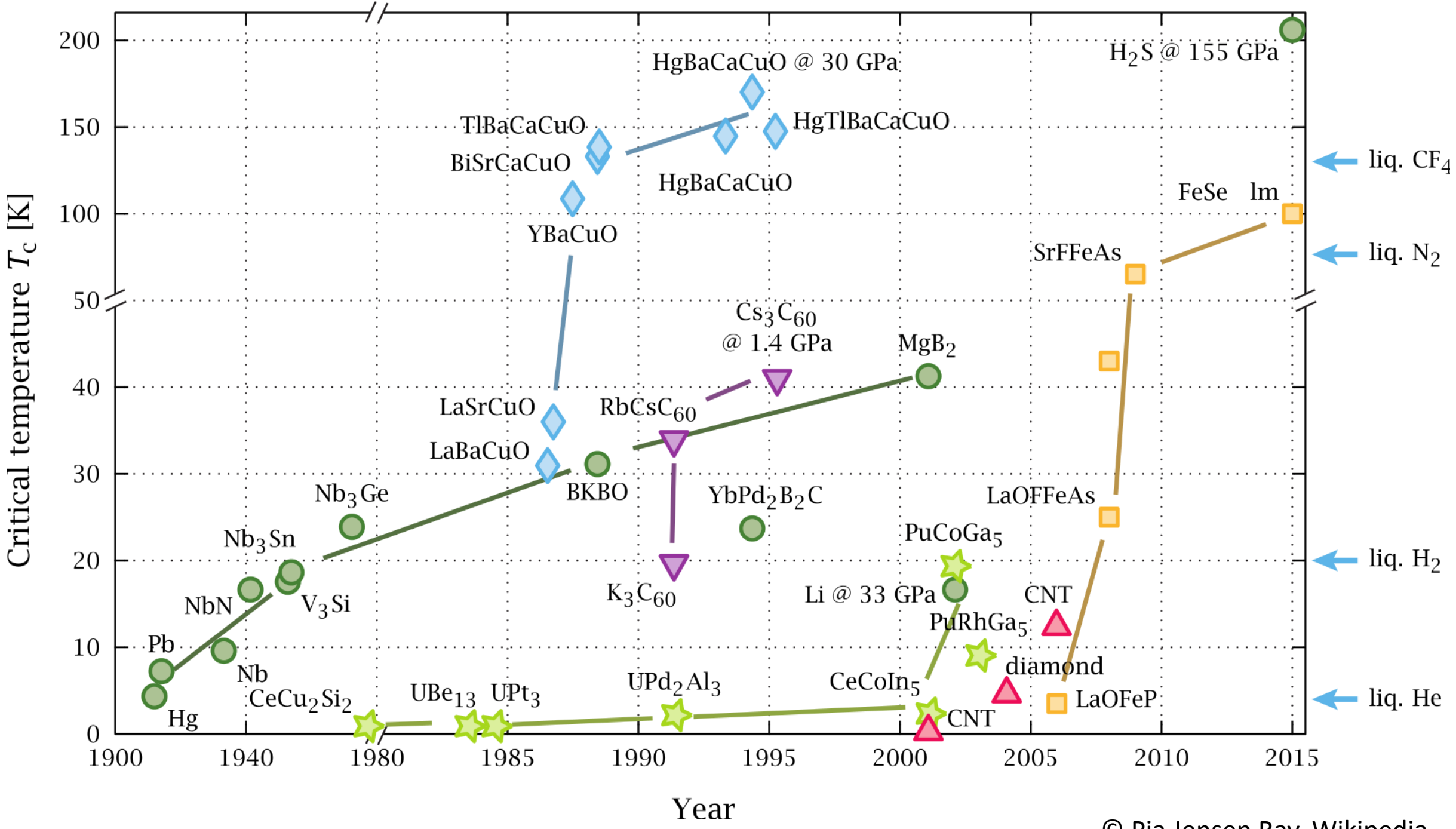


Aluminum (Al)

Type I superconductor

$T_c = 1.2$ K

$\Delta = 0.34$ meV $\sim 2\pi \times 82$ GHz $(\sim 7/2 k_B T_c)$

Niobium (Nb)

Type II superconductor

$T_c = 9.26$ K

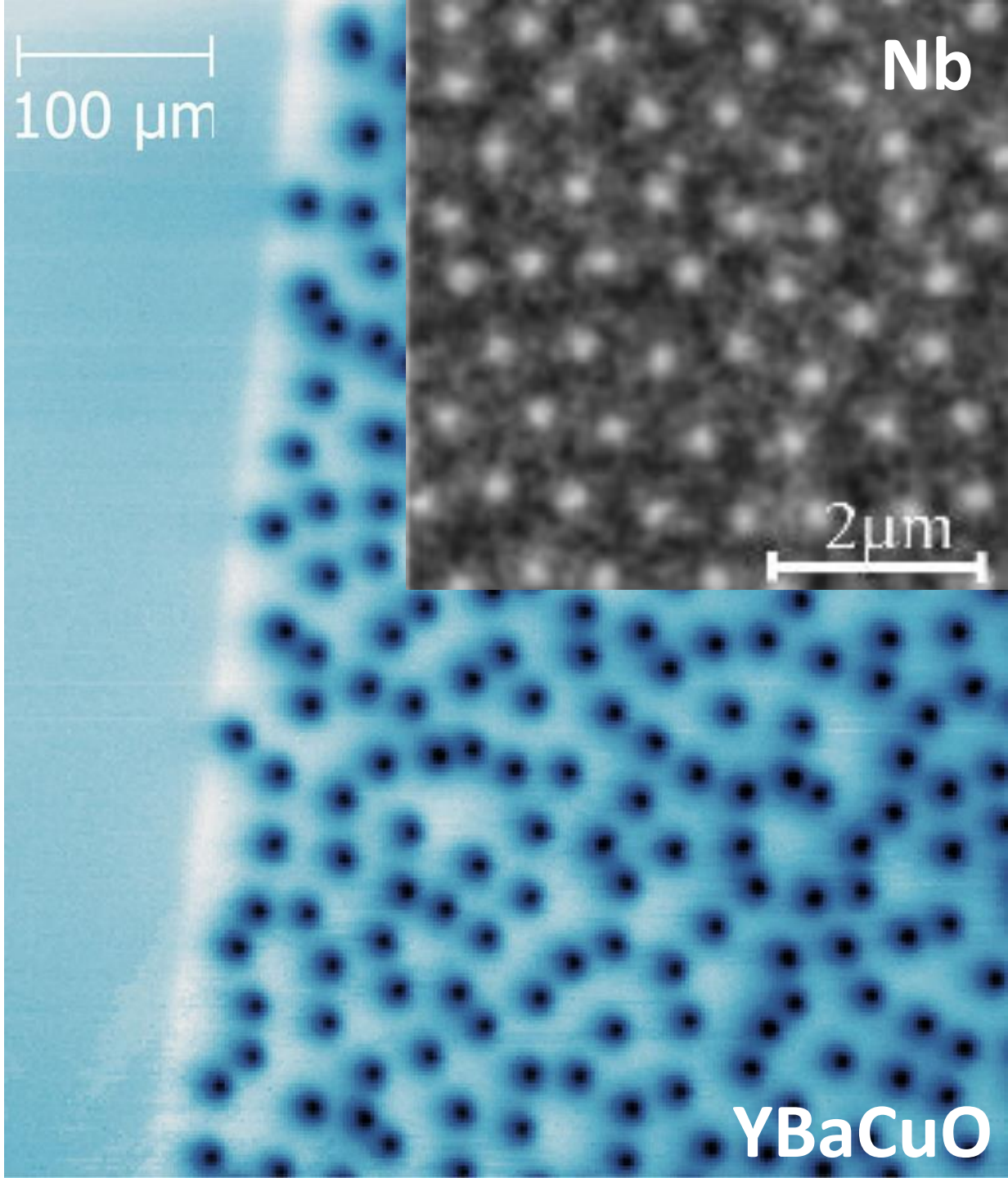
$\Delta = 30.4$ meV $\sim 2\pi \times 735$ GHz

YBaCuO

Preliminary circuits for military RF applications

F.S.Wells et al Sci Rep 5, 8677 (2015)

A. Volodin et al EPL 58 (4), p. 582 (2002)



Low temperature Physics

Typical energy scales

Microwaves, 1- 30 GHz

Associated temperatures

T ~ 0.05 - 1.5 K

Work in dilution refrigerators

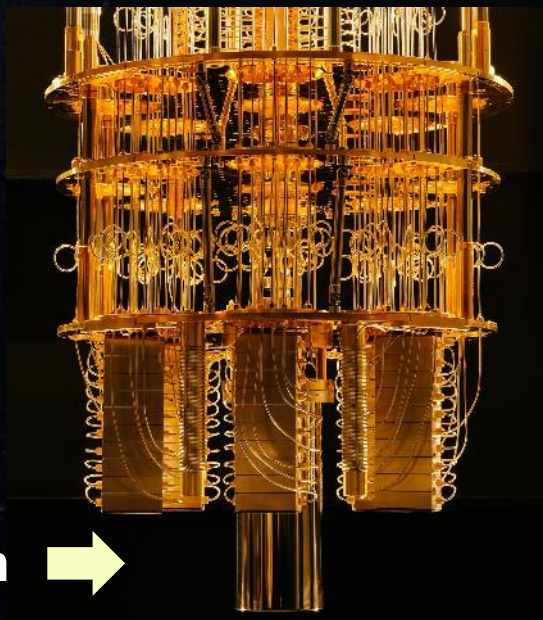
T ~ 11-20 mK

Superconductors:

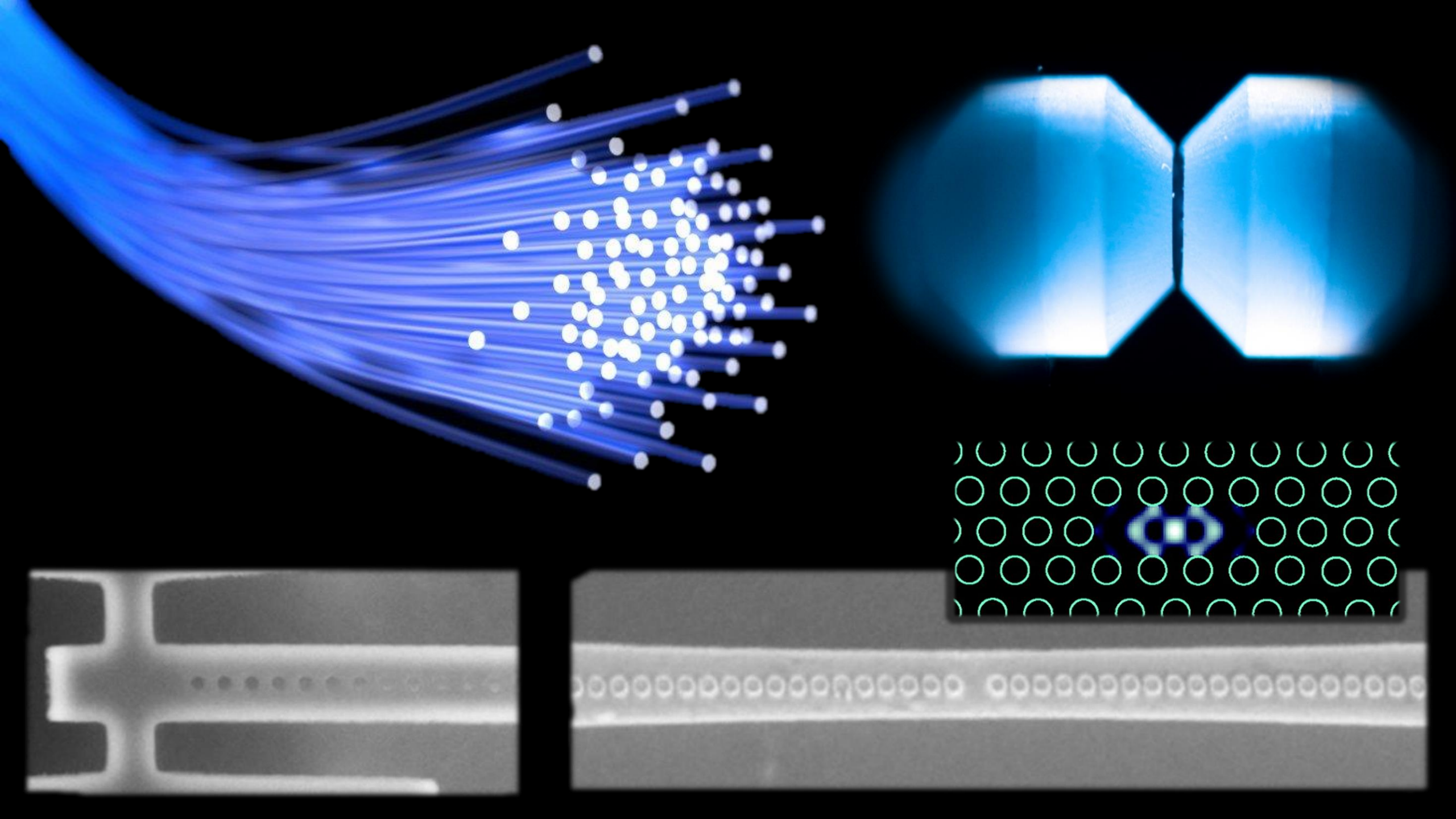
Al, Nb, ...

Size, heating? Interface to outer world?
Amplification & detection? ...

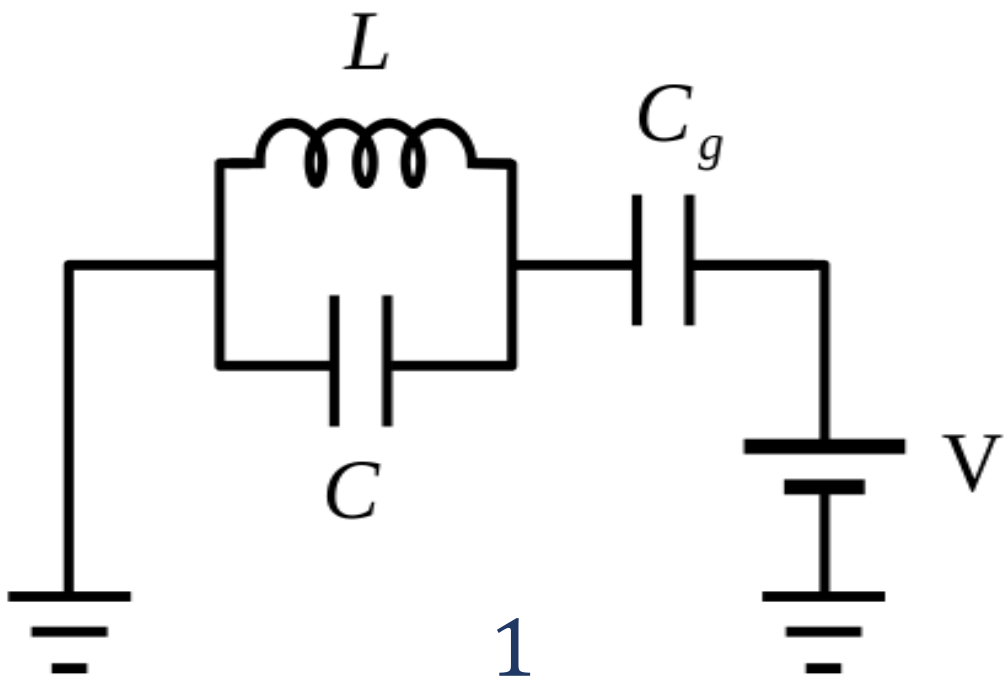
2.7 Kelvin



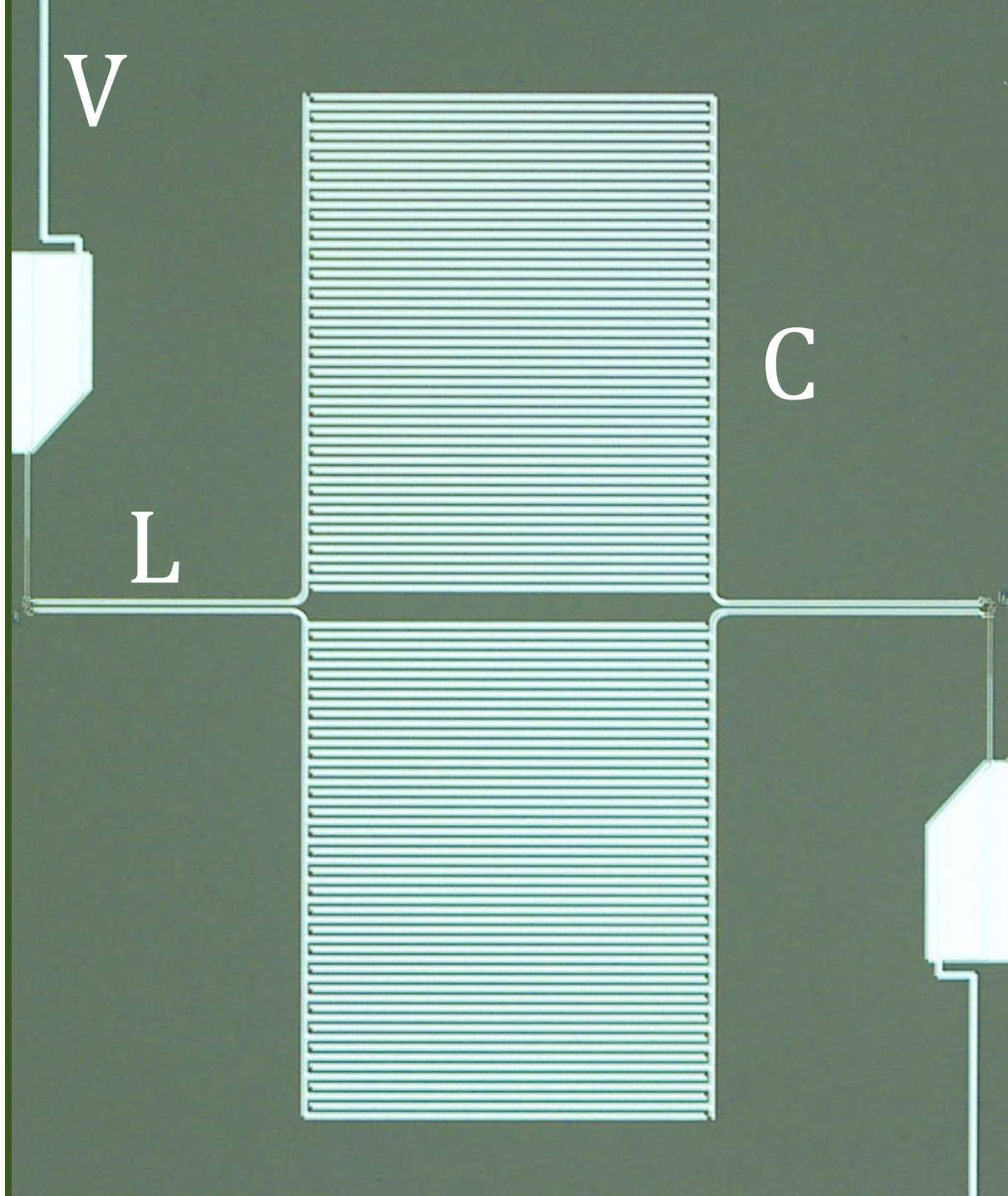
0,01 Kelvin



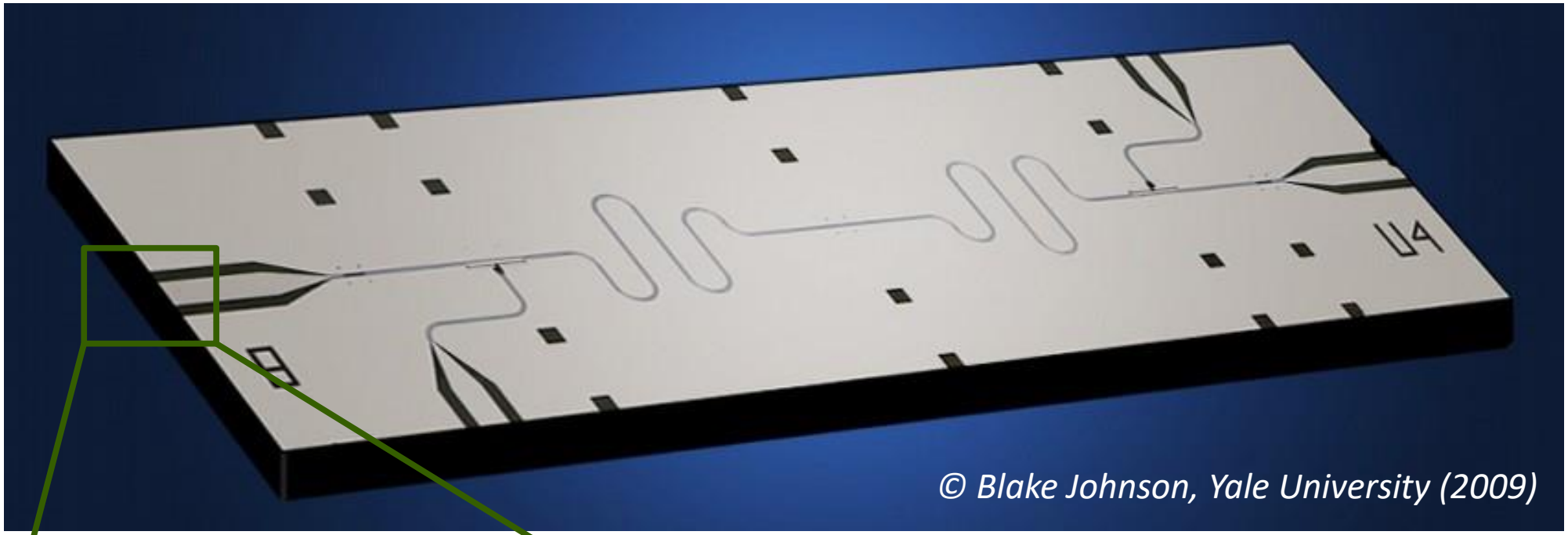
Zero-mode LC resonator

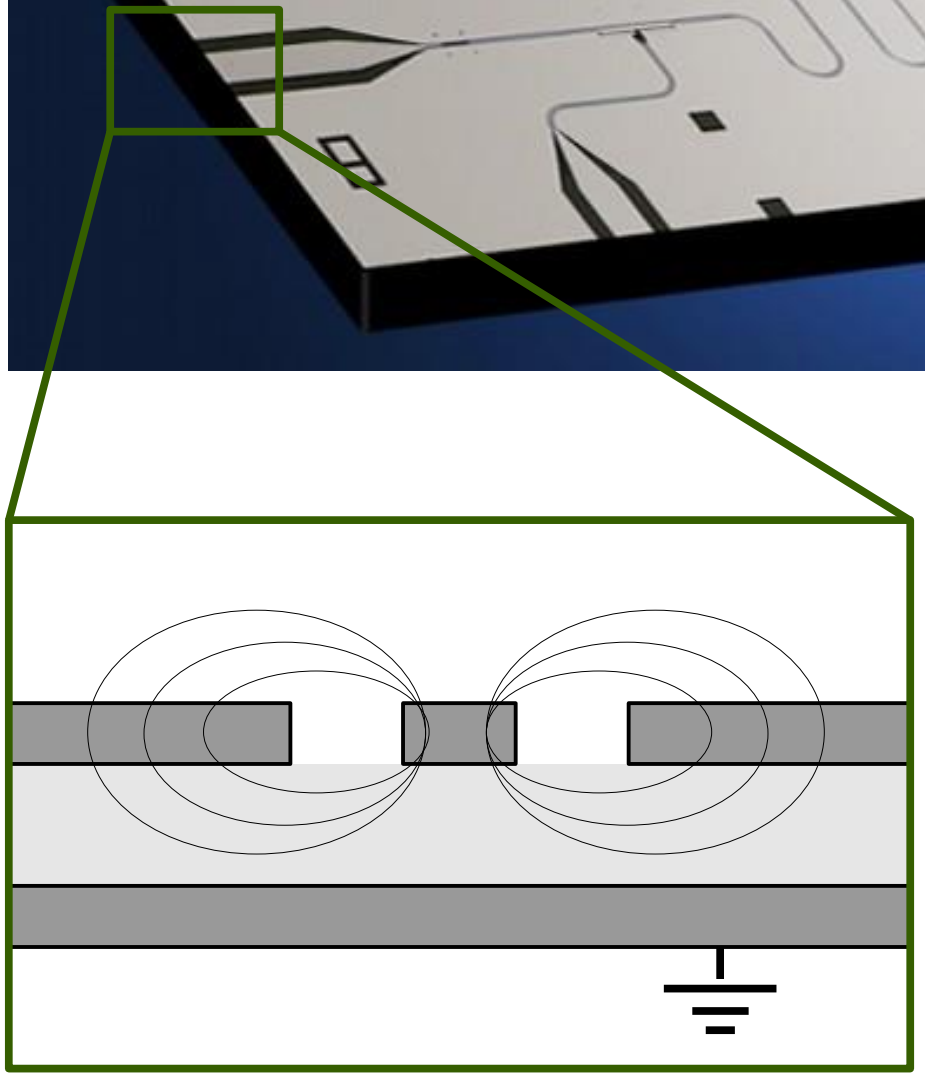


$$\omega = \frac{1}{\sqrt{LC}}$$



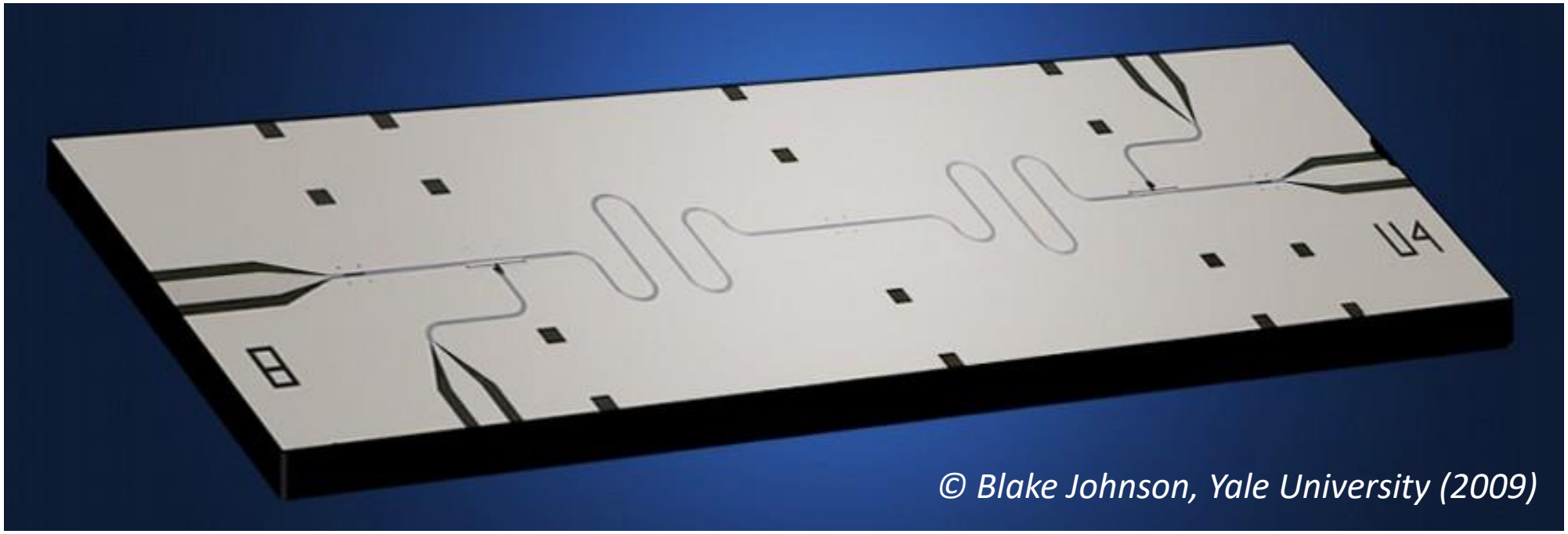
P. Forn-Díaz et al, PRL 105, 237001 (2010)



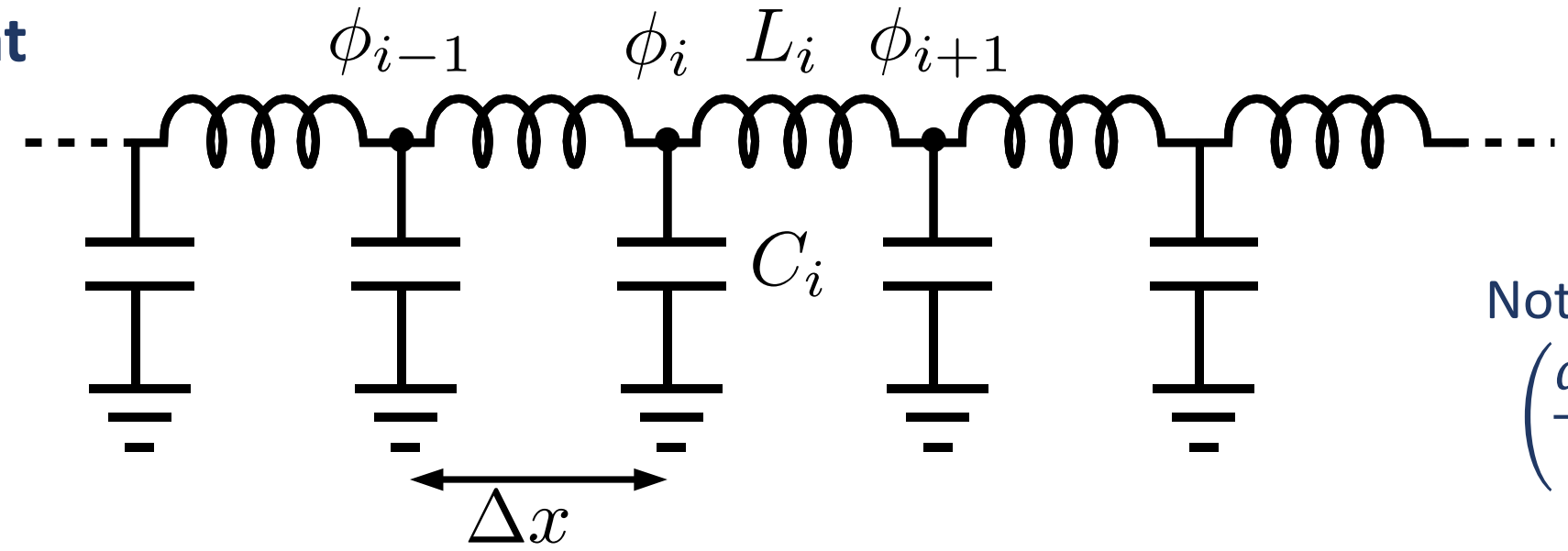


Waveguide:

Confined electromagnetic field among two or more conducting plates, on an isolating substrate.

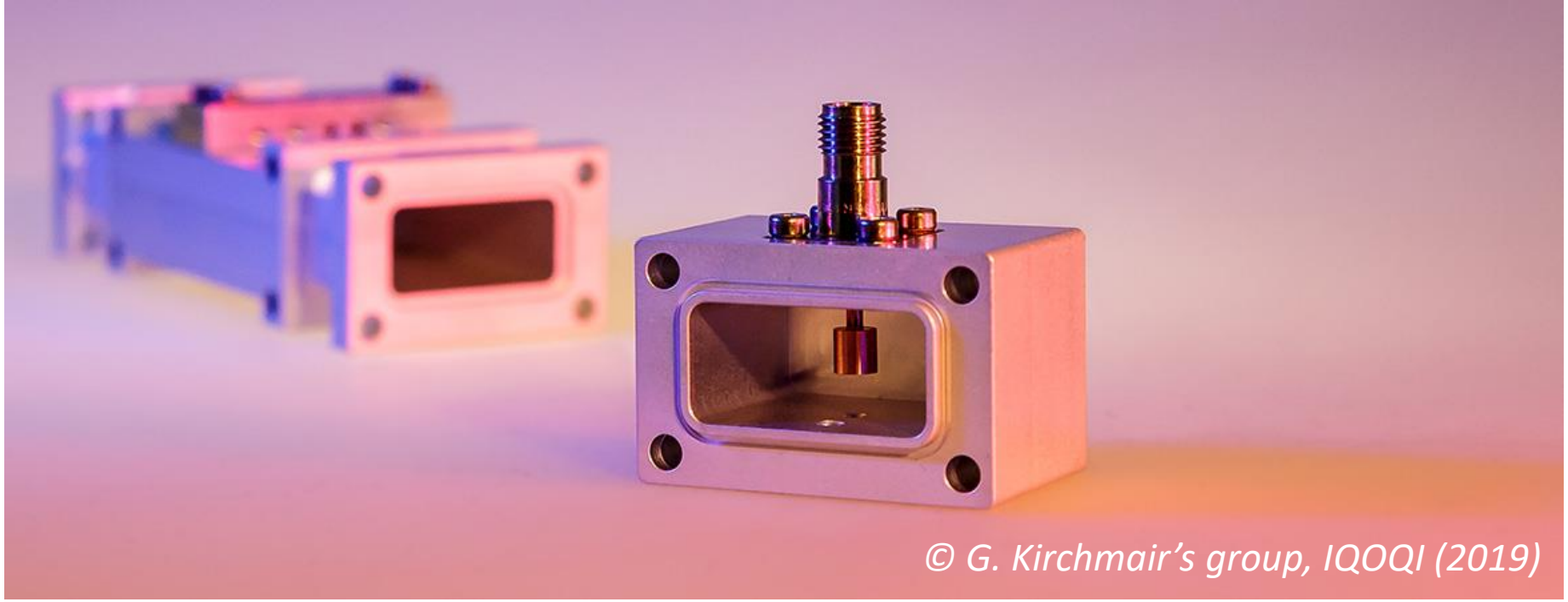


"Equivalent circuit"



Note:

$$\left(\frac{d\phi_i}{dt} = V_i\right)$$



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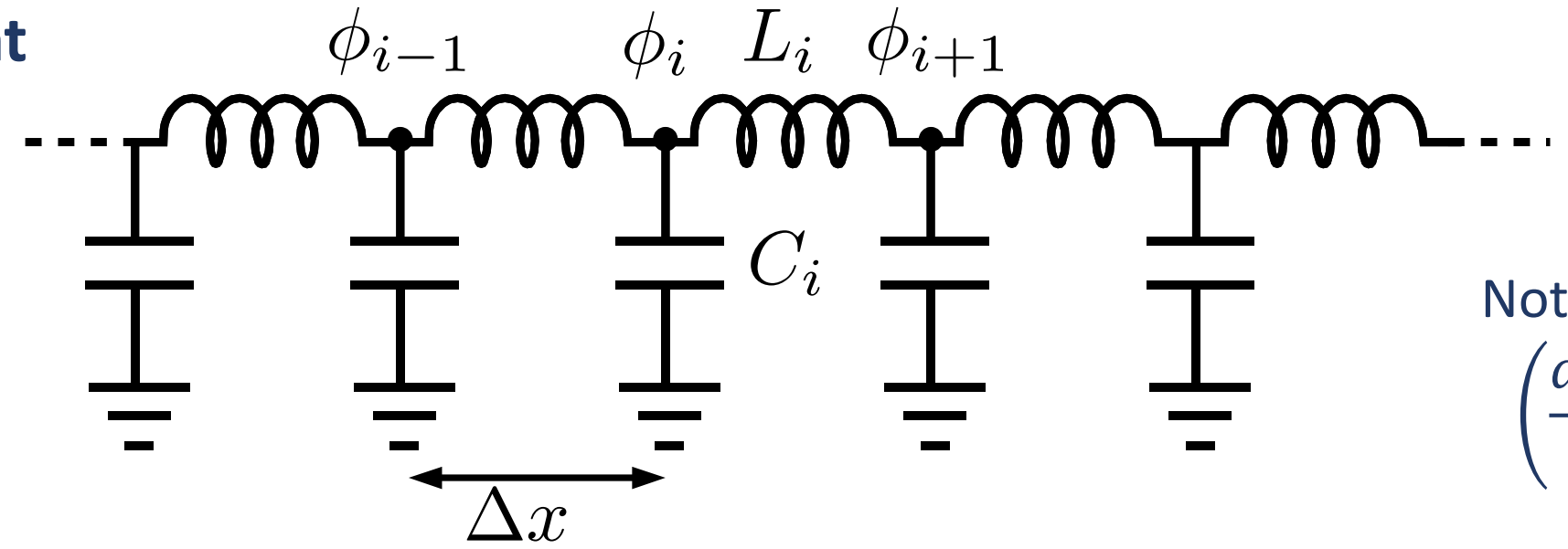

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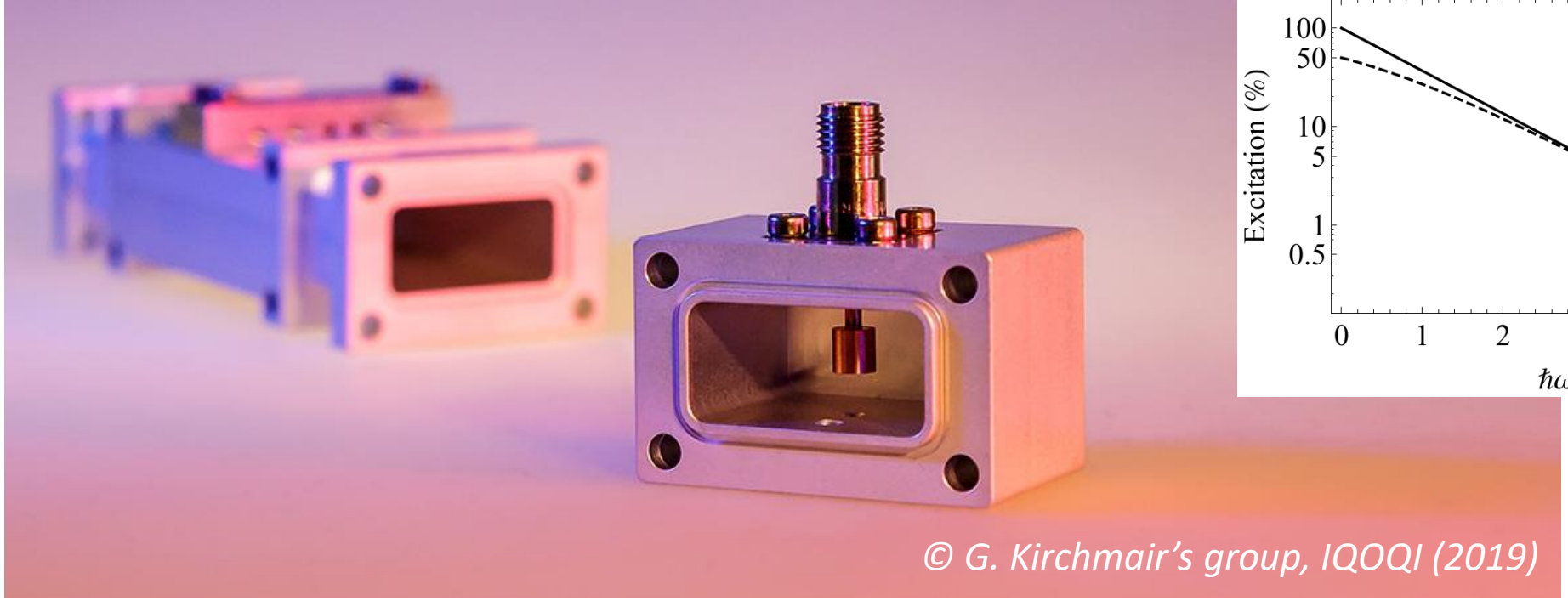


Normal mode description

$$H = \sum_k \hbar\omega_k a_k^+ a_k$$

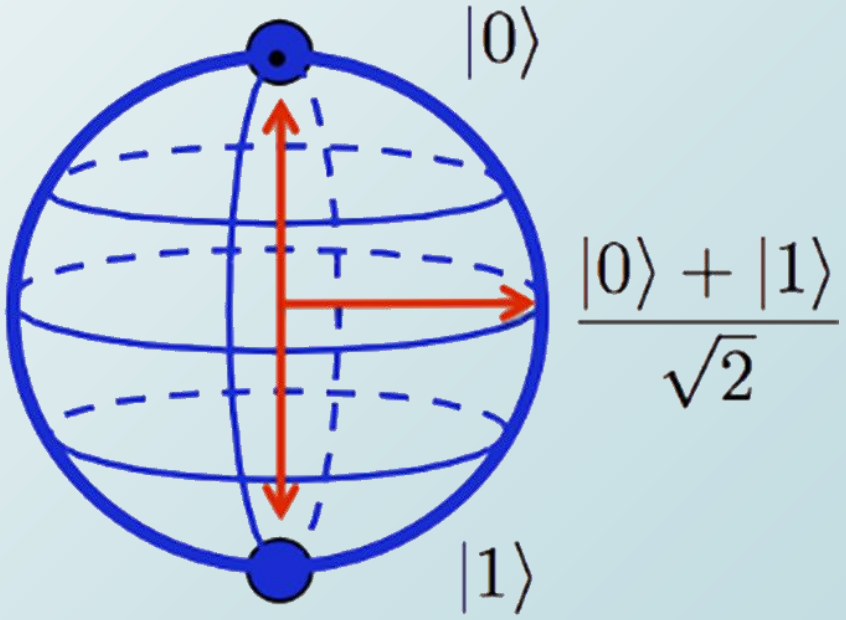
Dispersion relation

$$\omega_k \simeq m^{-1}k^2 + \omega_0$$

EM modes

$$u_k(x, y, z)$$

Qubits

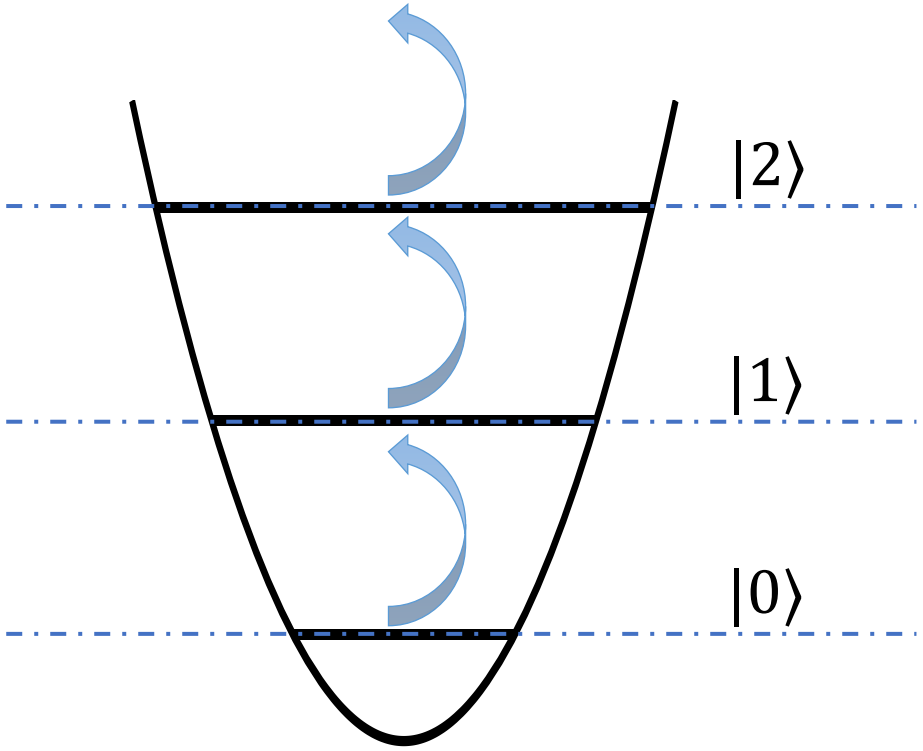


Hey, resonator:
You want to be a qubit?
Be nonlinear!

#QuantumHaiku

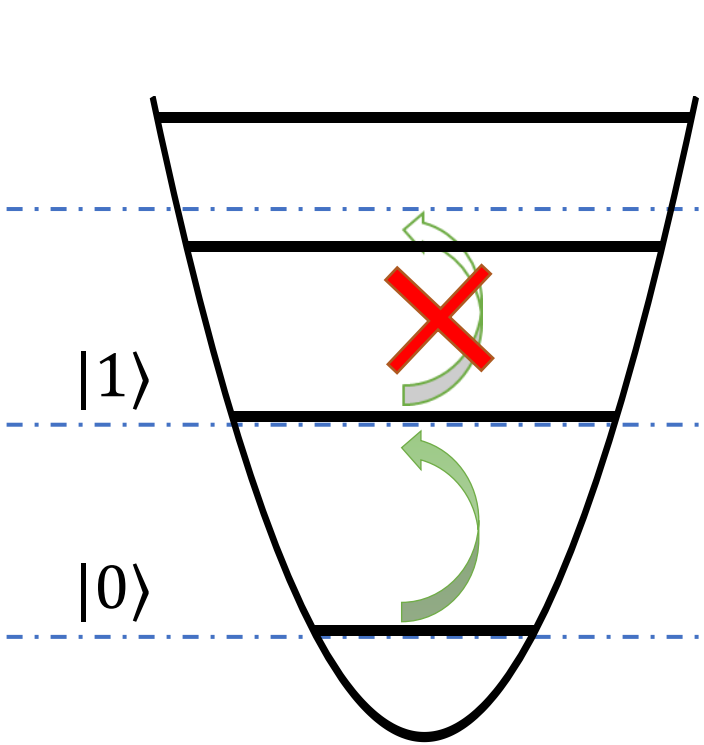
J. Preskill @preskill

Harmonic oscillator



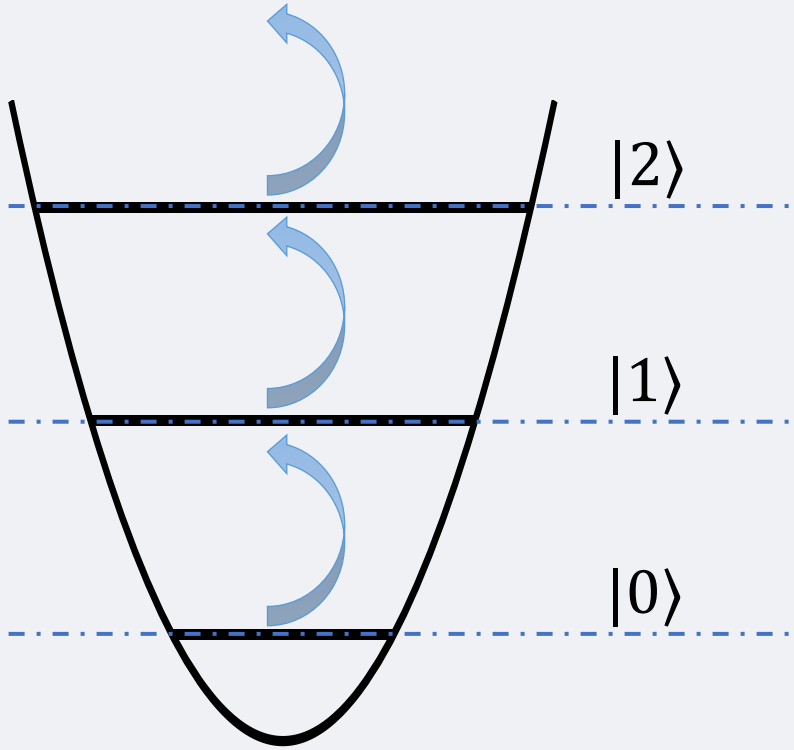
$$E_n = \hbar\omega n$$

Qubit



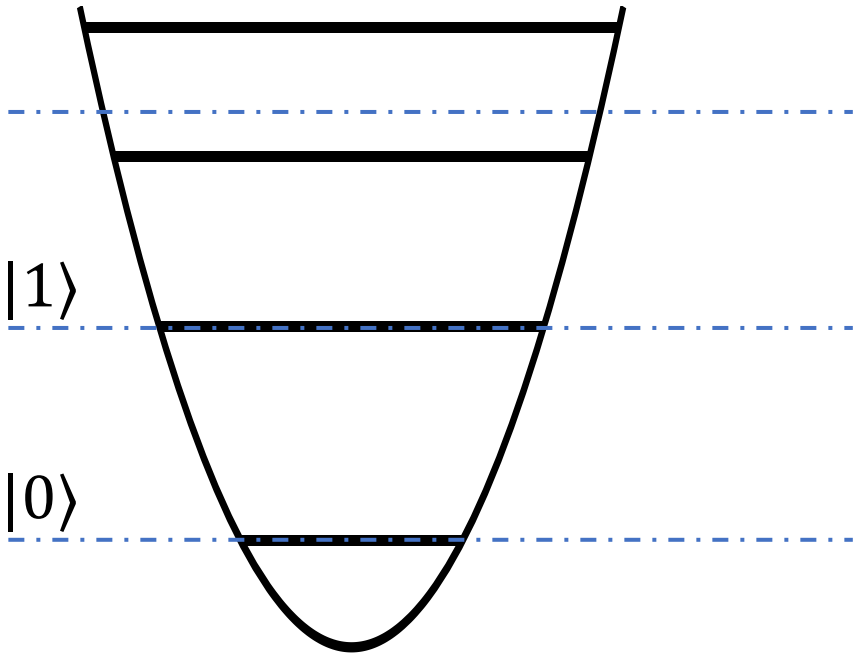
$$E_n = \hbar\omega n - \alpha n(n-1)$$

Harmonic oscillator



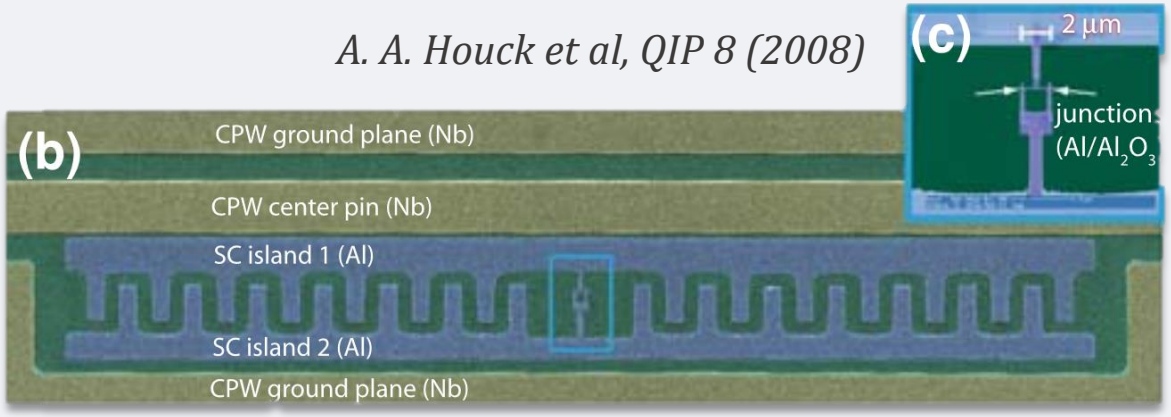
$$E_n = \hbar\omega n$$

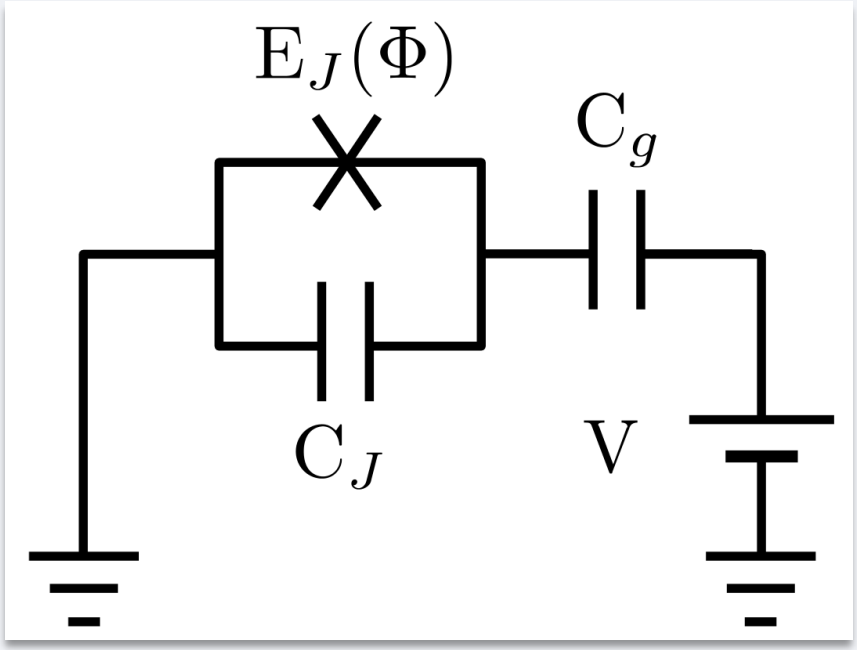
Transmon Qubit



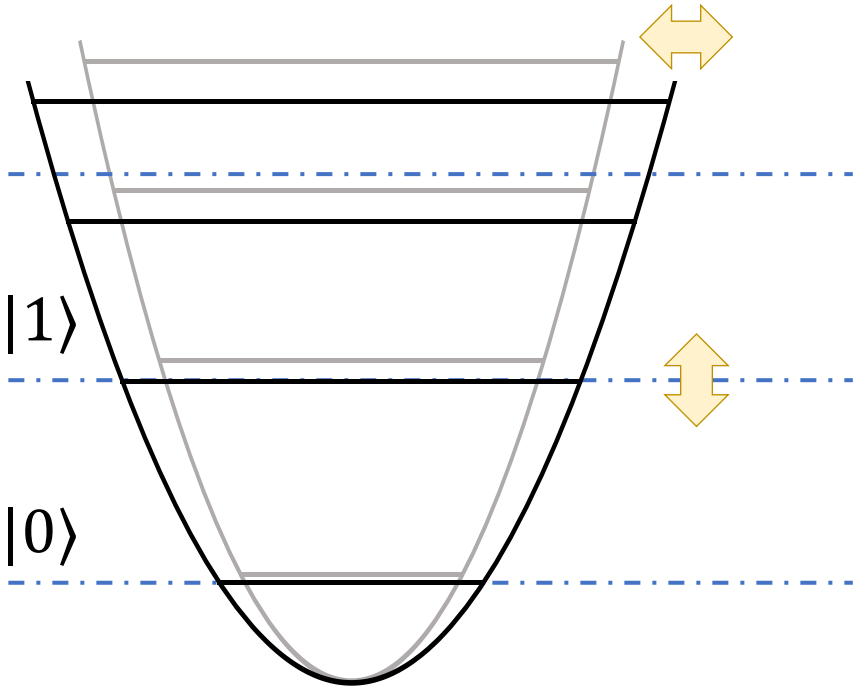
$$E_n = \hbar\omega n - \alpha n(n-1)$$

A. A. Houck et al, QIP 8 (2008)



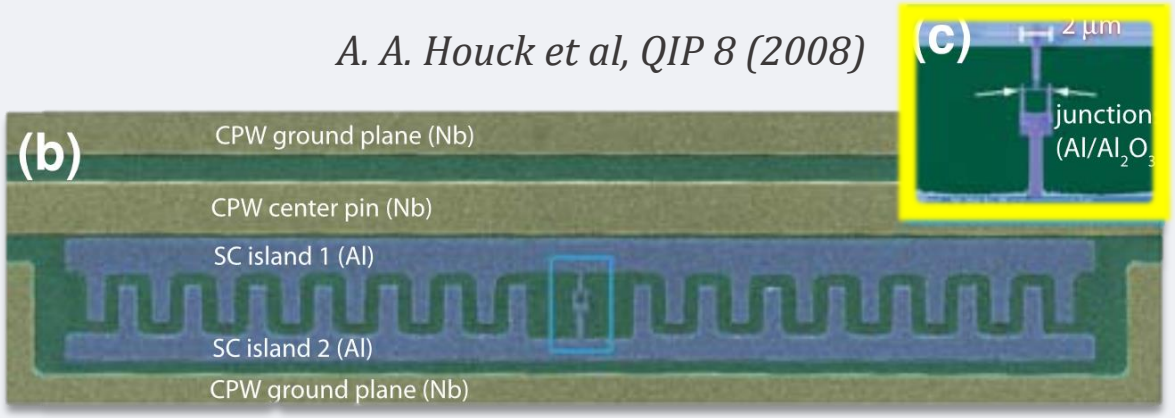


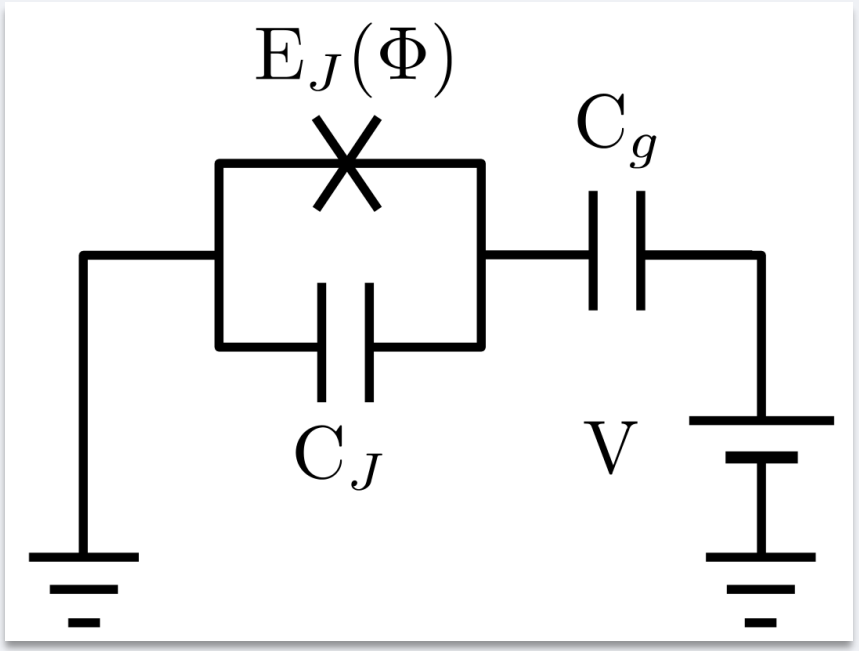
(tuneable) Transmon Qubit

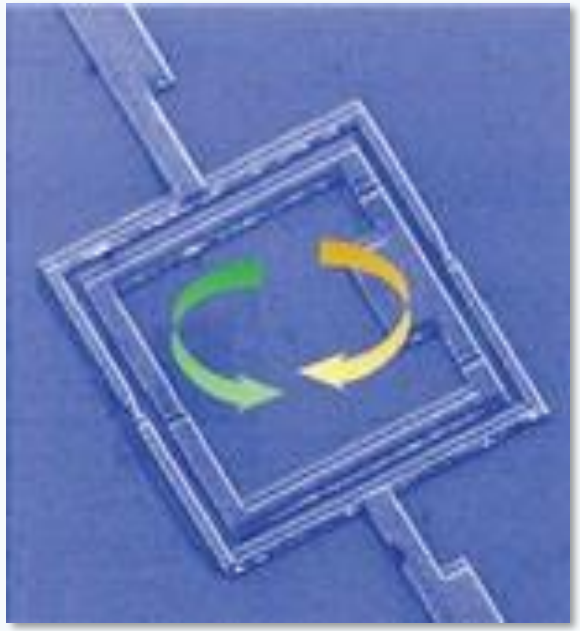


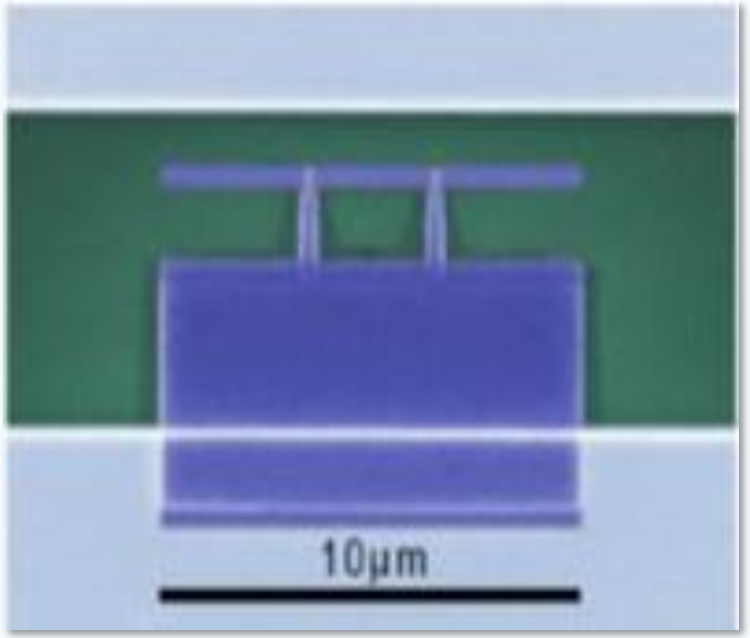
$$E_n = \hbar\omega n - \alpha n(n-1)$$

A. A. Houck et al, QIP 8 (2008)









Artificial atoms zoo

Charge qubit

Phase qubit

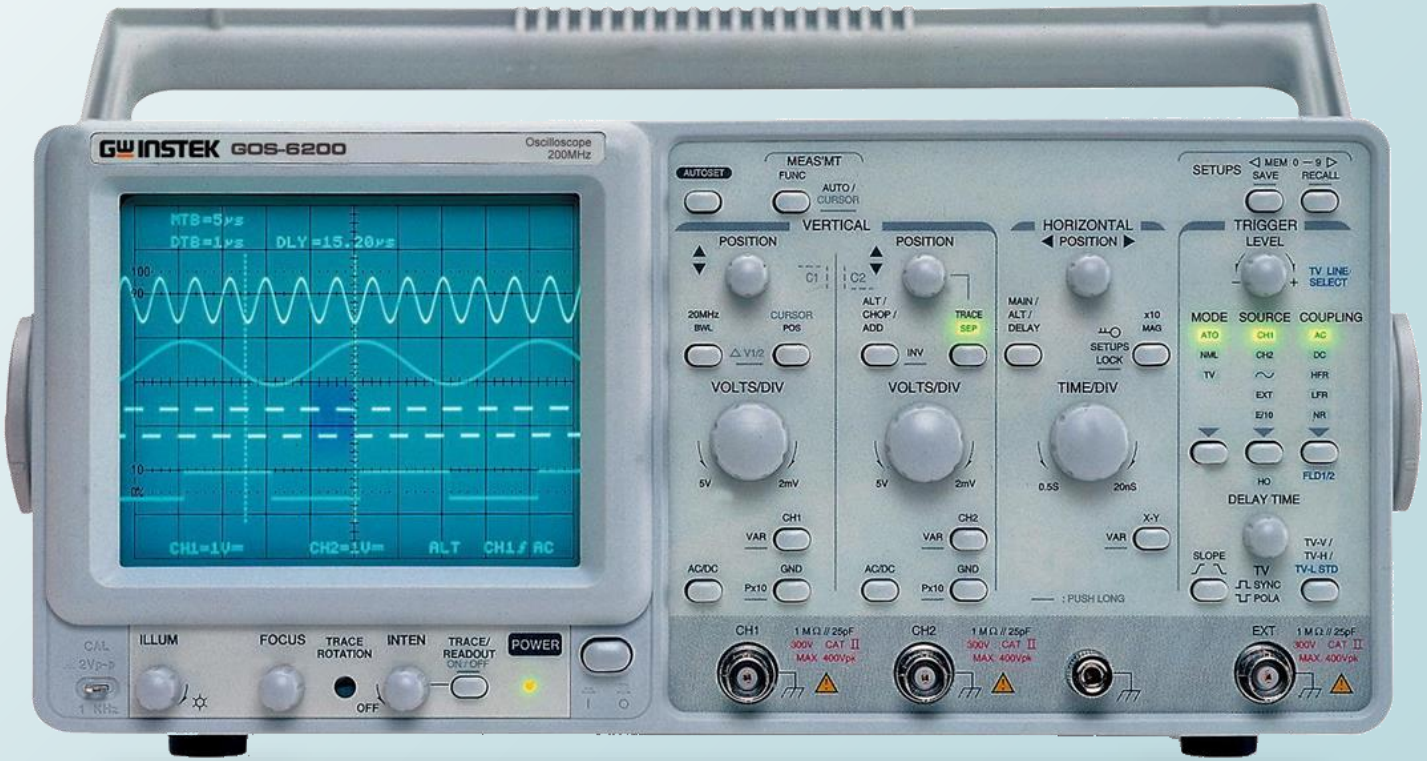
3 junction flux qubit

Transmon qubit

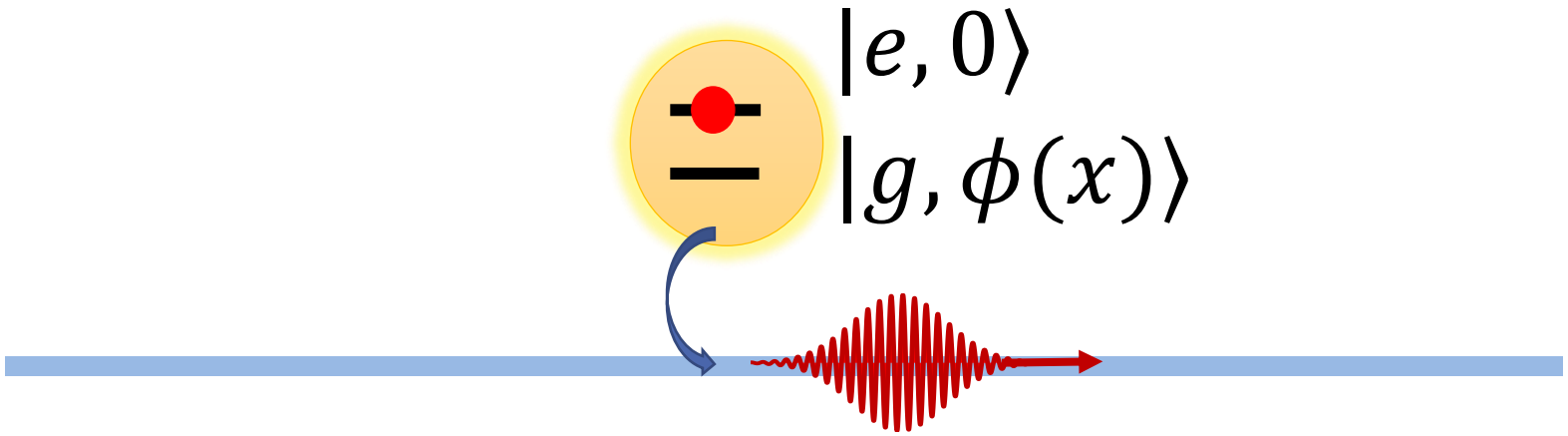
Fluxonium

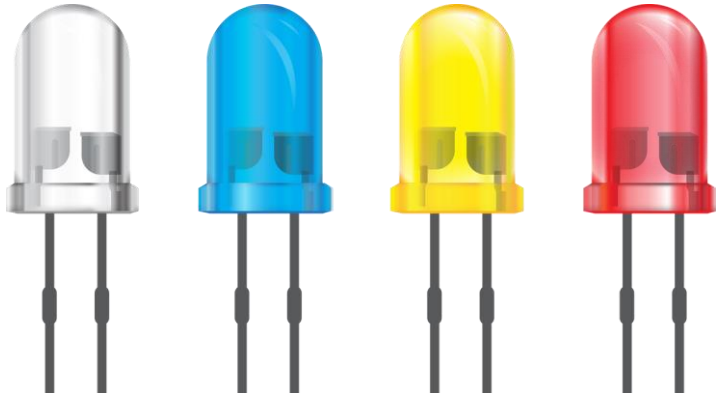
Capacitively shunted flux qubit…

Circuit QED

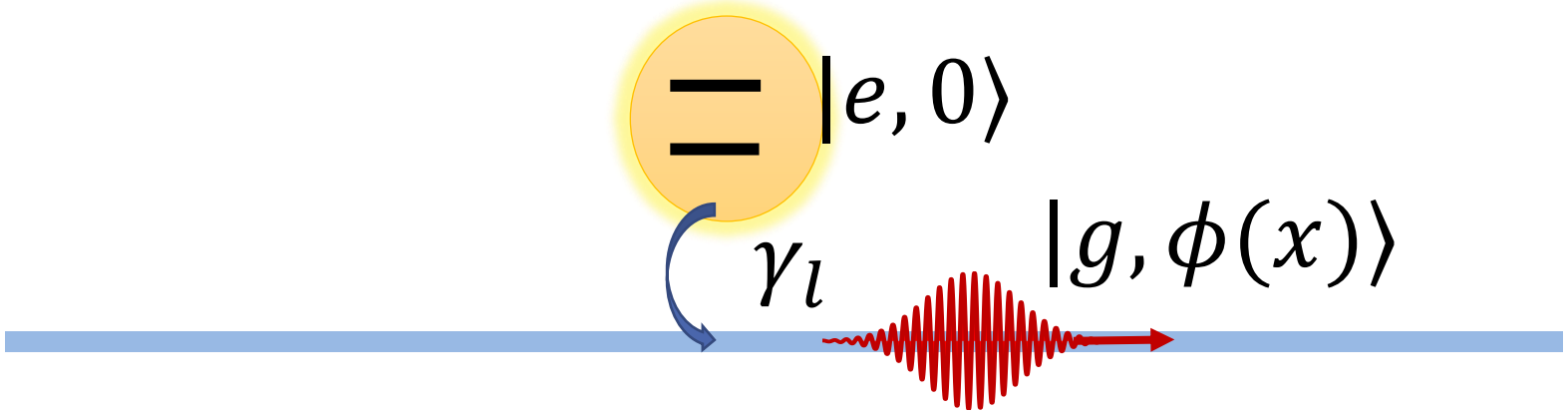

GW INSTEK GOS-6200
Oscilloscope 200MHz
MT8=5μs
DT8=1μs
DLY=15.20μs
CH1=1V⎓
CH2=1V⎓
ALT
CH1 ƒ AC
AUTOSET
MEAS'MT
FUNC
AUTO / CURSOR
SETUPS
SAVE
RECALL
VERTICAL
POSITION
HORIZONTAL
TRIGGER
LEVEL
VOLTS/DIV
TIME/DIV
MODE
SOURCE
COUPLING
DELAY TIME
ILLUM
FOCUS
TRACE ROTATION
INTEN
TRACE/ READOUT ON/OFF
POWER
CH1
CH2
EXT

Spontaneous emission

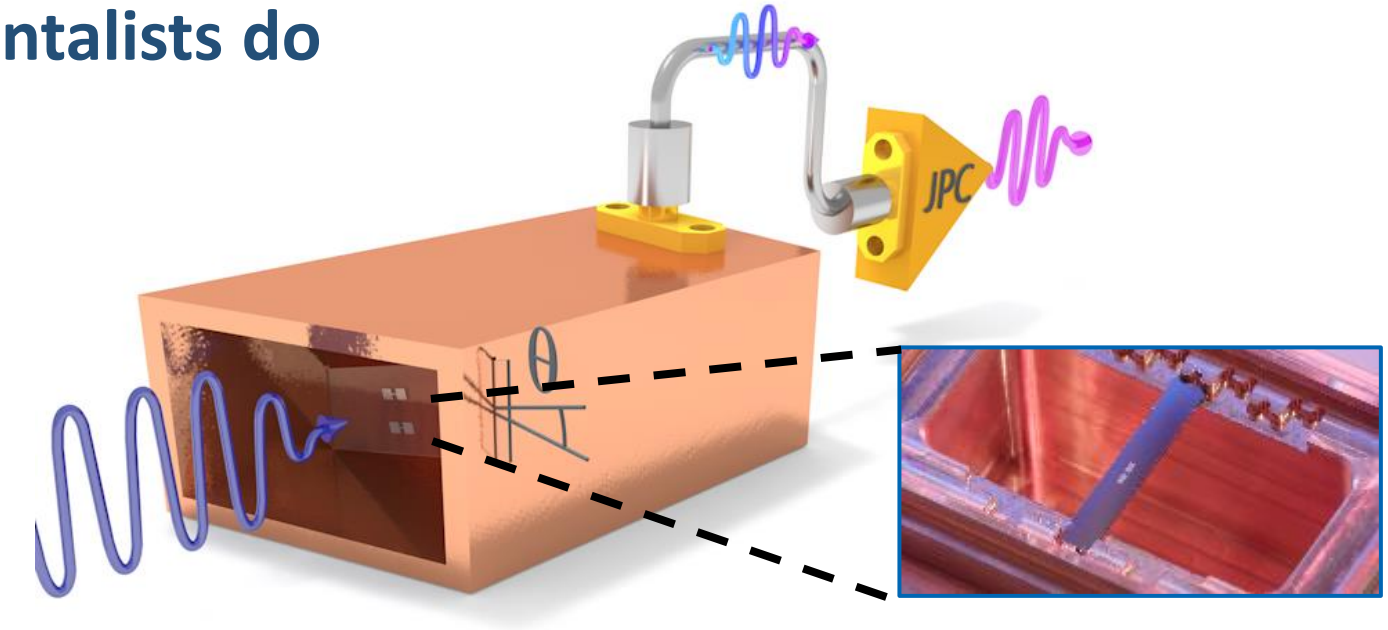


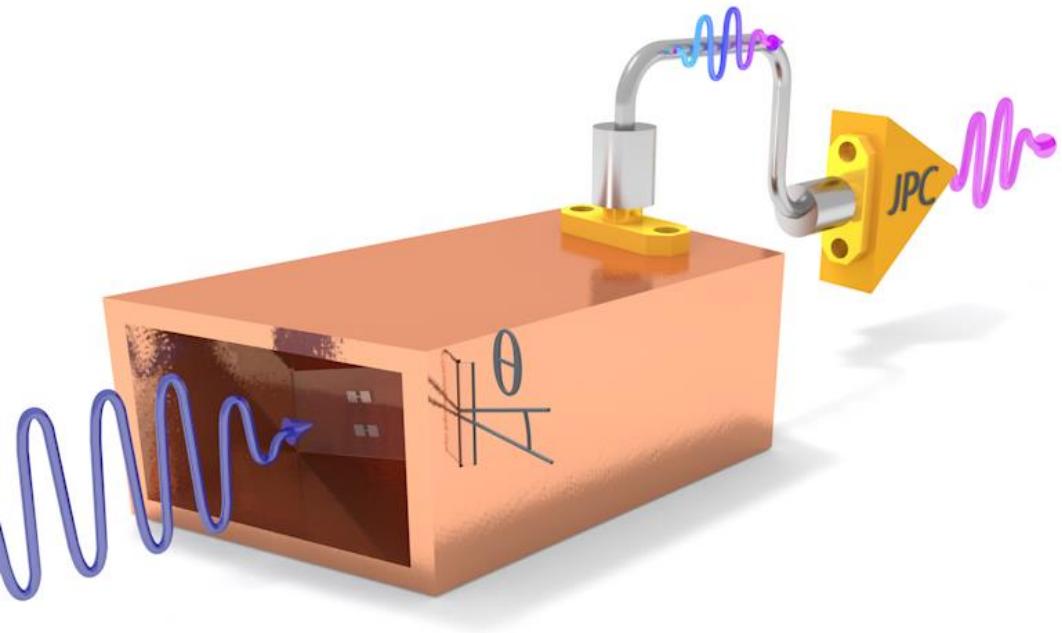


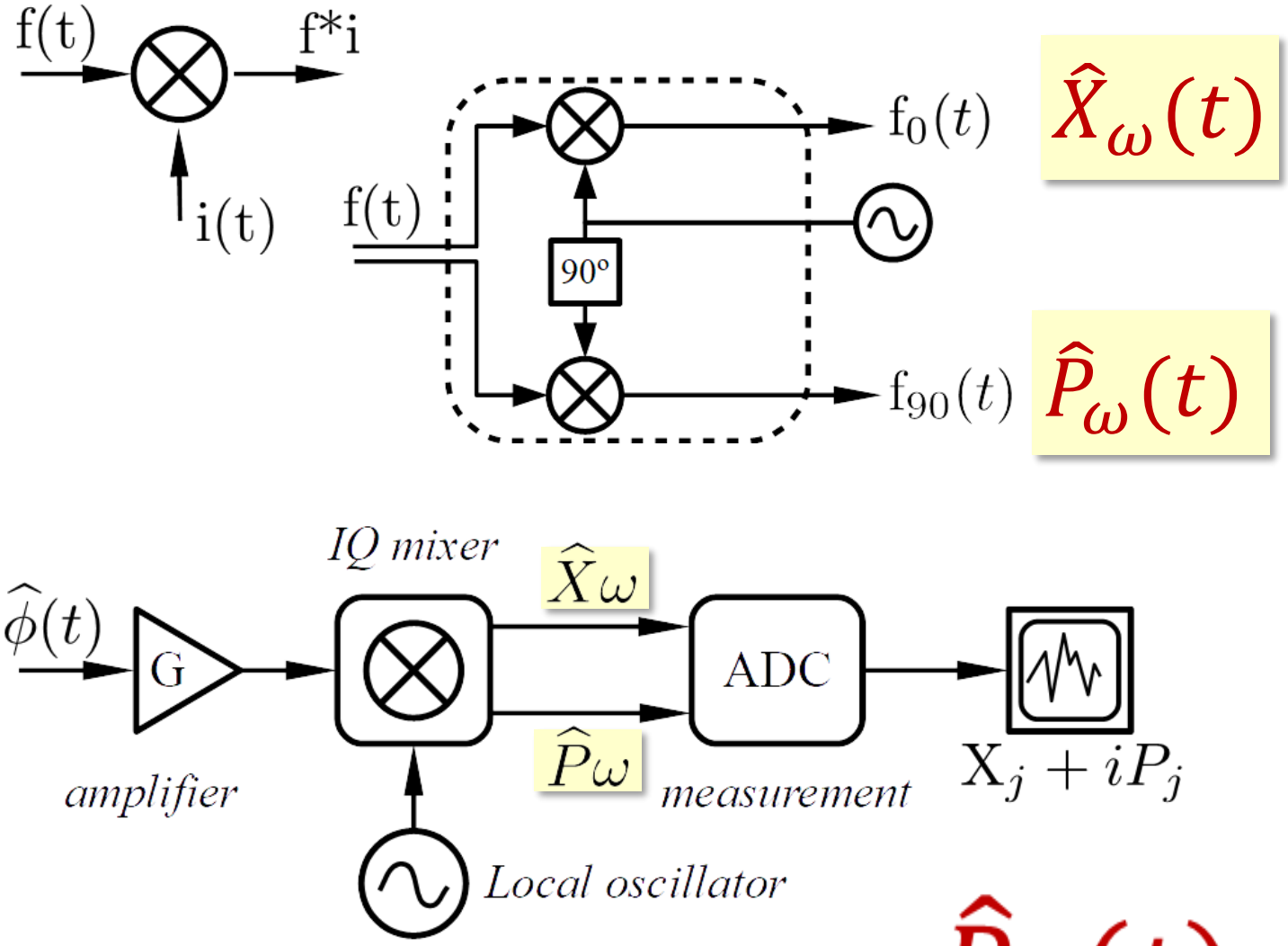
What theoreticians see



What experimentalists do

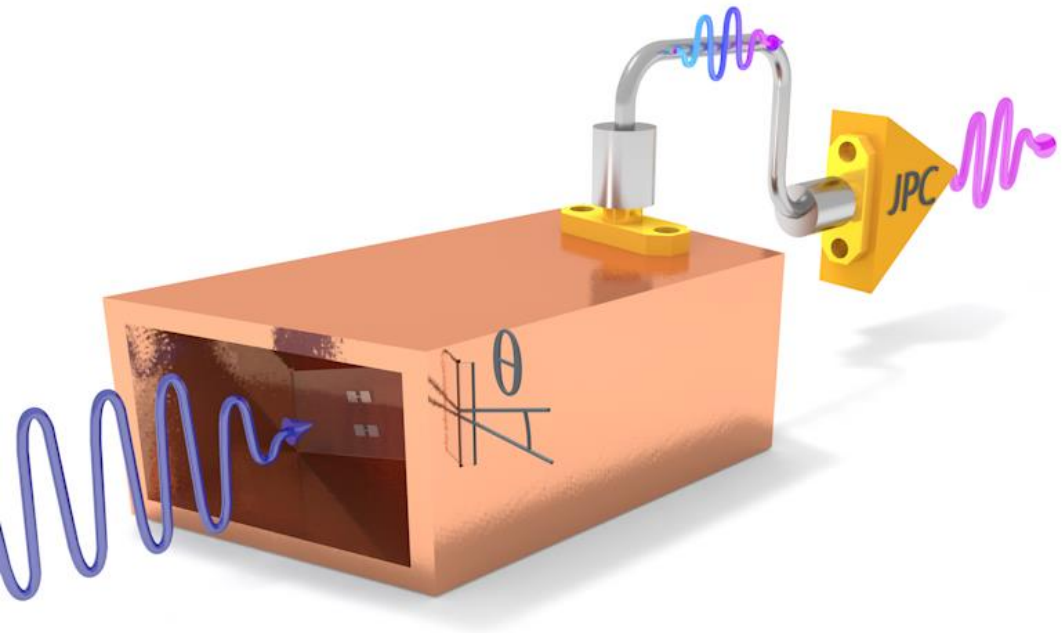


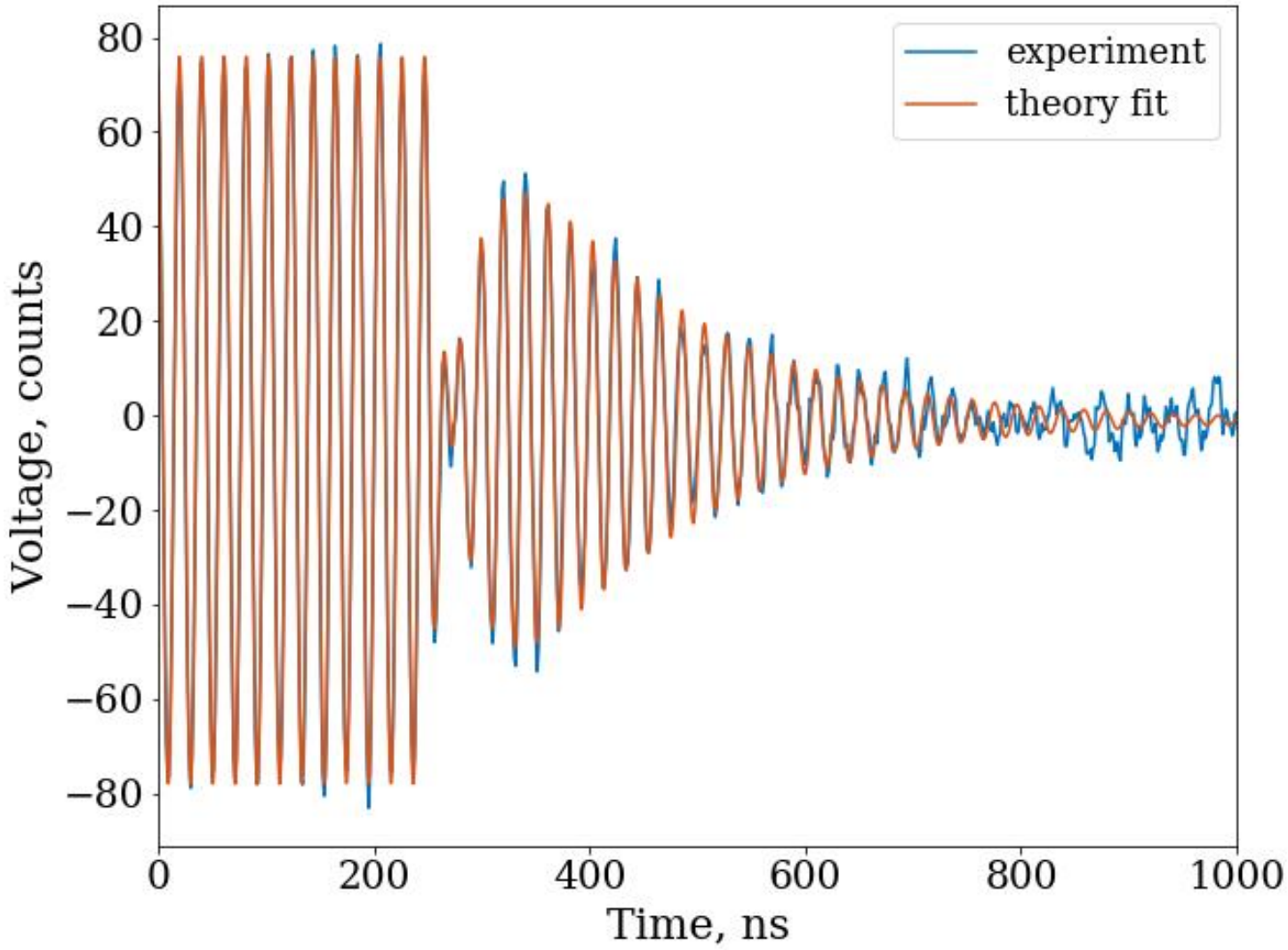




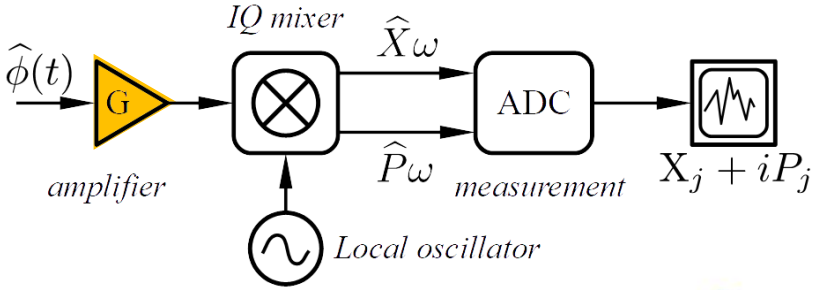
$\hat{P}_\omega(t)$

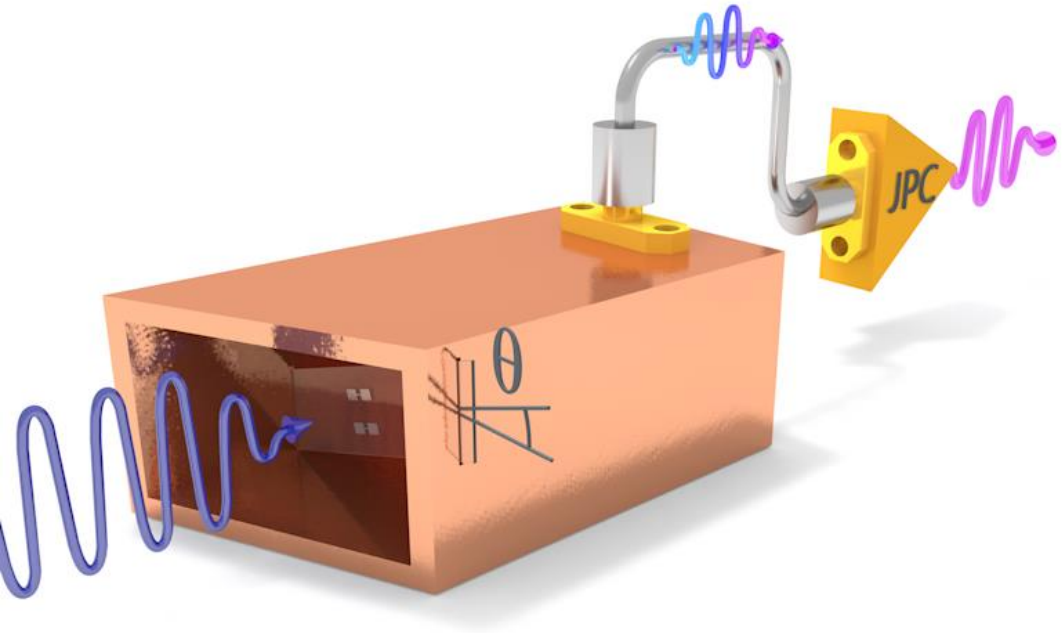
A. Sharafiev et al, arXiv:2001.09737

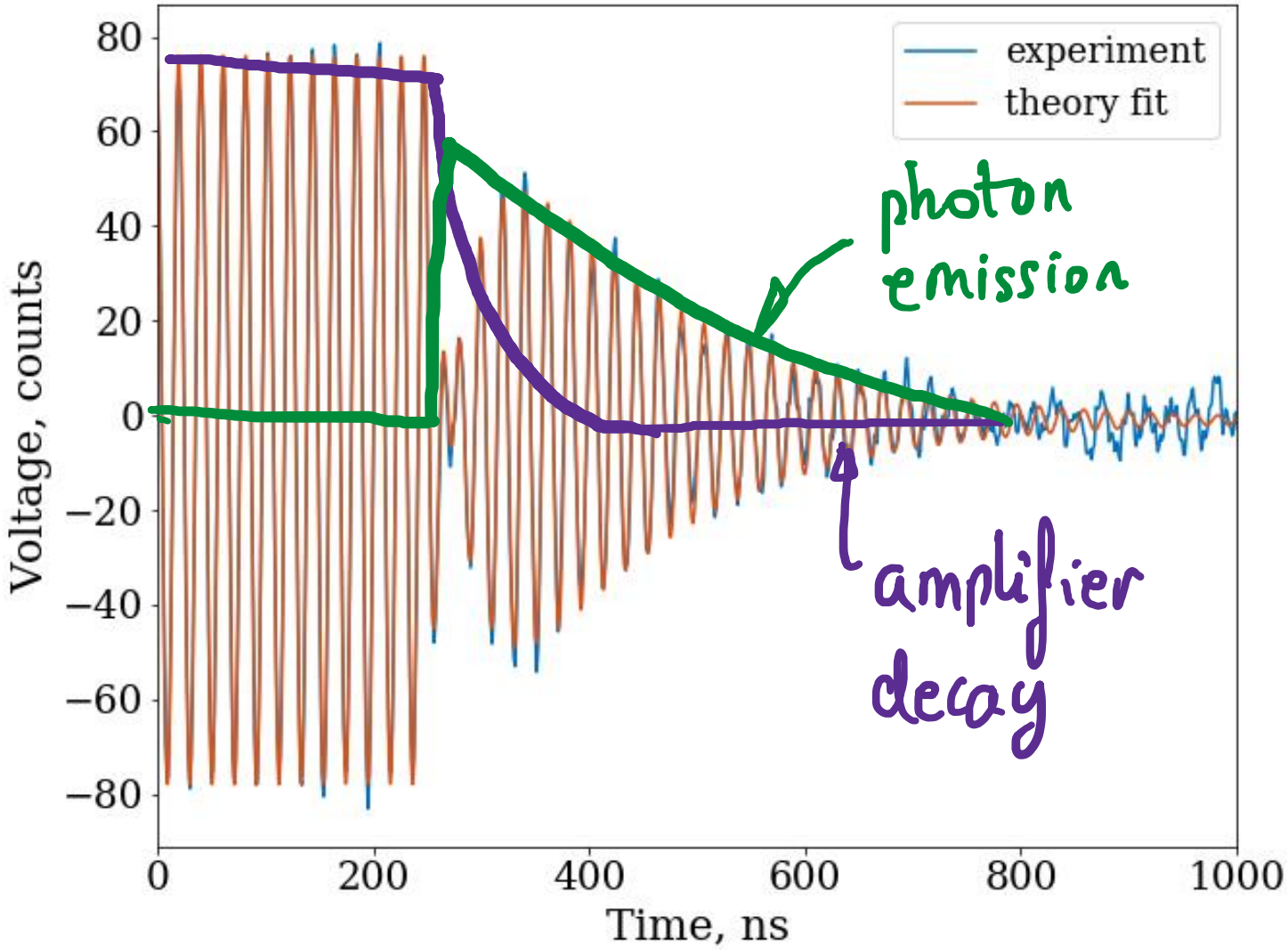




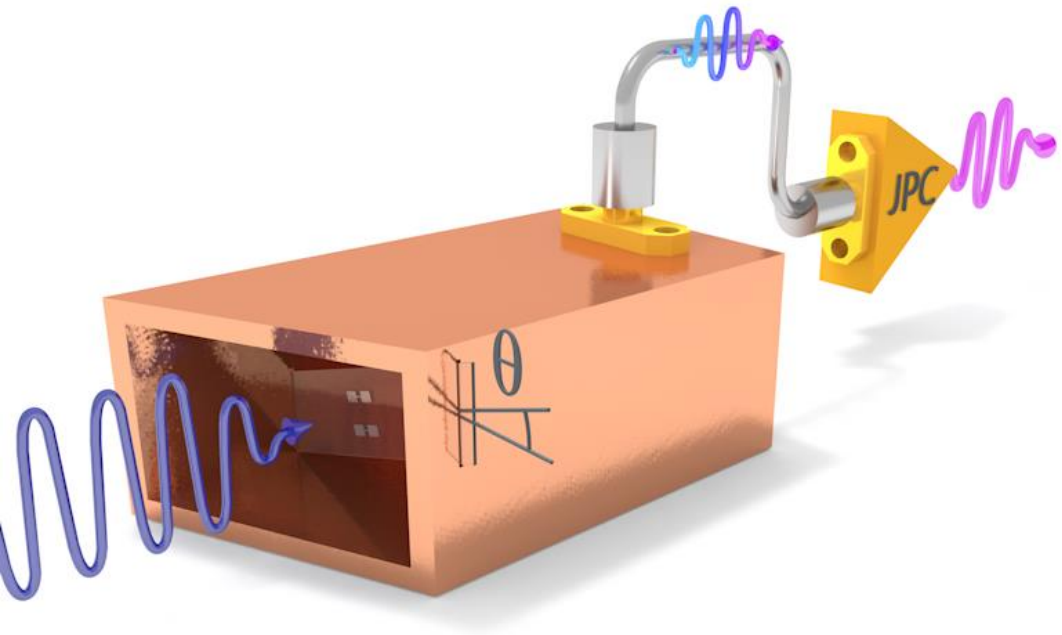
A. Sharafiev et al, arXiv:2001.09737

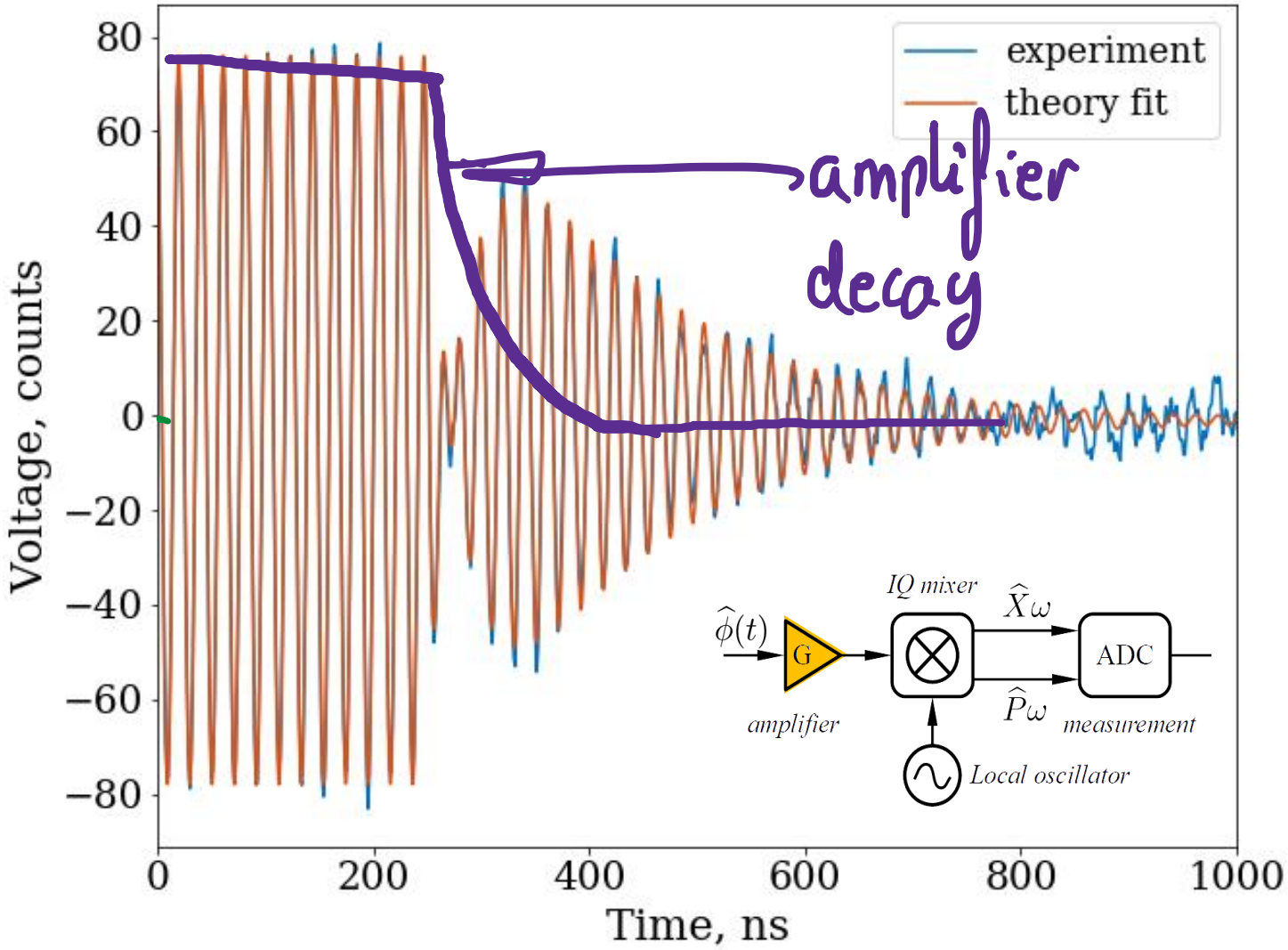




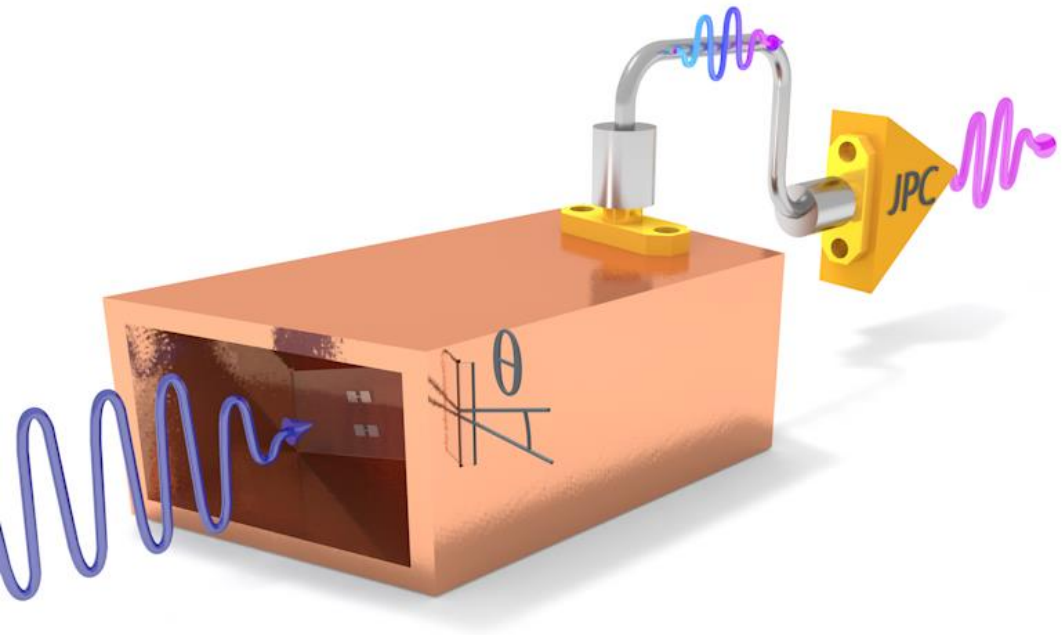


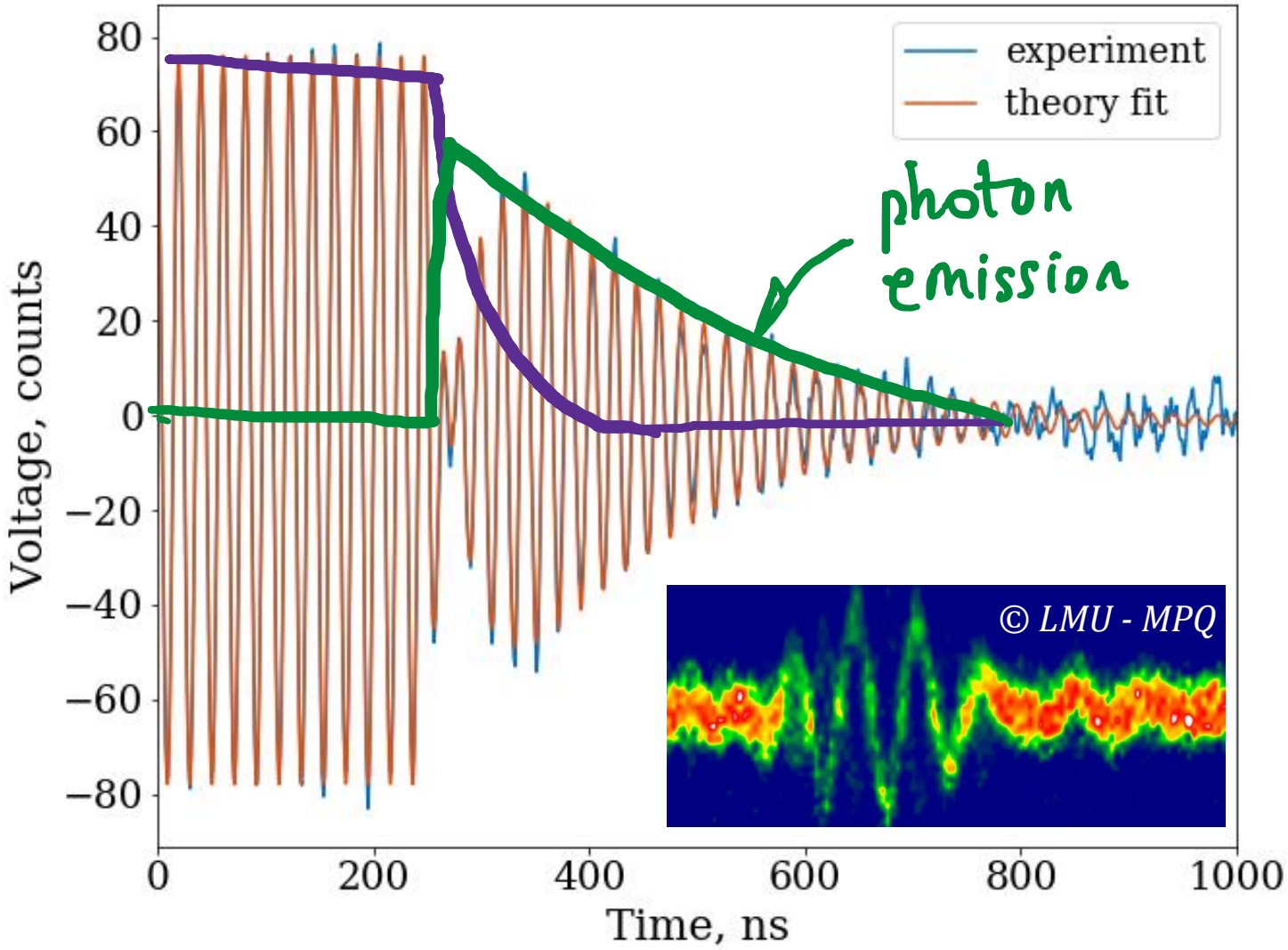
A. Sharafiev et al, arXiv:2001.09737



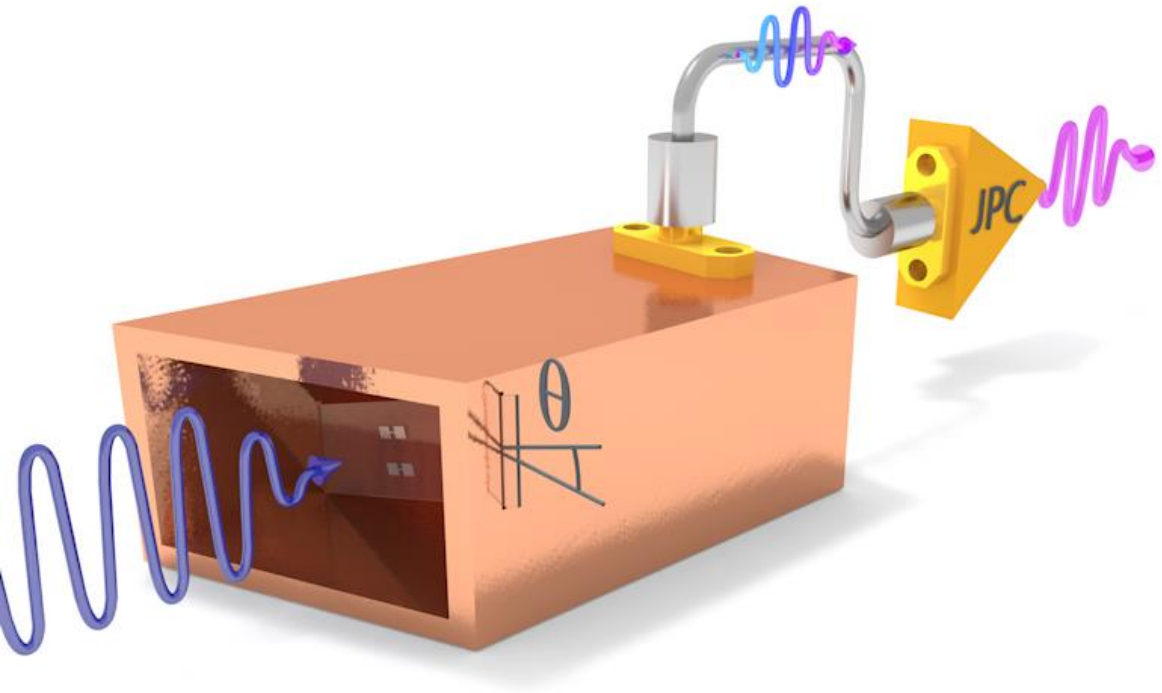


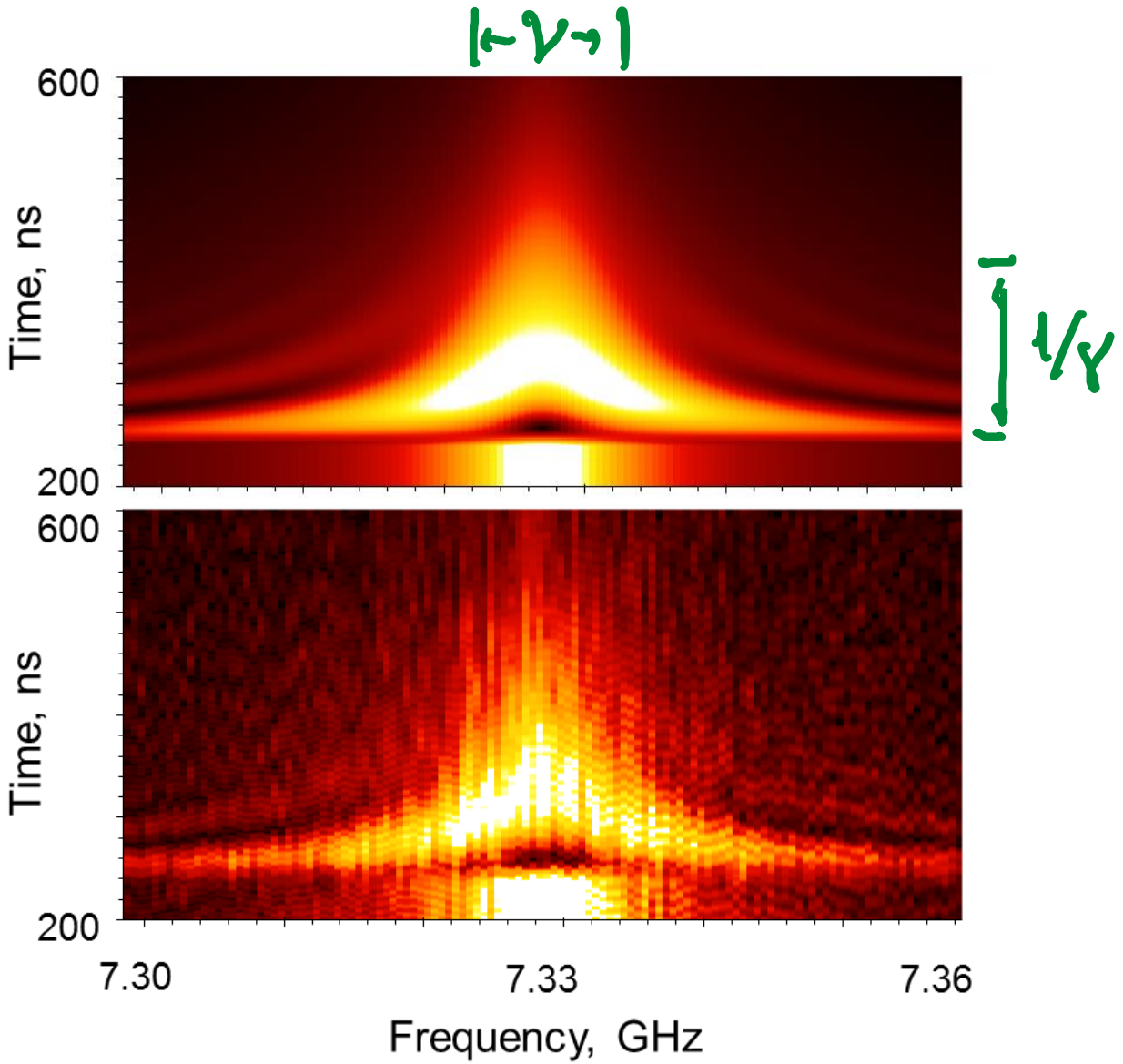
A. Sharafiev et al, arXiv:2001.09737





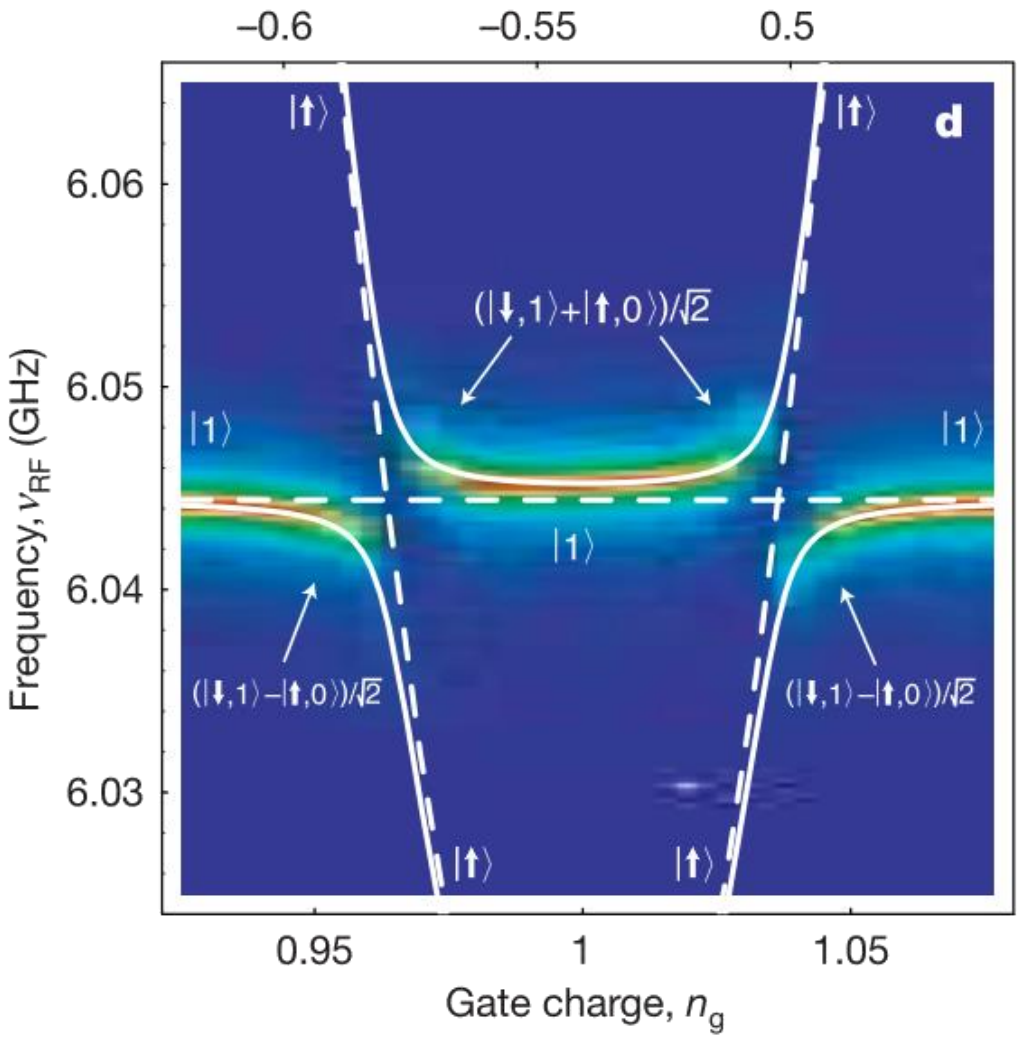
A. Sharafiev et al, arXiv:2001.09737



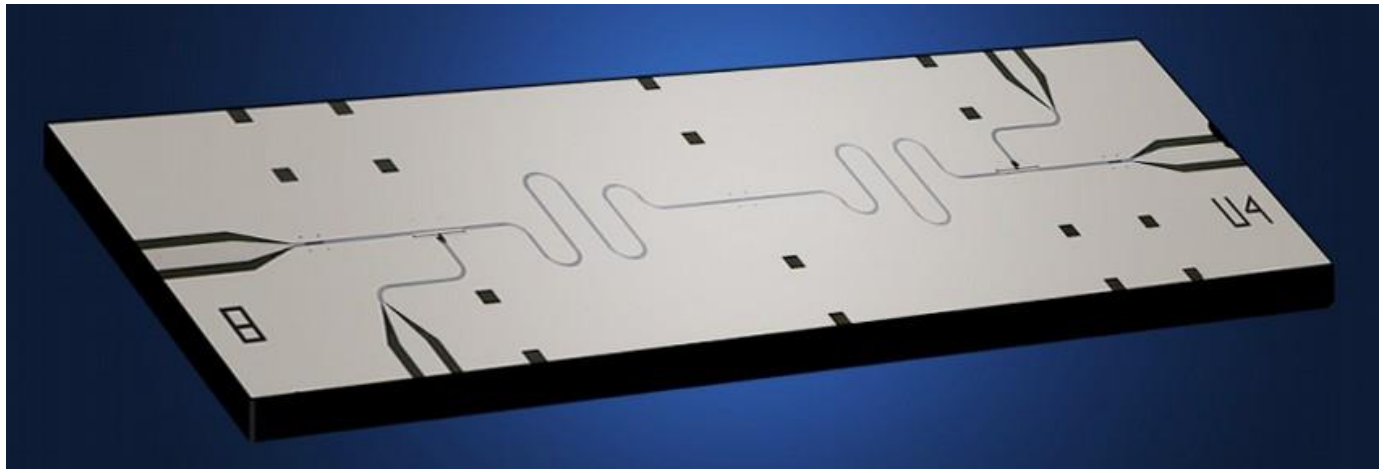


A. Sharafiev et al, arXiv:2001.09737

Strong coupling



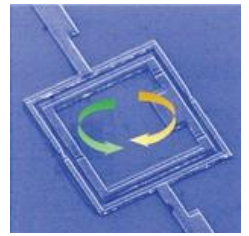
A. Wallraff et al, Nature 431, 162 (2004)

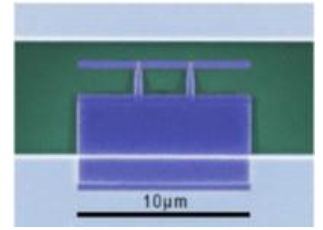


Jaynes-Cummings model

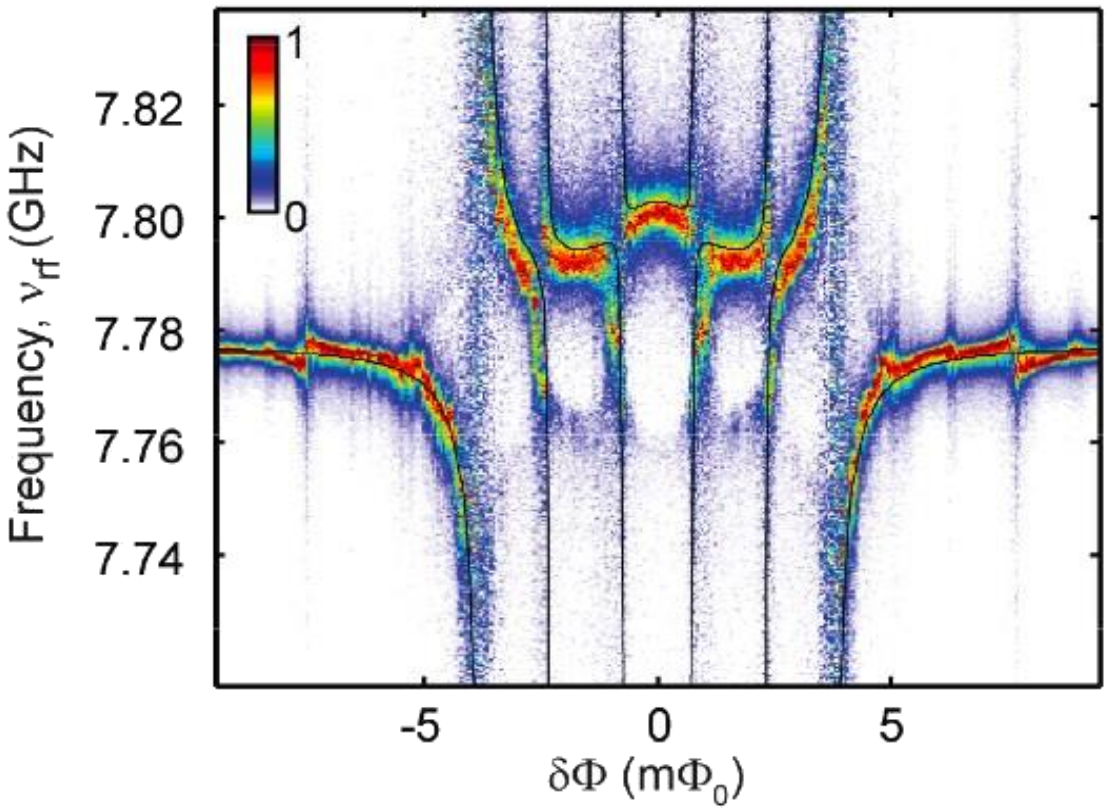
$$\mathrm{H} = \frac{\Delta}{2}\,\sigma^z + \frac{\epsilon}{2}\,\sigma^x + \omega a^+ a$$

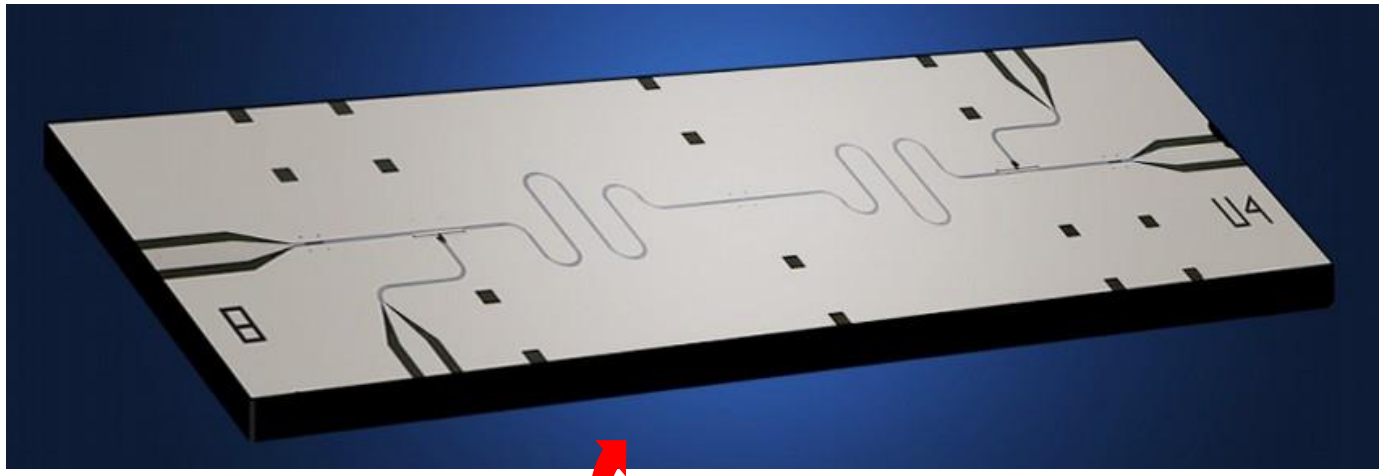
$$+ g\,(\sigma^+ a + \sigma^- a^+)$$

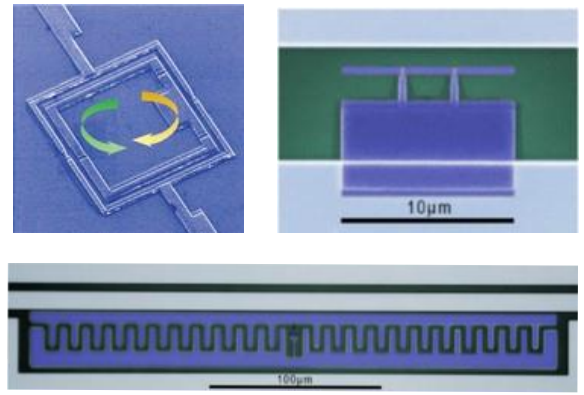




Ultra-strong coupling

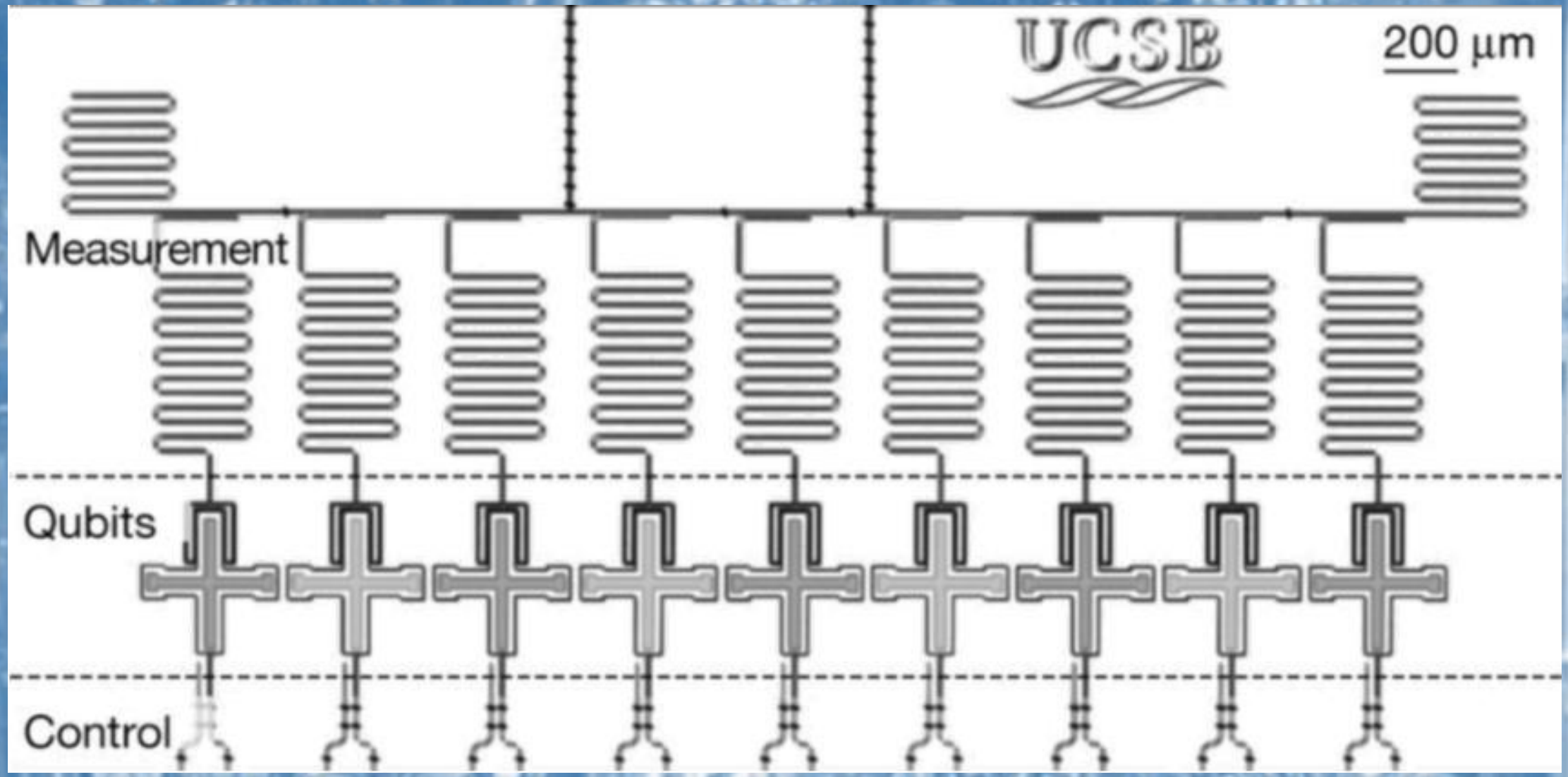




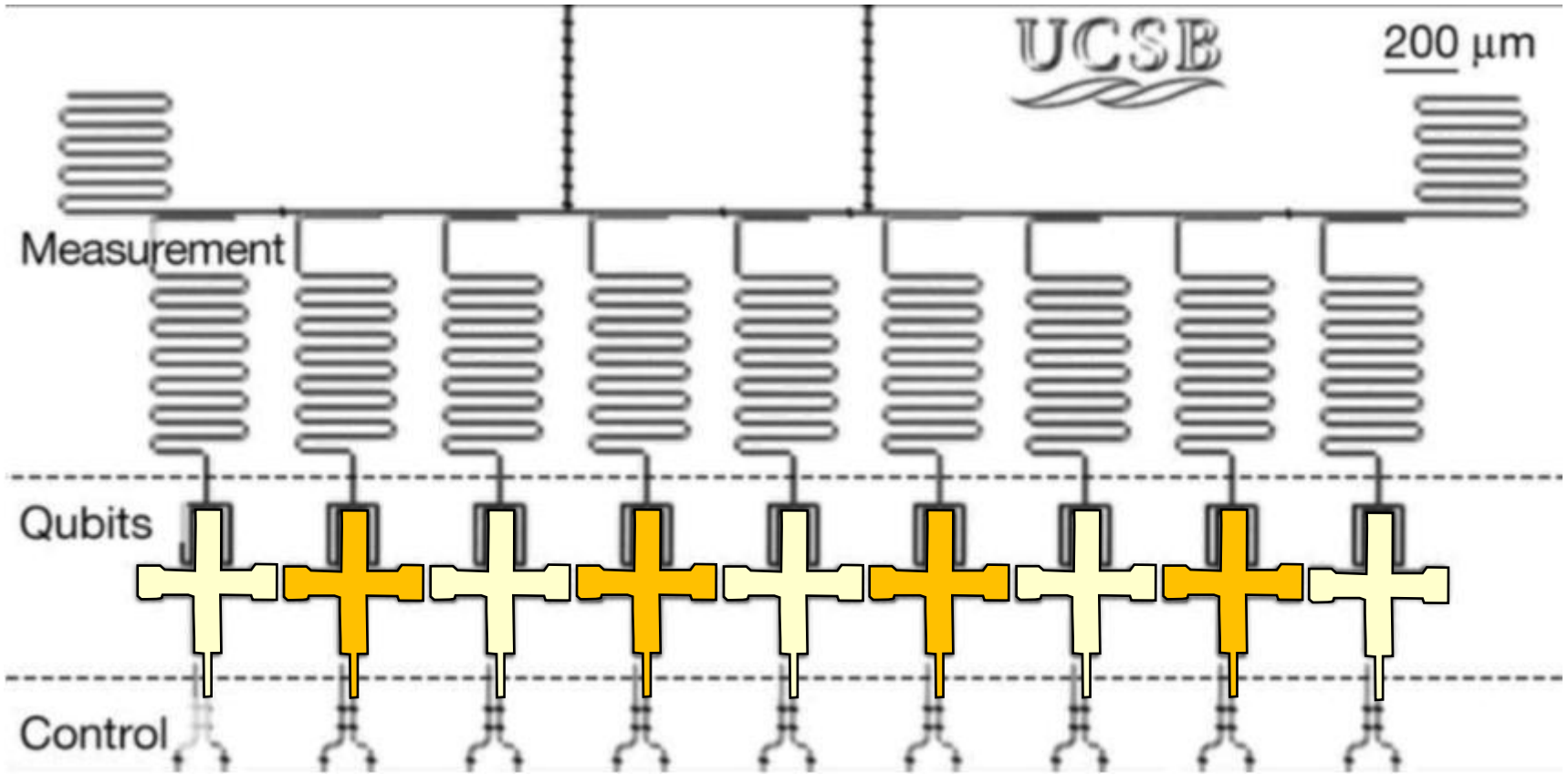


Great impedance match!

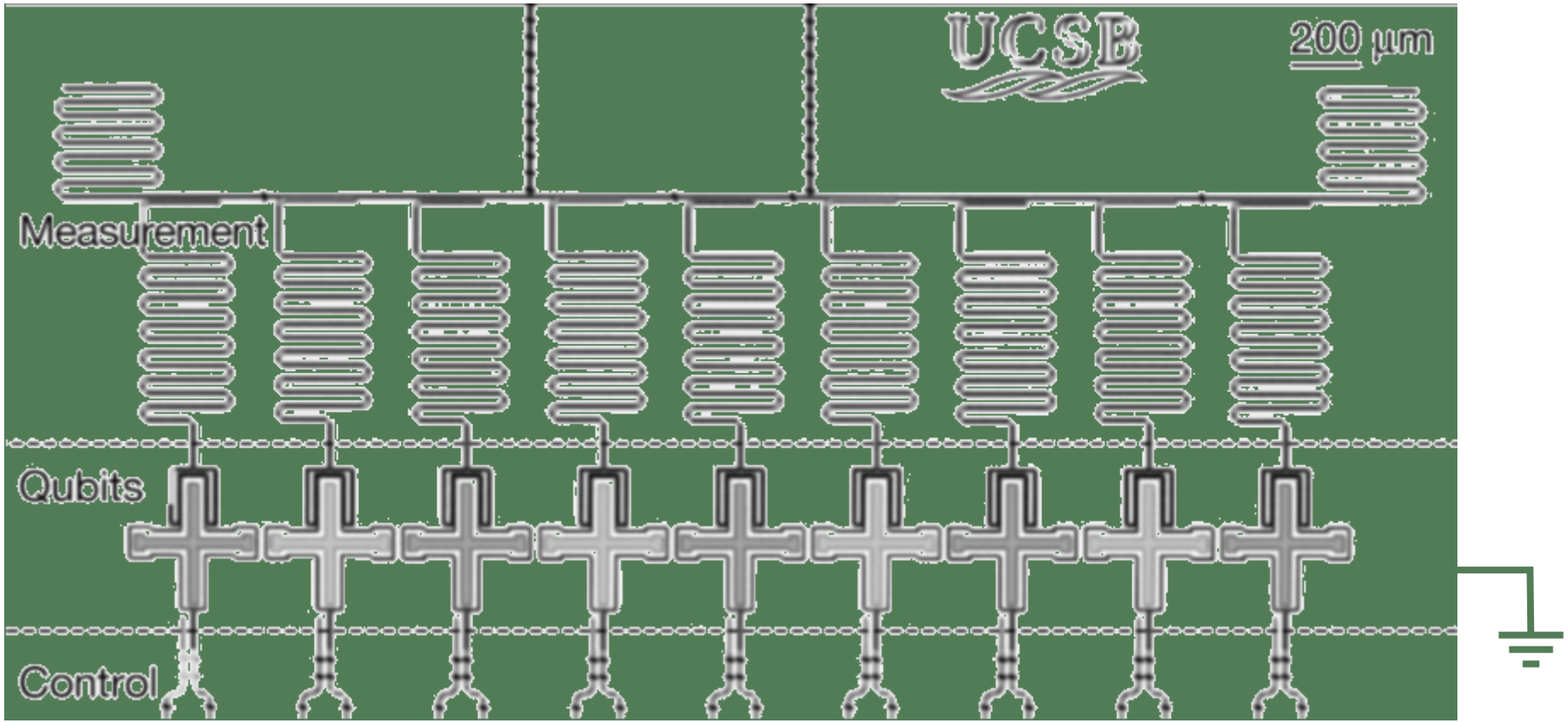
T. Niemczyk et al, Nature Physics ***6****,772–776 (2010)*


UCSB
200 µm
Measurement
Qubits
Control

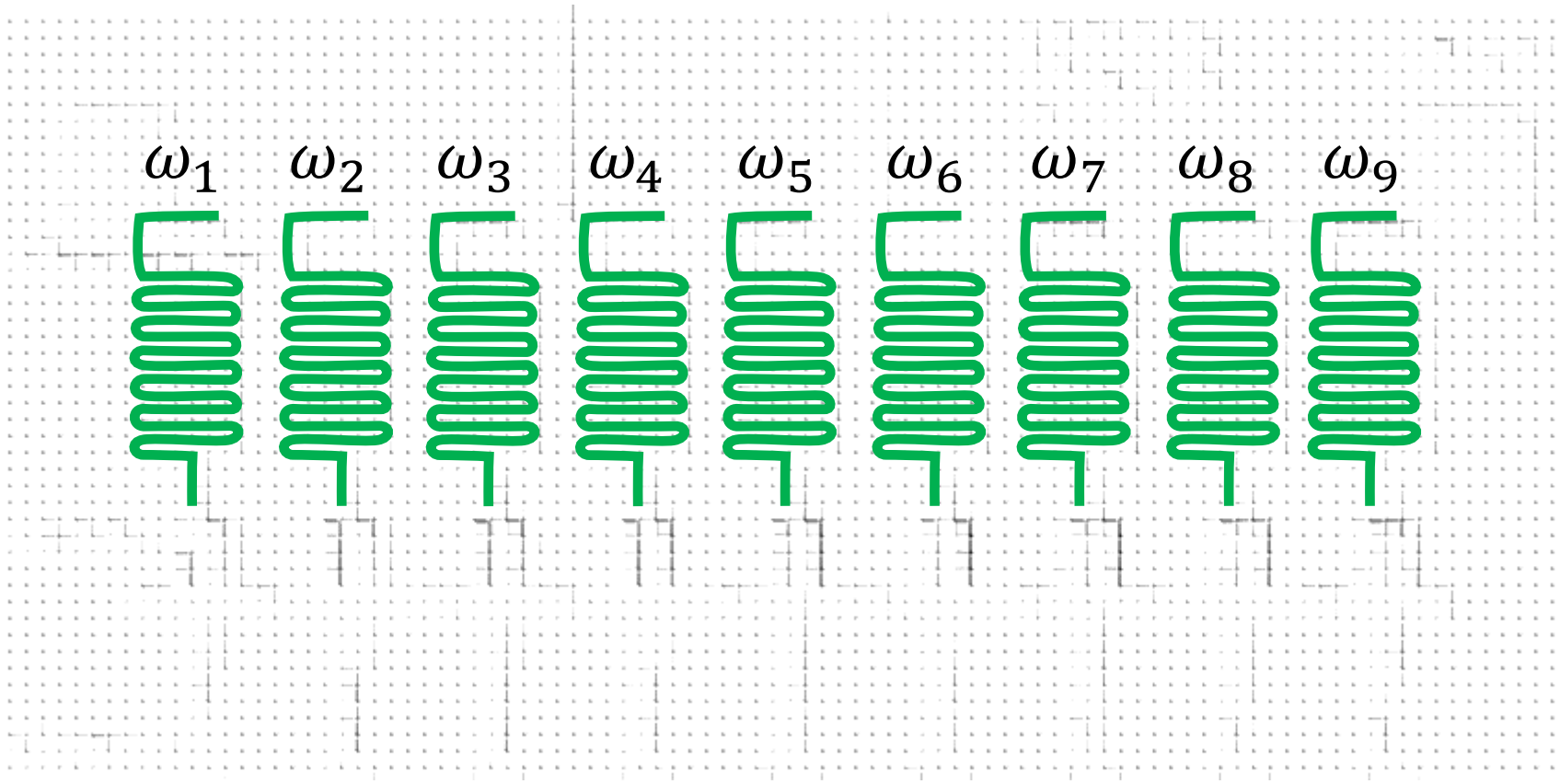
Superconducting qubits



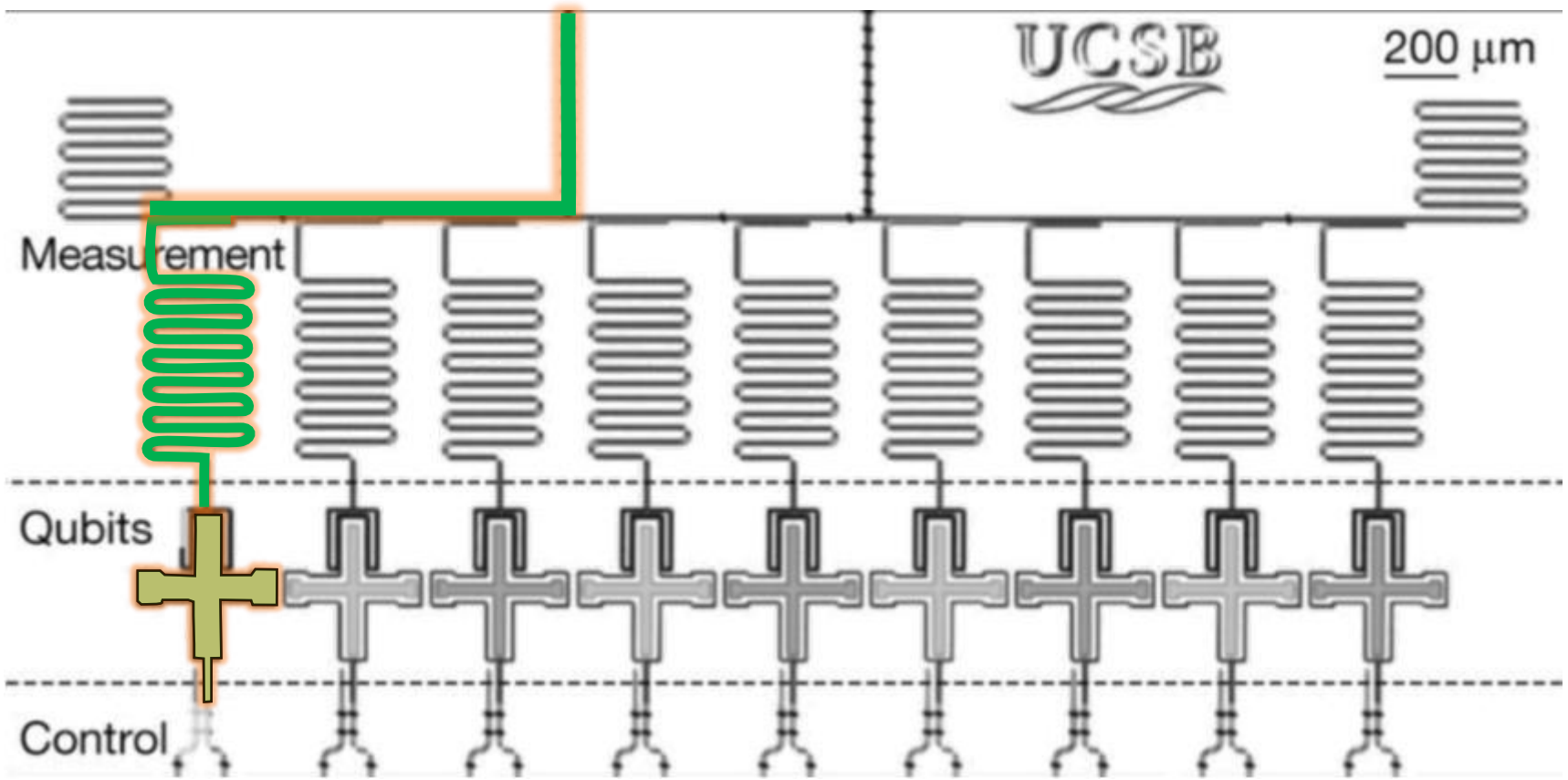
Quantum filters



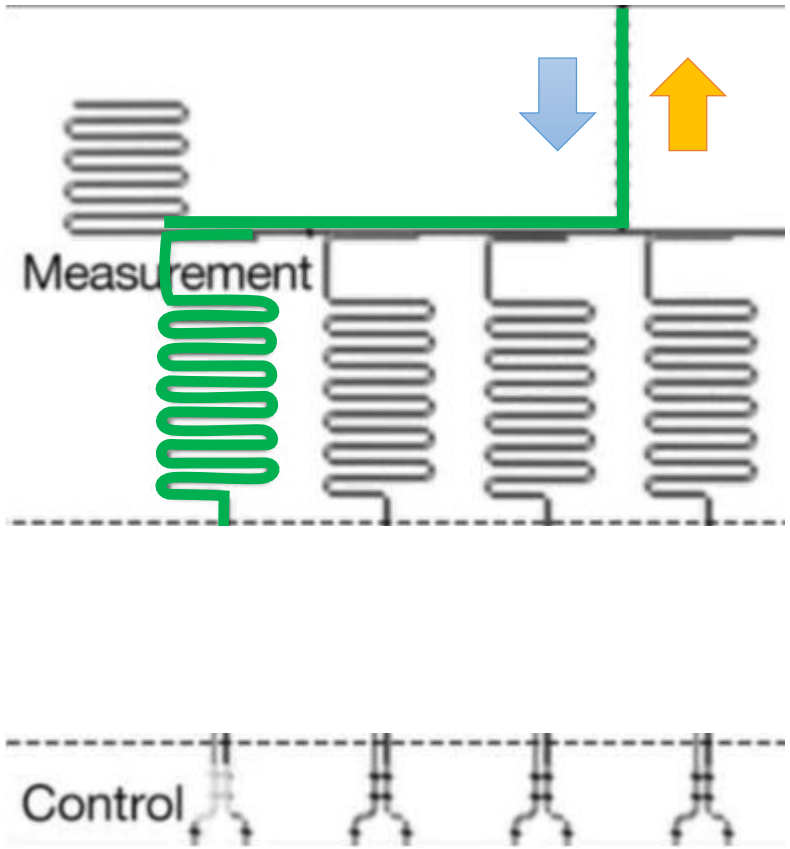
Quantum filters

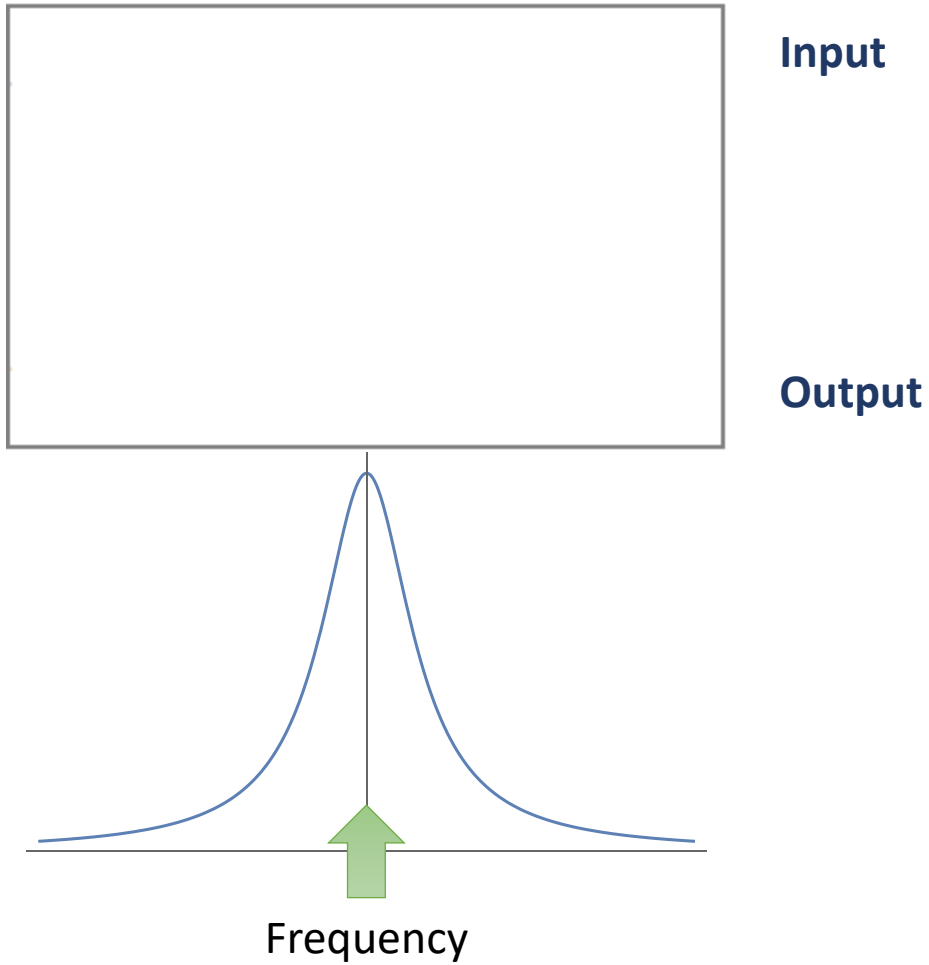


1 qubit operations

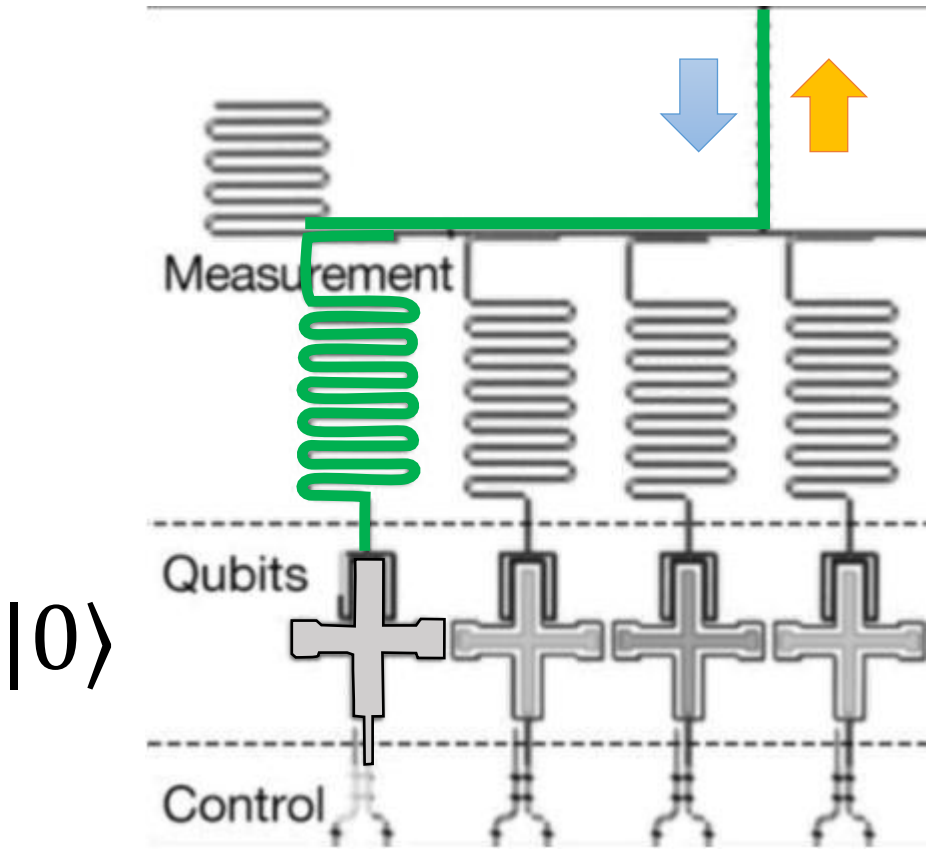


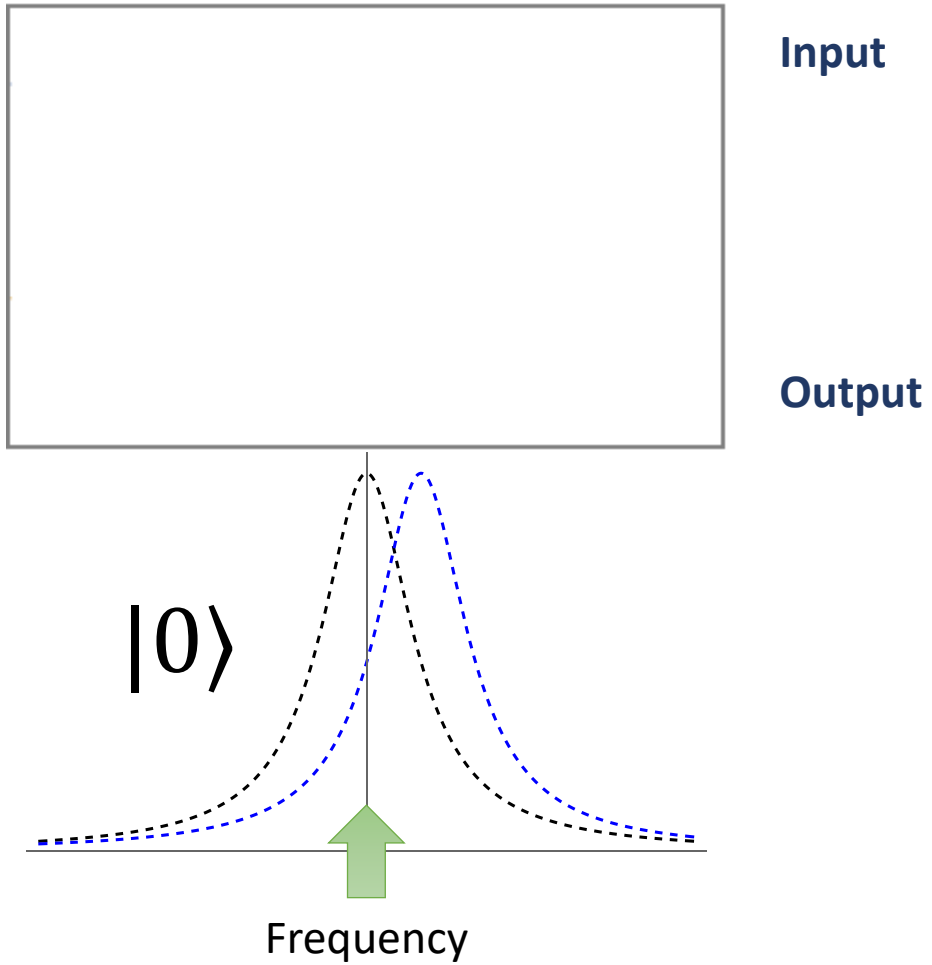
Measurements



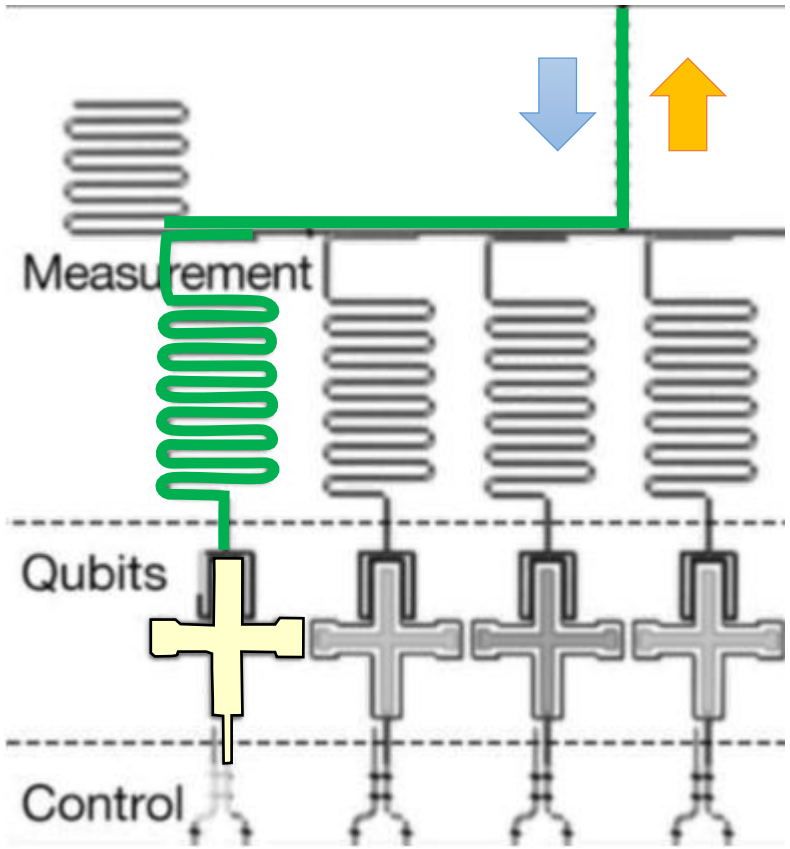


Measurements

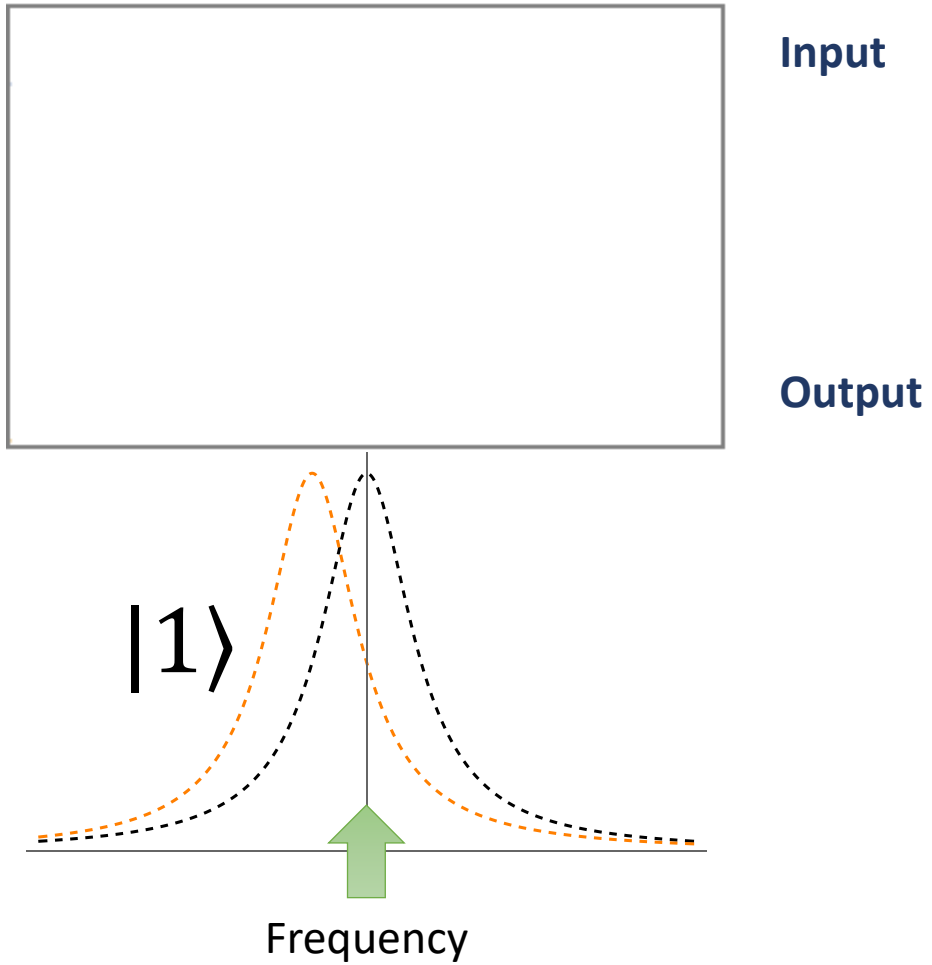




Measurements

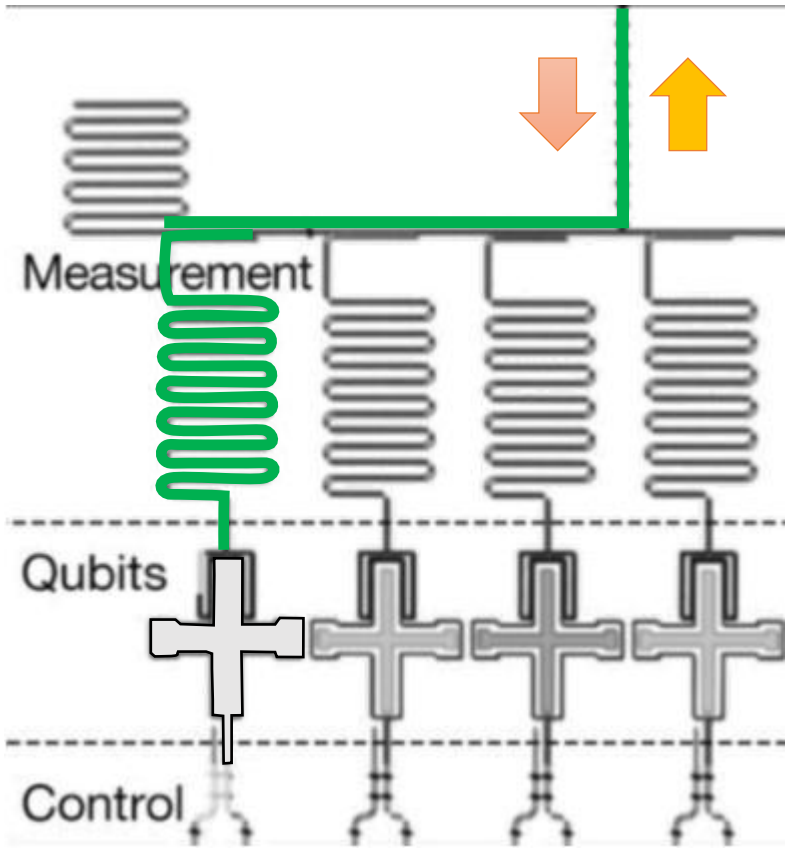


$|1\rangle$

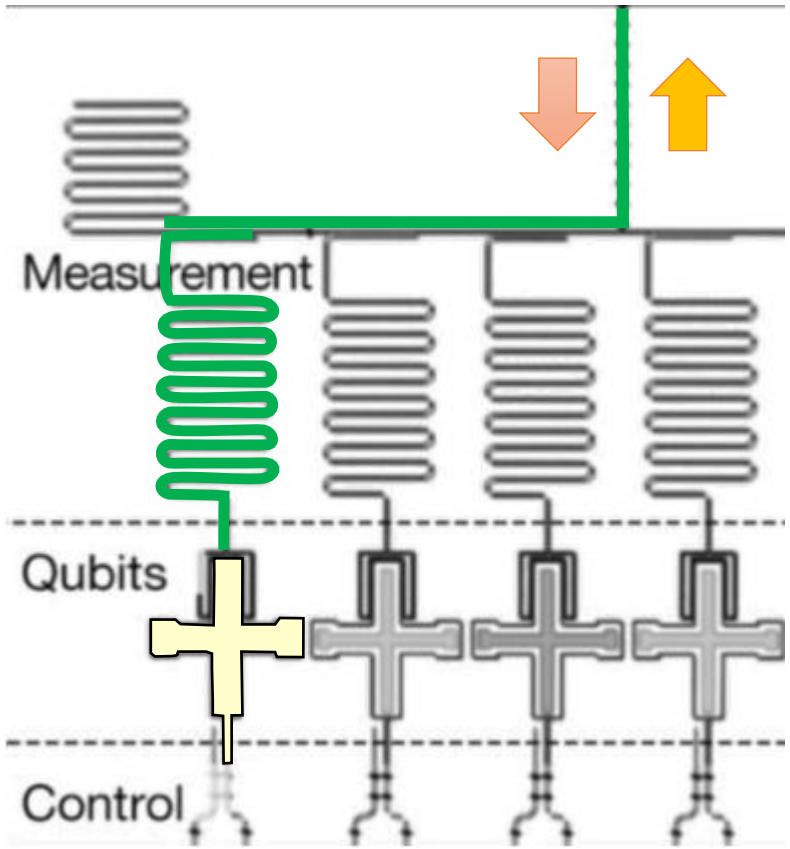


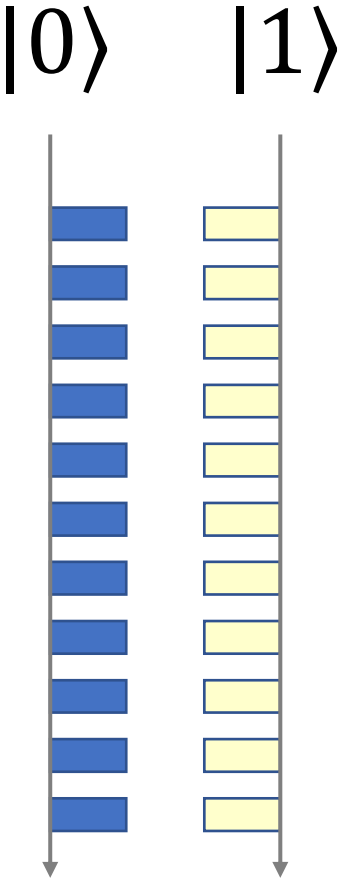
$|1\rangle$

Measurements

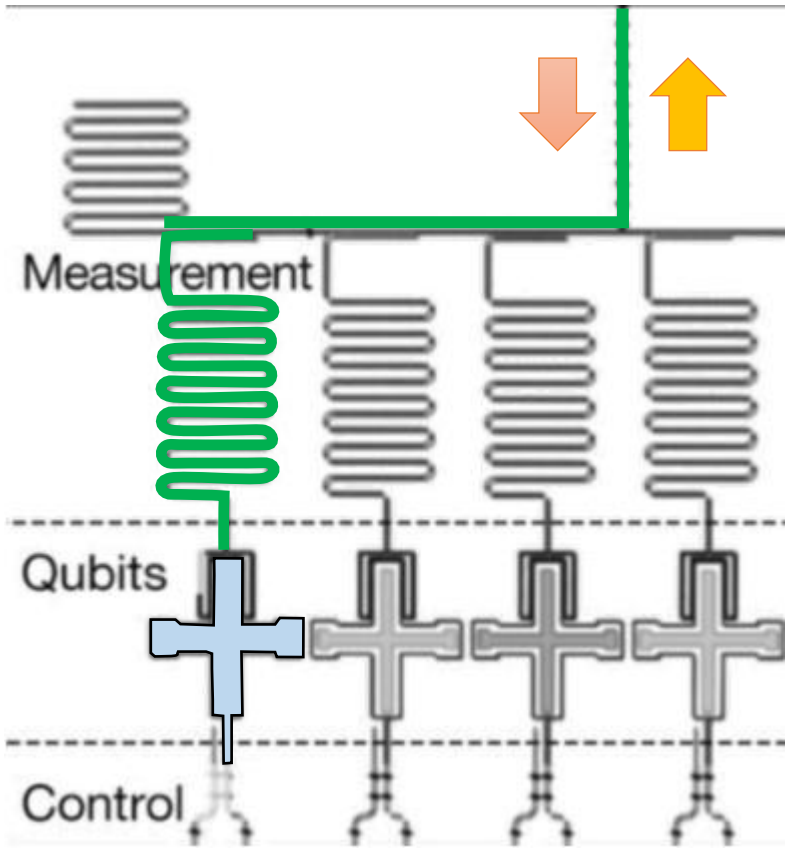


Measurements

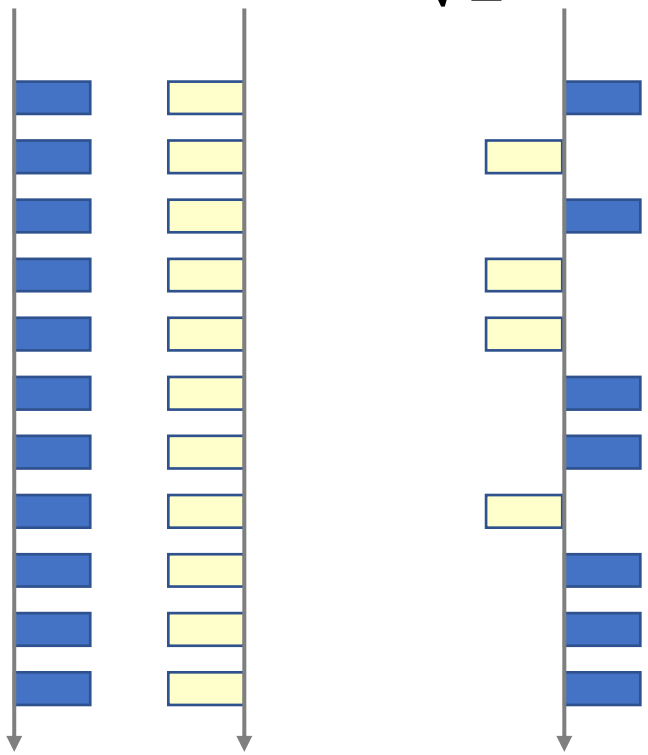




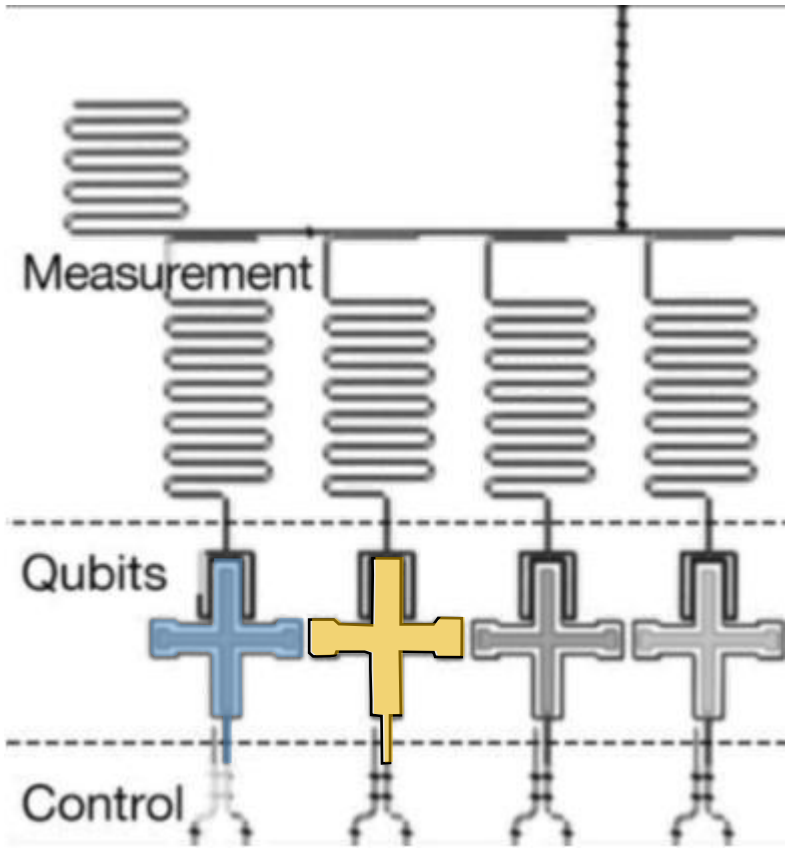
Measurements



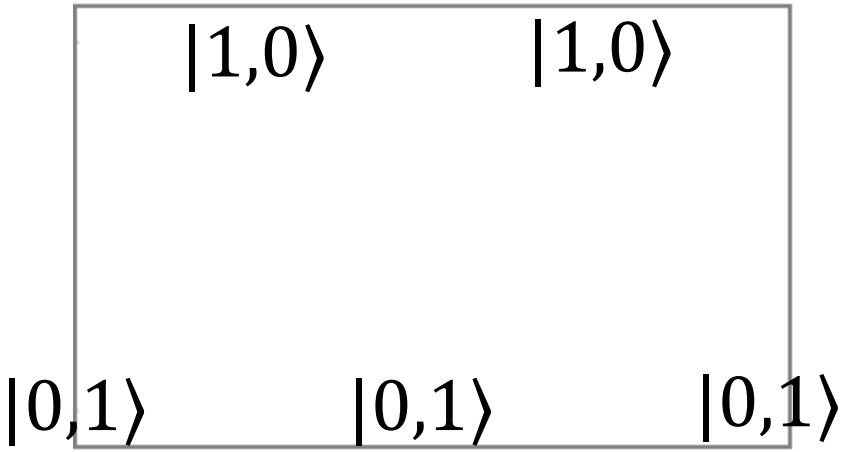
$|0\rangle$ $|1\rangle$ $\frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$



Quantum gates: e.g. “swap”

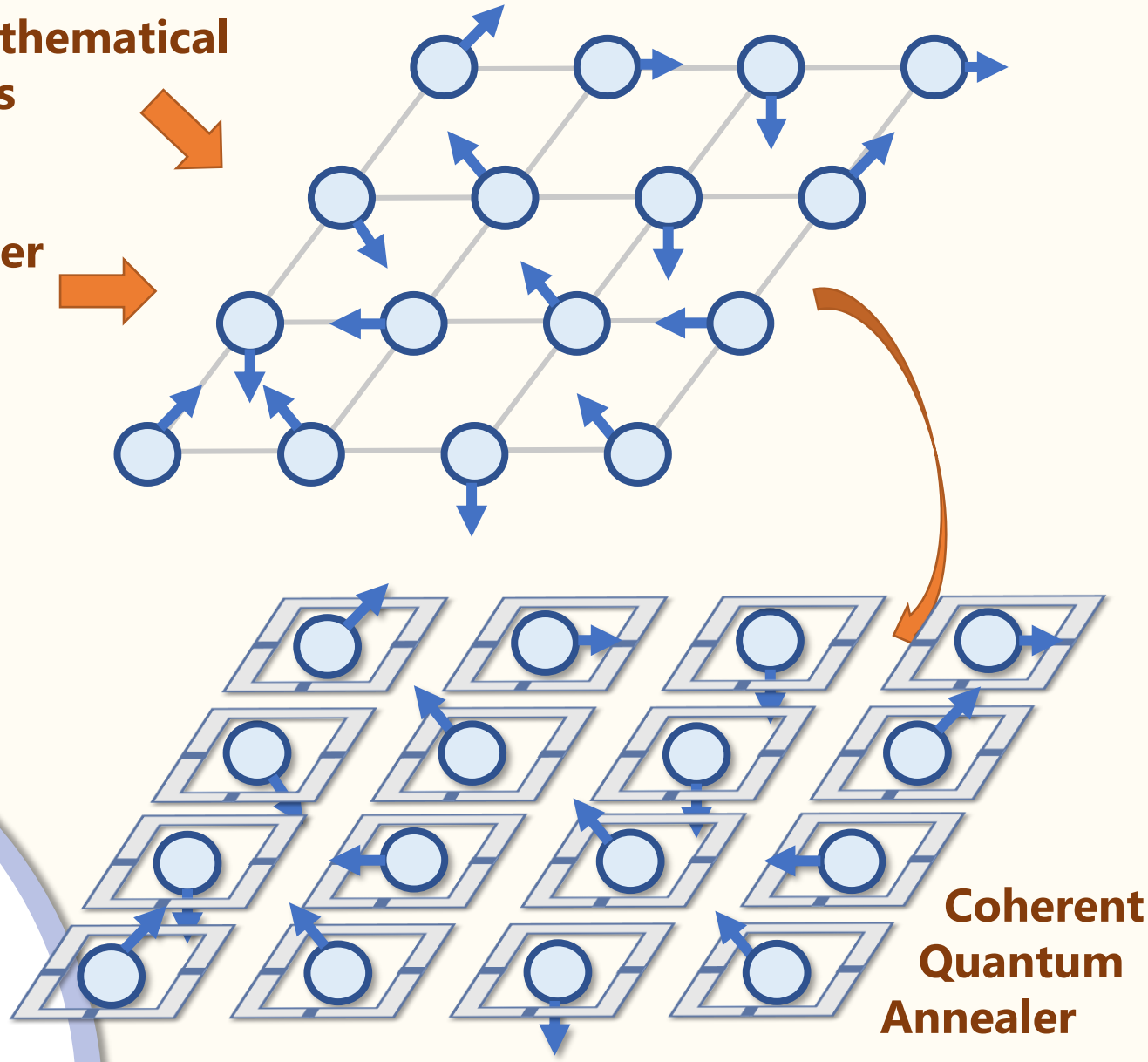


Probability to measure “1”



Hard mathematical problems

Quantum matter models



Coherent Quantum Annealer

Avaqus

http://avaqus.eu

European Commission

Institut de Física d'Altes Energies

EXCELENCIA SEVERO OCHOA

BIST Barcelona Institute of Science and Technology

NÉEL institut

cnrs

Delft Circuits

Hardware for quantum engineers.

KIT

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University of Glasgow

HQS QUANTUM SIMULATIONS

QILIMANJARO QUANTUM TECH

SuperQuLAN

http://superqulan.eu

European Commission

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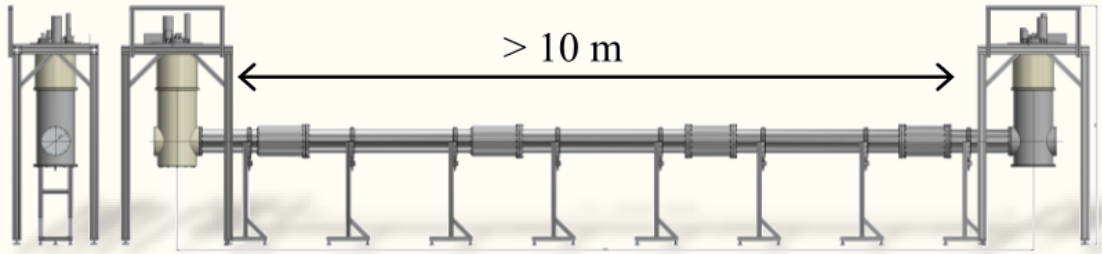
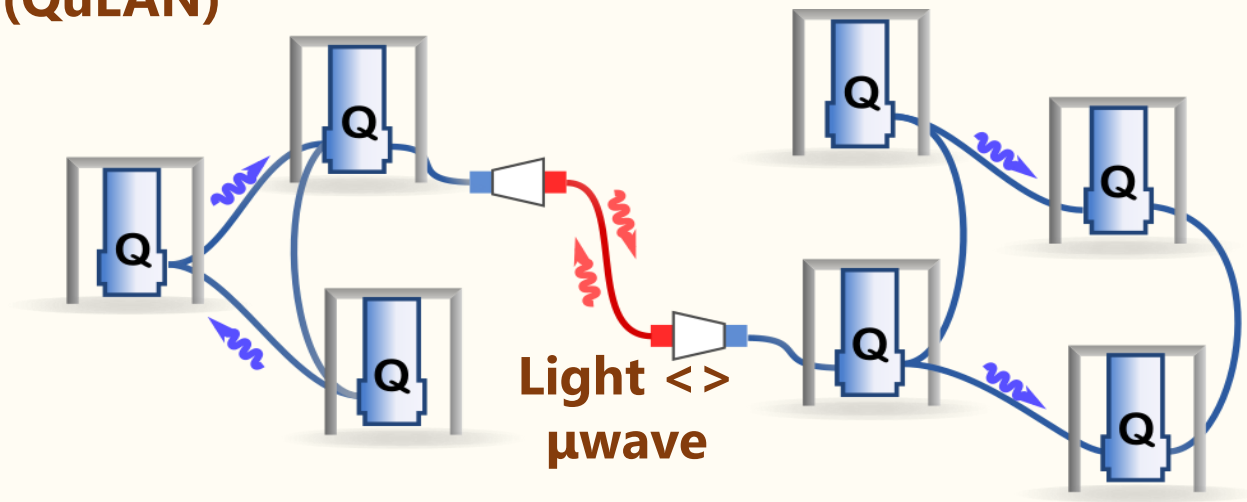


Quantum Local Area Network (QuLAN)



Distributed superconducting quantum computers

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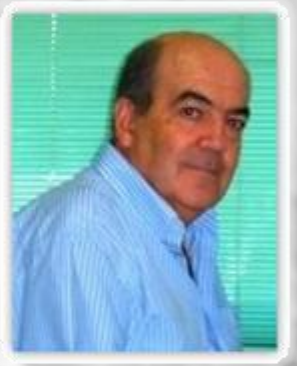
Tomás Ramos


Juan León


Alejandro Valido


Diego G. Olivares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