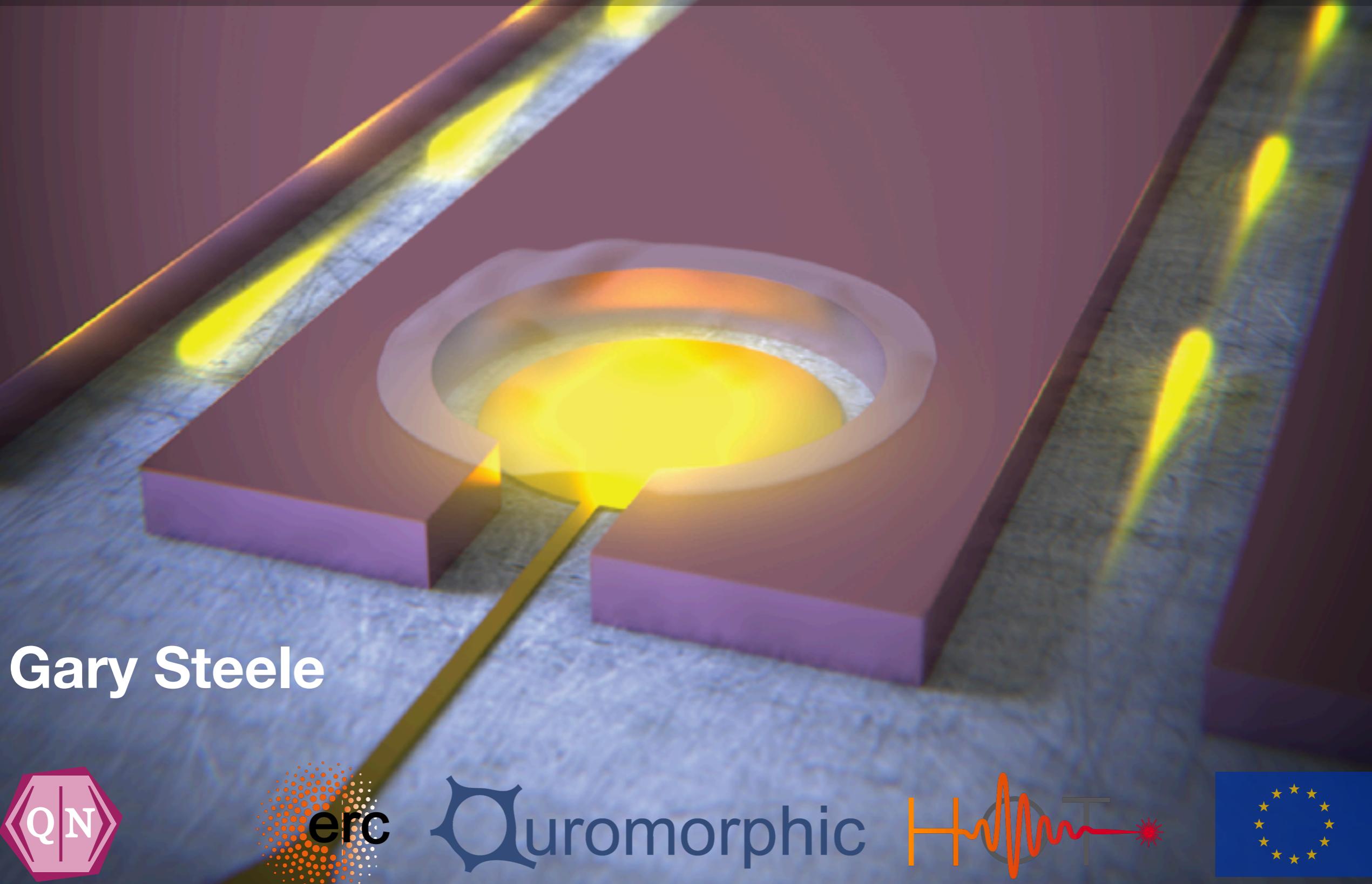
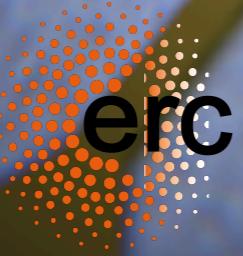


Quantum Circuits and Mechanics

For Quantum Sensing and Simulation



Gary Steele



Quromorphic



Quantum Nanoscience in Delft



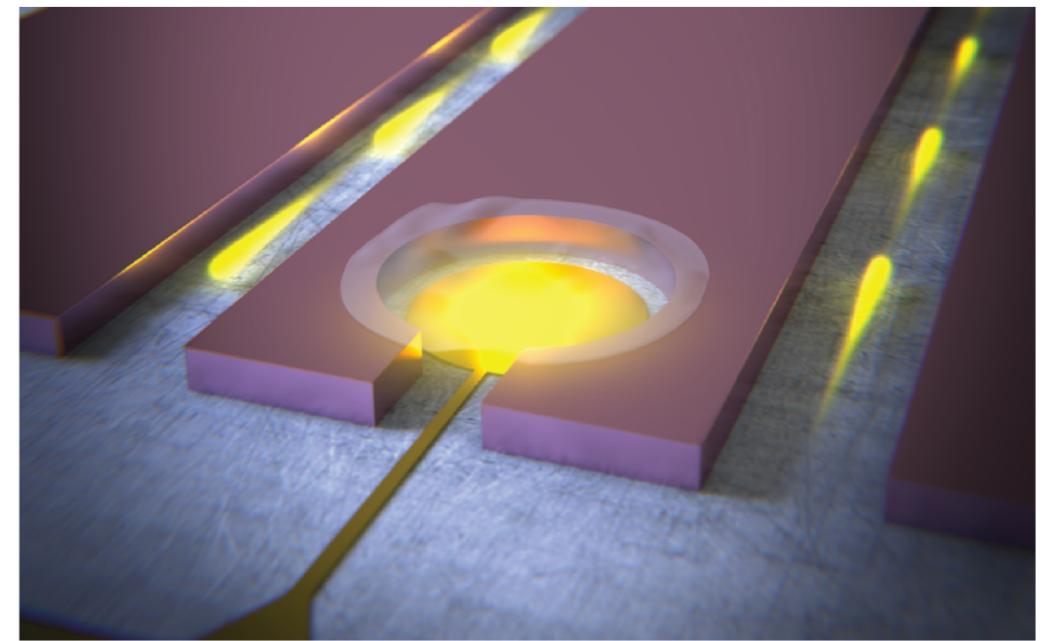
Department of Quantum Nanoscience

Opening the quantum world for innovation

We are hiring, Tenure Track and Senior



TUDelft



Quantum MATTER

Quantum SENSING

Quantum TRANSDUCTION

qn.tudelft.nl

A growing quantum community



Quantum Delta
the Netherlands

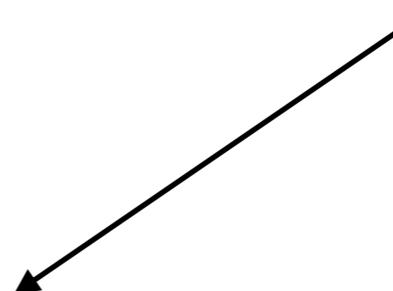


Quantum Delft
Ecosystem for innovation

Quantum Science



QuTech



Quantum Industry



SINGLE QUANTUM



Microsoft



Orange Quantum Systems



°BLUE FORS

My group

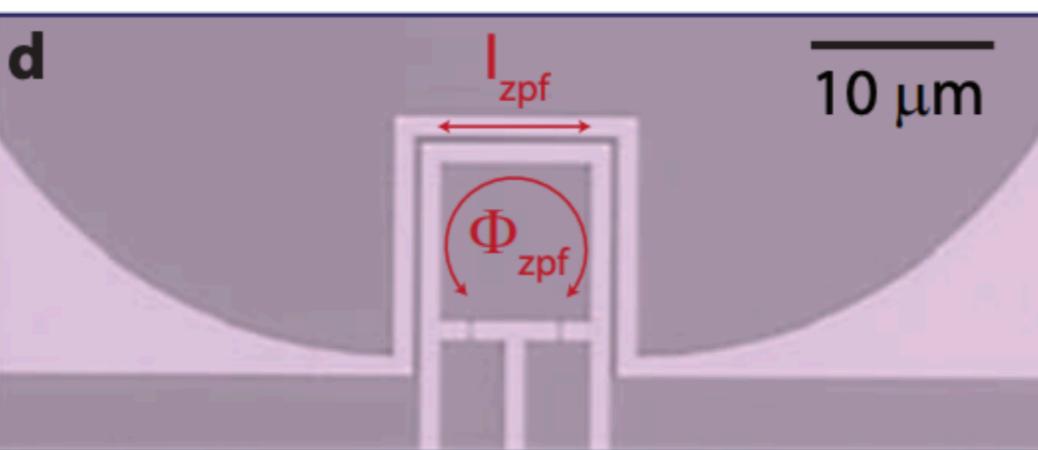
Quantum Sensing



\hbar

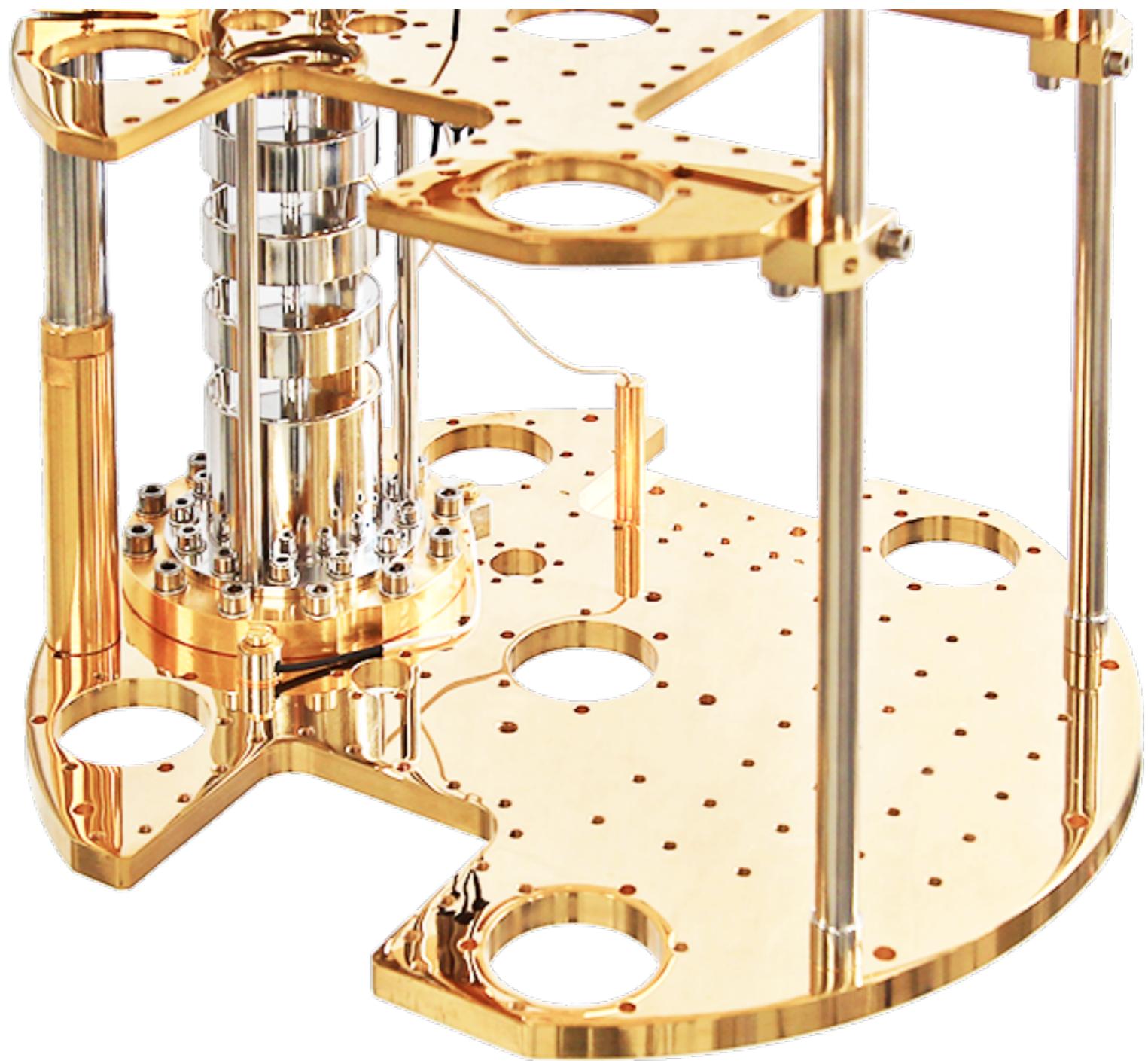
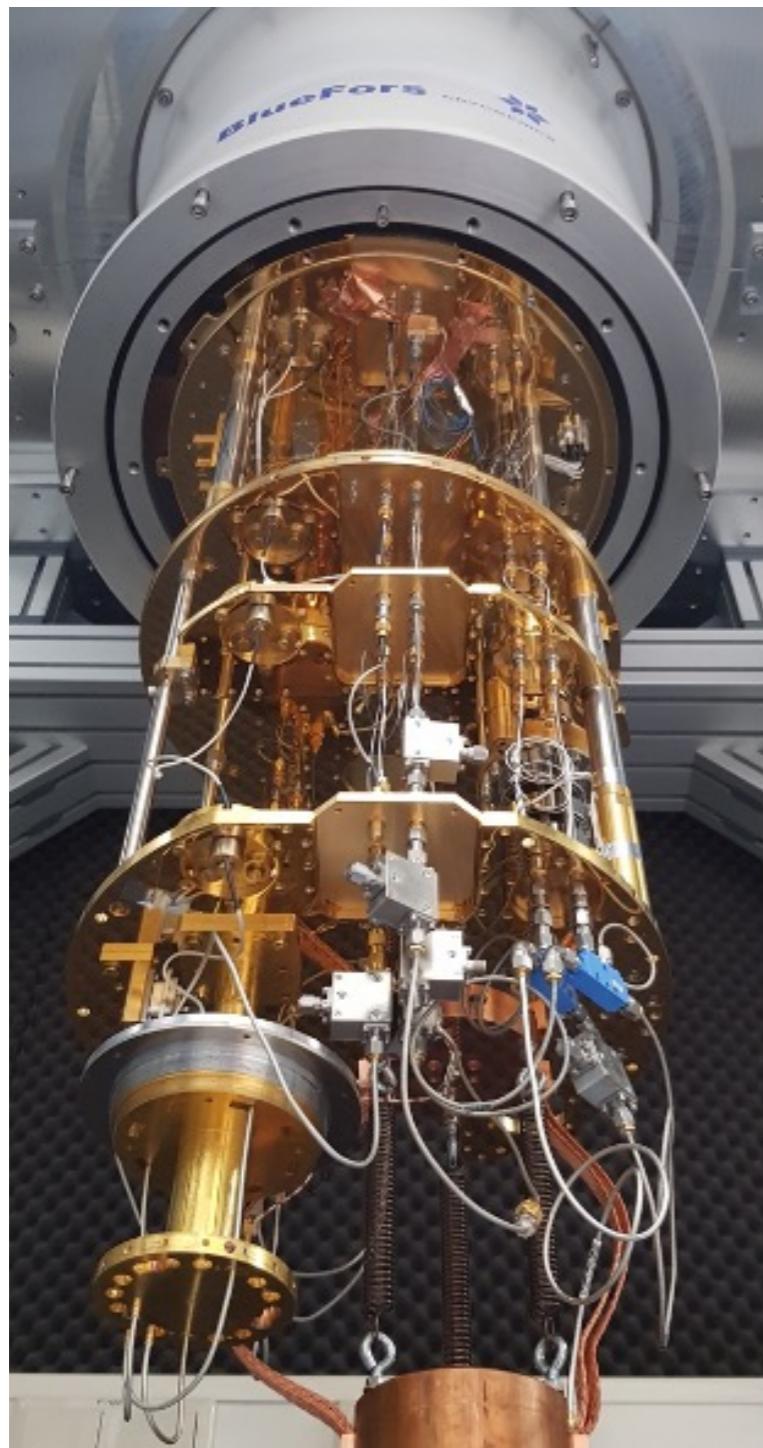
Quantum Simulation

$\hat{\mathcal{H}}$

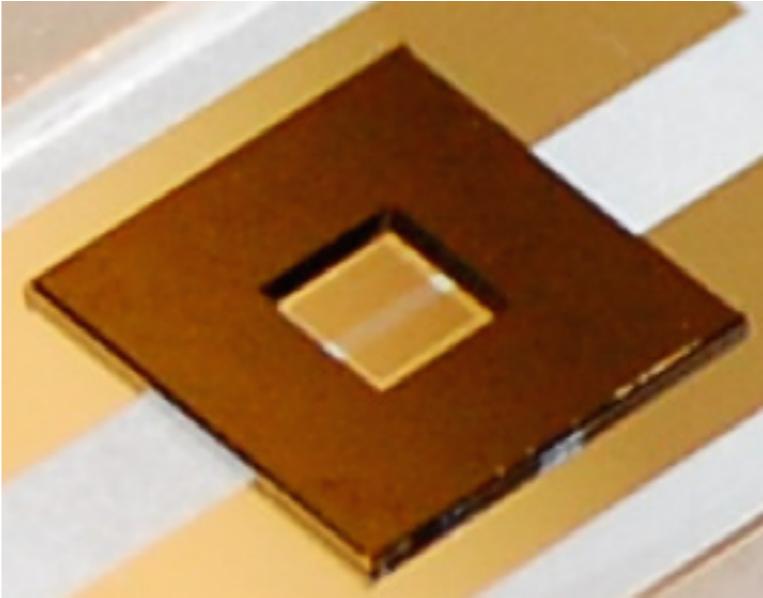
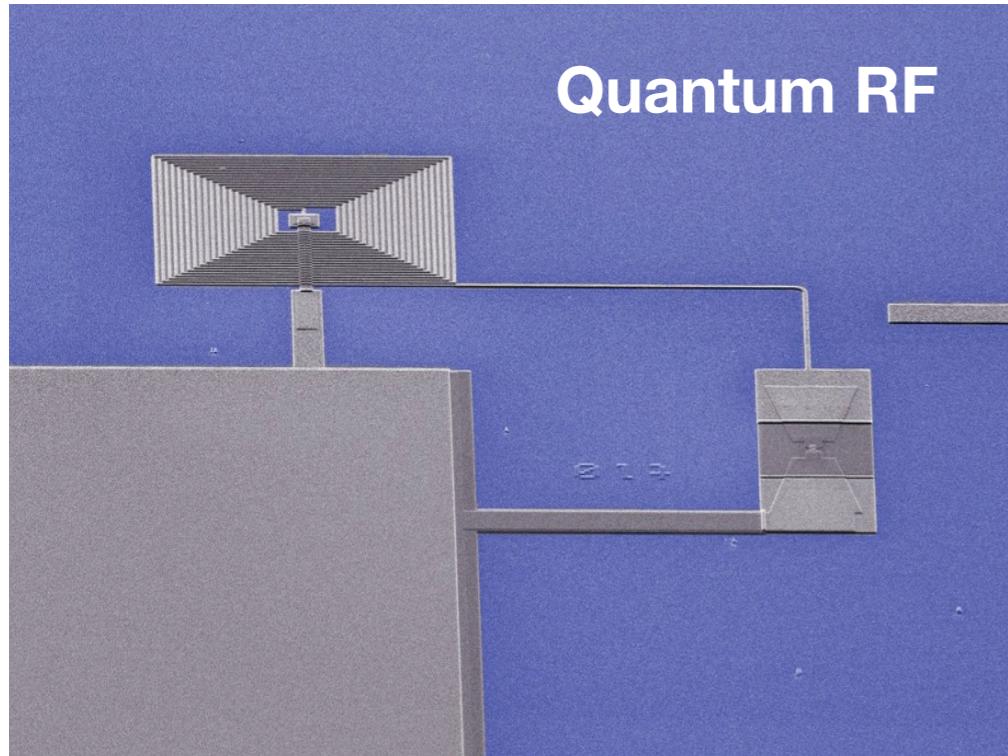


Superconducting circuits

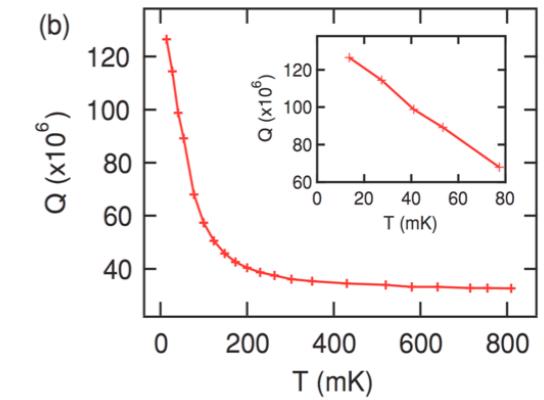
What it looks like



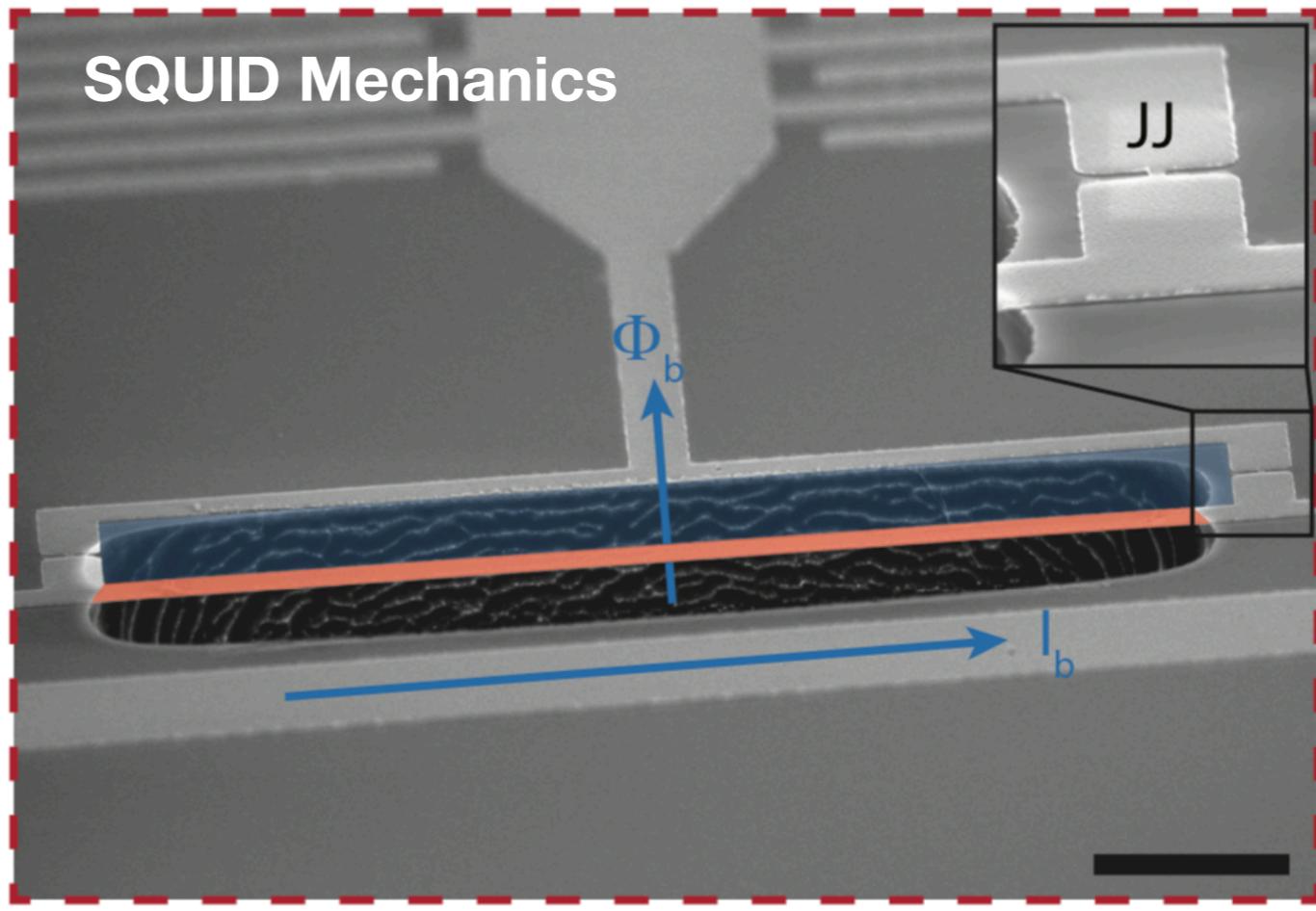
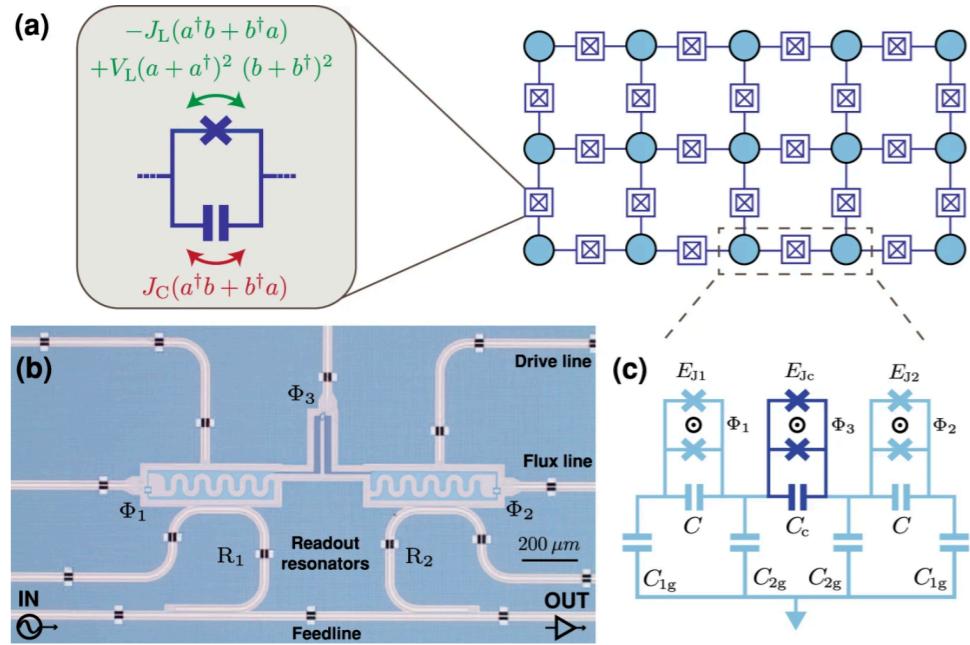
Devices we make



Ultracoherent mK Mechanics



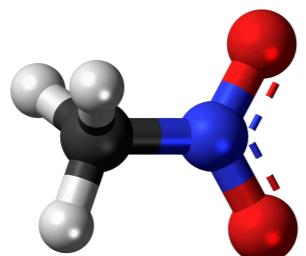
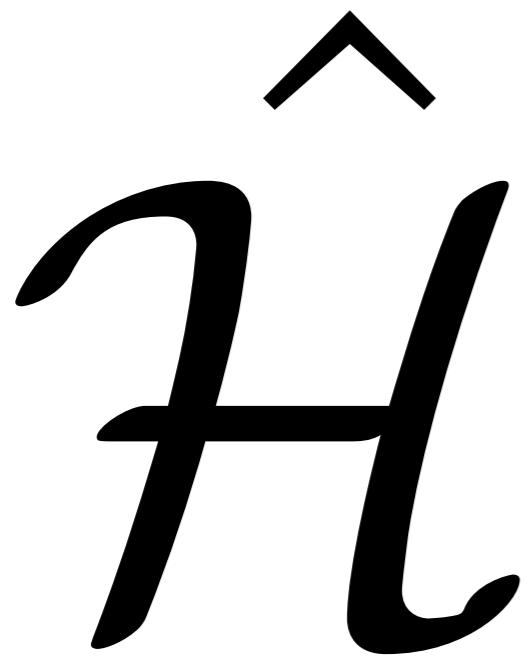
Tunable Qubit Couplers



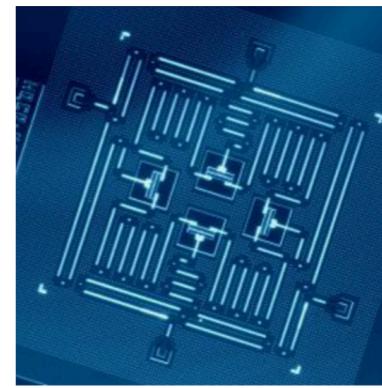
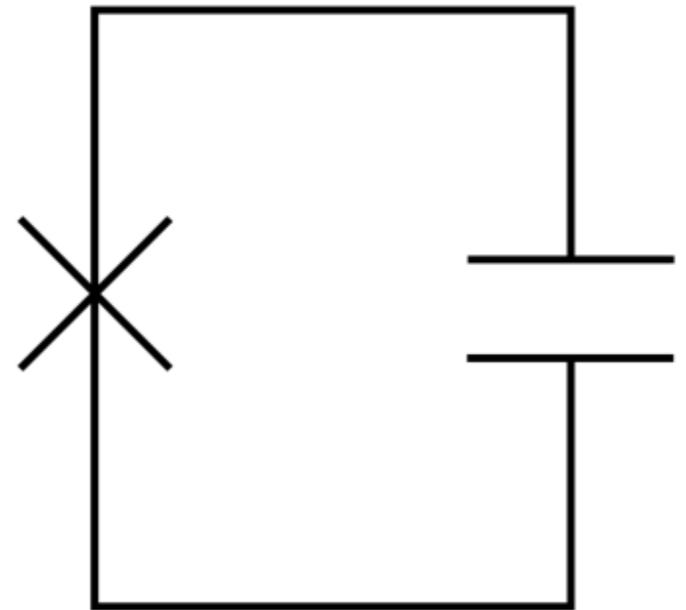
Quantum Simulation

If can't calculate it, make it?

Problem to solve

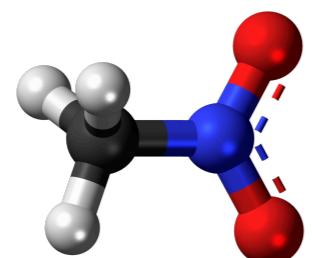
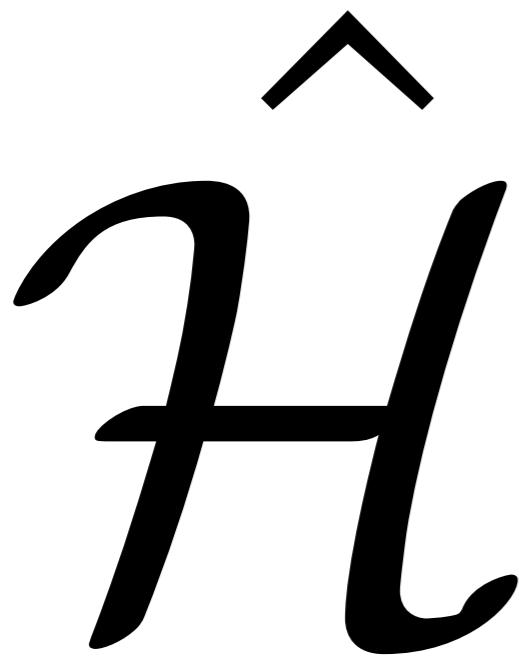


Hardware you have



If can't calculate it, make it?

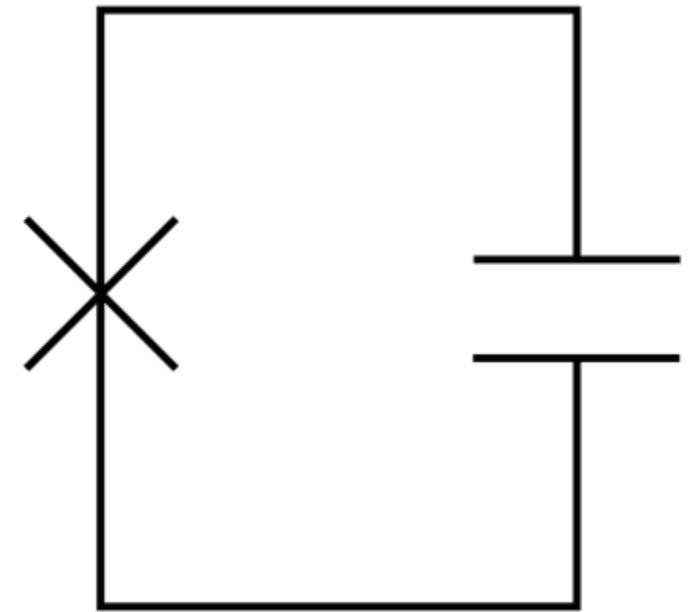
Problem to solve



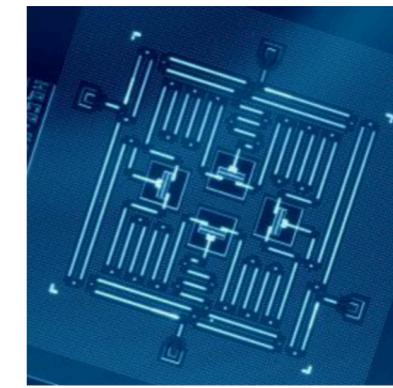
Encode in gates

Digital Simulation

Hardware you have



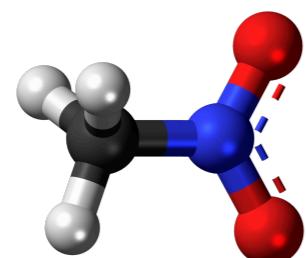
Approximate as qubit



If can't calculate it, make it?

Problem to solve Analog Simulation Hardware you have

$\hat{\mathcal{H}}$



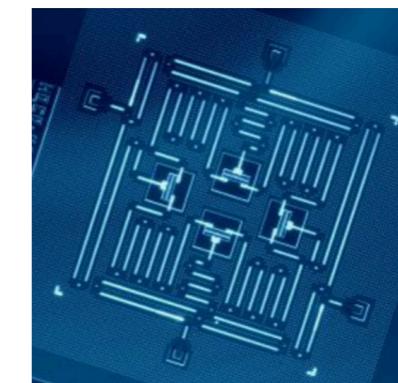
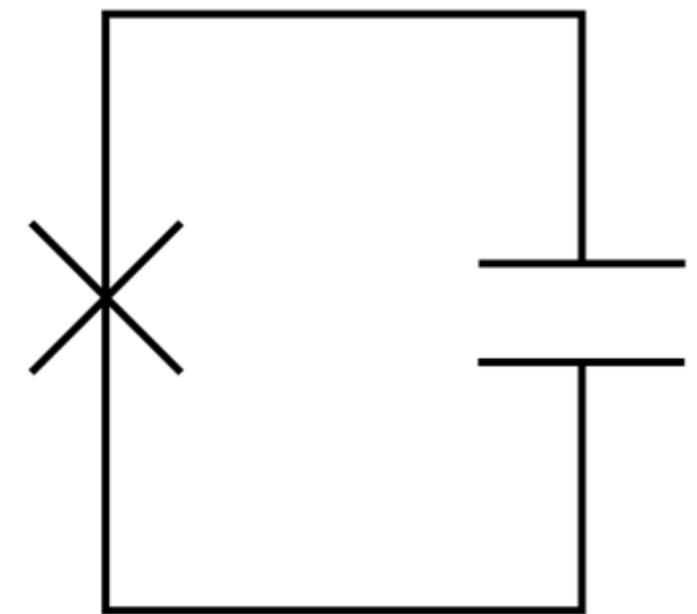
Encode in gates

Digital Simulation

Analog Simulation

Try to build
 $\hat{\mathcal{H}}$ in hardware

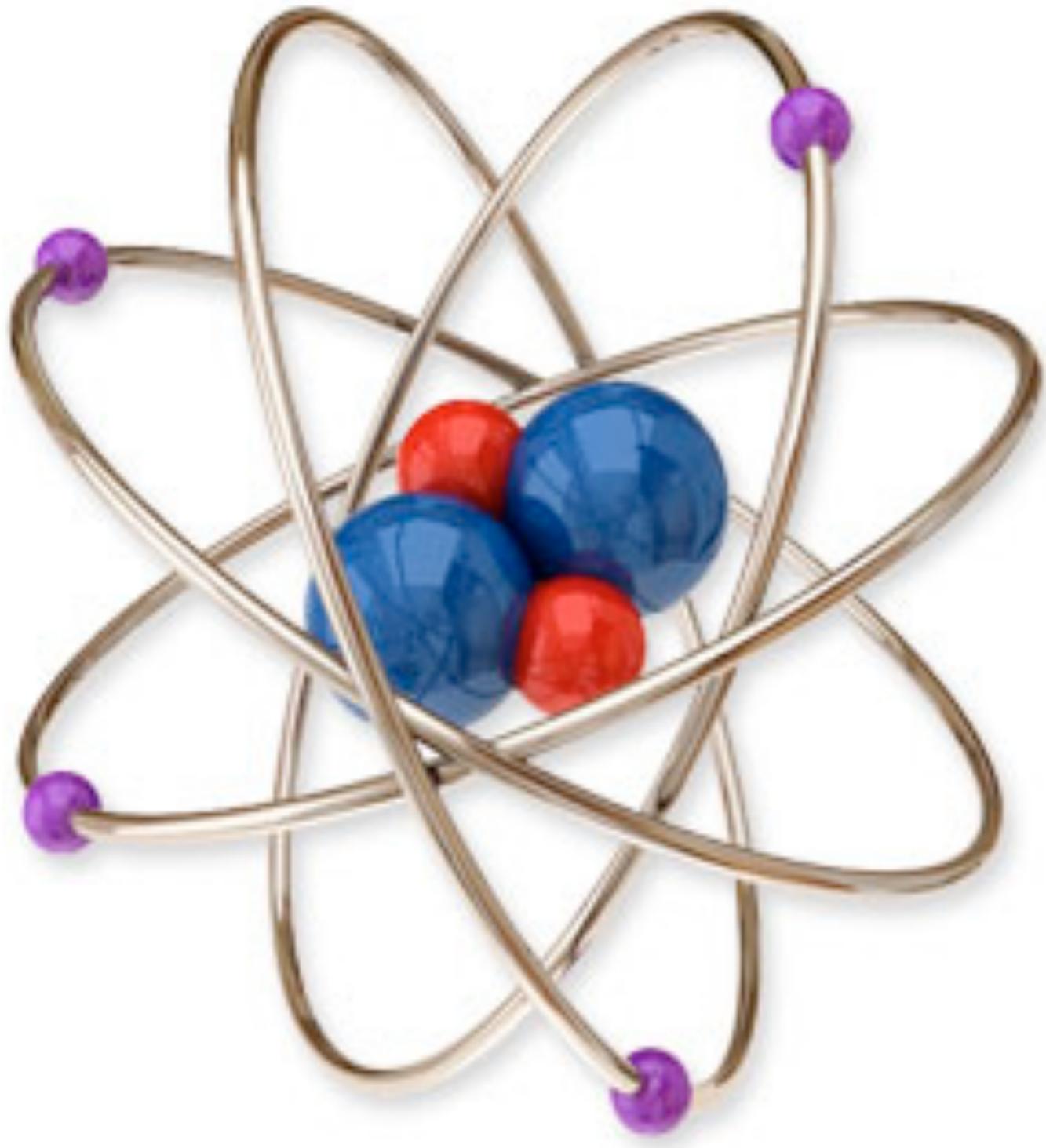
Approximate as qubit



Quantum Sensing

What is it and why would I want it?

What is quantum sensing?



A working definition:

“sensing with something quantum”

What is “quantum”?

Atoms are quantum

Photons are (probably) quantum?

Is light quantum?

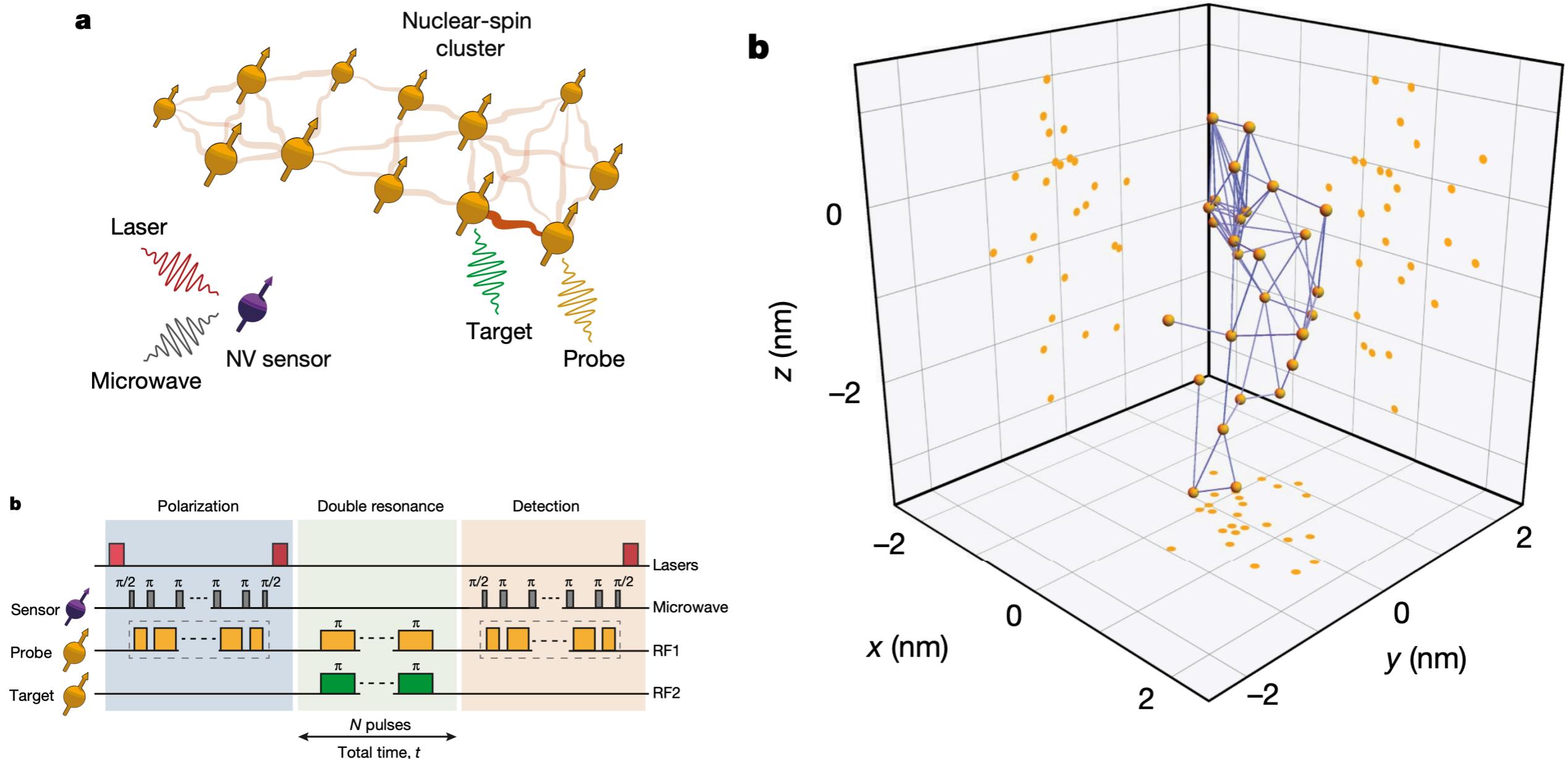
Am I quantum?

Maybe a better question:

Is “quantum” useful for sensing?

Is it better than “classical”?

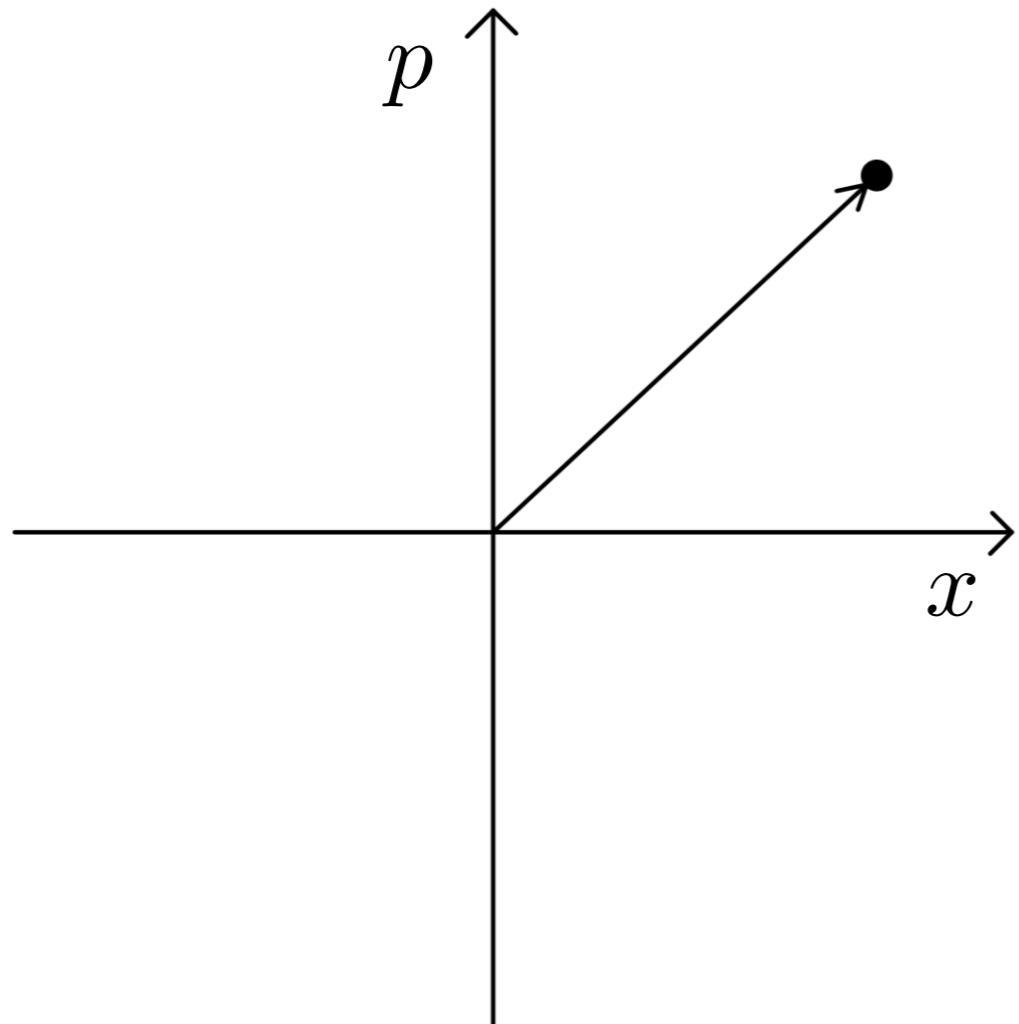
Example “Sensing with Quantum Stuff”



Atomic-scale imaging of a 27-nuclear-spin cluster using a quantum sensor
M. H. Abobeih, ..., T. H. Taminiau, *Nature* 576, 411–415 (2019)

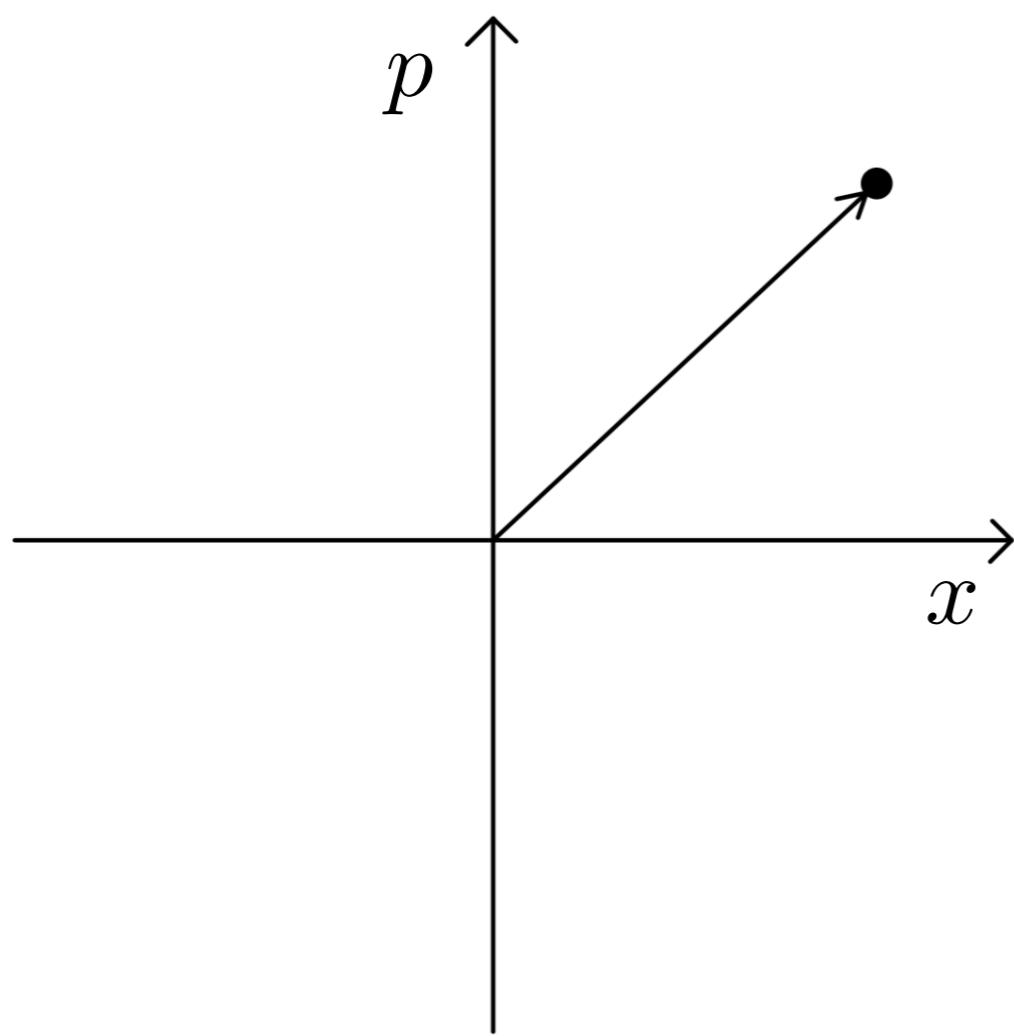
**But: is there a sensing
“quantum advantage”?**

Sensing better than classical?



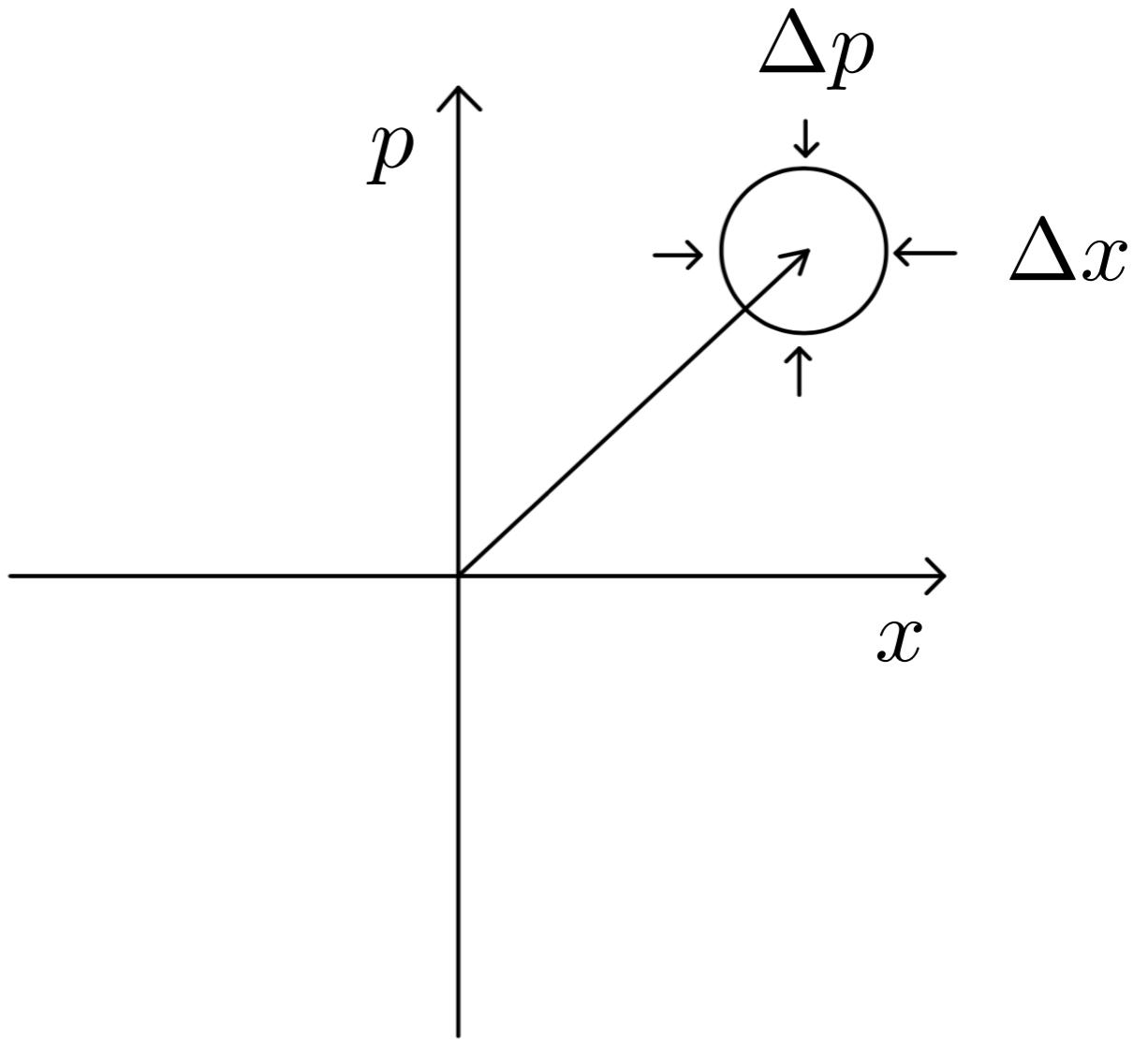
Particle in 1D

Sensing better than classical?



Classical:

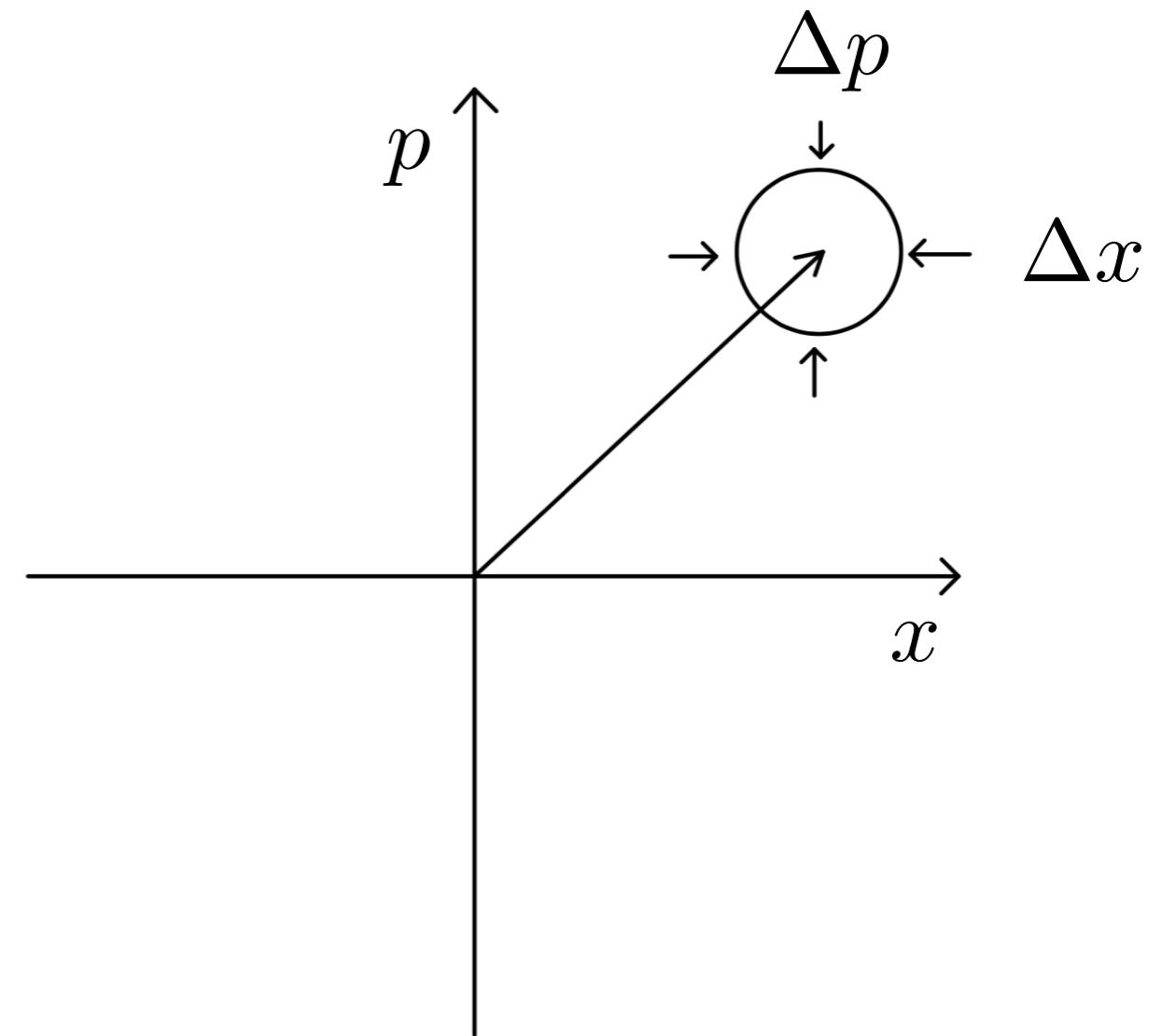
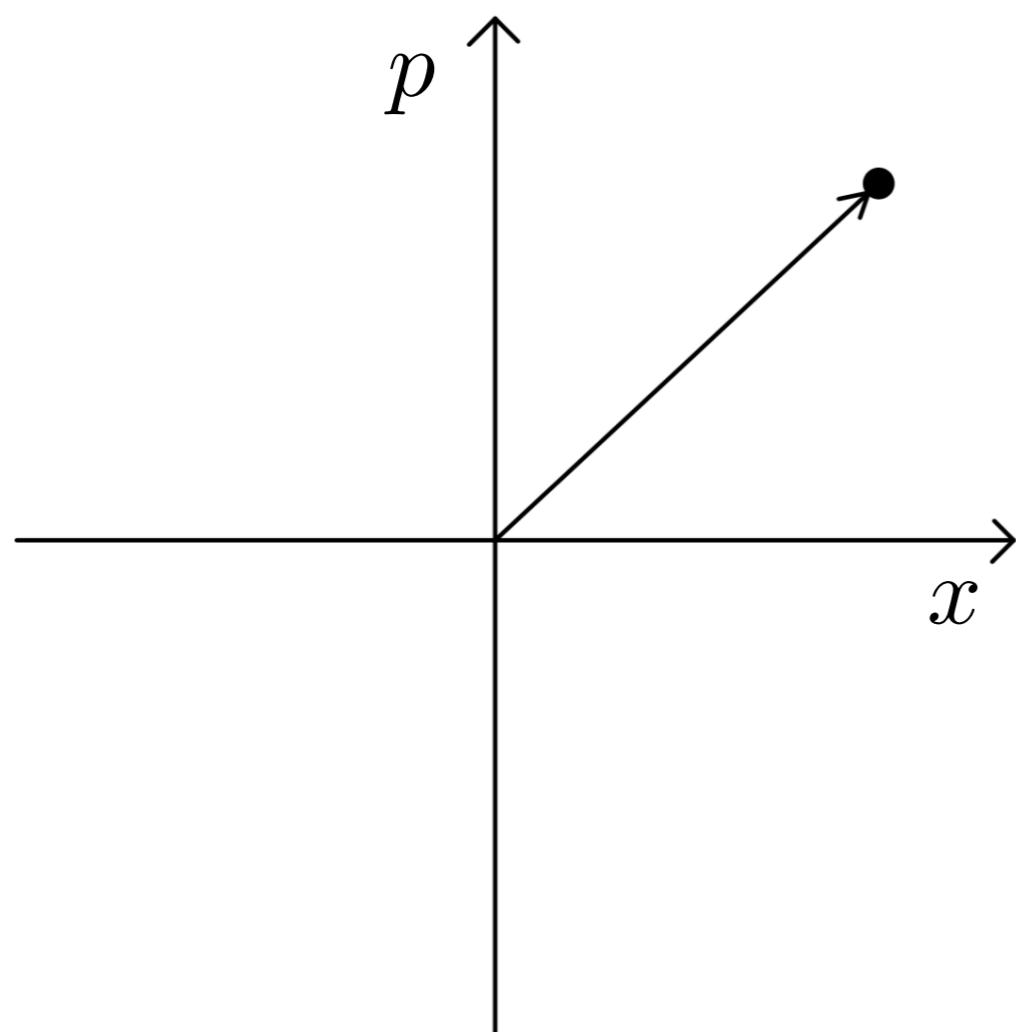
$$\Delta x \Delta p \geq 0$$



Quantum:

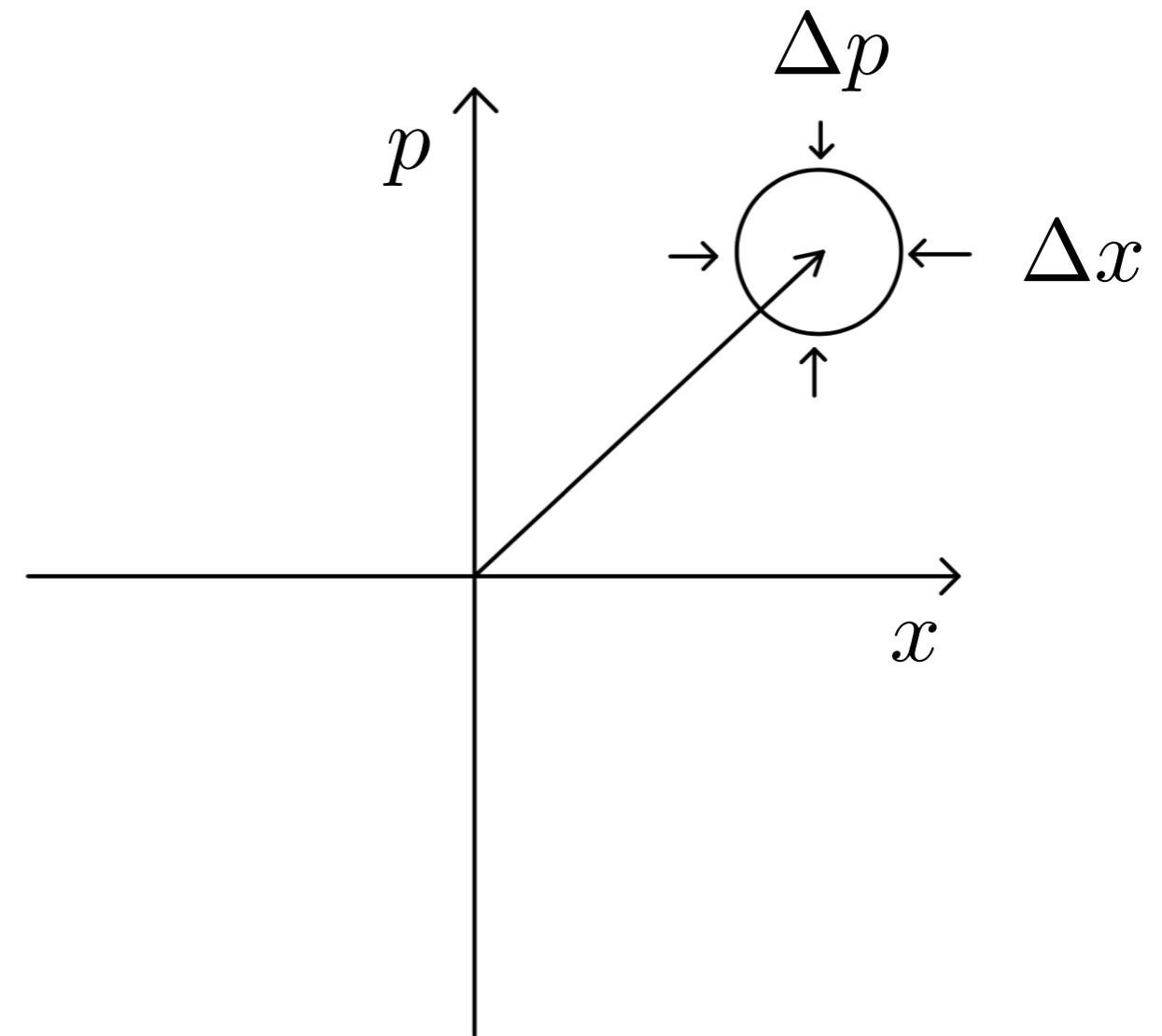
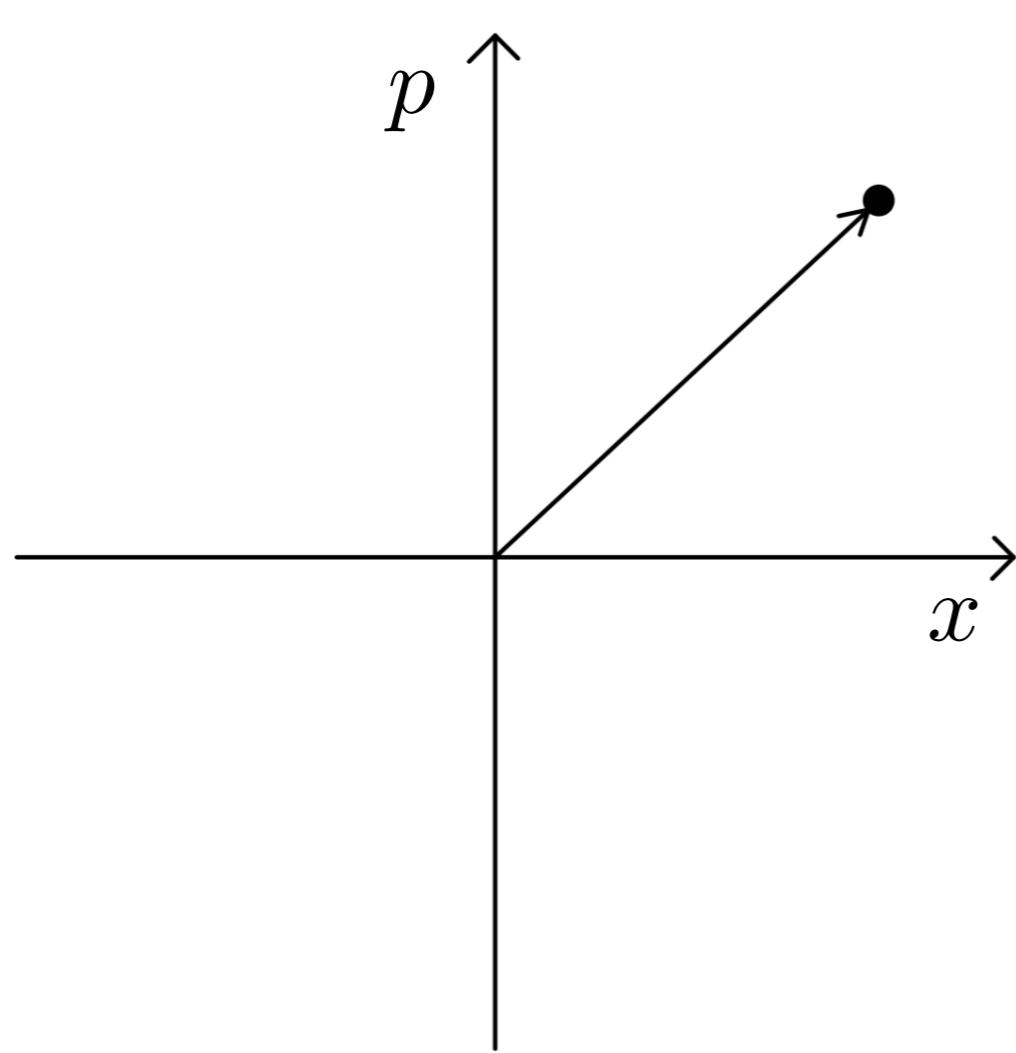
$$\Delta x \Delta p \geq \hbar/2$$

Sensing better than classical?



**Quantum Sensing is always *fundamentally*
worse than classical sensing!**

Sensing better than classical?

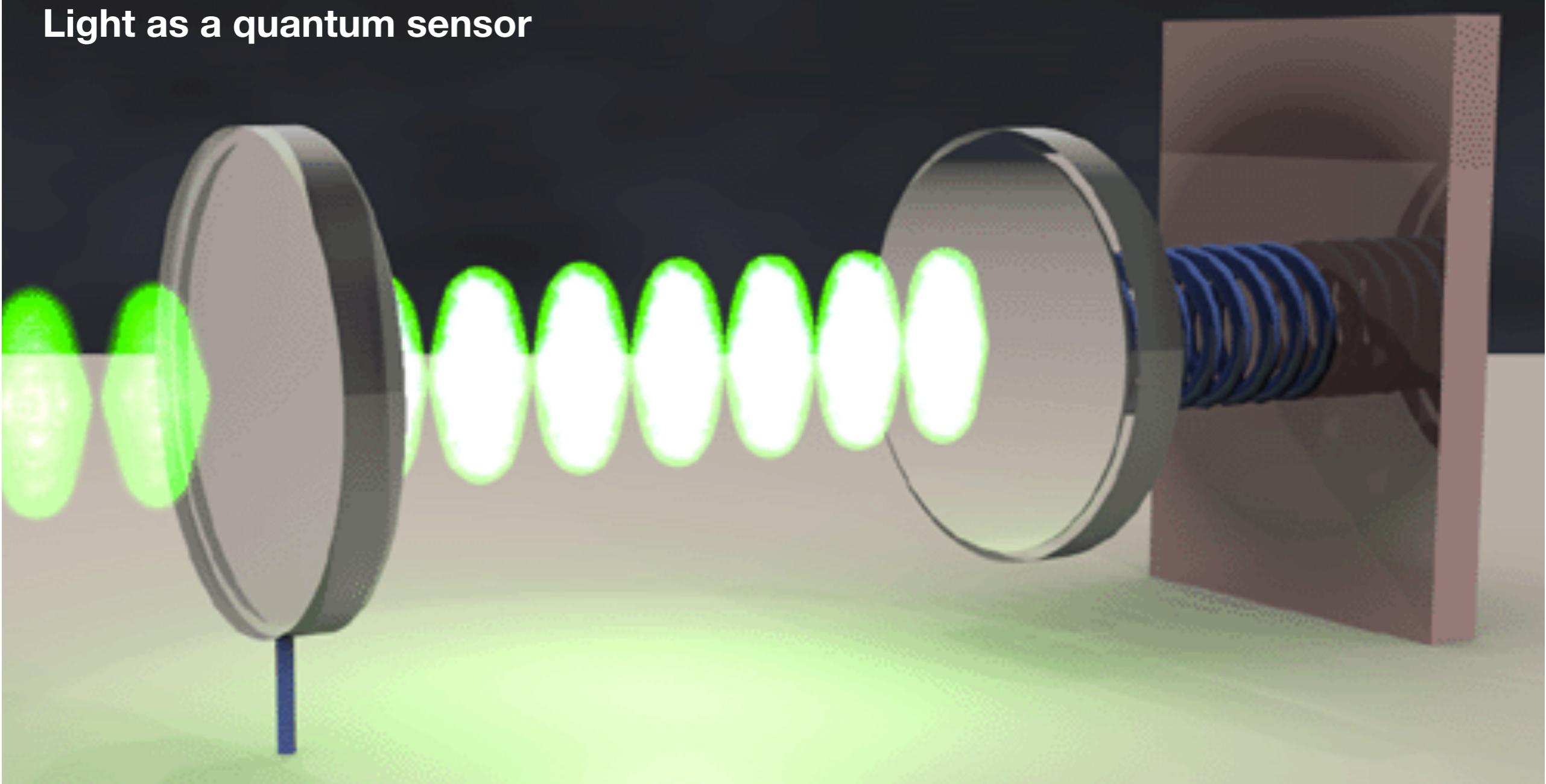


Quantum Sensing is always *fundamentally* worse than classical sensing!

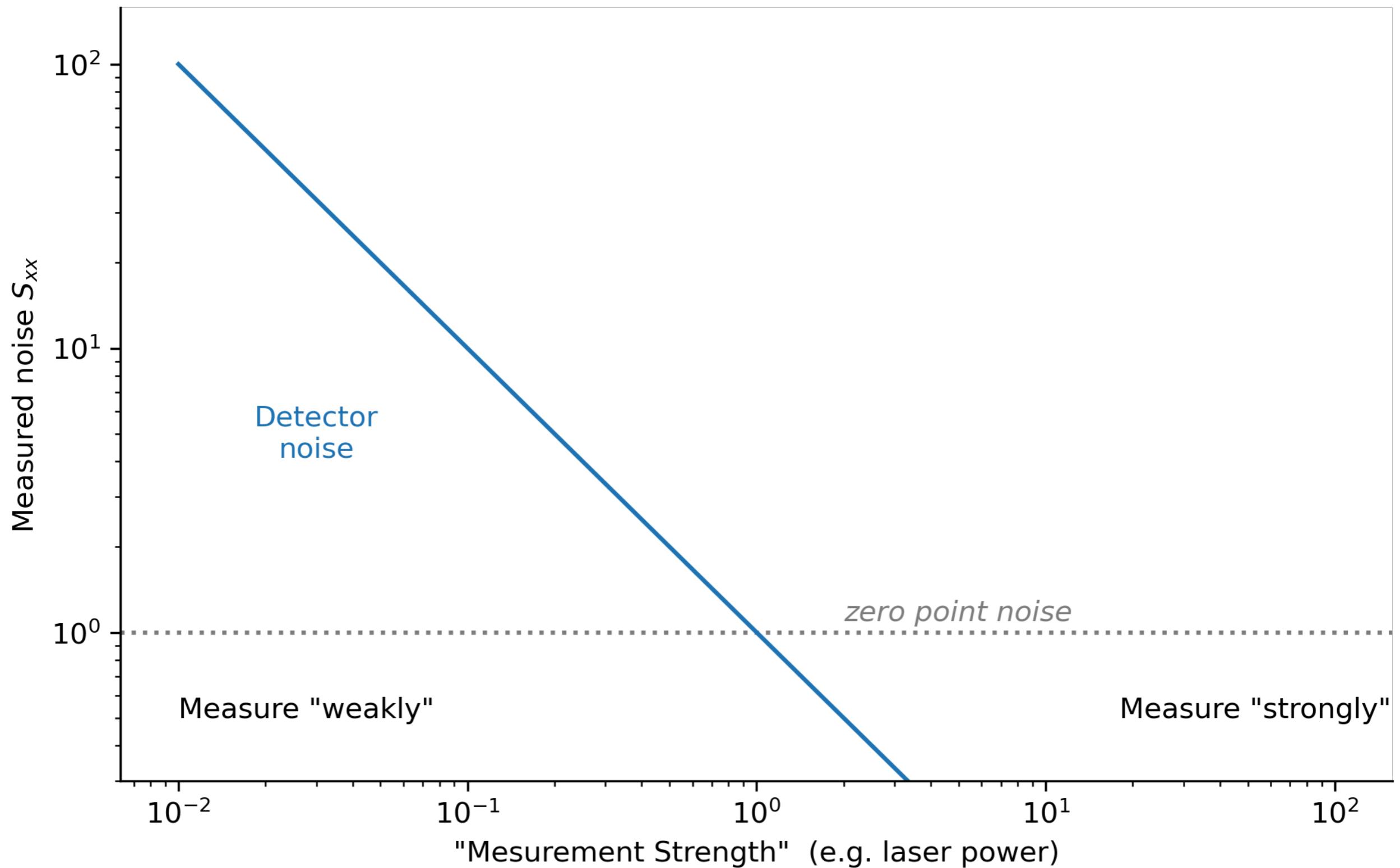
But sensing at the quantum limit is already challenging and can be exciting!

Example: Optomechanics

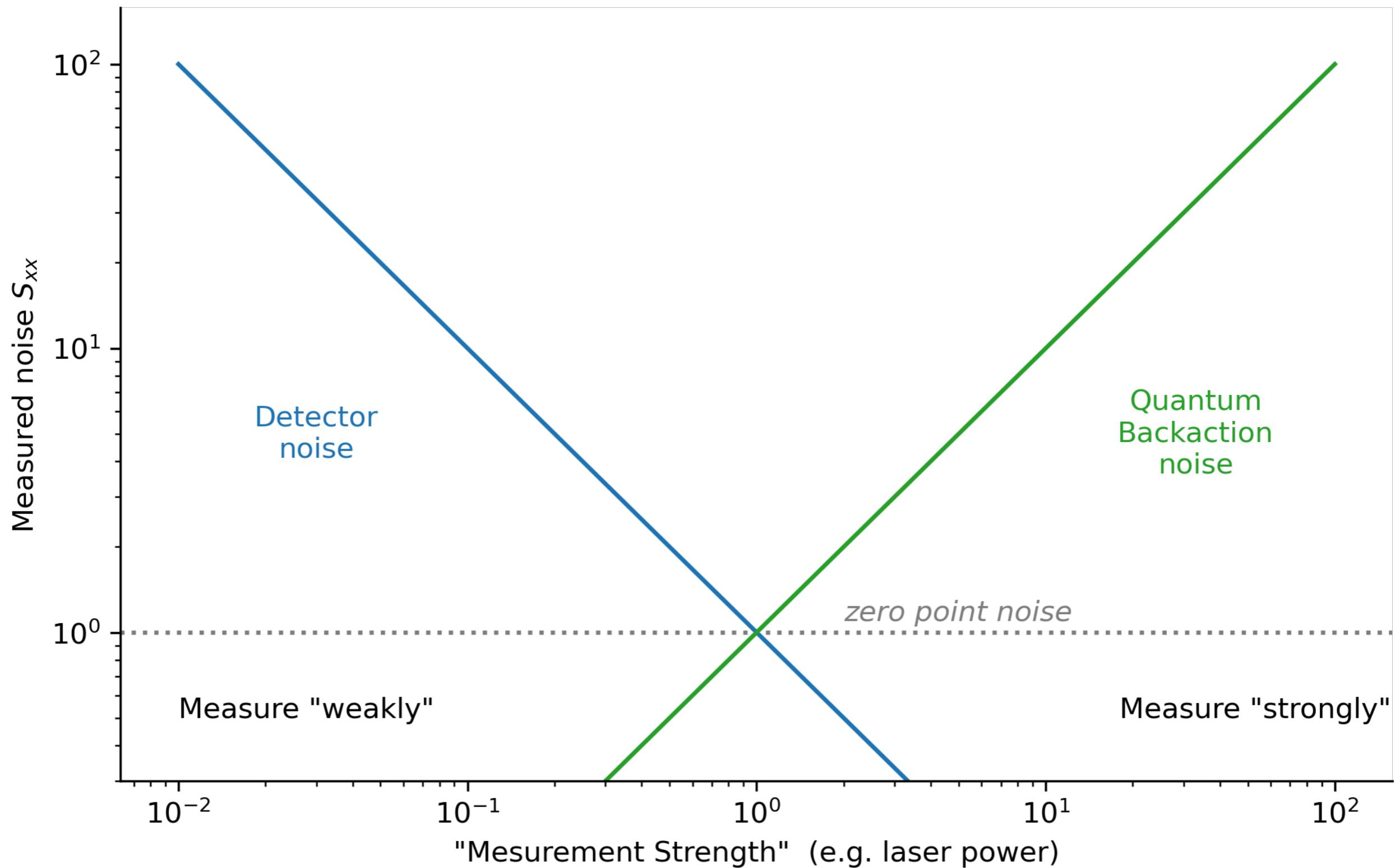
Light as a quantum sensor



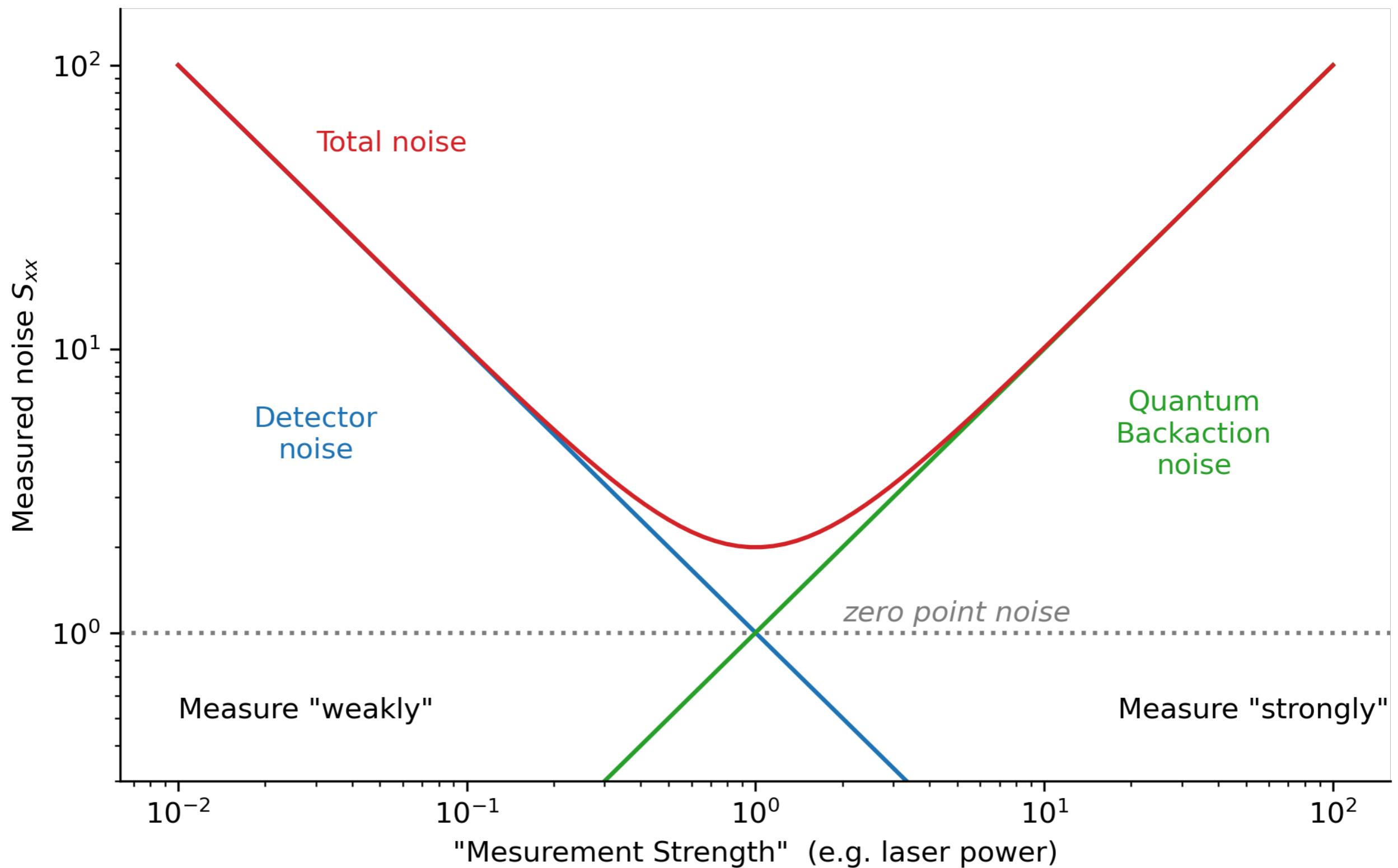
Standard Quantum Limit



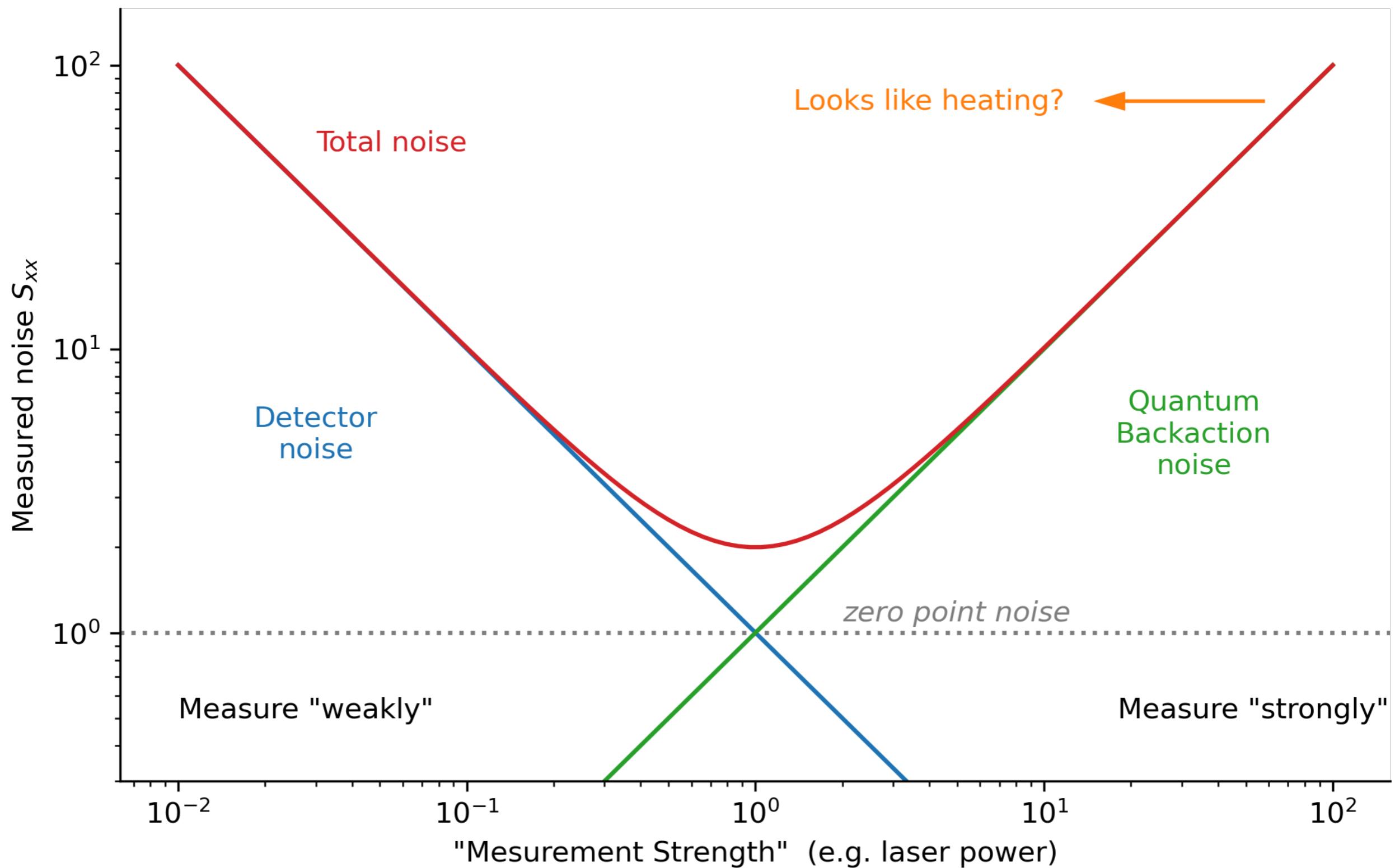
Standard Quantum Limit



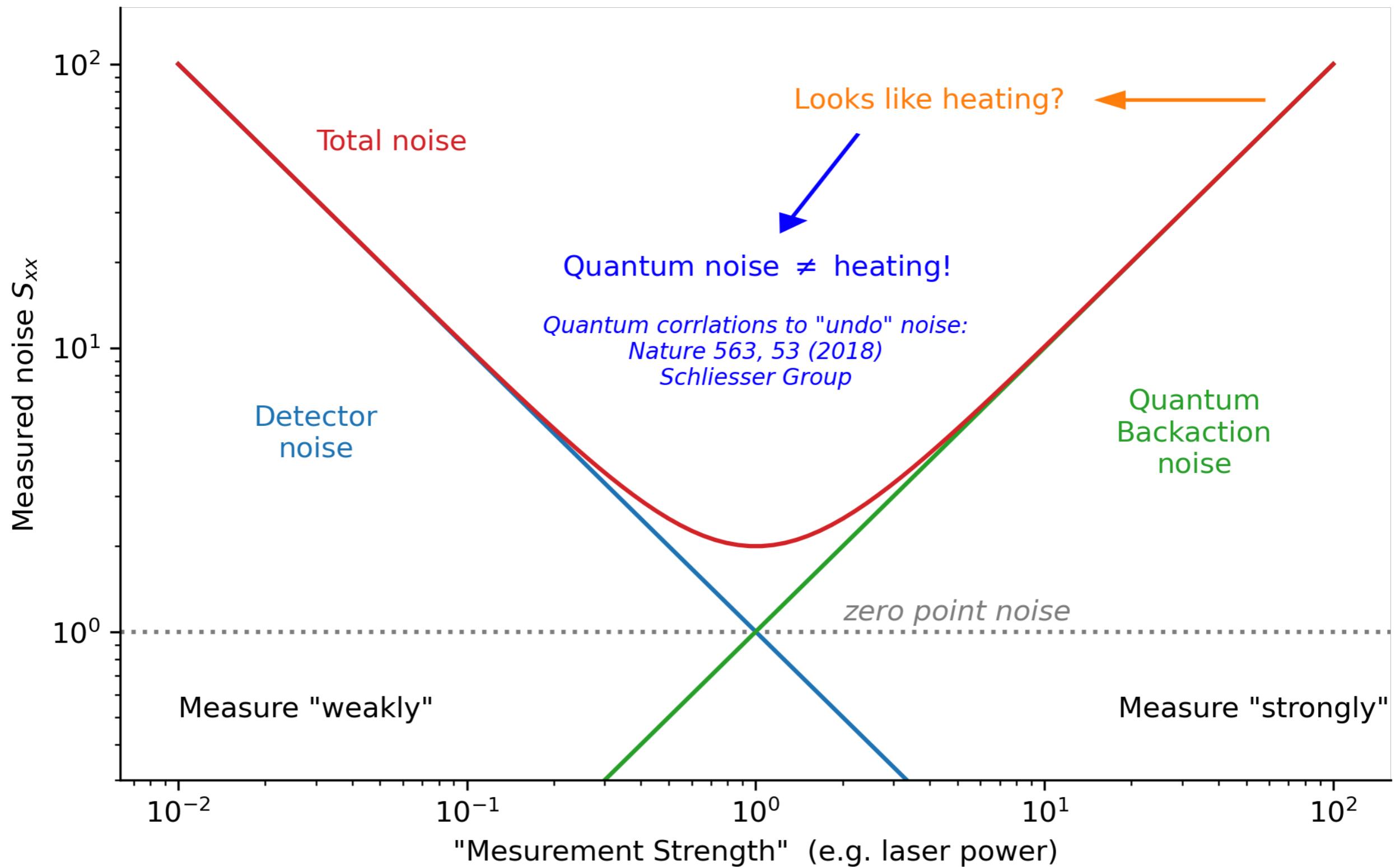
Standard Quantum Limit



Standard Quantum Limit



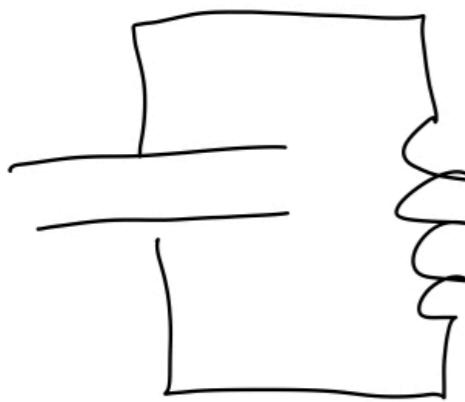
Standard Quantum Limit



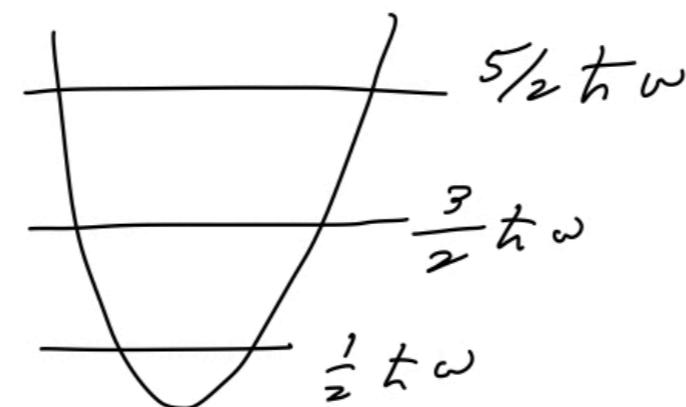
Superconducting Circuits 101

**Building Photons, Atoms, and Quantum Amplifiers
on a chip**

Photons



$$\frac{Q}{C} + L \frac{d^2 Q}{dt^2} = 0 \quad E_C = \frac{1}{2} \frac{Q^2}{C} \quad E_L = \frac{1}{2} L I^2$$



\downarrow

QED: \hat{Q} \hat{I}
 \downarrow \downarrow
 \hat{x} \hat{p}

$$[\hat{Q}, \hat{I}] \neq 0$$

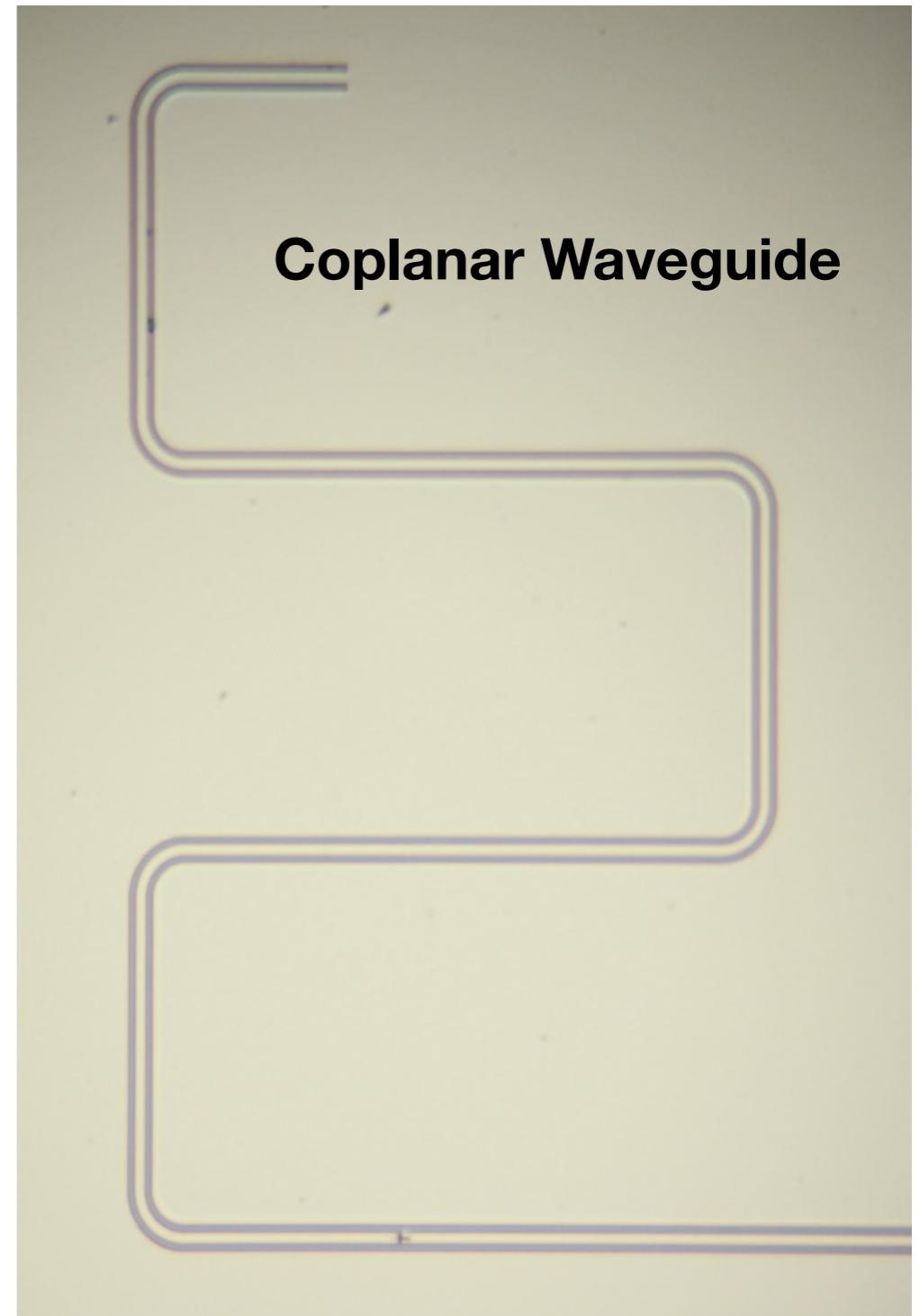
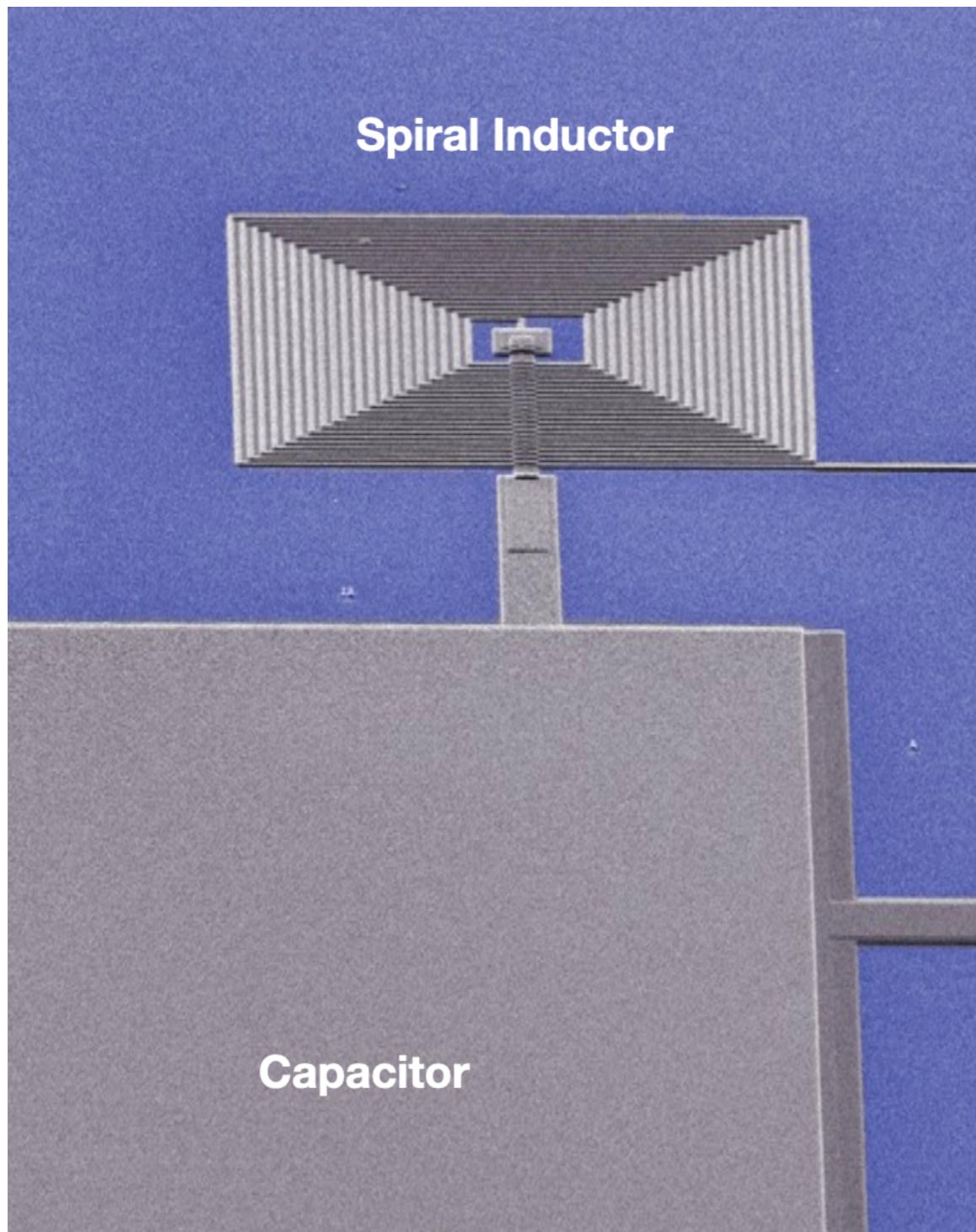
Photons = excitation number
of Le circuit

“Quantum” if:

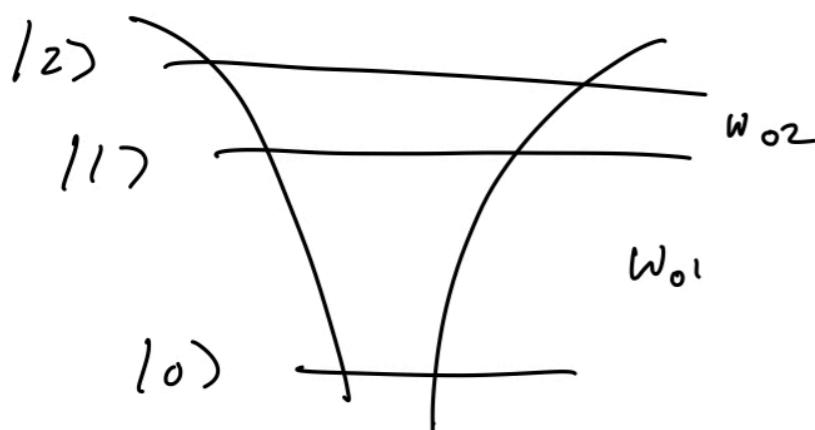
$$\hbar\omega \gg kT$$

1 GHz => 40 mK

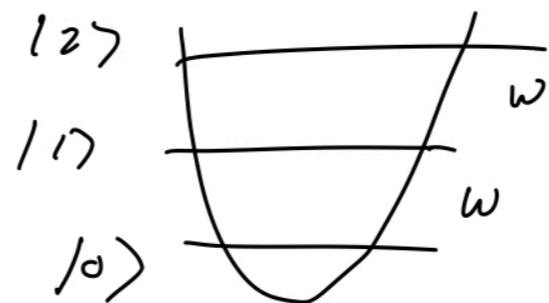
What our photons look like



Atoms



Atom



Harmonic
Oscillator

Atom:

$$\omega_{12} \neq \omega_{01}$$

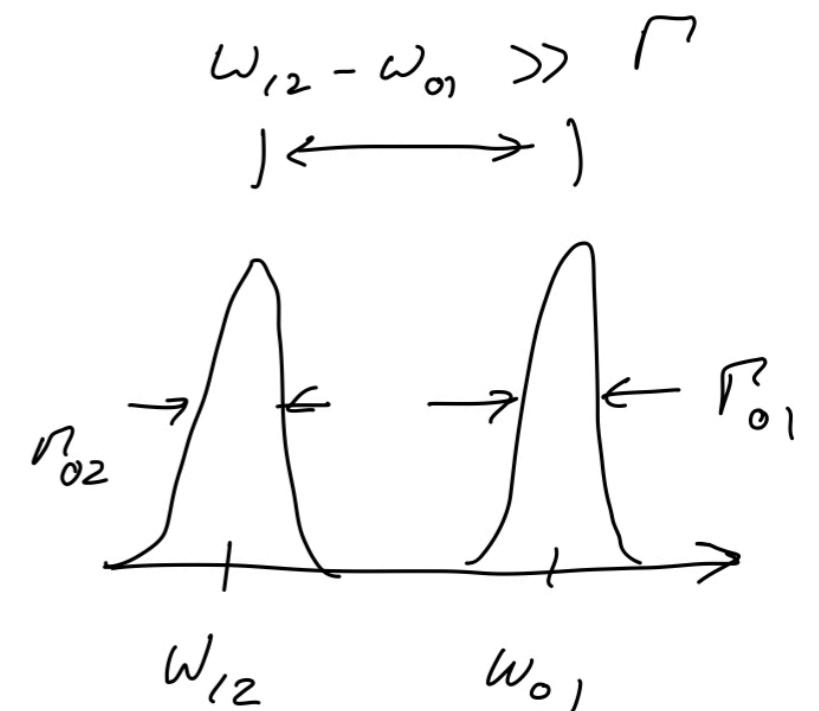
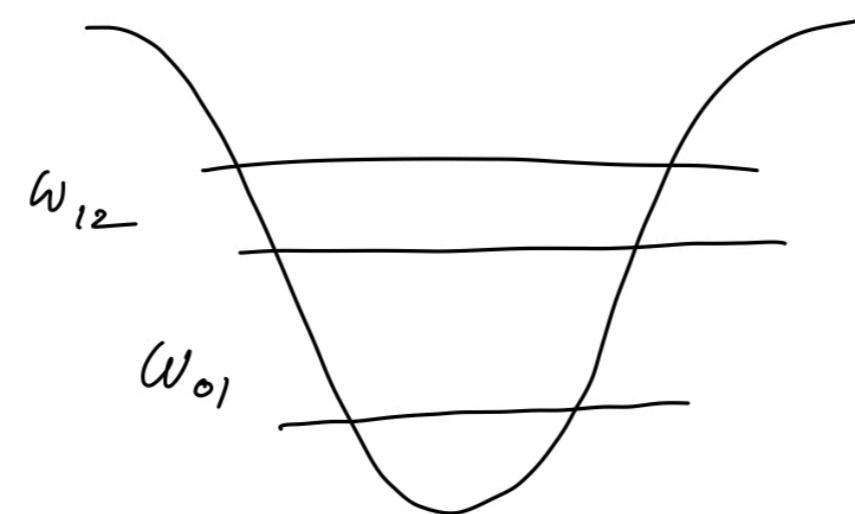
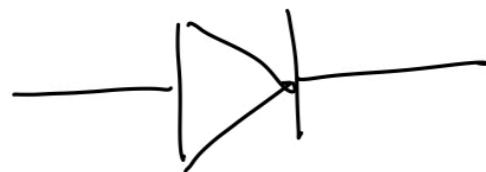
need nonlinearity

How do we get nonlinearity in our circuit?

Nonlinear Circuits?

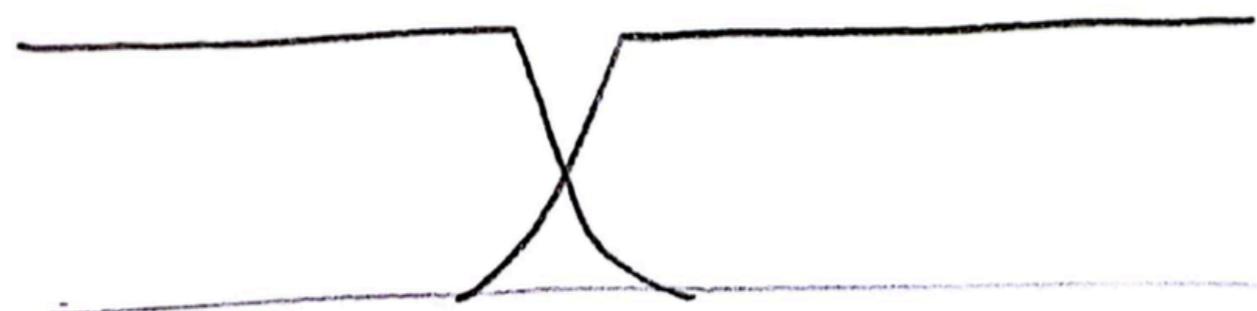
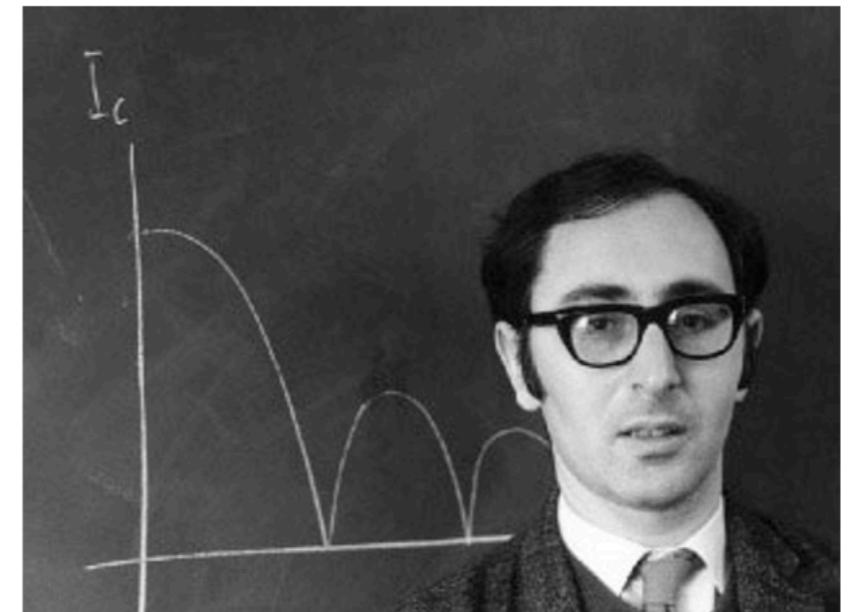
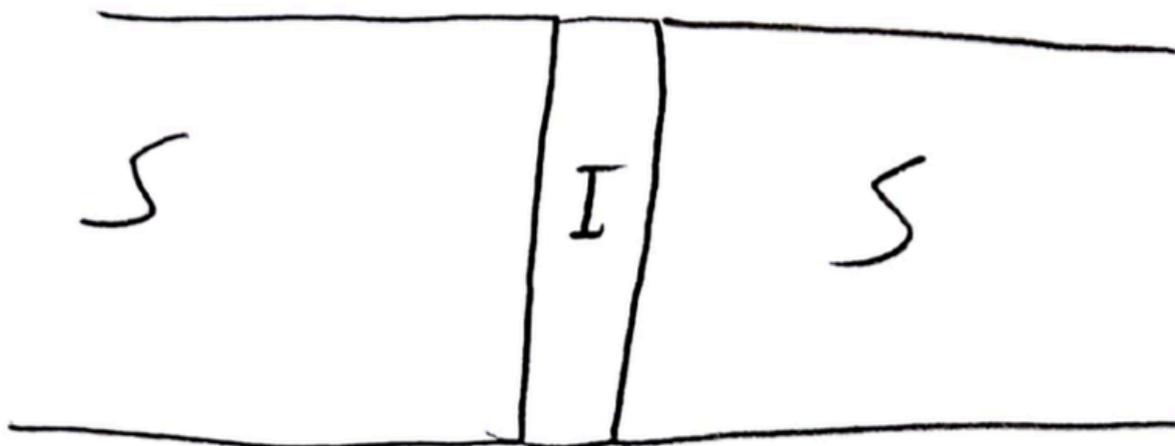


diode ?



Need STRONG nonlinearity with VERY LOW loss!

Josephson Junctions



$$\psi = \rho e^{i\theta_1}$$

$$\psi = \rho e^{i\theta_2}$$

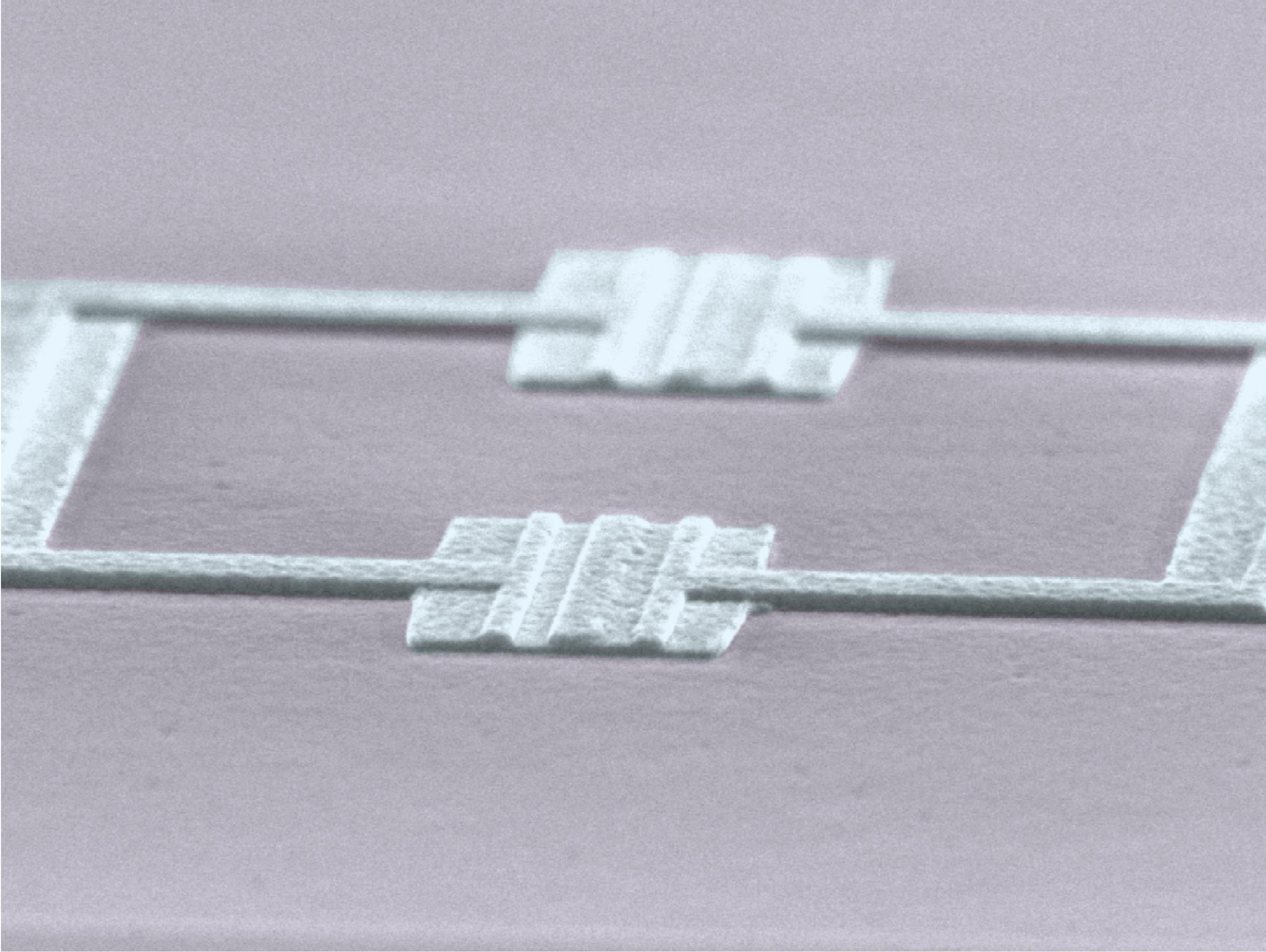
Josephson Relations:

$$I = I_c \sin \phi$$

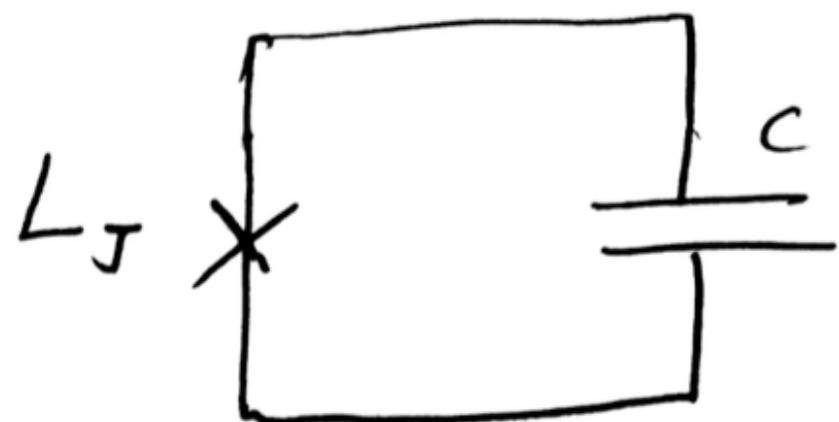
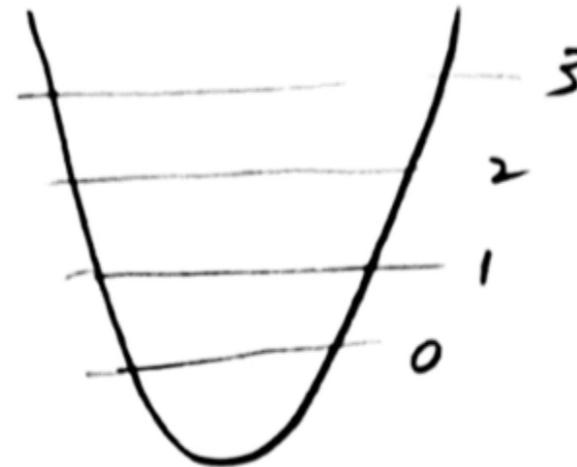
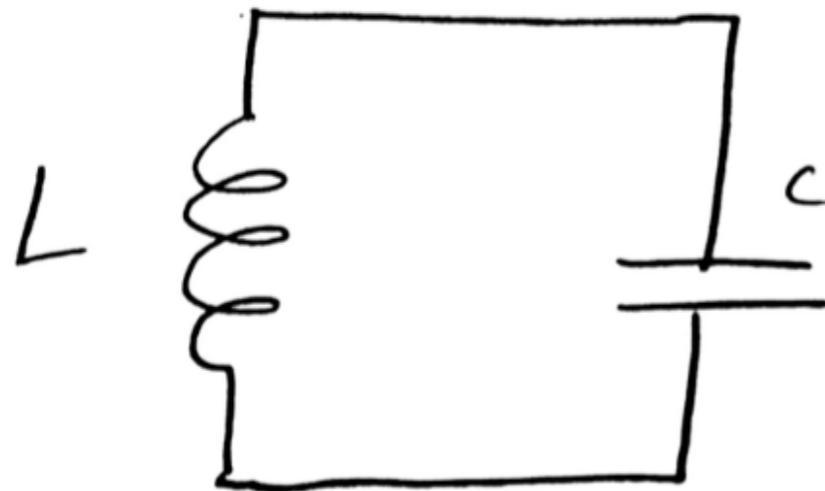
$$V = \frac{h}{2e} \frac{d\phi}{dt}$$

Insulating tunnel barrier between two superconductors

$$\phi = \theta_2 - \theta_1$$



Lossless nonlinear inductor



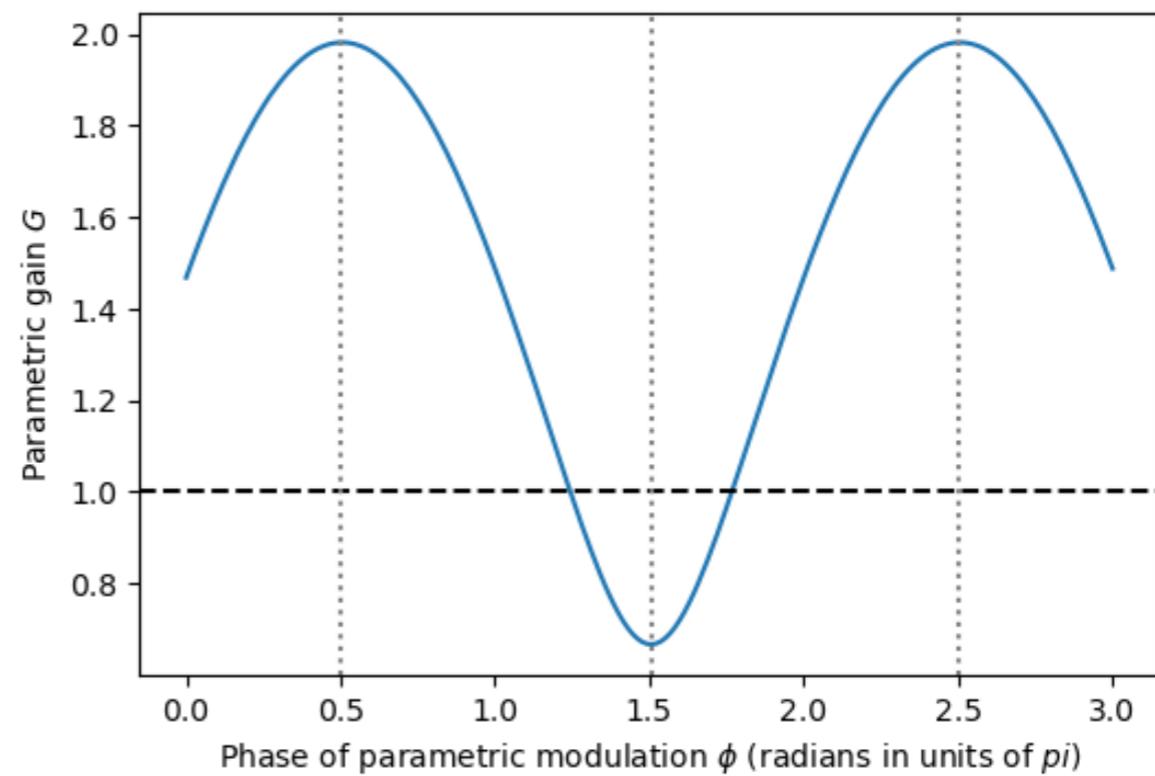
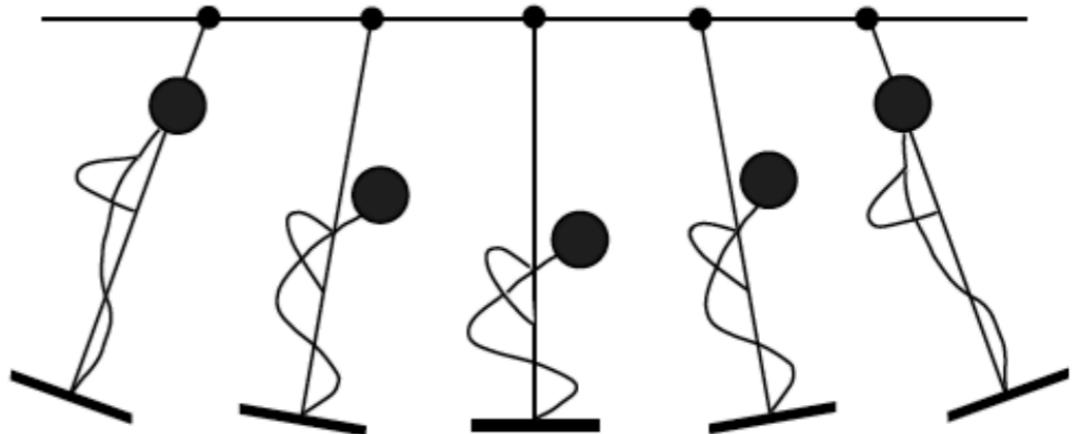
$$\omega_{12} \neq \omega_{01}$$

Quantum Amplifiers

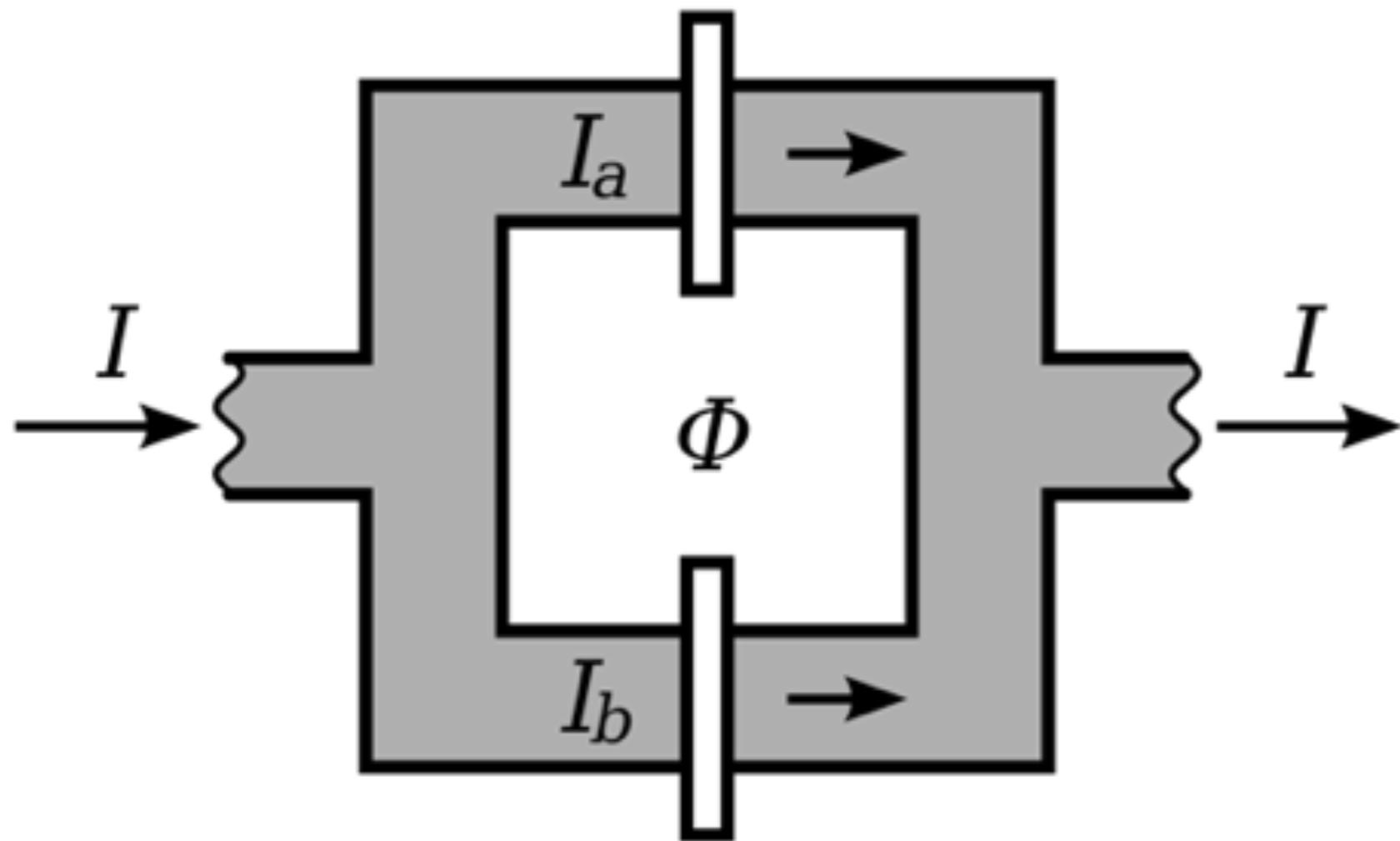
Josephson Junction: quantum pendulum



Swing your legs?



Quantum Interference

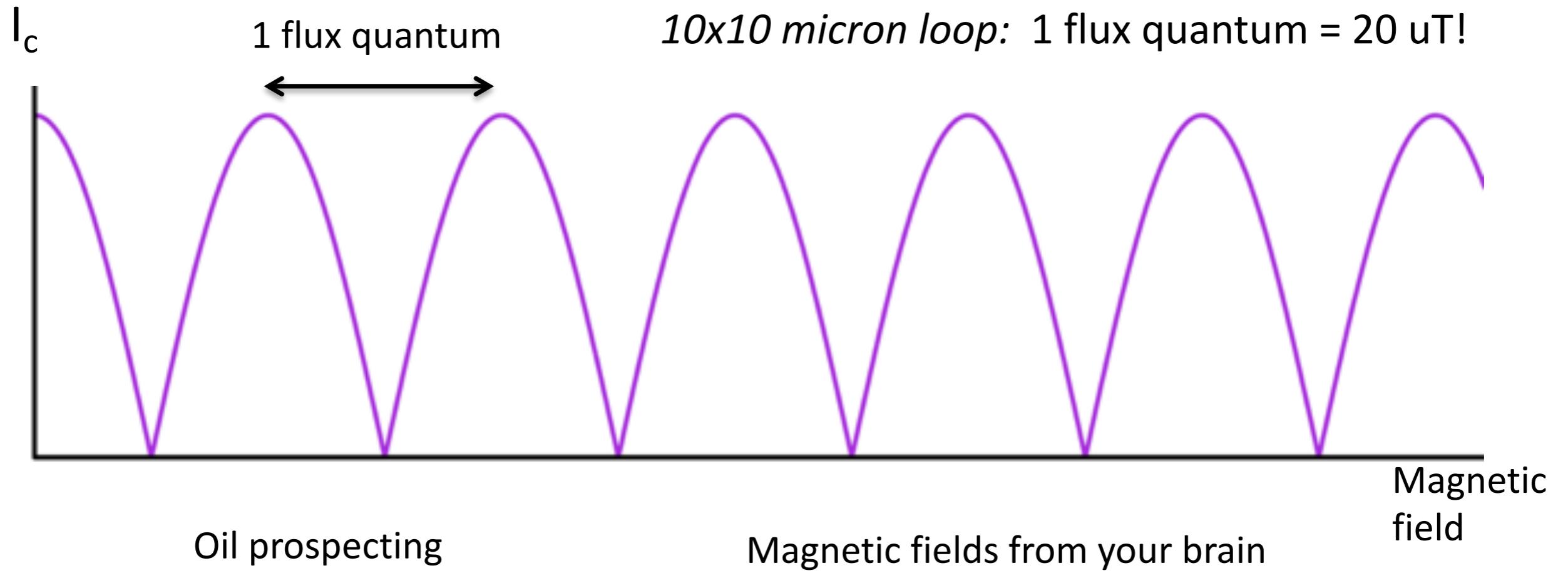


Quantum
Interference
of supercurrent

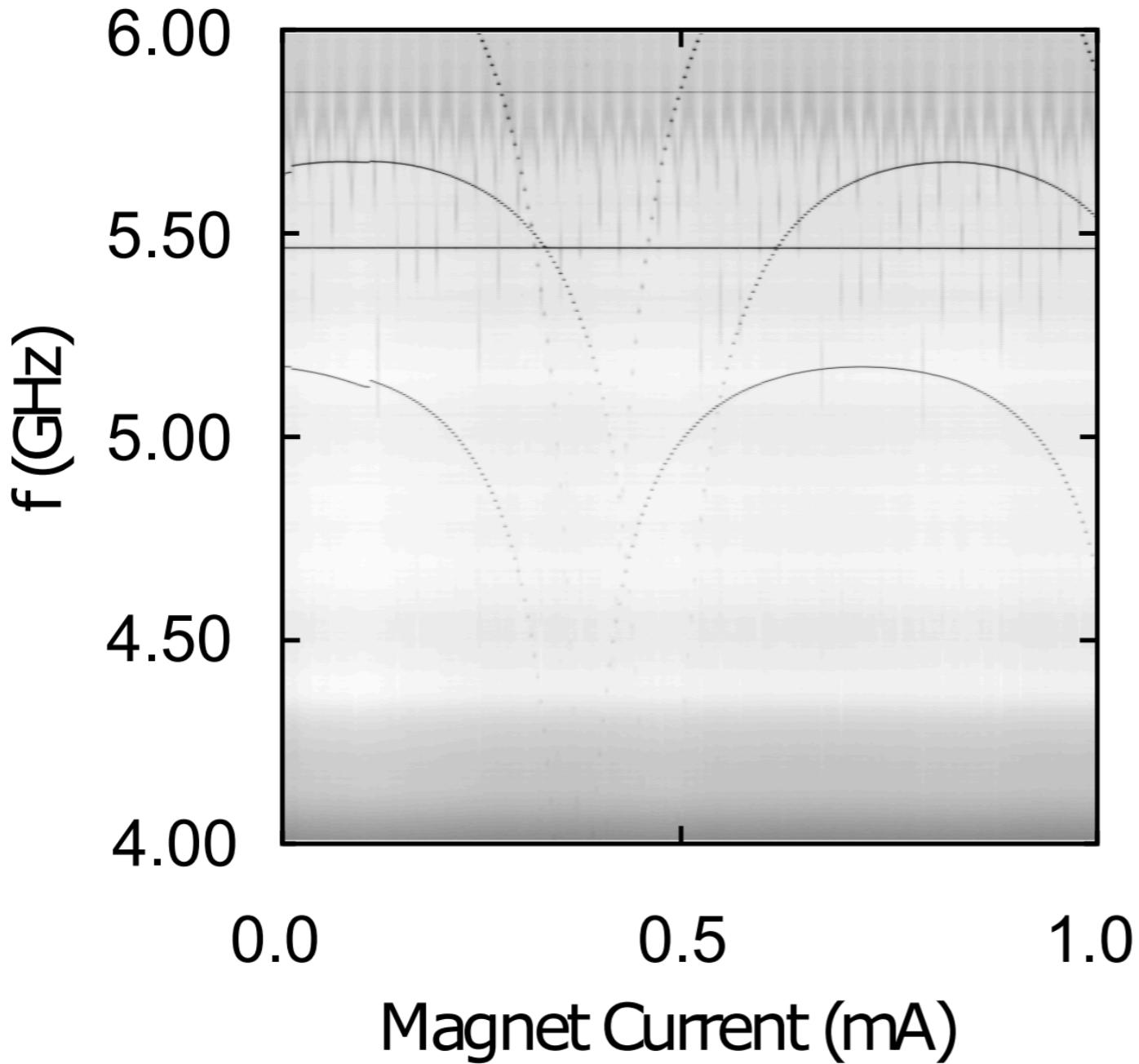
Critical current
oscillates due to
Aharonov-Bohm
phase acquired
around loop

$$I_c = 2I_0 \cos\left(\frac{e}{\hbar}\Phi_B\right)$$

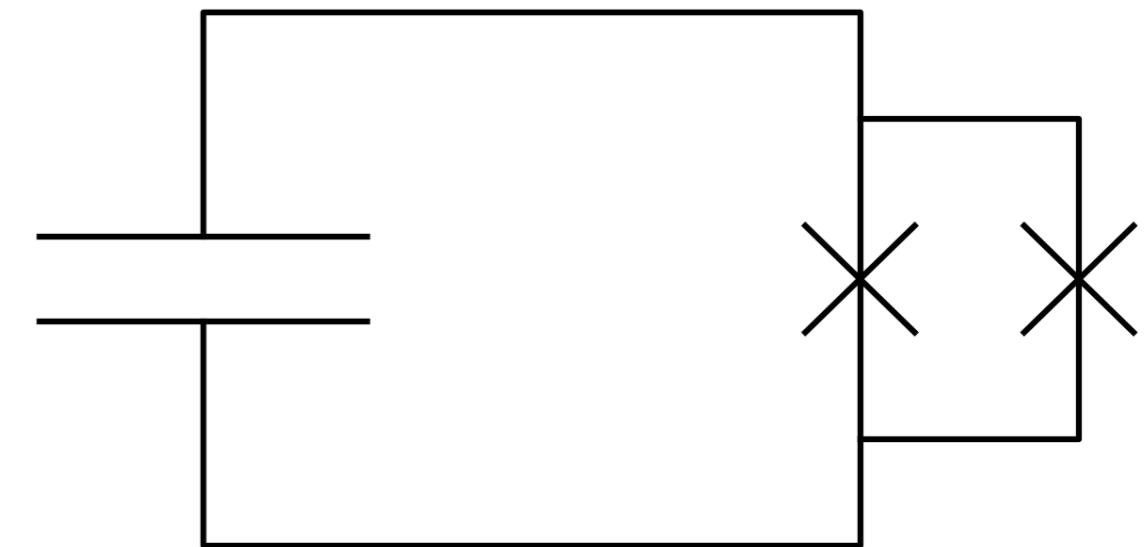
High flux sensitivity



Swinging quantum legs

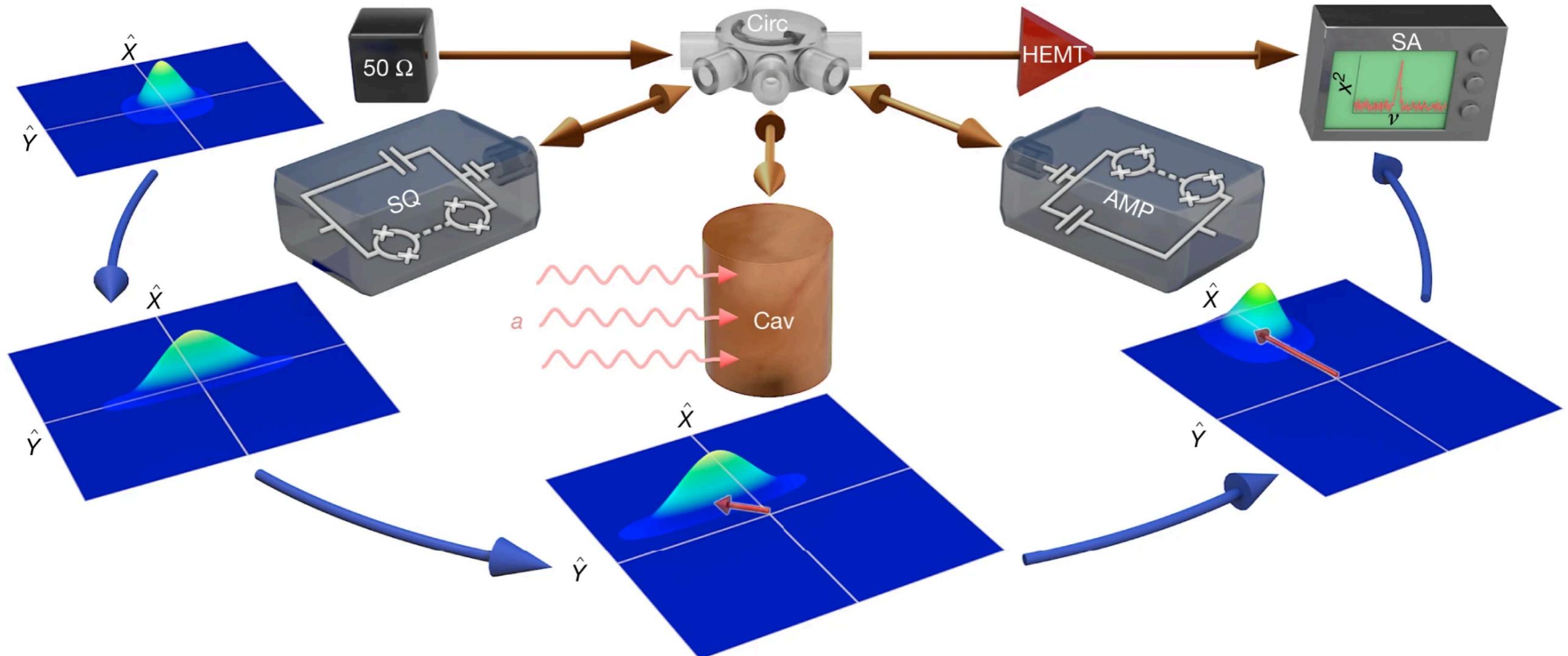


$$I_c(\Phi) \rightarrow L_J(\Phi) \rightarrow \omega_c(\Phi)$$



A quantum enhanced search for dark matter axions

K. M. Backes , D. A. Palken, S. Al Kenany, B. M. Brubaker, S. B. Cahn, A. Droster, Gene C. Hilton, Sumita Ghosh, H. Jackson, S. K. Lamoreaux, A. F. Leder, K. W. Lehnert, S. M. Lewis, M. Malnou, R. H. Maruyama, N. M. Rapidis, M. Simanovskaia, Sukhman Singh, D. H. Speller, I. Urdinaran, Leila R. Vale, E. C. van Assendelft, K. van Bibber & H. Wang



From GHz to MHz



RQU:

RF Quantum
Up converter

RF => Microwave

(See end of talk for
related “Photon Pressure”
devices)

Abstract: J60.00003 : Electromagnetic sensing below the Standard Quantum Limit: 3 kHz to 300 MHz*

Nicholas M. Rapidis

Abstract: J60.00004 : Precision Metrology with Radiofrequency Quantum Upconverters*

Jyotirmai Singh

Abstract: J60.00006 : Radio-frequency quantum upconverters for spin metrology*

Elizabeth van Assendelft

Quantum Sensing from my group

Massive objects, RF Photons, and RF currents

Quantum sensing with massive objects

Sensing quantum gravity?

BLOCK 1

a panel discussion on
**Optomechanical Interfaces of
Quantum Mechanics and Gravity**

17TH FEBRUARY 2021

1400



Angelo Bassi
University of Trieste,
Italy



Miles Blencowe
Dartmouth College,
U.S.A.



Andrew Geraci
Northwestern University,
U.S.A.

Chaired by



Hendrik Ulbricht
University of Southampton, UK



Sofia Qvarfort
Imperial College London, UK



Ivette Fuentes
University of Southampton
U.K.



Caslav Brukner
University of Vienna
Austria

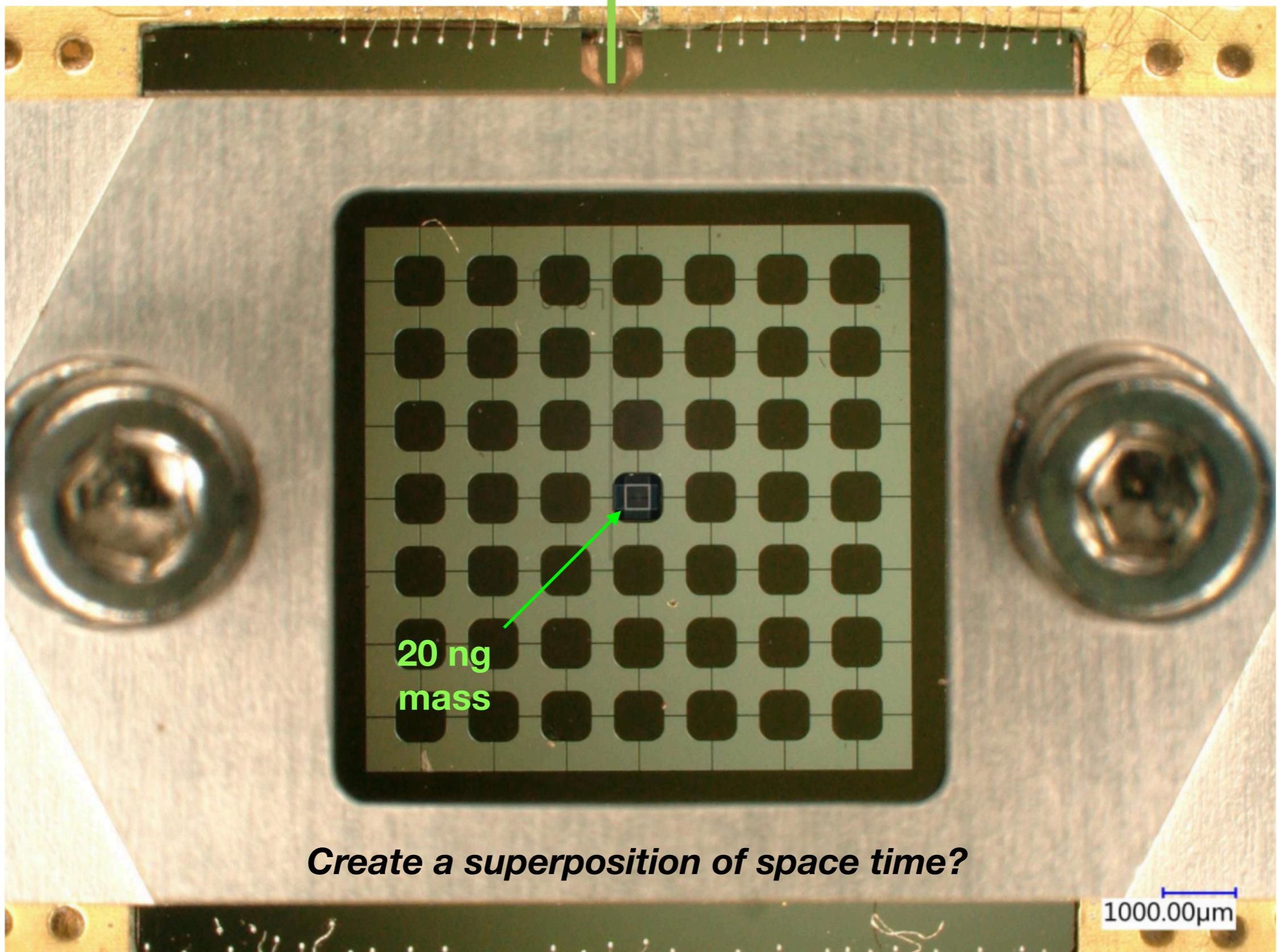


Gary Steele
TU Delft,
The Netherlands

UniK RN

Live-stream link:
<https://youtu.be/YwGN0JbTJdM>

Macroscopic membranes



Quantum Sensing: RF Photons

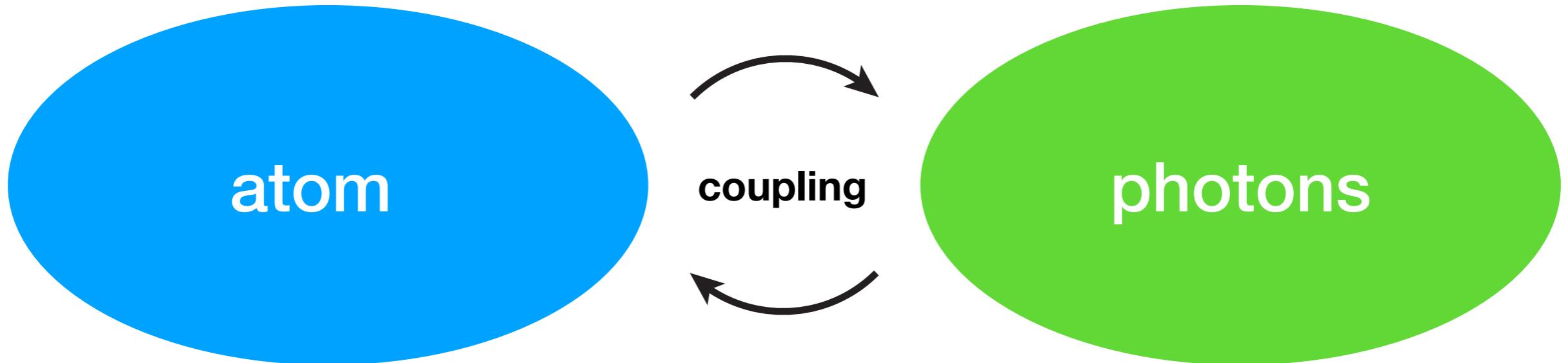


Science 363, 1072 (2019)

Mario F. Gely, Marios Kounalakis, Christian Dickel, Jacob Dalle, Rémy Vatré,
Brian Baker, Mark D. Jenkins, Gary A. Steele

Hear more: <https://youtu.be/860y52bFWdM>

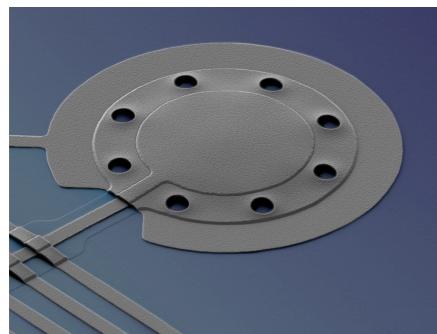
Sensing RF Photons



GHz

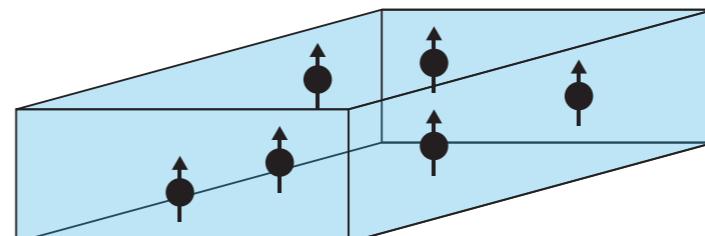
MHz

Why would I want quantum RF photons?



Drums

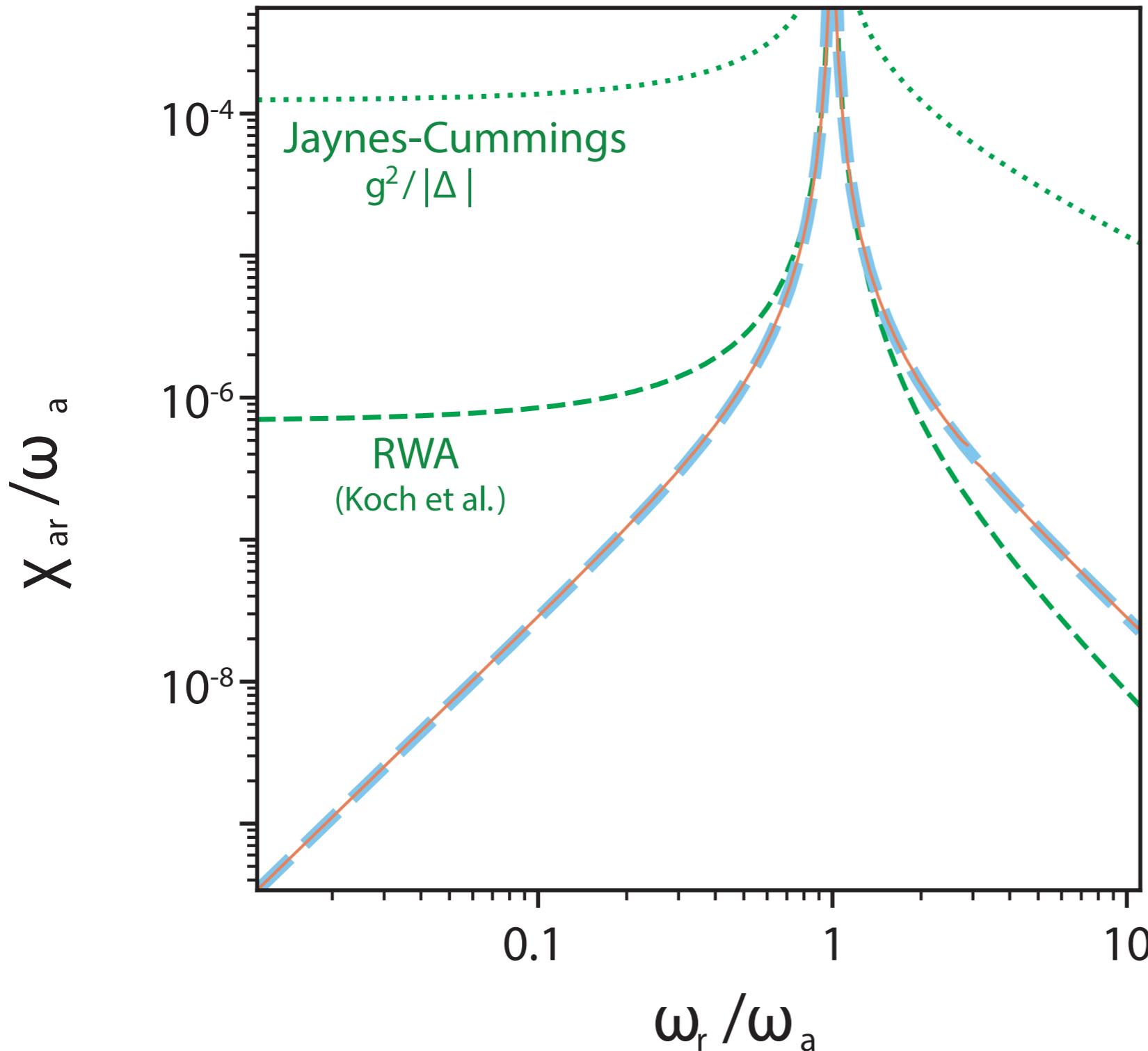
Spin Ensembles



$$kT > \hbar\omega$$

Observe “real”
thermal photons?

Why is this hard?



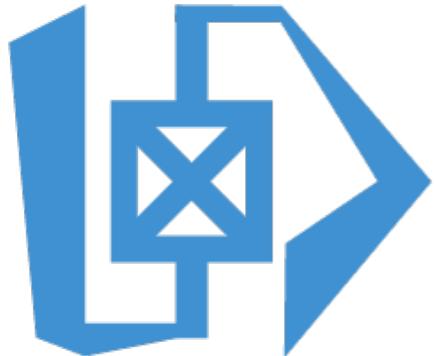
Month 2 of PhD:

Include counter-rotating
terms at very large
detuning

Analytically derives that
his project will not work

Unless...?

Is there a solution?



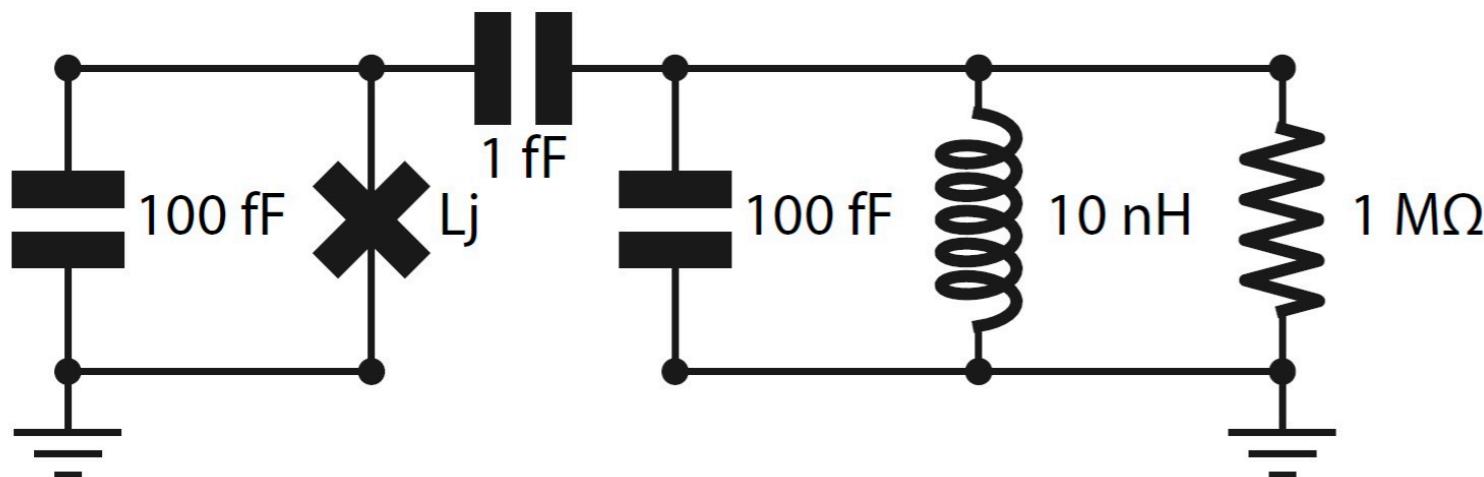
Spin-off: QuCAT

QUantum Circuit Analyzer Tool

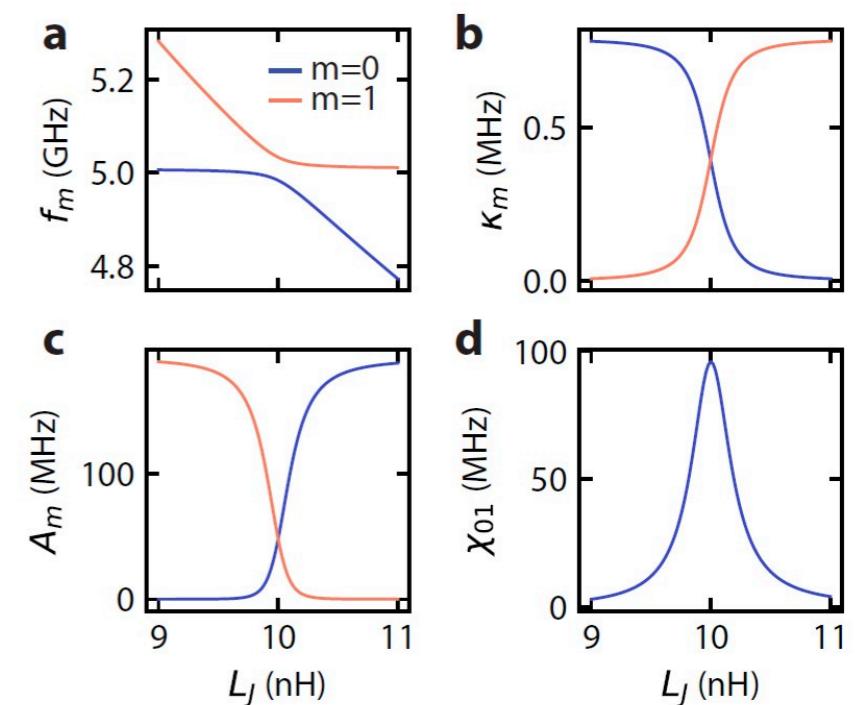
Python
Open Source

<https://qucat.org/>

```
import qucat
circuit = qucat.GUI('netlist.txt')
circuit.show()
```



```
f,k,A,chi = circuit.f_k_A_chi()
Lj = numpy.linspace(11e-9,9e-9)
```

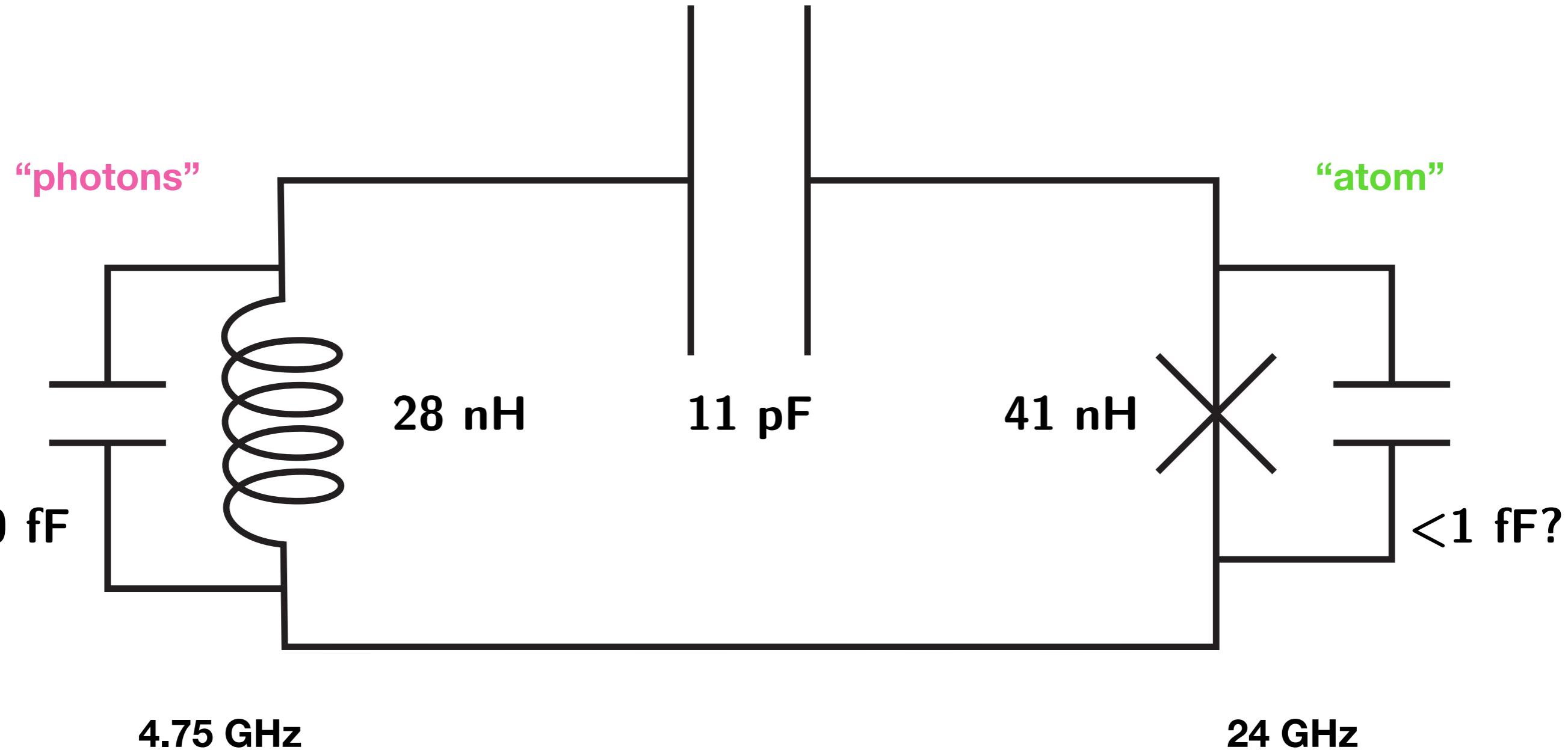


```
H = circuit.hamiltonian(Lj = 10e-9,
    mode = [0,1], taylor = 4, excitations = [10,12])
```

$$\sum_{m \in \text{mode}} f_m a_m^\dagger a_m + \sum_{j \in \text{junctions}} \frac{E_j}{12} \left[\sum_{m \in \text{mode}} \varphi_{m,j} (a_m + a_m^\dagger) \right]^4$$

Out-of-box circuit idea

HUGE capacitor

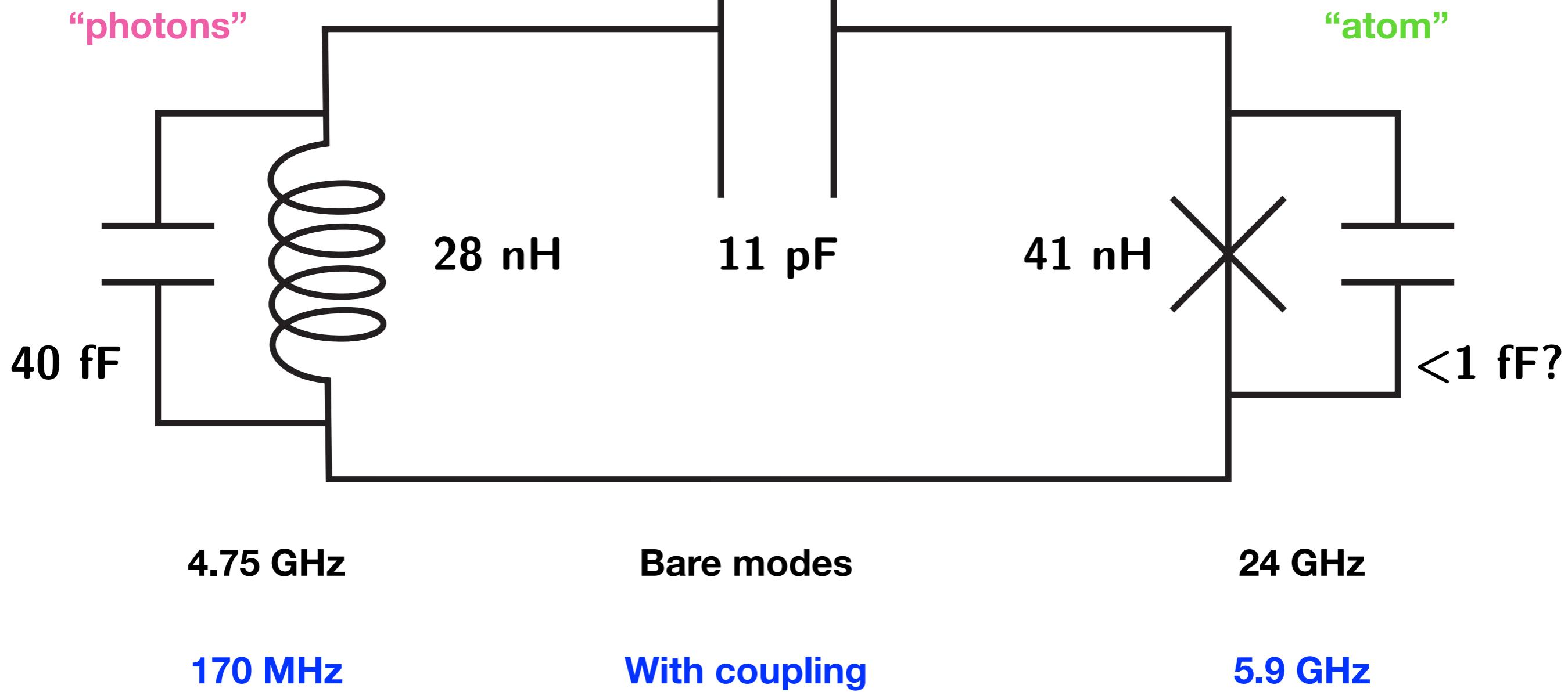


ULTRA strong coupling!

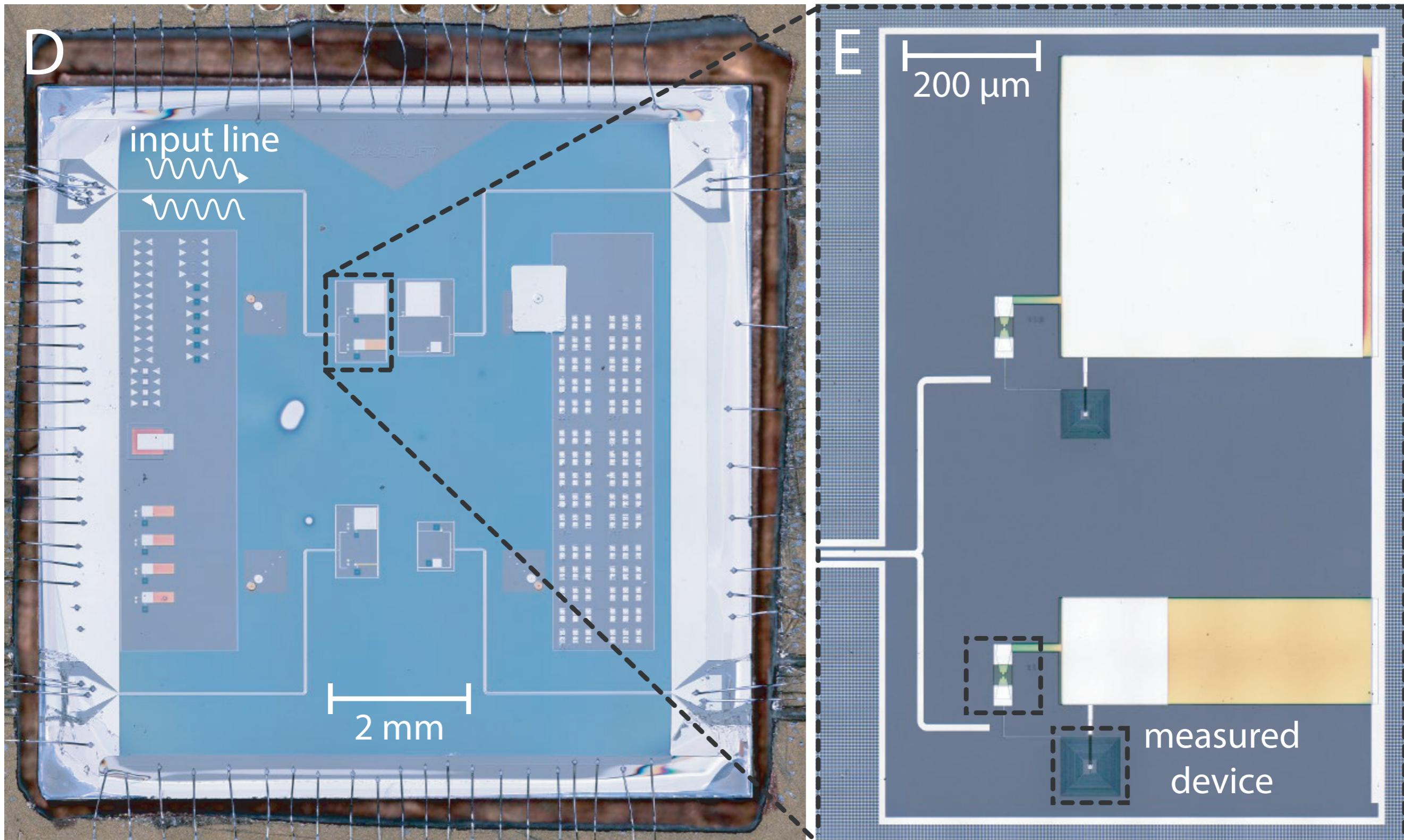
Bare coupling:

$$g \approx \frac{\sqrt{\omega_r \omega_q}}{2} \approx 5.3 \text{ GHz}$$

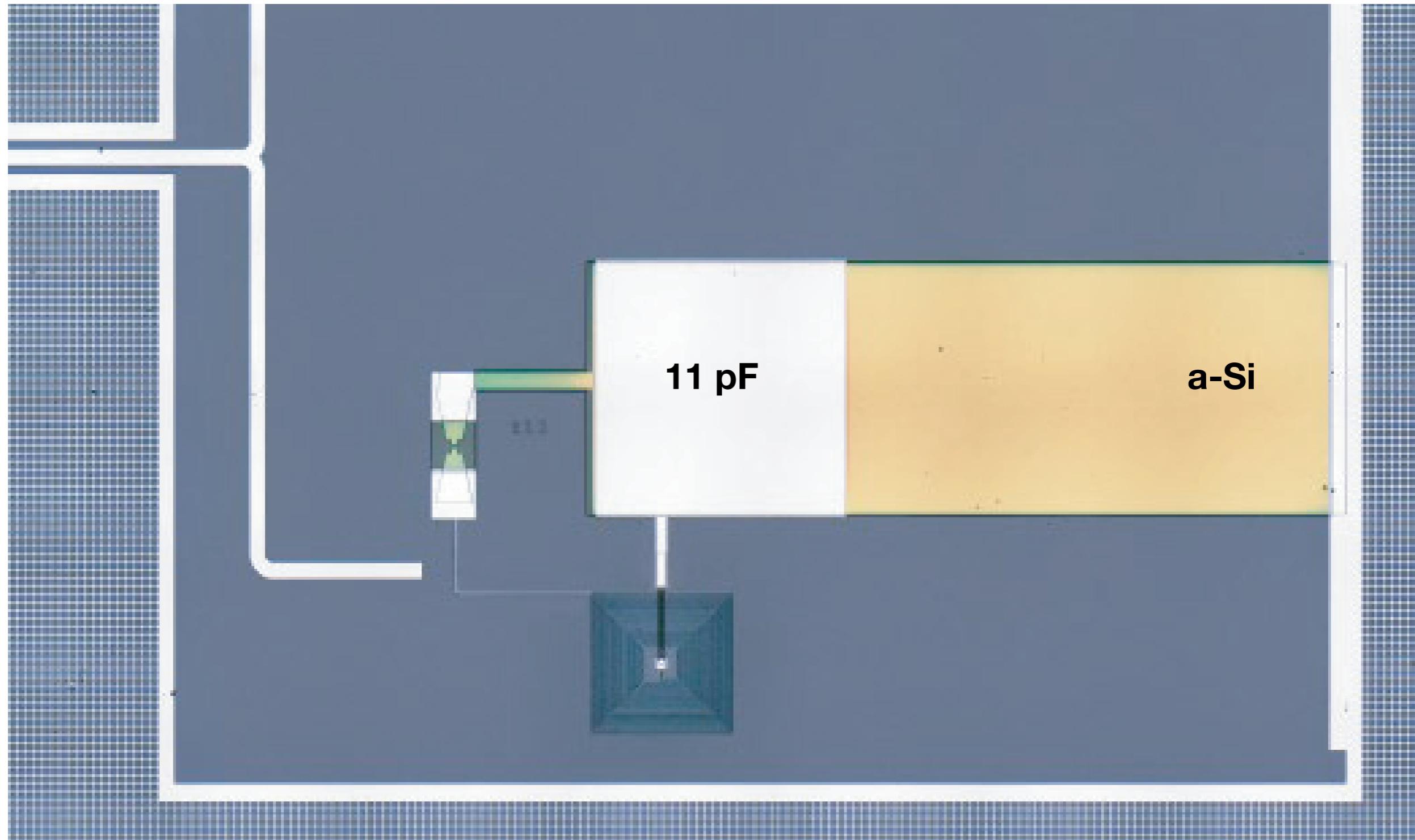
99% of theoretical limit!



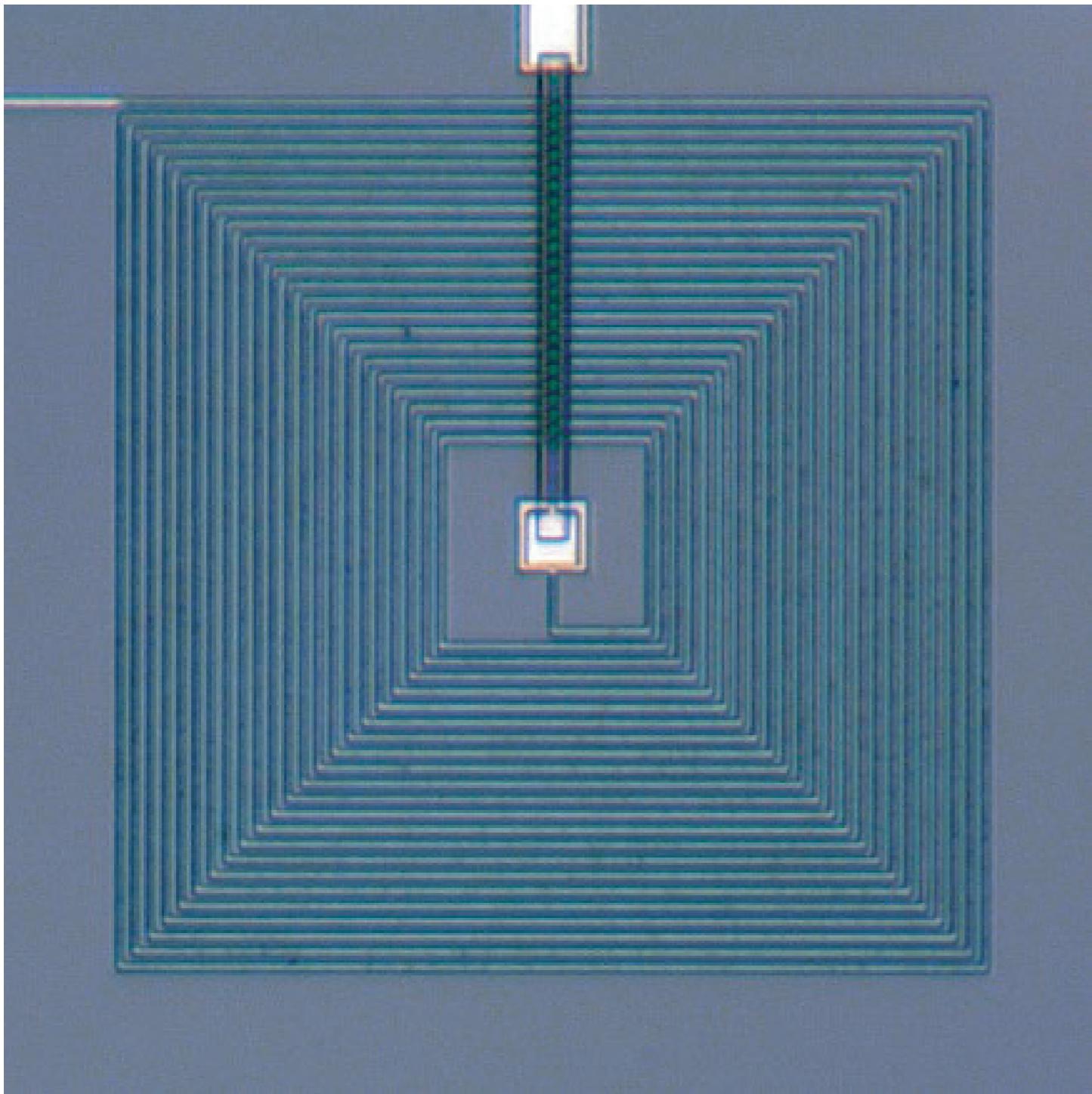
Making it



BIG capacitor!



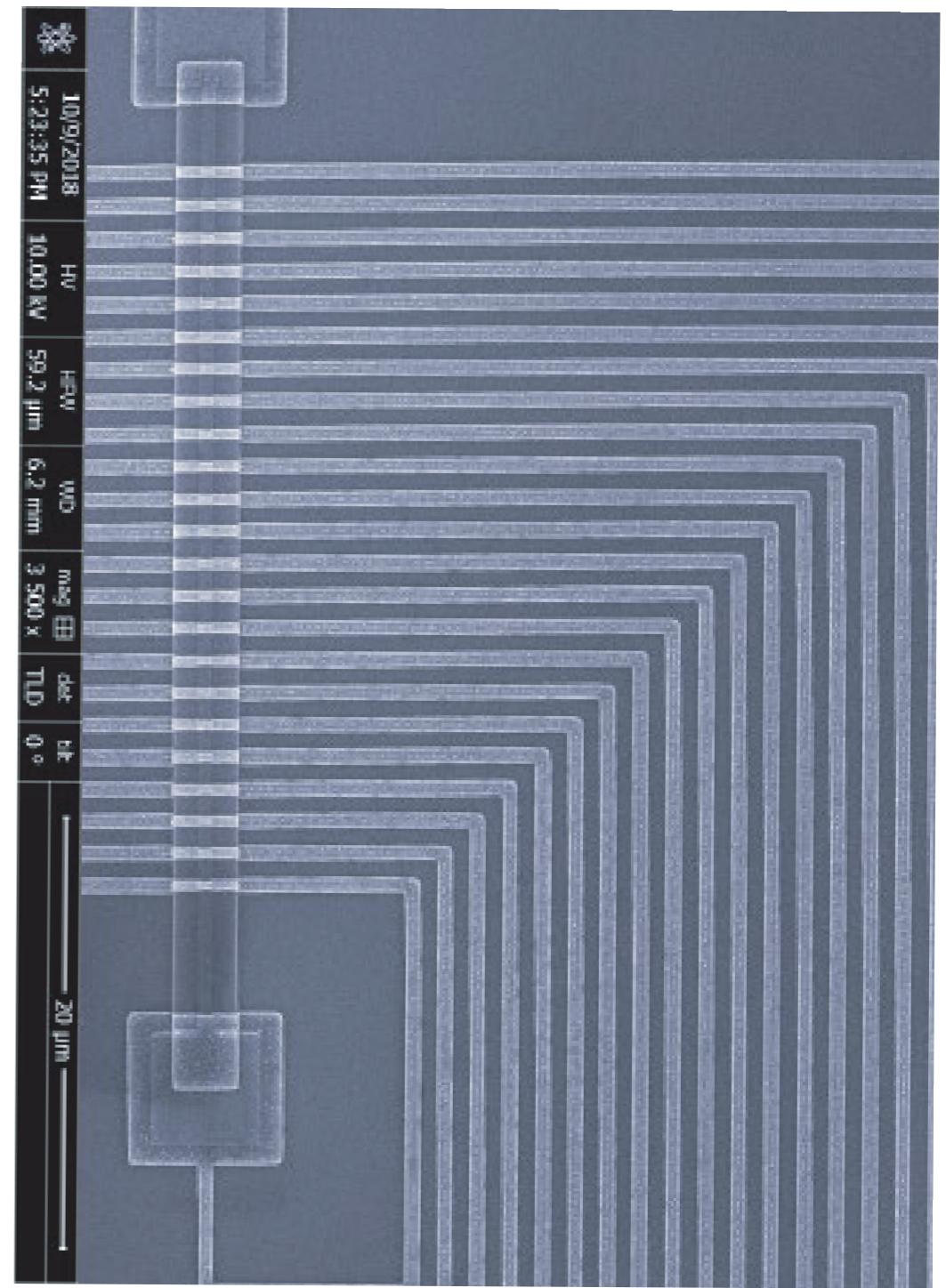
Spiral Inductor



500 nm width

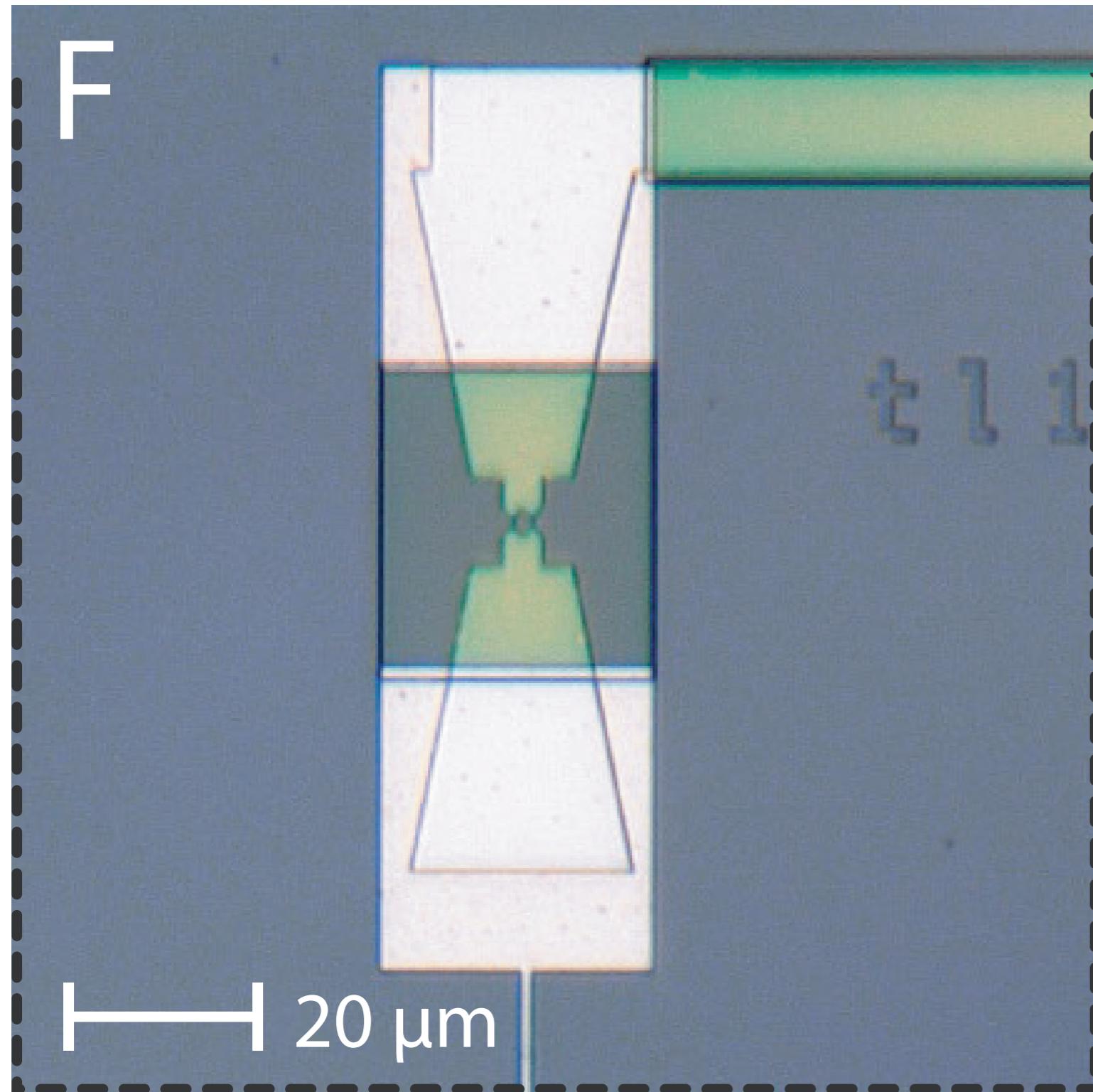
Sputter Al1%Si

a-Si crossovers



“Patch” with ion milling to connect different layers

Low critical current inductor

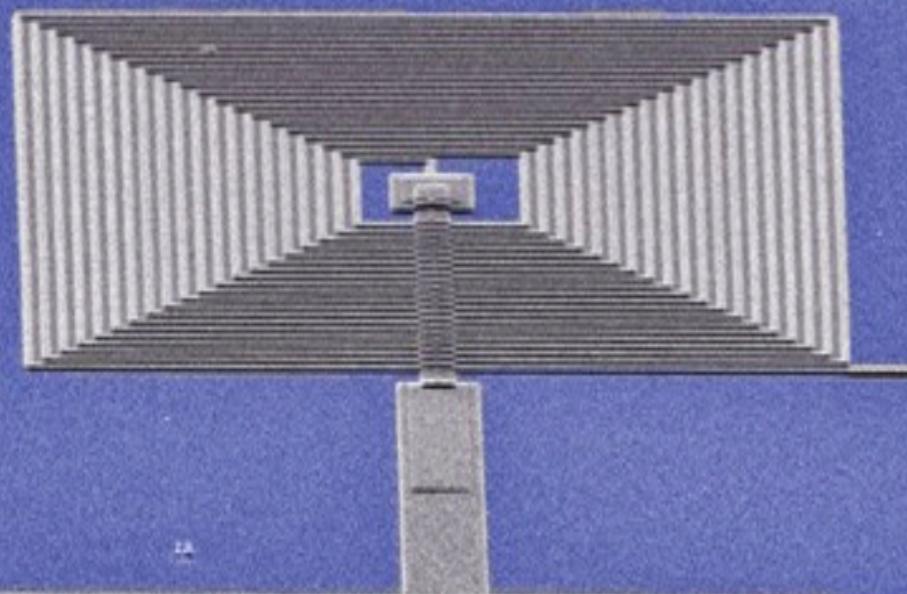


**Needed for high
inductance**

**Encapsulated in
amorphous silicon:**

Protection during Cl
dry etching of the
spiral inductor

Spiral Inductor



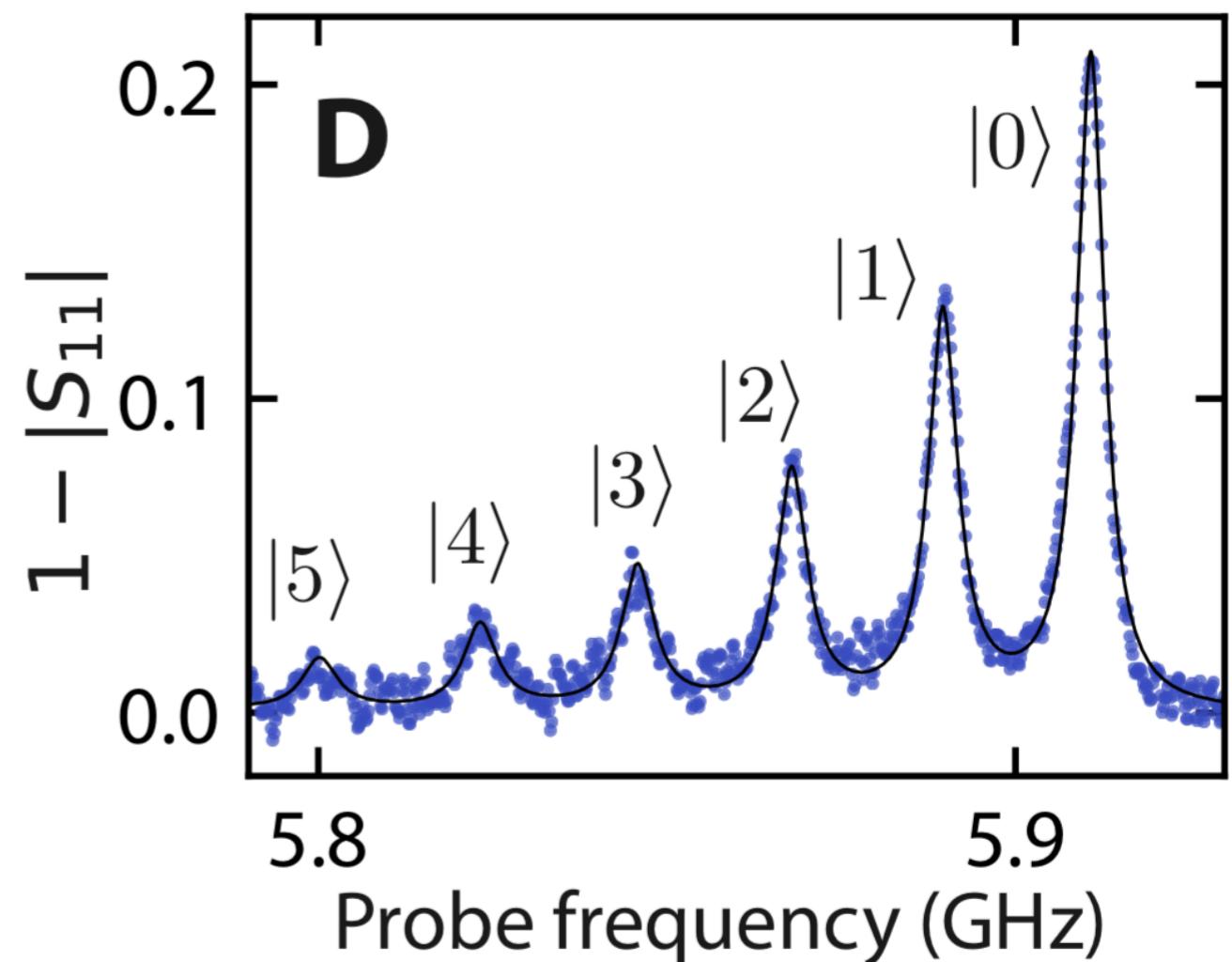
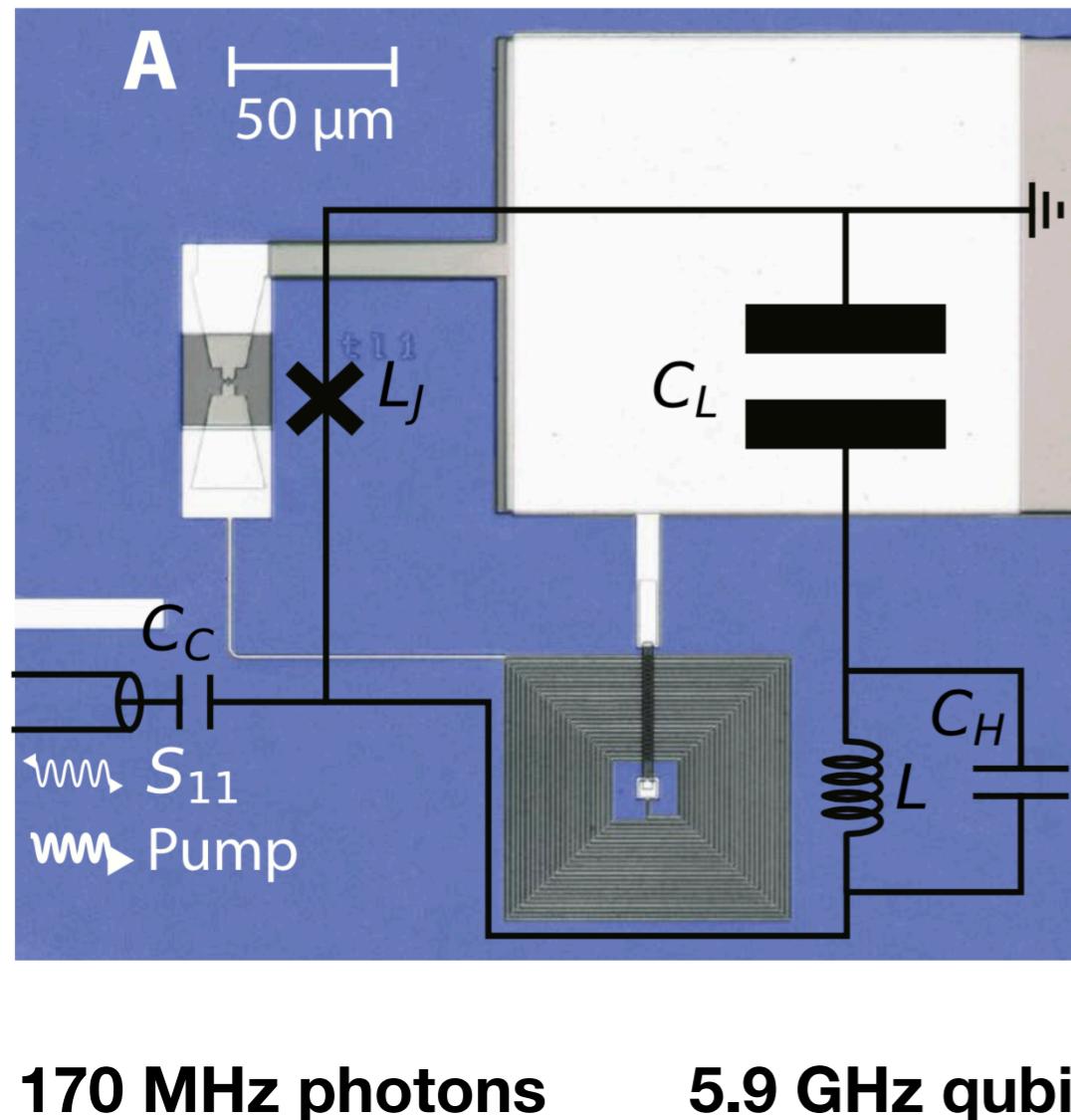
Feedline



Junction (SQUID)

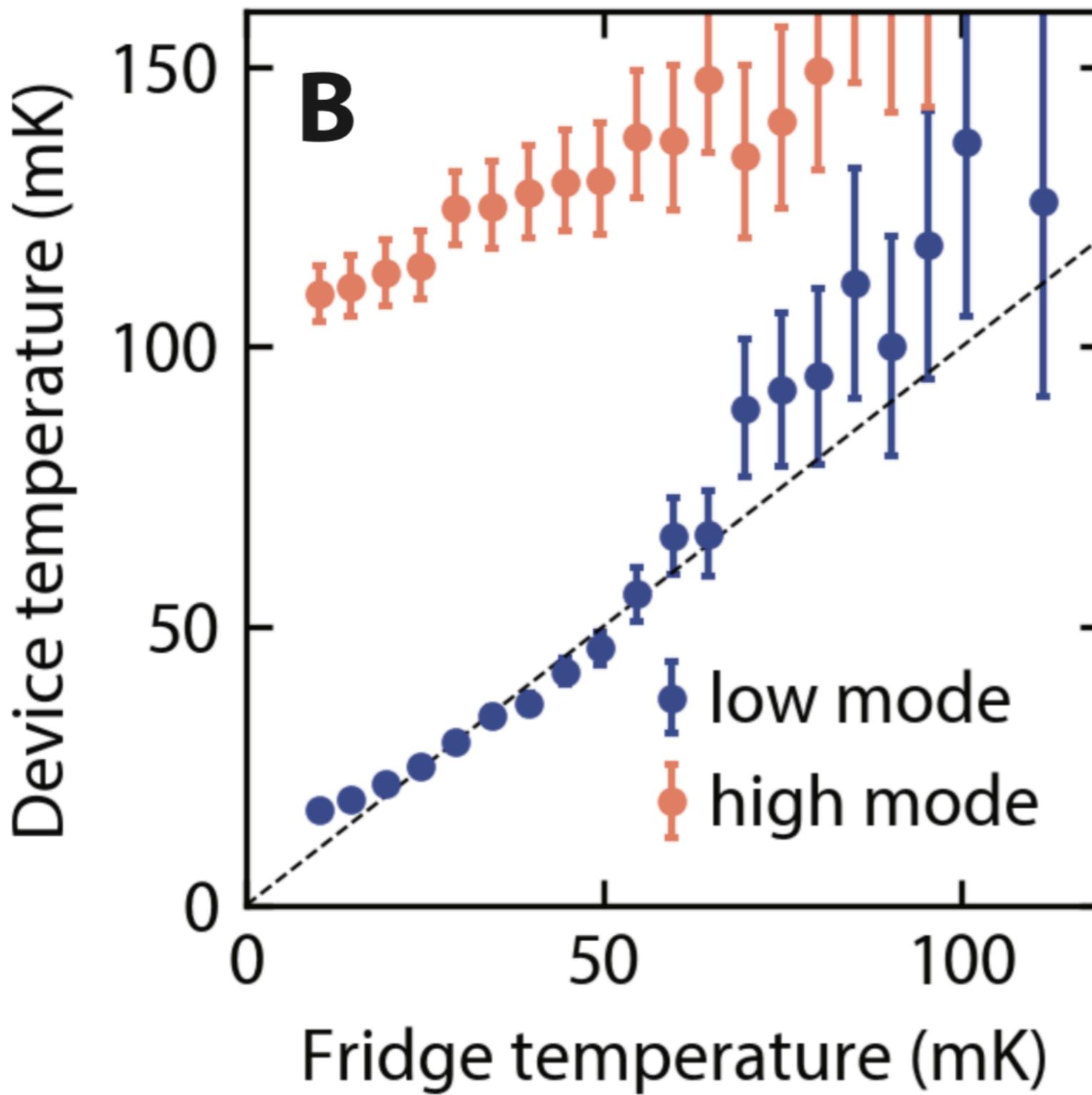
Capacitor

Observing quantisation of RF Fields



Building on our understanding of ultra-strong coupling

Primary Thermometry



Area under peaks:

Direct measure of thermal photon distribution

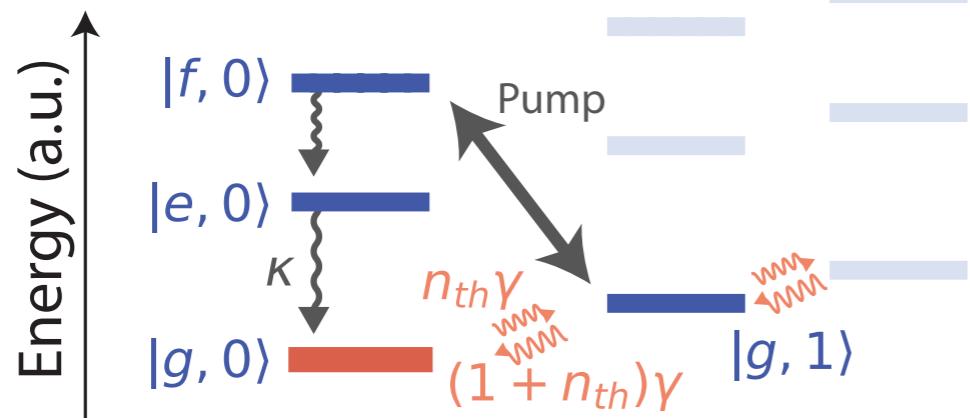
Photons cold, qubit hot?

(Consistent with recent results from Yale noise filtering)

Cool!

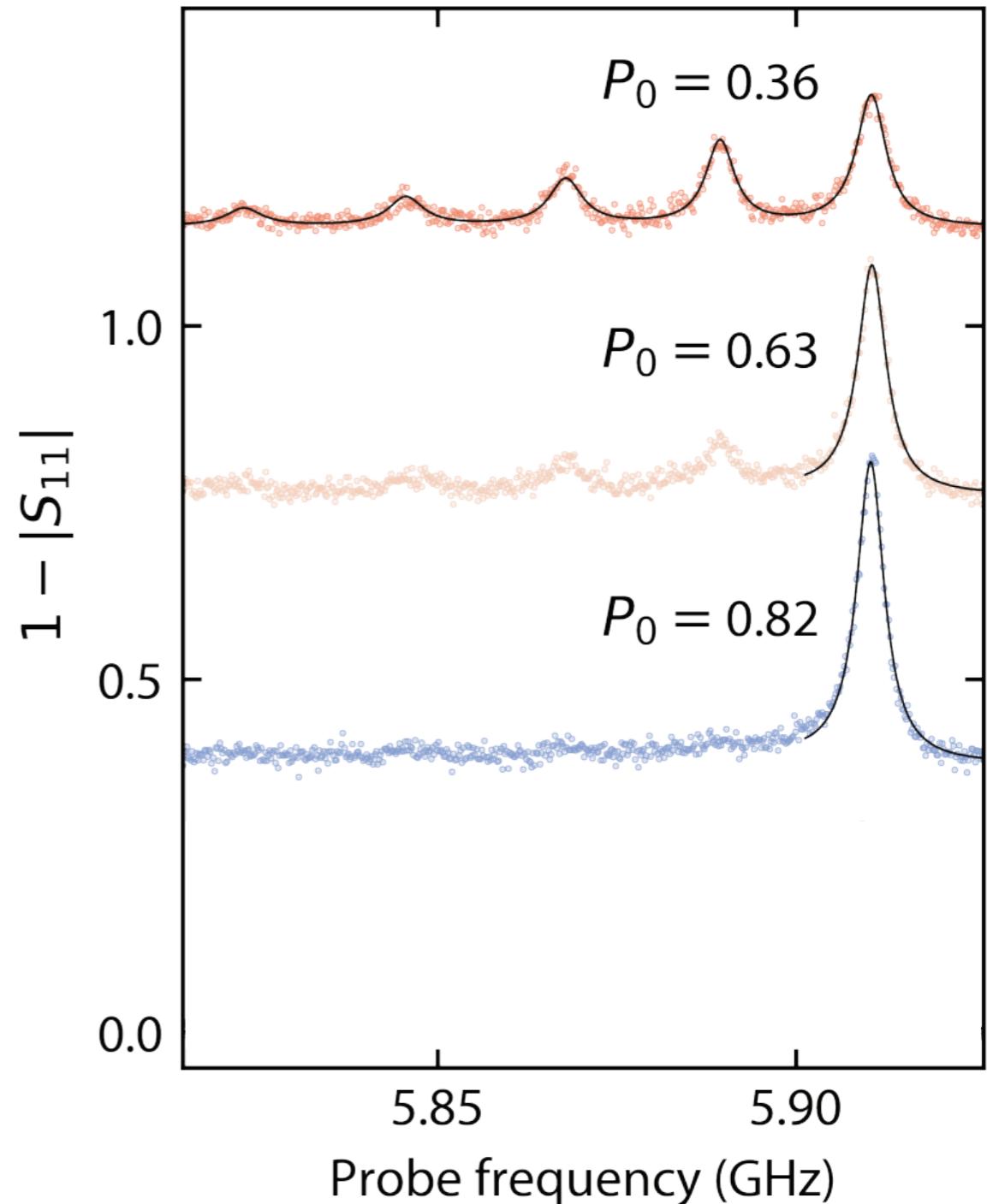
But what if we don't want MHz thermal photons?

Cooling

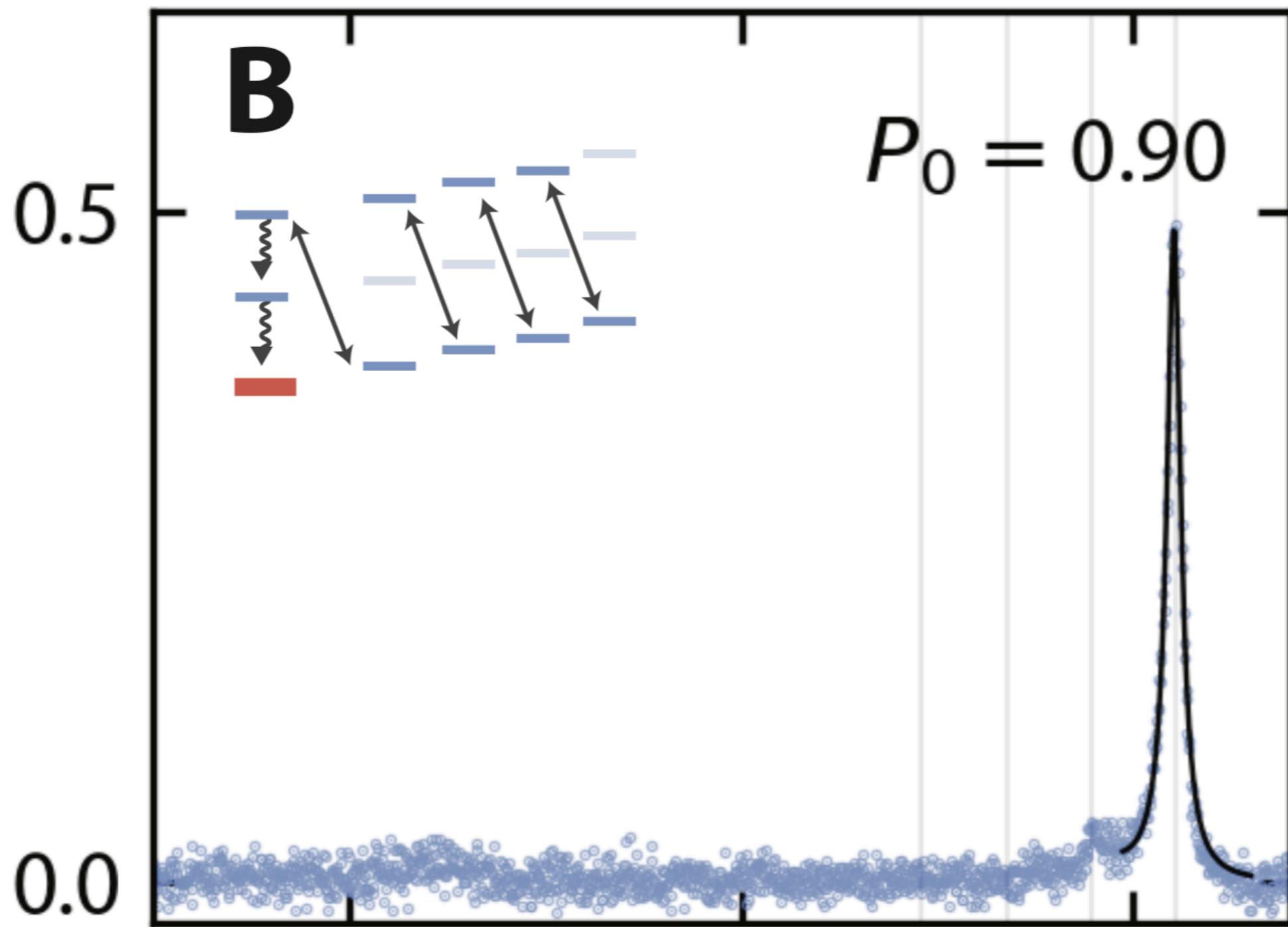


Drive + Dissipation =
“Entropy Vacuum Cleaner”

Ground state with
82% fidelity!



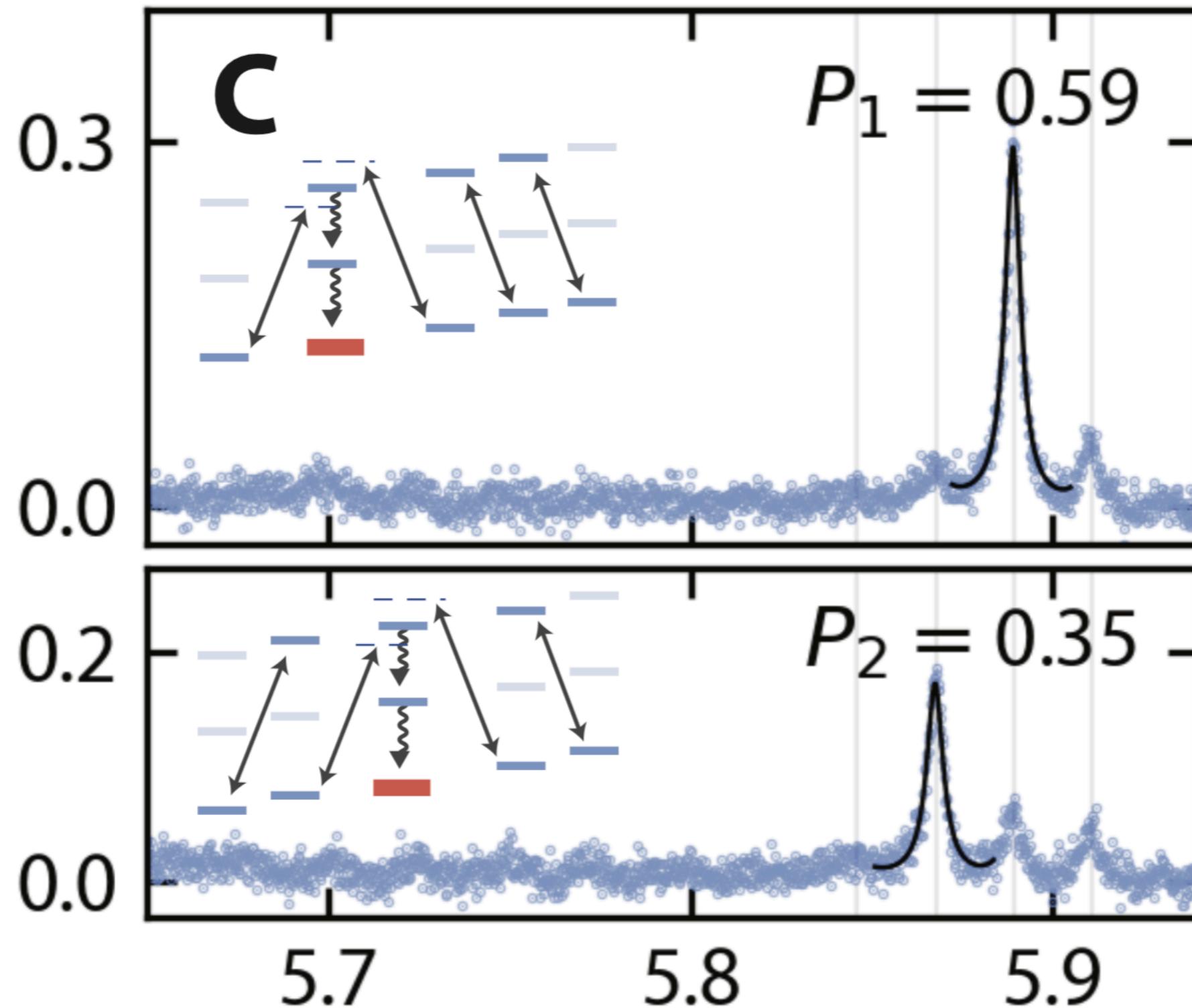
Multitone cooling



Suppress
Instability

Better
Cooling

Flip arrows: Stabilize Fock states!



Quantum Sensing with SQUIDs

I. C. Rodrigues



D. Bothner



Coupling microwave photons to a mechanical resonator using quantum interference

I. C. Rodrigues, D. Bothner, G. A. Steele

Nature Communications 10, 5359 (2019)

Photon-Pressure Strong-Coupling between two Superconducting Circuits

D. Bothner, I.C.Rodrigues, G.A.Steele

Nature Physics 17, 85 (2021)

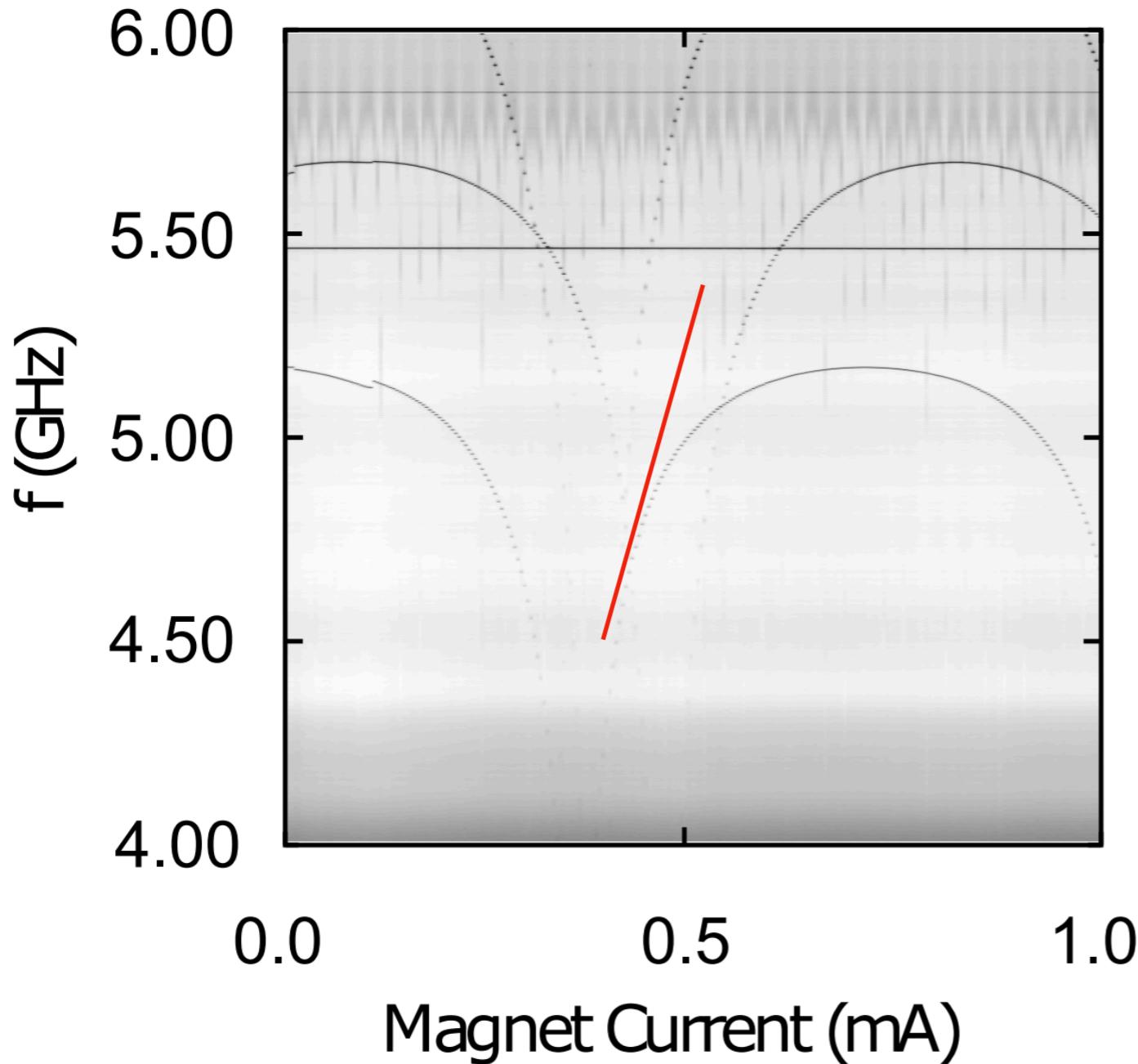
Photon-pressure coupling with a hot radio-frequency circuit in the quantum regime

I.C. Rodrigues, D. Bothner, G.A. Steele

<https://arxiv.org/abs/2010.07975>

Hear more: <https://youtu.be/860y52bFWdM>

Sensing with SQUID Cavities

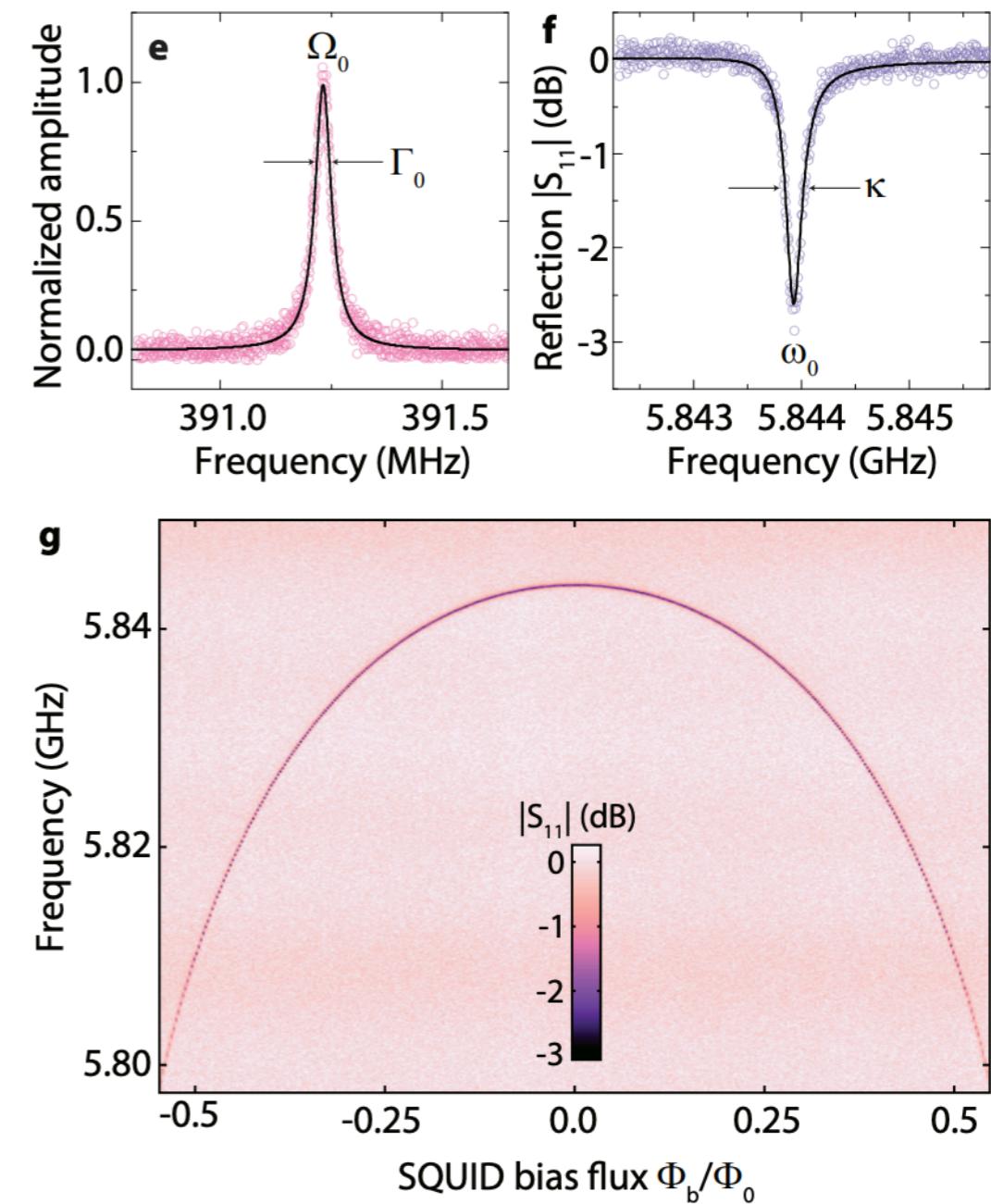
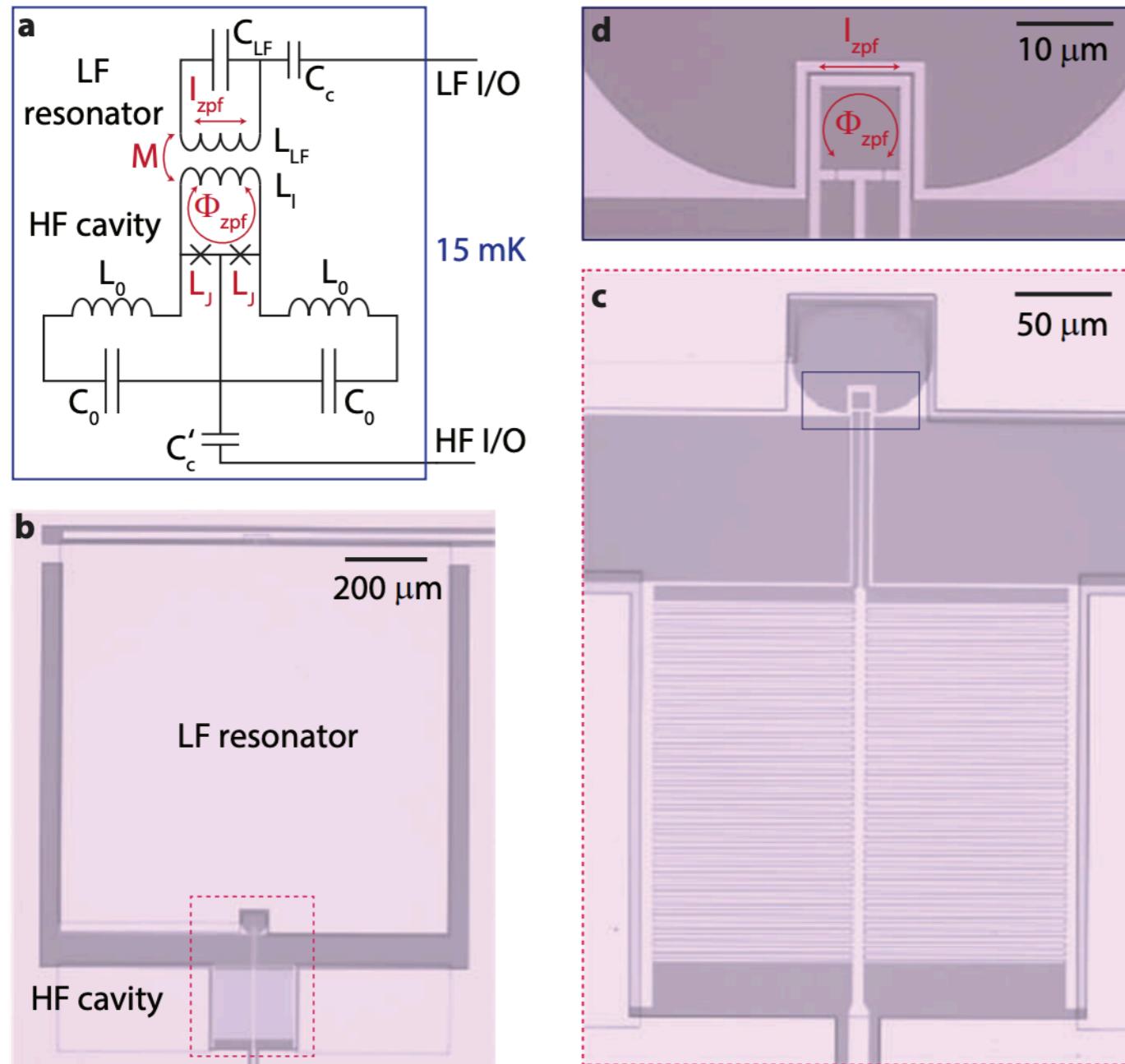


Steep slope + High Q:

**Sensing down to
quantum level**

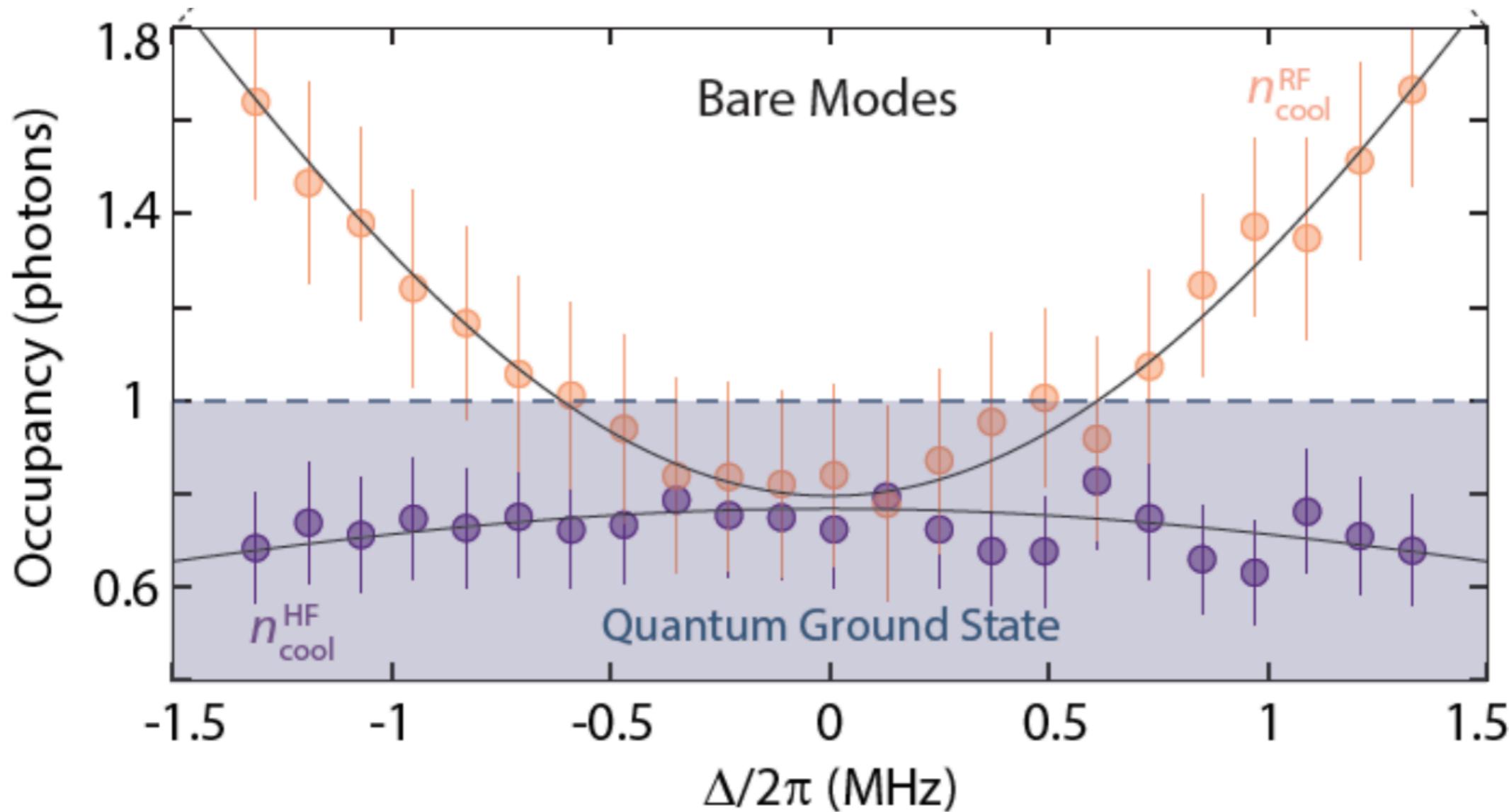
A quantum galvanometer

Sensing quantum fluctuations of current



New device: Ground State!

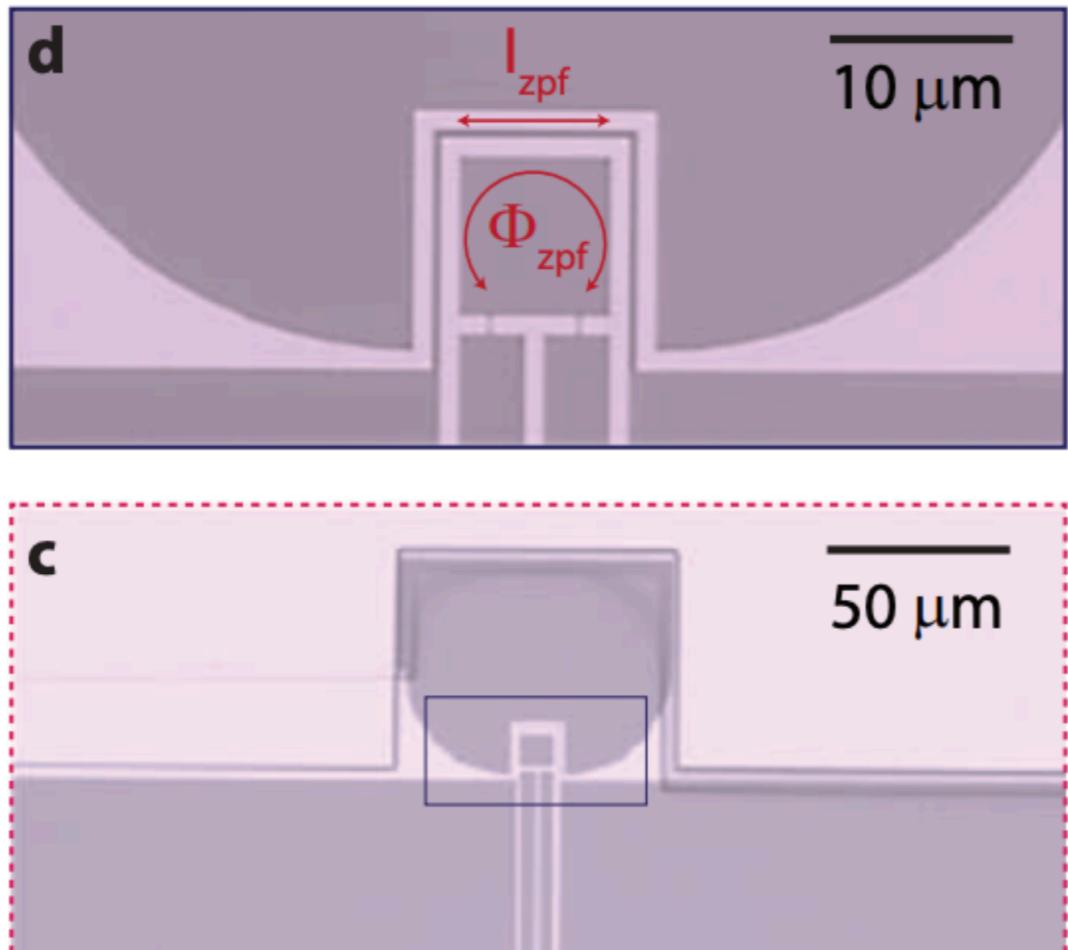
Cooling RF currents to their quantum ground state



New data: Quantum limited
sensing of RF fields using!

Summary

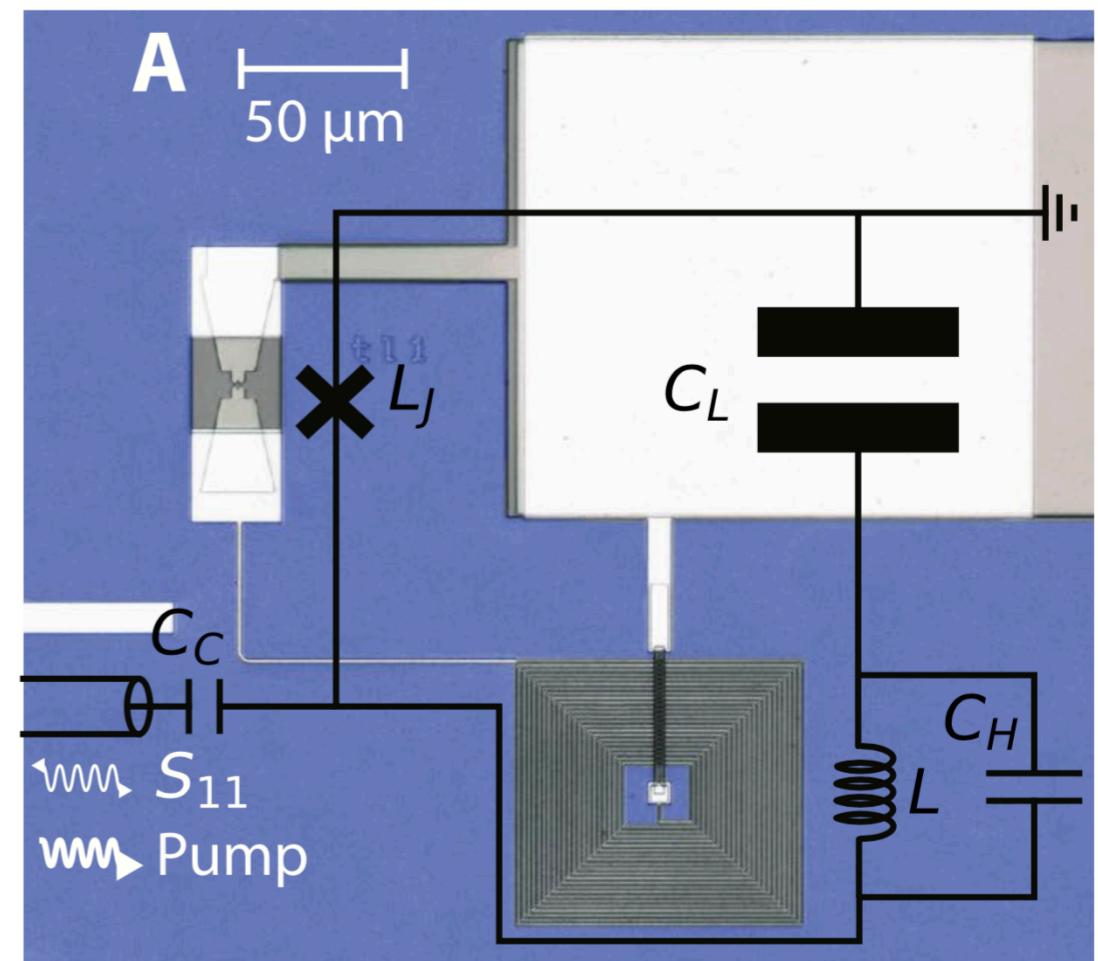
Quantum Sensing



Push sensing to quantum limit

Force sensing, Transduction,
Quantum Spacetime?

RF Quantum Photonics



Sensing with Quantum Things

Observing quantum mechanics in
new regimes

