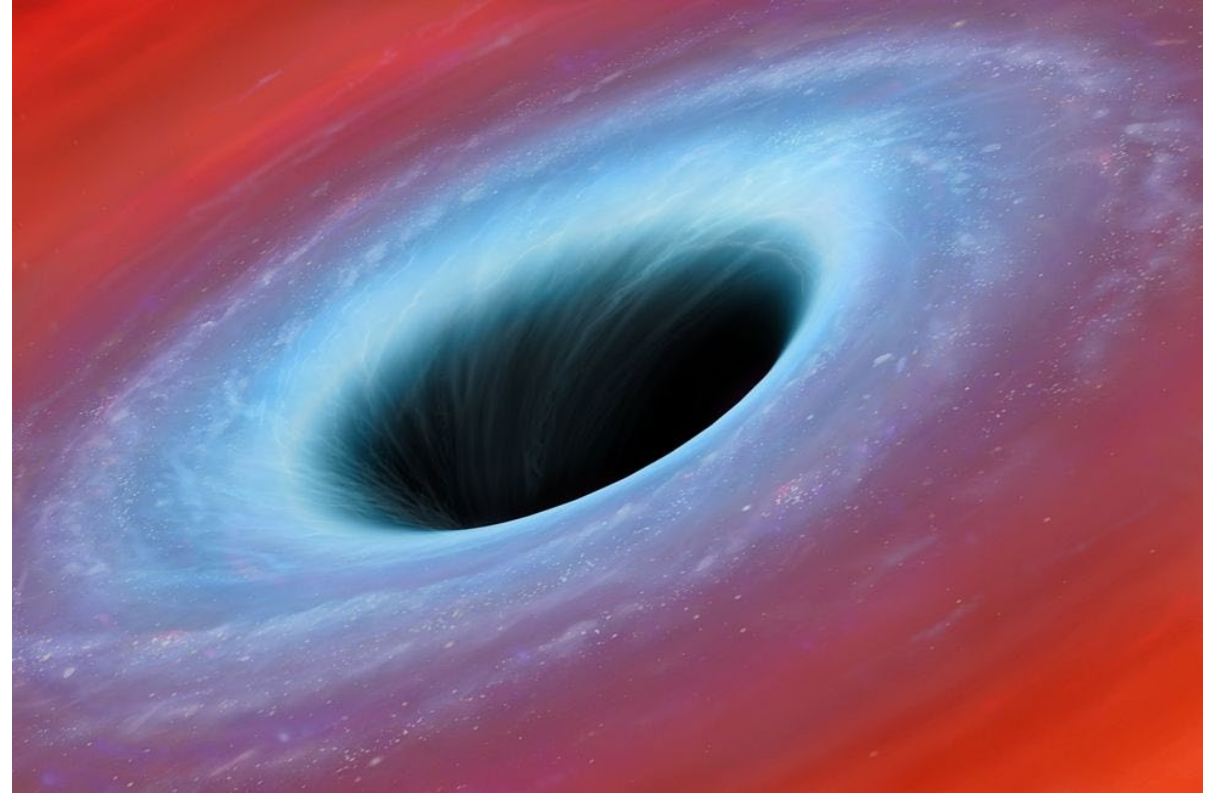
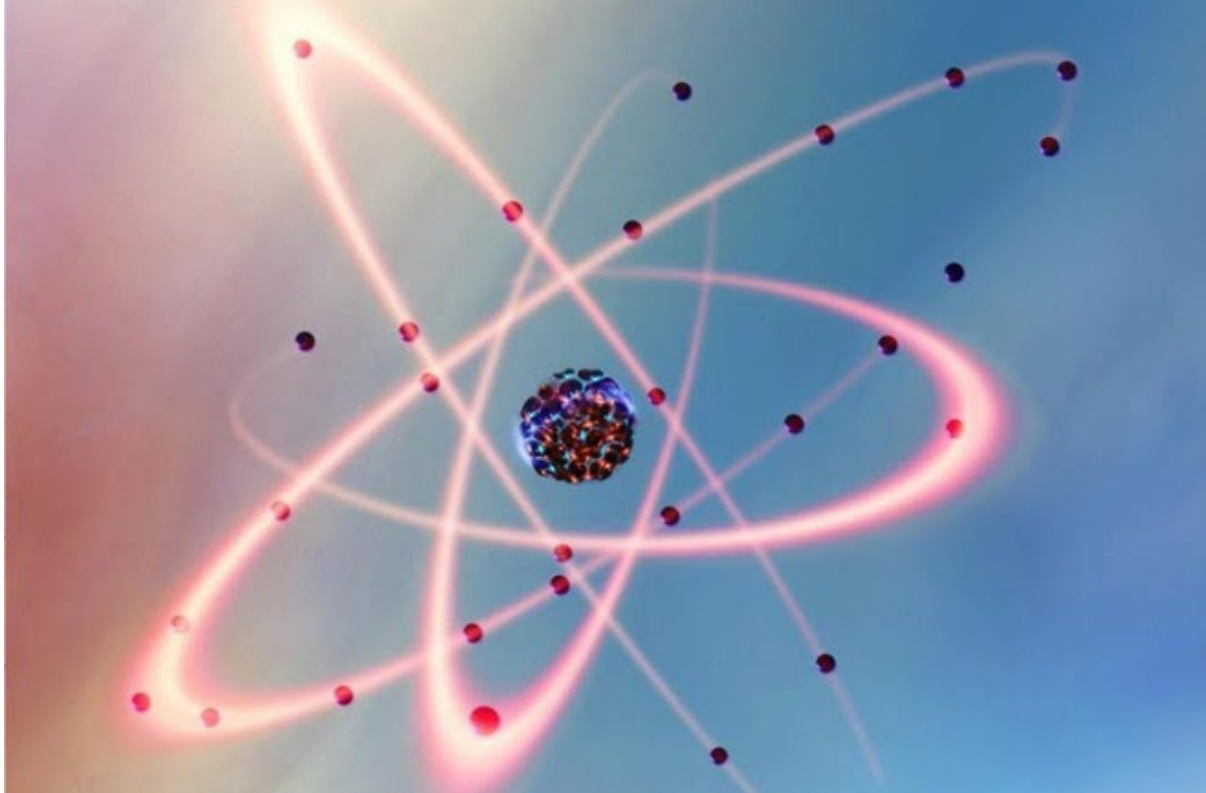




Testing if Gravity is Quantum

using superpositions of massive objects

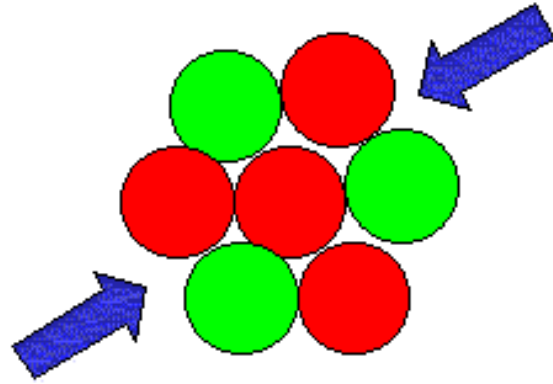


What can we test and how can we do it?

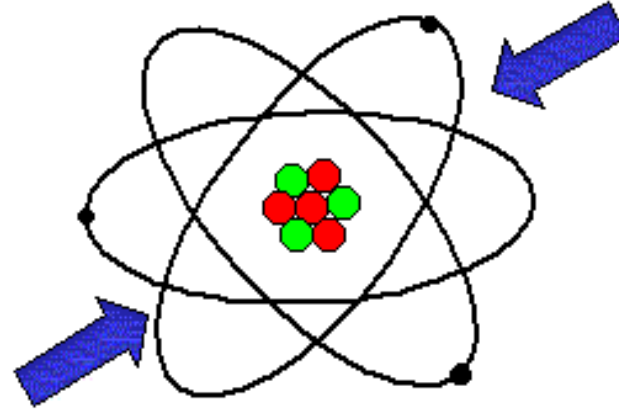
Prof. Gary Steele

Why?

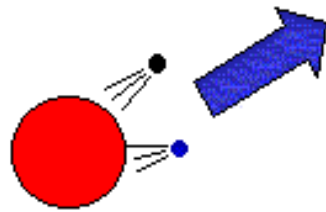
Forces of nature



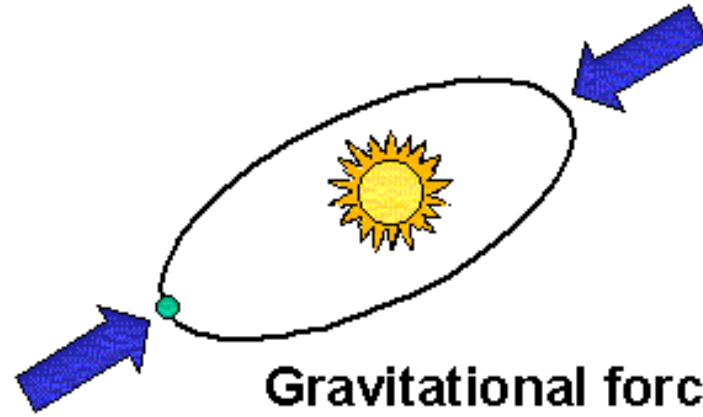
**Strong force
binds the nucleus**



**Electromagnetic
force binds atoms**



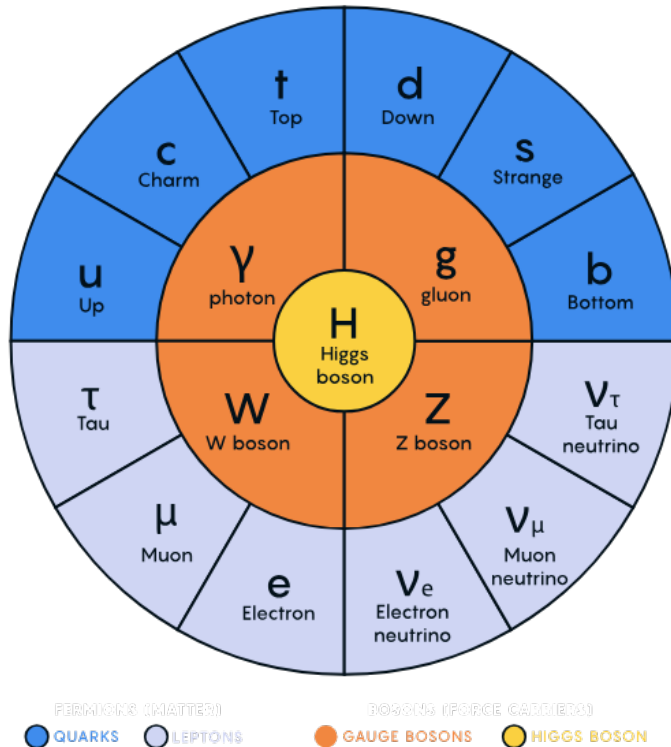
**Weak force in
radioactive decay**



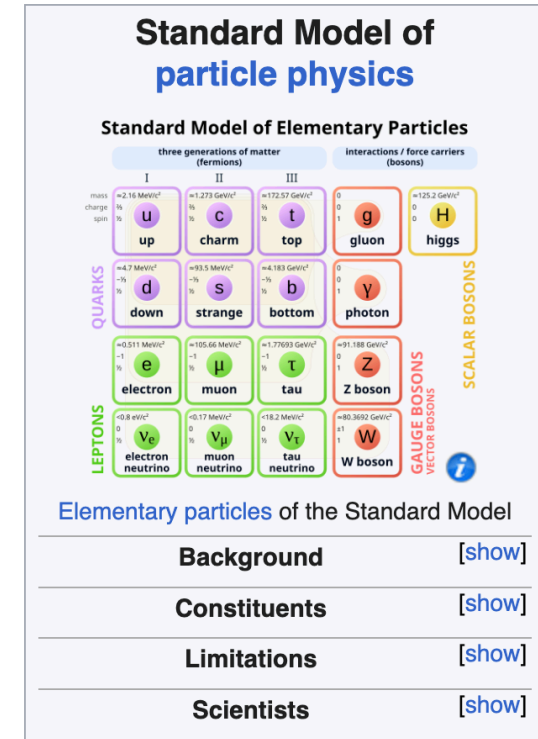
**Gravitational force
binds the solar system**

Quantum Forces: Quantum Field Theory

The Standard Model



The **Standard Model** of [particle physics](#) is the [theory](#) describing three of the four known [fundamental forces](#) ([electromagnetic](#), [weak](#) and [strong interactions](#) – excluding [gravity](#)) in the [universe](#) and classifying all known [elementary particles](#). It was developed in stages throughout the latter half of the 20th century, through the work of many scientists worldwide,^[1] with the current formulation being finalized in the mid-1970s upon [experimental confirmation](#) of the existence of [quarks](#). Since then, proof of the [top quark](#) (1995), the [tau neutrino](#) (2000), and the [Higgs boson](#) (2012) have added further credence to the Standard Model. In addition, the Standard Model has predicted various properties of [weak neutral currents](#) and the [W and Z bosons](#) with great accuracy.



Quantum Field Theory description of *all* forces!

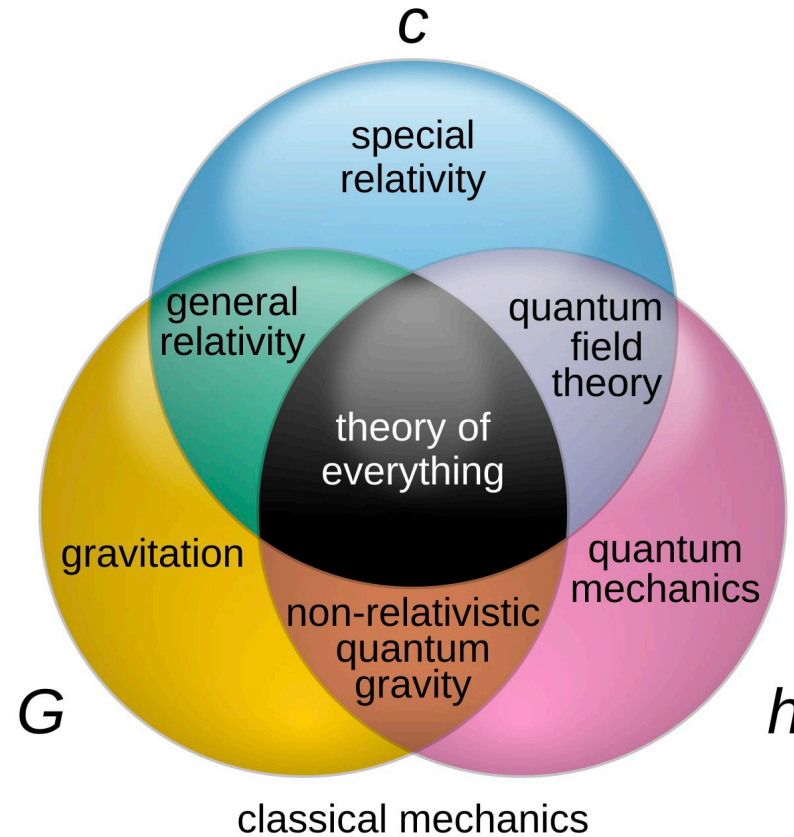
Except gravity

Quantum And Gravity

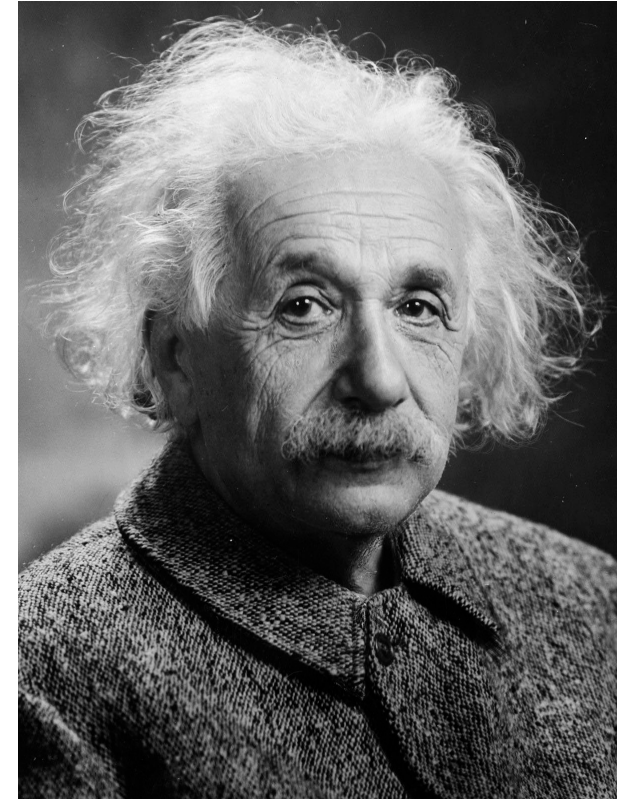


Quantum Mechanics

**Quantum Field theories of
space time**



Low energies: Linearized effective field
theory works fine



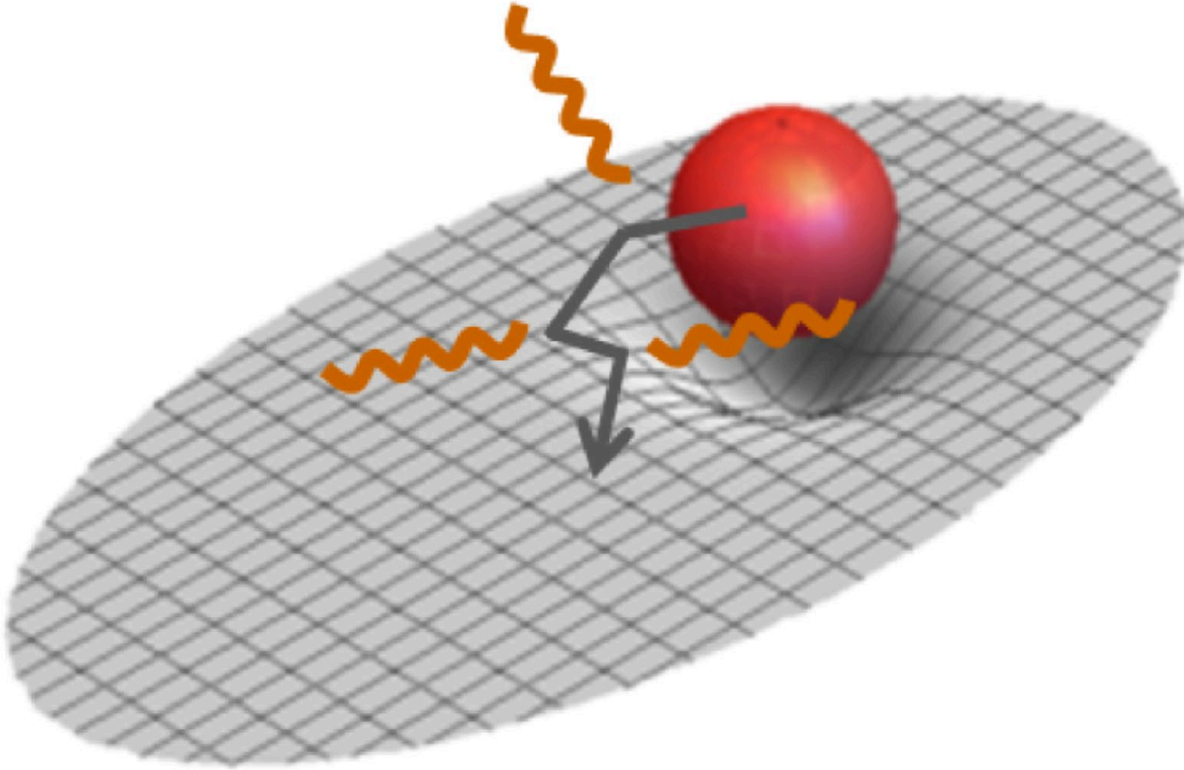
General Relativity

High energy:
“Convergence problems”

Maybe gravity is **not** quantum?

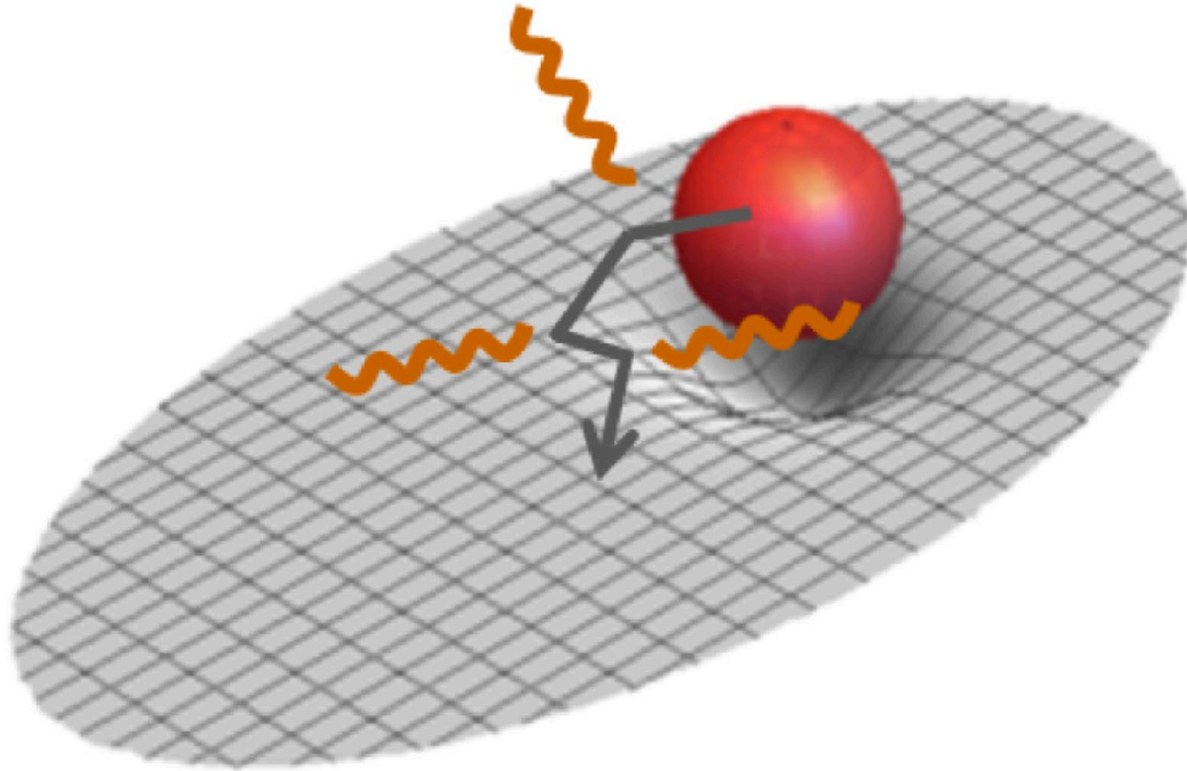
Modifications of Quantum Mechanics:

Maybe gravity is **not** quantum?



Modifications of Quantum Mechanics:
Collapse noise

Maybe gravity is **not** quantum?



Modifications of Quantum Mechanics:
Collapse noise

“Continuous Spontaneous Localization” (CSL)

$$d|\psi_t\rangle = \left[-\frac{i}{\hbar} H dt + \frac{\sqrt{\gamma}}{m_0} \int d^3x (M(\mathbf{x}) - \langle M(\mathbf{x}) \rangle_t) dW_t(\mathbf{x}) - \frac{\gamma}{2m_0^2} \int \int d^3x d^3y G(\mathbf{x} - \mathbf{y}) (M(\mathbf{x}) - \langle M(\mathbf{x}) \rangle_t) (M(\mathbf{y}) - \langle M(\mathbf{y}) \rangle_t) \right] |\psi_t\rangle, (2)$$

for each point of space, with average equal to zero. They are “white” in time, while they have a Gaussian correlation function in space:

$$\mathbb{E}[W_t(\mathbf{x})W_s(\mathbf{y})] = \delta(t-s)G(\mathbf{x}-\mathbf{y}), \quad G(\mathbf{x}-\mathbf{y}) = \frac{1}{(4\pi r_C^2)^{3/2}} \exp[-(\mathbf{x})^2/4r_C^2]. \quad (3)$$

Two free parameters:

r_C Collapse Radius

γ_C Collapse Rate

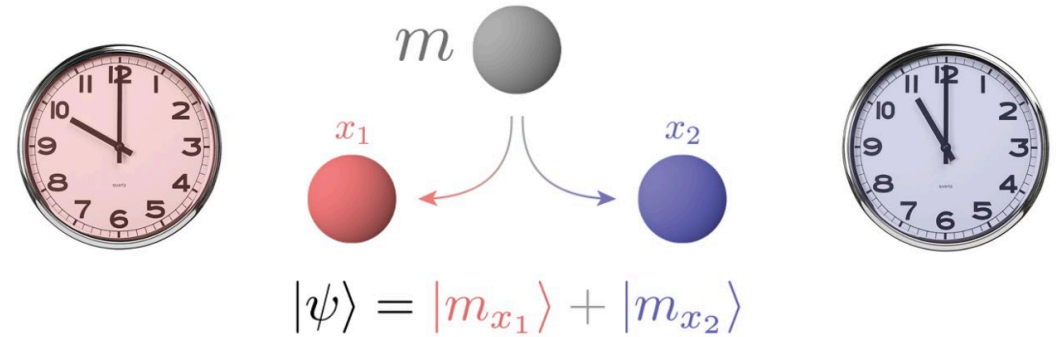
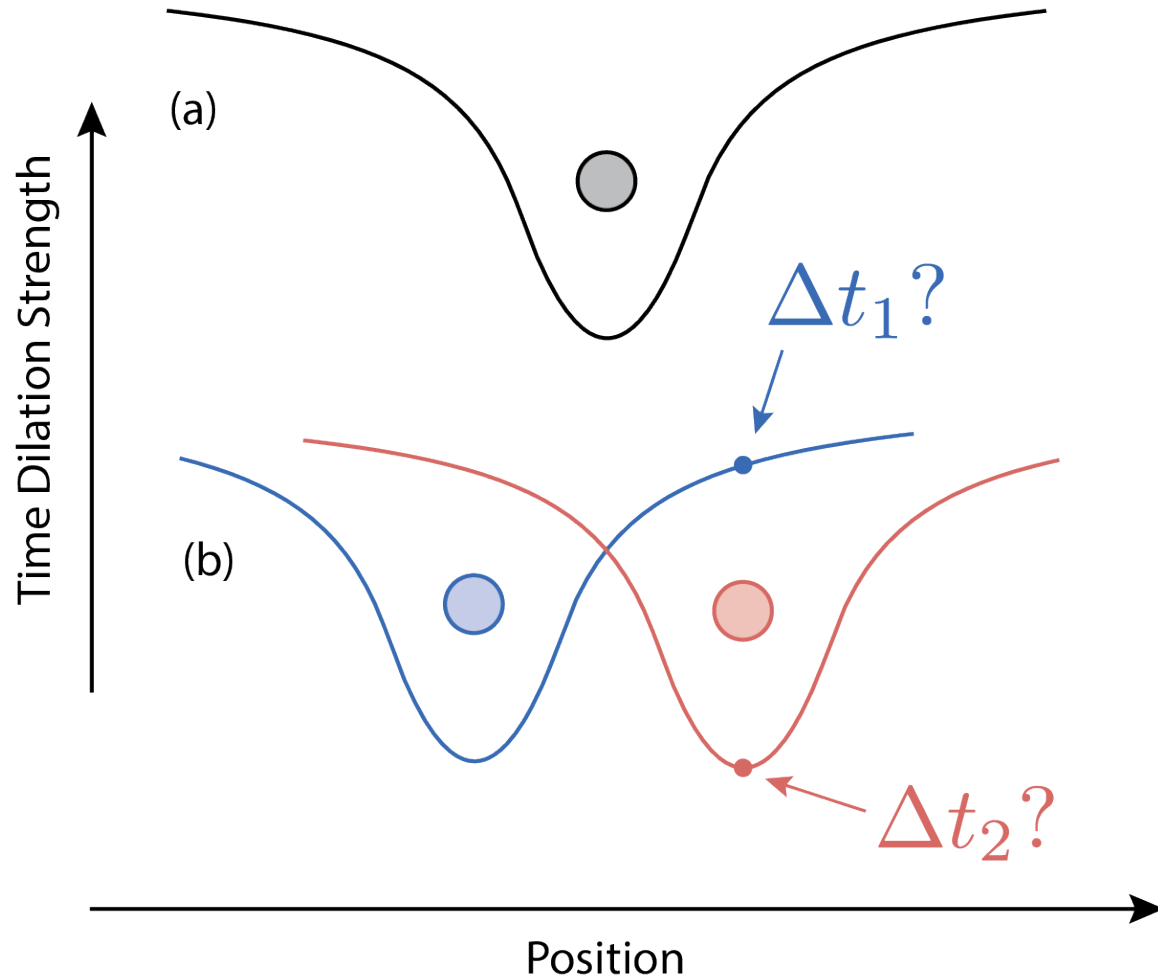
Diosi-Penrose: Gravitationally motivated CSL

$$d|\psi_t\rangle = \left[-\frac{i}{\hbar} \hat{H} dt + \int d^3\mathbf{x} \left(\hat{M}(\mathbf{x}) - \langle \hat{M}(\mathbf{x}) \rangle_t \right) dW_t(\mathbf{x}) - \frac{1}{2} \iint d^3\mathbf{x} d^3\mathbf{y} \mathcal{G}(\mathbf{x} - \mathbf{y}) \left(\hat{M}(\mathbf{x}) - \langle \hat{M}(\mathbf{x}) \rangle_t \right) \left(\hat{M}(\mathbf{y}) - \langle \hat{M}(\mathbf{y}) \rangle_t \right) dt \right] |\psi_t\rangle, \quad (1)$$

Nonlinear term explicitly linked to gravity

One parameter: Collapse radius fixes collapse rate (decoherence time)

How big is the decoherence time?



Uncertainty in time =>
Uncertainty in phase

$$t_G = \frac{\hbar R}{Gm^2}$$

Towards experiments: what is the timescale?

$$t_G = \frac{\hbar R}{Gm^2}$$

R = cutoff you choose

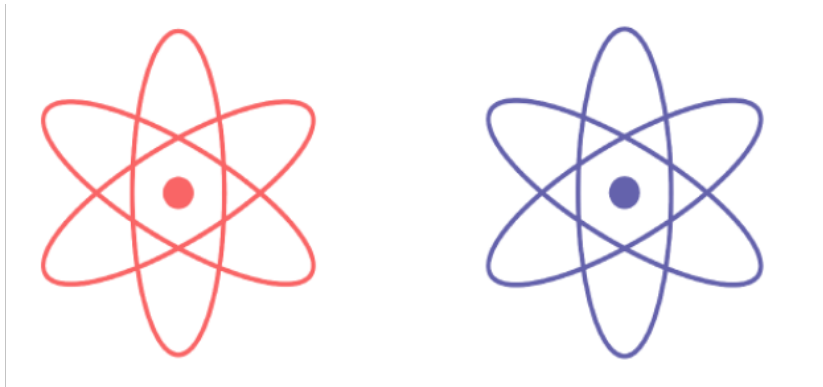
Nuclear diameter: reasonable choice for an optimistic lower bound

Towards experiments: what is the timescale?

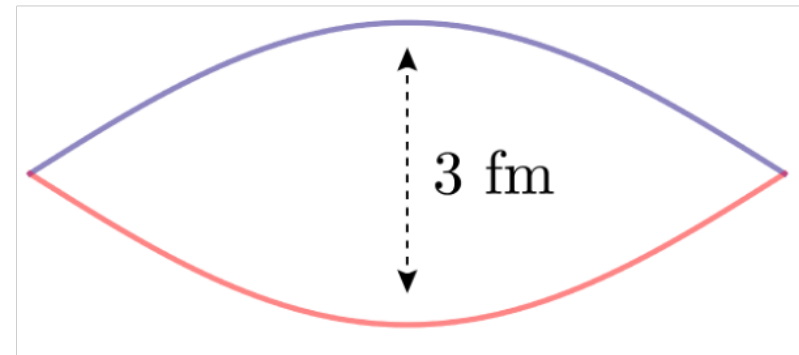
$$t_G = \frac{\hbar R}{Gm^2}$$

R = cutoff you choose

Nuclear diameter: reasonable choice for an optimistic lower bound



$$m = 4 \times 10^{-23} \text{ g}$$
$$t_G = 2000 \text{ years}$$



$$m = 2 \text{ ng}$$
$$t_G = 1 \text{ ms}$$

What do you need?

$$t_{dec} > t_G$$

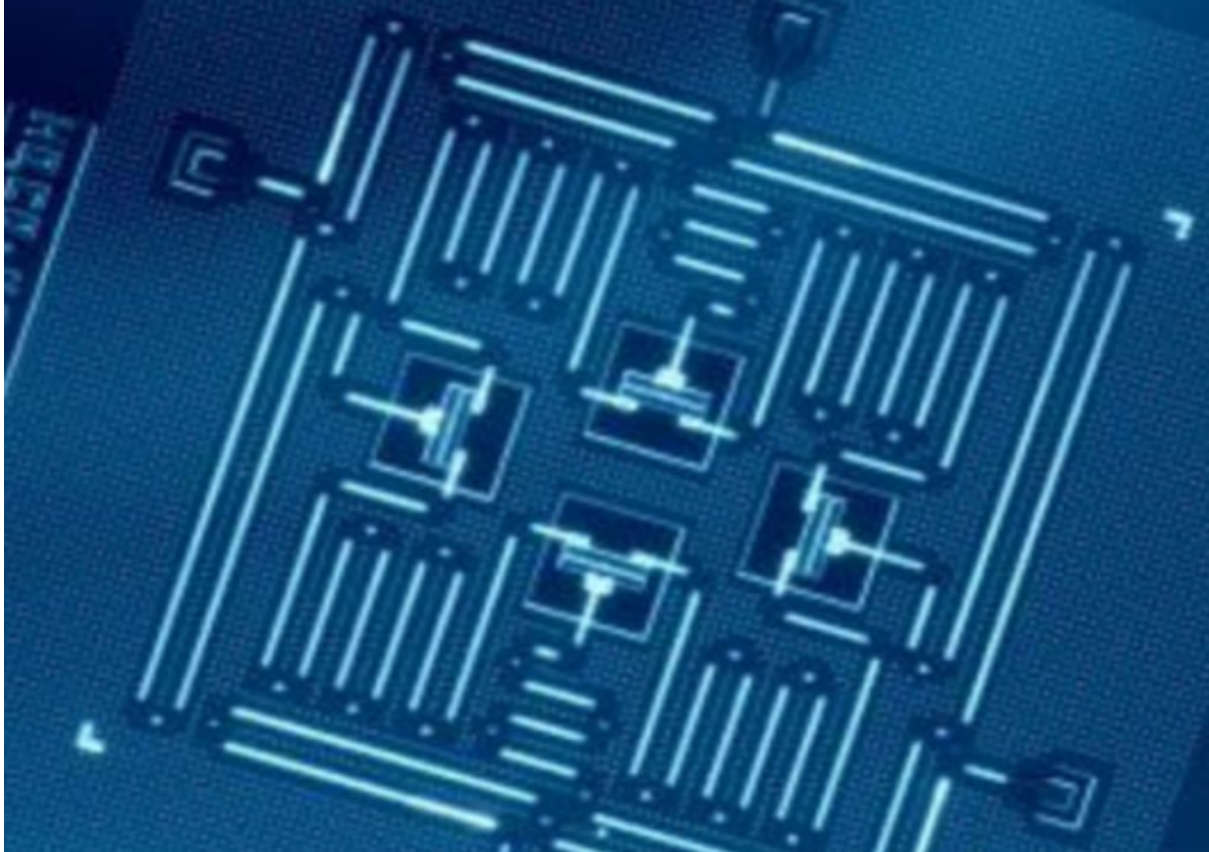
High Coherence

Large Mass

Large (enough) Superposition

Our Toolbox

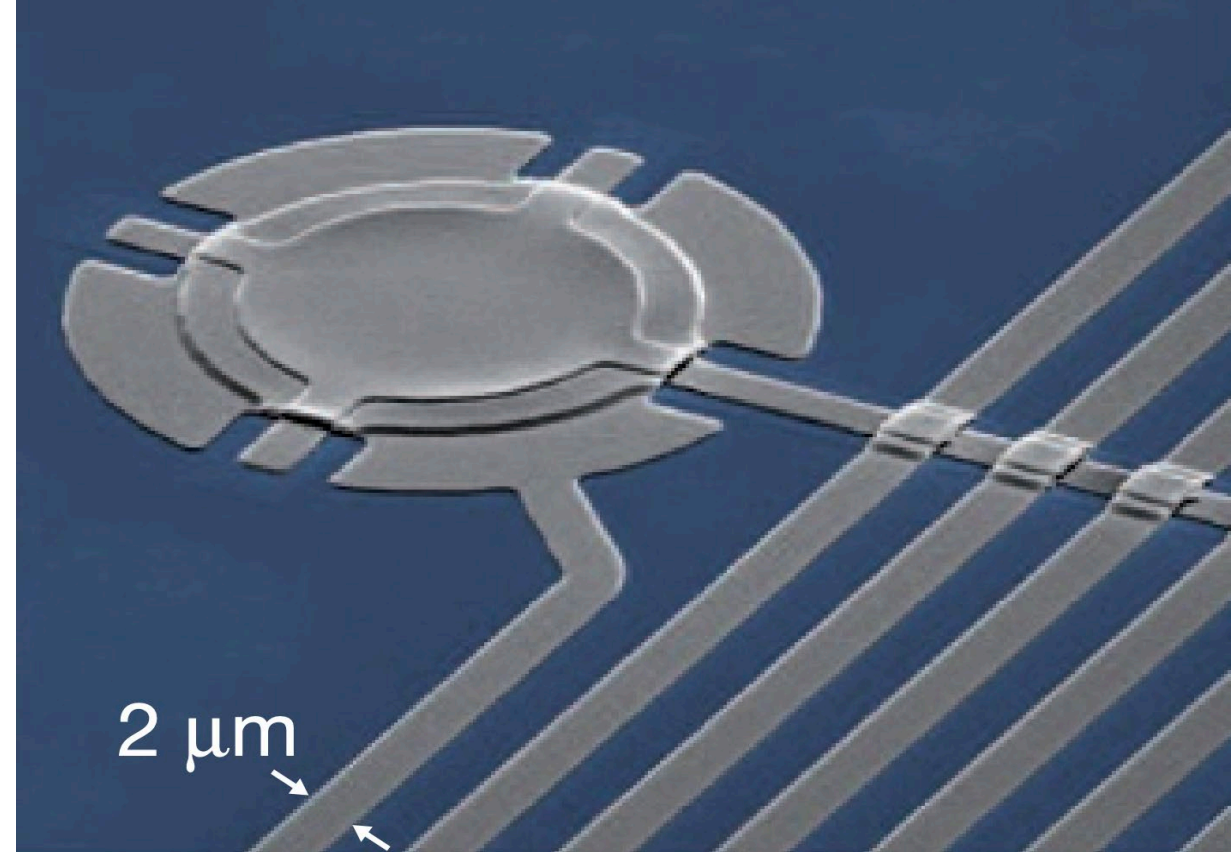
IBM Quantum



Circuit QED

Create Superpositions

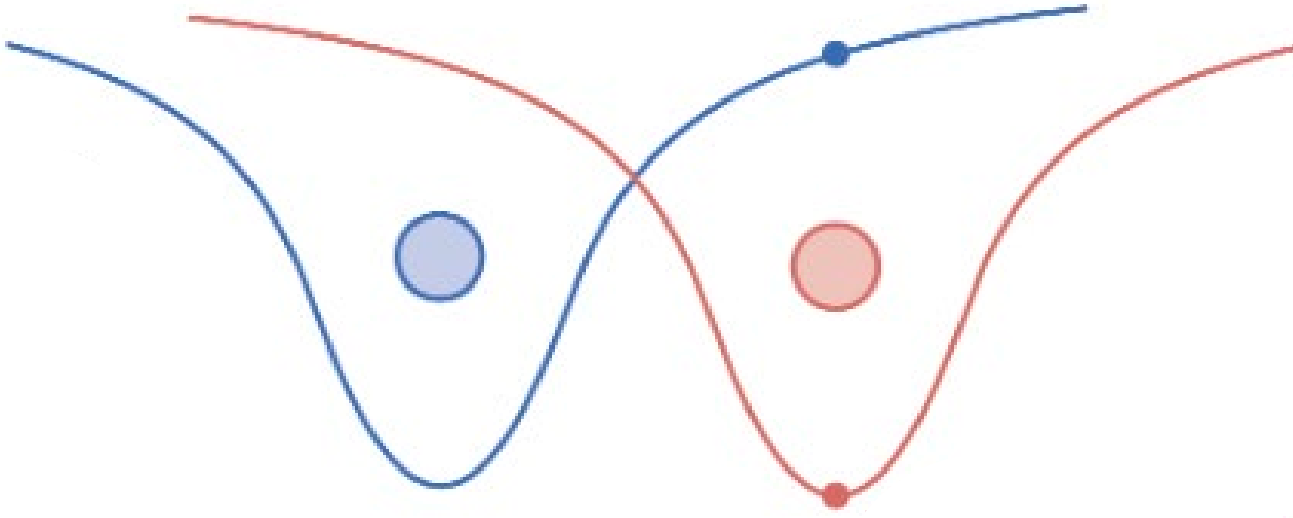
NIST / JILA



Cavity Optomechanics

Interface to Mechanical Devices

How to pick a resonator



$$t_G = \frac{\hbar R}{Gm^2}$$

"Normal" coherence of that superposition longer than t_G

Superposition size larger than your cutoff

Important: decoherence in an oscillator increases linearly with size (Haroche)

What mechanical resonator can you use?

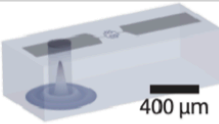
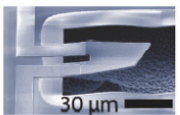
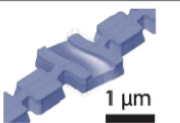
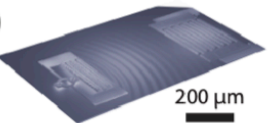
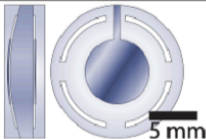
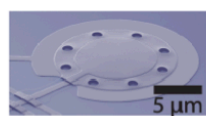
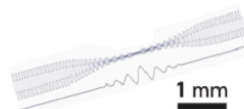
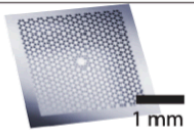
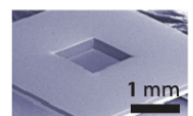
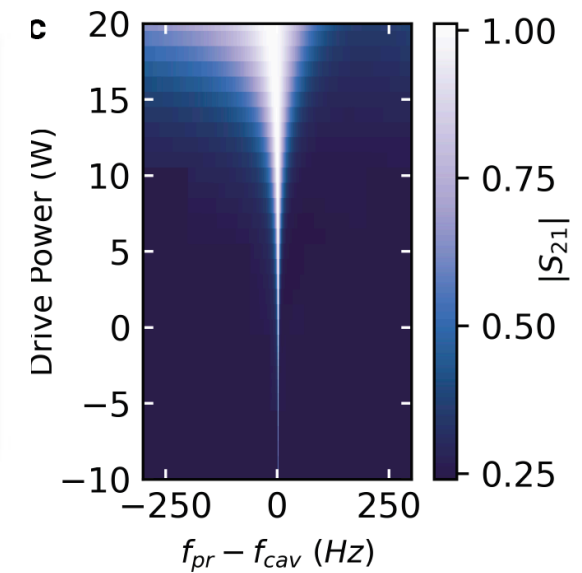
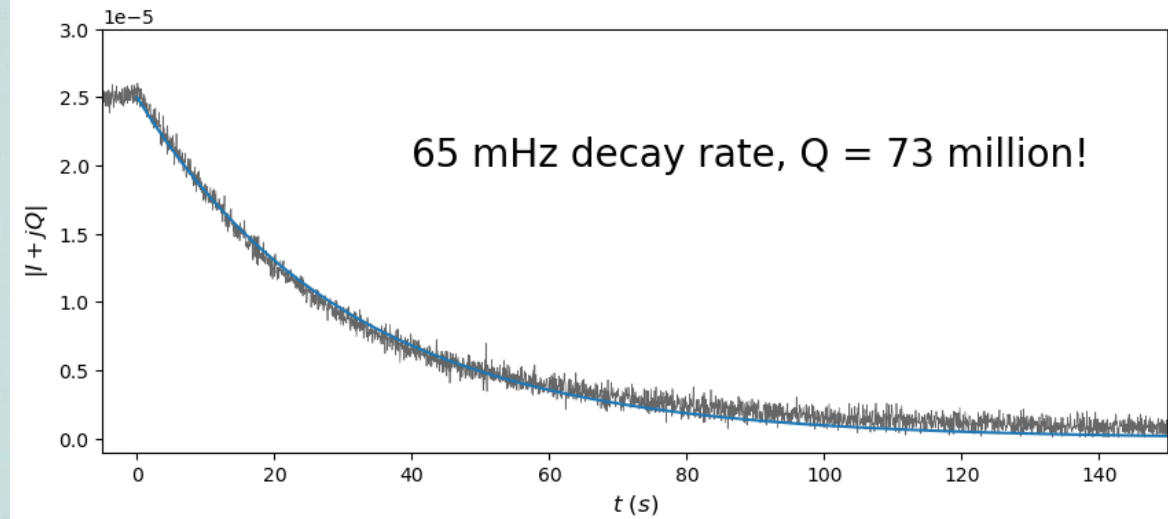
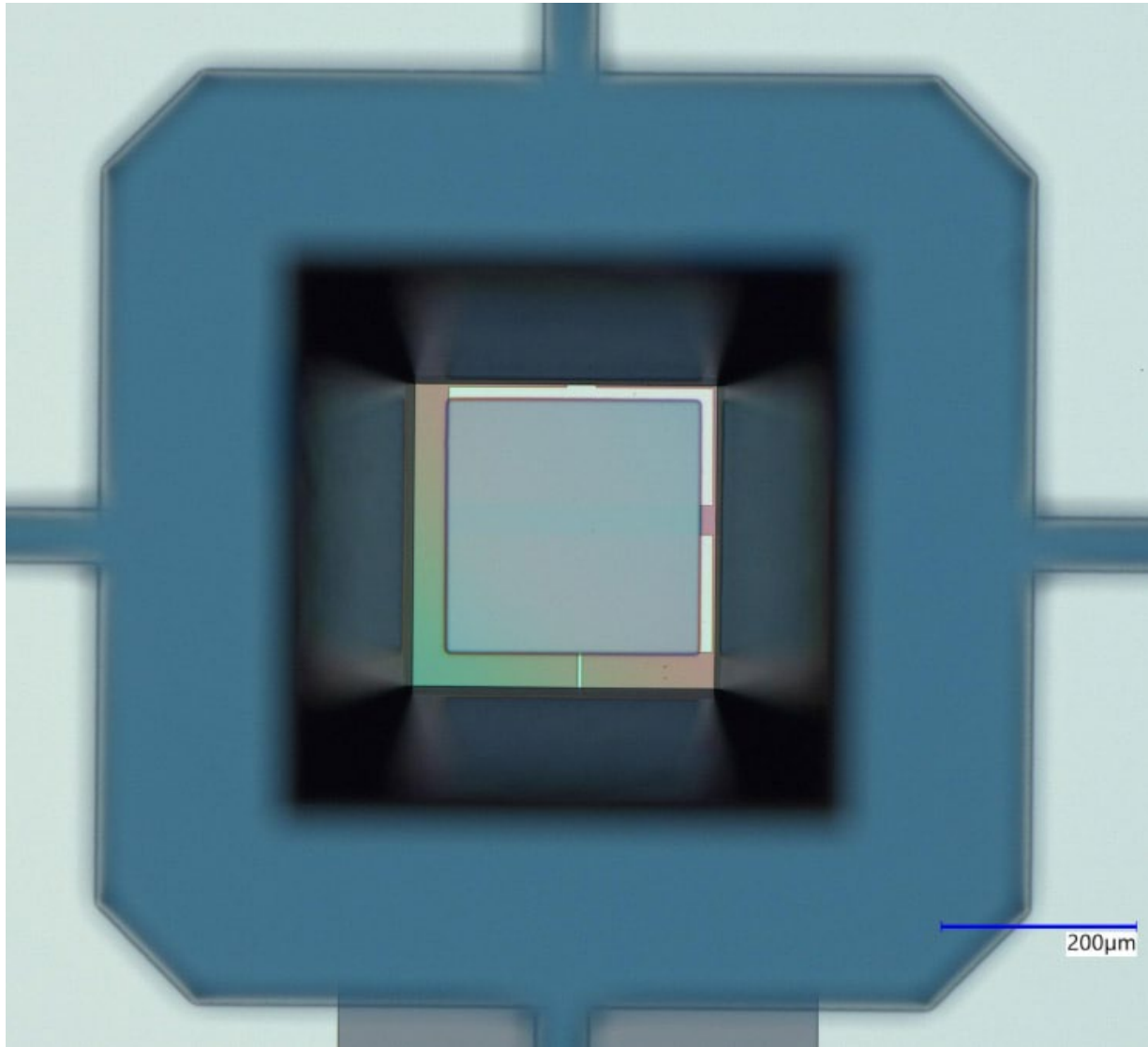
	f_m	m	x_{zpf}	n	Q	t_{coh}	t_{GR}
(a) 	7 GHz	50 μg	0.2 am	3×10^8	2×10^6	60 fs	60 ns
(b) 	6 GHz	2 ng	30 am	8×10^3	300	0.4 ps	2 ms
(c) 	5 GHz	0.1 pg	4 fm	0/1	4×10^6 * T_2	60 μs	20 s
(d) 	2 GHz	2 pg	1 fm	4	6×10^3	60 ns	2 s
(e) 	0.8 GHz	0.2 μg	7 am	10^5	6×10^4 *4K	40 ps	10 μs
(f) 	20 MHz	5 mg	0.3 am	7×10^7	2×10^9	6 ns	0.6 ns
(g) 	10 MHz	50 pg	4 fm	0/1	7×10^5	0.1 ms	60 ms
(h) 	2 MHz	5 pg	30 fm	0/1	8×10^8 *RT	0.2 s	0.6 s
(i) 	1 MHz	2 ng	2 fm	2	1×10^9 *10K	90 ms	1 ms
(j) 	200 kHz	0.5 μg	0.3 fm	90	10^8	0.3 ms	7 μs

Figure 14: Resonators from literature with coherence times able to test gravity Our recent analysis [13] identified three mechanical resonators with coherence parameters that can reach the general relativity time scale. The superposition states of (i) and (j) would be feasible to create using cQED, and form the basis of this proposal.

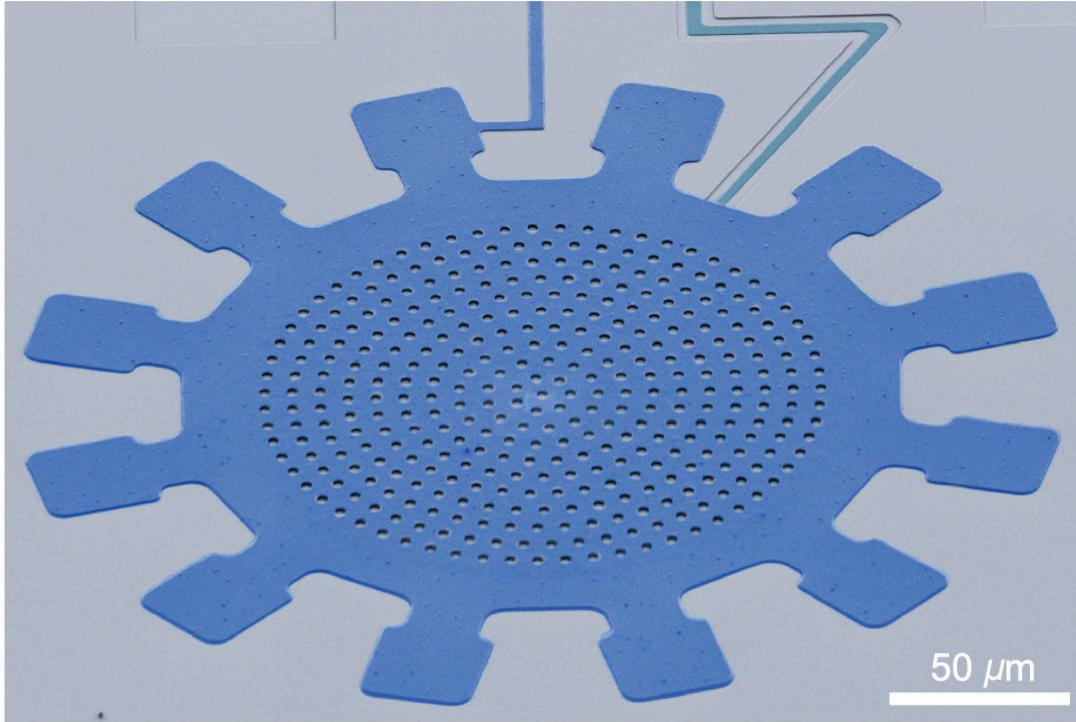
Silicon Nitride Membranes



NEW generation Metal Drums!

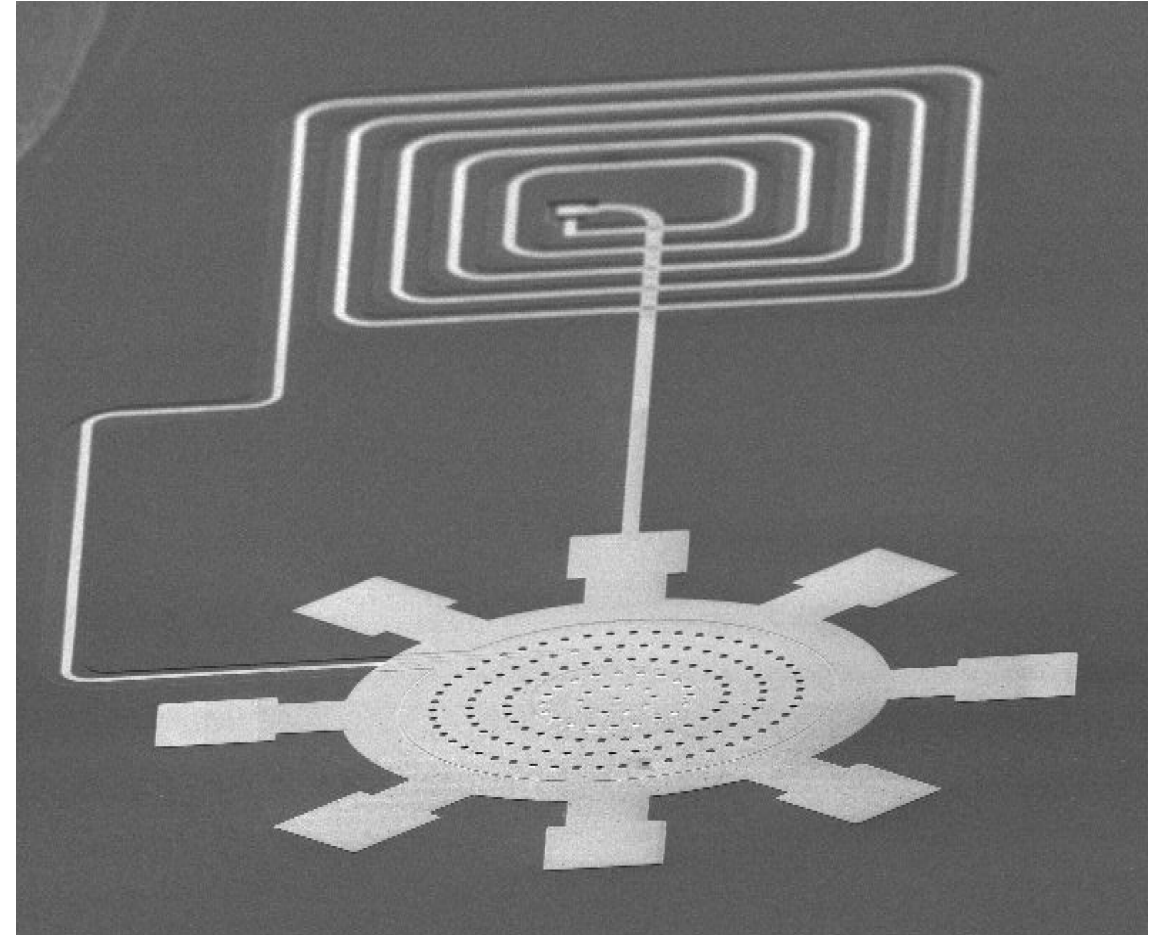
EPFL

SteeleLab



A squeezed mechanical oscillator with milli-second quantum decoherence

Amir Youssefi, Shingo Kono, Mahdi Chegnizadeh, Tobias J. Kippenberg



Order of magnitude in mass, two in coherence: viable for Diosi-Penrose tests!

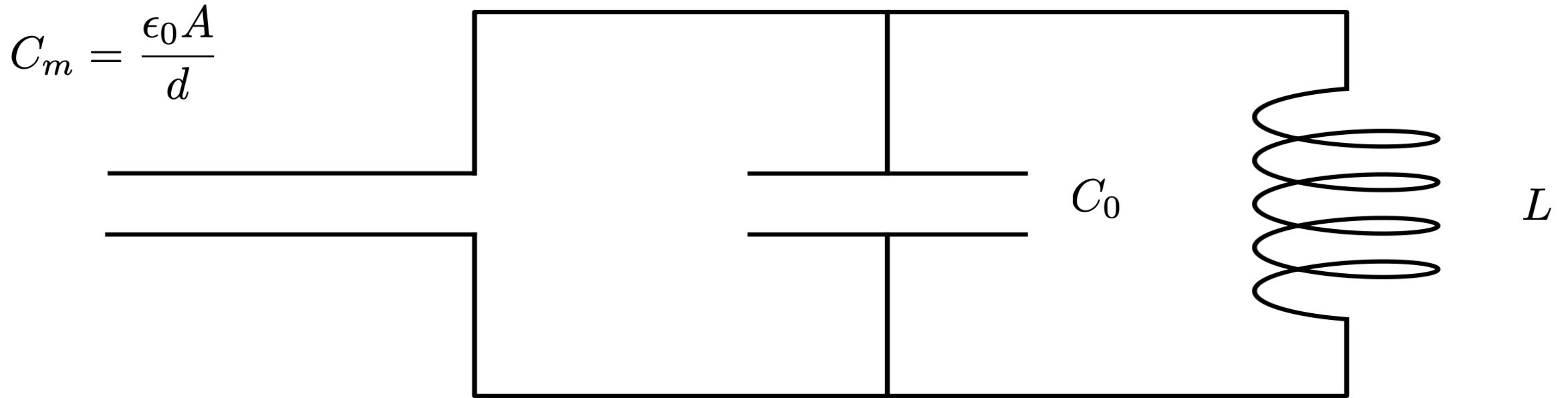
Plan: Make Mechanical Cats!



Are they coherent on gravitational timescales?

How?

Cavity Electromechanics / Optomechanics



$$H = \hbar g_0 a^\dagger a (b + b^\dagger)$$

“optomechanical coupling”

$$g_0 = \frac{\omega_c}{2} \frac{x_{zpf}}{d} \underbrace{\frac{C_m}{C_m + C_0}}_{\beta_C}$$

How big is g_0 ? And what do I compare it to?

$$g_0 = \frac{\omega_c}{2} \frac{x_{zpf}}{d} \frac{C_m}{C_m + C_0}$$

If you're pretty good: 10 Hz

If you're awesome: 100 Hz

Both cases: useless on its own

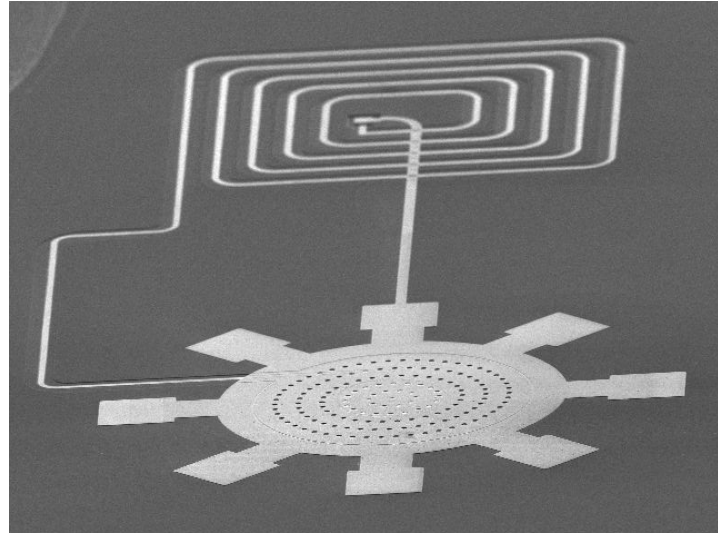
$$\gamma_m \sim 1 \text{ mHz} - 10 \text{ Hz}$$

$$\kappa \sim 50 \text{ kHz}$$

Mechanics is not the
problem

Cavities are a
problem!

Solution: Drive it hard

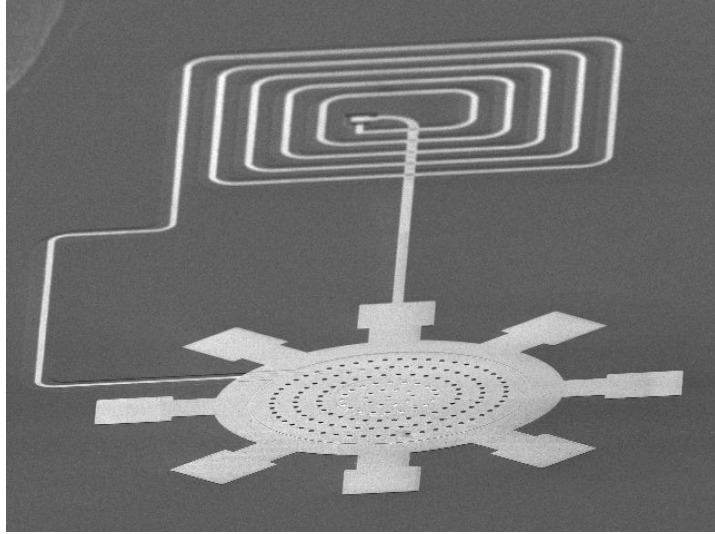


No driving: weak parametric interaction

$$\hbar g_0 a a^\dagger (b + b^\dagger)$$

$$V^2 \quad x$$

Solution: Drive it hard



$$g = \sqrt{N} g_0$$

No driving: weak parametric interaction

$$\hbar g_0 a a^\dagger (b + b^\dagger)$$

$$V^2$$

$$x$$

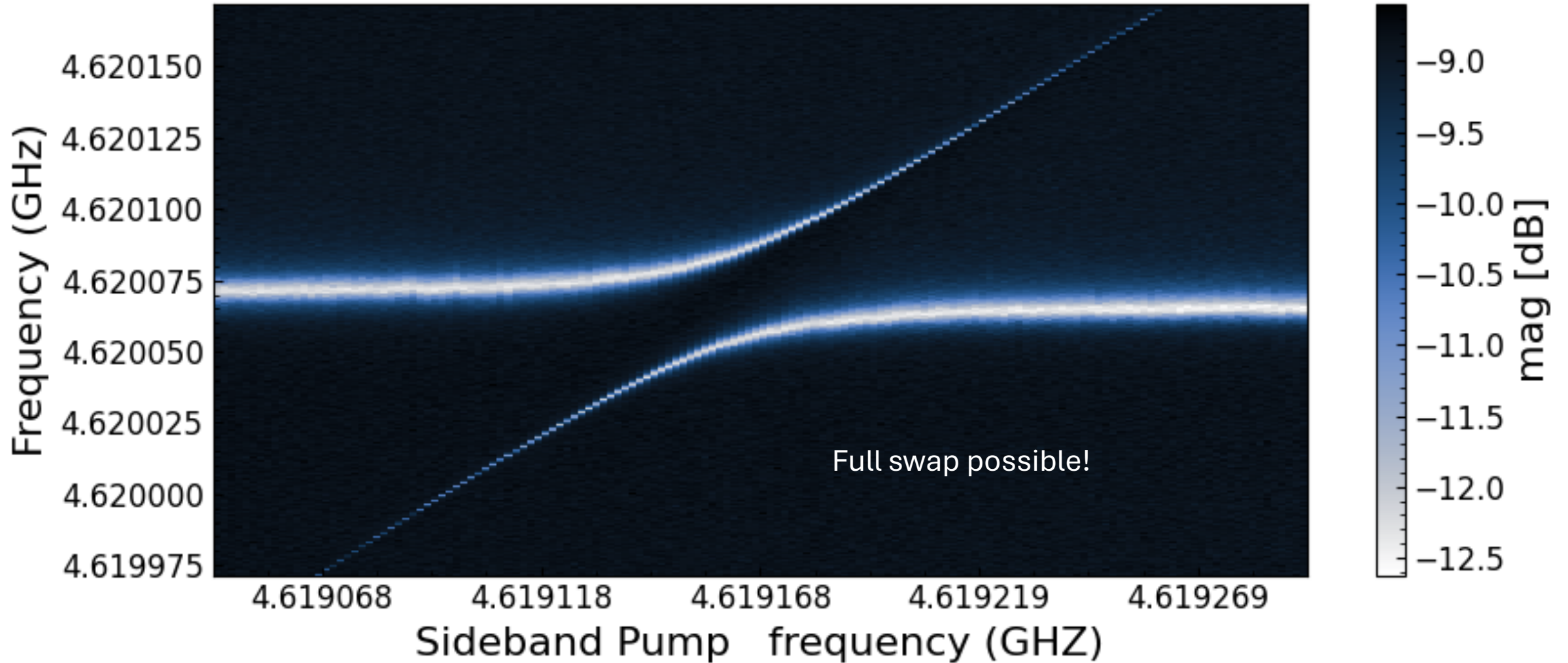
Drive it : Strongly Coupled Pendula!

$$\hbar g (a + a^\dagger) (b + b^\dagger)$$

$$V$$

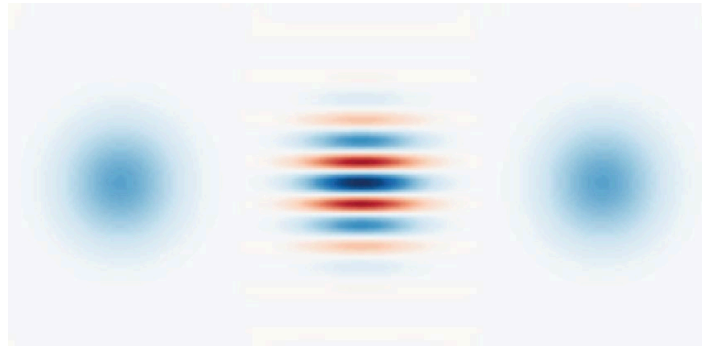
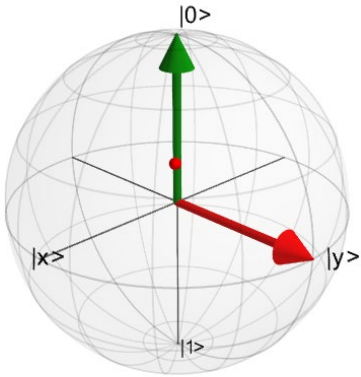
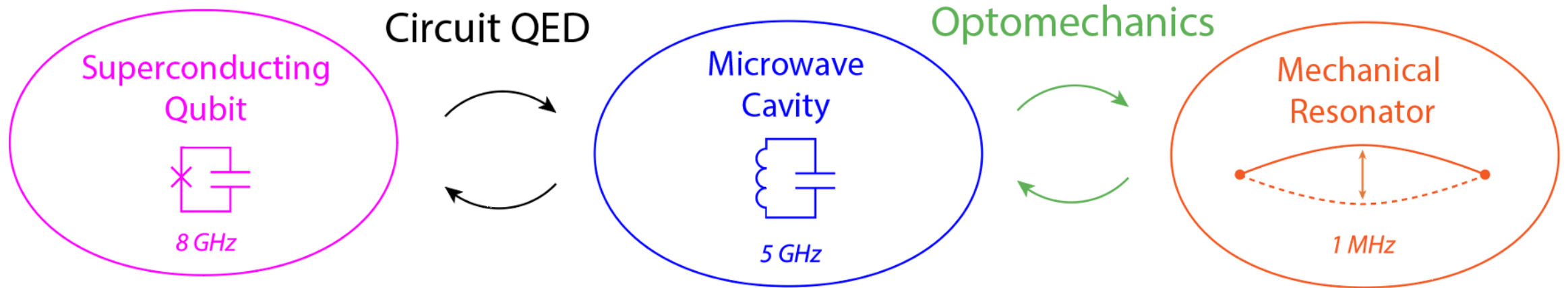
$$x$$

Hybridize, up to strong coupling!



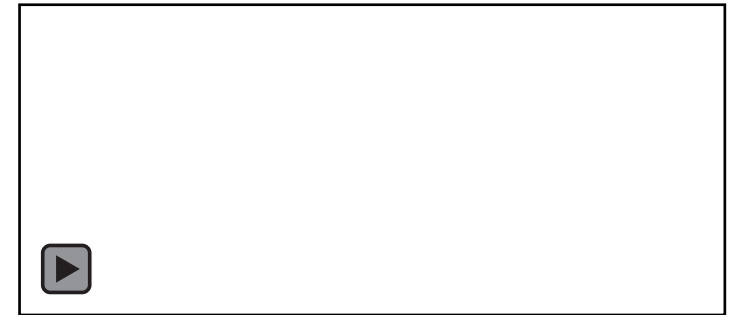
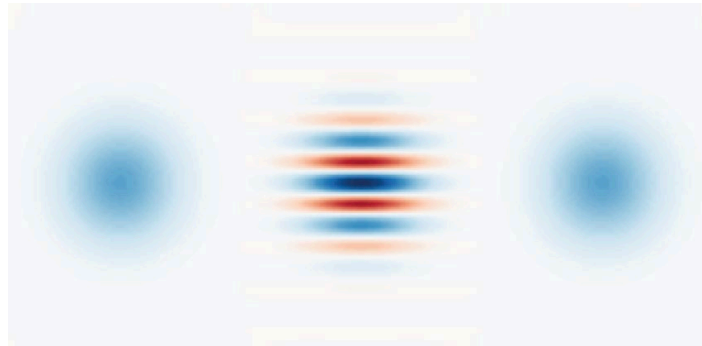
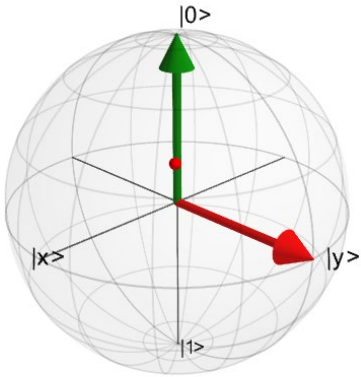
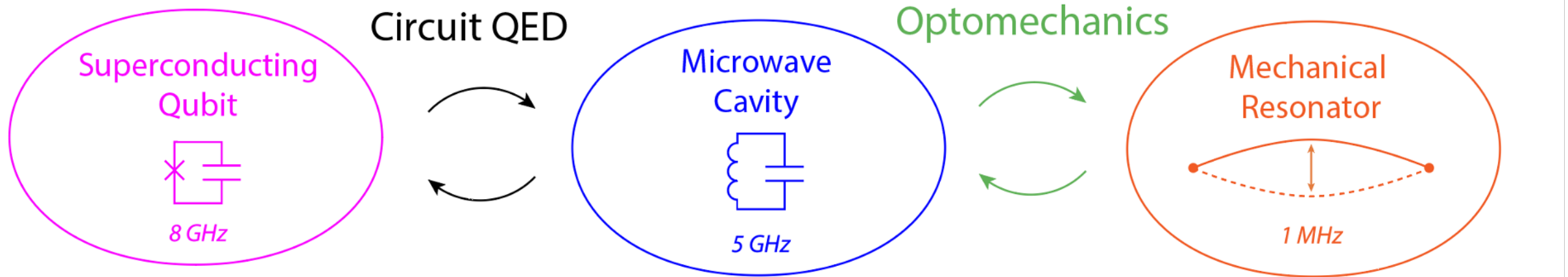
“Frequency translating swap” enabled by frequency of the pump

Straightforward solution: "Swap-Swap"



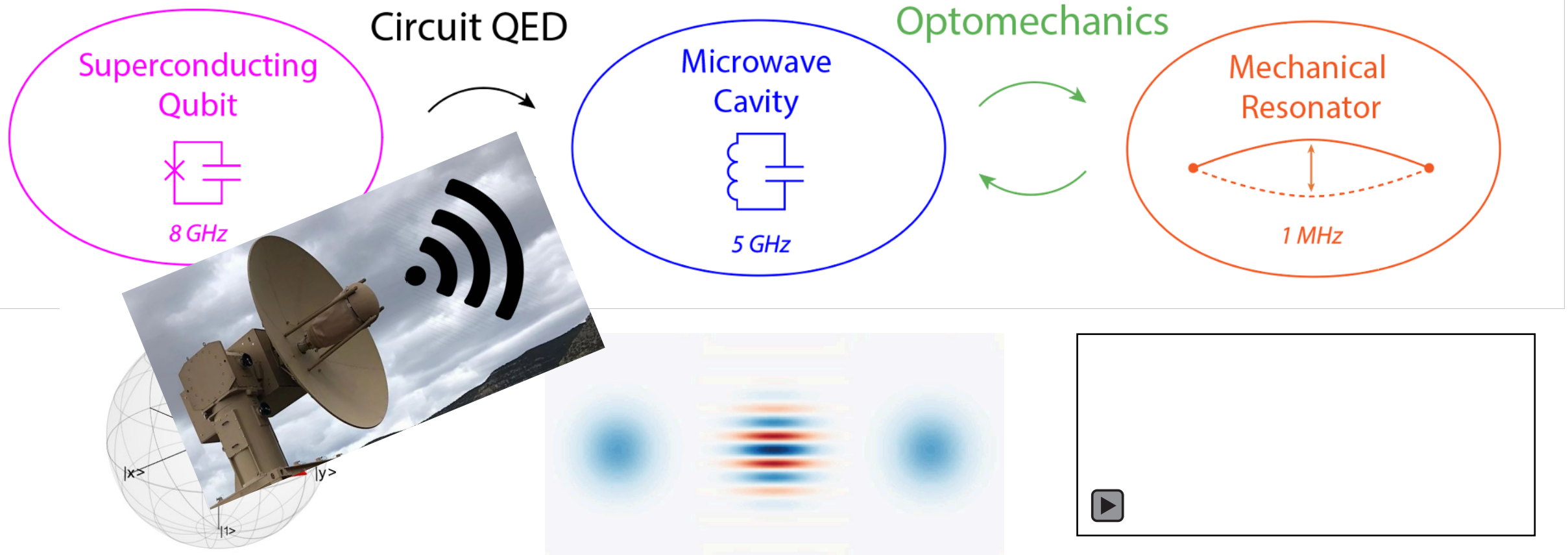
Use cQED to make a microwave cat

Straightforward solution: "Swap-Swap"



Use Optomechanics to swap to drum

Problem: $N = 10^6$



cQED doesn't like $N = 10^6$

Solutions?

New “parameteric” cQED!

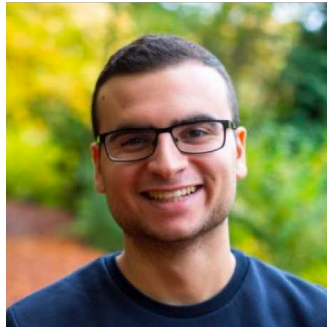
Clinton Potts



Robin Dekker



Sercan Deve



Erik Strijbis



“Normal” (dipole) cQED

$$a^\dagger a (b + b^\dagger) \quad a^\dagger q + q^\dagger a$$

“Normal” (dipole) cQED

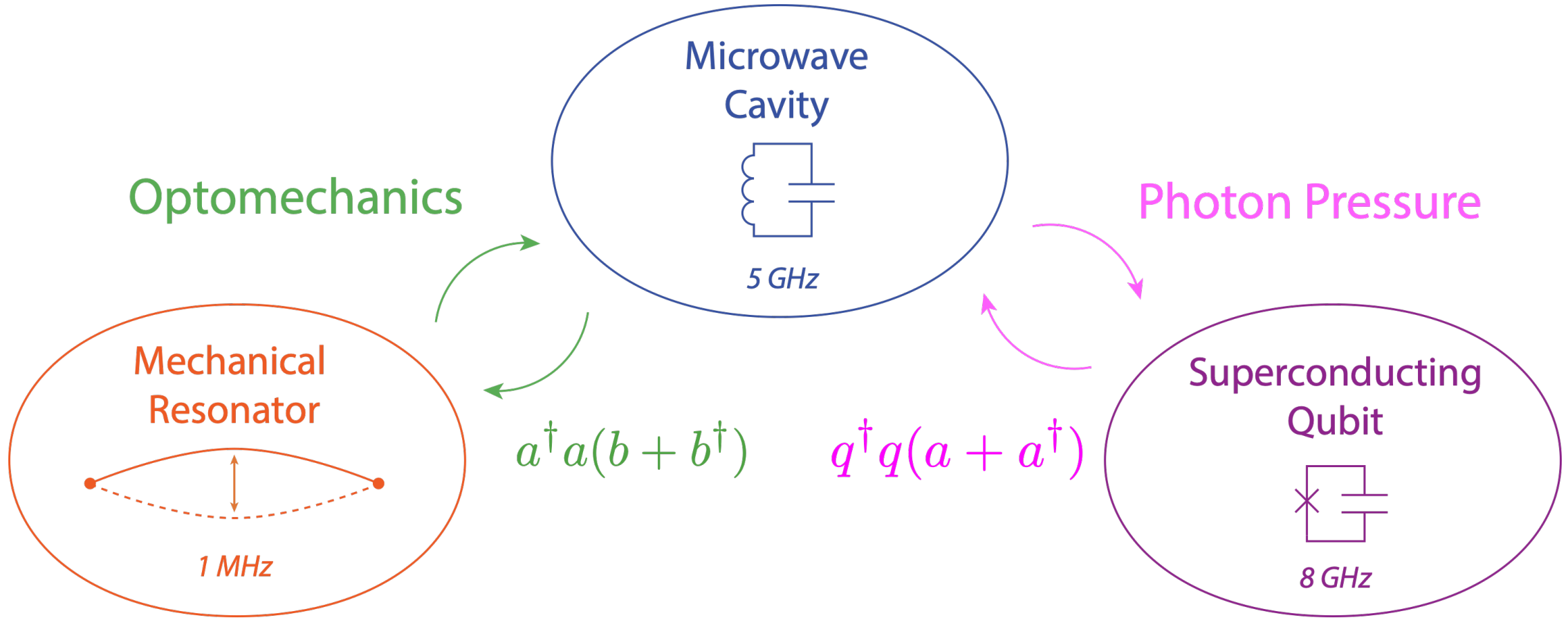
$$a^\dagger a(b + b^\dagger) \quad a^\dagger q + q^\dagger a$$

Problem: Jaynes-Cummings
photons are not “photons”, they
are hybridized with the qubit!

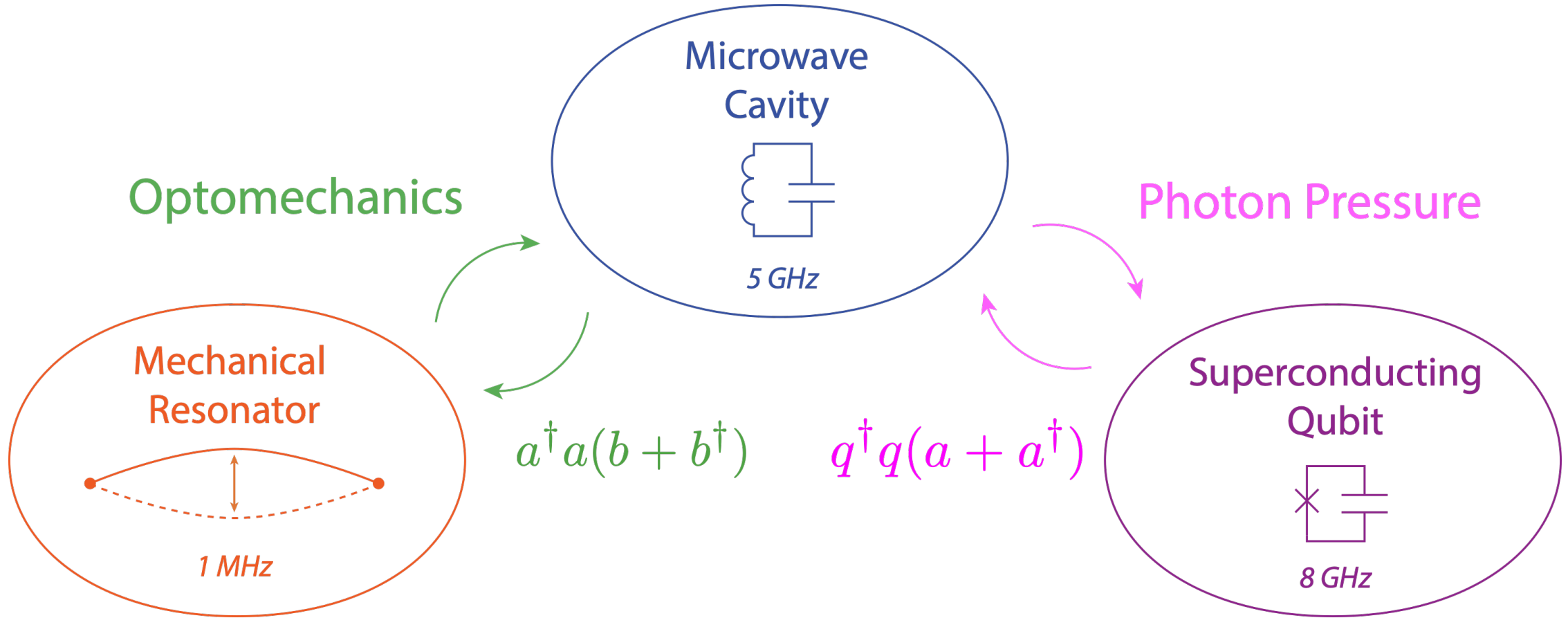
$$\alpha \sim 100 \text{ Hz}$$
$$N_c \sim 100$$

Optomechanics
needs 10^7 photons!

New parametric cQED



New parametric cQED



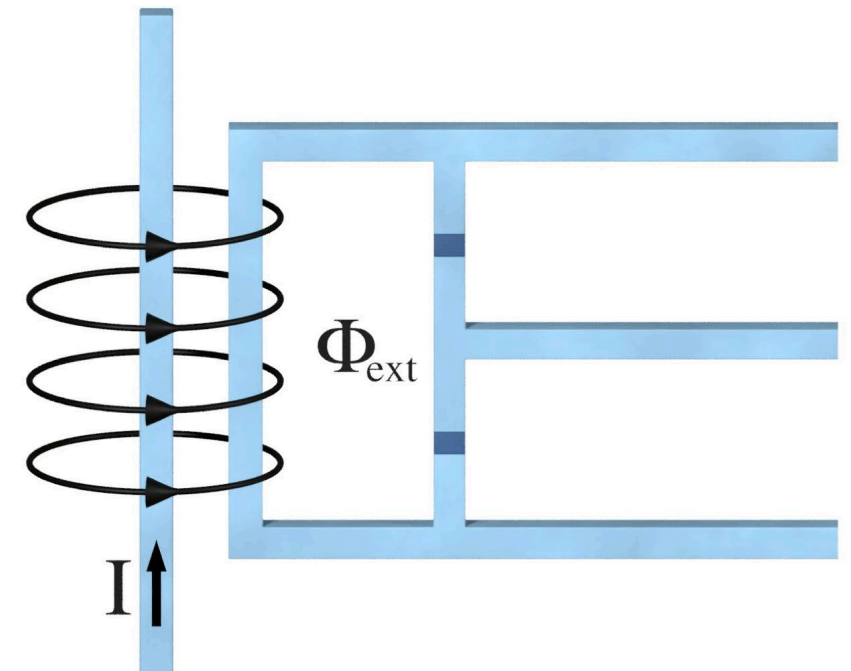
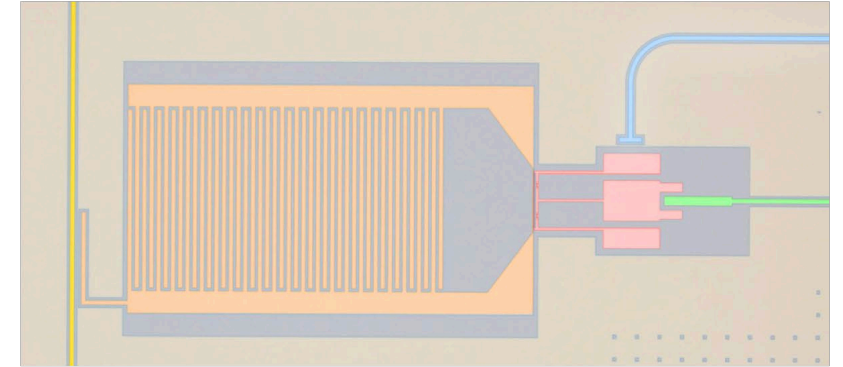
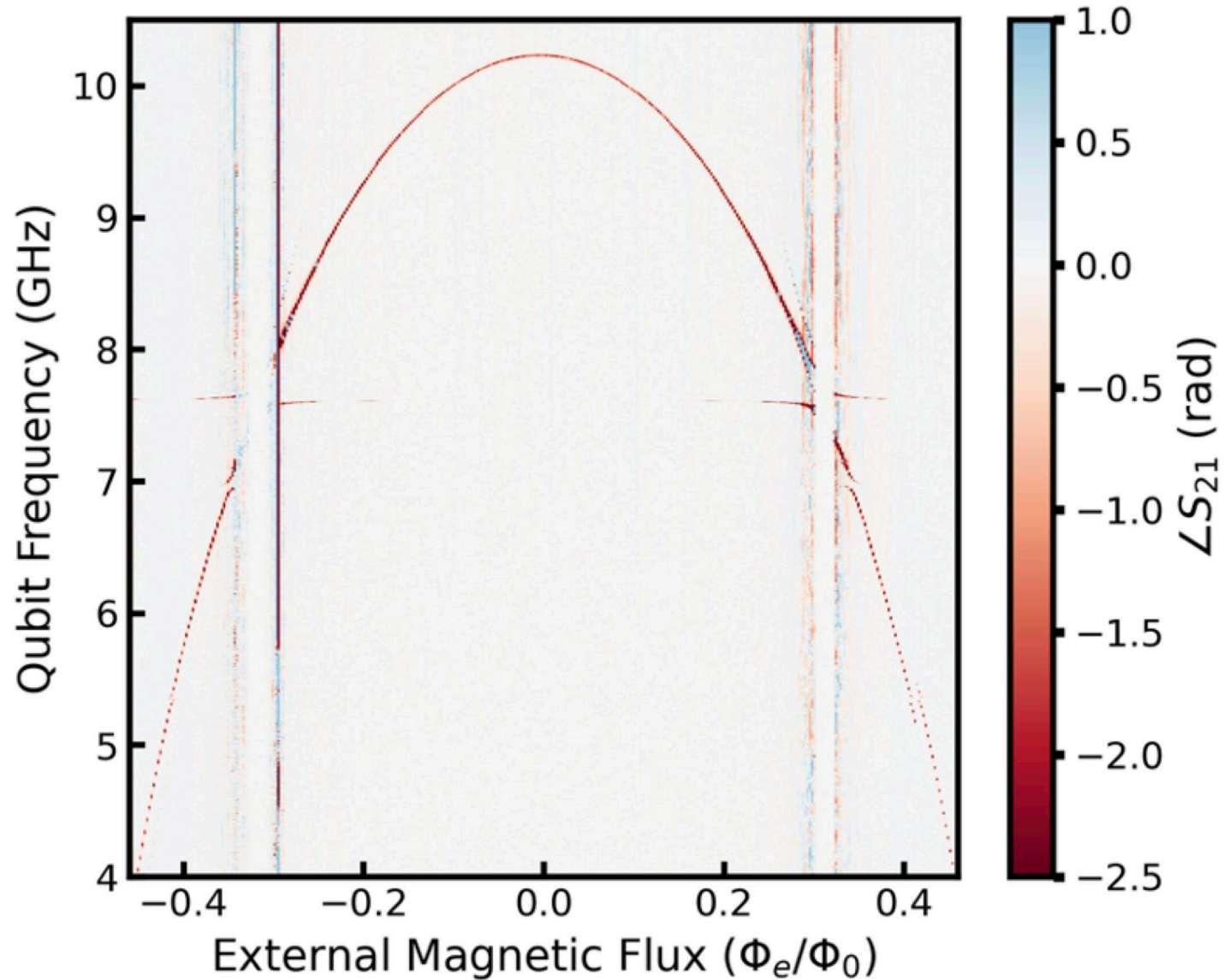
No Hybridization!

**NO nonlinearity of
microwave cavity!**

$$N_c = \infty$$

How?

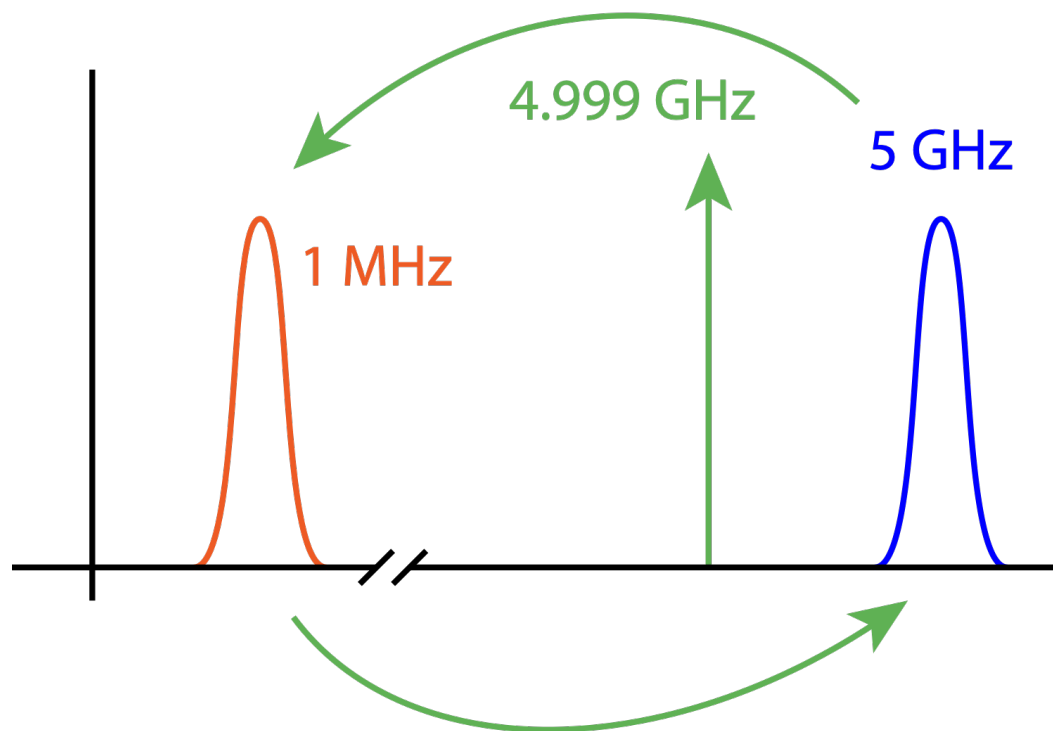
Parametric coupling via flux



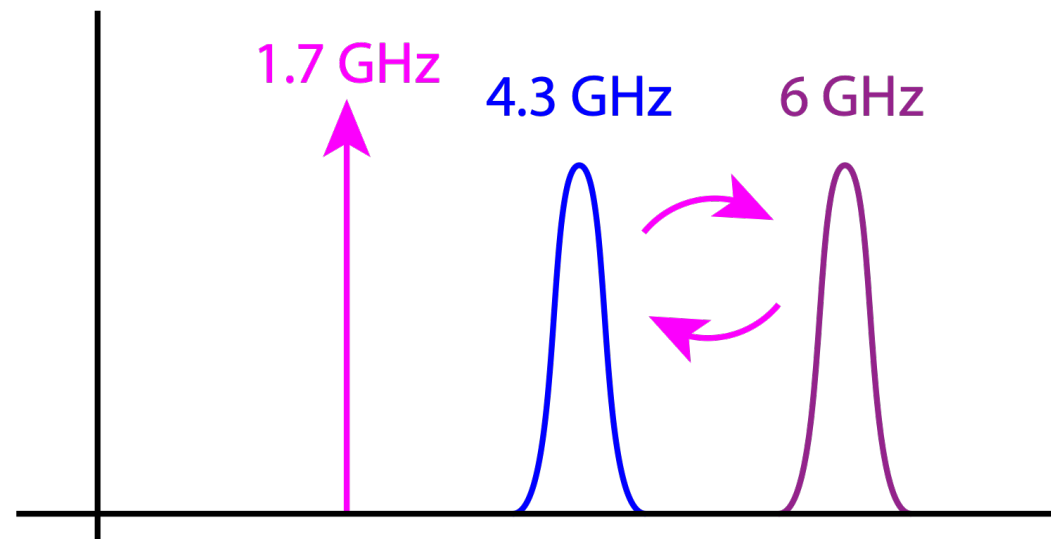
How to interact with the qubit?

Just like “regular” optomechanics

(But with much bigger Δ)

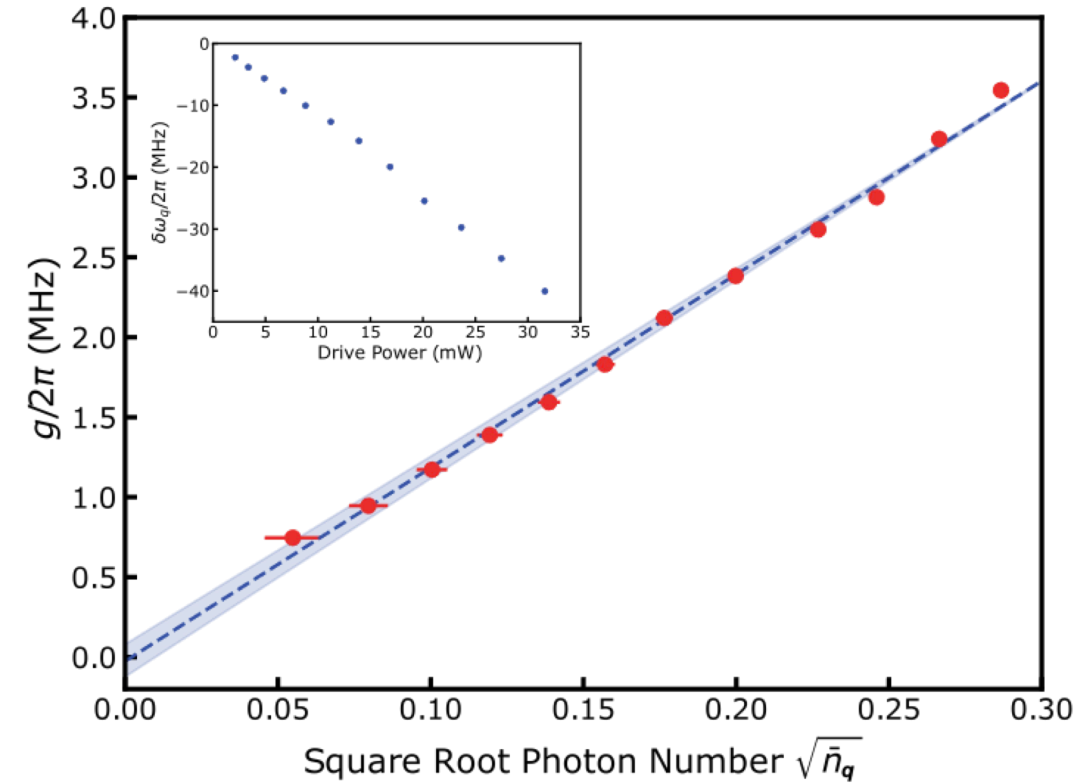


OM Red sideband



Parametric cQED Red sideband

Single photon parametric strong coupling

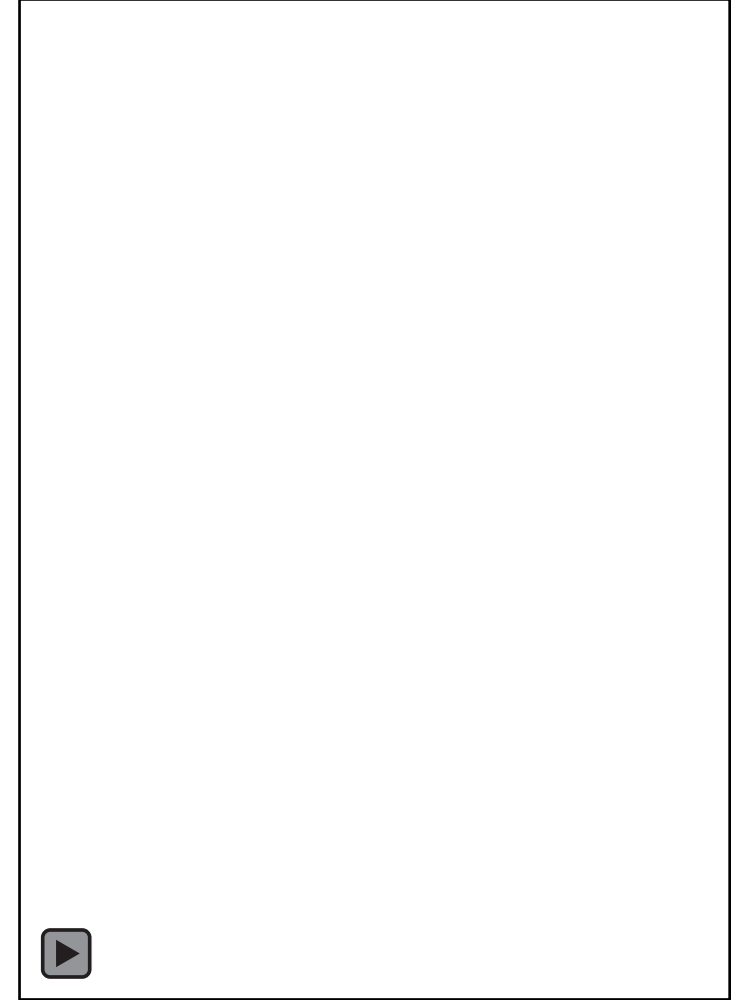
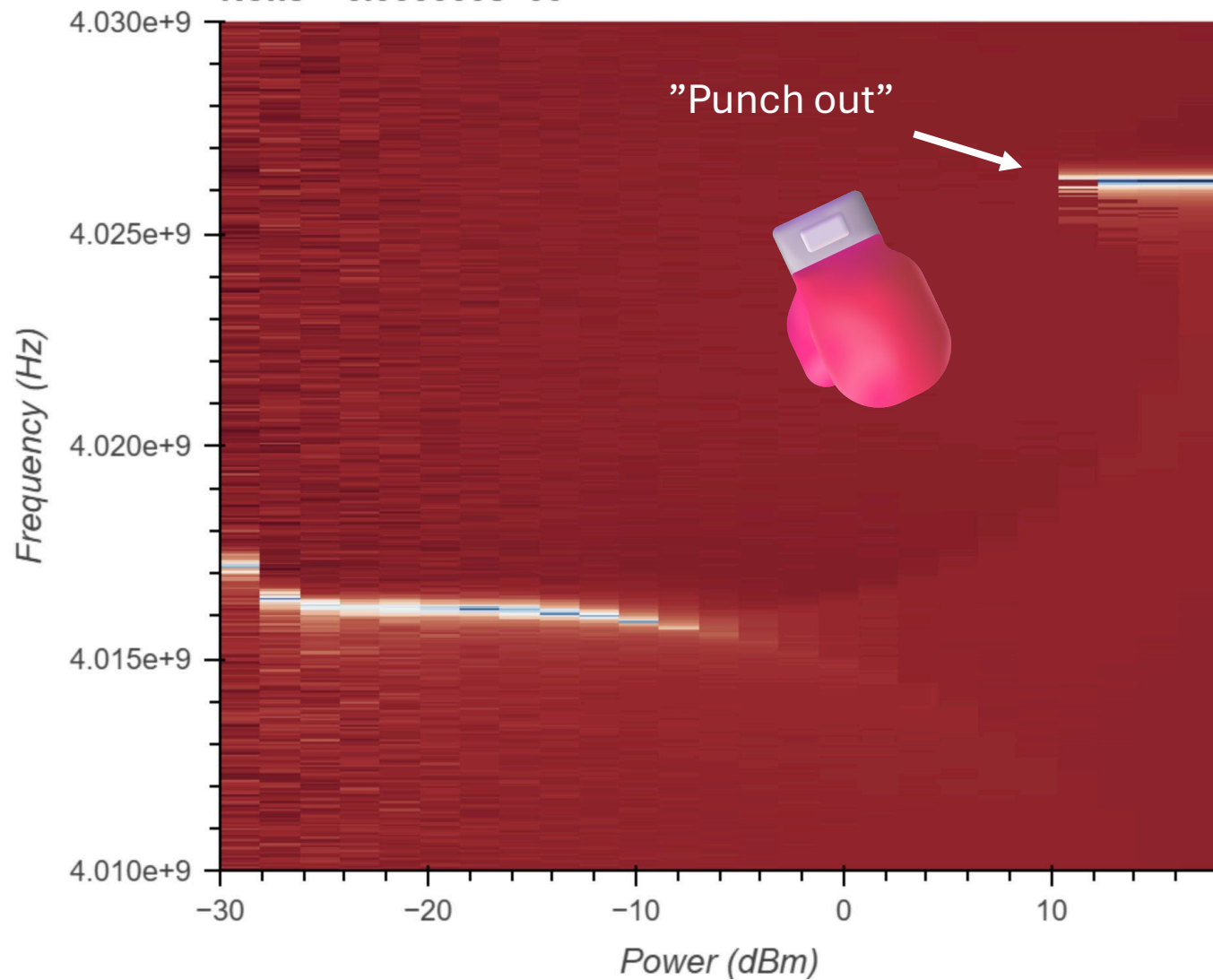


Upper limit from residual hybridisation: 100,000 photons!

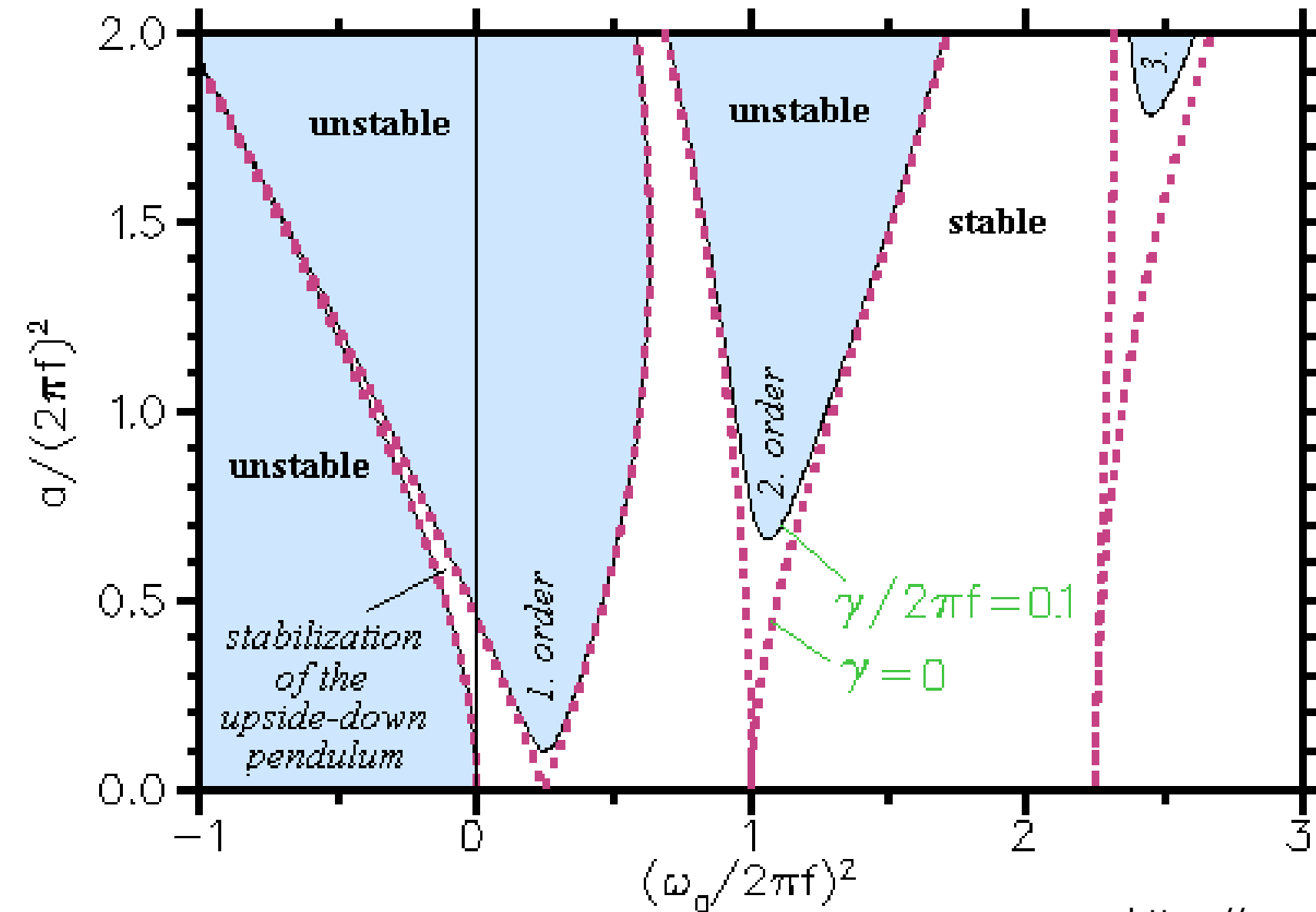
Not so simple!

(Ionisation)

Problem: Qubits do not like cavities with $N = 10^8$

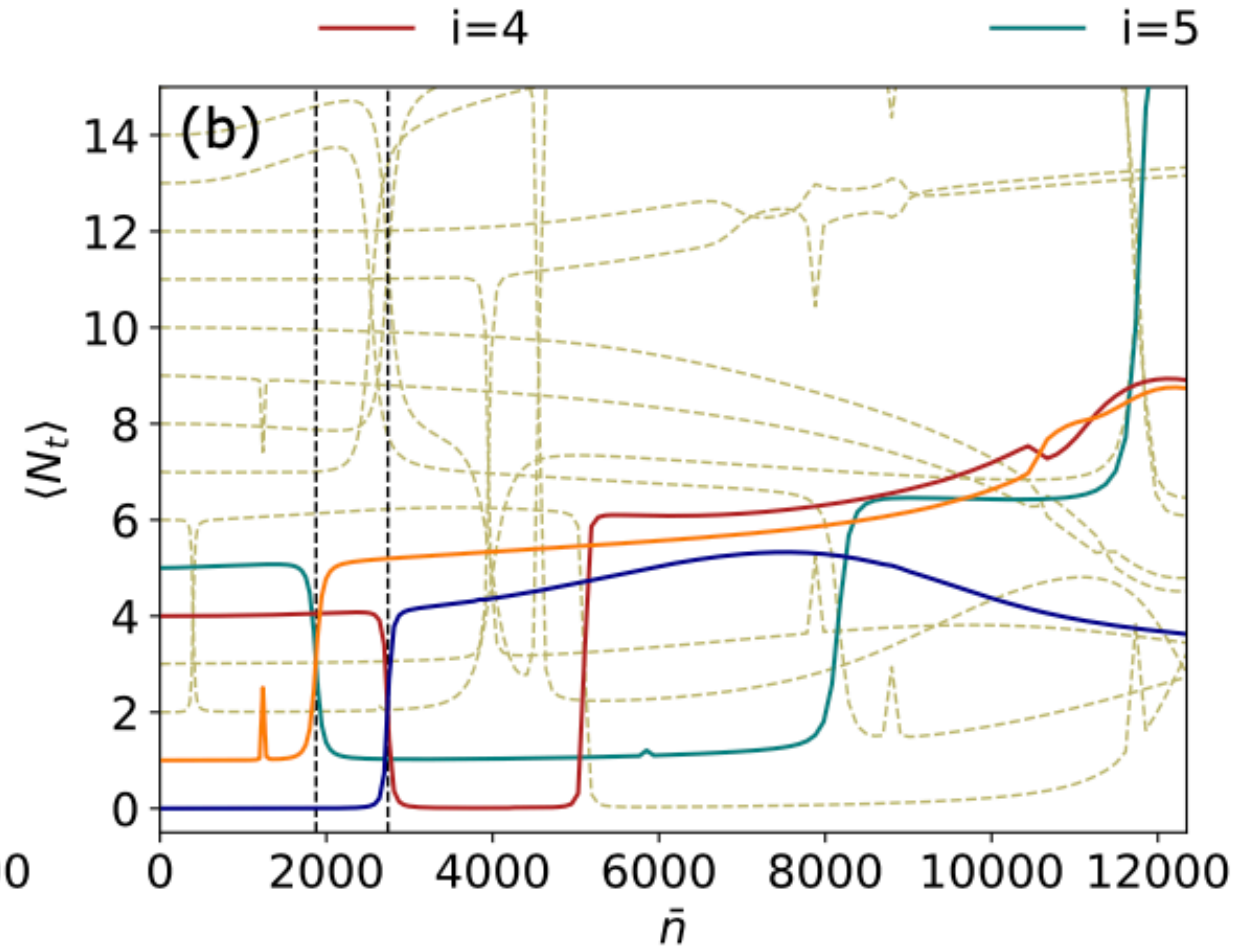
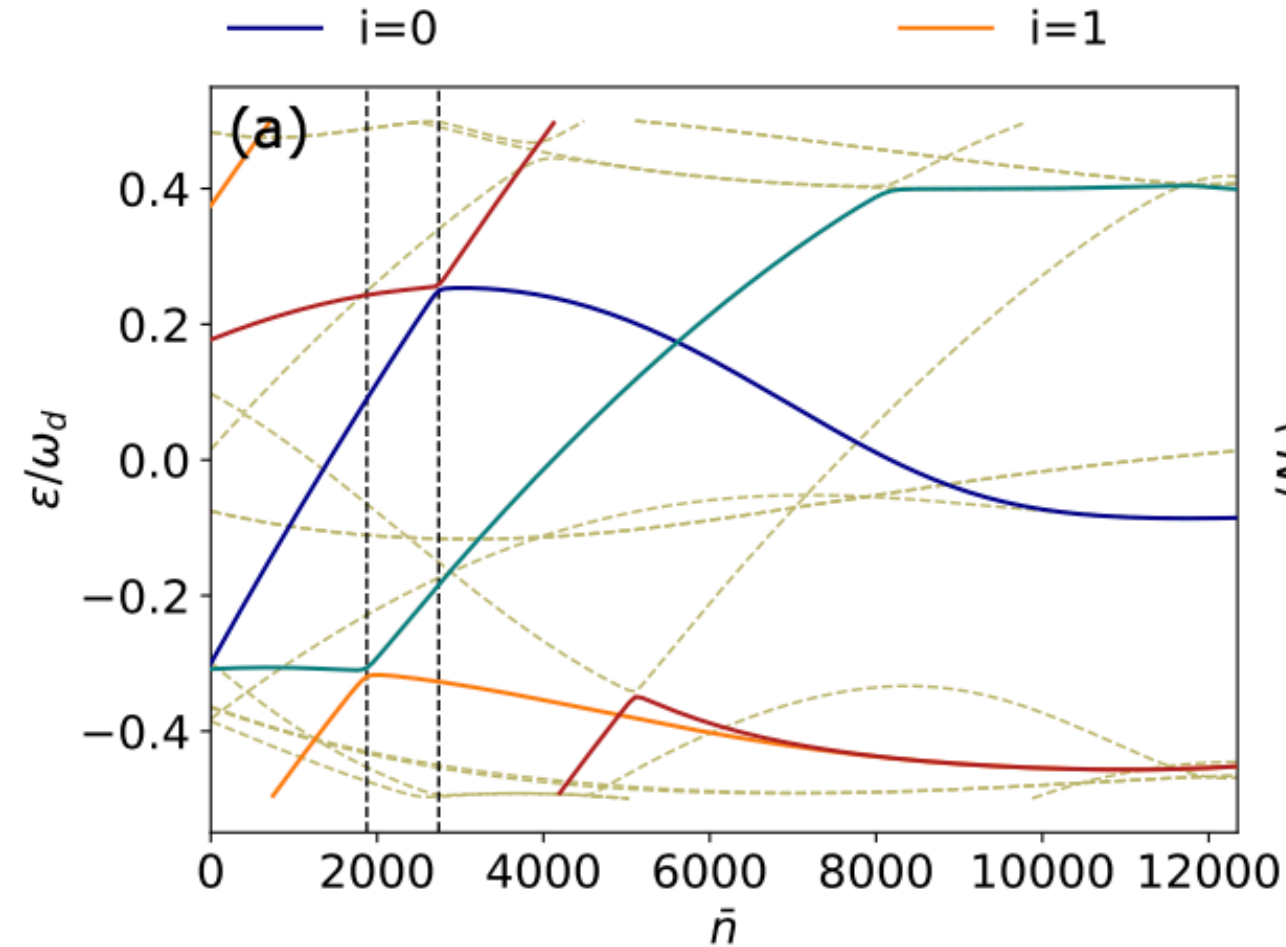


Physics: Mathieu Equation



**Parametric
resonance:**

Floquet branch Analysis



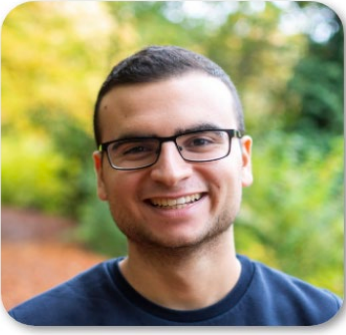
Marijn Morssink, MSc Thesis, 2026

Measurement-Induced Transmon Ionization

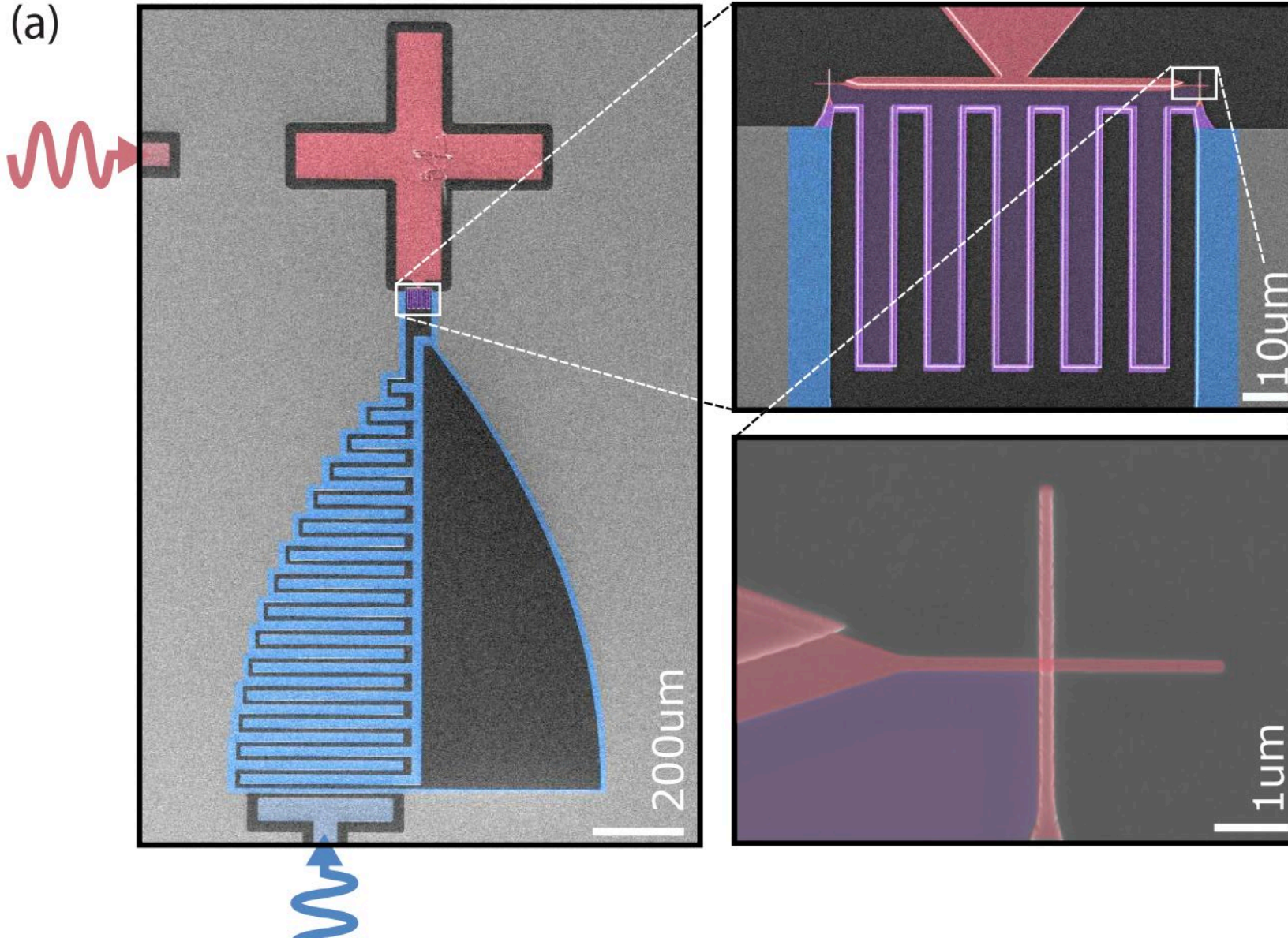
Marie Frédérique Dumas, Benjamin Groleau-Paré, Alexander McDonald, Manuel H. Muñoz-Arias, Cristóbal Lledó, Benjamin D'Anjou, Alexandre Blais

Parametric cQED: The Next Generation

Marius Villier, Sercan Deve, Marijn Morssink, Robin Dekker



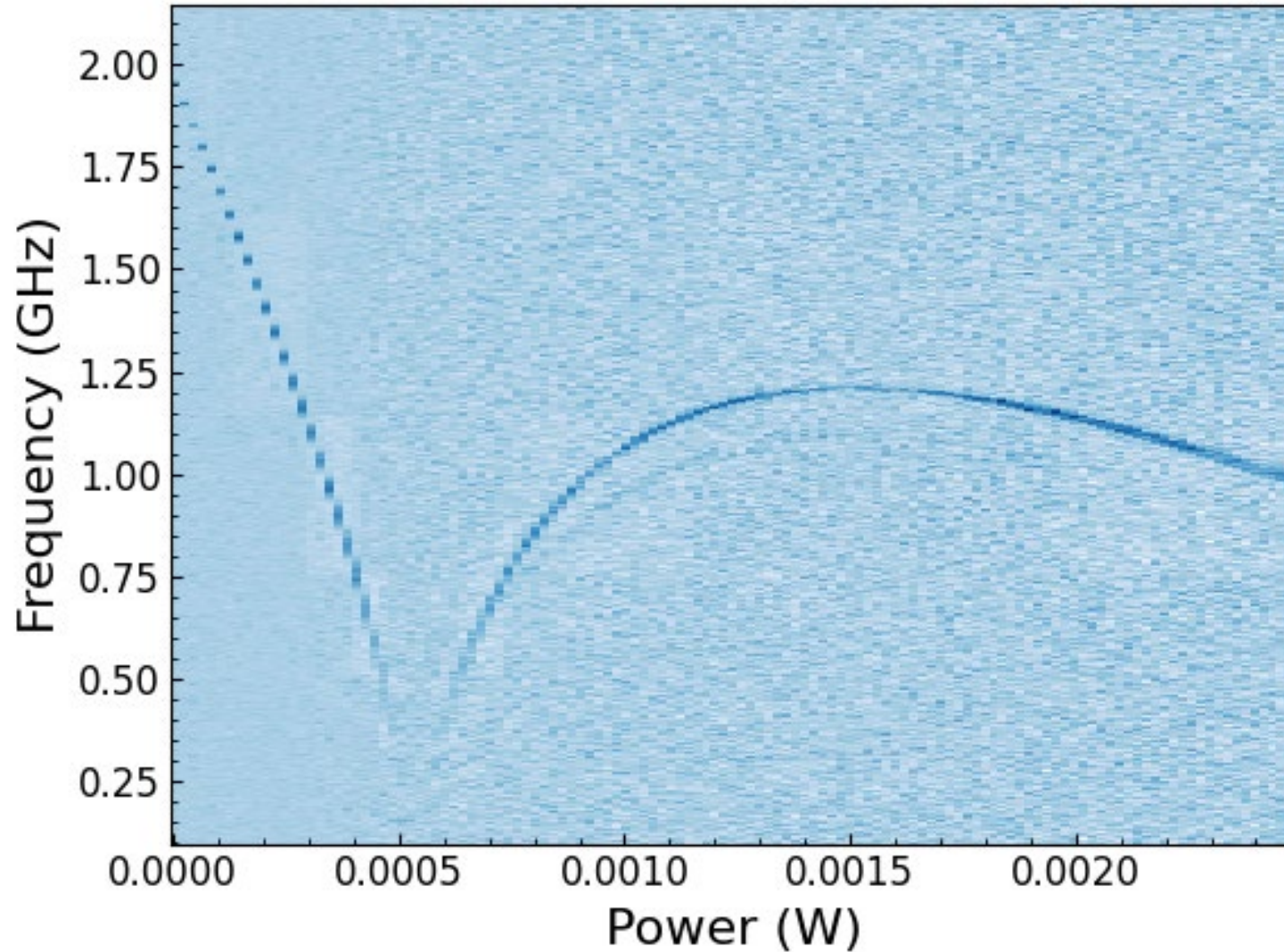
New device



**Careful engineering
to avoid spurious
resonances**

**Floquet
simulations while
designing the
layout**

Drive it up to 25,000 photons!!!

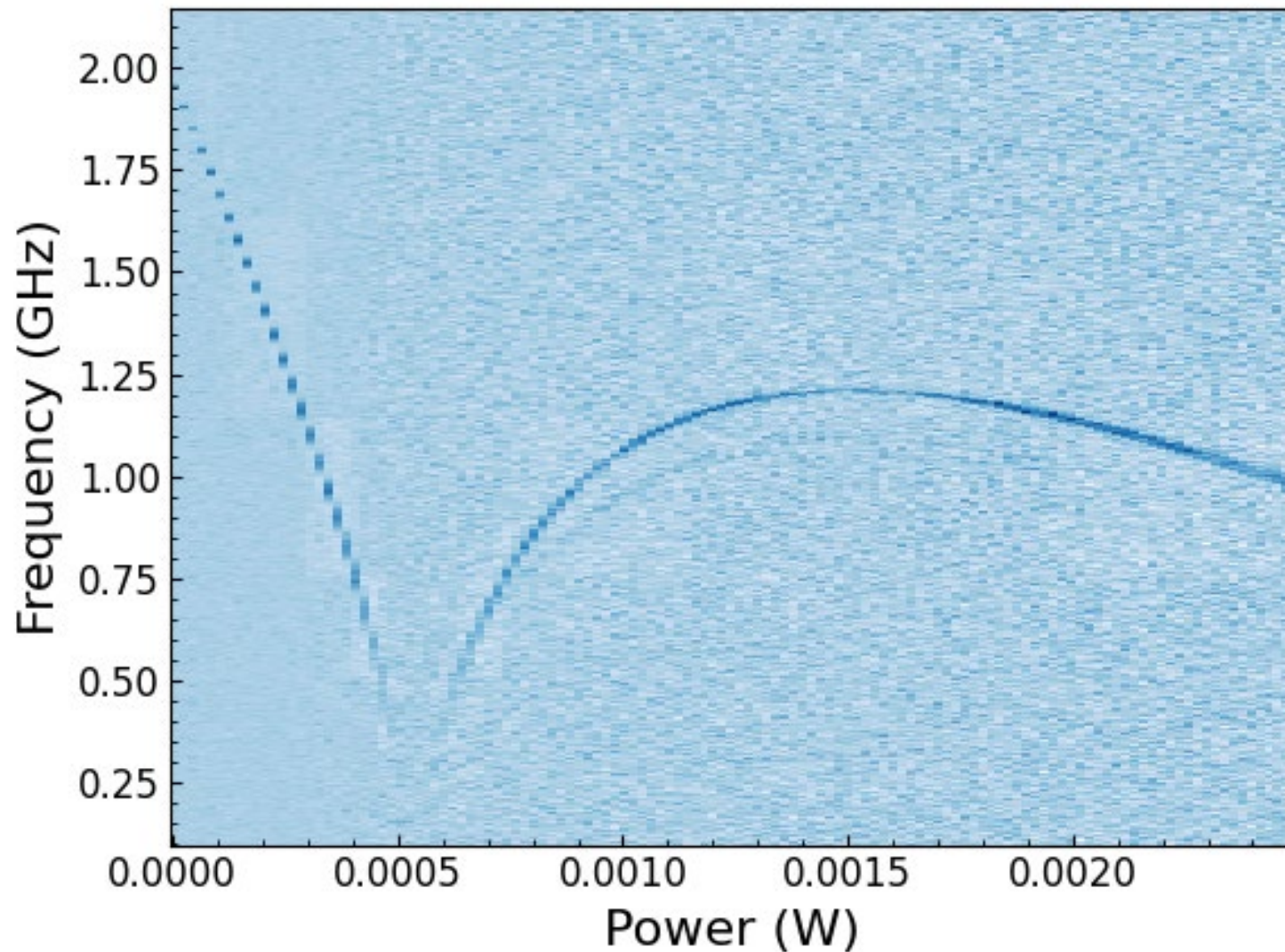


Stark Shift of 2 GHz!

All the way to zero

And beyond...?

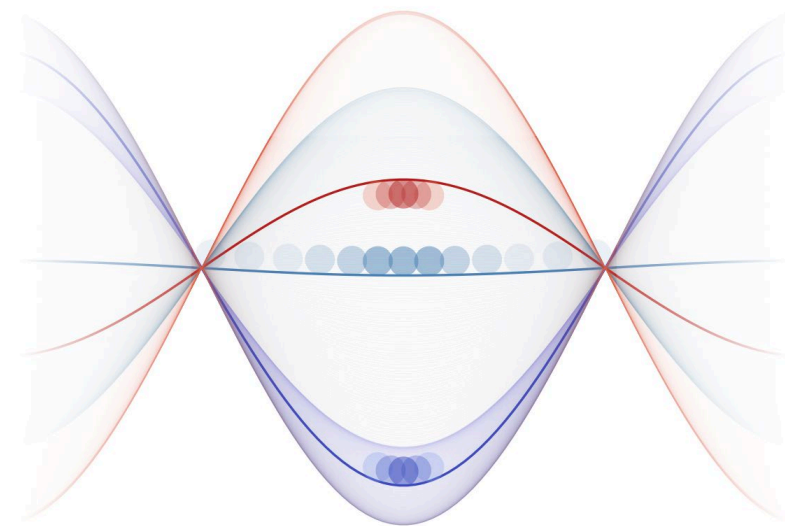
Drive it up to 25,000 photons!!!



Stark Shift of 2 GHz!

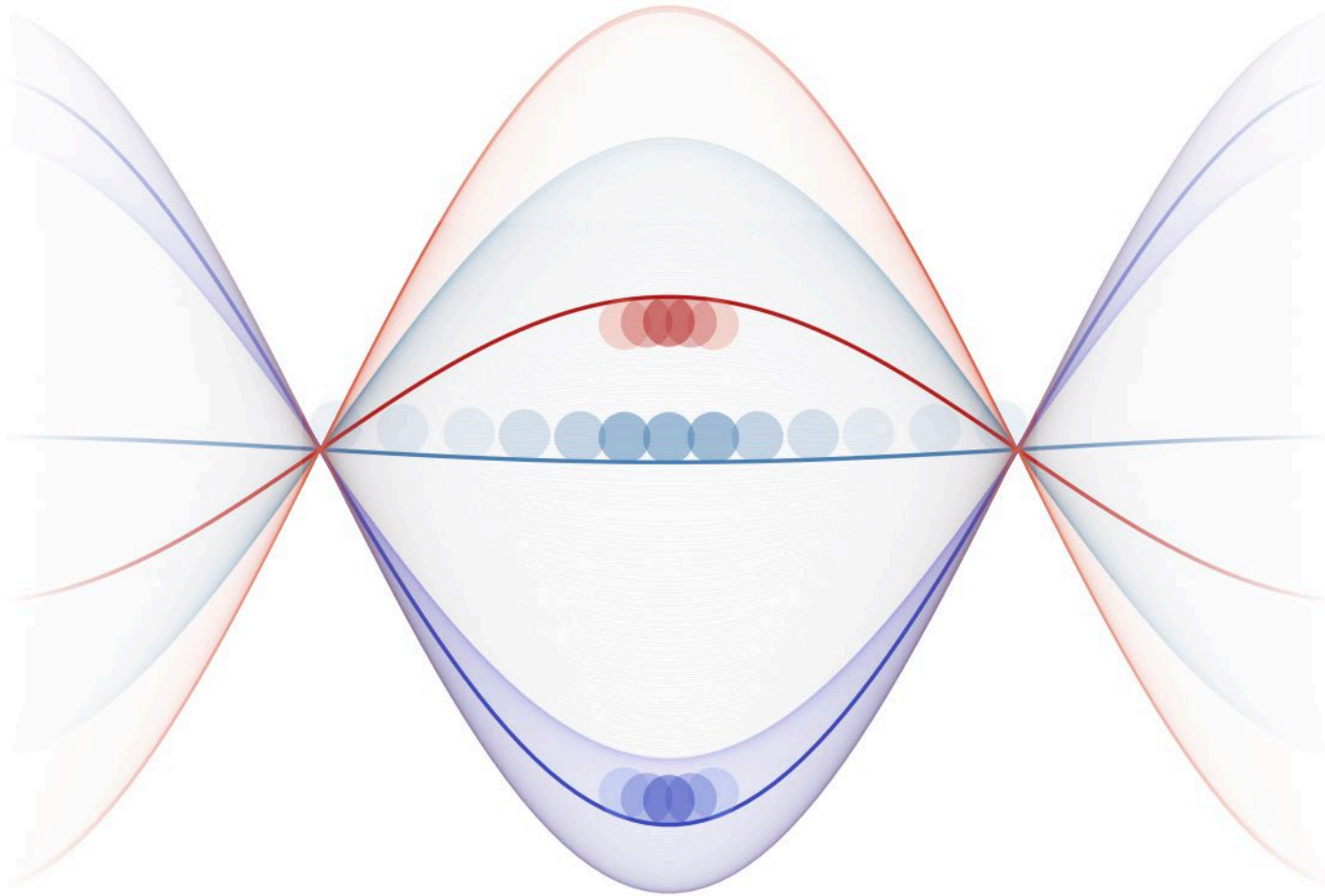
All the way to zero

And beyond...?



**Qubit stabilized
"upside down"**

Dynamically stabilized upside-down qubit?



Future: Stabilize up and down
at the same time

New qubit **fully protected**
from all errors!

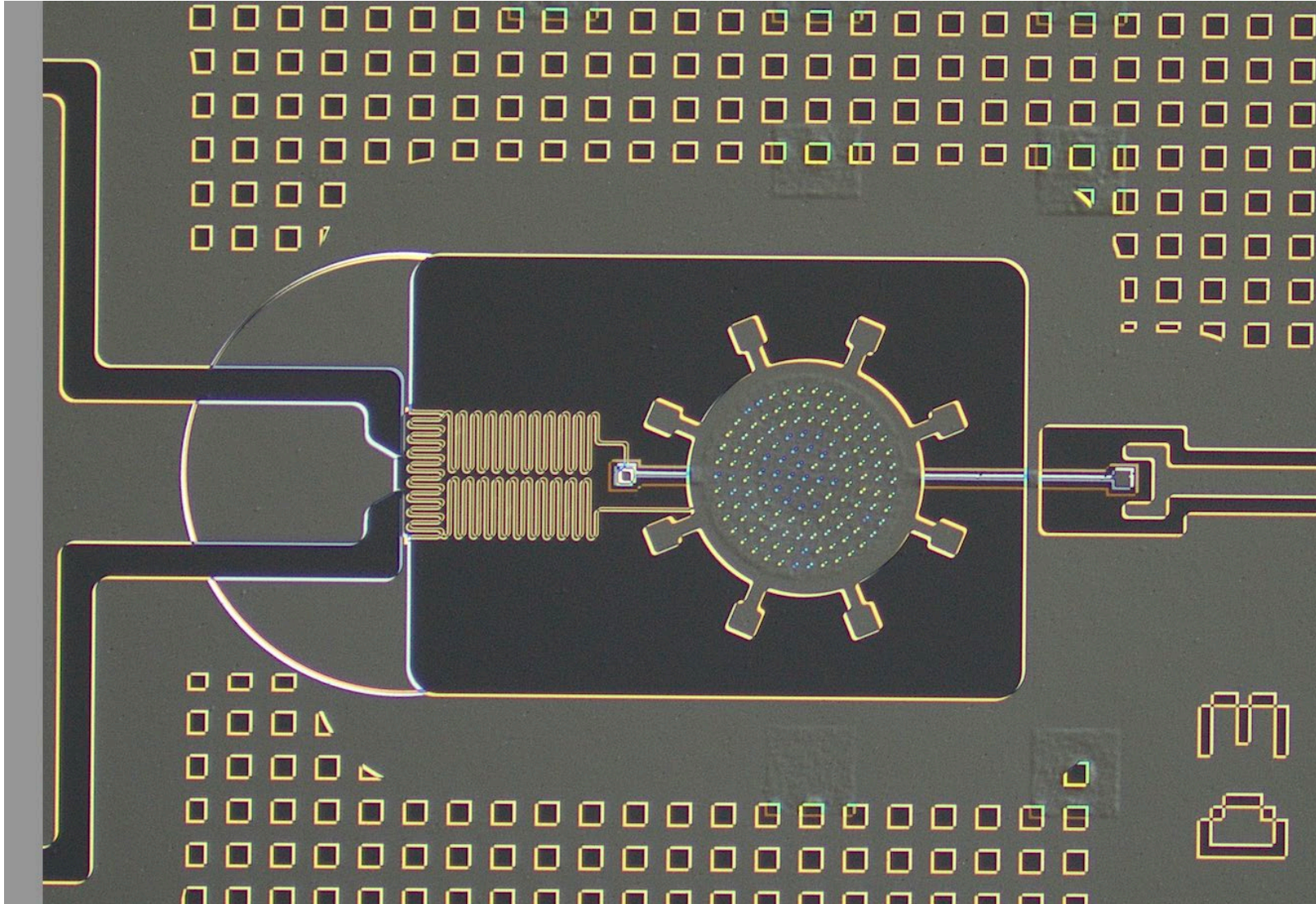


Mechanics and Parametric cQED

Jels van Aragon, Matteo Arfini, Marius Villiers



Put it all together!



Qubit

Parametric coupling cQED

Drum

Optomechanics

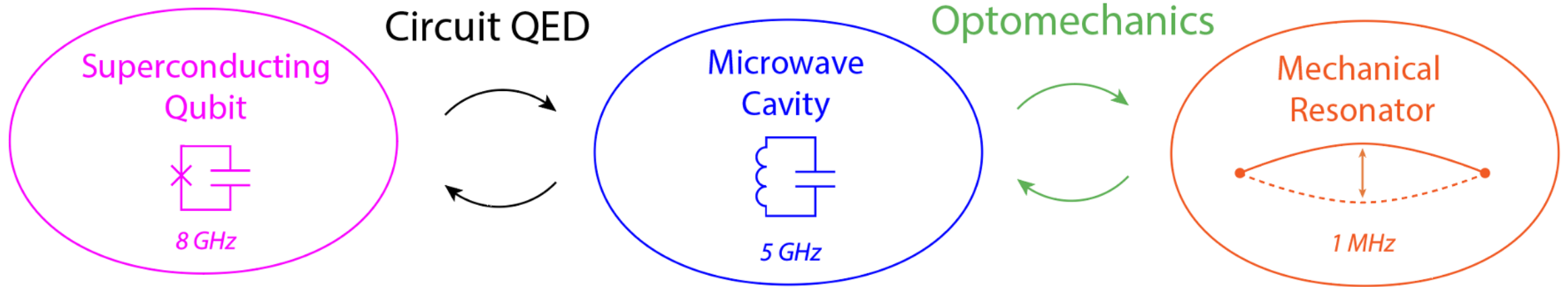
All on one chip!

See Jels' talk on
Wednesday!

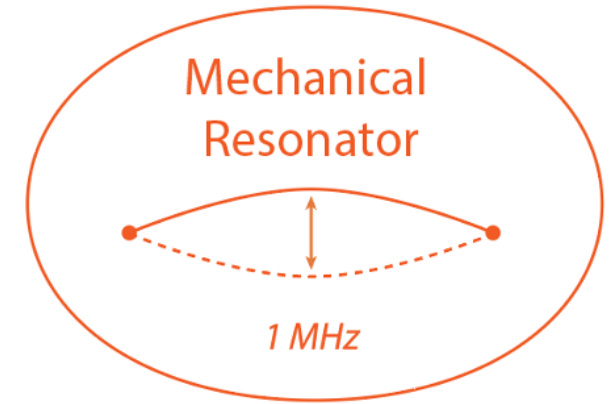
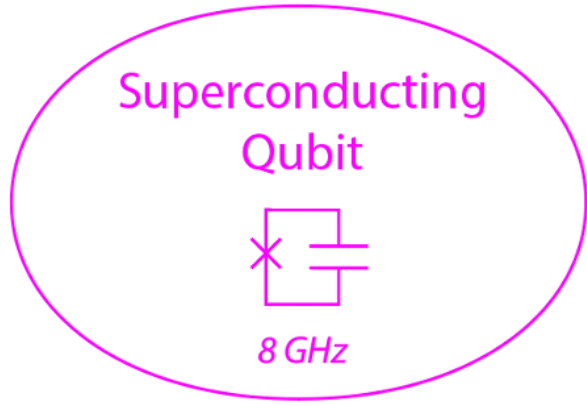
The Future

ERC and some new ideas

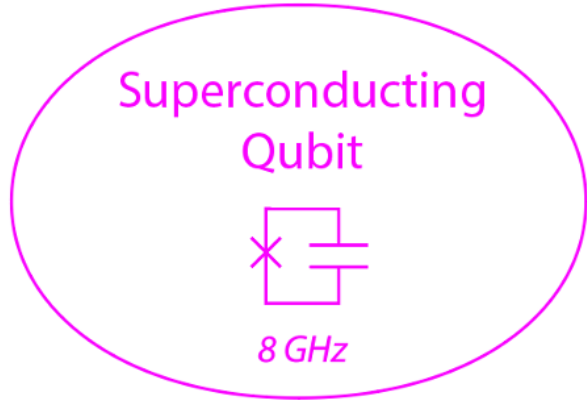
Idea: Cut out the middle man!



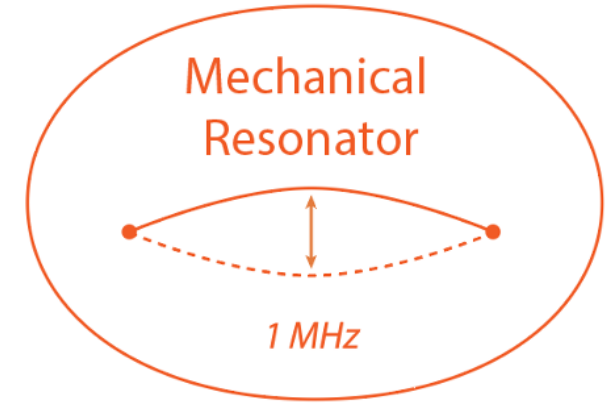
Idea: Cut out the middle man!



Idea: Cut out the middle man!

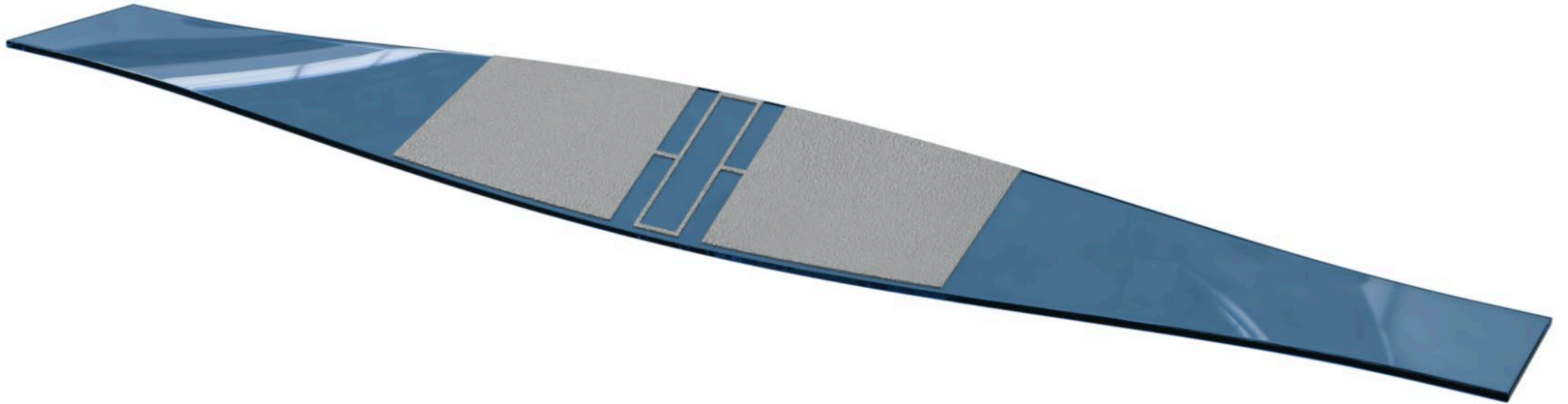


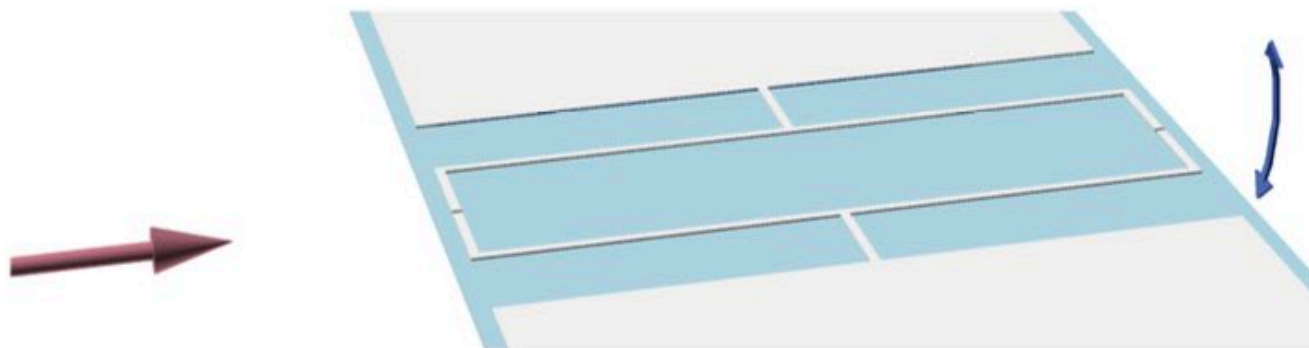
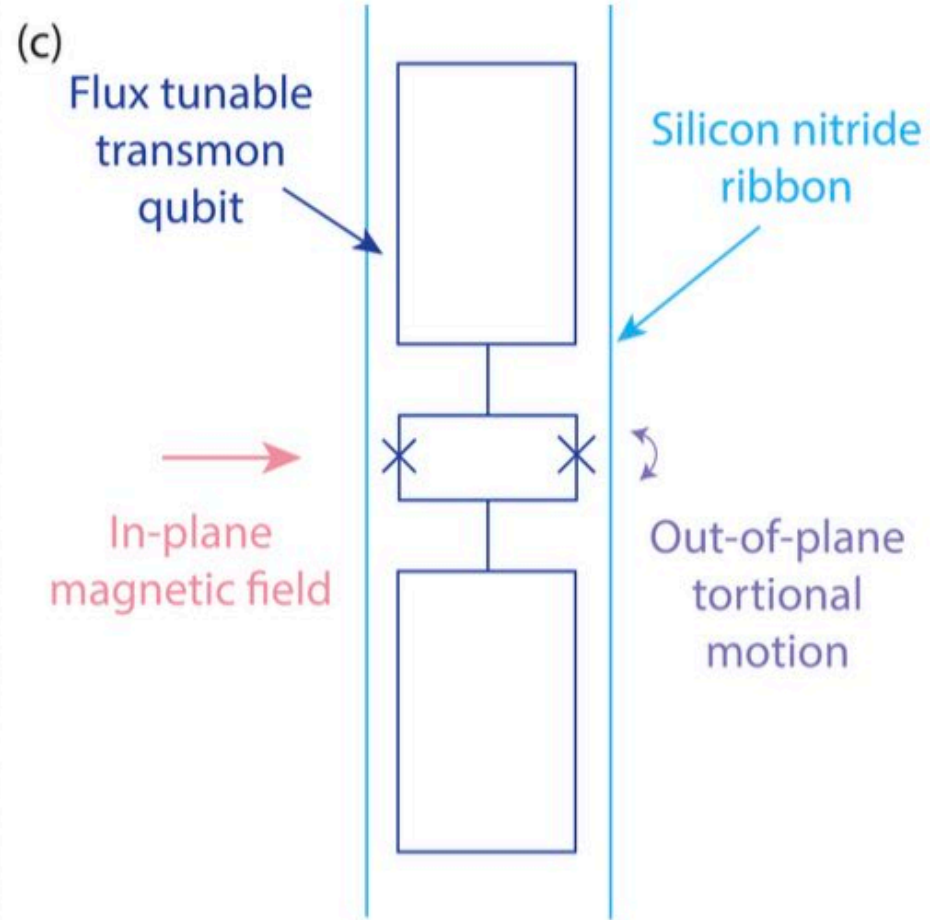
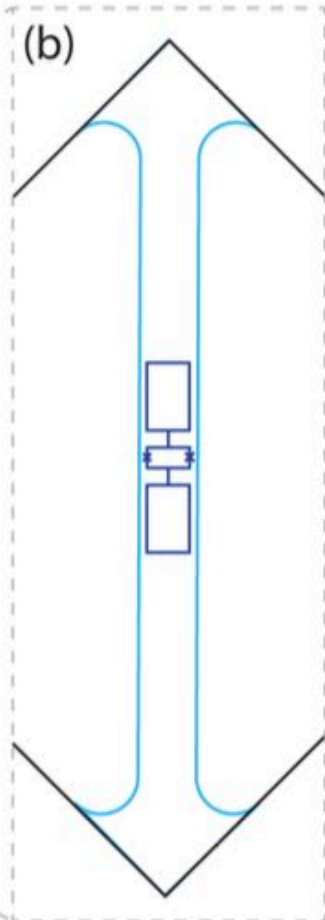
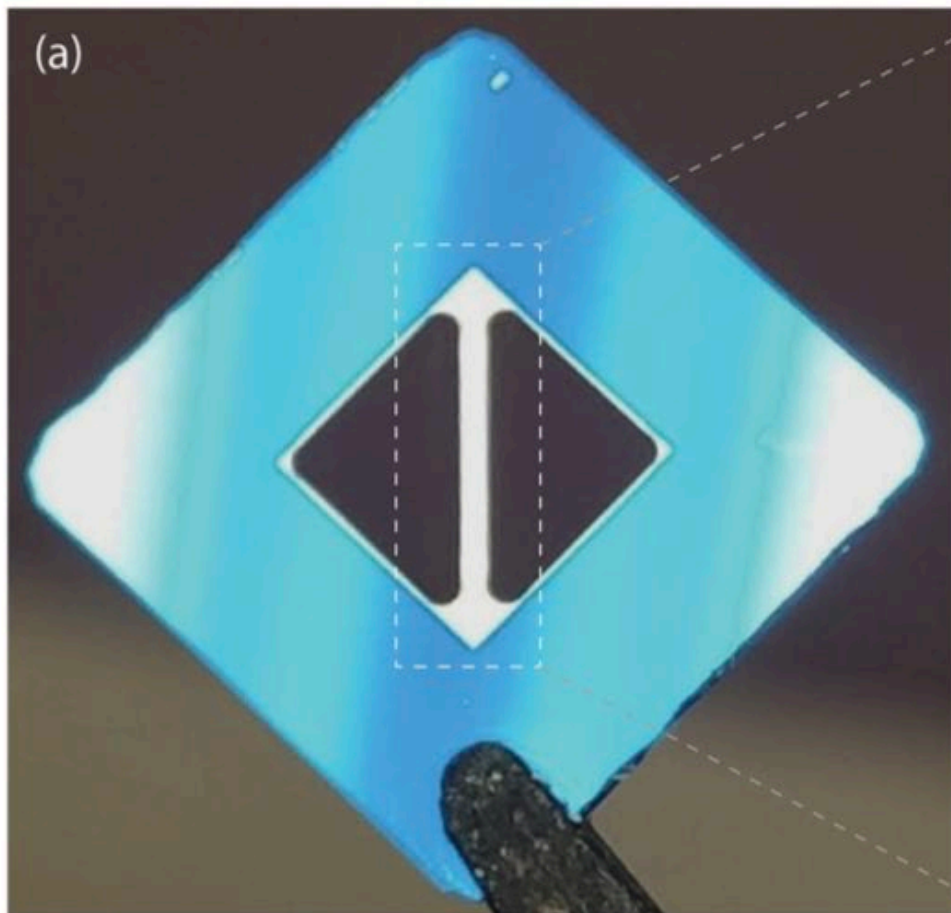
How to couple them?



ERC Advanced Grant 2025
Research proposal [Part B1]

Quantum Torsional Resonators **(QTORSION)**





Strong coupling

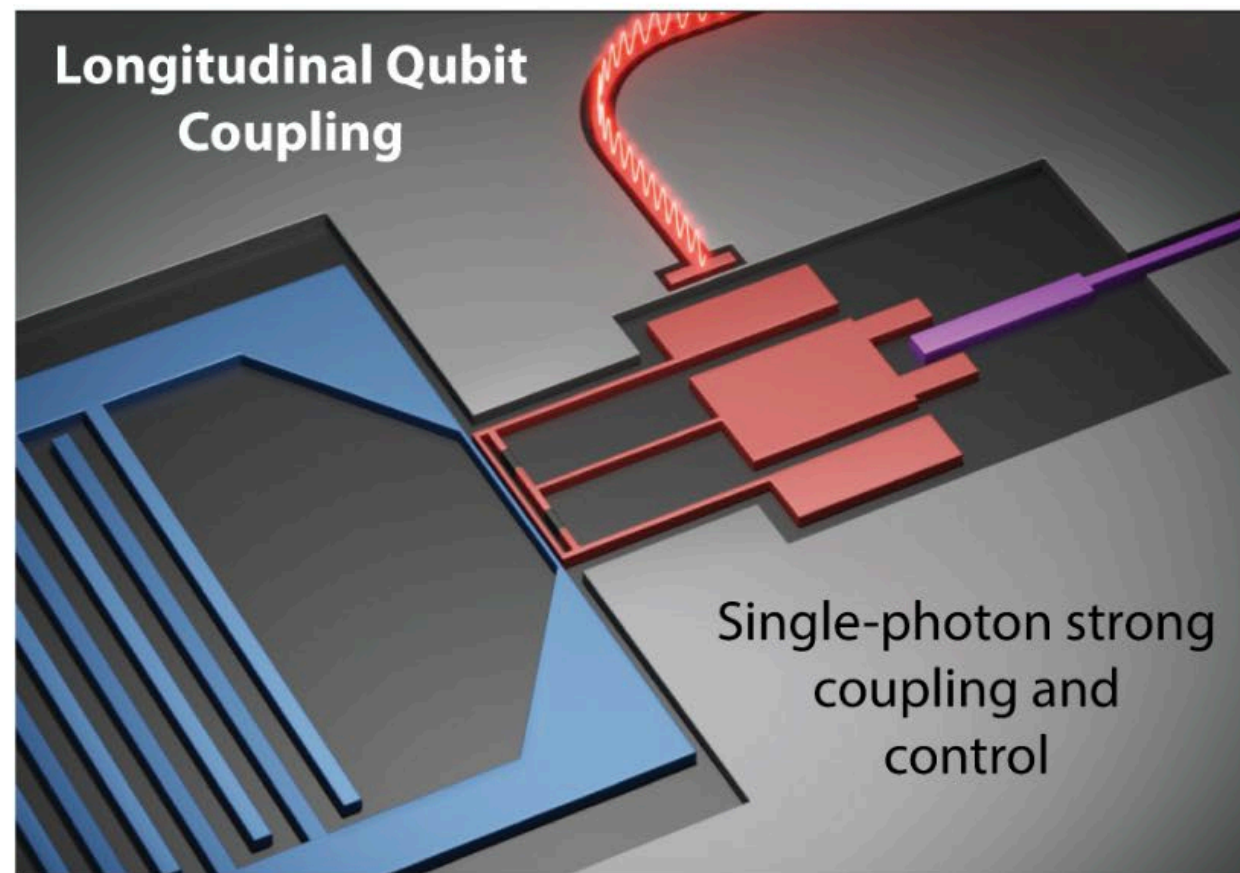
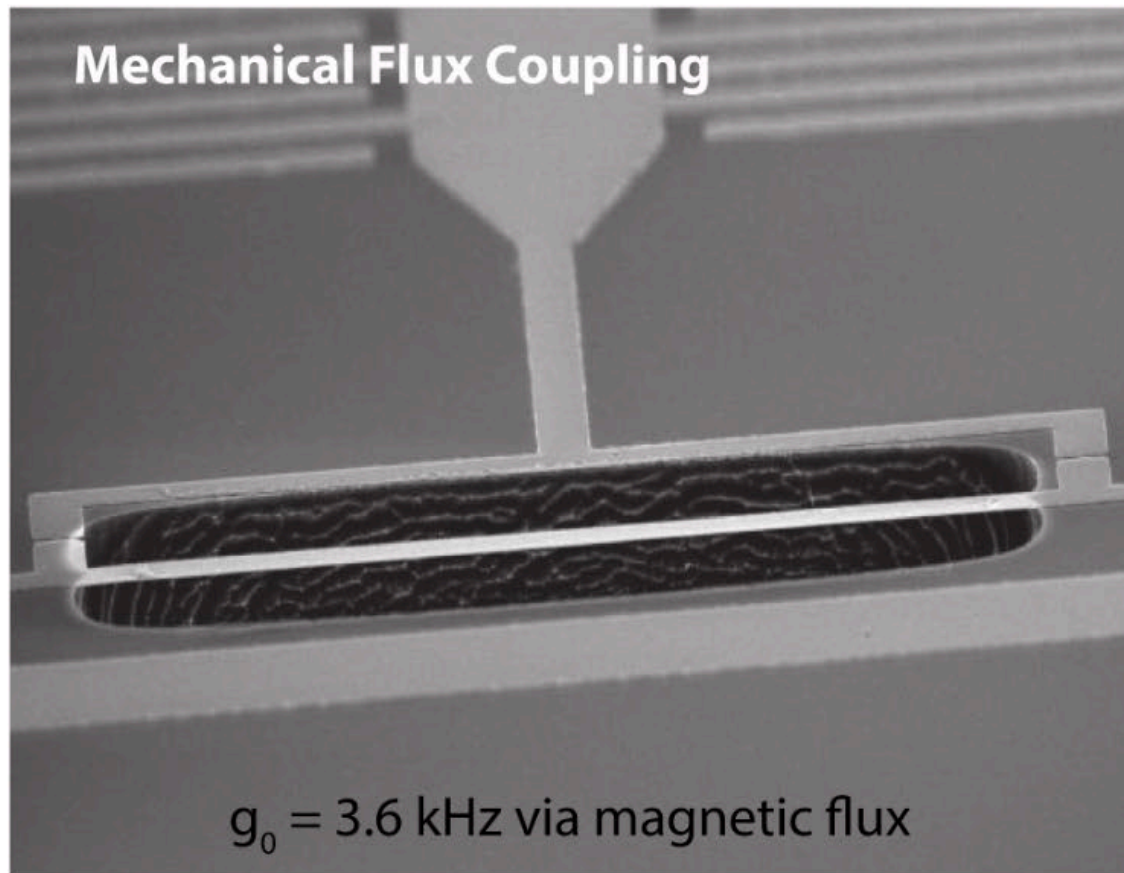
$$g > \Gamma_q, \gamma_m$$

Exceptional coherence

$$T_m^{th} = 1 \text{ s}$$

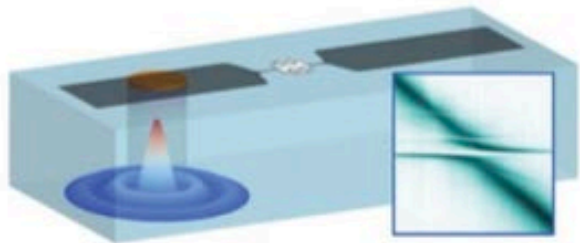
Large Mass $m = 800 \text{ ng}$

Flux based coupling!



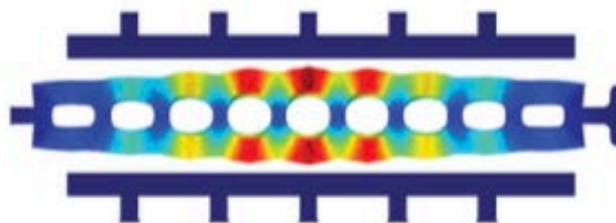
Unprecedented Quantum Cooperativity

$\hbar$ BAR Quantum acoustics (2018)



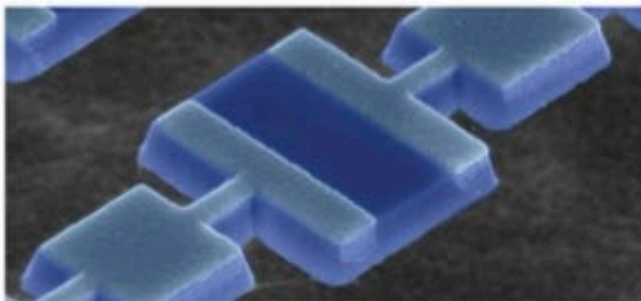
(a) $C_q = 10^4$

Capacitive nanobeam (2025)



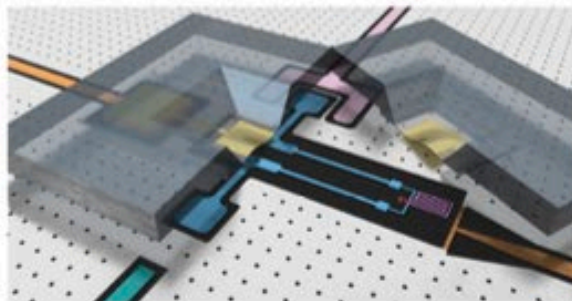
(c) $C_q = 150$

Nanopiezo resonators (2019)



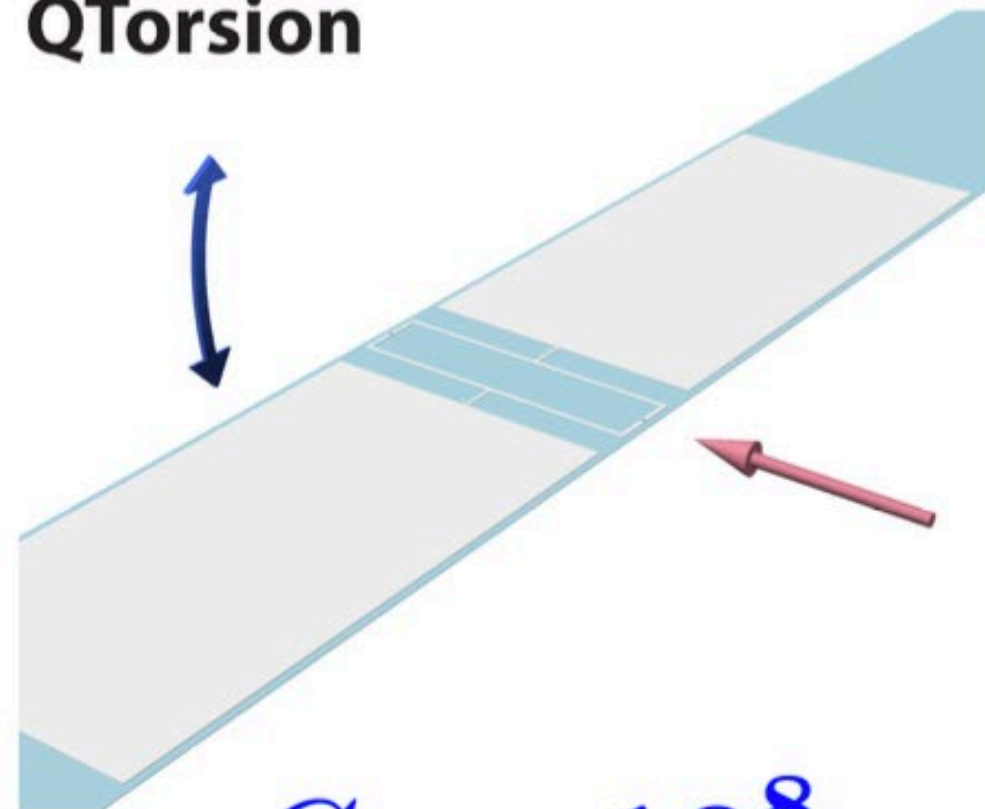
(b) $C_q = 4000$

Capacitive membrane (2025)



(d) $C_q = 0.2$

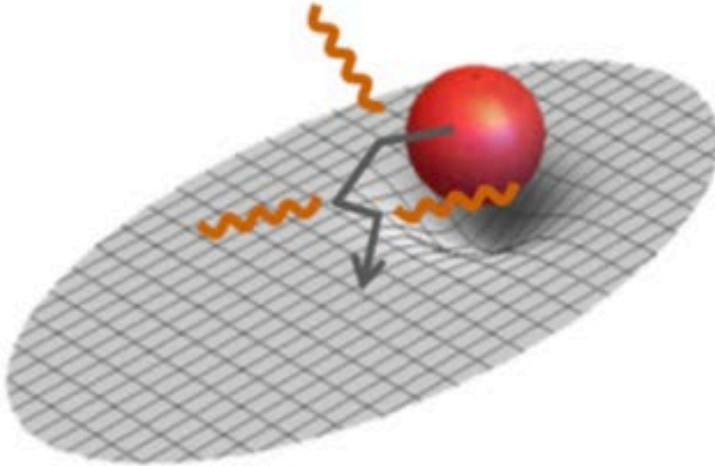
QTorsion



(e) $C_q > 10^8$

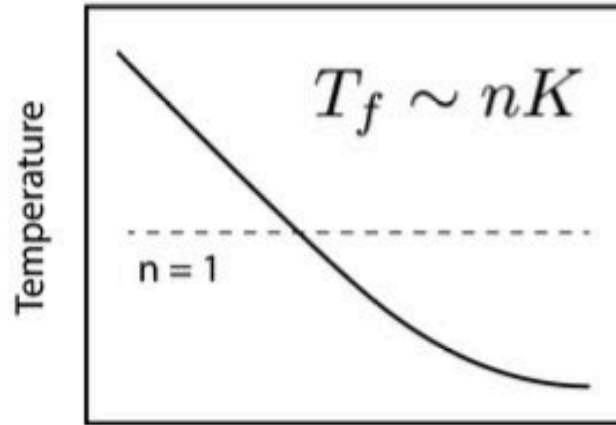
Impact

Phase 1: Detect



Qubit detection of diffusion,
absolute thermometry
Exclusion of non-white-noise
gravitational collapse models

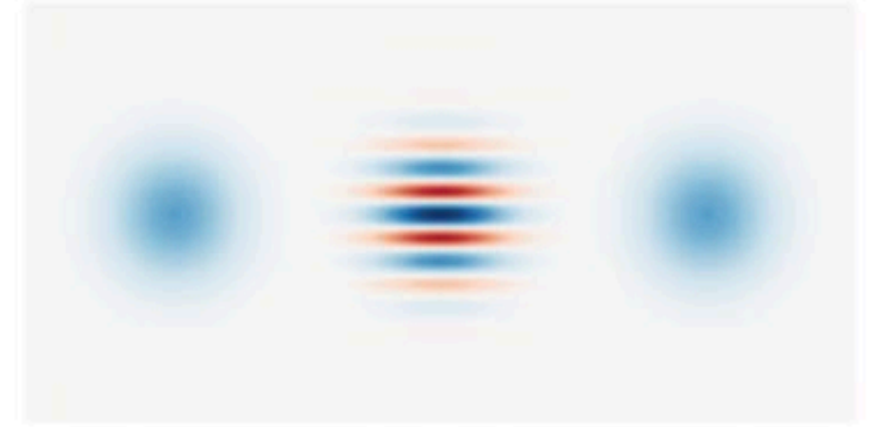
Phase 2: Cool



Feedback Cooling Strength

Ground state of a 52 kHz,
microgram scale
oscillator, record low
nK temperatures

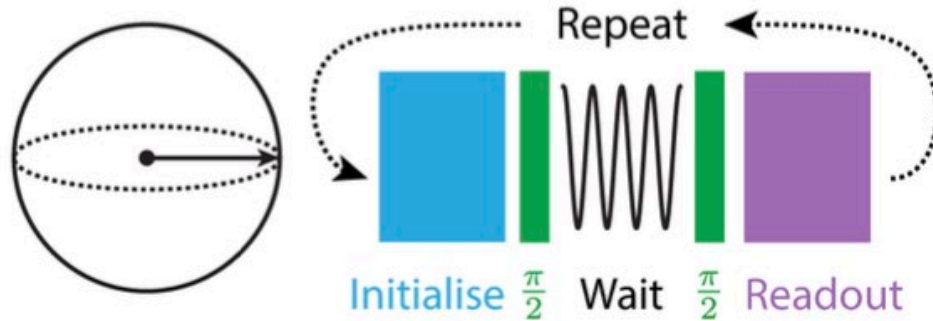
Phase 3: Quantum Control



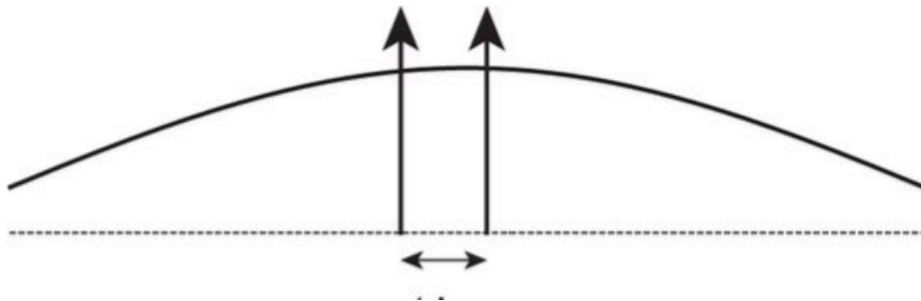
Unprecedented large and heavy
quantum superpositions:
100 fm cat states, 800 ng mass
Direct interferometric tests of
quantum nature of gravity

Challenges and ideas

(b) Position detection via Ramsey sequence

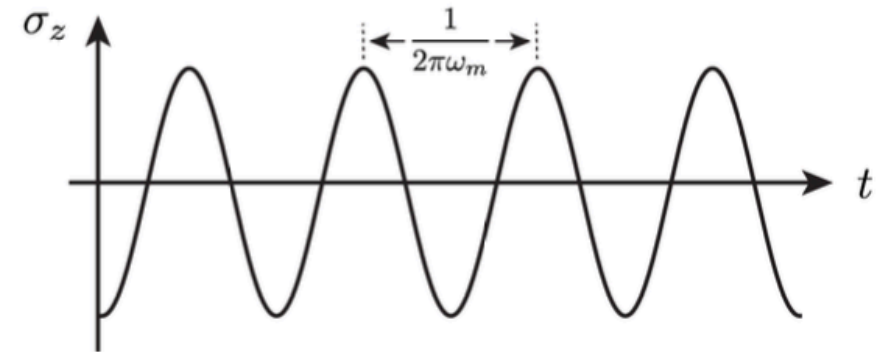


(c) Torque from two-tone qubit driving

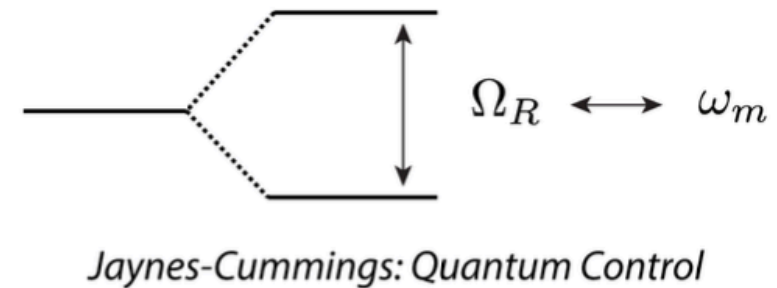


Quantum control in non-resolved sideband limit but with huge quantum cooperativity?

(d) Oscillating torque from Rabi Oscillations



(e) Dipole coupling to dressed atom?



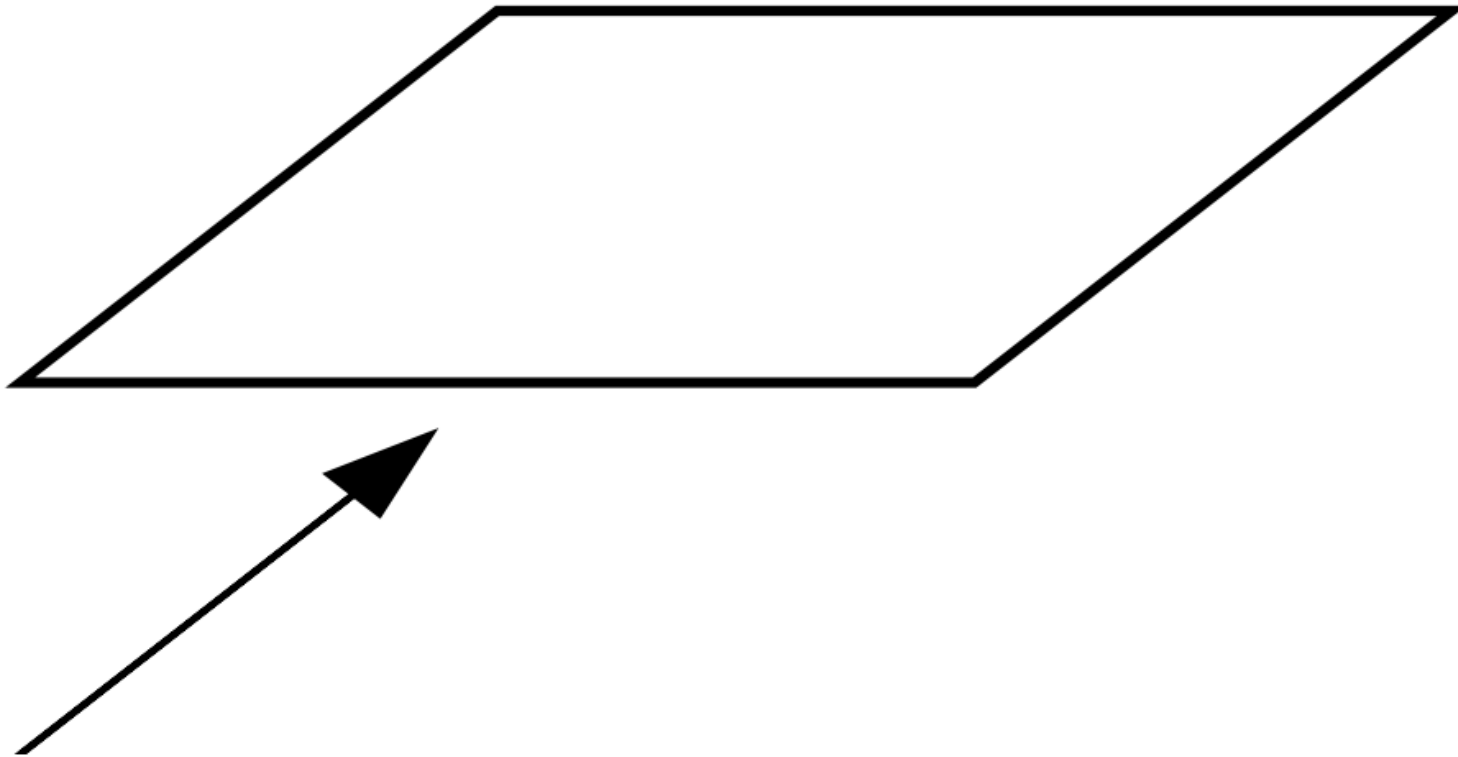
Jaynes-Cummings: Quantum Control

Schemes to exploit nonlinearity and feedback for quantum state preparation>

Teaser: Quantum loop!

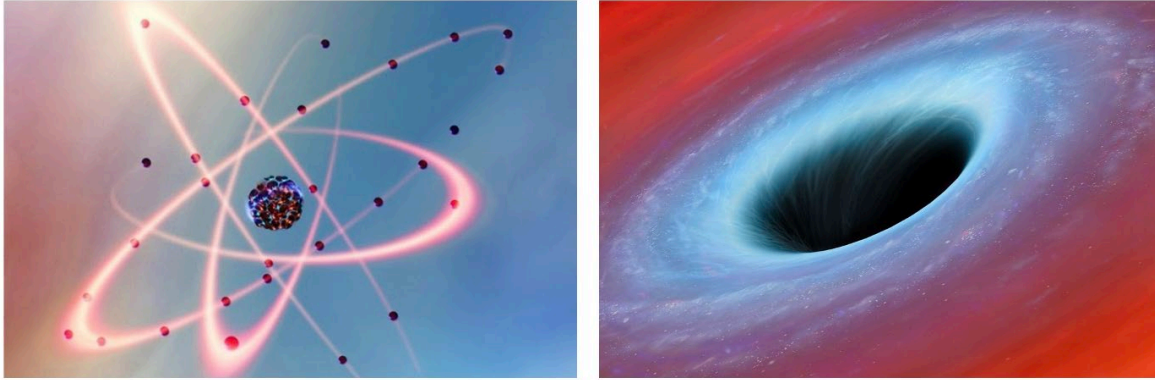
Use Meissner to
change directions of a
magnetic field

Working on testing it
now already with
membranes!

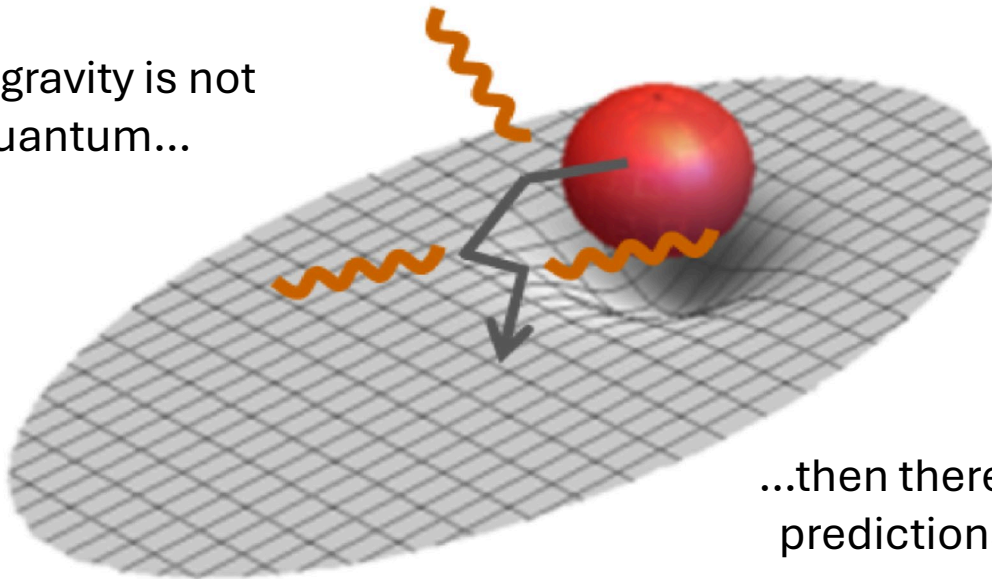


Summary

Quantum and Gravity have a problem

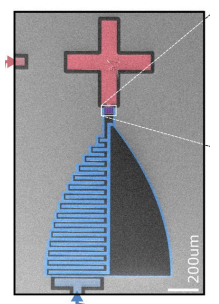
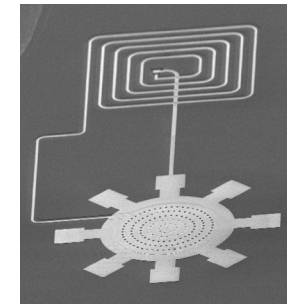
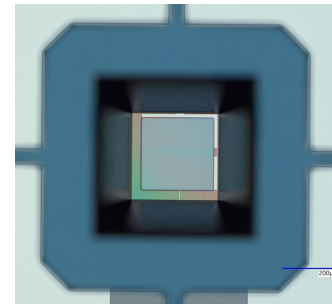
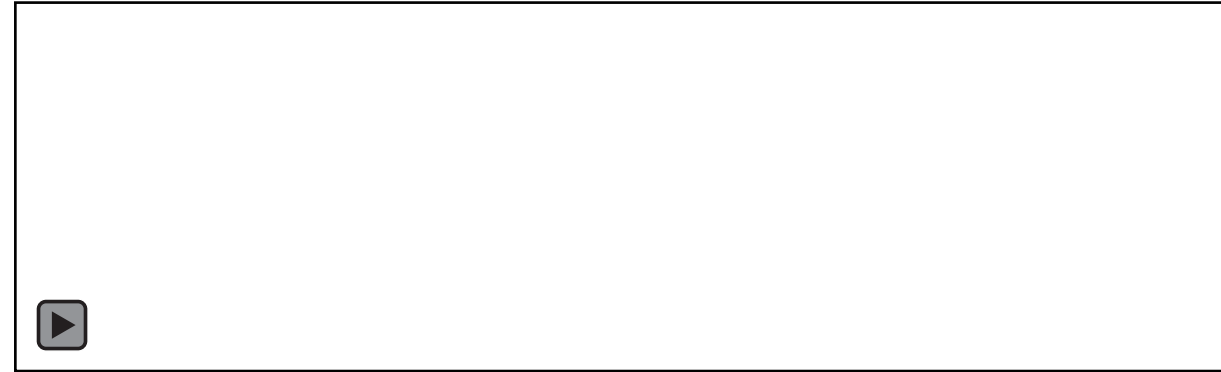


If gravity is not quantum...



...then there are predictions we can test!

SteeleLab: Let's try and do it!



Innovation in mechanics and cQED!

