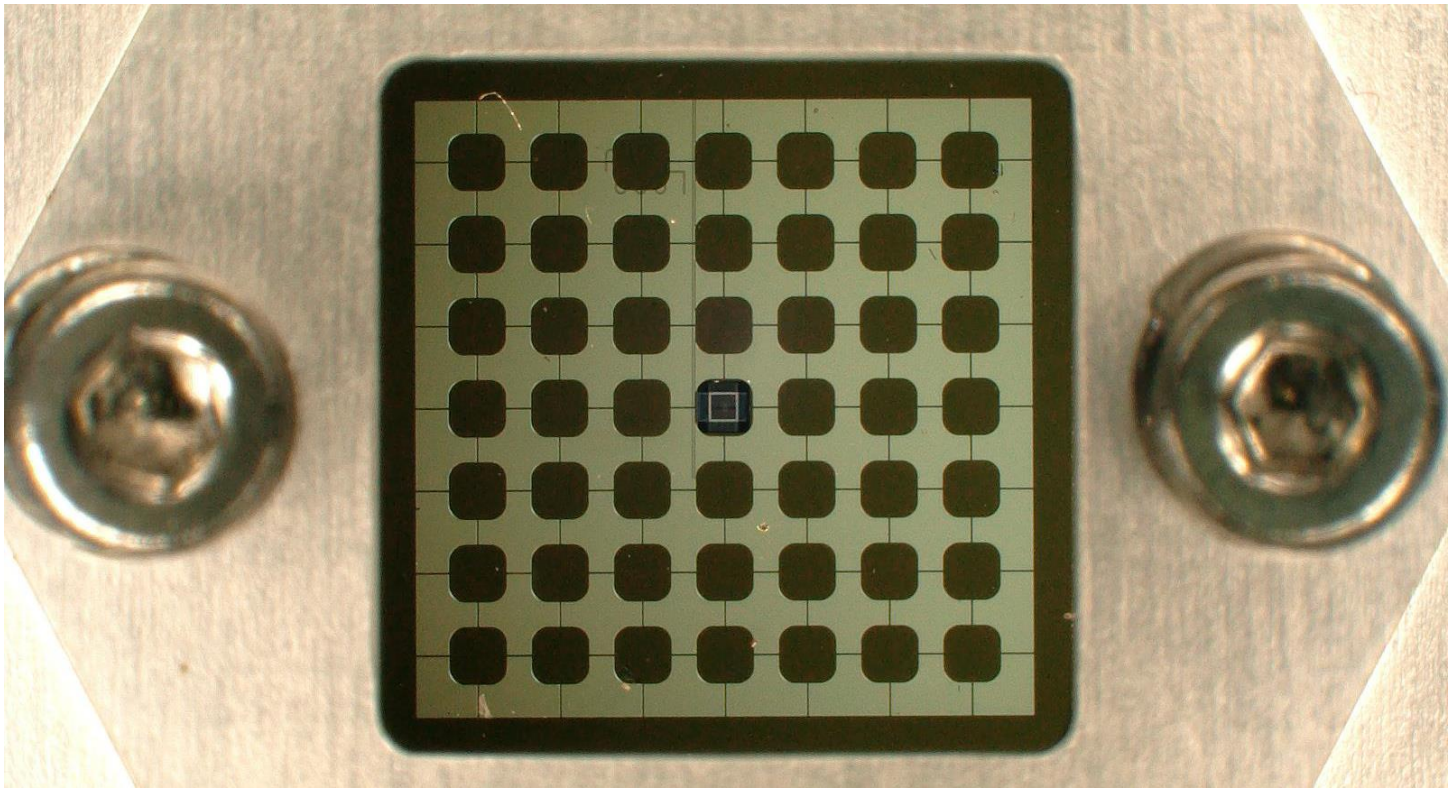
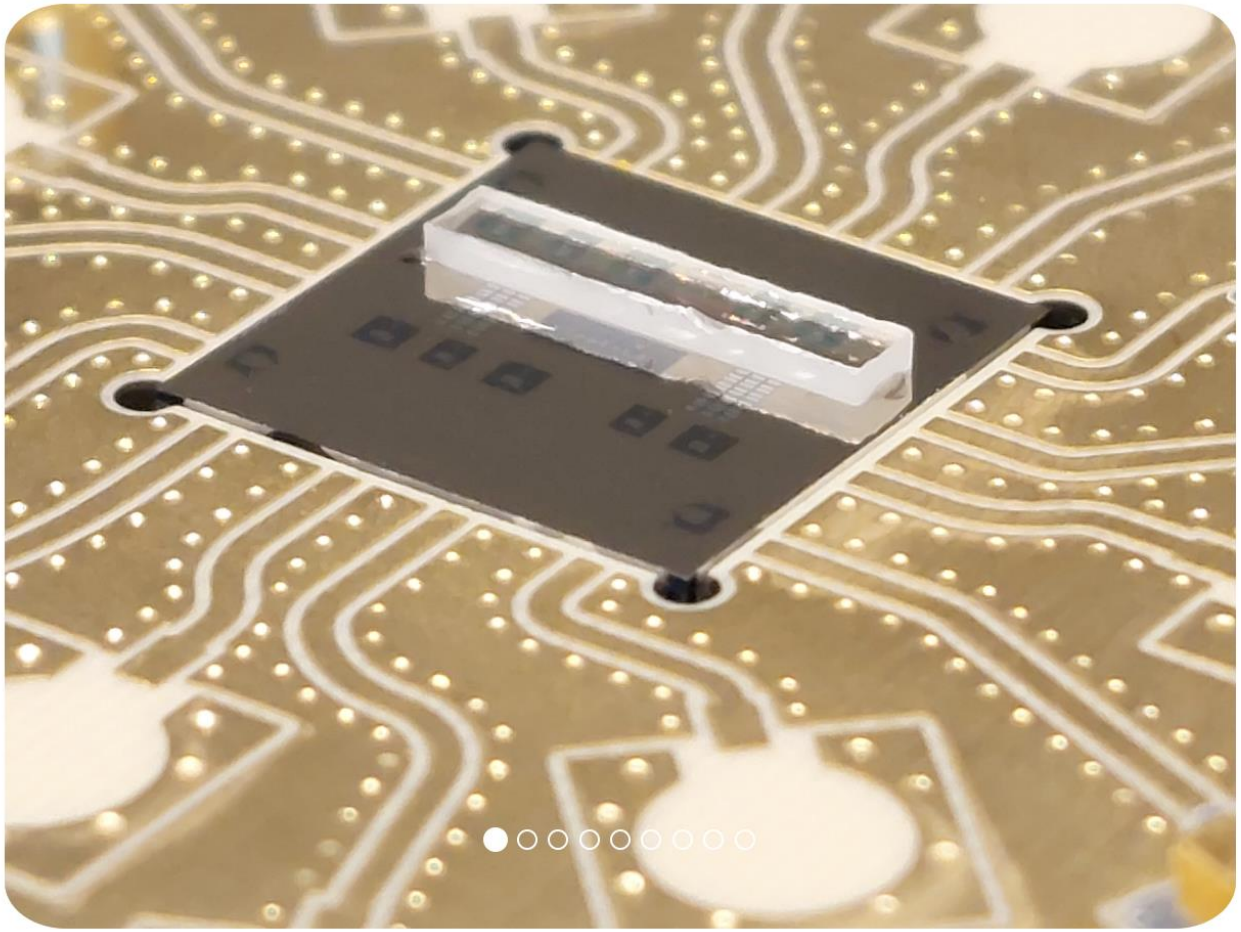
Superconducting Electromechanics



to explore the effects of general relativity in massive superpositions

Gary Steele, TU Delft

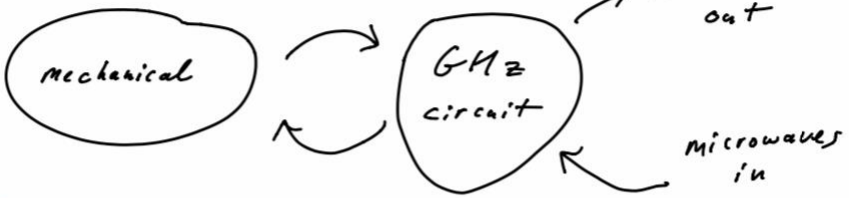
SteeleLab: Quantum Circuits and Mechanics



In the SteeleLab, we study **Quantum Circuits and Mechanics**: superconducting quantum circuits and mechanical resonators.

https://steelelab.tudelft.nl/

Mechanics



"Ultracohent"

millimeter sized Silicon nitride membranes

$T_{th} \gtrsim 100\,ms$ $T_{gr} \sim 10\,ms$

Coupling to mechanics with magnetic flux

SQUIDs + mechanics

"shaking inductors"

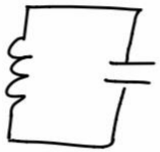
Single photon strong coupling?

Quantum acoustics

resonant piezoelectric coupling, multimode?

(Superconducting) "Quantum" Circuits

Circuit QED



Engineer Quantum optics at microwave frequencies

Multimode ultra strong coupling

$g \gg\gg \kappa$, $g \sim \omega$

convergence of Lamb shift?

How "quantum" is Lamb shift?

Quantum RF $\hbar\omega$ @ 170 MHz

Extending cQED to new frequency regimes

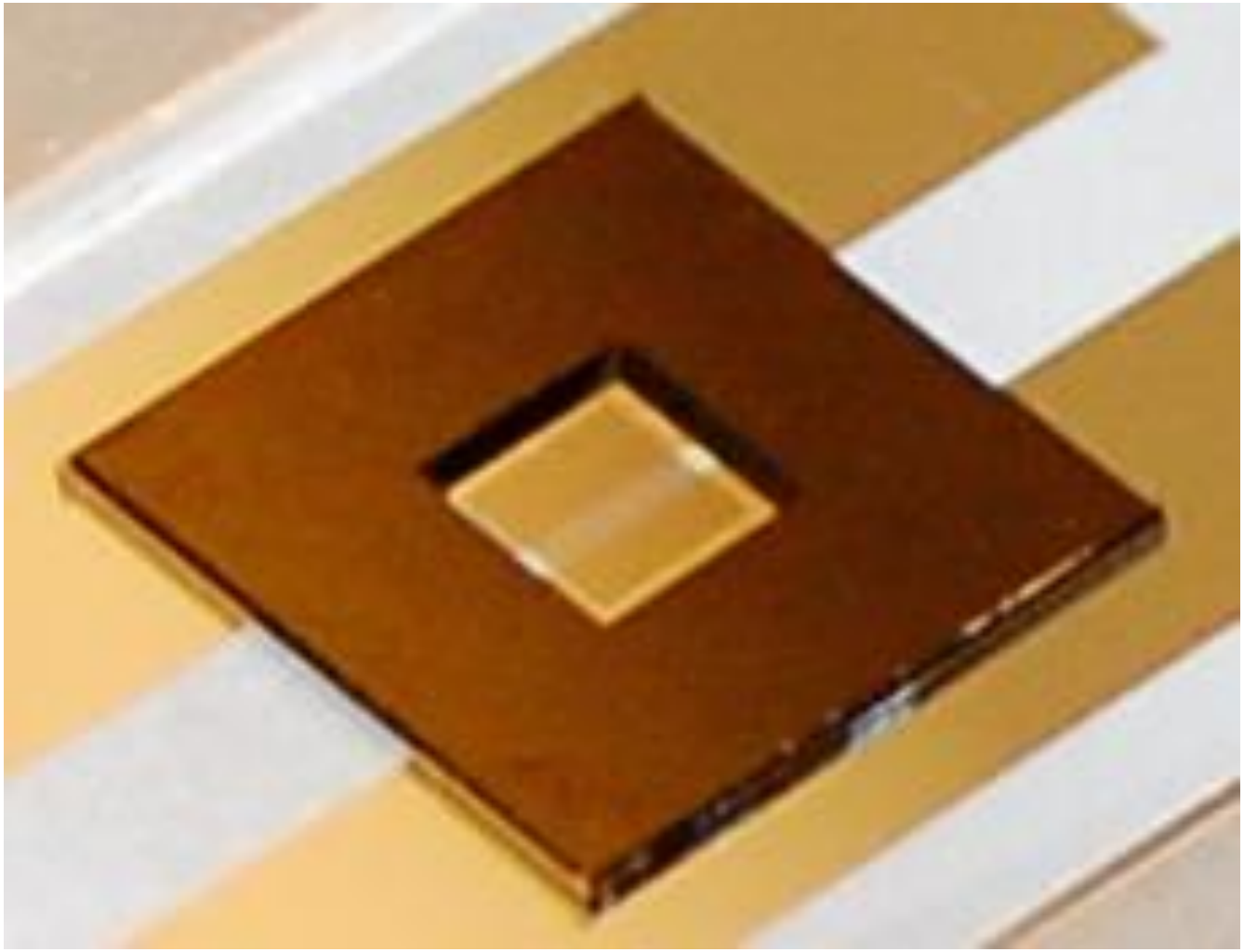
Quantum in thermal limit?

Photon pressure Coupling

Single photon strong coupling?

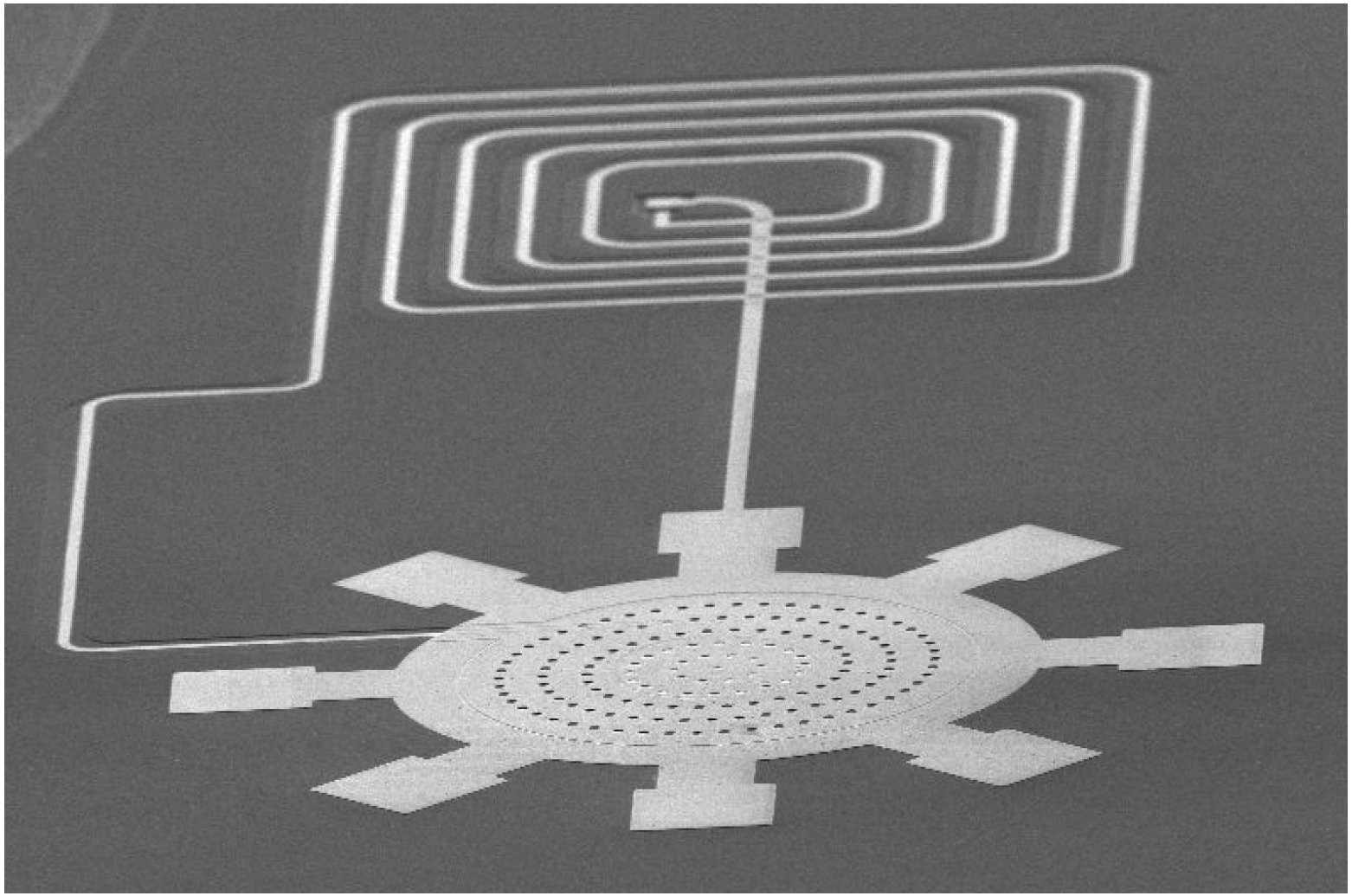
GKP states?

Our platform: Mechanical Resonators



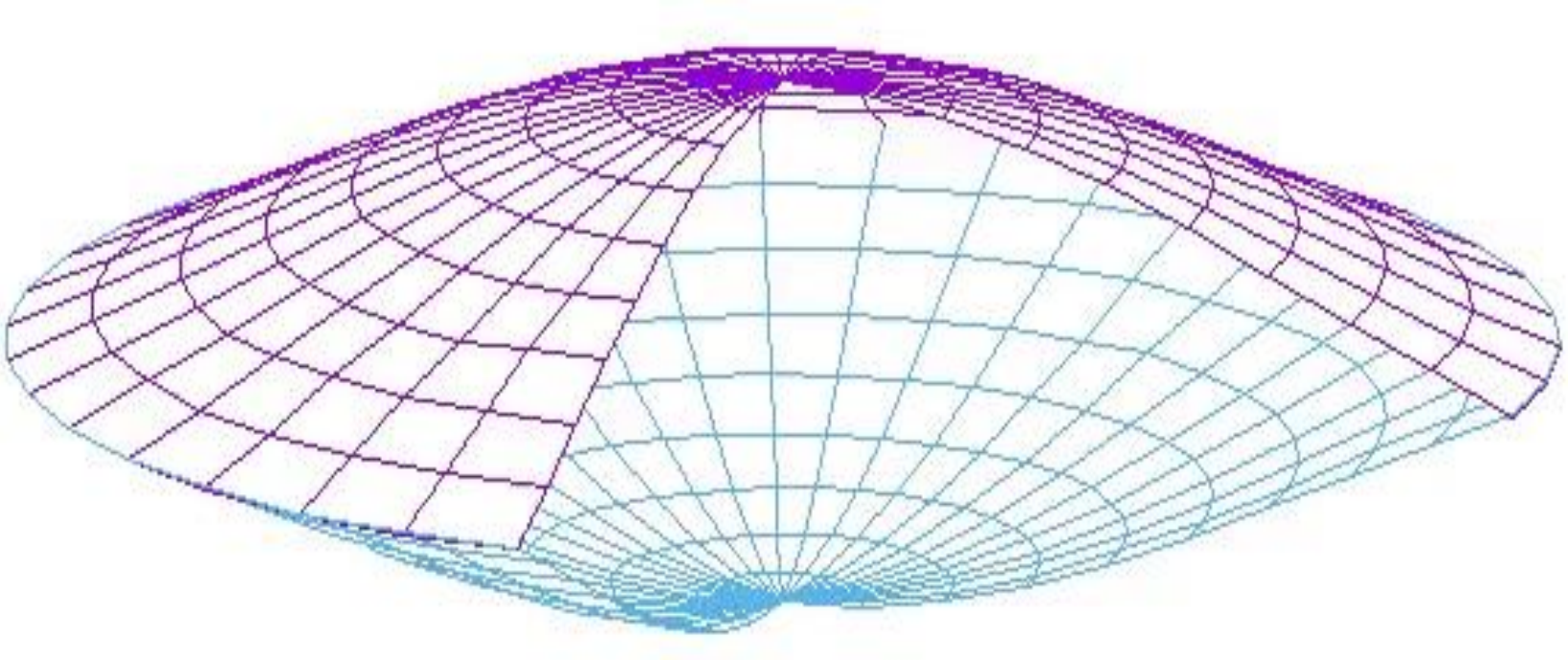
Metallized Silicon Nitride Membrane

Our platform: Mechanical Resonators



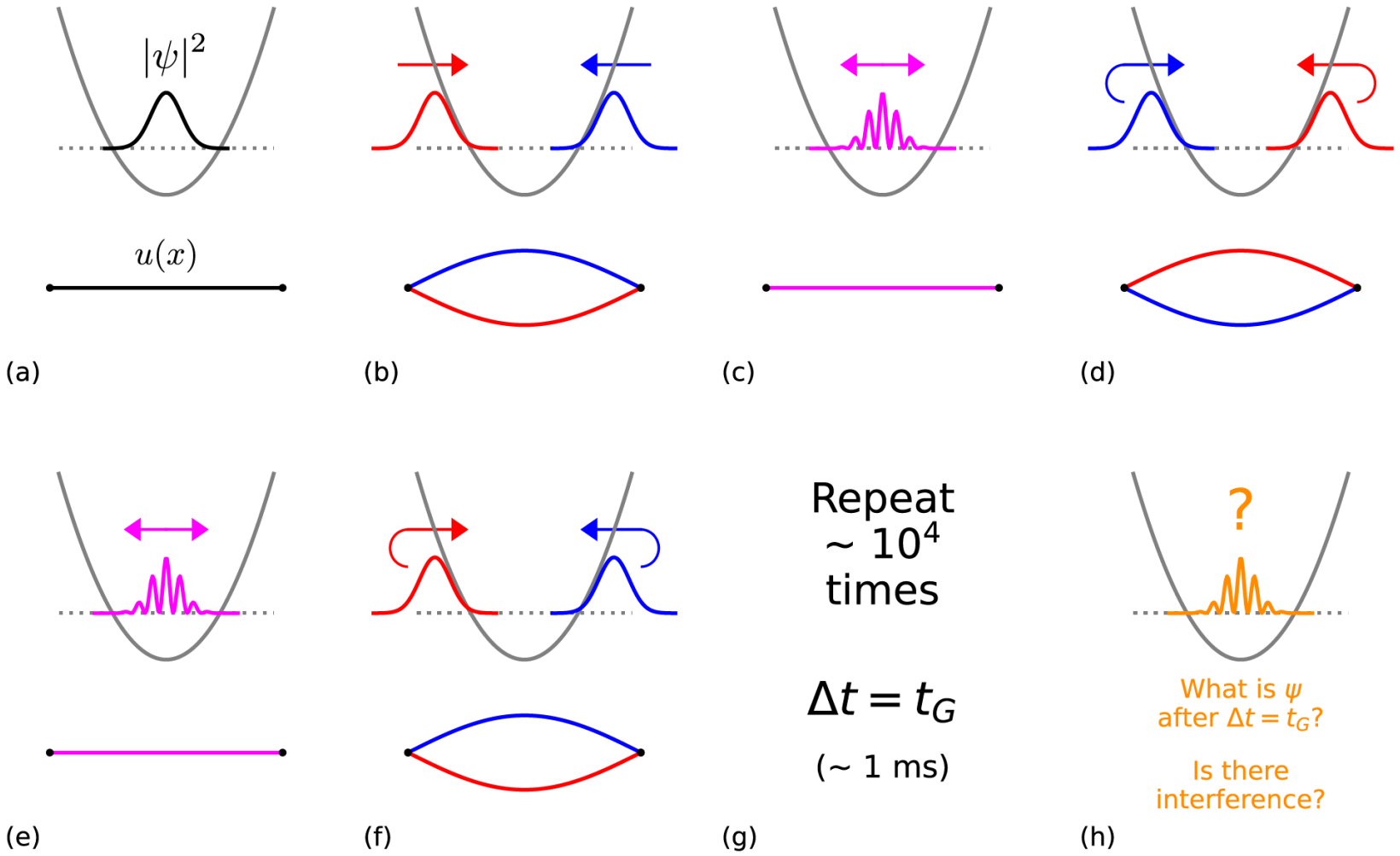
Aluminum Plate Resonators

Goal: Quantum Superpositions

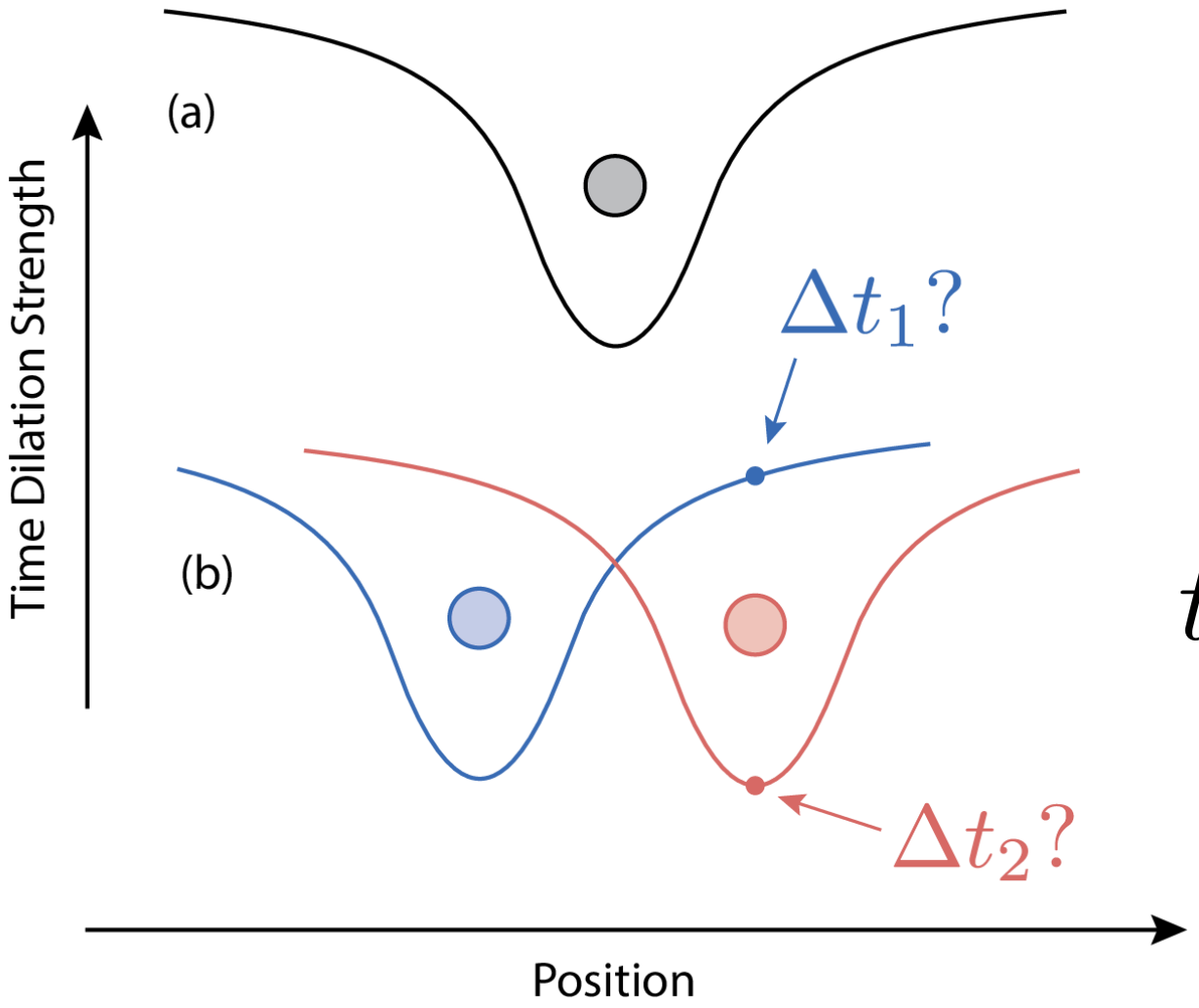


Make “mechanical” Schroedinger cat in membrane

How? “Cat” Interferometry



What can we test?



Diosi-Penrose timescale

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

What do you need?

$$t_{dec} > t_G$$

Large Mass

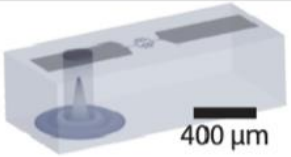
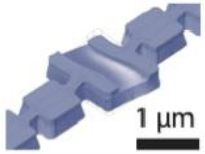
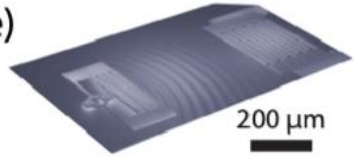
Large Superposition

High Coherence

Challenge:

How to make **large enough superpositions** of **heavy** and **coherent** enough objects?

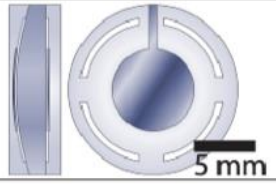
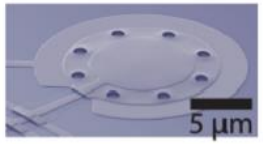
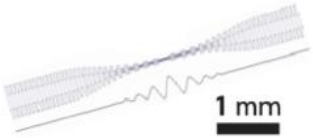
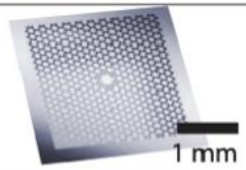
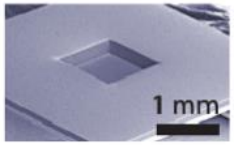
Do we have the coherence and mass?

		f_m	m	x_{zpf}	n	Q	t_{coh}	t_{GR}	
(a)		7 GHz	50 µg	0.2 am	$3x10^8$	$2x10^6$	60 fs	60 ns	No
(b)		6 GHz	2 ng	30 am	$8x10^3$	300	0.4 ps	2 ms	No
(c)		5 GHz	0.1 pg	4 fm	0/1	$4x10^6$ *T_2	60 µs	20 s	No
(d)		2 GHz	2 pg	1 fm	4	$6x10^3$	60 ns	2 s	No
(e)		0.8 GHz	0.2 µg	7 am	10^5	$6x10^4$ *4K	40 ps	10 µs	No

Superconducting electro-mechanics to test Diósi-Penrose effects of general relativity in massive superpositions

Mario F. Gely, Gary A. Steele

Do we have the coherence and mass?

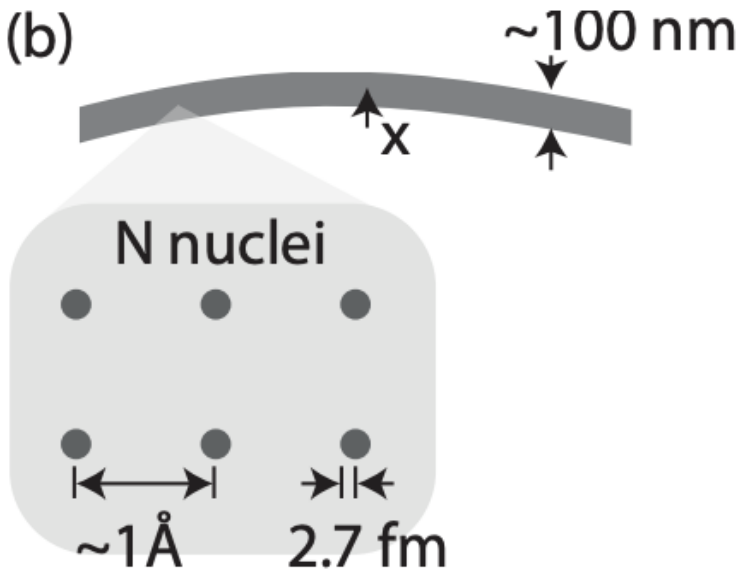
		f_m	m	x_{zpf}	n	Q	t_{coh}	t_{GR}	
(f)		20 MHz	5 mg	0.3 am	7×10^7	2×10^9	6 ns	0.6 ns	Hard…
(g)		10 MHz	50 pg	4 fm	0/1	7×10^5	0.1 ms	60 ms	No
(h)		2 MHz	5 pg	30 fm	0/1	8×10^8 *RT	0.2 s	0.6 s	No
(i)		1 MHz	2 ng	2 fm	2	1×10^9 *10K	90 ms	1 ms	Yes
(j)		200 kHz	0.5 µg	0.3 fm	90	10^8	0.3 ms	7 µs	Yes

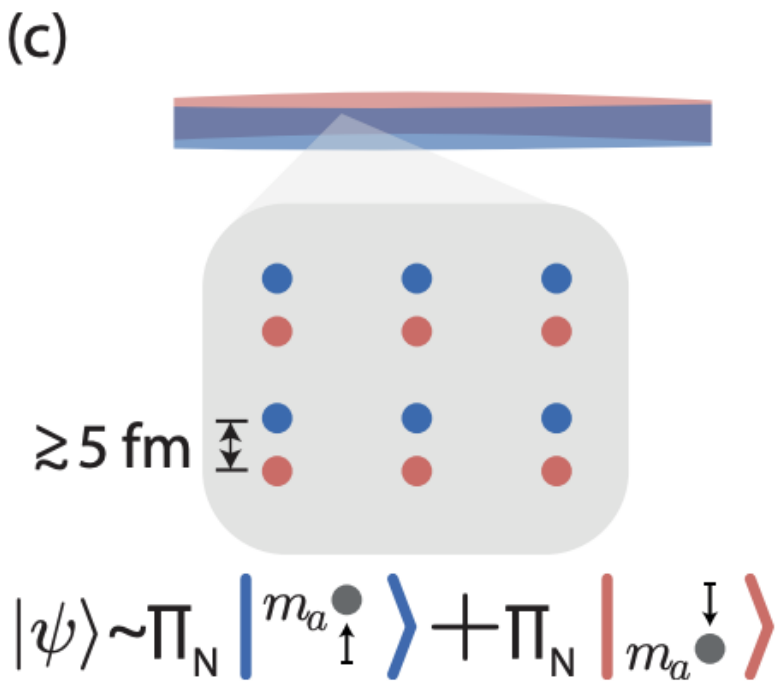
M_p / 40!

Superconducting electro-mechanics to test Diósi-Penrose effects of general relativity in massive superpositions

Mario F. Gely, Gary A. Steele

Caveat: Mass radius





$$t_G = \frac{\hbar R}{G m^2}$$

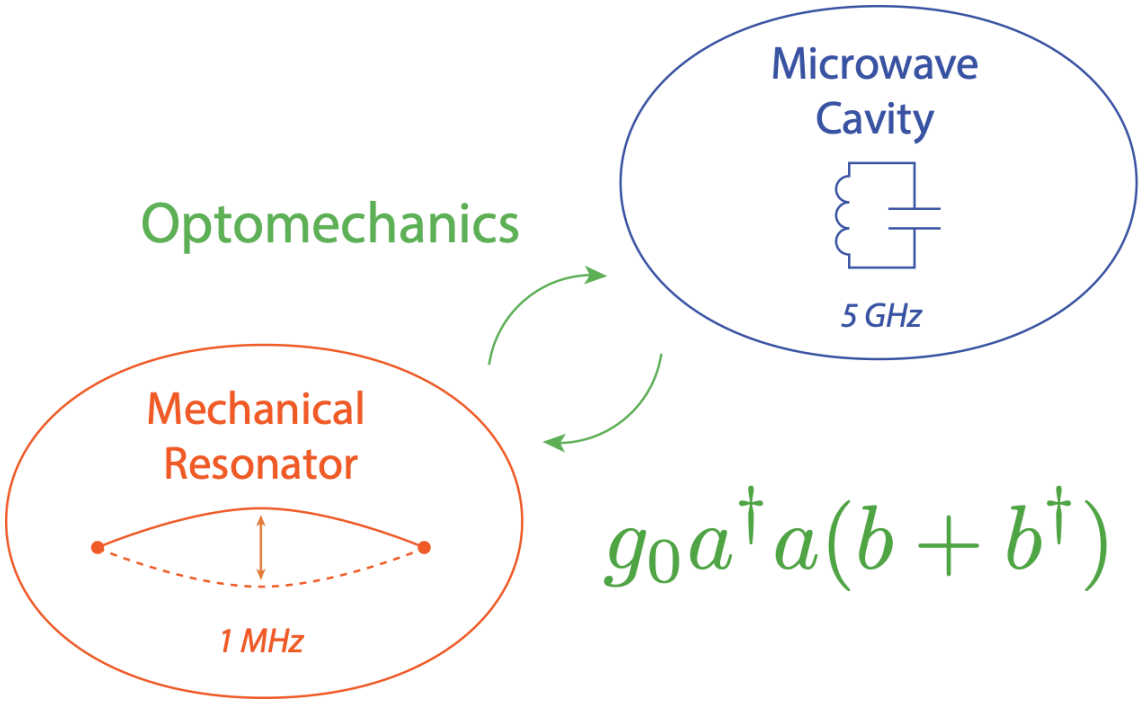
Numbers based on R = 3 fm

Assume: superposition in reference frame of rigid reference frame is relevant

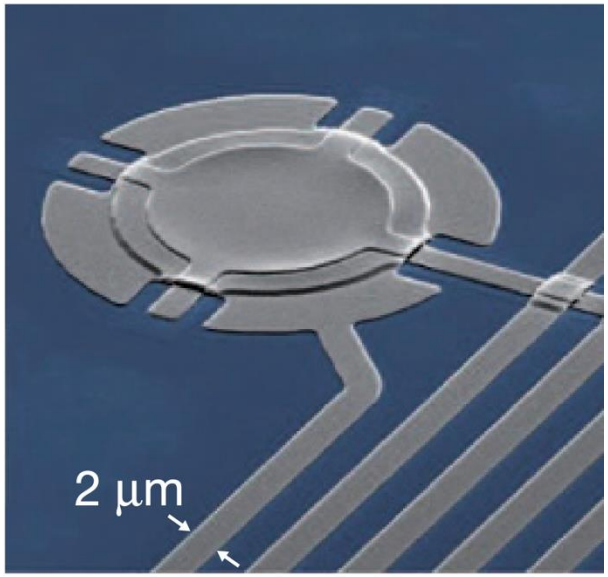
Nuclear Lattice ZPF? Justification?

Creating and measuring superpositions

Cavity Optomechanics



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



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

$$g_0 \sim 10 - 100 \text{ Hz}$$

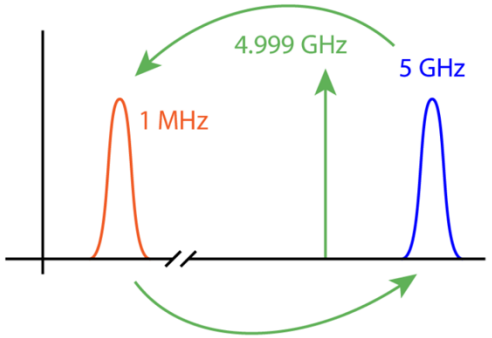
Strong Driving:

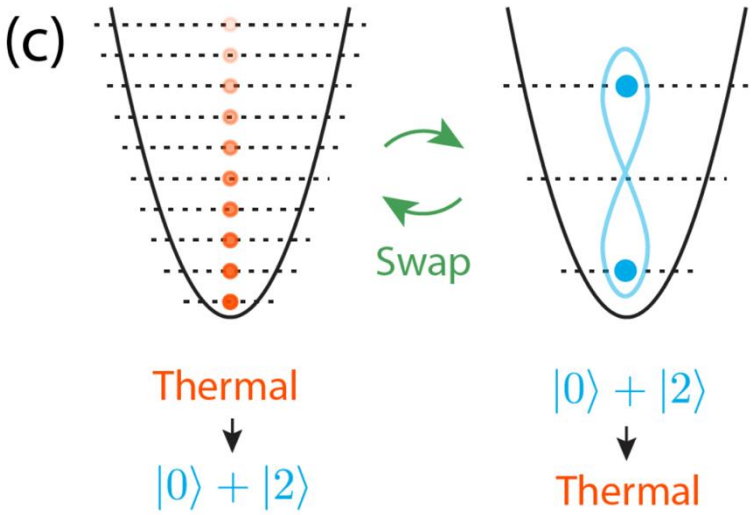
$$g(a^\dagger b + b^\dagger a)$$

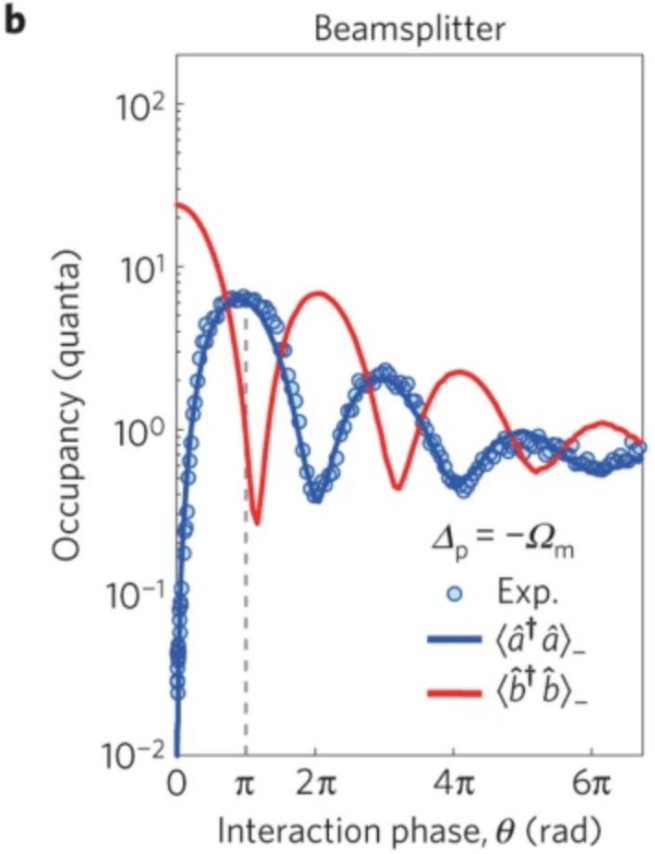
$$g = \sqrt{N} g_0$$

$$N \sim 10^6$$

Optomechanical Swap + Cooling

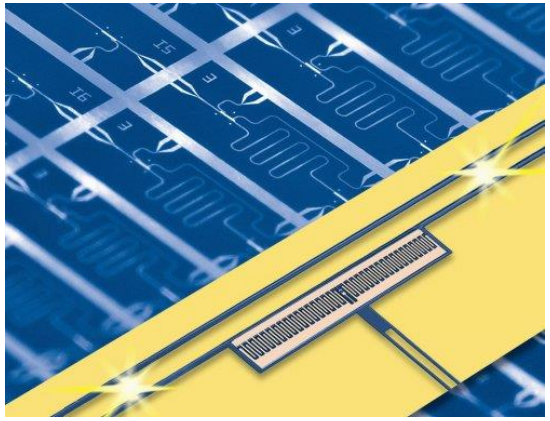


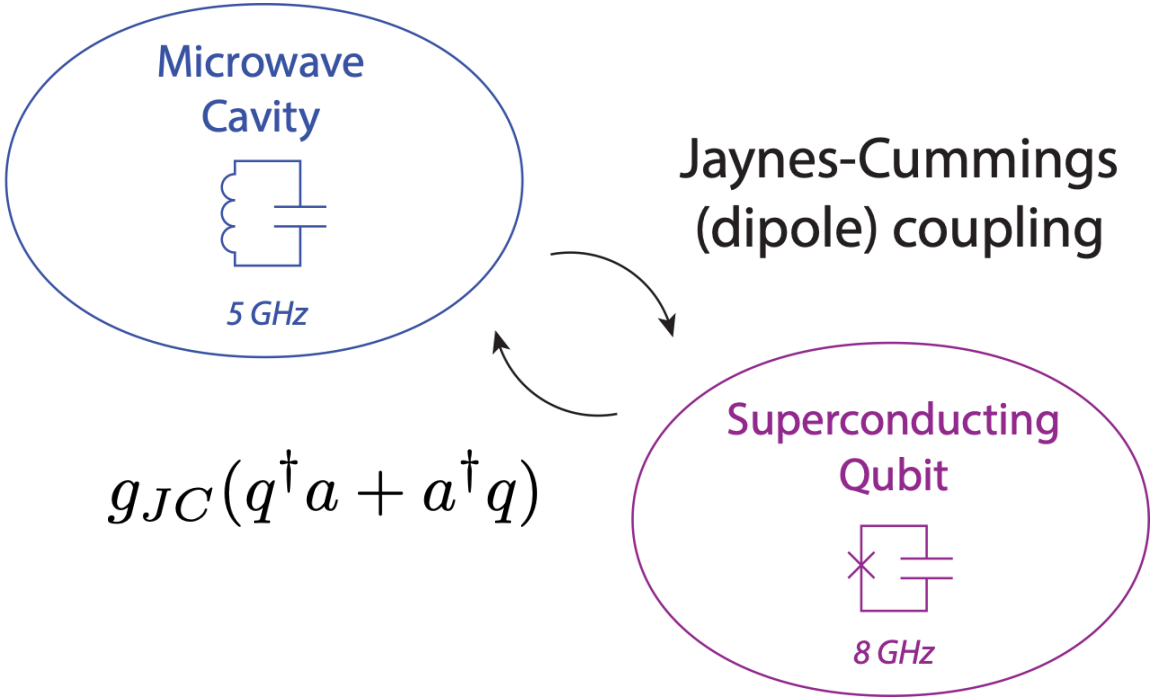




Nature Physics 11, 635 (2015)
(NIST group)

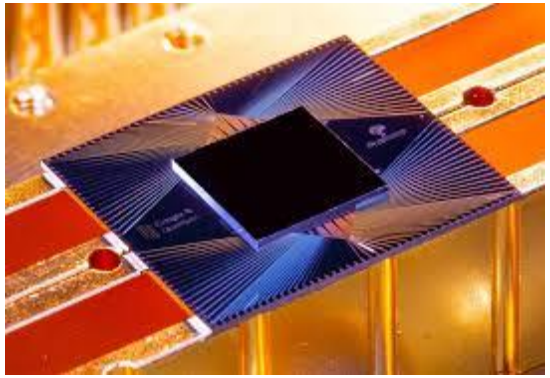
Circuit QED



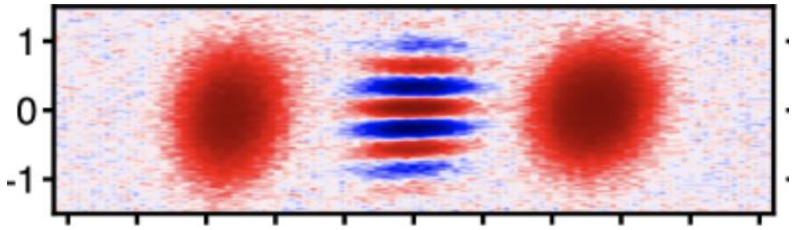


$$g_{JC}(q^\dagger a + a^\dagger q)$$

Quantum Processor



Microwave Quantum State Engineering



https://arxiv.org/abs/2406.03389v1

cQED for Mechanical Cats

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

Optomechanics

Microwave Cavity

5 GHz

$g_{JC}(q^\dagger a + a^\dagger q)$

Jaynes-Cummings (dipole) coupling

Mechanical Resonator

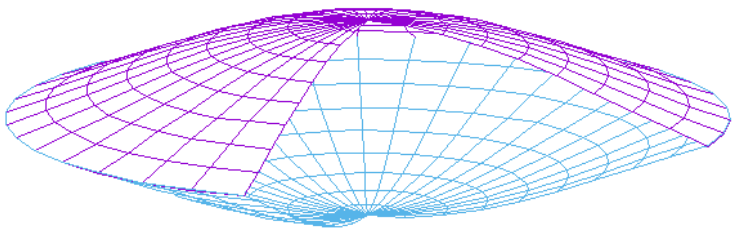
1 MHz

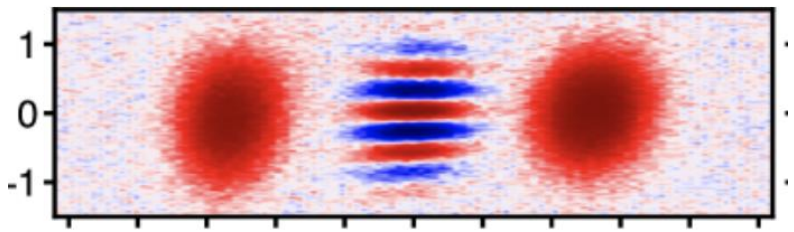
Swap!

Make cavity cat

Superconducting Qubit

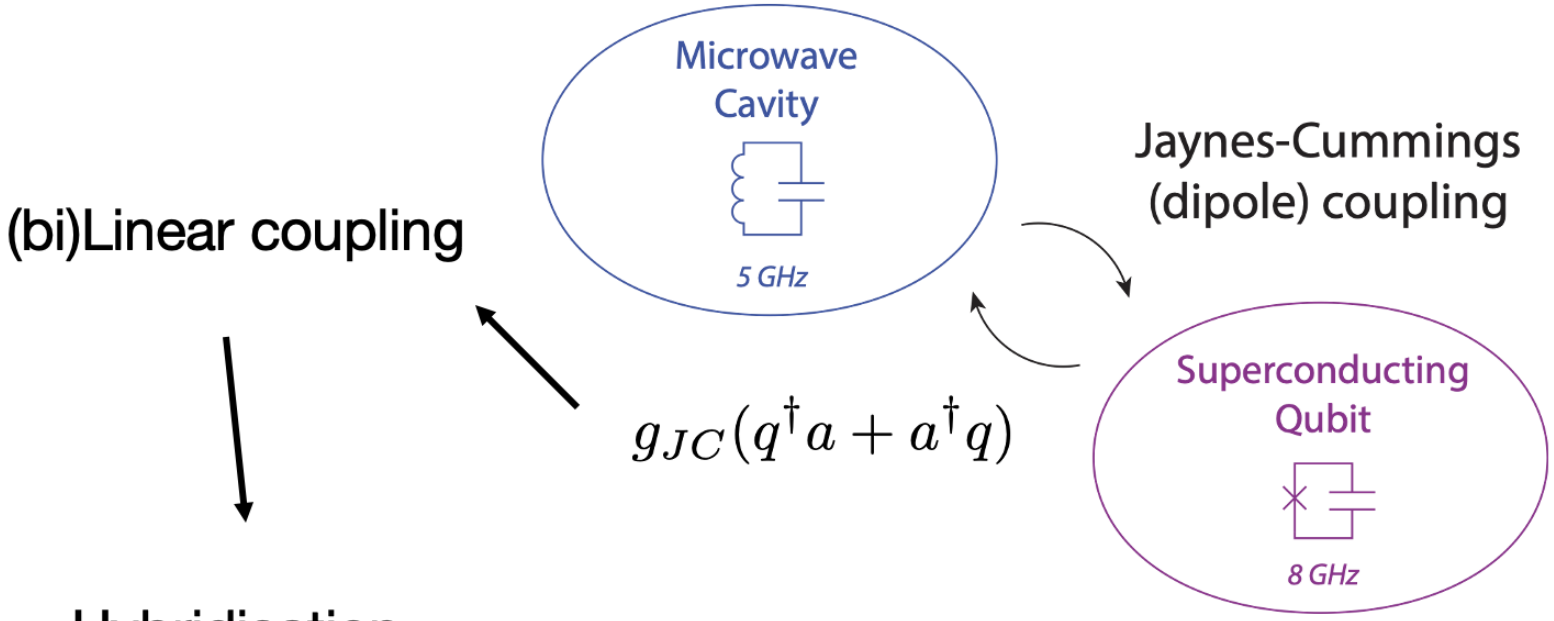
8 GHz





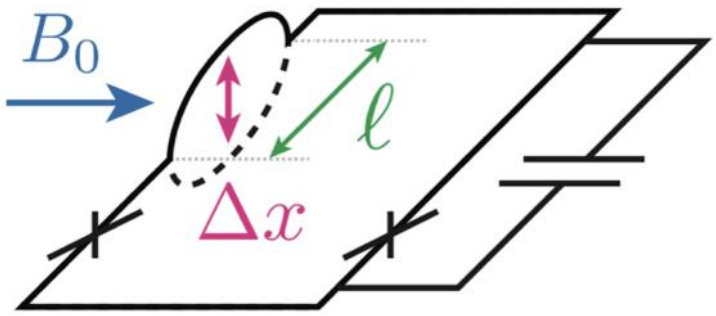
Challenge: cQED + Optomechanics

Snake in the grass…



Solutions?

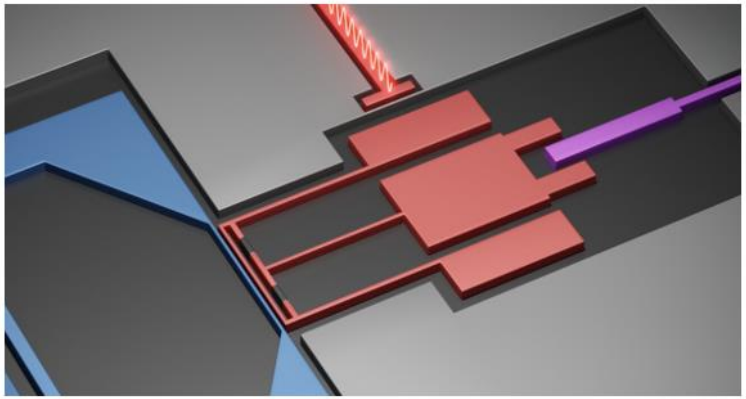
Increase Couling g_0?



Flux Optomechanics, ***g_0 = 3.6 kHz***

(Recently: Innsbruck, Bangalore: even higher! 100 kHz, MHz?)

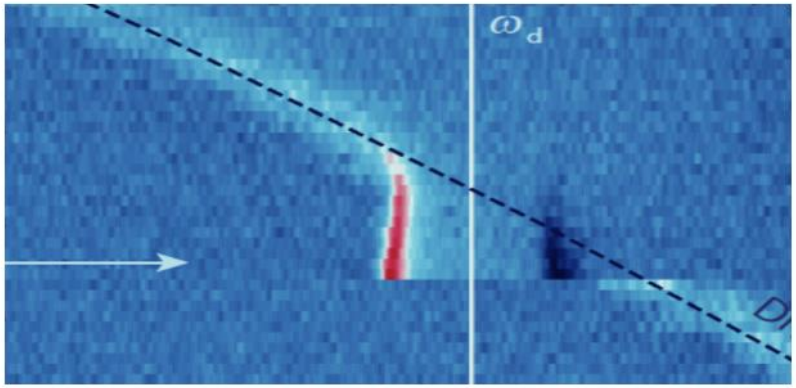
New cQED?

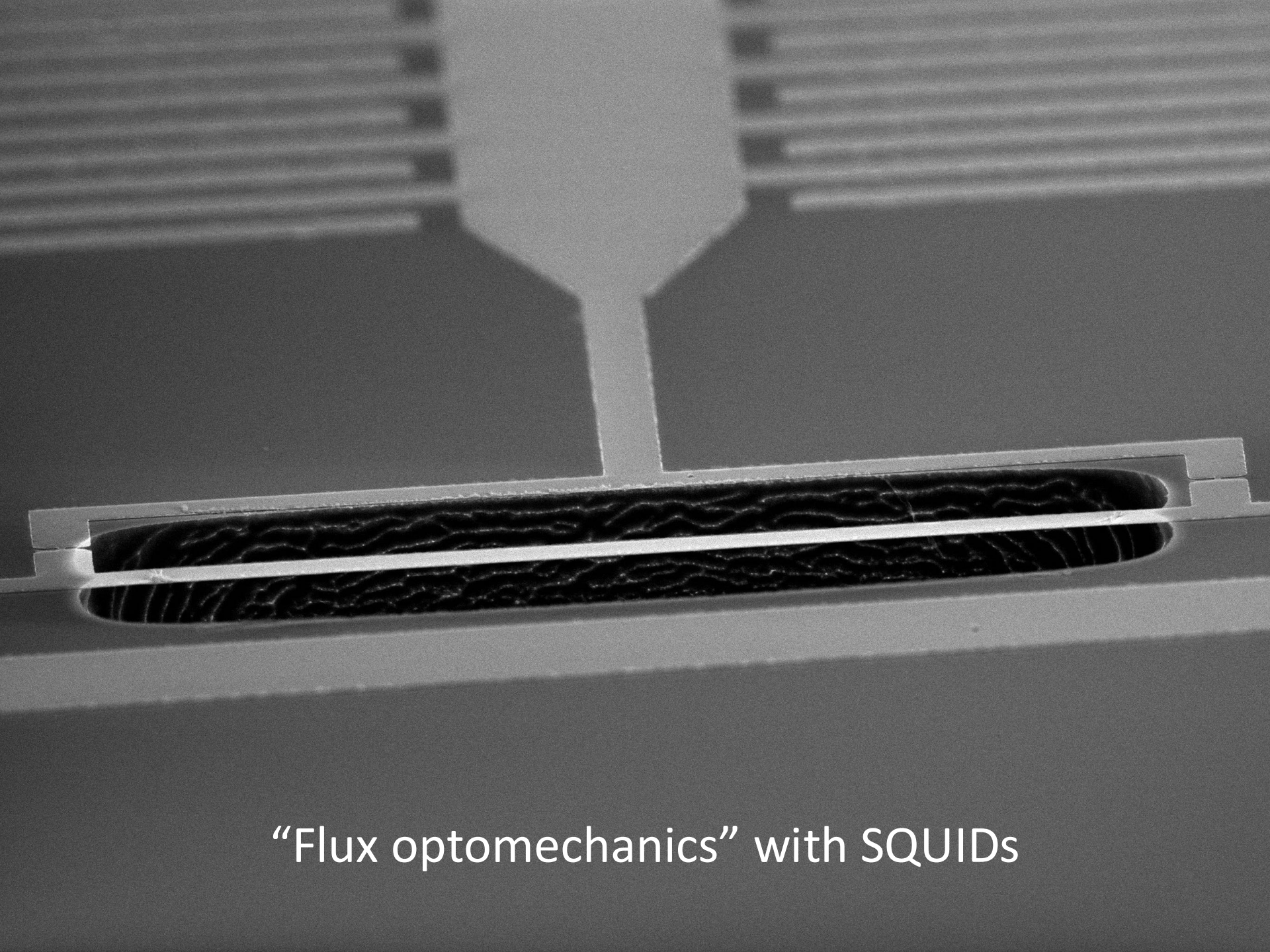


"Photon Pressure", ***N_{max} = 10^5***

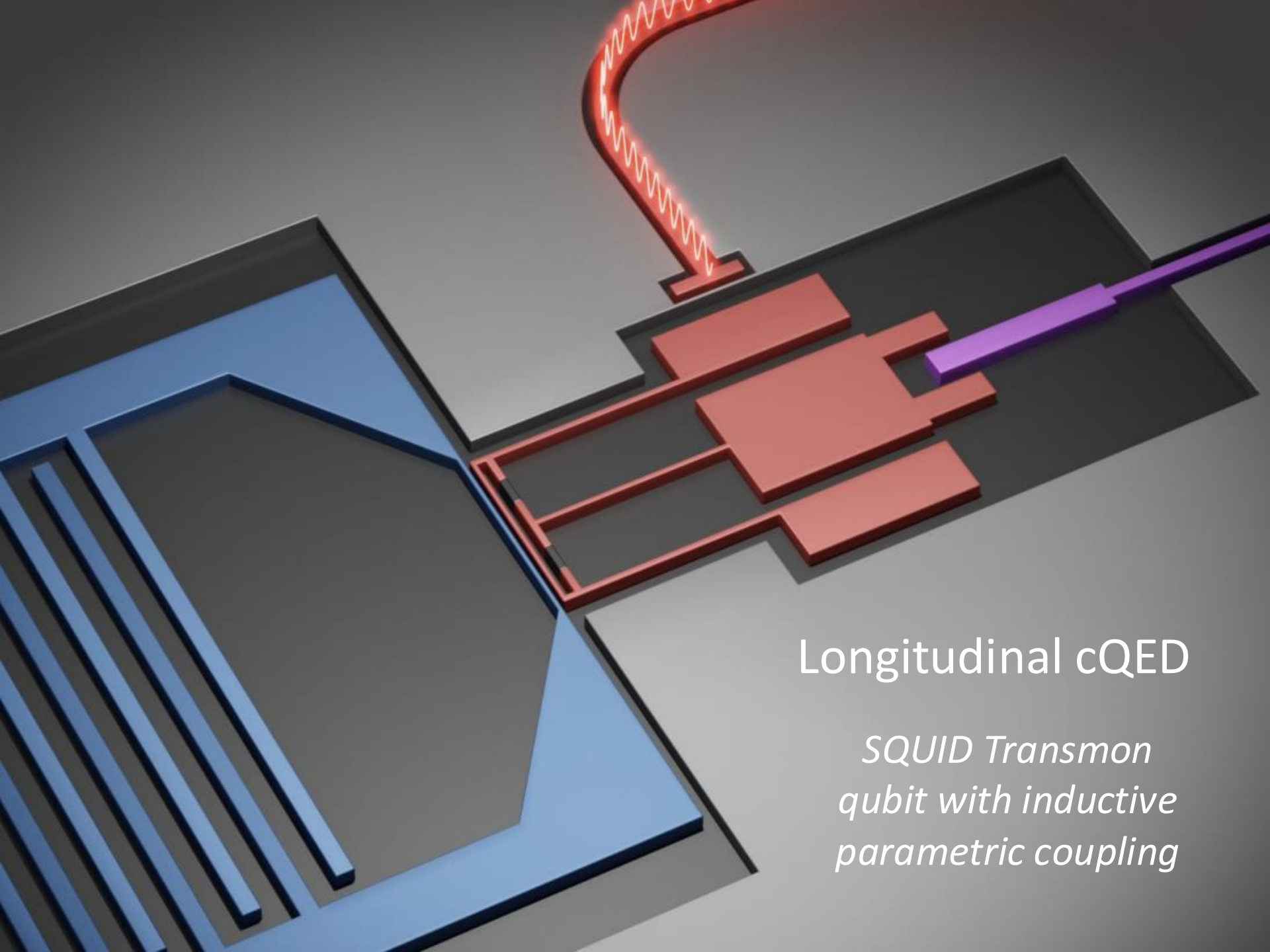
Embrace Nonlinearity?

Maybe ways to live with it?

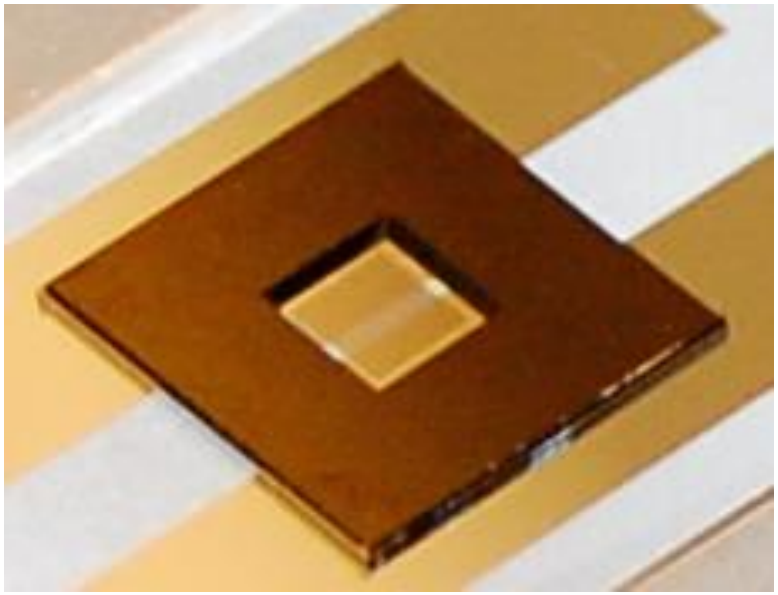


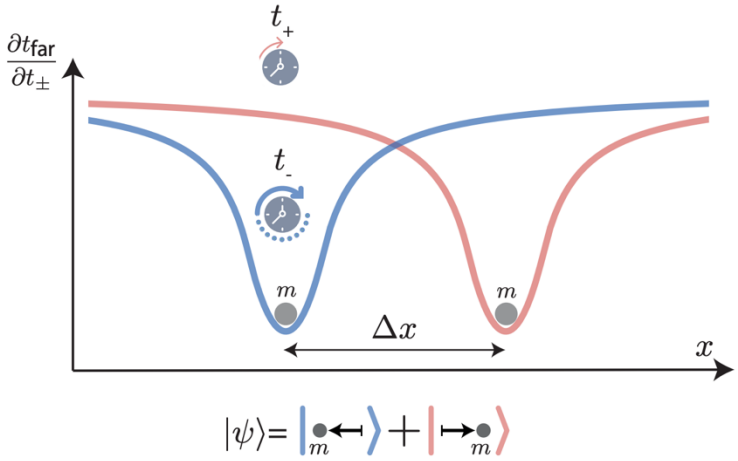


“Flux optomechanics” with SQUIDs

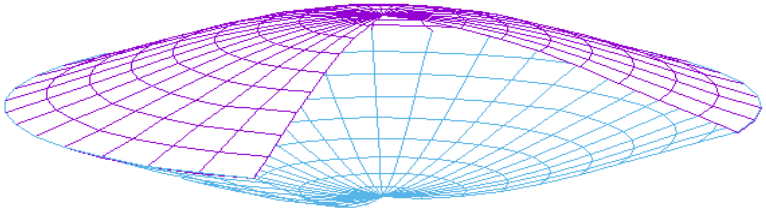

Longitudinal cQED
SQUID Transmon
qubit with inductive
parametric coupling

Superconducting Electromechanics





Optomechanics + cQED:
Control and detection of mechanical quantum states



High mass, High coherence, and large quantum fluctuations

Talent Program (Vidi, Vici)

Superpositions of masses approaching Planck mass scale