Microwave-optics quantum frequency conversion and optically heralded microwave photons

October 31, 2022

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Department of Applied Physics and Ginzton Laboratory

Stanford University

Why microwave-optics QFC, why it’s hard, and what’s next?

~~October 31, 2022~~

March 11, 2025

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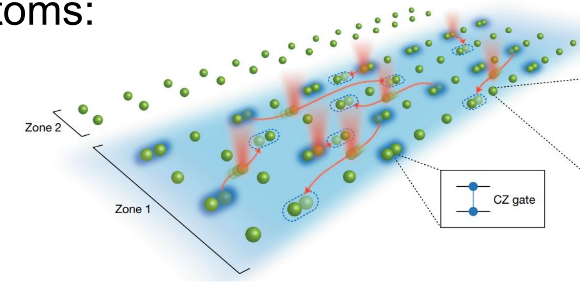
~~Stanford University~~

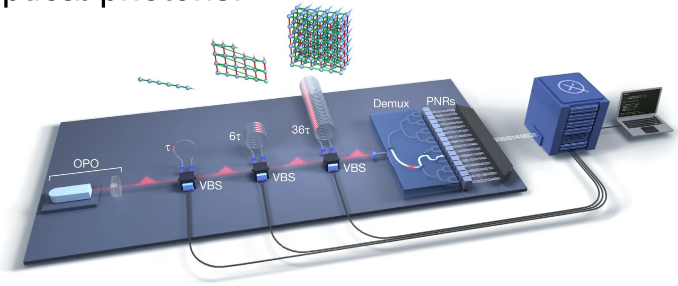
QC Implementations

Atoms:



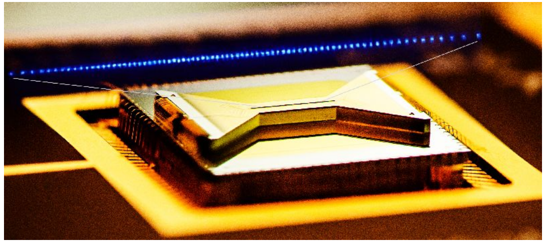
https://www.quera.com/
https://atom-computing.com/

Optical photons:



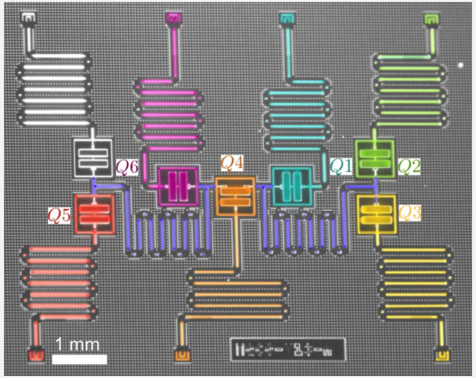
https://psiquantum.com/
https://www.xanadu.ai/

Trapped ions:



https://www.quantinuum.com/
https://ionq.com/

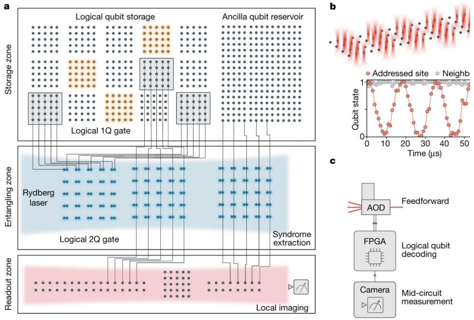
Superconducting circuits



https://quantumai.google/hardware
https://www.ibm.com/quantum

QC Implementations

Atoms:



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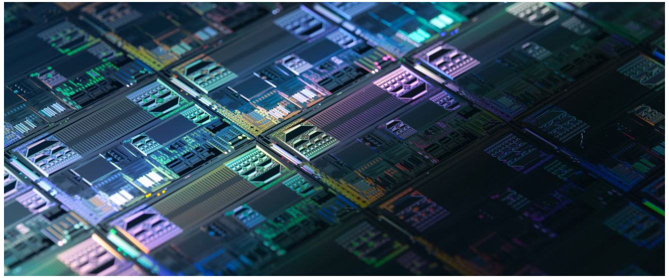
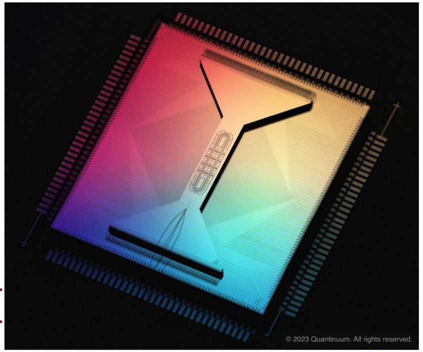
Optical photons:



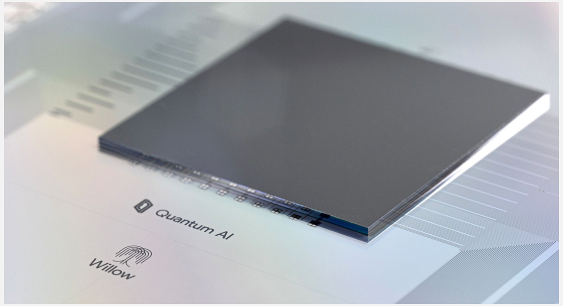
https://psiquantum.com/
https://www.xanadu.ai/

Trapped ions:

https
https



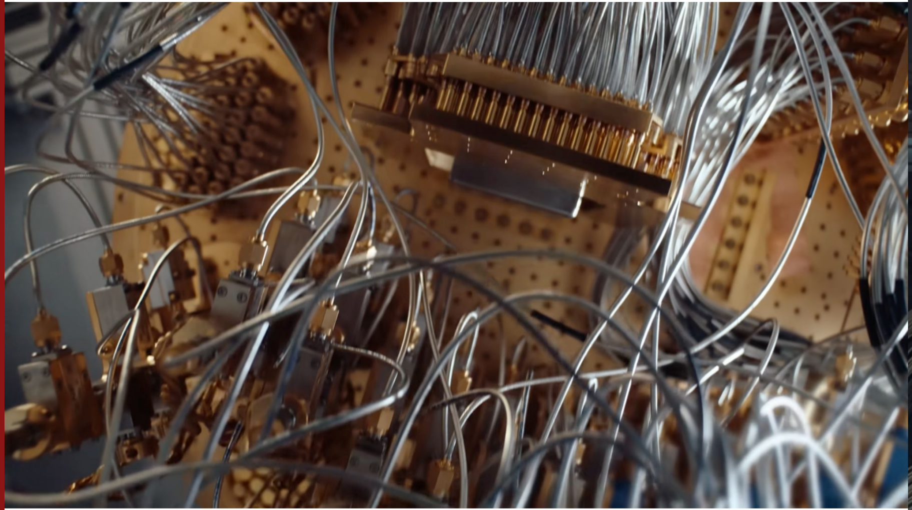
Superconducting circuits



https://quantumai.google/hardware
https://www.ibm.com/quantum

Too many cables…
(And they only work when cold)

At room T: lossy (1 dB/m) & noisy (n ~ 1000)



https://www.youtube.com/watch?v=FgZ-8NFSysA&ab_channel=GoogleQuantumAI

Too many cables…
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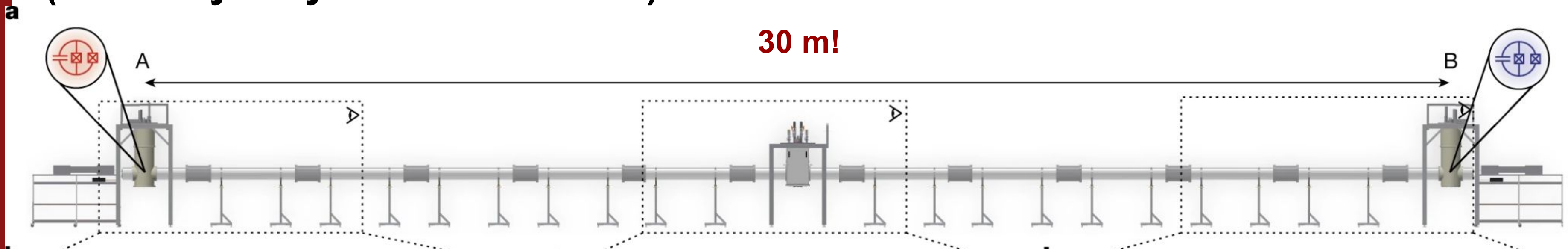
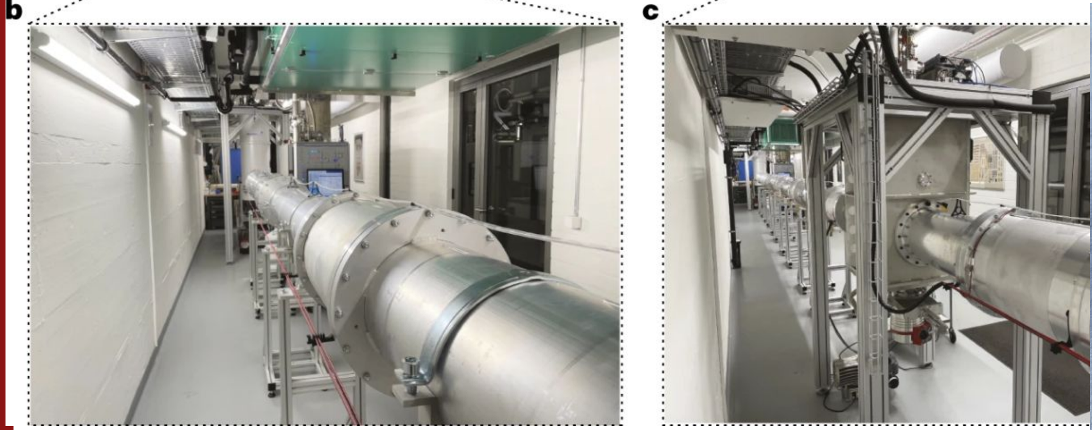
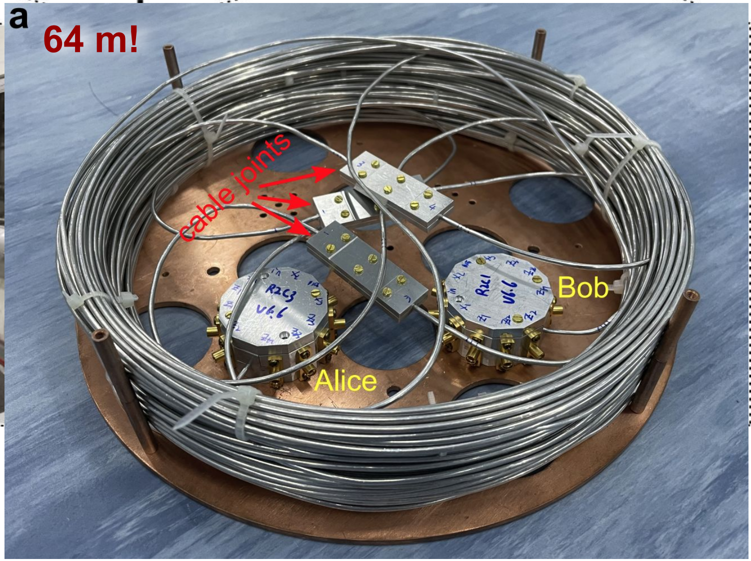




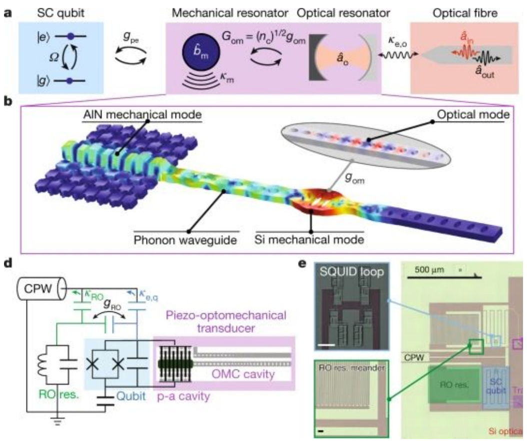
Storz (2023), ETH Zurich



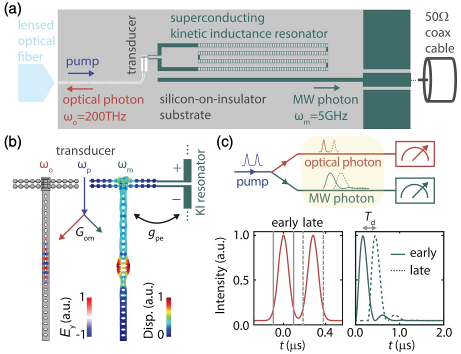
0.3 dB/km!
(fiber: 0.2 dB/km)
(don't get fooled)

Qiu (2023), SUSTech

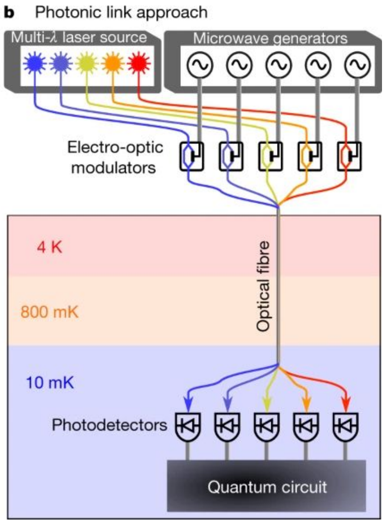
We want fibers



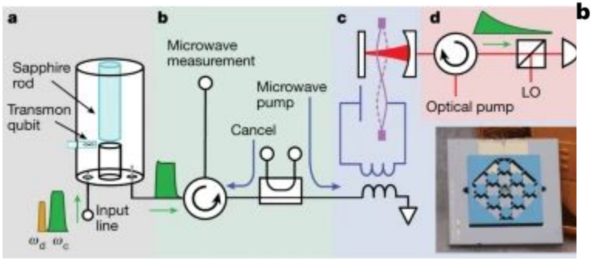
Mirhosseini (2020), Caltech



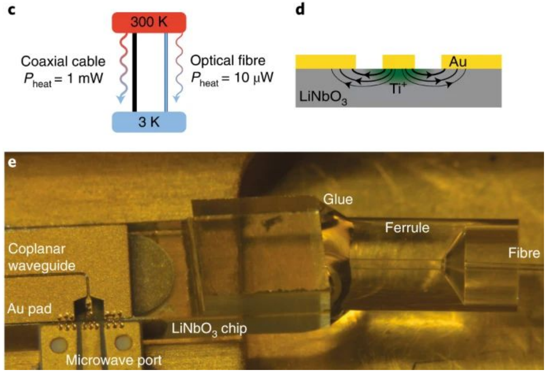
Meesala (2024), Caltech



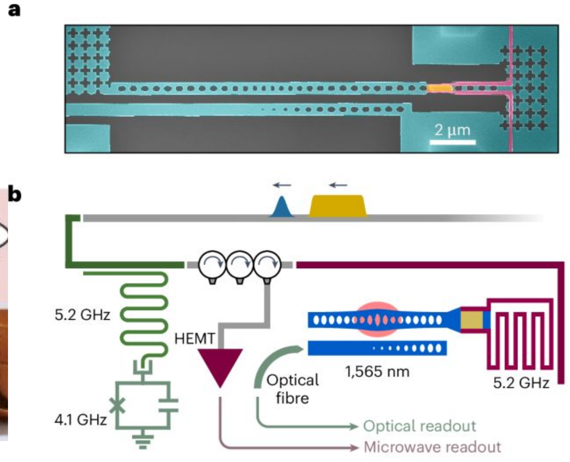
Lecocq (2021), NIST



Delaney (2022), JILA

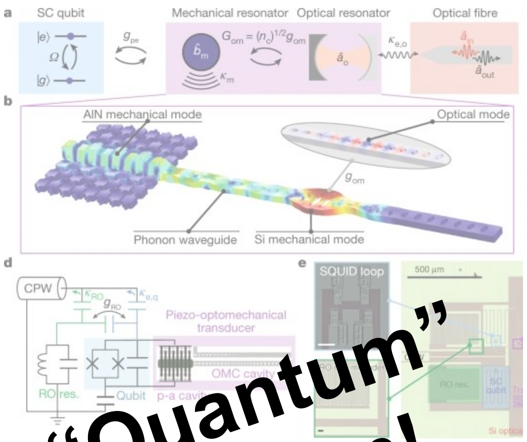


Youssefi (2021), EPFL



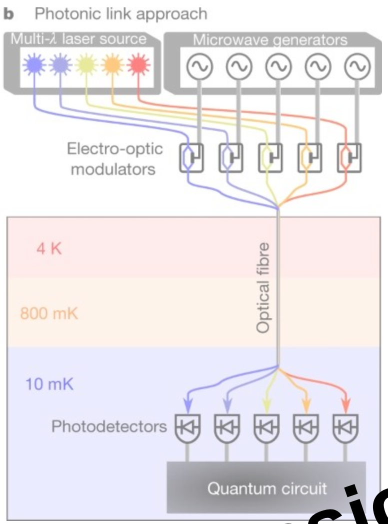
van Thiel (2025), QphoX/Delft

We want fibers

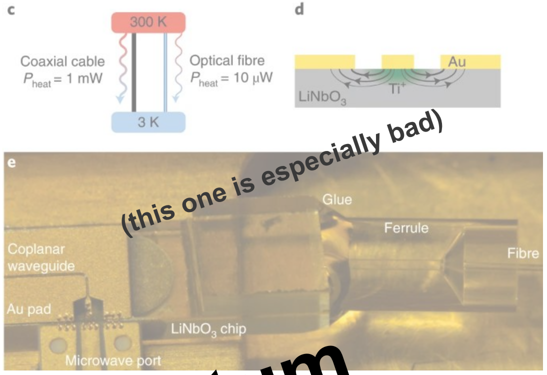


Mirhosseini (2020), Caltech

“Quantum” quantum!



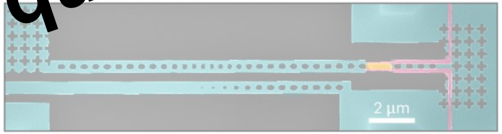
Lecocq (2021), NIST

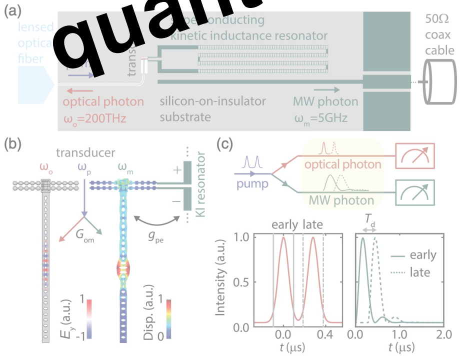


(this one is especially bad)

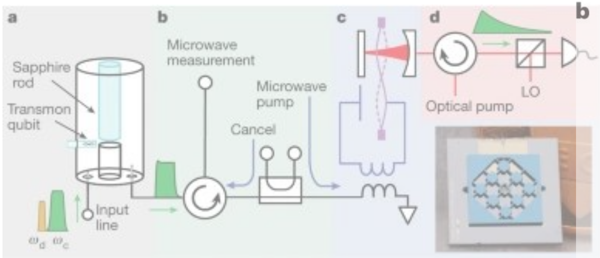
Youssefi (2021), EPFL

“Classical” quantum

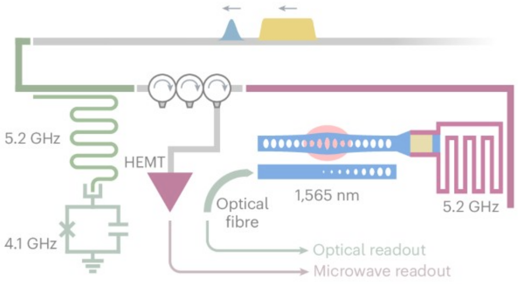




Meesala (2024), Caltech

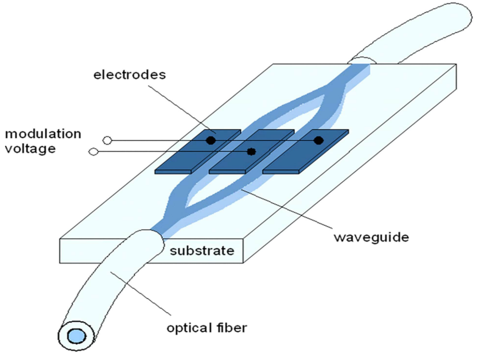


Delaney (2022), JILA



van Thiel (2025), QphoX/Delft

Commercial electro-optic (EO) modulators



V_pi ~ 5 V

Microwave impedance = 50 Ohms

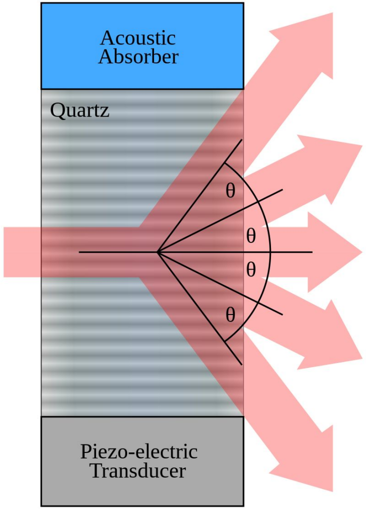
Voltage from one 100 ns microwave photon ~ 5e-8 V

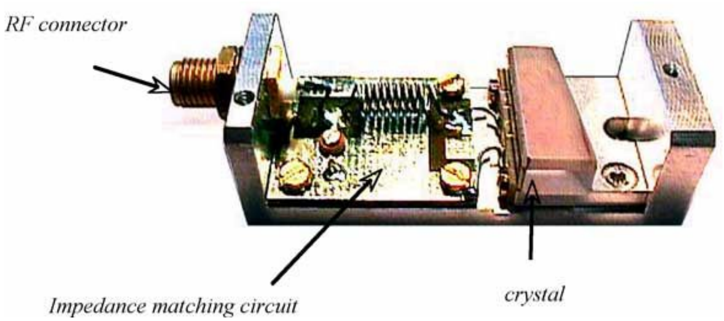
Efficiency **~ 1e-8** with **1 mW** optical pump

Fridge cooling power **~ 10 uW**

https://www.jenoptik.com/products/optoelectronic-systems/light-modulation/integrated-optical-modulators-fiber-coupled

Commercial acousto-optic (AO) modulators



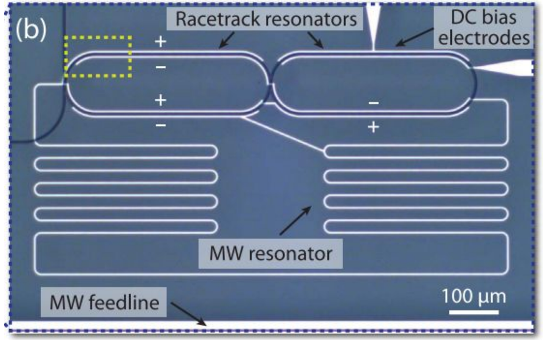


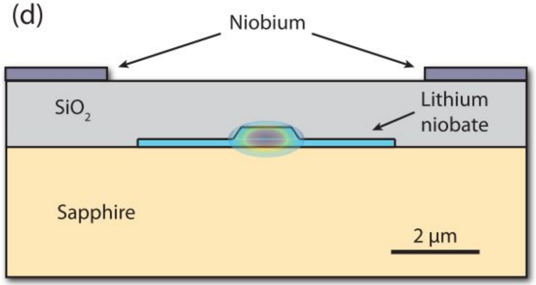
RF power ~ 1 W ~ 1e24 photon/s

1 mW optical power ~ 1e14 photon/s

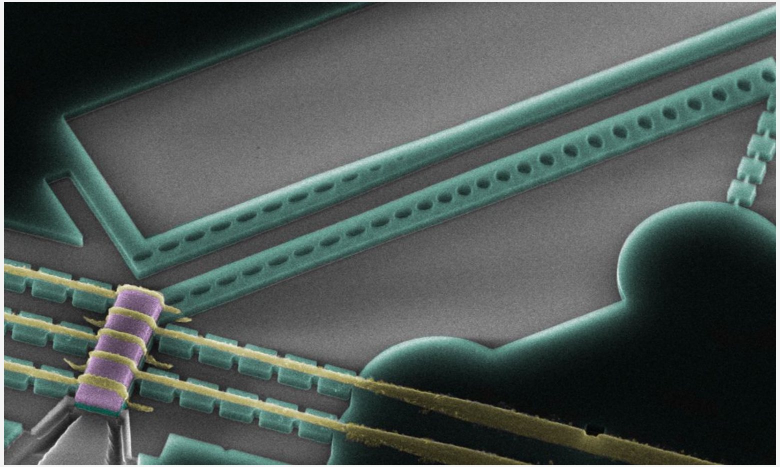
Efficiency ~ **1e-10**

EO & AO modulator, but quantum



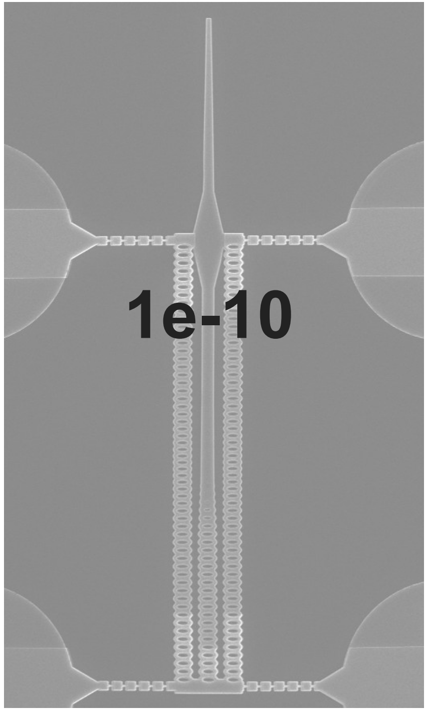


McKenna, Timothy P., et al. Optica 7.12 (2020): 1737-1745.



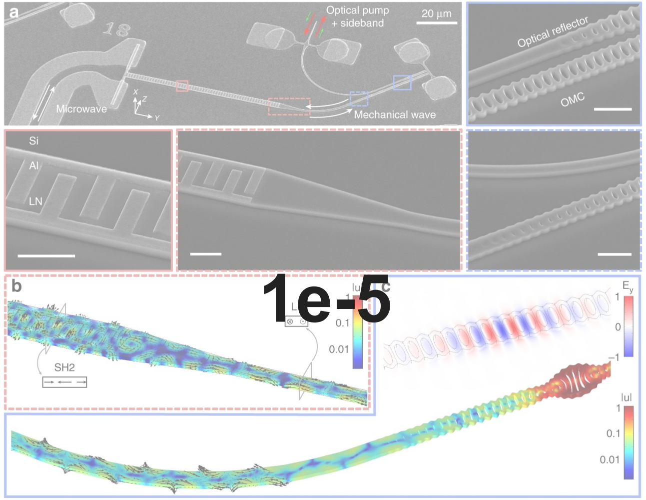
Jiang, Wentao, et al. Nature Physics (2023).

Lambert, Nicholas J., et al. Advanced Quantum Technologies 3.1 (2020): 1900077.
Han, Xu, et al. Optica 8.8 (2021): 1050-1064.



1e-10

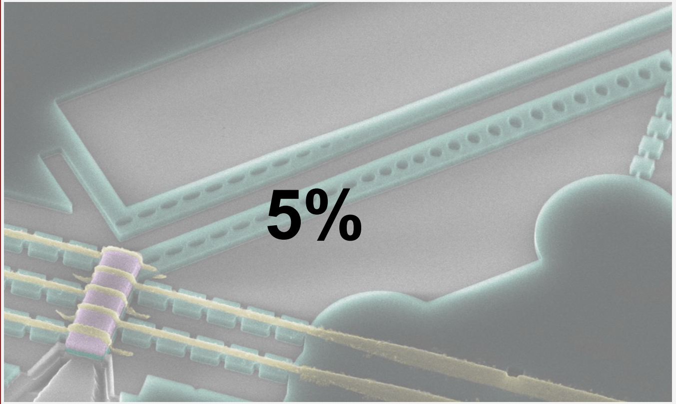
Jiang, Wentao, et al. Optica 6.7 (2019): 845-853.



1e-5

Jiang, Wentao, et al. Nature communications 11.1 (2020): 1-7.

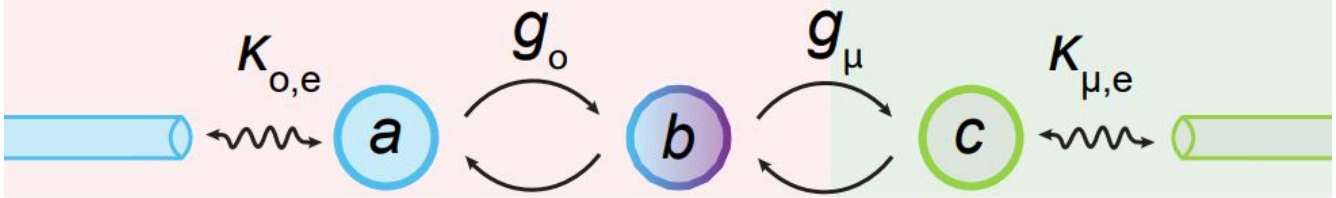
LN transducer + silicon optomechanical crystal



5%

Jiang, Wentao, et al. Nature Physics (2023).

How hard could this be?



$$G_o = \sqrt{n_a} g_o$$

$$\gamma_{om} = 4G_o^2/\kappa_o$$

$$\gamma_\mu = 4g_\mu^2/\kappa_\mu$$

$$\eta_o \equiv \kappa_{o,e}/\kappa_o$$

$$\eta_\mu \equiv \kappa_{\mu,e}/\kappa_\mu$$

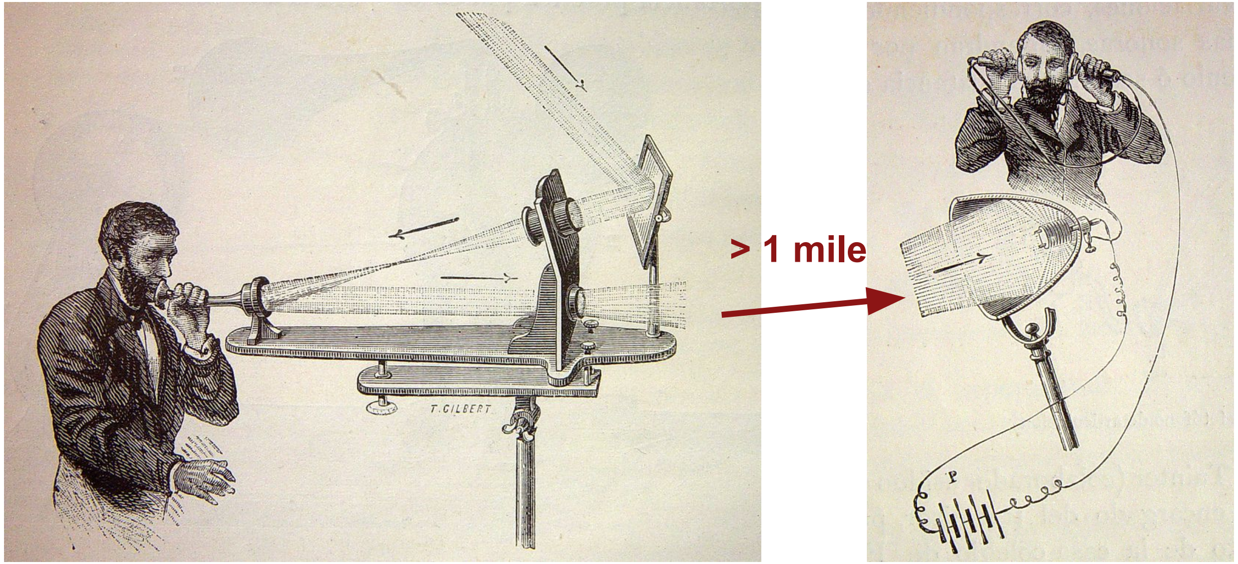
$$\eta = \eta_o\eta_\mu \frac{4\gamma_{om}\gamma_\mu}{(\gamma_i + \gamma_{om} + \gamma_\mu)^2}$$

- Match & maximize rate
- Minimize spill

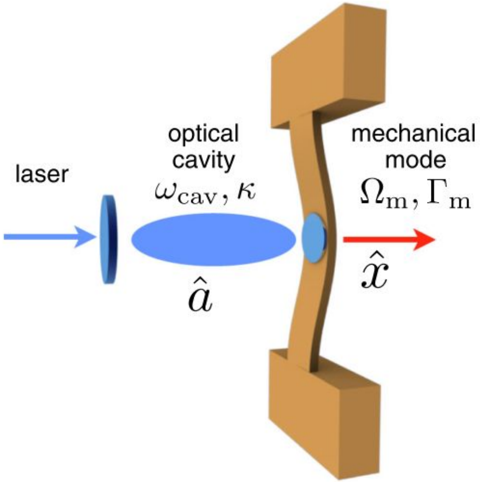
How hard could this be?

- **Higher optomechanical coupling rate?**
- Higher piezoelectric coupling rate?
- How do we make it?
- How do we wire it up?

Optomechanics

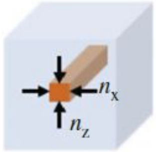


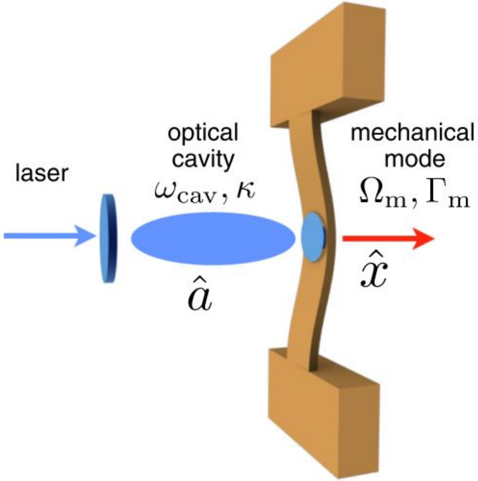
Bell, Alexander Graham. American Journal of Science (1880-1910) 20.118 (1880): 305.

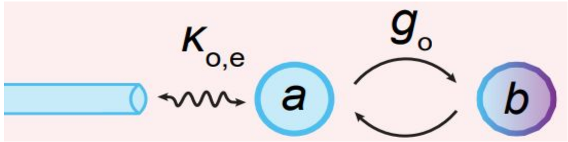


Aspelmeyer *et al.* Rev. Mod. Phys. (2014)

Higher OM coupling



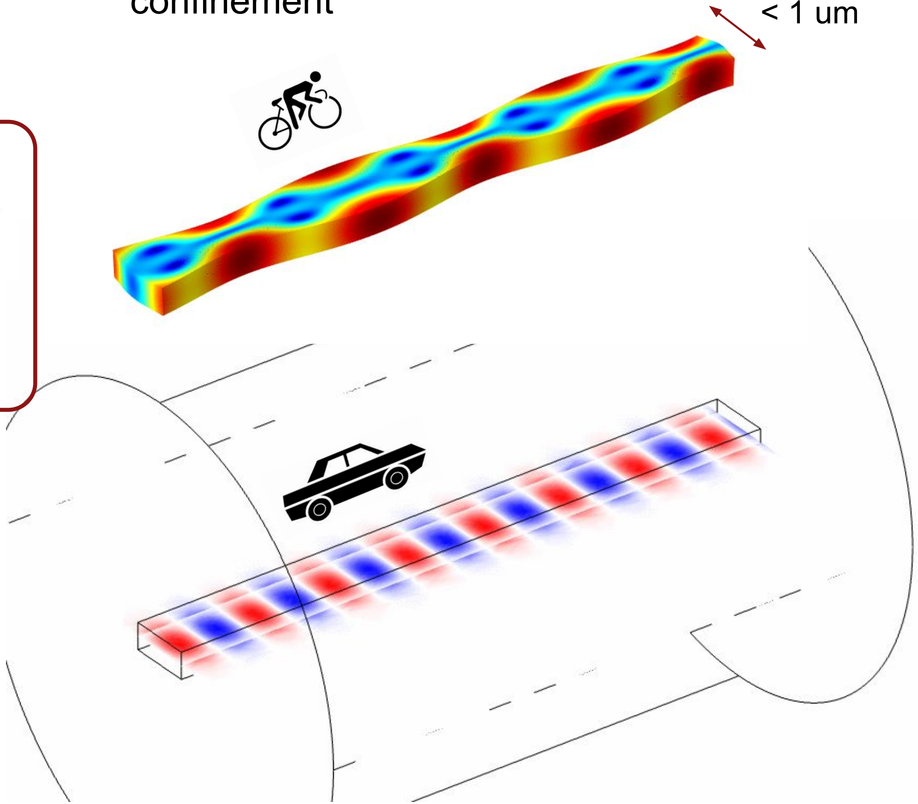




Larger $\dfrac{\partial \omega_{cav}}{\partial x}$

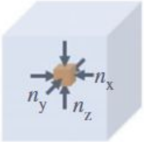
Larger x_{zp}

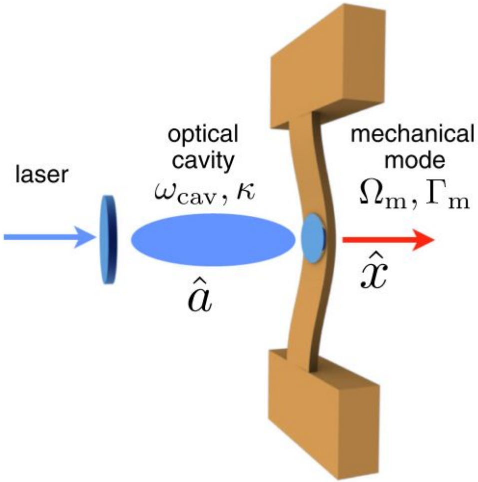
Si wire: 2D wavelength scale confinement

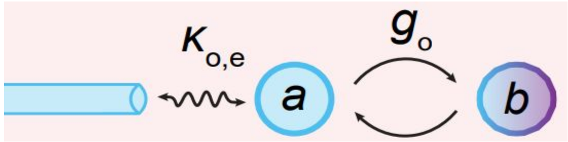


Aspelmeyer *et al.* Rev. Mod. Phys. (2014)
Edvinsson, Tomas. Royal society open science 5.9 (2018): 180387.

Optomechanical crystal (OMC)



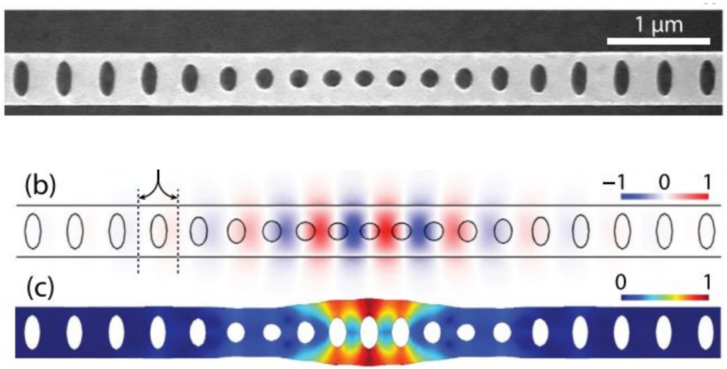


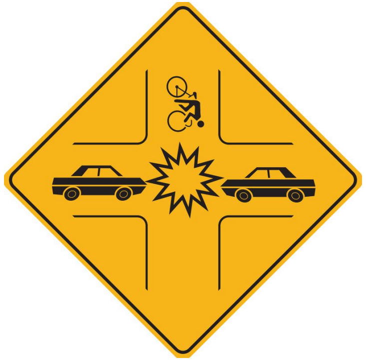


Larger $\frac{\partial \omega_{cav}}{\partial x}$

Larger x_{zp}

Si wire with holes: 3D confinement



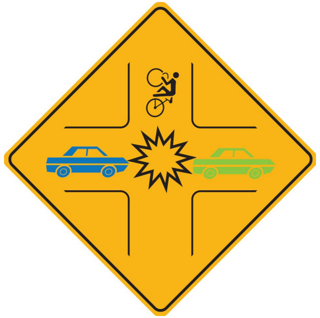


Aspelmeyer *et al.* Rev. Mod. Phys. (2014)
Chan, Jasper, et al. Applied Physics Letters 101.8 (2012): 081115.

Linearize the three-wave mixing

squeezer
(entanglement)

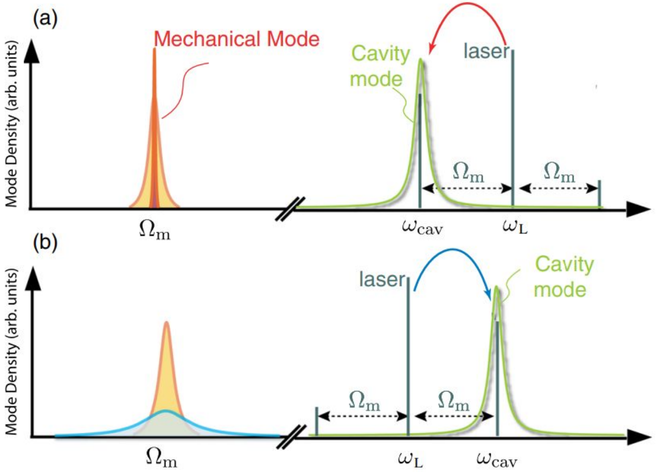
$\delta\hat{a}^\dagger\hat{b}^\dagger + \hat{b}\delta\hat{a}$



beam-splitter
(cooling)

$\delta\hat{a}^\dagger\hat{b} + \hat{b}^\dagger\delta\hat{a}$

Optomechanical cooling & amplification:



$$H_{\text{int}} = \hbar g_0 a^\dagger a (b + b^\dagger)$$

$$\hat{H}^{(\text{lin})}_{\text{int}} = -\hbar g_0 \sqrt{\bar{n}_{\text{cav}}}(\delta\hat{a}^\dagger + \delta\hat{a})(\hat{b} + \hat{b}^\dagger)$$

Aspelmeyer *et al.* Rev. Mod. Phys. (2014)

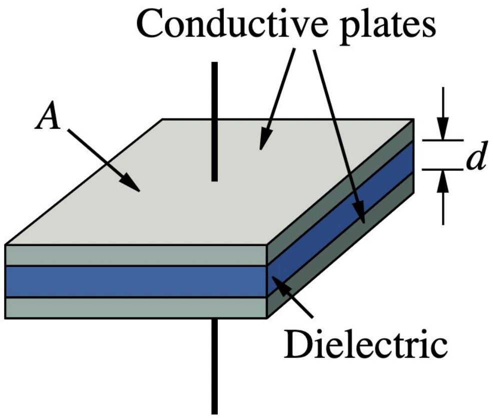
How hard could this be?

- Higher optomechanical coupling rate?
- **Higher piezoelectric coupling rate?**
- How do we make it?
- How do we wire it up?

Challenge: impedance matching

Mechanical mode impedance: **10k ~ 100k** Ohms

Microwave coax impedance: **50** Ohms



$$Y = i\omega C = i\omega \frac{\epsilon_0 \epsilon_r A}{d}$$

$$G \sim \omega \frac{\epsilon_0 (\epsilon_r^T - \epsilon_r^S) A}{d} \sim \frac{1}{100\ \mathrm{k\Omega}}$$

Assuming **lithium niobate (LN)**

A = 1 um^2, d = 1 um

Challenge: impedance matching

Mechanical mode impedance: **10k ~ 100k** Ohms

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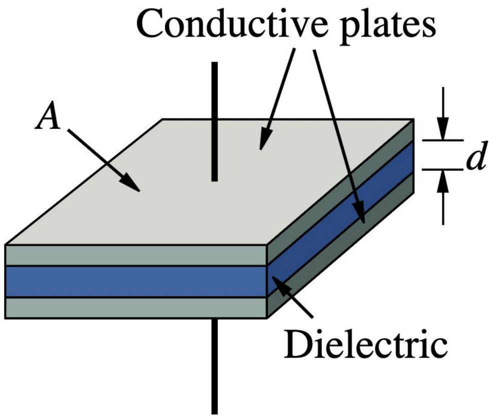
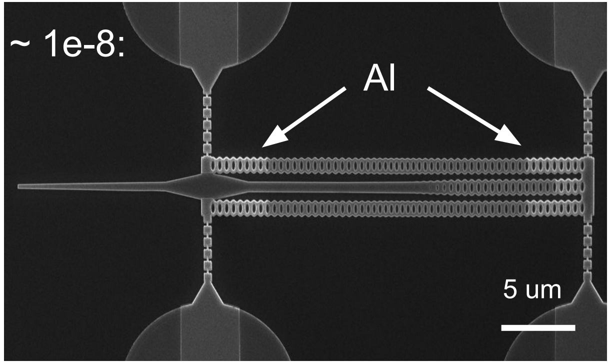
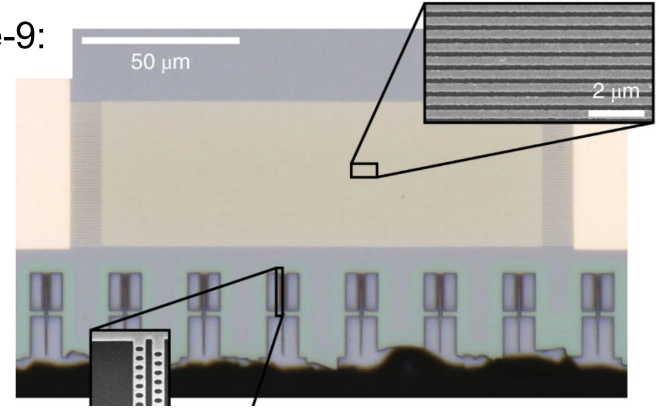


$$G \sim \omega \frac{\epsilon_0(\epsilon_r^T - \epsilon_r^S)A}{d} \sim \frac{1}{100\ \mathrm{k}\Omega}$$



Jiang, Wentao, et al. Optica 6.7 (2019): 845-853.

~ 1e-9:

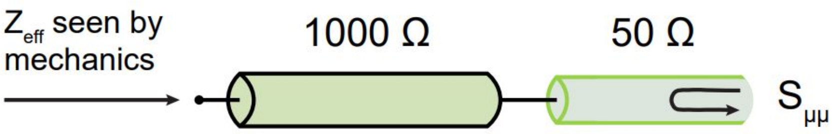


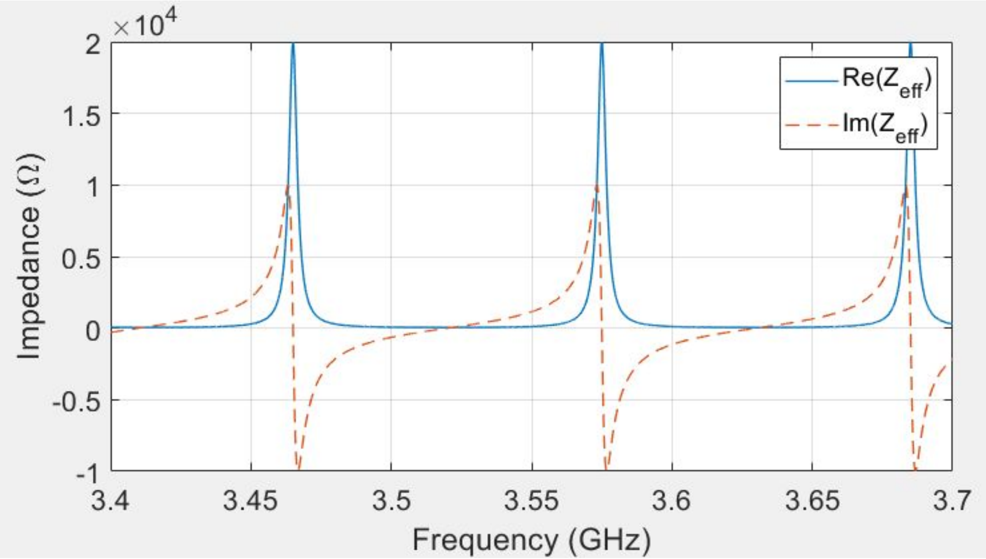
Forsch, Moritz, et al. Nature Physics 16.1 (2020): 69-74.

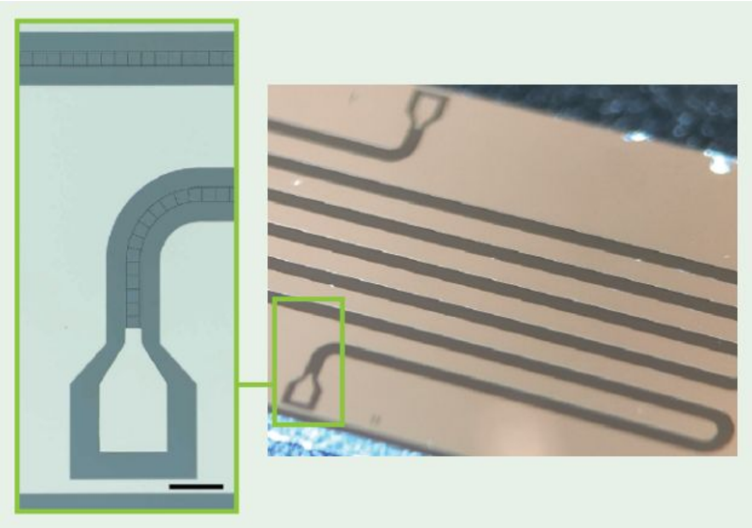
Microwave resonator for impedance matching

High kinetic inductance from thin NbTiN

Magnetically tunable (~ 3% @ 5 mT)



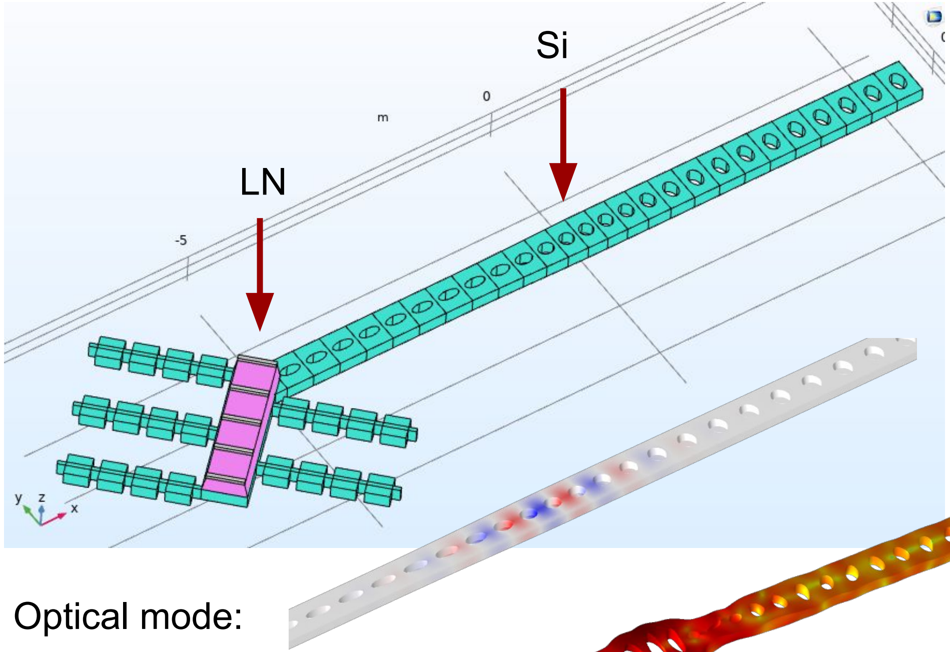




How hard could this be?

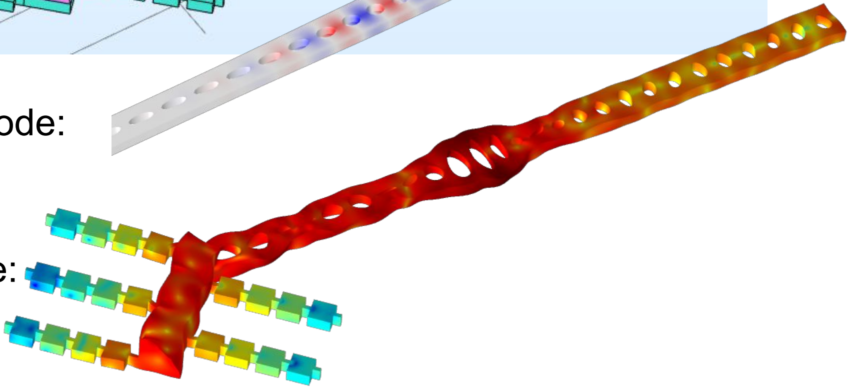
- Higher optomechanical coupling rate?
- Higher piezoelectric coupling rate?
- **How do we make it?**
- How do we wire it up?

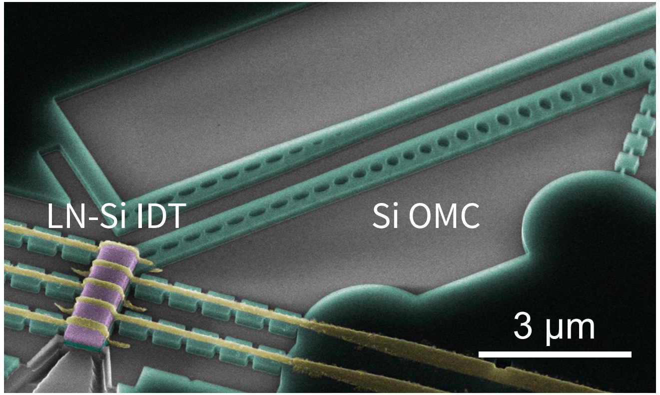
Transducer design



Optical mode:

Mech mode:





- OM and piezo mechanics coupling

$$J/2\pi \sim 42\ \mathrm{MHz}$$

- Optomechanical

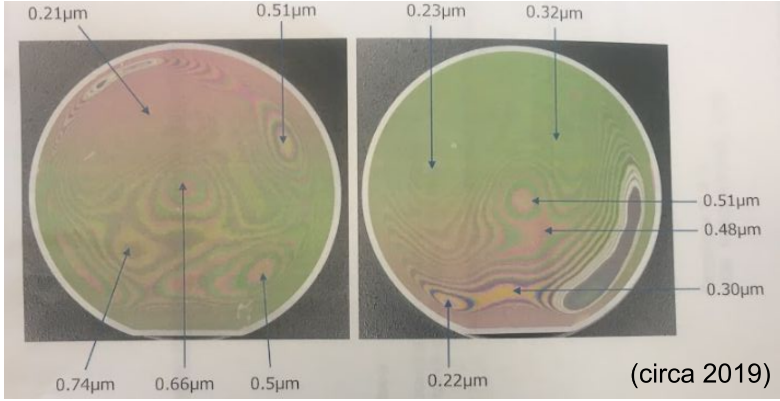
$$g_0/2\pi \sim 700\ \mathrm{kHz}$$

- Piezoelectric

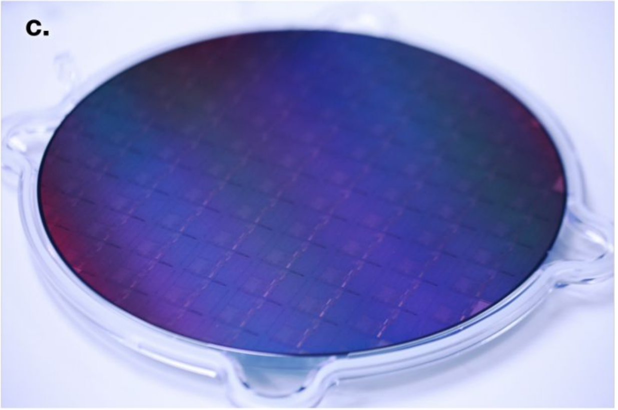
$$g_{\mathrm{p}}/2\pi = 4 \sim 14\mathrm{MHz}$$

Fabrication: issue with LN-on-SOI

Thickness variation:

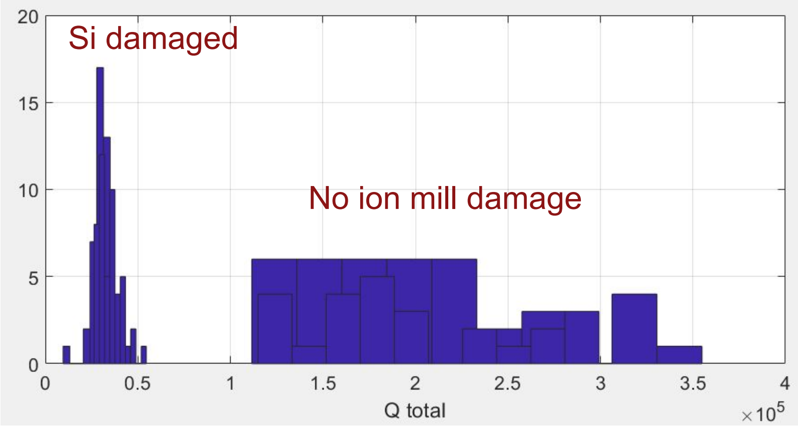


Meanwhile…



PsiQuantum Team, 2025

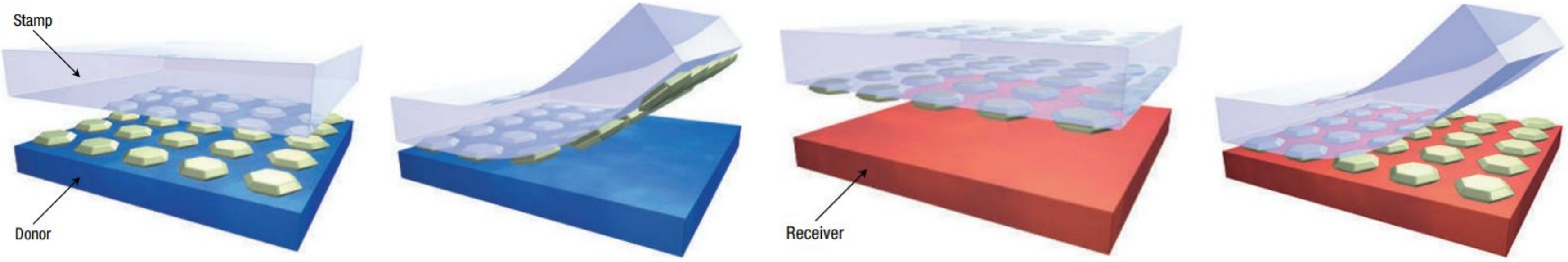
LN etching damages Si: **low optical Q**



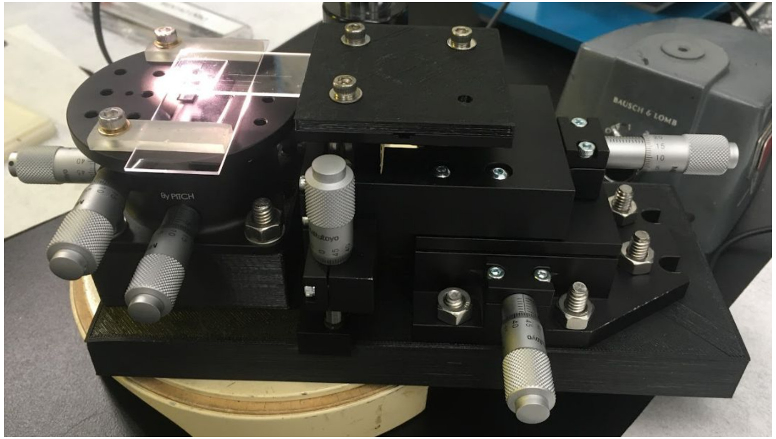
Transfer print

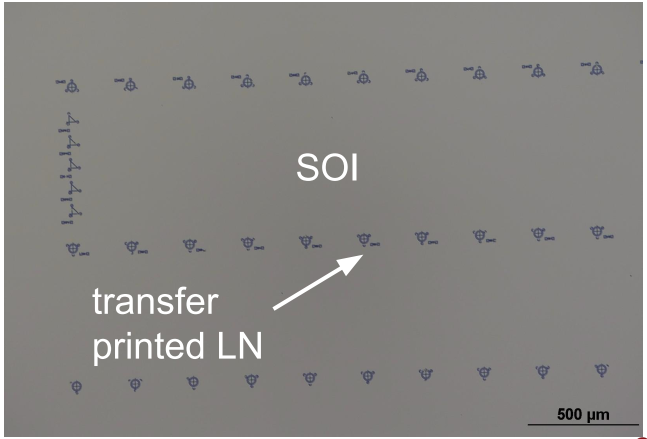
fast peel-back

slow peel-back



Meitl, Rogers, Nature materials (2006)



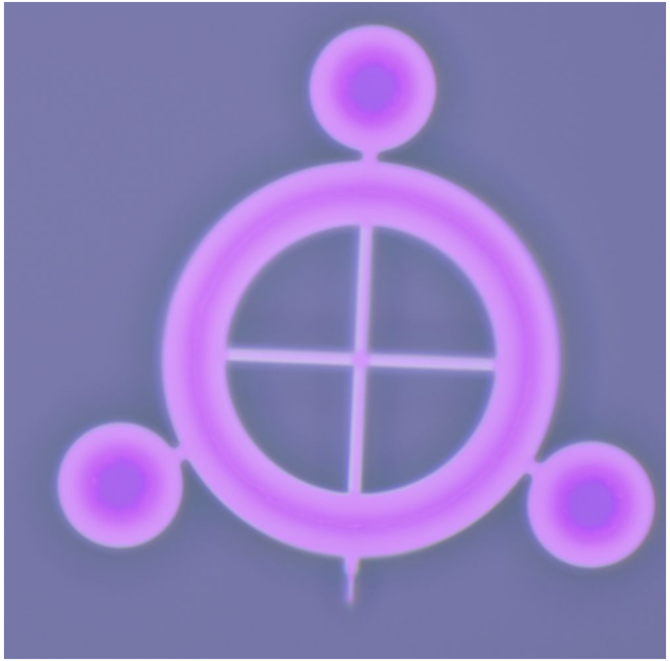


yield > 99%

up to 10 mm x 15 mm chip size

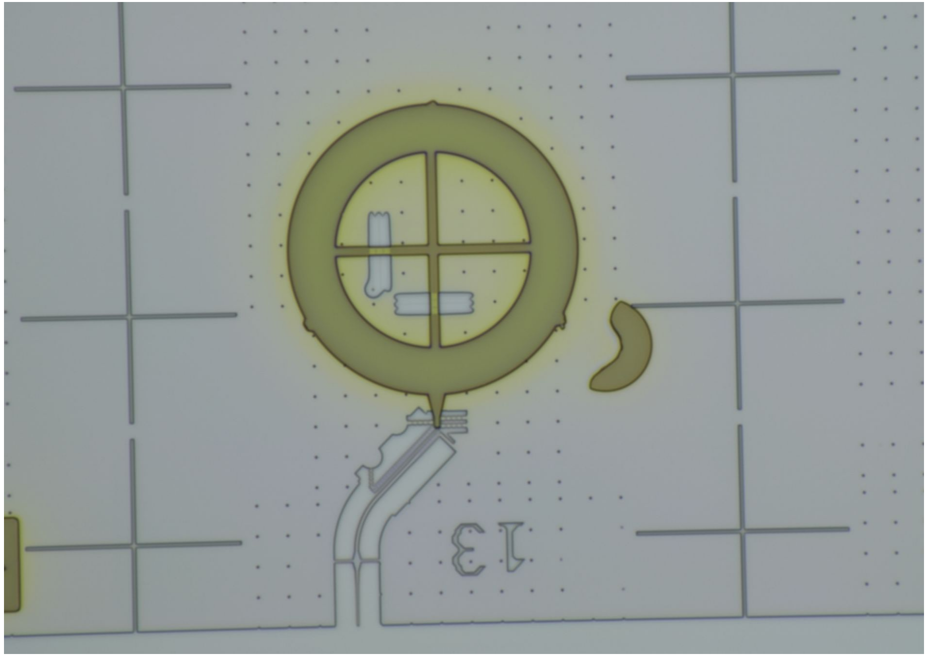
Transfer print

After release:



30 um

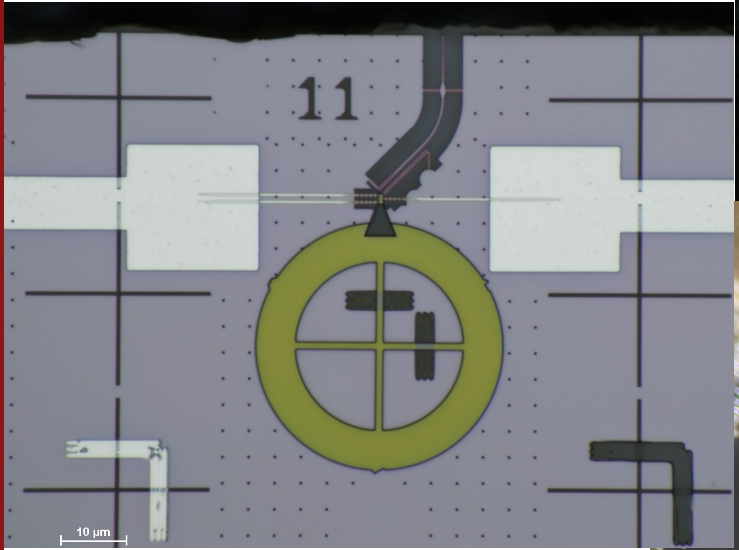
After transfer-print:

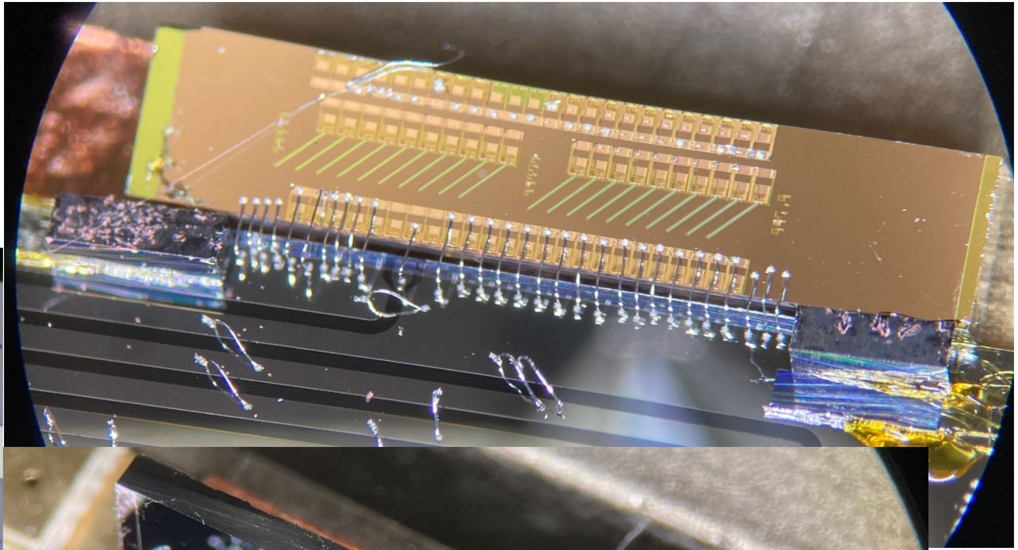


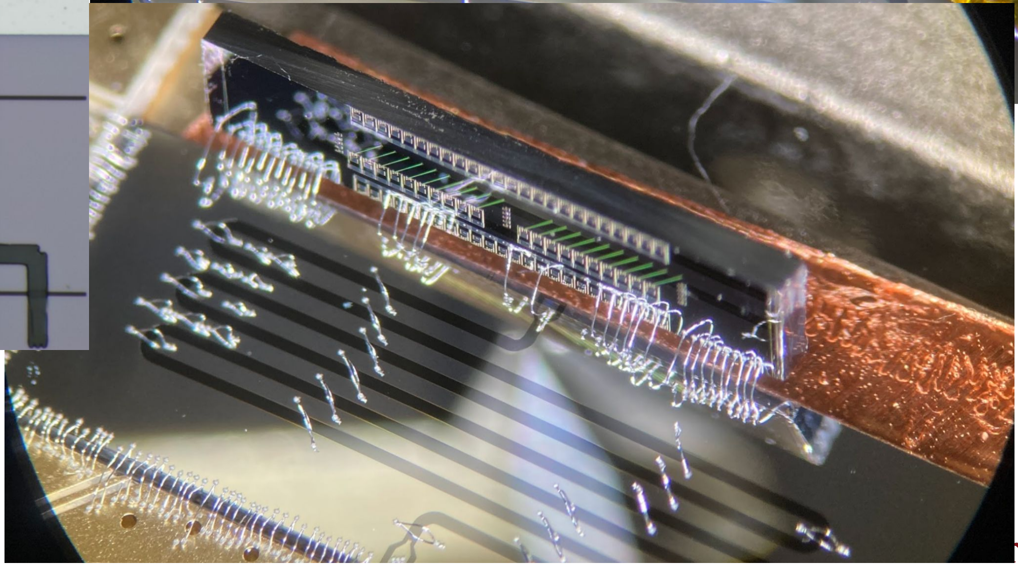
How hard could this be?

- Higher optomechanical coupling rate?
- Higher piezoelectric coupling rate?
- How do we make it?
- **How do we wire it up?**

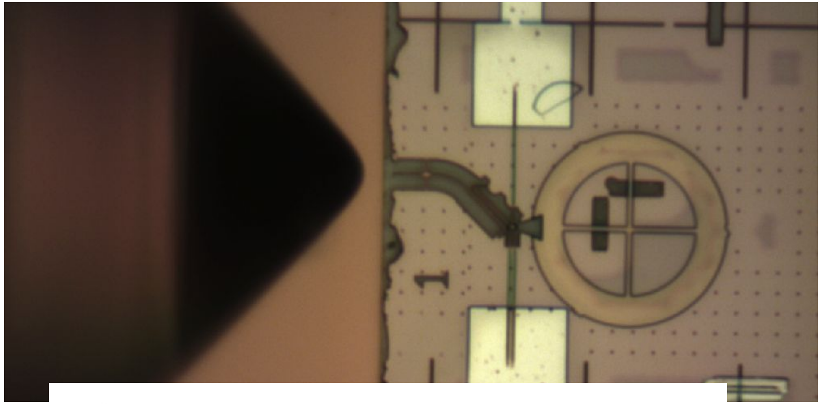
Wirebond + flipchip

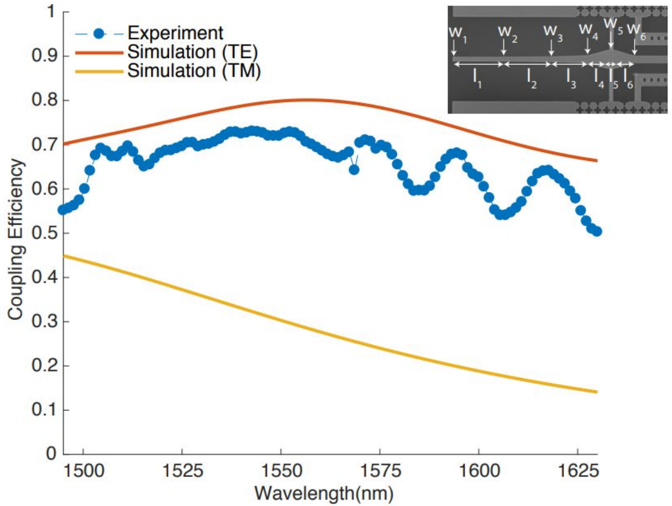


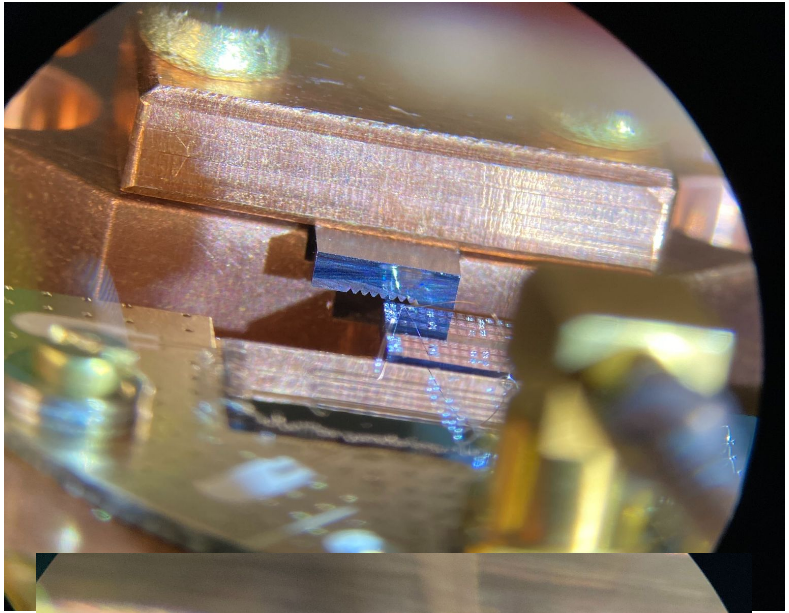


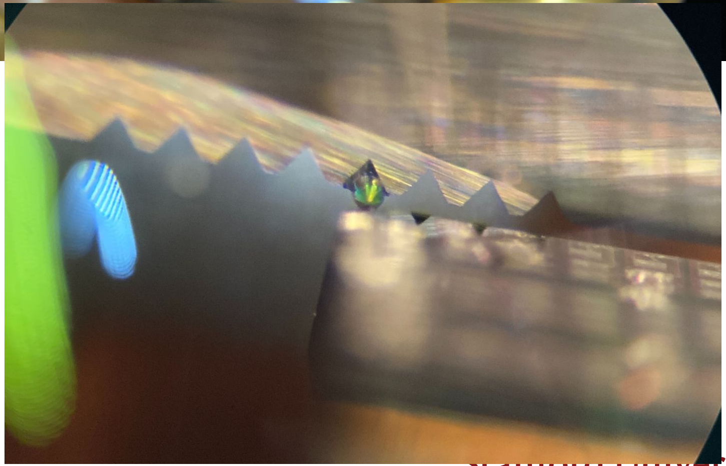


Optical coupling



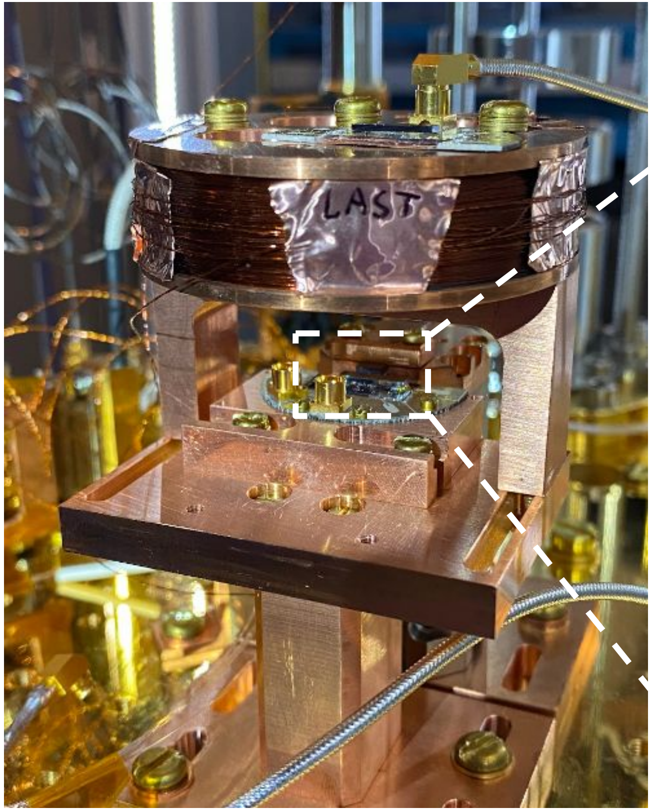


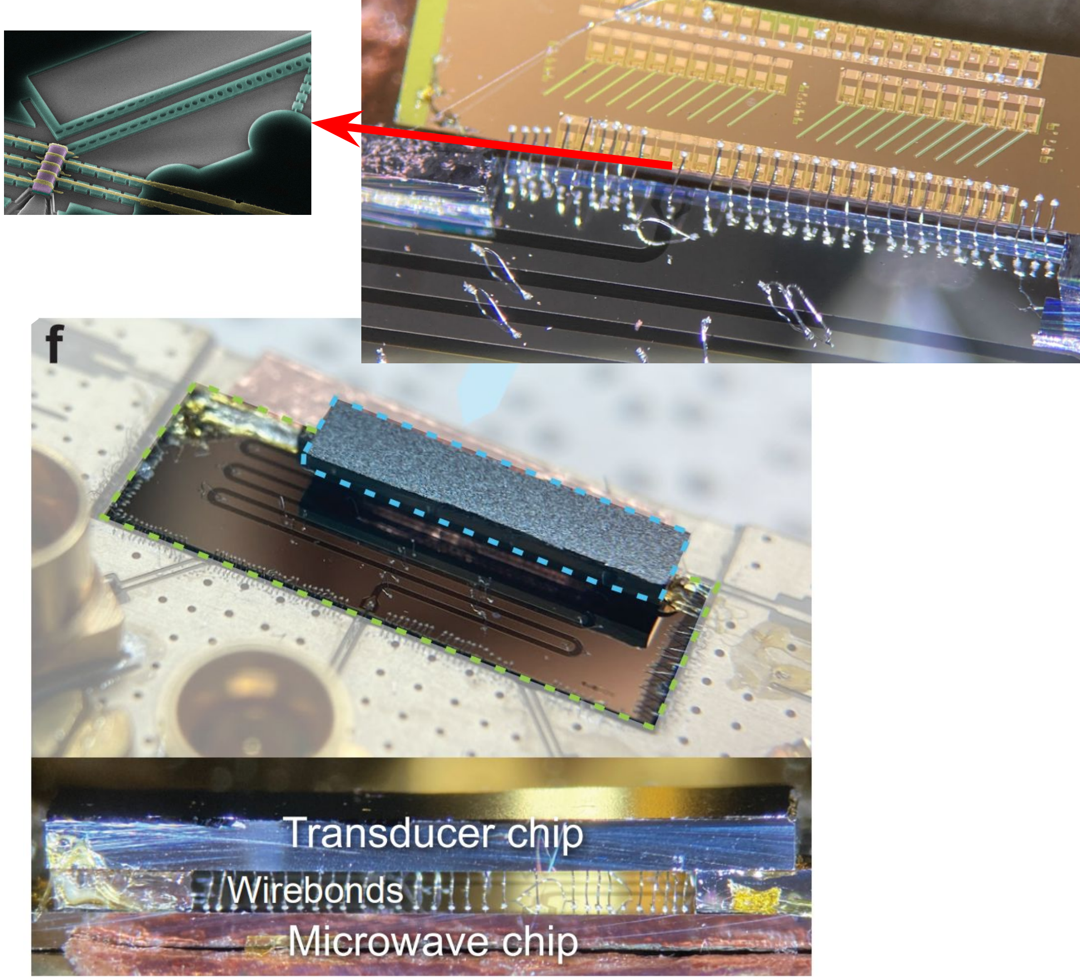




Patel, Rishi N., et al. Physical review letters 121.4 (2018): 040501.

Packaging

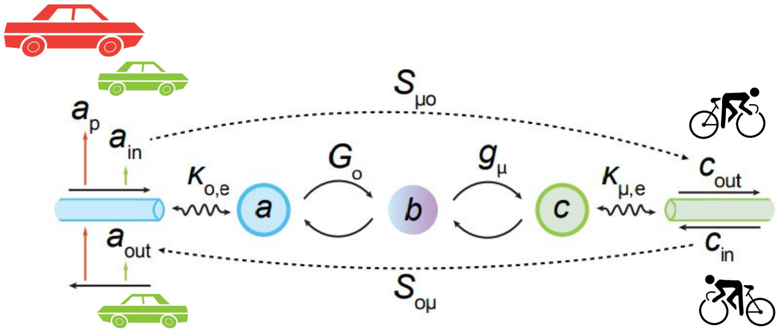




How well did it work?

How well did it work?

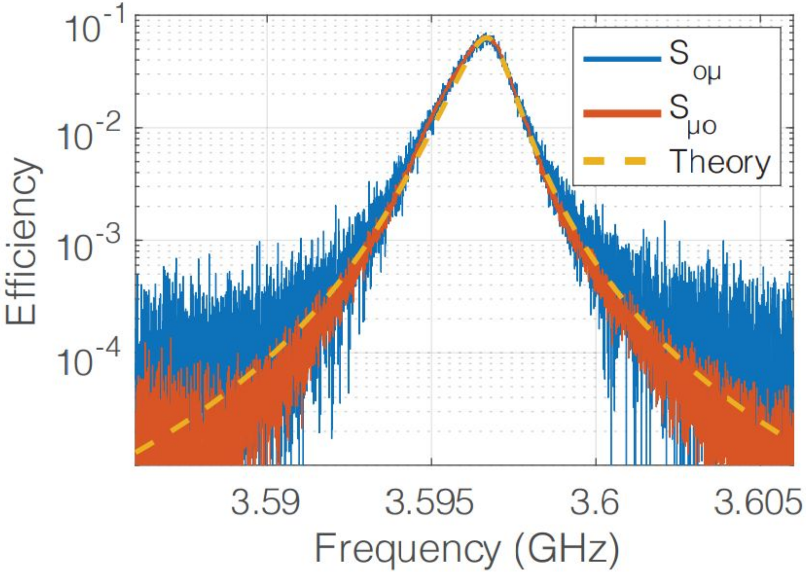
Frequency conversion measurement:



Efficiency = **4.9%**, BW = **1.5 MHz**

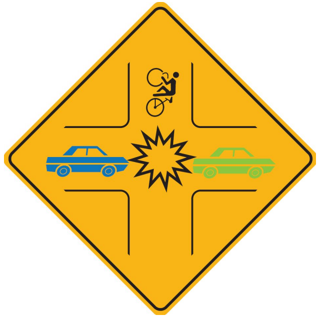
Added noise ~ 100.

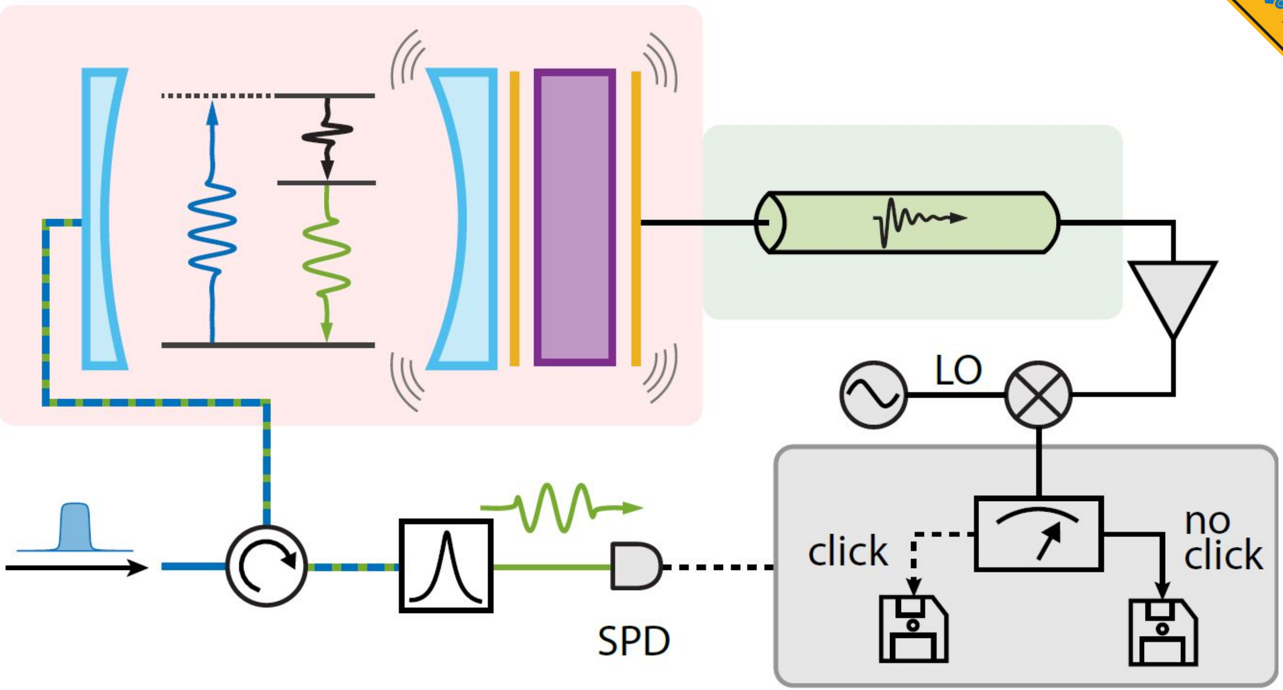
10 uW continuous pump.



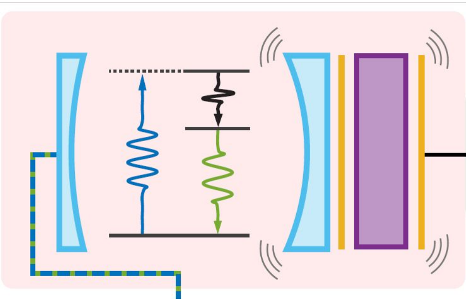
Stanford University

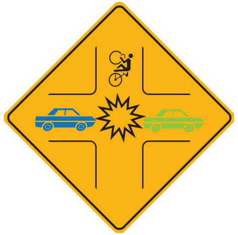
Optically heralded microwave photons



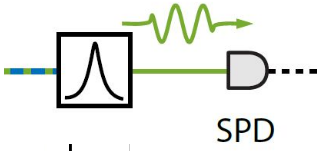


Optically heralded microwave photons

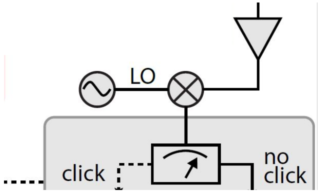




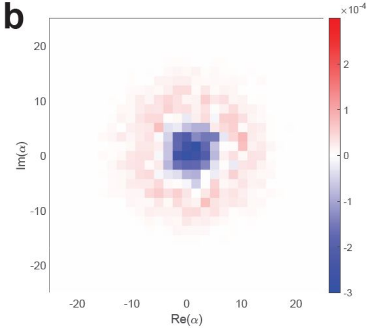
- Pulsed entangled pair generation



- Optical single photon detection

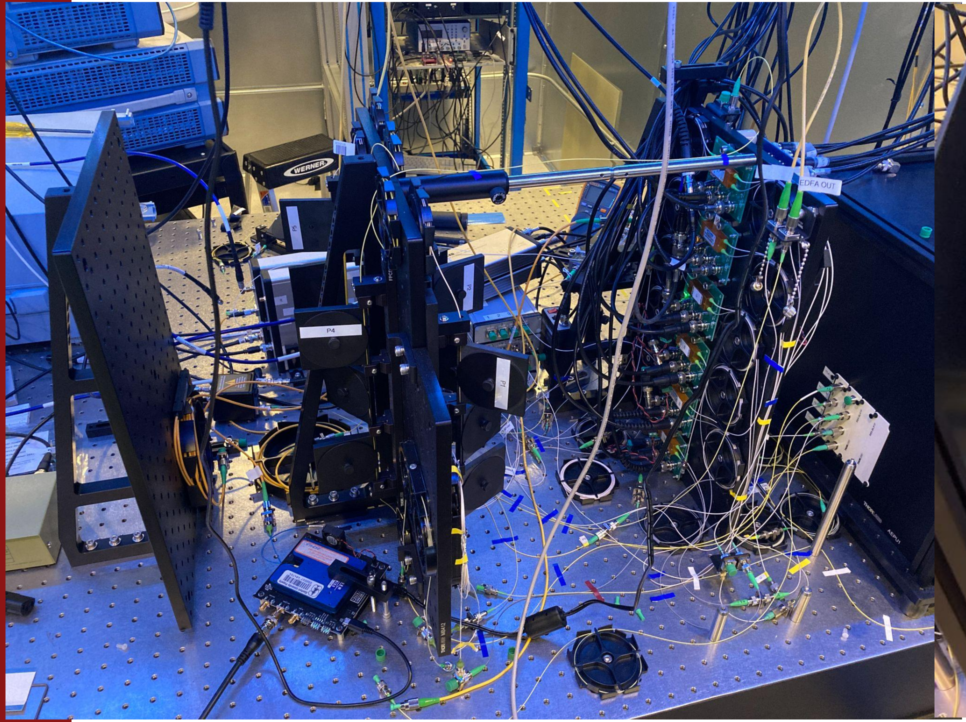


- Microwave tomography

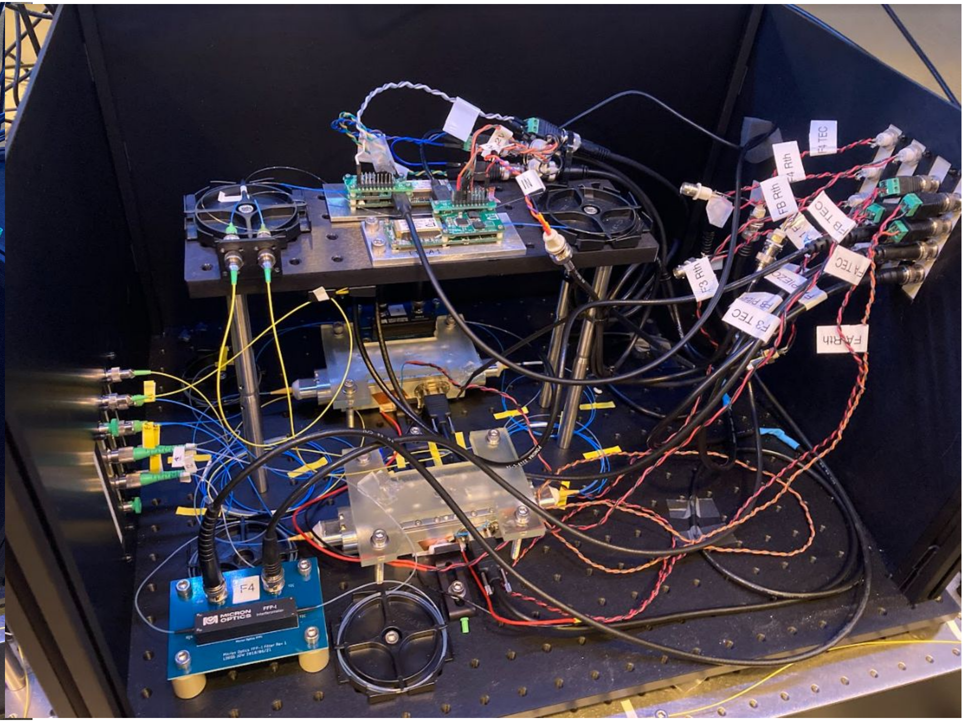


- Optically heralded microwave photon

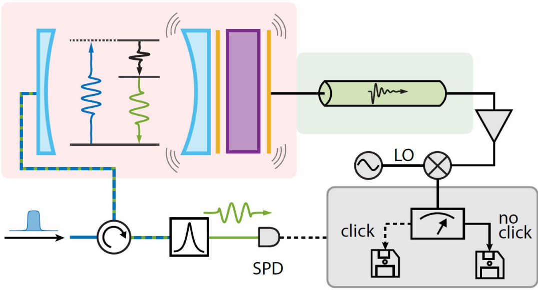
Pulse generation & routing



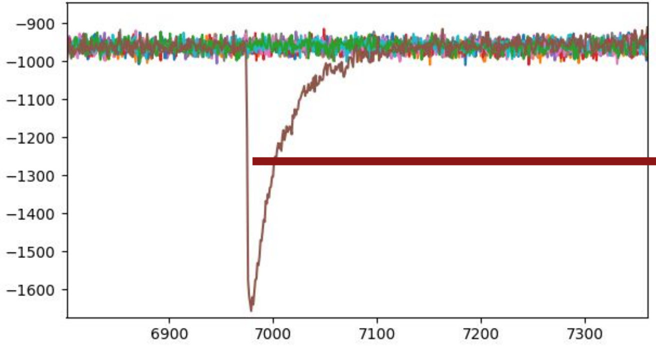
Laser stabilization & sideband filtering



Optical single photon detection

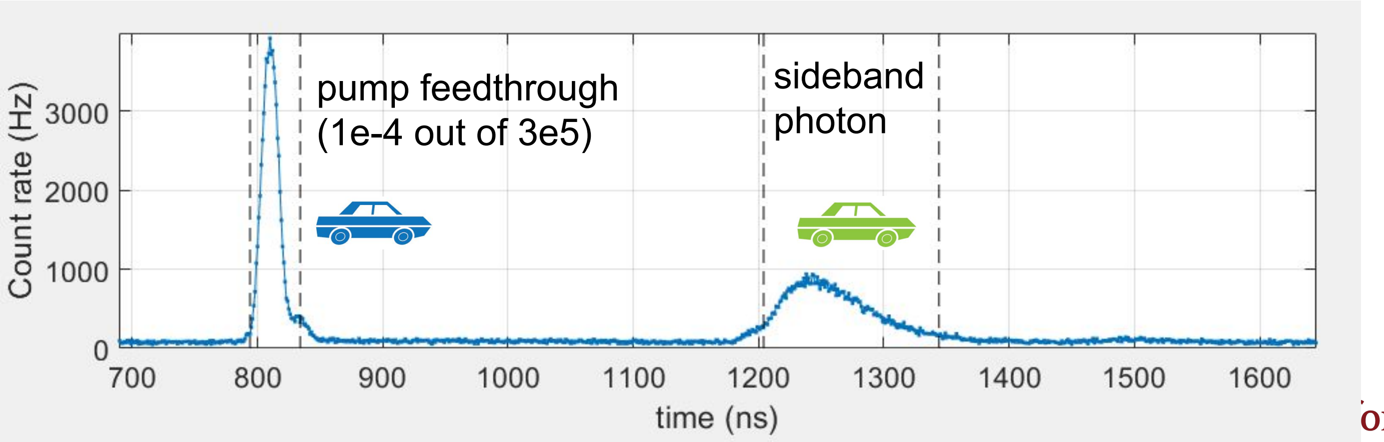


One click:

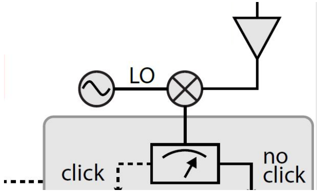


get the click time

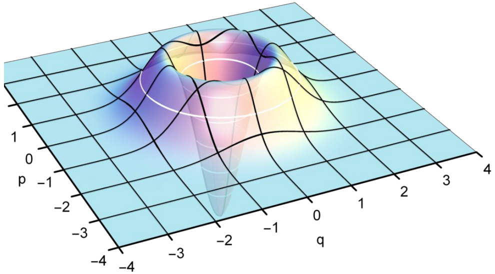
Many clicks from many (~ billions) runs:



Microwave tomography



one photon:



Balanced homodyne: amplitude measurement of selected phase component

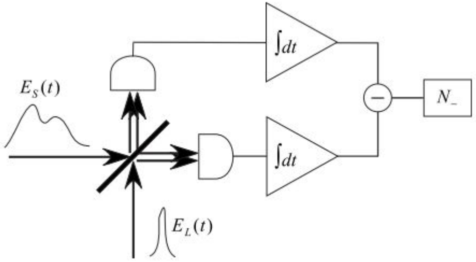
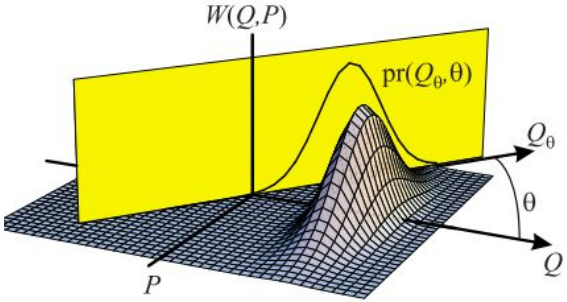
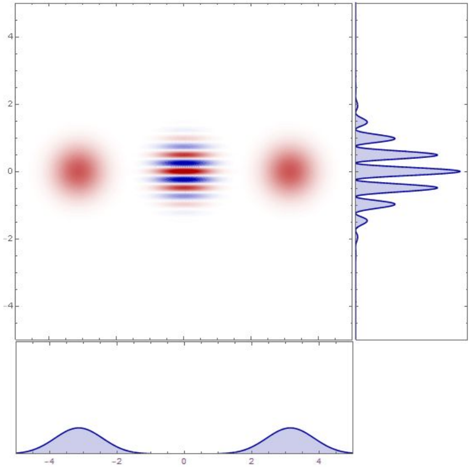


FIG. 1. Balanced homodyne detection.



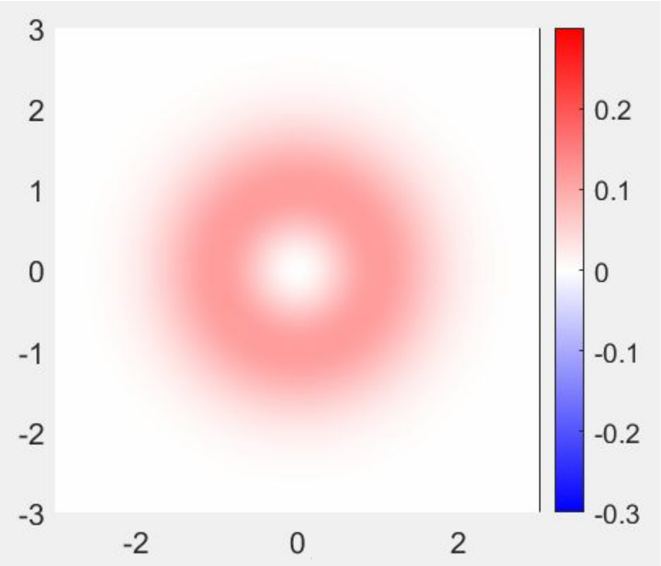
cat state:



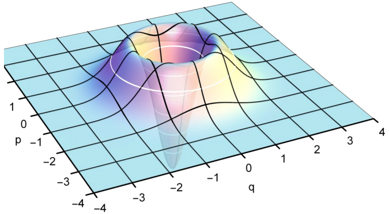
Lvovsky, Alexander I., and Michael G. Raymer. "Continuous-variable optical quantum-state tomography." Reviews of modern physics 81.1 (2009): 299.
https://en.wikipedia.org/wiki/Wigner_quasiprobability_distribution

Optically heralded microwave photons: $Q_{\mathrm{click}}(\alpha)$

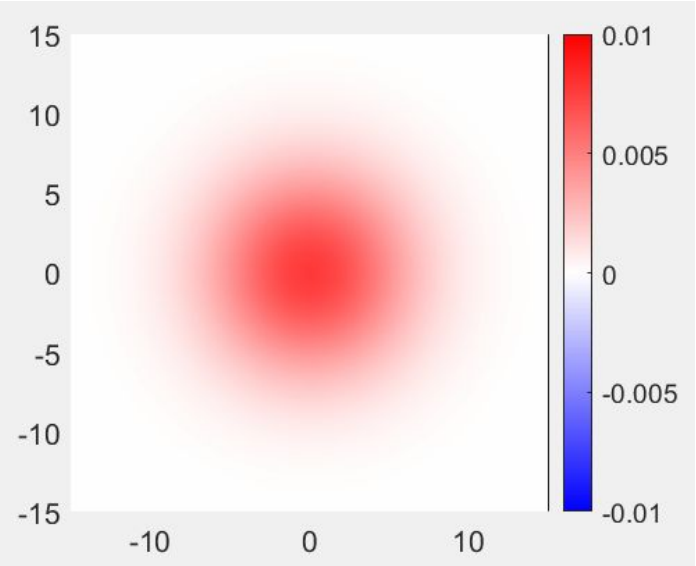
Expectation:



one-photon
Wigner function:



"Reality" (theory):

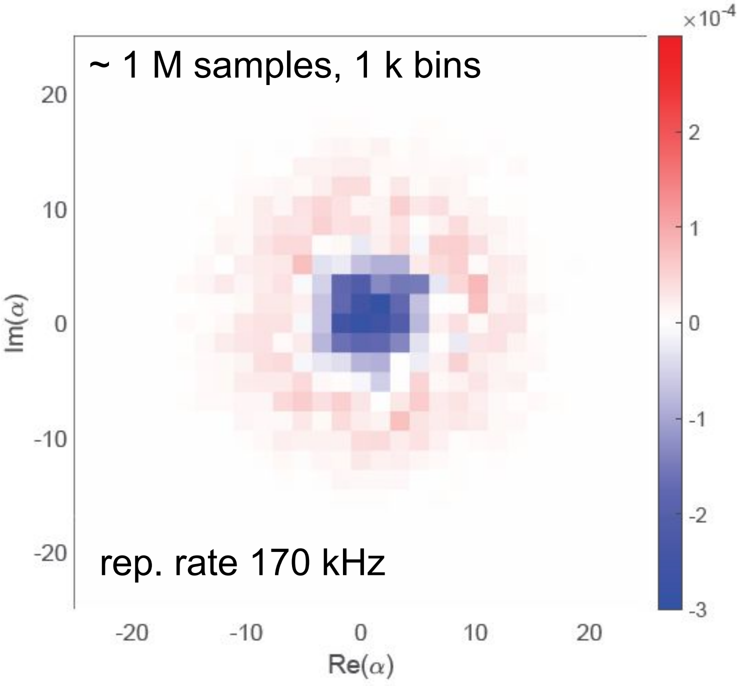


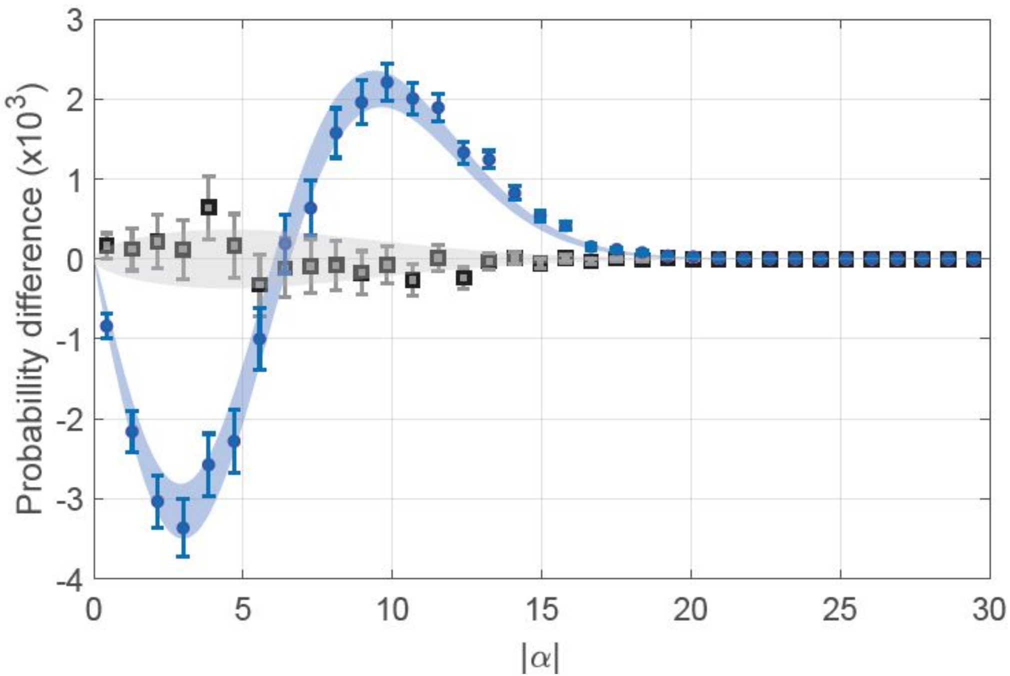
Excess noise smoothed out the donut

Stanford University

Optically heralded microwave photons:

Learning from Wallraff: look at the difference: $Q_{\text{click}}(\alpha) - Q_{\text{no-click}}(\alpha)$





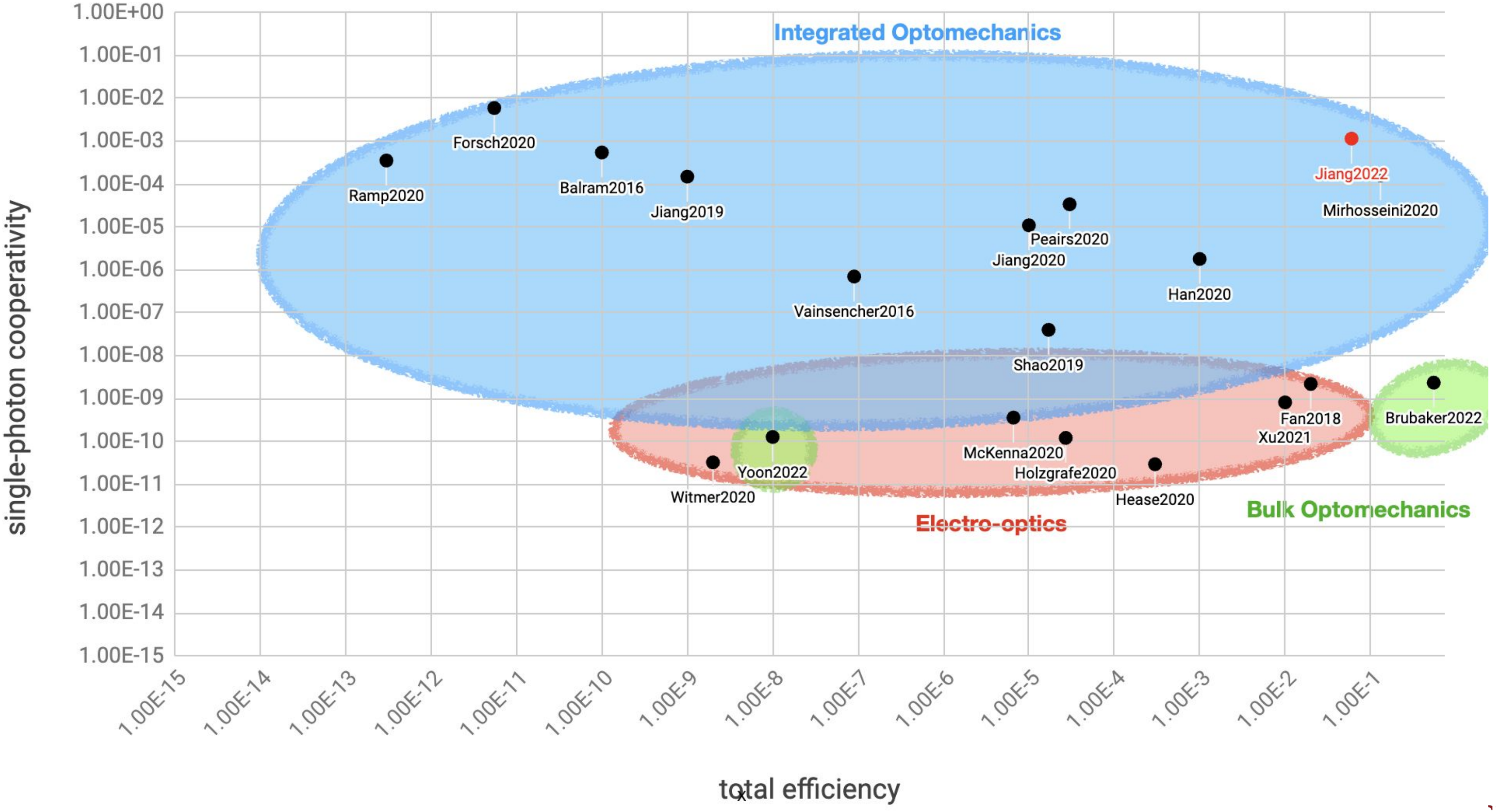
Excess noise ~ 39
Noise from TWPA ~ 2.4

Black: randomly selected instead of post-selected

Stanford University

How well did we do?

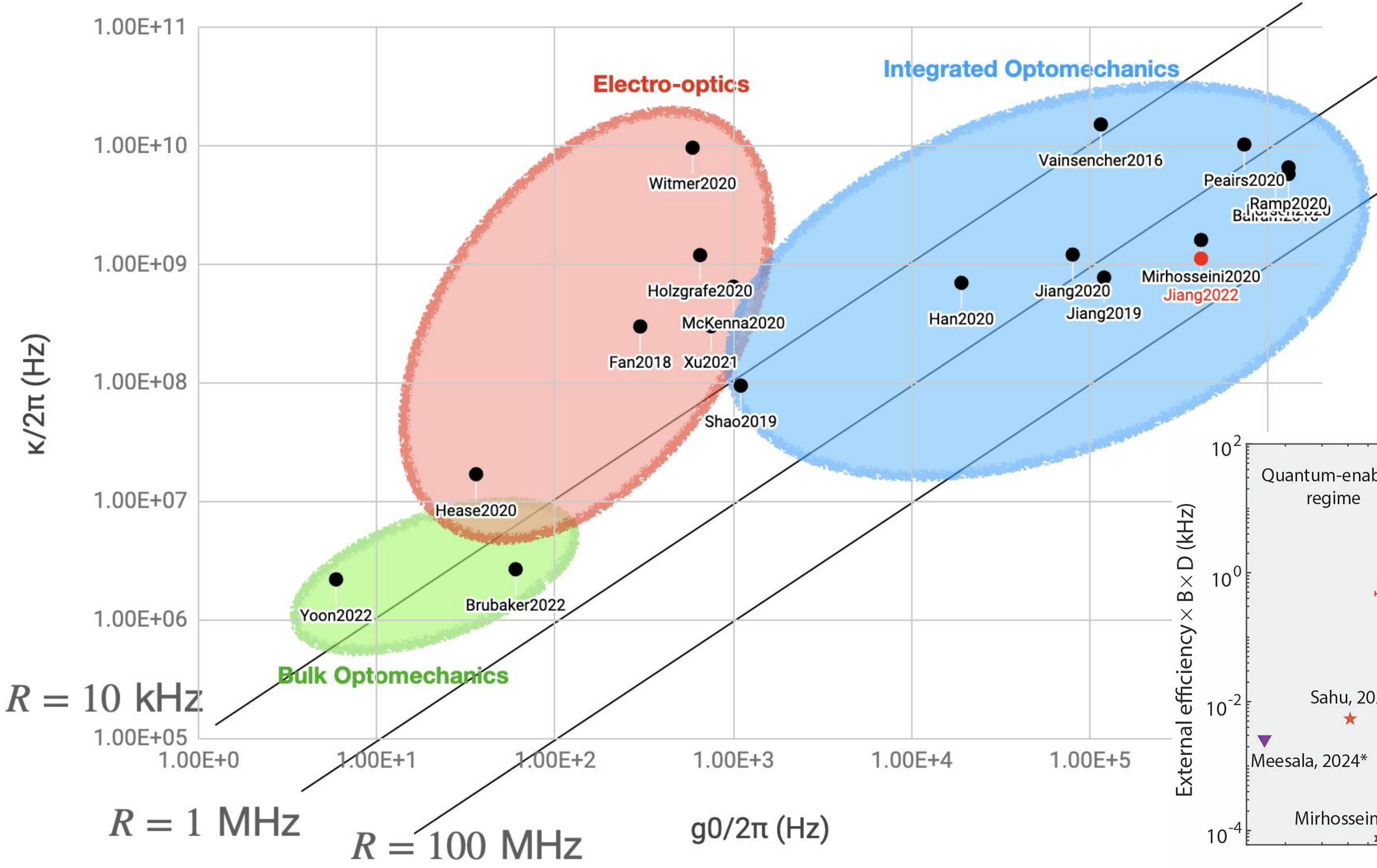
Efficiency



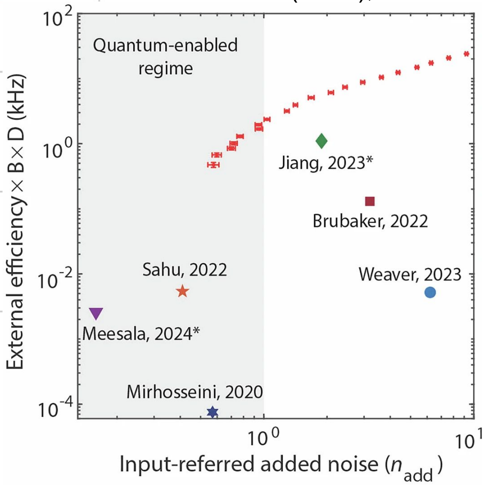
Integrated Optomechanics
Electro-optics
Bulk Optomechanics
single-photon cooperativity
total efficiency
1.00E+00
1.00E-01
1.00E-02
1.00E-03
1.00E-04
1.00E-05
1.00E-06
1.00E-07
1.00E-08
1.00E-09
1.00E-10
1.00E-11
1.00E-12
1.00E-13
1.00E-14
1.00E-15
1.00E-15
1.00E-14
1.00E-13
1.00E-12
1.00E-11
1.00E-10
1.00E-9
1.00E-8
1.00E-7
1.00E-6
1.00E-5
1.00E-4
1.00E-3
1.00E-2
1.00E-1
Forsch2020
Ramp2020
Balram2016
Jiang2019
Jiang2022
Mirhosseini2020
Peairs2020
Jiang2020
Han2020
Vainsencher2016
Shao2019
Fan2018
Xu2021
Brubaker2022
McKenna2020
Holzgrafe2020
Hease2020
Yoon2022
Witmer2020

Energy / heralding rate

$$E_{\text{qubit}} = \hbar\omega_c \kappa\kappa_i / g_0^2 / (4\eta_o\eta_m)$$



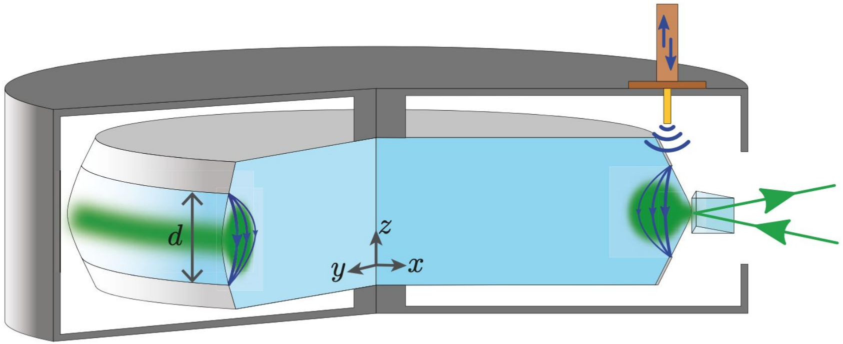
Zhao (2025), Caltech



The actual rate?

Electro-optics:

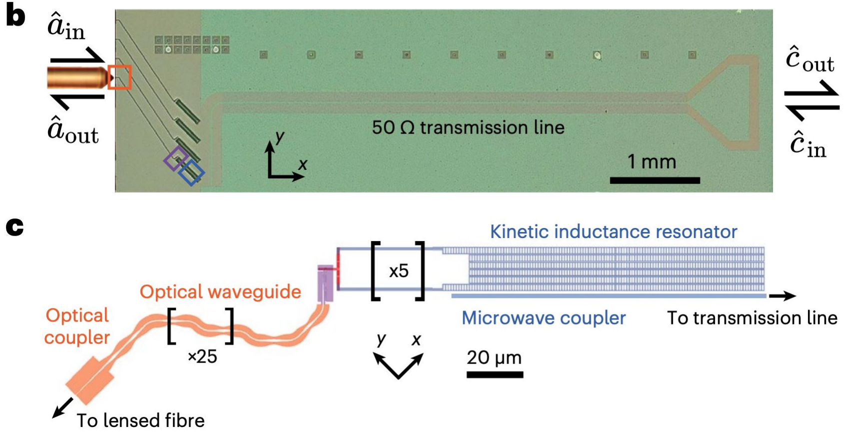
- 2 Hz repetition rate
- 0.22 ebit/s



Sahu (2023), science, ISTA
Sahu (2023), thesis, ISTA

Piezo-optomechanics:

- 50 kHz repetition rate
- 0.26 Hz heralding rate



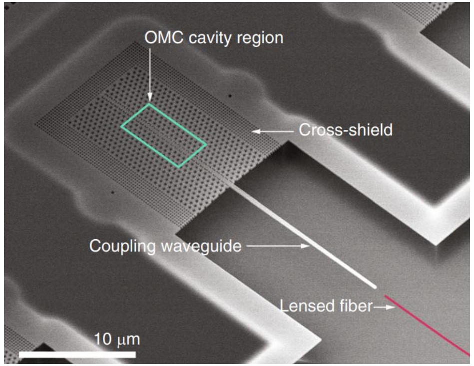
Meesala (2024), Nat. Phys., Caltech
Meesala (2024), PRX, Caltech

How long was our measurement:

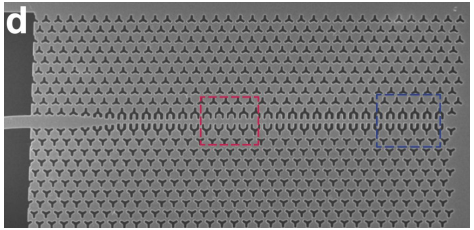
- 2% scattering rate, 1% detection efficiency, 170 kHz repetition = **34 Hz** heralding rate
- Need ~1 M samples
- **~ 8 h**

What's next?

Better thermalization:

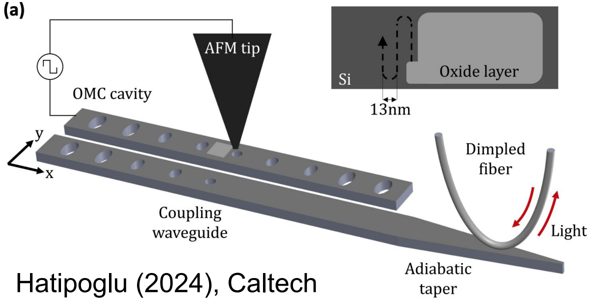


Ren (2020), Stanford

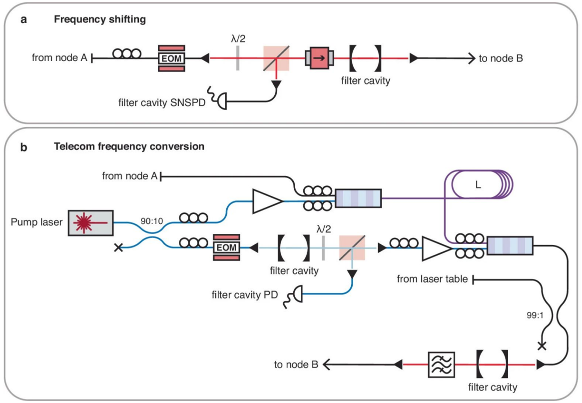


Mayor (2024), Stanford

Frequency tuning/matching:

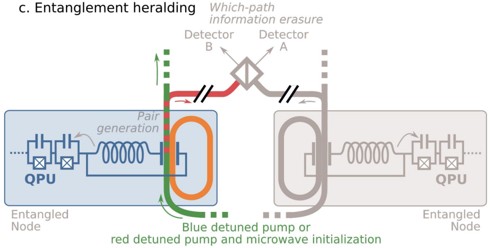


Hatipoglu (2024), Caltech

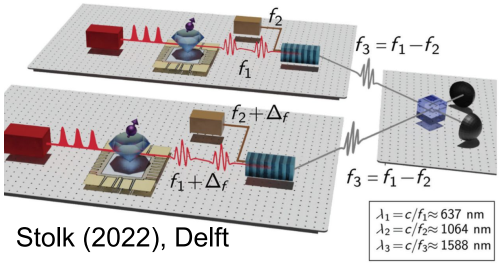


Knaut (2024), Harvard

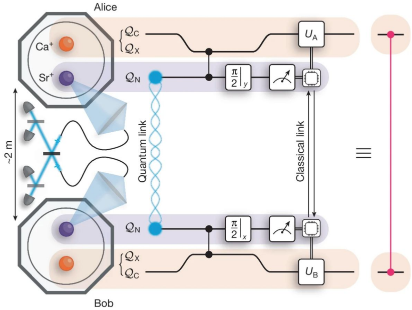
And one day…



Krastanov (2021), MIT



Stolk (2022), Delft



Main (2025), Oxford

Thanks!

Questions?

NSF

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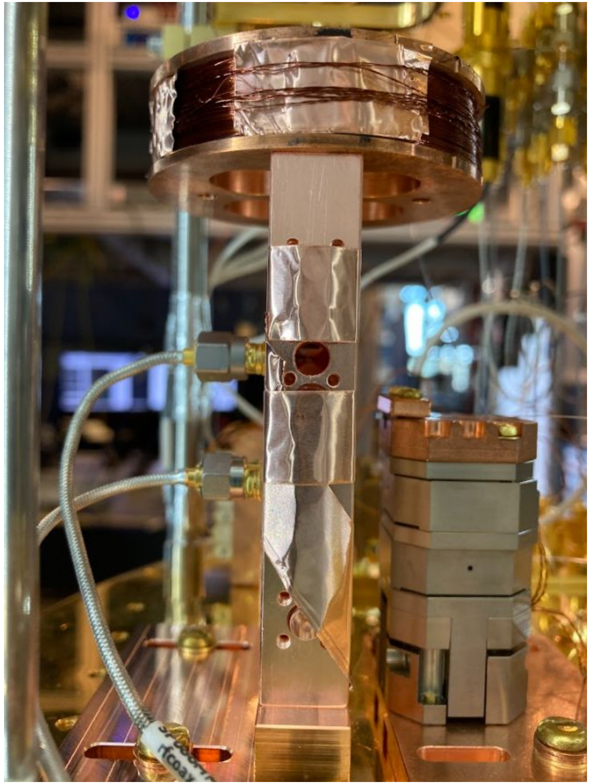
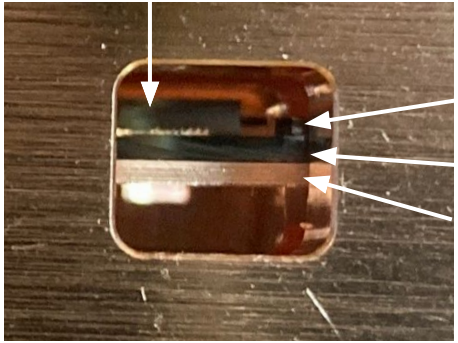
AIR FORCE OFFICE OF SCIENTIFIC RESEARCH UNITED STATES AIR FORCE

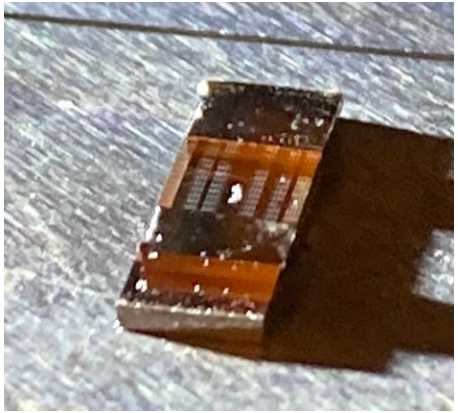
aws

NTT Research

Packaging, gen 1







Full transducer & packaging:

- LN-SOI transducer
- NbTiN microwave resonator
- 3D readout cavity
- NbTi tuning coil