IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), May 2022.
Invited presentation ED7-2-INV was given at The International Symposium on Superconductivity, Virtual, December 2, 2021.

Control and readout of a superconducting qubit using a photonic link

F. Lecocq, F. Quinlan, K. Cicak, J. Aumentado, S. A. Diddams, J. D. Teufel

F. Lecocq, *et al*, Nature **591** 575-579 (2021)

National Institute of Standards and Technology
U.S. Department of Commerce

University of Colorado Boulder

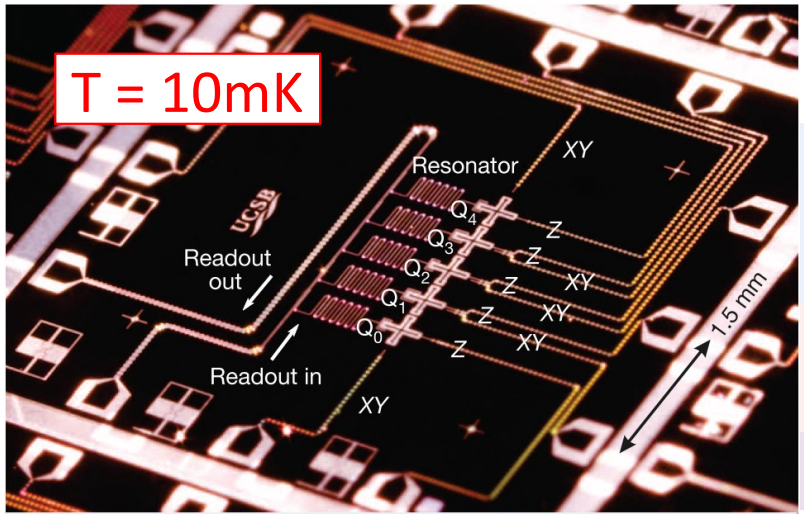
NIST Boulder
Advanced Microwave Photonics Group

Superconducting quantum processor

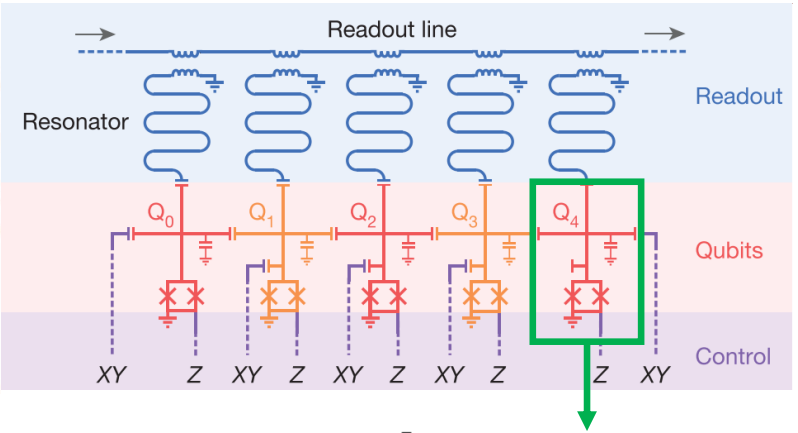
NIST

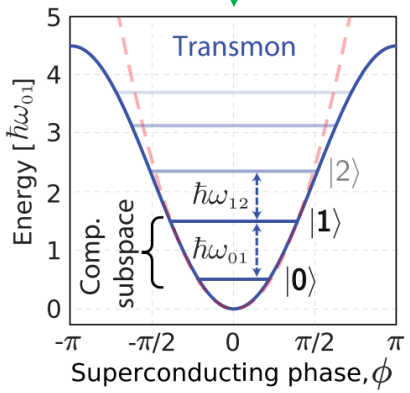
- ☐ Scalability
- ☑ Initialization
- ☑ Coherence
- ☑ Gates
- ☑ Measurements

D. DiVicenzo, **Fortschritte der Physik** *48 (2000)*



R. Barends, … , J. M. Martinis, ***Nature*** *508 (2014)*





P. Krantz, … , W. D. Oliver, ***App. Phys. Rev.*** *6 (2019)*

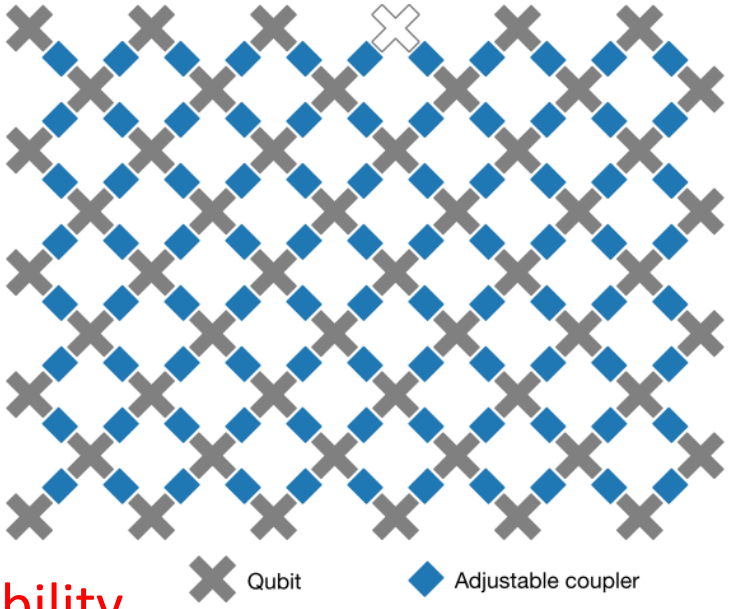
Qubits = non-linear LC resonant circuits (4-8GHz)

Control and readout with <u>microwave pulses</u>

Scalability?

- ☒ Scalability
- ☑ Initialization
- ☑ Coherence
- ☑ Gates
- ☑ Measurements

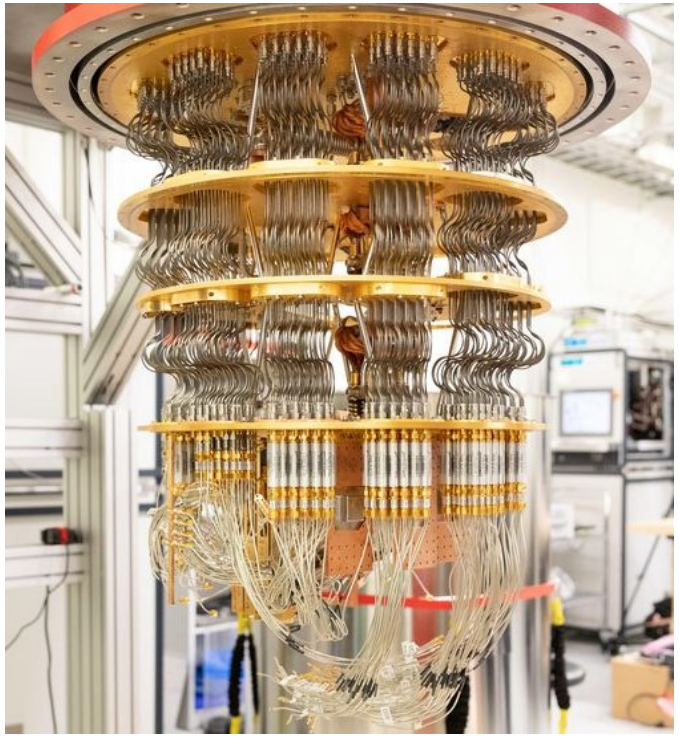
F. Arute, … , J. M. Martinis, ***Nature*** *574 (2019)*



53 qubits

Head load and space limitations prevent scalability beyond 10^3 qubits

S. Krinner, … , A. Wallraff, ***EJP Q. Tech.*** *6 (2019)*



232 coaxial lines

A universal computer will realistically require 10^6 qubits

Fowler et all, ***PRA*** *86 (2012)*
M. Reiher et al, ***Proc. Natl Acad. Sci.*** *11 (2017)*

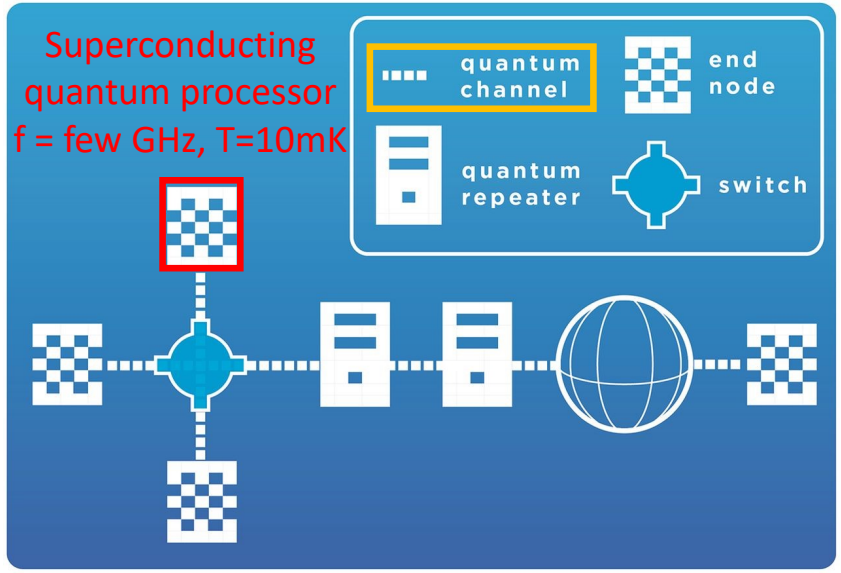
Overcoming the scalability challenge

- Distribute entanglement over multiple fridges
- Make bigger fridges
- Pack more qubits per fridge

Overcoming the scalability challenge

- Distribute entanglement over multiple fridges

Building a quantum *microwave* network



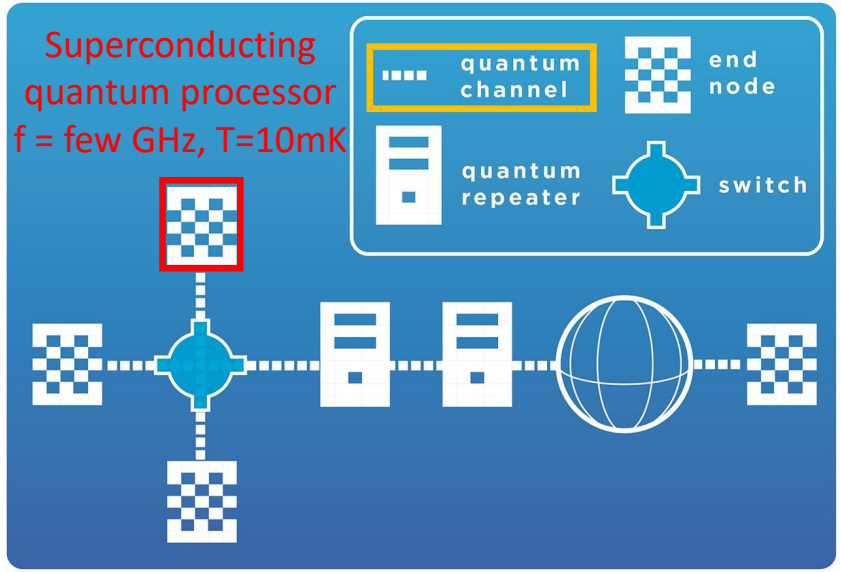
S. Wehner, ***Science*** *362 (2018)*

Overcoming the scalability challenge

NIST

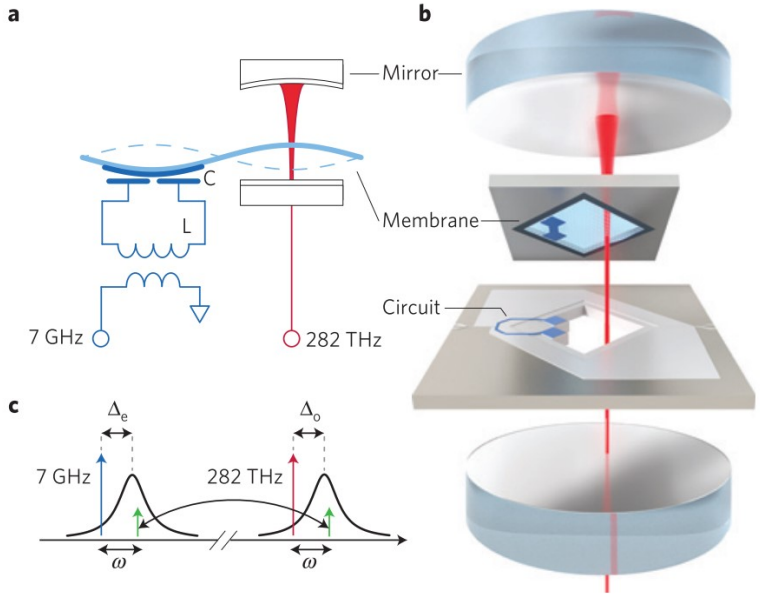
- Distribute entanglement over multiple fridges

Building a quantum *microwave* network



S. Wehner, ***Science*** *362 (2018)*

Quantum coherent microwave-to-optical conversion:



Andrews, … , Lehnert, ***Nat. Phys.*** *10 (2014)*

Higginbotham, … , Regal, ***Nat. Phys.*** *14 (2018)*

$\eta \approx 47\%$, some added noise…

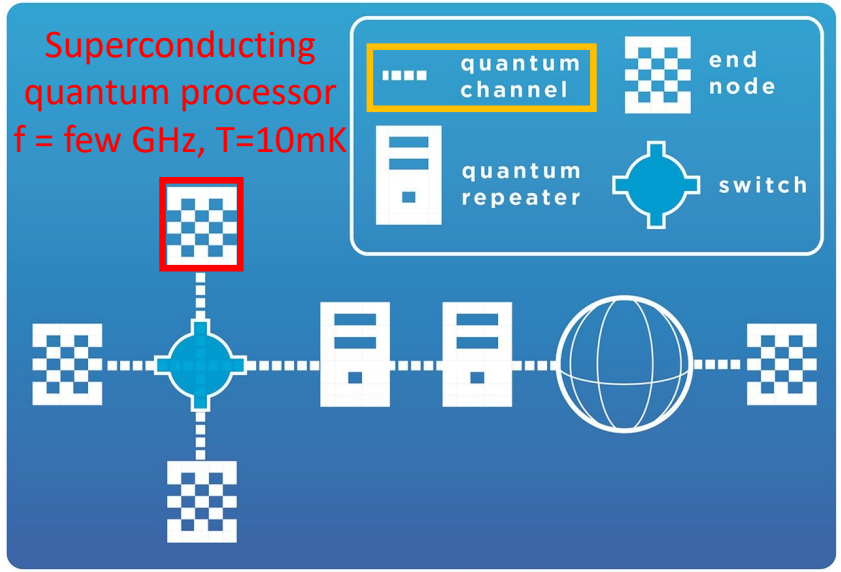
NEW: Delaney, … , Lehnert, ***Arxiv*** *2110.09539 (2021)*

Overcoming the scalability challenge

NIST

- Distribute entanglement over multiple fridges

Building a quantum *microwave* network



S. Wehner, ***Science*** *362 (2018)*

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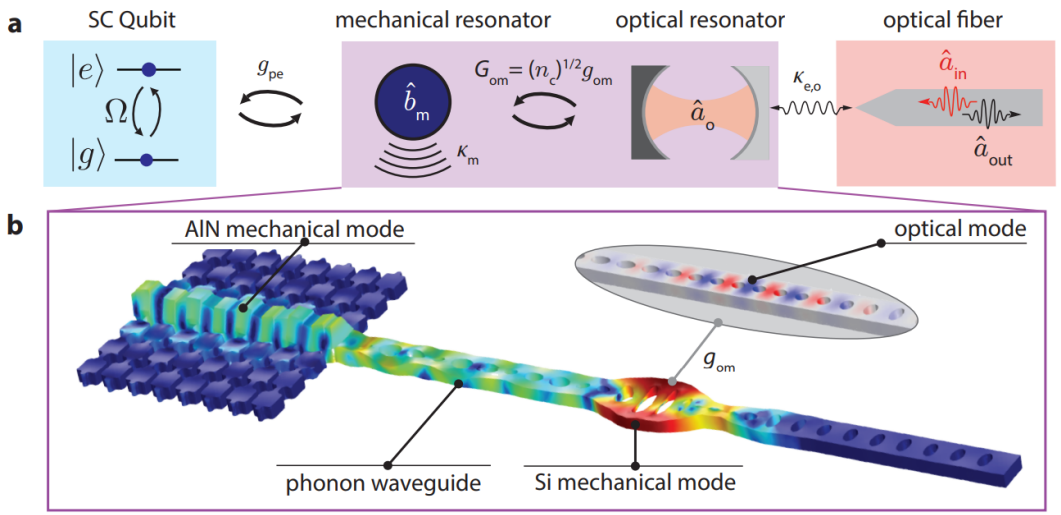


M. Mirhosseini, … , O. Painter, ***Nature*** *588 (2020)*

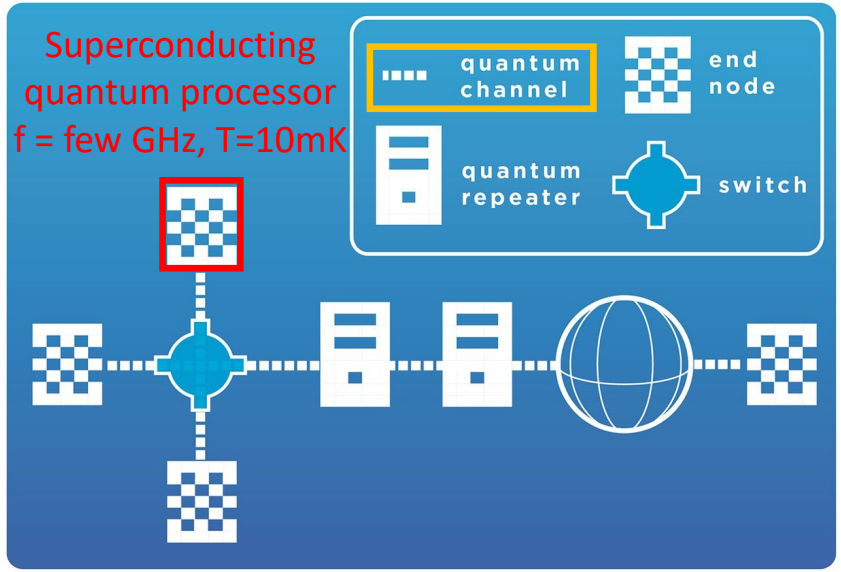
$$\eta \approx 10^{-5}$$

Overcoming the scalability challenge

NIST

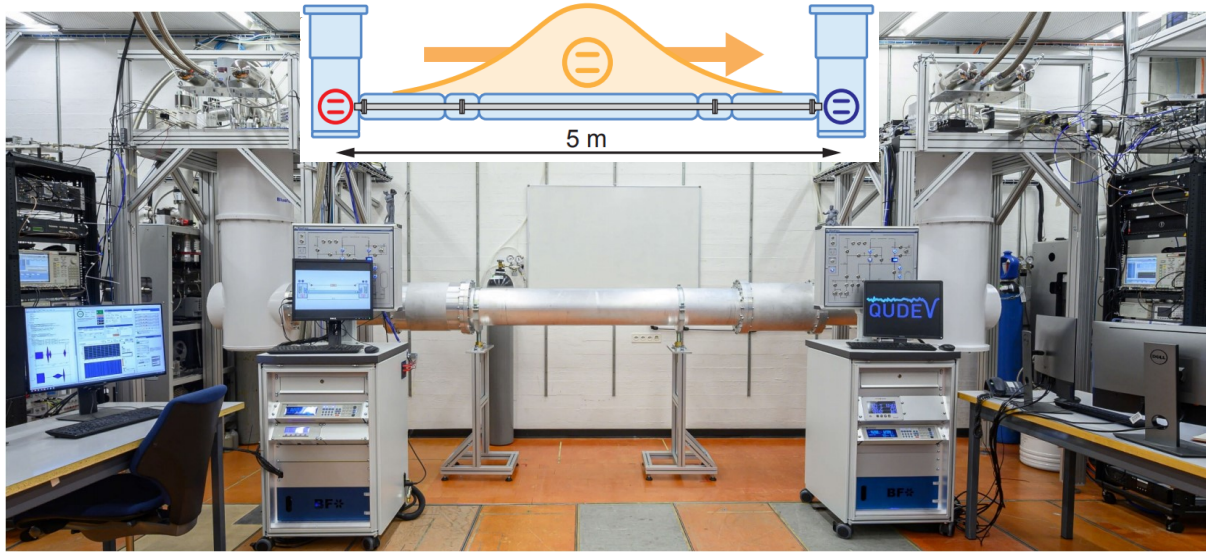
- Distribute entanglement over multiple fridges

Building a quantum *microwave* network



S. Wehner, ***Science*** *362 (2018)*

Quantum coherent microwave links:



Magnard, … , Wallraff, ***PRL*** *125 (2020)*

$$F \approx 80\%$$

Overcoming the scalability challenge

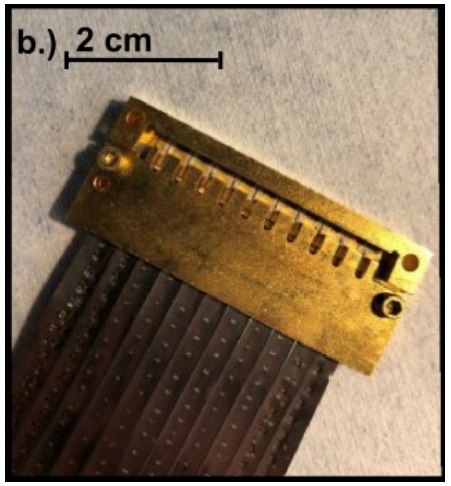
- Distribute entanglement over multiple fridges
- Make bigger fridges
- Pack more qubits per fridge

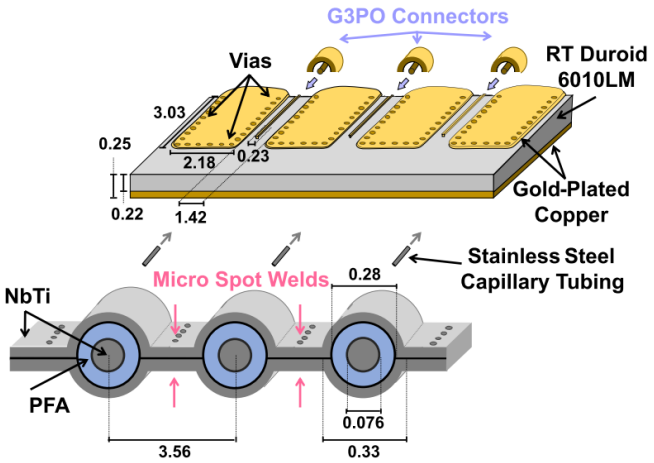
Credit: Connie Zhou/IBM and the internet

Overcoming the scalability challenge

- Distribute entanglement over multiple fridges
- Make bigger fridges
- Pack more qubits per fridge

Higher density wiring:





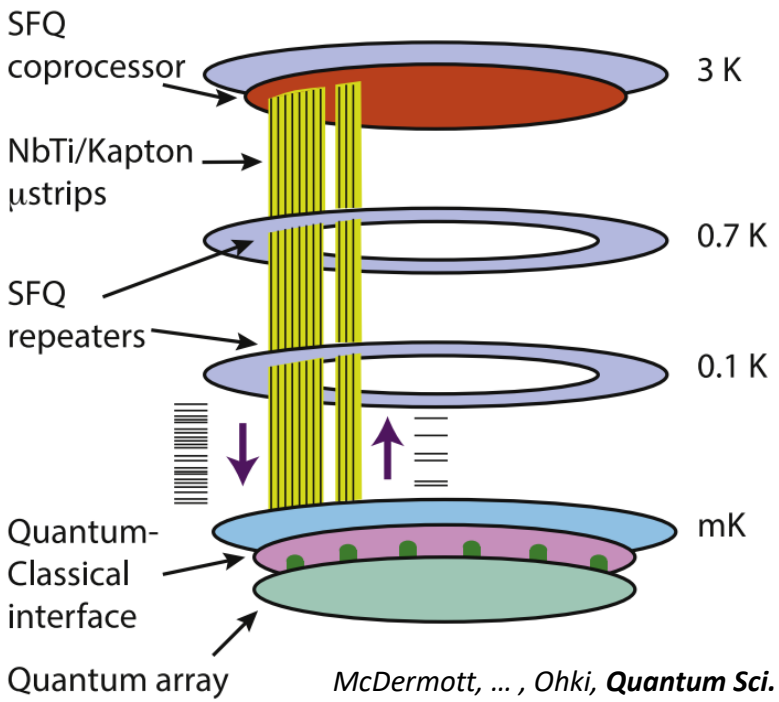
Smith, … , Fruitwala, ***IEEE Trans. Appl. Supercond.*** *31 (2021)*

Overcoming the scalability challenge

NIST

- Distribute entanglement over multiple fridges
- Make bigger fridges
- Pack more qubits per fridge

SFQ coprocessors:



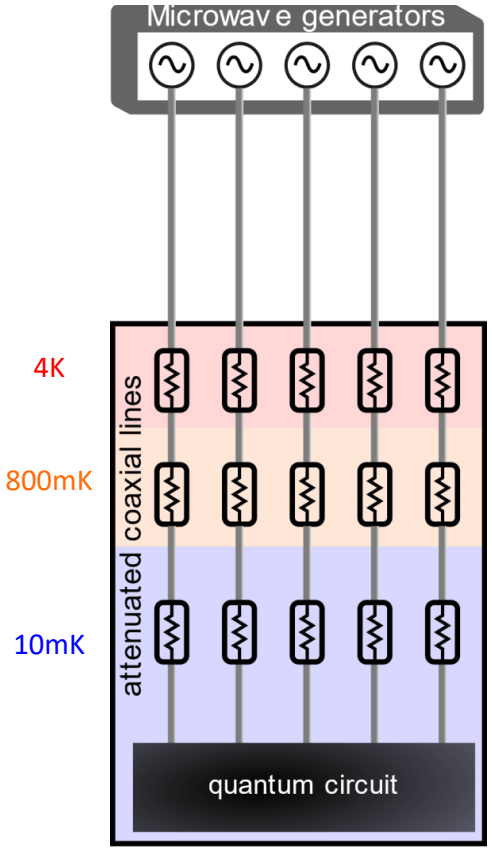
McDermott, … , Ohki, ***Quantum Sci. Technol.*** 3 *(2018)*
Leonard, … , McDermott, ***Phys. Rev. Applied*** 11 *(2019)*

Also cryo CMOS:
Bardin, … , Martinis ***IEEE Journal of SSC*** *54 (2019)*
Xue, … , Vandersypen*,* ***Nature*** 593 *(2021)*

Nature 591 575-579 (2021)

Alternative approach: the photonic link

NIST

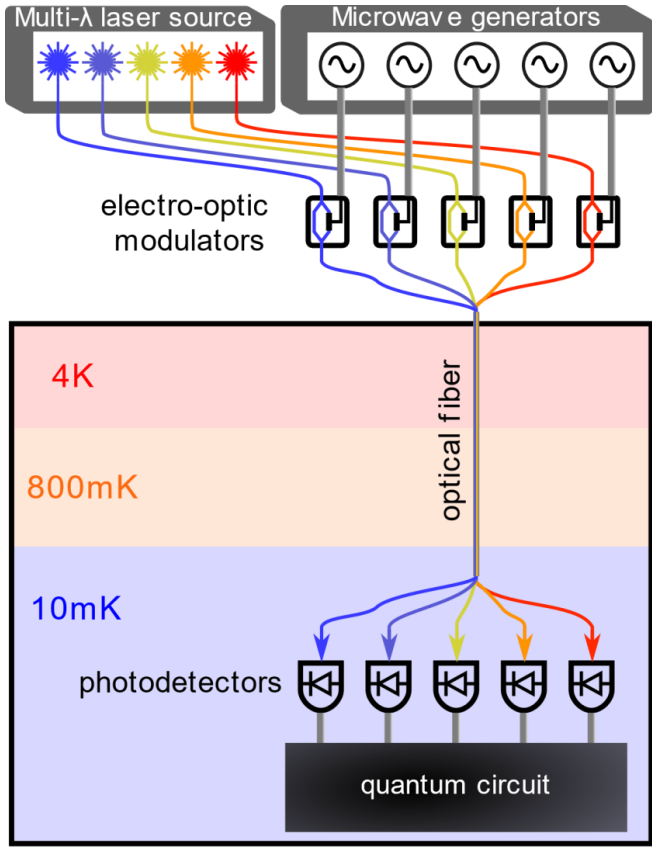


RF photonics is a mature technology (Room Temp) and optical fibers are:

- Cheap
- Small
- High bandwidth
- Low thermal conductivity

Can this approach:

1. **work at all?**
2. **scale to 10^6 qubits?**



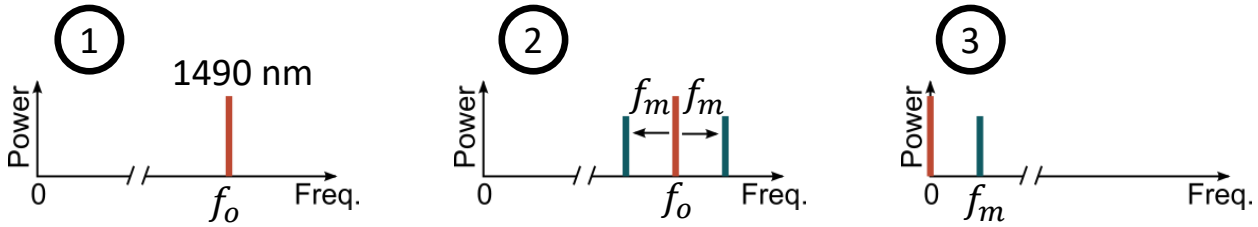
Nature 591 575-579 (2021)

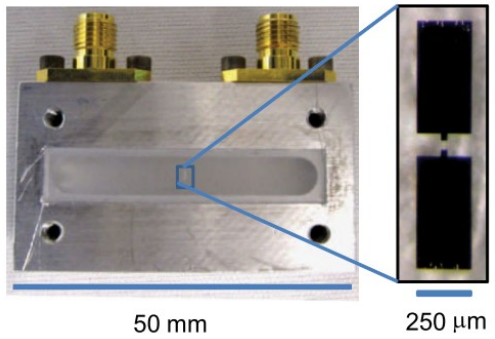
Proof of principle using a 3D transmon

NIST

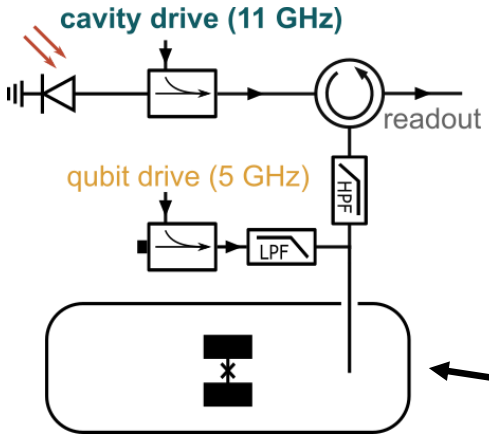
Photonic link = EOM + photodiode (*InGaAs*)

J Davila-Rodriguez,…, F. Quinlan, ***CLEO*** *SF2N.1 (2019)*

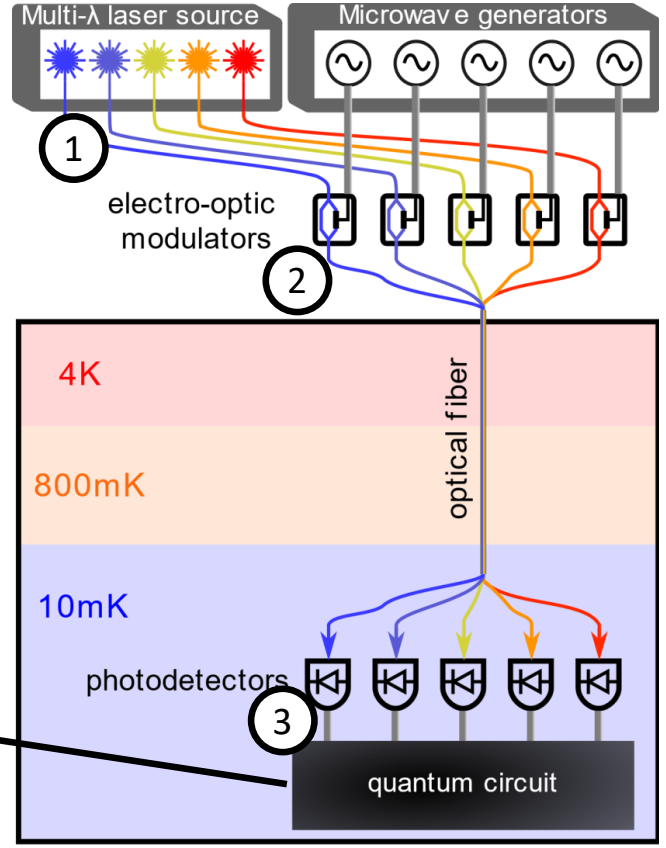




H. Paik, … , R. J. Schoelkopf, ***PRL*** *107 (2011)*



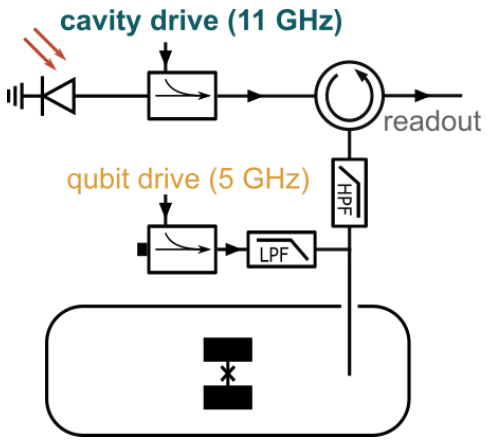
3D transmon

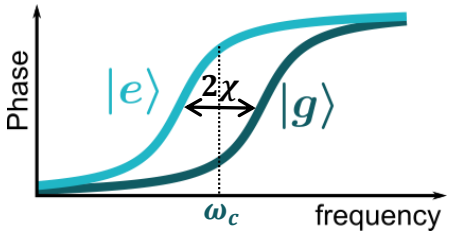


Qubit readout

Nature 591 575-579 (2021)

NIST

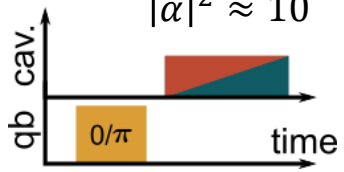




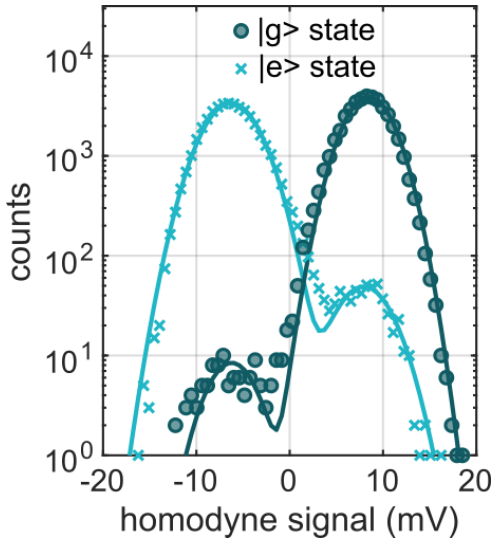
Qubit state dependent cavity frequency

$P_\mu \approx -120\ dBm$

$|\alpha|^2 \approx 10$

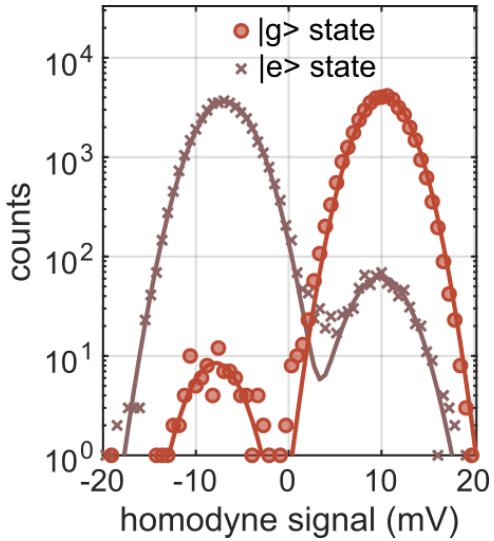


coaxial



$I \approx 20\ nA$

photonic link



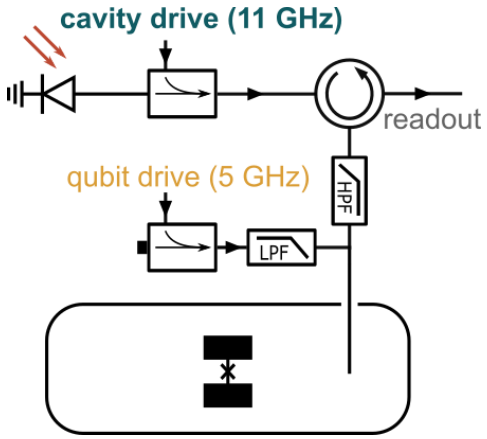
$F \approx 98\%$

High Fidelity
Single-shot
QND readout

Qubit readout

Nature 591 575-579 (2021)

NIST



P. Krantz, … , W. D. Oliver, ***App. Phys. Rev.*** *6 (2019)*

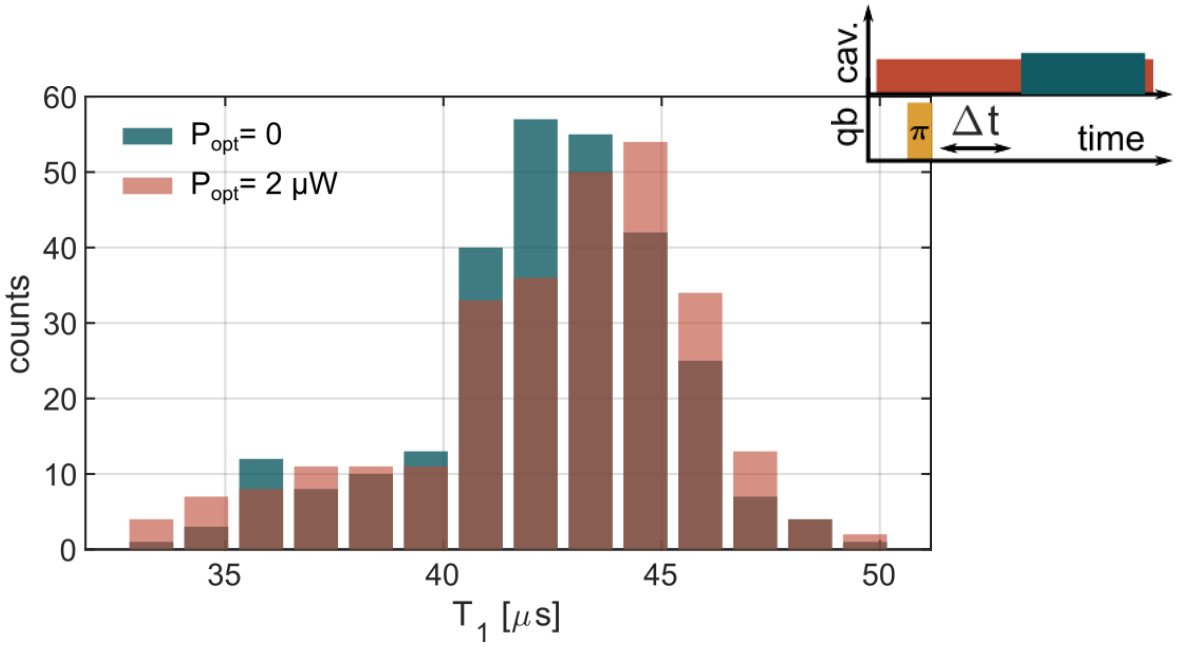
3D transmon coherence can be affected by:

- non-equilibrium quasi-particles (T_1)

T_1 is not affected

=

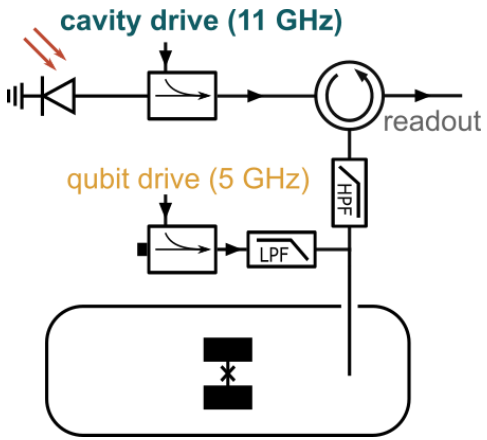
No stray optical light



Qubit readout

Nature 591 575-579 (2021)

NIST



P. Krantz, … , W. D. Oliver, ***App. Phys. Rev.*** *6 (2019)*

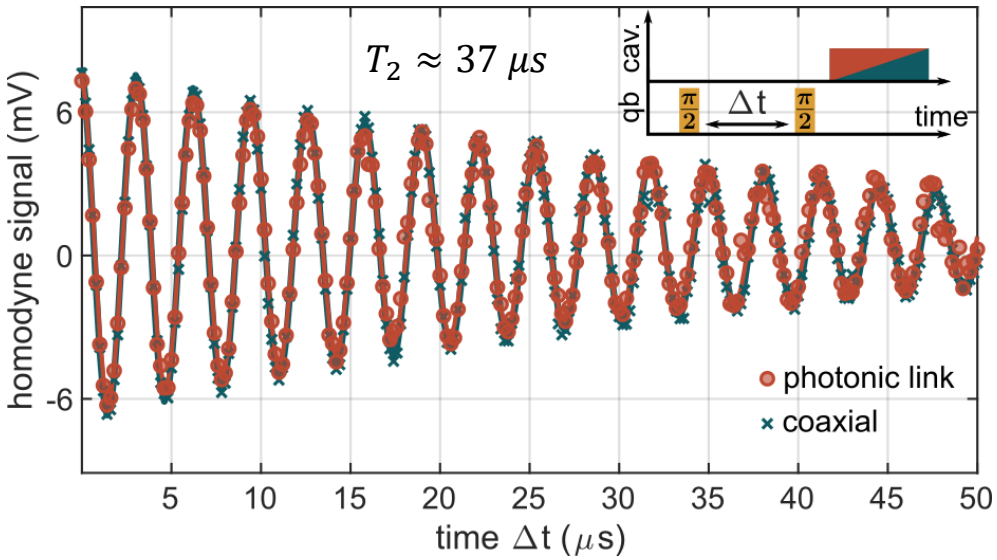
3D transmon coherence can be affected by:

- non-equilibrium quasi-particles (T_1)
- microwave noise in readout cavity (T_ϕ)

T_2 is not affected

=

No noise when light is off



$I \approx 20\ nA$

Qubit control

Nature 591 575-579 (2021)

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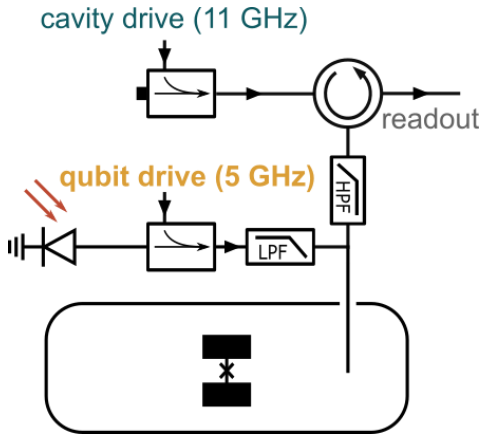
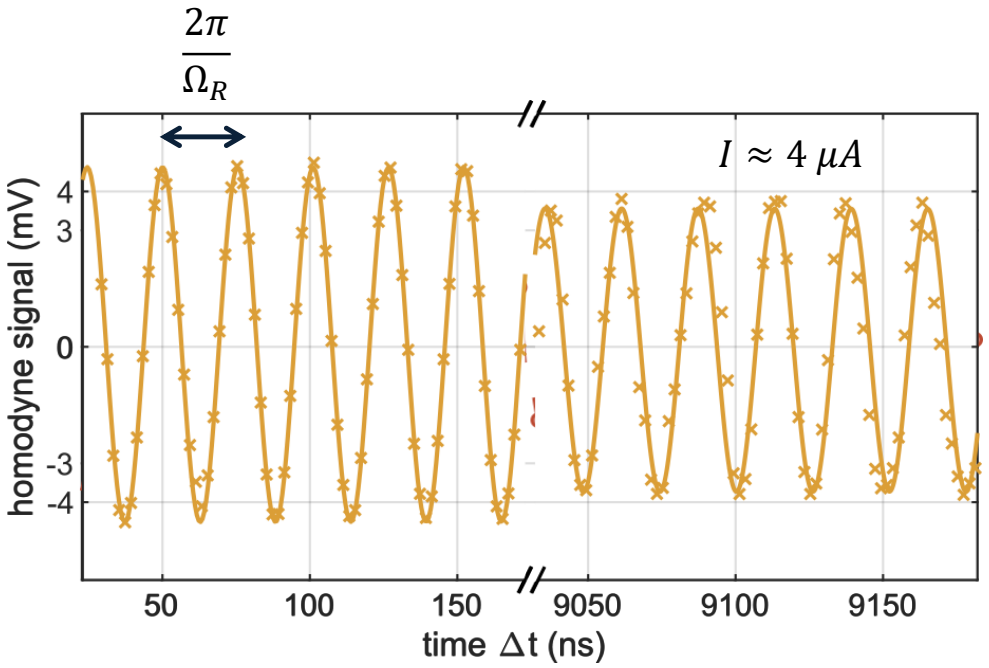
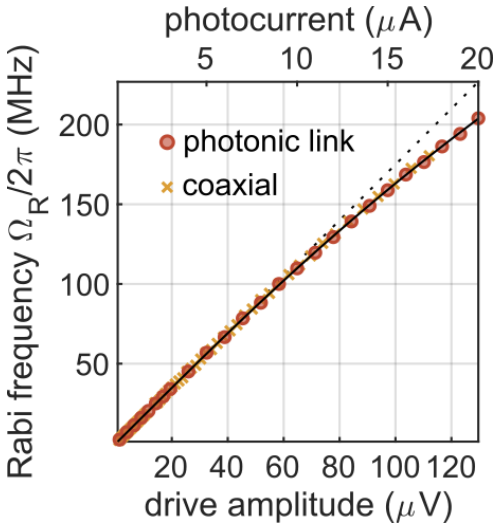


$P_\mu \approx -80\ dBm$

The photonic link can deliver signals strength beyond the transmon two-level approximation

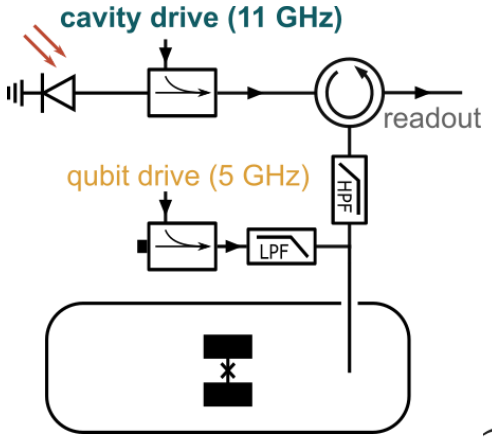




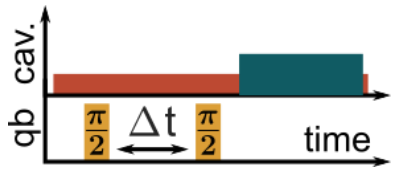
J. Claudon, … , O. Buisson, ***PRL*** *93 (2004)*

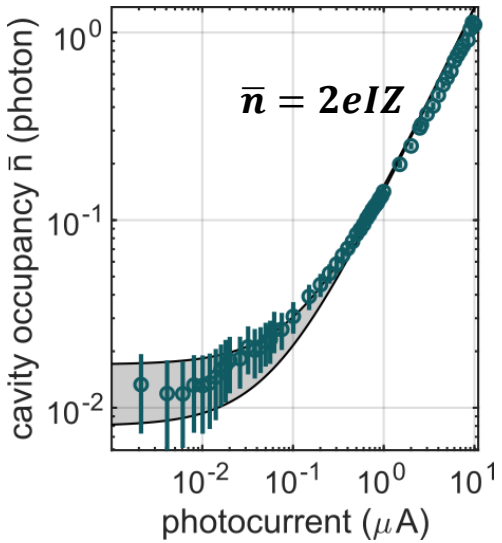
Nature 591 575-579 (2021)

Using the qubit as a sensitive detector



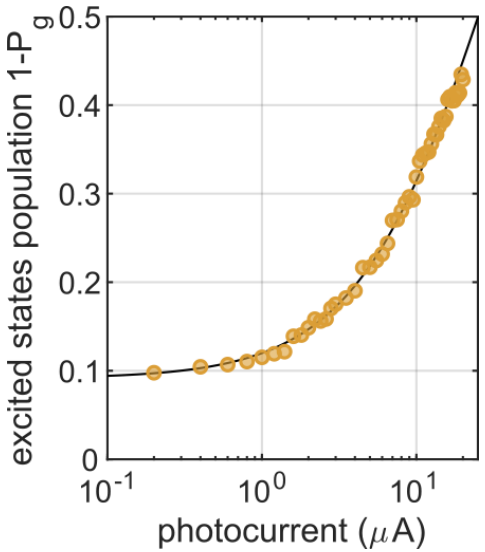
Poisson statistics of the light leads to output microwave noise

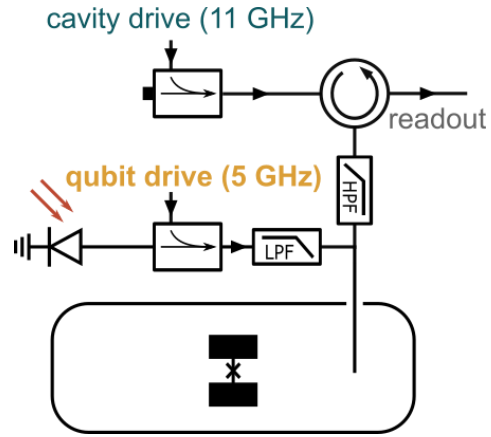




Noise @ cavity frequency = Qubit dephasing

$$\frac{1}{T_2} \propto \bar{n}$$





Noise @ qubit frequency = Qubit transitions

Using the qubit as a sensitive detector

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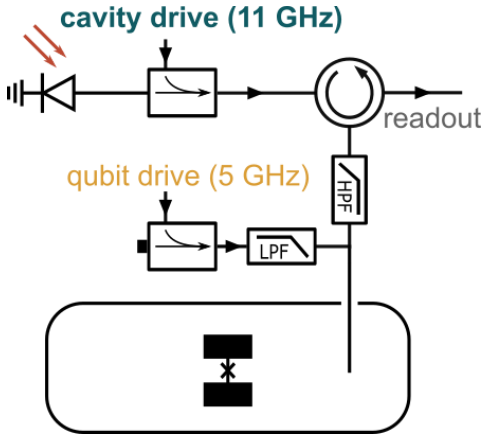
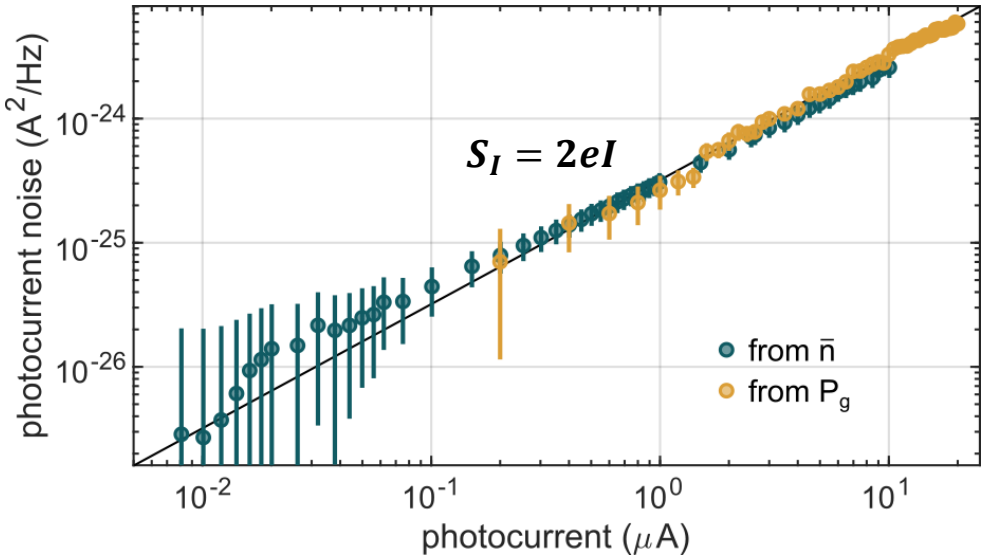
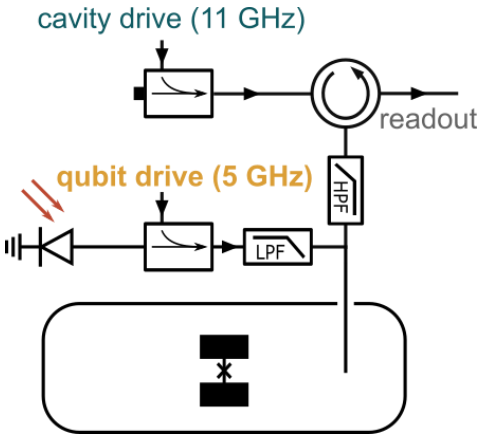


Referring back to the photodiode reveals
shot-noise limited microwave





Scaling estimation

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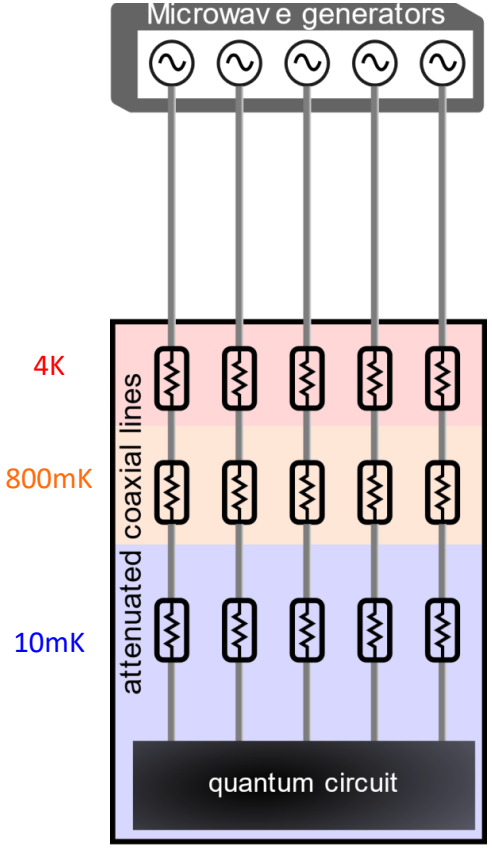
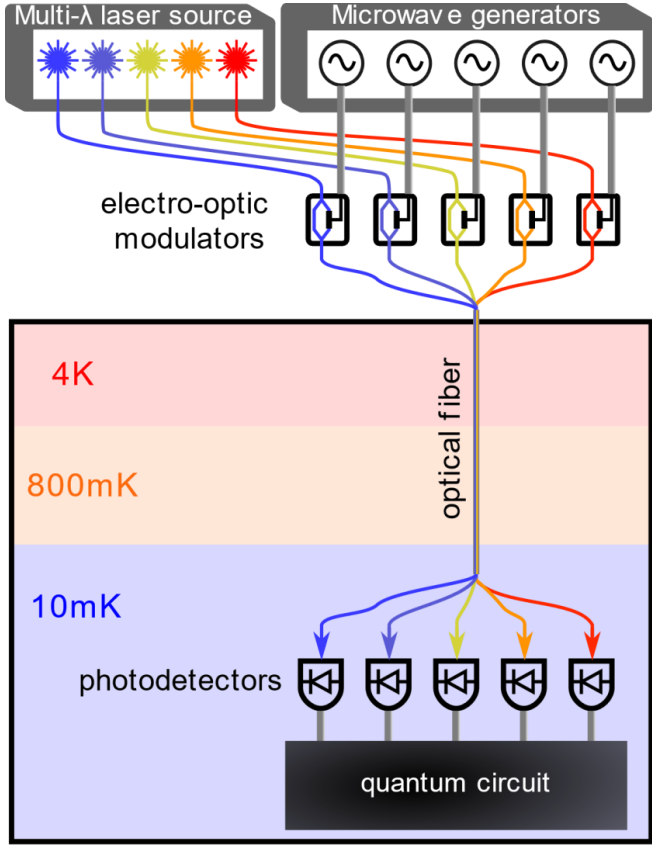
NIST



Can this approach:

1. **work at all? YES!!!**
2. **scale to 10^6 qubits?**



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Heat load and scaling estimation

$P_{cool} = 20\ \mu W$ $\quad n_{qubit} = P_{cool}/\ P_{load}$

Passive heat load: *S. Krinner, … , A. Wallraff,* ***EJP Q. Tech.*** *6 (2019)*

- Coax = 14nW
- Fiber = 3pW

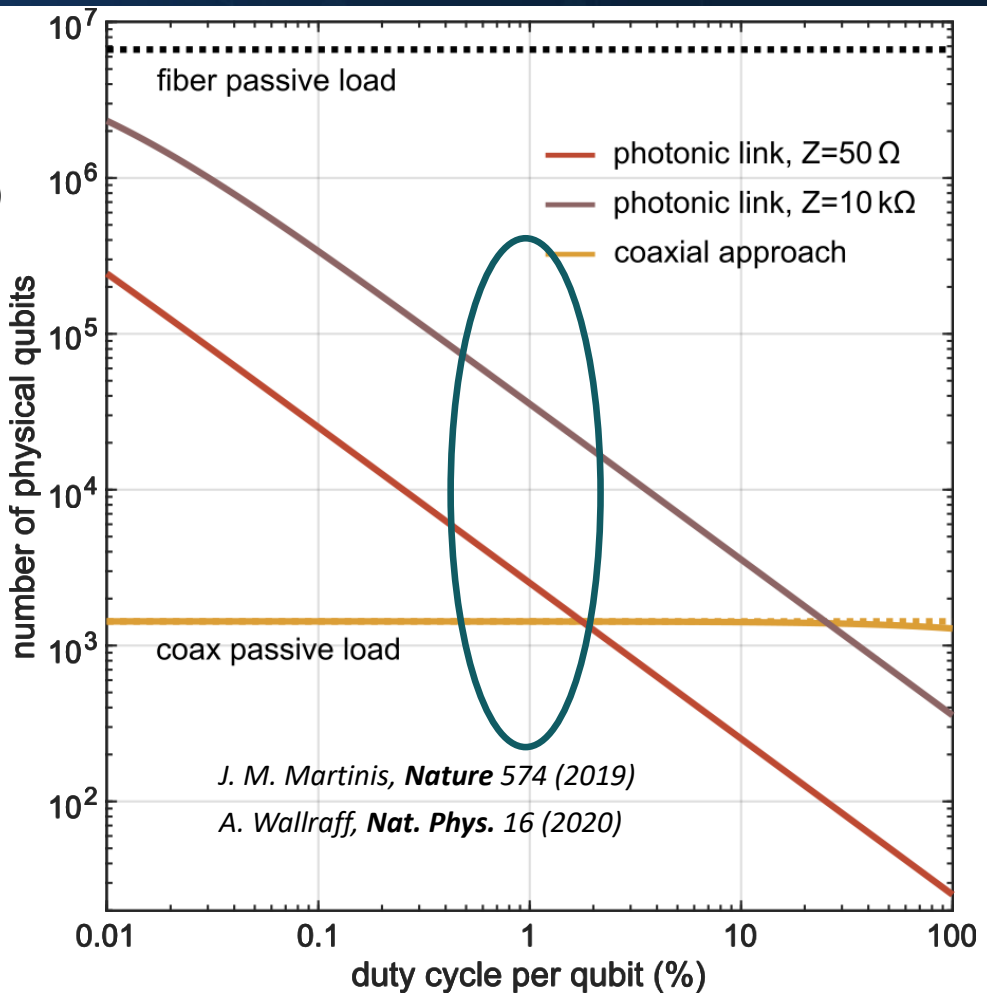
There is a path to 10^6 qubits!

Active heat load:

- Coax = cold attenuators
- Photonic link = Optical dissipation

Total heat load:

$P_{load} = P_{pass} + D_{cycle} \times P_{act}$



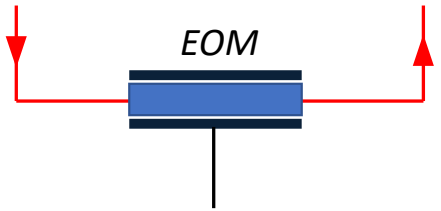
Photonic link: final considerations

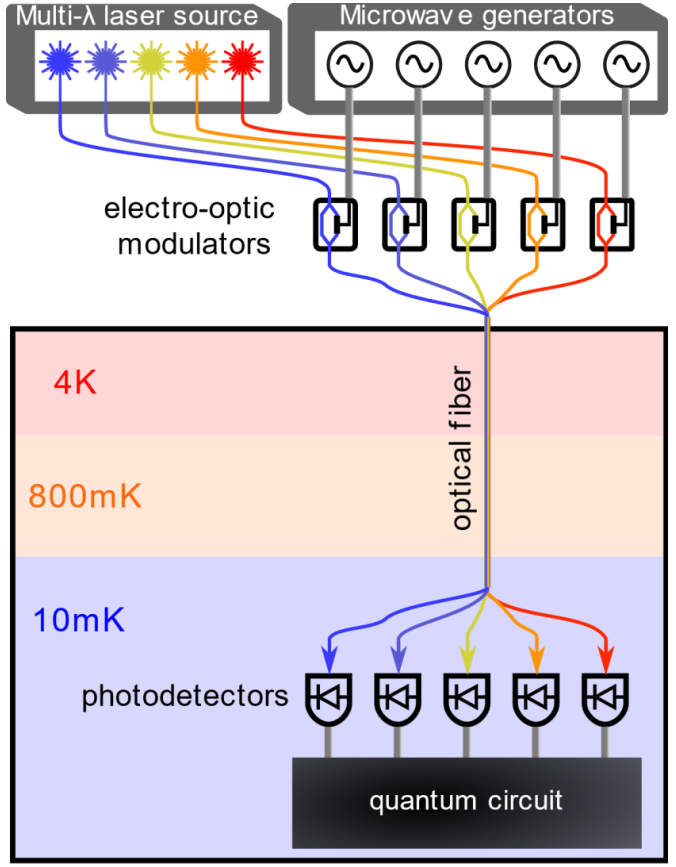
*Nature **591** 575-579 (2021)*

NIST

- Applies to any system that needs massive signal delivery at cryogenic temperatures
  - Large arrays of detectors for astronomy / 4K electronic
  - Other MW application (amplifier, cat/GKP codes, etc)
- Heat load reduction
  - Higher impedance and integration
  - Detection of short pulses
- Photodiodes are NOT quantum transducers
- Other type of photonic link?

*A. Youssefi, **Nat. Elec.** 4 (2021)*





Nature *591 575-579 (2021)*

Pursuing US patent

Thank you

F. Quinlan

S. A. Diddams

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