IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), January 2021.
Presentation Tue-WKS-13 given at IEEE Quantum Week, Virtual, October 13, 2020.

Hardware for efficient measurements and massive signal delivery in superconducting quantum processors

PIs:
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Current Team:
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F. Lecocq
B. Miller
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Collaborators:
S. A. Diddams
F. Quinlan
L. Ranzani

Photonic link: *Arxiv* ***2009.01167*** *(2020)*

Nonreciprocal amplifier: *Arxiv* ***2009.08863*** *(2020)*

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

University of Colorado Boulder

NIST Boulder
Advanced **M**icrowave **P**hotonics Group

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Outline

NIST

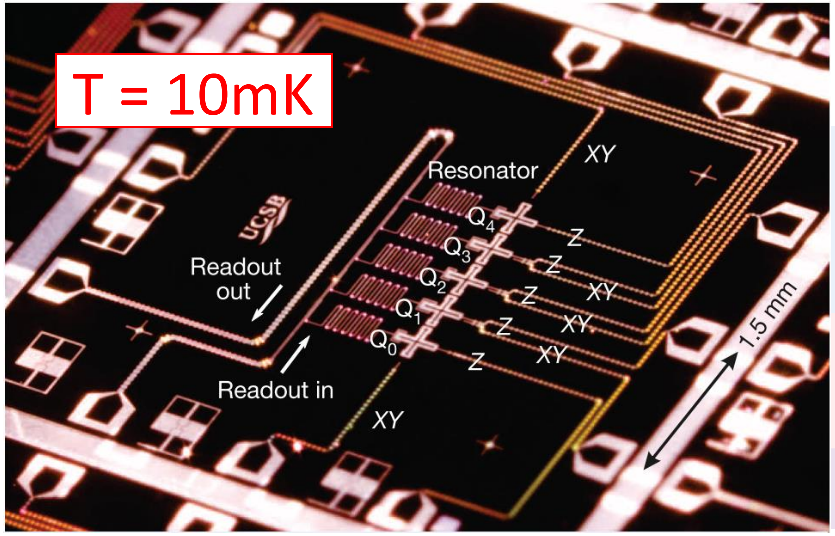
- The scalability challenge
- Signal delivery with a photonic link — *Arxiv **2009.01167** (2020)*
- Nonreciprocal parametric devices — Phys. Rev. Applied, **7** 024028 (2017); Phys. Rev. Applied, **13** 044005 (2020); *Arxiv **2009.08863** (2020)*

Superconducting quantum processor

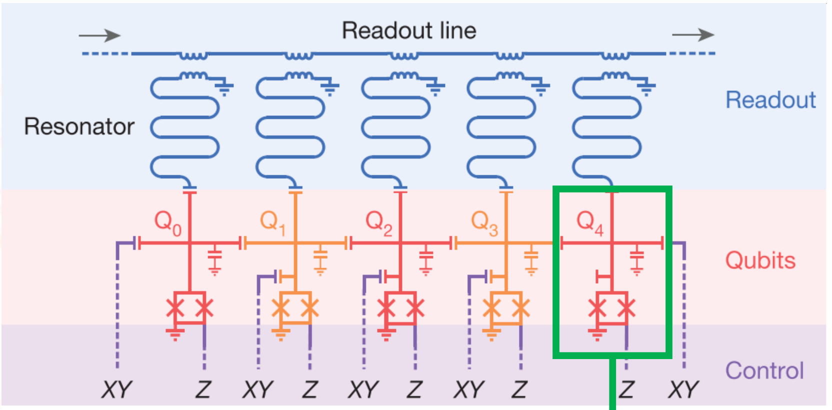
NIST

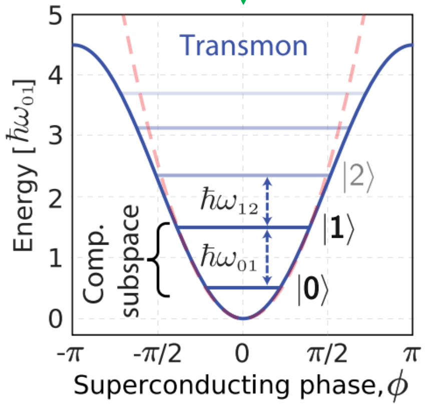
- ❑ Scalability
- ☑ Initialization
- ☑ Coherence
- ☑ Gates
- ☑ Measurements

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



Barends, … , Martinis, ***Nature*** *508 (2014)*





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

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

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

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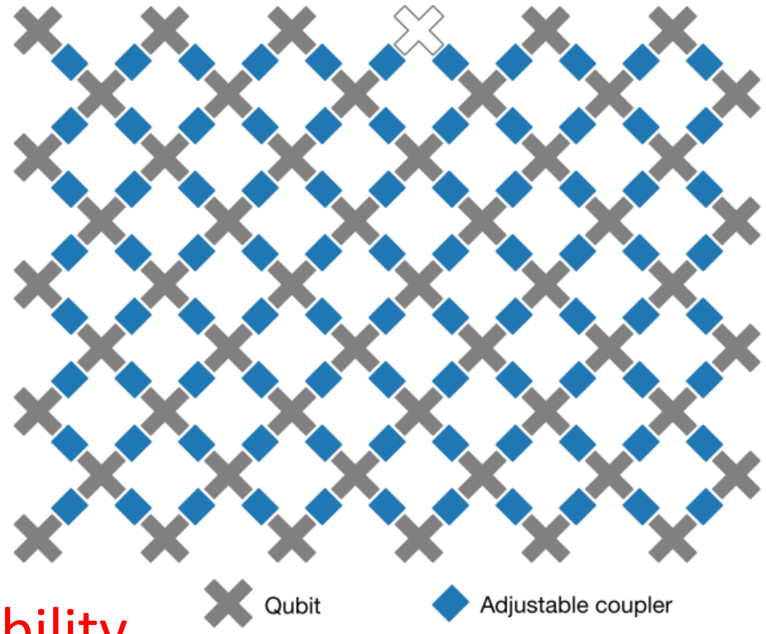
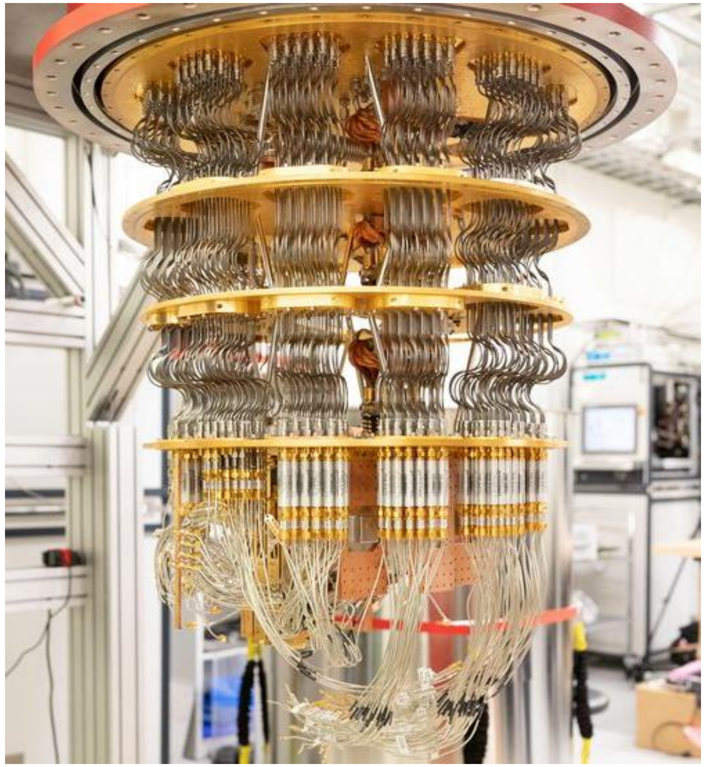
Scalability?

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

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



53 qubits



232 coaxial lines

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

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

A universal computer will realistically require 10^6 qubits

*Fowler, …, Cleland, **PRA** 86 (2012)*
*Reiher ,…, Troyer, **PNAS** 114 (2017)*

The scalability challenge

NIST

- Make bigger fridges
- Distribute entanglement over multiple fridges
- More qubits per fridge

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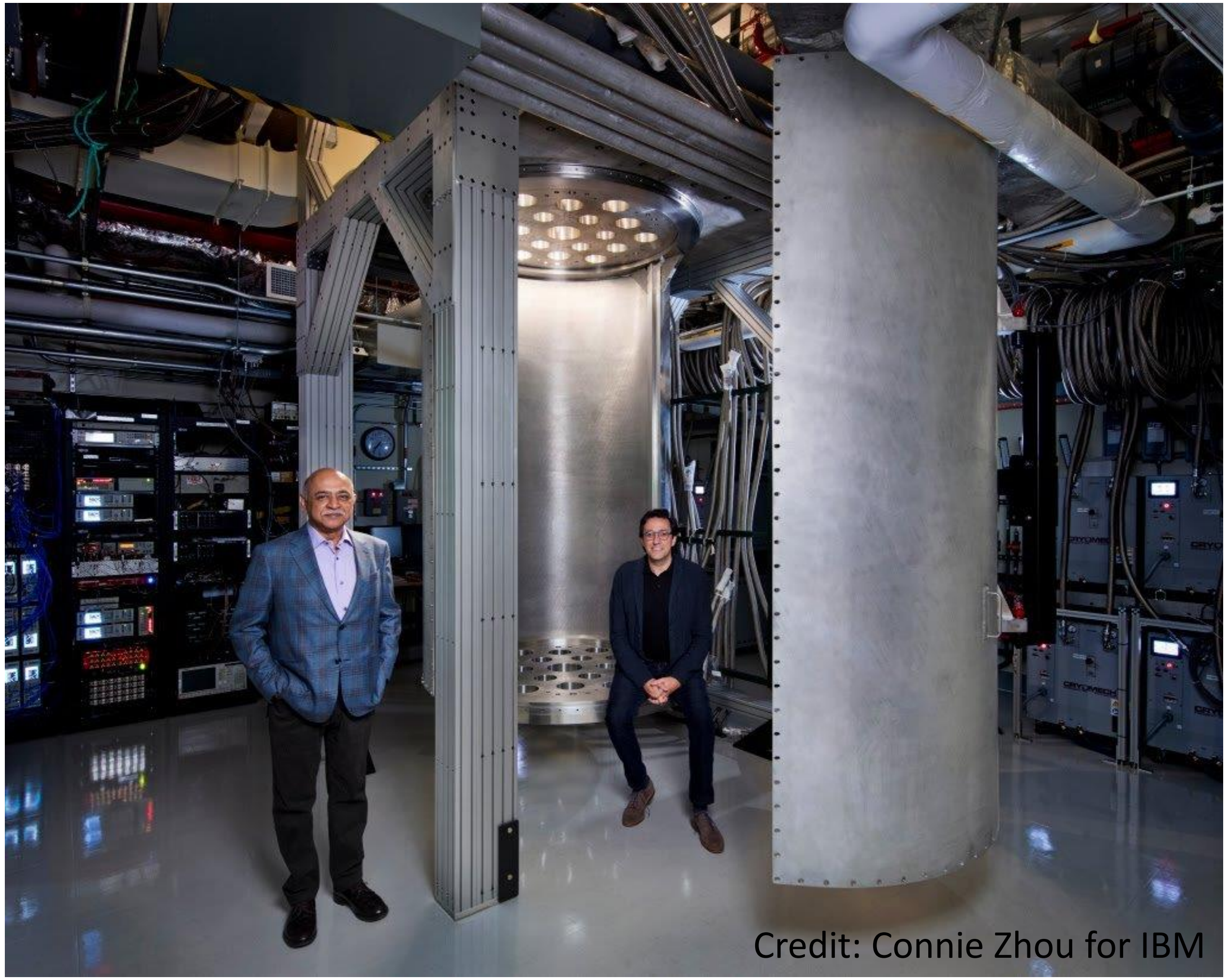

Credit: Connie Zhou for IBM

The scalability challenge

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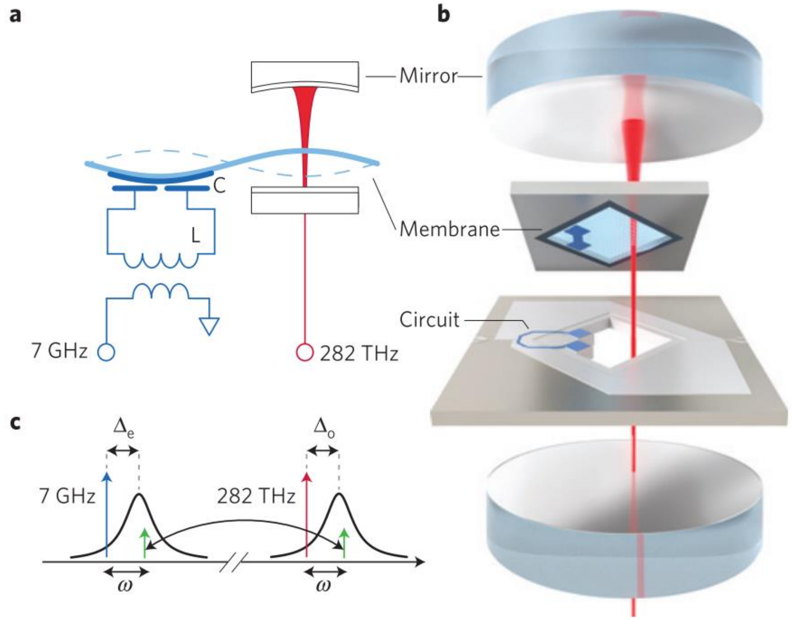
- Distribute entanglement over multiple fridges
- More qubits per fridge

Quantum coherent microwave-to-optical conversion:



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

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

Other options: *Mirhosseini, … , Painter,* ***ArXiv.*** *2004.04838 (2020)*

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The scalability challenge

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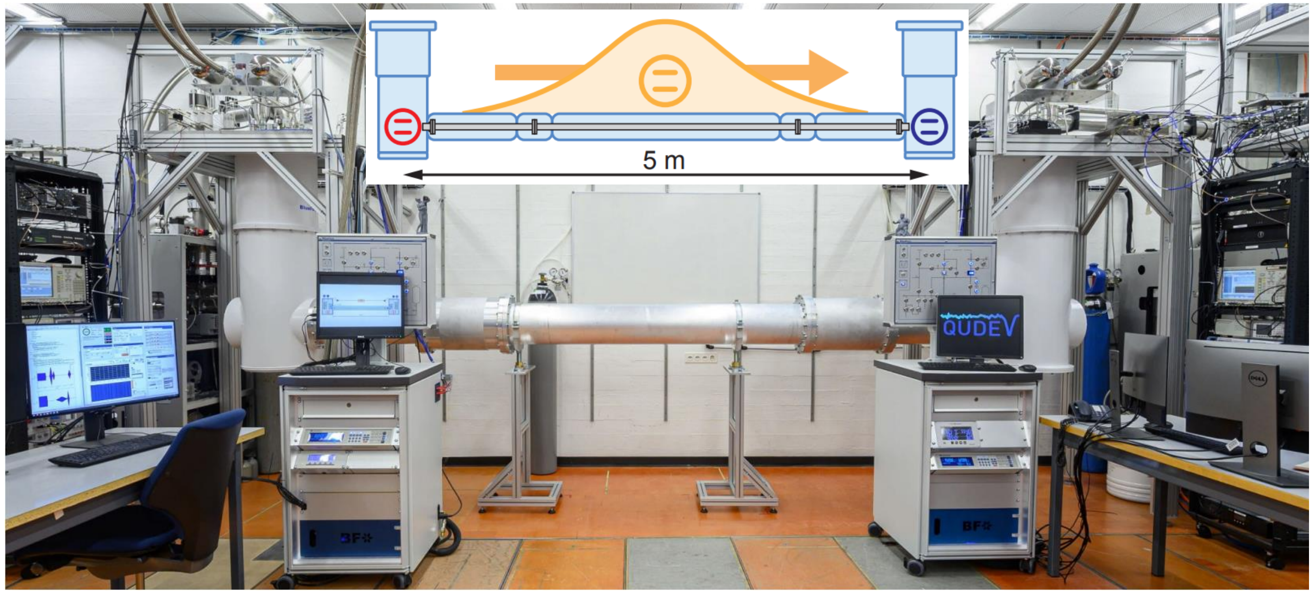
Quantum coherent microwave links:



PMagnard, … , Wallraff, ***ArXiv*** *2008.01642 (2020)*

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The scalability challenge

NIST

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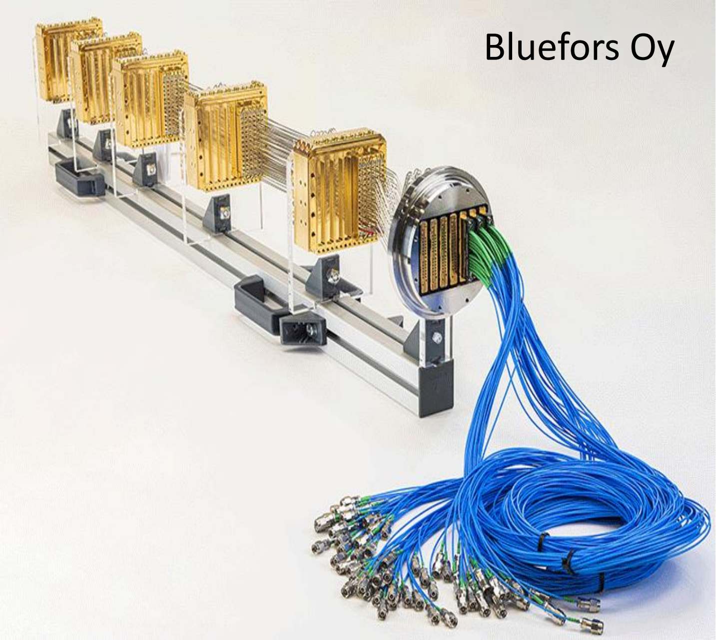
- Distribute entanglement over multiple fridges
- More qubits per fridge

Higher density wiring:



Also cryo CMOS:

Barding, … , Martinis ***IEEE Journal of SSC*** *54 (2019)*

Xue, … , Vandersypen, ***Arxiv*** 2009.14185 *(2020)*

or SFQ coprocessors:

McDermott, … , Ohki, ***Quantum Sci. Technol.*** 3 *(2018)*

Leonard, … , McDermott, ***Phys. Rev. Applied*** 11 *(2019)*

Outline

NIST

- The scalability challenge
- Signal delivery with a photonic link — *Arxiv **2009.01167** (2020)*
- Parametric non-reciprocal devices

Arxiv 2009.01167 (2020)

Alternative approach: the photonic link

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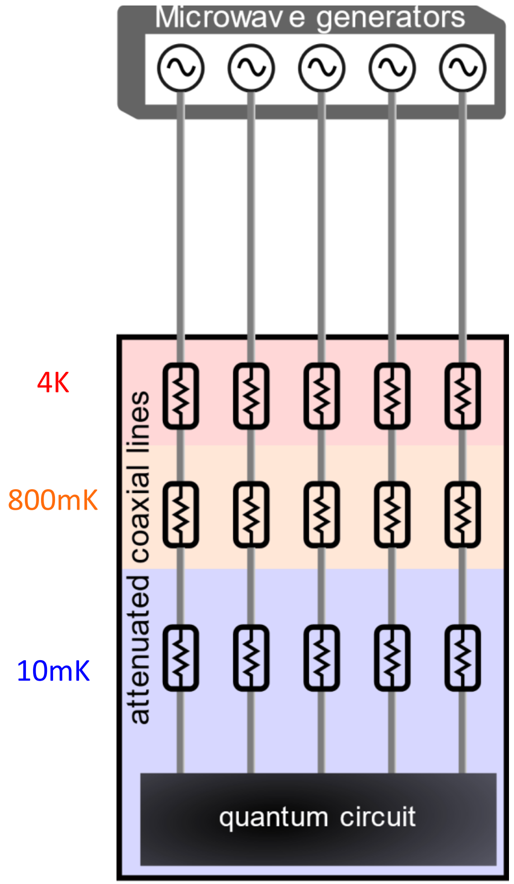
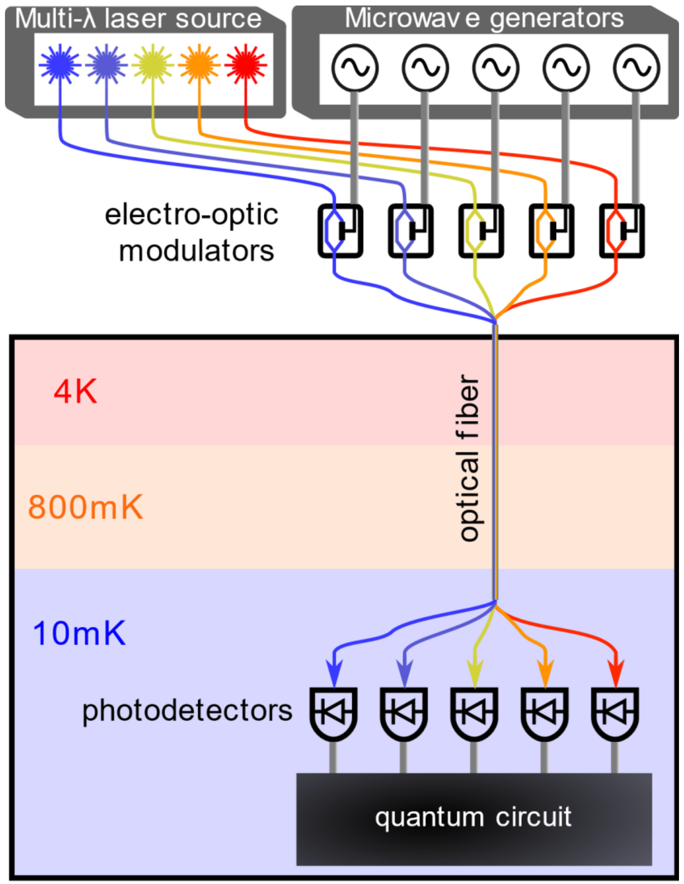


RF photonics is a mature technology (Room Temp) and optical fibers are:

- Cheap
- Small
- High bandwidth
- Low thermal conductivity



Can this approach:

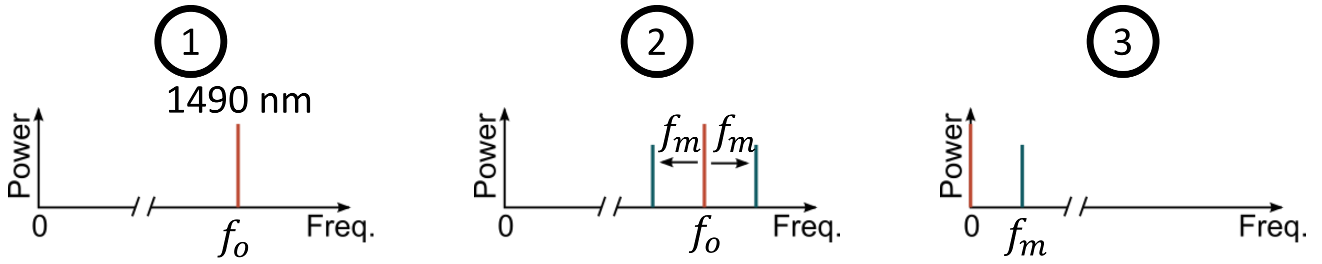
1. **work at all?**
2. **scale to 10^6 qubits?**

Arxiv 2009.01167 (2020)

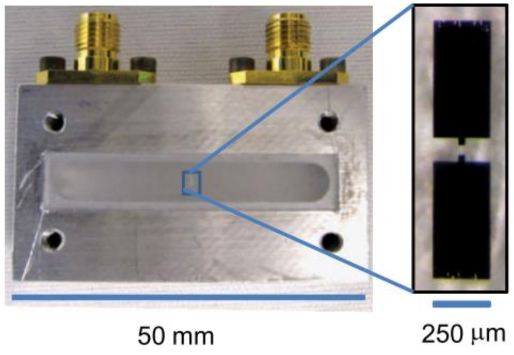
Proof of principle using a 3D transmon

NIST

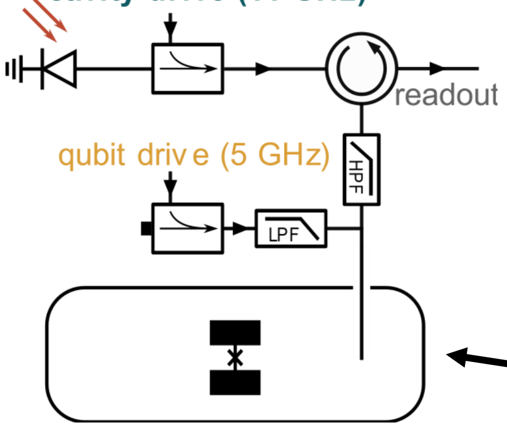
Photonic link = EOM + photodiode (*InGaAs*)



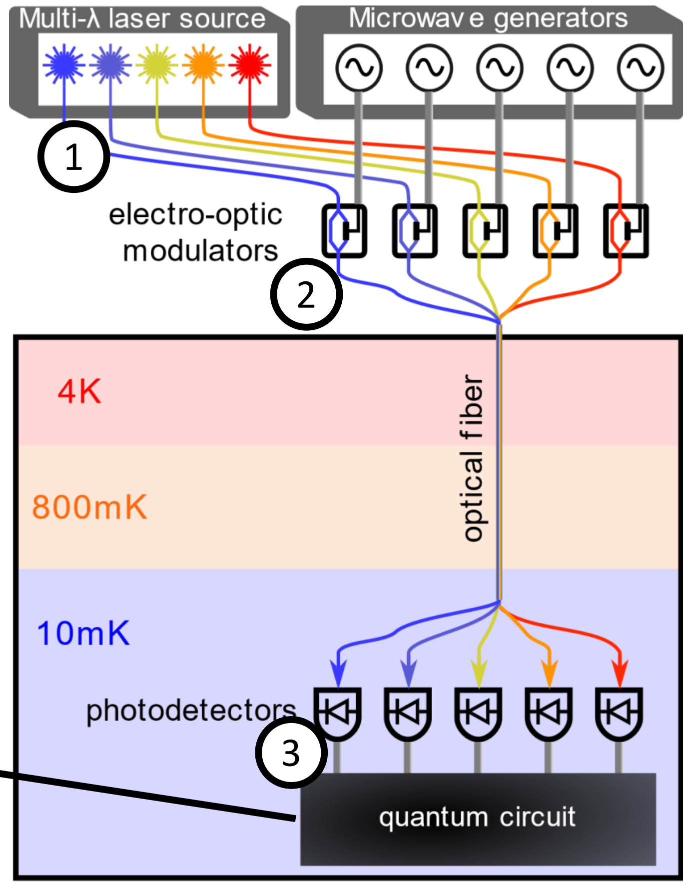
J Davila-Rodriguez,..., F. Quinlan, ***CLEO*** *(2019)*



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



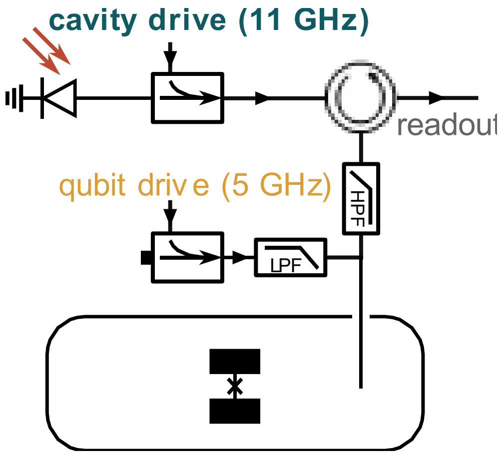
3D transmon

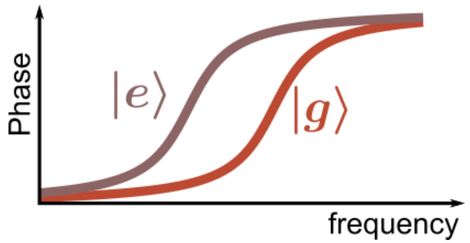


Arxiv 2009.01167 (2020)

NIST

Qubit readout with a photonic link

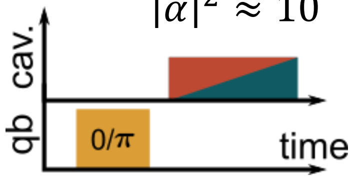




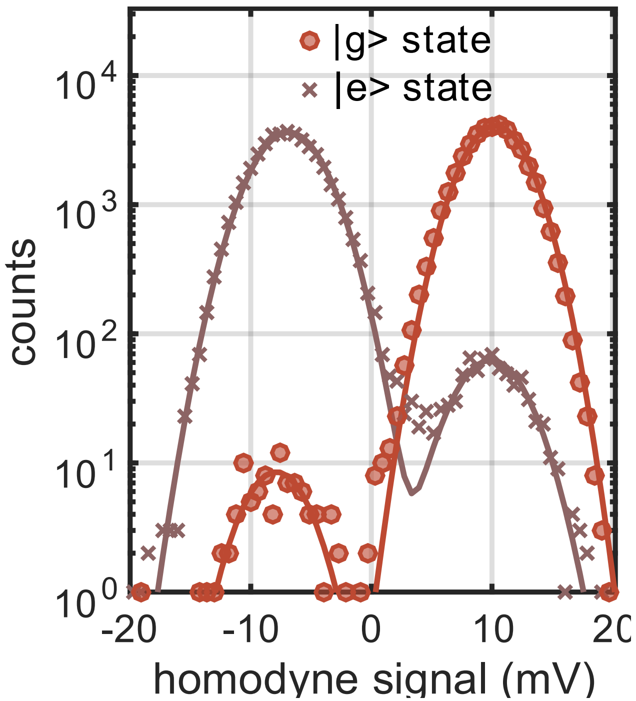
Qubit state dependent cavity frequency

$P_\mu \approx -120\ dBm$

$|\alpha|^2 \approx 10$



$I \approx 20\ nA$



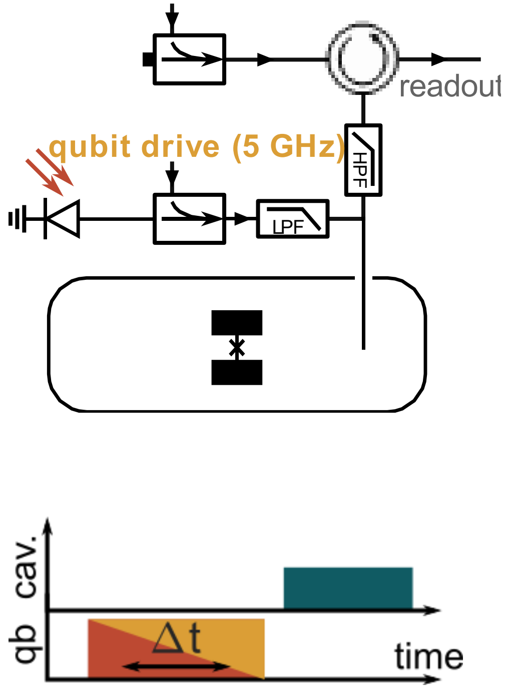
$\boldsymbol{F \approx 98\%}$

High Fidelity Single-shot QND readout

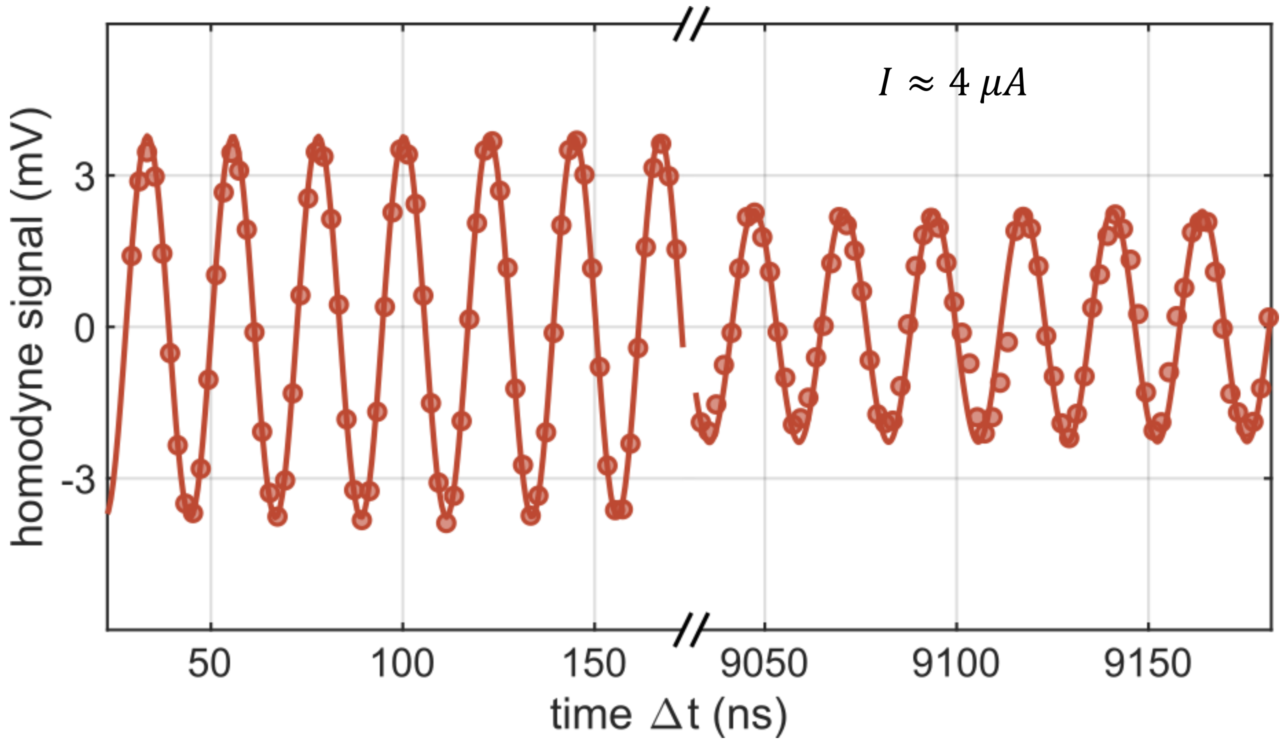
Qubit control with a photonic link

***Arxiv** 2009.01167 (2020)*

NIST



$P_{\mu} \approx -80\ dBm$



Fast Rabi oscillations

Heat load and scaling estimation

Arxiv *2009.01167 (2020)*

NIST

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

<u>Passive heat load:</u> *Krinner, … , Wallraff,* ***EJP Q. Tech.*** *6 (2019)*

- Coax = 14nW
- Fiber = 3pW

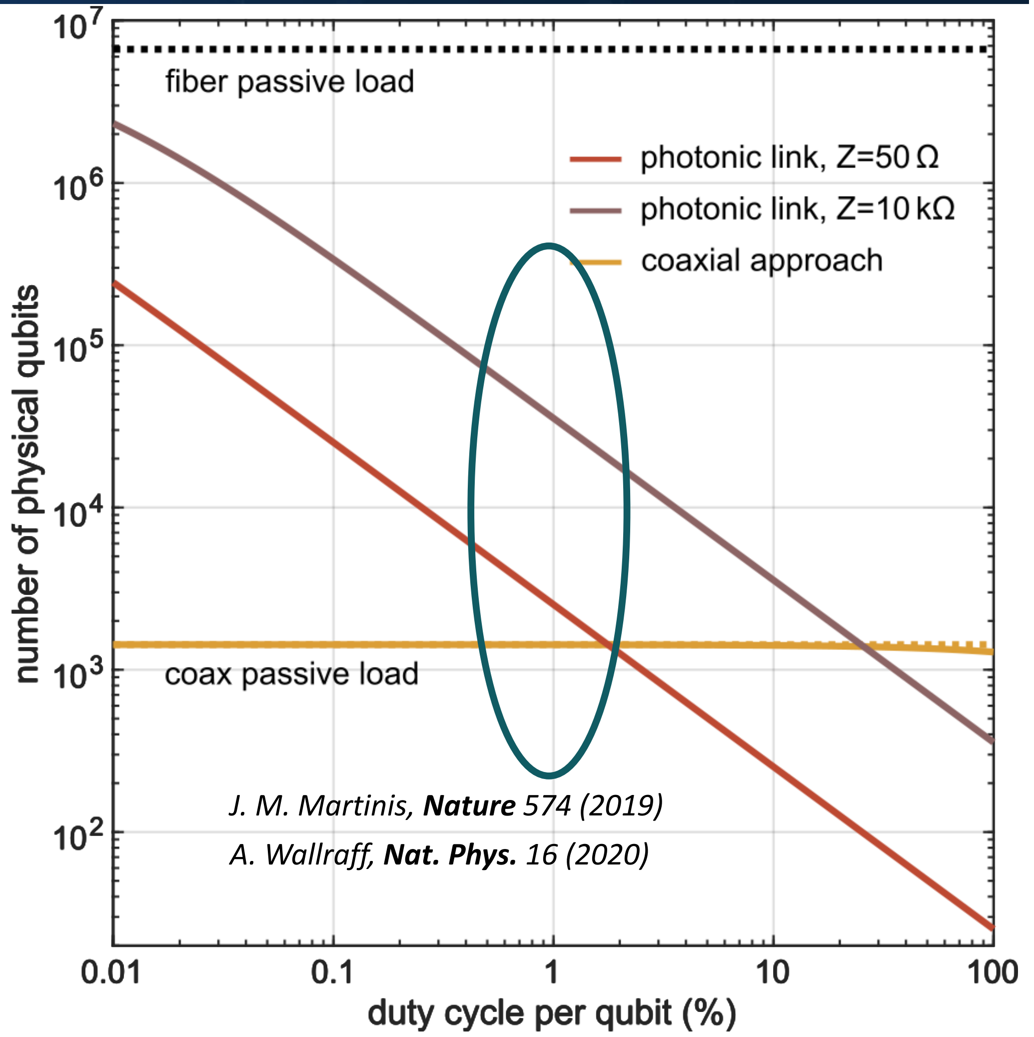
There is a path to 10^6 qubits!

<u>Active heat load:</u>

- Coax = cold attenuators
- Photonic link = Optical dissipation

<u>Total heat load:</u>

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

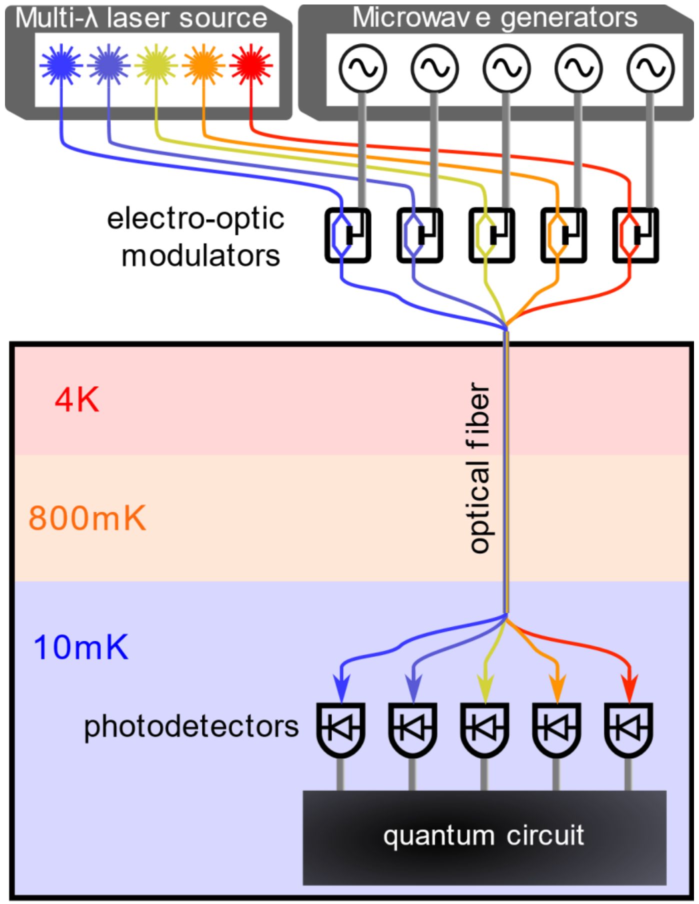


Arxiv *2009.01167 (2020)*

NIST

Photonic link: final considerations

- Applies to any system that needs massive signal delivery at cryogenic temperatures
  - Large arrays of detectors for astronomy
  - 4K electronic
- Other type of photonic link?
  - Anything that would enable optical fiber wiring
- Getting signals back to room temperature is still a challenge



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- Signal delivery with a photonic link
- Nonreciprocal parametric devices

Phys. Rev. Applied, **7** 024028 (2017)

Phys. Rev. Applied, **13** 044005 (2020)

*Arxiv **2009.08863** (2020)*

Scalability?

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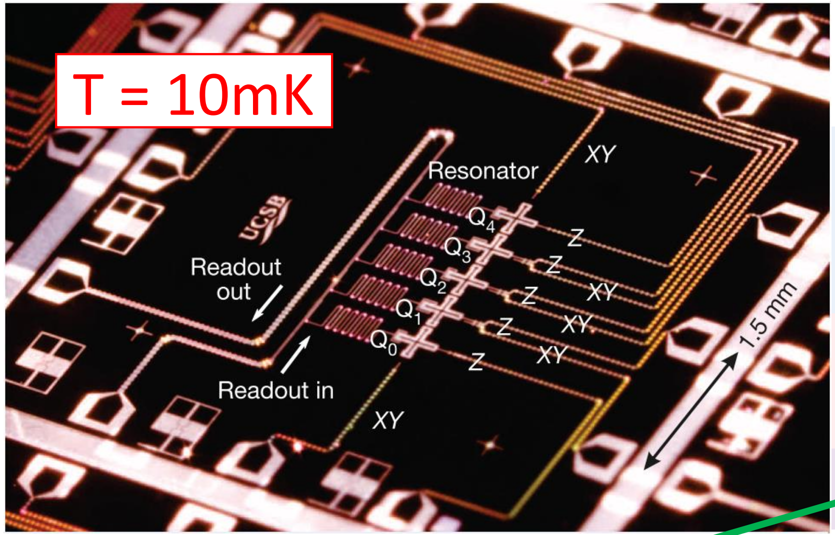
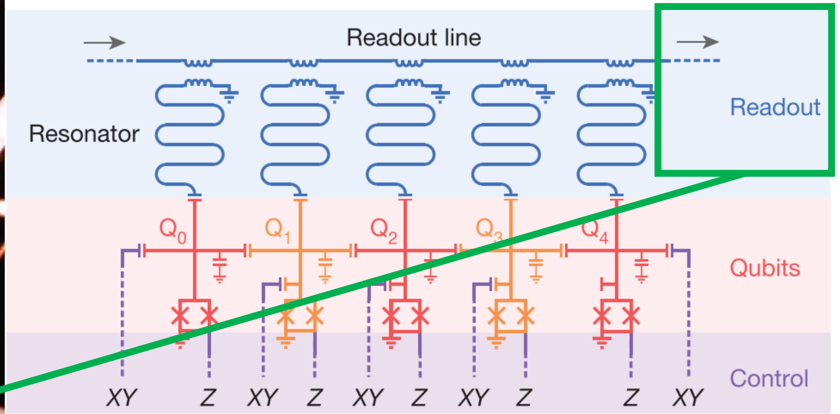
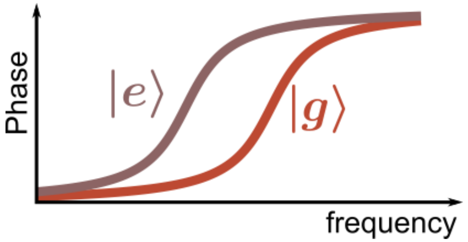
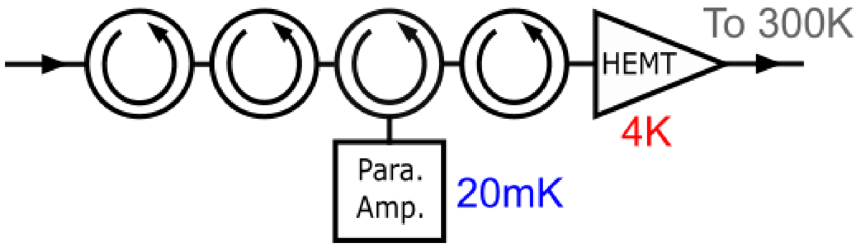


*Barends, … , Martinis, **Nature** 508 (2014)*







High fidelity readout needs a low-noise measurement chain

*J. Aumentado, **IEEE MW magazine** 21 (2020)* *L. Ranzani, J. Aumentado, **IEEE MW magazine** 20 (2019)*

Scalability?

NIST

- ☒ Scalability
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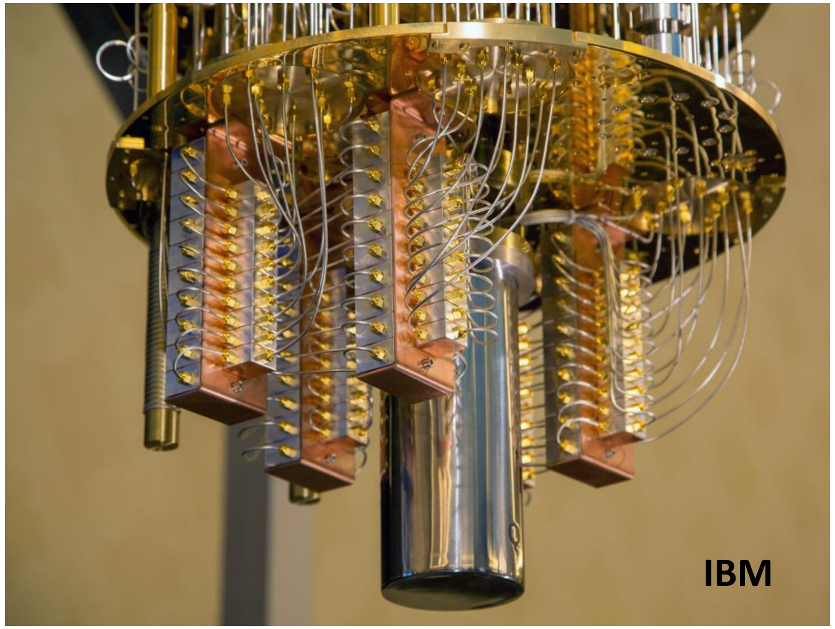
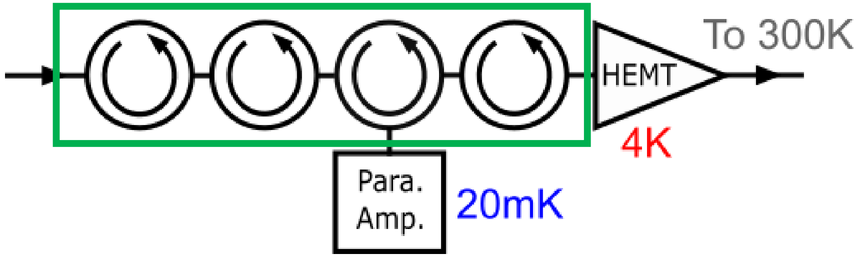


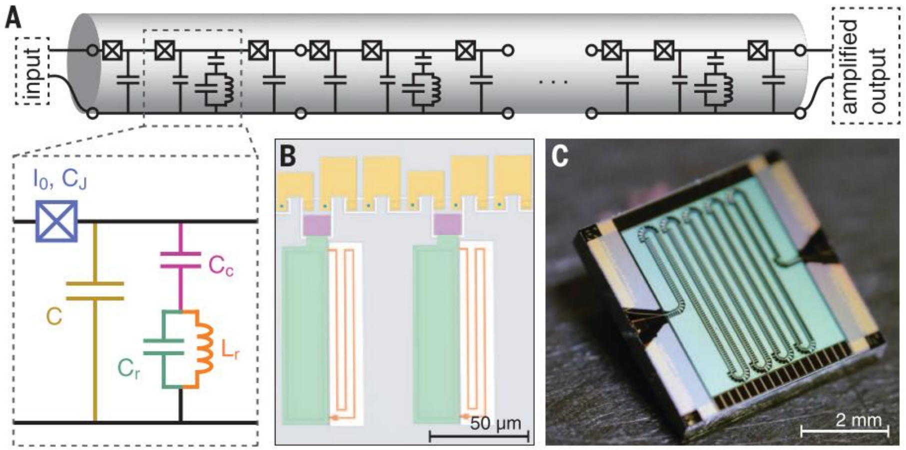
MW circulators issues:
Loss
Magnetic field
Size

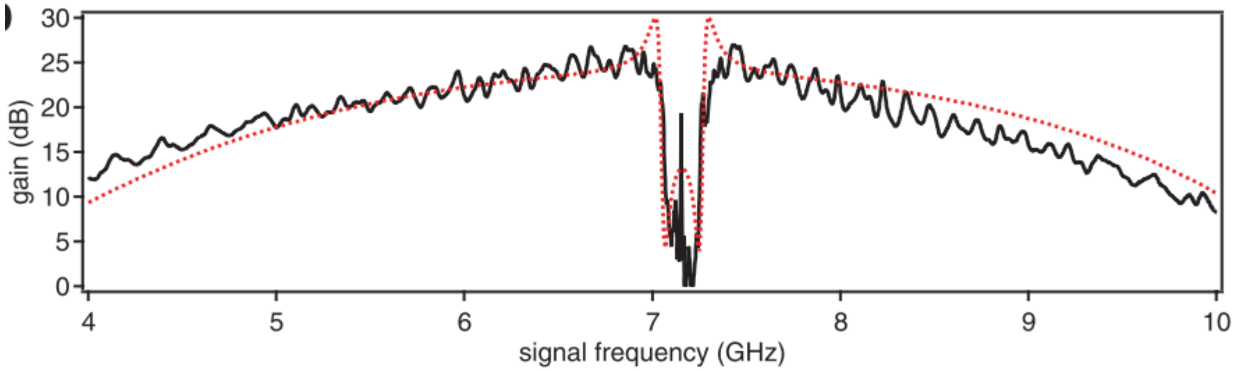


Can we integrate directionality within the quantum circuits?

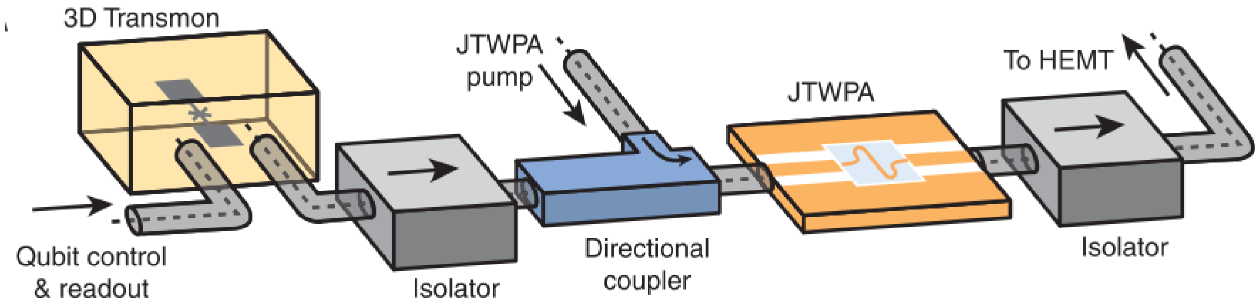
*J. Aumentado, **IEEE MW magazine** 21 (2020)* *L. Ranzani, J. Aumentado, **IEEE MW magazine** 20 (2019)*

Traveling wave amplifiers





Macklin, … , Siddiqi, ***Science*** 350 *(2015)*



Also: *Planat, … , Roch,* ***PRX*** 10 *(2020)*

Pros:

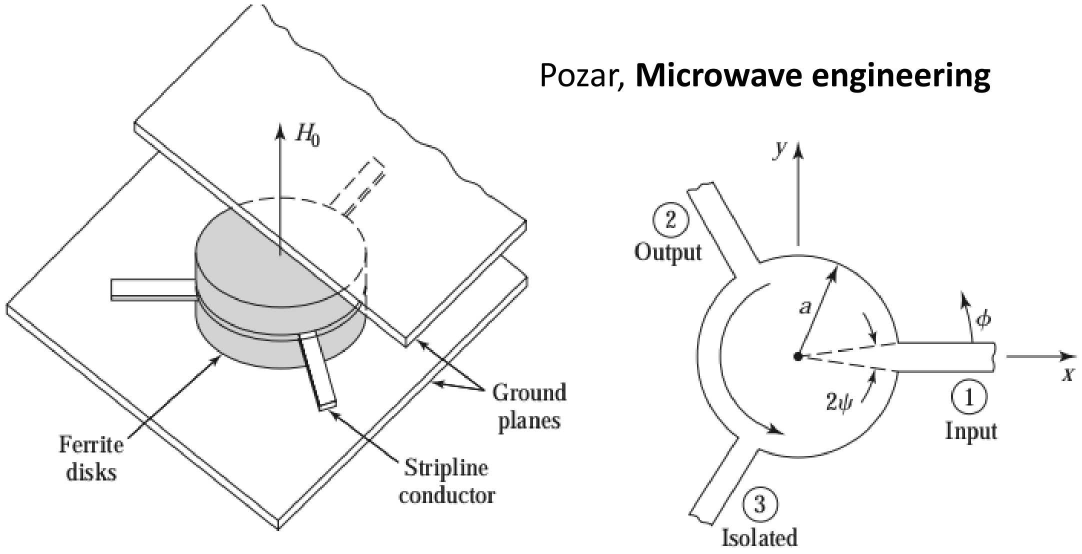
- **Many GHz of bandwidth**
- **High dynamic range**

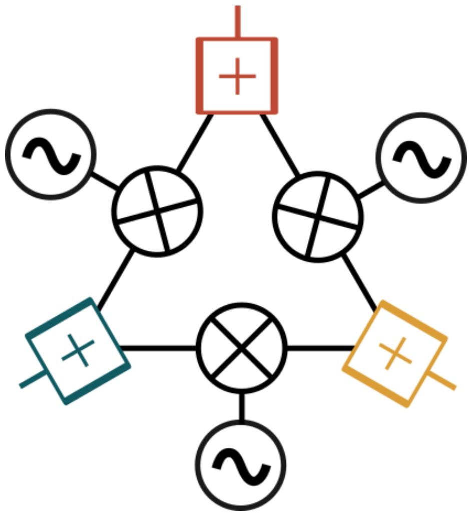
Cons:

- **High pump power**
- **Residual reverse gain**

Parametric nonreciprocity

Pozar, **Microwave engineering**





Necessary ingredients:

- **Interferometer**
- **Nonreciprocal phase shift**

Parametric implementation:

- **Superconducting resonators**
- **Parametric frequency conversion**

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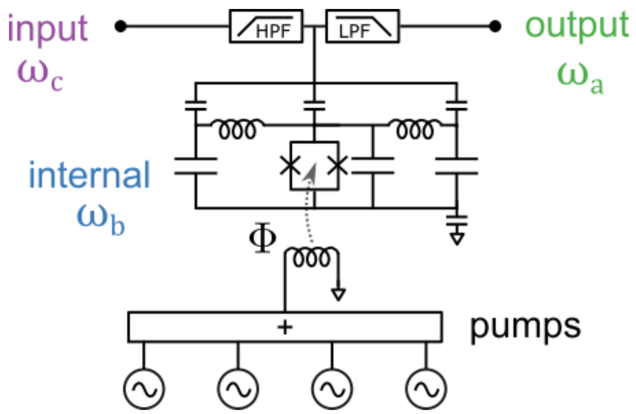
Field Programmable Josephson Amplifier

NIST



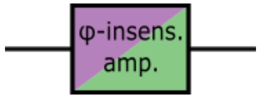
- 3 resonators
- 1 SQUID
- All-to-all parametric coupling

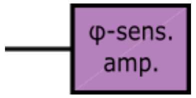
*Phys. Rev. Applied, **7** 024028 (2017)*
*Phys. Rev. Applied, **13** 044005 (2017)*

No pump: open circuit

1 pump: Frequency converter

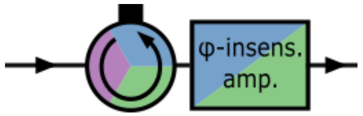
Phase sensitive or insensitive amplifier



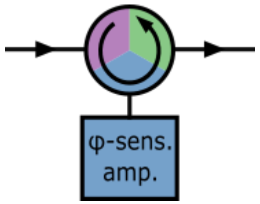


3 pumps: Circulator

Directional phase insensitive amplifier



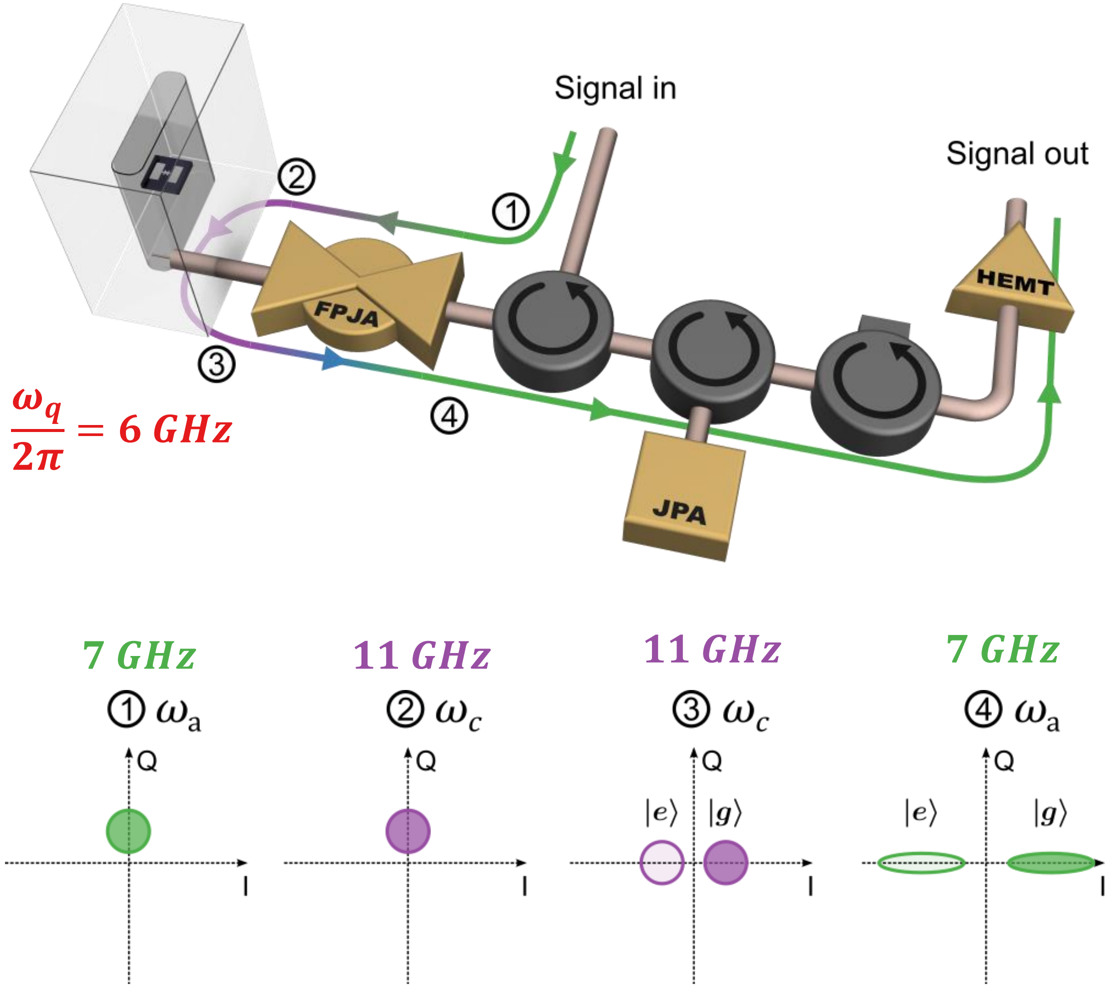
4 pumps: Directional phase sensitive amplifier



Efficient qubit measurement

Arxiv 2009.01167 (2020)

NIST



Pros:

- **Ultra-low noise**
- **Fully integrable on-chip**

Cons:

- **Limited bandwidth**
- **Limited dynamic range**

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Arxiv 2009.01167 (2020)

Nonreciprocal amps: final considerations

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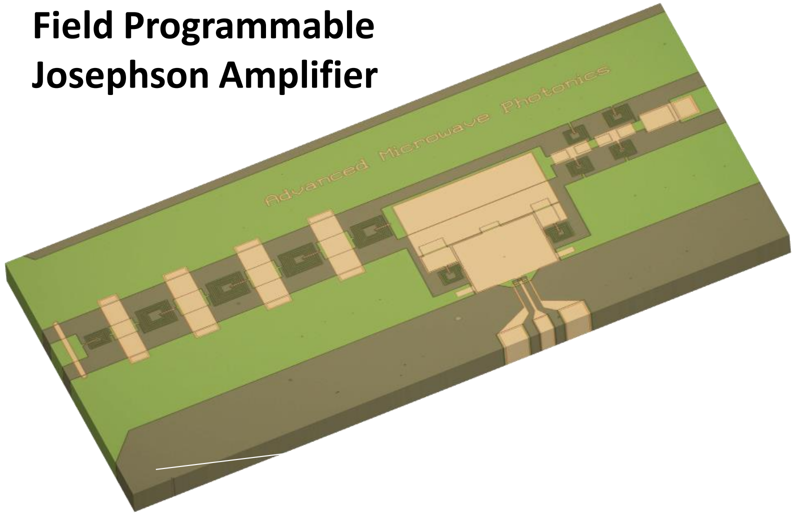
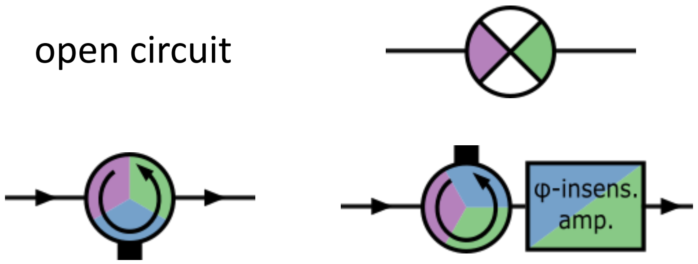
Field Programmable Josephson Amplifier



In-situ programable readout cavity:



- High efficiency for quantum feedback
- Transform readout cavities into tunable coupler and nonreciprocal amplifiers
  - Phase insensitive gain to benefit from isolation
  - Tunable coupling in real time

Hardware for efficient measurements and massive signal delivery in superconducting quantum processors

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