IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), No. 49, March 2021.
Plenary presentation Wk2P4 given at the virtual ASC 2020, November 4, 2020.

MIT Center for Quantum Engineering
cqe.mit.edu

EQuS ENGINEERING QUANTUM SYSTEMS
equs.mit.edu

# Quantum Engineering of Superconducting Qubits and Quantum Computers

**William D. Oliver**

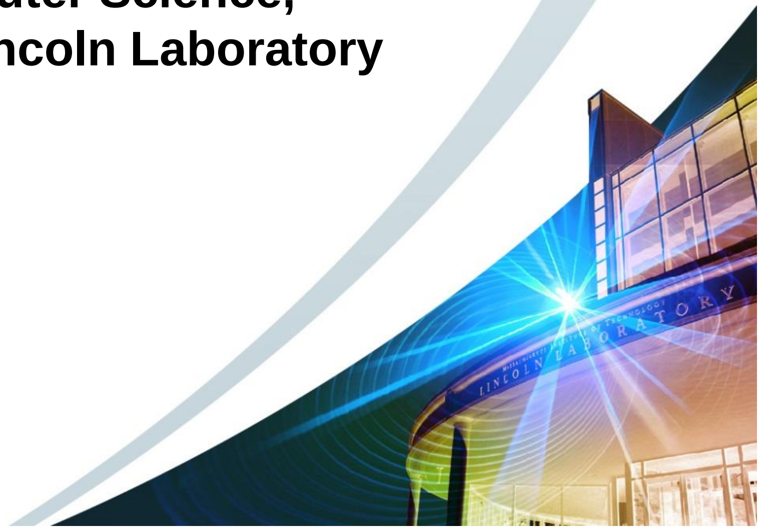
**Department of Electrical Engineering and Computer Science,
MIT Research Laboratory of Electronics, and MIT Lincoln Laboratory**

**ASC 2020**

**4 November 2020**

MIT RLE AT MIT RESEARCH LABORATORY OF ELECTRONICS AT MIT

LINCOLN LABORATORY MASSACHUSETTS INSTITUTE OF TECHNOLOGY

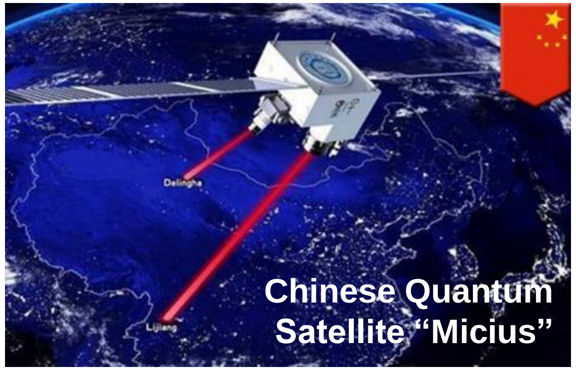


# Quantum Information Science and Technology

## Quantum Sensing


Improves sensitivity, drift, & spatial resolution

## Quantum Networks




Enables distributed quantum states

## Quantum Computing

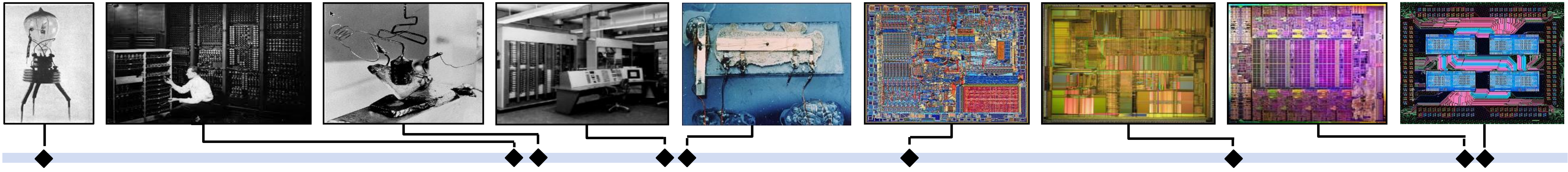

Solves select problems that are intractable with classical computing

**Quantum Information Science utilizes a quantum mechanical description of nature to sense, communicate, and process/compute information in ways unobtainable by means based on a classical description of nature**

# Computing Development Timeline

## Classical Computing (Electronic)

Vacuum tube (1906) · ENIAC (1946) · Transistor (1947) · TX-0 (1956) · Integrated circuit (1958) · 2K transistors i4004 (1971) · 5.5M transistors Pentium Pro (1995) · 18 cores 5.5B transistors Xeon Haswell (2014) · 32 cores 19.2B transistors Epyc GPU (2017)



**Quantum computing is transitioning from scientific curiosity to technical reality.**

**Advancing from discovery to useful machines takes time & engineering**

**You must be in the game to play**

## Quantum Computing

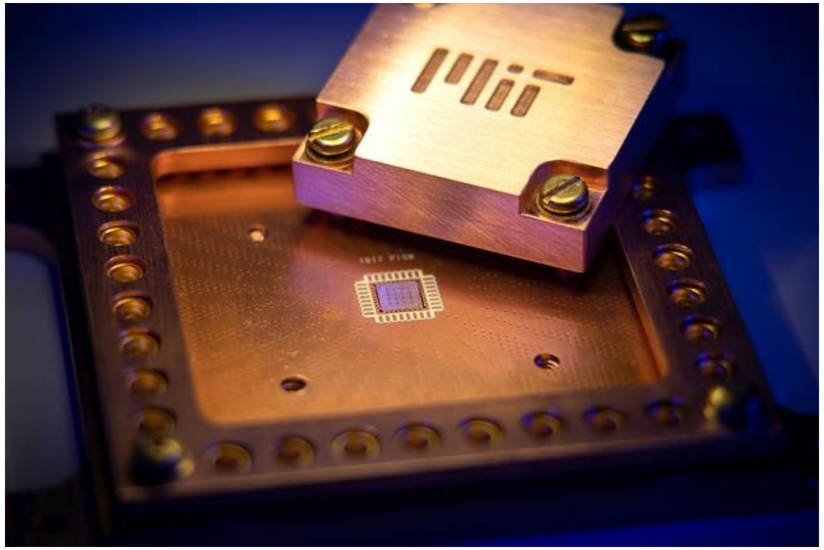
Grover (1996) · Factor 15 (2002) · Few-qubit processors (2010-2016)


Quantum simulator proposed (1981) · Shor's algorithm & CSS error correction (1994-95) · Quantum annealing & adiabatic QC (1998-2000) · Cloud-based QCs (2017) · Quantum Advantage 53-qubit QCs (2019)

# Outline

- Introduction to quantum computing
- Superconducting qubits
- Engineering quantum systems
- Algorithms and 3D integration

**32-pin Package**
**5x5 $mm^2$ silicon qubit chip**



Y. Sung, …, WDO, Nature Communications (2019)

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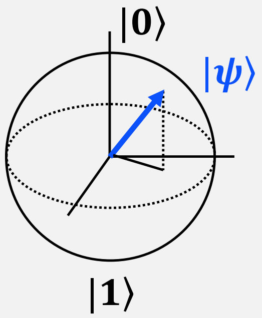
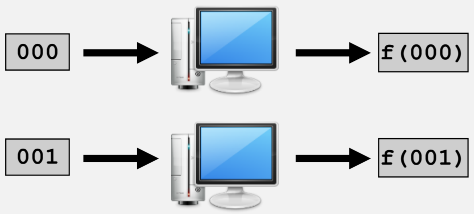
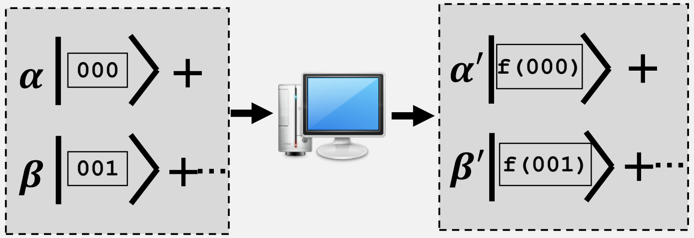
# How is a Quantum Computer Different?

| | Classical Computer | Quantum Computer |
|---|---|---|
| **Fundamental logic element** | **"Bit" : classical bit** (transistor, spin in magnetic memory, …) | **"Qubit" : quantum bit** (any coherent two-level system) |
| **State** | **0 "Or" 1** |   **Superposition:** $\alpha\|0\rangle + \beta\|1\rangle$<br>$\|0\rangle$ **"And"** $\|1\rangle$<br>$\|\psi\rangle = \alpha \begin{bmatrix} 1 \\ 0 \end{bmatrix} + \beta \begin{bmatrix} 0 \\ 1 \end{bmatrix}$ |
| **Measurement** | • ***Discrete*** **states**<br>• **Deterministic measurement:**<br>**Ex: Set as 1, measure as 1** | • ***Superposition*** **states**<br>• **Probabilistic measurement:**<br>**Ex: If $\|\alpha\| = \|\beta\|$, 50% $\|0\rangle$, 50% $\|1\rangle$** |

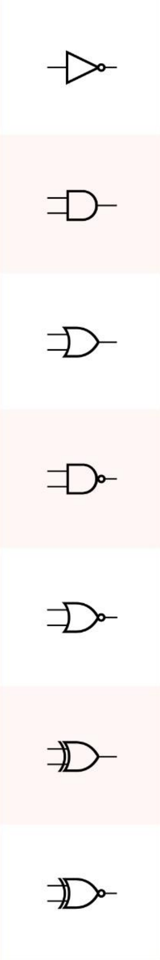
**Quantum computers rely on encoding information in a fundamentally different way than classical computers**

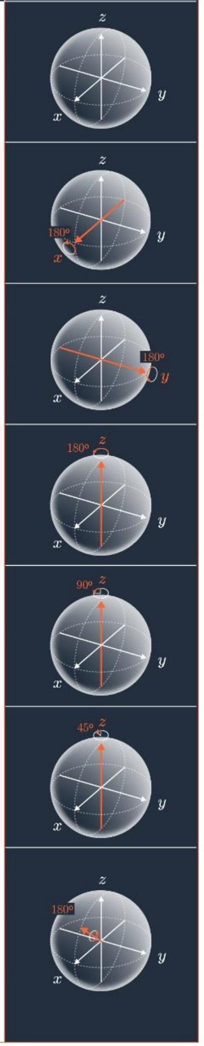
# How is a Quantum Computer Different?

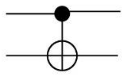
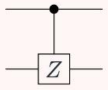
| | Classical Computer | Quantum Computer |
|---|---|---|
| Fundamental logic element | "Bit" : classical bit (transistor, spin in magnetic memory, …) | "Qubit" : quantum bit (any coherent two-level system) |
| Computing | • N bits: One N-bit state<br>000, 001, …, 111 (N = 3)<br>• Change a bit: new calculation (classical parallelism)<br> | • N qubits: $2^N$ components to one state<br>$\alpha\|000\rangle + \beta\|001\rangle + \cdots + \gamma\|111\rangle$ (N = 3)<br>• Quantum parallelism & interference<br> |

**Quantum computers rely on encoding information in a fundamentally different way than classical computers**

# Classical and Quantum Gates

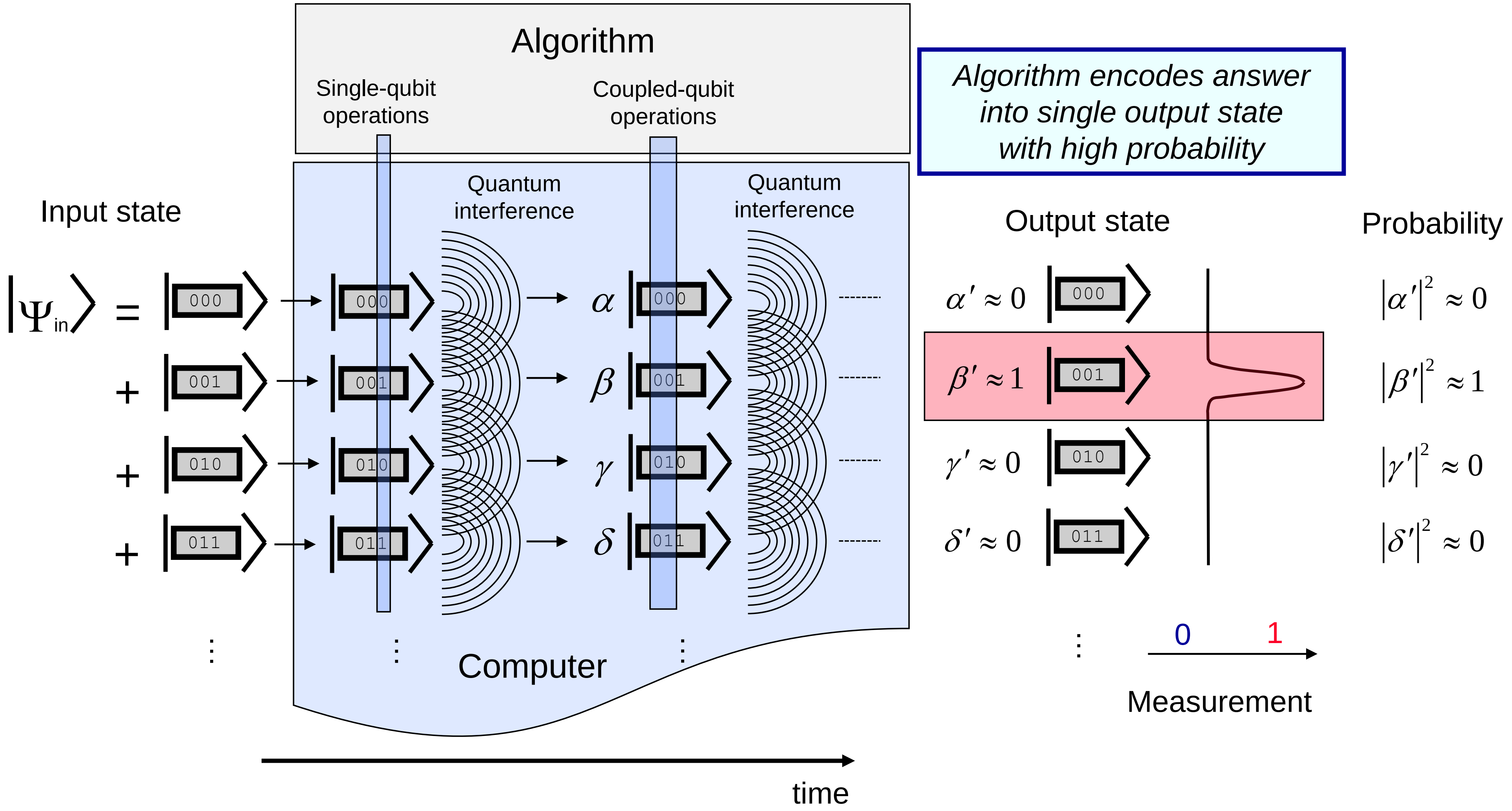
| GATE | | CIRCUIT REPRESENTATION | TRUTH TABLE Input | TRUTH TABLE Output |
|---|---|---|---|---|
| *NOT* | The output is 1 when the input is 0 and 0 when the input is 1. |  | 0<br>1 | 1<br>0 |
| *AND* | The output is 1 only when both inputs are 1, otherwise the output is 0. | | 0 0<br>0 1<br>1 0<br>1 1 | 0<br>0<br>0<br>1 |
| *OR* | The output is 0 only when both inputs are 0, otherwise the output is 1. | | 0 0<br>0 1<br>1 0<br>1 1 | 0<br>1<br>1<br>1 |
| *NAND* | The output is 0 only when both inputs are 1, otherwise the output is 0. | | 0 0<br>0 1<br>1 0<br>1 1 | 1<br>1<br>1<br>0 |
| *NOR* | The output is 1 only when both inputs are 0, otherwise the output is 0. | | 0 0<br>0 1<br>1 0<br>1 1 | 1<br>0<br>0<br>0 |
| *XOR* | The output is 1 only when the two inputs have different value, otherwise the output is 0. | | 0 0<br>0 1<br>1 0<br>1 1 | 0<br>1<br>1<br>0 |
| *XNOR* | The output is 1 only when the two inputs have the same value, otherwise the output is 0. | | 0 0<br>0 1<br>1 0<br>1 1 | 1<br>0<br>0<br>1 |

| GATE | CIRCUIT REPRESENTATION | MATRIX REPRESENTATION | TRUTH TABLE Input | TRUTH TABLE Output | BLOCH SPHERE |
|---|---|---|---|---|---|
| *I* Identity-gate: no rotation is performed. | —[I]— | $I = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$ | $\vert 0\rangle$<br>$\vert 1\rangle$ | $\vert 0\rangle$<br>$\vert 1\rangle$ |  |
| *X* gate: rotates the qubit state by $\pi$ radians (180°) about the x-axis. | —[X]— | $X = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$ | $\vert 0\rangle$<br>$\vert 1\rangle$ | $\vert 1\rangle$<br>$\vert 0\rangle$ | |
| *Y* gate: rotates the qubit state by $\pi$ radians (180°) about the y-axis. | —[Y]— | $Y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}$ | $\vert 0\rangle$<br>$\vert 1\rangle$ | $i\vert 1\rangle$<br>$-i\vert 0\rangle$ | |
| *Z* gate: rotates the qubit state by $\pi$ radians (180°) about the z-axis. | —[Z]— | $Z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$ | $\vert 0\rangle$<br>$\vert 1\rangle$ | $\vert 0\rangle$<br>$-\vert 1\rangle$ | |
| *S* gate: rotates the qubit state by $\frac{\pi}{2}$ radians (90°) about the z-axis. | —[S]— | $S = \begin{pmatrix} 1 & 0 \\ 0 & e^{i\frac{\pi}{2}} \end{pmatrix}$ | $\vert 0\rangle$<br>$\vert 1\rangle$ | $\vert 0\rangle$<br>$e^{i\frac{\pi}{2}}\vert 1\rangle$ | |
| *T* gate: rotates the qubit state by $\frac{\pi}{4}$ radians (45°) about the z-axis. | —[T]— | $T = \begin{pmatrix} 1 & 0 \\ 0 & e^{i\frac{\pi}{4}} \end{pmatrix}$ | $\vert 0\rangle$<br>$\vert 1\rangle$ | $\vert 0\rangle$<br>$e^{i\frac{\pi}{4}}\vert 1\rangle$ | |
| *H* gate: rotates the qubit state by $\pi$ radians (180°) about an axis diagonal in the x-z plane. This is equivalent to an X-gate followed by a $\frac{\pi}{2}$ rotation about the y-axis. | —[H]— | $H = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$ | $\vert 0\rangle$<br>$\vert 1\rangle$ | $\frac{\vert 0\rangle + \vert 1\rangle}{\sqrt{2}}$<br>$\frac{\vert 0\rangle - \vert 1\rangle}{\sqrt{2}}$ | |

| GATE | CIRCUIT REPRESENTATION | MATRIX REPRESENTATION | TRUTH TABLE Input | TRUTH TABLE Output |
|---|---|---|---|---|
| Controlled-NOT gate: apply an X-gate to the target qubit if the control qubit is in state $\vert 1\rangle$ |  | $CNOT = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix}$ | $\vert 00\rangle$<br>$\vert 01\rangle$<br>$\vert 10\rangle$<br>$\vert 11\rangle$ | $\vert 00\rangle$<br>$\vert 01\rangle$<br>$\vert 11\rangle$<br>$\vert 10\rangle$ |
| Controlled-phase gate: apply a Z-gate to the target qubit if the control qubit is in state $\vert 1\rangle$ |  | $cZ = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$ | $\vert 00\rangle$<br>$\vert 01\rangle$<br>$\vert 10\rangle$<br>$\vert 11\rangle$ | $\vert 00\rangle$<br>$\vert 01\rangle$<br>$\vert 10\rangle$<br>$-\vert 11\rangle$ |

- **Classical universal set**
  - **NOT, AND**
  - **NAND**
  - **…**
- **Quantum universal set**
  - **H, S, T, CNOT**
  - **…**

# Quantum Algorithm (Universal)



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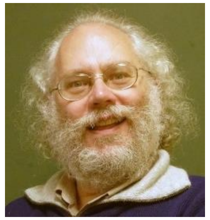
# Quantum Algorithms and Speed-Up

| Algorithm | Classical Time | Quantum Time | Speedup | Limitation |
|---|---|---|---|---|
| Simulation[1] (quantum chemistry) | $2^N$ (for N atoms) | $N^c$ | Exp. in space, polynomial in time | Mapping problem to qubits |
| Factoring[2] (+ related number theoretic) | $2^N$ (for N digits) | $N^3$ | Exponential | Classical runtime limit unproven |
| Linear systems[3] (Ax=b) | $2^N$ (for N digits) | ~N | Exponential | Strict conditions, e.g. sparse matrix |
| Optimization[4] | $2^N$ | ? | ? | Empirical |
| Search[5] (unsorted / unstructured data) | N | $\sqrt{N}$ | Polynomial ($\sqrt{N}$) | Data loading |


*Seth Lloyd*[1,3]
*MIT Mech. Eng. & Physics*


*Peter Shor*[2]
*MIT Math*

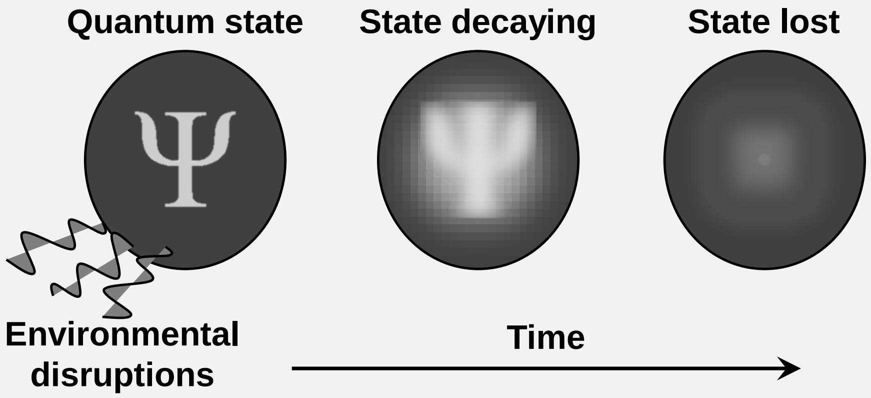

*Aram Harrow*[3]
*MIT Physics*


*Eddie Farhi*[4]
*MIT Physics, Google*


*Michael Sipser*[4]
*MIT Math*

# Decoherence & Gate Time

**Coherence time $t_{coh}$: The qubit's lifetime**



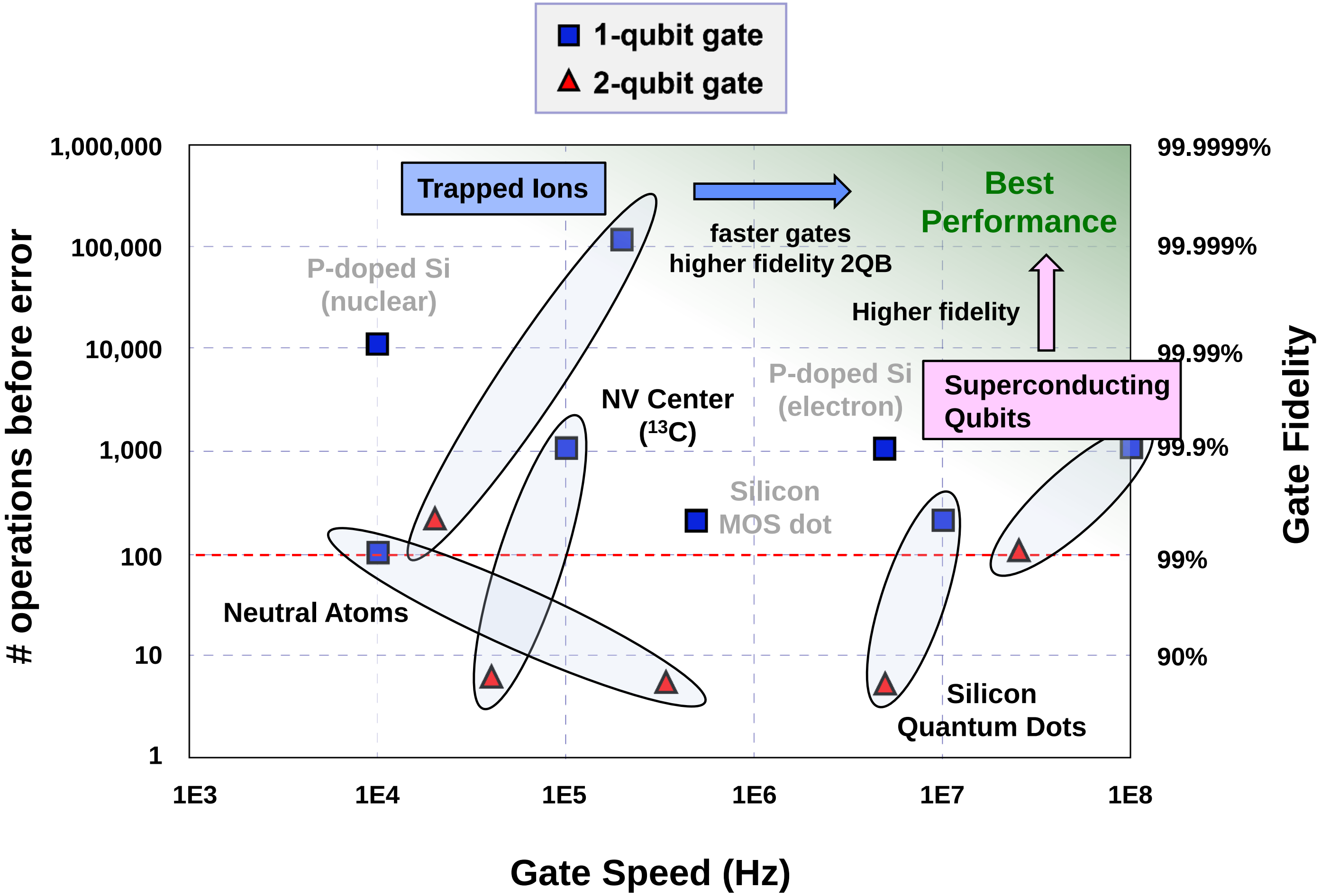

**Gate time $t_{gate}$: Time required for a single gate operation**

**Figure of Merit * : # of gates per coherence time = $t_{coh}/t_{gate}$**

( * Rigorous metric: gate & readout fidelity)

**Long coherence times are not sufficient, it's the number of gates before an error**

# Qubit Modalities

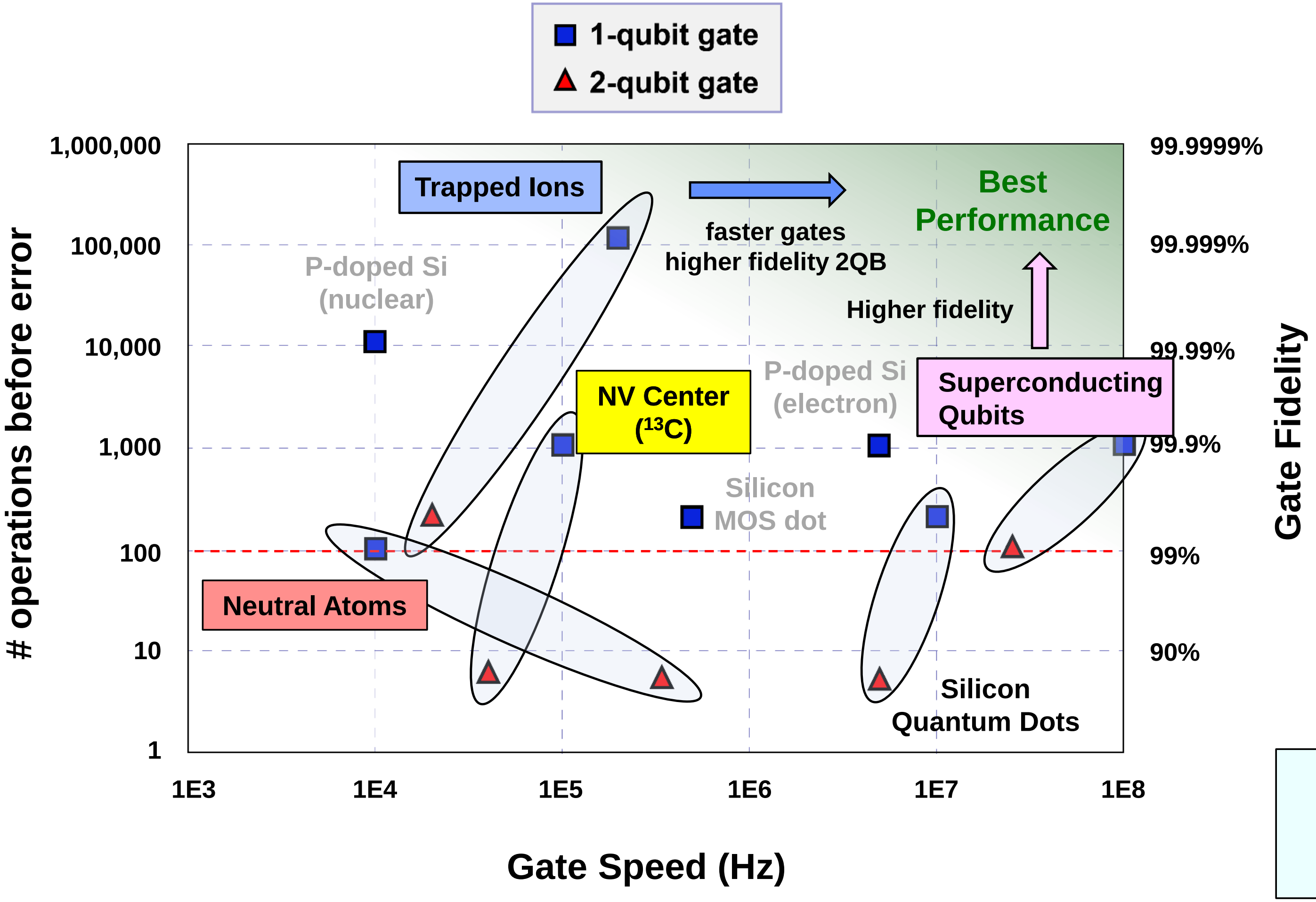



## MIT Campus / MIT Lincoln Lab


**and large teams at MIT & LL**

Thanks to: P. Cappellaro, J. Chiaverini, D. Englund, T. Ladd, A. Morello, J. Petta, M. Saffman, J. Sage

# Qubit Modalities




*Vladin Vuletic*
*MIT Physics*

*Wolfgang Ketterle*
*MIT Physics*

*Martin Zwierlein*
*MIT Physics*

*Dirk Englund*
*EECS*

*Paola Cappellaro*
*NSE*

*Danielle Braje*
*QuIIN*

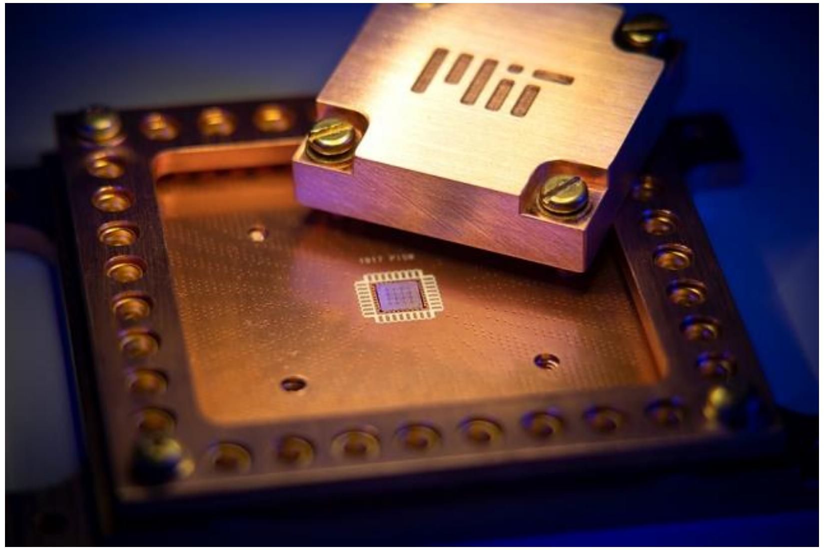
**Many candidate technologies under development to realize the promise of quantum computation**

**Thanks to: P. Cappellaro, J. Chiaverini, D. Englund, T. Ladd, A. Morello, J. Petta, M. Saffman, J. Sage**

# Outline

- Introduction to quantum computing
- Superconducting qubits
- Engineering quantum systems
- Algorithms and 3D integration

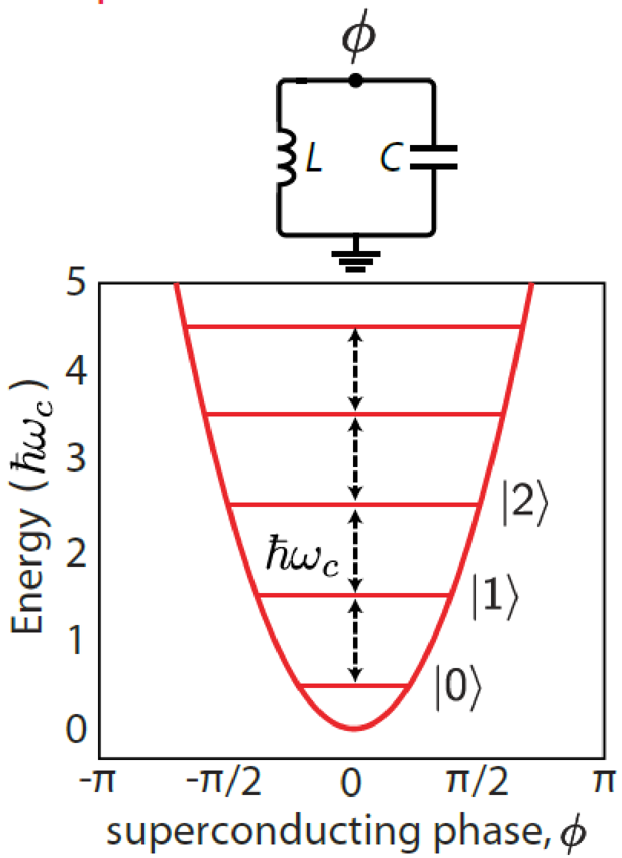
**32-pin Package**
**5x5 $mm^2$ silicon qubit chip**



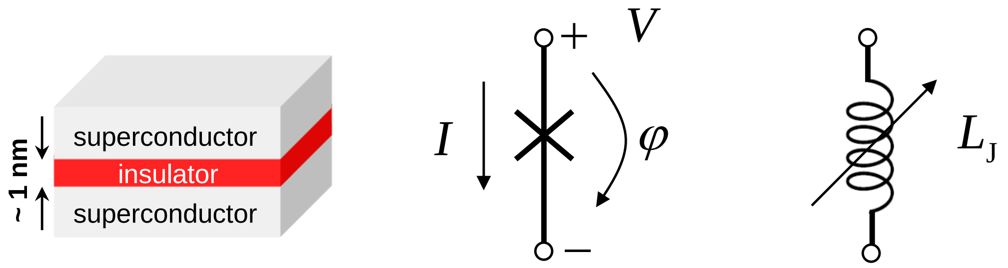
Y. Sung, …, WDO, Nature Communications (2019)

# How to Build a Superconducting Qubit

quantum harmonic oscillator



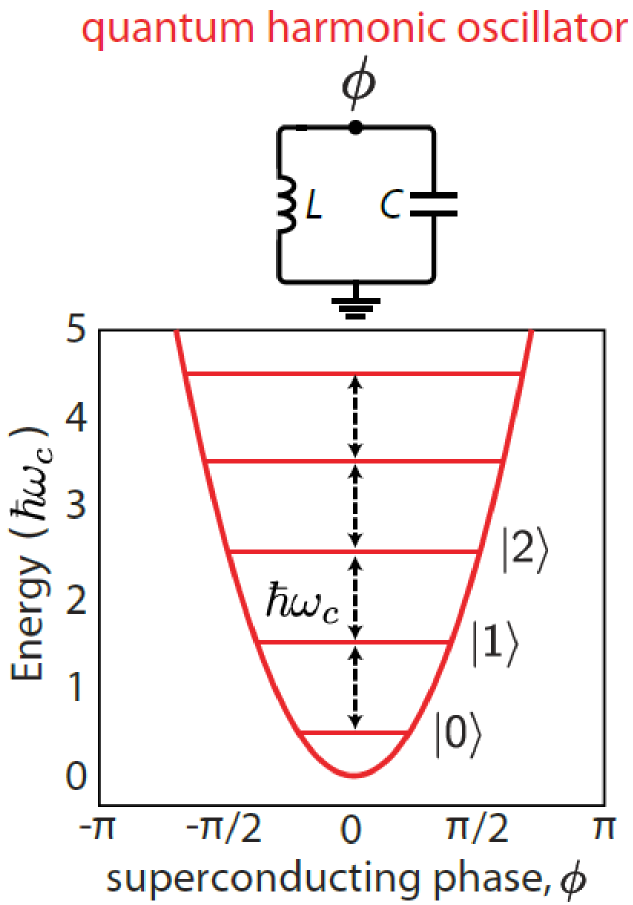

**Josephson Junction → nonlinear inductor**

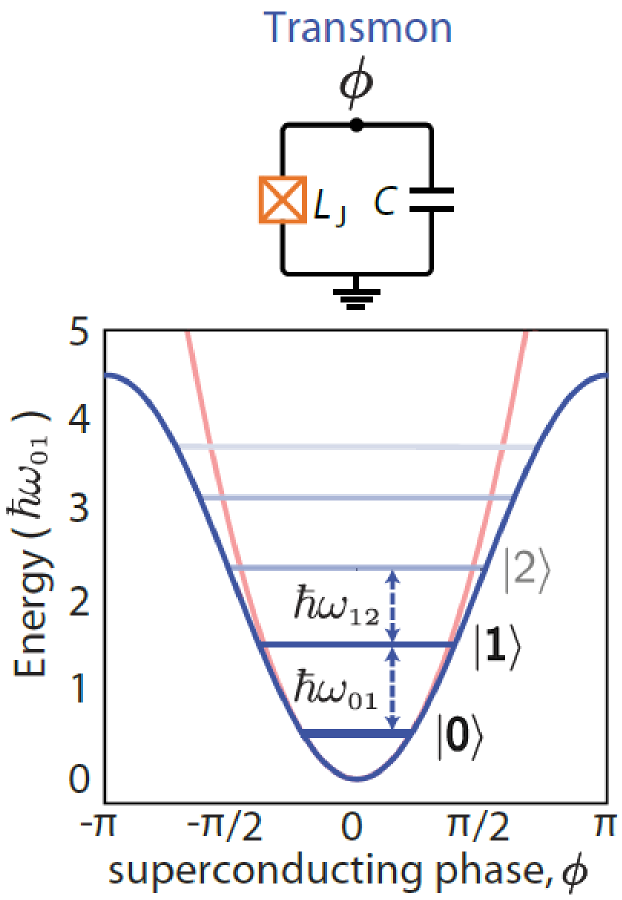





P. Krantz, WDO, et al., Appl. Phys. Rev. 6, 021318 (2019); arXiv:1905.13641

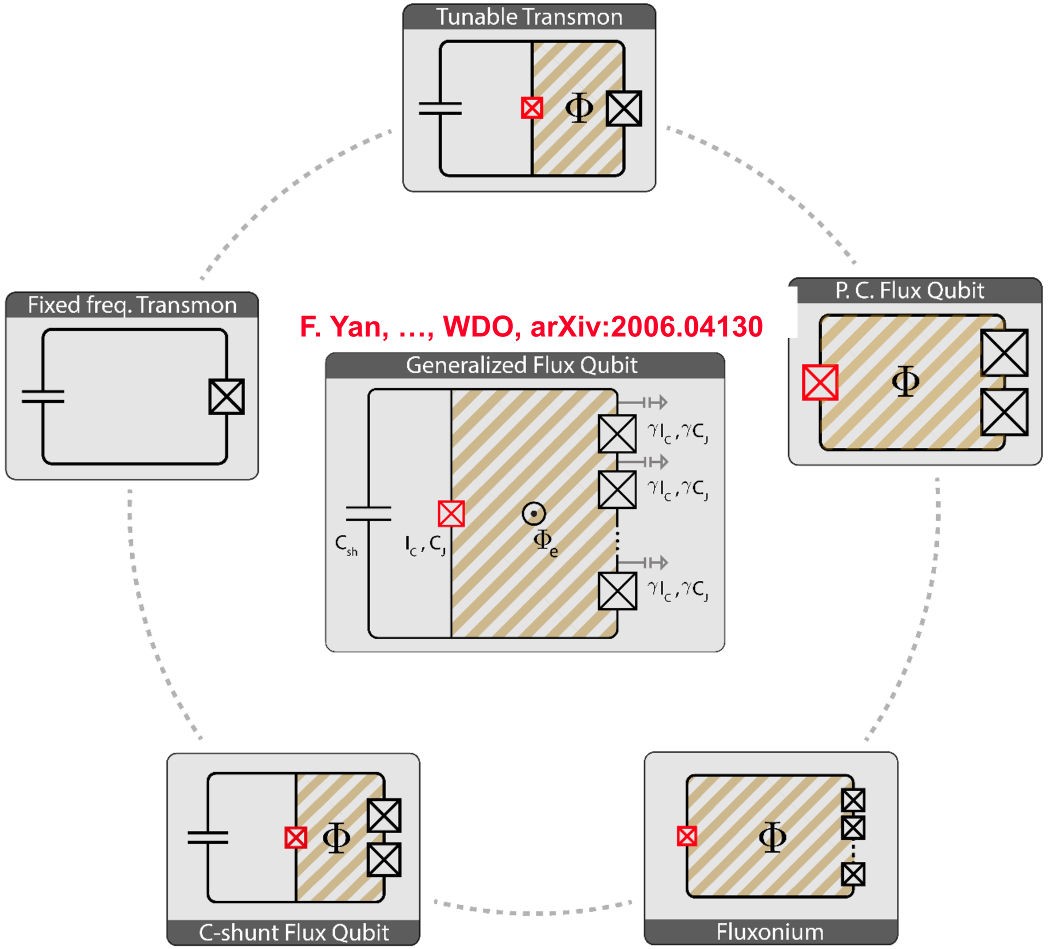
# How to Build a Superconducting Qubit




P. Krantz, WDO, et al., Appl. Phys. Rev. 6, 021318 (2019); arXiv:1905.13641

# Design Space for Superconducting Qubits




Koch et al., *PRA* (2007)
Yan,…,WDO, *Nature Comm.* (2016)

Orlando et al., *PRB* (1999)
Manucharyan et al., *Science* (2009)

**Design Parameters:**

- $I_C$: critical current of small junction
- $C_J$: junction self-capacitance
- $C_{sh}$: shunt capacitance
- $N$: # of array junctions / shunt inductance
- $\gamma$: big/small JJ size ratio

**Qubit Properties:**

- $E_{01}$: Qubit frequency (3-6 GHz)
- $A$: Anharmonicity
- $T^{\Phi}$: Sensitivity to flux-noise
- $T^{Q}$: Sensitivity to charge-noise
- $T^{\kappa}$: Sensitivity to cavity-loss
- $T^{\delta}$: Sensitivity to quasiparticles

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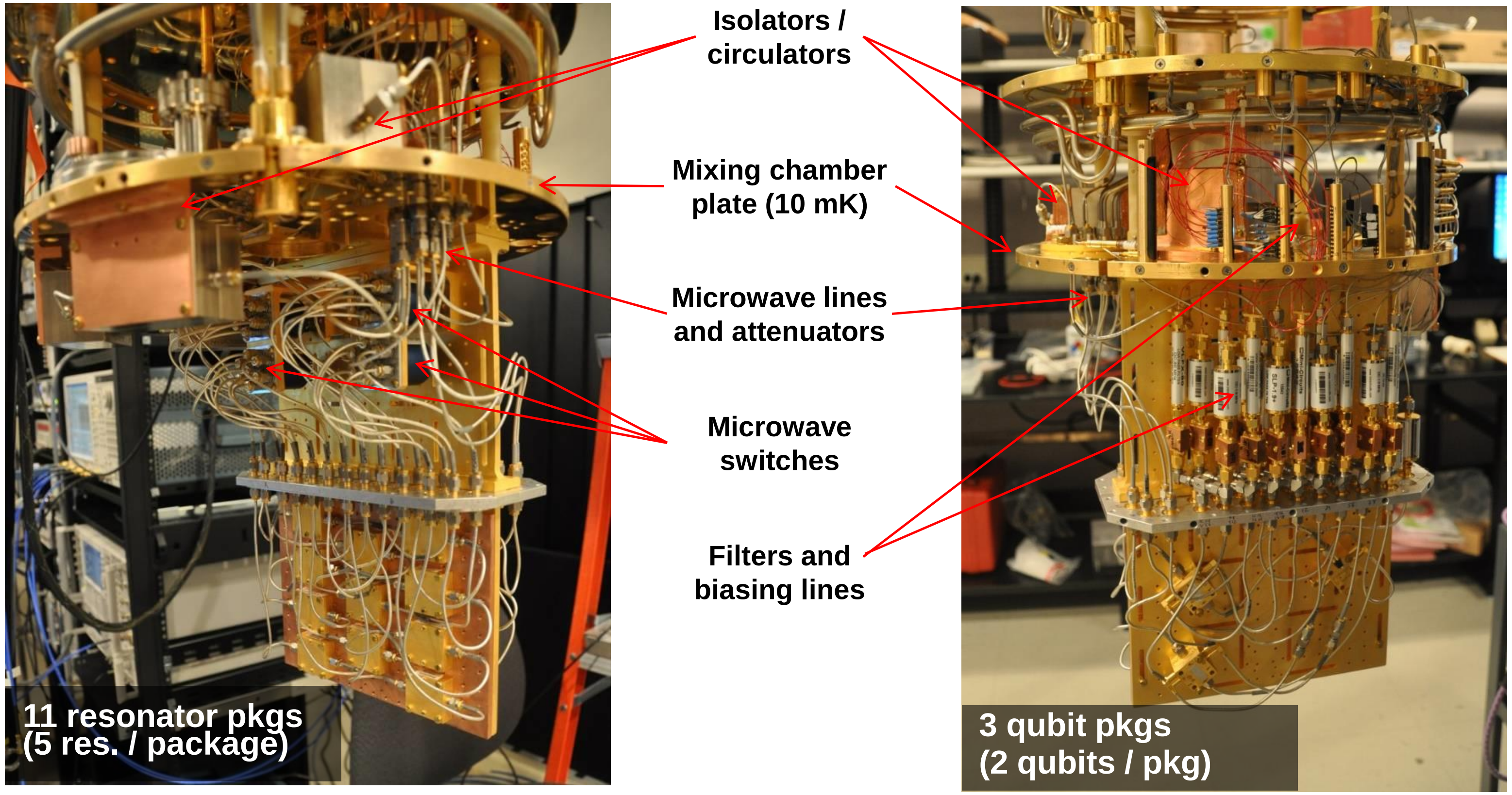
# Cryogenic Engineering




**5 GHz has a thermal energy of 250 mK → operate at 20 mK.**

**Commercially available, turn-key dilution refrigerators**

S. Krinner, et al., EPJ Quantum Technology 6, 2 (2019)

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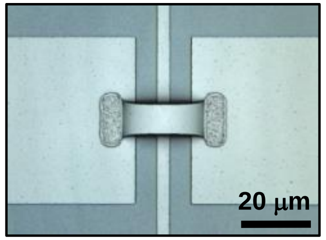
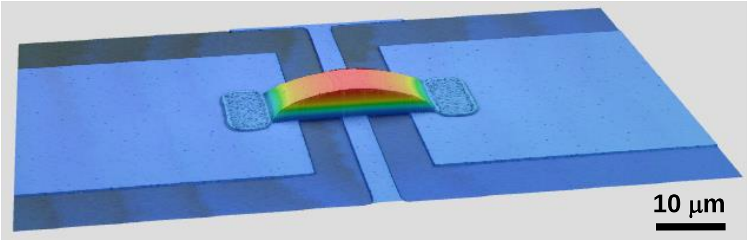
# Fabrication Engineering

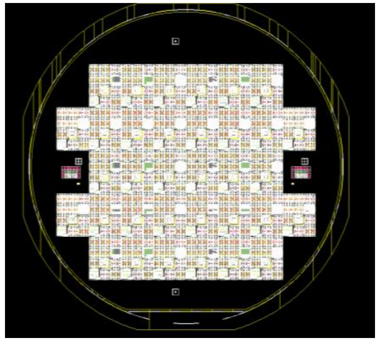
- **Manufactured/designed qubits**
- **Lithographic scalability (silicon)**

**High-coherence air-gap cross-overs (optical microscope and confocal images)**

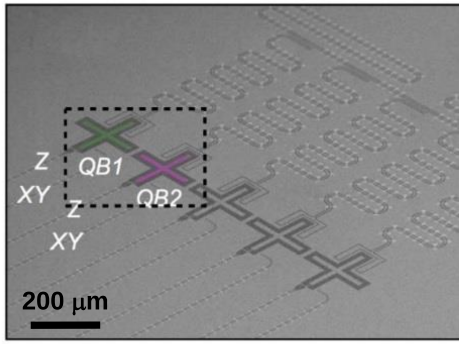


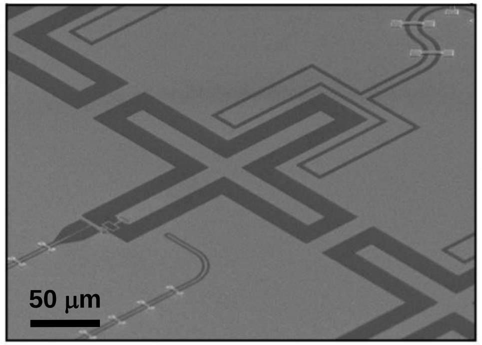

**200-mm wafers (49 Reticles × 16 chips)**



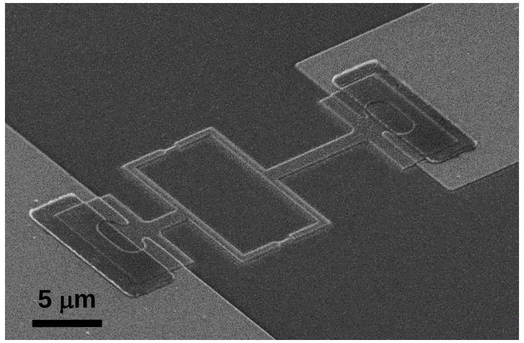
**5-Transmon chip with readout resonators**



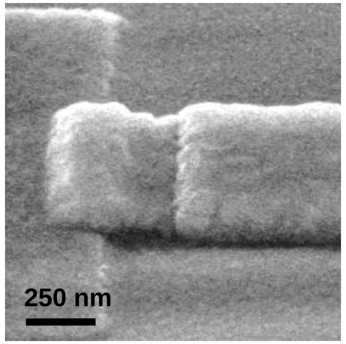

**Transmon capacitor and control lines**




**Tunable transmon qubit loop with junctions**



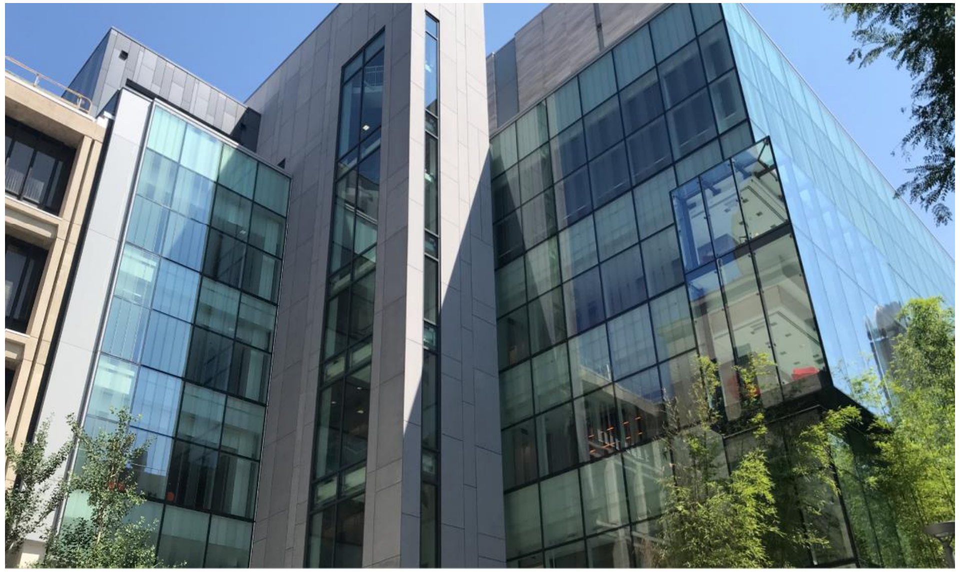

**Josephson junctions (aluminum)**



# Materials and Fabrication Engineering

## MIT.nano Laboratory

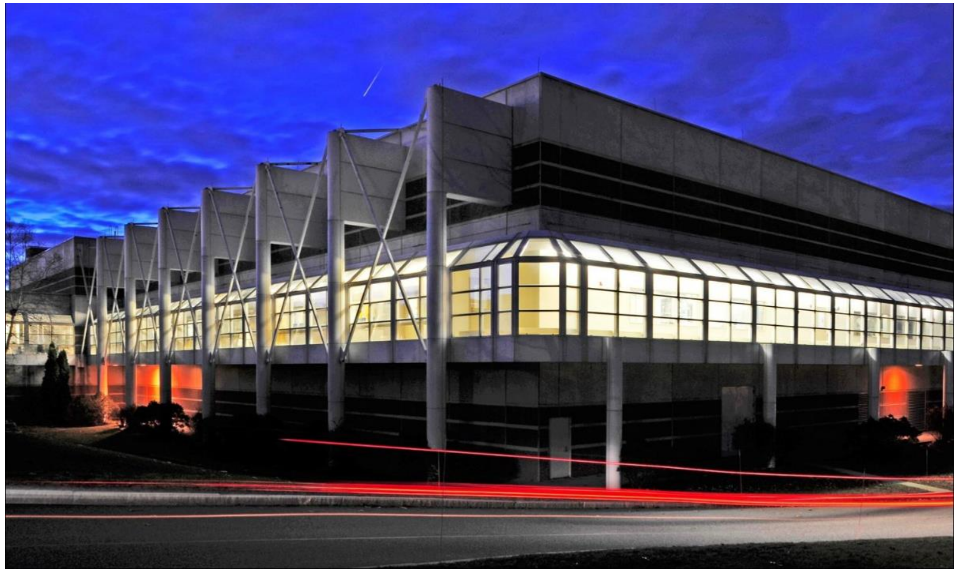
**>2x larger than other US academic facilities**



**Novel, rapid-development processes:**
**→ exploratory research & prototypes**
**(50 mm, 200 mm wafers)**

## LL Microelectronics Laboratory (ML)

**ISO-9001 Certified, DoD Trusted Foundry**

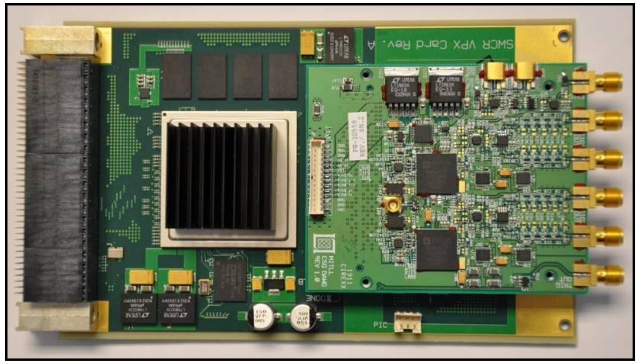


**High-yield, reproducible processes:**
**→ larger-scale development & testbeds**
**(200 mm wafers)**

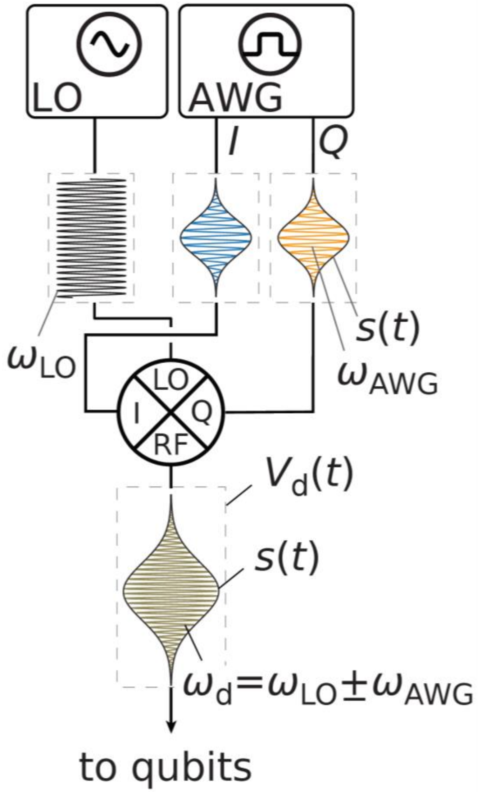
# Microwave Engineering and Control

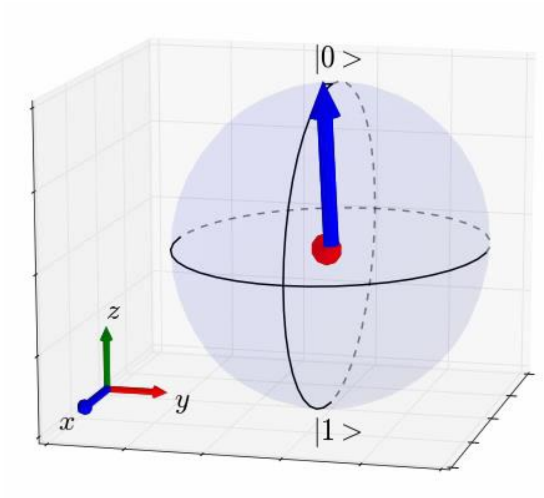
- **Manufactured/designed qubits**
- **Lithographic scalability (silicon)**
- **RF and microwave control**
- **100 MHz gate operations**

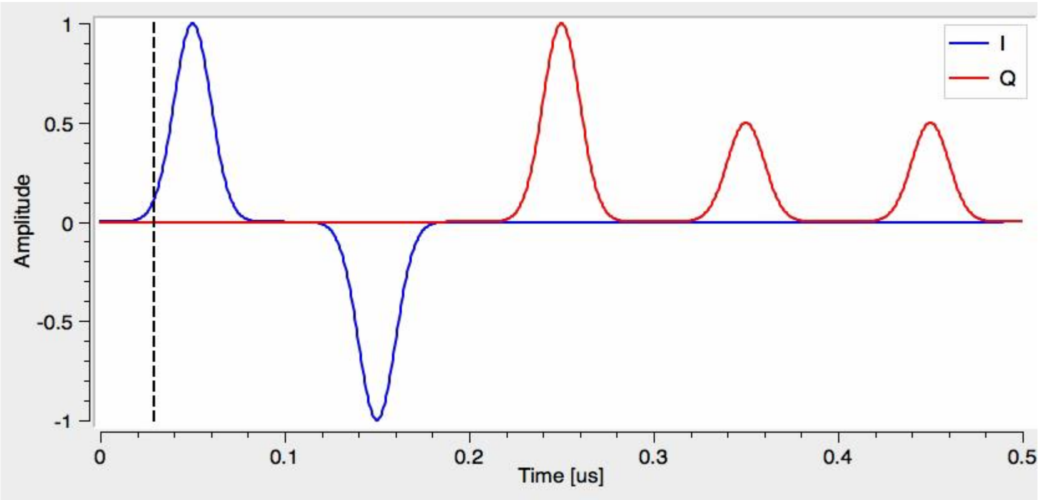
**Dual-Channel, 2GS/s, 14-bit AWG**



**Qubit Control via Microwave Pulses**




**I: in-phase (0⁰) → x axis**

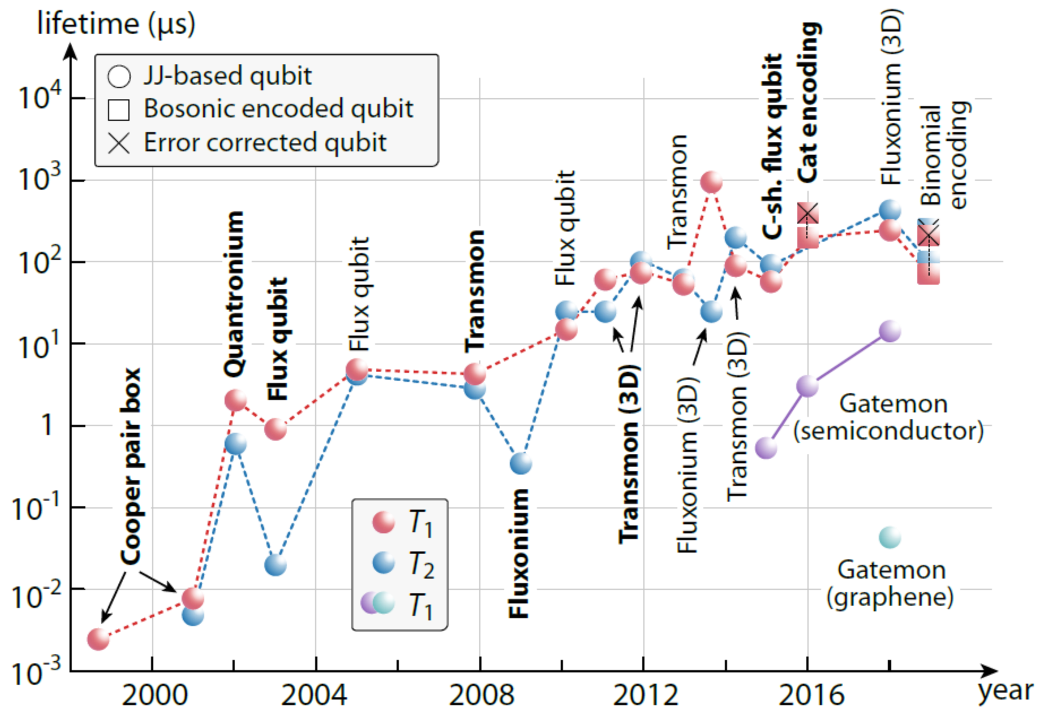
**Q: quadrature (90⁰) → y axis**

# Engineering Improved Coherence

- **Remarkable improvement in $T_{1,2}$**
  - **Materials**
  - **Fabrication**
  - **Design**

- **Major qubit types at MIT & LL**
  - **Flux qubit: $T_2$ = 23 us**
  - **2D transmon: $T_2$ = 100 us**
  - **3D transmon: $T_2$ = 150 us**
  - **C-shunt flux qubit: $T_2$ = 100 us**
  - **Gatemon (C): $T_2$ = 50 ns**

**“Moore’s Law” for $T_2$**



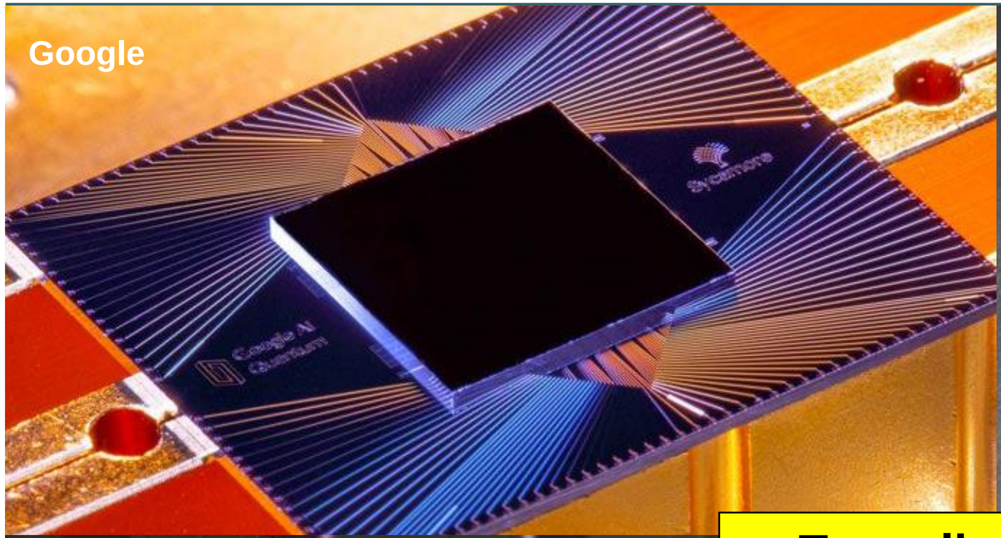

**Remarkable improvement in coherence from improvements to materials, fabrication, and design**

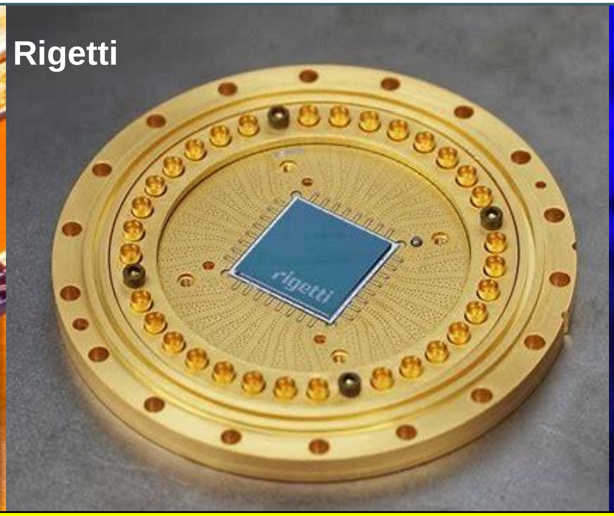
M. Kjaergaard, WDO, et al., arXiv:1905.13641

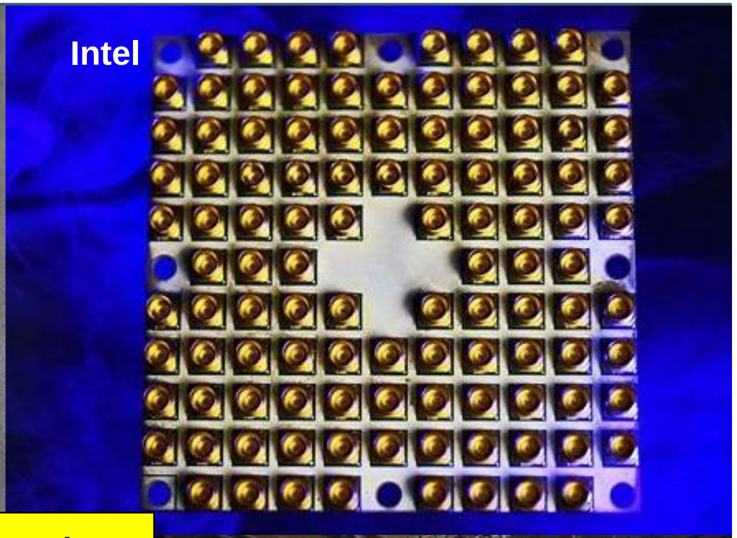
P. Krantz, WDO, et al., Appl. Phys. Rev. 6, 021318 (2019); arXiv:1905.13641
WDO & Welander, MRS Bulletin (2013)

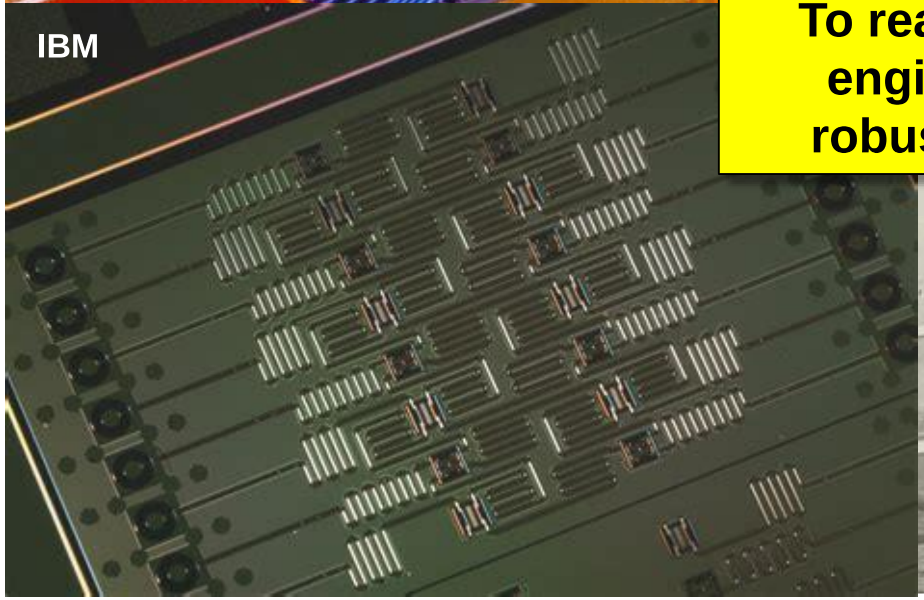
IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), No. 49, March 2021.
Plenary presentation Wk2P4 given at the virtual ASC 2020, November 4, 2020.

# Nascent Commercial Quantum Processors

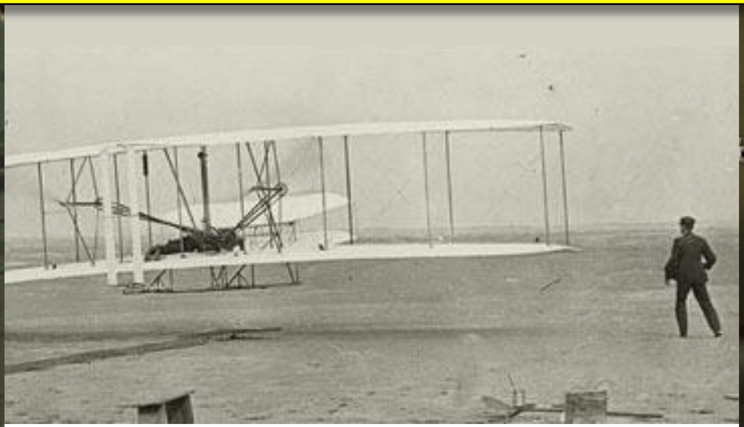


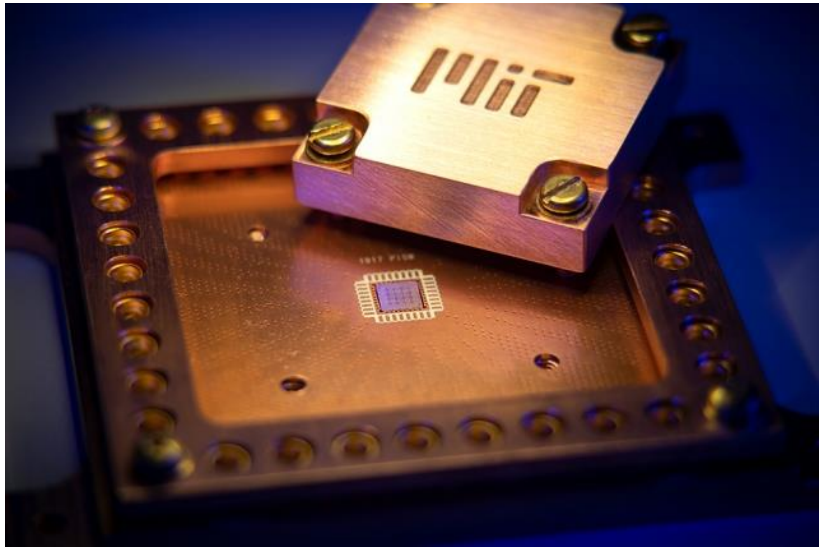

**To realize the promise of QC, we must engineer quantum systems that are robust, reproducible, and extensible.**



# Outline

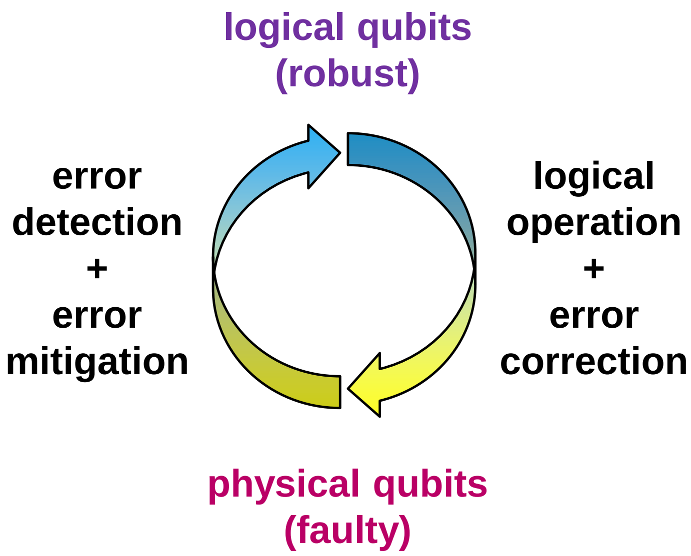
- Introduction to quantum computing
- Superconducting qubits
- ➡ Engineering quantum systems
- Algorithms and 3D integration

**32-pin Package**
**5x5 mm$^2$ silicon qubit chip**

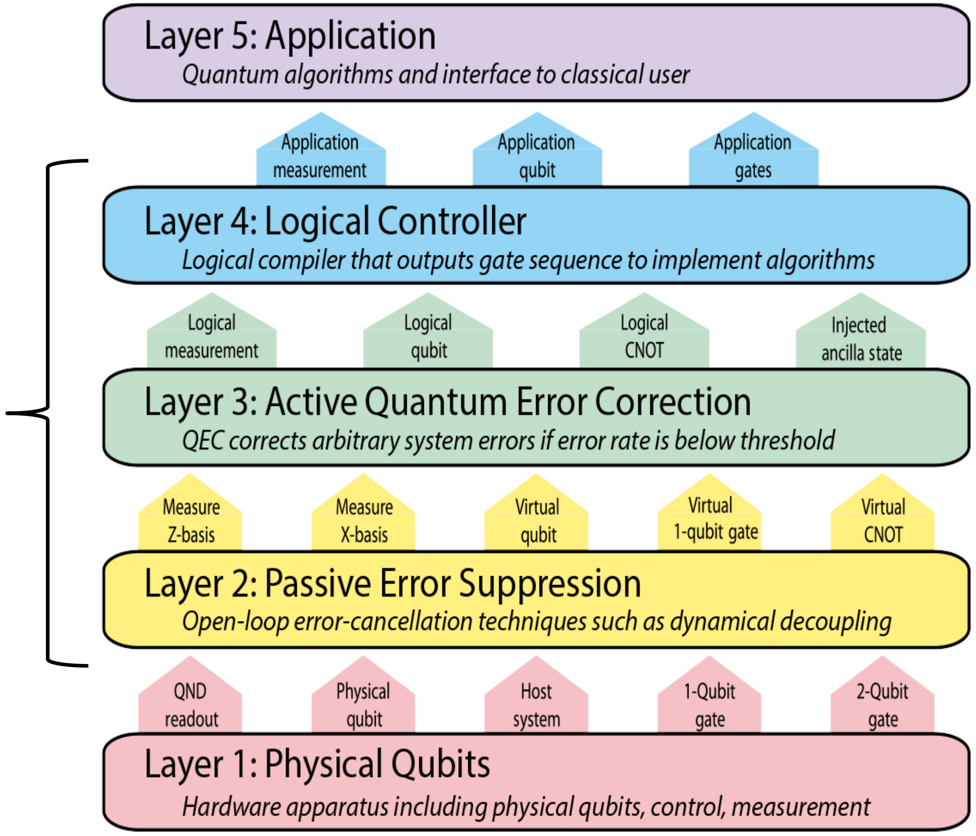


Y. Sung, …, WDO, Nature Communications (2019)

# Architectural Layers of a QIP




## Layered Architecture




N.C. Jones PRX 2, 031007 (2012)

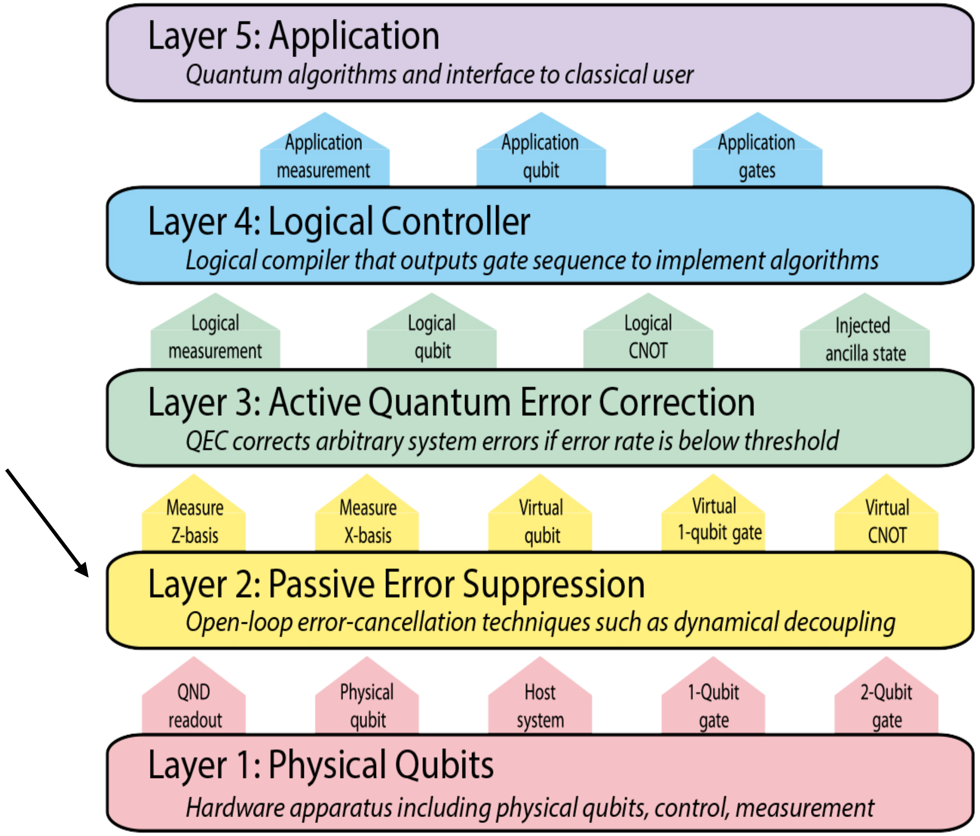
IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), No. 49, March 2021.
Plenary presentation Wk2P4 given at the virtual ASC 2020, November 4, 2020.

# Architectural Layers of a QIP

## Engineered Error Mitigation: Dynamical Decoupling

### Eg. Lacrosse Cradling

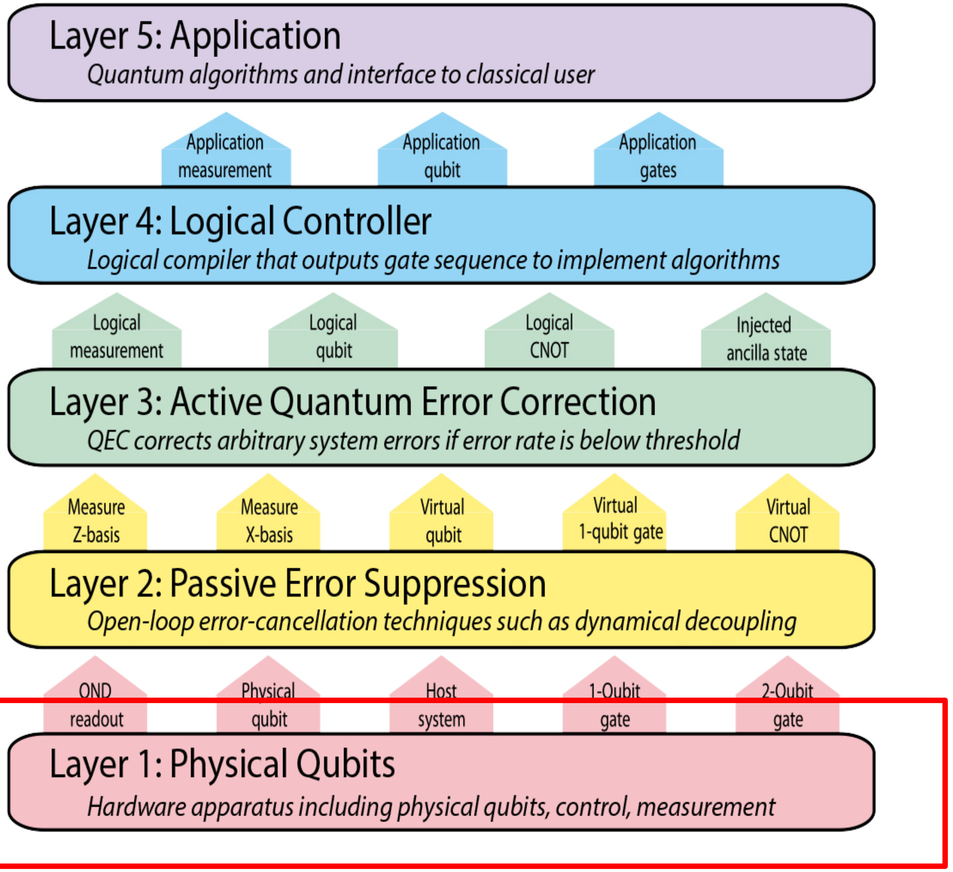
## Layered Architecture




N.C. Jones PRX 2, 031007 (2012)

# Lacrosse in the Presence of Noise

## Layered Architecture




N.C. Jones PRX 2, 031007 (2012)

IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), No. 49, March 2021.
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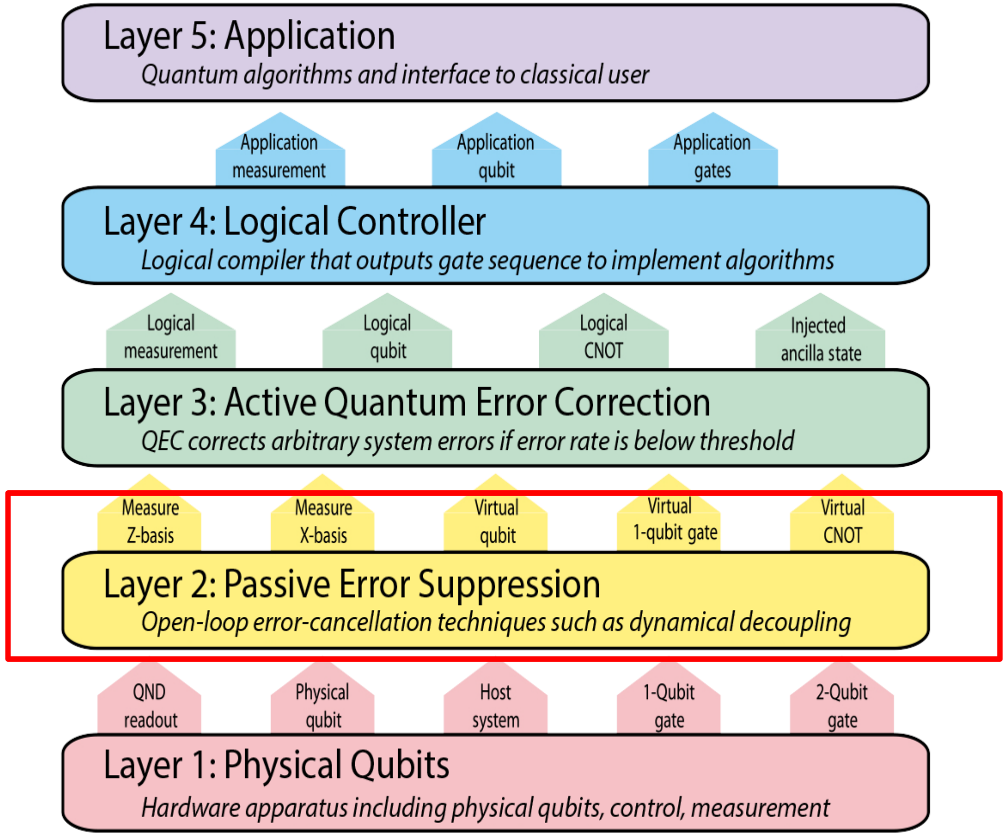
# Dynamical Decoupling from Running "Noise"

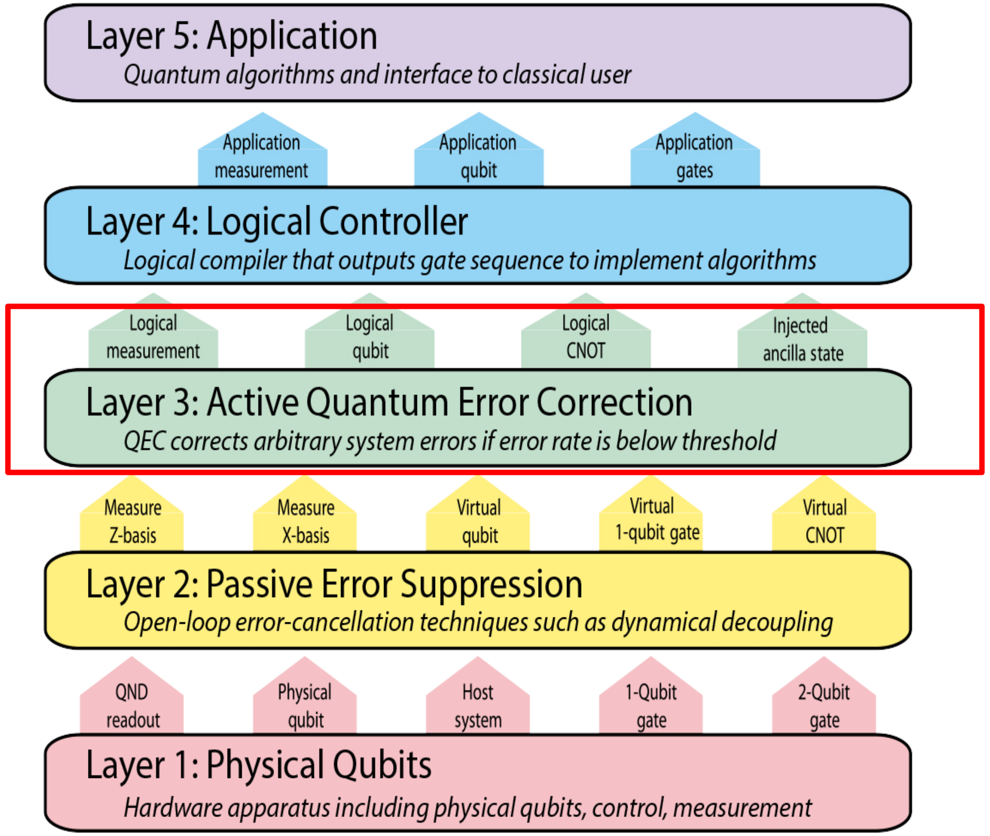
## Layered Architecture




N.C. Jones PRX 2, 031007 (2012)

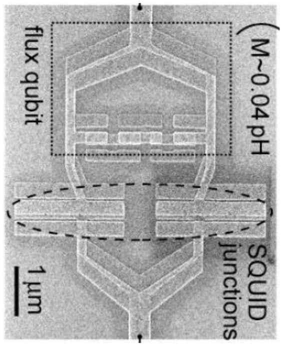
# "Active Error Correction" in Lacrosse

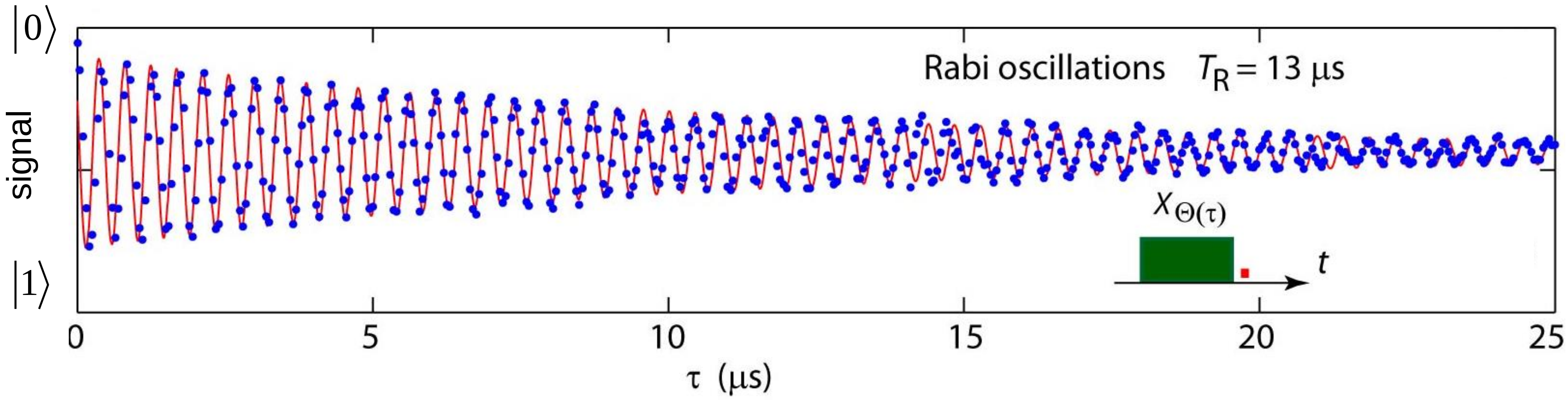
## Layered Architecture



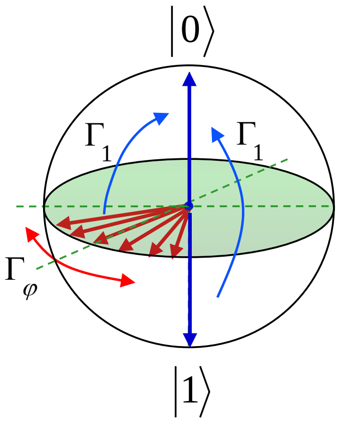

N.C. Jones PRX 2, 031007 (2012)

# Coherence Times




- **Relaxation rate:** $\Gamma_1 = 1/T_1$
- **Decoherence rate:** $\Gamma_2 = \frac{1}{T_2} = \frac{1}{2T_1} + \frac{1}{T_\varphi}$
- **Dephasing rate:** $\Gamma_\varphi = 1/T_\varphi$




$T_1 = 12\ \mu s$

$T_2 = 2.5\ \mu s$

**Can we improve the dephasing time?**

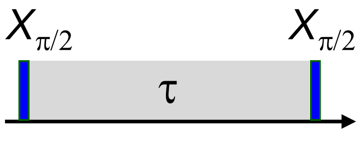


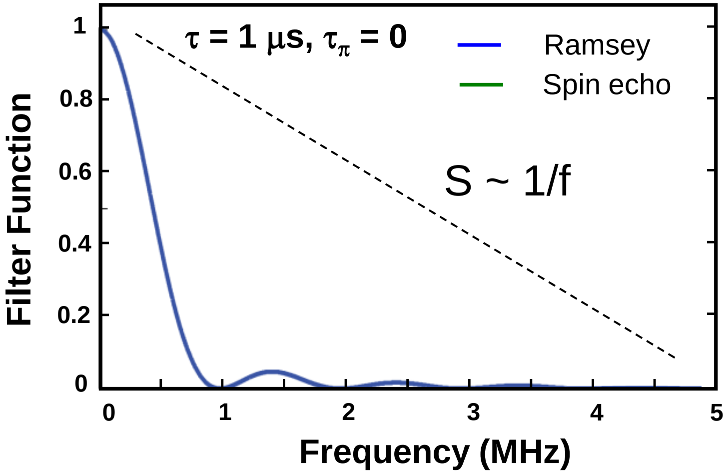

**J. Bylander, …, WDO, Nature Physics 7, 565 (2011)**

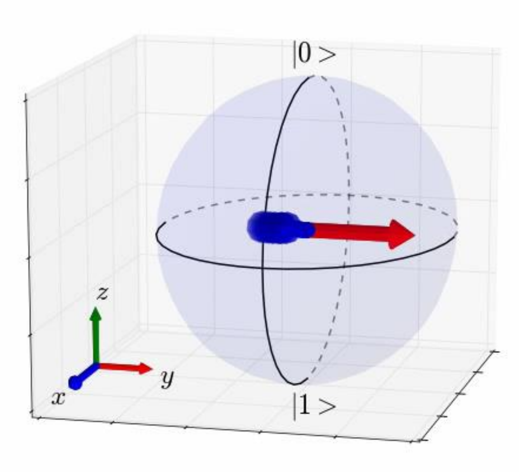
# Dynamical Decoupling:
## Noise Shaping Filters

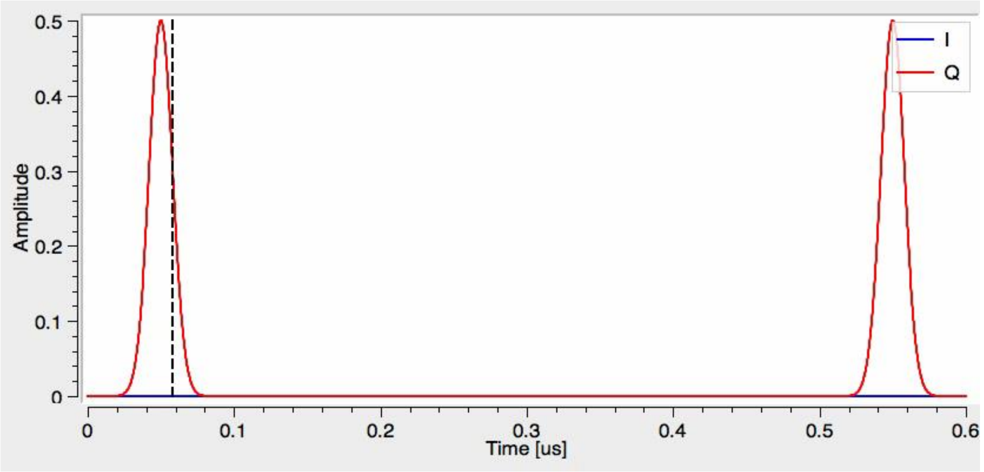
NO Dynam. Decoup.

(Ramsey, N=0)






J. Bylander, …, WDO, Nature Physics 7, 565 (2011)

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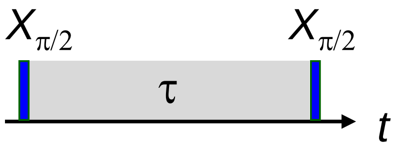
# Dynamical Decoupling:
## Noise Shaping Filters with 1 $\pi$-pulse

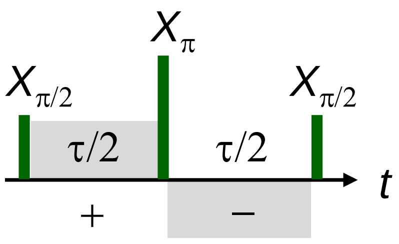
NO Dynam. Decoup.

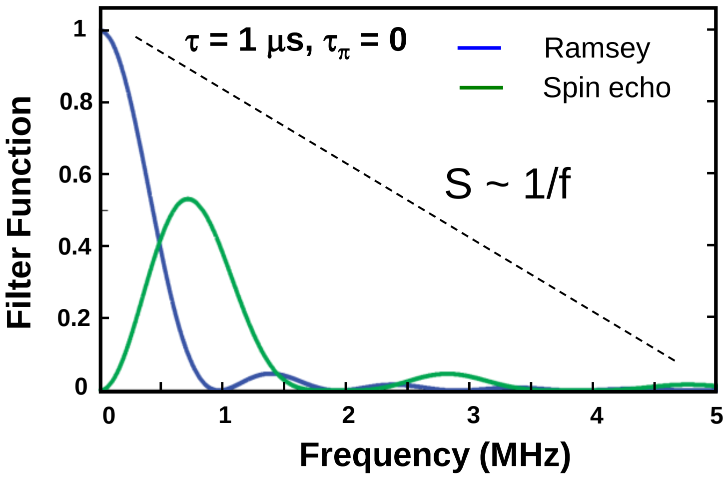
(Ramsey, N=0)

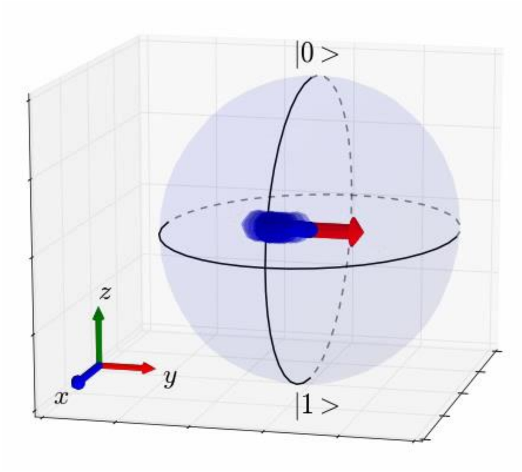


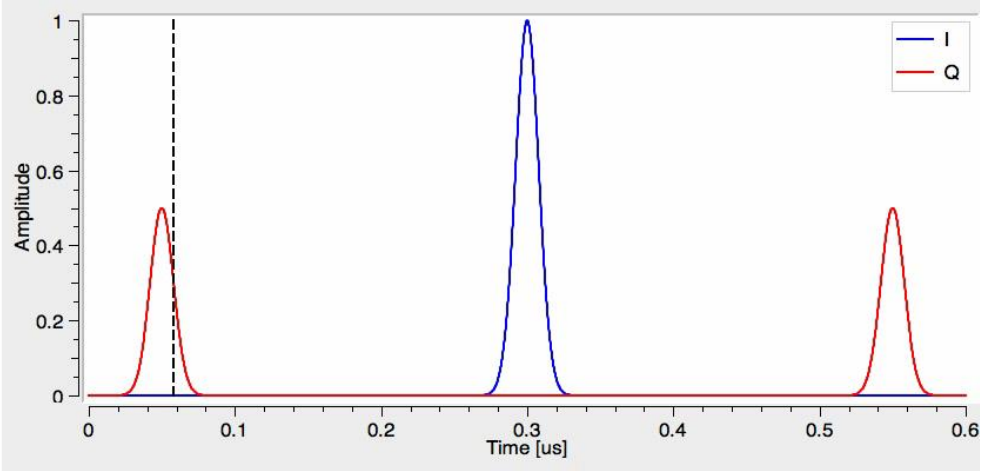

WITH Dynam. Decoup.

(spin echo, N=1)







J. Bylander, …, WDO, Nature Physics 7, 565 (2011)

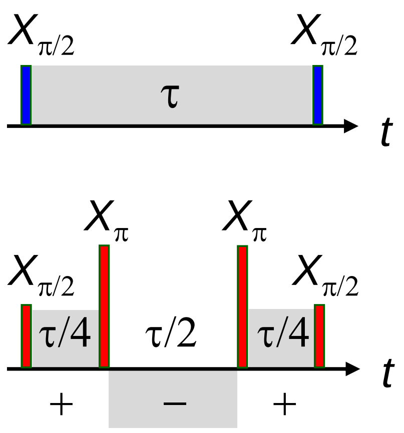
# Dynamical Decoupling:
## Noise Shaping Filters with 2 $\pi$-pulses

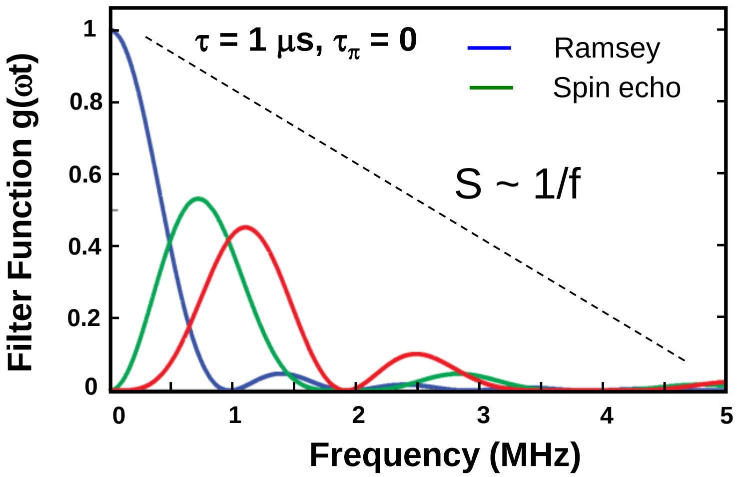
NO Dynam. Decoup.

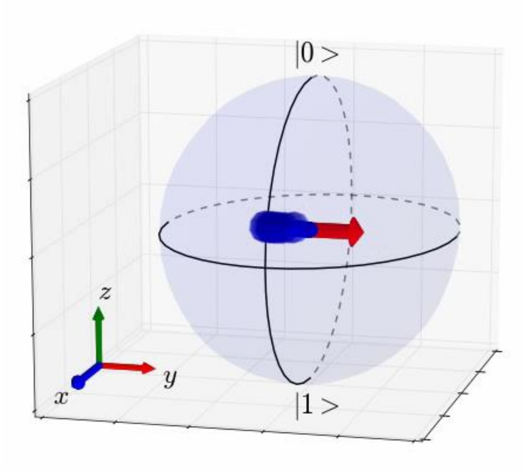
(Ramsey, N=0)

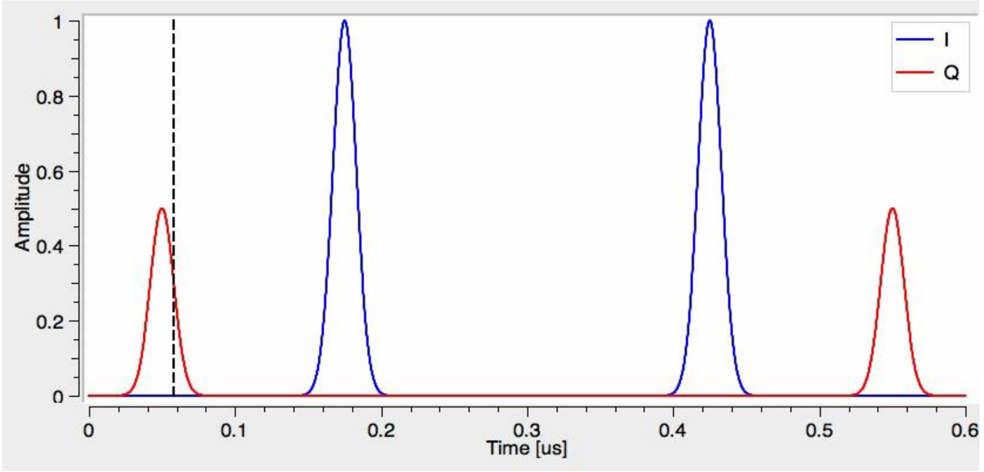
WITH Dynam. Decoup.

(CPMG, N=2)



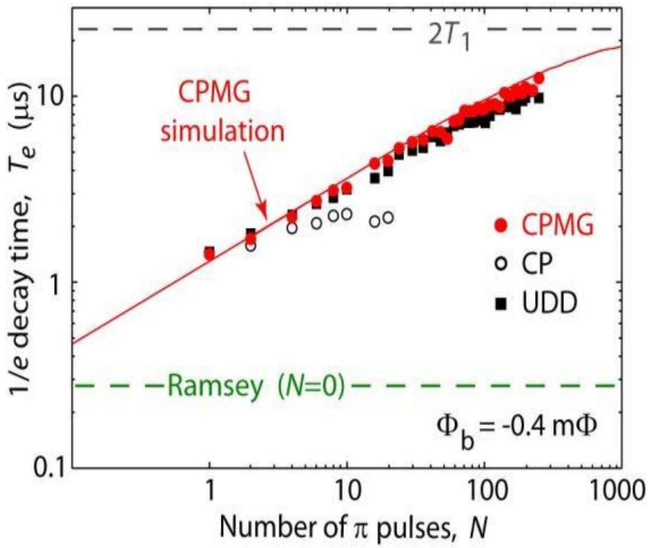



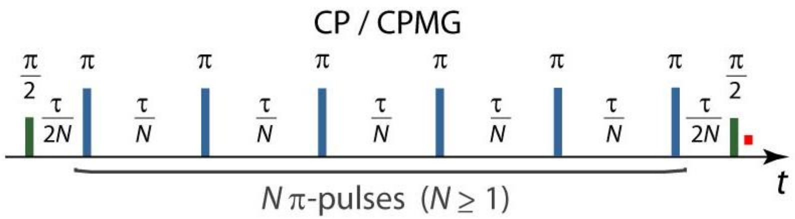

J. Bylander, …, WDO, Nature Physics 7, 565 (2011)

# Dynamical Decoupling:
## Noise Shaping Filters with $N$ $\pi$-pulses

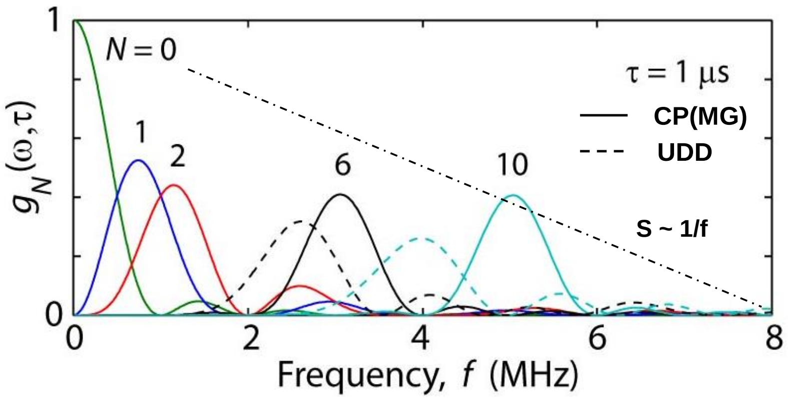
### Engineered Error Mitigation: Dynamical Decoupling
**(improves the physical qubit error rate)**




### Carr – Purcell (– Meiboom – Gill) Sequence



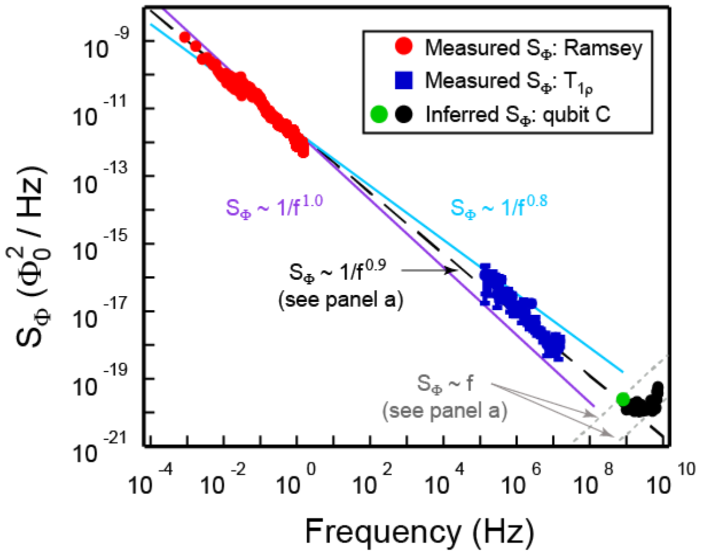

### Noise-Shaping Filter Functions




**J. Bylander, …, WDO, Nature Physics 7, 565 (2011)**

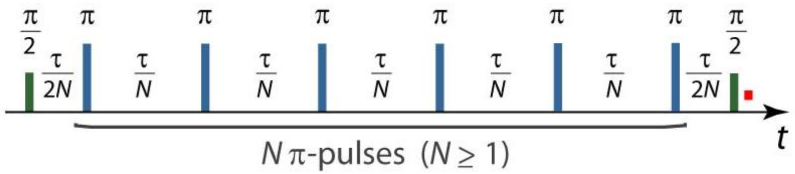
# Noise Spectroscopy

## Qubit Noise Spectroscopy
## Filter Engineering & Optimal Control

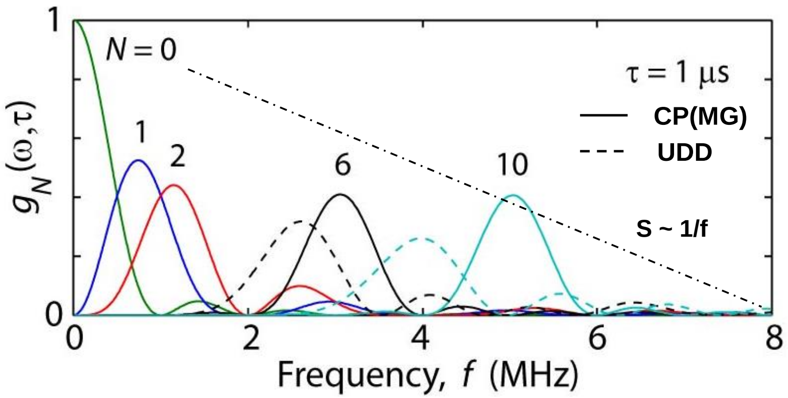



**Y. Sung, …, WDO, Nature Communications 10, 3715 (2019)**
**F. Yan, …, WDO, Nature Communications 7, 12964 (2016)**
**F. Yan , …, WDO, Nature Communications 4, 2337 (2013)**

## Carr – Purcell (– Meiboom – Gill) Sequence




## Noise-Shaping Filter Functions

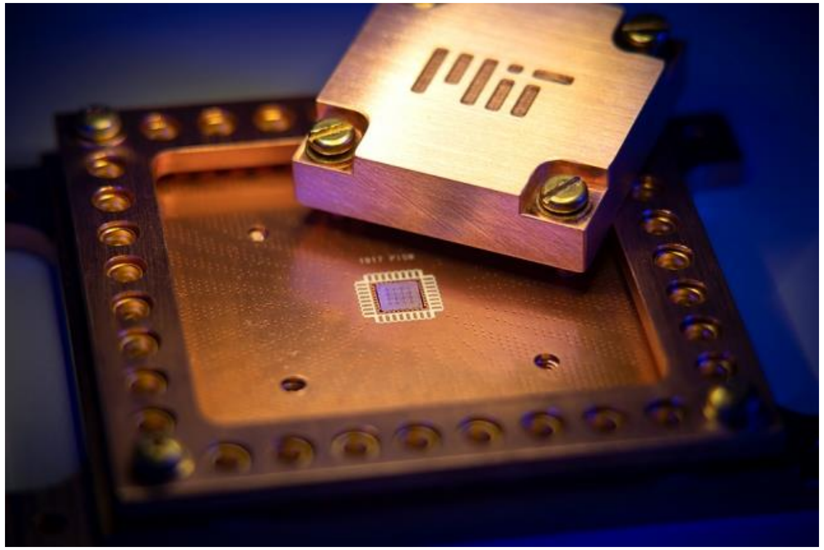



**J. Bylander, …, WDO, Nature Physics 7, 565 (2011)**

# Outline

- Introduction to quantum computing
- Superconducting qubits
- Engineering quantum systems
- Algorithms and 3D integration

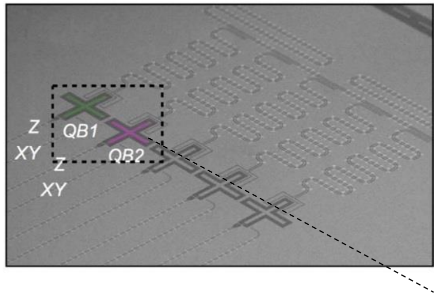
**32-pin Package**
**5x5 mm$^2$ silicon qubit chip**

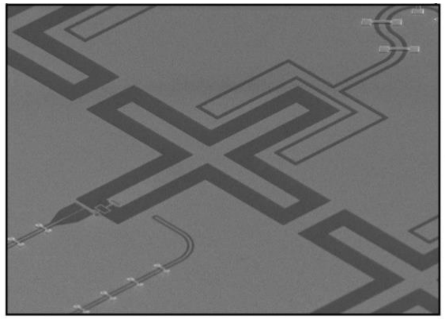


Y. Sung, …, WDO, Nature Communications (2019)

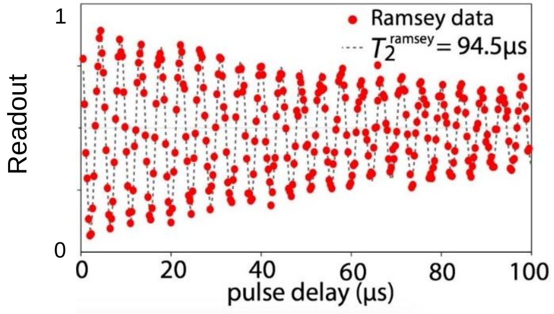
# Gate Model Superconducting Qubits

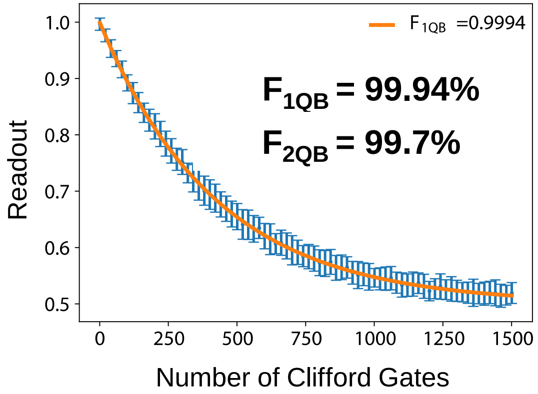
## Superconducting Qubits



## Coherence & Gate Fidelity

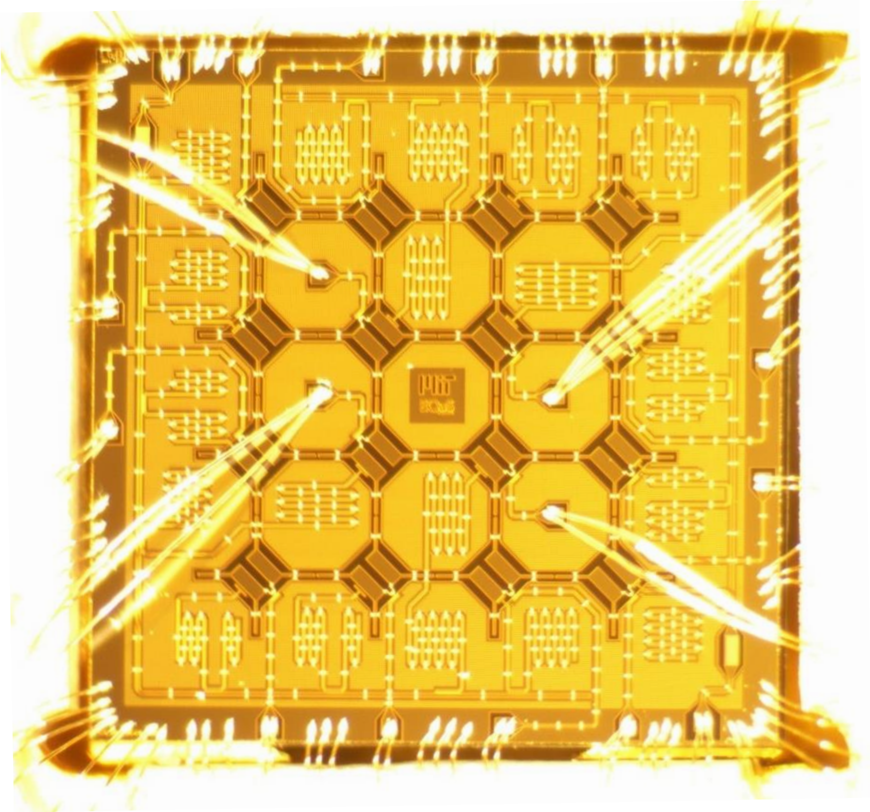



M. Kjaergaard, M. Schwartz, …, WDO, arXiv:2001.08838

## 2D Arrays of Qubits

Lattices, Error Propagation, Coherent Errors, …

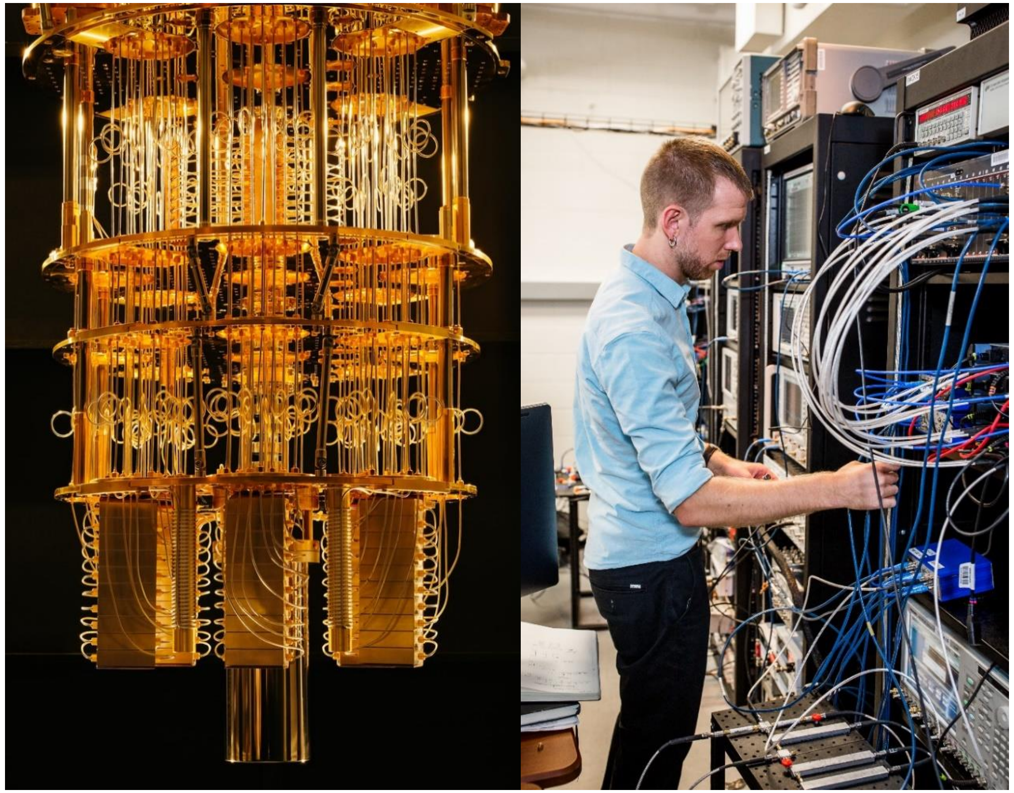


Y. Yanay, …, WDO, C. Tahan, arXiv:1910.00933
Accepted to npj Quantum Information (2020)

# 3D Integrated Superconducting Qubit Platform

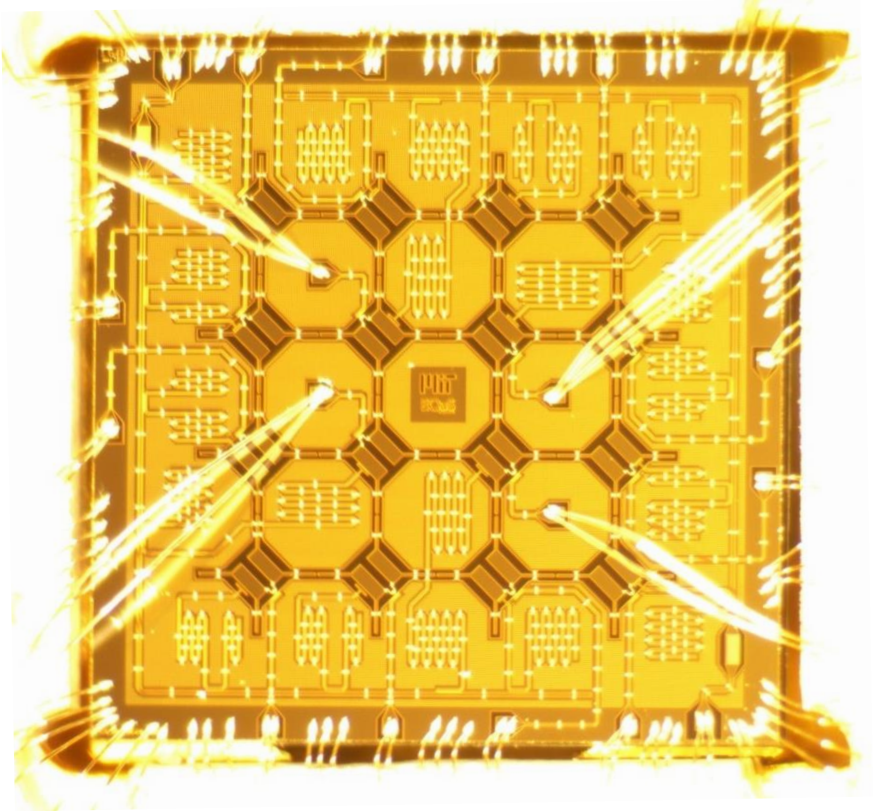
## 64-Qubit Quantum Testbed

**Building in 2020**



## 2D Arrays of Qubits

**Lattices, Error Propagation, Coherent Errors, …**

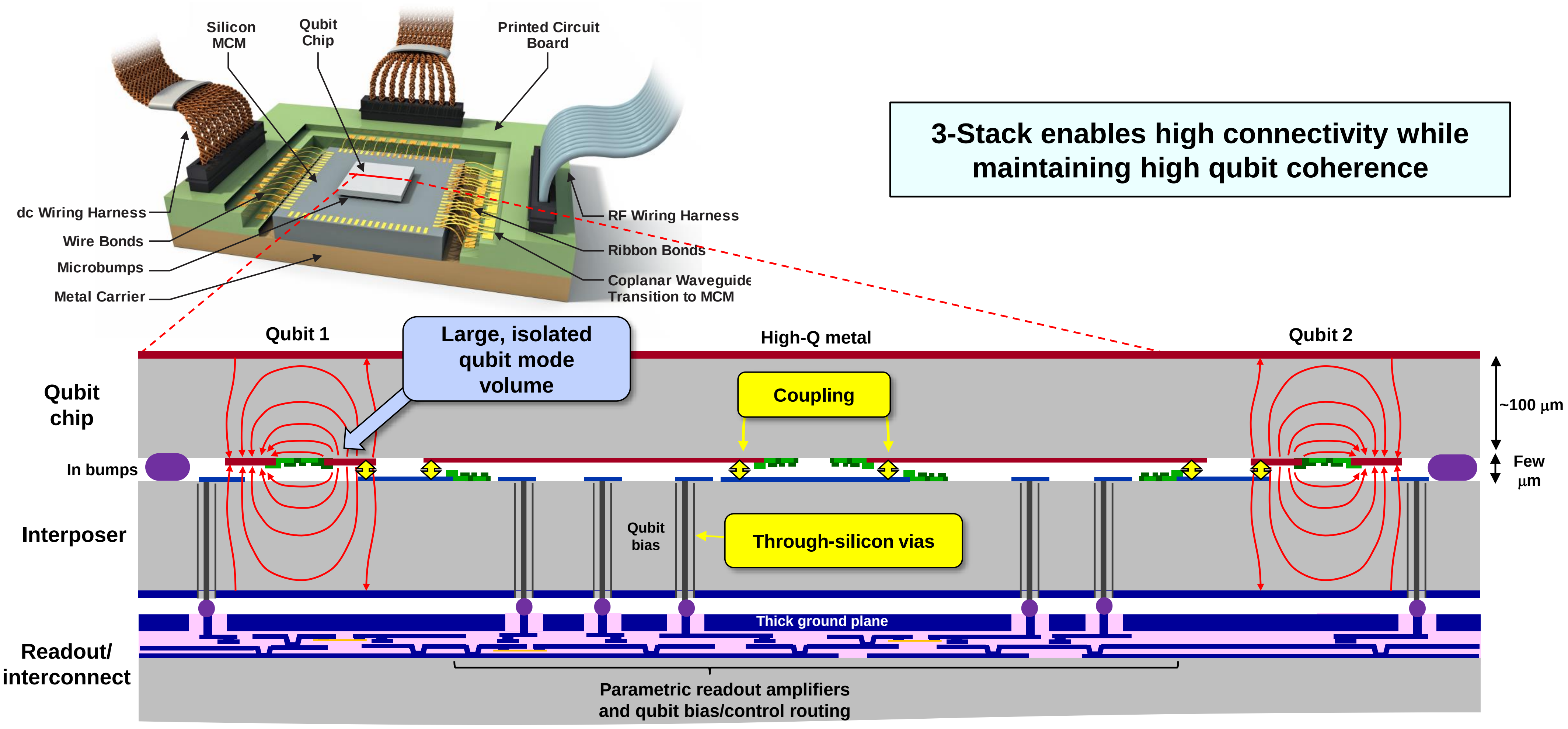


**Y. Yanay, …, WDO, C. Tahan, arXiv:1910.00933**
**Accepted to npj Quantum Information (2020)**

# 3D Integration for Quantum Processors

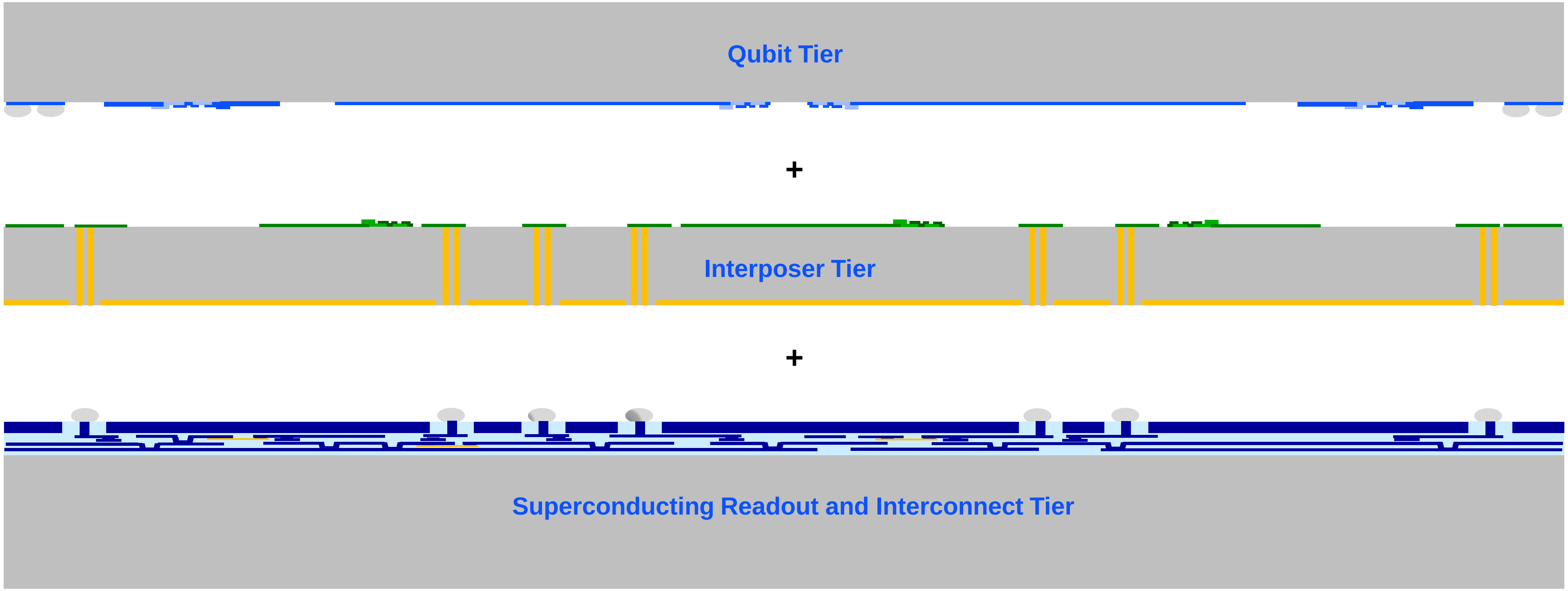
## IARPA Quantum Enhanced Optimization

**3-Stack enables high connectivity while maintaining high qubit coherence**




A.J. Kerman and WDO (2015)

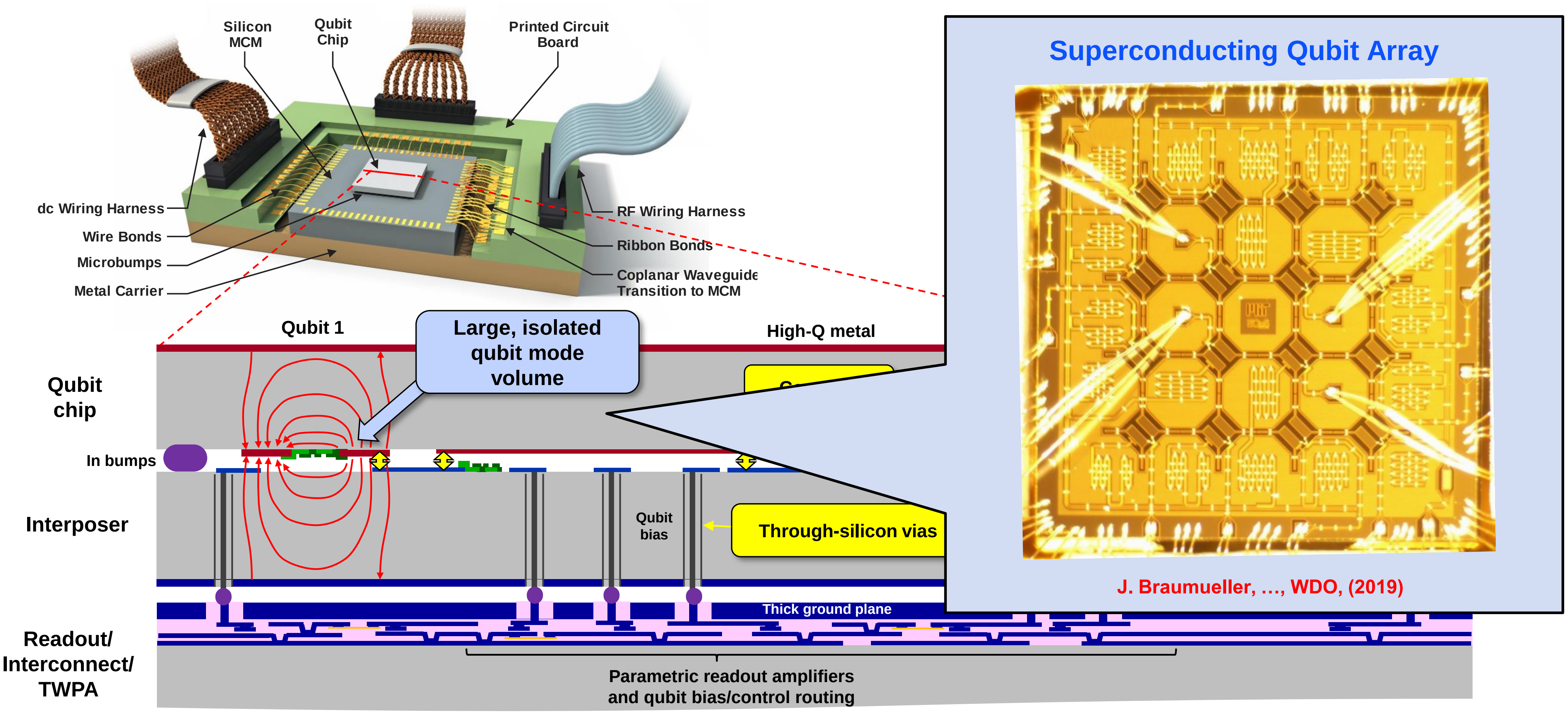
# 3D Integration for Quantum Processors




**Maintaining process independence for each wafer / layer enables separate optimization and retains focus on high-coherence qubits**

# 3D Integration for Quantum Processors

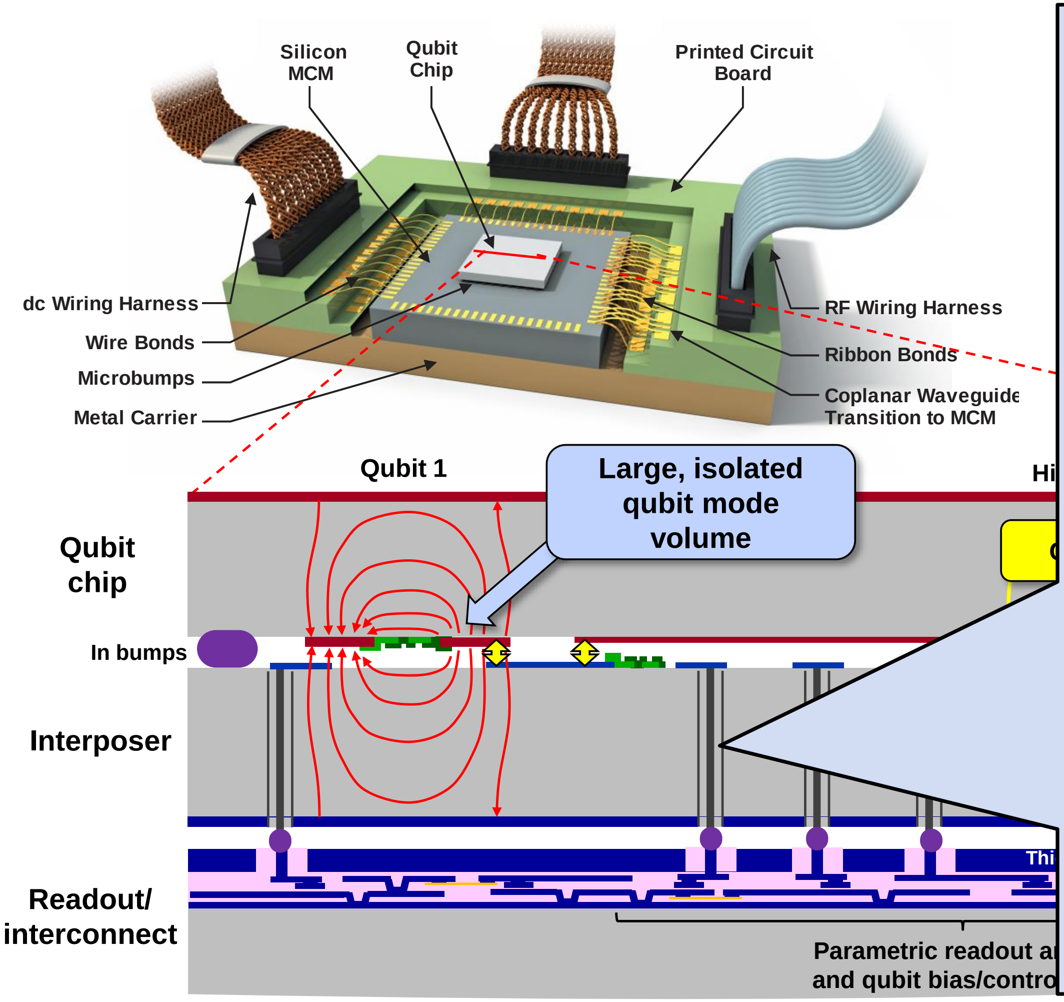
## IARPA Quantum Enhanced Optimization



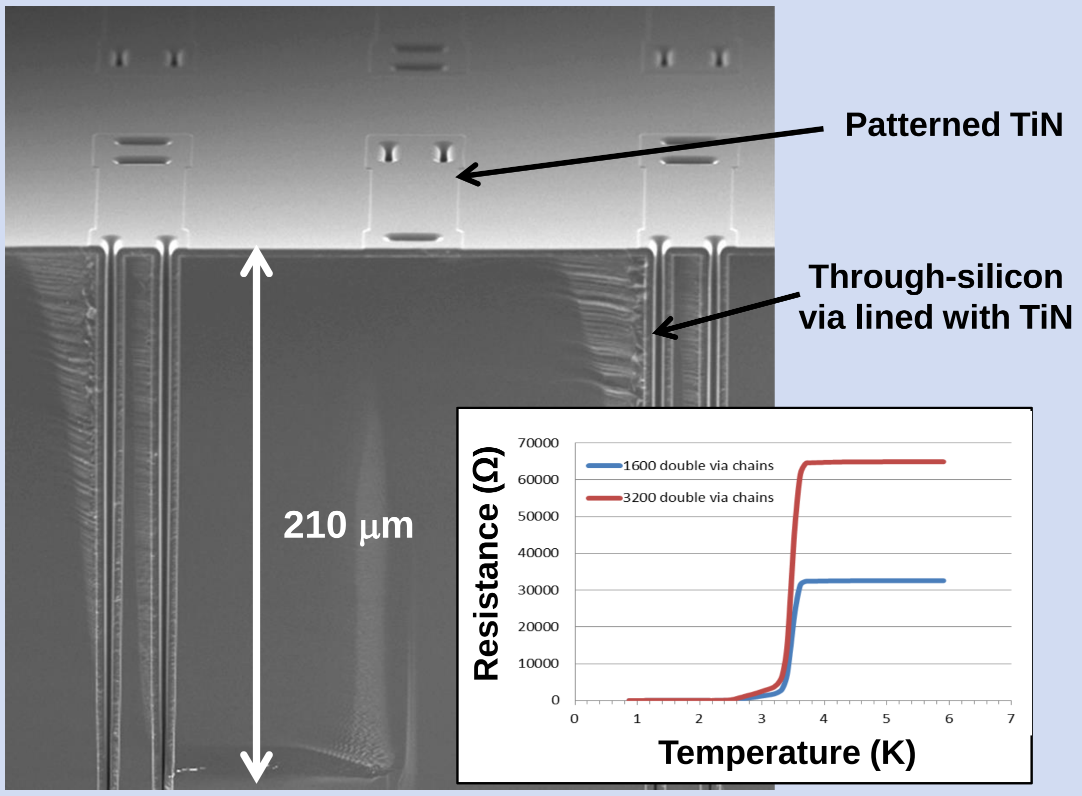

D. Rosenberg, et al., npj Quantum Information 3, 42 (2017)

# 3D Integration for Quantum Processors

## IARPA Quantum Enhanced Optimization



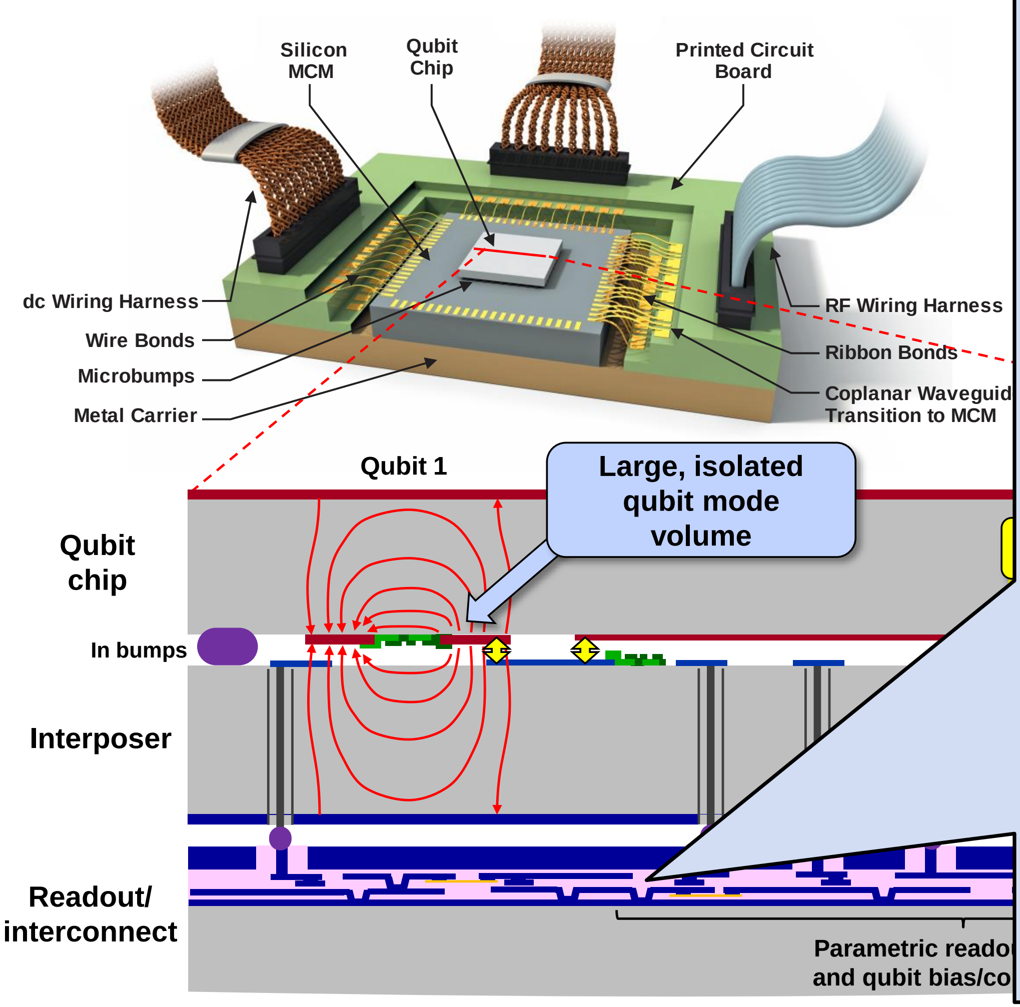

**Interposer isolates qubit from readout/interconnect layer.**
**Superconducting through-silicon vias provide connectivity.**




D. Yost, M. Schwartz, …, WDO, arXiv:1912.03322 (to appear npj Quantum Info.

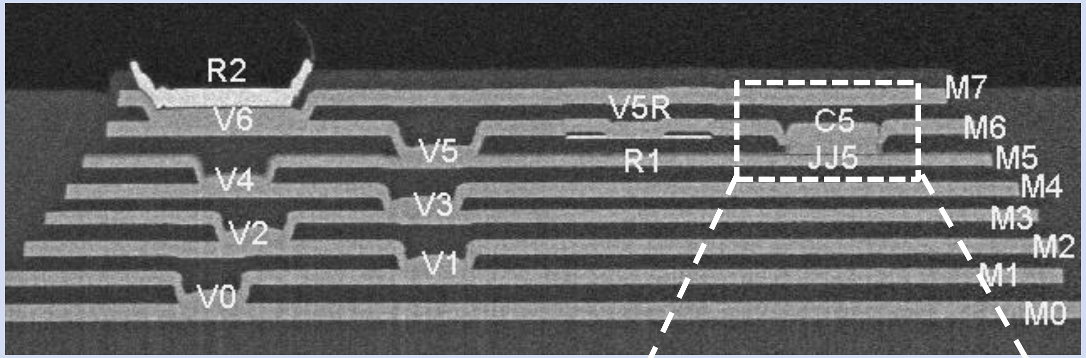
# 3D Integration for Quantum Processors

## IARPA Quantum Enhanced Optimization

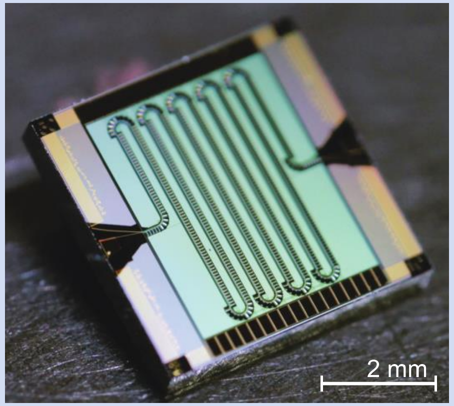



**Readout/interconnect layer routes wires and amplifies signals**

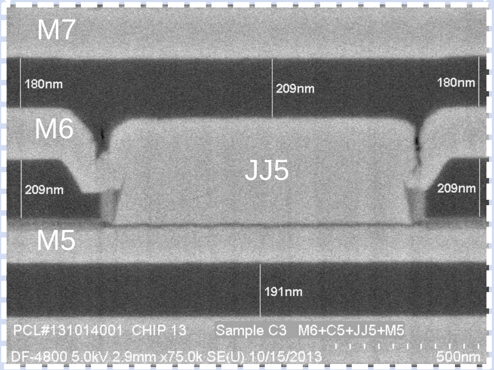
8-layer planar Niobium process for efficient wire routing




Traveling Wave Parametric Amplifier




Josephson Junction




Macklin, WDO, et al., Science 350, 307 (2015)

Tolpygo, …, WDO, IEEE Trans. (2015)

IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), No. 49, March 2021.
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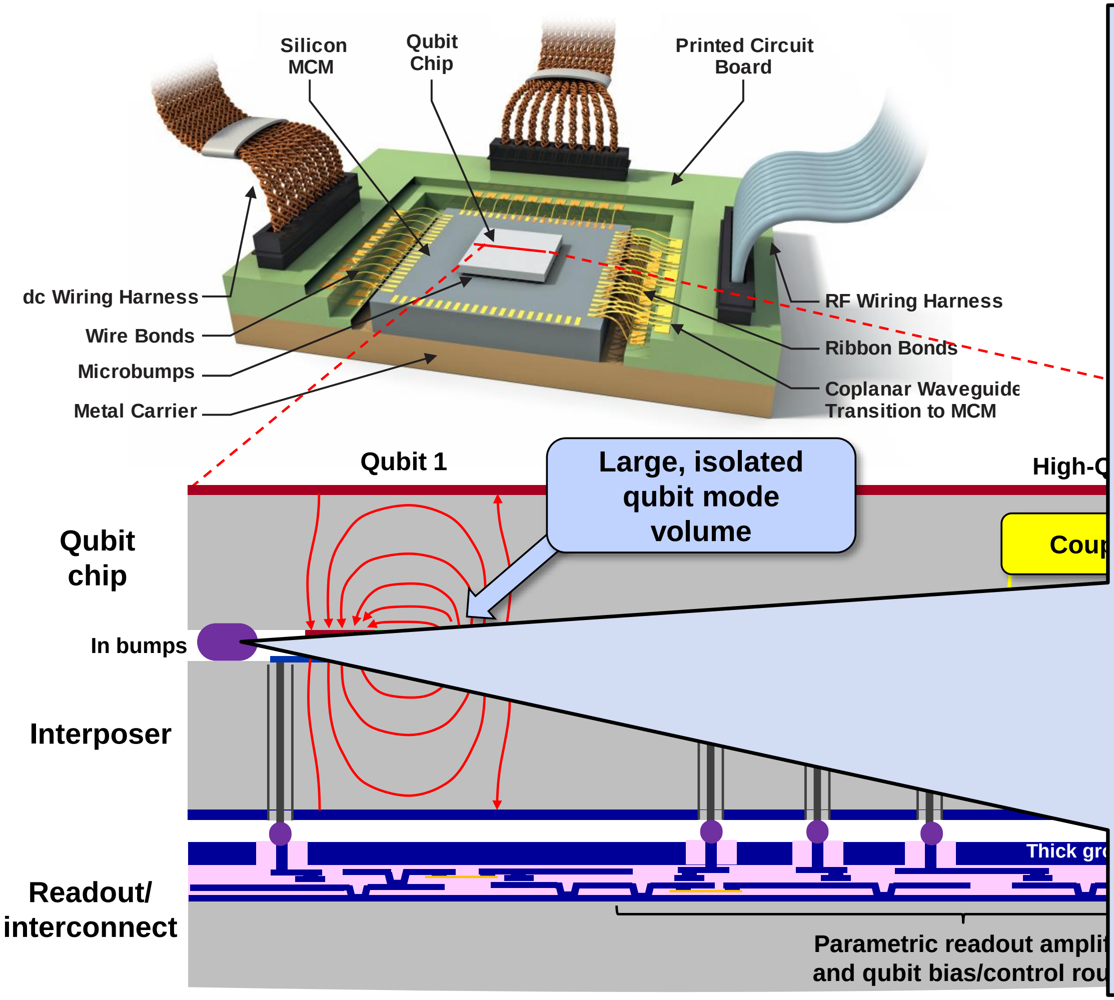
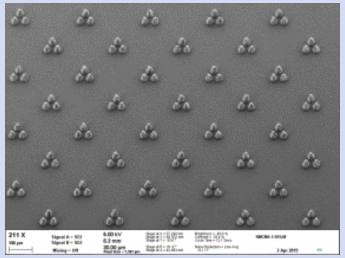
# 3D Integration for Quantum Processors

## IARPA Quantum Enhanced Optimization

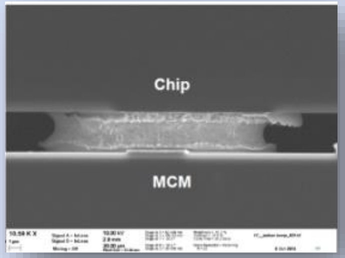



**Indium bumps provide electromechanical joining <u>without impacting coherence times</u>**

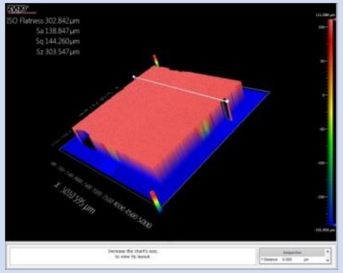
Fabricated In bumps



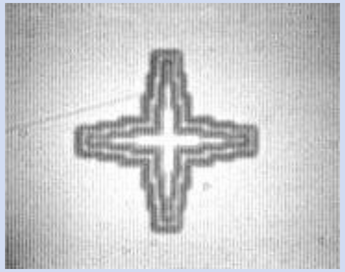
Cross-section of bump-bonded chips




3D image of bump-bonded chips



IR image of bump-bonded chips



**Tilt < 0.25 mrad**

**Alignment ~1 μm**

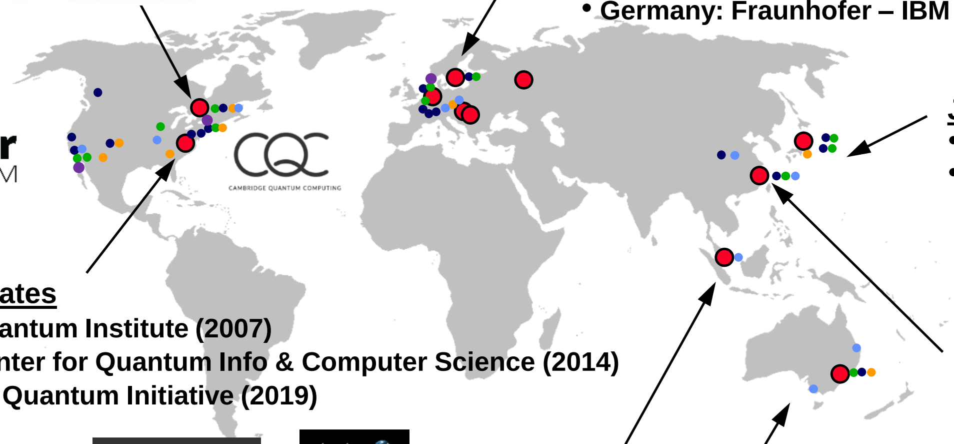
Danna Rosenberg, …, WDO, npj Quantum Information (2017)

# Quantum Worldwide

## (not an exhaustive list)

**Canada**
- Inst. for Quantum Computing (2002)
- Inst. Quantique (2015)

**Europe**
- Netherlands: QuTech (2014)
- United Kingdom: National Quantum Technologies Program, $0.5B (2014)
- EU: Quantum Flagship, $1B (2016)
- Sweden: Wallenberg Center for Quantum Technology, $0.2B (2017)
- Germany: Fraunhofer – IBM alliance, $0.8B (2019)



**Japan**
- Gate-model and QA
- JST, RIKEN, AIST, NICT

**United States**
- Joint Quantum Institute (2007)
- Joint Center for Quantum Info & Computer Science (2014)
- National Quantum Initiative (2019)

**China**
- Key Lab, Quantum Information, CAS (2001)
- Satellite quantum communication (2016)
- Alibaba – CAS cloud computer - $15B (2018)

**Australia**
- ARC Centers of Excellence
  - Center for Quantum Computing Technology (2000)
  - Engineered Quantum Systems (2011)
- CommBank – Telstra – UNSW (2015)

**Singapore**
- Research Center on Quantum Information Science and Technology (2007)

● Superconducting qubits ● Ion trap qubits ● Semiconducting qubits ● Quantum optics ● NV centers

* European Commission

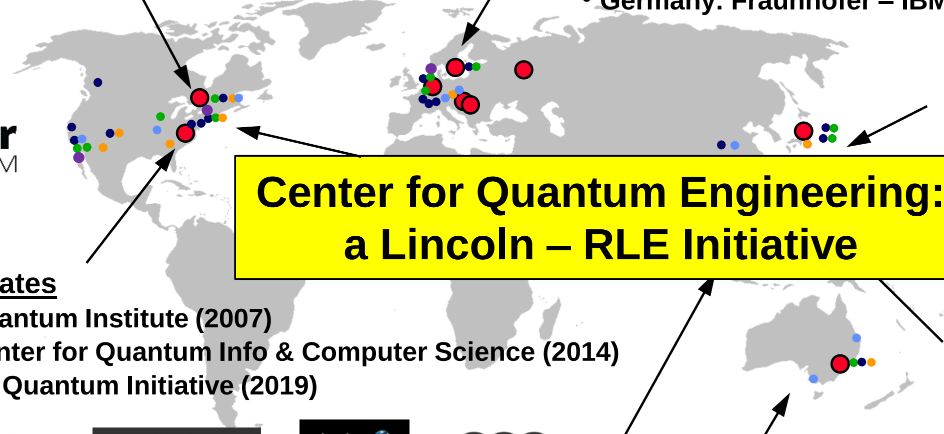
# Quantum Worldwide

## (not an exhaustive list)

**Canada**
- Inst. for Quantum Computing (2002)
- Inst. Quantique (2015)

**Europe**
- Netherlands: QuTech (2014)
- United Kingdom: National Quantum Technologies Program, $0.5B (2014)
- EU: Quantum Flagship, $1B (2016)
- Sweden: Wallenberg Center for Quantum Technology, $0.2B (2017)
- Germany: Fraunhofer – IBM alliance, $0.8B (2019)

**Japan**
- Gate-model and QA
- JST, RIKEN, AIST, NICT



**Center for Quantum Engineering: a Lincoln – RLE Initiative**

**United States**
- Joint Quantum Institute (2007)
- Joint Center for Quantum Info & Computer Science (2014)
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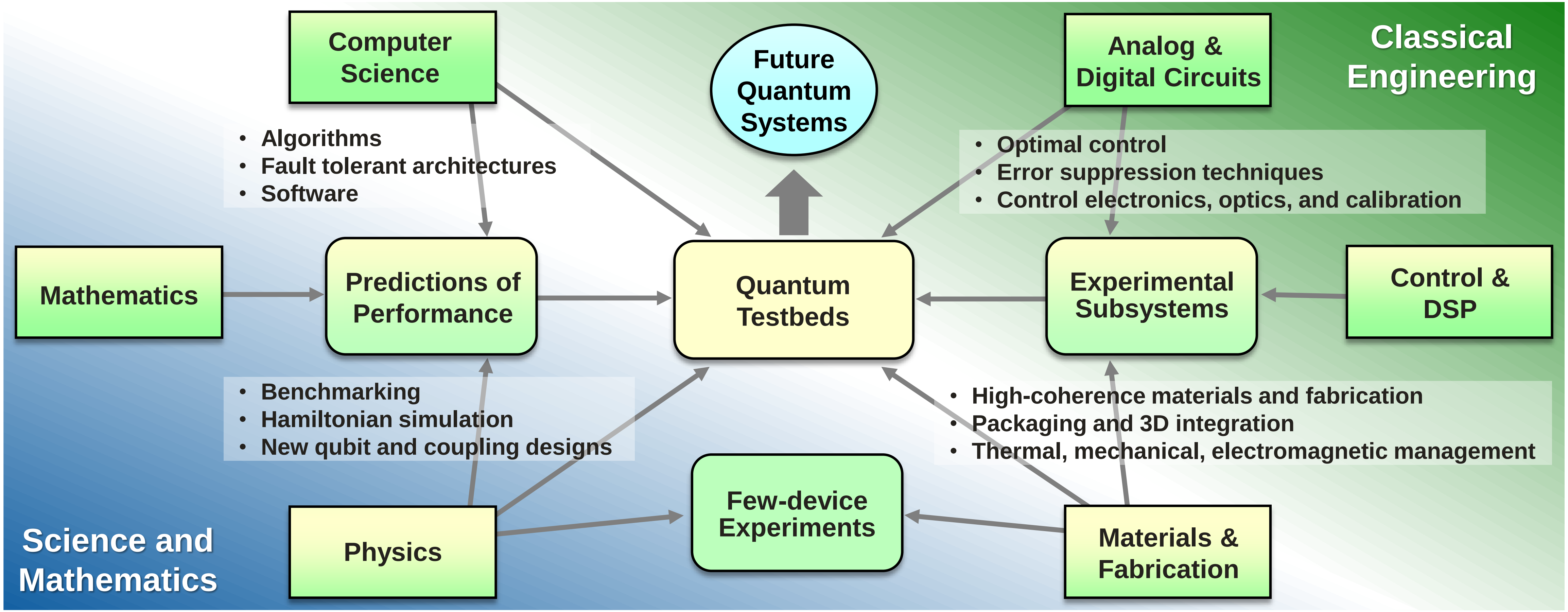
# MIT Center for Quantum Engineering

- **<u>Mission Statement:</u>**
  - ***We establish an initiative dedicated to the academic pursuit and practice of quantum engineering to accelerate the practical application of quantum technologies***
- **<u>Objectives:</u>**
  - **Define quantum engineering**
  - **Educate tomorrow's quantum engineers**
  - **Partner with industry via consortium model**
  - **Advance quantum science and engineering**


**www.rle.mit.edu/cqe**

# Quantum Engineering




**Quantum Engineering is the bridge connecting science, mathematics, and classical engineering**

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## MIT Engineering Quantum Systems (EQuS)

**William D. Oliver, Simon Gustavsson, Terry Orlando, Mirabella Pulido**

**Postdocs:** Jochen Braumüller, Agustin Di Paolo, Morten Kjaergaard, Antti Vepsäläinen, Joel Wang, Roni Winik

**PhD students:** Aziza Almanakly, Junyoung An, Charlotte Bøttcher, Leon Ding, Ami Greene, Bharath Kannan, Amir Karamlou, Rebecca Li, Benjamin Lienhard, Chris McNally, Tim Menke, Sarah Muschinske, Jack Qiu, David Rower, Gabriel Samach, Youngkyu Sung

**Master's Student:** Cole Hoffer

**Undergraduates:** Matthew Baldwin, Thomas Bergamaschi, Grecia Castelazo, Thao Dinh, Elaine Pham, Megan Yamoah

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