Canonical Phase Measurement in Quantum Mechanics

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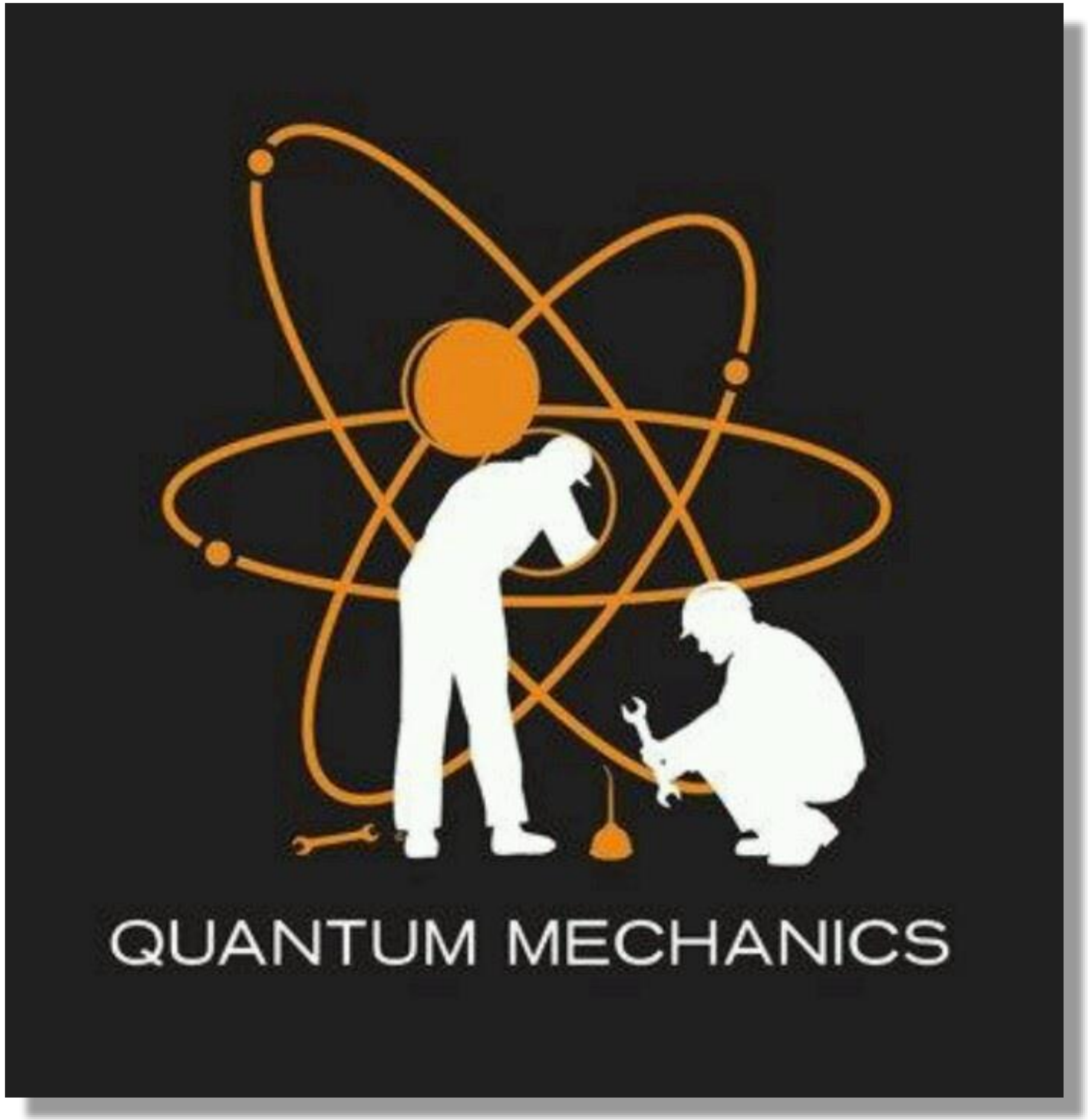
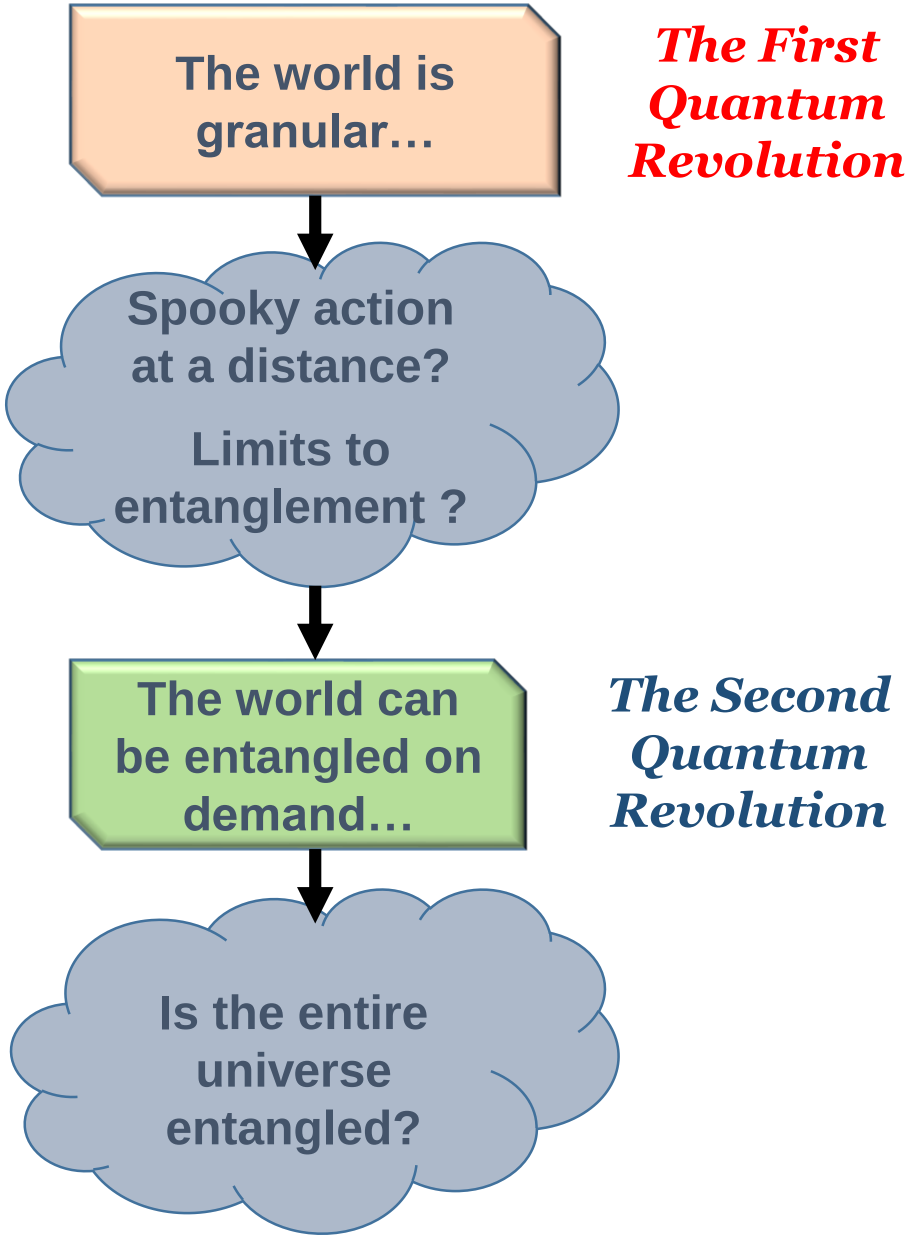
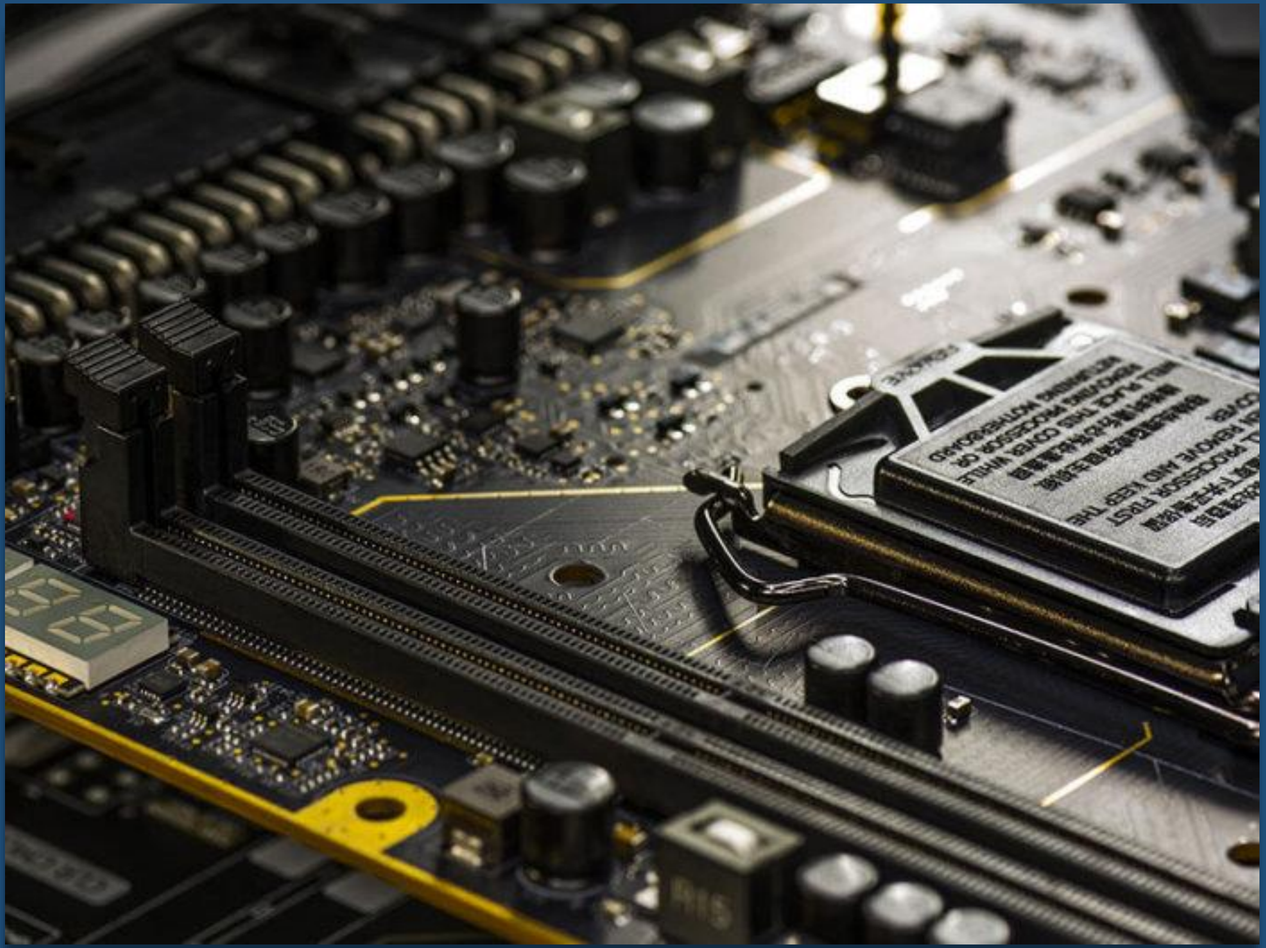
REVOLUTIONS IN QUANTUM THEORY



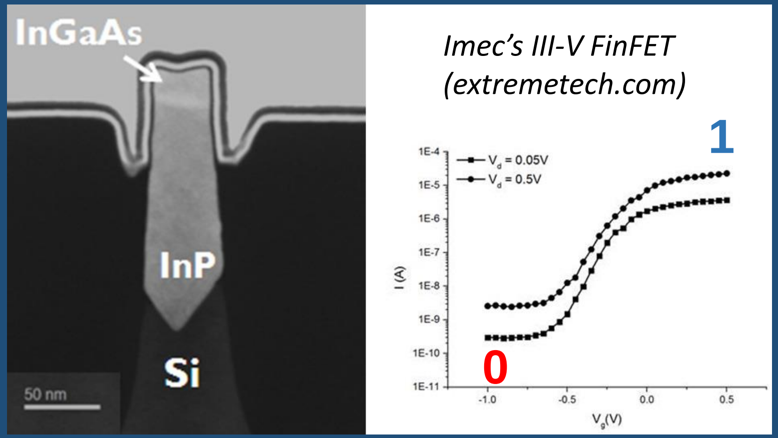


THE QUANTUM INFORMATION PARADIGM SHIFT



(Z370: www.pcworld.com)

- Start with a good switch…



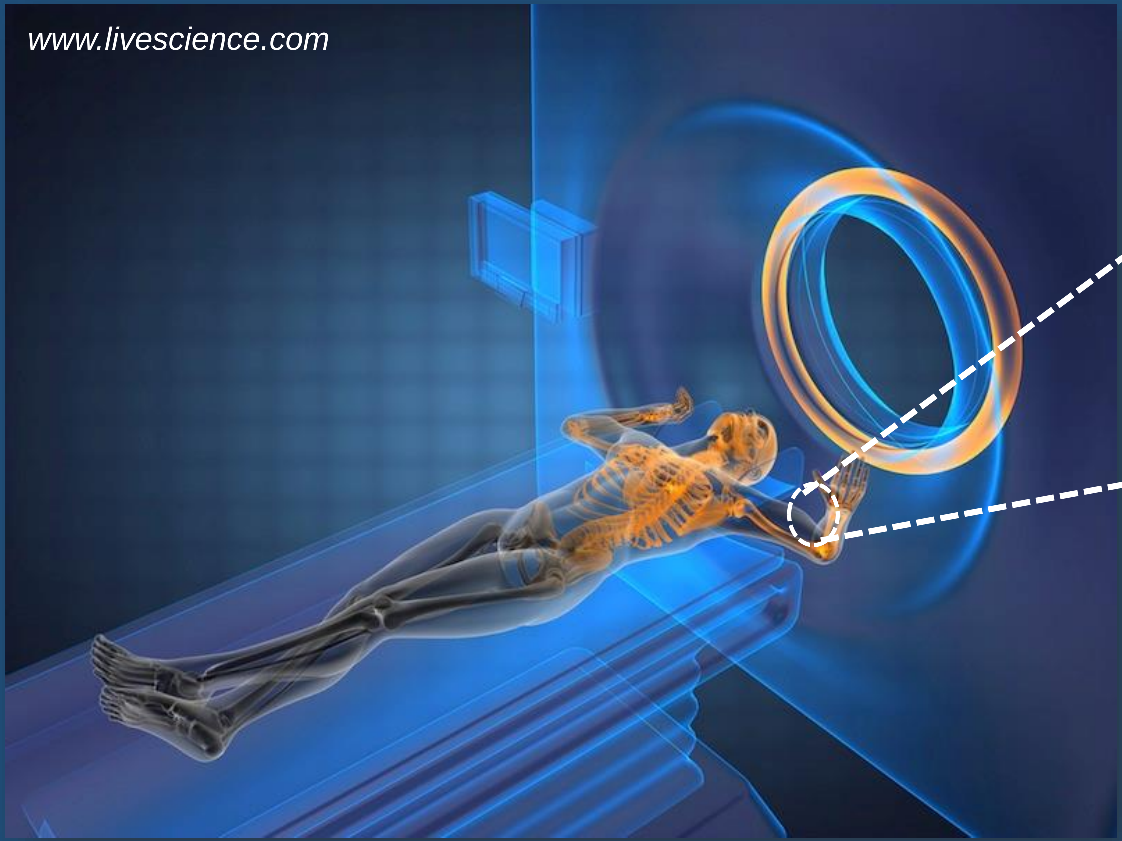
- Advanced materials science, electromagnetism, and thermodynamics at the nm scale
- Different functional units (processor, memory,..)
- Highly developed instruction sets

- Qubits: Write 0 *and* 1 , Read 0 *or* 1
- N quantum bits *entangle* to form 2^N states ! (compare to 2N for classical bits)

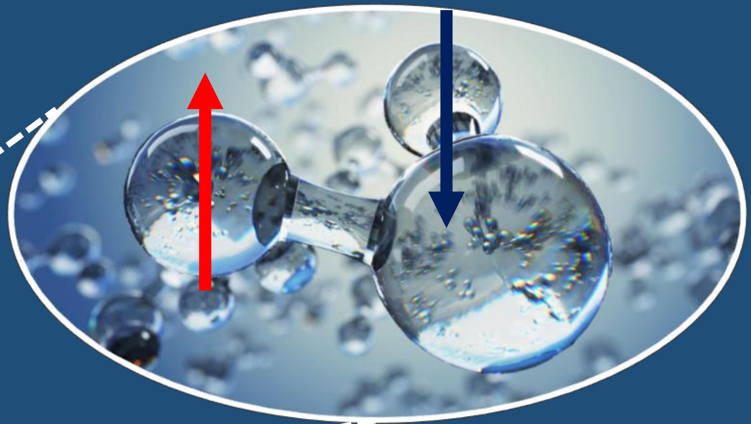
QUANTUM IS FUNDAMENTALLY DIFFERENT AT ALL LEVELS!

THE QUANTUM WORLD AROUND US

A MRI Scan Relies on Quantum Mechanics!



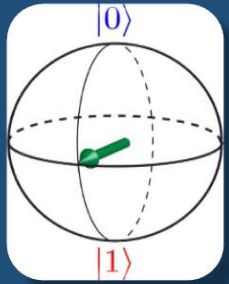
Water molecules have two hydrogens which have nuclear spin (up or down)



www.medicalnewstoday.com

Apply magnetic field to measure spin

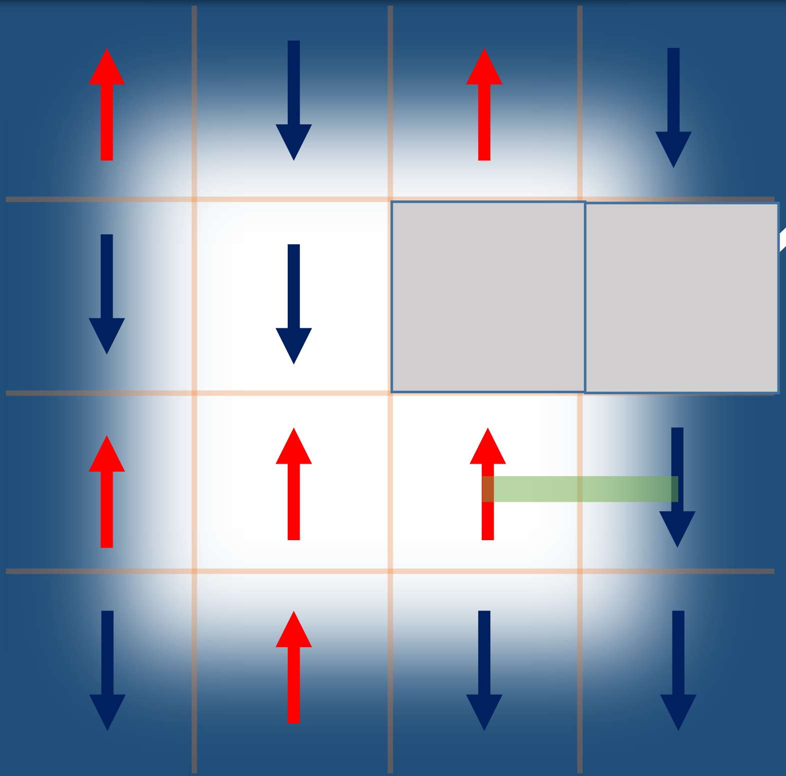
- Always observe ↑ or ↓
- Prepare superposition: ← = ↑ + ↓
- Would measure: 50% ↑ , 50% ↓



QUANTUM SYSTEMS CAN EXIST IN MANY DIFFERENT CONFIGURATIONS, EVEN IF WE CAN'T OBSERVE ALL OF THEM!

THE POWER OF ENTANGLEMENT

- Let's build a computer one spin (quantum bit) at a time !
- Unlike MRI which measures average properties of a group of spins, we need to address each spin individually



- Measurement reveals state to be ↑
- If we don't observe, state is (**a** · ↑ + **b** · ↓) and described by 2 numbers {a,b}
- Adjacent bit is (**c** · ↑ + **d** · ↓) and described by 2 numbers {c,d}
- Couple these two bits and consider product: (a · ↑ + b · ↓) X (**c** · ↑ + **d** · ↓)

ac · ↑↑ + **ad** · ↑↓ + **bc** · ↓↑ + **bd** · ↓↓

cannot describe

Entangled State → ↑↑ + ↓↓

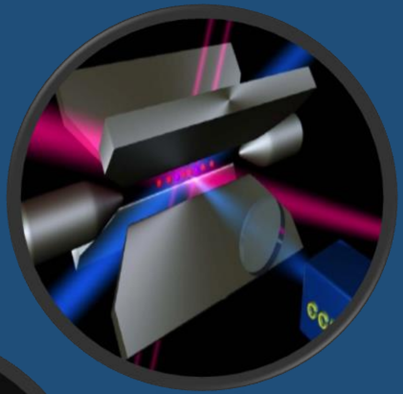
If a = 0, lose **ac** · ↑↑

If d = 0, lose **bd** · ↓↓

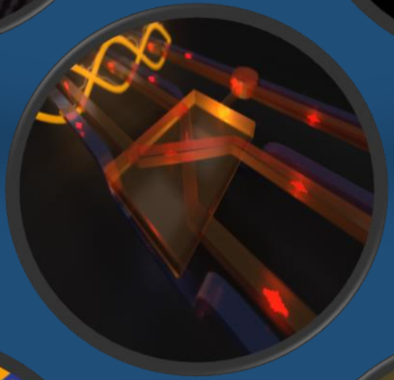
2^N >> 2N: NEED MORE NUMBERS THAN PARTICLES IN THE UNIVERSE TO DESCRIBE ~ 300 ENTANGLED QUBITS

Dopants in Silicon / Diamond
www.sciencedaily.com

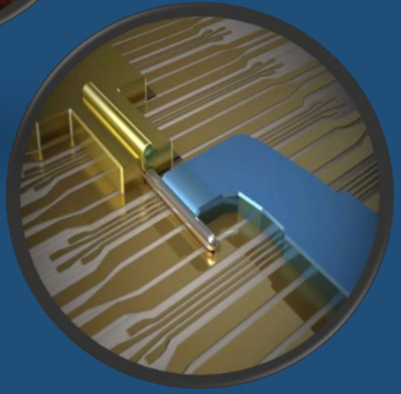
Trapped Ions
www.quantumoptics.at



Photonic Circuits
www.phys.org



Superconducting Circuits
www.qnl.berkeley.edu



Topological Wires
www.microsoft.com

PHYSICAL IMPLEMENTATIONS

	Leading technologies in NISQ era[1]		Candidate technologies beyond NISQ		
Qubit type or technology	**Superconducting[2]**	**Trapped ion**	**Photonic**	**Silicon-based[3]**	**Topological[8]**
Description of qubit encoding	Two-level system of a superconducting circuit	Electron spin direction of ionized atoms in vacuum	Occupation of a waveguide pair of single photons	Nuclear or electron spin or charge of doped P atoms in Si	Majorana particles in a nanowire
Physical qubits[4,5]	IBM: 20, Rigetti: 19, Alibaba: 11, Google: 9	Lab environment: AQT[6]: 20, IonQ: 14	6×3[9]	2	target: 1 in 2018
Qubit lifetime	~50–100 µs	~50 s	~150 µs	~1–10 s	target ~100 s
Gate fidelity[7]	~99.4%	~99.9%	~98%	~90%	target ~99.9999%
Gate operation time	~10–50 ns	~3-50 µs	~1 ns	~1–10 ns	–
Connectivity	Nearest neighbors	All-to-all	To be demonstrated	Nearest neighbor	–
Scalability	No major road-blocks near-term	Scaling beyond one trap (>50 qb)	Single photon sources and detection	Novel technology potentially high scalability	?
Maturity or technology readiness level	TRL[10] 5	TRL 4	TRL 3	TRL 3	TRL 1
Key properties	Cryogenic operation Fast gating Silicon technology	Improves with cryogenic temperatures Long qubit lifetime Vacuum operation	Room temperature Fast gating Modular design	Cryogenic operation Fast gating Atomic-scale size	Estimated: Long lifetime High fidelities

Sources: BCG analysis; expert interviews.
[1]Noisy Intermediate-Scale Quantum devices era.
[2]Currently only technology with external cloud access; several forms (charge, flux, phase) of qubits exist but most pursue a less noise-sensitive charge-based qubit (transmon).
[3]Additional approaches include Si and SiGe quantum dots.

QUANTUM COMPUTING: FROM ART TO ARCHITECTURE

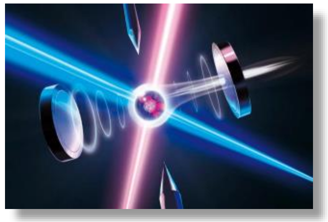
of Physical Qubits

1

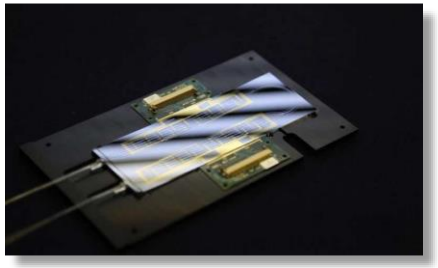
100

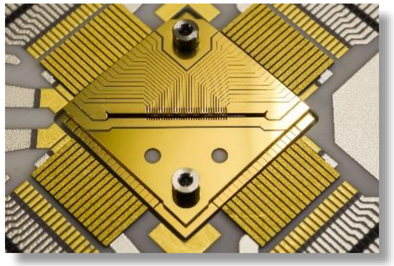
10,000

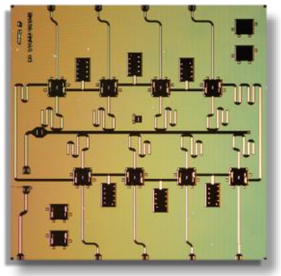
1,000,000



Communication & Sensing







Noisy, Intermediate Scale Quantum (NISQ) Era

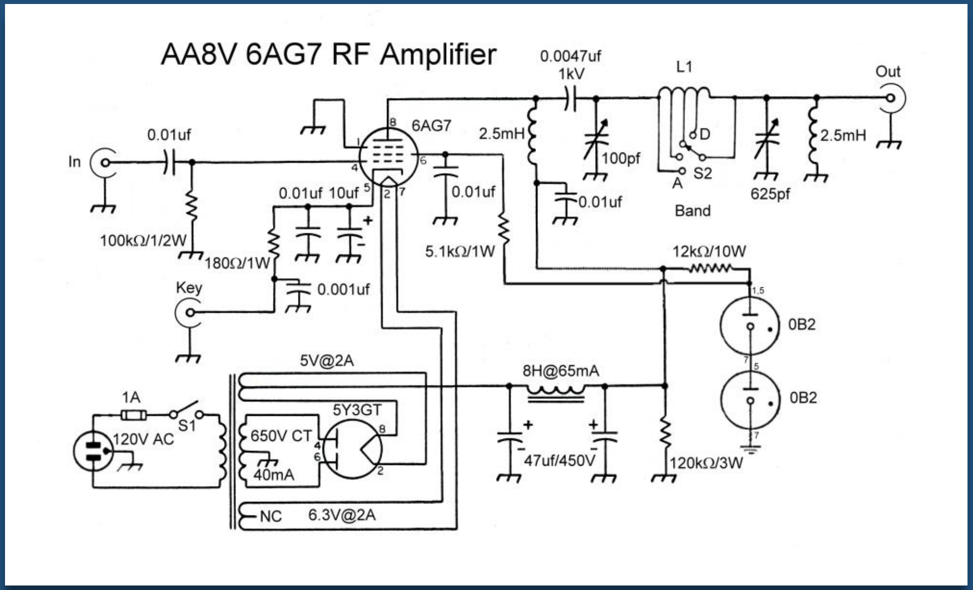
- 10-100 physical qubits
- Minimal error correction
- Purely quantum & hybrid algorithms
- < 100 Logical gate operations

- Cannot be simulated by classical devices
- First quantum computations
- Reveal scaling of quantum advantage
- Growth of error resilience; novel QEC
- Growth of new classical computing hardware

Fault-tolerant, Universal Computation

MAKING AN ELECTRICAL CIRCUIT QUANTUM

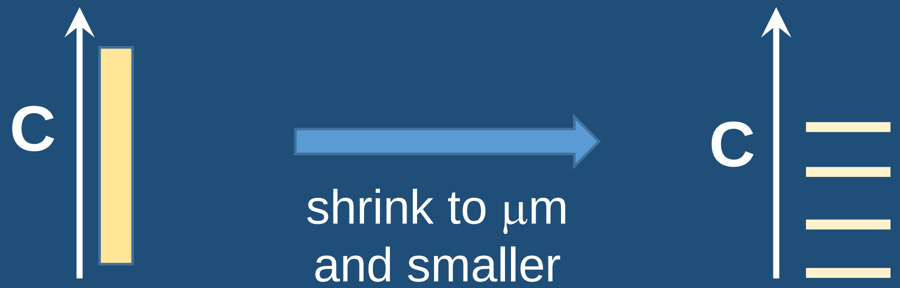
ACCESSING THE QUANTUM WORLD



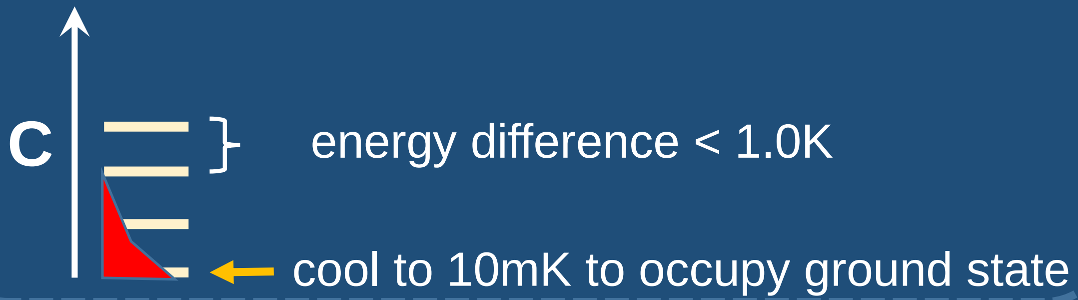
- Combination of *R*, *L*, *C* (linear or nonlinear)
- Excite with voltages / currents (AC or DC)
- Classically, these quantitates can take on any continuous values

QUANTUM MECHANICS SAYS THESE QUANTITIES ARE FUNADEMENTALLY DISCRETE!

- Granularity becomes apparent at the nanoscale



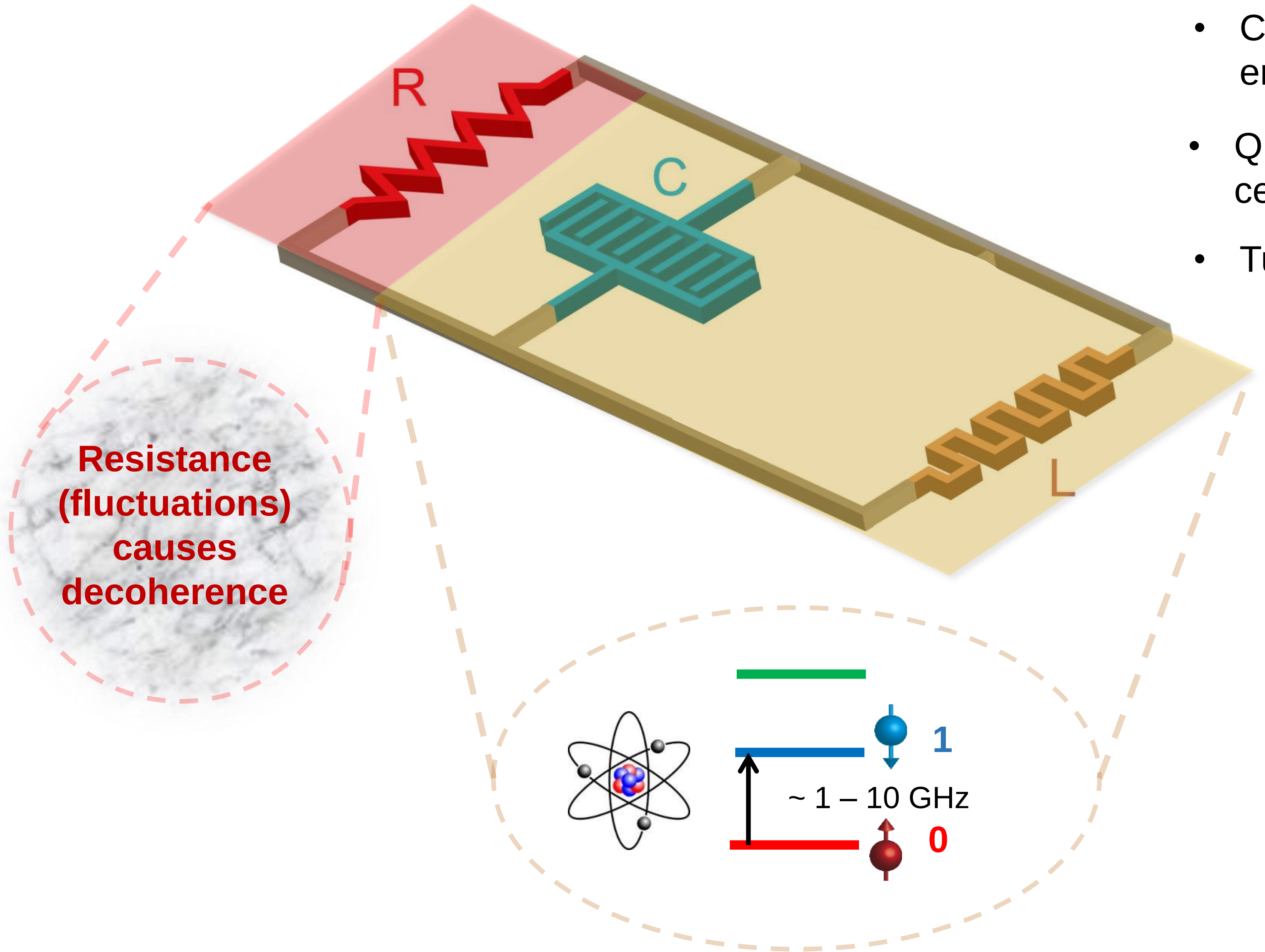
- Cryogenic operation to occupy single state

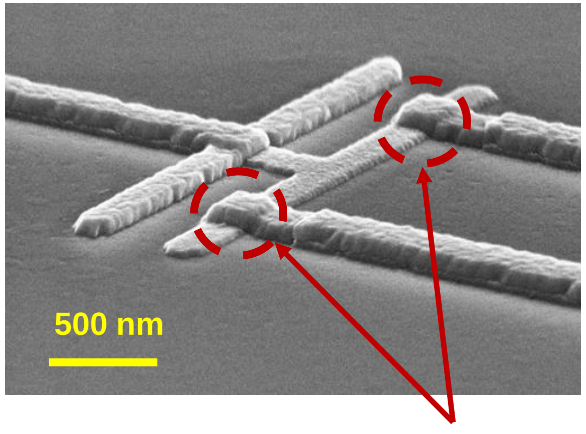


- Isolate from environment (loss/dephasing)

A QUBIT IS JUST A NONLINEAR OSCILLATOR

- Classical harmonic oscillator: all energies (currents) are allowed
- Quantum harmonic oscillator: only certain energies (currents) are allowed
- Tunnel junction → Nonlinear, isolate **0**, **1**

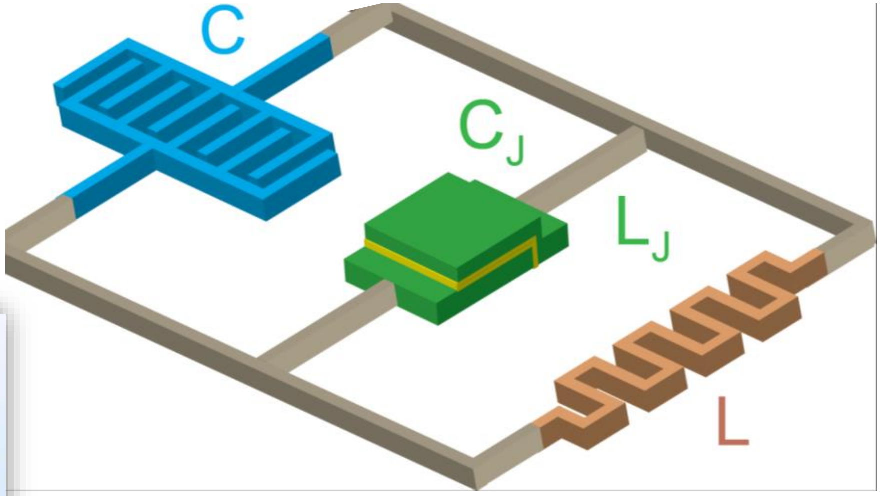




OTHER WAYS TO RELAX QUANTUM SUPERPOSITION...

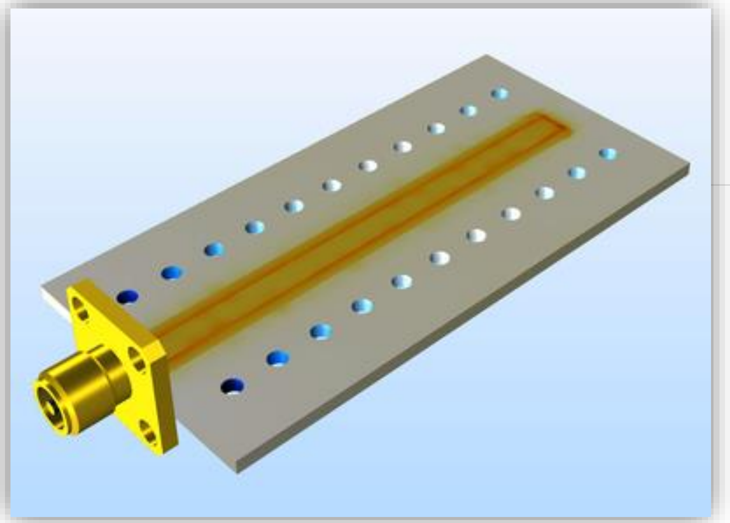
Radiative Losses

R ~ 377 Ω

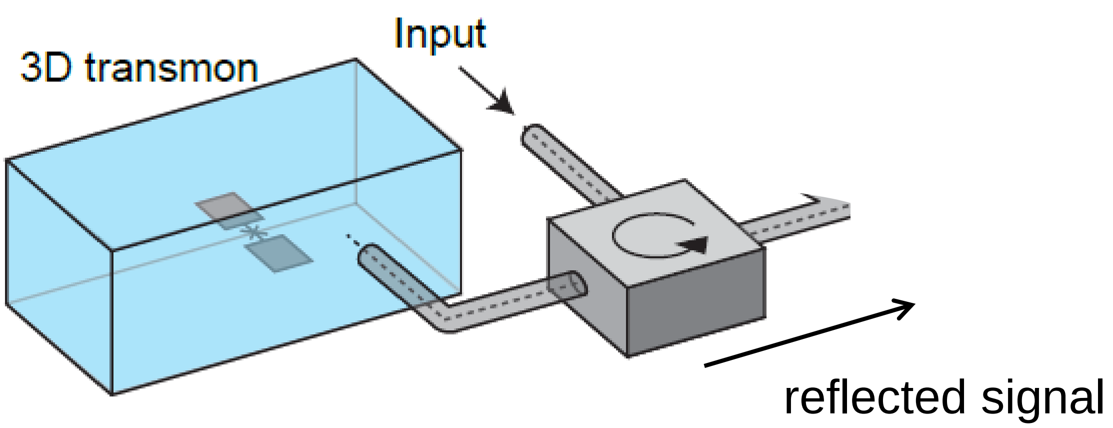


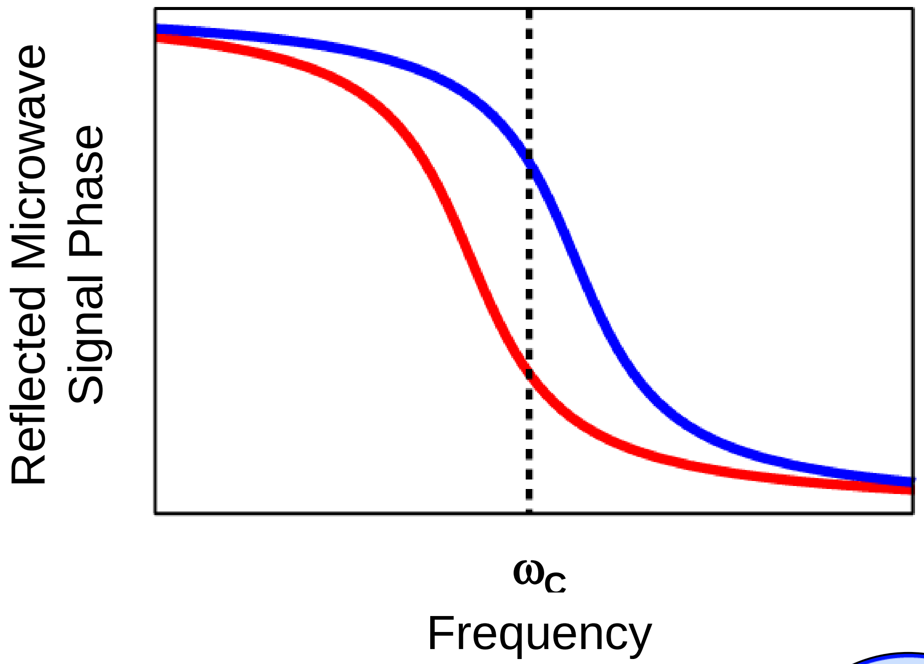
Coupling Losses

R ~ 50 Ω

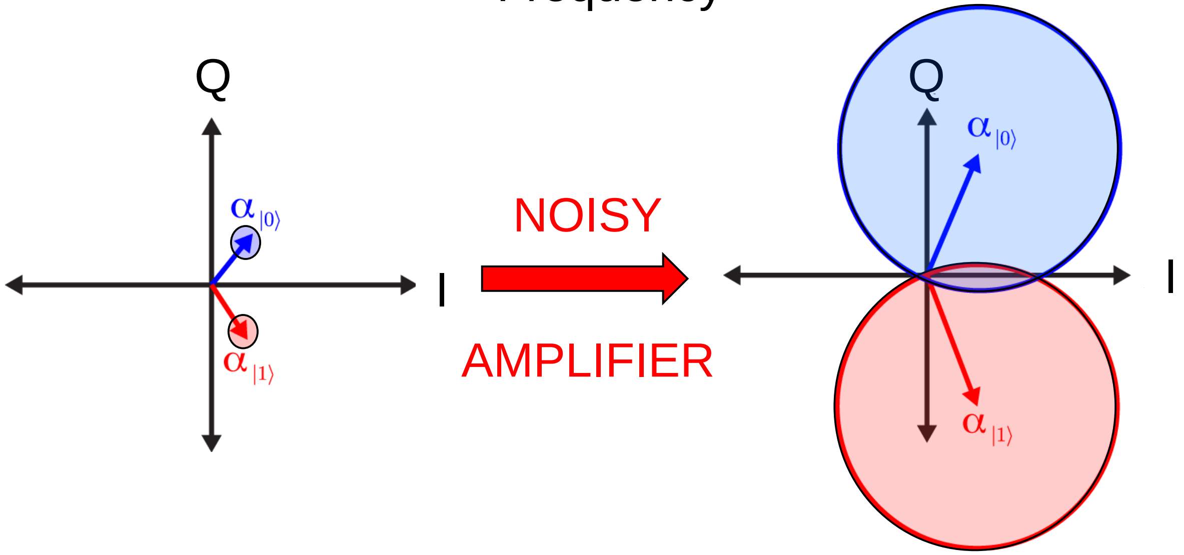


MEASURING QUBIT STATES: MICROWAVE REFLECTOMETRY

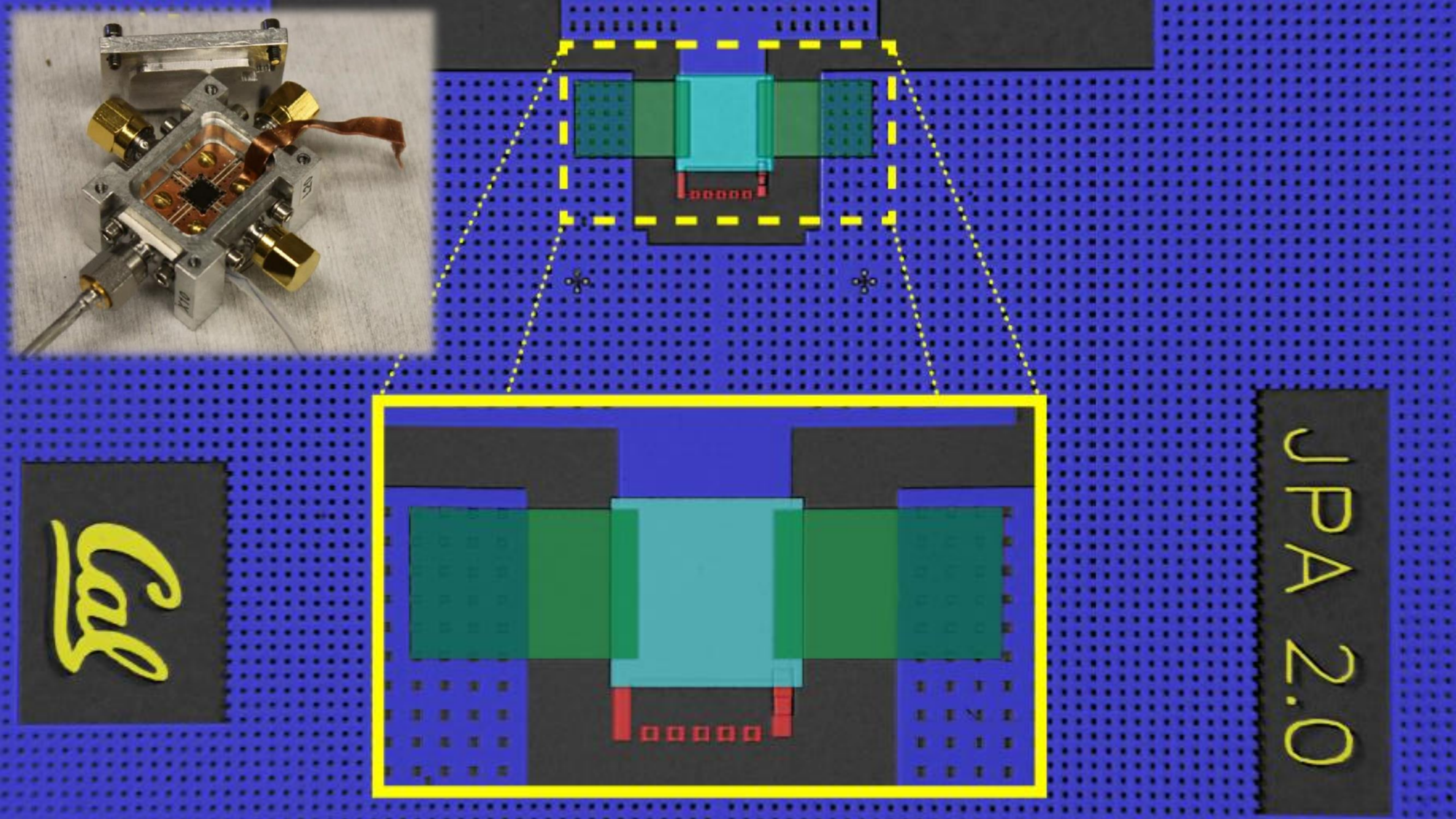




$$A\sin(\omega t+\phi) = A\sin(\omega t)\cos(\phi) + A\cos(\omega t)\sin(\phi)$$
$$= \underbrace{[A\cos(\phi)]}_{I}\sin(\omega t) + \underbrace{[A\sin(\phi)]}_{Q}\cos(\omega t)$$



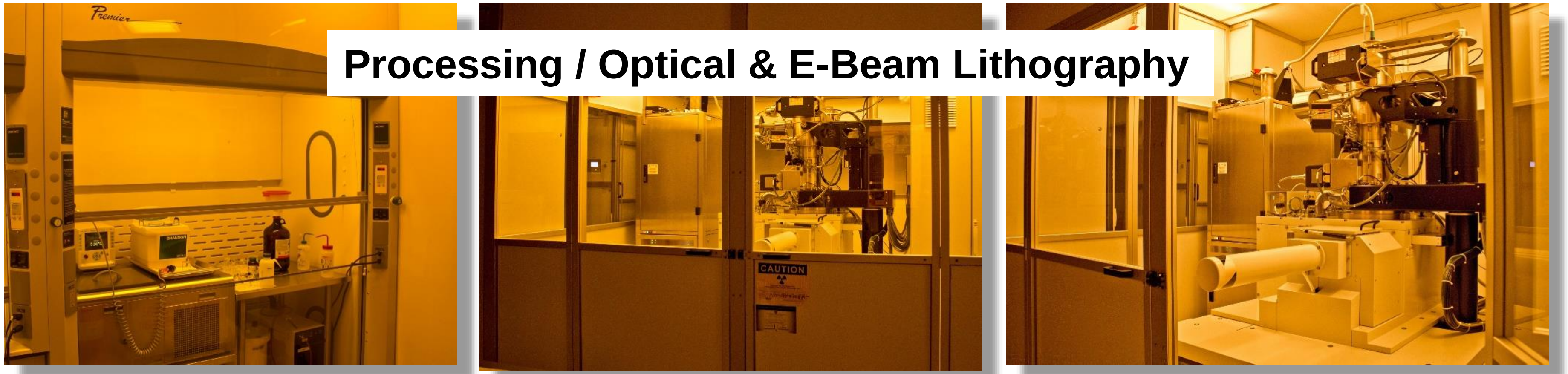
- Measure Single Quadrature
- Homodyne Measurement: Voltage (Phase 'Q')


Cal
JPA 2.0

WAFER SCALE PRODUCTION OF SC DEVICES

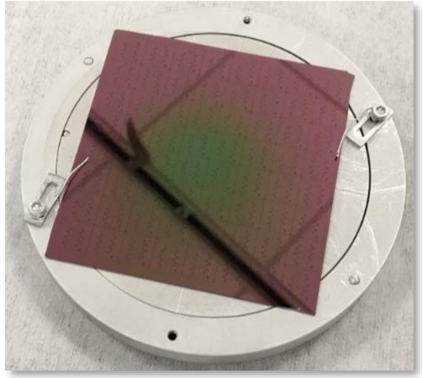
Deposition / Packaging / Inspection

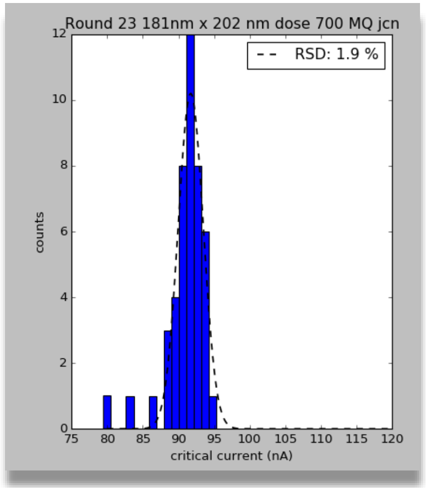
PARTICLE CLASS: 10,000 1000



Processing / Optical & E-Beam Lithography

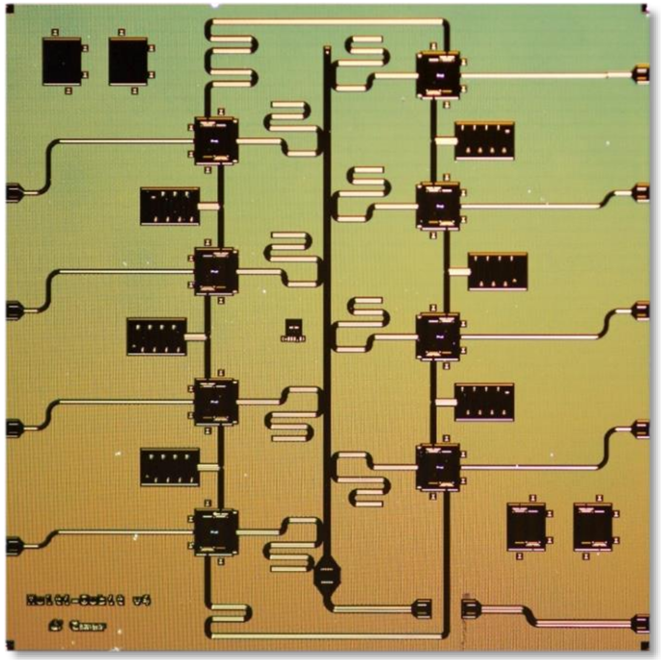
100 100 10





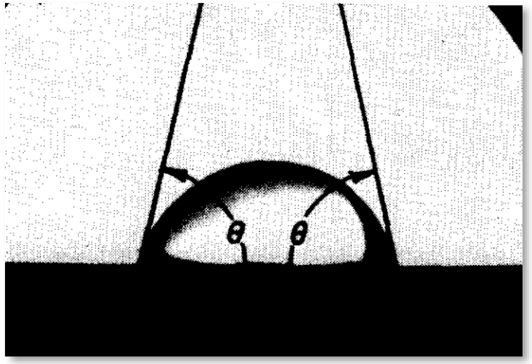
- 64 x 8-qubit processors
- 2 days / wafer for junction processing
- 99.4% test junction yield

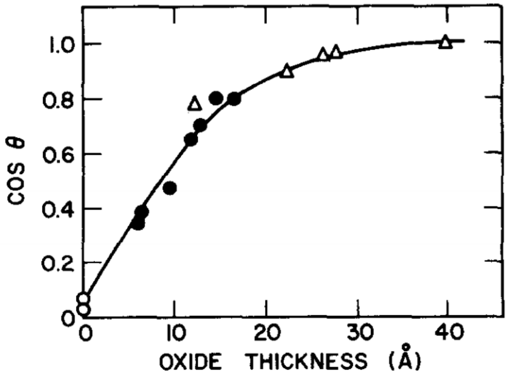
QUBITS AND THEIR MANY FACETS



Qubit	f_{qubit} (GHz)	T_1 (μs)	T_2 (μs)	T_2^* (μs)
1	5.231	57	91	58
2	5.382	57	66	34
3	5.096	42	54	33
4	5.326	63	74	47
5	5.184	58	95	53
6	5.308	63	112	37
7	5.343	56	96	50
8	5.221	69	98	57
	Average	**58**	**86**	**46**

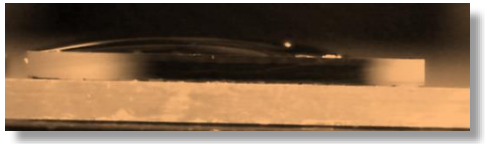
- Planar devices have many surfaces/interfaces that can host defects



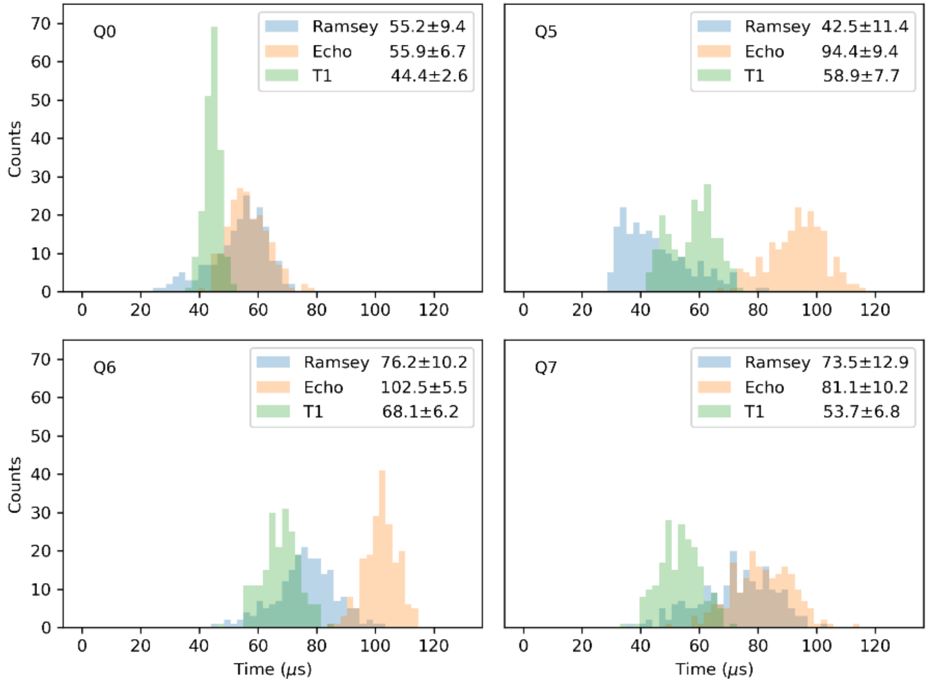


R. Williams and A.M. Goodman. "Wetting of thin layers of SiO_2 by water." Appl. Phys. Lett. 25, 531 (1974)

- Rapid non-destructive hydro-metrology!

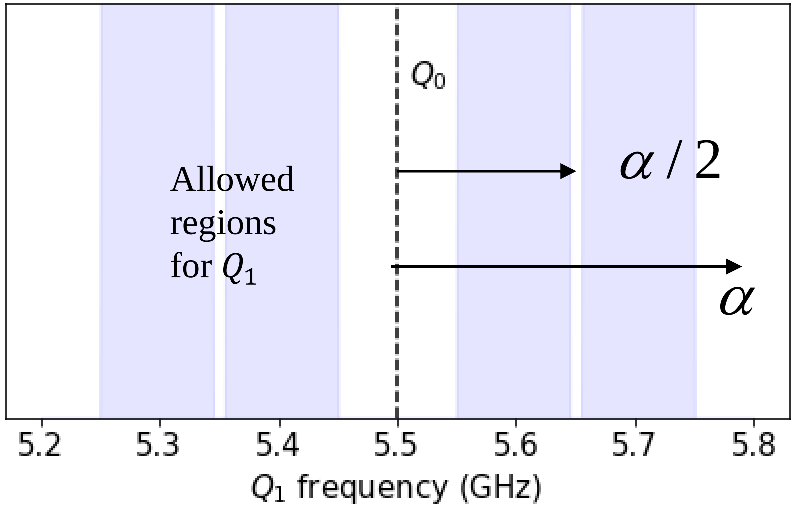


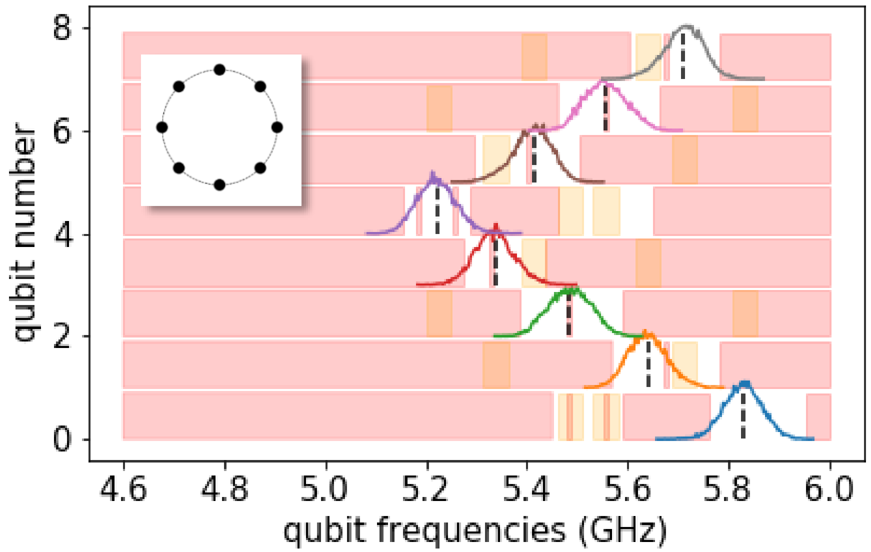
targeted HF etch → **doubled T_1**



NEED LOCAL, 3D DEFECT MAPS (CHEMICAL/STRUCTURAL) & MODELING

8 QUBIT CHIP UNIFORMITY REQUIREMENTS





Forbidden frequency regions for nearest neighbors (red) and next nearest neighbors (orange)

- Two-qubit gate (cross resonance gate) places strict requirements on detuning of neighboring qubits relative to anharmonicity (α).

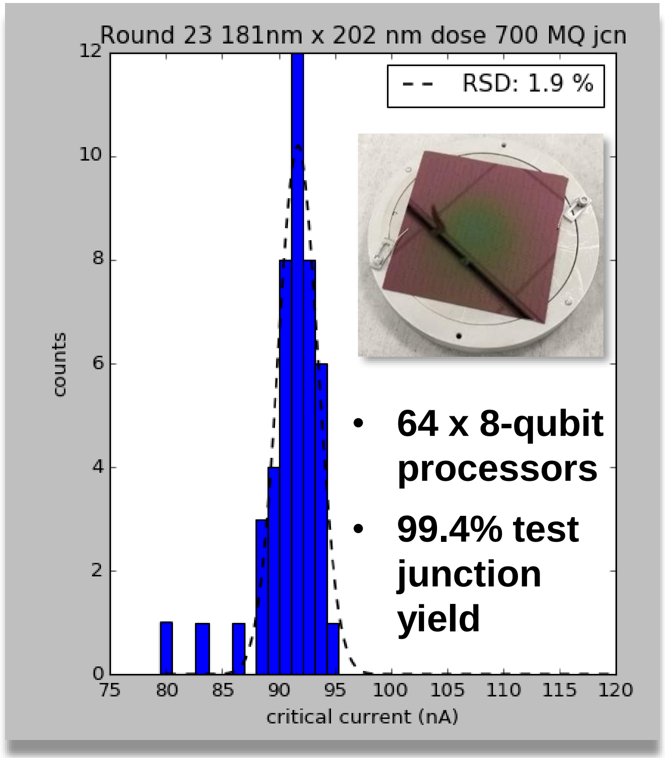
Based in part on work by IBM: J. Hertzberg et al. "Frequency precision in fixed-frequency transmon qubits, and implications for scalable fault-tolerant quantum computing circuits." http://meetings.aps.org/Meeting/MAR18/Session/A33.3

- Target qubit frequency distributions (colored lines) optimized for maximum yield with Monte-Carlo simulations.

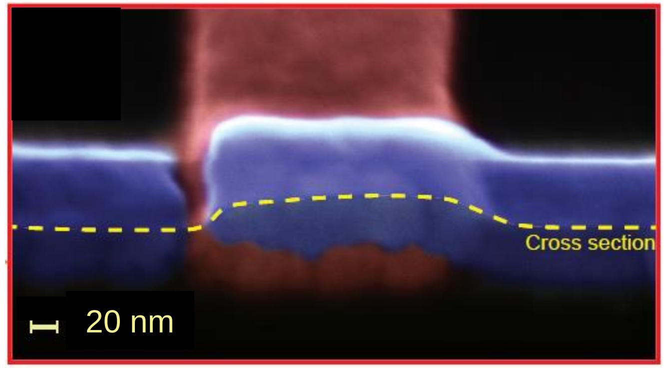
- For σ = 50 MHz

(2% critical current variation) Predicted yield is 10%.

CO-DESIGN OF MATERIALS / ARCHITECTURE / ALGORITHMS

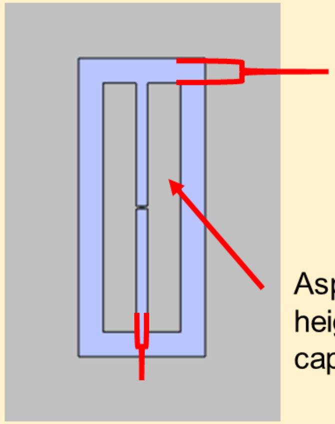


- **64 x 8-qubit processors**
- **99.4% test junction yield**



SUPPRESSING QUANTUM CHATTER

Parameters Varied:



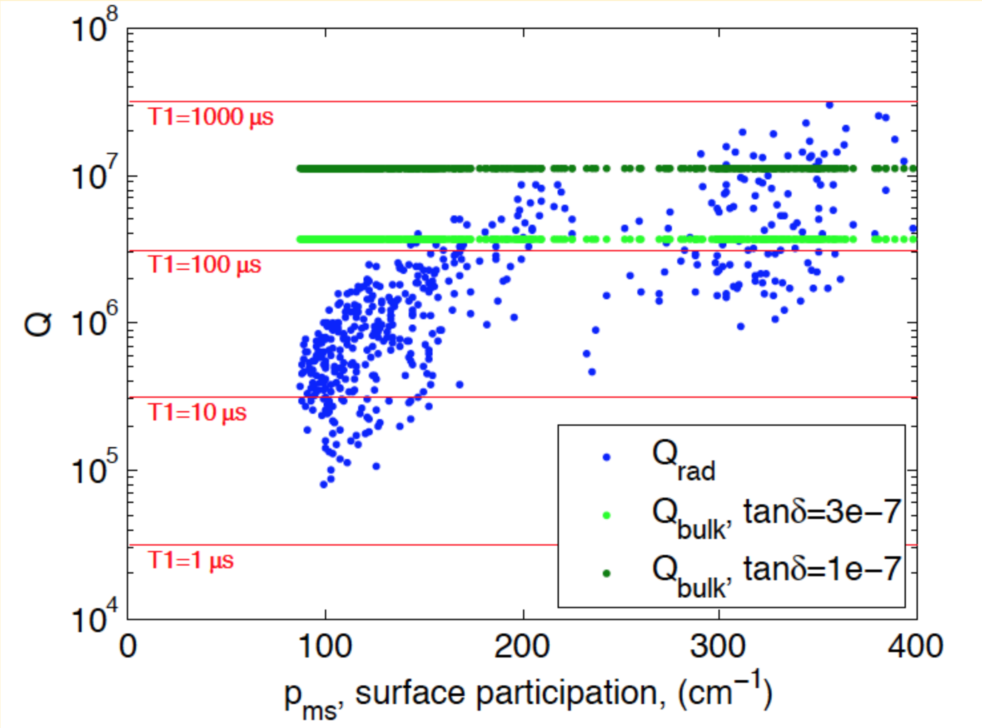
ground plane gap

Aspect Ratio: height/width of capacitor pad

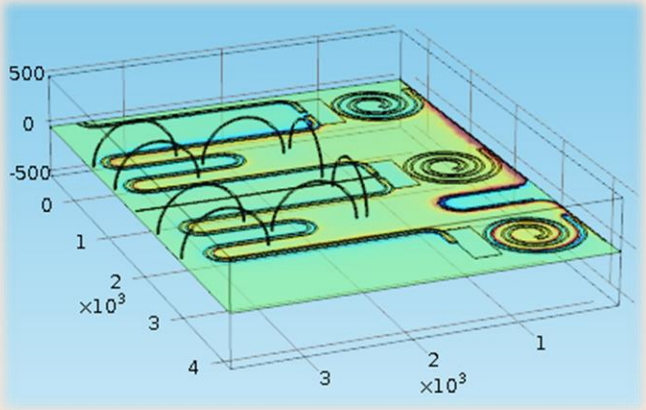
gap

Resonance freq. 5-6 GHz

Geometry: Radiation Q vs. Surface Loss

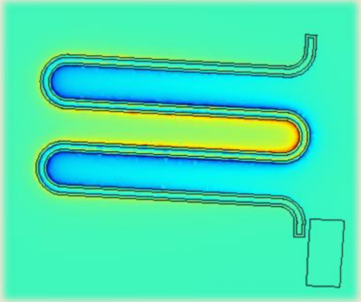


Spurious mode Identification

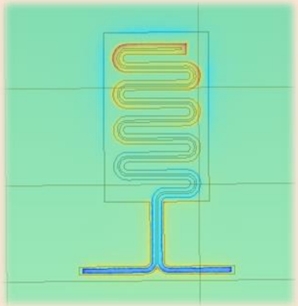


Hybrid CPW-CPS Resonators

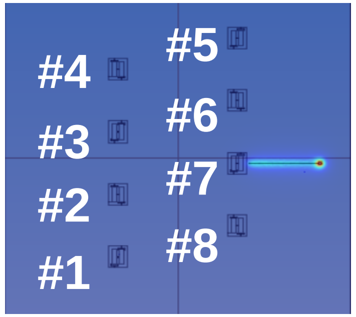
10 GHz slotline mode



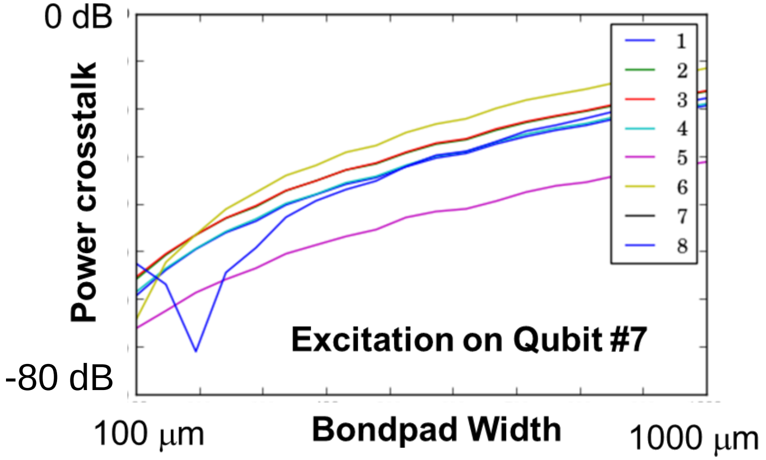
17 GHz slotline mode



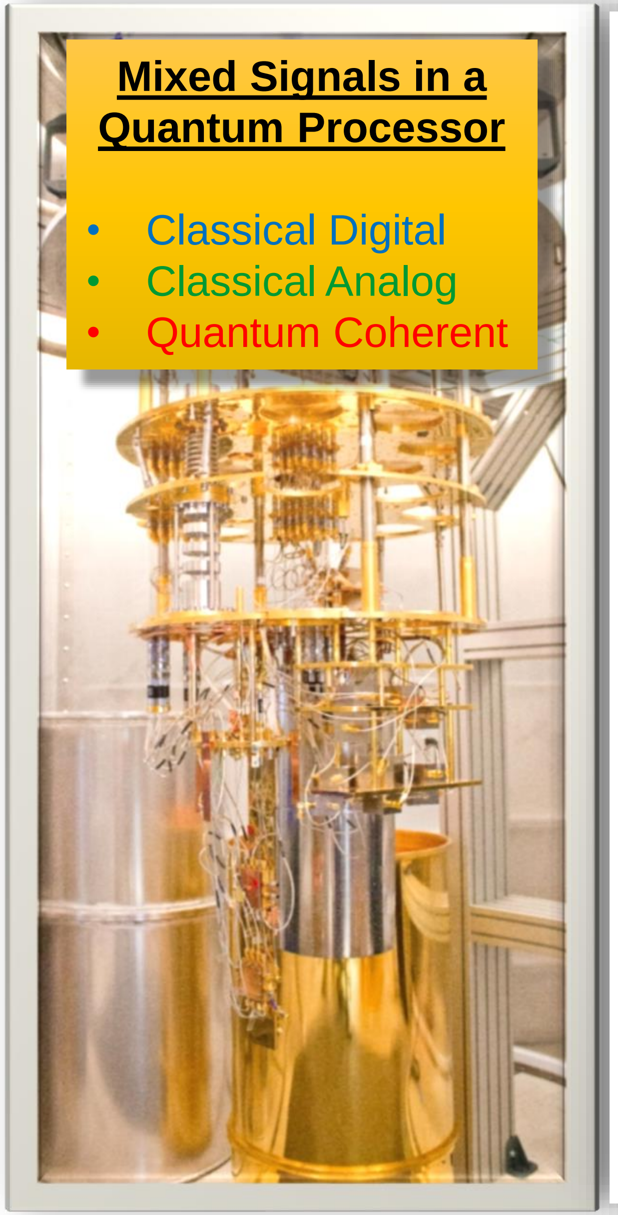
Crosstalk

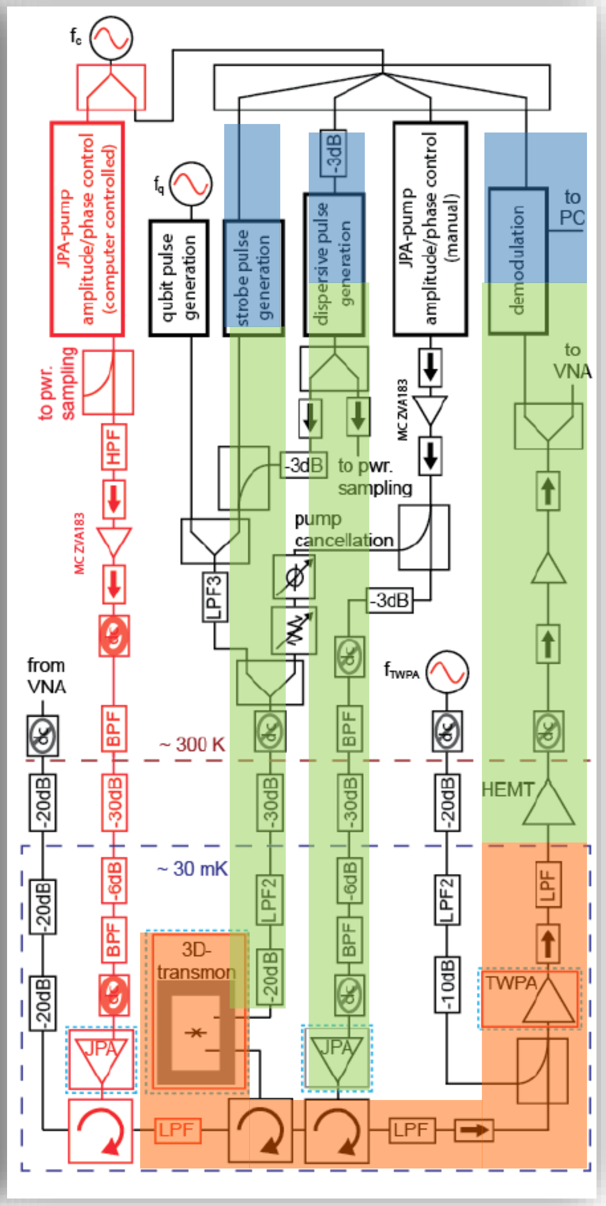


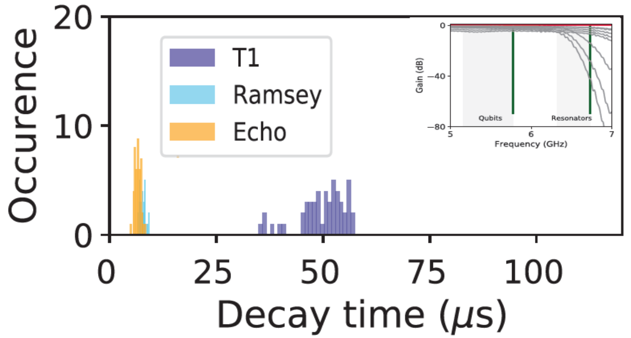
100x100 um^2 bondpad

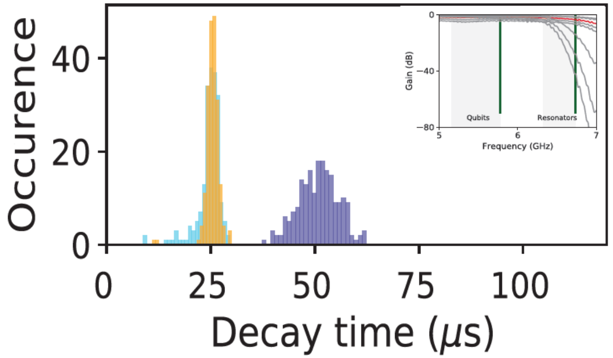


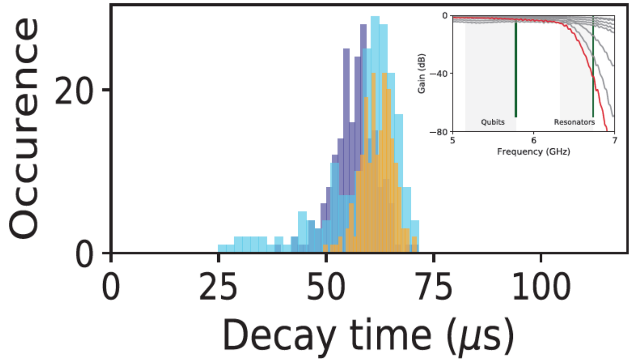
THE TYRANNY OF WIRES







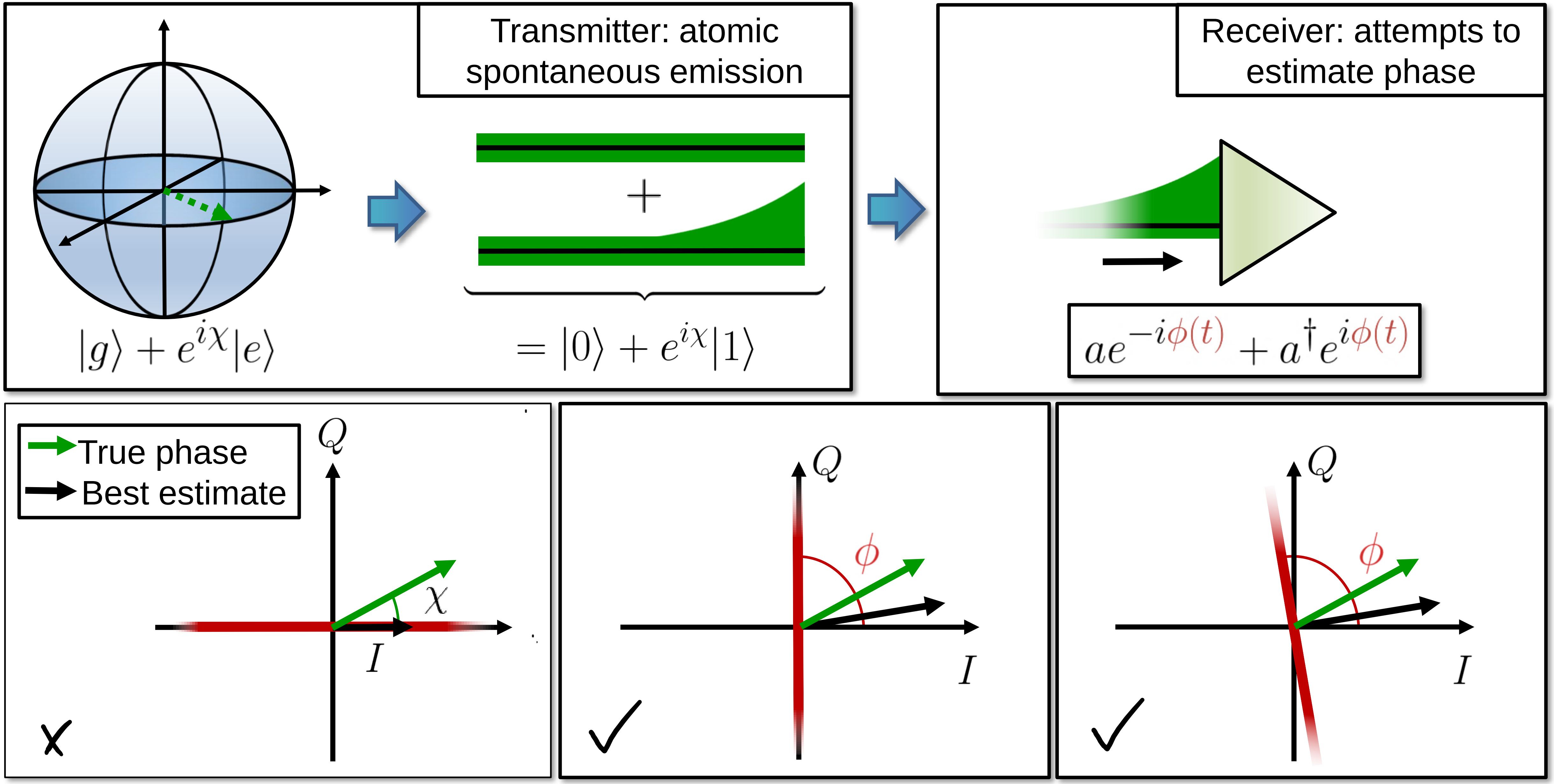




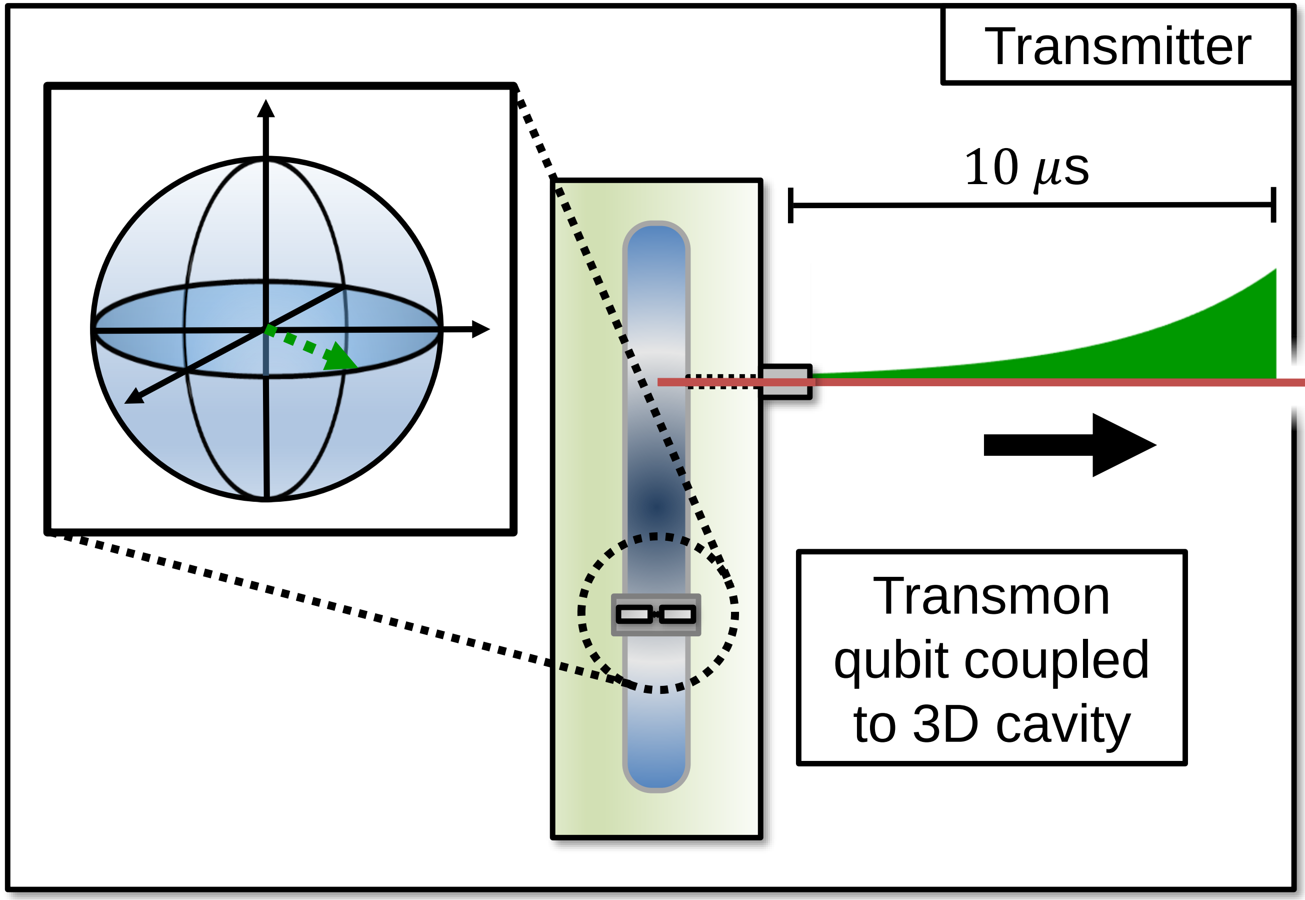
- **Need to reduce wire count !**
- **Need to reduce wire complexity**
- **Quantum data transmission & conversion**
  - optical
  - acoustic
  - classical analog
  - classical digital
- **Cryogenic data processing ?**

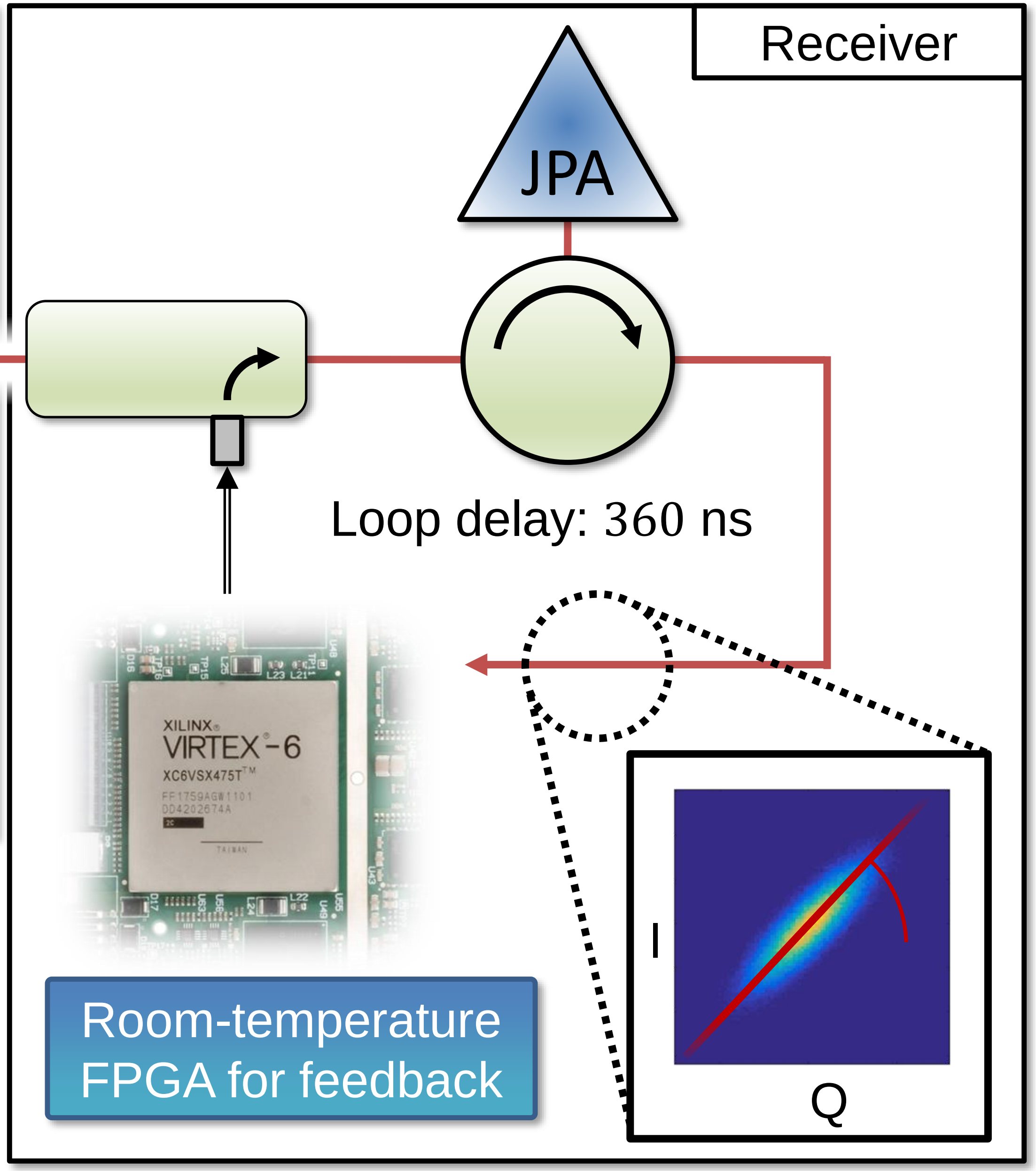
TRUE MEASUREMENTS OF PHASE

ADAPTIVE PHASE MEASUREMENT



EXPERIMENTAL SETUP – ADAPTIVE DETECTION





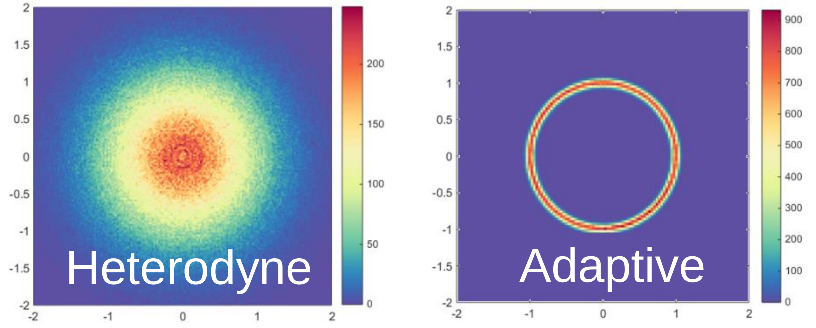
Experimental sequence

- Transmitter prepares photon with chosen phase
- Receiver adapts measurement as photon arrives
- Perform qubit state tomography

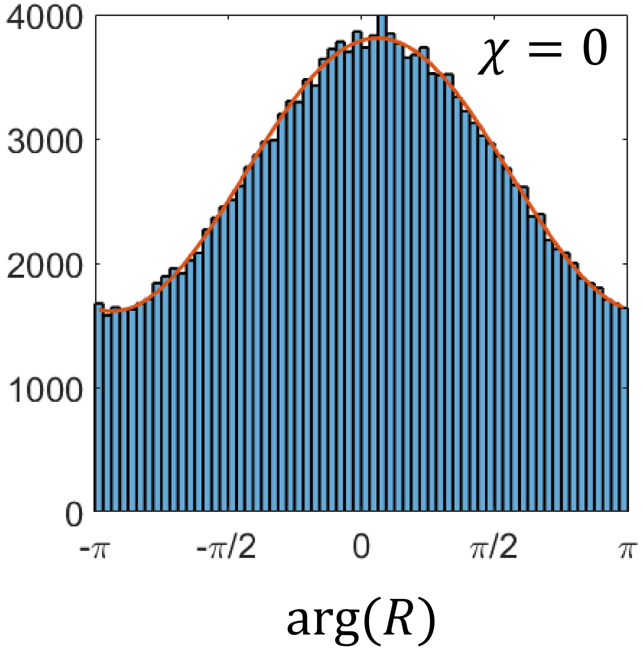
PHASE ESTIMATION: RECEIVER PERFORMANCE

$$R \equiv \int_0^\infty e^{i\phi(t)} \sqrt{u(t)} V(t) dt$$

Amplifier phase | Photon mode shape | Amplifier output



Estimation of photon phase: $\arg(R)$



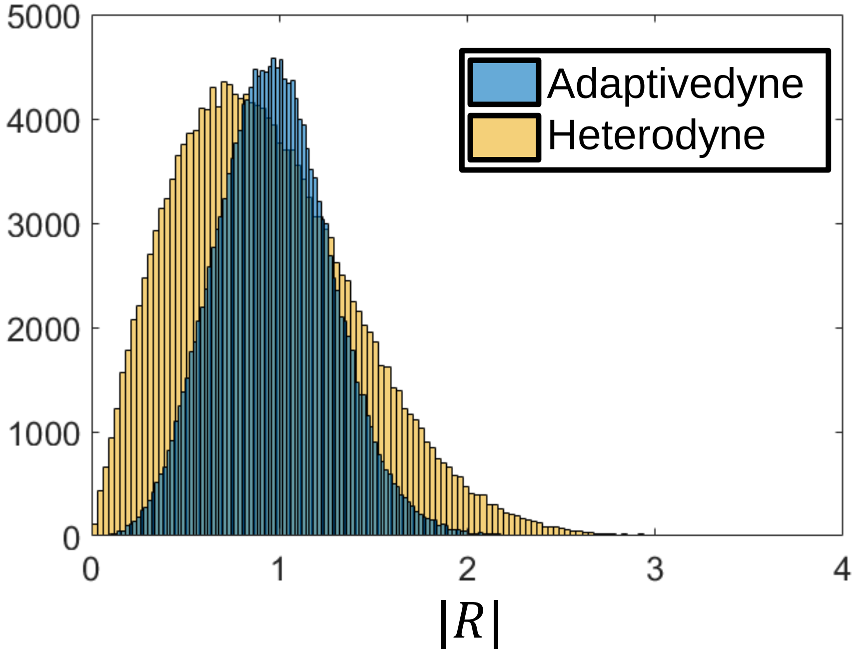
Holevo variance

Adaptivedyne:
19.4 ±0.3

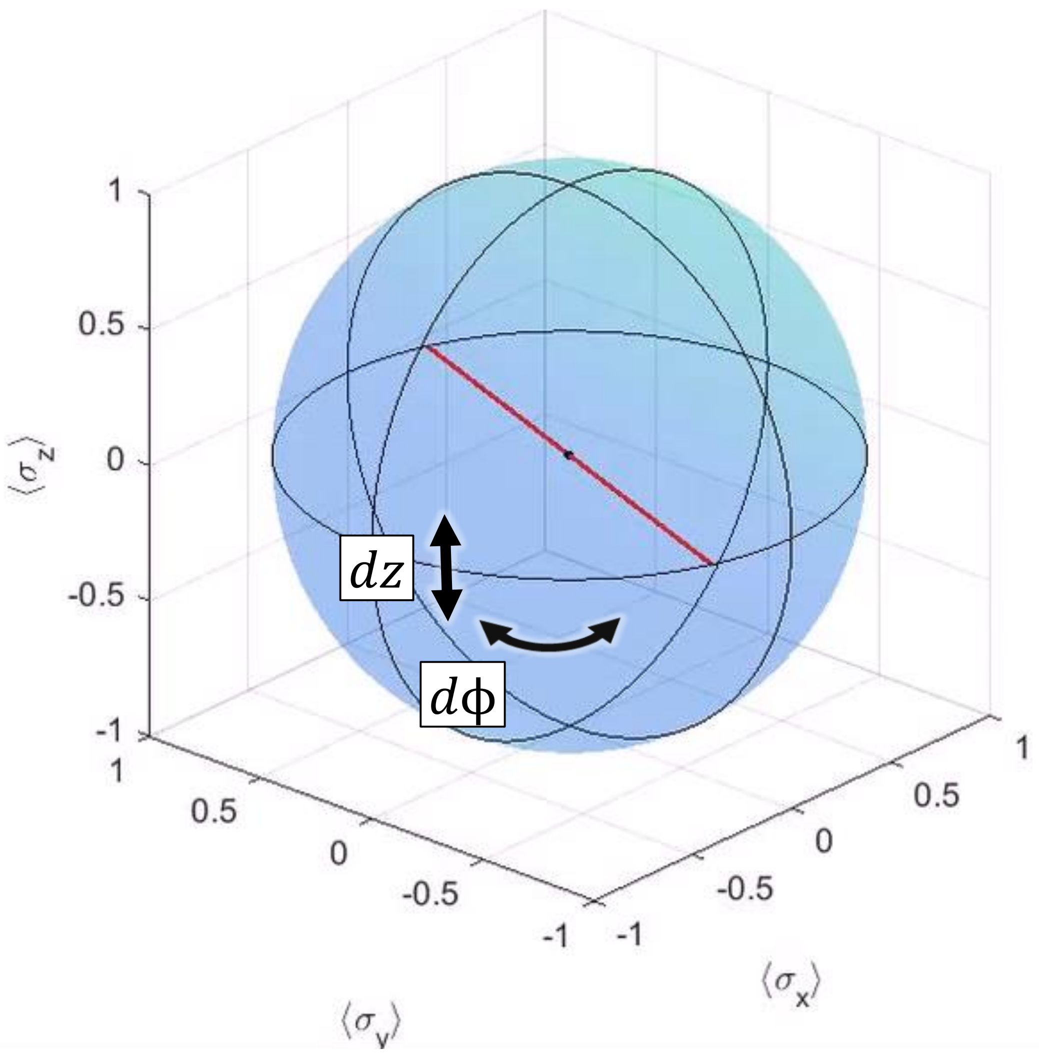
Heterodyne
22.8 ± 0.4

Quantum limit (η=0.21)
17.7

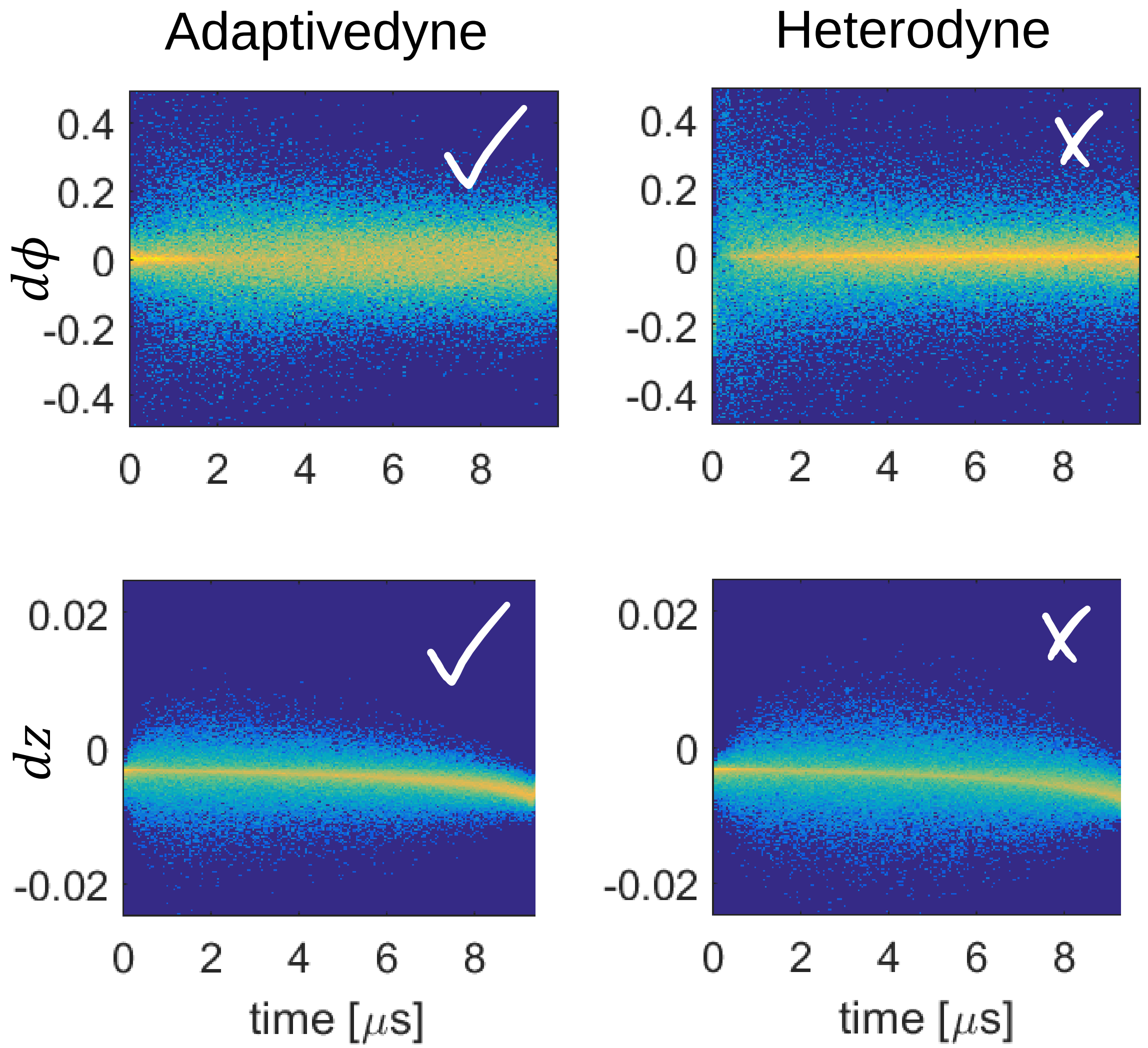
Photon number information: $|R|$



EXPERIMENTAL ADAPTIVEDYNE BACK-ACTION

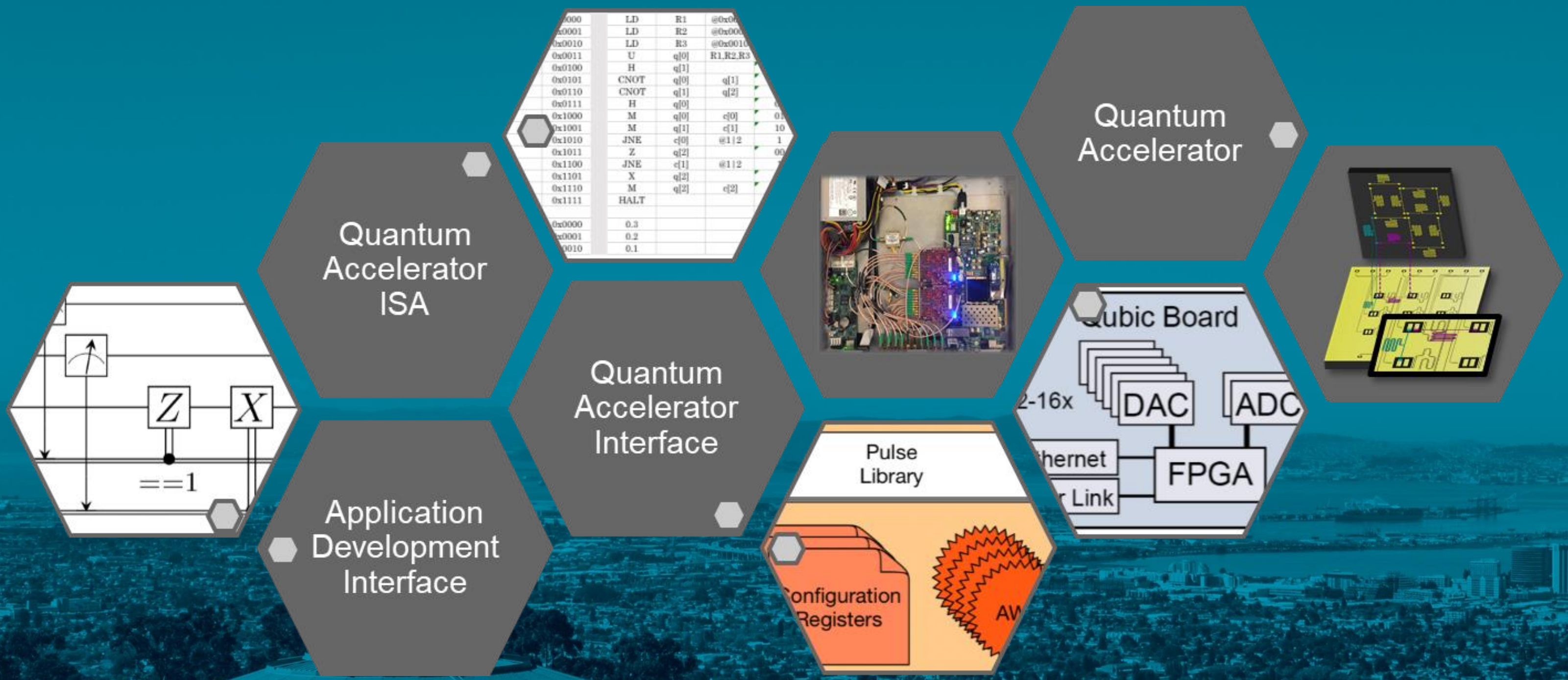


Comparison of back-action
(histogram of $d\rho$, 50 ns time step)



ADVANCED QUANTUM TESTBED

ASCR: TESTBED



- **Full, open access to all levels of the stack**
- **Modular structure to benchmark different technologies**
- **AQT scientists partner with community users to run algorithms**
- **Broad science mandate**
- **Complementary to focused industry efforts**

KEY QUESTIONS FOR THE NEXT 5 - 10 YEARS

How do we stabilize quantum coherence in an open many-body quantum system? What does physics look like at the edge of the complexity frontier?

How can we efficiently sample the information in a many-body quantum system?

Can we conceive of machines to treat data fully quantum mechanically?

How do we parameterize, verify, and validate the information capacity of a complex quantum system in a “universal” way ?

What is the role of entanglement in different flavors of quantum computations?

How do we express quantum advantage? How fundamental are the classical resources needed to stabilize quantum mechanics at the many particle scale?