IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), September 2019.
Plenary presentation 4-EO-PL3 given at EUCAS, 1- 5 September 2019, Glasgow, UK.

SUPERCONDUCTING QUANTUM CIRCUITS: BALANCING ART & ARCHITECTURE

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& Lawrence Berkeley National Laboratory

BERKELEY LAB

EUCAS 2019 Plenary: Glasgow, UK

Berkeley

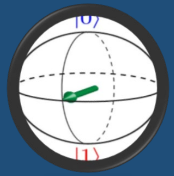
the Hertz FOUNDATION freedom to innovate

NSF

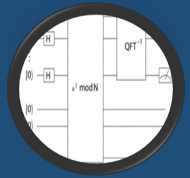
IARPA

LPS

ONR

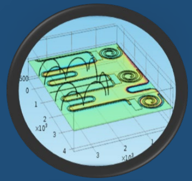


- ***CLASSICAL VERSUS QUANTUM INFORMATION***

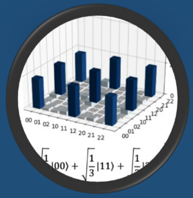


- ***QUANTUM ALGORITHMS***

- ***A SUPERCONDUCTING QUANTUM BIT***



- ***QUANTUM PROCESSORS: MATERIALS & WIRES***

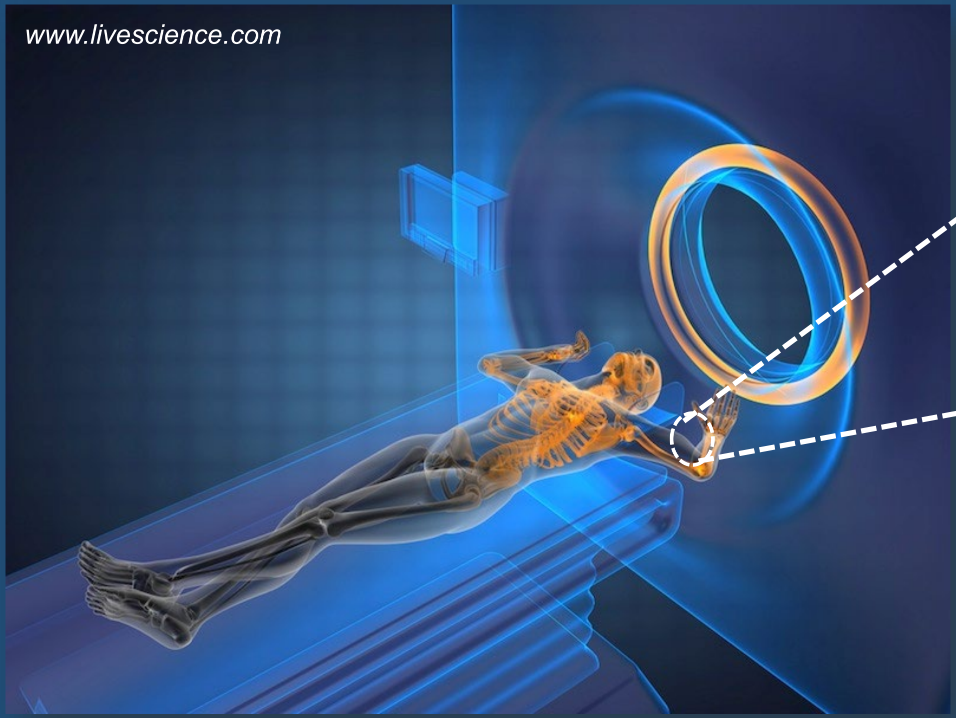


- ***EARLY COMPUTATIONS***

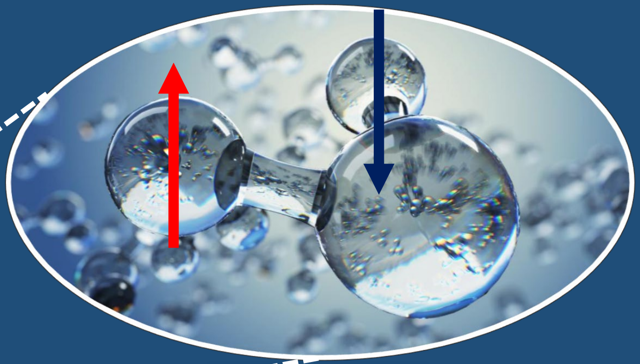
- ***THE ADVANCED QUANTUM TESTBED***

THE QUANTUM WORLD AROUND US

A MRI Scan Relies on Quantum Mechanics!



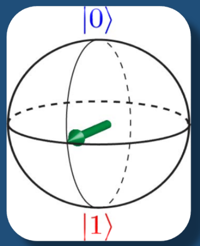
Water molecules have two hydrogens which have nuclear spin (up or down)



www.medicalnewstoday.com

Apply magnetic field to measure spin

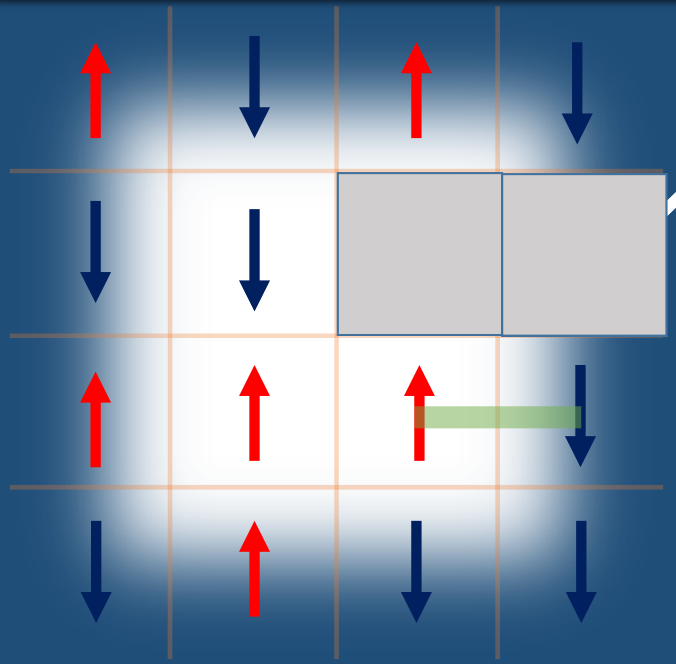
- Always observe ↑ or ↓
- Prepare superposition: ← = ↑ + ↓
- Would measure: 50% ↑ , 50% ↓



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

GATE BASED QUANTUM ALGORITHMS

QUANTUM POWER

- Pattern detection / Fourier analysis
- Efficiently searching a large database
- Finding energy (cost) minima
- Matrix math
  - Linear algebra
  - Machine learning
  - Diagonalization

Challenges:

i. Decoherence limits complexity (need >100 gates with 99.9 fidelity)

ii. Scaling of classical resources still unknown

(data input/output, error correction, …)

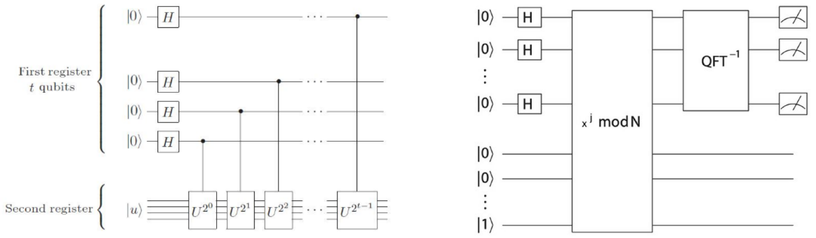
High-tech	• Machine learning and artificial intelligence, such as neural networks • Search • Bidding strategies for advertisements • Cybersecurity • Online and product marketing • Software verification and validation	IBM Alibaba Google Microsoft	Telstra Baidu Samsung
Industrial goods	• Logistics: scheduling, planning, product distribution, routing • Automotive: traffic simulation, e-charging station and parking search, autonomous driving • Semiconductors: manufacturing, such as chip layout optimization • Aerospace: R&D and manufacturing, such as fault-analysis, stronger polymers for airplanes • Material science: effective catalytic converters for cars, battery cell research, more-efficient materials for solar cells, and property engineering uses such as OLEDS	Airbus NASA Northrop Grumman Daimler Raytheon	BMW Volkswagen Lockheed Martin Honeywell Bosch
Chemistry and Pharma	• Catalyst and enzyme design, such as nitrogenase • Pharmaceuticals R&D, such as faster drug discovery • Bioinformatics, such as genomics • Patient diagnostics for health care, such as improved diagnostic capability for MRI	BASF Biogen Dow Chemical	JSR DuPont Amgen
Finance	• Trading strategies • Portfolio optimization • Asset pricing • Risk analysis • Fraud detection • Market simulation	J.P. Morgan Commonwealth Bank	Barclays Goldman Sachs
Energy	• Network design • Energy distribution • Oil well optimization	Dubai Electricity & Water Authority	BP

Source: BCG analysis.

PURE QUANTUM ROUTINES

Shor Factoring Algorithm:

- Exponential speed up over best known classical algorithms
- Modular arithmetic and period finding (QFT)

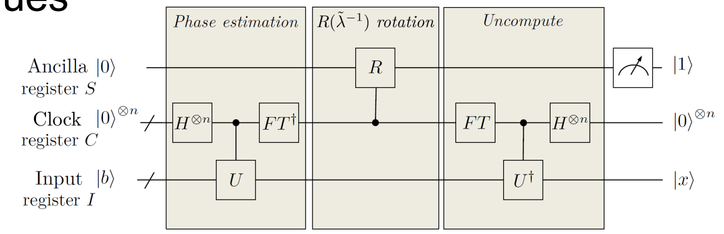


HHL Linear Equation Algorithm:

- Exponential speed up over best known classical algorithms
- Use phase estimation to approximate eigenvalues

$A\vec{x} = \vec{b}$

$A|x\rangle = |b\rangle$

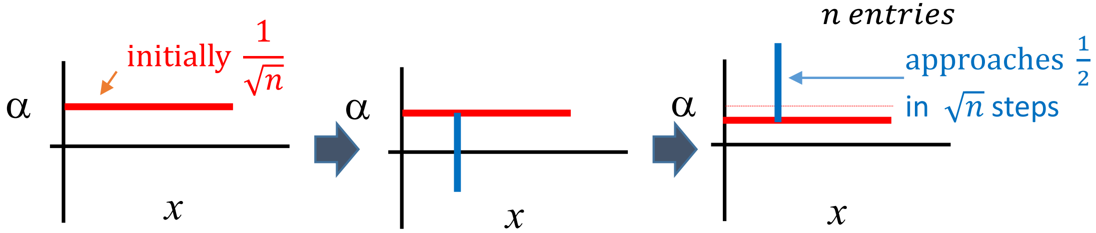


arXiv:1802.08227v1

Grover Search Algorithm:

- Polynomial speed up over best known classical algorithms $\sqrt{n}$ versus n
- Relies on phase inversion and mean subtraction

$f(x) = 1 \; for \; x = x^* \;\; else \; f(x) = 0 \qquad |\Psi\rangle = \sum_{n \; entries} \alpha_n |x\rangle$



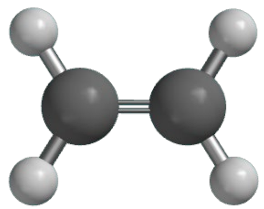
Some Challenges..
- deep quantum circuits (many gates)
- fault tolerance, error correction
- Q-RAM
- often have fine print…

Quantum Algorithms Make use of Entanglement, Superposition, Interference, Projection,..
- need to understand resource allocation
- influence classical algorithms!

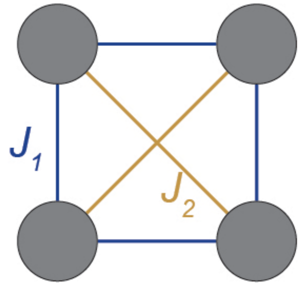
HYBRID ALGORITHMS: VQE

Goal: Minimize *cost function **H***

H encodes problem of interest, such as:



molecular structure

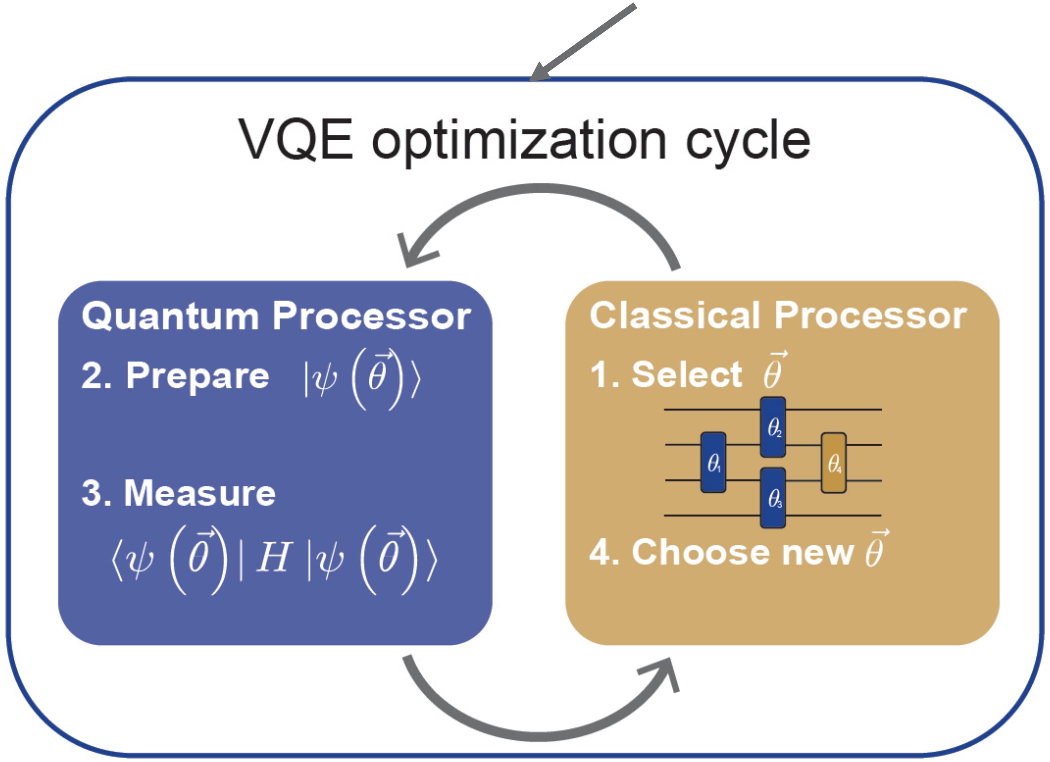


Highly correlated materials

Applications

- Drug design
- Better N_2-fixation for fertilizer production
- Understanding High-T_c superconductivity

Procedure: Map ***H*** to qubit Hamiltonian $\hat{H}$



Repeat 2-4 until convergence

OTHER HYBRID ROUTINES: OPTIMIZATION, MACHINE LEARNING, …

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QUANTUM INSPIRED CLASSICAL ROUTINES

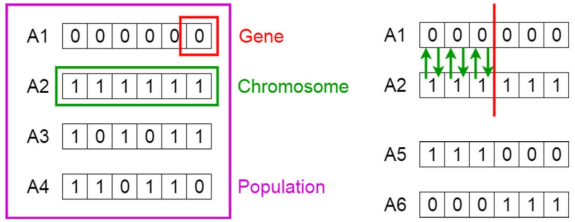
Matrix Completion Problem

(see also the Netflix problem):

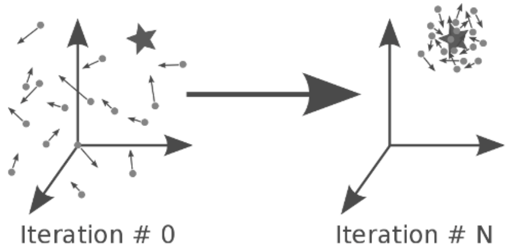
i) Sample preference matrix T_{ij} for users (i) and products (j)
ii) Low rank approximation
iii) Generate suggestions for users

T (n x m matrix): O[poly(k)poly(mn)]
Reduced rank k

Genetic Algorithms



Social Behavior Routines



Quantum Recommendation System

Iordanis Kerenidis*[1] and Anupam Prakash†[2]

1 CNRS, IRIF, Université Paris Diderot, Paris, France and Centre for Quantum Technologies, National University of Singapore, Singapore
jkeren@liafa.univ-paris-diderot.fr
2 Centre for Quantum Technologies and School of Physical and Mathematical Sciences, Nanyang Technological University, Singapore
aprakash@ntu.edu.sg

T (n x m matrix): O[poly(k)polylog(mn)]
Reduced rank k

QUANTUM COMPUTING

Major Quantum Computing Advance Made Obsolete by Teenager

- *ℓ^2 - norm sampling*

Quantum-inspired genetic algorithms

Ajit Narayanan and Mark Moore
Department of Computer Science
University of Exeter
Exeter, United Kingdom, EX4 4PT
ajit@dcs.exeter.ac.uk

- *Interfere different "universes" in parallel*

Genetic Quantum Algorithm and its Application to Combinatorial Optimization Problem

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- *Each gene is a classical superposition*
- *Use rotating gates for diversity*

Quantum-Inspired Particle Swarm Optimization Algorithm Encoded by Probability Amplitudes of Multi-Qubits

Xin Li[1], Huangfu Xu[2], Xuezhong Guan[2]
[1]School of Computer and Information Technology, Northeast Petroleum University, Daqing, China
[2]School of Electrical and Information Engineering, Northeast Petroleum University, Daqing, China
Email: lixin_dq@163.com

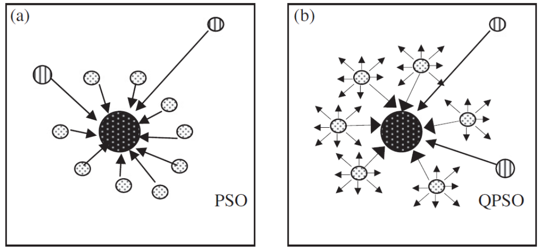
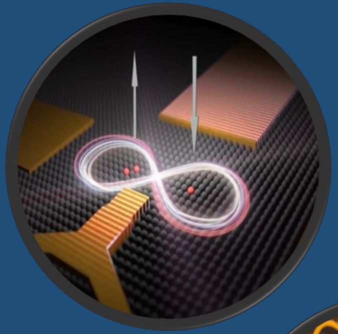


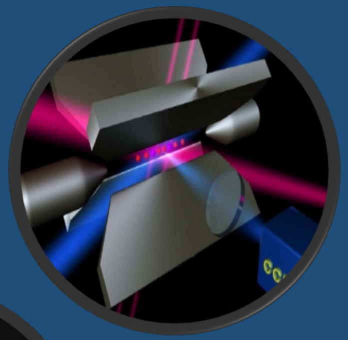
Fig. 1. The movements of particles in PSO and QPSO; (a) PSO (b) QPSO.

PHYSICAL IMPLEMENTATIONS

Dopants in Silicon / Diamond
www.sciencedaily.com

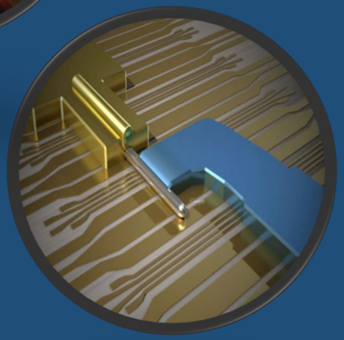


Trapped Ions
www.quantumoptics.at



Photonic Circuits
www.phys.org

Superconducting Circuits
www.qnl.berkeley.edu

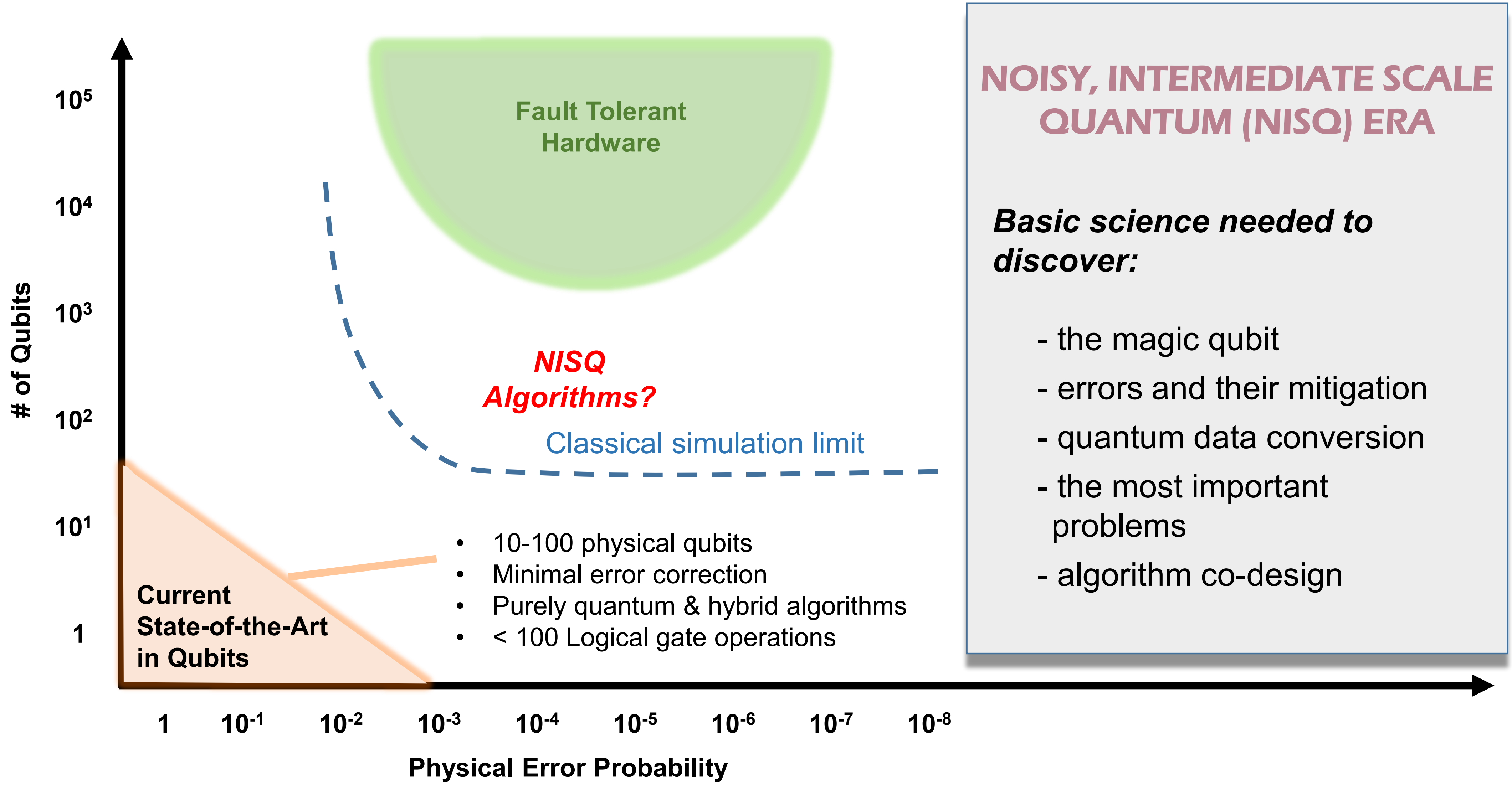


Topological Wires
www.microsoft.com

	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

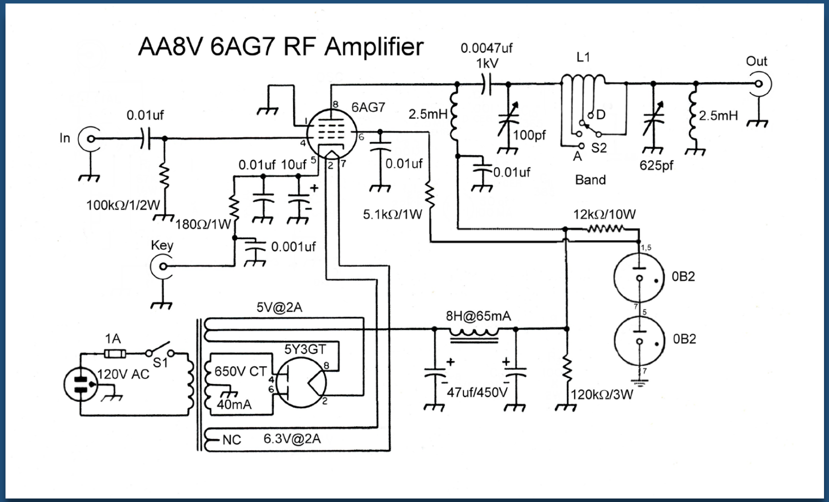
Sources: BCG analysis; expert interviews.
[1]Noisy Intermediate-Scale Quantum devices era.
[2]Currently only technology with external cloud access; several forms (charge, flux, phase) of qubits exist but most pursue a less noise-sensitive charge-based qubit (transmon).
[3]Additional approaches include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

SURPASSING THE CLASSICAL LIMIT



MAKING AN ELECTRICAL CIRCUIT QUANTUM

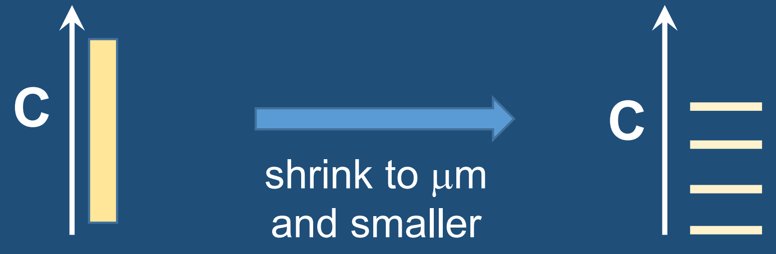
ACCESSING THE QUANTUM WORLD



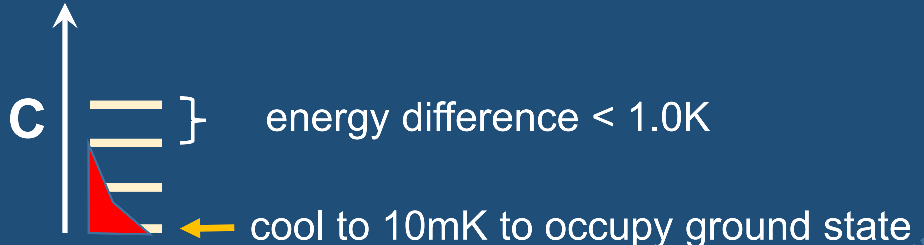
- Combination of *R, L, C* (linear or nonlinear)
- Excite with voltages / currents (AC or DC)
- Classically, these quantitates can take on any continuous values

QUANTUM MECHANICS SAYS THESE QUANTITIES CAN BE FUNADEMENTALLY DISCRETE!

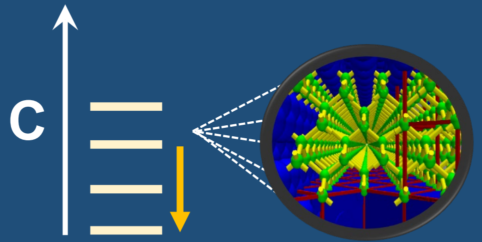
- Granularity becomes apparent at the nanoscale



- Cryogenic operation to occupy single state



- Isolate from environment (loss/dephasing)



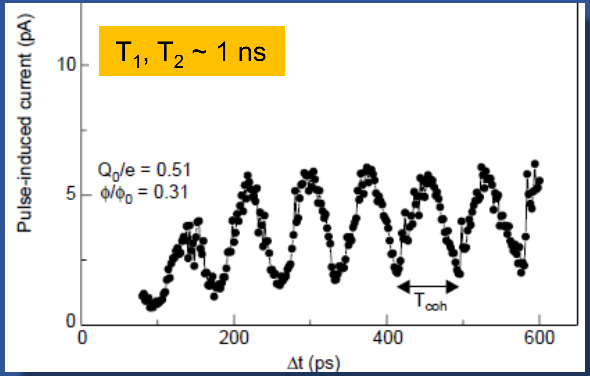
decoherence due to coupling to unwanted resonances

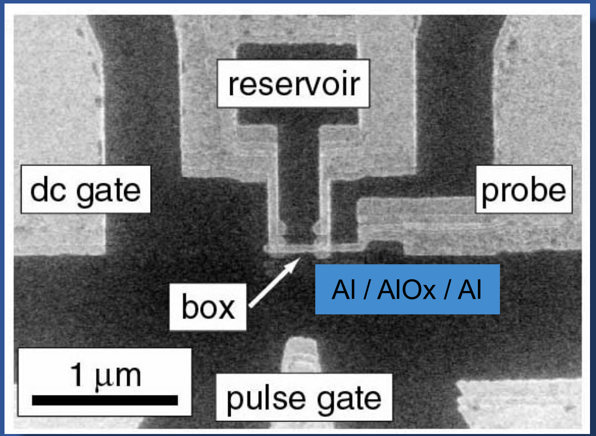
TWENTY YEARS OF COHERENCE

Coherent control of macroscopic quantum states in a single-Cooper-pair box

Y. Nakamura*, Yu. A. Pashkin† & J. S. Tsai*

** NEC Fundamental Research Laboratories, Tsukuba, Ibaraki 305-8051, Japan*
† CREST, Japan Science and Technology Corporation (JST), Kawaguchi, Saitama 332-0012, Japan





- NEC demonstrates coherent oscillations in 1999! (~ns coherence)
- **3D Transmon**: Reduce sensitivity to charge noise, shunt with low loss capacitors, all microwave control and readout (~ ms coherence)
  → Al/AlOx/Al Josephson junctions can be highly coherent !

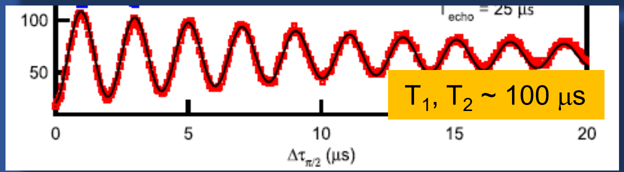
MINIMALIST QUBIT ENABLES MANY, WELL CONTROLLED EXPERIMENTS & ALLOWS US TO ENTER THE 10-100 QUBIT ERA

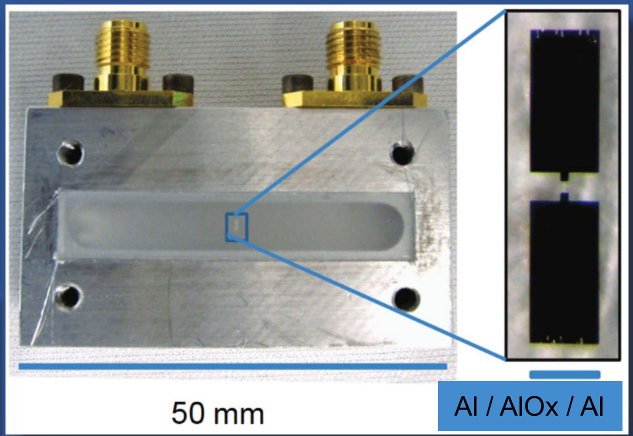
MANY OTHER, MORE FLEXIBLE DESIGNS TO EXPLORE: TUNABLE, TOPOLOGICAL CIRCUITS, NON S-WAVE MATERIALS, NOVEL TUNNEL BARRIERS

Observation of High Coherence in Josephson Junction Qubits Measured in a Three-Dimensional Circuit QED Architecture

Hanhee Paik,[1] D. I. Schuster,[1,2] Lev S. Bishop,[1,3] G. Kirchmair,[1] G. Catelani,[1] A. P. Sears,[1] B. R. Johnson,[1,4] M. J. Reagor,[1] L. Frunzio,[1] L. I. Glazman,[1] S. M. Girvin,[1] M. H. Devoret,[1] and R. J. Schoelkopf[1]

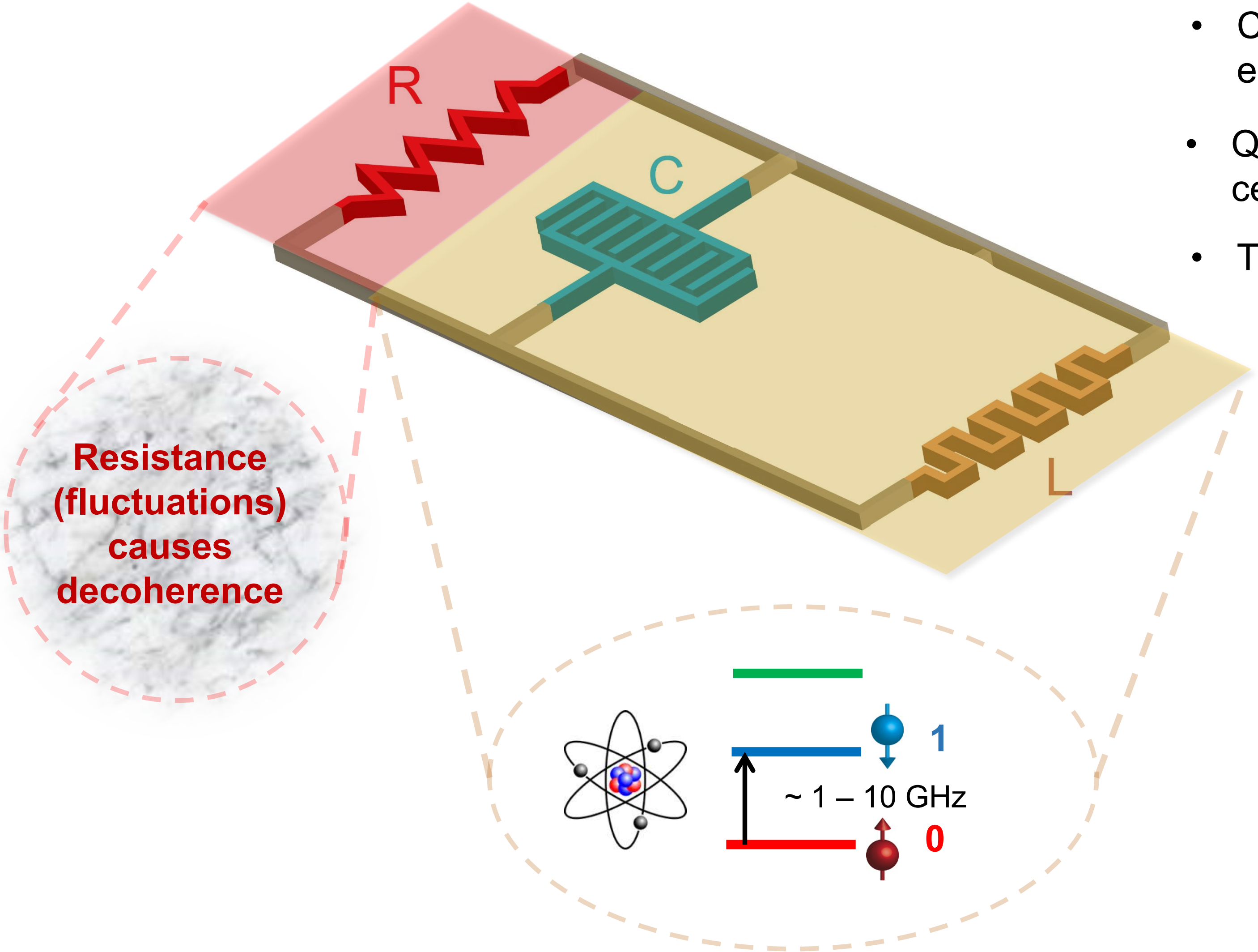
[1]*Department of Physics and Applied Physics, Yale University, New Haven, Connecticut 06520, USA*
[2]*Department of Physics and James Franck Institute, University of Chicago, Chicago, Illinois 60637, USA*
[3]*Joint Quantum Institute and Condensed Matter Theory Center, Department of Physics, University of Maryland, College Park, Maryland 20742, USA*
[4]*Raytheon BBN Technologies, Cambridge, Massachusetts 02138, USA*

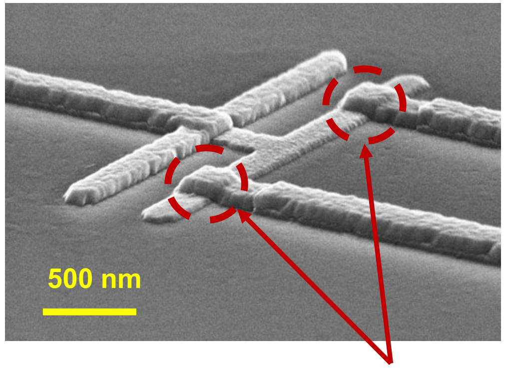




A QUBIT IS JUST A NONLINEAR OSCILLATOR

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



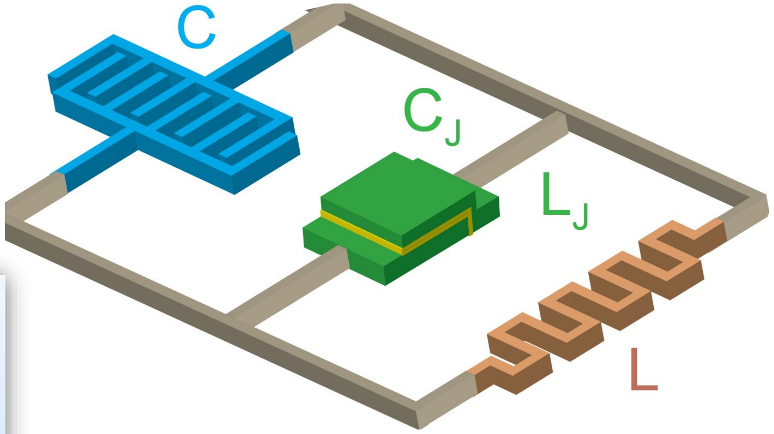


Al/AlOx/Al Josephson tunnel junctions

OTHER WAYS TO RELAX QUANTUM SUPERPOSITION…

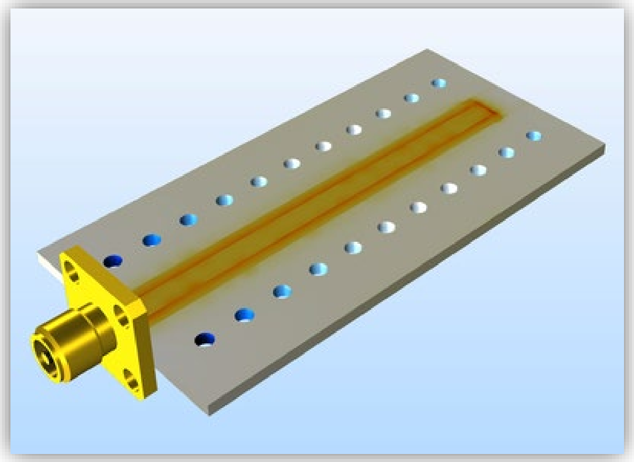
Radiative Losses

R ~ 377 Ω

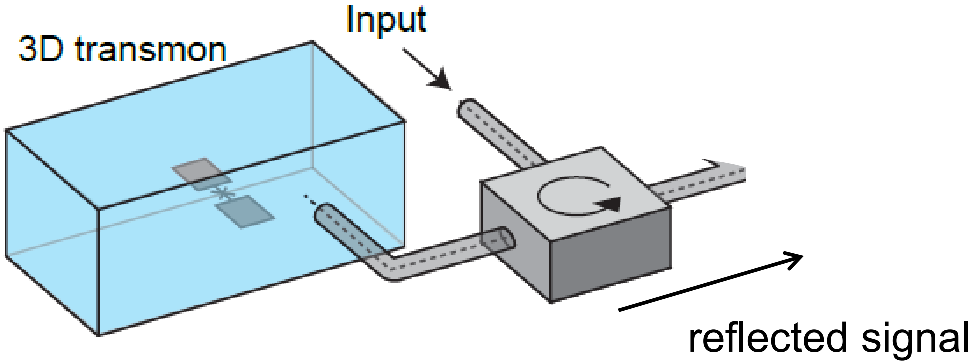


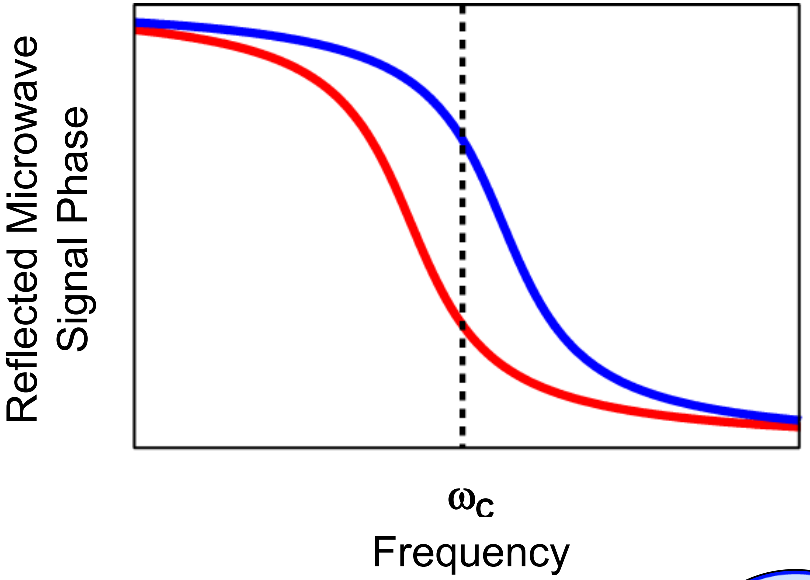
Coupling Losses

R ~ 50 Ω

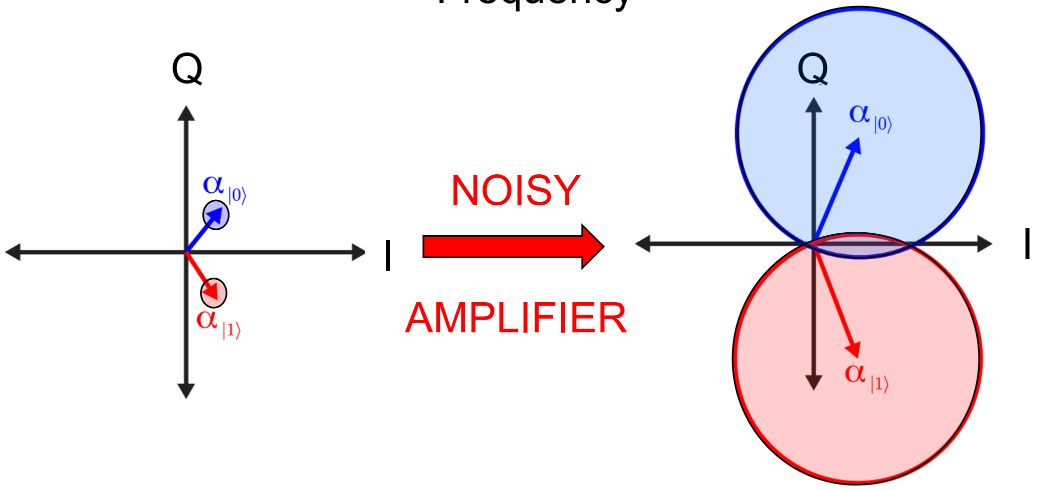


MEASURING QUBIT STATES: MICROWAVE REFLECTOMETRY

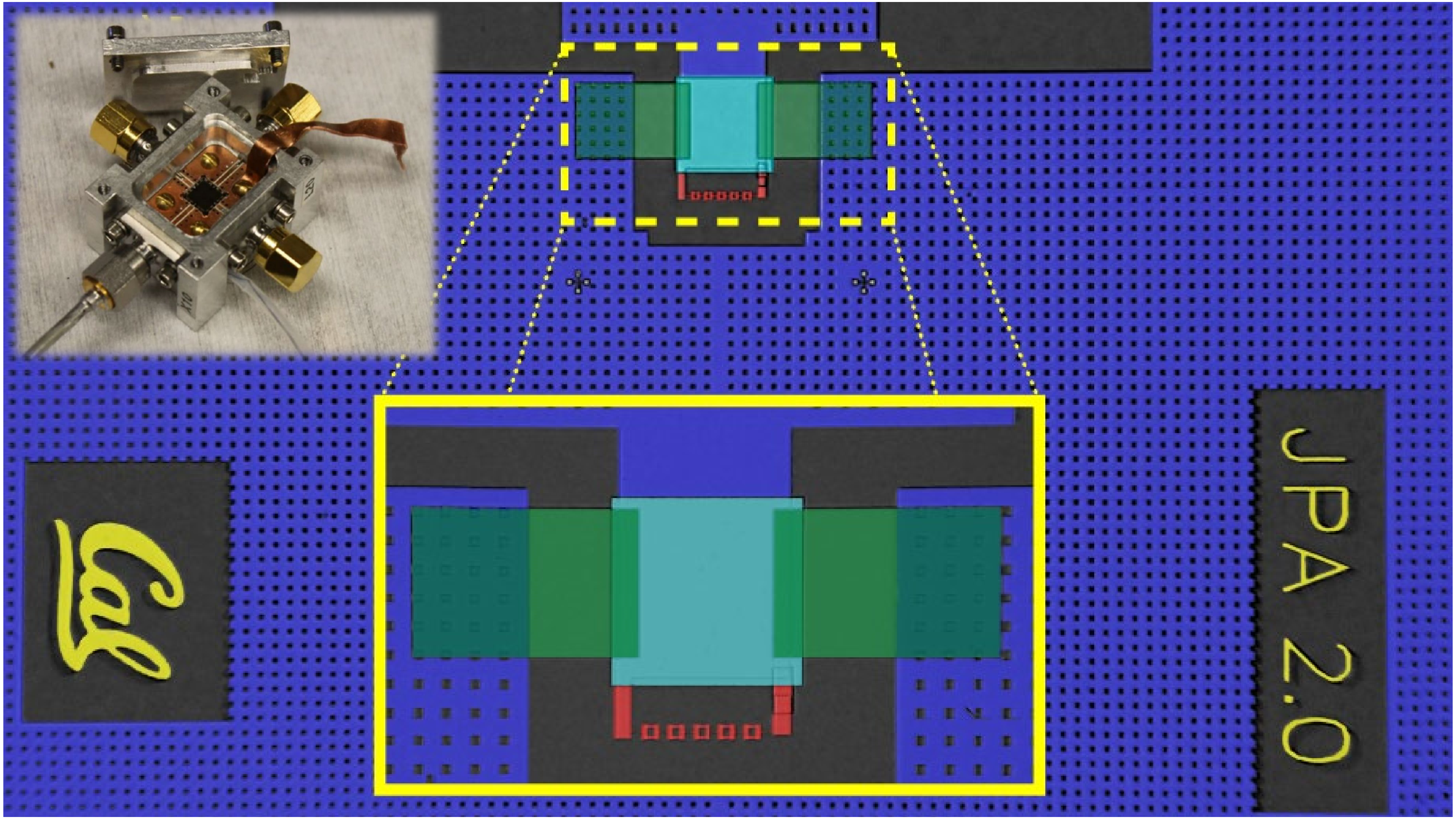




$$A\sin(\omega t+\phi) = A\sin(\omega t)\cos(\phi) + A\cos(\omega t)\sin(\phi)$$
$$= \underbrace{[A\cos(\phi)]}_{I}\sin(\omega t) + \underbrace{[A\sin(\phi)]}_{Q}\cos(\omega t)$$



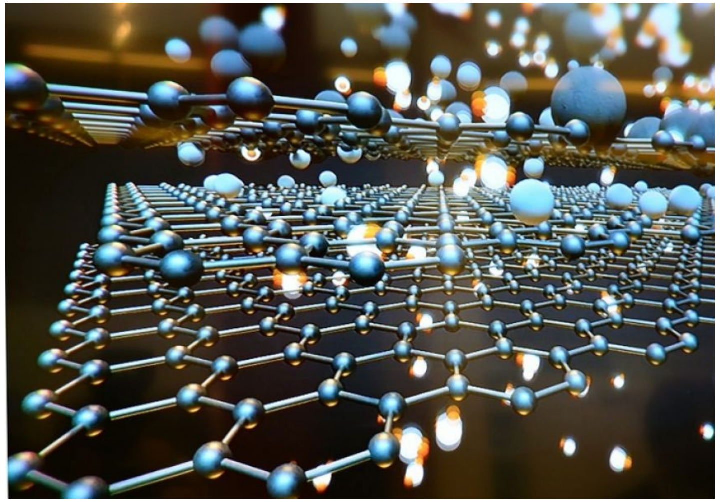
- Measure Single Quadrature
- Homodyne Measurement: Voltage (Phase 'Q')

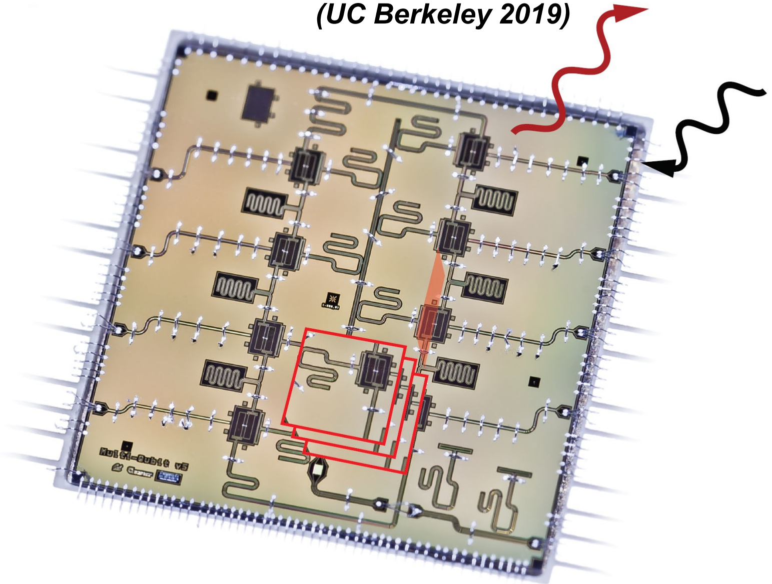

Cal
JPA 2.0

SCALING UP TO QUANTUM PROCESSORS

- **High-Coherence Materials**
- **Signal Processing**

ENGINEERING SINGLE QUANTA FOR QIS





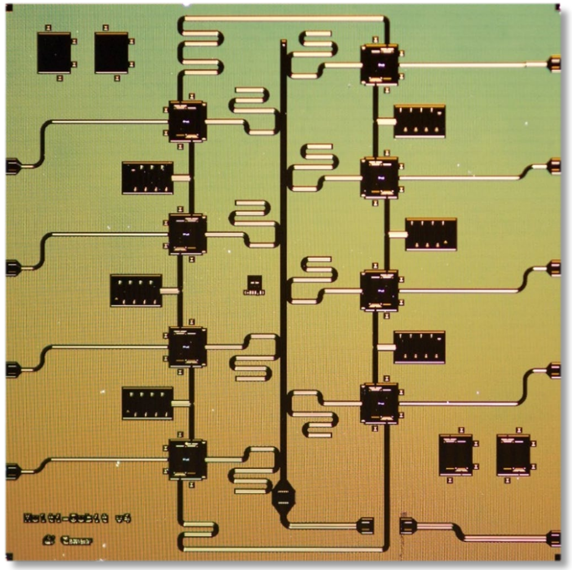
Quantum Materials

- Assist / encourage nature to assemble complex structures
- Quantum coherence is preserved via structural perfection & symmetry
- Engineering applications harness emergent phenomena

Quantum Devices

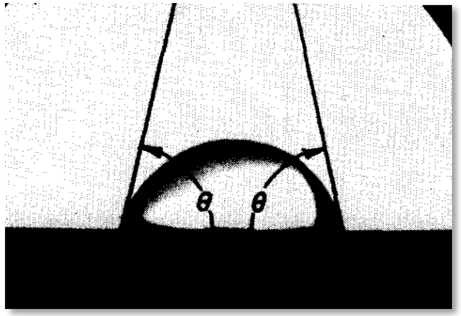
- Complete design and synthesis of quantum matter!
- Quantum coherence sensitive to (needed) surfaces/interfaces & asymmetry
- Read / write access to individual quanta
- Can access active control

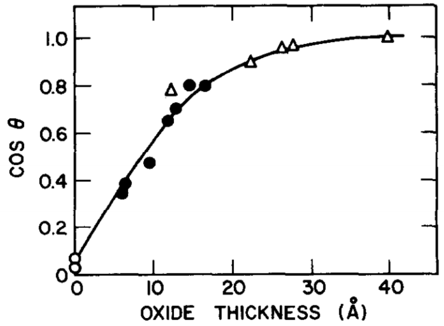
QUBITS AND THEIR MANY FACETS



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**

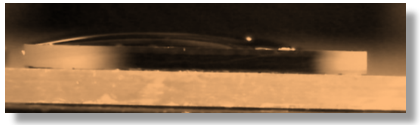
- Planar devices have many surfaces/interfaces that can host defects



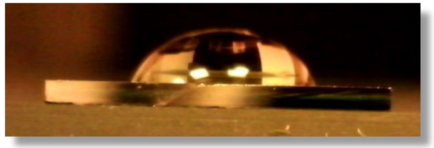


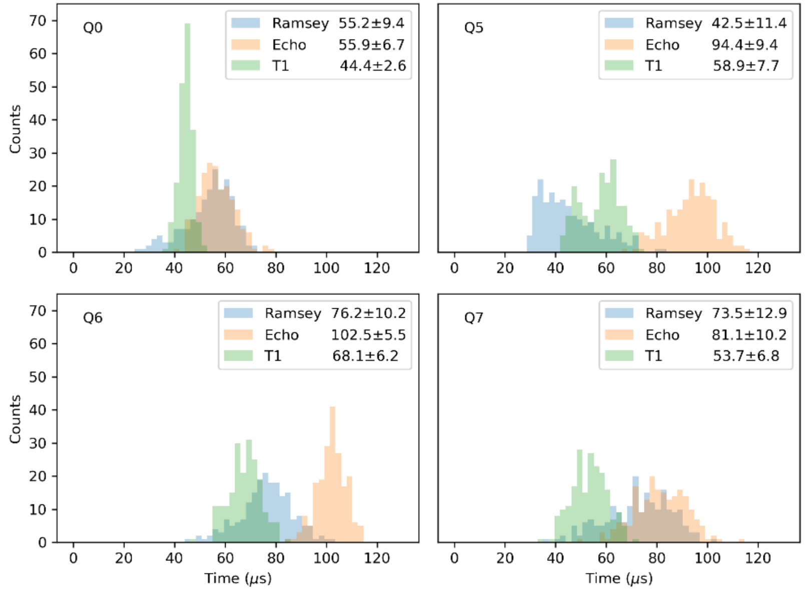
R. Williams and A.M. Goodman. “Wetting of thin layers of SiO_2 by water.” Appl. Phys. Lett. 25, 531 (1974)

- Rapid non-destructive hydro-metrology!



targeted HF etch → **doubled T_1**



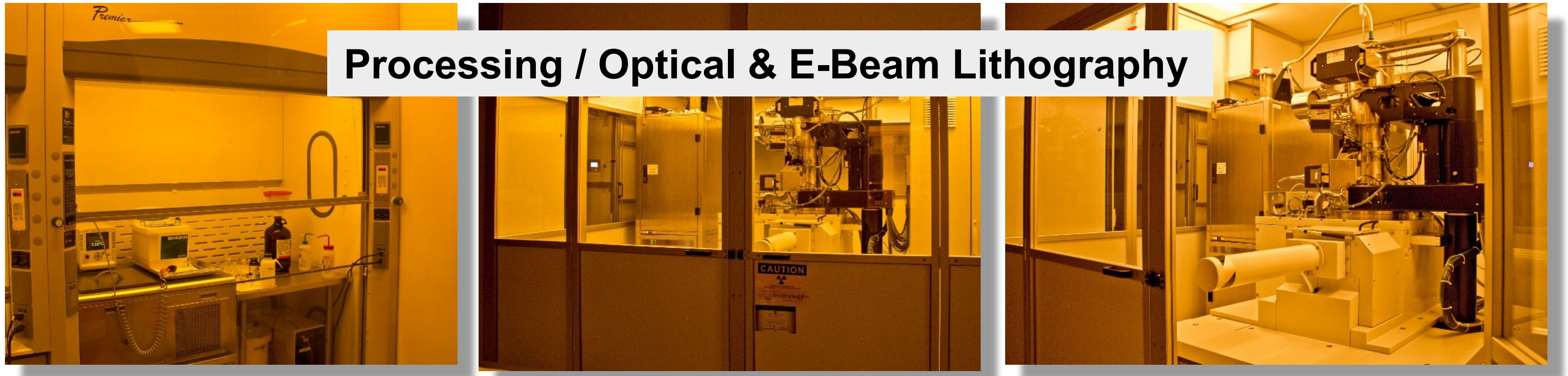


WAFER SCALE PRODUCTION OF SC DEVICES

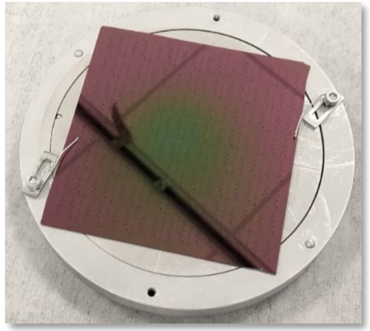
Deposition / Packaging / Inspection

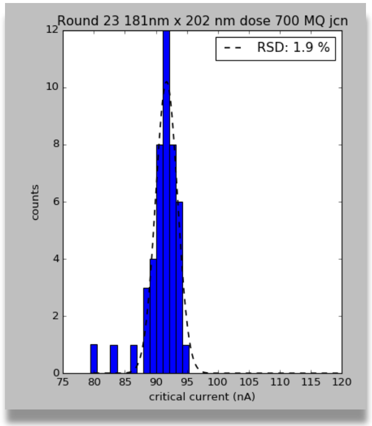
PARTICLE CLASS: 10,000 1000

Processing / Optical & E-Beam Lithography



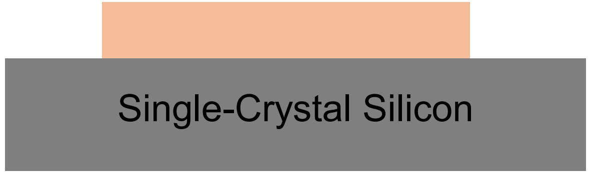
100 100 10



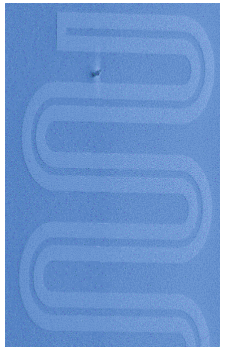


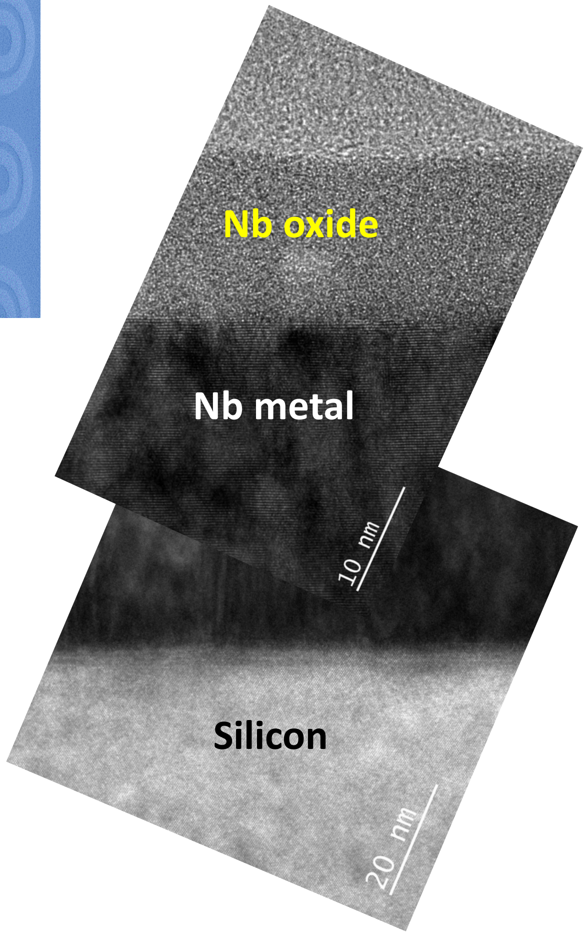
- 64 x 8-qubit processors
- 2 days / wafer for junction processing
- 99.4% test junction yield

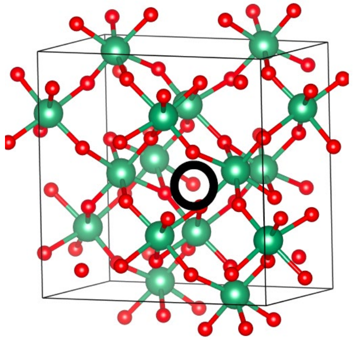
RESONATORS IN SUPERCONDUCTING CIRCUITS



The resonator structure



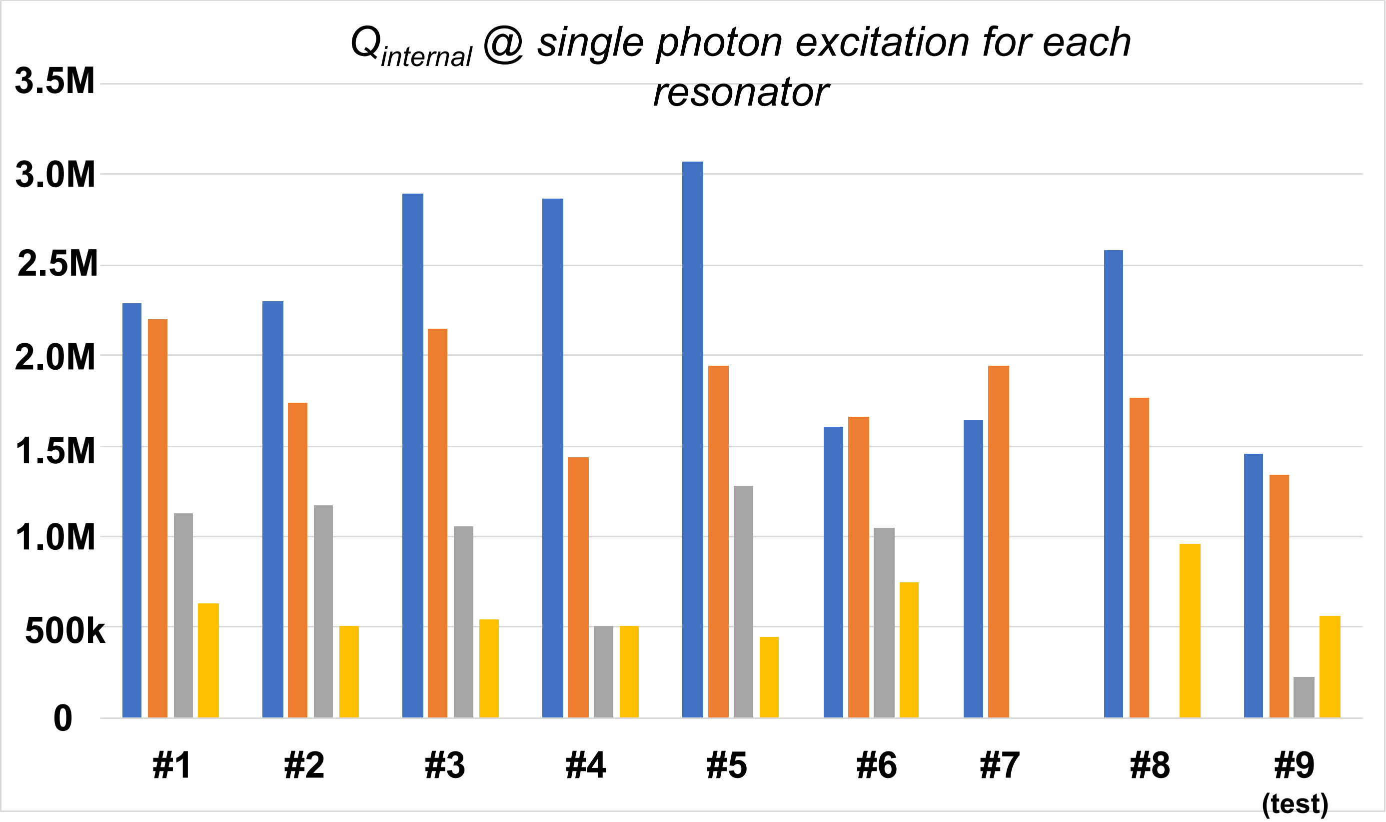


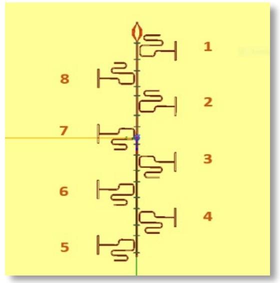


Niobium Oxides under strain or with oxygen vacancies may be magnetic (theory)

X-ray Depth Profile through Niobium

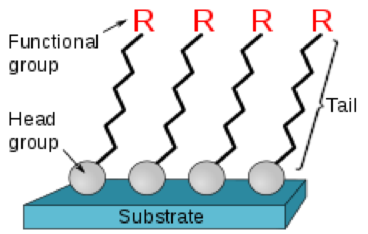
TRYING TO CLEAN UP OUR ACT!





Standard process

SAM under Nb



SAM in gaps + etch

Etch

Planar Superconducting Resonators with Internal Quality Factors above One Million

A. Megrant,[1,2] C. Neill,[1] R. Barends,[1] B. Chiaro,[1] Yu Chen,[1] L. Feigl,[2] J. Kelly,[1] Erik Lucero,[1] Matteo Mariantoni,[1,3] P. J. J. O'Malley,[1] D. Sank,[1] A. Vainsencher,[1] J. Wenner,[1] T. C. White,[1] Y. Yin,[1] J. Zhao,[1] C. J. Palmstrøm,[2,4] John M. Martinis,[1,3] and A. N. Cleland[1,3, a)]

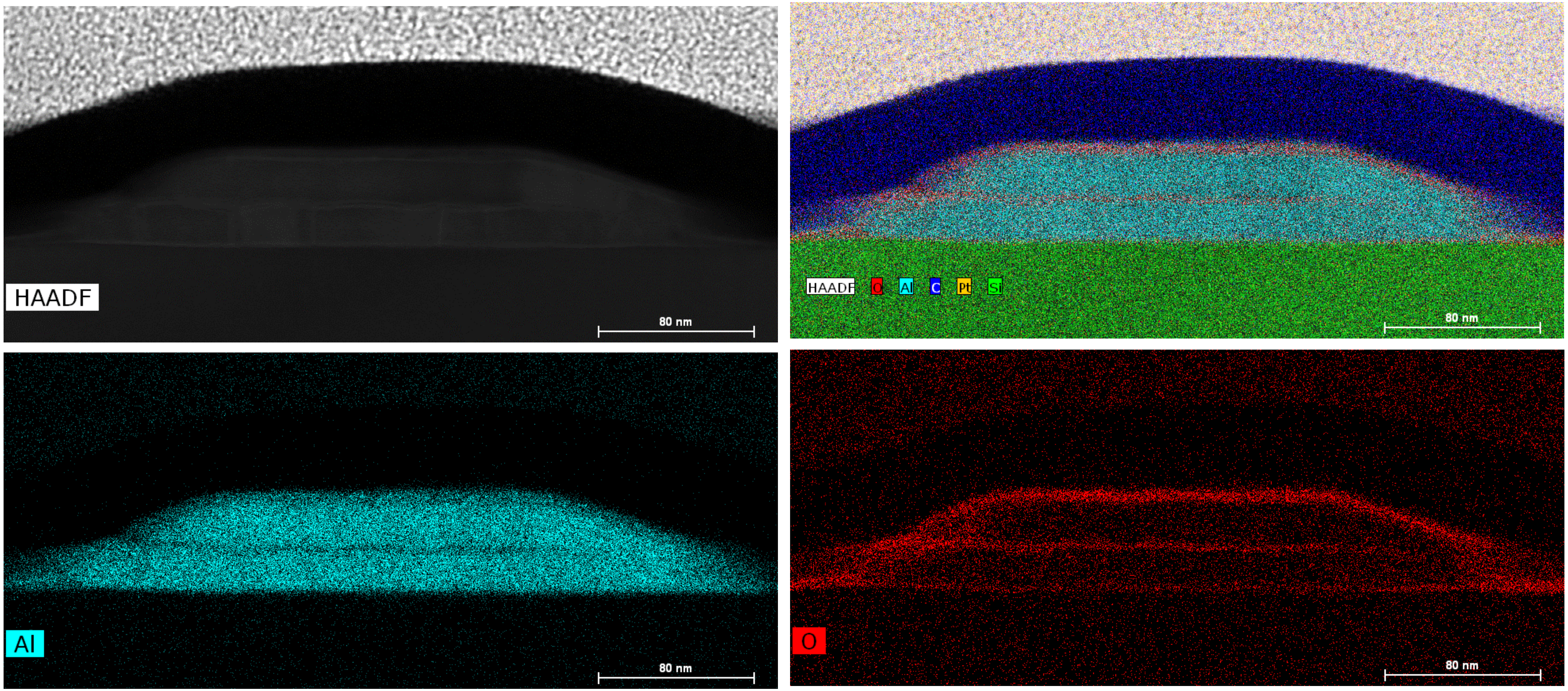
Arxiv:1201:3384 Q ~ 1.7M (6.1 GHz)

Reducing intrinsic loss in superconducting resonators by surface treatment and deep etching of silicon substrates

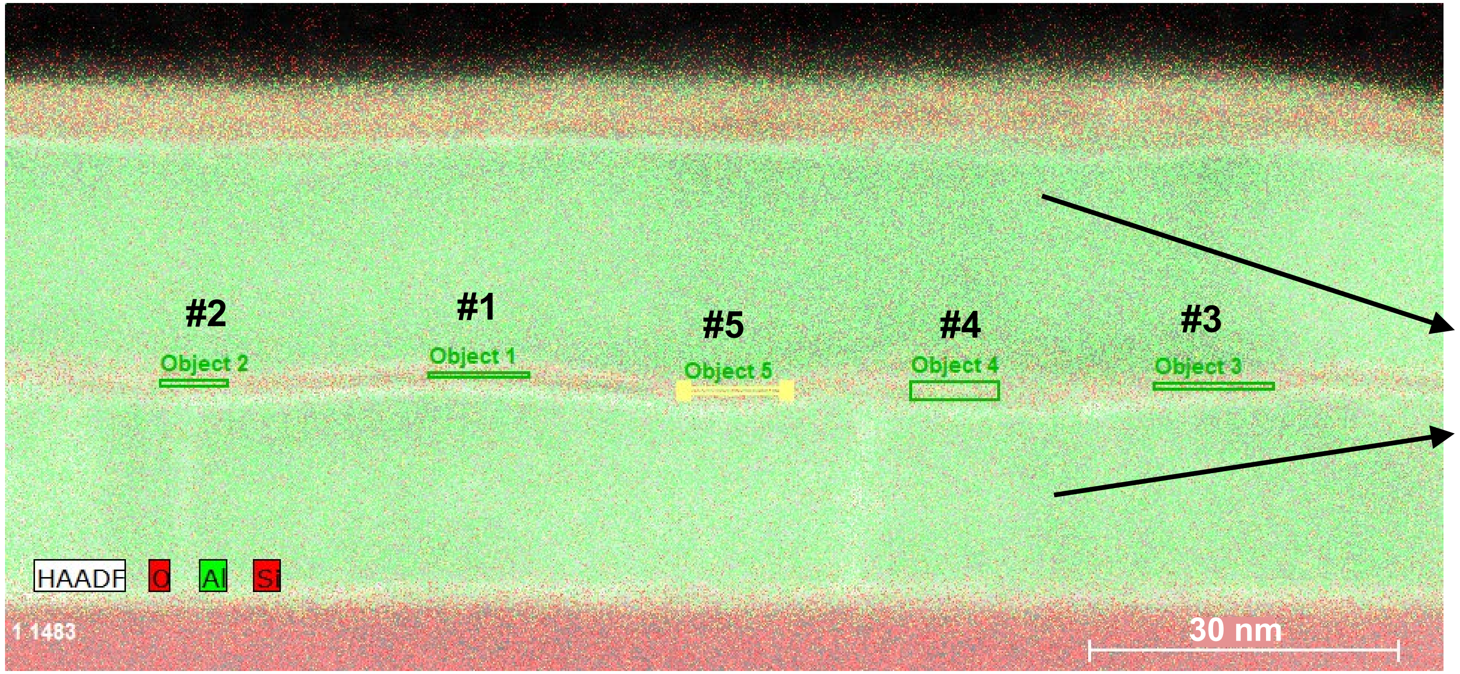
A. Bruno,[1] G. de Lange,[1] S. Asaad,[1] K. L. van der Enden,[1] N. K. Langford,[1] and L. DiCarlo[1]
QuTech Advanced Research Center and Kavli Institute of Nanosicence, Delft University of Technology, Lorentzweg 1, 2628 CJ Delft, The Netherlands

Arxiv:1504:04082 Q ~ 1.3M (4.57 GHz)

HIGH RESOLUTION EDS MAPPING TO SHOW THE AL/ALOX/AL/SI MATERIALS CONFIGURATION



COMPOSITION: TOP-AL, BOTTOM-AL, AND THE BARRIER



	Al	O
Top-Al	91.9	8.1
Bottom-Al	91.9	8.1

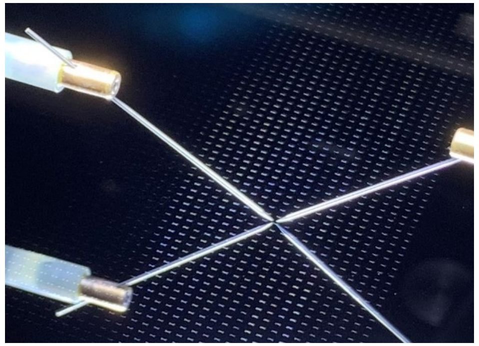
	Al	O	Cr	Si	Fe
#1	46.2	49.8	0.4	3.5	/
#2	46.3	49.9	0.4	3.3	/
#3					/
#4	65	35	/	/	/
#5	65.4	31.7	0	2.5	0.4

- Non-uniform tunnel barrier
- Thick oxide layer on top

JUNCTION UNIFORMITY IMPROVEMENTS

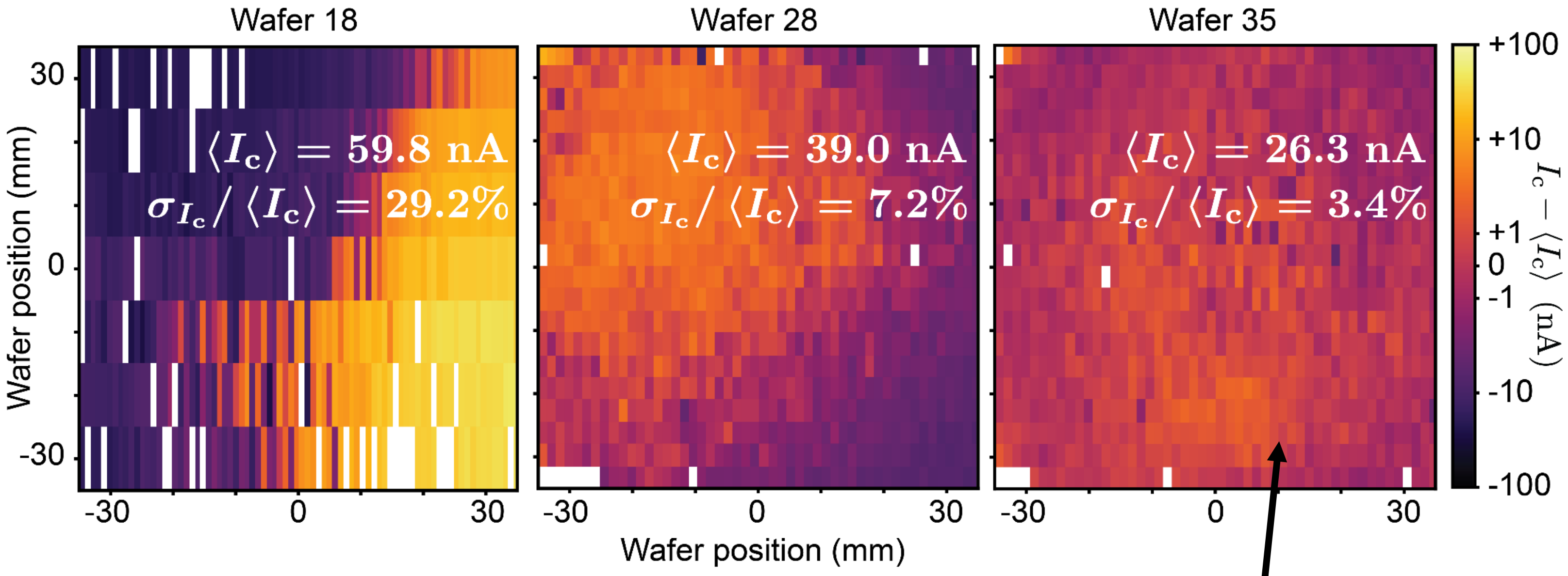
36 wafer systematic study to:

- Mitigate sources of I_c drift across ~ 50 cm^2
- Improve yield



Automated probe station gathering statistics from 3,000 co-fabricated junctions

Snapshots of improvements for 6:1 asymmetric squids



The most uniform areas of this wafer show < 0.6% RSD in frequency over a few cm^2!

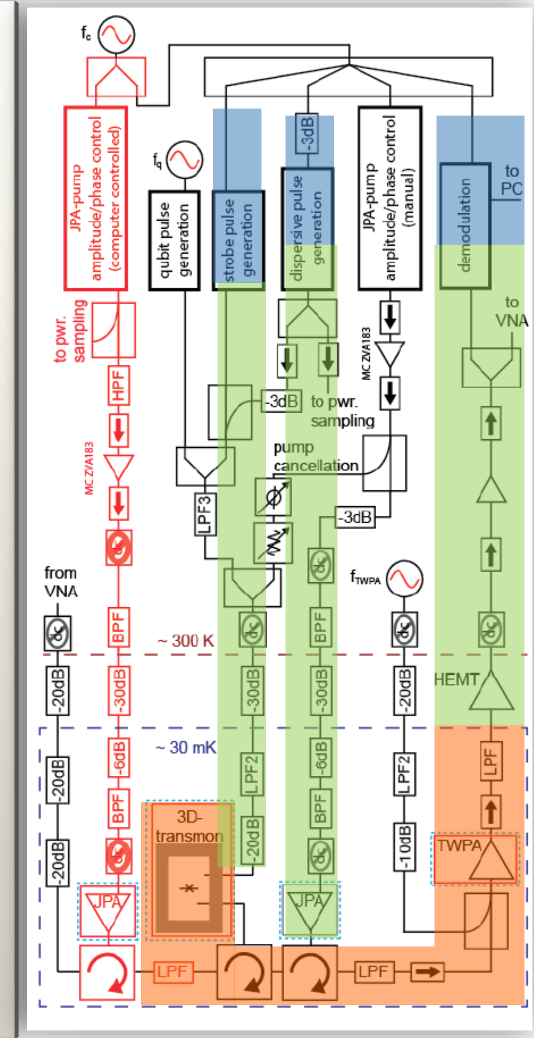
Key discoveries:

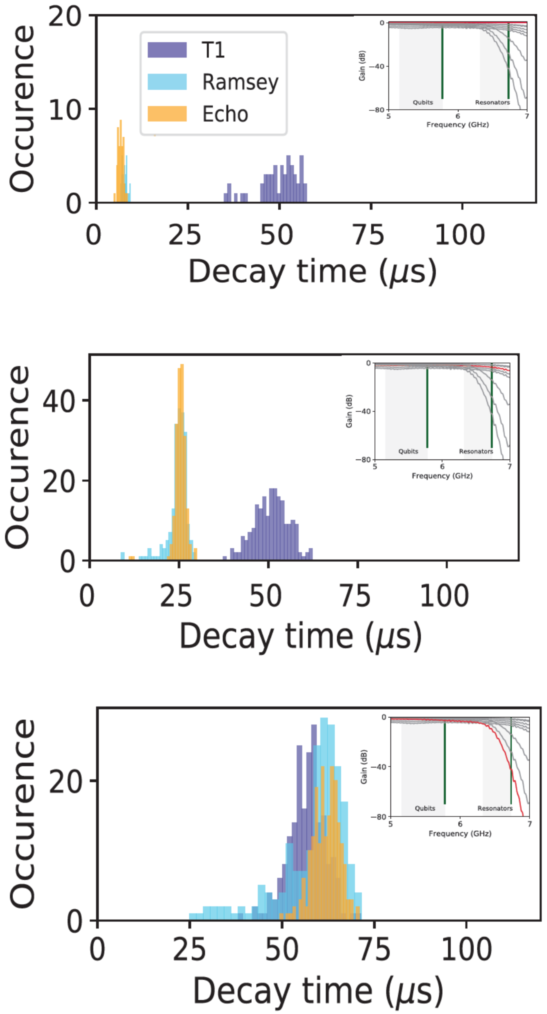
- Ashing (and its uniformity) has strong effect on I_c
- ~3% wafer-scale drift currently dominated by junction area variations
- Ultrasonicated development drastically improves yield for sub 100 nm junctions

J.M. Kreikebaum, et al., (in preparation)

UNPACKING QUANTUM INFORMATION

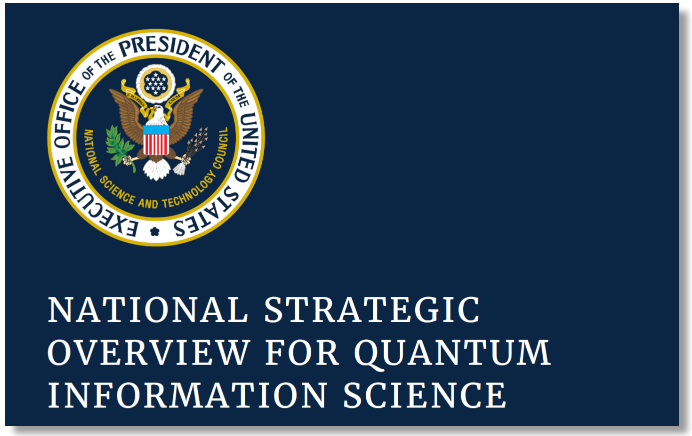
THE TYRANNY OF WIRES

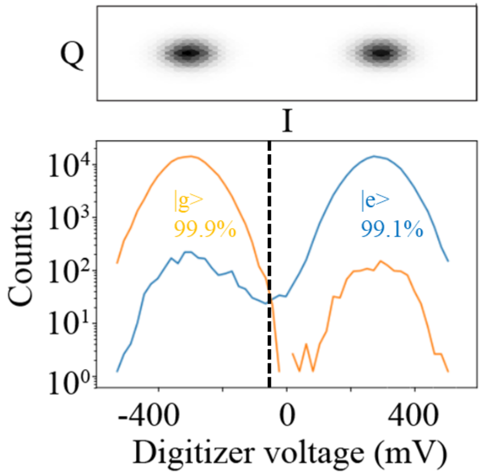


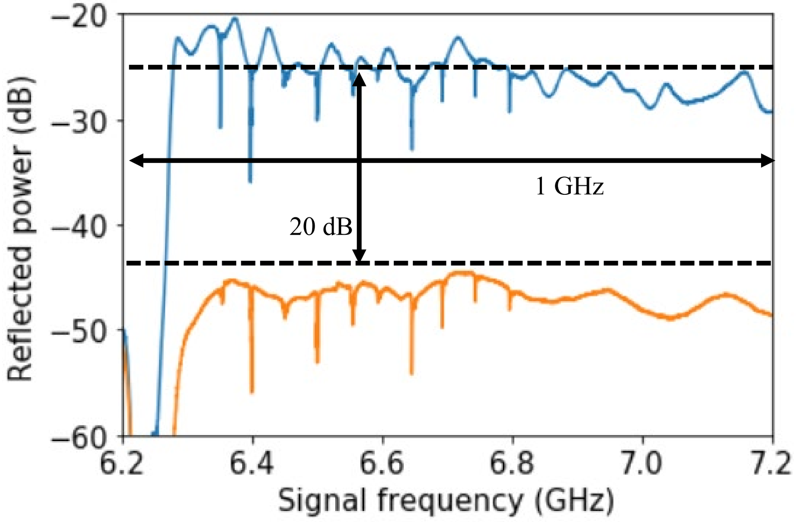


- **Need to reduce wire count !**
- **Need to reduce wire complexity**
- **Quantum data transmission & conversion**
  - optical
  - acoustic
  - classical analog
  - classical digital
- **Cryogenic data processing ?**

HIGH FIDELITY QUANTUM STATE READOUT



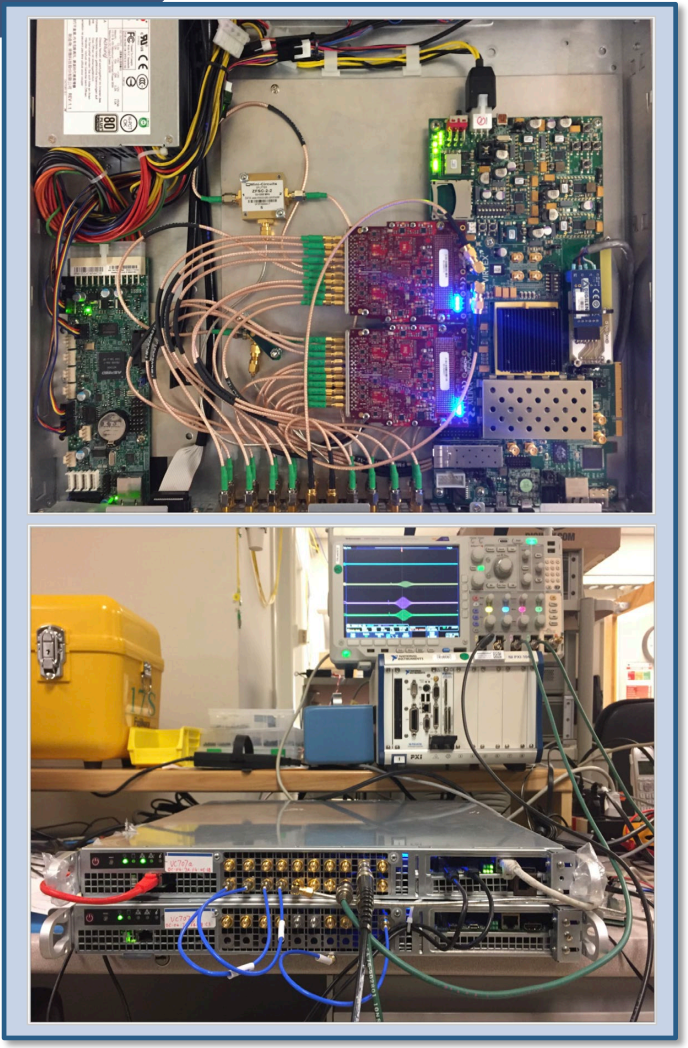




JTWPA: 99.5% average assignment fidelity w/ multiplexing capability

PROTOTYPE CONTROLS FROM THE ACCELERATOR DIVISION

- Scalable
- Low cost per channel
- Optical interconnects
- On board signal processing
  - AD9736 14-Bit, 1200 MSPS Digital-analog convertor (DAC)
  - 2 DAC on one low-pin count mezzanine card
  - Standard (LVDS) pin assignment for multiple potential carrier board

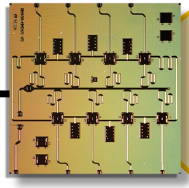


IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), September 2019.
Plenary presentation 4-EO-PL3 given at EUCAS, 1- 5 September 2019, Glasgow, UK.

QUANTUM: THERE'S A LOT OF INFORMATION IN THAT CHIP !

Initialize System

Quantum Processor



Entanglement
(N qubits → 2^N)

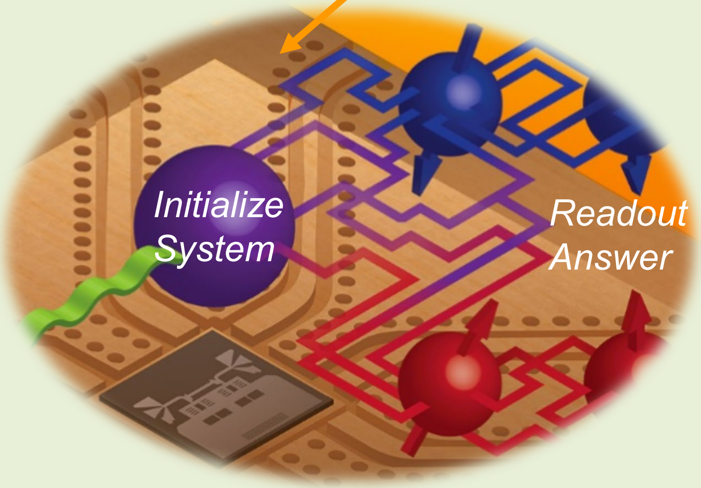
- Tomography
- Error Correction / Calibration
- Gate Set Tomography
- State Tracking/Feedback

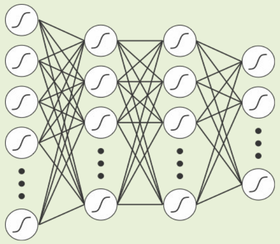
Readout Answer

Classically: A lot of data!

Machine Learning:
- Purely quantum based algorithms
- Quantum assisted classical routines
- Classical methods for large data

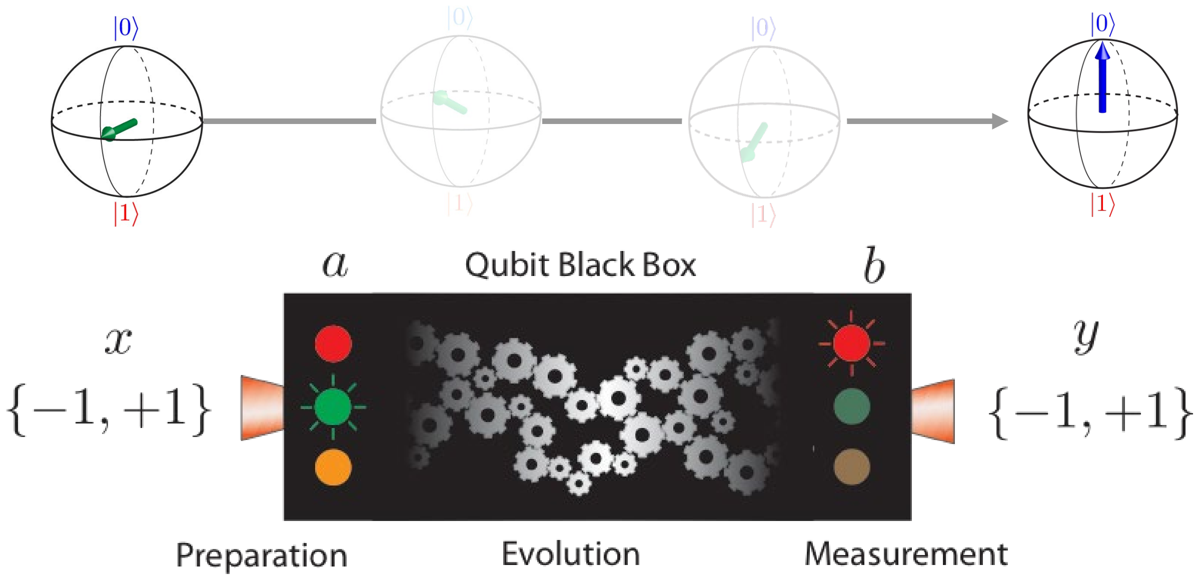
Trajectory Reconstruction & Validation: A lot of classical data!





10^6 instances per minute

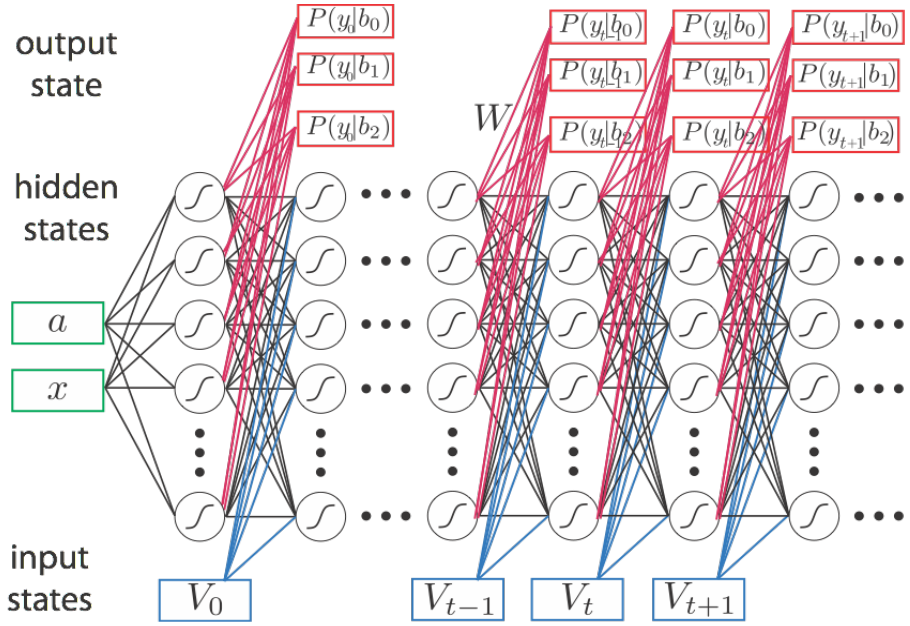
CAN WE TEACH A MACHINE QUANTUM MECHANICS ?



$$P(y|x, a, b, V_0, ..., V_t, ..., V_T) = \frac{\mathrm{Tr}(|y\rangle\langle y|\hat{B}\hat{\Omega}_{V_T}...\hat{\Omega}_{V_t}...\hat{\Omega}_{V_0}\hat{A}\rho_x\hat{A}^\dagger\hat{\Omega}^\dagger_{V_0}...\hat{\Omega}^\dagger_{V_t}...\hat{\Omega}^\dagger_{V_T}\hat{B}^\dagger)}{\mathrm{Tr}(\hat{\Omega}_{V_T}...\hat{\Omega}_{V_t}...\hat{\Omega}_{V_0}\hat{A}\rho_x\hat{A}^\dagger\hat{\Omega}^\dagger_{V_0}...\hat{\Omega}^\dagger_{V_t}...\hat{\Omega}^\dagger_{V_T})}$$

$$\vec{h}_{t+1} = \sigma(W.\vec{h}_t + \vec{W}_{ih}V_t + \vec{b})$$

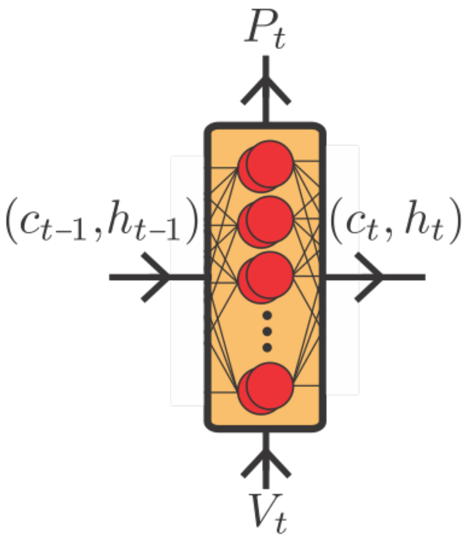
$$P(y_t|\vec{b}) = \sigma(W_{ho}.\vec{h}_t + \vec{\beta})$$

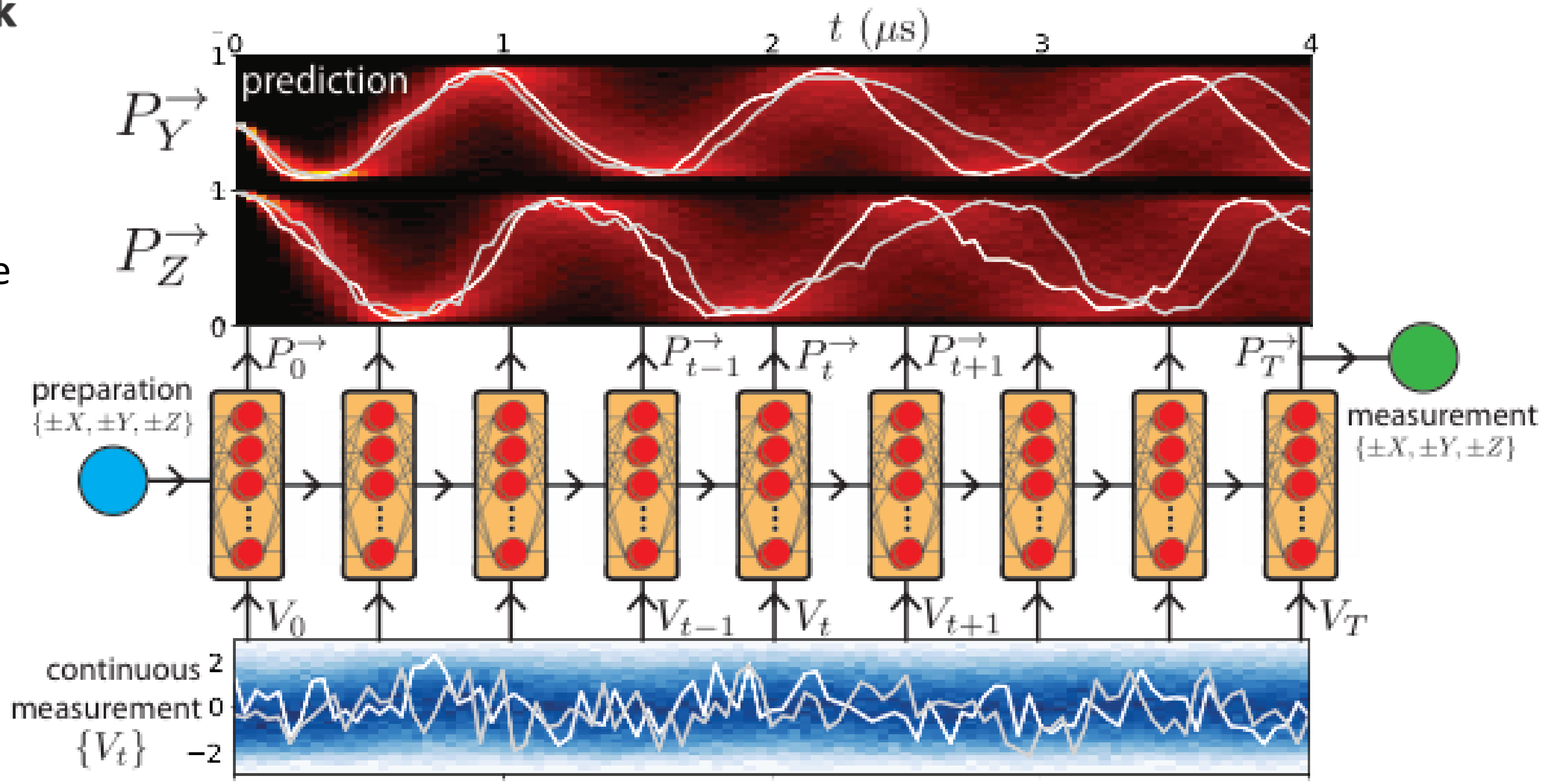


RNN RESULTS: RABI OSCILLATIONS

Recurent Neural Network

- Long-Short Term Memory
- 64 Neurons per layer
- 30,000 weight parameters
- 0.8 ms of training per trace with a K80 GPU





STARTING TO COMPUTE!

HYBRID ALGORITHMS & CHEMISTRY

PHYSICAL REVIEW X **8**, 011021 (2018)

Featured in Physics

Computation of Molecular Spectra on a Quantum Processor with an Error-Resilient Algorithm

J. I. Colless, V. V. Ramasesh, D. Dahlen, M. S. Blok, and M. E. Kimchi-Schwartz[‡]
Quantum Nanoelectronics Laboratory, Department of Physics, University of California, Berkeley, California 94720, USA; and Center for Quantum Coherent Science, University of California, Berkeley, California 94720, USA

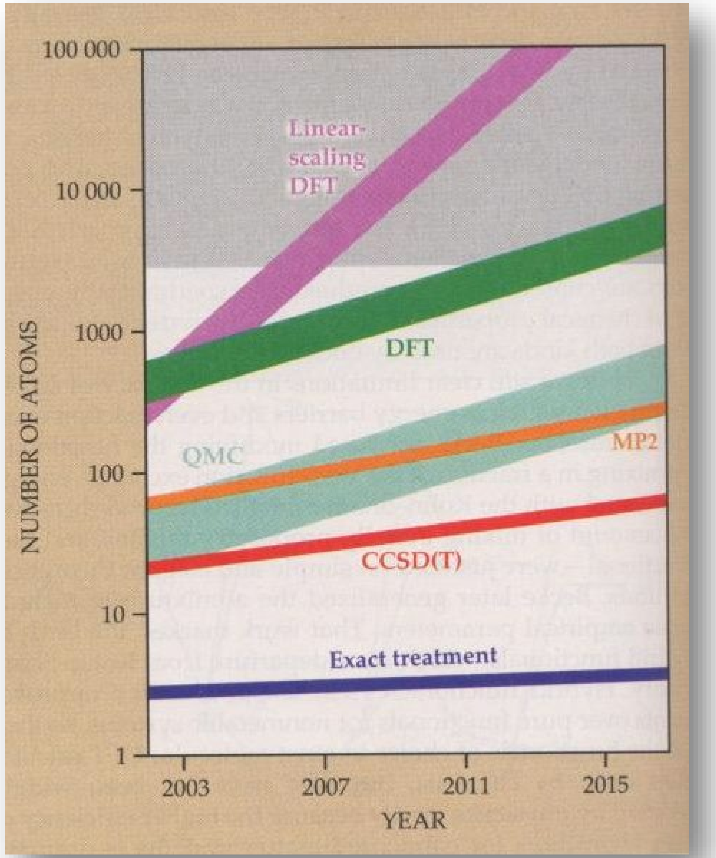
J. R. McClean,[†] J. Carter, and W. A. de Jong
Computational Research Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA

I. Siddiqi[*]
Quantum Nanoelectronics Laboratory, Department of Physics, University of California, Berkeley, California 94720, USA; Center for Quantum Coherent Science, University of California, Berkeley, California 94720, USA; and Materials Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA

Memory Requirements for Exact
(Full Configuration Interaction)

System	Memory (PB)	Max Qubits
TACC Stampede	0.192	43
Titan	0.71	45
K Computer	1.4	46
APEX2020	4-10	48-49

M. Head-Gordon, M. Artacho, ***Physics Today*** 4 (2008)



VARIATIONAL QUANTUM EIGENSOLVER (VQE)

Variational Formulation: Minimize $\langle\Psi|H|\Psi\rangle$

Decompose as: $\mathcal{H} = h^i_\alpha \sigma^i_\alpha + h^{ij}_{\alpha\beta}\sigma^i_\alpha\sigma^j_\beta + h^{ijk}_{\alpha\beta\gamma}\sigma^i_\alpha\sigma^j_\beta\sigma^k_\gamma + \ldots$

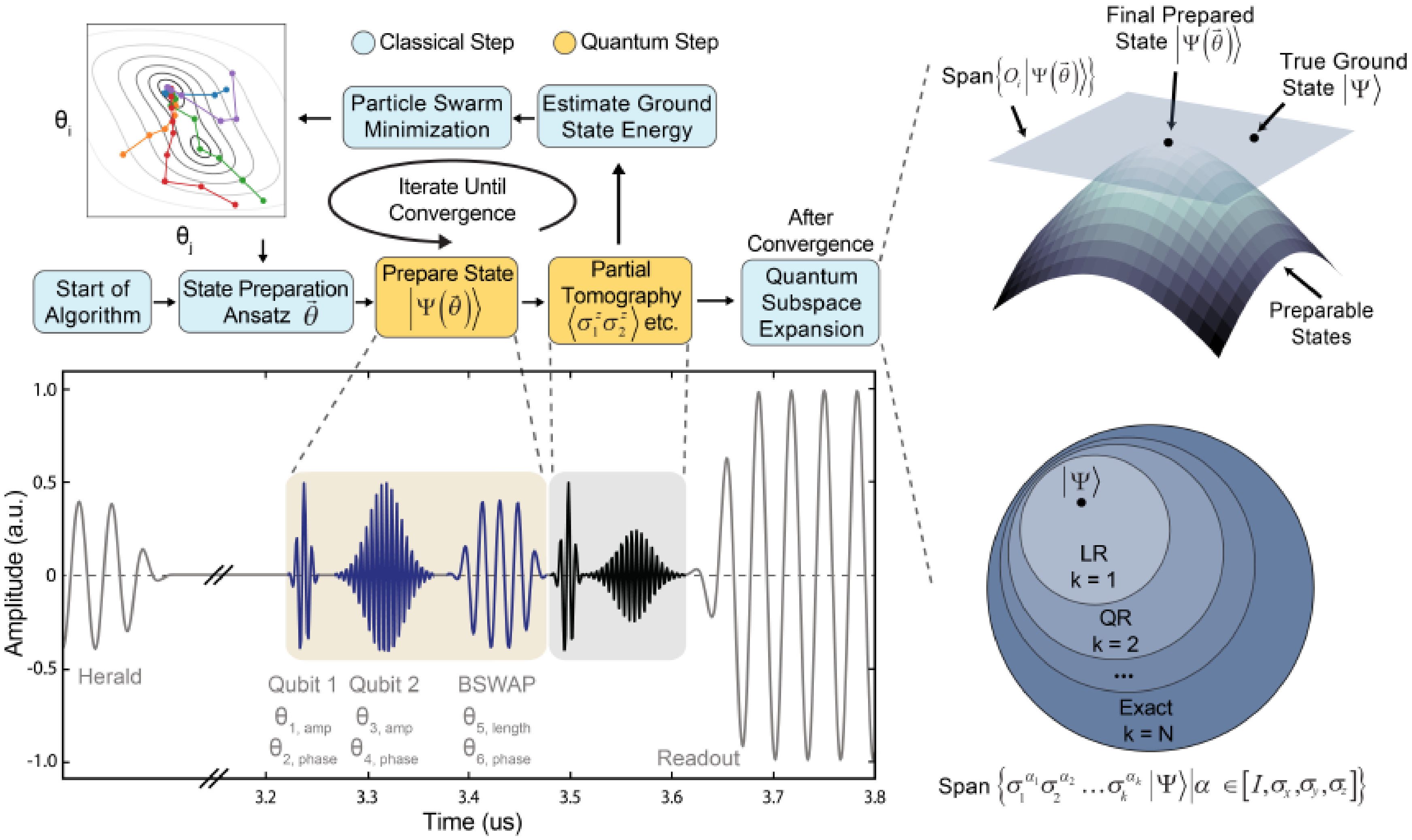
By Linearity: $\langle\psi|\mathcal{H}|\psi\rangle \equiv \langle\mathcal{H}\rangle = \mathcal{H} = h^i_\alpha\langle\sigma^i_\alpha\rangle + h^{ij}_{\alpha\beta}\langle\sigma^i_\alpha\sigma^j_\beta\rangle + h^{ijk}_{\alpha\beta\gamma}\langle\sigma^i_\alpha\sigma^j_\beta\sigma^k_\gamma\rangle + \ldots$

Easy for a Quantum Computer: $\langle\sigma^i_\alpha\sigma^j_\beta\sigma^k_\gamma\ldots\rangle$ → **Easy for a Classical Computer:** $+, \times \rightarrow \langle H\rangle$

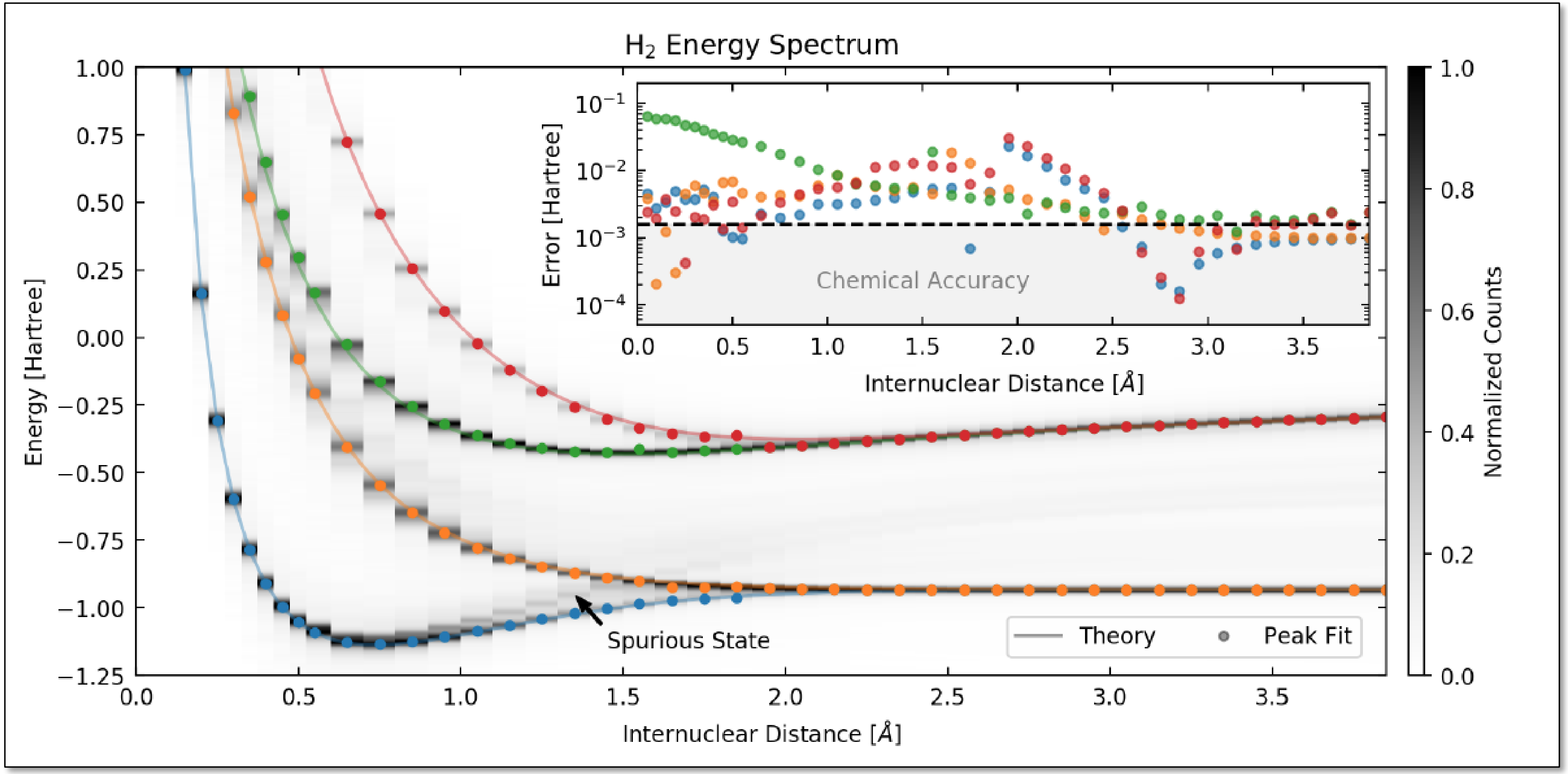
Hybrid Scheme:

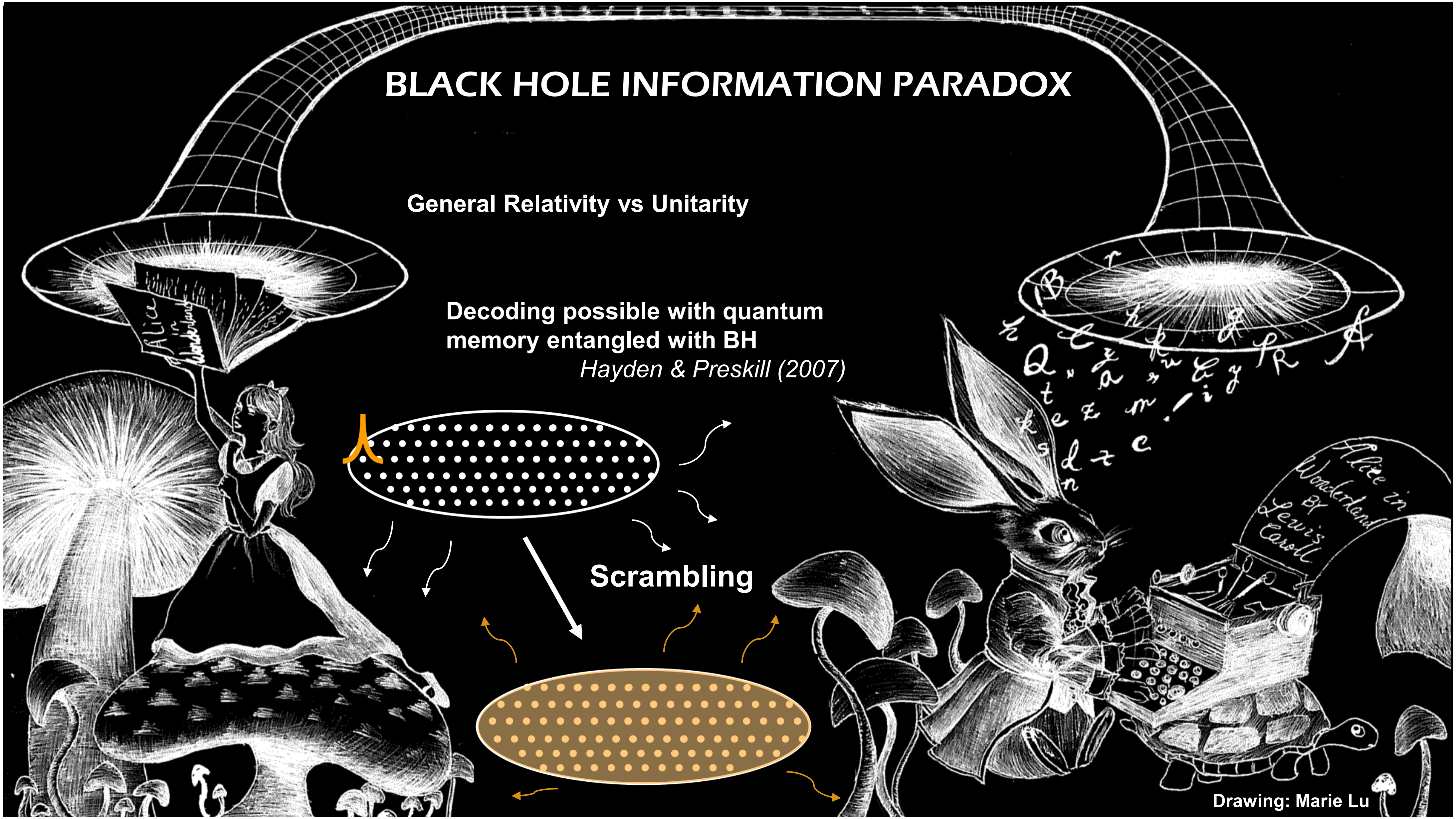
- Parameterize quantum state with classical experimental parameters
- Compute averages using quantum computer
- Update state using classical minimization algorithm (e.g. particle swarm)

VQE ALGORITHM



H_2 REVISITED




BLACK HOLE INFORMATION PARADOX
General Relativity vs Unitarity
Decoding possible with quantum memory entangled with BH
Hayden & Preskill (2007)
Scrambling
Alice in Wonderland
Alice in Wonderland By Lewis Caroll
Drawing: Marie Lu

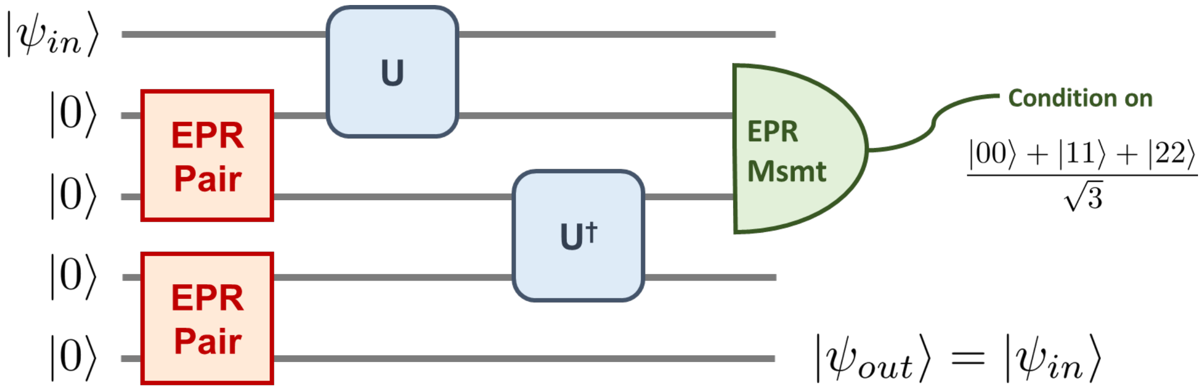
SIMULATING THE COSMOS

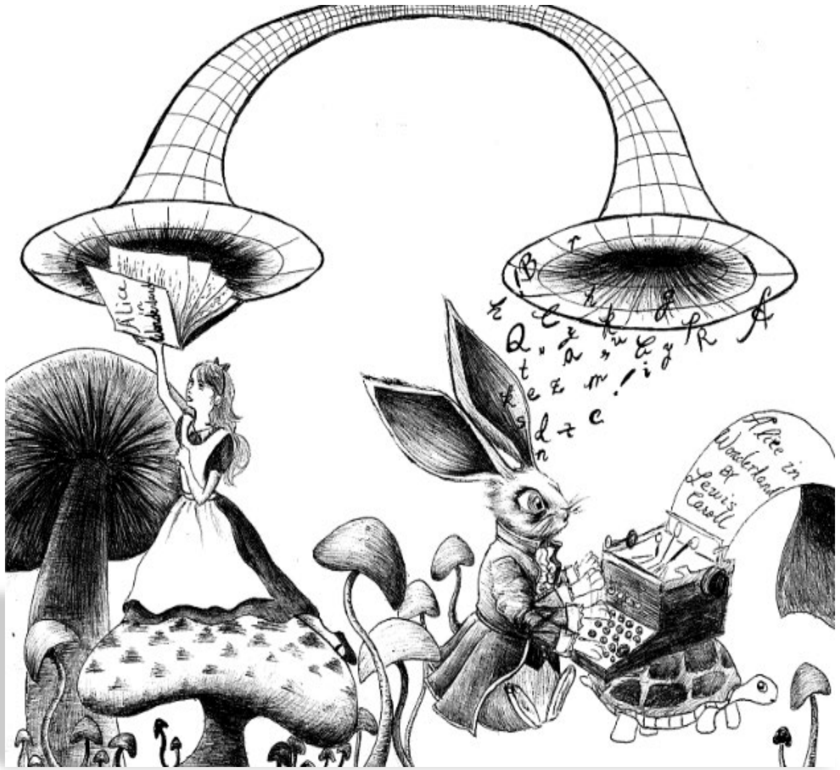
Disentangling Scrambling and Decoherence via Quantum Teleportation

Beni Yoshida[1] and Norman Y. Yao[2,3]

[1] *Perimeter Institute for Theoretical Physics, Waterloo, Ontario N2L 2Y5, Canada*
[2] *Department of Physics, University of California Berkeley, Berkeley, California 94720, USA*
[3] *Materials Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*

(Dated: March 30, 2018)



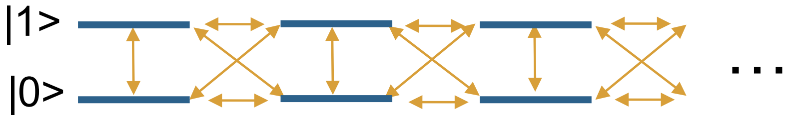


Qutrit EPR pair:
$\mathcal{N}(|00\rangle + |11\rangle + |22\rangle)$

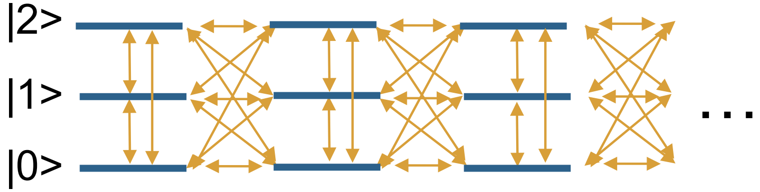
Scrambling unitary:
$U\,|i, j\rangle = |2i + j, i + j\rangle$

QUTRITS VERSUS QUBITS

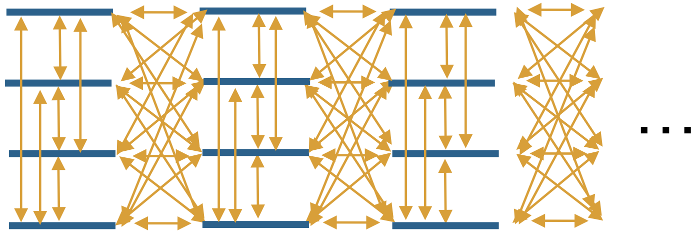
Qubits: $D = 2^N$; quantum advantage ~ 50



Qutrits: $D = 3^N$; quantum advantage ~ 32



Ququarts: $D = 4^N$; quantum advantage ~ 25



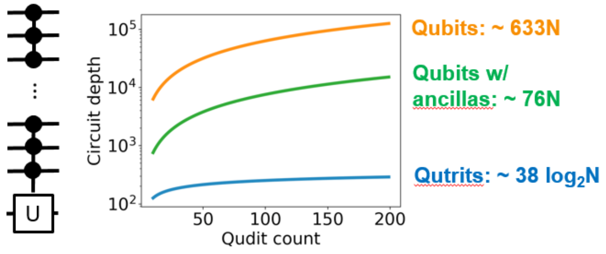
<u>Increased computational power</u>

Larger Hilbert Space

Effective Connectivity

Hardware efficient

Lower-depth compilation toffoli-gate



Gokhale et al., QIP 2019

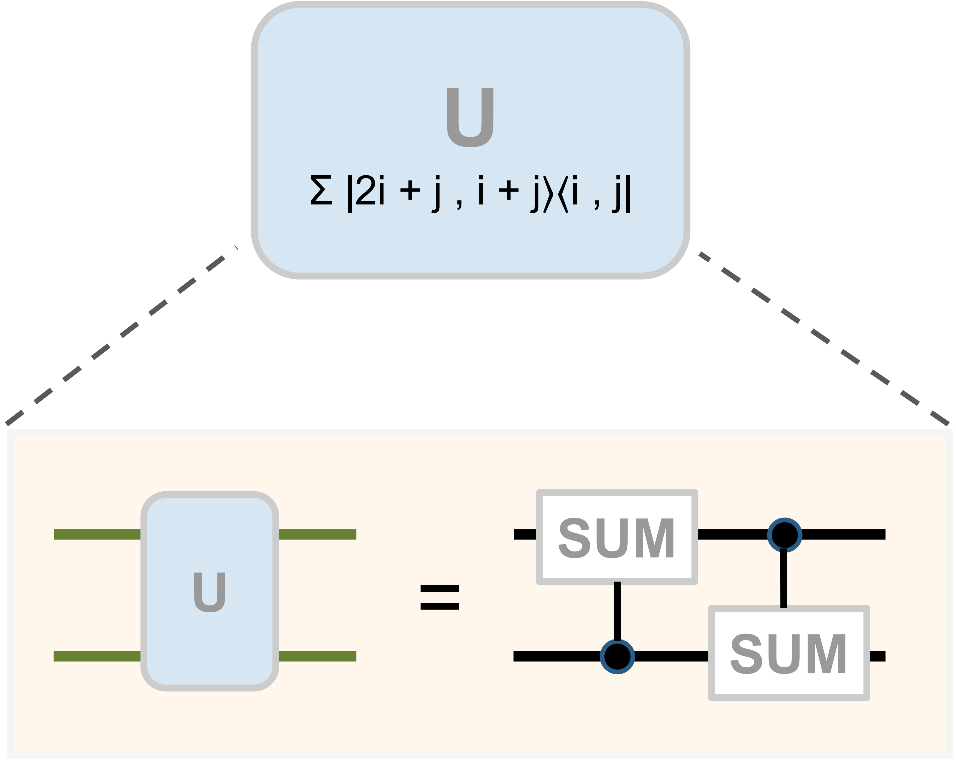
<u>Contextuality</u> (minimal system: 1 qutrit)
Single-qubit has a non-contextual ("classical") description
(i.e. measurement independent)

'Magic of quantum computing' — Howard *et al*, Nature (2016)
Certified RNG — Kulikov *et al* PRL (2017)

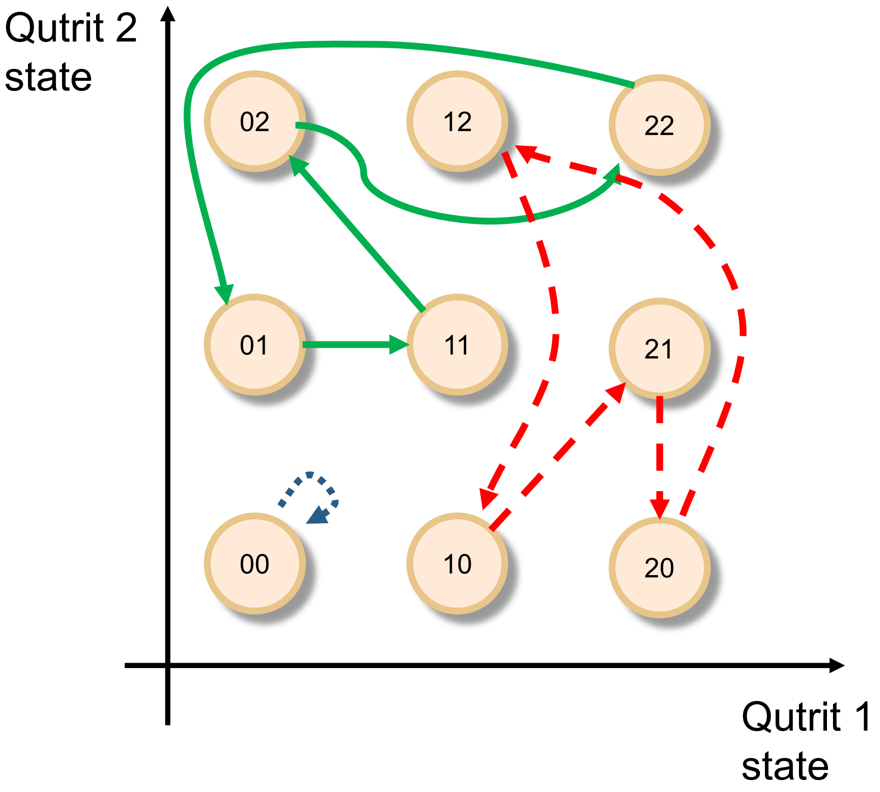
<u>Scrambling</u> (minimal system: 2 qutrits)
Strongly interacting systems
black holes are conjectured to be fastest scramblers

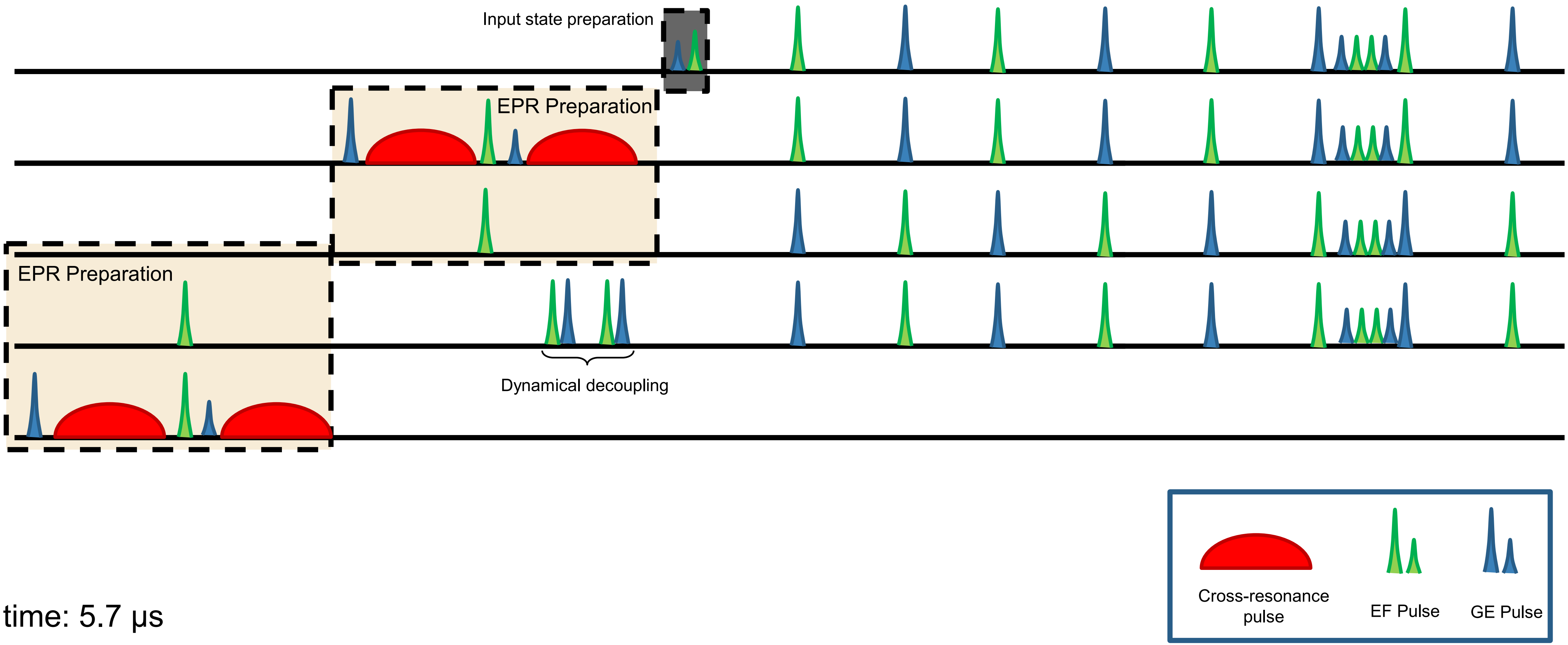
IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), September 2019.
Plenary presentation 4-EO-PL3 given at EUCAS, 1- 5 September 2019, Glasgow, UK.

SCRAMBLING UNITARY: A CLOSER LOOK

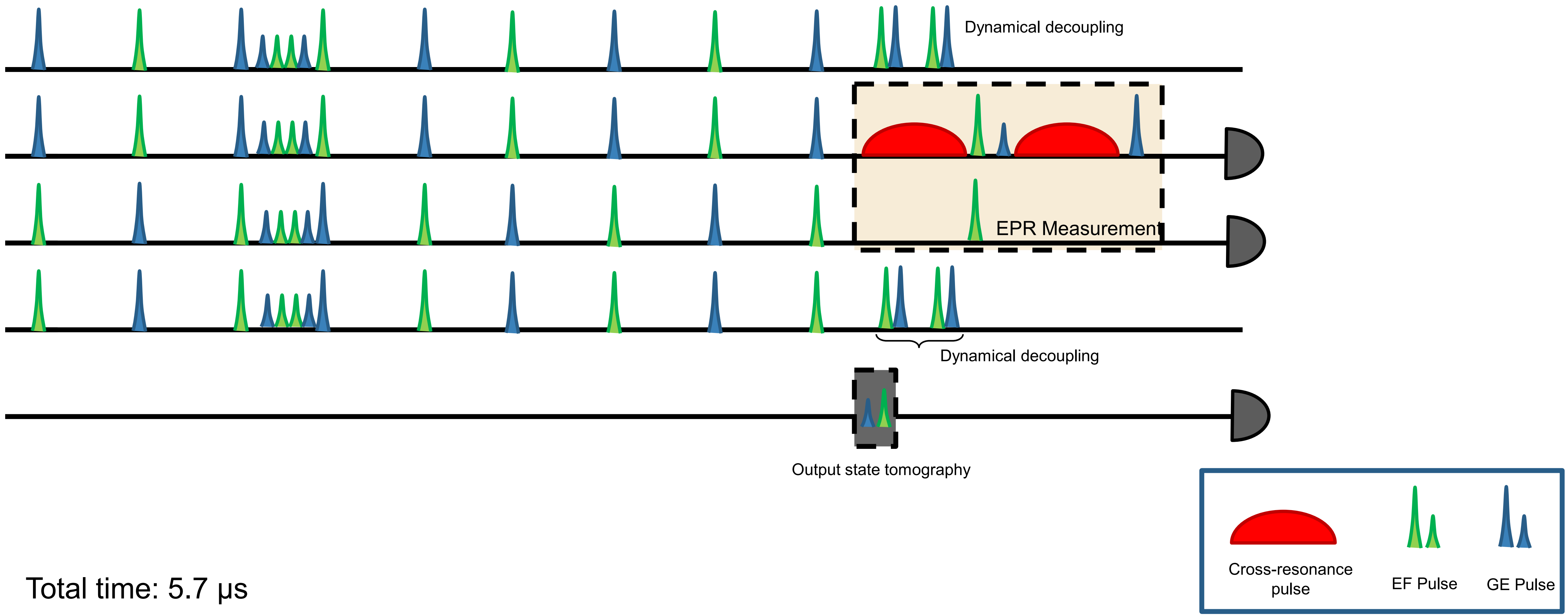


CSUM |i , j⟩ = |i , i + j⟩

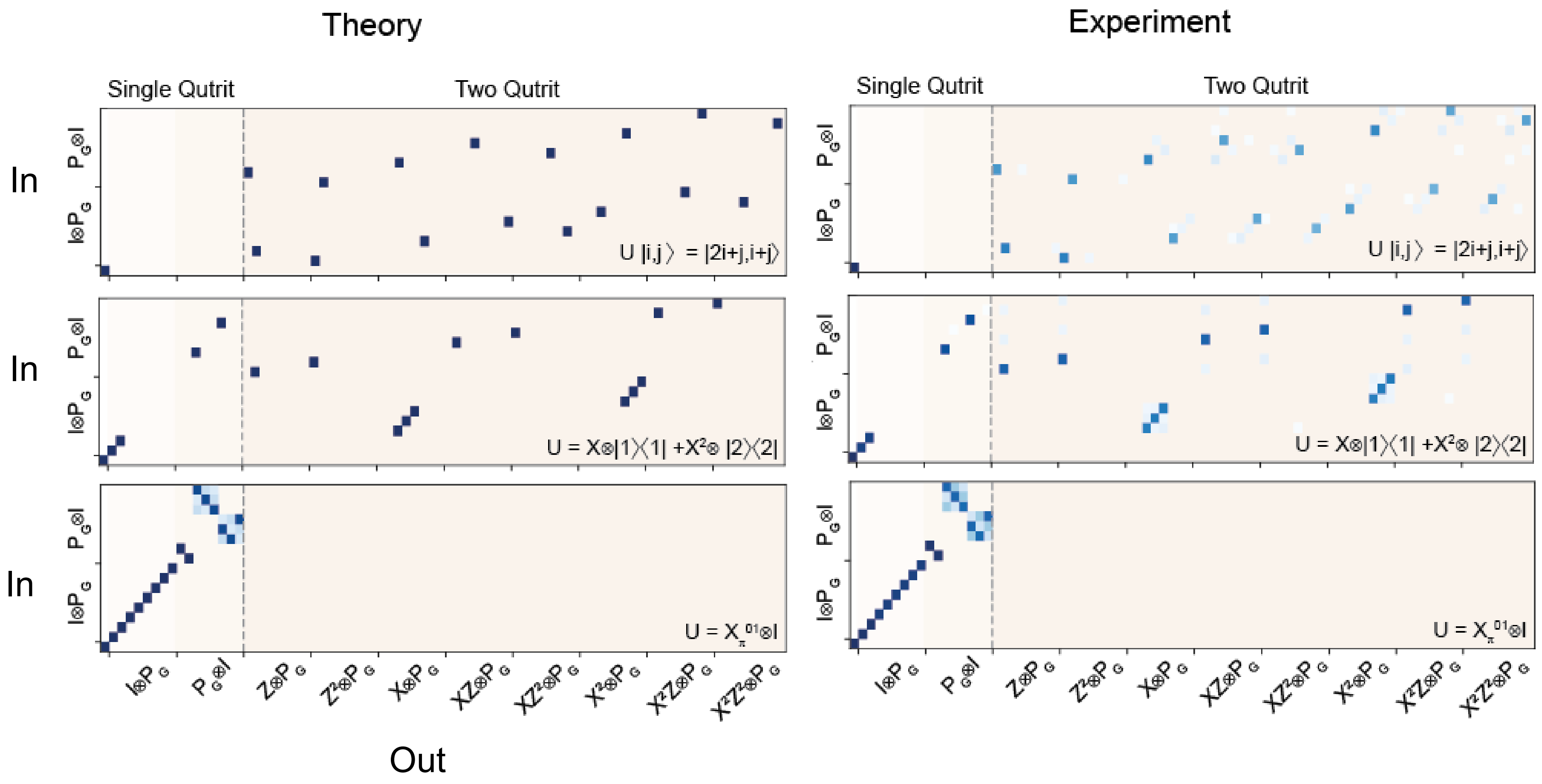




Total time: 5.7 μs


Dynamical decoupling
EPR Measurement
Dynamical decoupling
Output state tomography
Total time: 5.7 μs
Cross-resonance pulse
EF Pulse
GE Pulse

PROCESS TOMOGRAPHY OF THE SCRAMBLER

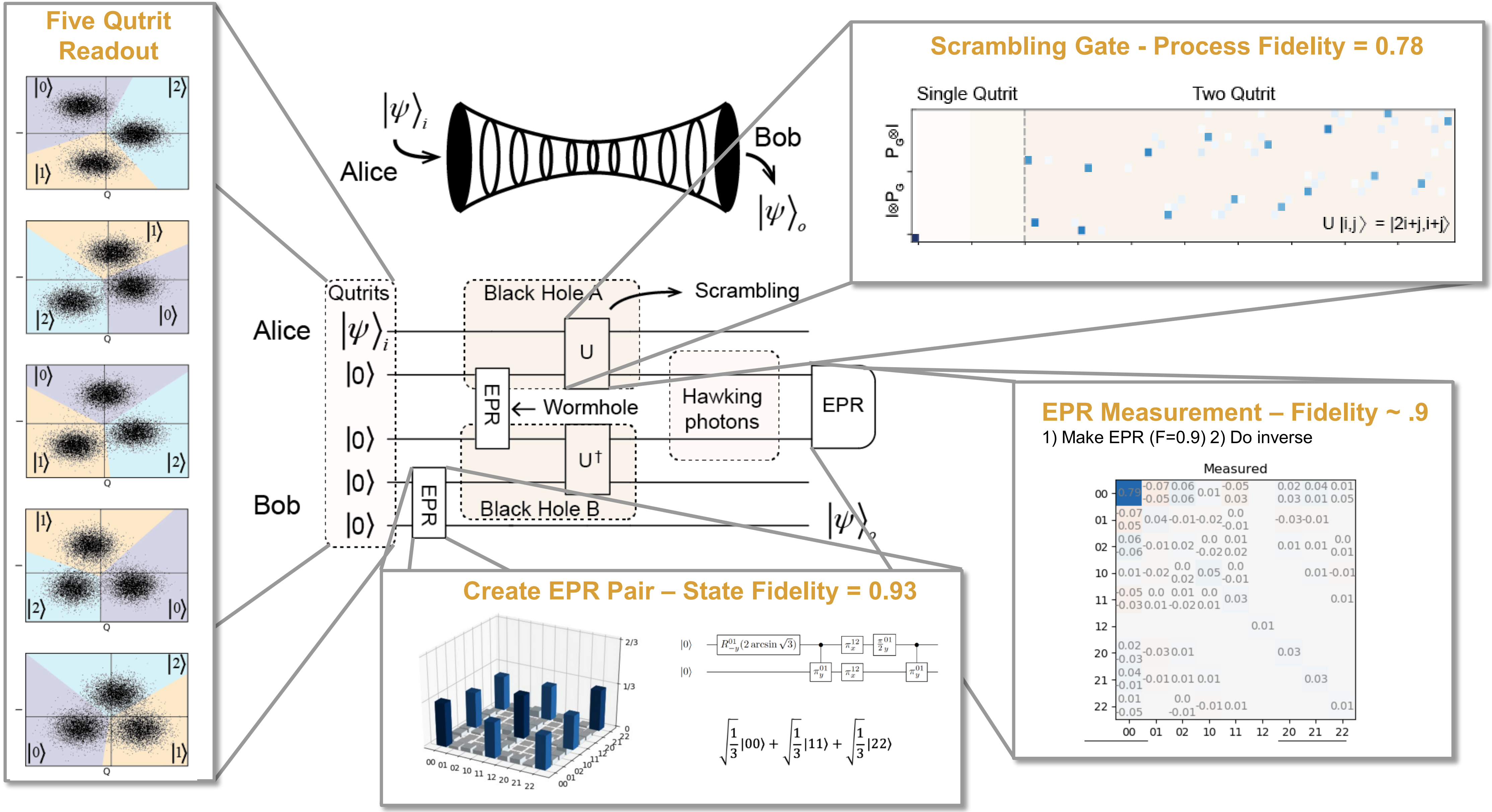


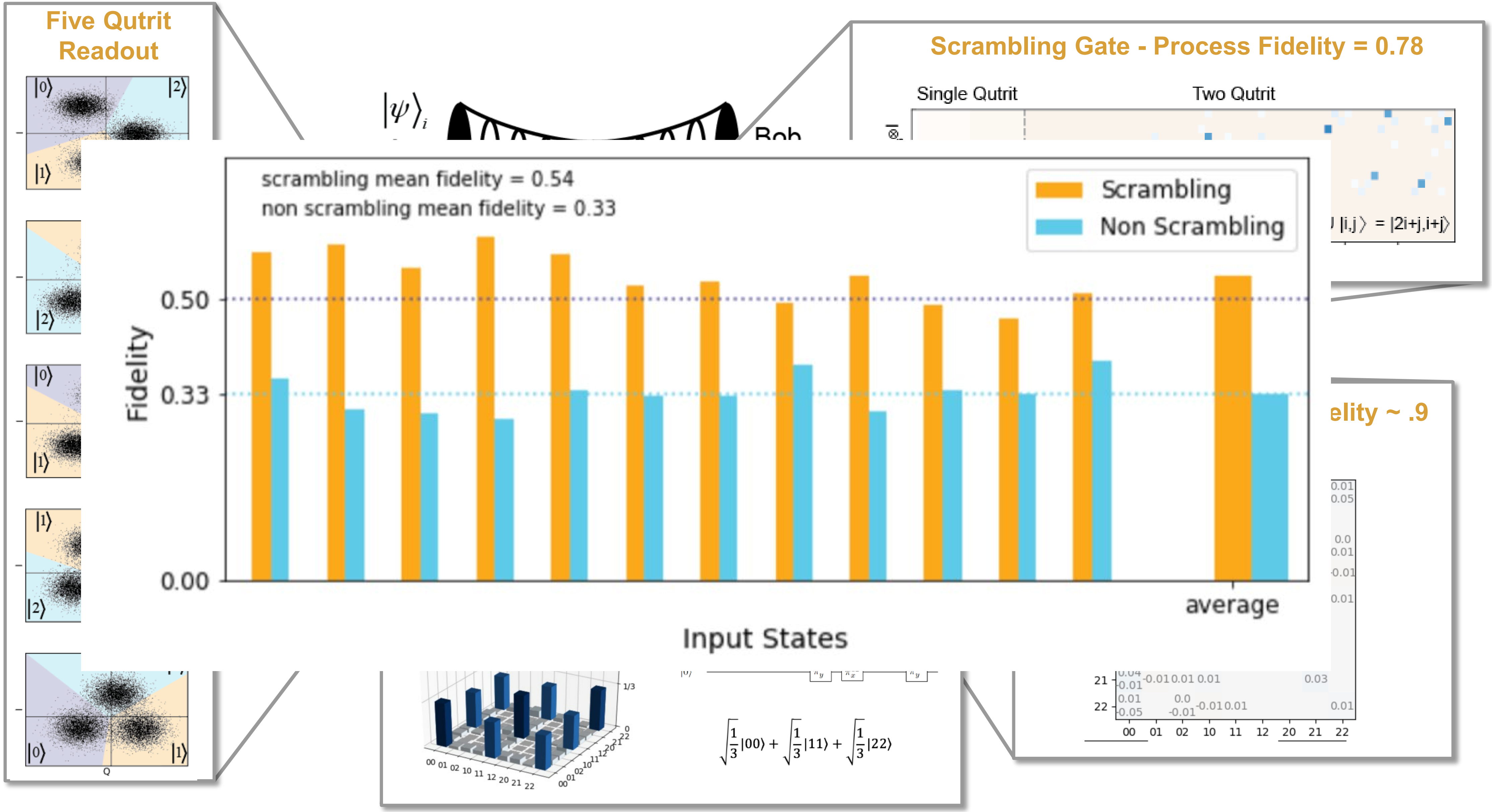
Scrambling Gate
Process Fidelity = 0.78

Entangling Gate
Process Fidelity = 0.88

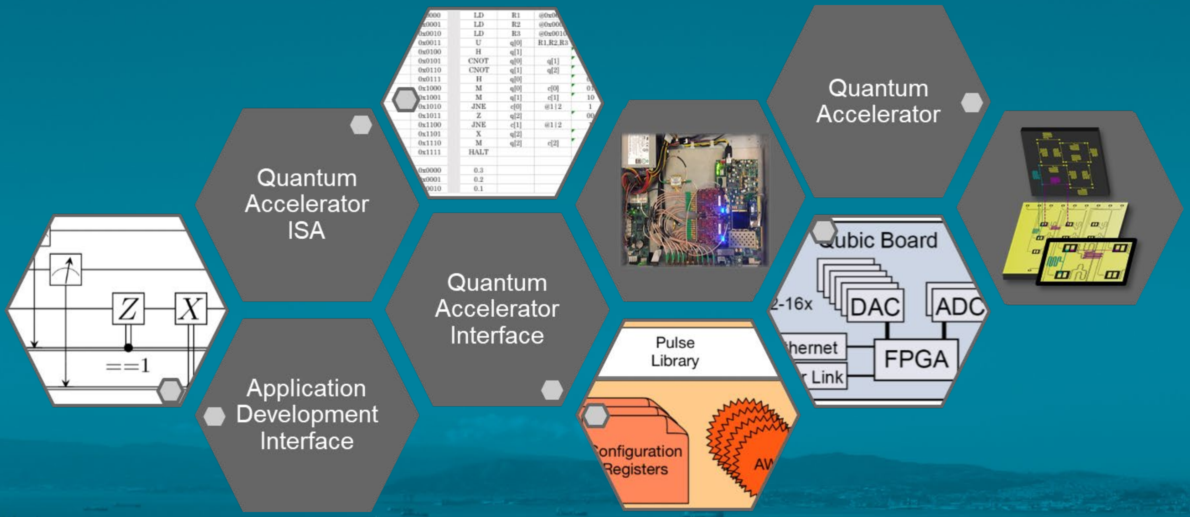
Local Gate
Process Fidelity = 0.97

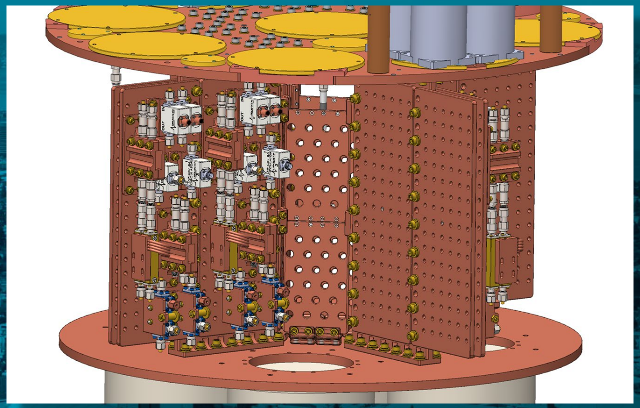
$P_G = \{Z, Z^2, X, XZ, XZ^2, X^2, X^2Z, X^2Z^2\}$


Five Qutrit Readout
Scrambling Gate - Process Fidelity = 0.78
Single Qutrit
Two Qutrit
U |i,j〉 = |2i+j,i+j〉
Alice
Bob
Qutrits
Black Hole A
Scrambling
U
EPR
Wormhole
Hawking photons
U†
Black Hole B
EPR Measurement – Fidelity ~ .9
1) Make EPR (F=0.9) 2) Do inverse
Measured
Create EPR Pair – State Fidelity = 0.93
$\sqrt{\frac{1}{3}}|00\rangle + \sqrt{\frac{1}{3}}|11\rangle + \sqrt{\frac{1}{3}}|22\rangle$


Five Qutrit Readout
Scrambling Gate - Process Fidelity = 0.78
Single Qutrit
Two Qutrit
Bob
scrambling mean fidelity = 0.54
non scrambling mean fidelity = 0.33
Scrambling
Non Scrambling
Fidelity
0.50
0.33
0.00
average
Input States
elity ~ .9

ADVANCED QUANTUM TESTBED



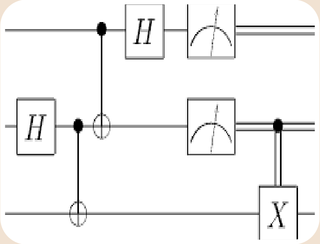


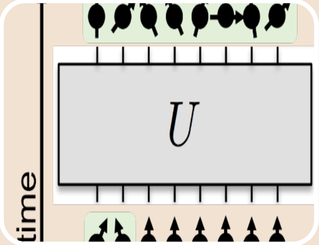
- **Open**
- **Modular**
- **Community partnership**
- **Broad science**

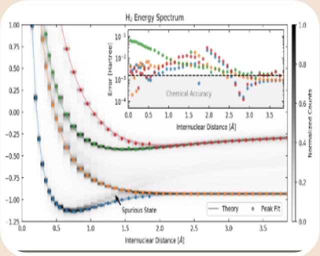
BERKELEY LAB

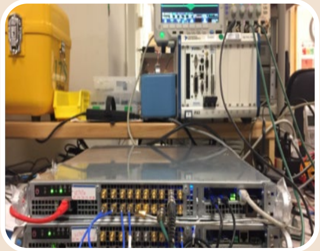
Berkeley

QUANTUM INFORMATION SYSTEMS









Foundations

- Tests of quantum theory
- Verification / Validation

Algorithms

- Pure quantum
- Hybrid
- Quantum inspired

Materials

- Coherence
- Sensing
- Novel qubits

Science

- Simulations / Emulations
- Many-body science
- Gravity

Computation

- Gate based
- Ground state
- Q. walks
- QEC

Engineering

- Classical sim
- Signal proc.
- Control
- Transduction

SOME NEW FOUNDATIONAL QUESTIONS

How do we stabilize quantum coherence in an open many-body quantum system? What decoherence mechanisms emerge and what states are robust?

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?