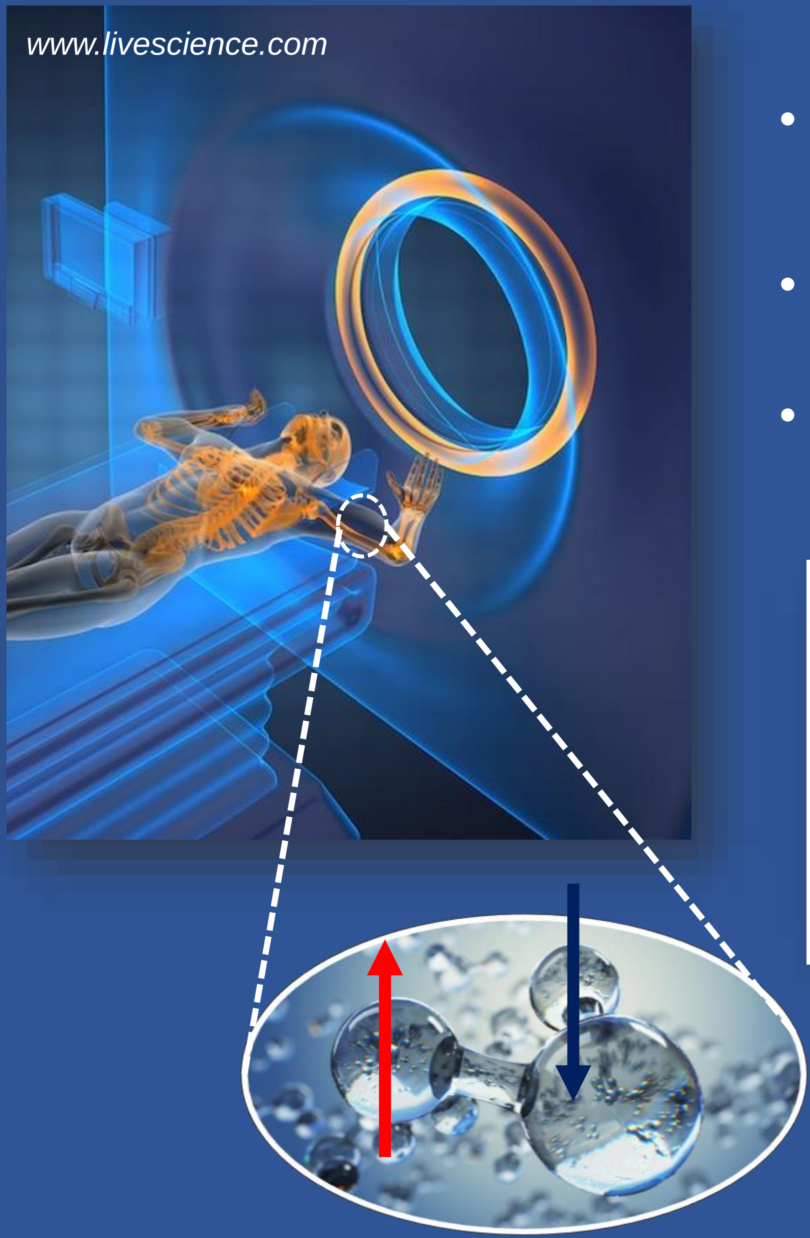
Superconducting Quantum Circuits: Balancing Art & Architecture

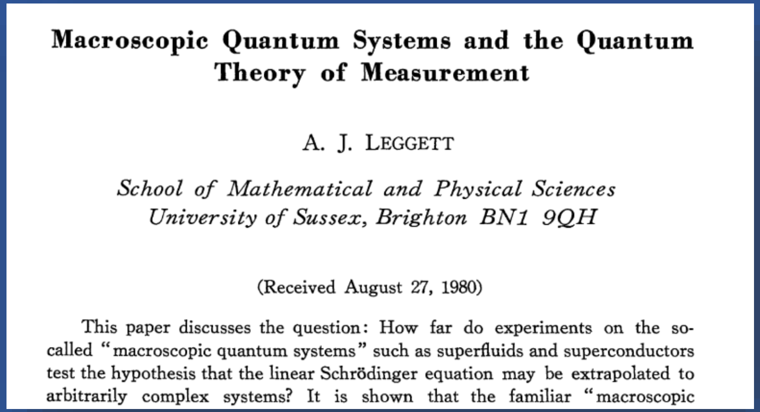
Irfan Siddiqi

Lawrence Berkeley National Laboratory & Physics Department
University of California, Berkeley

ENGINEERING QUANTA FOR QIS



- Aspire to engineer, control, and probe individual quantum systems and quanta !
- Interplay between foundational science / technology
- Are macroscopic systems described by collective degrees of freedom truly quantum ?



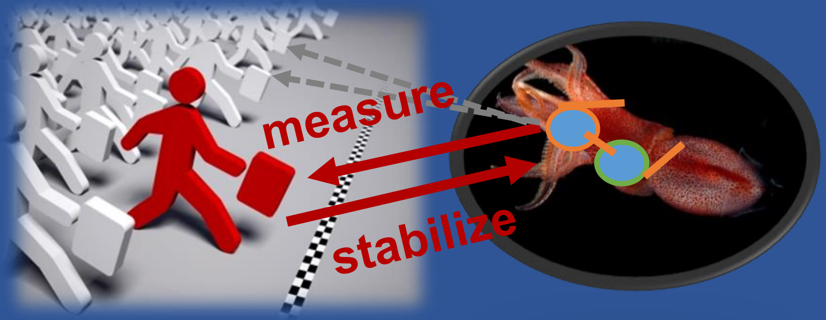
Macroscopic Quantum Systems and the Quantum Theory of Measurement

A. J. LEGGETT

School of Mathematical and Physical Sciences
University of Sussex, Brighton BN1 9QH

(Received August 27, 1980)

This paper discusses the question: How far do experiments on the so-called "macroscopic quantum systems" such as superfluids and superconductors test the hypothesis that the linear Schrödinger equation may be extrapolated to arbitrarily complex systems? It is shown that the familiar "macroscopic



www.thegradstudentway.com

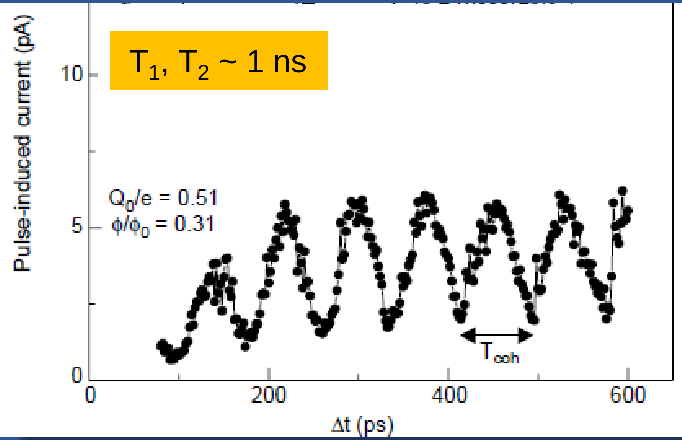
HOW DO WE <u>CREATE</u> & <u>PROBE</u> A LONG-LIVED, OPEN QUANTUM SYSTEM USING SUPERCONDUCTING CIRCUITS ?

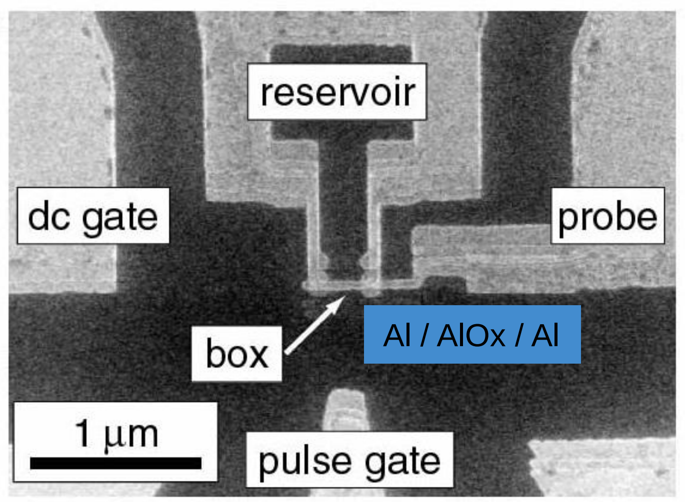
TWENTY YEARS OF COHERENCE

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 !

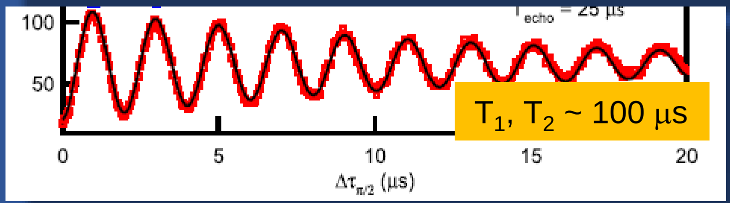
MINIMALIST QUBIT ENABLES MANY, WELL CONTROLLED EXPERIMENTS & ALLOWS US TO ENTER THE 10-100 QUBIT ERA

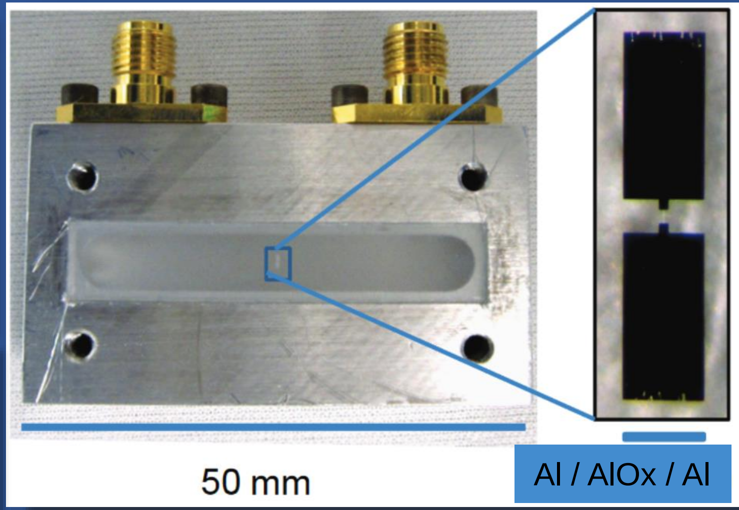
MANY OTHER, MORE FLEXIBLE DESIGNS TO EXPLORE: TUNABLE, TOPOLOGICAL CIRCUITS, NON S-WAVE MATERIALS, NOVEL TUNNEL BARRIERS

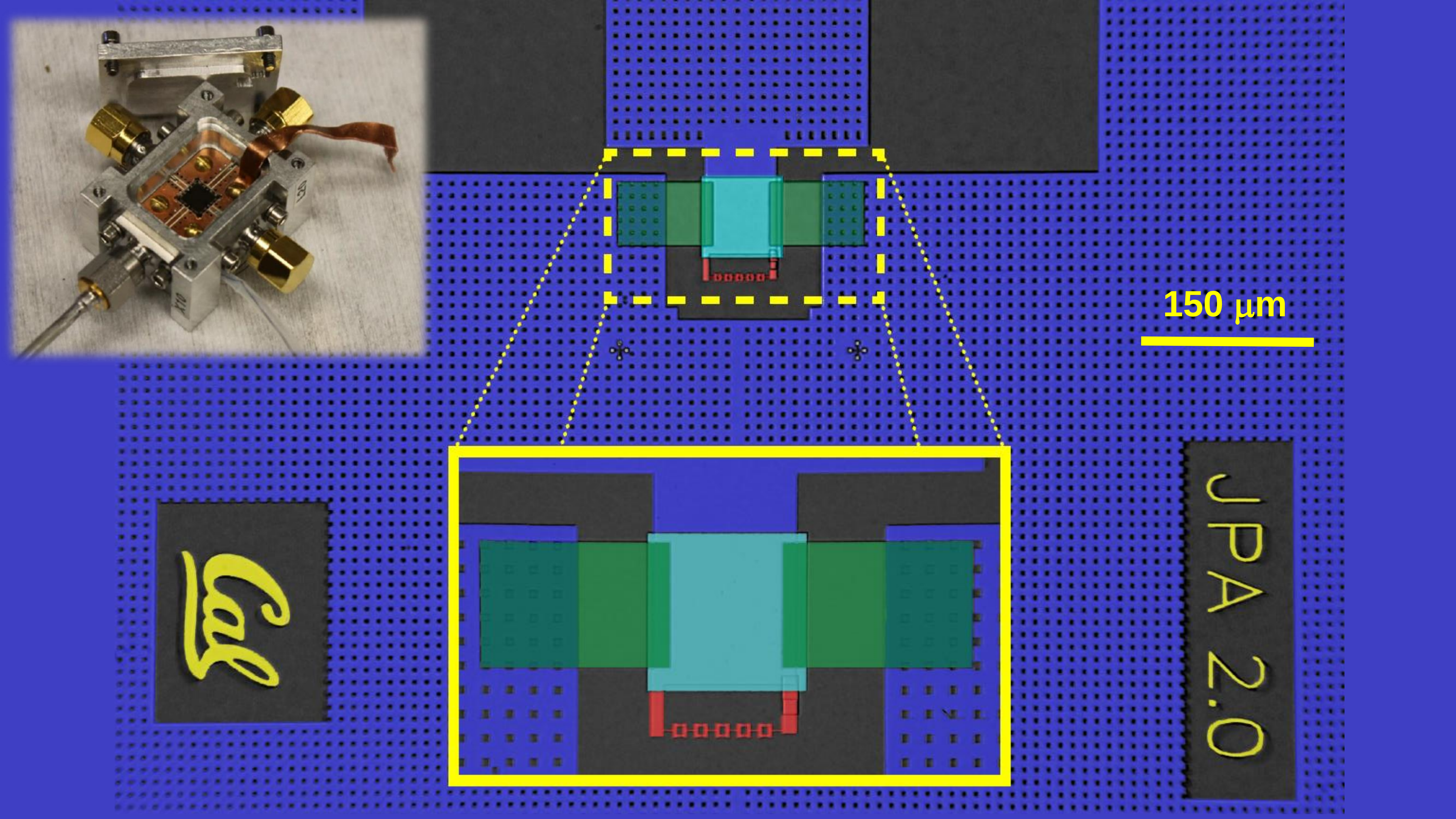
Observation of High Coherence in Josephson Junction Qubits Measured in a Three-Dimensional Circuit QED Architecture

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*







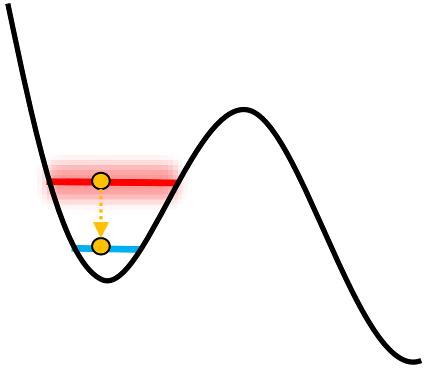
150 μm
Cal
JPA 2.0

SINGLE SHOT MEASUREMENT

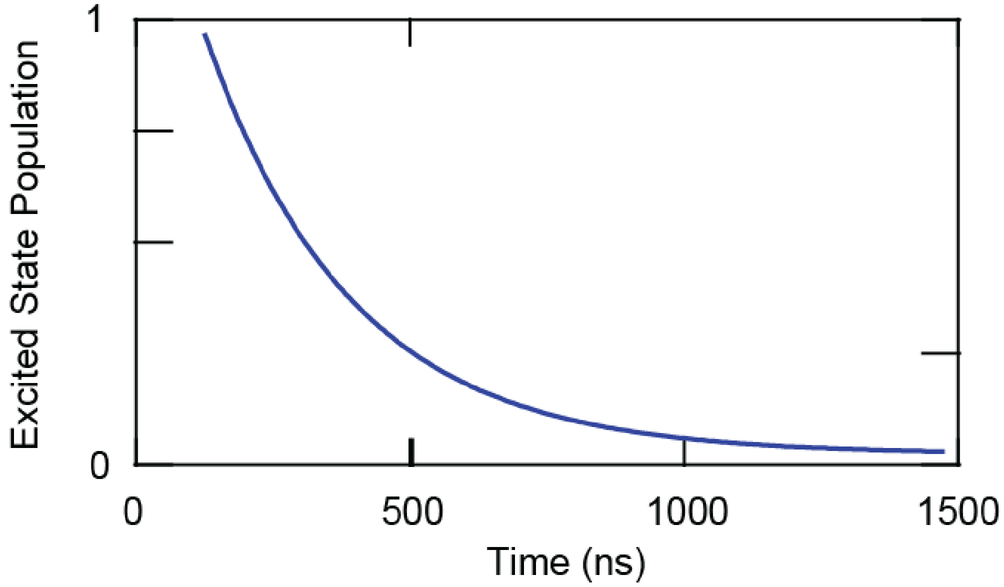
PRL 106, 110502 (2011) PHYSICAL REVIEW LETTERS week ending 18 MARCH 2011

Observation of Quantum Jumps in a Superconducting Artificial Atom

R. Vijay, D. H. Slichter, and I. Siddiqi
Quantum Nanoelectronics Laboratory, Department of Physics, University of California, Berkeley, California 94720, USA



STRONG PROJECTIVE MEASUREMENT

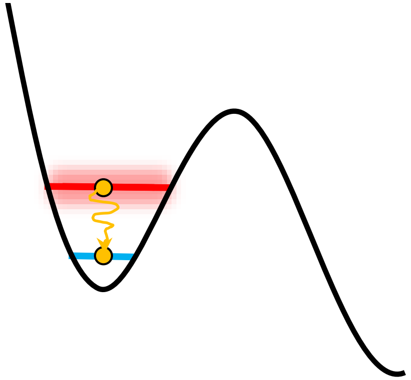


LETTER

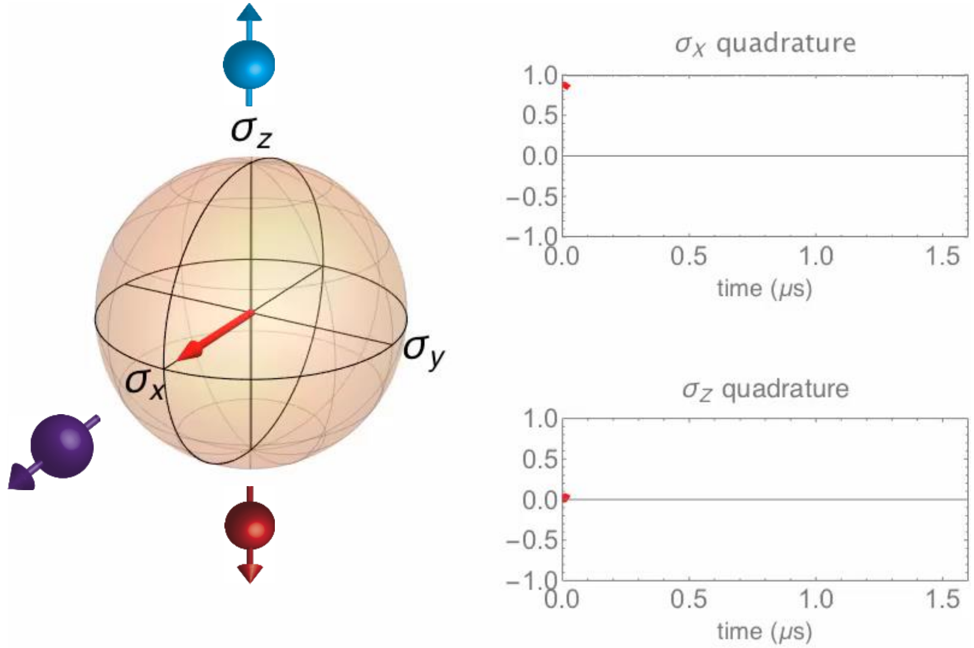
doi:10.1038/nature12539

Observing single quantum trajectories of a superconducting quantum bit

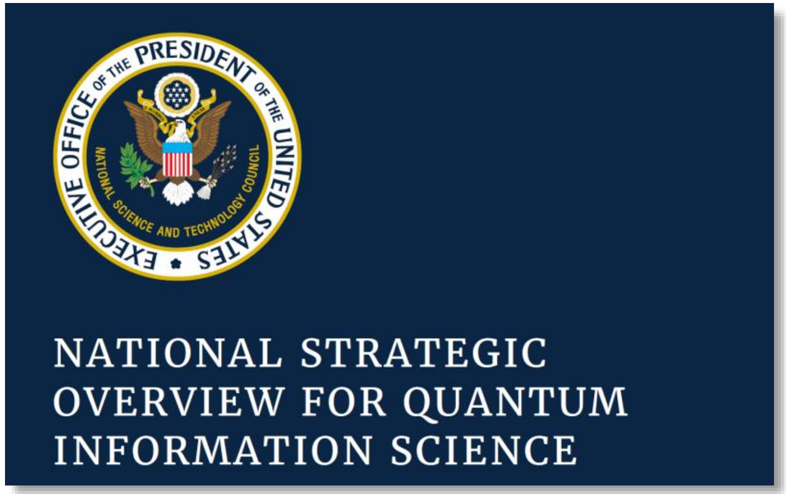
K. W. Murch[1,2], S. J. Weber[1], C. Macklin[1] & I. Siddiqi[1]

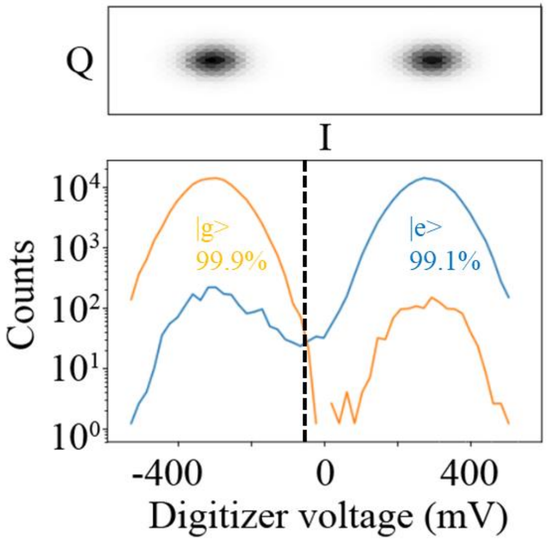


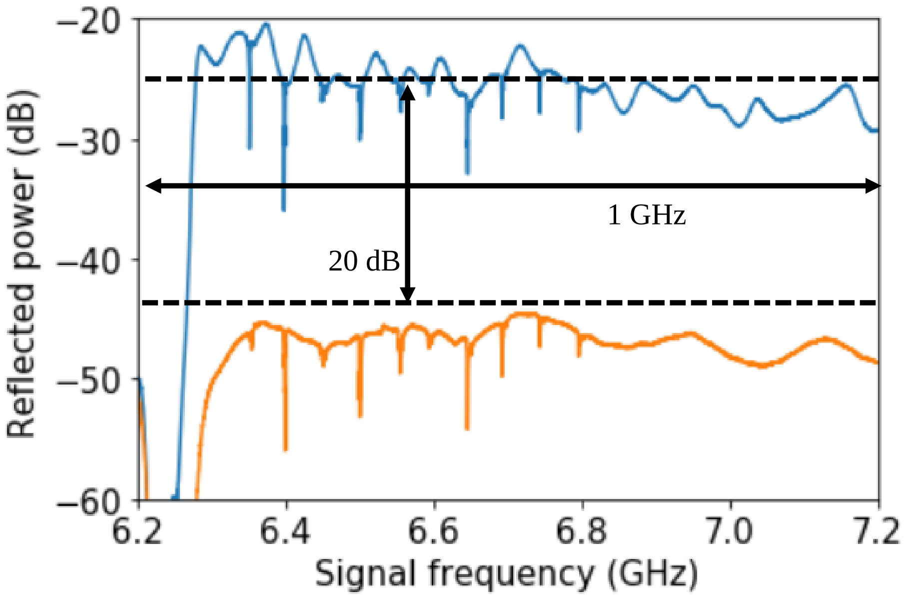
WEAK CONTINUOUS MEASUREMENT

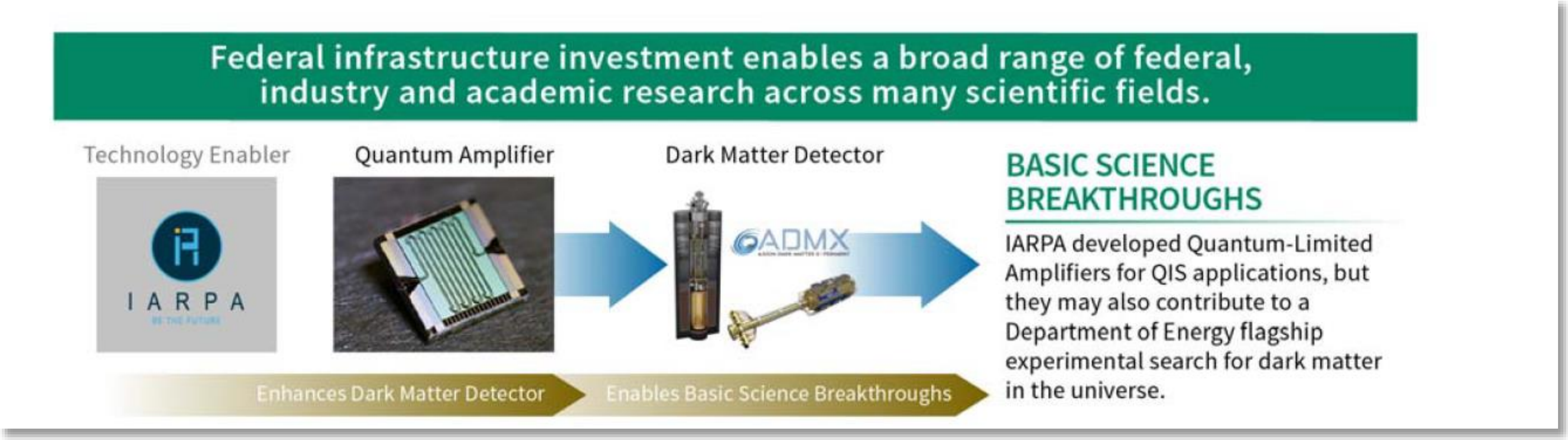


HIGH FIDELITY QUANTUM STATE READOUT









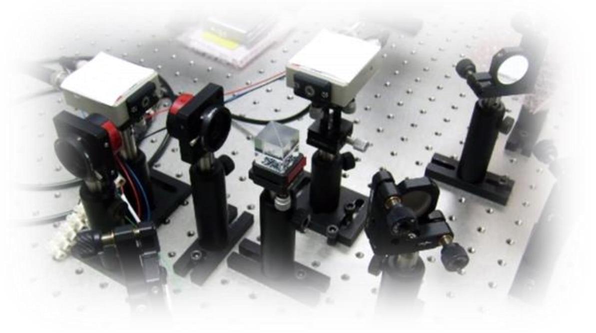
JTWPA: 99.5% average assignment fidelity w/ multiplexing capability

CAN MEASURE THE PHASE OF A QUANTUM SIGNAL ?

Power $a^\dagger a = \hat{N} \rightarrow |n\rangle\langle n|$

Amplitude

$$(a^\dagger + a) = \hat{x} \rightarrow \delta(\hat{x} - x_0)$$
$$(a^\dagger - a)/i = \hat{p} \rightarrow \delta(\hat{p} - p_0)$$



Can we measure phase?

$$|\theta\rangle\langle\theta| \equiv \sum_n e^{in\theta}|n\rangle\langle n|$$

VOLUME 75, NUMBER 25 PHYSICAL REVIEW LETTERS 18 DECEMBER 1995

Adaptive Phase Measurements of Optical Modes: Going Beyond the Marginal Q Distribution

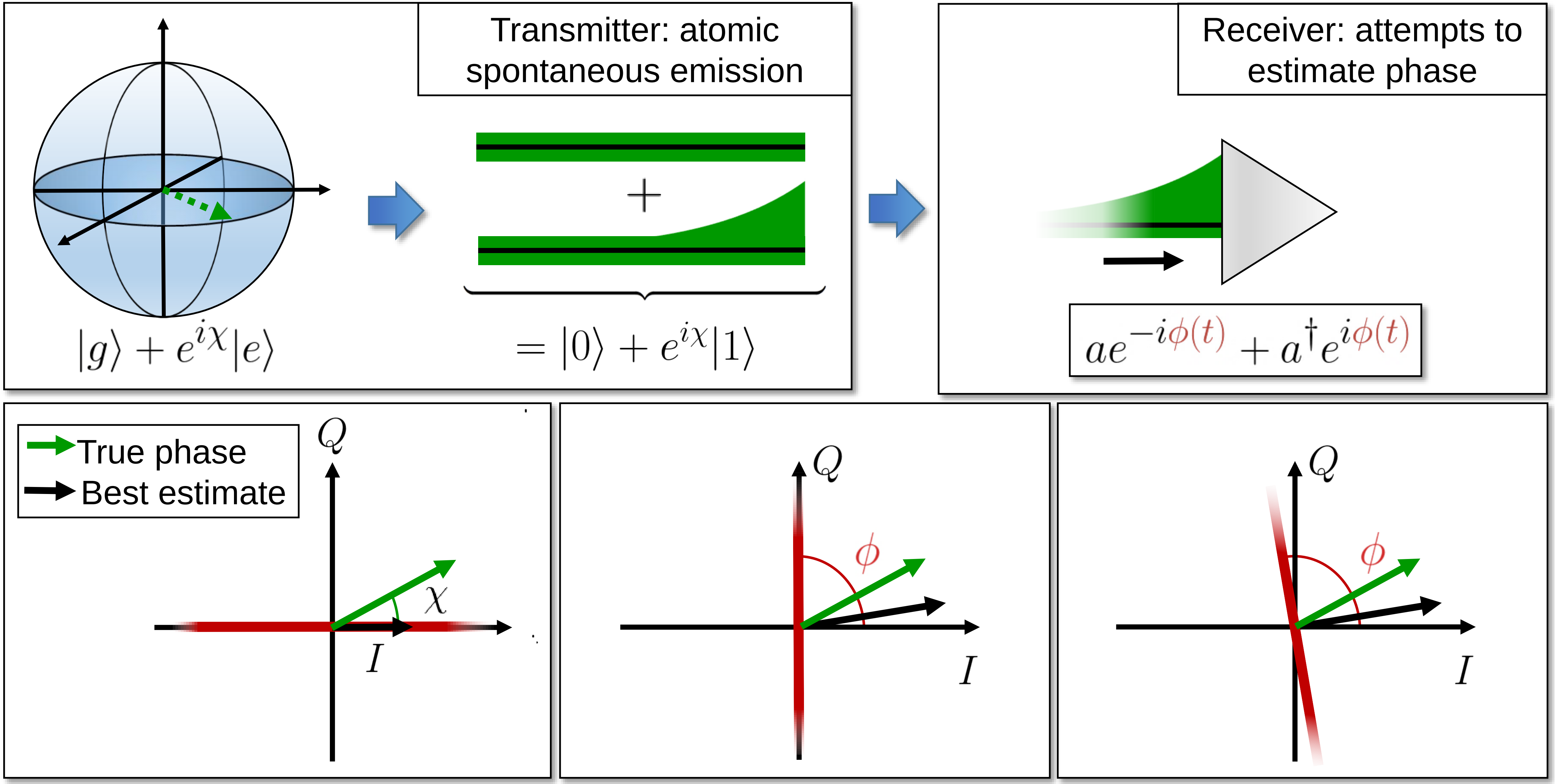
H. M. Wiseman*

Department of Physics, University of Auckland, Auckland, New Zealand
(Received 20 March 1995; revised manuscript received 31 August 1995)

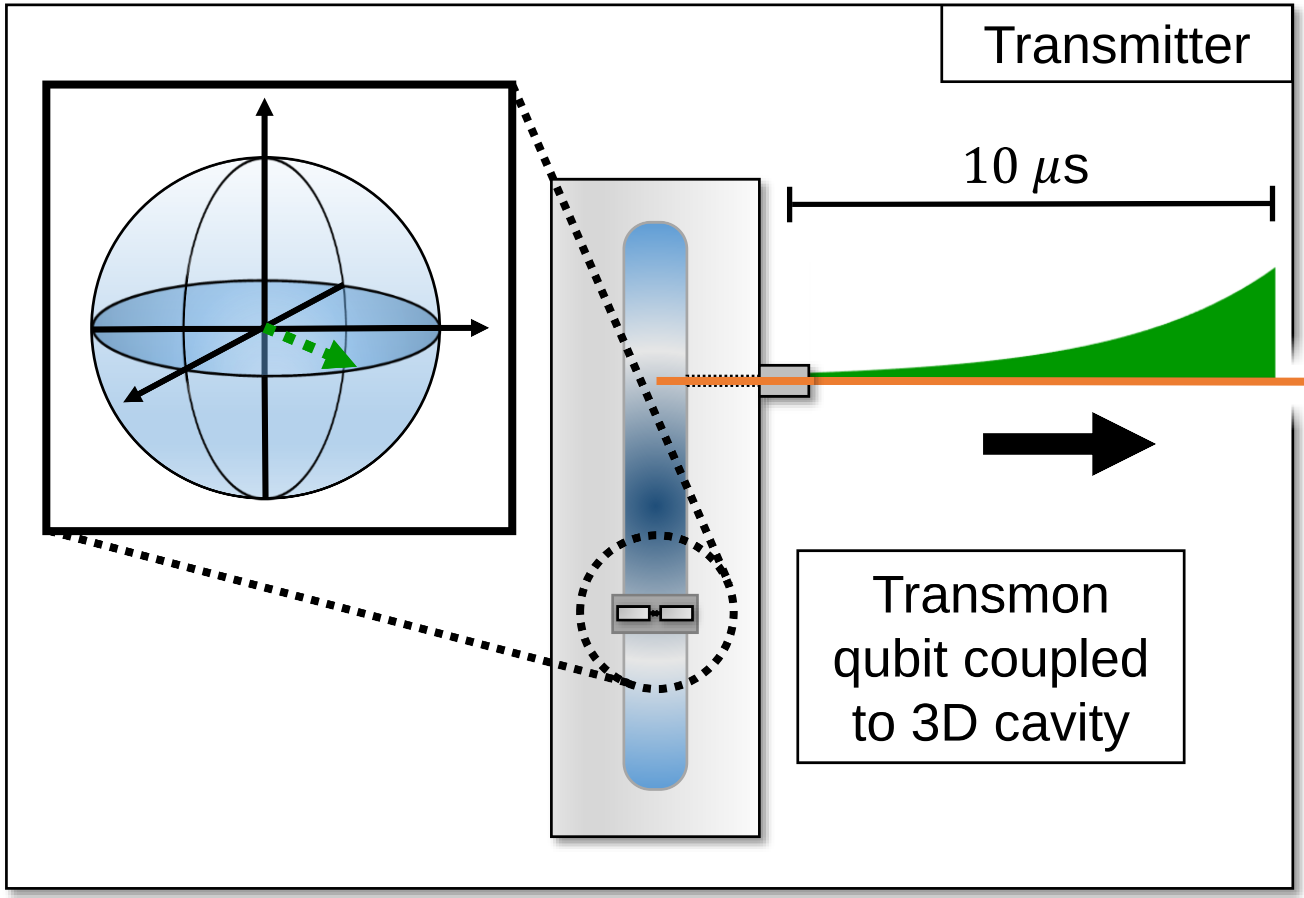
In standard single-shot measurements of the phase of an optical mode, the phase and amplitude quadratures are jointly measured, and the latter information discarded. These techniques are consequently suboptimal. Here I suggest an adaptive scheme, whereby the phase is estimated from the results so far and fed back to control the phase of the local oscillator so as to measure the (estimated) phase quadrature only. I show that adaptive phase measurements can approach optimal phase measurements for states with both low and high mean photon numbers.

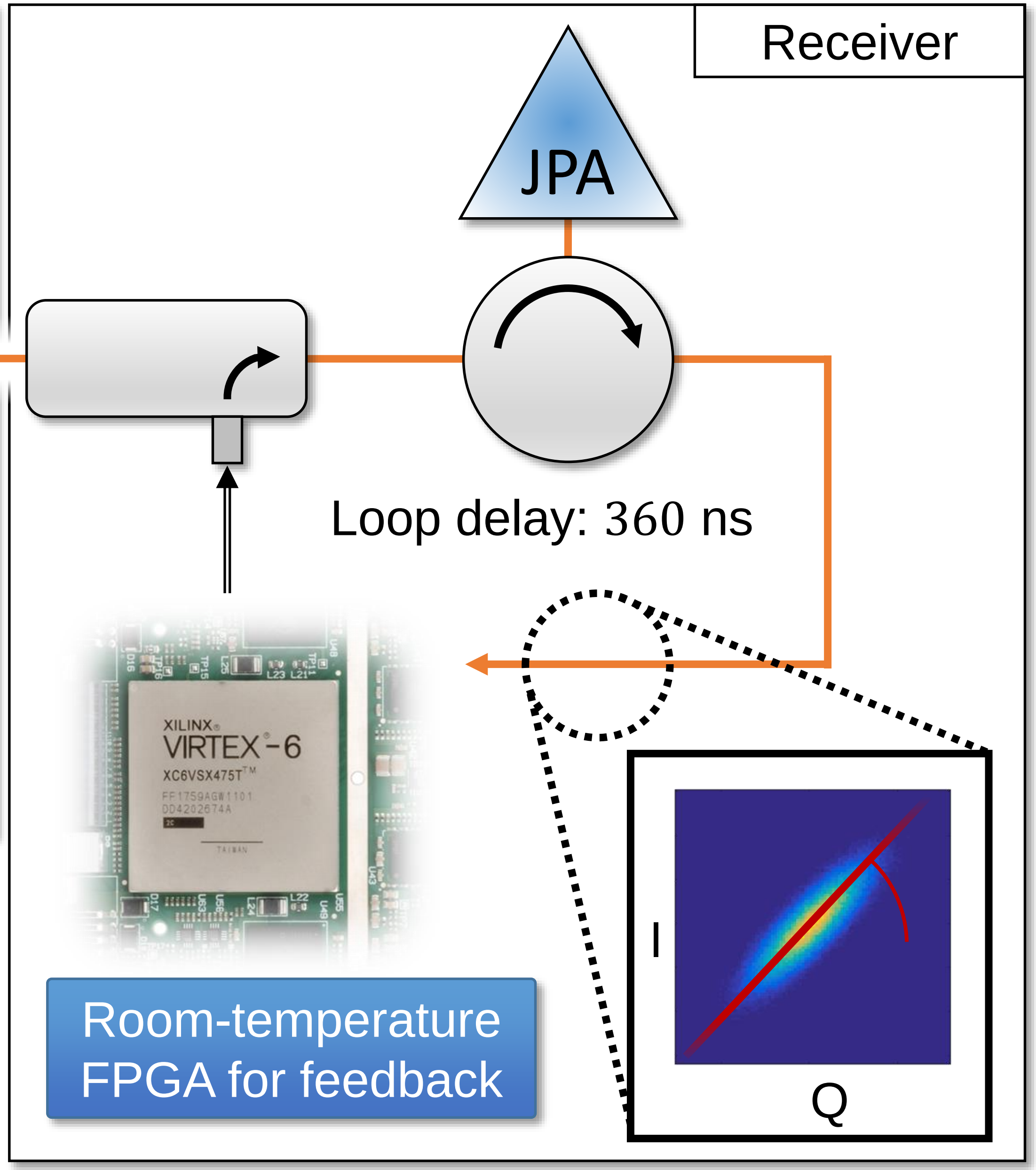
PACS numbers: 42.50.Dv, 03.65.Bz, 42.50.Lc

ADAPTIVE PHASE MEASUREMENT



EXPERIMENTAL SETUP – ADAPTIVE DETECTION





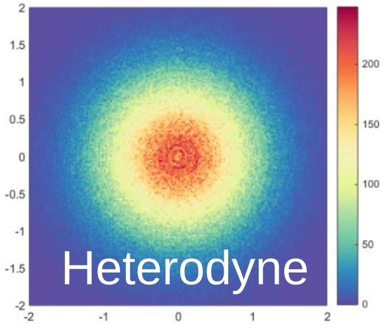
Experimental sequence

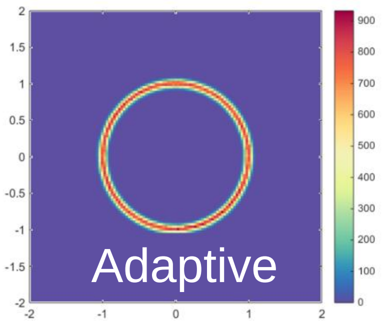
- Transmitter prepares photon with chosen phase
- Receiver adapts measurement as photon arrives
- Perform qubit state tomography

PHASE ESTIMATION: RECEIVER PERFORMANCE

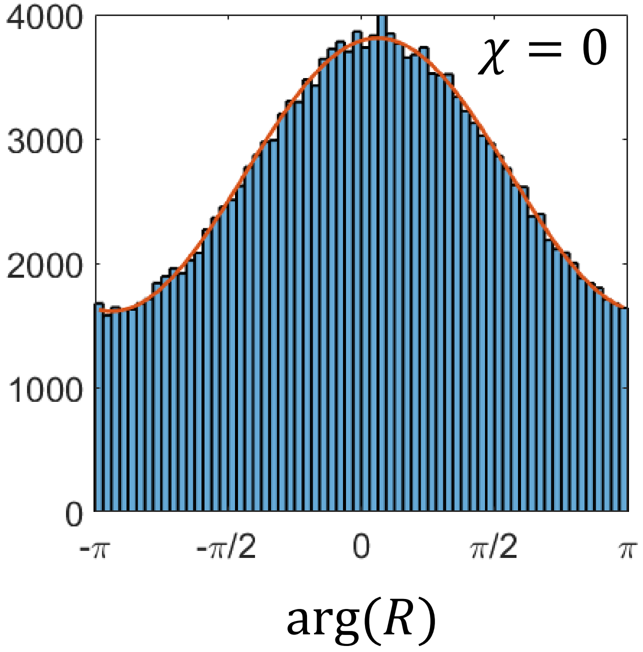
$$R \equiv \int_0^\infty e^{i\phi(t)} \sqrt{u(t)} V(t) dt$$

Amplifier phase | Photon mode shape | Amplifier output





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



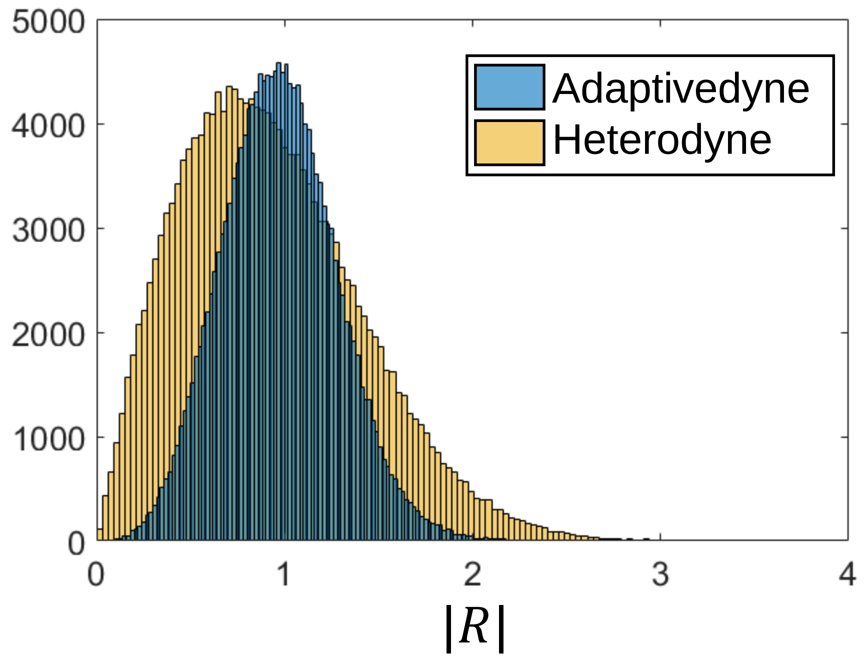
Holevo variance

Adaptivedyne:
19.4 ±0.3

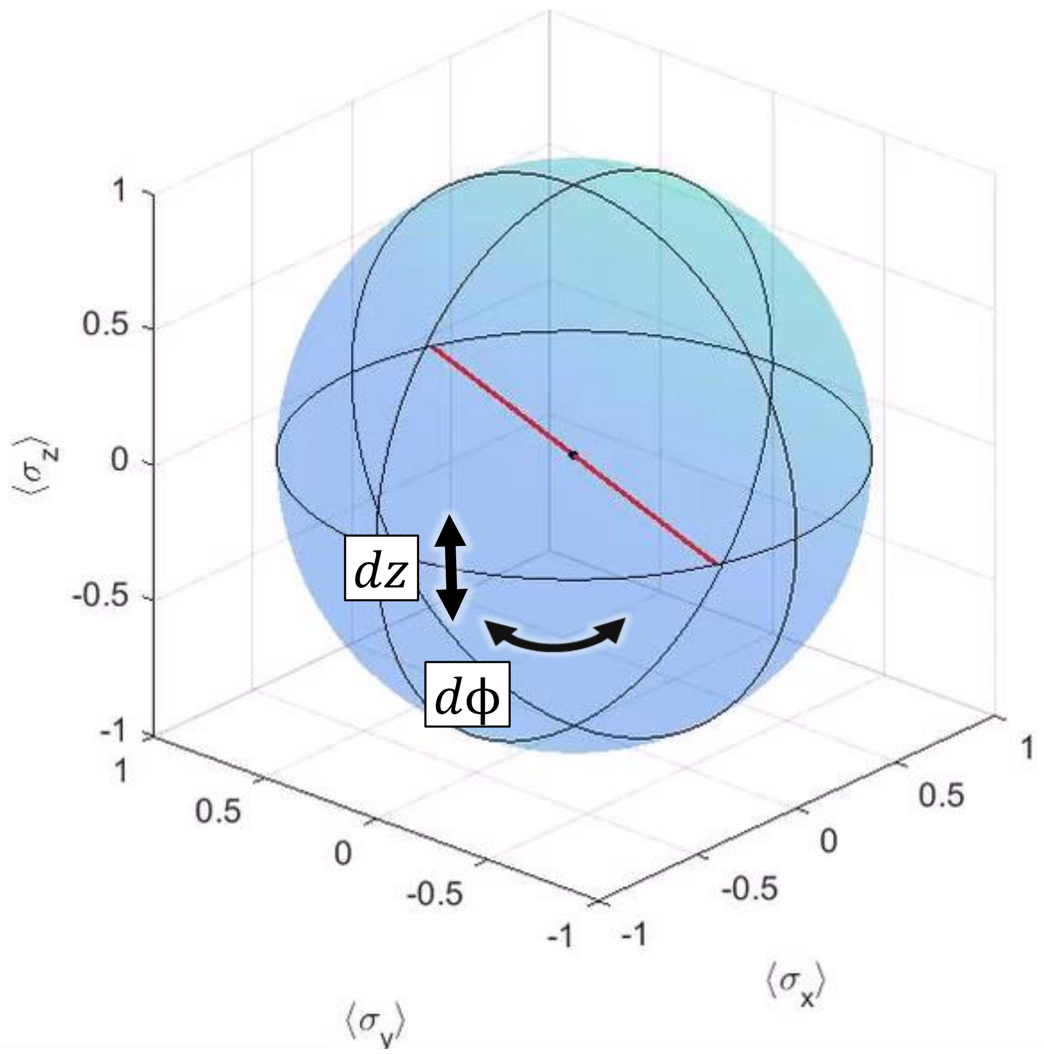
Heterodyne
22.8 ± 0.4

Quantum limit (η=0.21)
17.7

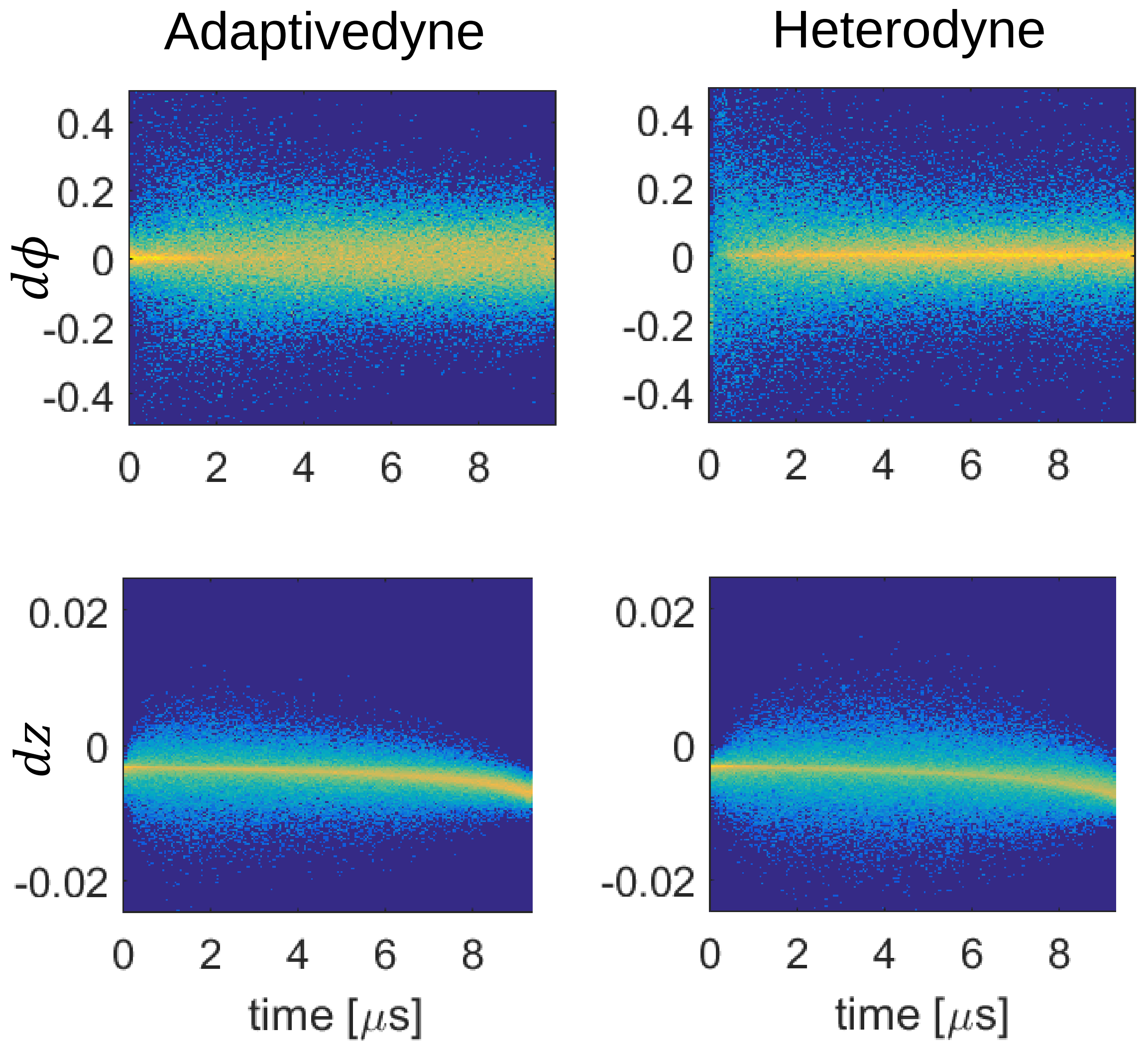
Photon number information: $|R|$



EXPERIMENTAL ADAPTIVEDYNE BACK-ACTION



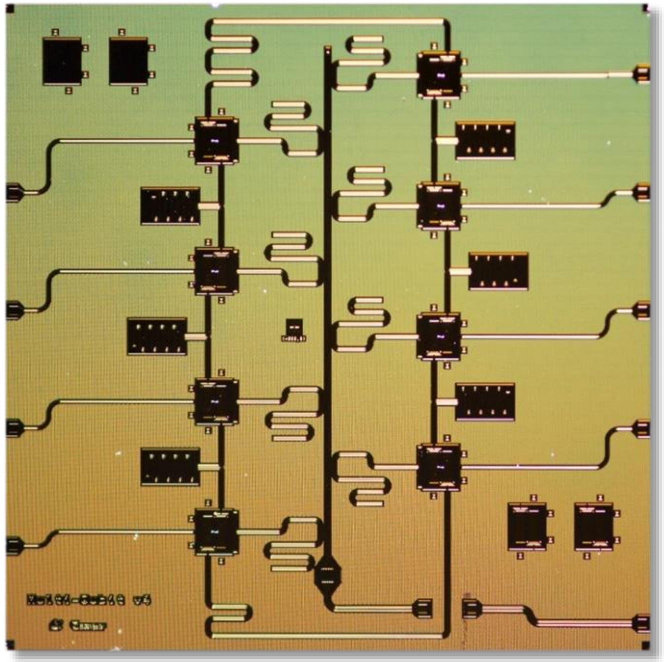
Comparison of back-action
(histogram of $d\rho$, 50 ns time step)



LIFE BEYOND A FEW QUBITS

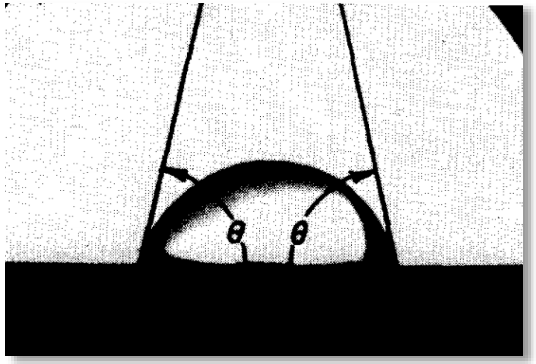
- Decoherence in many particle systems
- Control and data processing
- Optimizing quantum protocols

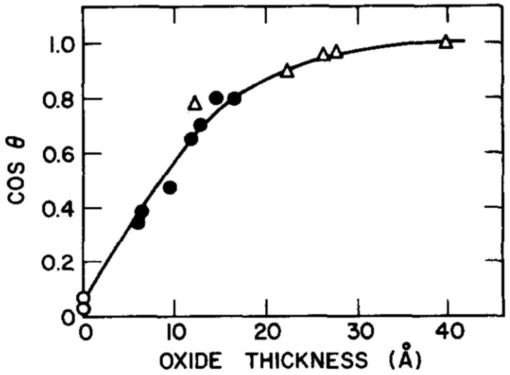
QUBITS AND THEIR MANY FACETS



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

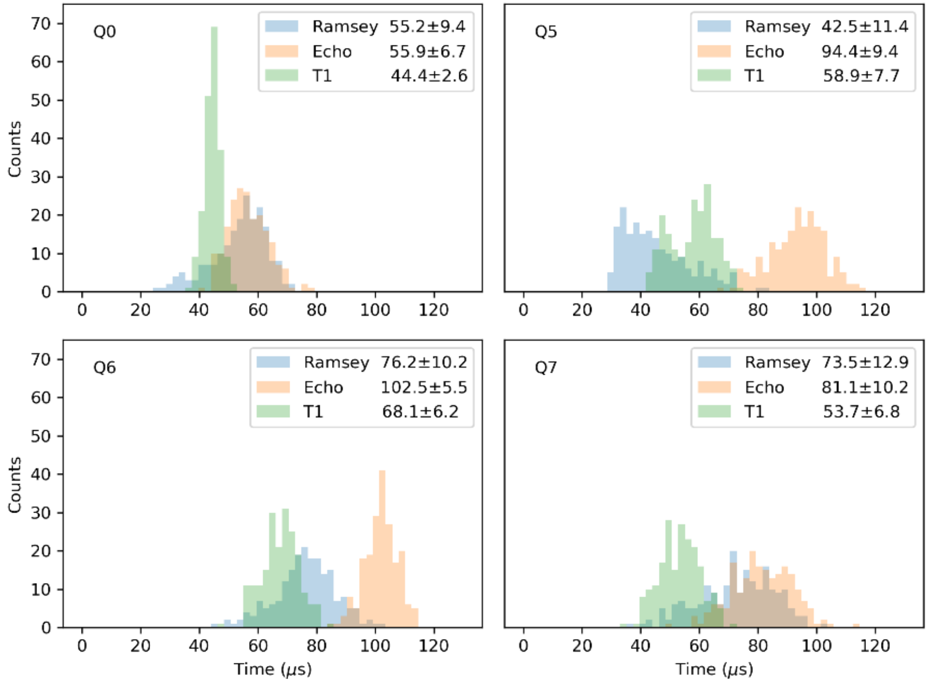




R. Williams and A.M. Goodman. “Wetting of thin layers of SiO_2 by water.” Appl. Phys. Lett. 25, 531 (1974)

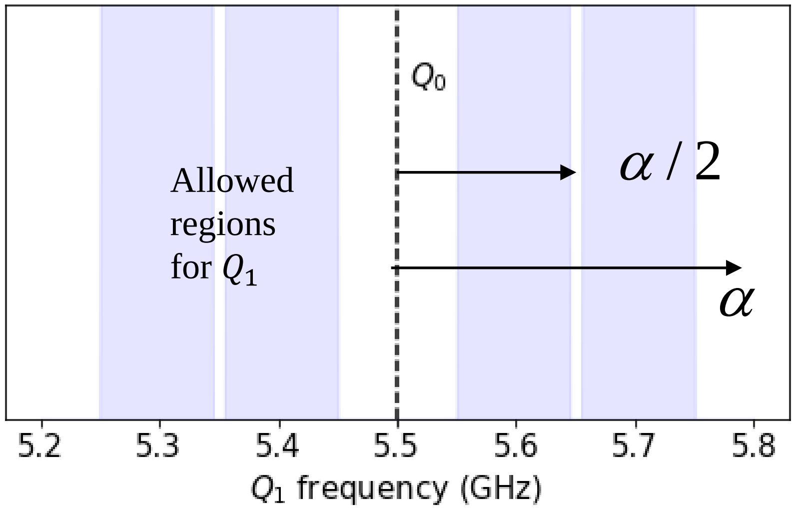
- Rapid non-destructive hydro-metrology!

targeted HF etch → **doubled T_1**



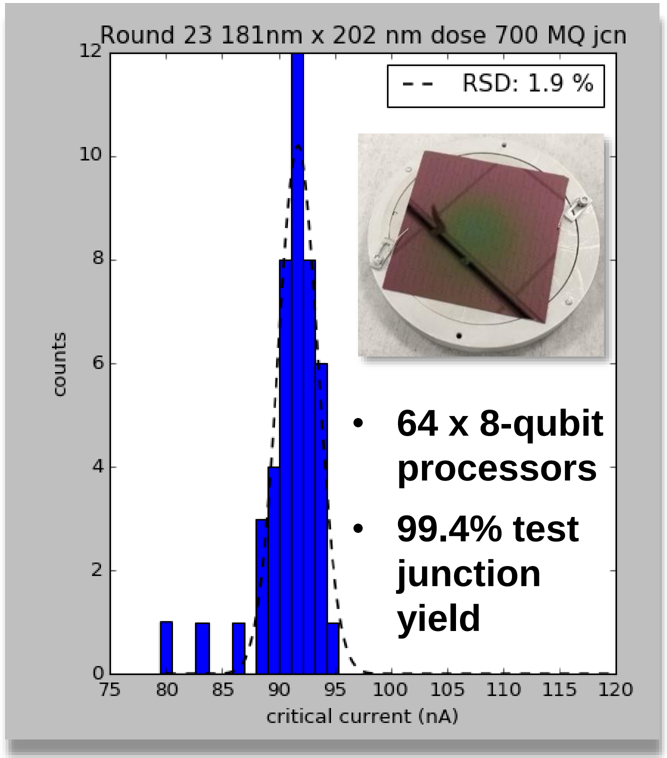
NEED LOCAL, 3D DEFECT MAPS (CHEMICAL/STRUCTURAL) & MODELING

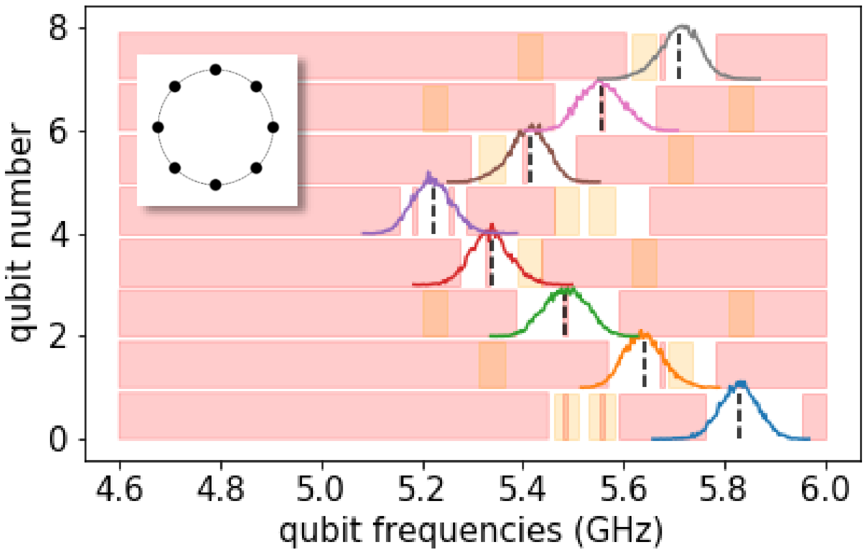
8 QUBIT CHIP UNIFORMITY REQUIREMENTS



- 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



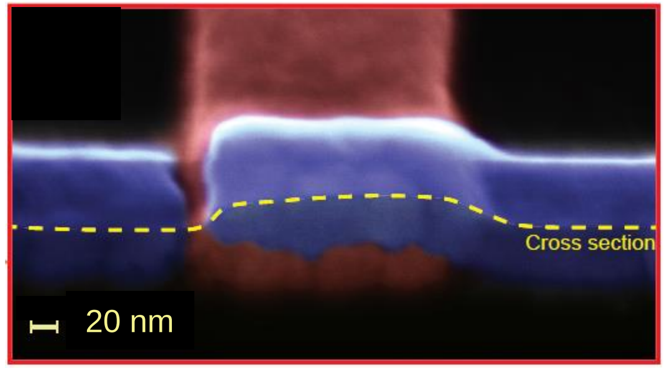


Forbidden frequency regions for nearest neighbors (red) and next nearest neighbors (orange)

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

- For σ = 50 MHz

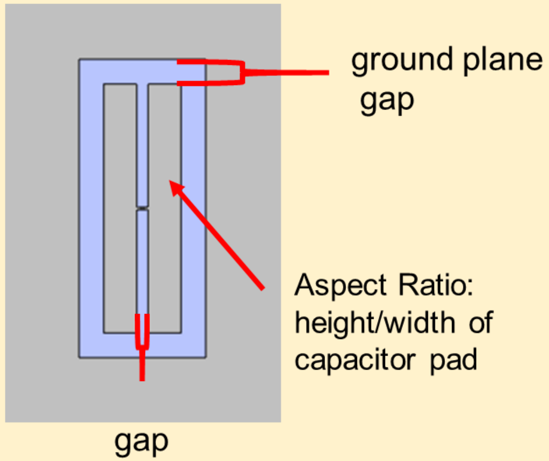
(2% critical current variation)
Predicted yield is 10%.



CO-DESIGN OF MATERIALS / ARCHITECTURE / ALGORITHMS

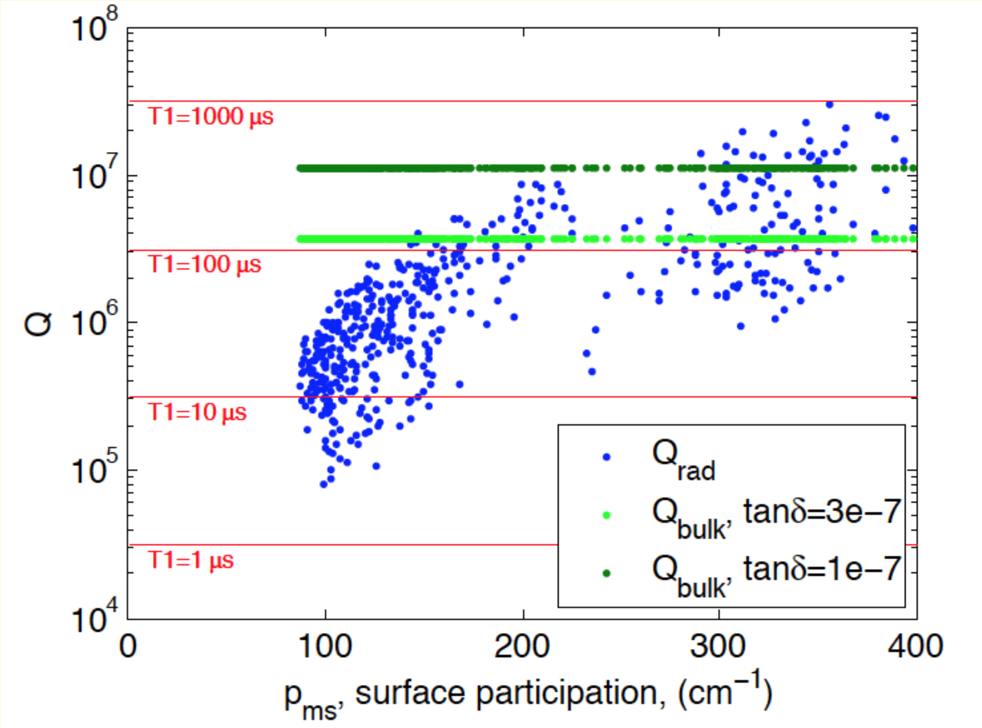
SUPPRESSING QUANTUM CHATTER

Parameters Varied:

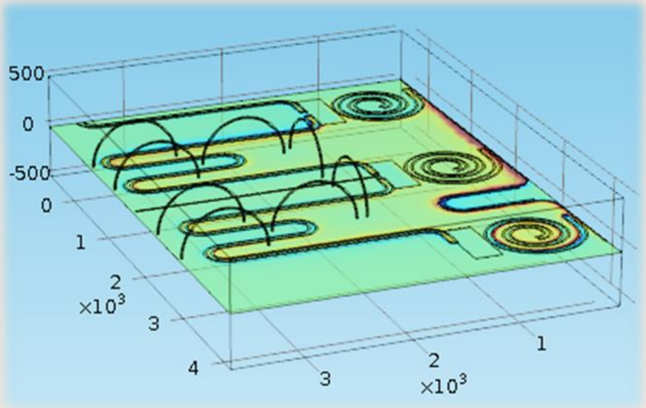


Resonance freq. 5-6 GHz

Geometry: Radiation Q vs. Surface Loss



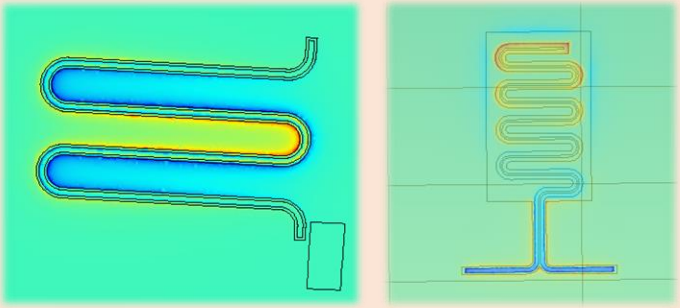
Spurious mode Identification



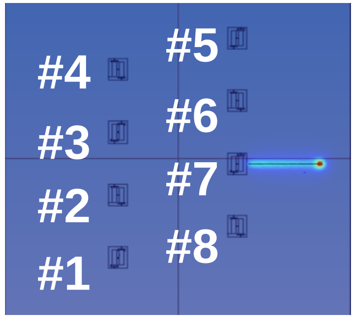
Hybrid CPW-CPS Resonators

10 GHz slotline mode

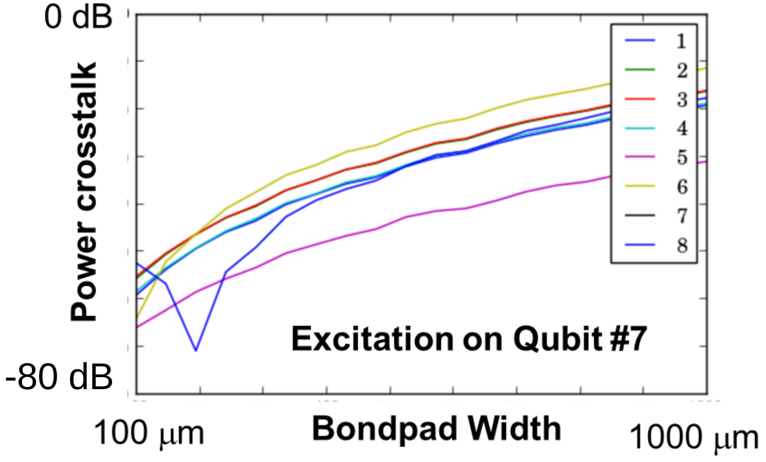
17 GHz slotline mode



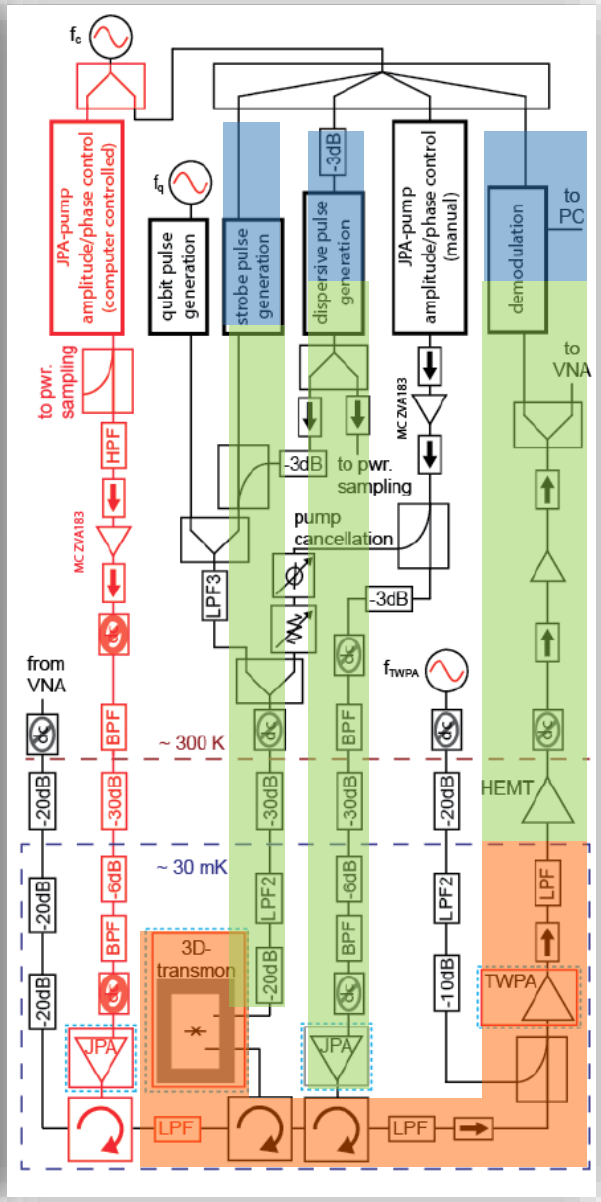
Crosstalk

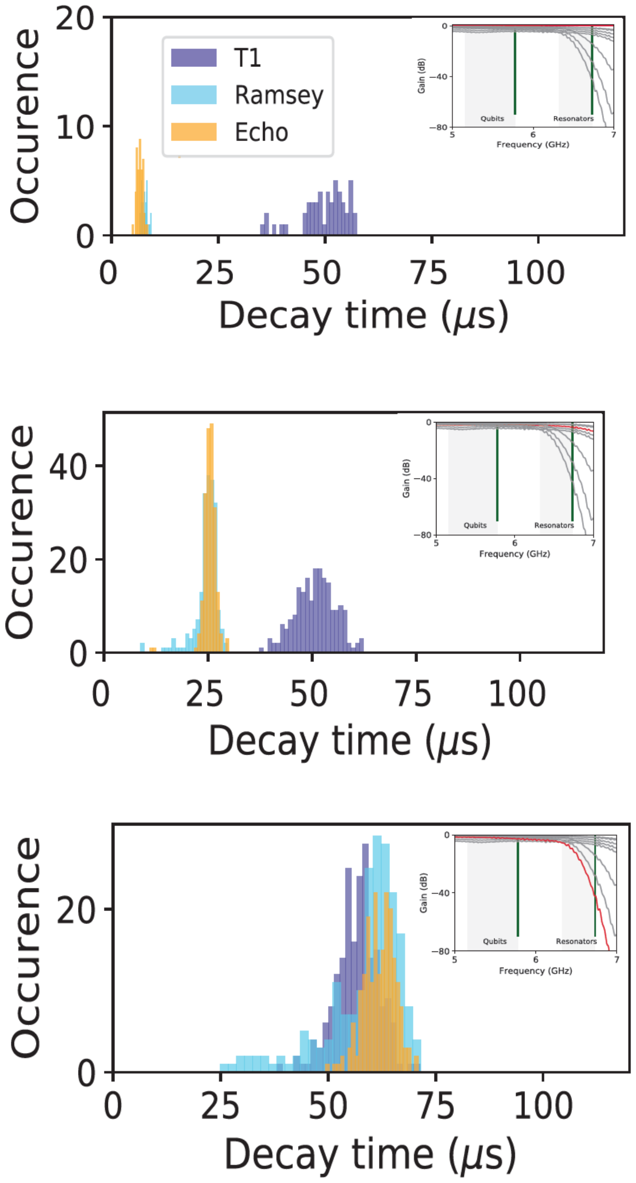


100x100 um^2 bondpad



THE TYRANNY OF WIRES



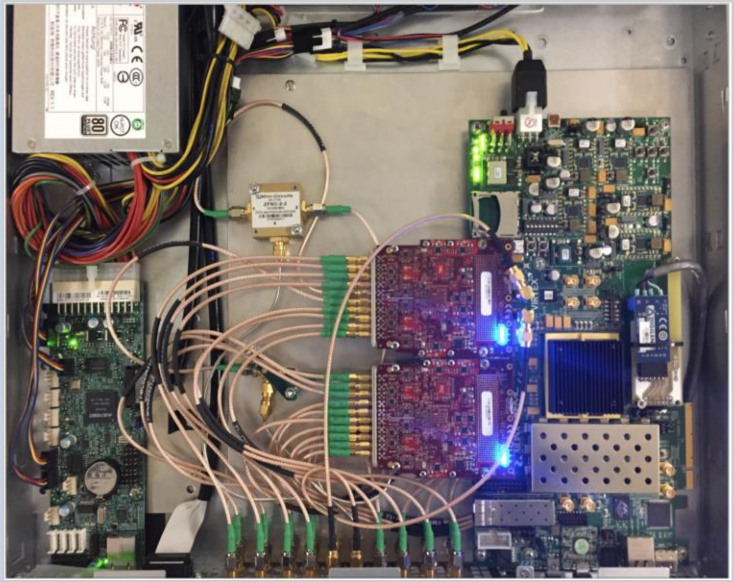


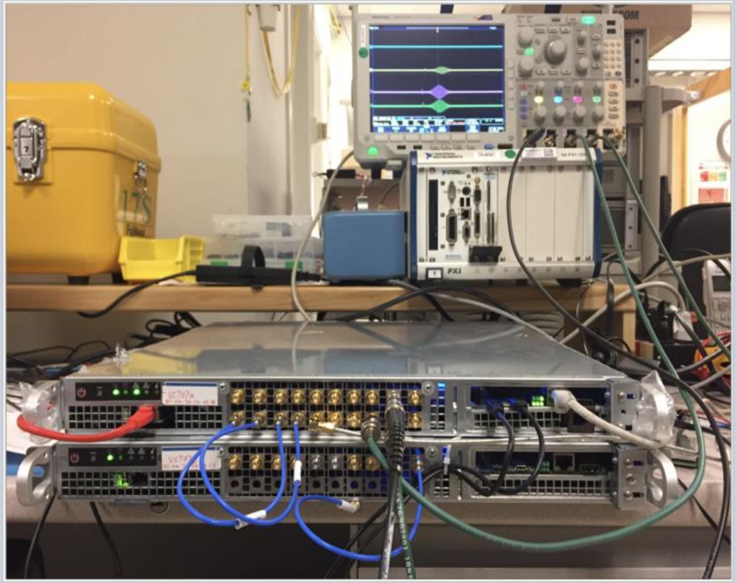
- **Need to reduce wire count !**
- **Need to reduce wire complexity**
- **Quantum data transmission & conversion**
  - optical
  - acoustic
  - classical analog
  - classical digital
- **Cryogenic data processing ?**

THAT'S A LOT OF DATA!

PROTOTYPE CONTROLS FROM THE ACCELERATOR DIVISION

- Scalable
- Low cost per channel
- 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
  - Schematic design finished, layout started

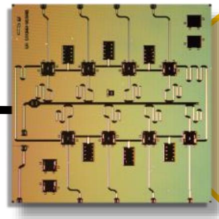




QUANTUM: THERE'S A LOT OF INFORMATION IN THAT CHIP !

Initialize System

Quantum Processor



Entanglement
(N qubits → 2^N)

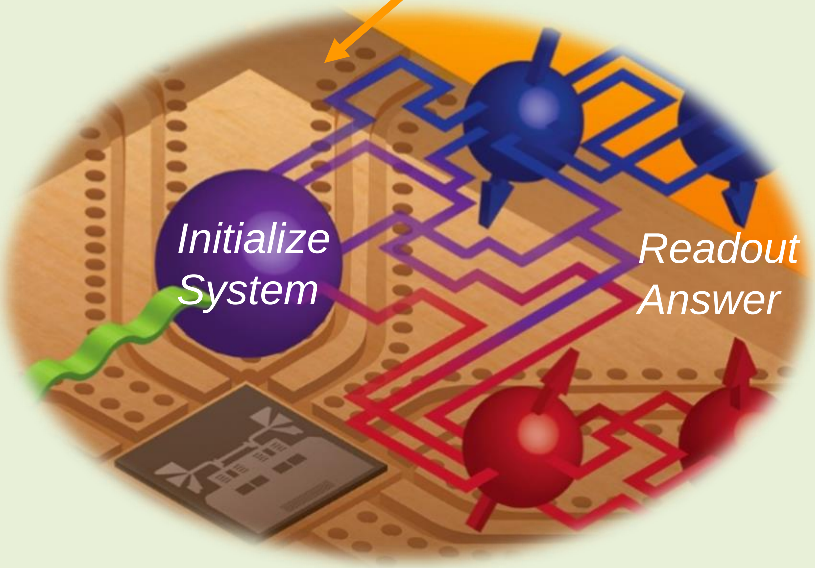
- Tomography
- Error Correction / Calibration
- Gate Set Tomography
- State Tracking/Feedback

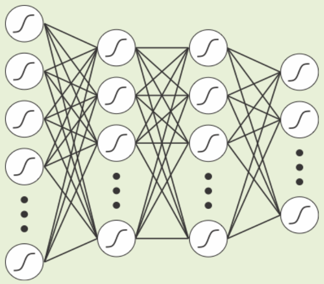
Readout Answer

Classically: A lot of data!

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

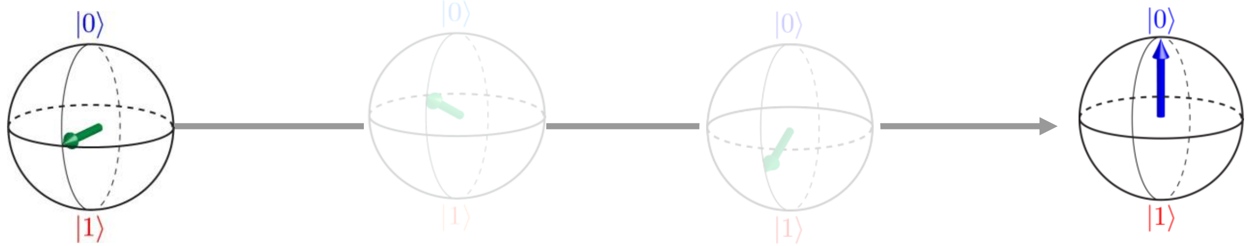
Trajectory Reconstruction & Validation: A lot of classical data!

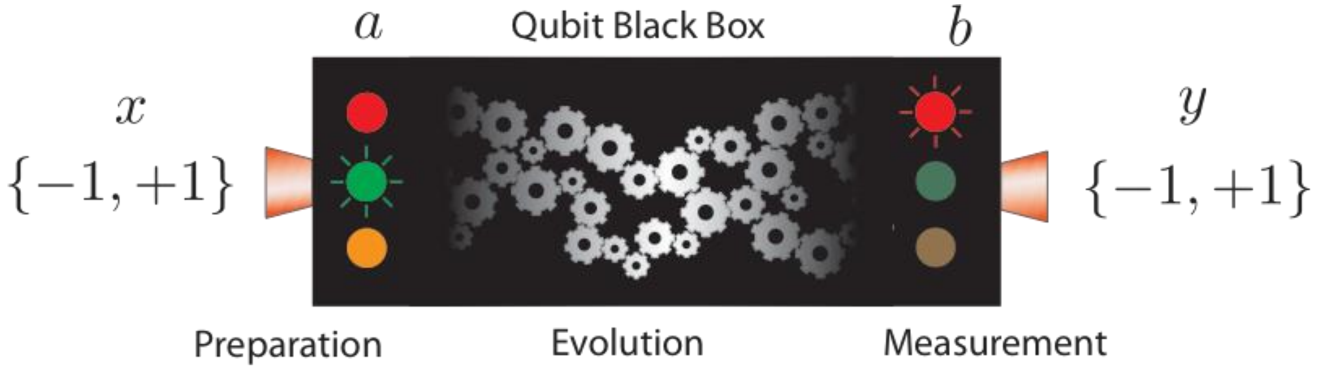




10^6 instances per minute

CAN WE TEACH A MACHINE QUANTUM MECHANICS ?

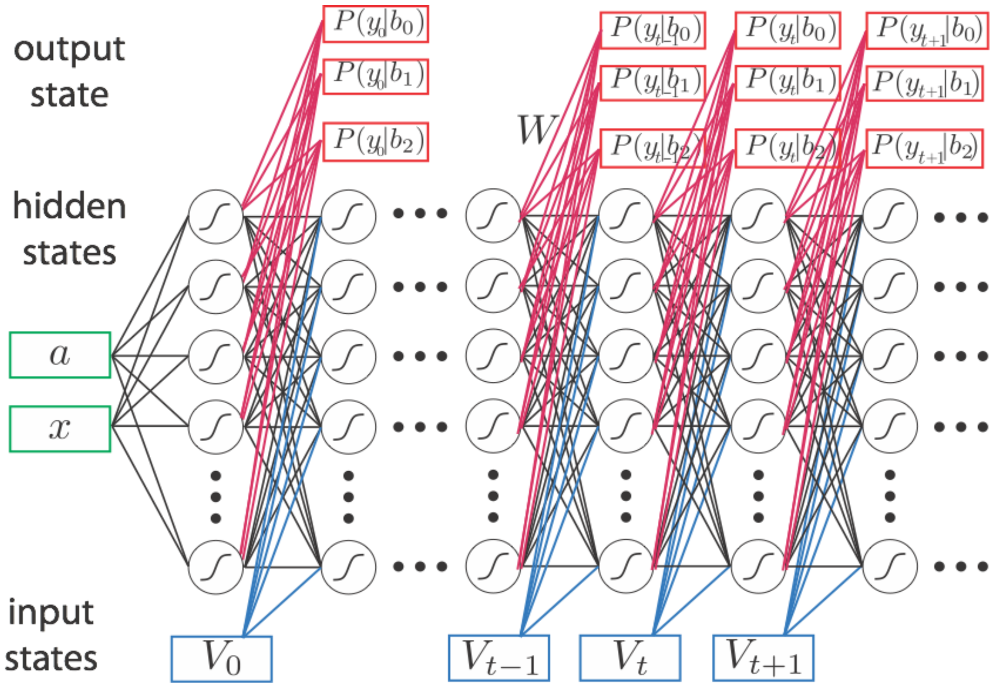




$$P(y|x, a, b, V_0, ..., V_t, ..., V_T) = \frac{\mathrm{Tr}(|y\rangle\langle y|\hat{B}\hat{\Omega}_{V_T}...\hat{\Omega}_{V_t}...\hat{\Omega}_{V_0}\hat{A}\rho_x\hat{A}^\dagger\hat{\Omega}^\dagger_{V_0}...\hat{\Omega}^\dagger_{V_t}...\hat{\Omega}^\dagger_{V_T}\hat{B}^\dagger)}{\mathrm{Tr}(\hat{\Omega}_{V_T}...\hat{\Omega}_{V_t}...\hat{\Omega}_{V_0}\hat{A}\rho_x\ha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

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

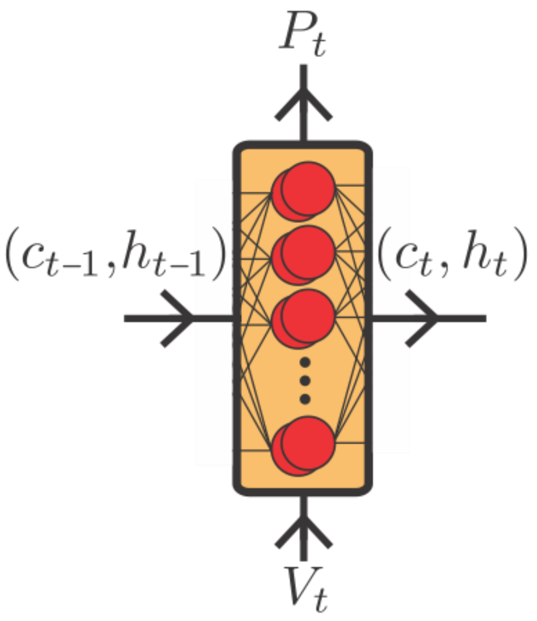
$$P(y_t|\vec{b}) = \sigma(W_{ho}.\vec{h}_t + \vec{\beta})$$

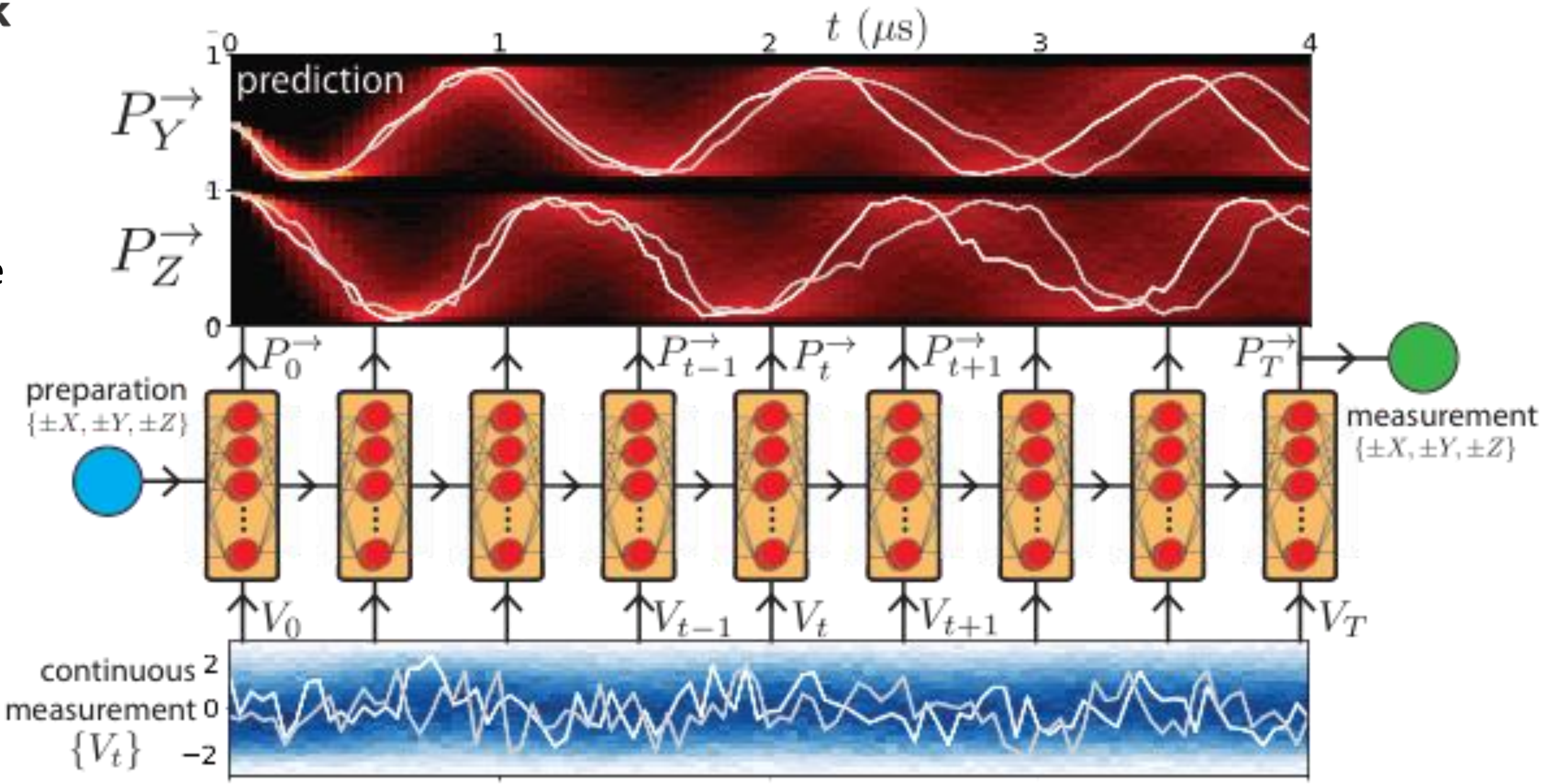


RNN RESULTS: RABI OSCILLATIONS

Recurent Neural Network

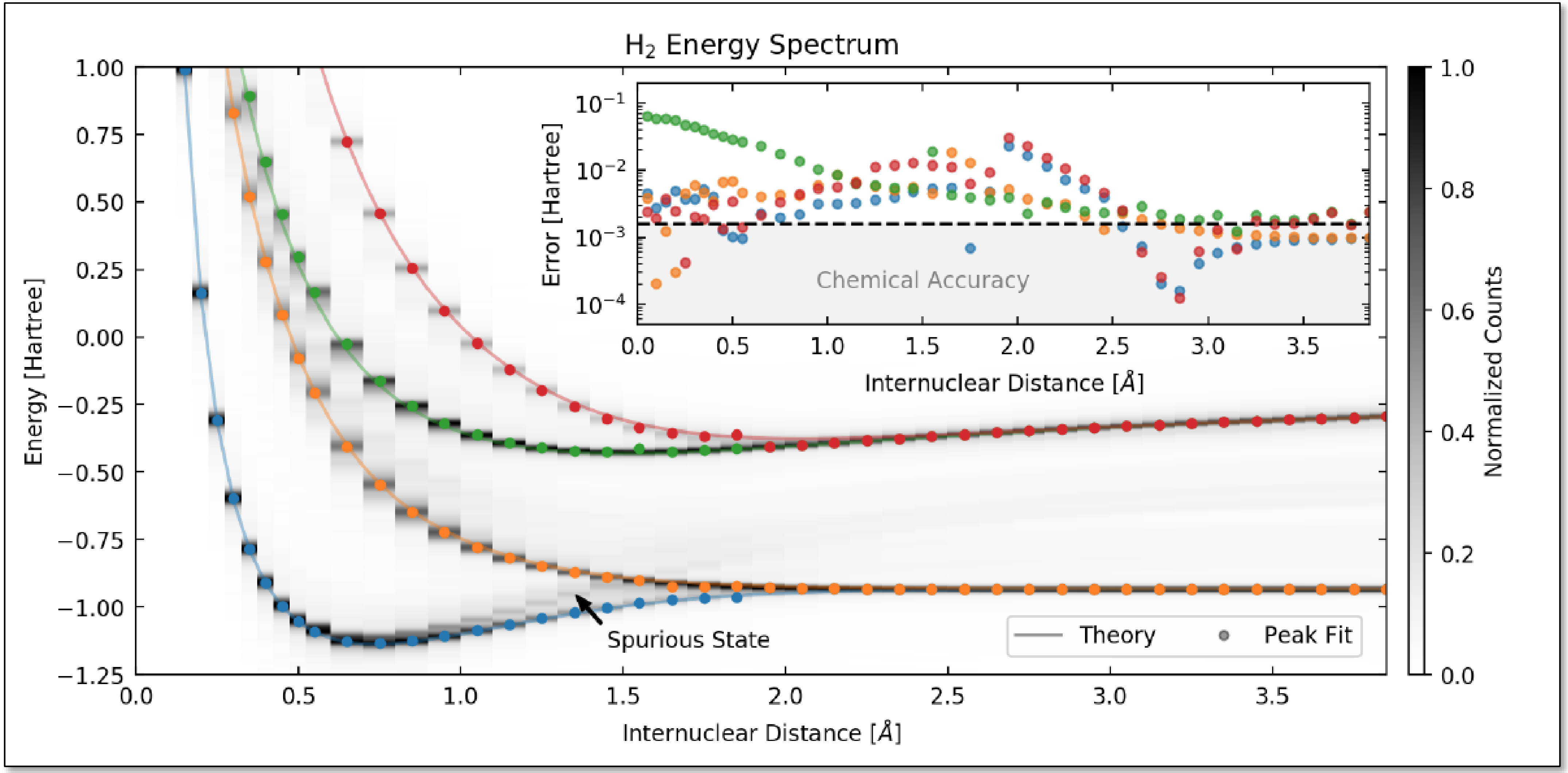
- Long-Short Term Memory
- 64 Neurons per layer
- 30,000 weight parameters
- 0.8 ms of training per trace with a K80 GPU



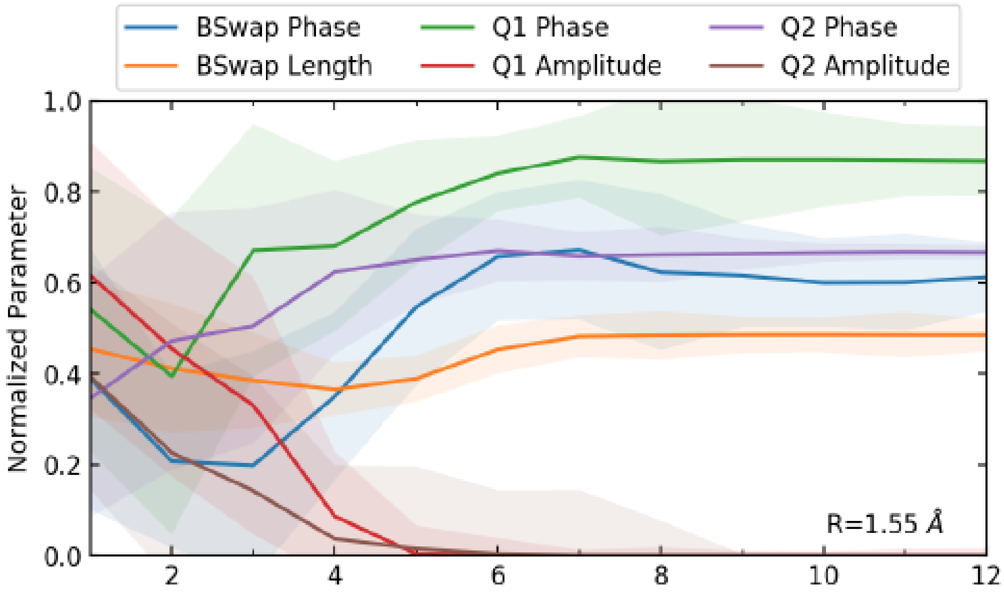


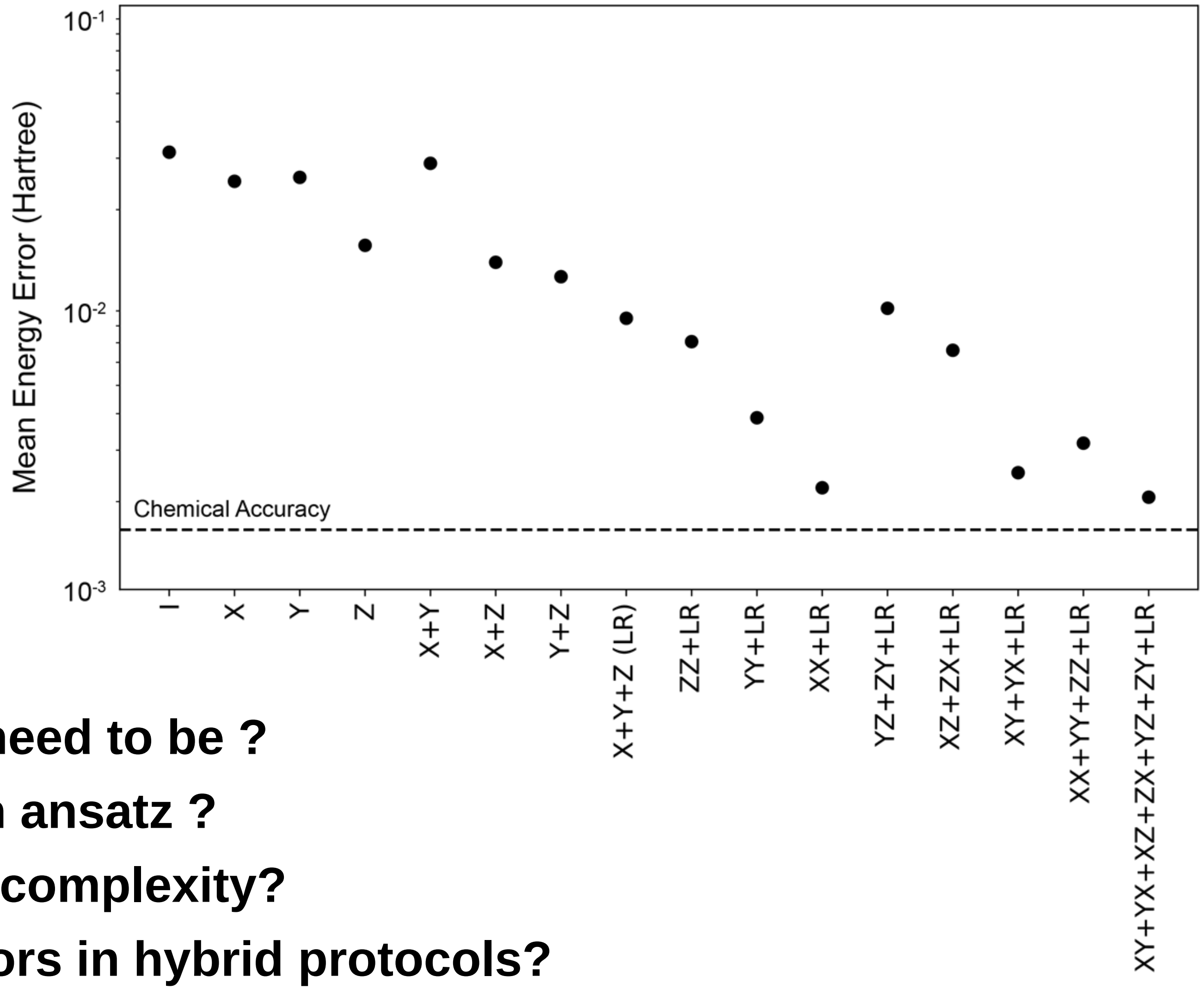
QUANTUM SIMULATION EXPERIMENTS

H_2 REVISITED



MORE QUESTIONS THAN ANSWERS !





- **How do errors scale with system size ?**
- **How stable do our gates/measurements need to be ?**
- **How difficult is it to effectively prepare an ansatz ?**
- **Is there a tradeoff between accuracy and complexity?**
- **How do we suppress/mitigate/correct errors in hybrid protocols?**

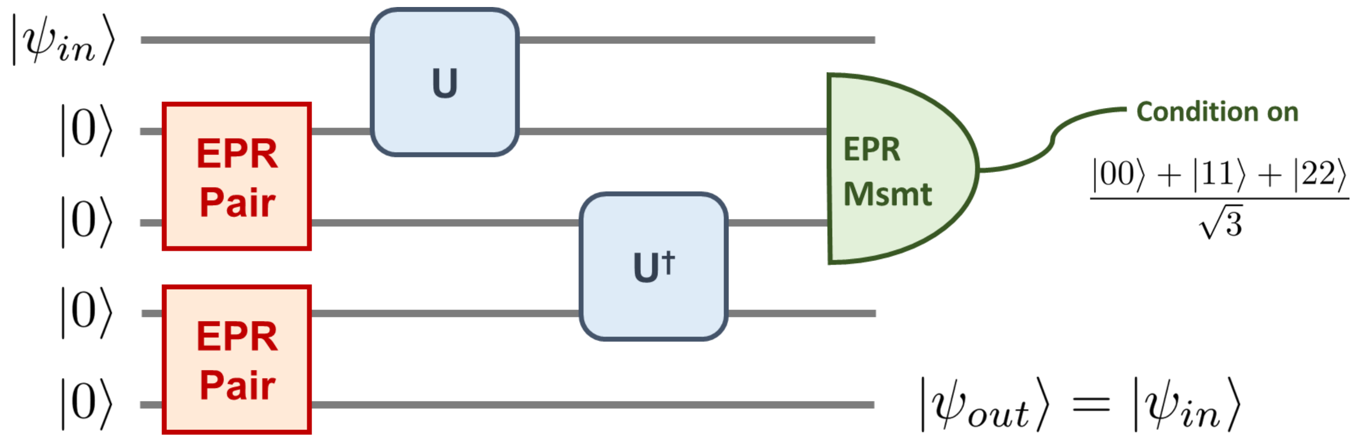
SIMULATING THE COSMOS

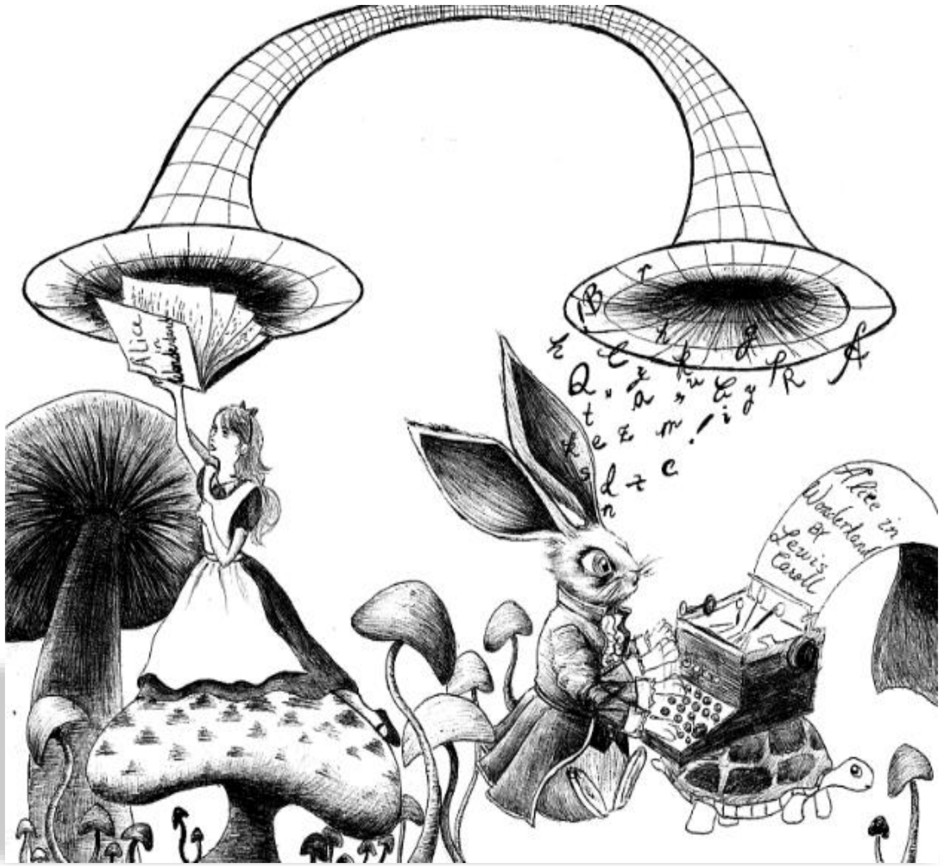
Disentangling Scrambling and Decoherence via Quantum Teleportation

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)

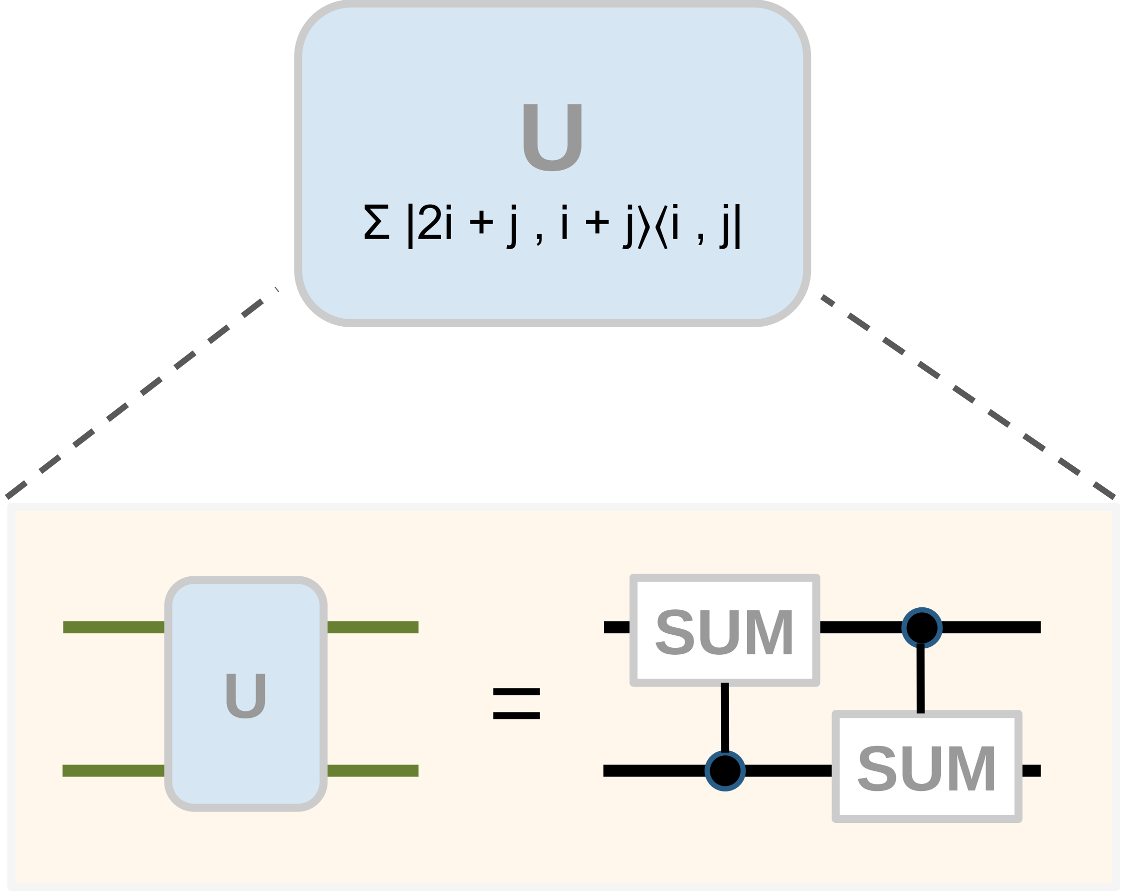




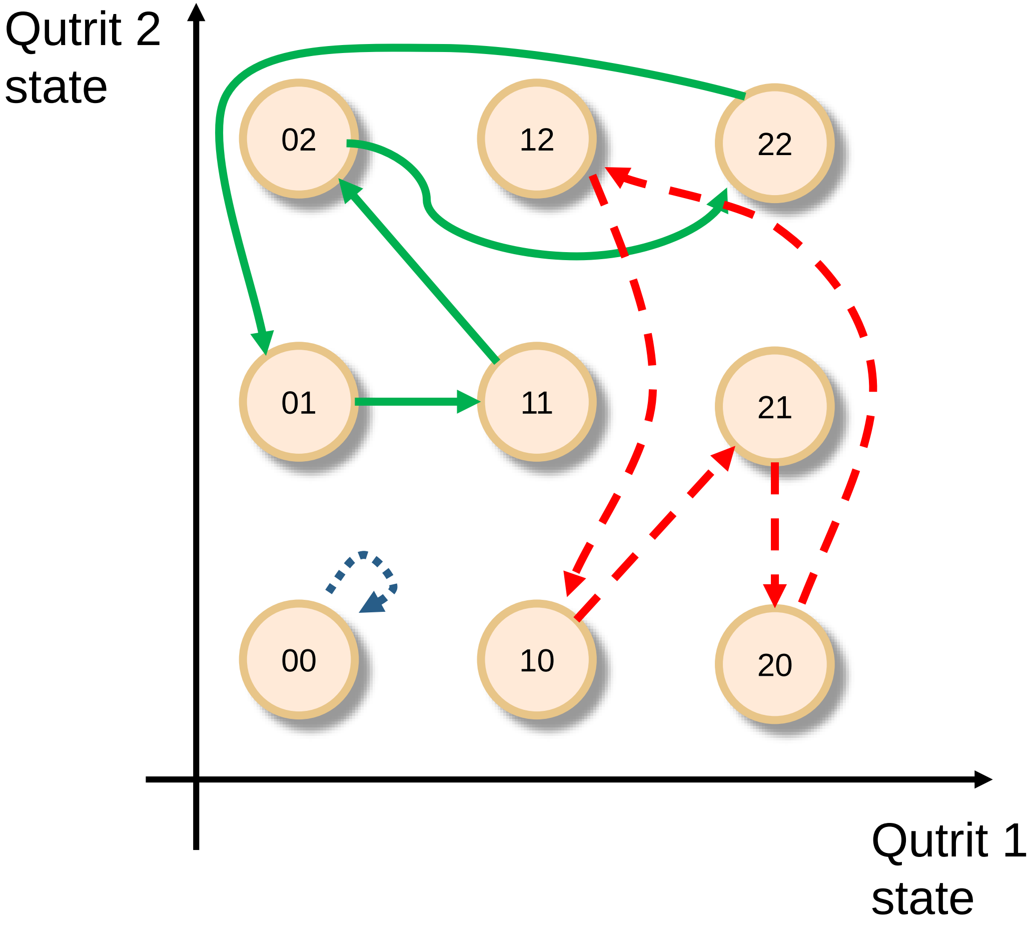
Qutrit EPR pair:
$\mathcal{N}(|00\rangle + |11\rangle + |22\rangle)$

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

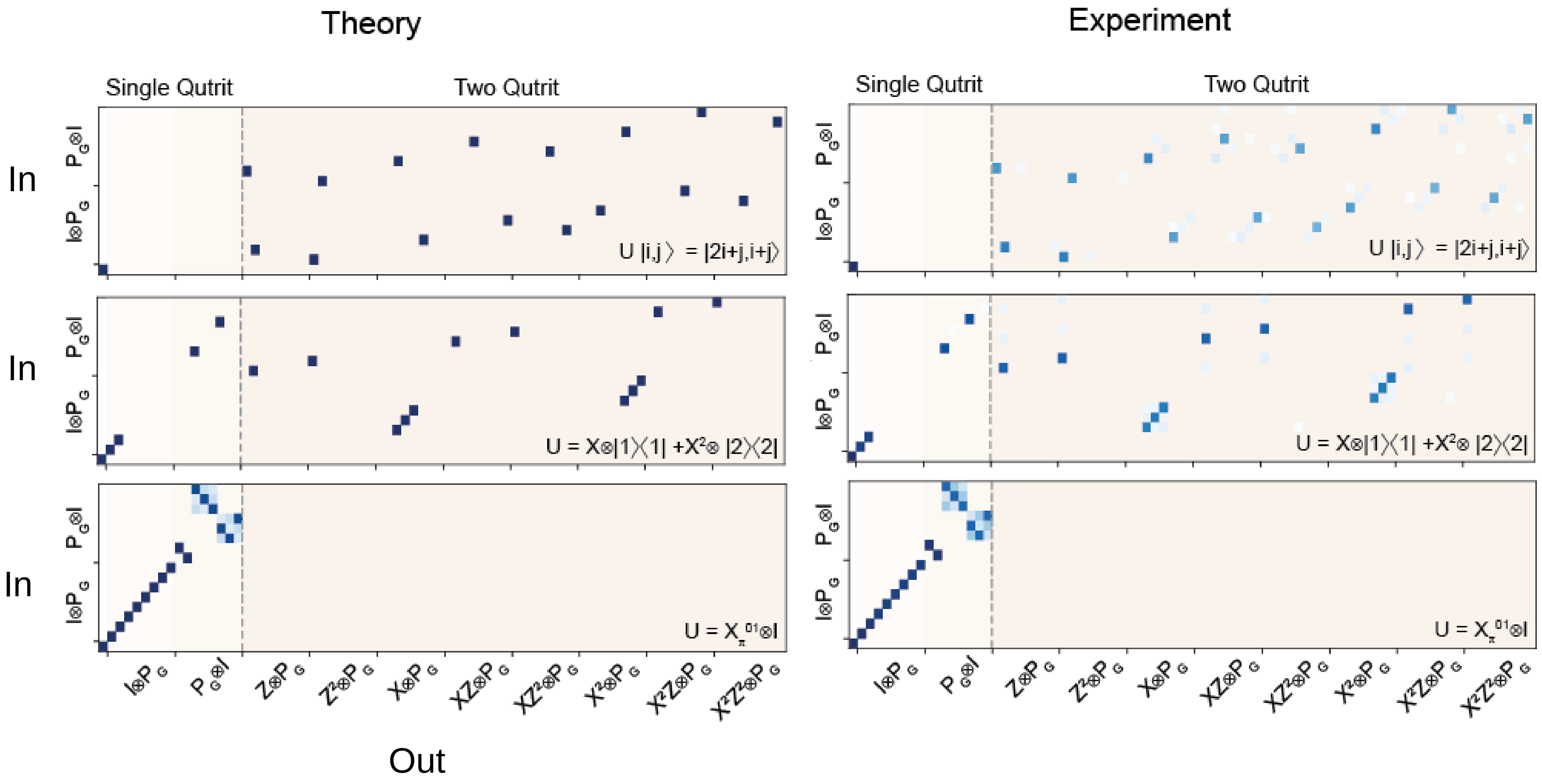
SCRAMBLING UNITARY: A CLOSER LOOK



CSUM |i , j⟩ = |i , i + j⟩



PROCESS TOMOGRAPHY OF THE SCRAMBLER

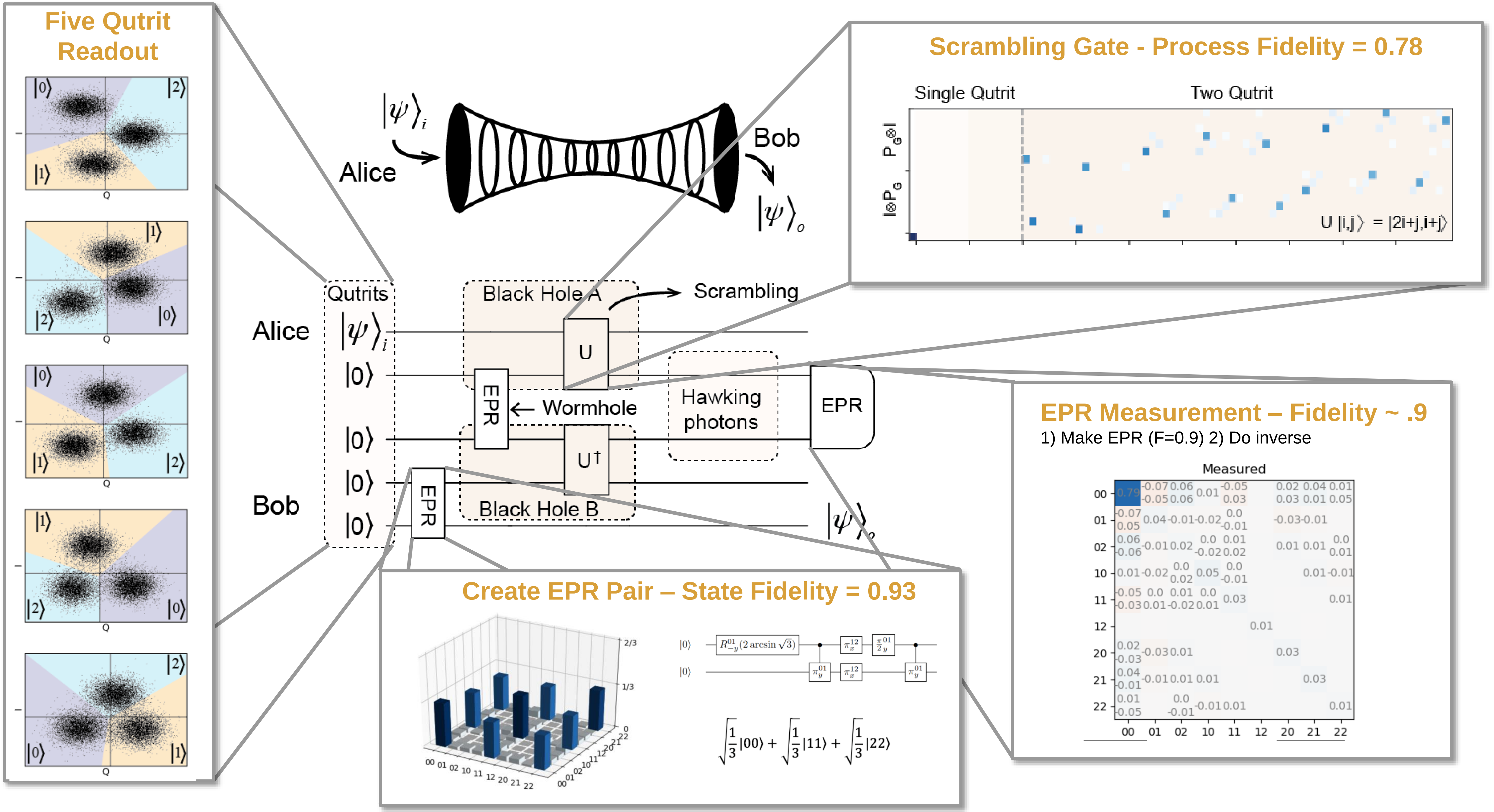


Scrambling Gate
Process Fidelity = 0.78

Entangling Gate
Process Fidelity = 0.88

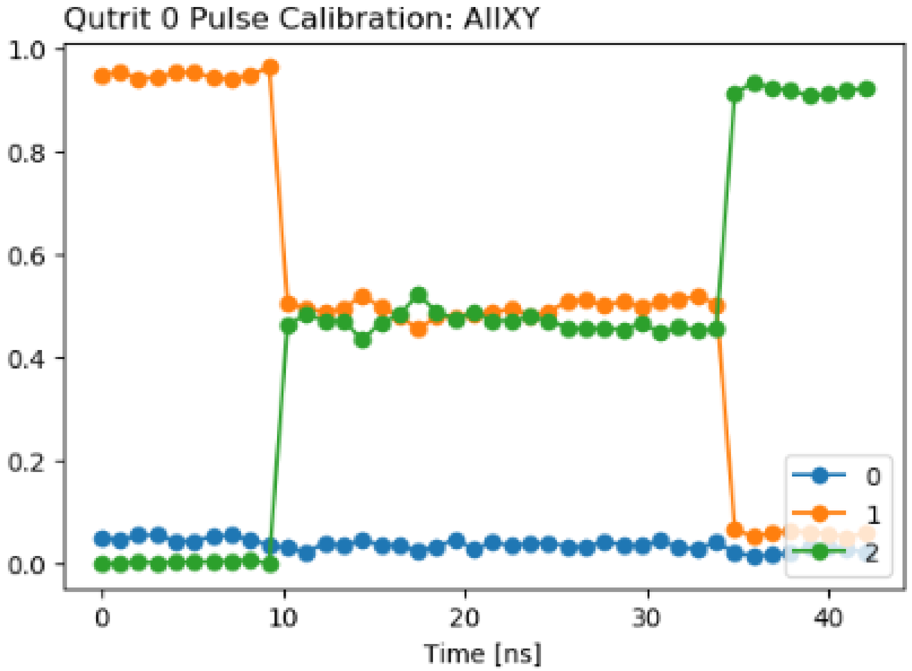
Local Gate
Process Fidelity = 0.97

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

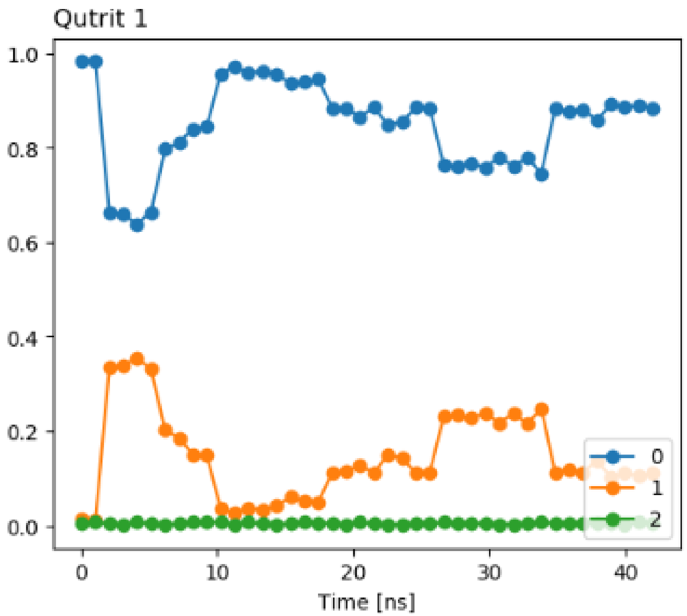


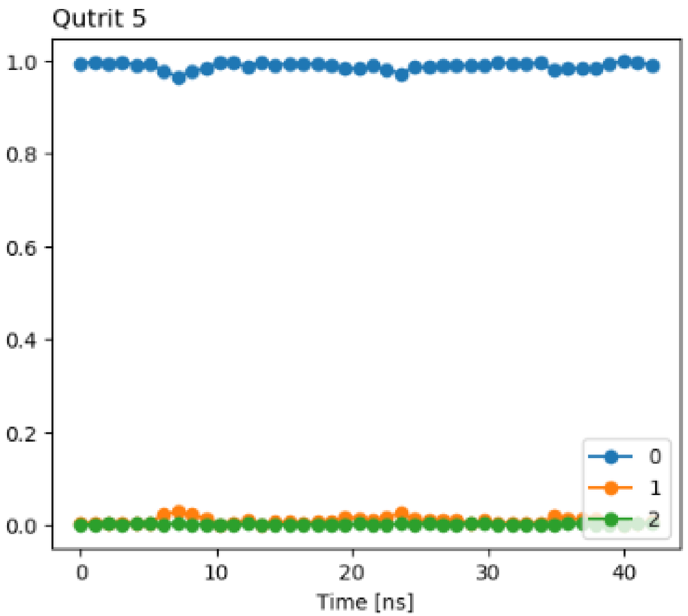
Five Qutrit Readout
Q
$|\psi\rangle_i$
Alice
Bob
$|\psi\rangle_o$
Qutrits
Alice
$|\psi\rangle_i$
$|0\rangle$
$|0\rangle$
$|0\rangle$
$|0\rangle$
Bob
Black Hole A
Scrambling
U
EPR
← Wormhole
$U^\dagger$
Black Hole B
Hawking photons
EPR
$|\psi\rangle_o$
Scrambling Gate - Process Fidelity = 0.78
Single Qutrit
Two Qutrit
$P_G \otimes I$
$I \otimes P_G$
U |i,j⟩ = |2i+j,i+j⟩
EPR Measurement – Fidelity ~ .9
1) Make EPR (F=0.9) 2) Do inverse
Measured
Create EPR Pair – State Fidelity = 0.93
2/3
1/3
$|0\rangle$
$|0\rangle$
$R^{01}_{-y}(2\arcsin\sqrt{3})$
$\sqrt{\frac{1}{3}}|00\rangle + \sqrt{\frac{1}{3}}|11\rangle + \sqrt{\frac{1}{3}}|22\rangle$

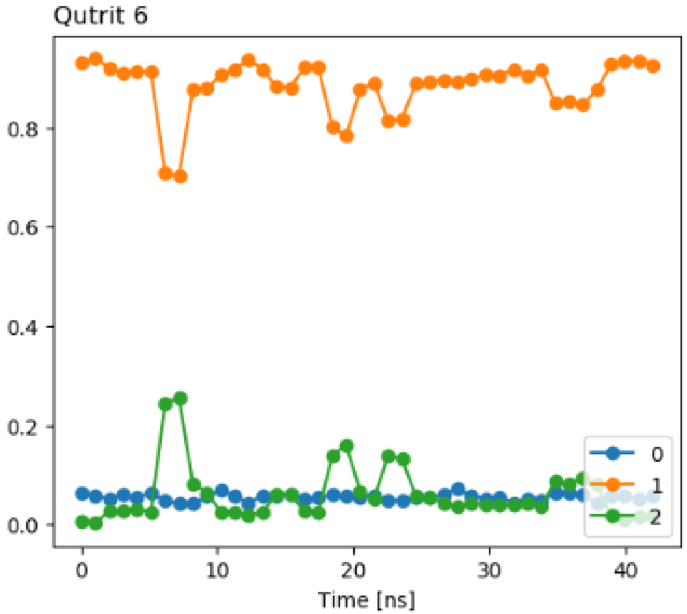
CLASSICAL CROSSTALK

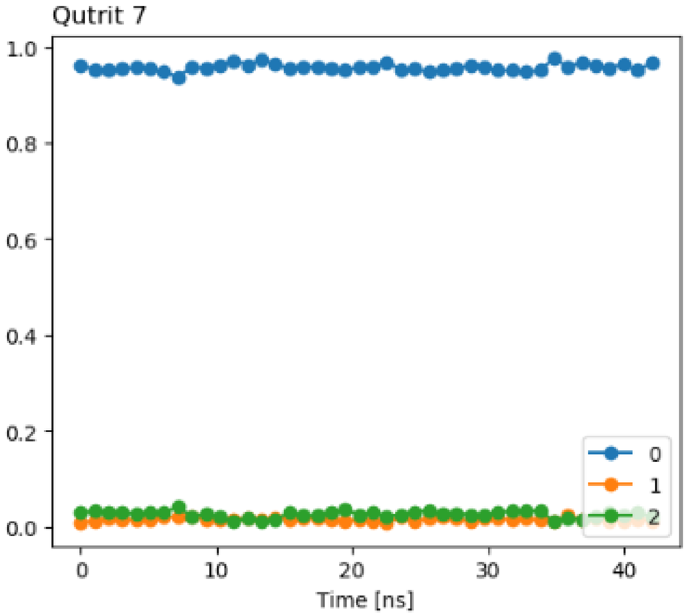


V5.57	01- transition Freq (GHz)	12- transition Freq (GHz)
Q0	5.633 GHz	5.368 GHz
Q1	5.447 GHz	5.177 GHz
Q5	5.430 GHz	5.159 GHz
Q6	5.619 GHz	5.350 GHz
Q7	5.778 GHz	5.513 GHz

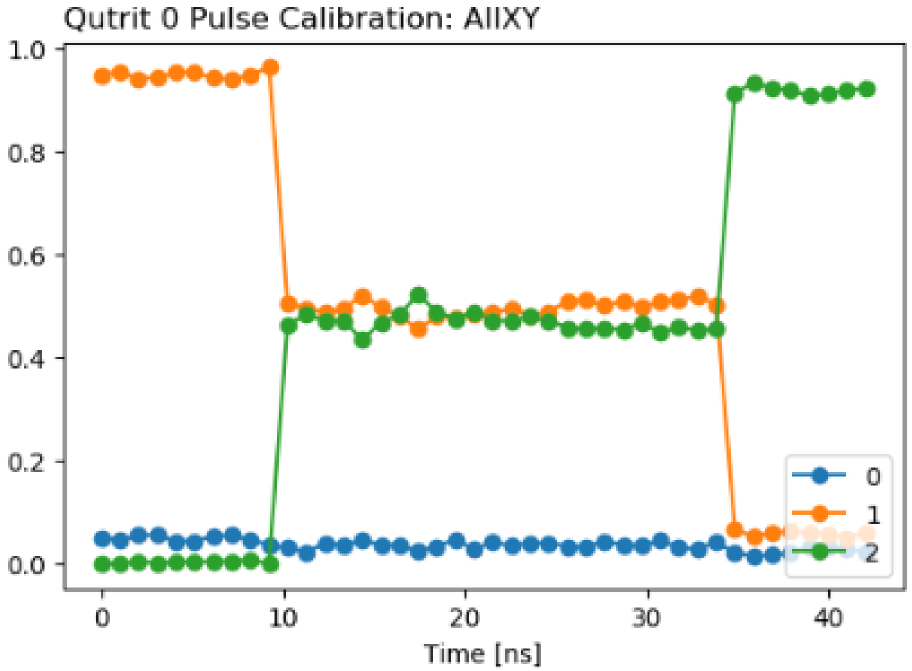


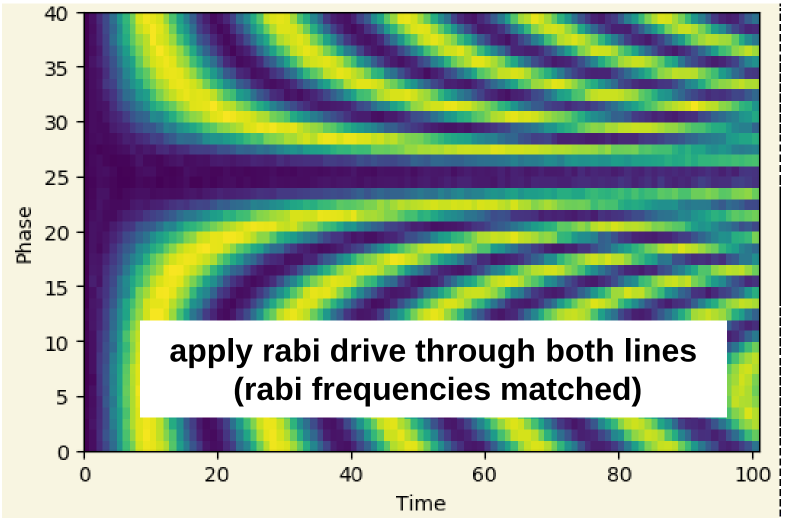


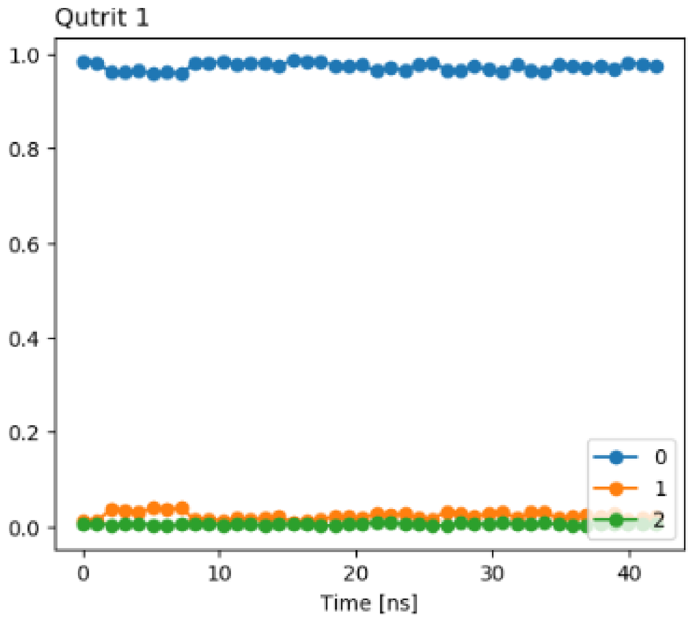


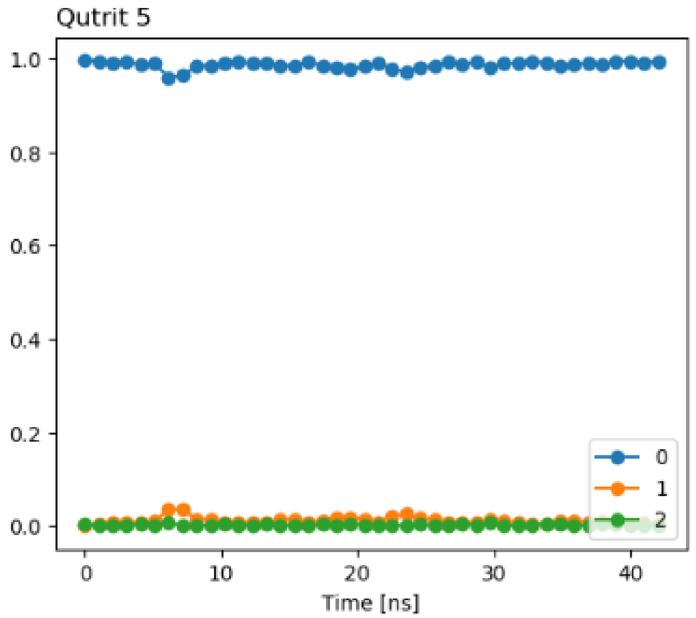


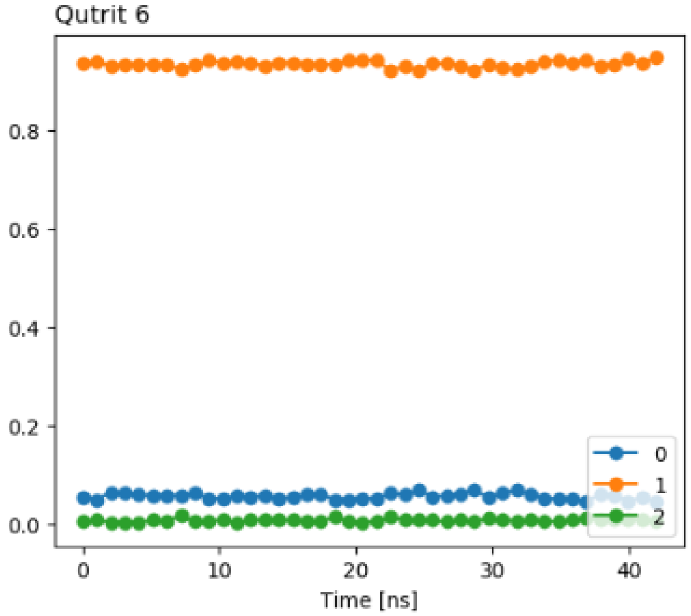
ACTIVE CANCELLATION

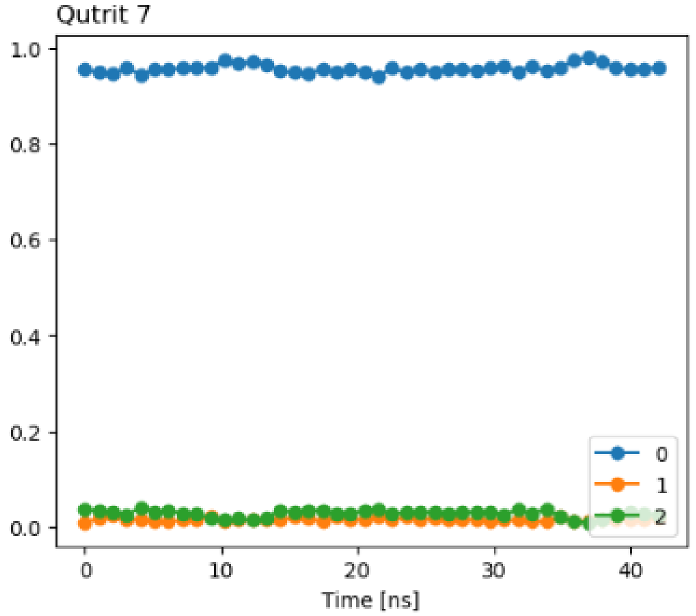






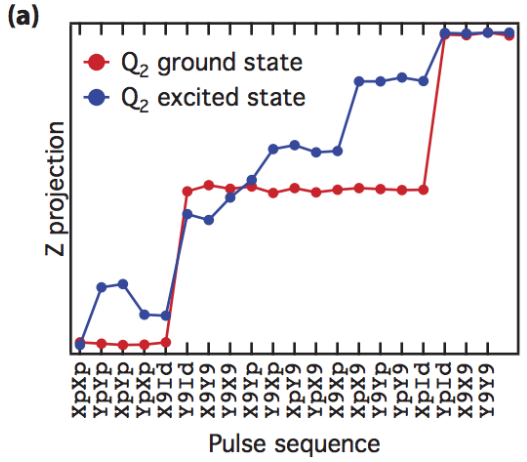




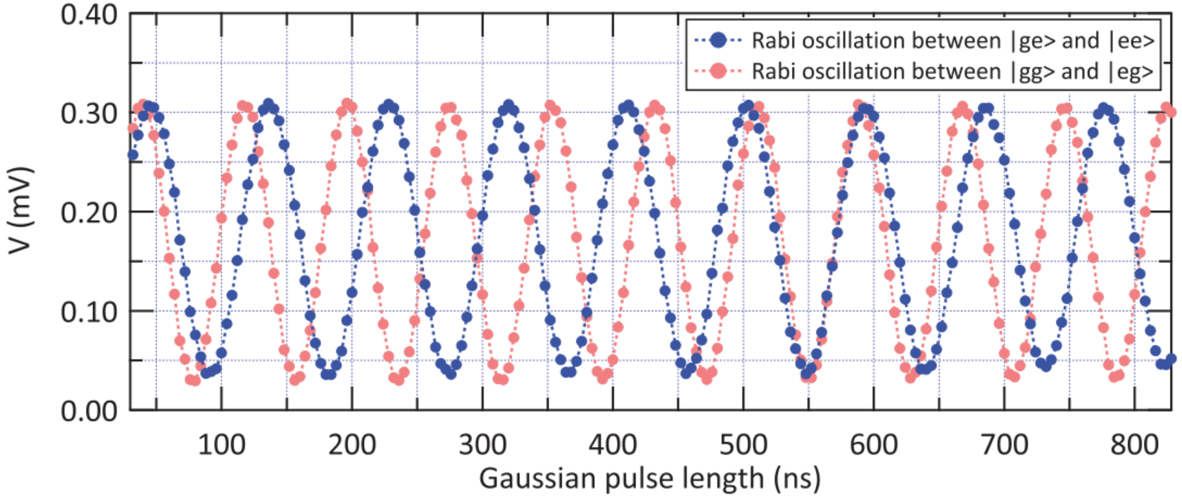


QUTRITS HELP QUBITS !

From Matt Reed's thesis (Schoelkopf lab, Yale):

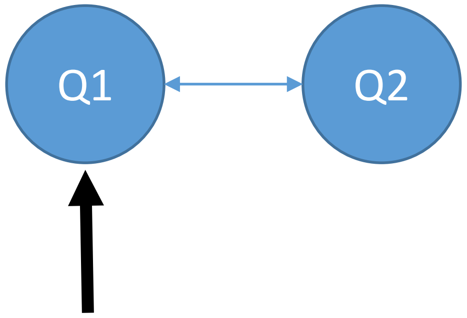


Error syndrome: Power error

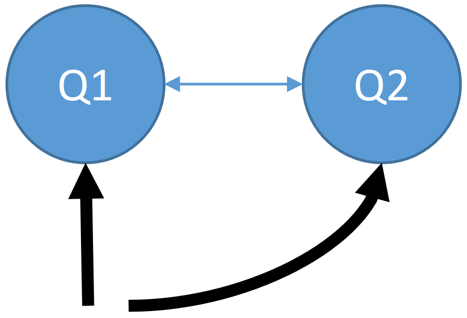


- AllXY calibration sequence: pulses are run on Qubit 1 while Qubit 2 is (ideally) untouched.
- Well calibrated when Q2 is in its ground state. If Q2 in its excited state, the particular error syndrome we see indicates the pulses are either too high or too low in **power.**

Ideally:

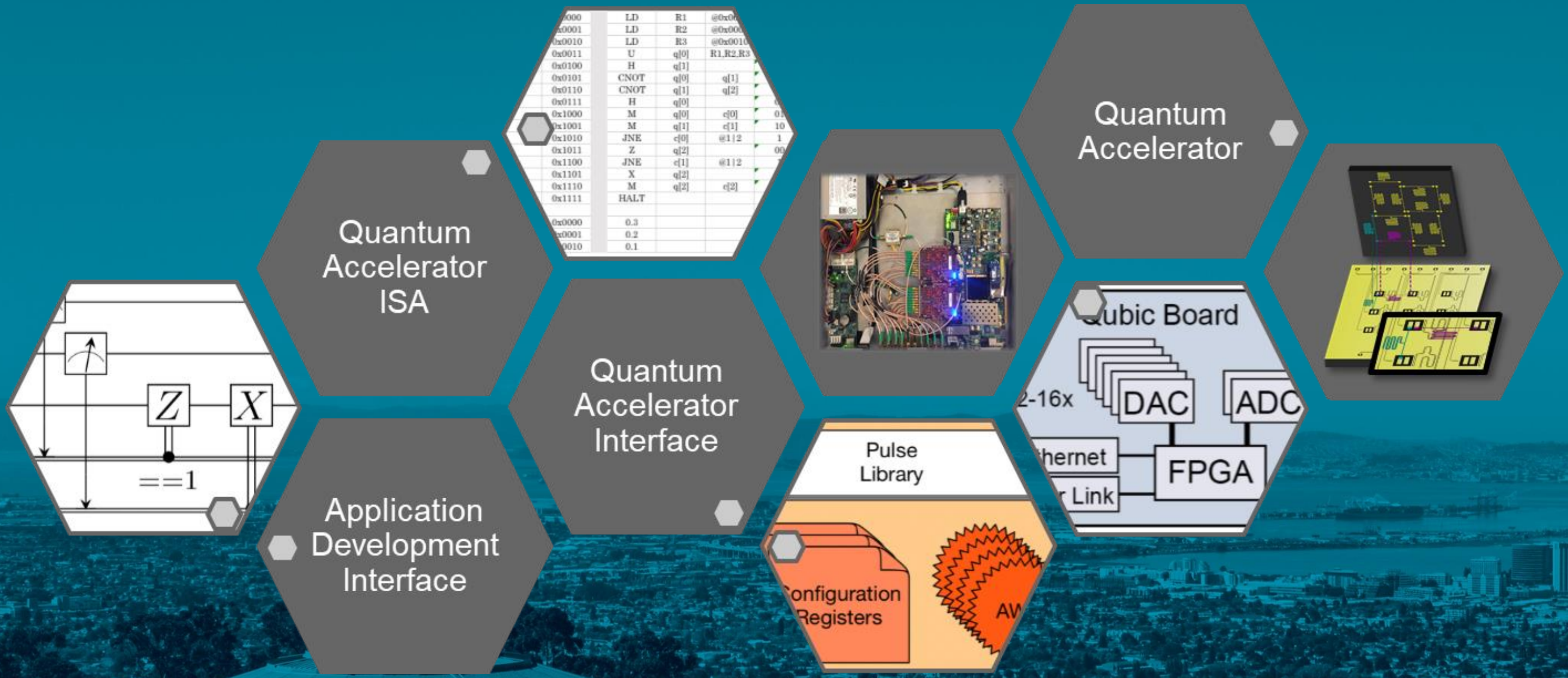


In reality:



Postulate that cross-talk drives a cross-resonance interaction that can be mitigated by active cancellation

ADVANCED QUANTUM TESTBED

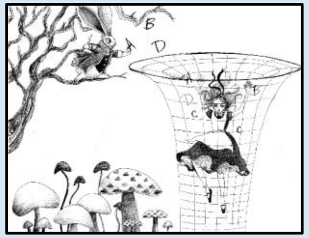


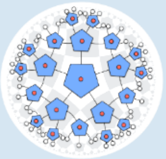
- **Full, open access to all levels of the stack**
- **Modular structure to benchmark different technologies**
- **AQT scientists partner with community users to run algorithms**
- **Broad science mandate**
- **Complementary to focused industry efforts**

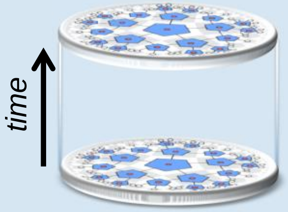
SCIENCE APPLICATIONS OVERVIEW

Quantum Field Theory

- Black Holes and Scrambling Dynamics
- Error Correction and Holography
- ADS/CFT Correspondence

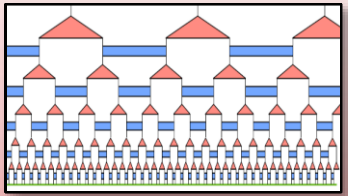


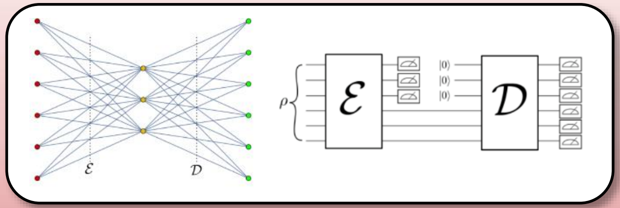




New Quantum Algorithms

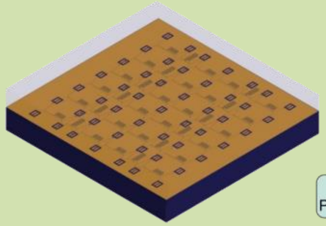
- QAOA & Other Optimization
- MERA
- Machine Learning

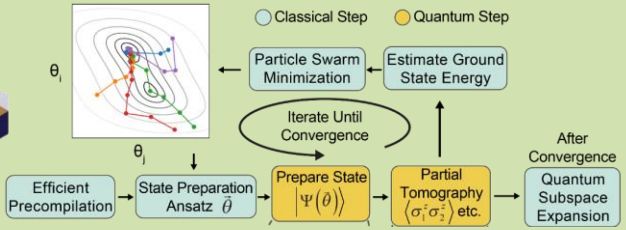




Quantum Chemistry

- Large-Scale Chemical Simulations
- Scaling Properties of VQE
- Nuclear Dynamics





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?