137A Lecture
04/26/2022

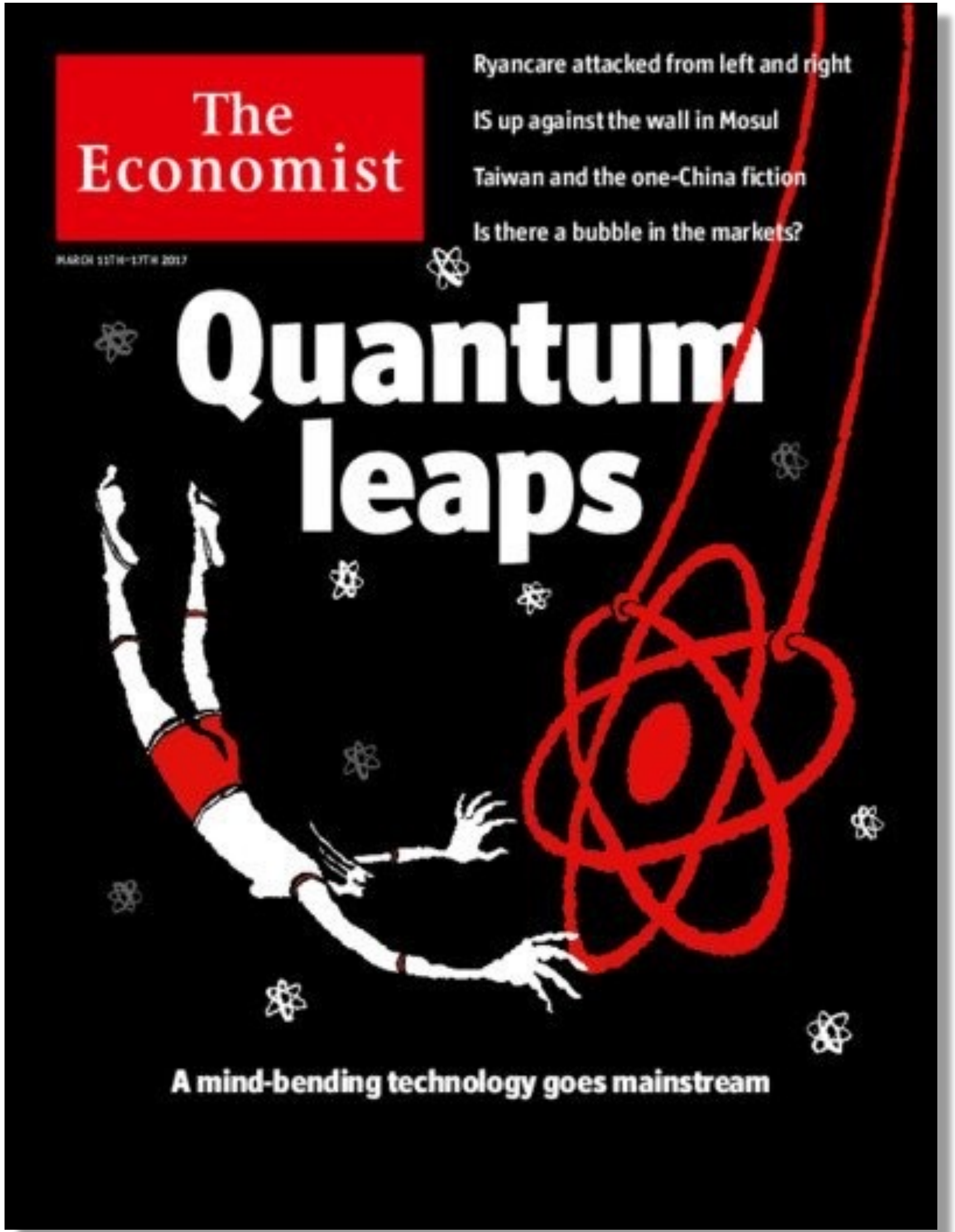
# The Intellectual & Technical Challenge of Quantum Computing

**Irfan Siddiqi**

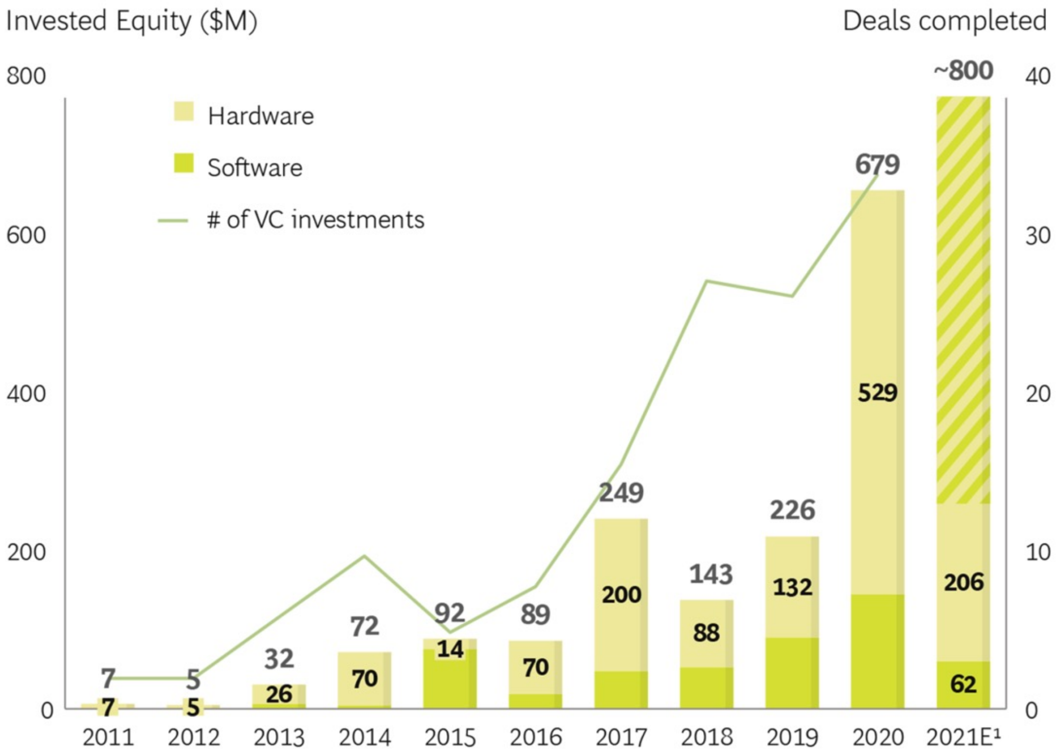
*Department of Physics*
*University of California, Berkeley*

*AMCR & MSD*
*Lawrence Berkeley National Laboratory*

BERKELEY LAB




# What Happens When ‘If’ Turns to ‘When’ in Quantum Computing?




BCG
THE BOSTON CONSULTING GROUP

JULY 21, 2021

By Jean-François Bobier, Matt Langione, Edward Tao, and Antoine Gourévitch

BCG estimates that quantum computing could create value of $450 billion to $850 billion in the next 15 to 30 years. Value of $5 billion to $10 billion could start accruing to users and providers as soon as the next three to five years.

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SOLVAY CONFERENCE 1927

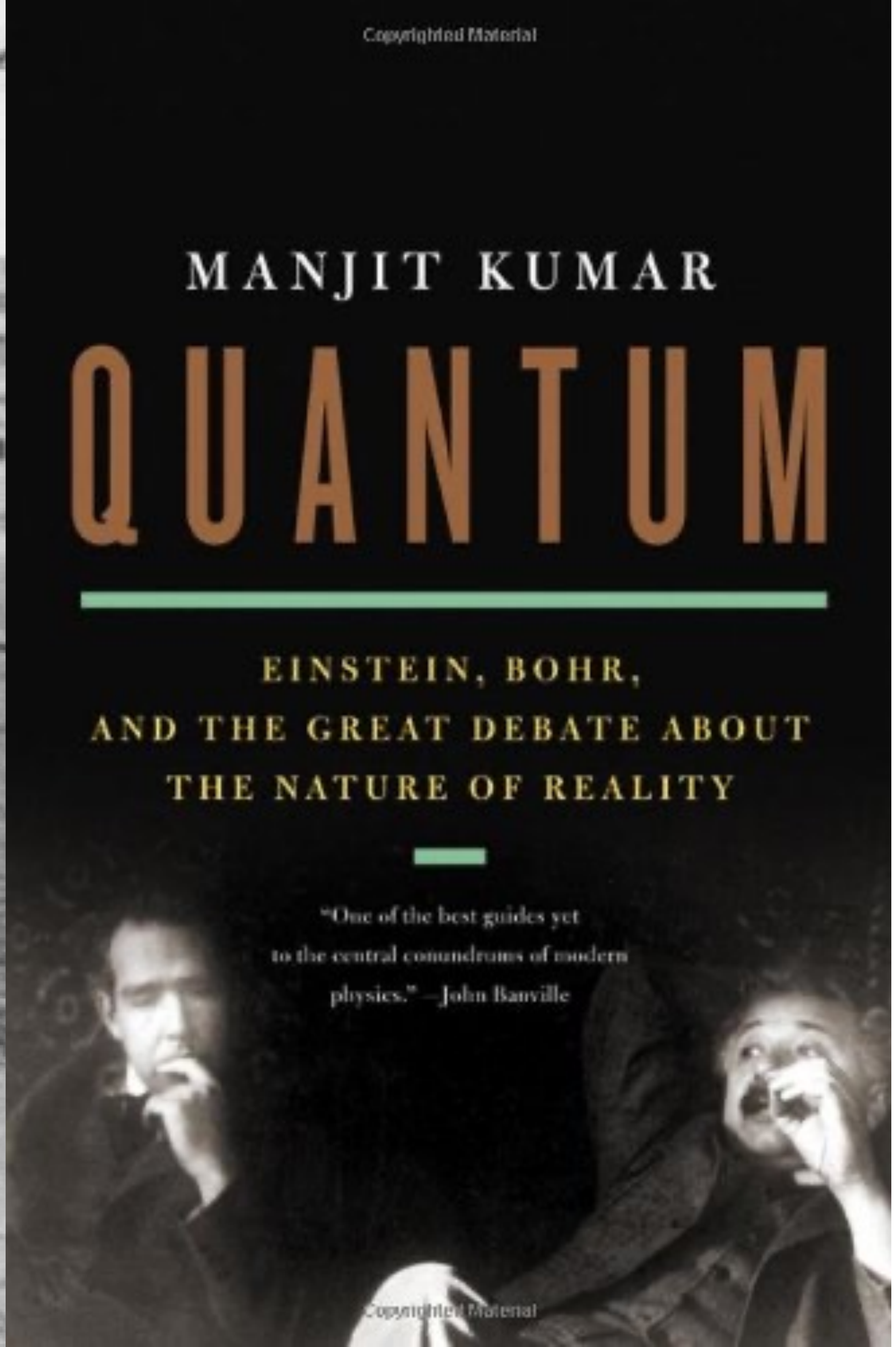
A. PICARD E. HENRIOT P. EHRENFEST Ed. HERSEN Th. DE DONDER E. SCHRÖDINGER E. VERSCHAFFELT W. PAULI W. HEISENBERG R.H FOWLER L. BRILLOUIN

P. DEBYE M. KNUDSEN W.L. BRAGG H.A. KRAMERS P.A.M. DIRAC A.H. COMPTON L. de BROGLIE M. BORN N. BOHR

I. LANGMUIR M. PLANCK Mme CURIE H.A. LORENTZ A. EINSTEIN P. LANGEVIN Ch.E. GUYE C.T.R. WILSON O.W. RICHARDSON

Absents : Sir W.H. BRAGG, H. DESLANDRES et E. VAN AUBEL

Einstein & Bohr in 1930
(AIP Emilio Segre)




Our *observations* of the world around reflect only some aspects of a much more complex, hidden reality!

We *need* this underlying structure to explain basic observations, even though we cannot directly measure it

We are now entering an era where we can finally use the quantum nature of matter as an <u>engineering resource</u>

**1** Quantum-advantaged mathematical function

**Sparse matrix math**

**4** Computational problem types

**100+** High-value industry use cases
*Sizing at tech maturity

| Simulation | Optimization | Machine Learning | Cryptography |
| --- | --- | --- | --- |
| Pharma: Drug discovery<br>$40-80B | Finance: Portfolio optimization<br>$20-50B | Automotive: Automated vehicles, AI algorithms<br>$0-10B | Government: Encryption and decryption<br>$20-40B |
| Aerospace: Computational fluid dynamics<br>$10-20B | Insurance:<br>Risk management<br>$10-20B | Finance: Anti-fraud, anti-money laundering<br>$20-30B | Corporate: Encryption and decryption<br>$20-40B |
| Chemistry: Catalyst design<br>$20-50B | Logistics:<br>Network optimization<br>$50-100B | Tech: Search/<br>ads optimization<br>$50-100B | |
| Energy: Solar conversion<br>$10-30B | Aerospace:<br>Route optimization<br>$20-50B | | |
| Finance: Market simulation (e.g. derivative pricing)<br>$20-35B | | | |

Machine learning applications to impact most, if not all, industries

# Using Quantum for the Heavy Lifting

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**Pharma Now**

- $2.5 Billion / new drug
- Pre-clinical research selects 0.1% of small molecules for clinical trial
- 10% of clinical trials are successful

→ *Problem is that quantum effects in molecules evade classical simulation*

**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*

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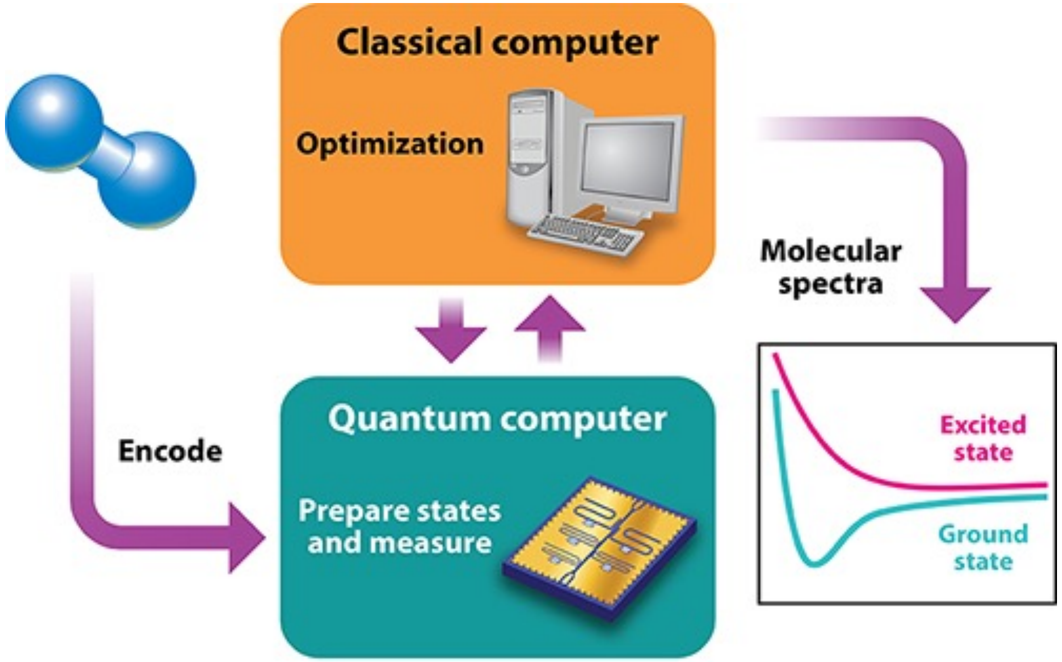
Physics
VIEWPOINT

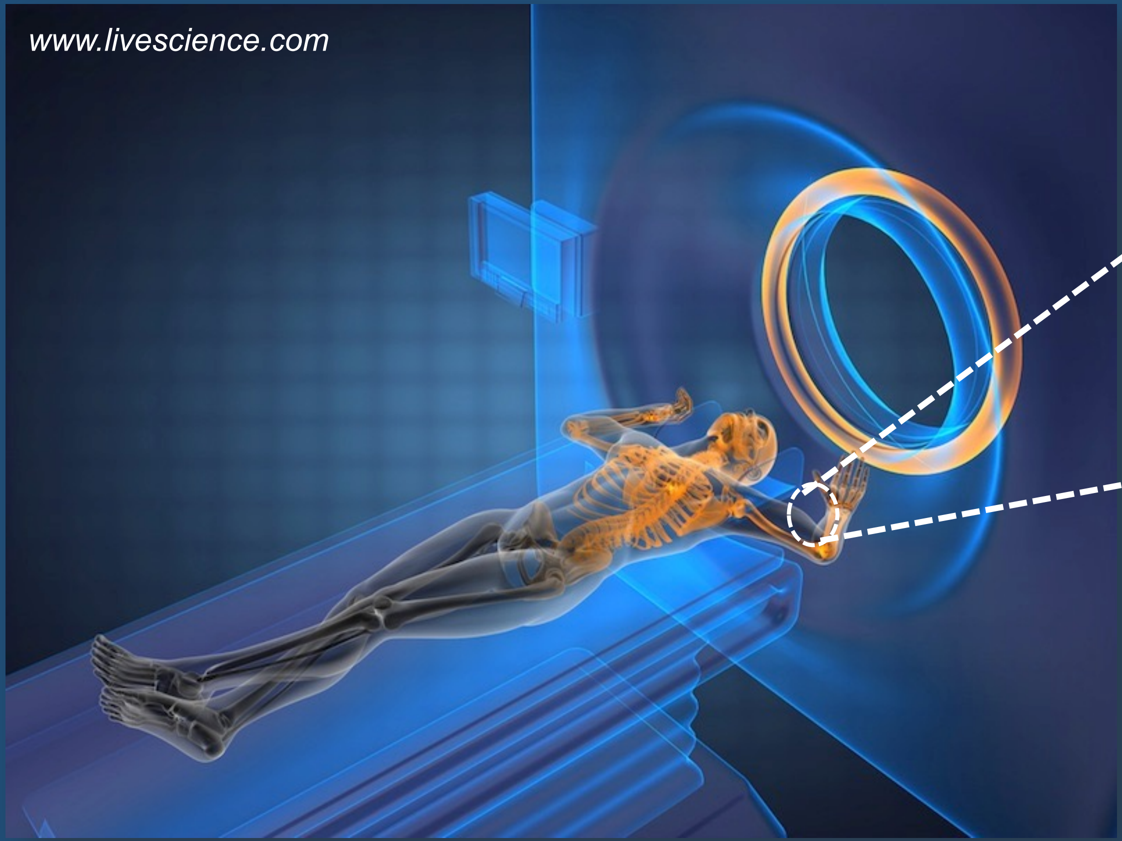
**Quantum Computer Simulates Excited States of Molecule**

**Excited-state energies of the hydrogen molecule have been calculated using a two-qubit quantum computer.**

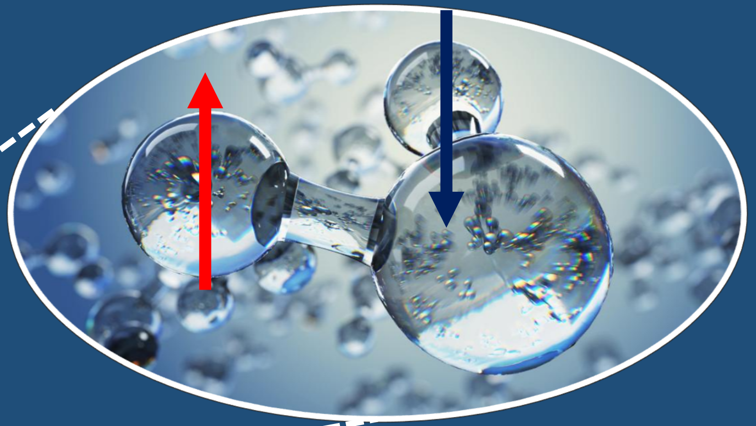


# The Quantum World Around Us

*A MRI Scan Relies on Quantum Mechanics!*



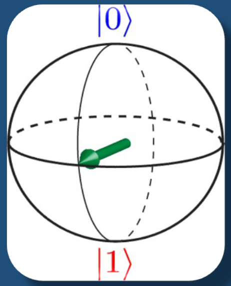

*Water molecules have two hydrogens which have nuclear spin (up or down)*



*www.medicalnewstoday.com*

*Apply magnetic field to measure spin*

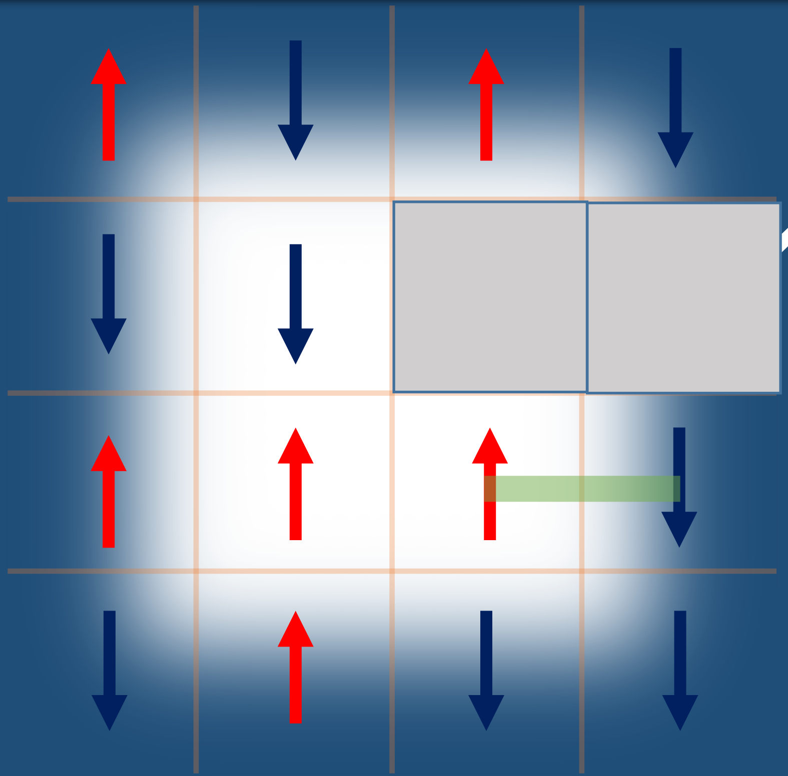
- Always observe $\uparrow$ or $\downarrow$
- Prepare superposition: $\leftarrow = \uparrow + \downarrow$
- Would measure: 50% $\uparrow$ , 50% $\downarrow$




***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 <u>average properties of a group of spins</u>, we need to address each spin individually



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

**ac** · $\uparrow\uparrow$ + **ad** · $\uparrow\downarrow$ + **bc** · $\downarrow\uparrow$ + **bd** · $\downarrow\downarrow$

***cannot describe***

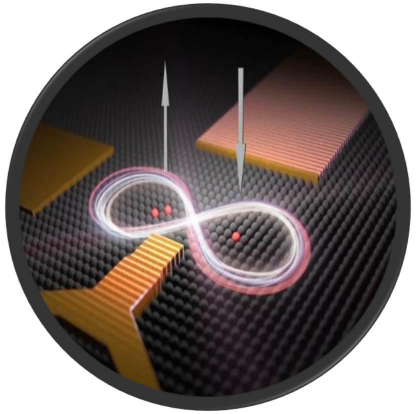
***Entangled State*** → $\uparrow\uparrow$ + $\downarrow\downarrow$

If a = 0, lose **ac** · $\uparrow\uparrow$

If d = 0, lose **bd** · $\downarrow\downarrow$

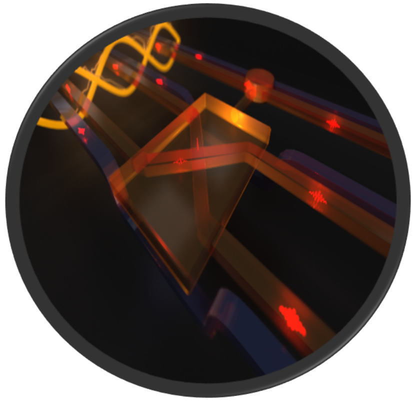
***$2^N$ >> 2N: NEED MORE NUMBERS THAN PARTICLES IN THE UNIVERSE TO DESCRIBE ~ 300 ENTANGLED QUBITS***

# Types of Quantum Bits & Progress

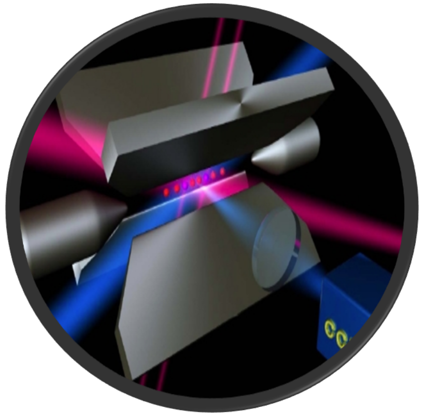


***Dopants in Silicon / Diamond***
*www.sciencedaily.com*

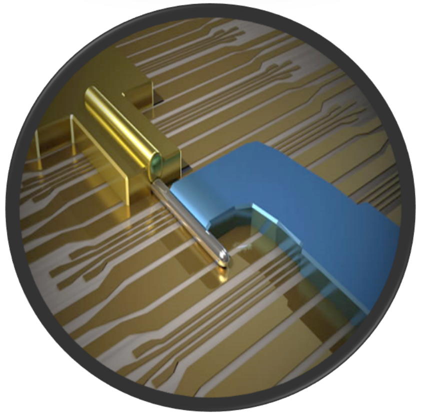
***Superconducting Circuits***
*www.qnl.berkeley.edu*



***Photonic Circuits***
*www.phys.org*



***Trapped Ions***
*www.quantumoptics.at*



***Topological Wires***
*www.microsoft.com*

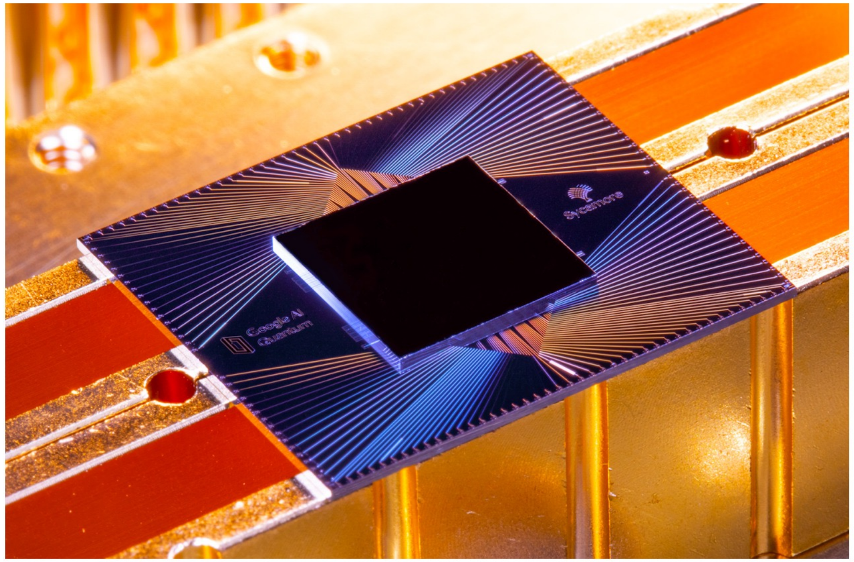
The New York Times

## Why Google's Quantum Supremacy Milestone Matters

The company says its quantum computer can complete a calculation much faster than a supercomputer. What does that mean?

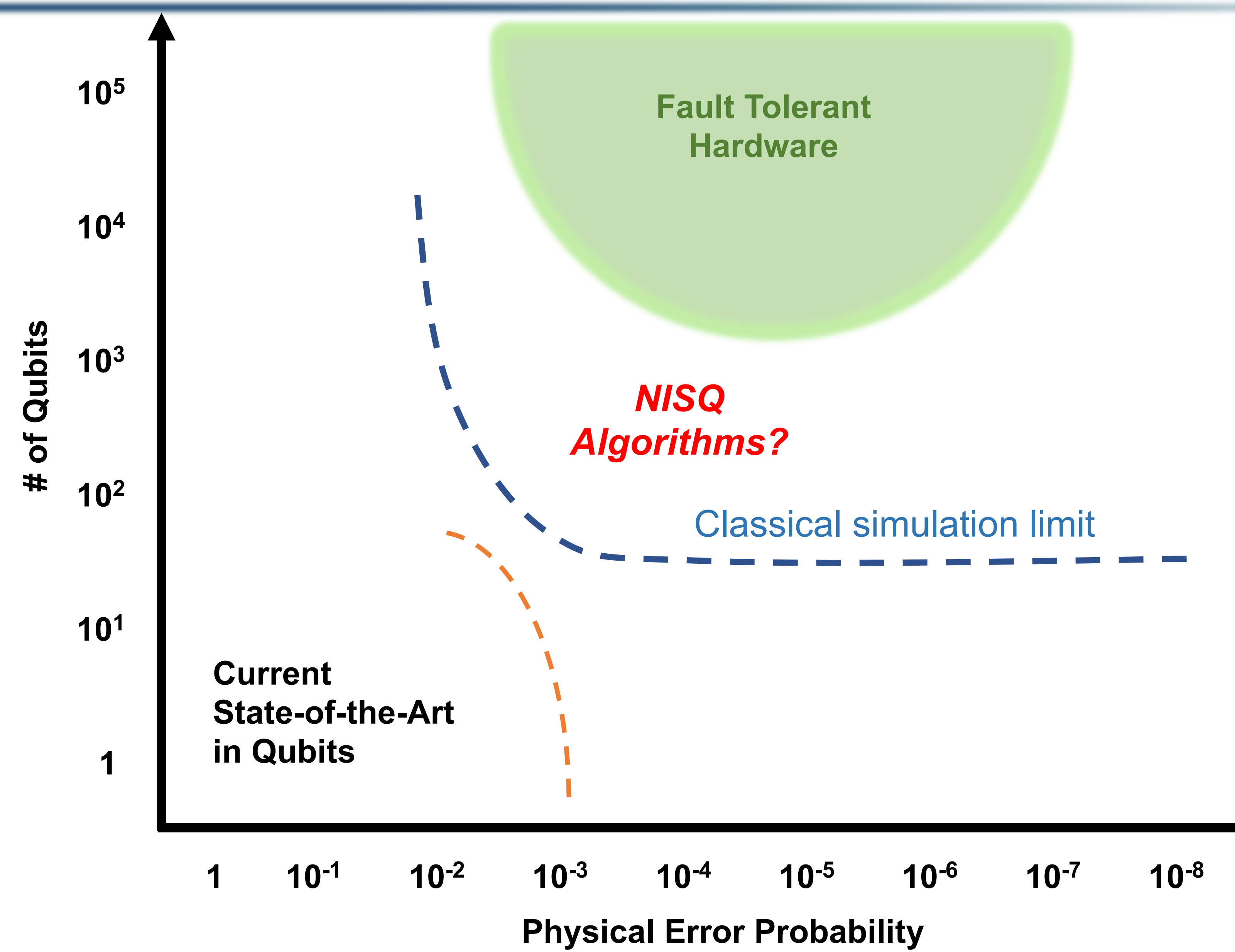
**By Scott Aaronson**

Dr. Aaronson is the founding director of the Quantum Information Center at the University of Texas at Austin.



Google A.I. Quantum's Sycamore processor. Erik Lucero/Google

# Surpassing the Classical Limit

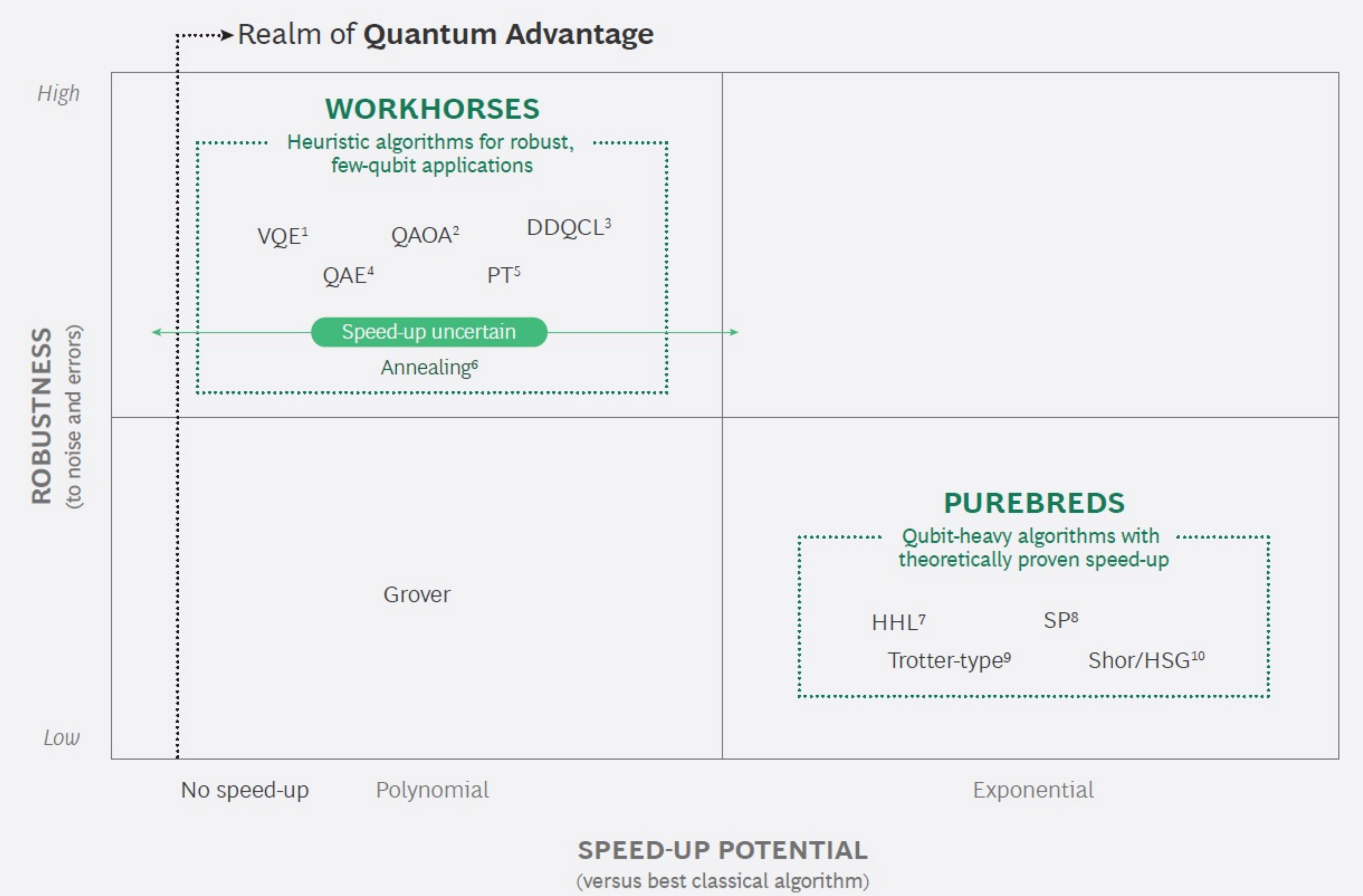



## NOISY, INTERMEDIATE SCALE QUANTUM (NISQ) ERA

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

***Today, we will talk about…***

- Building better superconducting qubits (materials & architecture)
- Characterizing noise using quantum circuits (algorithms)
- Tailoring noise to improve performance

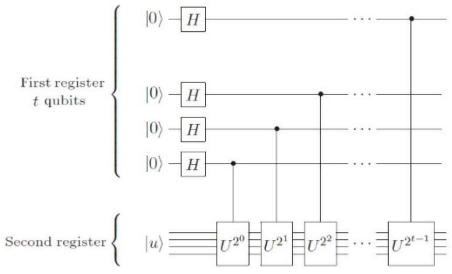


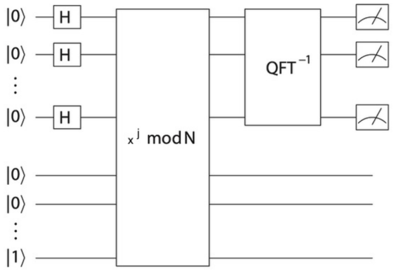

**Sources:** BCG analysis; expert interviews.

# PURE QUANTUM ROUTINES

## Shor Factoring Algorithm:

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



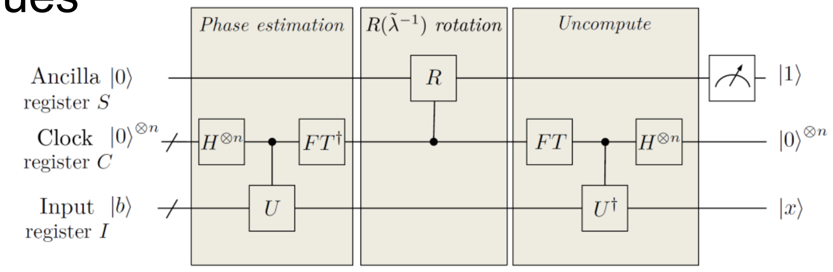




## HHL Linear Equation Algorithm:

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

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

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

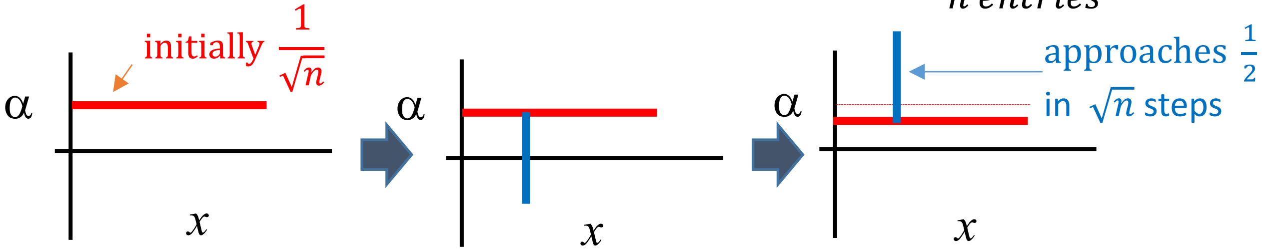



arXiv:1802.08227v1

## 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!

# QUANTUM INSPIRED CLASSICAL ROUTINES

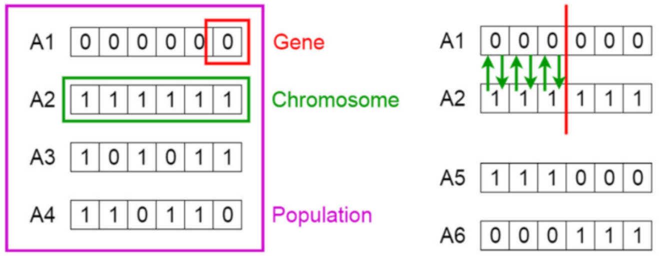
## *Matrix Completion Problem*

*(see also the Netflix problem):*

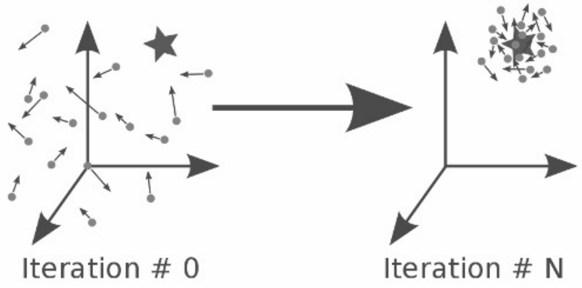
i) Sample preference matrix $T_{ij}$ for users (i) and products (j)
ii) Low rank approximation
iii) Generate suggestions for users

*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**

- *$\ell^2$ - 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


**Kuk-Hyun Han**
Dept. of Electrical Engineering, KAIST,
373-1, Kusong-dong Yusong-gu
Taejon, 305-701, Republic of Korea
khhan@vivaldi.kaist.ac.kr

**Jong-Hwan Kim**
Dept. of Electrical Engineering, KAIST,
373-1, Kusong-dong Yusong-gu
Taejon, 305-701, Republic of Korea
johkim@vivaldi.kaist.ac.kr


- *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

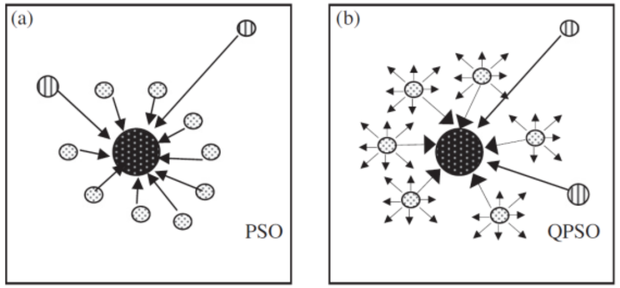
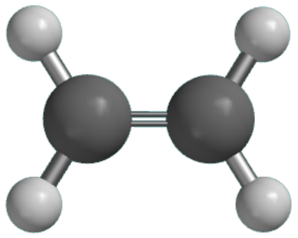




**Fig. 1.** The movements of particles in PSO and QPSO; (a) PSO (b) QPSO.

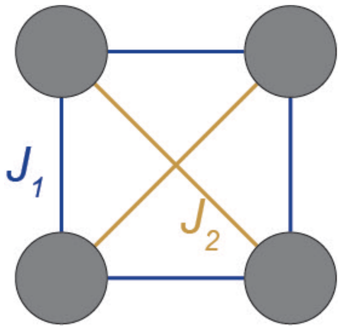
# VARIATIONAL QUANTUM EIGENSOLVER (VQE)

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

***H*** encodes problem of interest, such as:



molecular structure



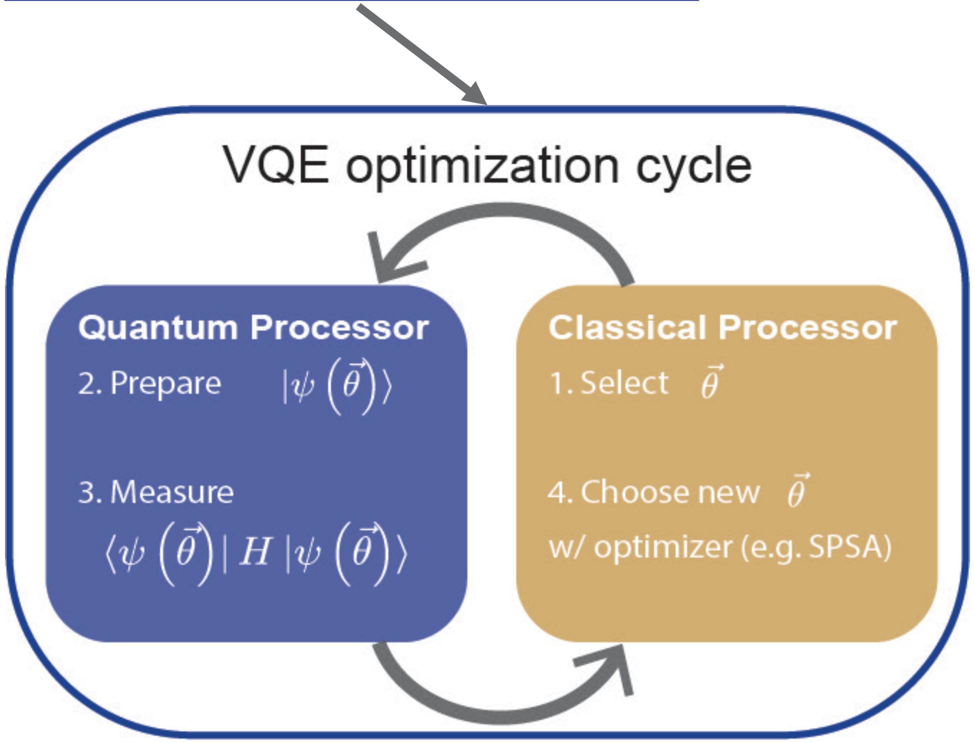

Highly correlated materials

Applications

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

**Procedure**:

Map ***H*** to qubit Hamiltonian *H*

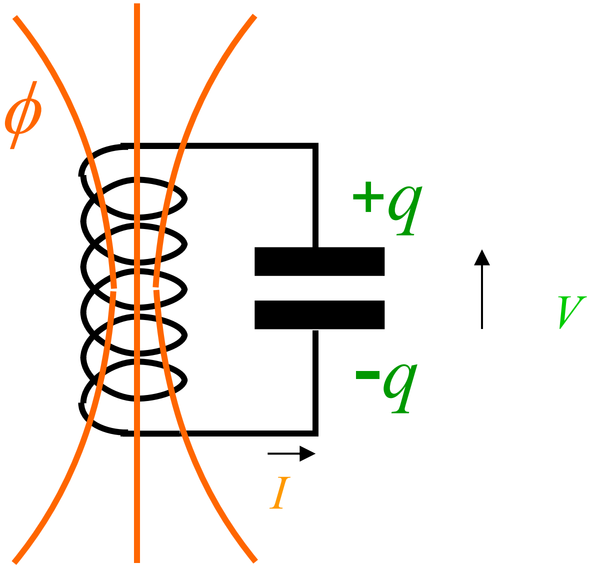


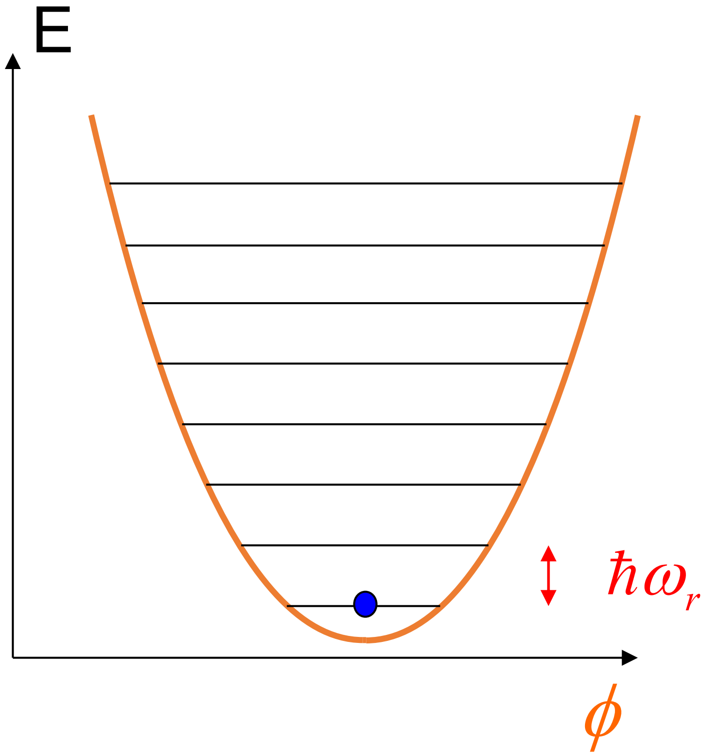

Repeat 2-4 until convergence

# *Superconducting Quantum Hardware*

# LC OSCILLATOR AS A QUANTUM CIRCUIT

Berkeley UNIVERSITY OF CALIFORNIA




$$[\phi, q] = i\hbar$$

$$\phi = LI$$

$$q = CV$$

$$\hbar\omega_r > k_B T$$

1GHz (~ 50 mK)

10mK

# A Qubit is just a Nonlinear Oscillator

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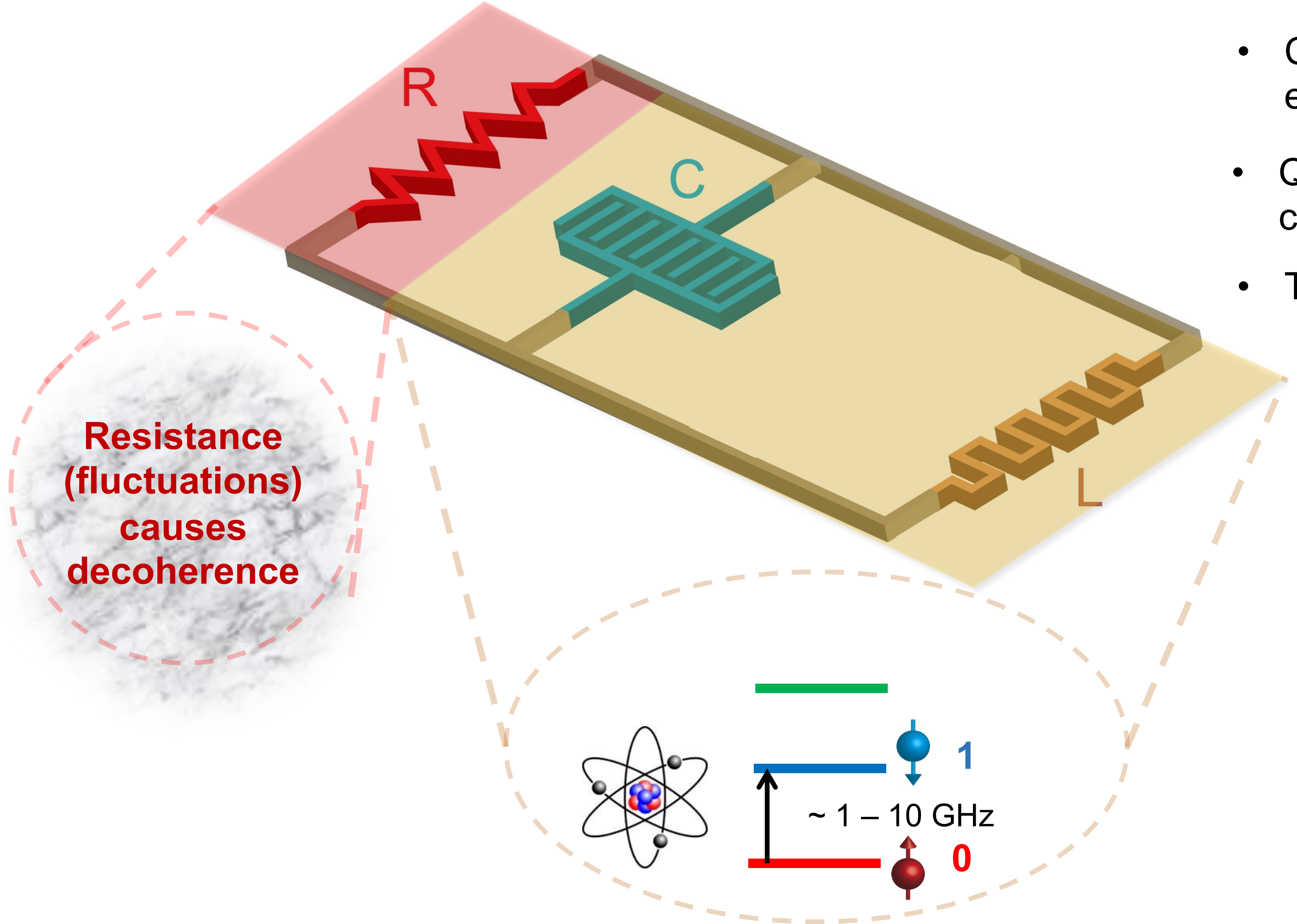
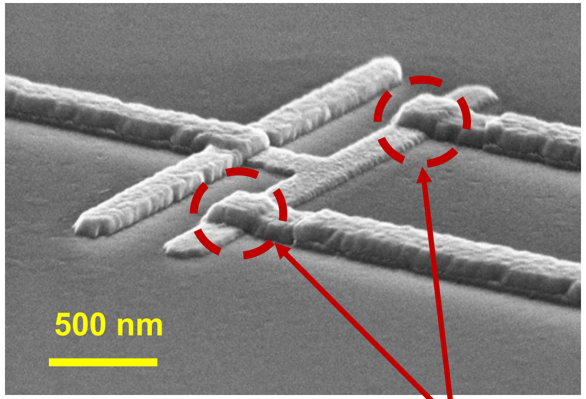
- Classical harmonic oscillator: all energies (currents) are allowed
- Quantum harmonic oscillator: only certain energies (currents) are allowed
- Tunnel junction → Nonlinear, isolate **0**, **1**

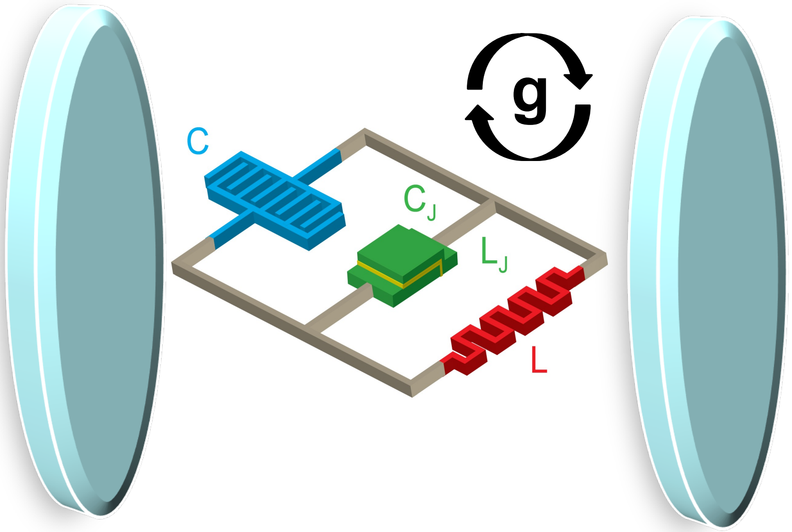


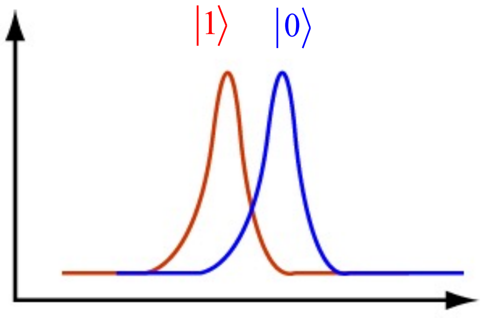




Al/AlOx/Al Josephson tunnel junctions

# MEASUREMENT : COUPLE TO E-M FIELD OF CAVITY

## (Jaynes-Cummings)

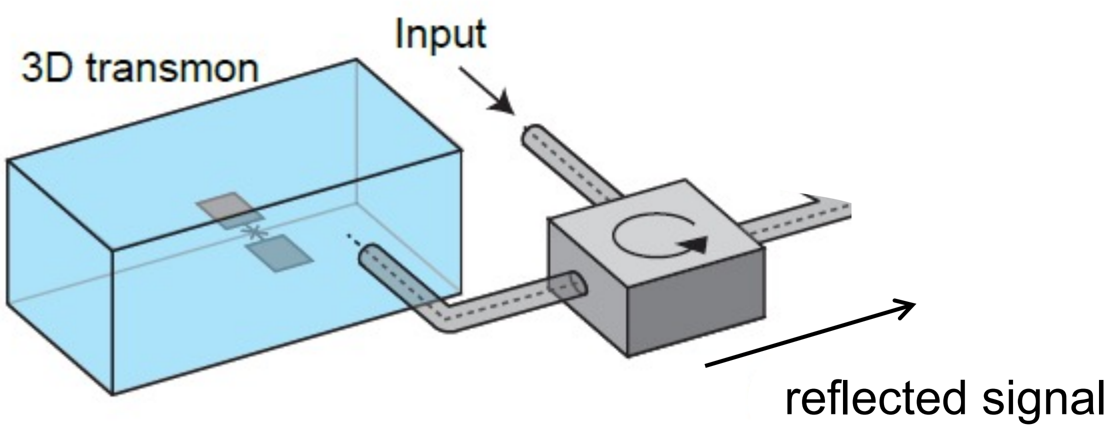


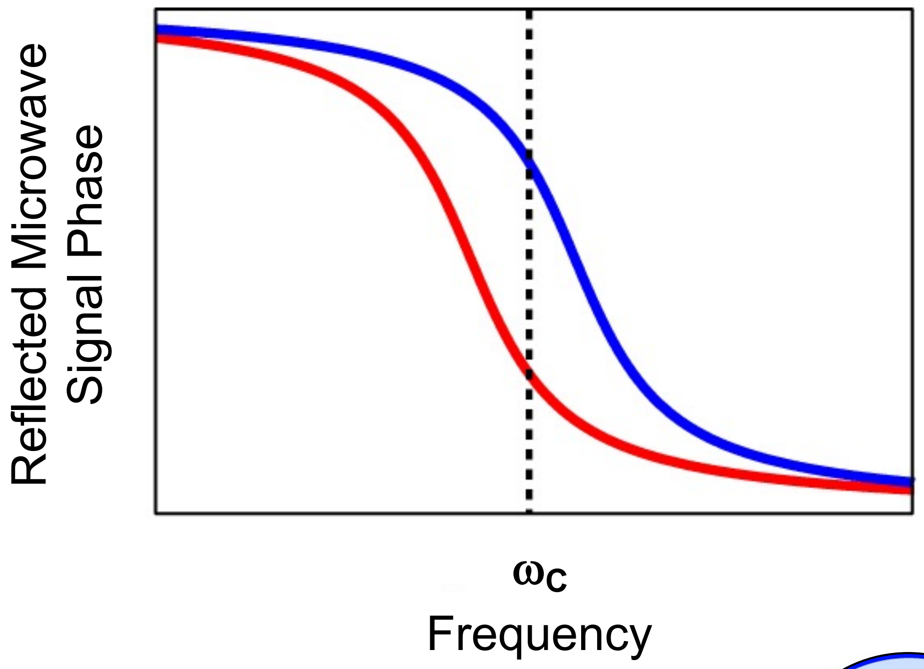




$$H = \frac{1}{2}\hbar\omega_q\sigma_z + \hbar\omega_r(a^\dagger a + \frac{1}{2}) + \hbar g(a^\dagger\sigma_- + a\sigma_+)$$

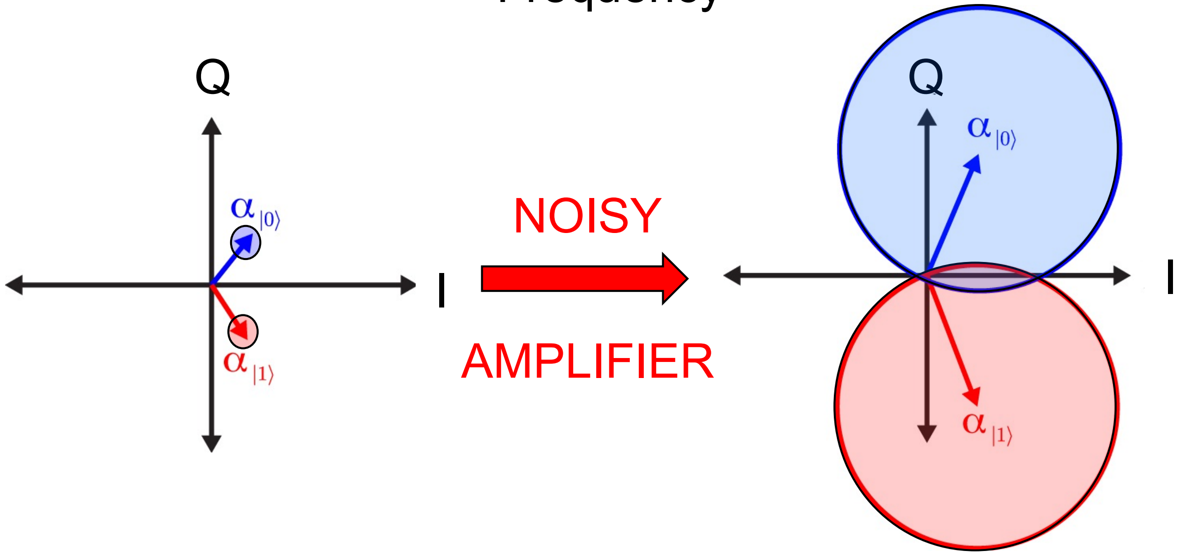
$$H_{disp} = \frac{1}{2}\hbar\omega_q\sigma_z + \hbar\,(\omega_r + \boxed{\chi\sigma_z)}\,(a^\dagger a + \frac{1}{2})$$

# MEASURING QUBIT STATES: MICROWAVE REFLECTOMETRY




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




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

# 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*

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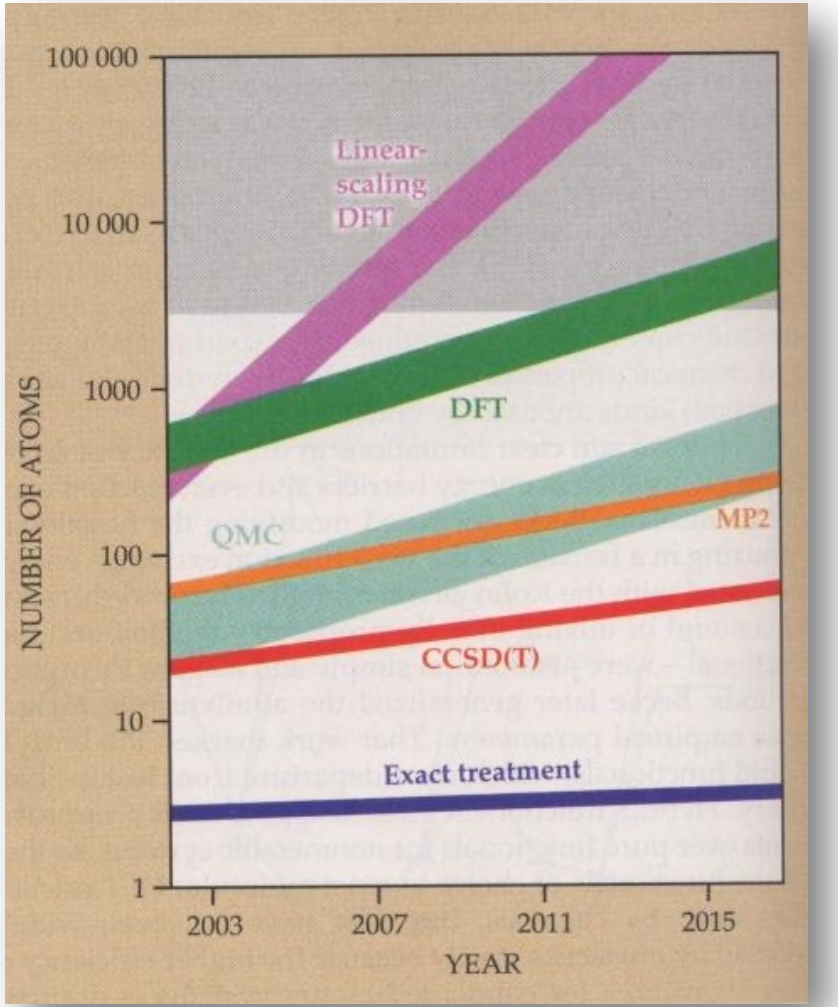
*Quantum Nanoelectronics Laboratory, Department of Physics, University of California, Berkeley, California 94720, USA; Center for Quantum Coherent Science, University of California, Berkeley, California 94720, USA; and Materials Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 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)



# GRAND SOLUTIONS FROM A GRAND DEVICE

**Humans: Haber Process**

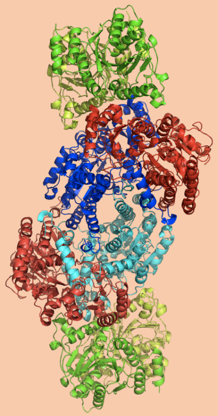
400 C & 200 atm

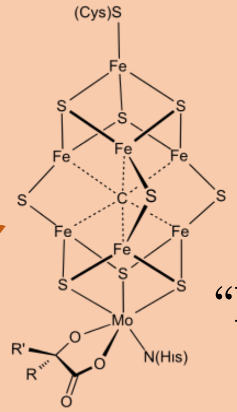
1-2% of ALL energy on earth, used on Haber process

$$N_2 + 3\,H_2 \rightarrow 2\,NH_3$$

**Nature: Nitrogenase**

25 C & 1 atm






"FeMoco"

Beyond all current classical methods

Both electronic structure and substrate attachment almost totally unknown

**Classically** – No clear path to accurate solution
**Quantum Mechanically** – 150-200 logical qubits for solution

# VARIATIONAL QUANTUM EIGENSOLVER (VQE)

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

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

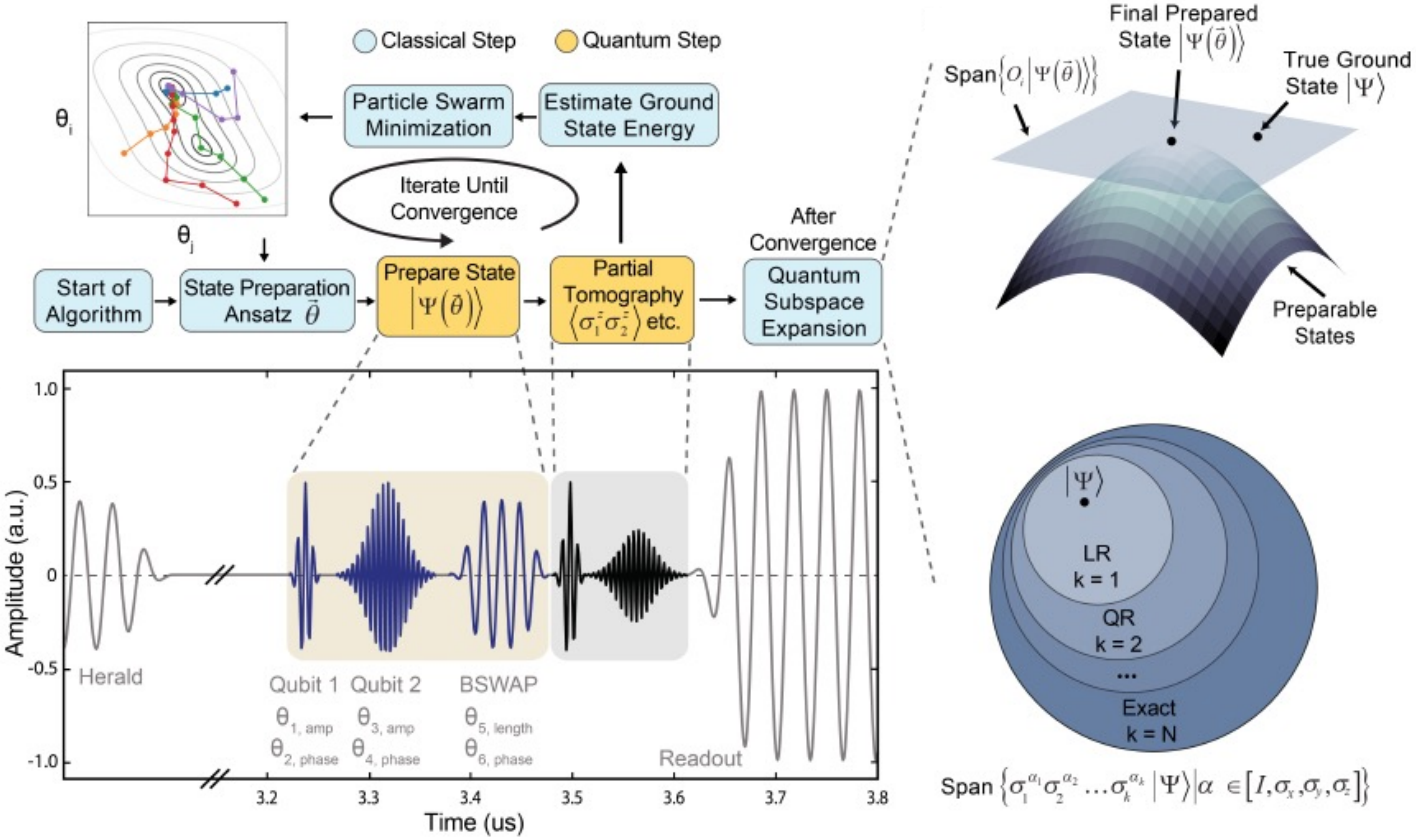
By Linearity: $\langle \psi | \mathcal{H} | \psi \rangle \equiv \langle \mathcal{H} \rangle = \mathcal{H} = h^i_\alpha \langle \sigma^i_\alpha \rangle + h^{ij}_{\alpha\beta} \langle \sigma^i_\alpha \sigma^j_\beta \rangle + h^{ijk}_{\alpha\beta\gamma} \langle \sigma^i_\alpha \sigma^j_\beta \sigma^k_\gamma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

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

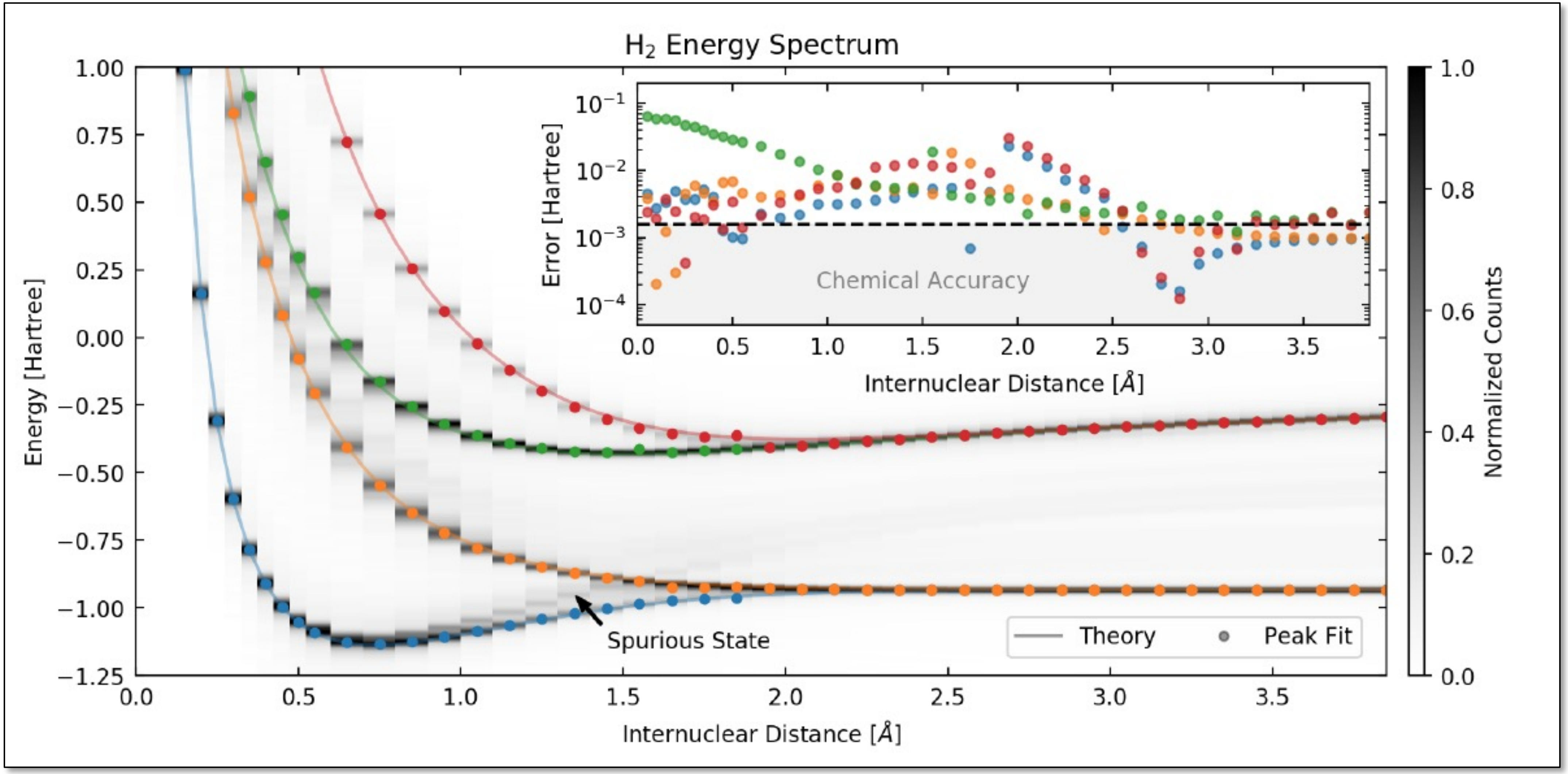
**Hybrid Scheme:**

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

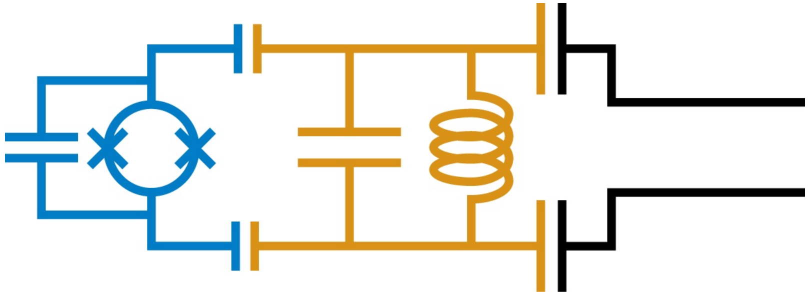
# VQE ALGORITHM

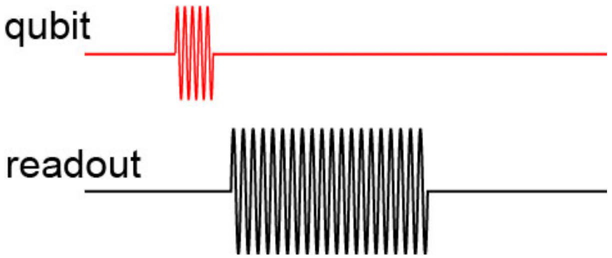


# $H_2$ REVISITED

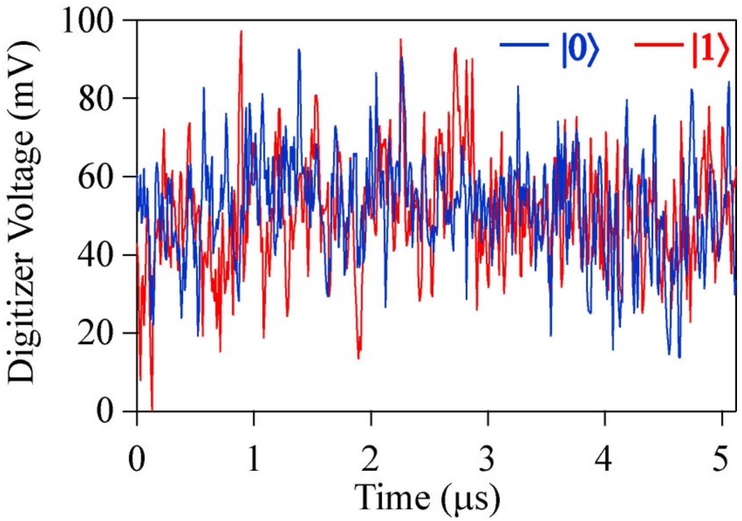


# SINGLE SHOT MEASUREMENTS



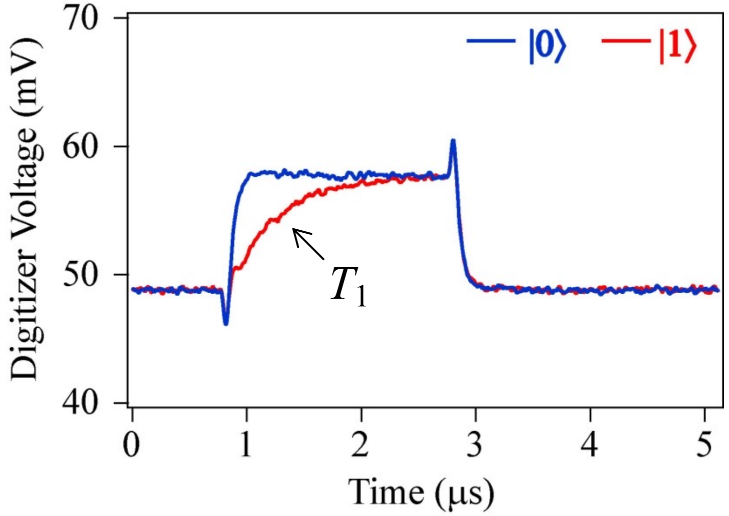



Single measurement trace



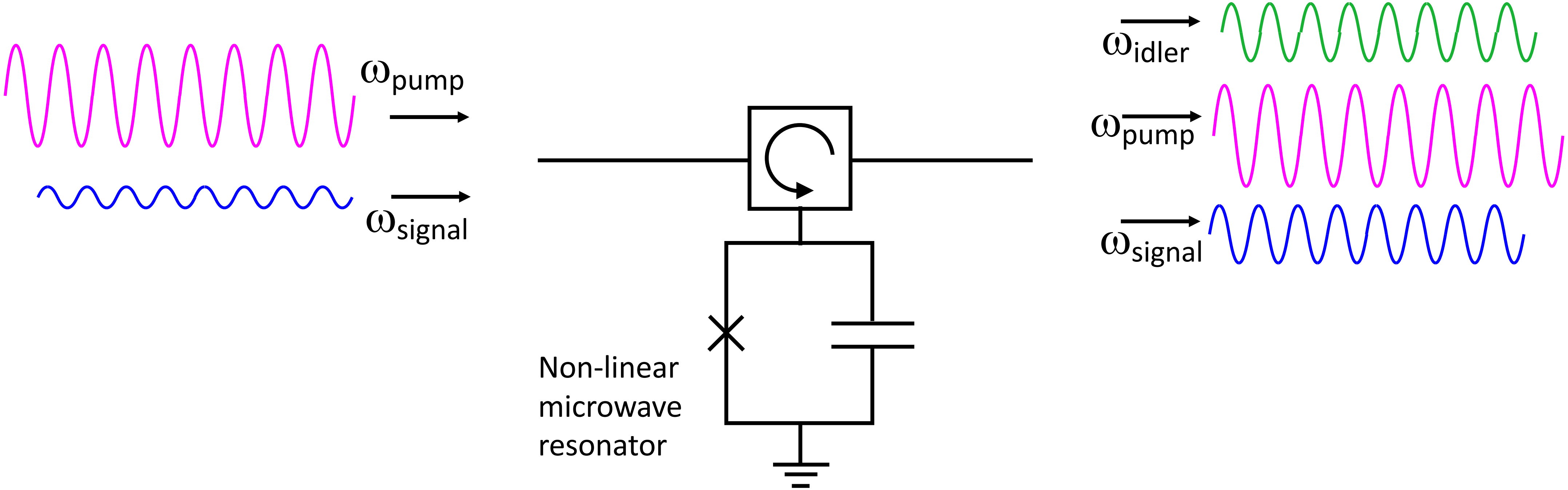

$10^4$
Averages

Averaged measurement trace

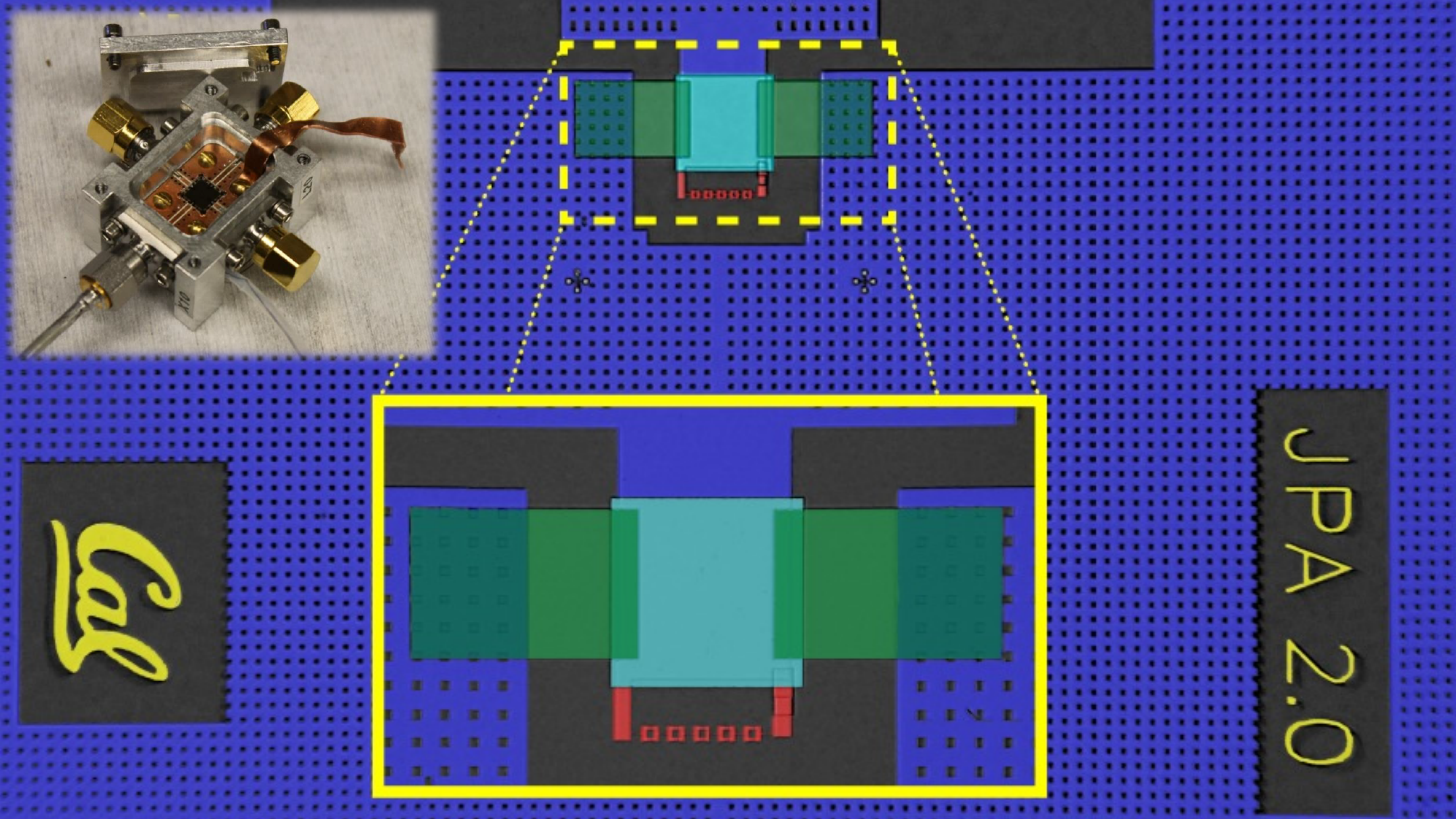



Amplifier ($T_{SYS}$ = 7K) noise masks qubit state information

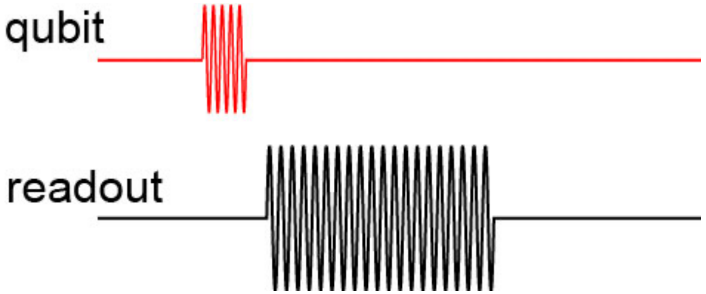
# SUPERCONDUCTING PARAMETRIC AMPLIFIERS
## (RESONANT CAVITY BASED)

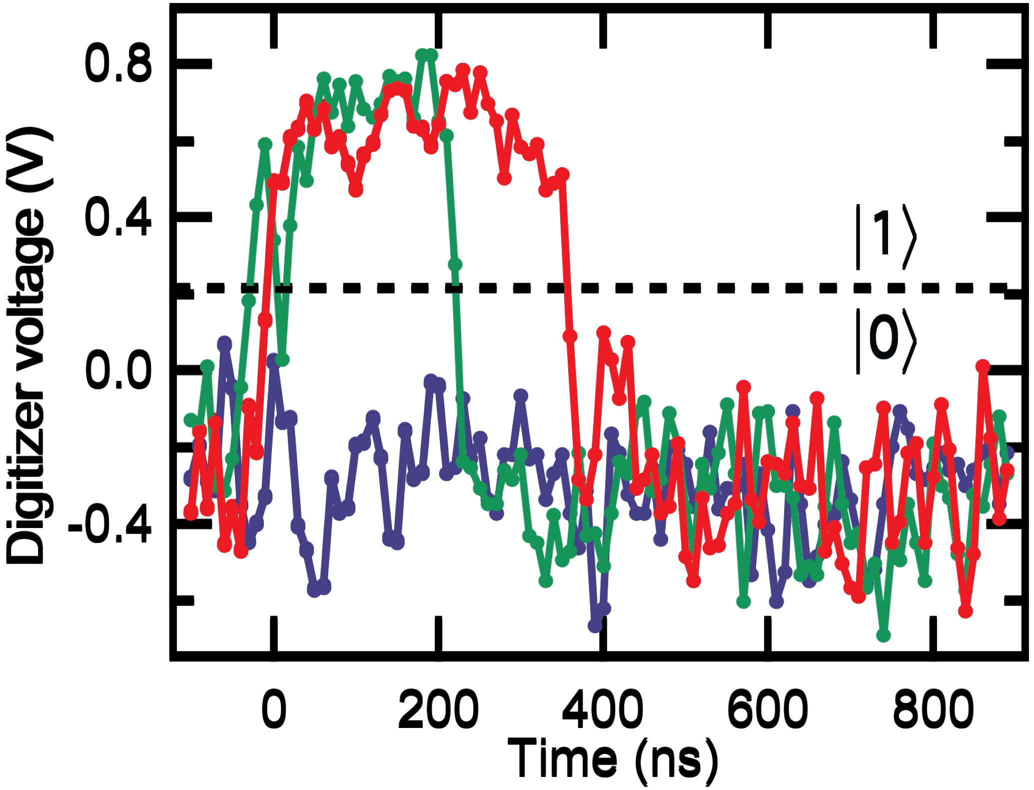



$G = 20$ dB
$f_0 = 4\text{-}8$ GHz
$f_{-3dB} = 10\text{-}50$ MHz
$T_N \sim 1.2\ T_Q$


Cal
JPA 2.0

# SINGLE SHOT MEASUREMENTS




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

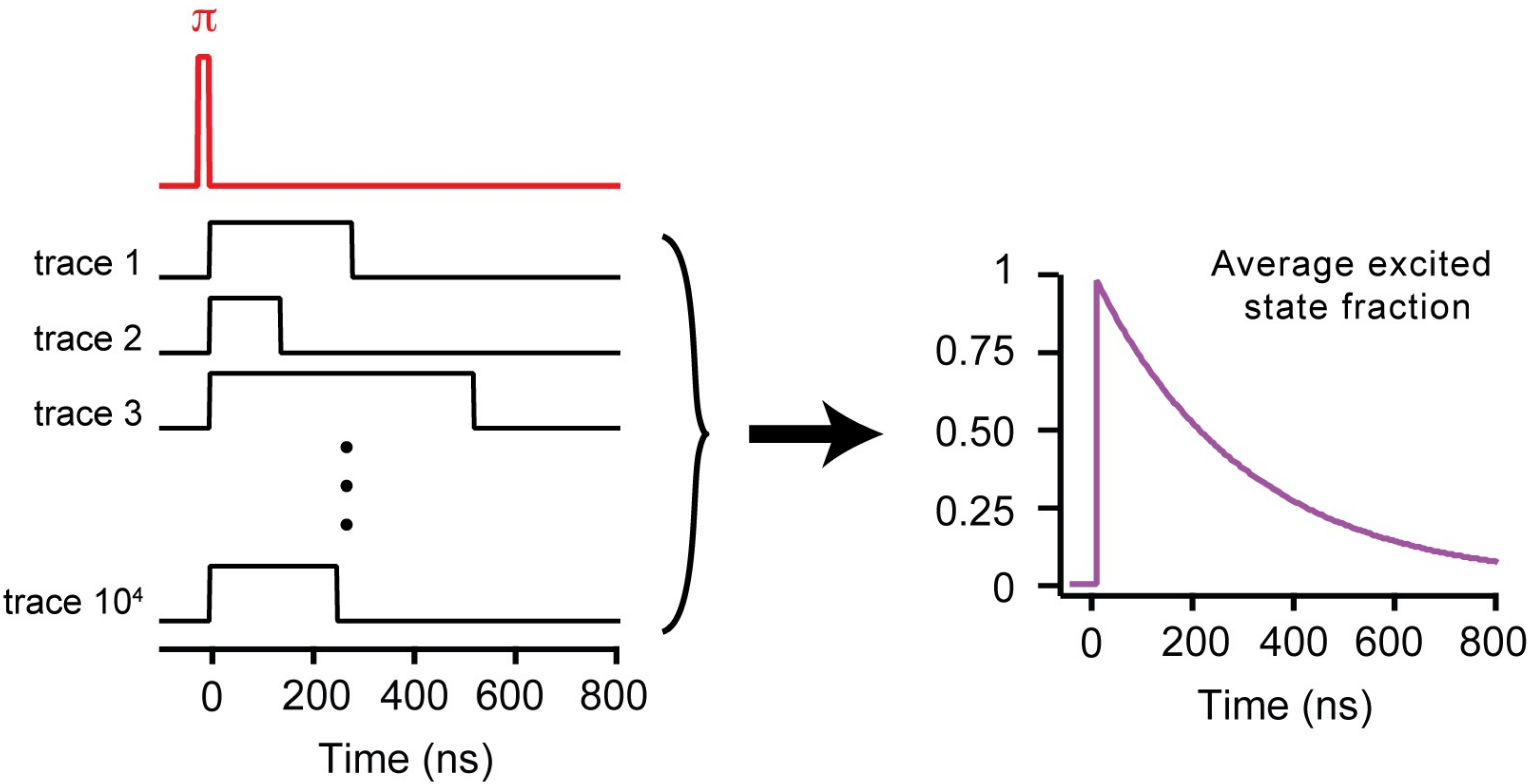
**Observation of Quantum Jumps in a Superconducting Artificial Atom**

R. Vijay, D. H. Slichter, and I. Siddiqi

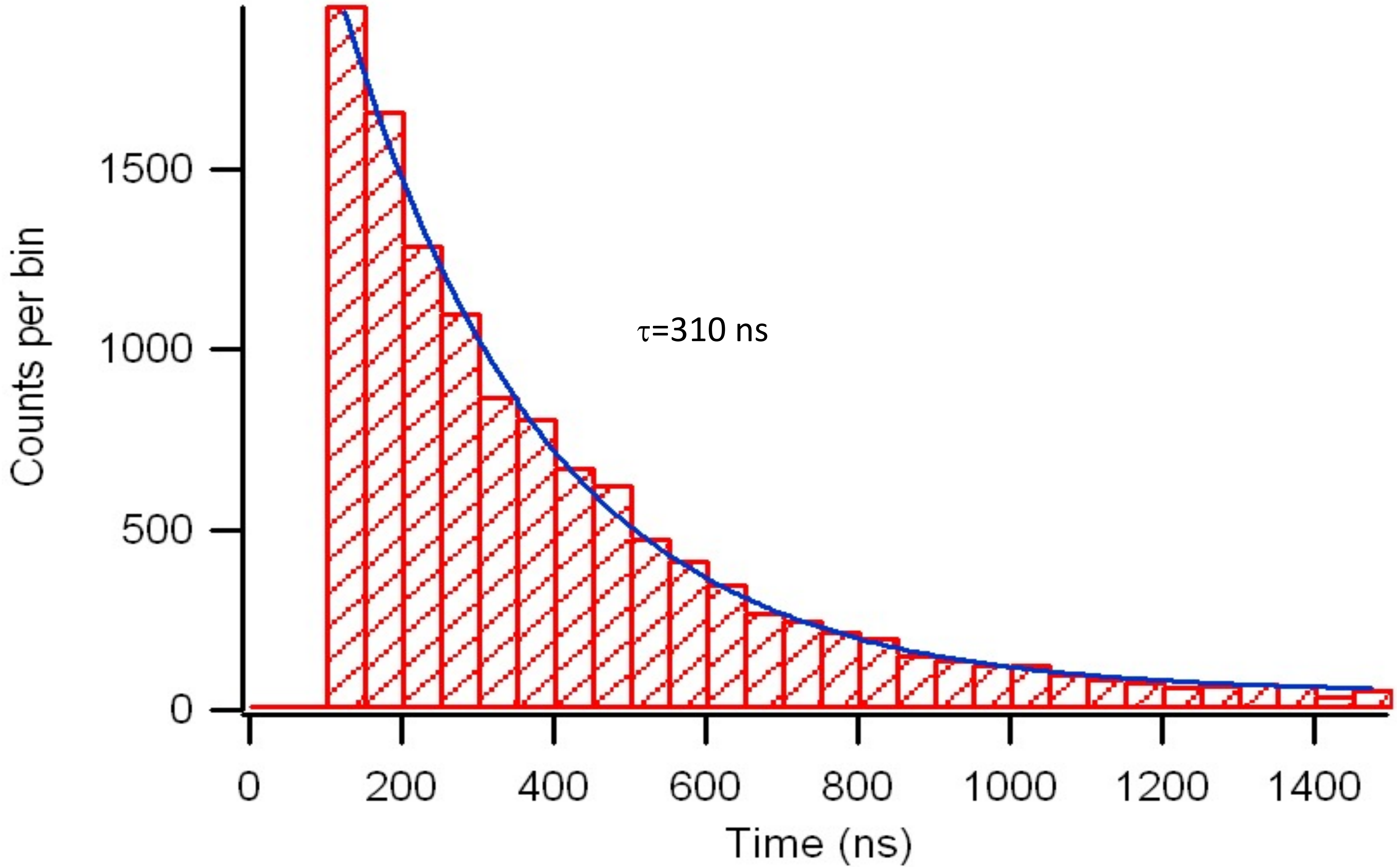
*Quantum Nanoelectronics Laboratory, Department of Physics, University of California, Berkeley, California 94720, USA*

# *Unraveling the Ensemble*

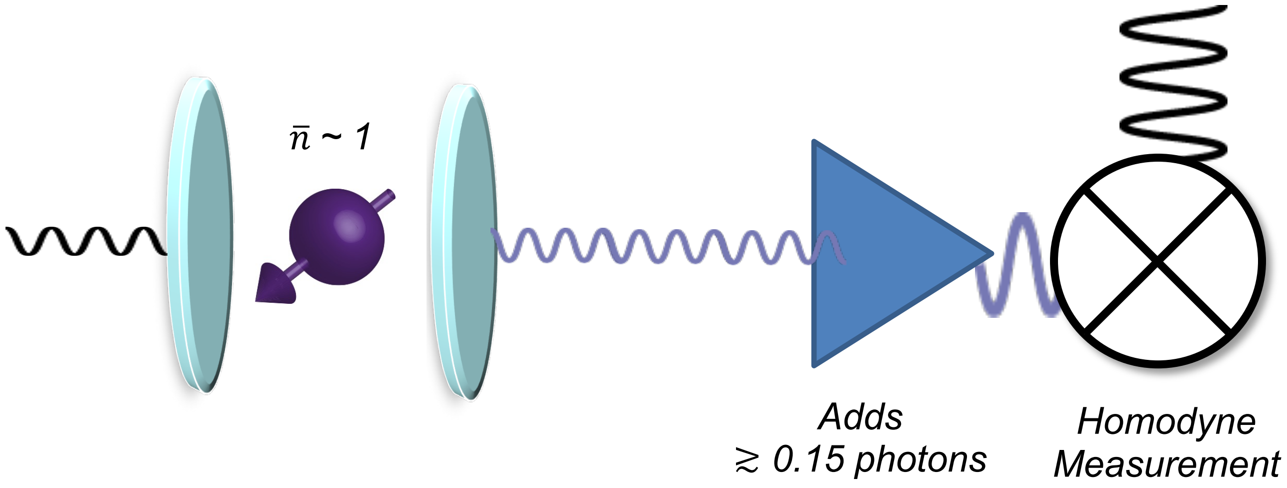
# STOCHASTIC QUANTUM JUMPS

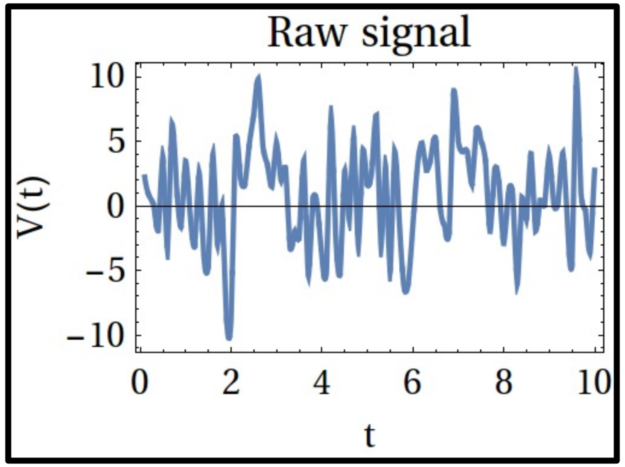


# JUMP STATISTICS

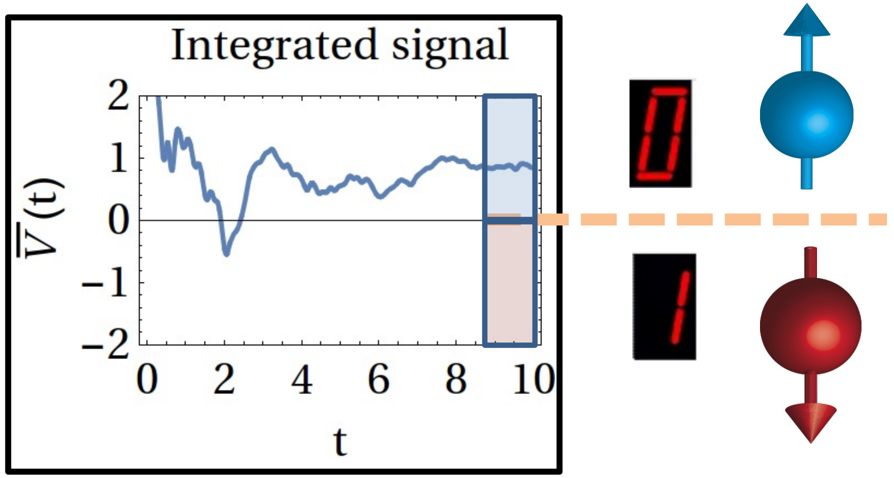


# HOMODYNE DETECTION



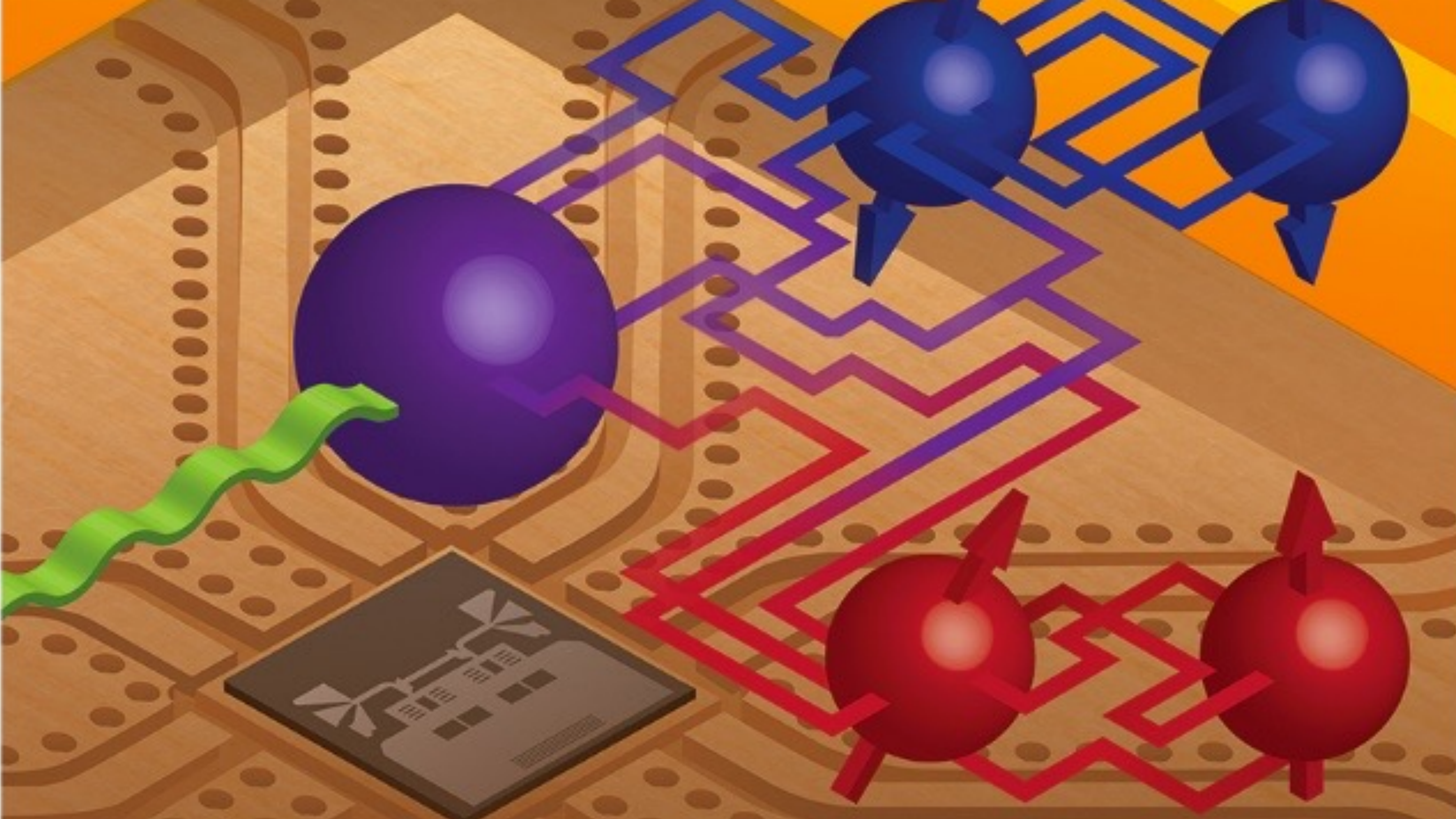

**(Weak Measurement)**



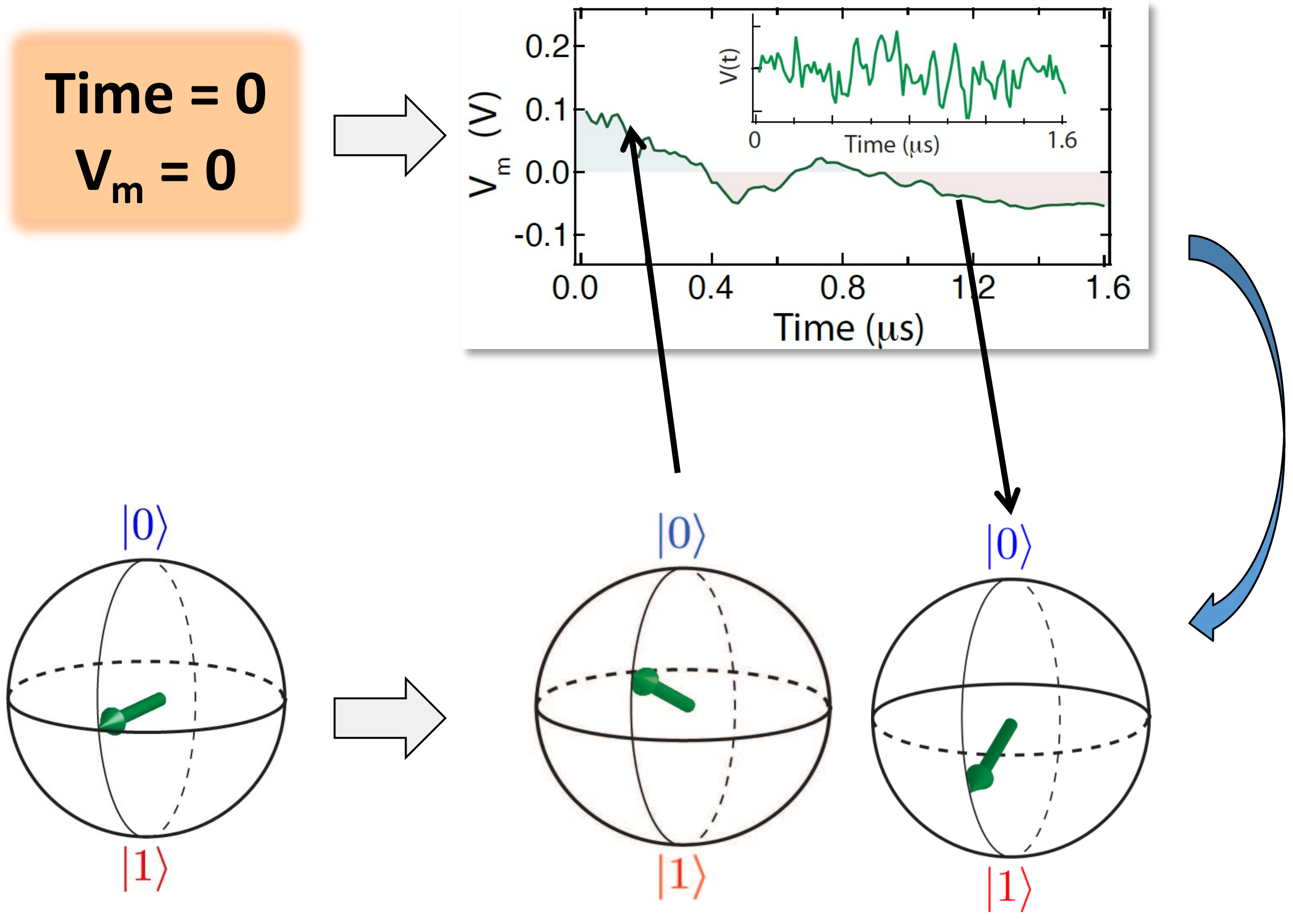

**(Strong Measurement)**

**THE NATIVE ANALOG INFORMATION CAN BE USED FOR…**

- Trajectory Reconstruction
- Entanglement Generation
- Quantum Feedback
- Validate Measurements



# RECONSTRUCTING THE QUBIT STATE

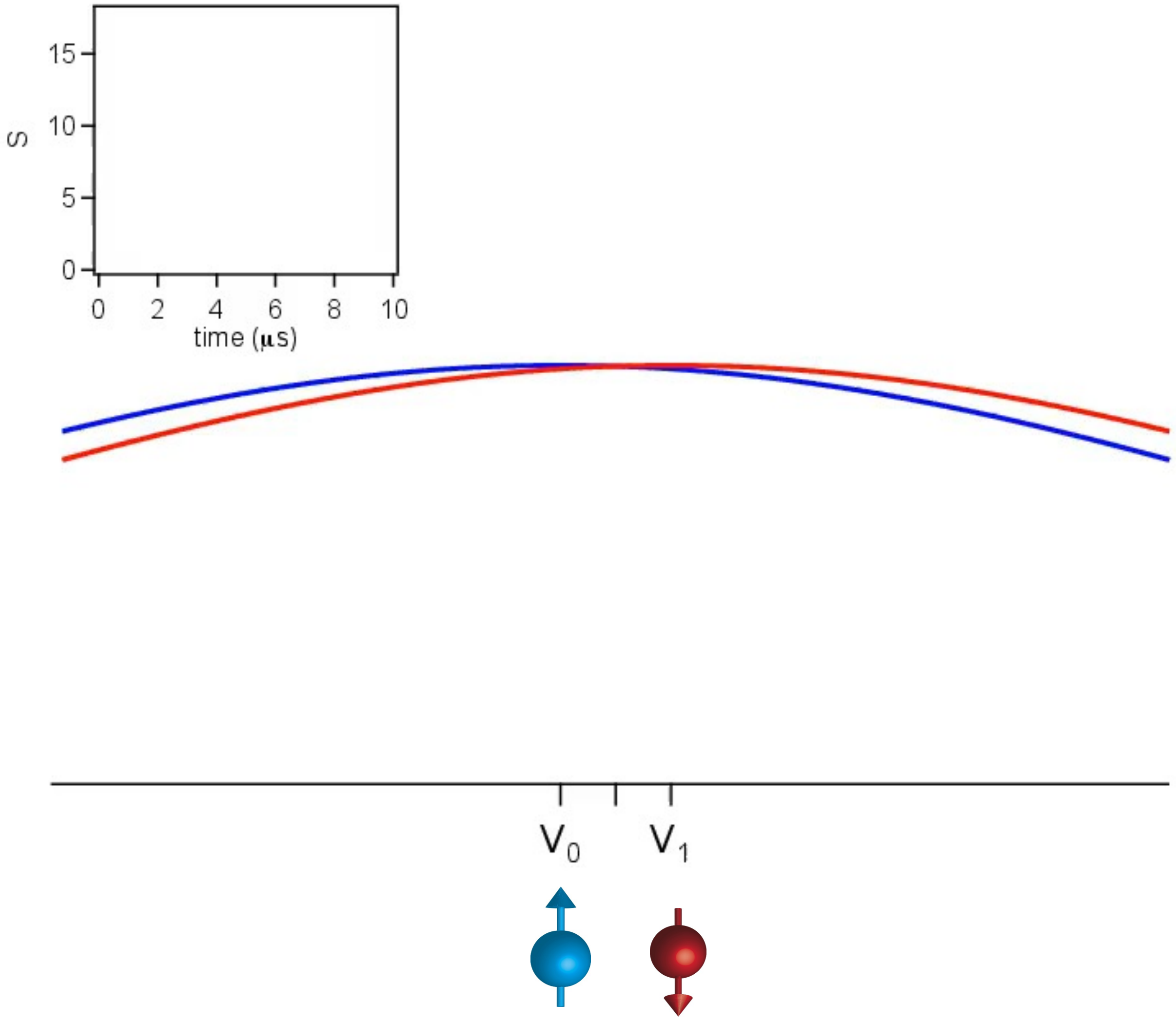



Thomas Bayes
1701-1761

<u>BAYES RULE</u>

- Update guess based on new information
- Update qubit state based on $V_m(t)$
- Widely used in economics, math, engineering, law,…

# MEASURING SPIN UP & SPIN DOWN




histogram separation

$$S = \frac{\Delta V^2}{\sigma^2}$$

histogram width

$$S = \frac{64\tau\chi^2\bar{n}\eta}{\kappa}$$

$\tau$: measurement time

$\chi$: dispersive shift

$\bar{n}$: photon number

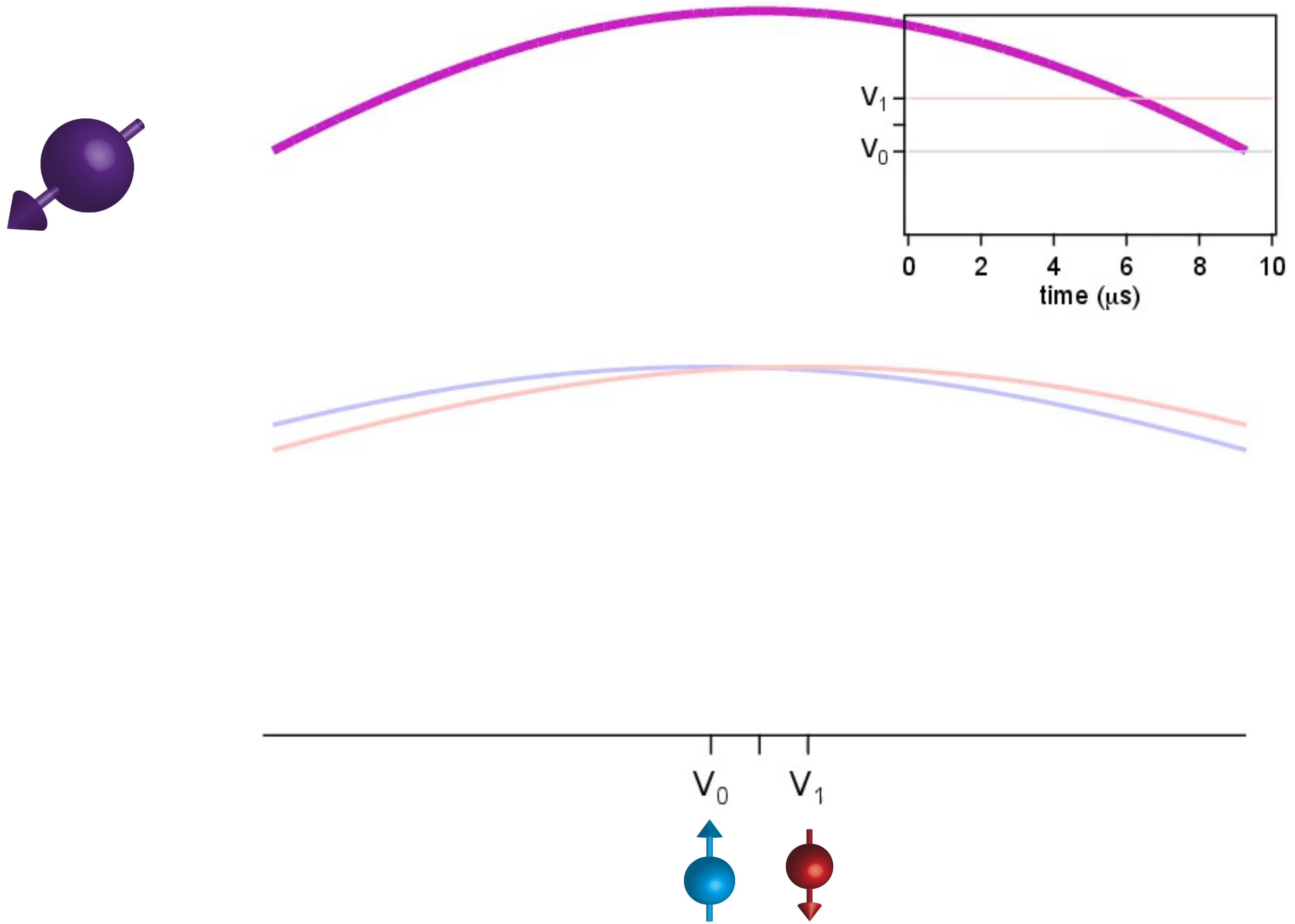
$\kappa$: cavity decay rate

$\eta$: detector efficiency

$$\eta = 0.49$$

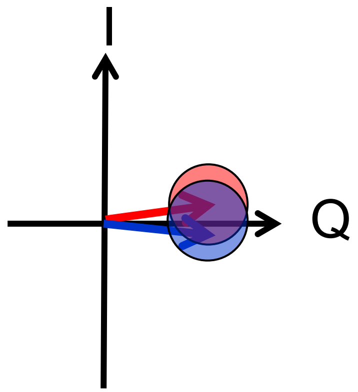
# INTEGRATED VOLTAGE: TRAJECTORY

$$V_m(\tau) = \frac{1}{\tau}\int_0^{\tau} V(t)dt$$

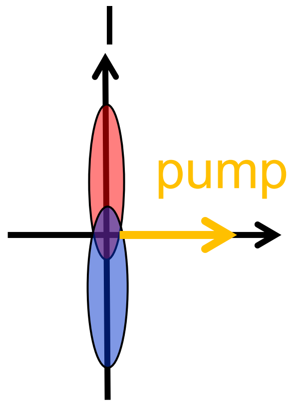


# BACKACTION OF SINGLE QUADRATURE MEASUREMENT

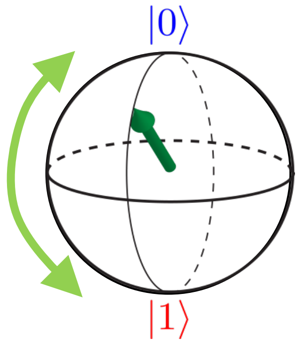
Cavity Output $\theta=0$



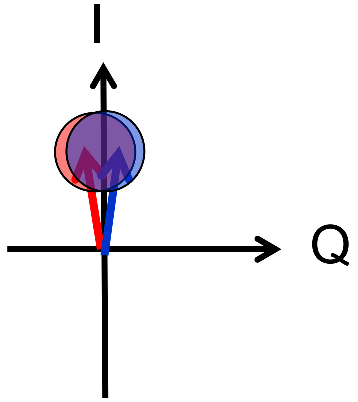

After Amplification $\theta=0$



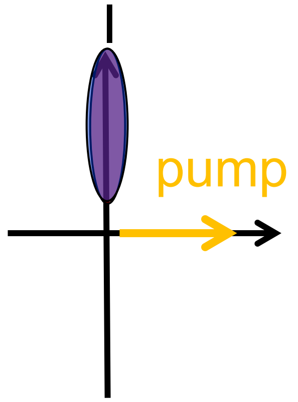

- Obtain qubit state information
- Tip Bloch vector



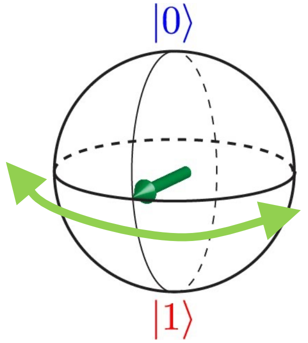

Cavity Output $\theta=\pi/2$



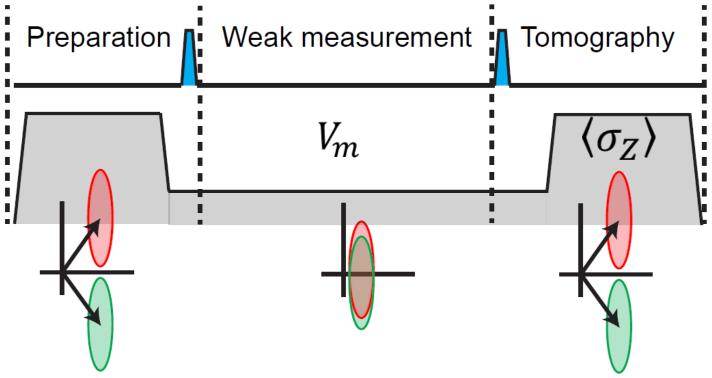

After Amplification $\theta=\pi/2$



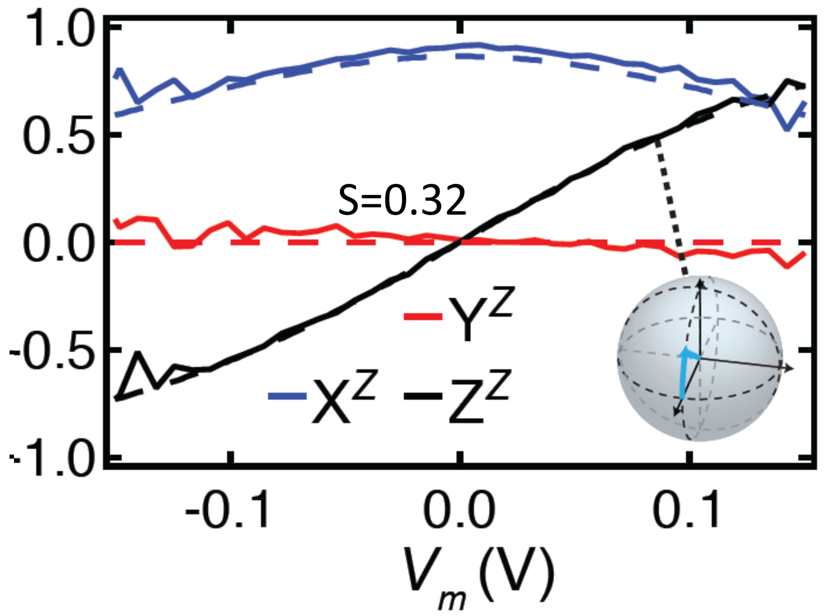

- Obtain cavity photon number information
- Rotate Bloch vector



# VERIFYING BAYESIAN UPDATING



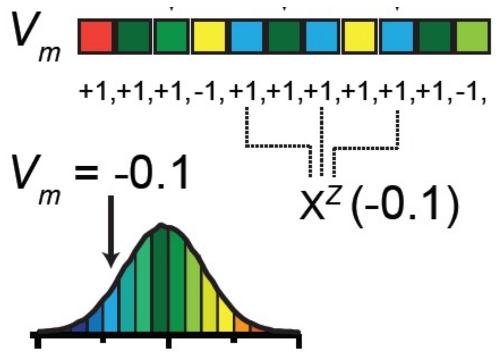

- Initial state along +X
- Measure Z (phase quadrature)




**WANT TO EVALUATE:**

$$\langle\sigma_Z\rangle|V_m \stackrel{\text{def}}{=} Z^Z$$
$$\langle\sigma_X\rangle|V_m \stackrel{\text{def}}{=} X^Z$$
$$\langle\sigma_Y\rangle|V_m \stackrel{\text{def}}{=} Y^Z$$

**TOMOGRAPHIC PROCEDURE:**



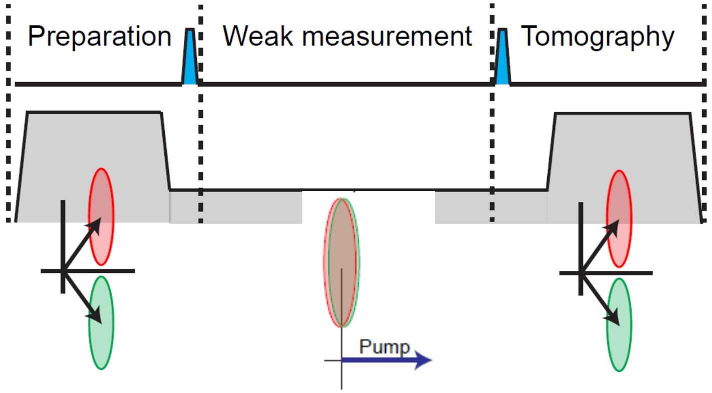

**BAYES RULE:**

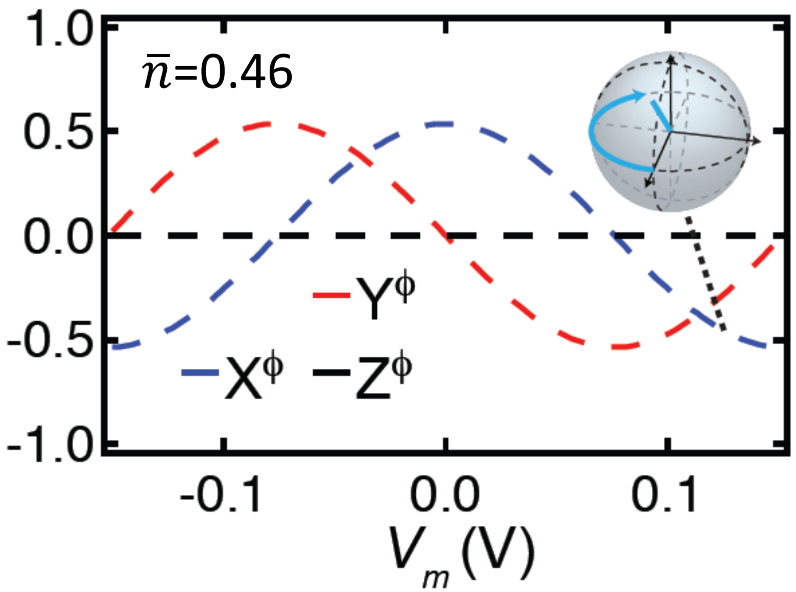
$$Z^Z = \tanh(\frac{V_m S}{2\Delta V})$$

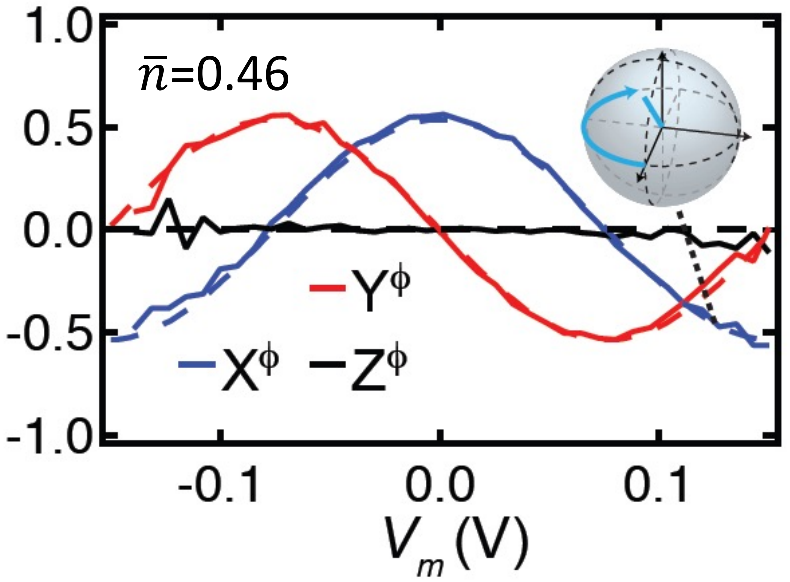
$$X^Z = \sqrt{1-\langle\sigma_Z\rangle^2}e^{-\gamma\tau}$$

$$\gamma = 8\chi^2\bar{n}(1-\eta)/\kappa + 1/T_2^*$$

# WEAK MEASUREMENT OF THE PHOTON NUMBER




**WANT TO EVALUATE:**

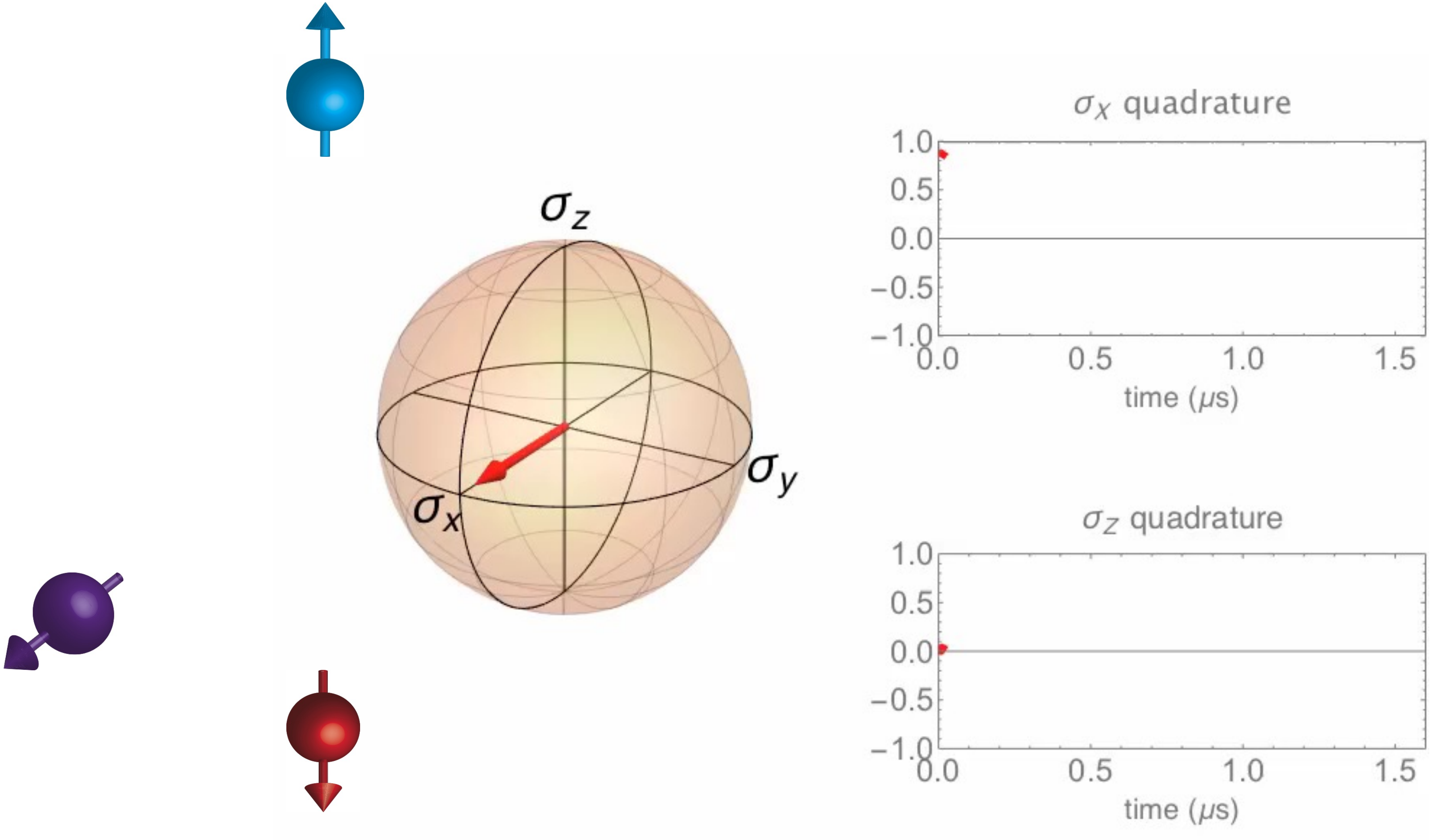
$$\langle\sigma_Z\rangle|V_m \stackrel{\text{def}}{=} Z^\phi$$
$$\langle\sigma_X\rangle|V_m \stackrel{\text{def}}{=} X^\phi$$
$$\langle\sigma_Y\rangle|V_m \stackrel{\text{def}}{=} Y^\phi$$

**BAYES RULE:**

$$X^\phi = \cos\left(\frac{SV_m}{2\Delta V}\right)e^{-\gamma\tau}$$

$$Y^\phi = \sin\left(\frac{SV_m}{2\Delta V}\right)e^{-\gamma\tau}$$

# A SINGLE QUANTUM TRAJECTORY




K. Murch et al., *Nature* **502**, 211 (2013).