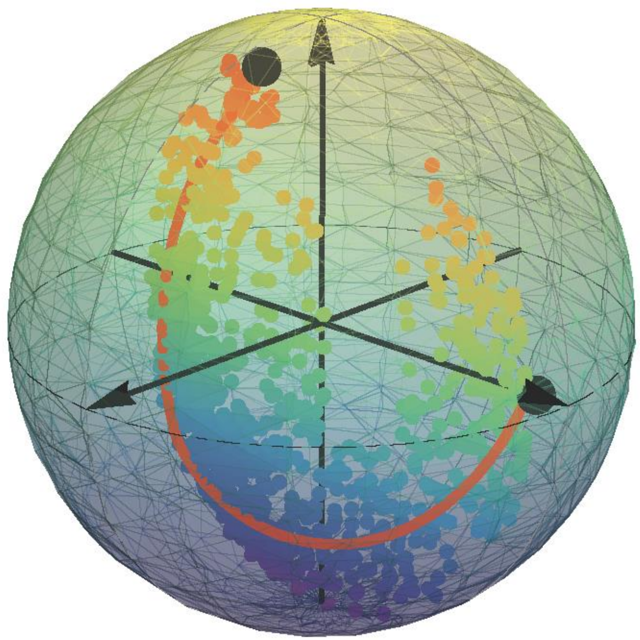
SUPERCONDUCTING QUBITS



IRFAN SIDDIQI

Quantum Nanoelectronics Laboratory
Department of Physics, UC Berkeley

Theory Collaborators

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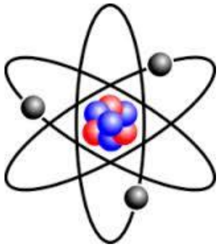
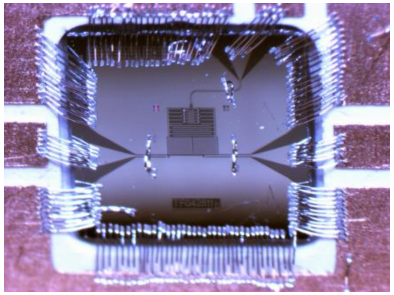
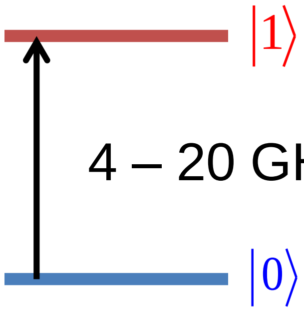
Prof. A. Clerk (McGill)
Prof. L. Friedland (HUJI)
Prof. A.N. Korotkov (UCR)
Prof. S.M. Girvin (Yale)
Prof. L. Glazman (Yale)
Prof. A. Jordan (UR)
Dr. M. Sarovar (Sandia)
Prof. B. Whaley (UCB)

MICROWAVE OPTICS & SUPERCONDUCTING ARTIFICAL ATOMS



ATOM/CAVITY

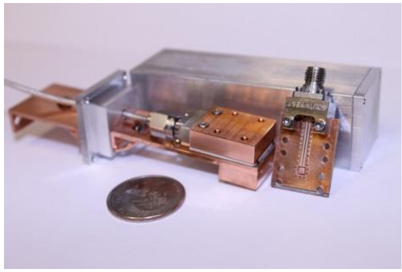




LIGHT SOURCE

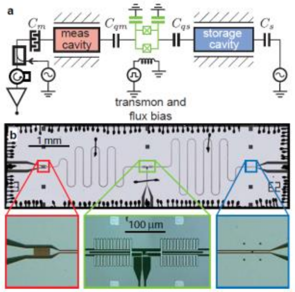
Tunable f, ϕ

DETECTOR



M. Hatridge et al., *Phys. Rev. B* **83** (2011)

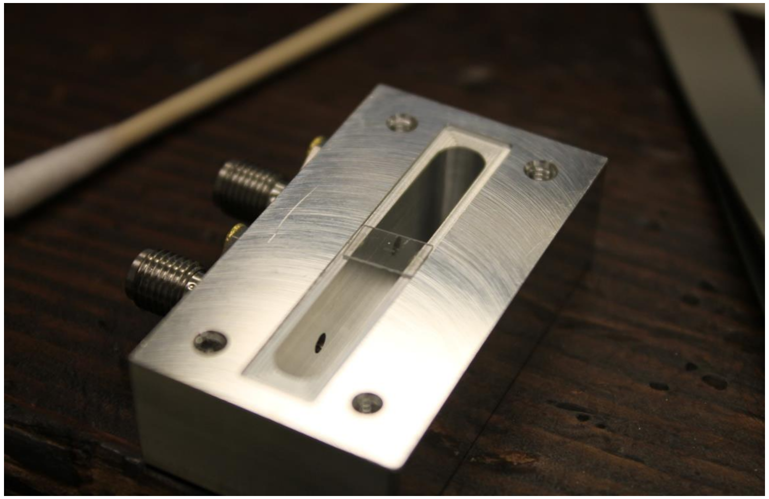
HOMODYNE



B.R. Johnson et al., *Nature Physics* **6** (2010)

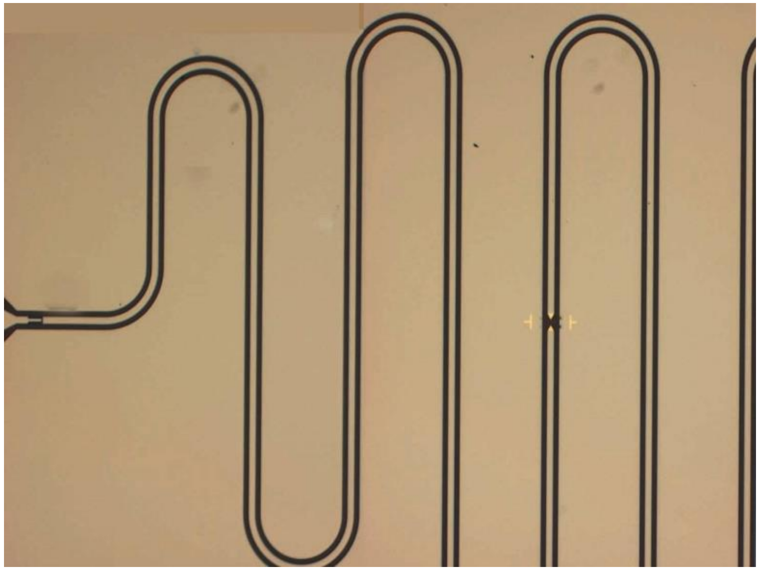
COUNTING

4-8 GHz LINEAR CAVITIES



3D Waveguide

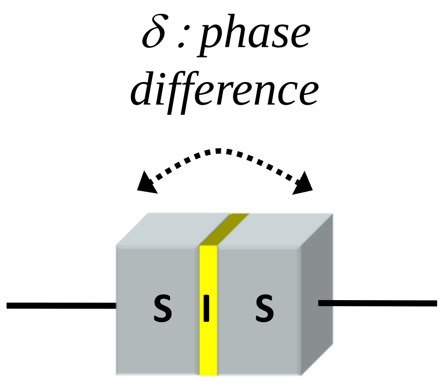
Q ~ 10^6-10^9…



2D Planar

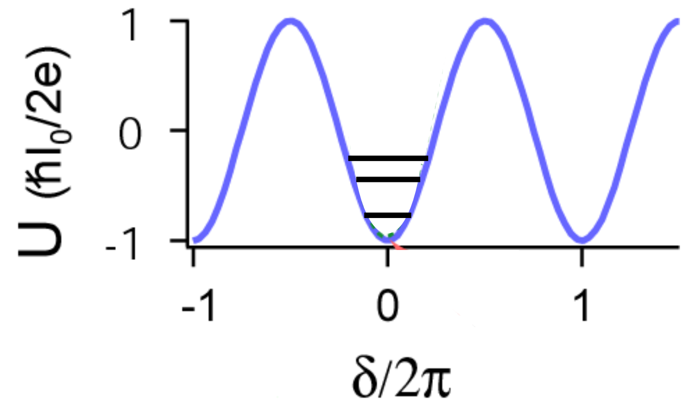
Q ~ 10^5-10^6…

THE NON-DISSIPATIVE JOSEPHSON JUNCTION OSCILLATOR



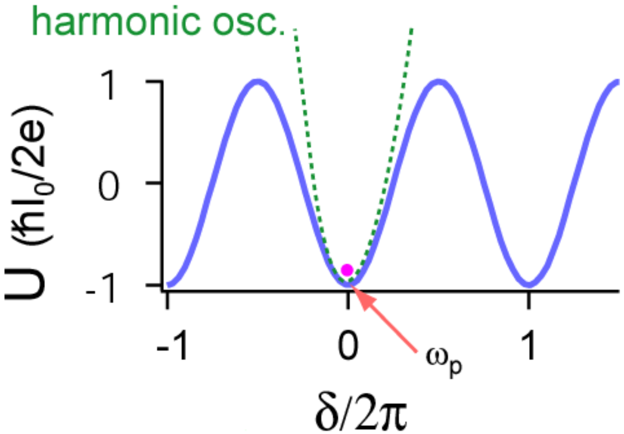
$I_0 \sim nA$

Quantized Levels



$I_0 > \mu A$

Non-linear Oscillator



$$\begin{cases} I(\delta) = I_0 \sin(\delta) \\ V(t) = \dfrac{\hbar}{2e}\dfrac{d}{dt}(\delta) \end{cases}$$

$$U(\delta) = -\frac{\hbar}{2e} I_0 \cos(\delta)$$

THE DAWN OF COHERENCE

T_1, T_2 ~ 1 ns | Al / AlOx / Al

T_1, T_2 ~ 100 μs | Al / AlOx / Al

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

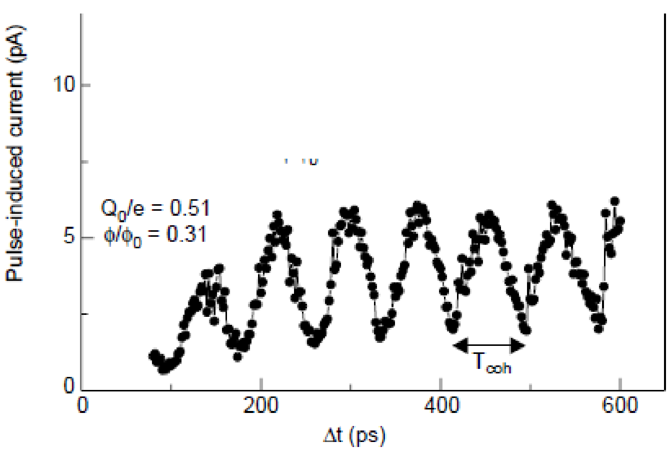
Y. Nakamura*, Yu. A. Pashkin† & J. S. Tsai*

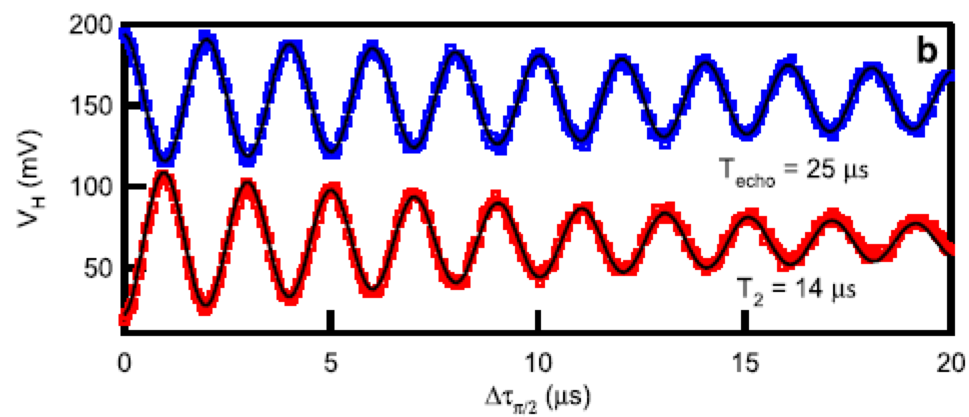
* *NEC Fundamental Research Laboratories, Tsukuba, Ibaraki 305-8051, Japan*
† *CREST, Japan Science and Technology Corporation (JST), Kawaguchi, Saitama 332-0012, Japan*

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

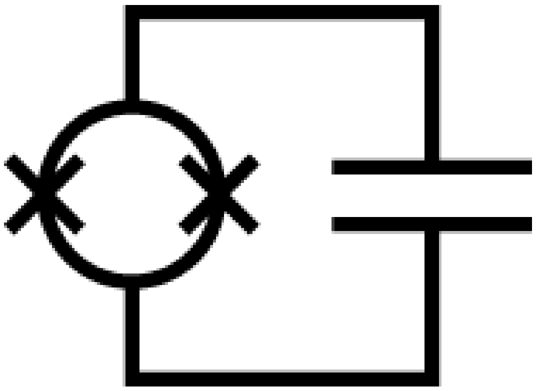
Hanhee Paik,[1] D. I. Schuster,[1,2] Lev S. Bishop,[1,3] G. Kirchmair,[1] G. Catelani,[1] A. P. Sears,[1] B. R. Johnson,[1,4] M. J. Reagor,[1] L. Frunzio,[1] L. I. Glazman,[1] S. M. Girvin,[1] M. H. Devoret,[1] and R. J. Schoelkopf[1]

[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*

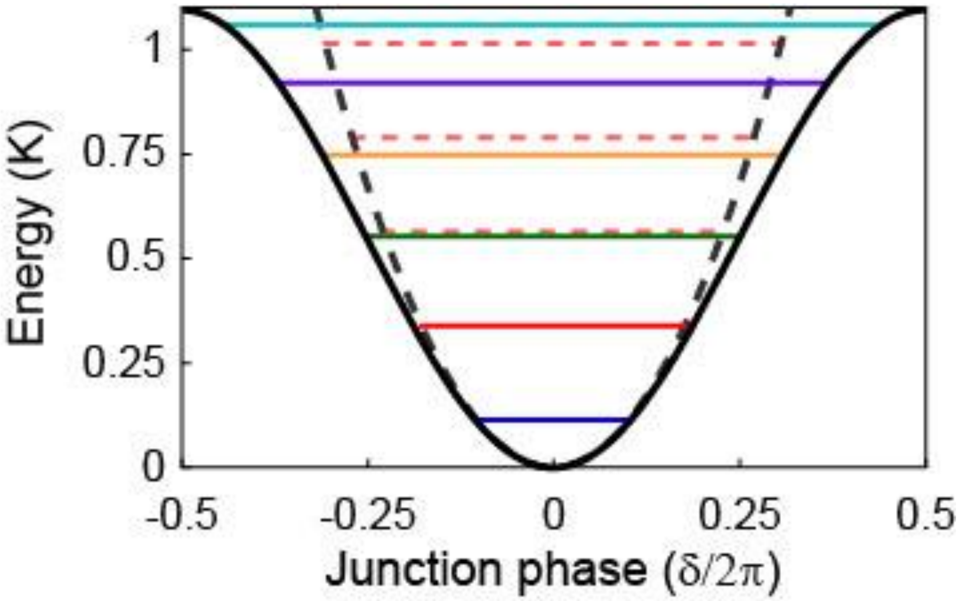




SUPERCONDUCTING TRANSMON QUBIT



$L_J \sim 13$ nH $C \sim 70$ fF

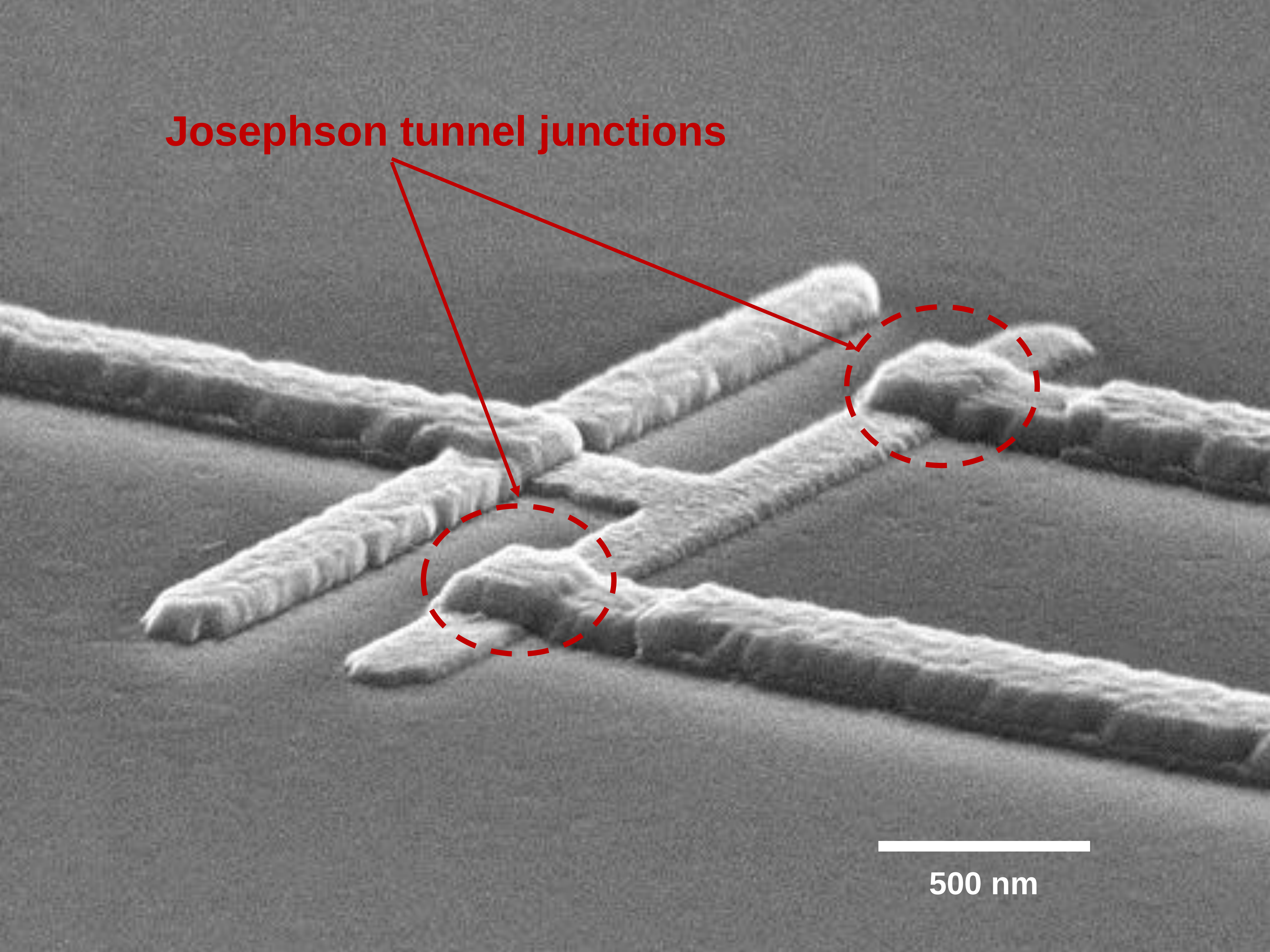


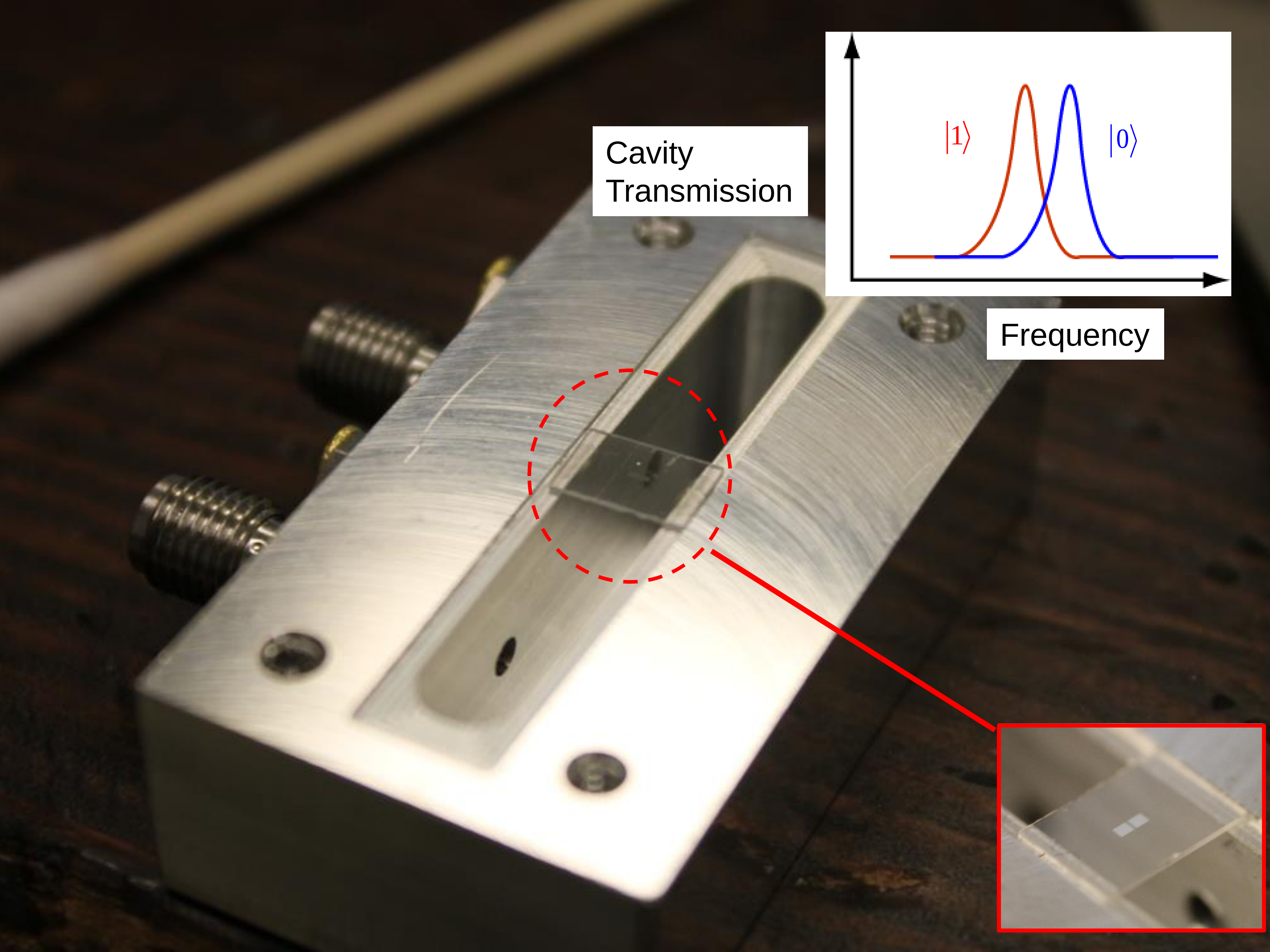
$$\omega_{01} \simeq \frac{1}{\sqrt{L_J C}}$$

$$\omega_{01} \neq \omega_{12}$$

- Tunable qubit frequency
- $\omega_{01} \sim$ 5-8 GHz
- T_1 , $T_2 \sim$ 100s μs

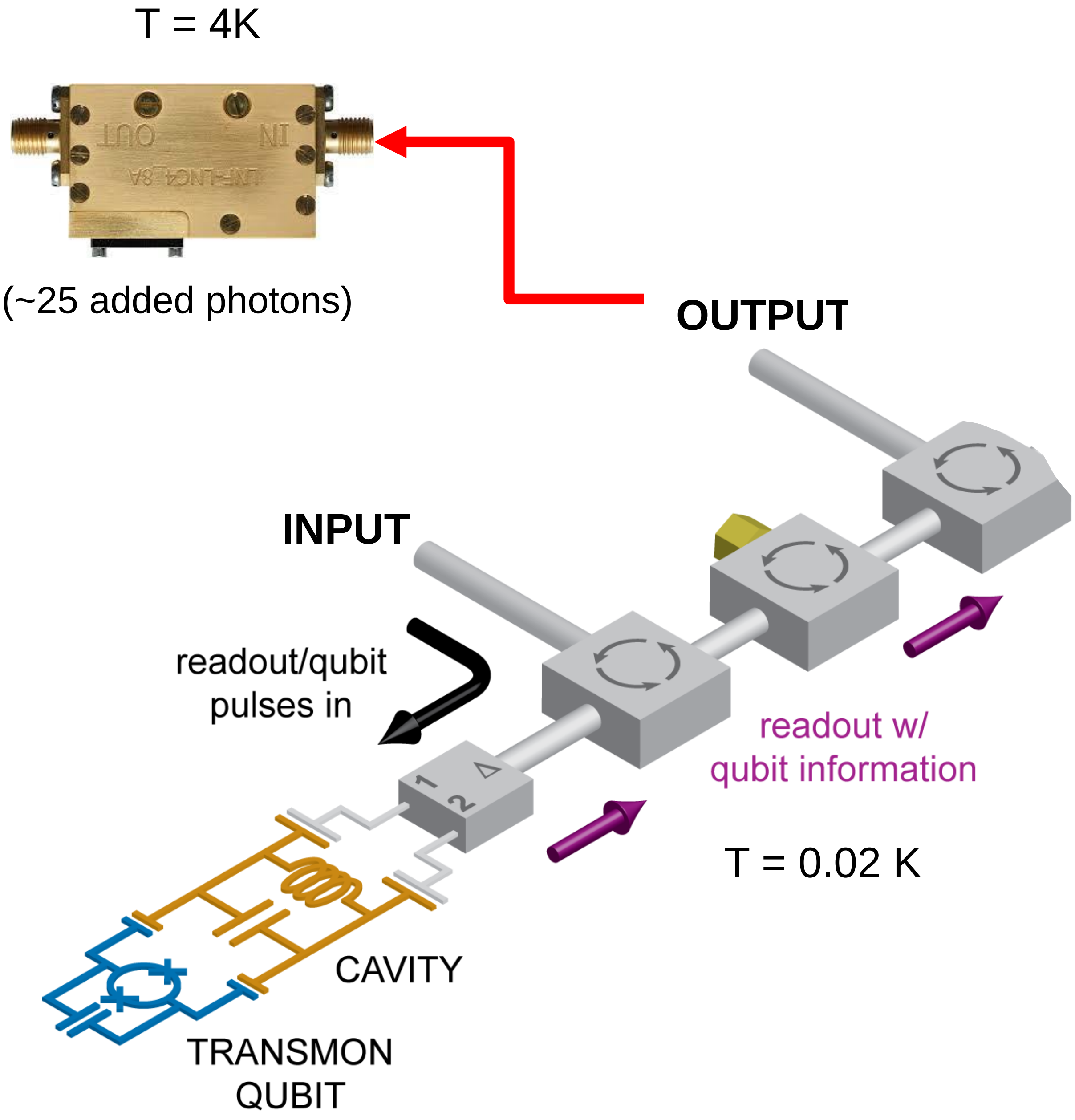
J. Koch et al., *Physical Review A* ***76,*** 042319 (2007)


Josephson tunnel junctions
500 nm

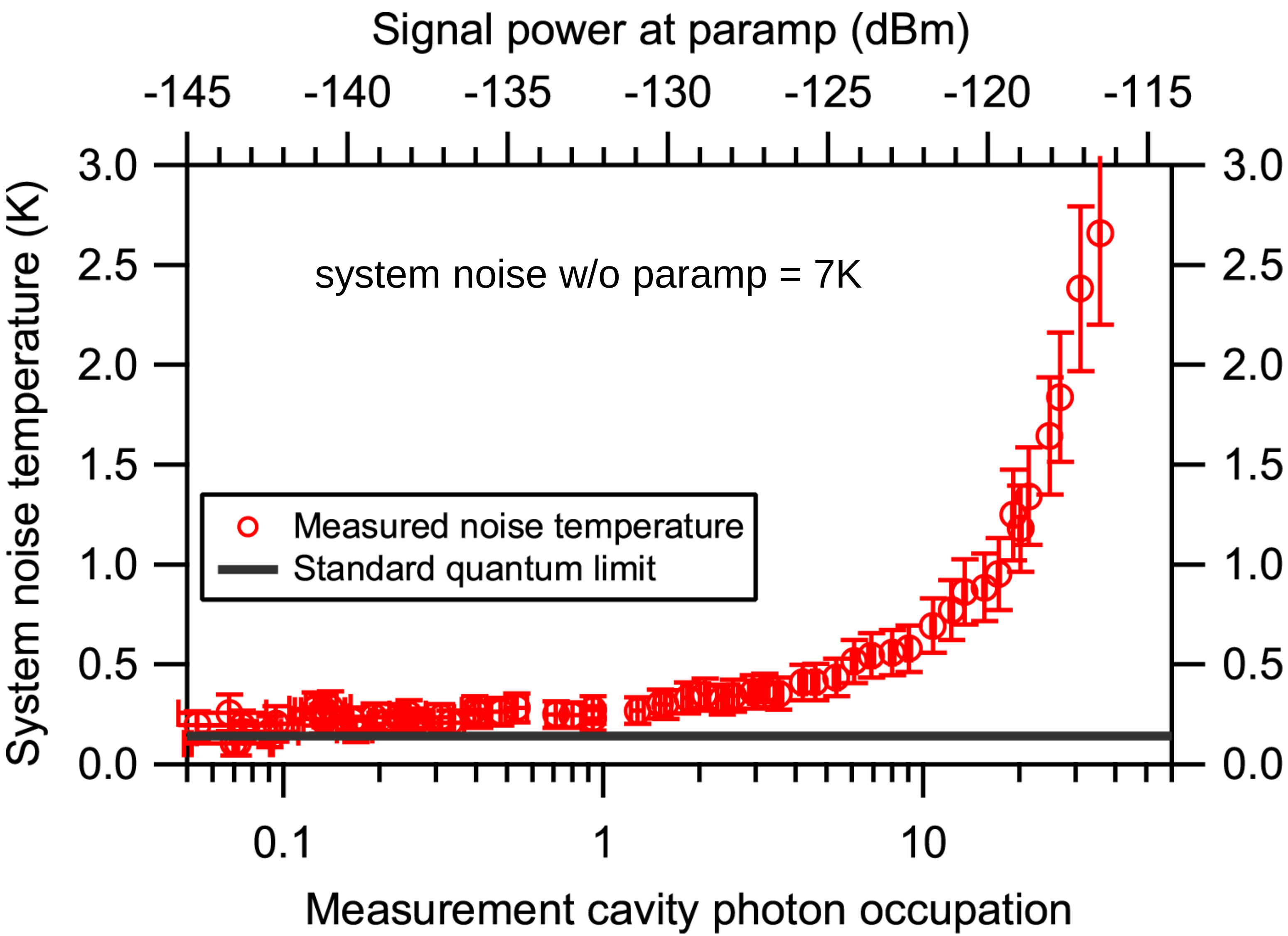


Cavity Transmission
$|1\rangle$
$|0\rangle$
Frequency

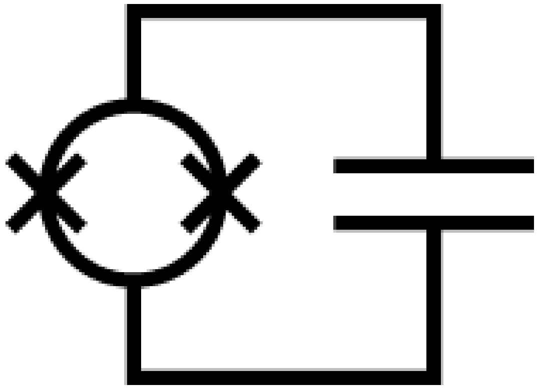
EXPERIMENTAL SETUP



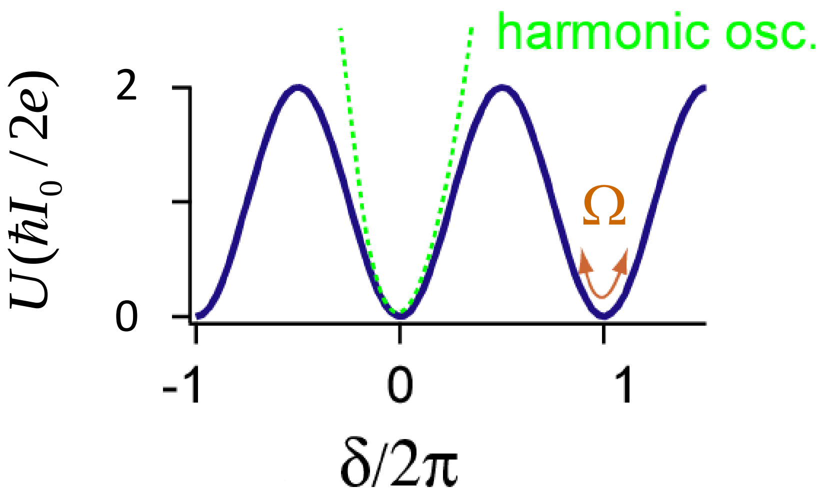
SYSTEM NOISE TEMPERATURE

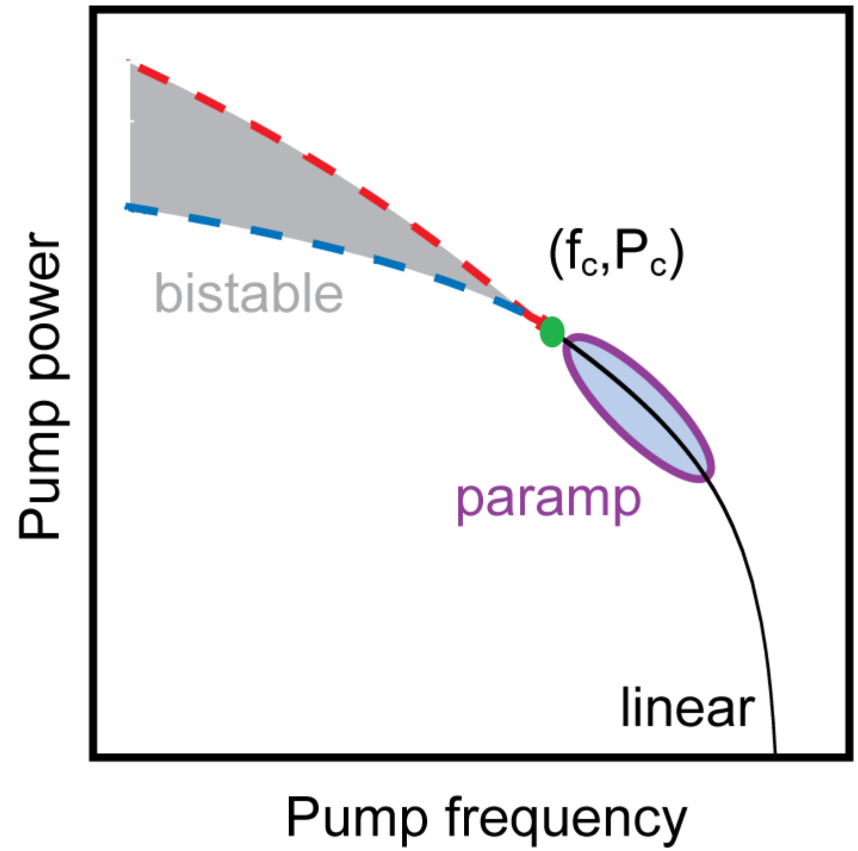


PARAMETRIC AMPLIFICATION

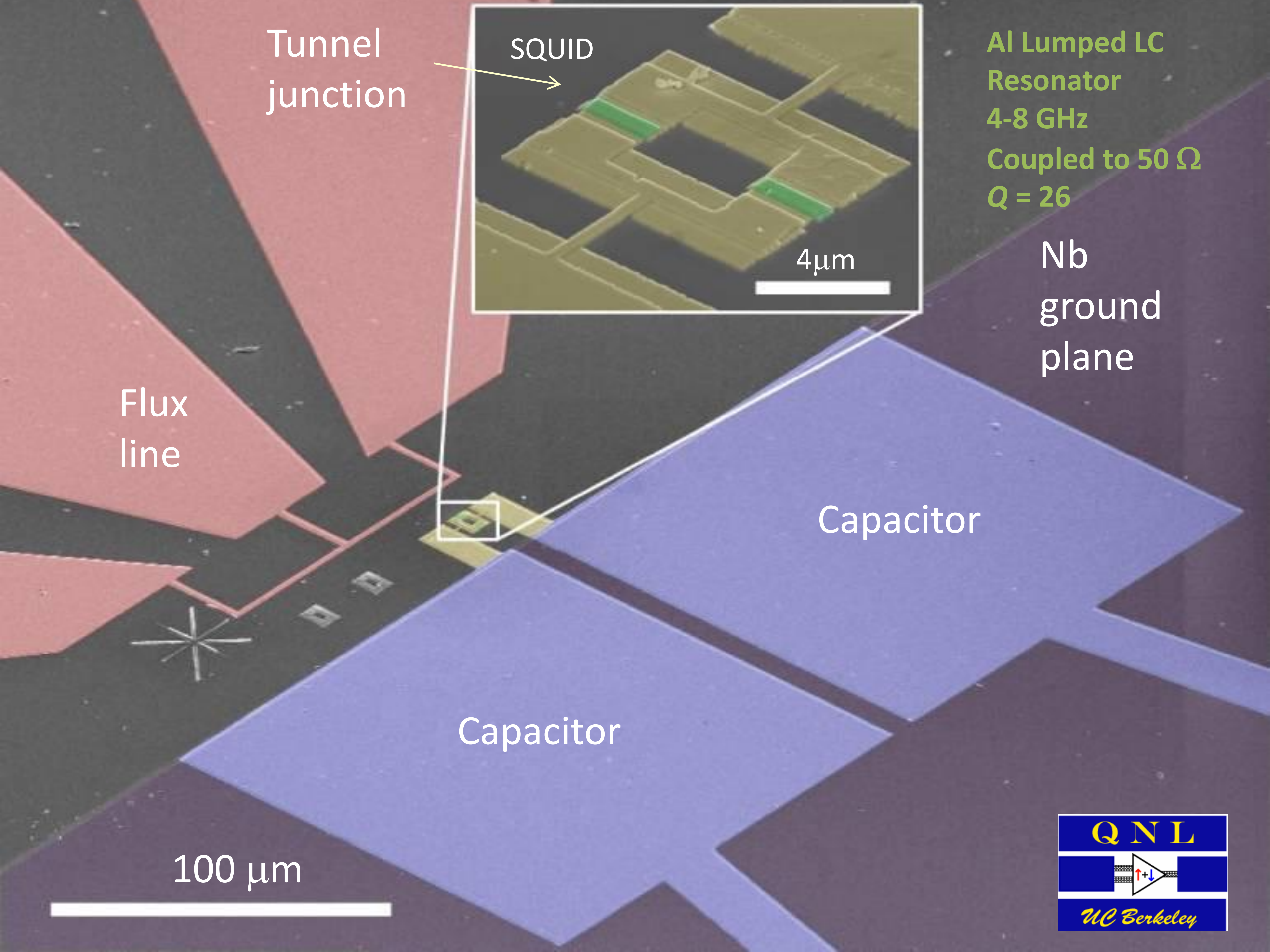


$L_J \sim 0.1$ nH $C \sim 10000$ fF

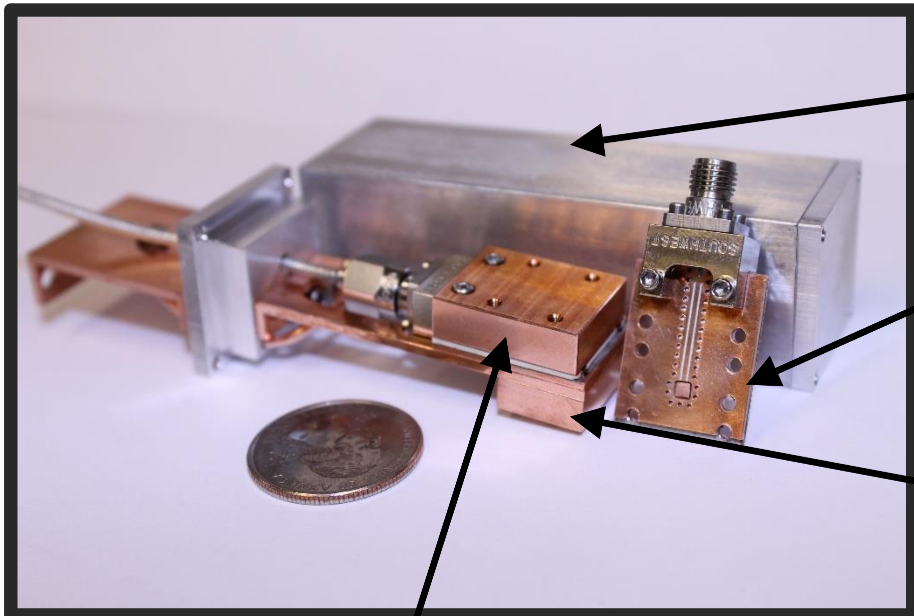




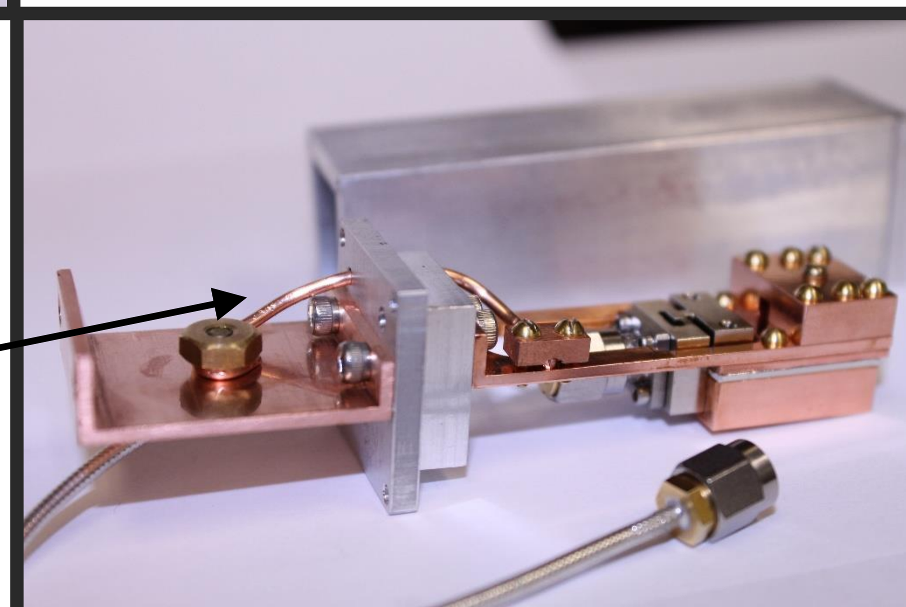
M. J. Hatridge et al., *Phys. Rev.* B **83**, 134501 (2011)

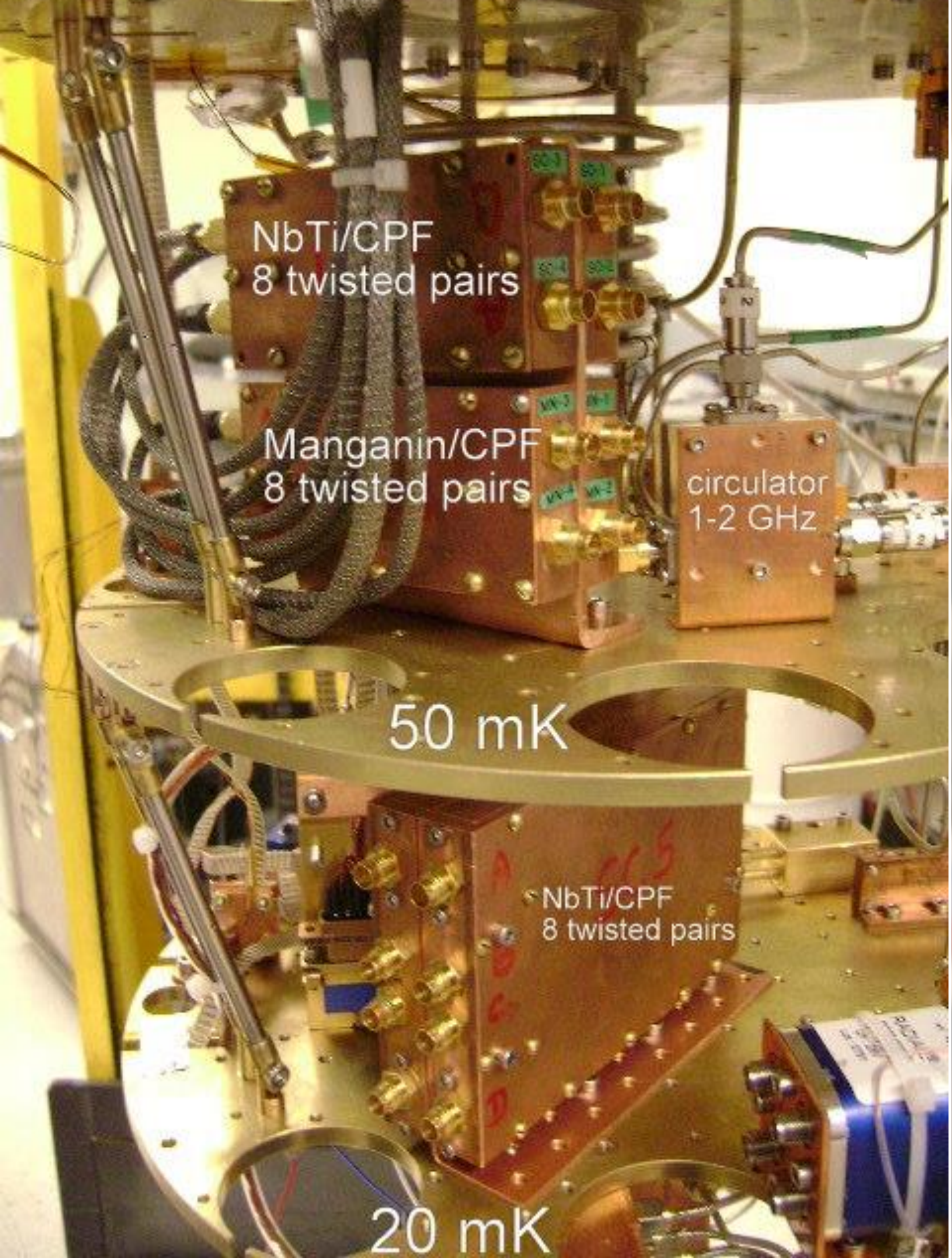
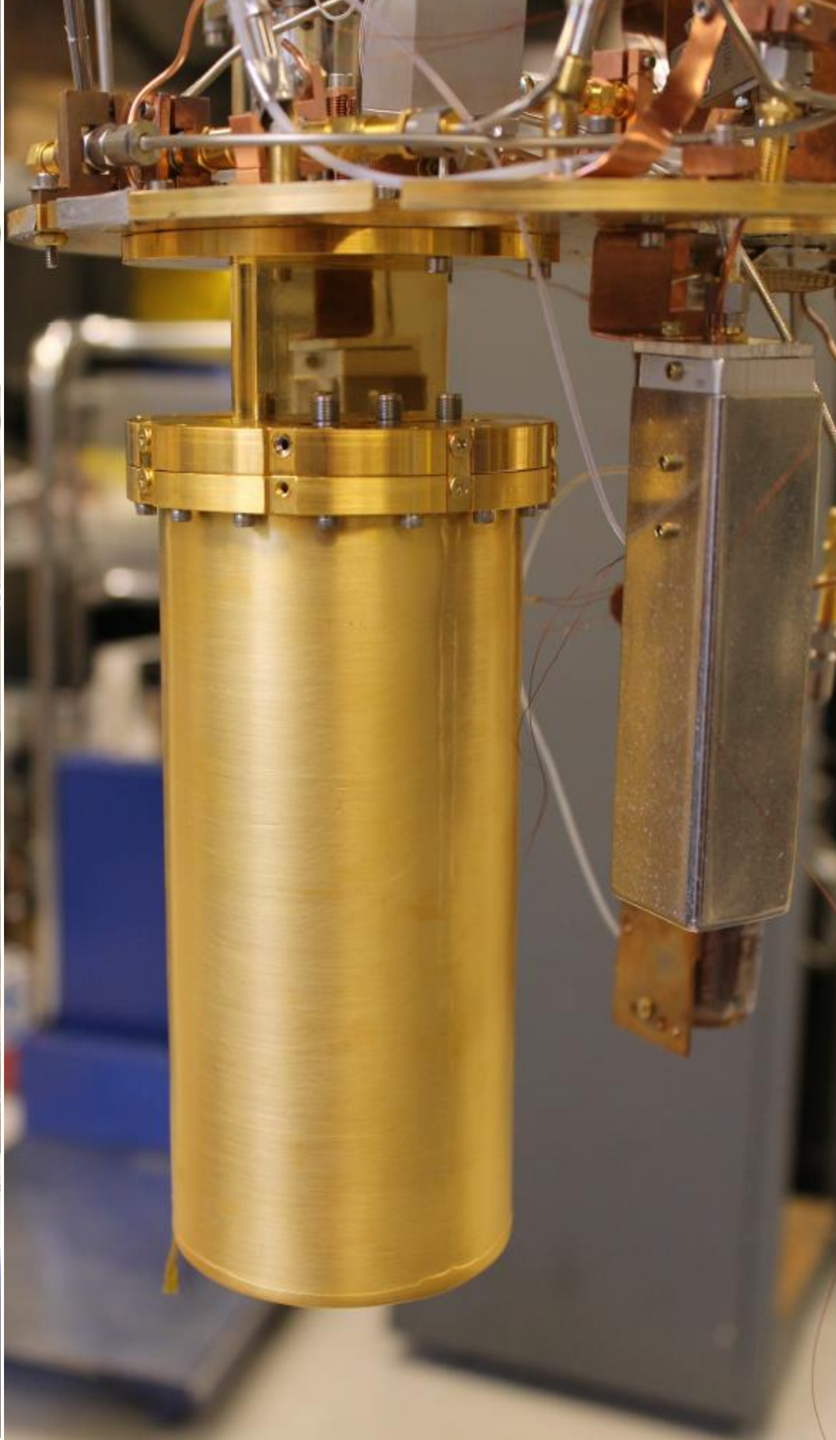

Tunnel junction
SQUID
4μm
Al Lumped LC Resonator
4-8 GHz
Coupled to 50 Ω
Q = 26
Nb ground plane
Flux line
Capacitor
Capacitor
100 μm
Q N L
UC Berkeley

4^{th} GENERATION CRYOPACKAGE



- Aluminum superconducting shield
- Removable CPW launch
- Magnet for tuning frequency
- Copper cover
  (prevents any coupling to box mode)
- Thermalizing strap



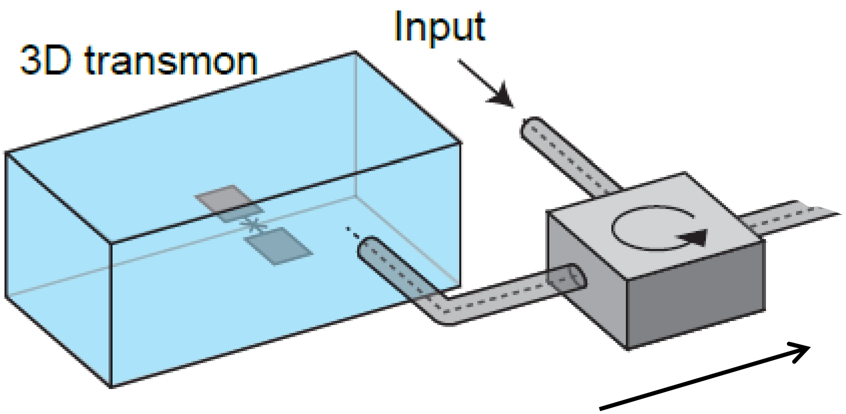

NbTi/CPF
8 twisted pairs
Manganin/CPF
8 twisted pairs
circulator
1-2 GHz
50 mK
NbTi/CPF
8 twisted pairs
20 mK


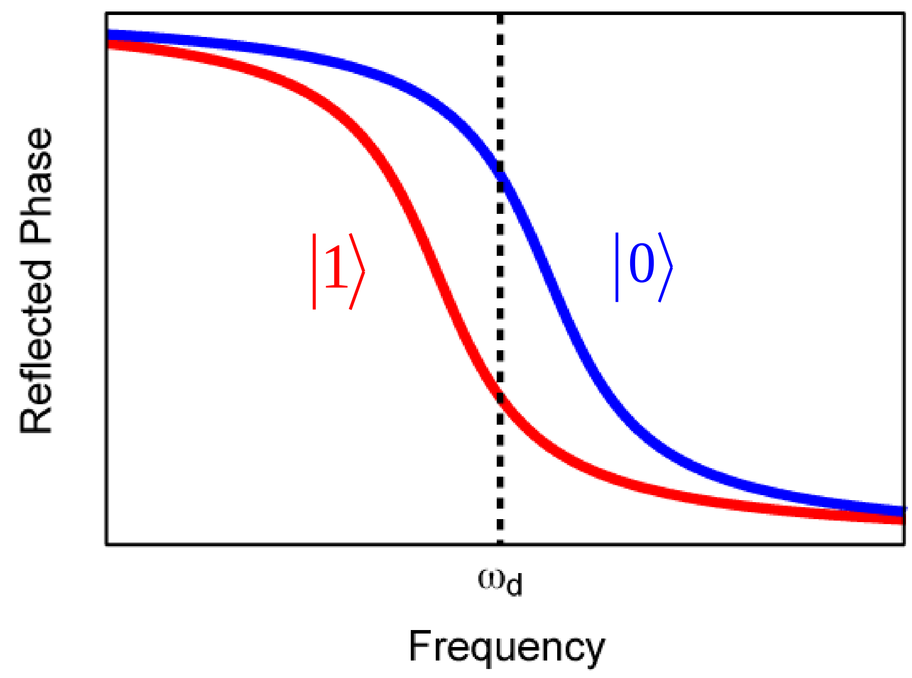
OUTLINE

- **WEAK MEASUREMENT**
- **SINGLE QUBIT EXPERIMENTS**
  - Individual Quantum Trajectories
  - Distribution of Quantum Trajectories
- **TWO QUBIT MEASUREMENTS**
  - Remote Entanglement

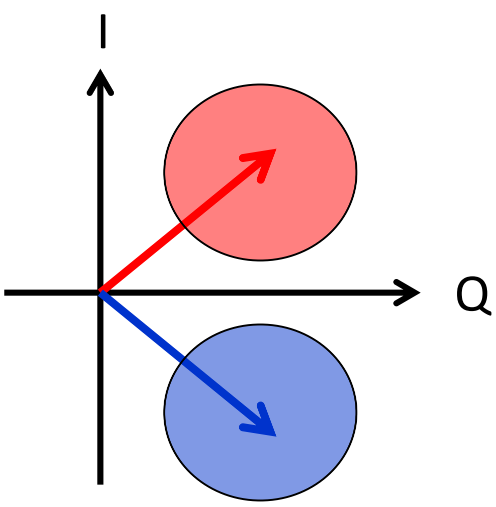
WEAK MEASUREMENT

QUBIT STATE ENCODED IN PHASE SHIFT



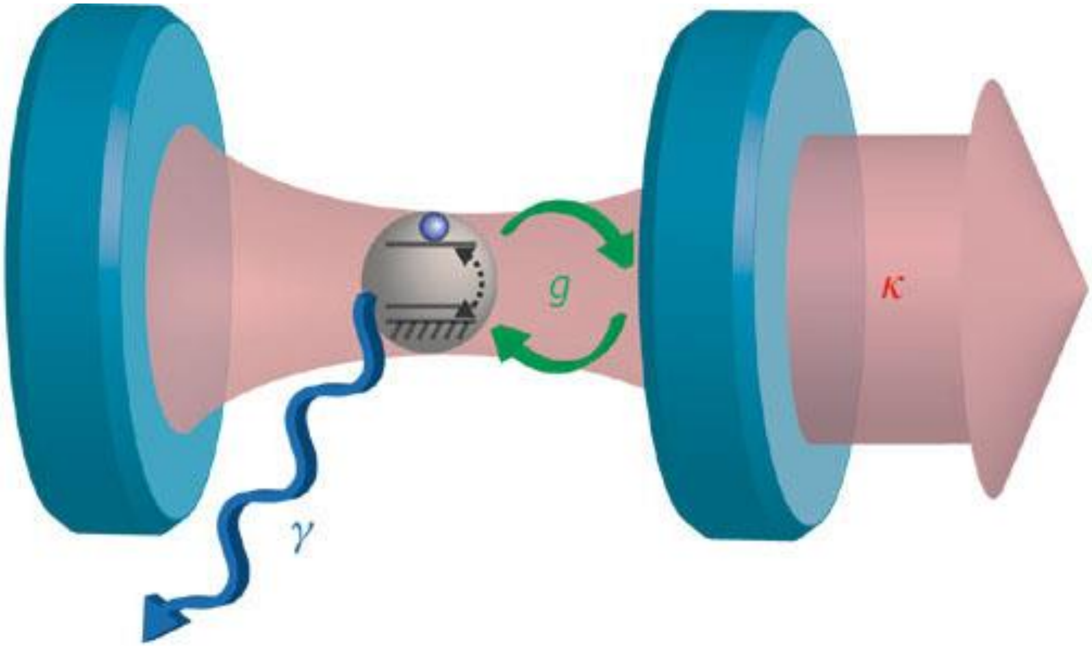


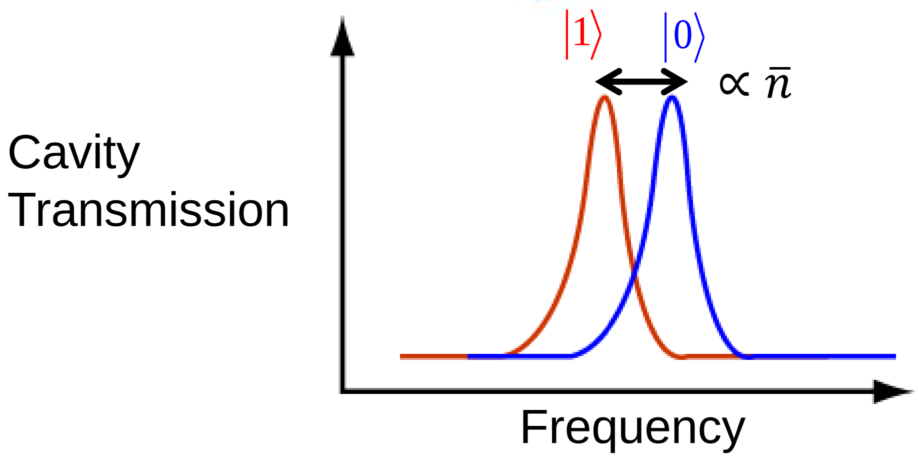
$$A\sin(\omega t+\phi) = A\sin(\omega t)\cos(\phi) + A\cos(\omega t)\sin(\phi)$$
$$= \underbrace{[A\cos(\phi)]}_{I}\sin(\omega t) + \underbrace{[A\sin(\phi)]}_{Q}\cos(\omega t)$$



PHASE SENSITIVE HOMODYNE MEASUREMENT

MEASUREMENT: COUPLE TO E-M FIELD OF CAVITY (Jaynes-Cummings)

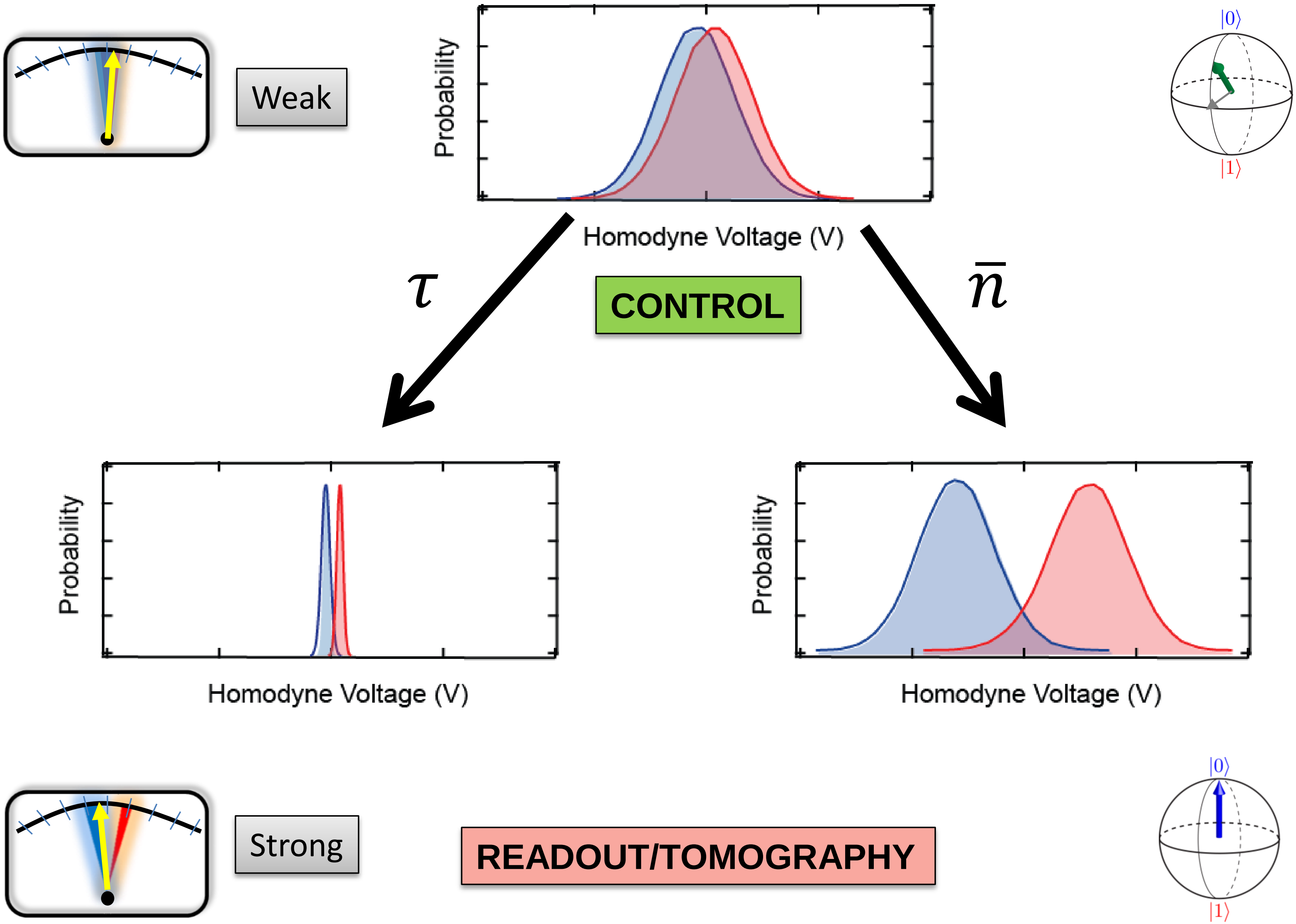




VARY MEASUREMENT STRENGTH USING DISPERSIVE SHIFT & PHOTON NUMBER

NEED TO DETECT ~ SINGLE MICROWAVE PHOTONS in T_1 ~ μs

STRONG vs. WEAK MEASUREMENT



MEASUREMENT STRENGTH

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

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

τ: measurement time

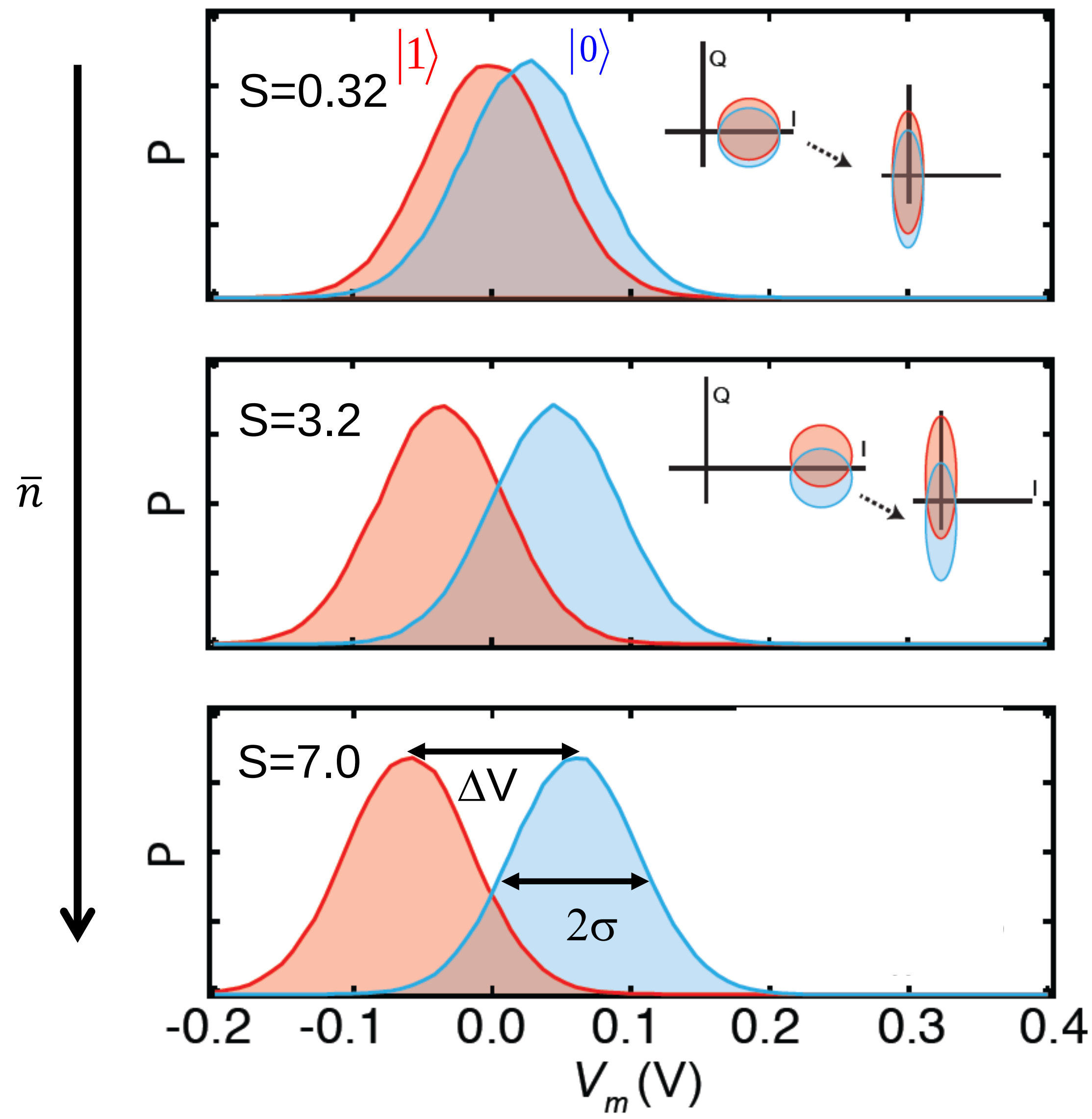
χ: dispersive shift

$\bar{n}$: photon number

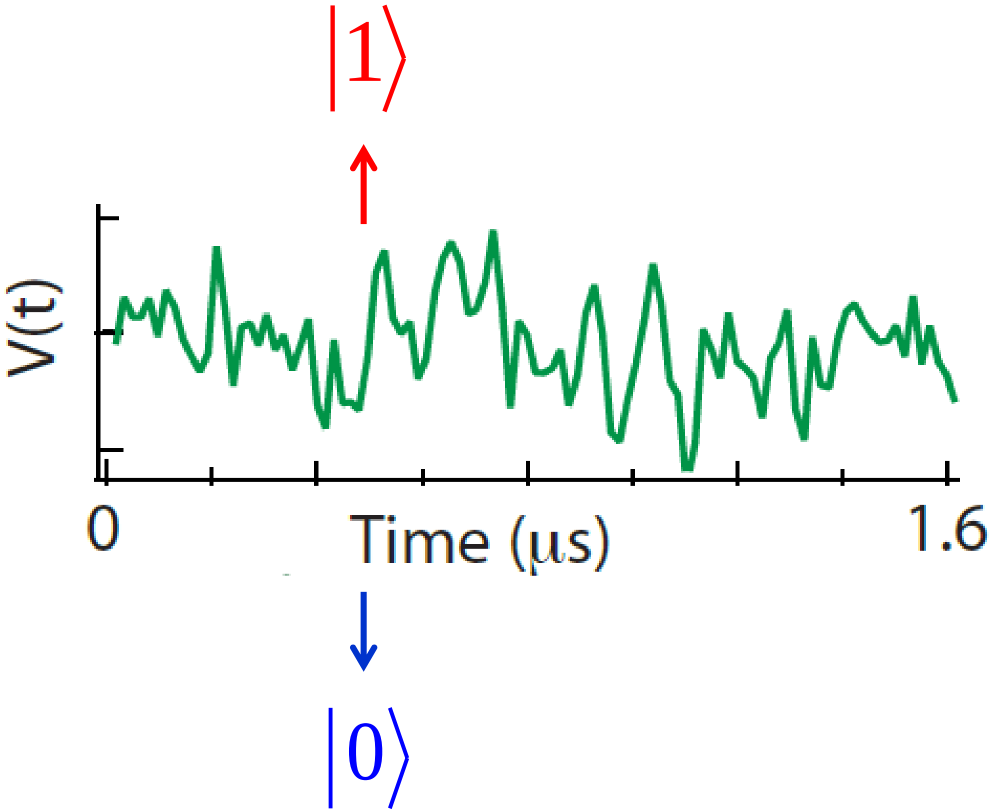
κ: cavity decay rate

η: detector efficiency

$$\eta = 0.49$$

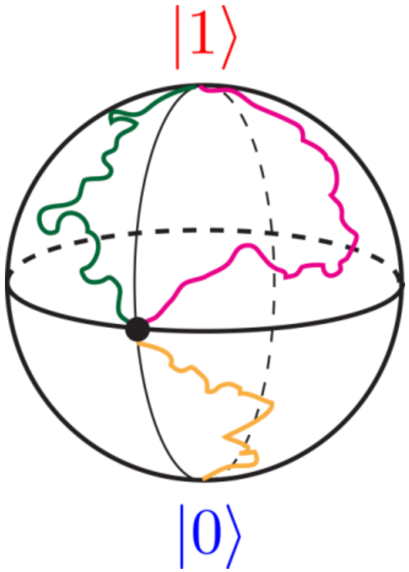


WHAT DO YOU DO WITH THIS WEAK MEASUREMENT SIGNAL?



- Control Signal for Feedback (eg. Stabilized Rab Osc.)
- Construct Trajectories
- Feed it to Another Qubit to Generate Entanglement

CAN WE TRACK A PURE STATE ON THE SURFACE OF THE BLOCH SPHERE?

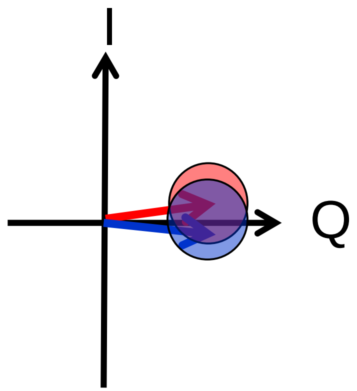


OBSERVING SINGLE QUANTUM TRAJECTORIES OF A SUPERCONDUCTING QUBIT

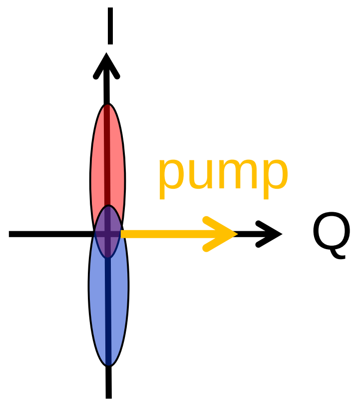
K. Murch et al., *Nature* **502**, 211 (2013).

BACKACTION OF SINGLE QUADRATURE MEASUREMENT

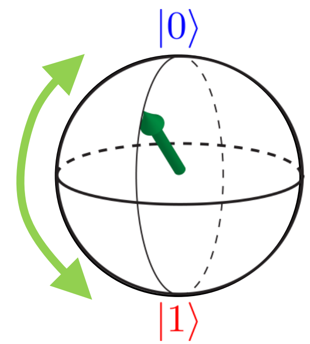
Cavity Output $\theta=0$



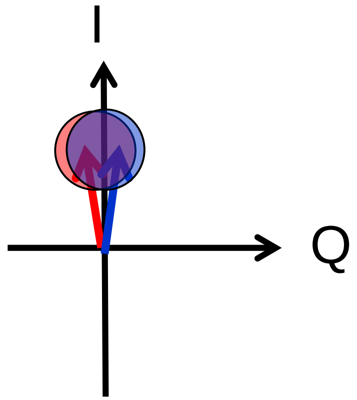
After Amplification $\theta=0$



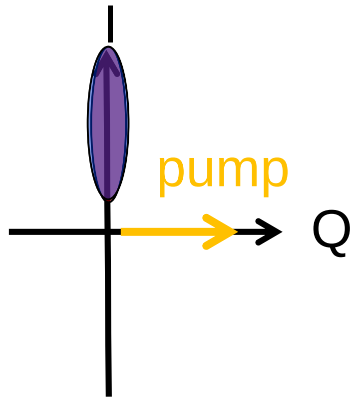
- Obtain qubit state information
- Tip Bloch vector



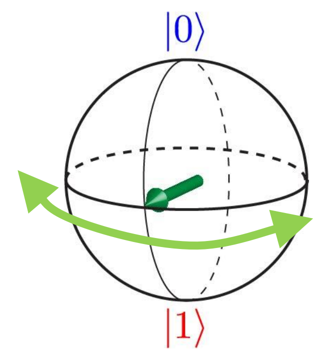
Cavity Output $\theta=\pi/2$



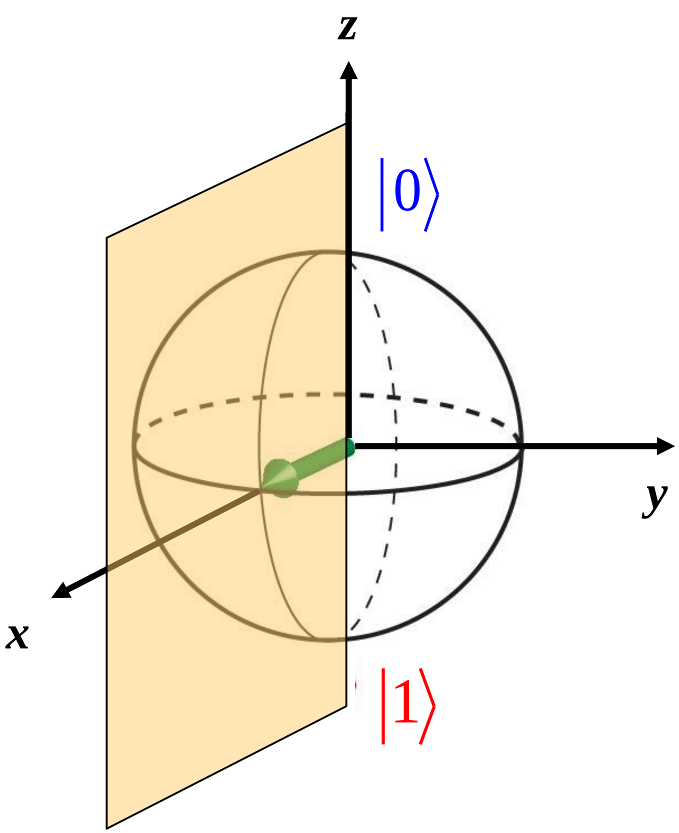
After Amplification $\theta=\pi/2$

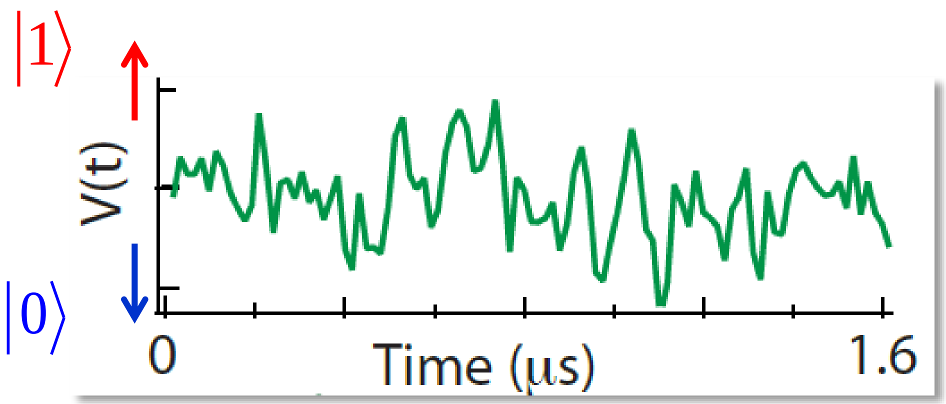


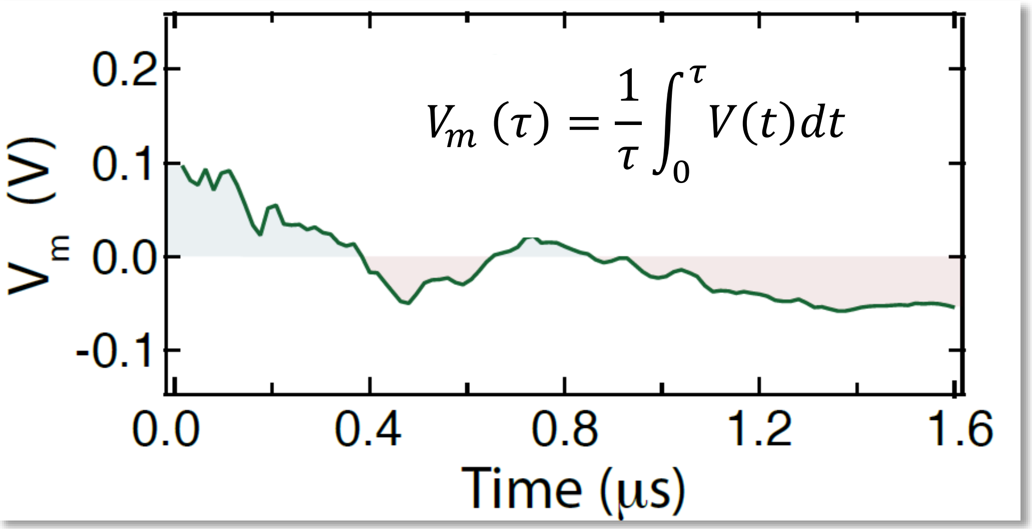
- Obtain cavity photon number information
- Rotate Bloch vector



INDIVIDUAL TRAJECTORIES







- Prepare state along $+x$
- Continuous weak measurement
- Integrated readout is trajectory

BAYESIAN UPDATE

Event:

A = Avalanche S = Snow > 10 feet

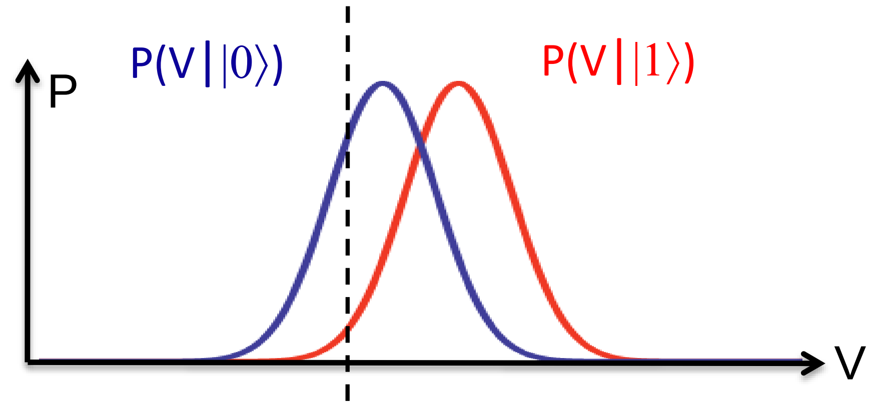
Likelihood: Prob. snow accompanied avalanche

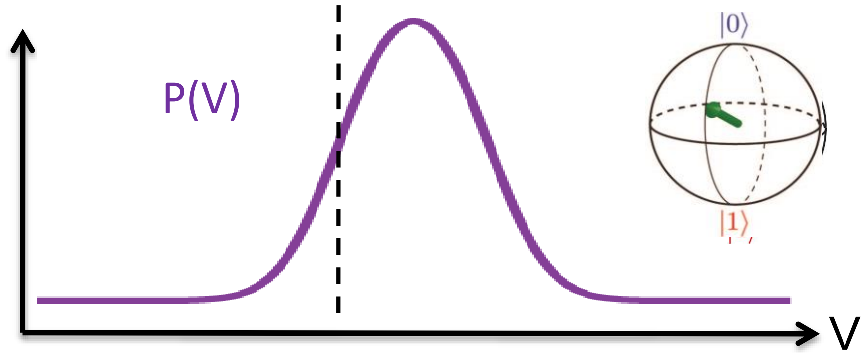
Prior: Historic chance of an avalanche

$$\underbrace{P(A|S)} = \frac{P(S|A)P(A)}{P(S)}$$

Posterior: Chance of an avalanche given snow

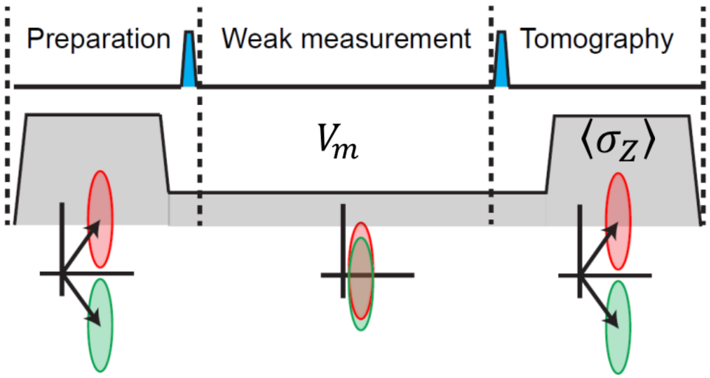
Prob. of Snow



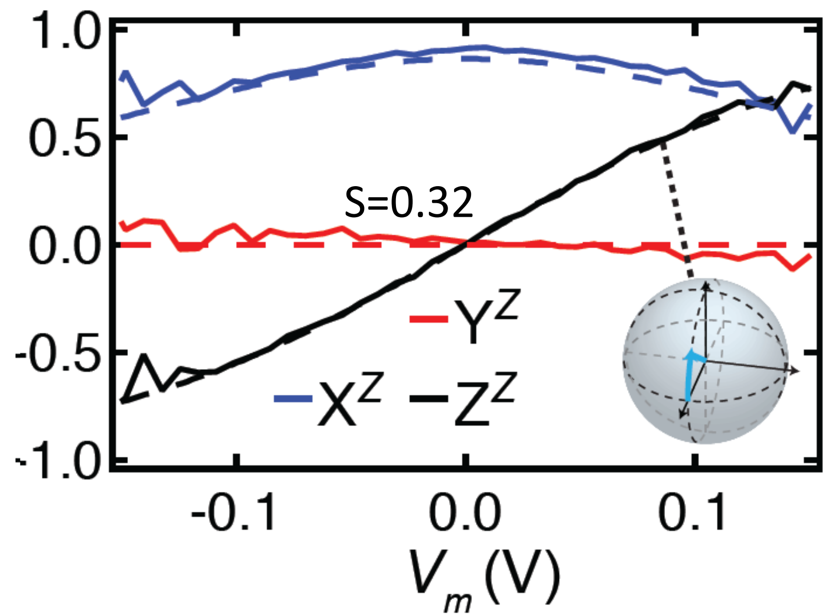


$$P(|0\rangle \mid V) = \frac{P(V \mid |0\rangle)\, P(|0\rangle)}{P(V)}$$

WEAK MEASUREMENT OF THE QUBIT STATE



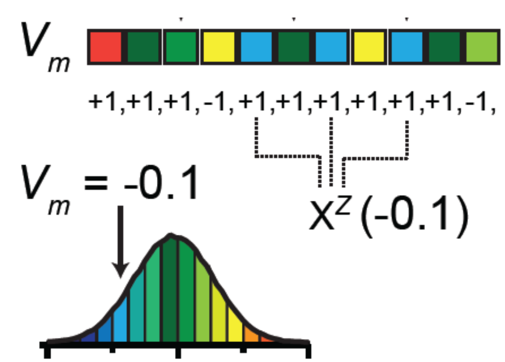
- Initial state along +X
- Measure Z (phase quadrature)



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:



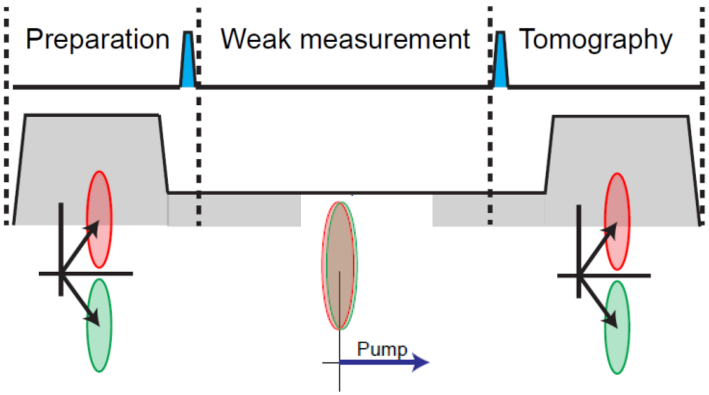
BAYES RULE:

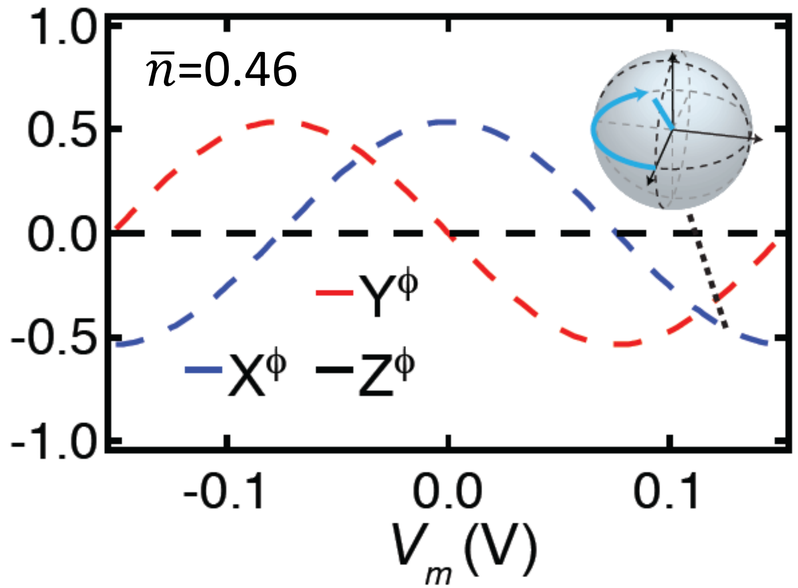
$$Z^Z = \tanh\left(\frac{V_m S}{2\Delta V}\right)$$

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

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

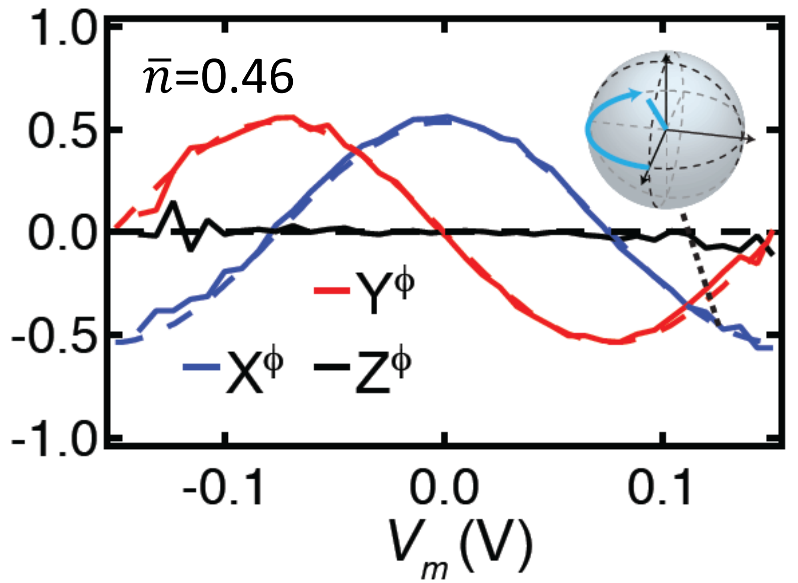
WEAK MEASUREMENT OF THE PHOTON NUMBER





WANT TO EVALUATE:

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



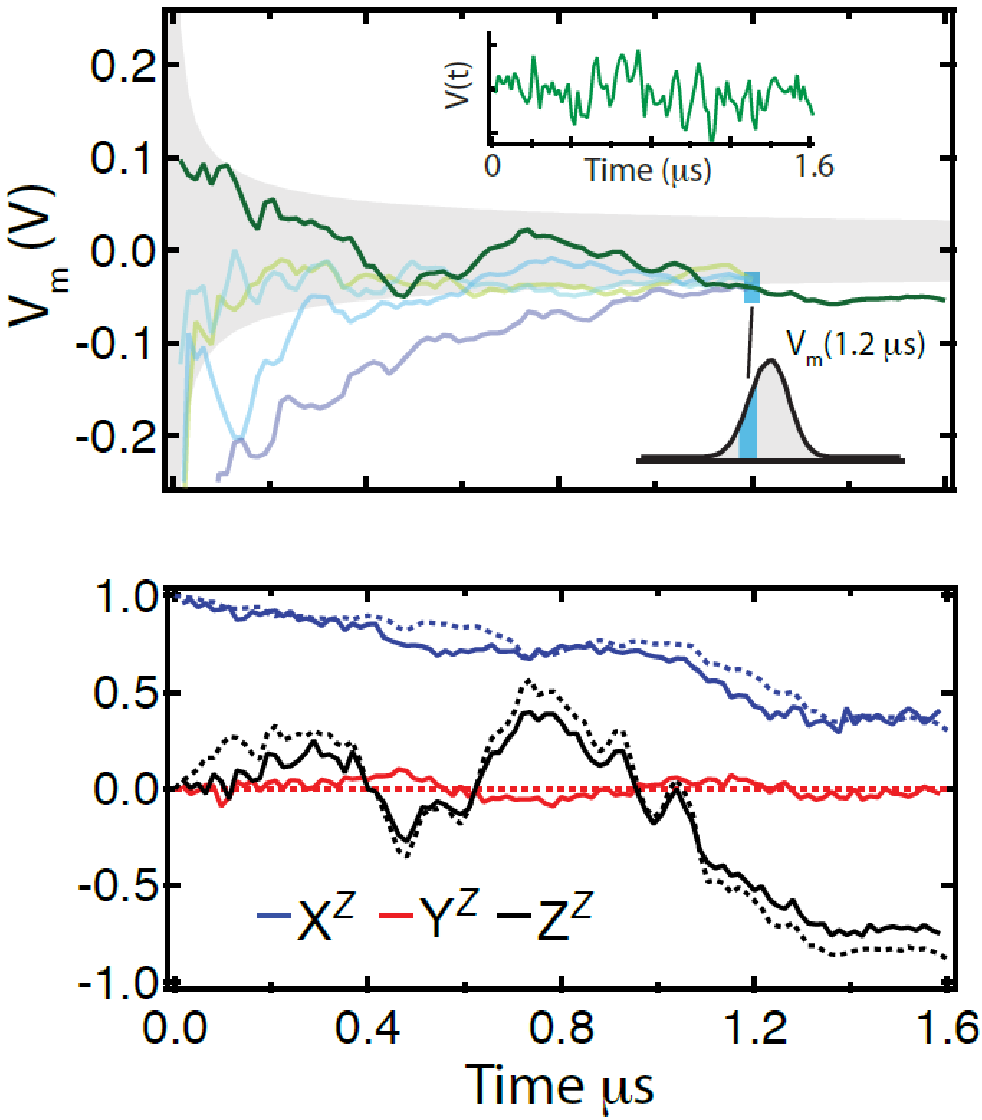
BAYES RULE:

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

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

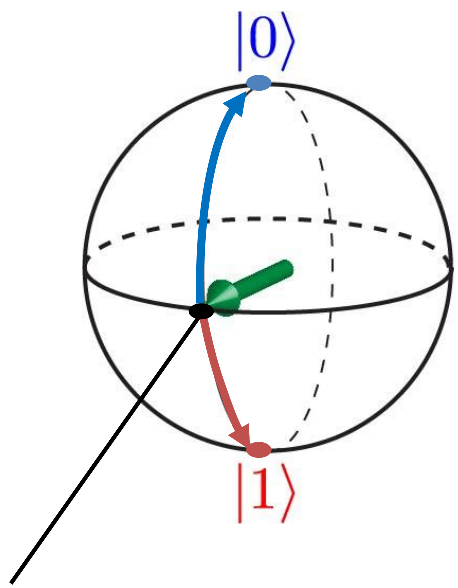
REALTIME TRACKING

- Prepare qubit along X axis
- Evolve under measurement
- Use Bayes rule to update our guess of the qubit state (dots)
- Perform tomography for each time step (solid)

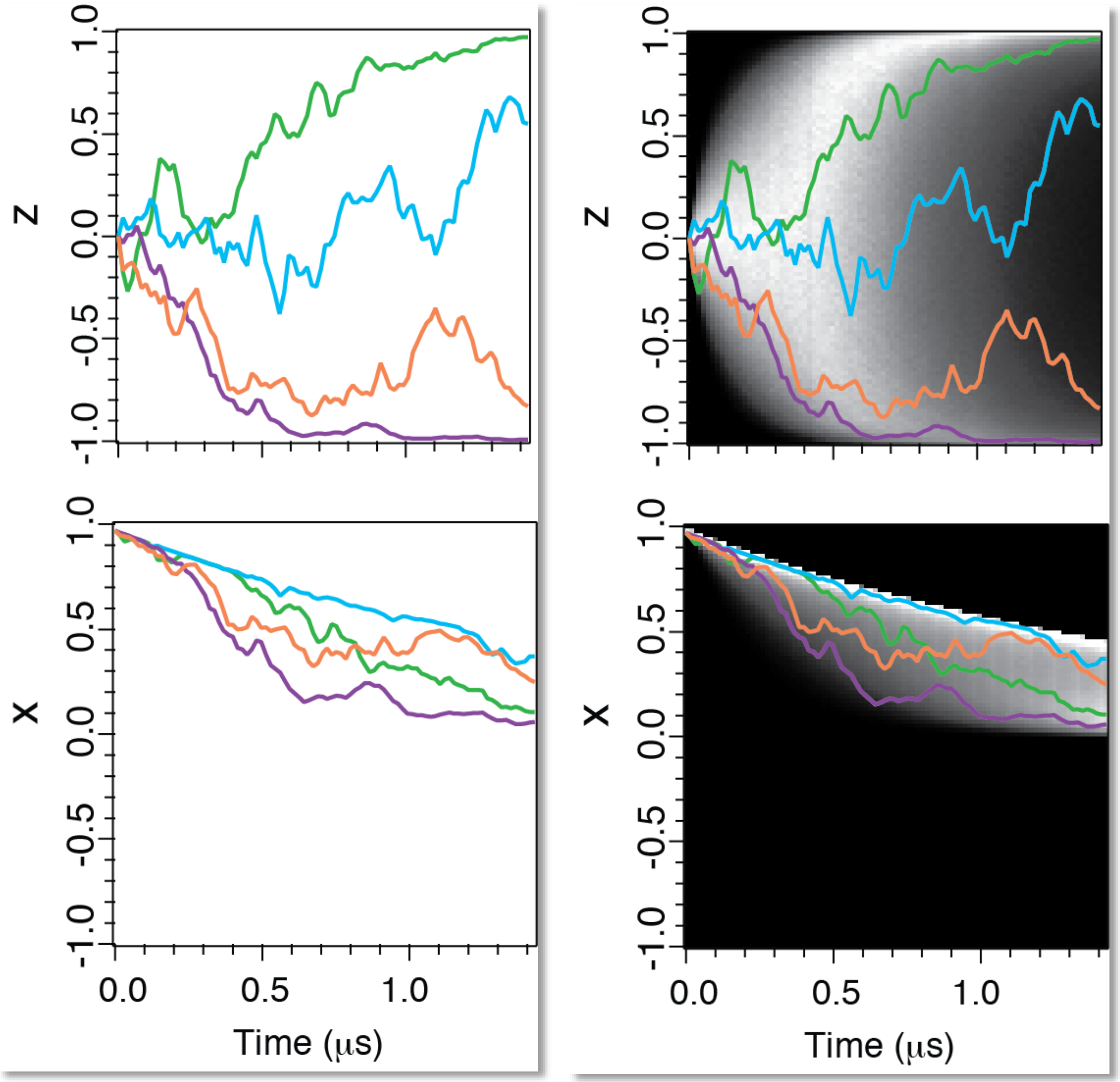


DISTRIBUTION OF QUANTUM TRAJECTORIES

MEASUREMENT INDUCED DYNAMICS ONLY

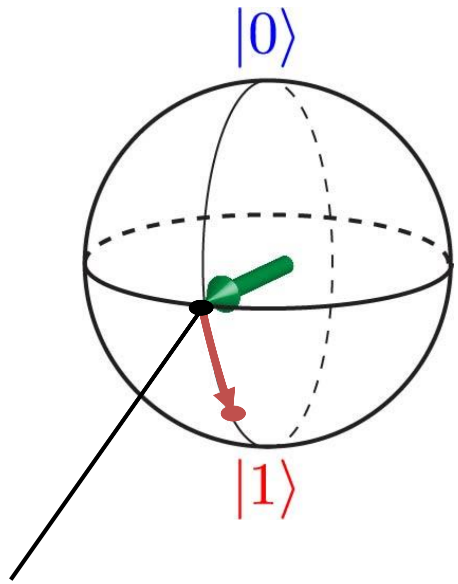


Initial State along $+x$

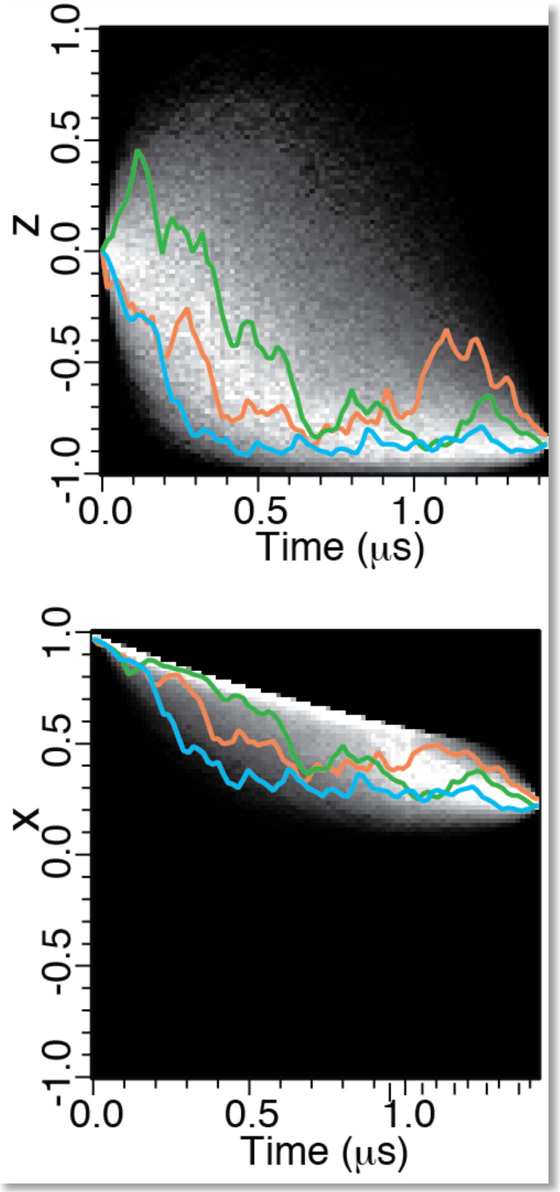


Integration time τ needed to resolve state: 1.25 μs

MEASUREMENT w. POSTSELECTION



Initial State along $+x$
Final State at z = -0.85



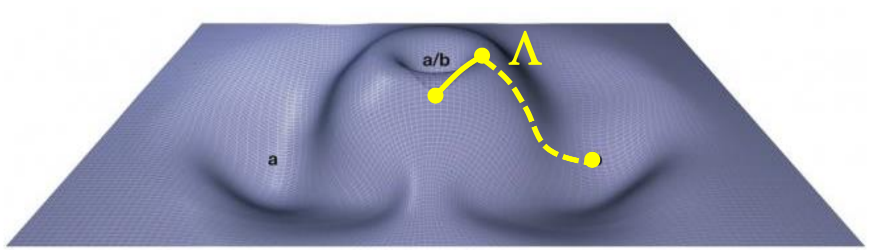
Can Identify Most Likely Path

Predict with Theory?

EXTREMIZING THE QUANTUM ACTION

Classical Example: Kramer's Escape

- Consider paths to saddle point Λ
- Establish canonical phase space (p,q)
- Define action *S*
- Calculate most favorable path, etc…



Quantum Case for Pre/Post-Selected Trajectories:

A. Chantasri, J. Dressel, A.N. Jordan, *PRA* 2013

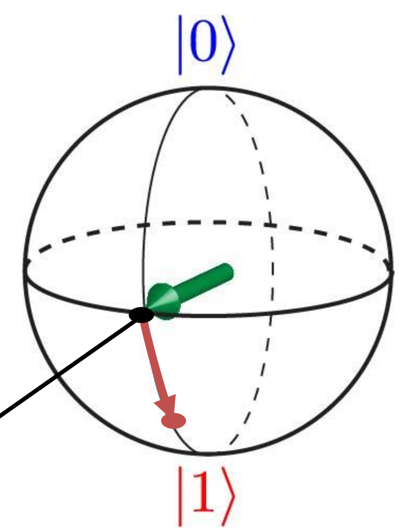
- Consider paths connecting quantum state $\boldsymbol{q}_I \rightarrow \boldsymbol{q}_F$
- Double quantum state space (→ canonical)
- Express joint probability of measurement & trajectories as path integral
- Minimize action → ODE for equation of motion

$$\mathcal{P} = \delta^d(\boldsymbol{q}_0 - \boldsymbol{q}_I)\delta^d(\boldsymbol{q}_n - \boldsymbol{q}_F)\prod_{k=0}^{n-1} P(\boldsymbol{q}_{k+1}, r_k|\boldsymbol{q}_k).$$

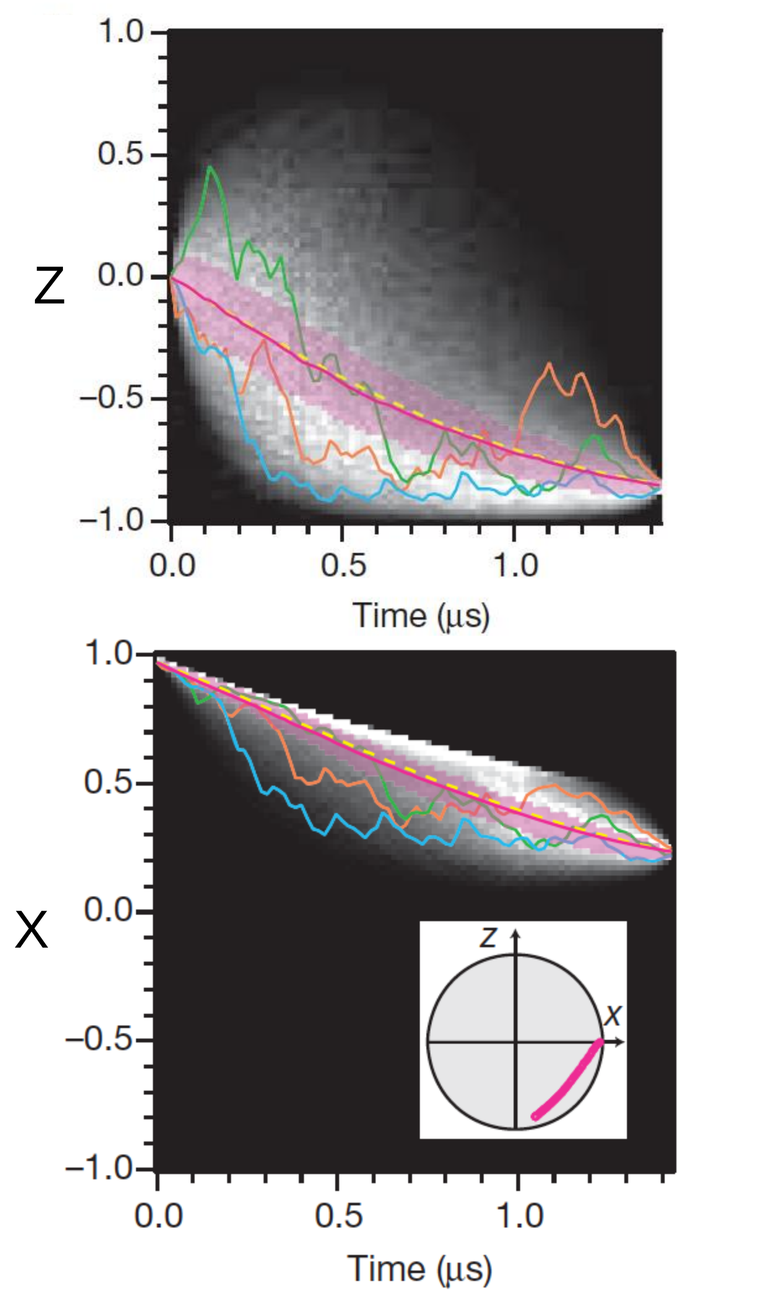
$$\mathcal{P} = \int \mathcal{D}\boldsymbol{p}\, e^{\mathcal{S}} = \int \mathcal{D}\boldsymbol{p}\, \exp\left[\int_0^T \mathrm{d}t\left(-\boldsymbol{p}\cdot\dot{\boldsymbol{q}} + \mathcal{H}[\boldsymbol{q},\boldsymbol{p},r]\right)\right]$$

- Calculate statistical distributions
- Treat case of measurement backaction with control pulses **Ω** (Schrödinger dynamics)

MEASUREMENT w. POSTSECLECTION: THEORY



Initial State along $+x$
Final State at $z = -0.85$



<u>EOM for Optimized Path</u>

$$\dot{x} = -\gamma x + \Omega z - xzr/\tau,$$

$$\dot{z} = -\Omega y + (1 - z^2)r/\tau,$$

$$\dot{p}_x = \gamma p_x + \Omega p_z + p_x z r/\tau,$$

$$\dot{p}_z = -\Omega p_z + (p_x x + p_y y + 2p_z z - 1)r/\tau,$$

<u>No Driving (Ω=0)</u>

$$\bar{x}(t) = e^{-\gamma t}\mathrm{sech}(\bar{r}t/\tau)$$

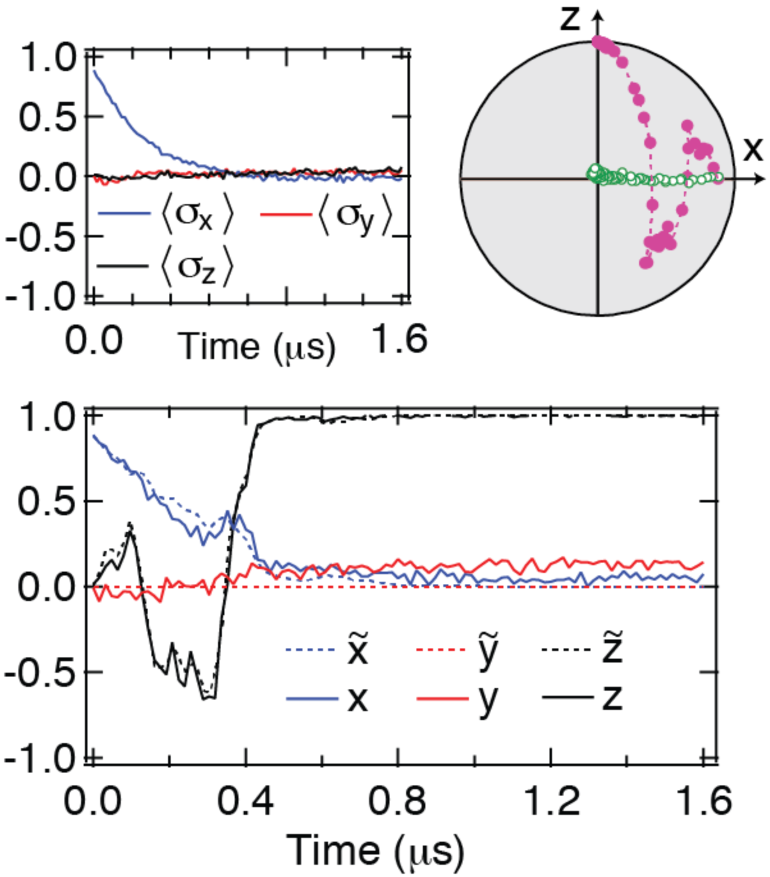
$$\bar{z}(t) = \tanh(\bar{r}t/\tau)$$

r: detector output
max likelihood

QUANTUM TRAJECTORIES

WITH RABI DRIVING

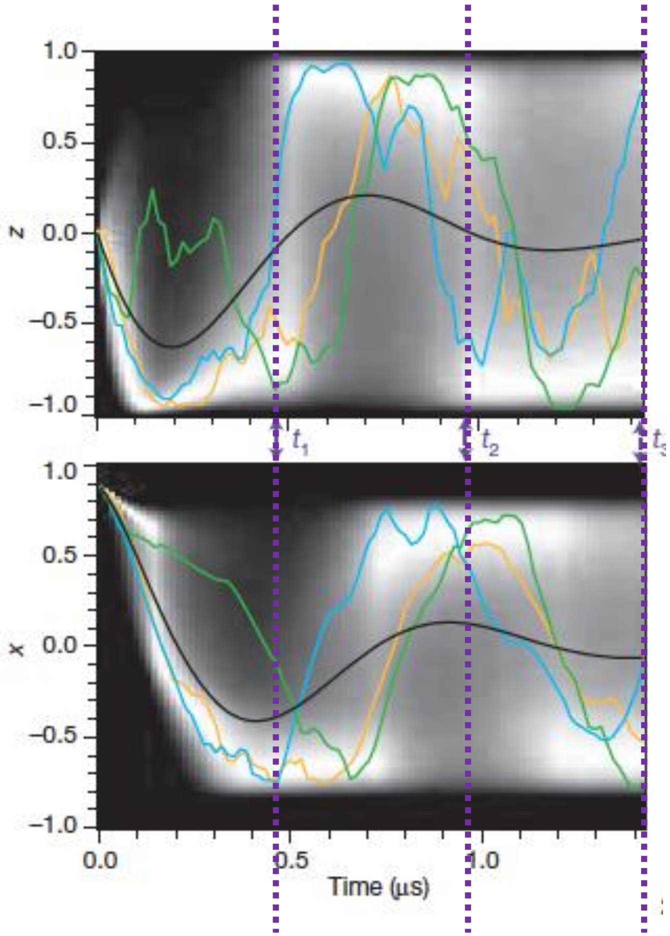
TRAJECTORIES w. RABI DRIVE: TOMOGRAPHY



NO RABI DRIVE

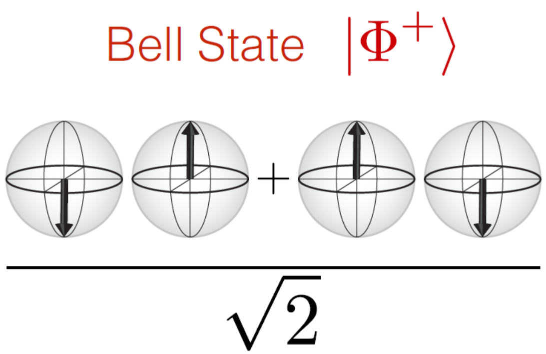
- Trajectories w. Rabi drive: two step update (master eqn. + Bayes)
- Individual trajectories show “high purity”

DISTRIBUTION OF RABI TRAJECTORIES



Excellent agreement with ODE solutions

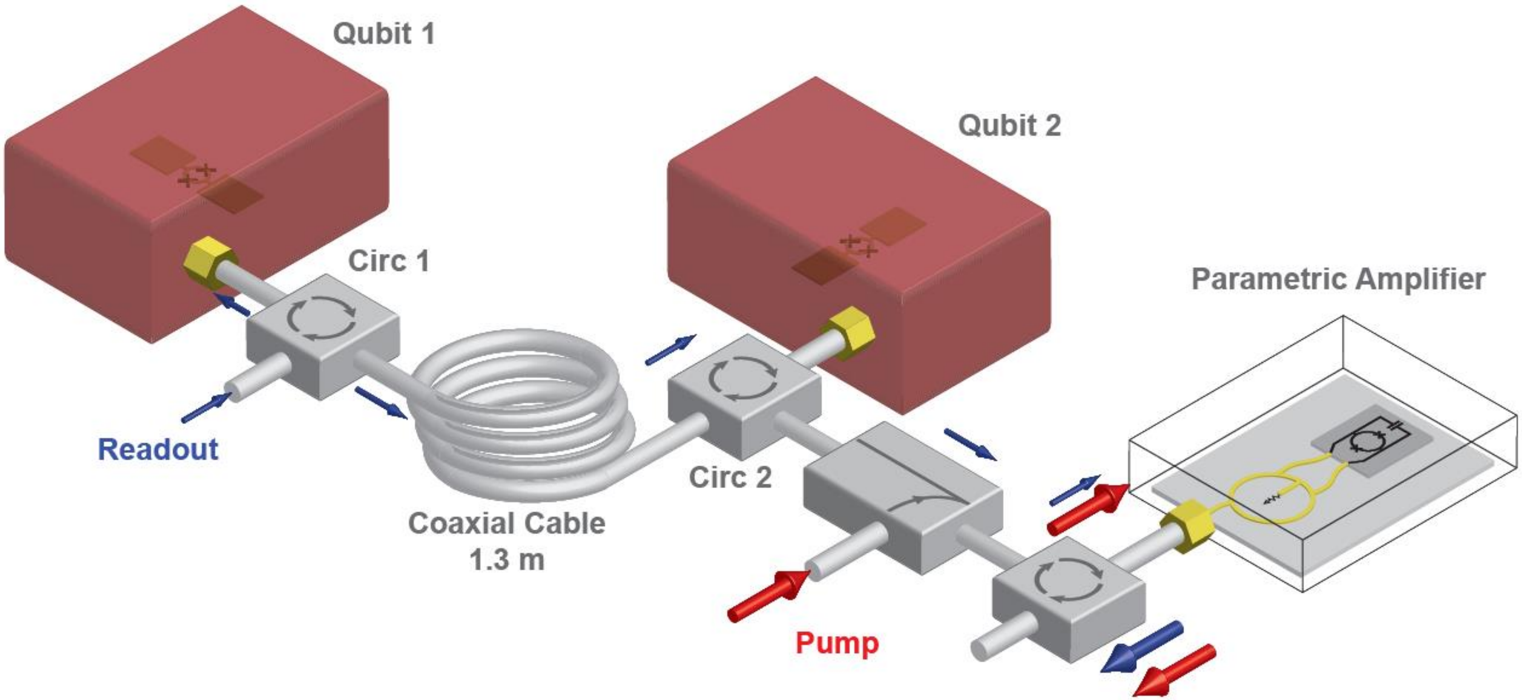
CAN WE ENTANGLE TWO REMOTE SUPERCONDUCTING QUBITS via MEASUREMENT ?



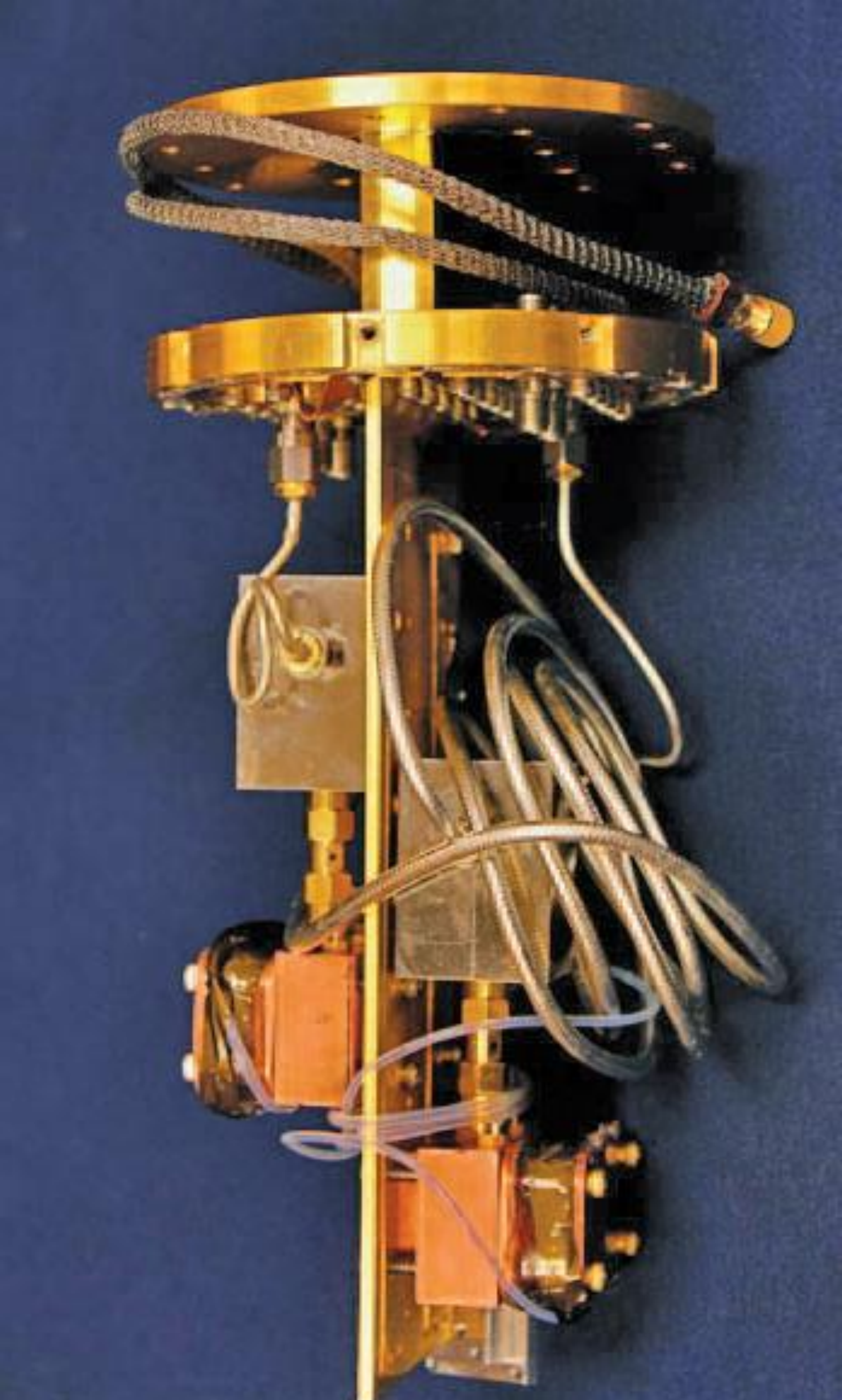
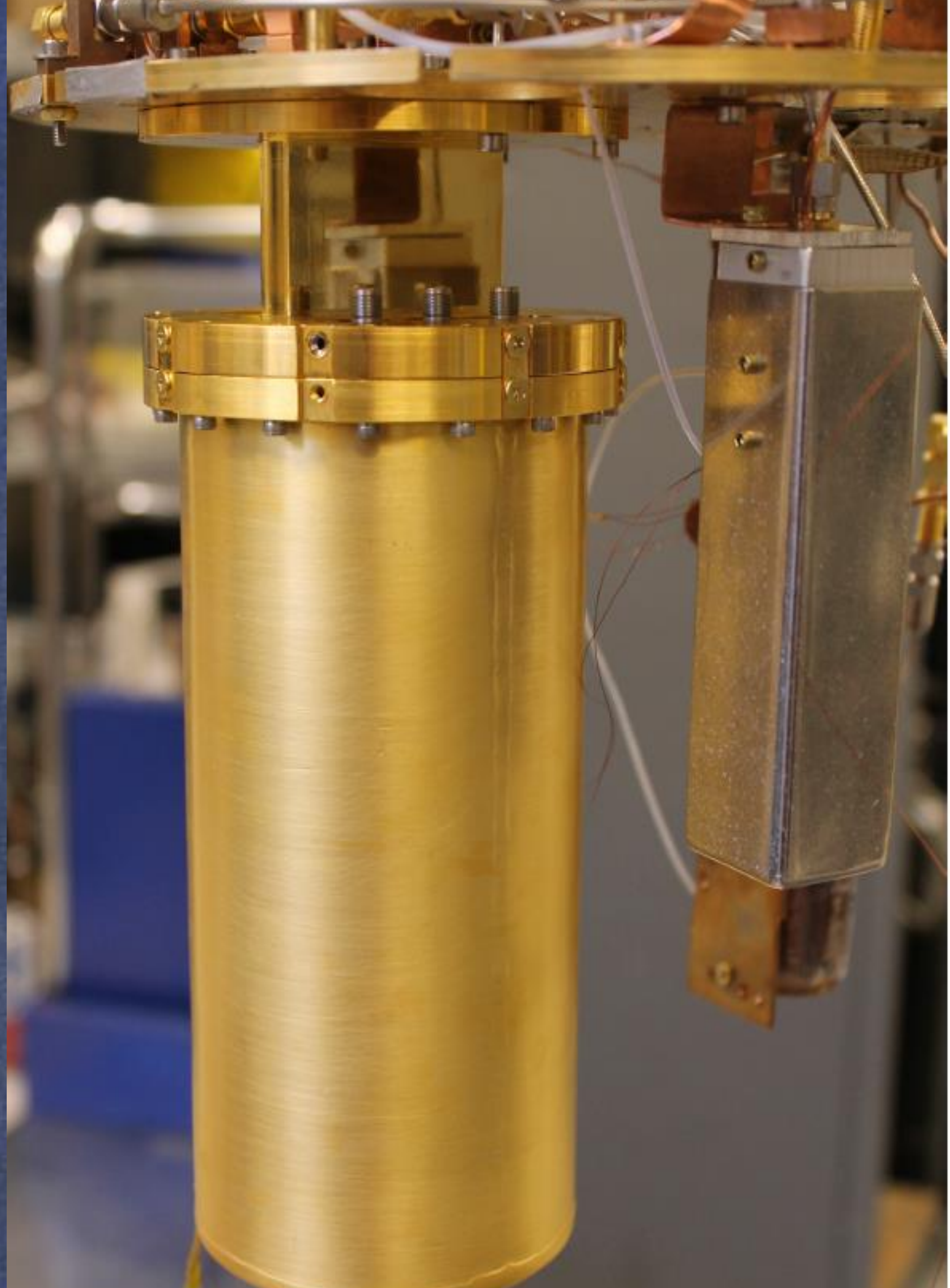
“TRACKING ENTANGLEMENT GENERATION BETWEEN TWO SPATIALLY SEPARATED SUPERCONDUCTING QUBITS”

N. Roch et al., *PRL* **112**, 170501, 2014

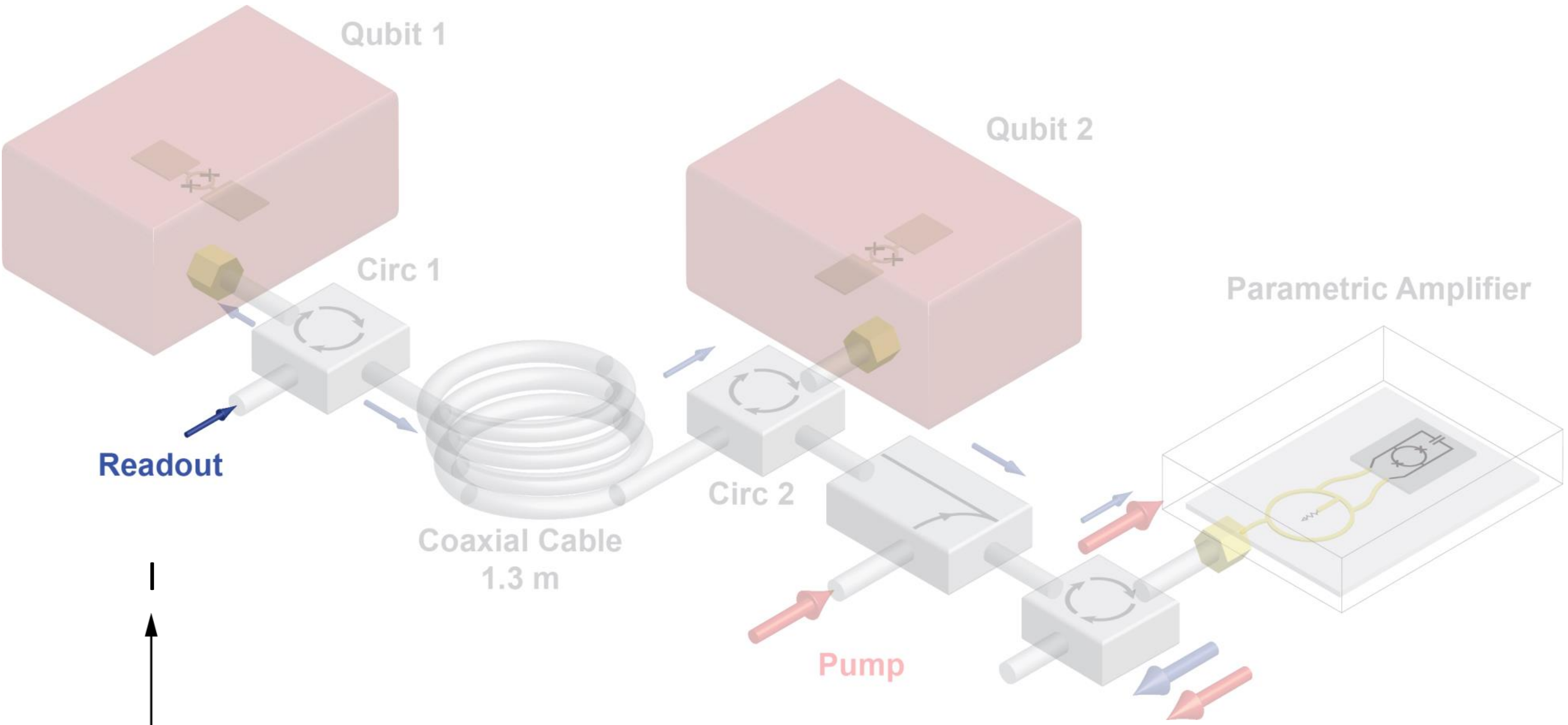
TWO DISTANT QUBITS

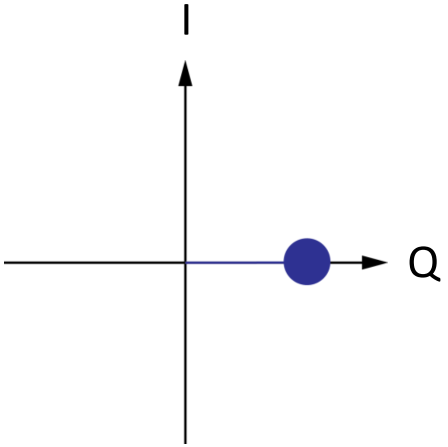


Theoretical proposal:
Kerckoff, Bouten, Silberfarb & Mabuchi,
Phys Rev A (2009)

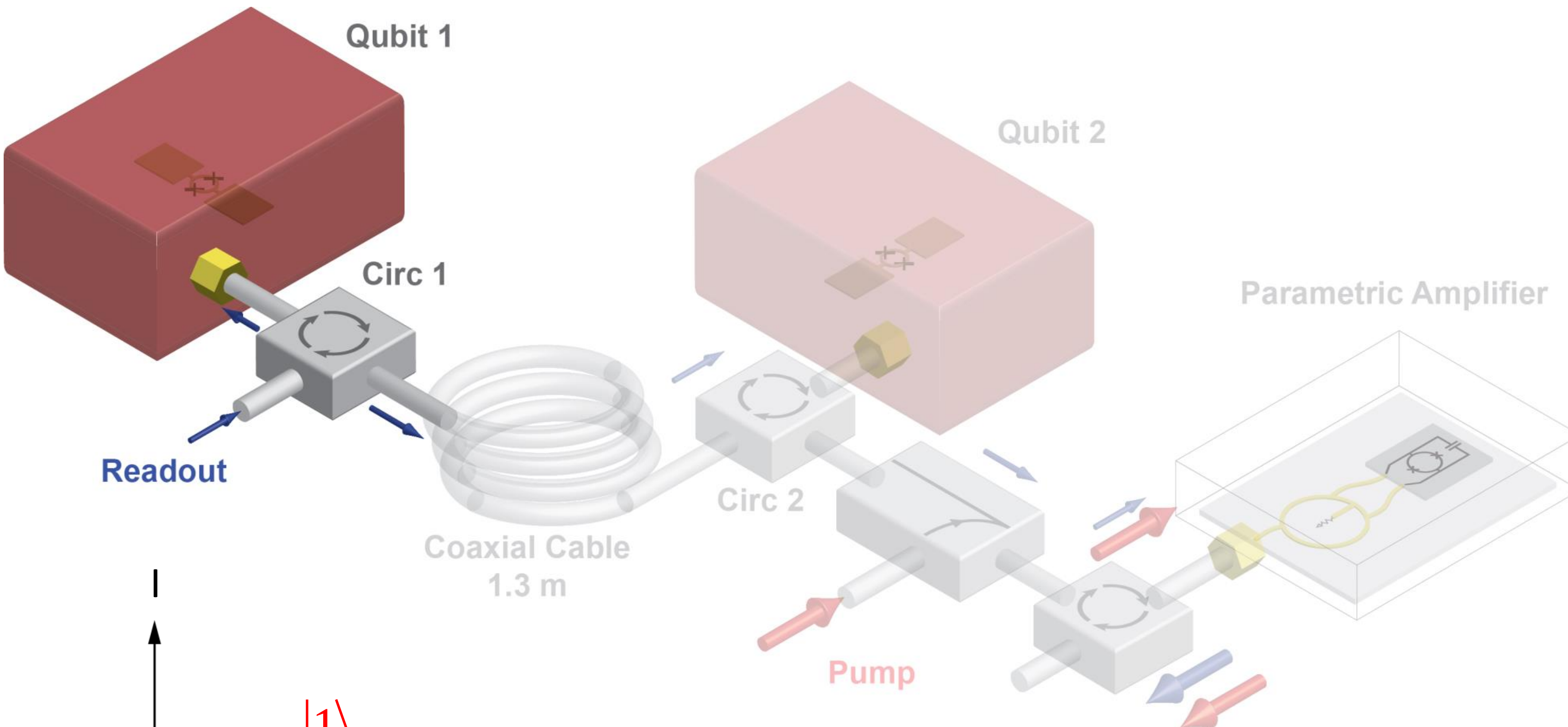
JOINT DISPERSIVE MEASUREMENT

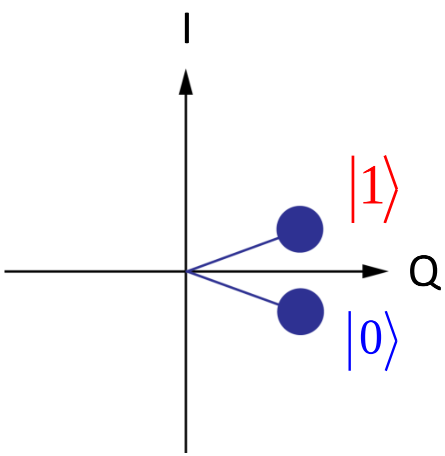




Theory Proposal:
Kerckhoff et al., **Phys Rev A** 2009

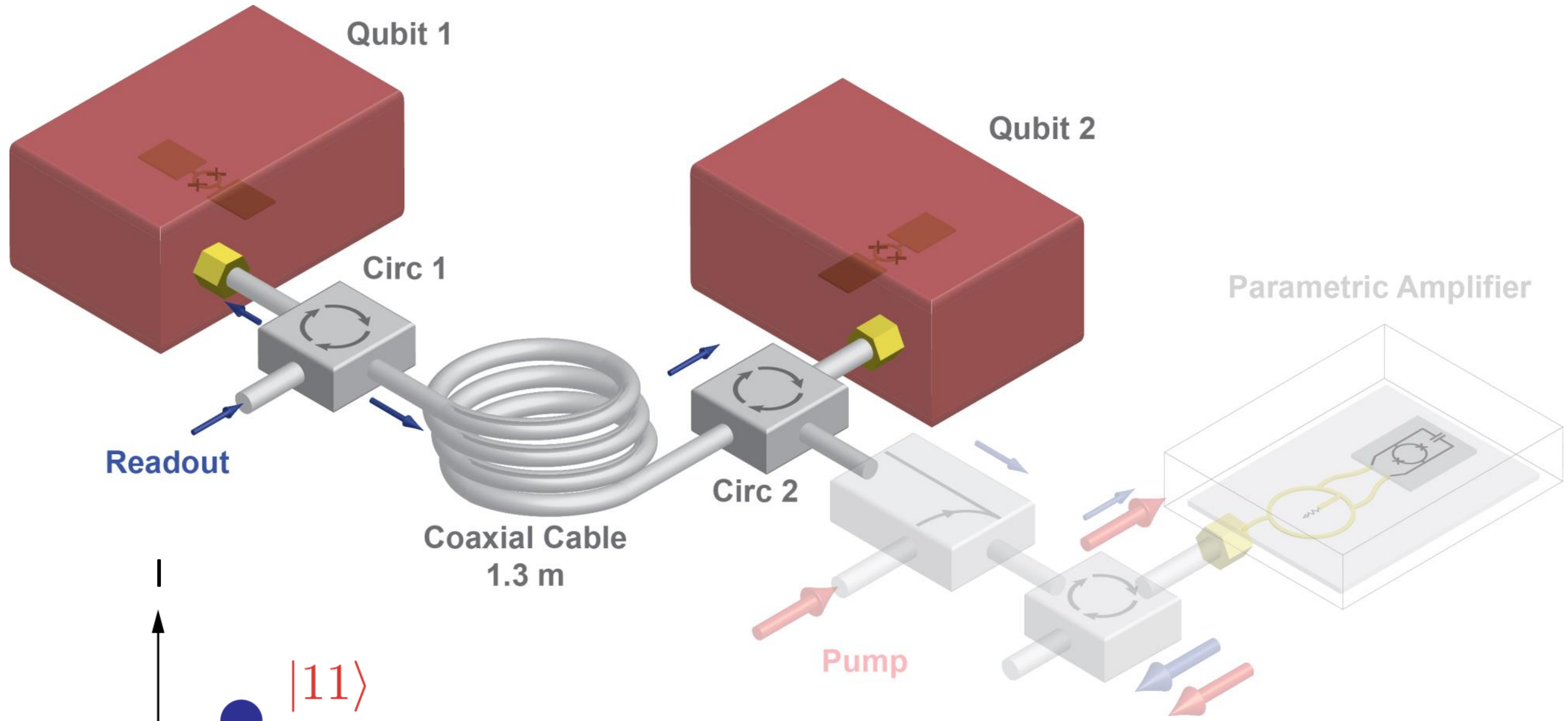
JOINT DISPERSIVE MEASUREMENT

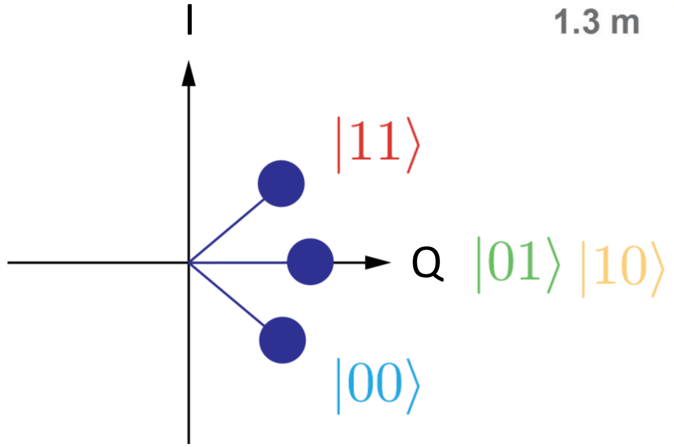




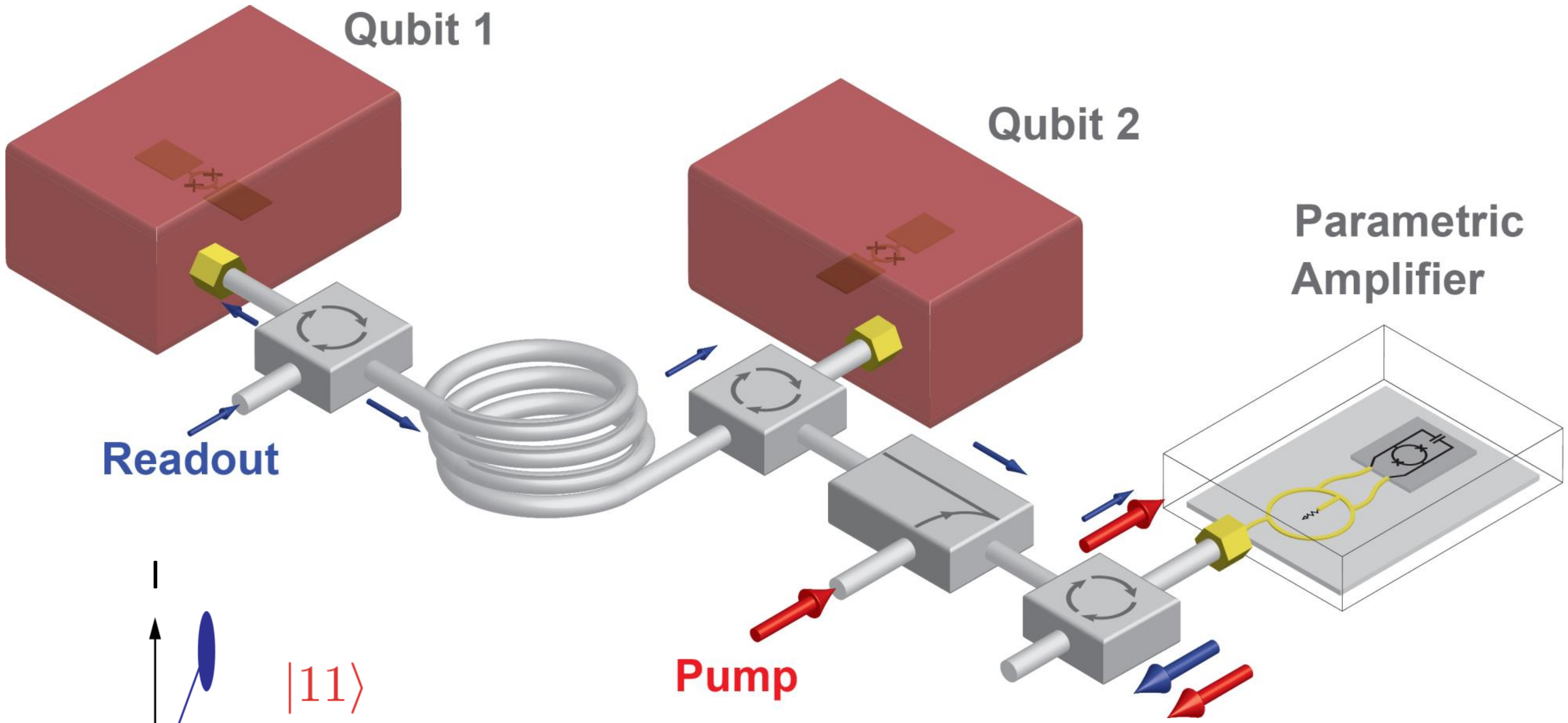
Theory Proposal:
Kerckhoff et al., **Phys Rev A** 2009

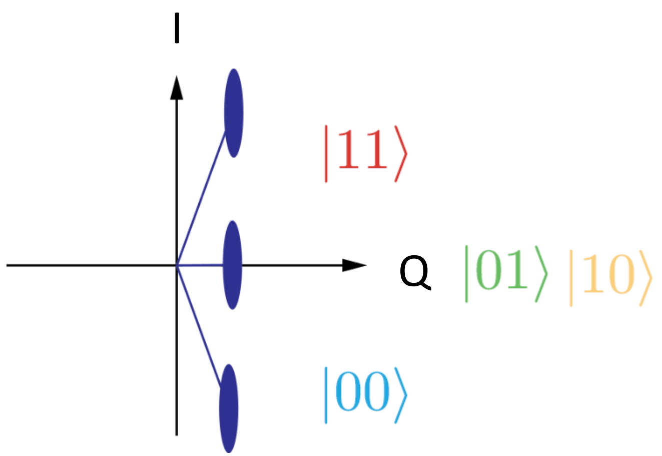
JOINT DISPERSIVE MEASUREMENT



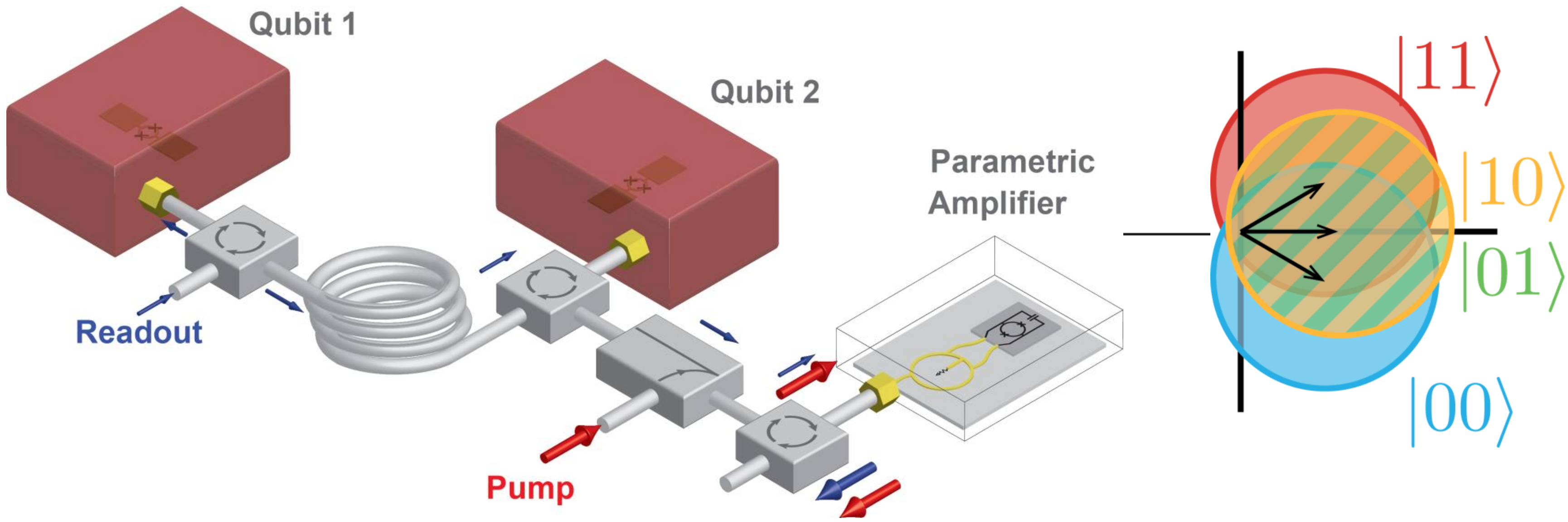


JOINT DISPERSIVE MEASUREMENT





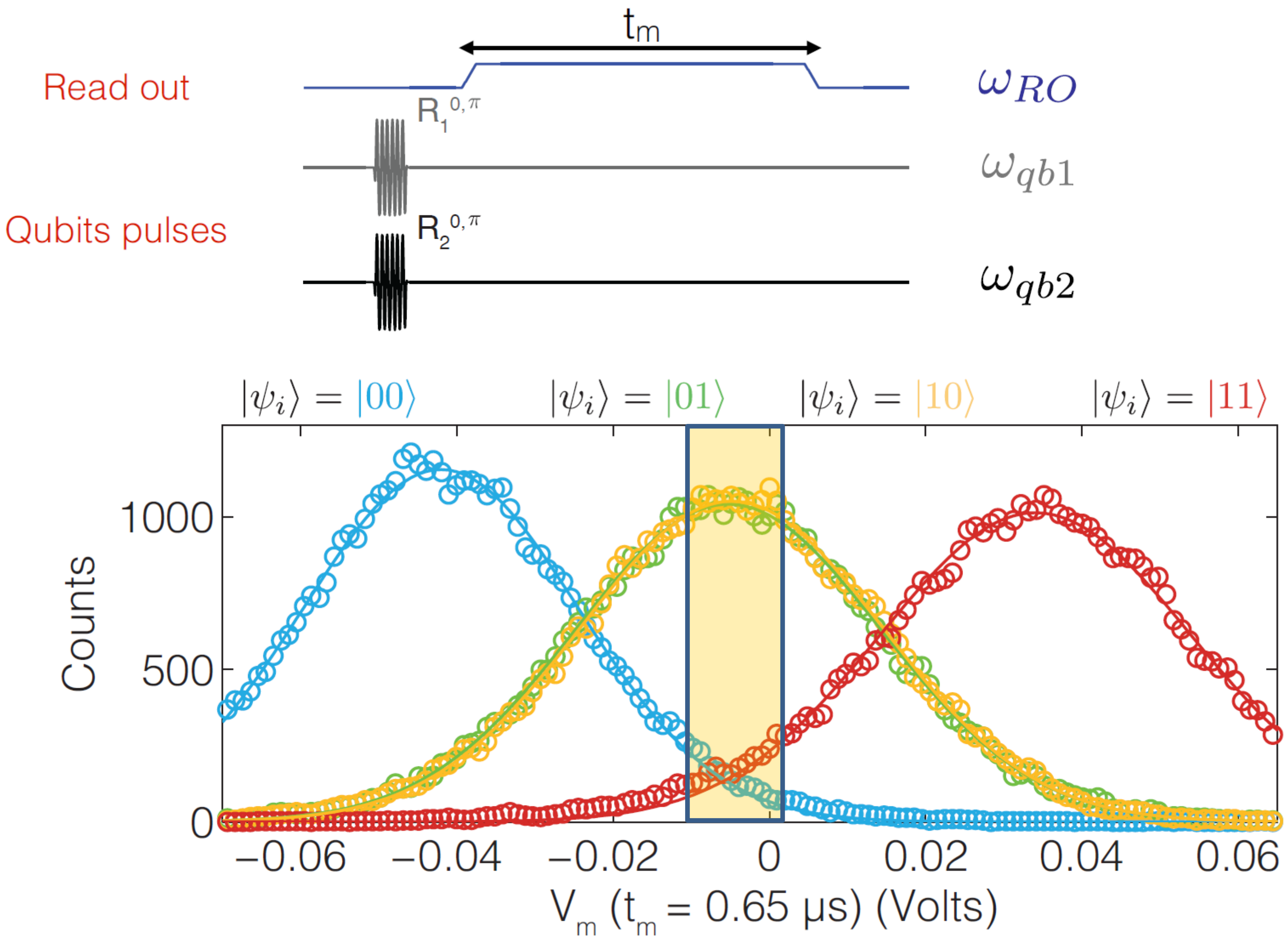
WEAK CONTINUOUS MEASUREMENT



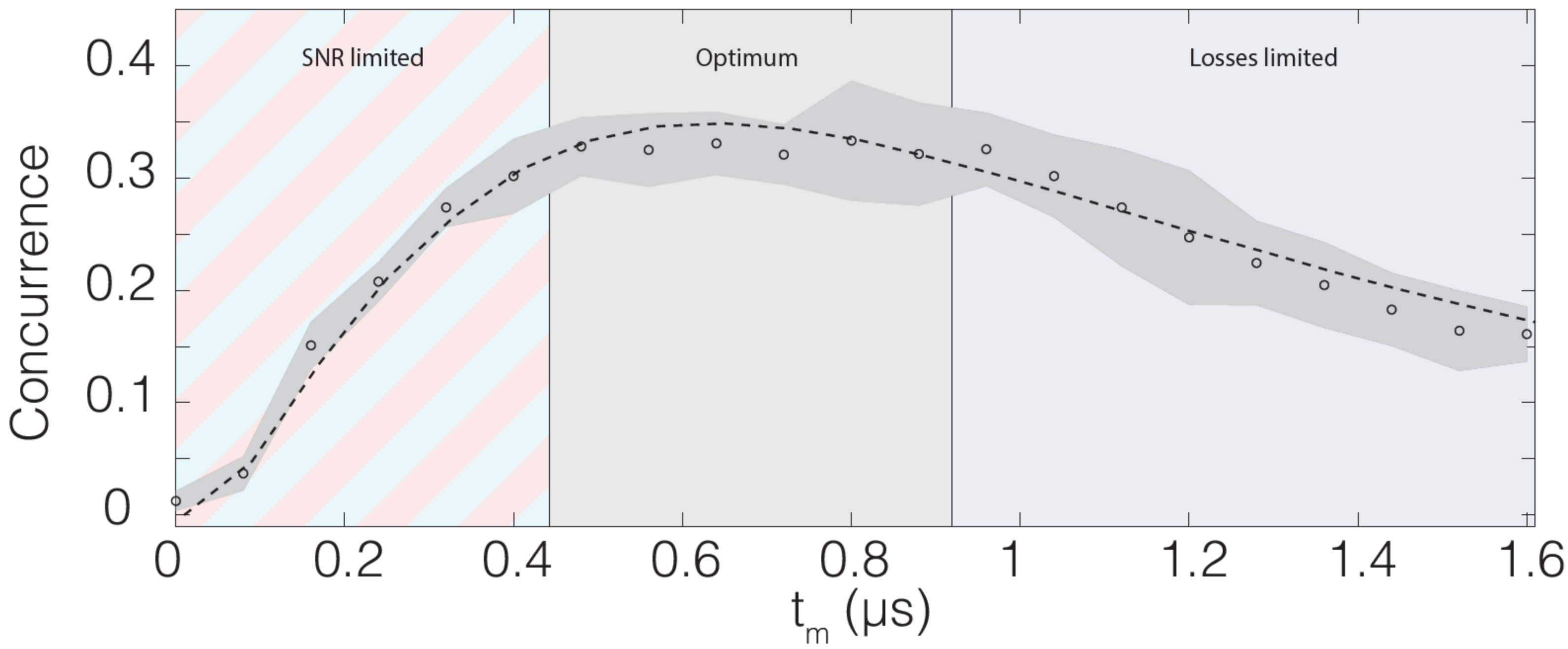
No classical OR quantum observer can discriminate eigenstates; system is perturbed, but not projected, by measurement.

Hatridge et al., **Science** 2013

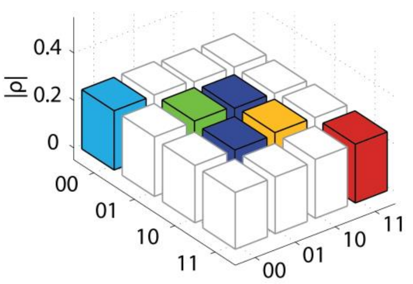
MEASUREMENT HISTOGRAMS

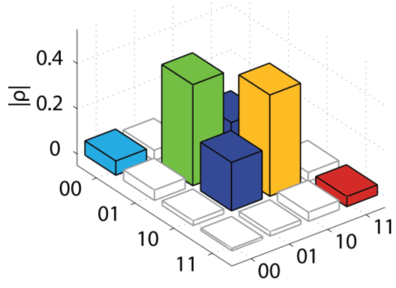


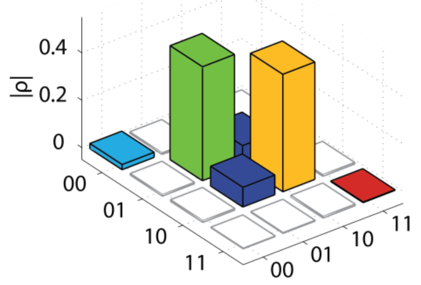
MEASUREMENT INDUCED ENTANGLEMENT



Quantifying the entanglement: $\mathcal{C} = \max(0, |\rho_{01,10}| - \sqrt{\rho_{00,00}\rho_{11,11}})$

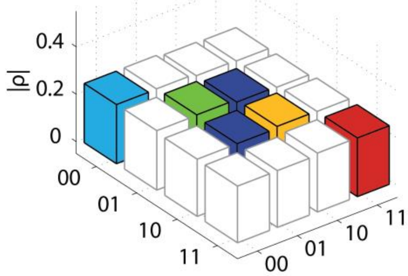


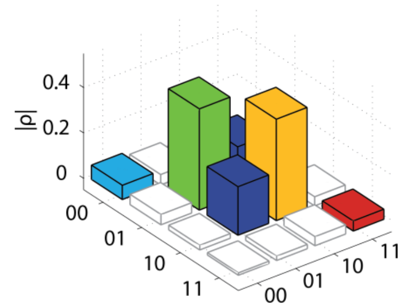




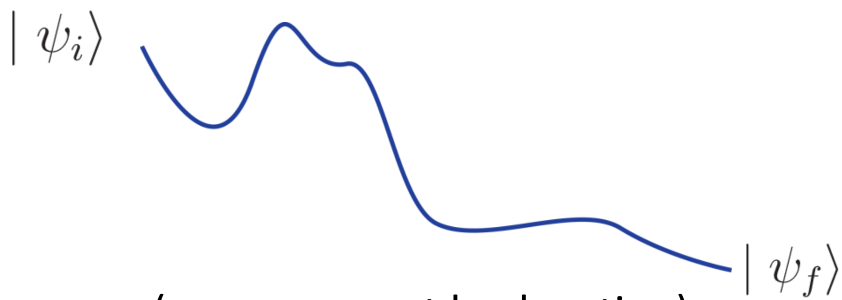
TRAJECTORIES

Ensemble measurements:





Single experimental realization:

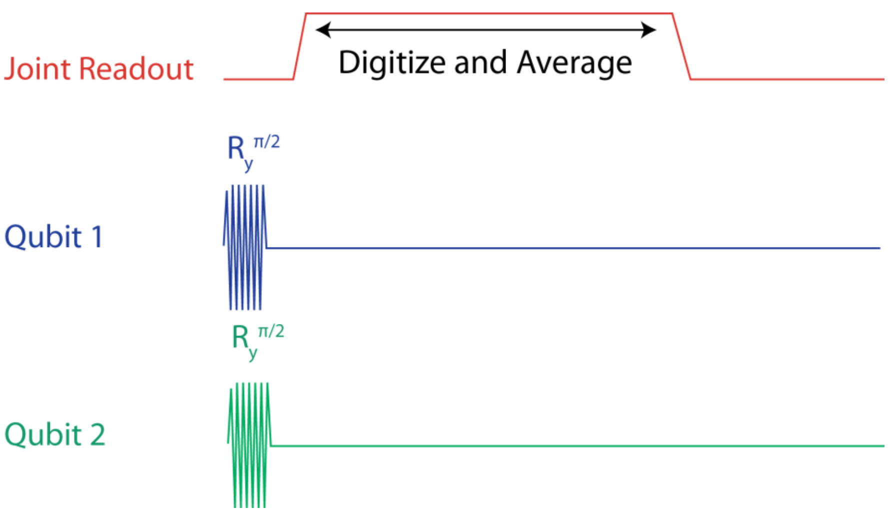


(measurement back-action)

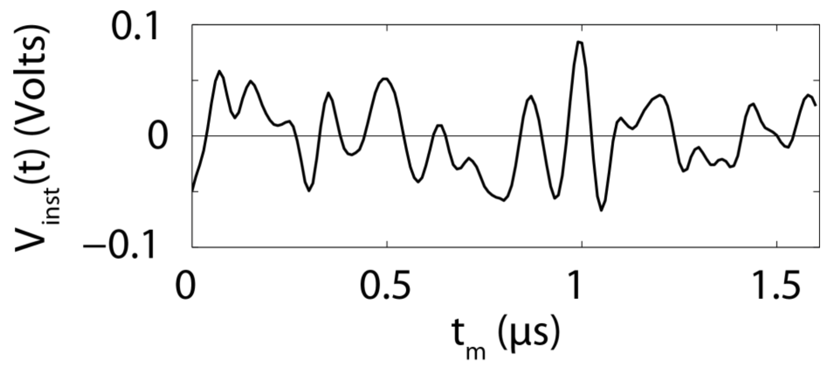
Quantum trajectory reconstruction allows us to directly observe quantum state evolution under measurement

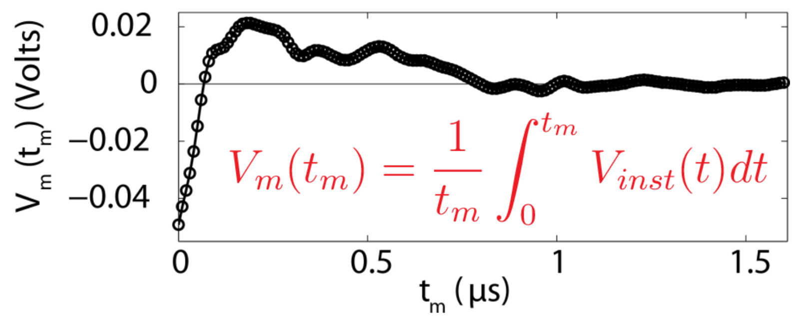
Single Qubit Trajectories: Murch et al., **Nature** 2013
Weber et al., **Nature** 2014

PULSE SEQUENCE & ANALYSIS



$$|\psi_i\rangle = \frac{|00\rangle + |01\rangle + |10\rangle + |11\rangle}{2}$$

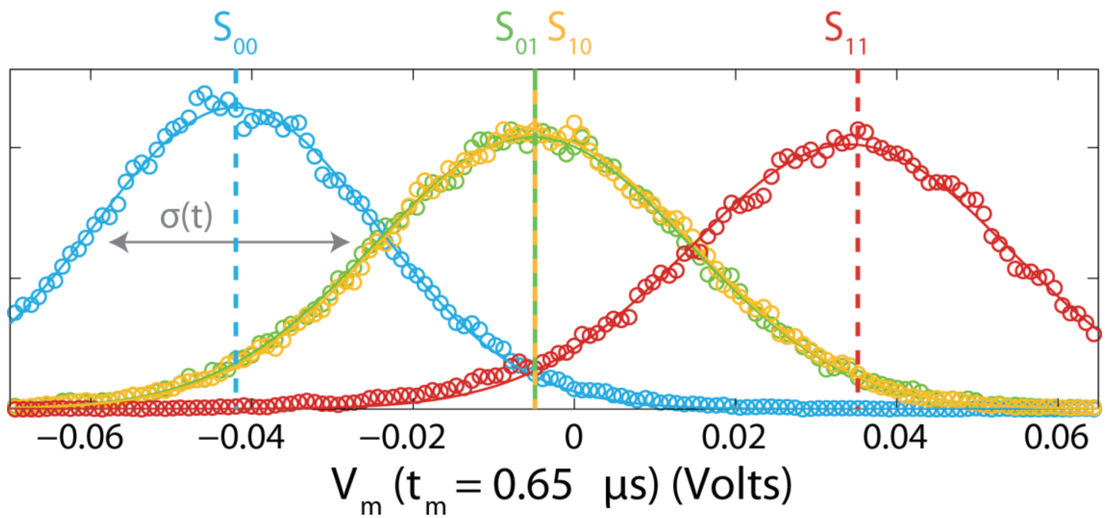




QUANTUM BAYESIAN UPDATE

$$p(x|y) = \frac{p(x)p(y|x)}{p(y)}$$

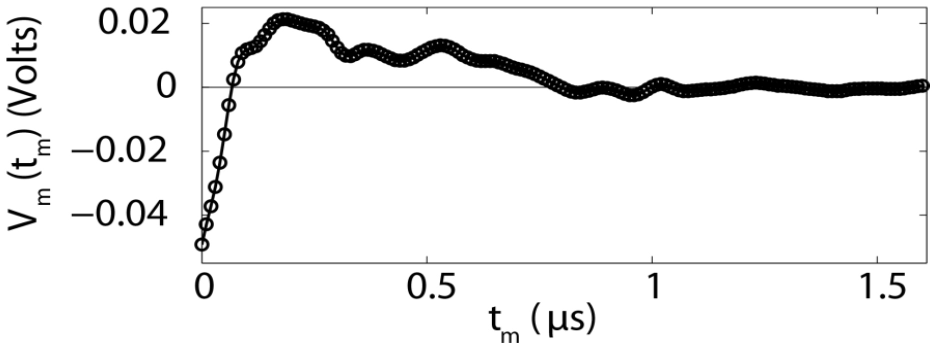
$$p(|ij\rangle|V_m) = \frac{p(|ij\rangle)p(V_m||ij\rangle)}{p(V_m)}$$

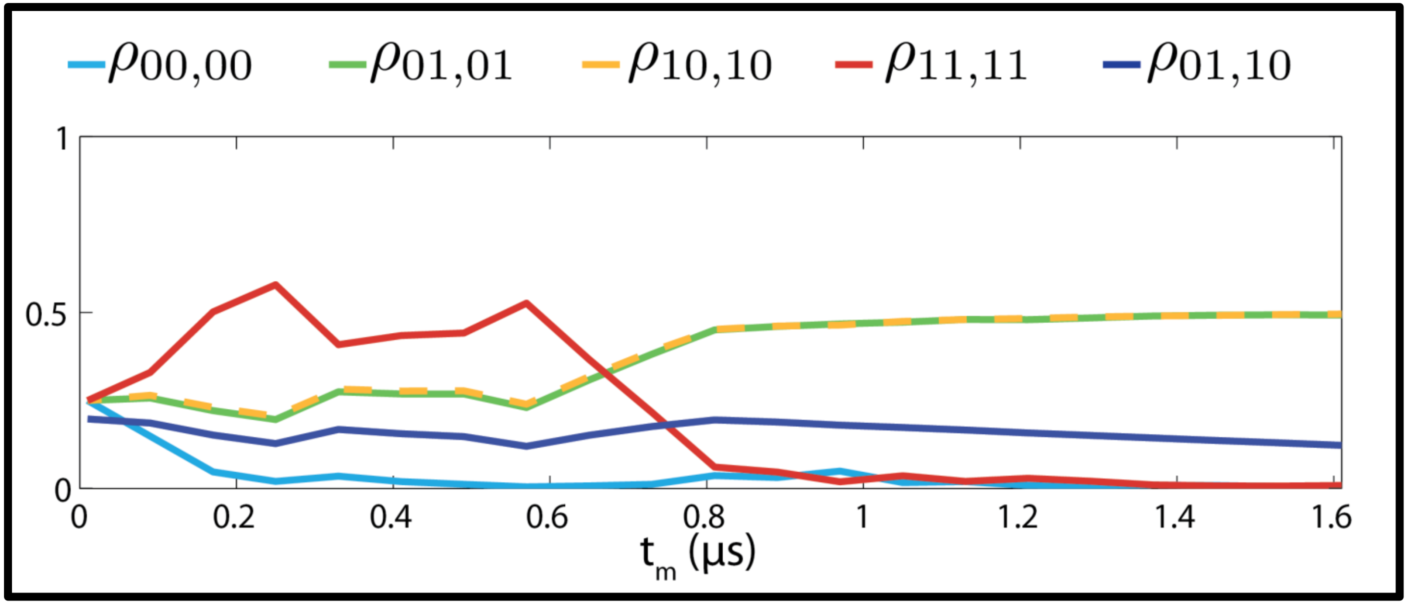


$$f_{i,j}(V_m, t) = \frac{1}{\sqrt{2\pi}\sigma(t)} e^{-(V_m - S_{ij})^2/2\sigma^2(t)}$$

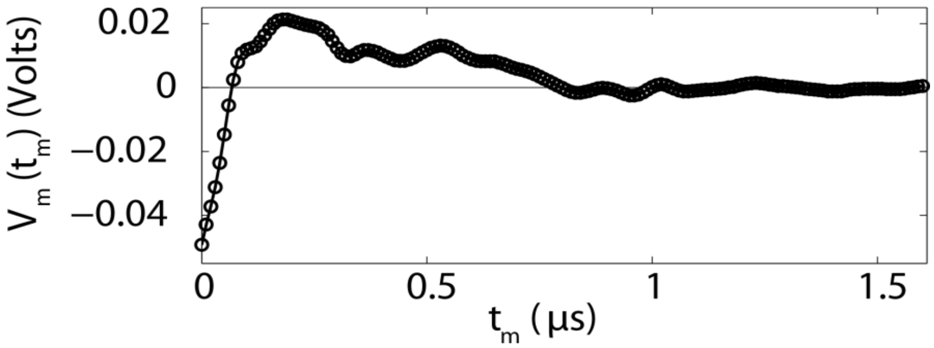
$$\sigma(t) = \frac{1}{2\sqrt{\eta_{meas} t}}$$

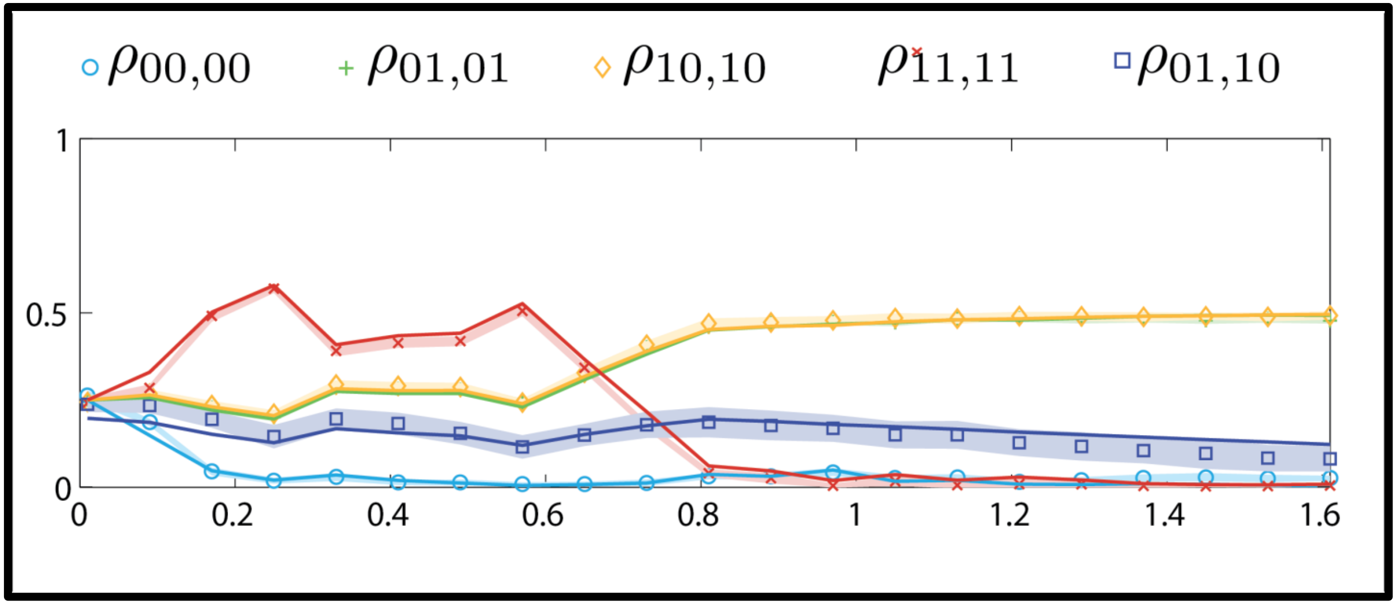
BAYESIAN TRAJECTORY RECONSTRUCTION



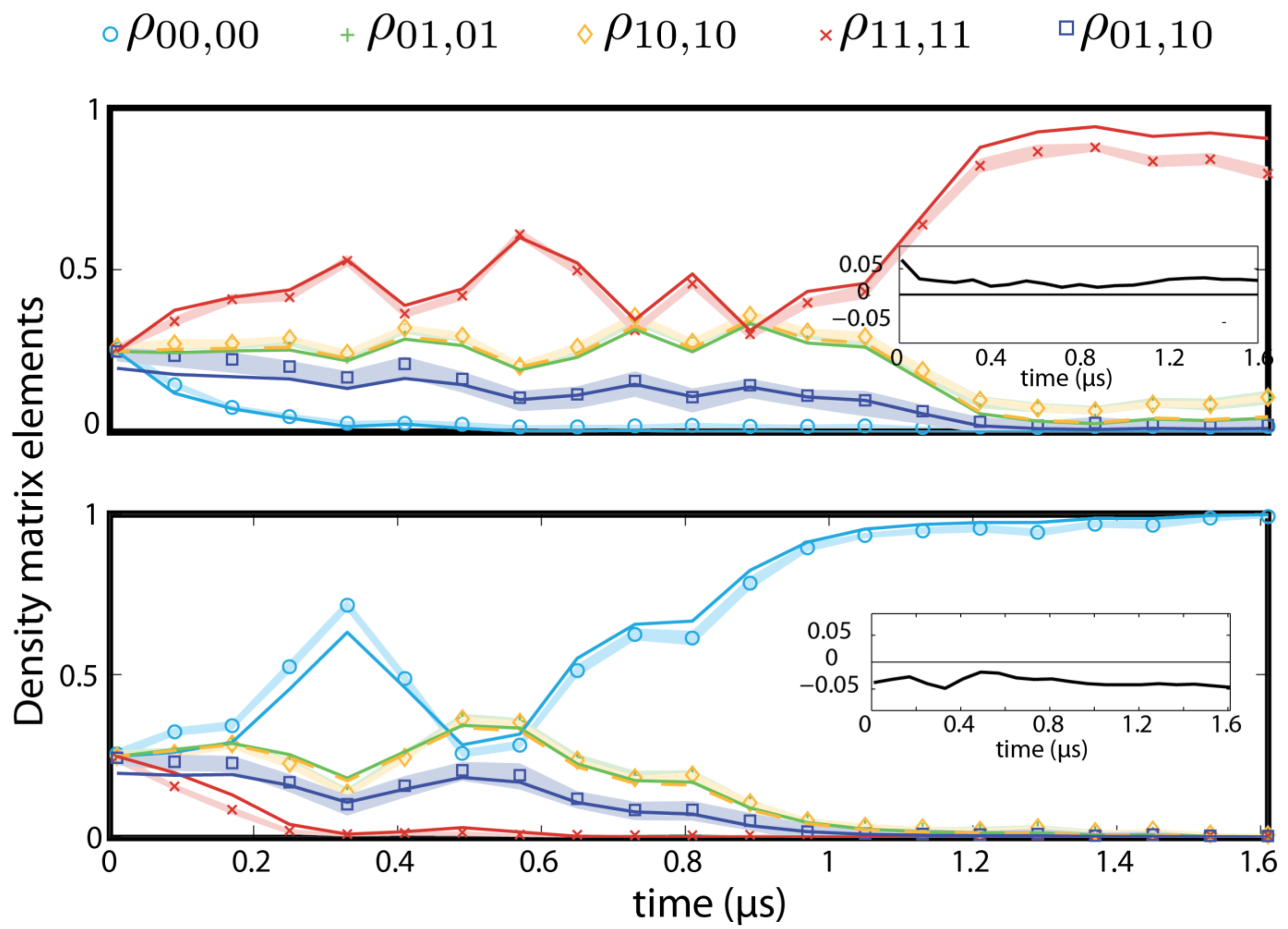


BAYESIAN TRAJECTORY RECONSTRUCTION





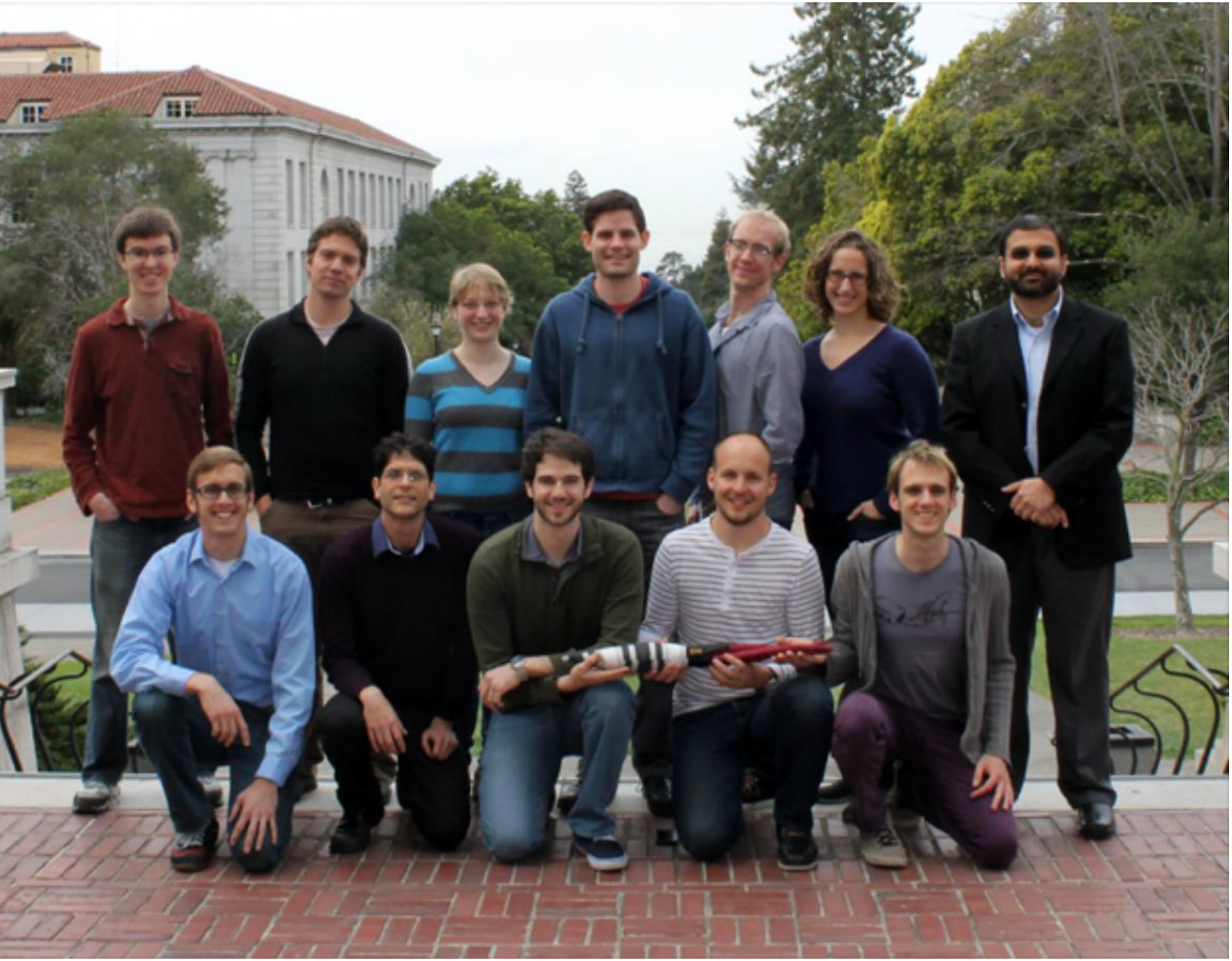
CONDITIONAL TOMOGRAPHY MAPPING



FUTURE DIRECTIONS

- IMPROVE DETECTION EFFICIENCY (ON-CHIP PARAMPS)
- TRAVELING WAVE AMPLFIERS (BW ~ 2 GHz)
- FEEDBACK STABILIZATION OF ENTANGLEMENT
- WEAK MEASUREMENT IN QUBIT CHAINS

  → Adaptive State Estimation (cf. tomography)
  → Weak Value Amplification of Errors/Couplings
  → Information Flow / Equilibration / Perturbations



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