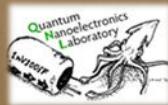


# *THE EVOLUTION OF QUANTUM TRAJECTORIES: FROM OBSERVATION TO FEEDBACK*

*Irfan Siddiqi*

*Department of Physics, UC Berkeley  
Lawrence Berkeley National Laboratory*



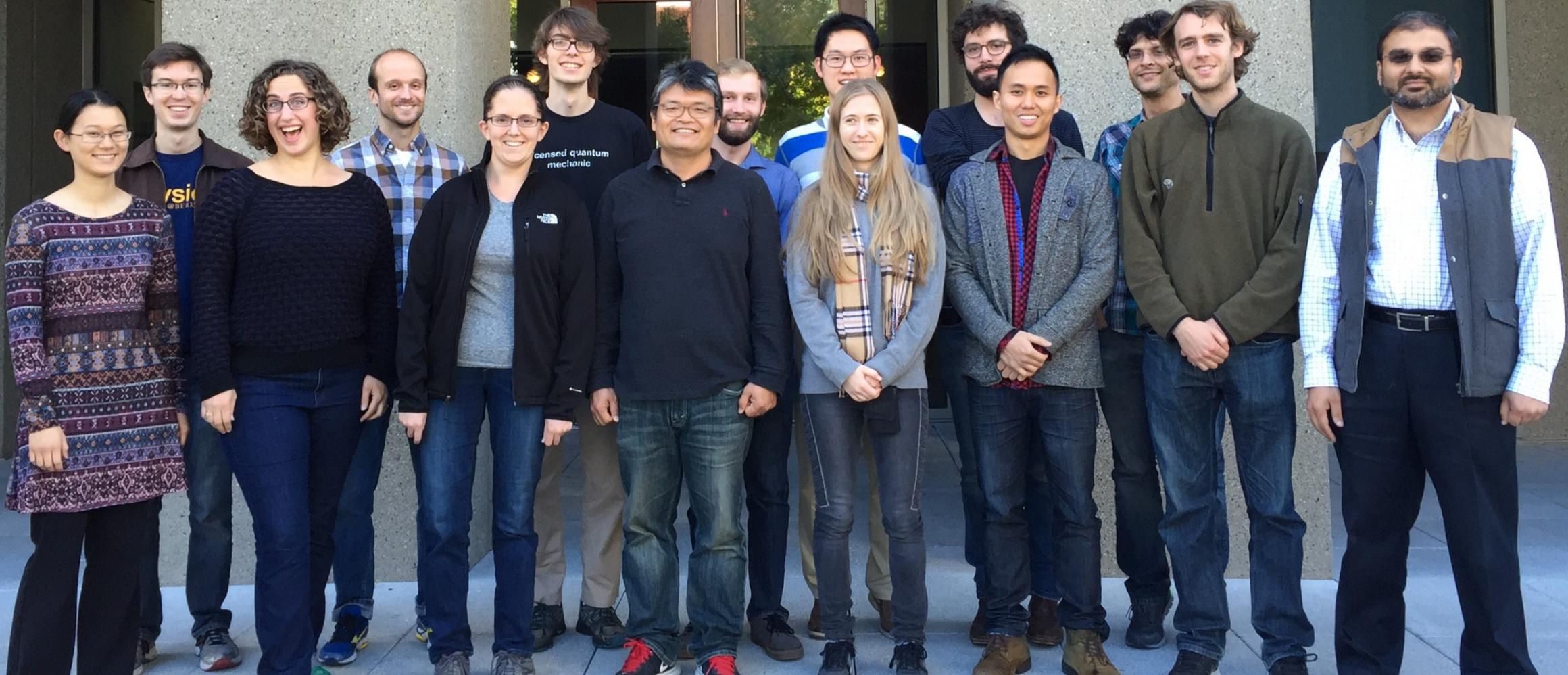
**KITP Quantum Thermodynamics Conference  
6/25/2018**



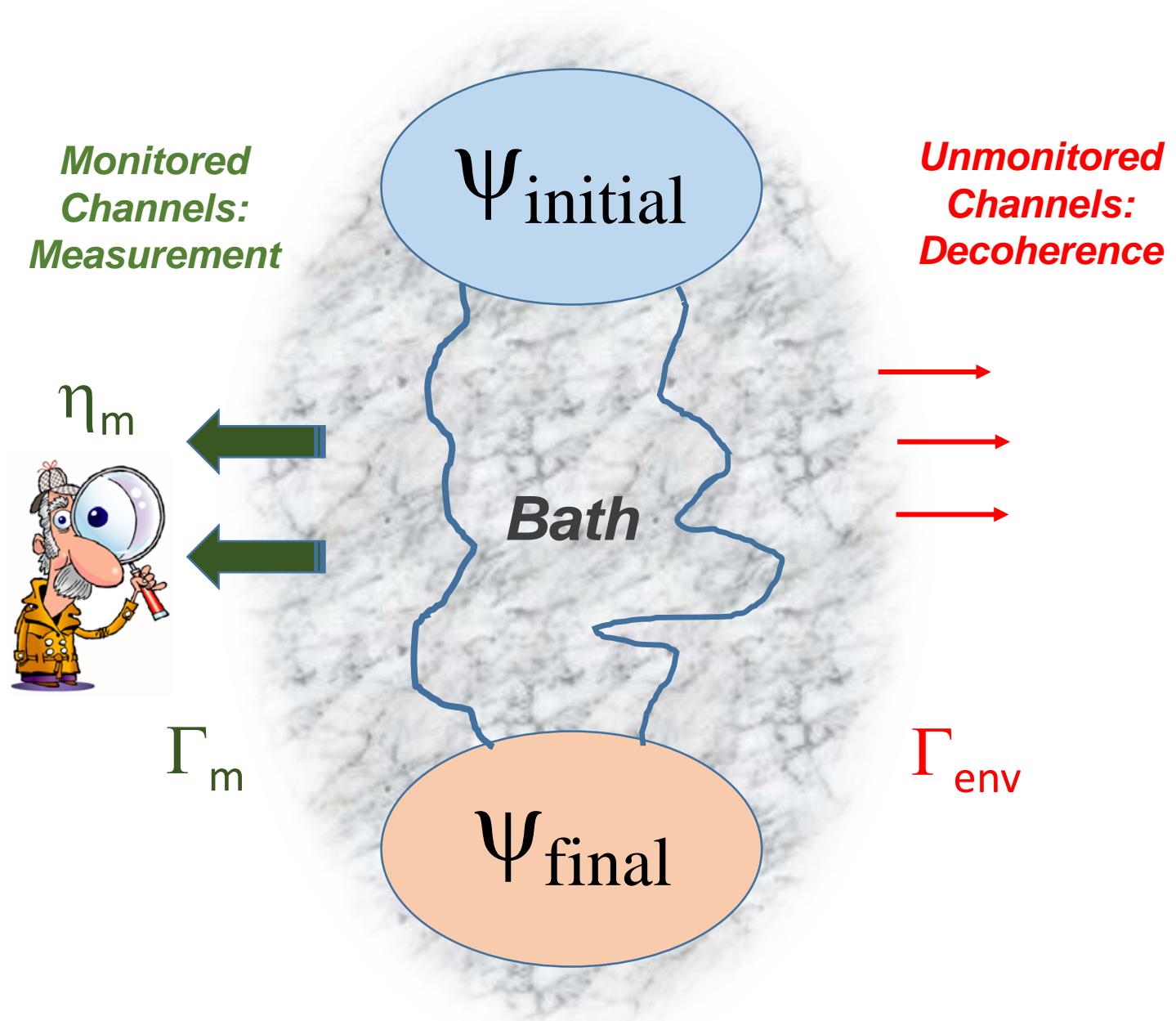
**The Hertz  
FOUNDATION**  
*freedom to innovate*



IARPA



# OPEN QUANT. SYSTEMS: DECOHERENCE, MEASUREMENT, & THE BATH

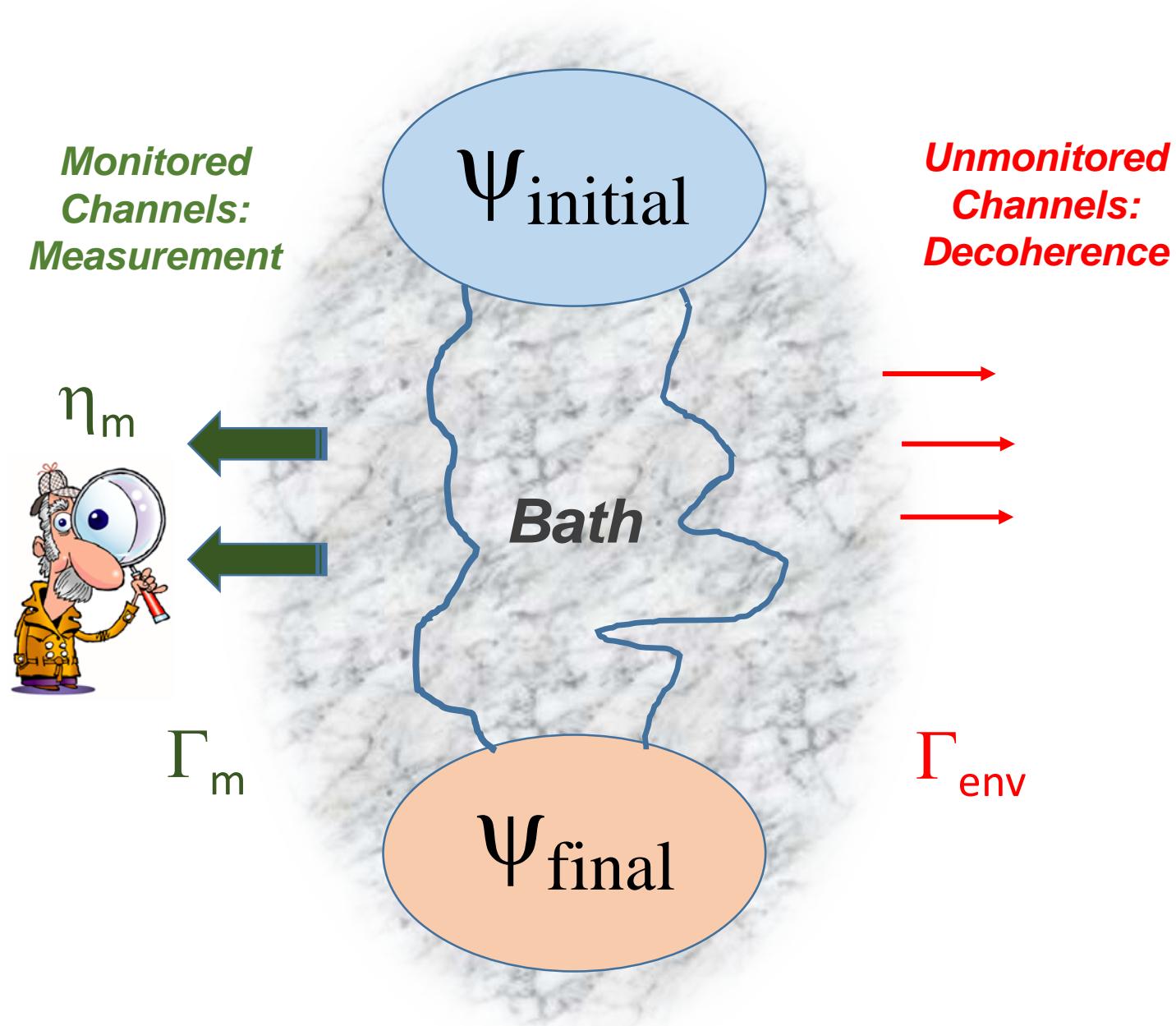


$$\begin{aligned}\Gamma_m &\gg \Gamma_{\text{env}} \\ \eta_m &\rightarrow 1 \quad (0.85 \text{ possible}) \\ \Gamma_{\text{observer}} &> \Gamma_m\end{aligned}$$

- Measurement  $\leftrightarrow$  Quantum Dynamics
- Unravel individual trajectories
- Define bath, predict trajectories
- Measure trajectories, study baths

- I: Single Spin  $\frac{1}{2}$ , Single Observable
- II: Single Spin  $\frac{1}{2}$ , Adaptive Observable
- III: Single Spin 1, Scrambler (Black Hole)

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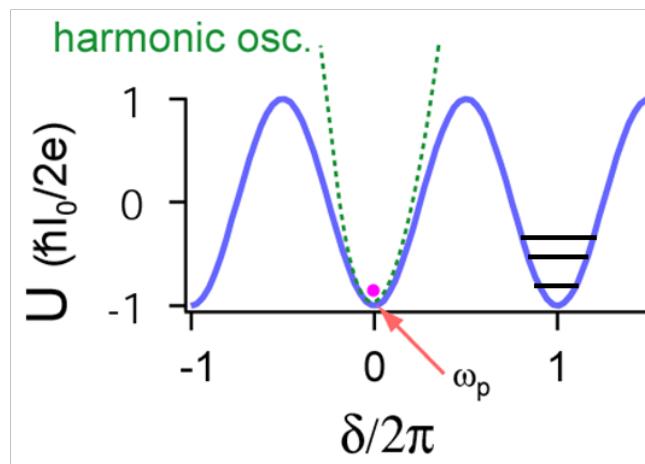
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# TRANSMON QUBIT

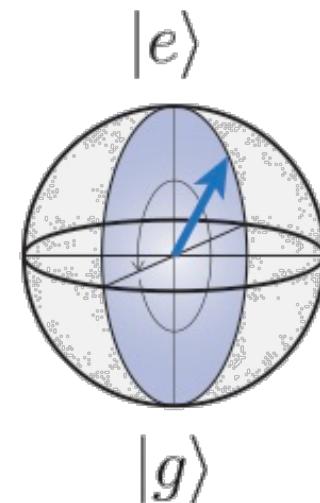


$$U(\delta) = -\frac{\hbar}{2e} I_0 \cos(\delta)$$

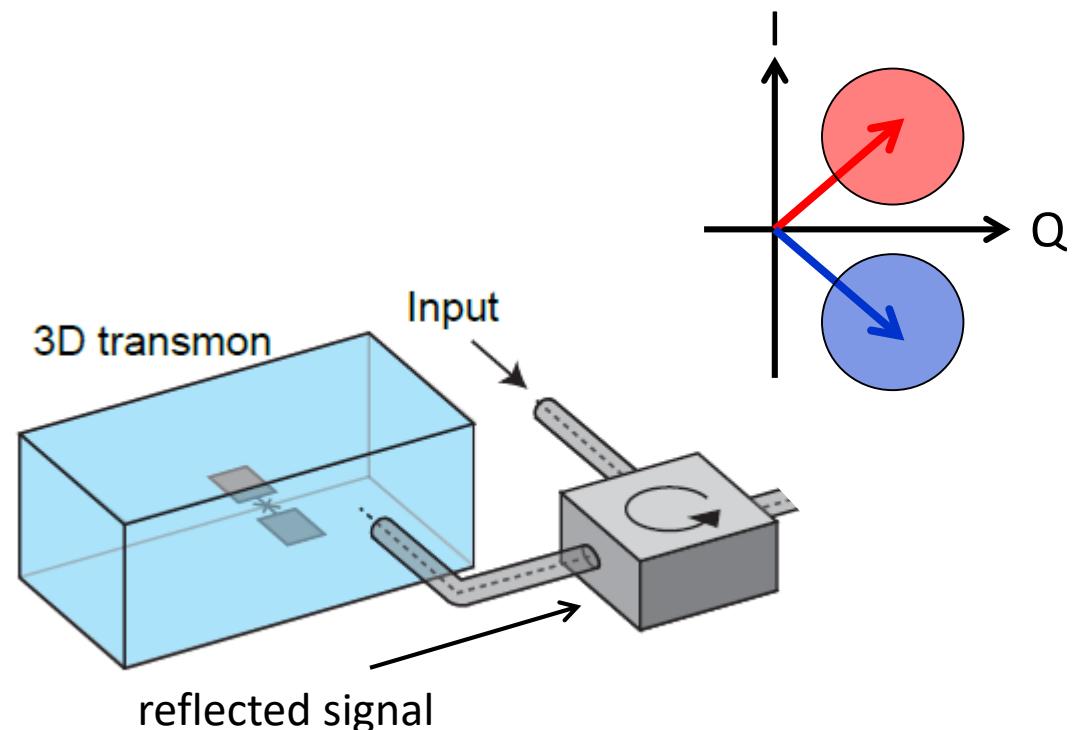


PARTICLE IN A “COSINE BOX”

$$H = \hbar \omega_q \frac{\sigma_z}{2}$$



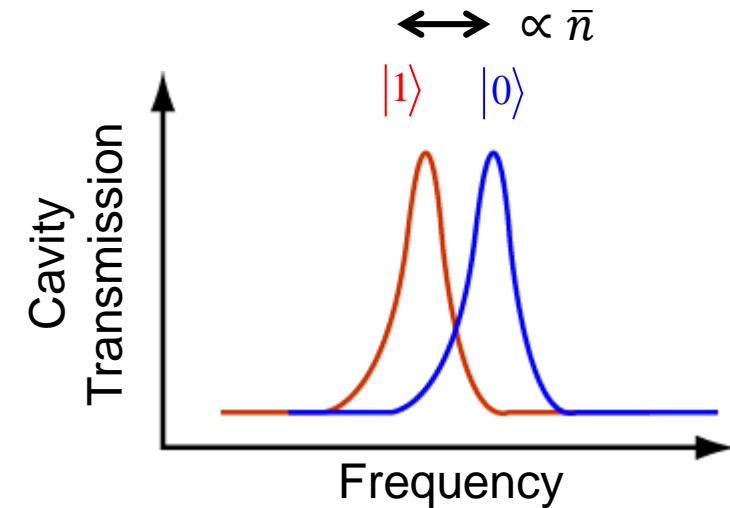
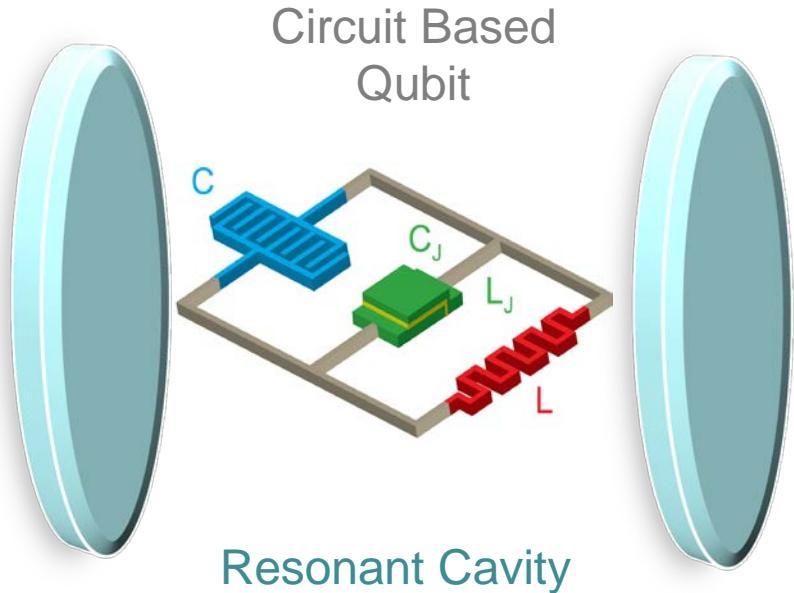
$$\omega_q \sim 4 \text{ GHz}$$



$$\begin{aligned} A \sin(\omega t + \phi) &= A \sin(\omega t) \cos(\phi) + A \cos(\omega t) \sin(\phi) \\ &= [A \cos(\phi)] \sin(\omega t) + [A \sin(\phi)] \cos(\omega t) \end{aligned}$$

VOLTAGE  $\leftrightarrow$  QUANTUM STATE

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



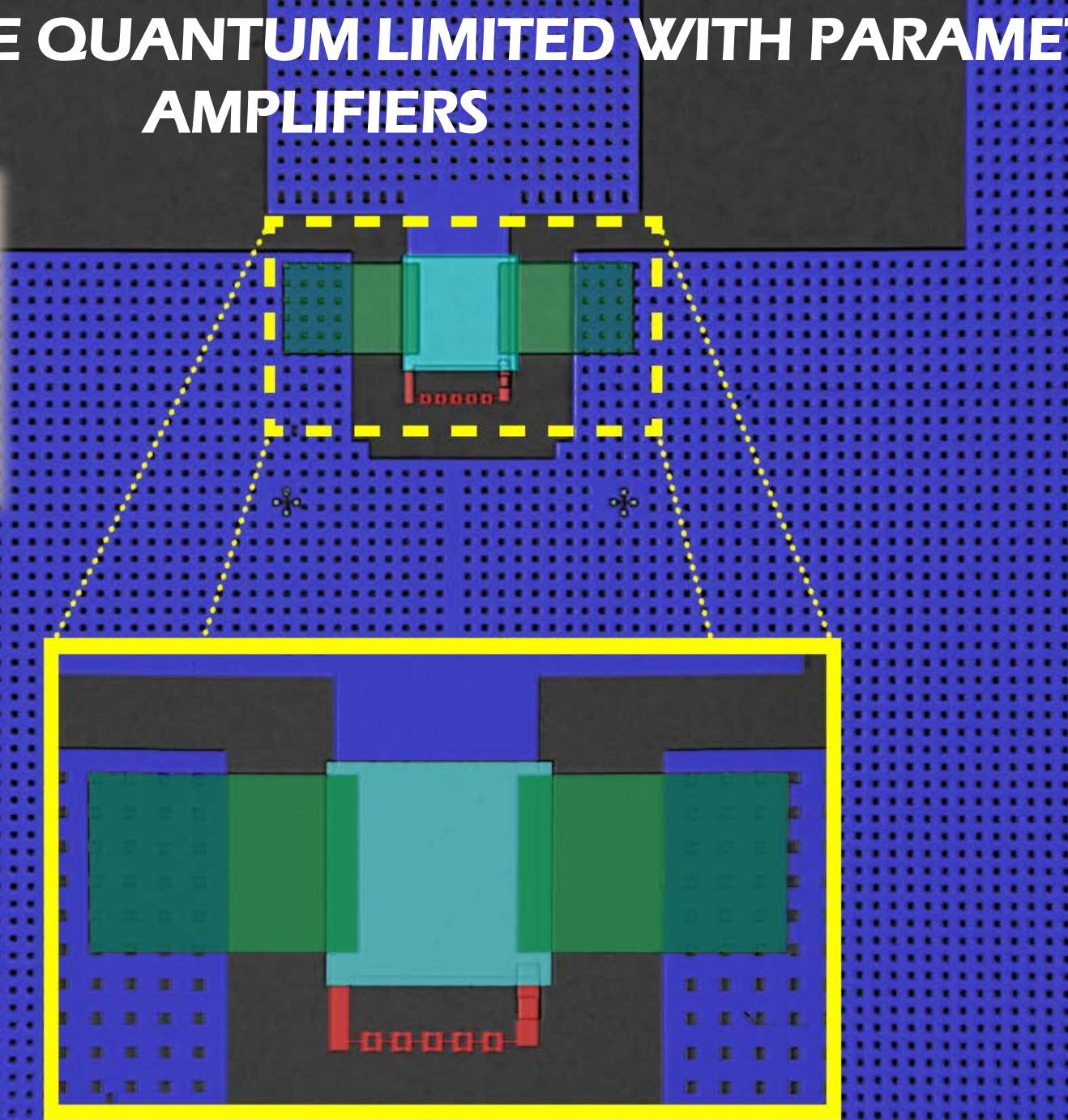
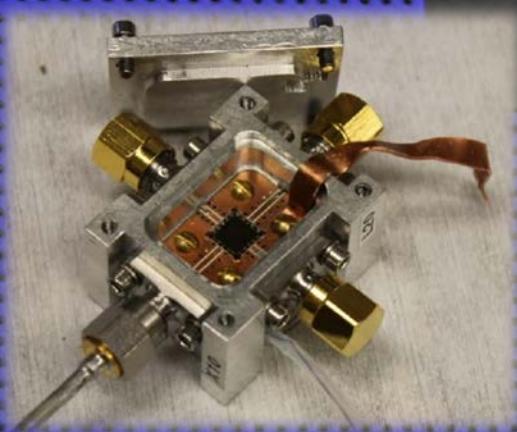
$$H = \frac{1}{2}\hbar\omega_q\sigma_z + \hbar\omega_r(a^\dagger a + \frac{1}{2}) + \hbar g(a^\dagger\sigma_- + a\sigma_+)$$

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

VARY MEASUREMENT STRENGTH  
USING DISPERSIVE SHIFT &  
PHOTON NUMBER

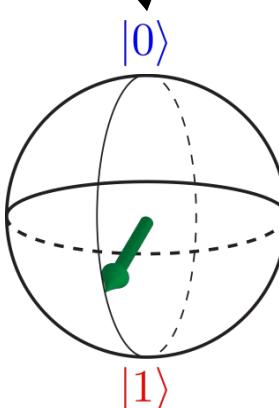
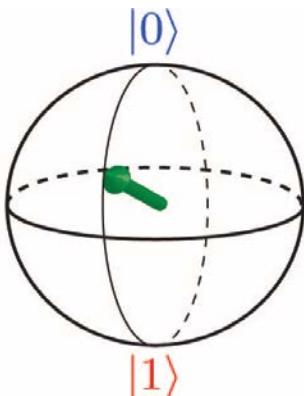
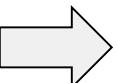
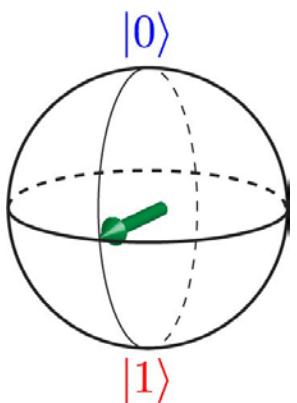
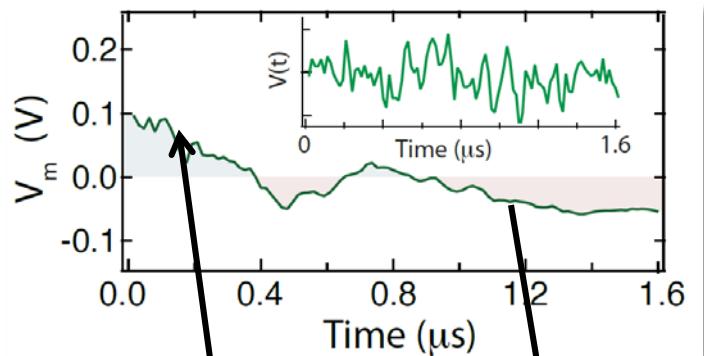
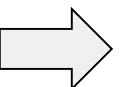
NEED TO DETECT ~ SINGLE  
MICROWAVE PHOTONS in  $T_1 \sim \mu s$

# APPROACHING THE QUANTUM LIMITED WITH PARAMETRIC AMPLIFIERS



# RECONSTRUCTING THE QUBIT STATE

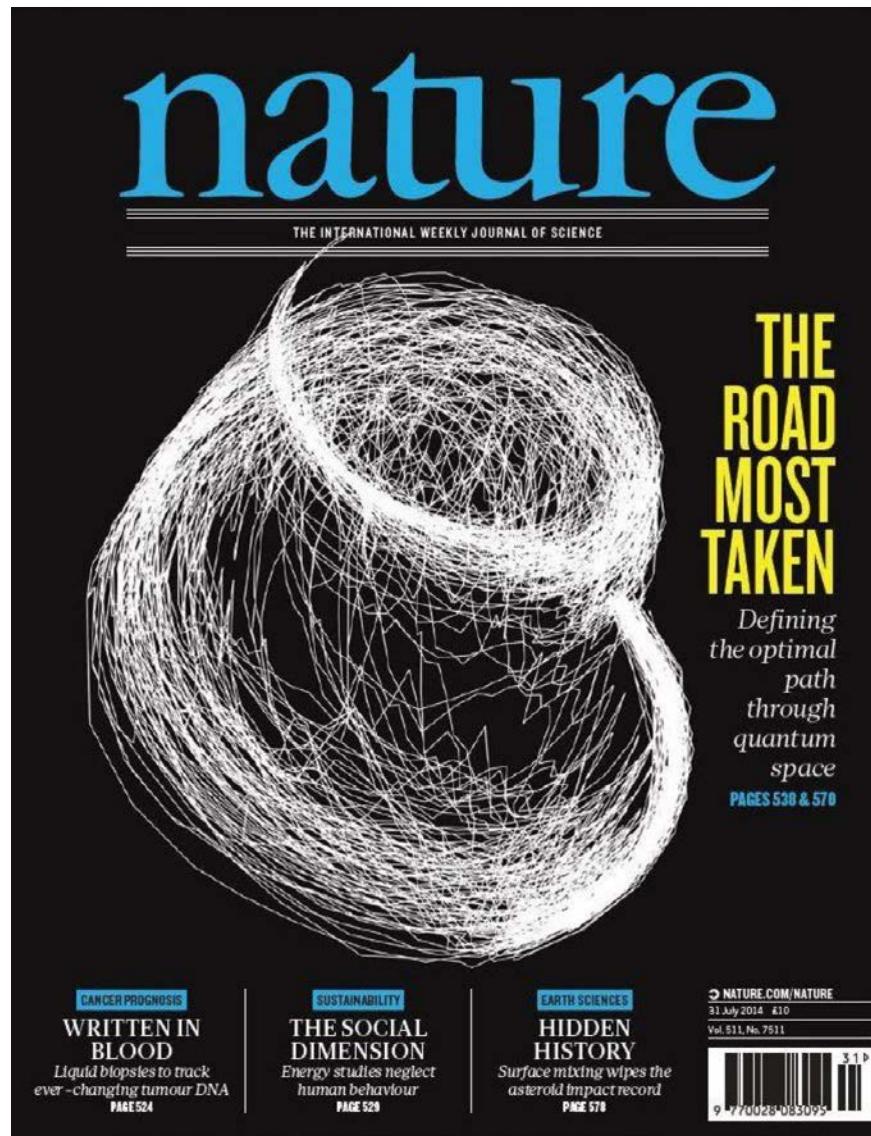
Time = 0



## BAYES RULE

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

# TRAJECTORIES, TRAJECTORIES, TRAJECTORIES,...



## LETTER

doi:10.1038/nature19762

### Quantum dynamics of simultaneously measured non-commuting observables

Shay Hacohen-Gourgy<sup>1,2\*</sup>, Leigh S. Martin<sup>1,2,3\*</sup>, Emmanuel Flurin<sup>1,2</sup>, Vinay V. Ramasesh<sup>1,2</sup>, K. Birgitta Whaley<sup>3,4</sup> & Irfan Siddiqi<sup>1,2</sup>

## PHYSICAL REVIEW X

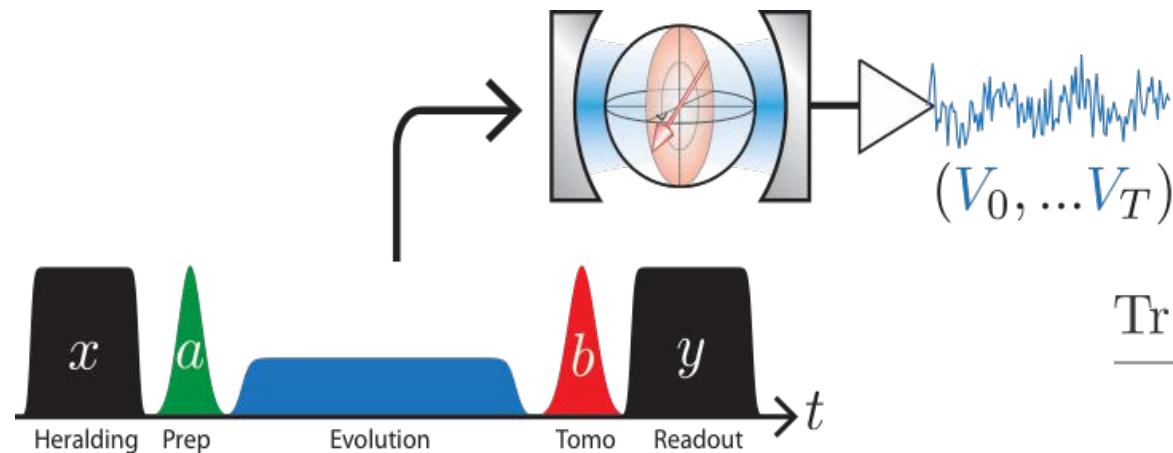
Highlights   Recent   Subjects   Accepted   Collections   Authors   Referees   Search   Press

Open Access

### Quantum Trajectories and Their Statistics for Remotely Entangled Quantum Bits

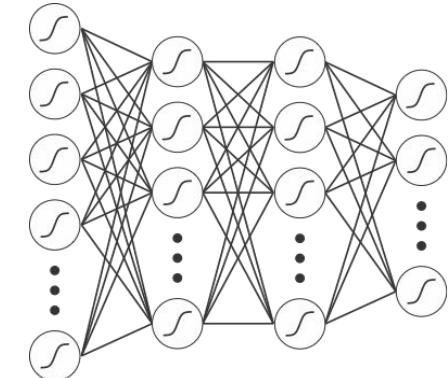
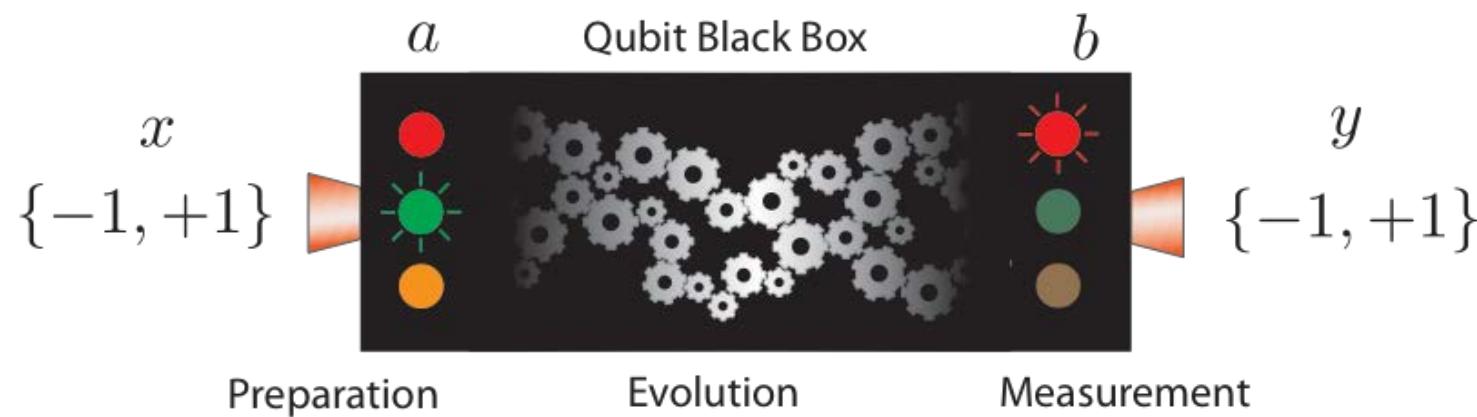
Areeya Chantasri, Mollie E. Kimchi-Schwartz, Nicolas Roch, Irfan Siddiqi, and Andrew N. Jordan  
Phys. Rev. X **6**, 041052 – Published 14 December 2016

# CAN WE TEACH A MACHINE QUANTUM MECHANICS ?



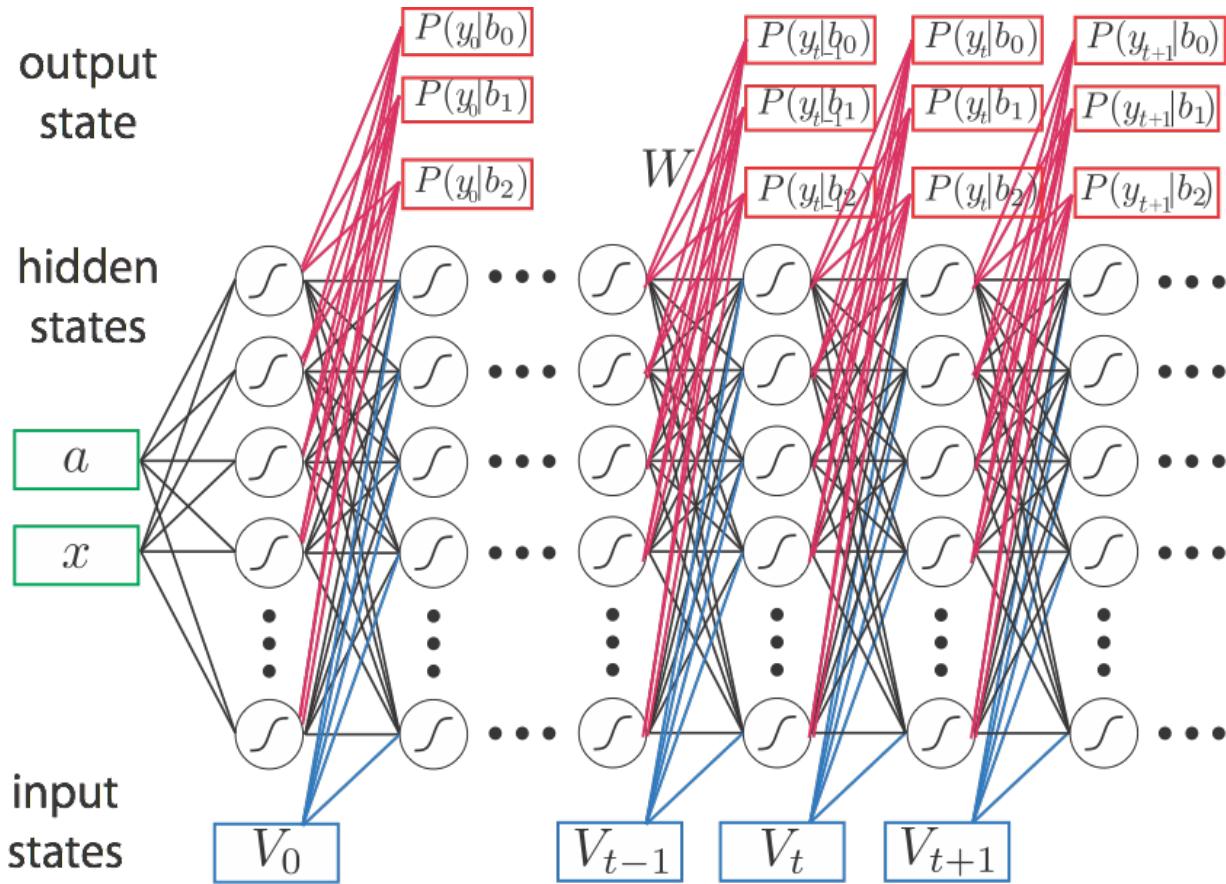
$$P(y|x, \mathbf{a}, \mathbf{b}, V_0, \dots, V_t, \dots, V_T) =$$

$$\frac{\text{Tr}(|y\rangle\langle y| \hat{B} \hat{\Omega}_{V_T} \dots \hat{\Omega}_{V_t} \dots \hat{\Omega}_{V_0} \hat{A} \rho_x \hat{A}^\dagger \hat{\Omega}_{V_0}^\dagger \dots \hat{\Omega}_{V_t}^\dagger \dots \hat{\Omega}_{V_T}^\dagger \hat{B}^\dagger)}{\text{Tr}(\hat{\Omega}_{V_T} \dots \hat{\Omega}_{V_t} \dots \hat{\Omega}_{V_0} \hat{A} \rho_x \hat{A}^\dagger \hat{\Omega}_{V_0}^\dagger \dots \hat{\Omega}_{V_t}^\dagger \dots \hat{\Omega}_{V_T}^\dagger)}$$



**Superconducting circuits provide  $10^6$  instances per minute**

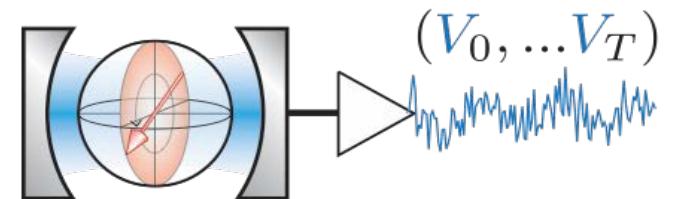
# RECURRENT NEURAL NETWORK



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

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

## Experiment



$$H = \frac{\Omega}{2} \sigma_x \quad \text{with} \quad \Omega = 2\pi \times 1 \text{ MHz}$$

$$\Gamma = \sqrt{\gamma} \sigma_z \quad \text{with} \quad \gamma = 2\pi \times 0.6 \text{ MHz}$$

$[H, \Gamma] \neq 0$  non-QND measurement

$$\eta = 36\%$$

$a$  10 preparation angles

$b$  6 tomography angles

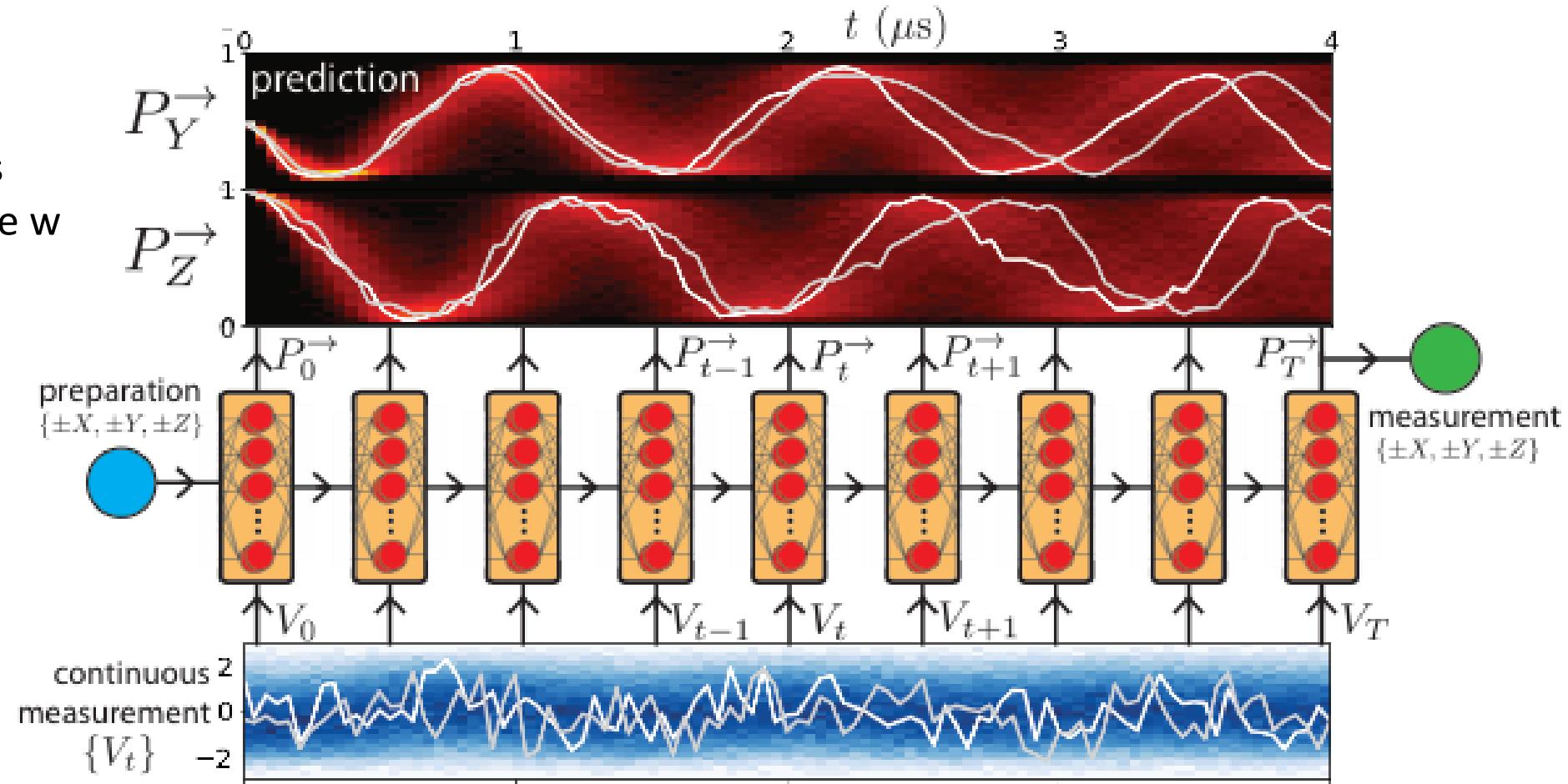
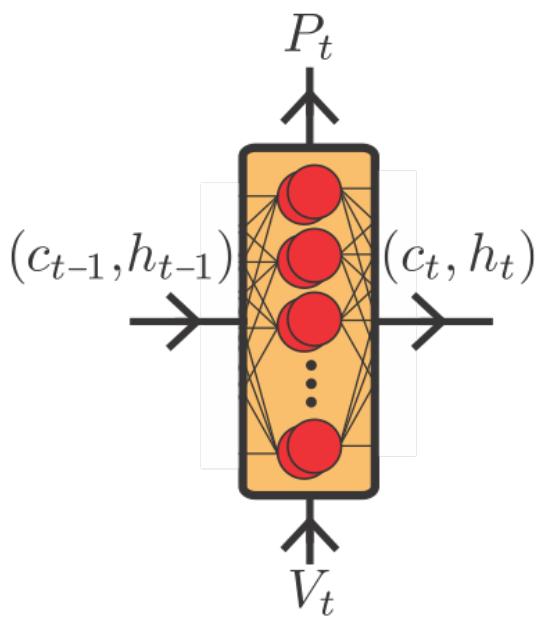
$T$  20 evolution times

1.5 millions repetitions  
at a rate of 0.5 ms

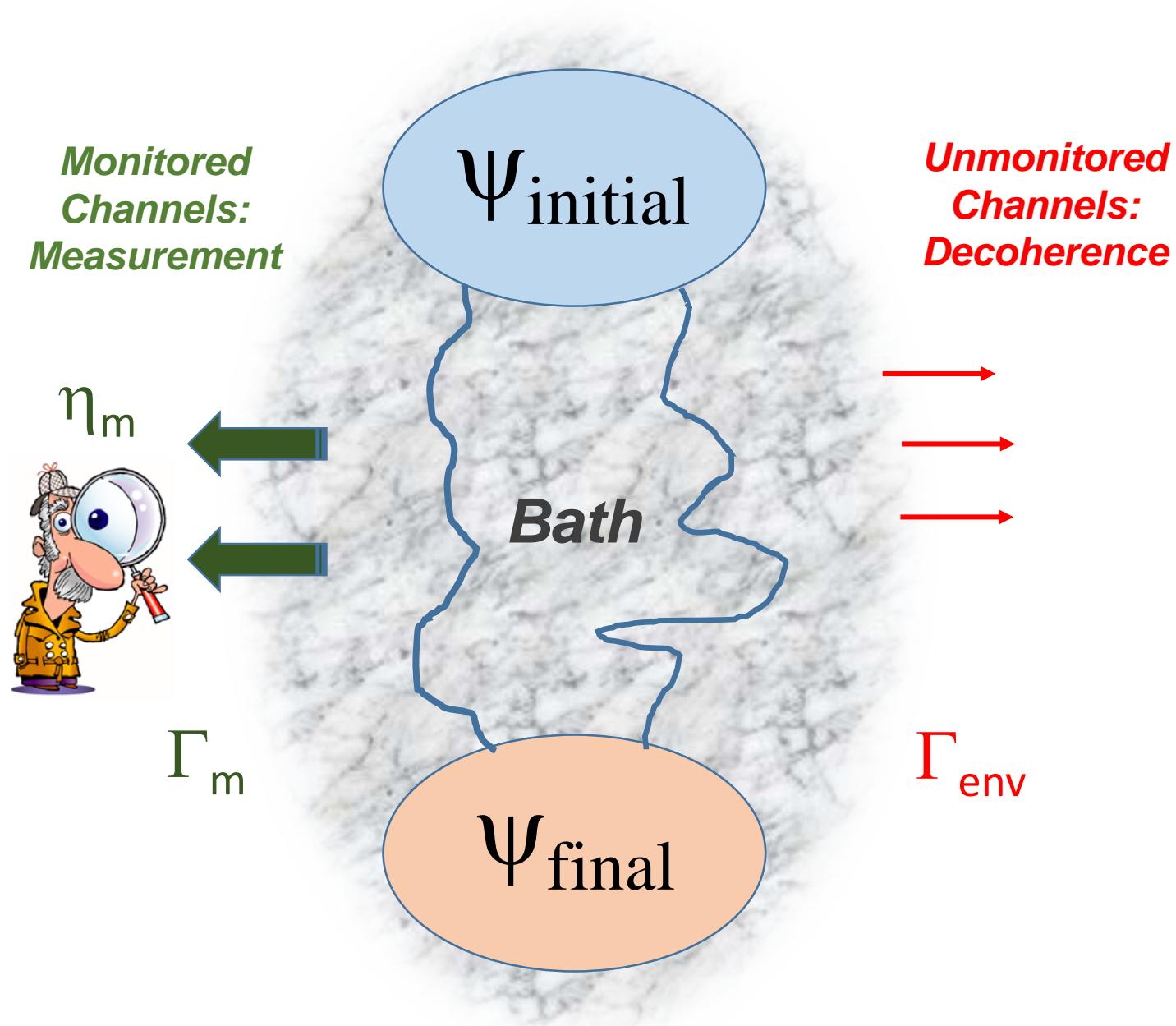
# RNN RESULTS: RABI OSCILLATIONS

## Recurrent Neural Network

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



# OPEN QUANT. SYSTEMS: DECOHERENCE, MEASUREMENT, & THE BATH



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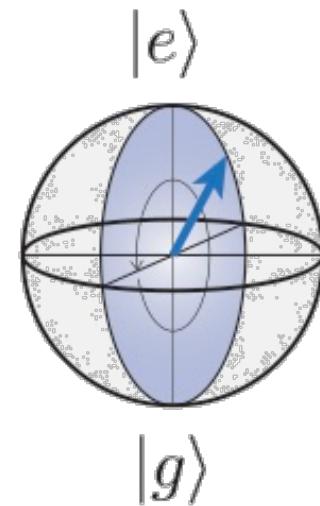
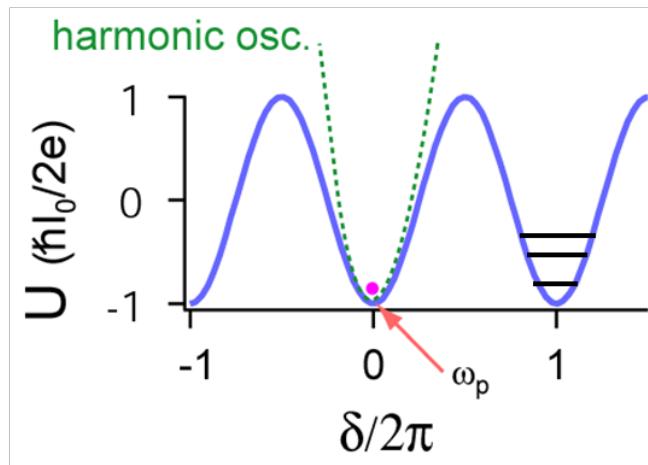
- I: Single Spin  $\frac{1}{2}$ , Single Observable
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# DRESSED TRANSMON QUBIT

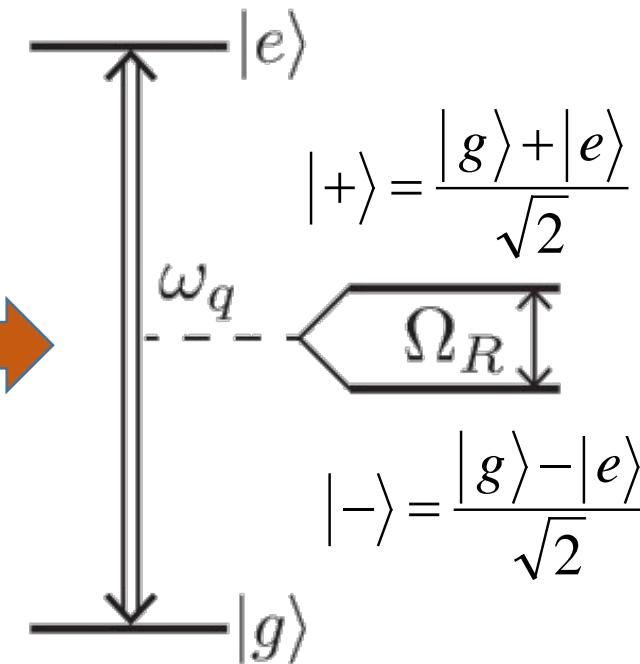


$$H = \hbar\omega_q \frac{\sigma_z}{2}$$

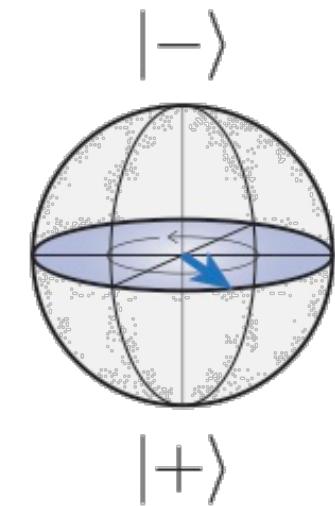
$$U(\delta) = -\frac{\hbar}{2e} I_0 \cos(\delta)$$



*Rabi*  
*flop*



$$H = \hbar\Omega_R \frac{\sigma_x}{2}$$

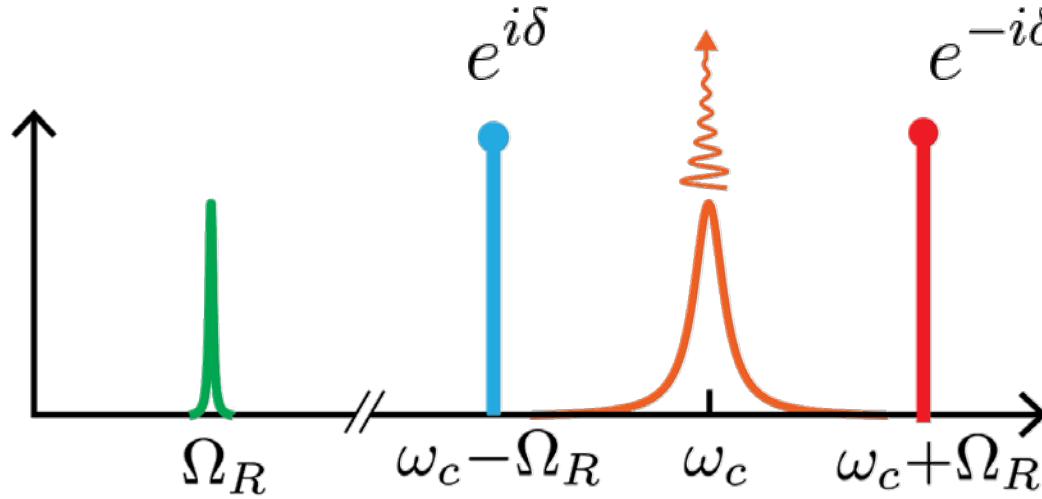


PARTICLE IN A “COSINE BOX”

$\omega_q \sim 4$  GHz

$\Omega_R \sim 40$  MHz

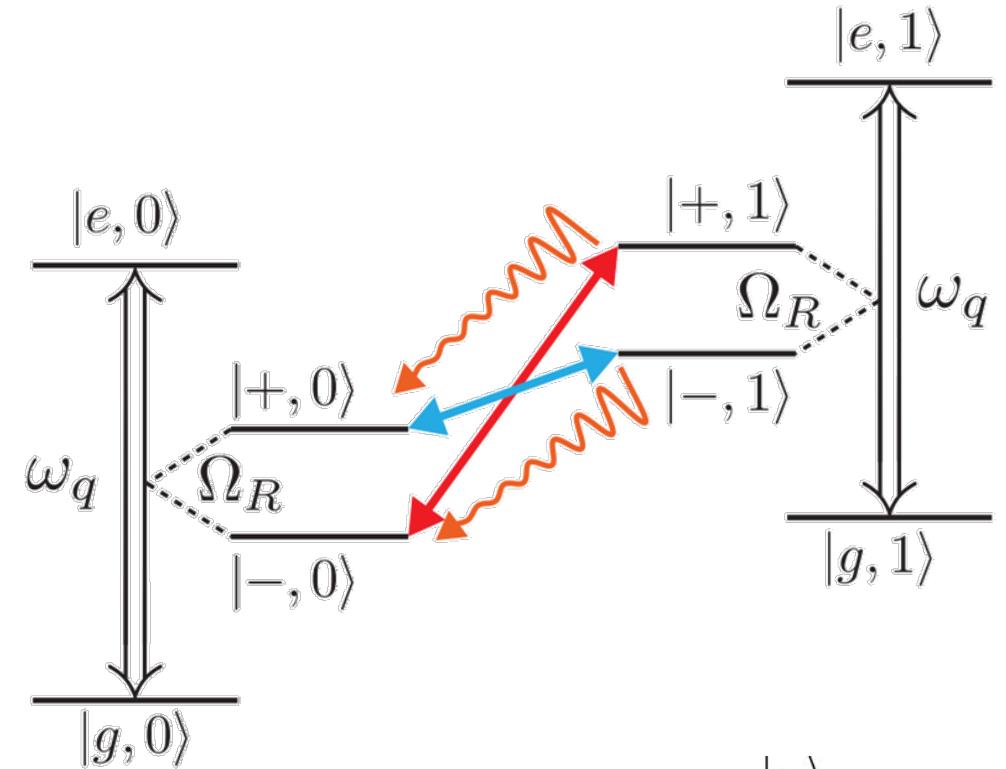
# SIMULTANEOUS COOLING AND HEATING...



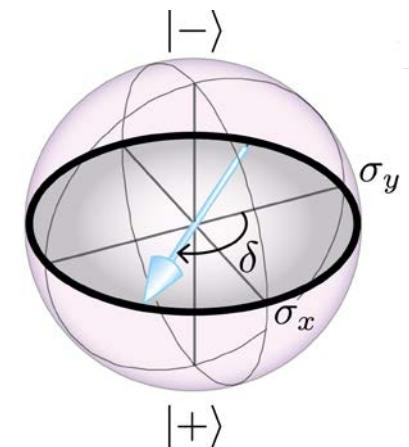
side-band cooling  $a^\dagger \sigma e^{i\delta} + a \sigma^\dagger e^{-i\delta}$

+

side-band heating  $a^\dagger \sigma^\dagger e^{i\delta} + a \sigma e^{-i\delta}$



- Bath stabilizes  $\sigma_\delta$
- Measures  $\sigma_\delta$



# OPTICAL PHASE NOT TYPICALLY ACCESSIBLE

Power

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

Amplitude

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

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



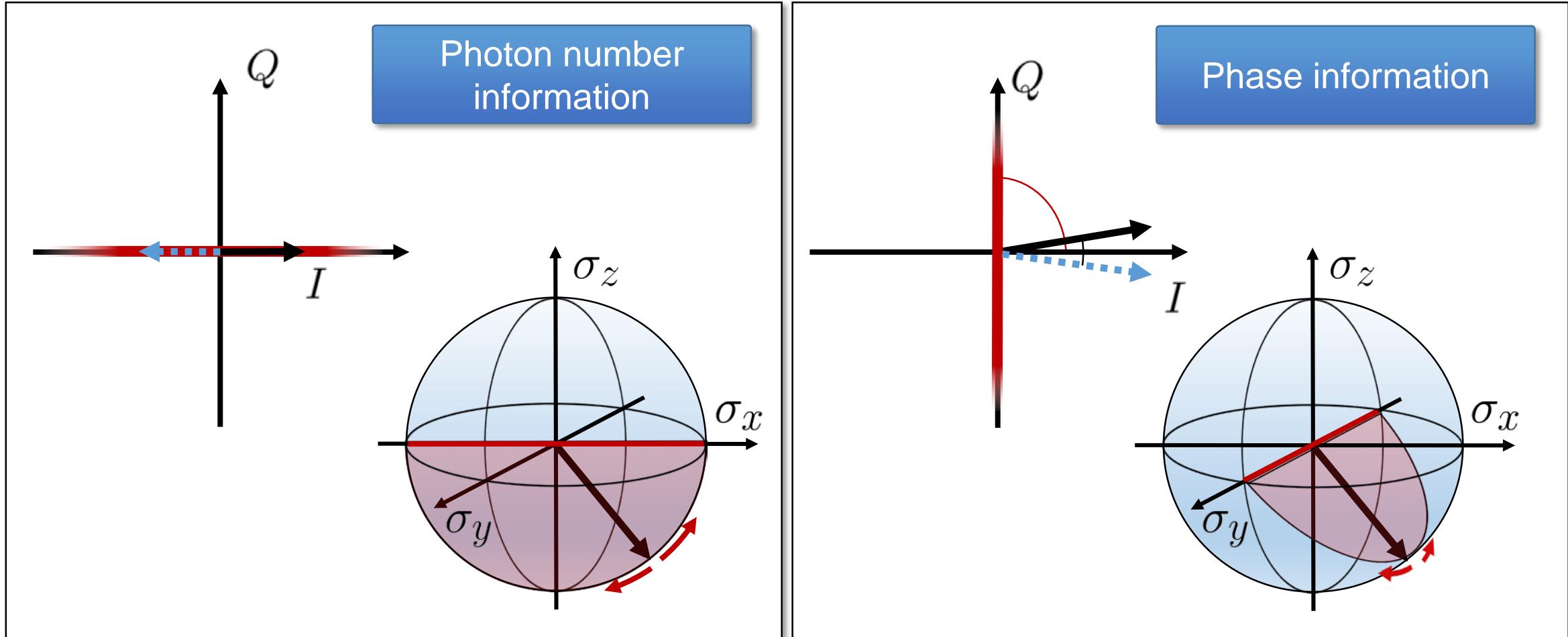
Can we measure phase?

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

?

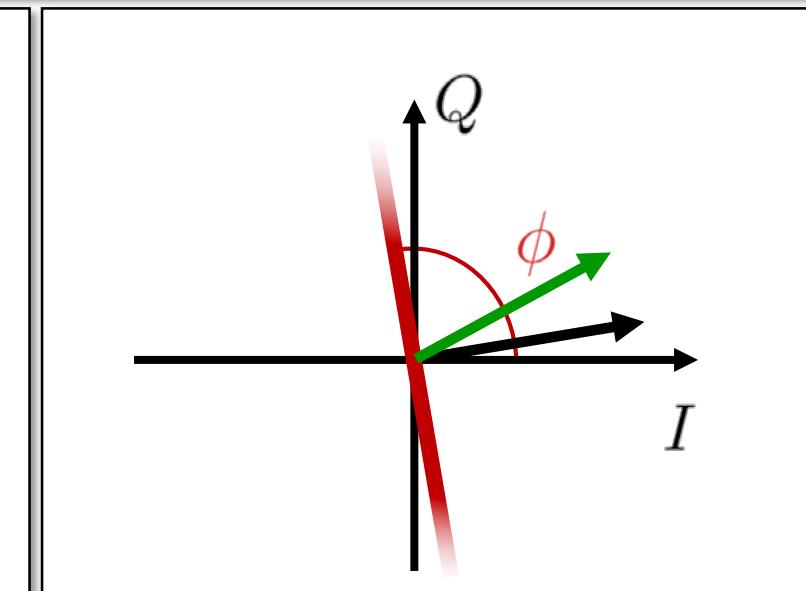
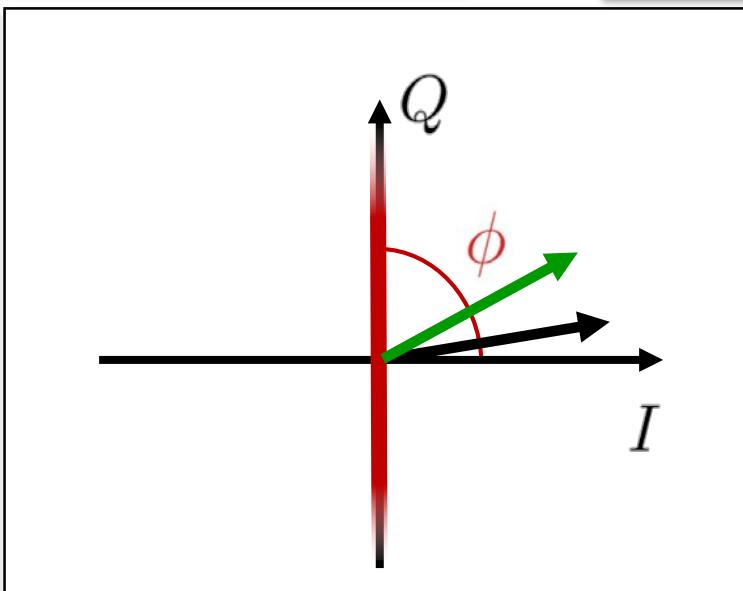
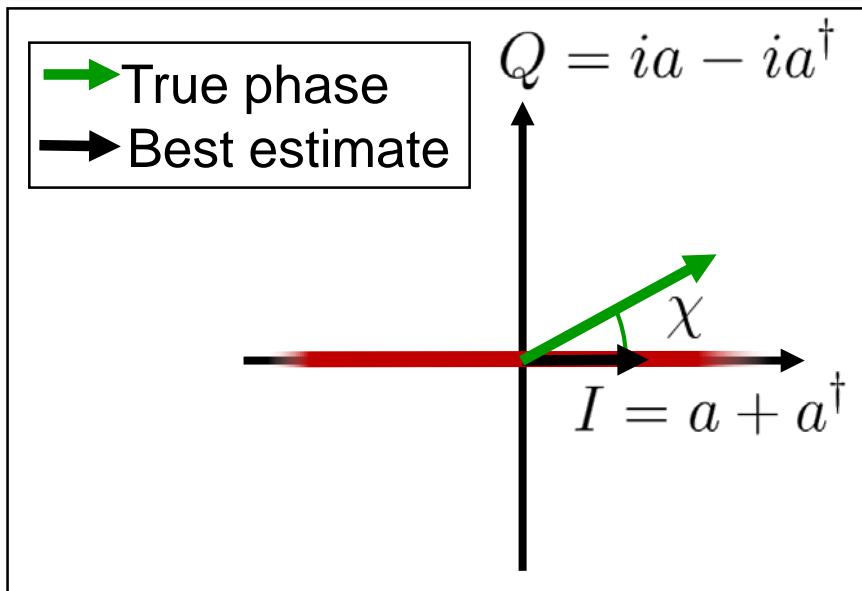
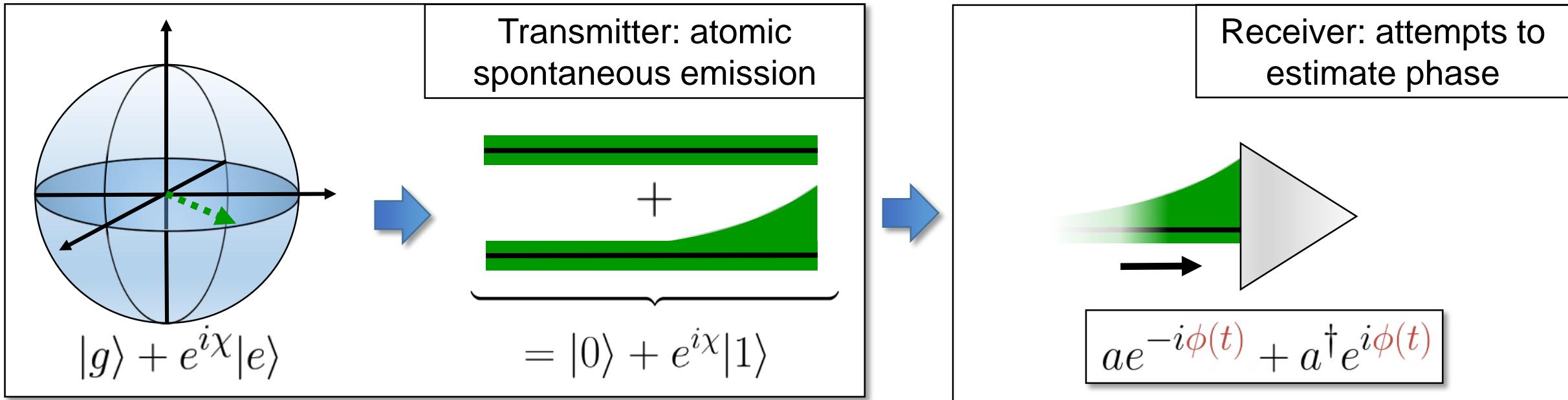
# VALIDATING RECEIVER PERFORMANCE

- As measurement induces disturbance, dynamics of the transmitter contains information about the receiver

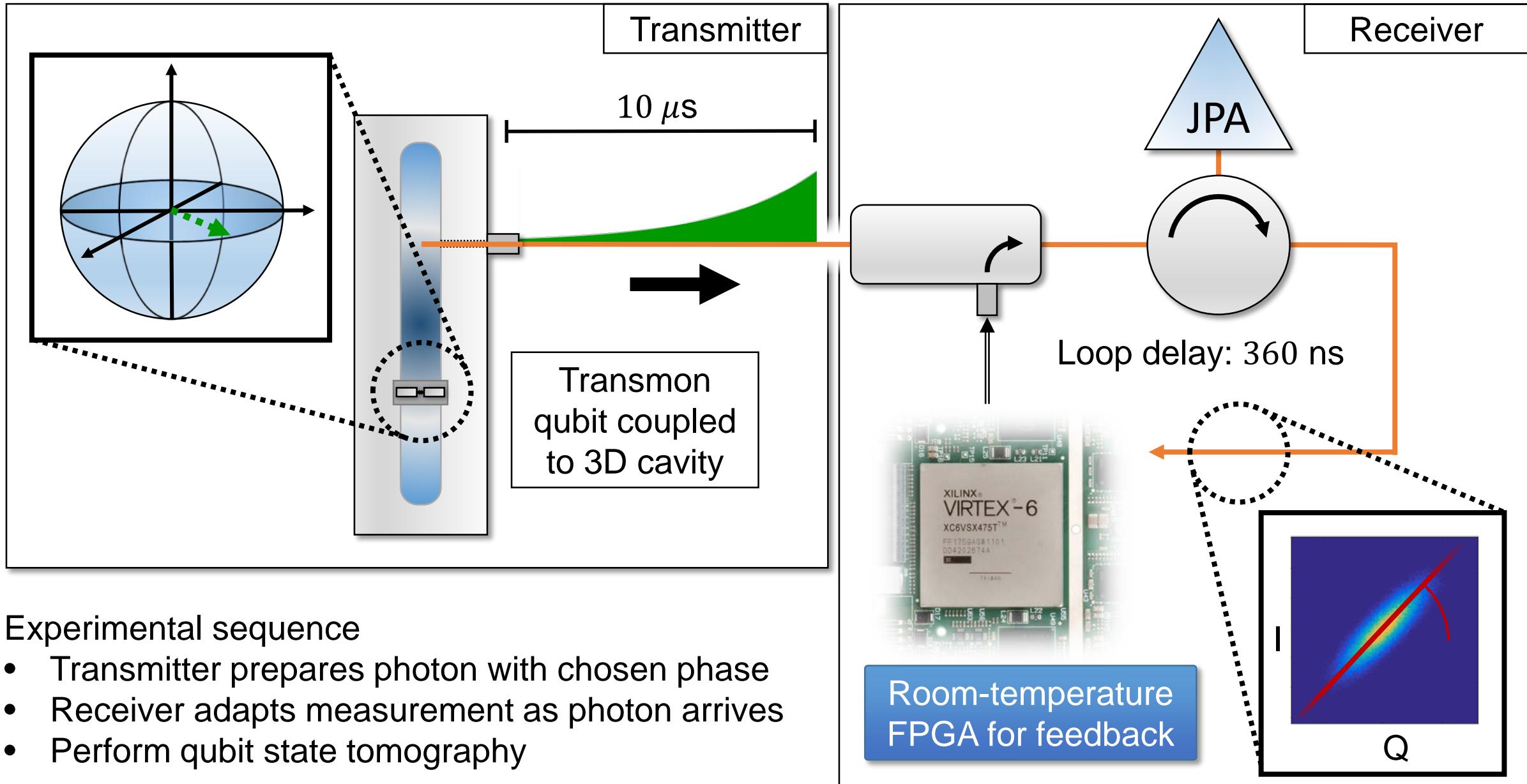


→ Observe quantum trajectories of the system

# ADAPTIVE PHASE MEASUREMENT



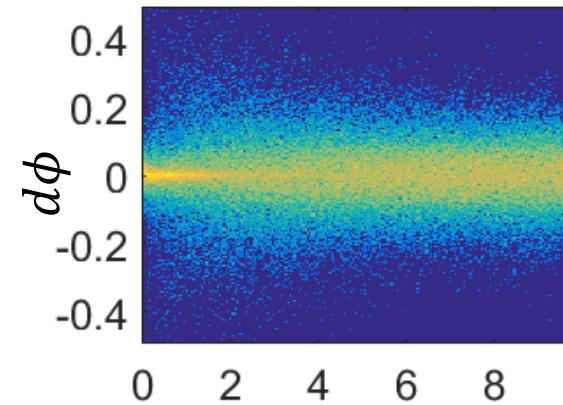
# EXPERIMENTAL SETUP – ADAPTIVE DETECTION



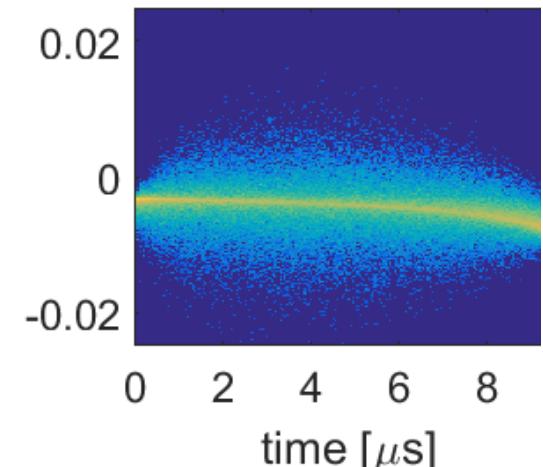
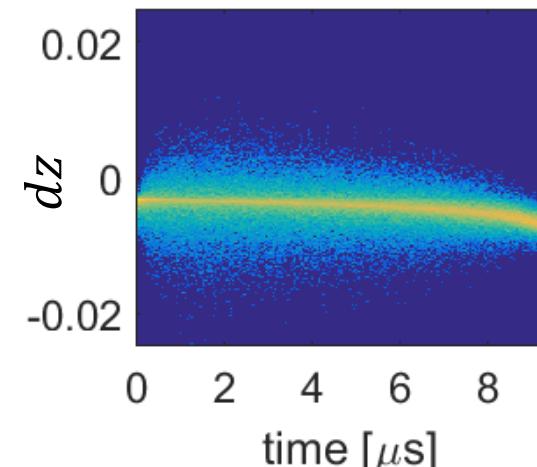
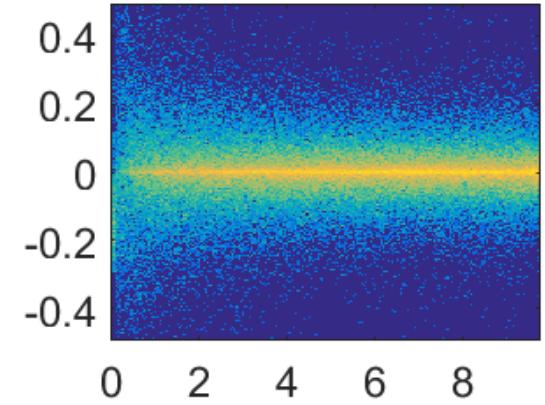
# EXPERIMENTAL ADAPTIVEDYNE BACK-ACTION

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

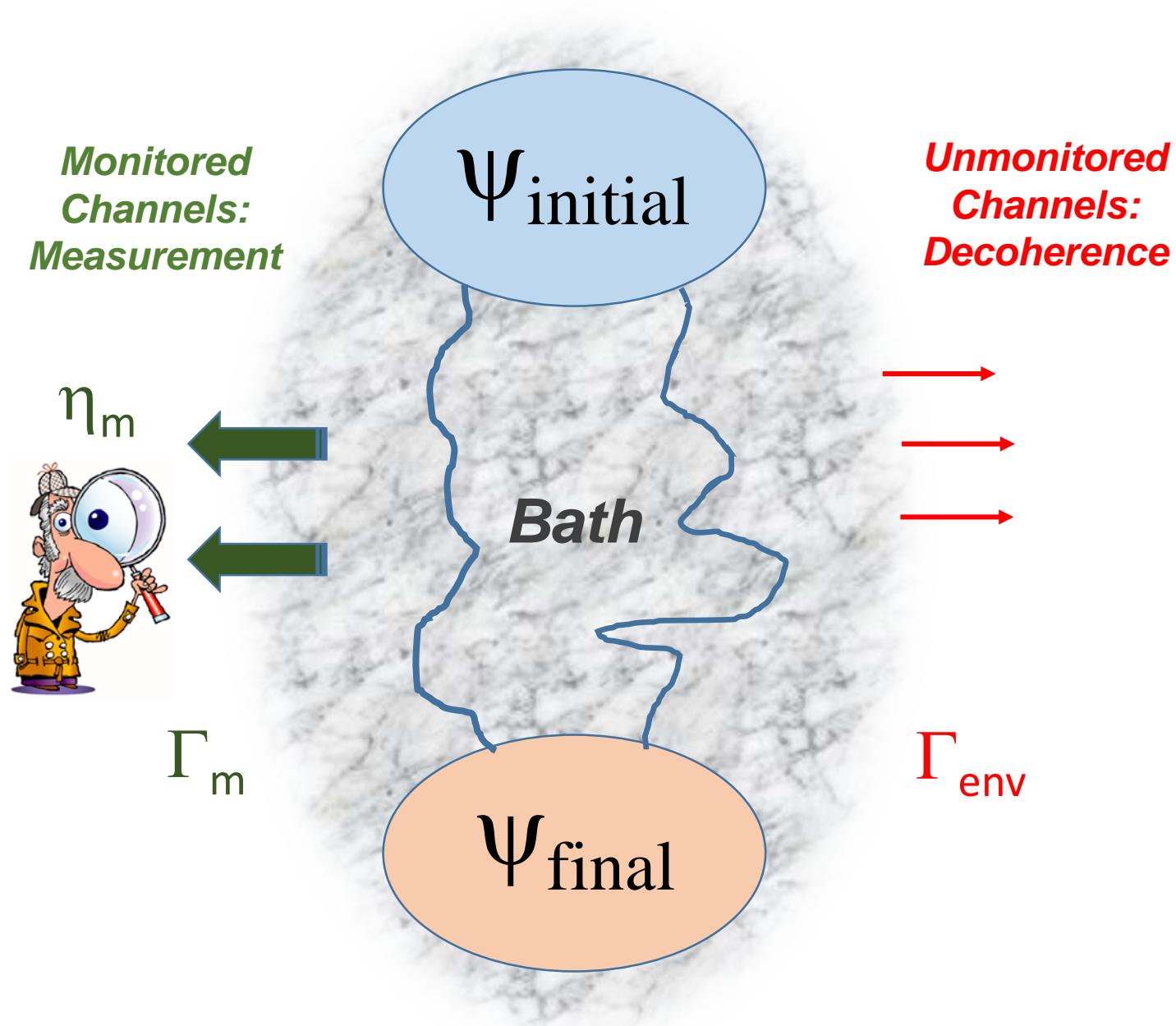
Adaptivedyne



Heterodyne



# OPEN QUANT. SYSTEMS: DECOHERENCE, MEASUREMENT, & THE BATH

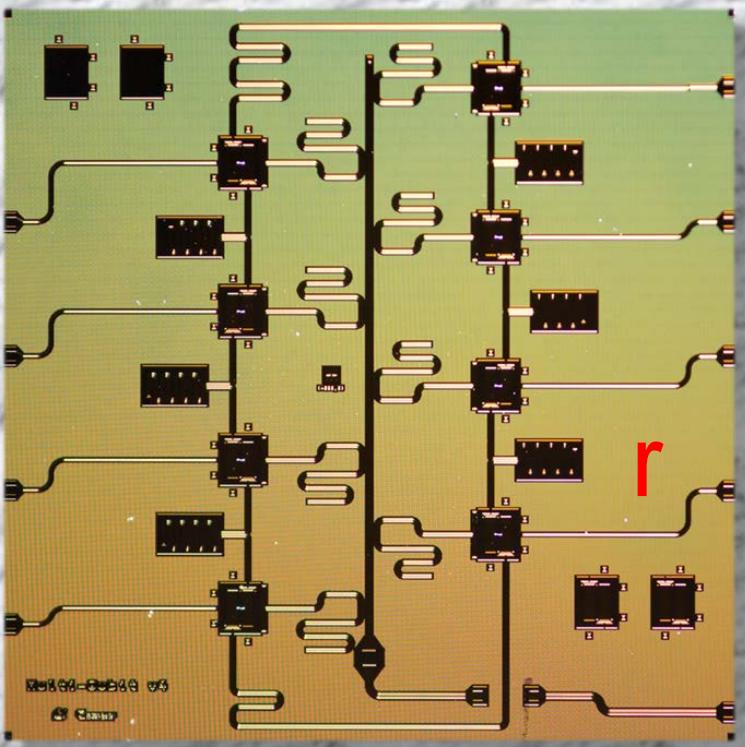


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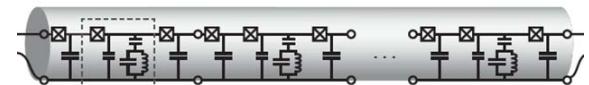
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# CREATING A CONFIGURABLE BATH

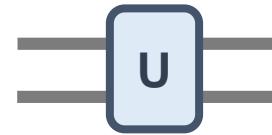


R

R:

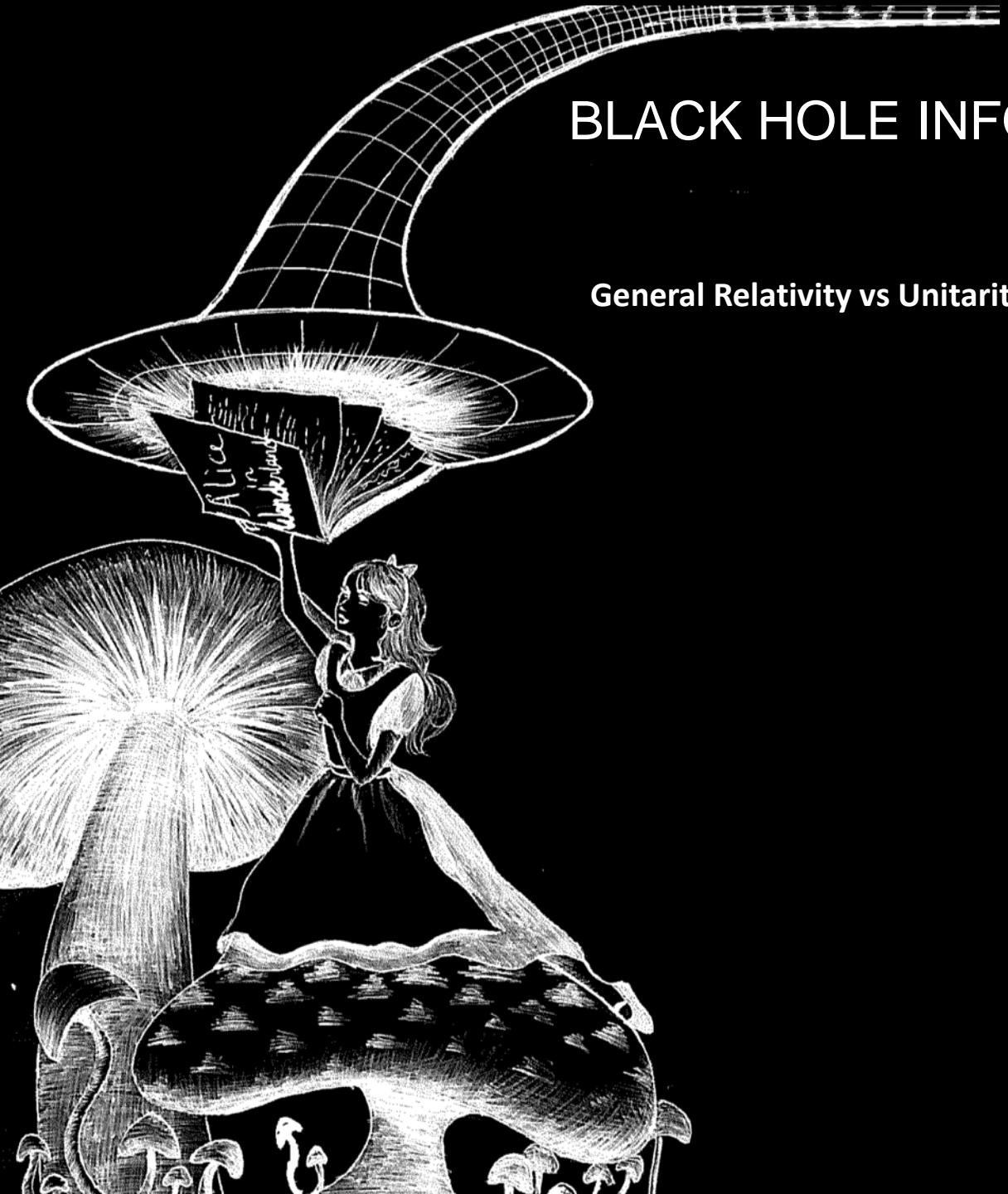


Infinite transmission line  
(eg. Caldeira-Leggett model)



CSUM  $|i, j\rangle = |i, i + j\rangle$

Scrambling Gate  
(eg. Sachdev-Ye-Kitaev model)

A black and white illustration of Alice from Lewis Carroll's "Alice's Adventures in Wonderland". Alice is standing in a fantastical landscape with large mushrooms and a caterpillar. Above her, a large, curved surface represents spacetime, with a grid pattern. A speech bubble from Alice contains the text "General Relativity vs Unitarity".

# BLACK HOLE INFORMATION PARADOX

General Relativity vs Unitarity

# BLACK HOLE INFORMATION PARADOX

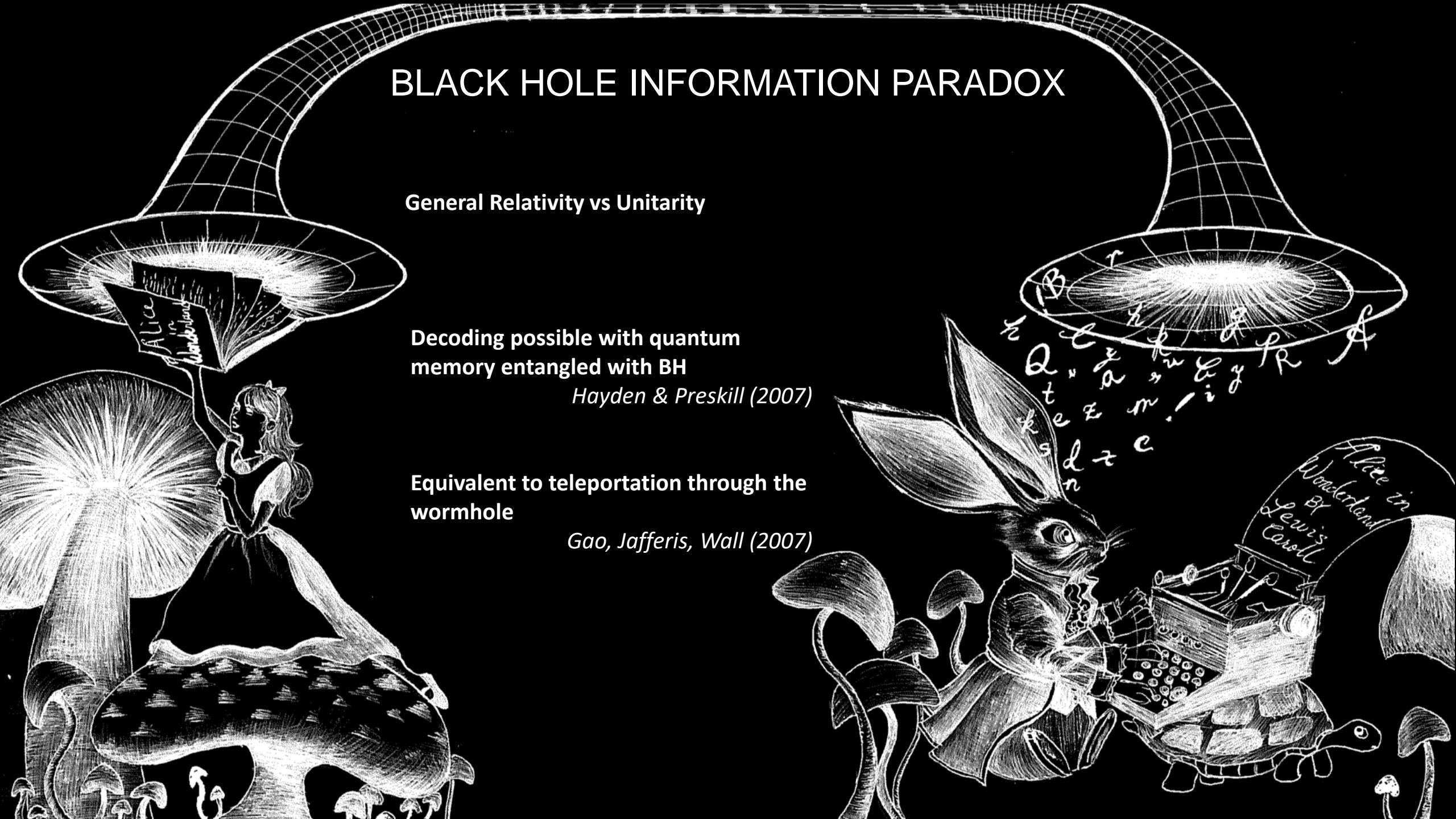
## General Relativity vs Unitarity

# Decoding possible with quantum memory entangled with BH

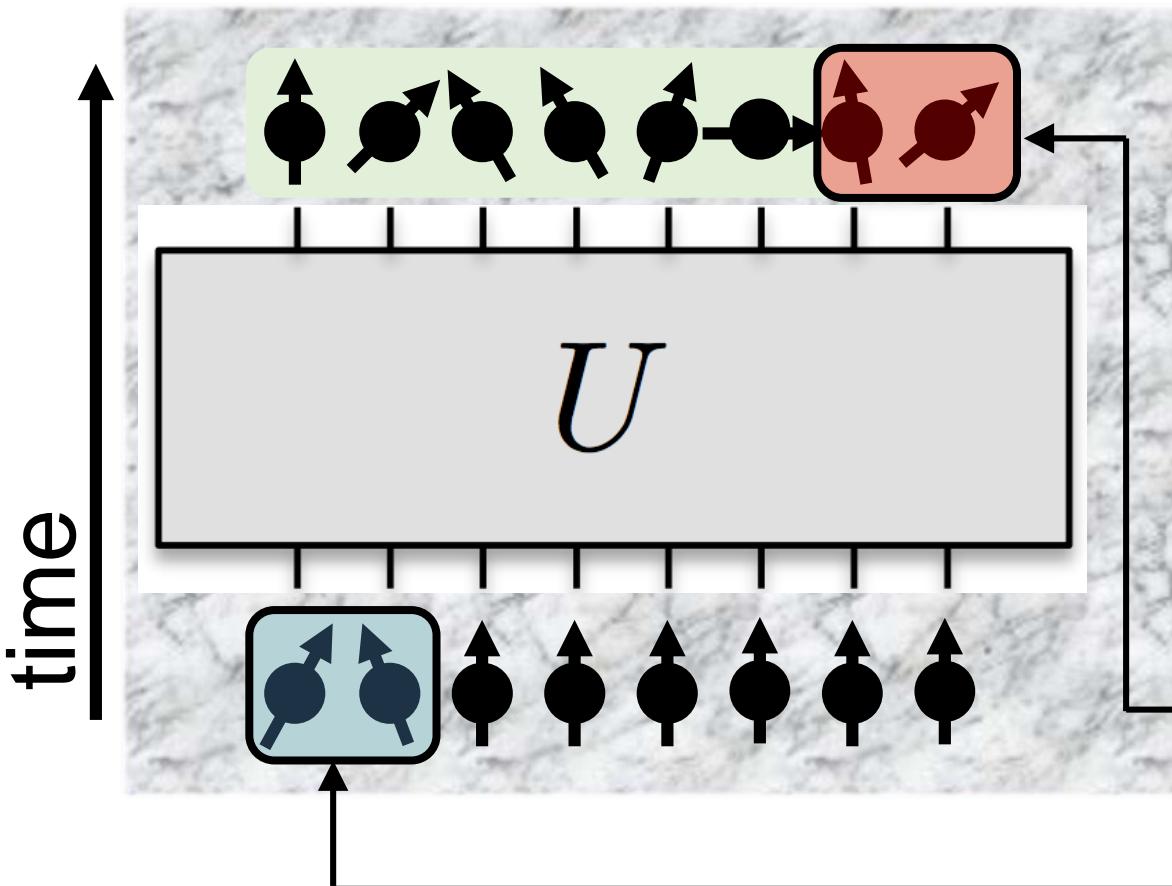
*Hayden & Preskill (2007)*

**Equivalent to teleportation through the wormhole**

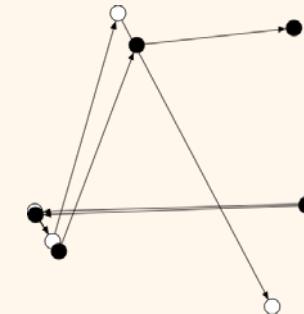
Gao, Jafferis, Wall (2007)



# MOTIVATION: STUDYING SCRAMBLING VIA OTOC



**Classical chaos:**  
Trajectories diverge exponentially

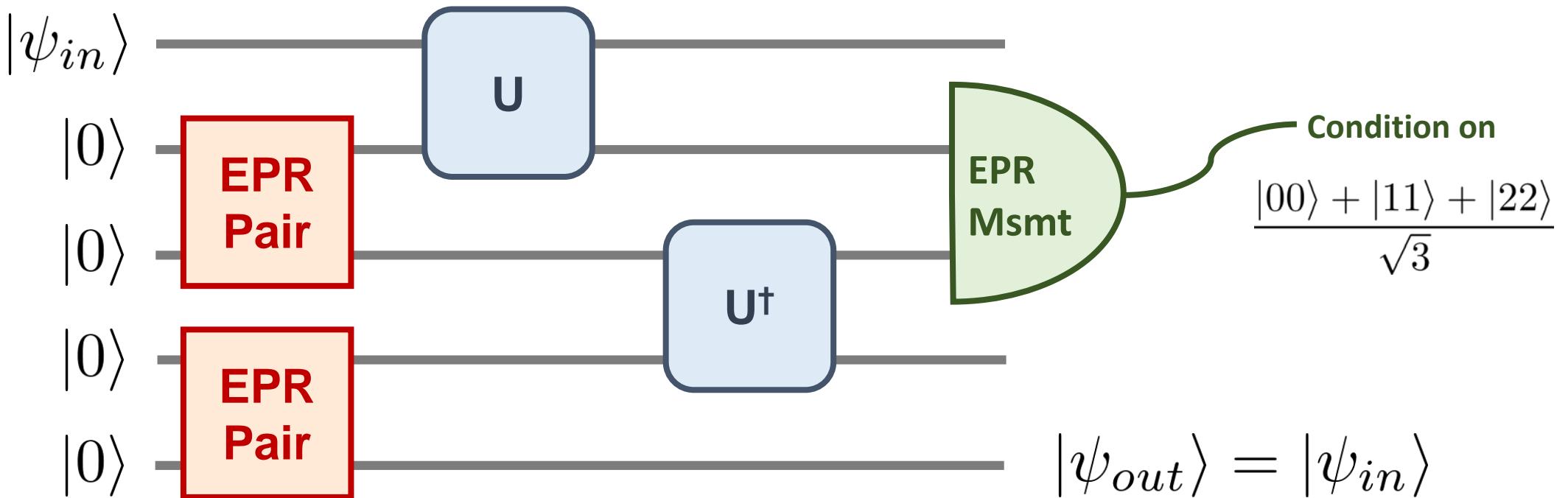


$$\frac{|\delta \mathbf{Z}(t)|}{|\delta \mathbf{Z}(0)|} \approx e^{\lambda t}$$

**Quantum scrambling:**  
Spread of correlations induces OTOC decay

$$\text{OTOC} = \langle V^\dagger W(t)^\dagger V W(t) \rangle$$

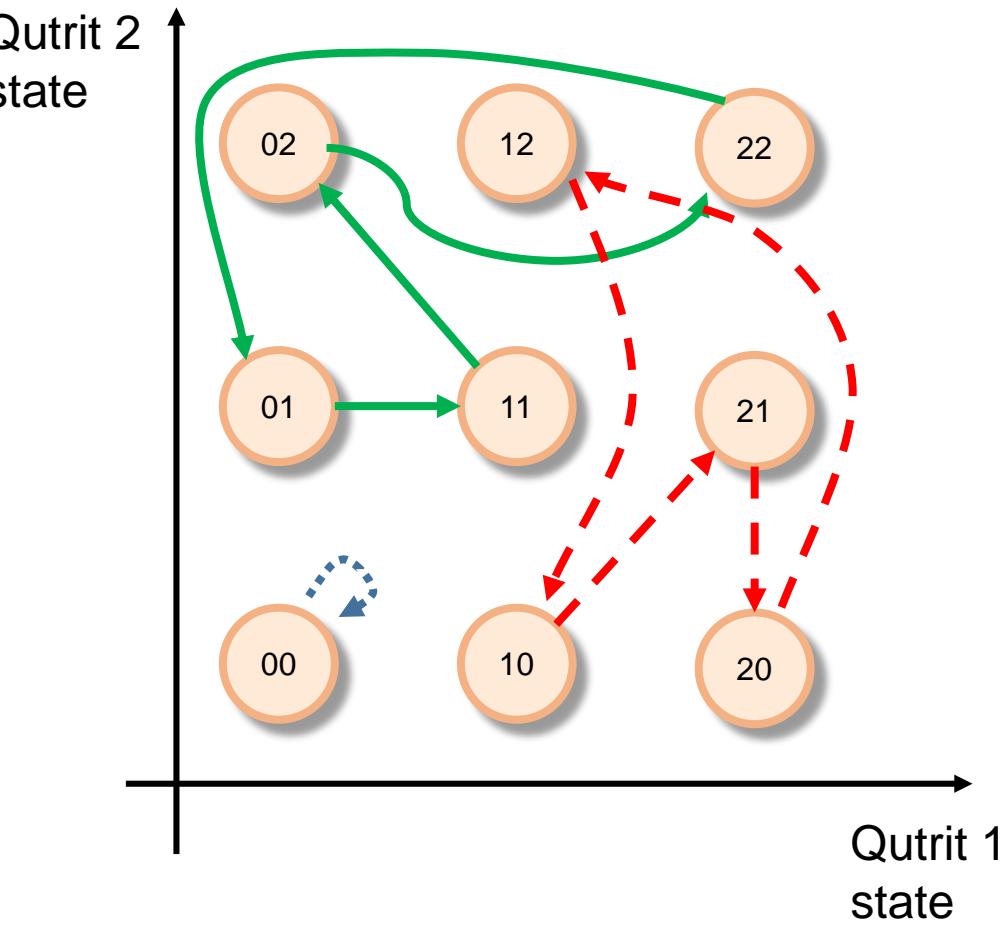
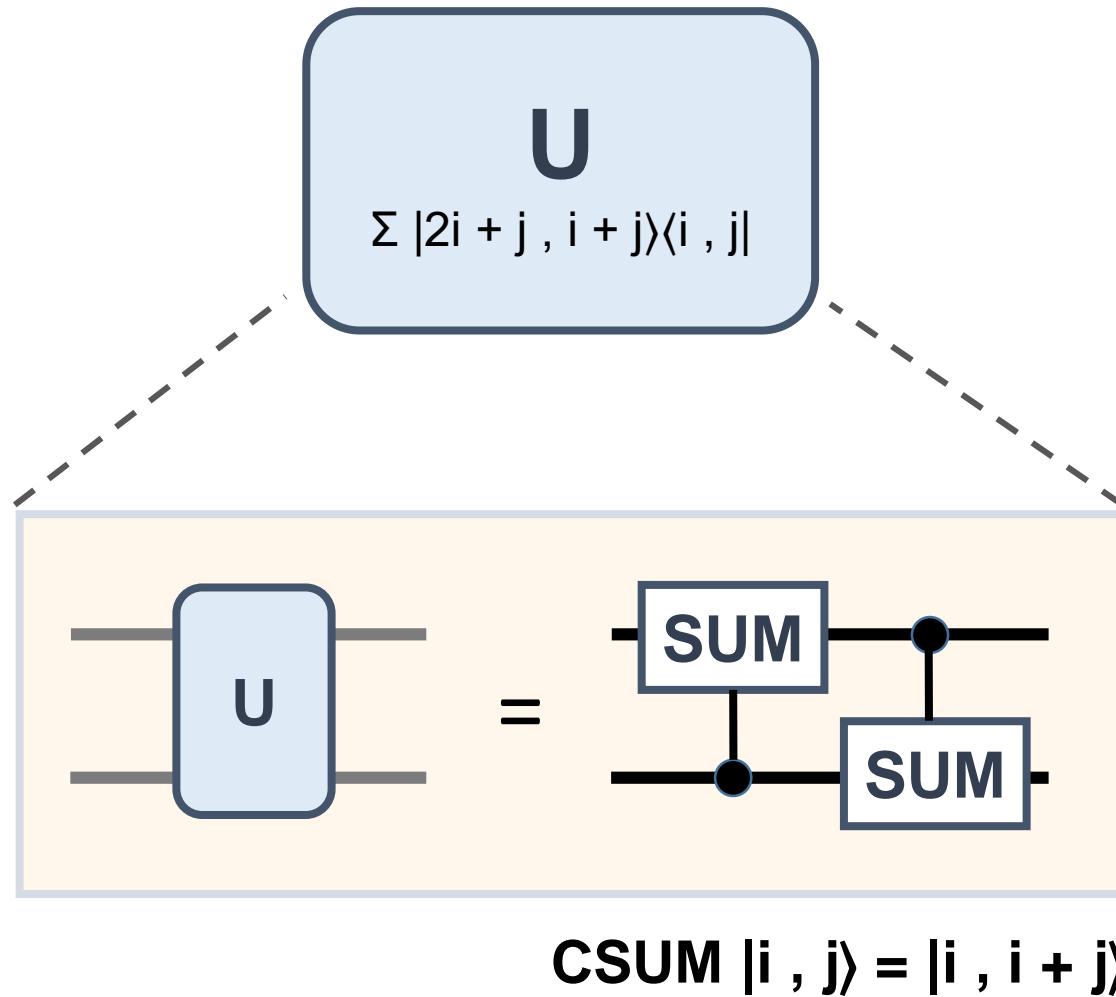
# QUTRIT TELEPORTATION CIRCUIT



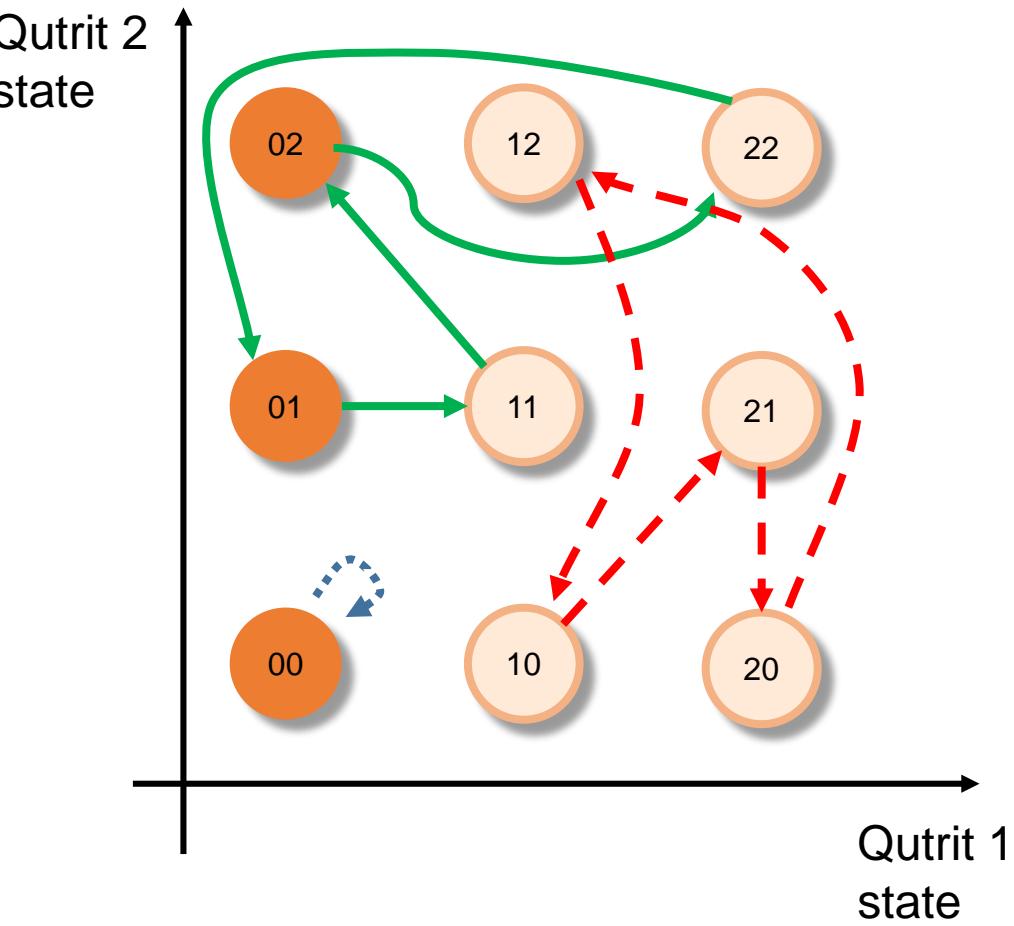
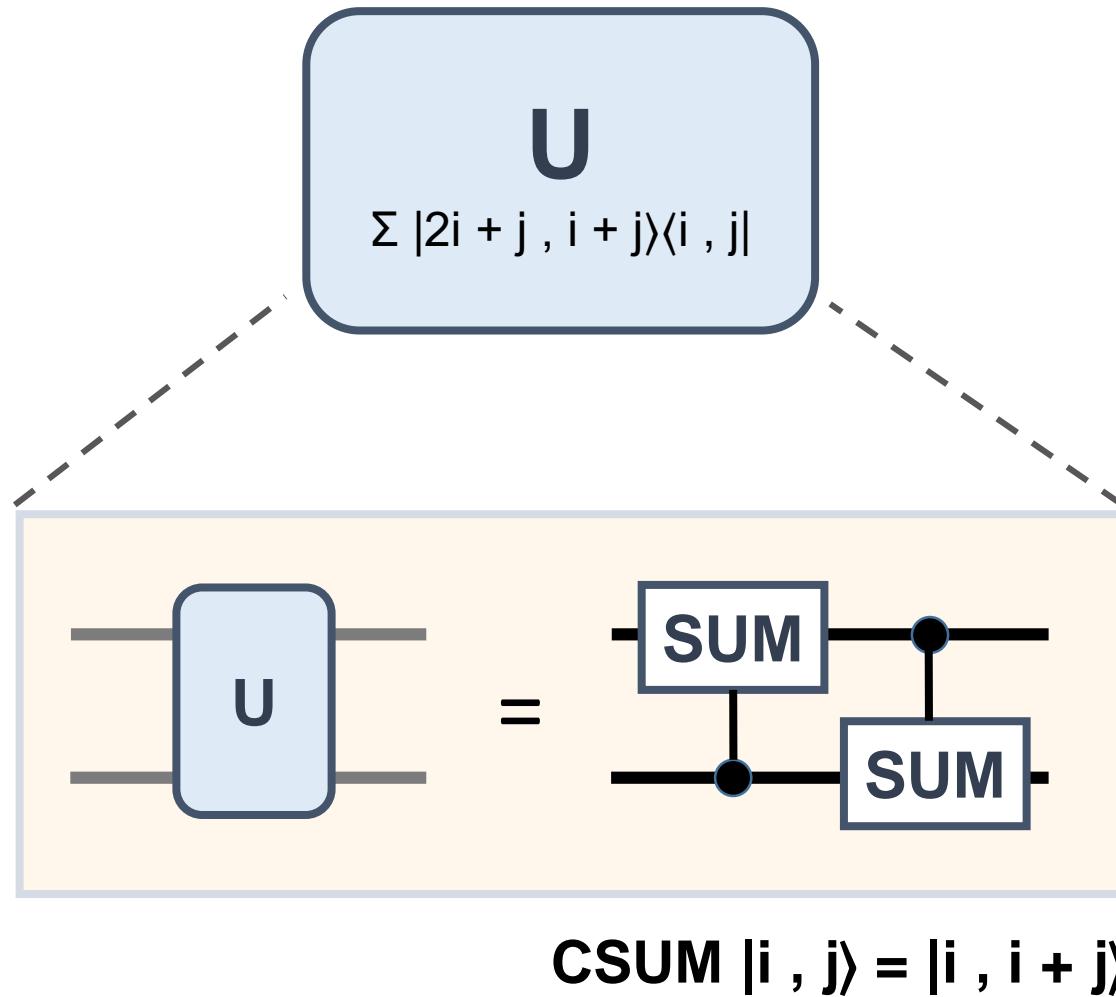
Qutrit EPR pair:  
 $\mathcal{N}(|00\rangle + |11\rangle + |22\rangle)$

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

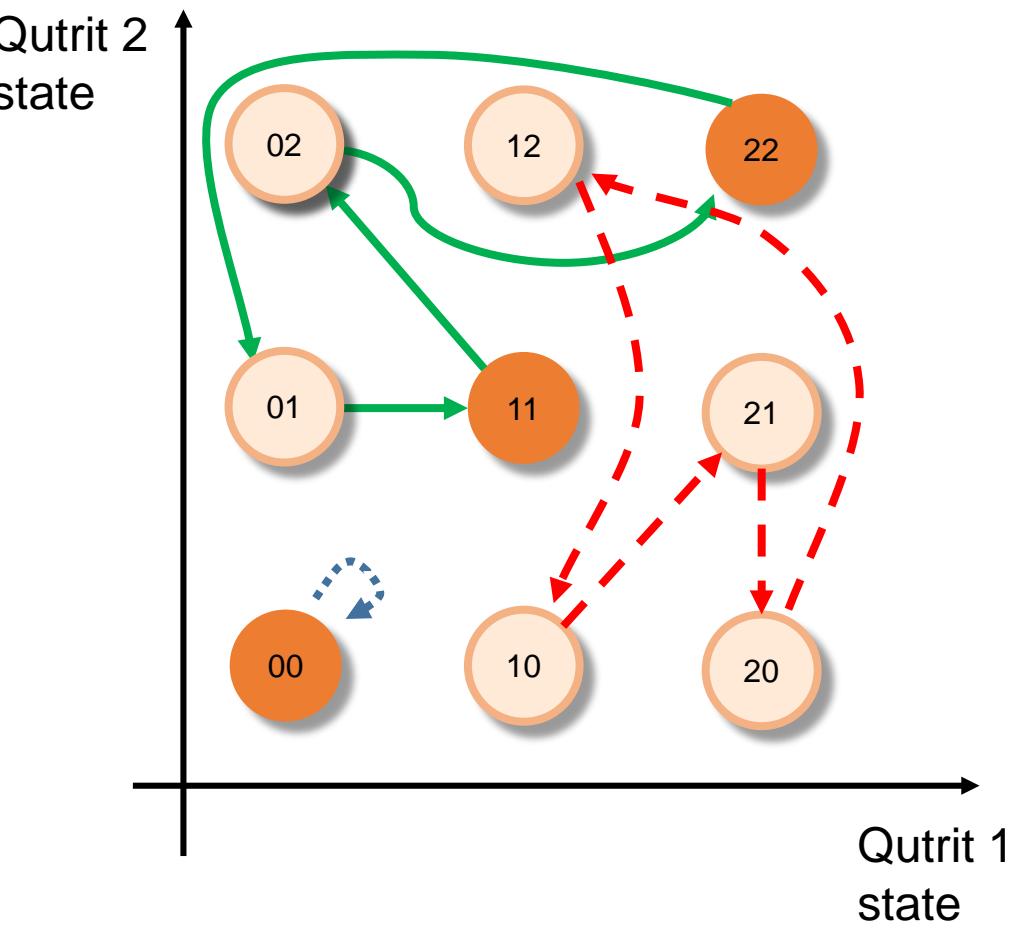
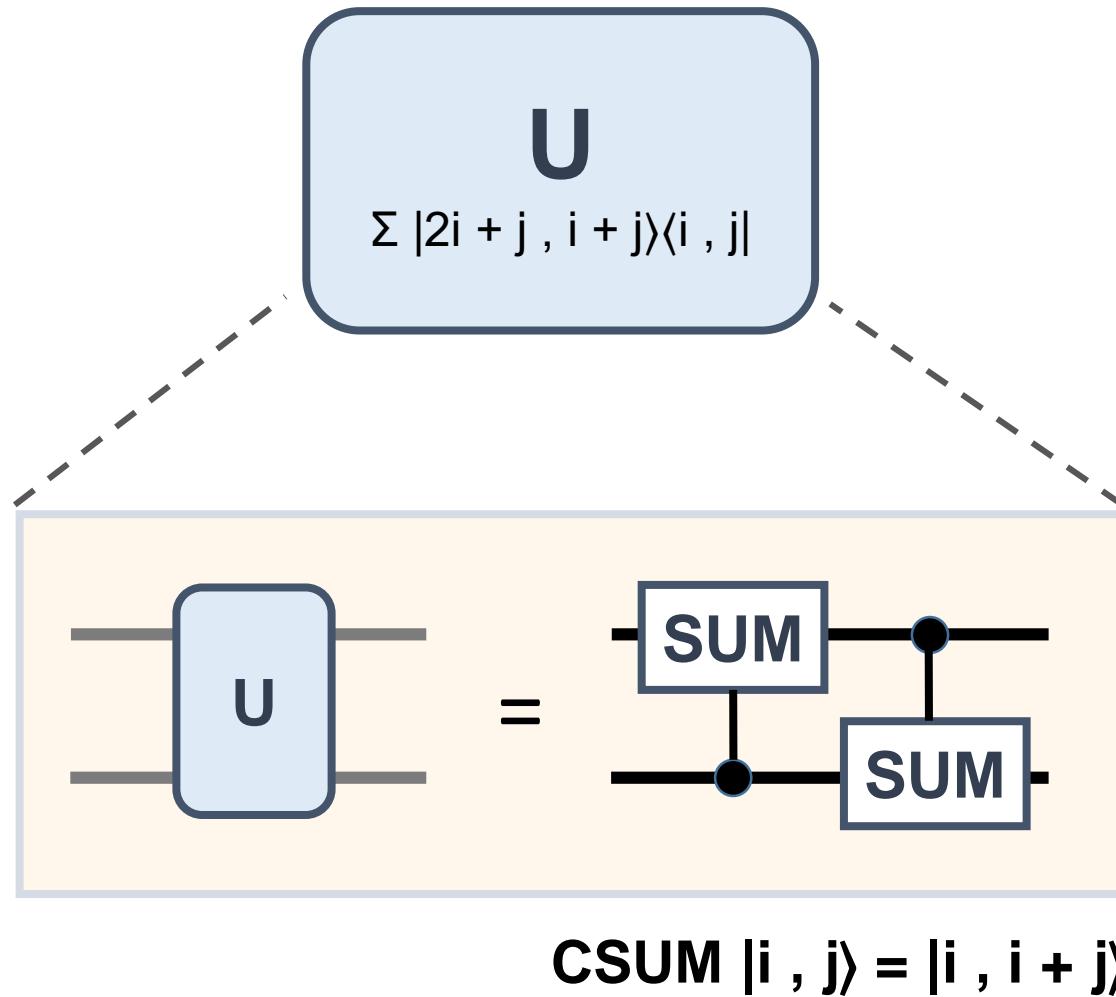
# SCRAMBLING UNITARY: A CLOSER LOOK



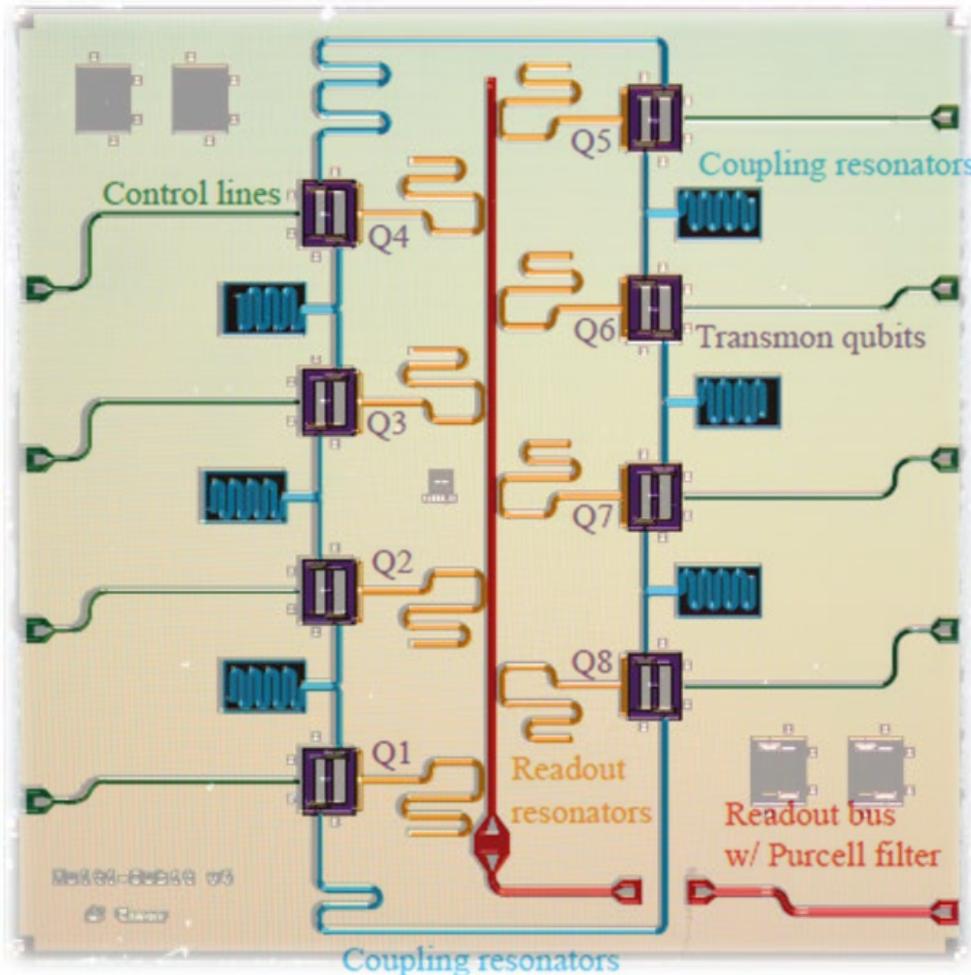
# SCRAMBLING UNITARY: A CLOSER LOOK



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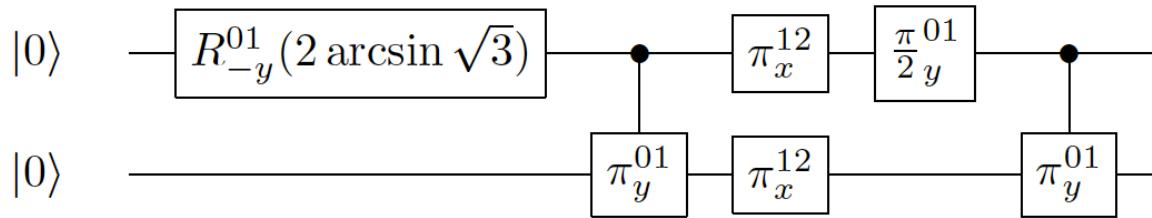
# 8 TRANSMON-RING QUANTUM PROCESSOR



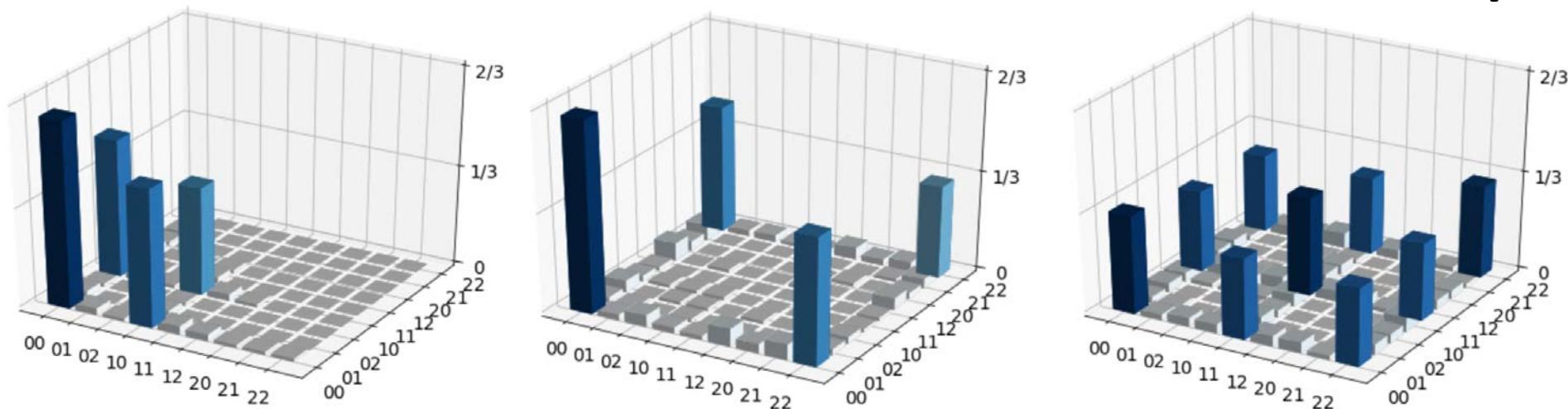
Readout: 99% (Average assignment fidelity)  
Single-qubit gates: 99.9% (20 ns, RB)  
Two-qubit gate: 94.7% (150 ns, CR-Gate, RB)

	$T_1$ ( $\mu\text{s}$ )	$T_2$ Ramsey ( $\mu\text{s}$ )	$T_2$ Echo ( $\mu\text{s}$ )	Frequency (GHz)
Q2	51 ( $\pm 3$ )	60 ( $\pm 6$ )	60 ( $\pm 3$ )	5.334
Q3	38 ( $\pm 7$ )	48 ( $\pm 1$ )	70 ( $\pm 1$ )	5.494
Q4	38 ( $\pm 5$ )	25 ( $\pm 5$ )	74 ( $\pm 7$ )	5.397
Q5	50 ( $\pm 1$ )	58 ( $\pm 5$ )	72 ( $\pm 1$ )	5.634
Q6	44 ( $\pm 4$ )	42 ( $\pm 9$ )	70.5 ( $\pm 2$ )	5.454
Q7	40	37	43	5.813
Q8				
Average	44 $\mu\text{s}$	47 $\mu\text{s}$	69 $\mu\text{s}$	

# EPR PAIR GENERATION



**F = 0.94**

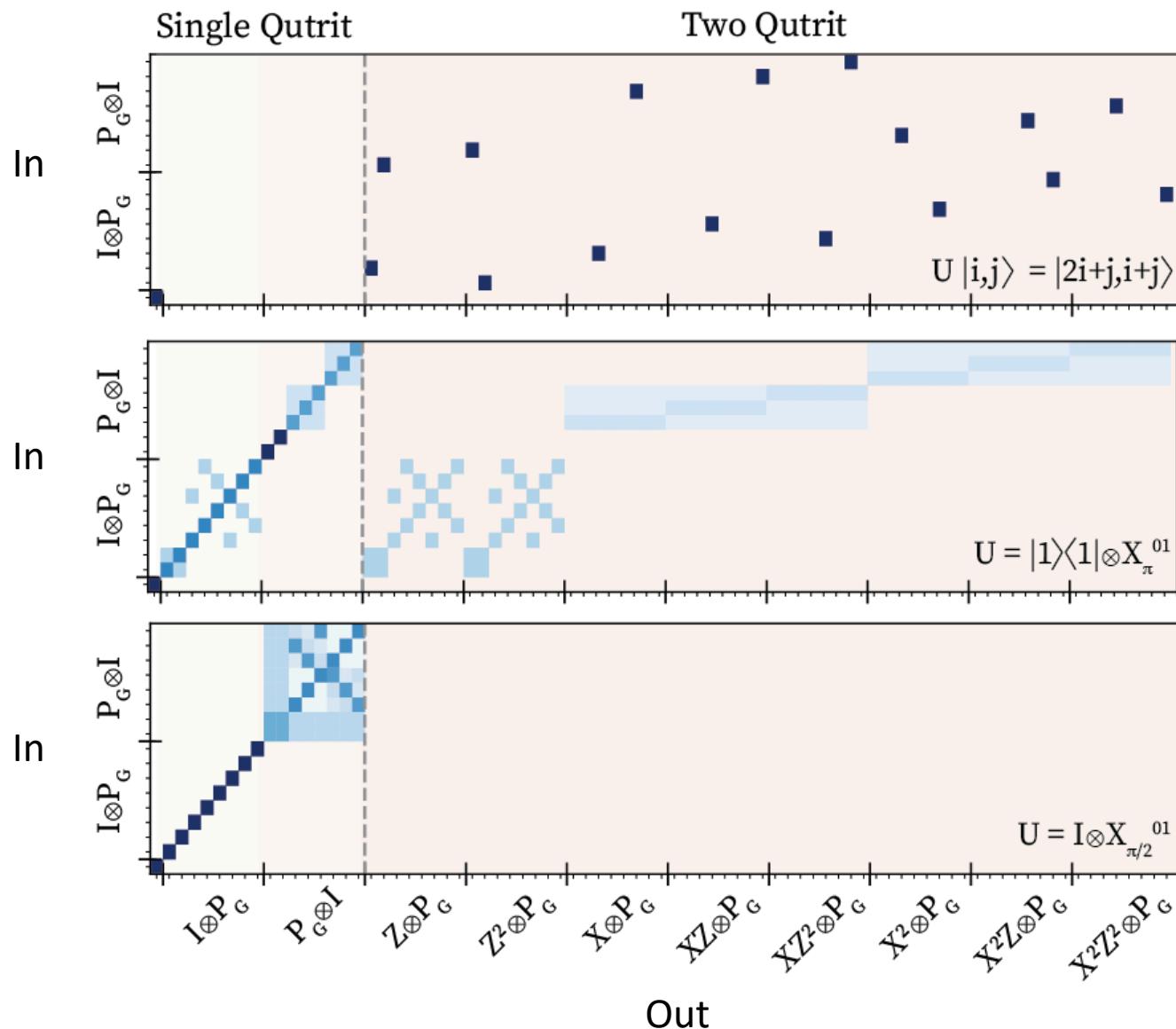


$$\sqrt{\frac{2}{3}}|00\rangle + \sqrt{\frac{1}{3}}|10\rangle$$

$$\sqrt{\frac{2}{3}}|00\rangle + \sqrt{\frac{1}{3}}|11\rangle$$

$$\sqrt{\frac{1}{3}}|00\rangle + \sqrt{\frac{1}{3}}|11\rangle + \sqrt{\frac{1}{3}}|22\rangle$$

# SCRAMBLING IN PROCESS TOMOGRAPHY



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

## Simulations

## PERSPECTIVES

- QUANTUM TRAJECTORIES ARE A DIAGNOSTIC TOOL
  - Parameter Estimation (A. Jordan, A. Korotkov, J. Dressel)
  - Improve two qubit gate fidelities ?
- TRAJECTORIES OF MANY BODY ENTANGLED STATES; TOMOGRAPHY ?
- MACHINE LEARNING ?
- REAL-TIME FEEDBACK, ADAPTIVE MEASUREMENTS
- QUANTUM PROCESSORS CAN SIMULATE DIFFERENT BATHS