Quantum measurement and control with superconducting qubits

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Outline:

- Possible violation of modified Helstrom bound (with Todd Brun)
- Generalized measurement of superconducting qubits (with Todd Brun)
- Suppression of Purcell relaxation in s/c qubit meas.
- Experiments with s/c qubits: entanglement by measurement and lifetime increase by uncollapse
- Future plans

UCR team partially supported by ARO MURI

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Supported papers since last review (Dec. 2013)

Published:

1. J. Dressel, T.A. Brun, and A.N. Korotkov, “Implementing generalized measurements with superconducting qubits”, *Phys. Rev. A*, 032302 (2014).
2. J. Dressel and A.N. Korotkov, “Avoiding loopholes with hybrid Bell-Leggett-Garg inequalities”, *Phys. Rev. A* 89, 012125 (2014).
3. A.V. Rodionov, A. Veitia, R. Barends, J. Kelly, D. Sank, J. Wenner, J.M. Martinis, R.L. Kosut, and A.N. Korotkov, “Compressed sensing quantum process tomography for superconducting quantum gates”, *Phys. Rev. B* 90, 144504 (2014).
4. Y.P. Zhong, Z.L. Wang, J.M. Martinis, A.N. Cleland, A.N. Korotkov, and H. Wang, “Reducing the impact of intrinsic dissipation in a superconducting circuit by quantum error detection”, *Nature Communications* 5, 3135 (2014).
5. E.A. Sete, J.M. Gambetta, and A.N. Korotkov, “Purcell effect with microwave drive: suppression of qubit relaxation rate, *Phys. Rev. B* 89, 104516 (2014).
6. E.A. Sete and H. Eleuch, “Strong squeezing and robust entanglement in cavity electromechanics, *Phys. Rev.* A 89, 013841 (2014).
7. A.N. Korotkov, “Quantum Bayesian approach to circuit QED measurement”, in Quantum machines: Measurement and Control of engineered quantum systems, edited by M. Devoret et al. (Oxford Univ. Press, 2014), 533.

Supported papers since last review (cont.)

Published:

8. N. Roch, M.E. Schwartz, F. Motzoi, C. Macklin, R. Vijay, A.W. Eddins, A.N. Korotkov, K. B. Whaley, M. Sarovar, and I. Siddiqi, “Observation of measurement-induced entanglement and quantum trajectories of remote superconducting qubits”, *Phys. Rev. Lett.* 112, 170501 (2014).
9. S. Pang, J. Dressel, and T.A. Brun, “Entanglement-assisted weak value amplification”, *Phys. Rev. Lett.* 113, 030401 (2014).

Submitted:

1. J. Dressel, T.A. Brun, and A.N. Korotkov, ”Violating the modified Helstrom bound with nonprojective measurements”, arXiv:1410.0096.
2. K.Y. Bliokh, J. Dressel, and F. Nori, “Conservation of the spin and orbital angular momenta in electromagnetism”, arXiv:1404.5486.
3. E.A. Sete, H. Eleuch, and C.H.R. Ooi, “Light-to-matter entanglement transfer in optomechanics”, arXiv:1401.5205.

Violating the modified Helstrom bound with nonprojective (generalized) measurements

J. Dressel, T.A. Brun, and A.N. Korotkov, arXiv:1410.0096

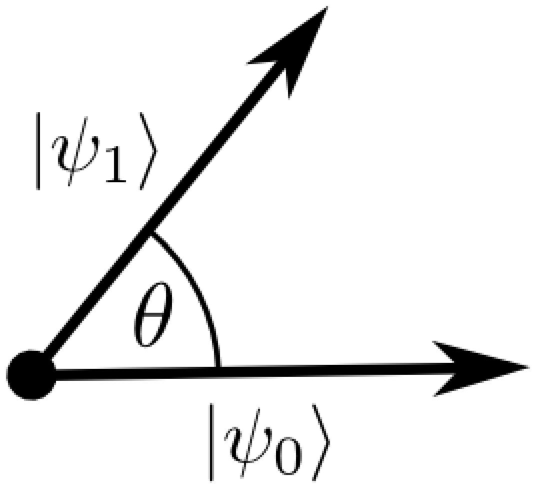
Motivation

Superconducting qubits can now implement generalized measurements (more on this later)

$$|\psi_{\rm fin,r}\rangle = \frac{M_{\rm r}\,|\psi_{\rm in}\rangle}{\rm Norm} \qquad \sum_{\rm r} M_{\rm r}^{\dagger} M_{\rm r} = 1$$

What is another good example where they are better than projective measurements (besides quantum feedback, etc.)?

State discrimination



Alice prepares one of two states with equal probability

Bob measures the state and guesses which it is

Minimum error probability (***Helstrom Bound***):

$$\min p_w = \frac{1}{2}\left(1 - \sin\theta\right)$$

C.W. Helstrom, Inf. Control 10, 254 (1967)

An option to decline

If Bob can decline to guess,
the problem becomes more interesting.

Two of the three outcomes are unfavorable,
and can be penalized differently.

Generalized measurements can be better.
(All three outcomes are nontrivially included.)

Unambiguous State Discrimination is a special case
with zero error and minimum declined guesses.

I.D. Ivanovic, Phys. Lett. A 123, 257 (1987)
D. Dieks, Phys. Lett. A 126, 303 (1988)
A. Peres, Phys. Lett. A 128, 19 (1988)

Cost function

Relative penalty

$$C = p_w + k\, p_d$$

Wrong guess

Decline

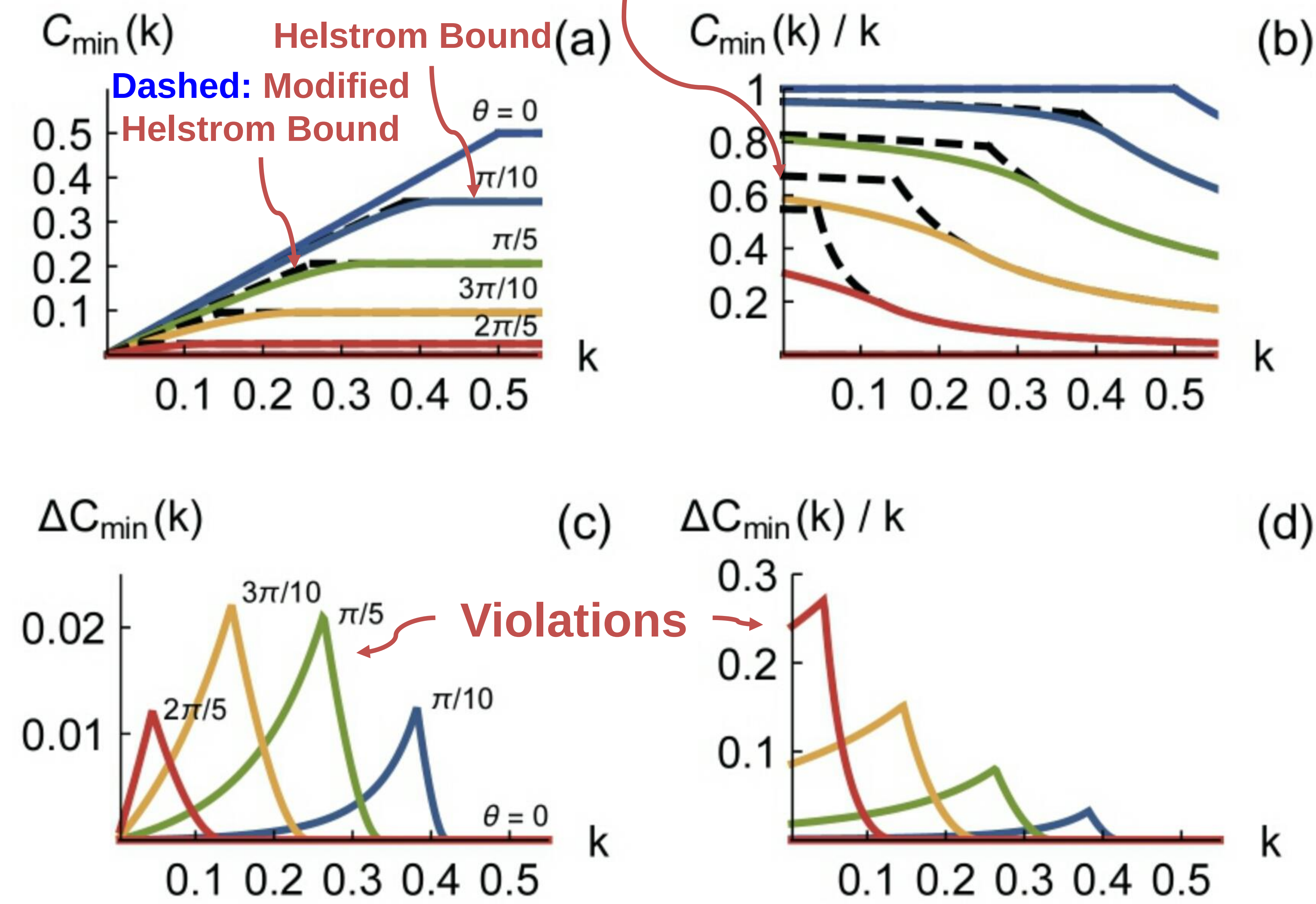
Minimizing this cost finds the
optimal measurement strategy

The minimum cost obtainable with **projective** measurements is the ***modified Helstrom Bound***

$$C_{\mathrm{MH}} = \min\Big\{(1-|\sin\theta|)/2,\ \big[1+2k-\sqrt{1-2k(1-k)(1+\cos 2\theta)}\big]/4\Big\}.$$

Solid: optimized over generalized measurements

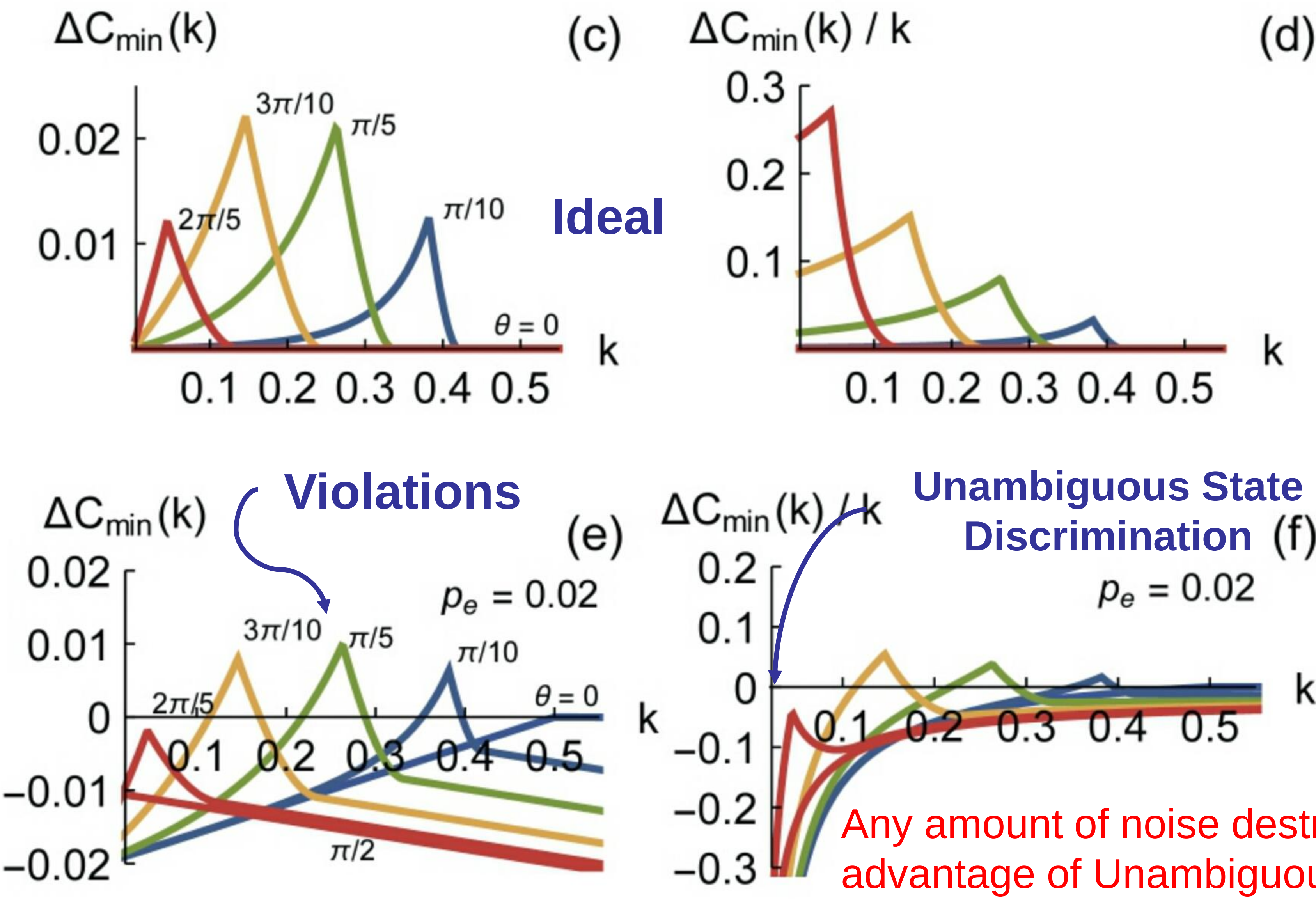
Unambiguous State Discrimination



What about experimental imperfections?

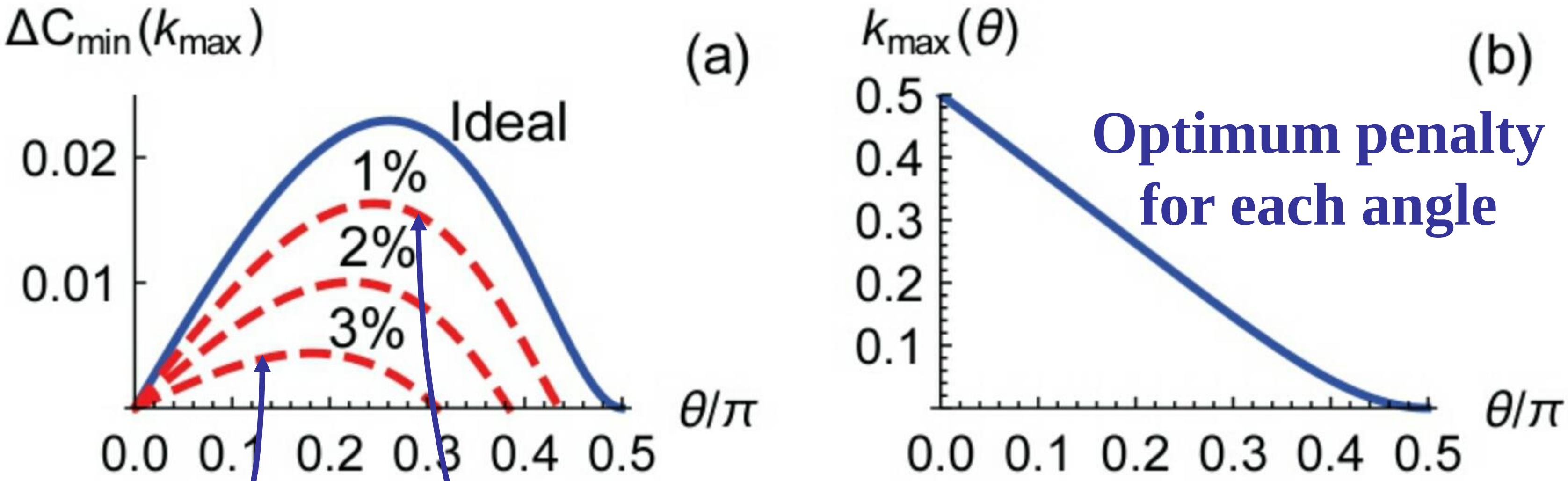
Does the advantage persist?

2% misidentification noise



Any amount of noise destroys advantage of Unambiguous State Discrimination

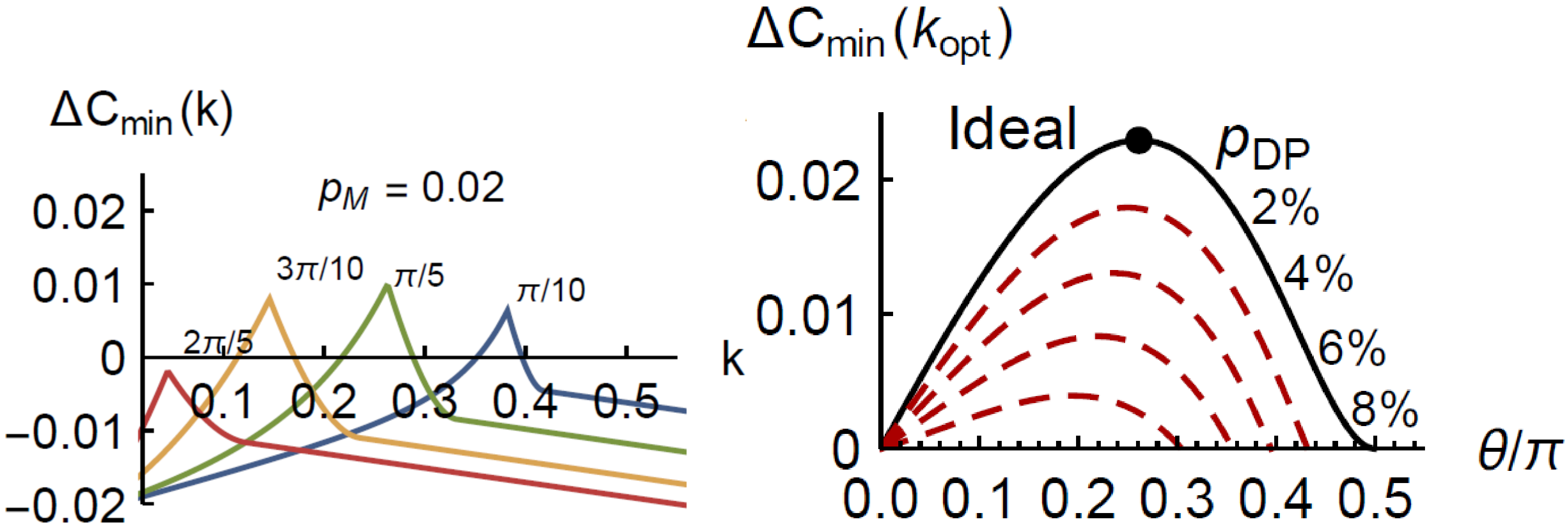
Maximum violation vs. angle



Current readout error at UCSB

Effect of noise

Effect of (depolarizing) decoherence



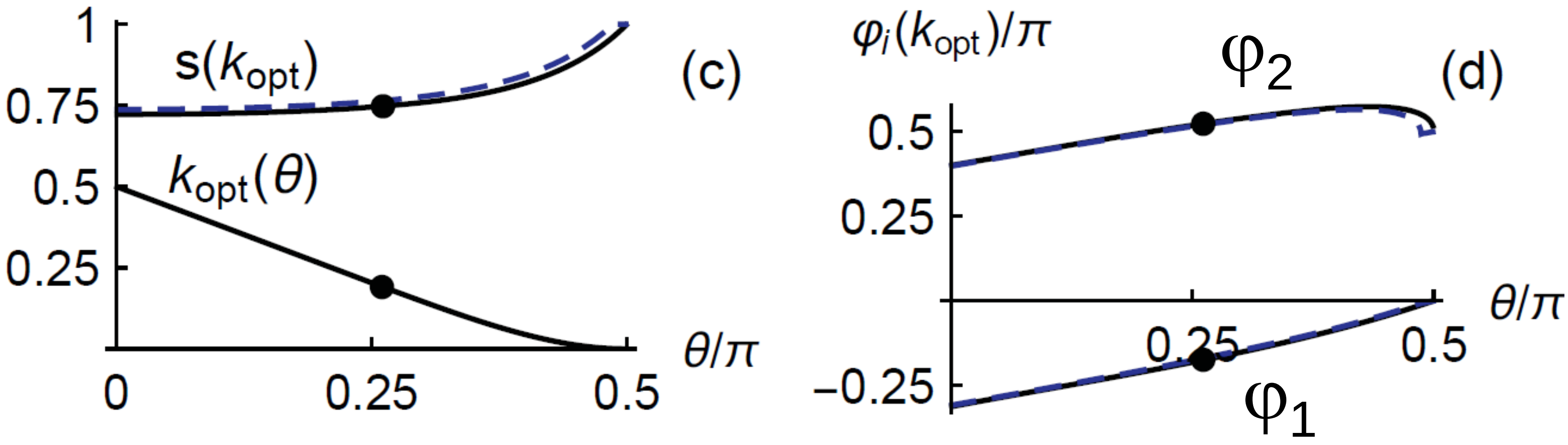
- Up to 10% decoherence can be tolerated for optimal cost
- For unambiguous state discrimination any decoherence is not tolerated
- Similar to misidentification noise

Implementation with superconducting qubits

Cascaded measurement:

1) Partial projection with strength *s* along direction φ_1

2) Projective measurement along direction φ_2



Summary
(violation of modified Helstrom bound)

Generalized measurements can **outperform** projective measurements in state discrimination.

The maximum improvements are small, but are **resilient** to < 4% readout noise and <10% decoherence.

Current technology at UCSB could measure this violation.

Advantage of unambiguous state discrimination is **destroyed** with **any** amount of noise.

Implementing generalized measurements with superconducting qubits

J. Dressel, T.A. Brun, and A.N. Korotkov,
Phys. Rev. A 90, 032302 (2014)

Any two-outcome generalized measurement of a qubit can be decomposed into **unitary gates** and **partial projections**.

Measurement operator

Unitary gates

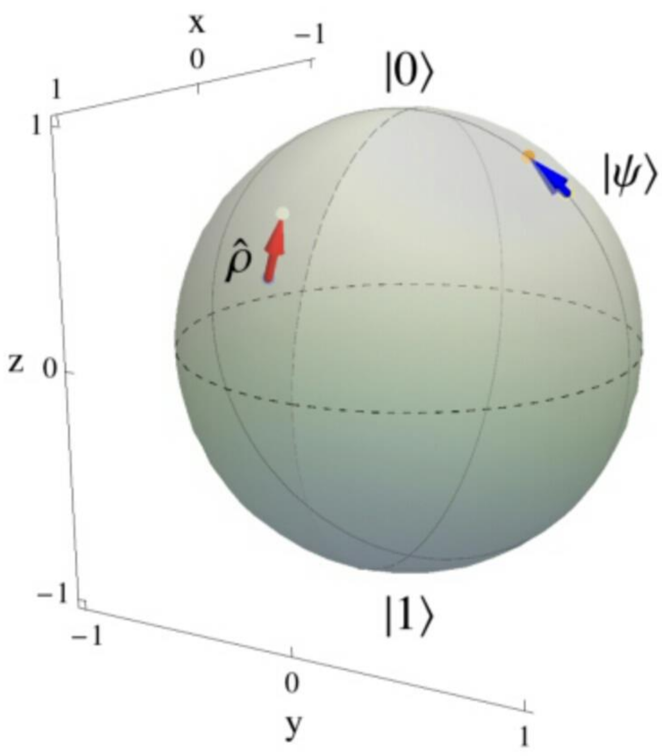
$$N_{0,1} = U_{0,1} D_{0,1} V^\dagger$$

Partial Projection

Many-outcome measurement of a qubit can be decomposed into sequences of two-outcome measurements.

Partial projections

Qubit only partially collapses ("nudged" toward 0 or 1)



Measurement Operators

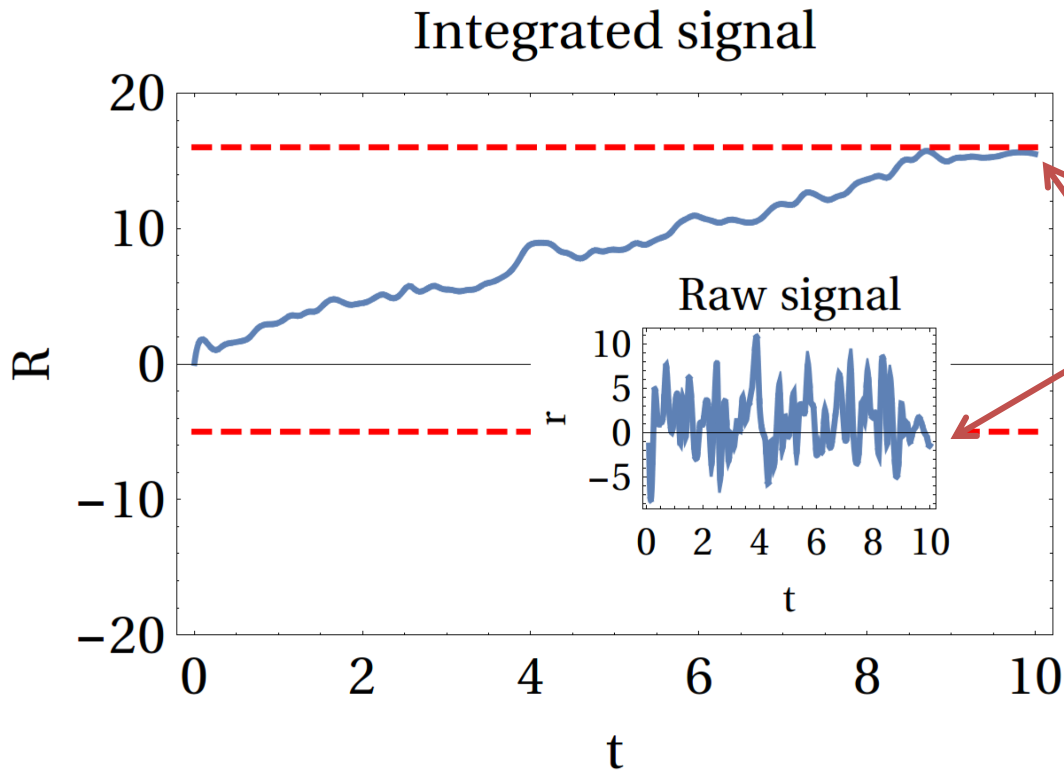
$$D_0 = \sqrt{p}\,|0\rangle\langle 0| + \sqrt{1-q}\,|1\rangle\langle 1|$$
$$D_1 = \sqrt{1-p}\,|0\rangle\langle 0| + \sqrt{q}\,|1\rangle\langle 1|$$

Partial projections implementations

1. **Continuous readout with thresholds**
   - Natural for UC Berkeley group technology
   - Limited by measurement efficiency
   - Simple procedure
   - No additional qubits

2. **Using ancilla qubit**
   - Natural for UCSB and other groups technology
   - Limited by decoherence and readout/gate fidelity
   - Standardized circuits (can be optimized)
   - Qubit technology-independent

Thresholded continuous readout
(quantum feedback by stopping)



Raw signal

$$r(t) = 2\,\frac{I(t) - I_c}{\Delta I}$$

Thresholds (for stopping)

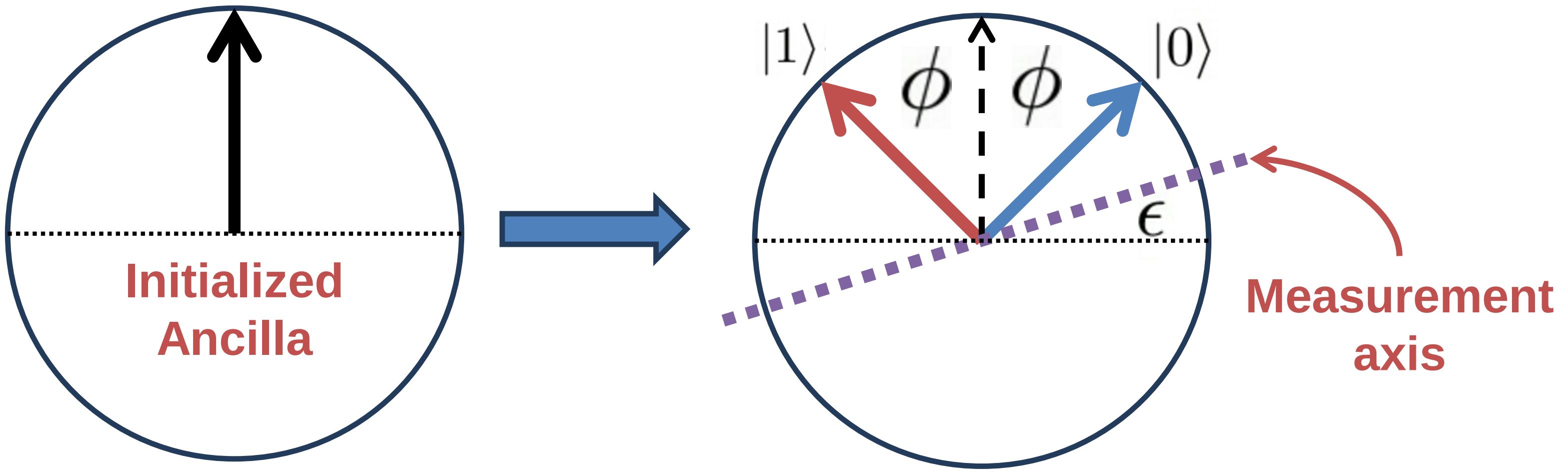
$$R_0 = \frac{1}{2}\ln\left(\frac{p}{1-q}\right)$$

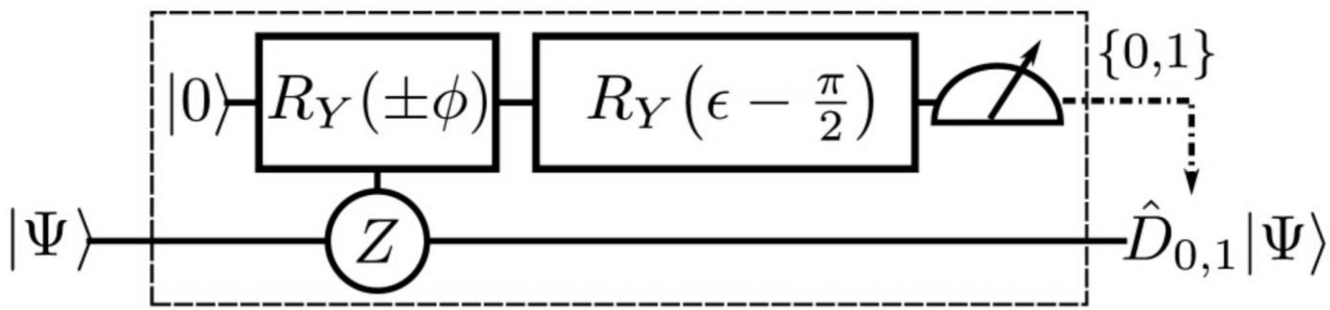
$$R_1 = -\frac{1}{2}\ln\left(\frac{q}{1-p}\right)$$

$$D_{0,1} = \sqrt{C_{0,1}}\left[e^{R_{0,1}/2}\,|0\rangle\langle 0| + e^{-R_{0,1}/2}\,|1\rangle\langle 1|\right]$$

Inefficient measurement degrades fidelity.

Ancilla-based partial projection

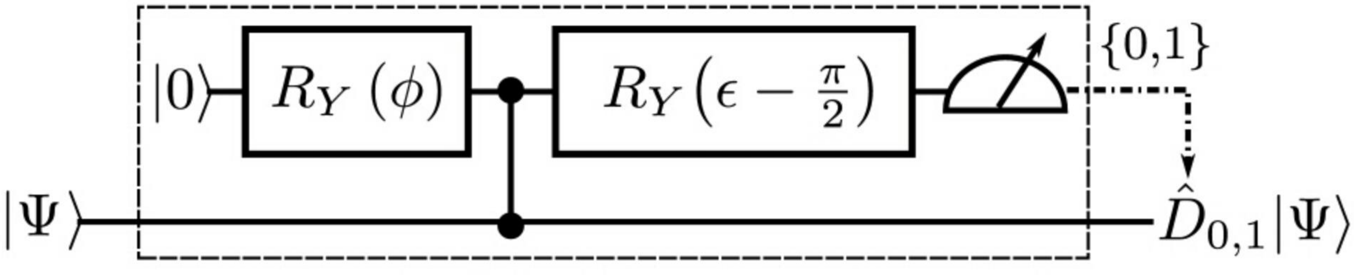




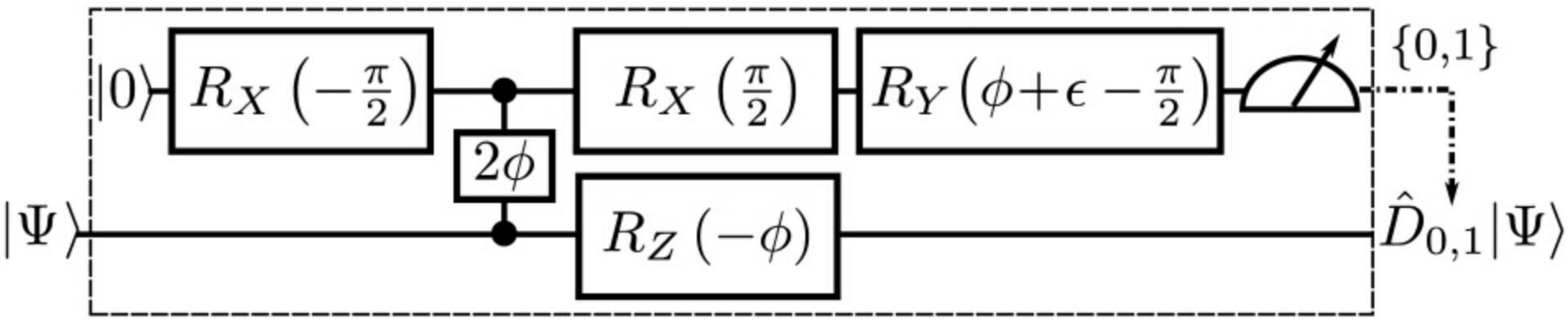
$$p = \frac{1}{2}\left[1 + \sin(\phi + \epsilon)\right] \qquad q = \frac{1}{2}\left[1 + \sin(\phi - \epsilon)\right]$$

Implementations

Control Z Entangling Gate



Control Phase Entangling Gate



Limited by dephasing, gate fidelity, and readout errors.

Fidelity for a single measurement outcome

$$\rho \mapsto \sum_{i,j} \chi_{ij} E_i \rho E_j^\dagger$$

Pauli operators

Process Matrix

Fidelity for an imperfect unitary gate

$$F = \mathrm{Tr}(\chi^{\mathrm{ideal}}\chi)$$

Fidelity for an imperfect purity-preserving operation (outcome k)

$$F^{(k)} = \frac{\mathrm{Tr}(\chi^{(k),\,\mathrm{ideal}}\chi^{(k)})}{\mathrm{Tr}(\chi^{(k),\,\mathrm{ideal}})\,\mathrm{Tr}(\chi^{(k)})}$$

$$p_k = \mathrm{Tr}(\chi^{(k)})$$

Normalized by average probability

Fidelity for generalized measurement (all outcomes)

Must include outcome fidelities and average probabilities

Proposal 1: Linear in outcome fidelities

$$F^{\rm tot} = \sum\nolimits_k \sqrt{p_k^{\rm ideal} p_k}\, F^{(k)} = \sum_k \frac{{\rm Tr}(\chi^{(k),{\rm ideal}}\chi^{(k)})}{\sqrt{{\rm Tr}(\chi^{(k),{\rm ideal}})\,{\rm Tr}(\chi^{(k)})}}$$

Proposal 2: Extension of probability distribution fidelity

$$\tilde{F}^{\rm tot} = [\sum\nolimits_k \sqrt{p_k^{\rm ideal} p_k\, F^{(k)}}]^2 = \left[\sum\nolimits_k \sqrt{{\rm Tr}(\chi^{(k),{\rm ideal}}\chi^{(k)})}\right]^2$$

Summary
(generalized measurements with s/c qubits)

Partial projections can be implemented by thresholding continuous readout, or with an ancilla qubit

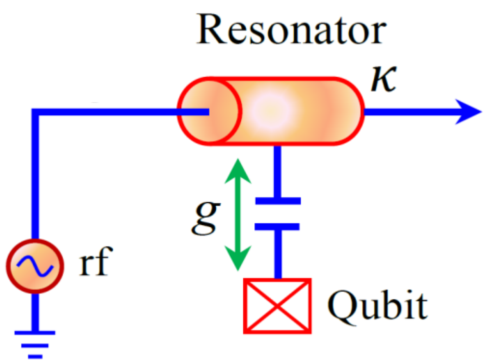
Any two-outcome generalized measurement can be decomposed into unitary gates and partial projections

Many-outcome measurements can be decomposed into sequences of two-outcome measurements

Introduced measurement fidelity definitions

Purcell effect with microwave drive: suppression of qubit relaxation rate

E. Sete, J. Gambetta, and A. Korotkov, PRB 89, 104516 (2014)



n photons in resonator on average (coherent state)

"Usual" Purcell effect: energy relaxation of a qubit via coupling with leaking resonator

$$\Gamma_0 = \kappa \frac{g^2}{\Delta^2}$$

κ – resonator bandwidth
g – qubit-resonator coupling
Δ – detuning (Δ>>g)

Will qubit relaxation rate increase or decrease if rf drive is applied (e.g. for measurement)?

Somewhat surprising answer: relaxation rate decreases with n in nonlinear regime

3 approaches:
- ad-hoc analytics (relatively simple)
- formal perturbation theory (quite lengthy)
- direct numerical calculation

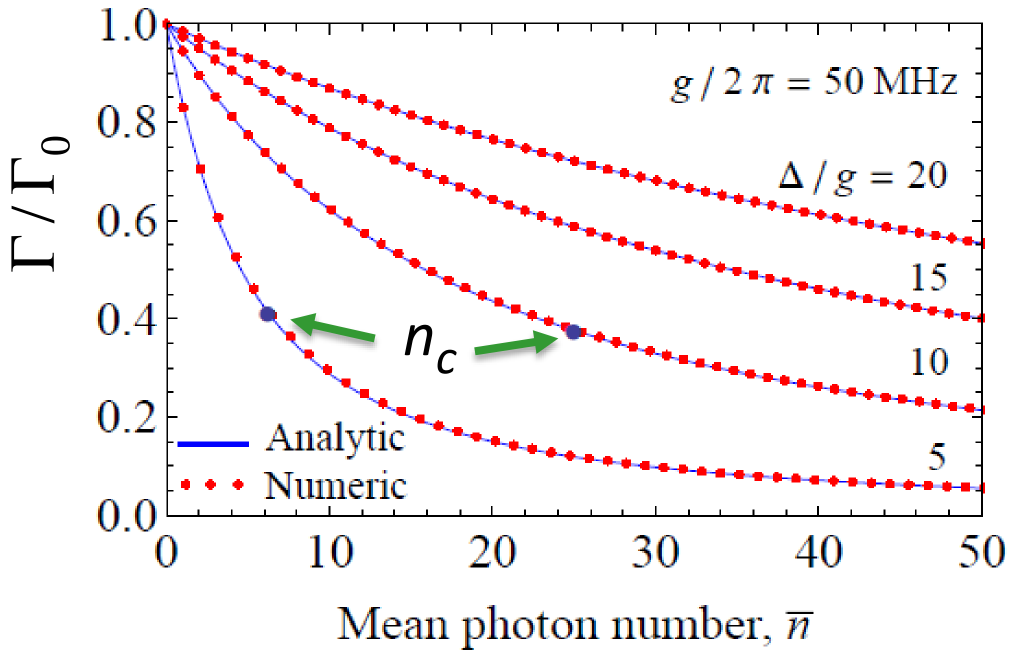
All results are in agreement with each other

Purcell rate suppression

$$\Gamma = \kappa \left| \overline{\langle g,n} | a | \overline{e,n\rangle} \right|^2 \qquad \Gamma = \frac{\kappa g^2}{\Delta^2} \left(\frac{1}{1+\bar{n}/n_c} + \frac{1}{\sqrt{1+\bar{n}/n_c}} \right)^2$$

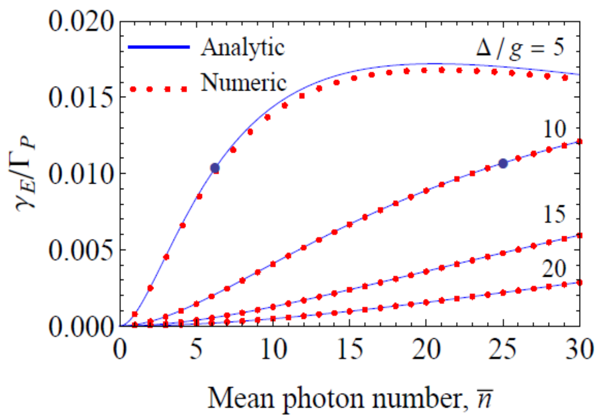
$$n_c = \Delta^2 / 4g^2$$

(critical photon number)



Also a weak qubit excitation

(much weaker than relaxation)



Some physical interpretation of suppression

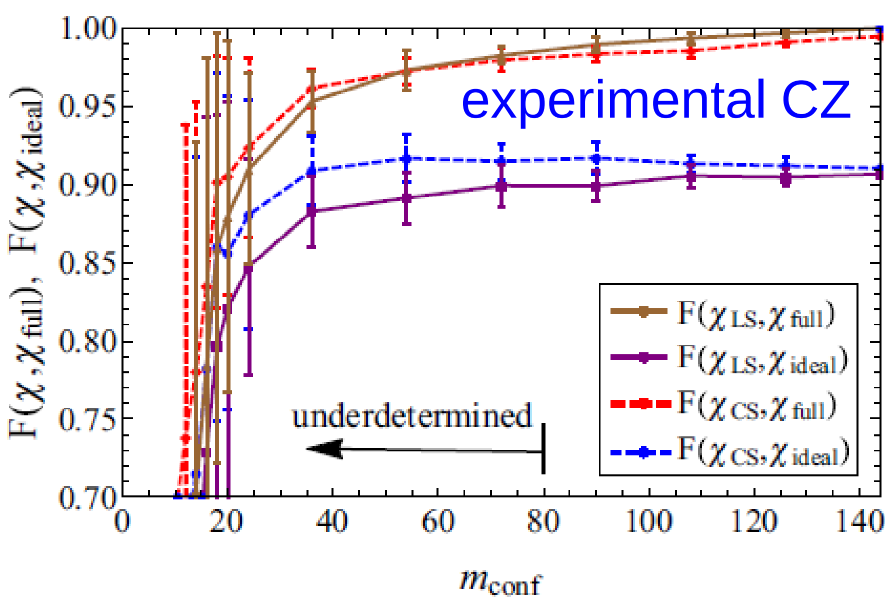
Due to ac Stark shift, which increases effective detuning
(but no quantitative agreement)

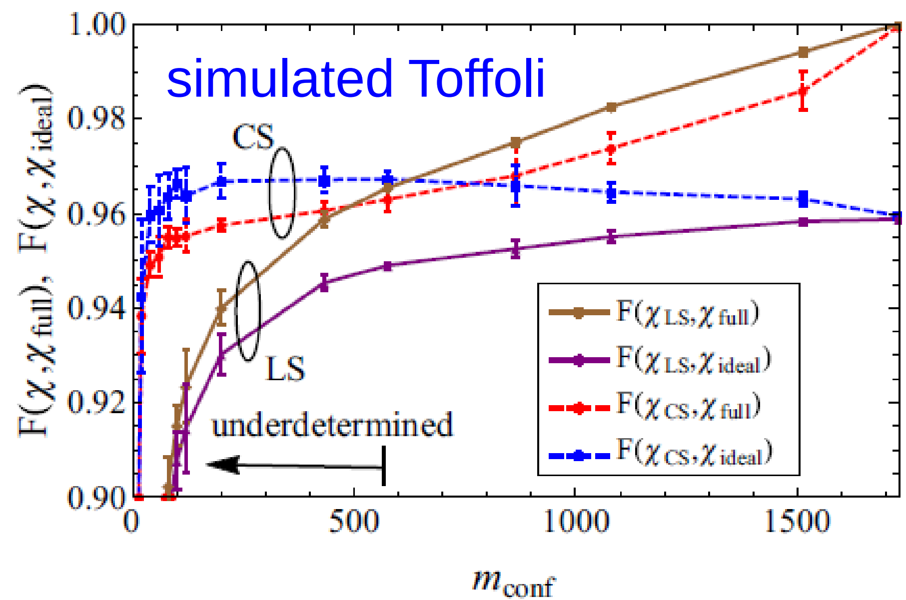
Probably has been observed experimentally (Delft, Berkeley)

Now we are working on generalization including Purcell filter

Compressed Sensing QPT

A.V. Rodionov, A. Veitia, R. Barends, J. Kelly, D. Sank, J. Wenner, J.M. Martinis, R.L. Kosut, and A.N. Korotkov, Phys. Rev. B 90, 144504 (2014)

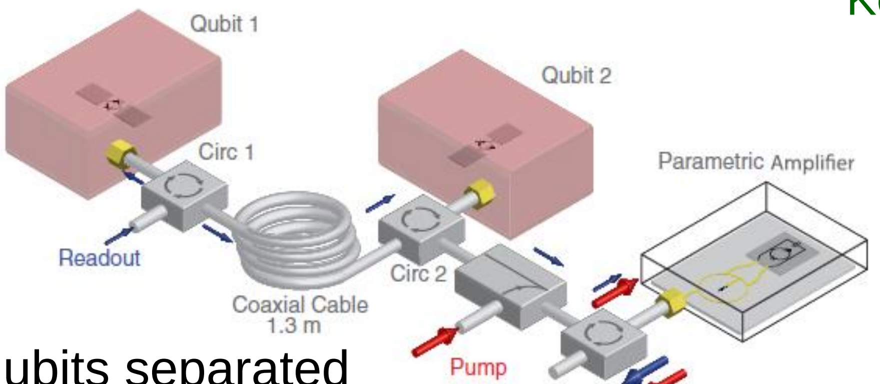




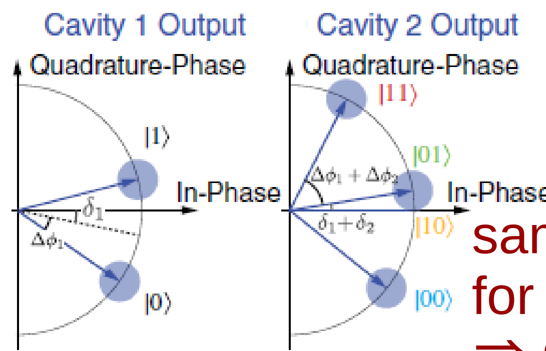
- Compressed Sensing Quantum Process Tomography can reduce amount of data by a factor of ~7 for 2-qubit CZ gate and a factor of ~40 for 3-qubit Toffoli
- CS QPT works better than least-square estimate in the underdetermined case
- Rapid scaling of computational resources makes it very difficult to extend the CS QPT to 4 and more qubits

Measurement-induced entanglement of remote qubits

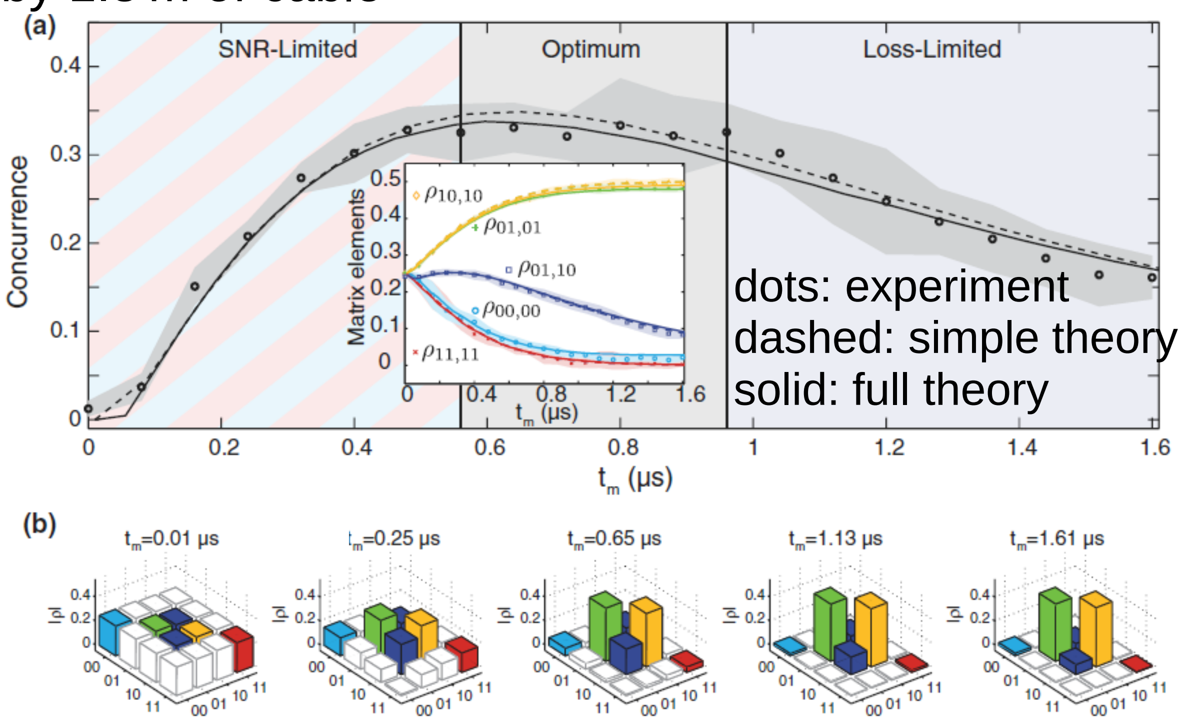
Roch, Schwartz, Motzoi, Macklin, Vijay, Eddins, Korotkov, Whaley, Sarovar, Siddiqi, PRL- 2014



qubits separated by 1.3 m of cable



same output signal for $|01\rangle$ and $|10\rangle$ $\Rightarrow$ entanglement



dots: experiment
dashed: simple theory
solid: full theory

- First demonstration of remote entanglement of superconducting qubits
- "Feedback" by selecting or not selecting
- Remote entanglement is much more difficult than local
- Simple theory is close to full quantum trajectory, fits well experimental data.

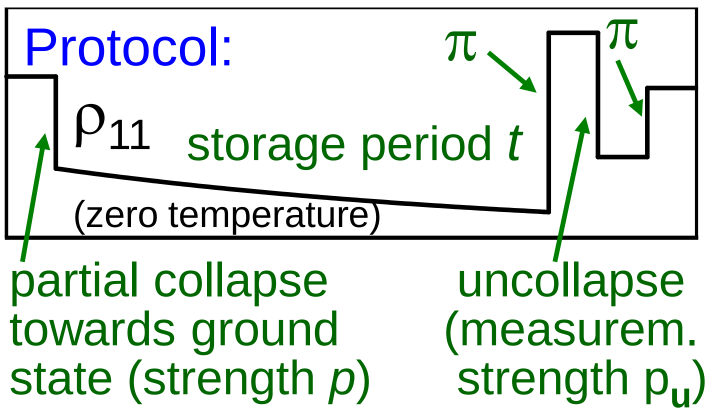
Increasing qubit lifetime by uncollapse

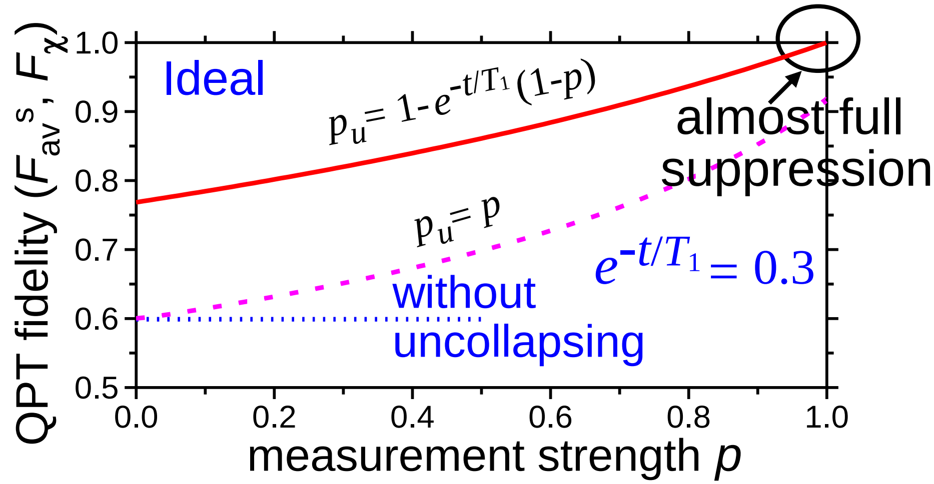
Y. P. Zhong, Z. L. Wang, J. M. Martinis, A. N. Cleland,
A. N. Korotkov, and H. Wang, *Nature Comm*. 5, 3135 (2014)

- First experiment, showing increase of intrinsic lifetime of a superconducting qubit (by a factor of ~3) using a quantum algorithm
- Based on uncollapsing, realized with partial quantum measurement
- Caveat: selective procedure ("quantum error detection", not "error correction")

Suppression of energy relaxation by uncollapse

A. Korotkov & K. Keane, PRA-2010





Ideal case (T_1 during storage only)

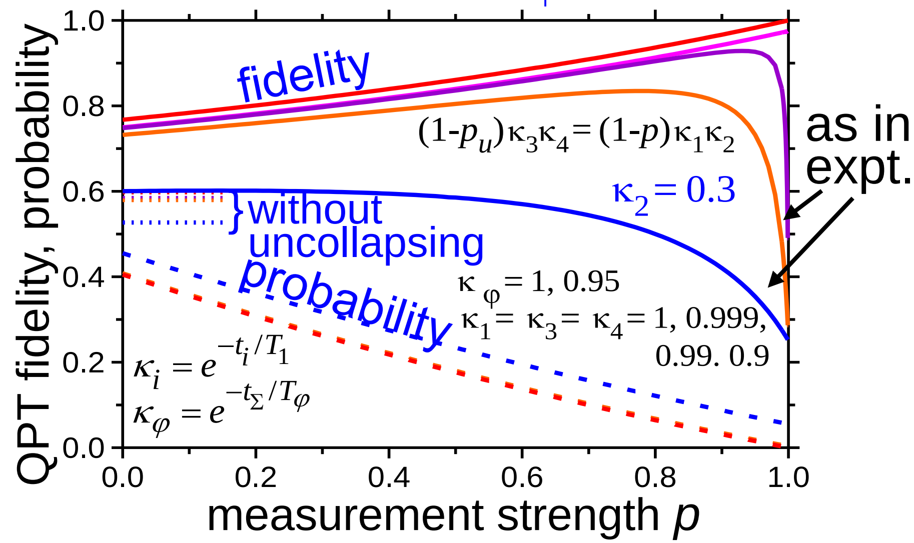
for initial state $|\psi_{in}\rangle = \alpha|0\rangle + \beta|1\rangle$

$|\psi_f\rangle = |\psi_{in}\rangle$ with probability $(1-p)\,e^{-t/T_1}$

$|\psi_f\rangle = |0\rangle$ with $(1-p)^2|\beta|^2 e^{-t/T_1}(1-e^{-t/T_1})$

procedure preferentially selects events without energy decay

Realistic case (T_1 and T_φ at all stages)

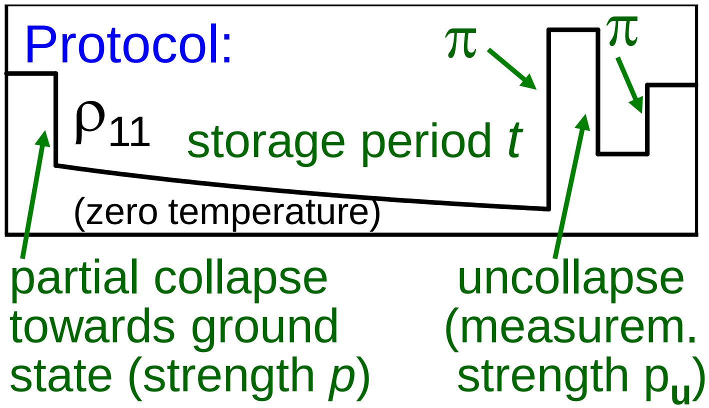


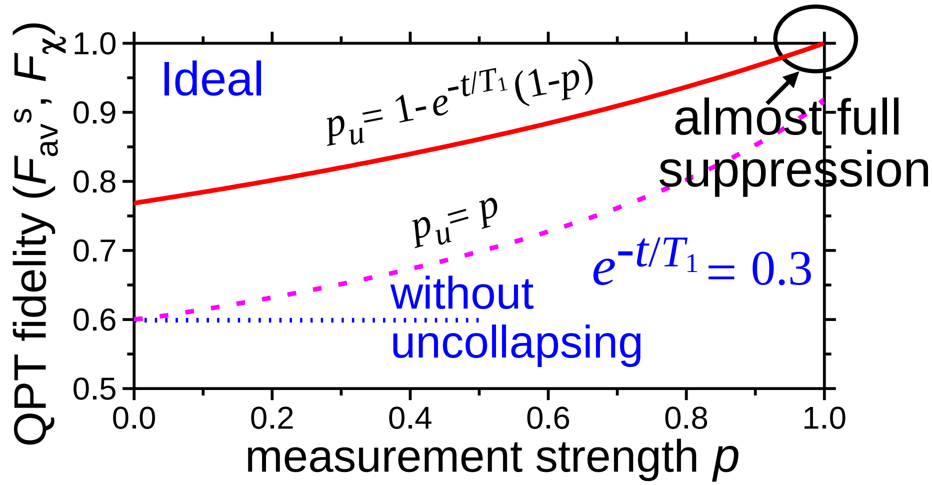
Uncollapse seems to be the only way to protect against energy relaxation without encoding in a larger Hilbert space (QEC, DFS)

Trade-off: fidelity vs. probability

Suppression of energy relaxation by uncollapse

A. Korotkov & K. Keane, PRA-2010





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procedure preferentially selects events without energy decay

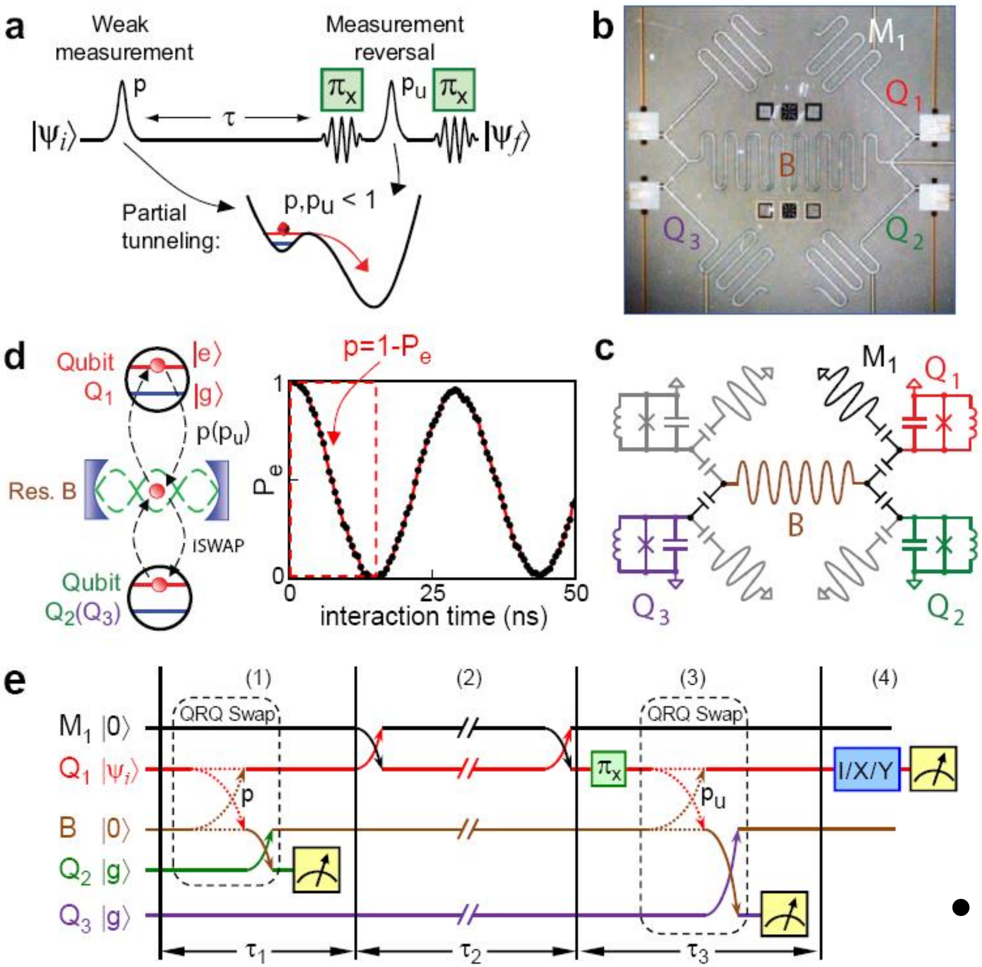
Uncollapse seems to be **the only way** to protect against energy relaxation without encoding in a larger Hilbert space (QEC, DFS)

"Sleeping beauty" analogy

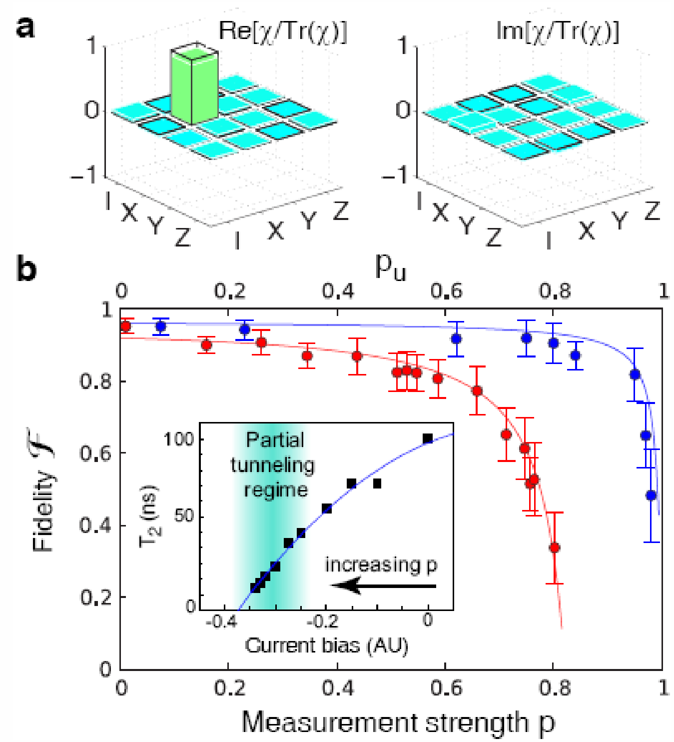
Realization with s/c phase qubits

Y. Zhong, Z. Wang, J. Martinis, A. Cleland,
A. Korotkov, and H. Wang, Nature Comm. (2014)

Quantum circuit and algorithm



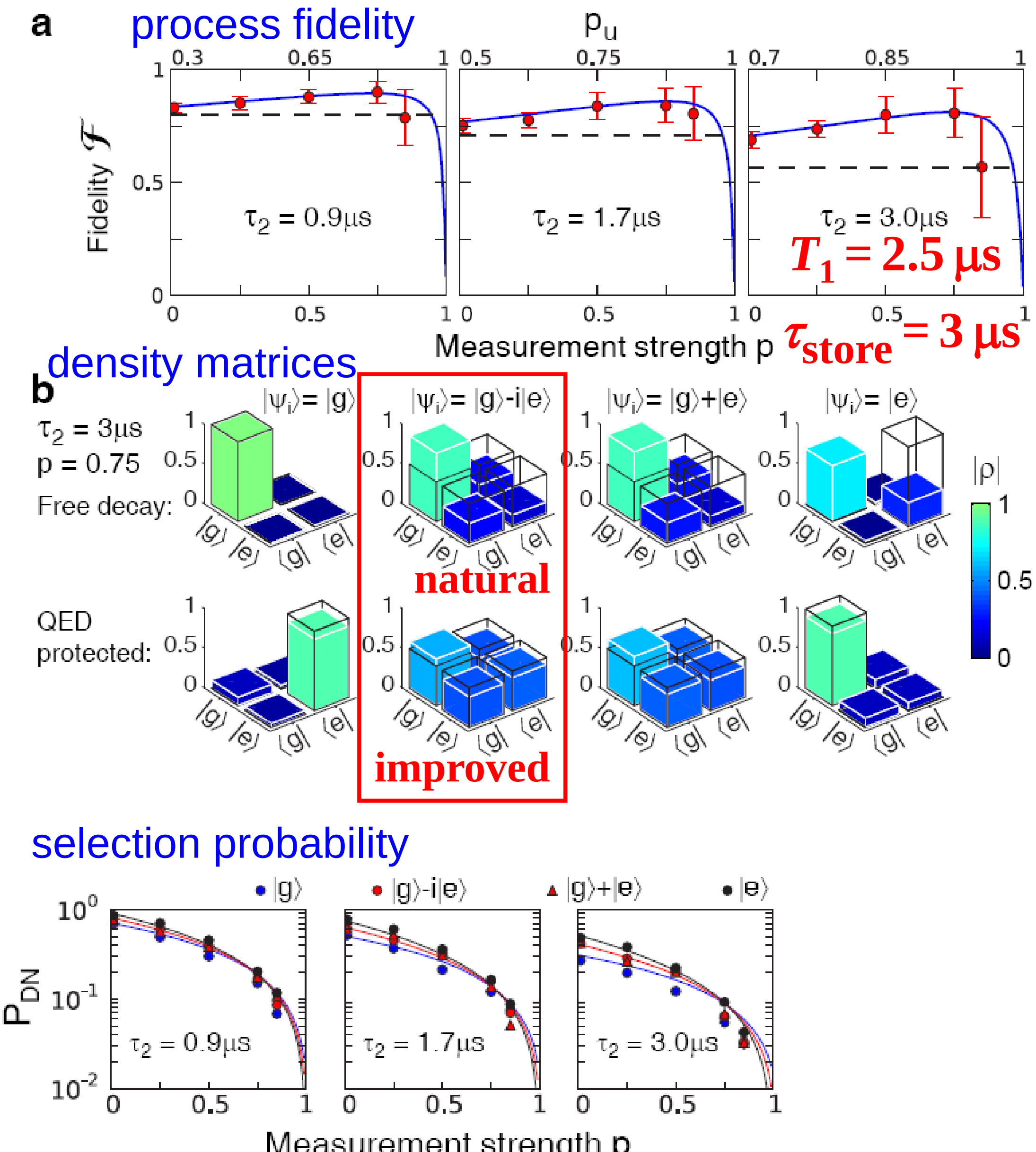
Basic uncollapse results



- Quantum state stored in resonator
- Weak measurement is implemented with ancilla qubit (better than partial)

Device with 4 phase qubits and 5 resonators,
3 qubits and 2 resonators used in the algorithm

Lifetime increase by uncollapse



Y. Zhong et al. (2014)

Uncollapse increases effective T_1 by ~3x

- “Quantum error detection” (not correction)
- First demonstration of real improvement (suppression of natural decoherence)

Thank you