Probing "inside" quantum collapse with solid-state qubits

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Outline:

- What is "inside" collapse? Bayesian framework.
  - broadband meas. (double-dot qubit & QPC)
  - narrowband meas. (circuit QED setup)
- Realized experiments
  - partial collapse (null-result & continuous)
  - uncollapse (+ entanglement preservation)
  - persistent Rabi oscillations, quantum feedback

Quantum mechanics =

Schrödinger equation (evolution)

+

collapse postulate (measurement)

1) Probability of measurement result $p_r = |\langle \psi | \psi_r \rangle|^2$

2) Wavefunction after measurement = ψ_r

- State collapse follows from common sense
- Does not follow from Schrödinger Eq. (contradicts)

What is "inside" collapse?

What if collapse is stopped half-way?

What is the evolution due to measurement? (What is "inside" collapse?)

- controversial for last 80 years, many wrong answers, many correct answers
- solid-state systems are more natural to answer this question

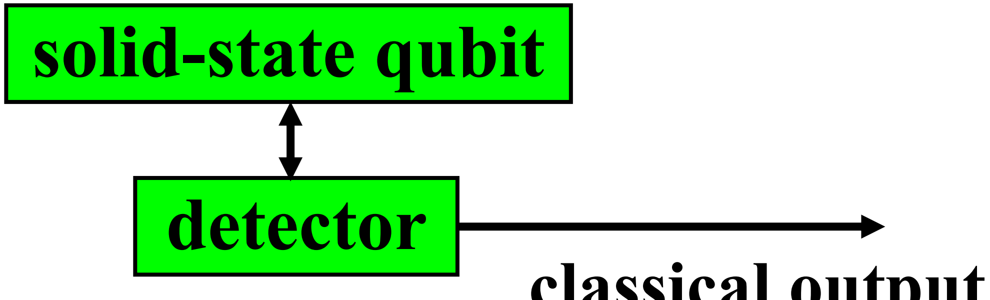
Various approaches to non-projective (weak, continuous, partial, generalized, etc.) quantum measurements

Names: Davies, Kraus, Holevo, Mensky, Caves, Knight, Walls, Carmichael, Milburn, Wiseman, Gisin, Percival, Belavkin, etc. (very incomplete list)

Key words: POVM, restricted path integral, quantum trajectories, quantum filtering, quantum jumps, stochastic master equation, etc.

Our limited scope:

(simplest system, experimental setups)



Quantum Bayesian framework

(slight technical extension of the collapse postulate)

1) Quantum back-action (spooky, physically unexplainable)
   simple: update the state using **information** from measurement and probability concept (Bayes rule)

2) Add "classical" back-action if any (anything with a physical mechanism)

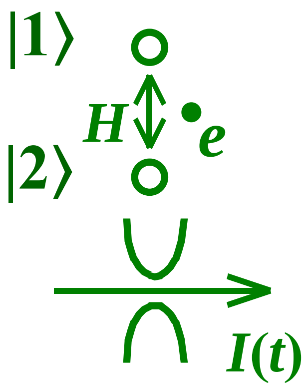
3) Add noise/decoherence if any

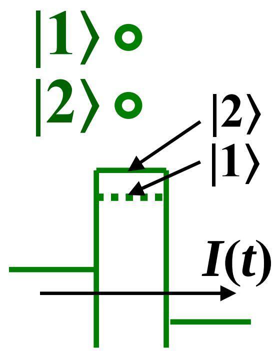
4) Add Hamiltonian (unitary) evolution if any

(Practically equivalent to many other approaches: POVM, quantum trajectory, quantum filtering, etc.)

"Typical" setup: double-quantum-dot qubit + quantum point contact (QPC) detector

Gurvitz, 1997





$$H = H_{\mathrm{QB}} + H_{\mathrm{DET}} + H_{\mathrm{INT}}$$

$$H_{QB} = \frac{\varepsilon}{2}\sigma_Z + H\sigma_X$$

$$I(t) = I_0 + \frac{\Delta I}{2} z(t) + \xi(t)$$

const + signal + noise

Two levels of average detector current: I_1 for qubit state $|1\rangle$, I_2 for $|2\rangle$

Response: $\Delta I = I_1 - I_2$ Detector noise: white, spectral density S_I

For low-transparency QPC

$$H_{DET} = \sum_l E_l a_l^\dagger a_l + \sum_r E_r a_r^\dagger a_r + \sum_{l,r} T(a_r^\dagger a_l + a_l^\dagger a_r)$$

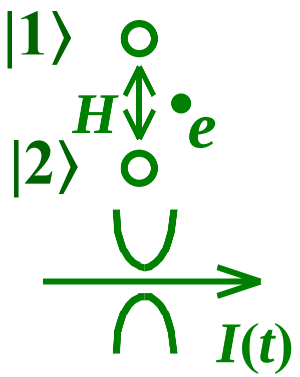
$$H_{INT} = \sum_{l,r} \Delta T\,(c_1^\dagger c_1 - c_2^\dagger c_2)\, a_r^\dagger a_l + \mathrm{h.c.}$$

$$S_I = 2eI$$

("broadband")

Bayesian formalism for DQD-QPC system

$H_{QB} = 0$



Qubit evolution due to measurement (quantum back-action):

$$\psi(t) = \alpha(t)\,|1\rangle + \beta(t)\,|2\rangle \quad \text{or} \quad \rho_{ij}(t)$$

1) $|\alpha(t)|^2$ and $|\beta(t)|^2$ evolve as probabilities,
i.e. according to the **Bayes rule** (same for ρ_{ii})

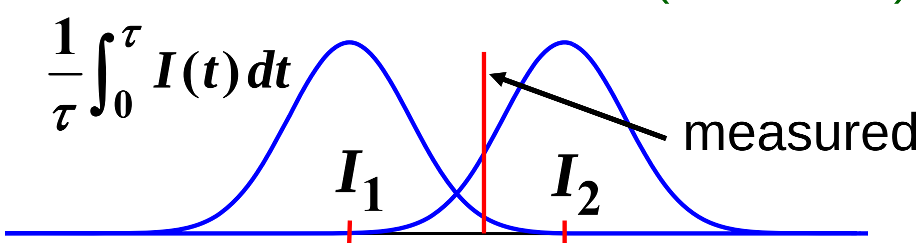
2) phases of $\alpha(t)$ and $\beta(t)$ do not change
(**no dephasing!**), $\rho_{ij}/(\rho_{ii}\,\rho_{jj})^{1/2} = \text{const}$

(A.K., 1998)

Bayes rule (1763, Laplace-1812):

posterior probability; prior probab.; likelihood

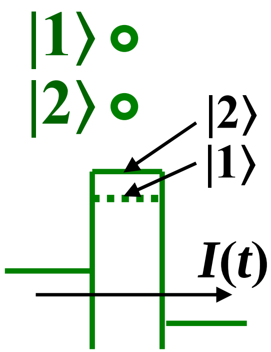
$$\underbrace{P(A_i\,|\,\text{res})}_{\text{posterior probability}} = \frac{\overbrace{P(A_i)}^{\text{prior probab.}}\ \overbrace{P(\text{res}\,|\,A_i)}^{\text{likelihood}}}{\sum_k P(A_k)\,P(\text{res}\,|\,A_k)}$$



So simple because:

1) no entanglement at large QPC voltage
2) QPC is ideal detector
3) zero qubit Hamiltonian

Now add classical back-action and decoherence

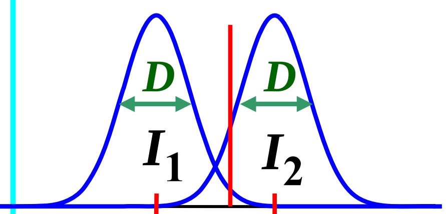


$\Delta I = I_1 - I_2$

noise S_I

$$I_m \equiv \frac{1}{\tau}\int_0^{\tau} I(t)\, dt$$

$$D = S_I / 2\tau$$



$$H_{qb} = 0$$

quantum backaction (non-unitary, "spooky", "unphysical")

$$\begin{cases} \dfrac{\rho_{11}(\tau)}{\rho_{22}(\tau)} = \dfrac{\rho_{11}(0)}{\rho_{22}(0)} \dfrac{\exp[-(I_m - I_1)^2/2D]}{\exp[-(I_m - I_2)^2/2D]} \\ \rho_{12}(\tau) = \rho_{12}(0)\sqrt{\dfrac{\rho_{11}(\tau)\,\rho_{22}(\tau)}{\rho_{11}(0)\,\rho_{22}(0)}}\exp(iKI_m\tau)\exp(-\gamma\tau) \end{cases}$$

no self-evolution of qubit assumed

decoherence

classical backaction (unitary)

Example of classical ("physical") backaction:

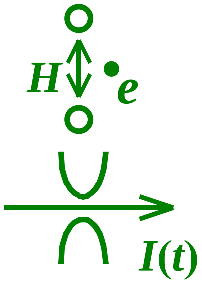
Each electron passed through QPC rotates qubit

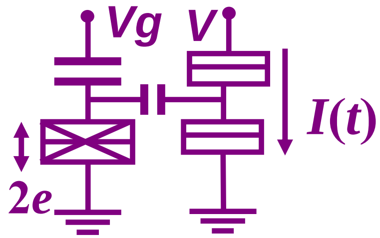
$$\arg(T^* \Delta T) \neq 0$$

$$H_{DET} = \sum_l E_l a_l^\dagger a_l + \sum_r E_r a_r^\dagger a_r + \sum_{l,r} T(a_r^\dagger a_l + a_l^\dagger a_r)$$

$$H_{INT} = \sum_{l,r} \Delta T\,(c_1^\dagger c_1 - c_2^\dagger c_2)\, a_r^\dagger a_l + \text{h.c.}$$

Now add Hamiltonian evolution





- Time derivative of the quantum Bayes rule
- Add unitary evolution of the qubit

$$\dot{\rho}_{11} = -\dot{\rho}_{22} = -2\frac{H}{\hbar}\,\mathrm{Im}\,\rho_{12} + \rho_{11}\rho_{22}\frac{2\Delta I}{S_I}[\underline{\underline{I(t)}} - I_0]$$

$$\dot{\rho}_{12} = i\varepsilon\rho_{12} + i\frac{H}{\hbar}(\rho_{11} - \rho_{22}) + \rho_{12}(\rho_{11} - \rho_{22})\frac{\Delta I}{S_I}[\underline{\underline{I(t)}} - I_0] - \gamma\rho_{12}$$

$\Delta I = I_1 - I_2$, $I_0 = (I_1 + I_2)/2$, S_I – detector noise

(A.K., 1998)

$\gamma = 0$ for QPC

For simulations: $I = I_0 + \frac{\Delta I}{2}(\rho_{11} - \rho_{22}) + \xi$

noise $S_\xi = S_I$

Evolution of qubit *wavefunction* can be monitored if γ=0 (quantum-limited)

Relation to "conventional" master equation

$$\dot{\rho}_{11} = -\dot{\rho}_{22} = -2H\,\mathrm{Im}\,\rho_{12} + \rho_{11}\rho_{22}\frac{2\Delta I}{S_I}[I(t)-I_0]$$

$$\dot{\rho}_{12} = i\varepsilon\rho_{12} + iH(\rho_{11}-\rho_{22}) + \rho_{12}(\rho_{11}-\rho_{22})\frac{\Delta I}{S_I}[I(t)-I_0]$$

$$+iK[I(t)-I_0]\rho_{12} - \gamma\rho_{12}$$

response ΔI
noise S_I

Averaging over measurement result $I(t)$ leads to usual master equation:

$$\dot{\rho}_{11} = -\dot{\rho}_{22}/dt = -2H\,\mathrm{Im}\,\rho_{12}$$

$$\dot{\rho}_{12} = i\varepsilon\rho_{12} + iH(\rho_{11}-\rho_{22}) - \Gamma\rho_{12}$$

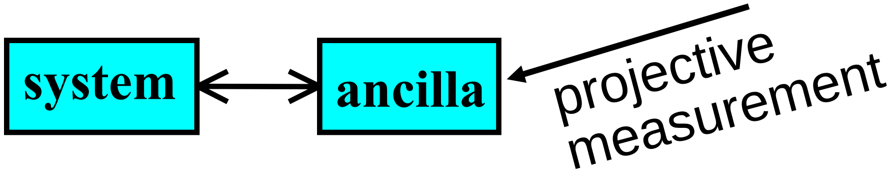
Γ – ensemble decoherence, $\Gamma = (\Delta I)^2/4S_I + K^2 S_I/4 + \gamma$
spooky physical dephasing

Quantum efficiency: $\eta = \dfrac{(\Delta I)^2/4S_I}{\Gamma}$ or $\tilde{\eta} = 1 - \dfrac{\gamma}{\Gamma}$

Quantum measurement in POVM formalism

Davies, Kraus, Holevo, etc.

(Nielsen-Chuang, pp. 85, 100)



Measurement (Kraus) operator M_r (any linear operator in H.S.) : $\psi \to \dfrac{M_r \psi}{\| M_r \psi \|}$ or $\rho \to \dfrac{M_r \rho M_r^\dagger}{\mathrm{Tr}(M_r \rho M_r^\dagger)}$

Probability : $P_r = \| M_r \psi \|^2$ or $P_r = \mathrm{Tr}(M_r \rho M_r^\dagger)$

Completeness : $\sum_r M_r^\dagger M_r = 1$

(People often prefer linear evolution and non-normalized states)

Relation between POVM and quantum Bayesian formalism:

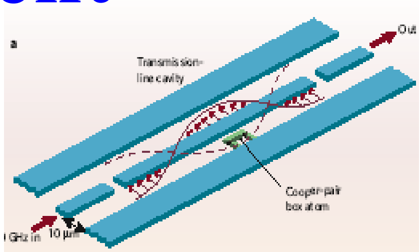
decomposition $M_r = U_r \sqrt{M_r^\dagger M_r}$

unitary (U_r), Bayes ($\sqrt{M_r^\dagger M_r}$)

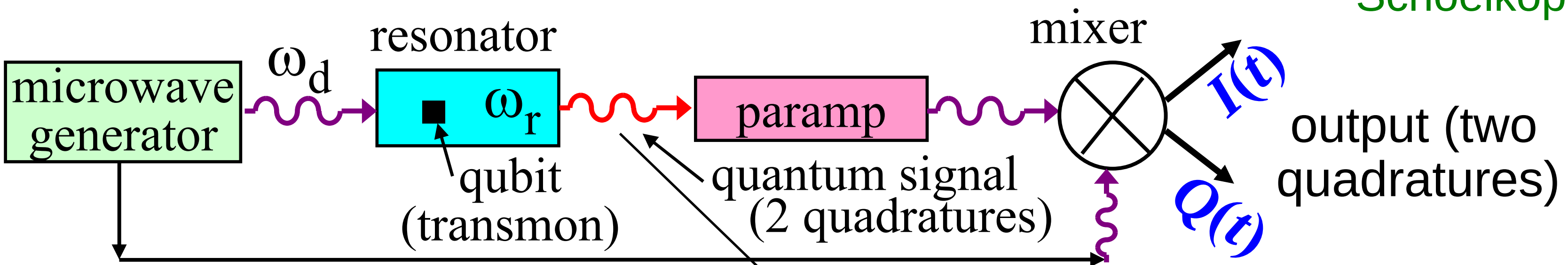
(almost equivalent)

Narrowband linear measurement
(circuit QED setup)

Difference from broadband: **two quadratures**
(two signals: $A(t)\cos\omega t + B(t)\sin\omega t$)



Schoelkopf et al.

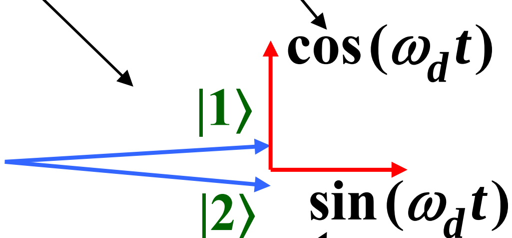


$$H = \frac{1}{2}\omega_{qb}\sigma_z + \omega_r a^\dagger a + \chi a^\dagger a\,\sigma_z$$

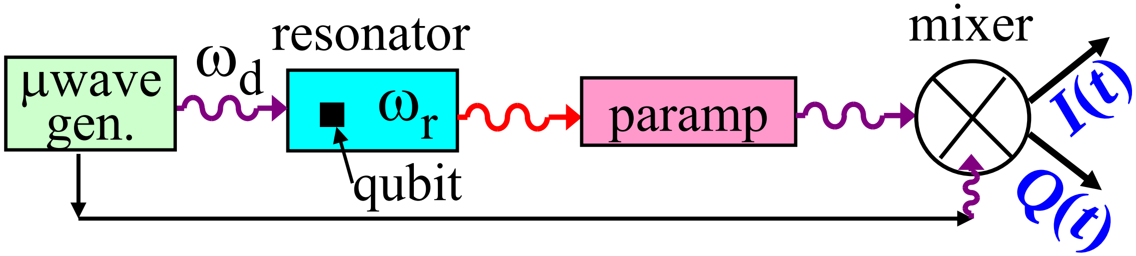
qubit state changes resonator freq.,
number of photons affects qubit freq.

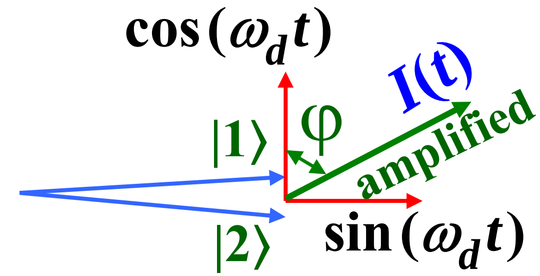
Blais et al., 2004
Gambetta et al., 2006, 2008

carries information about qubit
("quantum" back-action)



carries information about fluctuating
photon number in the resonator
("classical" back-action)





Phase-sensitive (degenerate) paramp

$\cos(\omega_d t+\varphi)$ is amplified: $I(t)$
$\sin(\omega_d t+\varphi)$ is suppressed

get some information ($\sim\cos^2\varphi$) about qubit state and some information ($\sim\sin^2\varphi$) about photon fluctuations

$$\begin{cases} \dfrac{\rho_{gg}(\tau)}{\rho_{ee}(\tau)} = \dfrac{\rho_{gg}(0)}{\rho_{ee}(0)} \dfrac{\exp[-(\bar I - I_g)^2/2D]}{\exp[-(\bar I - I_e)^2/2D]} \\ \rho_{ge}(\tau) = \rho_{ge}(0)\sqrt{\dfrac{\rho_{gg}(\tau)\,\rho_{ee}(\tau)}{\rho_{gg}(0)\,\rho_{ee}(0)}}\,\exp(iK\bar I\tau) \end{cases}$$

Bayes   unitary

(rotating frame)

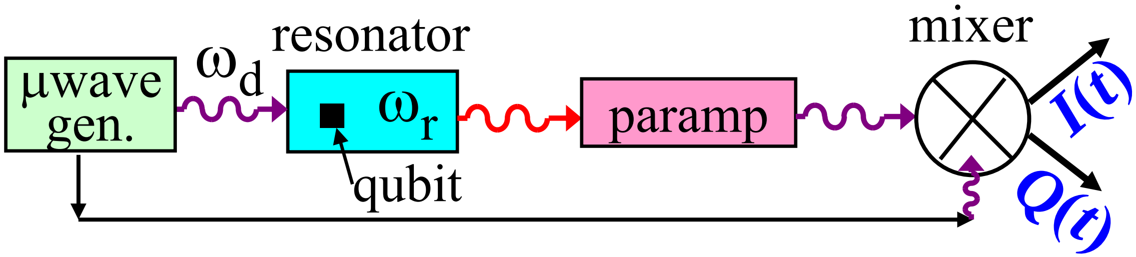
$$\bar I \equiv \frac{1}{\tau}\int_0^\tau I(t)\,dt \qquad D = S_I/2\tau$$

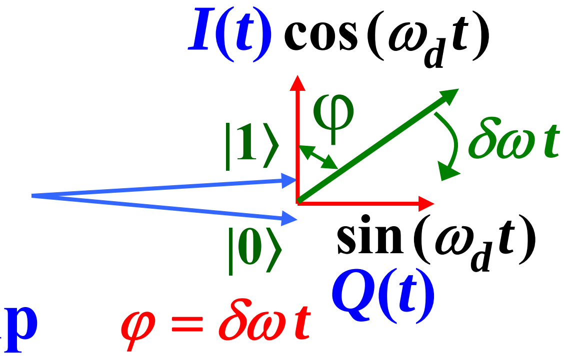
$$I_g - I_e = \Delta I\cos\varphi \qquad K = \frac{\Delta I}{S_I}\sin\varphi$$

$$\Gamma = \frac{(\Delta I\cos\varphi)^2}{4S_I} + K^2\frac{S_I}{4} = \frac{\Delta I^2}{4S_I} = \frac{8\chi^2\bar n}{\kappa}$$

Same as for QPC, but φ controls trade-off between quantum & classical back-actions (we choose if photon number fluctuates or not)

A.K., arXiv:1111.4016





Phase-preserving (nondegenerate) paramp

Now information in both $I(t)$ and $Q(t)$.

Choose
$I(t) \leftrightarrow \cos(\omega_d t)$ (qubit information)
$Q(t) \leftrightarrow \sin(\omega_d t)$ (photon fluct. info)

Small $\delta\omega \Rightarrow$ can follow $\varphi(t)$
Large $\delta\omega$ ($>>\Gamma$) $\Rightarrow$ averaging over φ (phase-preserving)

$$\begin{cases} \dfrac{\rho_{gg}(\tau)}{\rho_{ee}(\tau)} = \dfrac{\rho_{gg}(0)}{\rho_{ee}(0)} \dfrac{\exp[-(\bar{I} - I_g)^2/2D]}{\exp[-(\bar{I} - I_e)^2/2D]} \\ \rho_{ge}(\tau) = \rho_{ge}(0) \sqrt{\dfrac{\rho_{gg}(\tau)\,\rho_{ee}(\tau)}{\rho_{gg}(0)\,\rho_{ee}(0)}} \exp(iK\bar{Q}\tau) \end{cases}$$

Bayes   unitary

$$\bar{I} \equiv \frac{1}{\tau}\int_0^\tau I(t)\,dt \qquad \bar{Q} \equiv \frac{1}{\tau}\int_0^\tau Q(t)\,dt \qquad D = \frac{S_I}{2\tau}$$

$$I_g - I_e = \frac{\Delta I}{\sqrt{2}} \qquad K = \frac{\Delta I}{\sqrt{2S_I}}$$

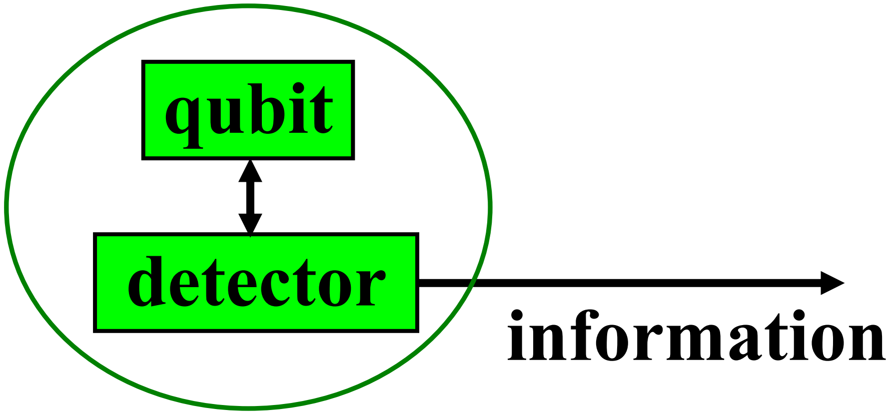
$$\Gamma = \frac{\Delta I^2}{8S_I} + \frac{\Delta I^2}{8S_I} = \frac{8\chi^2\bar{n}}{\kappa}$$

Understanding important for quantum feedback

Equal contributions to ensemble dephasing from quantum & classical back-actions

A.K., arXiv:1111.4016

Why not just use Schrödinger equation for the whole system?



Impossible in principle!

Technical reason: Outgoing information makes it an open system

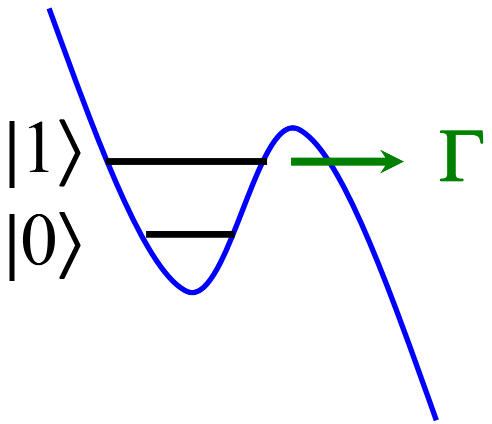
Philosophical reason: Random measurement result, but deterministic Schrödinger equation

Einstein: God does not play dice (actually plays!)
Heisenberg: unavoidable quantum-classical boundary

Superconducting experiments "inside" quantum collapse

- UCSB-2006 Partial collapse
- UCSB-2008 Reversal of partial collapse (uncollapse)
- Saclay-2010 Continuous measurement of Rabi oscillations
  (+violation of Leggett-Garg inequality)
- Berkeley-2012 Quantum feedback of persistent Rabi osc.
  (phase-sensitive paramp)
- Yale-2012 Partial (continuous) measurement
  (phase-preserving paramp)

Partial collapse of a Josephson phase qubit



N. Katz, M. Ansmann, R. Bialczak, E. Lucero, R. McDermott, M. Neeley, M. Steffen, E. Weig, A. Cleland, J. Martinis, A. Korotkov, Science-06

What happens if no tunneling?

Main idea:

$$\psi = \alpha\,|0\rangle + \beta\,|1\rangle \;\rightarrow\; \psi(t) = \begin{cases} |out\rangle, \text{ if tunneled} \\ \dfrac{\alpha\,|0\rangle + \beta\, e^{-\Gamma t/2} e^{i\varphi}\,|1\rangle}{\sqrt{|\alpha|^2 + |\beta|^2 e^{-\Gamma t}}}, \text{ if not tunneled} \end{cases}$$

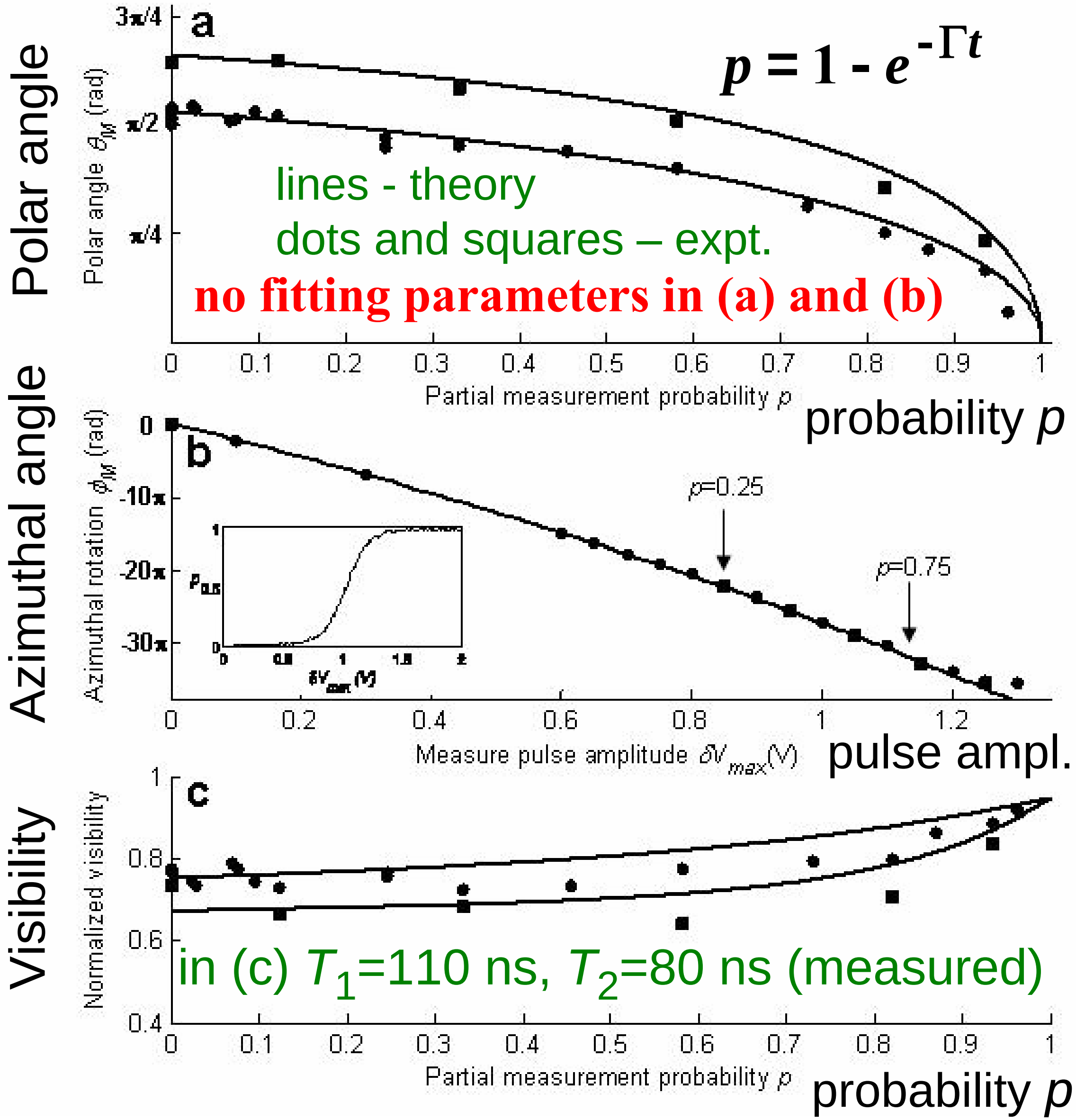
Non-trivial: • amplitude of state $|0\rangle$ grows without physical interaction

• finite linewidth only after tunneling

continuous null-result collapse

(idea similar to Dalibard-Castin-Molmer, PRL-1992)

Partial collapse: experimental results



N. Katz *et al.*, Science-06

- In case of no tunneling phase qubit evolves
- Evolution is described by the Bayesian theory without fitting parameters
- Phase qubit remains coherent in the process of continuous collapse (expt. ~80% raw data, ~96% corrected for T_1,T_2)

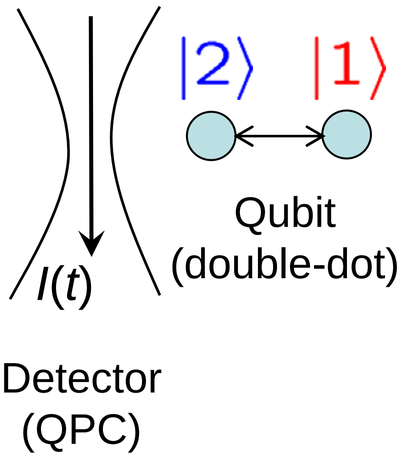
quantum efficiency

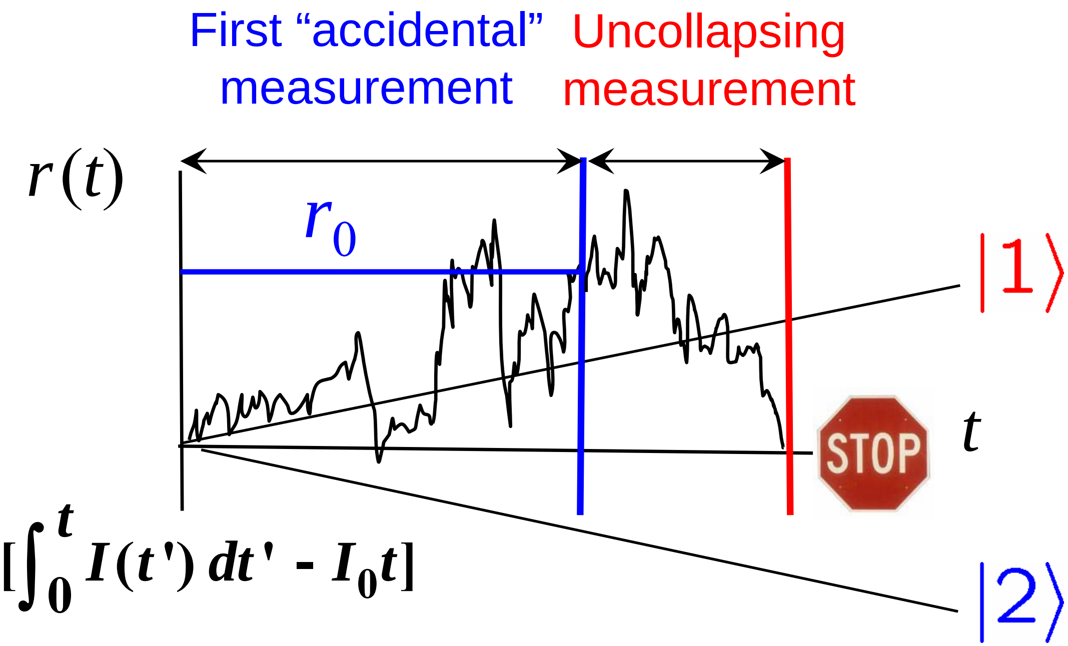
$\eta_0 > 0.8$

Good confirmation of the theory

Uncollapsing for qubit-QPC system (theory)

A.K. & Jordan, 2006





$$r(t) = \frac{\Delta I}{S_I}\left[\int_0^t I(t')\,dt' - I_0 t\right]$$

Simple strategy: continue measuring until *r*(*t*) becomes zero!

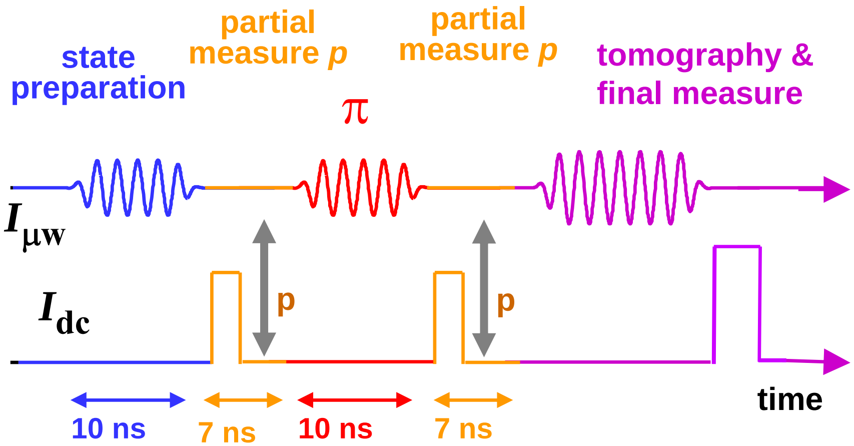
Then any unknown initial state is fully restored.

(same for an entangled qubit)

It may happen though that $r=0$ never happens;
then uncollapsing is unsuccessful.

Somewhat similar to quantum eraser of Scully and Druhl (1982)

Experiment on wavefunction uncollapse

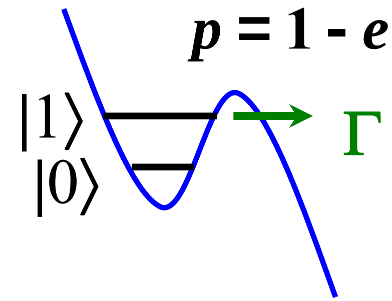


N. Katz, M. Neeley, M. Ansmann, R. Bialzak, E. Lucero, A. O'Connell, H. Wang, A. Cleland, J. Martinis, and A. Korotkov, PRL-2008

Uncollapse protocol:
- partial collapse
- π-pulse
- partial collapse (same strength)

If no tunneling for both measurements, then initial state is fully restored

$p = 1 - e^{-\Gamma t}$



$$\alpha|0\rangle + \beta|1\rangle \rightarrow \frac{\alpha|0\rangle + e^{i\phi}\beta e^{-\Gamma t/2}|1\rangle}{\text{Norm}} \rightarrow$$

$$\frac{e^{i\phi}\alpha e^{-\Gamma t/2}|0\rangle + e^{i\phi}\beta e^{-\Gamma t/2}|1\rangle}{\text{Norm}} = e^{i\phi}(\alpha|0\rangle + \beta|1\rangle)$$

phase is also restored ("spin echo")

Experimental results on the Bloch sphere

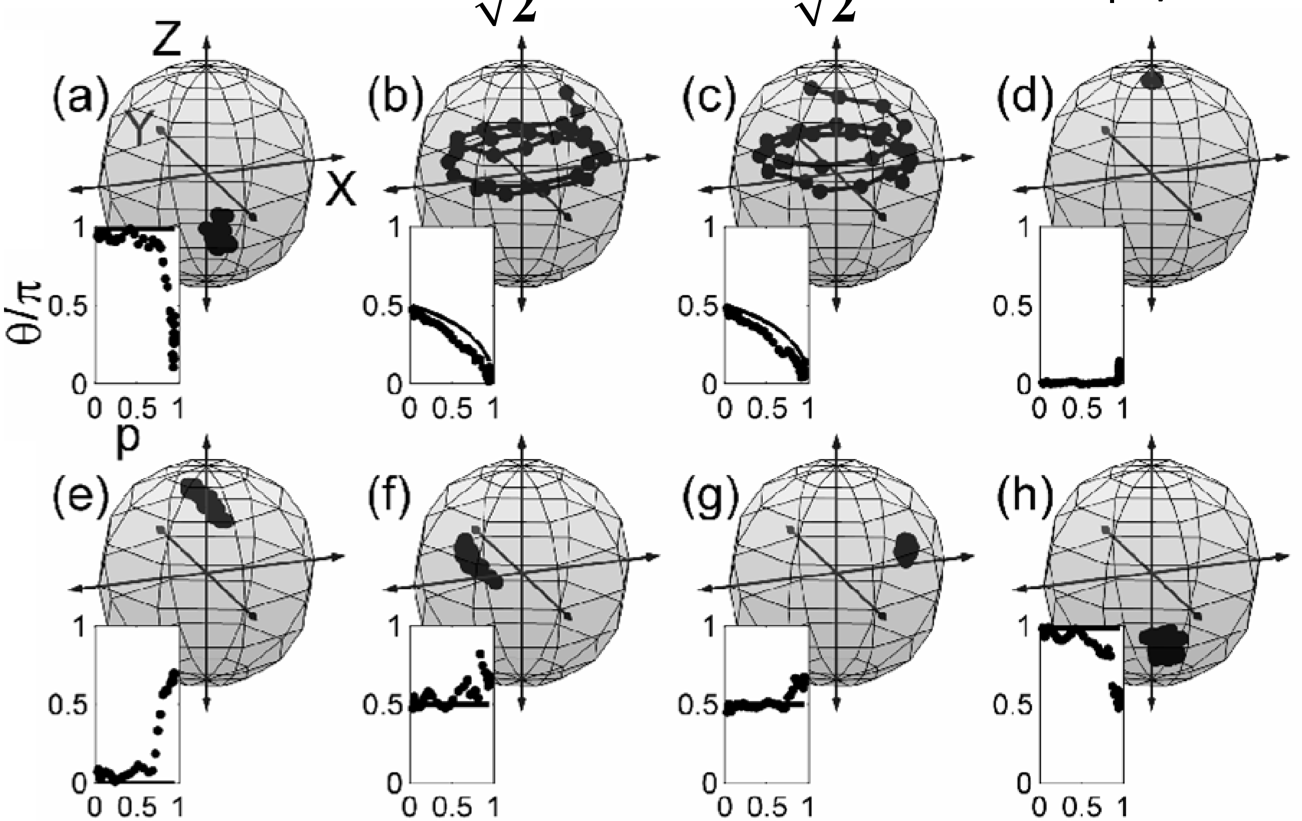
N. Katz et al.

Initial state: $|1\rangle$, $\frac{|0\rangle - i|1\rangle}{\sqrt{2}}$, $\frac{|0\rangle + |1\rangle}{\sqrt{2}}$, $|0\rangle$

Partially collapsed

Uncollapsed

uncollapsing works well

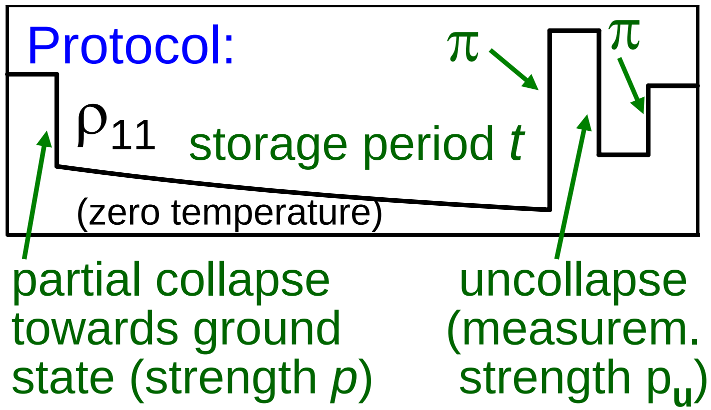


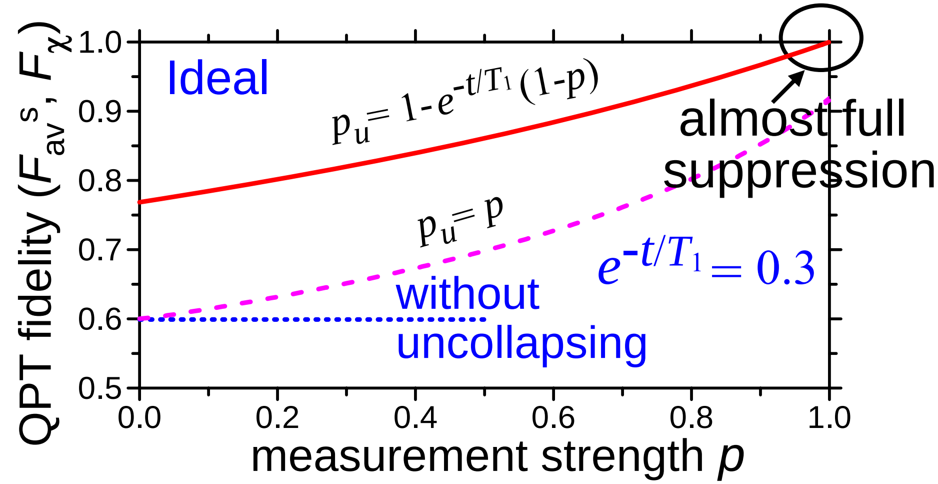
Both spin echo (azimuth) and uncollapsing (polar angle)

Difference: spin echo – undoing of an unknown unitary evolution, uncollapsing – undoing of a known, but non-unitary evolution

Suppression of T_1-decoherence by uncollapse

A.K. & Keane, PRA-2010





Ideal case (T_1 during storage only)

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

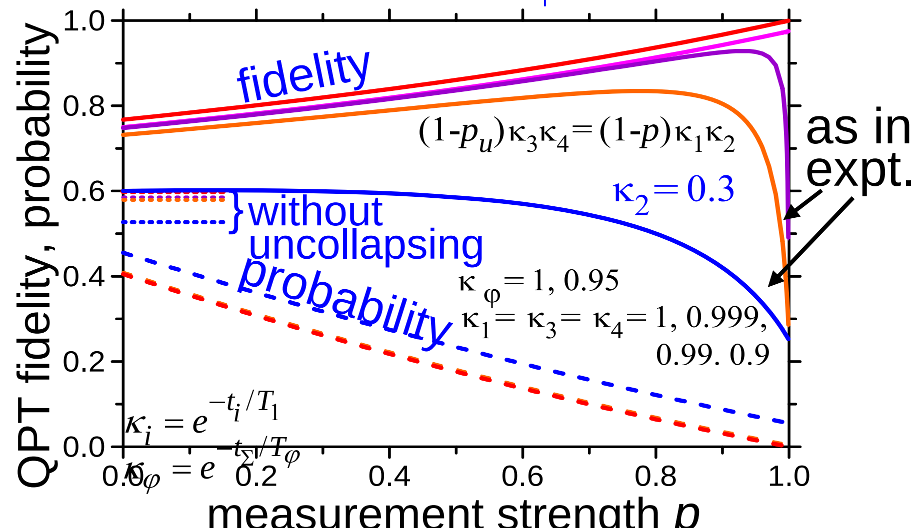
$|\psi_f\rangle = |\psi_{in}\rangle$ with probability $(1-p)\,e^{-t/T_1}$

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

procedure preferentially selects events without energy decay

Uncollapse seems to be **the only way** to protect against T_1-decoherence without encoding in a larger Hilbert space (QEC, DFS)

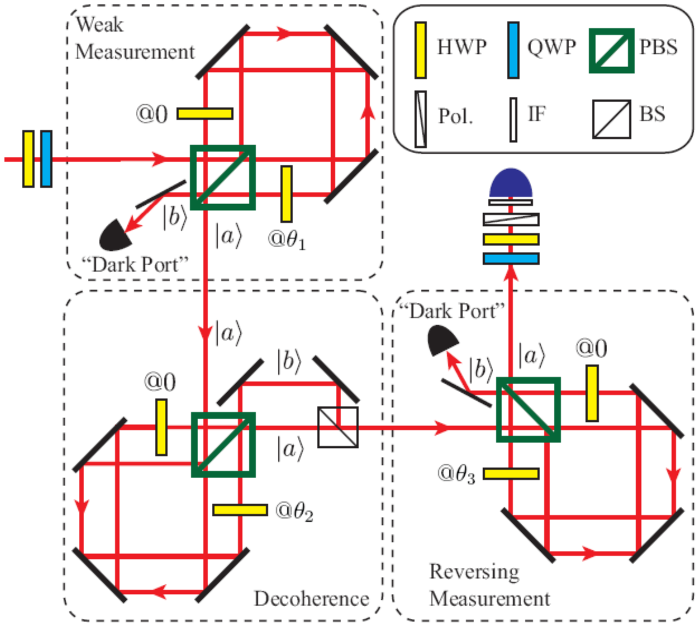
Realistic case (T_1 and T_φ at all stages)

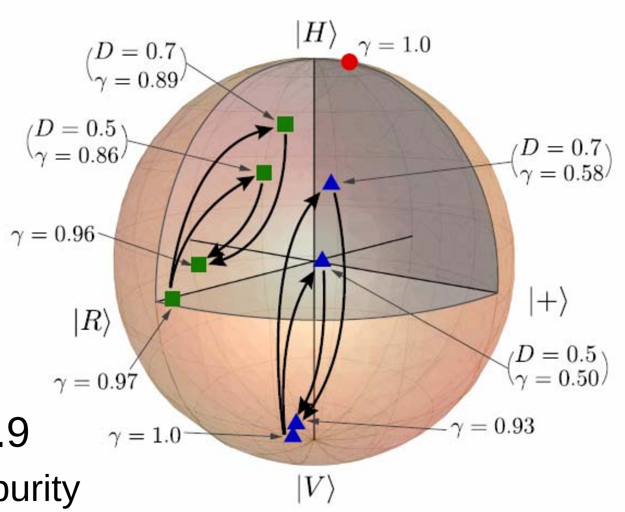


Trade-off: fidelity vs. probability

Realization with photons

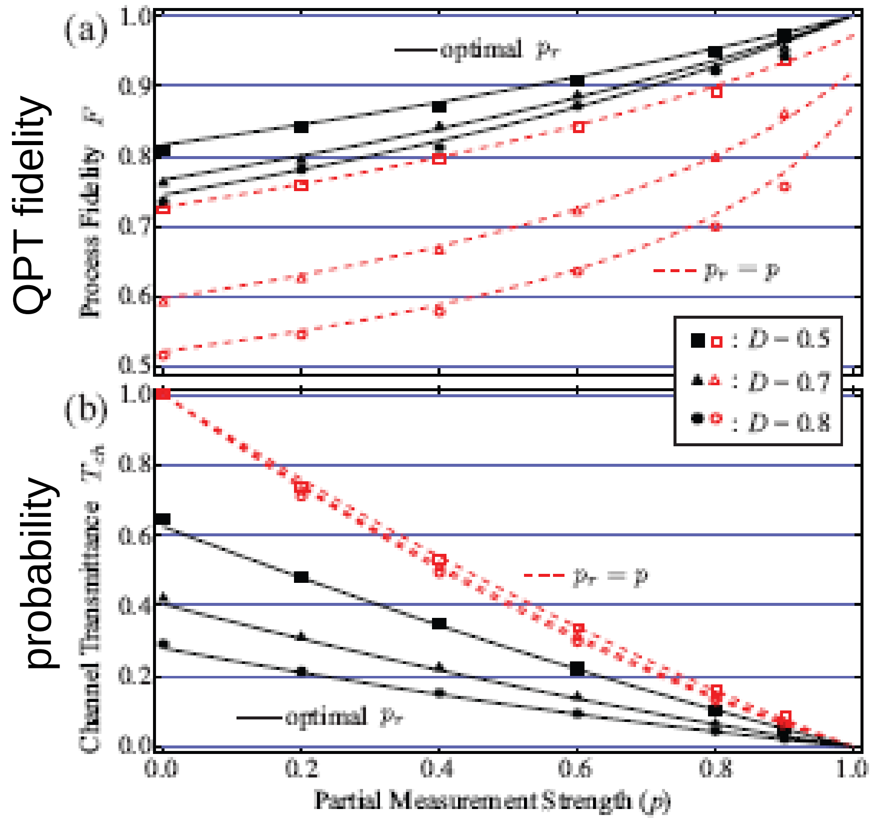
J.-C. Lee, Y.-C. Jeong, Y.-S. Kim, and Y.-H. Kim, Opt. Express-2011





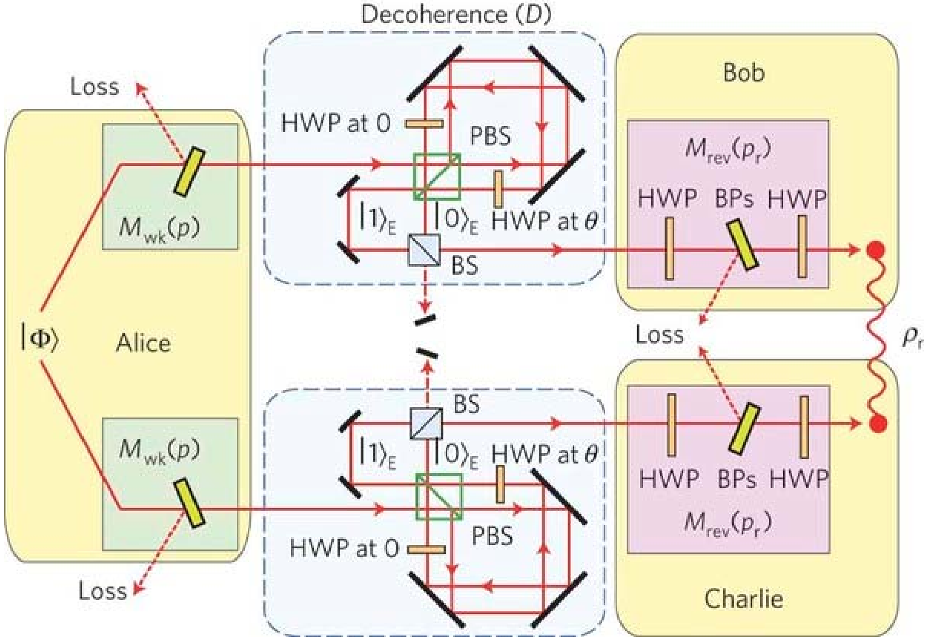
p=0.9

γ is purity

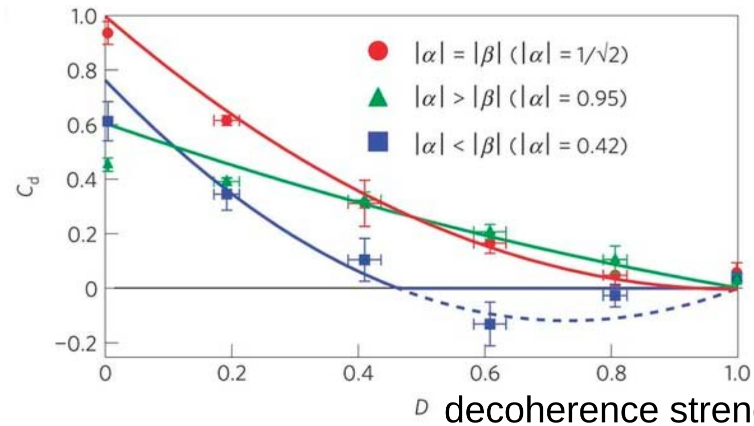


- Works perfectly (optics, not solid state!)
- Amplitude damping ("energy relaxation") decoherence is imitated in a clever way

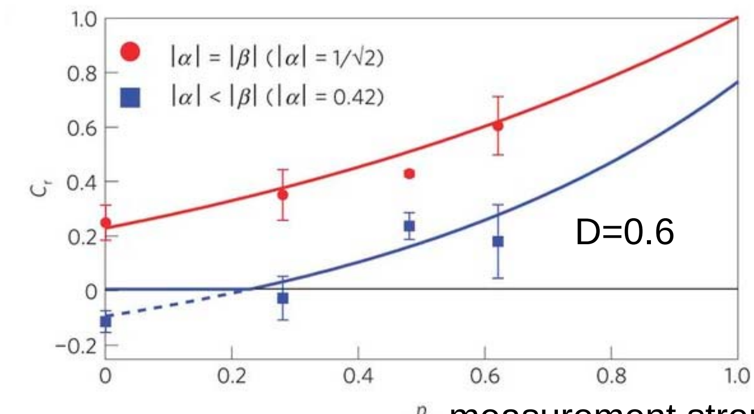
Uncollapsing preserves entanglement



Y.-S. Kim, J.-C. Lee, O. Kwon, and Y.-H. Kim, Nature Phys.-2012



decoherence strength



measurement strength

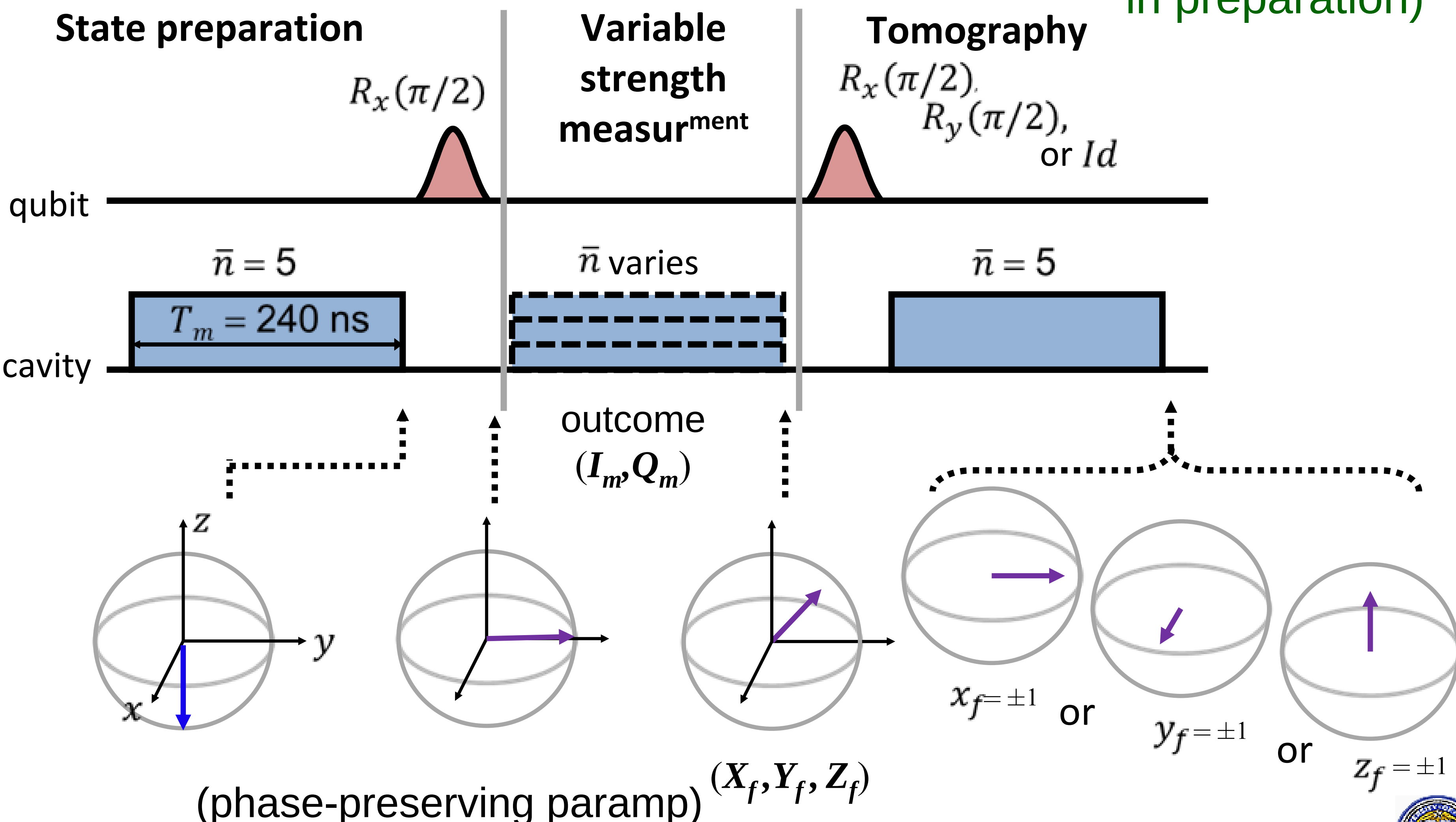
- Extension of 1-qubit experiment
- Revives entanglement even from "sudden death"

A.K., "Sleeping beauty approach", Nature Phys.-2012

Recent experiment in Michel Devoret's group

Courtesy of Michel Devoret
(Yale Univ., manuscript
in preparation)

MEASUREMENT PROTOCOL

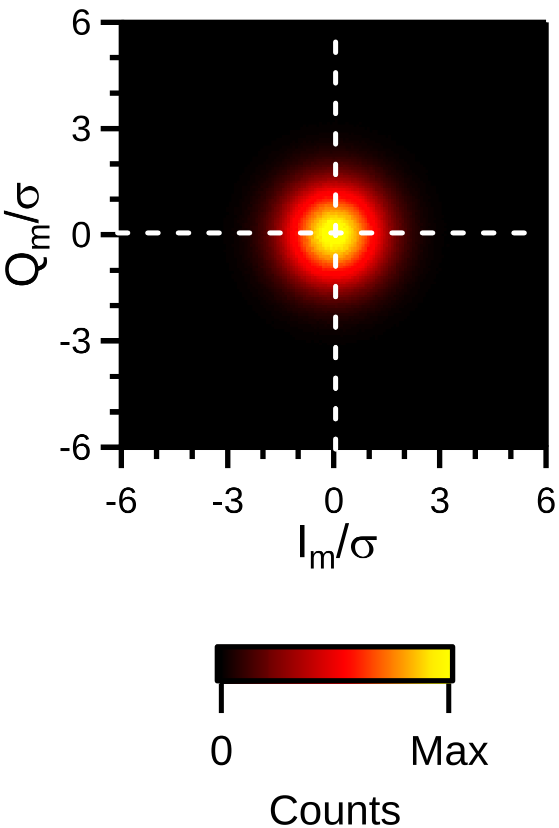


repeat 10,000,000 times

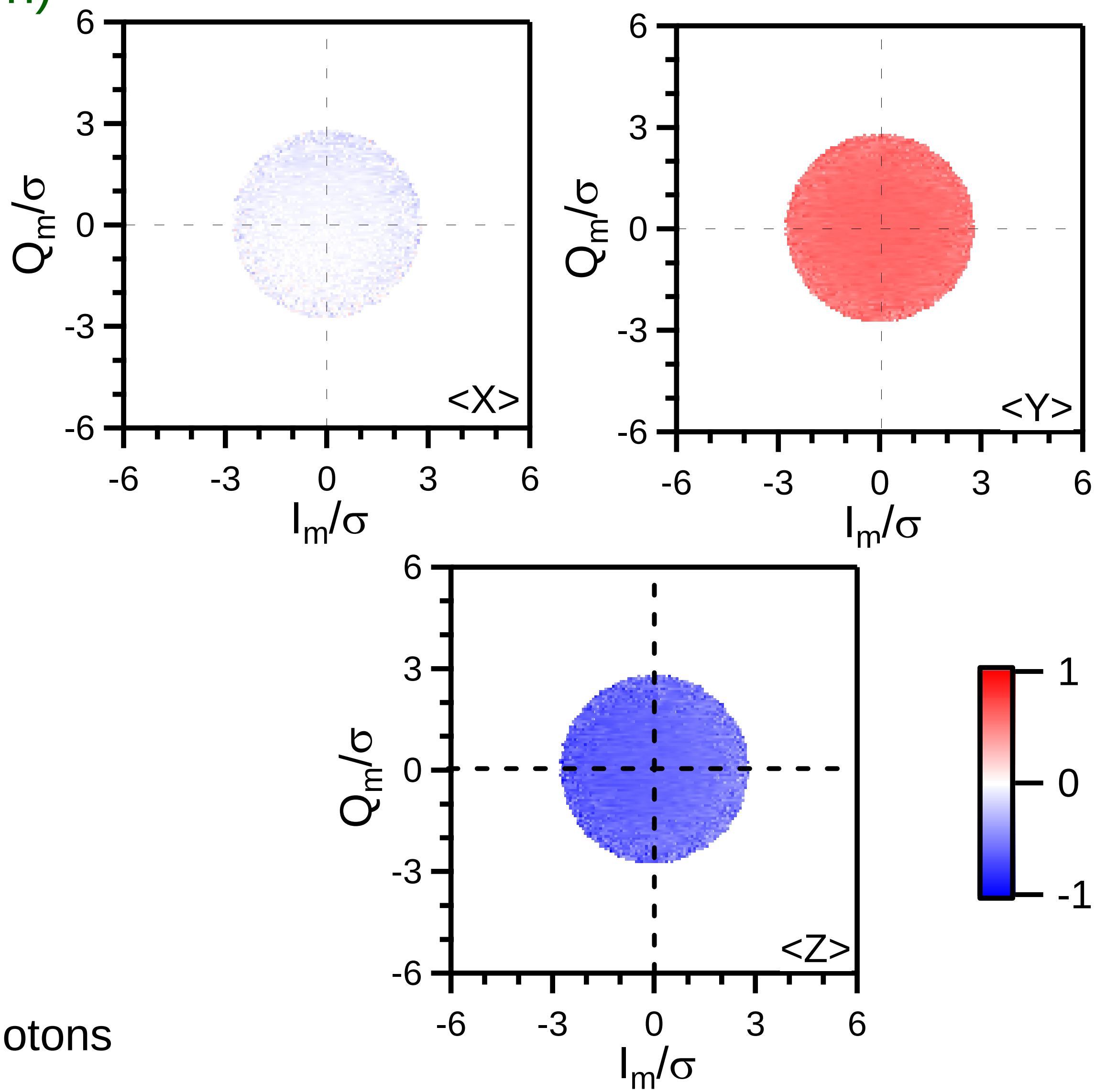
MEASUREMENT WITH $\bar{n} = 5 \times 10^{-4}$

Courtesy of Michel Devoret
(manuscript in preparation)

histogram of measurement outcomes



tomography along X, Y, Z after measurement



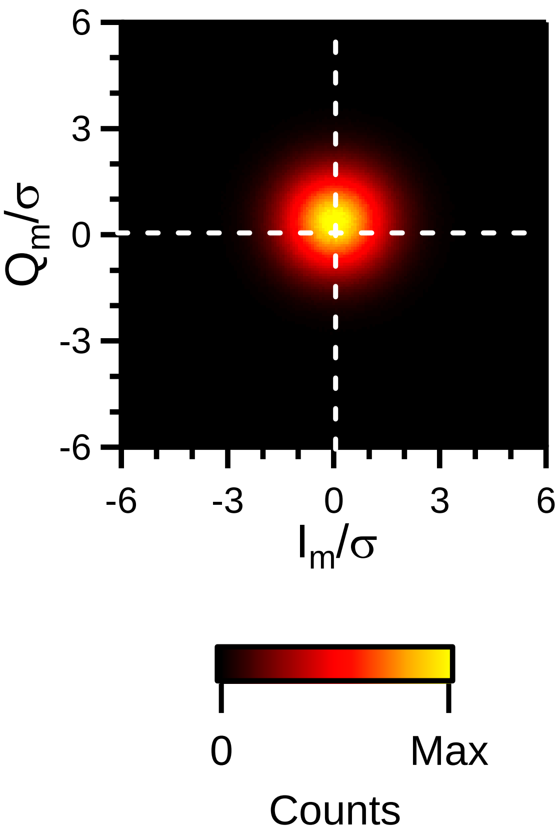
Cavity Drive = 5.0e-04 photons

$(I_m^g - I_m^e)/(2\sigma) = 0.046$

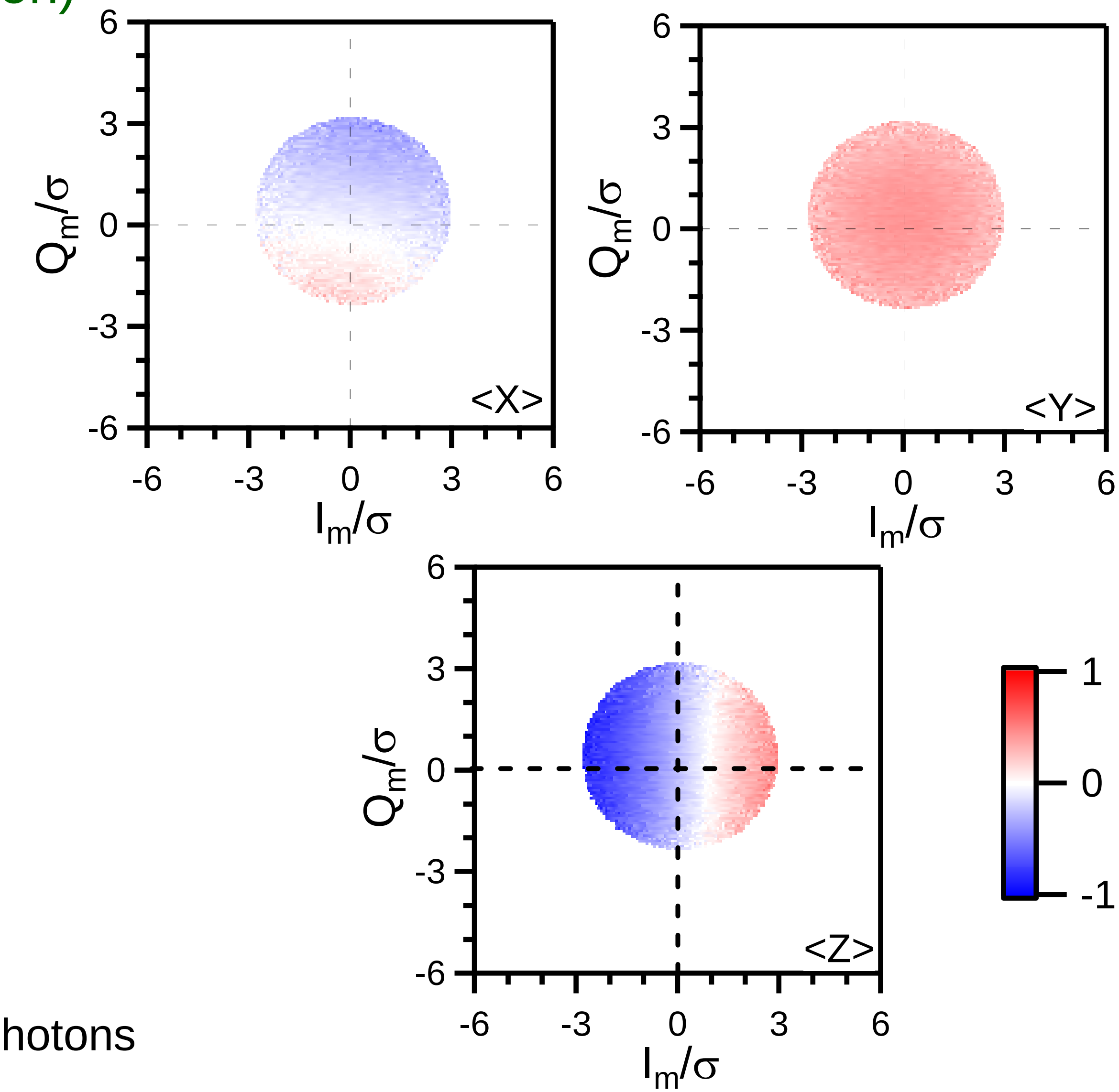
MEASUREMENT WITH $\bar{n} = 1.1 \times 10^{-1}$

Courtesy of Michel Devoret
(manuscript in preparation)

histogram of measurement outcomes



tomography along X, Y, Z after measurement



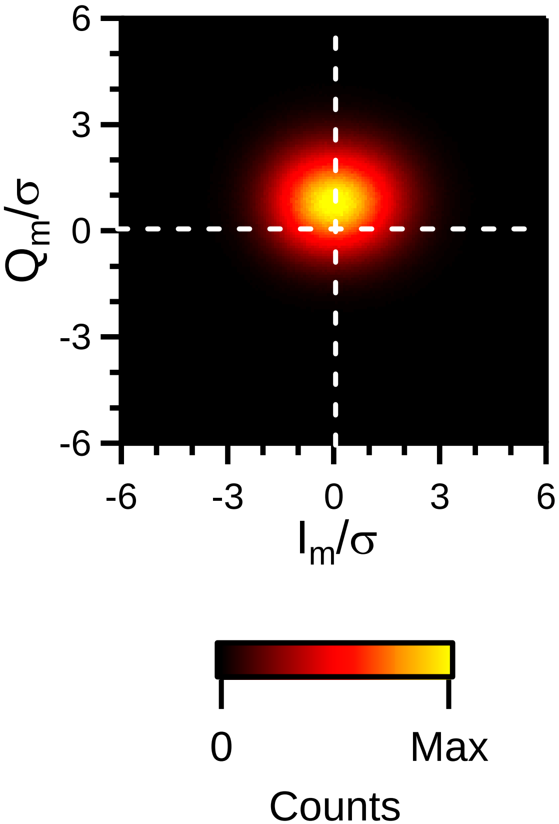
Cavity Drive = 1.1e-01 photons

$(I_m^g - I_m^e)/(2\sigma) = 0.543$

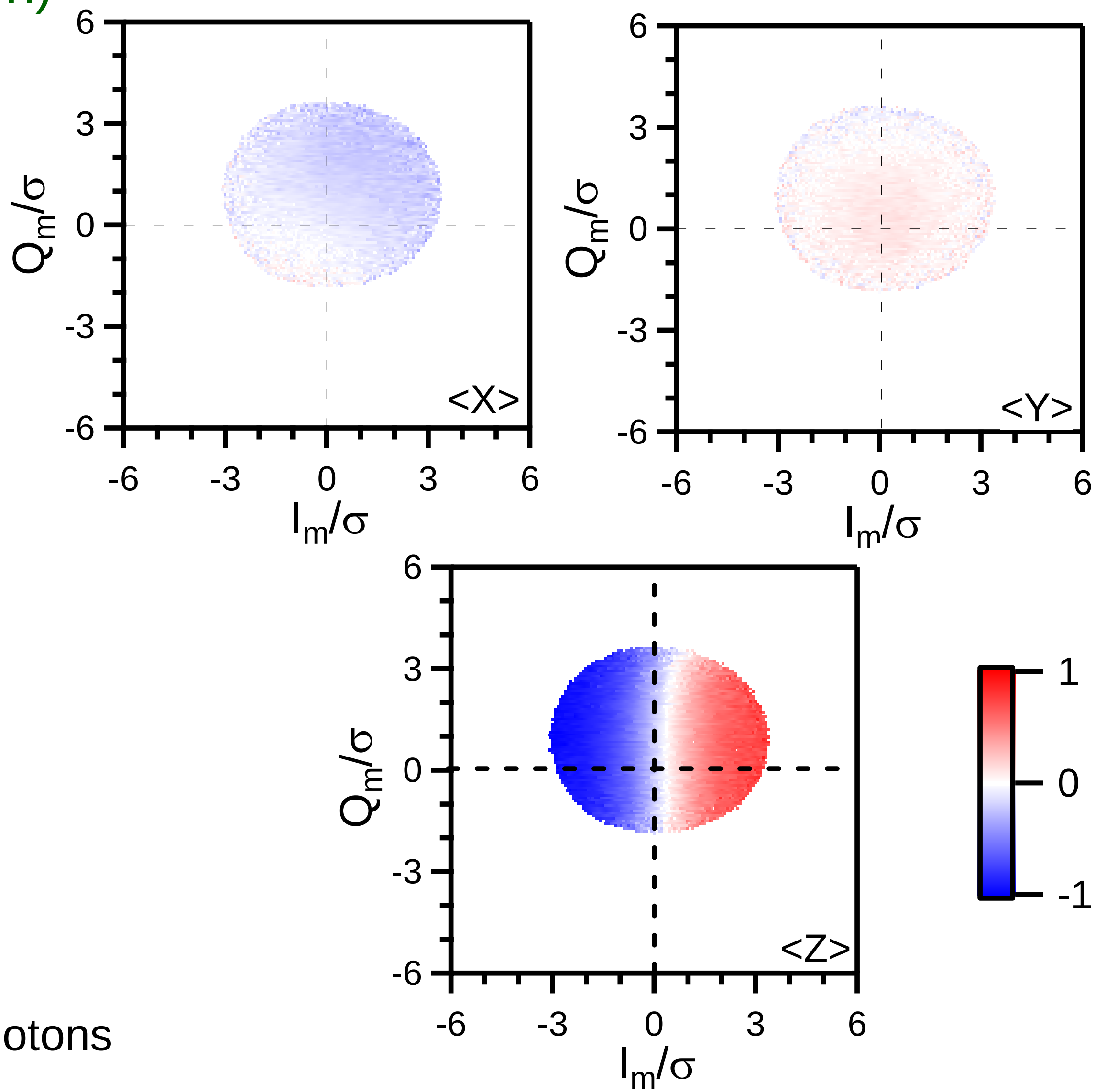
MEASUREMENT WITH $\bar{n}$ = 5 x 10^{-1}

Courtesy of Michel Devoret
(manuscript in preparation)

histogram of measurement outcomes



tomography along X, Y, Z after measurement



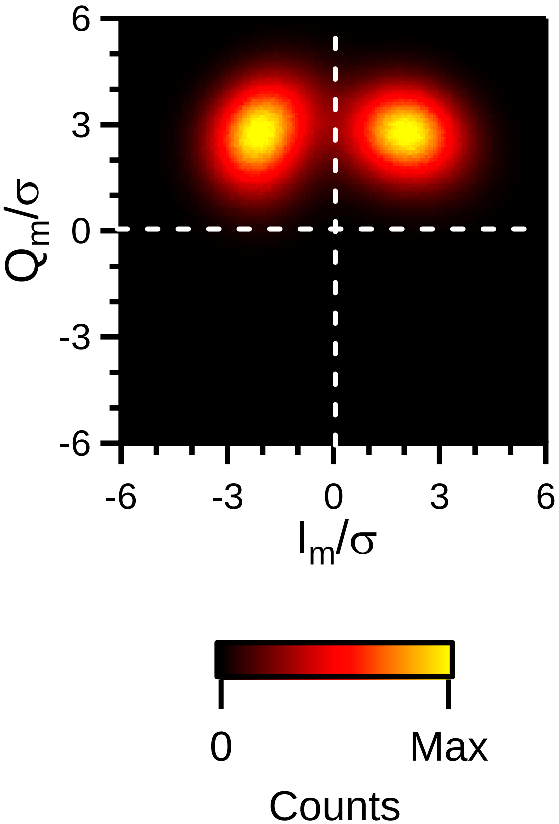
Cavity Drive = 5.1e-01 photons

$(I_m^g - I_m^e)/(2\sigma) = 1.223$

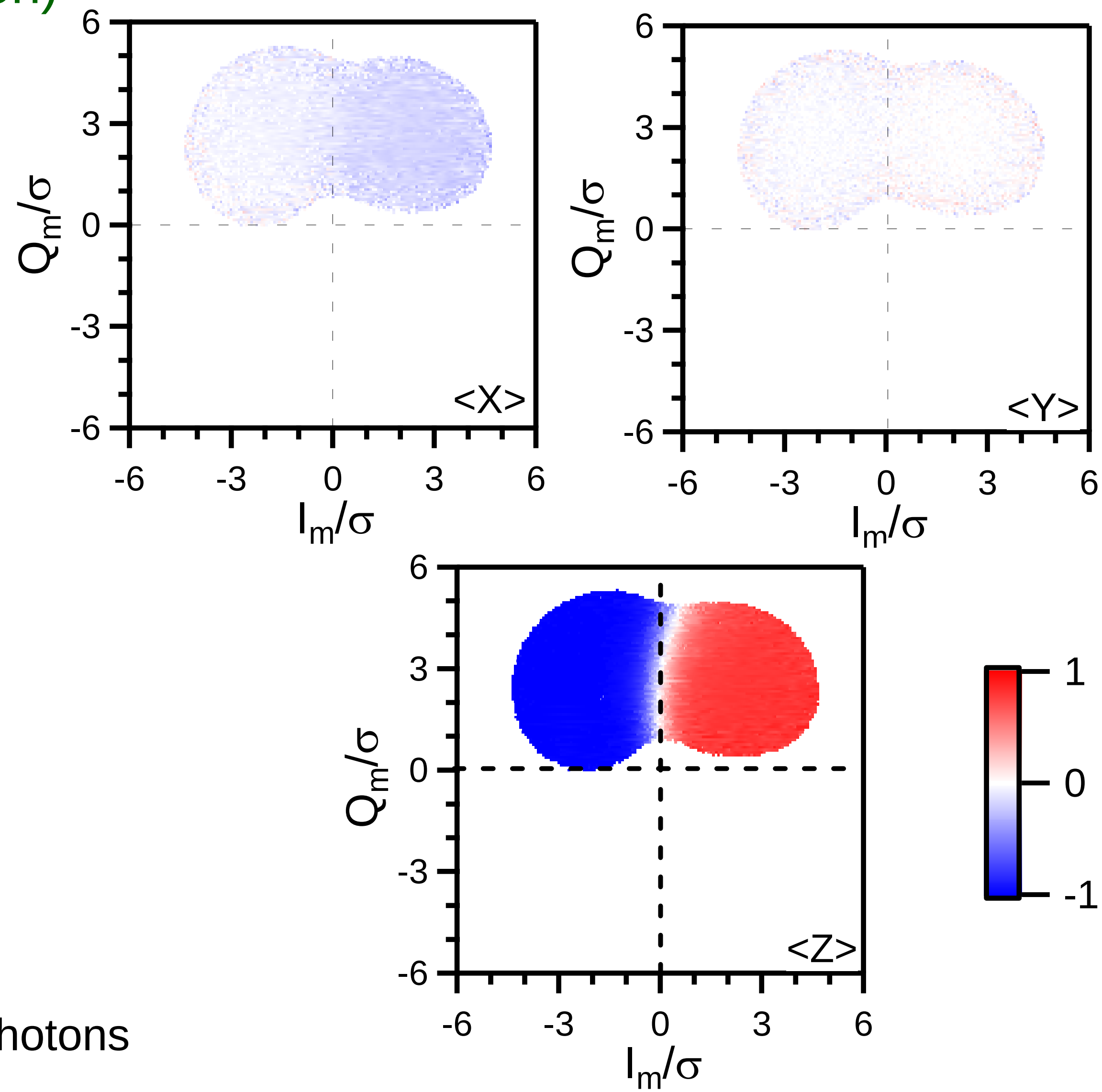
MEASUREMENT WITH $\bar{n}$ = 5

Courtesy of Michel Devoret
(manuscript in preparation)

histogram of measurement outcomes



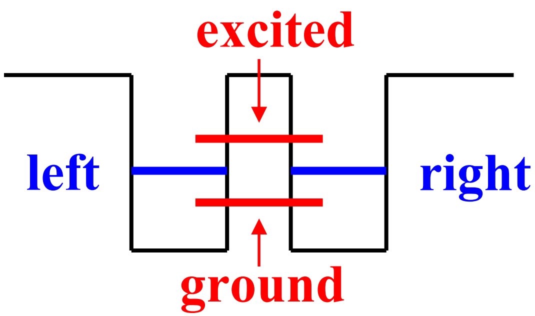
tomography along X, Y, Z after measurement



Cavity Drive = 5.0e+00 photons

$(I_m^g - I_m^e)/(2\sigma) = 4.100$

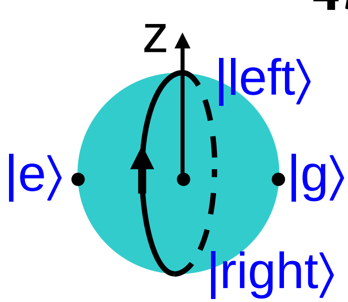
Non-decaying (persistent) Rabi oscillations

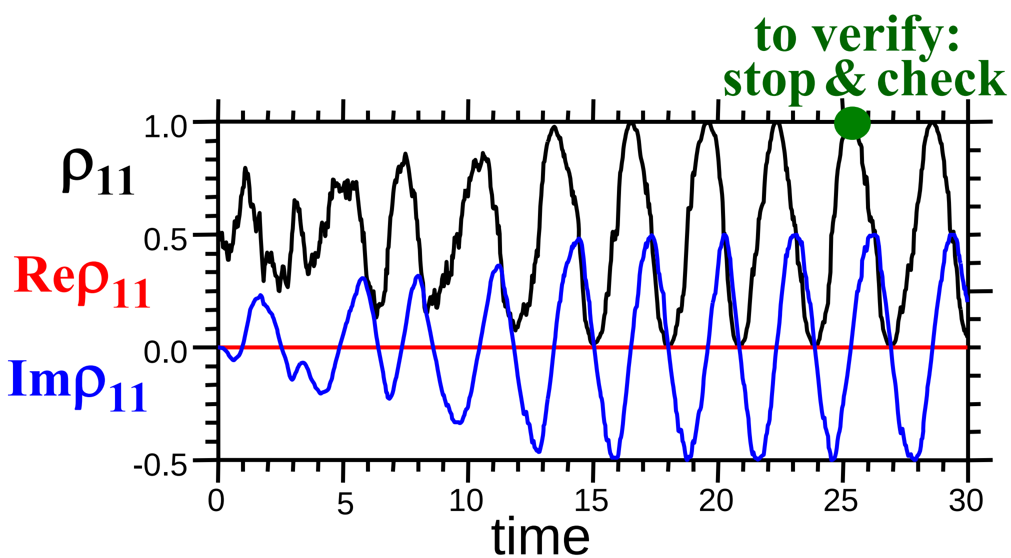


- Relaxes to the ground state if left alone (low-*T*)
- Becomes fully mixed if coupled to a high-*T* (non-equilibrium) environment
- Oscillates persistently between left and right if (weakly) measured continuously

$$\frac{(\Delta I)^2}{4S_I} << \Omega$$

("reason": attraction to left/right states)



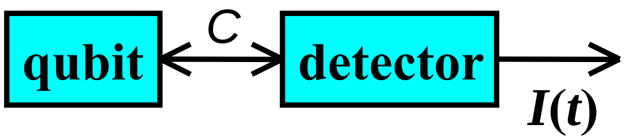


Direct experiment is difficult

A.K., PRB-1999

Indirect experiment: spectrum of persistent Rabi oscillations

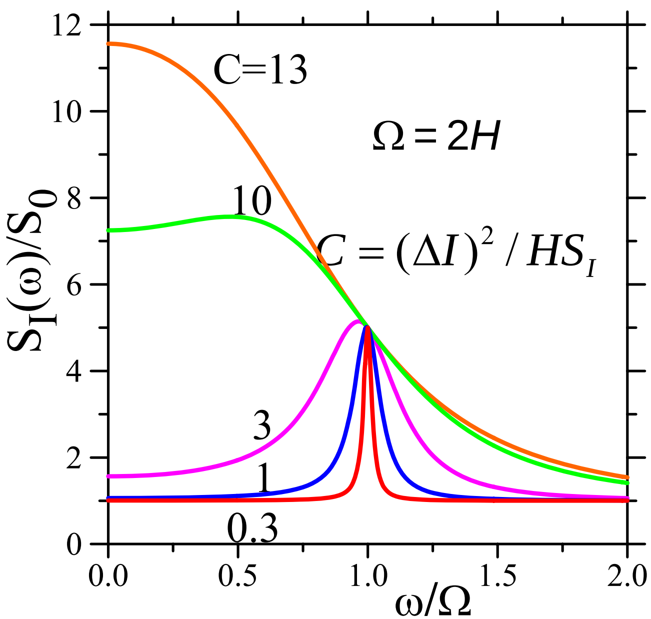
A.K., LT'1999
A.K.-Averin, 2000



$$I(t) = I_0 + \frac{\Delta I}{2} z(t) + \xi(t)$$

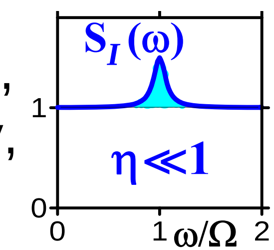
(const + signal + noise)

z is Bloch coordinate



Ω - Rabi frequency

amplifier noise ⇒ higher pedestal,
poor quantum efficiency,
but the peak is the same!!!



integral under the peak ⇔ variance $\langle z^2 \rangle$

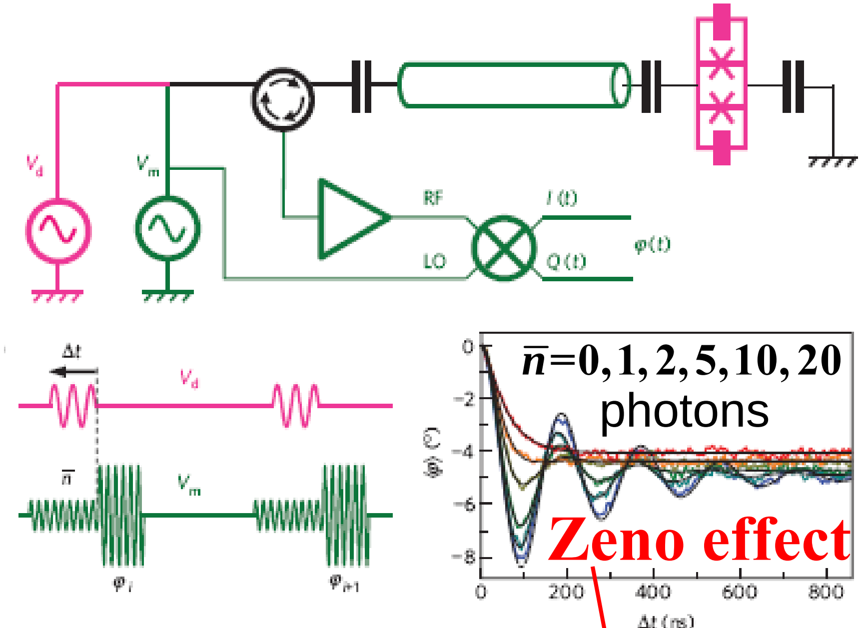
peak-to-pedestal ratio = $4\eta \le 4$

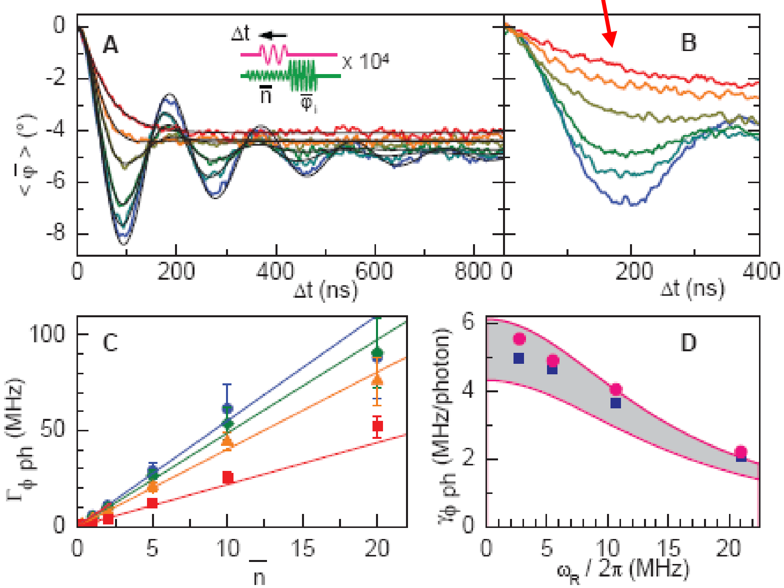
$$S_I(\omega) = S_0 + \frac{\Omega^2 (\Delta I)^2 \Gamma}{(\omega^2 - \Omega^2)^2 + \Gamma^2 \omega^2}$$

perfect Rabi oscillations: $\langle z^2 \rangle = \langle \cos^2 \rangle = 1/2$
imperfect (non-persistent): $\langle z^2 \rangle \ll 1/2$
quantum (Bayesian) result: $\langle z^2 \rangle = 1$ (!!!)

(demonstrated in Saclay expt.)

Saclay experiment





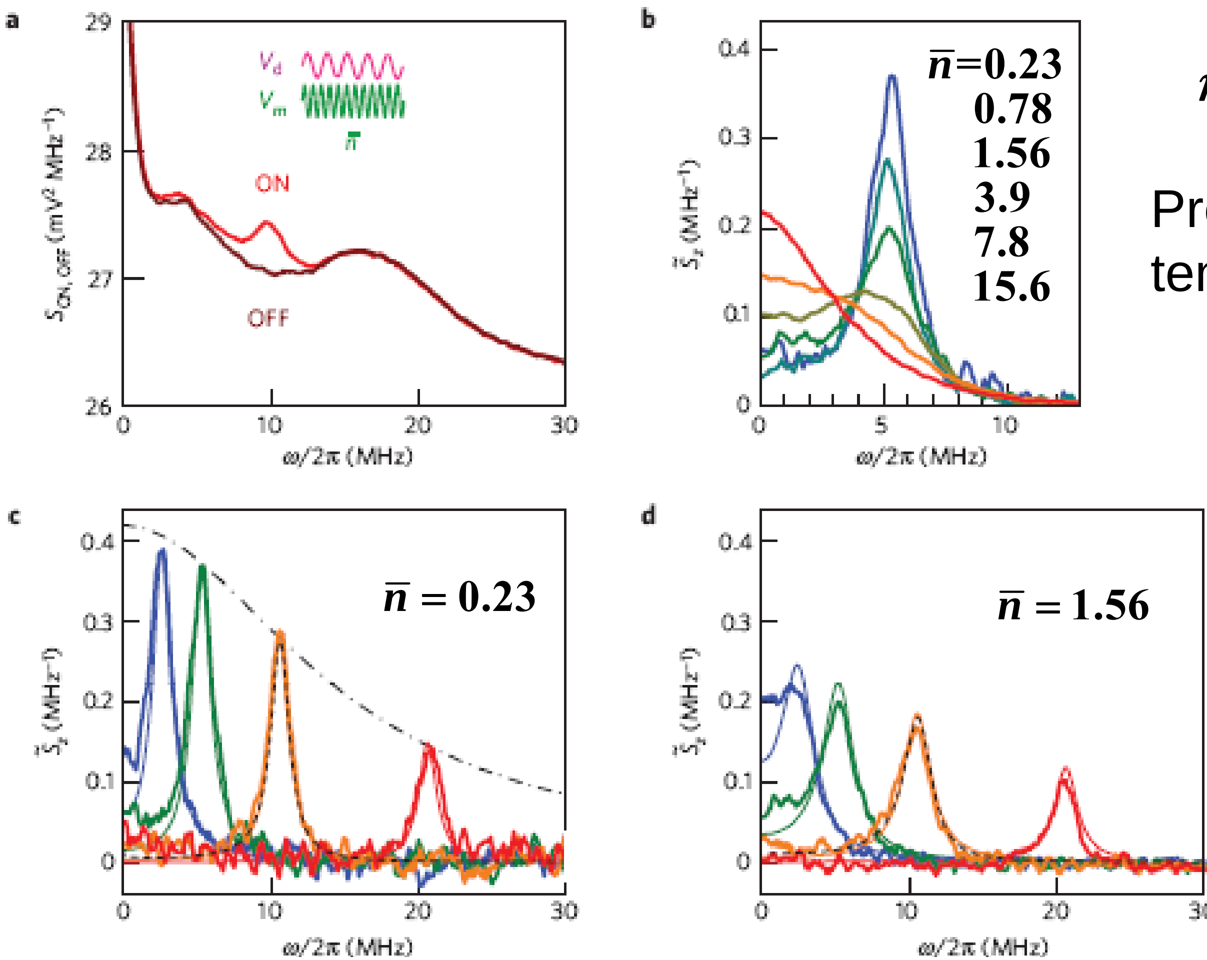
A.Palacios-Laloy, F.Mallet, F.Nguyen, P. Bertet, D. Vion, D. Esteve, and A. Korotkov, Nature Phys., 2010

- superconducting charge qubit (transmon) in circuit QED setup
- microwave reflection from cavity: full collection, only phase modulation
- driven Rabi oscillations (z-basis is |g>&|e>)

Standard (not continuous) measurement here: ensemble-averaged Rabi starting from ground state

Now continuous measurement

Palacios-Laloy et al., 2010



$$\eta = \frac{\Delta S}{4S} \sim 10^{-2}$$

Pre-amplifier noise temperature T_N= 4 K

$$\frac{1}{1+\dfrac{2T_N}{\hbar\omega}} \approx 0.03$$

Theory by dashed lines, very good agreement

Violation of Leggett-Garg inequalities

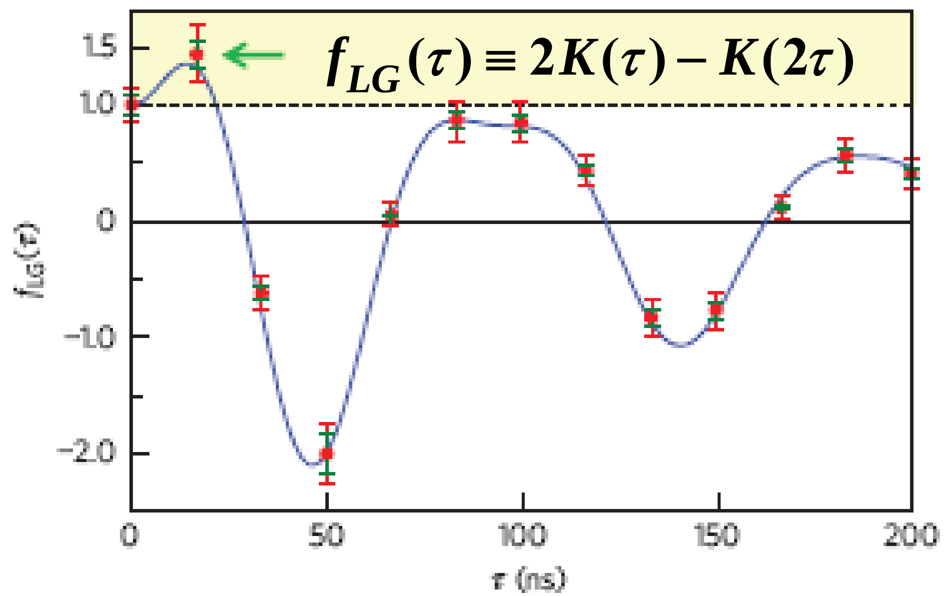
Palacios-Laloy et al., 2010

In time domain

Rescaled to qubit z-coordinate $\quad K(\tau) \equiv \langle z(t)\, z(t+\tau) \rangle$

$$K(\tau_1) + K(\tau_2) - K(\tau_1 + \tau_2) \le 1 \quad \Rightarrow 2K(\tau) - K(2\tau) \le 1$$

$$f_{LG}(0) = K(0) = \langle z^2 \rangle \qquad \langle z^2 \rangle = 1.01 \pm 0.15$$



$f_{LG}(17\,\text{ns}) = 1.44 \pm 0.12$ Ideal $f_{LG,max}$=1.5

Standard deviation $\sigma = 0.065 \Rightarrow$ violation by 5σ

Quantum feedback control of persistent Rabi oscillations

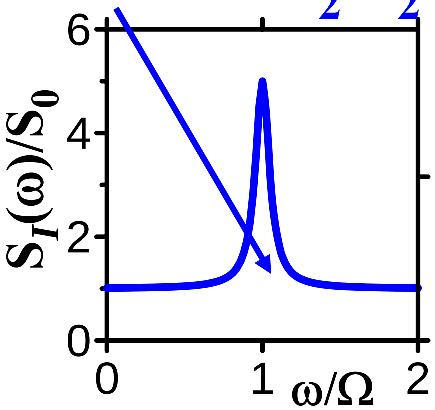
In simple monitoring the phase of persistent Rabi oscillations fluctuates randomly:

$$z(t) = \cos[\Omega t + \varphi(t)] \qquad \text{for } \eta=1$$

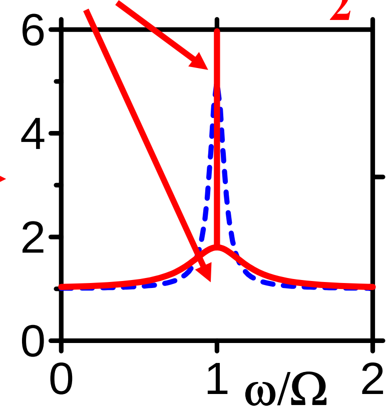
phase noise ⇒ finite linewidth of the spectrum

Goal: produce persistent Rabi oscillations without phase noise by synchronizing with a classical signal $z_{desired}(t) = \cos(\Omega t)$

integral $\langle z^2 \rangle = \frac{1}{2} + \frac{1}{2} = 1$



integral $\langle z^2 \rangle = \frac{1}{2}$



$$I(t) = I_0 + \frac{\Delta I}{2} z(t) + \xi(t)$$

$$S_I = S_0 + \frac{\Delta I^2}{4} S_{zz} + \frac{\Delta I}{2} S_{\xi z}$$

synchronized (S_{zz})

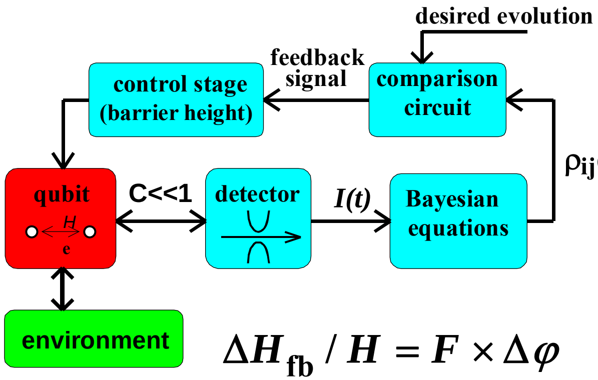
cannot synchronize ($S_{\xi z}$)

Several types of quantum feedback

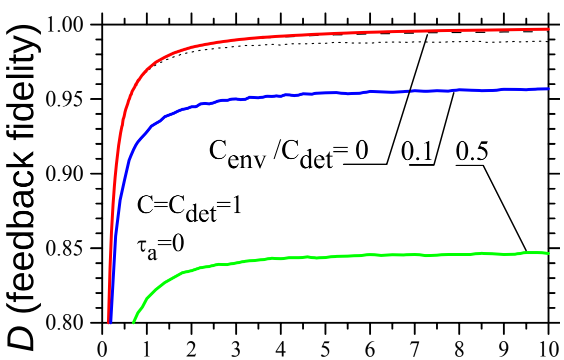
Bayesian

Best but very difficult

(monitor quantum state and control deviation)



$$\Delta H_{fb} / H = F \times \Delta\varphi$$



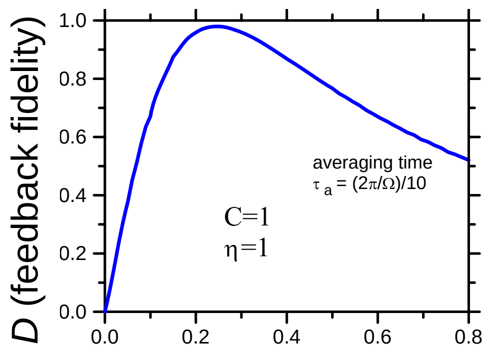
Ruskov & A.K., 2002

Direct

as in Wiseman-Milburn (1993)

(apply measurement signal to control with minimal processing)

$$\Delta H_{fb} / H = F \sin(\Omega t) \times \left(\frac{I(t) - I_0}{\Delta I / 2} - \cos \Omega t \right)$$



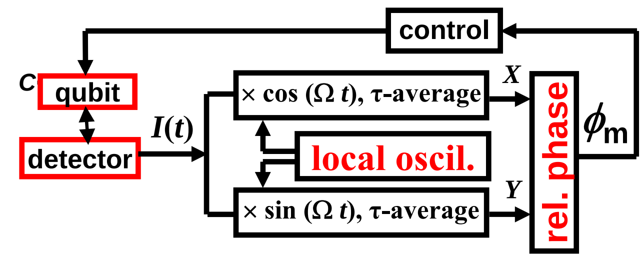
Ruskov & A.K., 2002

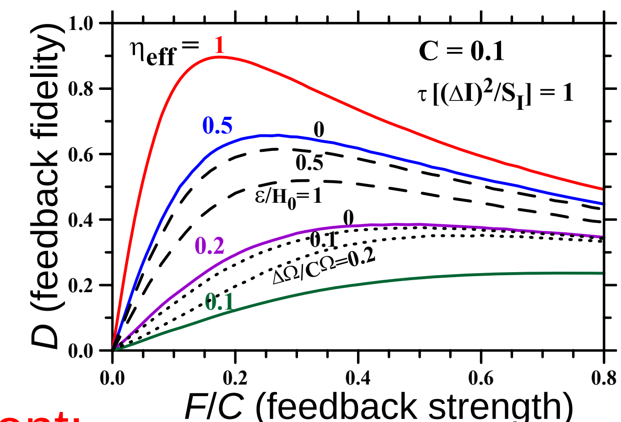
"Simple"

Imperfect but simple

(do as in usual classical feedback)

$$\frac{\Delta H_{fb}}{H} = F \times \phi_m$$



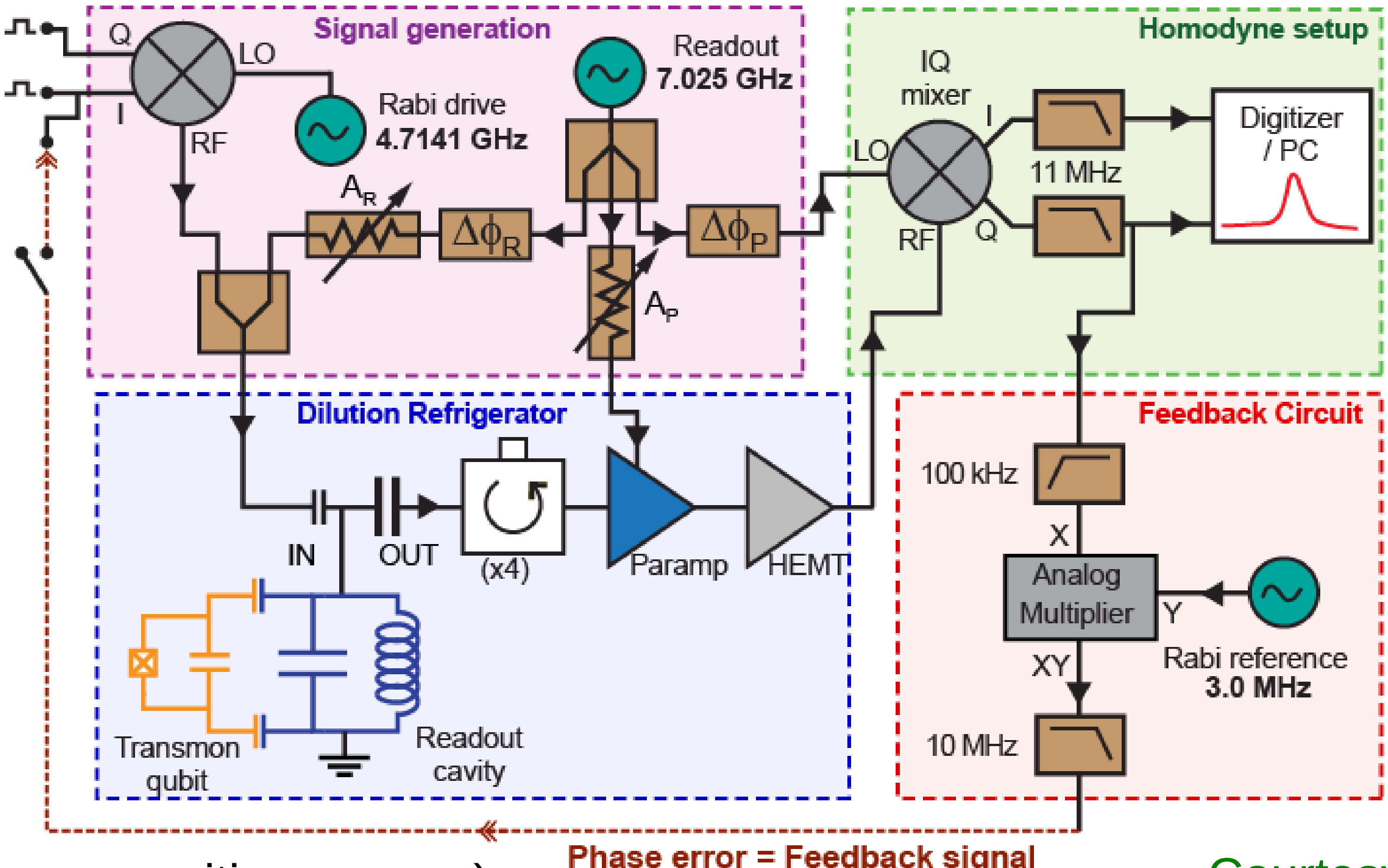


A.K., 2005

Berkeley-2012 experiment: "direct" and "simple"

Quantum feedback of Rabi oscillations

R. Vijay, C. Macklin, D. Slicher, S. Weber, K. Murch, R. Naik, A. Korotkov, and Irfan Siddiqi, 2012 (unpub.)

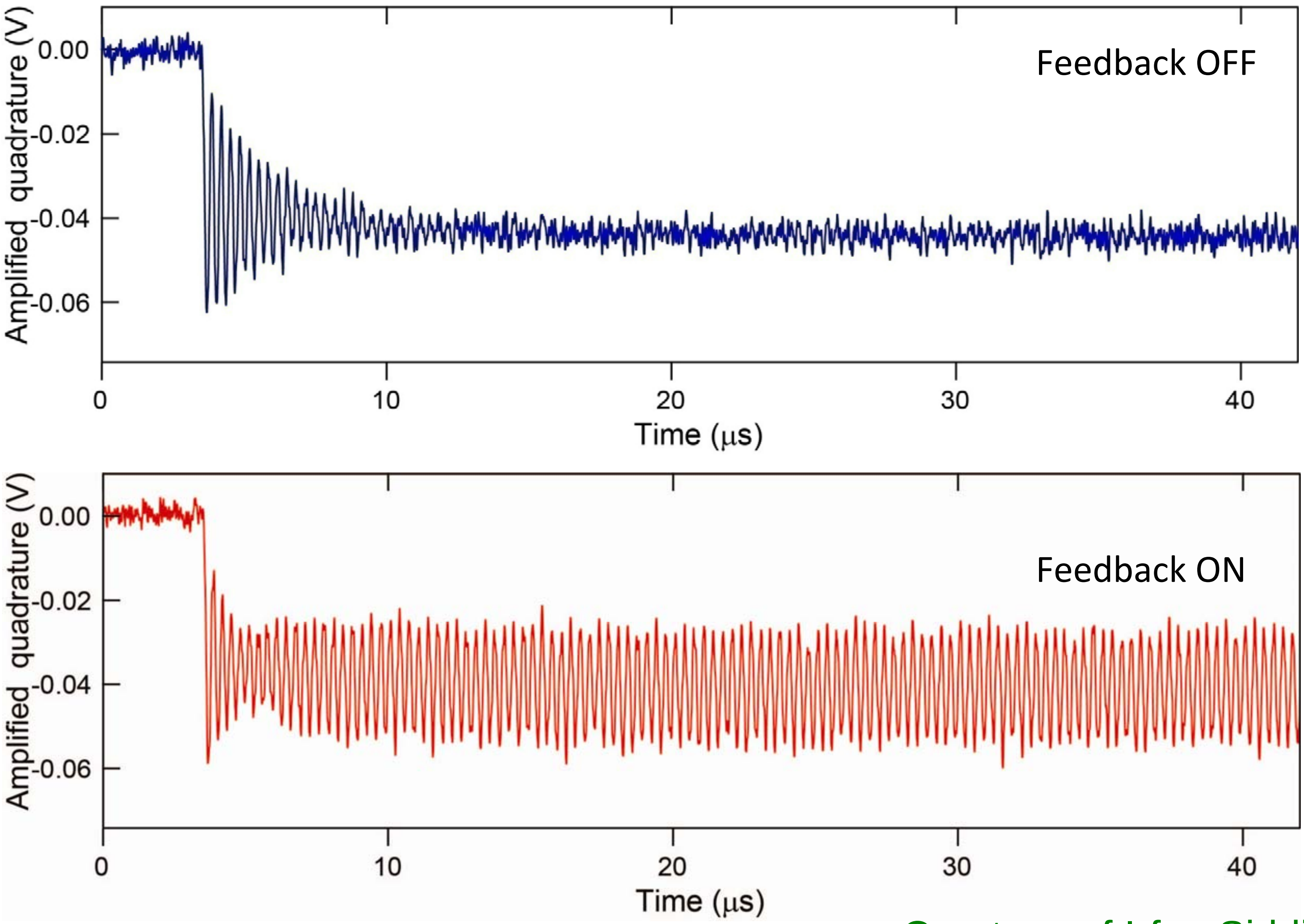


(phase-sensitive paramp)

Paramp BW 10 MHz, Cavity LW 8 MHz, Rabi freq. 3 MHz,
Meas. dephasing 0.25 MHz, Env. dephasing 0.05 MHz

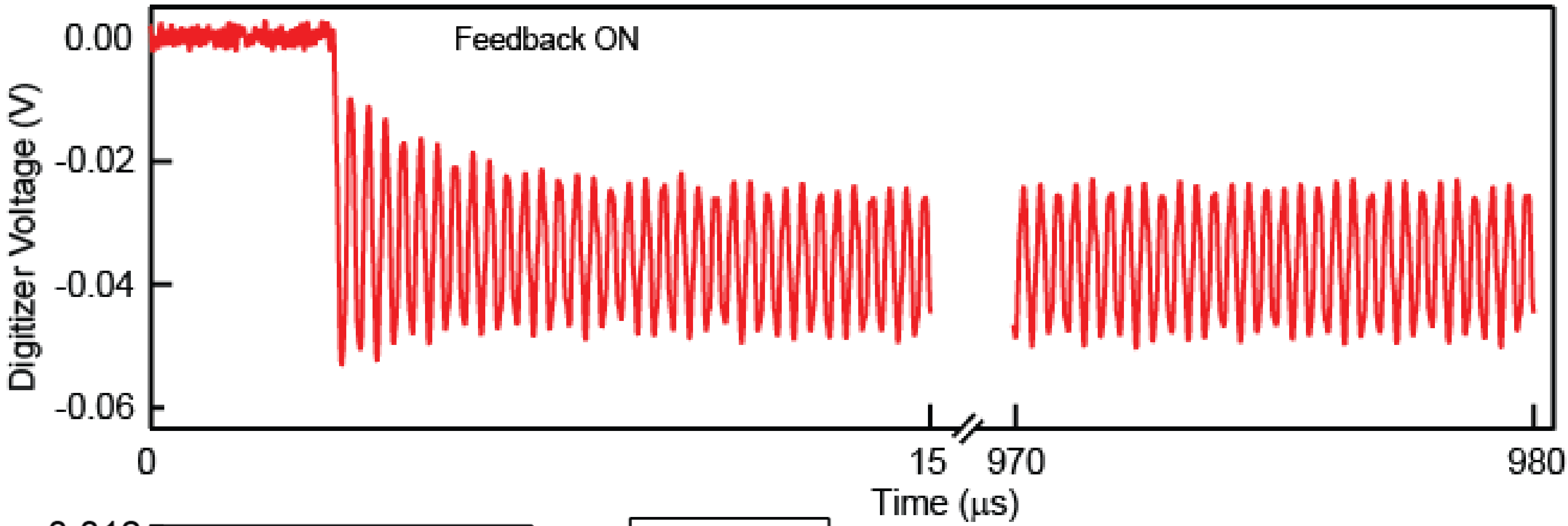
Courtesy of Irfan Siddiqi

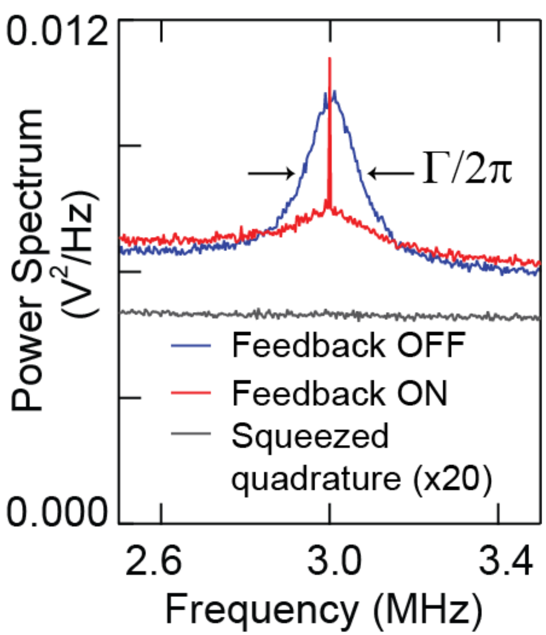
STABILIZED RABI OSCILLATIONS

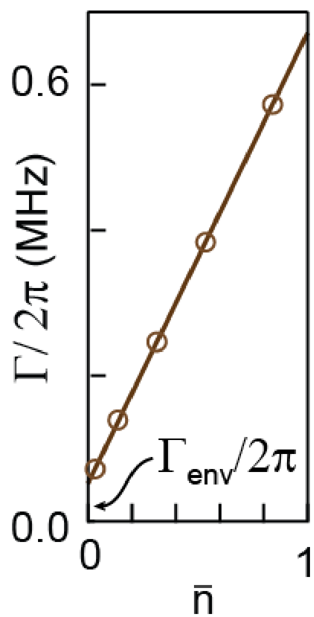


Courtesy of Irfan Siddiqi

STILL GOING…



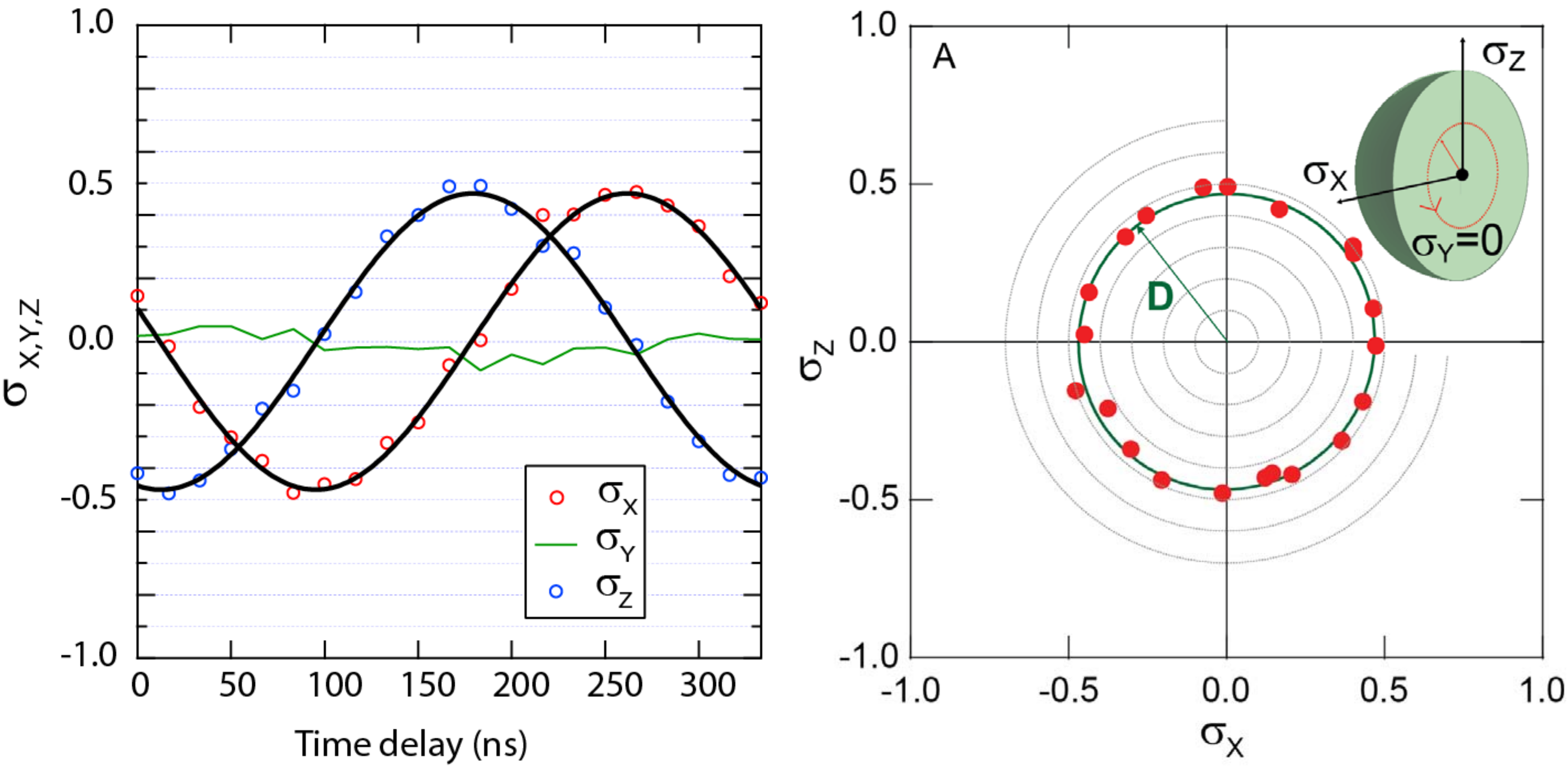




- Single quadrature measurement
- Operate with measurement dephasing dominant
- Appearance of narrow peak when PLL operational

Courtesy of Irfan Siddiqi

STATE TOMOGRAPHY



• Observe expected rotation in the X,Z plane

• Observe Bloch vector reduced to 50% of maximum

Courtesy of Irfan Siddiqi

FEEDBACK EFFICIENCY

$$D = \frac{2}{\frac{1}{\eta}\frac{F}{\Gamma/\Omega_R} + \frac{\Gamma/\Omega_R}{F}}$$

D: "feedback efficiency"

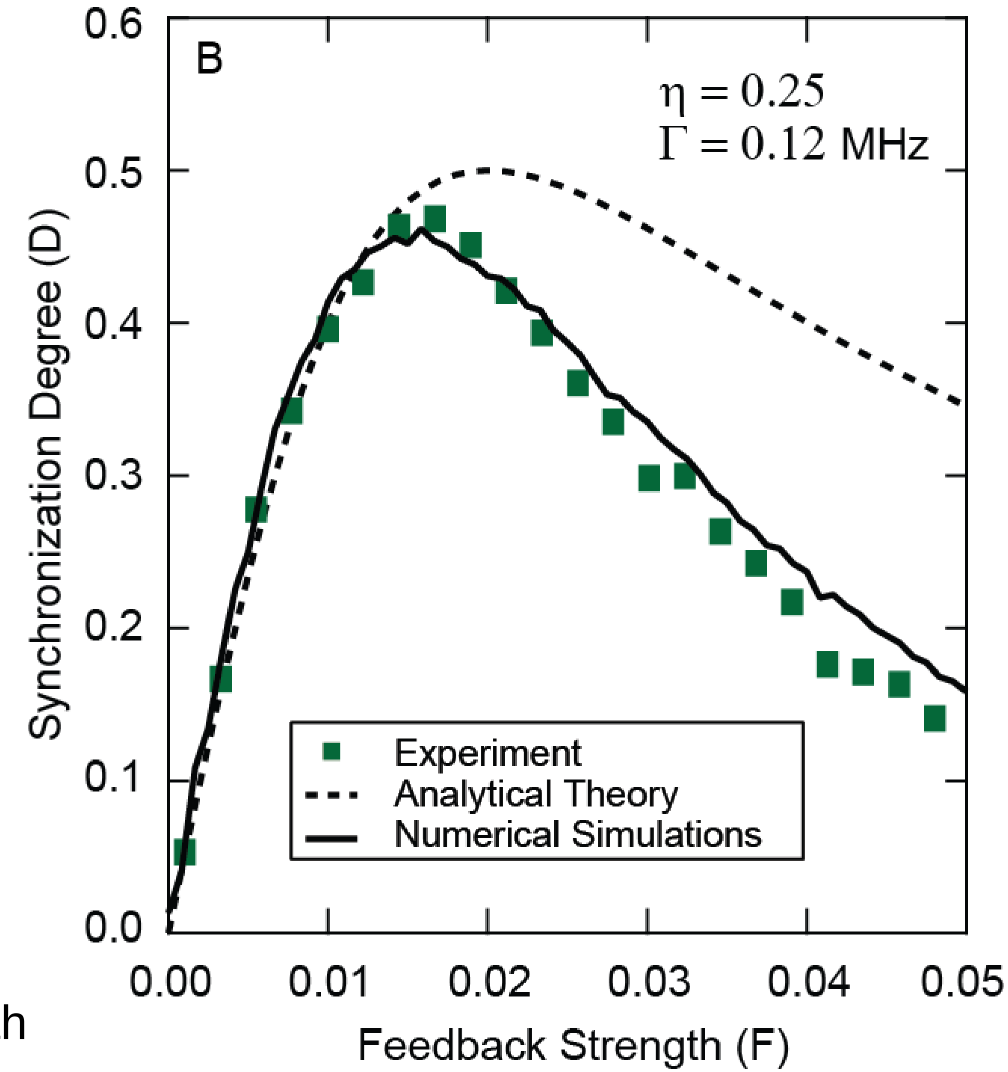
F: feedback strength

η: detector efficiency (0-1)

Γ: dephasing rate

Ω_R: Rabi frequency

- Analytics do not include delay time, finite bandwidth, T_1
- Numerics include delay and bandwidth → good agreement



Courtesy of Irfan Siddiqi

Conclusions

- It is easy to see what is “inside” collapse: simple Bayesian framework works for many solid-state setups

- Measurement backaction necessarily has a “spooky” part (informational, without a physical mechanism); it may also have a “classical” part (with a physically understandable mechanism)

- Five superconducting experiments so far:
  - partial collapse,
  - uncollapse,
  - monitoring of non-decaying Rabi oscillations,
  - quantum feedback of persistent Rabi oscillations,
  - partial measurement with continuous result

- Hopefully something useful in future