nic@qs13, Erice, Italy, 10/07/13

Continuous/partial quantum measurement and feedback of 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 (~10^1 so far, s/c qubits)
  - partial collapse (null-result & continuous)
  - uncollapse (+ decoherence suppression)
  - persistent Rabi oscillations, quantum feedback
  - entanglement by measurement

Copenhagen quantum mechanics =

Schrödinger equation
+
collapse postulate

1) Fundamentally random measurement result *r*
(out of allowed set of eigenvalues). Probability: $p_r = |\langle \psi | \psi_r \rangle|^2$

2) State after measurement corresponds to result: ψ_r

- Contradicts Schr.Eq. (spooky), but follows from common sense
- Needs “observer” to 1) ask a question, 2) **get information**

Why so strange (unobjective)?

- “Shut up and calculate”
- May be QM founders were stupid?
- Use proper philosophy?

Werner Heisenberg

Books:

Physics and Philosophy: The Revolution in Modern Science

Philosophical Problems of Quantum Physics

The Physicist's Conception of Nature

Across the Frontiers

Niels Bohr

Immanuel Kant (1724-1804), German philosopher

Critique of pure reason (materialism, but not naive materialism)

Nature - “Thing-in-itself” (noumenon, not phenomenon)

Humans use “concepts (categories) of understanding”;
make sense of phenomena, but never know noumena directly

A priori: space, time, causality

A naïve philosophy should not be a roadblock for good physics, quantum mechanics requires a non-naïve philosophy

Wavefunction is not a reality, it is only our description of reality

What is “inside” collapse?
What if collapse is stopped half-way?

When: - information comes gradually in time (noisy detector)
- information is inconclusive

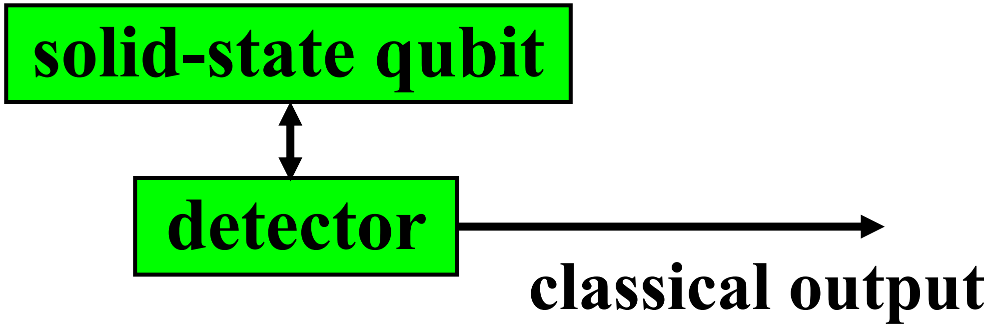
Various approaches to non-projective (weak, continuous, partial, generalized, etc.) quantum measurements

Names: Davies, Kraus, Holevo, Mensky, Caves, Knight, Walls, Carmichael, Milburn, Wiseman, Aharonov, 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)

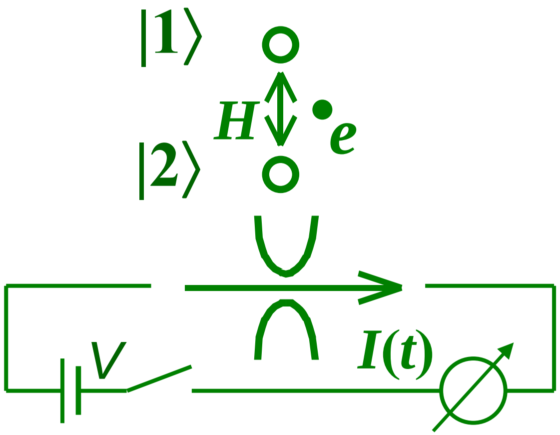


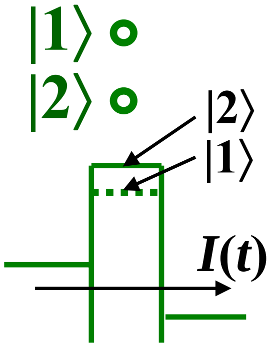
“Typical” solid-state setup (broadband)

double-quantum-dot (DQD) qubit
& quantum point contact (QPC) detector

Advantage:
very simple model

S. 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

$$H_{DET} = \sum\nolimits_l E_l a_l^\dagger a_l + \sum\nolimits_r E_r a_r^\dagger a_r + \sum\nolimits_{l,r} T(a_r^\dagger a_l + a_l^\dagger a_r)$$

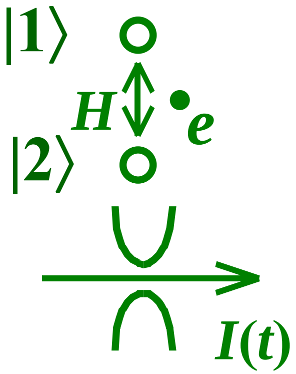
$$H_{INT} = \sum\nolimits_{l,r} \Delta T\,(c_1^\dagger c_1 - c_2^\dagger c_2)\,a_r^\dagger a_l + \mathrm{h.c.} \qquad S_I = 2eI$$

Question:

$$\frac{|1\rangle + |2\rangle}{\sqrt{2}} \rightarrow \;?\; \begin{matrix} \nearrow & |1\rangle \\ \searrow & |2\rangle \end{matrix}$$

Bayesian formalism for DQD-QPC system

$H_{QB} = 0$



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

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

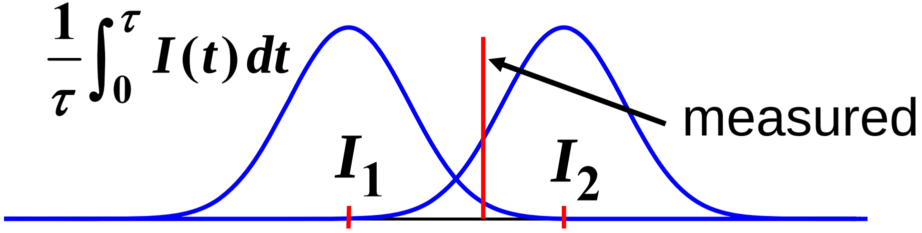
1) $|\alpha(t)|^2$ and $|\beta(t)|^2$ evolve as probabilities,
i.e. according to the **Bayes rule** (same for ρ_{ii})

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)

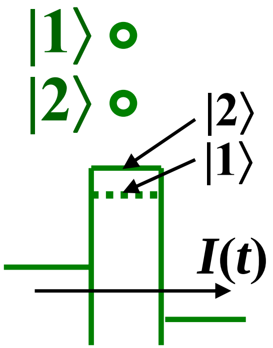
Bayes rule (1763, Laplace-1812):

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



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

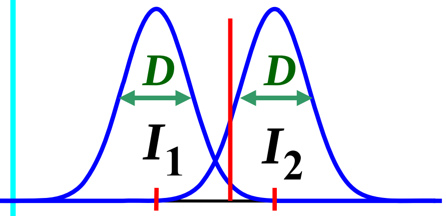


$\Delta I = I_1 - I_2$

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”)

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

no self-evolution of qubit assumed

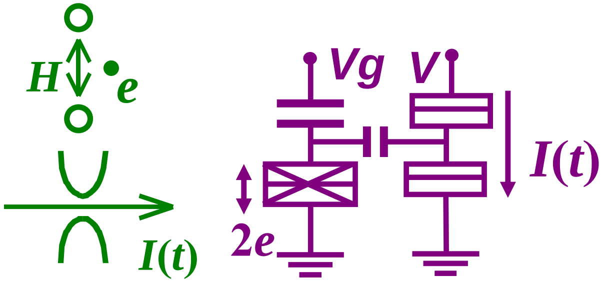
decoherence

classical backaction (unitary)

Example of classical (“physical”) backaction:

Each electron passed through detector shifts qubit phase

Now add Hamiltonian evolution



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

(Stratonovich form)

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

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

(A.K., 1998)

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

$\gamma = 0$ 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 detector)

Can be checked experimentally

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.)

Relation to “conventional” master equation

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

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

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

“physical” noise-backaction correlation

response ΔI
noise S_I
output $I(t)$

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

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

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

ensemble dephasing Γ

$$\Gamma = \underset{\text{“spooky”}}{(\Delta I)^2/(4S_I)} + \underset{\text{“physical”}}{K^2S_I/4} + \underset{\text{dephasing}}{\gamma}$$

“spooky” part: larger noise causes smaller dephasing

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

“spooky” = “informational”

What if detector output contains additional classical noise?

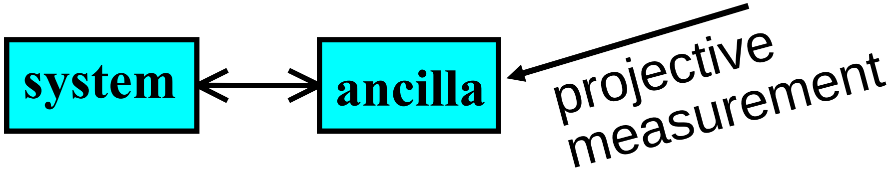
Same equations with larger noise S_I, same Γ, and increased dephasing γ.

decoherence = loss of information

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.):

$$\psi \rightarrow \frac{M_r\psi}{\|M_r\psi\|} \quad \text{or} \quad \rho \rightarrow \frac{M_r\rho M_r^\dagger}{\mathrm{Tr}(M_r\rho M_r^\dagger)}$$

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

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

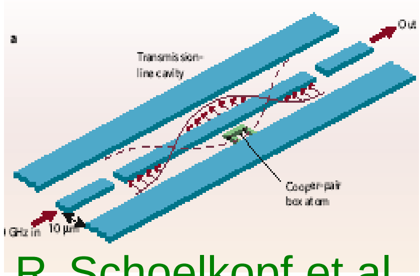
(People often prefer linear evolution and non-normalized states)

Relation between POVM and quantum Bayesian formalism:

decomposition $$M_r = \underset{\nearrow \atop \text{unitary}}{U_r}\underbrace{\sqrt{M_r^\dagger M_r}}_{\text{Bayes}}$$

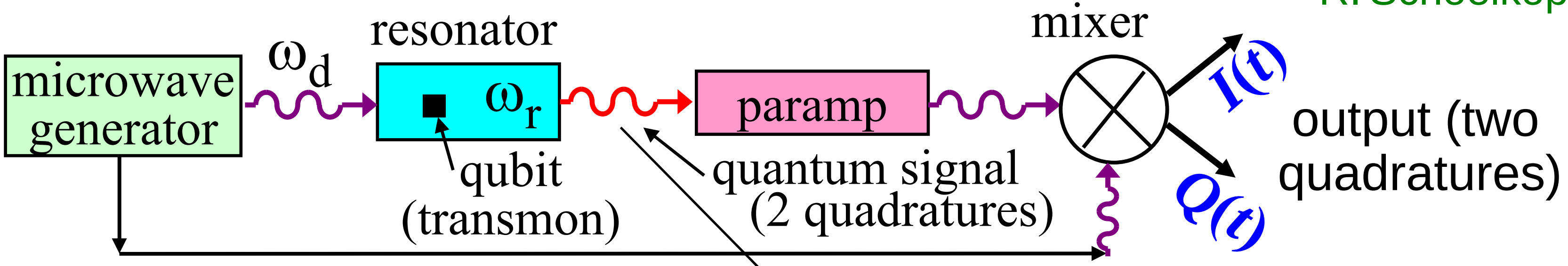
(almost equivalent)

Narrowband linear measurement
(circuit QED setup)



R. Schoelkopf et al.

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


microwave generator

ω_d

resonator

ω_r

qubit (transmon)

paramp

quantum signal (2 quadratures)

mixer

$I(t)$

$Q(t)$

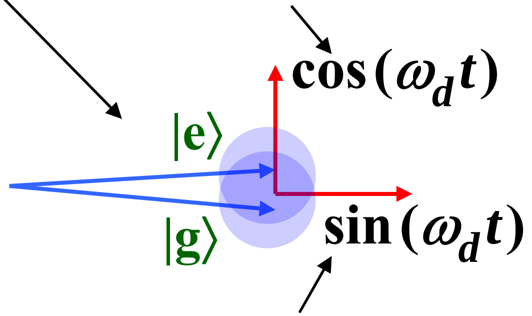
output (two quadratures)

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

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)

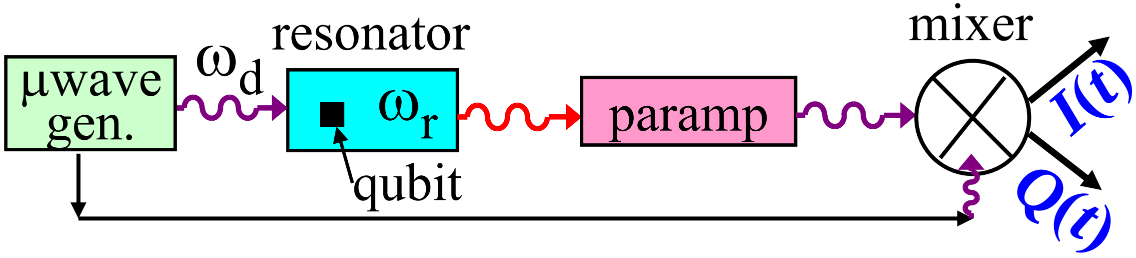

$\cos(\omega_d t)$

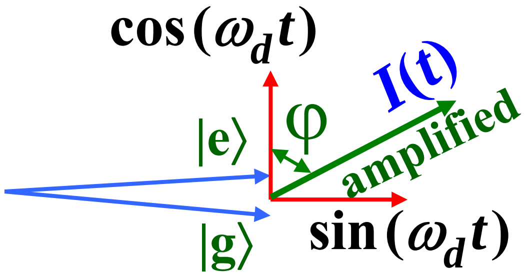
$|e\rangle$

$|g\rangle$

$\sin(\omega_d t)$

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

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

unitary

Bayes

(rotating frame)

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

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

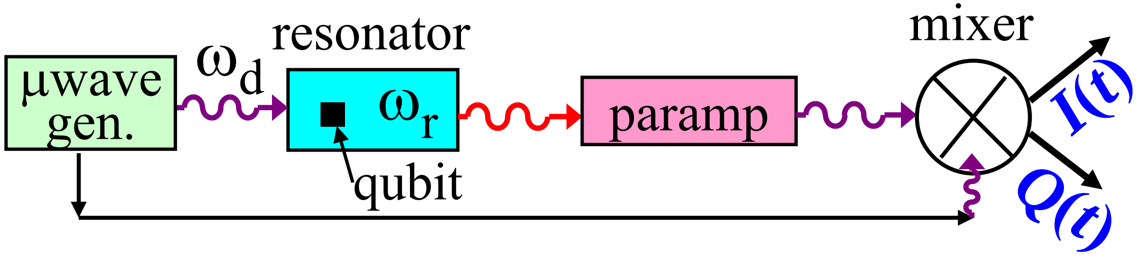
$$\Gamma = \frac{(\Delta I\cos\varphi)^2}{4S_I} + K^2\frac{S_I}{4} = \frac{\Delta I^2}{4S_I} = \frac{8\chi^2\bar{n}}{\kappa}$$

A.K., arXiv:1111.4016

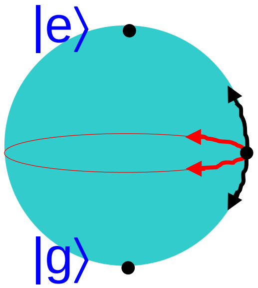
Same as for QPC, but φ controls trade-off between quantum & classical back-actions (we choose if photon number fluctuates or not)

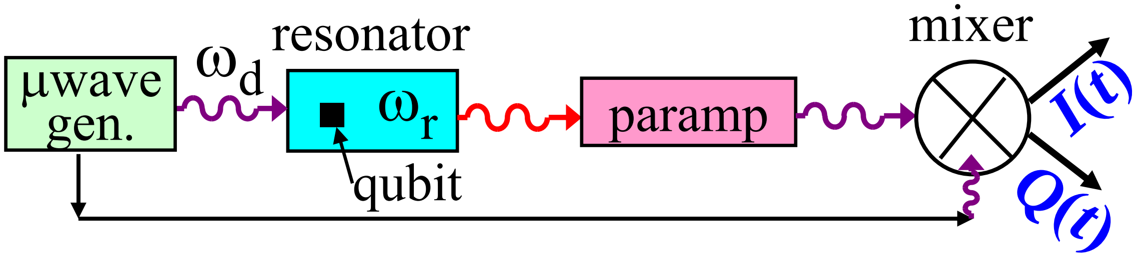
Causality in quantum mechanics

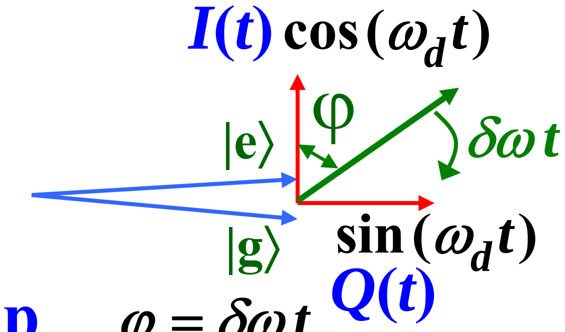
Ensemble-averaged evolution
cannot be affected back in time
(for a single realization it can)



We can choose direction of qubit evolution
to be either along parallel or along meridian
or in between (delayed choice)







Phase-preserving (nondegenerate) paramp

$\varphi = \delta\omega t$

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

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

Small δω ⇒ can follow φ(*t*)
Large δω (>>Γ) ⇒ averaging over φ (phase-preserving)

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

Bayes unitary

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

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

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

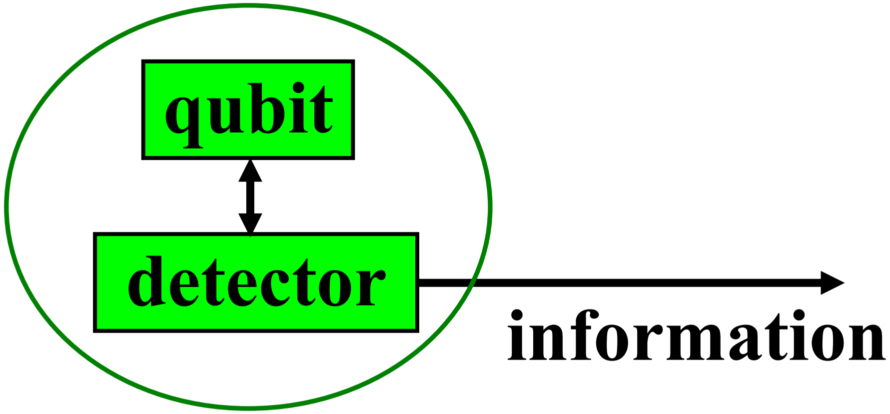
Separated information
in ***I*** and ***Q*** channels

(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?



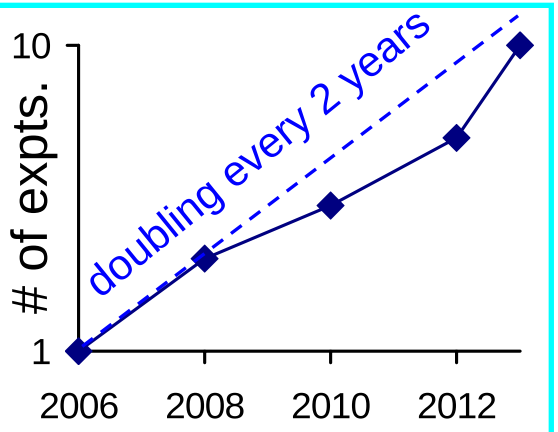
Impossible in principle!

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

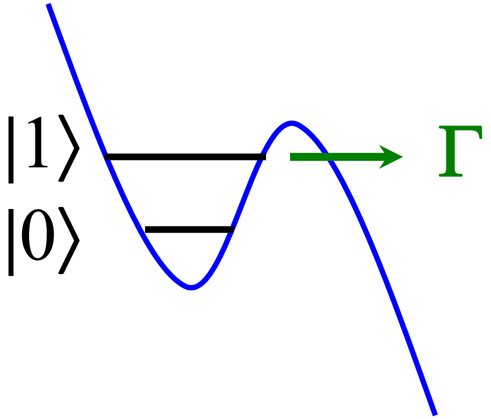
Superconducting experiments "inside" quantum collapse



- 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 oscil. (phase-sensitive paramp)
- Yale-2012/13 Partial (continuous) measurement (phase-preserving paramp)

2013: Berkeley (quantum traj., entanglement by measurement)
Delft (weak values/Leggett-Garg, entanglement by meas.)
Zhejiang/UCSB (3x increase of T_1 by uncollapsing)

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-2006

What happens if no tunneling?

Main idea:

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

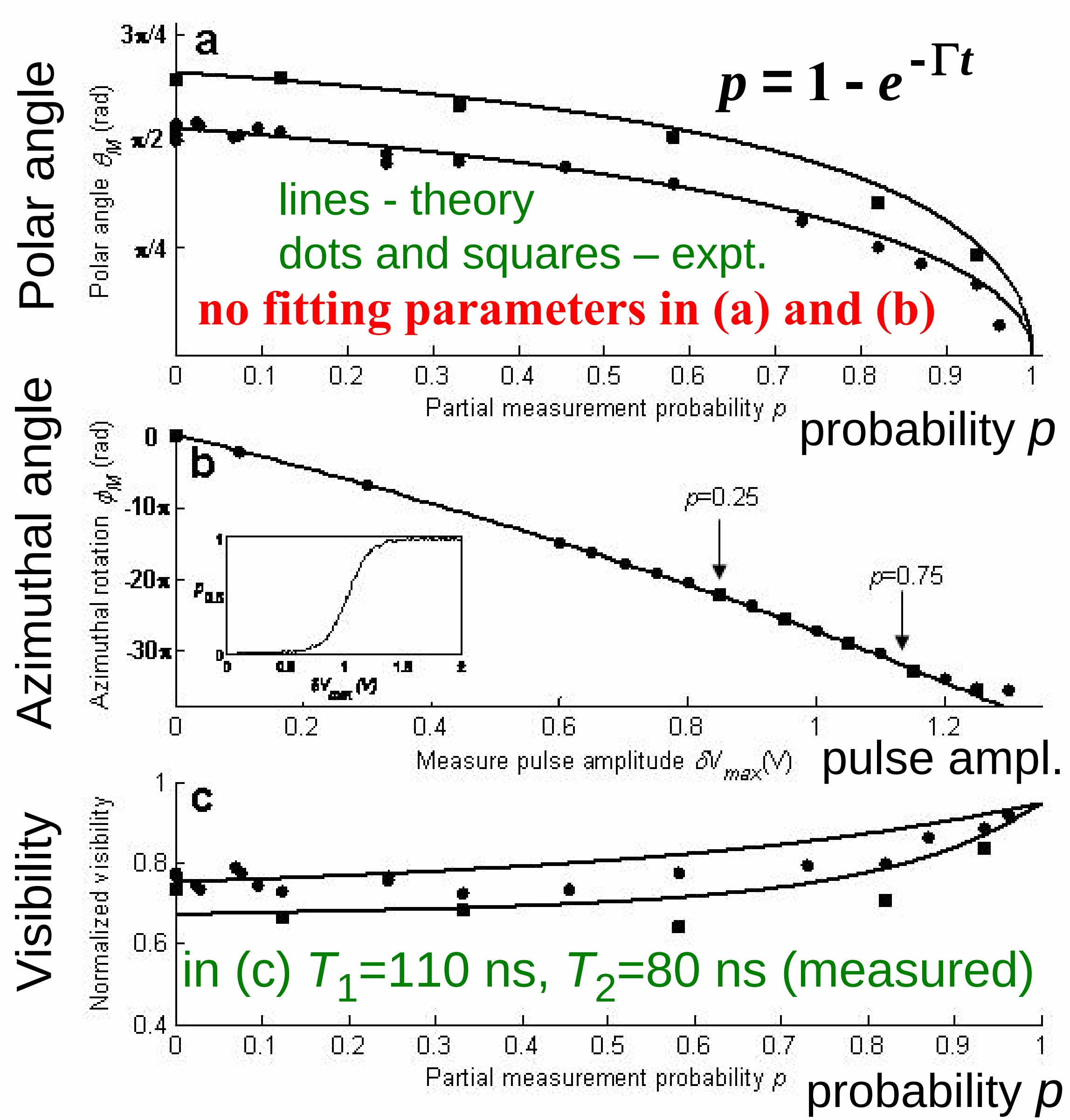
Non-trivial:
- amplitude of state |0⟩ grows without physical interaction
- finite linewidth only after tunneling

continuous null-result collapse

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

Partial collapse: experimental results

N. Katz *et al.*, Science-2006



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

lines - theory

dots and squares – expt.

no fitting parameters in (a) and (b)

probability p

pulse ampl.

in (c) T_1=110 ns, T_2=80 ns (measured)

probability p

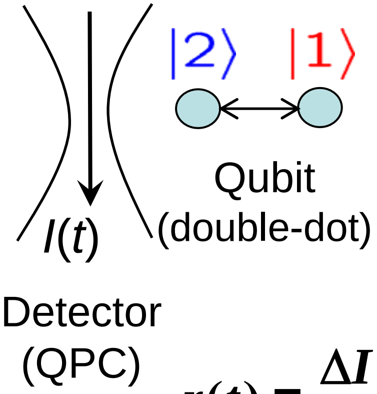
- In case of no tunneling phase qubit evolves
- Evolution is described by the Bayesian theory without fitting parameters
- Phase qubit remains coherent in the process of continuous collapse (expt. ~80% raw data, ~96% corrected for T_1,T_2)

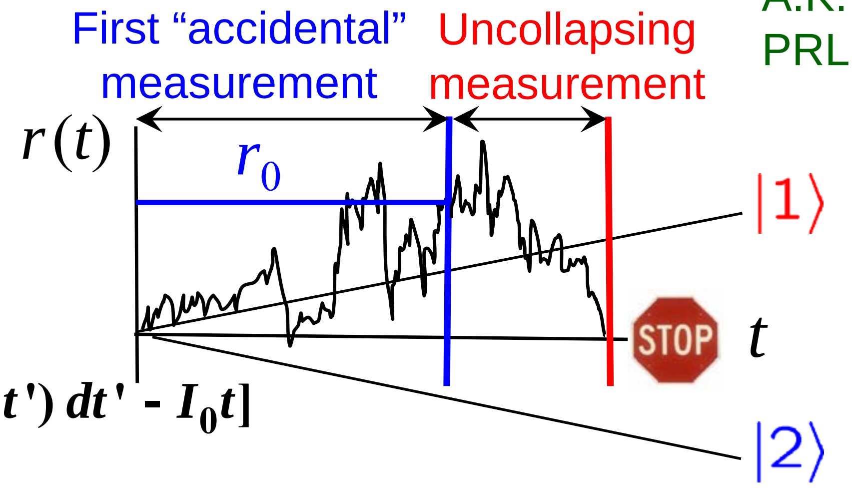
quantum efficiency
$\eta_0 > 0.8$

Good confirmation of the theory

Uncollapsing for qubit-QPC system (theory)

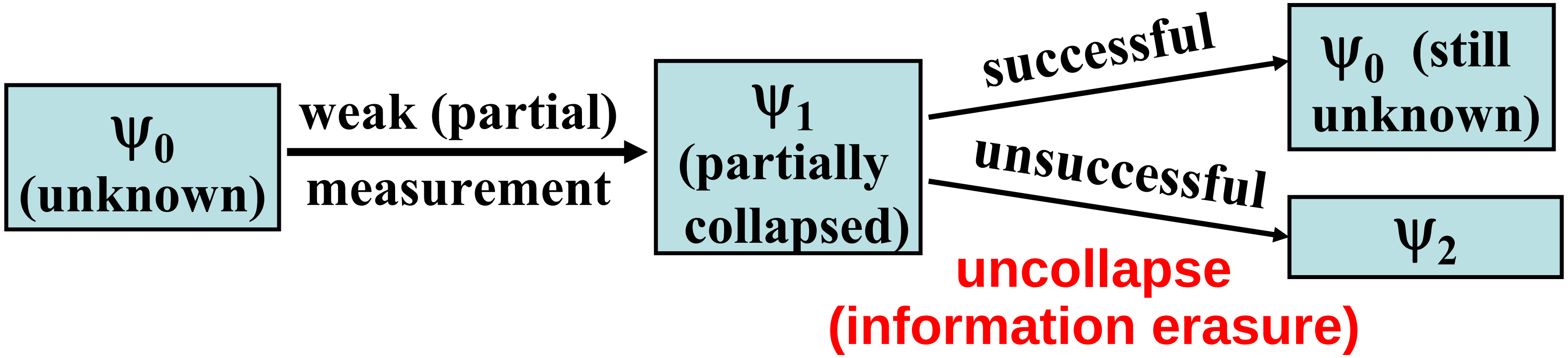
A.K. & A. Jordan, PRL-2006





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

Simple strategy: continue measuring until $r(t)$ becomes zero.
Then any unknown initial state is fully restored.
If $r = 0$ never occurs, then uncollapsing is unsuccessful.



ψ_0 (unknown) → weak (partial) measurement → ψ_1 (partially collapsed)

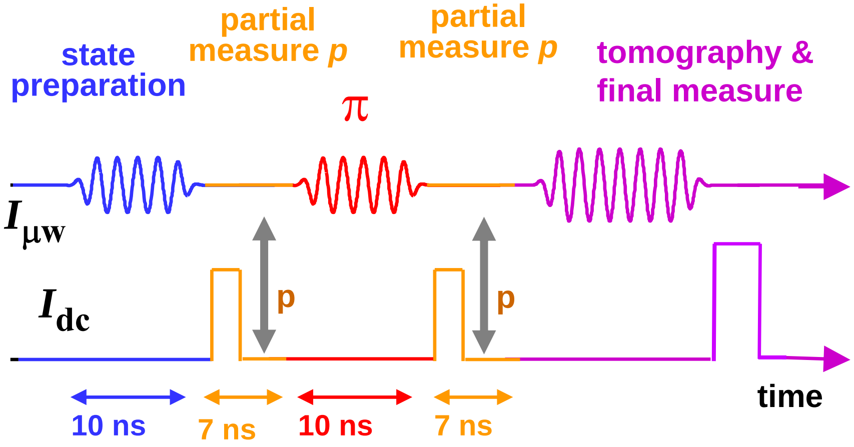
successful → ψ_0 (still unknown)

unsuccessful → ψ_2

uncollapse (information erasure)

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

Experiment on wavefunction uncollapse



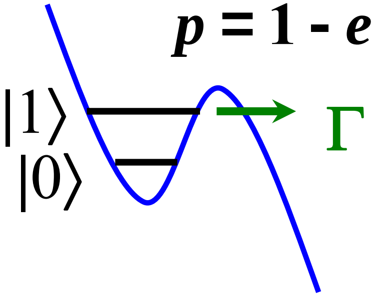
N. Katz, M. Neeley, M. Ansmann, R. Bialzak, E. Lucero, A. O'Connell, H. Wang, A. Cleland, J. Martinis, and A. Korotkov, PRL-2008

Uncollapse protocol:

- partial collapse
- π-pulse
- partial collapse (same strength)

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

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



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

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

phase is also restored ("spin echo")

Experimental results on the Bloch sphere

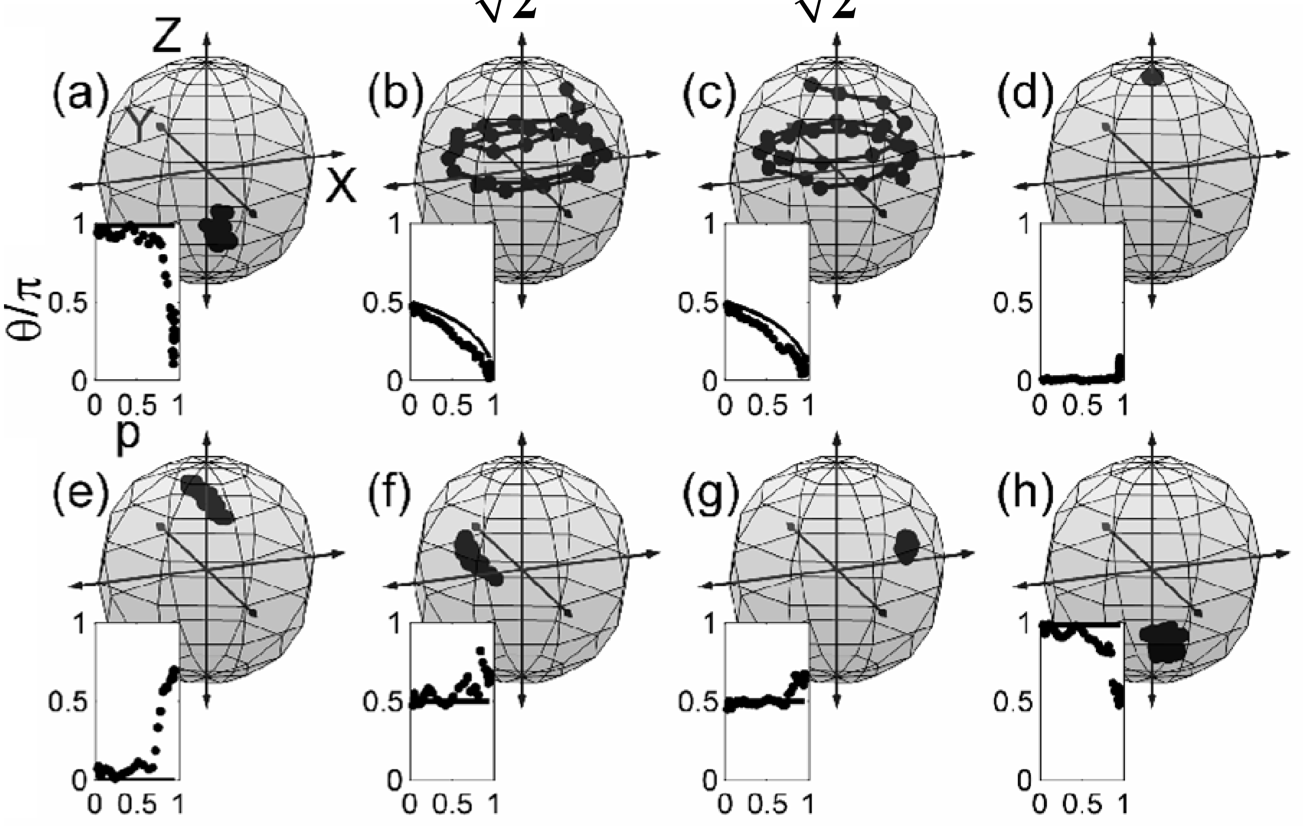
N. Katz et al., 2008

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

Partially collapsed

Uncollapsed

uncollapse works well

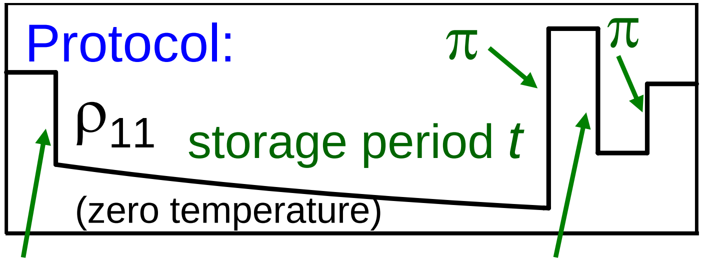


Both spin echo (azimuth) and uncollapsing (polar angle)

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. & K. Keane, PRA-2010



partial collapse towards ground state (strength p)

uncollapse (measurem. strength p_u)

Ideal case (T_1 during storage only)

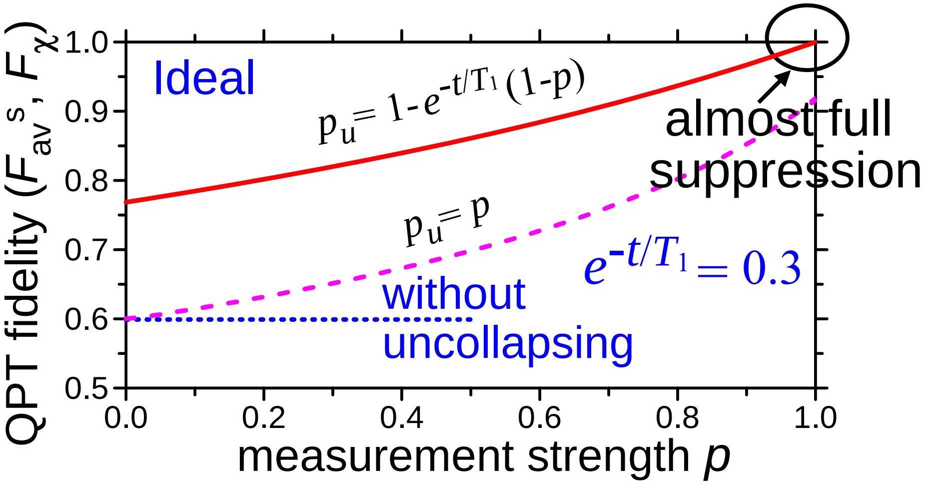
for initial state $|\psi_{in}\rangle = \alpha\,|0\rangle + \beta\,|1\rangle$

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

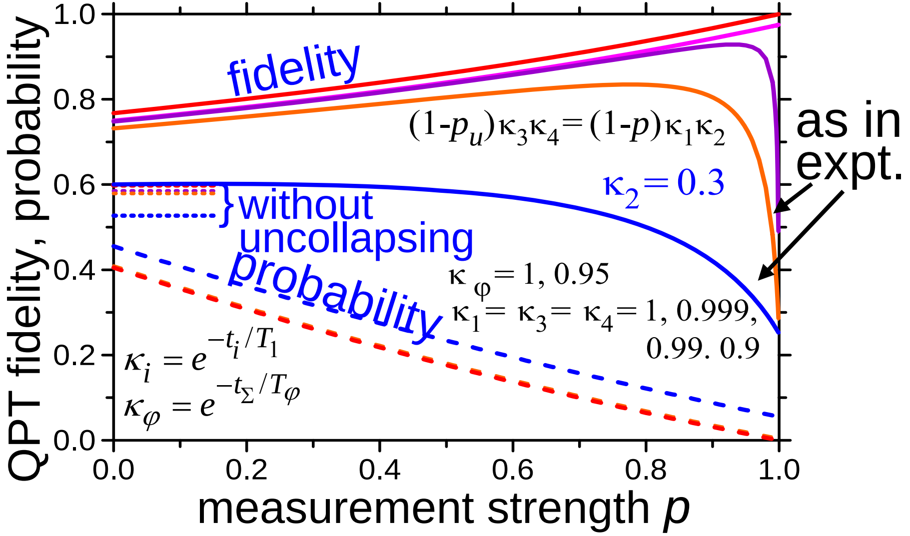
$|\psi_f\rangle = |0\rangle$ with $(1-p)^2 |\beta|^2 e^{-t/T_1}(1-e^{-t/T_1})$

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)

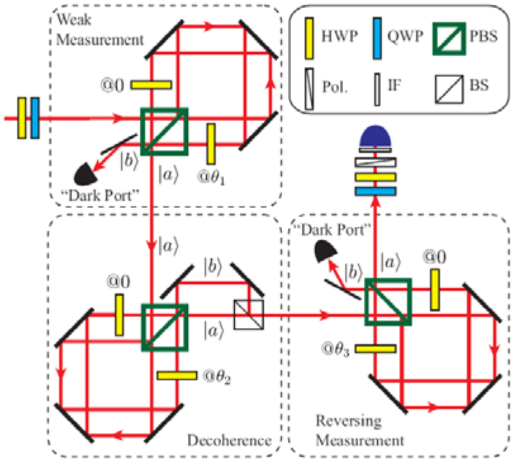


Realistic case (T_1 and T_φ at all stages)

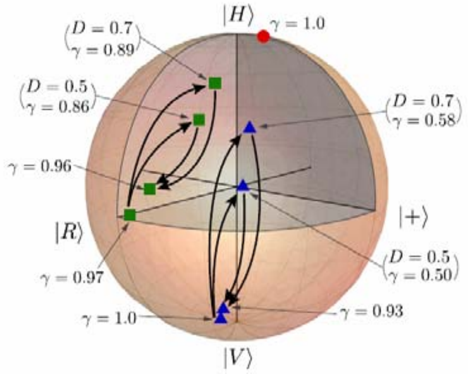


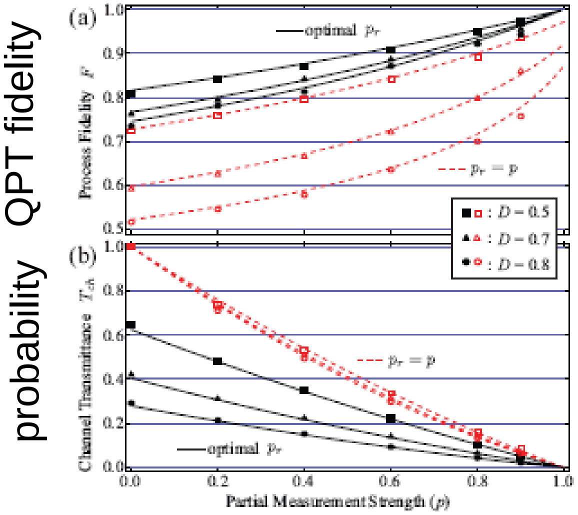
Trade-off: fidelity vs. probability

Realization with photons



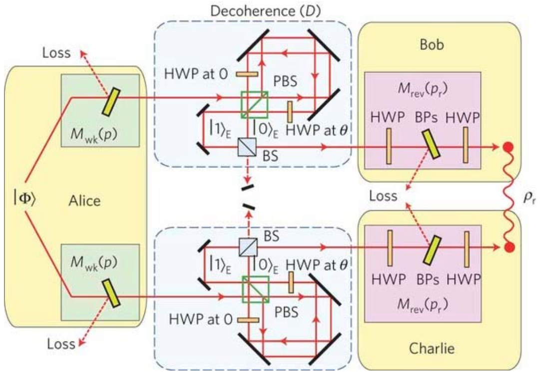
J.C. Lee, Y.C. Jeong, Y.S. Kim, & Y.H. Kim, Opt. Express-2011

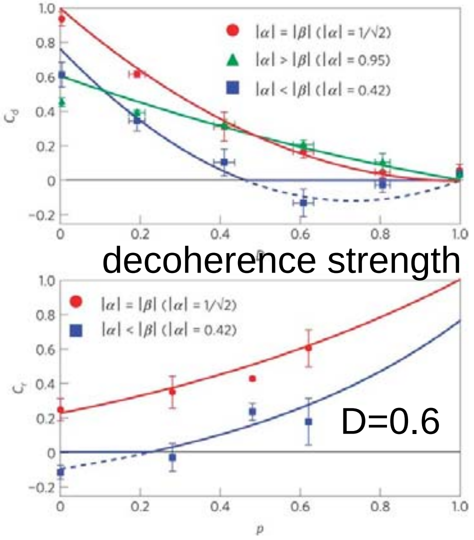




Entanglement preservation by uncollapsing

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





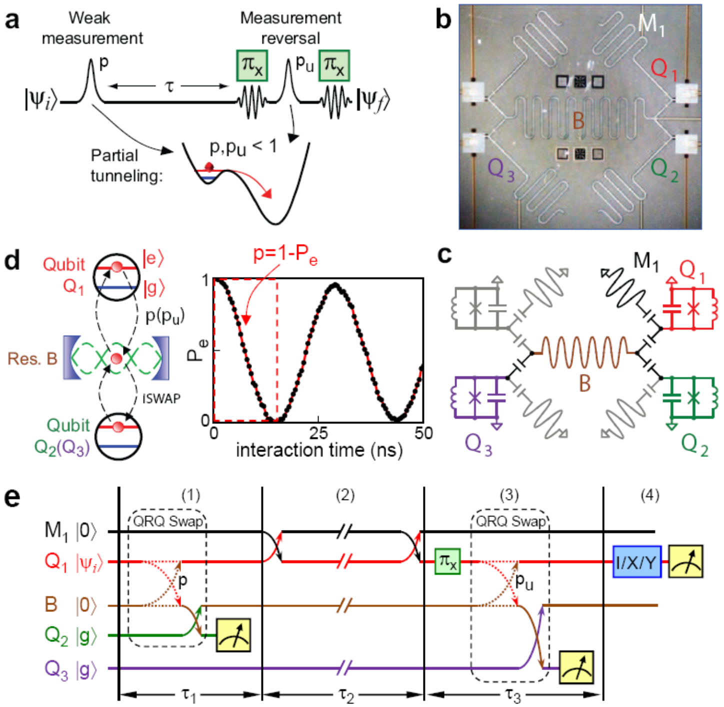
"Sleeping beauty" analogy (A.K., Nat. Phys.)

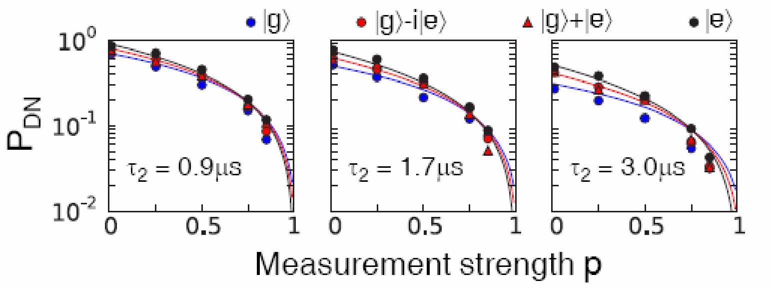
Revives entanglement from "sudden death"

- Works perfectly (optics, not solid state!)
- Energy relaxation is imitated (amplitude damping)

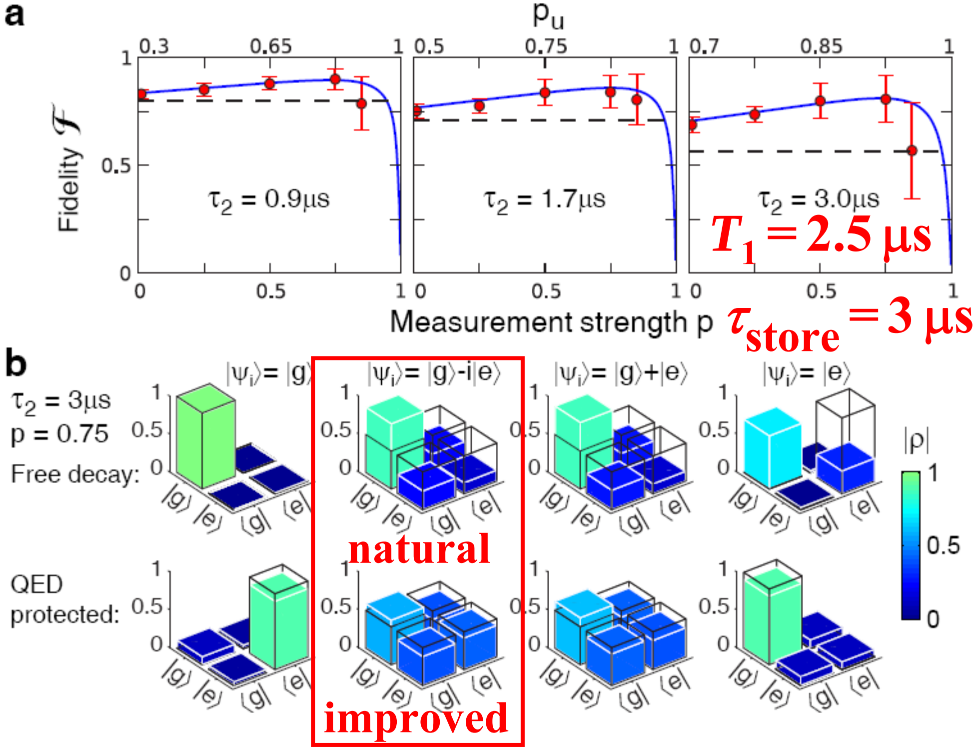
Realization with s/c phase qubits

Y. Zhong, Z. Wang, J. Martinis, A. Cleland, A. Korotkov, and H. Wang, arXiv:1309.0198



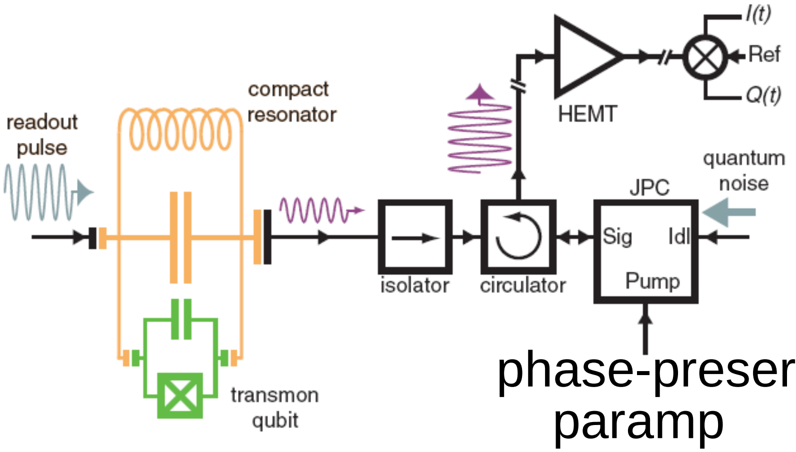


Uncollapsing increases effective T_1 by 3x



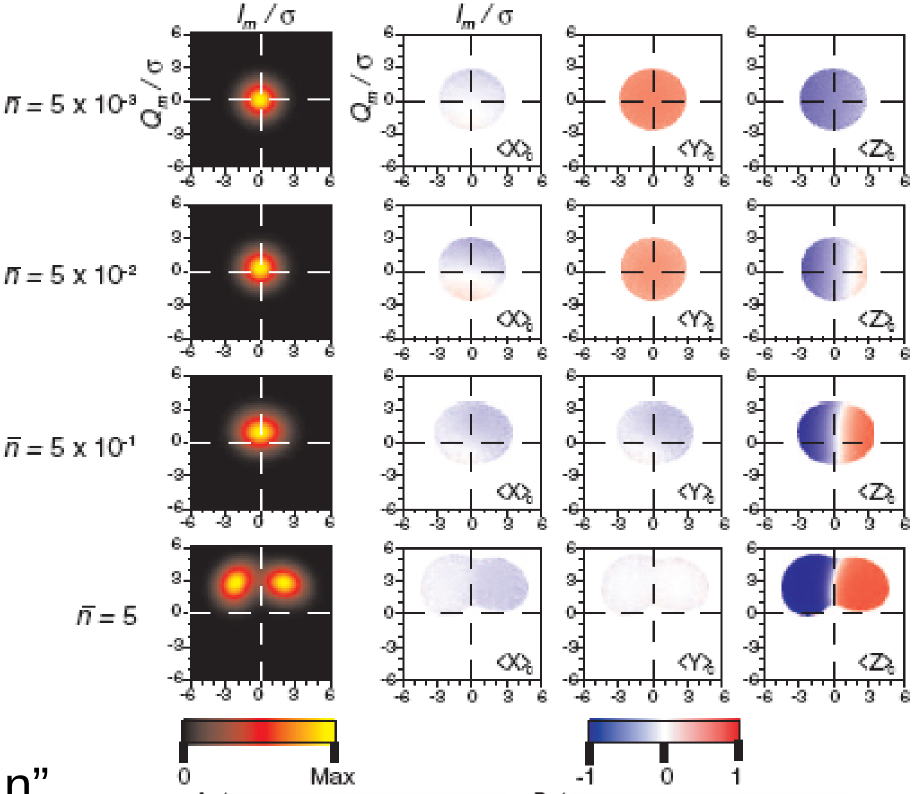
- Quantum state stored in resonator
- Weak measurement is implemented with ancilla qubit
- “Quantum error detection” (not correction)
- First demonstration of real improvement (natural decoherence suppressed)

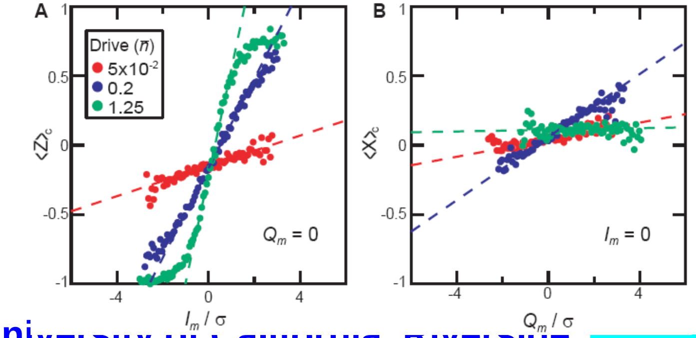
S/c qubit measurement with continuous result



phase-preserving paramp

M. Hatridge, S. Shankar, M. Mirrahimi, F. Schackert, K. Geerlings, T. Brecht, K. Sliwa, B. Abdo, L. Frunzio, S. Girvin, R. Schoelkopf, M. Devoret, Science-2013





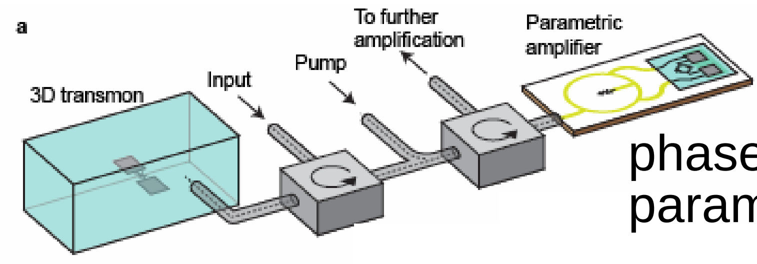
Protocol:

1) Start with |0>+|1>
2) Measure with controlled strength
3) Tomography of resulting state

Experimental findings:

- Result of *I*-quadrature measurement determines state shift along “meridian” of the Bloch sphere
- *Q*-quadrature meas. result determines shift along “parallel” (within equator)
- Agrees well with simple (Bayesian) theory

Single quantum trajectories of a s/c qubit

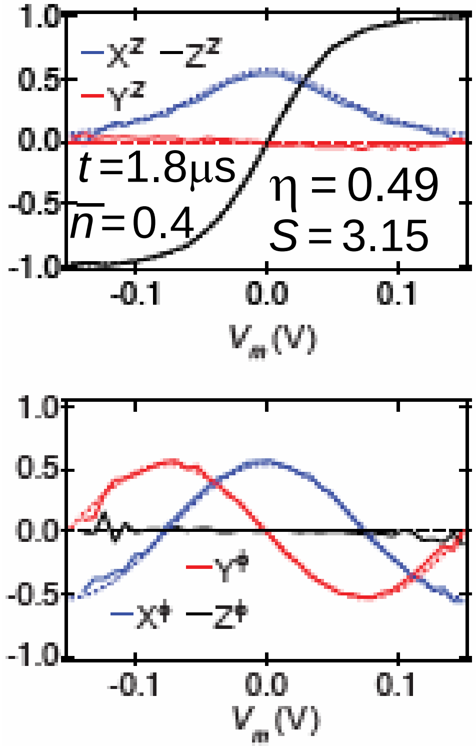


phase-sensitive
paramp

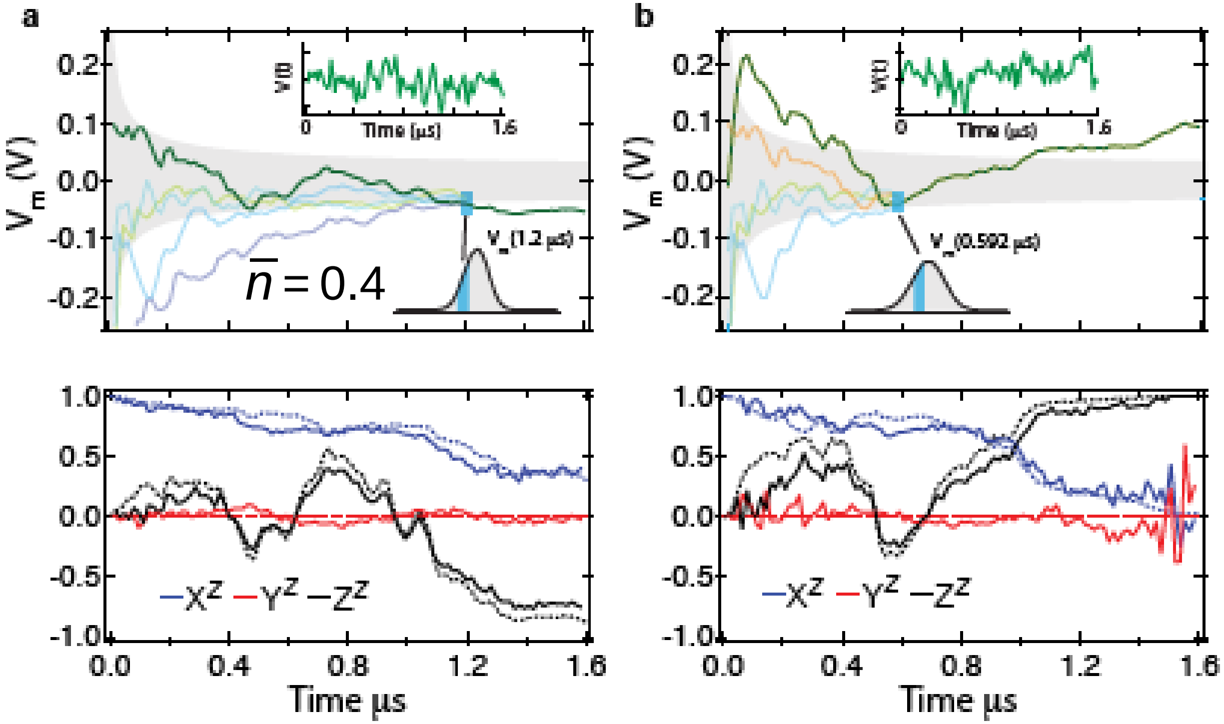
K. Murch, S. Weber, C. Macklin,
& I. Siddiqi, arXiv:1305.7270

Coupling 0.52 MHz
Cavity LW 10.8 MHz
Paramp BW 20 MHz

Partial measurement:
expt. vs. Bayesian theory

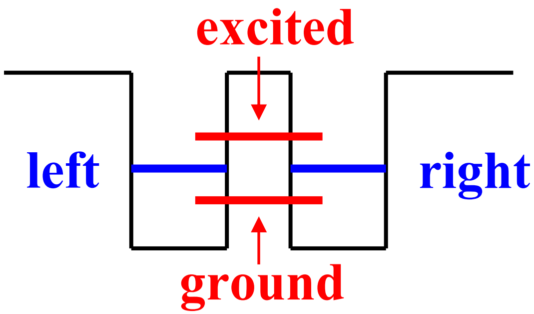


Individual quantum trajectories:
experiment vs. Bayesian theory



Excellent agreement with the Bayesian theory

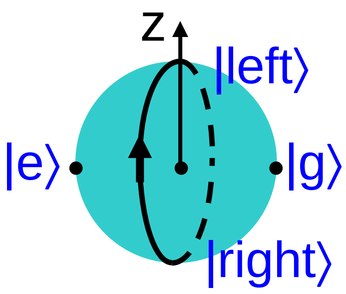
Non-decaying (persistent) Rabi oscillations

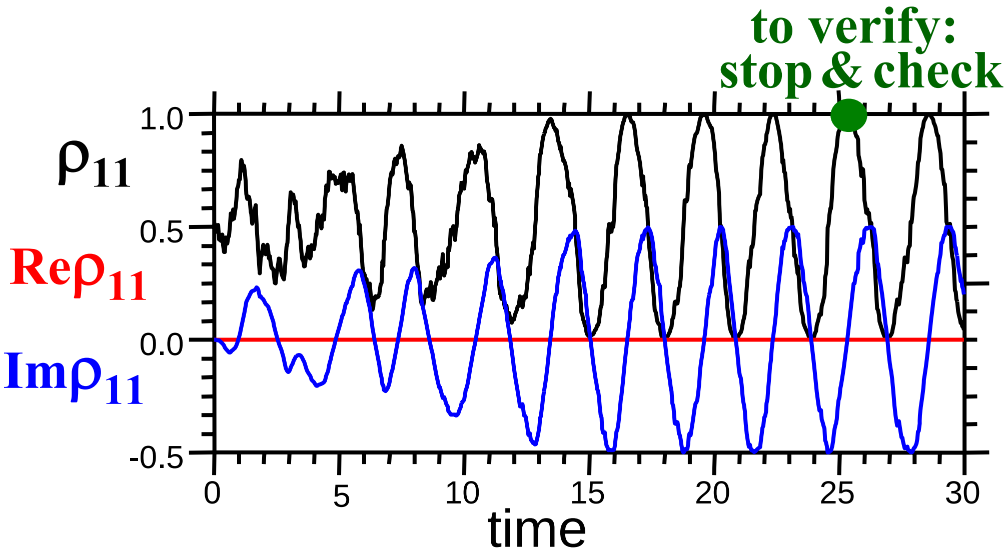


- Relaxes to the ground state if left alone (low-*T*)
- Becomes fully mixed if coupled to a high-*T* (non-equilibrium) environment
- Oscillates persistently between left and right if (weakly) measured continuously

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

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



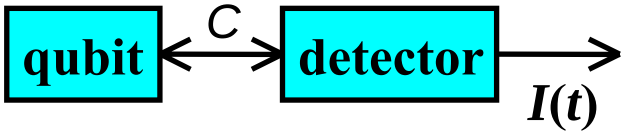


Direct experiment is difficult

A.K., PRB-1999

Indirect experiment: spectrum of persistent Rabi oscillations

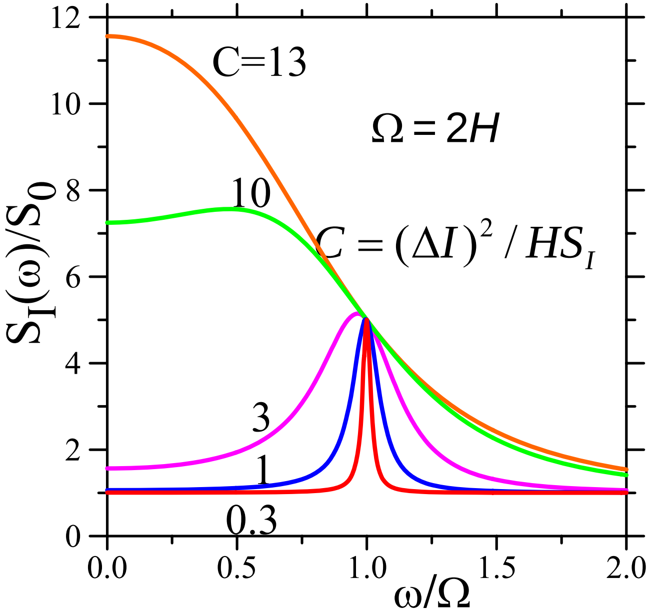
A.K., LT'1999
A.K.-Averin, 2000



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

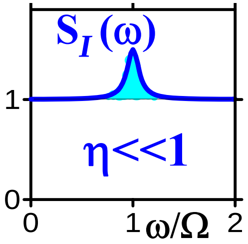
(const + signal + noise)

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 = 4η ≤ 4

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

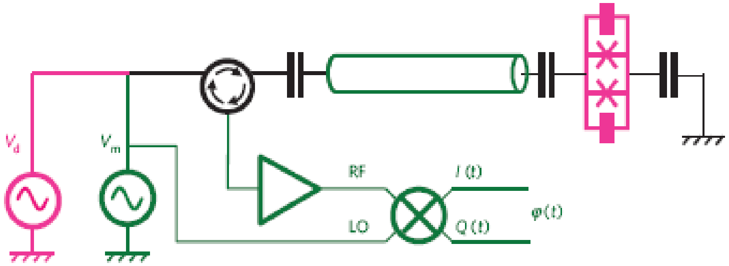
perfect Rabi oscillations: $\langle z^2 \rangle = \langle \cos^2 \rangle = 1/2$

imperfect (non-persistent): $\langle z^2 \rangle << 1/2$

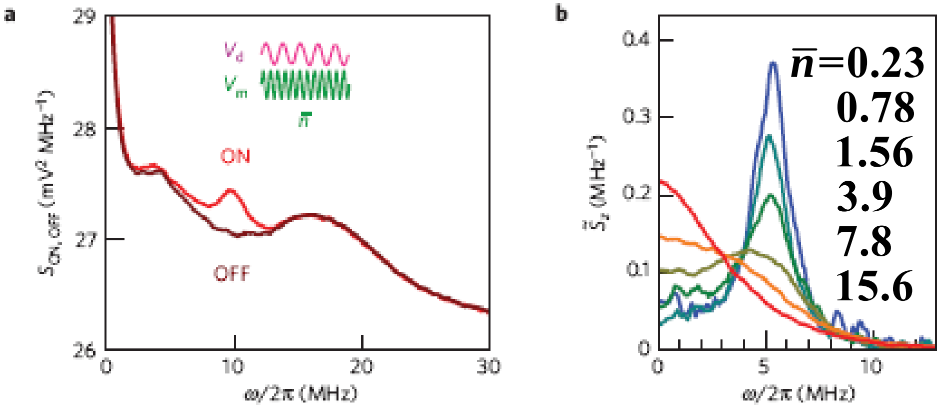
quantum (Bayesian) result: $\langle z^2 \rangle = 1$ (!!!)

(demonstrated in Saclay-2010 expt.)

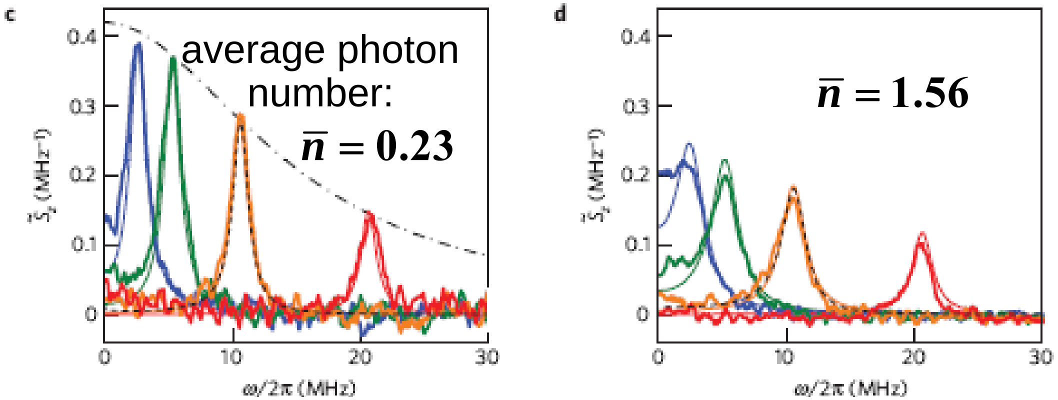
Continuous monitoring of Rabi oscillations



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



- superconducting qubit (transmon) in circuit QED setup
- microwave reflection from cavity
- driven Rabi oscillations (|g> ↔|e>)



Theory by dashed lines, very good agreement

Pre-amplifier noise temperature T_N= 4 K

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

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

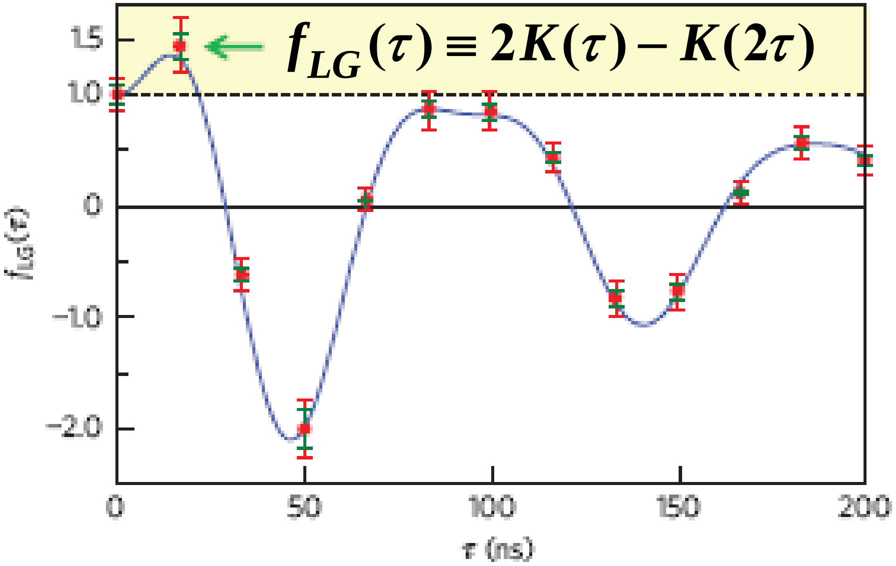
Violation of Leggett-Garg inequalities

A. Palacios-Laloy et al., 2010

In time domain

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

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



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

$$\langle z^2\rangle = 1.01 \pm 0.15$$

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

Ideal $f_{\text{LG,max}}$=1.5

Standard deviation $\sigma = 0.065$

⇒ violation by 5σ

Many later experiments on Leggett-Garg ineq. violation, incl. optics and NMR

M. Goggin et al., PNAS-2011
J. Dressel et al., PRL-2011
G. Walhder et al., PRL-2011

V. Athalye et al., PRL-2011
A. Souza et al., NJP-2011
G. Knee et al., Nat. Comm.-2011

J. Groen et al., PRL-2013
(s/c, DiCarlo's group)

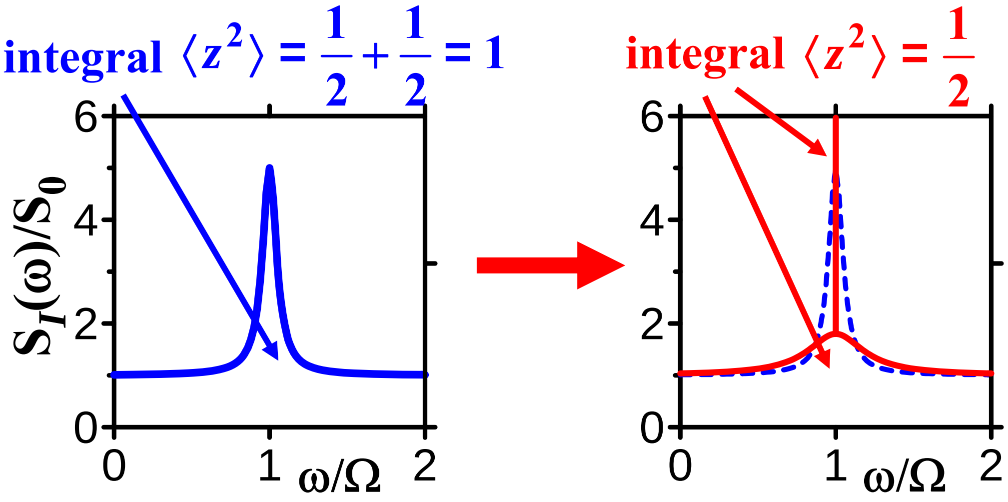
Quantum feedback control of persistent Rabi oscillations

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 $z_{\text{desired}}(t) = \cos(\Omega t)$



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

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

synchronized

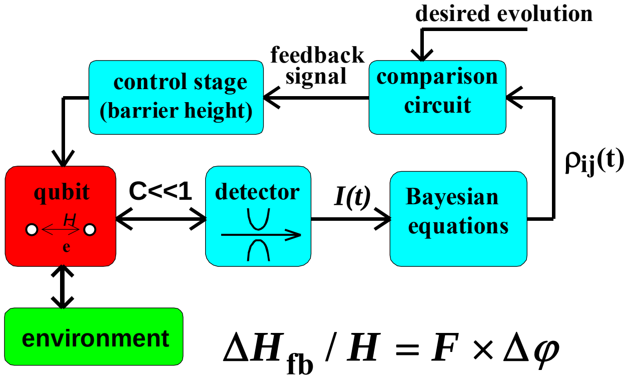
cannot synchronize

Several types of quantum feedback

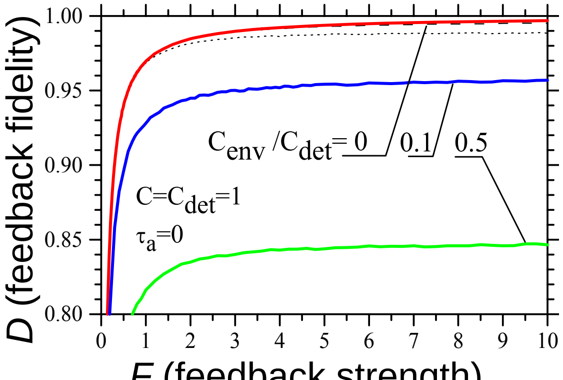
Bayesian

Best but very difficult

(monitor quantum state and control deviation)



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



R. Ruskov & A.K., 2002

A. Doherty, K. Jacobs, 1999

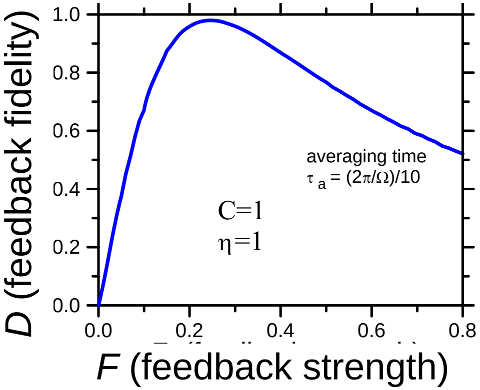
H. Wiseman, S. Mancini, J. Wang, 2002

"Direct"

as in Wiseman-Milburn (1993)

(apply measurement signal to control with minimal processing)

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



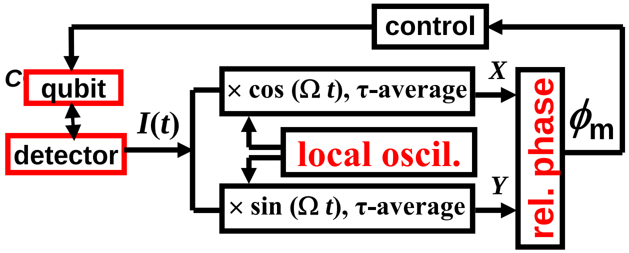
R. Ruskov & A.K., 2002

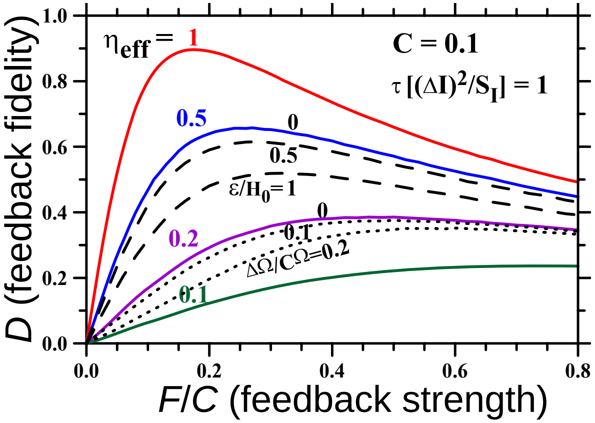
"Simple"

Imperfect but simple

(do as in usual classical feedback)

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





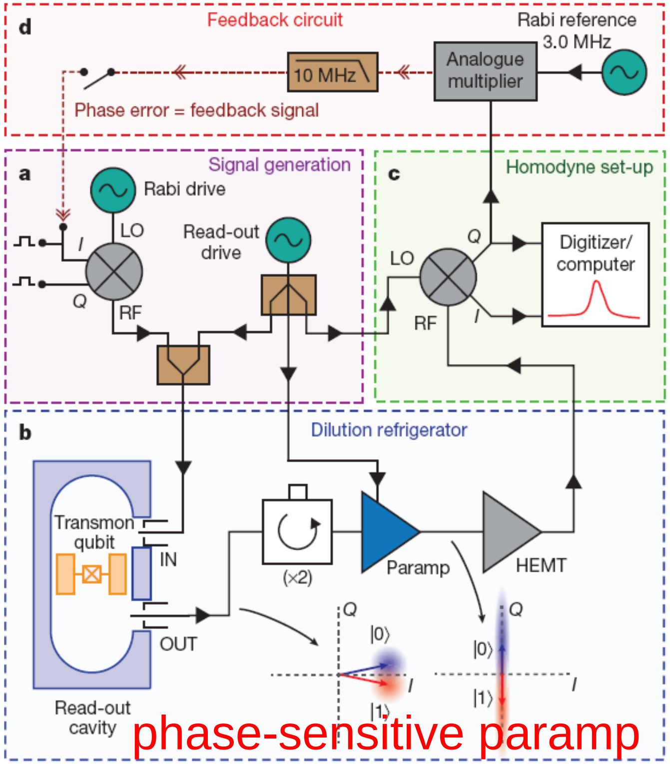
A.K., 2005

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

Quantum feedback of Rabi oscillations

R. Vijay, C. Macklin, D. Slichter, S. Weber, K. Murch,
R. Naik, A. Korotkov, and Irfan Siddiqi, Nature-2012

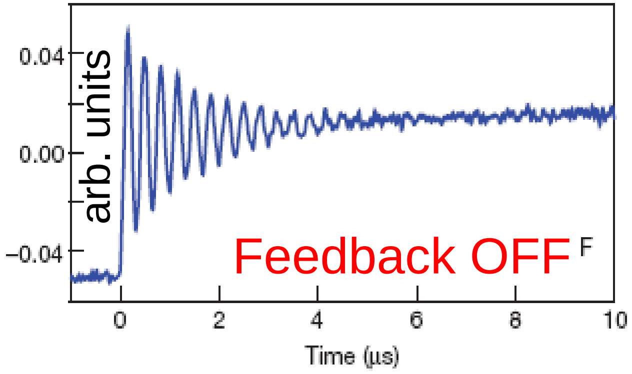
(quantum feedback with atoms, stabilizing photon number: C. Sayrin, … S. Haroche, Nature-2011)



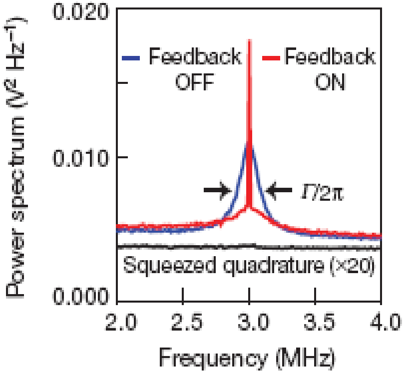
phase-sensitive paramp

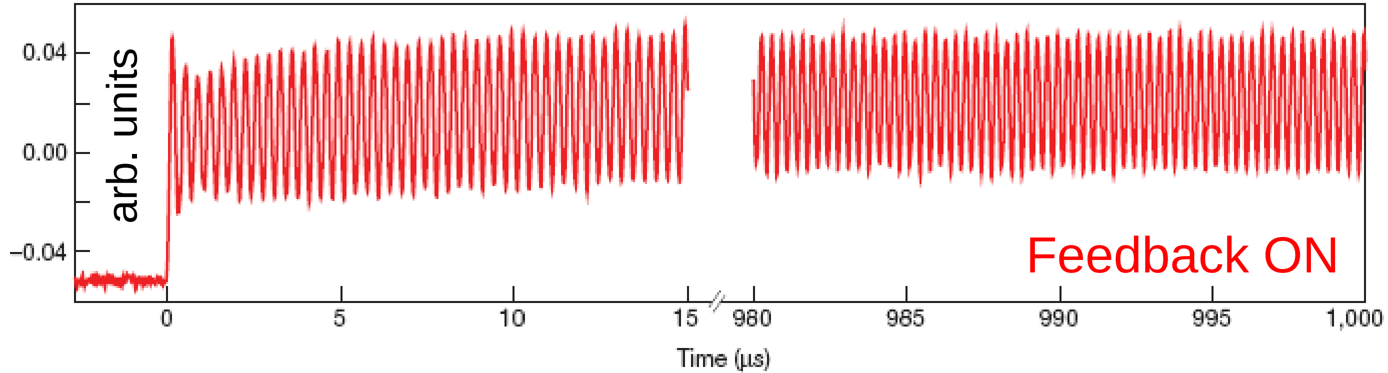
Simple idea: $I(t) \sim \cos(\Omega_R t - \theta_{ERR}) + \textbf{noise}$

$$\Delta\Omega_R / \Omega_R = -F\sin(\theta_{ERR}),\quad \sin(\theta_{ERR}) \sim \overline{I(t)\sin(\Omega_R t)}$$



Feedback OFF



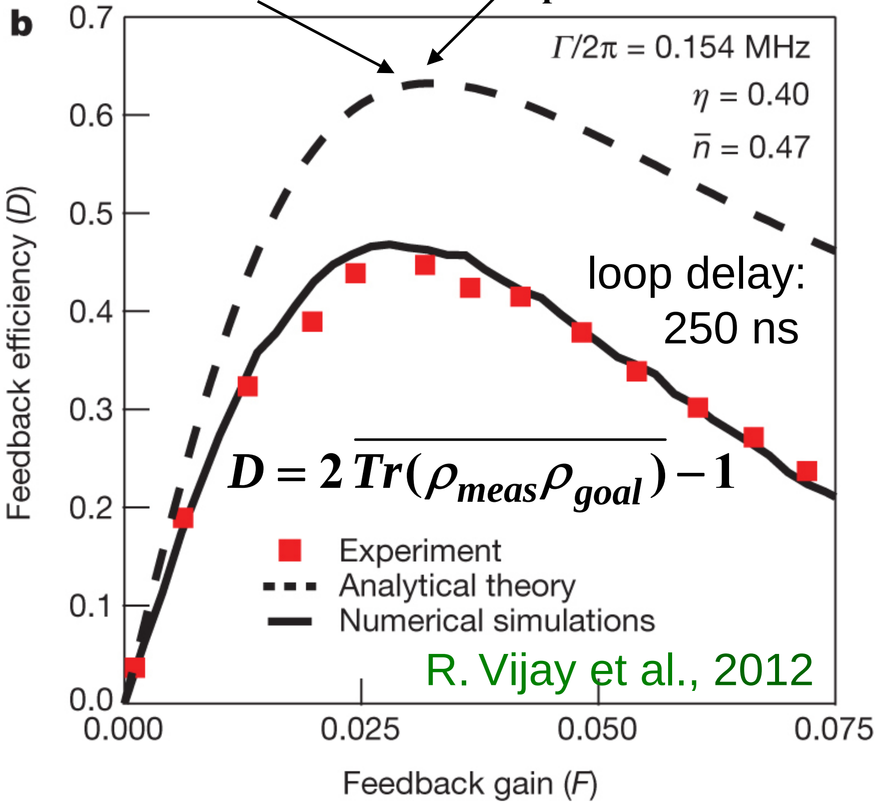


Feedback ON

Rabi freq. 3 MHz
Paramp BW 10 MHz
Cavity LW 8 MHz
Env. deph. 0.05 MHz

Quantum feedback efficiency

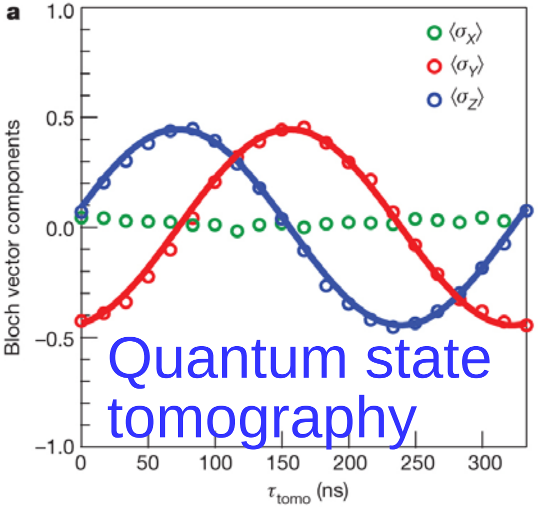
$$D_{\max} = \sqrt{\eta} \qquad F_{opt} = \sqrt{\eta}\,\Gamma/\Omega_R$$



loop delay:
250 ns

$$D = 2\,\overline{Tr(\rho_{meas}\rho_{goal})} - 1$$

R. Vijay et al., 2012



Quantum state tomography

Analytics

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

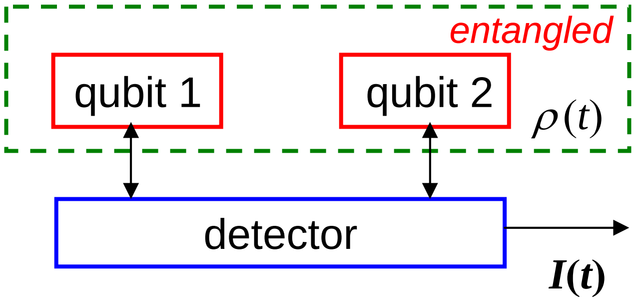
D: feedback efficiency
F: feedback strength
η: detector efficiency (<1)
Γ: dephasing rate
Ω_R: Rabi frequency

Maximum feedback efficiency $D = 0.45$

Main limiting factors: measurement efficiency η and loop delay time

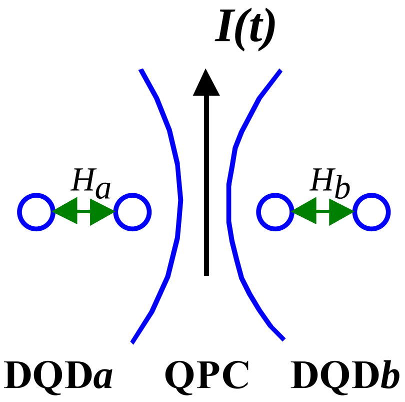
Analytics does not include loop delay, finite bandwidth, and T_1. Numerical simulations include these factors.

Entanglement by measurement (theory)

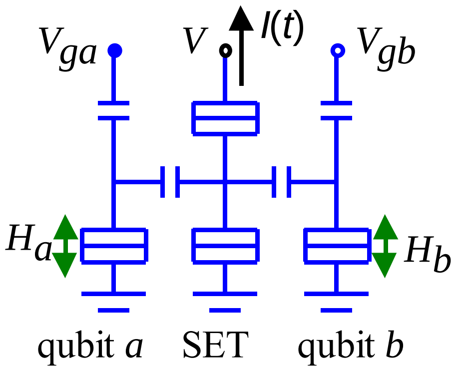


same current for |01> and |10>
⇒ entangles gradually

$$\frac{|0\rangle+|1\rangle}{\sqrt{2}}\otimes\frac{|0\rangle-|1\rangle}{\sqrt{2}}\rightarrow\frac{|10\rangle-|01\rangle}{\sqrt{2}}$$



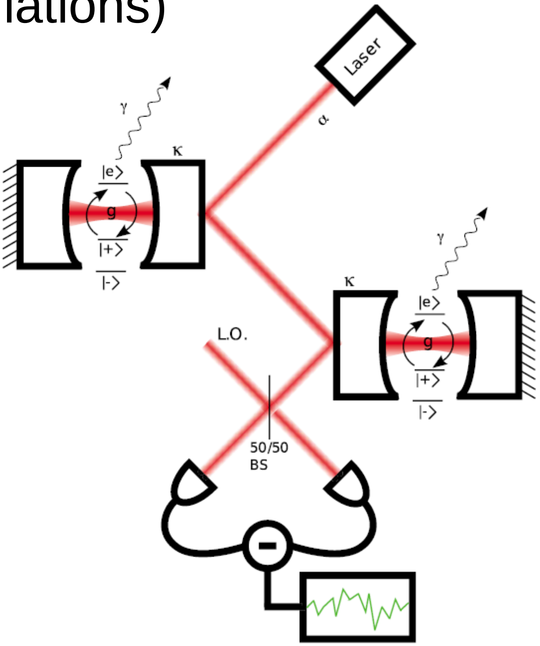
R. Ruskov & A.K., 2003



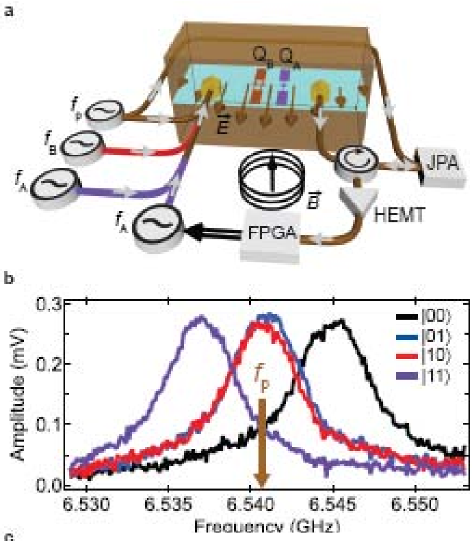
(probabilistically, even
with Rabi oscillations)

Similar proposal in optics

J. Kerckhoff, L. Bouten, A. Silberfarb,
and H. Mabuchi, 2009

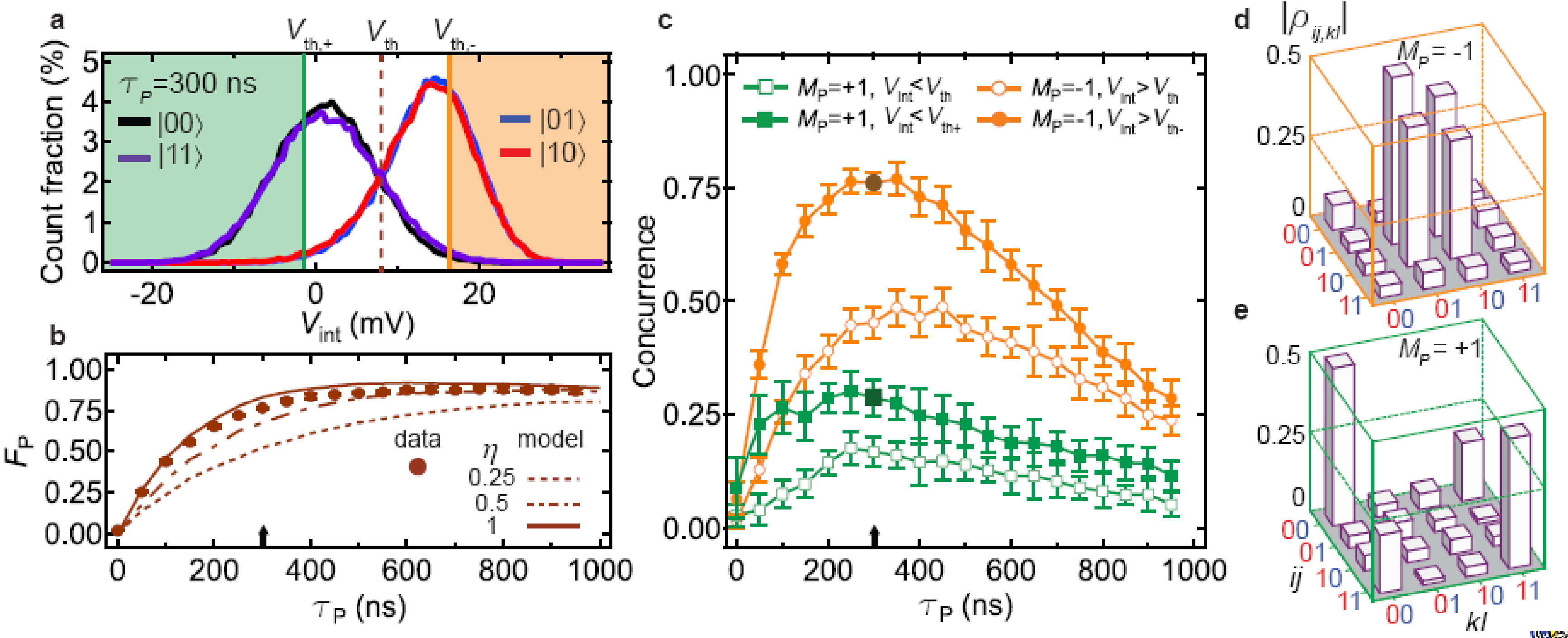


Entanglement by measurement (expt.)



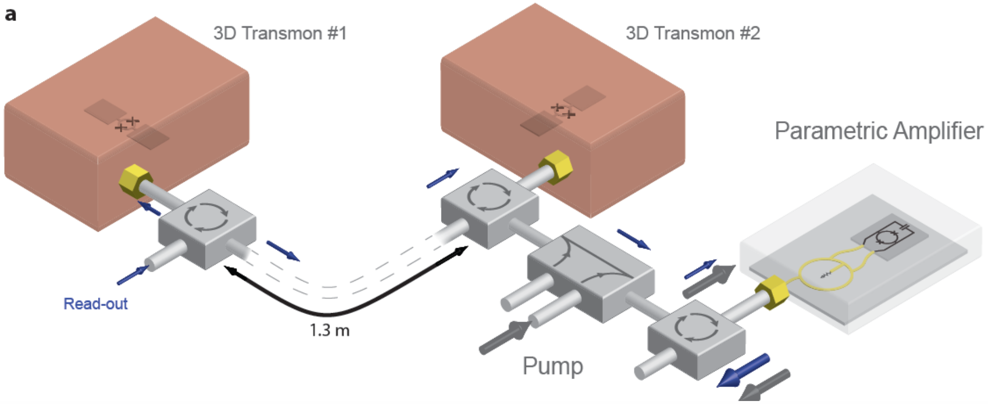
D. Riste, M. Dukalski, C. Watson, G. de Lange, M. Tiggelman, Ya. Blanter, K. Lehnert, R. Schouten, and L. DiCarlo, arXiv:1306.4002

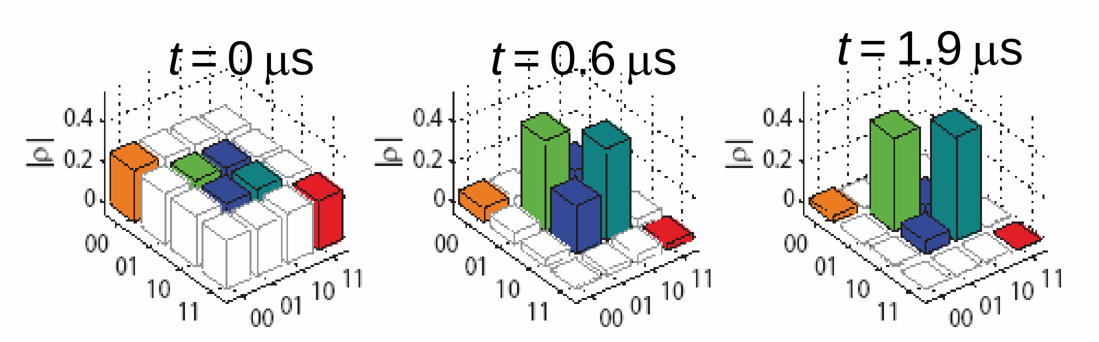
- Two superconducting qubits in the same resonator, indistinguishable |01> and |10>
- Max. concurrence 0.77
- Trick: |00> and |11> only slightly distinguishable
- Max. deterministic concurrence 0.34



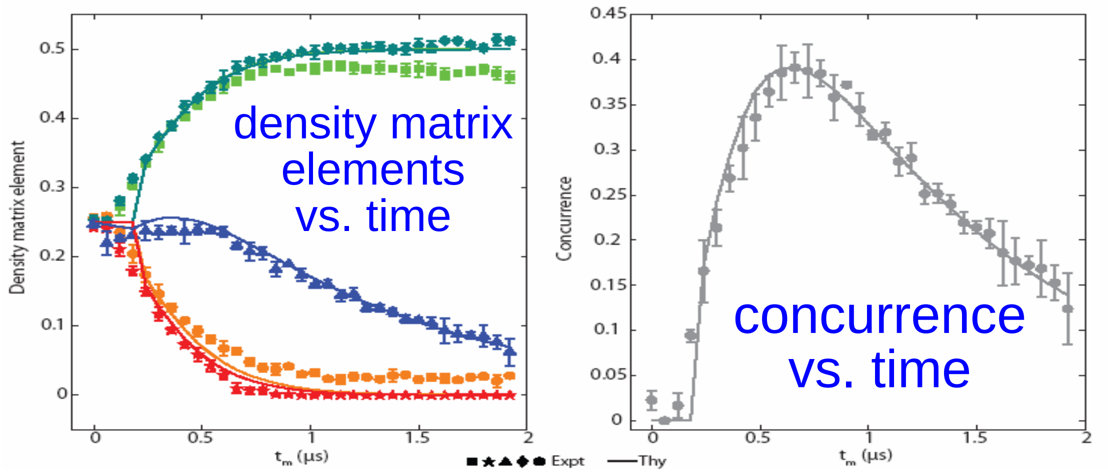
Entanglement in separated resonators

N. Roch, M. Schwartz,
I. Siddiqi et al. (unpub.)





- Qubits are separated by 1.3 m
- Bounce-bounce scheme
- Max. concurrence 0.4



density matrix elements vs. time

concurrence vs. time

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)

- About 10 superconducting experiments so far, including:
  - partial collapse and uncollapse,
  - continuous meas. using phase-sensitive and phase-preserving params
  - quantum feedback of persistent Rabi oscillations,
  - entanglement by measurement

  number of experiments seems to grow fast

- Hopefully something useful in future