Non-projective measurement of solid-state qubits: collapse and uncollapse (what is "inside" collapse)

Alexander Korotkov

University of California, Riverside

Outline:
- Introduction (weirdness of collapse)
- Bayesian formalism for quantum measurement
- Persistent Rabi oscillations (+ expt.)
- Wavefunction uncollapse (+ expts.)

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Saclay (D. Esteve, P. Bertet et al.)

Funding:

Quantum mechanics is weird…

Niels Bohr:

“If you are not confused by quantum physics then you haven’t really understood it”

Richard Feynman:

“I think I can safely say that nobody understands quantum mechanics”

Weirdest part is quantum measurement

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

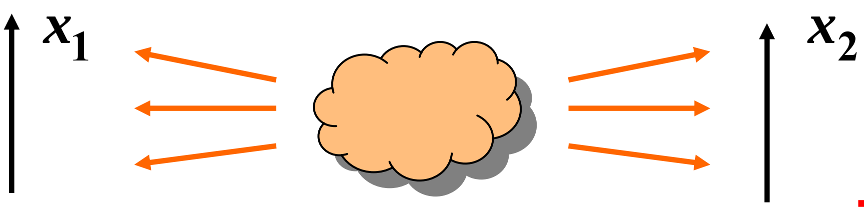
- State collapse follows from common sense
- Does not follow from Schrödinger Eq. (contradicts)

What is "inside" collapse?
What if collapse is stopped half-way?

Einstein-Podolsky-Rosen (EPR) paradox (1935)

$$\psi(x_1, x_2) = \sum_n \psi_n(x_2)\, u_n(x_1)$$ *(nowadays we call it entangled state)*

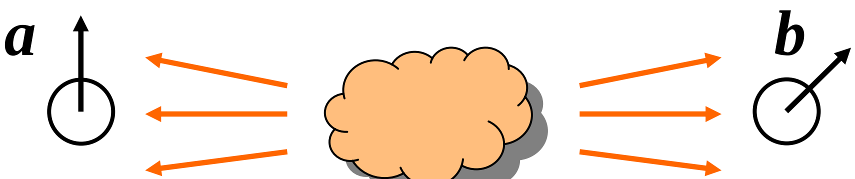
$$\psi(x_1, x_2) = \int_{-\infty}^{\infty} \exp[(i/\hbar)(x_1 - x_2)p]\,dp \sim \delta(x_1 - x_2)$$



Measurement of particle 1 cannot affect particle 2, while QM says it affects (contradicts causality)

=> Quantum mechanics is incomplete

Bell's inequality (John Bell, 1964)



(setup by David Bohm)

$$\psi = \frac{1}{\sqrt{2}}(\uparrow_1\downarrow_2 - \downarrow_1\uparrow_2)$$

Advantage: choice of meas. directions

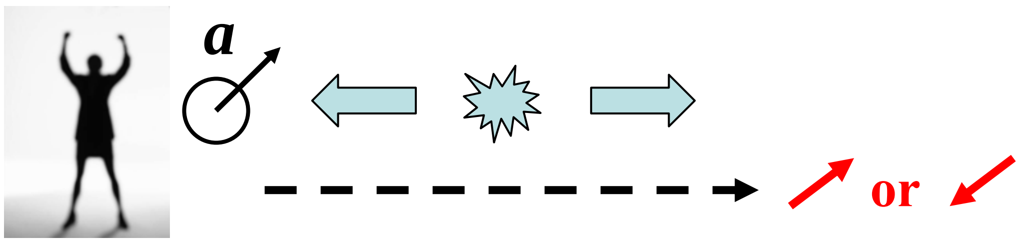
Is it possible to explain the QM result assuming local realism and hidden variables (without superluminal collapse)? No!!!

Experiment (Aspect et al., 1982; photons instead of spins, CHSH):

yes, "spooky action-at-a-distance"

What about causality?

Actually, not too bad: you cannot transmit your own information by choosing a particular measurement direction ***a***



Result of the other measurement does not depend on direction ***a***

Randomness saves causality

Collapse is still instantaneous: OK, just our recipe, not an "objective reality", not a "physical" process

Consequence of causality: No-cloning theorem

Wootters-Zurek, 1982; Dieks, 1982; Yurke

You cannot copy an unknown quantum state

Proof: Otherwise get information on direction ***a*** (and causality violated)

Application: quantum cryptography

Information is an important concept in quantum mechanics

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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

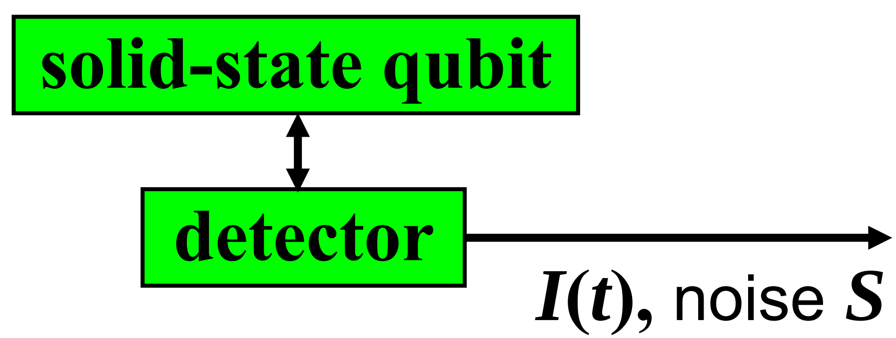
Various approaches to non-projective (weak, continuous, partial, generalized, etc.) quantum measurements

Names: Davies, Kraus, Holevo, Mensky, Caves, Knight, Plenio, 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.

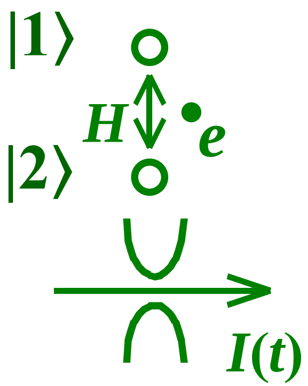
Our limited scope:

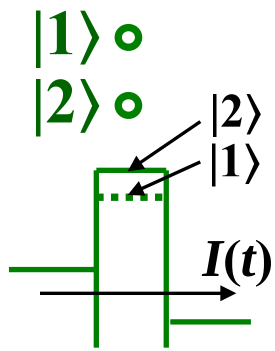
(simplest system, experimental setups)



“Typical” setup: double-quantum-dot (DQD) qubit + quantum point contact (QPC) detector

Gurvitz, 1997





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

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

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

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

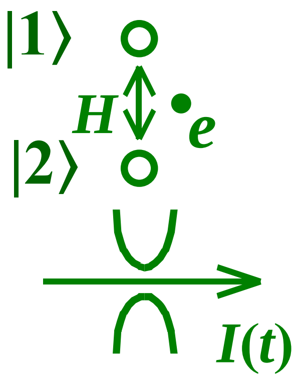
For low-transparency QPC

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

$$H_{INT} = \sum_{l,r} \Delta T\,(c_1^\dagger c_1 - c_2^\dagger c_2)(a_r^\dagger a_l + a_l^\dagger a_r) \qquad S_I = 2eI$$

Bayesian formalism for DQD-QPC system

$H_{QB} = 0$



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

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

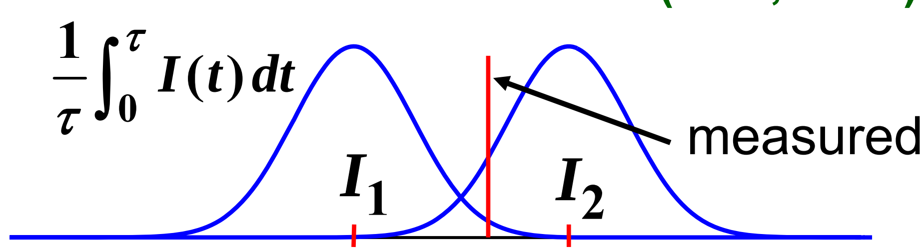
1) $|\alpha(t)|^2$ and $|\beta(t)|^2$ evolve as probabilities,
   i.e. according to the **Bayes rule** (same for ρ_{ij})

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

(A.K., 1998)

Bayes rule (1763, Laplace-1812):

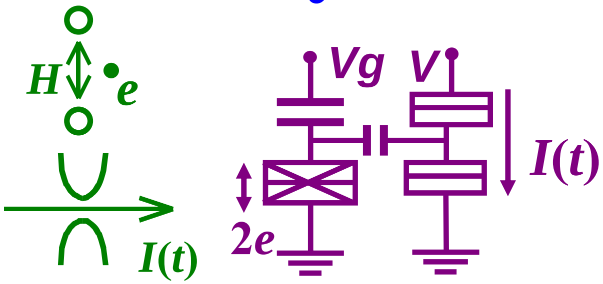
$$\overbrace{P(A_i\,|\,\text{res})}^{\text{posterior probability}} = \frac{\overbrace{P(A_i)}^{\text{prior probab.}}\;\overbrace{P(\text{res}\,|\,A_i)}^{\text{likelihood}}}{\sum_k P(A_k)\,P(\text{res}\,|\,A_k)}$$



So simple because:

1) no entaglement at large QPC voltage
2) QPC happens to be an ideal detector
3) no Hamiltonian evolution of the qubit

Bayesian formalism for a single qubit



- Time derivative of the quantum Bayes rule
- Add unitary evolution of the qubit
- Add decoherence γ (if any)

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

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

(A.K., 1998)

$\gamma = \Gamma - (\Delta I)^2/4S_I, \quad \Gamma$ – ensemble decoherence

$\gamma = 0$ for QPC detector

Averaging over result $I(t)$ leads to conventional master equation with Γ

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

Natural generalizations:
- add classical back-action
- entangled qubits

Assumptions needed for the Bayesian formalism:

- Detector voltage is much larger than the qubit energies involved

$eV >> \hbar\Omega$, $eV >> \hbar\Gamma$, $\hbar/eV << (1/\Omega, 1/\Gamma)$, $\Omega=(4H^2+\varepsilon^2)^{1/2}$

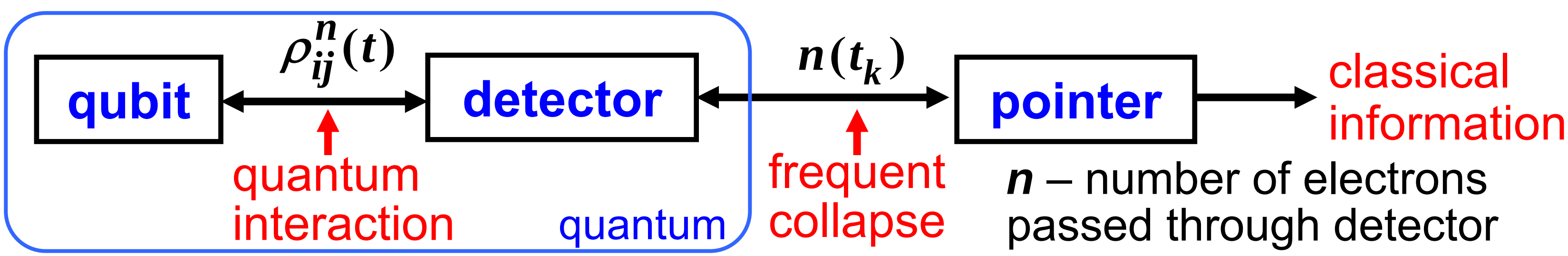
(no coherence in the detector, **classical output**, Markovian approximation)

- Simpler if weak response, $|\Delta I\,| << I_0$, (coupling $C \sim \Gamma/\Omega$ is arbitrary)

Derivations:

1) "logical": via correspondence principle and comparison with decoherence approach (A.K., 1998)

2) "microscopic": Schr. eq. + collapse of the detector (A.K., 2000)

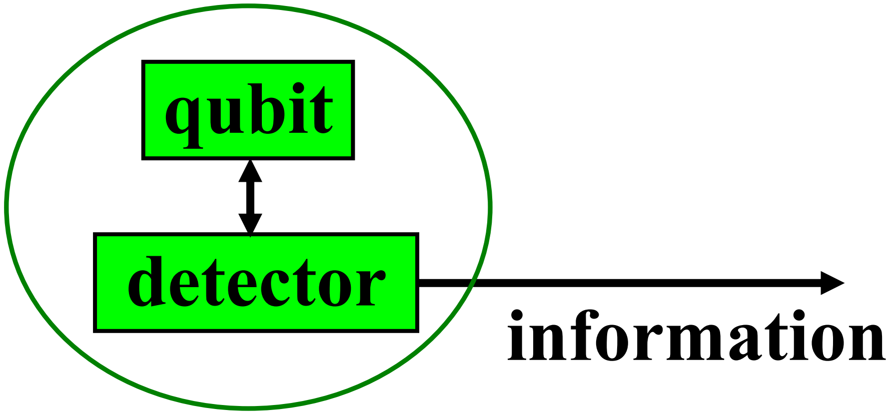


3) from "quantum trajectory" formalism developed for quantum optics (Goan-Milburn, 2001; also: Wiseman, Sun, Oxtoby, etc.)

4) from POVM formalism (Jordan-A.K., 2006)

5) from Keldysh formalism (Wei-Nazarov, 2007)

Why not just use Schrödinger equation for the whole system?



Impossible in principle!

Technical reason: Outgoing information (measurement result) makes it an open system

Philosophical reason: Random measurement result, but deterministic Schrödinger equation

Einstein: God does not play dice

Heisenberg: unavoidable quantum-classical boundary

Fundamental limit for ensemble decoherence

$\Gamma = (\Delta I)^2/4S_I + \gamma$

ensemble decoherence rate

~ information flow [bit/s]

single-qubit decoherence

"measurement time" (S/N=1)

$\tau_m = 2S_I/(\Delta I)^2$

$\gamma \geq 0 \Rightarrow \boxed{\Gamma \geq (\Delta I)^2/4S_I}$

$\Gamma \tau_m \geq \frac{1}{2}$

A.K., 1998, 2000
S. Pilgram et al., 2002
A. Clerk et al., 2002
D. Averin, 2000,2003

$$\eta = 1 - \frac{\gamma}{\Gamma} = \frac{(\Delta I)^2/4S_I}{\Gamma}$$

detector ideality (quantum efficiency)
$\eta \leq 100\%$

Translated into energy sensitivity: $(\varepsilon_O\, \varepsilon_{BA})^{1/2} \geq \hbar/2$

Danilov, Likharev, Zorin, 1983

ε_O, ε_{BA}: sensitivities [J/Hz] limited by output noise and back-action

Known since 1980s (Caves, Clarke, Likharev, Zorin, Vorontsov, Khalili, etc.)

$$(\varepsilon_O\, \varepsilon_{BA} - \varepsilon_{O,BA}^2)^{1/2} \geq \hbar/2 \;\;\Leftrightarrow\;\; \Gamma \geq (\Delta I)^2/4S_I + K^2 S_I/4$$

POVM vs. Bayesian formalism

General quantum measurement (POVM formalism) (Nielsen-Chuang, p. 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)

- POVM is essentially a projective measurement in an extended Hilbert space
- Easy to derive: interaction with ancilla + projective measurement of ancilla
- For extra decoherence: incoherent sum over subsets of results

Relation between POVM and quantum Bayesian formalism:

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

Mathematically POVM and quantum Bayes are almost equivalent

We focus not on the mathematical structures, but on particular setups and experimental consequences

Can we verify the Bayesian formalism experimentally?

Direct way:

prepare → **partial measur.** → **control (rotation)** → **projective measur.**

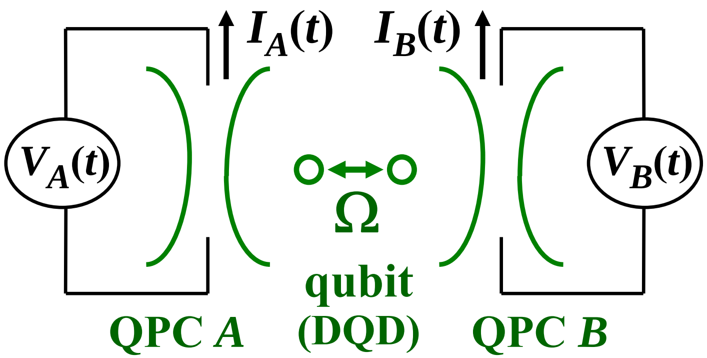
A.K.,1998

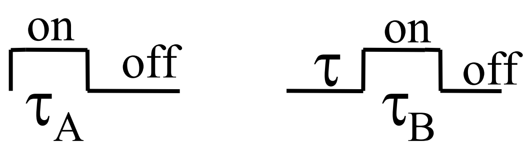
However, difficult: bandwidth, control, efficiency
(expt. realized only for supercond. phase qubits)

Tricks are needed for real experiments

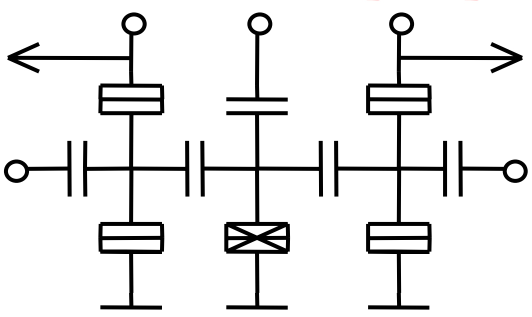
Bell-type measurement correlation

(A.K., PRB-2001)

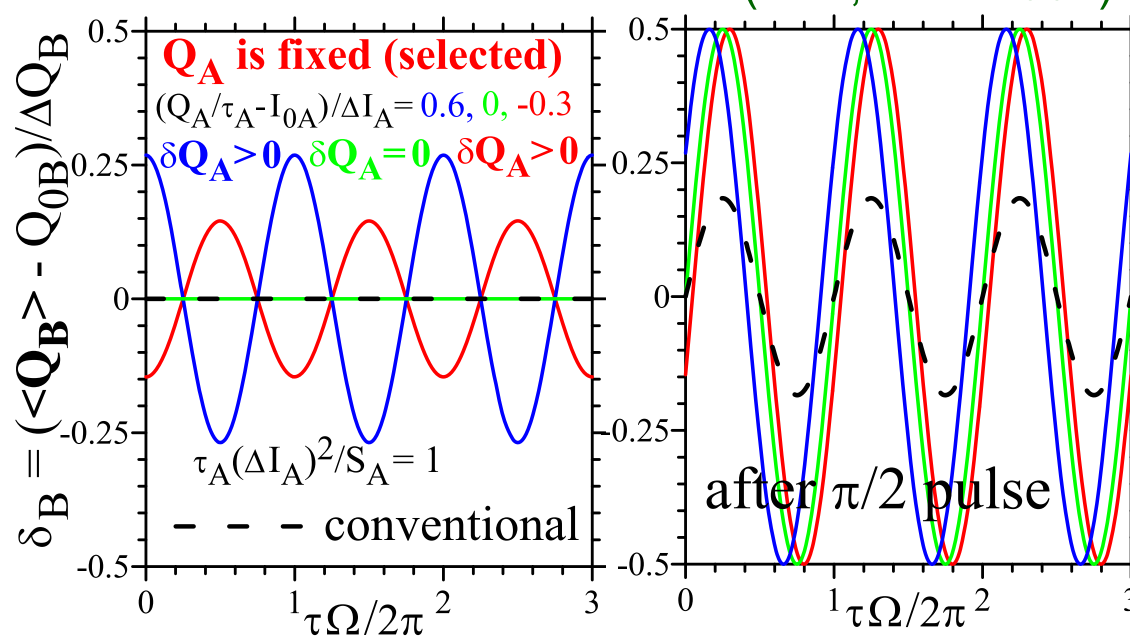




$Q_A = \int I_A dt$ $Q_B = \int I_B dt$



detector A qubit detector B



Idea: two consecutive measurements of a qubit by two detectors; probability distribution $\mathbf{P}(Q_A, Q_B, \tau)$ shows effect of the first measurement on the qubit state.

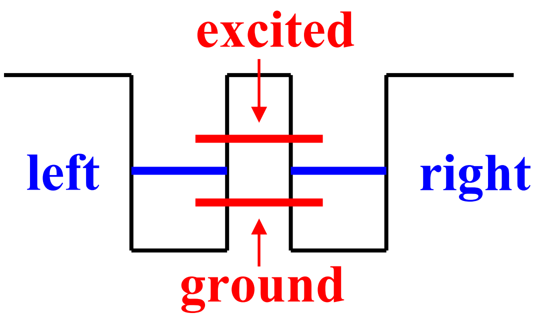
Advantage: solves the bandwidth problem

Same idea with another averaging → weak values

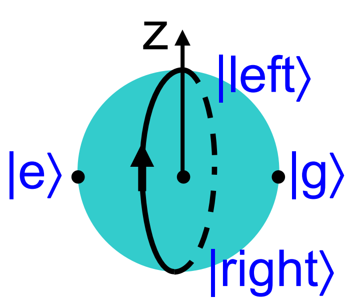
(Romito, Gefen, Blanter, PRL-2008)

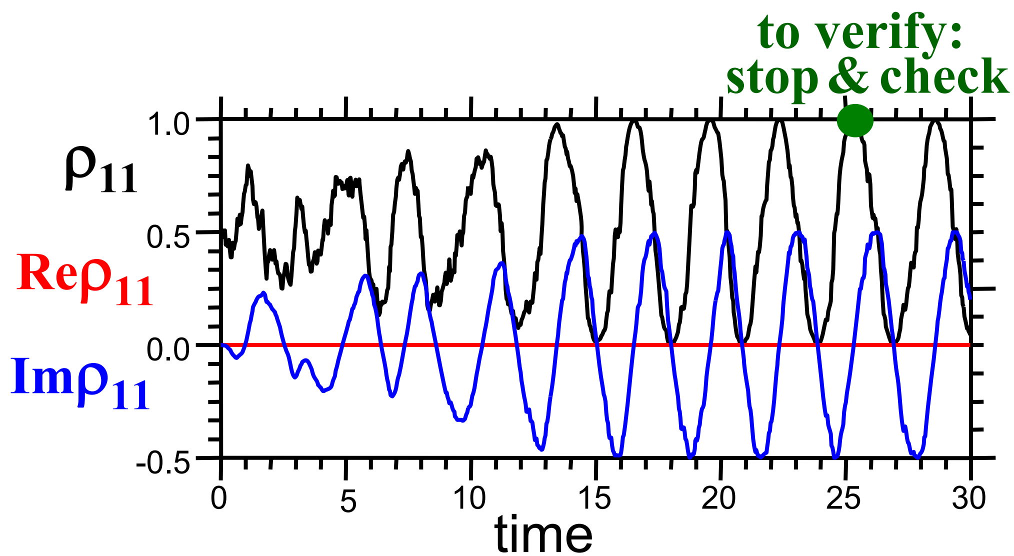
Alexander Korotkov University of California, Riverside

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



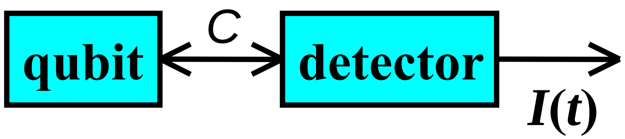


A.K., PRB-1999

Direct experiment is difficult

Indirect experiment: spectrum of persistent Rabi oscillations

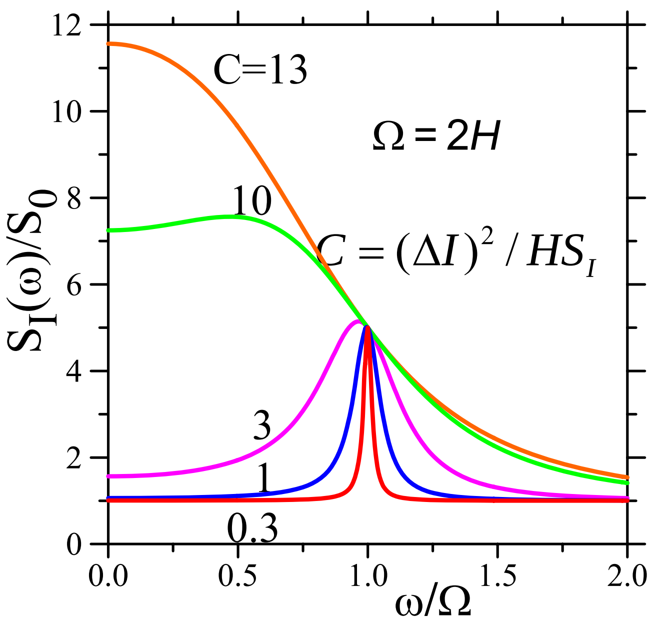
A.K., LT'1999
A.K.-Averin, 2000



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

(const + signal + noise)

z is Bloch coordinate

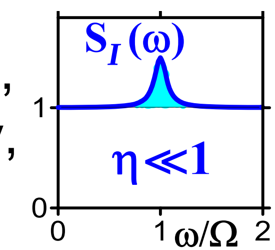


Ω - Rabi frequency

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

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

amplifier noise $\Rightarrow$ higher pedestal,
poor quantum efficiency,
but the peak is the same!!!

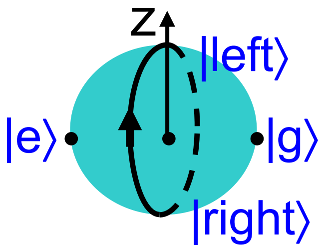


integral under the peak $\Leftrightarrow$ variance $\langle z^2 \rangle$

How to distinguish experimentally persistent from non-persistent? Easy!

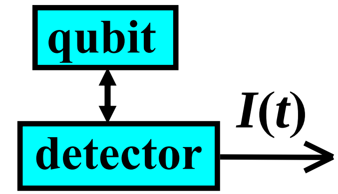
perfect Rabi oscillations: $\langle z^2 \rangle = \langle \cos^2 \rangle = 1/2$
imperfect (non-persistent): $\langle z^2 \rangle \ll 1/2$
quantum (Bayesian) result: $\langle z^2 \rangle = 1$ (!!!)

(demonstrated in Saclay expt.)



How to understand $\langle z^2 \rangle = 1$?

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



First way (mathematical)

We actually measure operator: $z \rightarrow \sigma_z$

$$z^2 \rightarrow \sigma_z{}^2 = 1$$

(What does it mean? Difficult to say…)

Second way (Bayesian)

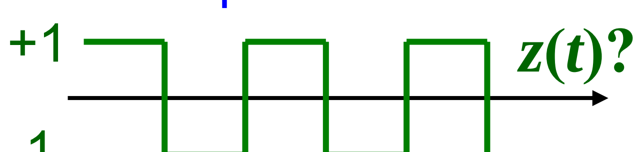
$$S_I(\omega) = S_{\xi\xi} + \frac{\Delta I^2}{4} S_{zz}(\omega) + \frac{\Delta I}{2} S_{\xi z}(\omega)$$

quantum back-action changes z in accordance with the noise ξ

Equal contributions (for weak coupling and η=1)

"what you see is what you get": observation becomes reality

Can we explain it in a more reasonable way (without spooks/ghosts)?



or some other $z(t)$?

No (under assumptions of macrorealism; Leggett-Garg, 1985)

Leggett-Garg-type inequalities for continuous measurement of a qubit

$\text{qubit} \longleftrightarrow \text{detector} \xrightarrow{I(t)}$

Ruskov-A.K.-Mizel, PRL-2006
Jordan-A.K.-Büttiker, PRL-2006

Assumptions of macrorealism (similar to Leggett-Garg'85):

$$I(t) = I_0 + (\Delta I/2)\, z(t) + \xi(t)$$

$$|z(t)| \leq 1, \quad \langle \xi(t)\; z(t+\tau) \rangle = 0$$

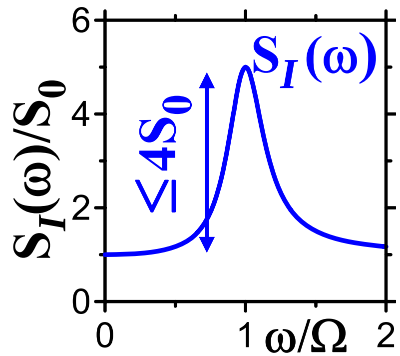
Leggett-Garg, 1985

$K_{ij} = \langle Q_i Q_j \rangle$

if $Q = \pm 1$, then

$1 + K_{12} + K_{23} + K_{13} \geq 0$

$K_{12} + K_{23} + K_{34} - K_{14} \leq 2$



Then for correlation function

$$K(\tau) = \langle I(t)\, I(t+\tau) \rangle$$

	quantum result	violation
$K(\tau_1) + K(\tau_2) - K(\tau_1 + \tau_2) \leq (\Delta I/2)^2$	$\frac{3}{2}(\Delta I/2)^2$	$\times \frac{3}{2}$

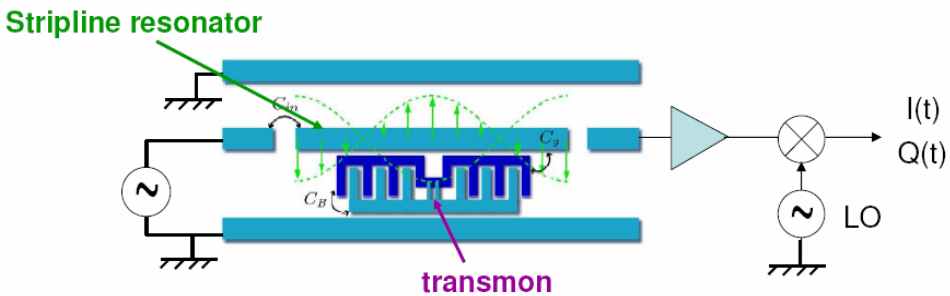
and for area under narrow spectral peak

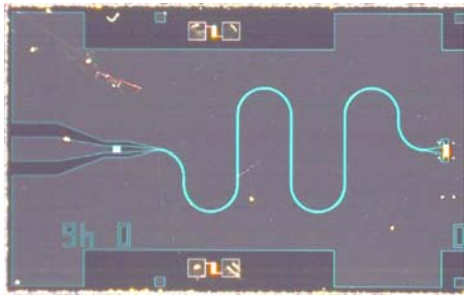
$\int [S_I(f) - S_0]\, df \leq (8/\pi^2)(\Delta I/2)^2$	$(\Delta I/2)^2$	$\times \frac{\pi^2}{8}$

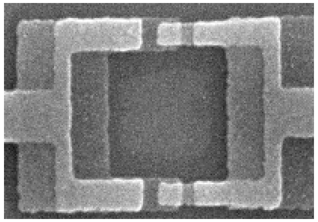
η is not important! **Experimentally measurable violation**

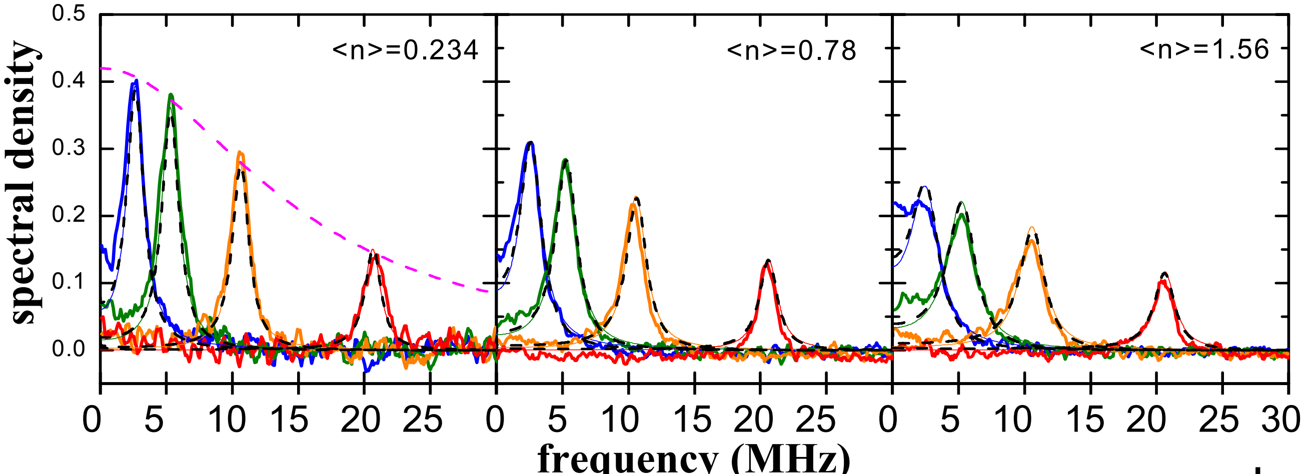
(Saclay experiment)

Recent experiment (Saclay group, unpub.)



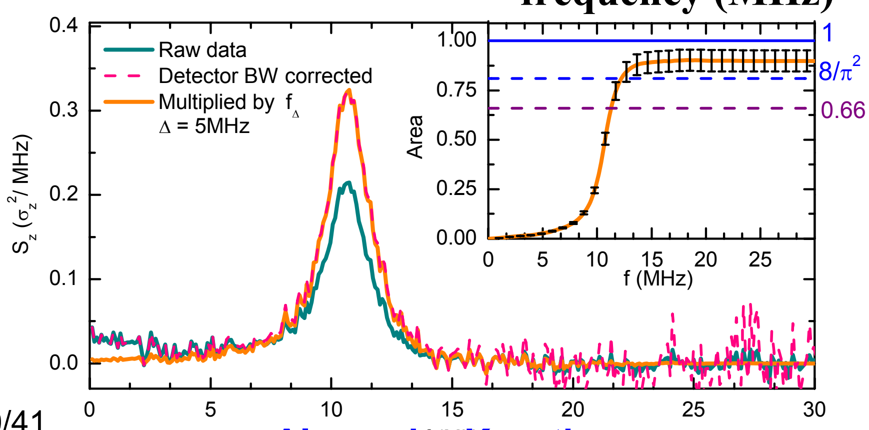






A. Palacios-Laloy et al. (unpublished)

courtesy of Patrice Bertet



- superconducting charge qubit (transmon) in circuit QED setup (microwave reflection from cavity)
- driven Rabi oscillations
- perfect spectral peaks
- LGI violation (both *K* and *S*)

Next step: quantum feedback (Useful?)

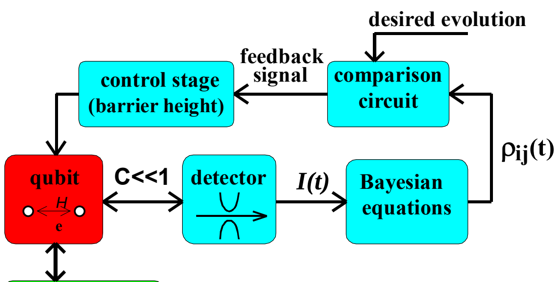
Goal: persistent Rabi oscillations with zero linewidth (synchronized)

Types of quantum feedback:

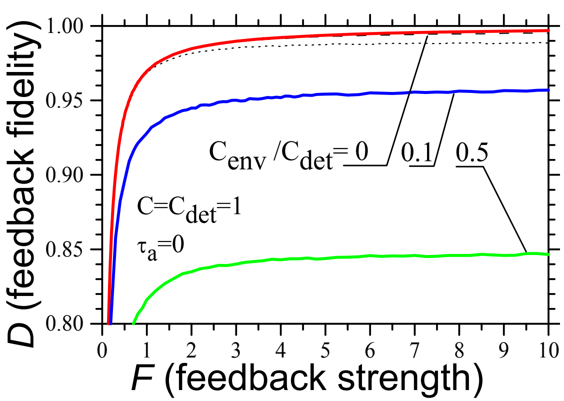
Bayesian

Best but very difficult

(monitor quantum state and control deviation)



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



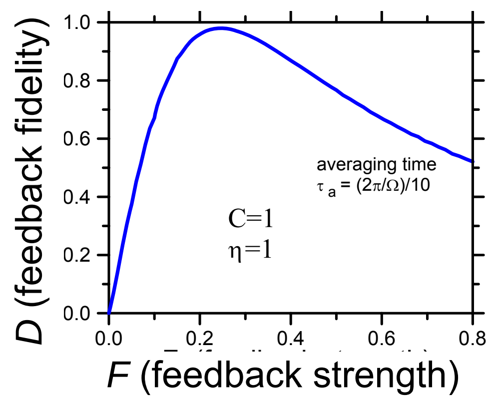
Ruskov & A.K., 2002

Direct

a la Wiseman-Milburn (1993)

(apply measurement signal to control with minimal processing)

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



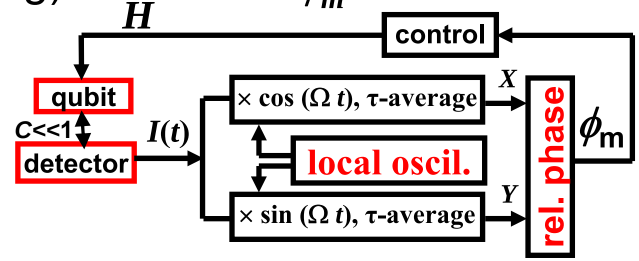
Ruskov & A.K., 2002

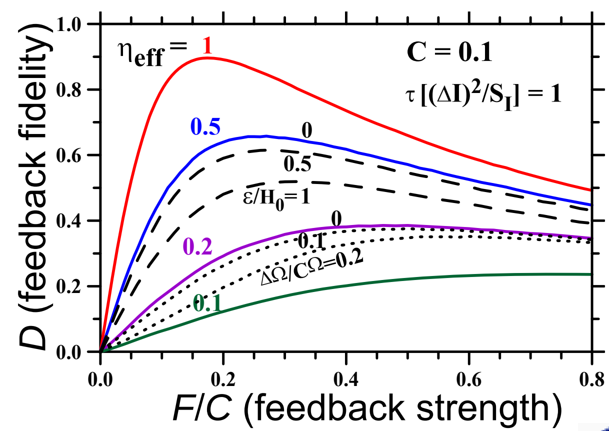
"Simple"

Imperfect but simple

(do as in usual classical feedback)

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





A.K., 2005

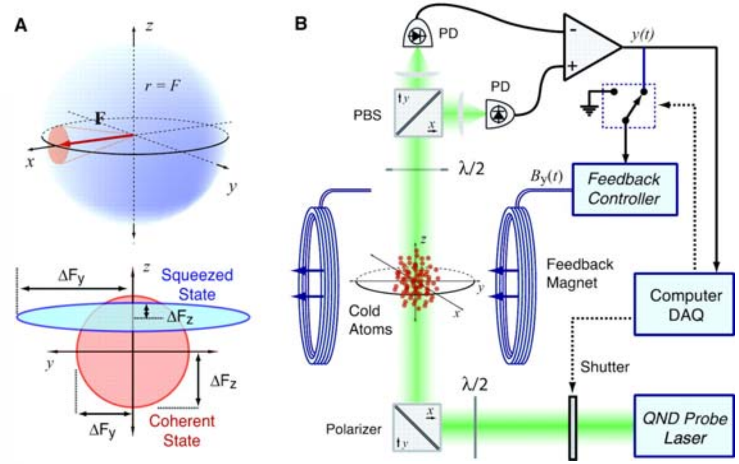
Quantum feedback in optics

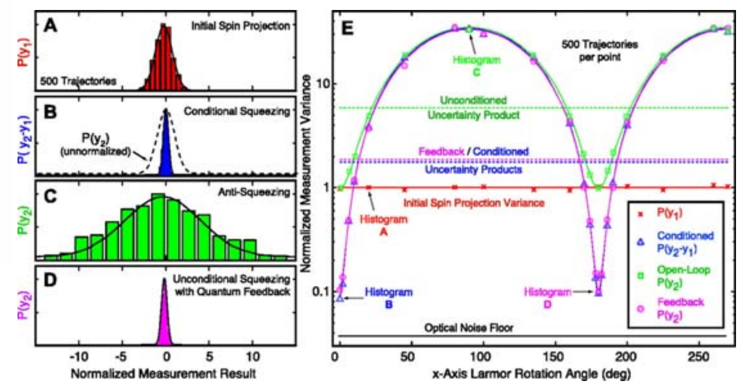
First experiment: Science 304, 270 (2004)

Real-Time Quantum Feedback Control of Atomic Spin-Squeezing

JM Geremia,* John K. Stockton, Hideo Mabuchi

Real-time feedback performed during a quantum nondemolition measurement of atomic spin-angular momentum allowed us to influence the quantum statistics of the measurement outcome. We showed that it is possible to harness measurement backaction as a form of actuation in quantum control, and thus we describe a valuable tool for quantum information science. Our feedback-mediated procedure generates spin-squeezing, for which the reduction in quantum uncertainty and resulting atomic entanglement are not conditioned on the measurement outcome.





First detailed theory:

H.M. Wiseman and G. J. Milburn,
Phys. Rev. Lett. 70, 548 (**1993**)

Quantum feedback in optics

First experiment: Science 304, 270 (2004)

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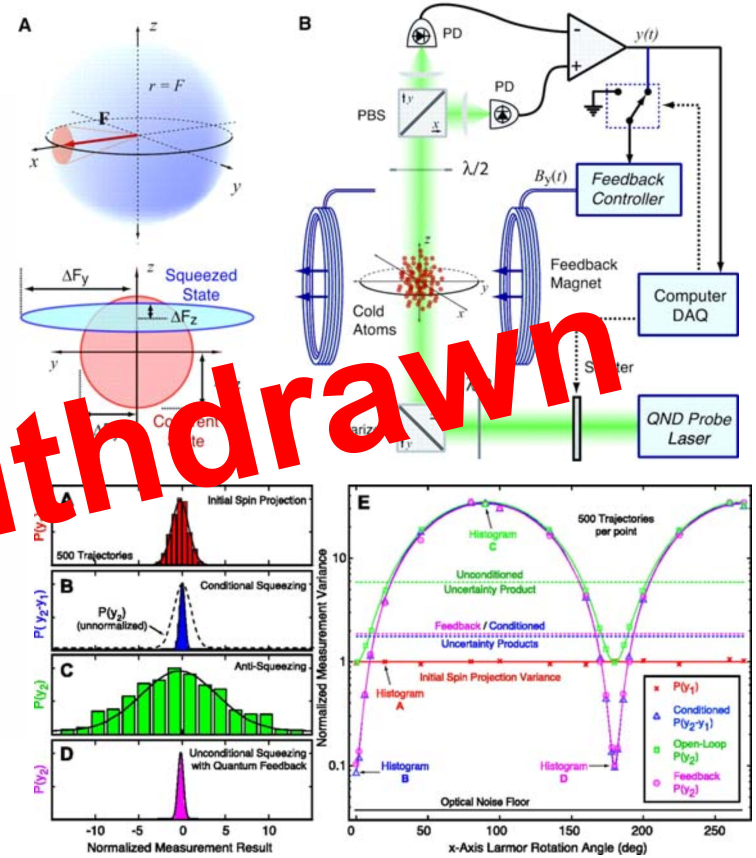
paper withdrawn



PRL 94, 203002 (2005) also withdrawn

First detailed theory:

H.M. Wiseman and G. J. Milburn,
Phys. Rev. Lett. 70, 548 (**1993**)

Recent experiment:

Cook, Martin, Geremia,
Nature 446, 774 (2007)
(coherent state discrimination)

Undoing a weak measurement of a qubit ("uncollapse")

A.K. & Jordan, PRL-2006

It is impossible to undo "orthodox" quantum measurement (for an unknown initial state)

Is it possible to undo partial quantum measurement?
(To restore a "precious" qubit accidentally measured)
Yes! (but with a finite probability)

If undoing is successful, an unknown state is **fully** restored

ψ_0 (unknown) $\xrightarrow{\text{weak (partial) measurement}}$ ψ_1 (partially collapsed)

ψ_1 $\xrightarrow{\text{successful}}$ ψ_0 (still unknown)

ψ_1 $\xrightarrow{\text{unsuccessful}}$ ψ_2

uncollapse (information erasure)

Quantum erasers in optics

Quantum eraser proposal by Scully and Drühl, PRA (1982)

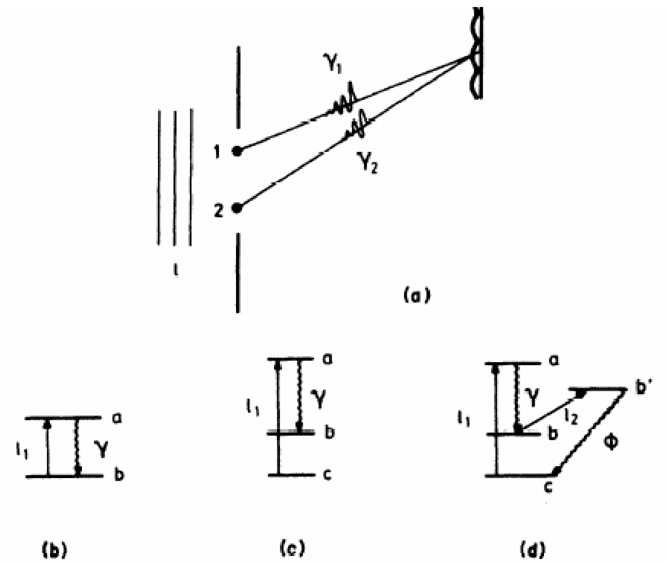


FIG. 1. (a) Figure depicting light impinging from left on atoms at sites 1 and 2. Scattered photons γ_1 and γ_2 produce interference pattern on screen. (b) Two-level atoms excited by laser pulse l_1, and emit γ photons in $a \rightarrow b$ transition. (c) Three-level atoms excited by pulse l_1 from $c \rightarrow a$ and emit photons in $a \rightarrow b$ transition. (d) Four-level system excited by pulse l_1 from $c \rightarrow a$ followed by emission of γ photons in $a \rightarrow b$ transition. Second pulse l_2 takes atoms from $b \rightarrow b'$. Decay from $b' \rightarrow c$ results in emission of ϕ photons.

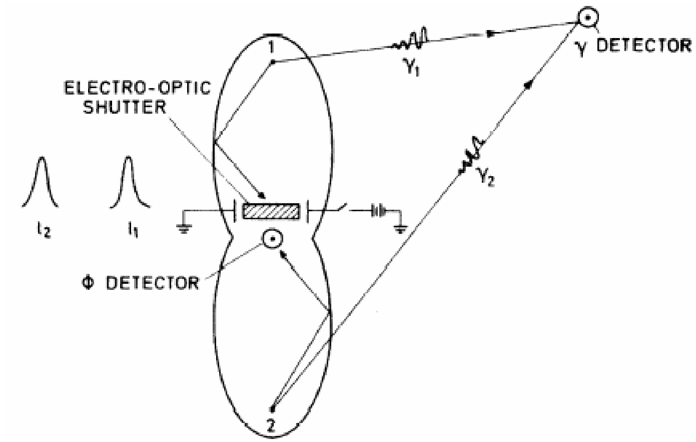


FIG. 2. Laser pulses l_1 and l_2 incident on atoms at sites 1 and 2. Scattered photons γ_1 and γ_2 result from $a \rightarrow b$ transition. Decay of atoms from $b' \rightarrow c$ results in ϕ photon emission. Elliptical cavities reflect ϕ photons onto common photodetector. Electro-optic shutter transmits ϕ photons only when switch is open. Choice of switch position determines whether we emphasize particle or wave nature of γ photons.

Interference fringes restored for two-detector correlations (since “which-path” information is erased)

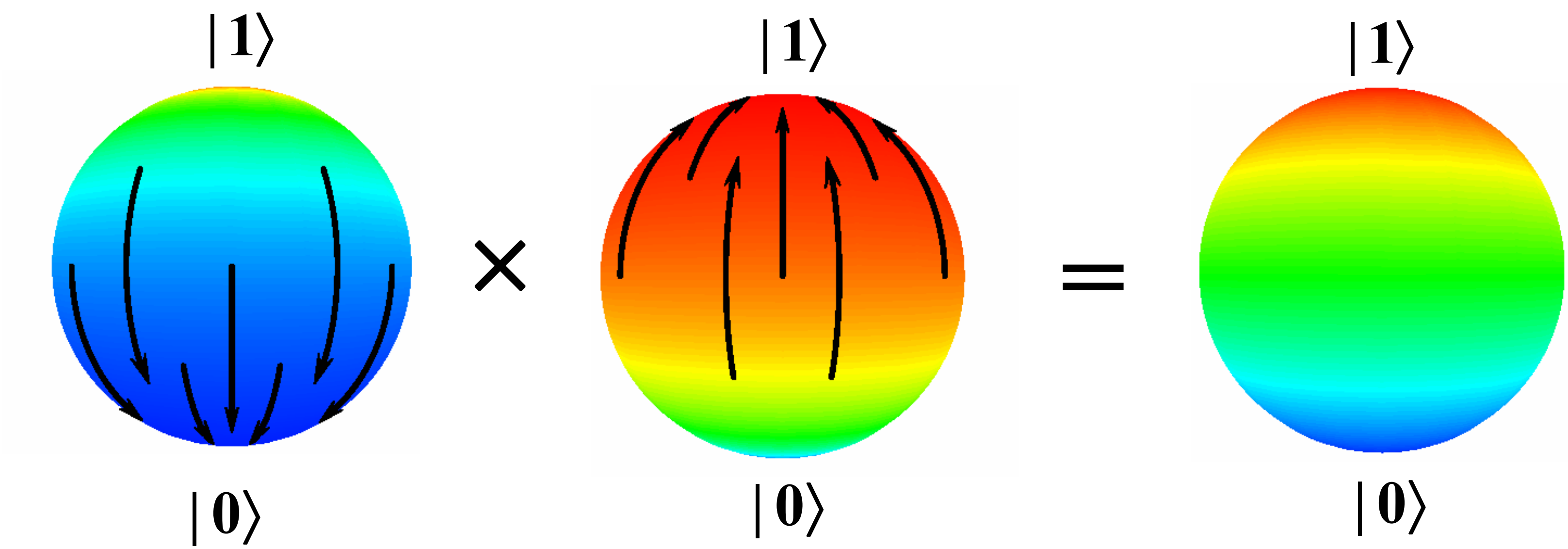
Our idea of uncollapsing is quite different:
we really extract quantum information and then erase it

Alexander Korotkov University of California, Riverside

Uncollapse of a qubit state

Evolution due to partial (weak, continuous, etc.) measurement is **non-unitary**, so impossible to undo it by Hamiltonian dynamics.

How to undo? One more measurement!



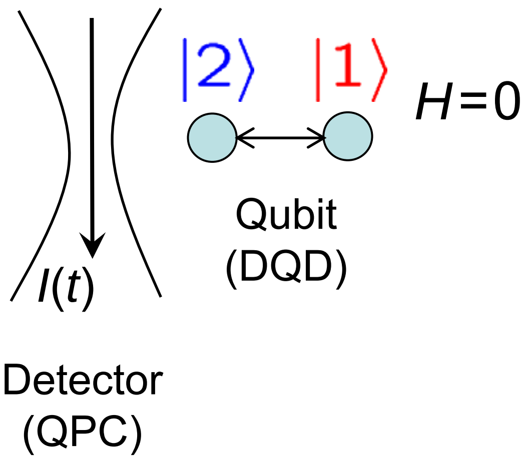
need ideal (quantum-limited) detector

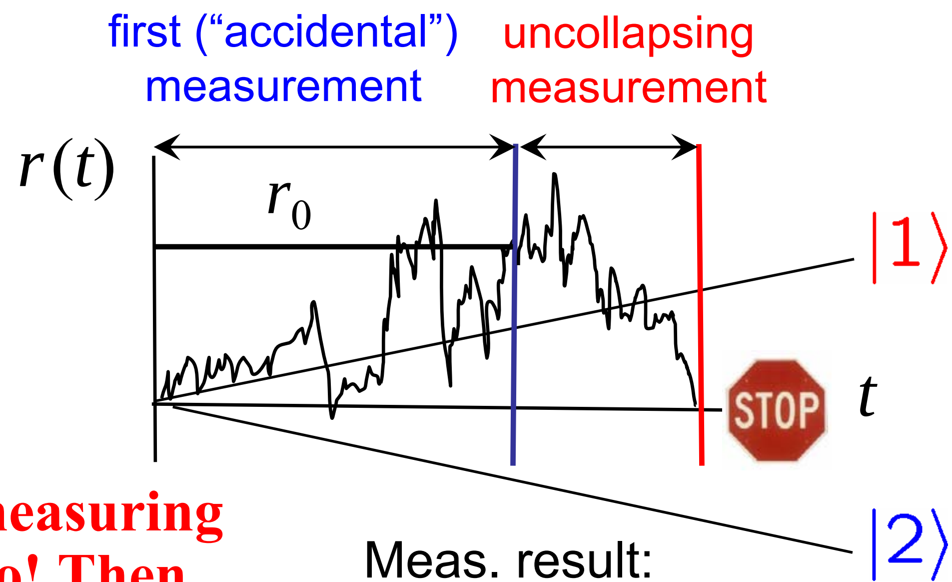
(similar to Koashi-Ueda, PRL-1999)

(Figure partially adopted from Jordan-A.K.-Büttiker, PRL-06)

Uncollapsing for DQD-QPC system

A.K. & Jordan, 2006





Simple strategy: continue measuring until result $r(t)$ becomes zero! Then any initial state is fully restored.

(same for an entangled qubit)

However, if r = 0 never happens, then uncollapsing procedure is unsuccessful.

Meas. result:

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

If r = 0, then no information and no evolution!

Probability of success:

$$P_S = \frac{e^{-|r_0|}}{e^{|r_0|}\rho_{11}(0) + e^{-|r_0|}\rho_{22}(0)}$$

General theory of uncollapsing

POVM formalism
(Nielsen-Chuang, p.100)

Measurement operator M_r: $\rho \rightarrow \dfrac{M_r \rho M_r^\dagger}{\mathrm{Tr}(M_r \rho M_r^\dagger)}$

Probability: $P_r = \mathrm{Tr}(M_r \rho M_r^\dagger)$ Completeness: $\sum_r M_r^\dagger M_r = 1$

Uncollapsing operator: $C \times M_r^{-1}$ (to satisfy completeness, eigenvalues cannot be >1)

$\max(C) = \min_i \sqrt{p_i}$, p_i – eigenvalues of $M_r^\dagger M_r$

Probability of success: $\boxed{P_S \le \dfrac{\min P_r}{P_r(\rho_{\mathrm{in}})}}$ A.K. & Jordan, 2006

$P_r(\rho_{\mathrm{in}})$ – probability of result r for initial state ρ_{in},

min P_r – probability of result r minimized over all possible initial states

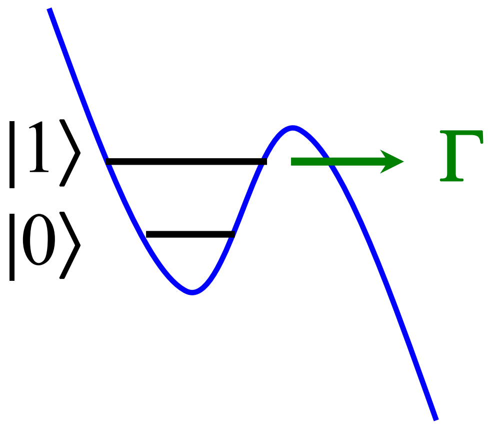
Averaged (over r) probability of success: $P_{av} \le \sum_r \min P_r$

(cannot depend on initial state, otherwise get information)

(similar to Koashi-Ueda, 1999)

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



How does a qubit state evolve in time before tunneling event?

(What happens when nothing happens?)

Main idea:

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

(better theory: Pryadko & A.K., 2007)

amplitude of state |0⟩ grows without physical interaction

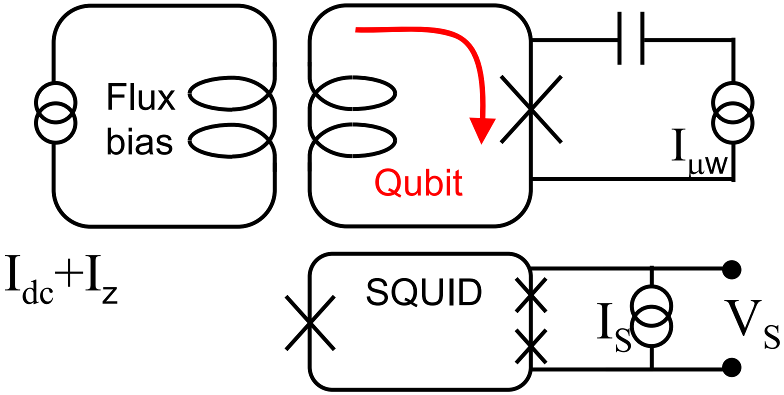
finite linewidth only after tunneling

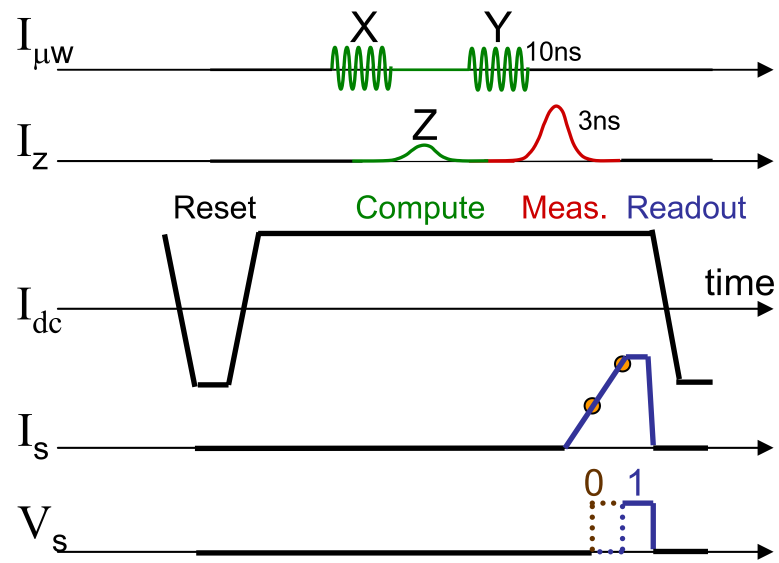
continuous null-result collapse

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

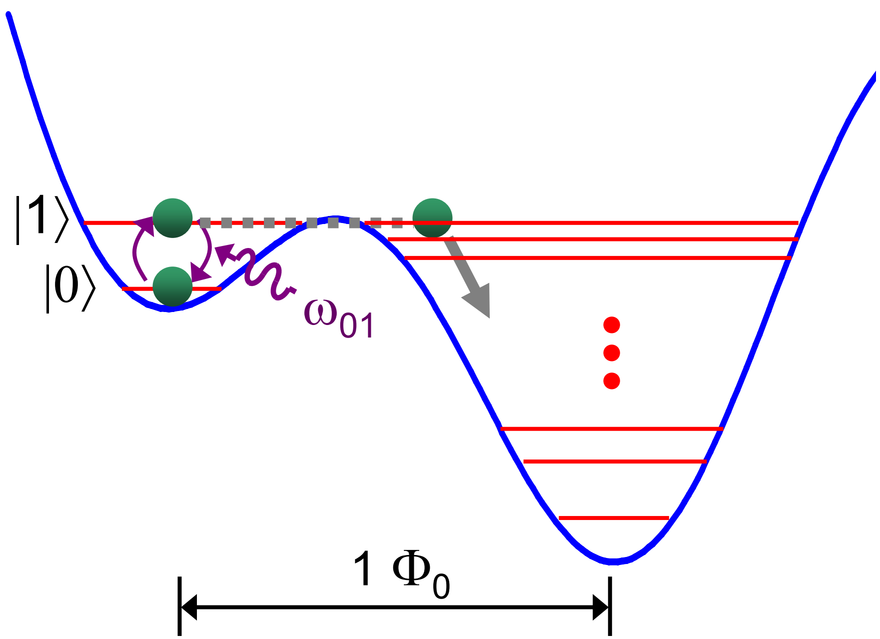
Superconducting phase qubit at UCSB

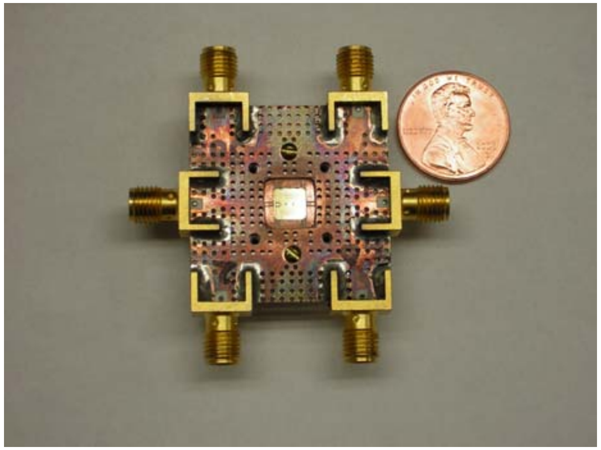
Courtesy of Nadav Katz (UCSB)





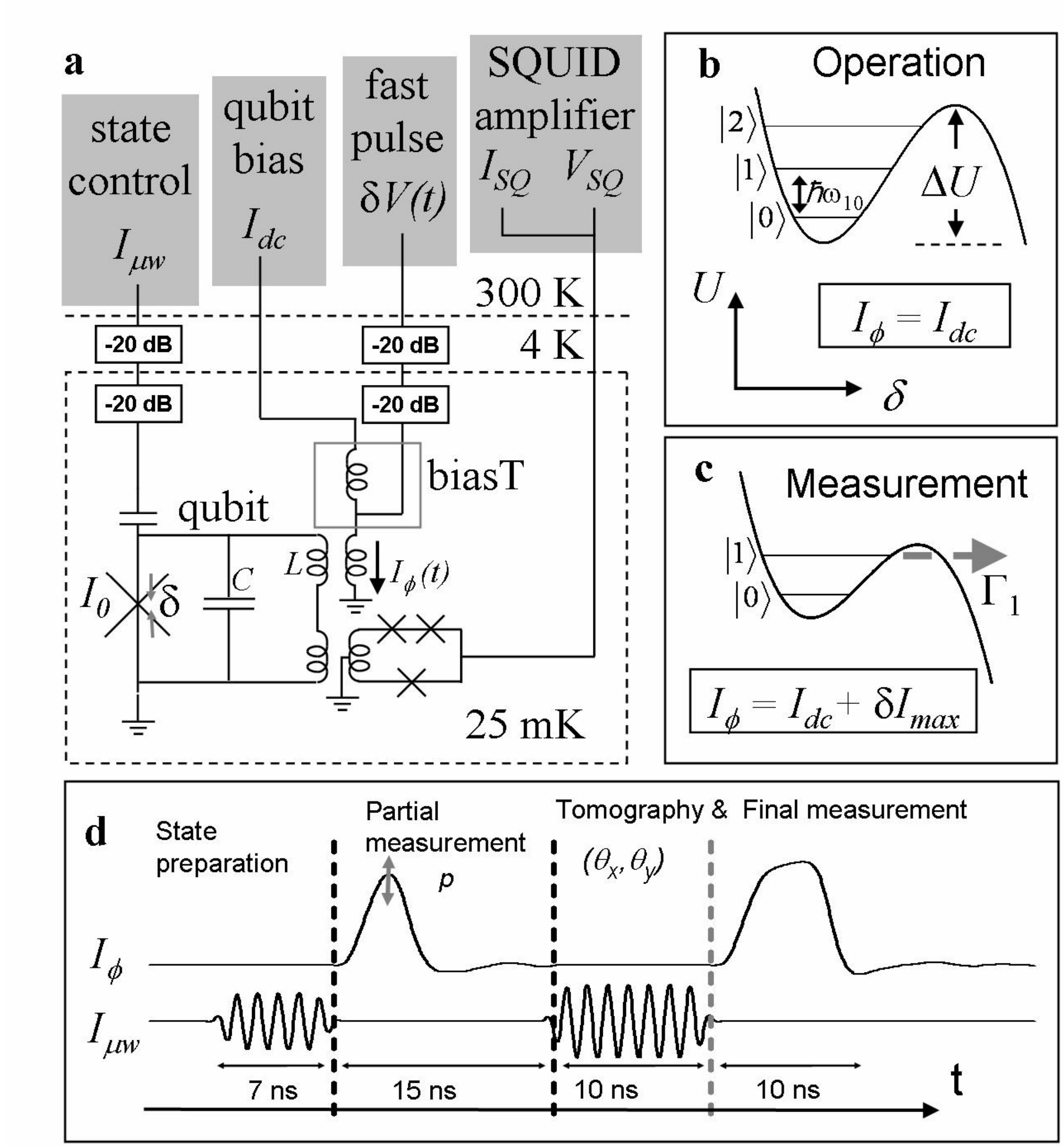
Repeat 1000x
prob. 0,1





Alexander Korotkov
University of California, Riverside

Experimental technique for partial collapse



Nadav Katz *et al.*
(John Martinis group)

Protocol:

1) State preparation (via Rabi oscillations)
2) Partial measurement by lowering barrier for time *t*
3) State tomography (micro-wave + full measurement)

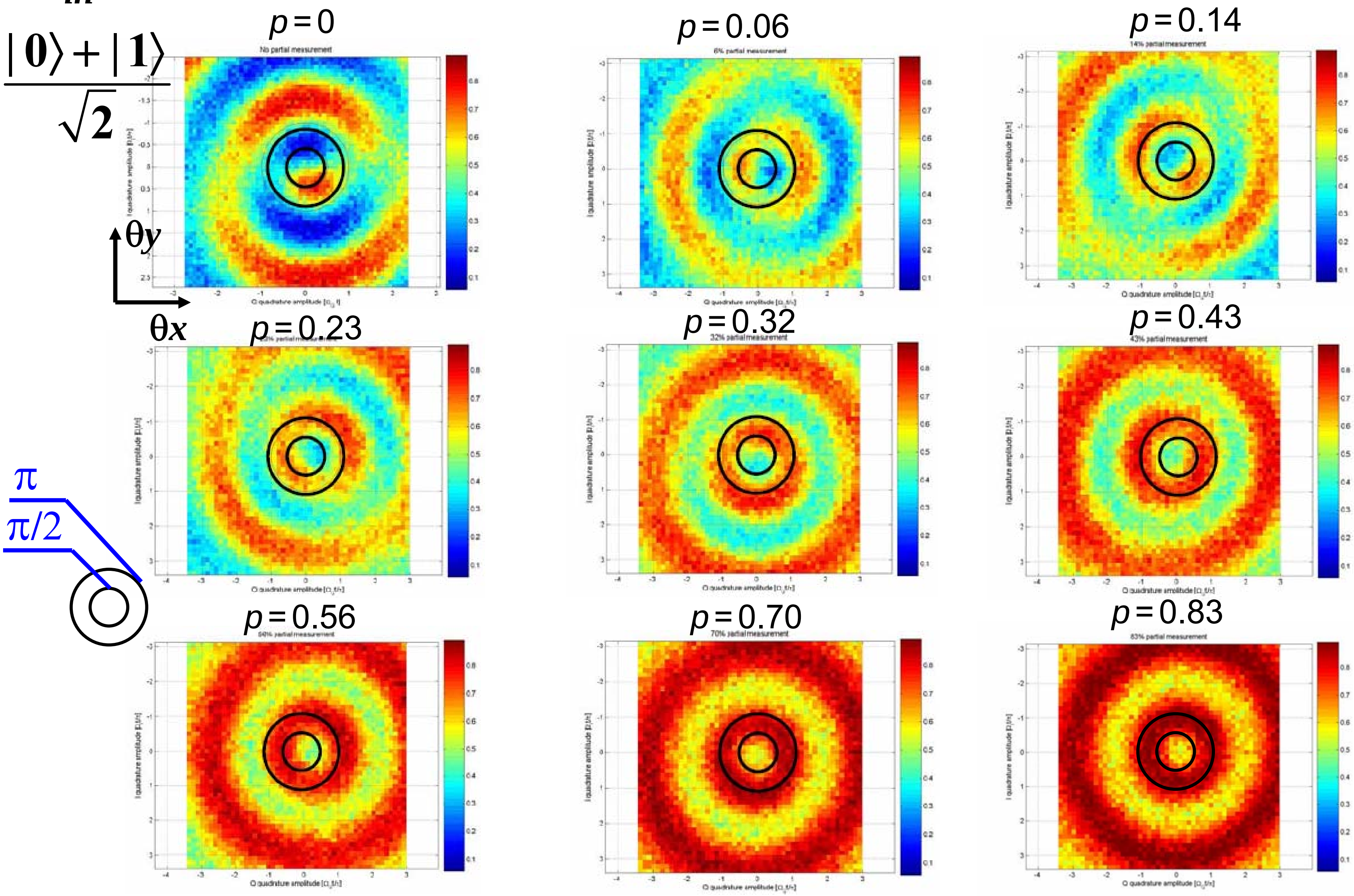
Measurement strength
$p = 1 - \exp(-\Gamma t)$
is actually controlled by Γ, not by *t*

$p=0$: no measurement
$p=1$: orthodox collapse

Experimental tomography data

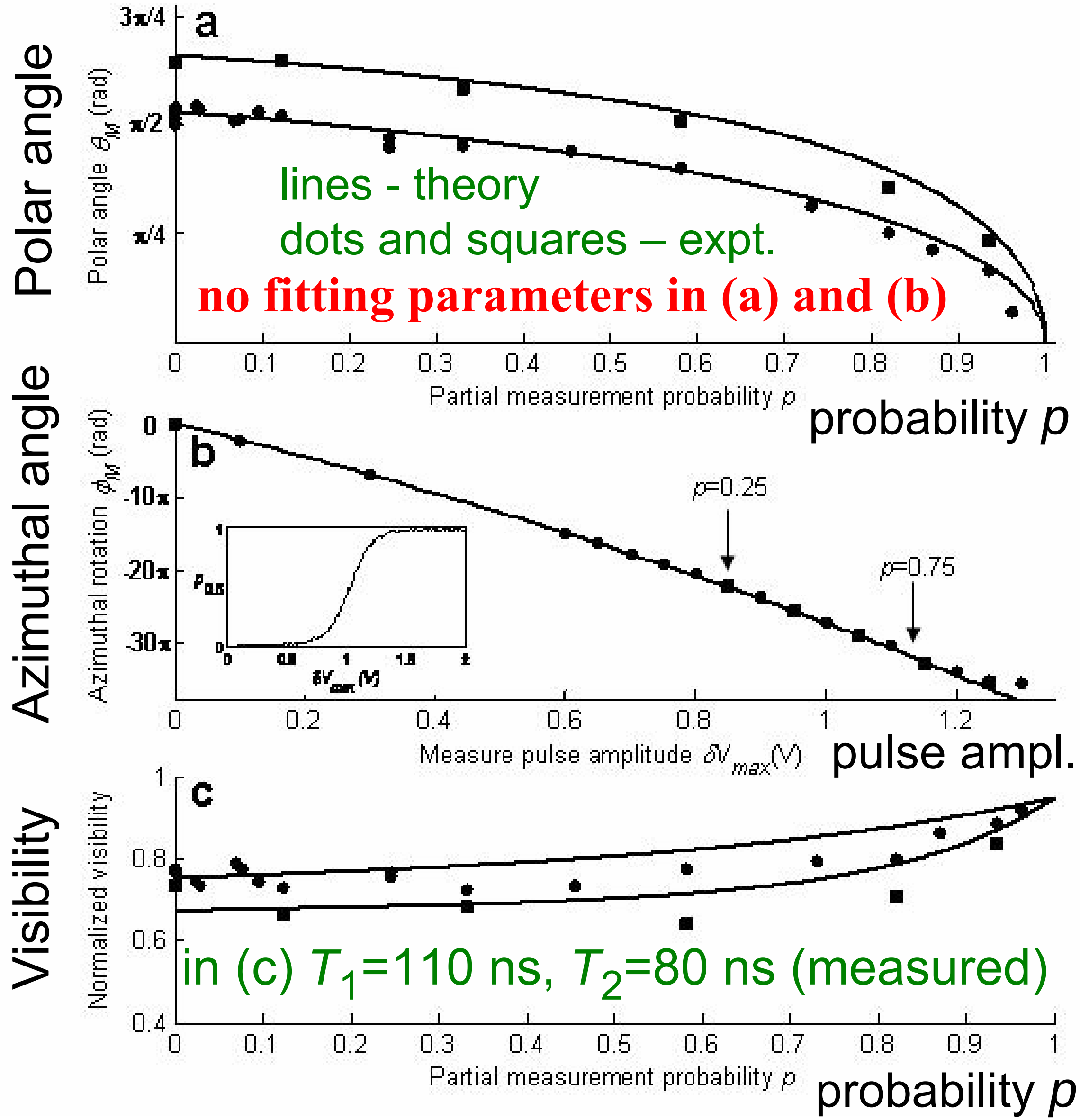
Nadav Katz *et al*. (UCSB, 2005)

$$\psi_{in} = \frac{|0\rangle + |1\rangle}{\sqrt{2}}$$



Partial collapse: experimental results

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



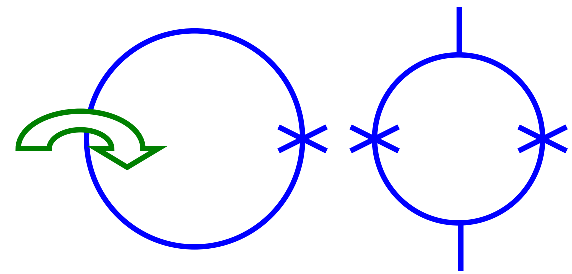
- In case of no tunneling phase qubit evolves
- Evolution is described by the Bayesian theory without fitting parameters
- Phase qubit remains coherent in the process of continuous collapse (expt. ~80% raw data, ~96% corrected for T_1,T_2)

quantum efficiency
$\eta_0 > 0.8$

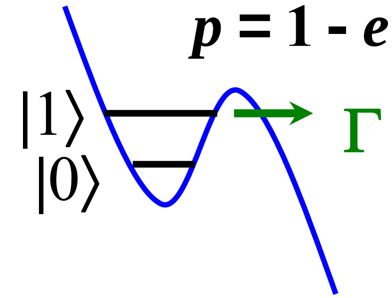
Uncollapse of a phase qubit state

A.K. & Jordan, 2006

1) Start with an unknown state
2) Partial measurement of strength p
3) π-pulse (exchange $|0\rangle \leftrightarrow |1\rangle$)
4) One more measurement with the **same strength** p
5) π-pulse



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



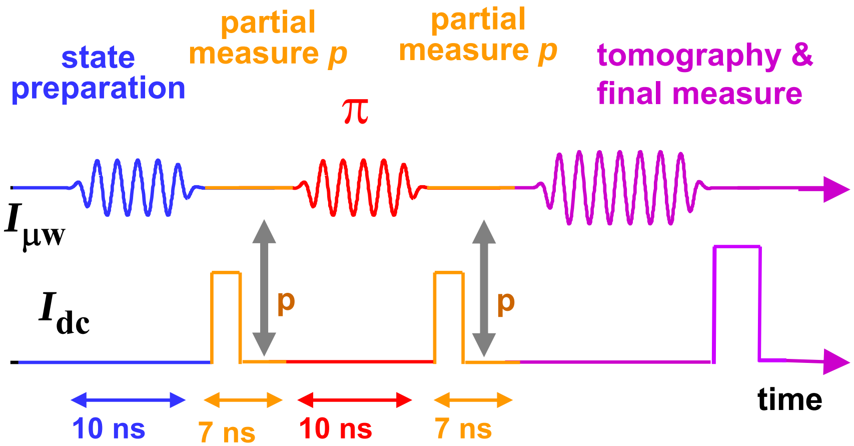
If no tunneling for both measurements, then initial state is fully restored!

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

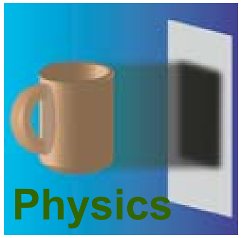
$$\frac{e^{i\phi}\alpha e^{-\Gamma t/2}|0\rangle + e^{i\phi}\beta e^{-\Gamma t/2}|1\rangle}{\text{Norm}} = e^{i\phi}(\alpha|0\rangle + \beta|1\rangle)$$

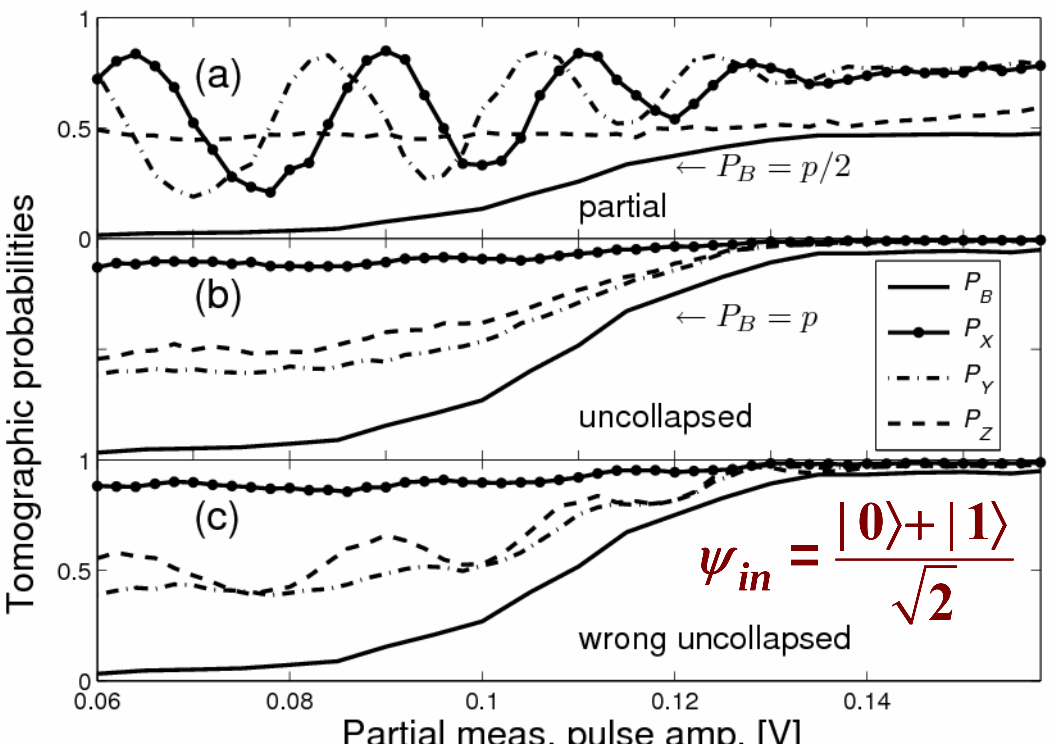
phase is also restored (spin echo)

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)

State tomography with *X*, *Y*, and no pulses

Background P_B should be subtracted to find qubit density matrix

Experimental results on the Bloch sphere

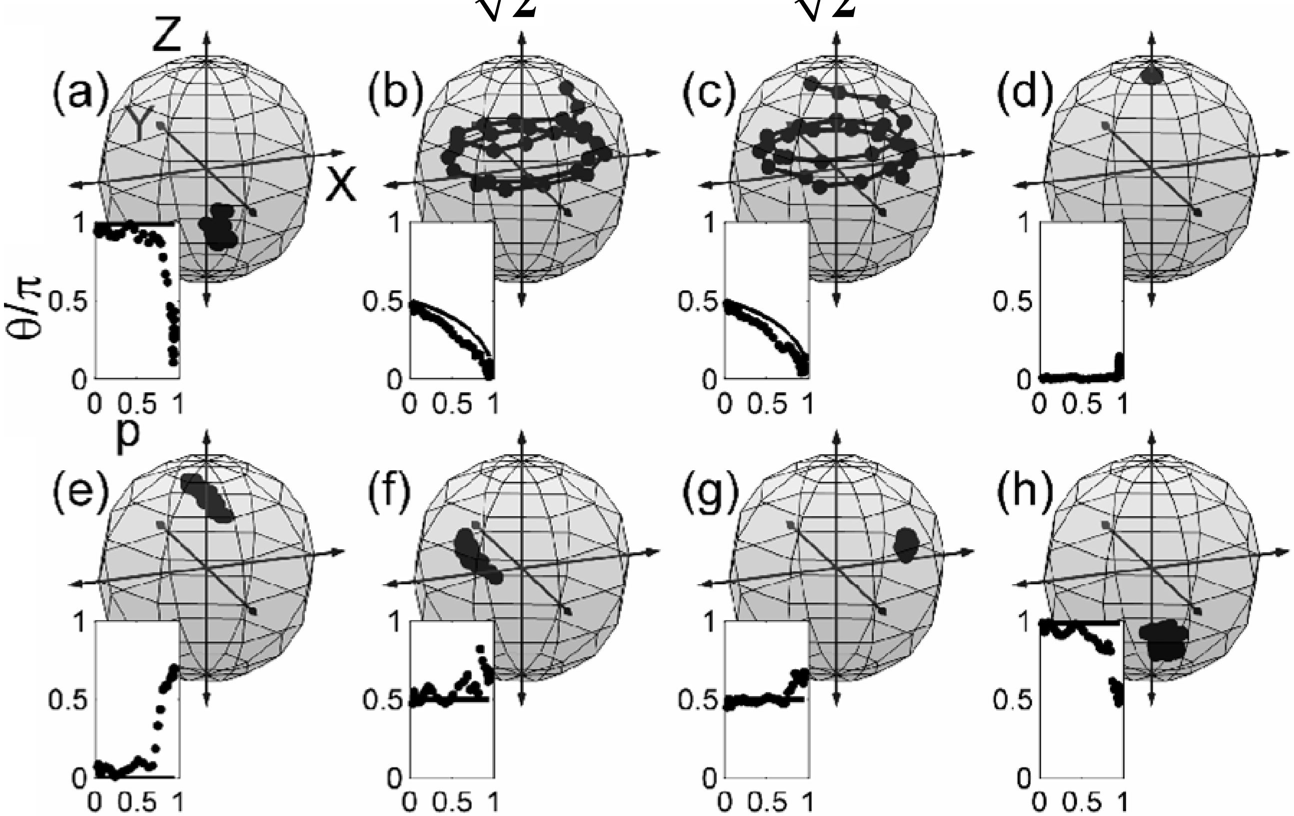
N. Katz et al.

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!

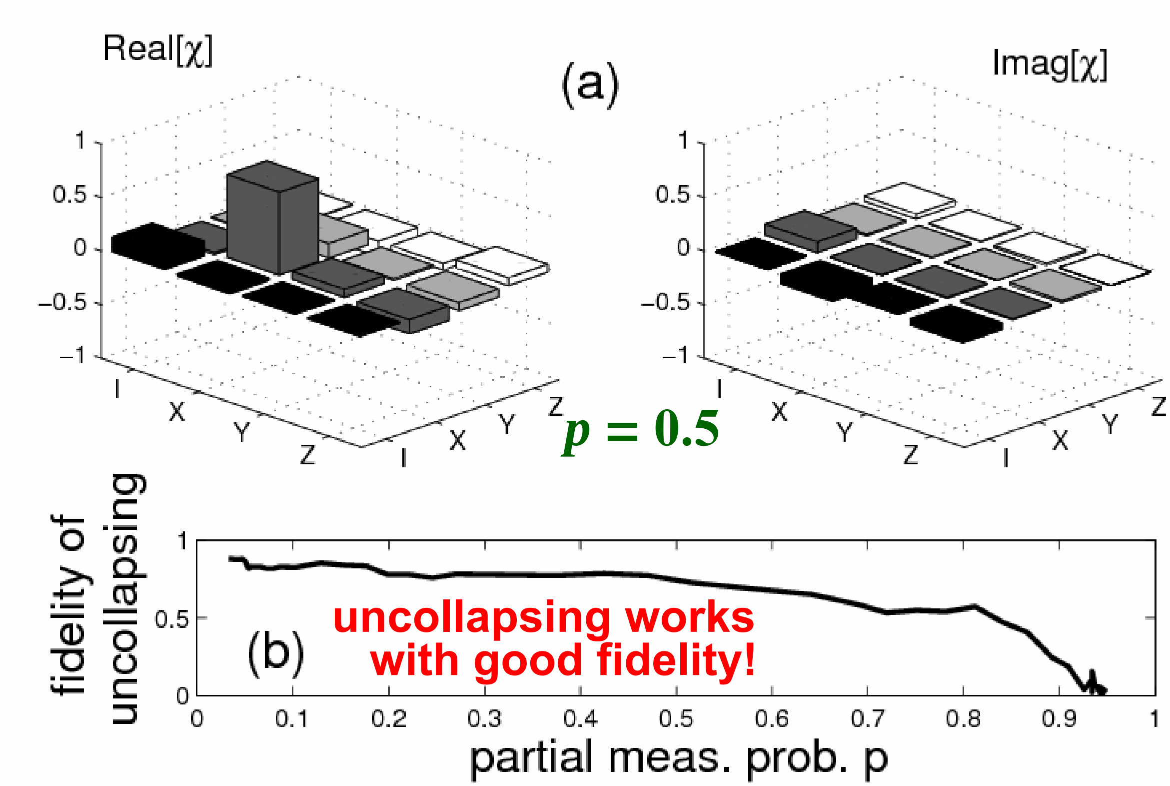


Both spin echo (azimuth) and uncollapsing (polar angle)

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

Quantum process tomography

N. Katz et al.
(Martinis group)



Why getting worse at $p>0.6$?

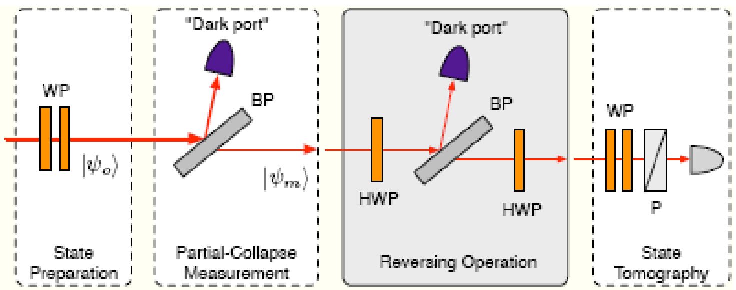
Energy relaxation $p_r = t/T_1 = 45\text{ns}/450\text{ns} = 0.1$

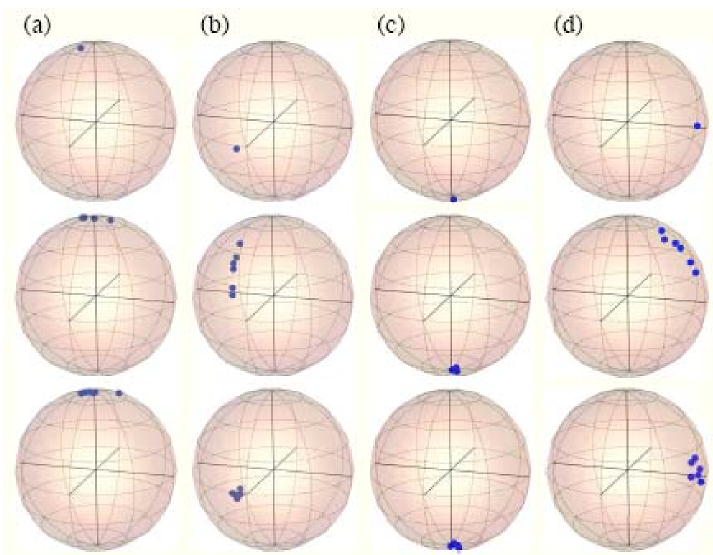
Selection affected when $1-p \sim p_r$

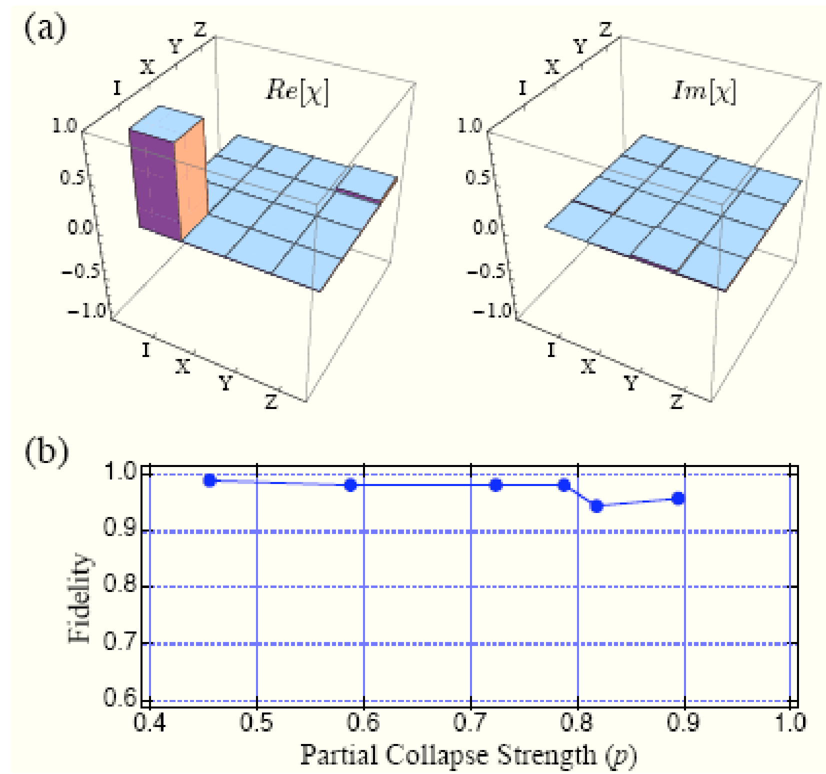
Overall: uncollapsing is well-confirmed experimentally

Recent experiment on uncollapsing using single photons

Kim et al., Opt. Expr.-2009



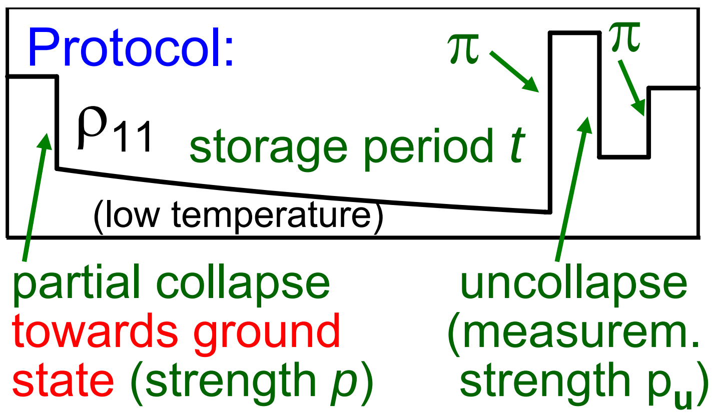




- very good fidelity of uncollapsing (>94%)
- measurement fidelity is probably not good (normalization by coincidence counts)

Suppression of T_1-decoherence by uncollapsing

Korotkov & Keane, arXiv:0908.1134



best for $1 - p_u = (1-p)\exp(-t/T_1)$

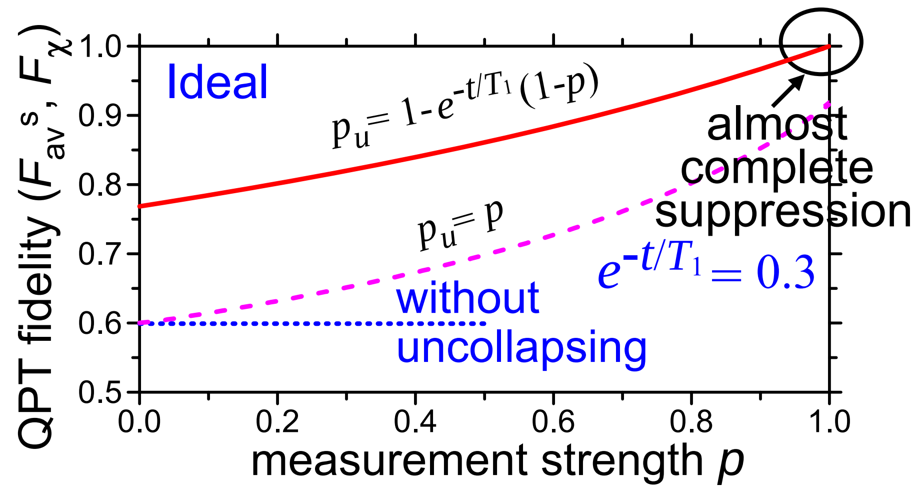
Ideal case (T_1 during storage only)

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

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

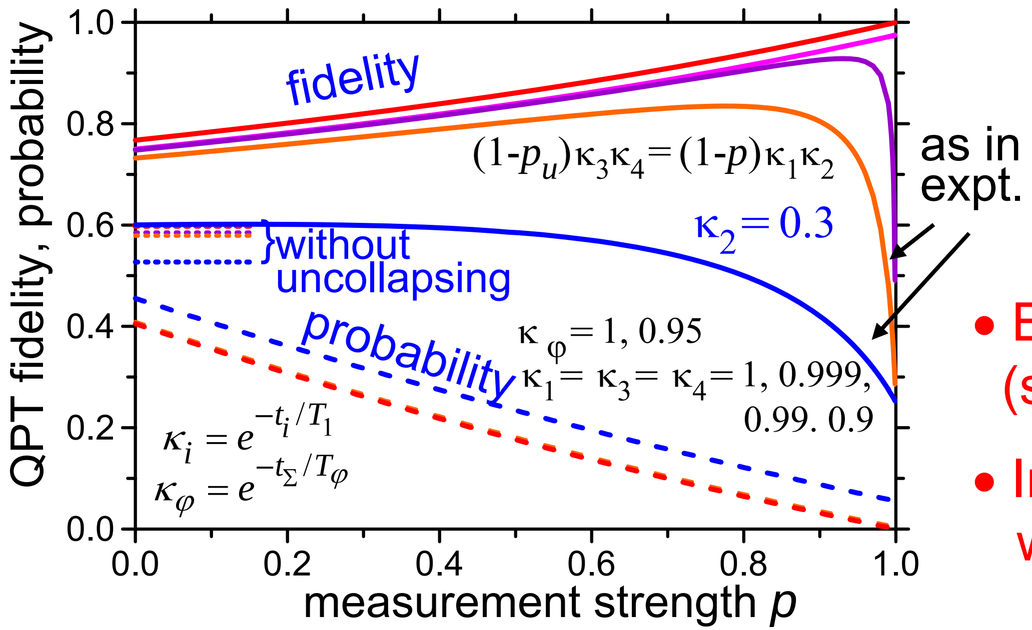
$|\psi_f\rangle = |0\rangle$ with $(1-p)^2|\beta|^2 e^{-t/T_1}(1-e^{-t/T_1})$

procedure preferentially selects events without energy decay



Trade-off: fidelity vs. probability

Realistic case (T_1 and T_φ at all stages)



- Easy to realize experimentally (similar to existing experiment)
- Improved fidelity can be observed with just one partial measurement

- Tφ-decoherence is not affected
- fidelity decreases at $p \to 1$ due to T_1 between 1st π-pulse and 2nd meas.

Uncollapse seems **the only way** to protect against T_1-decoherence without quantum error correction

A.K. & Keane, arXiv:0908.1134

Trade-off: fidelity vs. selection probability

Conclusions

- It is easy to see what is "inside" collapse: simple Bayesian formalism works for many solid-state setups
- Rabi oscillations are persistent if weakly measured
- Collapse can sometimes be undone if we manage to erase extracted information (uncollapsing)
- Continuous/partial measurements and uncollapsing may be useful
- Three direct solid-state experiments have been realized, many interesting experimental proposals are still waiting