Theoretical analysis of phase qubits

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I A R P A

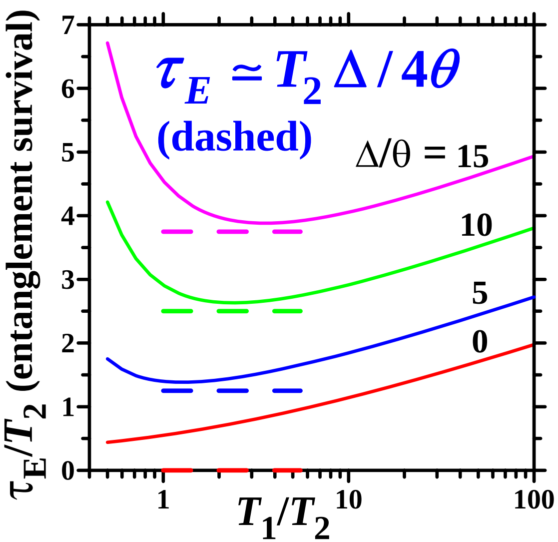
Research accomplishments since last review

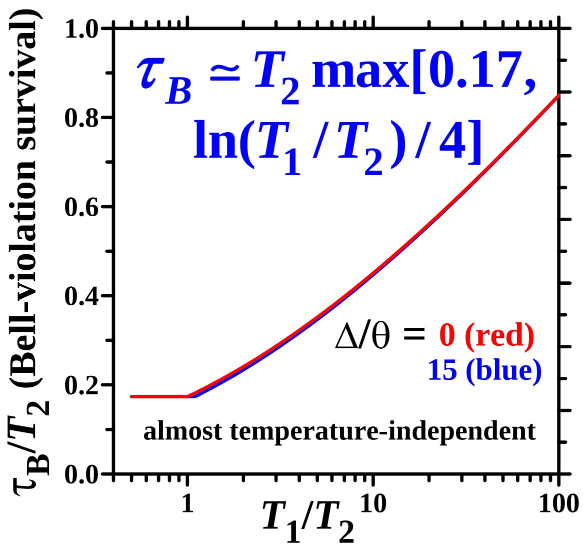
- 3 journal papers published + 4 submitted (18 journal papers published + 4 submitted since start of the grant in 2004)
- Analyzed relation between entanglement and Bell inequality violation in phase qubits; analyzed effect of decoherence on Bell inequality violation in phase qubits
- Performed numerical analysis of the √(iswap) gate fidelity for phase qubits; identified effect of non-local decoherence on the χ-matrix of the quantum process tomography
- Developed theory of quantum efficiency of binary-outcome solid-state qubit detectors (incl. phase qubit measurement)
- Continued work on quantum uncollapsing

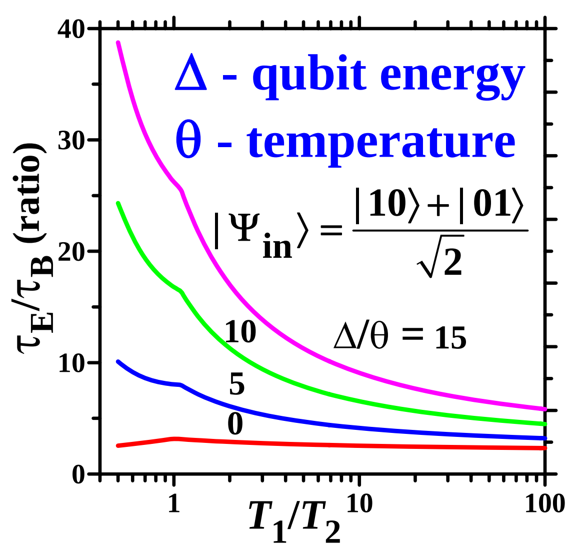
Entanglement vs. Bell inequality for phase qubits

Only 1.1% of entangled states violate Bell (CHSH) inequality
(our numerical result for Hilbert-Schmidt metric)

Therefore, under decoherence, entanglement-survival duration τ_E is significantly longer than Bell-inequality-violation duration τ_B





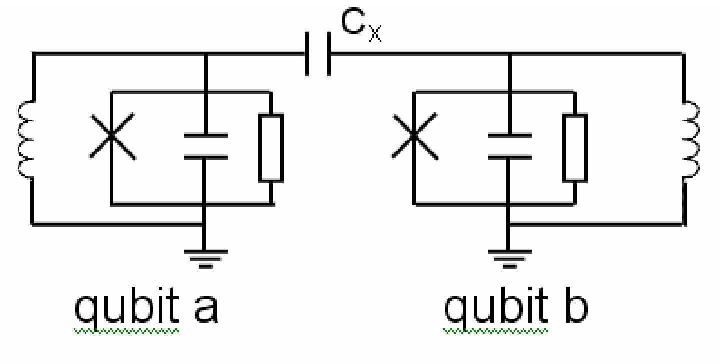


For present-day parameters of phase qubits entanglement should last 8 times longer than Bell inequality violation (470 ns vs. 60 ns)

Kofman & Korotkov, PRA 77, 052329 (2008)

Bell ineq. also studied in Kofman, arXiv:0804.4167

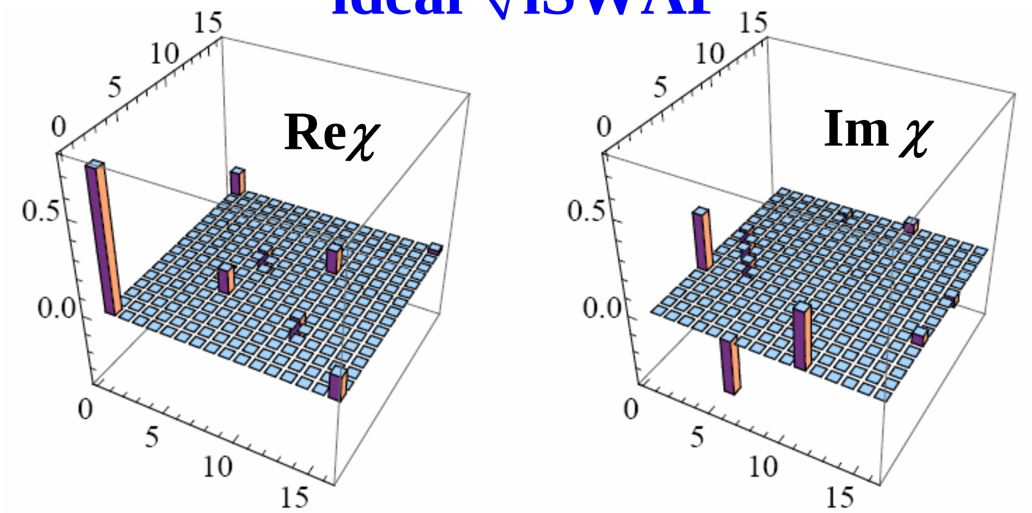
Analysis of QPT (quantum process tomography) for phase qubits



$$H_{\text{int}} = \frac{S}{2}\left(|10\rangle\langle 01| + |01\rangle\langle 10|\right)$$

$\sqrt{\text{iSWAP}}$: $U_{\sqrt{\text{iSWAP}}} = e^{-i(\pi/2S)H_{\text{int}}}$

ideal $\sqrt{\text{iSWAP}}$



(modified basis: *I*, *X*, *-iY*, *Z*)

Analyzed models of decoherence:

- Local decoherence (T_1, T_2)
- Non-local: correlated dephasing (e.g. due to correlated flux noise)
- Noisy coupling (fluctuating capacitance)

How to distinguish mechanisms?

Kofman & Korotkov, in preparation

Effects of decoherence on $\sqrt{\text{iSWAP}}$ gate

Weak decoherence $\Rightarrow$ different mechanisms approx. additive:

$\chi \approx \chi_{\text{ideal}} + d\chi_{\text{dec.1}} + d\chi_{\text{dec.2}} + \ldots$

Local decoherence

$S/h = 20$ MHz,

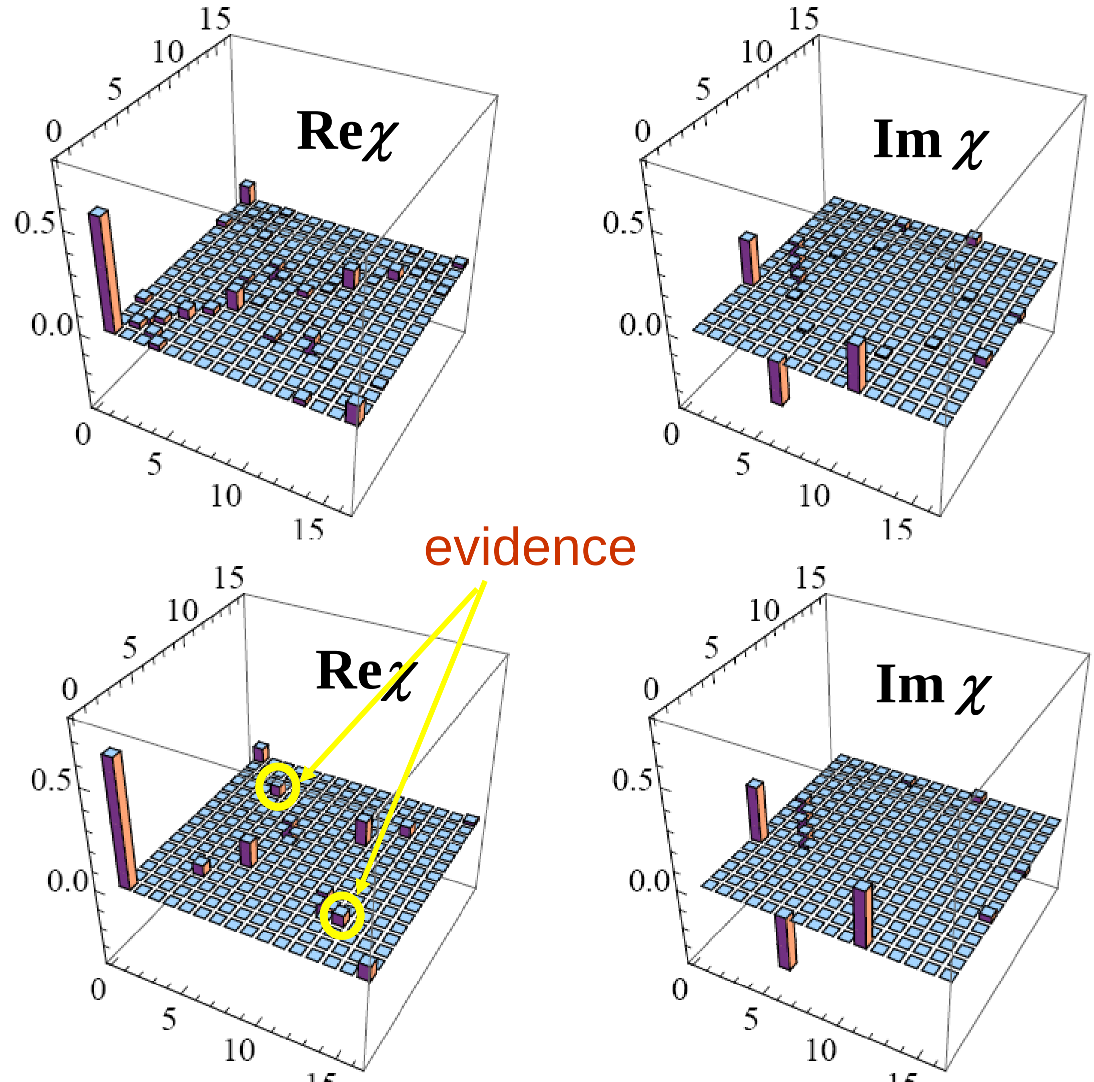
$T_1 = 90$ ns, $T_2 = 60$ ns

Non-local decoherence (correlated dephasing)

$S/h = 20$ MHz,

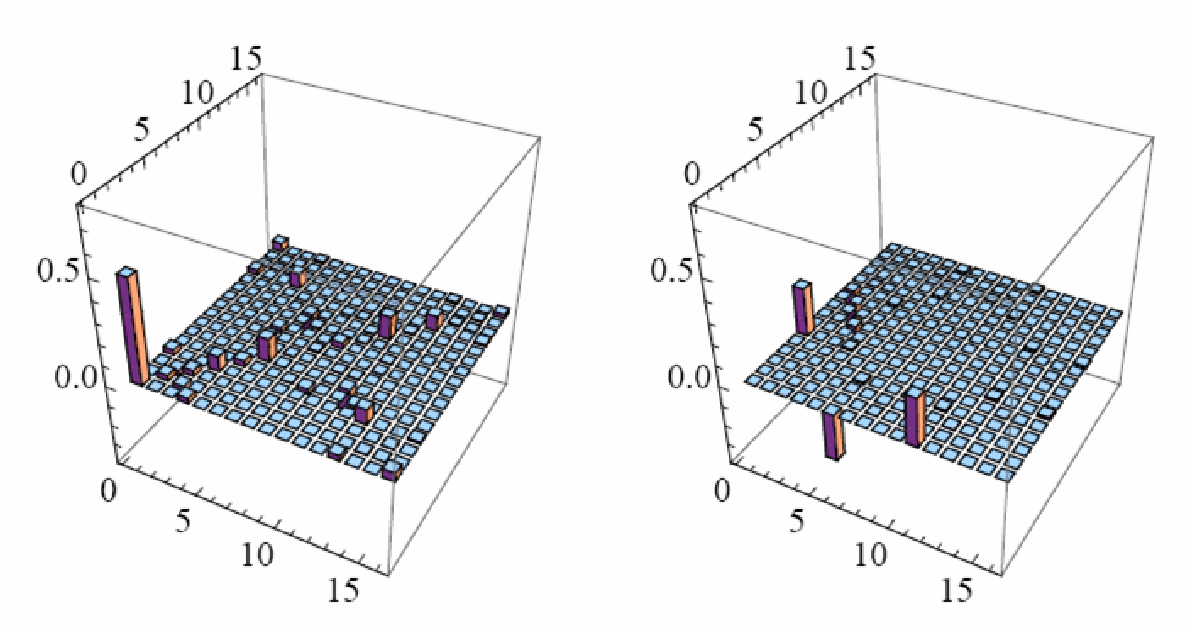
$T_{2\,\text{corr}} = 90$ ns

new peaks in Re χ: (IZ,ZI) and (ZI,IZ)



Energy relaxation & correlated dephasing

$$S/h = 20\text{ MHz},\ T_1 = T_2/2 = 90\text{ ns},\ T_{2,\text{corr.}} = 50\text{ ns}$$

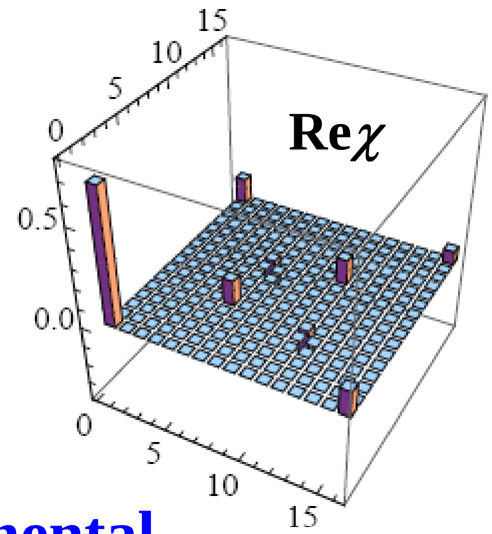


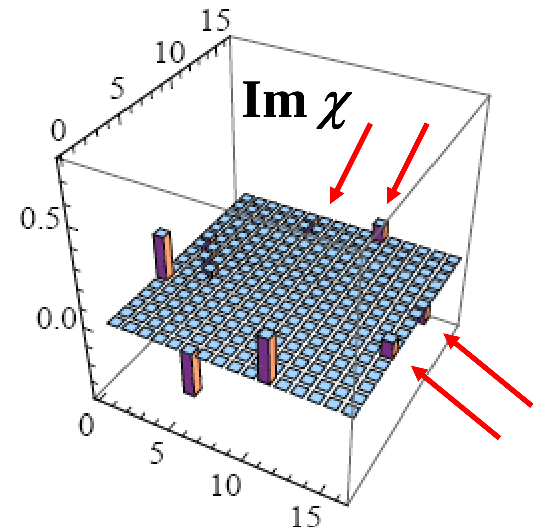
quantitative comparison with experiment in principle possible

$\sqrt{\text{iSWAP}}$: Decoherence due to noisy coupling

$$C_x(t) = \overline{C}_x + \Delta C_x(t)$$
$$\Gamma_{\text{noisy coupl.}} = 1/(90\text{ ns})$$
$$S/h = 20\text{ MHz}$$

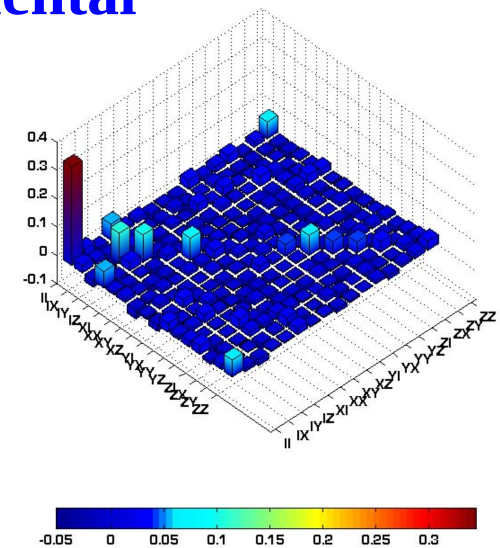
Same peak positions as ideal, but increasing peaks in Im χ: (*XX*,*ZZ*), (*YY*,*ZZ*), and symm.

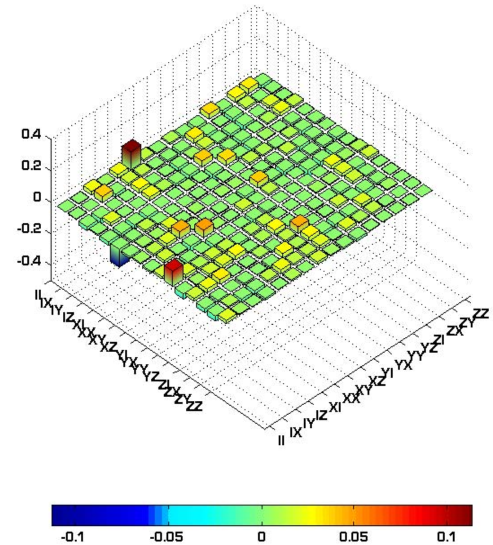




Comparison with experimental data (Martinis group)

No noticeable evidence for correlated dephasing or noisy coupling at present experimental accuracy





Quantum efficiency of binary-outcome solid-state qubit detectors

Quantum efficiency of linear solid-state detectors has been well studied. Let us introduce it similarly for binary-outcome qubit detectors (comparing actual decoherence with QM bound).

Assume QND detector (otherwise 10+18=28 parameters needed), then 6 parameters: fidelities F_0 and F_1, decoherences D_0 and D_1, and phases ϕ_0 and ϕ_1

qubit evolution for result 0:

$$\begin{pmatrix} \rho_{00} & \rho_{01} \\ \rho_{10} & \rho_{11} \end{pmatrix} \to \frac{1}{P_0} \begin{pmatrix} F_0\rho_{00} & \sqrt{F_0(1-F_1)}\, e^{-D_0} e^{i\phi_0} \rho_{01} \\ c.c. & (1-F_1)\rho_{11} \end{pmatrix}$$

probability: $P_0 = F_0\rho_{00} + (1-F_1)\rho_{11}$

(similar for result 1)

on average:

$$\begin{pmatrix} \rho_{00} & \rho_{01} \\ \rho_{10} & \rho_{11} \end{pmatrix} \to \begin{pmatrix} \rho_{00} & e^{-D_{av}} e^{i\phi_{av}} \rho_{01} \\ c.c. & \rho_{11} \end{pmatrix}$$

informational bound on ensemble decoherence:

$$D_{av} \geq D_{\min} = -\ln[\sqrt{F_0(1-F_1)} + \sqrt{(1-F_0)F_1}\,]$$

So, let us define quantum efficiency as:

$$\eta = D_{\min} / D_{av}$$

(averaged)

$$\eta_{0(1)} = D_{\min} / (D_{0(1)} + D_{\min})$$

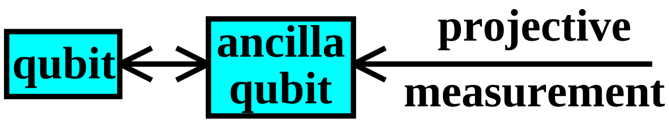
(for each outcome)

Why need? For quantum feedback, non-unitary gates, etc.

Korotkov, arXiv:0808.3547

Quantum efficiency for several models

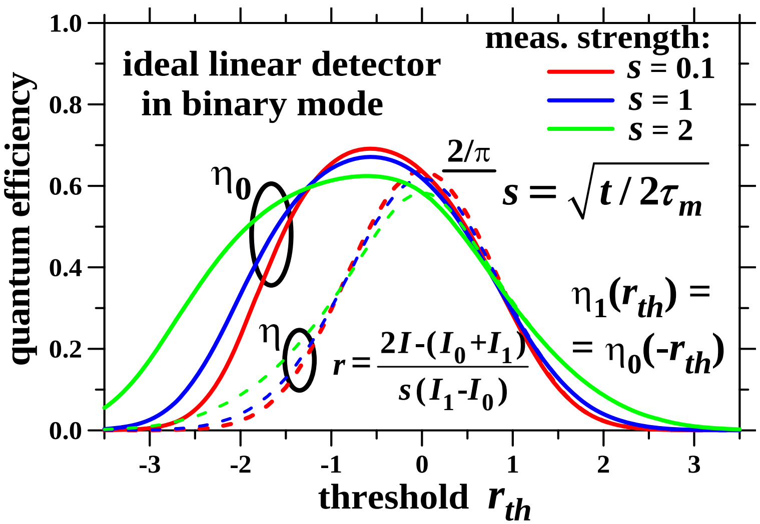
Indirect projective measurement



$\eta = \eta_0 = \eta_1 = 1$ **(ideal, but not practical)**

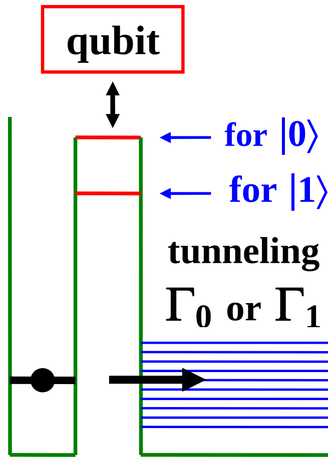
Linear detector in binary mode

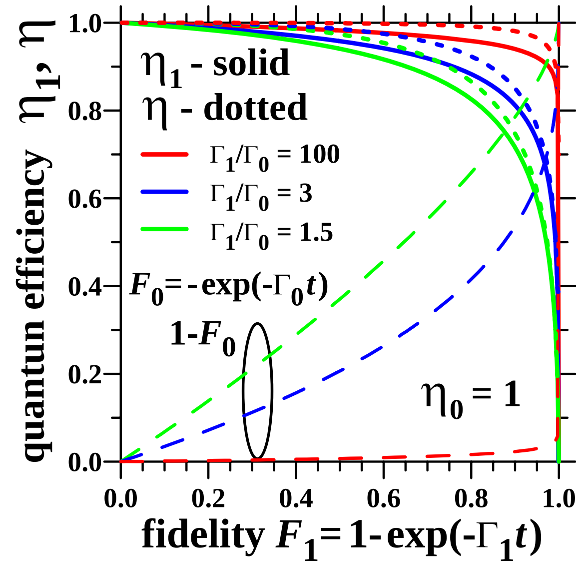
(compare result r with a threshold r_{th})



$\eta < 2/\pi, \ \ \eta_{0,1} < 0.7$ **(not good)**

Tunneling-into-continuum detector

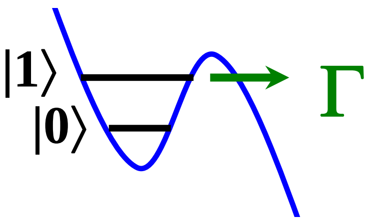




$\eta_0 = 1, \eta_1 \simeq 1, \eta \simeq 1$ **(much better!)**

Phase qubit detection

(η_1 and η undefined because destructive)



Theory: $\eta_0 = 1$

Expt.: $\eta_0 \simeq 0.8$

(using Katz et al., Science-06)

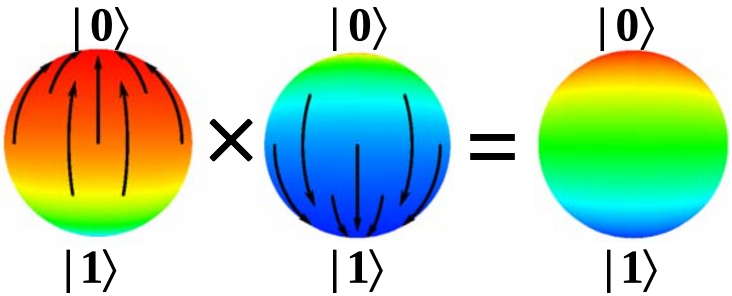
Korotkov, arXiv:0808.3547

Quantum uncollapsing

Featured as
Top story in
Nature News
Nature **454**, 8 (2008)

Theory (Korotkov and Jordan, PRL-06, long paper in preparation)

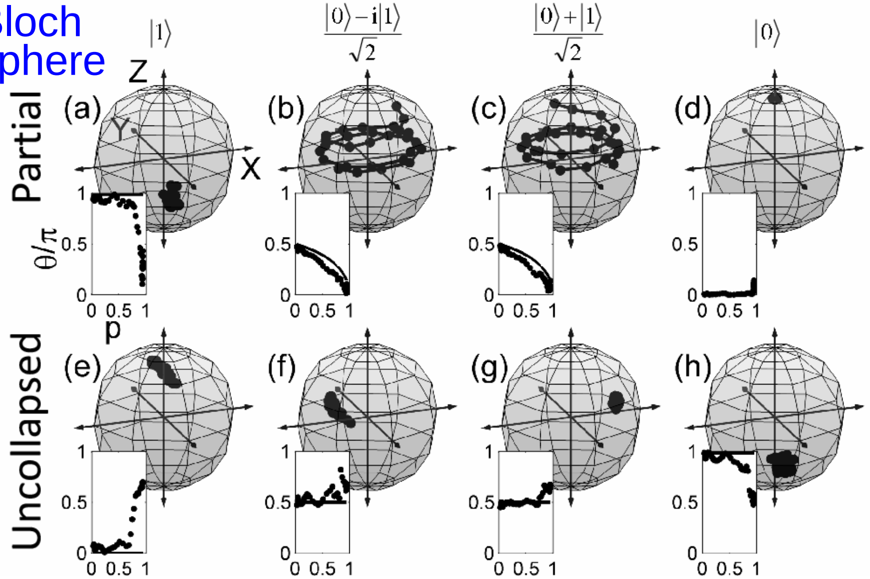
Partial collapse can be fully undone:



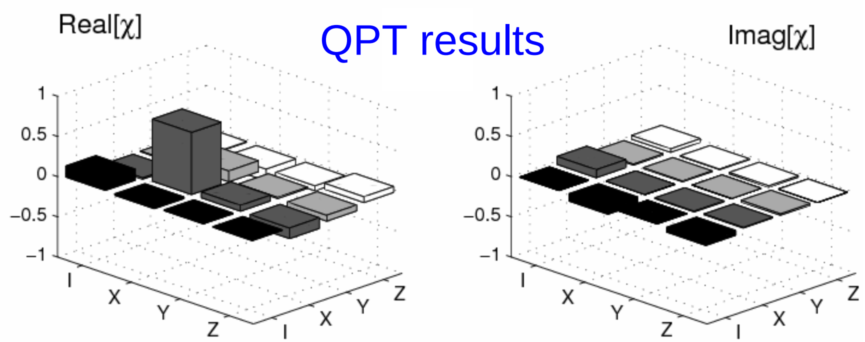
Experiment (Martinis group)

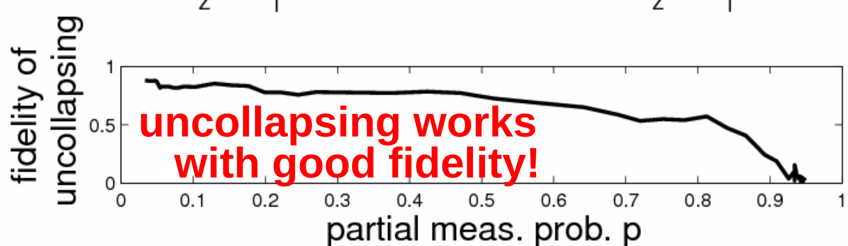
Katz, Neeley, Ansmann, Bialzak, Lucero, O'Connell, Wang, Cleland, Martinis, Korotkov, arXiv:0806.3547

Bloch sphere



QPT results





Research topics for the next year

- Analyze efficiency of multi-qubit measurement
- Compare performance of various ways to measure phase qubits
- Analyze benefits of tunable coupling in reducing measurement back-action
- Continue analysis of quantum process tomography for phase qubits