Theoretical analysis of phase qubits

Alexander Korotkov (*co-PI*)

University of California, Riverside

PI: John Martinis, UCSB

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Team and publications

UCR team: **1) Kyle Keane, *graduate student***
2) Dr. Ricardo Pinto, *postdoc*
3) Alexander Korotkov, *professor*

Since last review (August 2008)
Published: **3 journal papers**
Submitted: **3 journal papers**

1. N. Katz, M. Neeley, M. Ansmann, R. C. Bialczak, M. Hofheinz, E. Lucero, A. O'Connell, H. Wang, A. N. Cleland, J. M. Martinis, and A. N. Korotkov, "Reversal of the weak measurement of a quantum state in a superconducting phase qubit", Phys. Rev. Lett. 101, 200401 (2008).
2. A. N. Korotkov, "Quantum efficiency of binary-outcome detectors of solid-state qubits", Phys. Rev. B 78, 174512 (2008).
3. A. N. Korotkov, "Special issue on quantum computing with superconducting qubits", Quantum Inf. Process. 8, No. 2-3, 51 (2009). (Editorial paper.)
4. A.G. Kofman and A.N. Korotkov, "Two-qubit decoherence mechanisms revealed via quantum process tomography", arXiv:0903.0671.
5. A.N. Jordan and A.N. Korotkov, "Uncollapsing the wavefunction by undoing quantum measurements", arXiv:0906.3468.
6. A.N. Korotkov and K. Keane, "Decoherence suppression by uncollapsing", arXiv:0908.1134.

Research accomplishments since last review

- Analyzed tunable coupling of two phase qubits via negative mutual inductance and tunable Josephson inductance. Calculated residual coupling due to nonlinearity. Shown that ON/OFF ratio can reach 10^3.

- Developed theory for quantum process tomography of two coupled phase qubits, including resonant ($\sqrt{i}$swap) and detuned cases. Introduced a characteristic of decoherence non-locality. Shown ways to distinguish decoherence mechanisms using experimental χ-matrix.

- Shown that energy relaxation in phase qubits can be suppressed (theoretically almost completely) by uncollapsing procedure. Proposed demonstration experiment.

- (Editorial) As a Guest Editor of QIP, contributed to publication of the Special Issue on Quantum Computing with Superconducting Qubits.

Research topics for the next year

- Compute tunable coupling parameters using the higher order perturbation theory. Also analyze the design of tunable coupling with blocking capacitors.

- Compare efficiency of various ways of phase qubit measurement.

- Perform numerical simulations of experiments on uncollapsing with phase qubits. Analyze quantum process tomography characteristics (fidelity and elements of the χ-matrix).

Analysis of QPT (quantum process tomography) for phase qubits

Two ways: for qubits in resonance ($\sqrt{i}$swap) and for strongly detuned qubits (simpler!)

$$H_{\rm int} = (\hbar S/2)\,\sigma_{X,1}\sigma_{X,2}$$

QPT of strongly detuned qubits

$$\chi(t) \approx \chi^I + \delta\chi^c + \lambda\, t$$

$$\chi^I_{mn} = \delta_{m0}\delta_{n0}$$ (identity map)

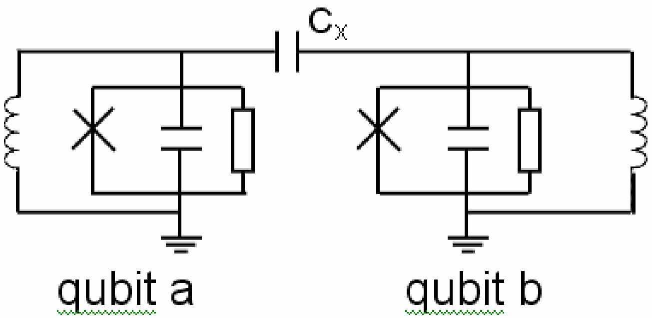
(here 0,1,2,..15 = *II*, *IX*, *IY*,.. *ZZ*)

$$\delta\chi^c_{09} = \delta\chi^c_{60} = -\delta\chi^c_{06} = -\delta\chi^c_{90} = iS/4\Delta\omega$$

(coherent evolution; small term only in the rotating frame of eigenfrequencies)

λ : matrix of Markovian decoherence

Using χ for several t, can find λ accurately and check if Markovian (by linearity in t)



Local vs. non-local decoherence (a simple way to distinguish)

For local: $\lambda = \lambda^{(1)} \otimes \lambda^{(2)}$

Decoherence non-locality parameter:

$$\varepsilon_{NL} = \frac{\mathrm{Tr}\,|\lambda - \tilde{\lambda}|}{\mathrm{Tr}\,|\lambda|}$$

$$\tilde{\lambda} = \tilde{\lambda}^{(1)} \otimes \chi^{I(2)} + \chi^{I(1)} \otimes \tilde{\lambda}^{(2)},$$

$$\tilde{\lambda}^{(1,2)} = \mathrm{Tr}_{2,1}\lambda,\ |A| = \sqrt{A^\dagger A},$$

Kofman & Korotkov, arXiv:0903.0671

λ-matrix for several decoherence mechanisms

$$\lambda = \lambda_{\rm EnRel} + \lambda_{\rm CorrPD} + \lambda_{\rm NoisyCpl}$$

Specific pattern for each mechanism!

Energy relaxation

$$\lambda_{00} = -1/2T_1^{(1)} - 1/2T_1^{(2)}$$
$$\lambda_{11} = \lambda_{22} = 1/4T_1^{(2)},\ \lambda_{44} = \lambda_{88} = 1/4T_1^{(1)}$$
$$\lambda_{03} = \lambda_{30} = 1/4T_1^{(2)},\ \lambda_{0,12} = \lambda_{12,0} = 1/4T_1^{(1)}$$
$$\lambda_{21} = -\lambda_{12} = i/4T_1^{(2)},\ \lambda_{84} = -\lambda_{48} = i/4T_1^{(1)}$$

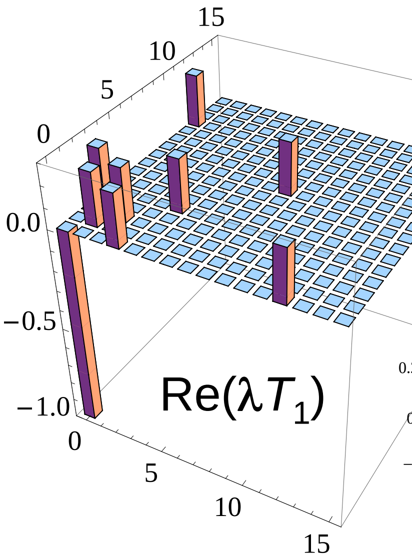
Partially correlated (nonlocal) dephasing

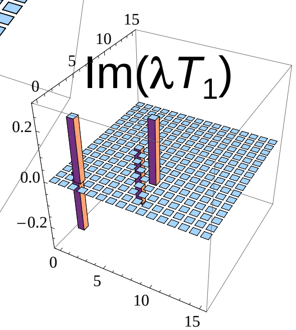
$$\lambda_{00} = -1/2T_\varphi^{(1)} - 1/2T_\varphi^{(2)}$$
$$\lambda_{33} = 1/2T_\varphi^{(2)},\ \lambda_{12,12} = 1/2T_\varphi^{(1)}$$
$$\lambda_{3,12} = \lambda_{12,3} = -\lambda_{0,15} = -\lambda_{15,0} = \kappa/2\sqrt{T_\varphi^{(1)}T_\varphi^{(2)}}$$

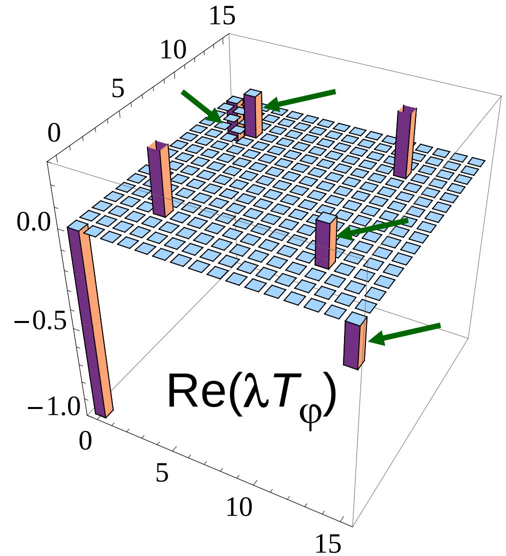
Noisy coupling (slightly different than in resonance)

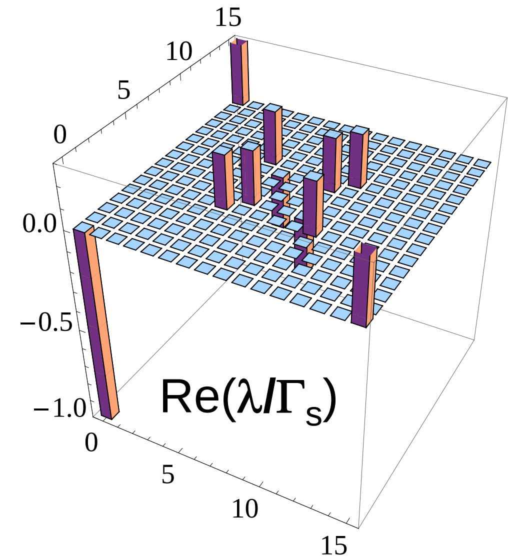
$$\lambda_{00} = -\Gamma_s,\quad \lambda_{0,15} = \lambda_{15,0} = \Gamma_s/2$$
$$\lambda_{55} = \lambda_{10,10} = \lambda_{5,10} = \lambda_{10,5} = \Gamma_s/4$$
$$\lambda_{66} = \lambda_{99} = -\lambda_{69} = -\lambda_{96} = \Gamma_s/4$$

κ - correlation factor



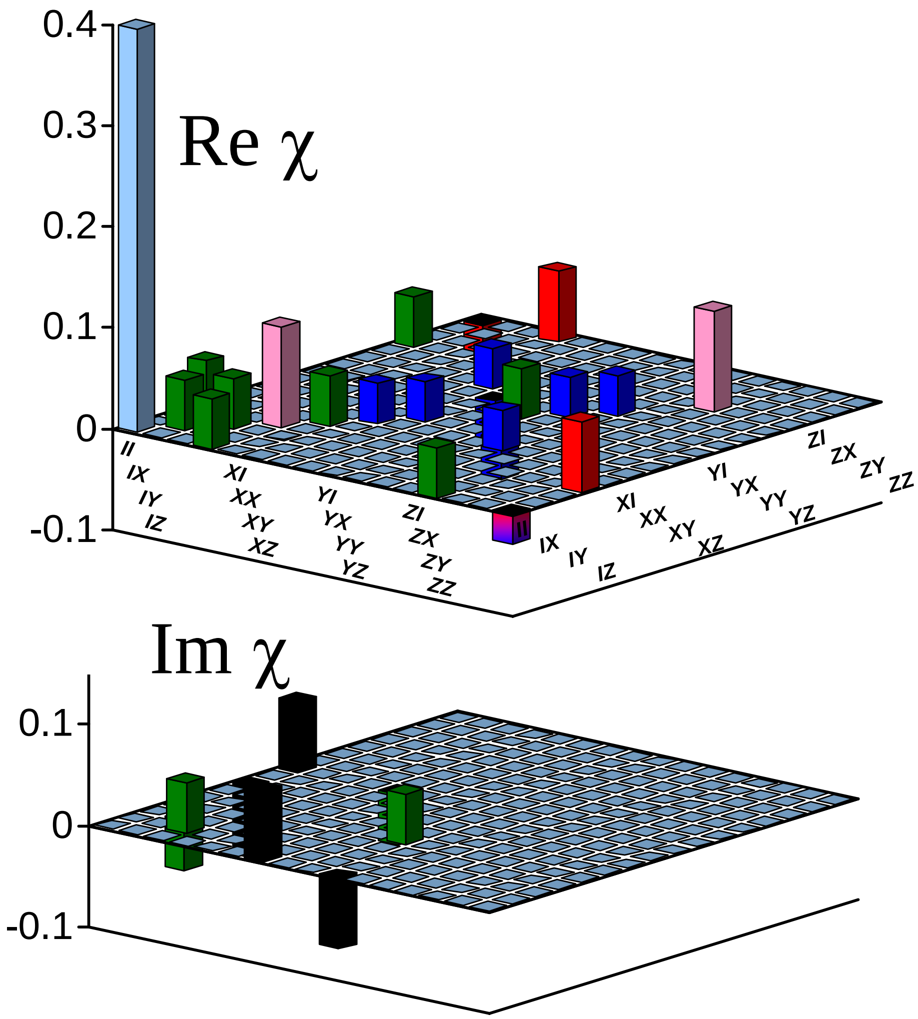






All positions (except 00=*II*,*II*) are also different from χ^I and $\delta\chi^c$

χ-matrix for strongly detuned qubits



Identity mapping

Remaining unitary evolution

Energy relaxation

Uncorrelated pure dephasing

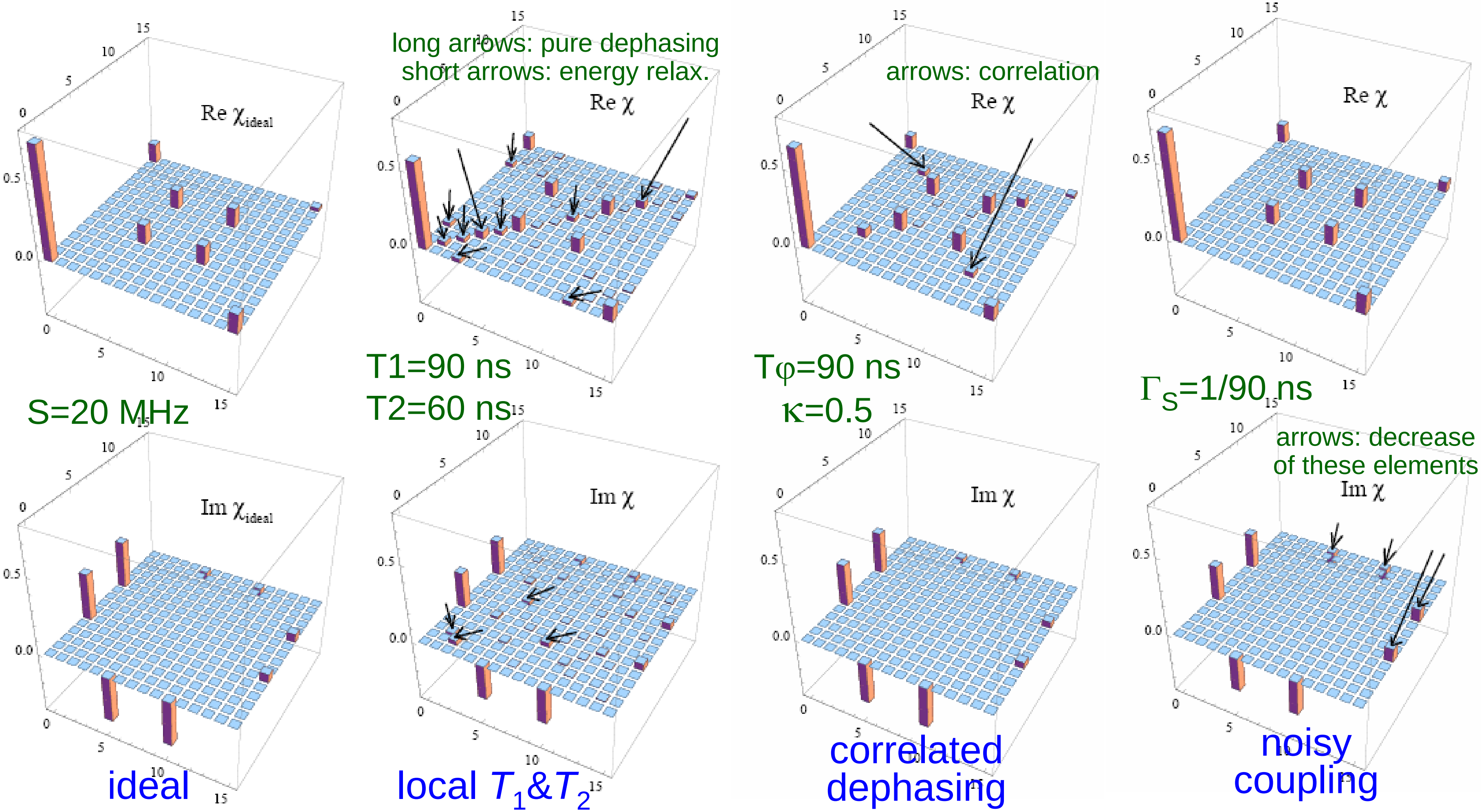
Correlated (non-local) pure dephasing

Noisy coupling

very simple to distinguish decoherence mechanisms

If qubits are in resonance, then not so easy: $\chi \neq \chi_{ideal} + \lambda t$

However, for $\sqrt{iswap}$ and for largest extra elements of χ, it is still a simple addition, that makes distinguishing decoherence mechanisms quite easy

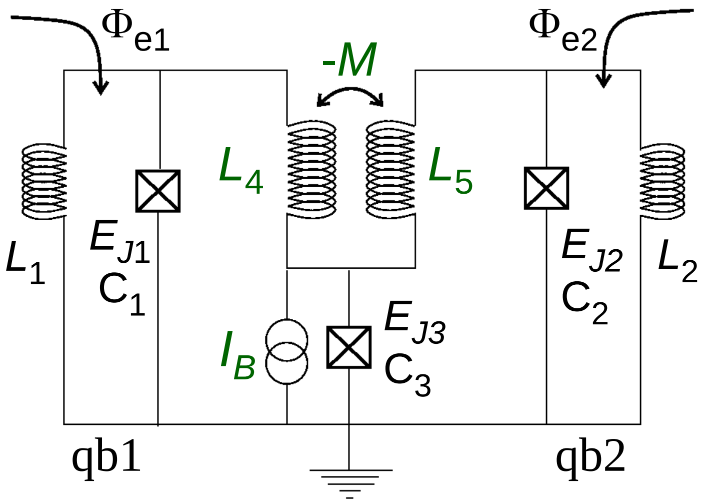


Interesting to compare decoherence data from resonant and strongly detuned qubits

Kofman & Korotkov, arXiv:0903.0671

Tunable coupling of phase qubits

Pinto & Korotkov, in preparation



$$H_{\text{int}} = \frac{\hbar\Omega_C}{2}\sigma_{X,1}\sigma_{X,2} + \underbrace{\hbar\Omega_{ZZ}\sigma_{Z,1}\sigma_{Z,2}}$$

Ω_C can be tuned by bias current I_B

small unwanted term due to non-linearity

physically:

$$H_{\text{int}} = \frac{M}{L_4L_5}\delta\Phi_1\delta\Phi_2 - \frac{1+M/L_5}{L_4}\delta\Phi_1\delta\Phi_3 - \frac{1+M/L_4}{L_5}\delta\Phi_2\delta\Phi_3$$

then perturbation theory, with account of non-linearity in qubits and coupling

$$\Omega_C = \frac{1}{L_4L_5\omega_{qb}\sqrt{C_1C_2}}\left(M - \frac{L_{JC}}{1-(\omega_{qb}/\omega_3)^2}\right)$$

$$\Omega_{ZZ} = \frac{b_1b_2/8}{L_4L_5\omega_{qb}\sqrt{C_1C_2}}(M - L_{JC})$$

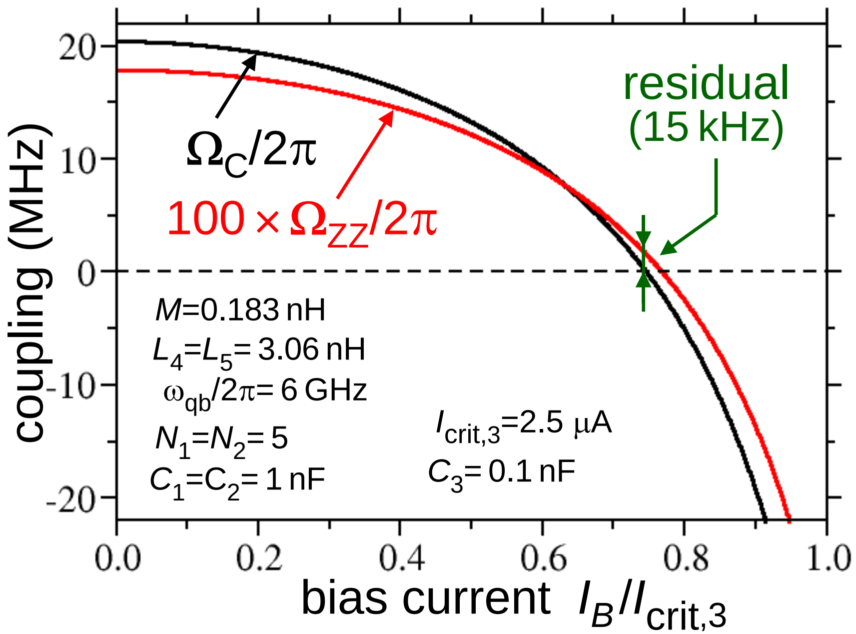
- main coupling Ω_C can be zeroed exactly
- unwanted coupling Ω_{ZZ} is much smaller ($\times b_1b_2/8$)
- coupling Ω_{ZZ} also crosses zero at a close point

where $b = \dfrac{\langle 1|\phi|1\rangle - \langle 0|\phi|0\rangle}{\langle 1|\phi|0\rangle} \approx \dfrac{1}{\sqrt{3N_{\text{levels}}}}$, $\quad L_{JC} = \dfrac{(1+M/L_4)(1+M/L_5)}{\omega_3^2C_3} \approx \dfrac{\Phi_0/2\pi}{\sqrt{I_{crit,3}^2 - I_B^2}}$

(ratio ω_{qb}/ω_3 is arbitrary)

Residual coupling

Simulation using experimental parameters



Ω_{ZZ} is unpleasant but not dangerous, can be compensated algorithmically.

Important for QC is how well the total coupling can be zeroed.

Residual coupling: Ω_{ZZ} when $\Omega_C = 0$

$$\Omega_{ZZ}^{\mathbf{res}} = \frac{b_1 b_2}{8} \frac{M}{L_4 L_5 \omega_{qb} \sqrt{C_1 C_2}} \left(\frac{\omega_{qb}}{\omega_3}\right)^2$$

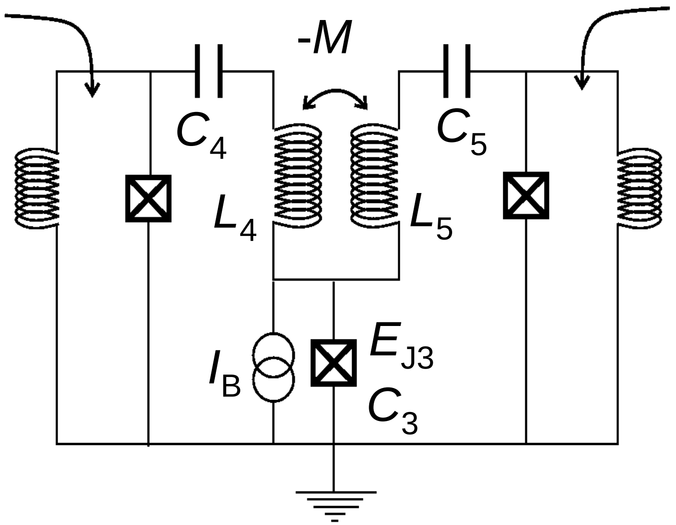
Nonlinearity in the coupling junction gives some corrections, but not quite important, main effect is due to nonlinearity in the qubits.

Still need to do:
- next order perturbation theory; it may affect residual coupling
- beyond-RWA corrections

$$\frac{\mathbf{OFF}}{\mathbf{ON}} \simeq \frac{b_1 b_2}{4} \left(\frac{\omega_{qb}}{\omega_3}\right)^2 \approx \frac{1}{12\, N_{\mathbf{levels}}} \left(\frac{\omega_{qb}}{\omega_3}\right)^2 \sim 10^{-3}$$

Pinto & Korotkov, in preparation

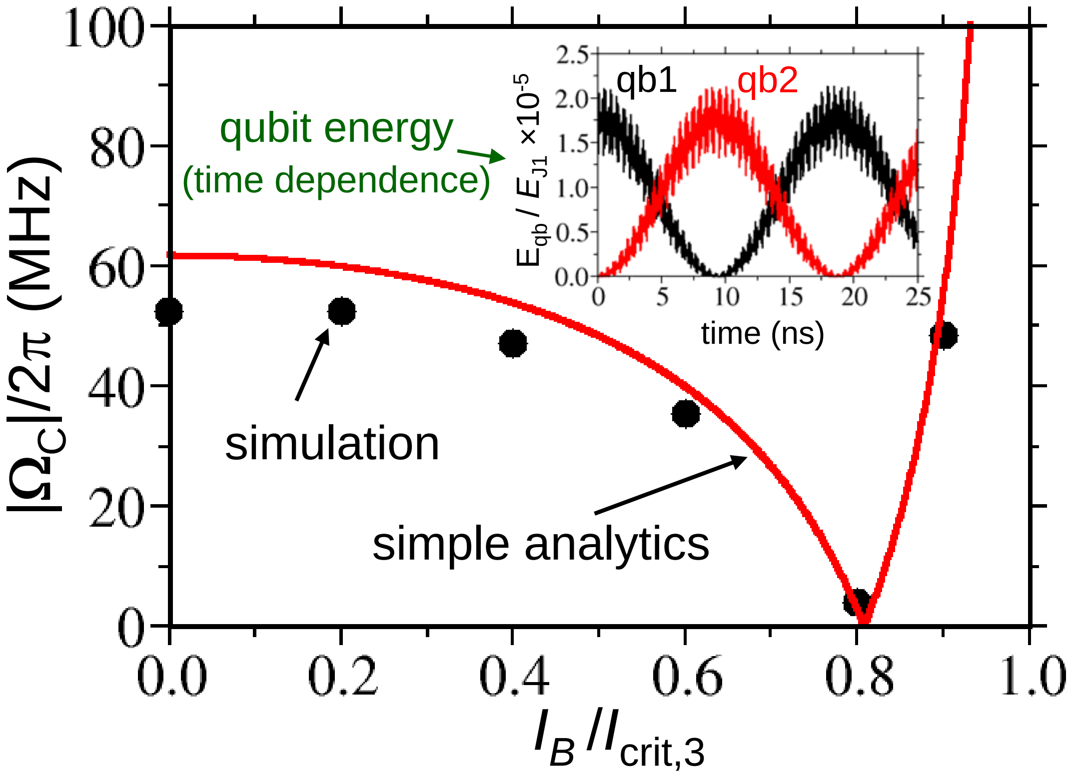
Another design of tunable coupling



From simple circuit analysis:

$$\Omega_C \approx \left(M - L_{JC}\right)\frac{C_4C_5}{\sqrt{C_1C_2}}\omega_{qb}^3$$

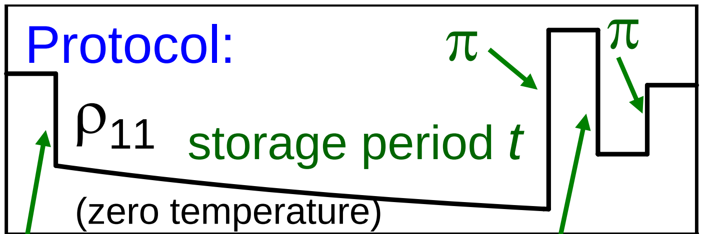
$$L_{JC} \approx \frac{\Phi_0/2\pi}{\sqrt{I_{crit,3}^2 - I_B^2}}$$



- Classical coupling simulated numerically; results close to what was expected
- Quantum coupling still to be analyzed (in progress)

Suppression of T_1-decoherence by uncollapsing

Korotkov & Keane, arXiv:0908.1134



partial collapse towards ground state (strength p)

uncollapse (measurem. strength p_u)

(almost same as existing experiment!)

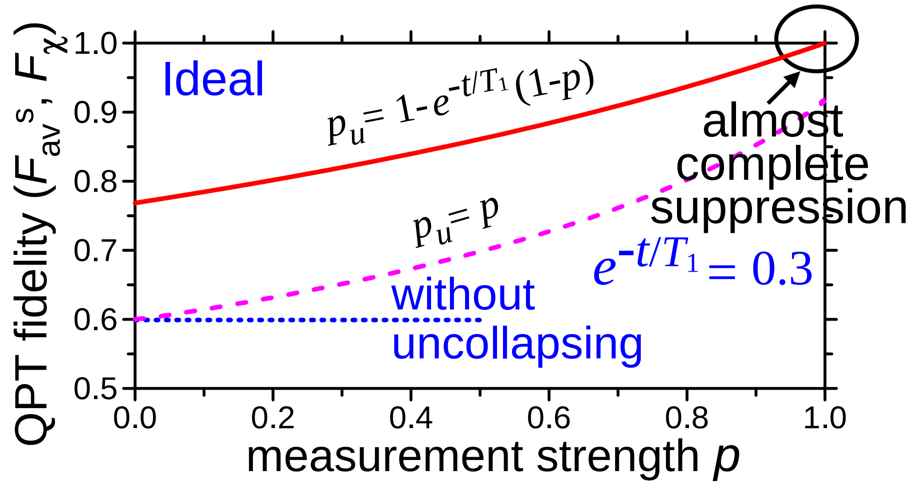
Ideal case (T_1 during storage only)

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



(Actually, QPT fidelity is not directly applicable to algorithms with selection (including linear optics QC); however, we have shown that "naïve" QPT fidelity is still very close to the scaled average state fidelity.)

Dynamical decoupling (NMR-like) cannot protect against T_1-decoherence, so uncollapsing is **the only** known to us way to protect without encoding in a larger Hilbert space (QEC, DFS)

Suppression of T_1-decoherence by uncollapsing (cont.)

Analytics for the ideal case

Average state fidelity

$$F_{av} = \frac{1}{2} + \frac{1}{C} + \frac{\ln(1+C)}{C^2}$$

"Naïve" QPT fidelity

$$F_\chi = -\frac{1}{4} + \frac{1}{4(1+C)} + \frac{4+C}{2(2+C)}$$

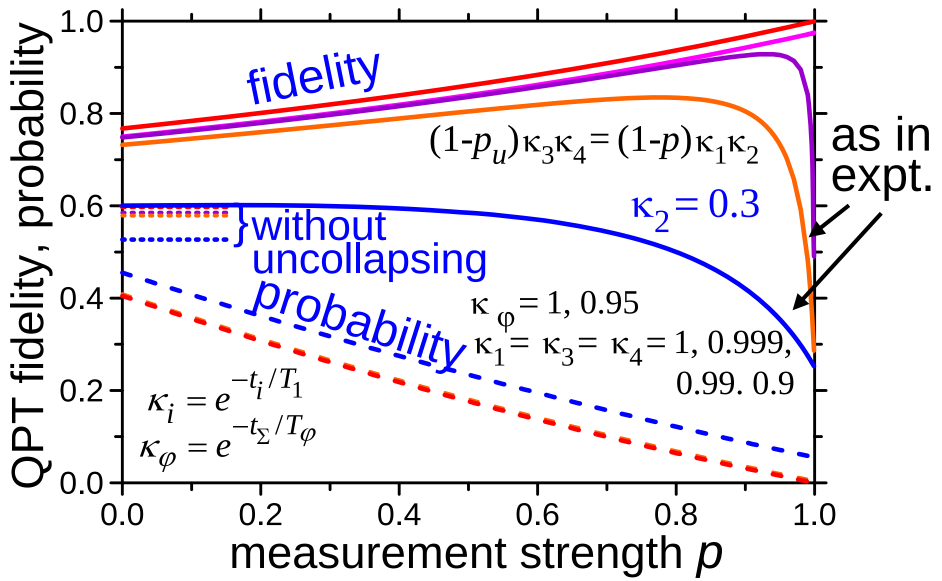
$$F_\chi \approx \frac{3F_{av}-1}{2} \quad \text{(very close)}$$

where $C = (1-p)(1-e^{-\Gamma t})$

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

Trade-off: larger p gives stronger decoherence suppression, but smaller selection probability

Realistic case (T_1 and T_φ at all stages)



- decoherence due to pure dephasing is not affected
- T_1-decoherence between first π-pulse and second measurement causes decrease of fidelity at p close to 1

Korotkov & Keane, arXiv:0908.1134

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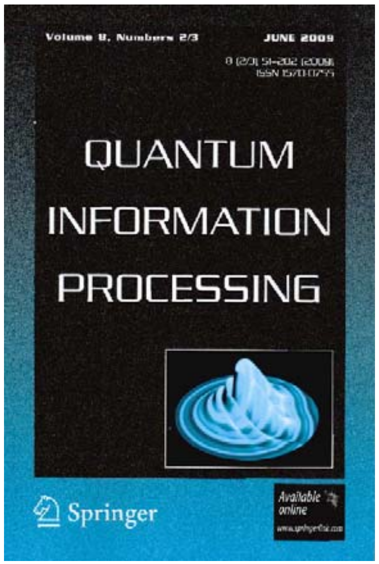

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The latest comprehensive collection of review papers on experimental Quantum Computing with Superconducting Qubits

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