Best regards from Norway.
Thanks for the invitation.

Saltdalsfjorden - Norway

Low-Frequency Noise as a Source of Non-Gaussian Decoherence in Qubits

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Support:

Norges forskningsråd

Outline

- Motivation
- Reminder: Qubits, single Cooper pair box, etc
- Dynamical defects (fluctuators) as a source of flicker-noise
- Decoherence in driven systems
- Non-Gaussian decoherence by a single fluctuator
- Effect of many fluctuators
- Conclusions
- Relation between energy relaxation and decoherence
- Decoherence close to optimal point
- Resonant interaction between qubit and fluctuators (talk by A. Ustinov)
- Role of non-stationary fluctuations

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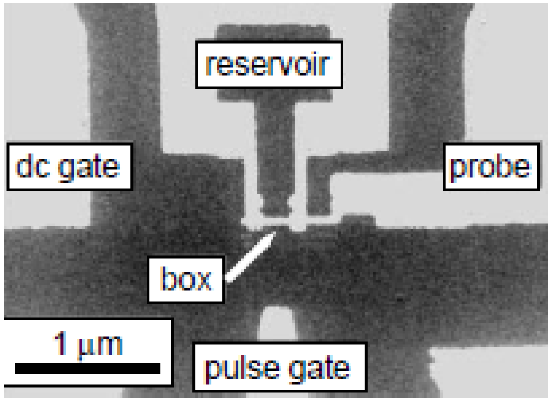
RUTGERS

Ivar Martin

Los Alamos NATIONAL LABORATORY

Motivation:

Q: In which way low frequency noise destroys quantum coherence?



Charge qubit

VOLUME 88, NUMBER 4 PHYSICAL REVIEW LETTERS 28 JANUARY 2002

Charge Echo in a Cooper-Pair Box

Y. Nakamura,[1] Yu. A. Pashkin,[2,*] T. Yamamoto,[1] and J. S. Tsai[1]

A spin-echo-type technique is applied to an artificial two-level system that utilizes a charge degree of freedom in a small superconducting electrode.

......

Comparison of the decay time of the observed echo signal with an estimated decoherence time suggests that low-frequency energy-level fluctuations due to the $1/f$ charge noise dominate the dephasing in the system.

What is a qubit?

Quantum two-level system equivalent to ½ spin

$\hat{\sigma}_i$ - Pauli matrices

The qubit is described by effective Hamiltonian

$$\mathcal{H}_{\mathrm{ctrl}} = -\frac{1}{2}B_z\hat{\sigma}_z - \frac{1}{2}B_x\hat{\sigma}_x \; .$$

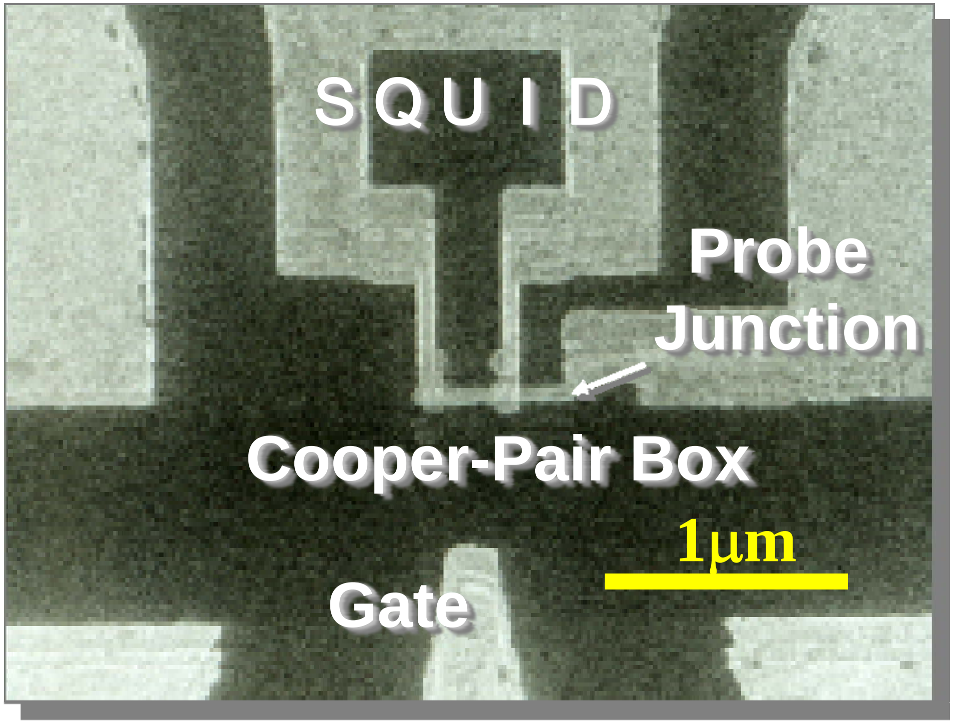
with tunable B_x and B_z to perform single-qubit operations.

A controllable interaction in the form

$$\mathcal{H}_{\mathrm{ctrl}}(t) = -\frac{1}{2}\sum_{i=1}^{N} B^i(t)\hat{\sigma}^i + \sum_{i\neq j} J_{ab}^{ij}(t)\hat{\sigma}_a^i\hat{\sigma}_b^j \; ,$$

(where a summation over spin indices $a, b = x, y, z$ is implied) to perform two-bit operations.

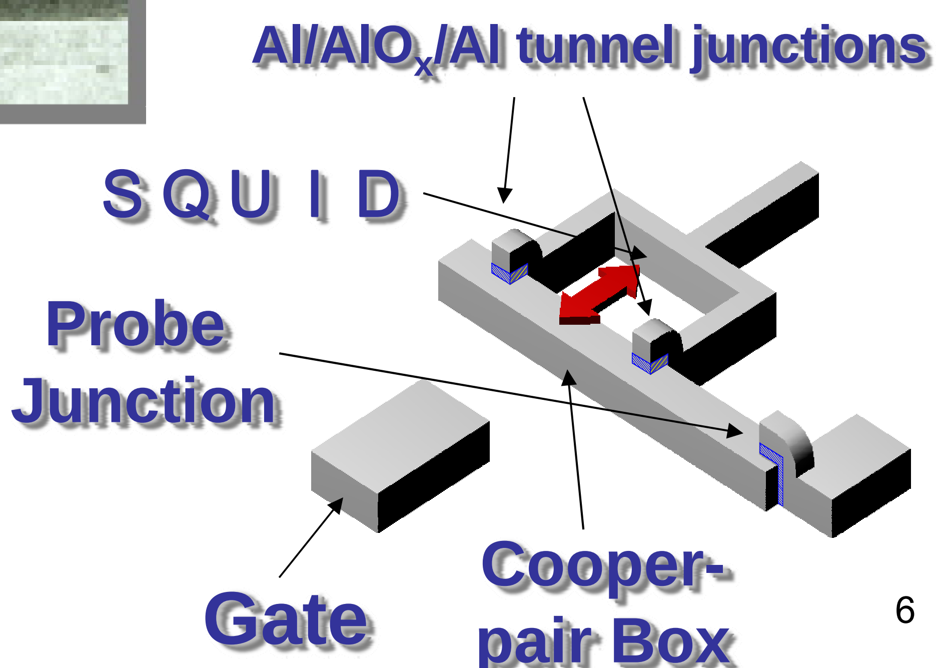
Josephson Charge Qubit: Reminder



Artificial ½-spin – Josephson qubit (NEC, Japan)

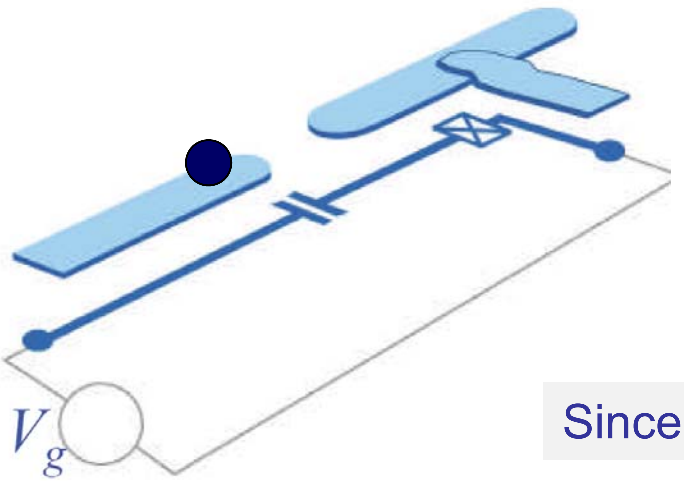
Nature 2003, 2004

Europhysics Prize, 2004



Why this system is a controllable ½ spin?

(Normal) single-electron box



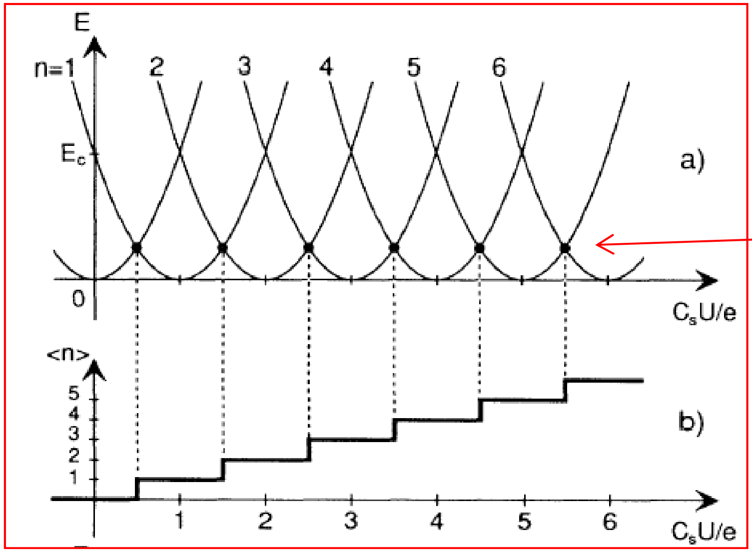
How much we pay to transfer *N* electrons?

$$E = \frac{Q^2}{2C} + QV_g \qquad E_{\min} = -\frac{CV_g^2}{2}$$

$$E - E_{\min} = \frac{(Q + CV_g)^2}{2C}$$

Since the electron charge is discrete, $Q = -eN \;\rightarrow$

$$E - E_{\min} = E_c(N - \alpha V_g)^2, \qquad E_C = \frac{e^2}{2C}, \; \alpha = \frac{C}{e}$$

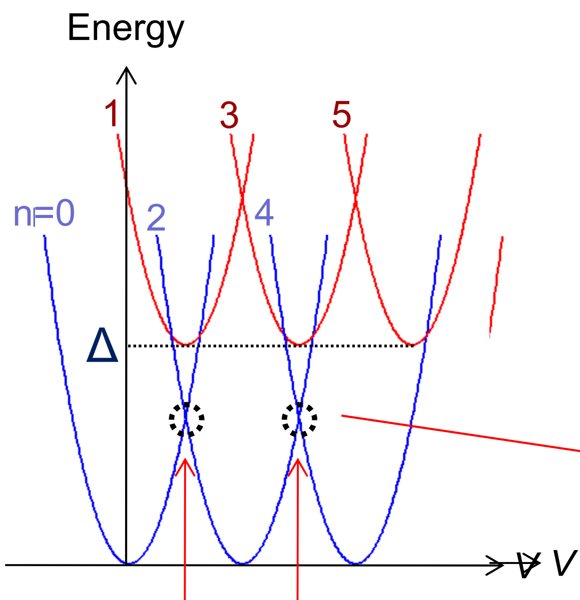


At some values of the gate voltage the electron transfer is free of energy cost!

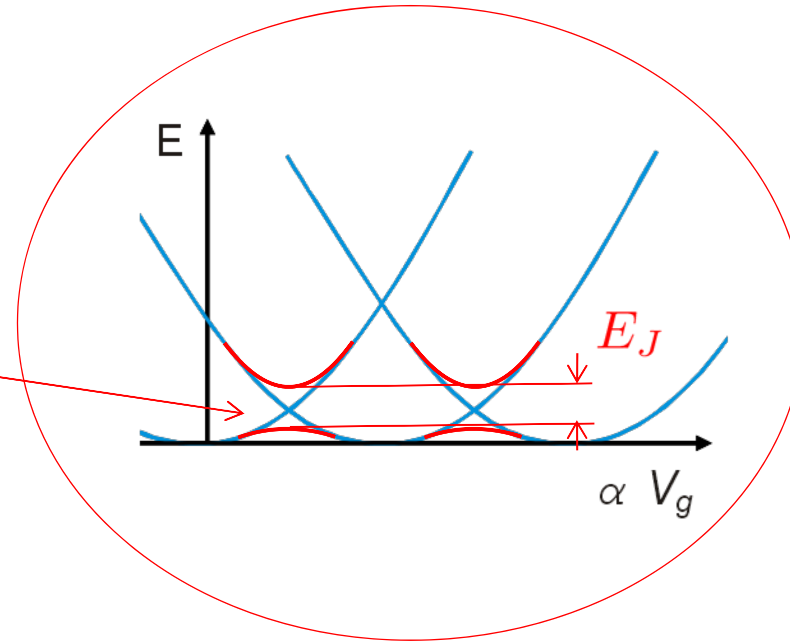
Otherwise the transfer is exponentially suppressed (Coulomb blockade)

In a superconductor, energy depends on the parity of the electron number

$$E(N) = E_C(N-\alpha V_g)^2 + \Delta_N$$
$$\Delta_N = \begin{cases} 0, & N = 2n \\ \Delta, & N = 2n+1 \end{cases}$$
$$E_C = (2e)^2/2C, \quad \Delta - \text{gap}$$



Cost free transfer of
Cooper pairs



The splitting is due to the Josephson tunneling of Cooper pairs:

$$\mathcal{H}_J = -\frac{E_J}{2}\left(|N\rangle\langle N+1| + (|N+1\rangle\langle N|\right)$$

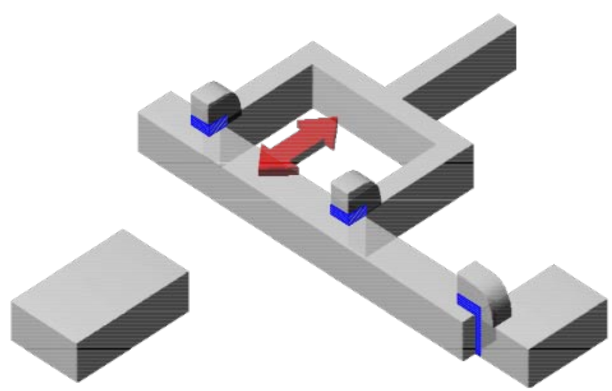
Effective Hamiltonian (in the space of excess Cooper pairs number):

$$\tilde{\mathcal{H}} = -\frac{1}{2}\underbrace{\boxed{E_C(1-\alpha V_g)}}_{B_z}\sigma_z - \frac{1}{2}\underbrace{\boxed{E_J}}_{B_x}\sigma_x$$

B_z can be tuned by the gate voltage. How can we tune the effective field B_x?

The Josephson junction is split into an interferometer. The energy is tuned by the magnetic flux in the SQUID loop , which modulates E_J.

$$E_J^{\text{eff}} = 2E_J \cos\left(\pi\frac{\Phi}{\Phi_0} + \varphi\right)$$



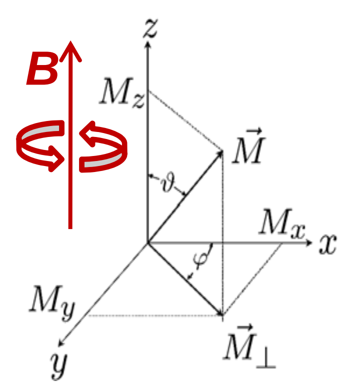
Single Cooper Pair Box

Mapping on the Bloch sphere

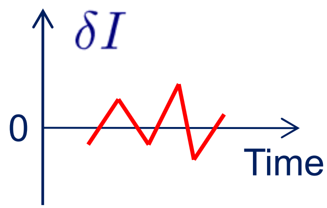
density matrix: $\hat{\rho} = \left(\hat{I} + \boldsymbol{M}\cdot\hat{\boldsymbol{\sigma}}\right)/2$

Hamiltonian: $\mathcal{H}_q = \boldsymbol{B}\cdot\boldsymbol{\sigma}/2$

Eq. of motion: $\dot{\boldsymbol{M}} = \boldsymbol{B}\times\boldsymbol{M}$

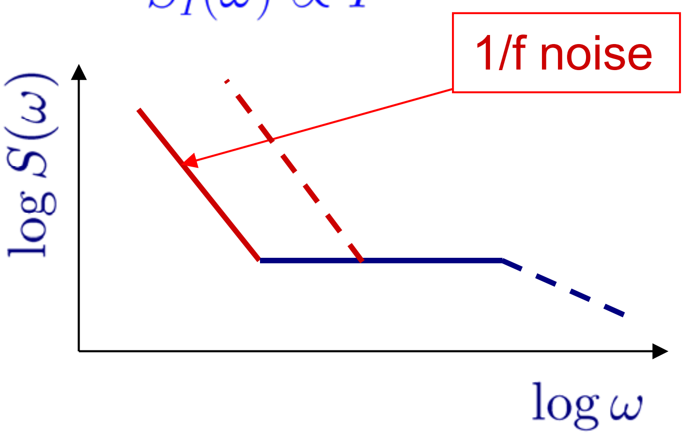


Noise (main properties)



Noise spectrum: $S_I(\omega) \equiv \int_0^\infty d\tau \, e^{i\omega\tau} \left\langle [\delta \hat{I}(t+\tau), \delta \hat{I}(t)]_+ \right\rangle$

$S_I(\omega) \propto I^2$



For fluctuations in electrical current – noise of resistance

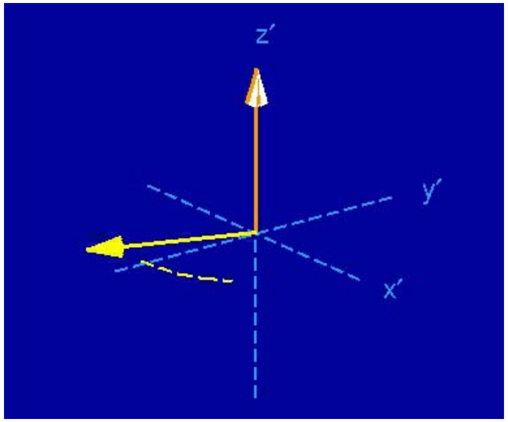
1/f noise is a generic phenomenon observed in numerous systems

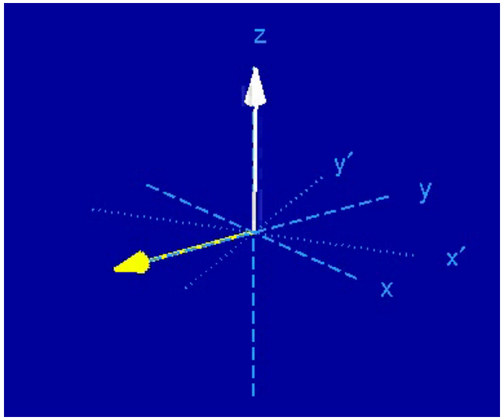
It is a non-equilibrium phenomenon, which is not described by fluctuation-to-dissipation theorem

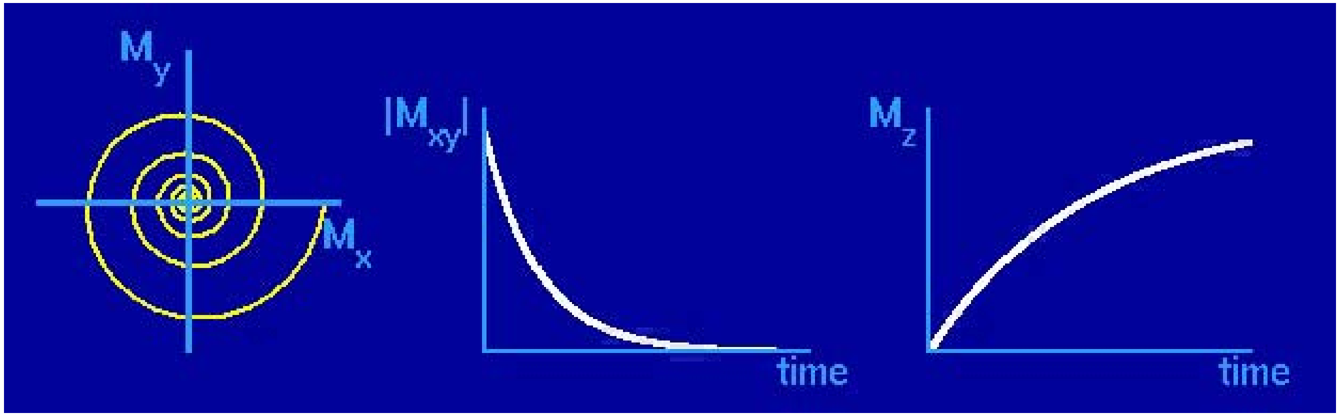
Spectrum is rather universal – there is no saturation even at very low frequencies (down to 10^{-7} Hz)

Q: In which way low frequency noise destroys quantum coherence?

Free induction protocol:







Noise-induced decoherence

Environment induces stochastic noise: $$\boldsymbol{B} = \boldsymbol{B}_0 + \boldsymbol{b}(t)\,, \quad \boldsymbol{b} \parallel \boldsymbol{B}_0$$

Let *b(t)* be a classical Gaussian random variable.

Fluctuations of V_g

Free induction signal:

$$m_+ \equiv \frac{M_x + iM_y}{\sqrt{M_x^2 + M_y^2}} \quad \rightarrow \quad m_+(t) = e^{i\int_0^t B(t')dt'} m_+(0)$$

$$\boxed{\phi(t) = B_0 t + \int_0^t b(t')dt' = \phi_0(t) + \varphi(t)}$$

Average: $$\langle m_+(t) \rangle = m_+(0) e^{i\phi_0(t)} \left\langle e^{i\varphi(t)} \right\rangle$$

Though the length $|\boldsymbol{M}|$ is conserved, the average $|\langle \boldsymbol{M} \rangle|$ decays in time – decoherence

Averaging:

$$p(\varphi) = \frac{1}{\sqrt{2\pi\langle\varphi^2\rangle}} e^{-\varphi^2/2\langle\varphi^2\rangle}, \quad \langle\varphi^2\rangle = 4\int_{-\infty}^{\infty} d\omega \frac{\sin^2\frac{\omega t}{2}}{\omega^2} S(\omega)$$

$$S(\omega) = \frac{1}{\pi}\int_0^\infty dt\, \langle b(t)b(0)\rangle\, \cos\omega t$$

Noise spectrum

Correlator of random “magnetic fields”

What about 1/f noise?

Since $\lim_{a\to\infty} \frac{\sin^2 ax}{\pi a x^2} = \delta(x)$ we get

$$\left\langle e^{i\varphi(t)}\right\rangle = e^{-\langle\varphi^2(t)\rangle/2} = e^{-t/T_2}, \quad T_2^{-1} = \pi S(0)$$

exponential decay of the signal at large times, the decrement being given by the noise power at zero frequency

Quantum theory: Spin-Boson Model (sketch)

A.J. Leggett et al, *Rev. Mod. Phys.* v.59, 1 (1987).
U. Weiss, ``Quantum Dissipative Systems", 2nd ed., (Word Scientific, Singapore, 1999).
A. Shnirman, Y. Makhlin, and G. Schon, *Physica Scripta* v.T102, 147 (2002)
D. Loss and D. DiVincenzo, *cond-mat/030411*

½-spin linearly coupled to a bath consisting of oscillators:

$$\mathcal{H}_{\text{s-b}} = \sigma_z \hat{\mathcal{X}}\,, \quad \hat{\mathcal{X}} = \sum_j C_j \left(\hat{b}_j + \hat{b}_j^\dagger\right)$$

Decoherence is expressed though bath noise spectrum:

$$S_{\mathcal{X}}(\omega) \equiv \left\langle \left[\hat{\mathcal{X}}(t), \hat{\mathcal{X}}(0)\right]_+ \right\rangle_\omega = 2J(\omega)\coth\frac{\hbar\omega}{2T}$$

$$J(\omega) \equiv \pi \sum_j C_j\, \delta(\omega - \omega_j)$$ - bath spectral density

Result:

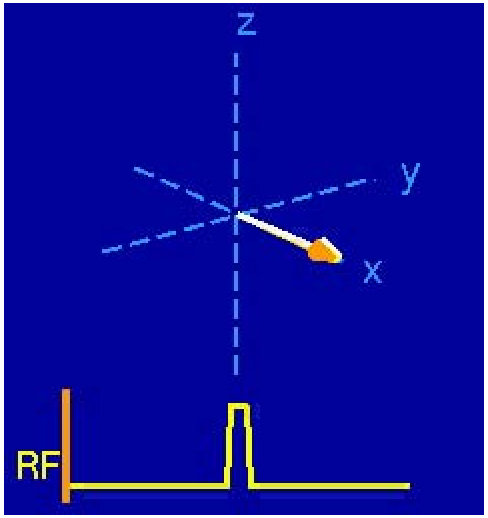
$$\boxed{\langle m_+(t)\rangle \propto e^{-\mathcal{K}(t)} \text{ where } \operatorname{Re}\mathcal{K}(t) = \frac{4}{\pi}\int_0^\infty \frac{d\omega\, S(\omega)}{\omega^2}\sin^2\frac{\omega t}{2}}$$

The noise is assumed to be Gaussian

Everything is determined by the power spectrum of the noise !!!

However, for 1/f noise the above integral is divergent.

Spin-echo protocol



The *spin echo amplitude* can be expressed as $\mathcal{P}(t) = e^{-\mathcal{K}_e(t)}$

where $$\mathrm{Re}\,\mathcal{K}(t) = 32\int_0^\infty d\omega\, S_\mathcal{X}(\omega)\frac{\sin^4(\omega t_{12}/2)}{\omega^2}$$

Questions:

- The result is expressed only through the power spectrum (i.e., pair correlator) of the forces. This is perfect for Gaussian processes.

Are non-Gaussian effects important?

- For low-frequency noise with 1/f spectrum the integral over frequencies is divergent, and it should be cut off

A. Shnirman, Y. Makhlin, and G. Schön, Physica Scripta **T102**, 147 (2002).

Which cut-off procedure is appropriate?

Our aim is to address these issue using a simple solvable model, which can be called spin-fluctuator model.

We will mostly discuss echo experiments since echo allows to find true dephasing.

More about 1/f noise

History:

Electronic emission in thermionic tube - Johnson (1925)

The name "flicker noise" belongs to Schottky (1926)

Carbon microphones – Christensen & Pearson (1936)

Various semiconductor devices – 1940-1950

"Explanation": The concept of non-exponential kinetics:

Assuming $\langle \delta I(t) \delta I(0) \rangle = \overline{(\delta I)^2} e^{-|t|/\tau}$ one obtains:

$$S_I(\omega) = 2 \int_0^\infty \langle \delta I(t) \delta I(0) \rangle \cos(\omega t)\, dt = \overline{(\delta I)^2} \frac{2\tau}{1 + \omega^2 \tau^2}$$

In more general case, $\delta I(t)$ is a superposition of many processes characterized by different relaxation times.

One can introduce a weight function, $p_I(\tau)$, including the number of the systems with given relaxation time

$$S_I(\omega) = \int_0^\infty d\tau\, p_I(\tau) \frac{2\tau}{1 + \omega^2 \tau^2}$$

Surdin 1939

$$p_I(\tau) \propto 1/\tau, \;\; \tau_1 \ll \tau \ll \tau_2$$

$$S_I(\omega) \propto 1/\omega, \;\; \tau_2^{-1} \ll \omega \ll \tau_1^{-1}$$

Distribution $p_I(\tau) \propto \tau^{-1}$ is rather common, this is the case if $\tau \propto e^W$ and *W* is smoothly distributed (tunneling, activation).

<u>Plan</u>

- identify fluctuators – entities with exponentially broad distribution of relaxation rates
- using a concrete protocol consider interaction of the fluctuators with a qubit and estimate the decoherence
- estimate both spectrum and intensity of the noise produced by the fluctuators
- relate the decoherence and the noise and answer the question whether the decoherence is fully determined by the noise

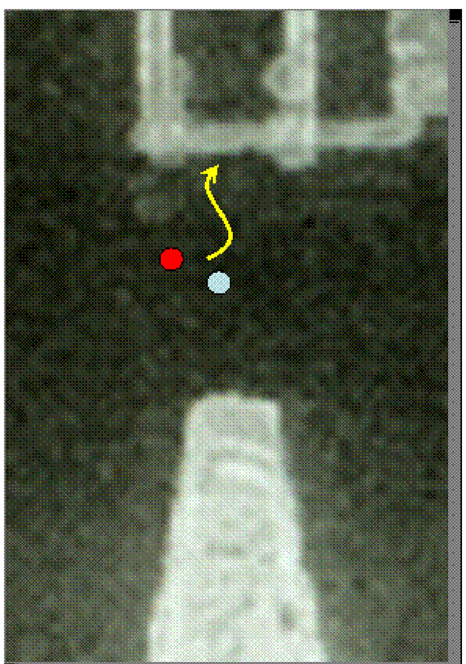
Decoherence and energy relaxation: Spin-Fluctuator Model

Fluctuators: structural defects, charge traps, which can exist in dielectric parts of the device

The fluctuators randomly switch between their states due to interaction with extended modes of environment – phonons or electrons.

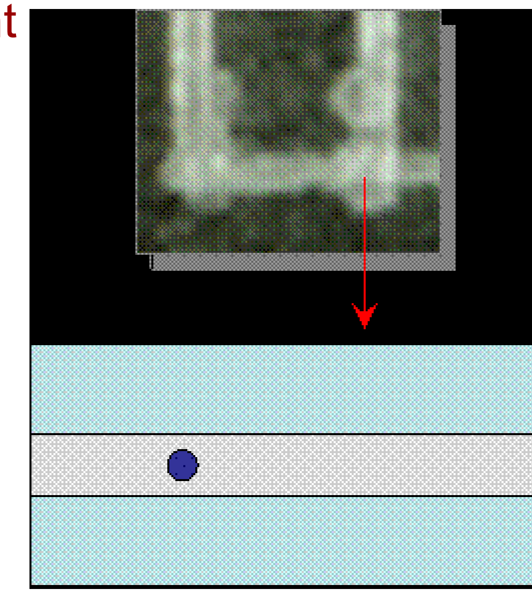
Switching $\Rightarrow$ random fields $\Rightarrow$ decoherence

Modulation of induced charge



$$-\frac{1}{2}B_z\sigma_z - \frac{1}{2}B_x\sigma_x$$

Modulation of critical Josephson current



Fluctuators during last 30 years

Pioneering ideas:

TLS in amorphous media:
P.W. Anderson, B. I. Halperin, and C. M. Varma, Phil. Mag. **25**, 1 (1972)
W. A. Phillips, J. Low Temp. Phys. **7**, 351 (1972)

Application to charge noise:
A. Ludviksson, R. Kree, A. Schmid, PRL 52, 950 (1984)
Sh.M. Kogan, K.E. Nagaev, Sol. St. Comm., 49, 387 (1984)

Extensive work in between:

Fluctuator-induced noise in point contacts and Josephson junctions:
V.I. Kozub, 1984 (several papers);
C. Rogers and R. Buhrman, PRL 53, 1272 (1984) + other experiments
YMG, V.G. Karpov, V.I.Kozub, 1989;
YMG, V.I. Gurevich, V.I. Kozub, 1989
+ other theoretical and experimental activities

Application to qubits:

Charge noise:
Paladino, Faoro, Falci, and Fazio, PRL 88, 228304 (2002); G. Falci *et al.* (2003-2005); Itakura & Tokura (2003); Schriefl *et al*. (2006)

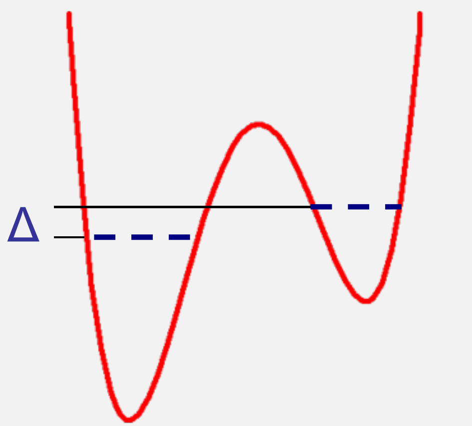
Fluctuations of J_c:
Martinis, Nam, Aumentado, Lang, and Urbina, PRB 67, 94510 (2003)

Hamiltonian:

$$\mathcal{H} = -(B/2)\,\sigma_z + (1/2)F(t)\sigma_x$$ qubit

fluctuator $$+(1/2)\sum E_i \tau_z^{(i)} + \mathcal{H}_{\rm env} + \mathcal{H}_{F-{\rm env}}$$

interaction $$+\sum_i \left(v_i\, \sigma_z^{(i)} \tau_z^{(i)} + \ldots \right)$$



$$E_i = \sqrt{\Delta_i^2 + \Lambda_i^2}$$

$$v_i = g(r_i)A(\mathbf{n}_i)(B_z/B)(\Delta_i/E_i)$$

$$\mathcal{H}_{\rm env} = \sum_\mu \omega_\mu \left(\hat{b}^\dagger \hat{b} + \frac{1}{2} \right)$$

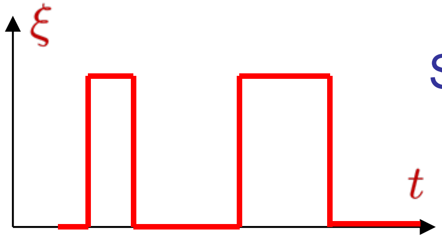
$$\mathcal{H}_{F-{\rm env}} = \sum_{i\mu} C_{i\mu} \tau_x^{(i)} \left(\hat{b}_\mu + \hat{b}_\mu^\dagger \right)$$

Simple classical model:

Classical low-frequency fluctuations $\xi_i(t)$ acting upon the qubit:

$$\mathcal{H}_{qF} = \mathcal{X}_1(t)\,\sigma_z\,, \quad \mathcal{X}_1(t) = \sum_i v_i \xi_i(t)$$

Uncorrelated random telegraph processes: $\xi_i(t) = 0 \text{ or } \xi_i(t) = 1$.



Switching times are distributed according to Poisson distribution

$$\langle \xi_i(t)\xi_k(t')\rangle = \delta_{ik} e^{-2\gamma_i|t-t'|}$$

The switching rates, γ, are calculated in the 2nd order in the interaction between the fluctuator and the thermal bath:

$$\gamma_i = (1/2)\gamma_0(T)\,(\Lambda_i/E_i)^2$$

$$\boxed{\Lambda \propto e^{-W} \;\rightarrow\; \mathcal{P}(\gamma) \propto \gamma^{-1}}$$

Q: Does ensemble of fluctuators produce 1/f noise?

$$
\begin{aligned}
S_{\mathcal{X}}(\omega) &= 2\int_0^\infty dt\, e^{i\omega t}\langle \mathcal{X}(t)\mathcal{X}(0)\rangle \\
&= 2\sum_i v_i^2 \int_0^\infty dt\, e^{i\omega t}\langle \xi_i(t)\xi_i(0)\rangle \\
&\propto \sum_i v_i^2 \frac{\gamma_i}{\omega^2+\gamma_i^2} \to \langle v^2\rangle \int \mathcal{P}(\gamma)\, d\gamma \frac{\gamma}{\omega^2+\gamma^2}
\end{aligned}
$$

For an exponentially-broad distribution of relaxation rates, $\mathcal{P}(\gamma) \propto 1/\gamma$,

and $S_{\mathcal{X}}(\omega) \propto 1/\omega$.

Interplay between decoherence and noise spectrum can depend on actual distribution of fluctuators in the device

Is it possible to reduce decoherence by driving fluctuators?

Idea: M. Constantin, C. C. Yu, and J. M. Martinis, Phys. Rev. B **79,** 94520 (2009).

PHYSICAL REVIEW B VOLUME 14, NUMBER 4 15 AUGUST 1976

Intrinsic decay lengths of quasimonochromatic phonons in a glass below 1 K

Brage Golding, John E. Graebner, and R. J. Schutz
Bell Laboratories, Murray Hill, New Jersey 07974

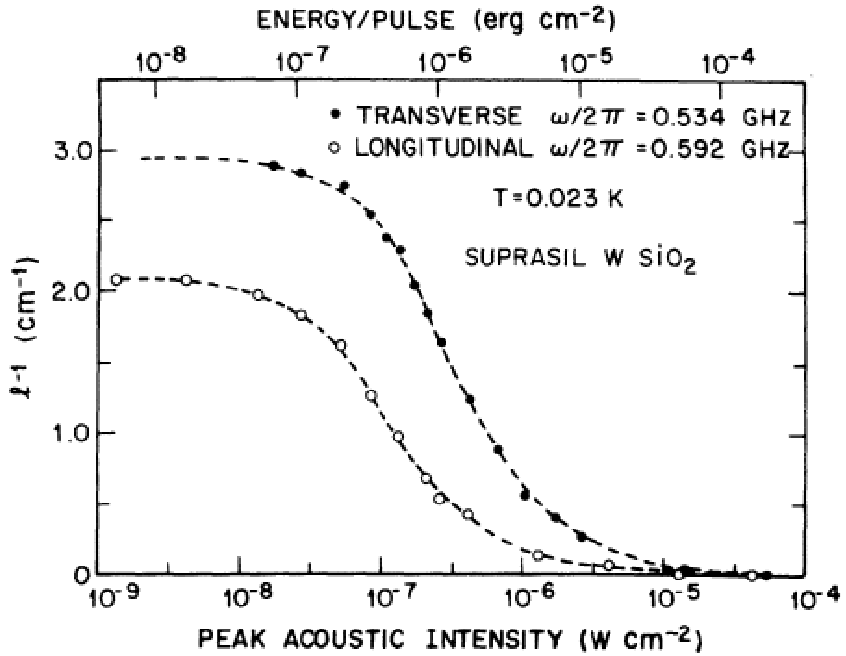
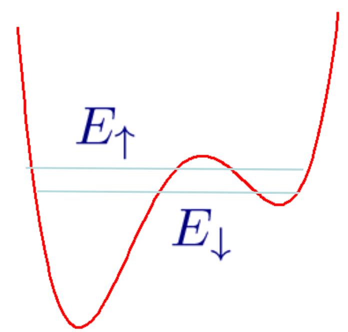


FIG. 1. Reciprocal decay lengths for 0.4-μsec phonon pulses in fused silica at 0.023 K as a function of incident intensity.

Resonant TLS

$$E_\uparrow - E_\downarrow = \hbar\omega$$



$$\ell^{-1} \propto n(E_\downarrow) - n(E_\uparrow)$$

The difference decreases with intensity increase -> resonant TLSs become inactive for absorption.

Hope: It may be also true for noise

Main conclusion of Constantin et al. - External driving at qubit frequency for typical ensembles of fluctuators will not have significant impact on the low-frequency noise because noise at low frequencies is mostly determined by TLSs with $E \lesssim kT \ll \hbar\omega$.

At the same time we [PRB **84,** 245416 (2011)] have shown that driving at relatively low frequencies can modify the noise spectrum decreasing noise at low frequencies.

The net effect of driving on the low-*E* fluctuators is almost entirely a shift in the frequency spectra from low to high frequencies.

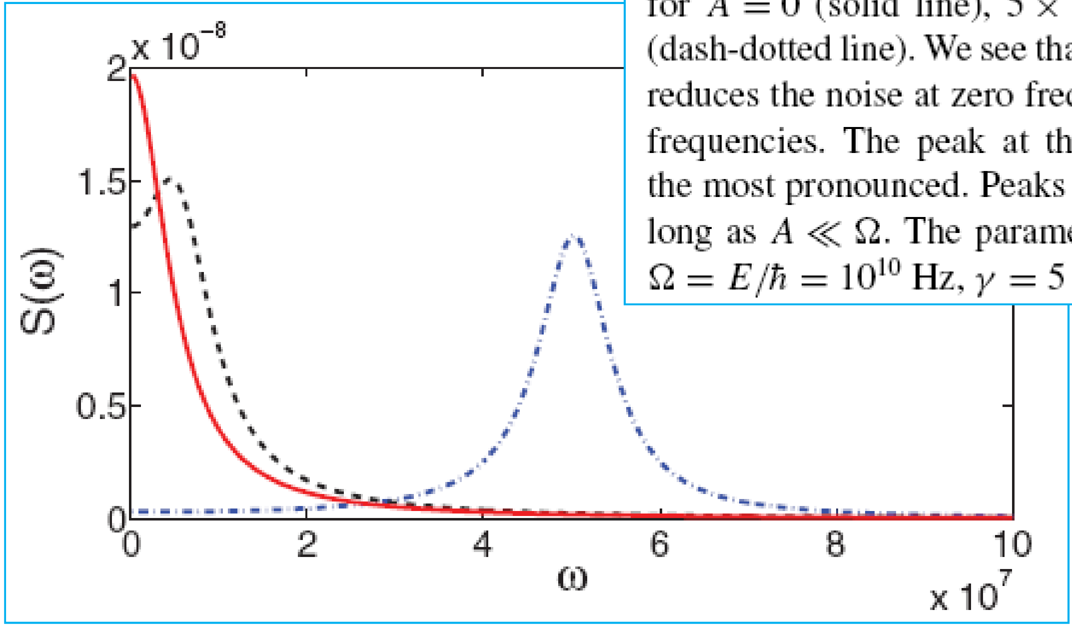


FIG. 2. (Color online) Noise spectrum induced by a single TLS for $A = 0$ (solid line), 5×10^6 Hz (dashed line), and 5×10^7 Hz (dash-dotted line). We see that with this choice of parameters, driving reduces the noise at zero frequency but enhances the noise at higher frequencies. The peak at the renormalized Rabi frequency, A', is the most pronounced. Peaks at higher frequencies are suppressed as long as $A \ll \Omega$. The parameters used in the figure are $T = 0.2$ K, $\Omega = E/\hbar = 10^{10}$ Hz, $\gamma = 5 \times 10^6$ s^{-1}, and $\gamma_0 = 10^7$ s^{-1}.

Back to classical 1/f noise in a non-driven qubit….

According to the model, for the qubit and a fluctuator we have:

$$\mathcal{H} = \frac{1}{2}\left[E_0 + \mathcal{X}(t)\right]\sigma_z + \frac{1}{2}F(t)\sigma_x + \frac{1}{2}\sum_i E_i \tau_z^{(i)}$$

where $E_0 = B + \mathcal{X}_1(0)\,, \quad \mathcal{X}(t) = \mathcal{X}_1(t) - \mathcal{X}_1(0)\,.$

Density matrix of the resonantly-manipulated qubit:

$$\hat{\rho} = \begin{pmatrix} n & -if\,e^{i\Omega t} \\ if^*\,e^{-i\Omega t} & 1-n \end{pmatrix}.$$

n and f represent slow dynamics in the rotating frame

Von Neumann equation:

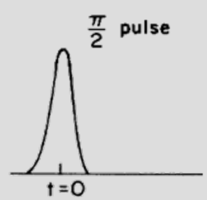
$$\begin{aligned}
\frac{\partial n}{\partial t} &= -2\gamma_q(n-n_0) - F\,\mathrm{Re}\,f\,, \\
\frac{\partial f}{\partial t} &= i\left[E_0 + \mathcal{X}(t) - \Omega\right] f - \gamma_q f + \frac{F}{2}(2n-1).
\end{aligned}$$

F – Rabi frequency, $\mathcal{X}(t)$ - random deviation of eigenfrequency

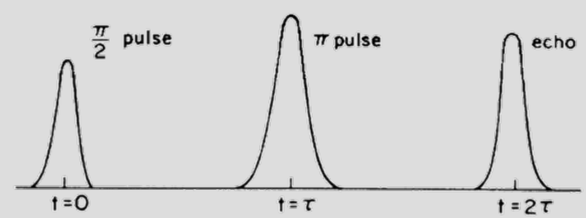
Stochastic differential equation

The external microwave is applied a set of pulses rotating the effective spin by some angle (manipulation protocol).

Typical protocols - profiles *F(t)*



Free induction



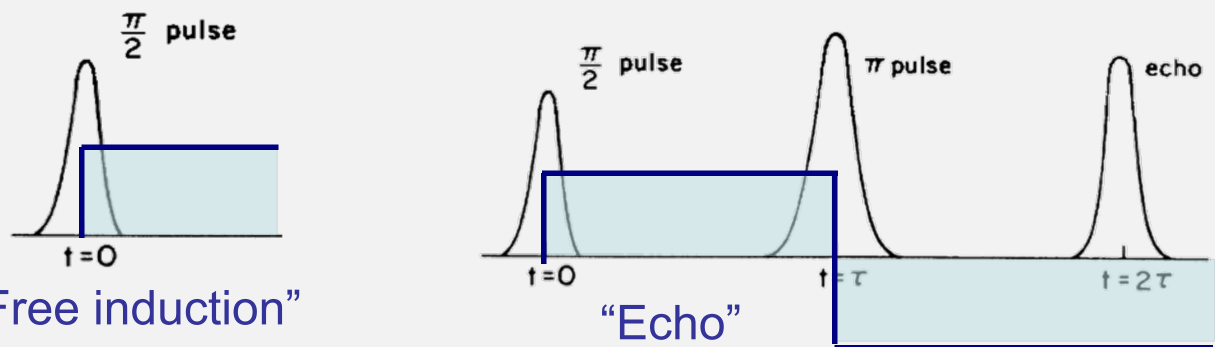
Two-pulse echo

In general, the signal under consideration can be expressed in terms of the phase-memory functional

$$\Psi[\beta(t'),t] = \left\langle \exp\left(i \int_0^t \beta(t') X(t')\, dt' \right) \right\rangle_{\xi_i}$$

$\beta(t)$ depends on the manipulation protocol

$\beta(t)$



"Free induction"

"Echo"

Similar to spectral diffusion in magnetic systems

R. Klauder and P. W. Anderson, Phys. Rev. **125**, 912 (1962).

and glasses

J. L. Black and B. I. Halperin, Phys. Rev. B **16**, 2829 (1977).

In the latter case fluctuators are structural two-level systems

Single Fluctuator

Simplification: $\xi^2(t)=0,1$ is a determined quantity

The phase-memory functional obeys the differential equation

$$\frac{d^2\psi}{d\psi^2} + \left(2\gamma - \frac{d\ln\beta}{dt} - iv\beta\right) - iv\gamma\beta^2 = 0$$

with initial conditions $\psi(0) = 0\,,\quad \frac{d\psi}{dt}|_{t=0} = \frac{iv}{2}\beta\,|_{t=-0}$

One can easily find exact solution of a simple manipulation protocol when $\beta = \pm 1$

Two parameters: switching rate, γ, and coupling strength, v

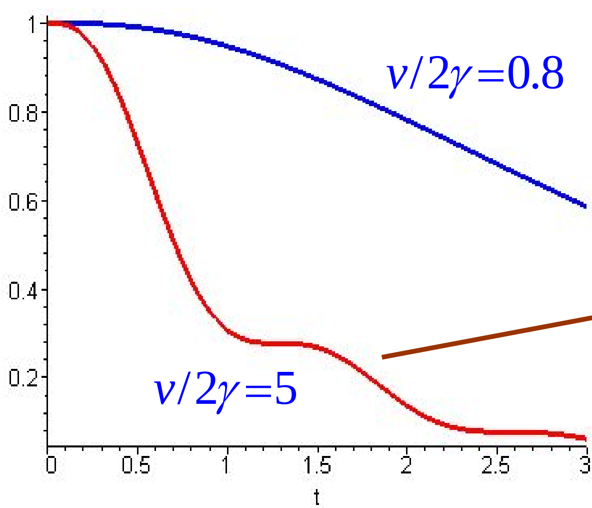
Strong coupling, $v \gg \gamma$:

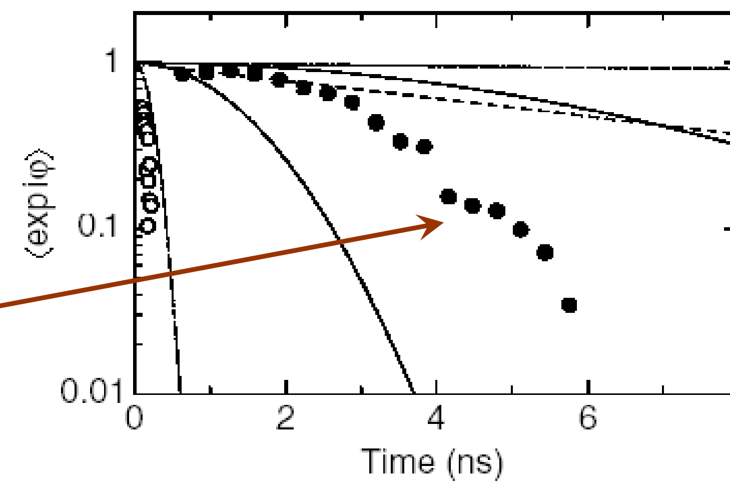
Echo decay

$$\psi(t) = e^{-2\gamma\tau}\left(1 + \frac{2\gamma}{v}\sin v\tau\right)$$

Plateaus at $v\tau \approx 2\pi k + 2\gamma/v$

Weak coupling, $v \ll \gamma$: $\psi(t) = e^{-v^2\tau/4\gamma}$

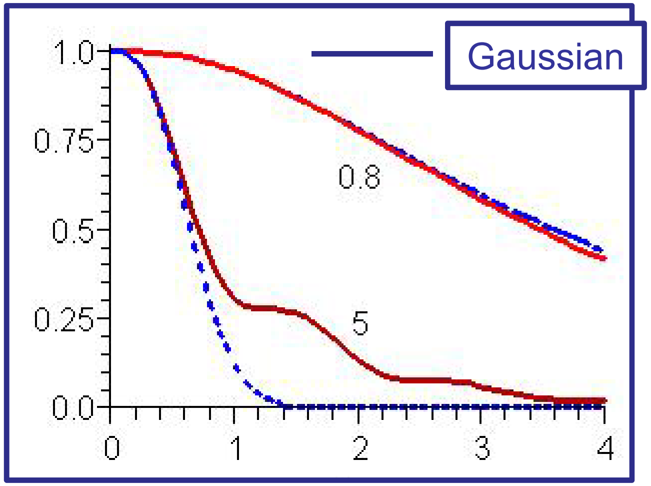




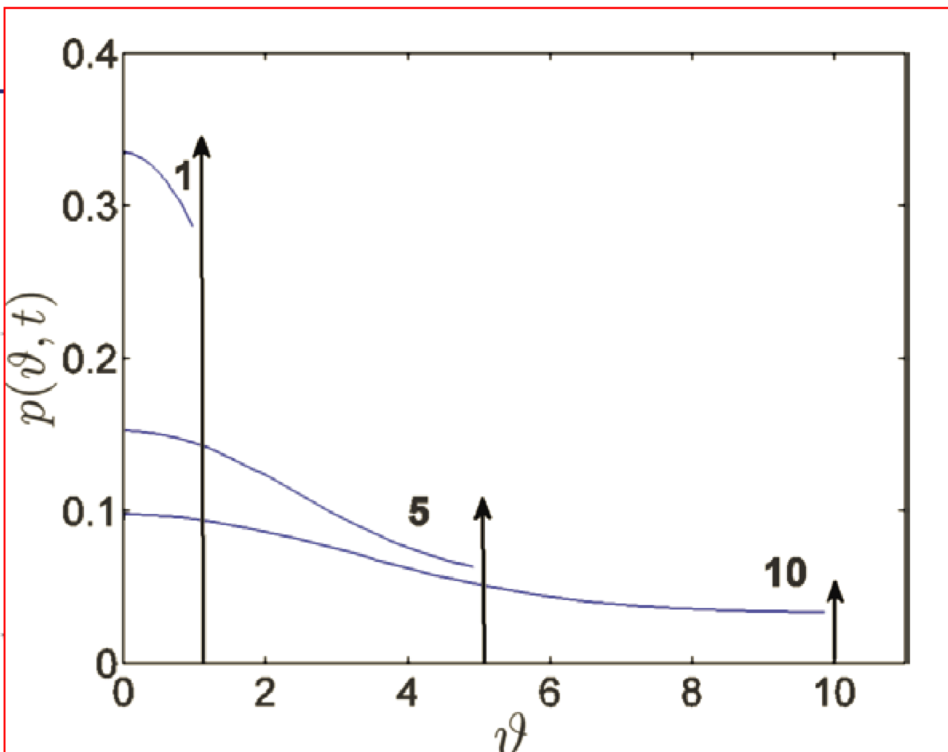
Nakamura et al., PRL 2002

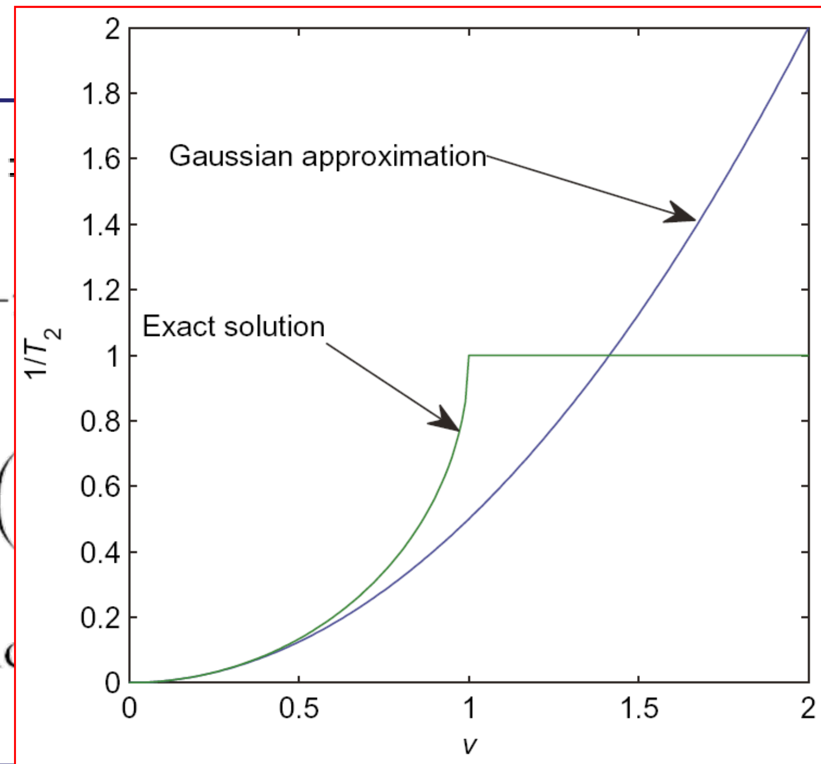
How good is the Gaussian assumption for a single fluctuator?

Good only in the case of weak coupling.

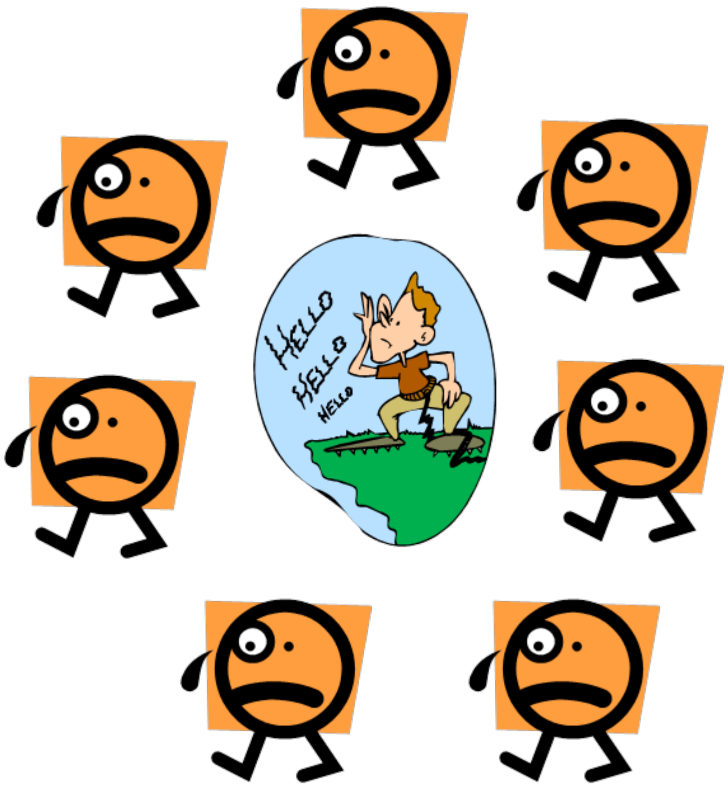


Reason: The distribution function of the phase shift is essentially non-Gaussian since the phase shift is limited by the quantity $2v\tau$





Many fluctuators (decoherence by 1/f noise)



Many fluctuators with exponentially broad distribution of switching rates produce 1/f noise.

- Can such noise be considered as Gaussian?
- What kind of model should describe decoherence by 1/f noise?
- Is the decoherence directly related to the 1/f noise?

Microscopic model leading to 1/f noise - many uncorrelated fluctuators

$$\Psi(t) = \prod_i \psi^{(i)}(t) = e^{\sum_i \ln \psi^{(i)}(t)}$$

Assuming self-averaging $\longrightarrow \quad e^{N\langle \ln \psi(t)\rangle_F} \equiv e^{-\mathcal{K}(t)}$

For $N >> 1$, $\quad \mathcal{K}(t) = N\,\langle 1-\psi(t)\rangle_F$

Holtsmark method: S. Chandrasekhar, RMP 15, 1 (1943)

To calculate the average one needs distributions of fluctuators' decay rates and coupling constants

Properties of distributions:

- Only the fluctuators with $E \leq kT$ are important, the rest are frozen in their ground states
- Relaxation rates: since $\Lambda \propto e^{-\lambda r}$ the distribution of the *logarithm of* Λ should be uniform

$$P(E,\theta) = \frac{P_0}{\sin\theta} \qquad \sin\theta \equiv \frac{\Lambda}{E}$$

- Distribution of v depends both on the interaction range and location of the fluctuators.

  In a bulk system, assuming that $v = g/r^3$ and the fluctuators are randomly distributed in space we get

$$\mathcal{P}(E,\theta,v) = \frac{\eta}{v^2 \sin\theta}, \quad \eta = \frac{g}{r_T^3}, \; r_T = (P_0 T)^{-1/3}$$

η is the typical coupling to a thermal fluctuator.

General expression:

$$\mathcal{K}(t) = \eta \int \frac{du}{u^2} \int_0^{\pi/2} \frac{d\theta}{\sin\theta} \left\{ 1 - \psi\left[\beta, t | u\cos\theta, \gamma_0 \sin^2\theta\right] \right\}$$

Echo signal:

Switching probability

$$\mathcal{K}(\tau) \sim \begin{cases} \eta\tau(\gamma_0\tau)\,, & \gamma_0\tau \ll 1 \\ \eta\tau\,, & \gamma_0\tau \gg 1 \end{cases}$$

Markovian

Non-Markovian

$$\boxed{T_2^{-1} \approx \min\{\eta, \sqrt{\eta\gamma_0}\}}$$

At $\tau \gg 1/\gamma_0$ decoherence is due to *optimal* fluctuators with

$$v(r_{\mathrm{opt}}) \approx \gamma_0(T)$$

Different from those which mainly contribute to the noise spectrum

Attempt to compare with experiment

Problem #1: It is the long-time decoherence that is most sensitive to the particular model of the noise. However, at long times the signal usually is weak and obscured by noise.

We have gotten access to extended data from NEC group on echo in flux qubits.

PRL **97**, 167001 (2006) PHYSICAL REVIEW LETTERS week ending 20 OCTOBER 2006

Decoherence of Flux Qubits due to $1/f$ Flux Noise

F. Yoshihara,[1] K. Harrabi,[2] A. O. Niskanen,[2,3] Y. Nakamura,[1,2,4] and J. S. Tsai[1,2,4]

Problem #2: Despite significant progress (e.g., talk by R. McDermott) the mechanism behind the flux noise is not fully understood.

Therefore we use the simplest model:

v and γ are uncorrelated, distribution of v is peaked at some value:

$$\mathcal{P}(v,\gamma) = \frac{P_0 T}{\gamma}\delta(v-\bar{v}), \quad \gamma_0 > \gamma > \gamma_{\min}.$$

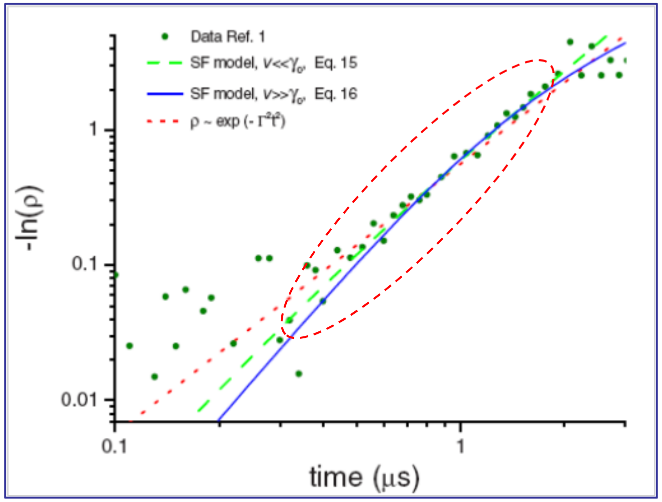
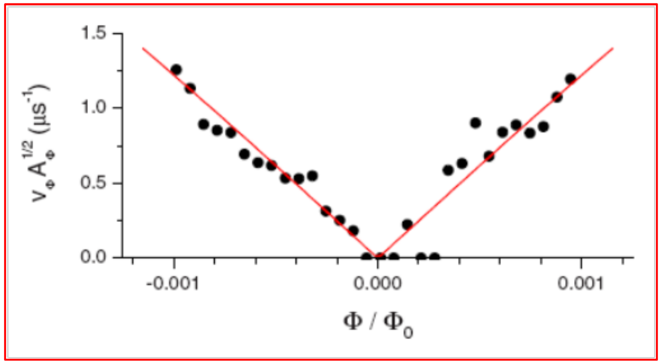


FIG. 1. (Color online) Dephasing component of the echo measurements replotted from Fig. 4(a) of Ref. 1 away from the optimal point. The curves show fits to the SF model, Eqs. (14) and (15), and to the $\rho = e^{-\Gamma^2 t^2}$ law (Ref. 38). The fitting took into account all data points including those that fall outside the range of the plot (e.g., those with $\rho > 1$).

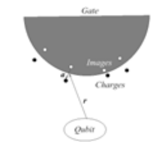
In the reliable region there is almost no difference between the Gaussian and SF model.



Still, if we use the SF model it is possible to extract the coupling between a typical fluctuator and the qubit.

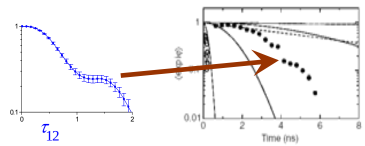
$$\approx 2 \times 10^{-5} \Phi_0$$

Summary and Conclusions

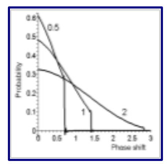


We considered extended spin-fluctuator model for

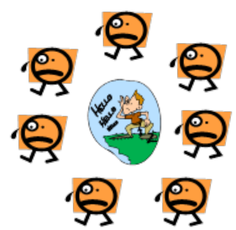
1. Echo & energy relaxation



2. Distribution of single-shot readouts

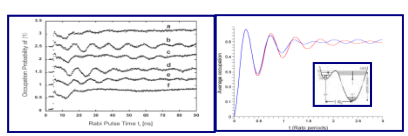


3. Decoherence by many fluctuators



4. Decoherence @ optimal point

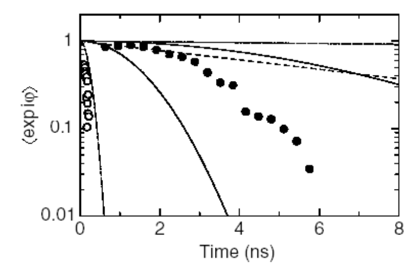
5. Fluctuator-mediated Rabi oscillations



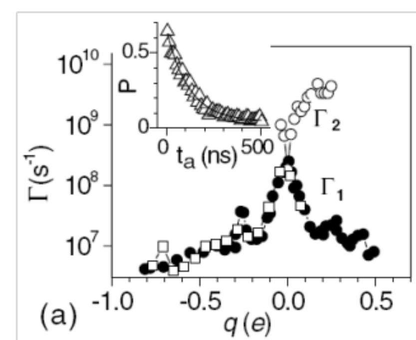
6. Decoherence due to “quenched” fluctuators

The model

explains observed features



shows pronounced non-Gaussian behavior – there is NO direct relation between the decoherence and noise spectrum

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