Interacting two-level defects as sources of fluctuating high-frequency noise in superconducting circuits

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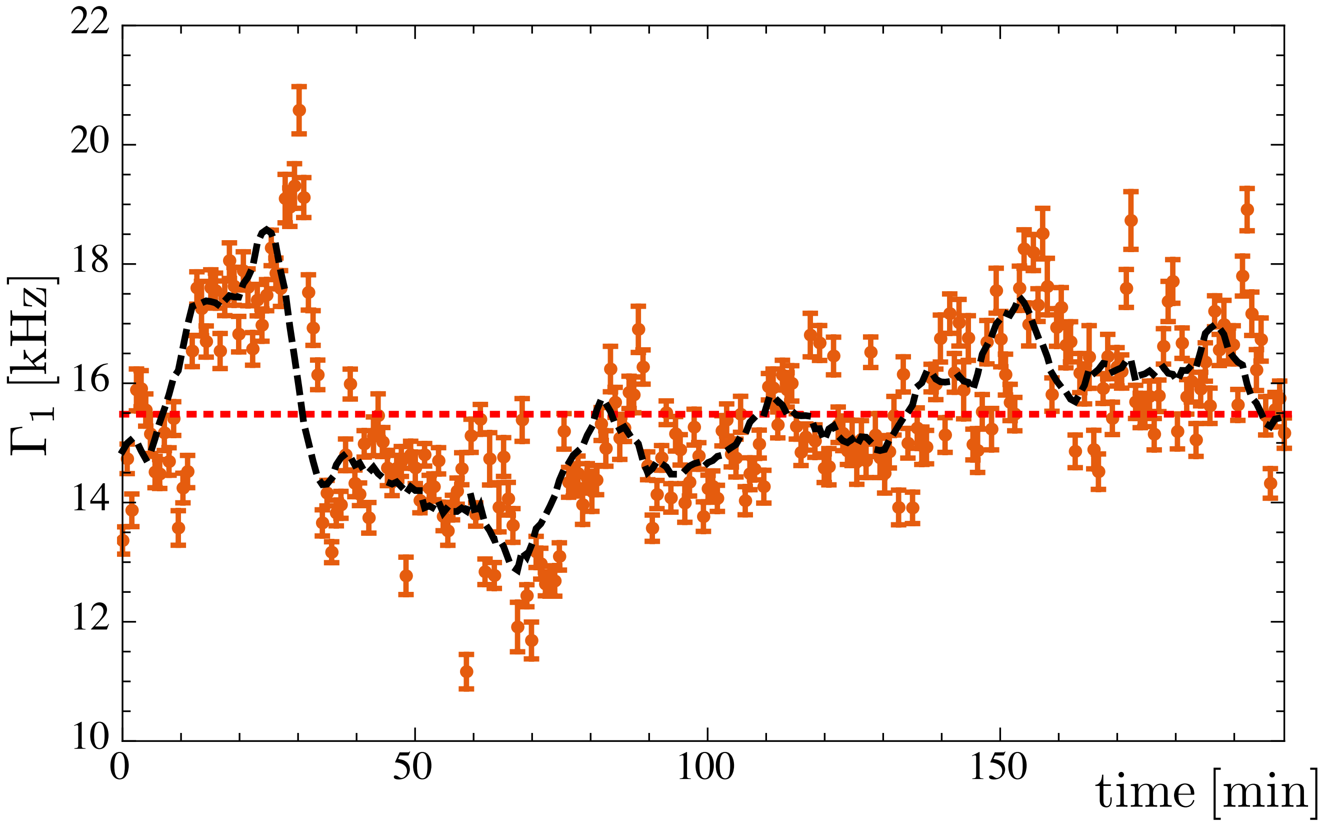
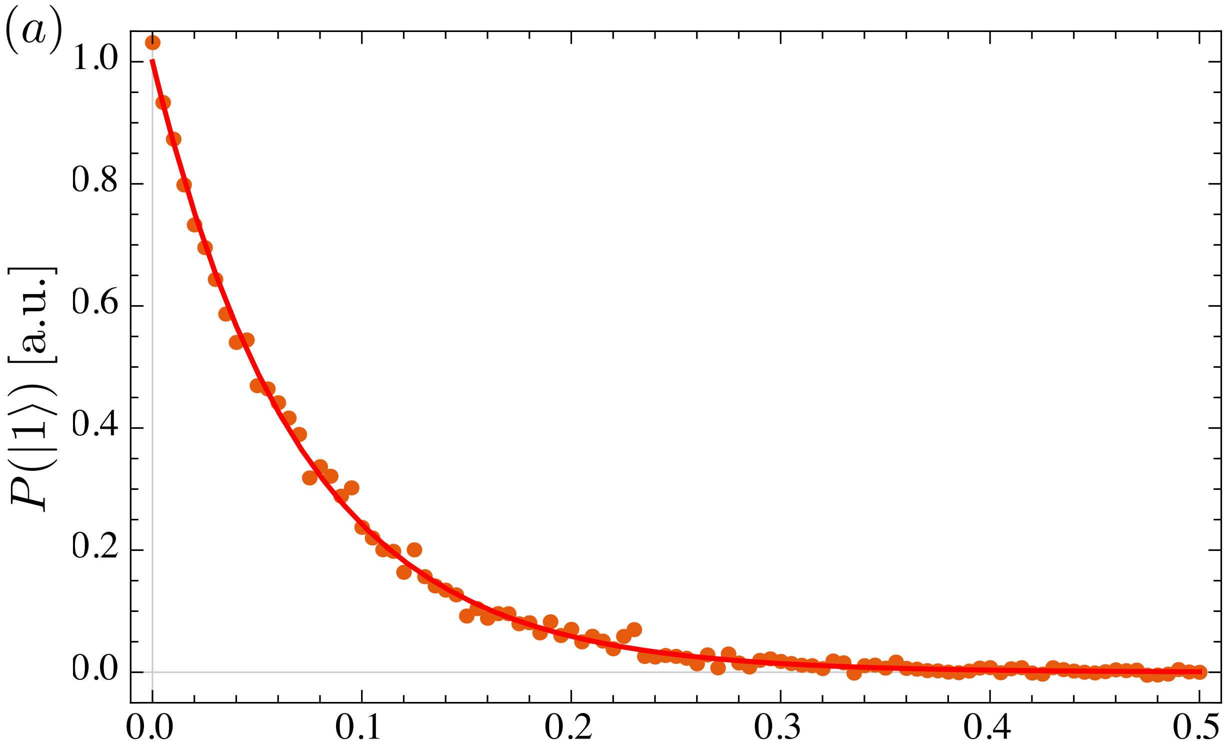
Clemens Müller, Jürgen Lisenfeld, Alexander Shnirman, and Stefano Poletto

Fluctuations in relaxation rate

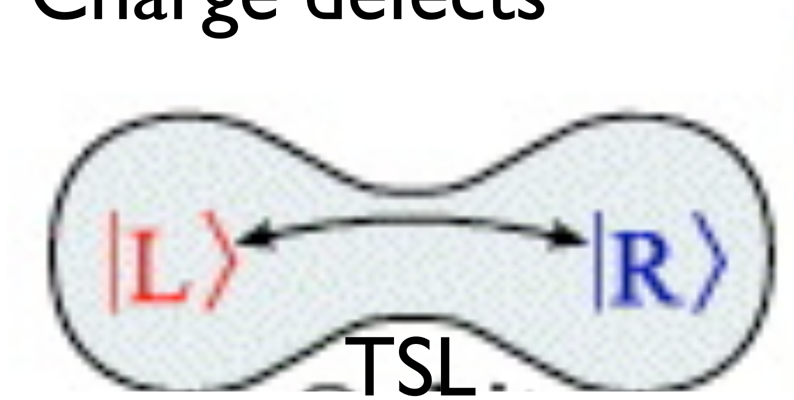




- Time needed to obtain single value of T_1 is ~min
- There is no apparent structure to fluctuations of T_1
- There are two level systems (TSL) inside the dieletric forming Josephson junctions (needed to realize the qubit)

Qualitative description of fluctuating T_1

Charge defects



$$\hat{H}_{\mathrm{TLS}} = -\frac{1}{2}\epsilon\sigma_z + \frac{1}{2}\Delta\sigma_x$$

Assimetry of DQW — Tunnel splitting

TSL coupling to the qubit via dipole moment~σ_z

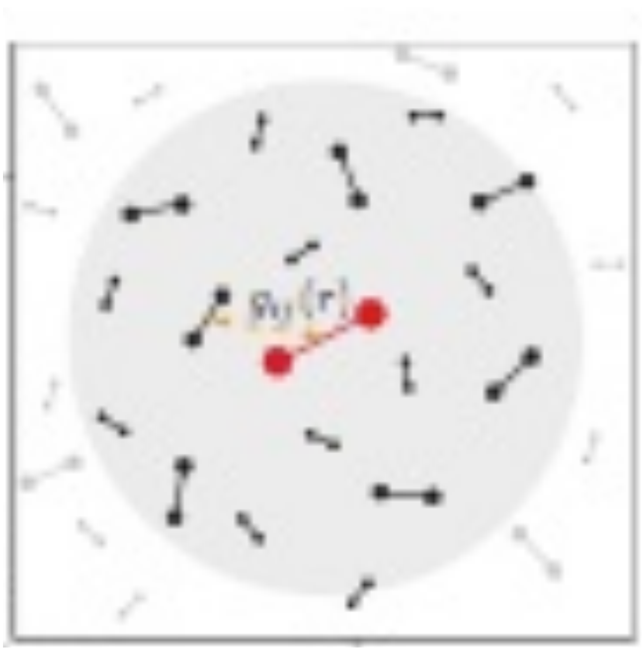
$$\Gamma_1 \propto C(\omega_{10})$$

qubit splitting

$$C(\omega) = \int dt\, \mathrm{e}^{-\mathrm{i}\omega t} \langle \sigma_z(t)\sigma_z(0)\rangle$$

TSL emsemble

i) High-frequency TS (E>>T, E~ω_{10})
ii) Low-frequency TF (E<<T)
iii) Slowly fluctuating TF



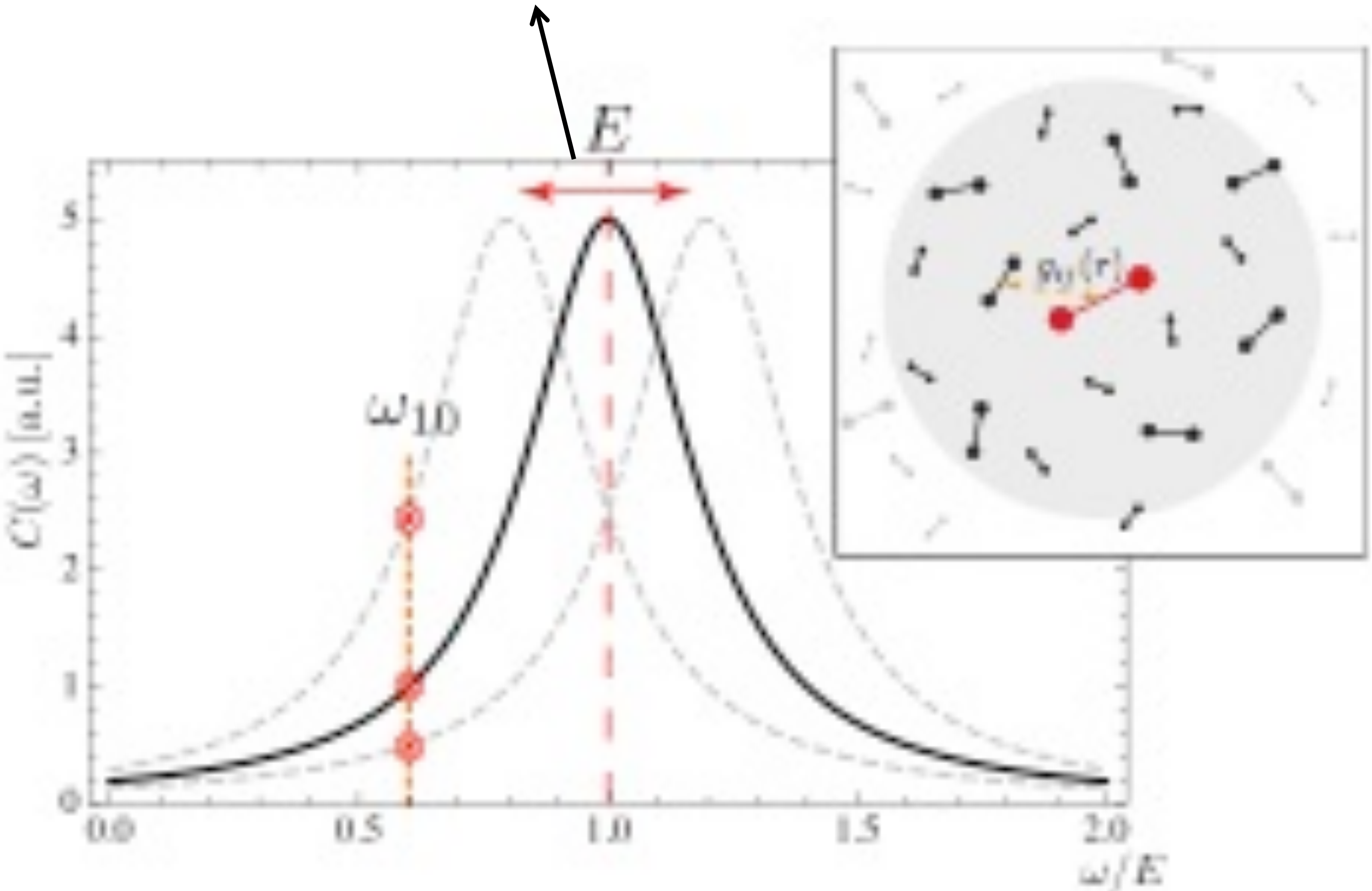
Qualitative description of fluctuating T_1

$$C(\omega) = \cos^2\theta \left[1 - \langle\sigma_z\rangle^2\right] \frac{2\gamma_1}{{\gamma_1}^2 + \omega^2} + \sin^2\theta \left[\frac{1 - \langle\sigma_z\rangle}{2}\right] \frac{2\gamma_2}{{\gamma_2}^2 + (\omega + E)^2} + \sin^2\theta \left[\frac{1 + \langle\sigma_z\rangle}{2}\right] \frac{2\gamma_2}{{\gamma_2}^2 + (\omega - E)^2}$$

Low-freq noise (from TFs)
due to thermal switching

High-freq noise (from TS)
leading to relaxation of the qubit

slow TFs



- The qubit relaxation via spin-flip process with TS
- slow TFs change E of TS
- TFs influence Υ_2

Calculation

Coupling between TSLs $$\hat{H} = \frac{1}{2} \sum_{<ij>} g_{ij} \tilde{\sigma}_{z,i} \tilde{\sigma}_{z,j}$$

Energy splitting of TSL $$\hat{E}_i = E_{i,0} - \sum_{<ij>} g_{ij} \tilde{\sigma}_{z,j} \qquad E_{i,0} = \sqrt{\epsilon_i^2 + \Delta_i^2}$$

Relaxation rate of the qubit due to TSL $$\hat{\gamma}_{q,i} = \cos^2\theta_i \frac{2\gamma_{2,i}}{{\gamma_{2,i}}^2 + (\omega_{10} - \hat{E}_i)^2}$$

↓ small coupling constant g

$$\hat{\gamma}_{q,i} = \gamma_{q,i}^{(0)} + \gamma_{q,i}^{(1)} \sum_{<ij>} g_{ij} \tilde{\sigma}_{z,j} + O(g^2)$$

$$\gamma_{q,i}^{(0)} = \cos^2\theta_i \frac{2\gamma_{2,i}}{\gamma_{2,i}^2 + (\omega_{10} - E_{i,0})^2},$$

$$\langle \tilde{\sigma}_z \rangle = \cos\theta \langle \sigma_z \rangle = \cos\theta \tanh\left(E/2k_B T\right)$$

$$\gamma_{q,i}^{(1)} = \left.\frac{\partial \gamma_{q,i}}{\partial E_i}\right|_{E_i = E_{i,0}} = \cos^2\theta_i \frac{4\gamma_{2,i}(\omega_{10} - E_{i,0})}{({\gamma_{2,i}}^2 + (\omega_{10} - E_{i,0})^2)^2}.$$

Distribution of parameters

Flat distribution of TLS barrier height

$$\rightarrow \quad P(\Delta) \sim 1/\Delta \quad \rightarrow \quad P(\gamma_1) \sim 1/\gamma_1$$

Assuming general distribution in ε $\quad P(\epsilon, \Delta) d\epsilon d\Delta = A \, \frac{\epsilon^{\alpha}}{\Delta} d\epsilon d\Delta$

Distribution of coupling constant assuming dipolar interaction between TSLs

$$P(g)dg = P(r)\frac{\partial r}{\partial g}dg = \rho_0 \left|g\right|^{-\frac{4}{3}} dg$$

coupling constant can take both positive and negative values

$$\downarrow$$

$$\int dg \, g P(g) = 0$$

Calculation of $\langle\Gamma_I\rangle$ and $\langle\Gamma_I(t)\Gamma_I(0)\rangle_\omega$

$$\langle\hat{\gamma}_{q,i}\rangle = \gamma_{q,i}^{(0)} + \gamma_{q,i}^{(1)} \sum_j g_j \cos\theta_j \tanh\frac{E_j}{2T}$$

$$= \gamma_{q,i}^{(0)} + \gamma_{q,i}^{(1)} \int dg\, d\theta\, dE\, P(g,\theta,E)\, g\cos\theta \tanh\frac{E}{2T}$$

$$\langle\hat{\gamma}_{q,i}(0)\hat{\gamma}_{q,i}(t)\rangle_\omega = \int dt\, \mathrm{e}^{-\mathrm{i}\omega t} \langle\hat{\gamma}_{q,i}(0)\hat{\gamma}_{q,i}(t)\rangle$$

$$= \left(\gamma_{q,i}^{(1)}\right)^2 \sum_{j,l} g_j g_l \langle\tilde{\sigma}_{z,j}(t)\tilde{\sigma}_{z,l}(0)\rangle_\omega$$

$$= \left(\gamma_{q,i}^{(1)}\right)^2 \int dg\, d\theta\, dE\, d\gamma_1\, P(g,\theta,E,\gamma_1) g^2 \cos^2\theta \left[1 - \tanh^2\left(\frac{E}{2T}\right)\right] \frac{2\gamma_1}{{\gamma_1}^2+\omega^2}$$

$$\int dg\, g^2 P(g) \propto \text{const} \qquad \int dE P(E)\left(1-\tanh^2\left(\frac{E}{2T}\right)\right) \approx \int_0^T dE E^\alpha = T^{\alpha+1}$$

Calculation of <Γ$_1$> and <Γ$_1$(t)Γ$_1$(0)>$_\omega$

Similarly, dephasing rate due to bath of TF $\gamma_2 \propto T^{\alpha+1}$

↓

Temp. dependence of avg. relaxation rate $\langle\Gamma_1\rangle \propto \frac{2\gamma_2}{{\gamma_2}^2+\delta\omega^2} \propto \begin{cases} T^{-(\alpha+1)} & , \quad \delta\omega \lesssim \gamma_2 \\ T^{\alpha+1} & , \quad \delta\omega \gg \gamma_2 \end{cases}$

$$\gamma_{q,i}^{(1)} = \frac{\partial\gamma_{q,i}}{\partial E_i}\Big|_{E_i=E_{i,0}} = \cos^2\theta_i \frac{4\gamma_{2,i}(\omega_{10}-E_{i,0})}{\left({\gamma_{2,i}}^2+(\omega_{10}-E_{i,0})^2\right)^2}$$

➔

$$\langle\hat{\gamma}_{q,i}(0)\hat{\gamma}_{q,i}(t)\rangle_\omega \propto \begin{cases} T^{-5(\alpha+1)} & , \quad \delta\omega \ll \gamma_{2,i} \\ T^{-3(\alpha+1)} & , \quad \delta\omega \sim \gamma_{2,i} \\ T^{2(\alpha+1)} & , \quad \delta\omega \gg \gamma_{2,i} \end{cases}$$

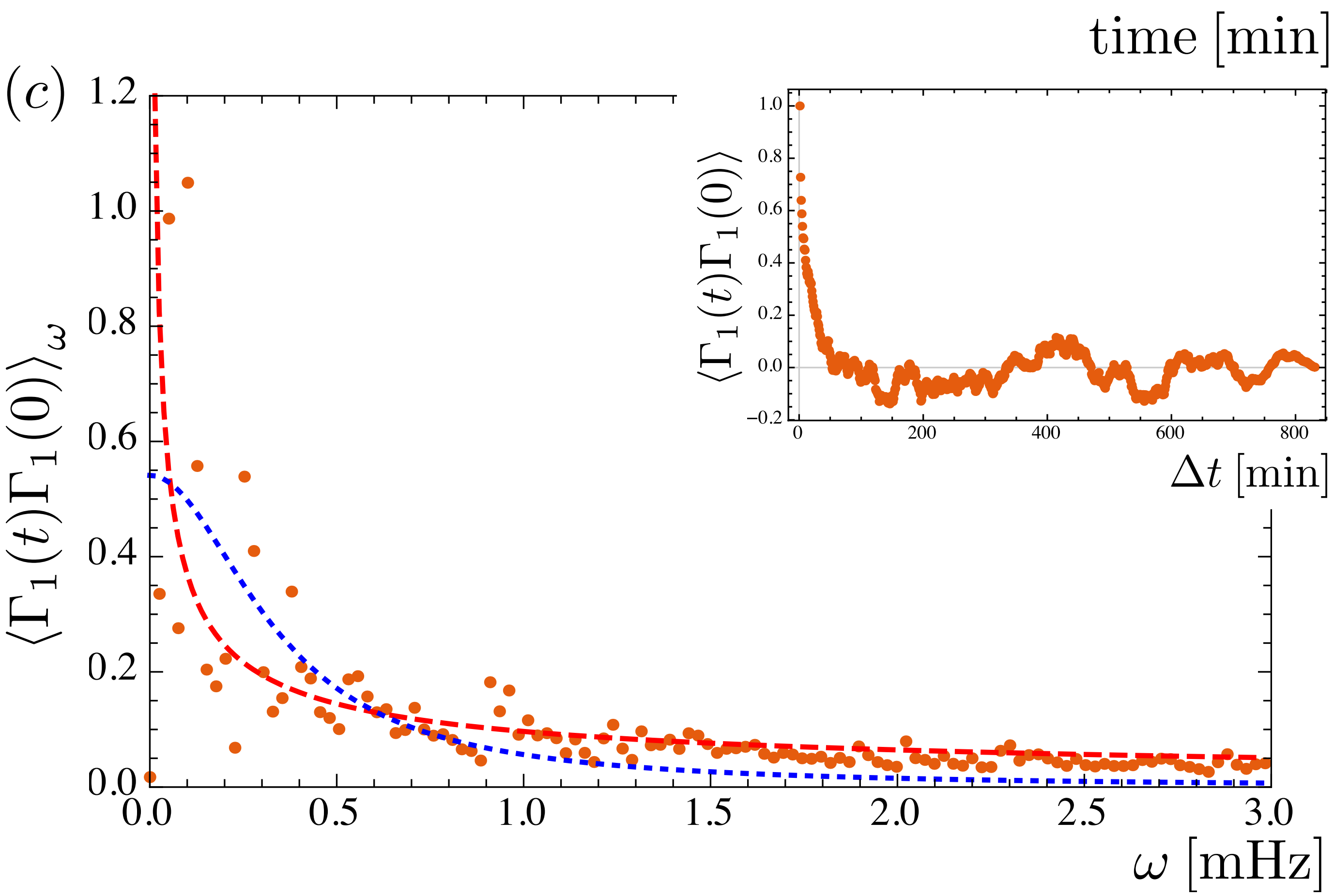
Frequency dependence <Γ$_1$(t) Γ$_1$(0)>$_\omega$ [$P(\gamma_1) \sim 1/\gamma_1$]

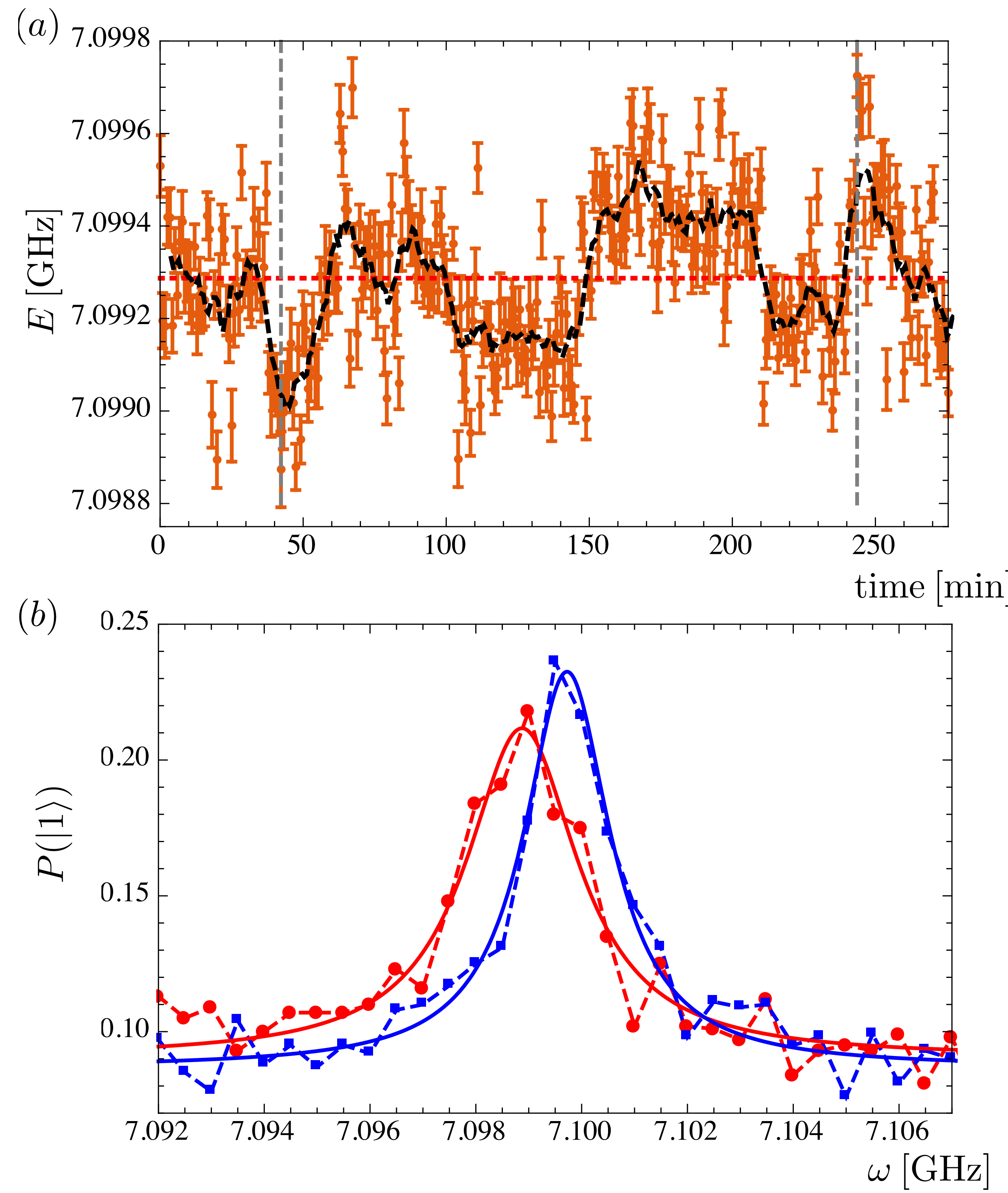
↓

$$\int_0^{\gamma_{\mathrm{Max}}} d\gamma_1 P(\gamma_1)\frac{2\gamma_1}{\gamma_1^2+\omega^2} = \frac{2\arctan\frac{\gamma_{\mathrm{Max}}}{\omega}}{\omega} \propto \begin{cases} \frac{1}{\omega} & , \quad \omega < \gamma_{\mathrm{Max}} \\ \frac{\gamma_{\mathrm{Max}}}{\omega^2} & , \quad \omega > \gamma_{\mathrm{Max}} \end{cases}$$

Experimental results

For their data, the temperature dependence of the fluctuation amplitude is inconclusive and does not give any indication if the model is accurate





black. **(c)** depicts the absolute value of the Fourier transform of the two-time correlation function of the relaxation rates $\langle\Gamma_1(t)\Gamma_1(0)\rangle$, with the inset showing the correlation function itself. The red (blue) dashed curve is the result of a fit of the data to a A/ω^α-spectrum (Lorentzian spectrum $A\gamma/(\gamma^2+\omega^2)$) with fit parameters $A = 0.097$ and $\alpha = 0.58$ ($A = 0.18$ and $\gamma = 0.34$ mHz), for details see text.

Alternative explanations

1) Fluctuations of the quasiparticle density in the superconductor

↓

Quasiparticle tunnelling across the circuit's Josephson junctions can induce relaxation and dephasing, but the quasiparticle induced noise is flat at high-frequencies

↓

to change the relaxation rate by 1 kHz ➔ $\delta N_{qp} \approx 1.5 \times 10^4$

2) the qubit level splitting was fluctuating as a function of time, e.g. due to changes in the critical current of the circuits Josephson junction

↓

This mechanism can however be ruled out since in our measurements the qubit is always resonantly excited

Conclusions

- A simple model of interacting TLS which offers a qualitative understanding of the observed fluctuations in relaxation time

- The model is grounded in experimental observations, grants a clear route towards further confirmation, and provides a way to verify and refine the existing microscopic TLS models

- Proposed model clearly indicates that parasitic TLS are a limiting factor in today's best performing superconducting circuits

  ➔A better understanding of this decoherence source is thus vital for further improving the fidelity of superconducting quantum circuits

THE END