Квантовая метрология на трансмоне в режиме кутрита

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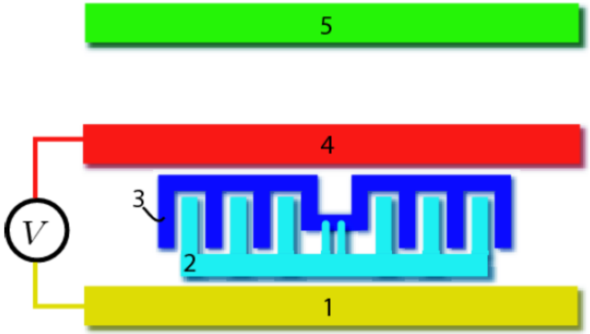
Долгопрудный

Классические измерения

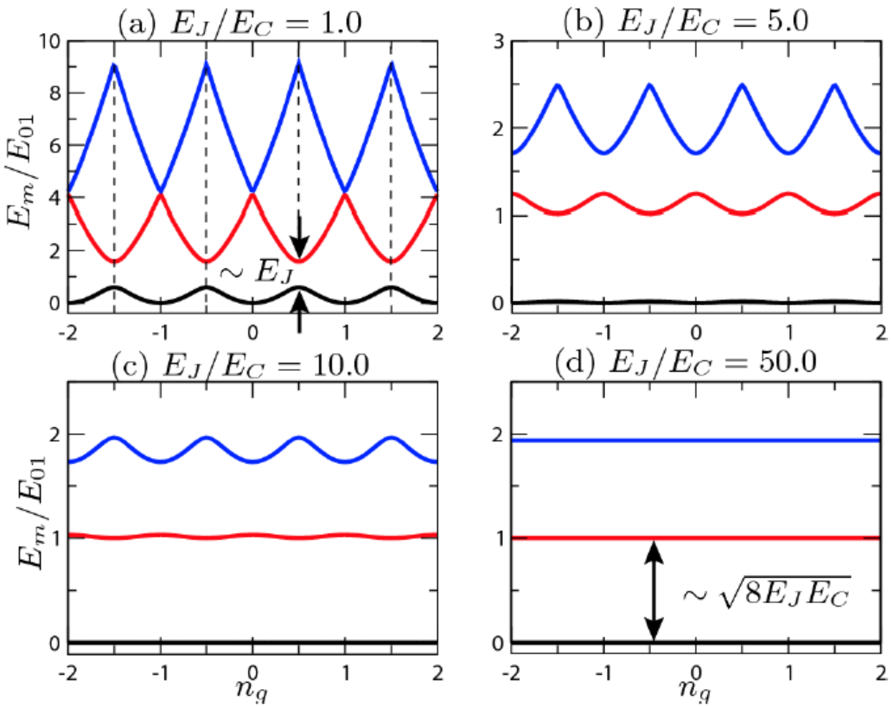
$$\sigma_P \propto \frac{1}{\sqrt{N}} \propto \frac{1}{\sqrt{t}}$$

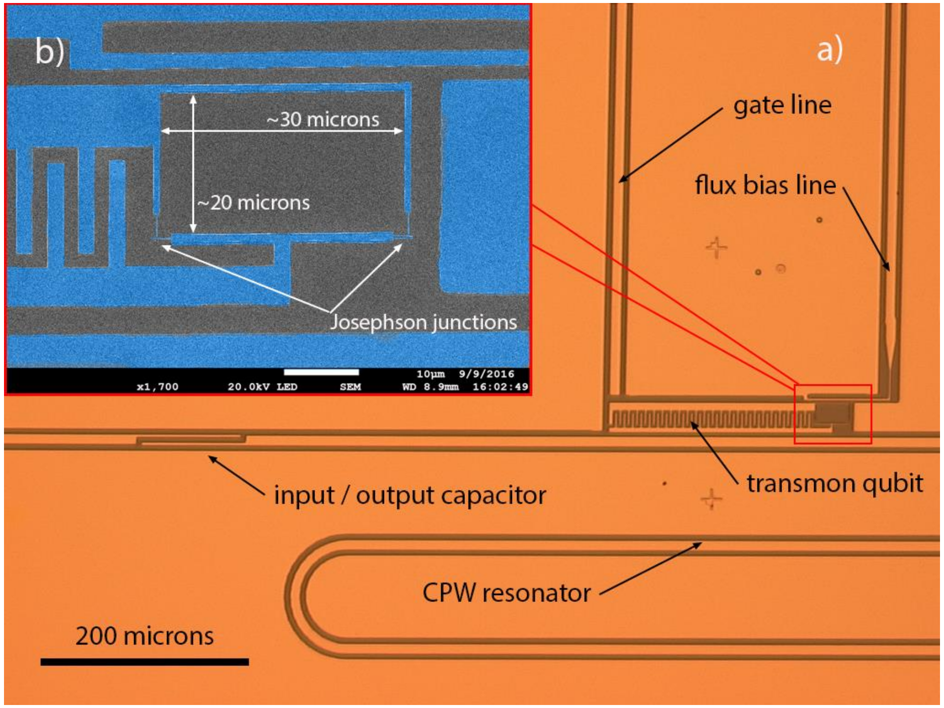
Гейзенберговский предел

$$\sigma_P \propto \frac{1}{N} \propto \frac{1}{t}$$



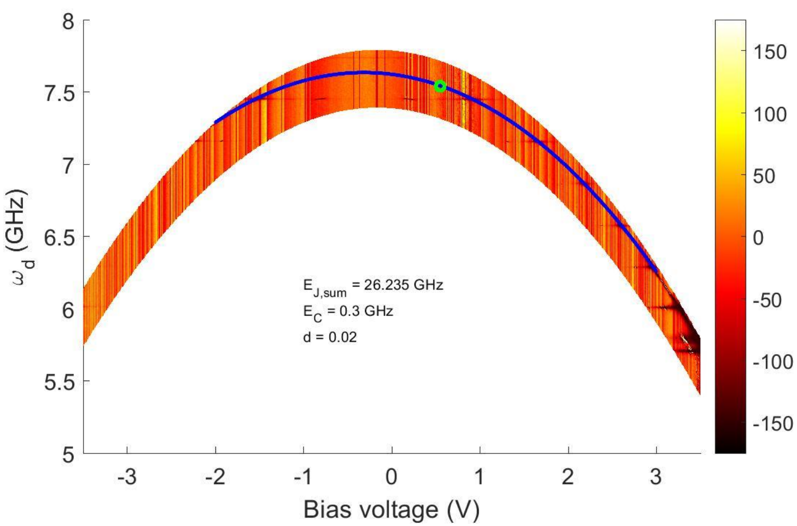
$$H = 4E_C\left(n - \frac{C_g V_g}{2e}\right)^2 |n\rangle\langle n| - \frac{E_J}{2}\left(|n+1\rangle\langle n| + |n\rangle\langle n+1|\right)$$

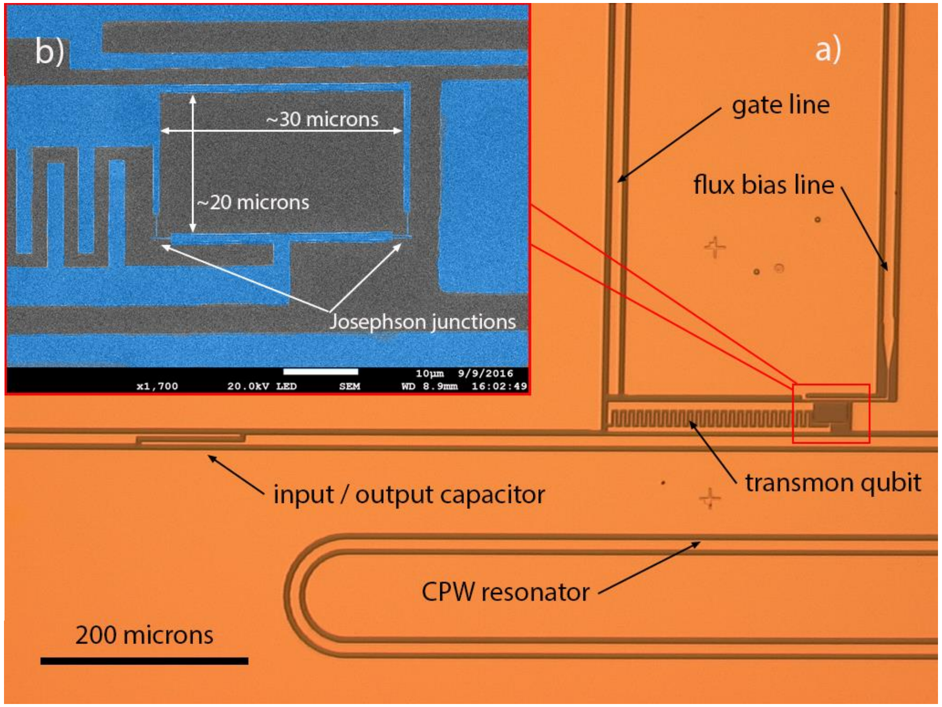




$$\hbar\omega_{01} = \sqrt{8E_J E_C \sqrt{\cos^2\left(\pi\frac{\Phi(V)}{\Phi_0}\right) + d^2\sin^2\left(\pi\frac{\Phi(V)}{\Phi_0}\right)}} - E_C, \qquad d = \frac{|E_{J1} - E_{J2}|}{E_{J1} + E_{J2}}$$

$$\delta\Phi \to \delta H \propto \begin{pmatrix} 0 & 0 & 0 \\ 0 & \omega & 0 \\ 0 & 0 & 2\omega \end{pmatrix}$$





$$H_{JC} = \sum_{j=1}^{N} \hbar\widetilde{\omega}_j |j\rangle\langle j| + \sum_{j=0}^{N-1} \hbar\Omega_{j,j+1} \left(|j+1\rangle\langle j| e^{-i\omega_{j,j+1}^{(\Omega)} t} + h.c. \right)$$

Переход в представление вращающейся волны

$$\mathrm{U} = \sum_{j=1}^{N} \exp\left[i \sum_{k=0}^{j-1} \omega_{k,k+1}^{(\Omega)}\, t \right] |j\rangle\langle j| , \qquad \mathrm{H} \to UHU^{+} + i\hbar \frac{dU}{dt} U^{+}$$

$$H_{JC} = \sum_{j=1}^{N} \hbar \left(\widetilde{\omega}_j - \widetilde{\omega}_0 - \sum_{k=0}^{j-1} \omega_{k,k+1}^{(\Omega)} \right) |j\rangle\langle j| + \sum_{j=0}^{N-1} \frac{\hbar\Omega_{j,j+1}}{2} \left(|j+1\rangle\langle j| + h.c. \right)$$

Ограничившись первыми 3мя уровнями

$$H = \begin{pmatrix} 0 & \Omega_{01}(t) & 0 \\ \Omega_{01}(t) & 2\delta_{01} & \Omega_{12}(t) \\ 0 & \Omega_{12}(t) & 2(\delta_{01} + \delta_{12}) \end{pmatrix}$$

$\delta_{j,j+1} = \widetilde{\omega}_{j+1} - \widetilde{\omega}_j - \omega_{j,j+1}^{(\Omega)}$ - отстройка

$$|\Psi_{\mathrm{i}}\rangle = |0\rangle$$

$$\hat{U}_{prep} = \exp\left[-i\begin{pmatrix} 0 & \Delta & 0 \\ \Delta & \epsilon & \Delta \\ 0 & \Delta & 0 \end{pmatrix}\right]$$

$$\frac{1}{\sqrt{3}}\left(e^{i\frac{\pi}{6}}|0\rangle + ie^{-i\epsilon}|1\rangle + e^{i\frac{5\pi}{6}}|2\rangle\right)$$

$$\hat{U}_{count}(\omega) = \exp\left[i\begin{pmatrix} 0 & 0 & 0 \\ 0 & \omega & 0 \\ 0 & 0 & 2\omega \end{pmatrix}t\right]$$

$$\frac{1}{\sqrt{3}}\left(e^{i\frac{\pi}{6}}|0\rangle + ie^{-i(\epsilon-\omega t)}|1\rangle + e^{i\frac{5\pi}{6}}e^{2i\omega t}|2\rangle\right)$$

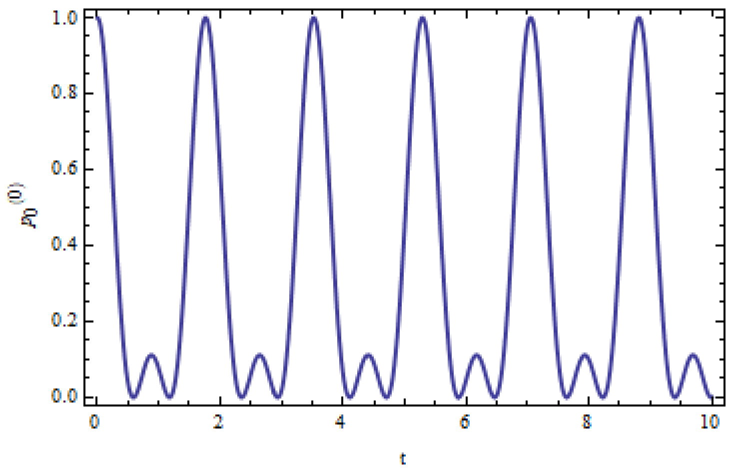
$$\hat{U}_{meas} = \exp\left[i\begin{pmatrix} 0 & \Delta & 0 \\ \Delta & \epsilon & \Delta \\ 0 & \Delta & 0 \end{pmatrix}\right]$$

$$\epsilon = 0.85246,$$
$$\Delta = -1.2953$$

$$|\Psi_f\rangle = \frac{1}{3}\begin{pmatrix} 1 + e^{i\omega t} + e^{2i\omega t} \\ -ie^{i\epsilon}e^{i\frac{\pi}{6}}\left(1 + e^{i\frac{4\pi}{3}}e^{i\omega t} + e^{i\frac{2\pi}{3}}e^{2i\omega t}\right) \\ e^{-i\frac{2\pi}{3}}\left(1 + e^{i\frac{2\pi}{3}}e^{i\omega t} + e^{i\frac{4\pi}{3}}e^{2i\omega t}\right) \end{pmatrix}$$

- $H = h_0\left(\frac{t_0}{3^0} + \frac{t_1}{3^1} + \cdots + \frac{t^{K-1}}{3^{K-1}}\right)$

- $p_i^{(0)} = \frac{1}{3}\left[1 + 2\cos\left(\omega(H)t - \frac{2\pi}{3}i\right)\right]^2, \quad i = 0,1,2$



Байесовская схема

- $P^{(i)}(\omega(H)|i) = \frac{P_i(\omega(H))P^{(i-1)}(\omega(H))}{P(i)}$

- $\omega \epsilon \{\omega_m\}_{m=1}^{M}$
- $P^{(0)}(\omega_m) = \frac{1}{\mathrm{M}}$

- $P\left(\omega(H) - \widetilde{\omega}|\vec{t}\right) = \frac{1}{2\pi}\frac{\sin^2[3^K(\omega(H)-\widetilde{\omega})t_K/2]}{3^K\sin[(\omega(H)-\widetilde{\omega})t_K/2]}$

$$|\Psi_{\mathrm{i}}\rangle = |0\rangle$$

$$\widehat{U}_{prep} = \exp\left[-i\begin{pmatrix} 0 & \Delta & 0 \\ \Delta & \epsilon & \Delta \\ 0 & \Delta & 0 \end{pmatrix}\right]$$

$$|\Psi_{\mathrm{prep}}\rangle = \frac{1}{\sqrt{3}}\left(e^{i\frac{\pi}{6}}|0\rangle + ie^{-i\epsilon}|1\rangle + e^{i\frac{5\pi}{6}}|2\rangle\right)$$

$$\widehat{U}_{count}(\omega) = \exp\left[i\begin{pmatrix} 0 & 0 & 0 \\ 0 & \omega & 0 \\ 0 & 0 & 2\omega \end{pmatrix}t\right]$$

$$\boldsymbol{\frac{d\rho}{dt} = \widehat{\mathcal{L}}\rho}$$

$$\rho$$

$$\widehat{U}_{meas} = \exp\left[i\begin{pmatrix} 0 & \Delta & 0 \\ \Delta & \epsilon & \Delta \\ 0 & \Delta & 0 \end{pmatrix}\right]$$

$$\rho_f$$

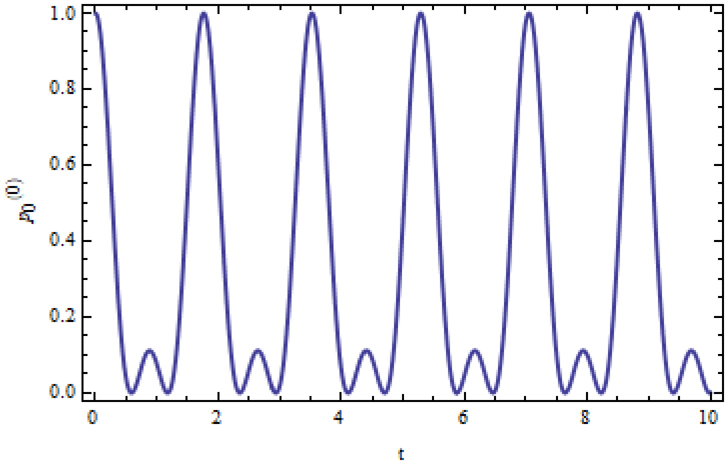
$\epsilon = 0.85246,$

$\Delta = -1.2953$

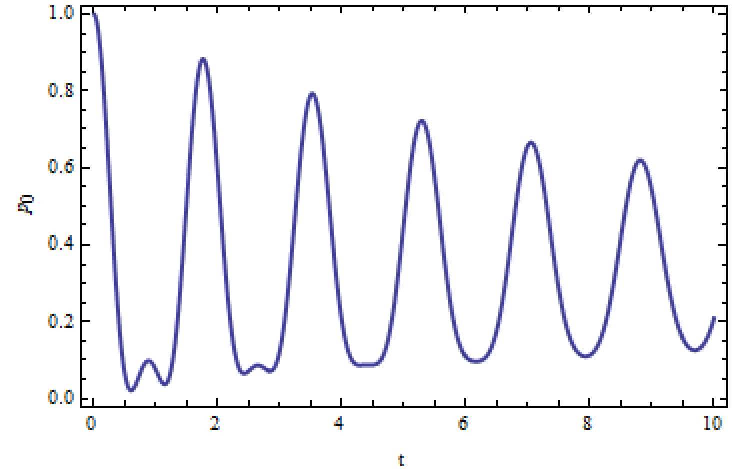
$$\frac{d\rho}{dt} = -i\left[\rho, \widehat{H}_{sys}\right] + \Gamma_{01} D[\sigma_{01}]\rho + \Gamma_{12} D[\sigma_{12}]\rho,$$

$$\langle \delta H(t) \rangle = 0, \qquad \langle \delta H(t)\delta H(t') \rangle = \left(\frac{d\omega}{dH}\right)^{-2} \Gamma_\varphi \delta(t - t')$$

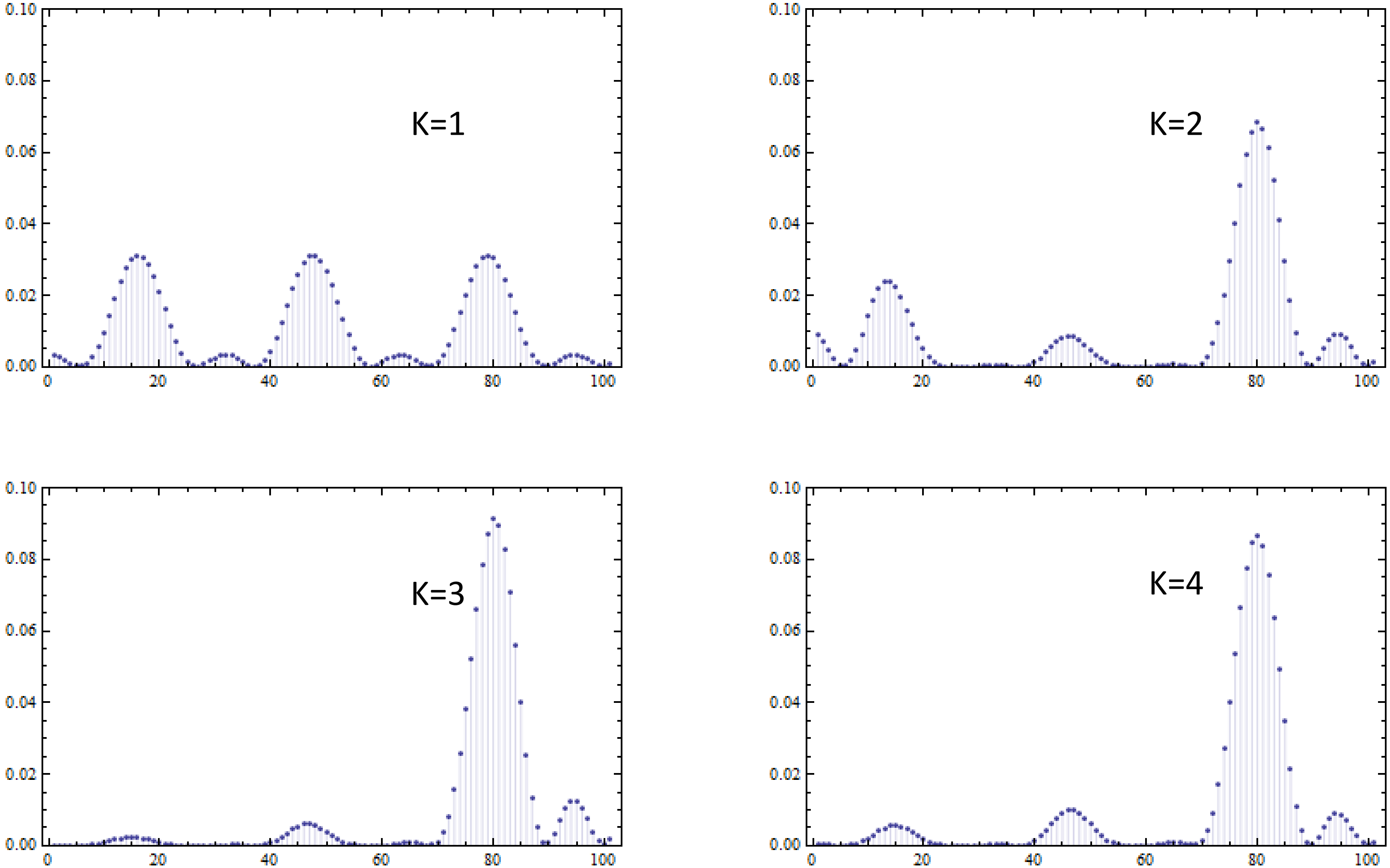
$$p_i^{(0)} = \frac{1}{3}\left[1 + 2\cos\left(\omega(H)t - \frac{2\pi}{3} i\right)\right]^2, \quad i = 0,1,2$$



$$p_i = \frac{1}{3} + \frac{2}{9}\cos\left(\omega(H)t - \frac{2\pi}{3} i\right) e^{-\frac{(\Gamma_{01}+\Gamma_\varphi)}{2} t} + \frac{2}{9}\cos\left(\omega(H)t - \frac{2\pi}{3} i\right) e^{-\frac{(\Gamma_{01}+\Gamma_{12}+\Gamma_\varphi)}{2} t} + \frac{2}{9}\cos\left(2\omega(H)t - \frac{4\pi}{3} i\right) e^{-\frac{(\Gamma_{12}+4\Gamma_\varphi)}{2} t}, \quad i = 0,1,2$$

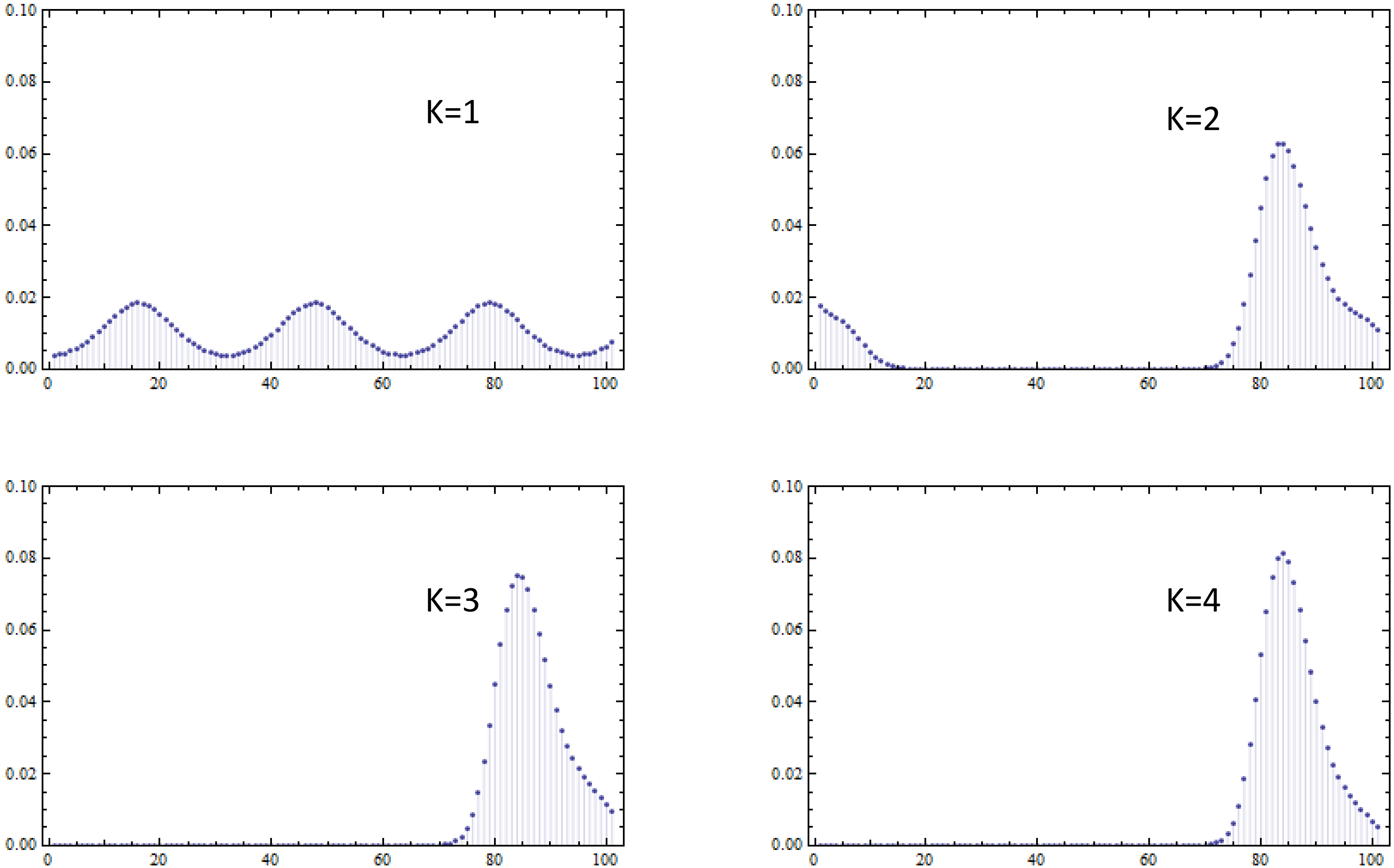


Случай слабой декогеренции: $t \ll T_2$



$$P\big(\omega(H) - \widetilde{\omega} | \vec{t}\big) = \frac{1}{2\pi} \frac{\sin^2[3^K(\omega(H) - \widetilde{\omega})t_K/2]}{3^K \sin[(\omega(H) - \widetilde{\omega})t_K/2]}$$

Случай сильной декогеренции: $t \approx T_2$



N=10

- $H\left(P^{(i)}(\omega)\right) = -\sum_{m=0}^{M} P^{(i)}(\omega_m) \ln P^{(i)}(\omega_m)$

- $H\left(P^{(i)}(\omega)\right) \rightarrow min \Rightarrow t_1^*$