Low frequency charge noise in coupled Josephson qubits

A. Mastellone, A. D'Arrigo, E. Paladino, and G. Falci

DMFCI, MATIS, CNR-INFM
Catania University

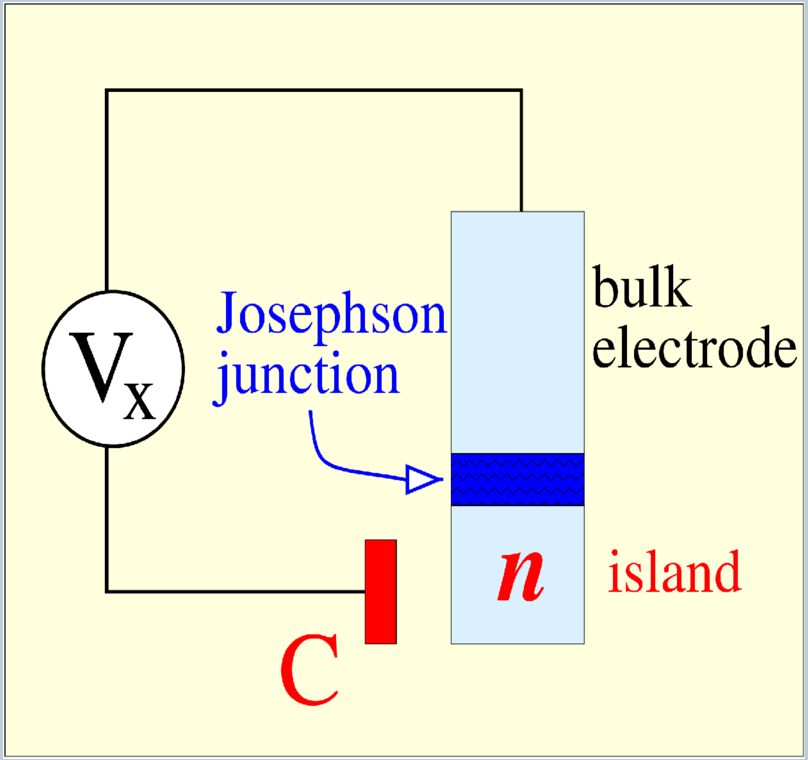
A. Mastellone, A. D'Arrigo, E. Paladino, and G. Falci, EPJ ST, *in press*
A. Mastellone, A. D'Arrigo, E. Paladino, and G. Falci, IJQC, *in press*
A. Mastellone, A. D'Arrigo, E. Paladino, and G. Falci, *in preparation*

Outline

- ✗ Josephson qubits
- ✗ Noise sources
- ✗ Coupled qubits and i-SWAP gate
- ✗ Slow noise : adiabatic approximation
- ✗ Switching probability decay

A. Mastellone, A. D'Arrigo, E. Paladino, and G. Falci, EPJ ST, *in press*
A. Mastellone, A. D'Arrigo, E. Paladino, and G. Falci, IJQC, *in press*
A. Mastellone, A. D'Arrigo, E. Paladino, and G. Falci, *in preparation*

Josephson qubits and noise



Cooper Pair Box (CPB)

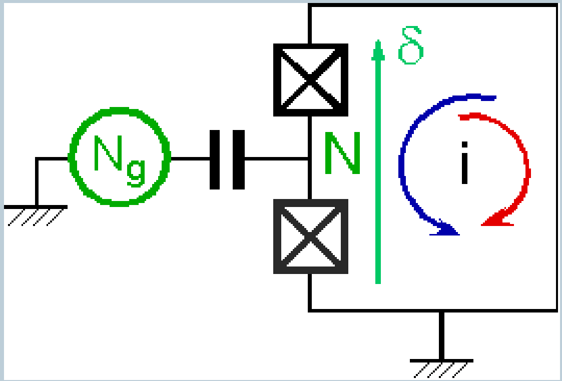
- Small (micron size) superconducting island with a Josephson junction

- Two relevant terms
  Charging energy E_C required to add one Cooper pair to island
  Josephson energy E_J related to the coherent tunneling across the junction

- The charging energy is **tunable** via the gate voltage V_X and this allows control of the pair number on the island → computational states = charge states

Nakamura et al., *Nature* 1999

Josephson qubits and noise



Quantronium

- Splitted Cooper Pair Box in a loop.

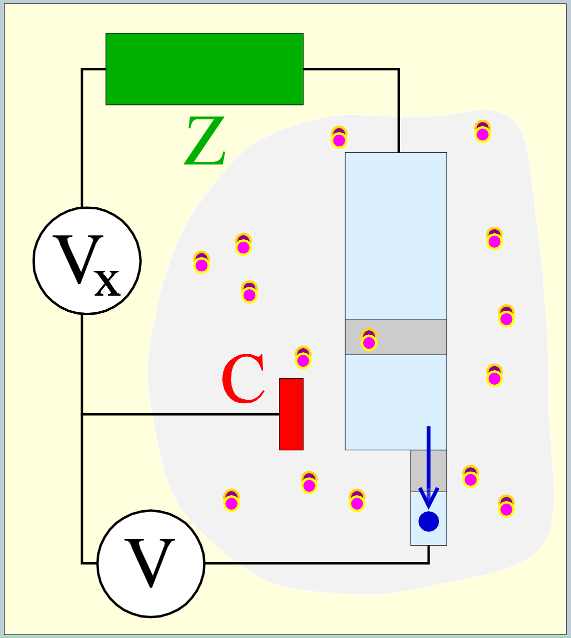
- Two control knobs : **gate voltage** and **loop phase** (magnetic flux) → energy levels tuning (and **noise** ! ☹)

- T → 0 : two lowest eigenstates correspond to the **computational basis**

Noise sources

Electromagnetic fluctuations of the circuit -> **impedance** Z

Discrete noise sources
- fluctuating background charges (BC) trapped in the substrate or in the junction
- trapped flux at the junctions
Modelled as **bistable fluctuators** (rate γ)



Vion et al., *Science* 2002; Paladino et al., *PRL* 2002; Ithier et al., *PRB* 2005

Optimal point

Quantronium Hamiltonian

$$\mathcal{H} = E_C(\hat{q} - q_x \mathbb{I})^2 - E_J(\delta)\cos\hat{\varphi}$$

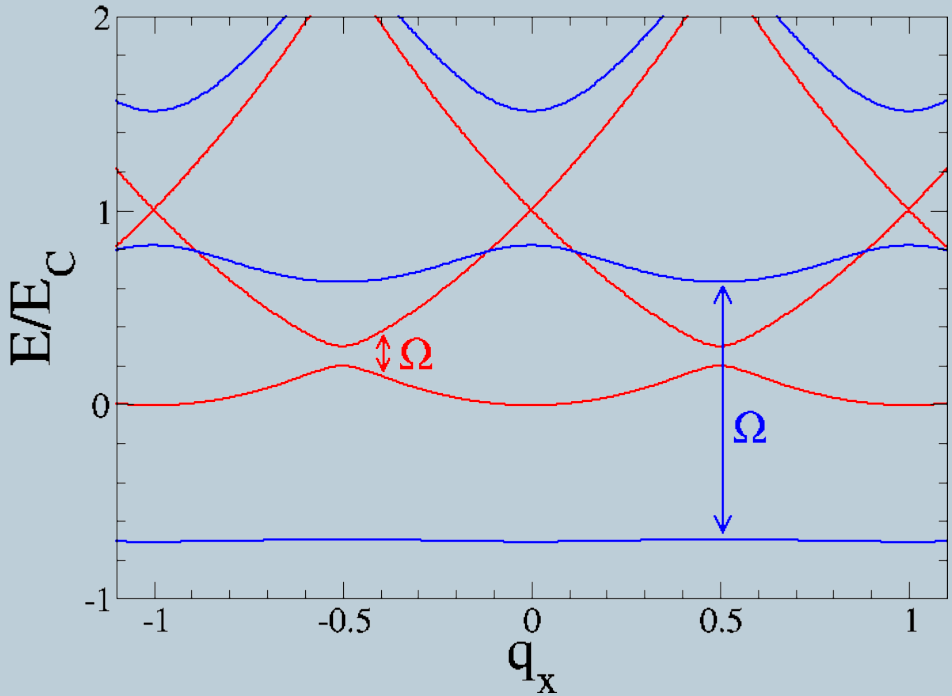
The control knobs introduce **noise** in the system ↔ **fluctuations** of q_x and δ

At the **optimal point** ($q_x=1/2$, $\delta=0$) the effect of fluctuations on energy levels is **minimized**

Charge fluctuations are most **detrimental** than the phase ones

In the charge-phase regime the splitting is less sensitive to charge fluctuations

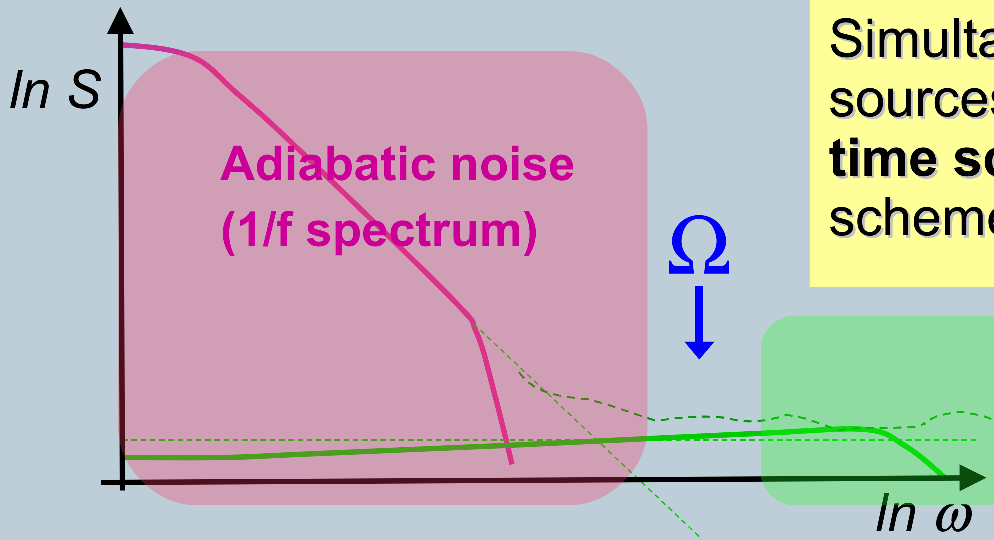
$E_J/E_C=0.1$ $E_J/E_C=1.5$



Vion et al., *Science* 2002; Falci et al., *OSID* 2006

Noise characterization

Variety of observations, material & device dependent



Simultaneous presence of noise sources with **different characteristic time scales** (different approximation schemes)

1/f noise : Adiabatic approximation

Quantum noise: Spontaneous decay, Markovian Master Equation

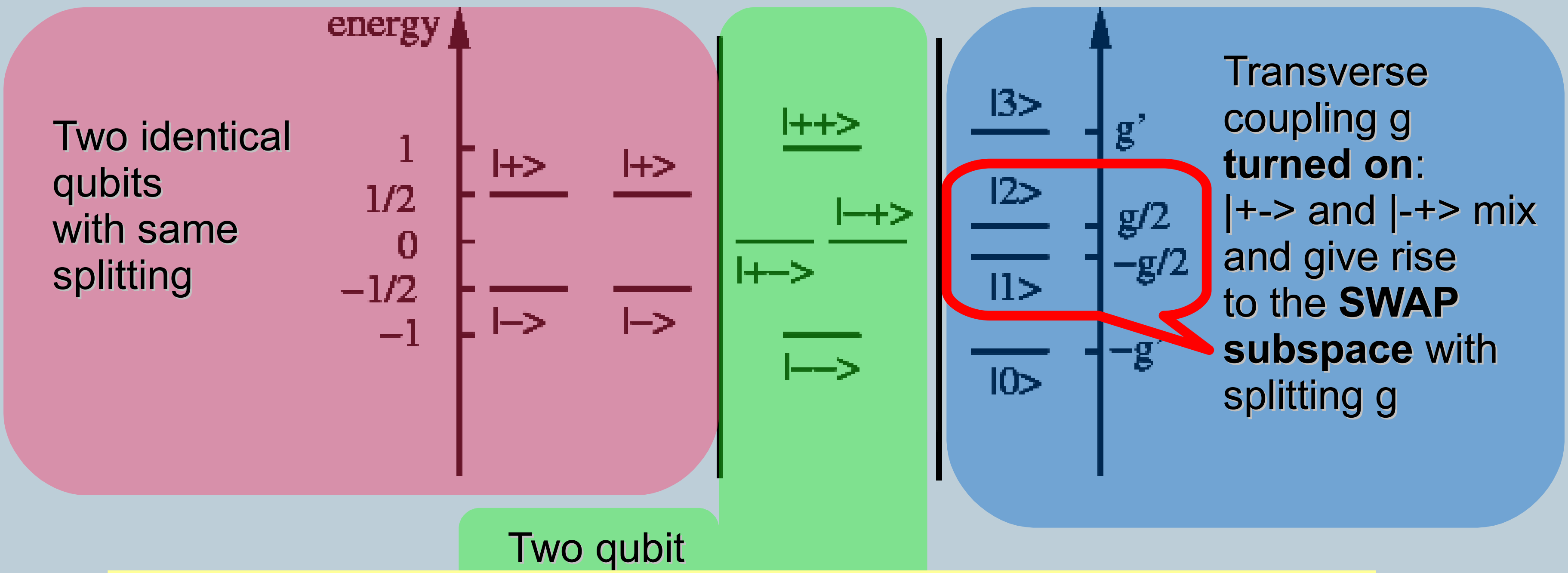
Here we consider only the **slow** (adiabatic noise) component

Astafiev et al., *PRL* 2004; Falci et al., *PRL* 2005; Paladino et al., *PRL* 2002

I-SWAP gate

A **two-qubit gate** is a **mandatory step** torward a quantum computer since it provides **entanglement**

Simple implementation in a fixed-coupling scheme: **i-SWAP** gate



SWAP space is fully **decoupled**: a system prepared in |+->
will freely evolve to the entangled one |+-> - i |-+>

Nielsen and Chuang, *Quantum Computation and Quantum Information*, 2000

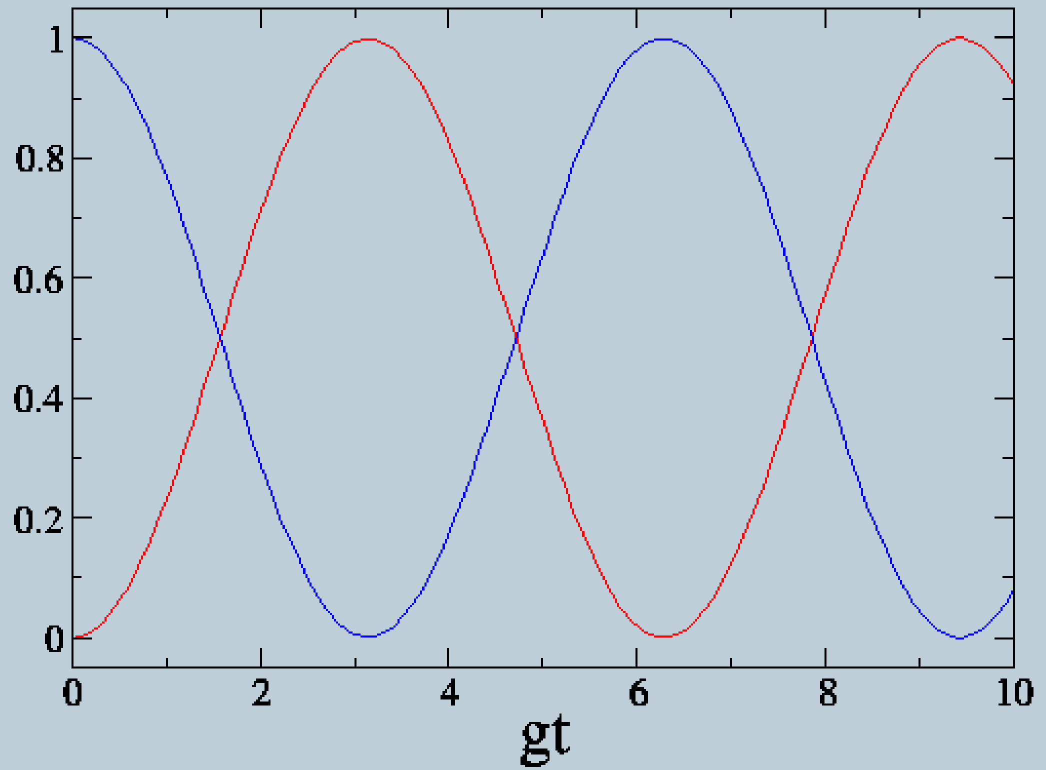
I-SWAP gate

Detection of i-SWAP gate:

P_1 : switching probability of qubit 1 from the initial state |+> to |->

P_2: probability of finding qubit 2 in the initial state |->

Anticorrelation !



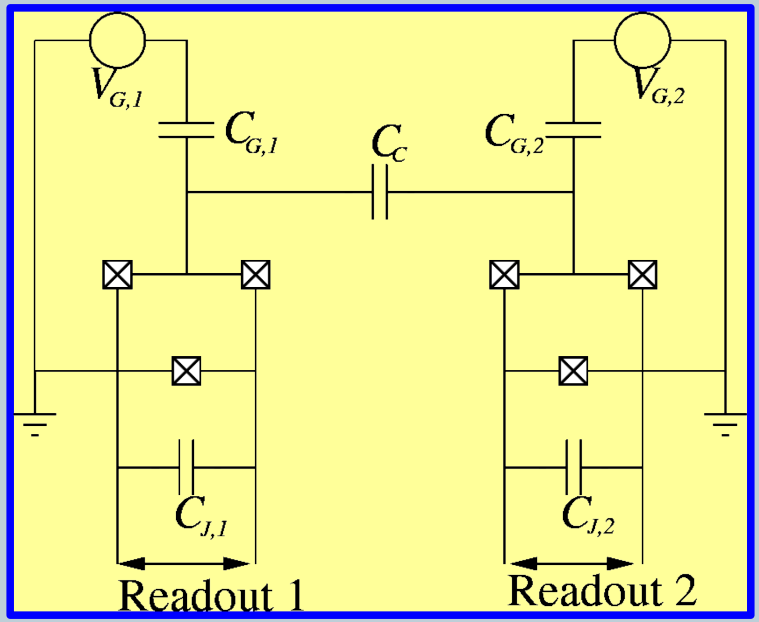
The anticorrelation of the probabilities **has been detected** !

D. Vion, *private communication*, 2007

Coupled Josephson qubits

Single qubit Hamiltonian

$$\mathcal{H}_\alpha = E_{\alpha,\mathrm{C}}(\hat{q}_\alpha - q_{\alpha,\mathrm{x}}\mathbb{I}_\alpha)^2 - E_{\alpha,\mathrm{J}}(\delta_\alpha)\cos\hat{\varphi}_\alpha$$



Two qubits with **fixed capacitive** coupling Hamiltonian

$$\mathcal{H} = \mathcal{H}_1 \otimes \mathbb{I}_2 + \mathbb{I}_1 \otimes \mathcal{H}_2 + E_{CC}(\hat{q}_1 - q_{1,\mathrm{x}}\mathbb{I}_1) \otimes (\hat{q}_2 - q_{2,\mathrm{x}}\mathbb{I}_2)$$

A. Mastellone, A. D'Arrigo, E. Paladino, and G. Falci, EPJ ST, *in press*
A. Mastellone, A. D'Arrigo, E. Paladino, and G. Falci, *in preparation*

Coupled Josephson qubits

Outline

Josephson qubits

Noise

i-SWAP

Coupled qubits

Slow noise

Adiabatic method

Coherence decay

Conclusions

Two qubits with **fixed capacitive** coupling Hamiltonian

$$\mathcal{H} = \mathcal{H}_1 \otimes \mathbb{I}_2 + \mathbb{I}_1 \otimes \mathcal{H}_2 + E_{CC}(\hat{q}_1 - q_{1,x}\mathbb{I}_1) \otimes (\hat{q}_2 - q_{2,x}\mathbb{I}_2)$$

At low temperature the Hamiltonian is truncated to the four lowest energy states and rewritten in the pseudospin formalism

$$\mathcal{H}_S = -\frac{1}{2}\sigma_3^{(1)} \otimes \mathbb{I}_2 - \frac{1}{2}\mathbb{I}_1 \otimes \sigma_3^{(2)} + \frac{g}{2}\sigma_1^{(1)} \otimes \sigma_1^{(2)}$$

Dimensionless in terms of the common splitting Ω

The qubits are at **resonance** (common splitting)
The coupling is **transverse** at charge optimal point !

A. Mastellone, A. D'Arrigo, E. Paladino, and G. Falci, EPJ ST, *in press*
A. Mastellone, A. D'Arrigo, E. Paladino, and G. Falci, *in preparation*

Slow noise: adiabatic method

CEWQO 2008 Belgrade

Charge noise as fluctuations in the control parameter

$$q_{\alpha,x} \to q_{\alpha,x} + \delta q_{\alpha,x} \qquad \mathcal{H} \to \mathcal{H} + \delta\mathcal{H}$$

Additional noise term in the pseudo-spin representation (neglecting correlations)

$$\delta\mathcal{H} = -\frac{1}{2} x_1 \sigma_1^{(1)} \otimes \mathbb{I}_2 - \frac{1}{2} x_2 \mathbb{I}_1 \otimes \sigma_1^{(2)}$$

$$x_\alpha = \frac{4 q_{+-}^{(\alpha)} E_{\alpha,C}}{\Omega} \delta q_{\alpha,x}$$

$$q_{+-}^{(\alpha)} = \langle + | \hat{q}_\alpha | - \rangle$$

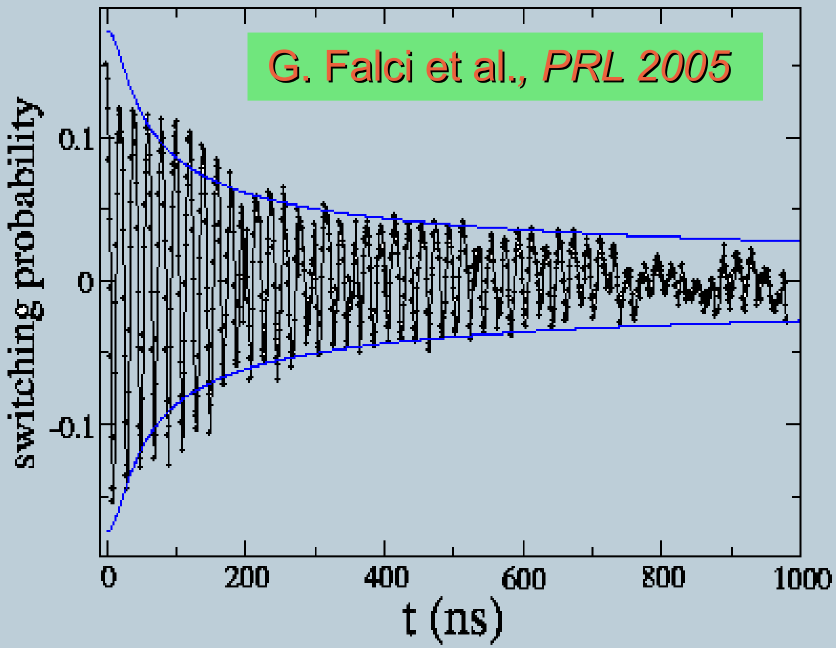
Slow noise: $\gamma_M < \Omega$ → **Adiabatic approximation**

- Qubit **populations** remain **constant**
- **Coherences: Static Path Approximation** → effects of uncontrolled device calibration in a repeated measurement scheme (analogous to the inhomogeneous broadening in NMR)

G. Falci, A. D'Arrigo, A. Mastellone, E. Paladino, *PRL 2005*

Static Path Approximation

Static path on Single qubit



Large number of fluctuators: gaussian distribution

$$P(x) = \frac{1}{\sqrt{2\pi}\sigma} e^{-x^2/(2\sigma^2)}$$

Variance is related to the noise power spectrum

$$\sigma^2 = \int_0^\infty (d\omega/\pi) S(\omega)$$

Initial suppression of the signal is fitted by $\sigma = 0.02$

Two qubit: switching probability

$$P_1 = \frac{1}{2} + \Re[\rho_{12}(t)]$$

$$\rho_{12}(\tau) = \rho_{12}(0) e^{i\omega_{12}^{(0)}\tau} \int dx_1 dx_2 P(x_1) P(x_2) \exp[i\delta\omega_{12}(x_1, x_2)\tau]$$

P_1 and SWAP coherence initial decays are **equivalent**

Coherence decay

Outline

Josephson qubits

Noise

i-SWAP

Coupled qubits

Slow noise

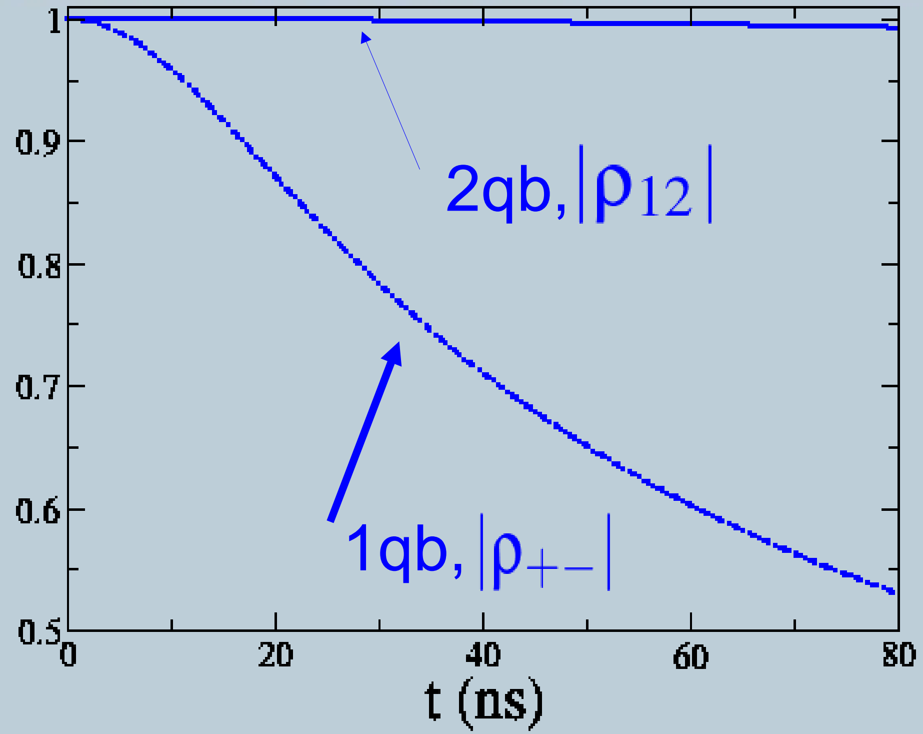
Adiabatic method

Coherence decay

Conclusions

Same noise as in the single qubit setup (σ=0.02 in both qubits)

The **2-qubits SWAP coherence** decays **much slower** than the **1-qubit coherence**



The coherence decay is **minimized** when the SWAP splitting ω_{12} shows a **reduced dependence** against noise parameters.

Variance over noise x_1,x_2

$$\sigma^2_{\delta\omega_{12}} = \frac{\sigma^2}{g}\left[(g^2-\sigma^2)^2+\sigma^4\right]$$

Minimized at g ~ σ

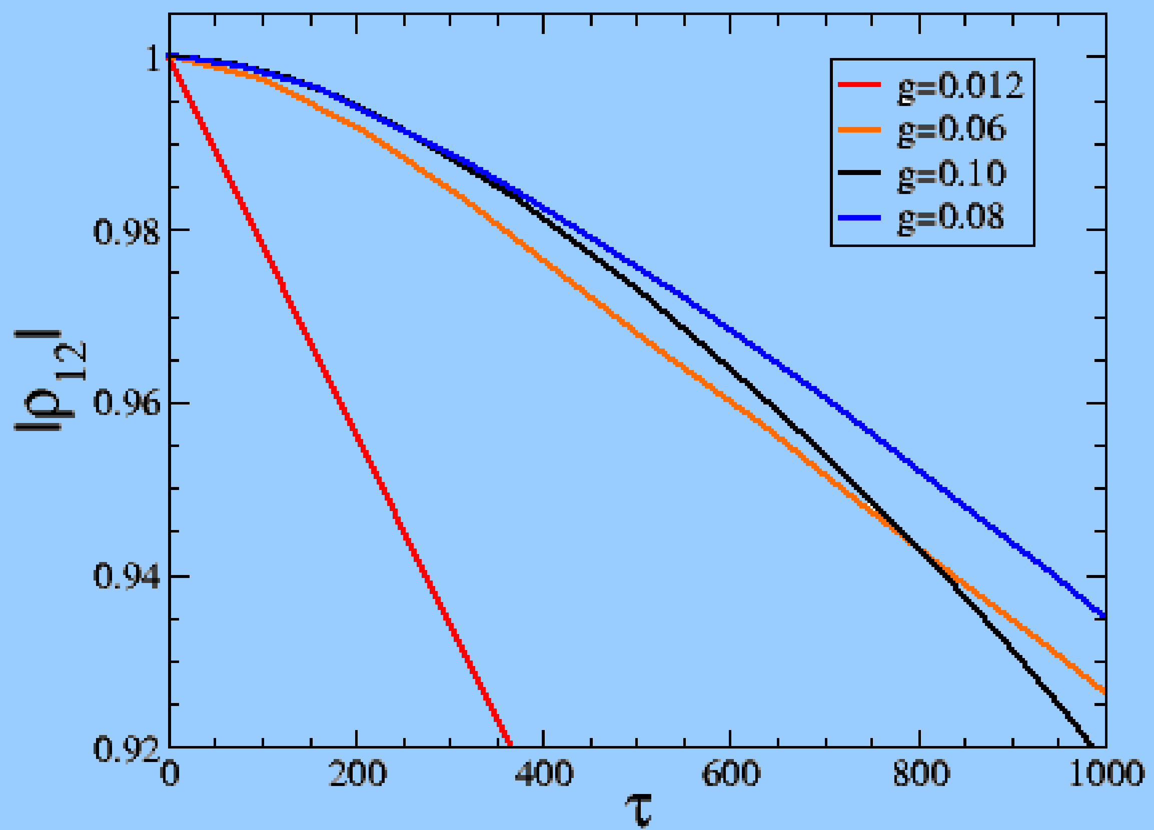
σ is **fixed** when the device is built up but one can always tune the coupling g !

A. Mastellone, A. D'Arrigo, E. Paladino, and G. Falci, *in preparation*

CEWQO 2008 Belgrade

Coherence decay

Strong noise level (σ=0.08)



Decay rate **minimized** at g=0.08 !

σ is **fixed** when the device is built up
but one can always tune the coupling g !

A. Mastellone, A. D'Arrigo, E. Paladino, and G. Falci, *in preparation*

Conclusions

- ✔ SWAP subspace is **protected** against charge noise
- ✔ Effects due to slow charge noise can be **minimized**
- ✔ Work **in progress**: fast charge noise, phase noise and charge noise correlations

Thank you for attention !

Powered by
GNU-Linux and OpenOffice
(preparation) (presentation)