Quantum dynamics in nano Josephson junctions

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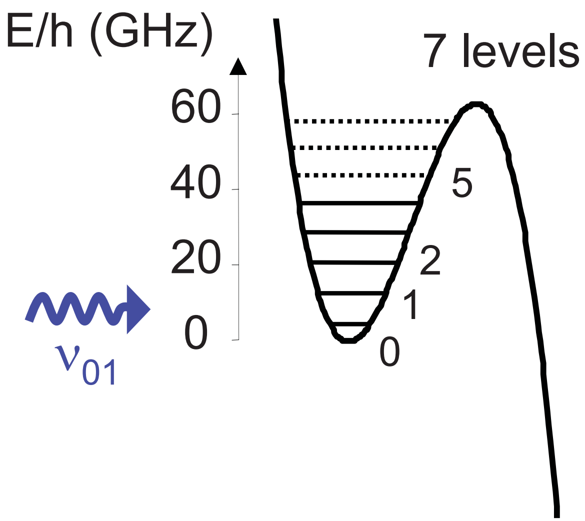
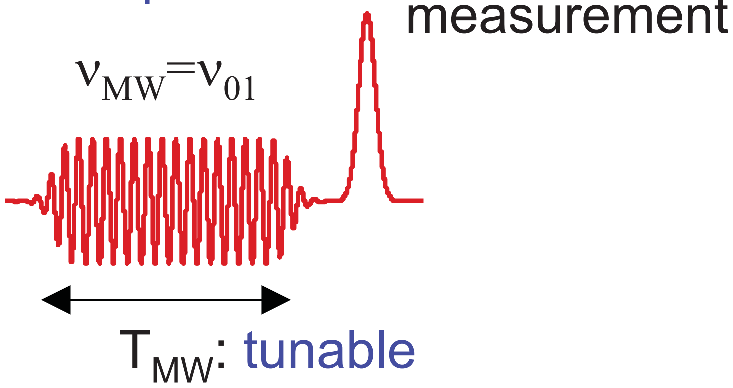
Coherent oscillations in a dc SQUID

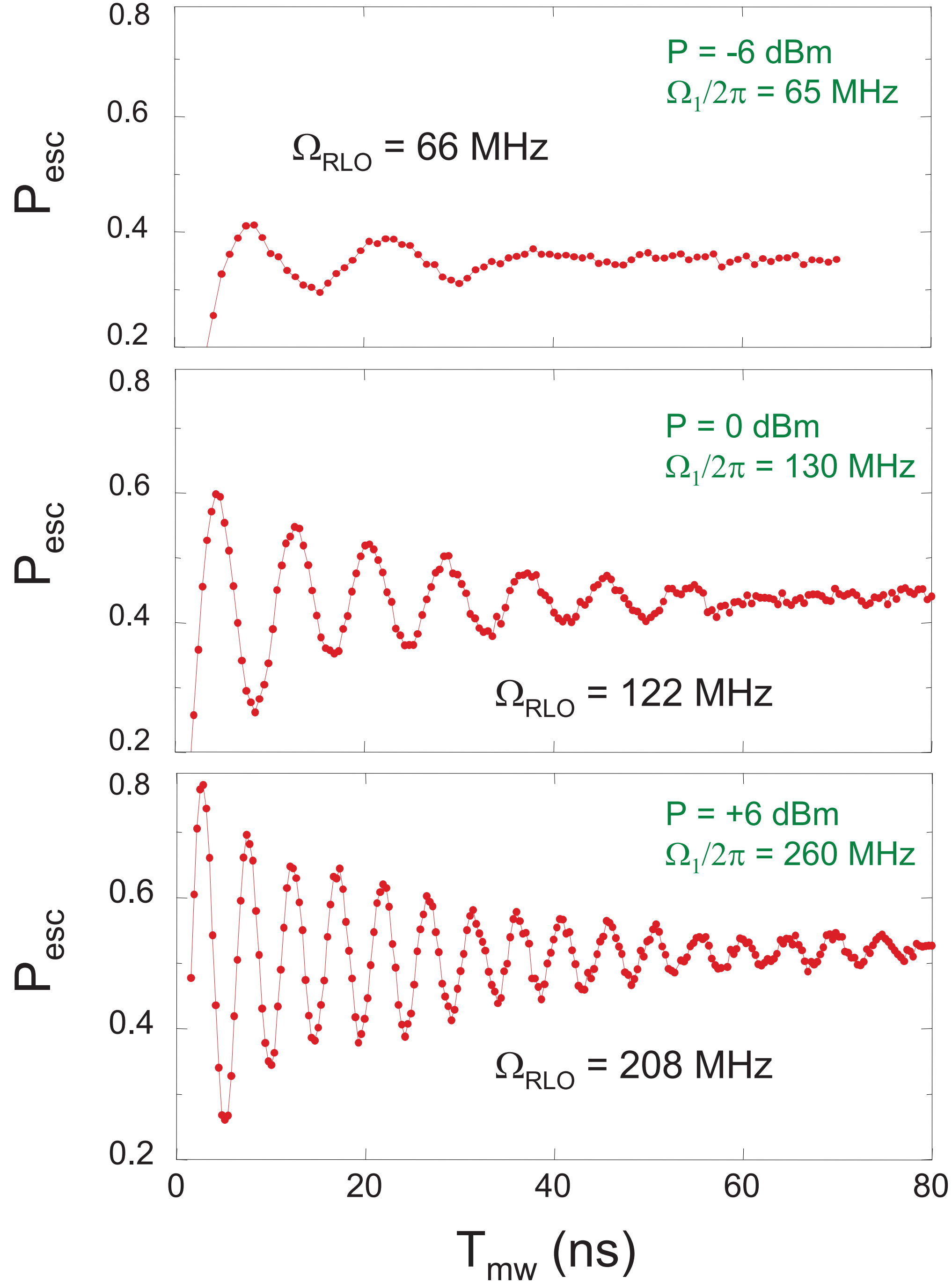
- Anharmonic oscillator:



Anharmonicity: $\nu_{01}-\nu_{12}$ = 160 MHz

- Flux-pulse sequence:





Outline

Introduction to superconducting qubits

Multi-levels artificial atom

- current-biased Josephson junction and dc SQUID
- quantum measurements
- quantum dynamics in a multilevel quantum system
- quantum or classical description
- optimal control
- decoherence processes

Two-degrees of freedom artificial atom

- inductive dc SQUID
- spectroscopy measurements
- strong non-linear coupling
- coherent oscillations

Multi-degrees of freedom system

- Josephson junction chains
- quantum phase slip
- charging effects

Optimal control for a current-biased SQUID

(H. Jirari, FH and O. Buisson, EPL 2009)

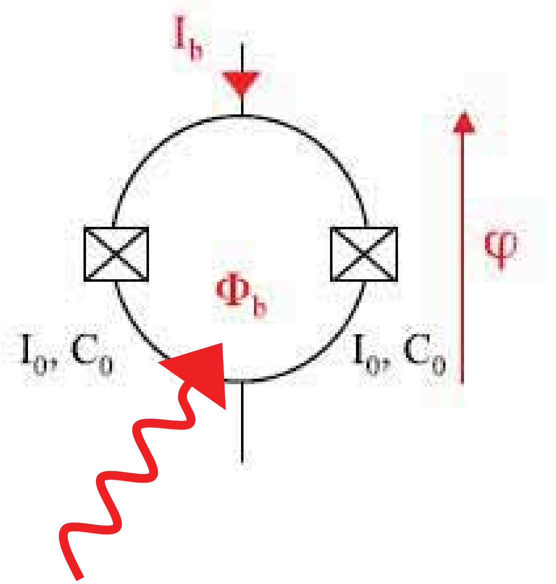
Total Hamiltonian: $\hat{H}_{\rm tot} = \hat{H}_\varphi + \hat{H}_{\rm c}$

system

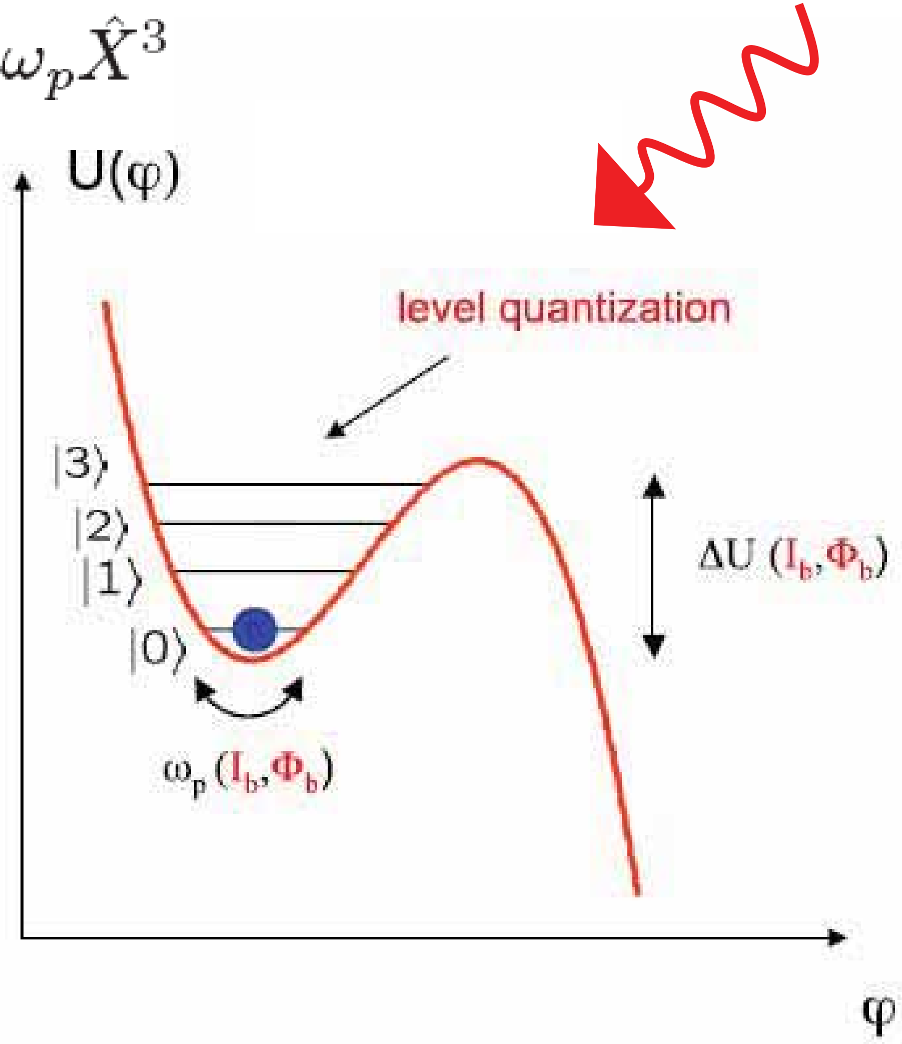
$$\hat{H}_\varphi = \frac{1}{2}\hbar\omega_p(\hat{P}^2 + \hat{X}^2) - \sigma\hbar\omega_p\hat{X}^3$$

control

$$H_{\rm c} = \hbar\omega_p\varepsilon(t)\hat{X}$$



$$\varepsilon(t) = \Phi_b(t)/\Phi_0$$



Statement of the problem

Desired time evolution of quantum system:

We seek a control field : $\varepsilon(t)$

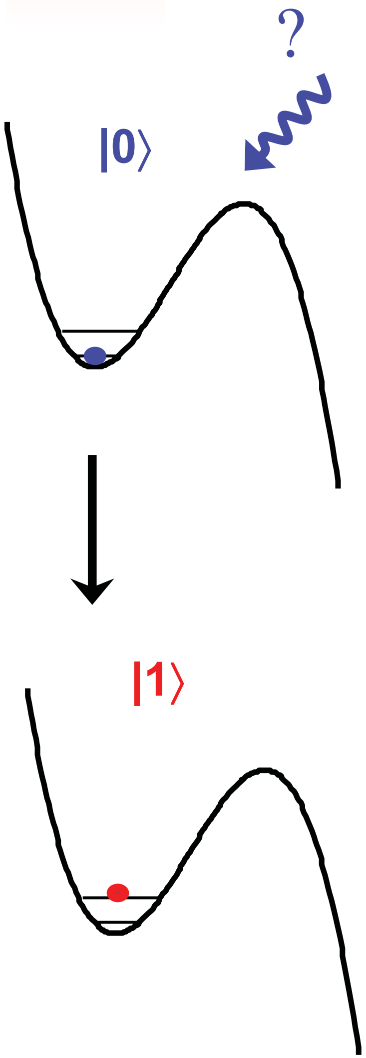
To have a reasonable control field, we add constraints:

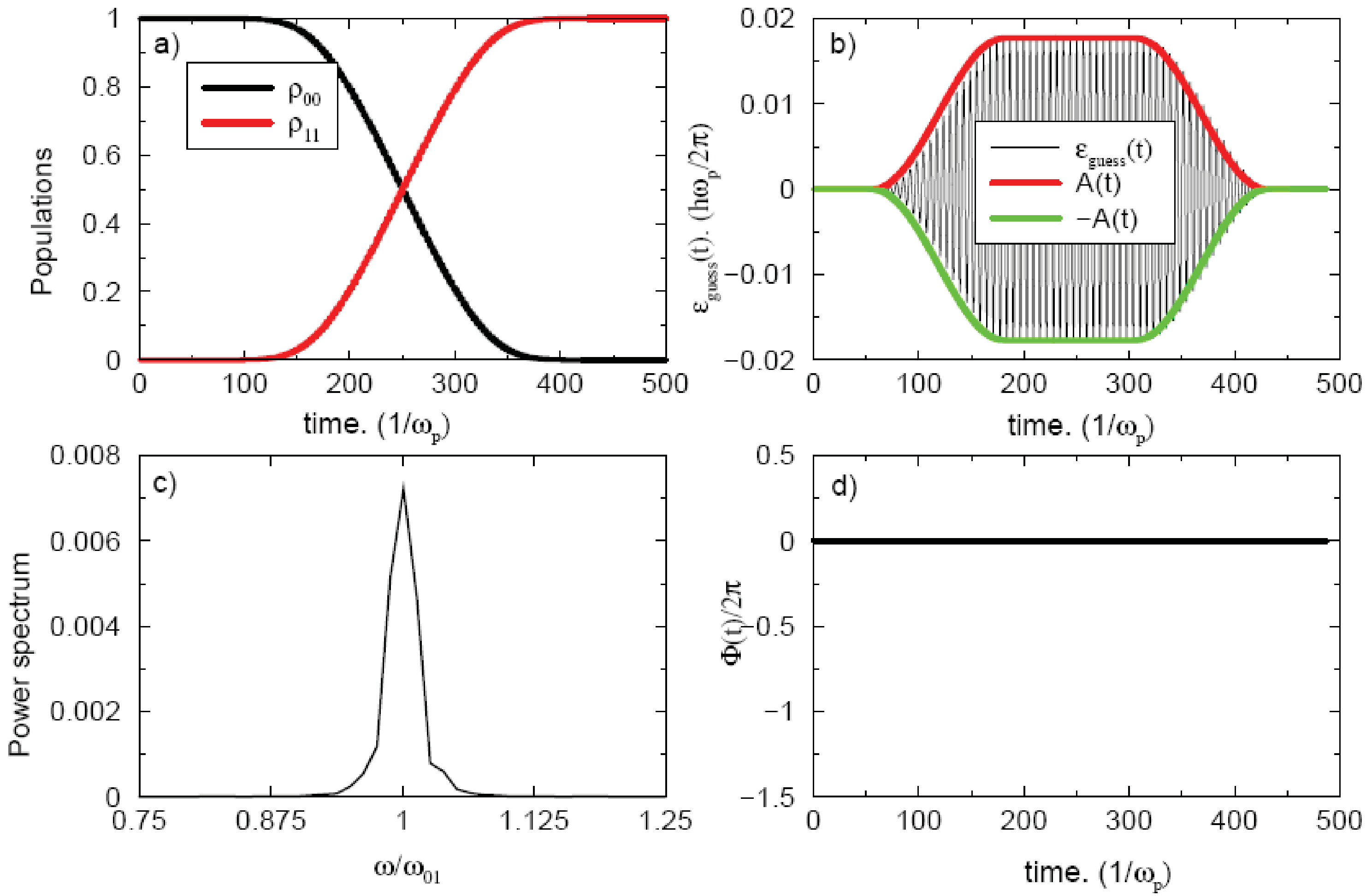
- on the amplitude
- on its time dependence

Test for a two-level system: π-pulse

(H. Jirari, FH and O. Buisson, EPL 2009)

$$\varepsilon_{guess}(t) = A(t)\cos\left[\omega_0 t + \phi(t)\right]$$

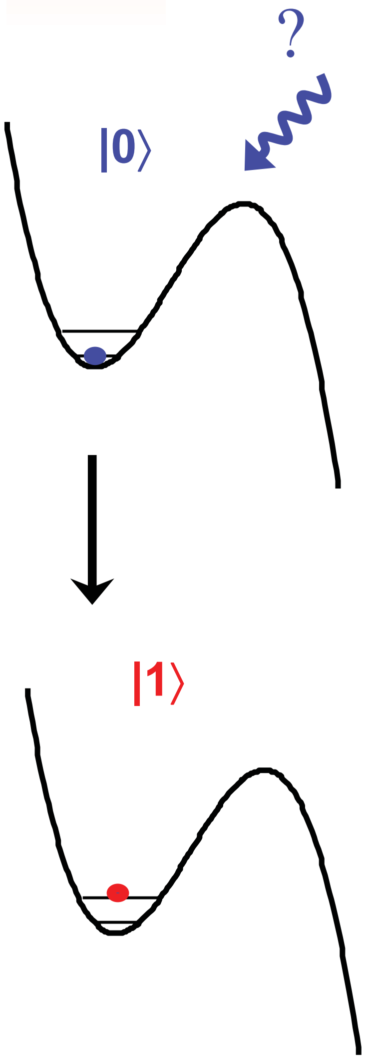


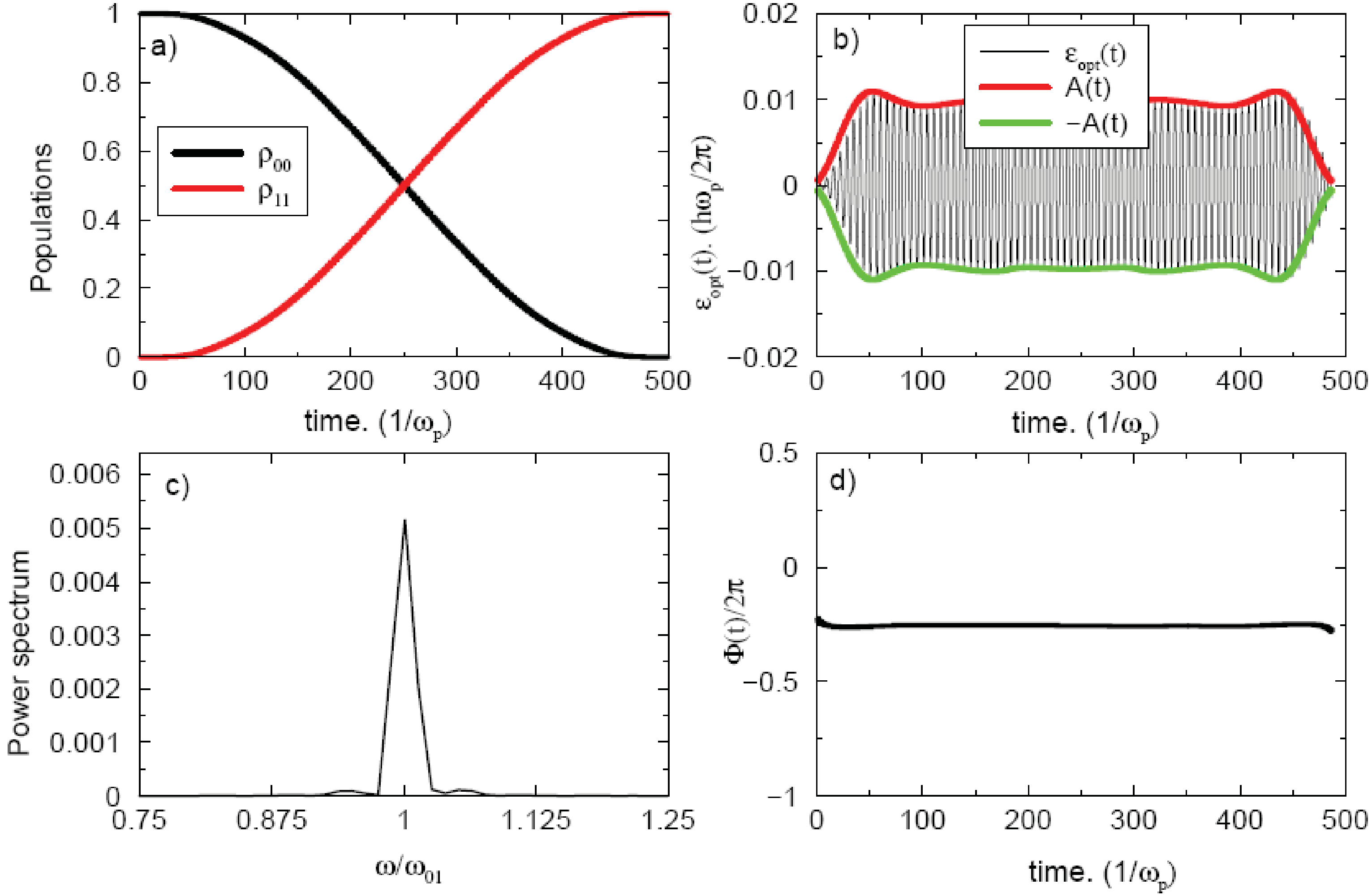


Use π-pulse as a guess for optimal control

(H. Jirari, FH and O. Buisson, EPL 2009)

$$\varepsilon_{\rm opt}(t) = A(t)\cos\left[\omega_0 t + \phi(t)\right]$$

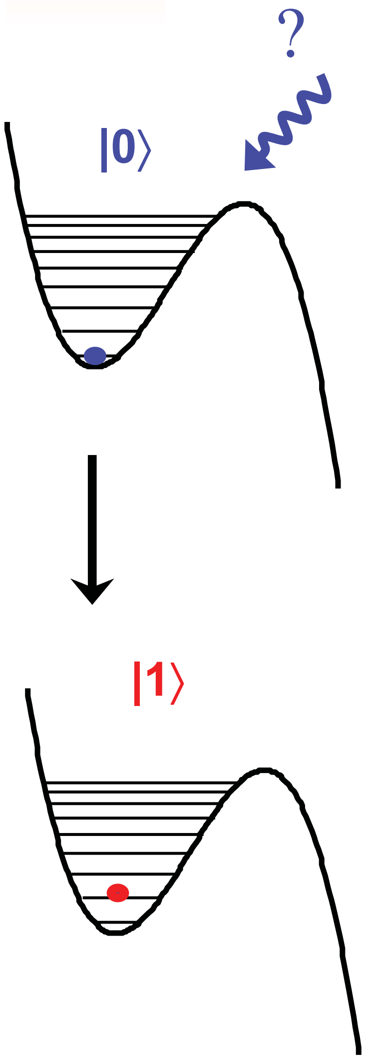


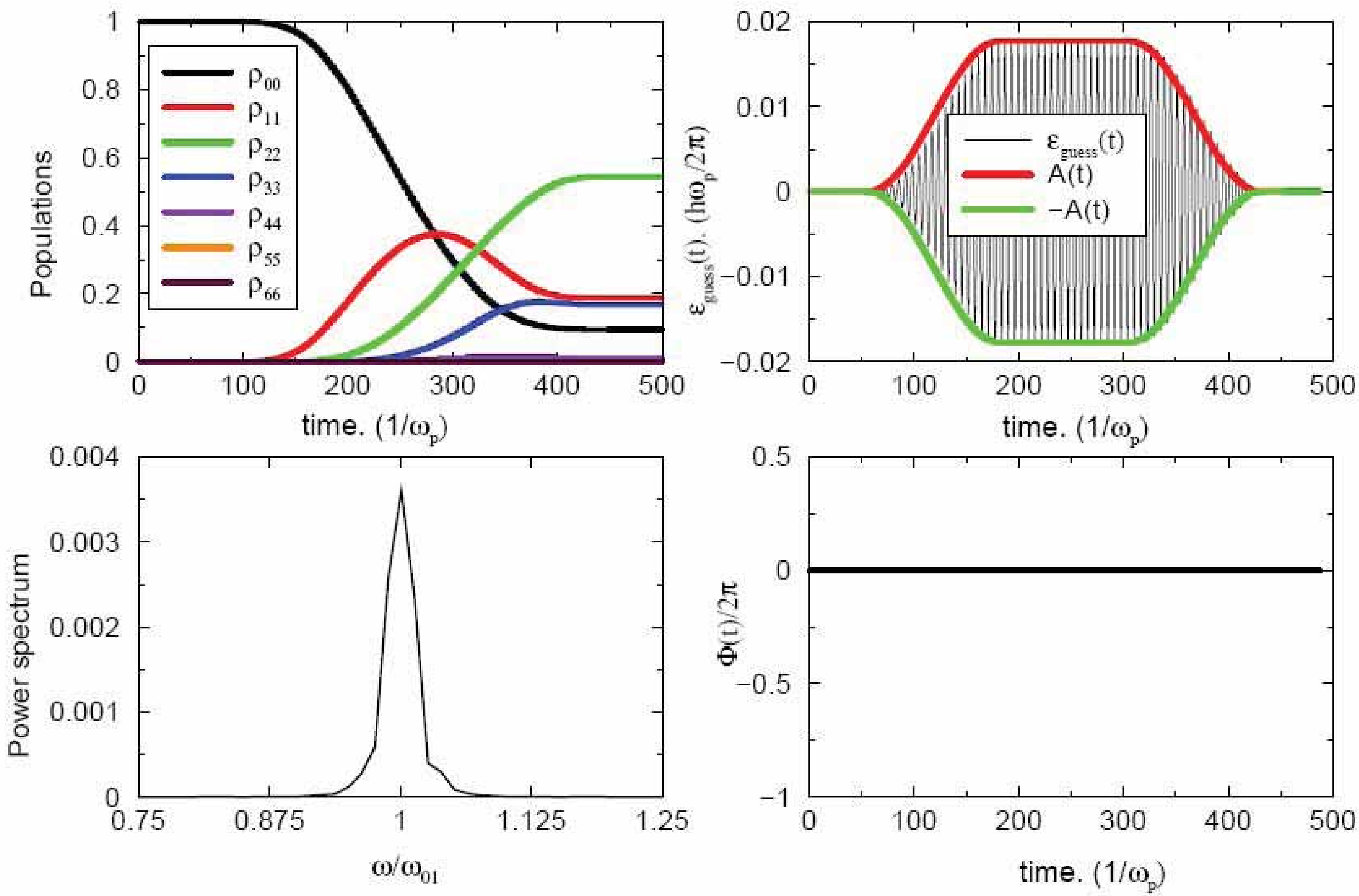


Effect of π-pulse in the presence of other levels

(H. Jirari, F. Hekking and O. Buisson, EPL 2009)

$$\varepsilon_{guess}(t) = A(t)\cos\left[\omega_0 t + \phi(t)\right]$$

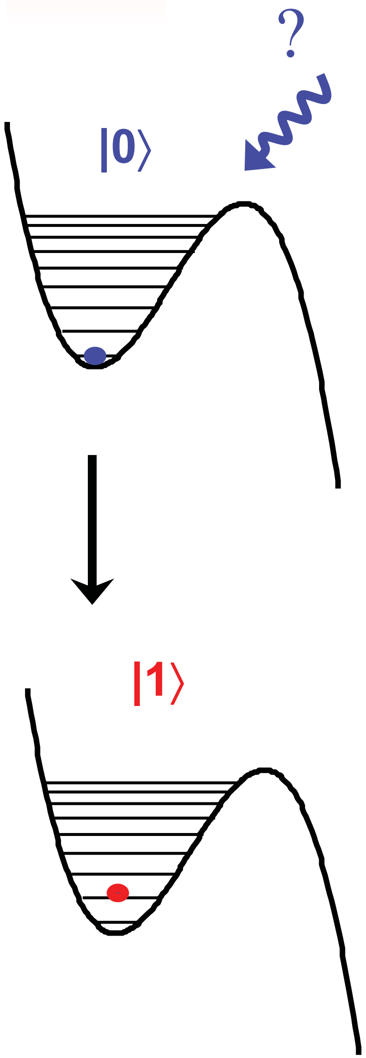


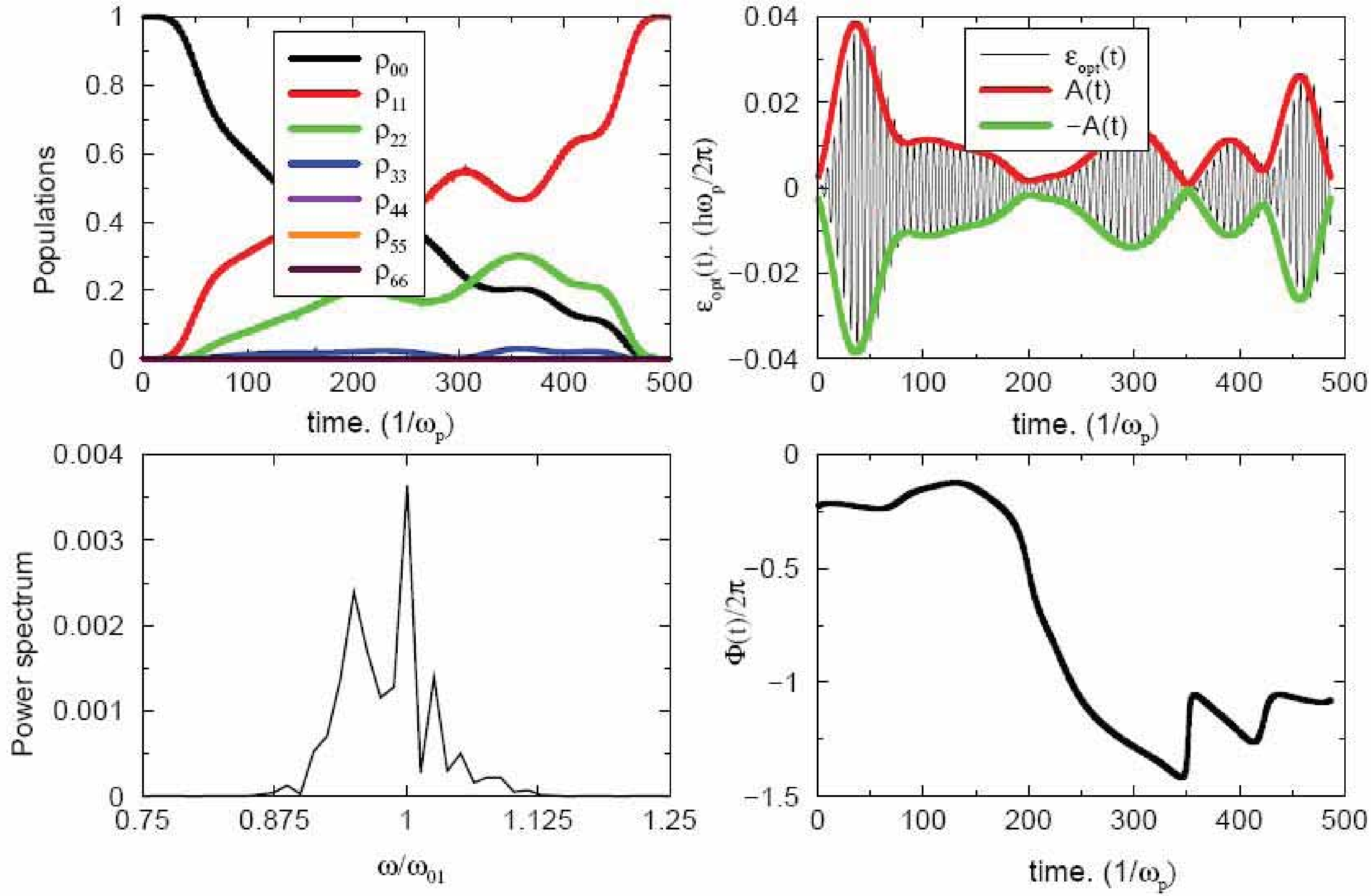


Optimal control in the presence of other levels

(H. Jirari, F. Hekking and O. Buisson, EPL 2009)

$$\varepsilon_{\mathrm{opt}}(t) = A(t)\cos\left[\omega_0 t + \phi(t)\right]$$

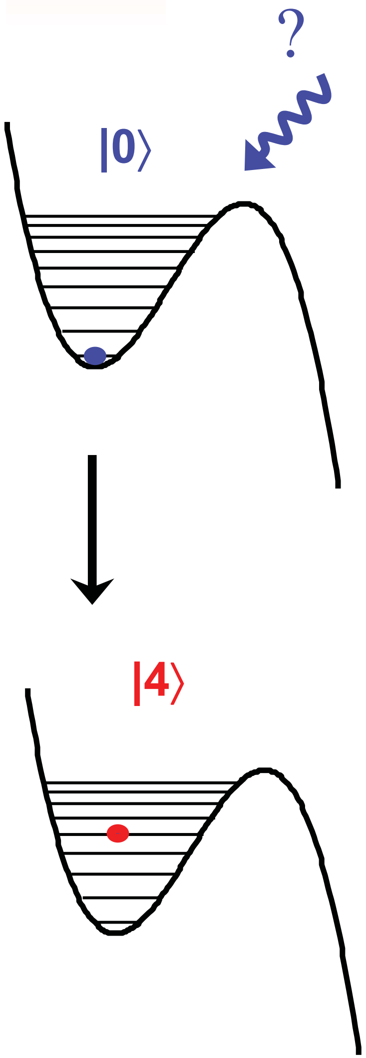


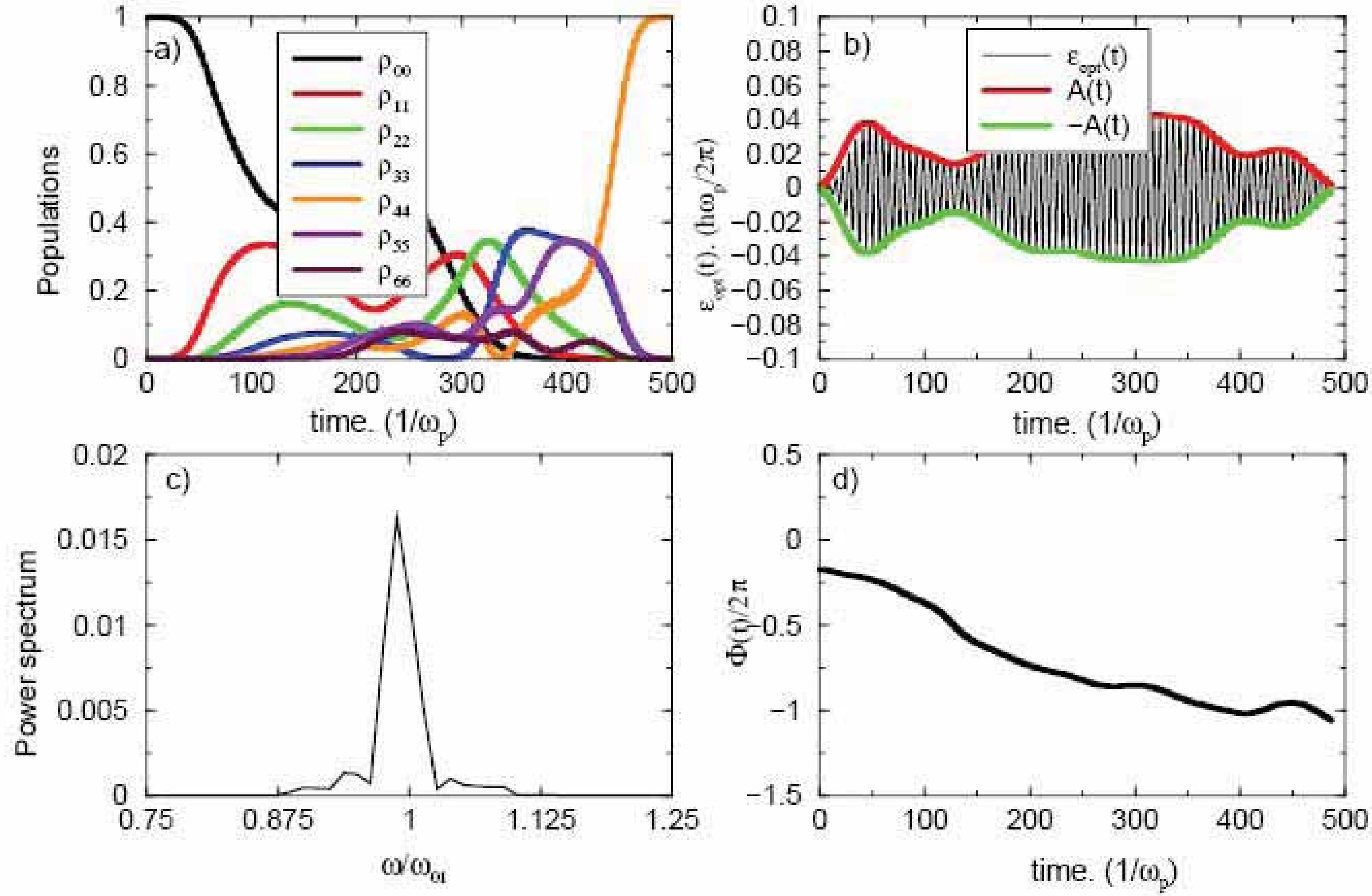


Optimal control for more complicated transitions

(H. Jirari, F. Hekking and O. Buisson, EPL 2009)

$$\varepsilon_{\text{opt}}(t) = A(t)\cos\left[\omega_0 t + \phi(t)\right]$$





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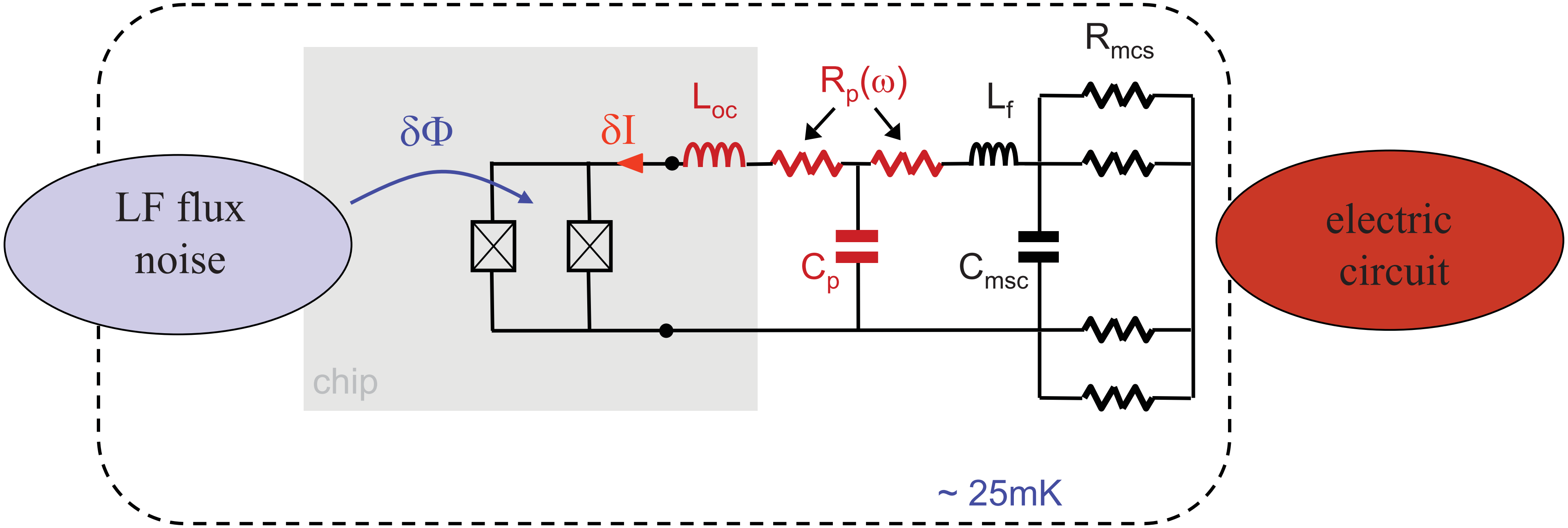
Relevant noise sources

Heavy filtering and shielding

➡ significant fluctuation sources located close to the SQUID



- HF fluctuations from electric circuit —— quantum fluctuation dissipation theorem → $S_I(\omega)$ (long correlation time ~30ns)
- LF flux noise —— MQT analysis → $\sqrt{\langle \delta\Phi^2 \rangle} = 5.5 \times 10^{-4}\ \Phi_0$
- Parasitic Two level fluctuators

Decoherence processes

J. Claudon, A. Fay, L.P. Lévy, and O. Buisson (PRB2006)

SQUID	coupling terms	environment
	linear	

eigenbasis { |0⟩ , |1⟩ }

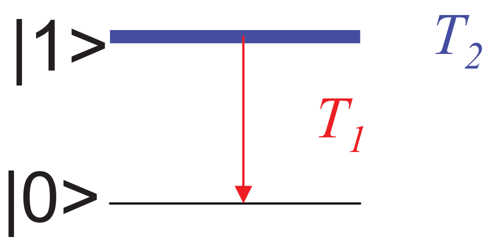
$$-\frac{1}{2}\hbar\omega_{01}\hat{\sigma}_z$$

$$-\frac{\hbar}{2}\left[\frac{f_I(\theta)}{\sqrt{C_0\hbar\omega_p}}\hat{\sigma}_x + \frac{\partial\omega_{01}}{\partial I_b}\hat{\sigma}_z\right]\delta I \leftarrow \text{current fluctuations}$$

$$-\frac{\hbar}{2}\left[\frac{2 f_\Phi(\theta)}{L_S\sqrt{C_0\hbar\omega_p}}\hat{\sigma}_x + \frac{\partial\omega_{01}}{\partial \Phi_b}\hat{\sigma}_z\right]\delta \Phi \leftarrow \text{flux fluctuations}$$

transverse → relaxation → T_1

longitudinal → "pure" dephasing → T_2

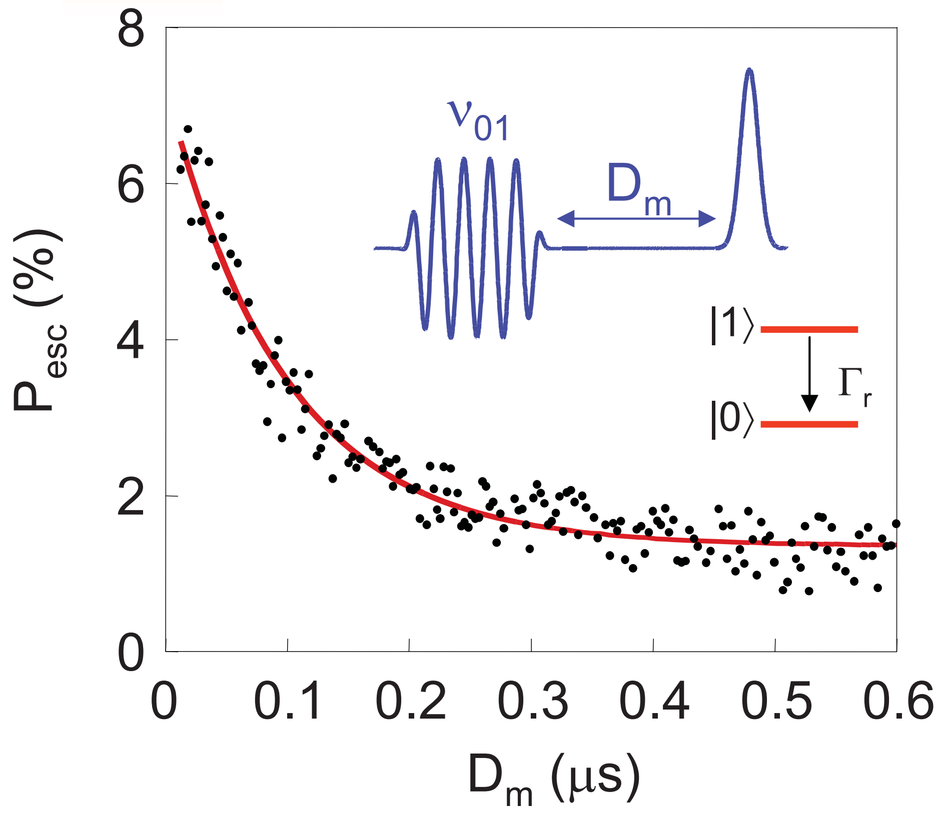


Not working at an optimum point !

Relaxation measurements

J. Claudon, A. Fay, L.P. Lévy, and O. Buisson (PRB2006)

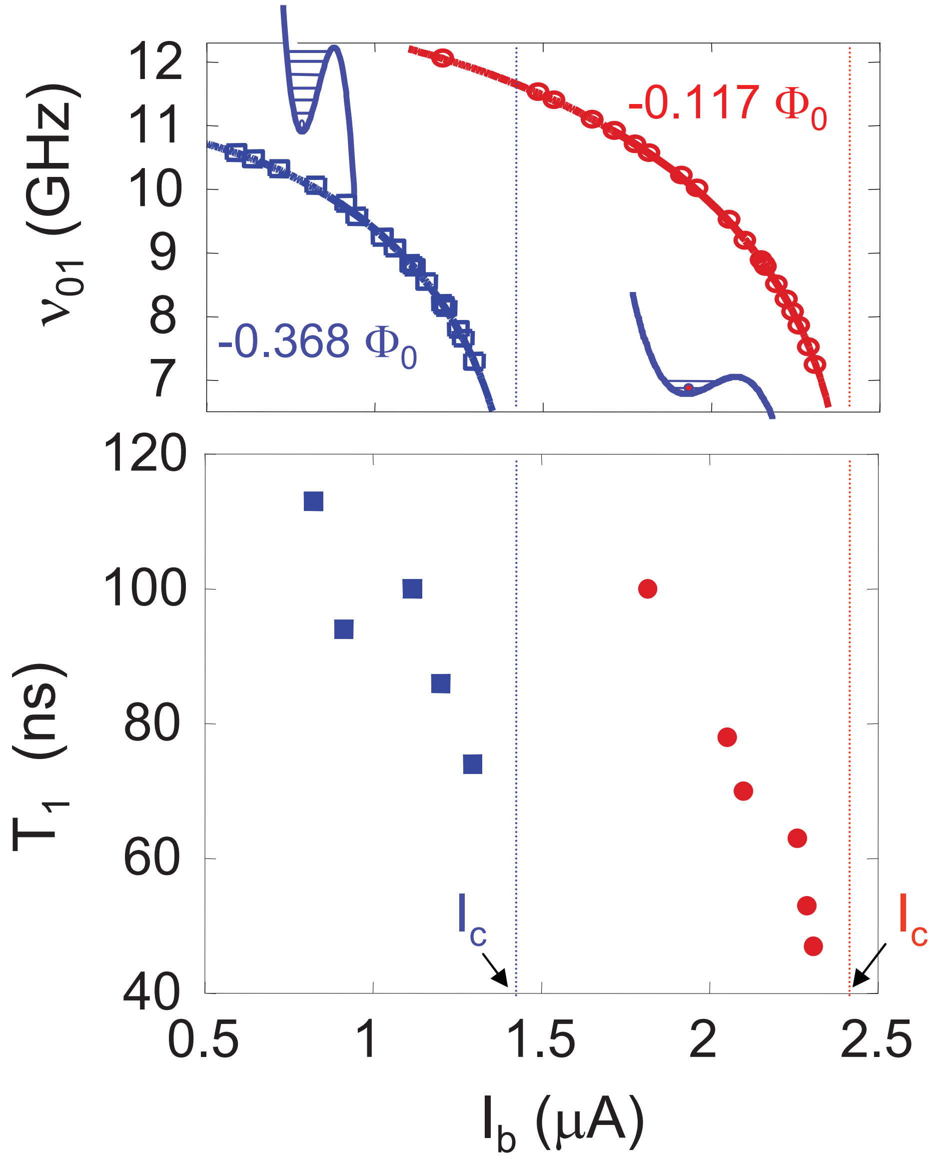
I_b = 2.222 μA, Φ_b = -0.117 Φ_0



solid line $\propto \exp(-D_m / T_1)$

T_1 = 90 ns
Q_r = 6000

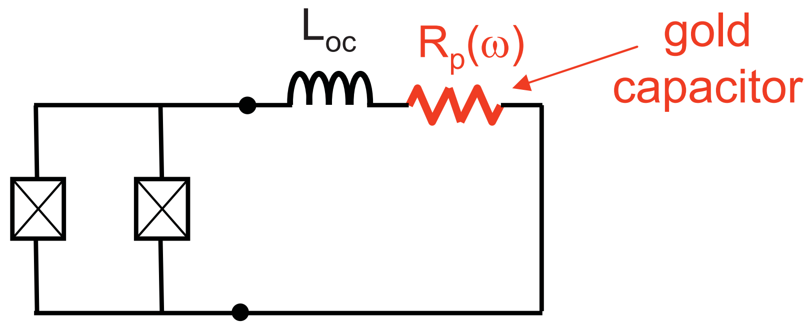
$1/T_1$ for different bias points



Relaxation measurements

J. Claudon, A. Fay, L.P. Lévy, and O. Buisson (PRB2006)

Environment at high frequencies (> 5GHz)



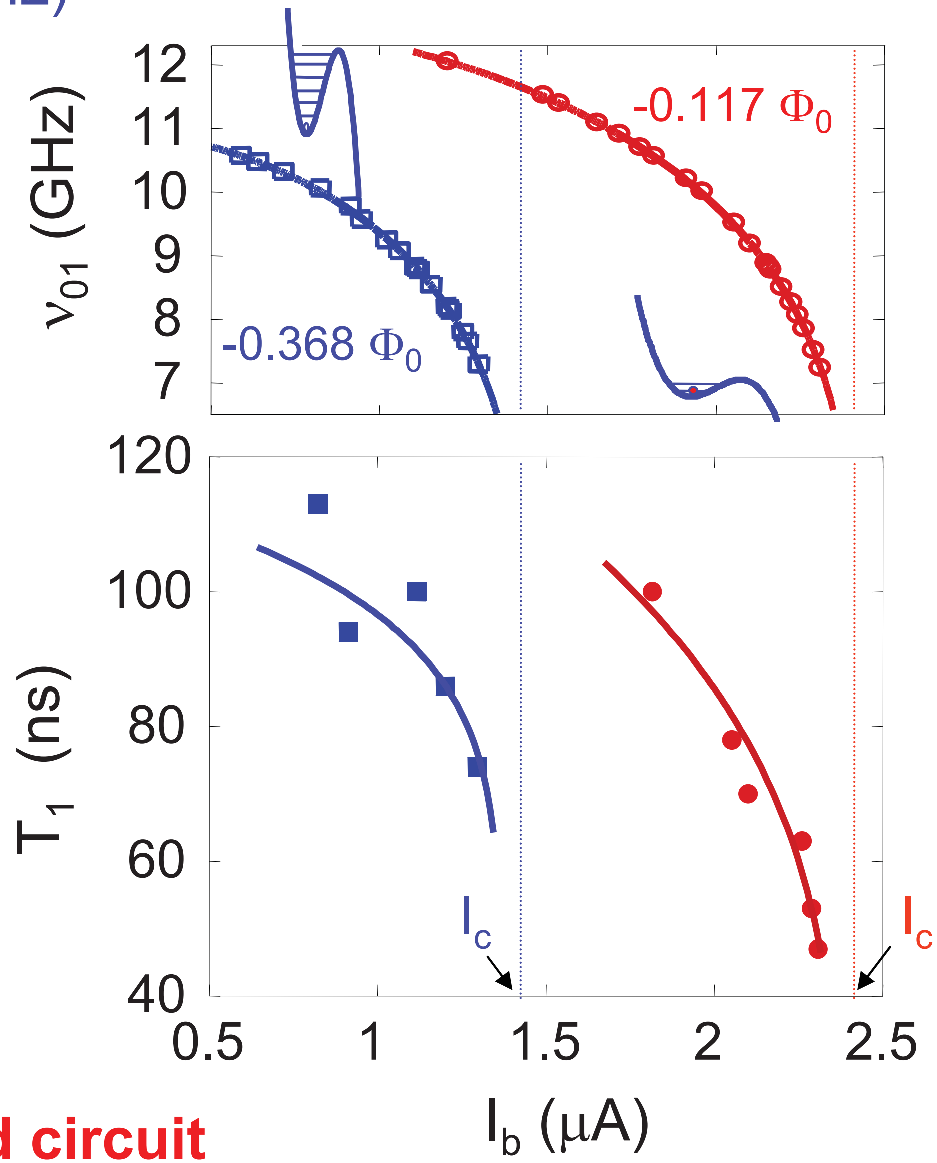
$$T_1 \approx 2C_0 \frac{L_{oc}^2 \ \omega_{01}^2}{R_p(\omega_{01})}$$

➡ $R_p(9\text{GHz}) = 4\Omega$

consistent with skin effect estimations

Effective resistance ~ $10^5\,\Omega$!

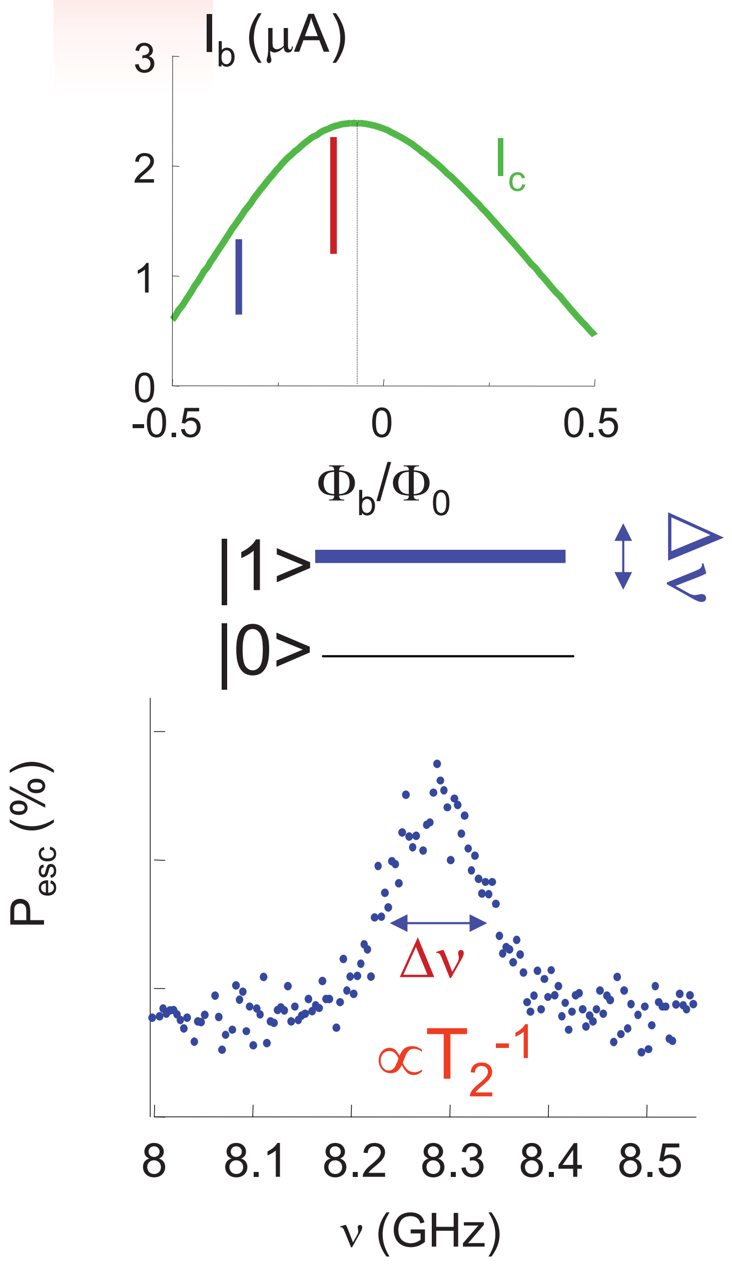
1/T_1 for different bias points

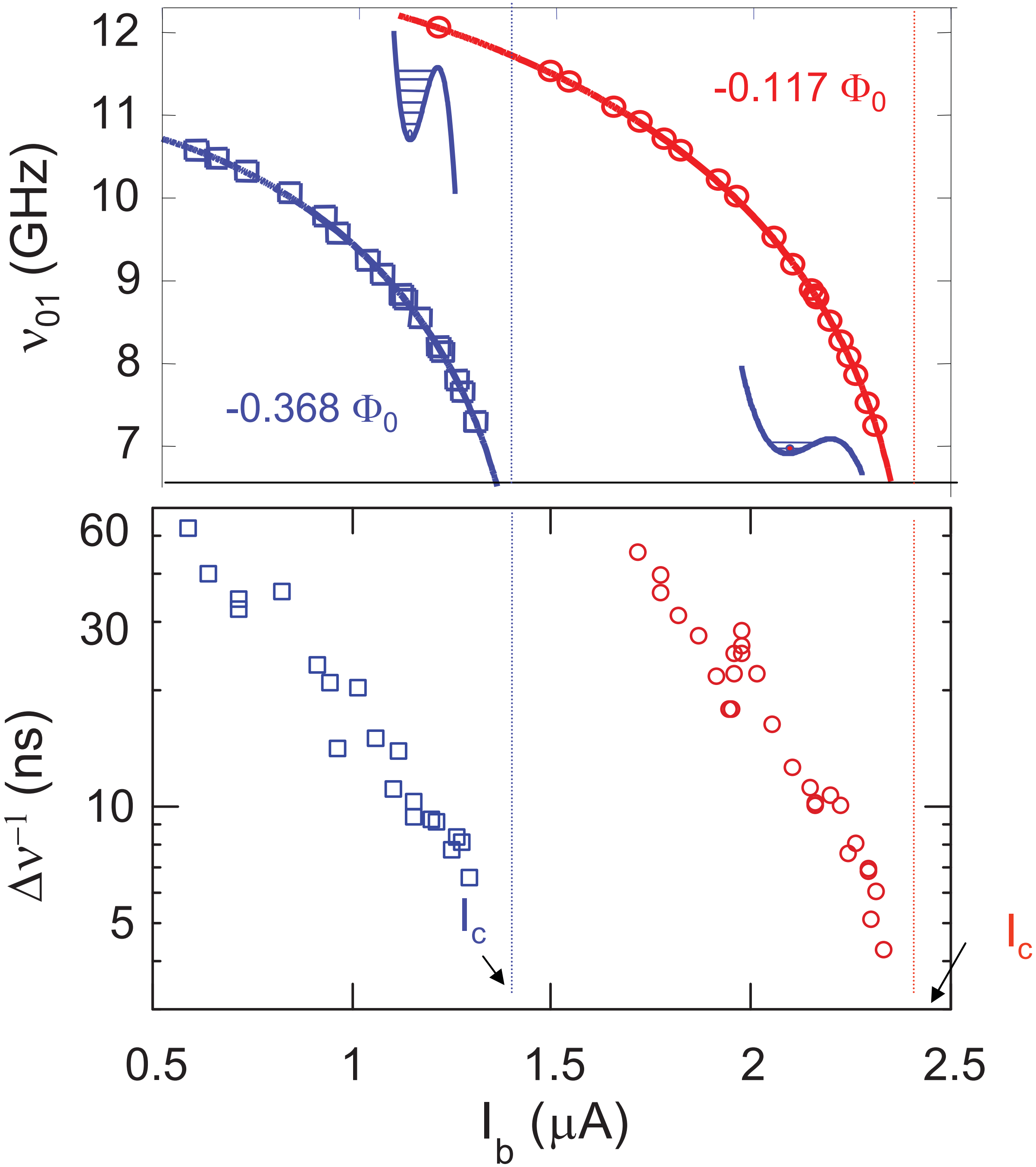


Long T_1 for a connected circuit

Low power spectroscopy

J. Claudon, A. Fay, L.P. Lévy, and O. Buisson (PRB2006)

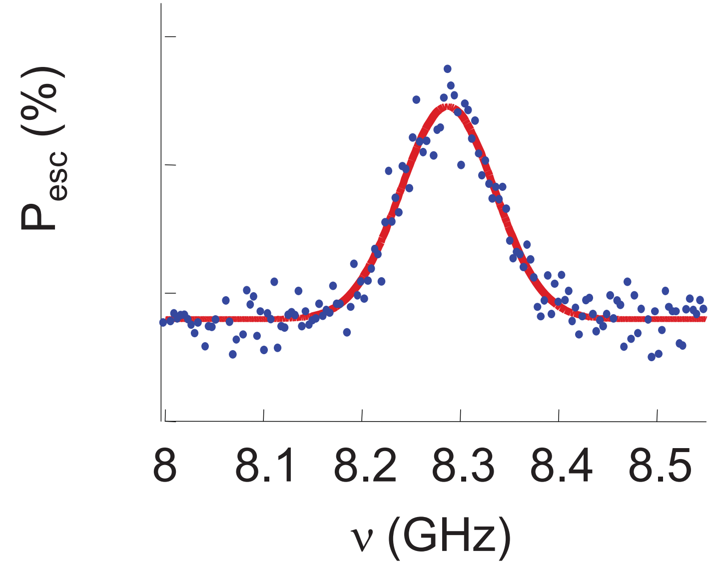




Low power spectroscopy

J. Claudon, A. Fay, L.P. Lévy, and O. Buisson (PRB2006)

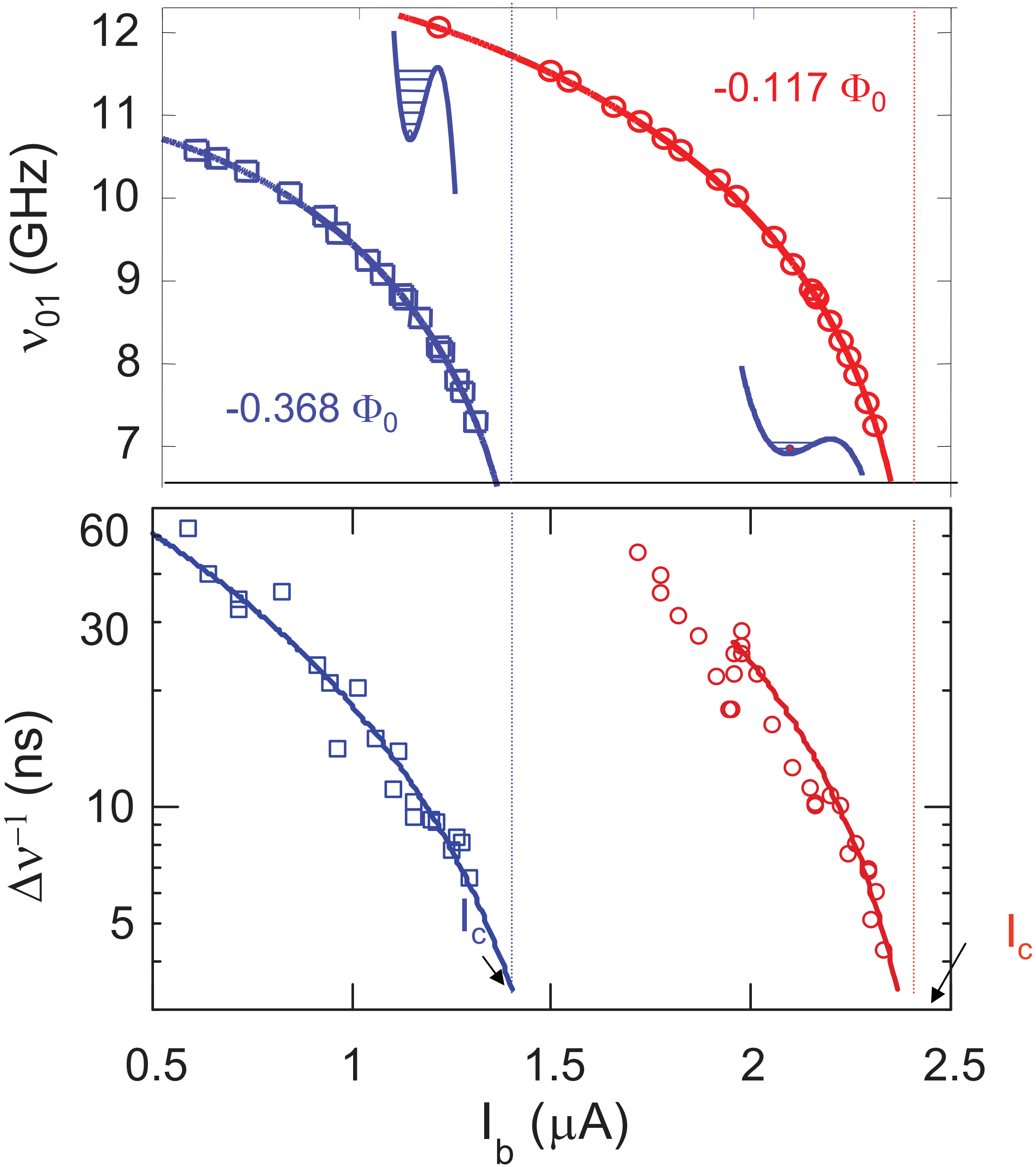
Main effect:
inhomogenous broadening due to current noise



$$\Delta\nu \propto \frac{\partial \omega_{01}}{\partial I}\sqrt{\left\langle \delta I^2 \right\rangle}$$

with $\sqrt{\left\langle \delta I^2 \right\rangle} = \sqrt{\frac{kT}{L_{OC}}} \approx 6nA$

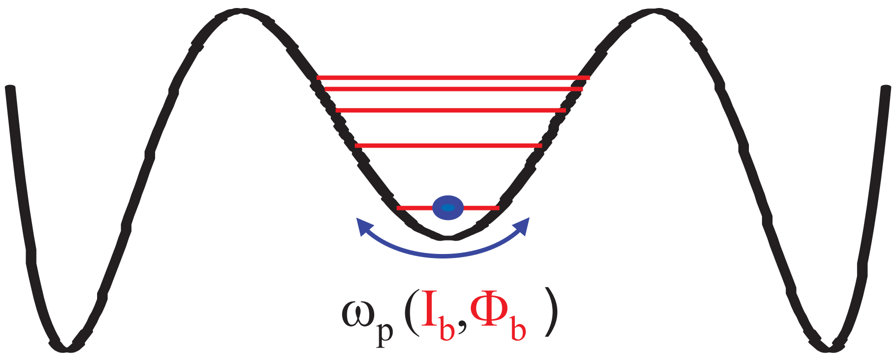
No free parameter!!

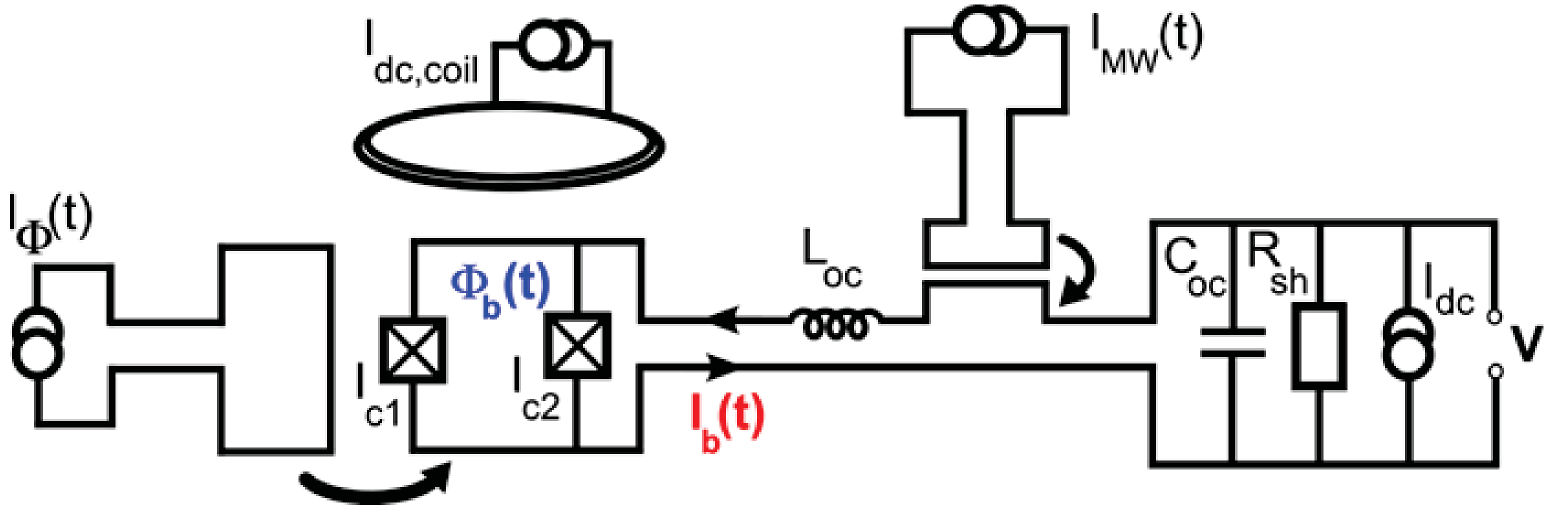


Manipulation at zero current bias

Hoskinson, Lecocq et al , PRL (2009)

At zero current: $$H = \hbar\omega\,(\hat{P}^2 + \hat{X}^2 - \delta\,\hat{X}^4)$$



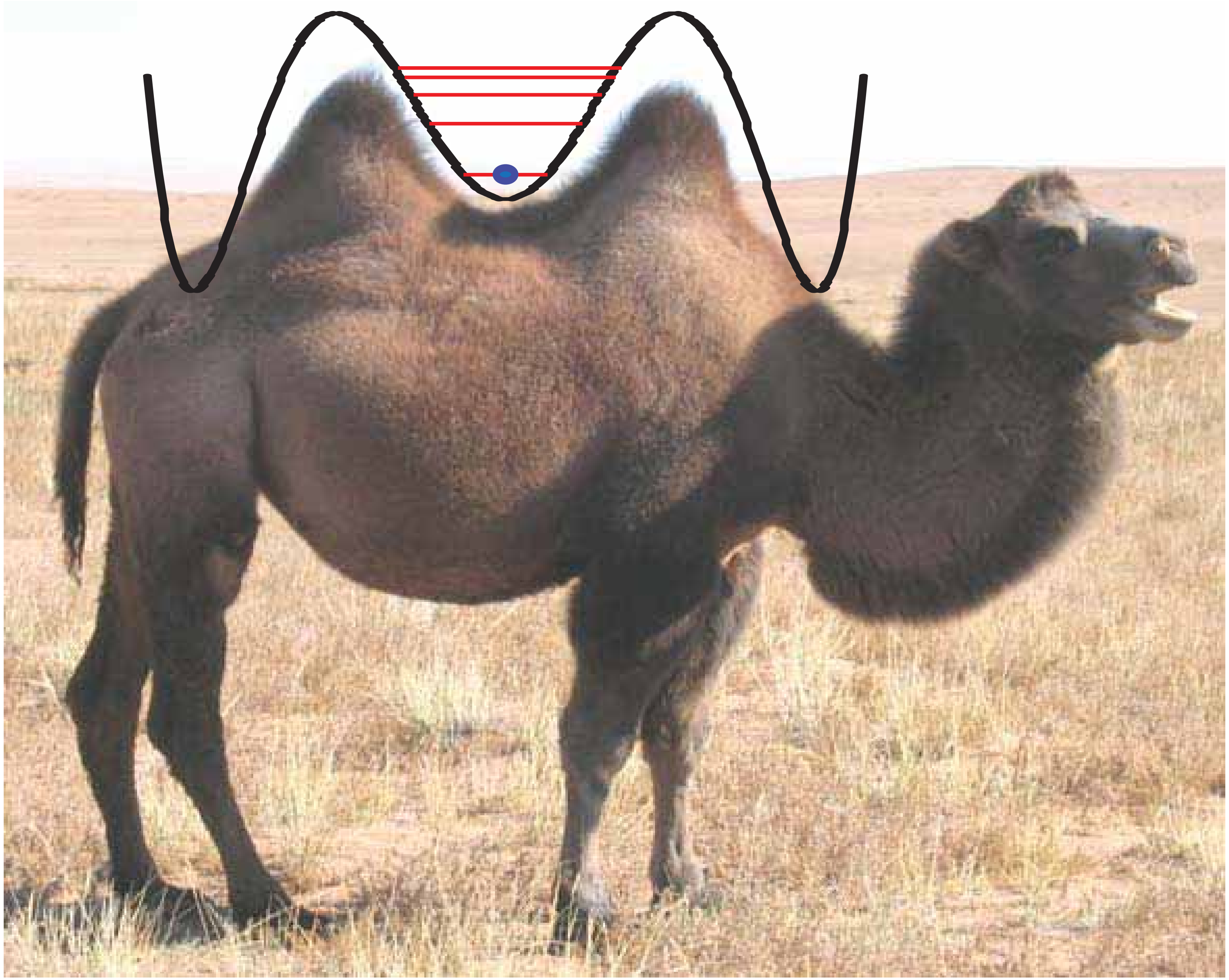


Manipulation ⟷ Microwave current: $I_b(t)$

$$-\hbar\Omega_1 \cos(2\pi\nu t)\sqrt{2}\widetilde{X}$$

Manipulation at zero current bias

Hoskinson, Lecocq et al , PRL (2009)

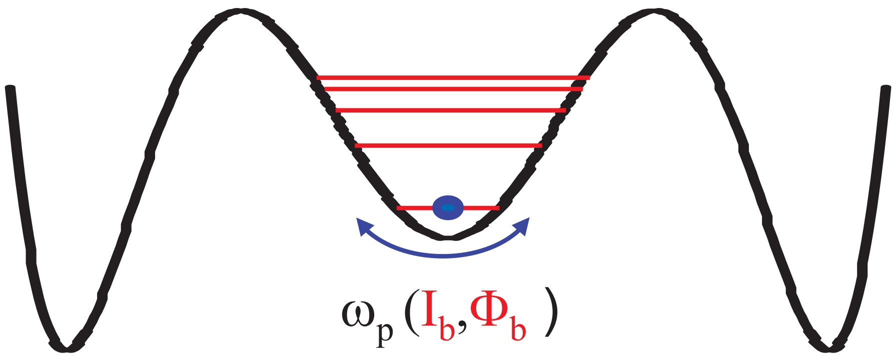


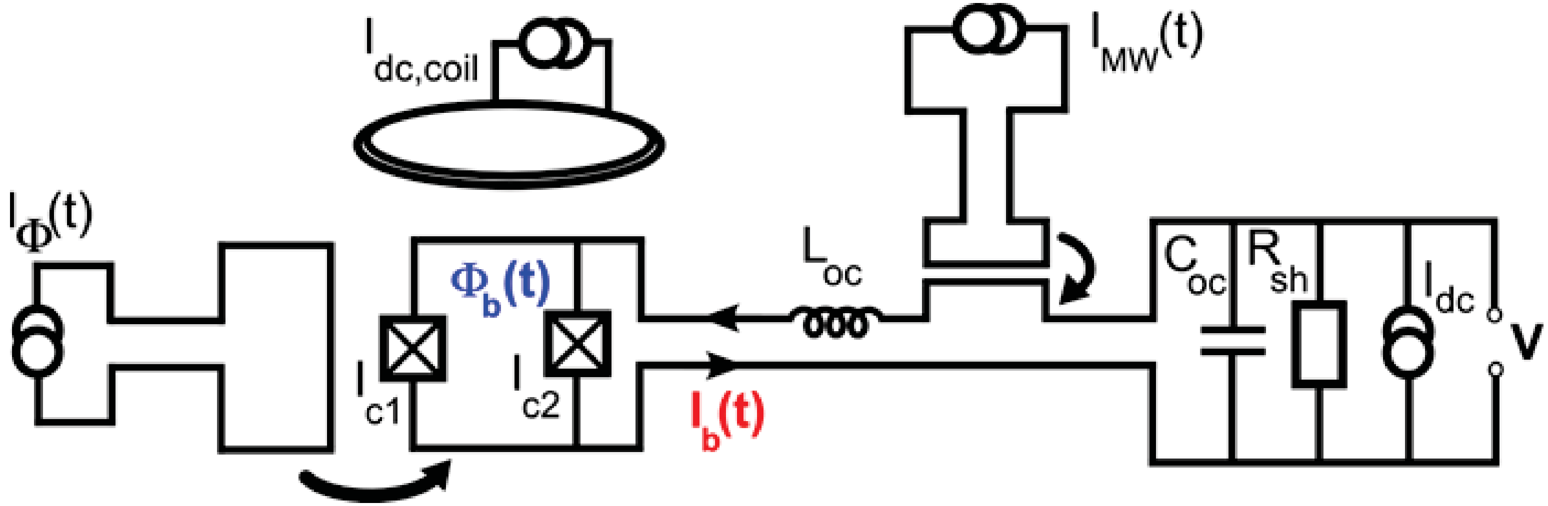
called: the Camelback phase qubit…

Camelback phase qubit

Hoskinson, Lecocq et al , PRL (2009)

At zero current: $H = \hbar\omega\,(\hat{P}^2 + \hat{X}^2 - \delta\,\hat{X}^4)$



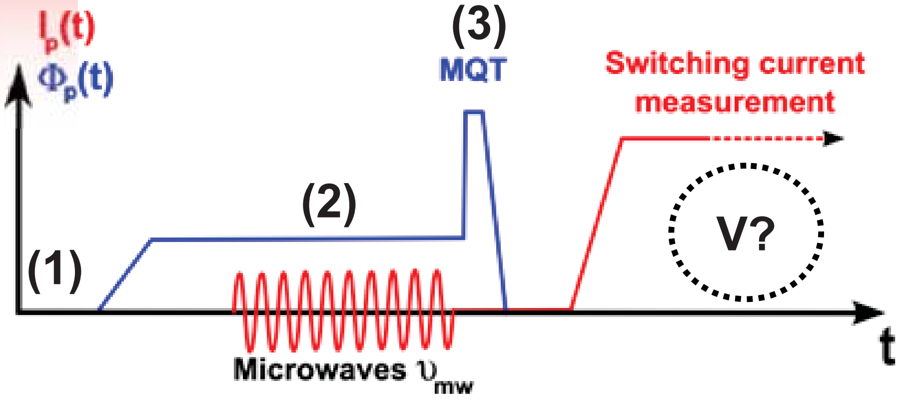


Manipulation ⟷ Microwave current: $I_b(t)$

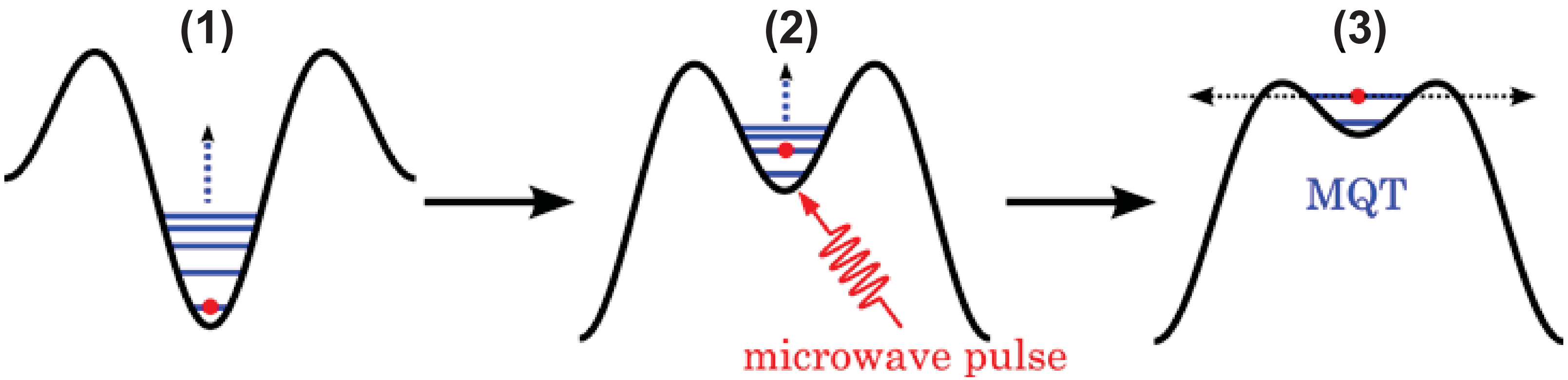
$$-\hbar\Omega_1 \cos(2\pi\nu t)\sqrt{2}\widetilde{X}$$

Spectroscopy at zero current bias

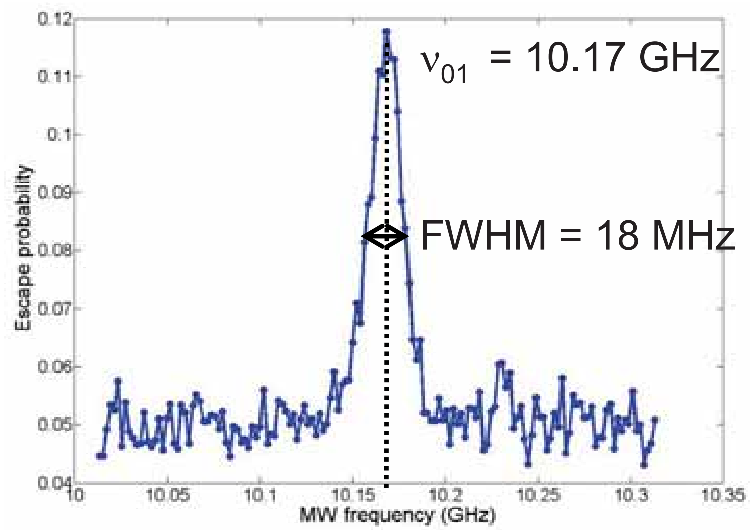
Hoskinson, Lecocq et al , PRL (2009)



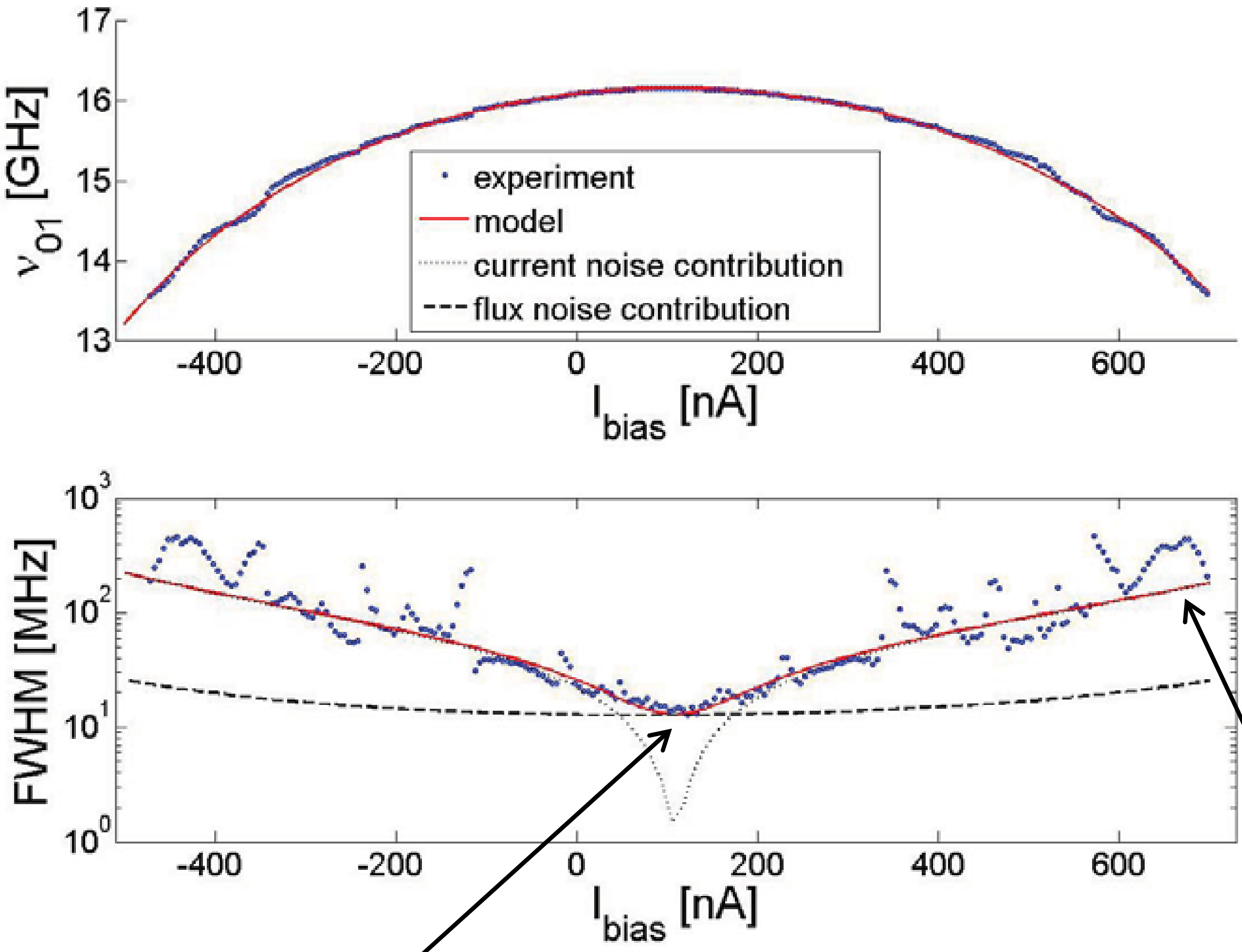
Nanosecond flux pulse and switching current measurement



The probability of escape increases when the system is excited



Demonstration of optimal current bias



- **Frequency is maximum at zero current biased**

$$\frac{\partial \omega_{01}}{\partial I} = 0$$

- Width $\Delta\nu_{01}$ (FWHM) due to low frequency fluctuations of ν_{01}

$$\Delta\nu_{01} = \sqrt{\Delta\nu_I^2 + \Delta\nu_\Phi^2}$$

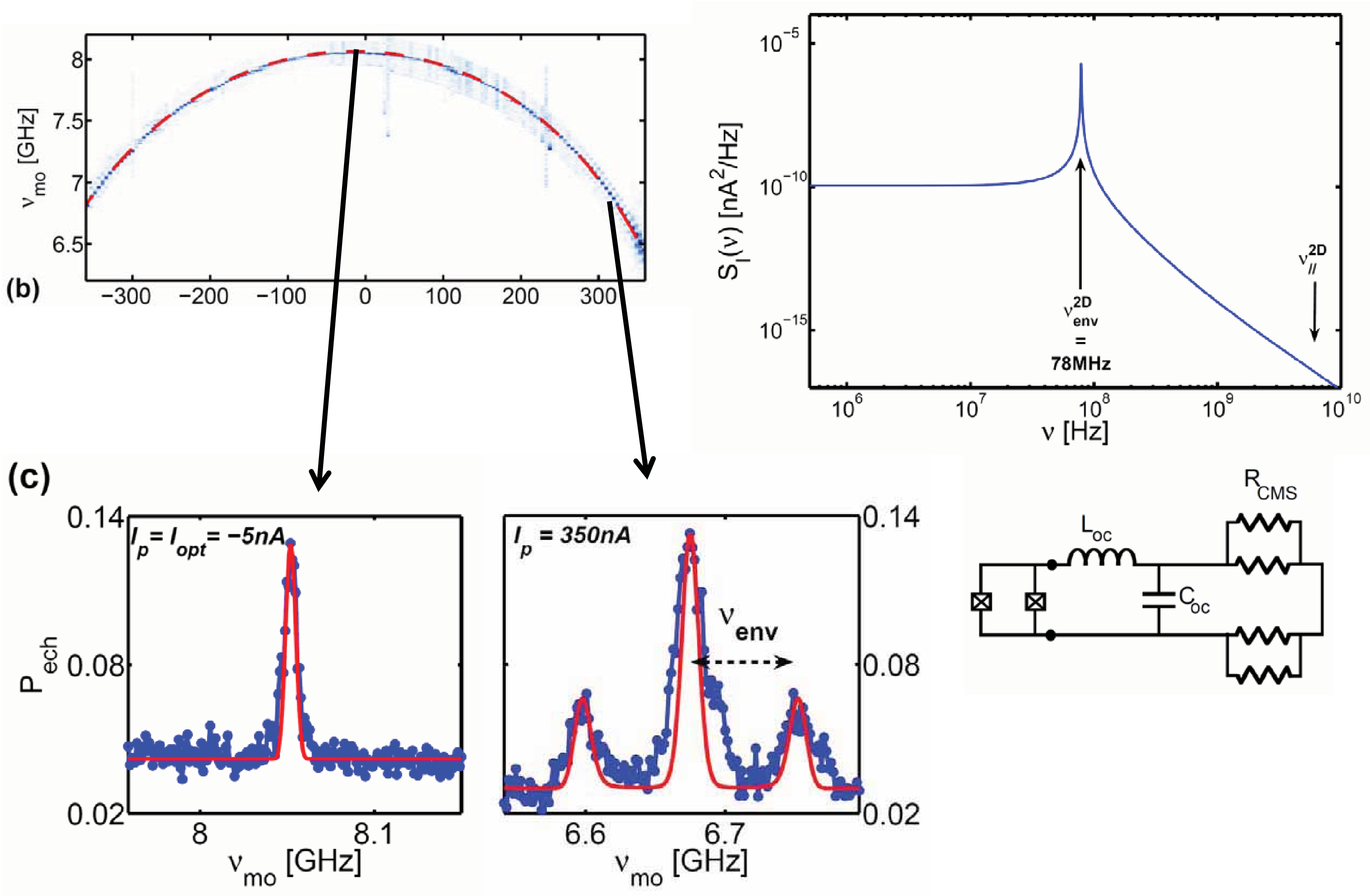
Current noise: $\Delta\nu_I = \frac{\partial\nu}{\partial I}\Delta I$

Flux noise: $\Delta\nu_\Phi = \frac{\partial\nu}{\partial\Phi}\Delta\Phi$

Close to the optimal line
Flux noise limited :
$40\mu\Phi_0$ (*RMS*)

Away from the optimal line
Current noise limited :
9nA (*RMS*)

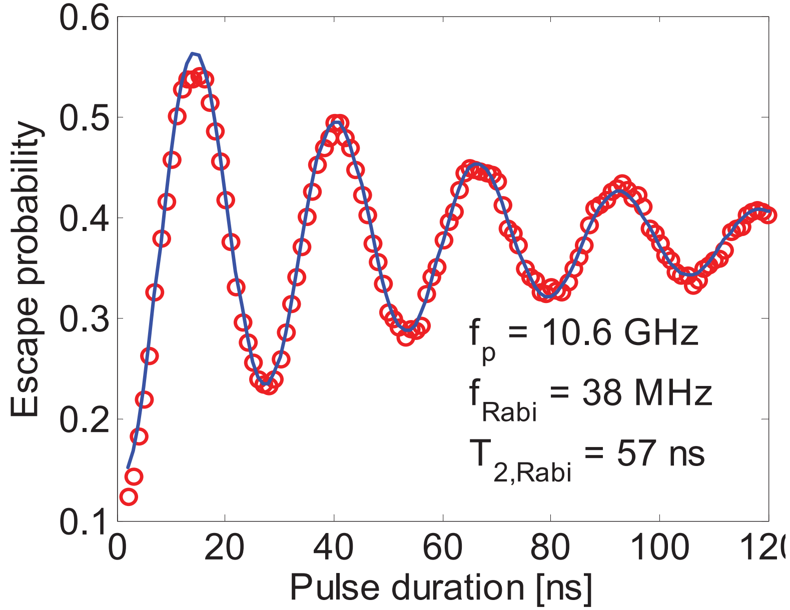
Side band resonances

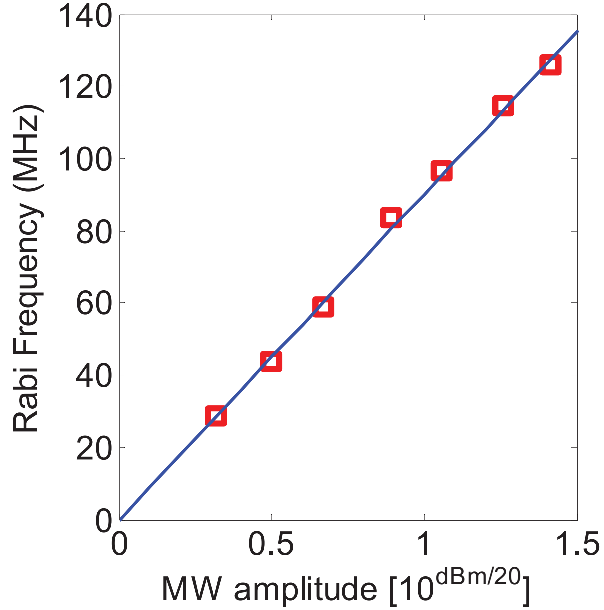


Side bands disappears @ sweet point

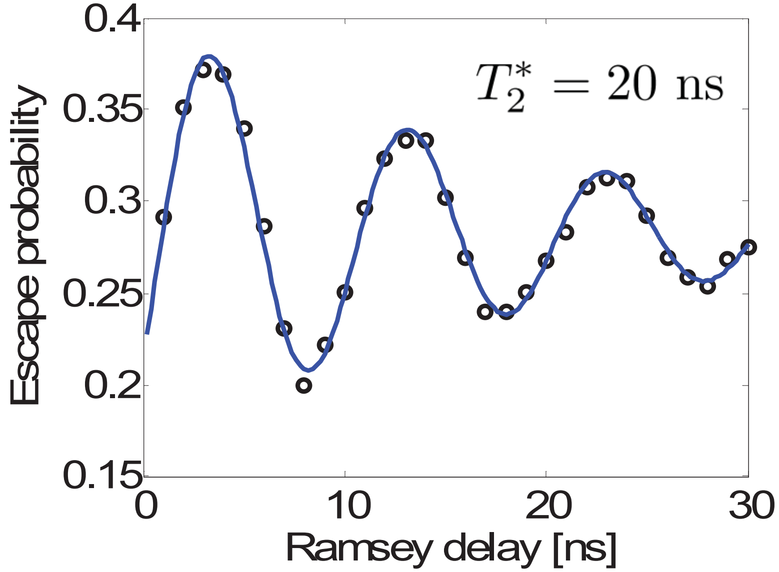
Coherent oscillations along the optimal line

Rabi oscillation

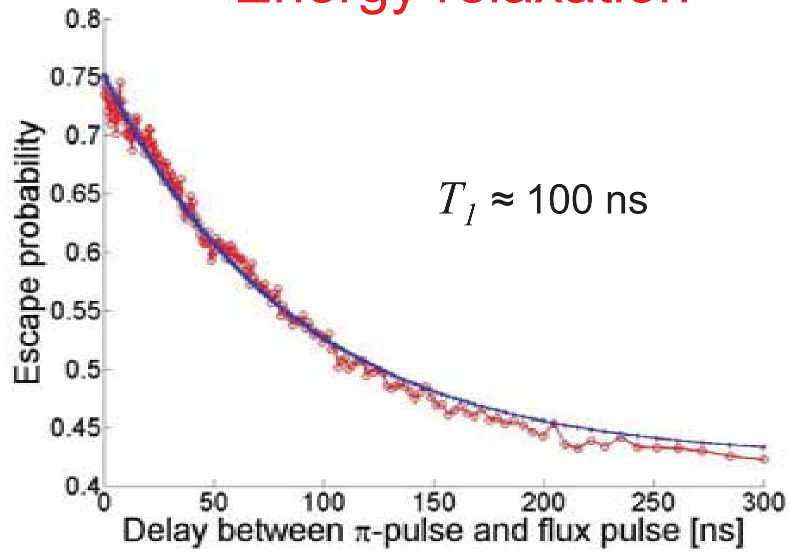




Ramsey oscillations



Energy relaxation



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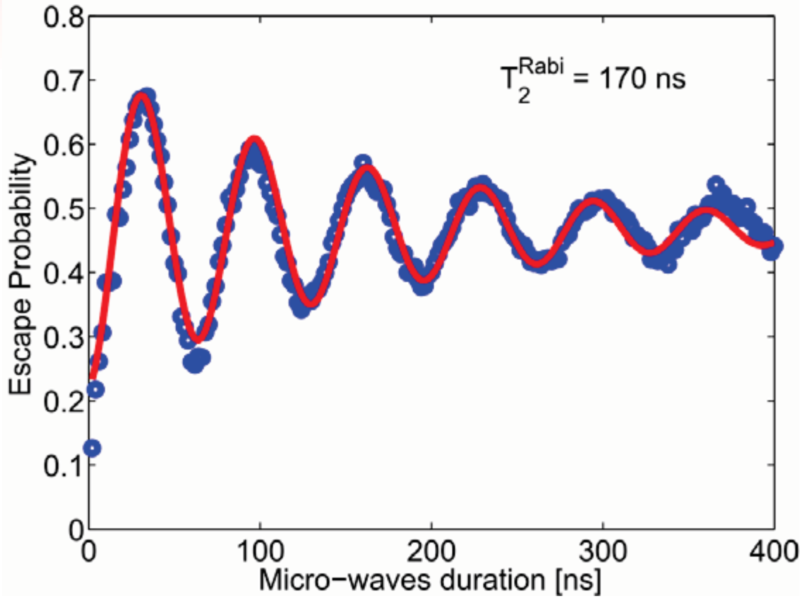
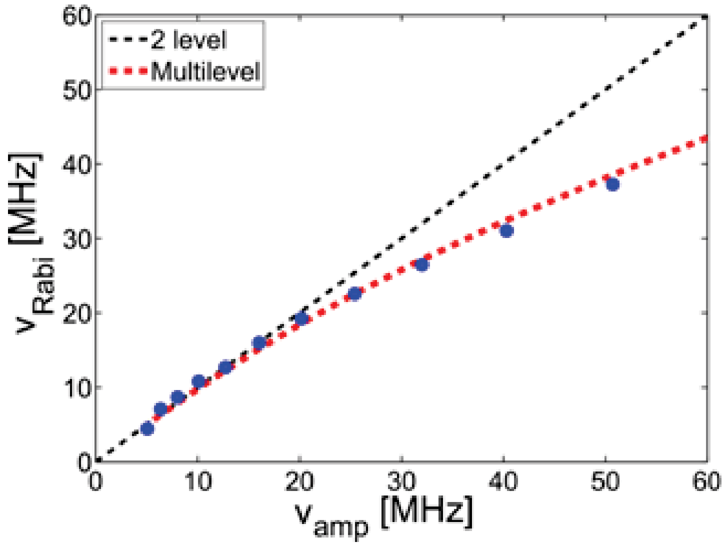


Anharmonicity



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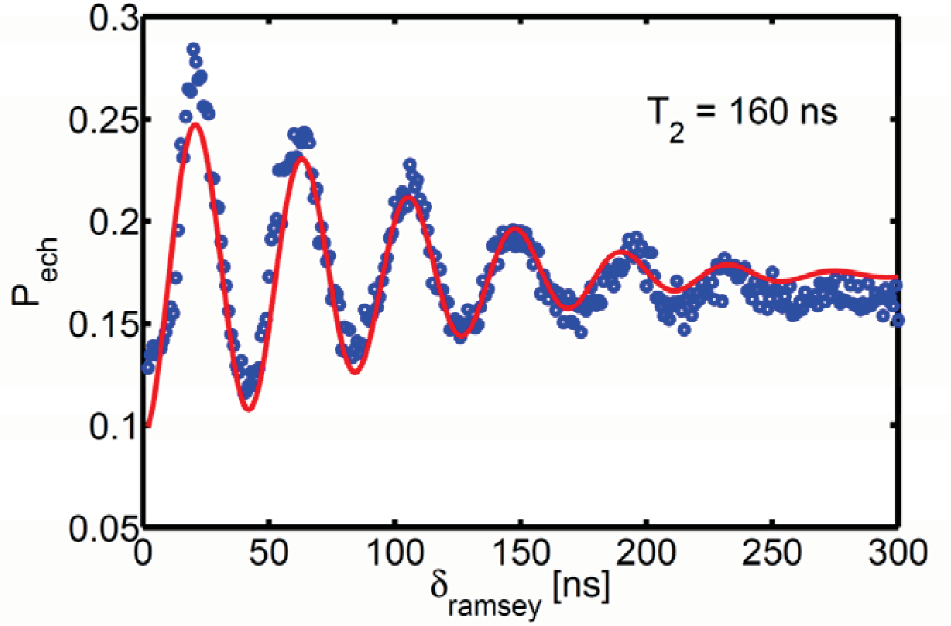
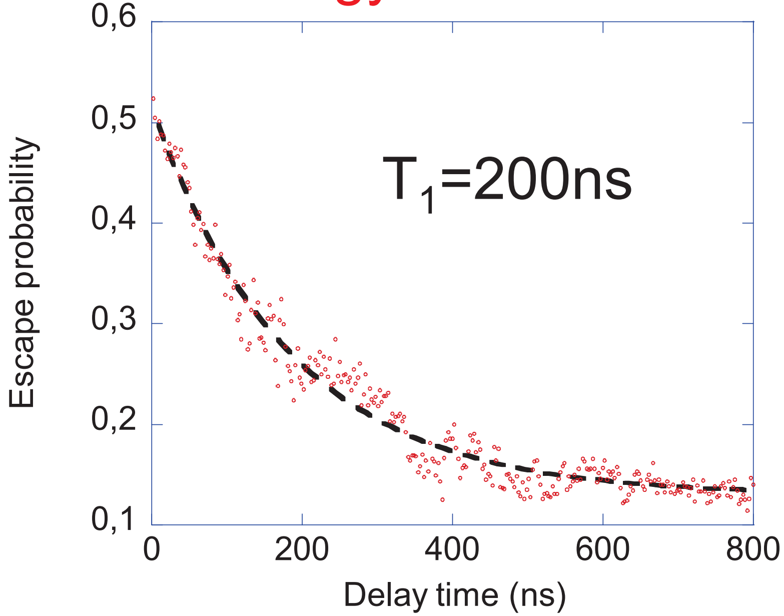
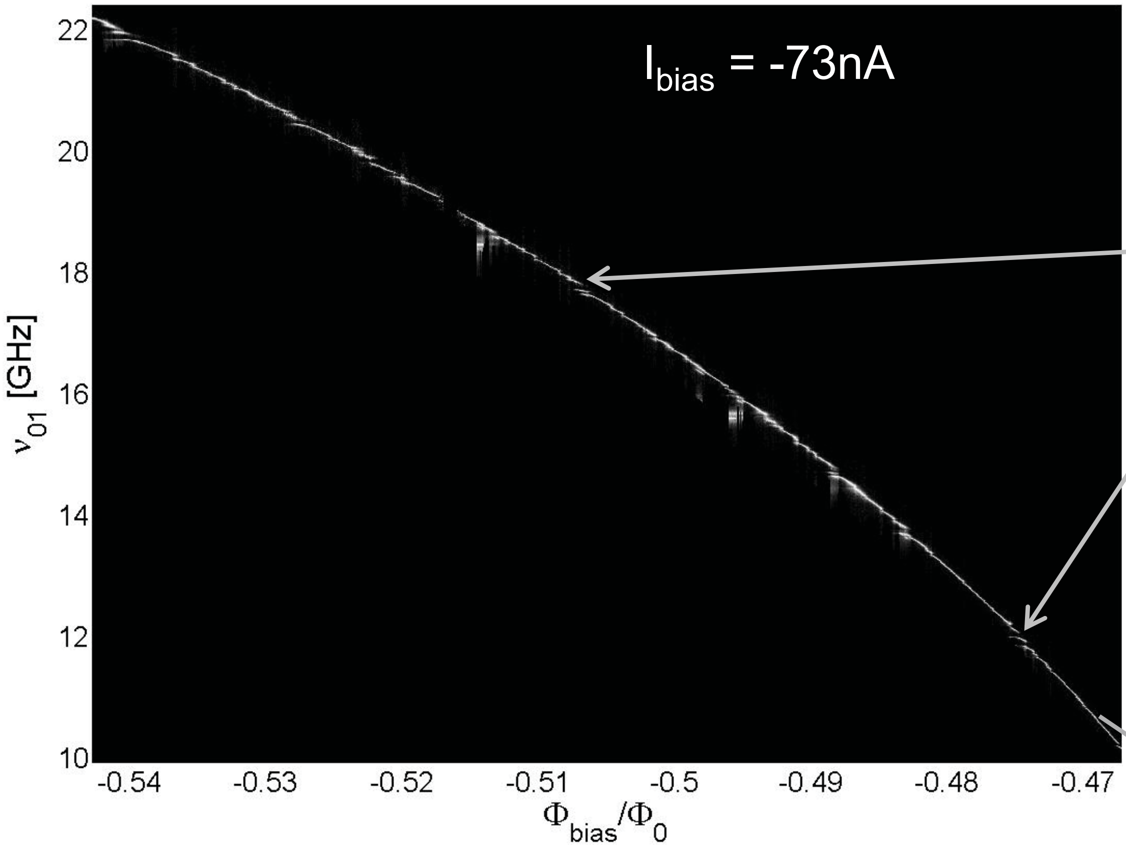
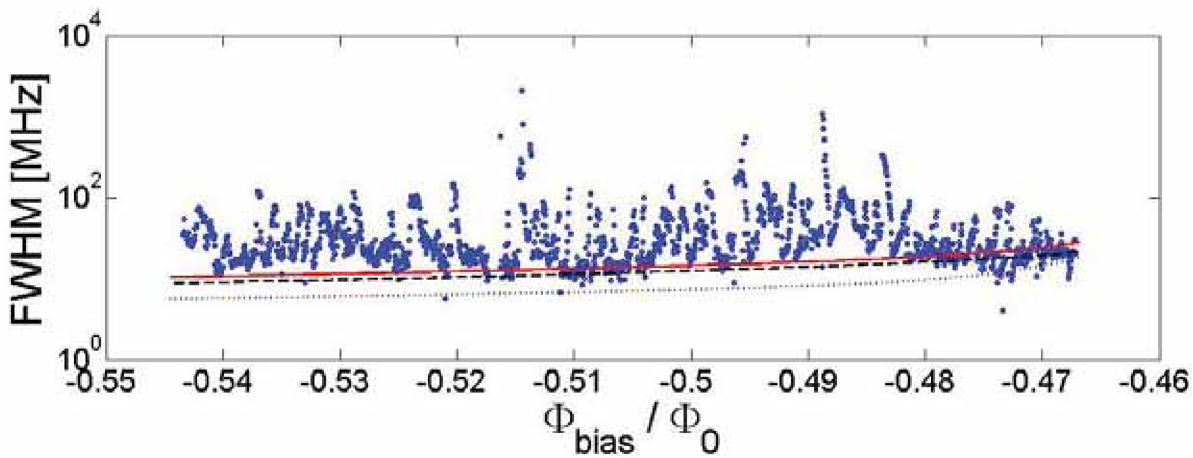


Energy relaxation

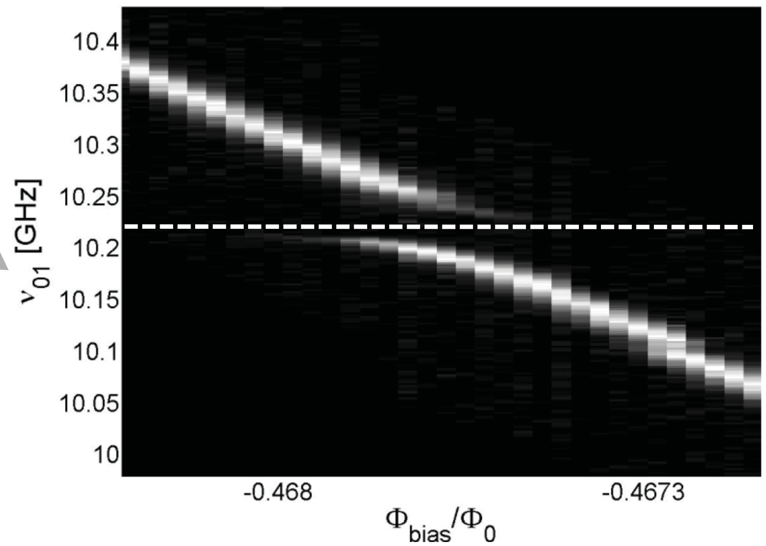


Spectroscopy versus flux bias, TLS limitation





~ 20 parasitical two level system (TLS) per GHz with a coupling to the Qubit varying from 5MHz to 150MHz



Conclusion

- Improvement of the coherence time along the optimal line.

- New potential along this line,
  preliminary results on double escape processes.

- Limitations : - Residual dephasing can be explained by a 40 $\mu\Phi_0$ RMS flux noise.
  - Too many parasitical two levels systems.
  - Unknown sources of noise (low frequency current noise)

Current works: - improvement on the Josephson junction quality