Models of environment and T_1 relaxation in Josephson Charge Qubit

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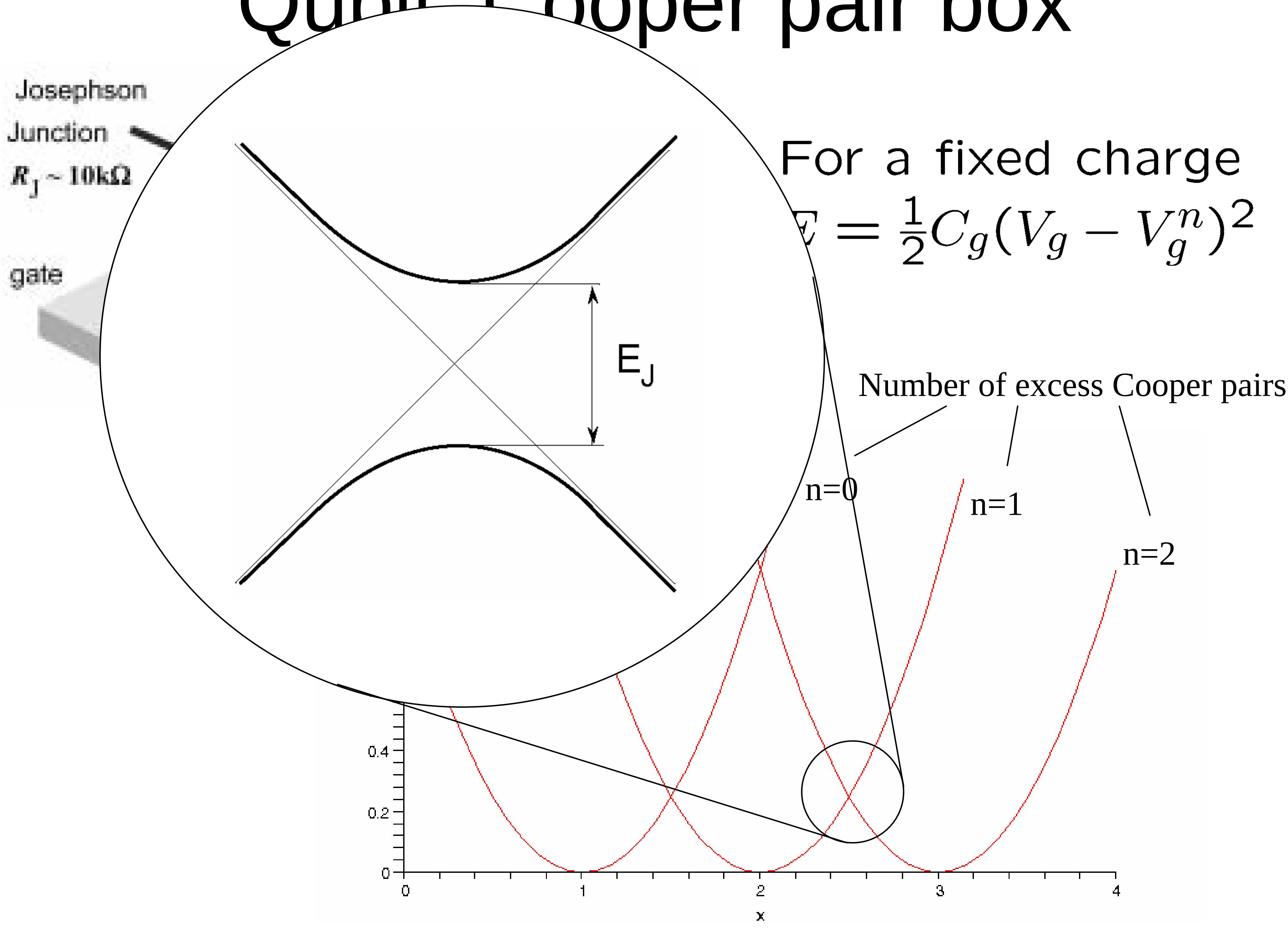
Outline

- Superconducting qubits
- Coherent quantum oscillations
- Noise sources
- Energy relaxation
- Models of environment
  - Phonons
  - Photons
  - Electrons
- Summary

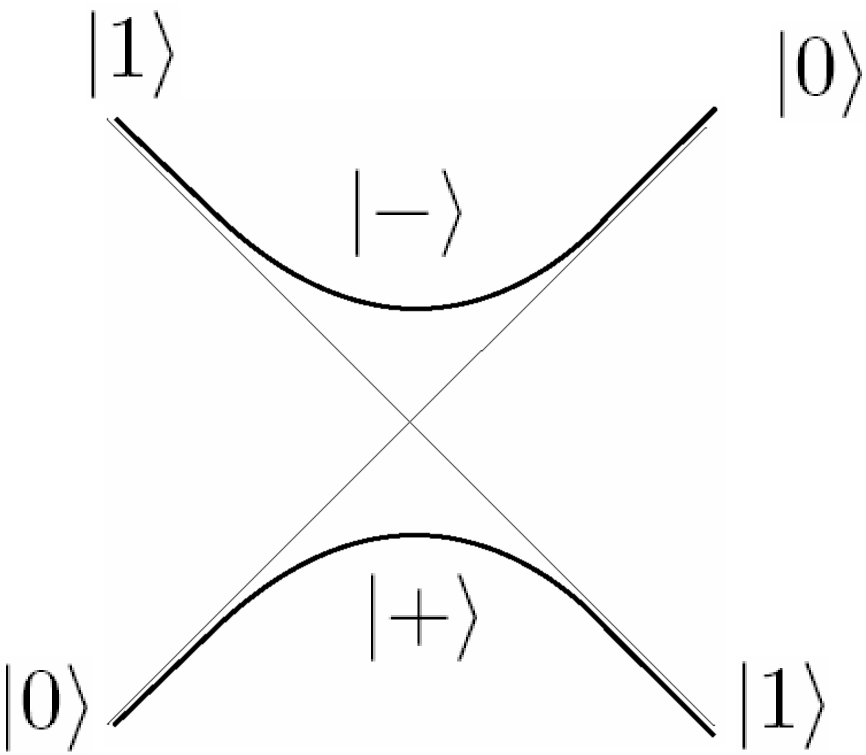
Qubit: Cooper pair box

For a fixed charge

$$E = \frac{1}{2}C_g(V_g - V_g^n)^2$$



Effective Hamiltonian

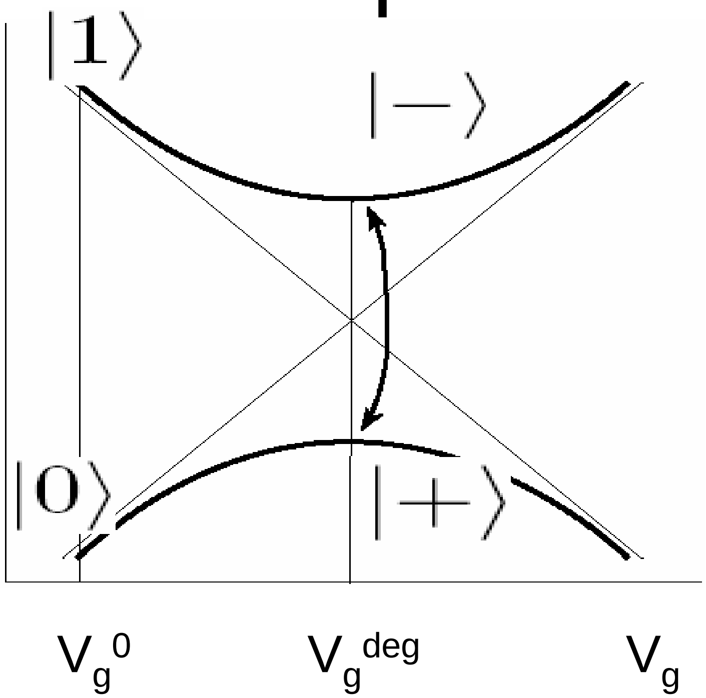


$$H = \frac{1}{2}B_z\sigma_z + \frac{1}{2}B_x\sigma_x$$

$$B_z = \frac{E_c C_g}{e}(V_g - V_g^{deg})$$
$$B_x = E_J$$

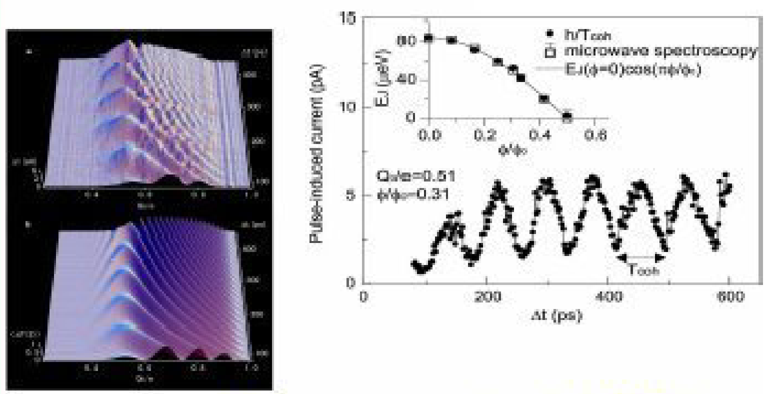
$$|+\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$$
$$|-\rangle = \frac{1}{\sqrt{2}}(|0\rangle - |1\rangle)$$

First experiment: Coherent manipulation

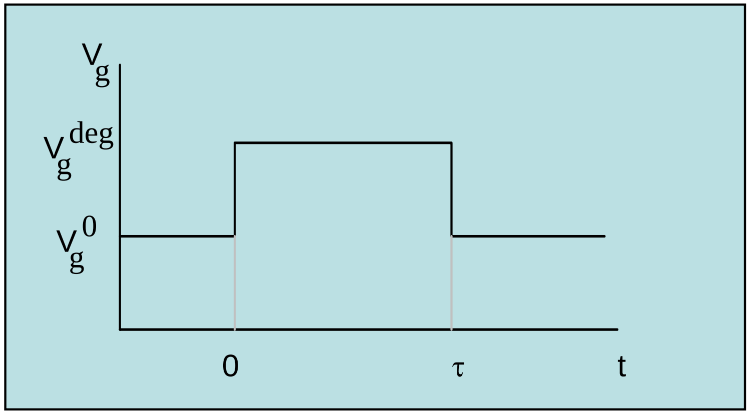


$$|0\rangle = \frac{1}{\sqrt{2}}(|+\rangle + |-\rangle)$$
$$\xrightarrow{time} \frac{1}{\sqrt{2}}\left(e^{-i\frac{B_x}{2}\tau}|+\rangle + e^{i\frac{B_x}{2}\tau}|-\rangle\right)$$
$$= \cos\frac{B_x}{2}\tau|0\rangle + \sin\frac{B_x}{2}\tau|1\rangle$$

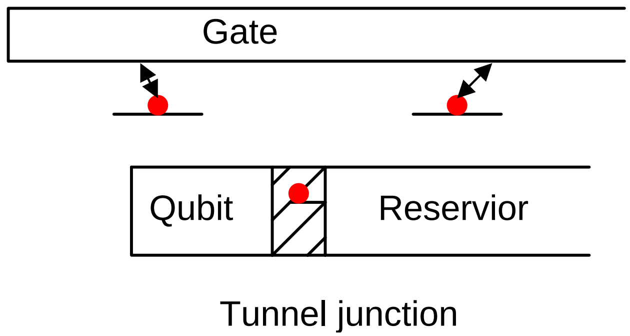
Measure
$$P_1 = \sin^2\frac{B_x}{2}\tau$$



Nakamura et. al. , Nature, 398, 786 (1999)



Noise



Fluctuating background charges: Localized electron states that can be either empty or occupied. Classical Random Telegraph Noise (RTN) fluctuators.

In the substrate:

Galperin et. al. cond-mat/0312490 (2003)

Paladino et. al. PRL 88, 228304 (2002)

Rabenstein et. al. cond-mat/0401519 (2004)

In the junction:

Van Harlingen et. al. cond-mat/0404307 (2004)

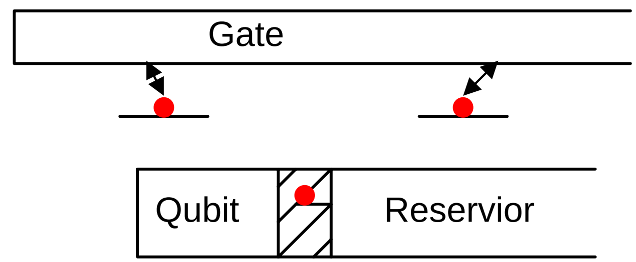
Classical model for noise

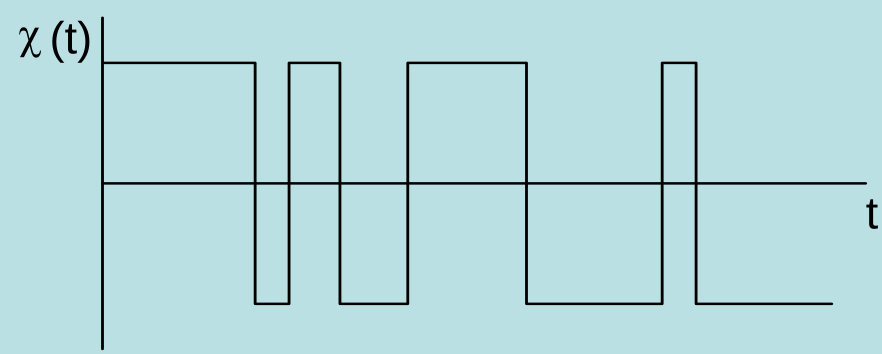
$$H = \frac{1}{2}(B_z + \nu_z(t))\sigma_z + \frac{1}{2}B_x\sigma_x$$

$$\nu(t) = \sum_i \nu_i \chi_i(t)$$

$\chi_i(t)$ are independent random telegraph processes

$$\chi_i(t) = \pm\frac{1}{2}$$

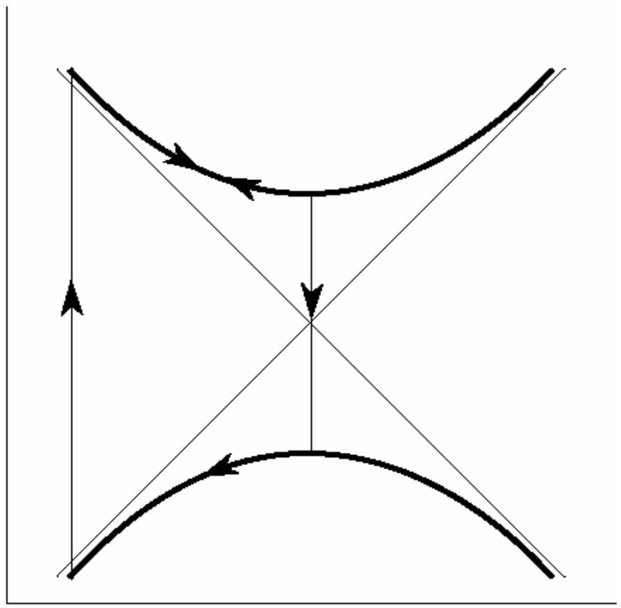


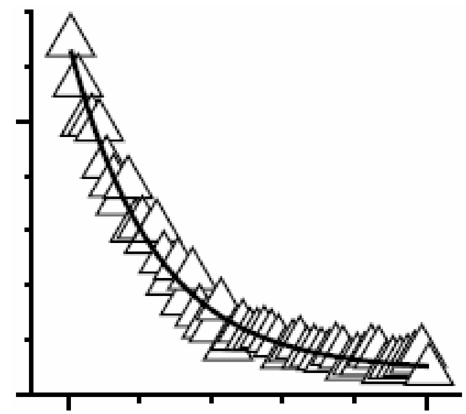


Probability for *n* jumps in time *t:*

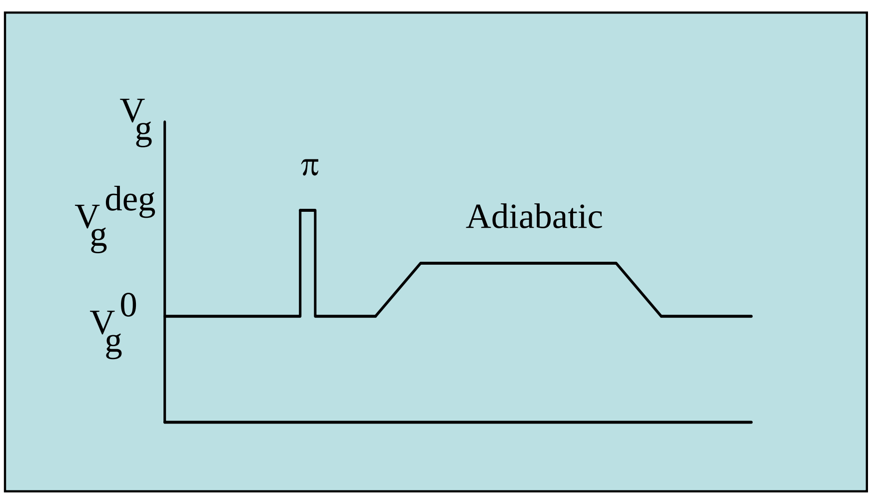
$$p_n = \frac{(\gamma t)^n}{n!}e^{-\gamma t}$$

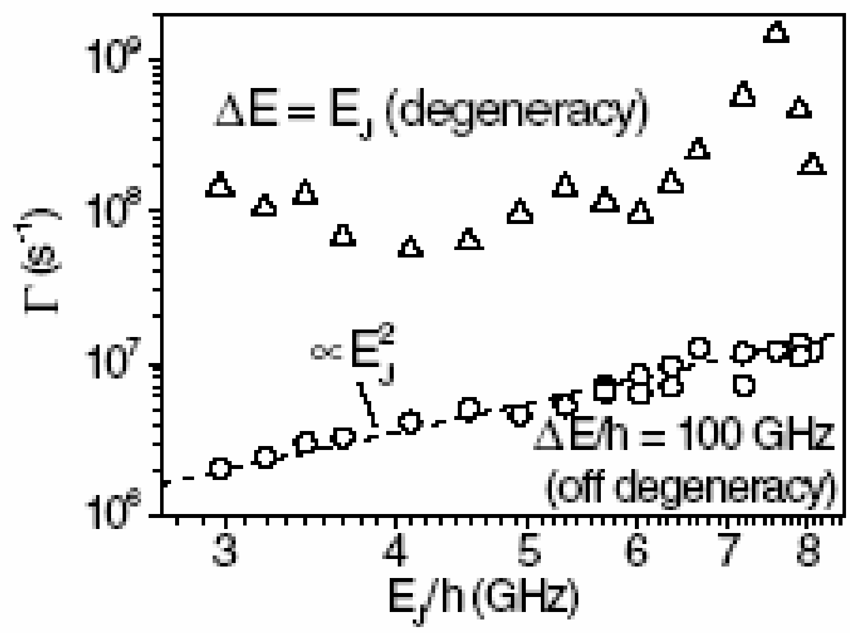
Second experiment: Energy relaxation





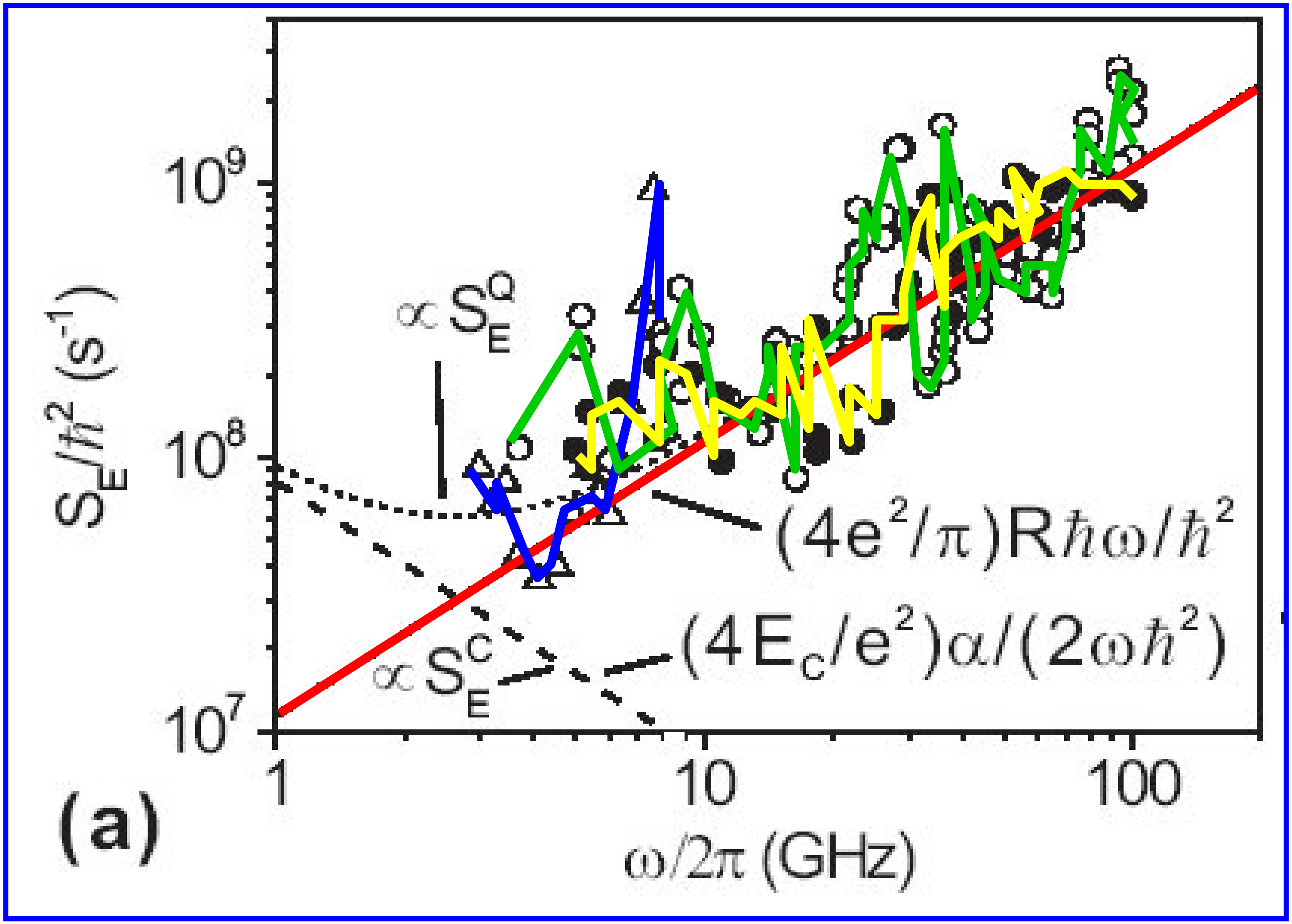
Astafiev et. al. PRL **93,** 267007 (2004)





Experimental results

Astafiev et. al. PRL **93,** 267007 (2004)



Relaxation rate is proportional to energy: $\Gamma_1 \propto \omega$

The fluctuations are reproducible for a given sample

In these experiments we have $E_J > T$

$\rightarrow$ Spontaneous emission

This means that we need to consider a quantum theory of the environment.

Analogous to an atom spontaneously emitting a photon. But what plays the role of the environment?

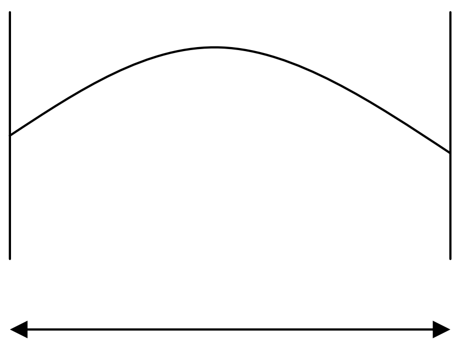
- Photons?
- Phonons?
- Electrons?

Phonons or photons?

Fermi's golden rule: $\Gamma \propto g(E_J)\ |T|^2$

We can get $\Gamma \propto E_J$ if $g(\omega) \propto \omega$ → Two dimensions

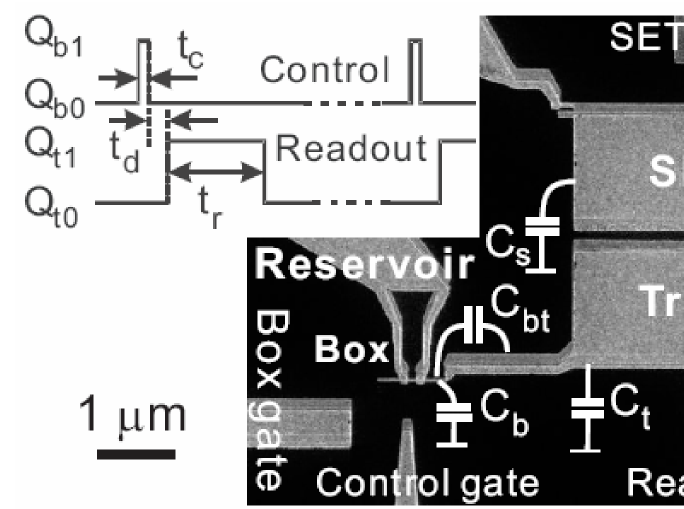
Can a phonon or photon mode account for the resonant peaks?



L

Charachteristic length:

L=c/f f=30 GHz

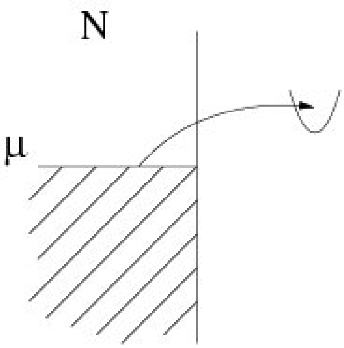


Sound: c = 1000 m/s → L = 30 nm

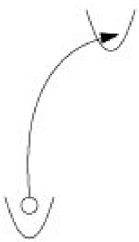
Light: c = 300000 m/s → L = 1 cm

Models of environment

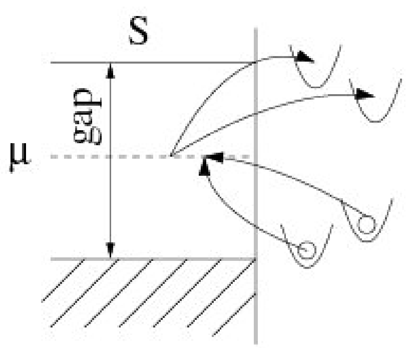
Faoro, Bergli, Altshuler and Galperin PRL 95, 046805 (2005)



Model I: the reservoir is a normal metal and tunneling of electrons happen from any state below the chemical potential to an unoccupied trap above the chemical potential or from an occupied trap to an extended state above the chemical potential

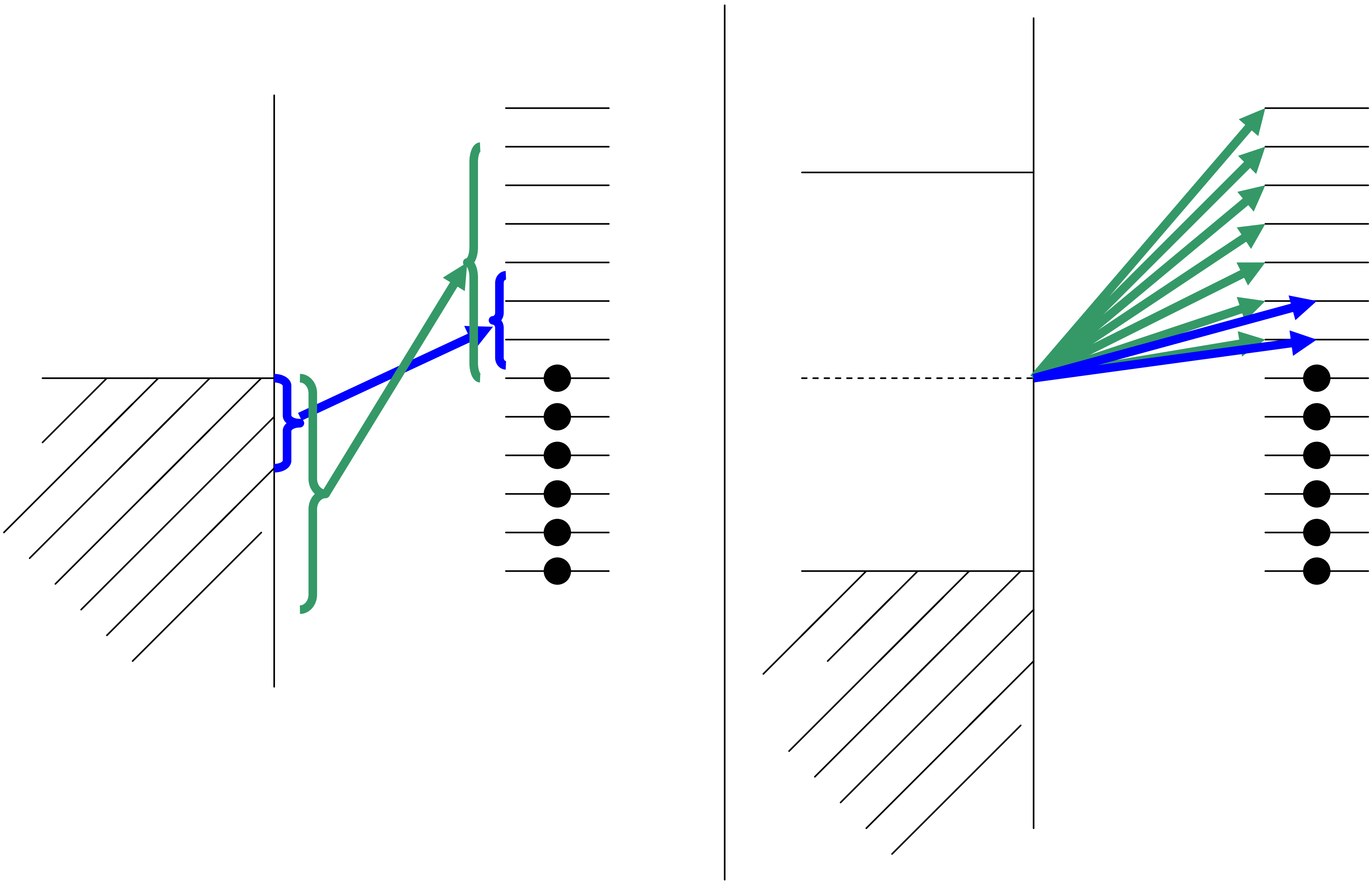


Model II: tunneling takes no place between the reservoir and the traps, but an electron in an occupied trap below the chemical potential is excited into an empty trap

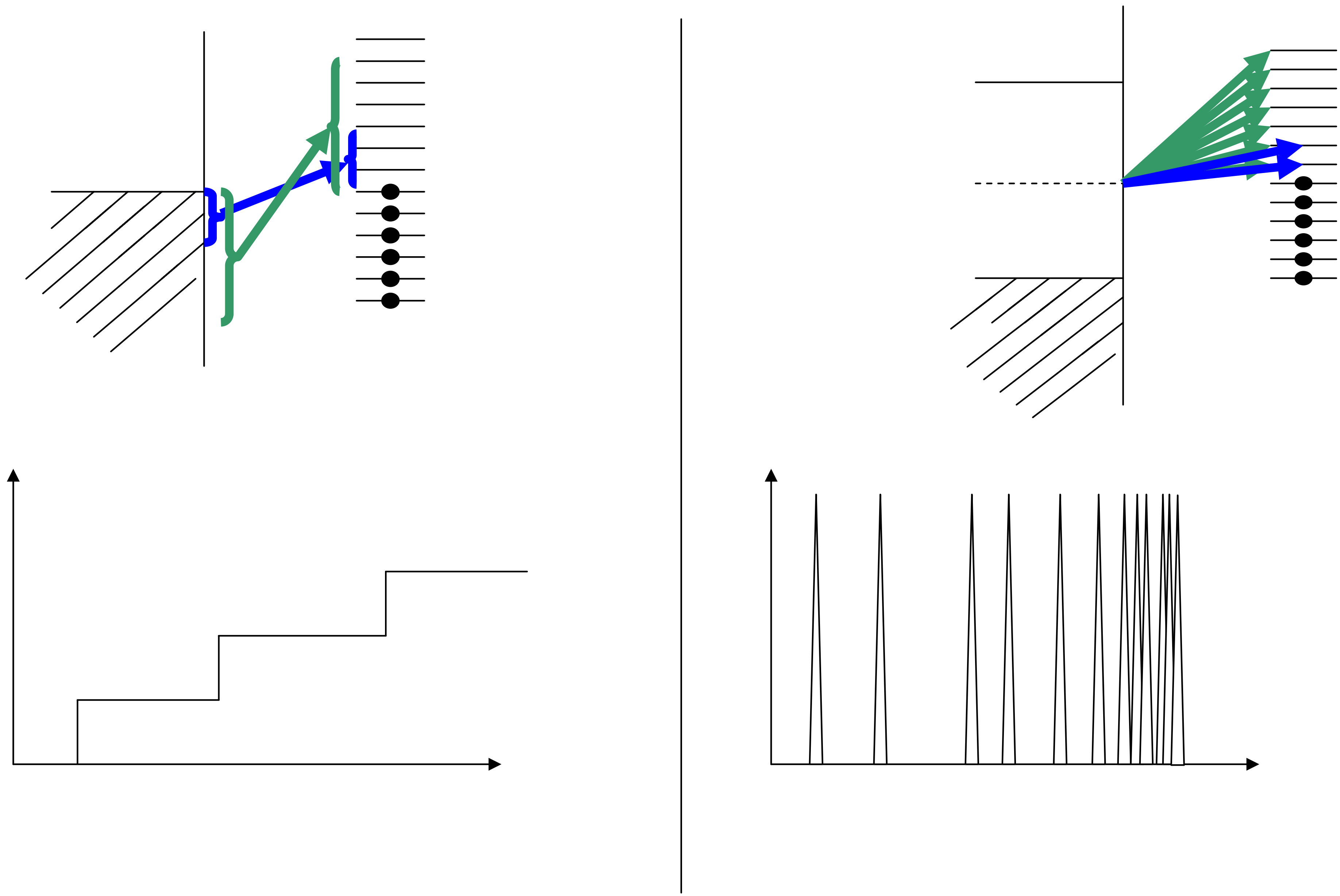


Model III: Cooper pair from the superconductor near the JQC is split and each of the electrons tunnels into an empty trap (Andreev fluctuator)

Linear average DOS



Fluctuations



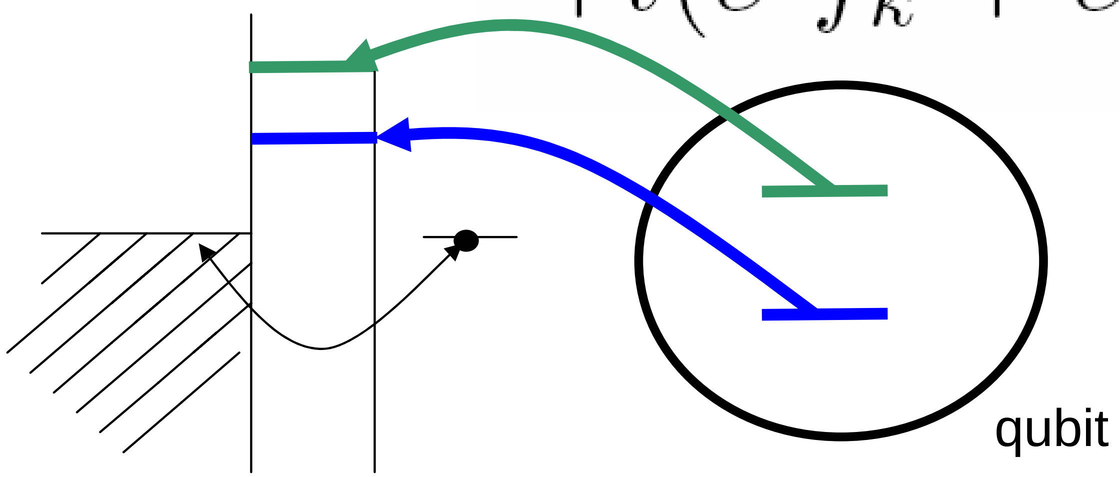
Barrier height

Fermi's golden rule: $\Gamma \propto g(E_J)\ |T|^2$ Assumes 1. order contribution

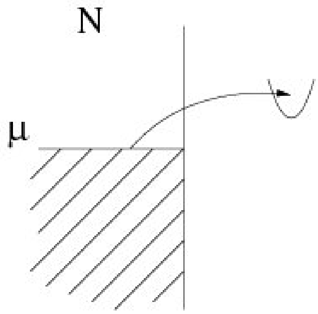
$$H_q = \frac{1}{2}\Delta\sigma_z + \frac{1}{2}E_J\sigma_x$$

$$H = H_q + v c^\dagger c \sigma_z + t_0(c^\dagger f_k + c f^\dagger)$$

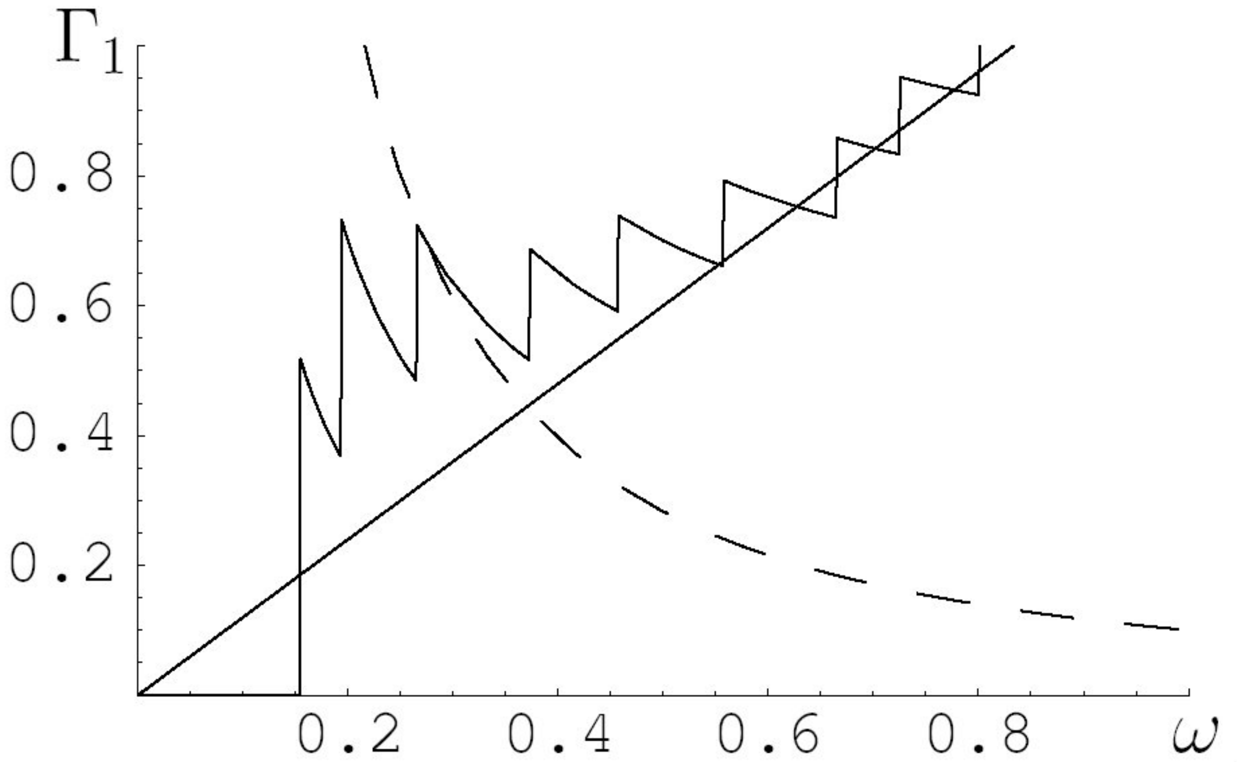
$$+\tilde{t}(c^\dagger f_k + c f^\dagger)\sigma_z$$



Model I.

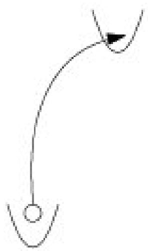


$$g(\omega) \propto \omega$$



- peaks are asymmetric
- correlations are long range
- amplitude of oscillations decreases with increasing ω

Model II.



$$g(\omega) \propto \omega$$

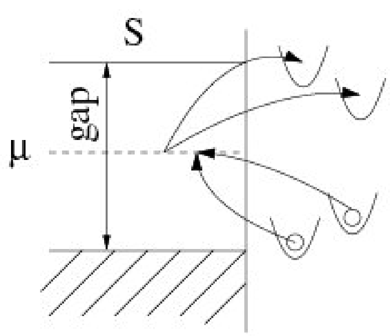
But the assumptions that the tunneling amplitude is independent of which pair of traps the electron tunnels between is unrealistic

Only traps which are close in space can exchange charge.
For such pairs the Coulomb interaction between the traps cannot be neglected

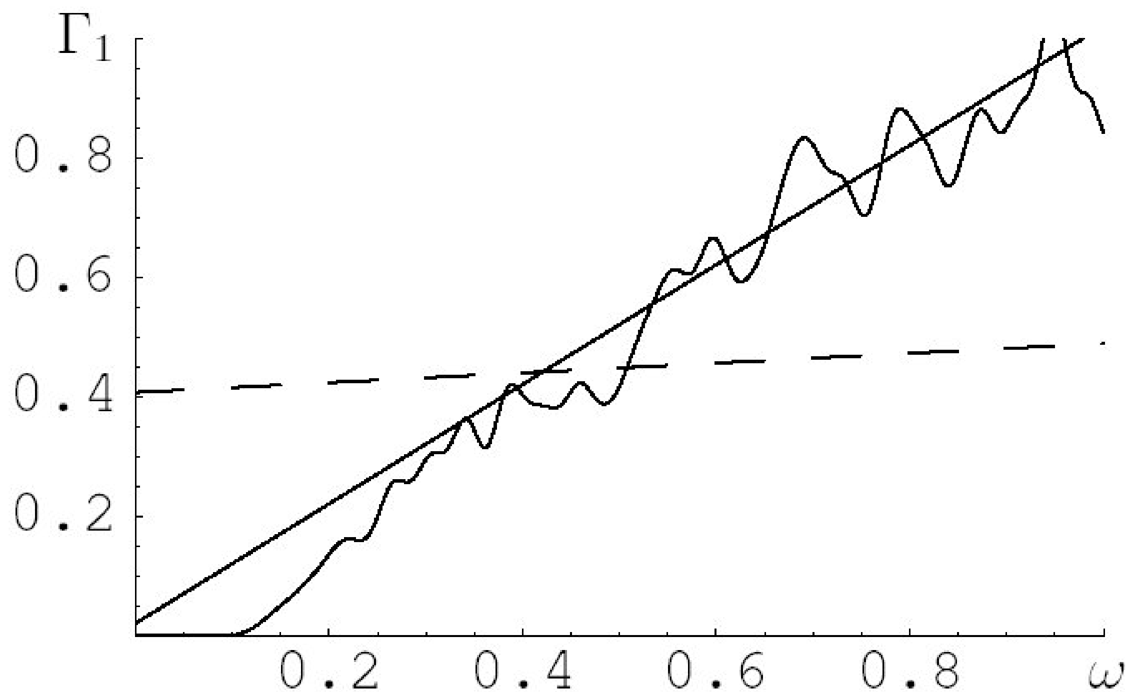
$$g(\omega) \propto constant \quad \Longrightarrow \quad \Gamma_1^{(1)} \propto constant$$

Missed the linear behavior seen by Astafiev et al. at high frequency

Model III.



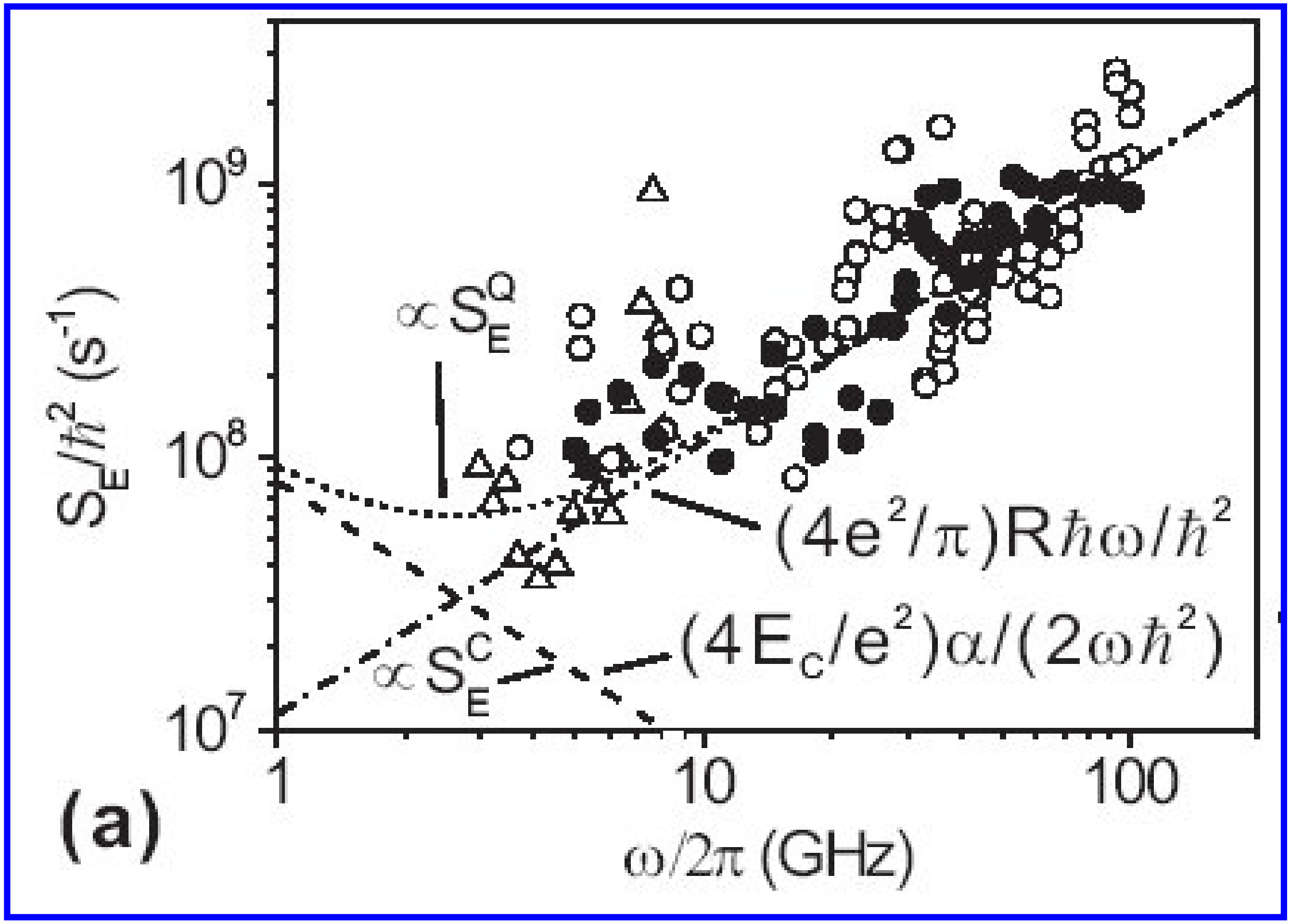
$$g(\omega) \propto \omega$$



- correlations are short range
- amplitude of oscillations increases with increasing ω

Oscillations similar to the ones seen in Astafiev et al. Experiments !!

Experimental results



Relaxation rate is proportional to energy: $\Gamma_1 \propto \omega$

The fluctuations are reproducible for a given sample

Summary

- Relaxation rate is proportional to energy
- There are fluctuations that are reproducible within a given sample
- We believe that the model of splitting Cooper pairs (Andreev fluctuators) to be in best agreement with experiment
- This can not be determined with great certainty, more experiments are needed!