Experiments on quantum statistics effects in Josephson junctions arrays

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Graph-shaped arrays

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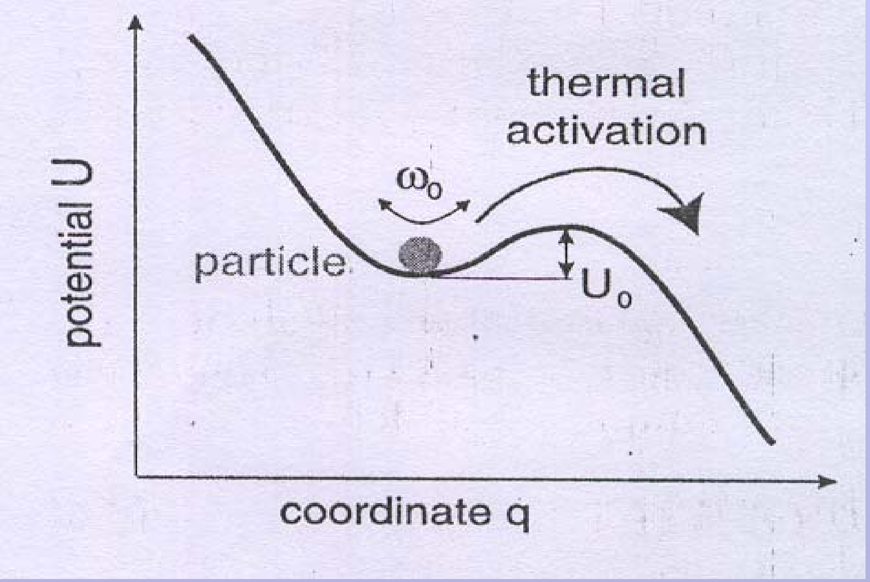
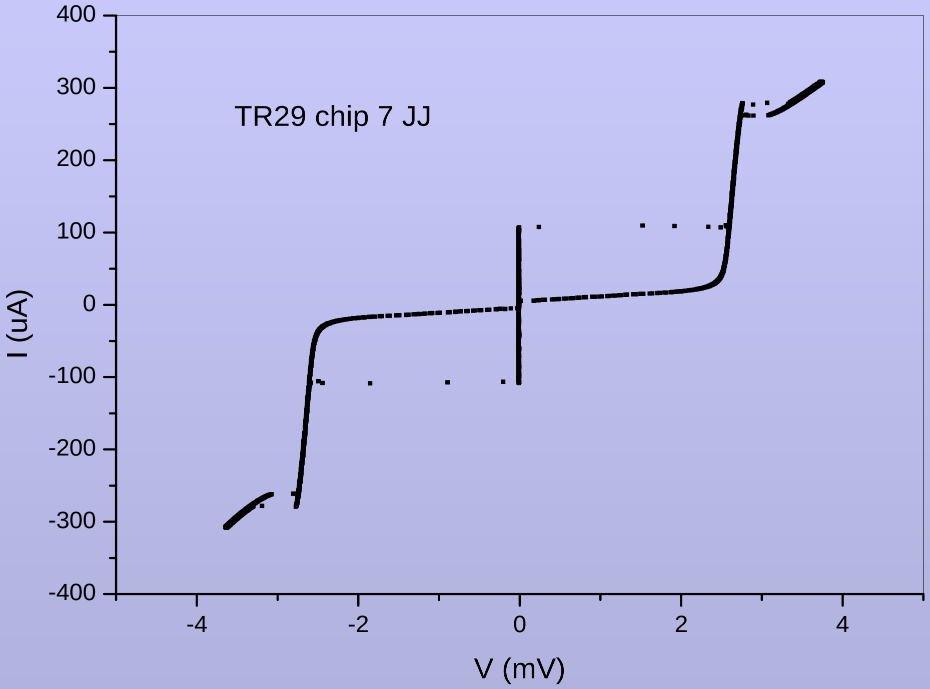
Thermal Activation in Josephson Junctions

Point Josephson junction (no spatial dependence of coordinate $q=\phi$, superconducting phase difference between electrodes)

$$U(\phi) = E_J\,(-\gamma\phi - \cos\phi) \qquad \text{with} \quad E_J = \Phi_0 I_c / 2\pi$$



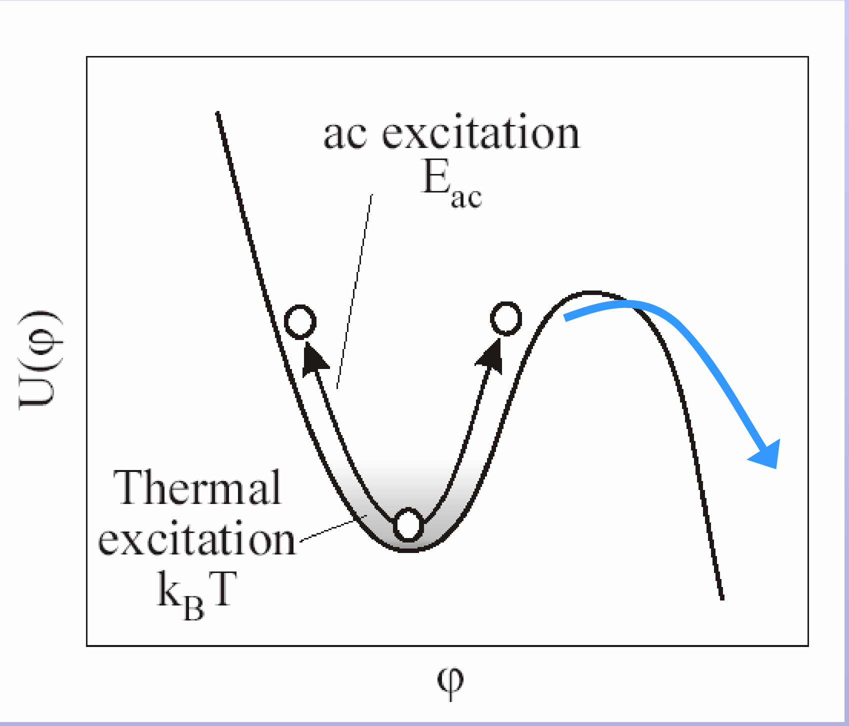


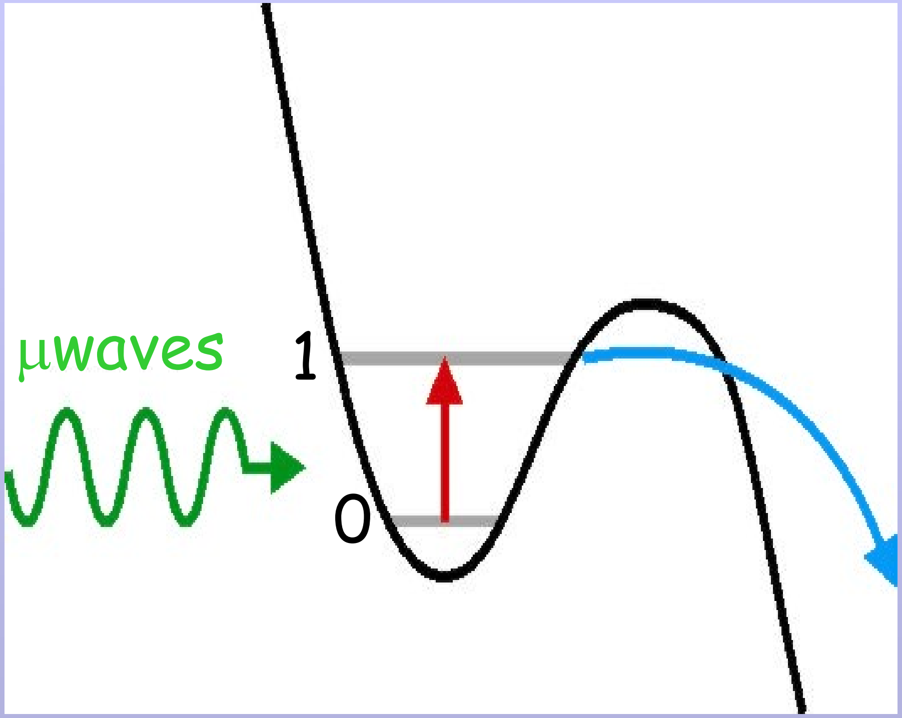
Rate of thermal escape from potential well, Γ :

$$\Gamma_{th} = (\omega_0/2\pi)\,\exp\,(-U_0/k_B T)$$

Γ_{th} can be directly correlated to measured switching distribution as a function of the bias current P(I)

Is it possible to quantize Josephson phase and flux ? [Caldeira and Leggett PRL 46, 211 (1981)]





The conditions for the observation of the quantum effects were said to be a quantum dissipation regime and a temperature such that

$$T < \hbar\omega_j / 2\pi k_B$$

Thermal escape under μwave

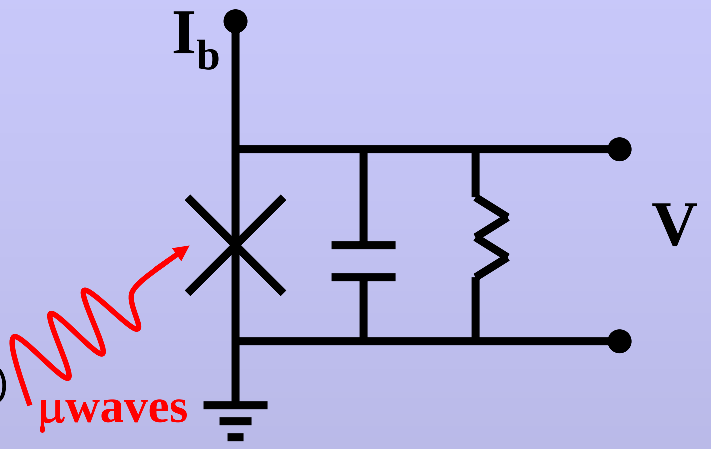
Escape of Josephson devices from the superconducting to the voltage state…

- Kramers, Physica 7, 294 (1940)
- Fulton and Dunkelberger, PRB), 4760 (1974)
- Han, Lapointe and Lukens, PRL 63, 1712 (1989)
- C. Cosmelli et al., PRL 82, 5357 (1999)

…+ Microwaves

- Martinis, Devoret and Clarke, PRL 55, 1543/1908 (1985)
- Martinis et al. PRL 89, 117901 (2002)
- Ustinov's group , PRL 90, 037003 (2003); Nature 425,155(2003)
- Claudon et al., PRL 93,187003 (2004)

Point Josephson junction and RCSJ



Our idea is to analyze the escape process when the system is irradiated by rf, but working at temperatures high enough to be in the classical regime: $T \geq \hbar\omega_j / 2\pi k_B$

Measurements procedure

We send rf at fixed frequency ω_d, and we ramp the bias current η until we record the switch from the superconducting to the voltage state.

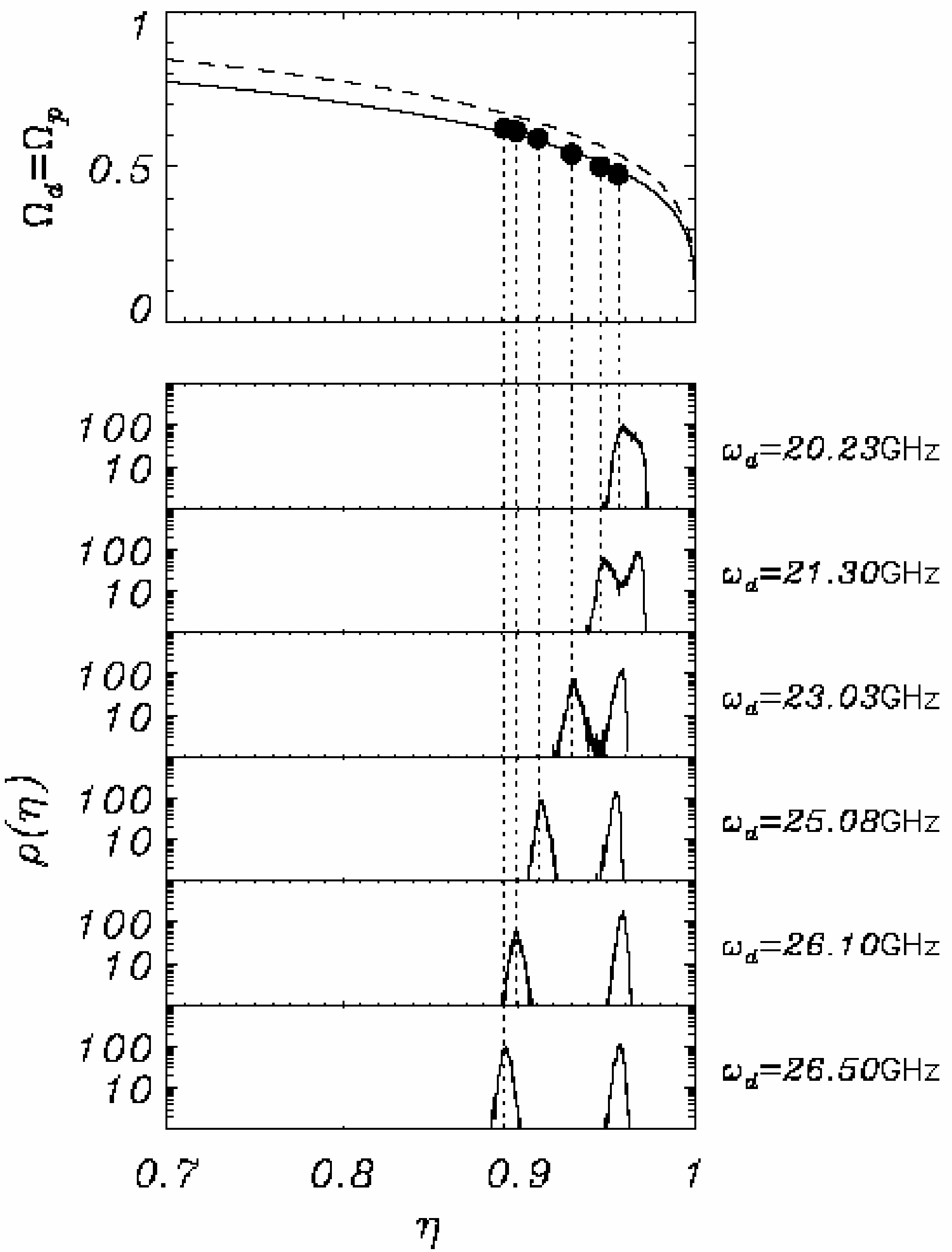
We repeat for 2-10'000 times and we evaluate the switching probability $\rho(\eta)$.

We find two peaks in the switching current distribution due to the enhancement of the escape due to the rf excitation driving the junction.

Junction parameters:

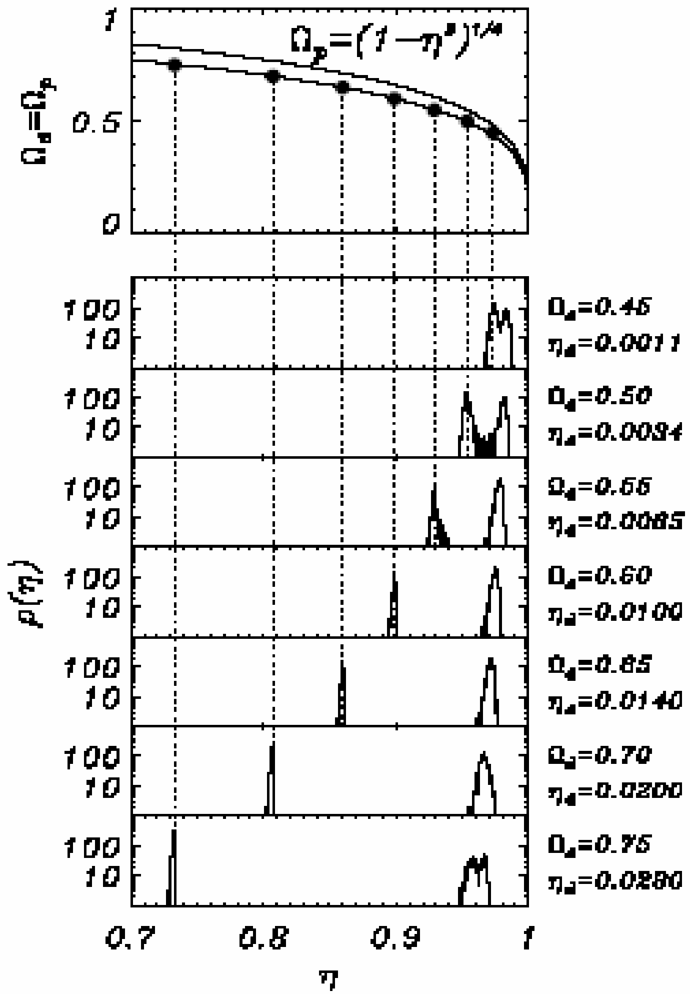
I_c=143 μA ; C=6pF ; f_j= 44GHz

T= 1,6 K ; dI_b/dt = 800mA/s

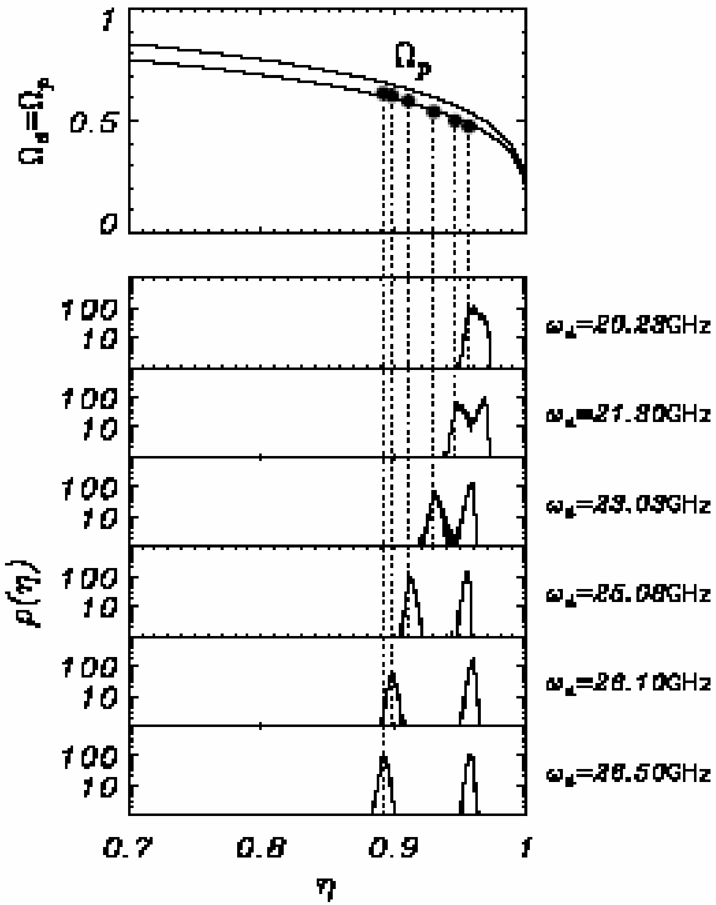


AC driven small classical JJ

$$\frac{kT}{E_J} = 4.76 \cdot 10^{-4}, T = 1.6K - \dot{\eta} = 2.1 \cdot 10^{-8}, \dot{I} = 0.8A/s - \alpha = 0.00845, R = 74\Omega - I_c = 143\mu A - T^* = 320mK.$$



Simulation

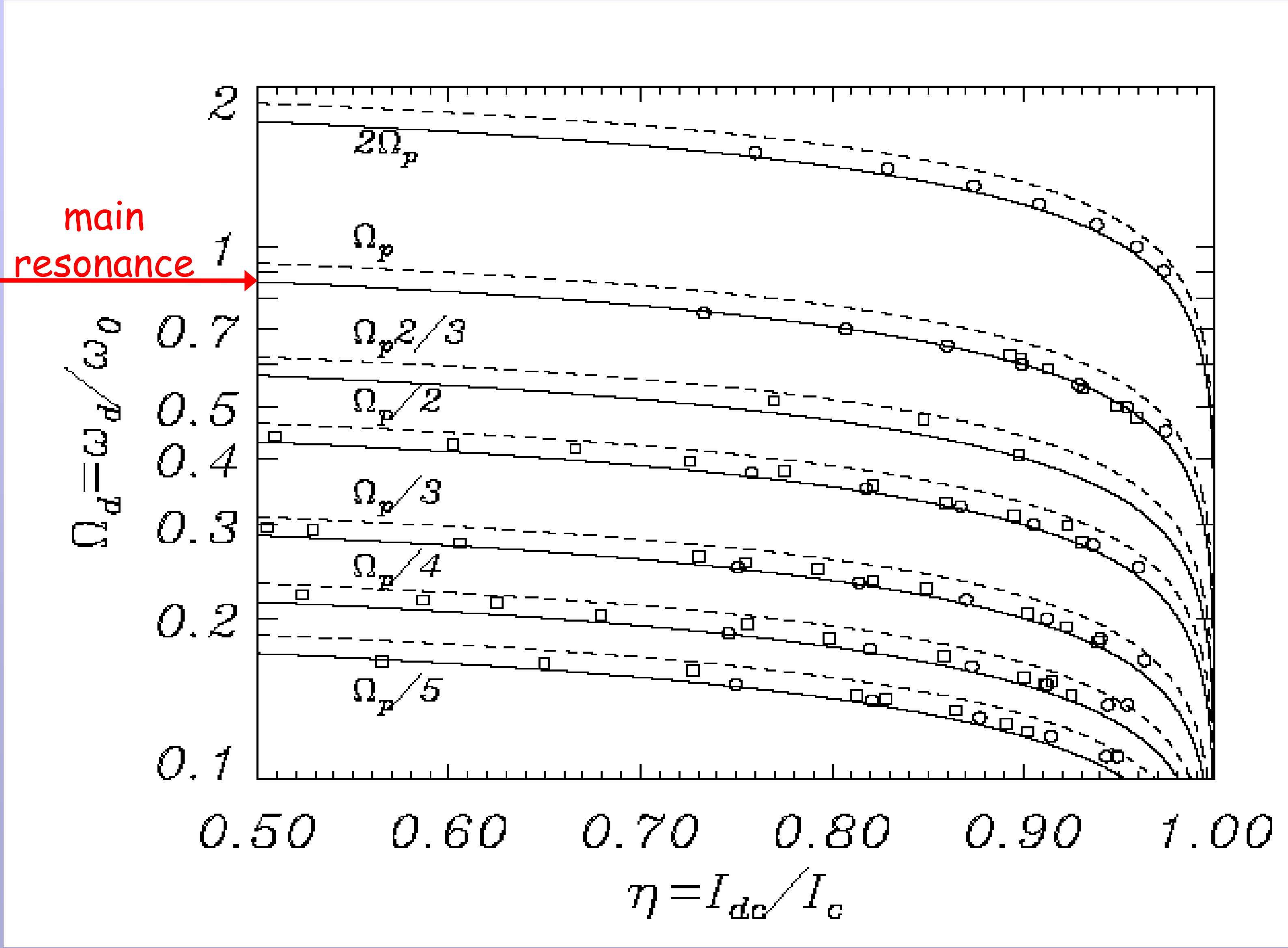


Experiment

● Circles: exp. results □ Square: simulation

- - - - Dashed: linear resonance —— solid: anharmonic

N.Grønbech-Jensen et al. *PRL* 93, 107002 (2004)



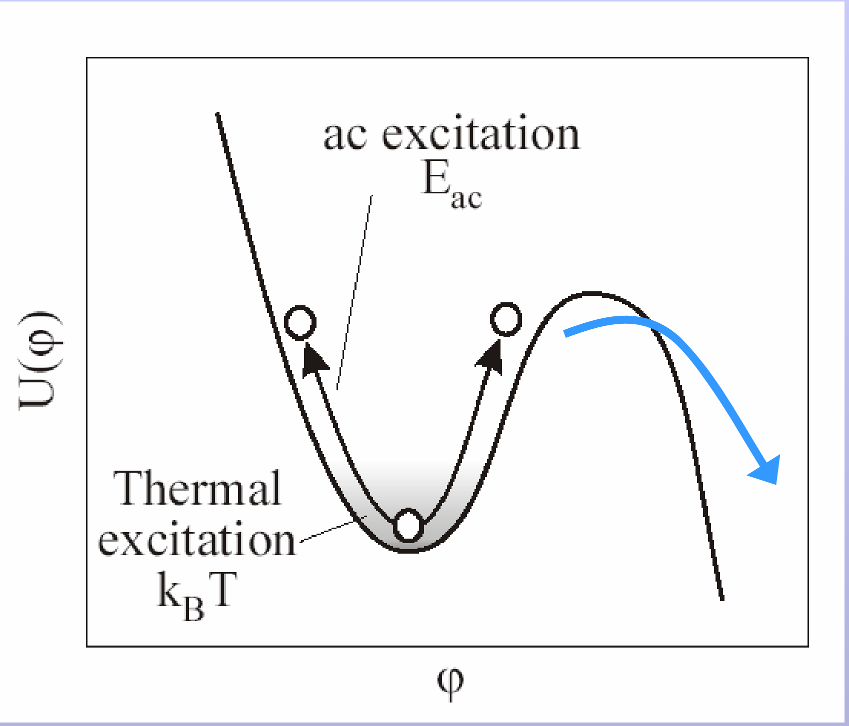
T=1,6 K

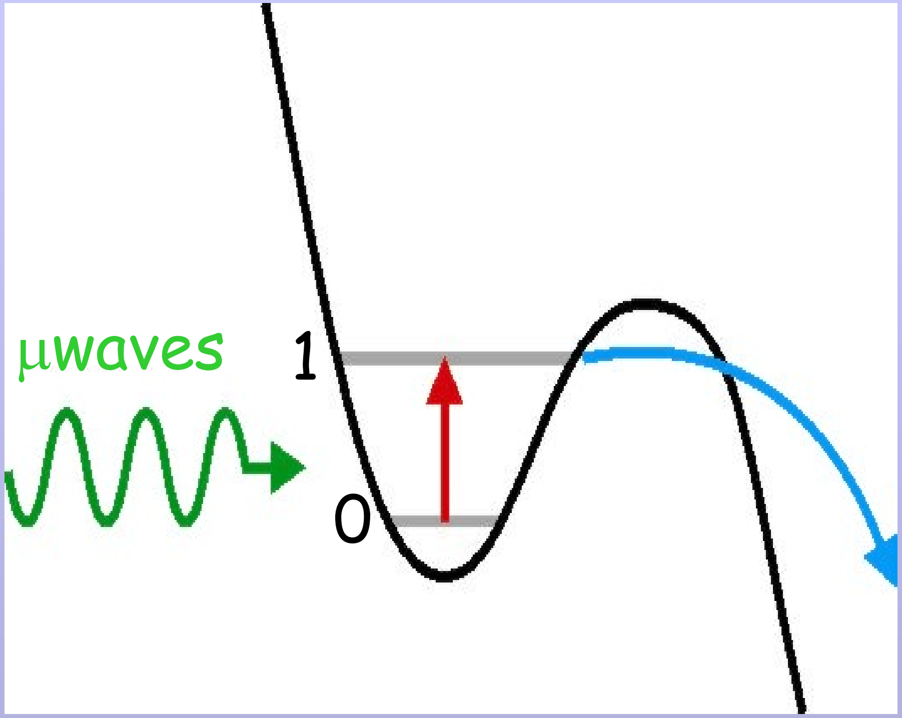
I_c=143μA

$\dot{I}$=0,8A/s

T^*=340mK

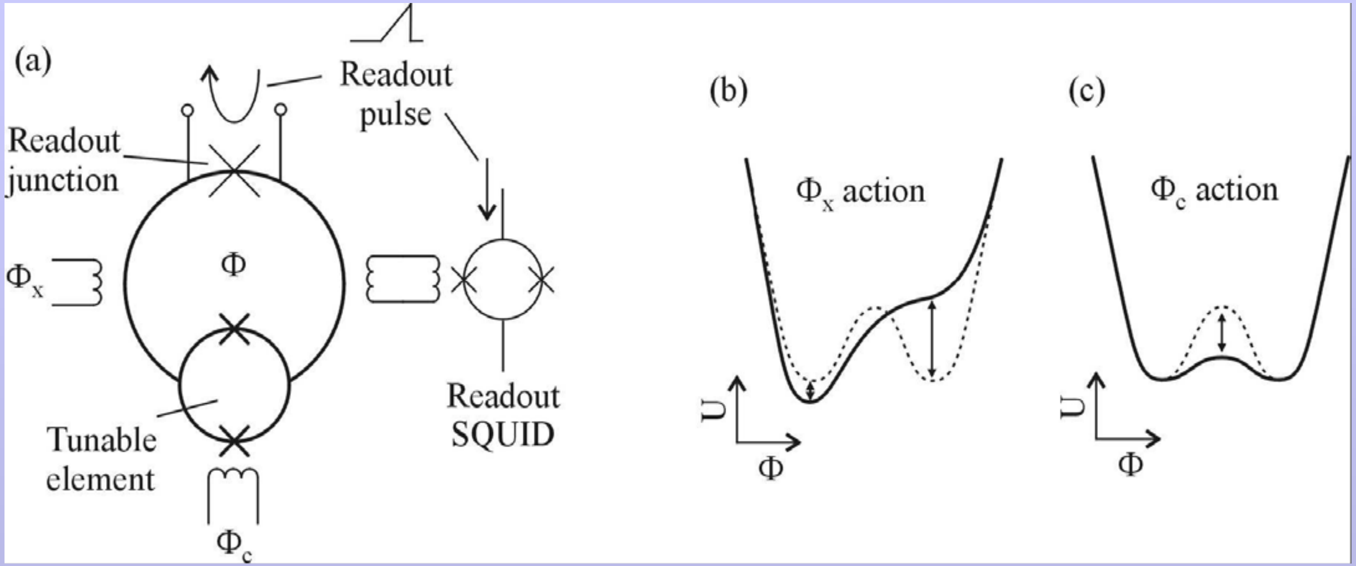
Effects in the thermal and quantum regime





The effect (enhanced escape) is the same, for the same frequency of microwaves. Also, excitation energies both derive from hν(=2eV)

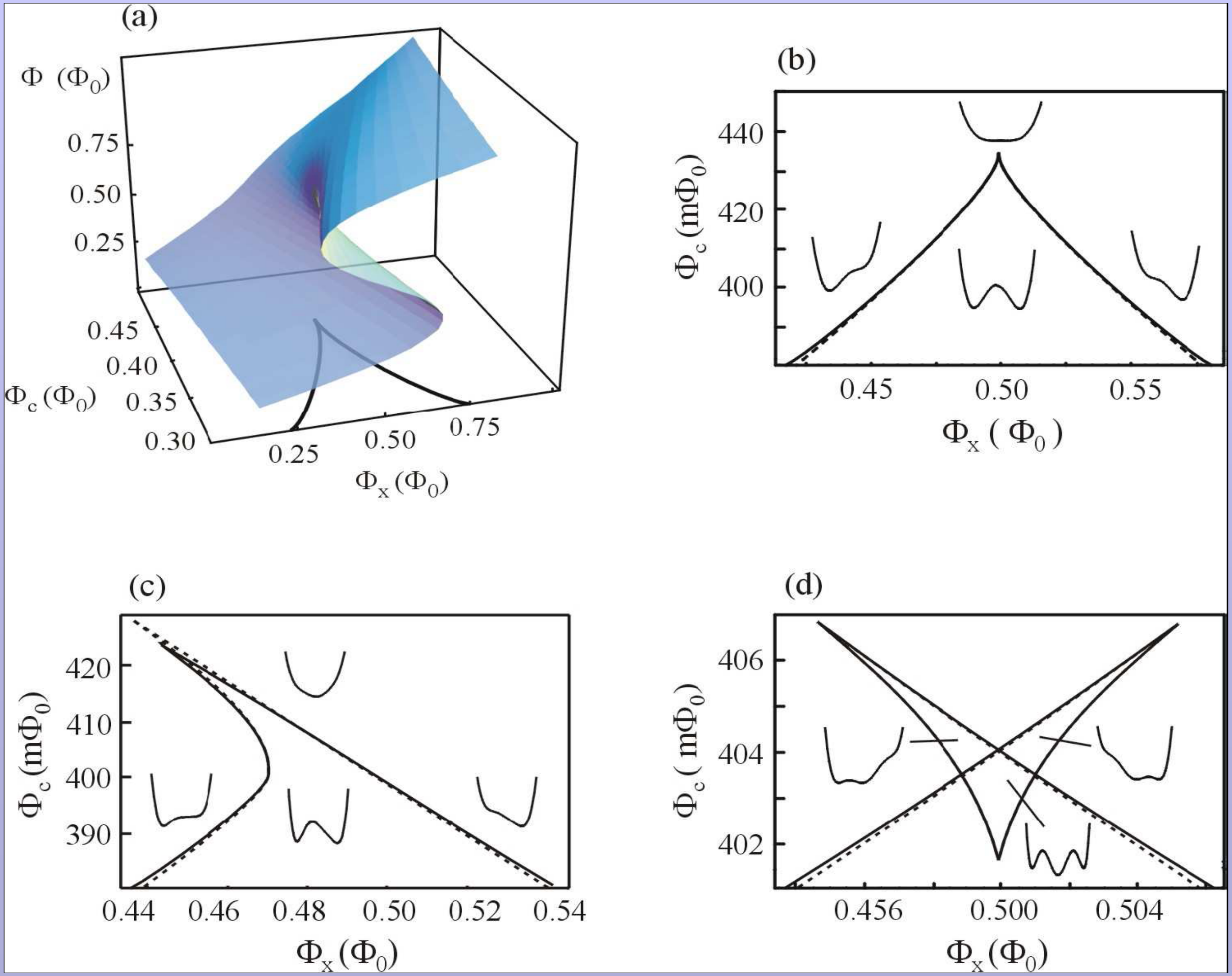
Flux variable, skip now microwaves



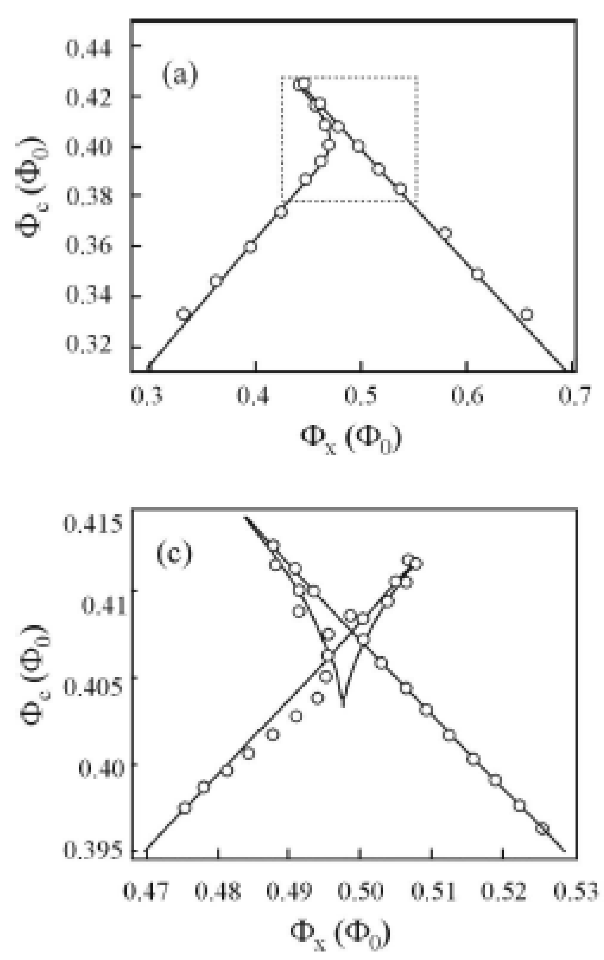
The approximate potential energy function reads (23)

$$U = \frac{1}{2}E_L(\varphi - \varphi_x)^2 - E_S \cos\varphi + E_D \sin\varphi - \frac{1}{2}E_I \cos^2\varphi \qquad (1)$$

$$\varphi_x = \varphi + \frac{E_S}{E_L}\sin\varphi + \frac{E_D}{E_L}\cos\varphi + \frac{E_I}{E_L}\sin\varphi\cos\varphi \qquad (2)$$



$$U=\frac{(\varphi-\pi)^6}{60}E_l-\frac{(\varphi-\pi)^4}{24}(4E_l-E_S)+\frac{(\varphi-\pi)^3}{6}E_D+ \\ +\frac{(\varphi-\pi)^2}{2}(E_L+E_l-E_S)-\varphi(E_D+\varphi_x-\pi) \tag{3}$$



EUROPHYSICS LETTERS 1 November 2000

Europhys. Lett., 52 (3), pp. 251–256 (2000)

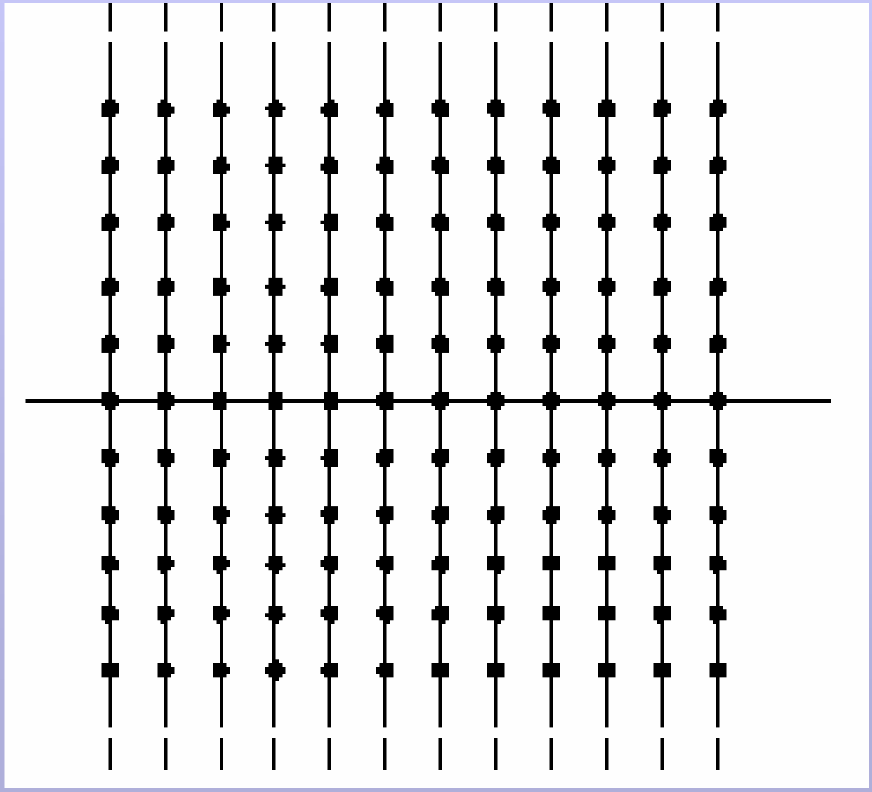
Bose-Einstein condensation in inhomogeneous Josephson arrays

R. Burioni [1], D. Cassi [1], I. Meccoli [1], M. Rasetti [3],
S. Regina [1], P. Sodano [2] and A. Vezzani [1]

$$H_{JJ} = -J_0 \sum_{(x,y,x',y')} \cos\left(\phi_{x,y} - \phi_{x',y'}\right)$$

$$T_c \approx \frac{J_0}{k_B}$$

$$I_c = 2eJ_o/\hbar$$



$$Eigenfunctions:$$

$$(e^{-h|y|} - e^{-h|y|-2L})e^{ik_0x}$$

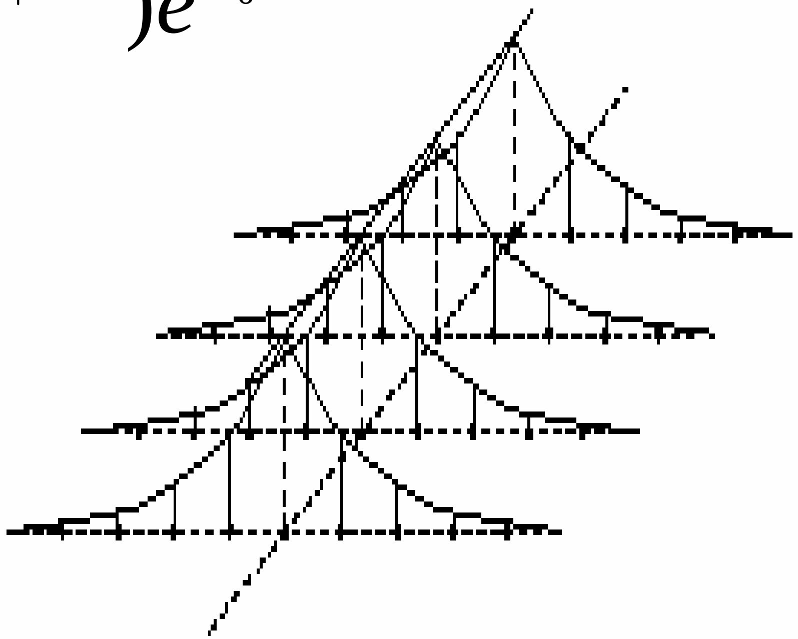
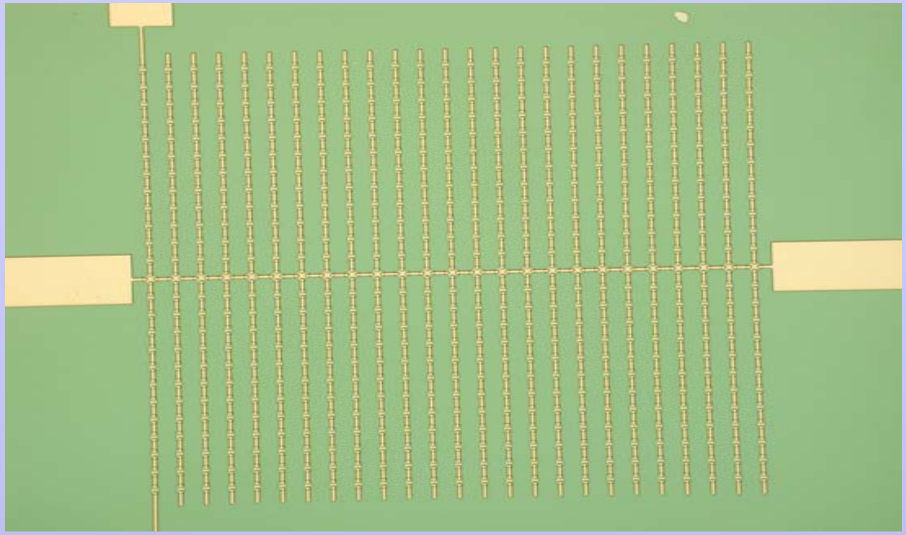
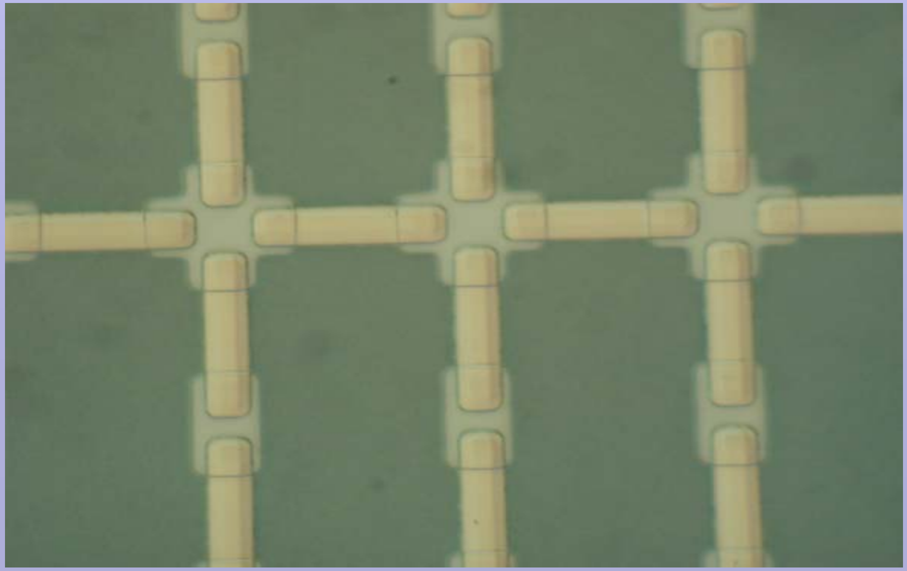


Fig. 3 – The eigenvector corresponding to the lowest energy state. It is constant along the backbone direction and it decreases exponentially as $\exp[-\mathrm{arcsh}(2)\cdot|x|]$ along the fingers.

M. Cirillo et al.

In "Quantum Computing in Solid State Systems", Springer 2005





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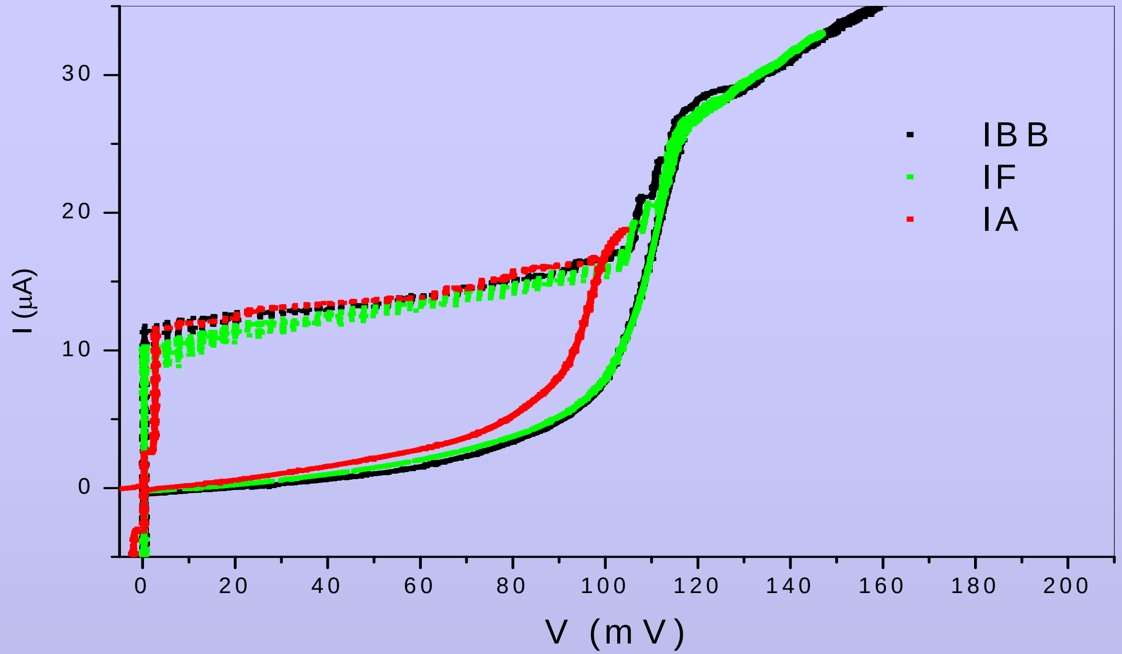

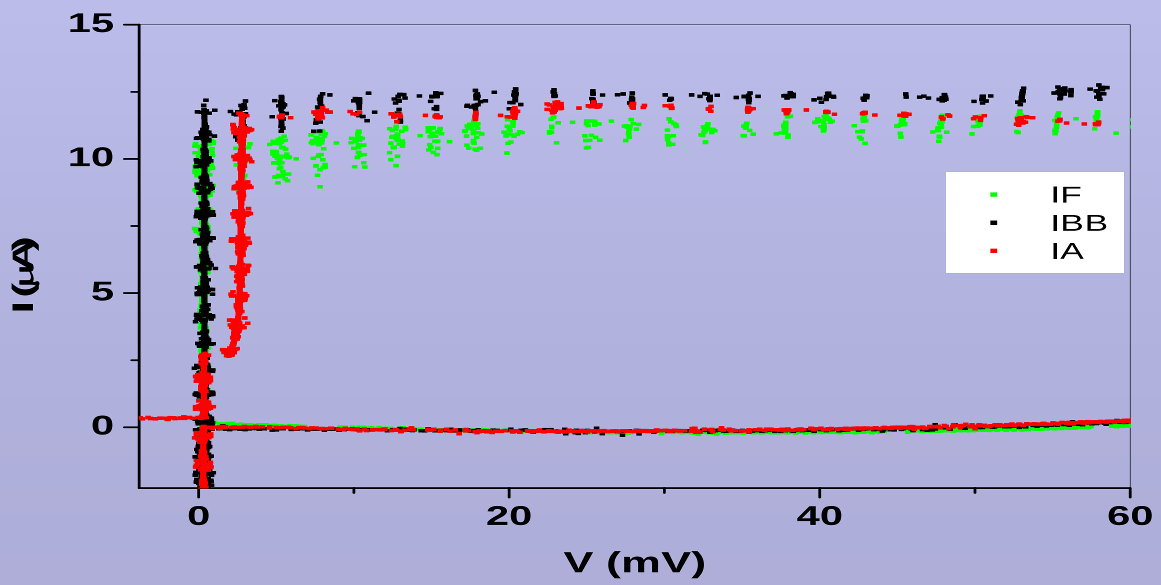

P. Silvestrini et al.

Cond-mat/0512478

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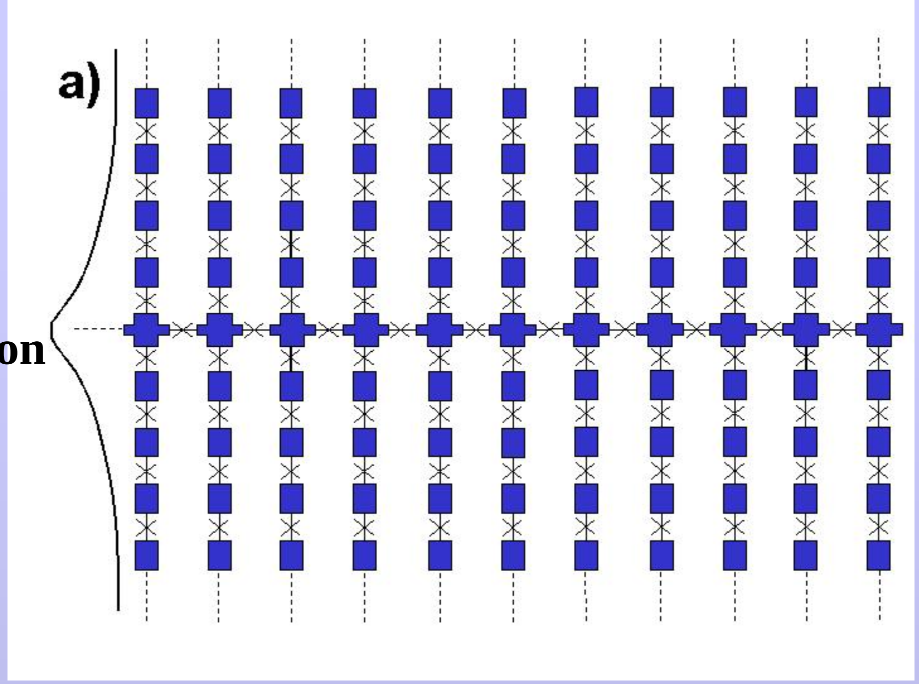

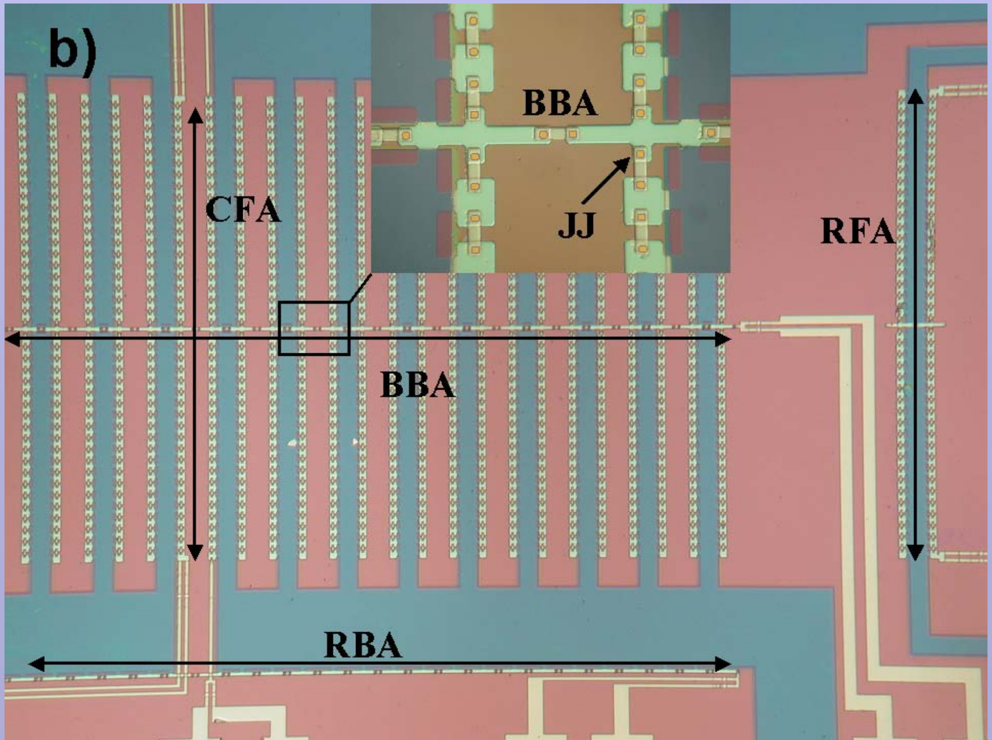

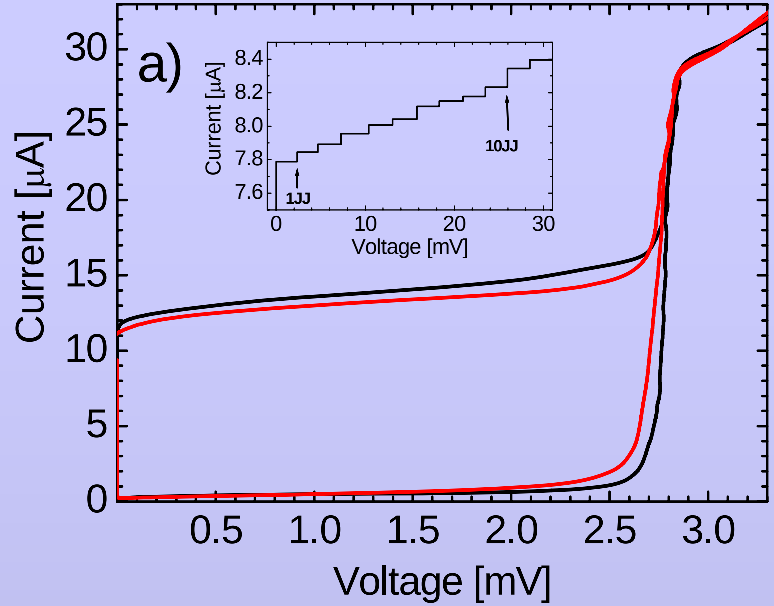

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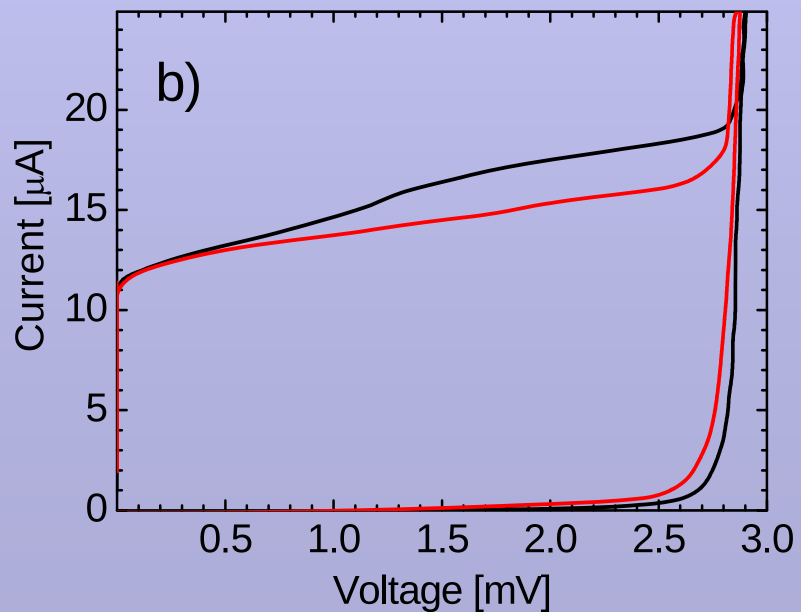

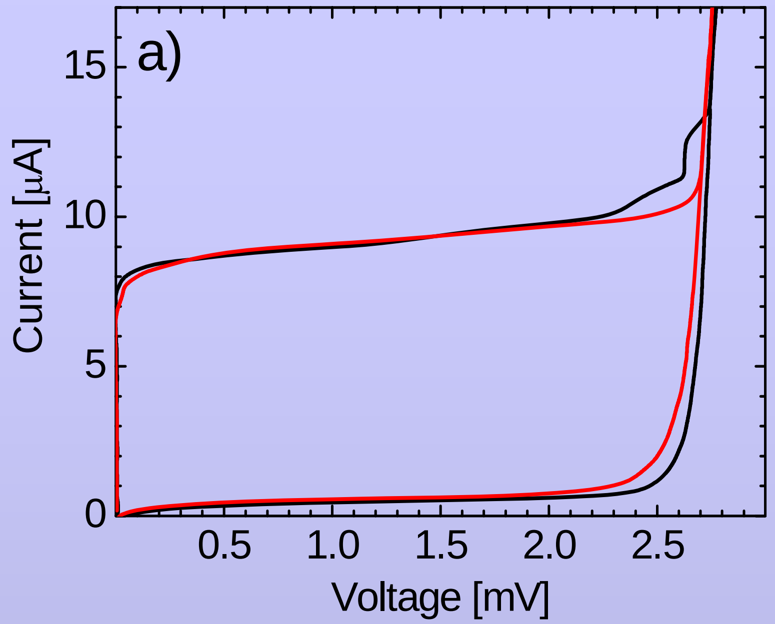

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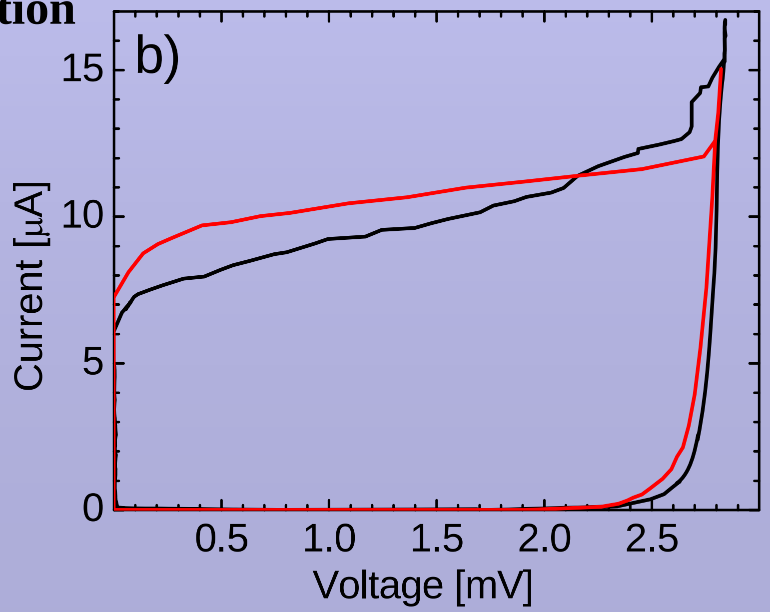

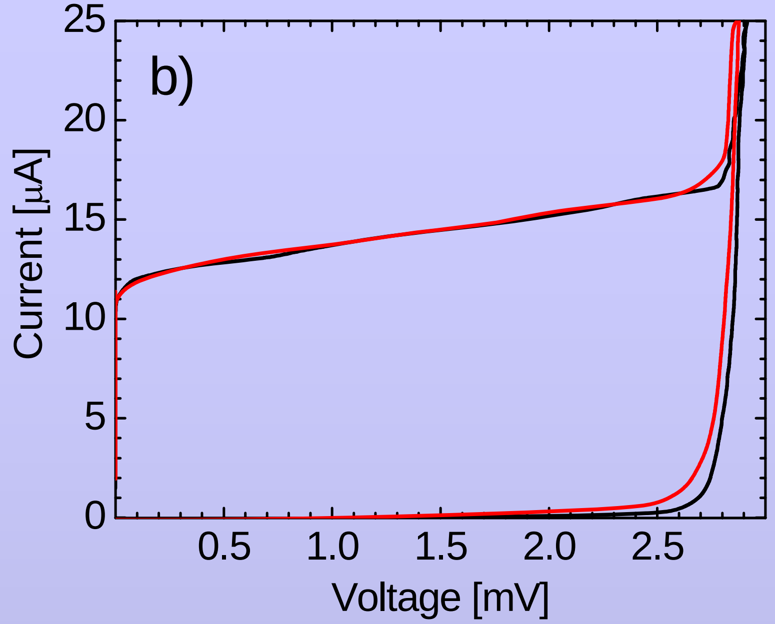

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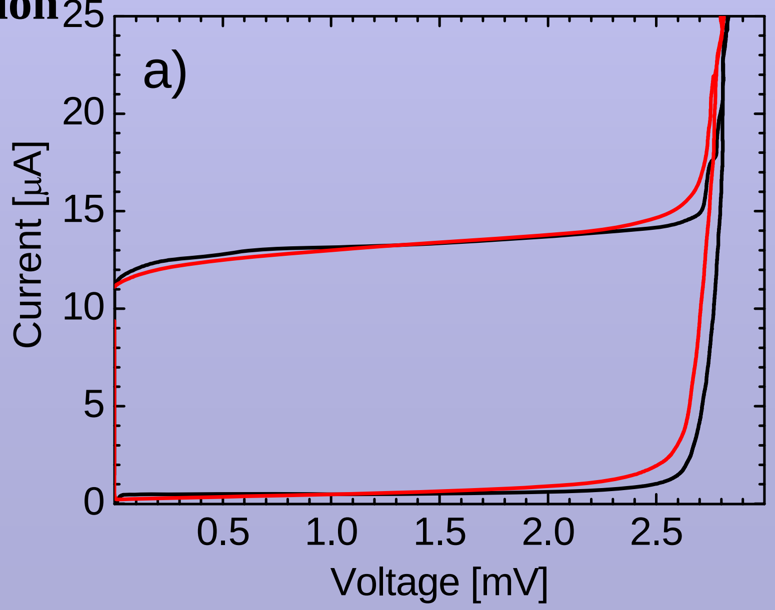

Conclusions

The new and interesting results on “classical” macroscopic quantum effects in the Josephson junctions demonstrate that it would be very desirable to produce unambiguous experimental evidence that Josephson phase and flux obey a “super” quantum description

It would be desirable as well to clarify the energy scales and the nature of the islands interaction leading to the anomalous gradients in the Josephson currents of the graph arrays. The experimental results show that mean field theories could (still) produce surprises when analyzing superconducting island interactions through Josephson potentials.