Single microwave photon counter based on current biased Josephson junction

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on behalf of the SIMP collaboration[1]

(1. see last slide)

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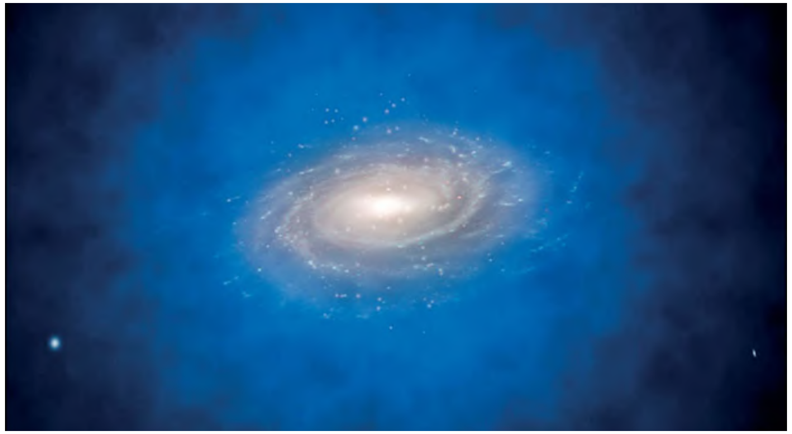
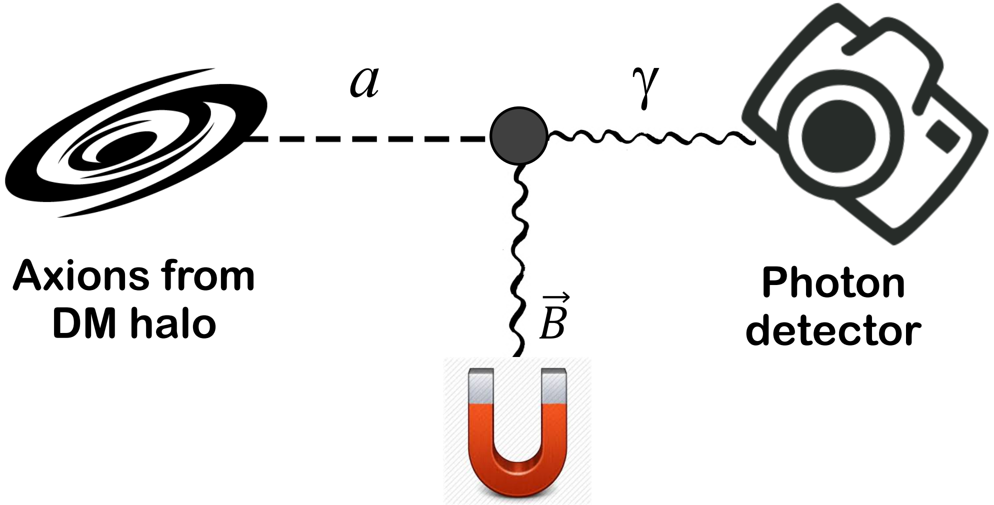
We use Josephson junctions as photon detectors for axion search

Axions arise from extensions of the Standard Model of particle physics and are good candidates of Dark Matter

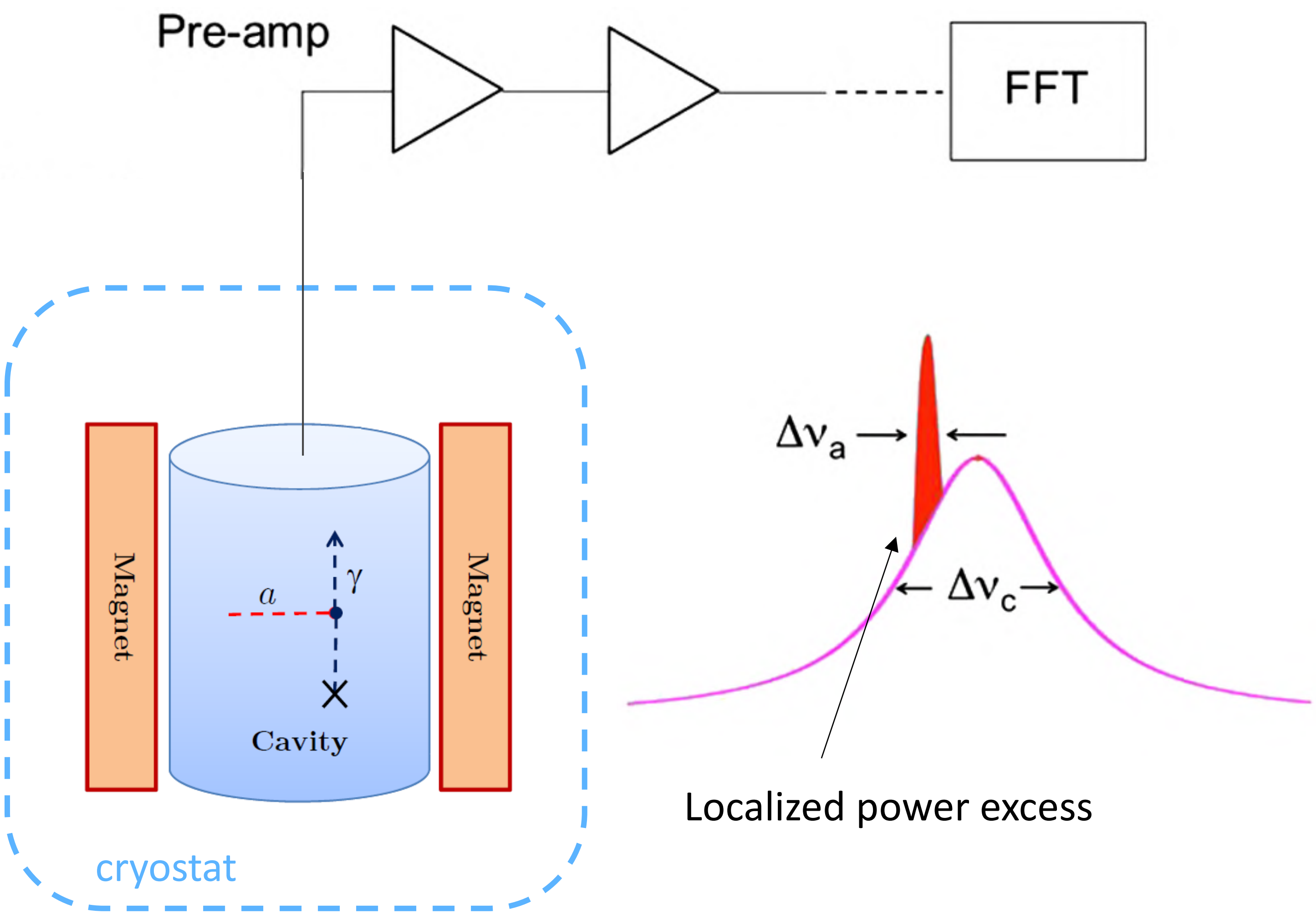


Axions have an interaction term with photons

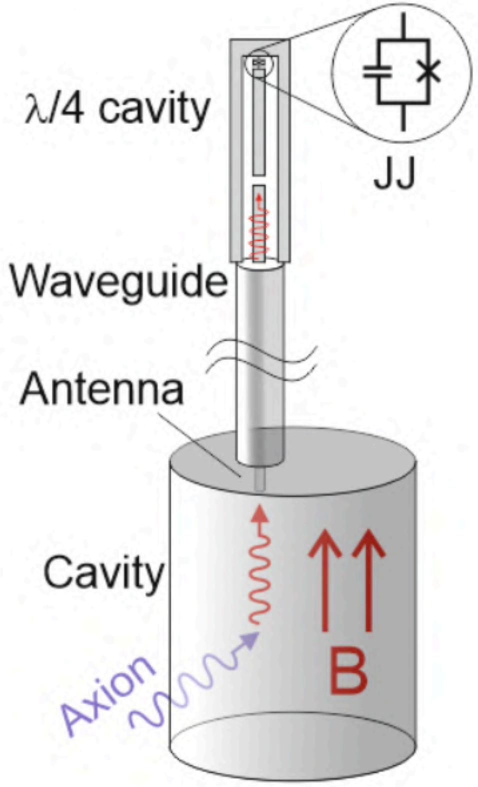
$$\mathscr{L}_{a\gamma\gamma} = -g_{a\gamma\gamma} a \, \vec{E} \cdot \vec{B}$$



Haloscope concept



SIMP (SIngle Microwave Photon) project



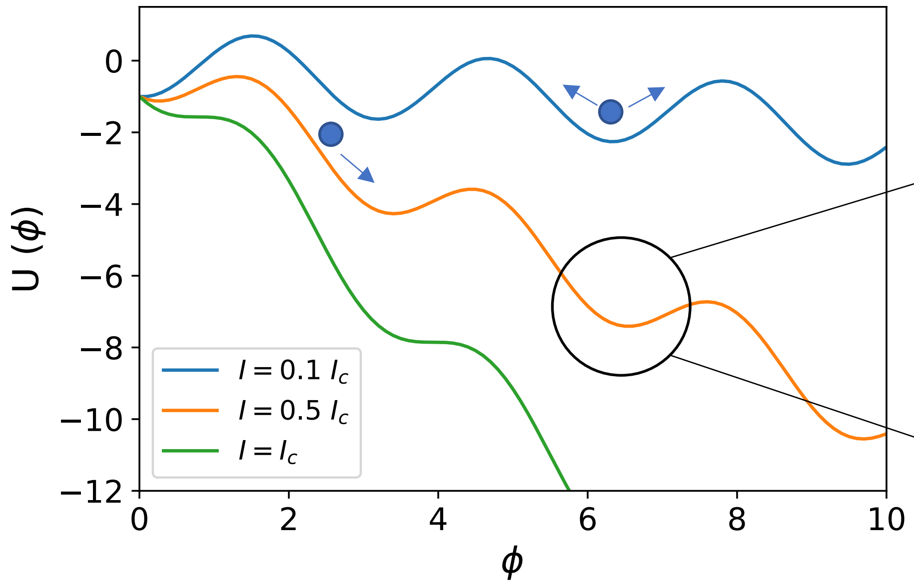
Current biased Josephson junctions as photon detectors

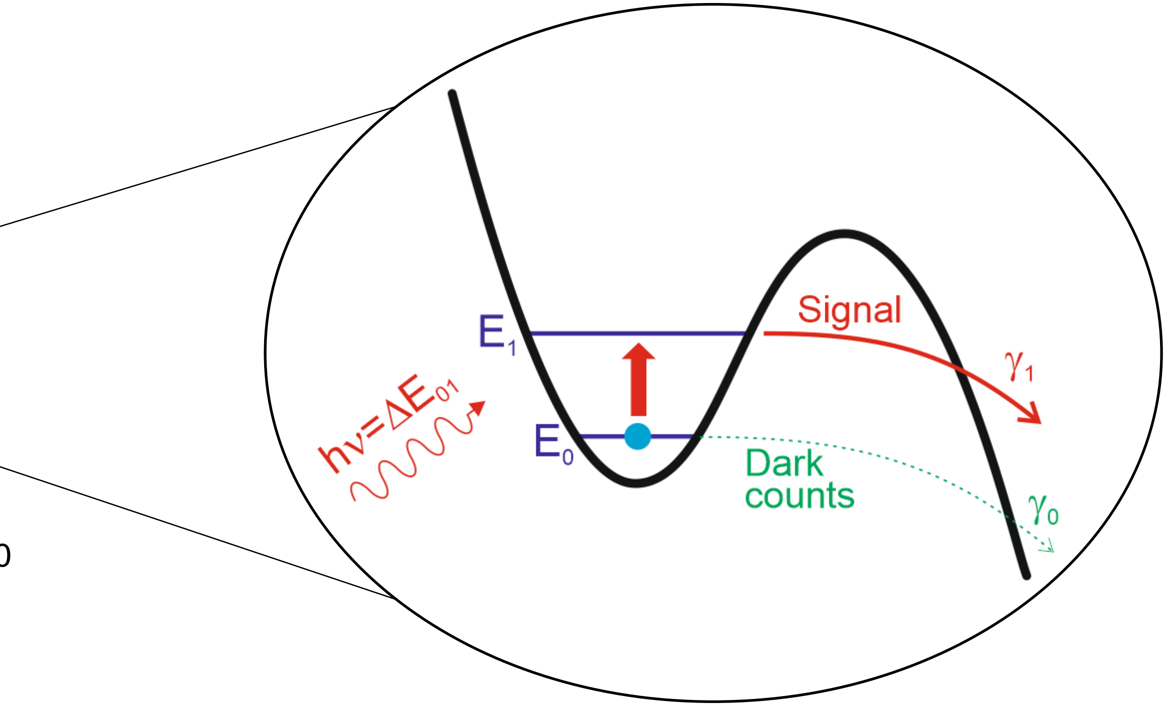
$$I = I_0 \sin\phi$$
$$\frac{\mathrm{d}}{\mathrm{d}t}\phi = \frac{2e}{\hbar}V$$

In order to use a JJ as a detector, it is convenient to bias it with a dc current just below I_0 through a suitable dc current source.

The occurrence of an external additional current can induce the switching of the junction from the zero to the finite voltage state.

Kuzmin et al, IEEE Trans. Appl. Supercond., VOL. 28, NO. 7 (2018)





Critical request: low dark counts

- We expect tiny signals from axions: $P_{ax} \lesssim 10^{-24}\ W$
- Single photon detector have better noise performances with respect to linear amplifiers above about $10\ GHz$

$$n = \frac{1}{e^{h\nu/k_B T} - 1}$$

$$\Delta\nu_a = \nu_c[GHz] \cdot 10^{-6}$$

$$\Delta\omega_c = \frac{1}{\tau_c} = \frac{2\pi\nu_c}{Q}$$

RMS of noise power for linear amplifiers:

$$P_{\text{lin}} = h\nu\,(n + 1)\sqrt{\frac{\Delta\nu_a}{t}}$$

and for single photon counters:

$$P_{\text{sp}} = h\nu\sqrt{\frac{n\Delta\omega_c + \nu_{\text{DC}}}{t}}$$

$n \approx 0$ →

$$\frac{P_{lin}}{P_{sp}} \approx \sqrt{\frac{\Delta\nu_a}{\nu_{DC}}}$$

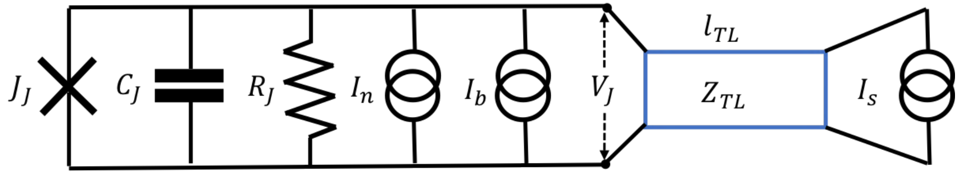
$$\nu_{DC} \approx 10\ kHz$$

at $10\ GHz$ freq

CBJJs have the potentiality to reach dark counts at mHz rate.

Switch in presence of signal

The simplest design for a photon detector is a transmission line (TL) terminated with a JJ



Circuit equation with flux variable ϕ

$$C\ddot{\phi} + \frac{\phi}{L} + \frac{1}{Z_0}\dot{\phi} = 2\frac{1}{Z_0}\dot{\phi}^{in} = 2I^{in}$$

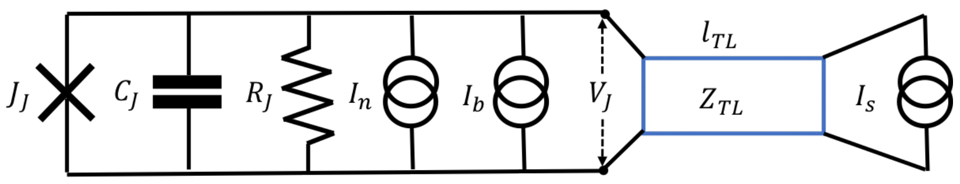
Peak current for 1 photon

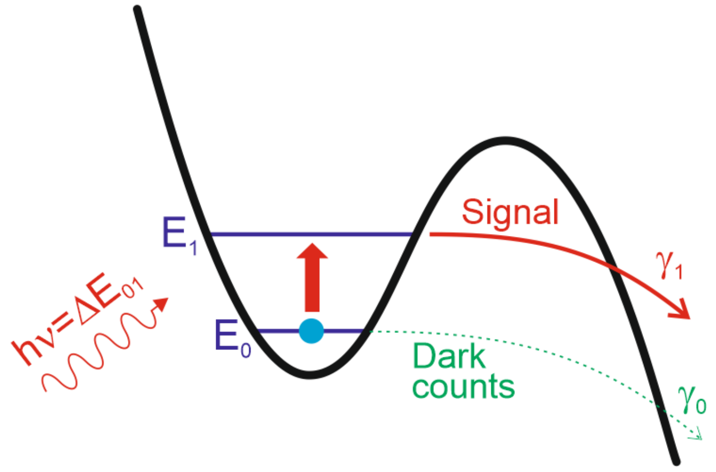
$$I_s^{photon} = 2\sqrt{\frac{\hbar\omega_0}{Z_0}\frac{2}{\sqrt{2\pi}\sigma_t}}$$

With a $\sigma_t = 600\ ps$ Gaussian wavepacket, the junction switches when:

- $2I^{in} = \mathbf{50\ nA}$ when isolated, corresponding to **4 photons**
- $2I^{in} = \mathbf{250\ nA}$ with a $50\ \Omega$ TL, corresponding to **100 photons**

Dark counts





Probability to cause a transition:

$$P_R = \frac{4\gamma_{TL}\gamma_{switch}}{(\gamma_{TL}+\gamma_{switch})^2}$$

Coupling of TL to the junction:

$$\gamma_{TL} = \omega_j Z_j / Z_0$$

$\gamma_{sw} \sim 10^3 \gamma_0$

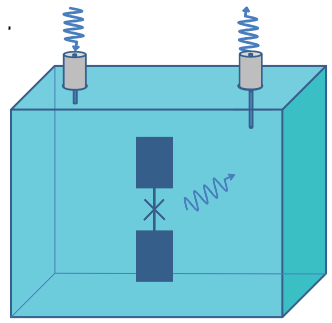
$\gamma_{TL} \sim 10\ GHz$

- P_R is maximum when $\gamma_{TL} = \gamma_{sw}$, but $\gamma_0 = 1$ MHz
- $P_R = 0.5 \cdot 10^{-3}$ when $\gamma_{sw} = 1$ MHz, $\gamma_0 = 1$ kHz
- $P_R = 4 \cdot 10^{-7}$ when $\gamma_{sw} = 1$ kHz, $\gamma_0 = 1$ Hz

Proper matching of the TL to the junction is an issue

Possible solutions to the matching issue

JJ directly coupled to a 3D cavity



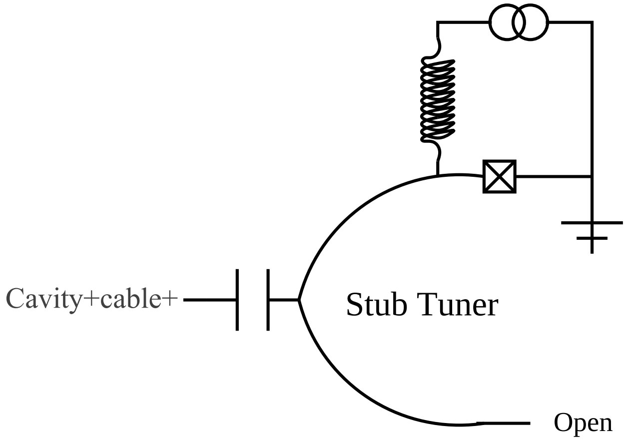
arXiv:1105.4652v4

In this case decoherence is given by τ_c

So, for copper cavities at 10 GHz:

$$\tau_c \sim 1\ \mu s$$
$$\gamma_c = 1/\tau_c \sim 1\ \text{MHz}$$

Stub tuner



If there is no matching, the photon is 'trapped' in the coplanar branches

Current situation

Simulations done

Single JJ measured

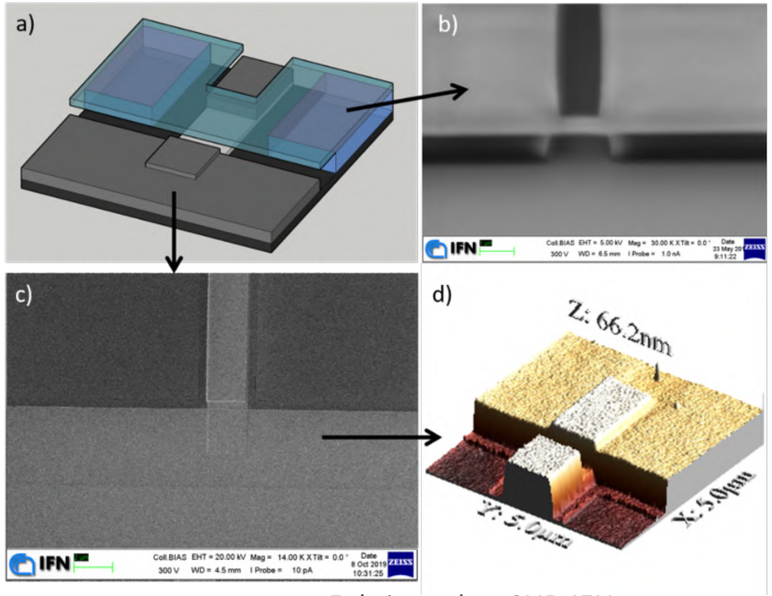
TL + JJ device fabricated

JJ fabrication and measurements

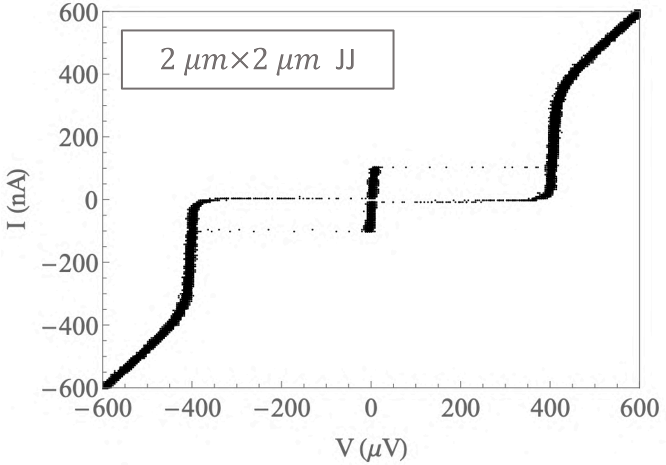
Shadow mask evaporation technique, with Electron Beam Litography

Material	Aluminum
Dimensions	$2\ \mu m \times 2\ \mu m$
I_0	$300\ nA$
C	$200\ fF$

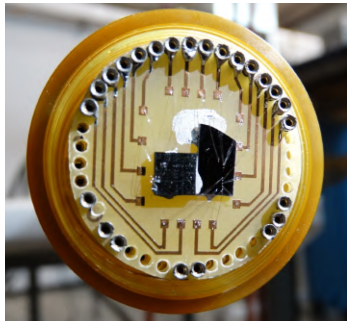
Material	Aluminum
Dimensions	$2\ \mu m \times 4\ \mu m$
I_0	$600\ nA$
C	$400\ fF$



Fabricated at CNR-IFN.



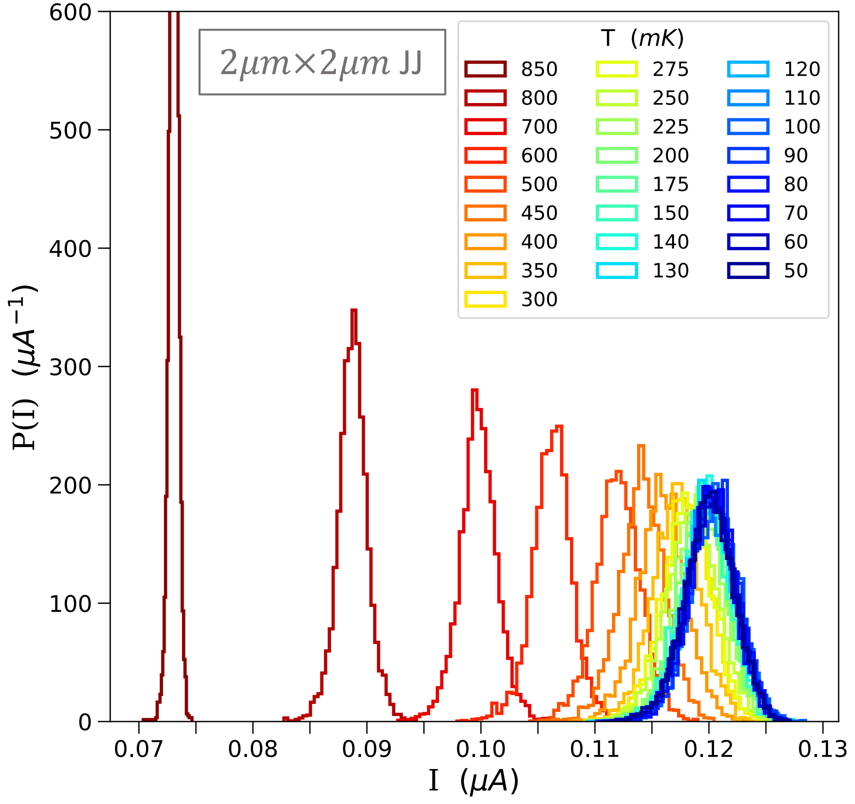
- I-V charachteristic
- Switching current distributions



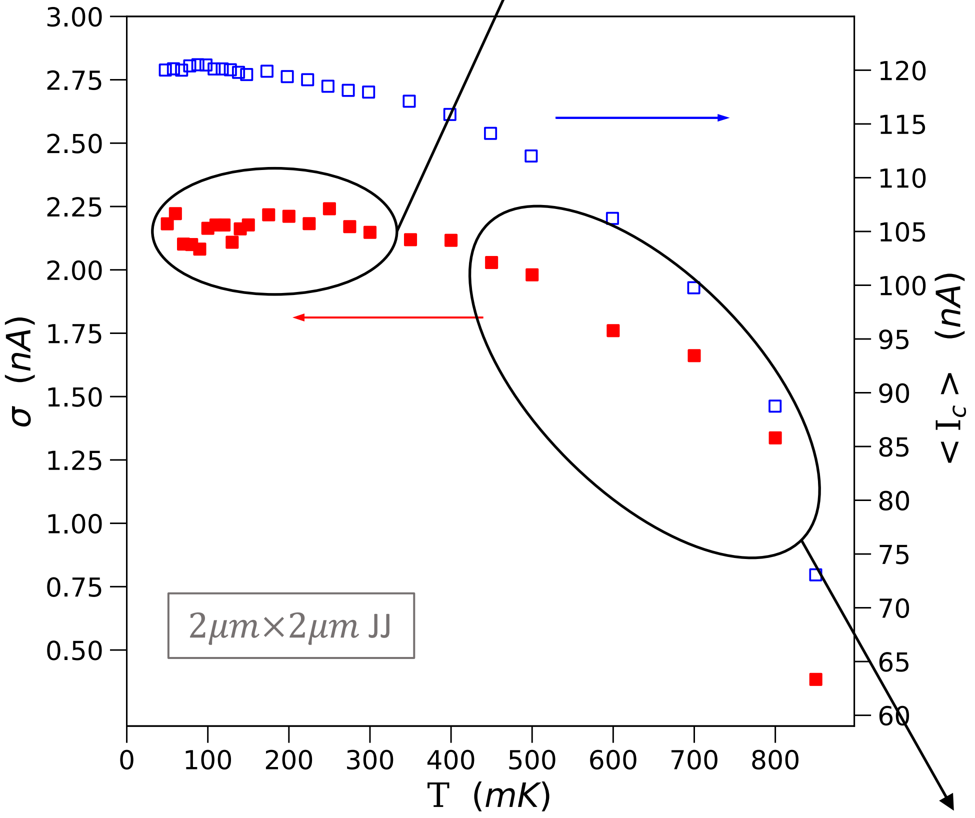
Chip mounted under the mixing chamber of the dilution refrigerator.

Switching current distributions

Range: $50mK - 850mK$



Expected from quantum tunneling



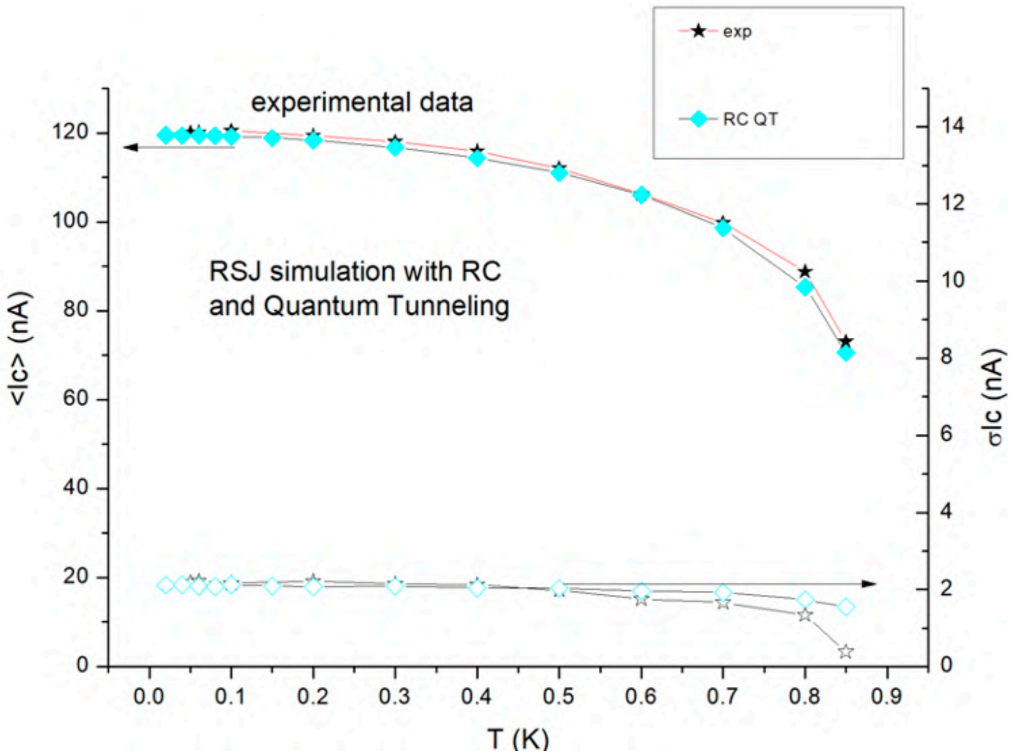
Decrease due to the dependence of $I_c(T)$ with temperature

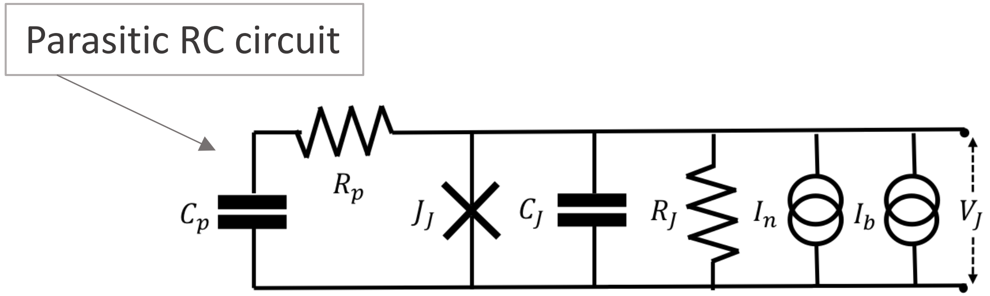
Interpretation and simulations to validate hypothesis

$$\frac{d^2\varphi}{d\tau^2} + \alpha\frac{d\varphi}{d\tau} + \sin\varphi = \gamma_b + \gamma_s(\tau) + \gamma_n(\tau) + \gamma_R$$

$$\frac{d\gamma_R}{d\tau} + \alpha_{RC}\gamma_R + \alpha_{int}\frac{d^2\varphi}{d\tau^2} = 0$$

$$\alpha_{RC} = \frac{1}{R_p C_p \omega_J}, \qquad \alpha_{int} = \frac{1}{R_p C_J \omega_J}, \qquad \gamma_R = \frac{I_R}{I_0}$$



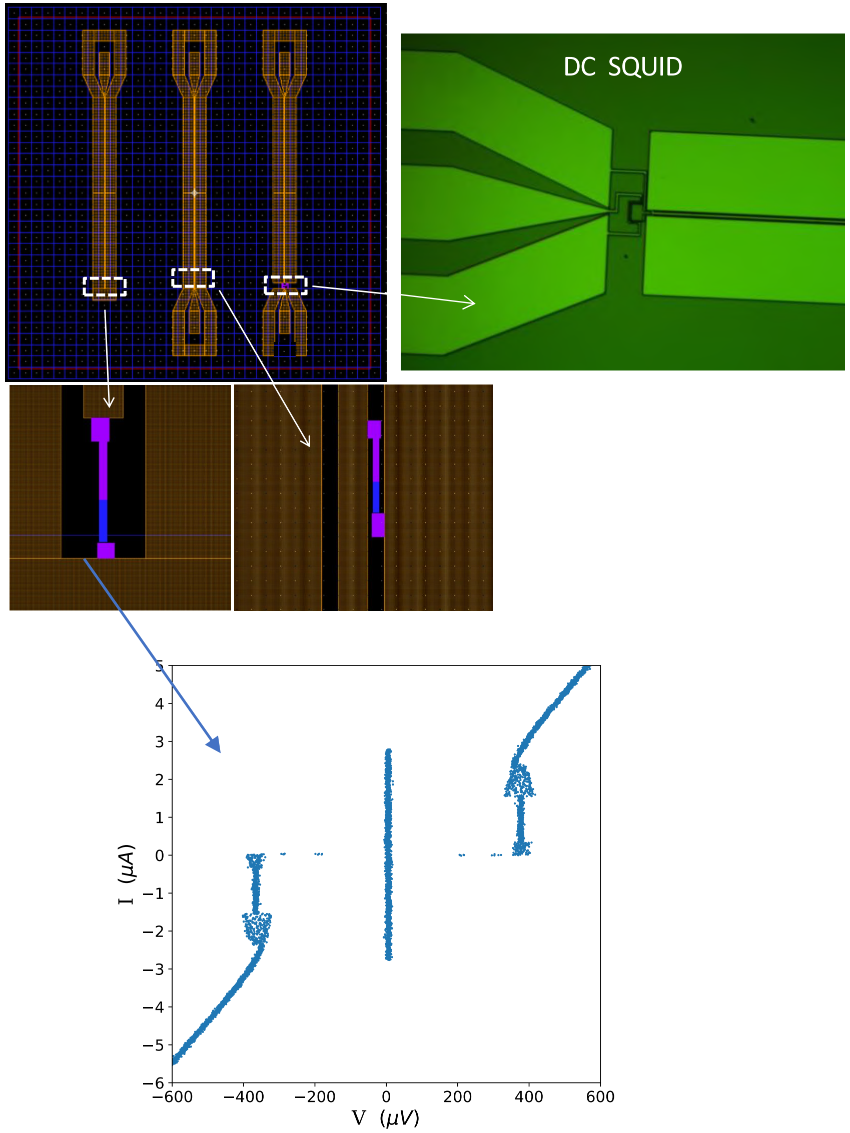


$$\frac{\omega_0}{2\pi}\exp\left(-\frac{\Delta U}{k_B T}\right) < \frac{\omega_0}{Q}$$

$$R < 2\pi Z_j \exp\left(\frac{\Delta U}{k_B T}\right)$$

Thermal activation is suppressed

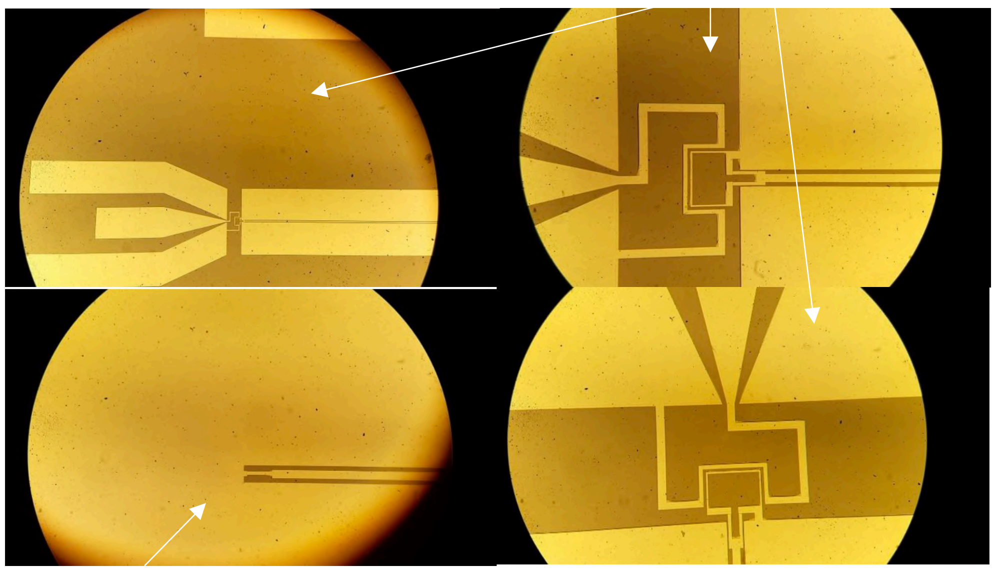
Ongoing: Transmission Line + JJ



Simplest design of photon detector fabricated

Measurements done by the end of March

DC SQUID



Coplanar waveguide
ended with JJ

Conclusions

- We need a single microwave photon counter for axion search
- It can be developed with Current Biased Josephson junctions
- We did simulations to obtain fabrication parameters
- We measured single Josephson junctions
- Testing Coplanar waveguide ended with Josephson junction

People from the SIMP collaboration working on current biased JJ

Alessio Rettaroli [6,1], David Alesini [1], Danilo Babusci [1], Carlo Barone [2,3], Bruno Buonomo [1], Matteo Mario Beretta [1], Gabriella Castellano [4], Fabio Chiarello [4,1], Daniele Di Gioacchino [1], Giulietto Felici [1], Giovanni Filatrella [5,3], Luca Gennaro Foggetta [1], Alessandro Gallo [1], Claudio Gatti [1], Carlo Ligi [1], Giovanni Maccarrone [1], Francesco Mattioli [4,1], Sergio Pagano [2,3], Simone Tocci [1] and Guido Torrioli [4,1]

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COLD Lab website:

http://coldlab.lnf.infn.it