Per aspera ad astra

Через тернии к звездам!

Chalmers University, MC2 | **Laboratory of Cryogenic Nanoelectronics** | **Nizhnij Novgorod State Technical University**

Single Photon Counter based on a Josephson Junction at 14 - 40 GHz for searching Galactic Axions for QUAX

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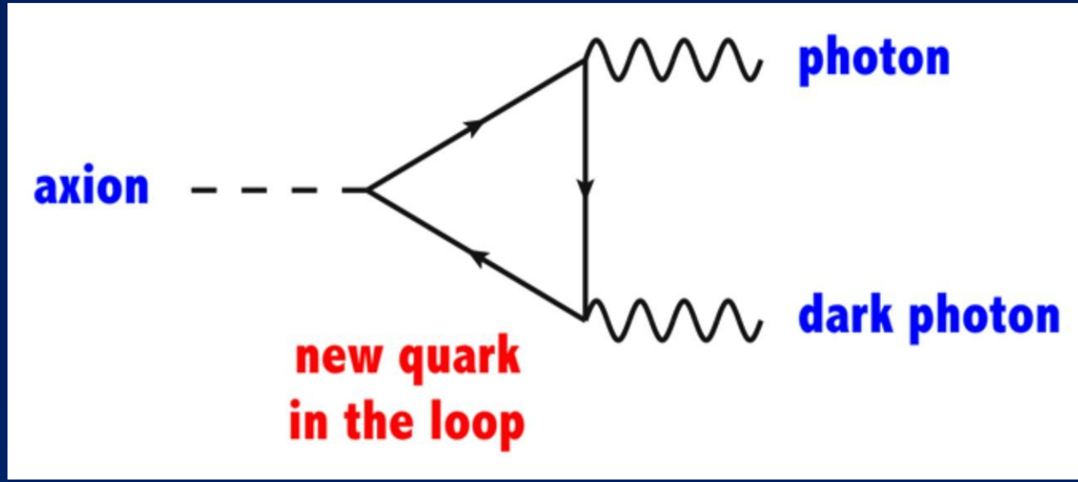

Outline

- **Searching for galactic axions**
- **Single Photon Counter based on a Josephson Junction at 14 GHz**
- **Matching to a high quality cavity**
- **First experimental tests**
- **Single Photon Counter for Quantum Circuits**
- **Conclusions**

Searching for galactic axions through magnetized media:The QUAX proposal

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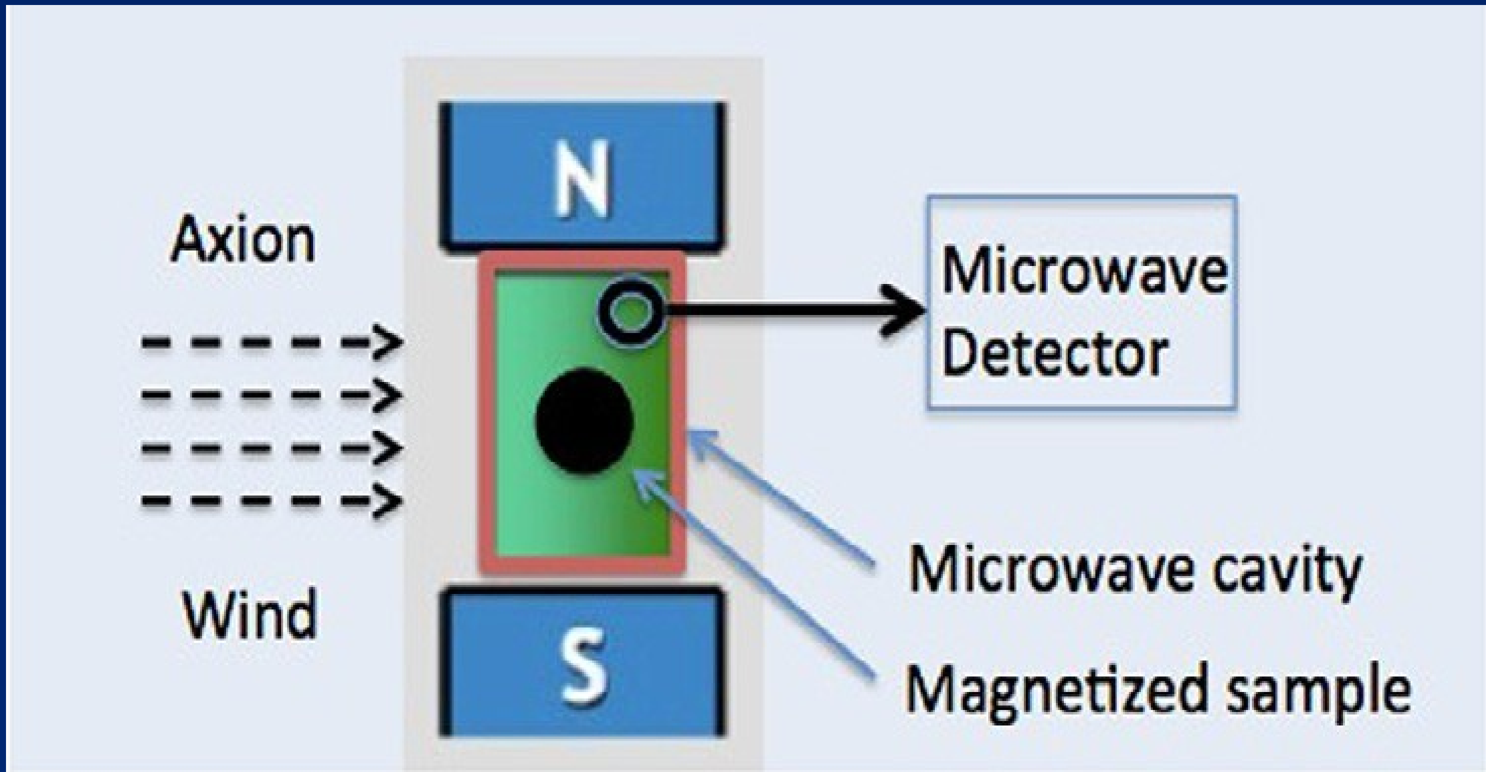


Principle scheme of the axion haloscope

Searching for galactic axions through magnetized media

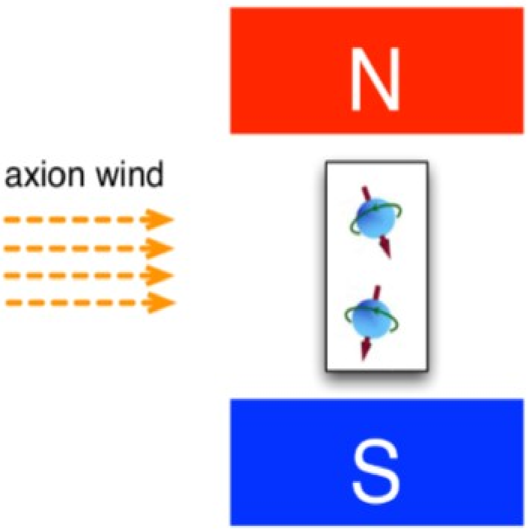
How to tune the receiver: ESR

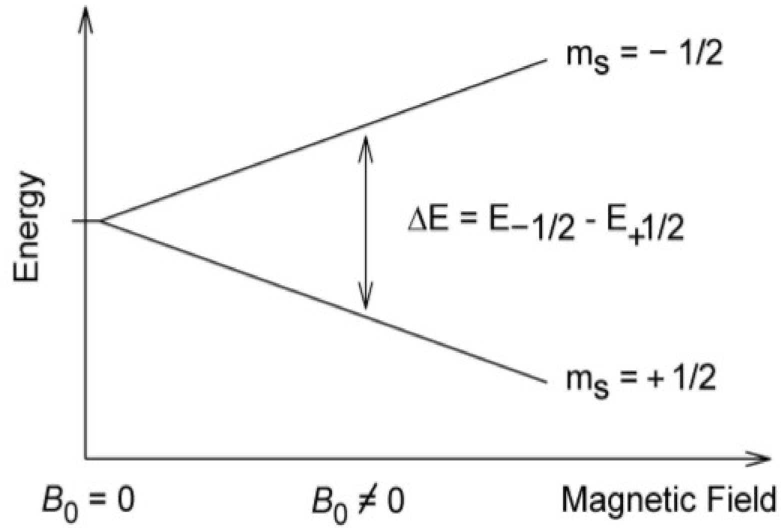
For an axion mass of $\sim 200\,\mu$eV, $m_a c^2 = \hbar\omega \Rightarrow \omega/2\pi \sim 48\,\text{GHz}$

The effective magnetic field $B_a = \frac{g_p}{2e}\nabla a$ is actually an RF field.

$\downarrow$

The sample spins are tuned to ω_L with a static field B_0

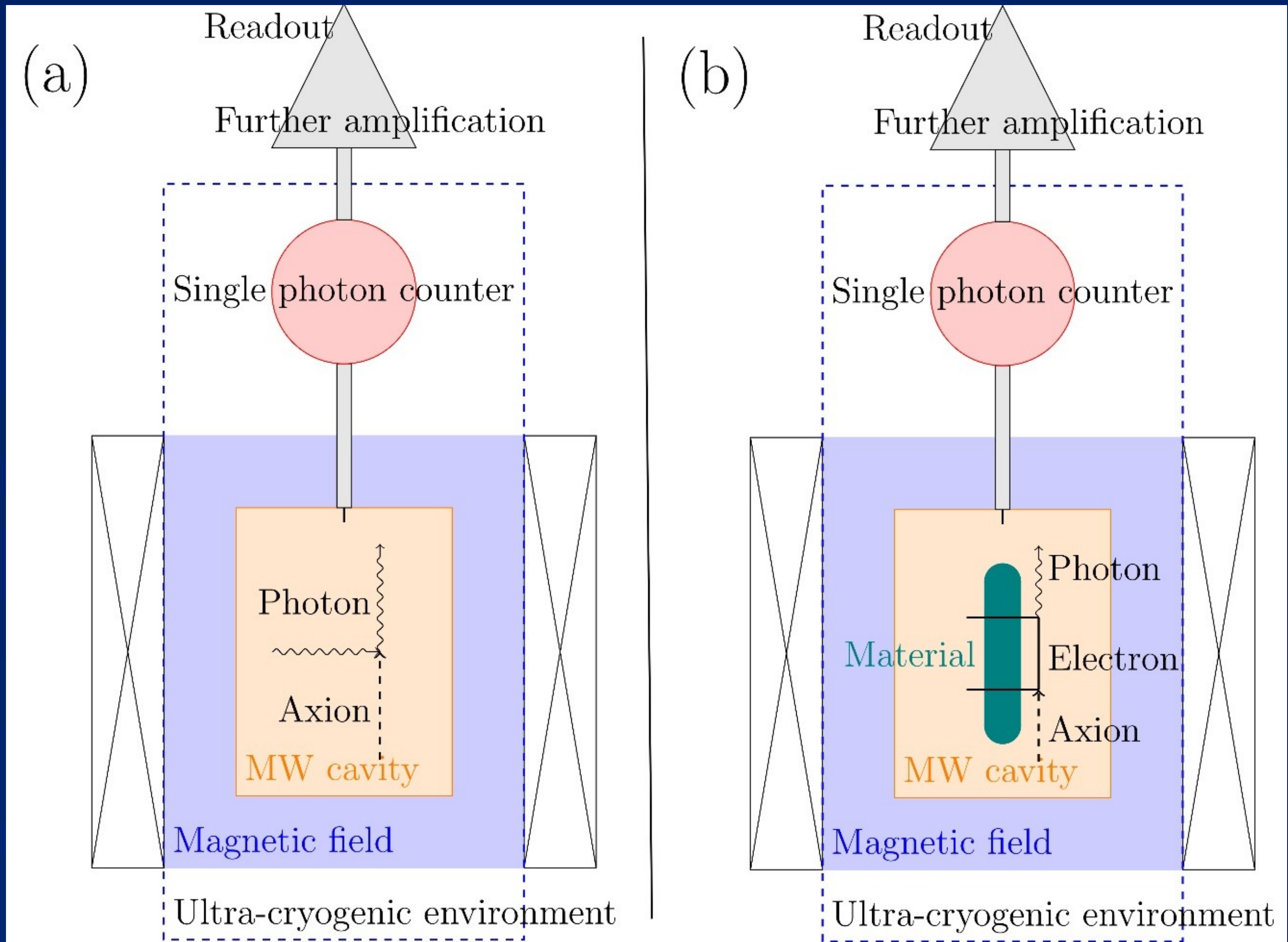




For example, $\omega_L/2\pi = 48\,\text{GHz} \Rightarrow B_0 = 1.7\,\text{T}$

∇a
RF field
$\Downarrow$
$\omega \Leftrightarrow m_a$
Mass
$\Downarrow$
ESP
$\Downarrow$
ω_L
Larmor
$\Downarrow$
B_0
Static field

Detection scheme for two processes involving a galactic axion:

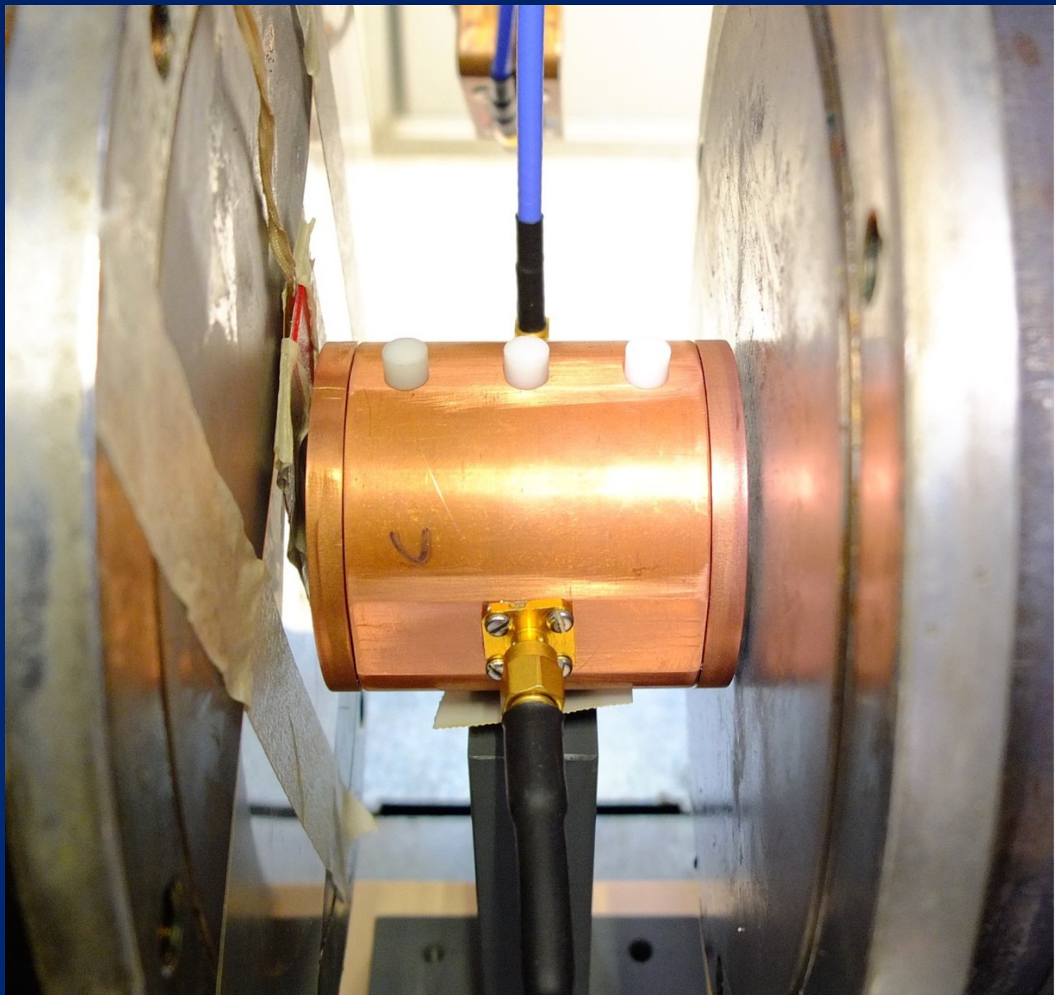


(a) the axion passing through a static magnetic field can be converted into a photon by means of the inverse Primakoff effect;

(b) an axion can resonantly interact with an electron in a static magnetic field, causing a spin-flip that eventually decays into a photon.

Cavity

Half of a 14 GHz resonant cavity with conical endcaps used for the Quax R&D.

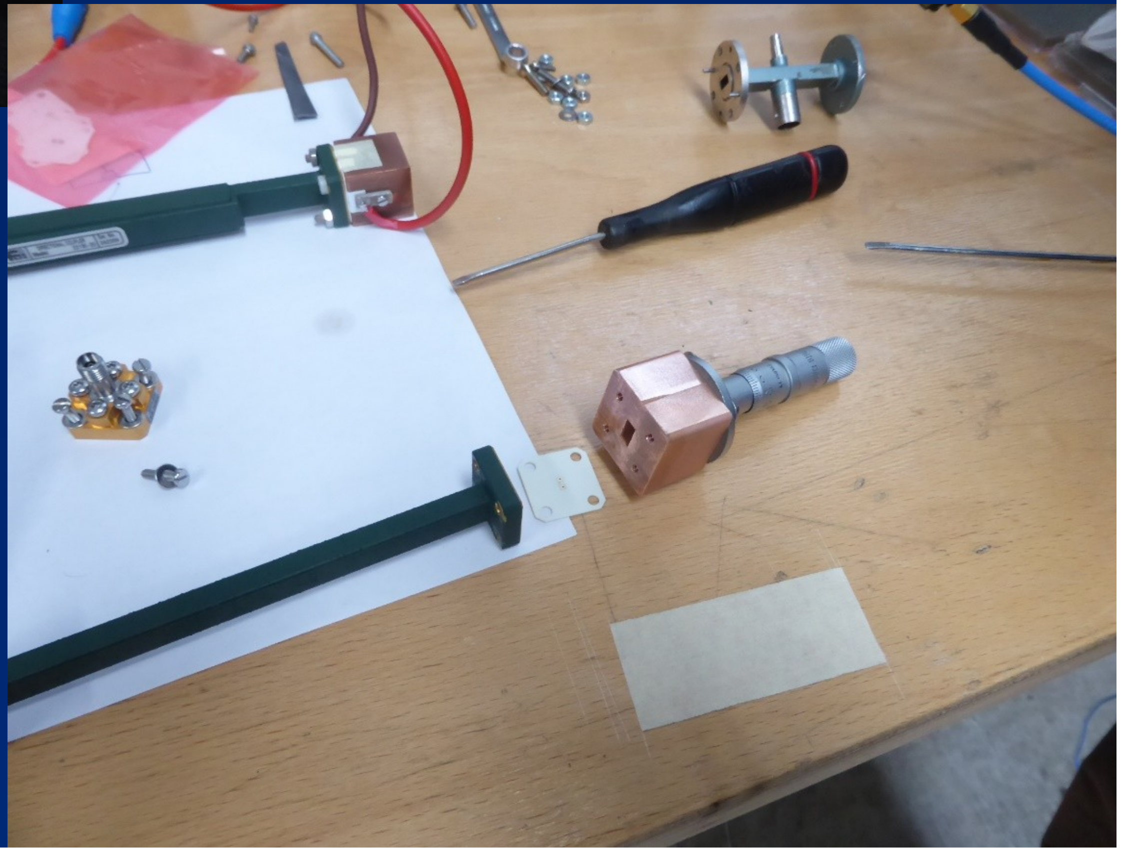


A cylindrical cavity with magnetized samples inserted from the top side during a test for the Quax R&D in magnetic field at room temperature.

Q quality factor = 50 000

Resonant search of axions is performed tuning the cavity frequency by means of metallic tuning rods.

The frequency is shifted in a range ±10% corresponding to ±1.4 GHz.



The need for a Single Microwave Photon Counter:

Frequency: f = 14 GHz +-10% (λ = 2cm)

Rate of photons: Tph = 3 000 sec/photon

Dark counting: Tdark = 10 000 sec/photon

Photon energy: hf = 9.1*10-24 J

Temperature: T =20 mK

Available Single Photon Counter for the moment:

Frequency: f = 140 THz (λ = 2μm)

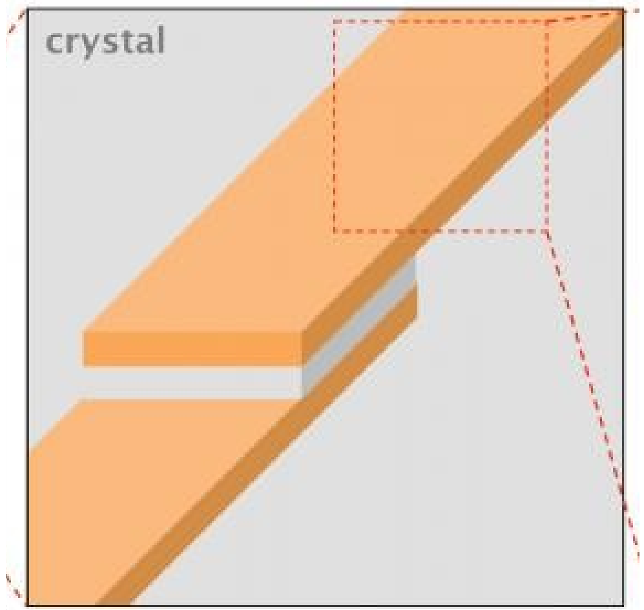
Photon energy: hf = 9.1*10-20 J

Temperature: T = 4.2 K

SIS single photon detector for GHz range

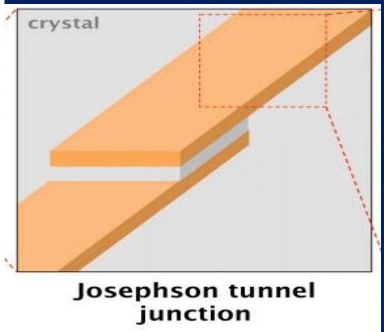
G. Oelsner, L.S. Revin, E. Il'ichev, A.L. Pankratov, H.-G. Meyer, L. Gronberg, J. Hassel, and L. S. Kuzmin - Underdamped Josephson junction as a switching current detector. // Appl. Phys. Lett. 103, 142605, 2013.

The switching current distribution of a SIS Josephson junction with a low critical current density of 30 A/cm^2 at temperatures from 10 mK to 1 K is measured. As a result of considering switching dynamics in the classical and quantum regions, a crossover temperature of about 56 mK was found. At temperatures below 50 mK, the width of the switching current distribution is only 4.5 nA, which indicates the possibility of using such a detector as a photon counter in the GHz range.

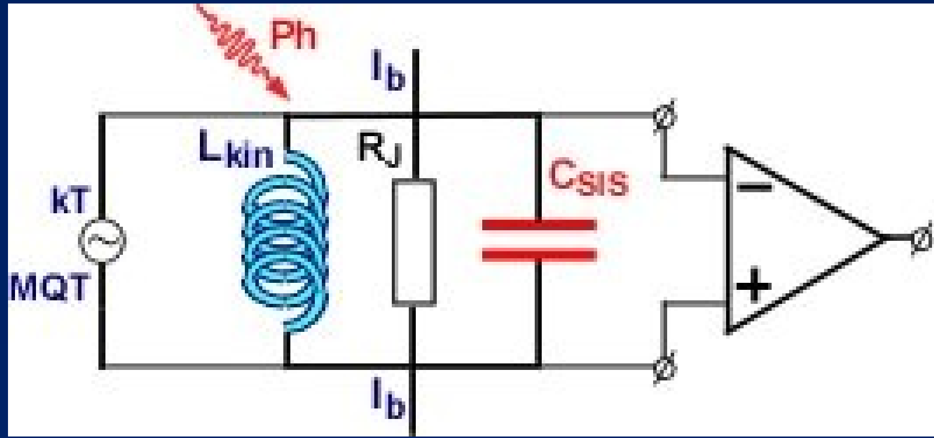


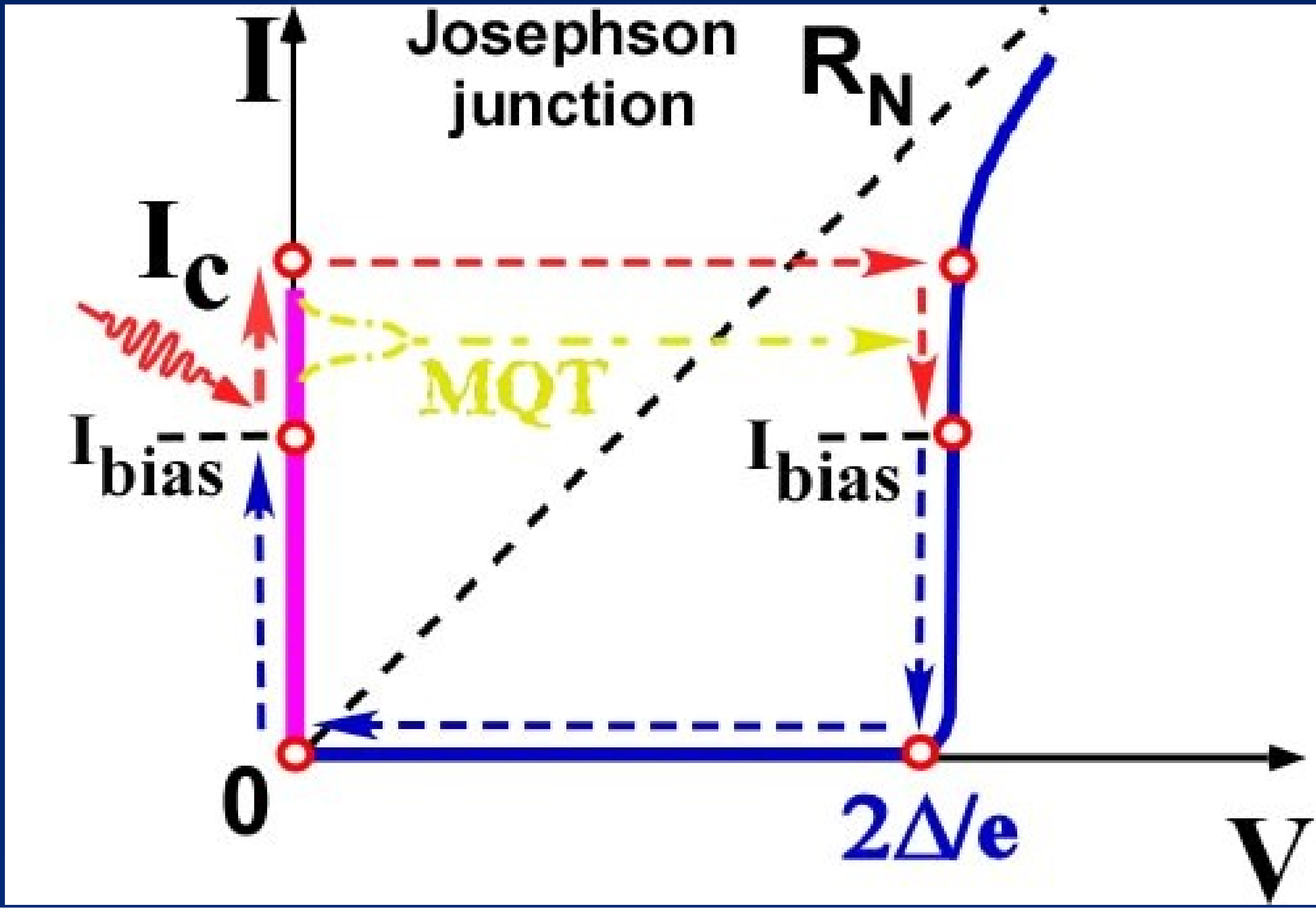
Josephson tunnel junction

SIS junction as a Single Photon Counter

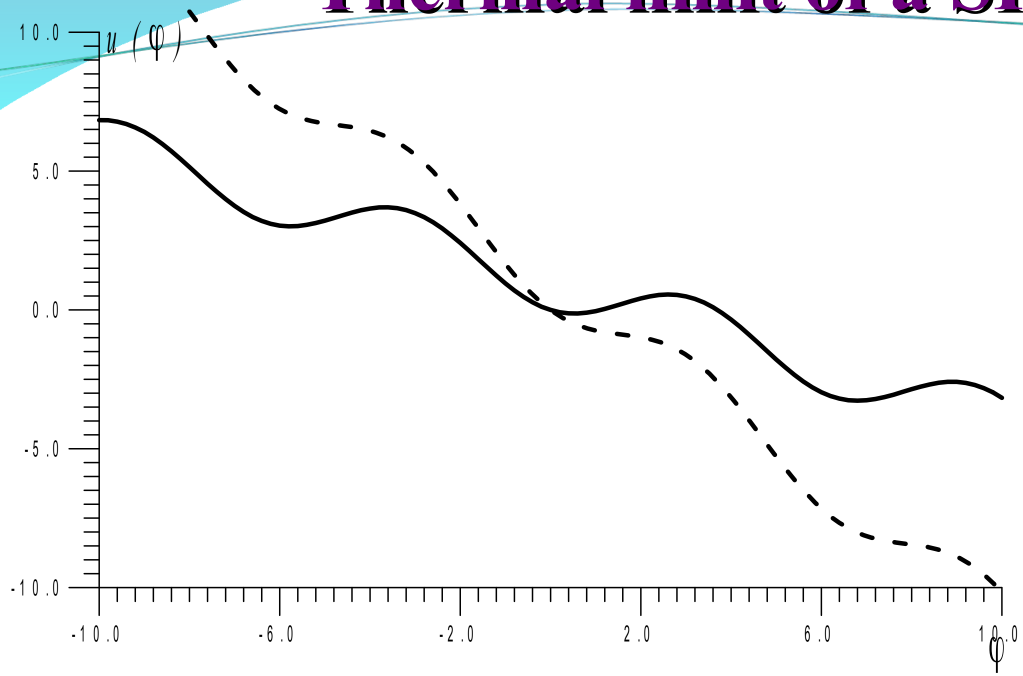


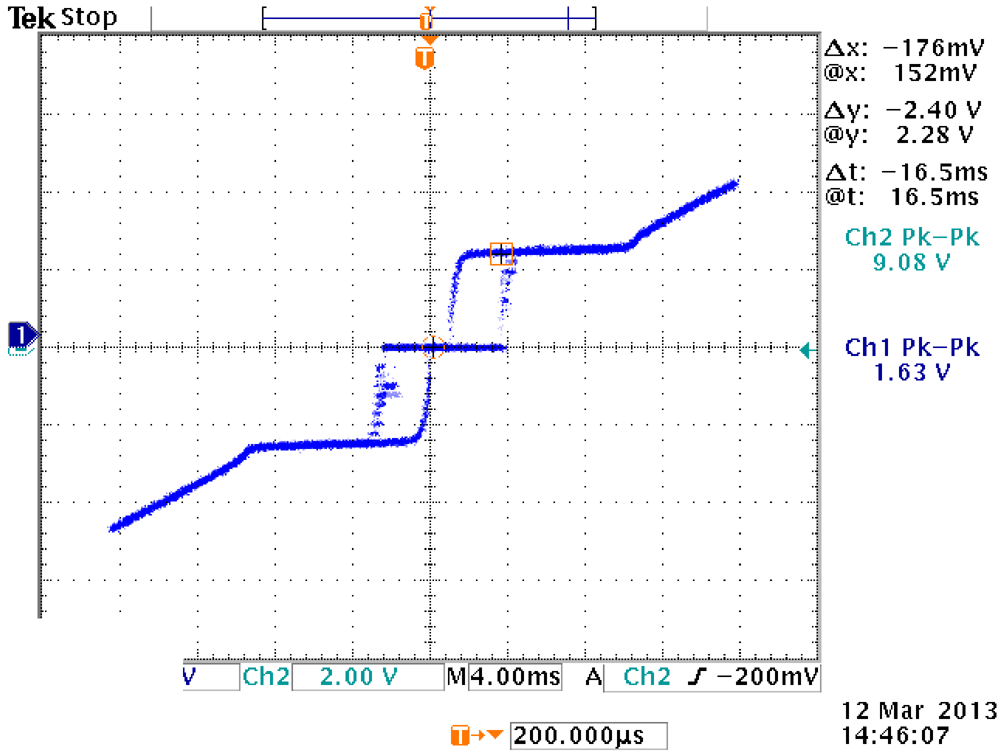
RF scheme of the SIS Josephson junction



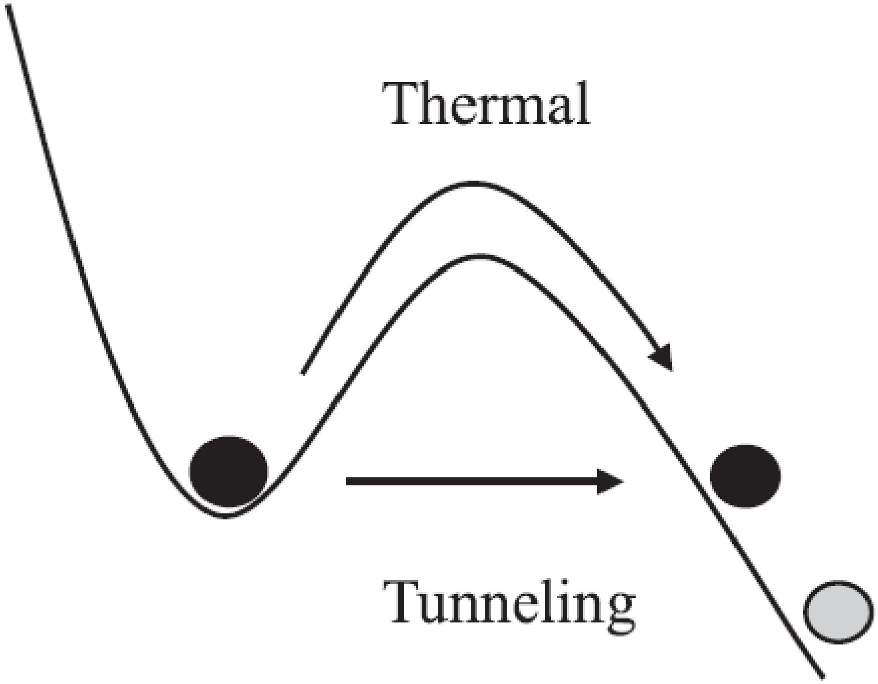


Thermal limit of a SIS junction as detector





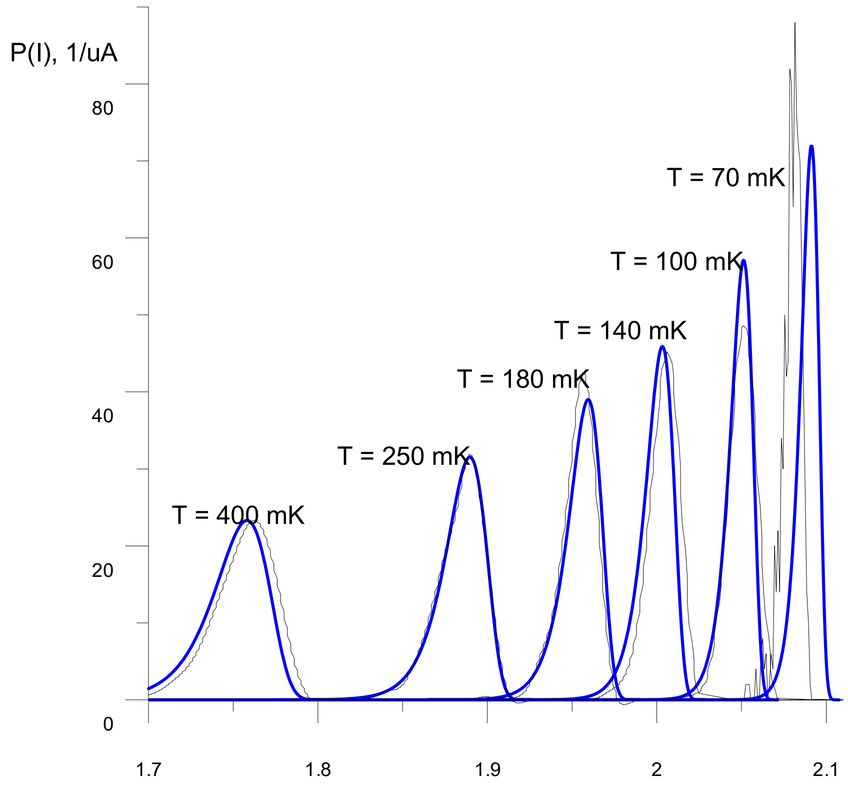
Typical IVC of a SIS junction.



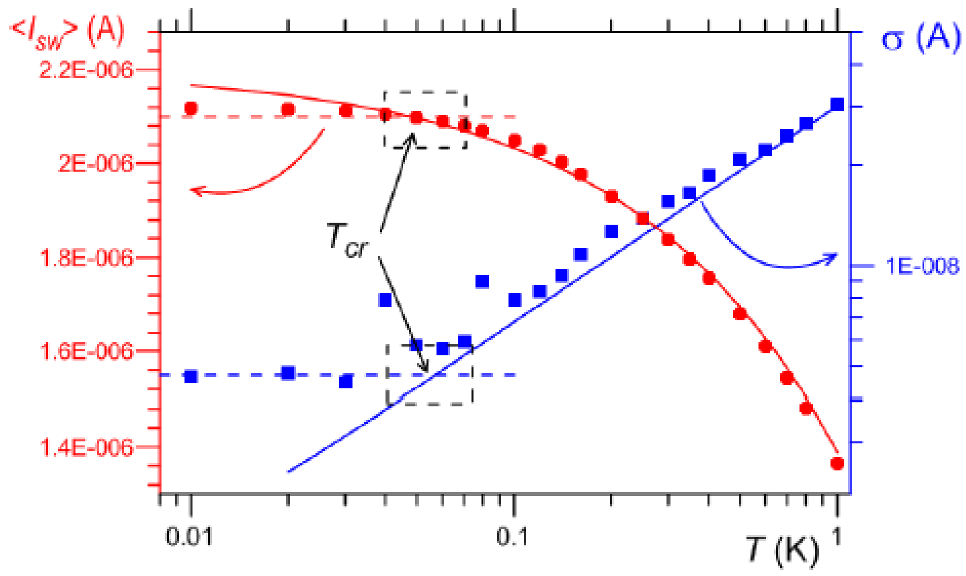
Potential profile.

$$\Gamma_q = \frac{\omega_0}{2\pi}\sqrt{\frac{B}{2\pi}}\,e^{-B}$$

Thermal limit of a SIS junction as detector



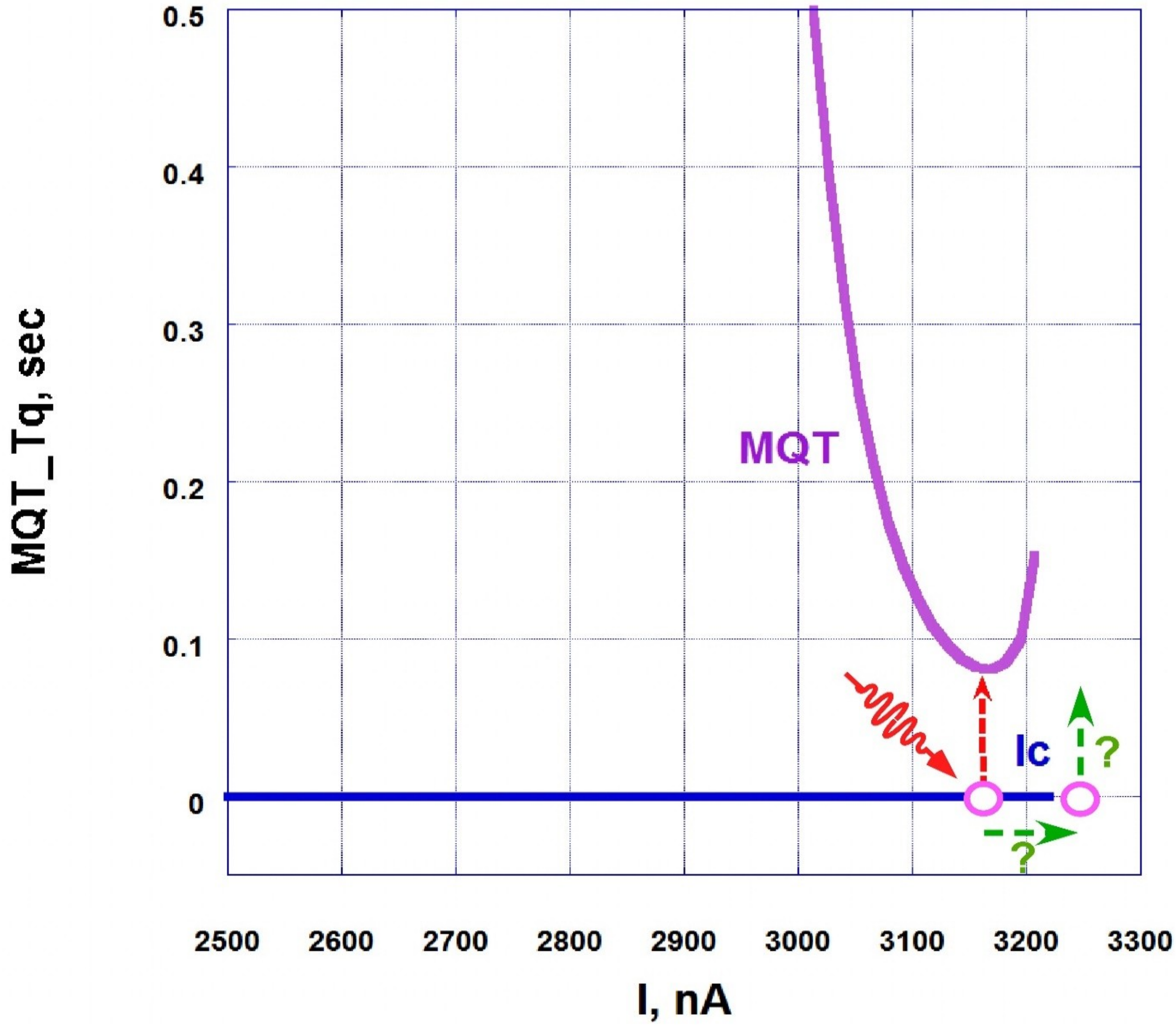
Probability density P versus switching current I_{sw}. Black curve –experiment, blue – theory based on thermal Kramers escape.



Mean and standard deviation of switching current versus temperature. Symbols – experiment, lines – theory for classical and quantum limits. The rectangle denotes the crossover region.

I. Nb-Nb Josephson junctions.

All parameters as in G. Oelsher et al., APL, 103, 142605 (2013).



Real disaster with MQT escaping time of Tq=0.1 sec for Iphot=50 nA!

It's 4 orders of magnitude less than expected appearance of photons from axions with time of 1000 sec/photon!

Optimization of SPC included 4 steps:

1. Decrease of C from 330 fF to 50 fF – better but far from the goal.
2. Decrease of R from 0.44 kOhm to 0.2 kOhm - better but far from the goal.
3. Replacement of Nb by Al (it's actual because Ic of Nb is too high for this delicate effect. Besides that, all experiments with qubits are made mainly with Al) – better but still not enough.
4. Suppression of I_c by magnetic field

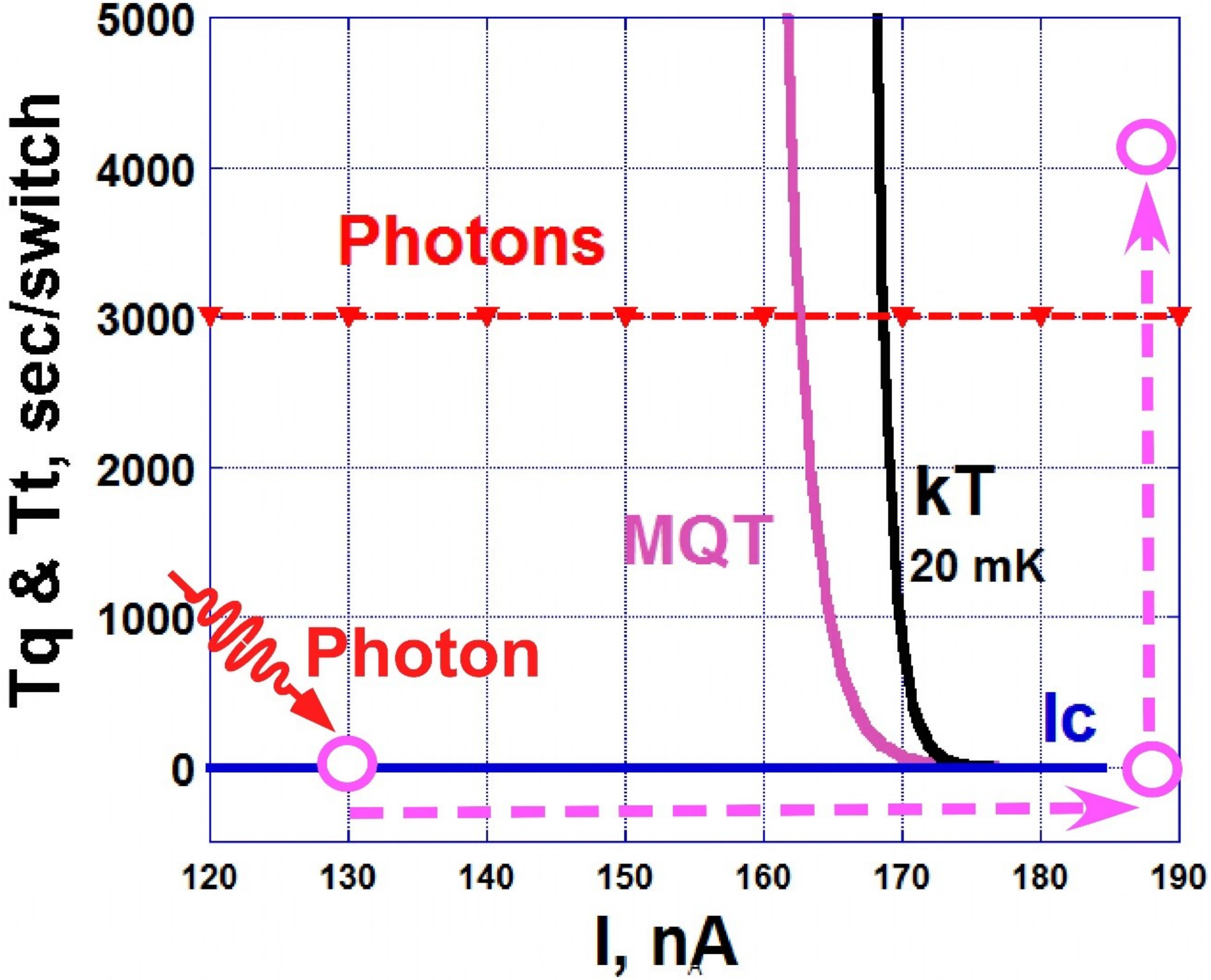
Finally we've got excellent results with

MQT Tq > Photon Tph=3000 sec.

Rate of MQT switches was improved from 0.1 to 3000 sec/switch (by 4 orders of magnitude)!

Single Photon Counter based on a Josephson Junction at 14 GHz for searching Galactic Axions.

L. Kuzmin, A. Sobolev, C.Gatti, D. Gioacchino, N. Crescini, A. Gordeeva, E.Il'ichev. IEEE TAS (2018)

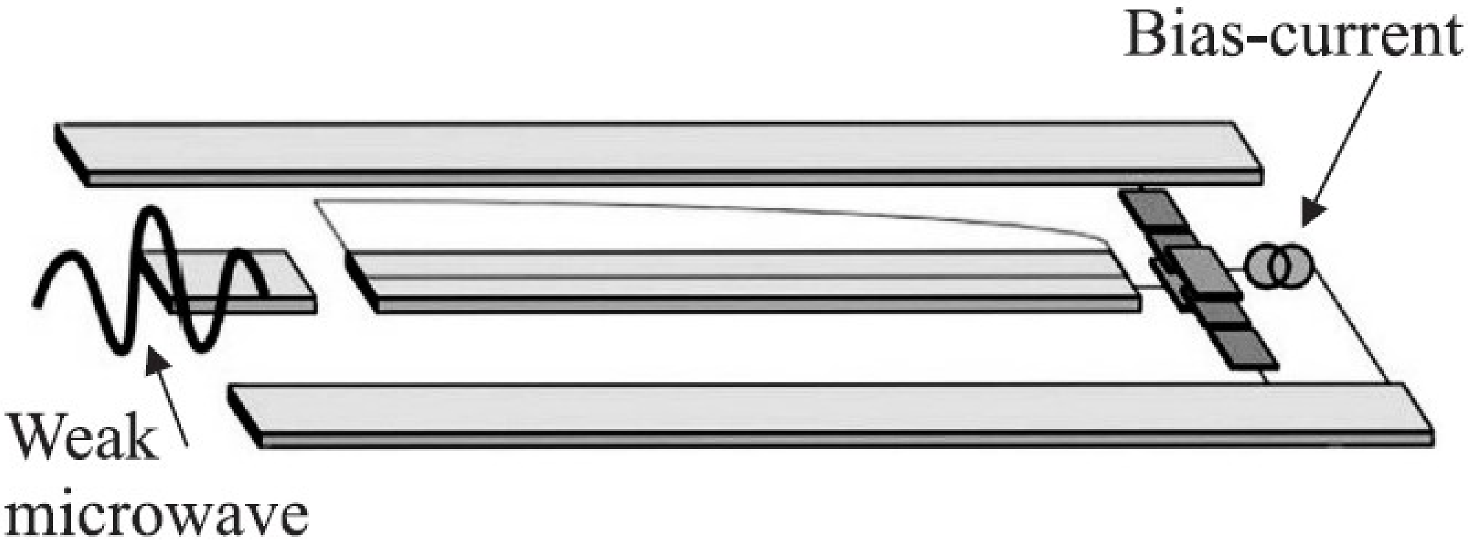


Red line shows expected period of appearance of protons 3000 sec/photon
Impulse of incoming photons is equal to 60 nA.
At bias point Io=130 nA we can stand any time expecting coming photons.

E. V. Il’ichev

A microwave photon detector

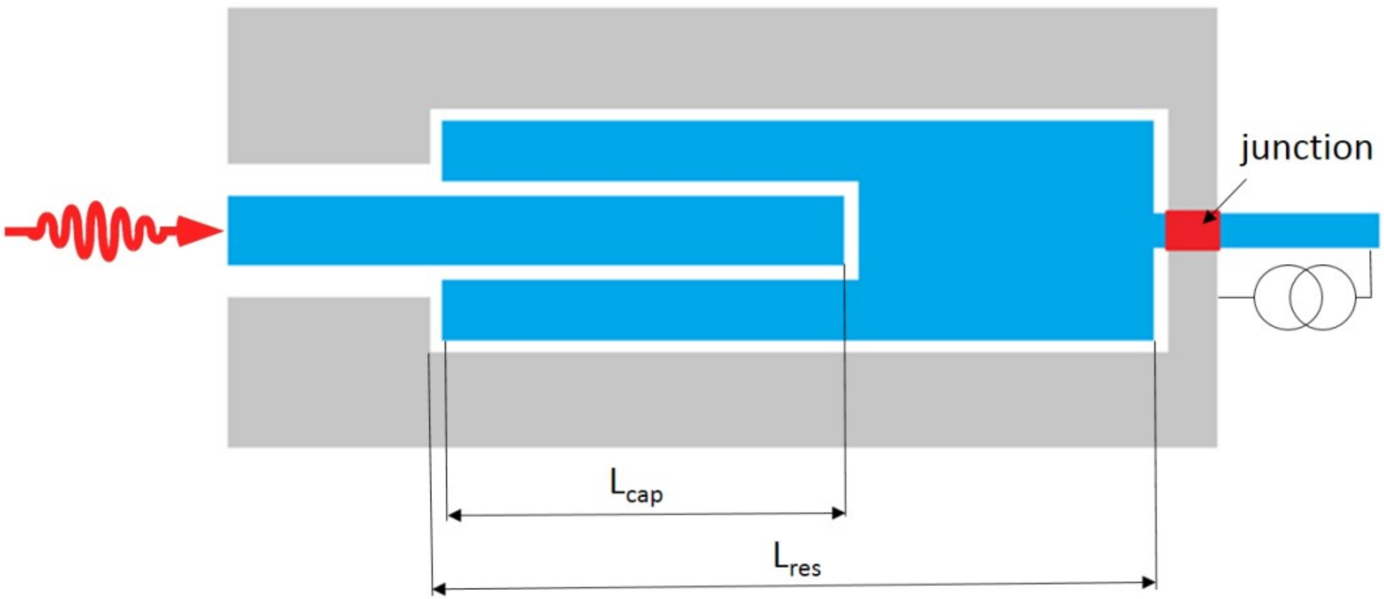
Physics of the Solid State, November 2016, Volume 58, Issue 11, pp 2160–2164

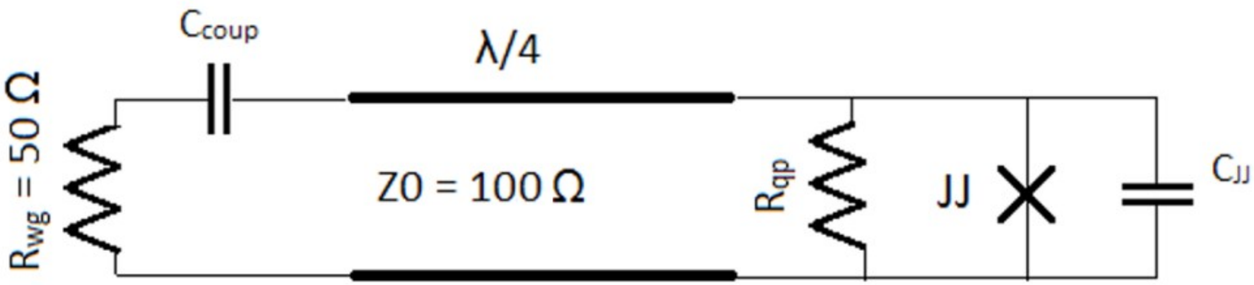


$$kT_{cr} = (\Phi_0 \Delta I)/2\pi$$

At temperatures below 50 mK, the width of the switching current distribution is only 4.5 nA, which indicates the possibility of using such a detector as a photon counter in the GHz range.

SPC layout

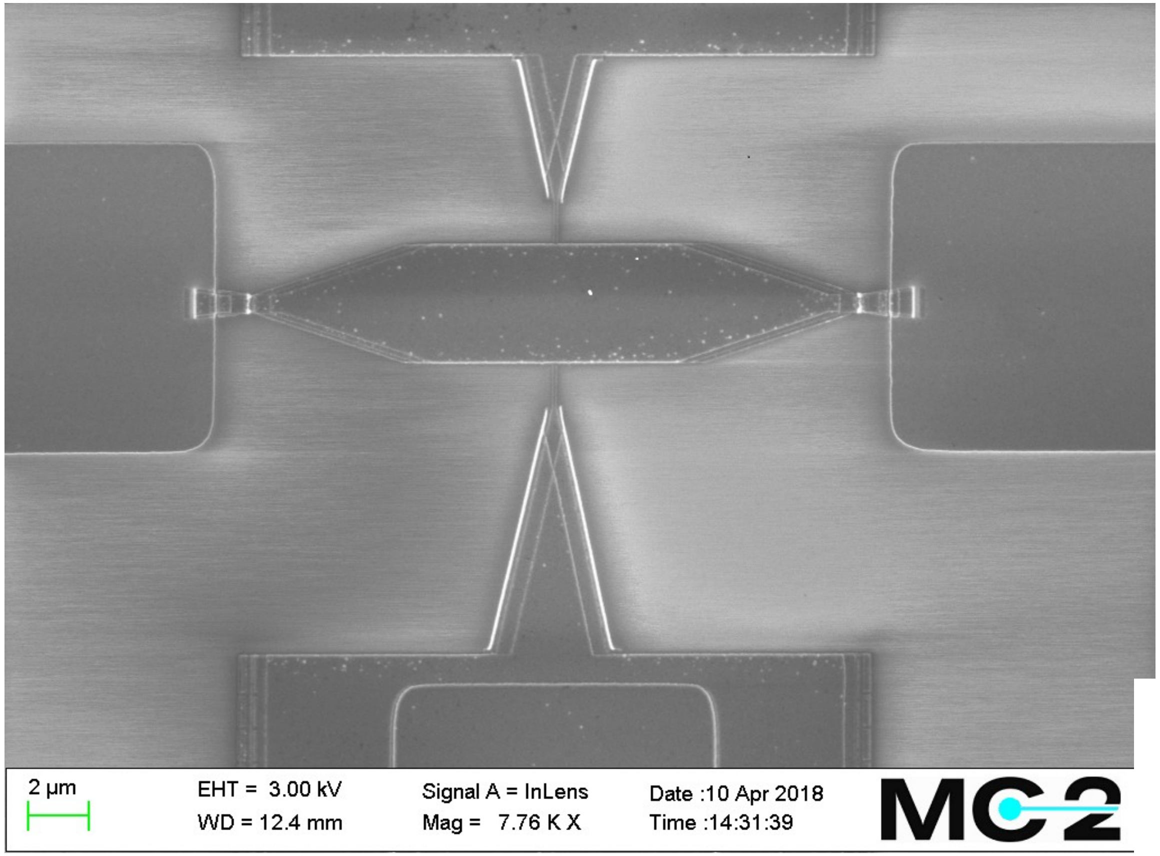




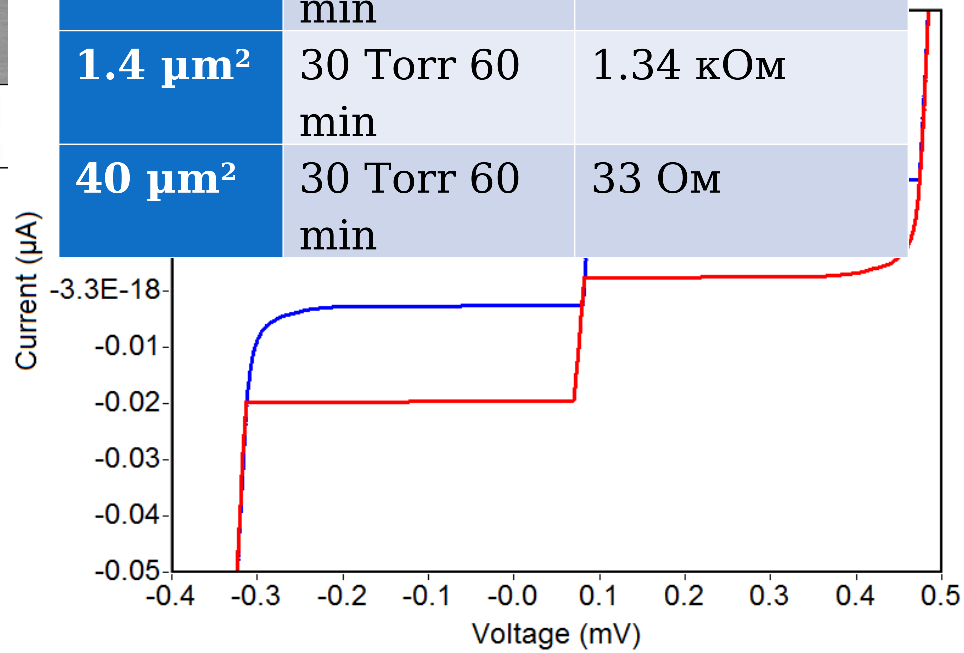
SPC layout (not in scale) and its equivalent rf-network.
The bottom electrode is shown in grey.

Blue color corresponds to the top electrode..

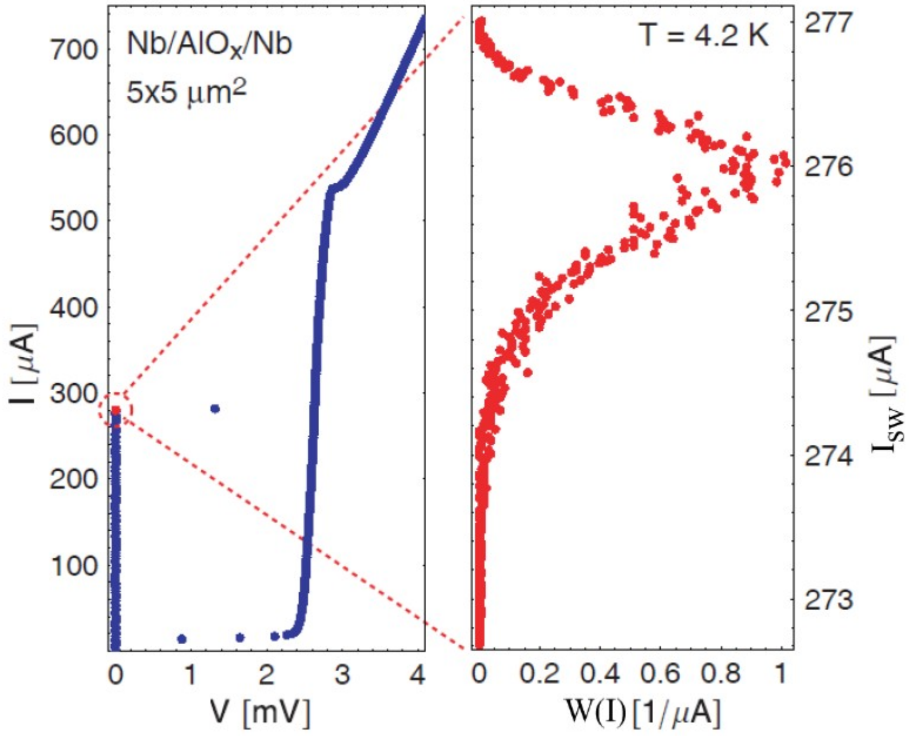
Al-Al Josephson Junctions

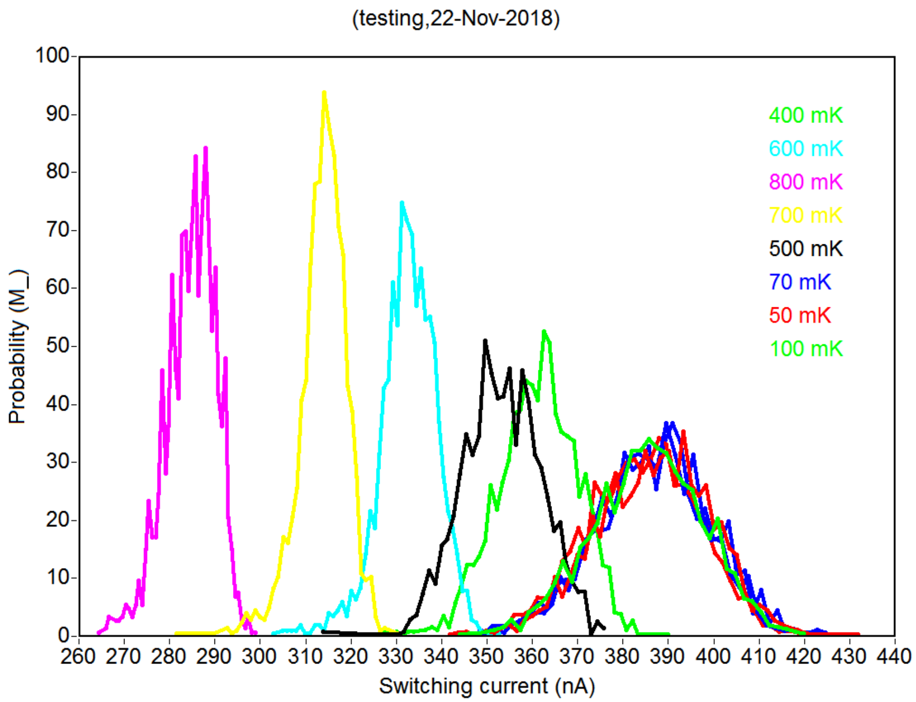


Площадь перехода	Режим оксисления	Сопротивление на комнате
14 µm²	10 Torr 10 min	163 Ом
0.7 µm²	10 Torr 10 min	1.5 кОм
1.4 µm²	10 Torr 10 min	812 Ом
40 µm²	10 Torr 10 min	26 Ом
14 µm²	30 Torr 60 min	480 Ом
0.7 µm²	30 Torr 60 min	4.6 кОм
1.4 µm²	30 Torr 60 min	1.34 кОм
40 µm²	30 Torr 60 min	33 Ом

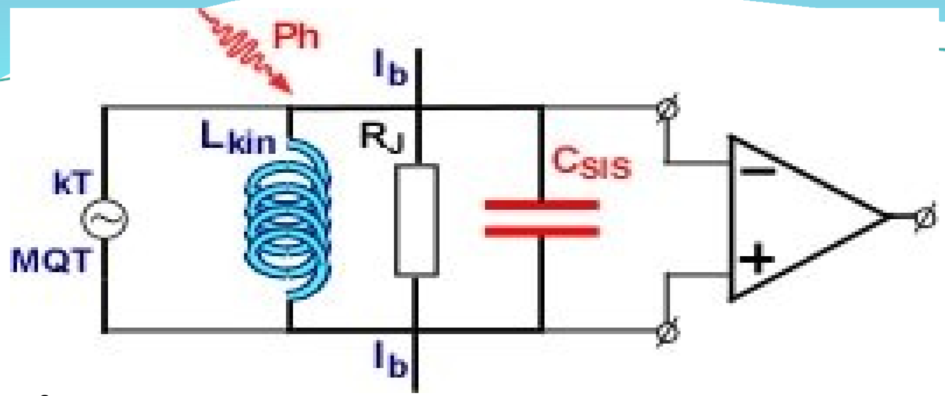


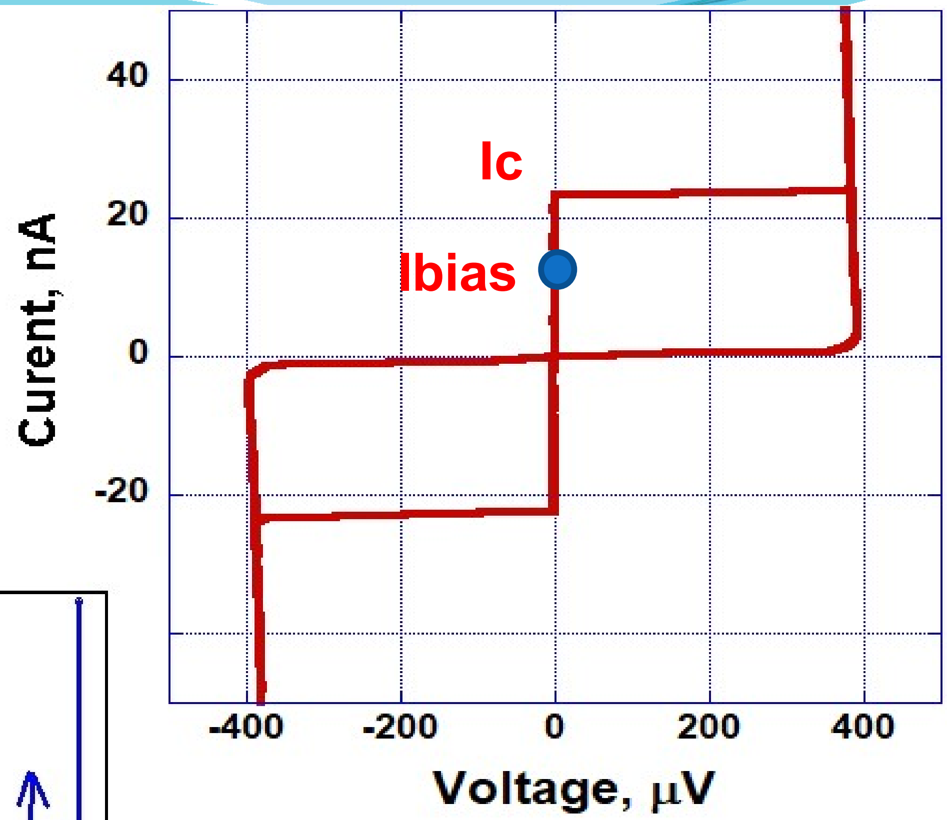
Histograms of Switching current distribution





Lifetime (dark counting) of the Al-Al Josephson junction at 10mK

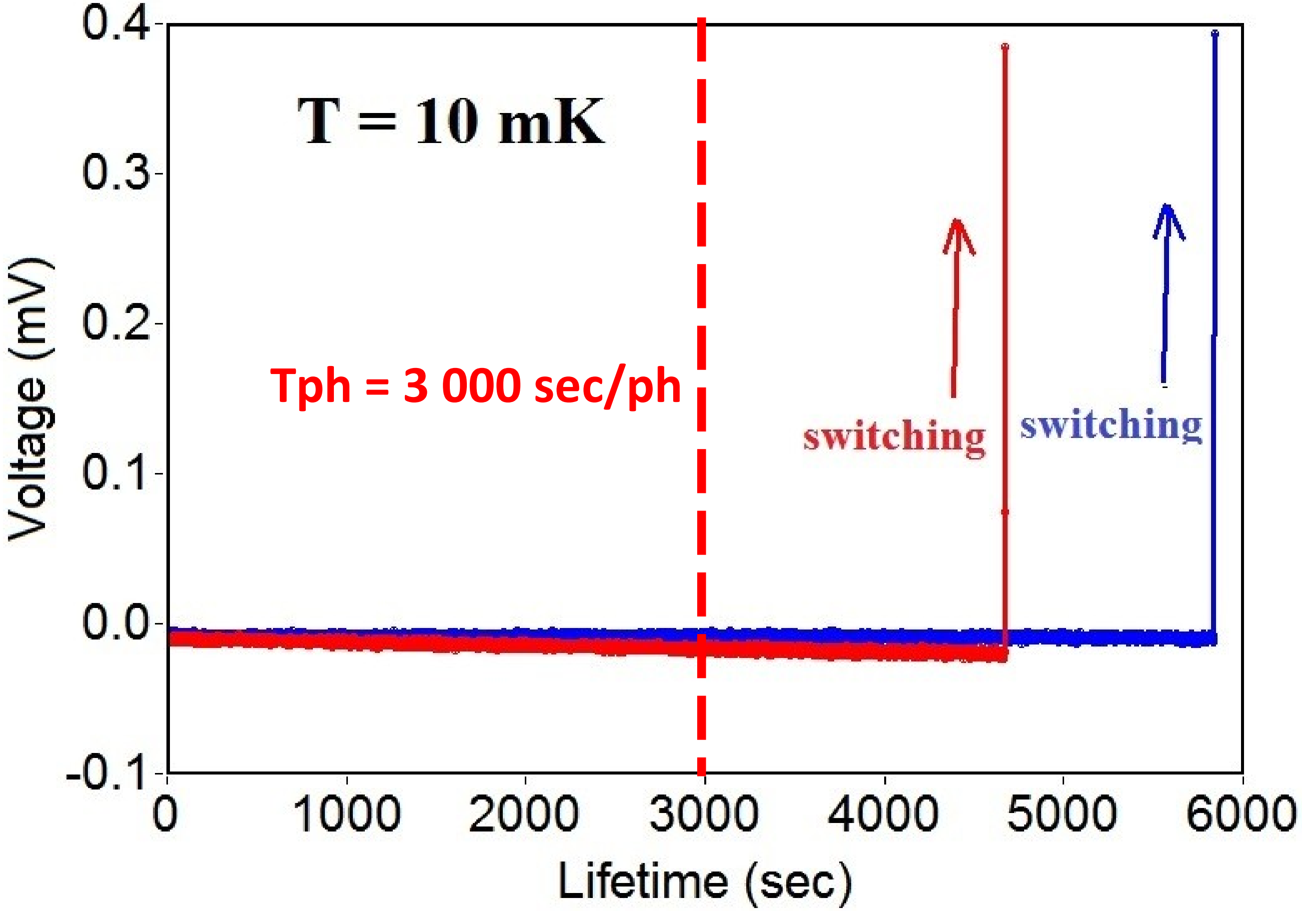




Requirements:

Rate of photons: Tph = 3 000 sec/photon

Dark counting: Tdark = 10 000 sec/photon

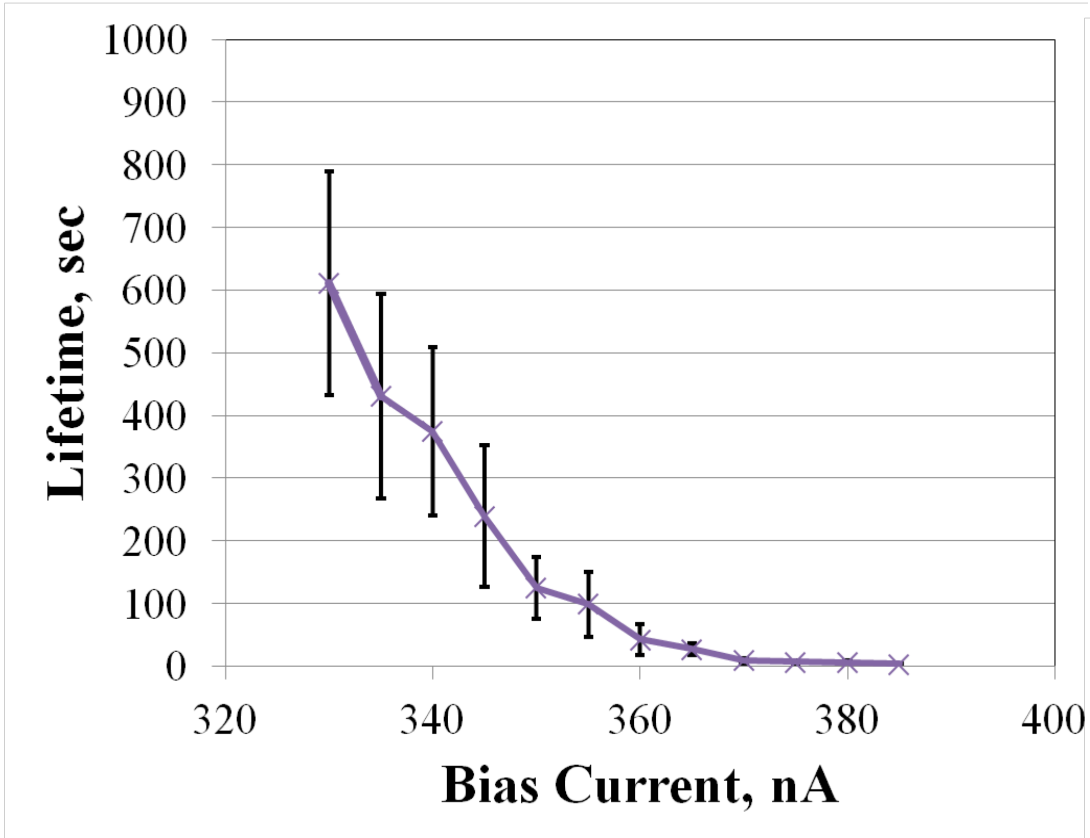


Ic = 40 nA
Ibias = 12 nA
Lj = 8.7 nH

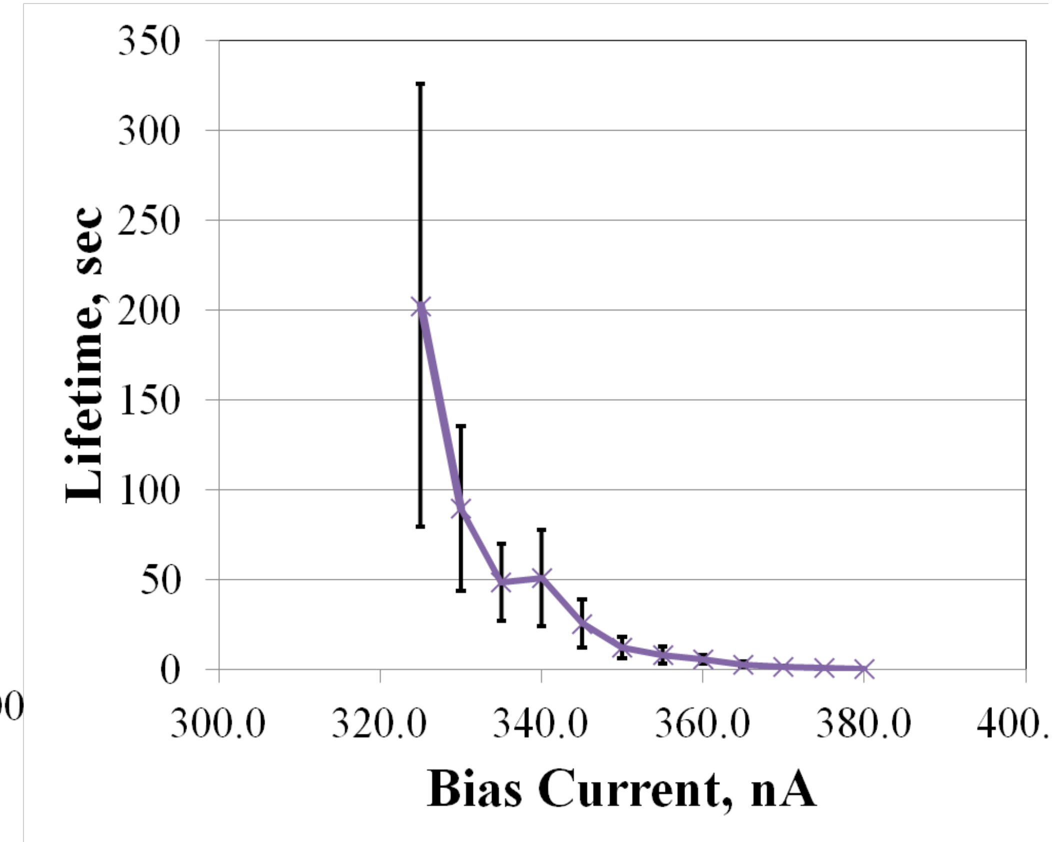
14 GHz photon:
hf = LIph^2/2
Iph = 45 nA

Lifetime (dark count rate)

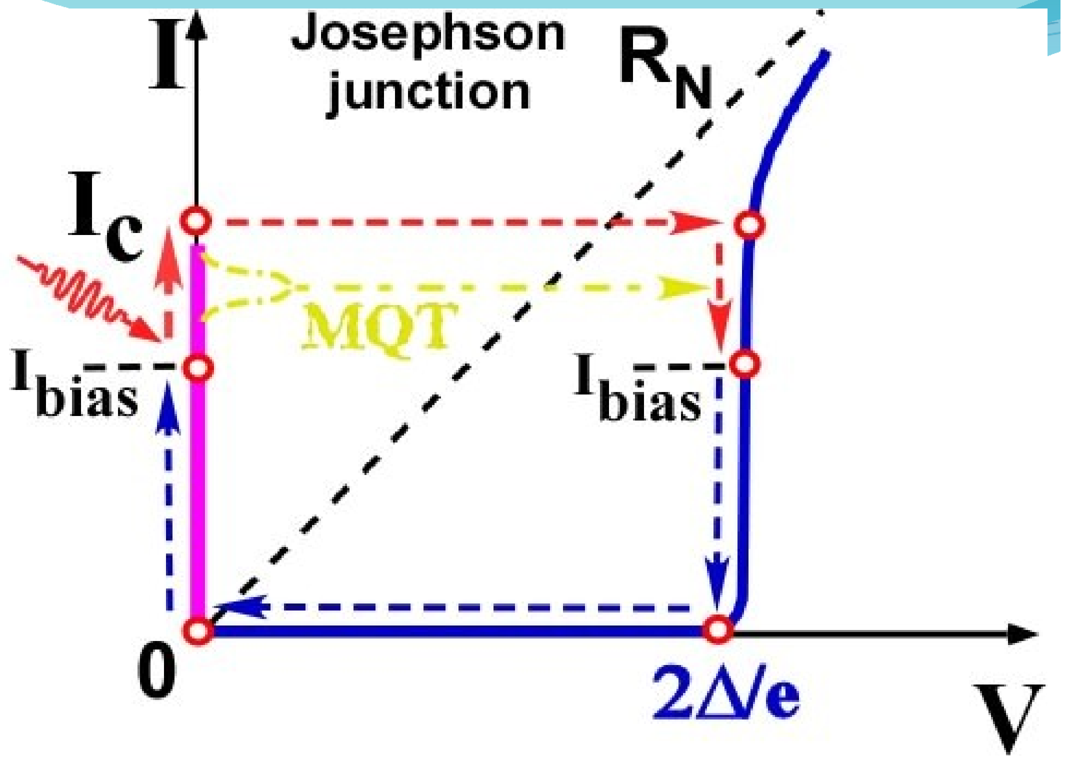
T = 100 mK

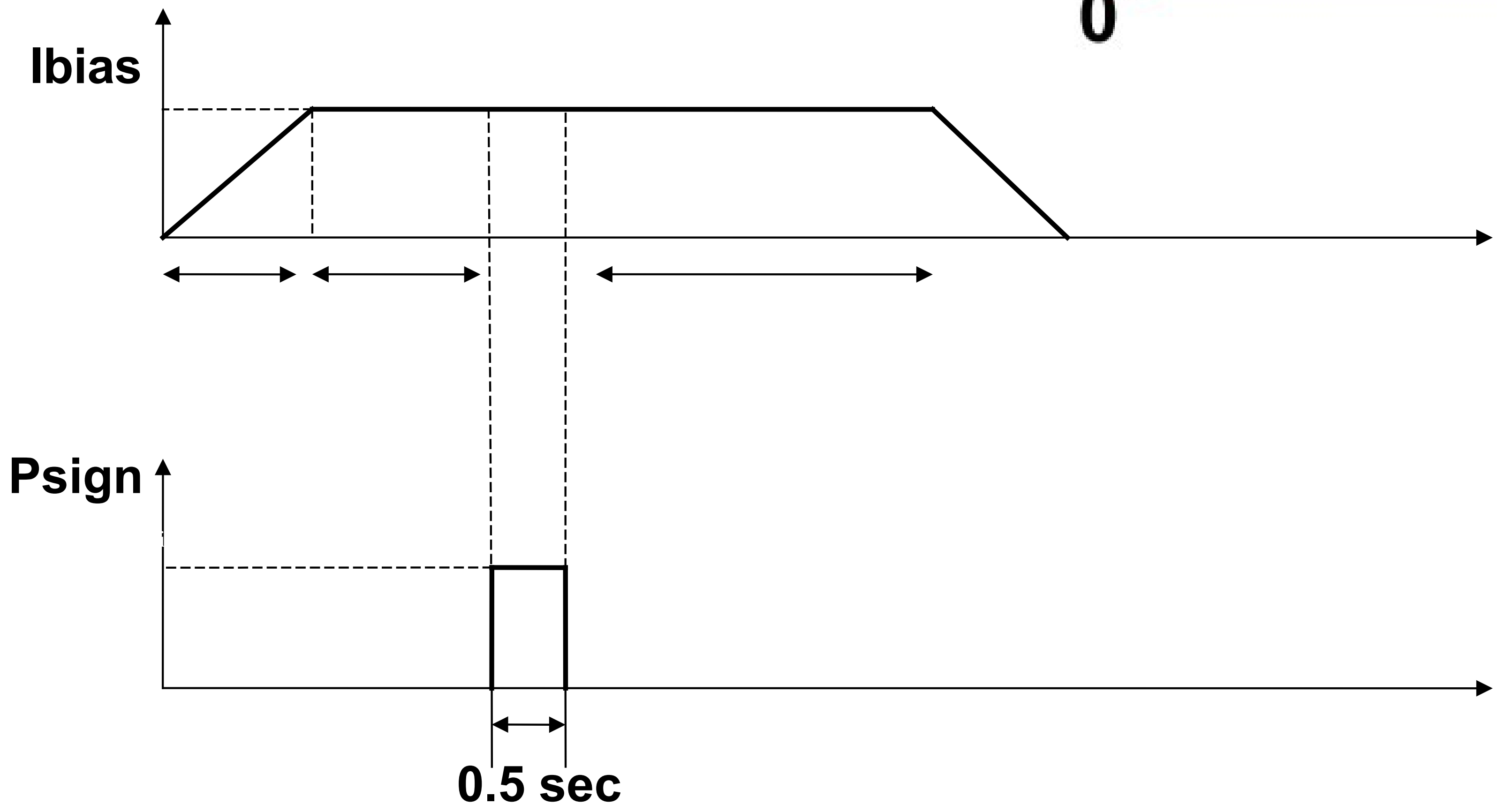


T = 500 mK

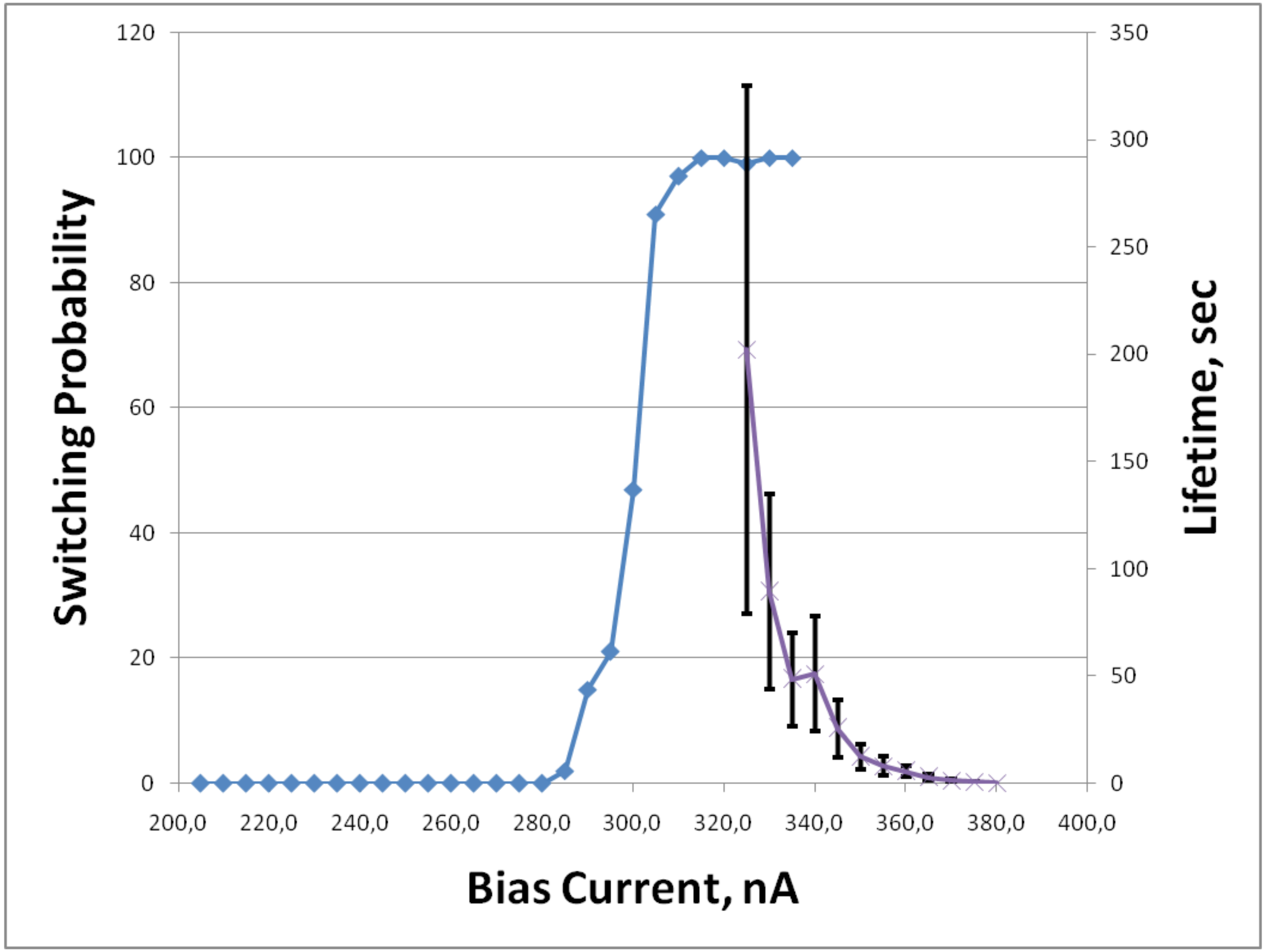


Experiment with 9 GHz pulses



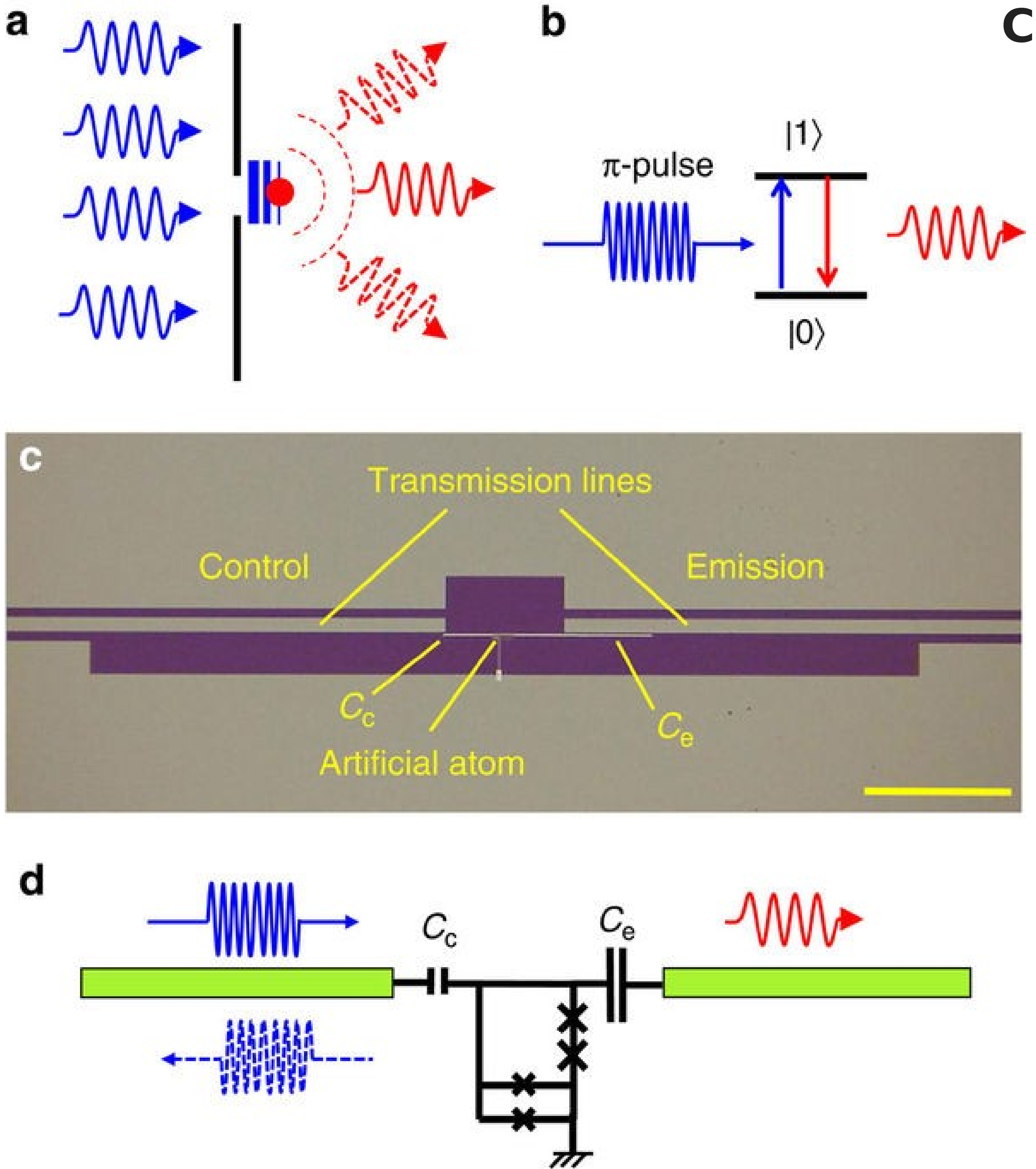


Experiment with 9 GHz pulses

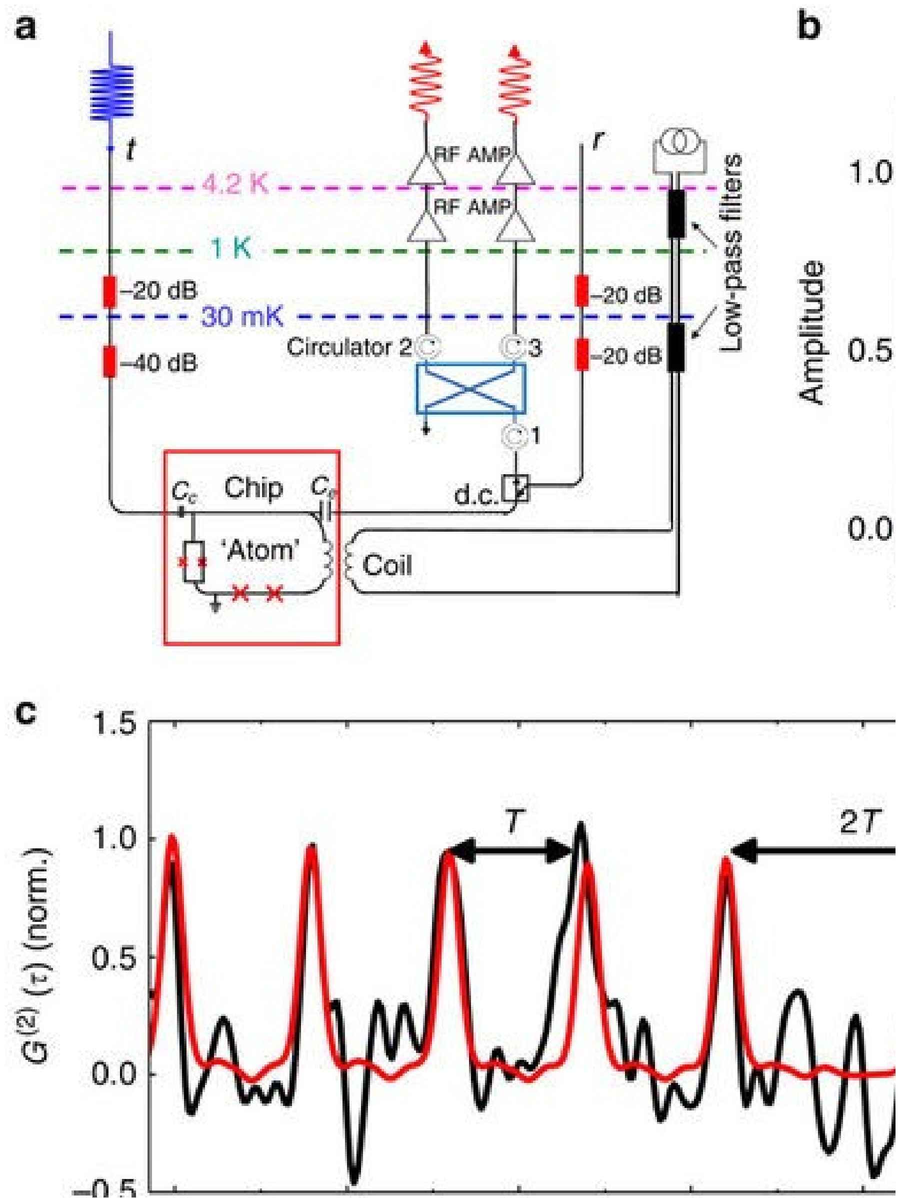


The single-photon source at 6 GHz

Nature Communications 2015, Astafiev et al.



Correlation function measureme



Conclusions

•Single Photon Counter at 14 GHz based on Al-Al Josephson Junction for searching galactic axions.

• Lifetime over 6000 sec at 10 mK.

Dark counting should be further improved

• Al-Al Single Photon Counter from 3 to 70 GHz.

Nb-Nb Single Photon Counter from 70 to 900 GHz.

• Single Photon Counter can be combined with a Single Photon Source at 6 GHz for Quantum Circuits

L. Kuzmin, A. Sobolev, C. Gatti, D. Gioacchino, N. Crescini, A. Gordeeva, E. Il'ichev. Single Photon Counter based on a Josephson Junction at 14 GHz for searching Galactic Axions. IEEE TAS, 2400505 (2018)