Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

THE SIMP PROJECT

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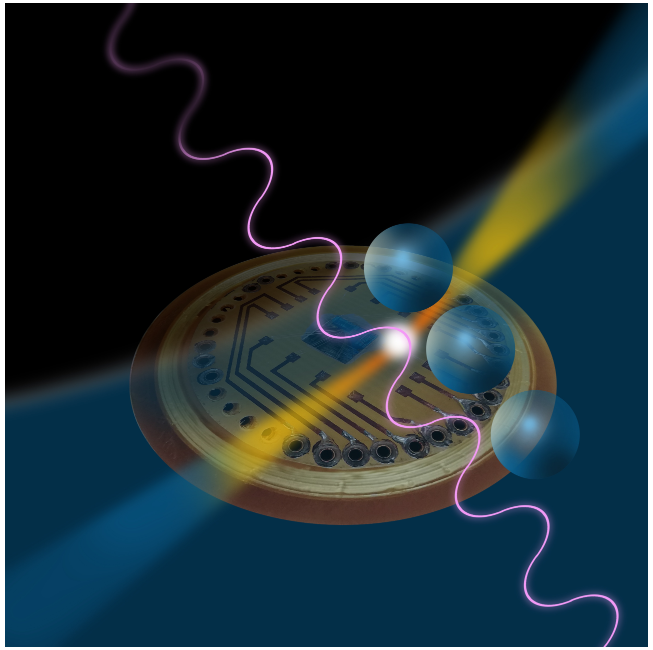


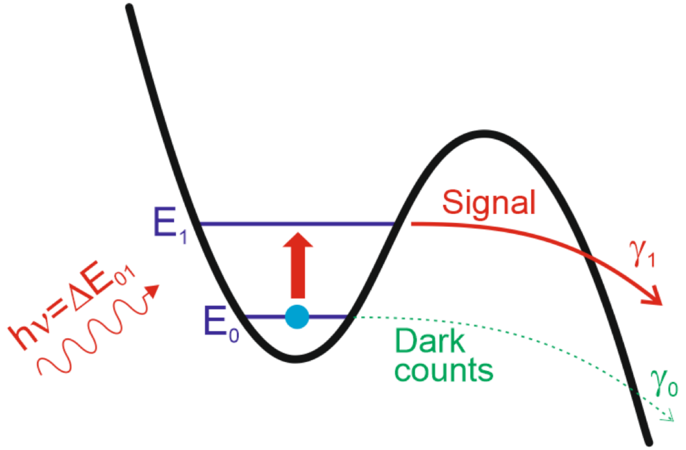
INTRODUCTION

SIMP: SIngle Microwave Photon detection

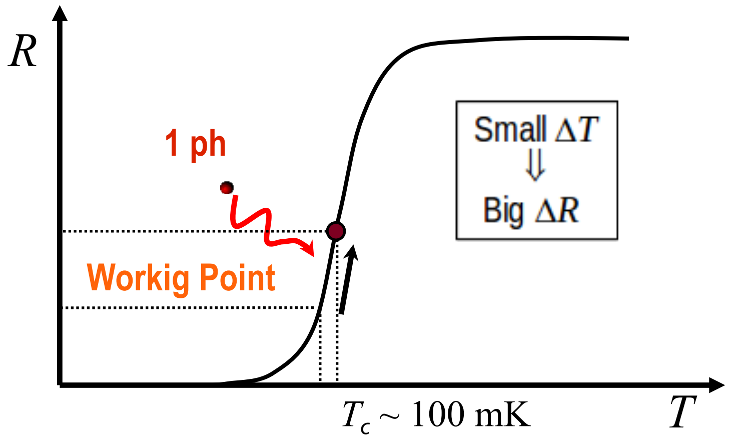
Development of single microwave photon counter (10-100 GHz) with two technologies:

1. Current biased Josephson Junction (LNF, Salerno, CNR-IFN)
2. Transition Edge Sensor (INFN-Pi, CNR Nano-NEST, TIFPA, INRIM)

Units
LNF (Nat Resp)
INFN Pi
INFN Sa
TIFPA-FBK
CNR Nano NEST
CNR IFN
INRIM



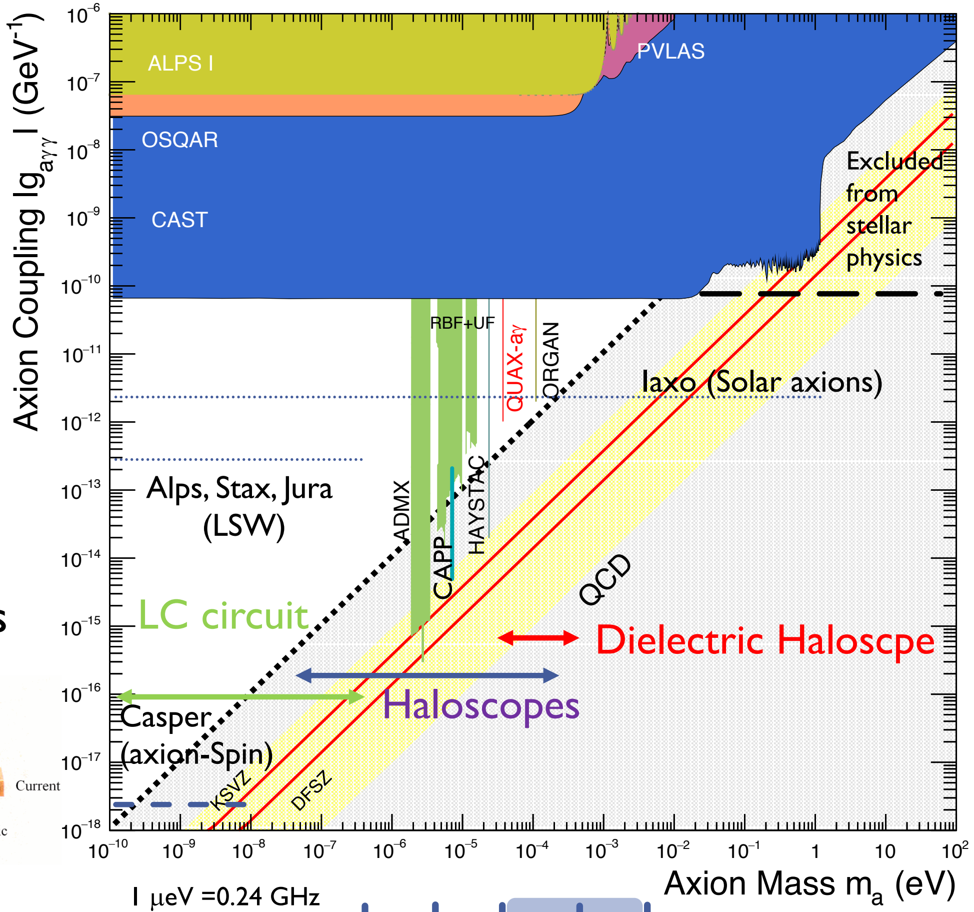
Based on sudden variation of voltage across the junction.



Based on steep variation of resistance.

3 years project approved in CSNV in 2018

Why single microwave-photon detection



1 μeV =0.24 GHz

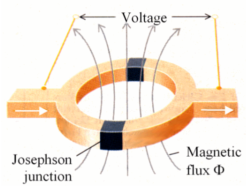
0.1 1 10 100 1000 ν[GHz]

Detection of faint e.m.-signals is performed efficiently in a wide range of frequencies from MHz to visible as in the search for galactic axions.

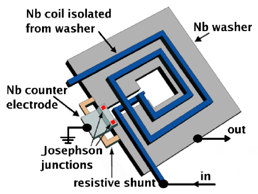
Linear-amplifier noise is prohibitively increased by standard quantum limit above 10-20 GHz while bolometers and photon counters are not sensitive enough (or too noisy) below the THz (see however Schuster et al., Nature 445, pp. 515 (2007)).

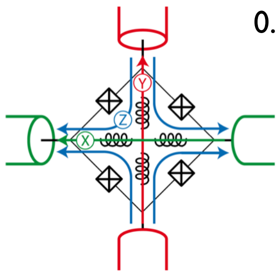
The ultimate sensitivity of experiments in the region 10-500 GHz can be reached only by low dark-count and efficient single microwave-photon detectors.

Amplifiers



SQUID (→1 MHz)

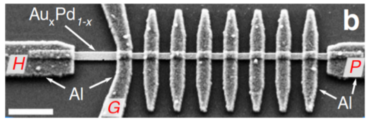




MSA SQUID (→ few GHz) JPA (→ 10-20 GHz)

Quantum limit

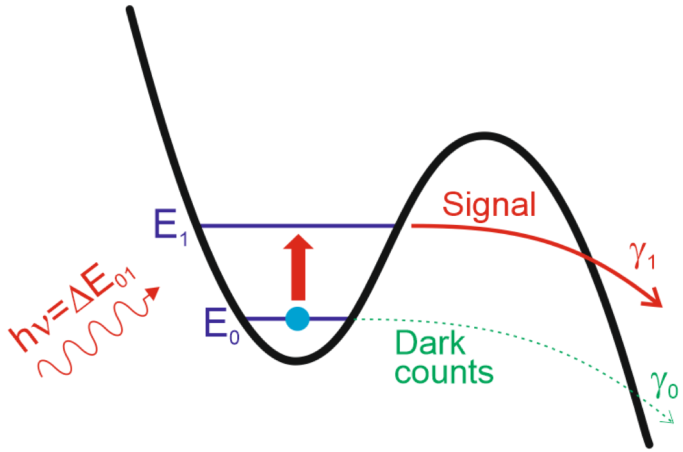
$$T_{noise}[mK] \approx 40\,\nu[GHz]$$



Bolometers
photon counters

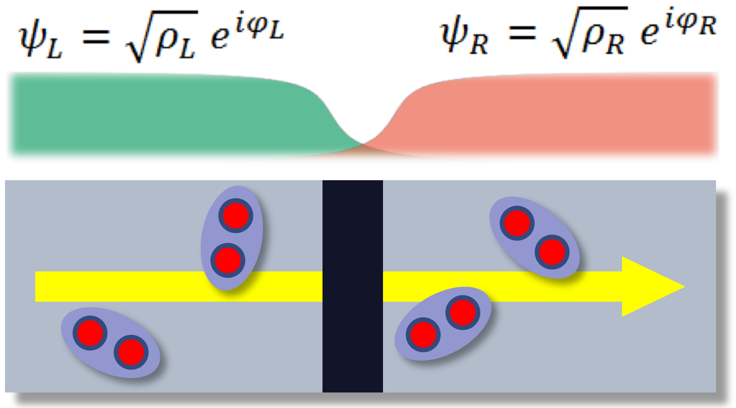
NEP=20 zW/√Hz → 400 GHz

Kokkoniemi et al. Nat. Com. Phys.
https://doi.org/10.1038/s42005-019-0225-6



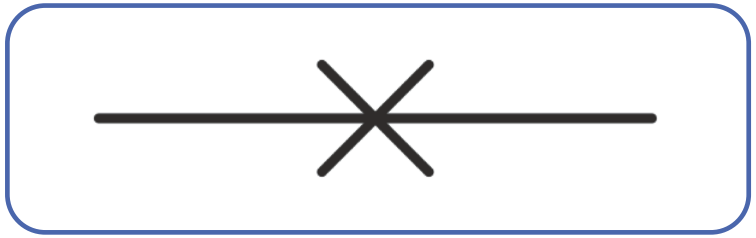
CURRENT BIASED JOSEPHSON JUNCTION

Artificial Atoms With Josephson Junctions



F.Chiarello CNR-IFN

Symbol



Josephson equations

Current flowing in the junction

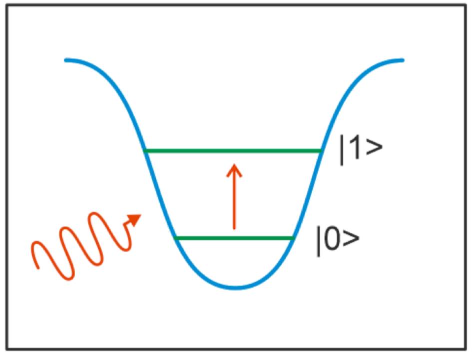
$$I = I_c \sin\varphi$$

Voltage at the junction

$$V = \frac{\hbar}{2e}\frac{d\varphi}{dt}$$

Phase difference across the junction

$$\varphi = \varphi_R - \varphi_L$$



Typical values for JJ

$$\omega/2\pi \sim 10\ \mathrm{GHz}$$

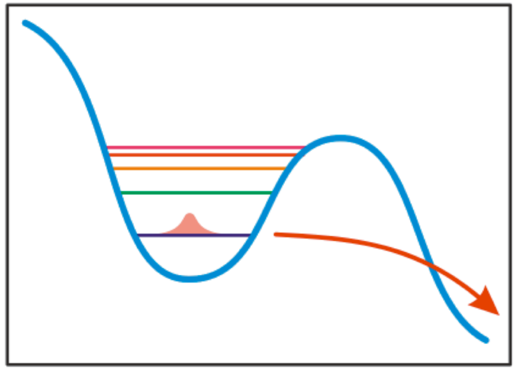
$$I_c \sim 10\ \mu\mathrm{A}$$

$$C_J \sim 1\ \mathrm{pF}$$

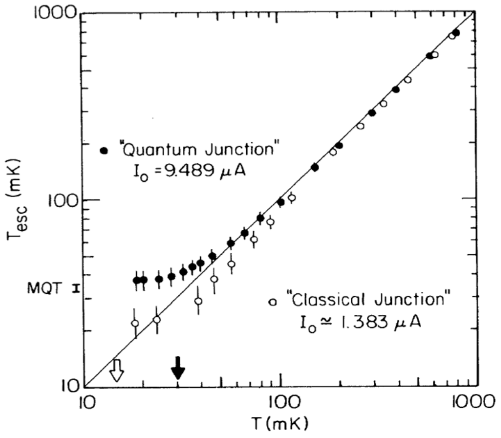
$$T_1 \sim 1\ \mu\mathrm{s}$$

Quantum Behaviour

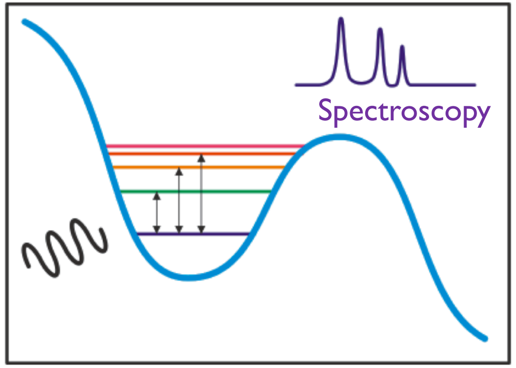
Tunnel Effect



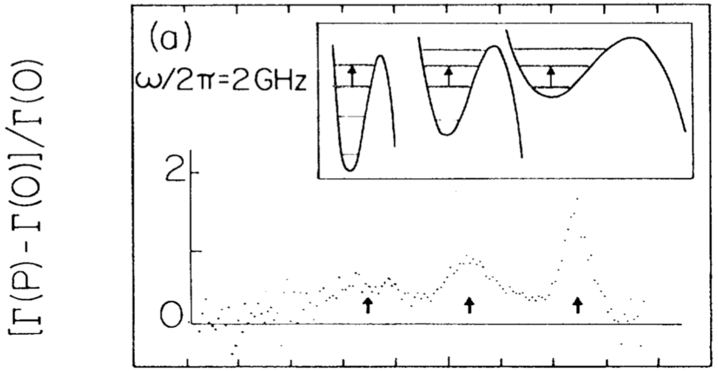
Devoret et al. PRL 55 (1985)



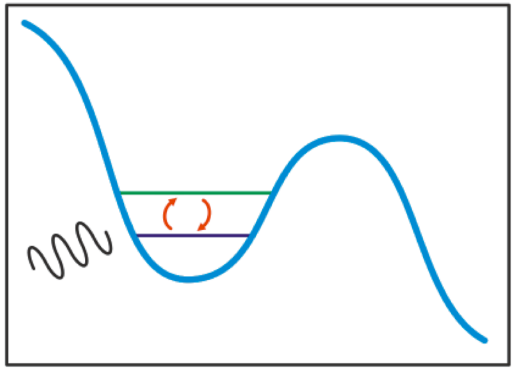
Energy Level Quantization



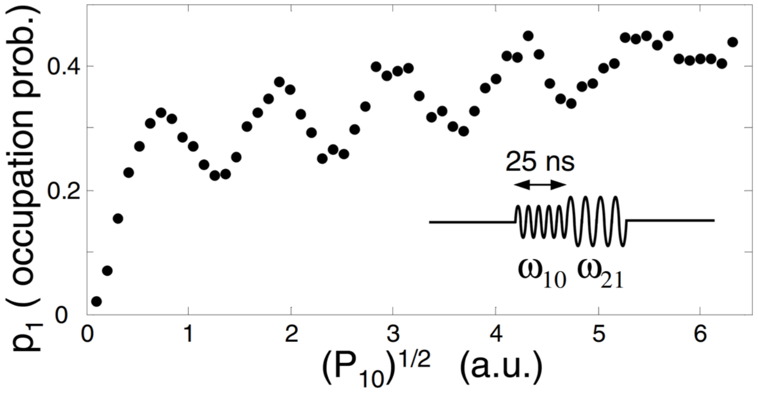
Martinis et al. PRL 55 (1985)



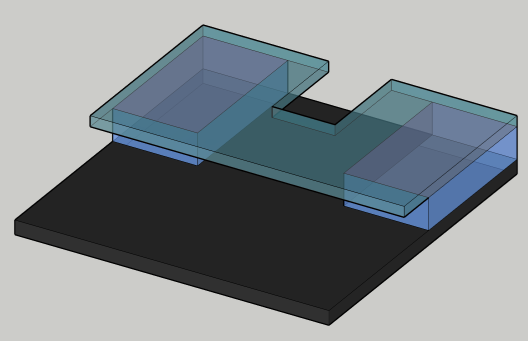
Rabi Oscillations

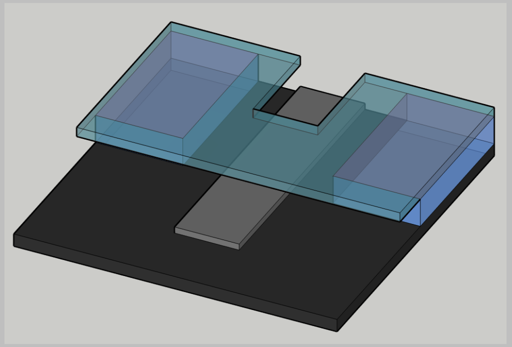


Martinis et al. PRL 89 (2002)

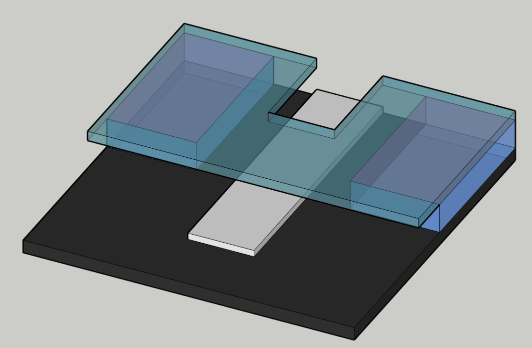


Fabrication Of Tunnel Josephson Junction

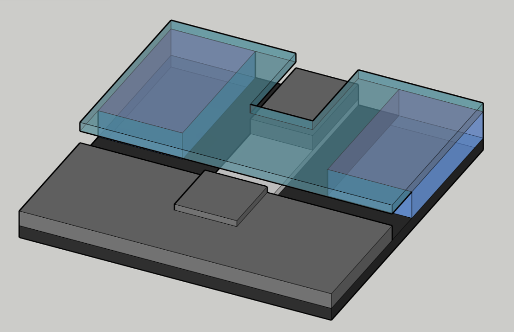




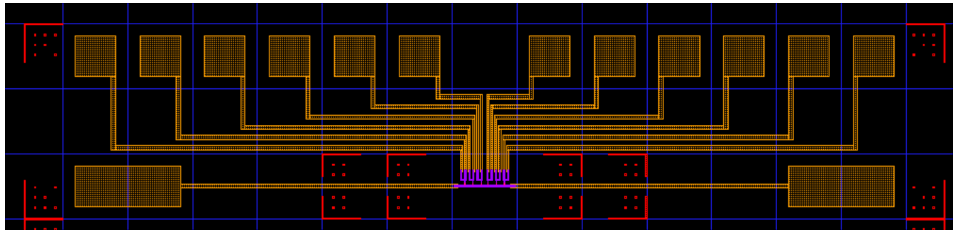
155° 300 Å Al

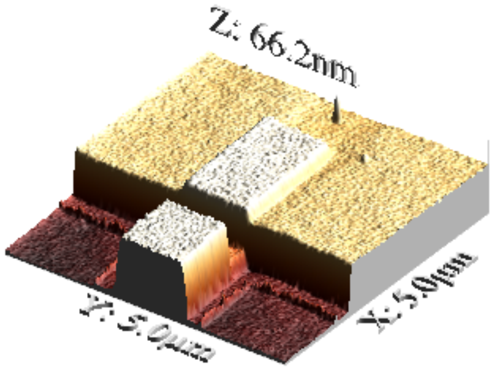


O_2 5 min. 5.0 mbar



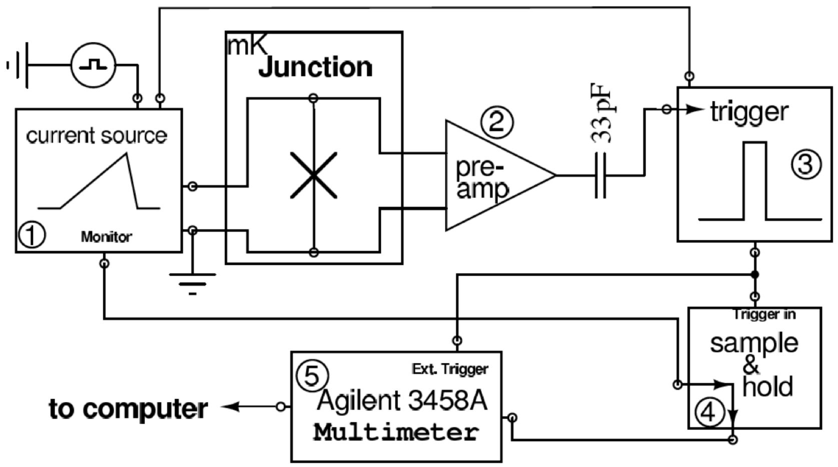
90° 300 Å Al



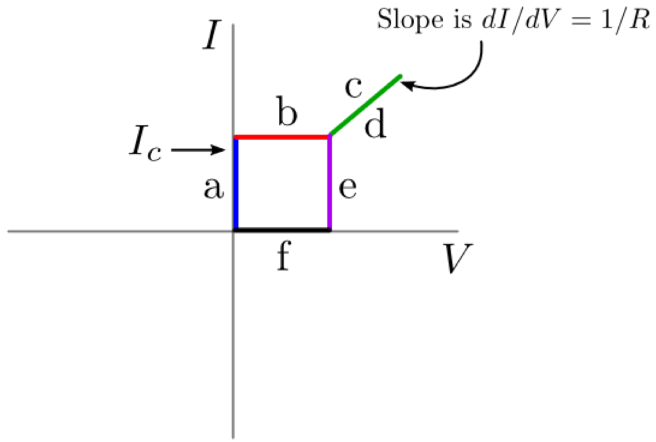


A (μm^2)	1÷8
Jc (nA/μm^2)	~ 50
C(fF/μm^2)	~ 50
ν(GHz)	~ 10

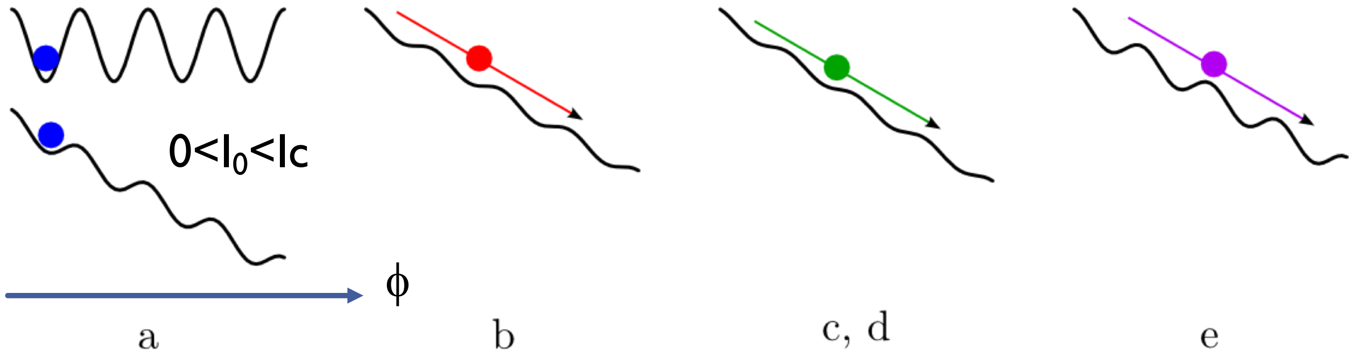
Current Biased Josephson Junction



$$V = \frac{\hbar}{2e}\frac{d\varphi}{dt}$$



$I_0=0$

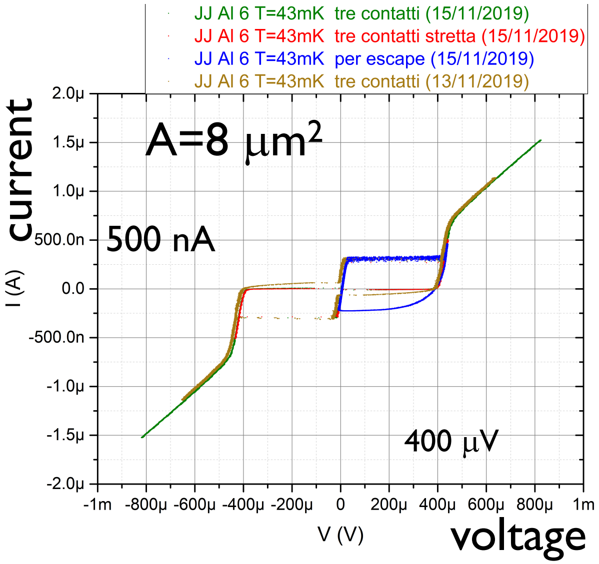


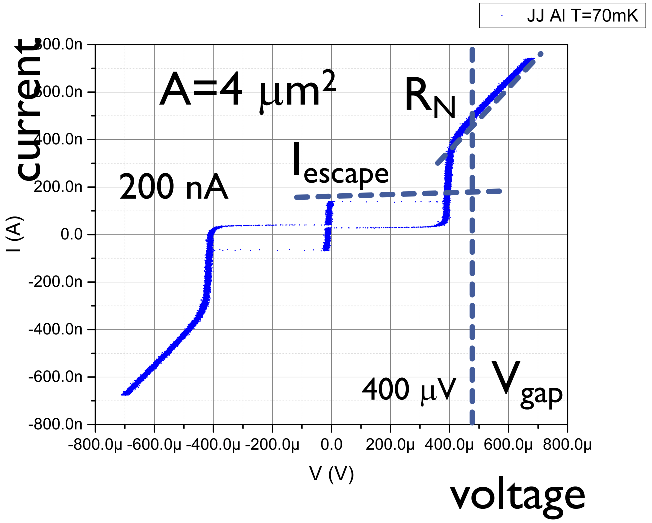
ϕ is the dynamical variable

$$H = \frac{Q^2}{2C_J} - E_J \cos\frac{2\pi\phi}{\phi_0} - I_0\phi$$

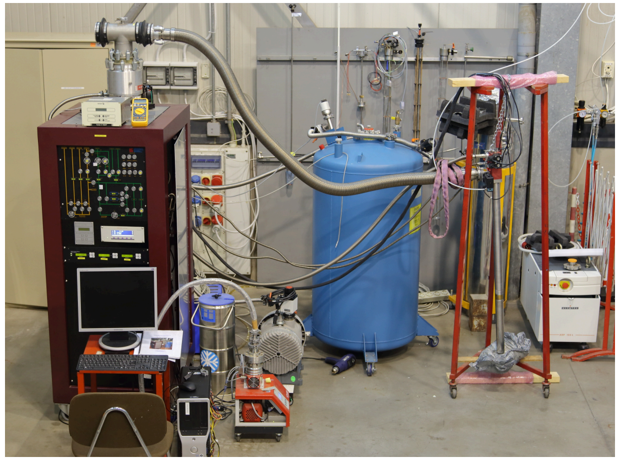
Bias current

Preliminary test of Al Josephson Junctions at LNF

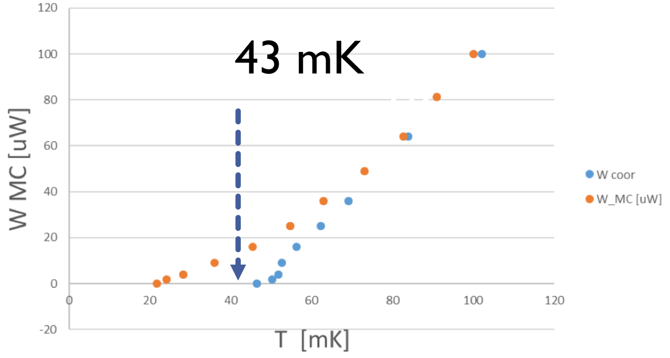




Leiden Cryogenics MCK50-100



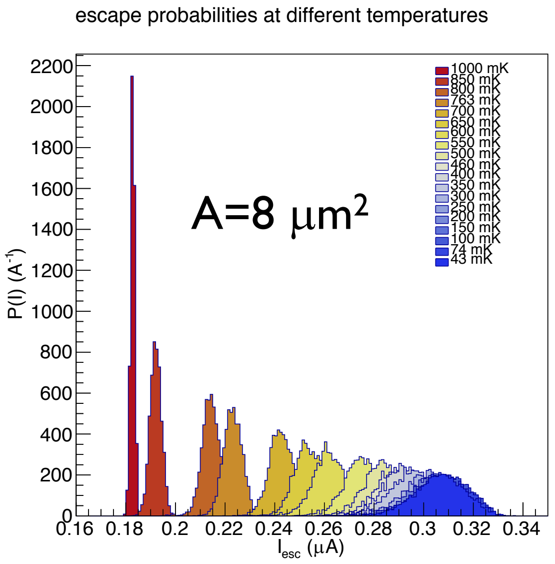
Equipped only for AC/DC test



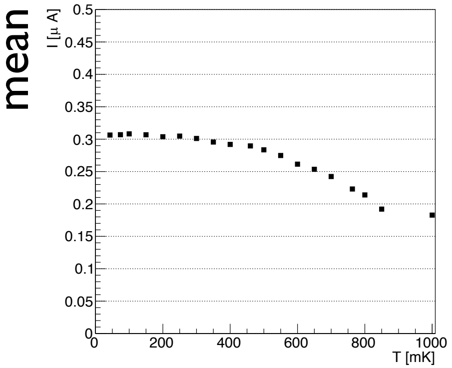
A(μm²)	V_{gap}(μV)	R_N(Ω)	$I_C=\pi/4\ V_{gap}/R_N$ (nA)	$T_C=V_{gap}/3.53\ k_B$ (K)
8	400	500	600	1.3
4	400	1000	300	1.3

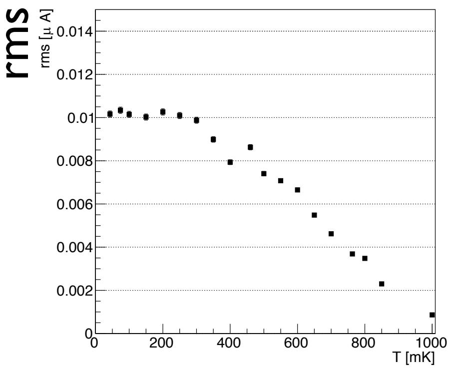
First test with non-optimal filtering and screening

Preliminary test of Josephson Junctions at LNF

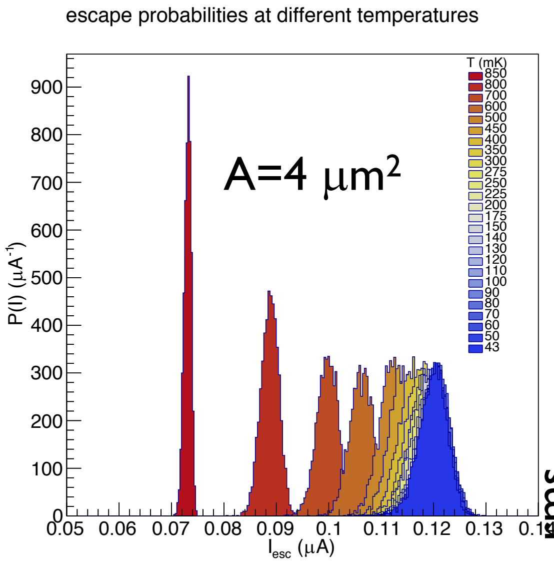


Escape current

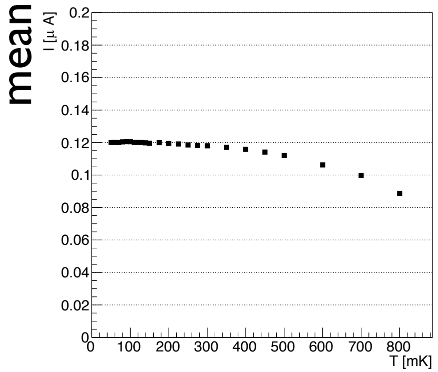


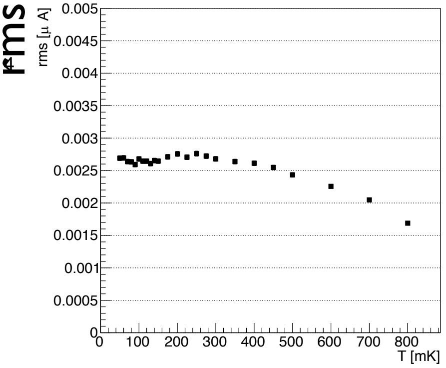


temperature



Escape current

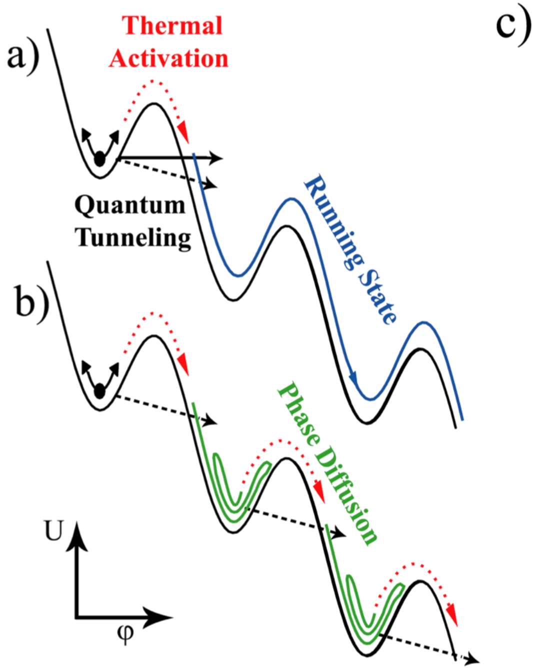




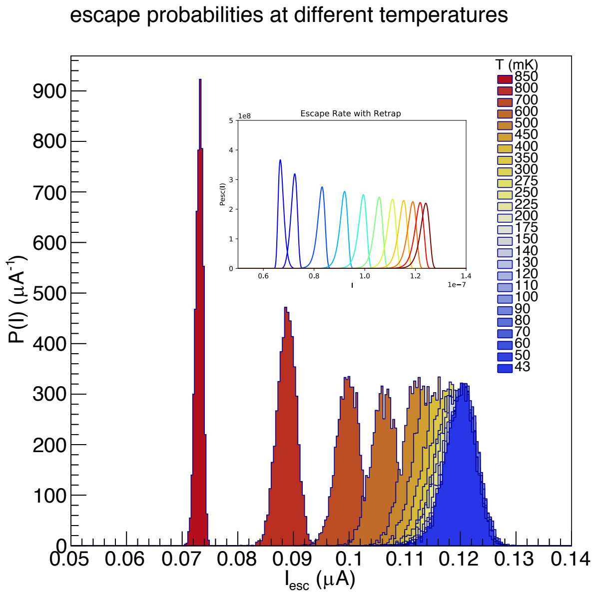
temperature

Preliminary test of Josephson Junctions at LNF

Attempting an interpretation including thermal activation, quantum tunneling, trapping and re-trapping.

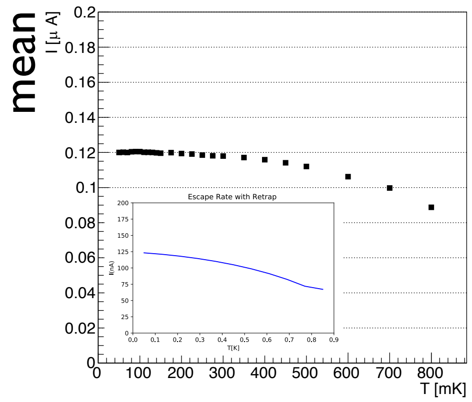


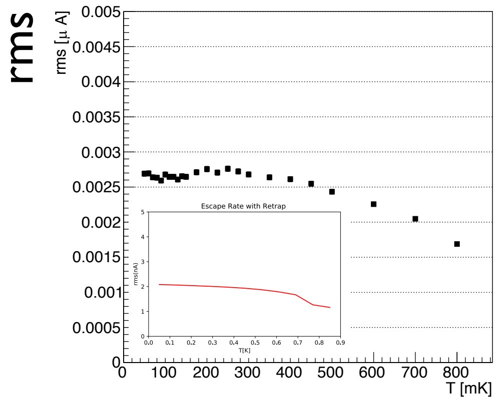
Longobardi et al. PRL 109 050601 (2012)



Escape current

A (μm^2)	4
Ic (nA)	150
C(pF)	0.2
ν(GHz)	6.5

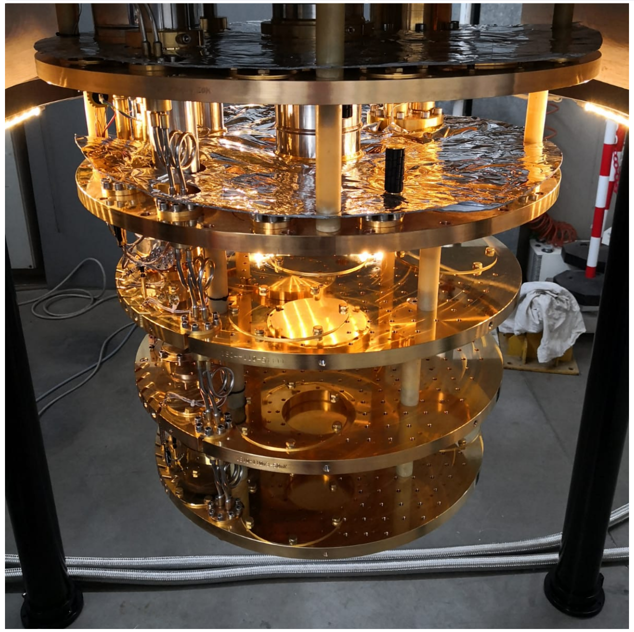




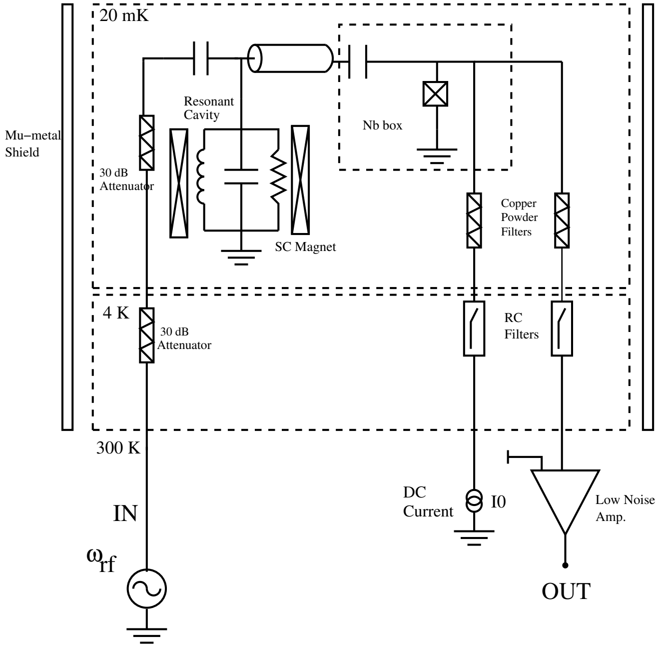
temperature

LNF Dilution Refrigerator For RF Measurements

Leiden CF-CS-110-1000	
Sumitomo PT	1.5 W at 4.2 K
Cooldown time (with LN)	2 days
Base temperature (measured)	8.5 mk
Cooling power at 100 mK (measured)	450 µW (up to 700 µW with a new pumping system)

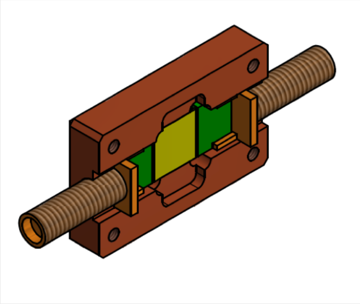


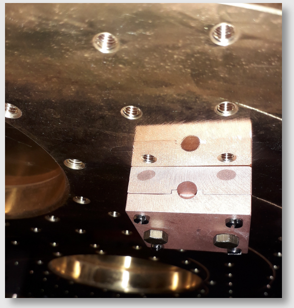
4 RF lines installed from 300 K to MC

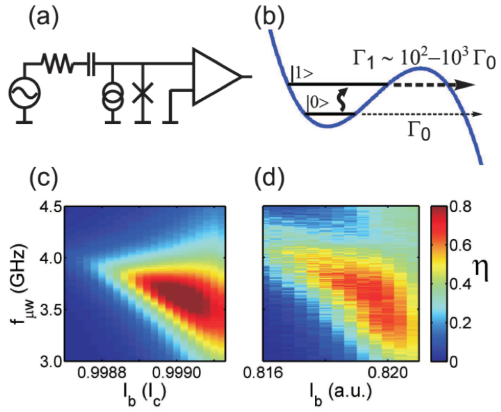


Next goal is to reproduce the results of
Chen et al. PRL 107, 217401 (2011)

Sample holder for RF chip

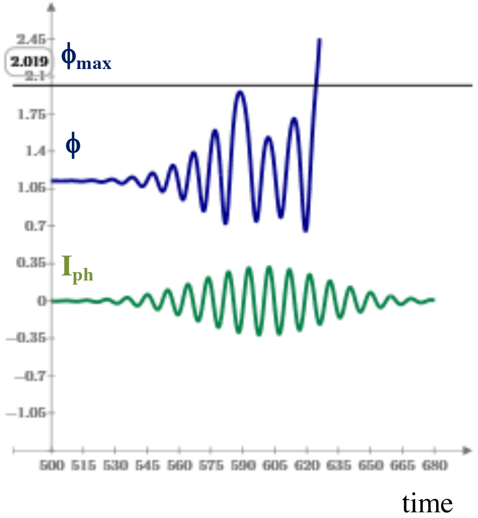






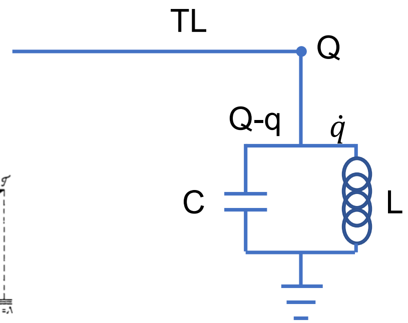
CBJJ Simulation

Classical description of a driven JJ

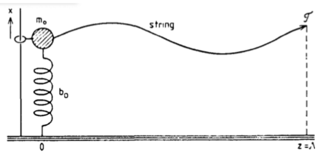


Transmission Line terminated with JJ

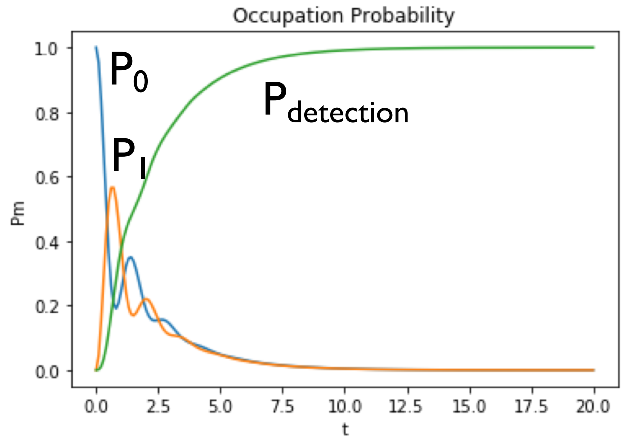
$$L=\frac{1}{2}\int_0^d dz\left[C_0\dot{\phi}(z,t)^2-\frac{1}{L_0}\phi'(z,t)^2\right]+\frac{1}{2}C_j\dot{\phi}(0,t)^2-\frac{1}{2L_J}\phi(0,t)^2+\frac{1}{6}I_0\left(\frac{2\pi}{\Phi_0}\right)^2\phi(0,t)^3$$



Mechanical equivalent

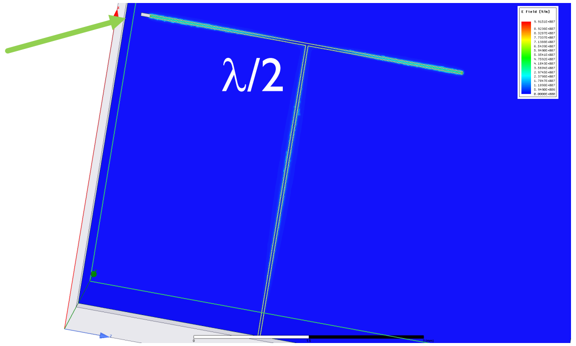


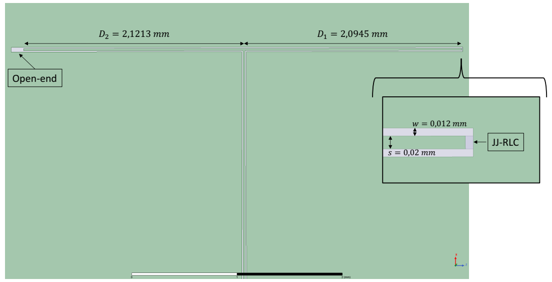
Simulation of quantum system TL+JJ

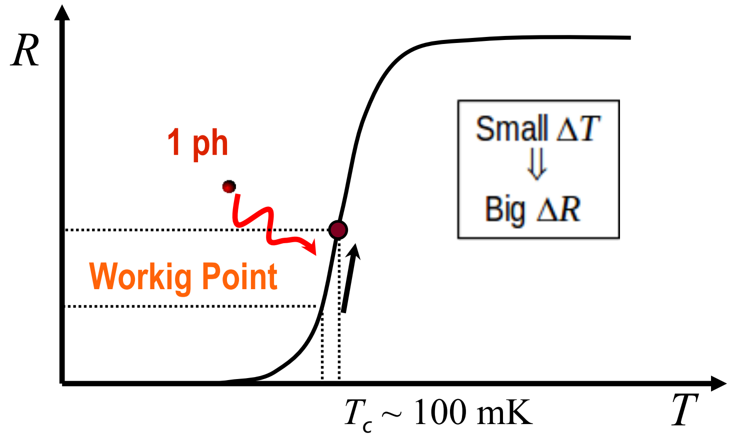


Simulation based on Schondorf et al. arXiv:1609.08887

Transmission Line terminated with λ/2 resonator + JJ system







TES

Transition Edge Sensors for 30-100 GHz

$$\sigma_E \propto \sqrt{k_B C T^2}$$

Lower temperature

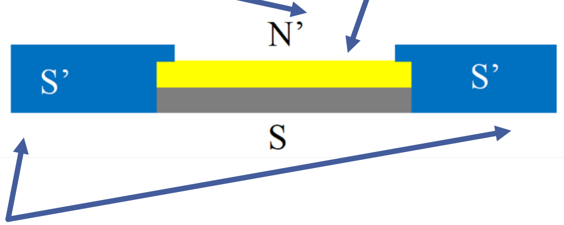
$$C = \gamma V T$$

Reduce volume

$$\begin{aligned} V &\sim 300 \times 80 \times 35 \text{ nm}^3 \\ \gamma &\sim 10^{-22} \text{ mJ/K}^2/\text{nm}^3 \\ T_c &\sim 40 \text{ mK} \\ \sigma_E &\sim 20\ \mu\text{eV} \sim 5 \text{ GHz} \end{aligned}$$

Tune transition temperature by proximity effect or induced superconductivity

nanowire



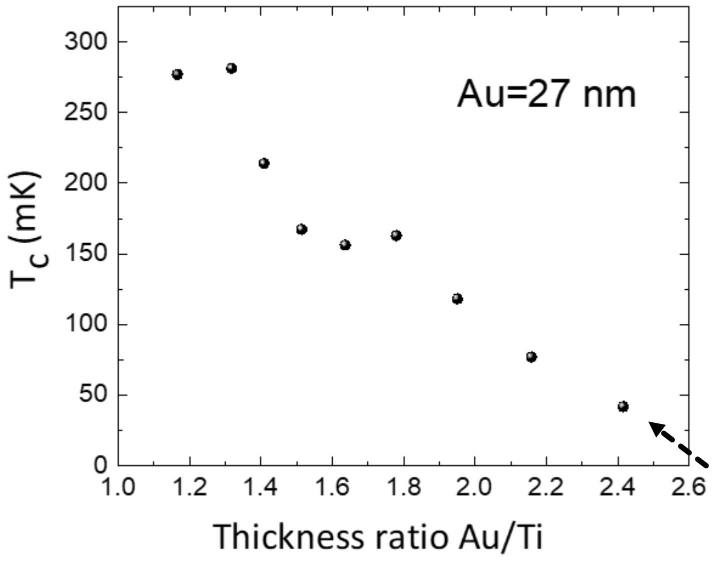
Andreev mirrors: electrons trapped in the nanowire

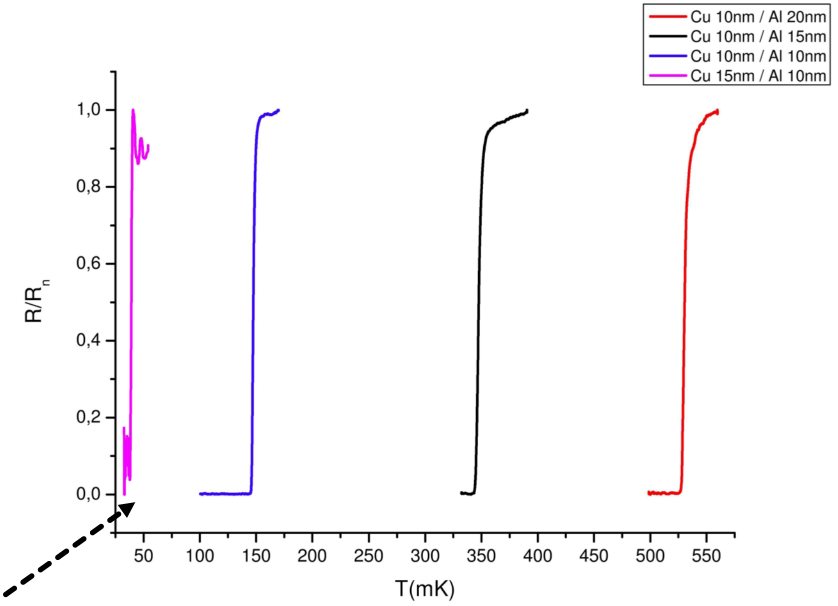
With C~10^{-21} J/K a 10 GHz photons → ΔT= few mK

TES Films with 40 mK T_C

Bilayer Ti(11 nm) Au(27 nm)
Tc=40 mK

Bilayer Al(10-20 nm) Cu(10-15 nm)
Tc=40 mK

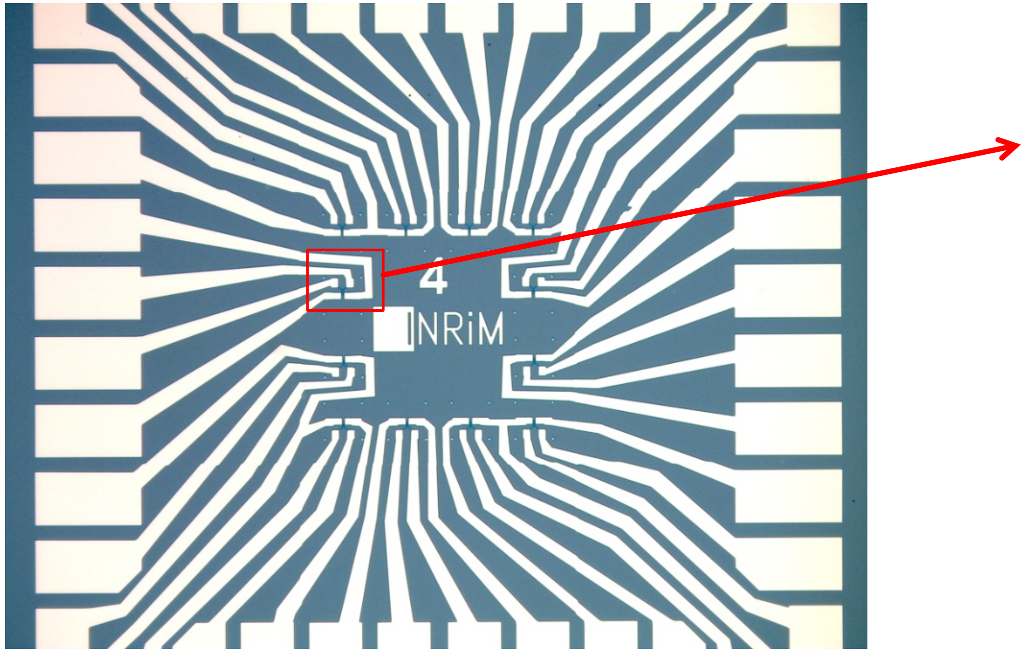




T_C= 40 mK

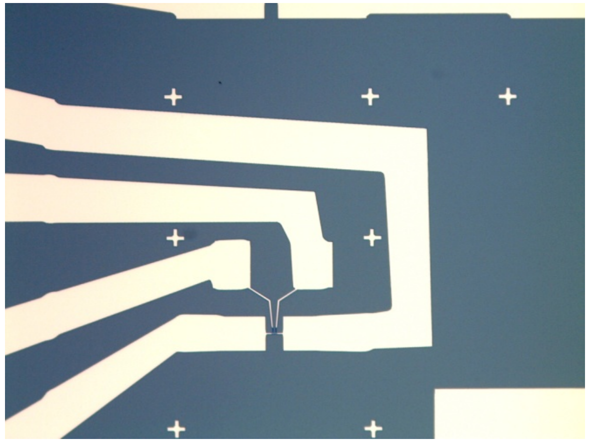
TES Nanowire

INRiM
ISTITUTO NAZIONALE
DI RICERCA METROLOGICA



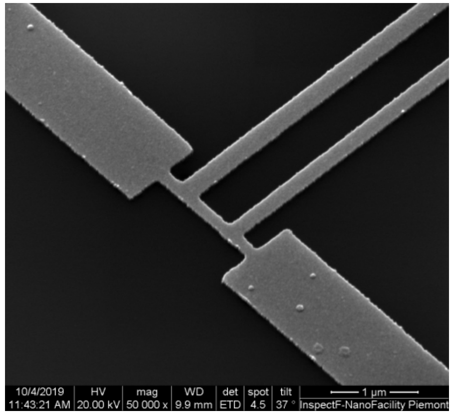
CHIP (4 mm x 4 mm) with 12 devices

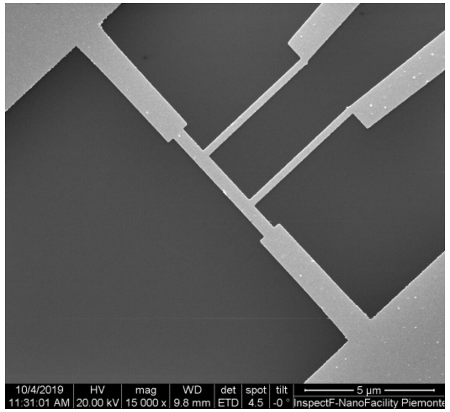
Nanowire characterization underway



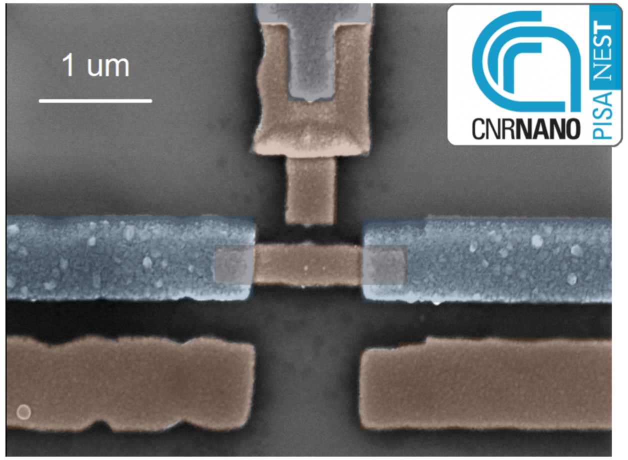
Ti/Au nanowires

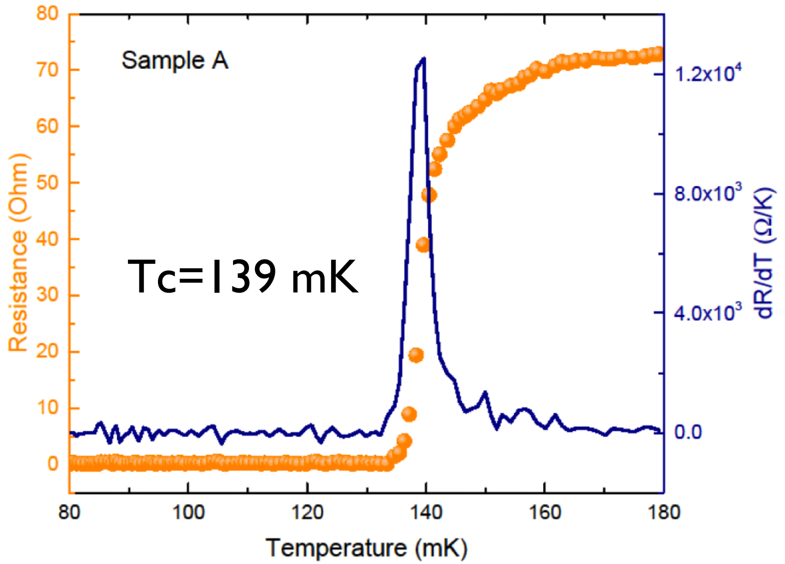
Lenght	1-2 μm
Width	150-300 nm
t_{Au}	27 nm
t_{Ti}	11 nm

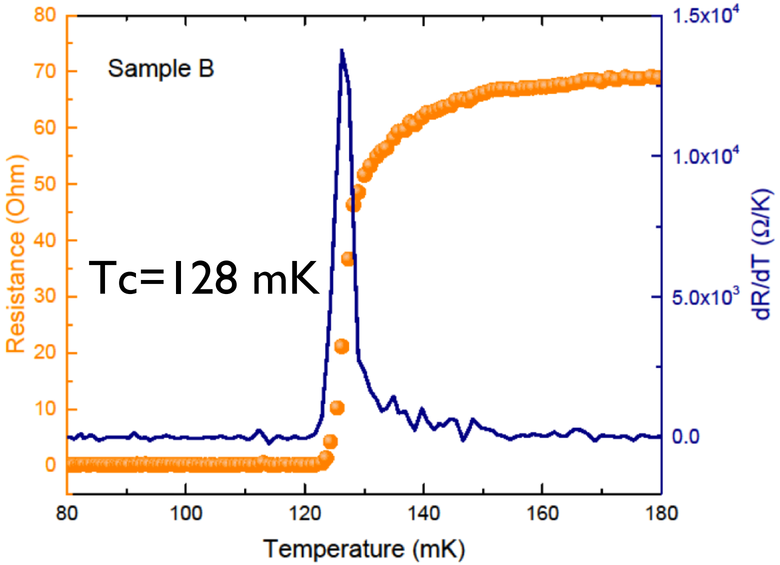




TES Nanowire







Lenght	1.5 μm
Width	100 nm
t_{Al}	10.5 nm
t_{Cu}	15 nm

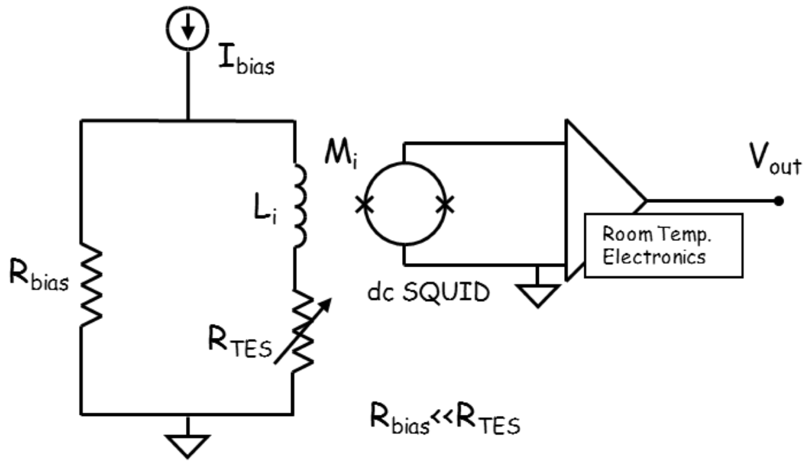
τ	5-10 μs
C	5×10^{-20} J/K
G	5×10^{-15} W/K
σ_{ν}	100-200 GHz
NEP	30-50 zW/√Hz

Direct measurement of nanowire properties:
Tc, transition steepness, e-ph coupling, bilayer E_{gap}.

Close to SIMP specifications!

Characterization Of TES Nanowire

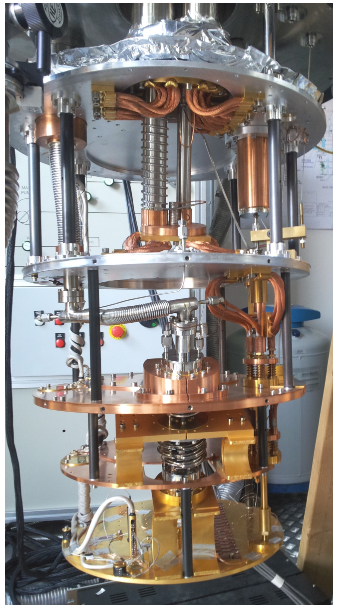
Chip in preparation with nanowires for TES bias and readout with SQUID



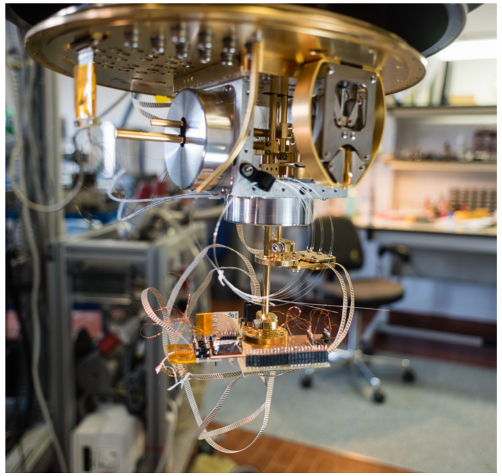
TIFPA
Trento Institute for
Fundamental Physics
and Applications

INRiM
ISTITUTO NAZIONALE
DI RICERCA METROLOGICA

TIFPA Dilution Refrigerator



Janis 100 μW a 100 mK T_{base} 20 mK

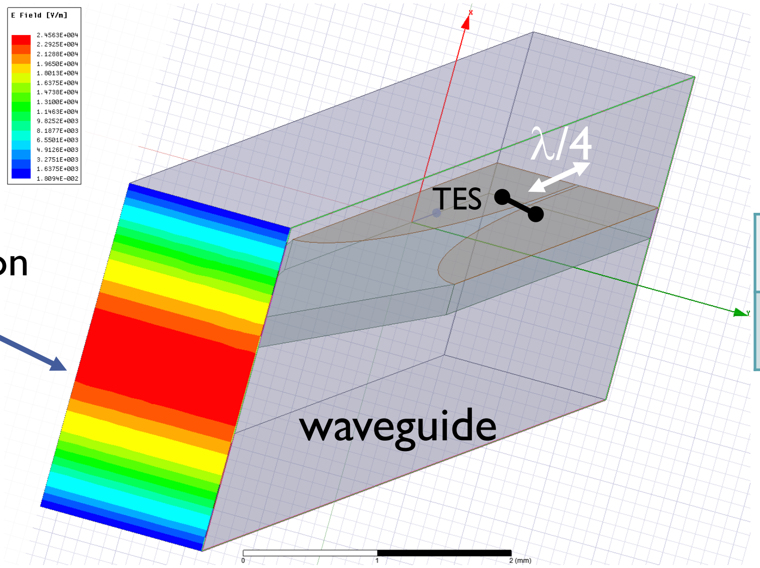


INRIM Adiabatic Demagnetization Refrigerator (30 mK)

Signal Collection In Waveguide

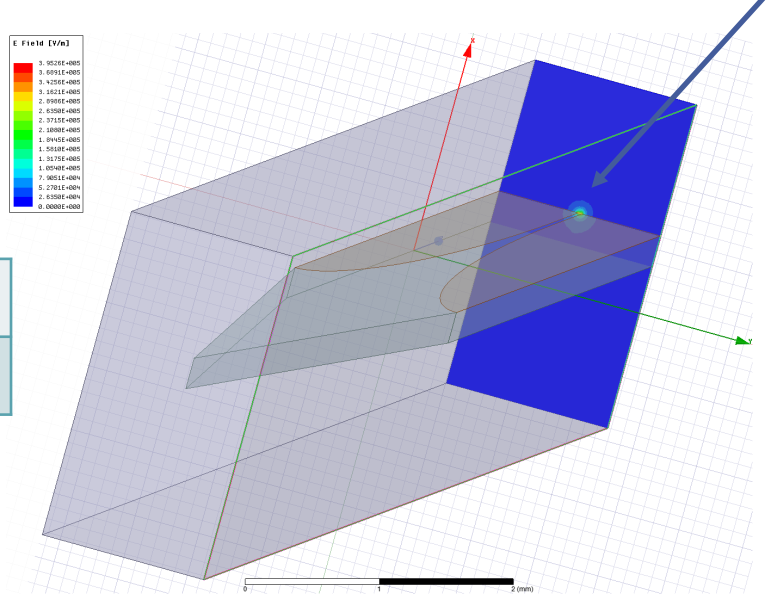
Simulation of finline with ANSYS HFSS, to match waveguide impedance to TES

Incoming photon

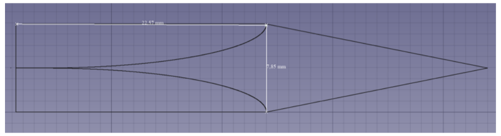


ν (GHz)	90
Δν (GHz)	20

Field collected on the finline

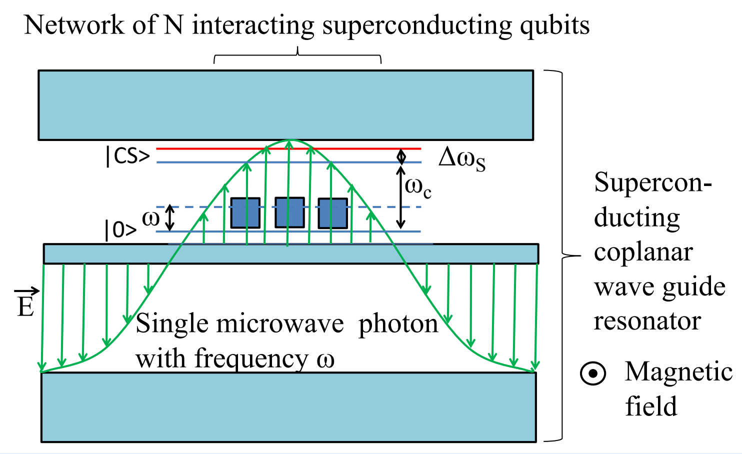


Fabrication of finline prototype underway



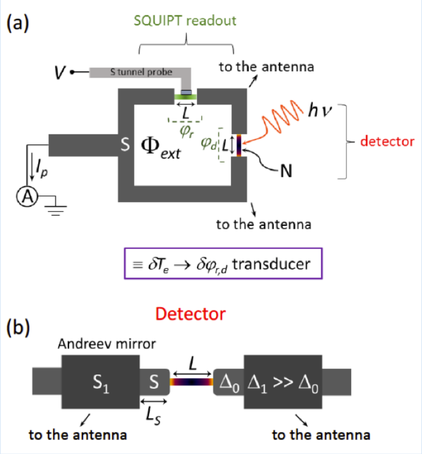
Related Projects

FET OPEN SUPERGALAX
CNR (IT, PI, exp)
INRIM (IT, exp)
INFN (IT, axion exp)
KIT (DE, exp)
Leibniz IPHT (DE, exp)
RUB (DE theory)
LU (UK, theory)



Measure a shift of cavity resonance peak (Stark shift) when there’s a photon

ATTRACT T Converse
INFN Pi
CNR-NANO Pi
SeeQC



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Conclusion

- Work is proceeding fast both for TES and CBJJ
- In the coming months we expect to:
  1. Couple nanowire to a SQUID
  2. Couple TES in waveguide and start photon-counting experiments
  3. Improve Tc of nanowires

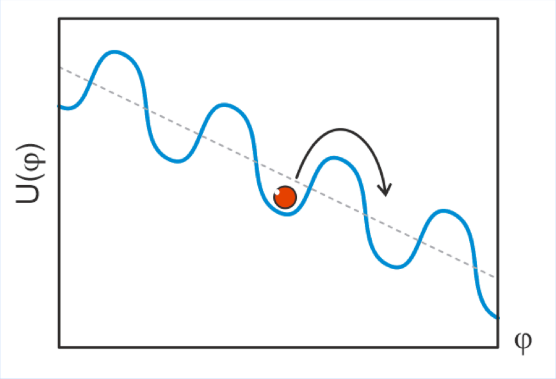
  1. Complete RF setup of dilution refrigerator
  2. Start RF test on TL+JJ device
  3. Improve simulation for selection of device parameters

Thank You!

Macroscopic Quantum Tunneling

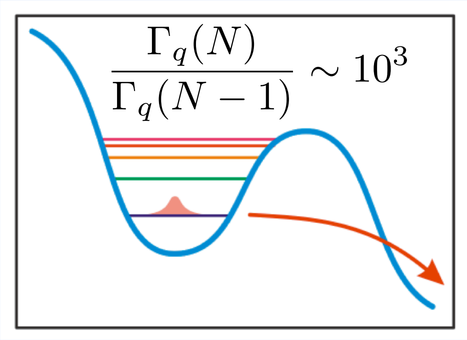
Thermal activation process

$$\Gamma_t = \frac{\omega_0}{2\pi} a_t \exp\left(-\frac{\Delta U}{k_B T}\right)$$

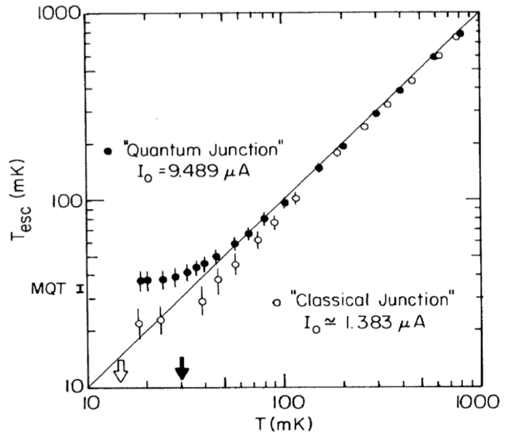


Macroscopic quantum tunneling

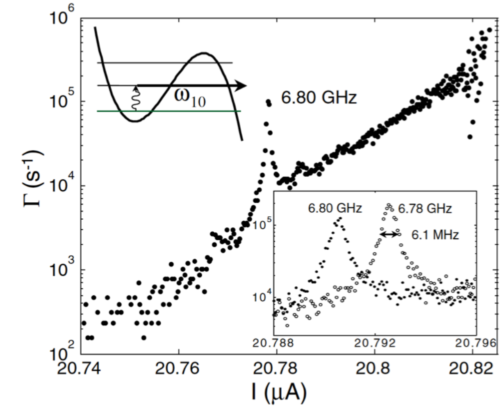
$$\Gamma_q \simeq \frac{\omega_0}{2\pi}\sqrt{\frac{7.2\Delta U}{\hbar\omega_0}} \exp\left(-\frac{7.2\Delta U}{\hbar\omega_0}\right)$$



$$\frac{\Gamma_q(N)}{\Gamma_q(N-1)} \sim 10^3$$



Devoret et al. PRL 55 (1985)



Martinis et al. PRL 89 (2002)