Single Microwave Photon detectoion with a Network of Superconducting Qubits

Dr. Mikhail Lisitskiy (SPIN-CNR, Italy)

SUPERGALAX Project: Highly sensitive detection of single microwave photons with coherent quantum network of superconducting qubits for searching galactic axions

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement N. 863313

CONSORTIUM – 7 groups, 3 Countries

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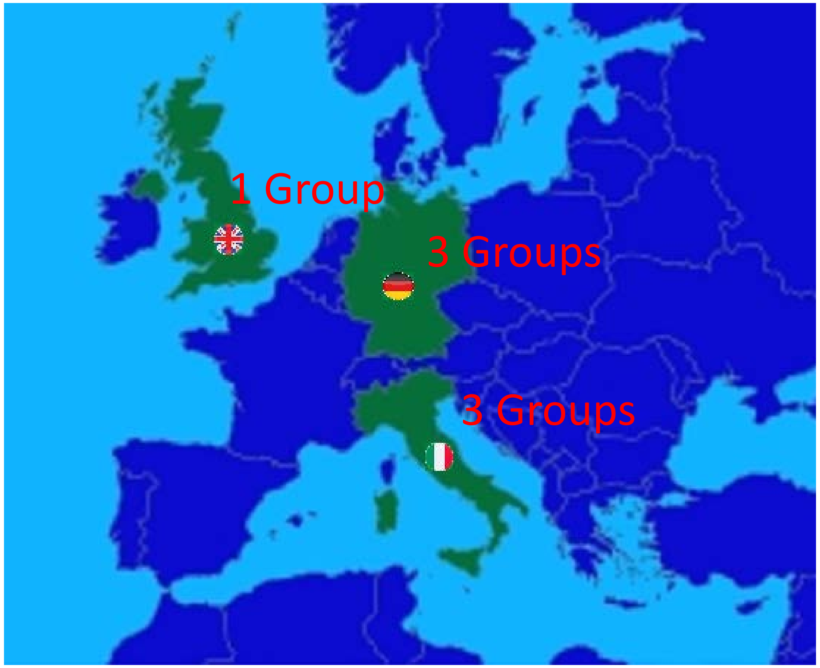


Main objective of the project

The ambition of the project is to develop and realize conceptually novel and practical quantum limited superconducting qubit network (SQN) detector capable to reveal single microwave photons for a photon frequency of ~10 GHz with the Heisenberg limit of sensitivity and the quantum limit noise with a view to apply it to the QUAX (QUaerere AXion) experiment, a search for galactic axions by means of normal “haloscopes”, funded by the National Institute of Nuclear Physics of Italy (INFN) .

Axions: physical properties

Astrophysical and cosmological observations indicate that 26% of the total energy density and 84% of the total matter content of the Universe is dark matter (DM), the identity and properties of which still remain a mystery. One of the leading candidates for cold DM is the axion, a pseudoscalar particle that was originally hypothesized by Peccei and Quinn to resolve the strong Charge-conjugation Parity symmetry (CP) problem of quantum chromodynamics (QCD) [*R.D. Peccei and Helen R. Quinn , PRL , 38, 1440 (1977)]*

Electrical charge: no electrical charge

Mass: Axion is a very light particle: $m_a \sim 10^{-6} - 10^{-2} eV/c^2$

Axion is a very weakly interacting

In the last decade the growing interest in axion search lies in the exploration of the mass range from few $\mu eV/c^2$ to hundreds of $\mu eV/c^2$

EXPERIMENT ON OBSERVATION OF AXIONS

Standard axion conversion can takes place in a strong magnetic field into a photon (Primakoff conversion) and subsequently coherently oscillating classical field is formed

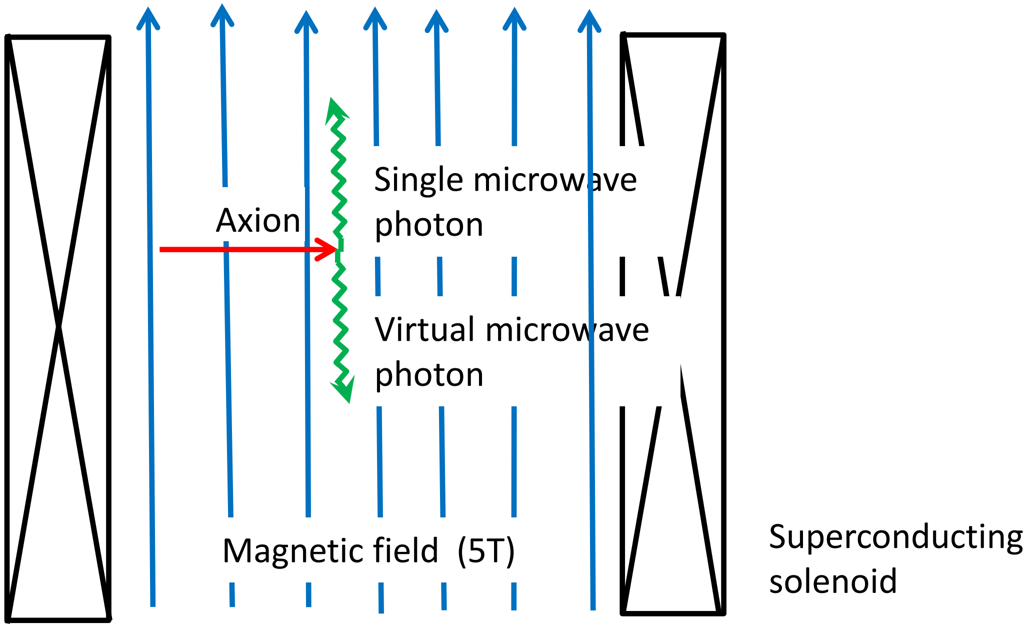
$a = a_0 \cos(\omega t)$,

with the angular frequency of oscillation given by

$$\omega \approx m_a c^2/\hbar$$

$m_a = 1 \mu eV/c^2$, $\omega/2\pi = 0{,}24$ GHz;

$m_a = 100 \mu eV/c^2$, $\omega/2\pi = 24$ GHz;



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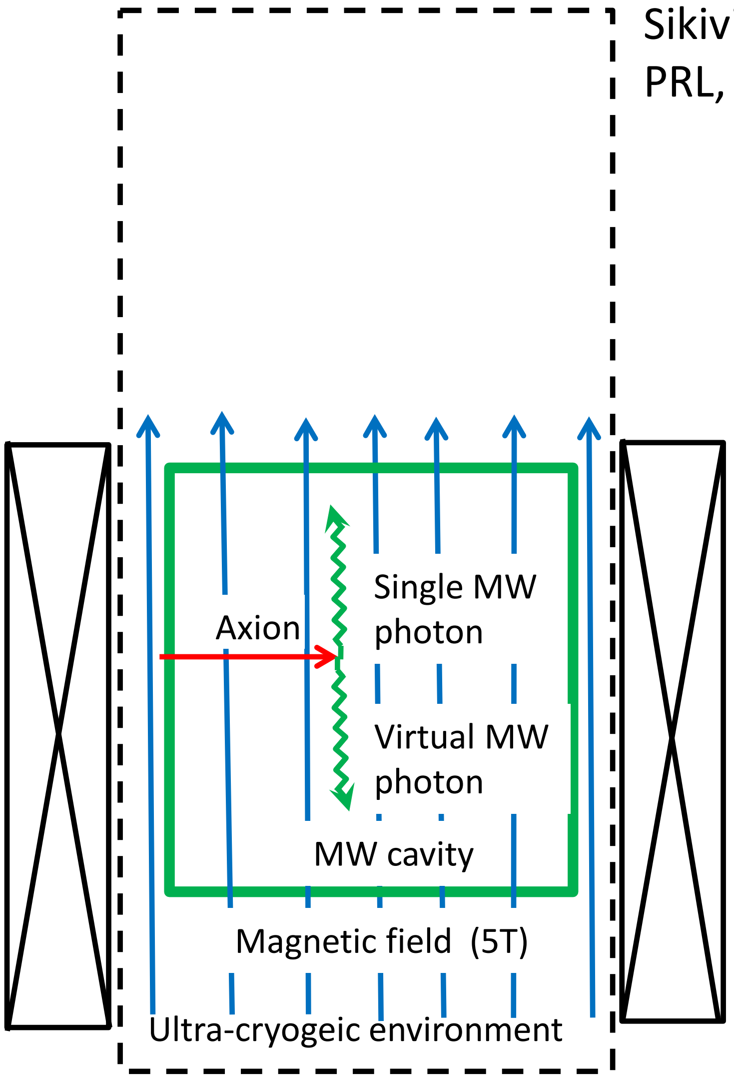
A high quality-factor microwave cavity immersed in a strong magnetic field converts axions into cavity –mode exitations when the resonance condition between cavity frequency and axion mass is met



Sikivie «haloscope» PRL, 31, 1415 (1983)

Cylinder –type Cavity (INFN):
H=26 cm
D=2.5 cm

TM010 mode
f= 8.5 GHz

Superconducting solenoid

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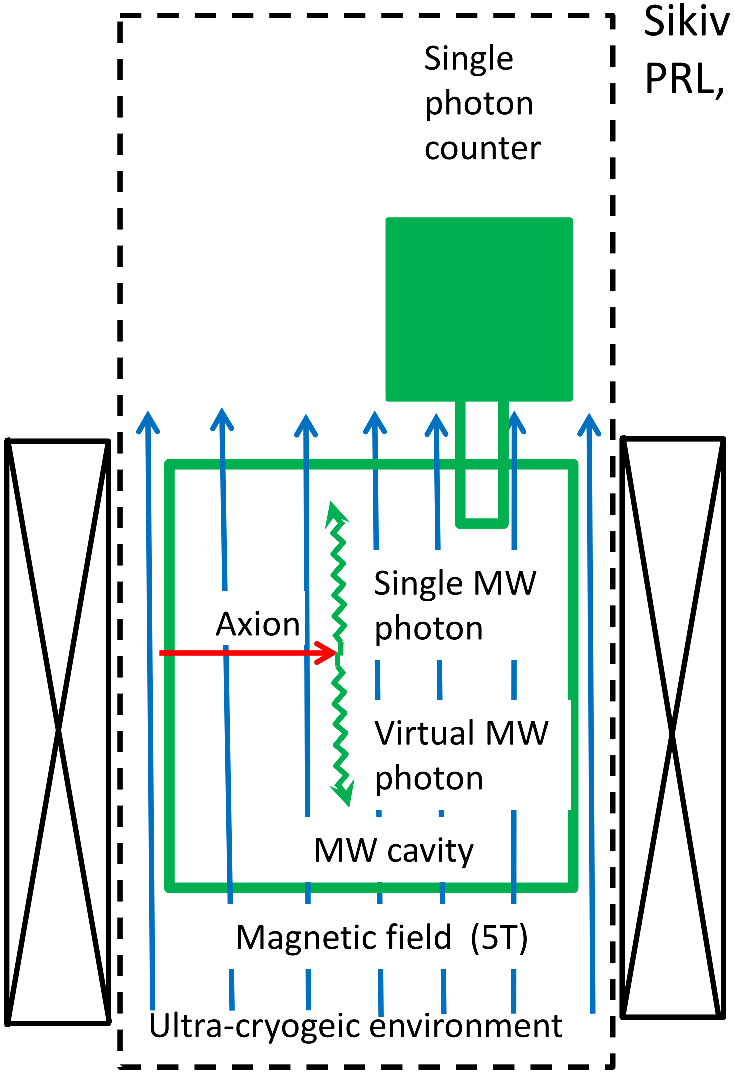

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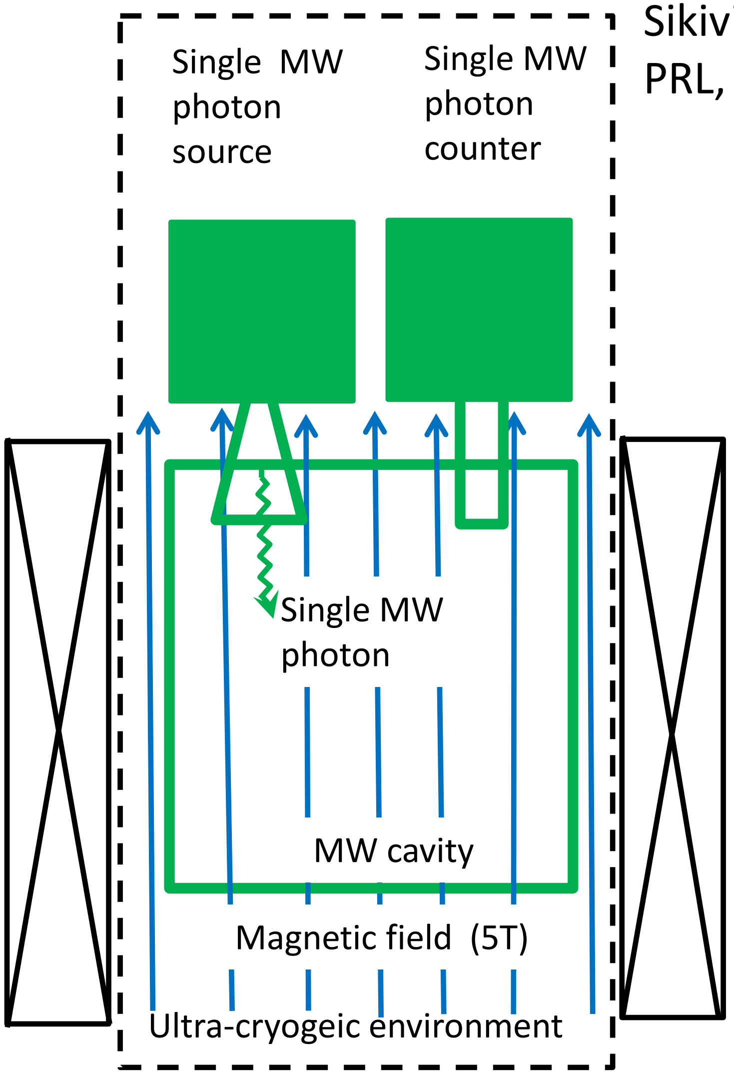

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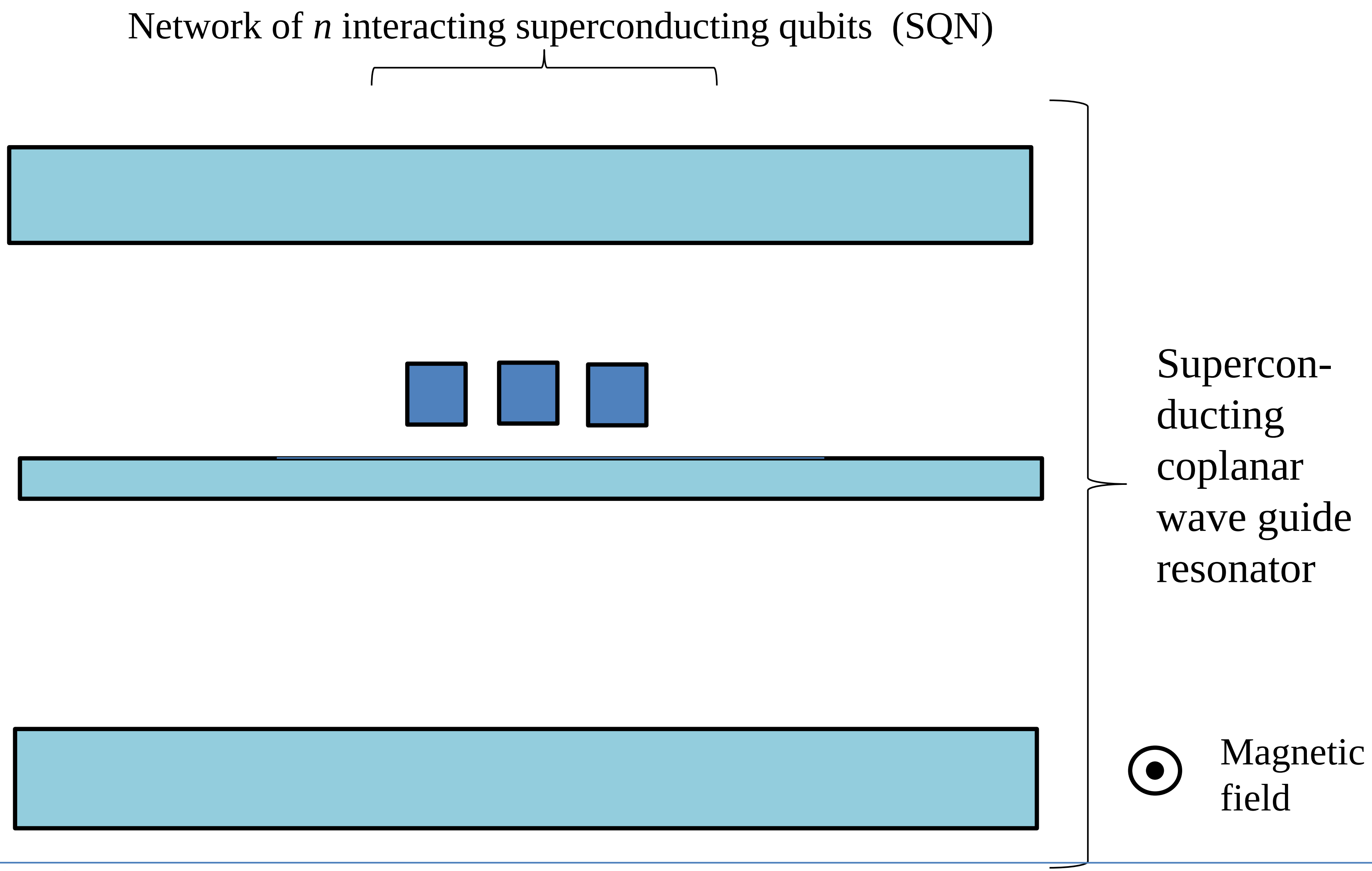
Working principle of the SQN detector of a single MW photon



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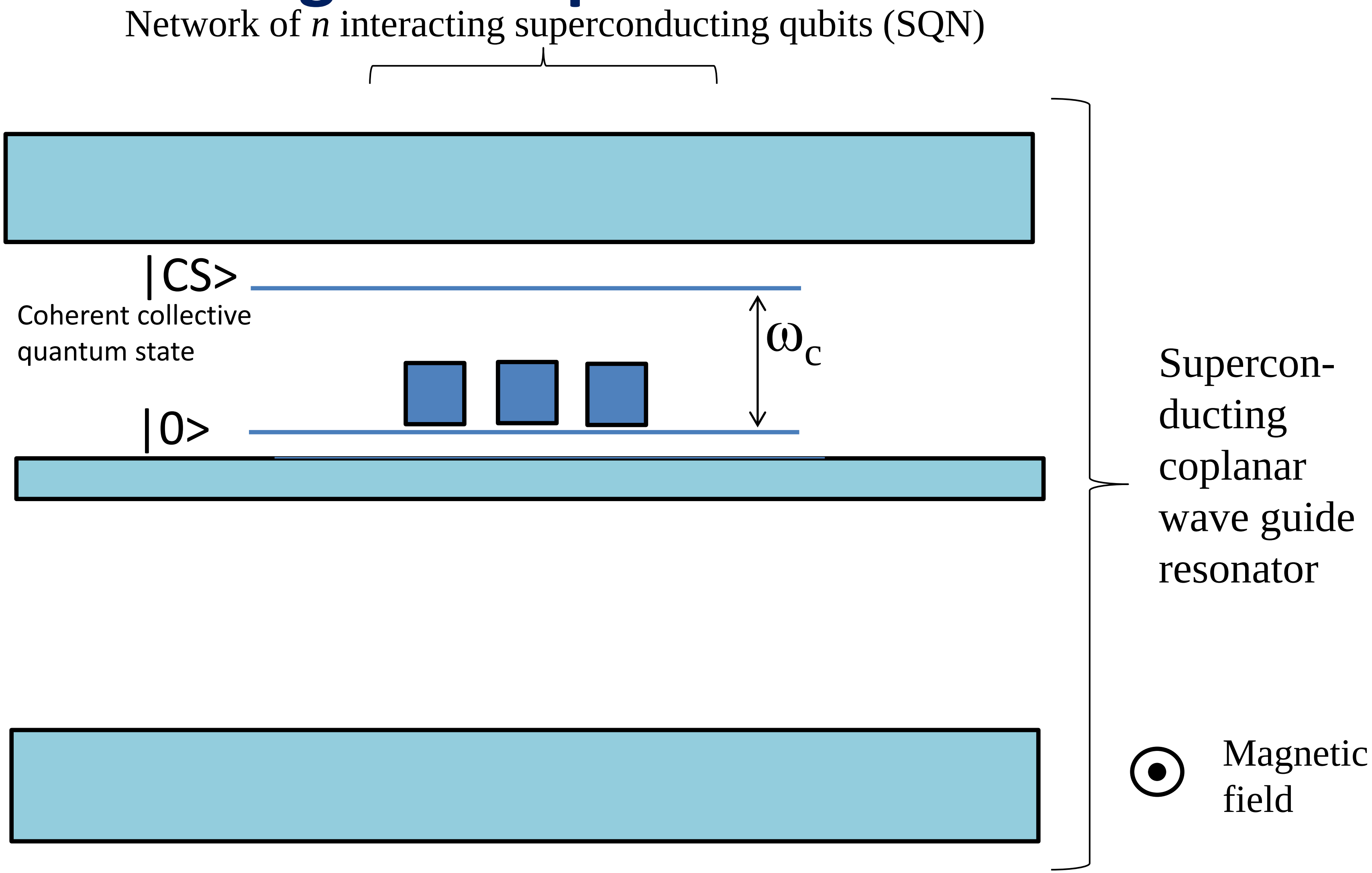

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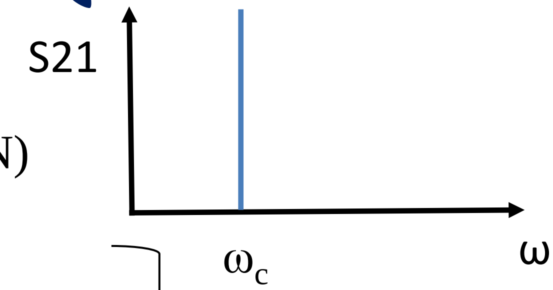
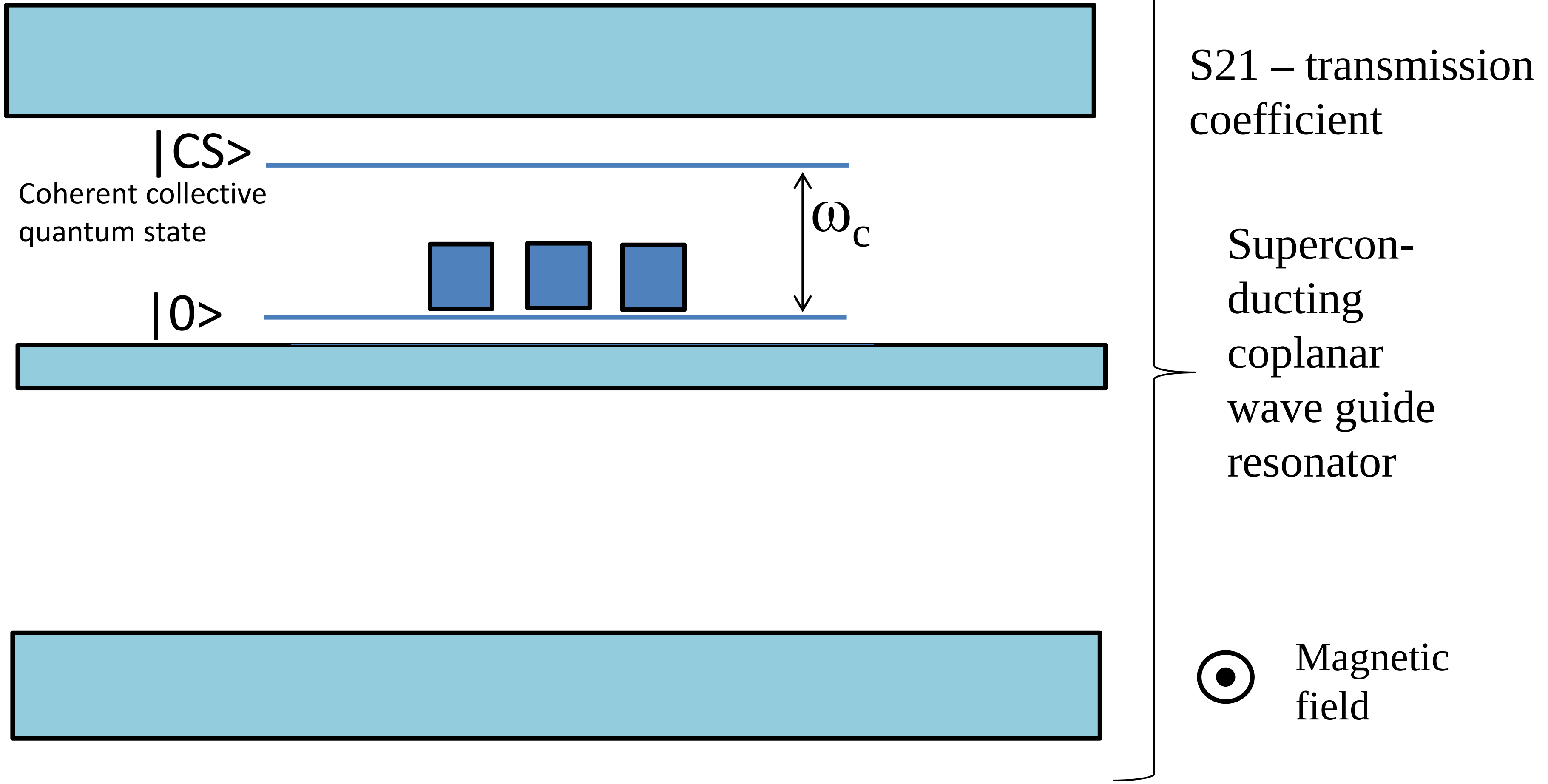


Network of *n* interacting superconducting qubits (SQN)



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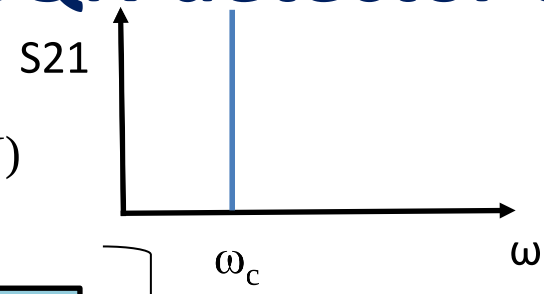

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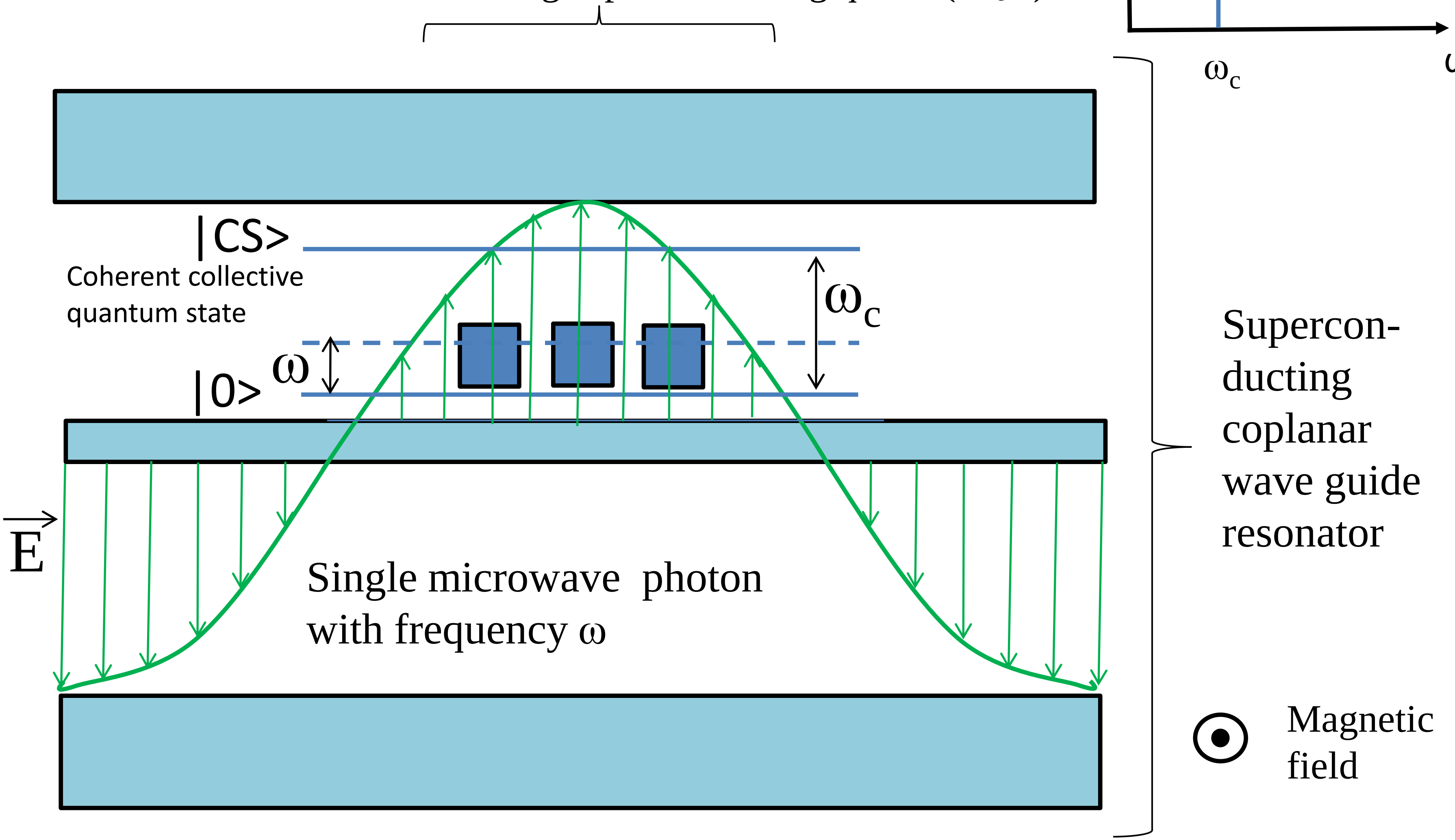

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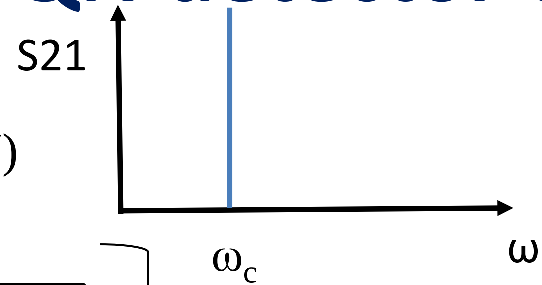

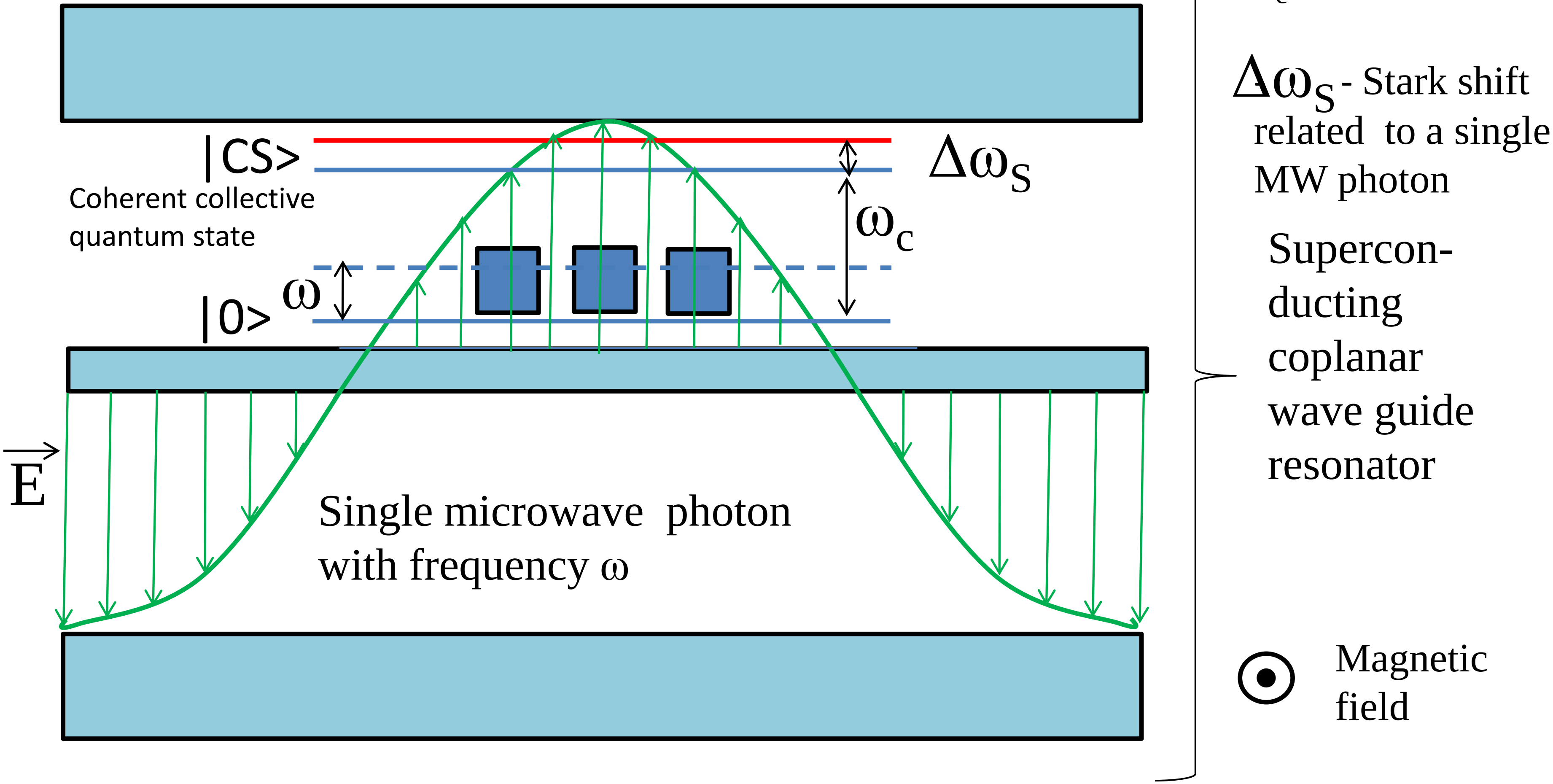

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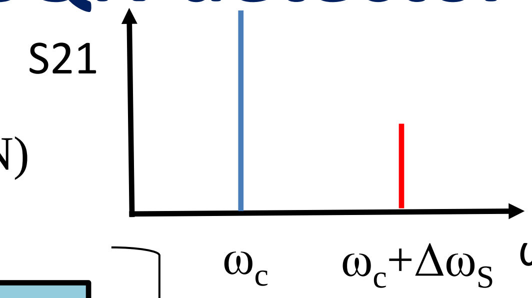

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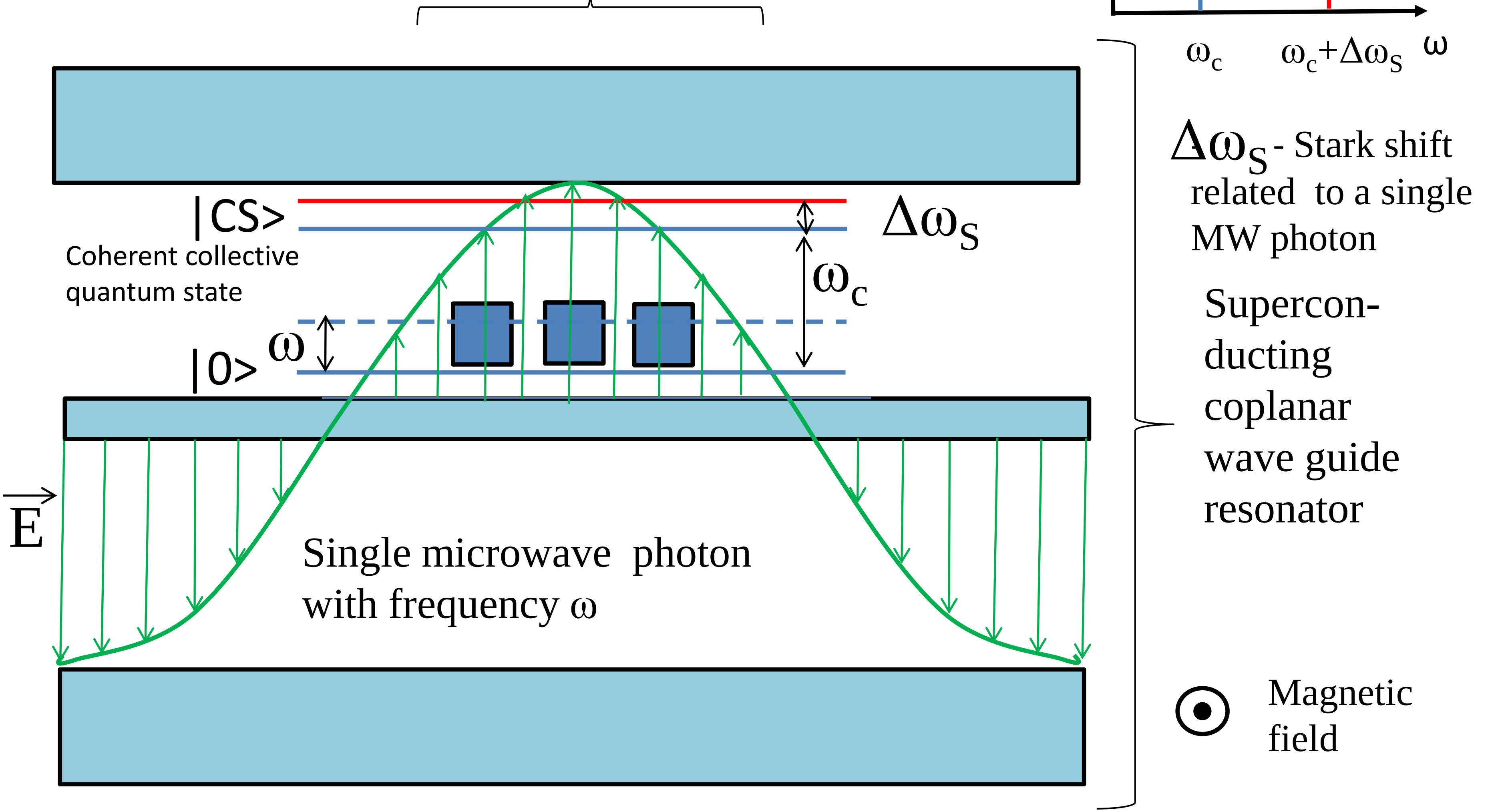


Specific objectives of the research activity

1. Development of a single microwave photon detector based on moderate size networks of interacting superconducting qubits (SQNs)

2. Development of the microwave photon source based on the Traveling Wave Josephson Parametric Amplifier

3. Integration of the microwave photon source with two single photon SQN detectors in a common setup

4. Installation of the single photon SQN detector integrated with the single photon source as a calibration element in a He free refrigerator of the QUAX Collaboration.

5. Experimental study of feasibility of the single microwave photon SQN detector for the “haloscope” type of axion searching

Theoretical Description

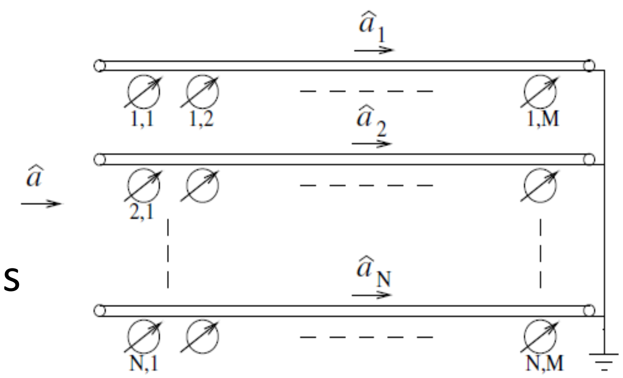
Theoretical investigation of working principle of the SQN detector

Loughborough University, Department of Physics (UK)

Model Hamiltonian describing the interaction of the qubit for general schematic representation of SQN where the signal propagates through *N* parallel waveguides containing *M* qubits each was developed

- $\widehat{H}(t) = \left[\sum_{\mu,\nu} R\left(\frac{t}{\tau_1} - \frac{1}{2}\right)\frac{h_\delta}{2}\,\hat{\sigma}^x_{\nu,\mu} + R\left(\frac{t-\tau_1}{\tau_2} - \frac{1}{2}\right)\frac{h_p}{2}\,\hat{\sigma}^z_{\nu,\mu}\,\hat{a}^+_\nu \hat{a}_\nu\right]$

where *R(t)* describes the pulse shape, *a* is the field modes



The optimal signal to noise ratio for single-photon detection is achieved in the case of a single waveguide with qubits inside.

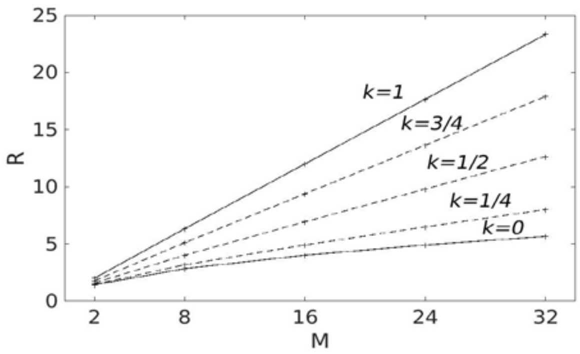
PRB, 103, 064503 (2021)

Theoretical investigation of working principle of the SQN detector

Loughborough University, Department of Physics (UK)

Signal-to-noise ratio as a function of qubit number *M* and parametrizes qubit correlations *k* in a single waveguide was calculated

$$SNR_n \equiv \frac{\langle \hat{S}'^z \rangle}{\sqrt{\langle \delta^2 \hat{S}'^z \rangle}} = R\sqrt{N}\, h_\delta \tau_1 \langle \sin(h_p \tau_2 \hat{a}'^+_{\nu,\mu}\, \hat{a}'_{\nu,\mu}) \rangle_n$$

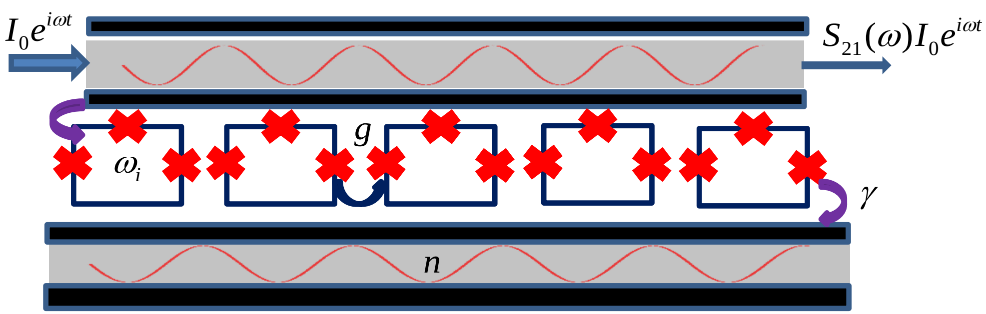


Signal-to noise ratio increases with increasing qubit namber M and degree of qubit correlation *k*

Theory of AC Stark effect in collective mode of a driven SQN

Theoretische Physik III, Ruhr-University Bochum, Germany

- Formulation of a generic quantum-mechanical model of disordered interacting SQNs (superconducting qubits networks) coupled to a low-dissipative resonator and transmission line was carried out.



$$\hat{H}_{SQN} = \sum_i \frac{\varepsilon_i}{2}\hat{\sigma}_i^z + \frac{\Delta_i}{2}\hat{\sigma}_i^x + \hat{H}_{\text{int}}\{\hat{\vec{\sigma}}_1 \ldots \hat{\vec{\sigma}}_N\} + $$
$$+\hbar\omega \hat{a}^+ \hat{a} + \gamma \sum_i \hat{\sigma}_i^z (\hat{a}^+ + \hat{a})$$

- Temporal quantum correlation function

$$C(t) = \langle \Psi_{in} | \left[\sum_i \hat{\sigma}_i^z(t) \right] \left[\sum_i \hat{\sigma}_i^z(0) \right] | \Psi_{in} \rangle$$

- Measurements (transmission coefficient)

$$\Delta S_{21}(\omega) \sim C(\omega) = \lim_{t_0 \to \infty} \frac{1}{t_0} \int_0^{t_0} dt e^{i\omega t} \operatorname{Im} C(t)$$

- An amplitude of the **dominant** resonance drastically increases as the interaction between qubits overcomes the disorder in qubit frequencies , and the collective state is formed.

Theory of AC Stark effect in collective mode of a driven SQN

Theoretische Physik III, Ruhr-University Bochum, Germany

- Preliminary calculation of AC Stark effect from the collective quantum states

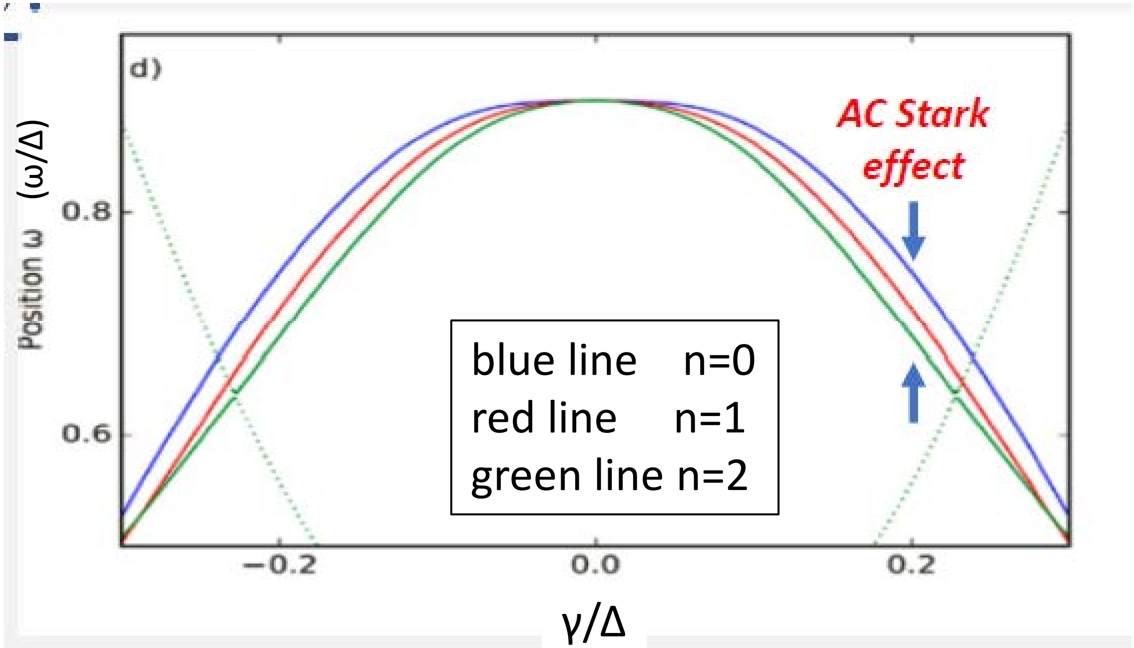
Transmission measurements

$$\Delta S_{21}(\omega) \sim C_{ph}(\omega)$$

$$C_{ph}(t) = \sum_n P_n C(t;n) = \sum_n P_n \sum_i < \Psi_0 \otimes n | \hat{\sigma}_i^z(t) \hat{\sigma}_i^z(0) | \Psi_0 \otimes n >$$

4 qubits+4 photon states
n is photon number

γ is the coupling strength between a single qubit and a resonator



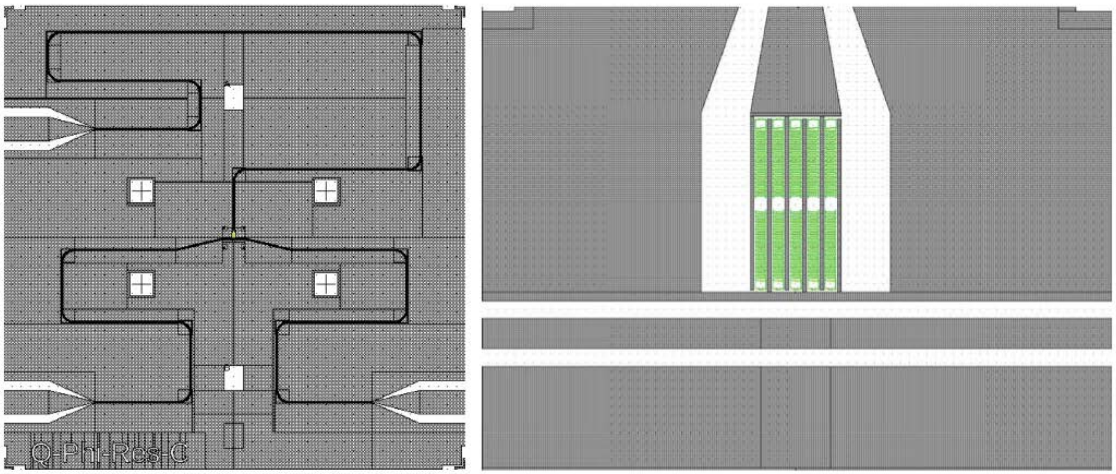
PRB, 105 , 104516 (2022)

EXPERIMENTS

Design of three-terminal SQN device

The Leibniz Institute of Photonic Technology (Leibniz IPHT), Jena Germany

The SQN design is so-called T-type three terminal device with two resonators at same frequency coupled by an array of 10 capacitor shunted flux qubits.



Mode	frequency (GHz)	Loaded quality factor
$\lambda/2$	2.6188	56722
λ	5.2376	33851
$3/2\lambda$	7.8564	23407
2λ	10.4752	17788

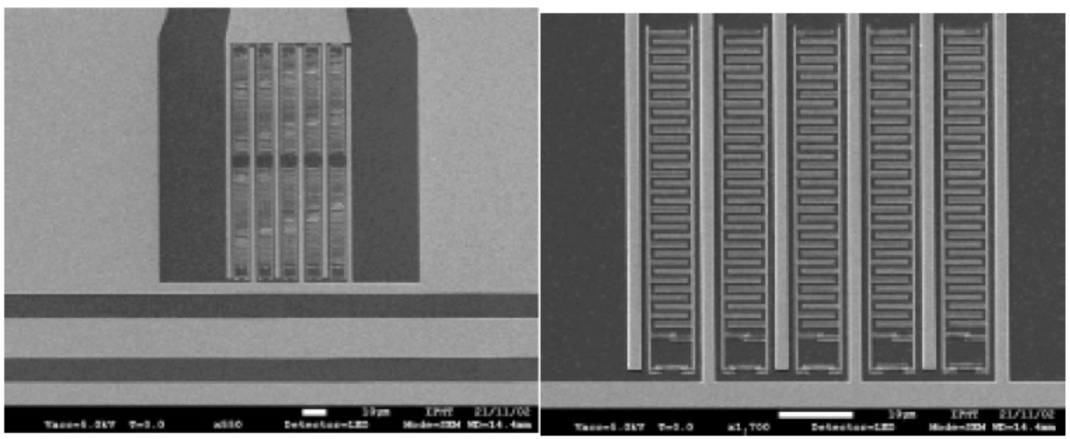
Left: Chip layout of the T-type three terminal device. Right: Magnified part of the layout with the 10 C-shunted flux qubits.

Estimated frequency modes and loaded quality factor of the resonators

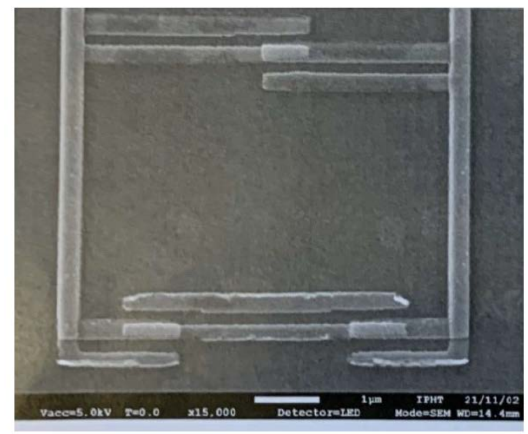
Fabrication of three-terminal SQN device

The Leibniz Institute of Photonic Technology (Leibniz IPHT), Jena Germany

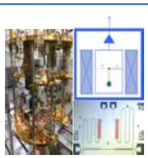
The 22 mm long resonators are fabricated by depositing a 200 nm thick Nb film on a silicon substrate that is structured by the RIE. The flux qubits are made of Al Josephson-junctions fabricated by two angle shadow evaporation technique. Every flux qubit of the SQN consists of a 6x4.5 μm^2 loop with three Josephson junctions. Two junctions are designed to have identical size of 0.2x0.87 μm^2 while the third is scaled by a factor $\alpha < 1$. For qubits of the SQN measured here, the factor $\alpha = 0.8$.



SEM picture of three-terminal device with 10 C-shunted flux qubits



SEM- image of a fabricated flux qubit



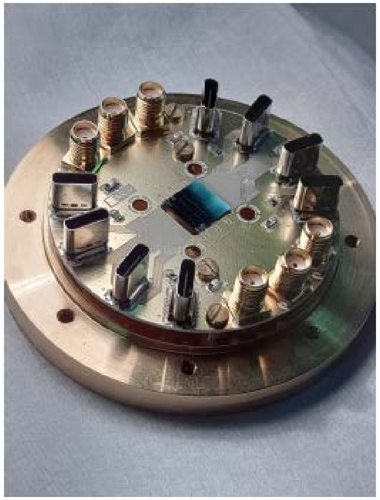
Experiment on four-terminal SQN device

Laboratori Nazionali di Frascati of the National Institute for Nuclear Physics (INFN) , Italy

“Haloscope” type of axion searching:

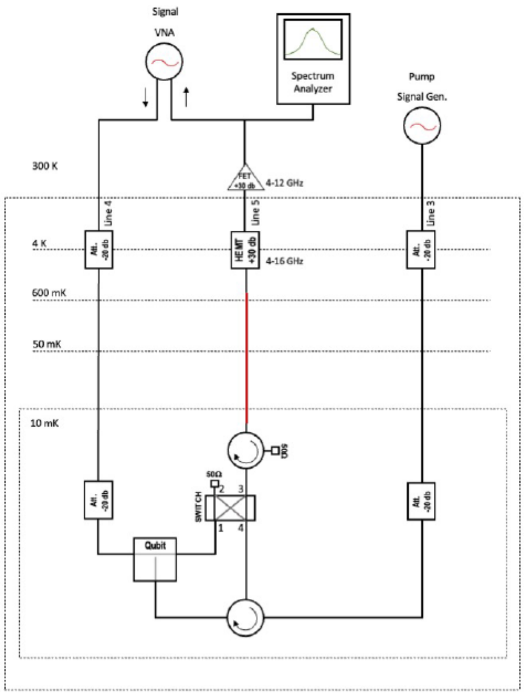
A new dilution refrigerator able to reach T= 8 mK instrumented with properly filtered lines for RF and DC signals and with low noise amplifiers to overcome room temperature noise was installed. The setup was fully characterized by performing measurements with quantum devices, namely, Josephson Travelling Wave Parametric Amplifier (JTWPA) from INRIM and Josephson Parametric amplifier based on a single Josephson junction.

Experimental set-up

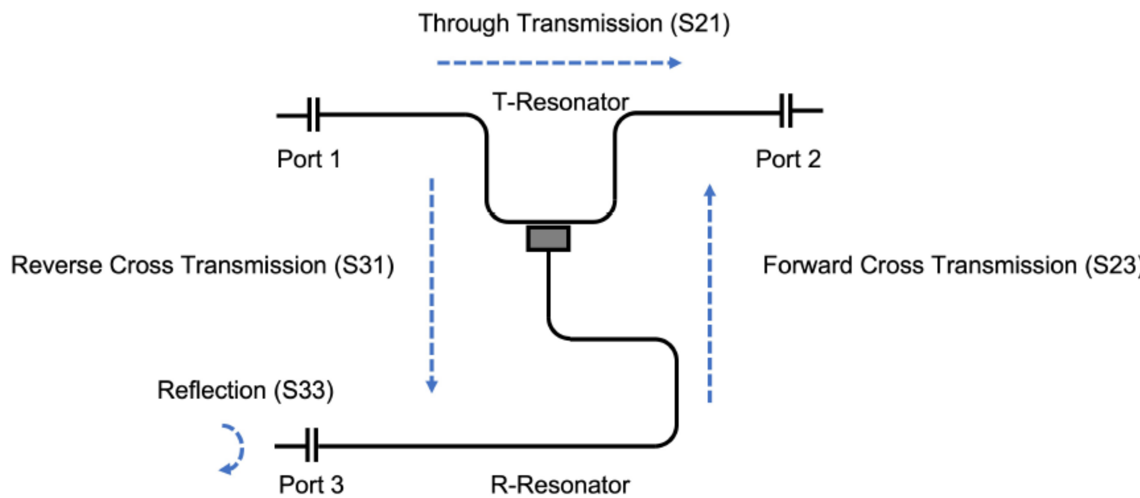


Left: Chip bonded on the sample holder. Right: Sample holder mounted in the dilution frige at Laboratori Nazionali di Frascati (LNF)

Experimental set-up

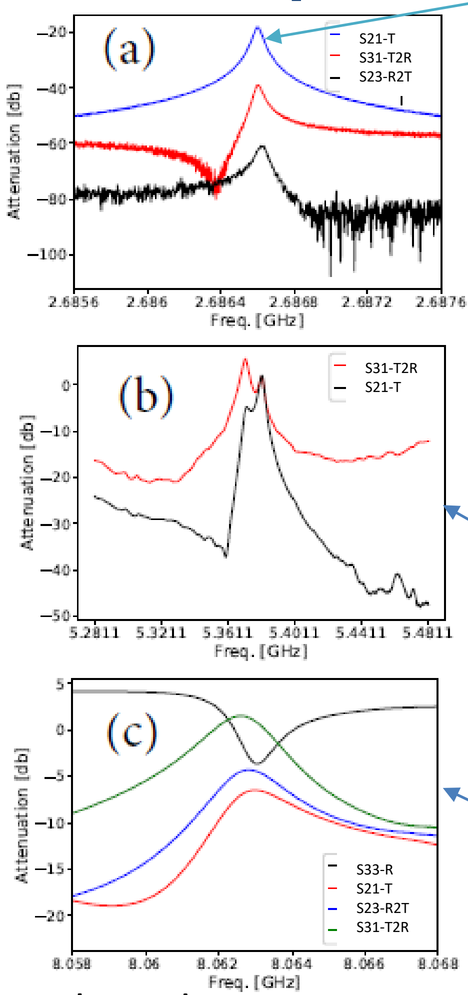


Experimental set-up for microwave measurements

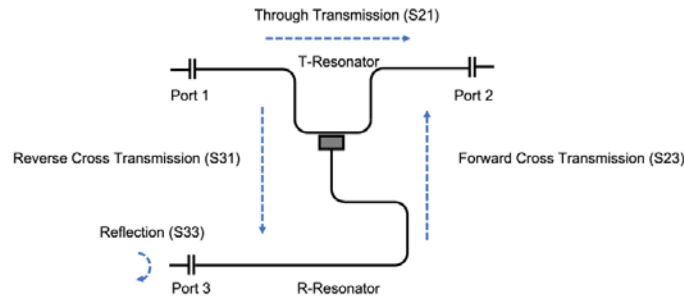


Cabling of T-type three terminal device

Measurement of scattering parameters of the three port device



Clear Lorentzian peak at frequency 2.687 GHz with quality factor of 55,000
Large isolation between two resonators



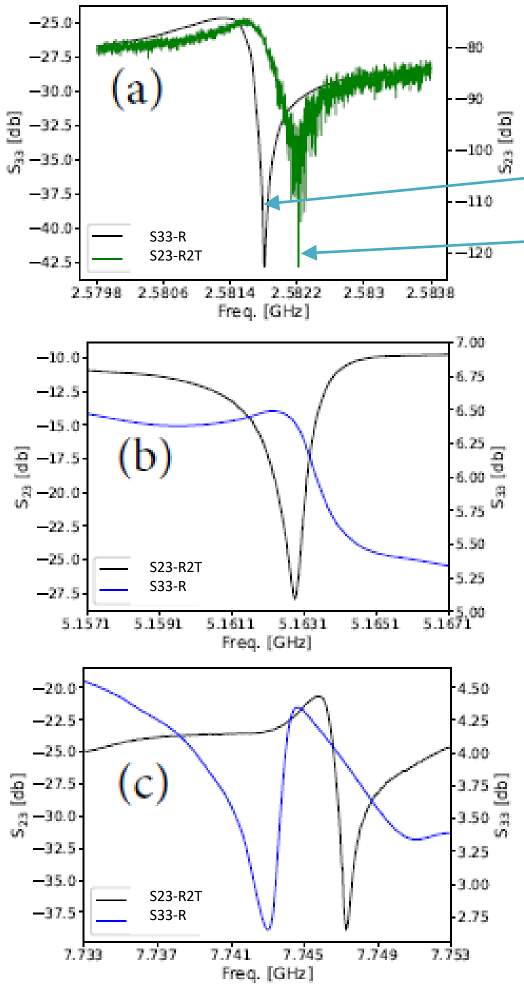
Wavelength λ corresponds to a resonator length-zero of currnet on the center.
Large capacitive coupling of T resonator to the qubits

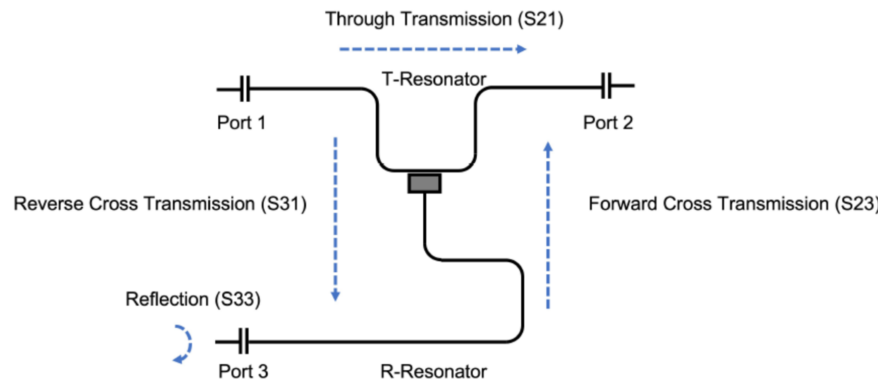
Large inductive coupling of T resonator to the qubits

Through and Cross Transmission coefficients for the first three T-resonator modes at multiples of 2.687 GHz, namely:(a) - first mode at 2.687 GHz; (b) - second mode at 5.38 GHz; (c) - 3/2λ mode at 8.06 GHz

Measurement of scattering parameters of the three port device

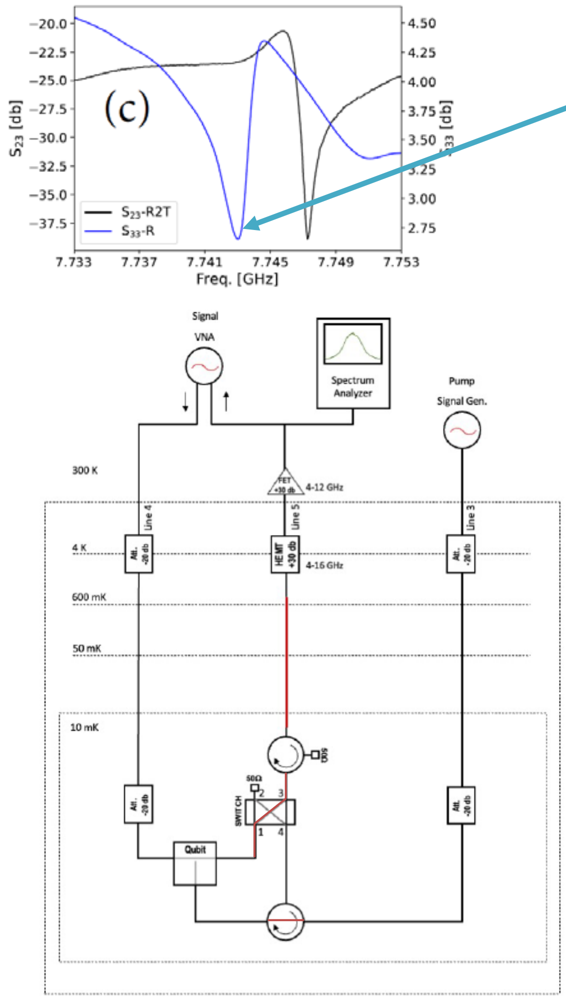
For each absorption peak (resonant drop) in the reflection spectrum (S33) we observe a deep absorption peak in the forward cross-transmission (S23). We interpreted this absorption effect as due to the presence of the qubits.





Reflection (S33) and forward cross-transmission coefficients for the first three R-resonator modes at multiples of 2.581 GHz namely: (a)-2.581 GHz; (b)- 5.162 GHz; (c) - 7.743 GHz.

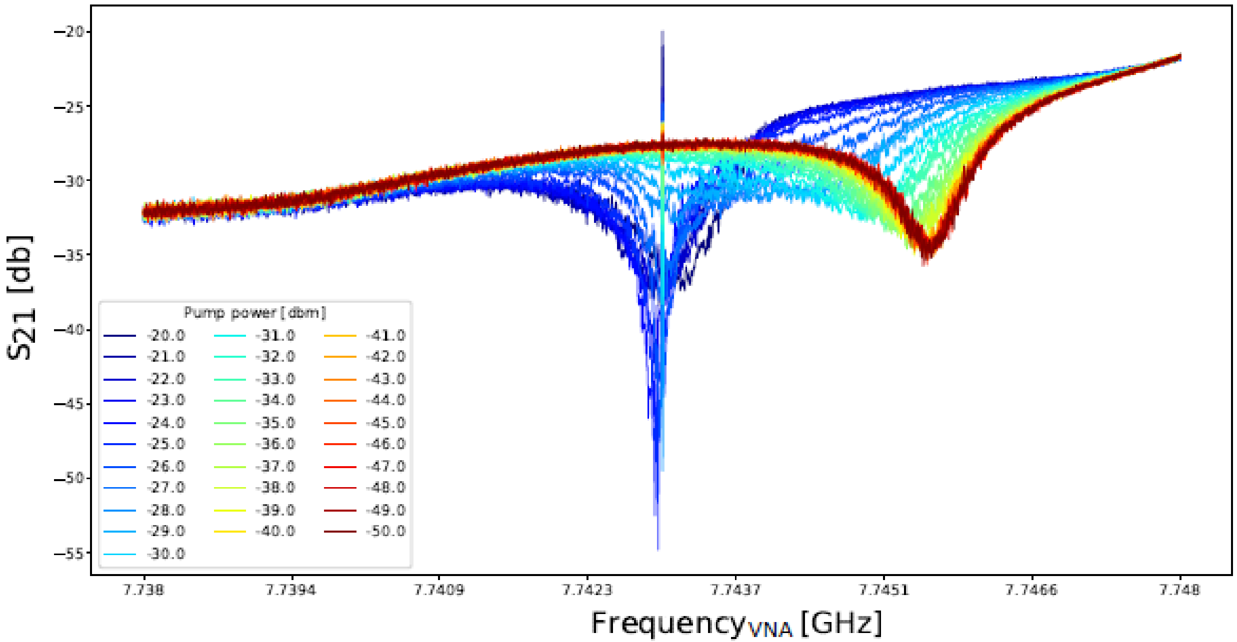
Measurement of two-tone spectra of the three-port SQN -device



We first considered the third-harmonic absorption-peak (resonant drop) of the R-resonator at 7.74 GHz.

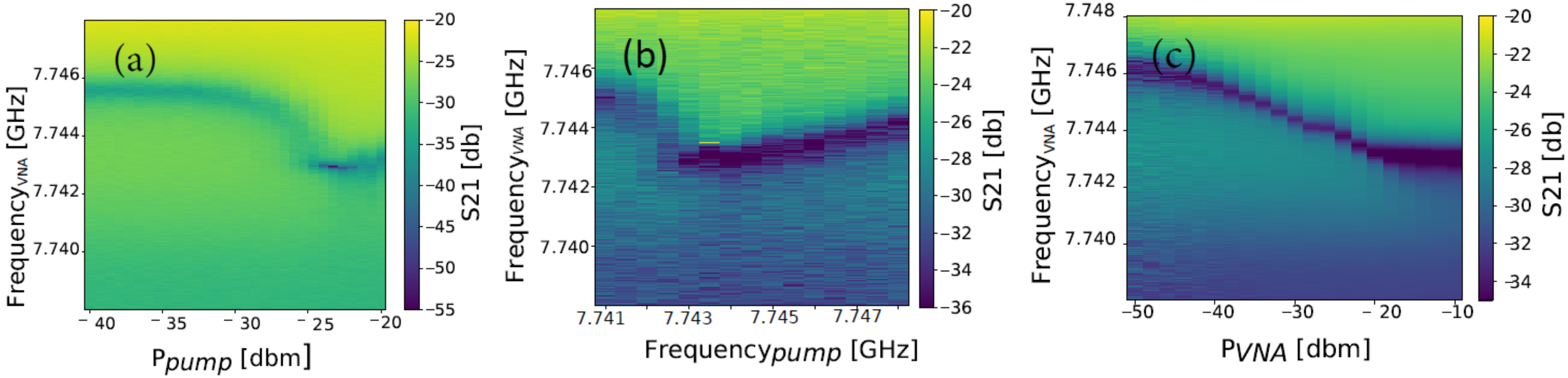
We set the VNA output-power to -40 dbm, corresponding to about -100 dbm at the device, and measured the through transmission (S21). At the same time, we sent a single tone of frequency 7.743 GHz to the R-resonator with the Rohde&Schwarz SMA100B connected to the Port 3, and varied the output power of the generator from -40 to -20 dbm. By increasing the power sent to Port 3 we clearly see a variation of the resonant-drop frequency in the through transmission-spectrum (S21).

Measurement of two-tone spectra of the three-port SQN -device



Two-tone spectra measurements at frequency 7.4 GHz. First-tone through-transmission (S21) vs VNA-frequency dependencies recorded at different powers of the second-tone signal of frequency of 7.4 GHz applied to the Port 3.

Measurement of two-tone spectra of the three-port SQN -device



(a) Dependence of the S21 as a function of the VNA frequency and second-tone power at stable frequency of 7.743 GHz; (b) Dependence of the S21 as a function of the VNA frequency and second-tone frequency slightly varied just near the main resonant frequency of 7.743 GHz. Power of second tone signal is of -25 dbm; (c) S21 versus VNA frequency and VNA power without second tonne signal.

Conclusions

1. Main theoretical description of a single microwave photon detector based on moderated size network of interacting superconducting qubits was developed;

2. Design of the layout of –type three terminals SQN detectors containing 10 flux qubits was developed and the samples were fabricated by Al-based technology;

3. The experimental setup for microwave spectroscopy of SQNs devices has been realized in the Laboratori Nazionali di Frascati (INFN);

4. Two-tone spectral measurements of the T-type three terminals SQN with 10 qubits were carried out at zero external magnetic field;

5. Non-linear effects such as shift of the absorption peak both by power and by frequency of the pump second tone signal were observed and clearly manifest non-linear inductance of Josephson junctions of flux qubits.

Thank you for your attention!