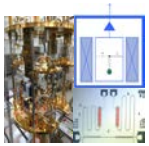
SUPEGALAX project: single microwave photon detector based on superconducting qubit network for searching galactic axions

Coordinator- Dr. Mikhail Lisitskiy (SPIN-CNR, Italy)

Project title: 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

M. Affronte[6], A. Balanov[1], G. Brida[7], C. Bonizzoni[6], N. Chikhi[5], M. Ejrnaes[5], E. Enrico[7], I. Eremin[2], L. Fasolo[7], M. Fistul[2], C. Gatti[8] , A. Ghirri[6], A. Greco[7], E. Il'ichev[3], A. Meda[7], P. Navez[1], G. Oelsner[3], M. Rajteri[7], S. Savel'ev[1], A. Ustinov[4], A. Zagoskin[1]

UNITED KINGDOM

[1] *Loughborough University, LE11 3TU, Loughborough,*

Germany

[2] *Ruhr-University Bochum, 44801, Bochum, Germany*

[3] *Leibniz Institute of Photonic Technology, 07745, Jena,*

[4] *Karlsruhe Institute of Technology, 76131, Karlsruhe,*

ITALY

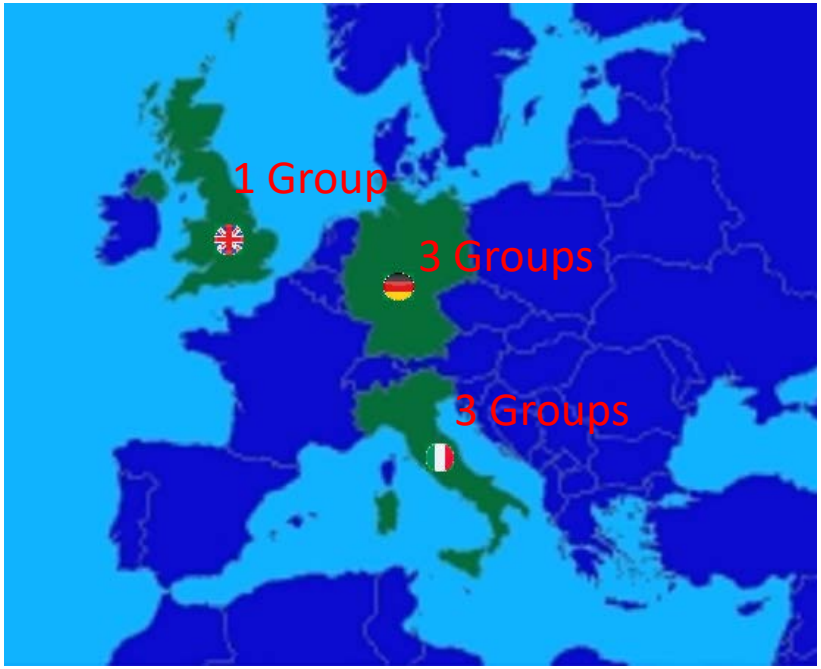
CNR group:

[5] *CNR-SPIN Institute of Superconductors, Innovative Materials and Devices, UOS-Pozzuoli, I-80078 Pozzuoli,*

[6] *CNR-NANO Institute of Nanoscience, UOS-Modena, I-41125, Modena,*

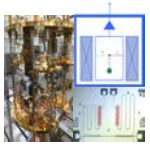
[7] *INRIM Italy's National Metrology Institute, I-10135, Torino,*

[8] *INFN National Institute for Nuclear Physics, I-00044, Frascati,*



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) .



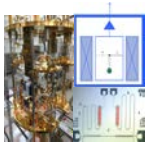
Axions: physical properties

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 ~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 μeV/c^2 to hundreds of μeV/c^2



SUPERGALAX Project

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

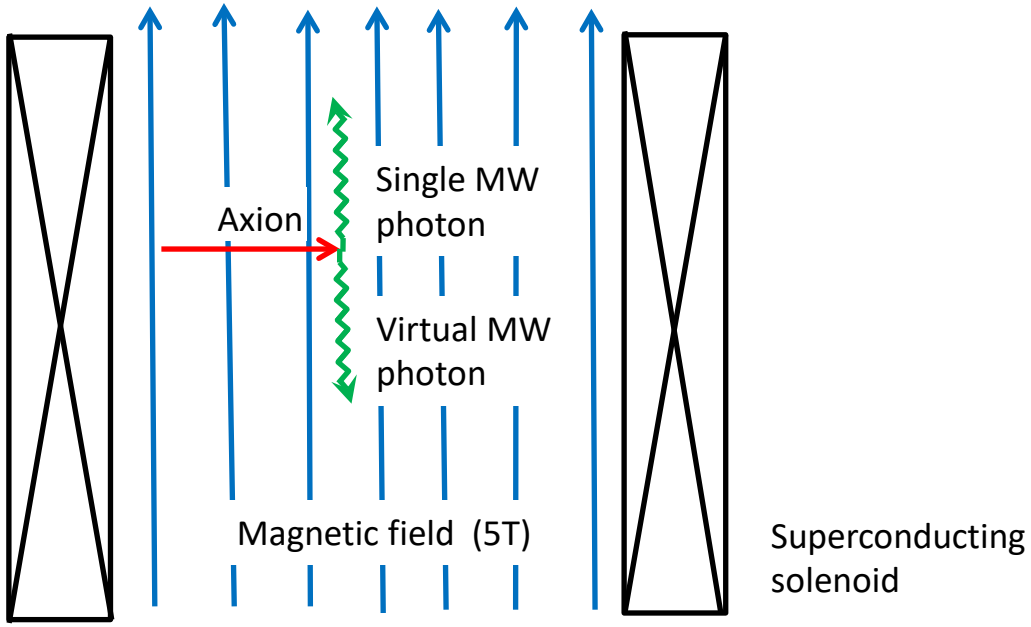
$a = a_0 \cos(\omega t)$,

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;



SUPERGALAX Project

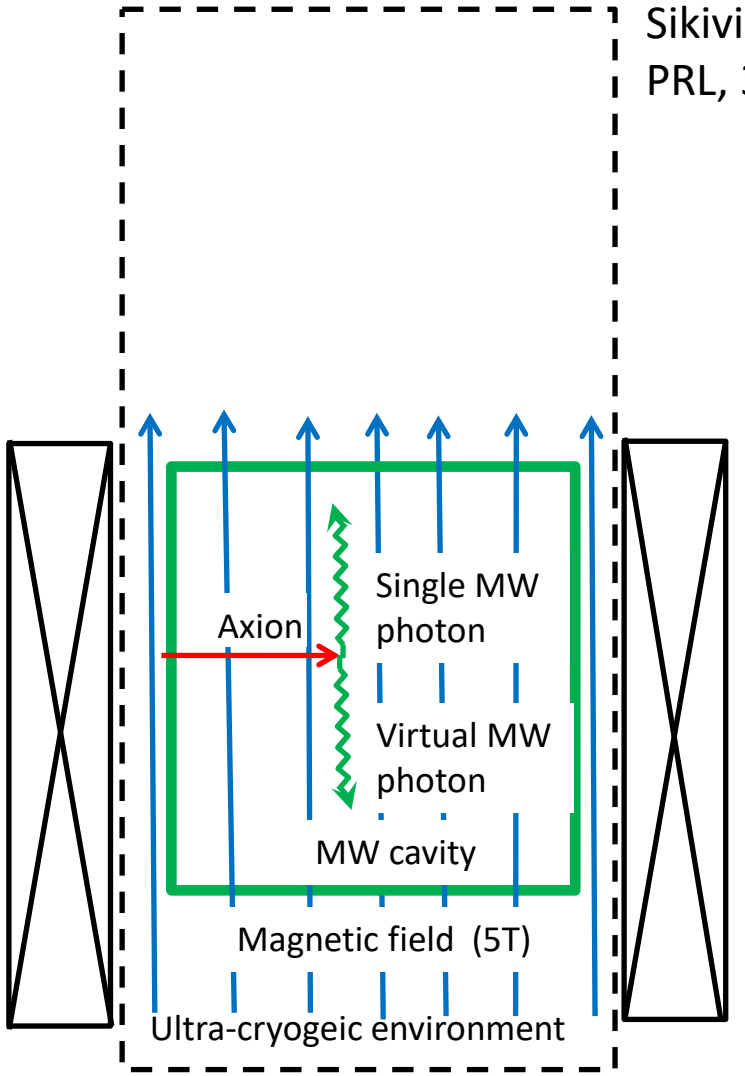
Standard axion conversion can takes place in a strong magnetic field into a photon (Primakoff conversion) and subsequently coherently oscillating classical field is formed

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

with the angular frequency of oscillation given by

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

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

SUPERGALAX Project

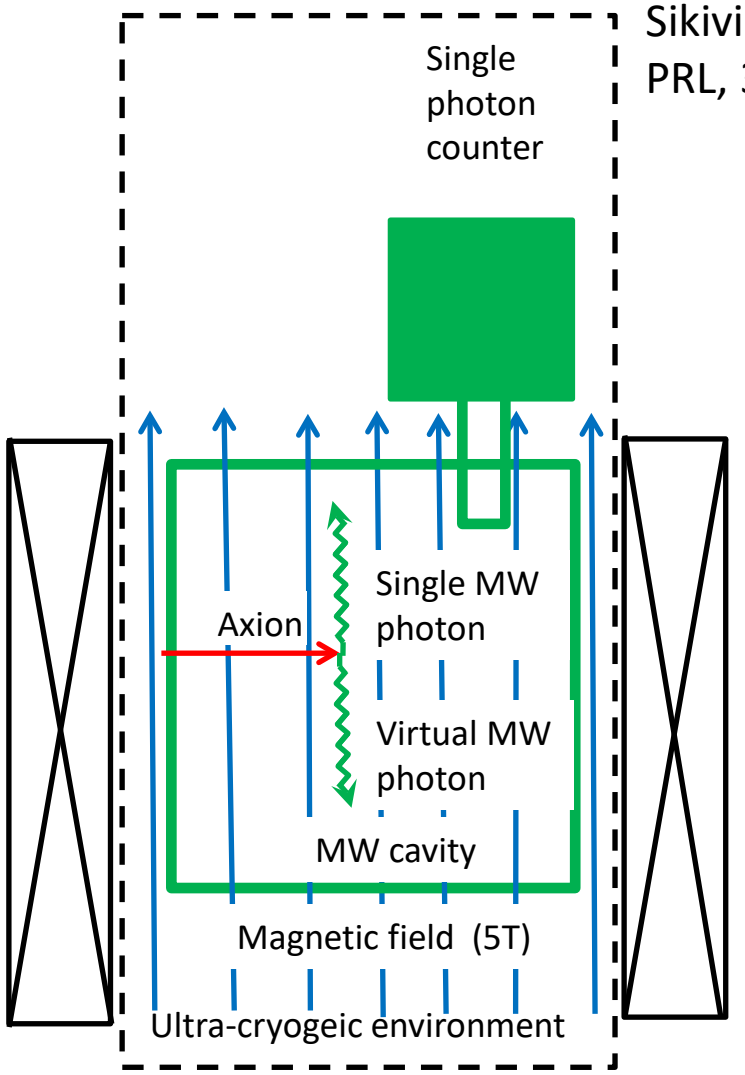
Standard axion conversion can takes place in a strong magnetic field into a photon (Primakoff conversion) and subsequently coherently oscillating classical field is formed

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

with the angular frequency of oscillation given by

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

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

SUPERGALAX Project

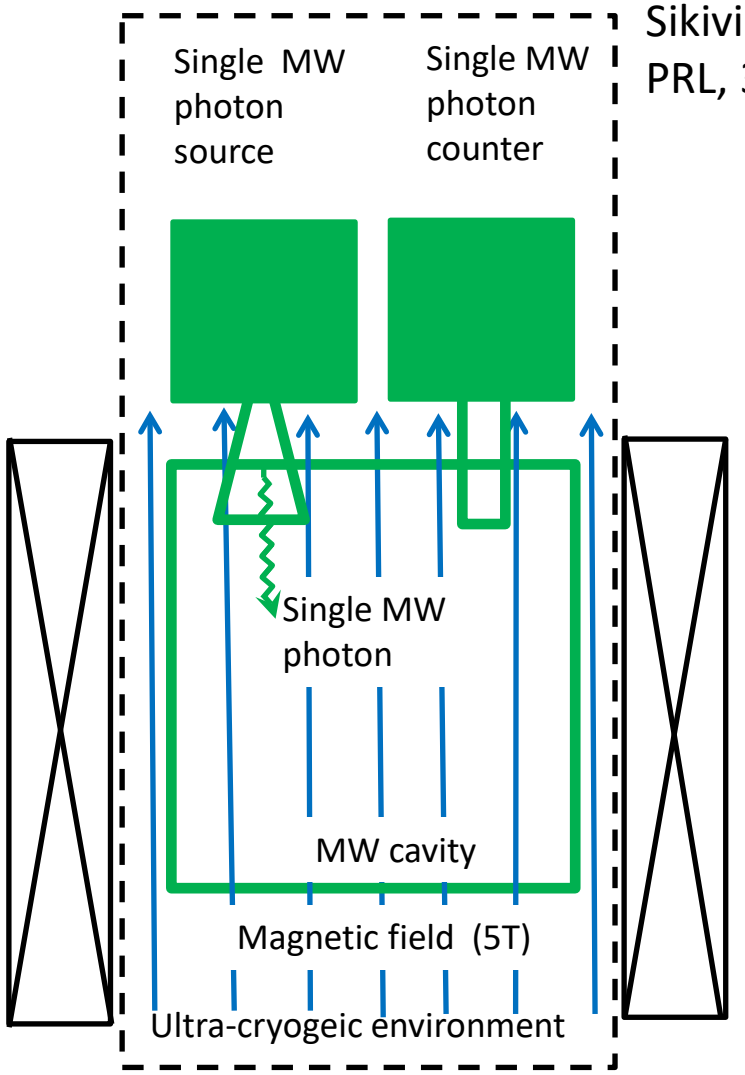
Standard axion conversion can takes place in a strong magnetic field into a photon (Primakoff conversion) and subsequently coherently oscillating classical field is formed

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

with the angular frequency of oscillation given by

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

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

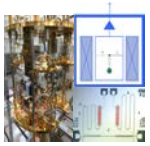


Sikivie «haloscope» PRL, 31, 1415 (1983)

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

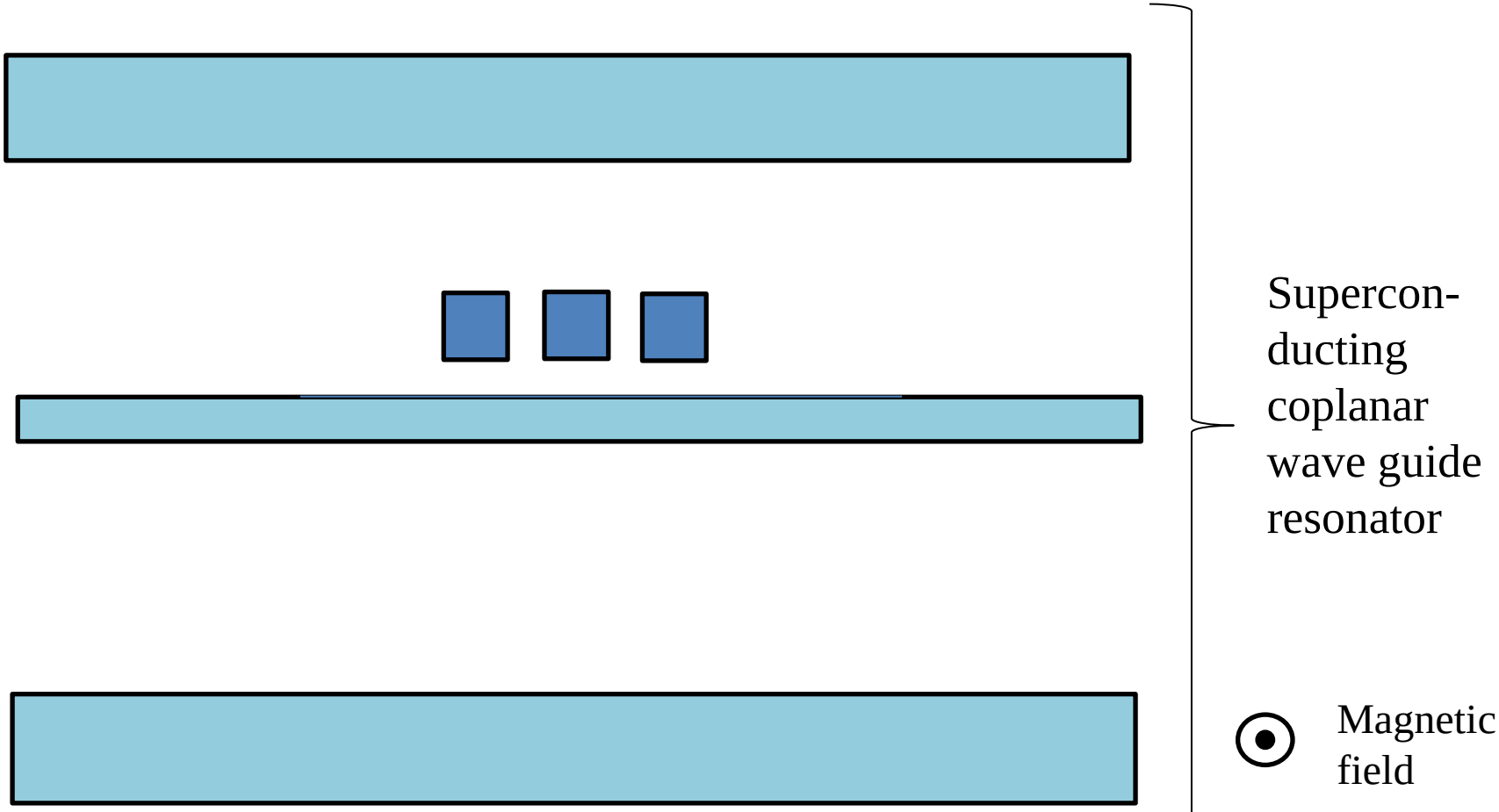
TM010 mode
f= 8.5 GHz

Superconducting solenoid

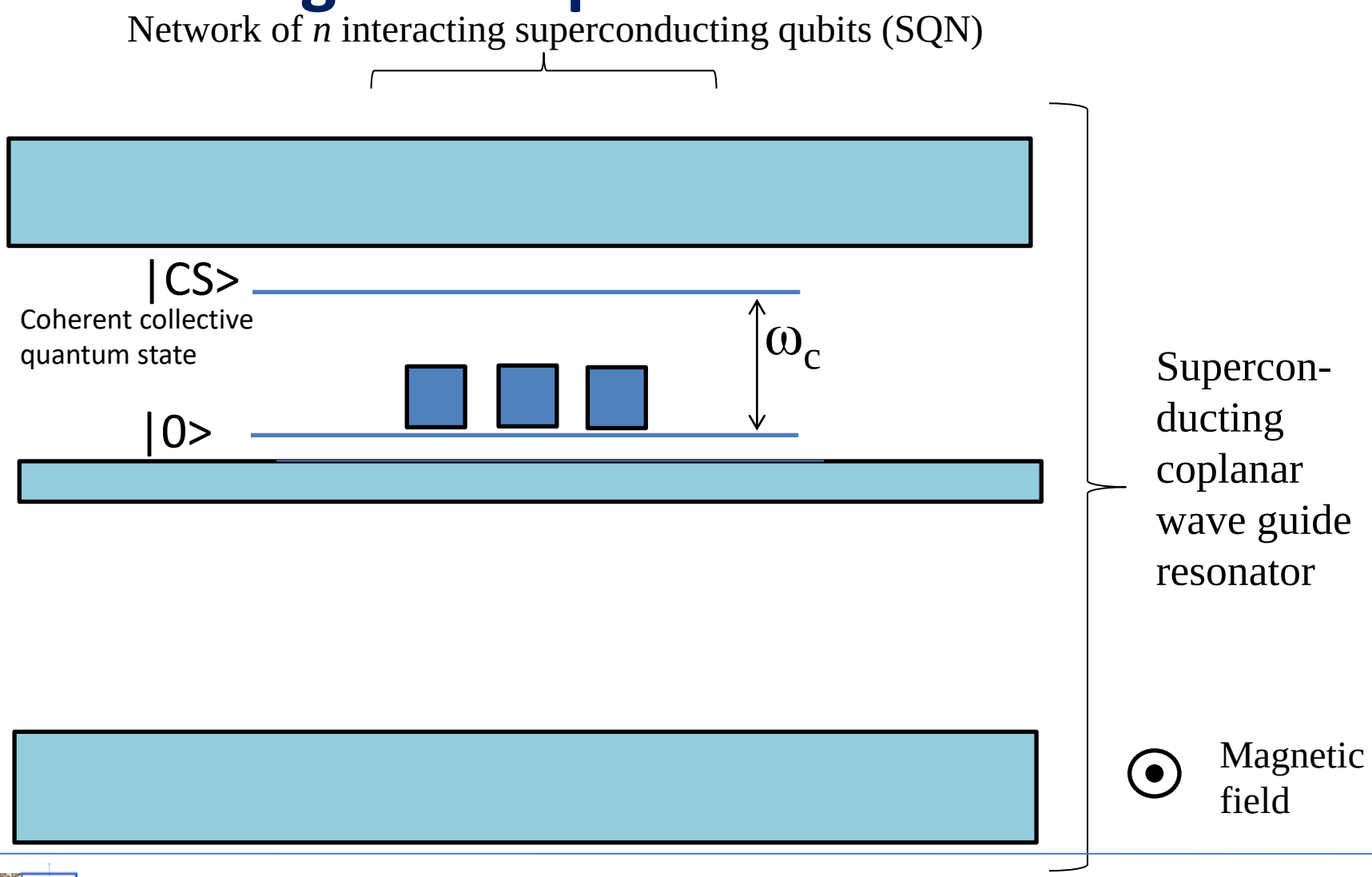


Working principle of the SQN detector of a single MW photon

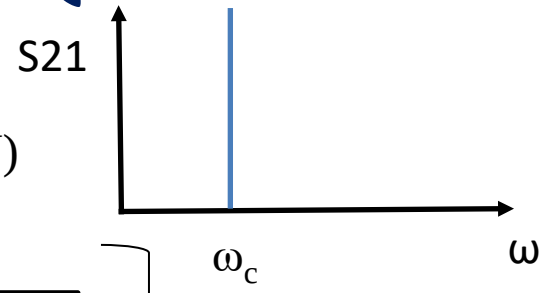
Network of *n* interacting superconducting qubits (SQN)



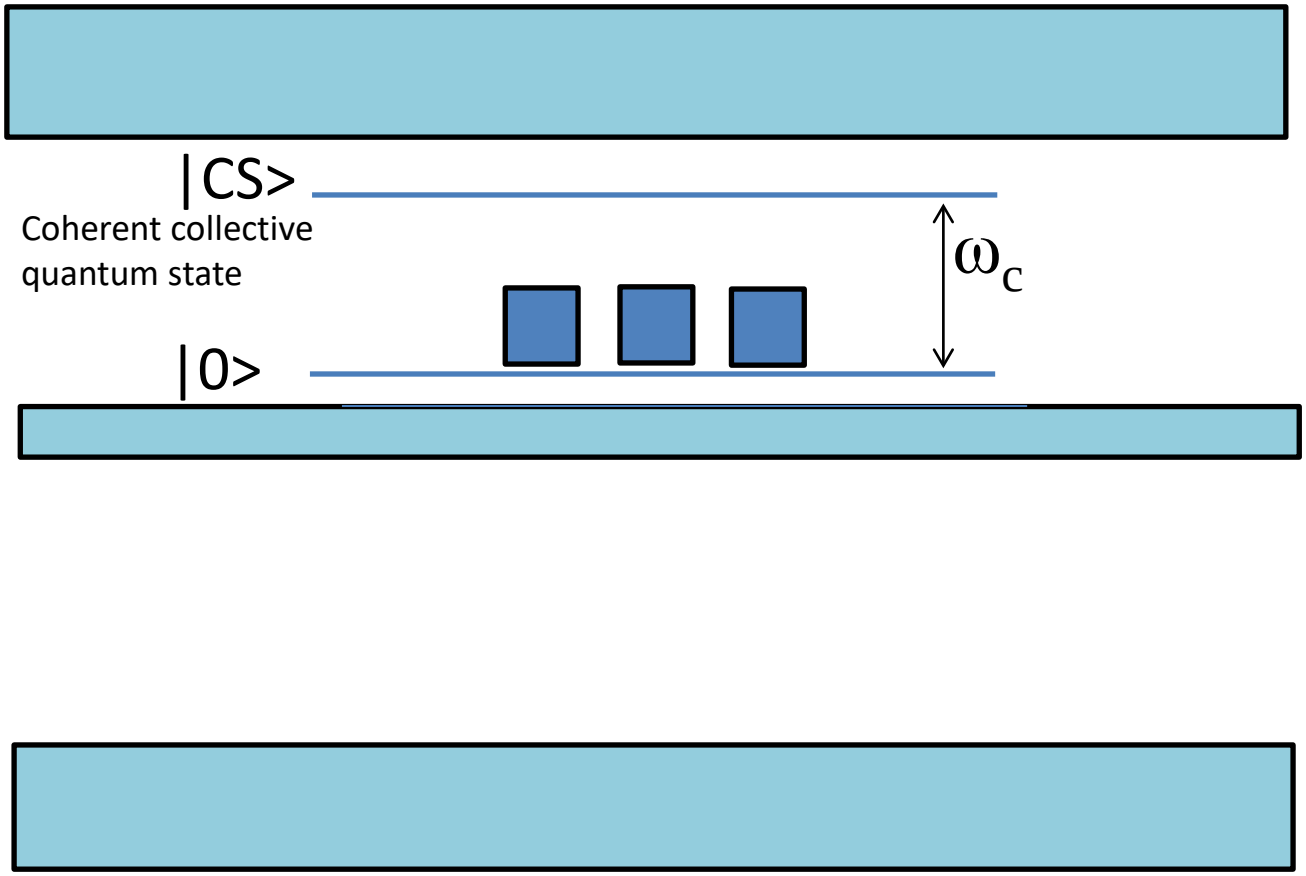
Working principle of the SQN detector of a single MW photon



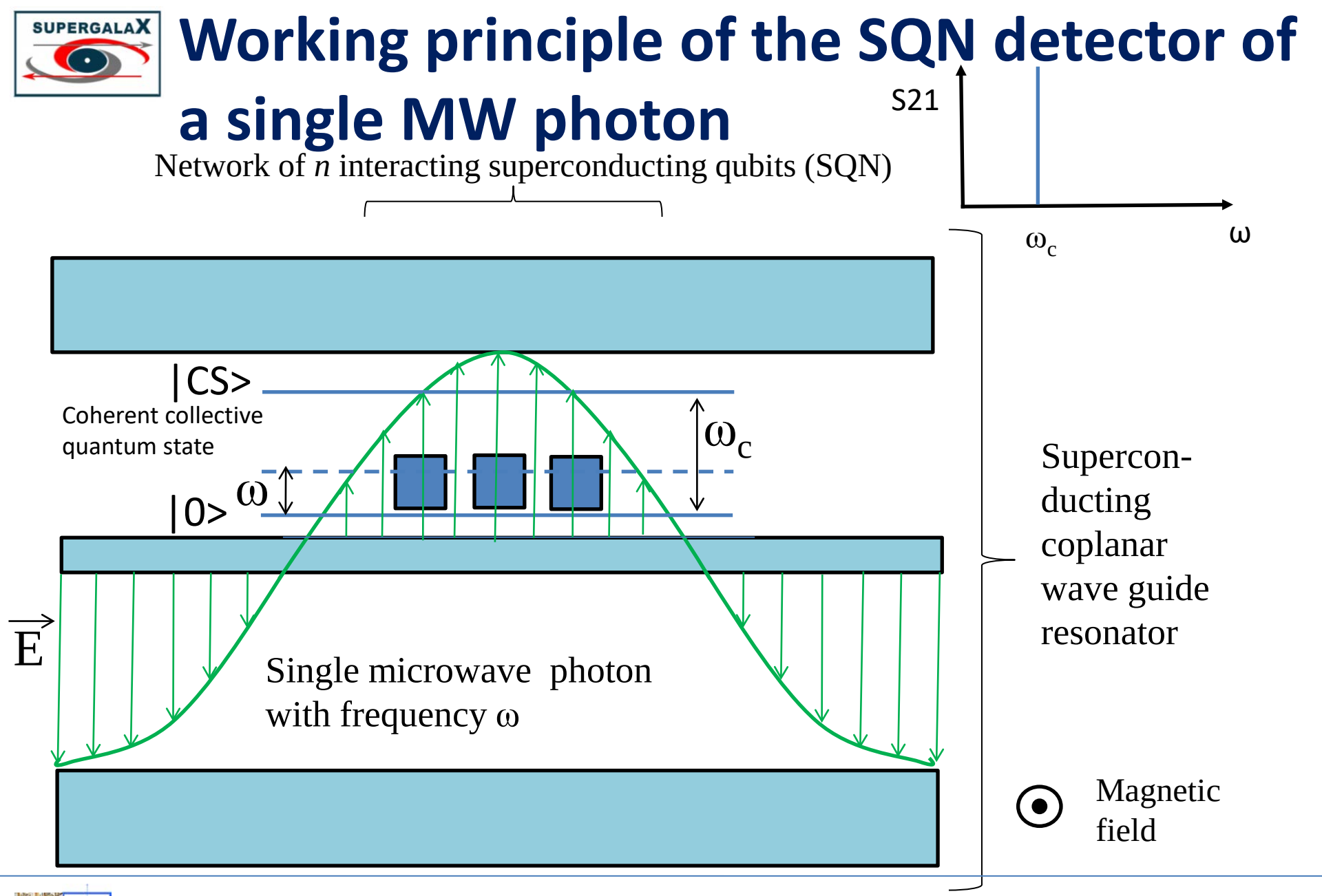
Working principle of the SQN detector of a single MW photon



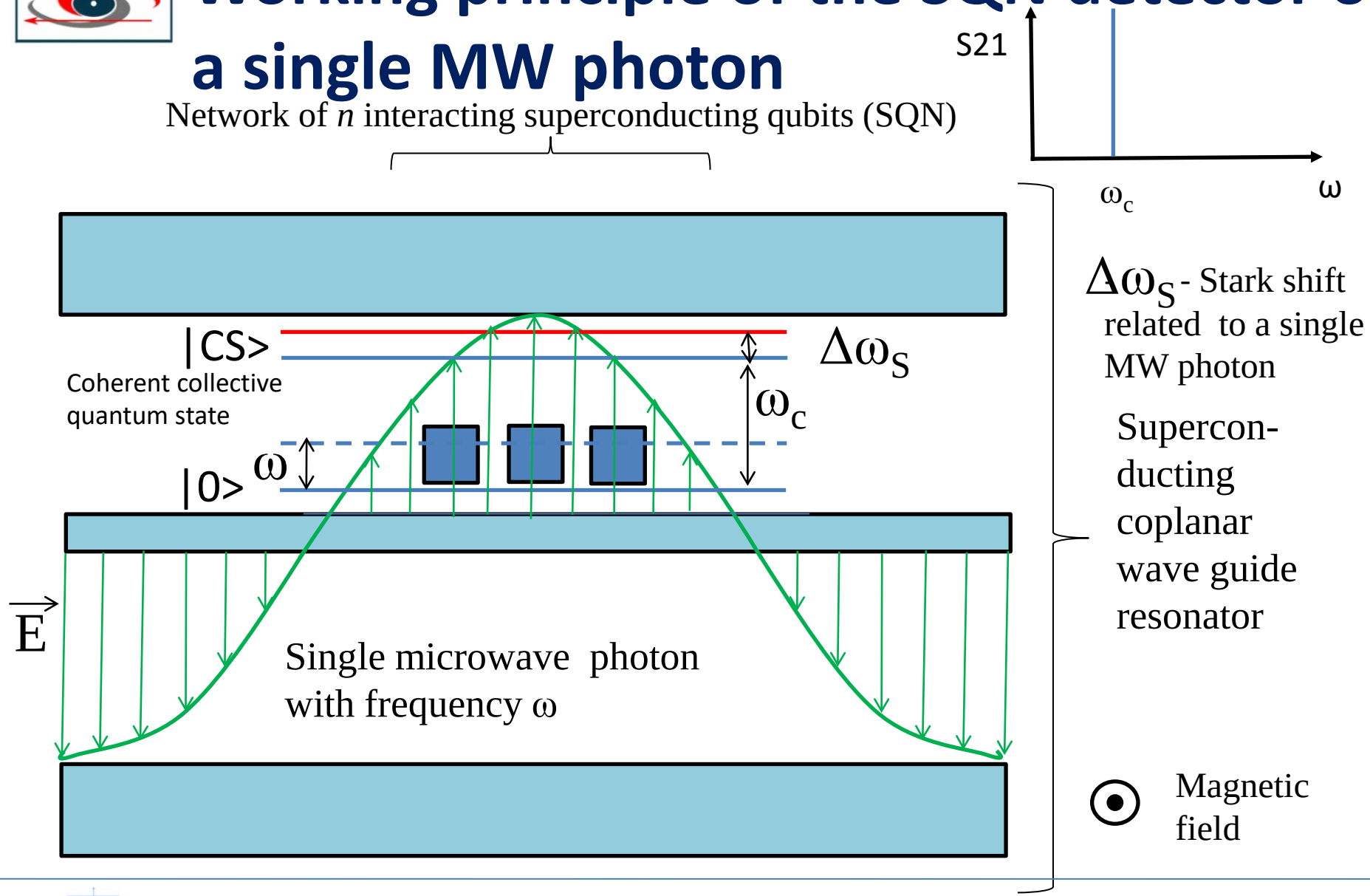
Network of *n* interacting superconducting qubits (SQN)



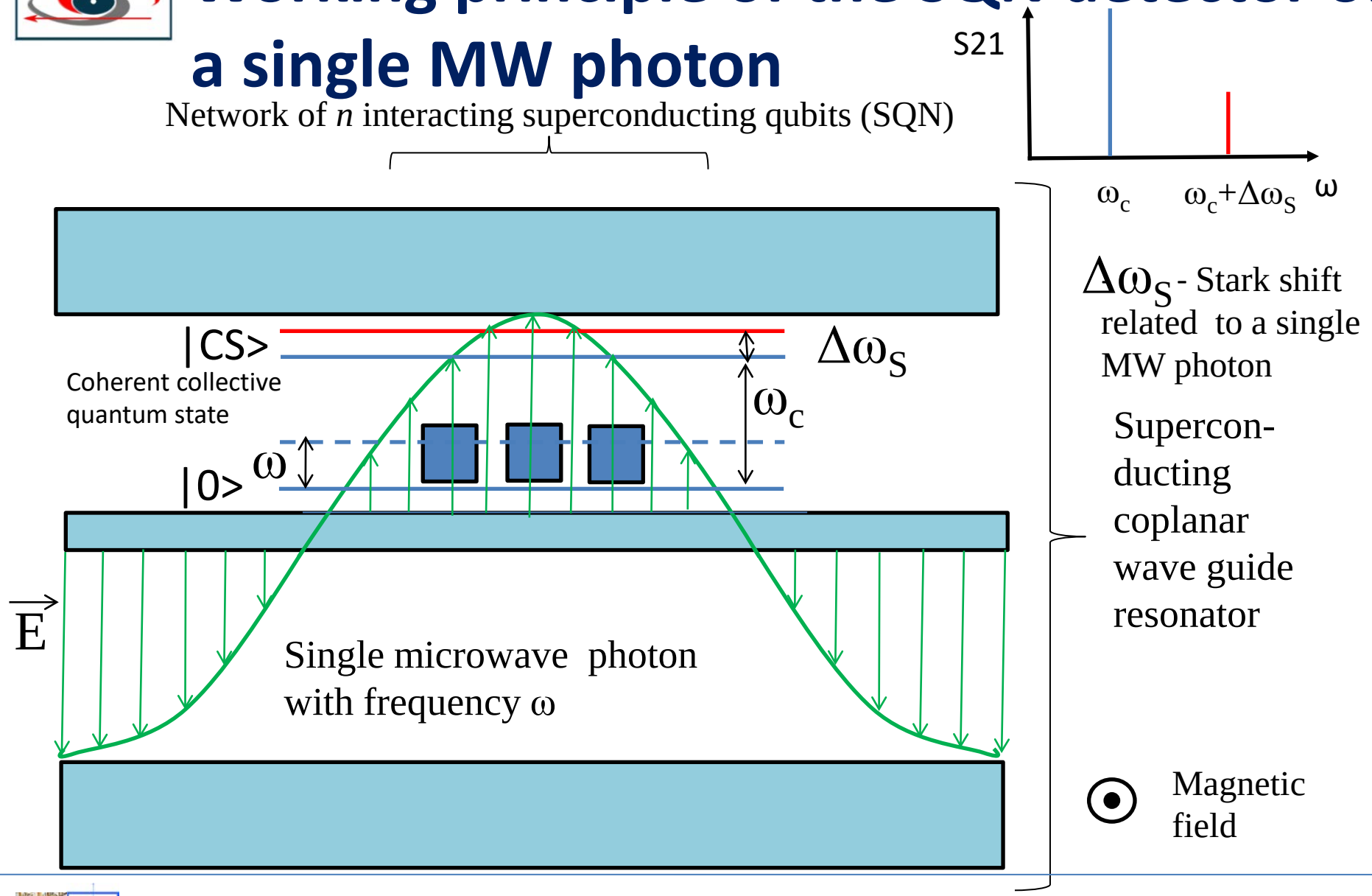
Working principle of the SQN detector of a single MW photon



Working principle of the SQN detector of a single MW photon



Working principle of the SQN detector of a single MW photon



Specific objectives of the project

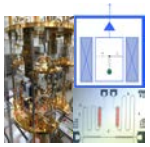
1. Development of a single microwave photon detector based on moderate size networks of interacting superconducting qubits (SQNs)

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



Consortium: contributions of the partners

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

WP1.Design and fabrication of single microwave photon detector based on moderate size SQNs

Prof. Evgeni Il'ichev and Dr. Gregor Oelsner

The National Research Council (CNR), Institute for superconductors, oxides and other innovative materials and devices (CNR-SPIN) and the Institute of Nanoscience (CNR-NANO), Italy-

WP2. Test measurements of fabricated SQNs,

Dr. Mikhail Lisitskiy , Dr. Mikkel Ejrnaes, Dr. Nassim Chikhi (CNR-SPIN), Prof. Marco Affronte, Dr. Claudio Bonizzoni, Dr. Alberto Ghirri (CNR-NANO) (contribution with measurements at low microwave power)

Loughborough University (LU), United Kingdom-

WP3. Theory of single photon detector with a quantum superconducting networks -Pfrof. Alexandre Zagoskin, Dr. Alexander Balanov , Dr. Sergei Saveliev, Dr. Patrick Navez

Ruhr University Bochum (RUB), Germany-

WP4. Theory of AC Stark effect in collective mode of a driven SQN

Prof. Ilya Eremin (PI), Dr. Mikhail Fistul, B.S. O. Neyenhuys, B.S. A.-B. Bastias

Consortium: contributions of the partners

Italy's National Metrology Institute (INRIM), Italy-

WP5. Design and fabrication of a heralded single MW photon source based on the Josephson travelling wave parametric amplifier

Dr. Alice Media, Dr. Giorgio Brida, Dr. Emanuele Enrico, Dr. Mauro Rajteri

Karlsruhe Institute of Technology (KIT), Karlsruhe Germany-

WP6. Experiments on detection of low MW power signals down to single photon counting by detectors based on moderate size SQNs

Prof. Alexey Ustinov, Dr. Kirill Shulga.

National Institute for Nuclear Physics (INFN) , Italy-

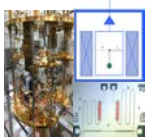
WP7. Experimental tests of the single MW photon detector based on SQNs for the "haloscope" type of axion searching

Dr. Claudio Gattiand Dr. Daniele Di Gioacchino

The National Research Council (CNR)-

WP8. Management and dissemination

Dr. Mikhail Lisitskiy



Main Results obtained by Consortium: Theoretical Activities

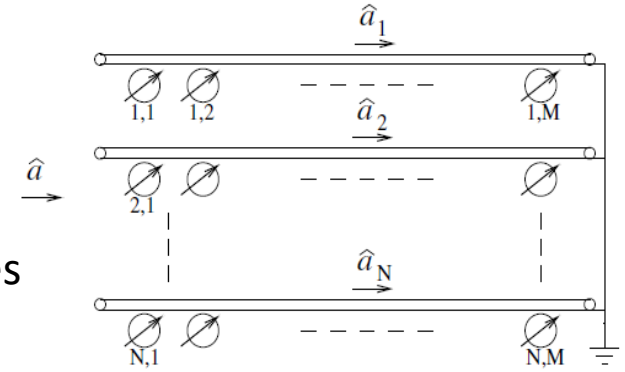
Loughborough University, Department of Physics (UK)

Theoretical investigation of working princile of the SQN detector:

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

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

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



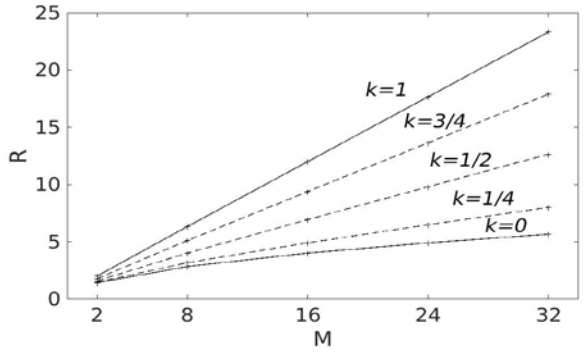
The optimal signal to noise ratio for single-photon detection is achieved in the case of a single waveguide with qubits inside.

Main Results obtained by Consortium: Theoretical Activities

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

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



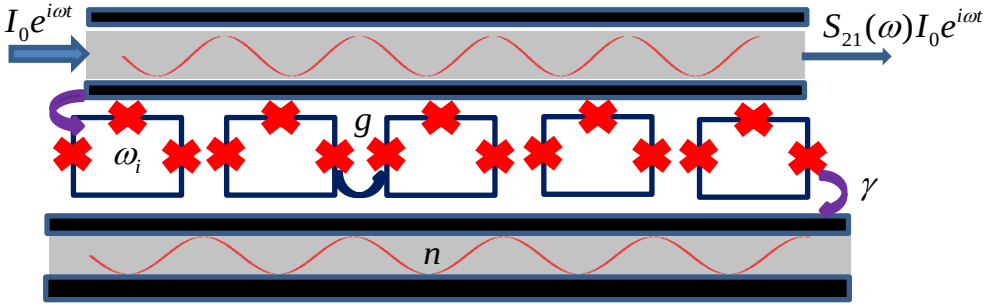
Signal-to noise ratio increases with increasing qubit namber M and degree of qubit correlation *k*

Main Results obtained by Consortium: Theoretical Activities

Theoretische Physik III, Ruhr-University Bochum, Germany

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

- 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.



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

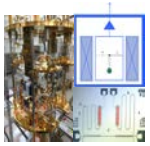
- Temporal quantum correlation function

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

- Measurements (transmission coefficient)

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

- 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.



Main Results obtained by Consortium: Theoretical Activities

Theoretische Physik III, Ruhr-University Bochum, Germany

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

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

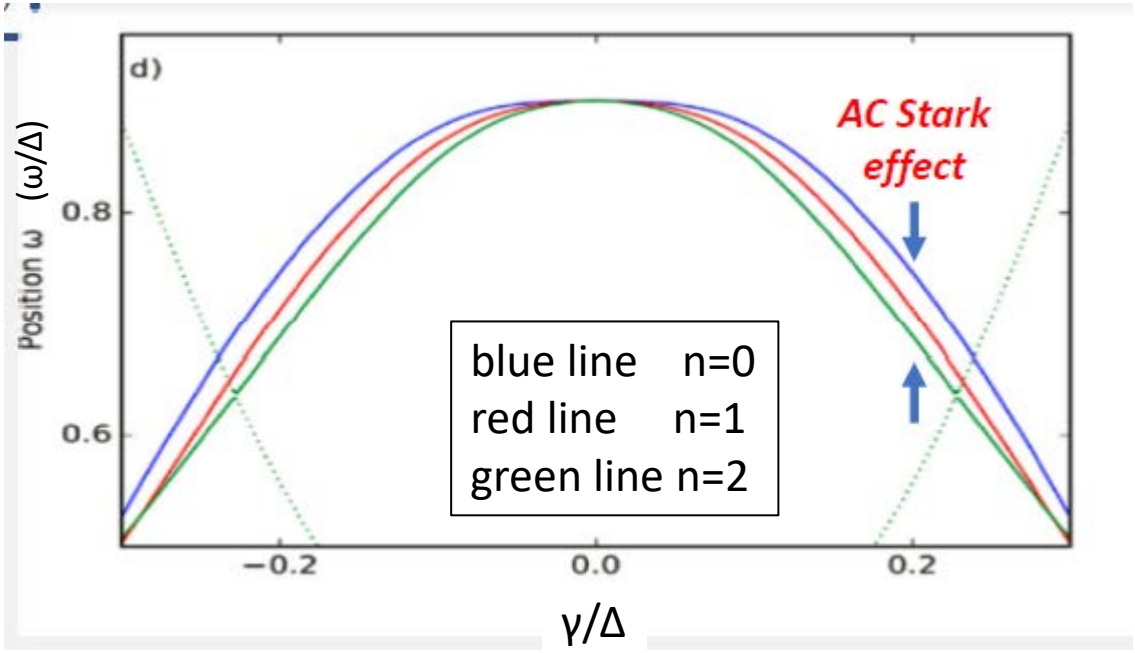
Transmission measurements

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

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

4 qubits+4 photon states
n is photon number

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

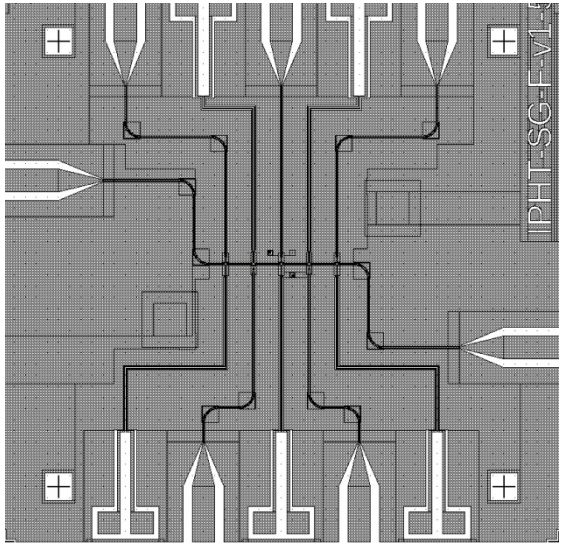


Main Results obtained by Consortium: Experiment

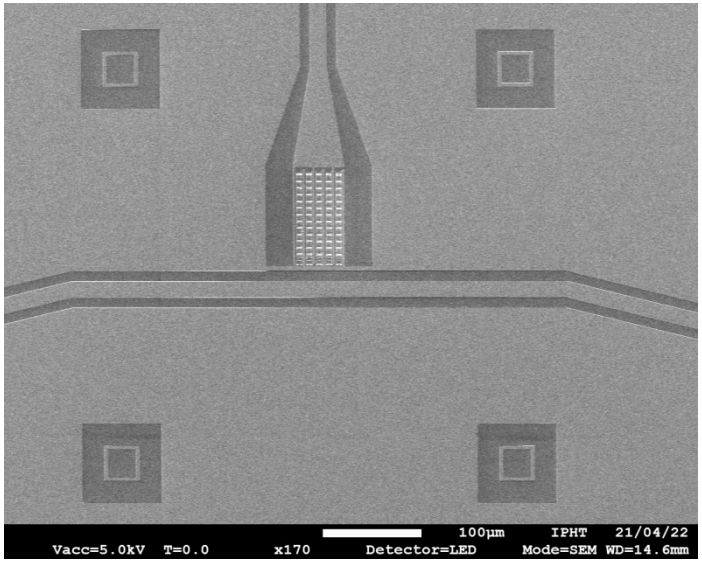
The Leibniz Institute of Photonic Technology (Leibniz IPHT), Jena Germany

Design and fabrication of SQN detector:

- Shadow evaporation technique for Al junctions has been improved
- Test array with 108 Al Josephson junctions have been successfully tested
- SQN detectors with 5 flux qubits (two-terminal device) have been fabricated
- SQN detectors with 5 C-shunted flux qubits (four-terminal device) have been fabricated



Chip layout of the SQN with 5 flux qubit



SEM picture of four-terminal device with 5 C-shunted flux qubits

Main Results obtained by Consortium: Experiment

Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany

Experiment on the detection of low MW power signals down to single photons:

SQN detectors with 8 transmons have been fabricated (Fig. 1).

The experimental setups for MW spectroscopy of SQNs have been realized. In test measurements we observed the collective quantum-mechanical behavior in SQNs with waveguide-mediated coupling between transmon qubits (Fig. 3).

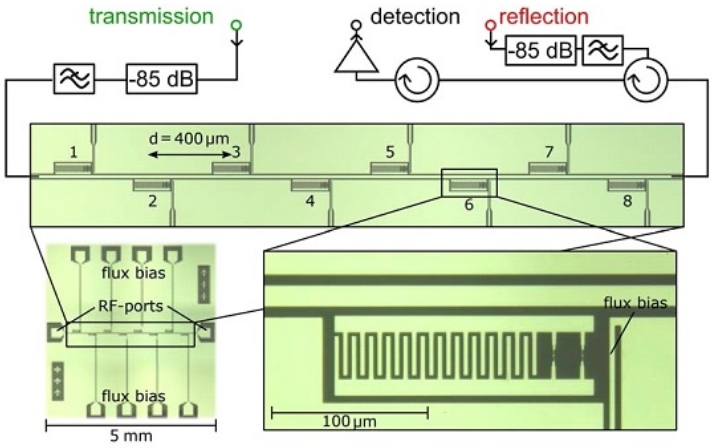


Figure 1. Test SQN with MW connections. The sample comprises 8 transmon qubits. The effective qubit-qubit interaction is mediated via a strong coupling to a common waveguide. Control lines at each qubit enable individual frequency control by applying a direct-current, which generates a magnetic flux through the SQUID loop of the qubit.

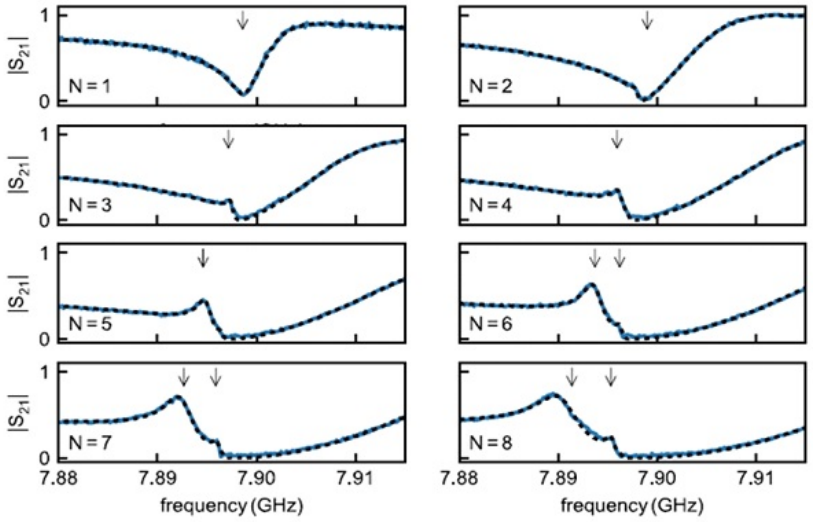
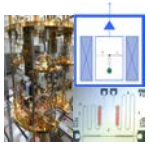


Fig. 2. Transmission coefficient |S21| at low powers for N resonant qubits at ω10/2π ~ 7.898GHz. Starting from n = 2, a second peak emerges, associated with a sub-radiant polariton mode. For n= 6 also the second brightest polariton mode is visible. The black dashed line is a fit to the corresponding T- matrix. Black arrows mark the real part of the relevant eigenfrequencies of Heff.



Main Results obtained by Consortium: Experiment

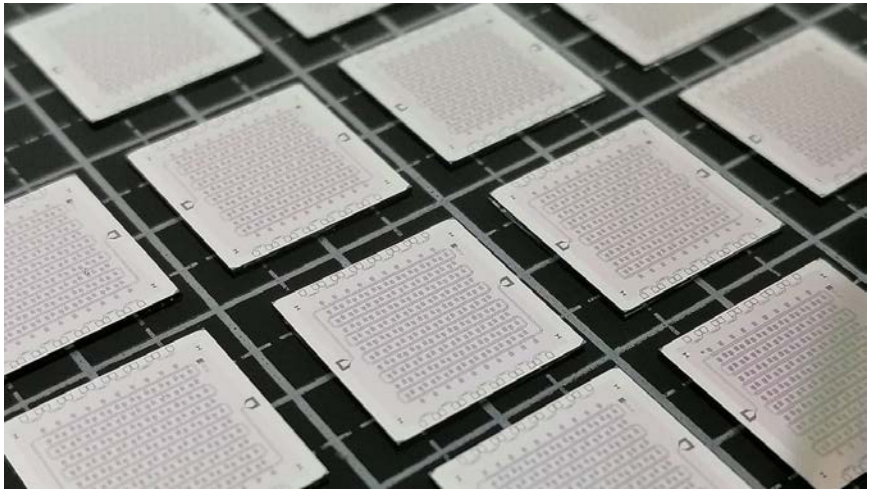
Italy's National Metrology Institute (INRIM), Italy

Development of a heralded single MW photon source:

Josephson Travelling Wave Parametric Amplifier (JTWPA)-the core of the heralded single microwave photon source- was designed and fabricated by Al-based technology. The INRiM in collaboration with the INFN (WP7) performed a preliminary measurement of the correlated signals at the output of JTWPA.



Josephson Junction fabrication facility



1x1 cm^2 Chip array containing 12 TWJPAs divided from a 2 inches wafer

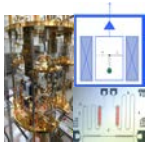
Main Results obtained by Consortium: Experiment

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, TWJPA from INRIM and Josephson Parametric amplifier based on a single Josephson junction.





Conclusions

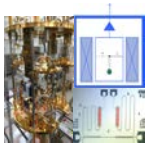
1. Main theoretical description of a single microwave photon detector based on moderated size network of interacting superconducting qubits was developed;

2. Design of the layout of SQN detectors containing 5 flux qubits and 8 transmons was developed and the samples were fabricated by Al-based technology;

3. The experimental setups for MW spectroscopy of SQNs have been realized. In test measurements on the SQNs with 8 transmons we observed the collective quantum-mechanical behavior in SQNs with waveguide-mediated coupling between transmon qubits;

4. Josephson Travelling Wave Parametric Amplifier (JTWPA)-the core of the heralded single microwave photon source- was designed and fabricated by Al-based technology.

5. As for «Haloscope» experiment, 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.



Thank you for your attention!

