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SUPERGALAX

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avez, A. Zagoskin

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atti, F. Chiarello,
ettaroli , A. D'Elia

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Quantum Collective States in Superconducting Qubit Networks – Part A 10 flux qubits

SPIN

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SQN PROJECTS

SPIN

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Centro Nazionale di Ricerca in HPC, Big Data and Quantum Computing

NQSTI
National Quantum Science and Technology Institute

PNRR 2022-2025
National Centre for HPC, Big Data and Quantum Computing – HPC
Centro Nazionale 01 – CN0000013

Budget of the project 100.000 €

Spoke 10

lize large-scale quantum computing hardware superconducting quantum computing tform.
ivity: "Experimental evaluation of the oherence source density in materials and rication processesused in superconducting it circuits"

PNRR 2022-2025
PARTENARIATO ESTESO PE000023 NATIONAL QUANTUM SCIENCE AND TECHNOLOGY INSTITUTE ("NQSTI")

Budget of the project 312.000 €

Spoke 6 Quantum Integration

Activities	Description	Milestones	Affiliates	Personnel
6.3.3 Superconducting quantum networks	6.3.3.1 Demonstration of quantum networks of qubits with highly entangled quantum phases appearing	M12-A6.3 M24-A6.3 M36-A6.3	CNR INFN	Lisitskiy (CNR-SPIN, Esposito (CNR ISASI, Salluzzo (CNR SPIN, Ruggiero (CNR ISASI Gatti (INFN LNF

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Budget of the project: 2 4562 32,50 €

SQN PROJECTS

PERGALAX Project (2019-2023):«Highly sensitive detection of single microwave photo
th coherent quantum network of superconducting qubits for searching galactic axions

Scientific Coordinator: M. Lisitskiy [1]

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teri[4], A. Rettaroli[9], B. Ruggiero[2], S. Savel'ev[6], P. Silvestrini[2], A. Ustinov[9], P. Vannacone[2], A. Zagoskin[6]

y
R group:
NR-SPIN, Pozzuoli
NR-ISASI Institute of Applied Sciences and Intelligent Systems "Eduardo
aniello", Pozzuoli
IR-NANO Modena,
IRIM Italy's National Metrology Institute, Torino,
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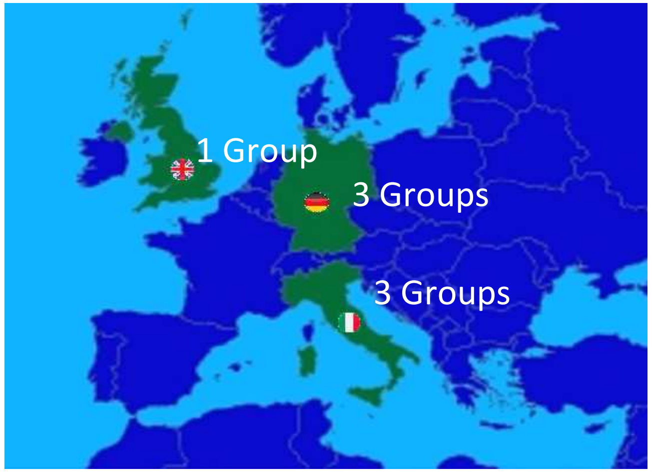
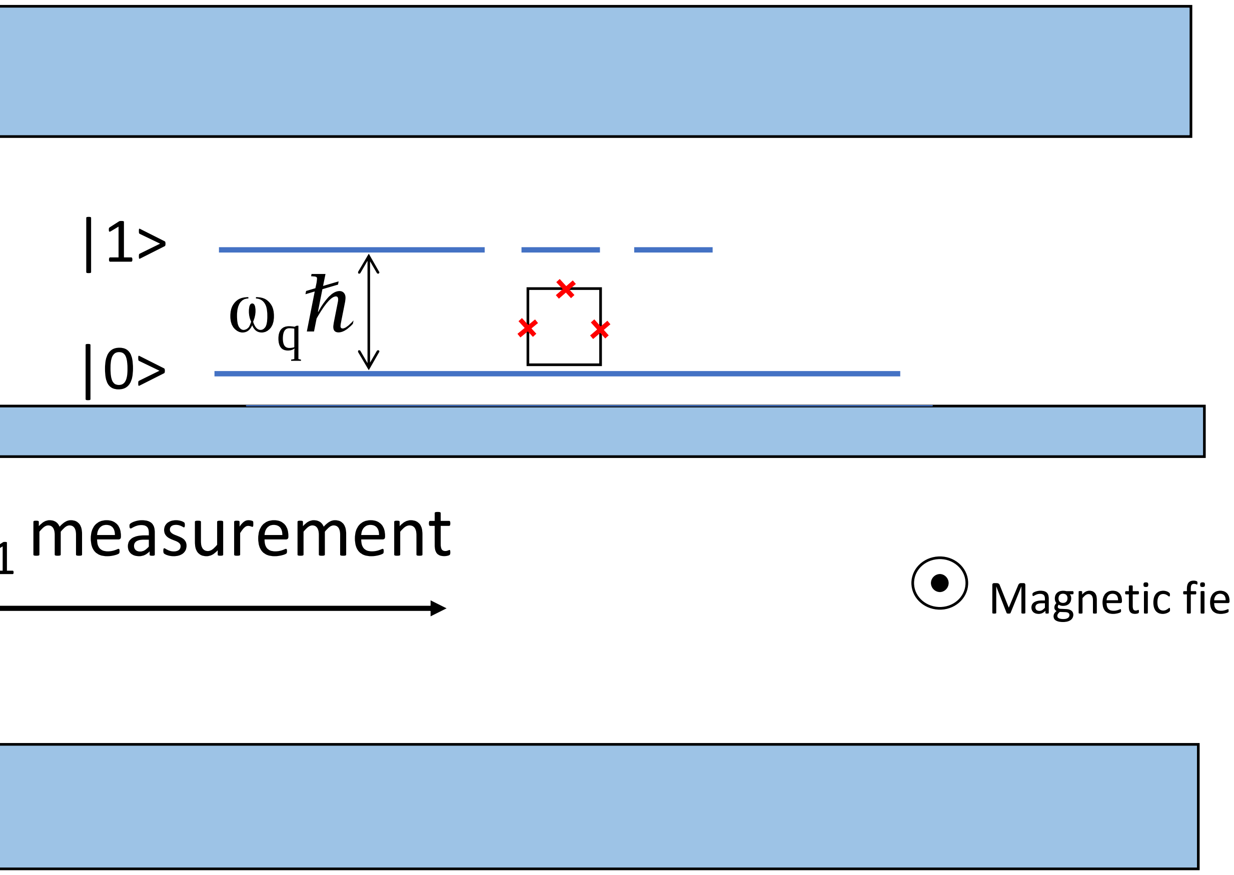


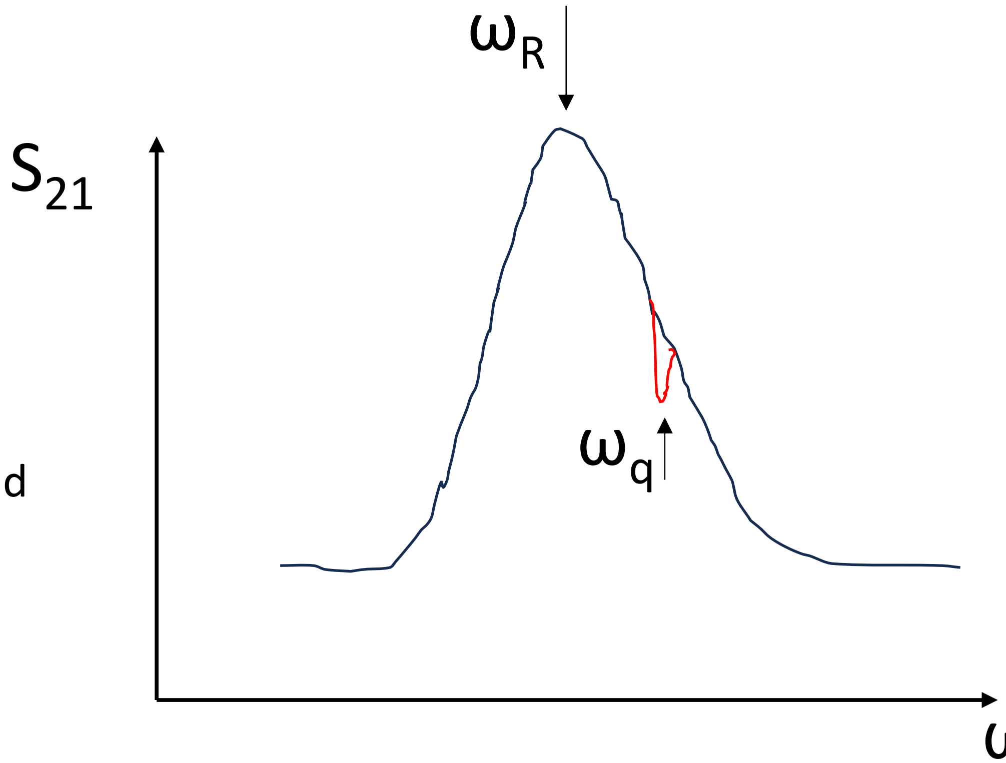
This project has received funding from the European Union's Horizon 2020 research an
innovation programme under grant agreement N. 863313

rsistent current superconducting flux qubit embidded in coplanar reson

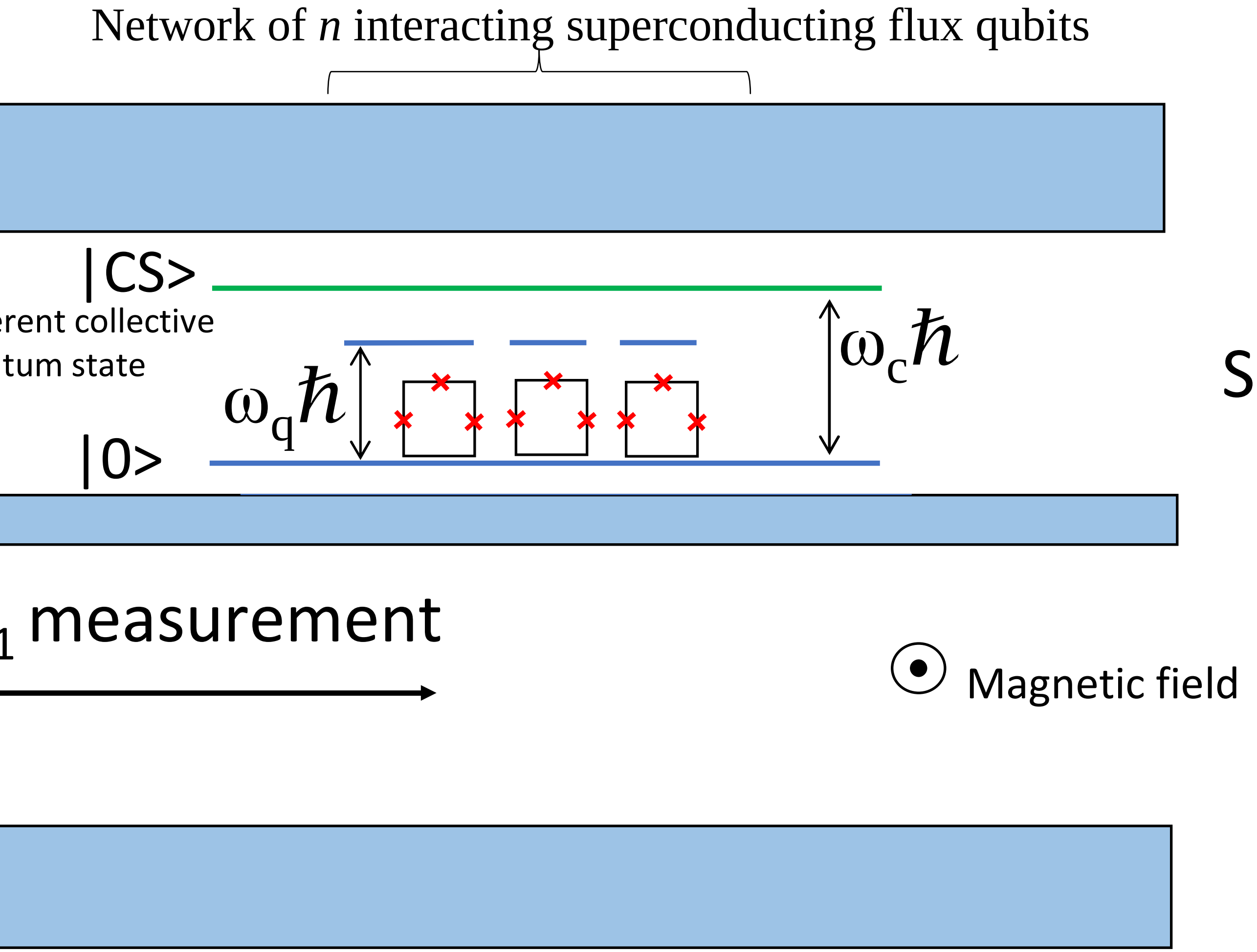
Superconducting coplanar waveguide (CPW) resonator



S_{21} is a transmission coefficient which indicates the insertion loss of a circuit

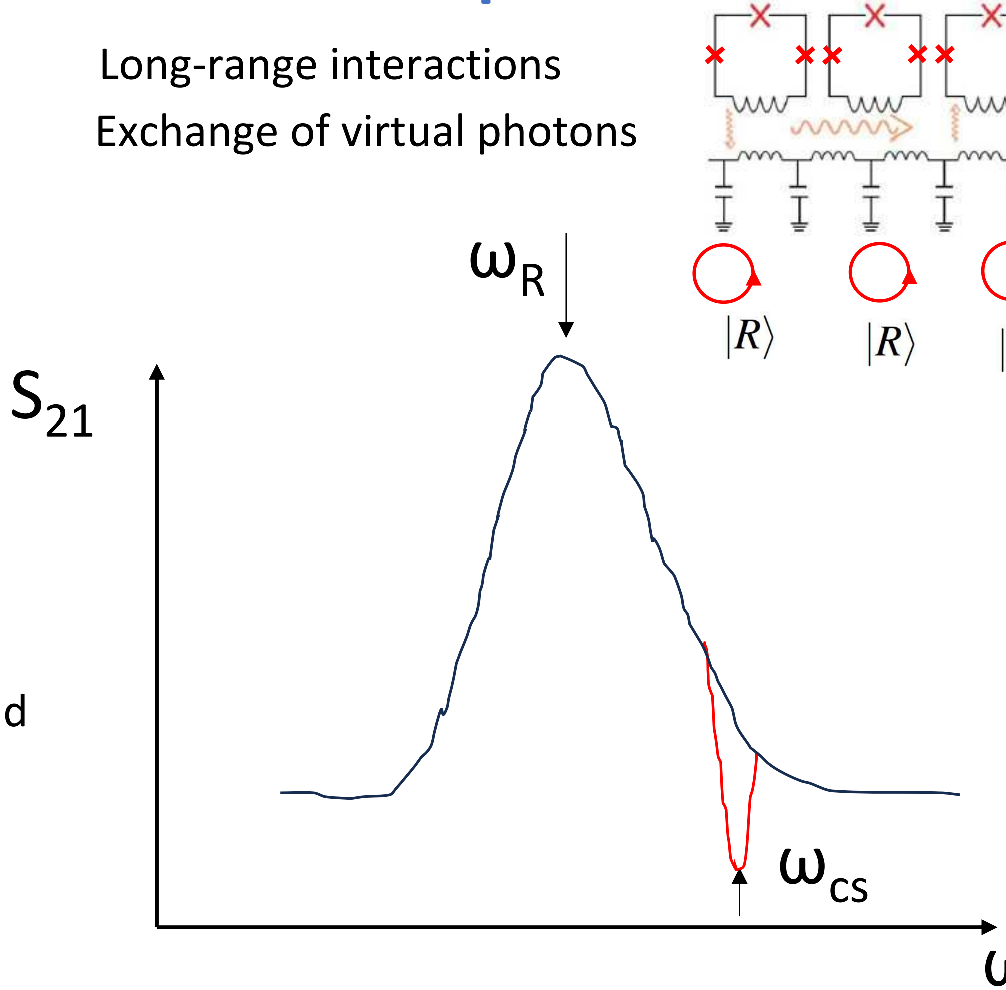


Superconducting qubit network (SQN) and collective quantum states



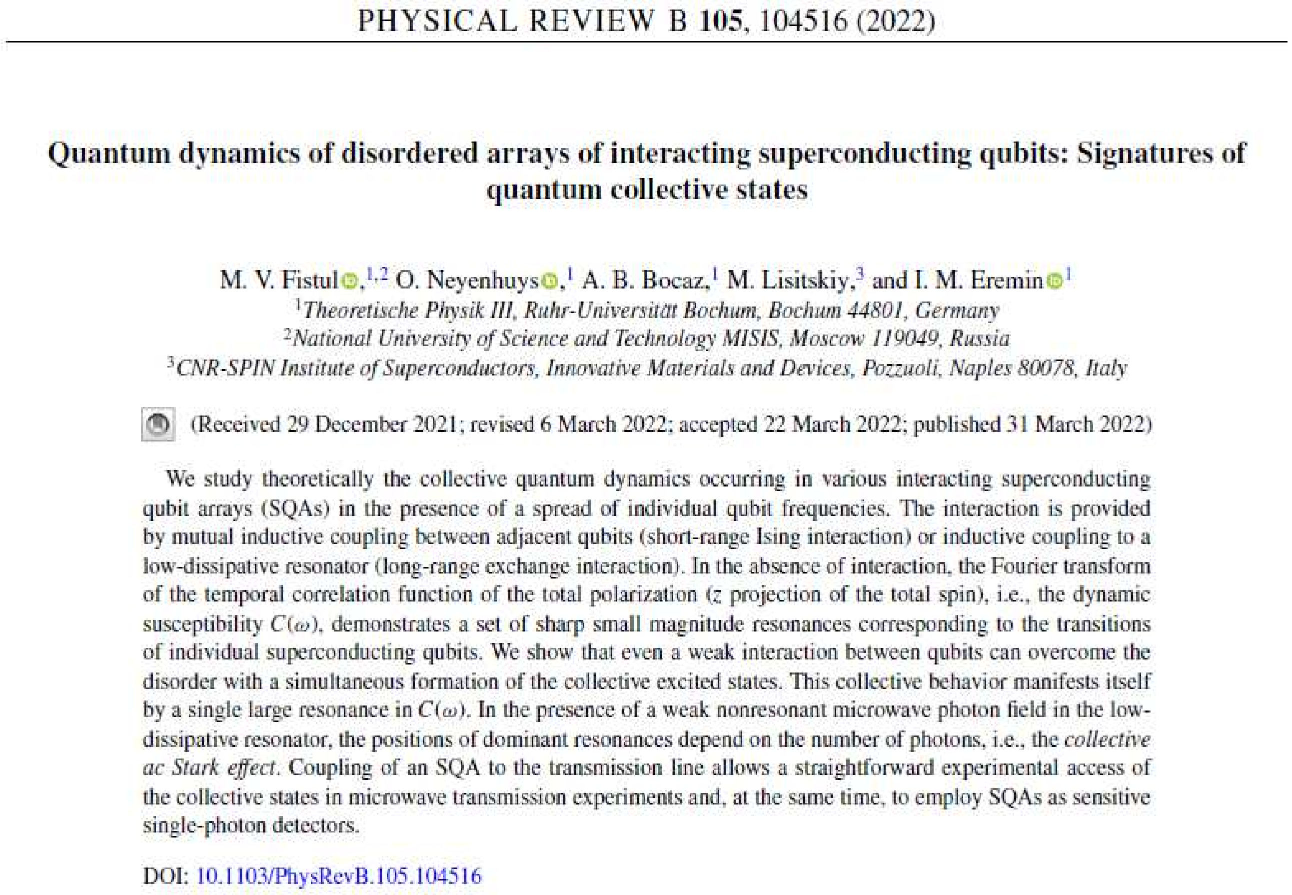
Long-range interactions

Exchange of virtual photons



Coherent Dynamics of interacting Superconducting qubit network

khail Fistul



PHYSICAL REVIEW B **105**, 104516 (2022)

Quantum dynamics of disordered arrays of interacting superconducting qubits: Signatures of quantum collective states

M. V. Fistul,[1,2] O. Neyenhuys,[1] A. B. Bocaz,[1] M. Lisitskiy,[3] and I. M. Eremin[1]
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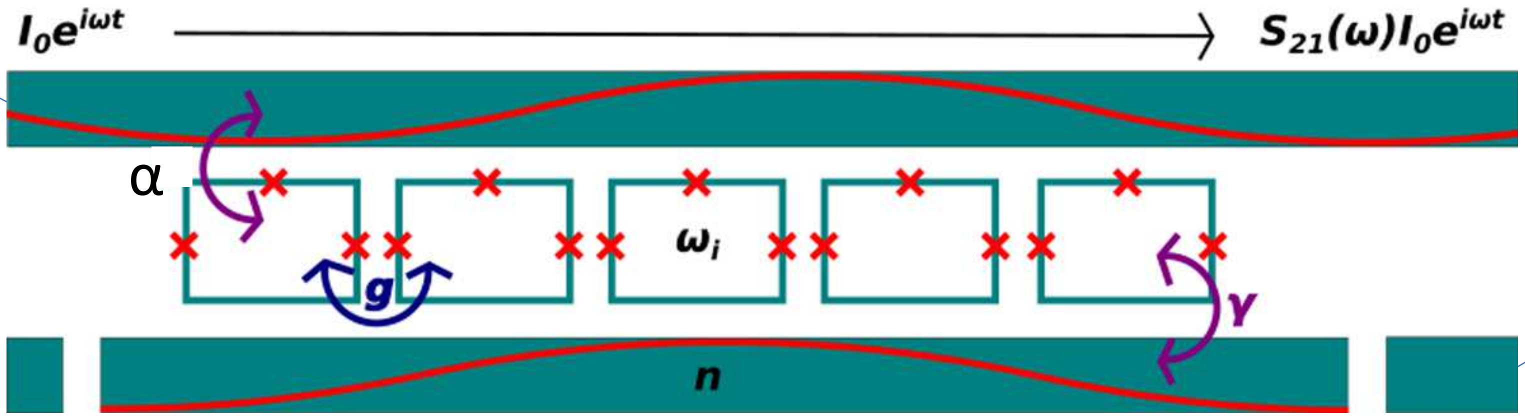
We study theoretically the collective quantum dynamics occurring in various interacting superconducting qubit arrays (SQAs) in the presence of a spread of individual qubit frequencies. The interaction is provided by mutual inductive coupling between adjacent qubits (short-range Ising interaction) or inductive coupling to a low-dissipative resonator (long-range exchange interaction). In the absence of interaction, the Fourier transform of the temporal correlation function of the total polarization (z projection of the total spin), i.e., the dynamic susceptibility $C(\omega)$, demonstrates a set of sharp small magnitude resonances corresponding to the transitions of individual superconducting qubits. We show that even a weak interaction between qubits can overcome the disorder with a simultaneous formation of the collective excited states. This collective behavior manifests itself by a single large resonance in $C(\omega)$. In the presence of a weak nonresonant microwave photon field in the low-dissipative resonator, the positions of dominant resonances depend on the number of photons, i.e., the *collective ac Stark effect*. Coupling of an SQA to the transmission line allows a straightforward experimental access of the collective states in microwave transmission experiments and, at the same time, to employ SQAs as sensitive single-photon detectors.

DOI: 10.1103/PhysRevB.105.104516

Generic setup of a superconducting qubit network

nsmission line



Low-dissipat
resonator

Flux- qubit SQN coupled to a low-dissipative resonatpr and a transmission line

α is the coupling strength between the qubits and the transmission line

γ is the coupling strength between a single qubit and resonator

Frequencies of individual qubits can differ significantly

Short- range coupling (interaction) between adjacent qubits is due to mutual inductance effects.

g is the strength of mutual inductive coupling between adjacent qubits.

Long-range coupling between well separated qubits is due to an exchange of virtual cavity photons

Total Hamiltonian

$$\hat{H}_{\text{tot}} = \hat{H}_{\text{SQN}} - \alpha I(t) \sum \hat{\sigma}_i^z ,$$

$$\hat{H}_{\text{SQN}} = \hat{H}_{\text{qb}} + \hat{H}_{\text{SR}} + \hat{H}_{\text{LR}} + \hat{H}_{\text{ph}} + \hat{H}_{\text{qb-ph}}$$

N is the number of qubits in a SQN

$$= \sum_{i=1}^{N} \left[\frac{\Delta_i}{2} \hat{\sigma}_i^x + \frac{\epsilon_i}{2} \hat{\sigma}_i^z \right]$$

Noninteracting part

$$= g_{\text{SR}} \sum_i \hat{\sigma}_i^z \hat{\sigma}_{i+1}^z$$

Short-range Ising exchange interaction term

$$= g_{\text{LR}} \sum_{i,j,i\neq j} \left[\hat{\sigma}_i^x \hat{\sigma}_j^x + \hat{\sigma}_i^y \hat{\sigma}_j^y \right]$$

Long-range exchange interaction term

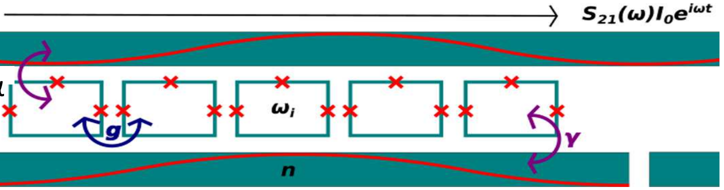
$$\hat{H}_{\text{ph}} = \hbar \omega_0 \hat{a}^\dagger \hat{a}$$

Term relateted to pho
the resonator

$$\hat{H}_{\text{qb-ph}} = \gamma \sum_{i=1}^{N} \hat{\sigma}_i^z (\hat{a}^\dagger + \hat{a})$$

Interaction of photons
with qubits

General theoretical approach



Hamiltonian $\hat{H}_{SQN}$

Method

Exact diagonalization

Numerical calculations $E_i\ ,\ \Psi_i(n)$

Eigenvalues and eigenfunctions

Temporal correlation function of total magnetization

- Nonequilibrium time-dependent correlation function

$$C_n(t) = \left\langle \Psi_i(n) \left| \left[\sum_{i=1}^{N} \hat{\sigma}_i^z(t) \right] \left[\sum_{i=1}^{N} \hat{\sigma}_i^z(0) \right] \right| \Psi_i(n) \right\rangle . \qquad (13)$$

$$\Psi\,(n) \sim |\downarrow\downarrow \ldots \downarrow\downarrow \oplus n>$$

- Dynamic suspectibility

$$C(\omega) = \lim_{t_0 \to \infty} \frac{1}{t_0} \int_0^{t_0} dt\ e^{i\omega t} \Im m C(t)$$

- Dynamic suspectibility in case of n photons

$$C_{ph}(\omega) = \sum_n P(n) C_n(\omega),$$

$P(n)$ is the probability to obtain the photon in the Fock state |n>

- Measurements

$$\Delta S_{21}(\omega) \simeq C(\omega).$$

n is the number of photons

n=4 max

Numerical analysis for N=2 t

Individual qubit frequency

$$\omega_i = \sqrt{\Delta_i^2 + \epsilon_i^2}/\hbar$$

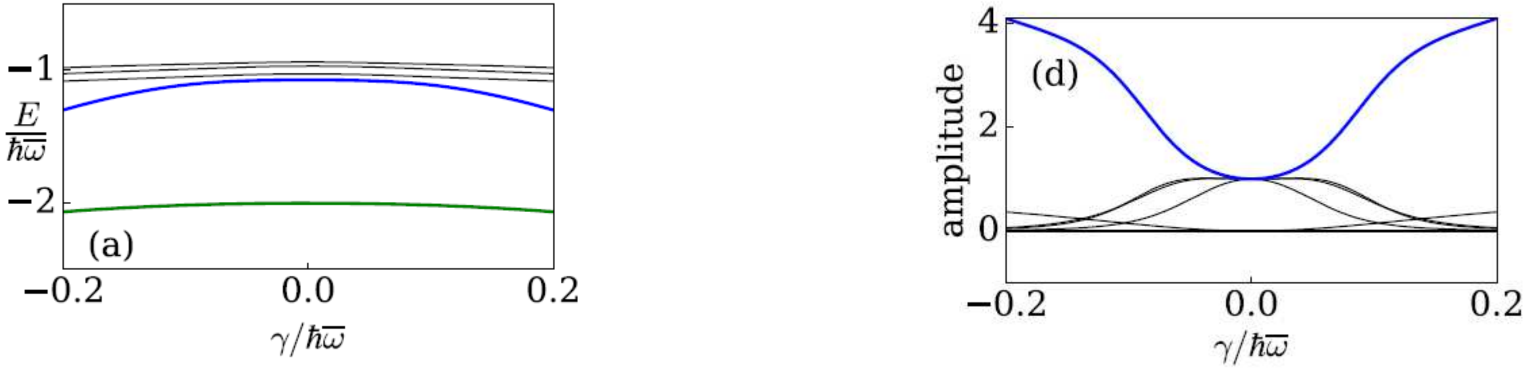
Δ_i and ϵ_i can be varied in external magnetic field

Strength of qubit disorder

$$\sigma = \sqrt{<(\omega_i - \bar{\omega})^2 >}/\bar{\omega}$$

$\bar{\omega} =< \omega_i >$ is the aver qubit frequ

Coherent quantum dynamics in disodered interacting SQN



e dependence of low-lying energy levels (a) and the amplitudes of resonances (b) on the coupling strength γ for th sordered SQNs composed of four qubits and four photon states for $C_0(\omega)$ (no photons in resonator). The dominar sonances correspond to the transitions between energy levels indicated by green and blue lines. The disorde ength is fixed as σ = 0.1.

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

Collective AC Stark effect in disodered interacting SQN

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

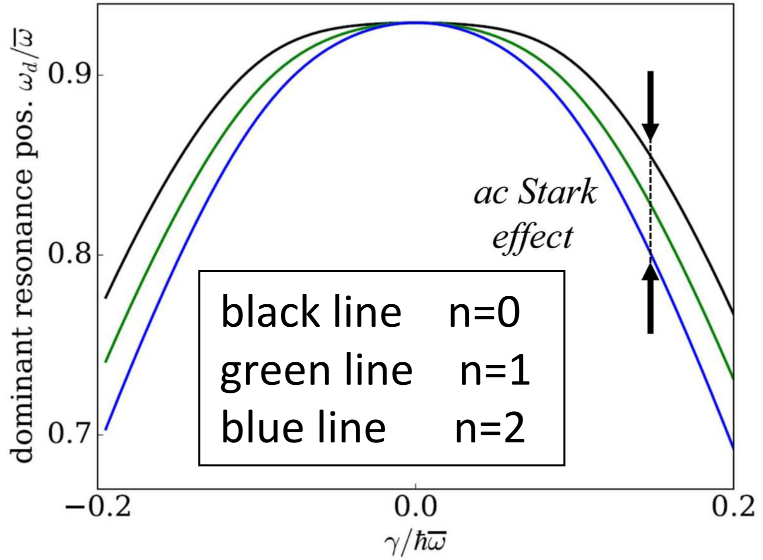
Transmission measurements

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

4 qubits+4 photon states
n is photon number

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

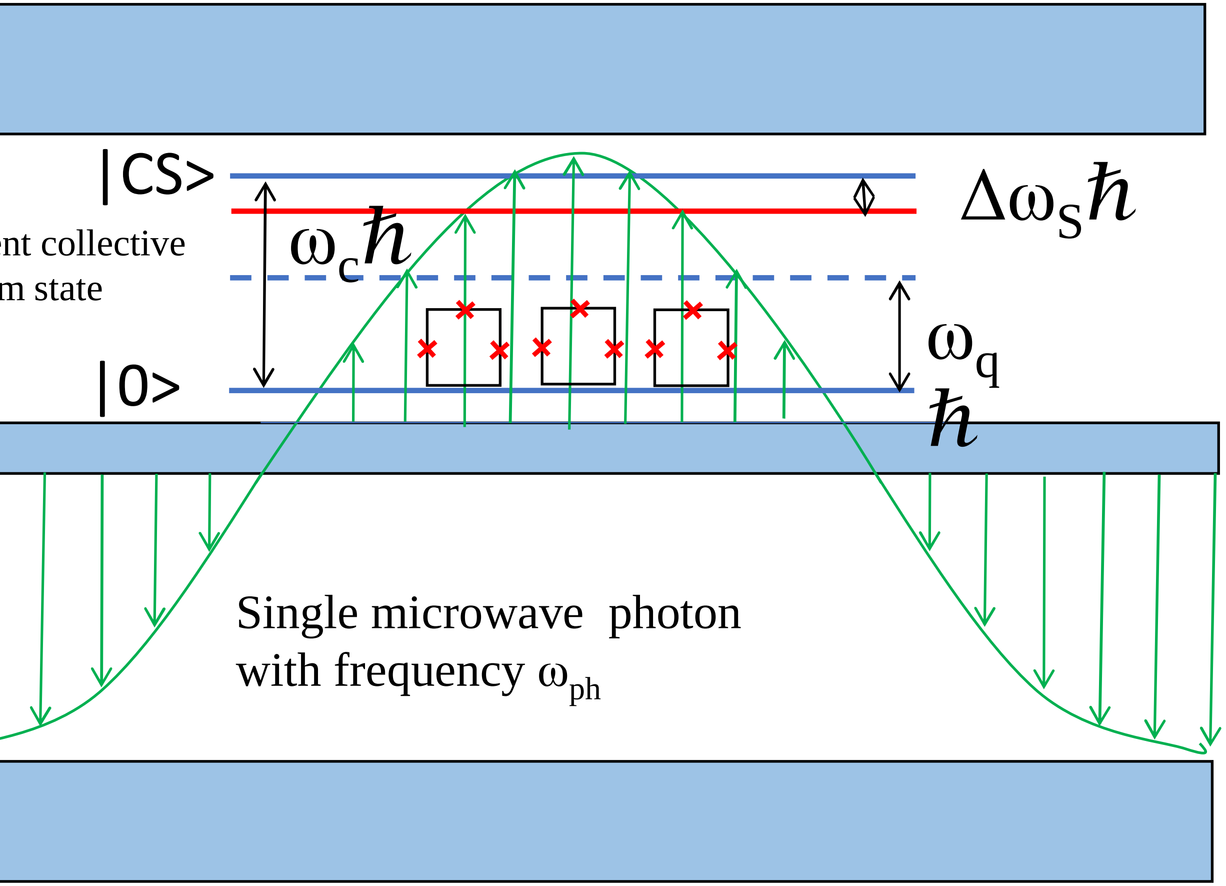
AC Stark effect (in electric field)



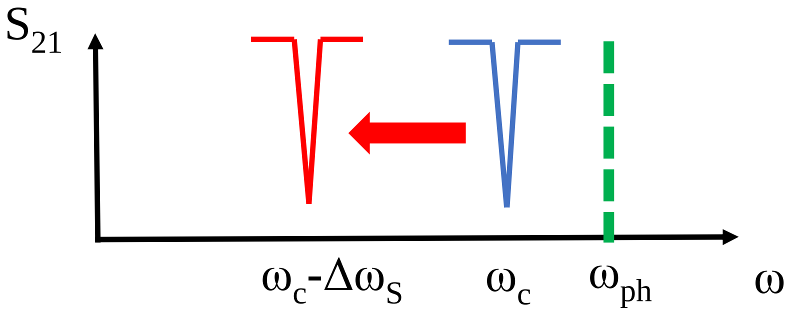
$\bar{\omega}$ is average qubit frequency

the presence of a weak non-resonant photon electric field, the position of resonances depends on the number of otons, i.e. the collective ac Stark effect is obtained

Working principle of the SQN detector of a single microwave photon



$\Delta\omega_S$ - Stark shift related to a single MW photo



A SQN embedded in a resonator produces collective quantu states.

In the presence of external microwave signal the frequency s of the collective mode takes place because of the AC Stark effect.

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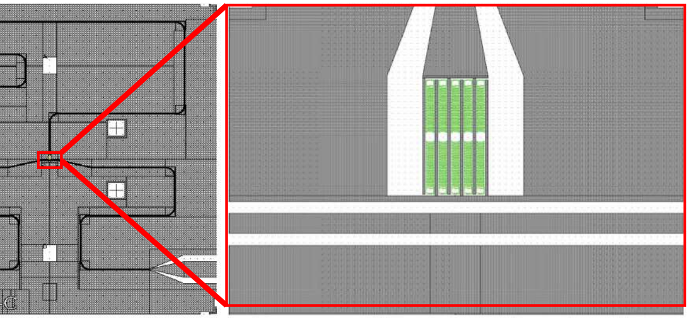
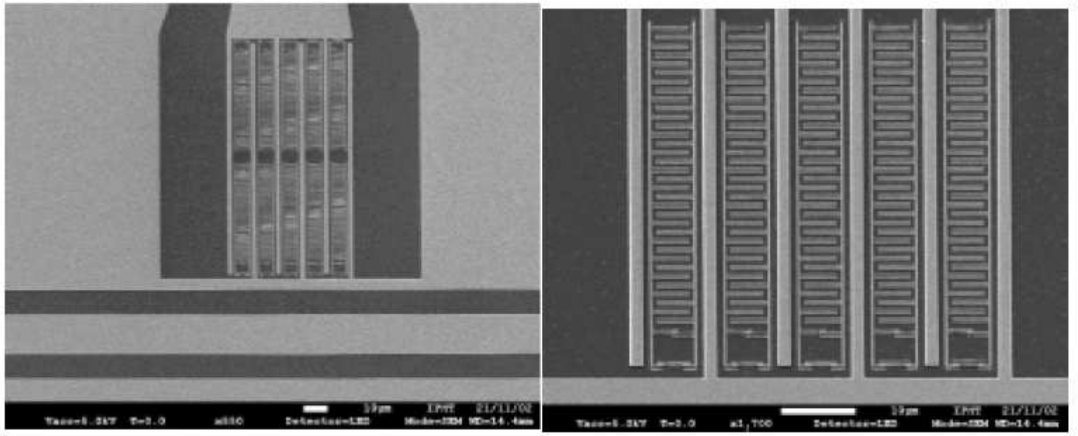
Fabrication of a T-type two resonator SQN device

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

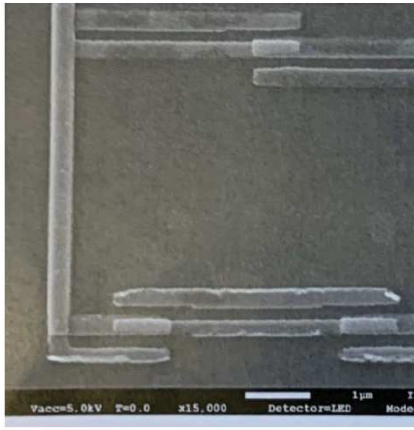
22 mm long resonators are fabricated by depositing a 200 nm thick Nb film on a silicon substrate that is structure
RIE. **The flux qubits are made of Al Josephson-junctions fabricated by two angle shadow evaporation techni**
ry flux qubit of the SQN consists of a 6x4.5 μm^2 loop with three Josephson junctions. Two junctions are designe
e 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,
or $\alpha = 0.8$.



hip layout of the T-type three terminal Two resonators at same frequency are d by an array of 10 capacitor shunted flux Right: Magnified part of the layout with 0 C-shunted flux qubits with three son junctions.



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

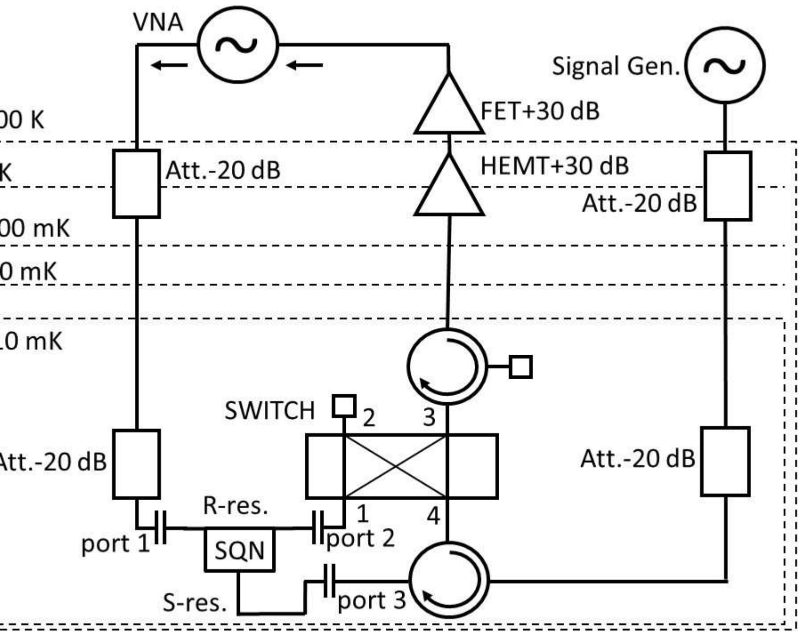


SEM- image of a fabricated qubit

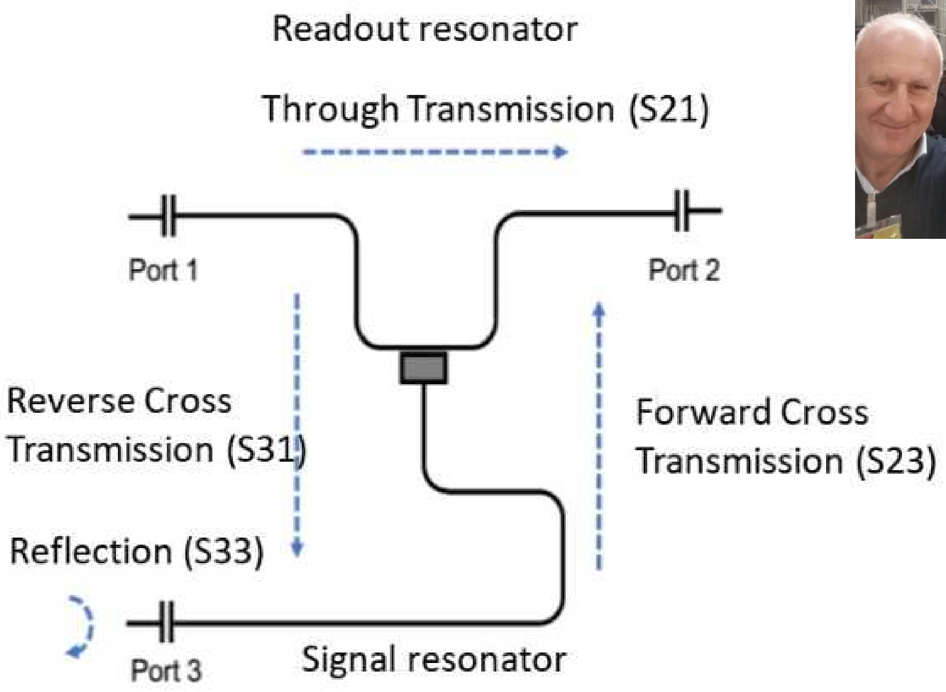
Microwave part of experimental set-up

Measurements of fabricated T-type SQN were carried out at the National Laboratory of Frascati (LNF) (Italy) in a Leiden Cryogenics CF-CS110-1000 dilution refrigerator at temperature of 15

Claudio C
(NFN)



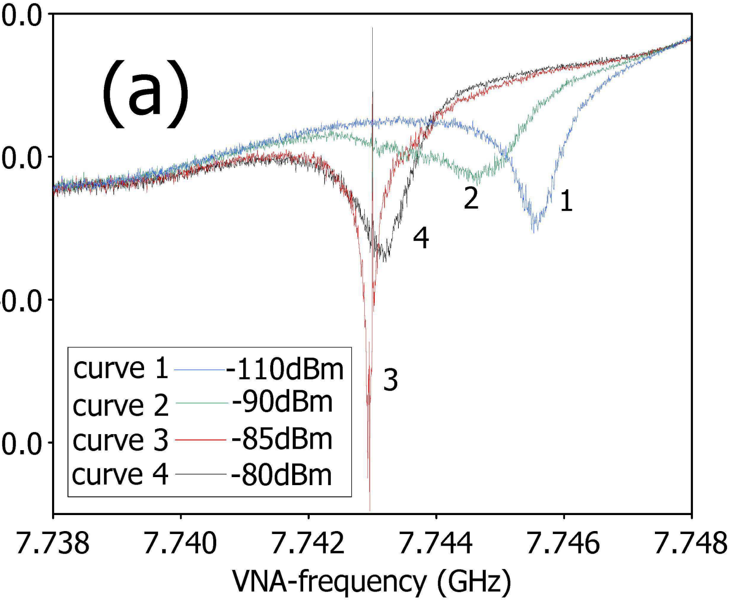
rimental set-up for double tone
owave measurements of the T-type



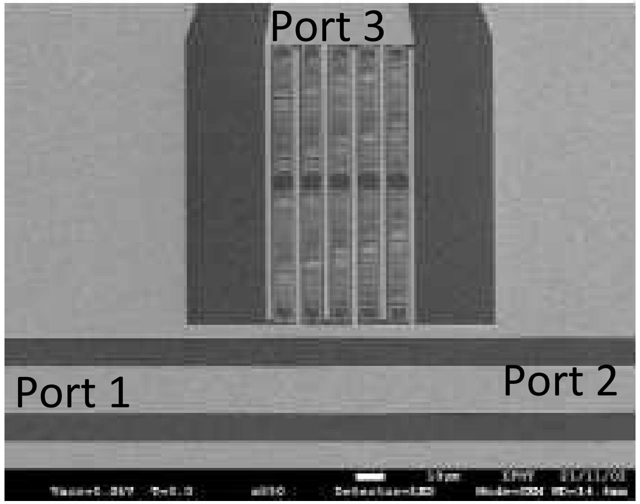
Cabling of T-type three terminal device

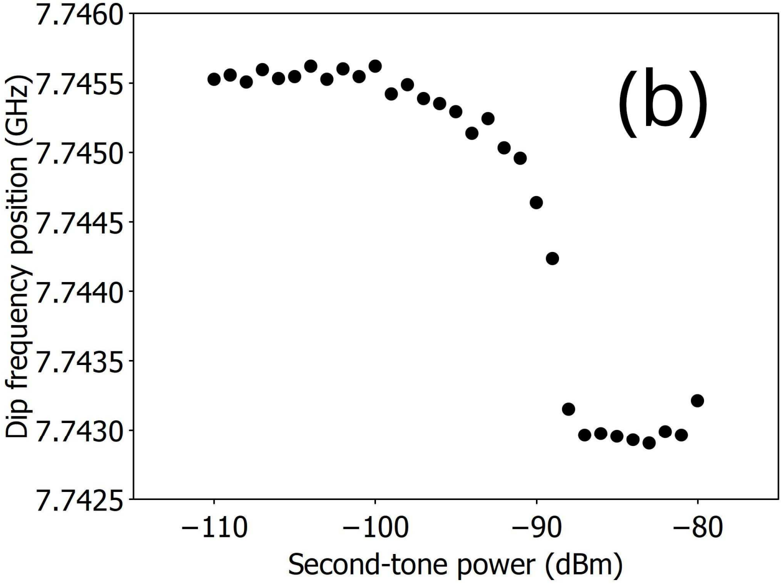
easurement of two-tone spectra of the T-type two resonator SQN -device

t the VNA output-power to -40 dbm, corresponding to about -100 dbm at the device, and measured the through transmission by first tone (S_{21}). A
me time, we sent a second tone of frequency 7.743 GHz to the Signal -resonator with the Rohde & Schwarz SMA100B connected to the Port 3, ar
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-dro
ency in the through transmission-spectrum (S_{21}).



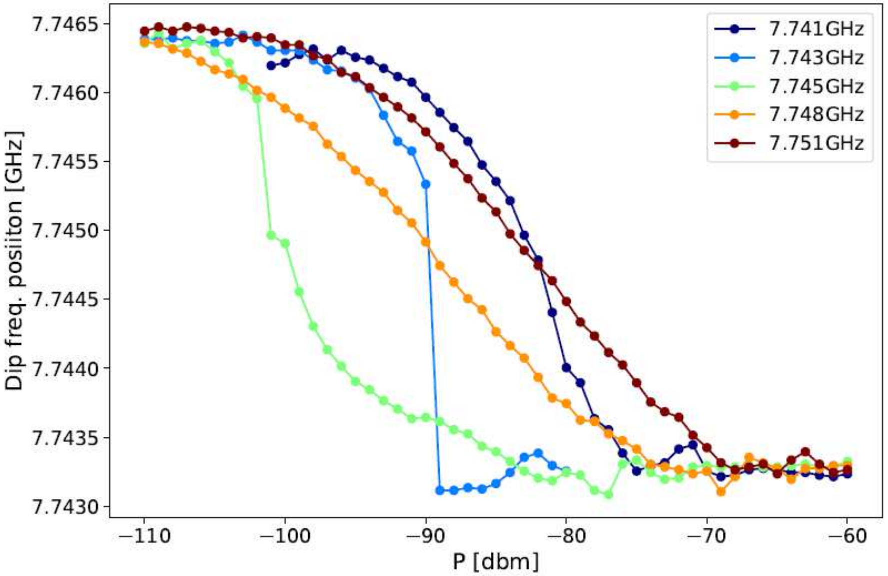
one Port 1-Port 2 -transmission coefficient (S_{21}) vs VNA-
ency dependencies recorded at different powers of the second-
signal of frequency of 7.743 GHz applied to the Port 3. T=15 mK
magnetic field.

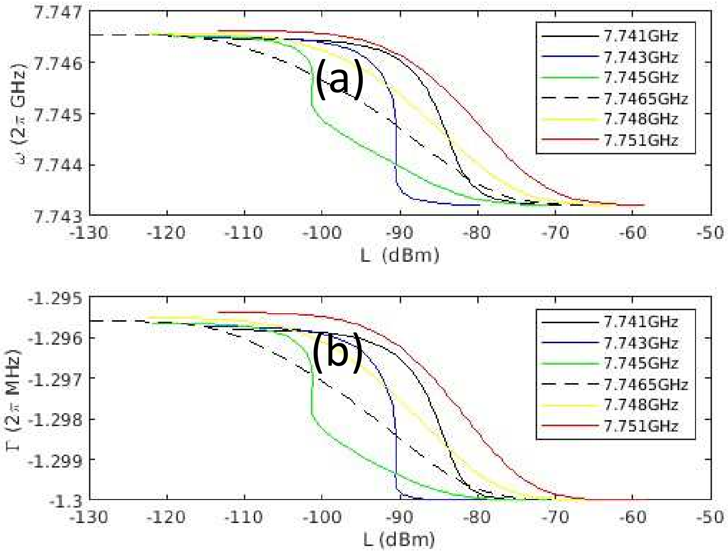




Dependence of the frequency position of the resonant drop repo
(a) as a function of the power of the second-tone signal

Loughborough Un
Department of P





P. Navez

A. Zagoskin

We observed the sensibility of the frequency position of the resonant drop both to the power of pump signal and to pump signal frequency.

Theoretically predicted values of frequency s (a) and linewidth (b) versus the input powe dBm

Experimental results are in a good agreement with the model based on a non-linear multiphoton interacti between pump microwave signal and a qubit system of the SQN where the frequency shift is the sum of t multiphoton AC Stark shift values of each qubit. (*P. Navez et al., in preparation*). This agreement permits attribute the absorption peak to the collective quantum state stimulated by the second tone microwave signal.

Conclusions

- Generic quantum-mechanical theory of disordered interacting SQNs coupled to a low-dissipative resonator was developed;

- 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;

- In the presence of a weak non-resonant photon electric field, the position of resonances depends on the number of photons, i.e. the collective ac Stark effect is established;

- Two-tone spectral measurements of the T-type three terminals SQN with 10 C-shunted flux qubits were carried out at zero external magnetic field. Non-linear effects such as shift of the absorption peak both by power and by frequency of the pump second tone signal were observed. Good agreement between experiment and theoretical model permits to attribute this absorption peak to the collective quantum state stimulated by the second tone microwave signal.

Thank very much for your attention!

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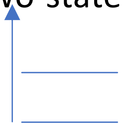
Persistent current superconducting flux qubit-fundamental elements

uantum bit –*Qubit*

wo-state quantum system

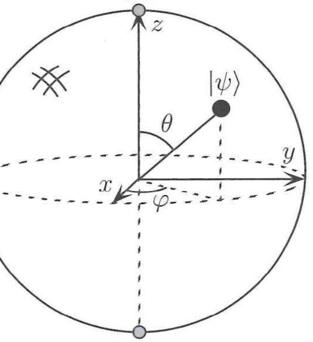


$|1\rangle$ = $|R\rangle$ Excited state

$|0\rangle$ = $|L\rangle$ Ground state

here representation of a qubit

d state $|0\rangle$



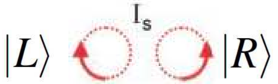
state $|1\rangle$

e is a linear superposition of states

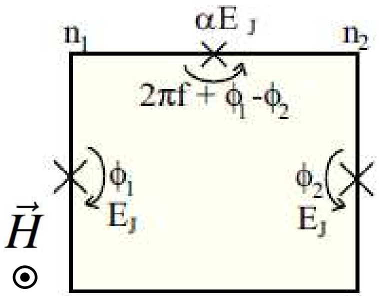
$$= \alpha\,|0\rangle + \beta\,|1\rangle.$$

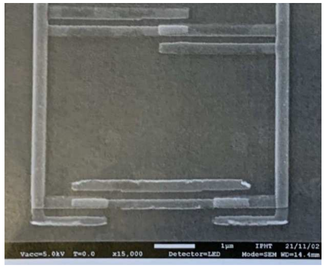
$$= \cos\frac{\theta}{2}|0\rangle + e^{i\varphi}\sin\frac{\theta}{2}|1\rangle$$

Persistent current directions are quantum states of a flux qubit



$$\Phi = \Phi_e - L_q I$$



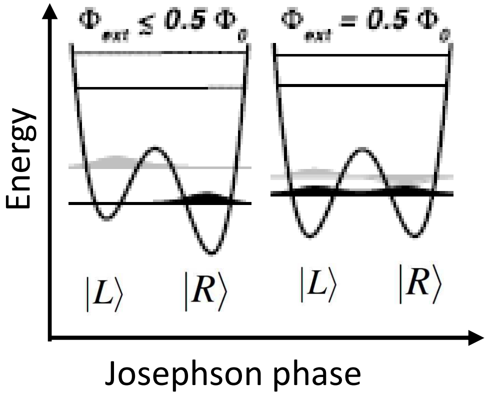


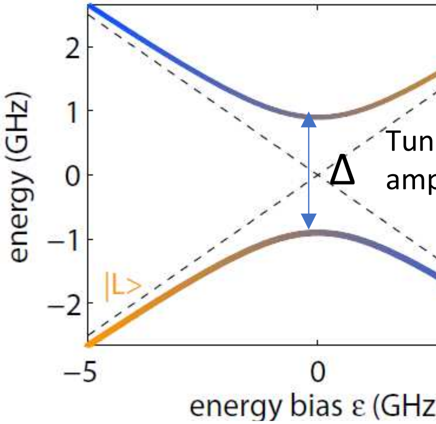
(Left) A flux qubit consists of a superconducting loop interrupted by three Josephson junctions. One of the junctions is designed to be smaller by a ratio α<1 (0.7-0.8). The other two effectively increase the inductance of the loop. The qubit is controlled by an externally applied flux Φ_e which for a small loop inductances can be identified with the internal flux Φ. (Right) SEM-image of a fabricated flux qubit (IPHT-SUPERGALAX project).

Energy bias $\varepsilon = \pm 2I_p(\Phi_e + \frac{\Phi_0}{2})$

I_p is persistent current of a flux qubit

Φ_0 is magnetic flux quantum





(Left) Schematic presentation of the loop's double-well potential wit levels for different values of Φ_e. (Right) The superposition of the flu illustrated as color gradient, gives the qubit's energy eigensta corresponding eigenenergies have a hyperbolic dependence on the en ε, which follows from the splitting at the degeneracy point. The coupli flux states is given by tunneling from one potential well to the ot amplitude Δ.

The eigenstates are given by superposition of flux states
|e> =sin ξ|L>+cos ξ|R>
|g> =-cos ξ|L>+sin ξ|R>
ξ=1/2 arctan (-Δ/ε) is so called mixing angle of the system
The difference between |e> and |g> eigenstates is given by

$\hbar\omega_q = \sqrt{\varepsilon^2 + \Delta^2}$ is an excite energy where ω_q is qubit exite freque