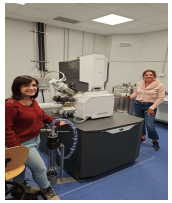
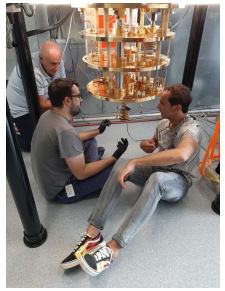
Finanziato dall'Unione europea NextGenerationEU | Ministero dell'Università e della Ricerca | Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA | NQSTI National Quantum Science and Technology Institute

Spoke 6 Quantum Integration

Quantum Collective States in Superconducting 5-Qubit Networks


B. Ruggiero MC E. Esposito MC C. Bonavolontà TD MC

M. Lisitskiy MC V. Di Meo TD MC

G. Brida, L. Fasolo, E. Enrico

P. Silvestrini

F. Romeo

M. Cirillo

ISASI | SPIN | INRiM Istituto Nazionale di Ricerca Metrologica | Università degli Studi della Campania Luigi Vanvitelli Dipartimento di Matematica e Fisica | Università degli Studi di Salerno Dipartimento di Fisica E.R. Caianiello | Tor Vergata

NQSTI - Roma February 6, 2025

Finanziato dall'Unione europea NextGenerationEU | Ministero dell'Università e della Ricerca | Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA | NQSTI National Quantum Science and Technology Institute

PNRR Partenariato Esteso

NATIONAL QUANTUM SCIENCE AND TECHNOLOGY INSTITUTE "NQSTI"

Spoke 6 Quantum Integration - The Role of ISASI

Quantum Collective States in Superconducting Qubit Networks (SQN)

	Scientific Item	MIllestones		MC TI CNR	
6.3.3 Superconducting quantum networks	**6.3.3.2 Demonstration of superconducting quantum networks topologies composed of interacting Josephson devices in 2D lattices.**	**M12-A6.3 M24-A6.3 M36-A6.3**	**CNR INFN**	**B. Ruggiero** (CNR ISASI, NA) **M. Lisitskiy** (CNR-SPIN, NA), **M. Salluzzo** (CNR SPIN, NA), **E. Esposito** (CNR ISASI, NA), **C. Gatti** (INFN LNF)	

2023 - 2025

Quantum Integration 400 KEuro (Spoke 6 ISASI -Pozzuoli)

SQN Superconducting Qubit Network

2022 2024

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

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

M. V. Fistul,[1,2] O. Neyenhuys,[1] A. B. Bocaz,[1] M. Lisitskiy,[3] and I. M. Eremin[1]
[1]*Theoretische Physik III, Ruhr-Universität Bochum, Bochum 44801, Germany*
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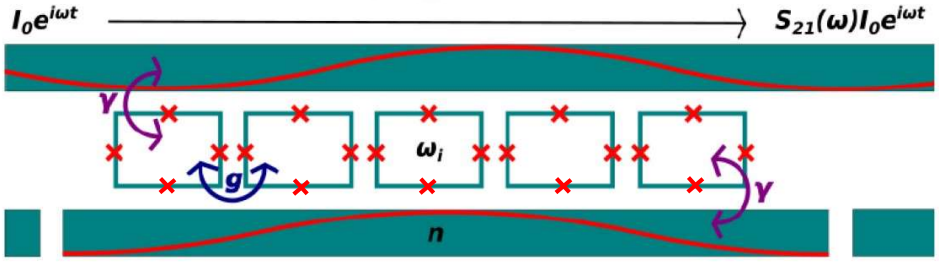


$$\hat{H}_{\rm tot} = \hat{H}_{\rm SQA} - \alpha I(t)\sum_i \hat{\sigma}_i^z, \qquad \hat{H}_{\rm SQA} = \hat{H}_{\rm qb} + \hat{H}_{\rm SR} + \hat{H}_{\rm LR} + \hat{H}_{\rm ph} + \hat{H}_{\rm qb-ph},$$

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

α are the coupling strength between qubits and the thransmission line
I(t) the current flowing along the transmission line

$\hat{a}^\dagger(\hat{a})$ are the creation (annihilation) photon operators

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

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

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

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

transmission coefficient

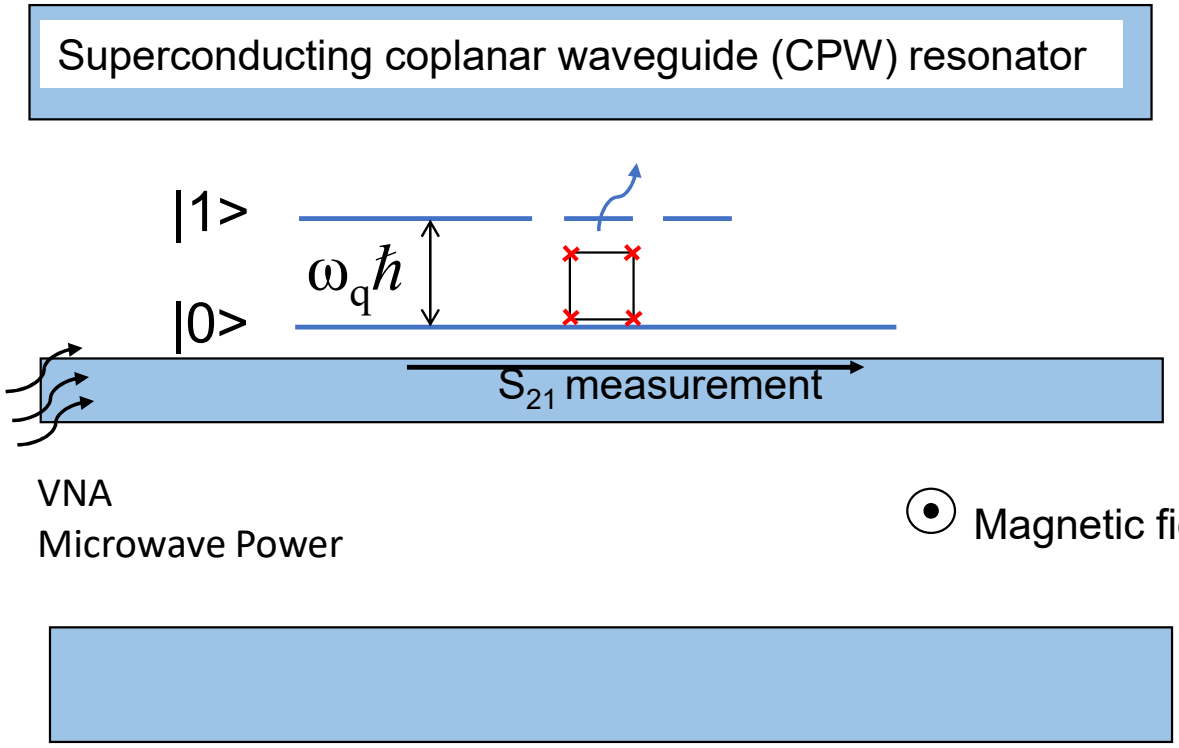
$$\Delta S_{21}(\omega) \simeq C(\omega).$$

dynamic susceptibility,

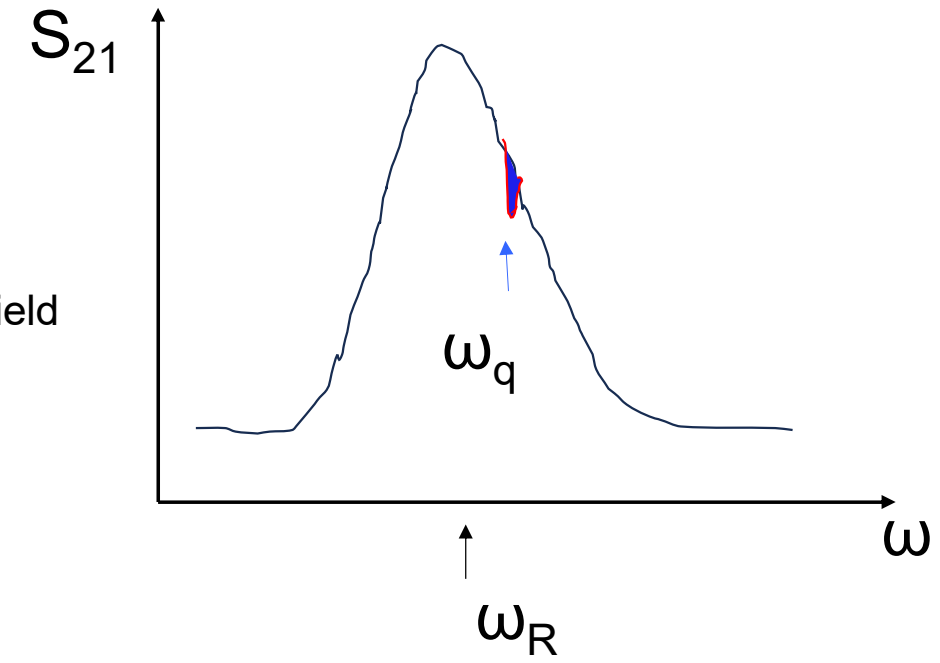
The schematic of an SQN with five flux qubits coupled to the low-dissipative cavity and the transmission line is presented.
The transmission line is used to establish an experimental setup for the measurements of S21

The transmission coefficient S_{21} vs frequency behaviour could present dips (absorption) when photons are exchanged in the resonant cavity

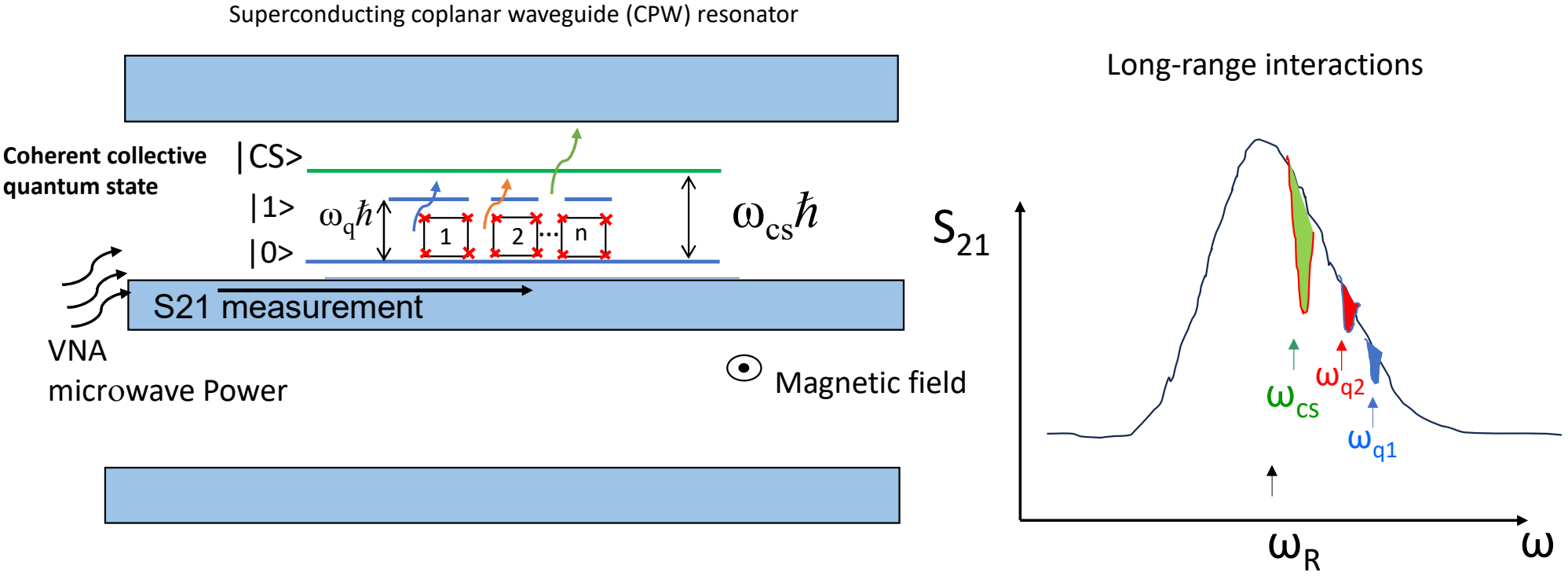
Nonlinear interactions between photons of energy level transitions in qubits and of microwave power



S_{21} vs ω
transmission coefficient as function of frequency



Superconducting qubit network (SQN) with 5 flux qubits with 4 JJ



Oscillations on S_{21} indicate the interaction between qubit and resonant circuit.

Main resonant dip…… is associated with COLLECTIVE QUANTUM STATE in SQN.

Experiments on two Resonators with SQN with 5 flux qubits

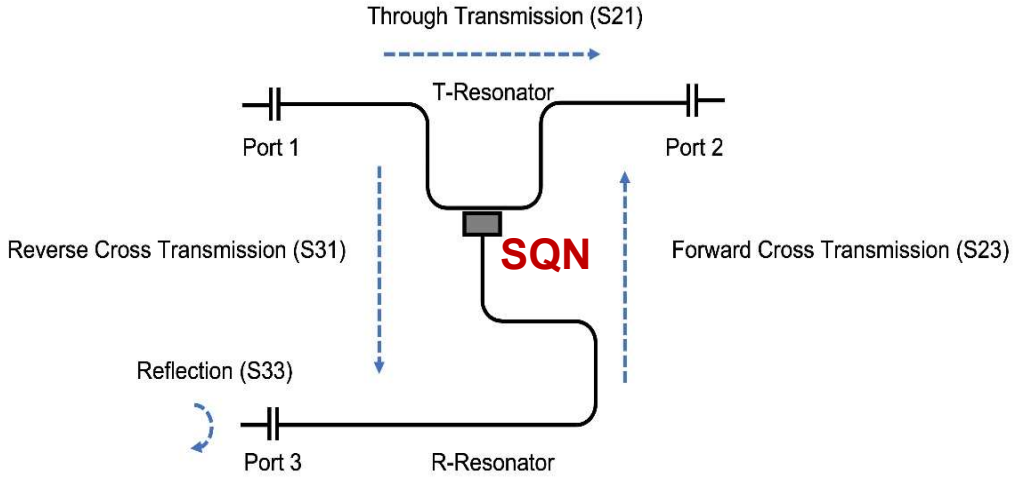
T = 20 mK

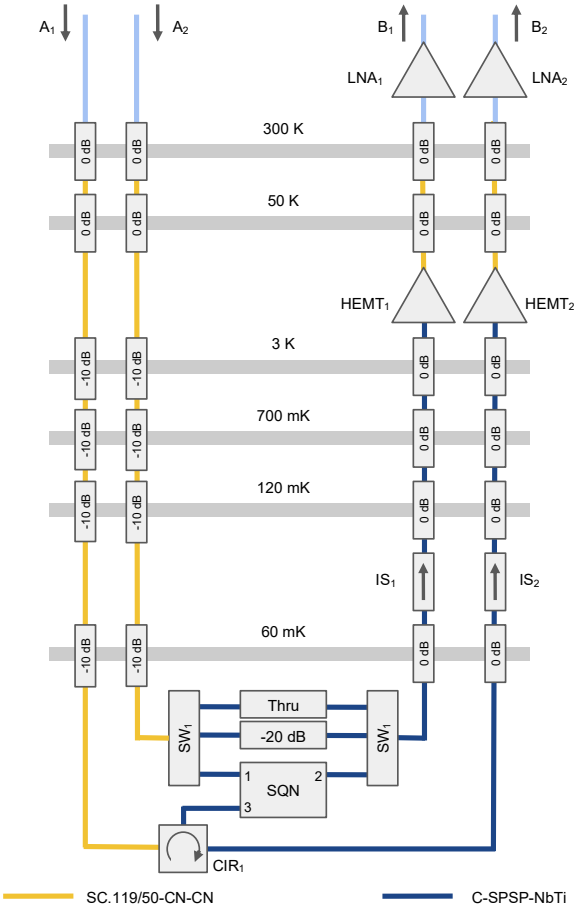
G. Brida and E. Enrico

2023/24

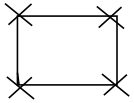
CNR SPIN Pozzuoli

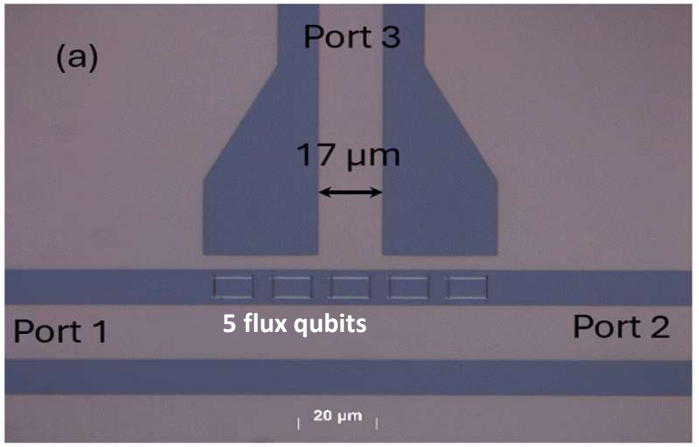
CNR ISASI Pozzuoli





4 JJ flux qubits





Enrico, E.; Bonavolontà, C.; Brida, G.; Coda, G.; Il'Ichev, E.; Fasolo, L.; Fistoul, M.; Meda, A.; Oberto, L.; Oelsner, G.; Rajteri, M.; Ruggiero, B.; Silvestrini, P.; Valentino, M.; Vanacore, P.; Lisitskiy, M. ***IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY*** 34 (3), p. 1500306 (2023)

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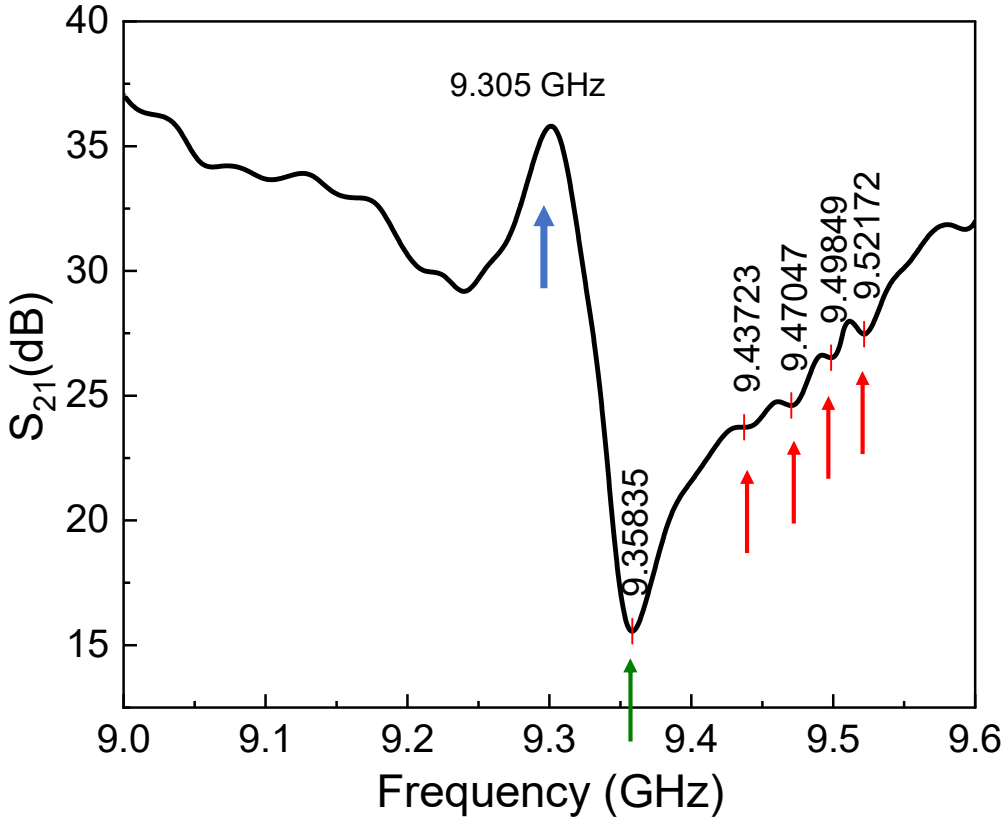
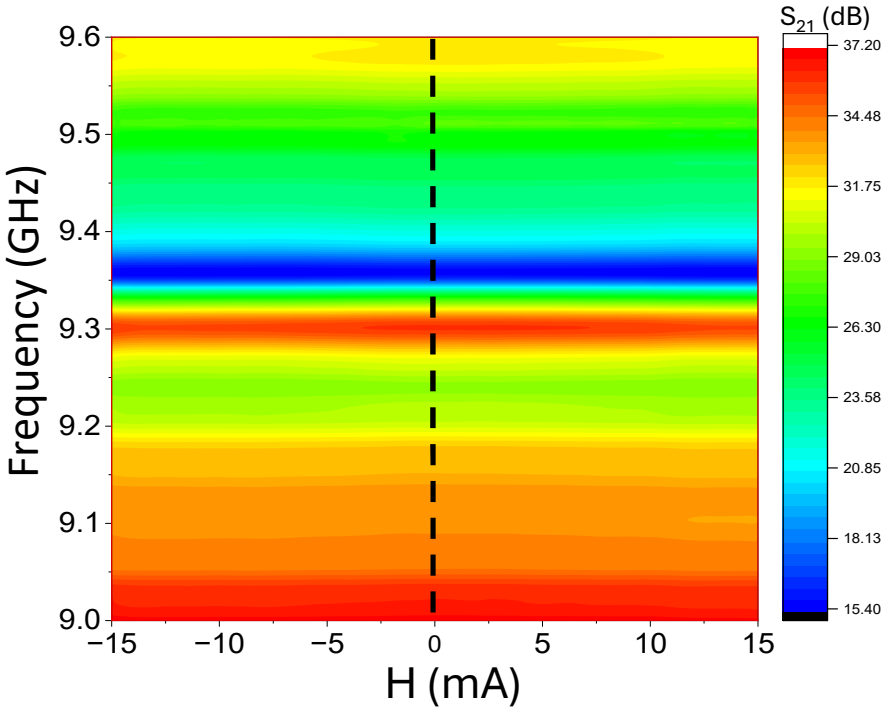
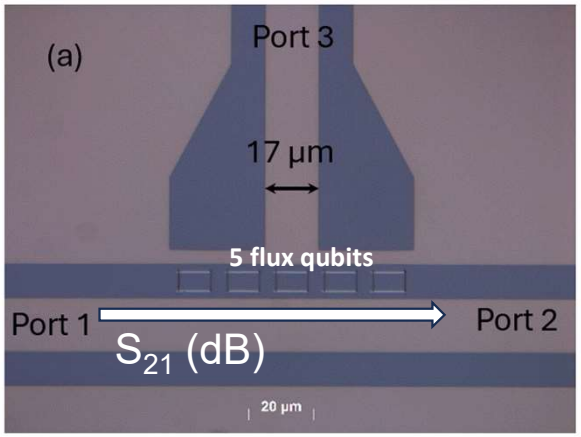
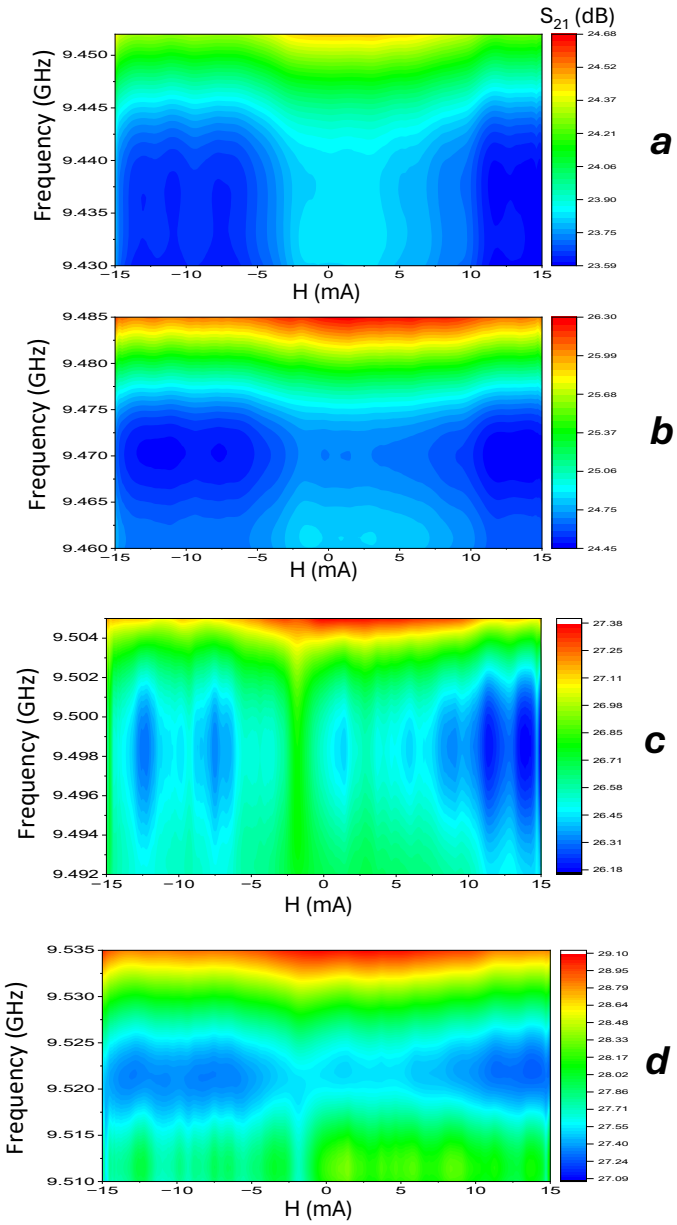
The transmission measurements of S21 versus frequency demonstrate the presence of number of resonant dips.



Color plot

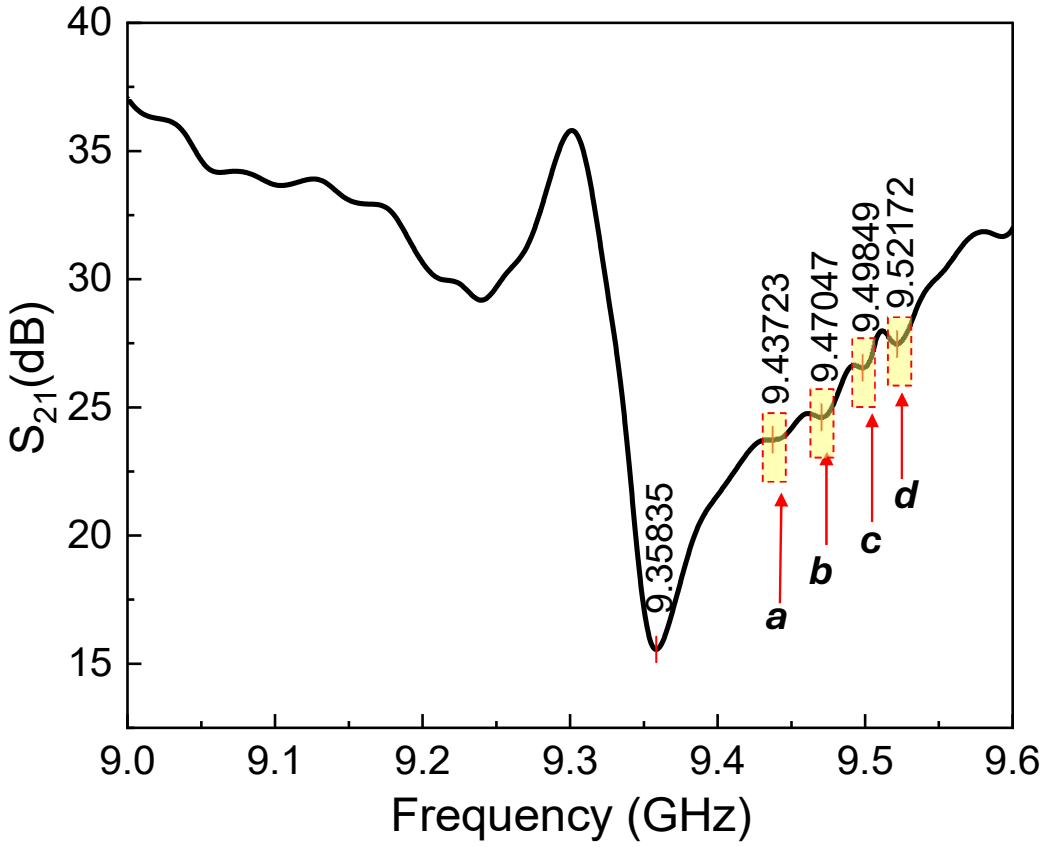


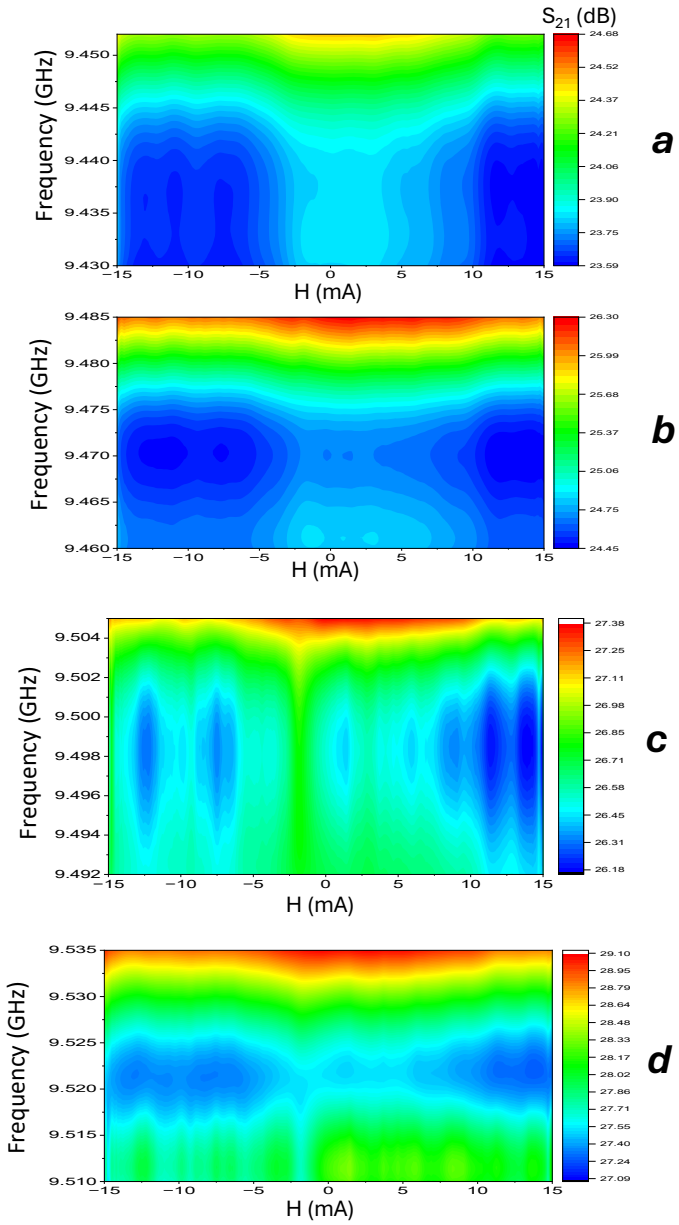




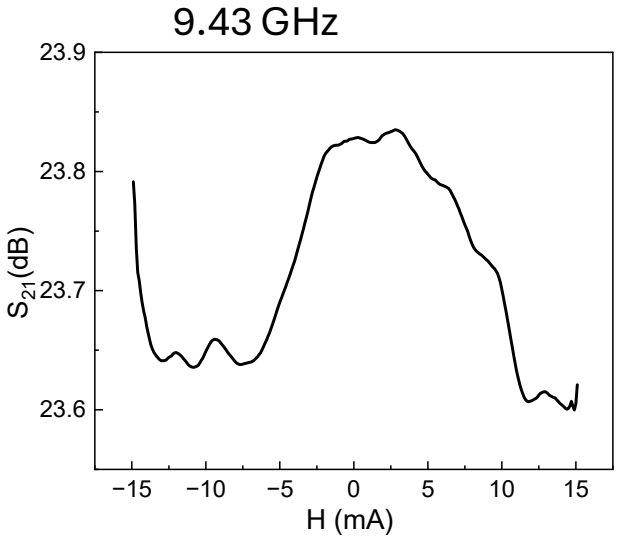
Periodic dependence of resonant dips as function of the external magnetic field is associated with the excitation of single qubits

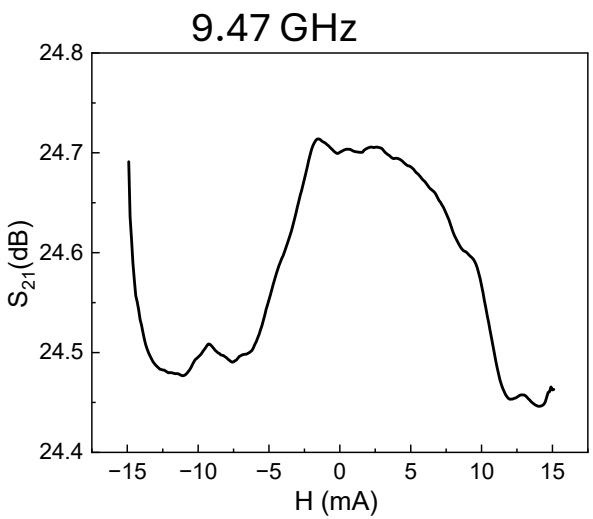
S_{21} resonance peaks as function of external magnetic field

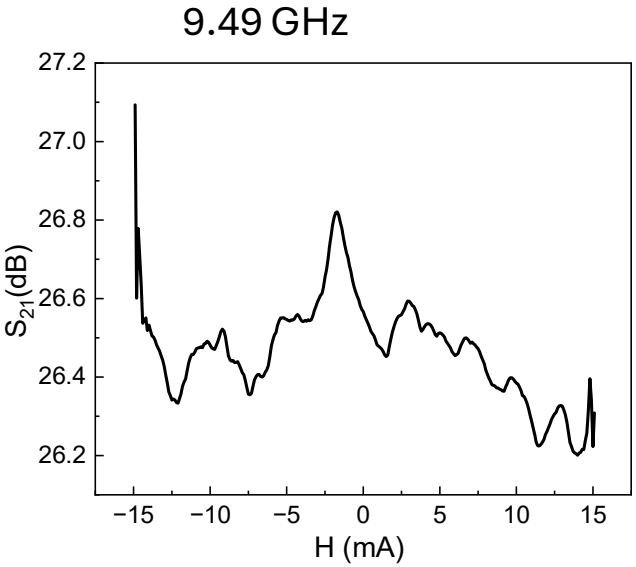


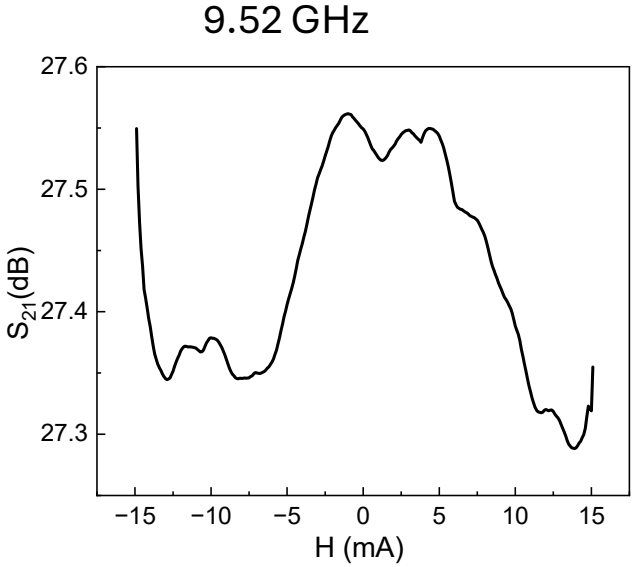


Periodic dependence of resonant dips as function of the external magnetic field is associated with the excitation of single qubits

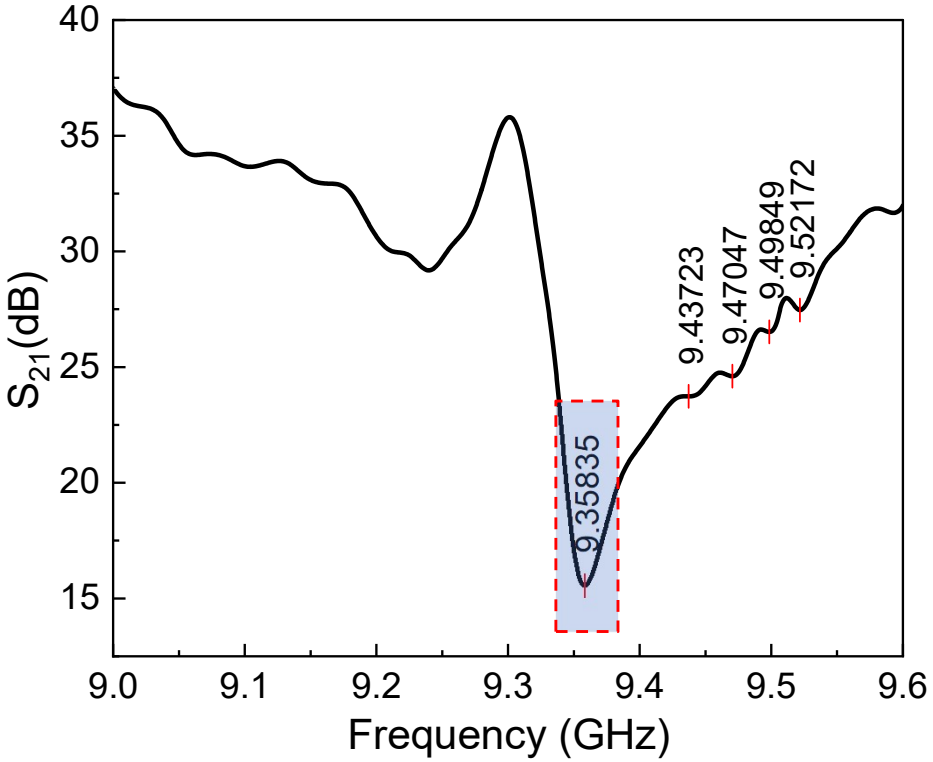




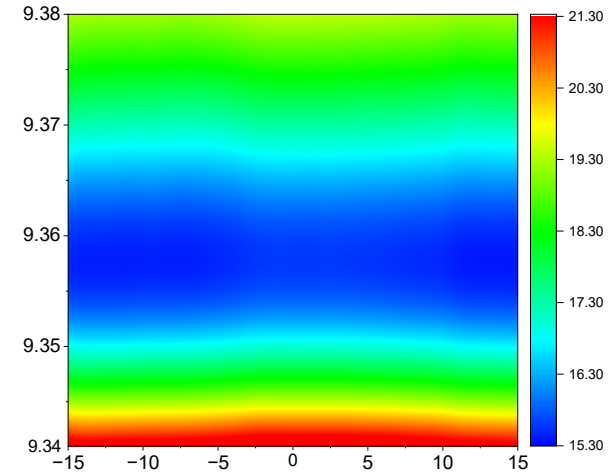


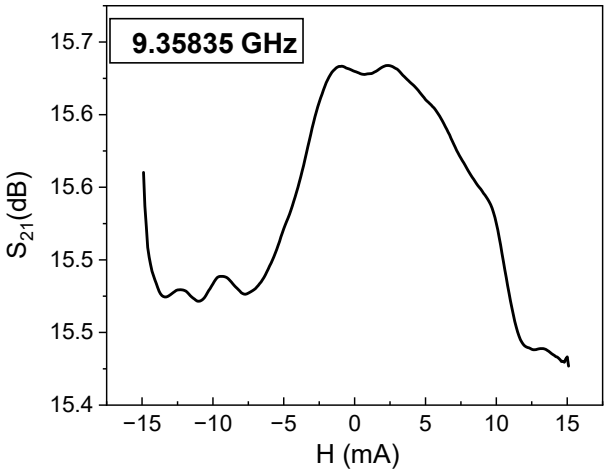


3 terminal SQN with 5 flux qubits



Color map S21 main dip resonance 9,35835 GHz





https://nqsti.it/research-highlights March 27th, 2024

The main resonant dip in $S_{21}(\omega)$ dependence and its periodic magnetic field oscillation indicate the presence of a strong long-range interaction between qubits leading to the quantum collective state

Is it possible to improve the robustness of Quantum Collective States in SQN?

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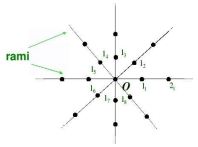
2 December 2024

Workshop Quantum Integration and Topology

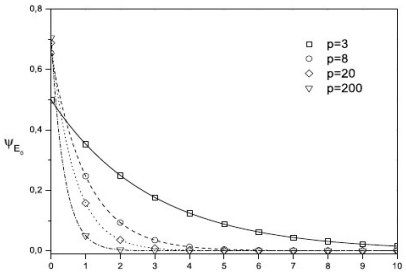
Topology-Induced Spatial Bose-Einstein Condensation in Inhomogeneous Josephson Junction Networks

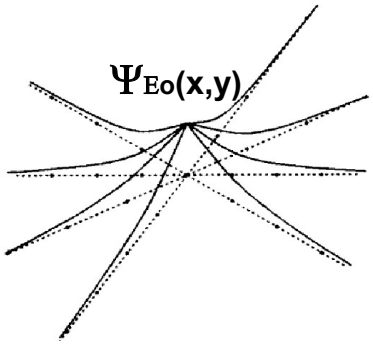
Experiments: ISASI/Tor Vergata

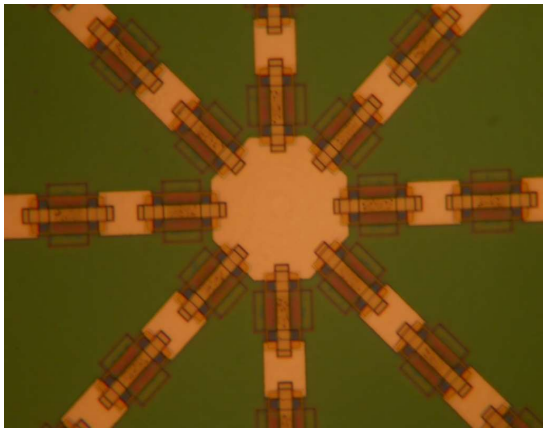
JJ STAR NETWORK

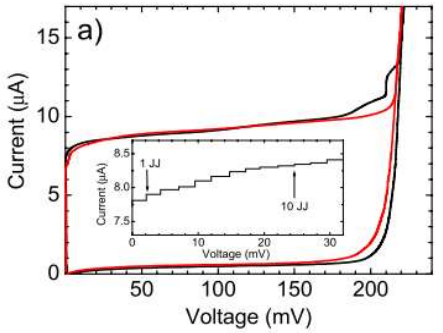


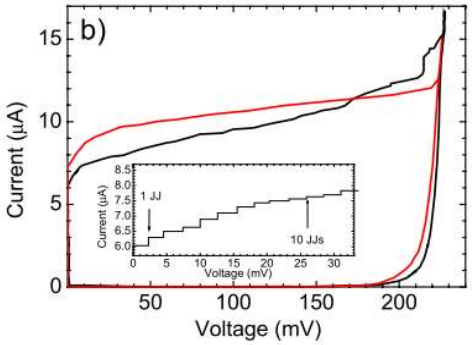
$$\psi_{E_0}^{star}(x,y) = \sqrt{\frac{p-2}{2p-2}} e^{-\frac{|x|}{\xi}} \qquad \xi = \frac{2}{\log(p-1)}$$











The observed phenomena evidence new and surprising behavior of transport properties in superconducting Josephson junctions Network

$T = 1.2\ k\ \Delta I_c = 15\ \%$

P. Sodano, A. Trombettoni, P. Silvestrini, R. Russo, B. Ruggiero
Inhomogeneous superconductivity in comb-shaped Josephson junction networks
New Journal of Physics 8, 327 (**2006**).

P. Silvestrini, R. Russo , V. Corato , B. Ruggiero, A. Trombrettoni
Topology-induced critical current enhancement in Josephson networks.
Physics Letters A370, 499 (**2007**).

M.Lucci, V.Campanari, D. Cassi, V. Merlo, F. Romeo, G. Salina, and M. Cirillo
Quantum Coherence in Loopless Superconductive Networks.
Entropy, 24, p.1690 **(2022)**

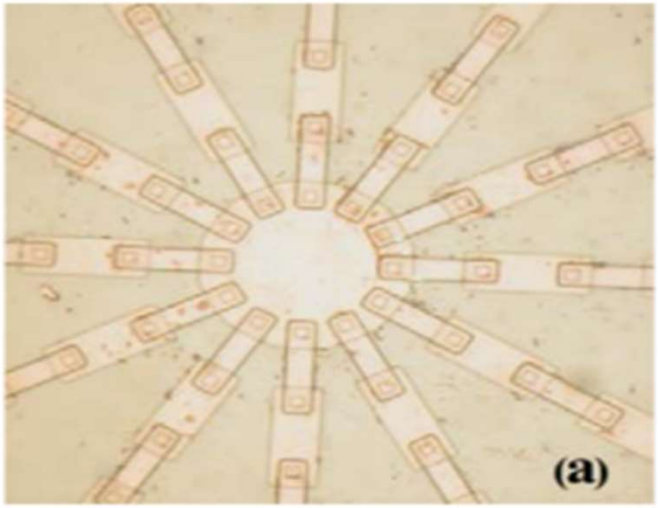
R. Bizzi, V. Campanari, D.Cassi, V. Merlo, and F. Romeo
Evidence of Long-Range Coherence in Superconducting Networks
IEEE Trans. On Appl. Supercond, 33, p. 1800106**, (2023)**

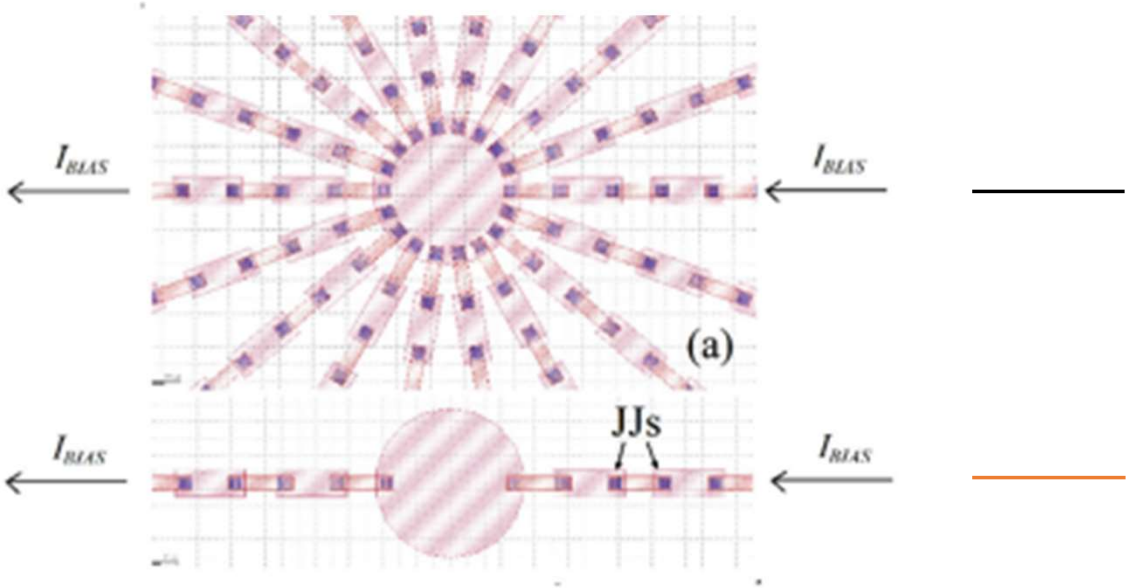
Macroscopically Coherent patterns of wave functions along specific directions

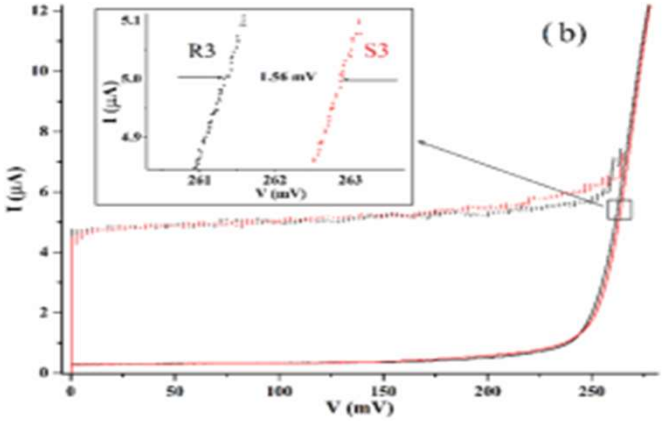
Existence of a Bose Einstein Consensation

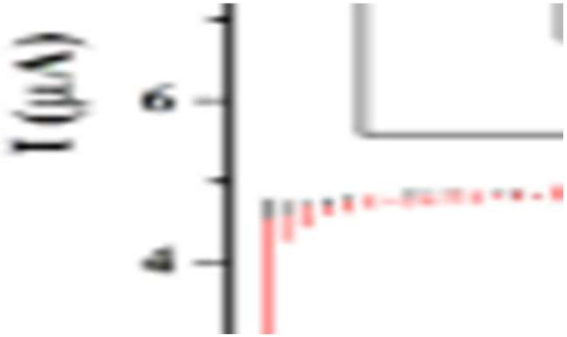
Enhancement of superconducting properties

2025





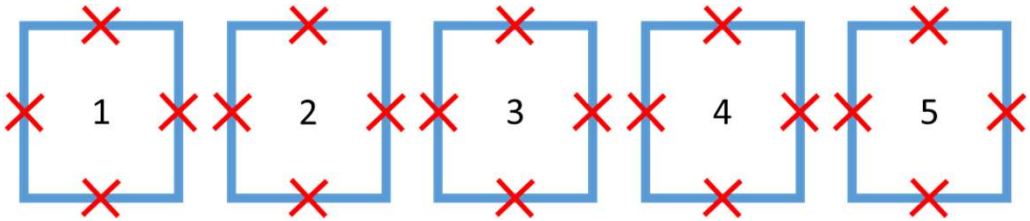




T= 4.2 k

ΔI_c= 8 %

Modeling Superconducting Qubit Networks with 5 flux qubit with inductive coupling



Assumptions

- **"ferromagnetic" inductive coupling**

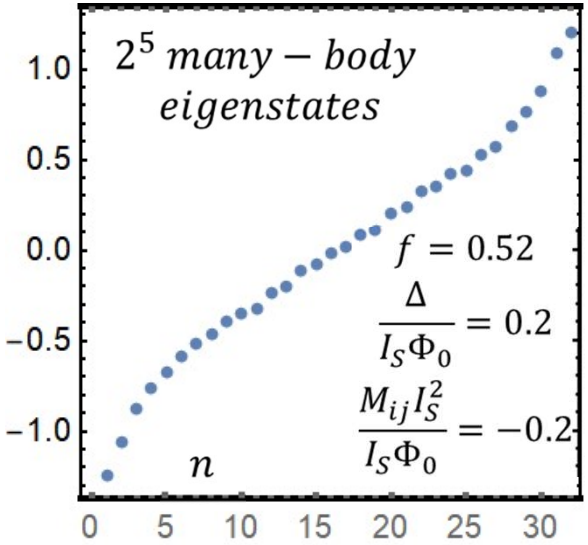
$$M_{ij} < 0$$

- **nearest neighbors inductive coupling**

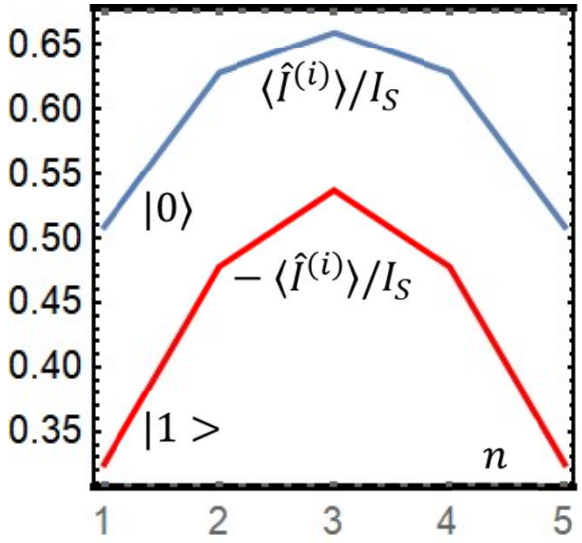
$$M_{ij} = 0, if\ |i-j| > 1$$

- **Absence of disorder**

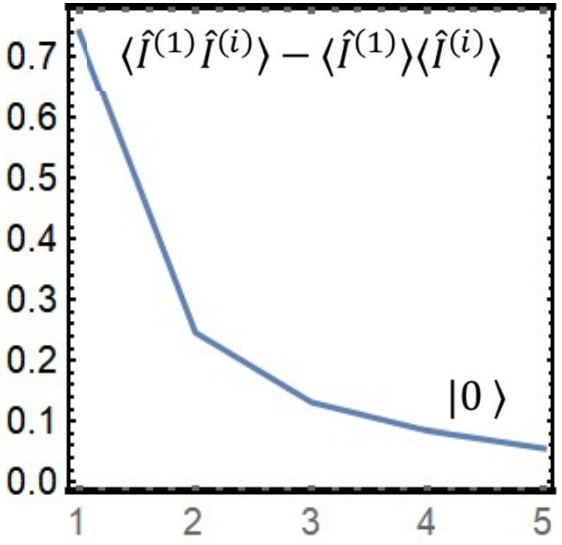
Energy eigenvalues (units $I_S\Phi_0$)



loop currents

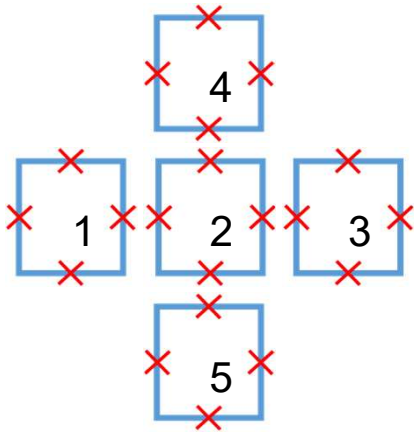


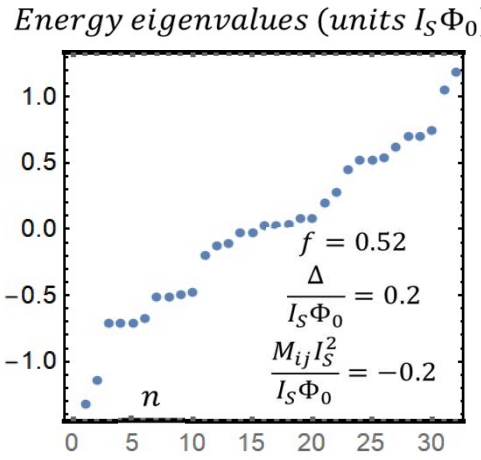
loop currents correlations

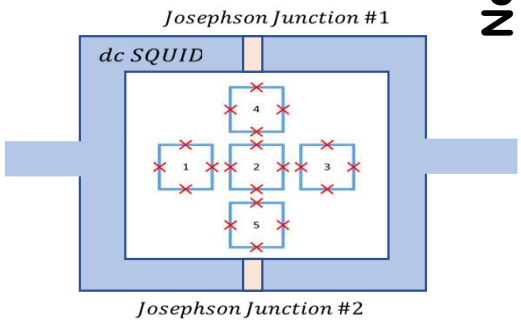


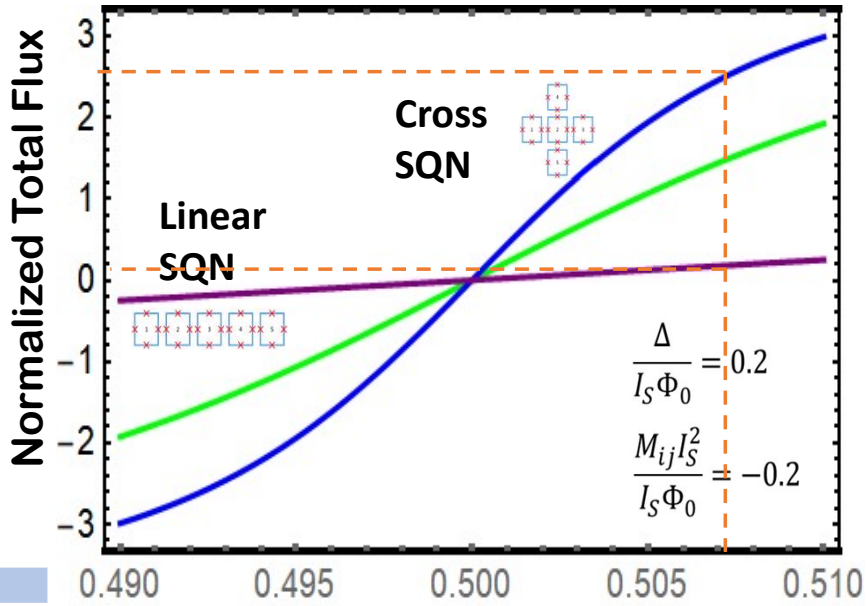
Insert Topology in Superconducting Qubit Networks with 5 flux qubit

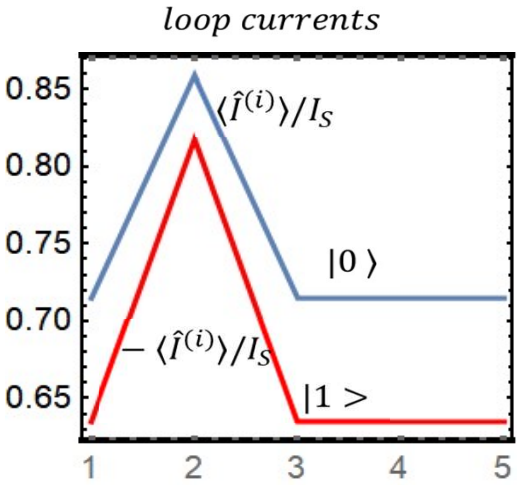
Cross SQN











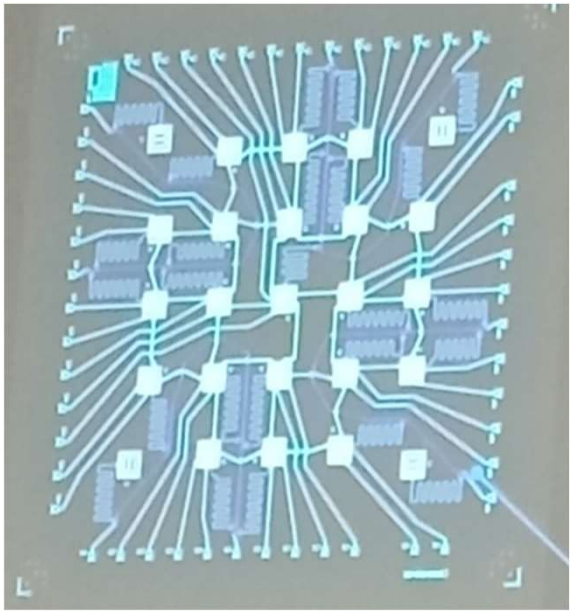
Topology-induced anharmonic spectral properties
Topology-induced loop currents enhancement

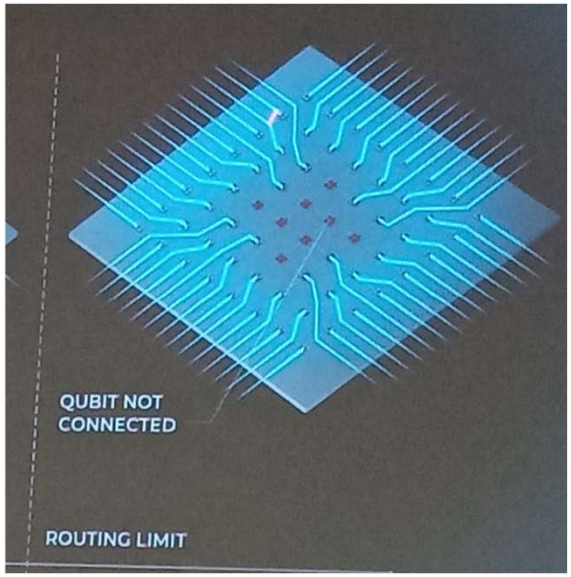
Robust QCS in SQN ?

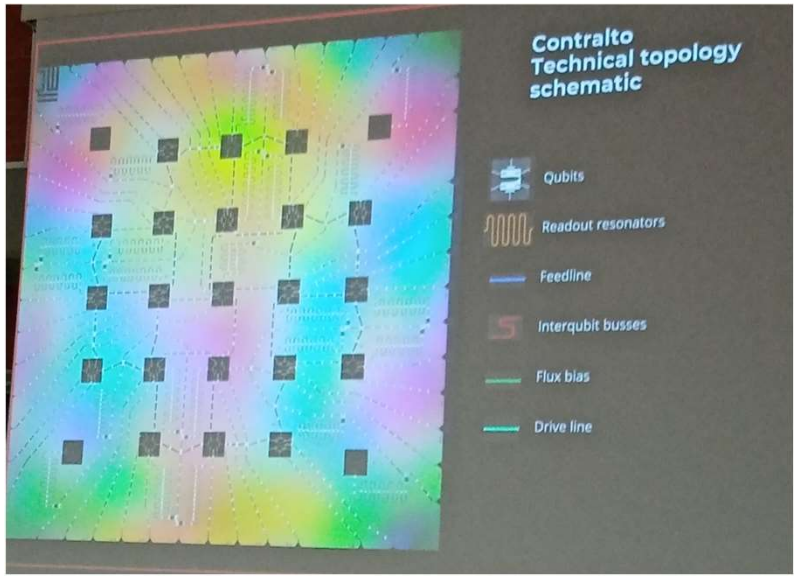
Topological Corrections in realising qubit chip

QC Companies

QuantumWare

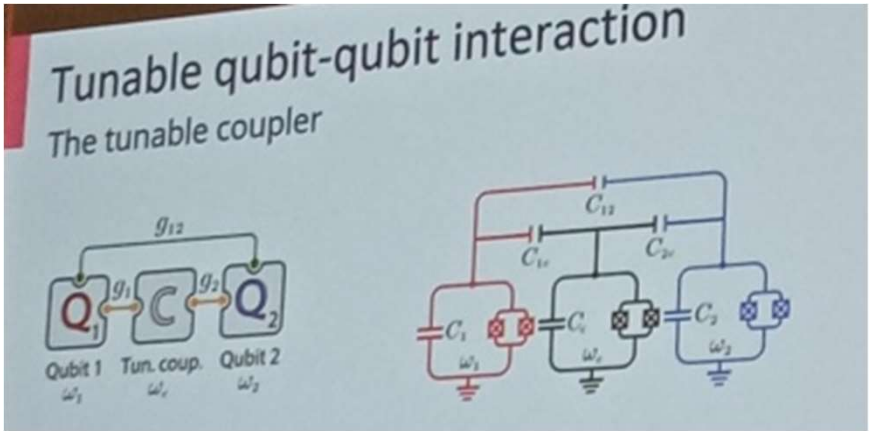






Rigetti

Qubit/qubit Interaction



Topology-induced Qubit/Qubit configurations …!!


Quantum Nexus – A Journey into Quantum Science and Technology
Città della Scienza – Napoli 9 Aprile 2025
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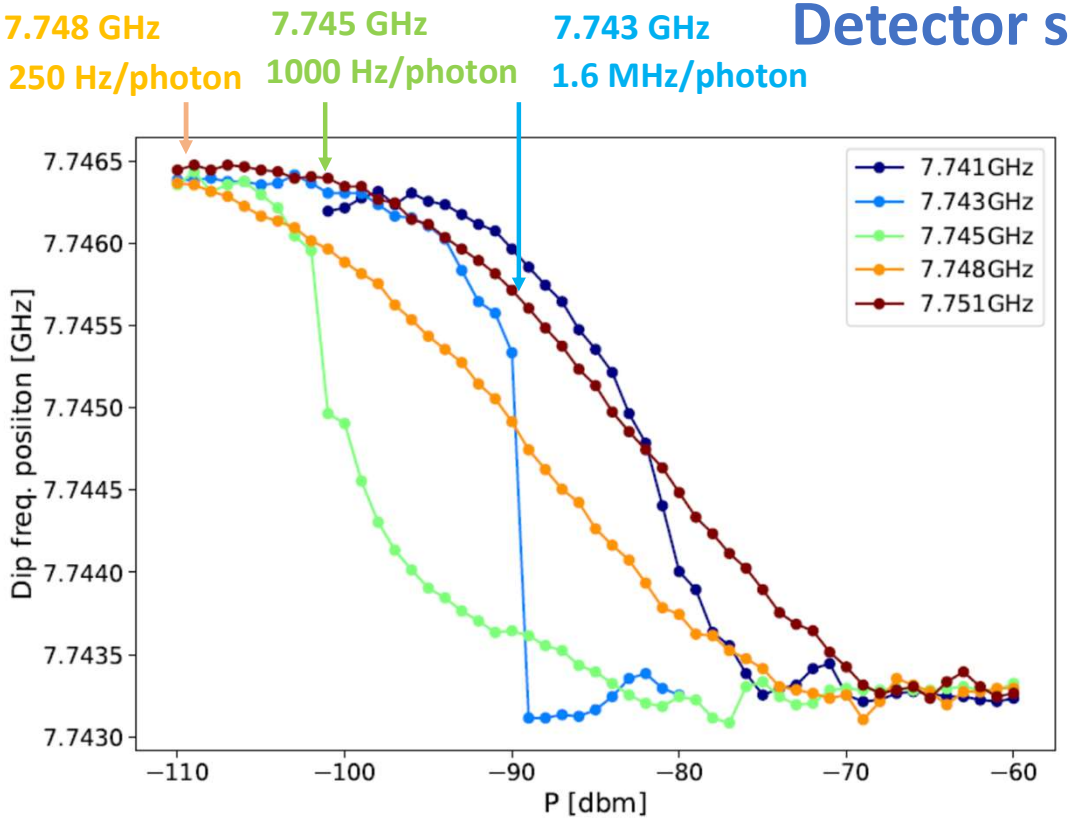
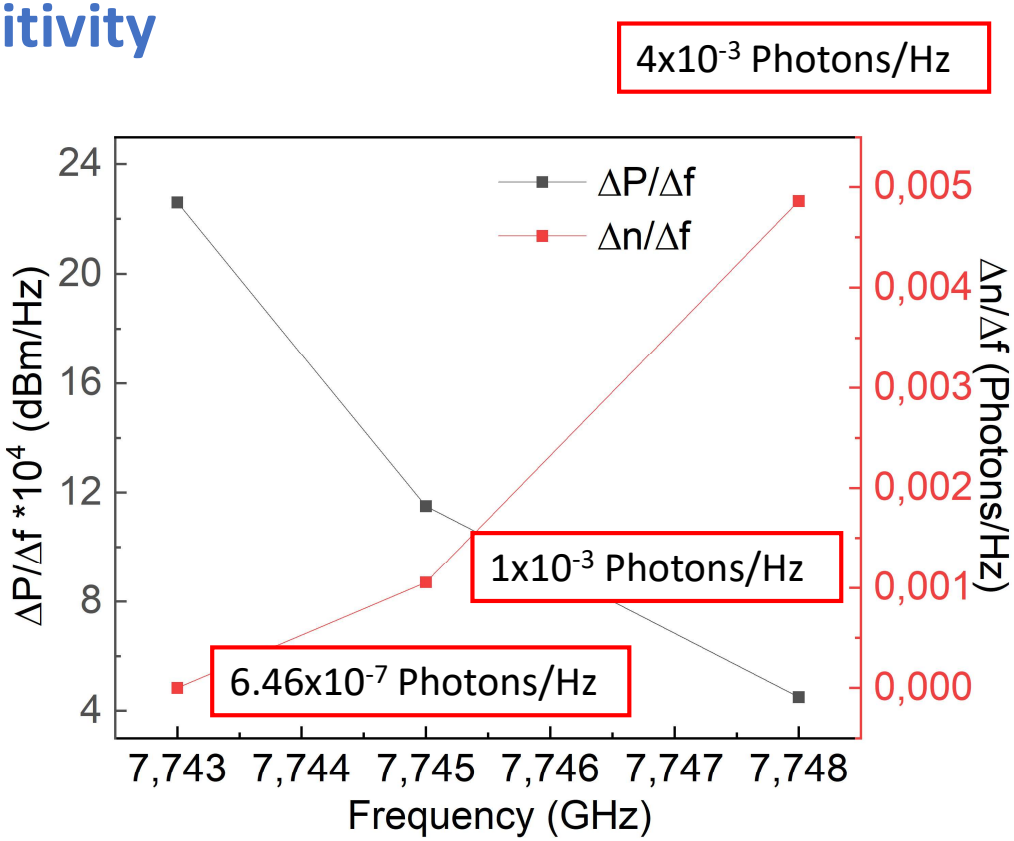
Detector sensitivity





Biasing the resonator at frequency of 7.743 GHz it could be possible to detect one photon in correspondence of the frequency dip shift of 1.6 MHz, which is an accessible frequency bandwidth included in the working limit of the device.

A) 1990-1999 ELQ, MQT, RMQT ICIB CNR

PHYSICAL REVIEW B VOLUME 54, NUMBER 2 1 JULY 1996-II

Resonant macroscopic quantum tunneling in SQUID systems

Paolo Silvestrini, Berardo Ruggiero, and Yuri N. Ovchinnikov*
Istituto di Cibernetica del C.N.R., I-80072, Arco Felice, Napoli, Italy
(Received 29 January 1996)

Nb

30 mK=T<Tcros

$$\Gamma(K) = \frac{dI}{dt}\frac{1}{\Delta I}\frac{P(K)}{\sum_{j=1}^{K_{max}} P(j) - \sum_{j=1}^{K} P(j)}.$$

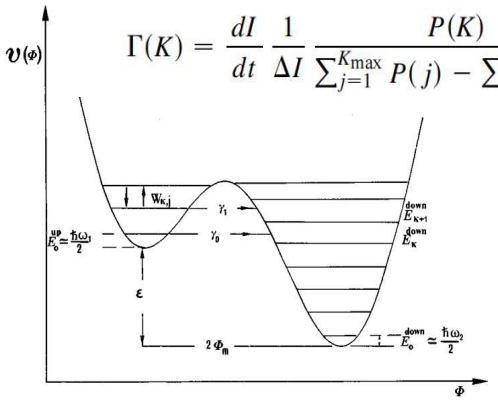


FIG. 1. Sketch of the potential $U(\Phi)$ describing the SQUID dynamics in a quantum picture.

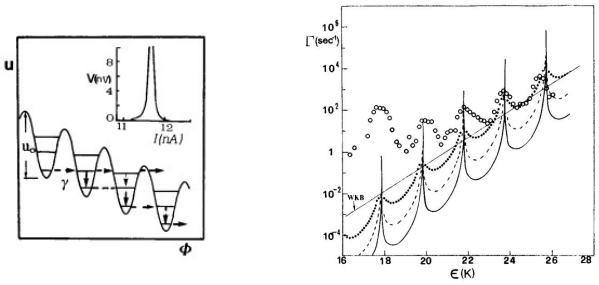
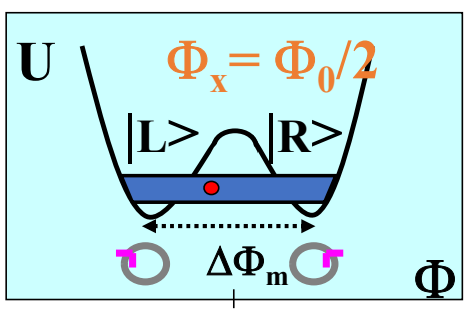
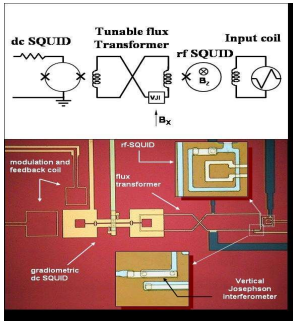


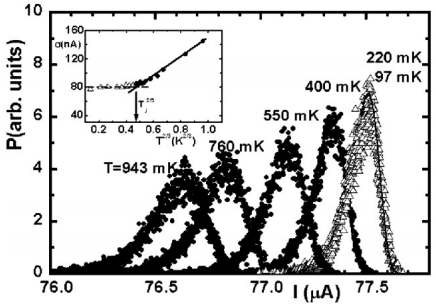
FIG. 2. Escape rate Γ vs ε. Open circles are data from Ref. 9, while three different values of resistance have been considered for the theoretical curves: $R/R_Q=100$ (solid line), $R/R_Q=10$ (dashed line); $R/R_Q=1$ (solid points); $R_Q=6.45$ kΩ. For all the curves $L=210$ pH, $C=80$ pF, and $\Delta U_0=16.3$ K.

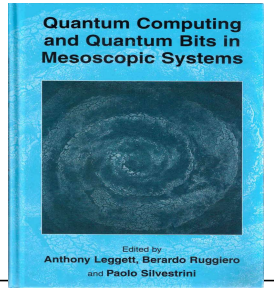
B) 2000-2013 MQC Group ICIB CNR

Nb









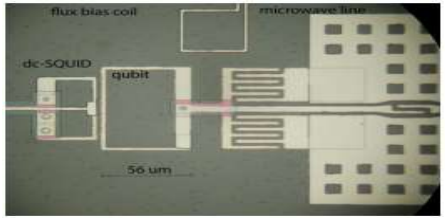
Nb rf-SQUID as a qubit

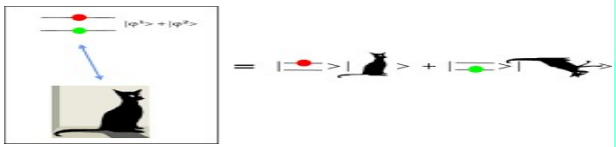
20 mK=T<Tcros

C) 2014-2018 MQC in phase qubits

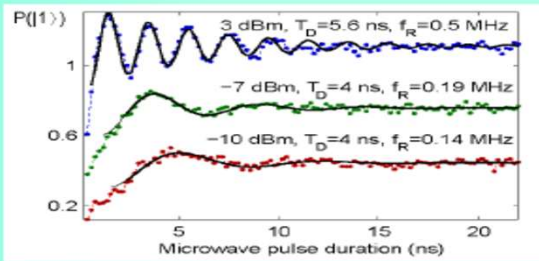
NbN based superconducting Josephson phase qubit with AlN tunnel barrier
M.P. Lisitskiy, et al IEEE Trans on Superc. pp.1-3 (2017)

NbN





Rabi oscillations



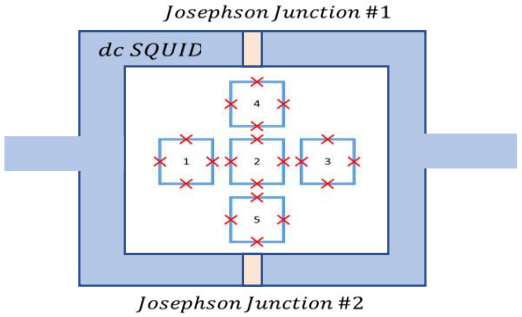
Rabi oscillations are measured by varying the duration of the resonant microwave pulse $\Delta t_{\mu W}$. The mean decay time is about of 3-5 ns.

Fabrication a) and Measurements b) (Cross SQN)

a) EBL ISASI CNR

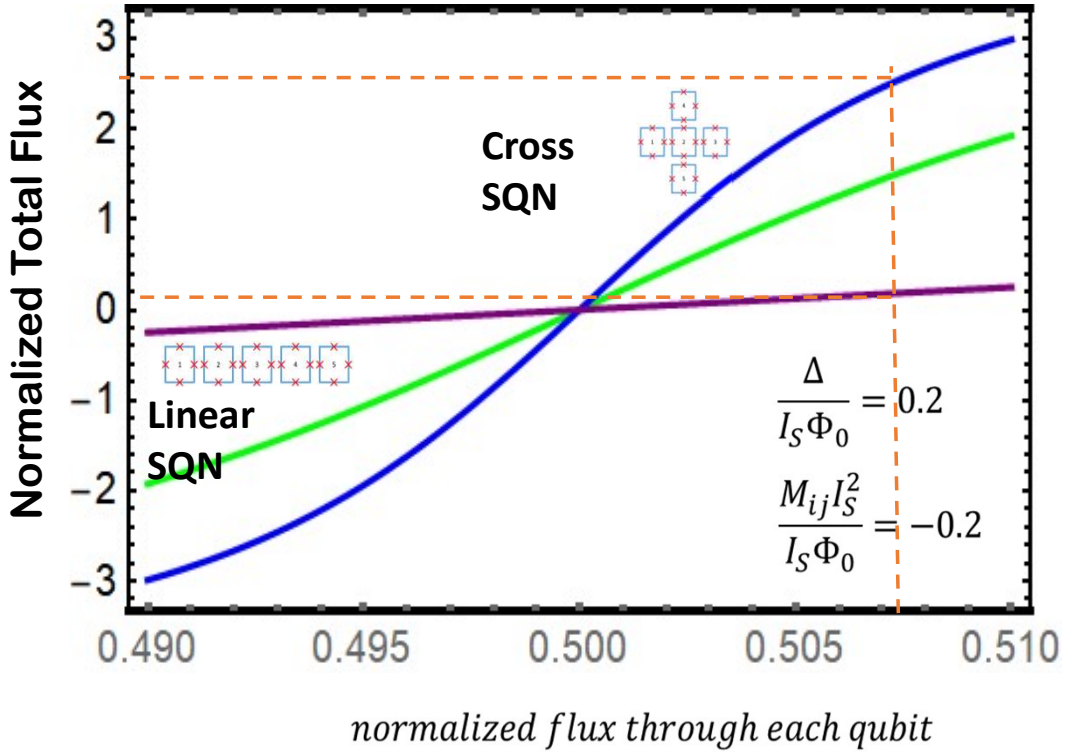
SQN with 5 flux Qubit with 4 Josephson Junction

Area JJ =0.2x0.5 μm²



b) ADR Helium Free Cryostat T= 50 mK @ SPIN/ISASI Pozzuoli CNR

Robust QCS in SQN ?

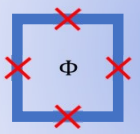


Modeling Superconducting Qubit Networks with 5 flux qubit with inductive coupling

F. Romeo et al. May 2024

a) 4 JJ Flux Qubit Effective Hamiltonian

Qubit effective Hamiltonian



$$\hat{H}_{eff} = -\epsilon(f)\,\sigma_z - \Delta\,\sigma_x$$

$$f = \frac{\Phi}{\Phi_0}$$

$$\epsilon(f) = I_S\Phi_0\left(f - \frac{1}{2}\right)$$

Coherent superposition of current states,

$$|g; f=0\rangle = \frac{1}{\sqrt{2}}(|\uparrow\rangle + |\downarrow\rangle)$$

$$|e; f=0\rangle = \frac{1}{\sqrt{2}}(|\uparrow\rangle - |\downarrow\rangle)$$

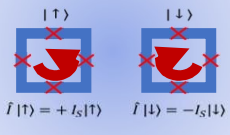
A two-level system

$$R(\theta) = \begin{pmatrix} \cos(\theta) & \sin(\theta) \\ \sin(\theta) & -\cos(\theta) \end{pmatrix}$$

$$\cos(\theta) = \frac{\epsilon}{\sqrt{\epsilon^2+\Delta^2}}, \quad \sin(\theta) = \frac{\Delta}{\sqrt{\epsilon^2+\Delta^2}}$$

Current Operator & Current states

$$\hat{I} = -\frac{\partial \hat{H}_{eff}}{\partial \Phi} = I_S\sigma_z$$

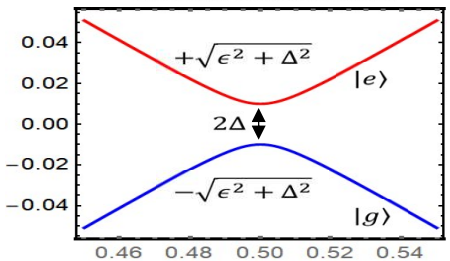


$$E_{\pm} = \pm\sqrt{\epsilon^2+\Delta^2}$$

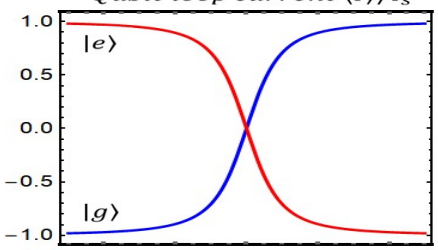
$$\langle\hat{I}\rangle_g = \langle g|\hat{I}|g\rangle = +I_s\cos(\theta)$$

$$\langle\hat{I}\rangle_e = \langle e|\hat{I}|e\rangle = -I_s\cos(\theta)$$

Energy eigenvalues

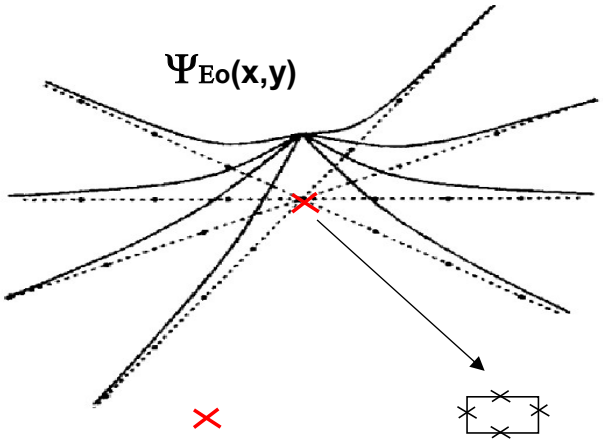


Qubit loop current $\langle\hat{I}\rangle/I_s$



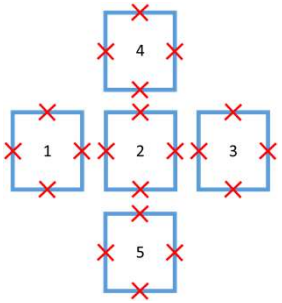
$$\cos(\theta) = \frac{\epsilon}{\sqrt{\epsilon^2+\Delta^2}} = \frac{f-\frac{1}{2}}{\sqrt{\left(f-\frac{1}{2}\right)^2+\Gamma^2}}, \Gamma = \frac{\Delta}{I_S\Phi_0}$$

b) SQN topology effects

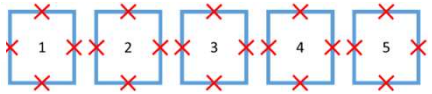


Josephson Junctions → 4 JJ Flux Qubit

Cross SQN



Linear SQN



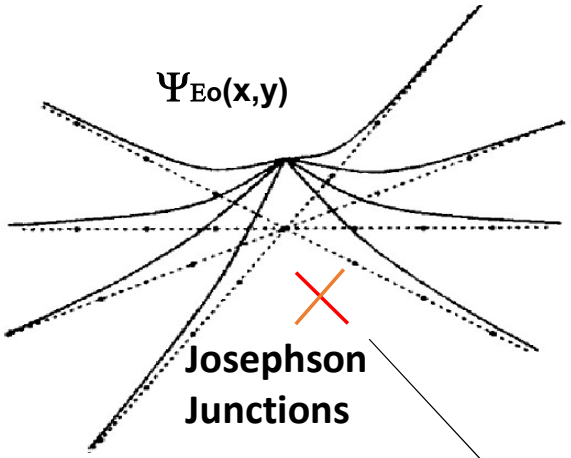
A Many-body Problem

$$H = \sum_i H_q^{(i)} + \frac{1}{2}\sum_{\substack{i,j \\ i\neq j}} U_{ij}$$

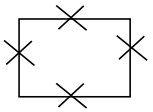
$$H_q^{(i)} = -\left[\epsilon_i(f)\,\sigma_z^{(i)} + \Delta_i\,\sigma_x^{(i)}\right]$$

$$U_{ij} = \sum_{\substack{i,j \\ i\neq j}} M_{ij}\,I_S^{(i)}I_S^{(j)}\sigma_z^{(i)}\sigma_z^{(j)}$$

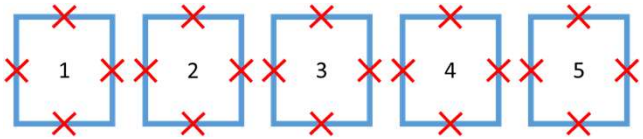
JJ STAR NETWORK



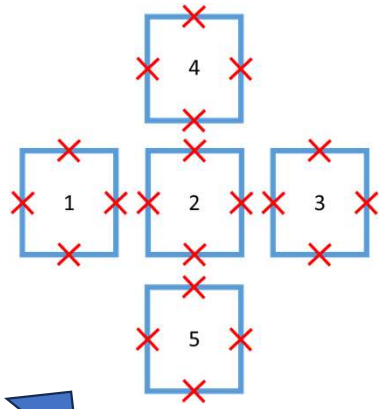
4 JJ Flux Qubit

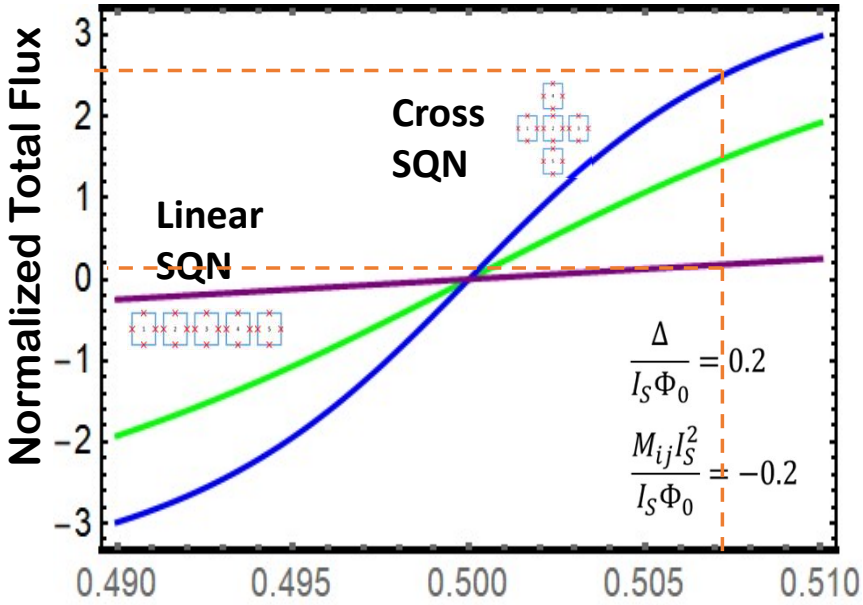


Linear SQN



Cross SQN for Quantum Integration





Robust QCS in SQN ?