The Qub-IT Project

Quantum Sensing with Superconducting Qubits for Fundamental Physics

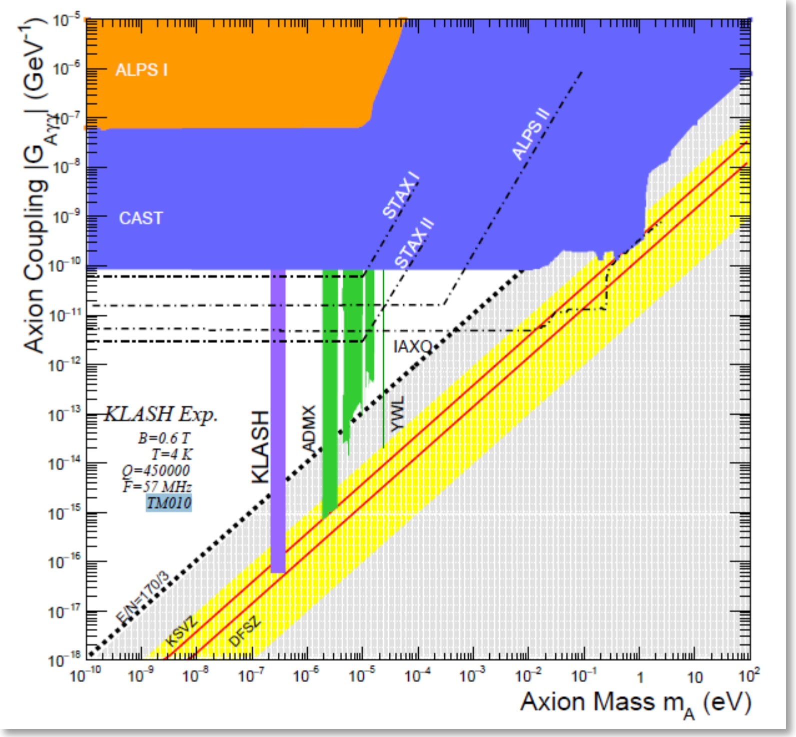
Preventivi GruppoV - G.Lamanna

28.6.2021

The SIMP project

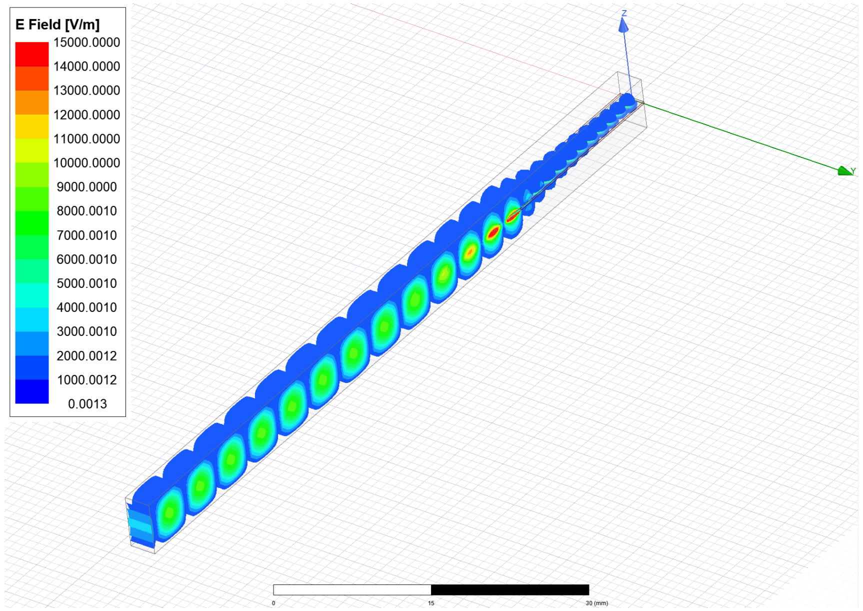
- The purpose of SIMP (2019->2021) was to investigate two different technologies for single photon detection in the microwave region:
  - TES (Transition Edge Sensors): in the region above 20 GHz
  - Current biased Josephson Junctions: in the region below 10 GHz

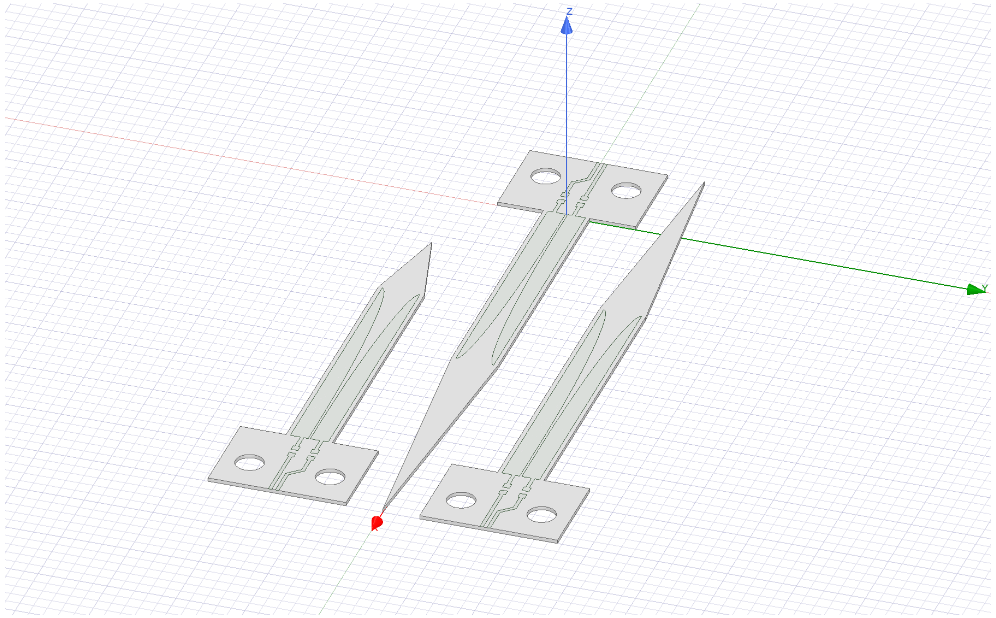
- Main reason: remove the limit of the electronic noise in searching for very rare processes (Axions, Dark Photons, …)

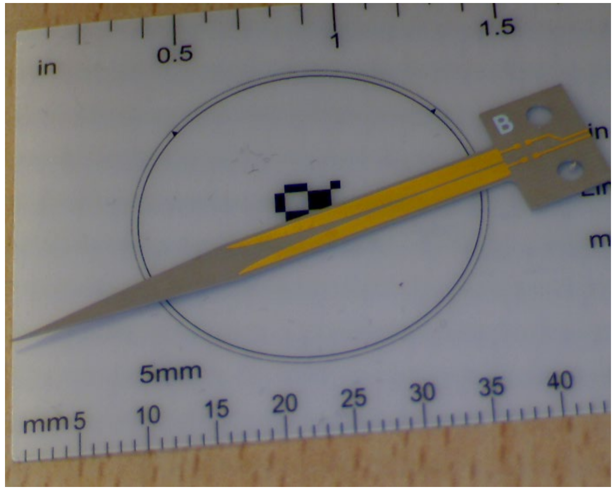


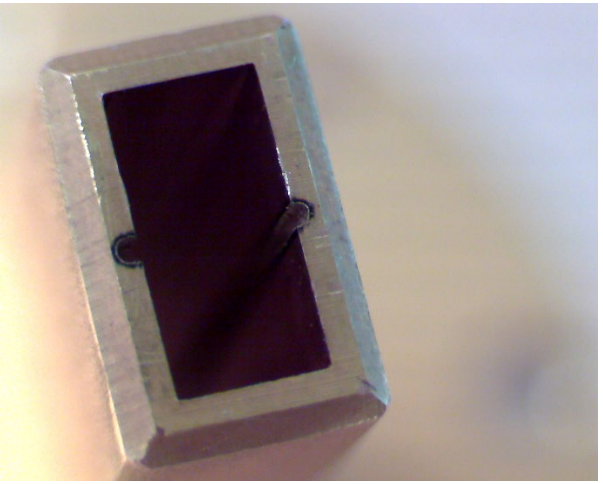
Pisa Activities

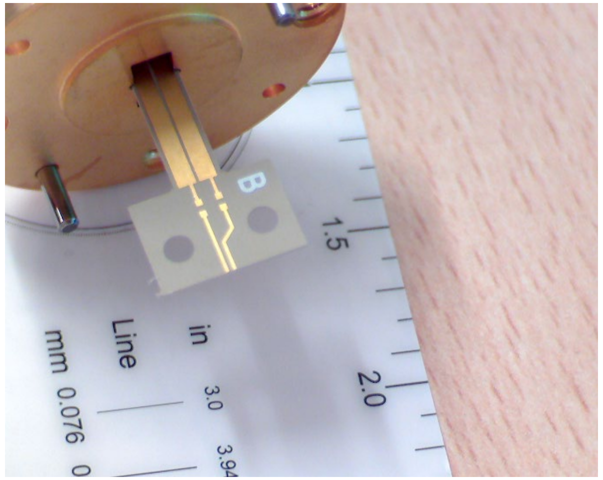
- In Pisa we mainly focus on TES detector and design of the antenna to collect signal from a 3D cavity

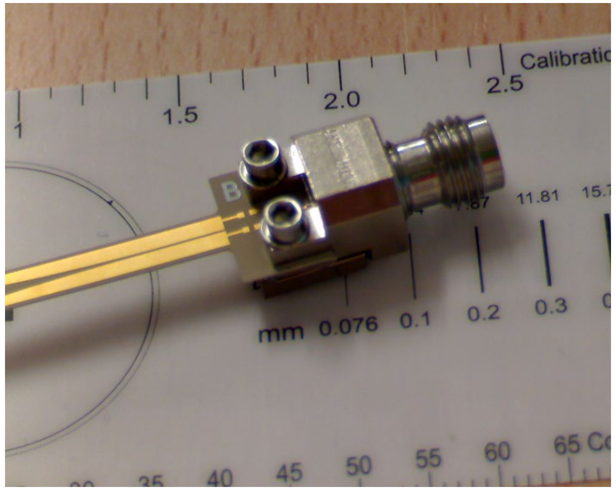


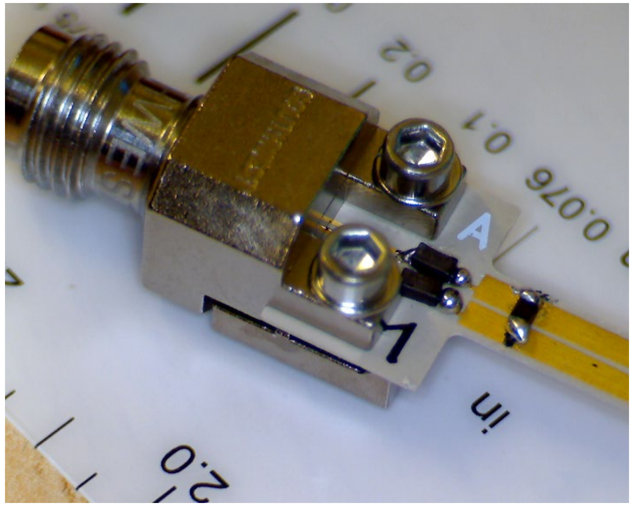


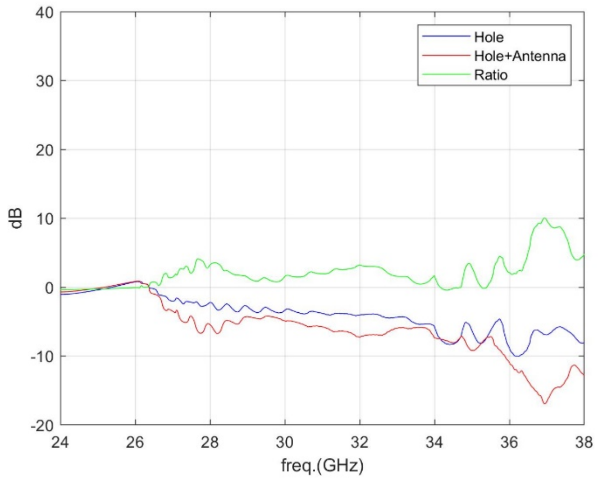

in
0.5
1
1.5
B
5mm
mm 5
10
15
20
25
30
35
40

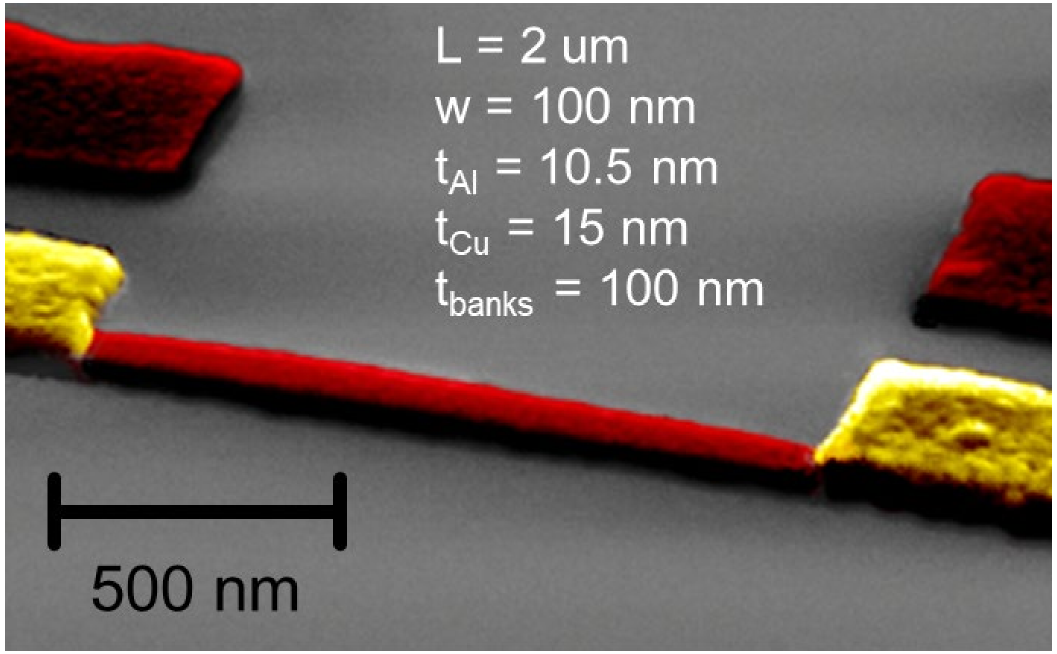



B
1.5
2.0
in
Line
mm
0.076
3.0


1
1.5
2.0
2.5
B
11.81
mm
0.076
0.1
0.2
0.3
40
45
50
55
60


A
in

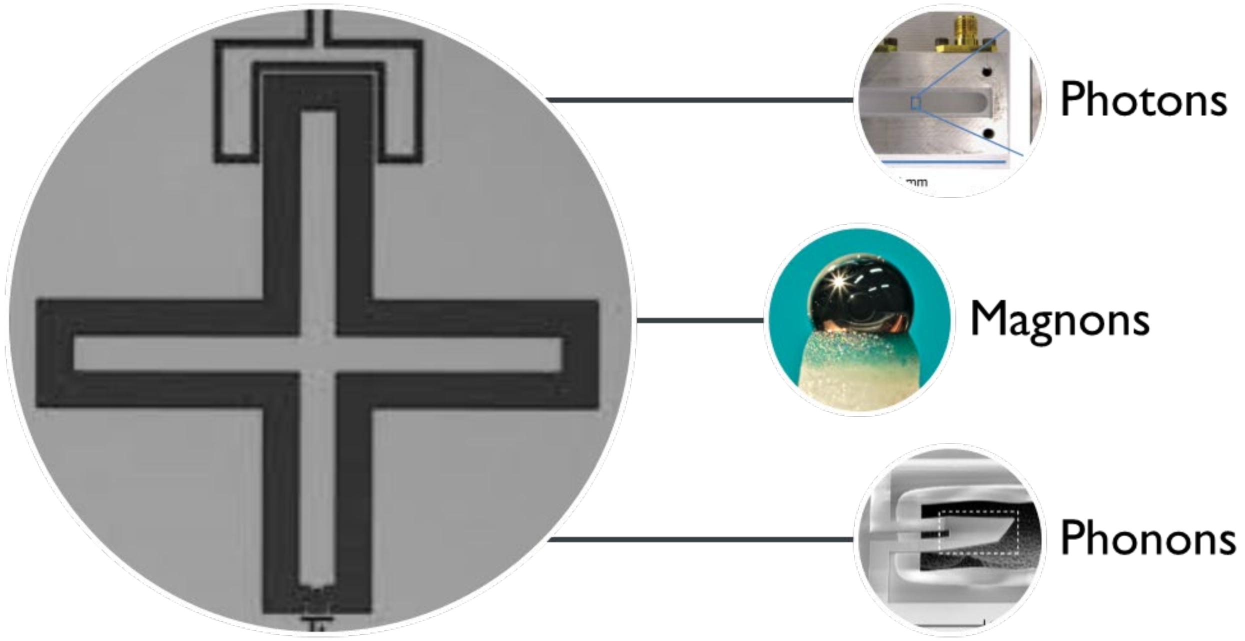

Hole
Hole+Antenna
Ratio
dB
40
30
20
10
0
-10
-20
24
26
28
30
32
34
36
38
freq.(GHz)



nano-TES	T_c (mK)	τ (μs)	τ_{eff} (μs)	NEP_{TFN} ($W/\sqrt{Hz}$)	NEP_{tot} ($W/\sqrt{Hz}$)	$\delta\nu$ (GHz)	$\nu/\delta\nu$ 100 GHz	300 GHz	1 THz
1	139	5	0.2	6.7×10^{-20}	6.7×10^{-20}	540	0.18	0.55	1.8
1*		5	0.2	1.5×10^{-16}	8.3×10^{-15}	1×10^{6}	8×10^{-5}	2×10^{-4}	8×10^{-4}
2	128	6	0.01	5.2×10^{-20}	5.2×10^{-20}	100	1	3	10
2*		6	0.01	1.1×10^{-16}	4.7×10^{-16}	2×10^{5}	4×10^{-4}	1×10^{-3}	4×10^{-3}

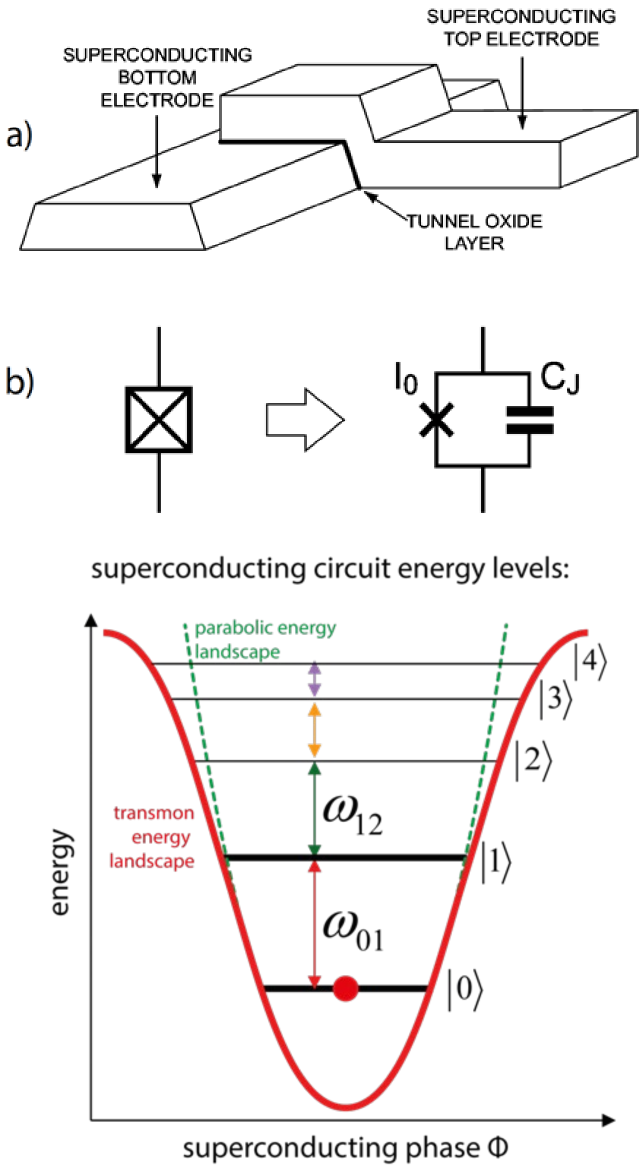
From SIMP to Qub-IT

- We realized that in the last years there has been a great progress in the ability to measure and manipulate “quanta” (photons, phonons, magnons), for different purposes.
- This opens new direction in the detection of Dark Matter, Fifth Forces, tests of quantum gravity and quantum mechanics in macroscopic objects
- The building block of this new era of quantum sensing are the superconducting qubits
- The JJ we studied in SIMP are SC qbits



SC Qubit

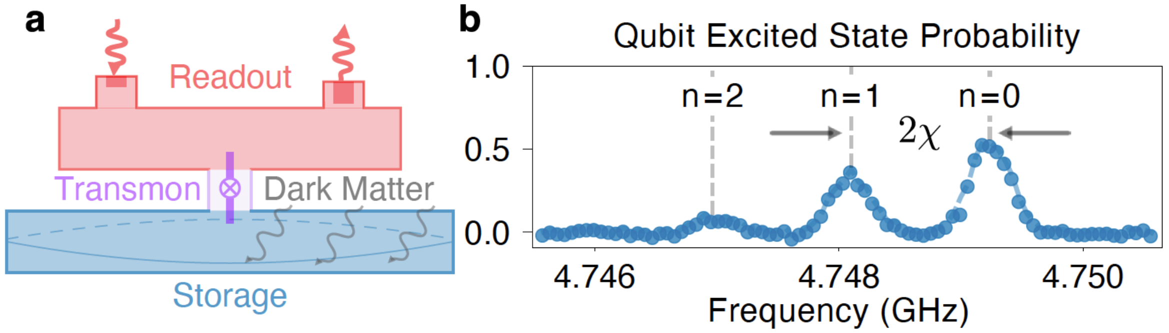
- Artificial Atoms can be built using current biased JJ
- The JJ are S-I-S in which the connection between the two SCs is done through tunnel effect in a very thin oxide layer
- The anharmonicity of the energy levels is the important characteristics to allow discrete states in the system
- An high coherence is requested to maintain the status as long as possibile
- The Transmon scheme (a type of charge qbit) is an active area of research for quantum computing
- The main purpose is to study this scheme for photons detection, but…

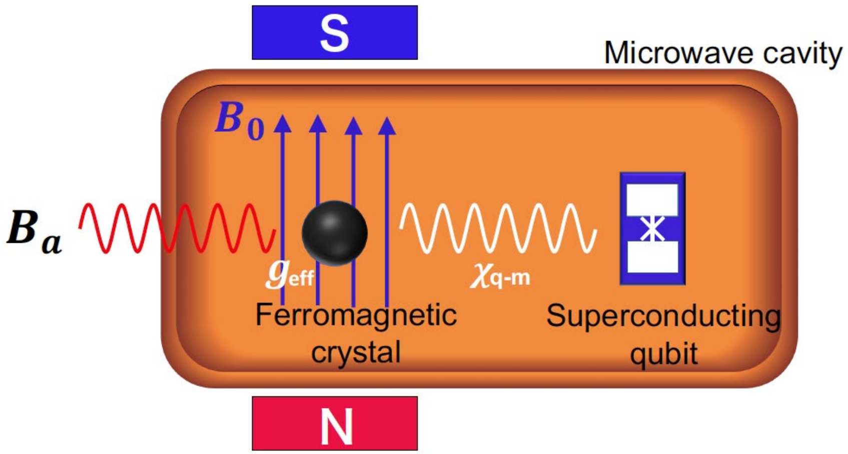


Dark Matter direct search with transmons

Photon sensing – Dark Photon

A V Dixit et al., "Searching for Dark Matter with a Superconducting Qubit," Phys. Rev. Lett. 126, 141302 (2021).

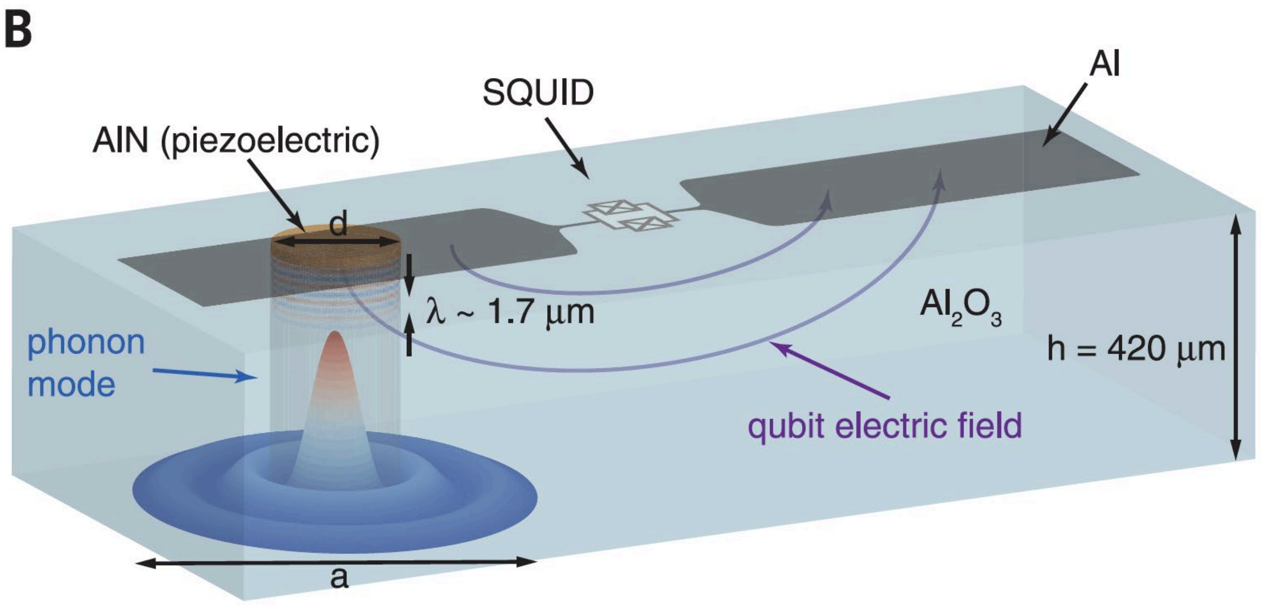




Magnon sensing – Axions

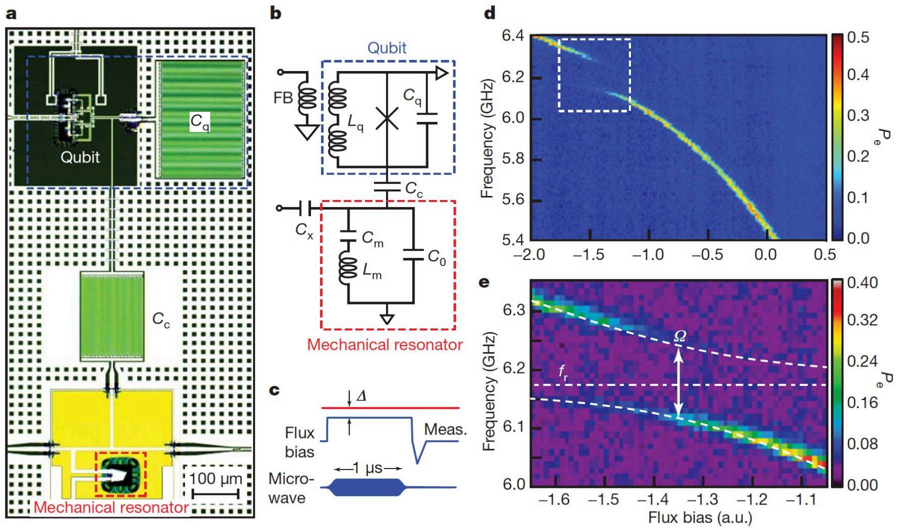
T Ikeda et al. "Axion search with quantum nondemolition detection of magnons," arXiv:2102.08764.

Measure single phonons with SC qbit



Chu et al, "Quantum acoustics with SC qubits," Science 358, 199 (2017)

A D O'Connell et al, "Quantum ground state and single-phonon control of a mechanical resonator," Nature 464 (2010)



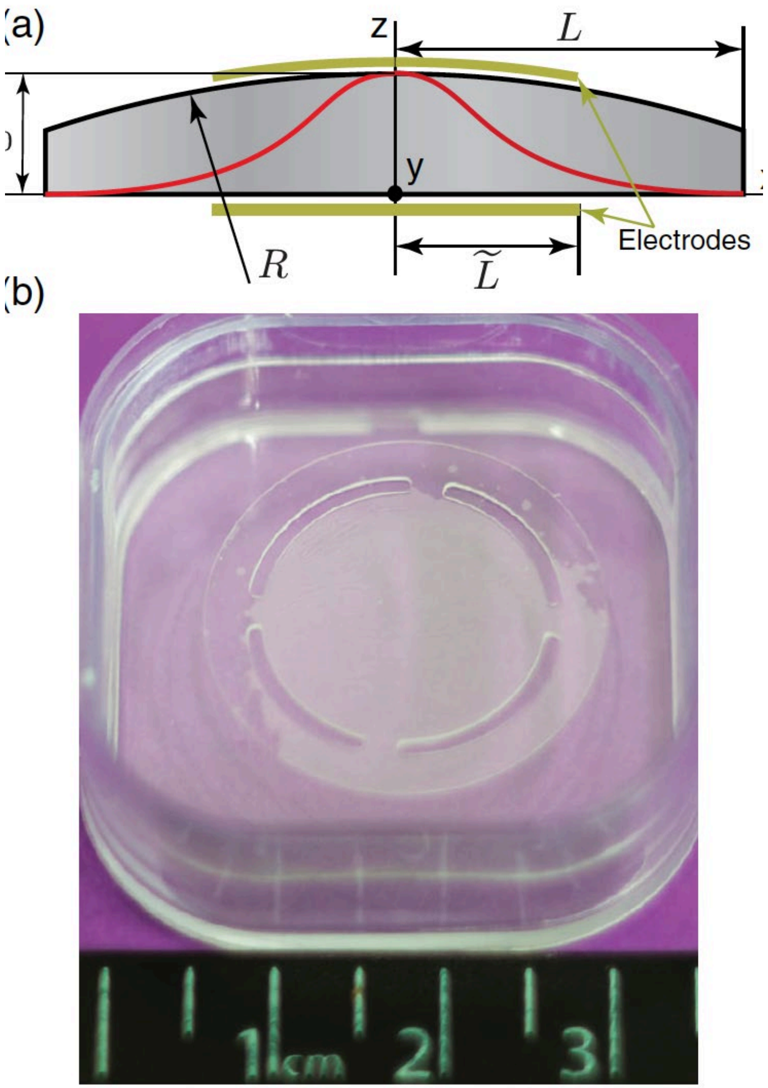
Dark Matter and GW with mechanical resonators

- Light Dark Matter or high frequency GW can induce oscillation (from MHz to GHz) of piezoelectric quartz bulk acoustic wave (BAW) resonators cooled at mK temperatures.

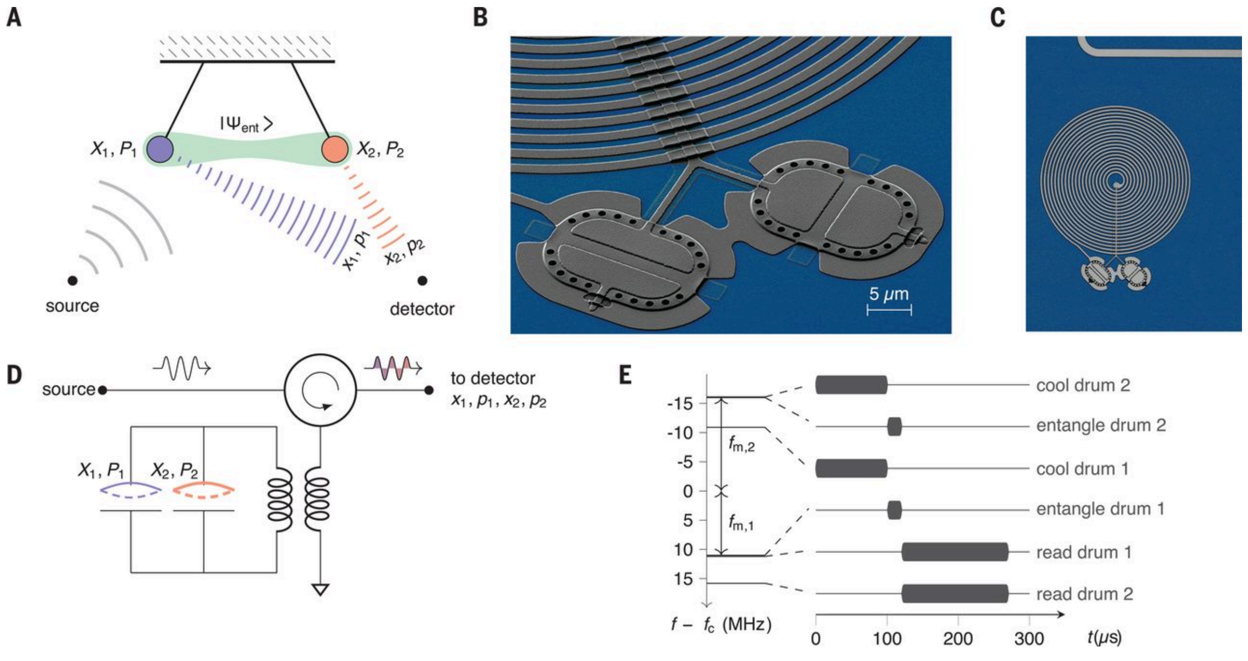
M Goryachev and M E Tobar, "Gravitational wave detector with high frequency phonon trapping acoustic cavities "PHYSICAL REVIEW D 90, 102005 (2014)

D Carney et al, "Mechanical quantum sensing in the search for dark matter," Quantum Sci. Technol. 6 (2021) 024002.

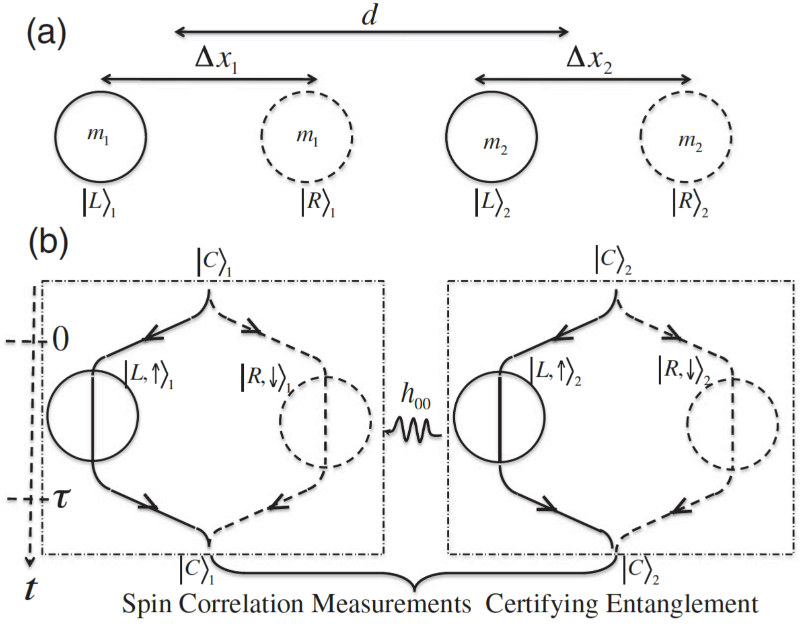
A Arvanitaki et al, "The sound of dark matter: searching for light scalars with resonant-mass detectors", Phis Rev Lett 116 031102 (2016).



Macroscopic entangled systems and quantum gravity



Kotler et al, "Direct observation of deterministic macroscopic entanglement," Science 372, 622 (2021)



Bose et al, "Spin Entanglement Witness for Quantm Gravity", PRL 119 240401 (2017)

Qub-IT Objectives

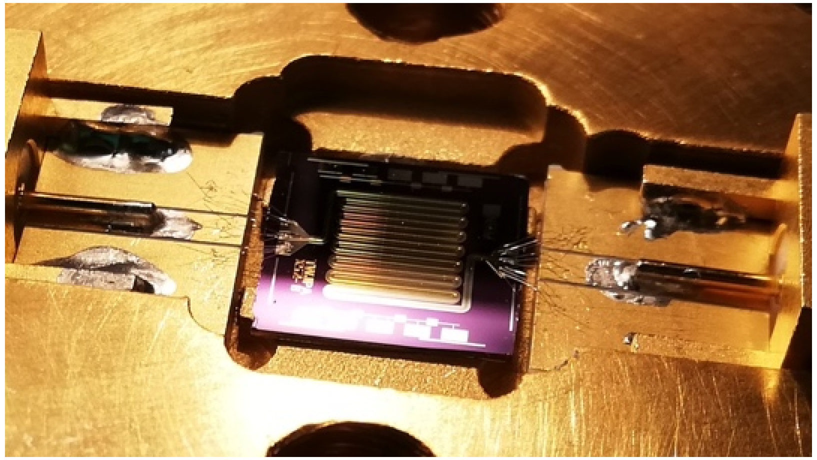
- Realization of a single-photon counter that surpasses present devices in terms of efficiency and low dark-count rates by exploiting quantum non destructive measurements of a single photon and entanglements in multiple qubits
- In details:
  1. Design and simulation of a SC qubit coupled to resonators
  2. Fabrication of superconducting circuits with SC qubit
  3. Single-shot measurement of SC qubit with quantum amplifier
  4. Control of SC qubit with FPGA-based board
  5. Quantum sensing experiment with entangled sensors

INFN experience in JJ

- Qub-IT wants to bring together skills and interests already present in INFN and other research institutions

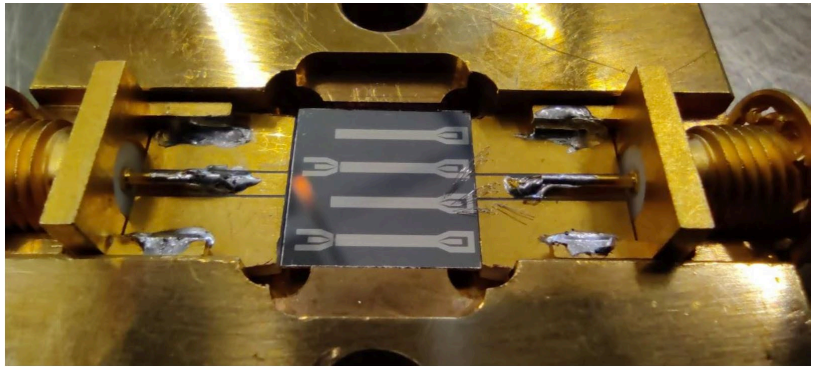
DART WARS

Detector array readout with travelling wave amplifieRS



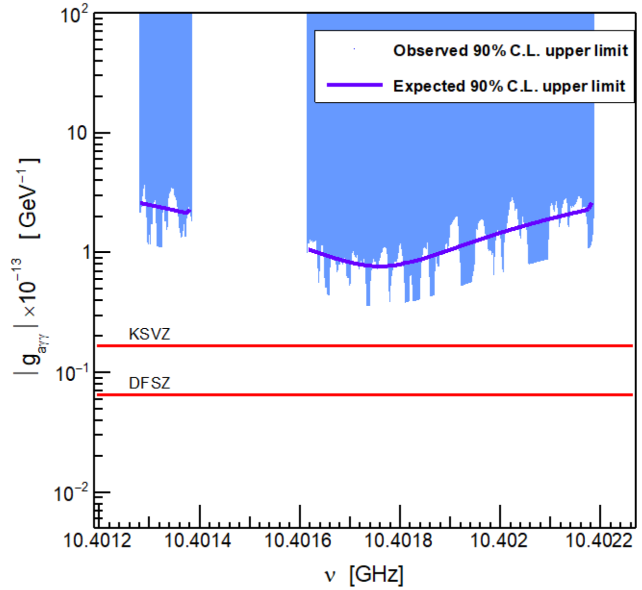
SIMP

Parametric amplification and resonant activation measured with JJ and DC-SQUID



QUAX

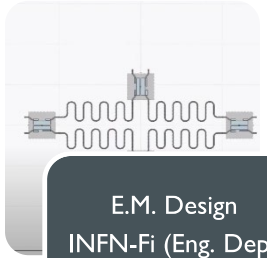
Sensitivity to QCD axions reached with a Josephson Parametric Amplifier (JPA)



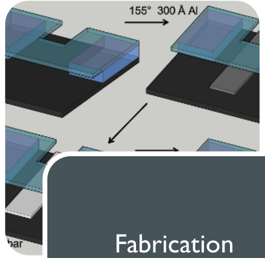
QUAX Coll. Phys Rev. D 103 102004 (2021)

Methodology – Design (INFN-PI involved)

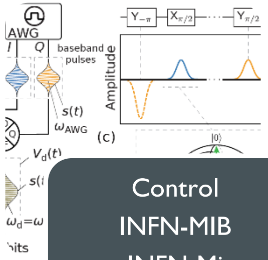
Theory
INFN-Fi (Phys Dept)



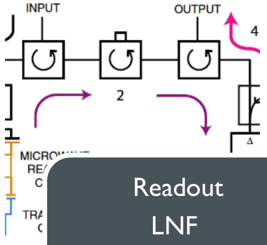
E.M. Design
INFN-Fi (Eng. Dept)
INFN-MIB
INFN-Pi (Eng. Dept)



Fabrication
FBK
CNR-IFN



Control
INFN-MIB
INFN-Mi
LNF
INFN-Pi
INFN-Fe

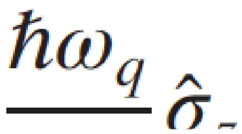


Readout
LNF
INFN-MIB
INFN-Sa
TIFPA

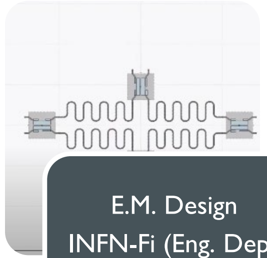
Experiment
LNF
INFN-MIB
INFN-Sa
TIFPA
INFN Pi

- Devices will be designed on IBM's Qiskit Metal, Ansys HFSS and Ansys Q3D. Qiskit Metal will be used to link the qubit quantum properties, described by Lagrangian parameters, to the circuit physical structure defined by the layouts of the qubit, the resonators, the coupling capacitors, and the wire-bonding pads.

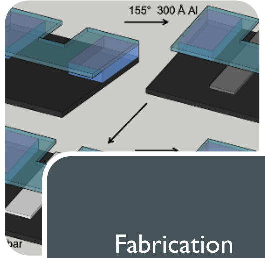
Methodology - Fabrication



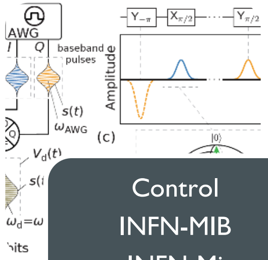
Theory
INFN-Fi (Phys Dept)



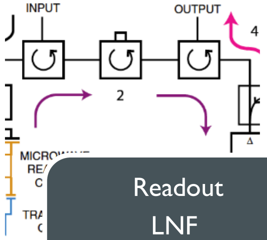
E.M. Design
INFN-Fi (Eng. Dept)
INFN-MIB
INFN-Pi (Eng. Dept)



Fabrication
FBK
CNR-IFN



Control
INFN-MIB
INFN-Mi
LNF
INFN-Pi
INFN-Fe

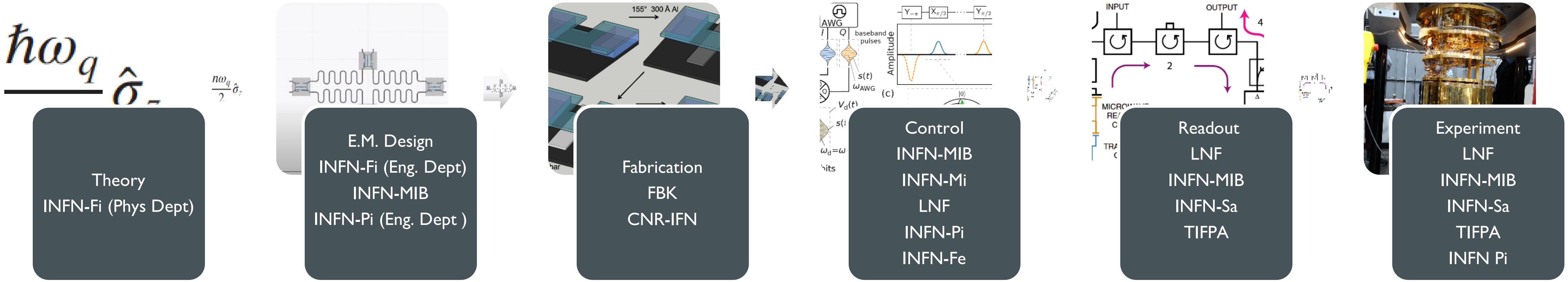


Readout
LNF
INFN-MIB
INFN-Sa
TIFPA

Experiment
LNF
INFN-MIB
INFN-Sa
TIFPA
INFN Pi

- Circuits elements will be fabricated with optical lithography on silicon or sapphire substrates and the qubits with a second lithography step with electron-beam.

Methodology – Control and Readout (INFN-Pi involved)

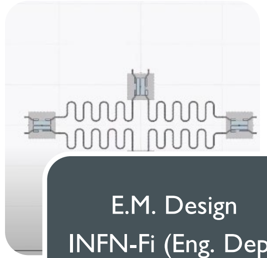


- Qubits are controlled with Rabi oscillations driven by resonant RF pulses with appropriate timing and duration. Fast operation and repetition of the measurement will be achieved by building SC qubit control and readout platforms using FPGAs. The control system will be developed on existing frameworks such as Qibo. The applicability of modern RF DACs with extra-wide bandwidths will be investigated to directly synthetize control pulses.

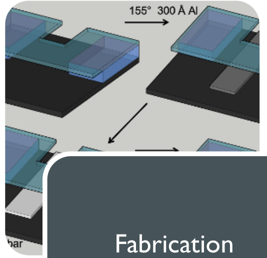
- High fidelity single-shot readout will be done with quantum amplifiers such as JPA or TWJPA.

Methodology – Experiment (INFN-Pi involved)

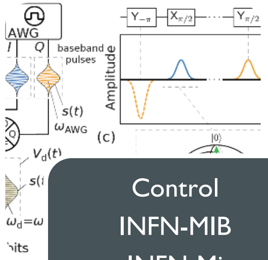
Theory
INFN-Fi (Phys Dept)



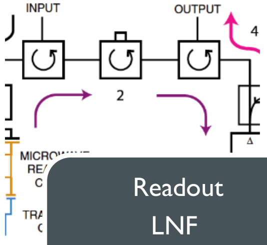
E.M. Design
INFN-Fi (Eng. Dept)
INFN-MIB
INFN-Pi (Eng. Dept)



Fabrication
FBK
CNR-IFN



Control
INFN-MIB
INFN-Mi
LNF
INFN-Pi
INFN-Fe



Readout
LNF
INFN-MIB
INFN-Sa
TIFPA

Experiment
LNF
INFN-MIB
INFN-Sa
TIFPA
INFN Pi

- Single photon detection experiments will be performed with both single and two resonators schemes. Based on the theoretical investigation on qubits resonators couplings, a device exploiting two qubits entanglement will be tested for enhanced single photon detection.

Project Organization

Qub-IT 2022-2024	FTE	
LNF (RN)	2.5	Coordination (WP5); Control Firmware (WP3); Sensing Experiments (WP4)
INFN MIB	1	Design (WP1); Control Software (WP3); Qubit Experiments (WP4)
INFN Mi	0.x (dtz)	Control Software (WP3)
INFN Sa	1.5	Simulation (WP1); Components characterization (WP4)
TIFPA	1.3	Components characterization and JPA (WP4)
INFN Pi	2	Design 3D Qubit (WP1); Fabrication 3D cavity (WP2); Control (WP3); Experiment 3D qubit (WP4)
INFN Fi	2.2	Design (WP1)
INFN Fe	0.5 (dtz)	Control Interfaces (WP3)
FBK	-	Fabrication (Optical) (WP2)
CNR-IFN	-	Fabrication (e-beam) (WP2)

- Responsabile nazionale: **Claudio Gatti (LNF)**

Preliminary budget

Qub-IT 2022-2024	K€	preliminary
LNF (RN)	55	Microwave components; Cryo Amplifier; consumables …
INFN MIB	55	FPGA board; Microwave Components; consumables …
INFN Mi	8	Travel, pc
INFN Sa	33	Microwave components ….
TIFPA	33	Microwave component …
INFN Pi	55	Cryo Amp; Circulators; RF amp roomT; Resonant cavity; RF DAC board
INFN Fi	22	Workstation, travel, pc
INFN Fe	15(Pi)+7	FPGA Board (Pi), pc, travel
FBK	45	Fabrication
CNR-IFN	45	Fabrication

TOT	2022	2023	2024
373 k€	130	133	110

Pisa Group & richieste

	%	Role
Filippo COSTA	20	RTDB - UNIPI – Elec. Eng. Dept.
Stefano DI PASCOLI	20	PA - UNIPI – Elec. Eng. Dept.
Francesco GIAZOTTO	20	I Ric - CNR-NANO
Gianluca LAMANNA	20	PA - UNIPI
Massimo MACUCCI	20	PO - UNIPI – Elec. Eng. Dept.
Giuliano MANARA	20	PO - UNIPI – Elec. Eng. Dept.
Paolo MARCONCINI	20	PA - UNIPI – Elec. Eng. Dept.
Federico PAOLUCCI	20	Ric – CNR-NANO
Paolo SPAGNOLO	20	I Ric - INFN
Alessandra TONCELLI	20	PA - UNIPI

- Attività di officina meccanica per la realizzazione di cavità 3D e altre minuterie per test a freddo
- I test "in casa" potranno essere fatti soltanto con il nuovo criostato a diluizione equipaggiato con linee opportune
- Eventuale possibilità di sviluppare piccoli prototipi con l'EBL del CISUP (per il momento non è messo tra i compiti di Pisa)