QUAX-aγ: Search for the QCD Axion with the LNF Haloscope

CLAUDIO GATTI FOR THE QUAX-LNF GROUP

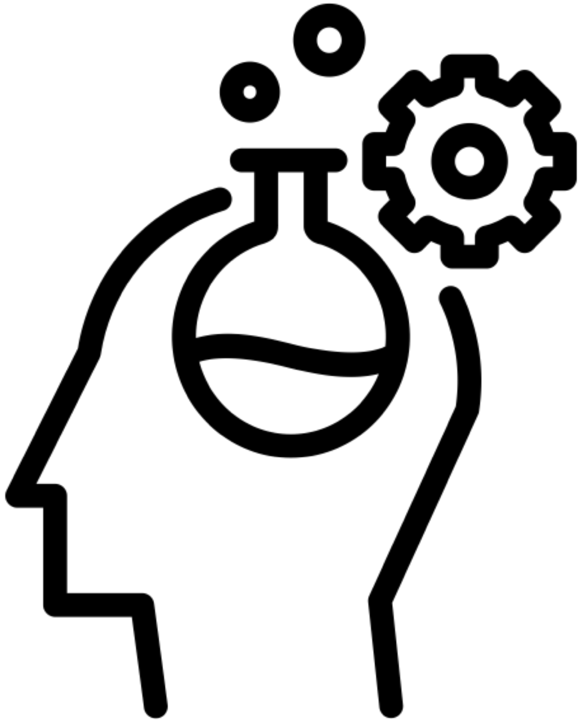
FFF - LNF January 13th 2021

OUTLINE

- QUAX R&D
- QUAX Experiment at LNF
  - Multicavity approach

  a. The Resonant Cavities
  b. The Magnet
  c. Signal Amplification
  d. Data Acquisition
  e. Single Photon Detection

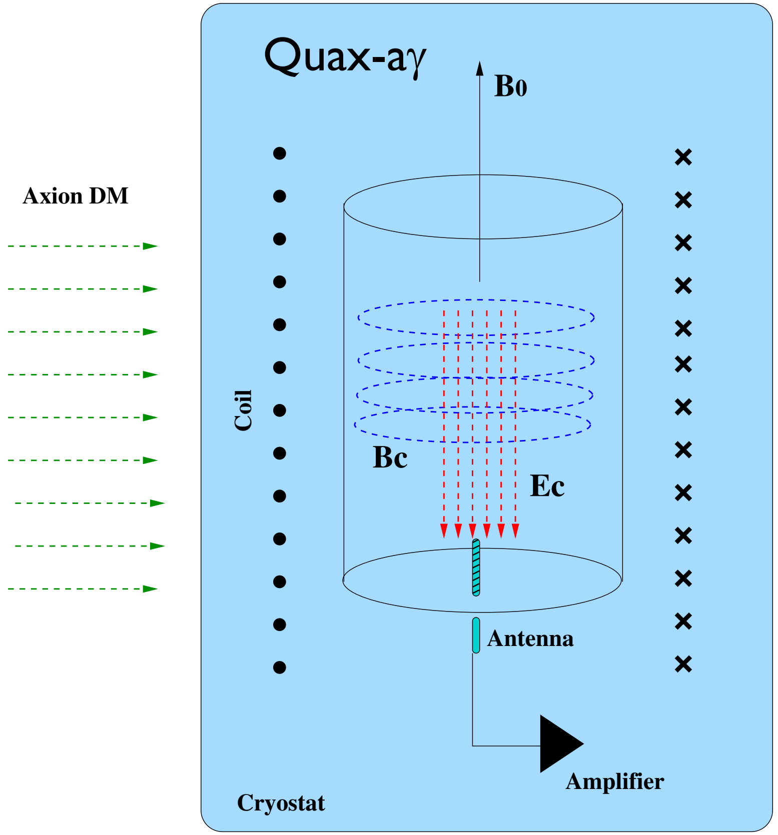
QUAX R&D 2018-2020

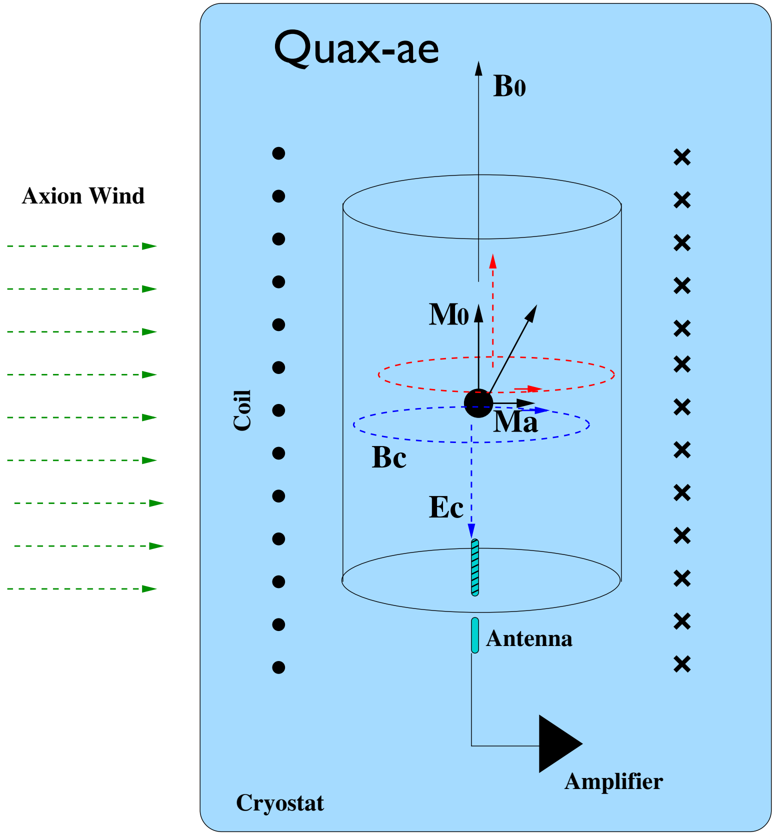


Created by Chameleon Design from Noun Project

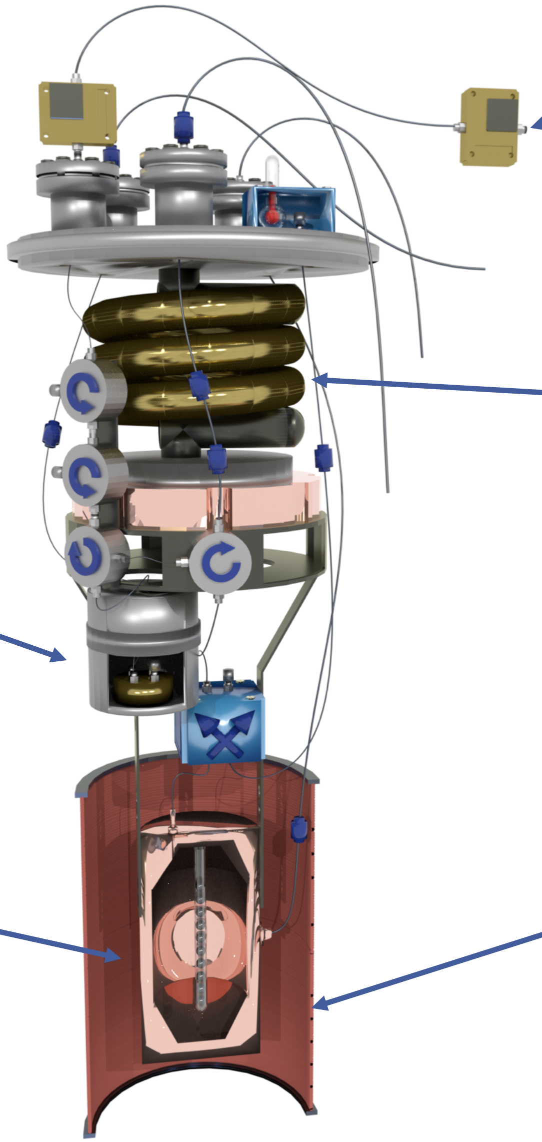
QUAX: Quest for Axions

$$\mathcal{L} = i\frac{g_d}{2}a\left(\bar{N}\sigma_{\mu\nu}\gamma^5 N\right)F^{\mu\nu} + i\frac{g_{aNN}}{2m_N}\partial_\mu a\left(\bar{N}\gamma^\mu\gamma^5 N\right)\boxed{+i\frac{g_{aee}}{2m_e}\partial_\mu a\left(\bar{e}\gamma^\mu\gamma^5 e\right) + g_{a\gamma\gamma}aE\cdot B}$$

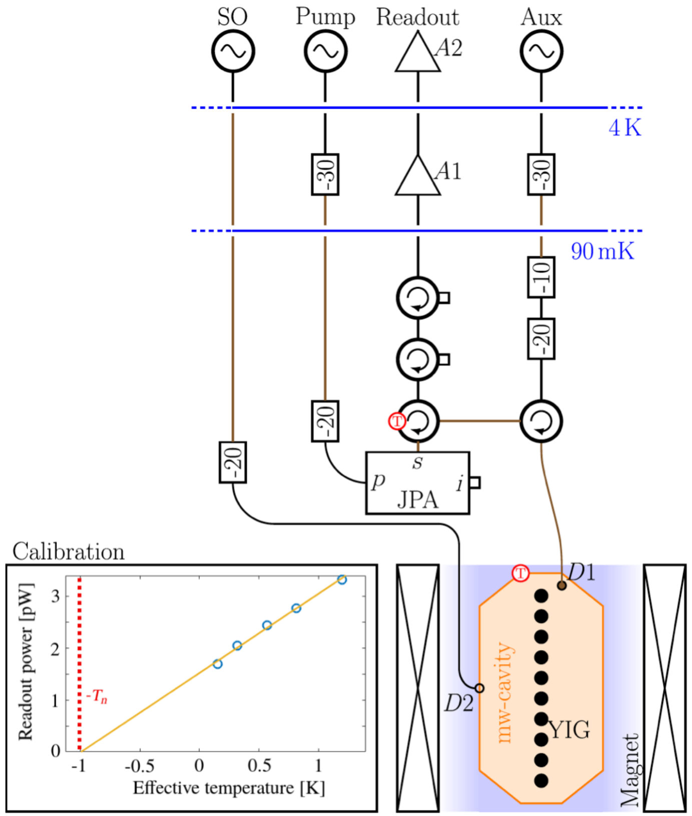




State of Art Haloscope



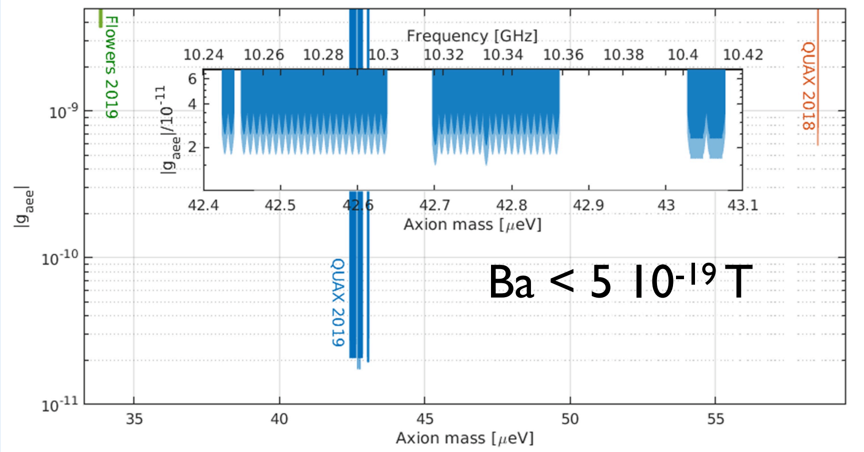
QUAX-ae with Quantum-Limited Ferromagnetic Haloscope

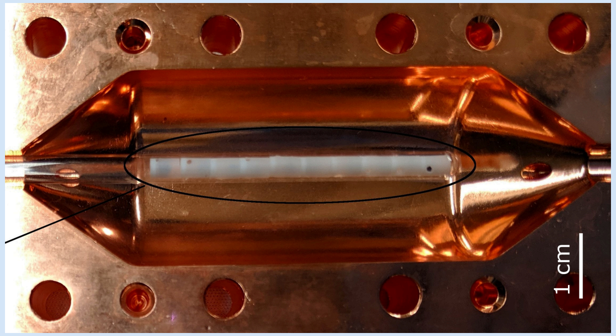


Experimental Setup	
B [T]	0.5
N. of GaYIG Sphere (diameter =2.1 mm)	10
n_s [spin/m^3]	2.1×10^{28}
τ_{min} [μs]	0.1
Frequency [GHz]	10.7
Cu-cavity Q (mode TM110)	50,000
T_{cavity} [mK]	90
T amplifier [K] (JPA)	0.5-1

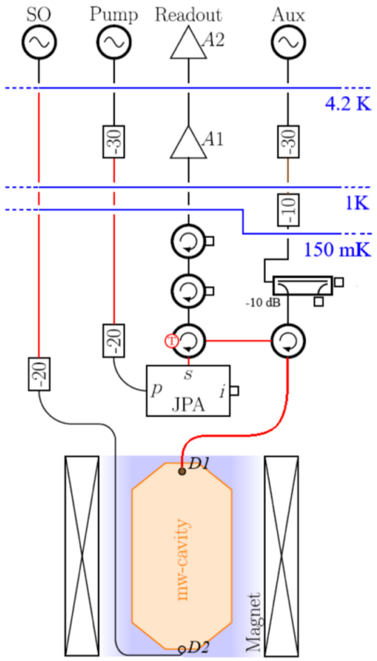
Phys. Rev. Lett. **124**, 171801 (2020)

EPJC (2018) 78:703

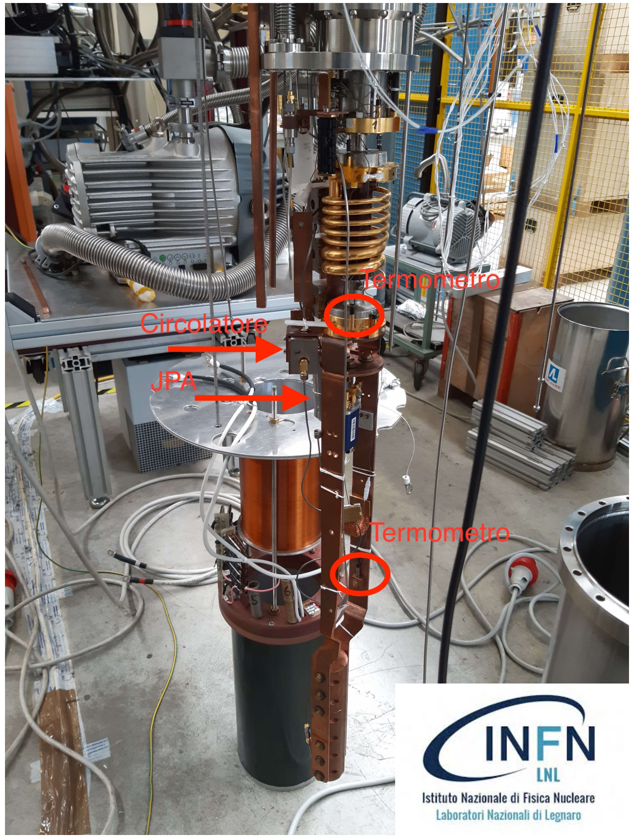


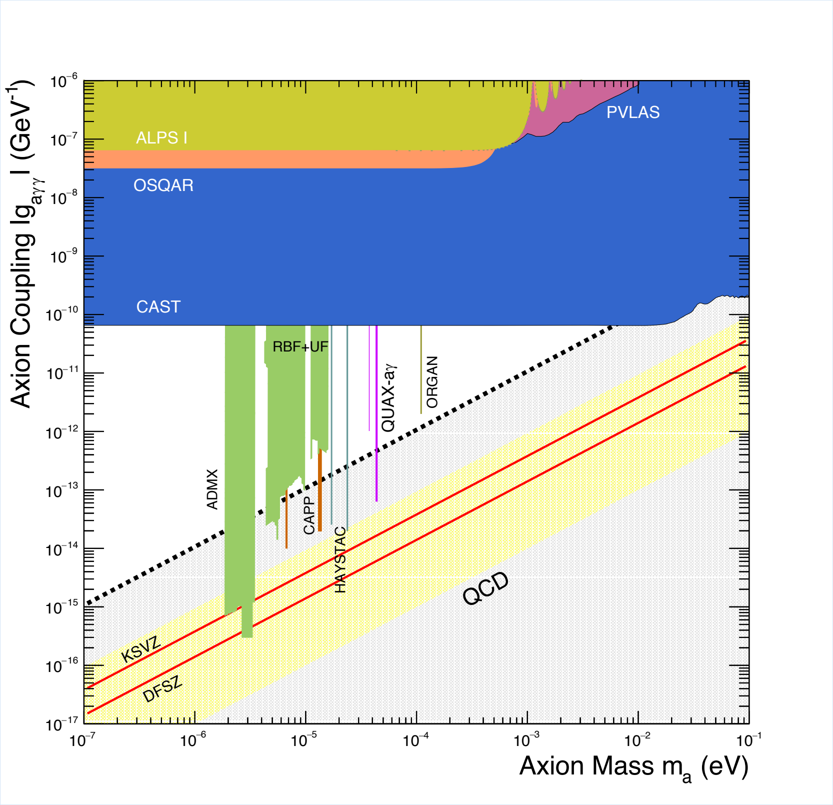


QUAX-aγ Searh for QCD Axion with m_a=43 μeV



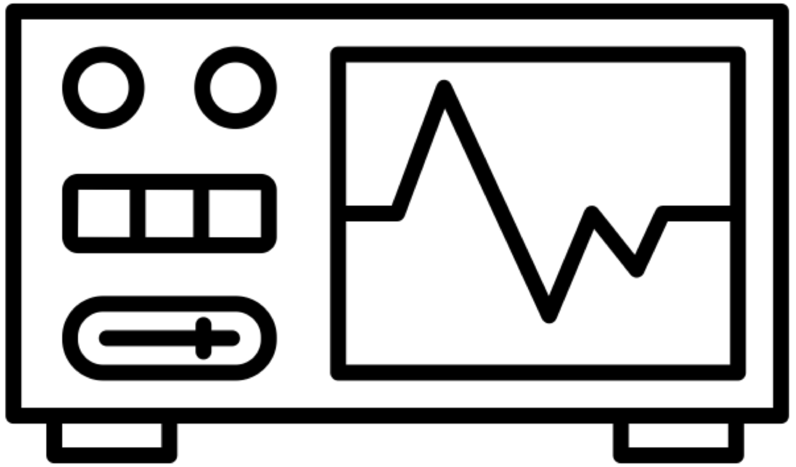
Experimental Setup	
B [T]	8
Frequency [GHz]	10.4
Cu cavity Q (mode TM010)	76,000
T_{cavity} [mK]	100
T amplifier [K] (JPA)	0.5





Arxiv:2012.09498

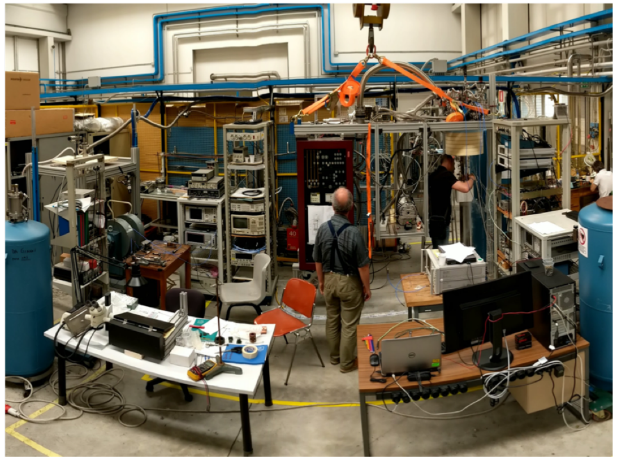
Phys. Rev. D **99**, 101101(R) (2019)

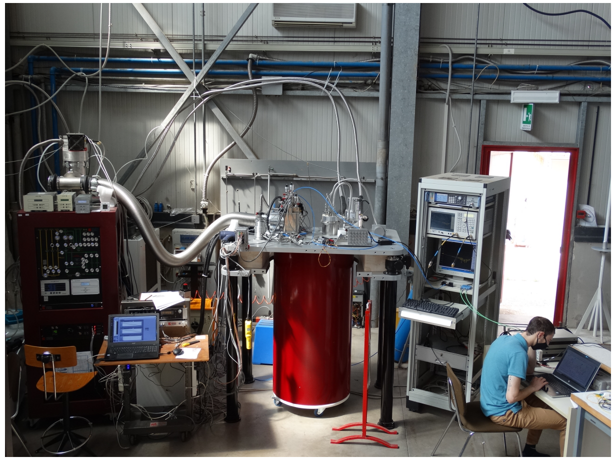


Created by Mohamed Mbarki from Noun Project

QUAX EXPERIMENT 2021-2025

QUAX 2021-2025





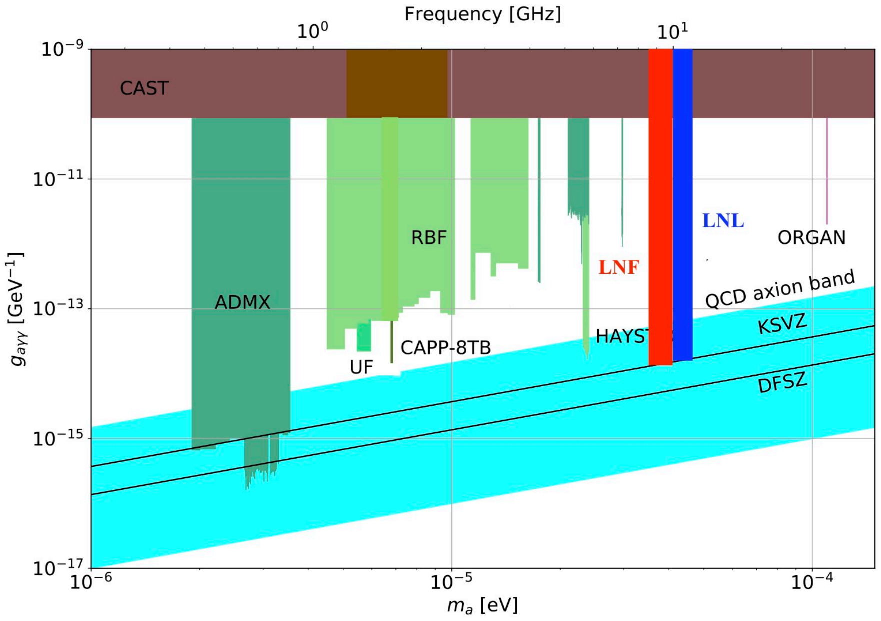
2021	2022	2023	2024	2025

Assembly of haloscopes at LNL and LNF

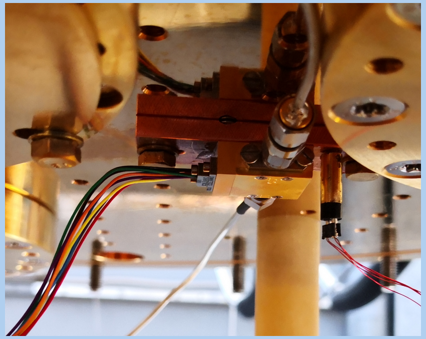
	LNF	LNL
Magnetic field	9 T	14 T
Magnet length	40 cm	50 cm
Magnet inner diameter	9 cm	12 cm
Frequency range	8.5 - 10 GHz	9.5 - 11 GHz
Cavity type	Hybrid SC	Dielectric
Scanning type	Inserted rod	Mobile cylinder
Number of cavities	7	1
Cavity length	0.3 m	0.4 m
Cavity diameter	25.5 mm	58 mm
Cavity mode	TM010	pseudoTM030
Single volume	$1.5 \cdot 10^{-4}$ m^3	$1.5 \cdot 10^{-4}$ m^3
Total volume	7$\otimes$0.15 liters	0.15 liters
Q_0	300 000	1 000 000
Single scan bandwidth	630 kHz	30 kHz
Axion power	$7 \otimes 1.2 \cdot 10^{-23}$ W	$0.99 \cdot 10^{-22}$ W
Preamplifier	TWJPA/INRIM	DJJAA/Grenoble
Operating temperature	30 mK	30 mK
Performance for KSVZ model at 95% c.l. with $N_A = 0.5$		
Noise Temperature	0.43 K	0.5 K
Single scan time	3100 s	69 s
Scan speed	18 MHz/day	40 MHz/day
Performance for KSVZ model at 95% c.l. with $N_A = 1.5$		
Noise Temperature	0.86 K	1 K
Single scan time	12500 s	280 s
Scan speed	4.5 MHz/day	10 MHz/day

Data Taking

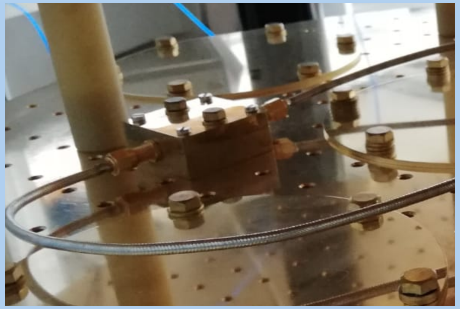
Scan in range 8.5 - 11 GHz



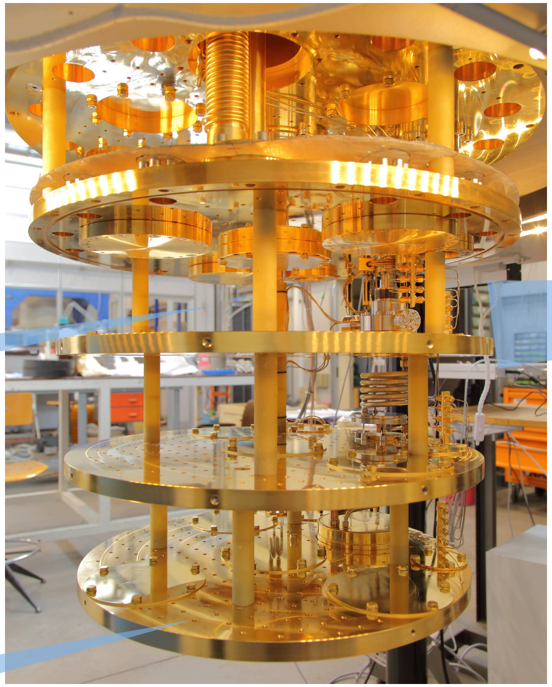
http://coldlab.lnf.infn.it



HEMT (6-20 GHz) 4K amplifier



Sample holder for SC chip at 10 mK for single photon device

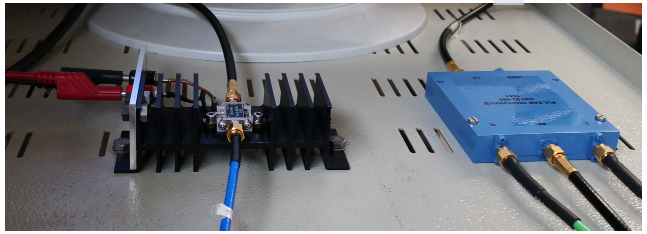


4 RF lines installed from 300 K to MixCh

Leiden CF-CS-110-1000	
Sumitomo PT	1.5 W at 4.2 K
Cooldown time (with LN)	2 days
Base temperature (measured)	8.5 mK
Cooling power at 100 mK (measured)	450 µW (up to 700 µW with a new pumping system)

VNA 20 GHz
WFG 20GHz
SA 20 GHz

FET LNA 8-12 GHz and IQ-mixer (10-12 GHz)



Room T ampli & DAQ

QUAX-LNF Haloscope

Tasks

Cavity design & Fabrication

Materials for resonant cavity

- Cu
- NbTi (LNL)
- Nb_3Sn (SQMS, LNL)
- YBCO (Enea, Uni Roma Tre)

Frequency tuning

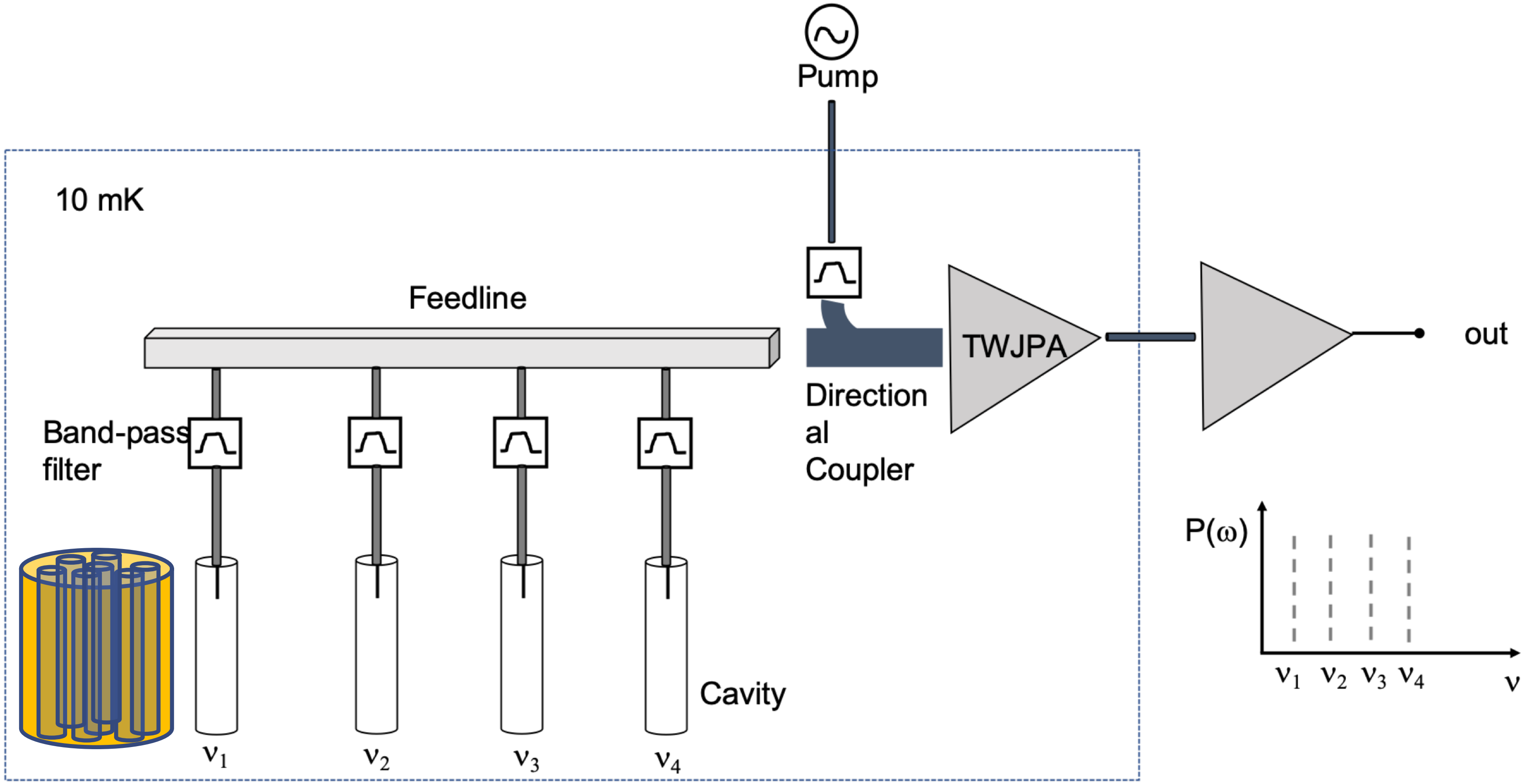
Feedline coupling

Signal Amplification
DART WARS
SIMP

Single Photon Detection
SIMP
SUPERGALAX

Digitization&Acquisition (1GHz)

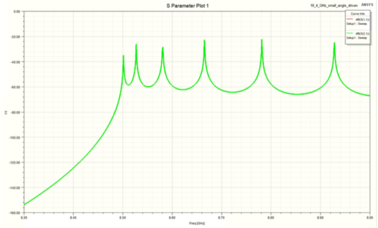
Data analysis

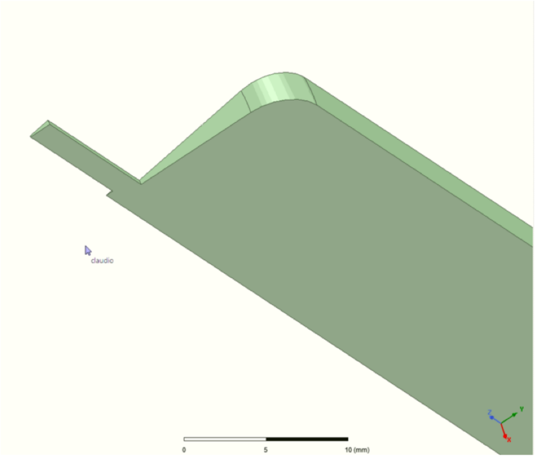


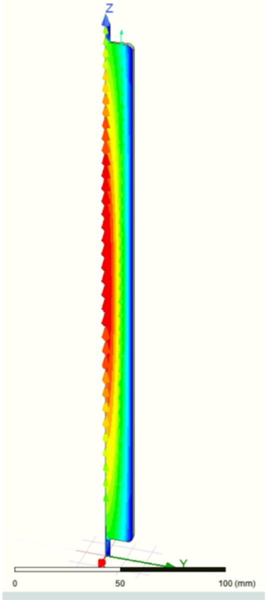
QUAX-LNF Resonant Cavity

1) HFSS simulation single cavity

- Length 30 cm
- TM010 8.5 GHz

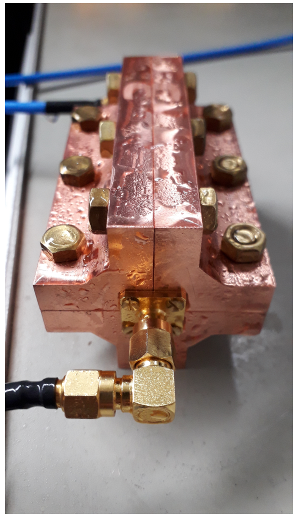


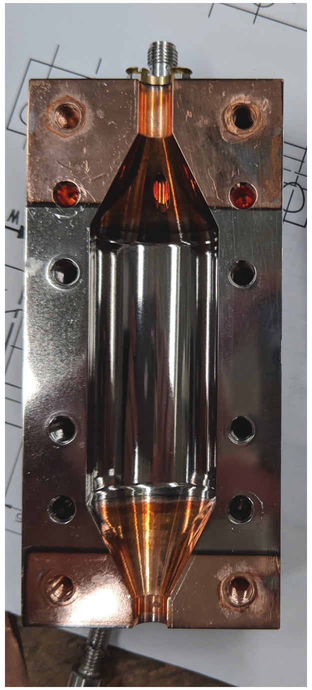




2) Superconducting coating

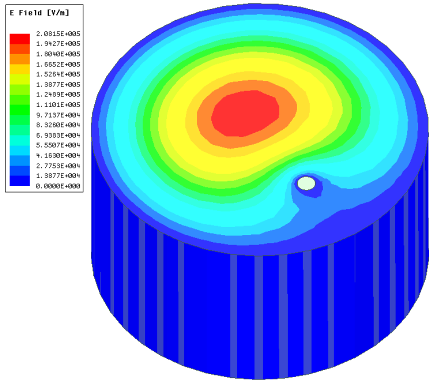
- NbTi
- Nb_3Sn
- YBCO



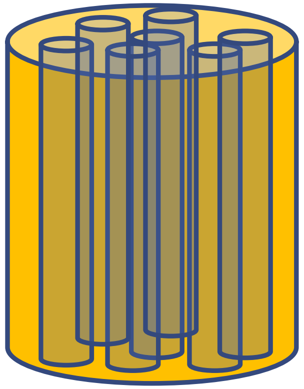


Di Gioacchino et al IEEE TRANS. APP. SUPERCOND. 29, 5 (2019)

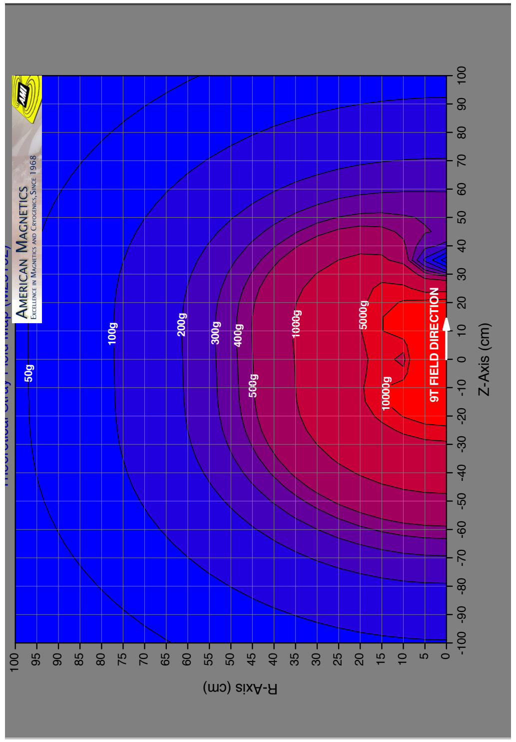
3) Frequency tuning

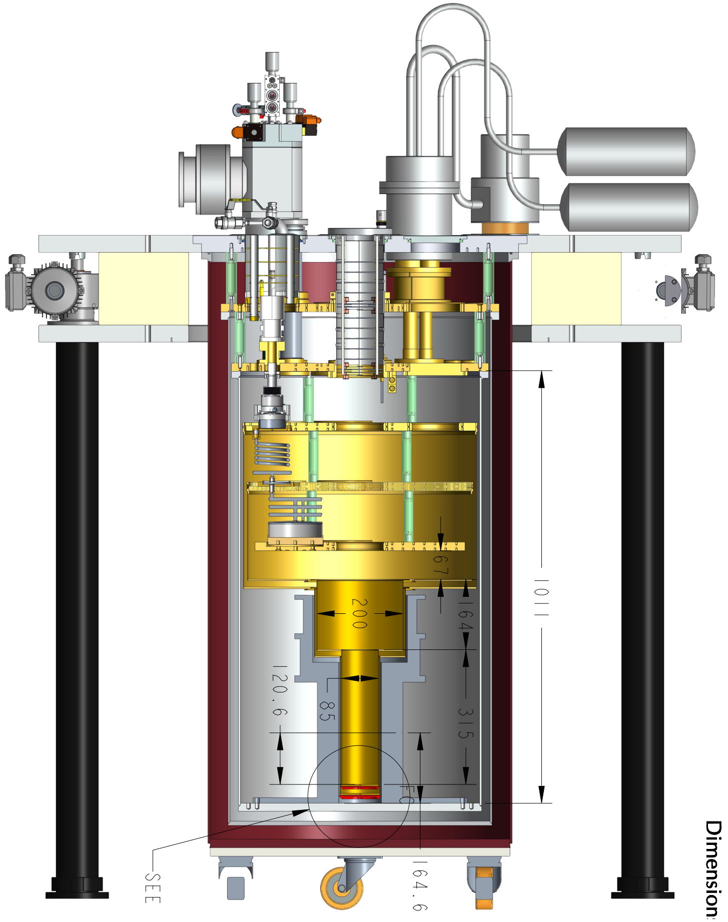


4) Multicavity fabrication



QUAX-LNF Magnet

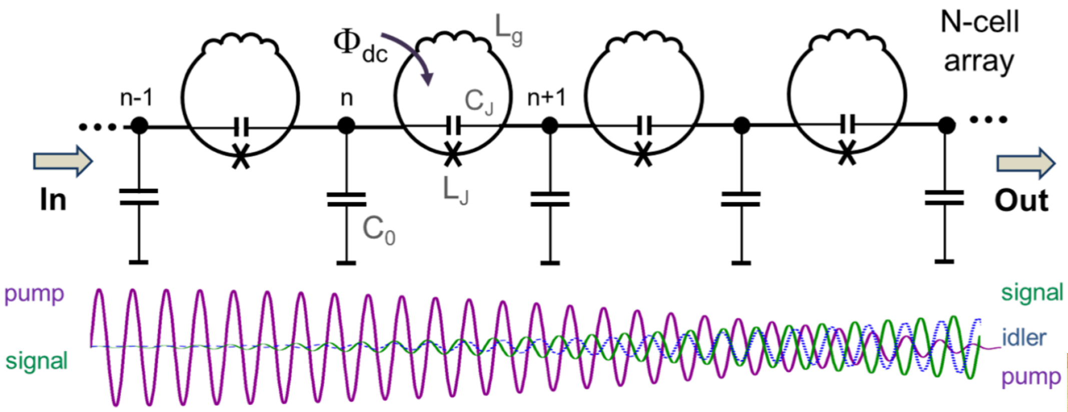


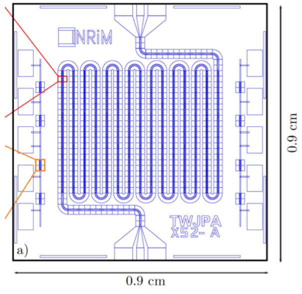


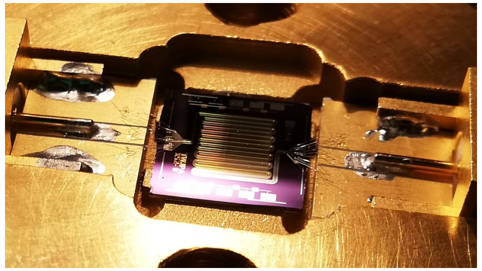
- 9T SC Magnet (AMI)
- 10 cm bore
- 40 cm height
- Cancellation coil to host SC devices
- New radiation screens
- Delivery Summer 2021

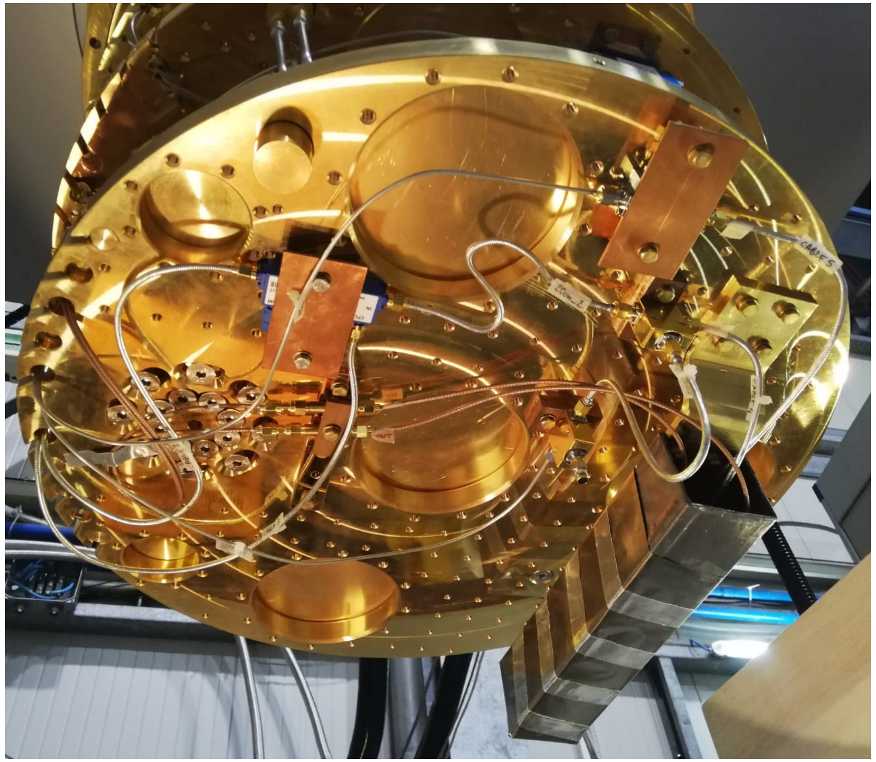
Signal Amplification (DART WARS): TWJPA

Travelling Wave Josephson Parametric Amplifiers amplify microwave signal over a broad range adding the minimum noise set by quantum mechanics.





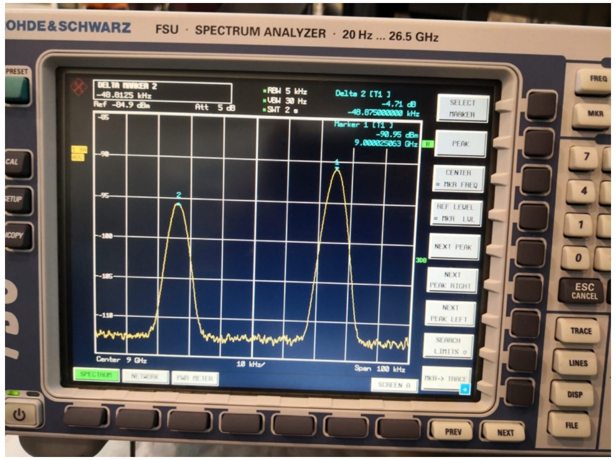




DART
WARS

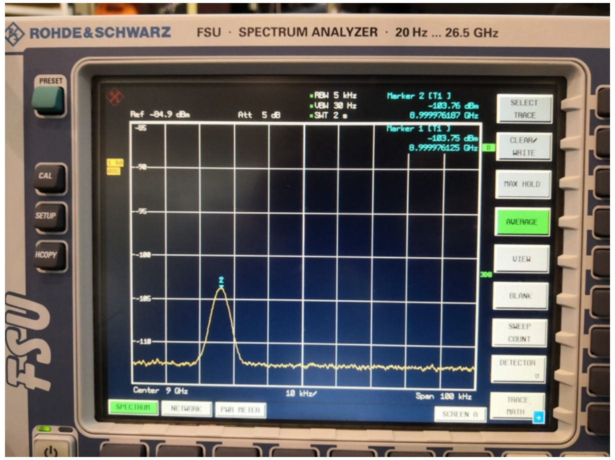
Detector Array Readout with Travelling Wave AmplifieRS Call GRV approved by INFN

Signal Amplification: TWJPA

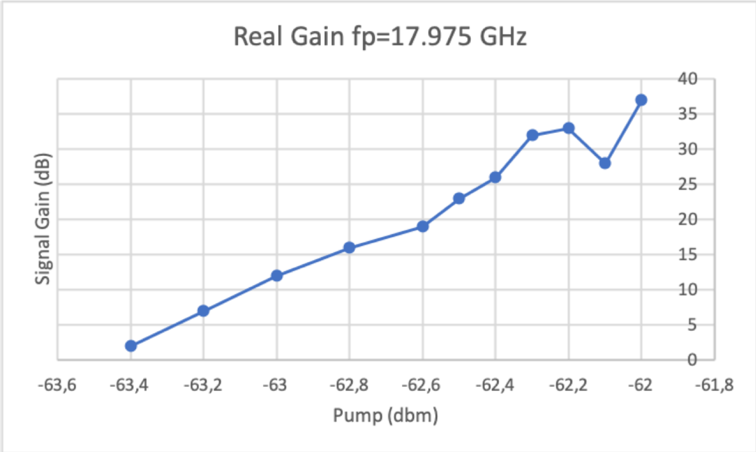


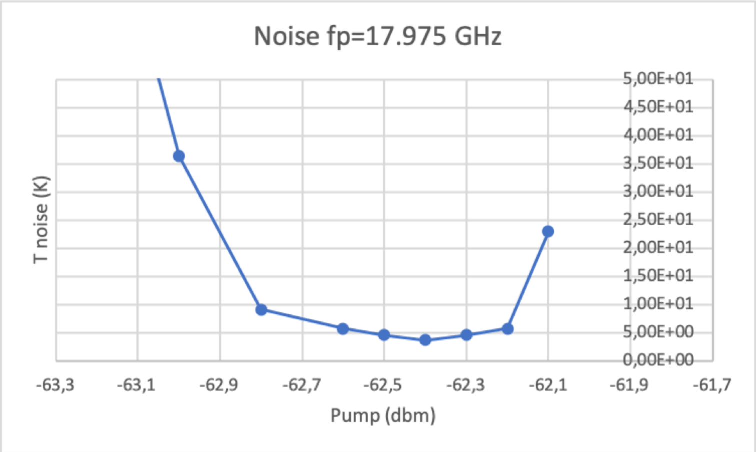
f_{pump}=18 GHz

Pump On



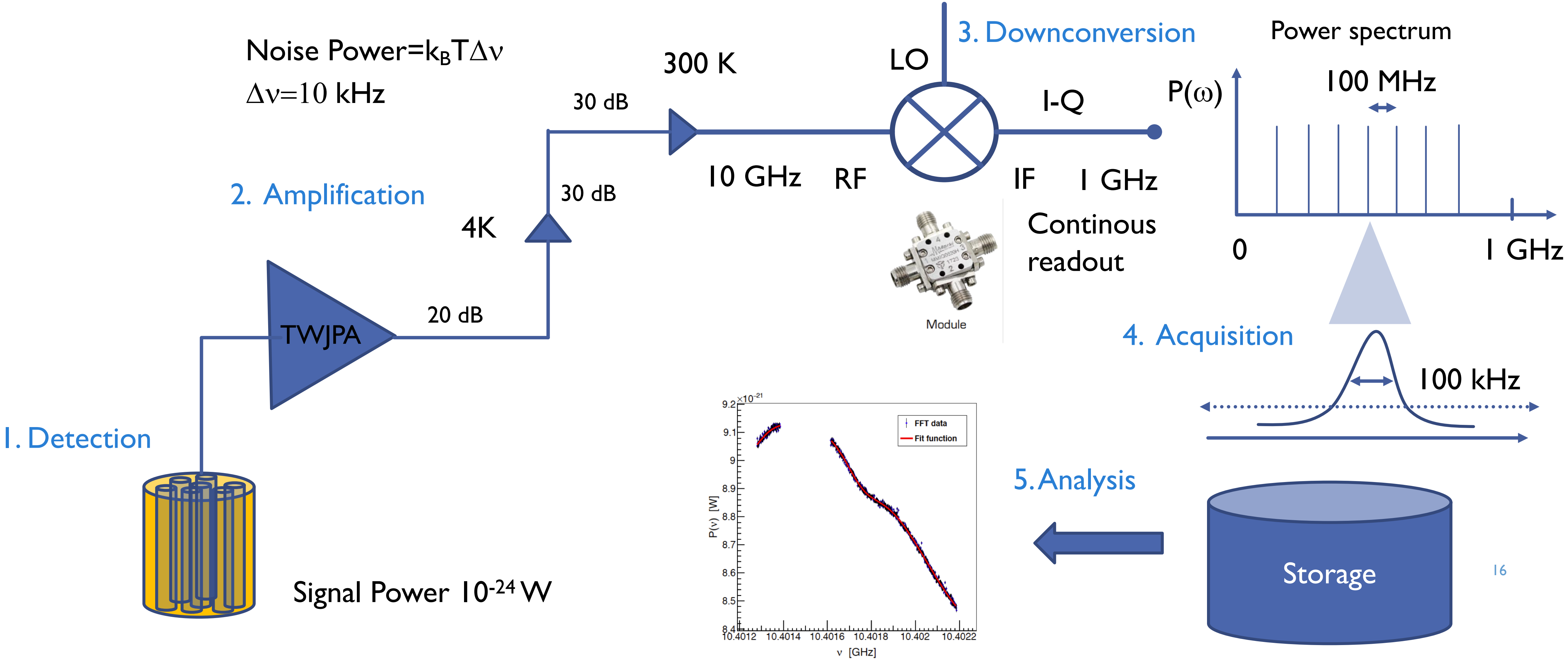
Pump Off



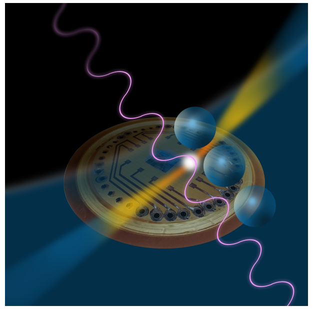


Preliminary results November 2020

DATA Acquisition and Analysis

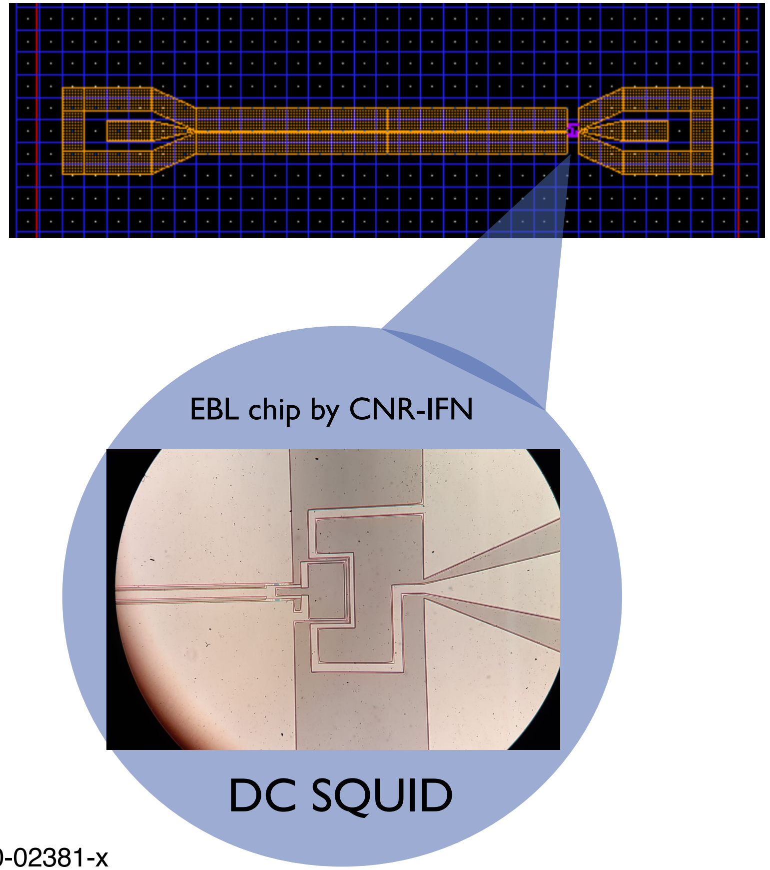


Single Microwave Photon Detection with JJ



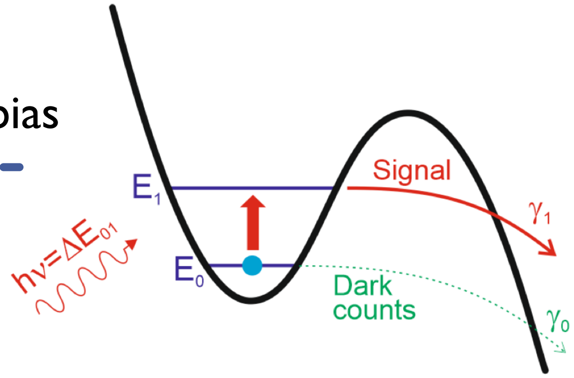
SIMP Single Microwave Photon detection

Incoming photon

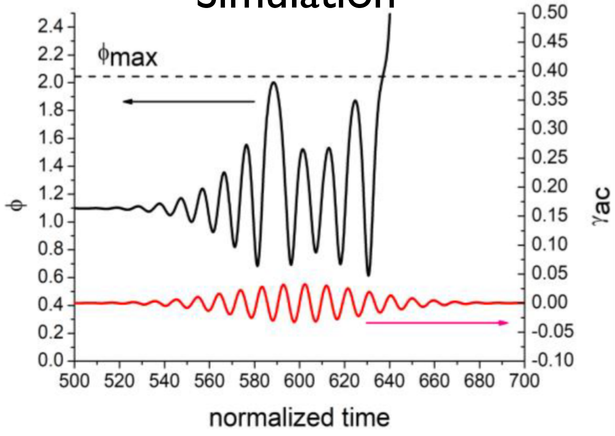


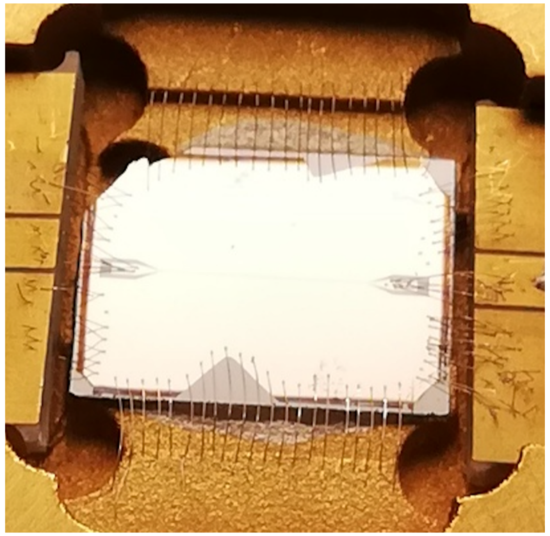
Flux bias

JJ switch induced by incoming photon



Simulation

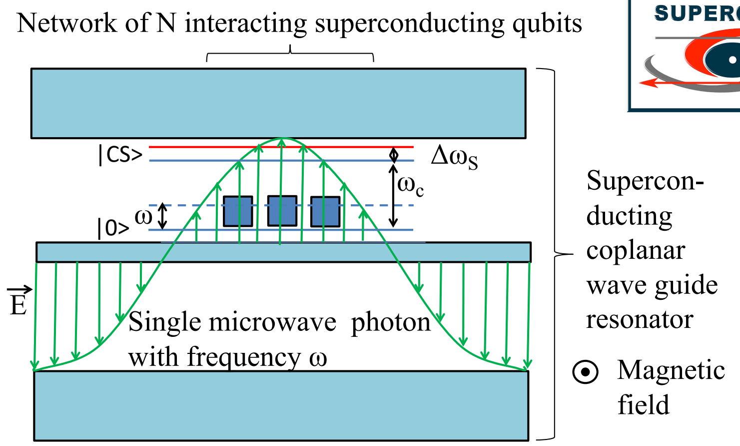


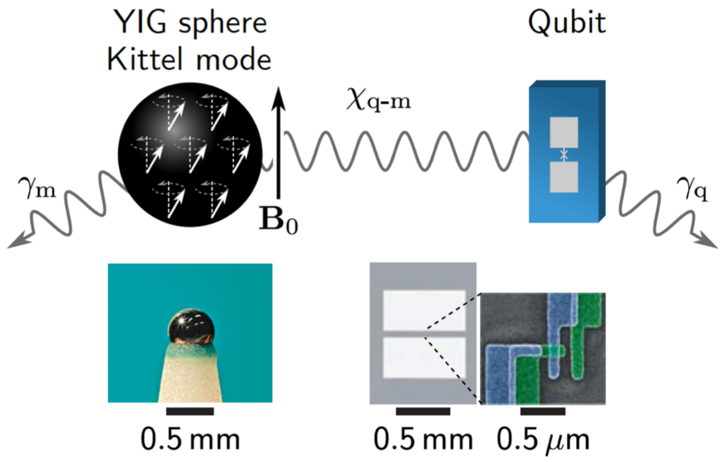


J. Phys.: Conf. Ser. 1559 012020

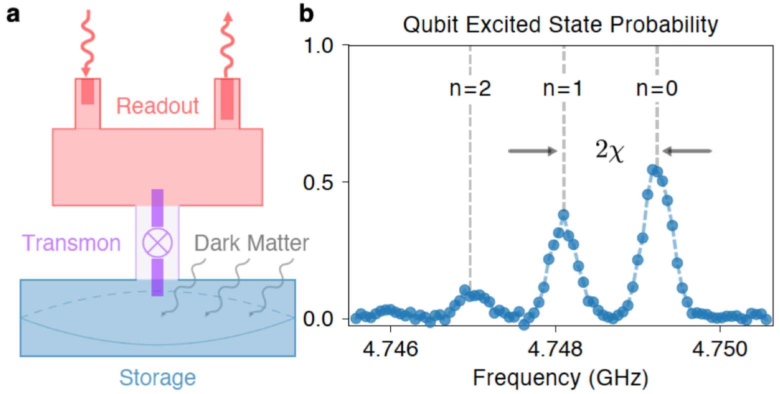
Journal of Low Temperature Physics https://doi.org/10.1007/s10909-020-02381-x

Single Microwave Photon Detection with Qubits

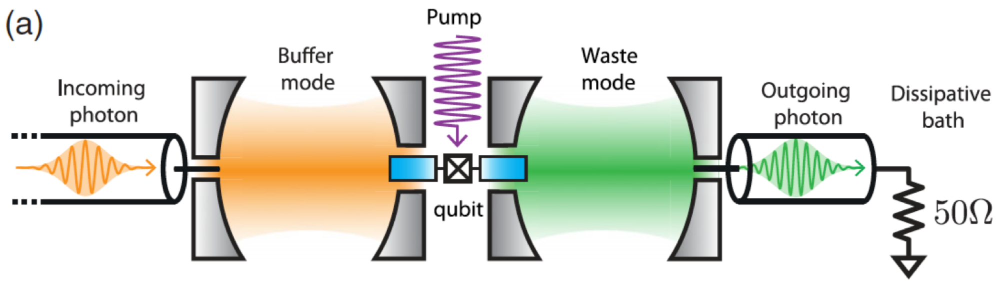




arXiv:2005.09250



arXiv:2008.12231



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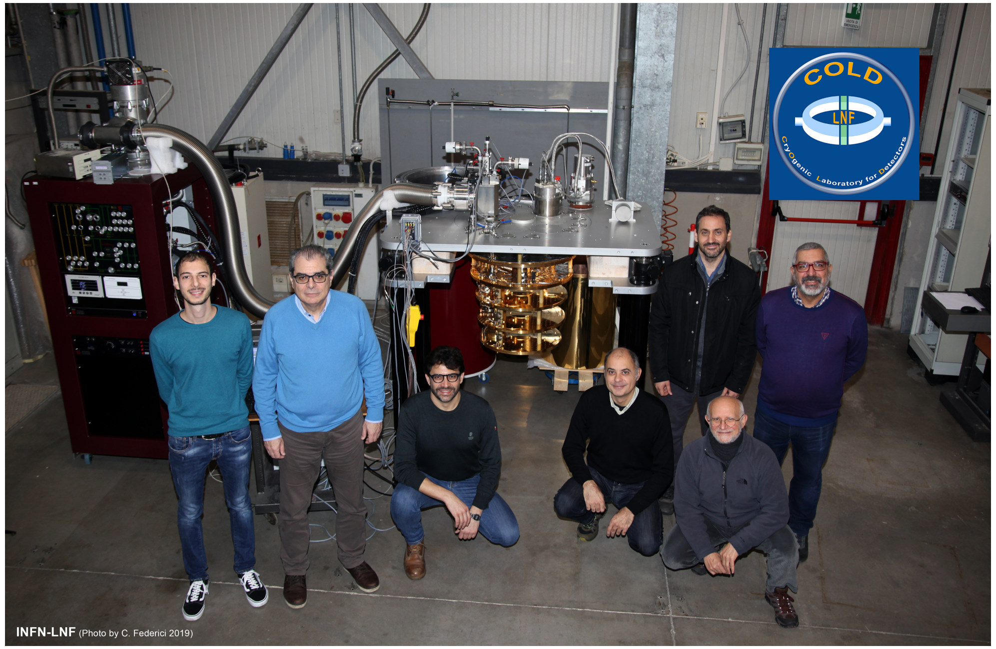

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G. Ceccarelli (mechanical support)
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Claudio Gatti (RN)
Giovanni Maccarrone
Alessio Rettaroli
Guido Torrioli
Luca Piersanti
David Alesini
Matteo Beretta
Carlo Ligi (RL)
Bruno Buonomo
Giulietto Felici
Luca Foggetta
Sandro Gallo

DART WARS LNF (Call CSN V)
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Carlo Ligi (RL)

SUPERGALAX LNF (H2020)
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