



# COLD lab

Claudio Gatti

67th LNF Scientific Committee

May 27th 2024





# Outline

- QUAX@LNF
  - First Physics Run
  - Program for next runs
- Quantum Devices
- FLASH
  - Successful test of the FINUDA magnet
  - Preparation of the FLASH proposal

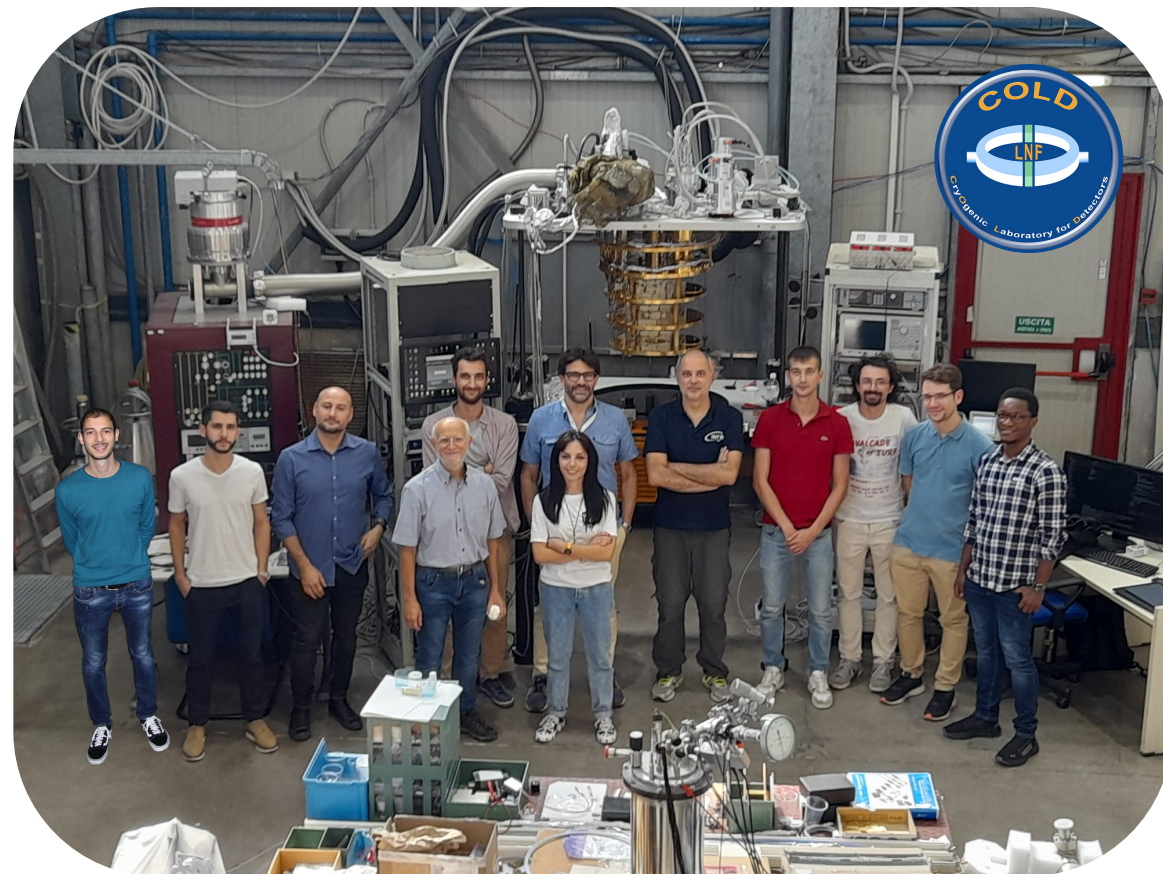
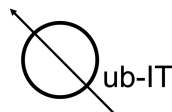
# COLD@LNF

## CryOgenic Laboratory for Detectors:

- Axion Dark Matter Experiments
- Quantum Sensing with Superconducting Devices
- Type II and HTC Superconducting Cavities



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



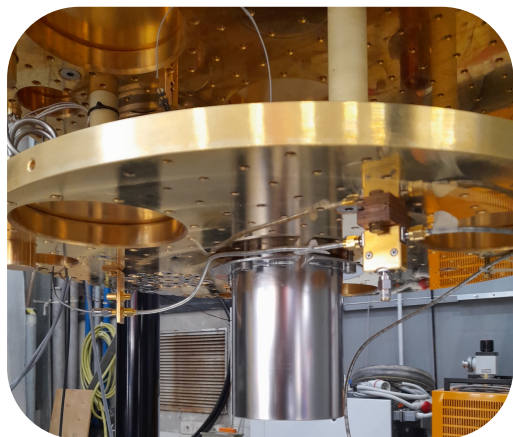






# The LNF Haloscope

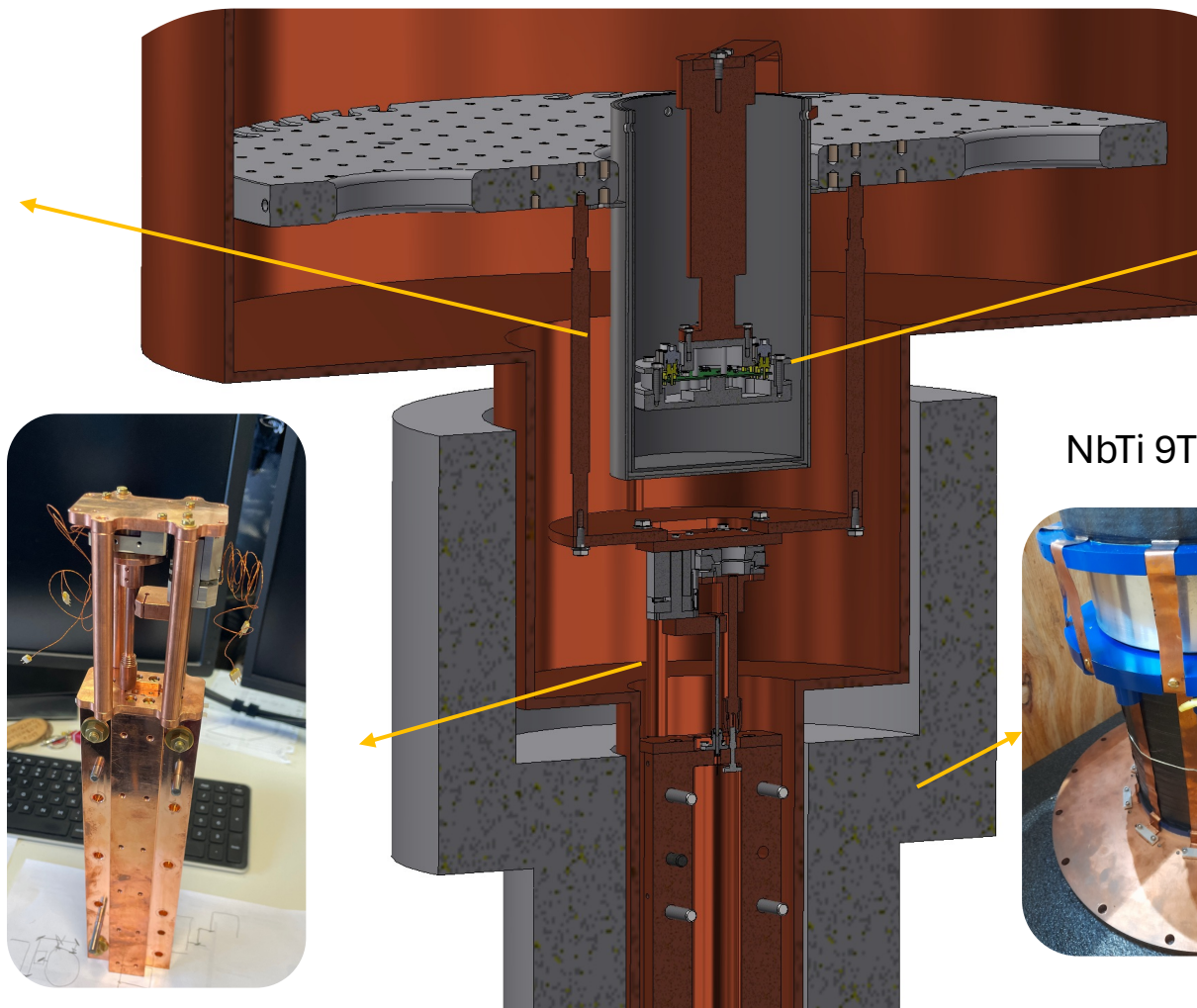
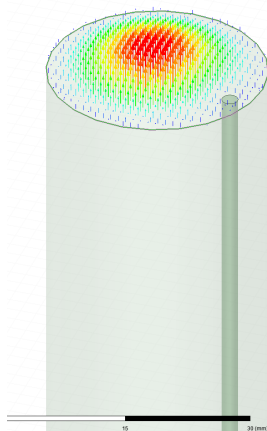
CryoPhi – Al magnetic shield



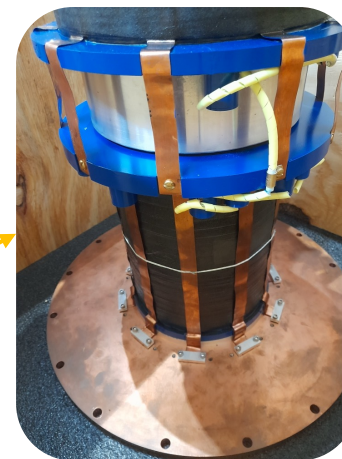
Sample holder for SC devices



Cavity with tuning system



NbTi 9T magnet

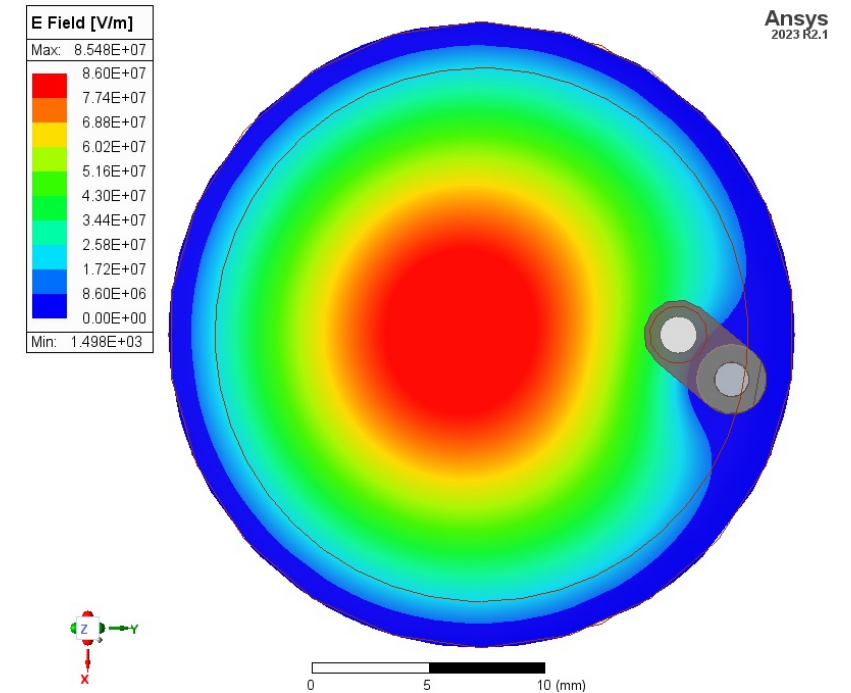
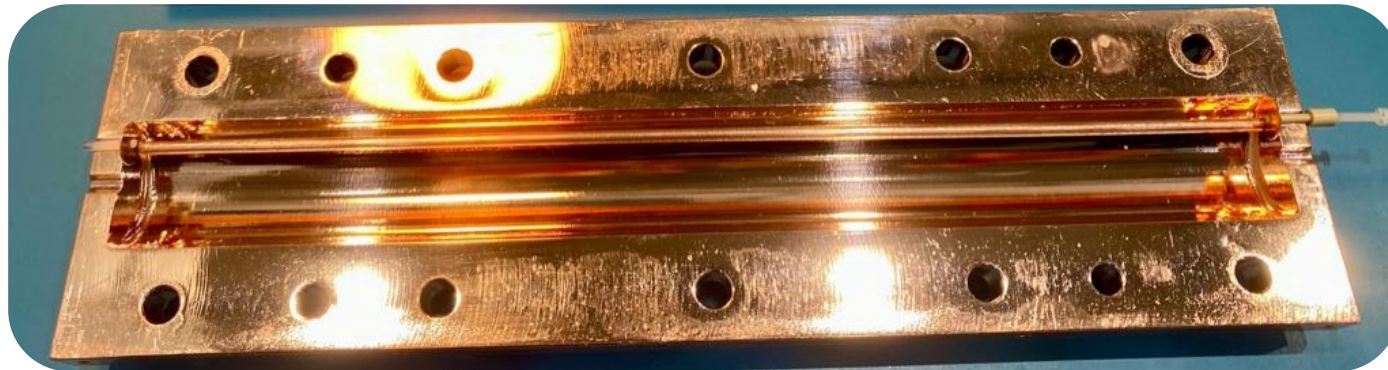
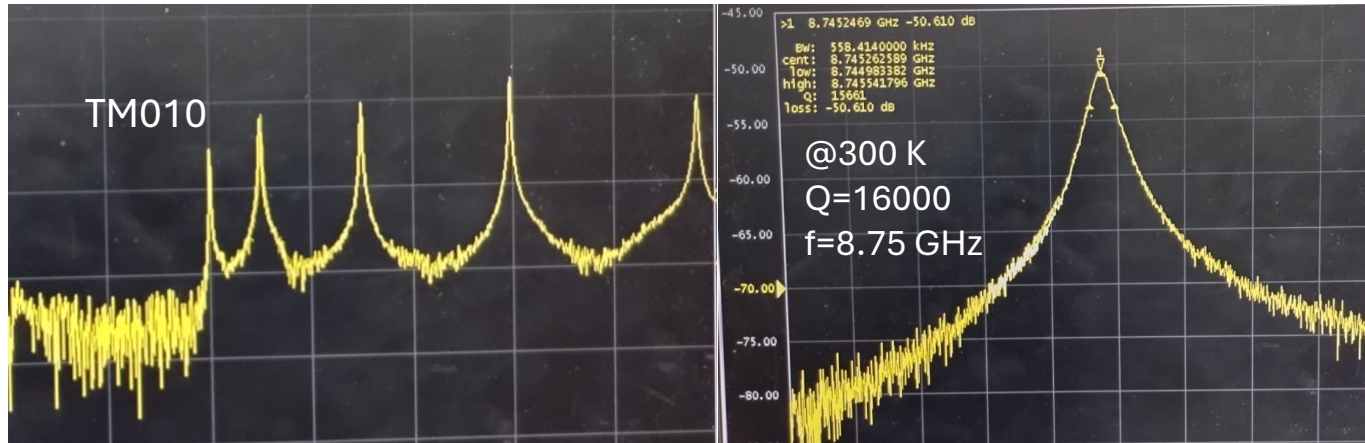


Magnet successfully operated at 9T





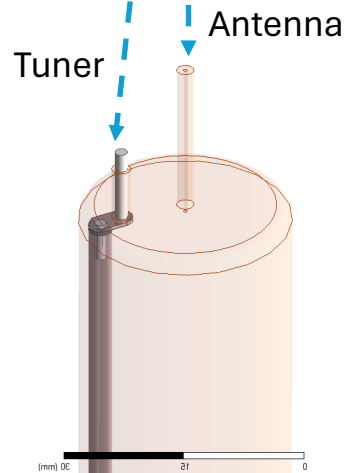
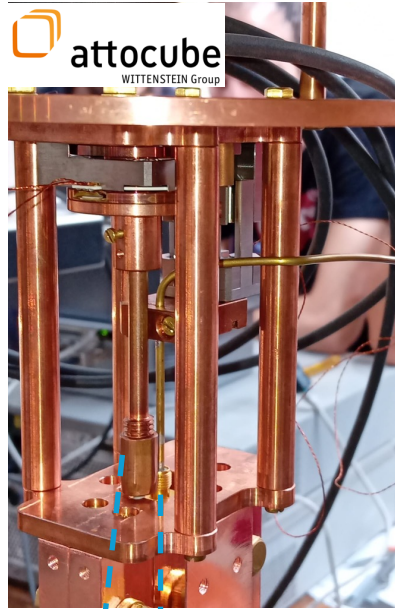
# Cavity Tuning



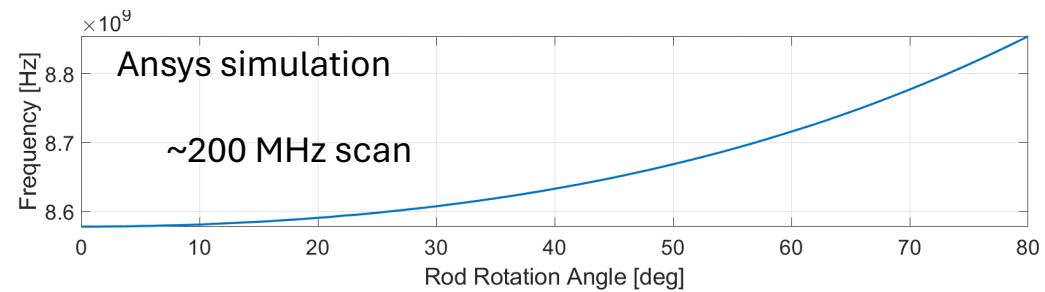
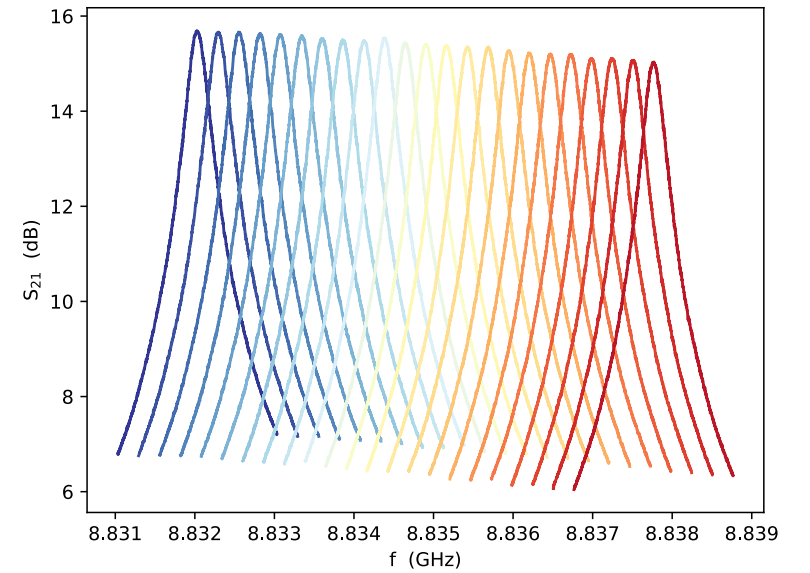
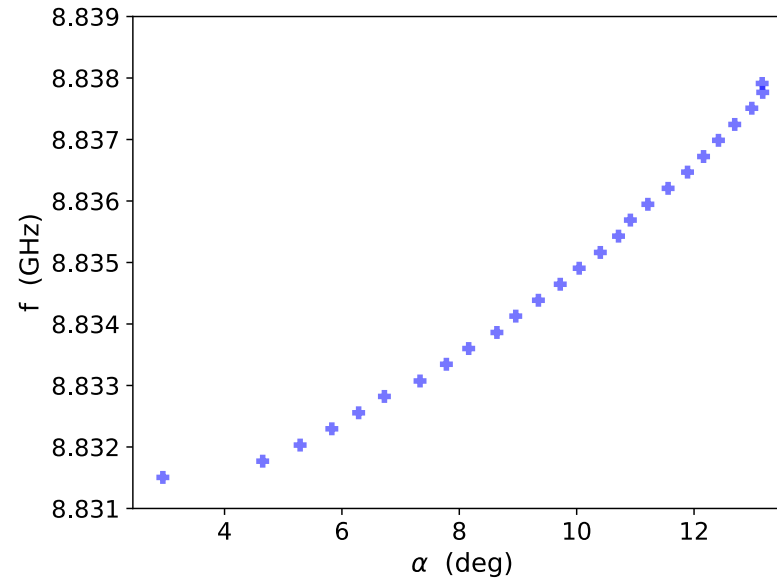
- Starting frequency ( $\alpha = 0^\circ$ ): 8.83 GHz
- Tuning  $\sim 300$  MHz with  $\Delta\alpha \sim 100^\circ$



# Cavity Tuning

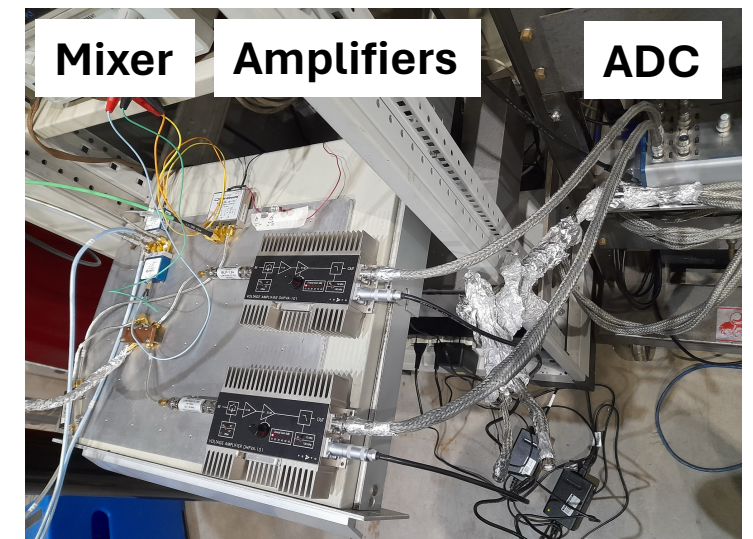
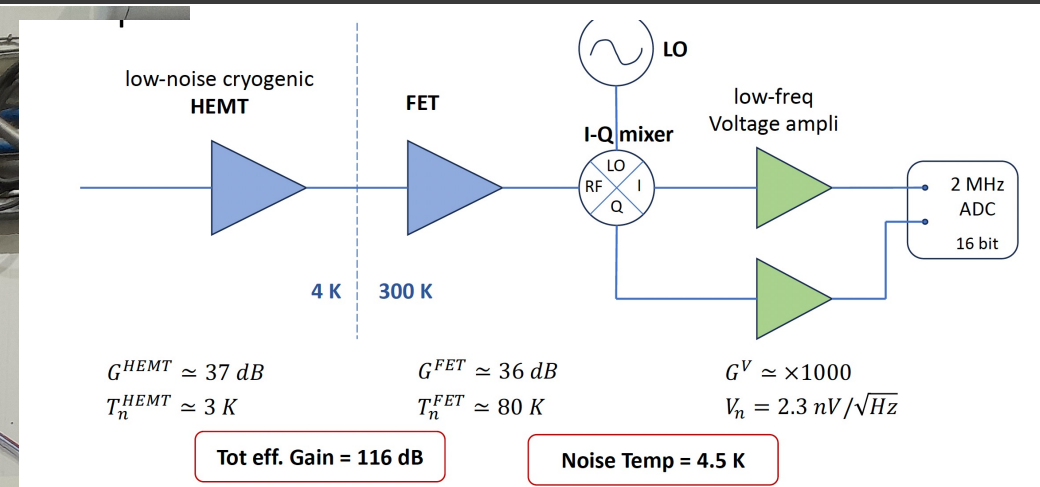
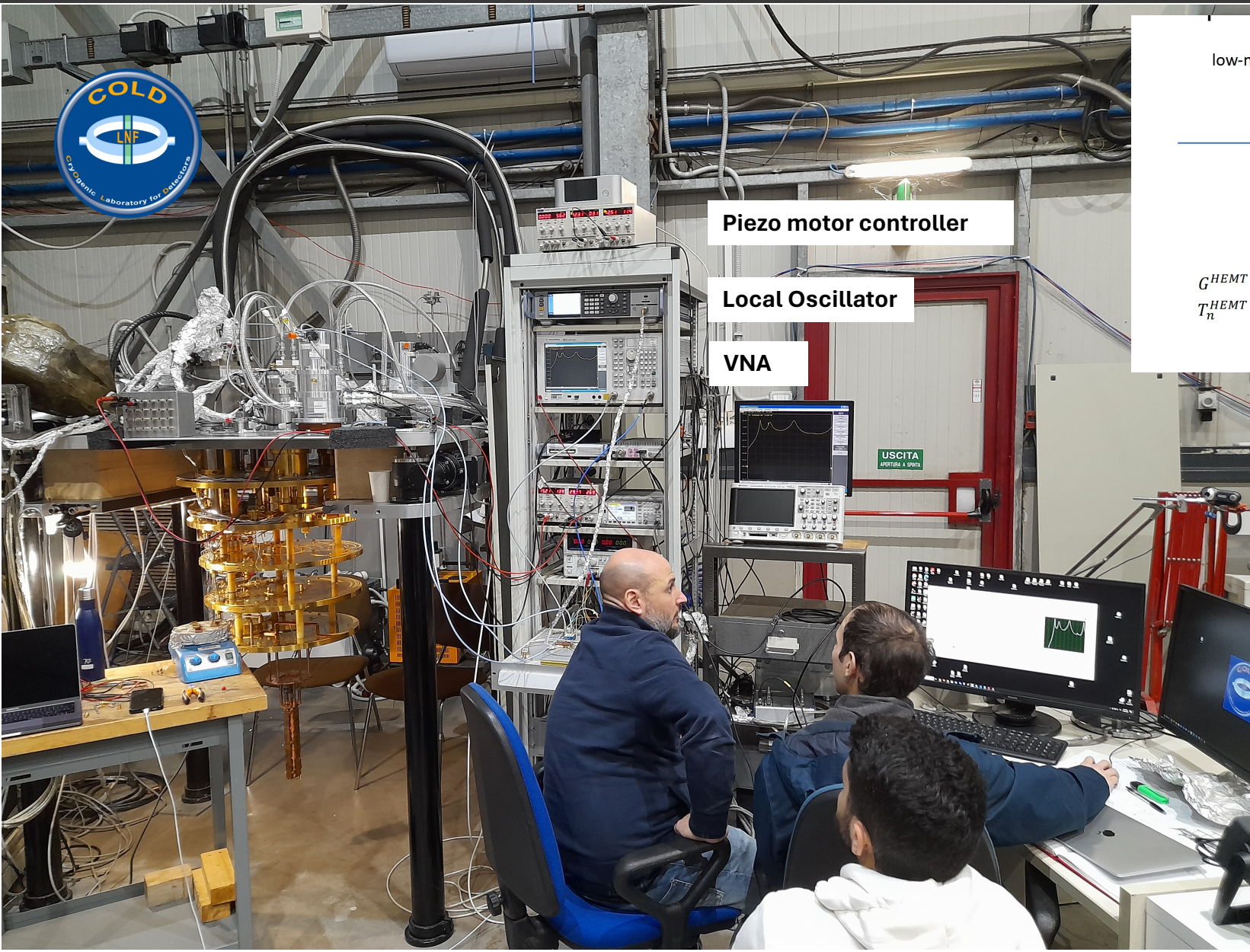


## 6 MHz of frequency scan

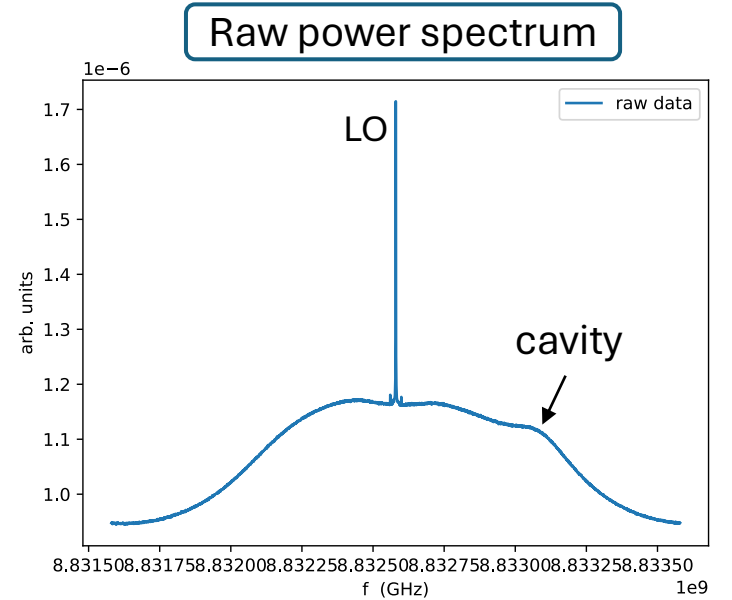
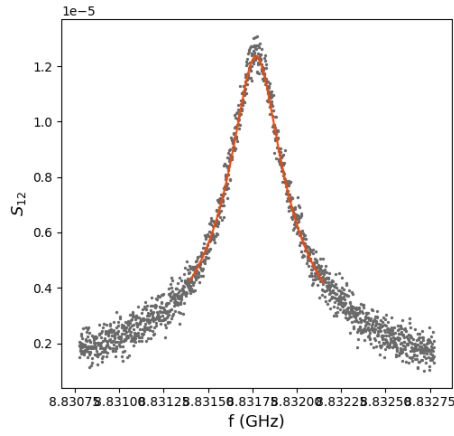
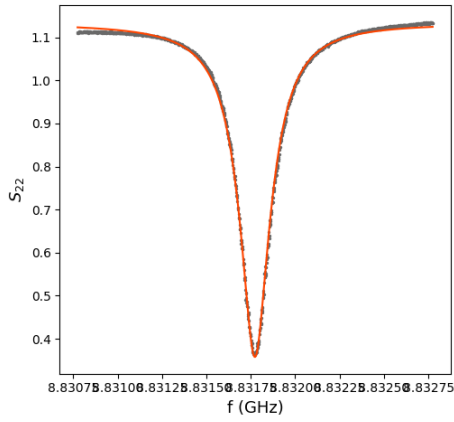
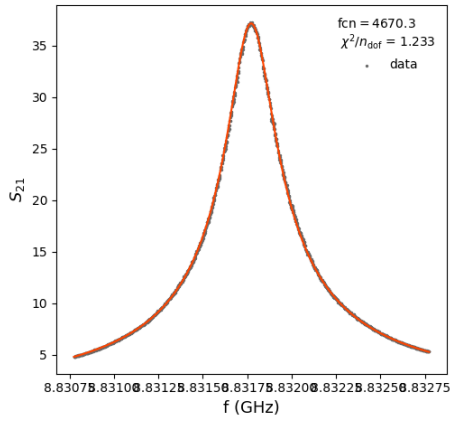




# Acquisition Chain



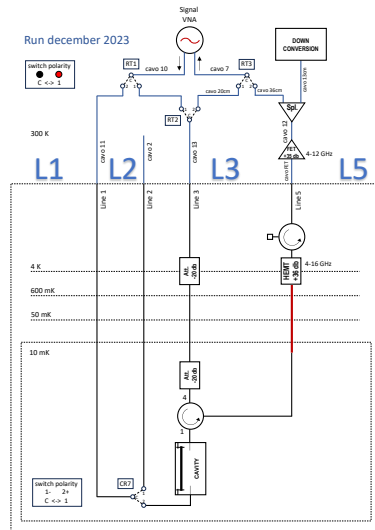




From fit we extract  
 $\nu_c, Q_0, \beta, \text{Gain}$

# Calibration

$$\begin{cases} S_{51} = L_1 + S_{21}^{cav}(\beta, \beta_2, \nu_c, Q_0) + L_5 \\ S_{13} = L_1 + S_{12}^{cav}(\beta, \beta_2, \nu_c, Q_0) + L_3 \\ S_{53} = L_3 + S_{22}^{cav}(\beta, \beta_2, \nu_c, Q_0) + L_5 \end{cases}$$

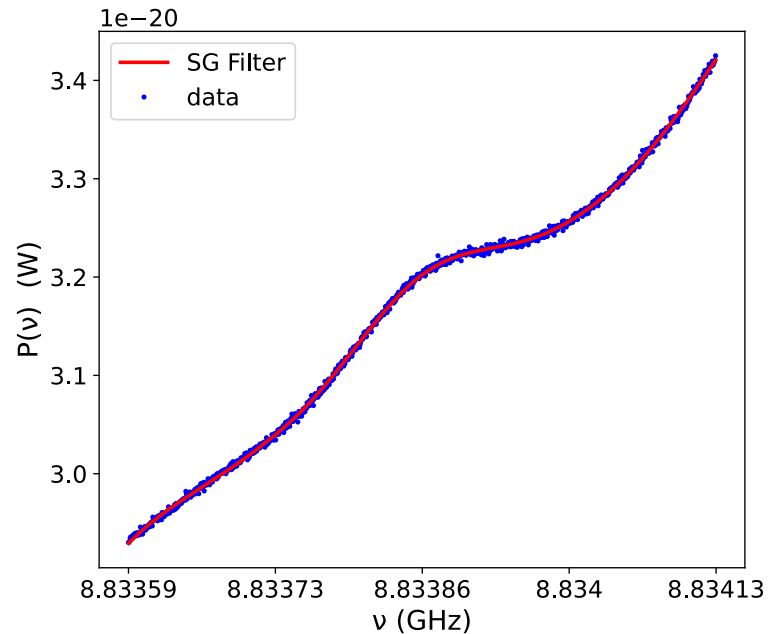


- $V = 0.141 \text{ l}$
- $f_{start} = 8.83 \text{ GHz}$
- $m_a = 36.5 \mu\text{eV}$
- $Q_0 = 50000$
- $\beta = 0.5$
- $C_{010} = 0.667$
- $B_0 = 8 \text{ T}$  ( $B_{av} = 6.5 B_0$ )
- $\Delta t = 3760 \text{ s}$
- $T_{cav} = 40 \text{ mK}$

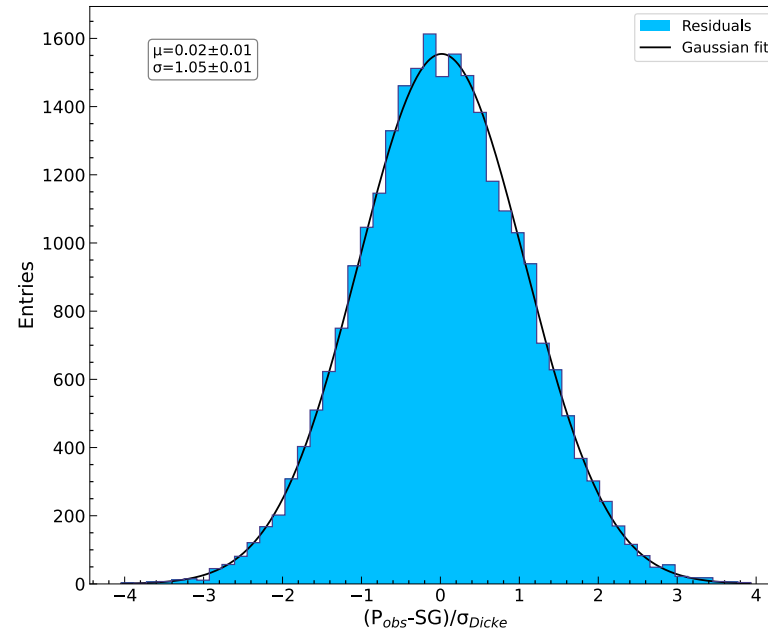
From the calibrated power spectrum we extract the noise temperature  
 $T_n \approx 4.5 \text{ K}$

# Signal Extraction

Example of power spectrum with SG fit



Cumulative normalized residuals over all scans



- Fit to power spectra with Savitzky-Golay filter to calculate residuals
- Maximum likelihood over all scans to estimate the best value  $\hat{g}_{a\gamma\gamma}$

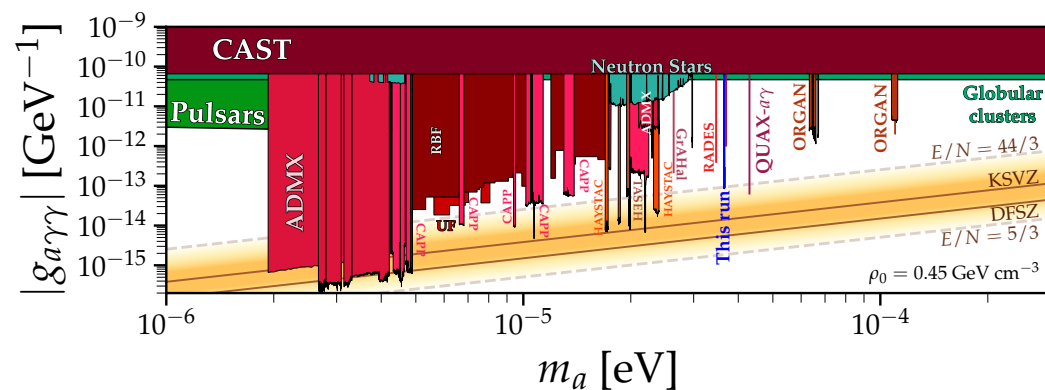
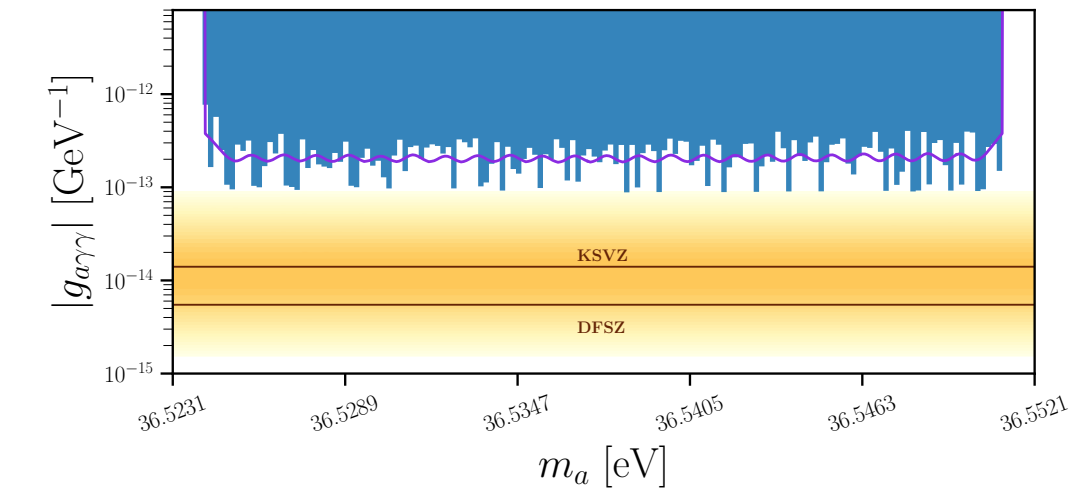
$$\chi^2 = \sum_{\alpha=1}^{N_{scan}} \sum_{i=1}^{N_{bin}} \left[ \frac{R_i^{(\alpha)} - S_i^{(\alpha)}(m_a, g_{a\gamma\gamma}^2)}{\sigma_{Dicke}^{(\alpha)}} \right]^2$$

- Calculate the efficiency of the SG filter by Monte Carlo simulations with fake axion signal ( $\varepsilon = 0.84$ )



# QUAX@LNF Results for 2023 Run

- 24 runs, 1 hour each, 250 kHz of frequency steps
- Average exclusion 90% c.l.  $g_{a\gamma\gamma} = 2 \times 10^{-13} \text{ GeV}^{-1}$
- Paper submitted to PRD. Preprint arXiv:2404.19063



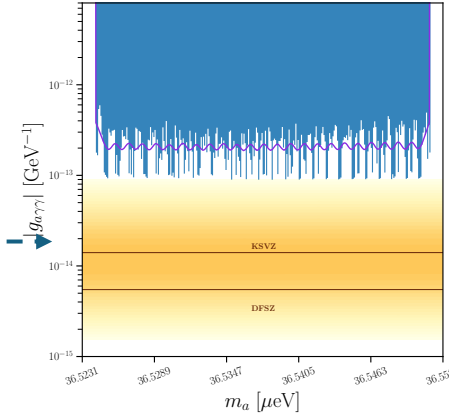
$\nu_c$ [GHz]	$Q_L$	$\beta$
8.83176900	32345	0.5206
8.83203080	32228	0.519
8.83229550	32273	0.5082
8.83255580	32332	0.5141
8.83282190	32387	0.5097
8.83307310	32401	0.5078
8.83334500	32300	0.5097
8.83360070	32503	0.5058
8.83386200	32540	0.5075
8.83412790	32752	0.5014
8.83438580	32573	0.5026
8.83464620	32904	0.5005
8.83490660	32957	0.4984
8.83516350	32863	0.4951
8.83542850	32872	0.4947
8.83568970	33326	0.4881
8.83594630	33051	0.489
8.83620570	33056	0.4894
8.83646975	33104	0.4857
8.83672330	33584	0.4823
8.83698660	33529	0.4803
8.83724500	33659	0.4823
8.83750860	33639	0.4793
8.83776640	33450	0.4793

# Program for Next Runs

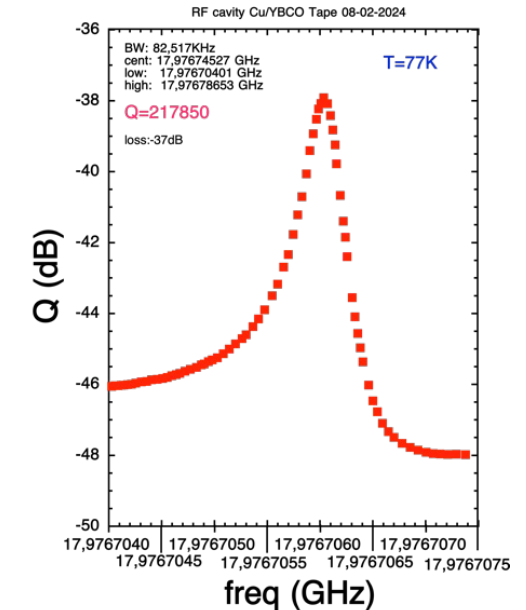
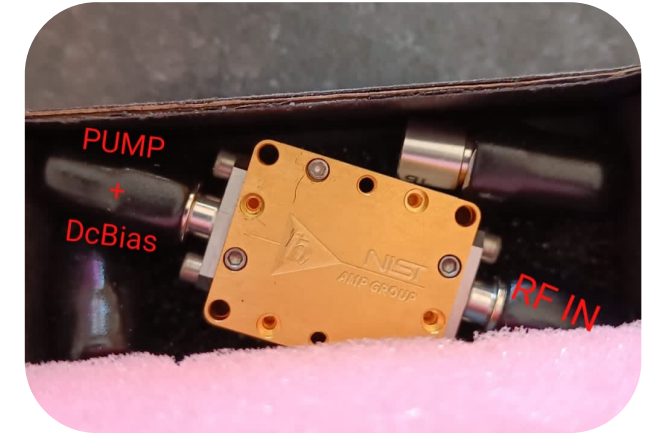
To reach sensitivity to KSVZ axion model:

1. Improve tuner design (vibrations, thermalization)
2. Improve isolation and thermalization of RF lines
3. Use JPA from NIST received within SQMS collaboration
4. Use YBCO cavity (in collab. with ENEA Frascati)

YBCO cavity  
 $Q_0 > 250,000$  @ 17 GHz and 77 K

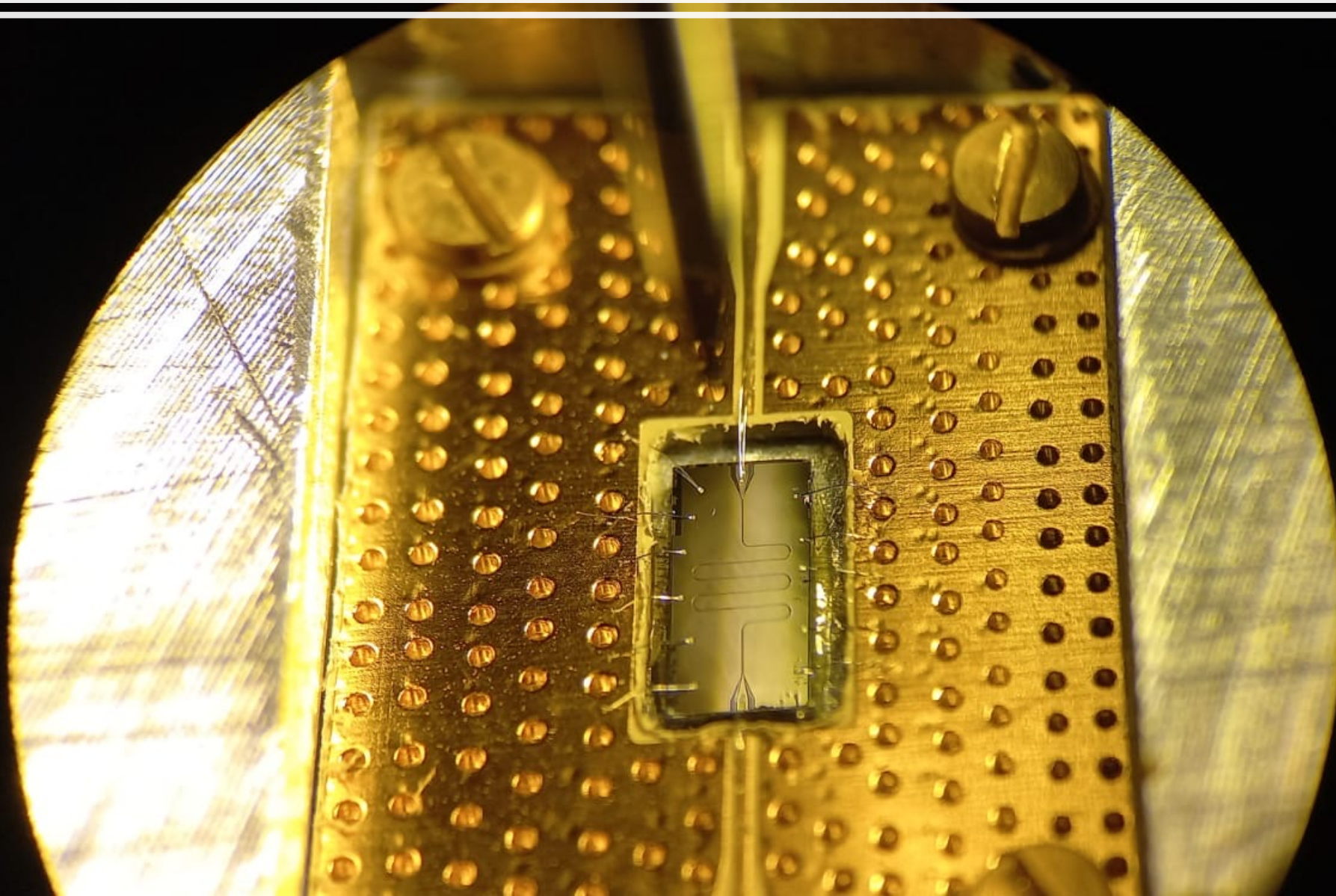


JPA (NIST) Tnoise 0.5 K

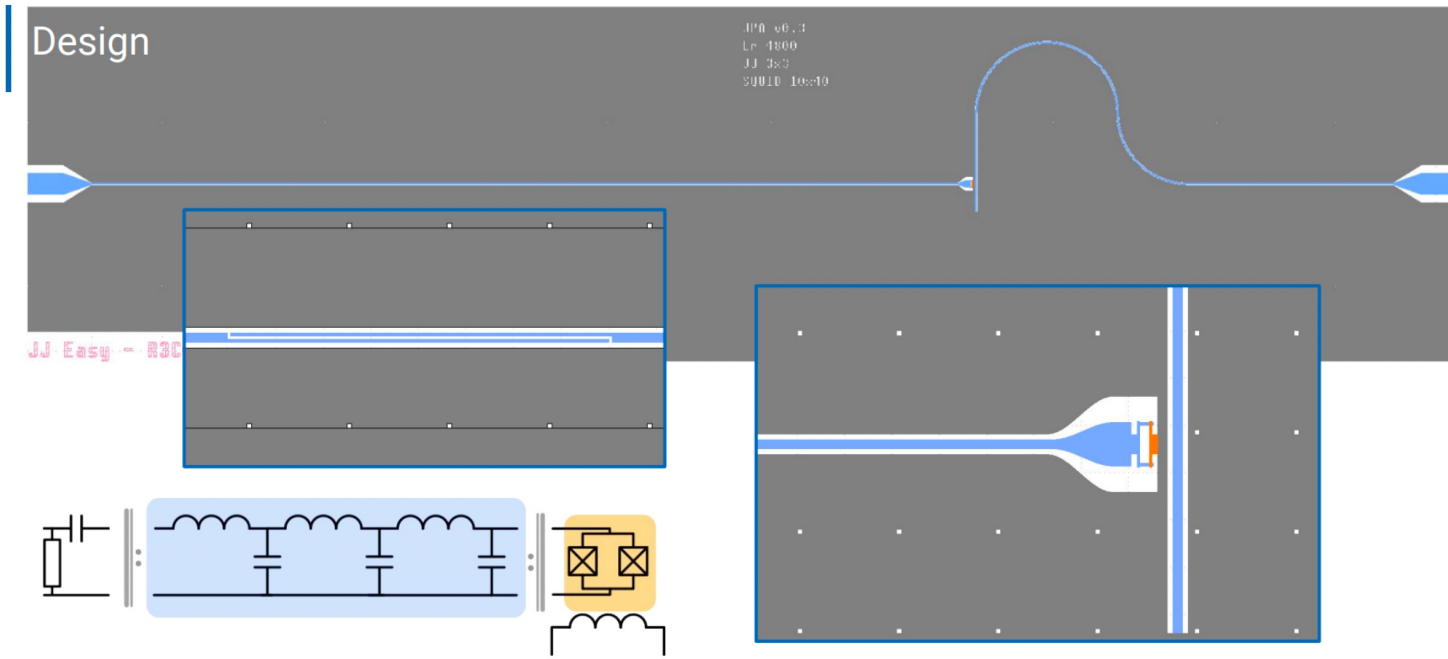




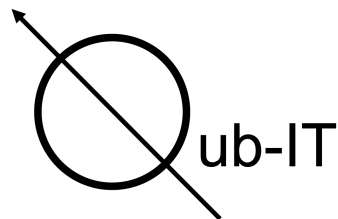
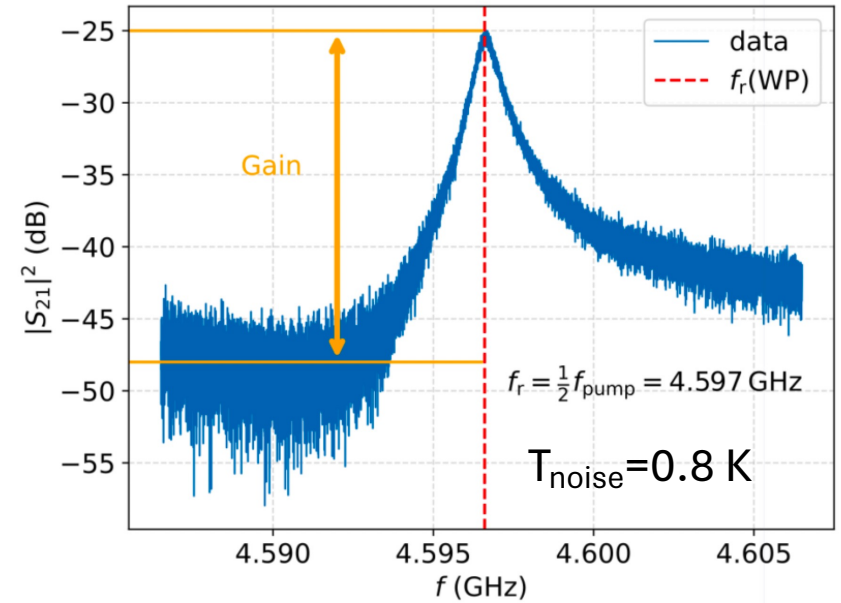
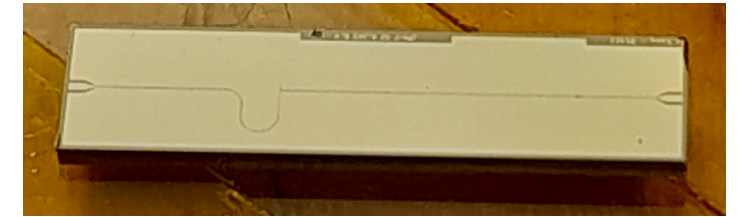
# Quantum Superconducting Devices



# Flux JPA at FBK



More designs are ready and will be tested in the future

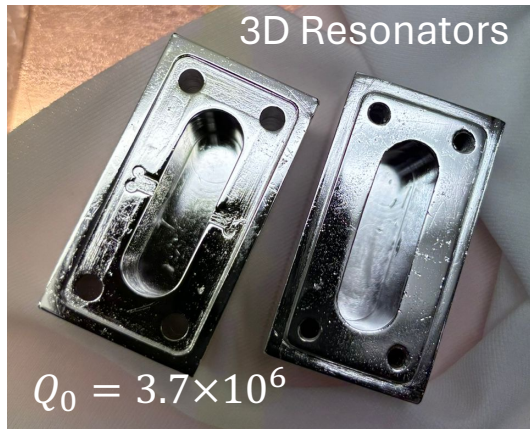
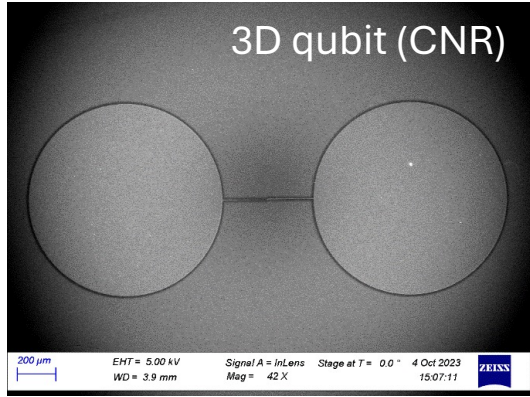


- Second generation of flux JPA fabricated at FBK within Qubit and PNRR projects
- Successfully tested in Trento
- Gain above 20 db and noise below 1 K

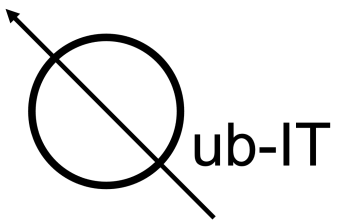
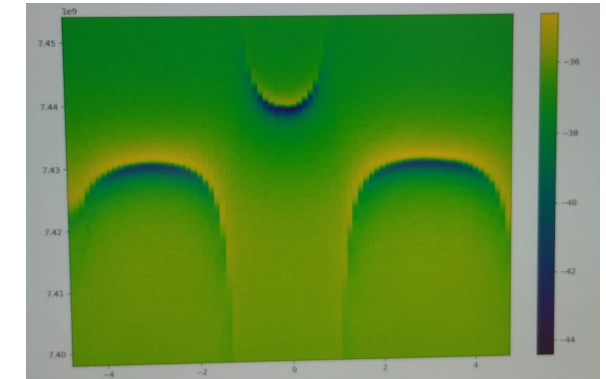
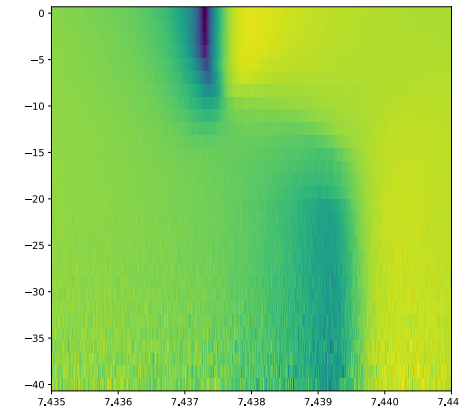
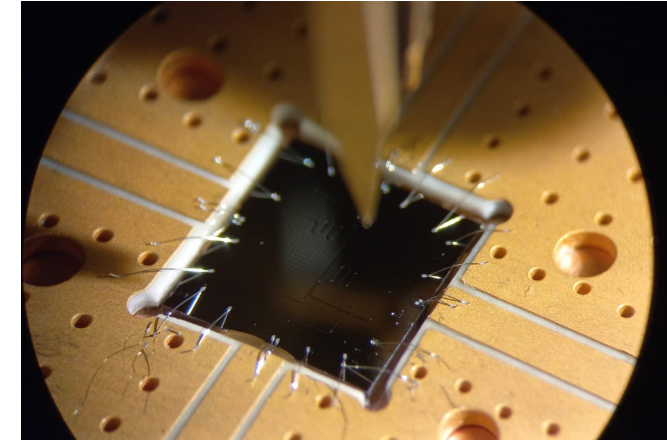
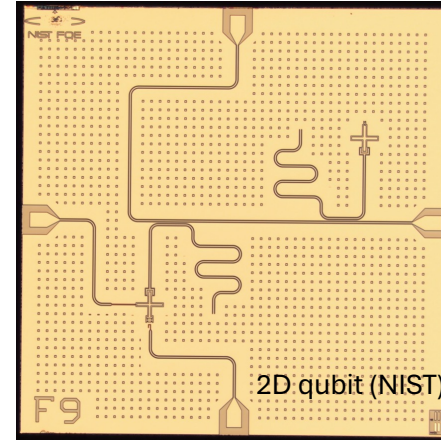
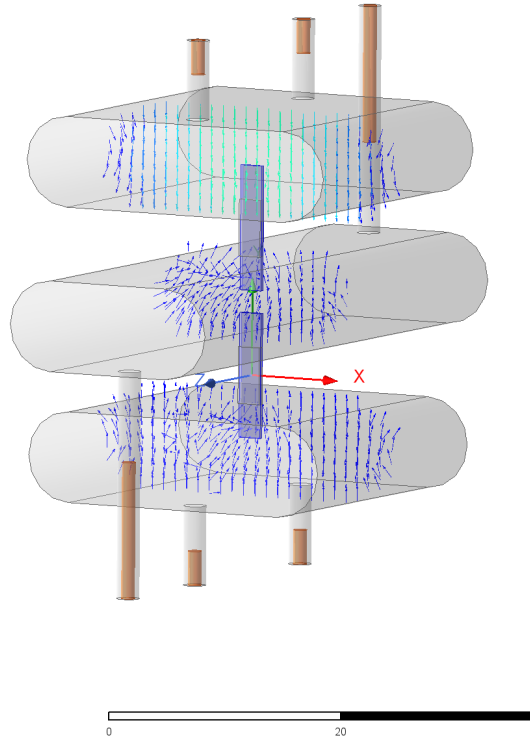




# Superconducting Qubits



Design of 2-qubits photon counter



Appl. Sci. 2024, 14(4), 1478

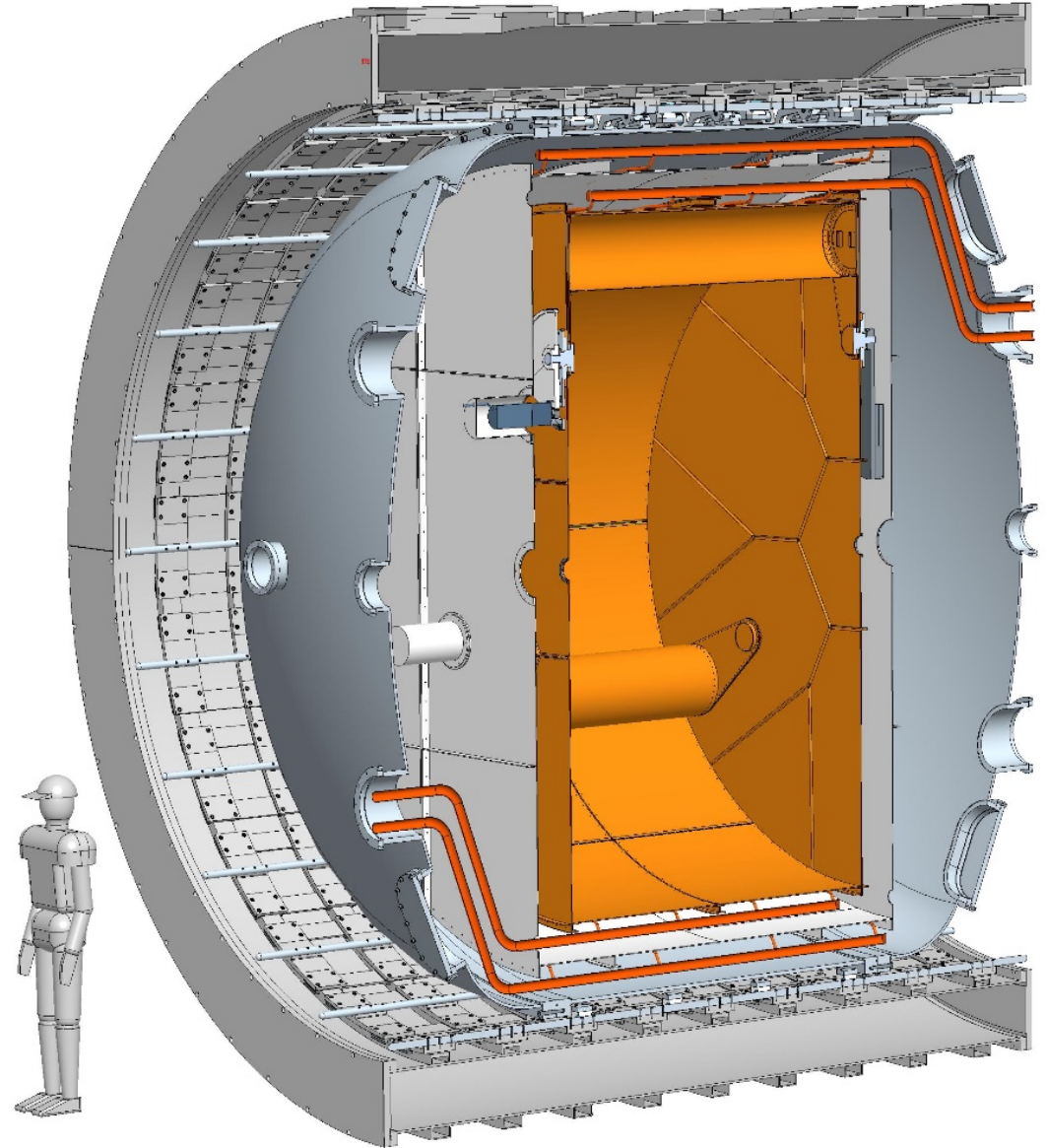
IEEE Transactions on Applied Superconductivity ( Volume: 34, Issue: 3, May 2024)



# FLASH

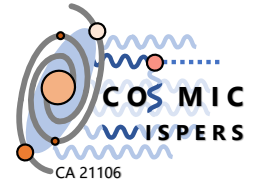
## Finuda magnet for Light Axion Search

Galactic axion search at 100  
MHz ( $0.5-1.5 \mu\text{eV}$ )

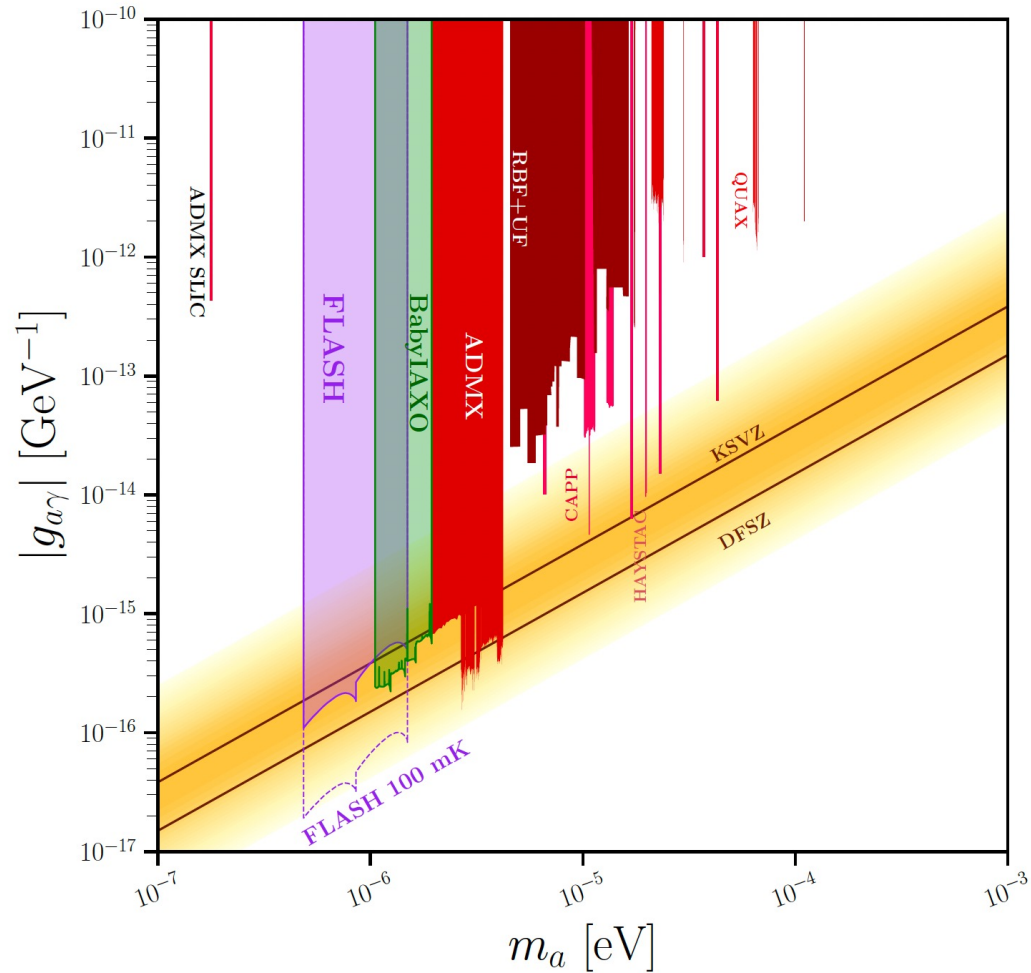




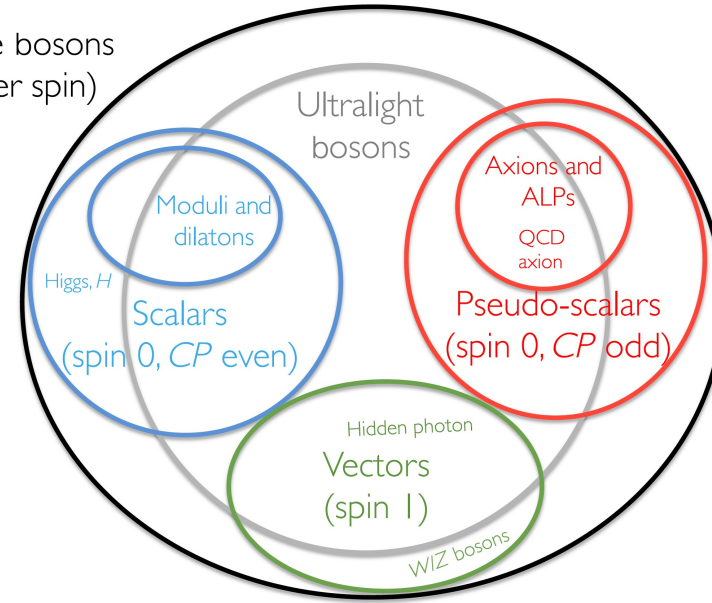
# Experiment for Light Dark Matter (WISPs) Searches



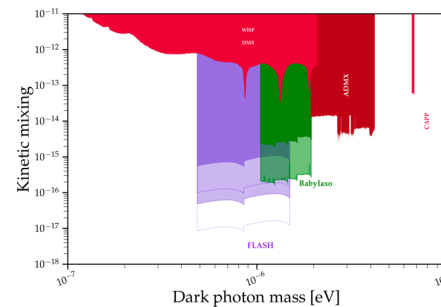
<https://cosmicwispers.eu>



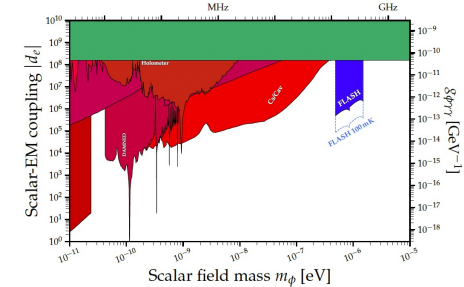
Massive bosons  
(integer spin)



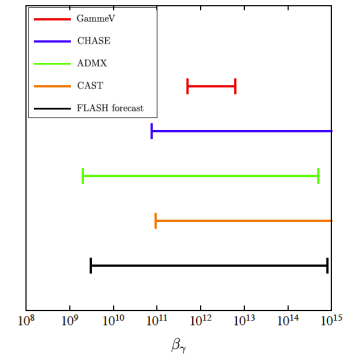
Vector Dark Matter



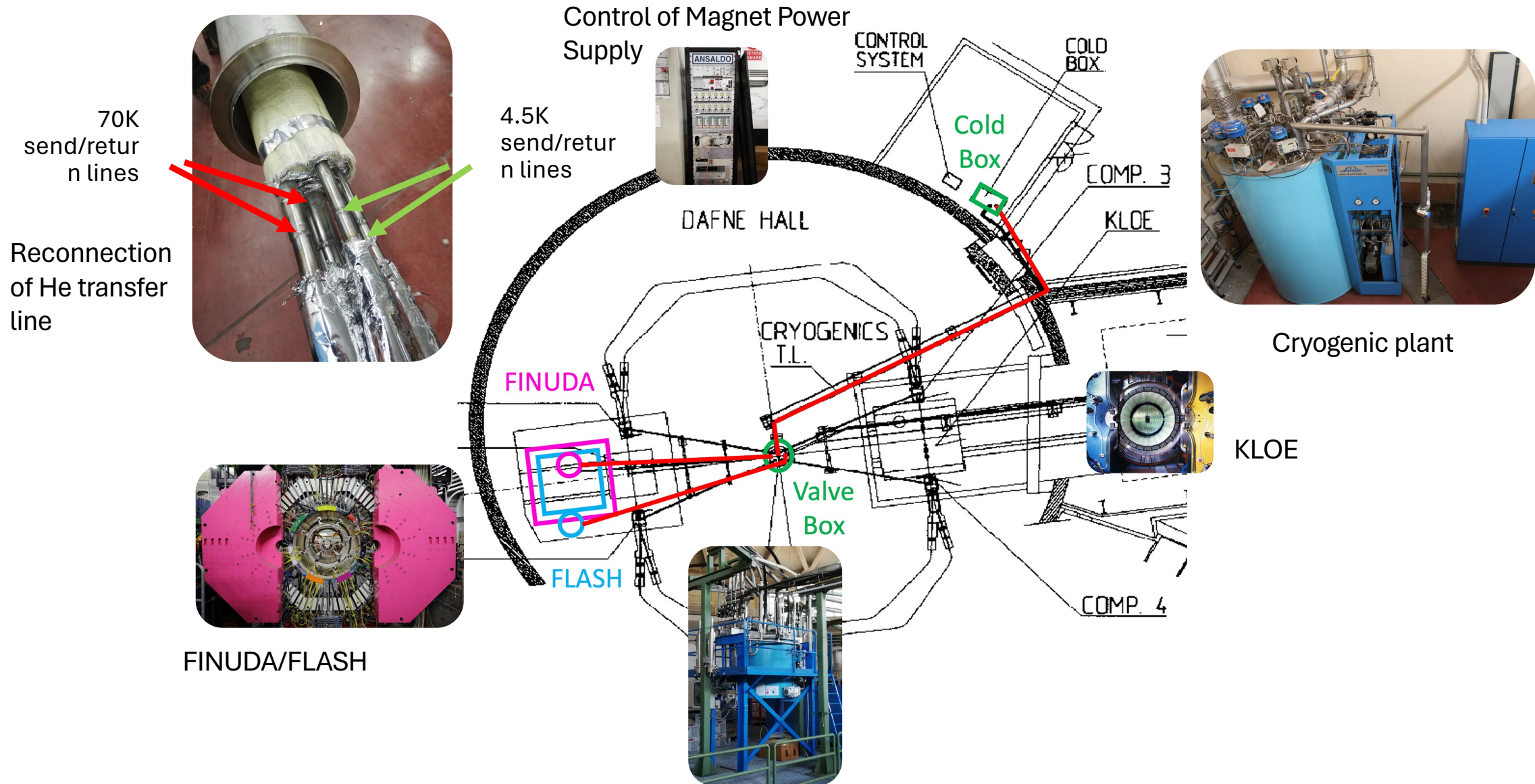
Scalar Dark Matter



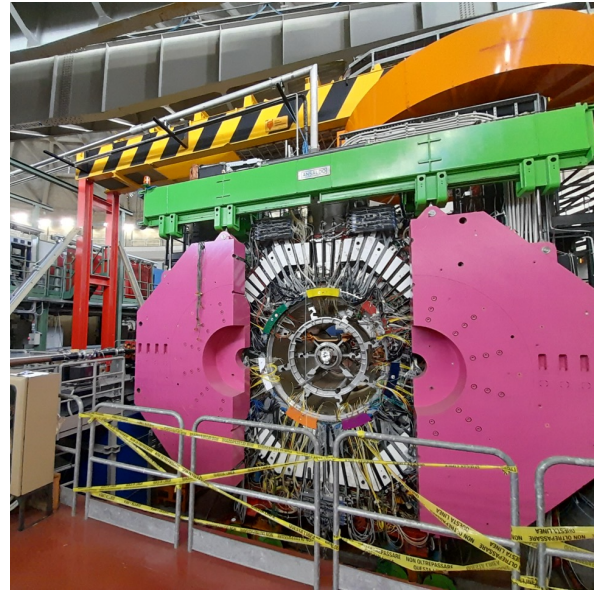
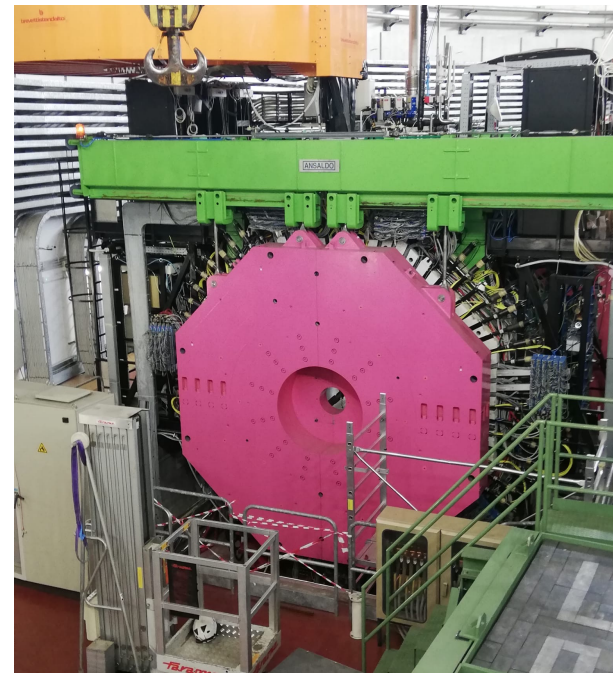
Theories of Dark Energy



# Commissioning of the FINUDA Magnet – Last Operated in 2007



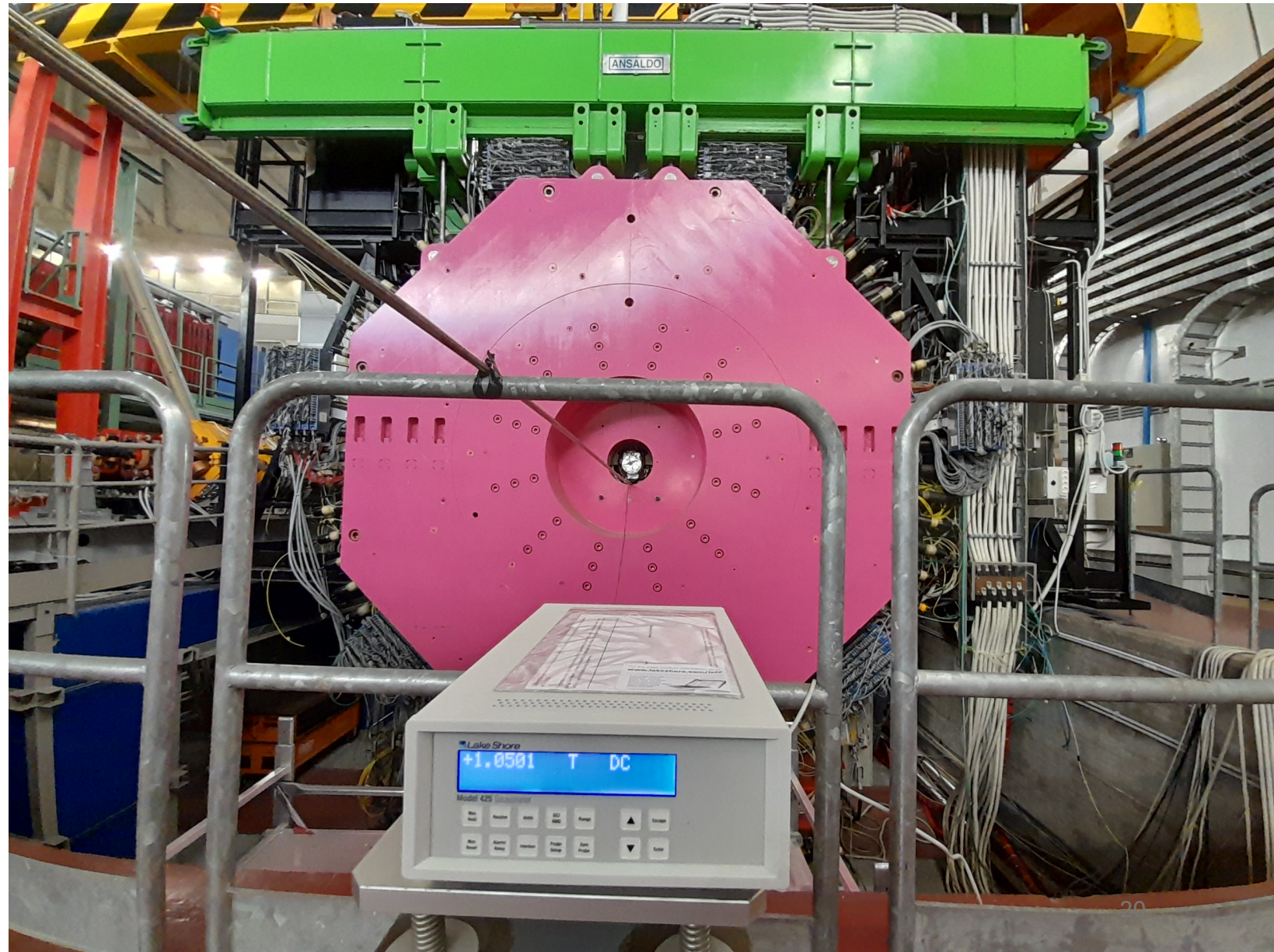






# Successful Test of the FINUDA Magnet

After a series of operations, the cryogenic plant was finally put back into operation. On Jan the 19th 2024, FINUDA was cooled down to 4 K and energized with a current of 2706 A, generating a magnetic field of 1.05 T.







Laboratori Nazionali di Frascati

INFN-18-09-LNF  
September 18, 2018

### The KLASH – Letter of Intent

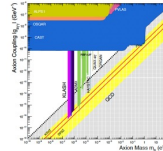
D.Alesini<sup>1</sup>, D.Babusci<sup>1</sup>, F.Bossi<sup>1</sup>, P.Ciambrone<sup>1</sup>, G.Corcella<sup>1</sup>, D.Di Gioacchino<sup>1</sup>, P.Falferi<sup>2</sup>, C.Gatti<sup>1</sup>, A.Ghigo<sup>1</sup>, G.Lamanna<sup>3</sup>, C.Ligi<sup>1</sup>, G.Maccarrone<sup>1</sup>, A.Mirizzi<sup>4</sup>, D.Montanino<sup>5</sup>, D.Moricciani<sup>1</sup>, A.Mostacci<sup>6</sup>, E.Nardi<sup>1</sup>, A.Paoloni<sup>1</sup>, L.Pellegrino<sup>1</sup>, A.Rettaroli<sup>1</sup>, R.Ricci<sup>1</sup>, L.Sabbatini<sup>1</sup>, S.Tocci<sup>1</sup>.



INFN-19-18/LNF  
November 7, 2019

### KLASH

Conceptual Design Report



Physics of the Dark Universe 42 (2023) 101370

Contents lists available at ScienceDirect

Physics of the Dark Universe

journal homepage: [www.elsevier.com/locate/dark](http://www.elsevier.com/locate/dark)

Full Length Article

### The future search for low-frequency axions and new physics with the FLASH resonant cavity experiment at Frascati National Laboratories

David Alesini<sup>a</sup>, Danilo Babusci<sup>a</sup>, Paolo Beltrame<sup>b</sup>, Fabio Bossi<sup>a</sup>, Paolo Ciambrone<sup>a</sup>, Alessandro D'Elia<sup>a,c</sup>, Daniele Di Gioacchino<sup>a</sup>, Giampiero Di Pirro<sup>a</sup>, Babette Döbrich<sup>c</sup>, Paolo Falferi<sup>d</sup>, Claudio Gatti<sup>a</sup>, Maurizio Giannotti<sup>e,f</sup>, Paola Gianotti<sup>a</sup>, Gianluca Lamanna<sup>g</sup>, Carlo Ligi<sup>a</sup>, Giovanni Maccarrone<sup>a</sup>, Giovanni Mazzitelli<sup>a</sup>, Alessandro Mirizzi<sup>h,i</sup>, Michael Mueck<sup>j</sup>, Enrico Nardi<sup>a,k</sup>, Federico Nguyen<sup>l</sup>, Alessio Rettaroli<sup>1</sup>, Javad Rezvani<sup>m,n</sup>, Francesco Enrico Teofilio<sup>o</sup>, Simone Tocci<sup>a</sup>, Sandro Tomassini<sup>a</sup>, Luca Visinelli<sup>o,p</sup>, Michael Zantedeschi<sup>o,p</sup>

<sup>a</sup> INFN, Laboratori Nazionali di Frascati, via Enrico Fermi 54, Roma, 00044, Italy  
<sup>b</sup> University of Liverpool Department of Physics, Oxford St, Liverpool, L69 7ZE, England  
<sup>c</sup> Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), Heisenberg Ring 1, München, 80805, Germany  
<sup>d</sup> Fondazione Bruno Kessler, Via Sommarive, Povo, Trento, I-38123, Italy  
<sup>e</sup> Department of Chemistry and Physics, Barry University, 11300 NE 2nd Ave., Miami, 33161, USA  
<sup>f</sup> Centro de Investigaciones y Física de Altas Energías (CIAFA), Universidad de Zaragoza, Zaragoza, 50009, Spain  
<sup>g</sup> INFN and University of Pisa, Largo Pontecorvo 3, Pisa, 56127, Italy  
<sup>h</sup> Dipartimento di Fisica "Michelangelo Martini", Via Amendola 173, Bari, 70126, Italy  
<sup>i</sup> INFN sezione di Bari, Via Orto Botanico 4, Bari, 70136, Italy  
<sup>j</sup> IZS SQUID, Herberner Strasse 9, Sim, 35764, Germany  
<sup>k</sup> Laboratory of High Energy and Computational Physics, HEP-C-NCPB, Rinvale 10, 10145, Tallinn, Estonia  
<sup>l</sup> INFN Centro Ricerche Frascati, Via E. Fermi 45, Prosecco, I-00044, Italy  
<sup>m</sup> Physics Division, School of Science and Technology, University of Camerino, Via Madonna delle Carceri 9, Camerino, 62032, Italy  
<sup>n</sup> University of Pisa, Largo Pontecorvo 3, Pisa, 56127, Italy  
<sup>o</sup> Tsing-Tao Lee Institute (TLI), 520 Shanghai Road, Shanghai, 201210, China  
<sup>p</sup> School of Physics and Astronomy, Shanghai Jiao Tong University, 800 Dongchuan Road, Shanghai, 200240, China



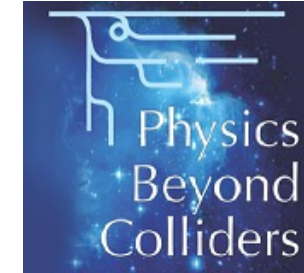
KLASH CDR arXiv:1911.02427  
FLASH paper Phys. Dark Univ. 42 (2023)

FLASH TDR		
Wednesday 15 May 2024, 14:30 → 18:00 Europe/Rome		
14:30 → 14:35	Introduction	5m
Speaker: Claudio Gatti (Istituto Nazionale di Fisica Nucleare)		
TDRMeetin...		
14:35 → 14:45	LNF	10m
Speaker: Claudio Gatti (Istituto Nazionale di Fisica Nucleare)		
14:45 → 15:00	Physics Reach	15m
Speaker: Prof. Luca Visinelli (Shanghai Jiao Tong University)		
LNF2024.p...		
15:00 → 15:15	Status of RF cavity design	15m
Speaker: Simone Tocci (Istituto Nazionale di Fisica Nucleare)		
FLASH_Sta...		
15:15 → 15:30	Cryostat design	15m
Speaker: Carlo Ligi (Istituto Nazionale di Fisica Nucleare)		
FLASH - Cr...		
15:30 → 15:45	Computing	15m
Speaker: Giovanni Mazzitelli (Istituto Nazionale di Fisica Nucleare)		
FLASH_co...		
15:45 → 16:00	MIB	15m
Speaker: Lucia Canonica (Istituto Nazionale di Fisica Nucleare)		
Canonica_...		
16:00 → 16:15	Mainz/Bonn	15m
Speaker: Kristof Schmieden (CERN)		
Flash_TDR...		
16:15 → 16:30	Uni Camerino	15m
Speaker: Seyed Javad Rezvani (LNF)		
UNICAM-F...		
16:30 → 16:45	Pisa	15m
Speaker: Gianluca Lamanna (Istituto Nazionale di Fisica Nucleare)		
FLASH_24...		
16:45 → 17:00	Trento	15m
Speaker: Paolo Falferi (Istituto Nazionale di Fisica Nucleare)		
Falferi - Tre...		
17:00 → 17:15	Valencia/Cartagena/Barcelona	15m
Speaker: Diaz Alejandro		
FLASH_AD...		
17:15 → 17:30	BAWs	15m
Speaker: Diego Blas Temiño		
FLASH_nrf		

# All experiments & proposals linked with Tech WG

## Updated list after reaching out to all experiments

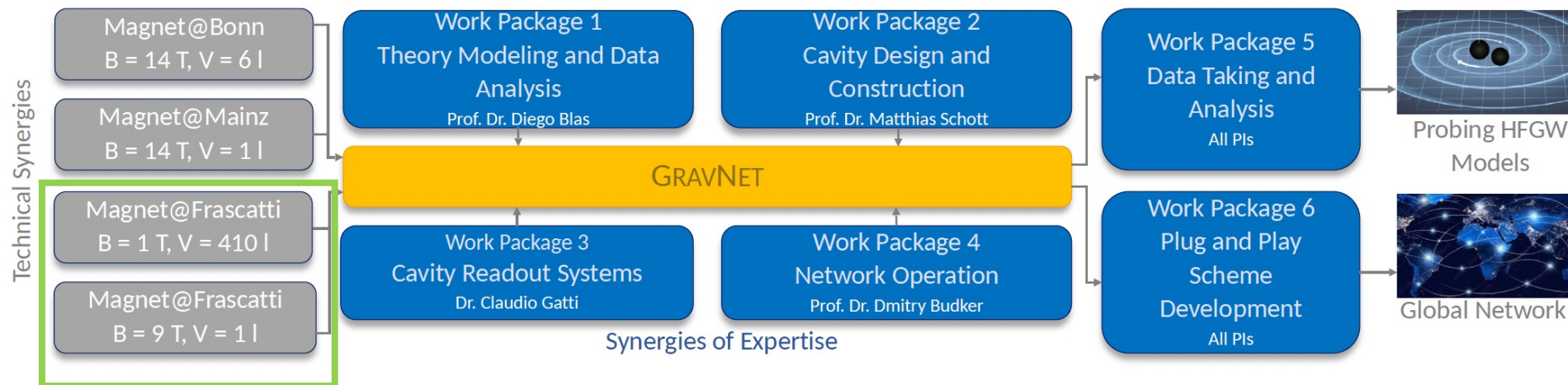
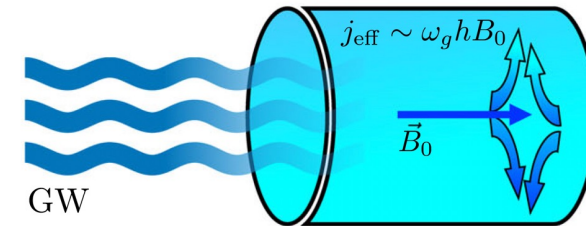
- ALPS-II (Joern Schaffran) -> axion search light-shining-through-wall with lasers
- BabylAXO (Matthias Mentink, Igor Garcia Irastorza) -> axion search from the sun
  
- GrAHal (Pierre Pugnati) -> axion search with RF cavities
- RADES/HTS (Jessica Golm) -> axion search with HTS RF cavities
- Advanced-KWISP (Giovanni Cantatore) -> search for Short Range Interactions
- Axion Heterodyne Detection (TBC) -> axion search with two-mode RF cavities
- AION-100 @ CERN (Oliver Buchmuller, Richard Hobson) -> vertical atom interferometer
  
- **NEW:** FLASH (Claudio Gatti) -> axion search with RF cavities



Ongoing discussion for technical support from PBC@CERN for the cryostat design



# GravNet: A Global Network for the Search for High Frequency Gravitational Waves



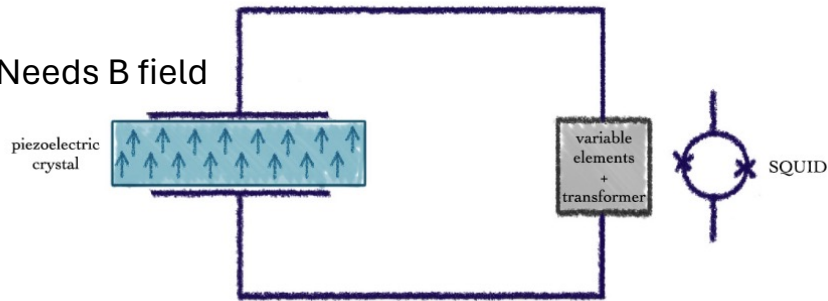
# Bulk Acoustic Wave Resonators for Light DM and HFGW

## Strong synergies with cavity experiments

### AXIONS

Piezoaxionic effect *PHYSICAL REVIEW D* 109, 072009 (2024)

Needs B field



BAW radius from 1 to 50 cm

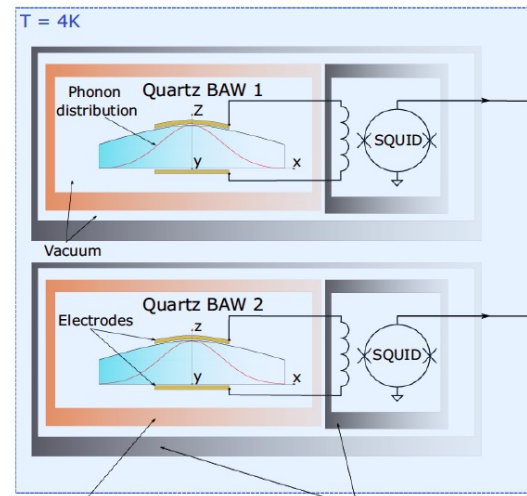
Use FLASH for larger devices/arrays

Smaller BAWs in other labs

### HFGW

The multi-mode acoustic gravitational wave experiment: MAGE. *Sci Rep* 13, 10638 (2023).

Needs network

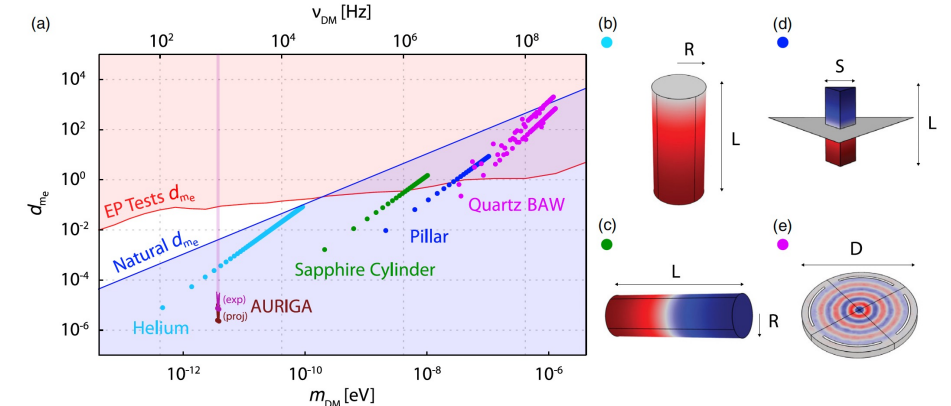


### SCALAR DM

Sound of Dark Matter *Phys. Rev. Lett.* 116, 031102 (2016)

Searching for Scalar Dark Matter with Compact Mechanical Resonators *PHYSICAL REVIEW LETTERS* 124, 151301 (2020)

Needs array + tuning



Synergies: Physics case, cryogenics, radiofrequency, quantum amplifiers/quantum sensing, DAQ and Data Analysis ... in some case also same research groups (e.g. M.Tobar's MAGE/ORGAN)



# Conclusion

- First Results from QUAX@LNF (submitted to PRD)!
- Quantum Amplifier JPA with good performance fabricated at FBK!
- Qubit design, fabrication and characterization ongoing (Appl. Sci. 2024, 14(4), 1478)!
- FINUDA Magnet operated successfully and FLASH-TDR proposal in preparation!
- Ongoing discussion with Physics Beyond Collider for support on cryostat design.
- Many young researchers and students
  - 4 Master students (2 from MiB, 1 from La Sapienza, 1 from Eng. Dept. Roma Tre)
  - 1 Erasmus+ student from Heidelberg
  - 3 Post Docs (DOE, csnV calls to be renewed on PNRR and PRIN)
  - 1 non permanent Technologist (PNRR)
  - 1 non permanent Technician (PNRR)
- Many colleagues visiting us from abroad: B. Dobrich (Munich), L. Visinelli (Shangai), M. Zantedeschi (Shangai), D. Blas (Barcelona), A. Iorio (Prague), S. Posen (Fermilab), Ray Simmond (NIST)
- Many colleagues coming from Italy for measurements and discussions
- Many new ideas for future experiments and collaborations within Cosmic Wispser COST action!

