FLASH (FINUDA magnet for Light Axion SearcH): R&D for TDR

(FIsica NUcleare a DAΦNE)

(Double Annular Factory for Nice Experiments)

FLASH will be a new haloscope: a detector of axions and exotic particles composed of a resonant cavity immersed in a strong magnetic field

ISTITUTI PARTECIPANTI
- Laboratori Nazionali di Frascati (LNF)
- University of Camerino
  Pisa University and INFN
- Trento Institute for Fundamental Physics and Applications (TIFPA)
- University of Bonn and University of Mainz
- Technical University of Cartagena (UPCT) & IFIC (CSIC-University of Valencia) & IFAE-ICREA
- University of Liverpool
- Tsung-Dao Lee Institute (TDLI), Shanghai
- University of Zaragoza

ALTRI PARTECIPANTI
- ezSQUID
- Technology Working Group of the Physics Beyond Collider@ CERN

Personale afferente 2025 in totale 10,9 FTE - 43 persone

Personale afferente 2025 al TIFPA 0,6 FTE - 2 persone
P. Falferi 30%, A. Vinante 30%

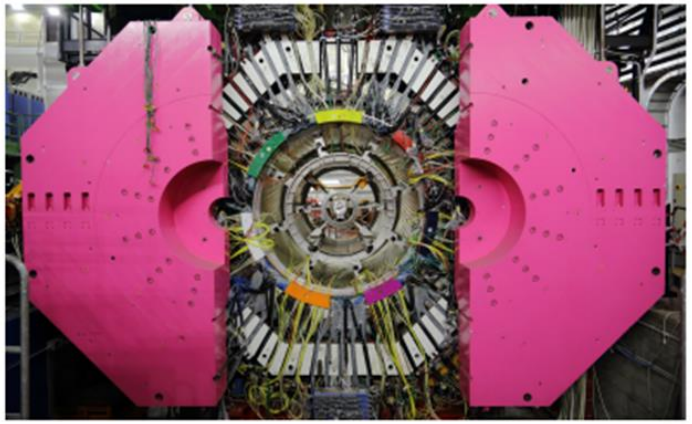
Durata esperimento 2 anni (R&D) (2025-2026)

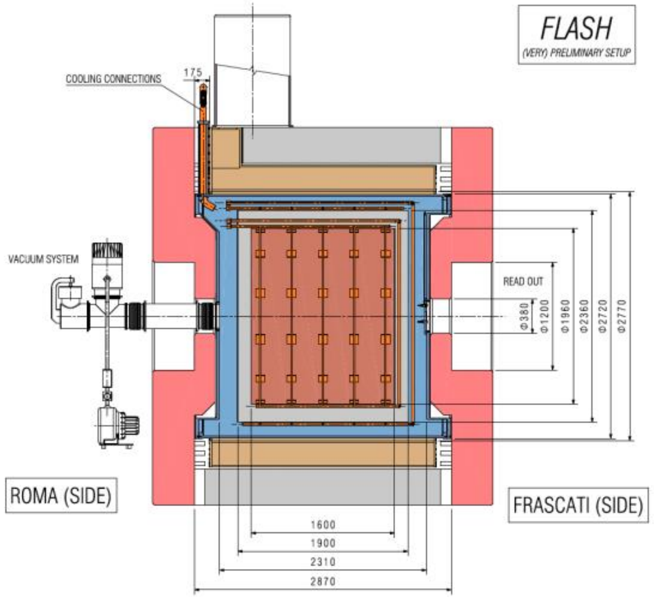
Responsabile nazionale
Claudio Gatti (LNF)
Responsabile locale
Paolo Falferi (TIFPA)

Finanziamento (k€)

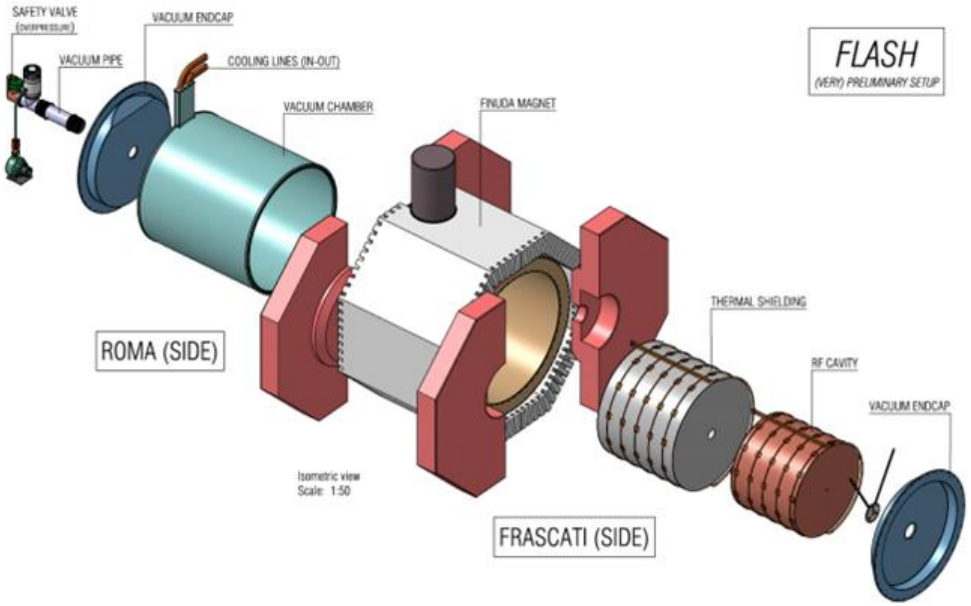
	2025 richiesto	2025 assegnato
Totale	168	113
TIFPA	34	31

FINUDA was (data tacking stopped in 2007) a non-focussing magnetic spectrometer

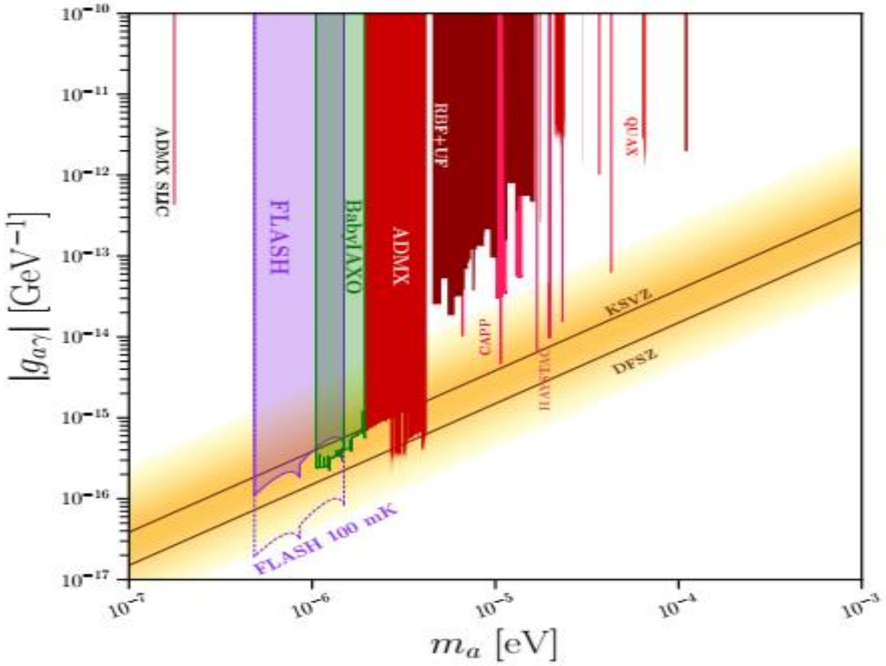




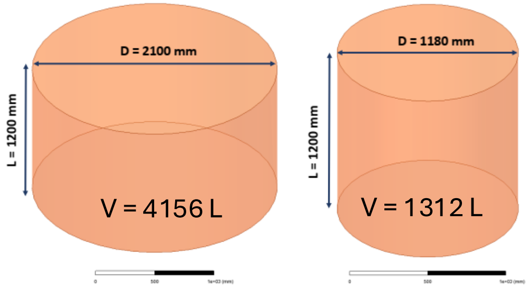
Idea: exploit FINUDA's cryogenic volume (≈6 m^3) and superconducting magnet (1.1 T over 15 m^3) to create a new haloscope @ LNF



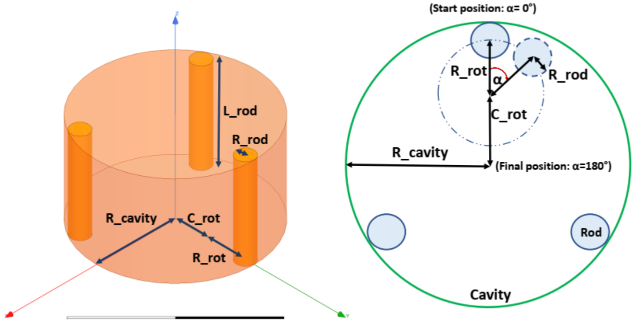
FLASH experiment: a new haloscope @ LNF to detect cosmic axions of masses around 10^{-6} eV, an unexplored mass window between the mass ranges of the experiments ADMX, BabyIAXO and DMRadio



The goal of the FLASH experiment is to cover the range 117-360 MHz by tuning with metallic movable rods the resonant frequency of the mode TM010 of two cavities.



Two cavities

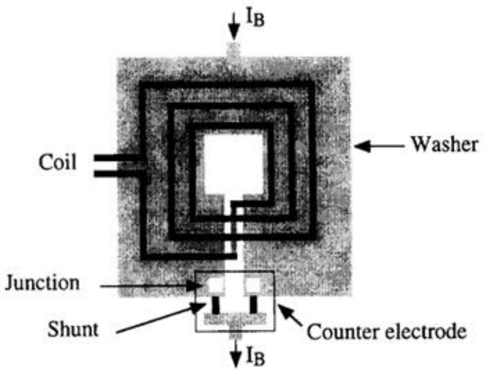


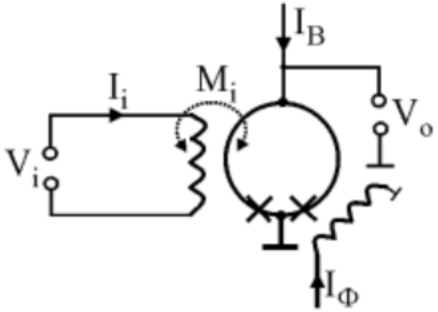
Resonance tuning with movable rods

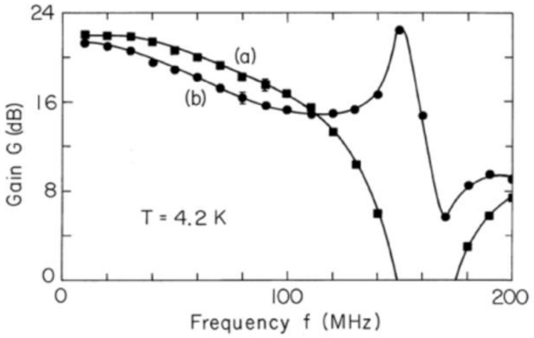
Given the operating frequency range the most suitable low noise amplifier is the MSA

Main differences between dc SQUID and Microstrip SQUID Amplifier (MSA)

«Standard» Square Washer SQUID



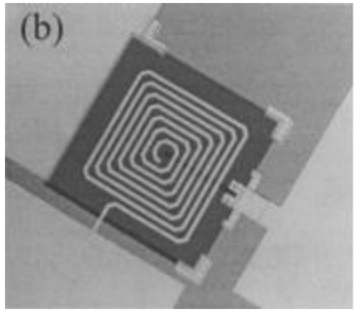


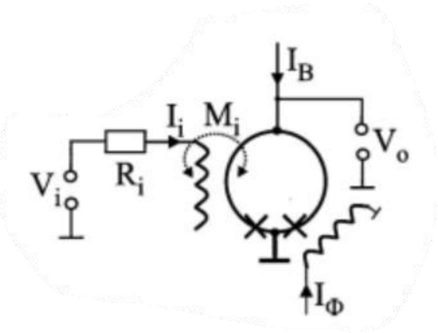


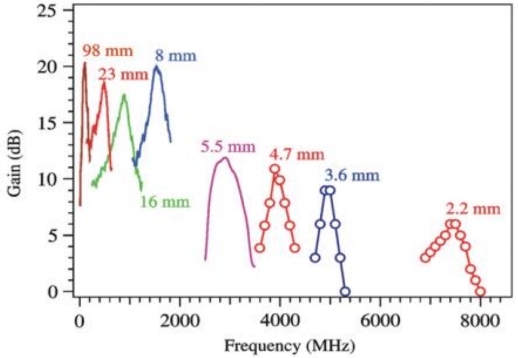
Input coil and SQUID washer form a capacitor in parallel to the input coil inductance -> Resonant circuit (typically $\nu_0 \approx 40$ MHz)

(a) negative and (b) positive V_Φ

Microstrip SQUID Amplifier







The effect of the parasitic capacitance between input coil and SQUID washer can be exploited to operate the input coil as a transmission line resonator

Amplifiers based on this principle have shown gains of 20 dB at frequencies below 1 GHz and up to 10 dB at 5 GHz

Mück and McDermott, Supercond. Sci. Technol. 23 093001 (2010)

Matching the Flash cavity bandwidth (117–206 and 206-360 MHz)

Tuning the microstrip resonator with a varactor diode

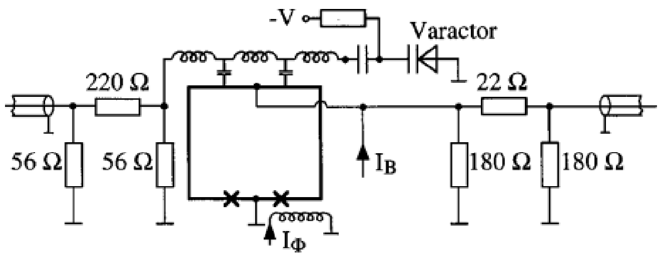


FIG. 1. Configuration of SQUID microstrip amplifier showing a varactor diode connected to one end of the microstrip. The input and output π-network attenuators match the impedances to 50 Ω.

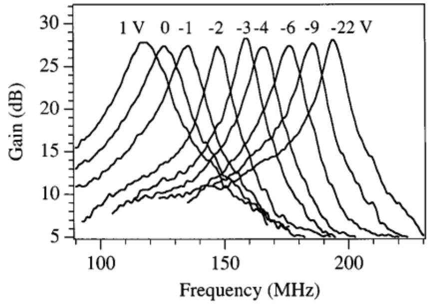
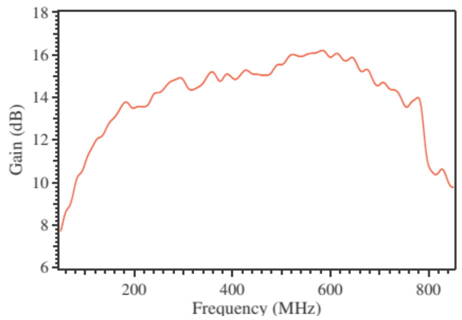


FIG. 2. Gain vs frequency for the SQUID microstrip amplifier with 31 turns at 4.2 K for nine values of bias voltage applied to the varactor diode.

It is possible to tune the resonant frequency of the MSA by terminating the microstrip resonator with a varactor diode.
The varactor doesn't change the noise temperature of the MSA (here 0.9K @ 200 MHz, 4.2K)

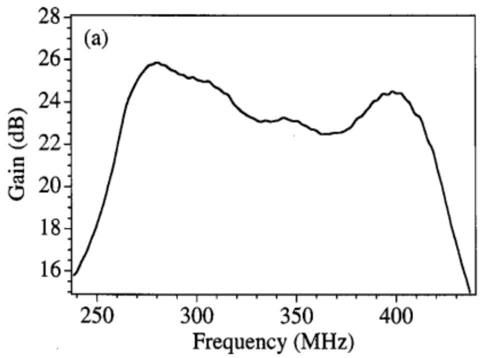
Mück et al. Appl. Phys. Lett., 75, 3545,1999

Lower MSA resonator Q -> wider bandwidth (but lower gain)



A broad bandwidth can be obtained with a lower quality factor of the resonator but at the expense of a lower gain

Two cascaded MSA tuned to different resonant frequencies



A broad bandwidth can be obtained with a second MSA as a postamplifier. Here the resonance frequencies of the first and second amplifiers were about 280 and 400 MHz, respectively.

Gantt Chart for the FLASH-TDR preparation

Year	2024	2025				2026	
Quarter	IV	I	II	III	IV	I	II
WP1 - Physics Reach		Modes & Frequencies				TDR Section on Physics Reach	
WP2 - Mechanical Design and Cryogenics	Envelope volume for RF cavity		Define MSA Position in Cryostat and Probe	Prototype Mechanical Design		Cryostat Design	TDR section on Mechanical Design
WP3 - RF Cavity			Cavity RF Design	Prototype RF Design	Fabrication of Cavity Prototype	Cryogenic Test of Cavity Protoype	TDR Section on RF Cavity
WP4 - Amplification and Acquisition		Gain and Noise Characterization of MSA	Test of Shielding in Magnetic Field	DAQ	Multiplexing Prototype Circuit	Full Chain Test with BAW resonator	TDR Section on Amplification & DAQ
WP5 - Data Analysis and Computing					Computing Cloud Model validated	TDR Section on Analysis & Computing	
WP6 - Decommissioning & Commissioning				Tools for FINUDA Decommissioning		TDR Section on Decommissioning &	
WP7 - Management	Periodic Meeting	Periodic Meeting	Periodic Meeting	Periodic Meeting	Periodic Meeting	TDR writing	Technical Design Report

R&D	Description	Initial TRL	Final TRL
RF Cavity	500 MHz cavity prototype	TRL4	TRL7
Superconductive Cavity	Feasibility of a FLASH SC cavity	TRL4	TRL5
SQUID Amplifier	MSA at 2 and 4 K and B field	TRL6	TRL9
SQUID Amplifier	Signal Multiplexing	TRL3	TRL7
DAQ	Test of the full amplification and DAQ chain	TRL4	TRL9
Computing	Validation of the Cloud Computing model	TRL7	TRL9

Table 9: WPs

WP1	Physics Reach
WP2	Mechanical Design and cryogenics
WP3	RF Cavity
WP4	Signal Amplification and Acquisition
WP5	Data Analysis and Computing
WP6	FINUDA Decommissioning and FLASH Commissioning
WP7	Project Management

Activity at TIFPA in 2025/2026 (WP4 Amplification and Acq)

Characterize a commercial MSA amplification system (SQUID + CryoAmp) in terms of gain, bandwidth and noise down to ultracriogenic temperatures

2025 status:

- Purchase and distribution to Pisa and Camerino of 3 of the 5 MSA complete systems (SQUID + CryoAmp)
- Test at room temperature of the low-noise semiconductor CryoAmp

TIFPA REQUESTS 2025/2026 (Dotazioni)

Capitolo di spesa	Descrizione	2025 richiesta	2025 assegnati	2025 disponibili	2026 richiesta
Inventario	5 sistemi completi MSA (per Tn, Pi, LNF, Camerino)	25 k€	25 k€	0.6 k€	0 k€
Consumo	Componenti RF e criogenici, liquidi criogenici	7 k€	5 k€	5 k€	3 k€
Missioni	Run sperimentali	2 k€	1 k€	0.4 k€	1 k€
	Totale	34 k€	31 k€	6 k€	4 k€

END

EXTRA MATERIALS

Table 20: Funding Requests

Descrizione	Capitolo di Spesa	Sezione INFN	2025	2026
4 sistemi completi MSA	Inventario	Trento+Pisa+LNF	25k	0
2 Digitizer >500 MHz	Inventario	Pisa + LNF	15k	0
Multimetro	Inventario	Pisa	6k	0
FPGA per DAQ	Inventario	Pisa	10k	0
Generatore 120 MHz	Inventario	LNF-UniCam	6k	0
Termometri da campo B	Inventario	LNF-UniCam	2k	0
Totale	Inventario		64k	0
Schermo campo B	Consumo	LNF-UniCam	3k	0
Flangia criostato LHe	Consumo	LNF	10 k	0
Discendente in Campo	Consumo	LNF-UniCam	5k	0
Materiale prototipo	Consumo	LNF	5k	0
Componenti RF	Consumo	LNF	5k	0
Componenti RF	Consumo	Pisa	6k	0
Schede multiplexing	Consumo	Pisa	5k	0
Componenti crio	Consumo	Pisa	3k	0
BAW	Consumo	Pisa	2k	0
Componenti RF e crio	Consumo	Trento	5k	1k
Liquidi crio - LN	Consumo	Trento	2k	0
LHe test prototipo	Consumo	LNF	10k	0
Liquidi crio - LN	Consumo	Pisa	2k	0
Totale	Consumo		63k	1
Licenze	Altro	Pisa	5k	0
Viaggi CERN	Missioni	LNF	18 k	2k
Viaggi UniCam-LNF	Missioni	LNF	5 k	1k
Viaggi test a Bonn	Missioni	LNF	2 k	0k
Viaggi test a LNF	Missioni	Trento	2k	1k
Viaggi test a LNF	Missioni	Pisa	3k	2k
Totale	Missioni		30k	6k
Totale			162k	7k

WP4 Signal Amplification and Acquisition

Participants: TIFPA/Trento, Pisa, Camerino, LNF, Bonn/Mainz

Coordinator: Paolo Falferi (MSA) (TIFPA/Trento), Gianluca Lamanna (Amplification/DAQ) (Pisa) WP

Objective: The objective of this WP is to acquire some complete commercial MSA amplification systems, characterize them in terms of gain, bandwidth and noise down to temperatures of the order of 300 mK and then operate them in conditions similar to those in Flash as far as concerns operating temperature, ambient magnetic field and resonating input load. It also includes the digitization and acquisition of the signal, and the definition of the calibration procedure.

Activity description

Task 4.1: MSA configurations Different MSA configurations will be considered and possibly tested: MSA with varactor diode for the tuning of its resonance frequency, MSA with lower resonance Q for a wider bandwidth, two cascaded MSA tuned to different resonant frequencies for a wider bandwidth. Gain, noise and bandwidth measurements will be carried out as a function of the operating temperature down to ultracryogenic temperatures. For a complete characterization of the noise, tests will be conducted with resonant loads at the input of the MSA.

Task 4.2: Stability High Q loads at the input of the MSA can lead to system instability. Cold damping networks will therefore be considered and possibly applied for the stabilization of the cavity/MSA system.

Task 4.3: Postamplifier If the MSA gain is not high enough to allow the use of a room temperature amplifier as postamplifier, low noise cryo amps capable of operating at 4K will be identified and tested.

Task 4.4: Magnetic shielding The MSA should operate in an environment with a low magnetic field (possibly << Gauss) and low vibrations so that the flux noise collected by the MSA SQUID loop remains << Φ_0 . In Flash, where the magnetic field reaches 1.1 T, this condition can be satisfied by appropriately shielding the magnetic field around the MSA and/or by moving the MSA sufficiently away. To evaluate whether this is possible, superconductor/cryoperm composite magnetic shields will be realized and tested and in the design of the Flash cryostat we will try to identify areas with a low residual magnetic field where the MSA can be safely housed. Tests of the shielded MSA in a 1.1 T magnetic field will be done.

Task 4.5: Multiplexing The possibility of operating two or more MSAs connected to the same antenna will be evaluated to simultaneously detect higher harmonics of the cavity but avoiding the MSAs interfering with each other.

Task 4.6: Replacement of the MSA In defining the design of the Flash cryostat and with prototype tests, the possibility of replacing the MSA without warming up the entire Flash cryostat to room temperature will be evaluated. In this way it would be possible to cover the entire range of Flash operating frequencies using some "bayonet design" MSAs optimized to operate on reduced frequency bandwidth.

Task 4.7: Secondary amplification and down conversion chain The RF amplification at room temperature will depend on the gain obtained in the cold stage and on the requirements of the digitization stage. Considering the non exceedingly high operating frequency (hundreds of MHz), the need for a potential down-conversion stage will be evaluated, based on noise control and acquisition bandwidth considerations.

Task 4.8: Digitization and data acquisition The Digitization and data acquisition stage will be defined according to the previous stage requirements. In addition, both commercial solutions (such as commercial fast FFT or a commercial digitizer) and custom-made solution based on RFSoc FPGA with high-end digitizer on board, will be considered. The second solution, although more complex, will offer greater flexibility and the possibility of applying data reduction and control algorithms directly in real-time.

Task 4.9: Full test of amplification chain with a BAW resonator Test of amplification and DAQ chain with a 100 MHz mode of a BAW in a cryogenic system to simulate the presence of the FLASH cavity. A full calibration procedure as in the real experiment will be implemented by measuring scattering parameters through ancillary lines and by means of calibrated thermal sources

Synergistic projects

• QUAX: QUAX is a CSN2 experiment looking for galactic axions with mass about 40 μeV. One ff the two haloscopes of the experiment is located in the COLD laboratory of LNF (https://coldlab.lnf.infn.it).
• BAUSCIA Project in Milano Bicocca with the objective of detecting HFGW with BAWs. Because of the strong synergies with the FLASH physics and involved technologies, the MiB team expressed a strong interest in collaborating with FLASH in the future, for searches at lower frequencies but also extending to the higher frequencies of FLASH.
• PNRR-NQSTI: The objective of the PNRR project NQSTI is the development of quantum technologies, including superconducting quantum devices. The LNF, Trento and Pisa teams are involved in this project.
• PNRR-ICSC: One of the objective of the PNRR project ICSC is to develop the infrastructure for scientific computing. The QUAX cloud computing is developed also within this project.
• Samara/SuperMad: The objective of this project in CSN5 are superconducting materials for axion cavities such as NbTi and Ybco. The LNF team is involved in this project. Solutions for sputtering the FLASH cavity with NbTi will be studied within SuperMAD if approved.
• Qubit/QUARTET: Superconducting devices. The LNF, Pisa and Trento teams are involved in this project.
• PRIN-2022bpjl2l (IRONMOON): The objective of the PRIN project IRONMOON is the study of superconducting materials for axion RF cavities. The LNF team is involved in this project.

Istituti	personale	FTE
LNF	10	2.6
Camerino	4	1.3
Pisa	12	2.3
TIFPA	2	0.6
Bonn/Mainz	5	2.1
Cartagena/Valencia	7	1.4
Shanghai	2	0.4
Zaragoza	1	0.2
TOT	43	10.9

Possible FLASH detection:

- QCD axion
- Axion-like particles
- Scalar dark matter
- Chameleons
- Hidden (dark) photons
- High frequency gravitational waves

Axion

An axion is a hypothetical elementary particle originally theorized in 1978 by Wilczek and Weinberg as a consequence of the Peccei–Quinn mechanism for solving the strong CP problem posed by quantum chromodynamics (QCD). If axions exist and have low mass within a specific range, they are of interest as a possible component of cold dark matter.

Strong CP problem

According to the current mathematical formulation of quantum chromodynamics, a violation of Charge Parity-symmetry in strong interactions could occur. However, no violation of the CP-symmetry has ever been seen in any experiment involving only the strong interaction. As there is no known reason in QCD for it to necessarily be conserved, this is a "fine tuning" problem known as the strong CP problem

Axion Models

Models in which the axion feebly couples to the Standard Model degrees of freedom:
Kim-Shifman-Vainshtein-Zakharov (KSVZ) model (1979/80)
Dine-Fischler-SrednickiZhitnitsky (DFSZ) model (1980/81)
These benchmark models belong to a larger class which is referred to as the “invisible” axion models.

Axion Experiments with haloscopes

Currently operating haloscopes: ADMX, HAYSTAC, ORGAN, CAPP-8T, CAPP-9T, CAPP-PACE, CAPP-18T, CAST-CAPP, CAPP-12TB, GrAHal, RADES, QUAX, and TASEH
Proposed haloscopes: FLASH, BabyIAXO/RADES, ABRACADABRA, DM-Radio, CADEx, MADMAX , ALPHA, WISPLC, DALI, BRASS, BREAD and SUPAX

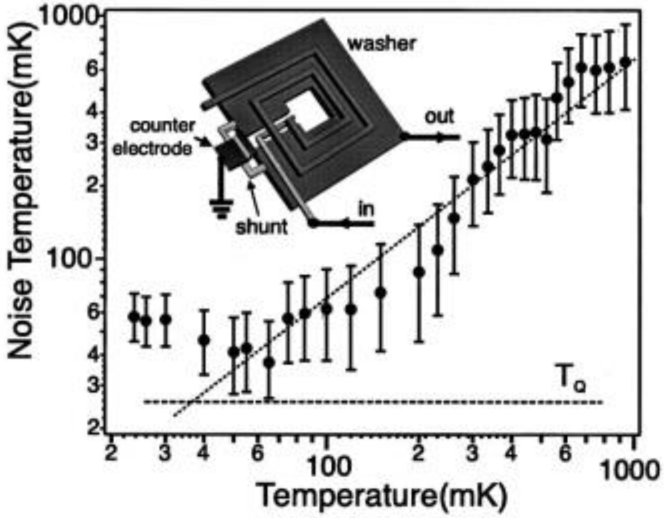


FIG. 2. Noise temperature of input microstrip SQUID at 538 MHz vs temperature measured with a resistive source. The dashed line through the data corresponds to $T_N \propto T$, and the horizontal dashed line indicates $T_Q = hf/k_B \approx 26$ mK. Inset shows configuration of microstrip SQUID with grounded counter electrode.

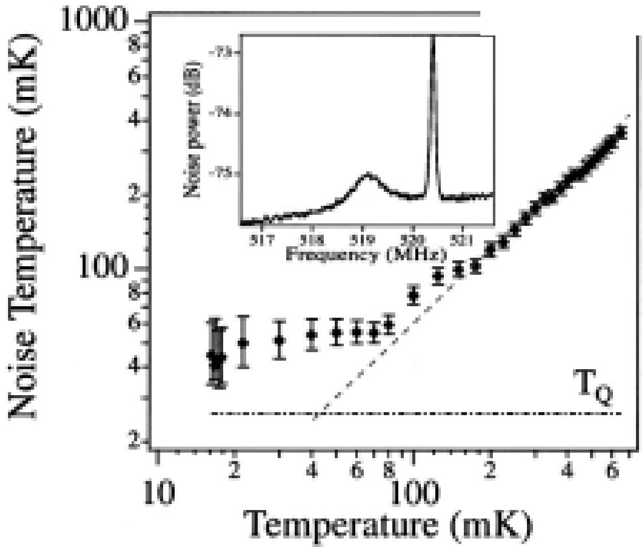


FIG. 3. Noise temperature of input microstrip SQUID at 519 MHz vs temperature measured with a resonant source. The dashed line through the data corresponds to $T_N \propto T$, and the dot-dashed line indicates $T_Q = hf/k_B \approx 25$ mK. Inset is noise peak produced by LC-tuned circuit at 20 mK. The upward trend of the baseline reflects the fact that the peak in the amplifier gain is at a higher frequency. The peak at 520.4 MHz is a calibrating signal.

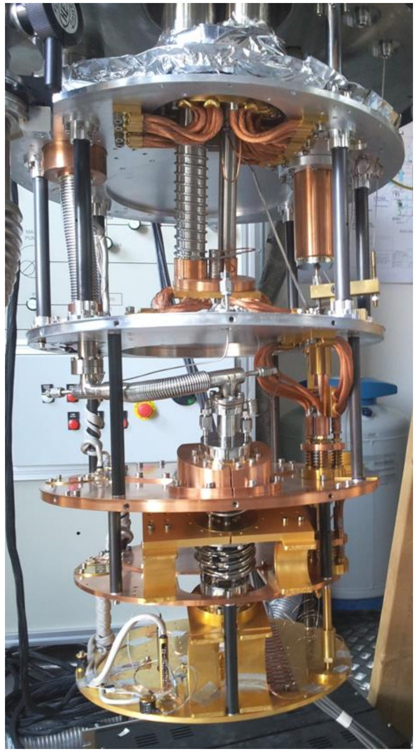
Mück et al., Appl. Phys. Lett. 78, 967 (2001)

FLASH – Trento Activity

Equipment available
- Dilution refrigerator -> MSA tests down to T_{base} = 20 mK
- Liquid helium transport and lab dewars -> MSAs-antenna tests at 1-4.2K
- Helium liquefier with gas recovery system -> liquid helium at affordable prices
- Electronics (Signal generators, VNA, oscilloscope/spectrum analyzer 500 MHz)

FTE: Paolo Falferi 30%, Andrea Vinante 30%

Purchases
- MSAs (4 k€ each)
- Low noise cryogenic and room temperature RF amplifiers
- Microwave-cryo-spares (filters, power splitters, cables, connectors…)
- Liquid helium



Dilution Refrigerator

Helium liquifiers with gas recovery system