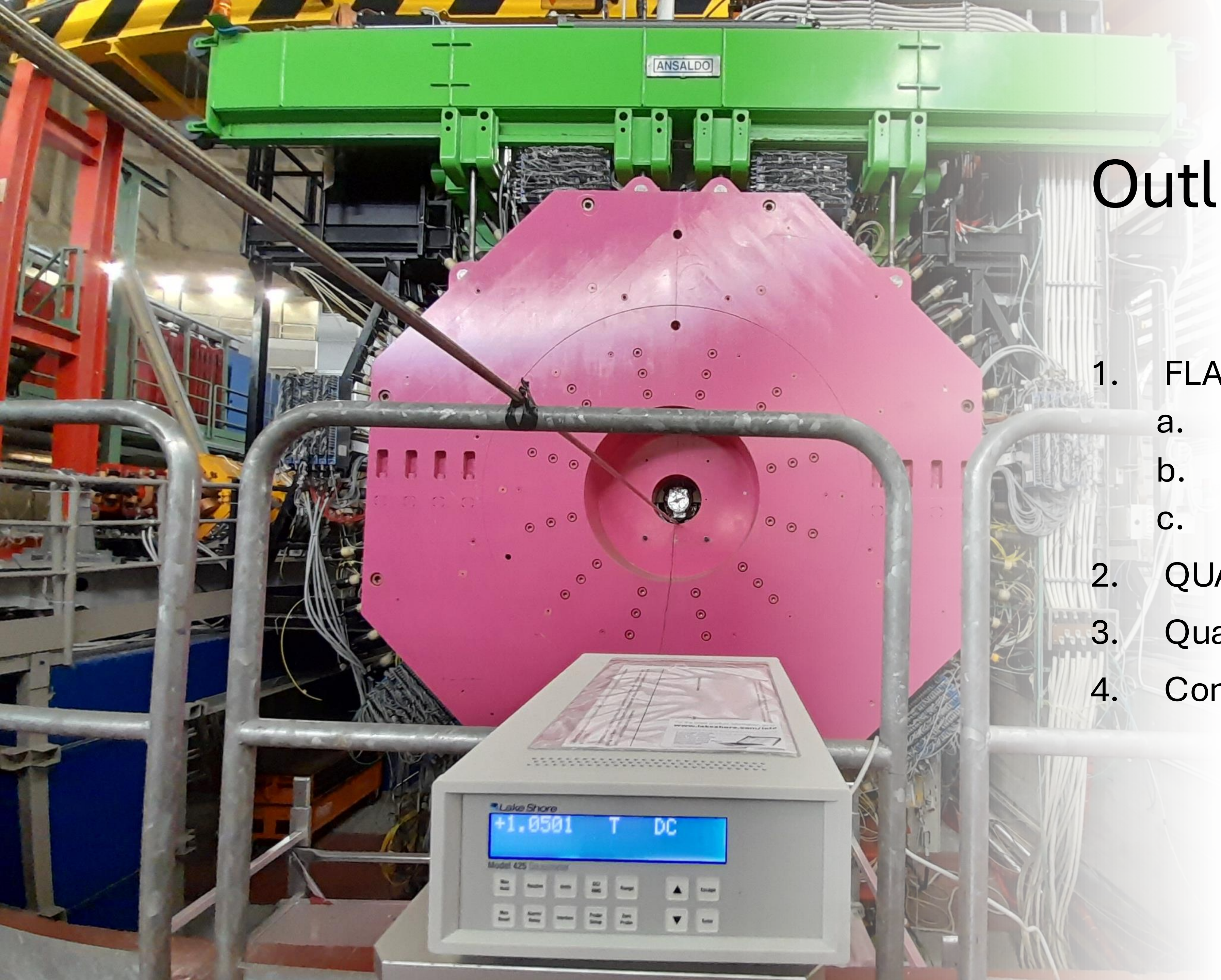
COLD Lab

Claudio Gatti

68th LNF Scientific Committee

Nov 20th 2024

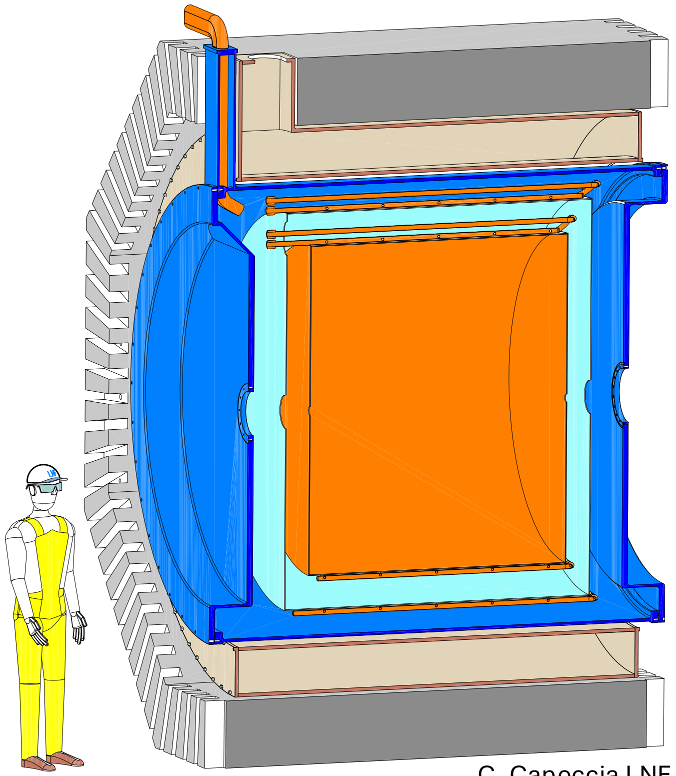


Outline

1. FLASH
   a. CDR Approval in CSN2
   b. GravNet - Synergy ERC
   c. LNF GravNet Activity
2. QUAX@LNF
3. Quantum Devices
4. Conclusions

FLASH Finuda magnet for Light Axion Search Haloscope

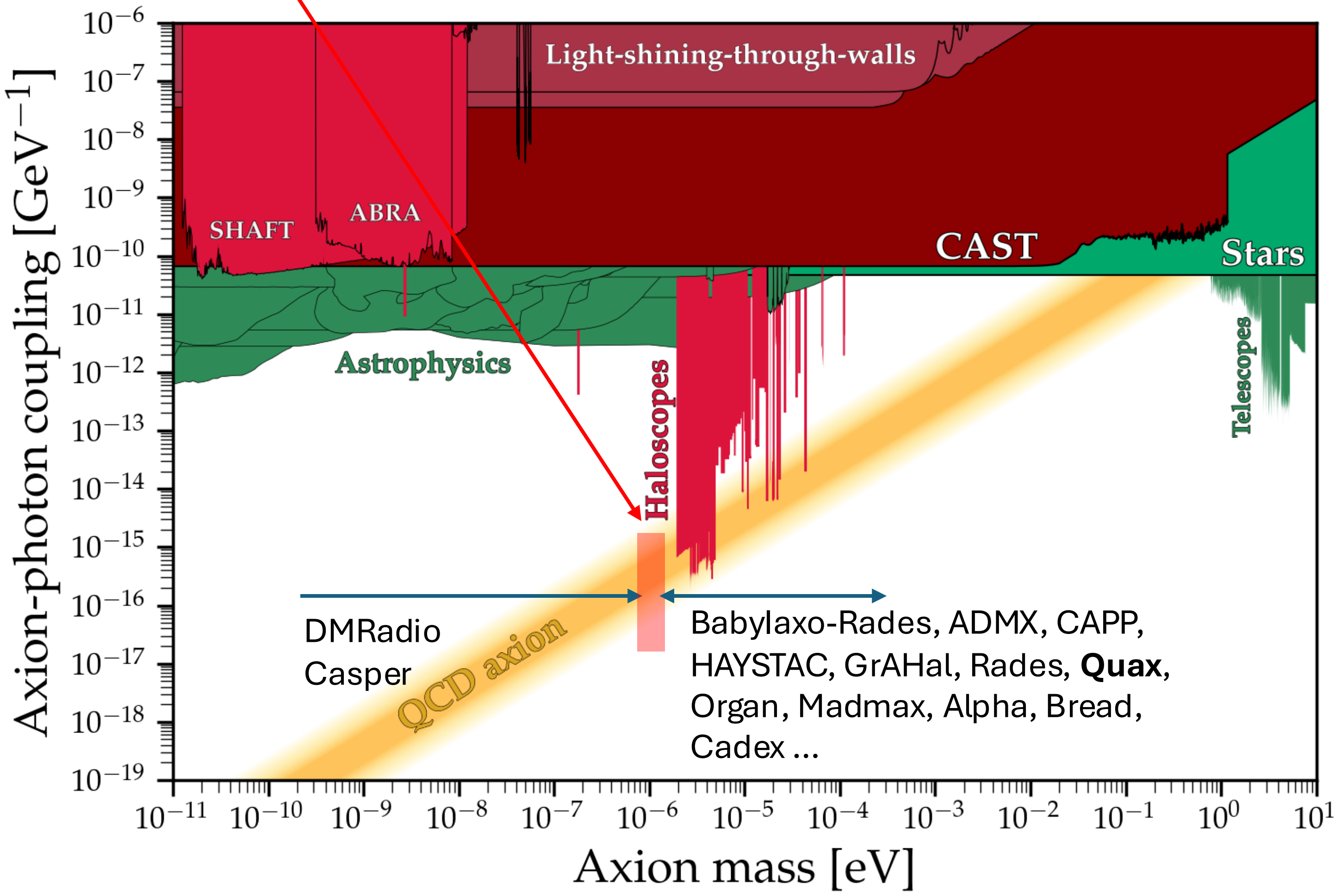
- FLASH CDR submitted in July to CSN2
- CSN2 approved the 2 years plan to write the TDR



C. Capoccia LNF

FLASH aims to probe the region between 0.5 and 1.5 μeV

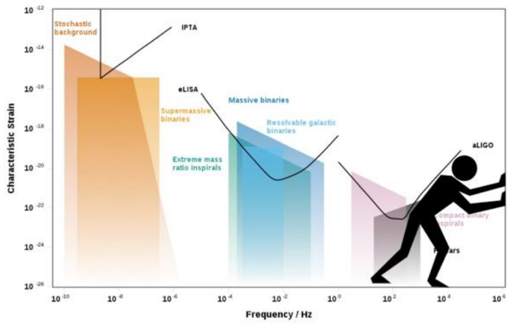
$1\mu eV = 250\ MHz \rightarrow \lambda = 1.2m$ → cavity with O(m) diameter



https://cajohare.github.io/AxionLimits/

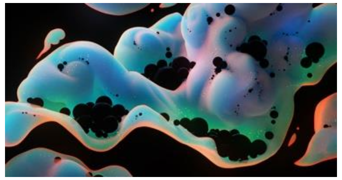
Main Goals

- Search of galactic axions at 100 MHz (0.5-1.5 μeV)
- Probe several light DM models: scalar, pseduscalar and vector DM.
- Extend the gravitational wave search region to higher (MHz-GHz) frequencies

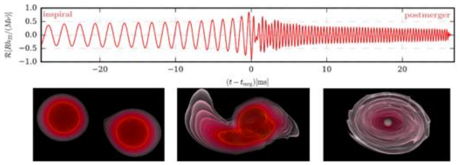


https://www.ctc.cam.ac.uk/activities/UHF-GW.php

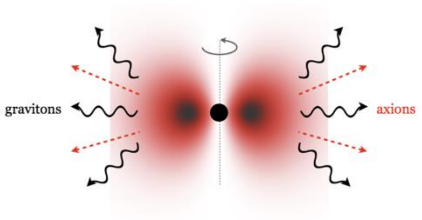
High Frequency Gravitational Waves



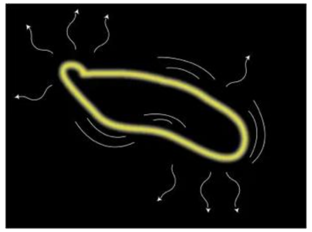
Primordial BH



Boson stars mergers

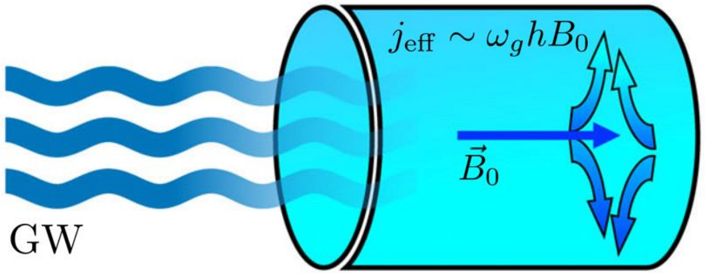


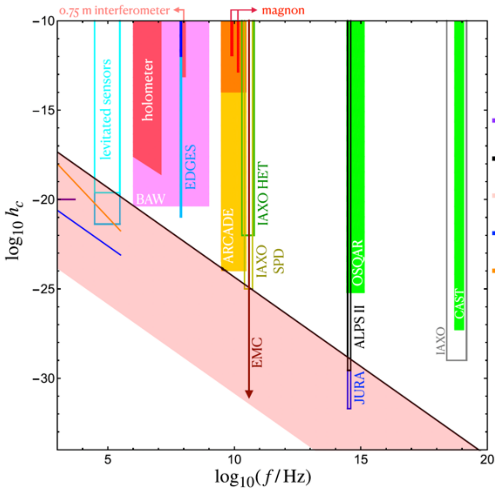
BH superradiance



Cosmic strings

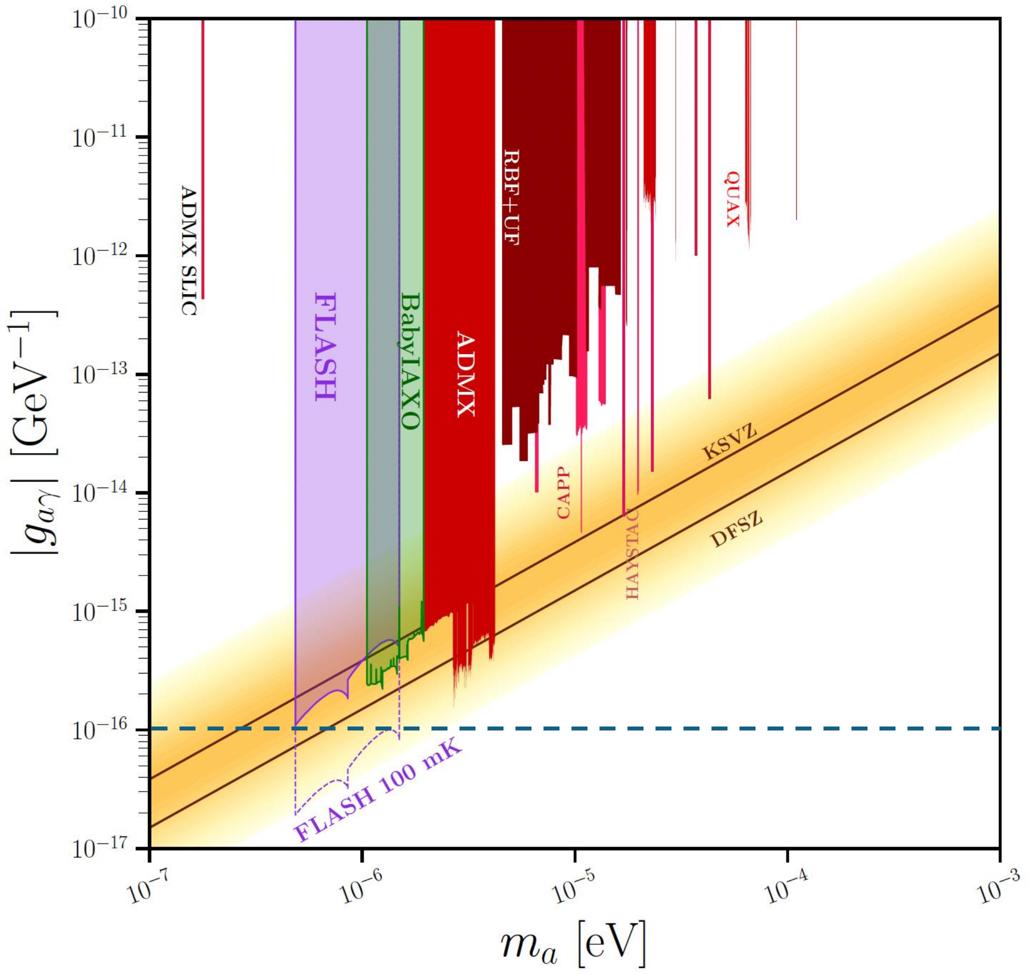
- The landscape of gravitational waves in the ultra-high frequency regime, above the kHz, is beyond the sensitivities of the present terrestrial experiments.
- HFGW could potentially be sourced by a collection of exotic physical phenomena originating both in the early and late Universe.
- Possibility to probe particle physics at energy scales many orders of magnitude beyond the reach of future particle colliders.





Aggarwal et al. Challenges and opportunities of gravitational-wave searches at MHz to GHz frequencies. Living Rev Relativ 24, 4 (2021).

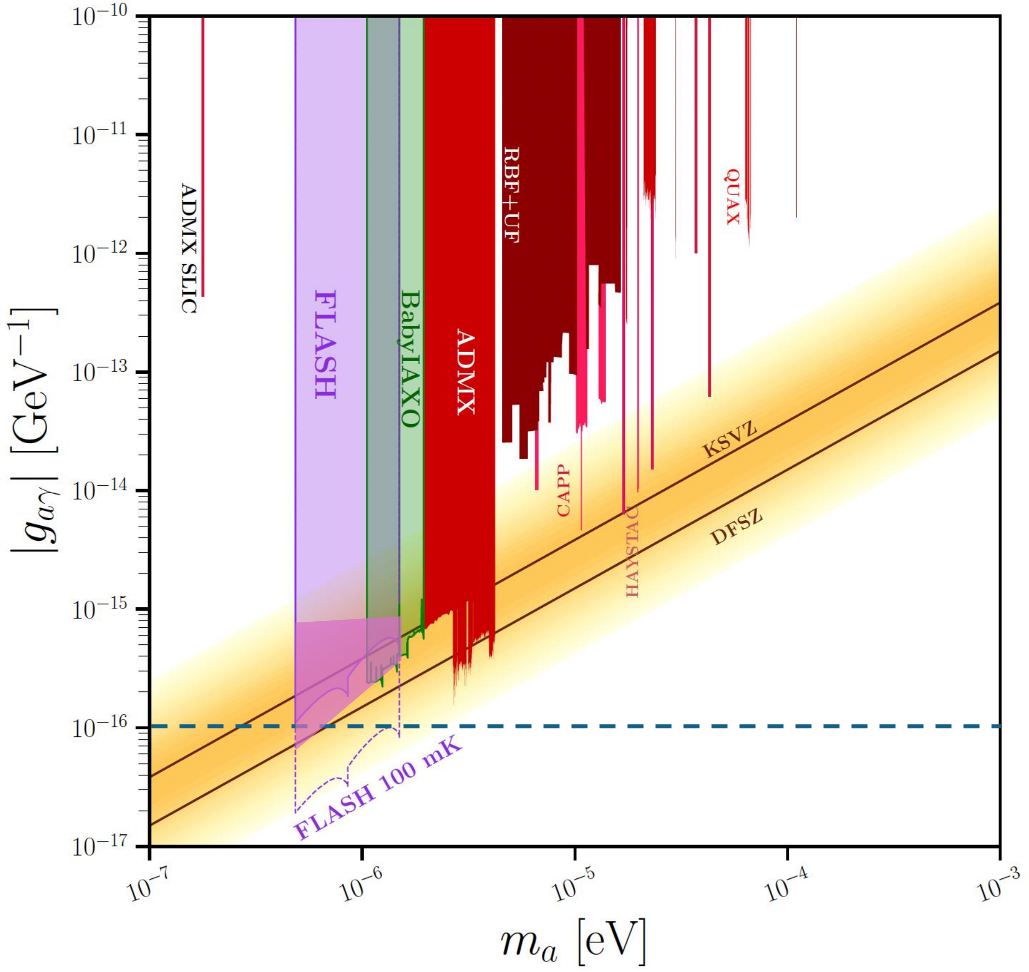
FLASH Physics Reach



With Cu cavity at 4.5 K

Parameter	Value
ν_c [MHz]	150
m_a [μeV]	0.62
$g_{a\gamma\gamma}^{\mathrm{KSVZ}}$ [GeV^{-1}]	2.45×10^{-16}
Q_L	1.4×10^5
C_{010}	0.53
$B_{\max}$ [T]	1.1
β	2
τ [min]	5
T_{sys} [K]	4.9
P_{sig} [W]	0.9×10^{-22}
Scan rate [Hz s^{-1}]	8
m_a [μeV]	0.49 - 1.49
$g_{a\gamma\gamma}$ 90% c.l. [GeV^{-1}]	$(1.25 - 6.06) \times 10^{-16}$

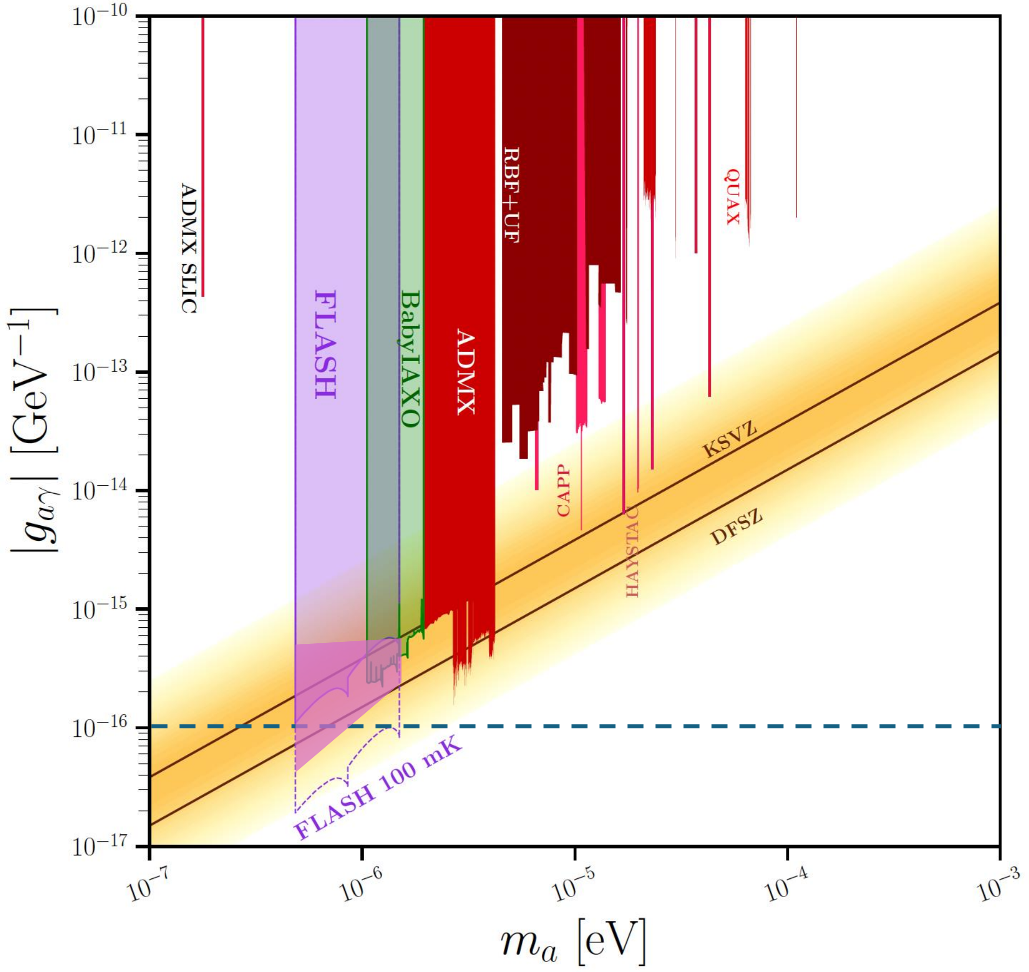
FLASH Physics Reach



With Cu cavity at 1.9 K

Parameter	Value
ν_c [MHz]	150
m_a [μeV]	0.62
$g_{a\gamma\gamma}^{\text{KSVZ}}$ [GeV^{-1}]	2.45×10^{-16}
Q_L	1.4×10^5
C_{010}	0.53
B_{max} [T]	1.1
β	2
τ [min]	5
T_{sys} [K]	4.9
P_{sig} [W]	0.9×10^{-22}
Scan rate [Hz s^{-1}]	8
m_a [μeV]	0.49 - 1.49
$g_{a\gamma\gamma}$ 90% c.l. [GeV^{-1}]	(0.8- 3.96) $\times 10^{-16}$

FLASH Physics Reach



SuperMAD

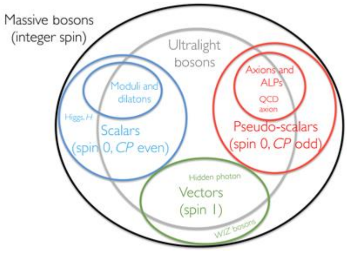
Superconducting RF **M**aterials for **A**xion **D**etectors

With NbTi cavity at 1.9 K

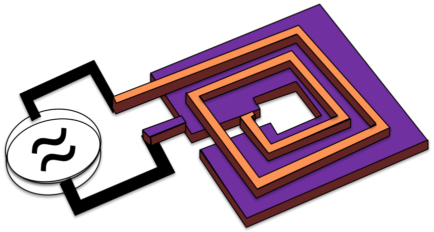
Parameter	Value
ν_c [MHz]	150
m_a [μeV]	0.62
$g_{a\gamma\gamma}^{\mathrm{KSVZ}}$ [GeV^{-1}]	2.45×10^{-16}
Q_L	6.7×10^5
C_{010}	0.53
B_{max} [T]	1.1
β	2
τ [min]	5
T_{sys} [K]	4.9
P_{sig} [W]	0.9×10^{-22}
Scan rate [Hz s^{-1}]	8
m_a [μeV]	0.49 - 1.49
$g_{a\gamma\gamma}$ 90% c.l. [GeV^{-1}]	$(0.37 - 1.8) \times 10^{-16}$

Design Study and R&D for the TDR

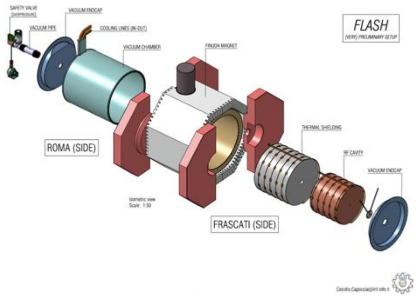
Approved by INFN in September 2024
Goal: TDR ready for Summer 2026



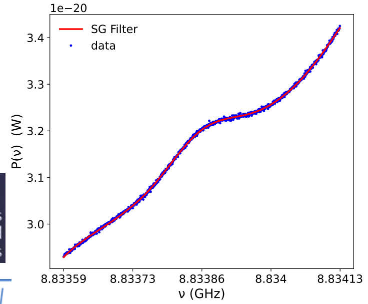
WP1 Physics Reach



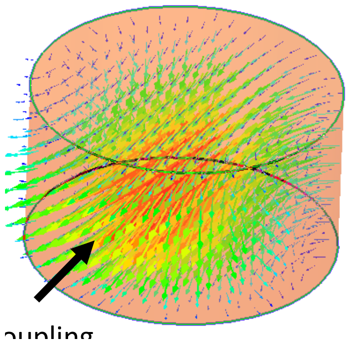
WP4 Signal Amplification and DAQ



WP2 Mechanical Design and Cryogenics



WP5 Data Analysis and Computing



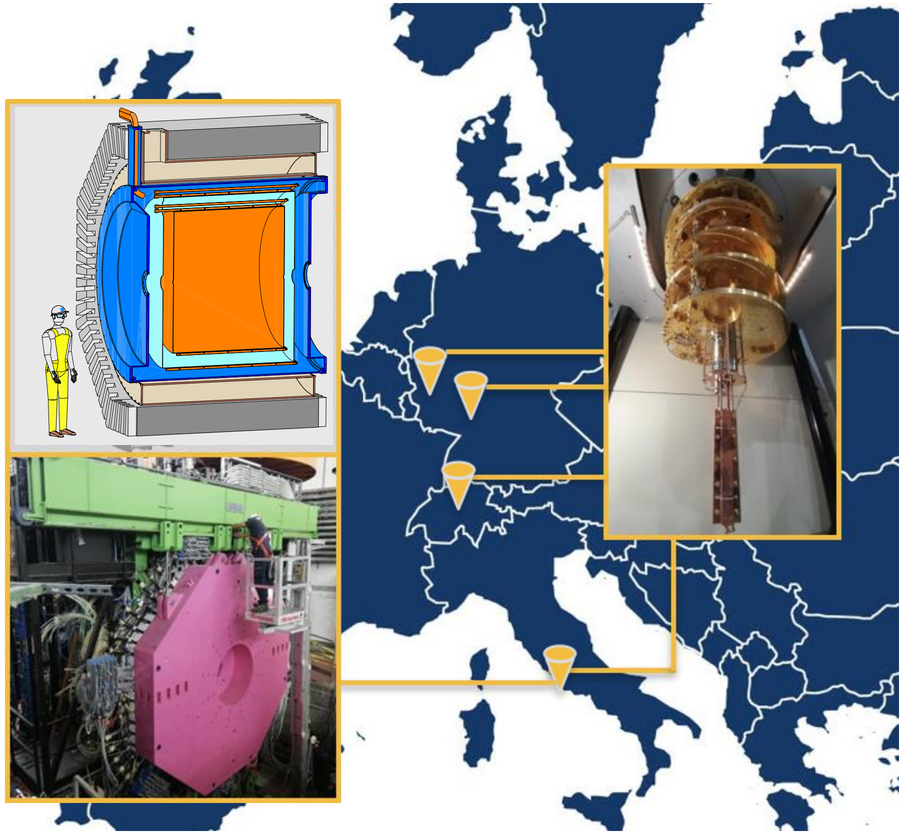
WP3 RF Cavity

FINUDA FRASCATI: 12 1996

WP6 Decommissioning of FINUDA and FLASH Commissioning

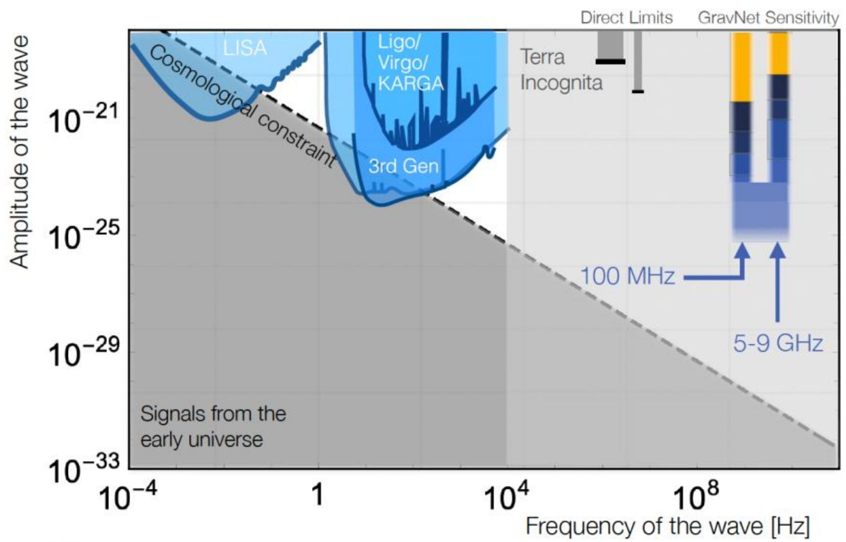
GravNet: A Global Network for the Search for High Frequency Gravitational Waves

ERC Synergy funded with 10 Meuro



European Research Council
Established by the European Commission

GravNet



GravNet

- GravNet Baseline
- Modelling and Data Analysis
- Cavity Design & Construction
- Quantum Amplifiers and Sensors
- Network Operation
- Combination of different frequencies
- Adding further detectors to network

Source Modeling and Data Analysis

- Precise signal description
- Advanced neural networks for combined data analyses

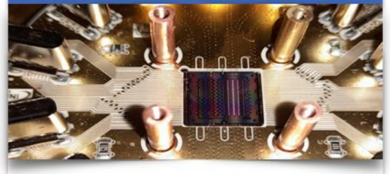
Blas / Schott

Optimize Cavity

- Shape to improve coupling
- Enhance quality factor with superconductors

Gatti / Blas / Schott

Drastically reduce noise in readout

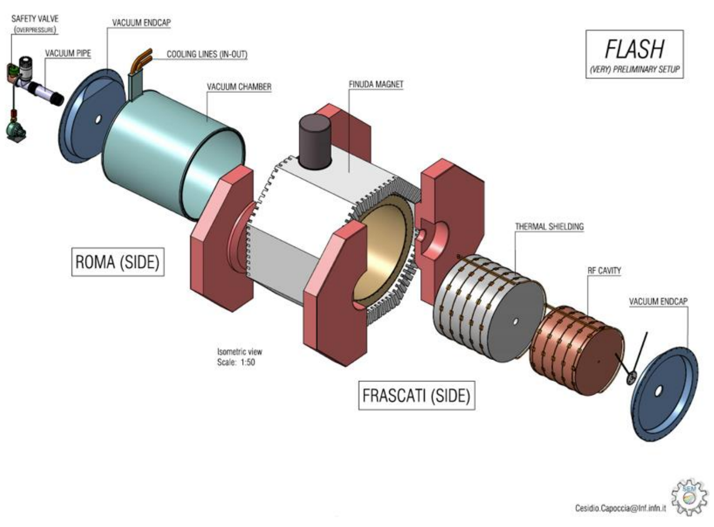


- Use of quantum sensing revolution
- Quantum non-demolition measurements
- Entanglement in two-qubit devices

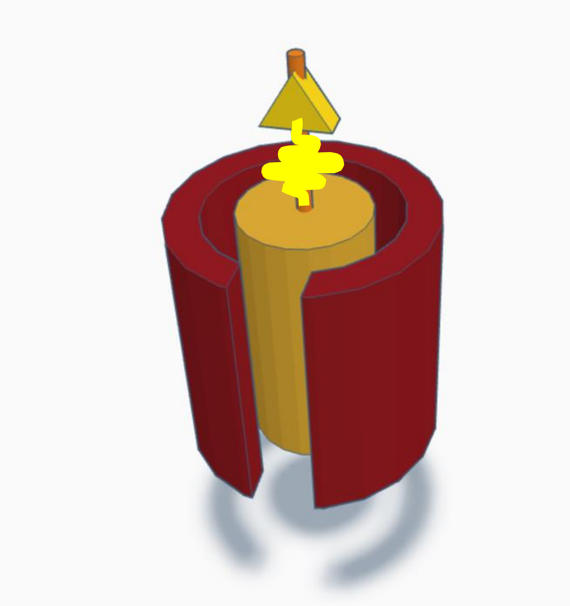
Budker / Gatti

LNF Tasks

5-10 GHz GW search



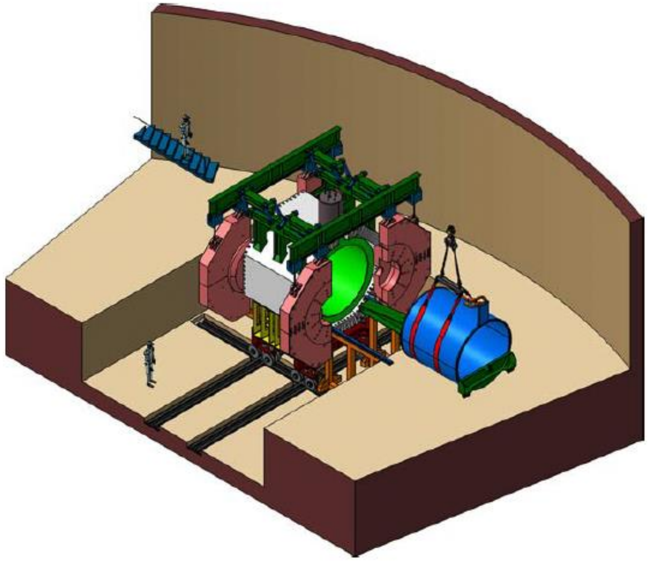
100 MHz GW search



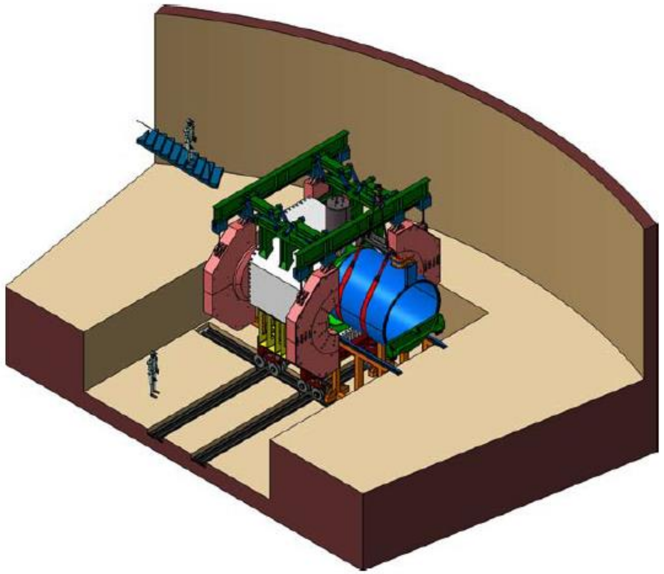
Signal Amplification
and
Photon Counting

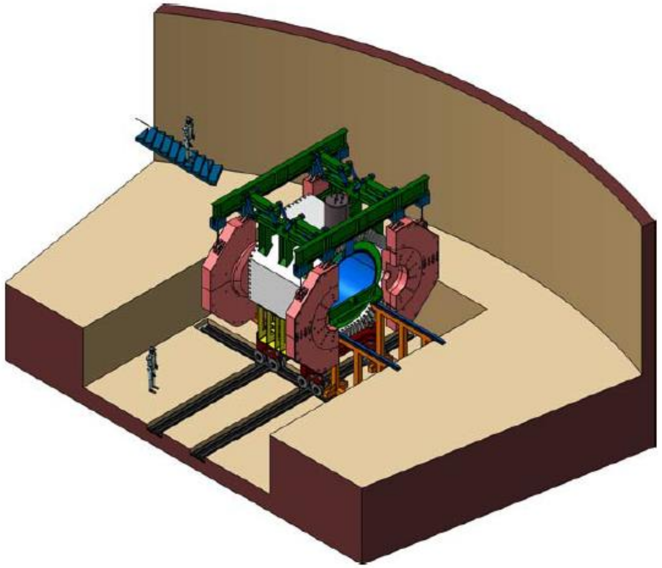
FLASH

1. Collaboration
    1. Kick Off meeting next week
    2. Weekly meetings of GravNet Pis
    3. PBC
2. Design
    1. 3D magnet model
    2. Vessel insertion scheme
3. Organization
    1. FLASH-LNF coordination meetings
    2. Project Budget
    3. Resource allocation
    4. WBS
    5. Personnel
4. Electronics
    1. Cryogenic test bed for SQUID at Uni Camerino
5. Dissemination/Proselytism
    1. Seminars
    2. Lectures
    3. Visits



C. Capoccia LNF





Quax@LNF

First results of QUAX@LNF published!

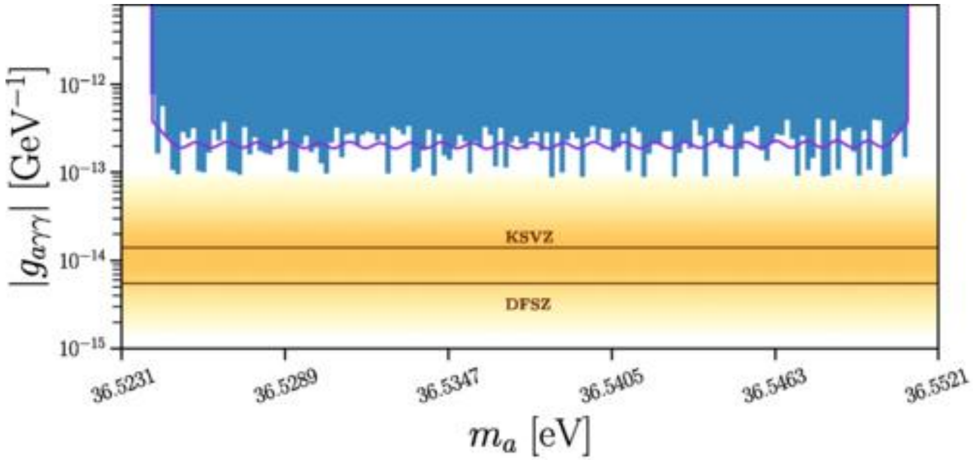
Physical Review D

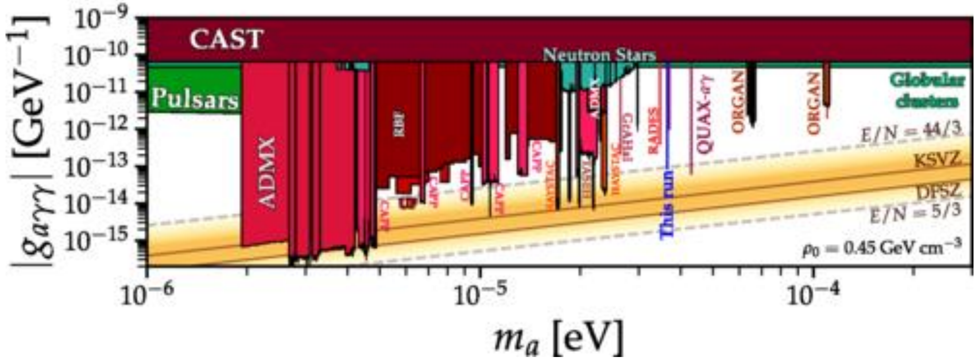
Search for axion dark matter with the QUAX–LNF tunable haloscope

A. Rettaroli[1], D. Alesini[1], D. Babusci[1], C. Braggio[2,3], G. Carugno[2], D. D'Agostino[4,5], A. D'Elia[1], D. Di Gioacchino[1], and R. Di Vora[6] *et al.* (QUAX Collaboration)

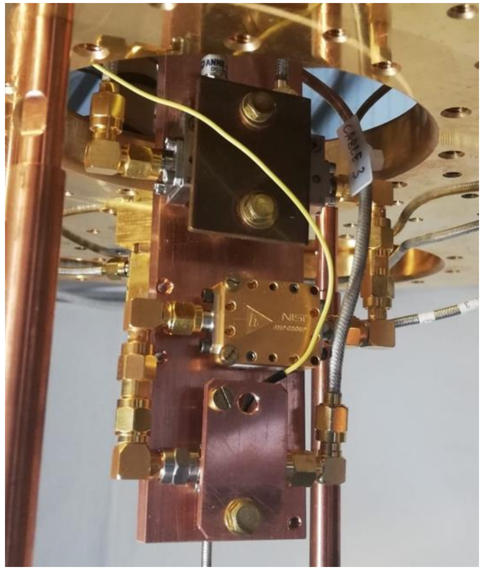
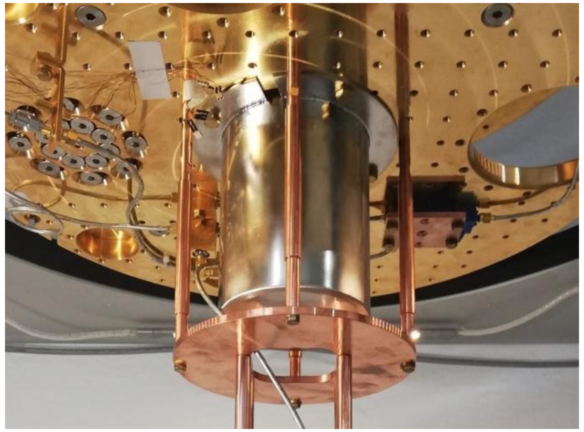
Show more

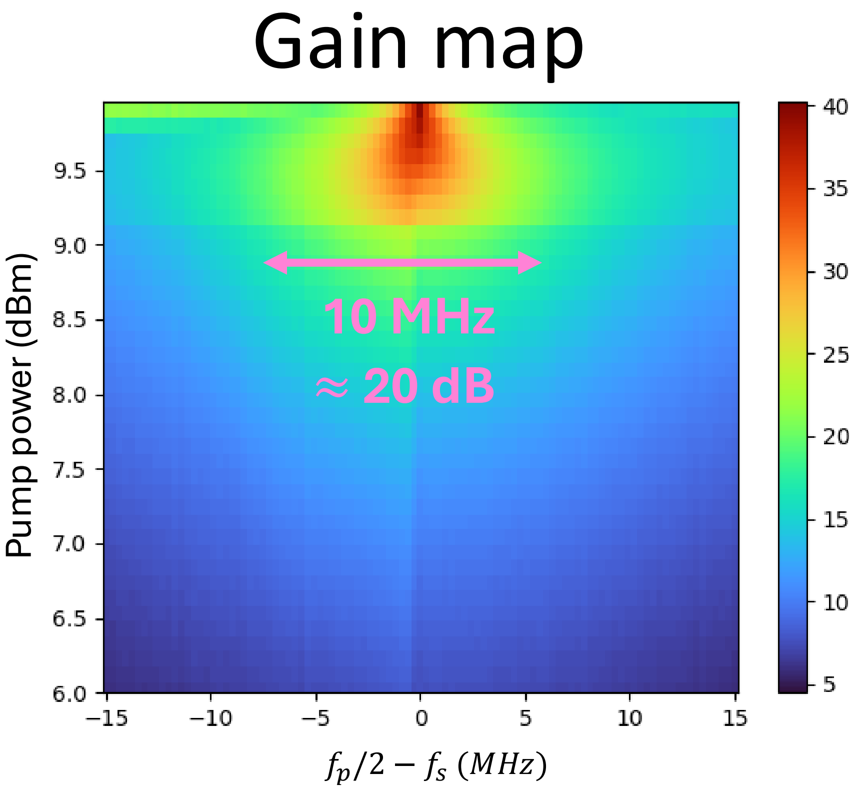
Phys. Rev. D **110**, 022008 – **Published 23 July, 2024**

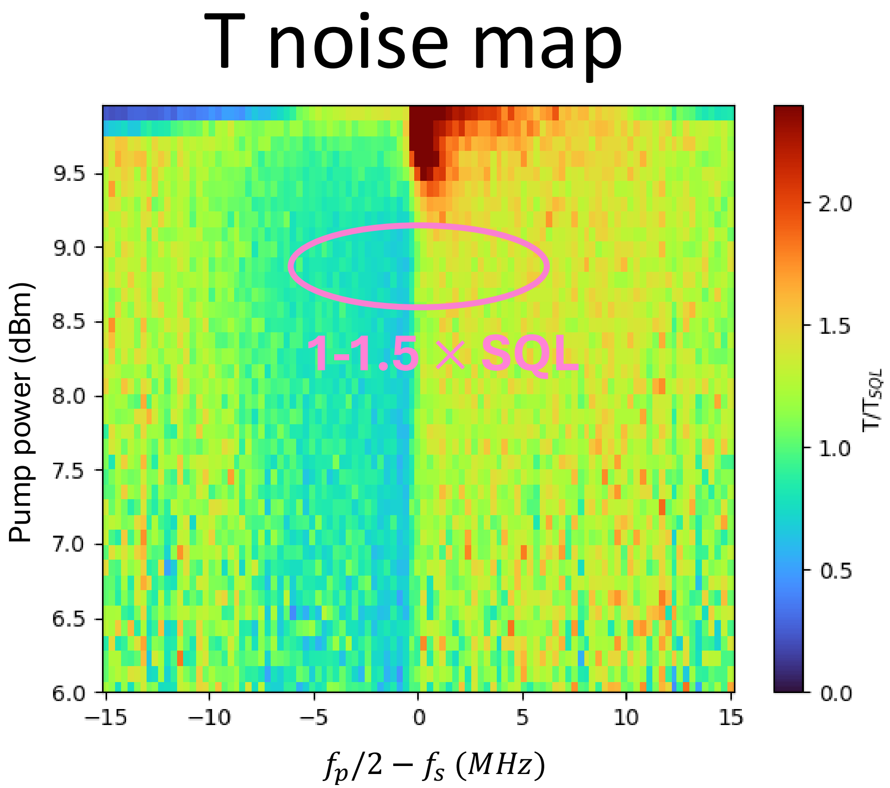




Josephson Parametric Amplifier





Standard quantum limit at f = 8.8 GHz

$$T_n = \frac{h\nu}{k_B} = 420\ mK$$

A. Rettaroli at 19th Patras Workshop on Axions, WIMPs and WISPs

Test with B Field On

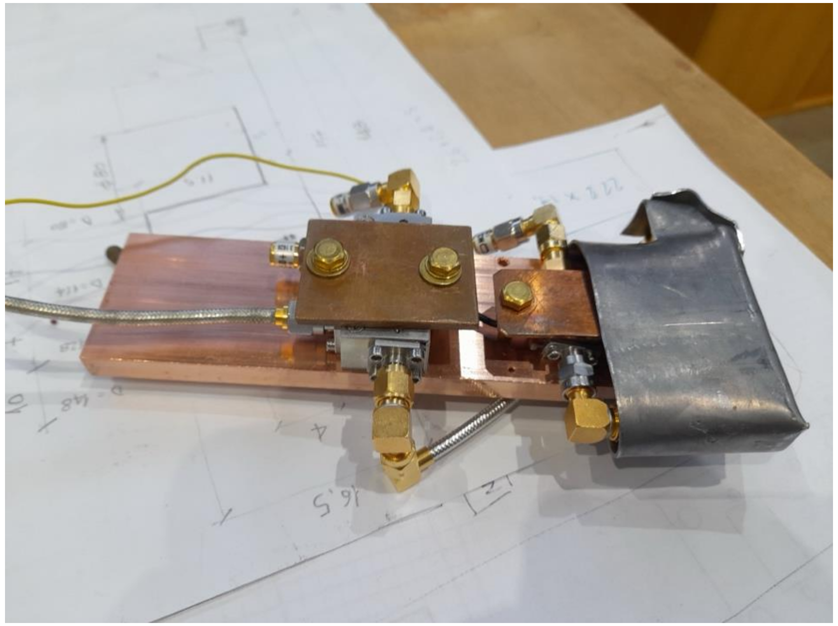
First test in magnetic field:

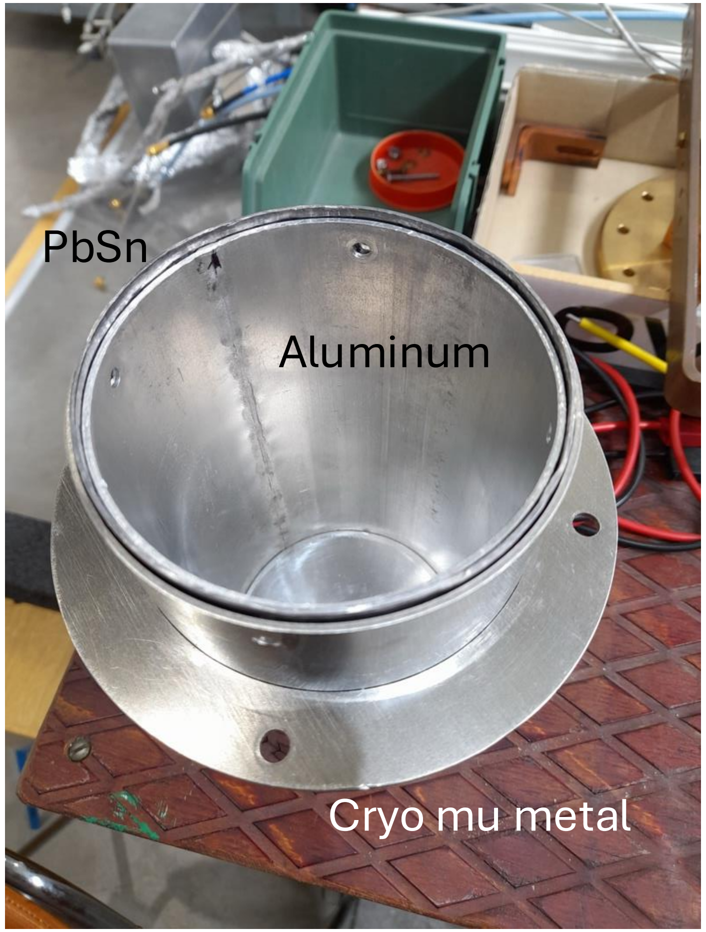
1. JPA frequency drift for B=1T
2. Estimated fraction of ϕ_0 /Tesla
3. JPA stops working at 3T

Improved shielding:

1. Added one layer of PbSn
2. JPA wrapped in PbSn
3. JPA works fine up to 9 T
4. Small frequency drift
5. Estimated few 10^{-3} ϕ_0 /Tesla

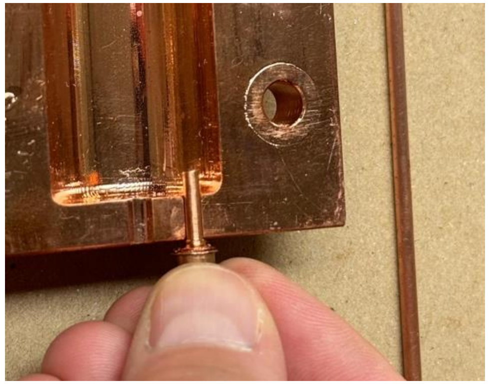
Shielding can be further improved with top cap in PbSn and/or additional shielding layer.



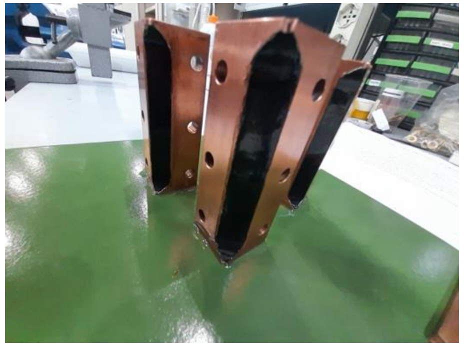


Ongoing Activities

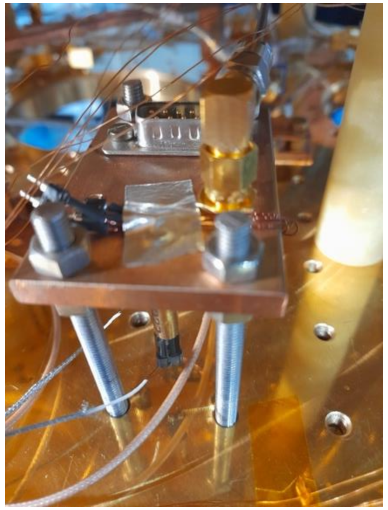
1. Improved mechanical design of the tuning system



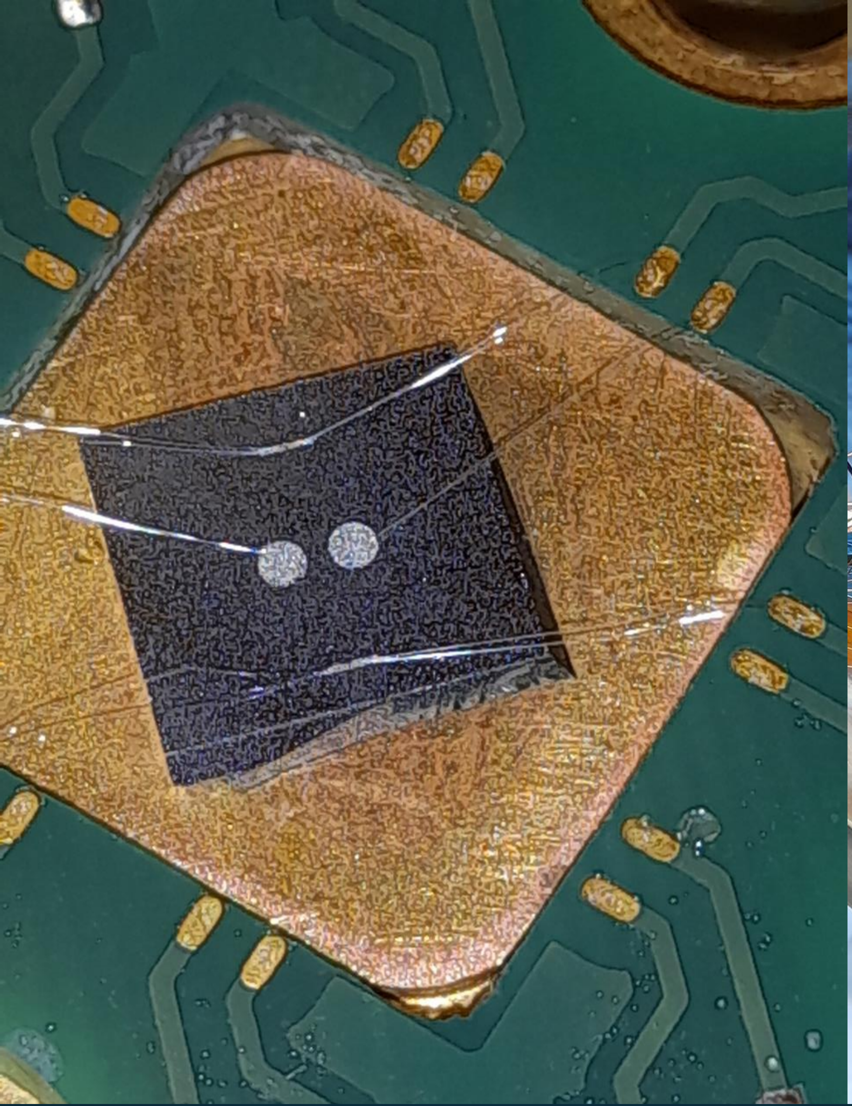
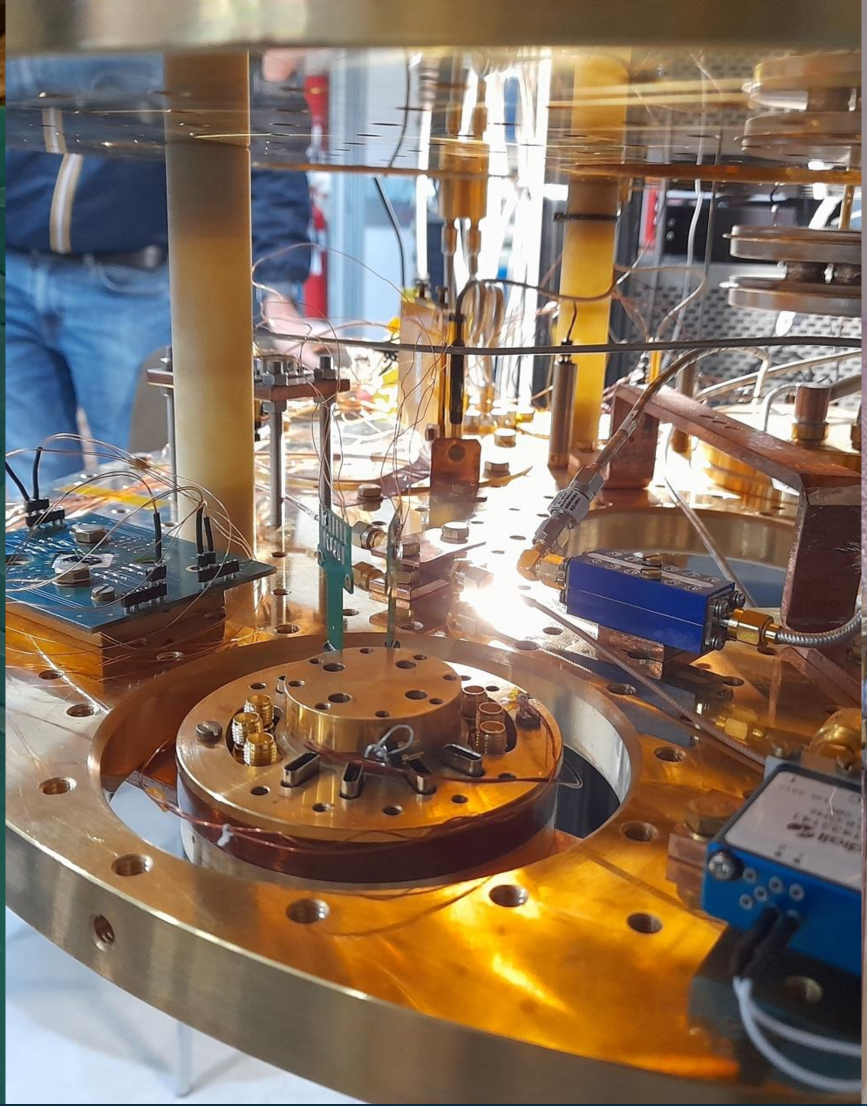
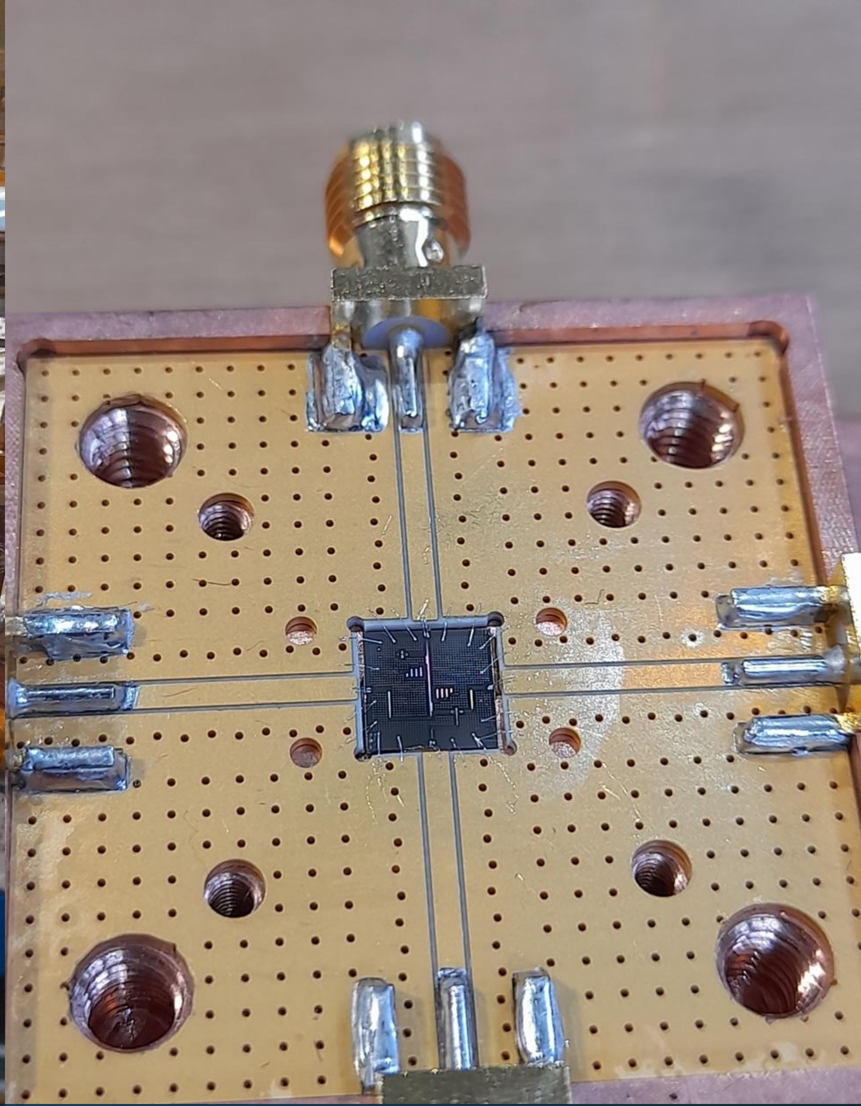
2. Further tests with Rebco tapes ongoing



3. New cryogenic noise source fabricated and tested

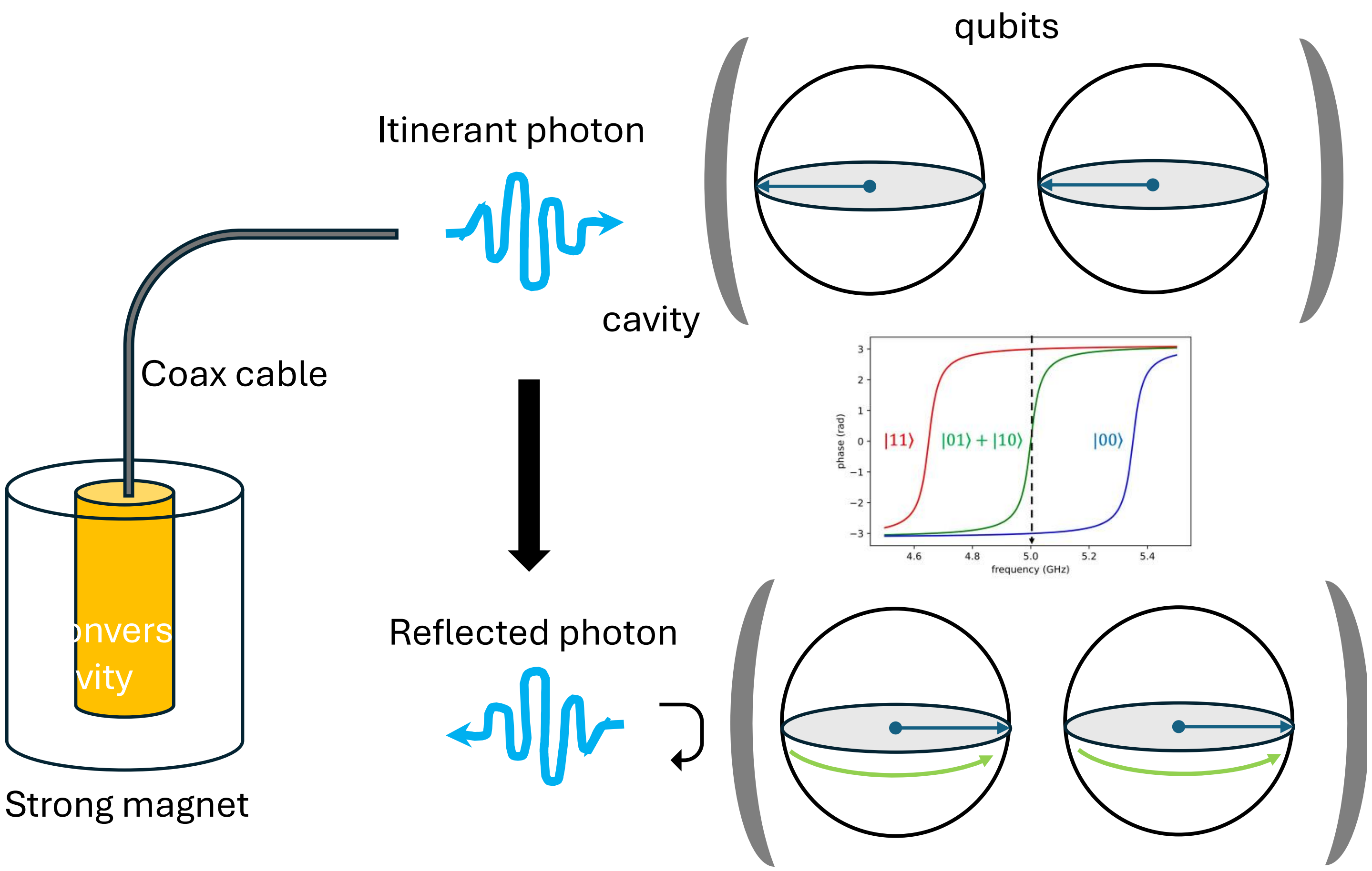


4. Digitization with FPGA for larger bandwidth
5. Testing MIDAS Data Acquisition System

Quantum Sensing

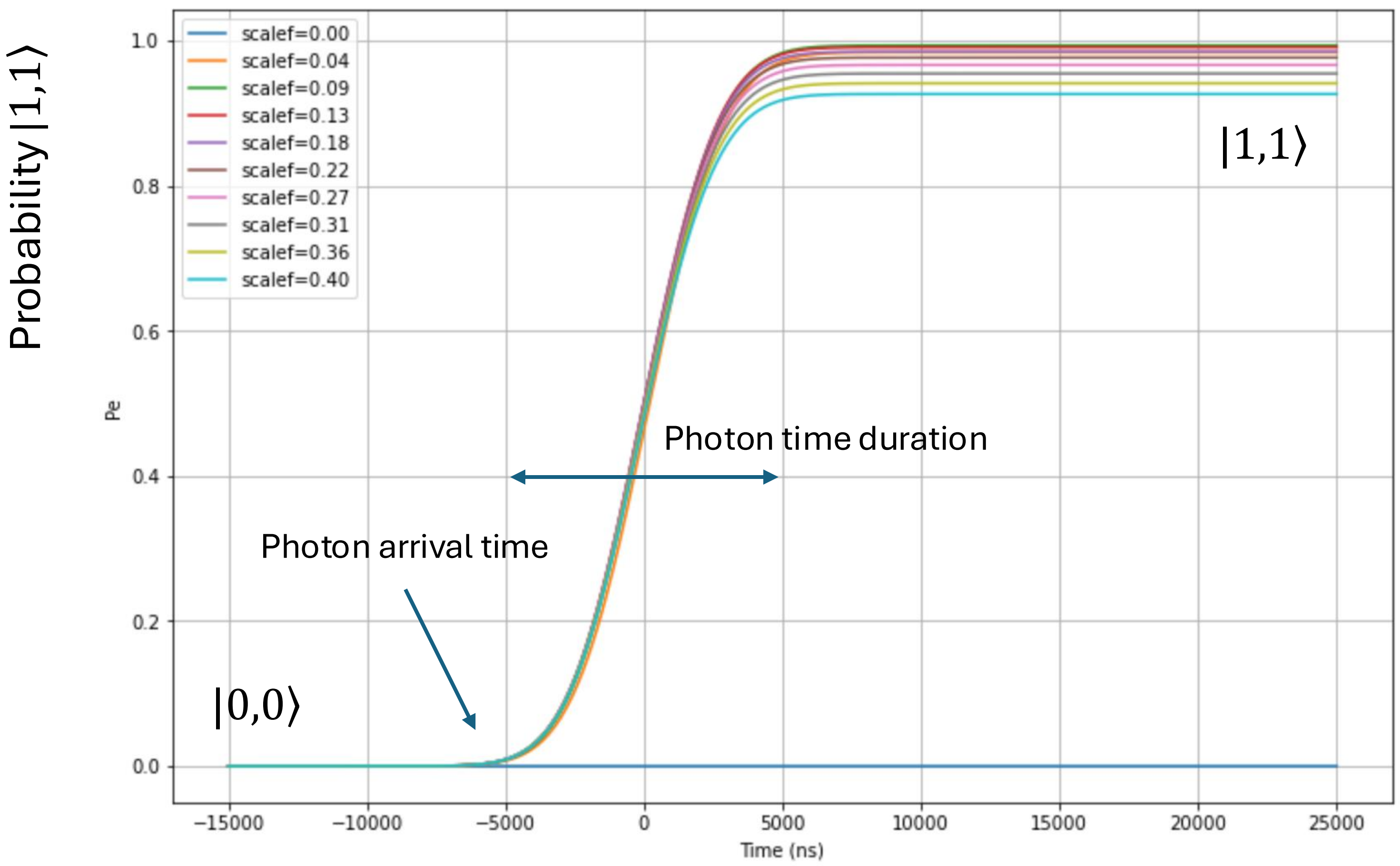
Two Qubits Detection Scheme



Kono et al. *Nature Phys* **14**, 546–549 (2018)

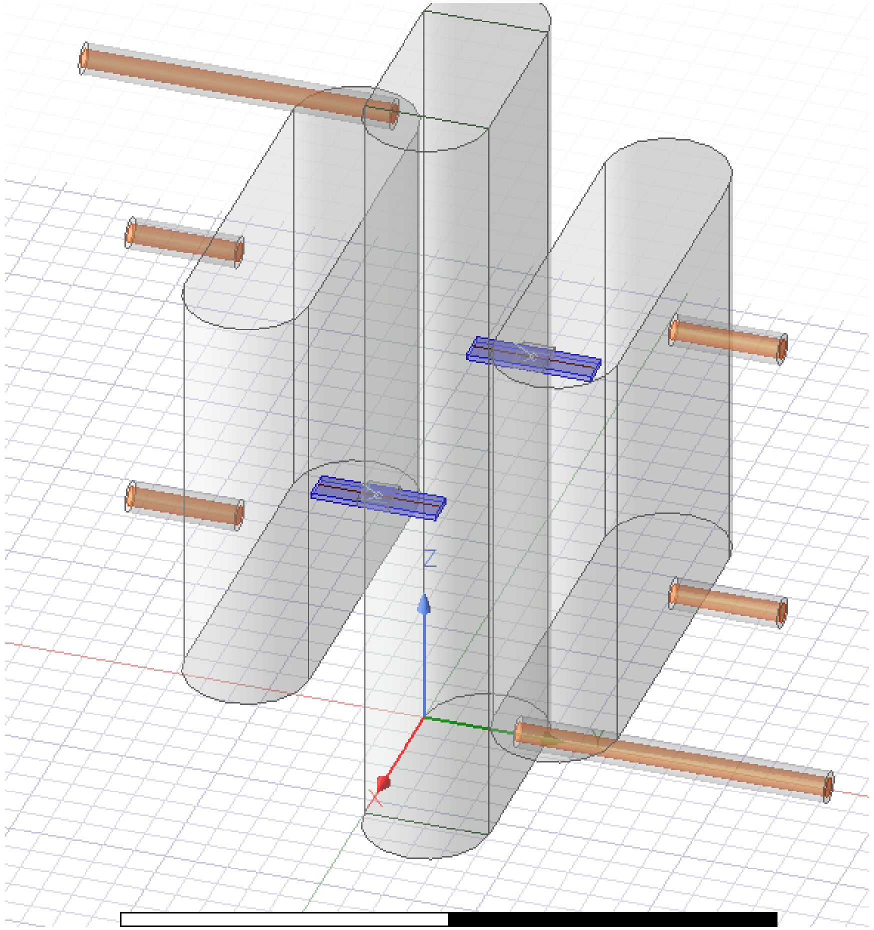
A D'Elia Appl. Sci. 2024, 14(4), 1478

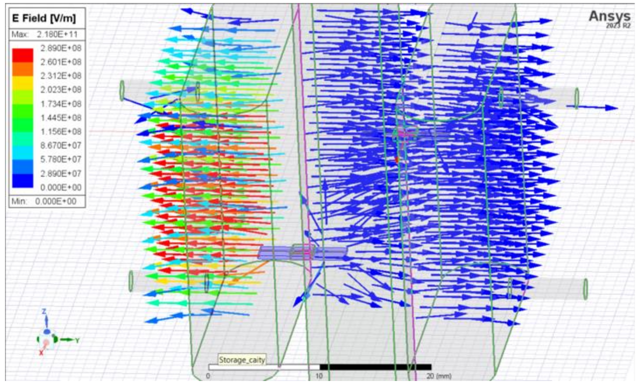
Evolution of the Quantum State

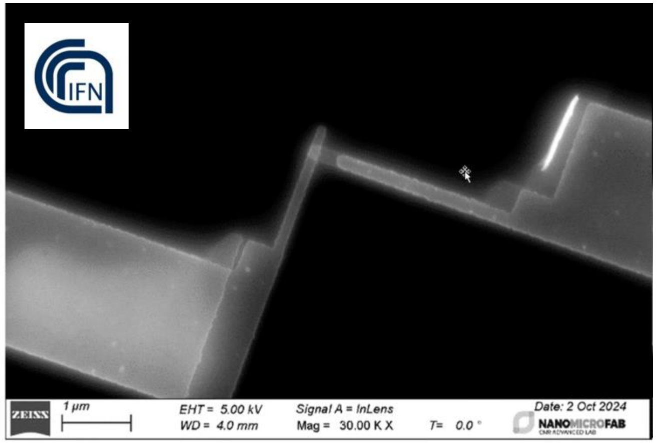


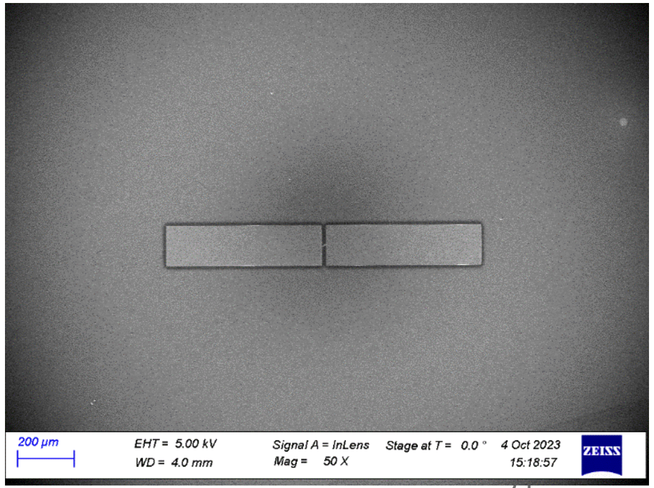
Density matrix time evolution determined from input-output approach plus Lindbald dissipation terms.

Two Qubits Detector









D. Milillo

Conclusions

With the awarding of ERC funding, some steps are changed and anticipated and this requires us to review our programs:

1. We must focus on HFGW. We will look for axions too but the priority now is different.
2. We had the largest fraction of the ERC funding (37%) but many tasks to do (100 MHz haloscope, 10 GHz haloscope, Quantum Sensing) and a remarkable fabrication commitment for FLASH.
3. All the tasks of the project were in our plans anyway.
4. The funds appear adequate but there are uncertainties (Vessel cost, infrastructure mantainance, etc.) and, in principle, the overhead (25% of 3M) are destinated to INFN. There will be a meeting with INFN managment about this point.
5. There are reasonable resource for hiring personnel, but must be distributed over the 6 years of the project. There are priorities. Permanent hiring of young researcher is xpected within these years.

As a final consideration, let me say that, after the results of COLD lab and QUAX@LNF, this award confirms that the research direction taken is the right one.

LNF - ADONE Cavity
Winter 2017-2018