UNIVERSITY OF LIVERPOOL

The FLASH experiment

HEP Meeting 2025
23/05/2025

Paolo Beltrame

Outline

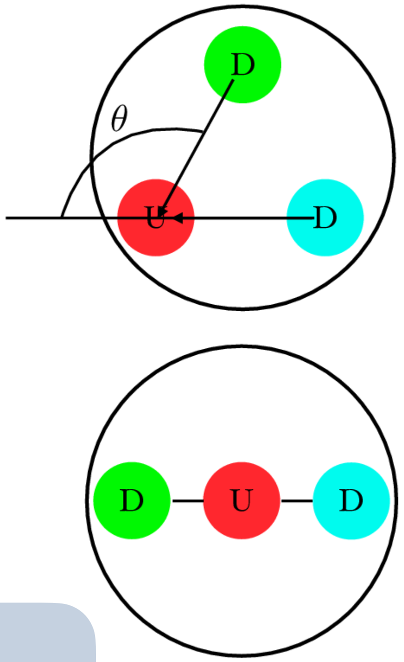
A. Physics investigation

B. Status design and plan

C. UoL involvement in FLASH

QCD Axions

- QCD sector needs a solution for the "strong-CP puzzle"
  - Distribution of quarks in n => electric dipole moment (EDM)
  - Experimentally: $|\theta| \leq 10^{-10}$



⇒ Quantity θ not a parameter but a field a (the axion)

$$\mathscr{L}_{QCD} \supset \theta \tilde{G}G \rightarrow \frac{a}{f_a}\tilde{G}G$$

Peccei, Quinn, PRL 38 (1977) 1440
Weinberg, PRL 40 (1978) 223
Wilczek, PRL 40 (1978) 279

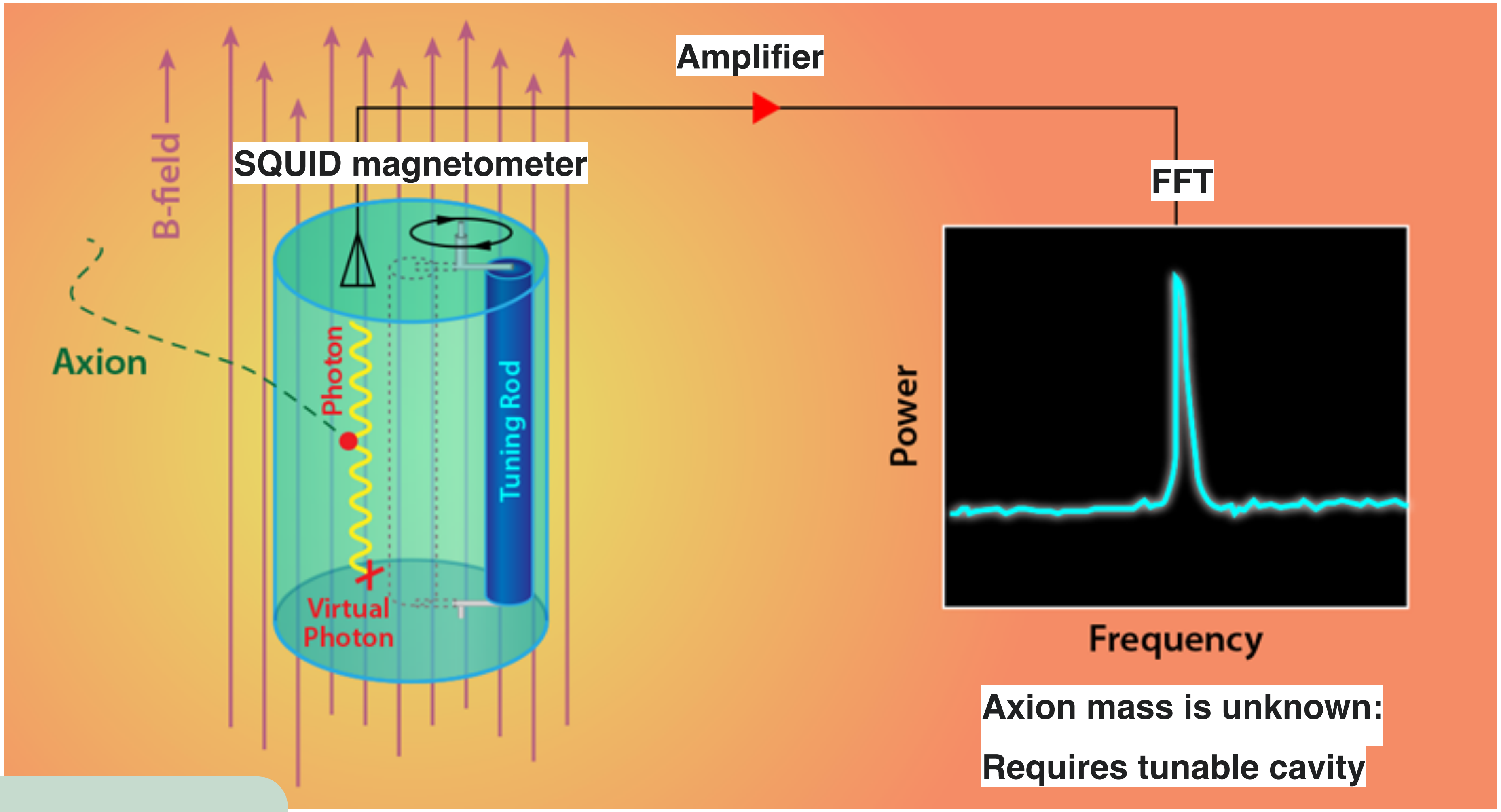
$$\mathscr{L} \supset g_{a\gamma} a \mathbf{E} \cdot \mathbf{B} + g_{af} (\nabla a) \cdot \mathbf{S} + g_{EDM} a \mathbf{S} \cdot \mathbf{E}$$

Coupling of the axion with the photon

Haloscope searches

- Axion-photon coupling $g_{a\gamma} a \mathbf{E} \cdot \mathbf{B}$ modifies Maxwell's equations
- Cavity resonating at frequency ν_c. Enhancement when $2\pi\nu_c \simeq m_a$

$m_a \sim \mu eV$
$\rightarrow \nu_c \sim GHz$



Sikivie Phys. Rev. D 32,11 (1985)

Courtesy of ADMX coll.

$$P = g_{a\gamma\gamma}^2 \frac{\rho_a}{m_a} \left(B_0^2 V C \frac{\beta}{1+\beta} Q_L \right)$$

"Wavy" Light Dark Matter

Interaction with the EM field

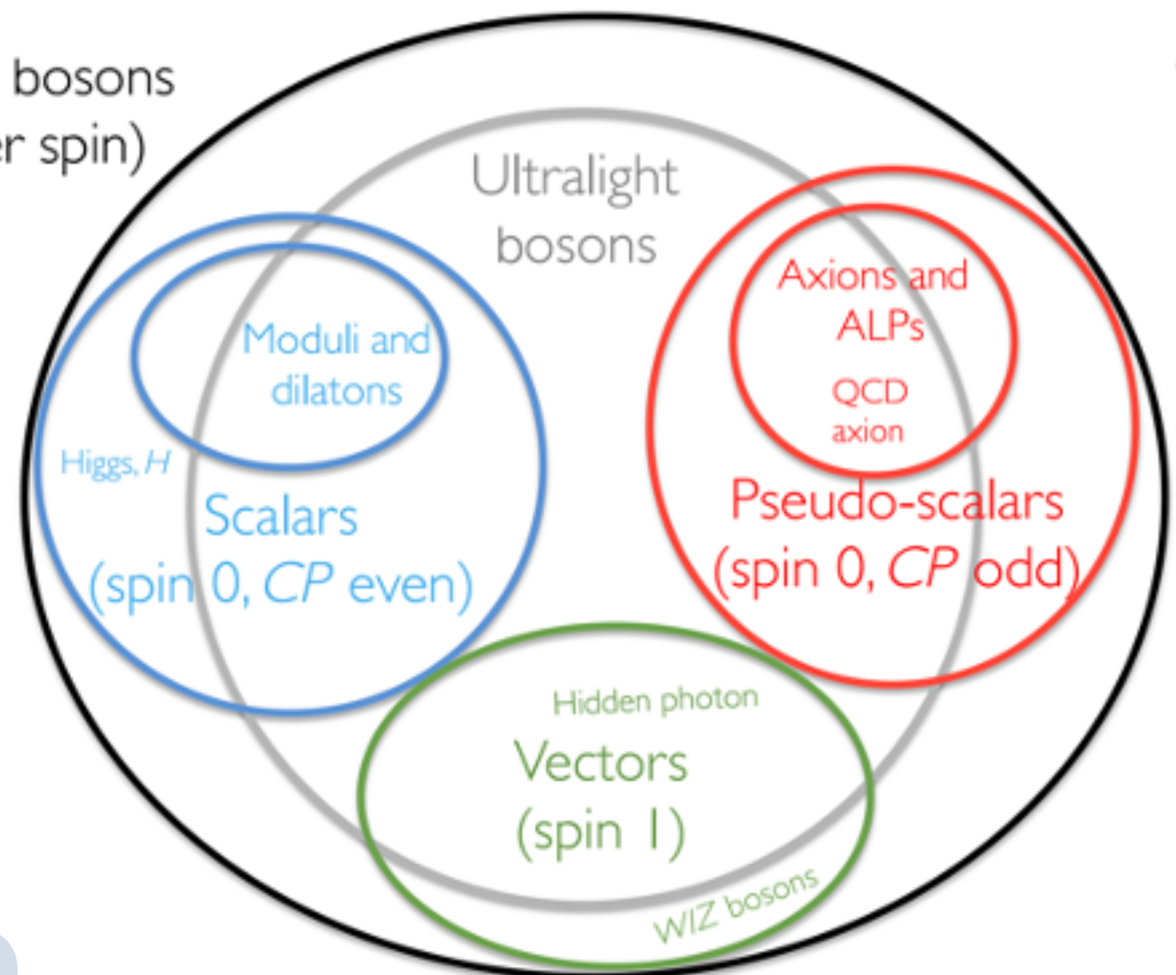
Scalar Dark Matter
Moduli, dilaton

$$\frac{1}{4} g_{\phi\gamma\gamma}\, \phi F_{\mu\nu} F^{\mu\nu}$$

Scalar extension of GR
Chameleons

$$\frac{1}{4} \exp\left(\frac{\beta_\gamma \phi}{M_{\mathrm{Pl}}}\right) F^{\mu\nu} F_{\mu\nu}$$

Massive bosons (integer spin)



Pseudoscalar Dark Matter
Axions, ALPS, Majoron

$$\frac{1}{4} g^{0}_{a\gamma\gamma}\, a \tilde{F}^{\mu\nu} F_{\mu\nu}$$

Vector Dark Matter
Dark photon

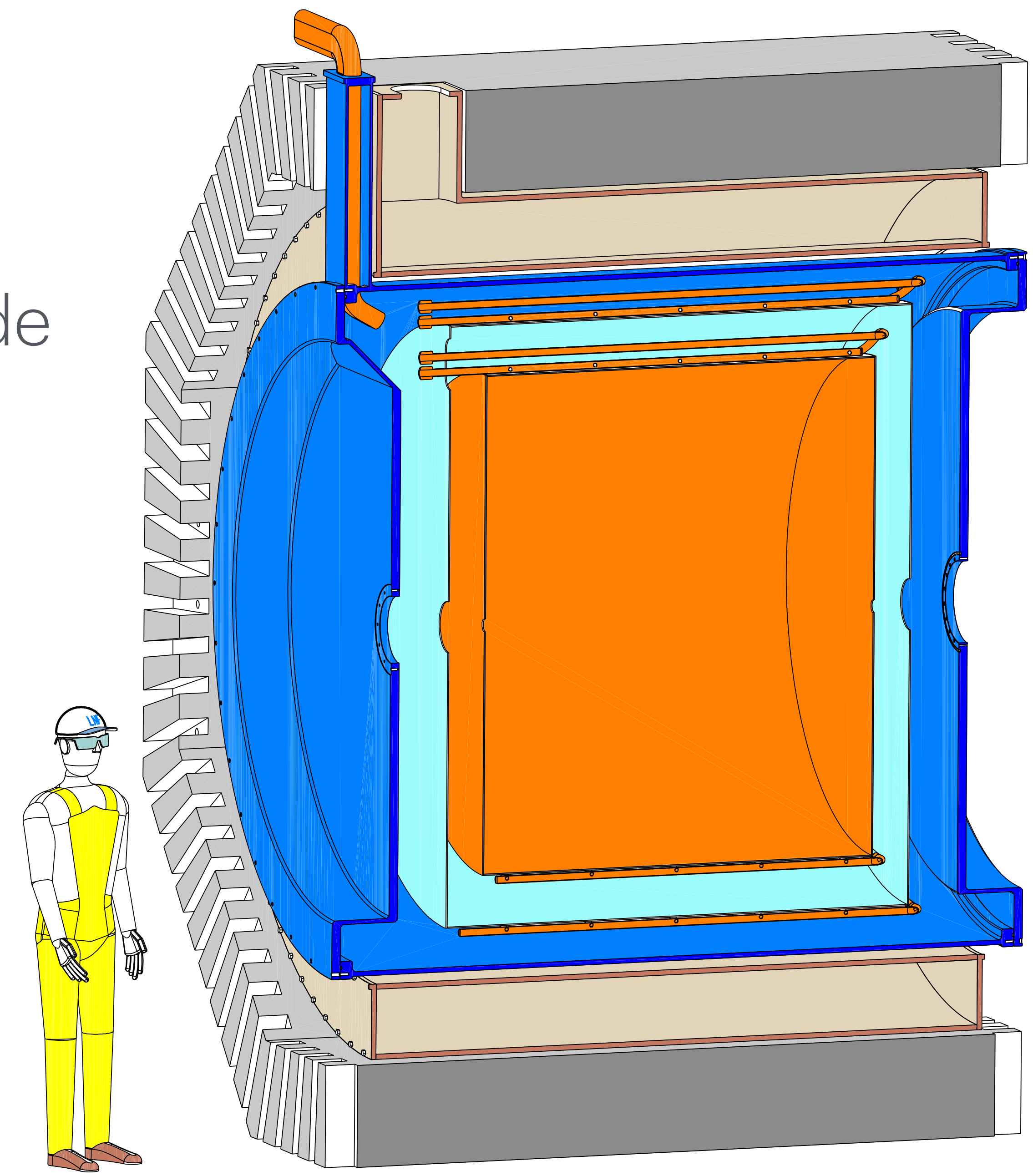
$$-\frac{m_X^2}{2}\left(X^\mu X_\mu + 2\chi X_\mu A^\mu\right)$$

Phys. Rev. D 104 095029, CERN-TH-2021-04 arXiv:2105.01406, Physics of the Dark Universe 42 (2023) 101370, Living Rev. Relativity 21 (2018), 1

FLASH: Resonance Cavity

FINUDA magnet for Light Axion Search Haloscope

- Range $\nu_c \sim (117 - 360)\ MHz$:
  cosmic axions of masses $\sim 10^{-6}\ eV$
- Resonant frequency tunable on the mode TM_{010} for the axion search
- Two cylindrical resonant cavities of different volumes, each with its tuning system
- The larger cavity $L = 1200\ mm$ and $R = 1050\ mm$

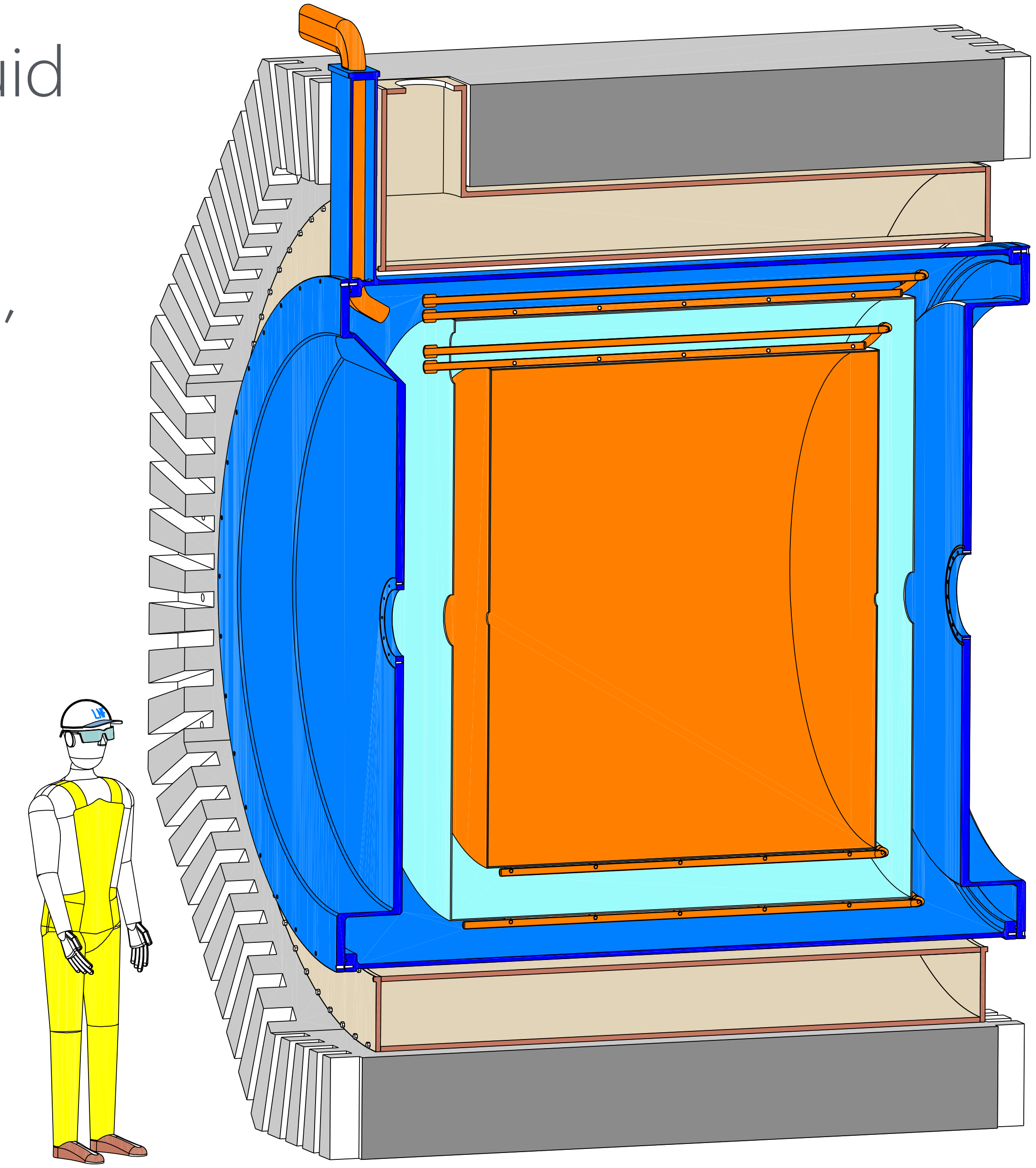


"The future search for low-frequency axions and new physics with the FLASH resonant cavity experiment at Frascati National Laboratories" Physics of the Dark Universe 42 (2023) 101370

FLASH: Cryogenics

FINUDA magnet for Light Axion Search Haloscope

- Cryostat and cooled at $4.5\ K$, using liquid helium
  - External stainless steel vacuum vessel, aluminum-alloy radiation shield, $\sim 70\ K$ by cold gaseous helium
  - Cooled in contact with pipes in which the helium flows

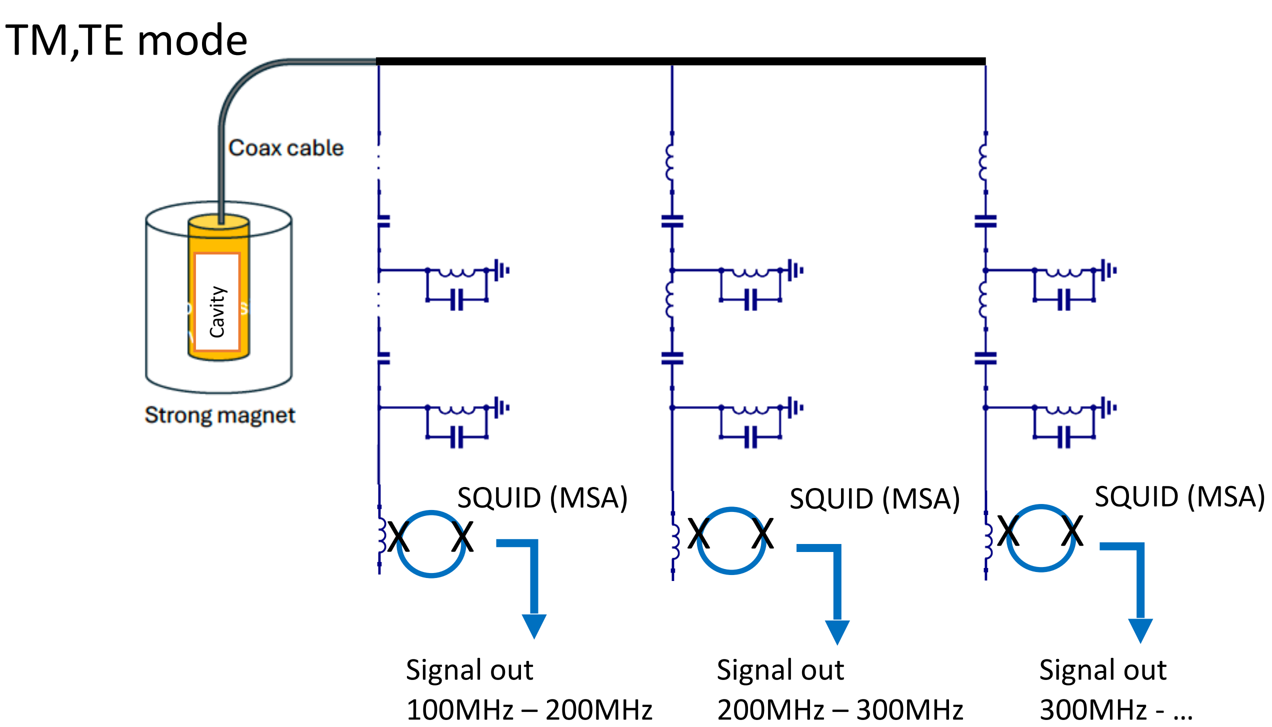


"The future search for low-frequency axions and new physics with the FLASH resonant cavity experiment at Frascati National Laboratories"
Physics of the Dark Universe 42 (2023) 101370

FLASH: Cryogenic amplifiers

FINUDA magnet for Light Axion Search Haloscope

- Superconducting QUantum Interference Device (SQUID)
  => Microstrip SQUID Amplifier (MSA)
- Low-noise, low-power-dissipation radio frequency and microwave amplifier
- Ultracryogenic temperatures, noise scales with the temperature down to $200 - 300\ mK$



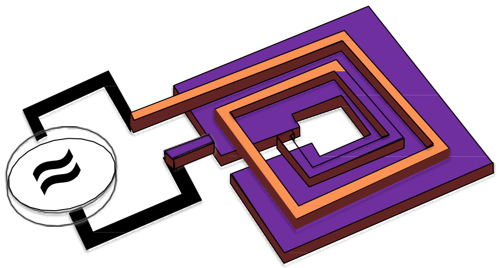
Characterization of noise and gain variation on T in autumn ($4\ K$ in Trento, mK in Pisa, 1 to $4\ K$ in Camerino)

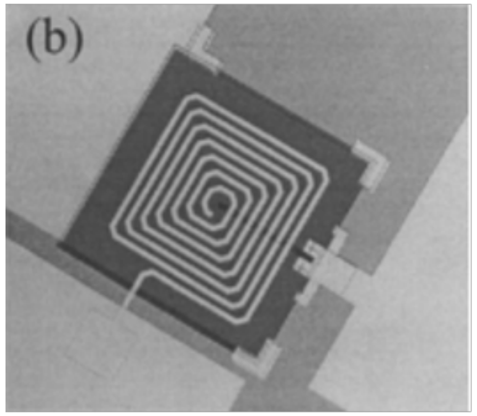
University of Liverpool responsible for designing the magnetic shielding of the SQUID, to be tested in Camerino with a DC magnetic field

Design Study and R&D for the TDR

Approved by INFN in Sept. 2024 ⇒ TDR ready in 2026

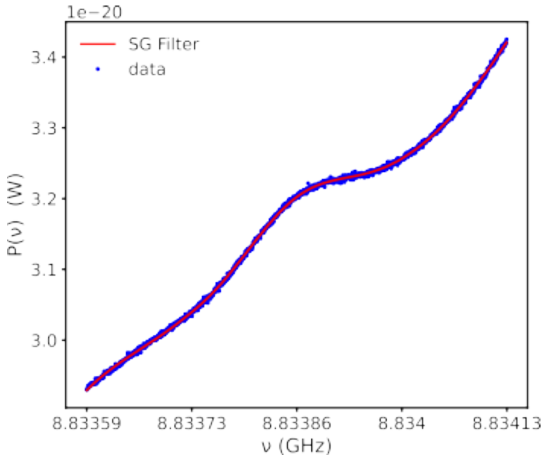
- Six WP ranging from Physics reach to old FINUDA detector and magnet decommissioning
- WP4: Responsibility for Signal Amplification and DAQ



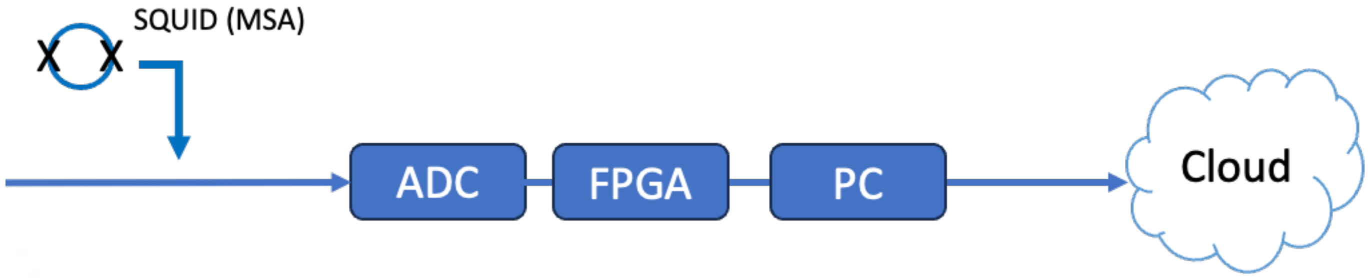


  - INFN Pisa
  - INFN Trento
  - Mainz University
  - Università di Camerino
  - University of Liverpool

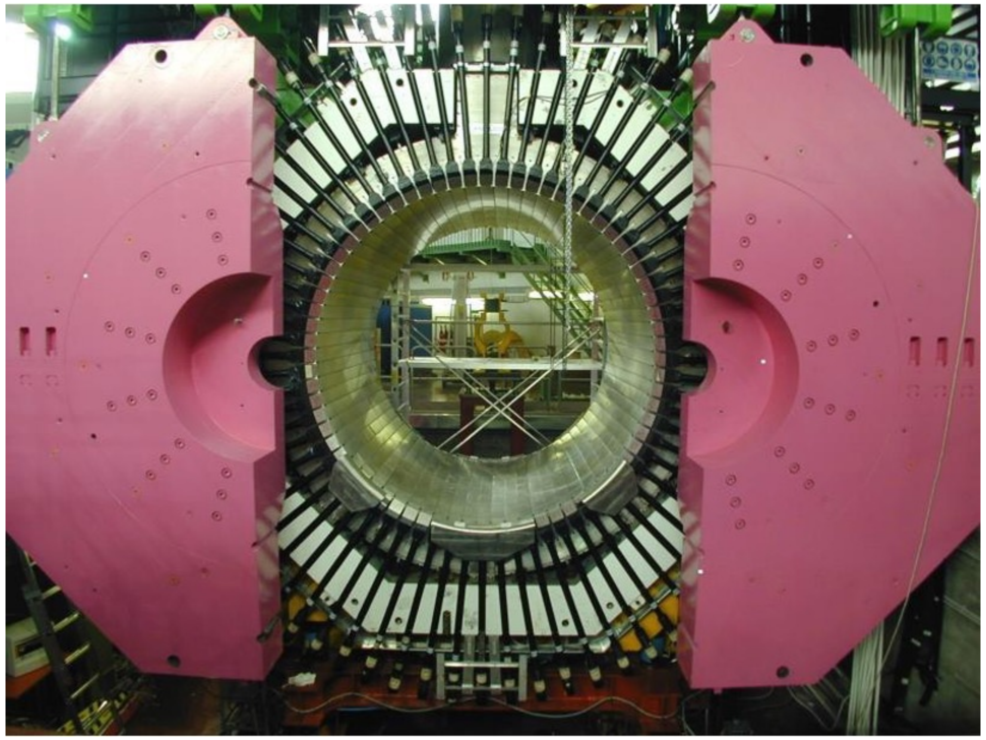
- WP5: Responsibility for Data Analysis and Computing



  - Mainz University
  - Bonn University
  - INFN Pisa
  - INFN Frascati
  - University of Liverpool



Project timeline



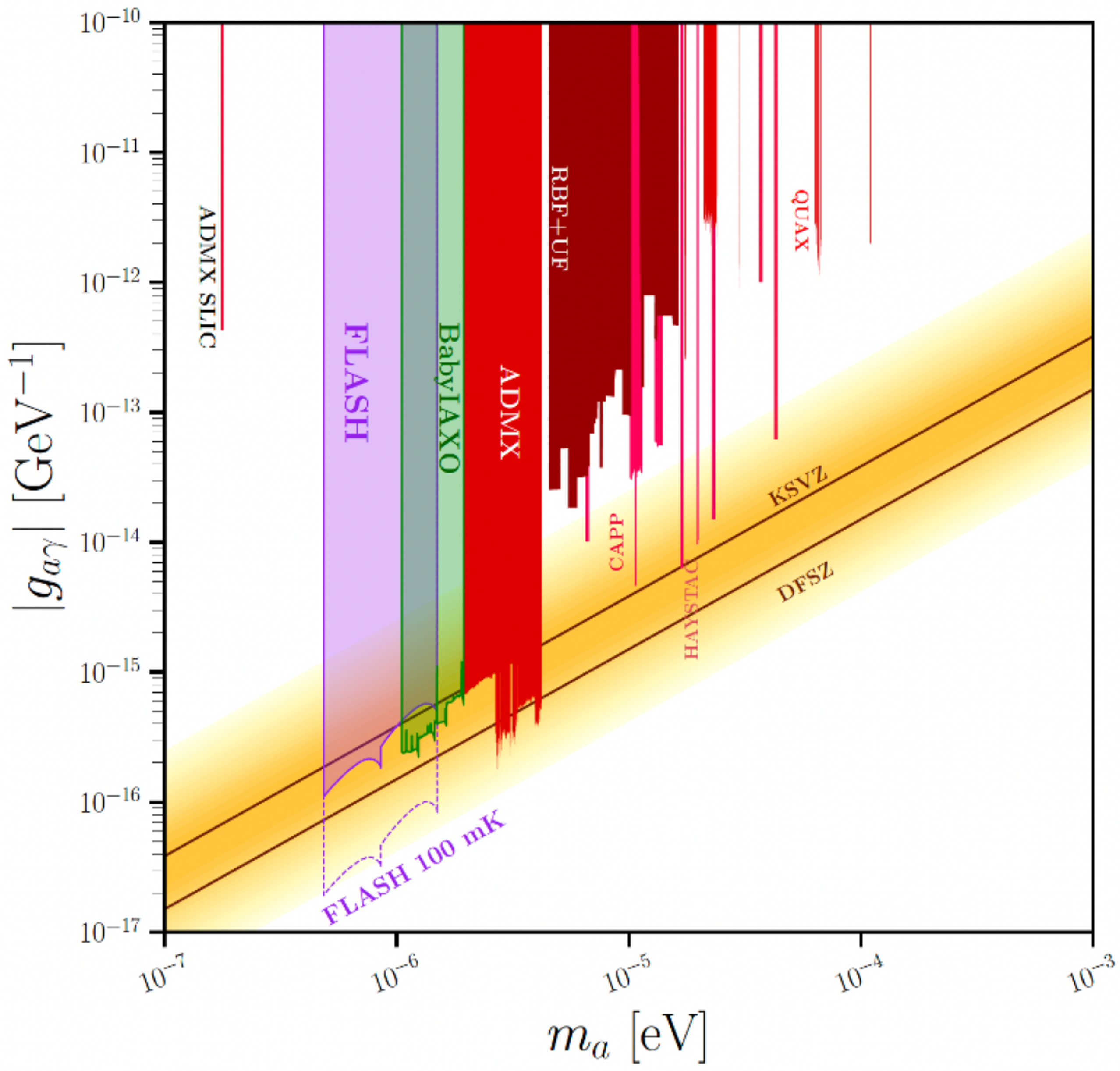
- **2025**
  - FINUDA decomissioning
  - Design FLASH and R&D
  - Formalisation of FLASH Collaboration
- **2026**
  - Certification and maintenance of the cryogenic system and magnet
  - Design FLASH
  - Fabrication 500 MHz FLASH cavity prototype (Bonn University)
  - Protoype characterization at 4K

- **2027**
  - Technical Design Report
  - Call of tender for cavity cryostat and RF cavity

- **2028 - 2030** Start fabrication & Data Taking

FLASH Physics reach

Axion searches



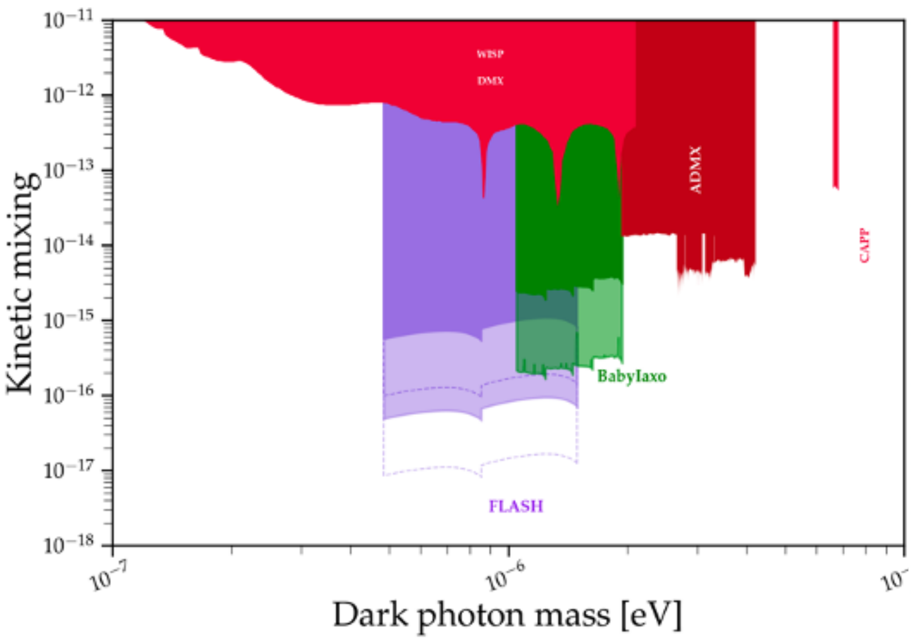
Cu cavity at 4.5 K

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}]	$(1.25 - 6.06) \times 10^{-16}$

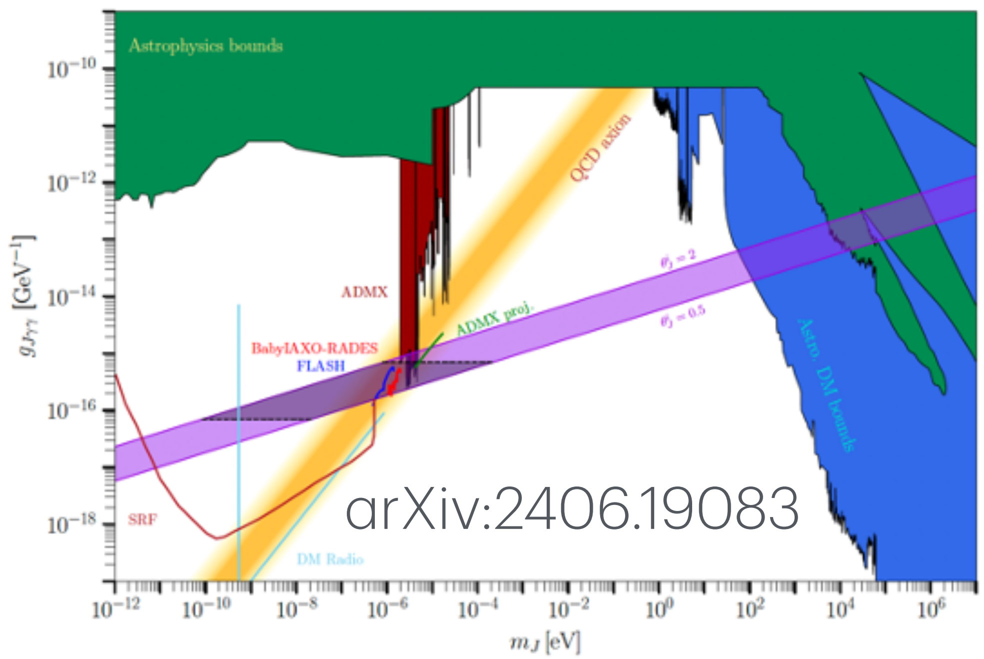
Physics reach

"Exotic" models

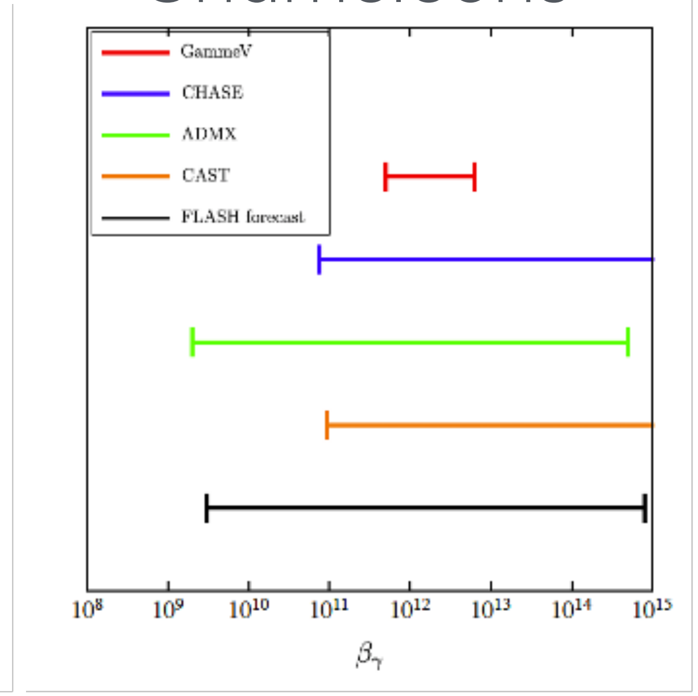
Vector Dark Matter



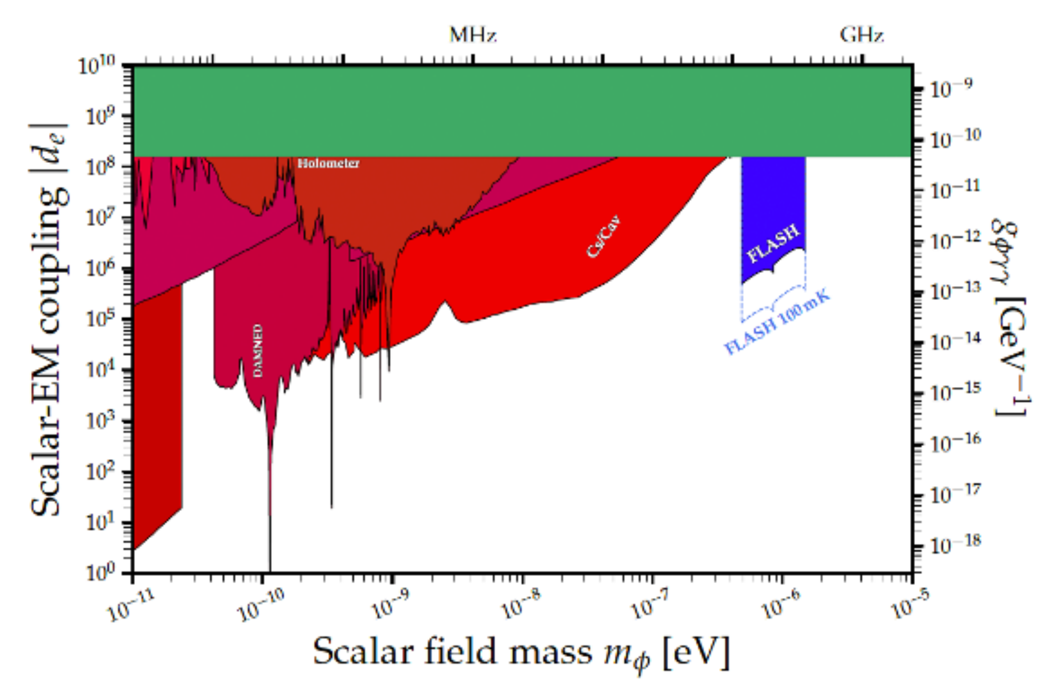
Majoron



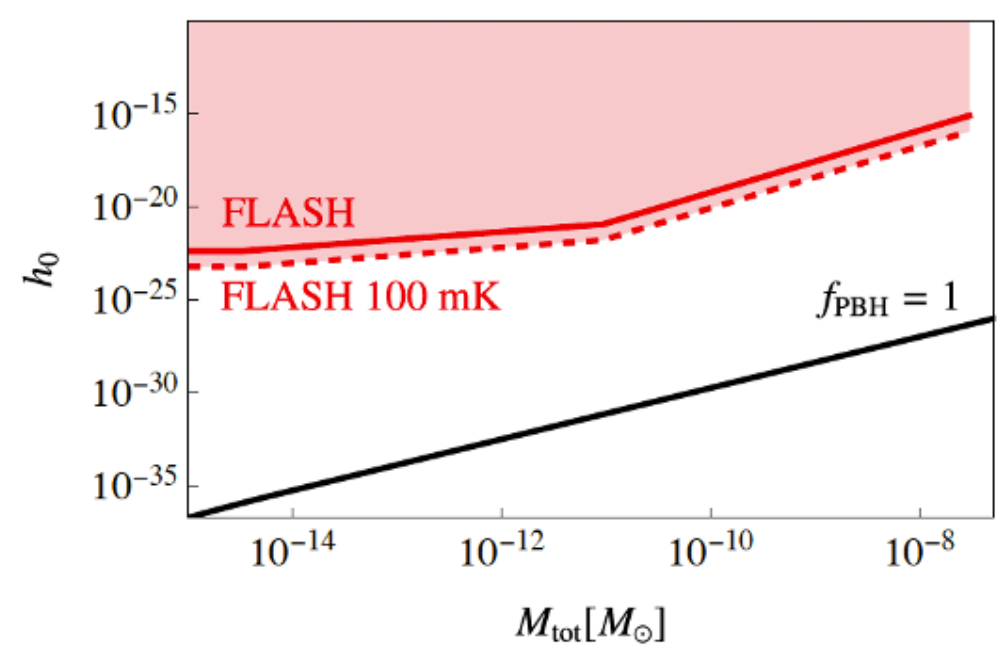
Chameleons



Scalar Dark Matter



HFGW



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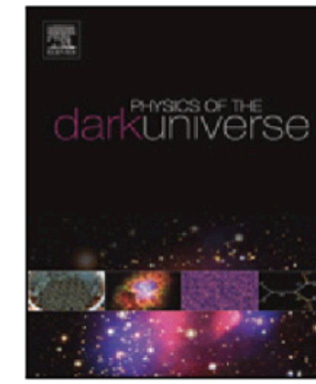
Physics of the Dark Universe 42 (2023) 101370

Contents lists available at ScienceDirect

Physics of the Dark Universe

journal homepage: www.elsevier.com/locate/dark



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

Thank you!

Back up

Axions

U(1)$_A$ problem

$$M_{\eta'} = 958 \text{ MeV} \gg M_\eta$$

S.Weinberg U(1) problem PRD 11 (1975)

Strong CP problem

$$\mathcal{L}^{\not{CP}}_{QCD} = \theta_{QCD} \frac{\alpha_s}{8\pi} G^a_{\mu\nu} \tilde{G}^{\mu\nu}_a$$

Phys Rev Lett 82, n.5 (1999) p.904

$$d_n < 2.9 \times 10^{-26} e \text{ cm}$$

$$\theta < 10^{-10}$$

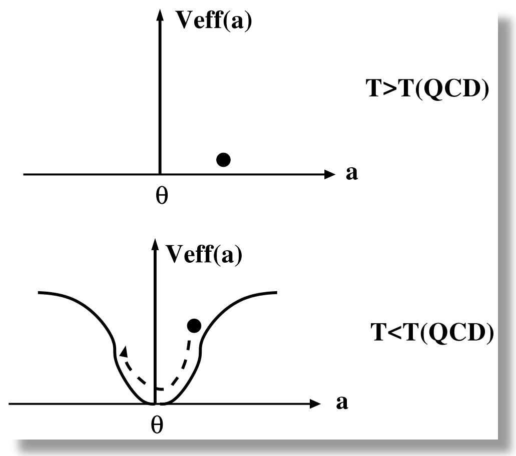
Axion

$$\mathcal{L}^{\not{CP}}_{QCD} = \left(\theta - \frac{a}{f_a}\right) \frac{\alpha_s}{8\pi} G^a_{\mu\nu} \tilde{G}^{\mu\nu}_a$$

- R.D.Peccei and H.R.Quinn, Phys. Rev. Lett. 38, 1440 (1977); Phys. Rev. D 16, 1791 (1977).
- S. Weinberg, Phys. Rev. Lett. 40, 223 (1978).
- F. Wilczek, Phys. Rev. Lett. 40, 279 (1978).

Axion Dark Matter

Misalignment mechanism



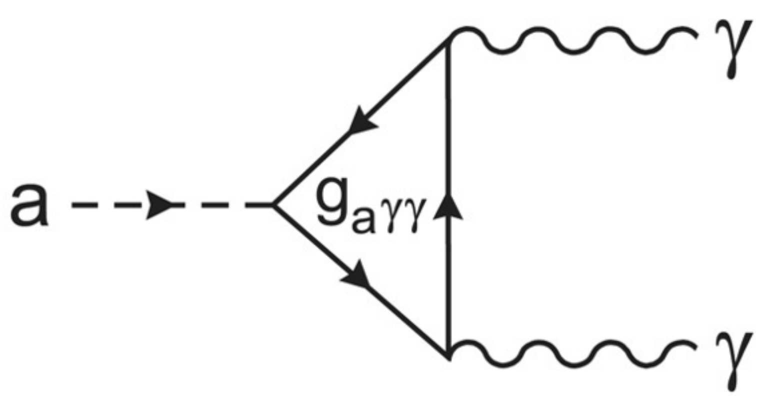
Axions

- Mass

$$m_a = 5.70(7)\left(\frac{10^{12}GeV}{f_a}\right)\mu eV \simeq \frac{m_\pi f_\pi}{f_a}$$

- Coupling

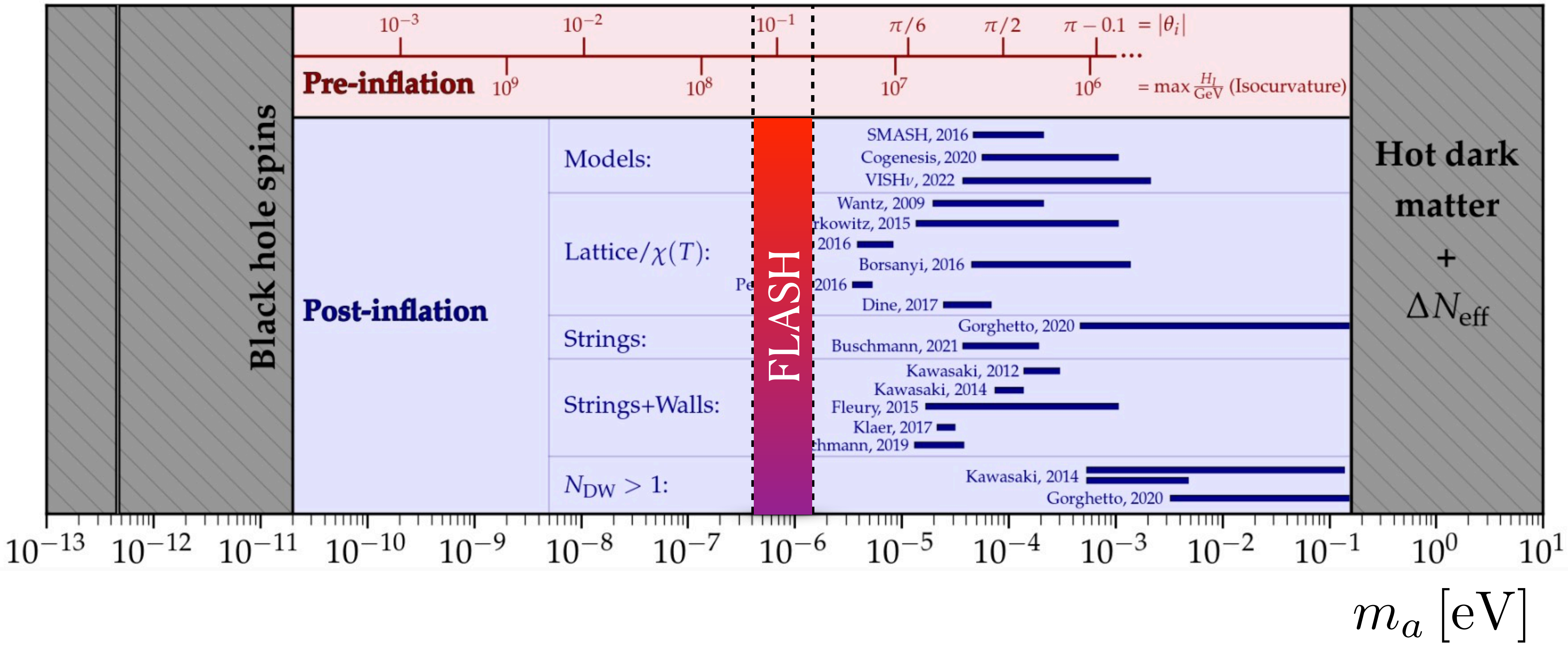
$$g_{a\gamma\gamma} = \frac{\alpha_{em}}{2\pi f_a}\left(\frac{E}{N} - 1.92(4)\right)$$



- Lifetime

$$\Gamma_{a\to\gamma\gamma} = \frac{g_{a\gamma\gamma}^2 m_a^3}{64\pi} = 1.1\times 10^{-24}s^{-1}\left(\frac{m_a}{eV}\right)^5$$

Cold axions as dark matter



Gravitational Waves searches

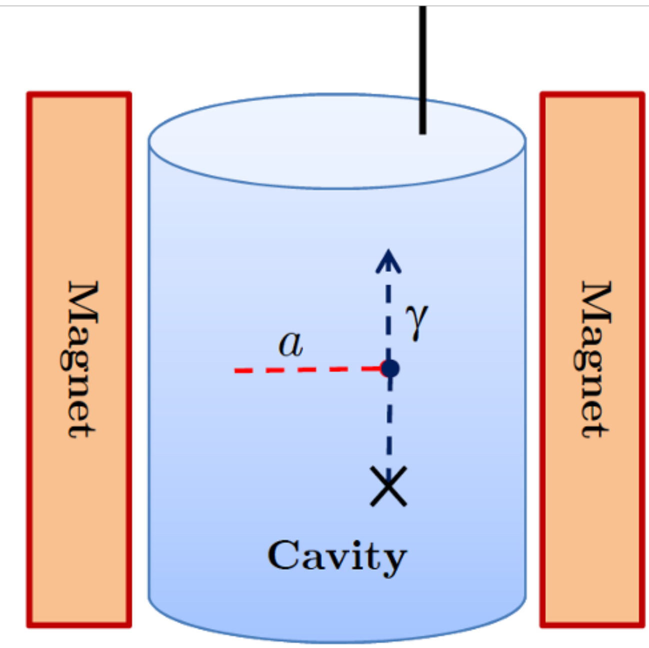
- Gravitational Waves (GWs) at $\boldsymbol{E}$ ~ scale of grand unification
  ⇒ frequencies in the MHz and GHz regime today

- Inverse Gertsenshtein effect which describes the conversion of GWs into photons in the presence of $\boldsymbol{B}$

  ⇒ Distortion of the CMB, which can serve as a detector for MHz to GHz gravitational wave sources active before reionization

Sikivie's Haloscope

Sikivie Phys. Rev. D 32,11 (1985)



$$\nabla^2 E - \partial_t^2 E = -g_{a\gamma\gamma} B_0 \partial_t^2 a$$

- Solving the equation inside a cylindrical resonant cavity, the signal power is

$$P_{\rm sig} = \left(g_\gamma^2 \frac{\alpha^2}{\pi^2} \frac{\hbar^3 c^3 \rho_a}{\Lambda^4} \right) \times \left(\frac{\beta}{1+\beta} \omega_c \frac{1}{\mu_0} B_0^2 V C_{mnl} Q_L \right)$$

β antenna coupling to cavity

V cavity volume

C_{mnl} mode dependent factor
~ 0.6 for TM_{010}

Q_L cavity "loaded" quality factor

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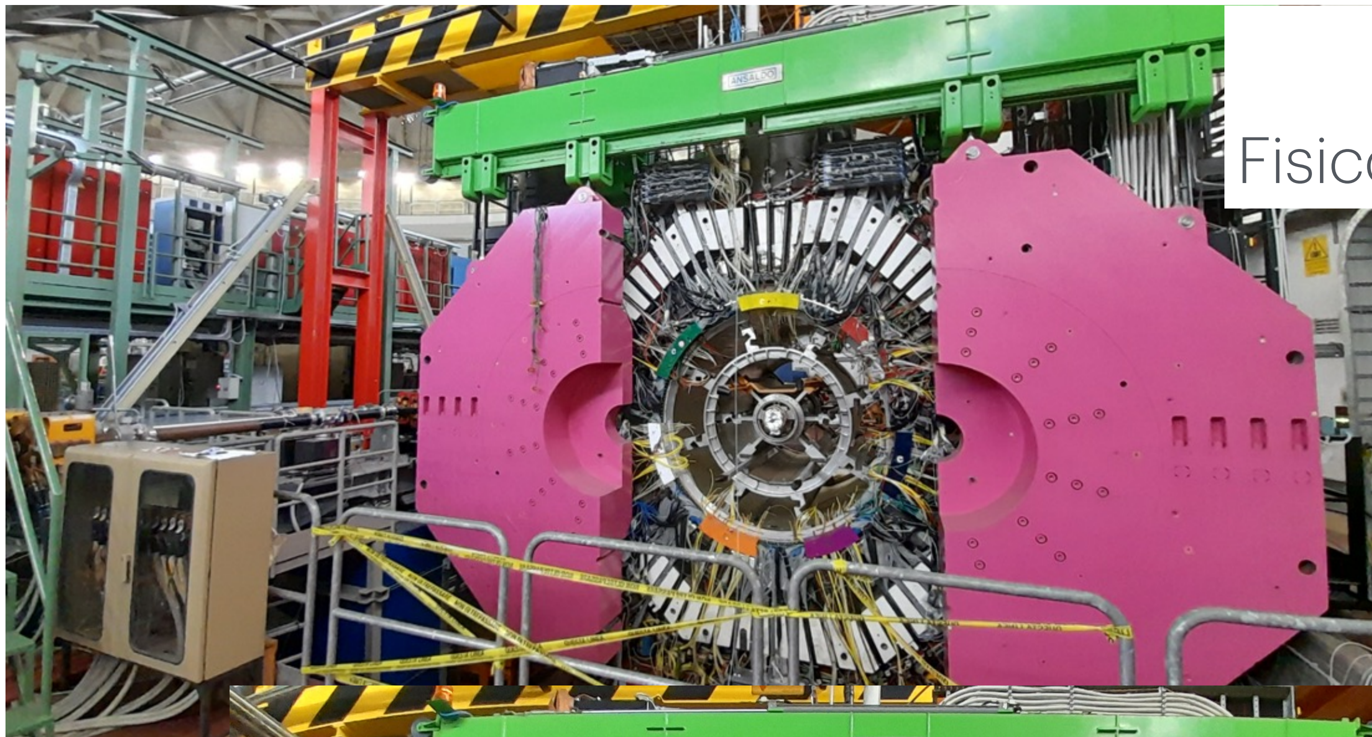
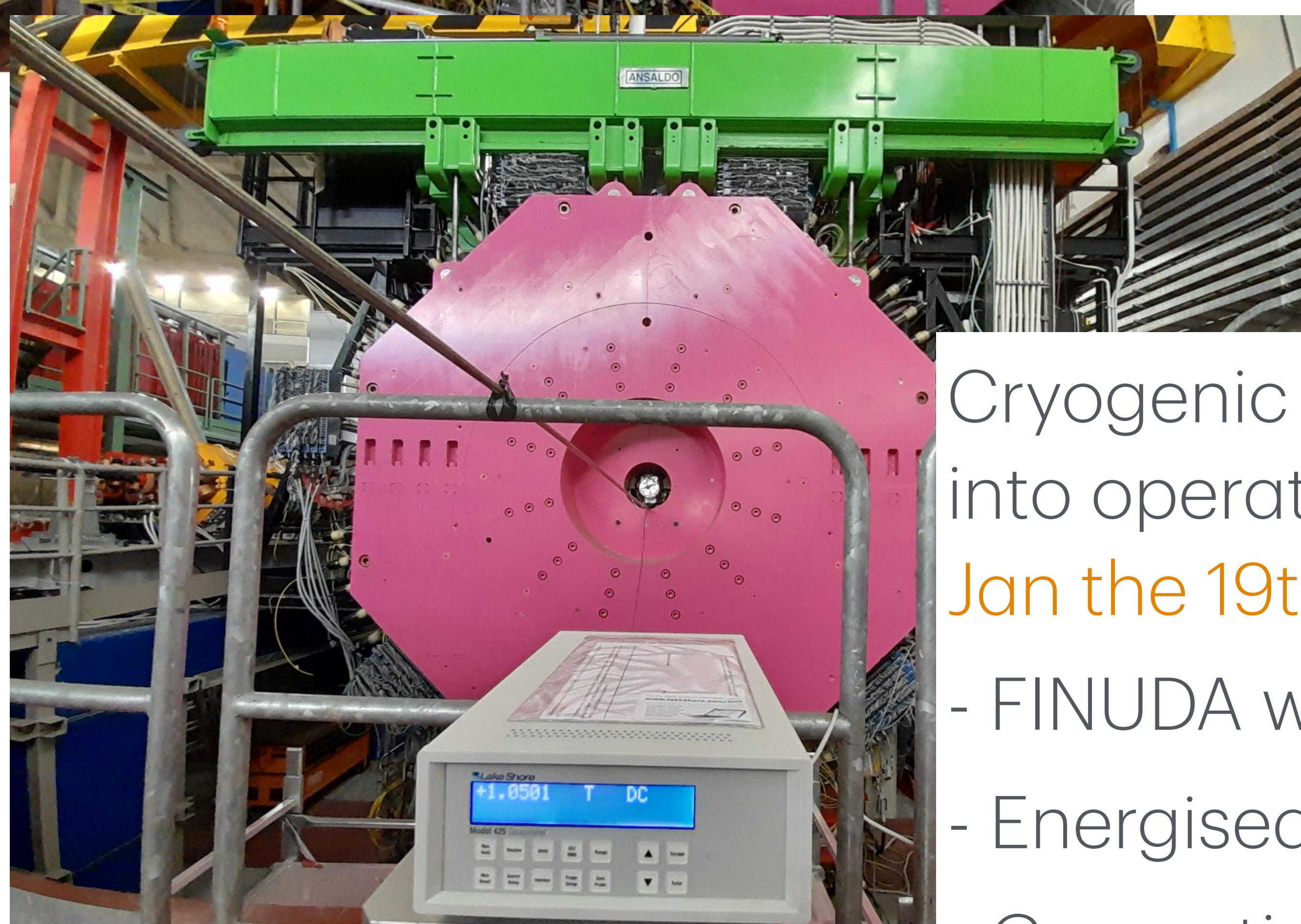
Magnet from FINUDA



FINUDA
Fisica Nucleare a DAΦNE

INFN LNF
Istituto Nazionale di Fisica Nucleare

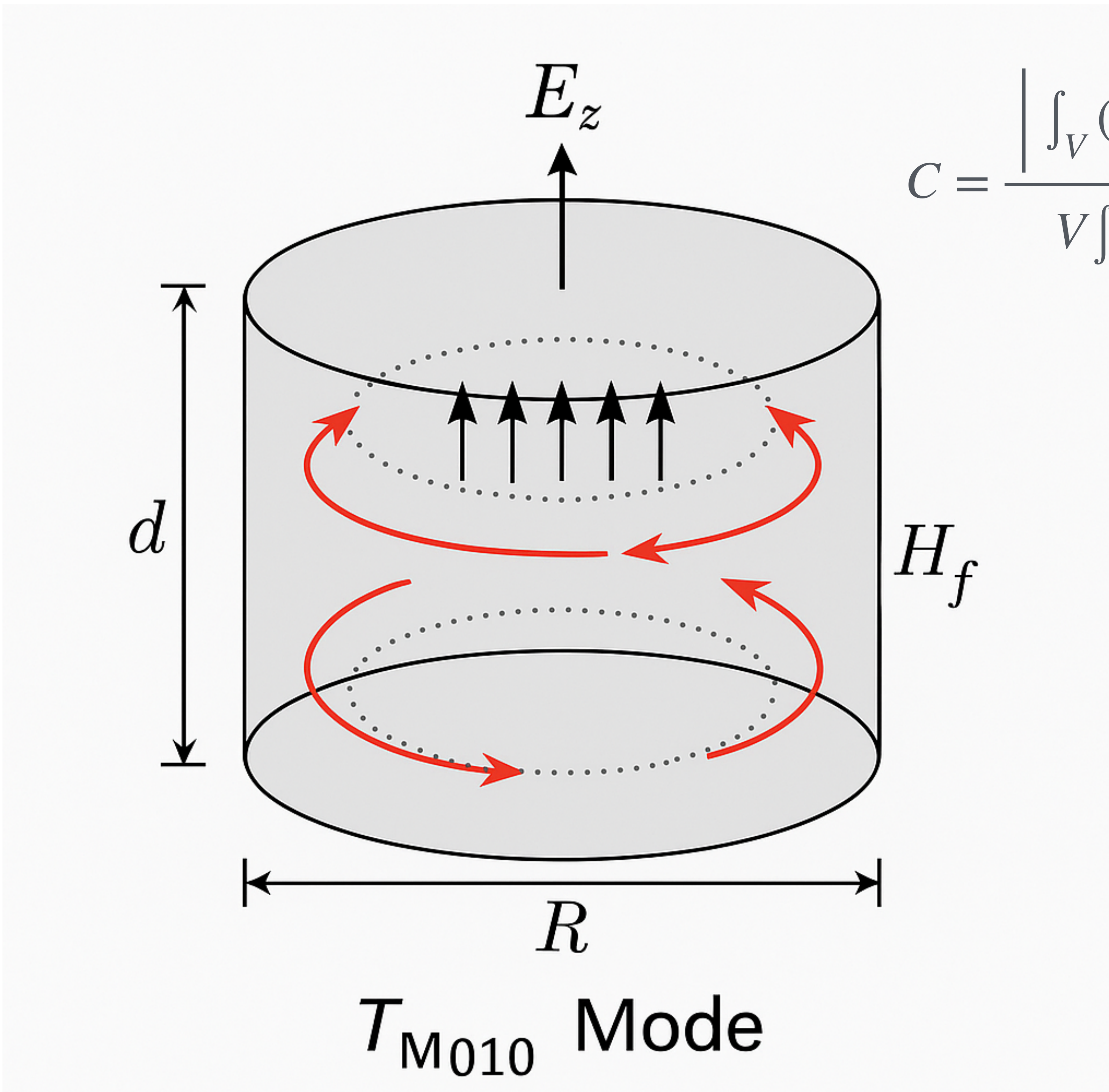
B [T]	1.1
R [m]	1.4
L [m]	2.2



Cryogenic plant put back into operation
Jan the 19th 2024

- FINUDA was cooled down to $4\ K$
- Energised with a current of $2706\ A$
- Generating a magnetic field of $1.05\ T$

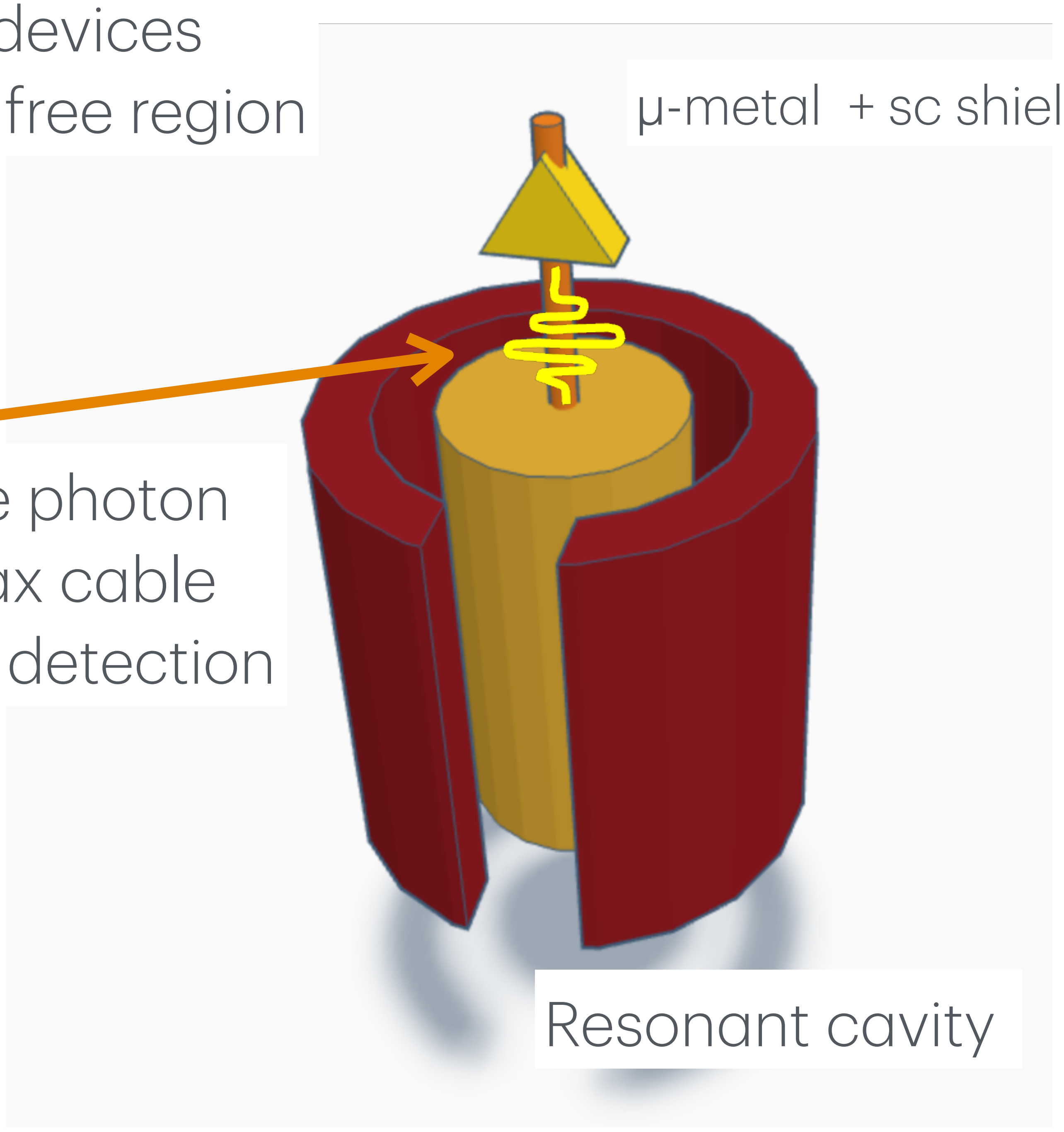
Resonance Cavity



$$C = \frac{\left| \int_V (\vec{E} \cdot \vec{B}_0)\, dV \right|^2}{V \int_V \varepsilon |\vec{E}|^2\, dV}$$

Itinerant Photon Detection

Superconducting devices
placed in a B-field free region

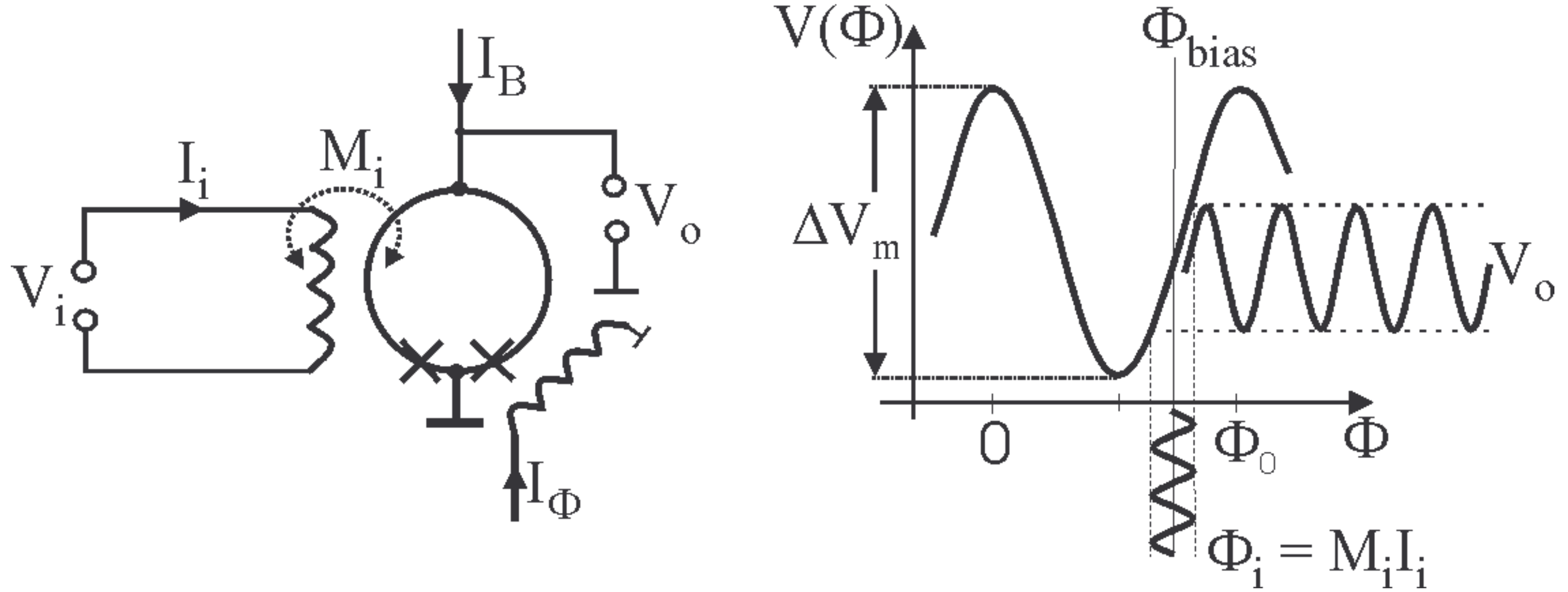


We must detect the photon
Traveling in the coax cable
=> Itinerant photon detection

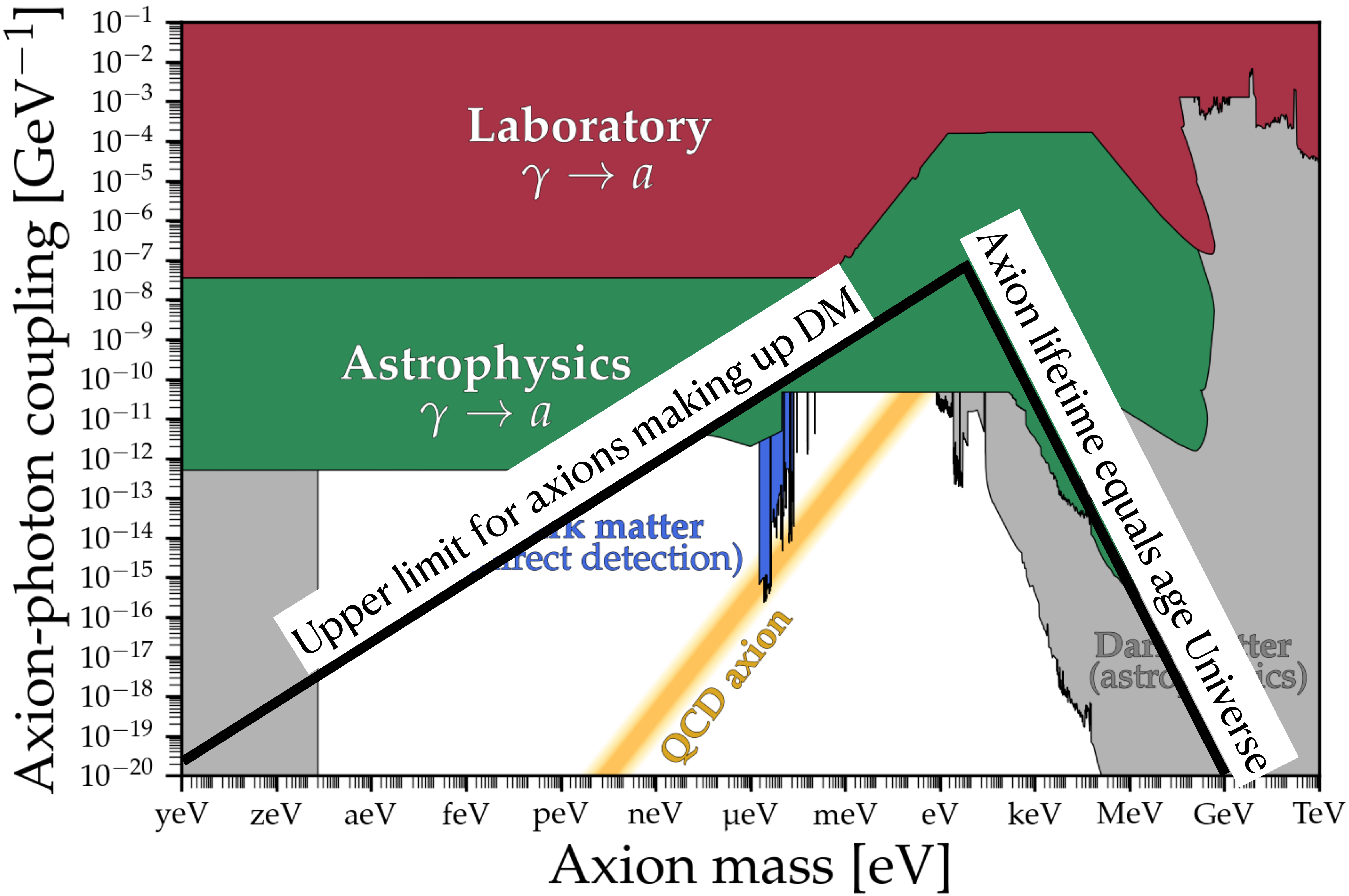
SQUID Radio Frequency Amplifiers

Superconducting Quantum Interference Device

- The most sensitive detector of magnetic flux available
- Low power dissipation and unsurpassed noise properties
- Input signal converted to current => flux in the SQUID, generates output voltage V_o
  - Function of the applied flux, the SQUID loop changes => the voltage across the current-biased SQUID changes periodicity Φ_0

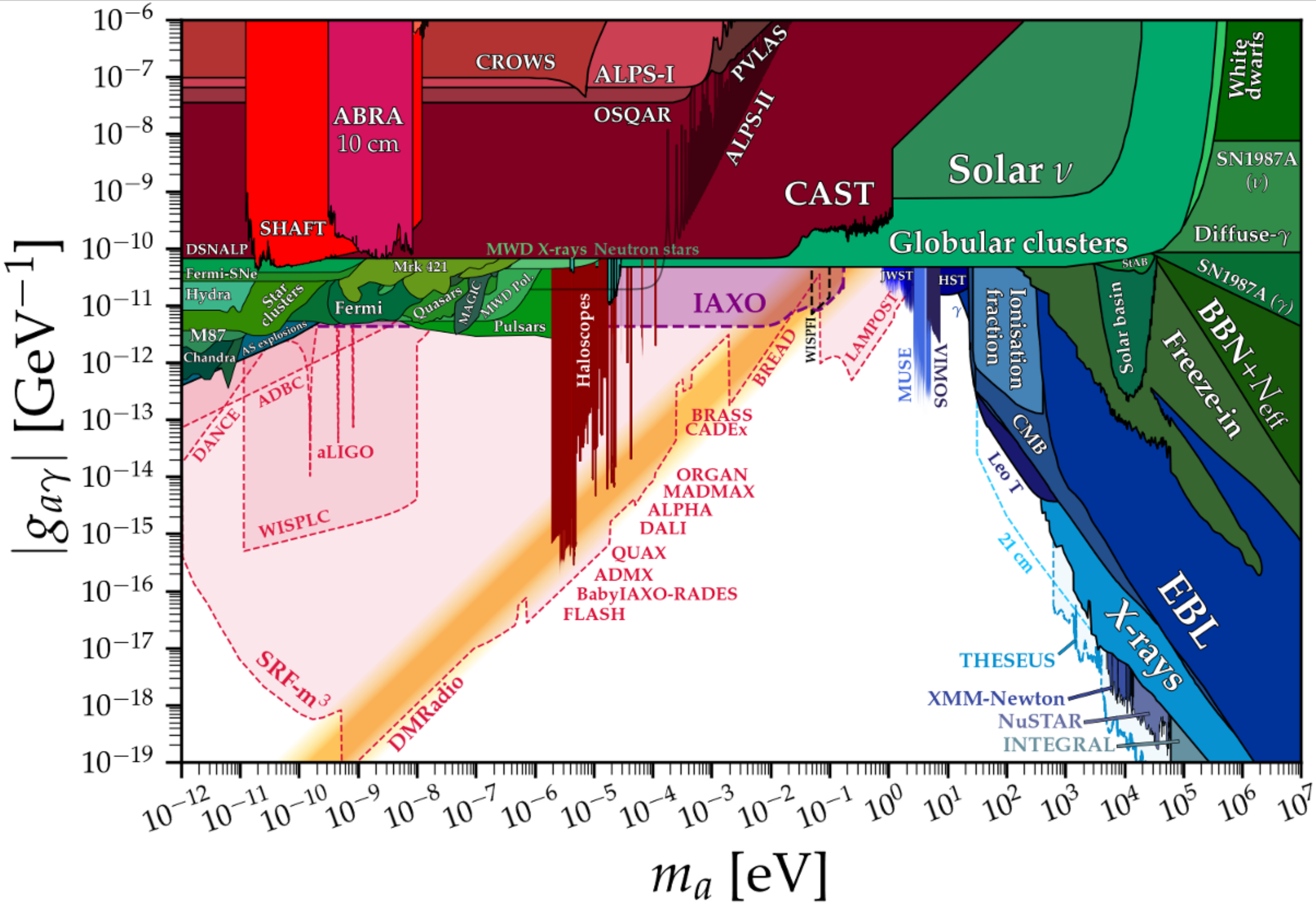


Coupling of the axion with the photon



Probing the Full QCD-Axion Band

Next 10 Years



ERC GravNet budget

Total ERC funds at INFN 3.75 Meuro:

...

0.5 Meuro from timesheet

0.7 Meuro for recruitment

1.5 Meuro full capitalized costs (FLASH detector)

0.25 Meuro consumables

0.05 Meuro travel + audit.

Expected costs:

FLASH 1.8 Meuro

FINUDA cost (magnet cryogenics + decommissioning) 100 keuro

...

Quantum Sensing (COLD Lab) 200 keuro

Audit 30 keuro

Additionally:

DAFNE Cryogenics Refurbishment (with LNF overheads)