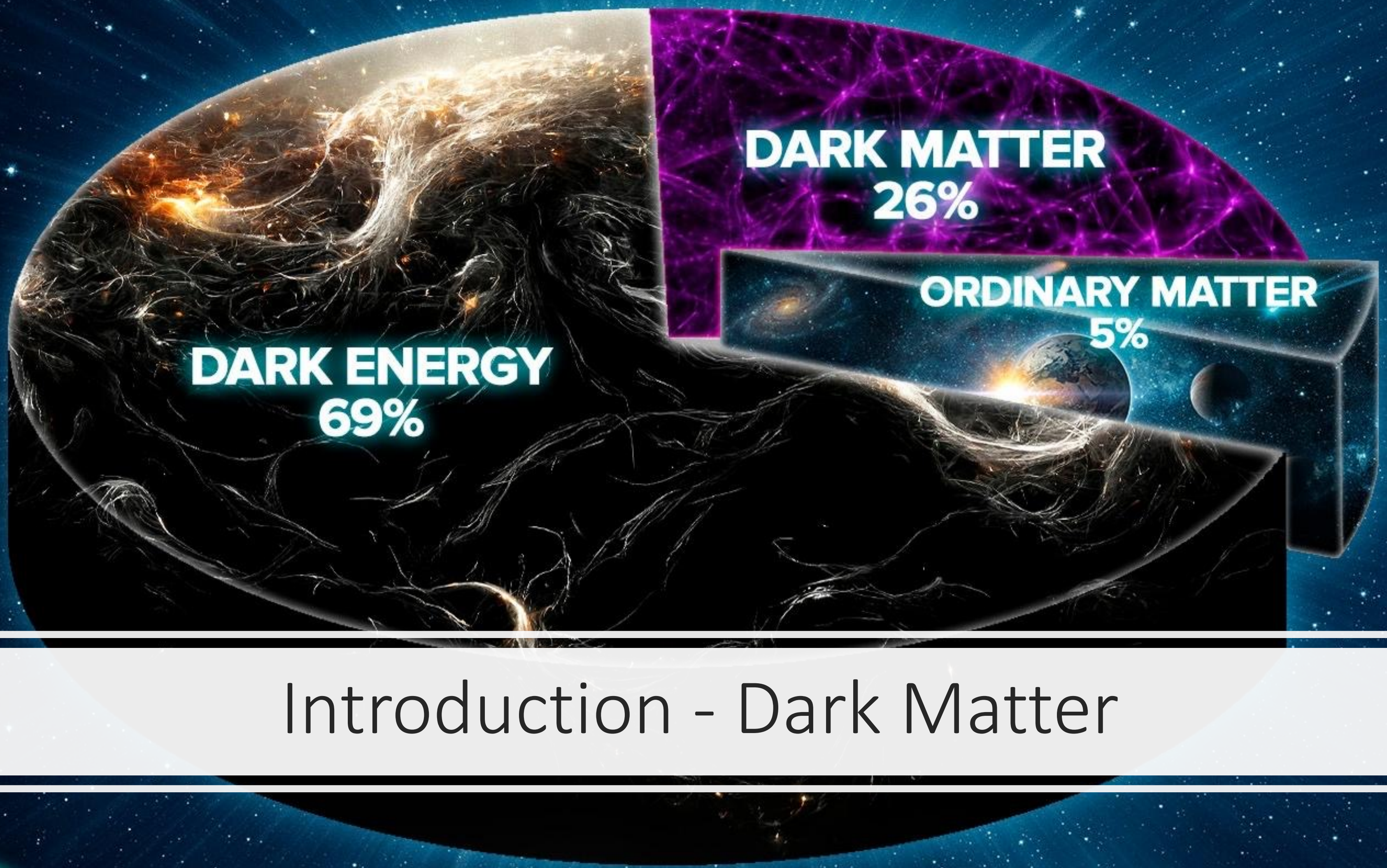
AXION Searches at LNF

QUAX@LNF a 9 GHz Haloscope
FLASH a 100 MHz Haloscope

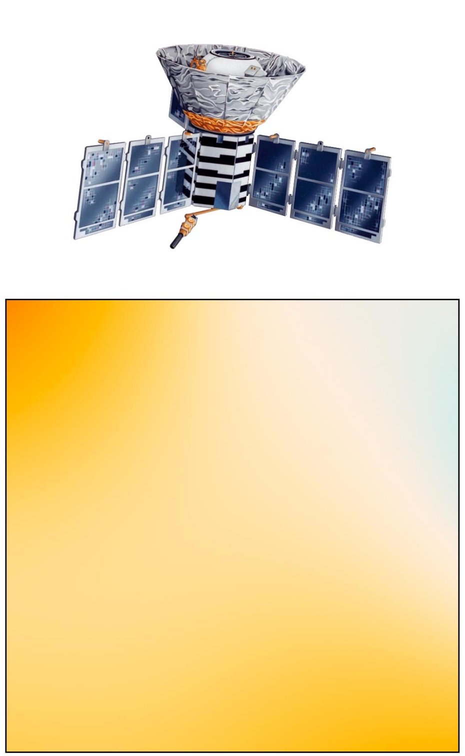
Claudio Gatti - LNF

University of Liverpool 16 October 2024



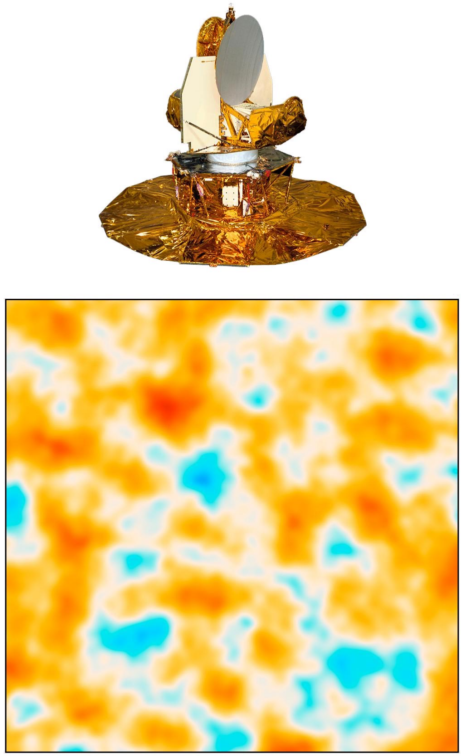
Introduction - Dark Matter

Cosmic Microwave Background - Anisotropy



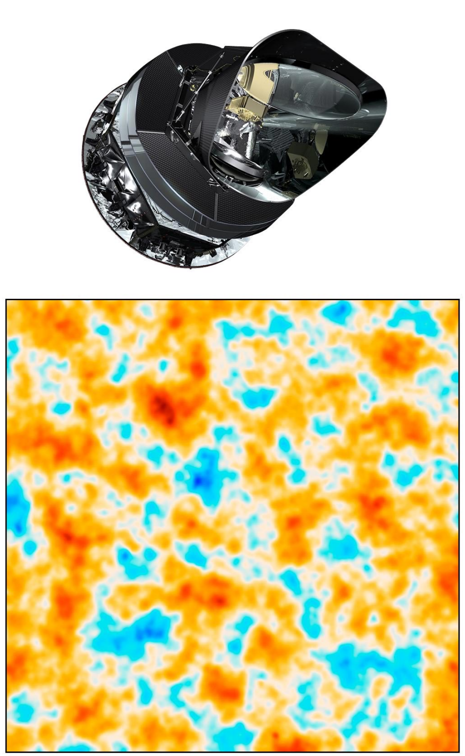
COBE

1989



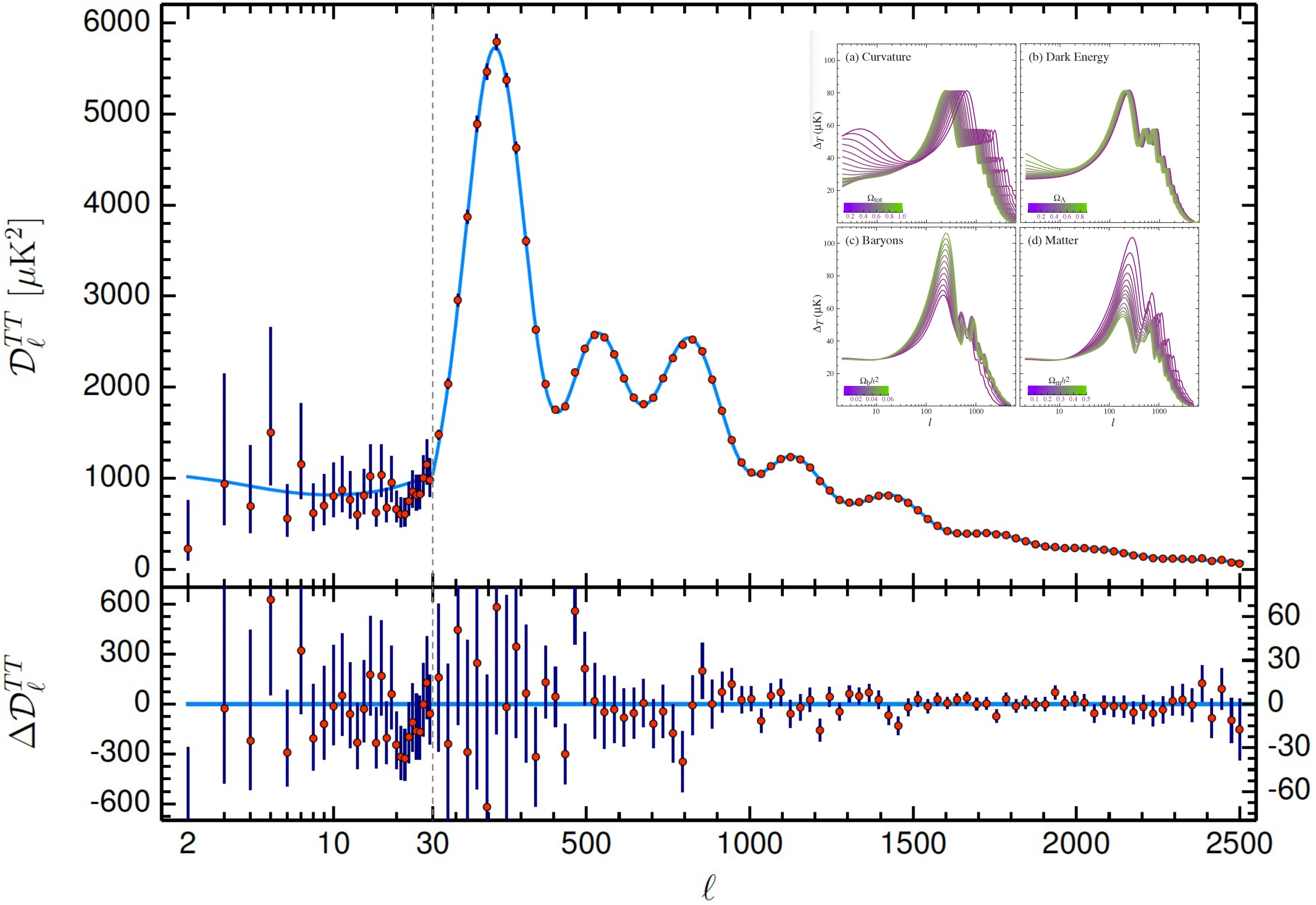
WMAP

2001



Planck

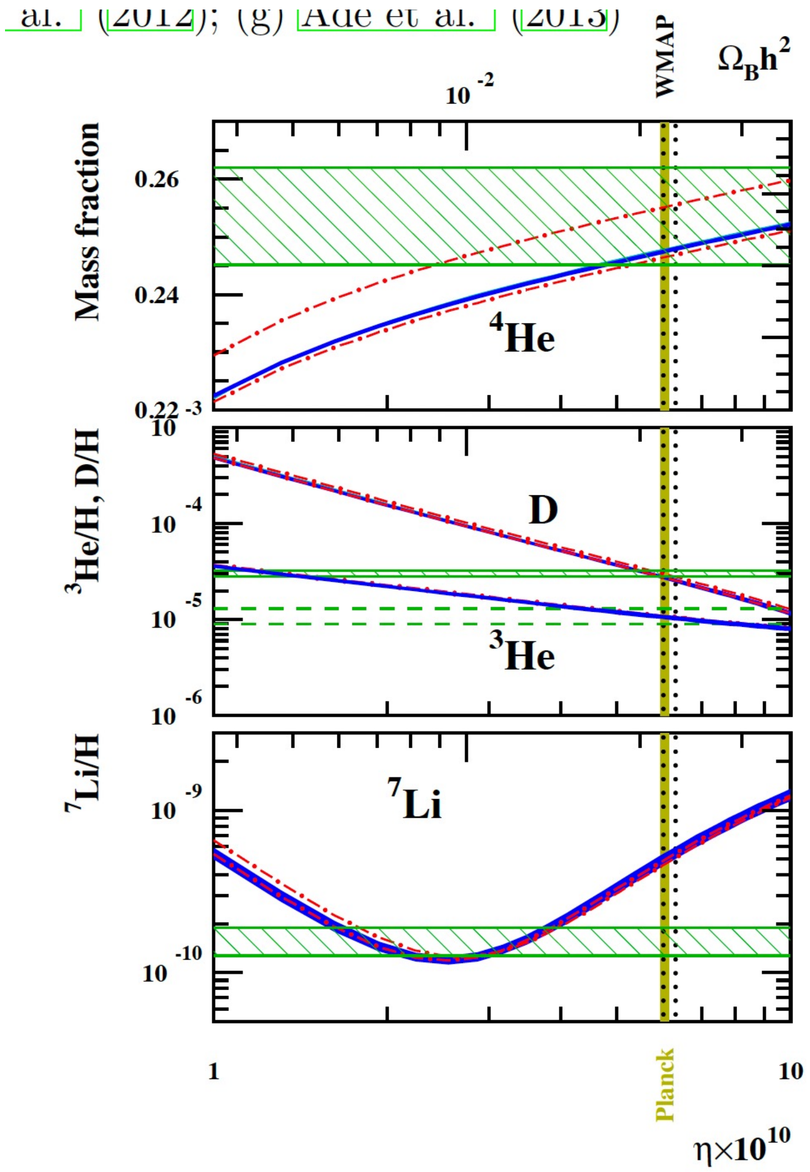
2009



$$\begin{cases} \Omega_\Lambda \approx 68\% \\ \Omega_{DM} \approx 26\% \\ \Omega_b \approx 6\% \end{cases}$$

Plank 2018 results - arXiv:1807.06209

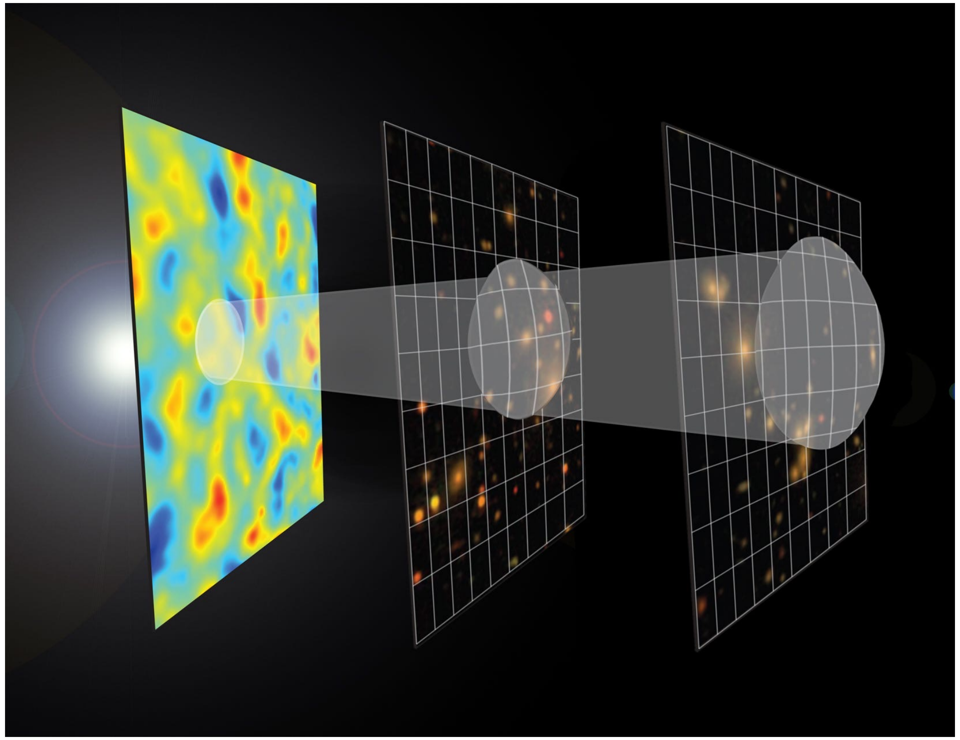
Ω_b - Big-Bang Nucleosynthesis



arXiv:1307.6955

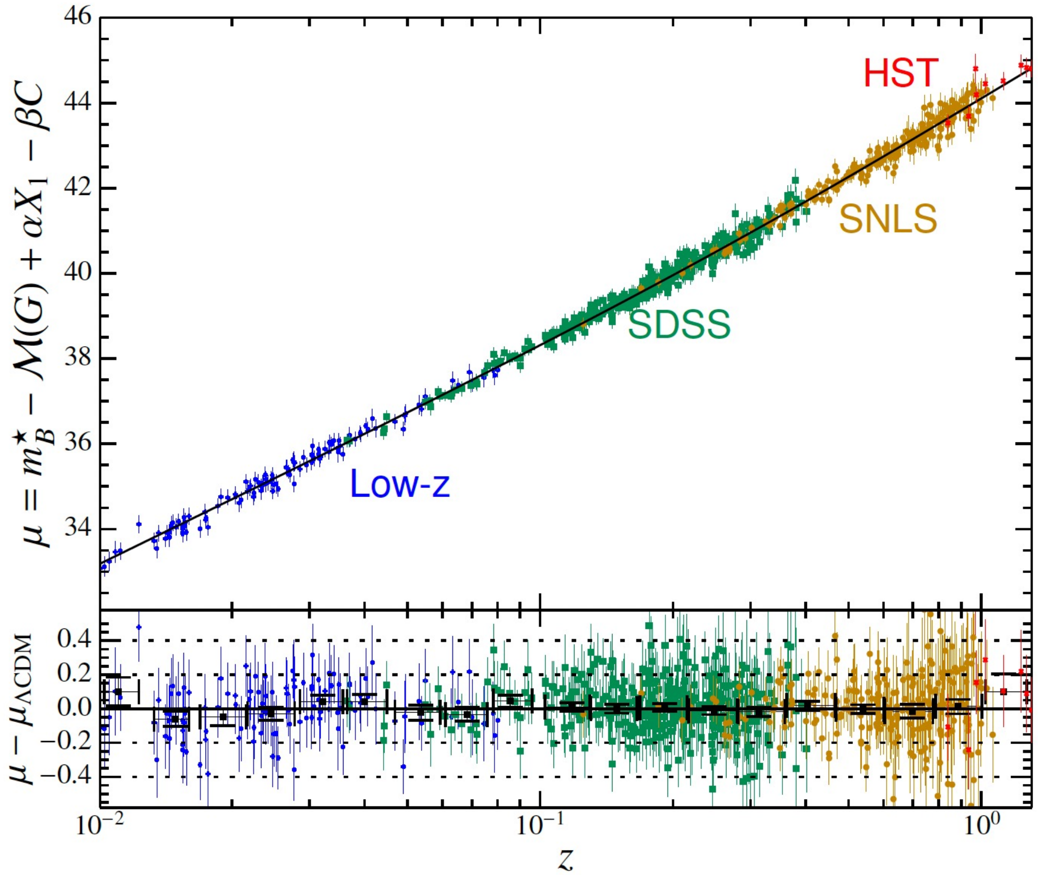
$$n + p \rightarrow D + \gamma$$

Ω_Λ and Ω_{DM+b}



arXiv:2404.03002

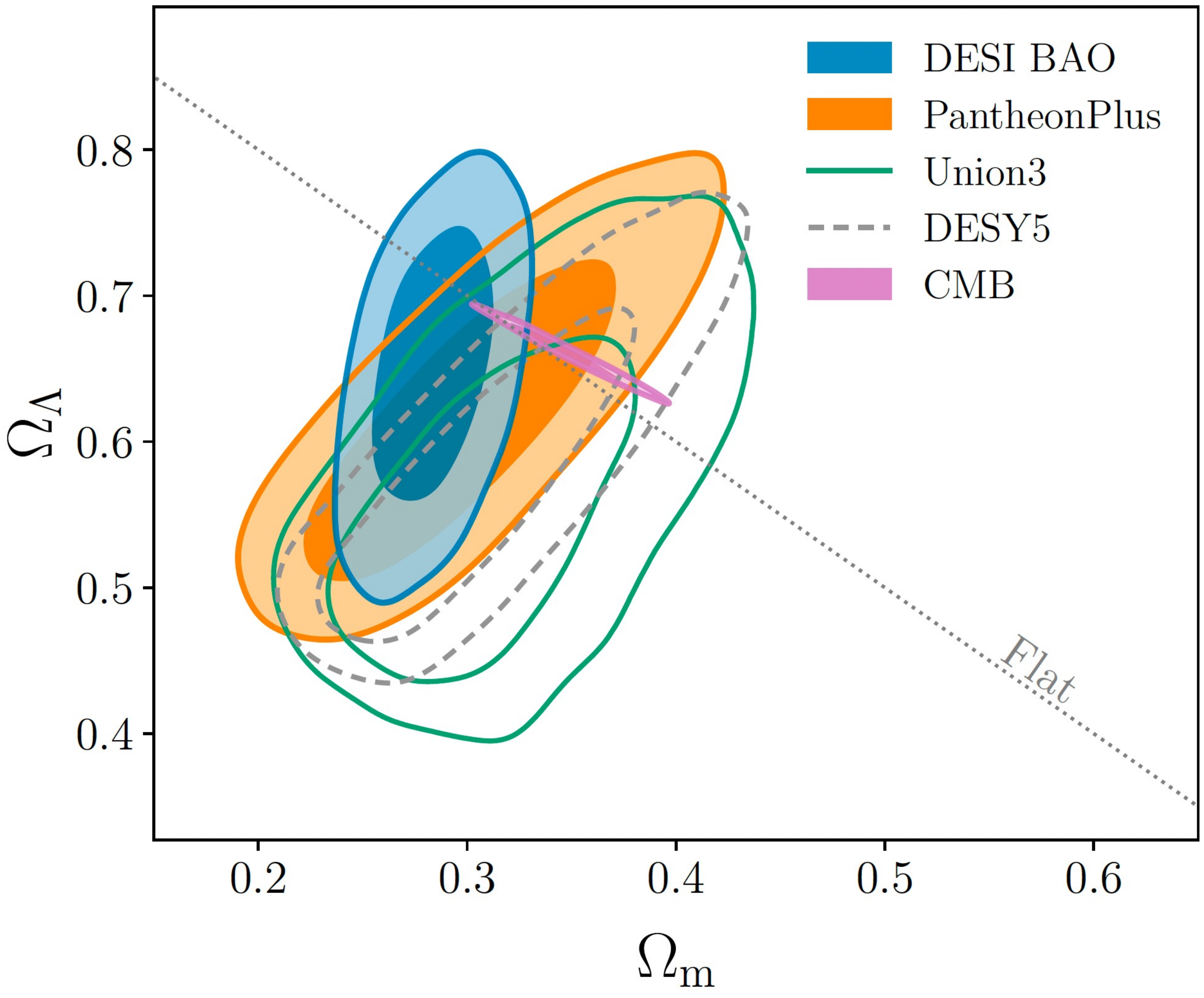
Baryon Acoustic Oscillations



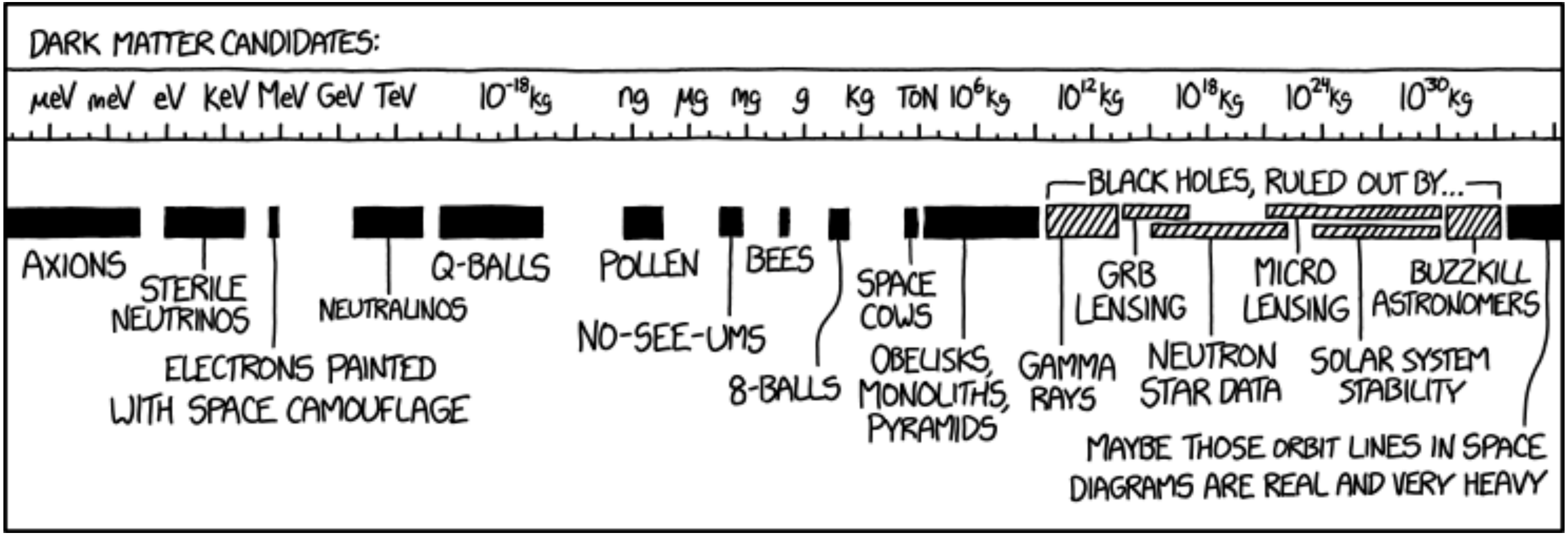
arXiv:1401.4064

Hubble Diagram from type Ia Supernovae

$$\begin{cases} \Omega_\Lambda \approx 68\% \\ \Omega_{DM} \approx 26\% \\ \Omega_b \approx 6\% \end{cases}$$



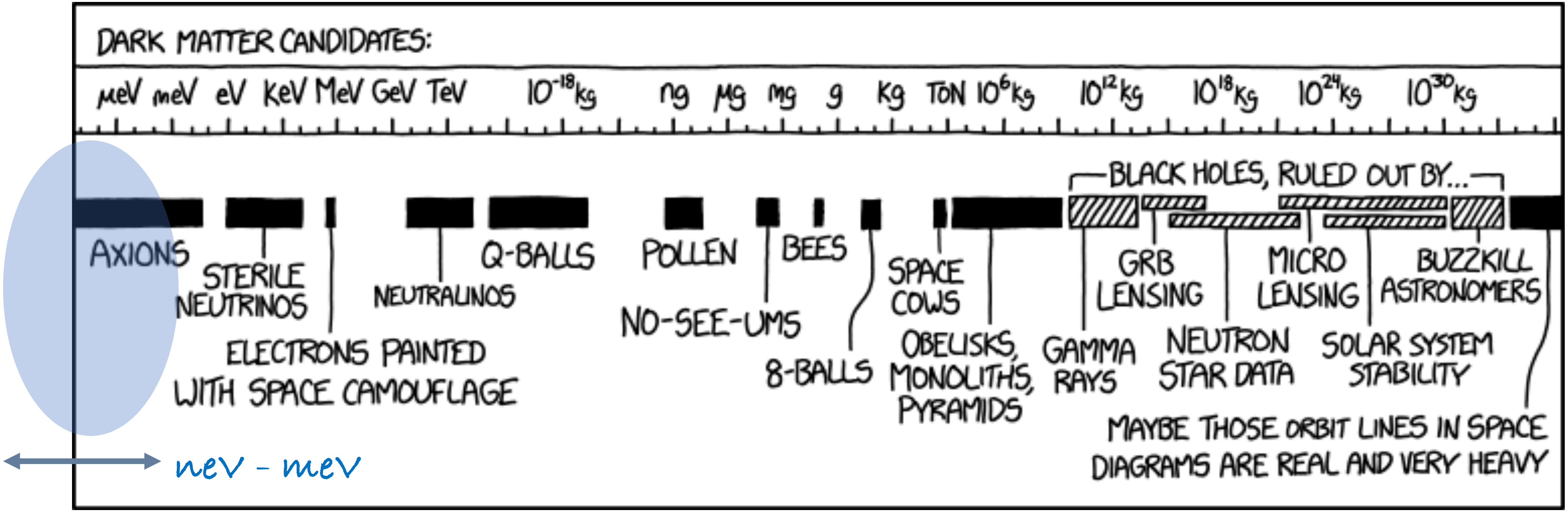
arXiv:2404.03002



https://www.explainxkcd.com/wiki/index.php/2035:_Dark_Matter_Candidates

Dark Matter Candidates

Dark Matter Candidates



https://www.explainxkcd.com/wiki/index.php/2035:_Dark_Matter_Candidates

"Wavy" Dark Matter
Scalars
Pseudo-scalars
Vectors

"Wavy" Light Dark Matter

Pseudoscalar Dark Matter
Axions, ALPS, Majoron

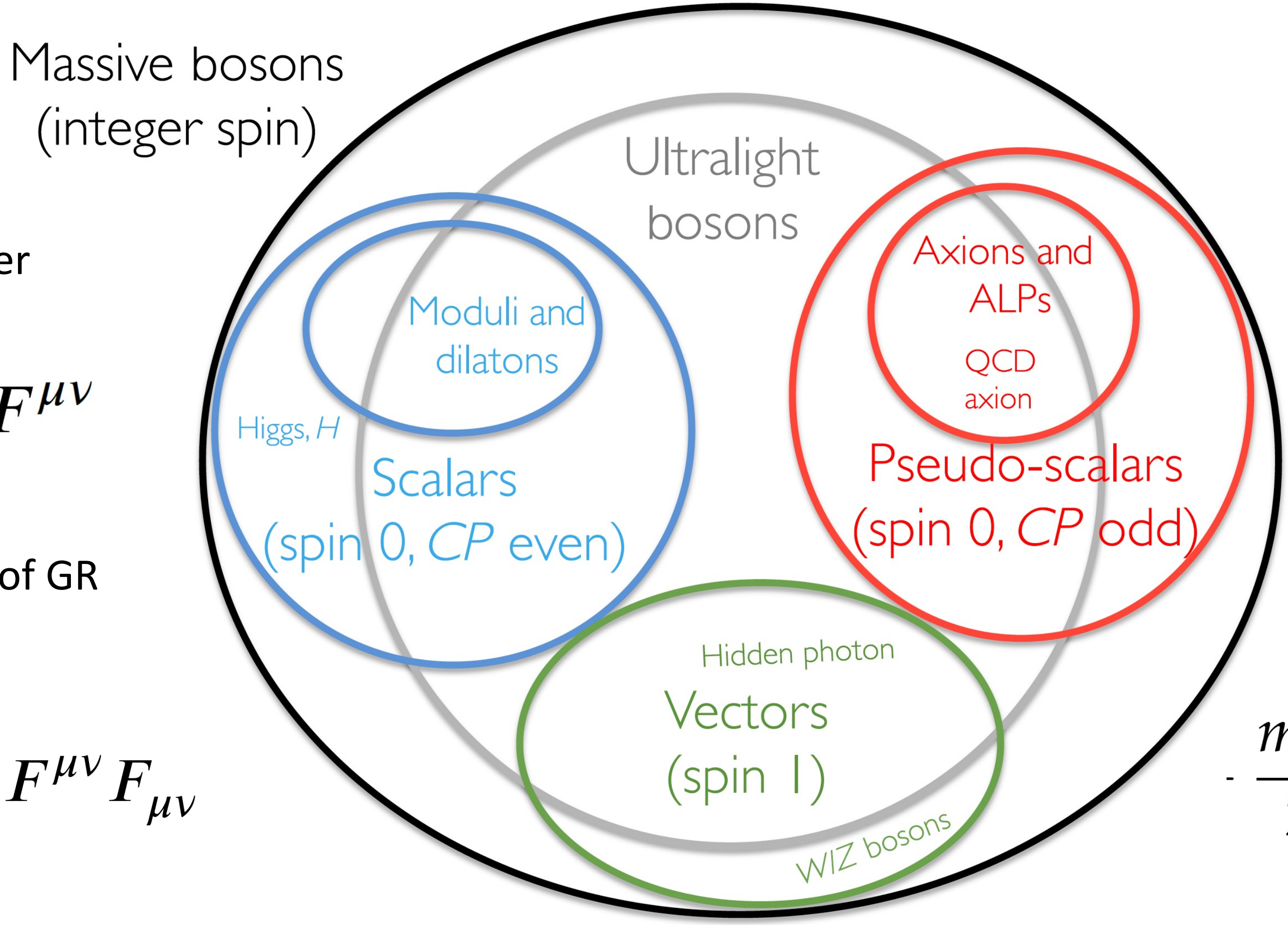
$$\frac{1}{4} g^{0}_{a\gamma\gamma} a \tilde{F}^{\mu\nu} F_{\mu\nu}$$

Scalar Dark Matter
Moduli, dilatons

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

Scalar extensions of GR
Chameleons

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



Vector Dark Matter
Dark Photons

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

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

Interaction with e.m. field

"Wavy" Light Dark Matter

Pseudoscalar Dark Matter
Axions, ALPS, Majoron

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

Scalar Dark Matter
Moduli, dilatons

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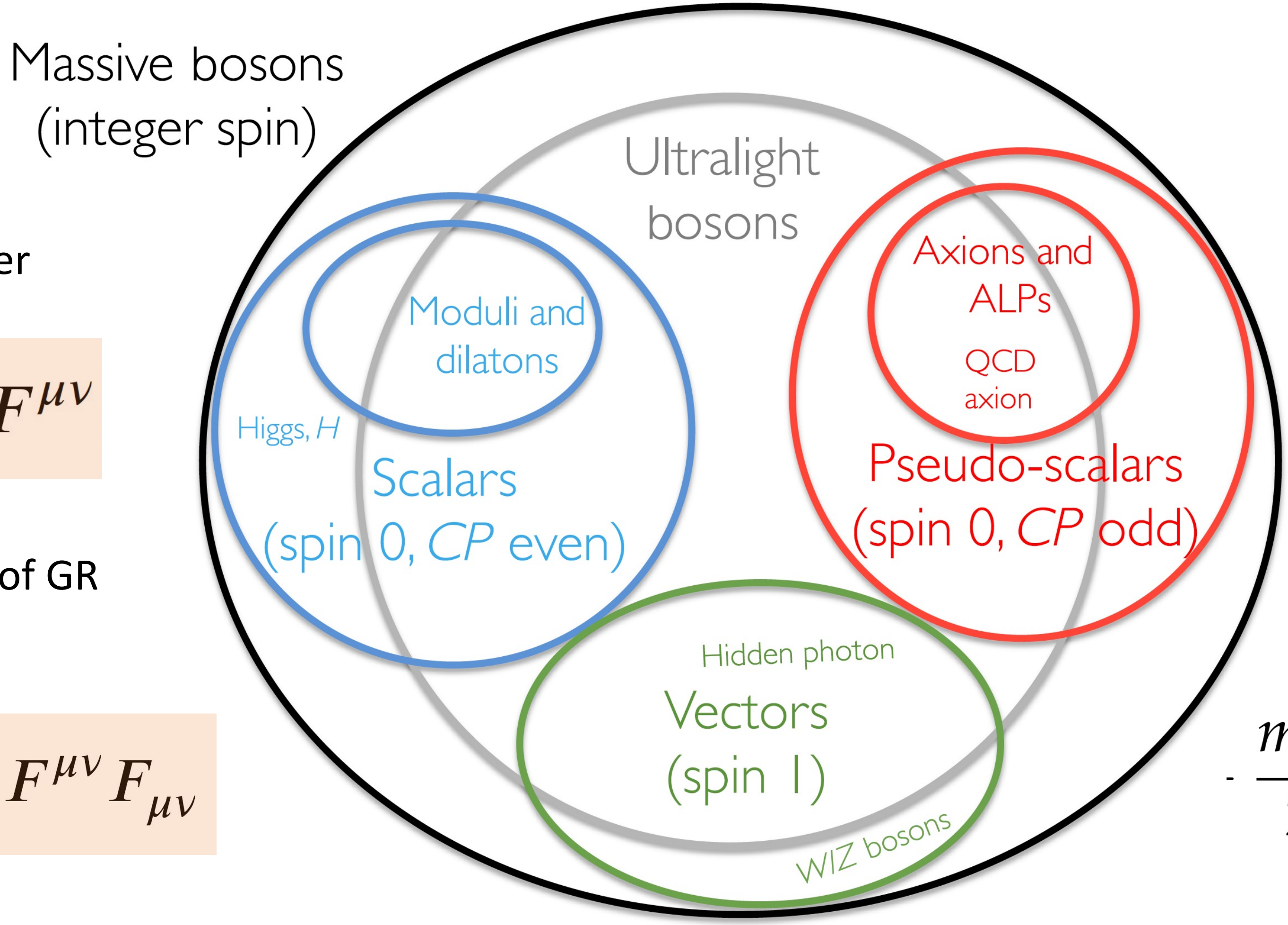


Vector Dark Matter
Dark Photons

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

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

"Wavy" Light Dark Matter Detector

Pseudoscalar Dark Matter

Axions, ALPS, Majoron

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

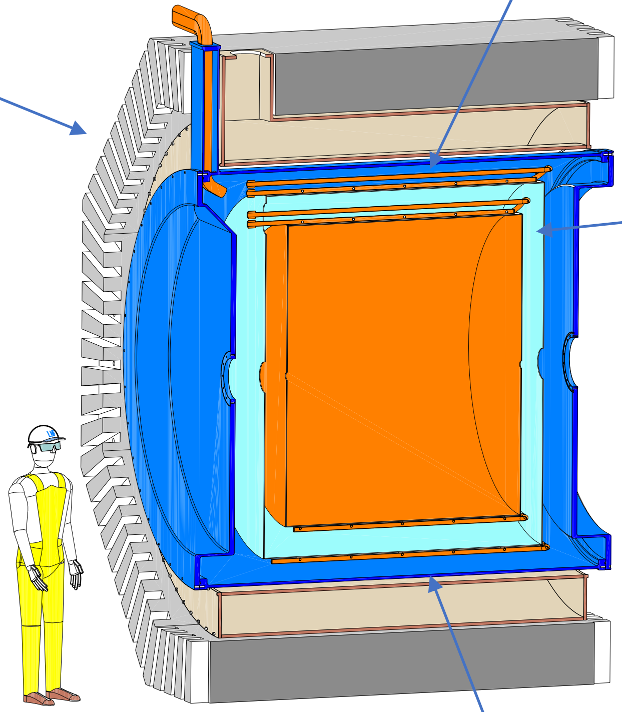
B-field provides high density of e.m. energy

Interaction rate proportional to **volume**

High Q factory quality provides signal amplification

Cavity **diameter** determines wave frequency/particle mass

Low T for low noise



Scalar Dark Matter

Moduli, dilatons

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

Scalar extensions of GR

Chameleons

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

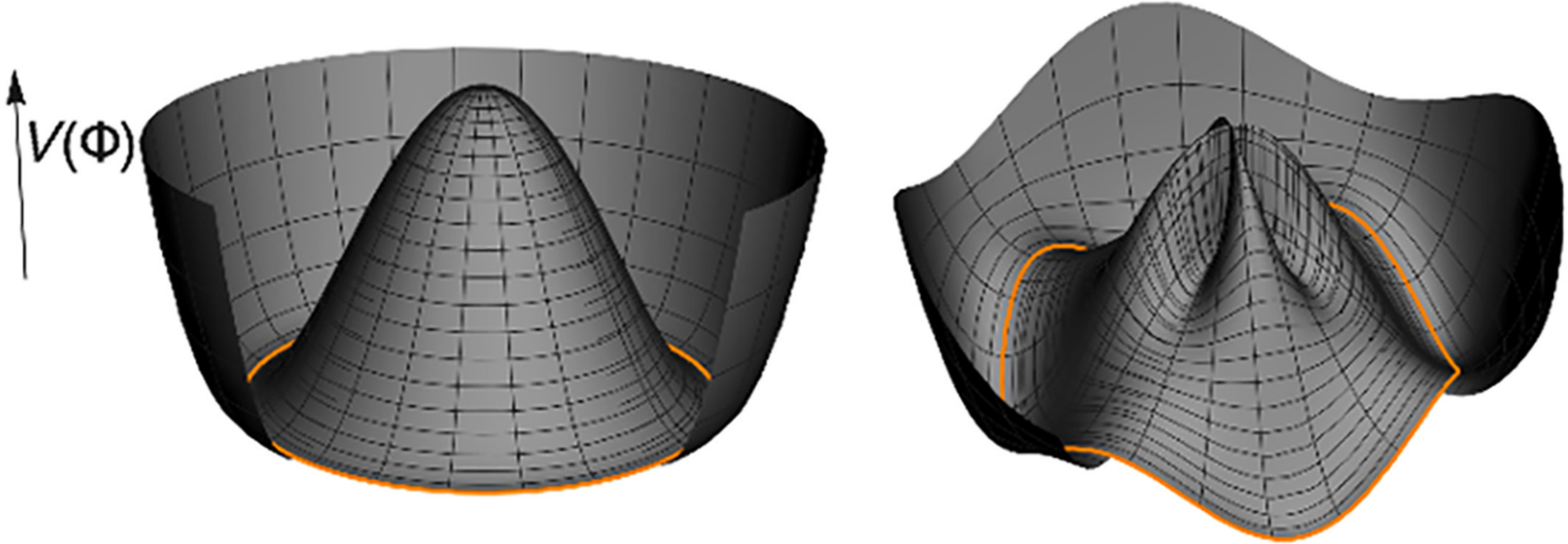
Vector Dark Matter

Dark Photons

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

Processes: $\gamma \to X \to \gamma$ oscillations $\gamma^{*} X \to \gamma$ conversion $X \to \gamma$ oscillations

Axions

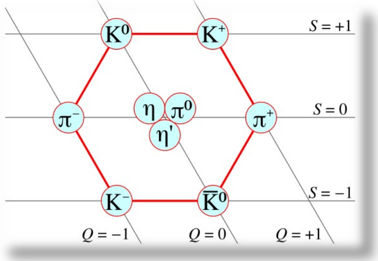


Axions

U(1)$_A$ problem

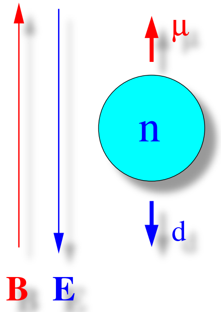
$$M_{\eta'} = 958\ \text{MeV} \gg M_\eta$$

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

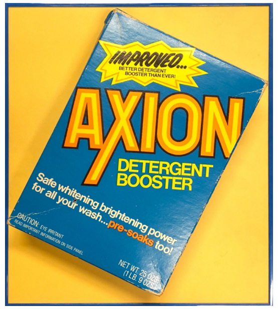
$$d_n < 2.9 \times 10^{-26} e\ \text{cm}$$

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

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).

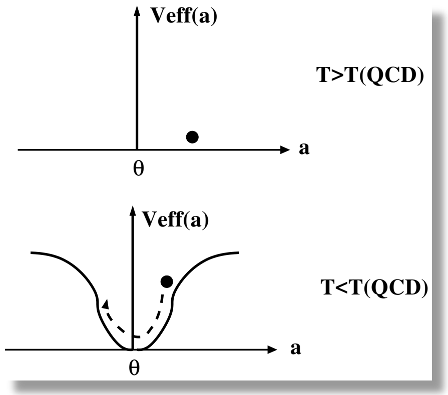
Axions

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



Axion Dark Matter

Misalignment mechanism



Mass

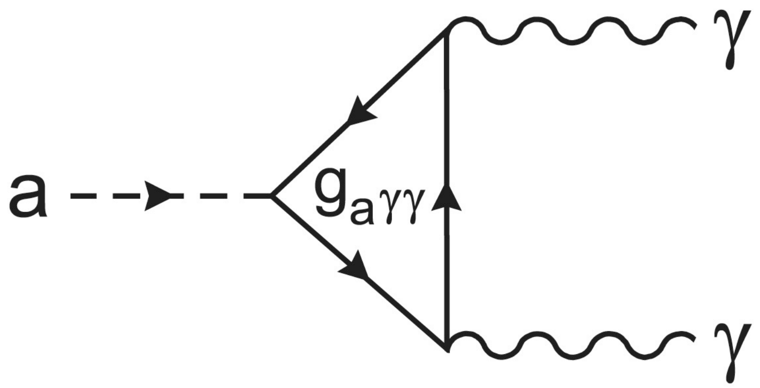
$$m_a = 5.70(7)\left(\frac{10^{12}GeV}{f_a}\right)\mu eV \simeq \frac{m_\pi f_\pi}{f_a}$$

Present limit:

$$f_a > 10^9 GeV$$

Coupling

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



Lifetime

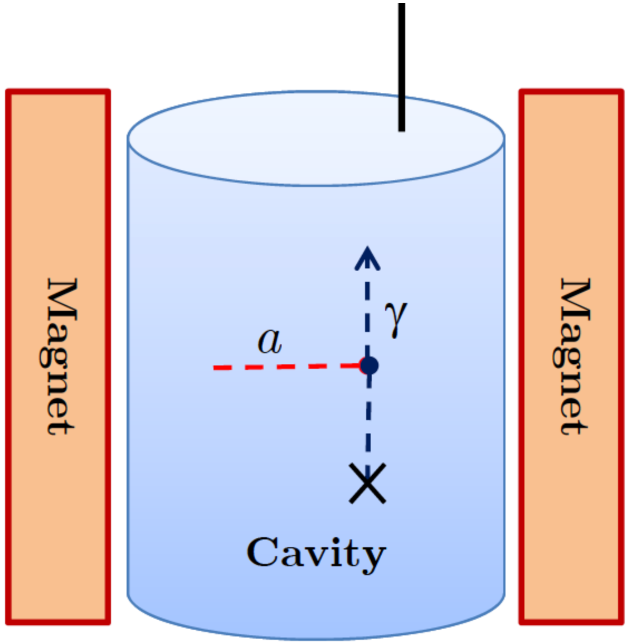
$$\Gamma_{a\rightarrow\gamma\gamma} = \frac{g_{a\gamma\gamma}^2 m_a^3}{64\pi} = 1.1\times 10^{-24}s^{-1}\left(\frac{m_a}{eV}\right)^5$$

Sikivie's Haloscope

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

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

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



β antenna coupling to cavity

V cavity volume

C_{mnl} mode dependent factor about 0.6 for TM010

Q_L cavity "loaded" quality factor

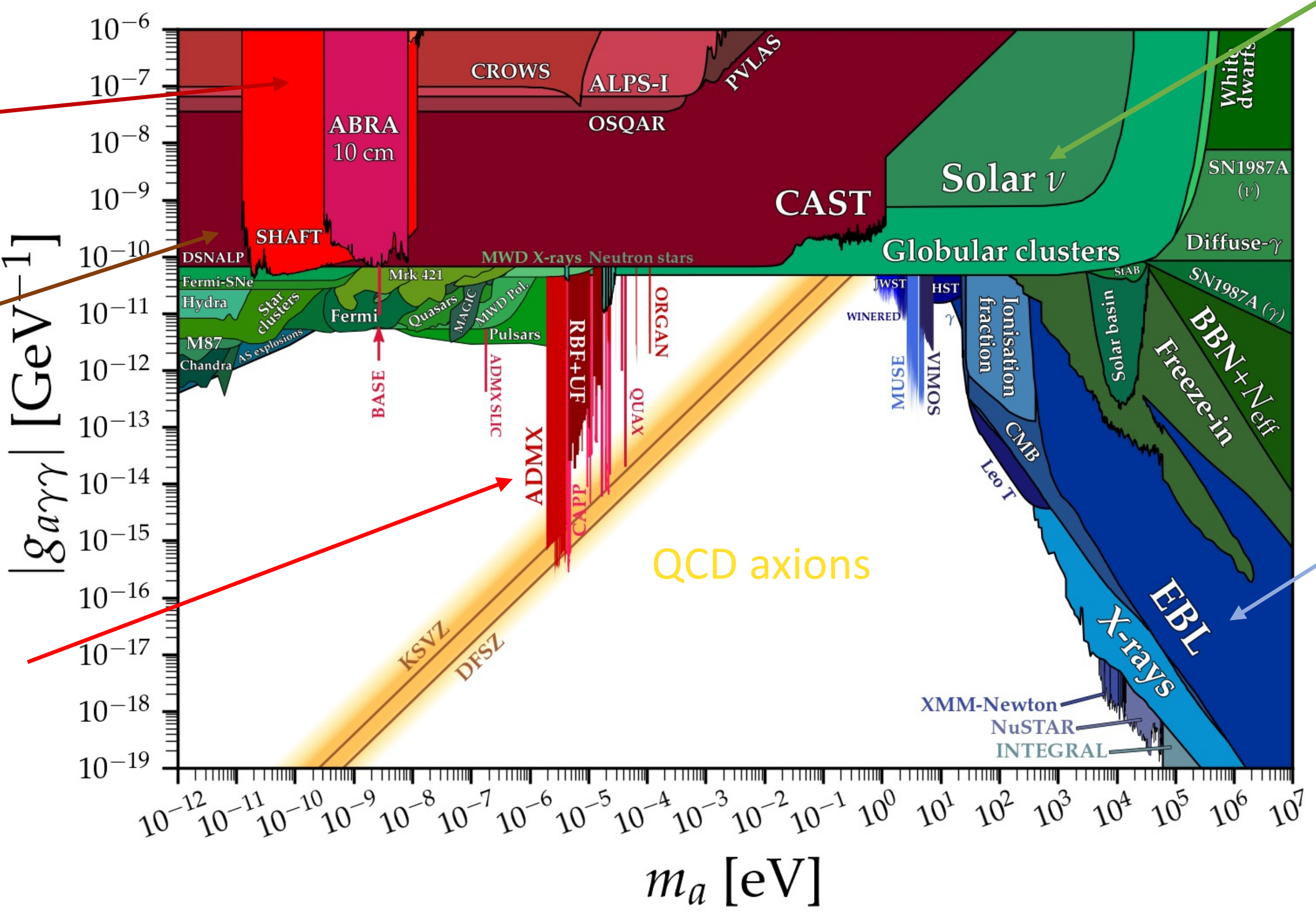
Sikivie Phys. Rev. D 32,11 (1985)

Axion Limits

Laboratory experiments

Detection of axions from the Sun (Helioscopes)

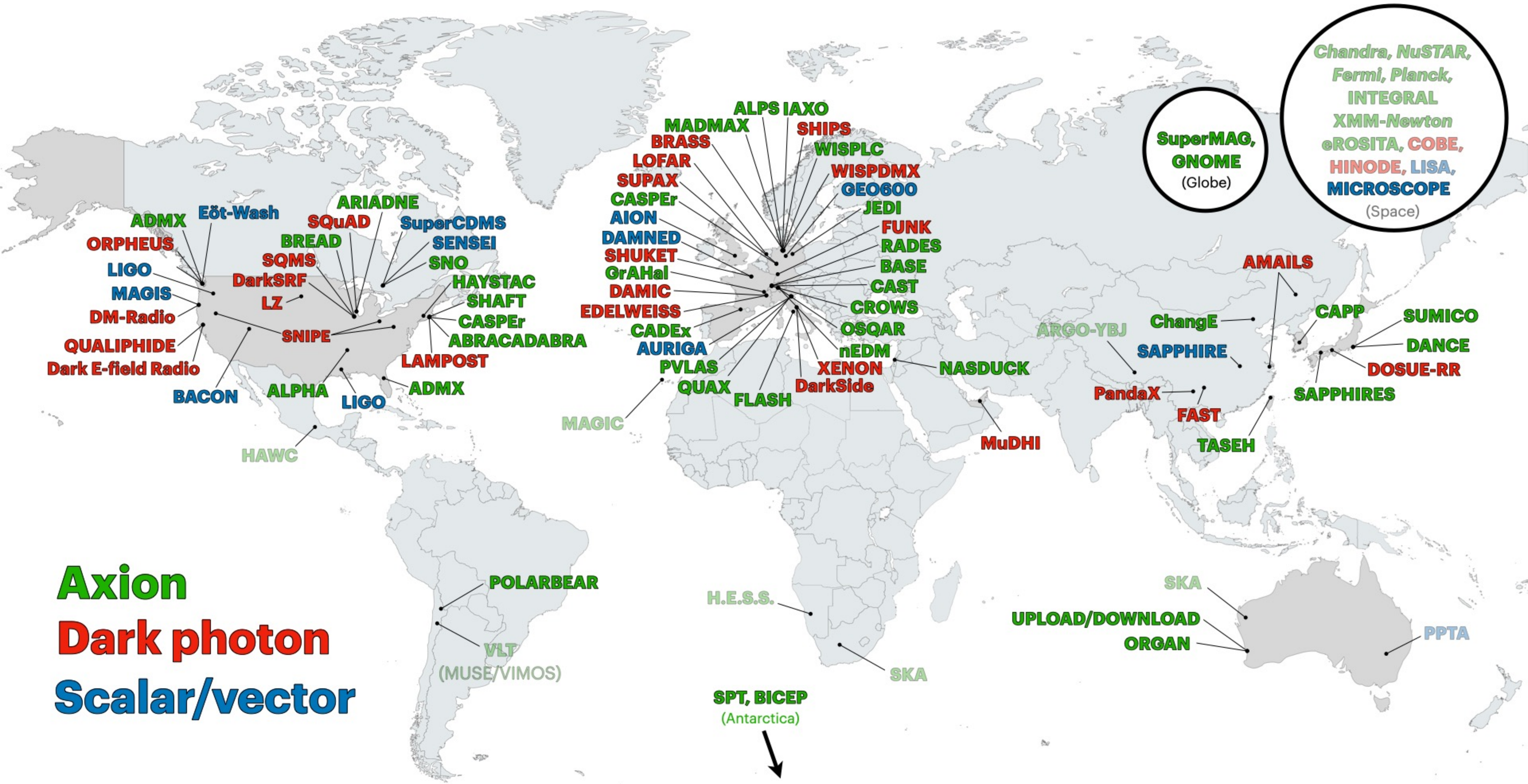
DM axion detection (Haloscopes)



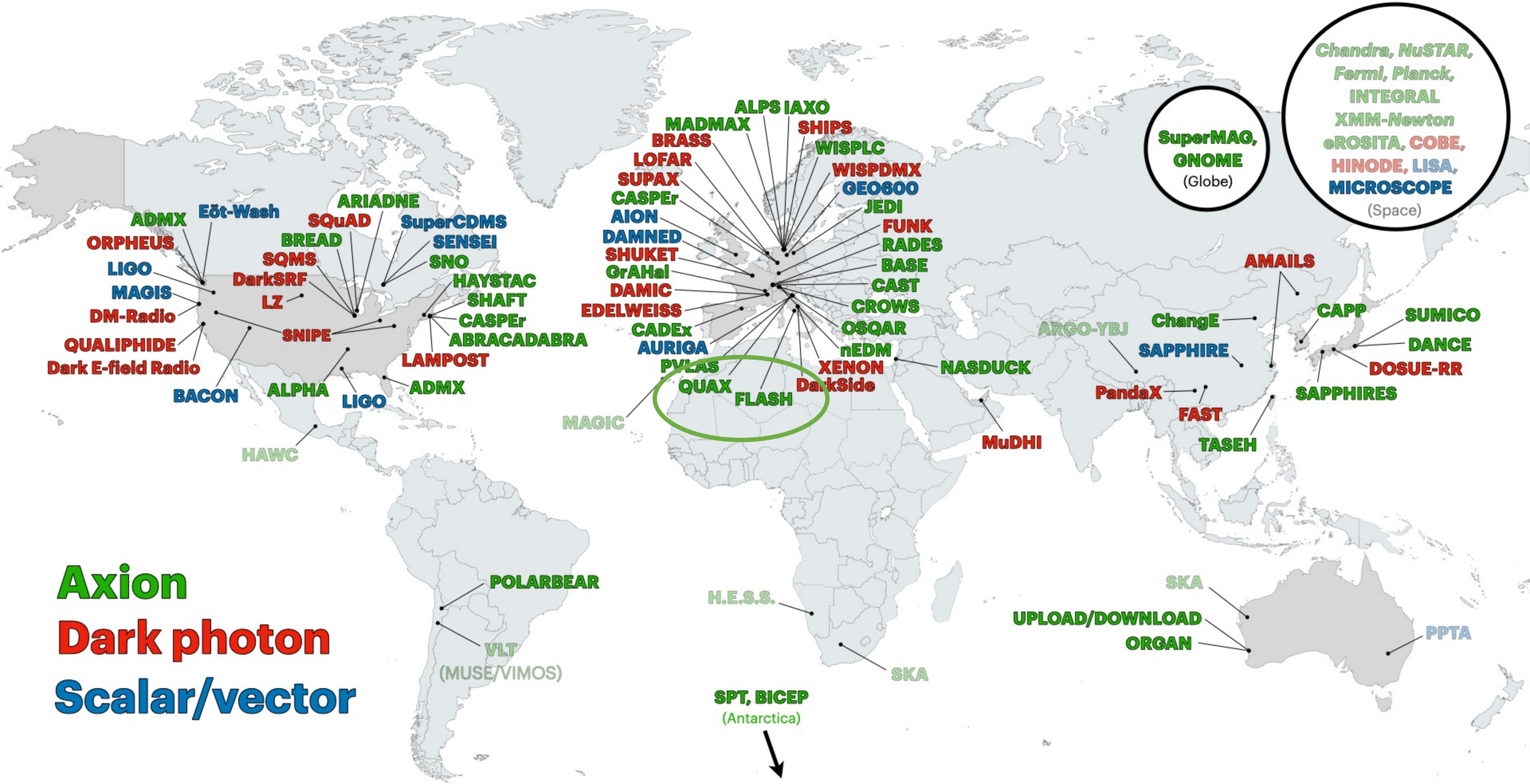
Stellar physics:
Constraints on stellar lifetime or energy-loss rates.

Astronomy:
No DM $a \rightarrow \gamma\gamma$ decays seen in the visible region from galaxies with telecopes.
Similar searches with X-rays and extragalactic background light (EBL) or H ionization.

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



Chandra, NuSTAR,
Fermi, Planck,
INTEGRAL
XMM-Newton
eROSITA, COBE,
HINODE, LISA,
MICROSCOPE
(Space)
SuperMAG,
GNOME
(Globe)
ALPS
IAXO
MADMAX
SHIPS
BRASS
WISPLC
LOFAR
WISPDMX
SUPAX
GEO600
CASPEr
JEDI
AION
FUNK
DAMNED
RADES
SHUKET
BASE
GrAHal
CAST
DAMIC
CROWS
EDELWEISS
OSQAR
CADEx
nEDM
AURIGA
XENON
PVLAS
DarkSide
QUAX
FLASH
NASDUCK
MAGIC
MuDHI
ADMX
Eöt-Wash
ARIADNE
SQuAD
SuperCDMS
ORPHEUS
BREAD
SENSEI
SQMS
SNO
LIGO
DarkSRF
HAYSTAC
MAGIS
LZ
SHAFT
DM-Radio
CASPEr
SNIPE
ABRACADABRA
QUALIPHIDE
LAMPOST
Dark E-field Radio
ALPHA
ADMX
BACON
LIGO
HAWC
AMAILS
CAPP
SUMICO
ChangE
ARGO-YBJ
DANCE
SAPPHIRE
DOSUE-RR
PandaX
SAPPHIRES
FAST
TASEH
POLARBEAR
H.E.S.S.
SKA
UPLOAD/DOWNLOAD
ORGAN
PPTA
VLT
(MUSE/VIMOS)
SKA
SPT, BICEP
(Antarctica)
Axion
Dark photon
Scalar/vector



Chandra, NuSTAR, Fermi, Planck, INTEGRAL XMM-Newton eROSITA, COBE, HINODE, LISA, MICROSCOPE
(Space)
SuperMAG, GNOME
(Globe)
ALPS
IAXO
MADMAX
SHIPS
BRASS
WISPLC
LOFAR
WISPDMX
SUPAX
GEO600
CASPEr
JEDI
AION
FUNK
DAMNED
RADES
SHUKET
BASE
GrAHal
CAST
DAMIC
CROWS
EDELWEISS
OSQAR
CADEx
nEDM
AURIGA
XENON
PVLAS
DarkSide
QUAX
FLASH
NASDUCK
MAGIC
MuDHI
ADMX
Eöt-Wash
ARIADNE
SQuAD
SuperCDMS
ORPHEUS
BREAD
SENSEI
LIGO
SQMS
SNO
MAGIS
DarkSRF
HAYSTAC
LZ
SHAFT
DM-Radio
CASPEr
SNIPE
ABRACADABRA
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QUAX

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Sezione di Padova

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INFN Gruppo Collegato di Salerno
Sezione di Napoli
Istituto Nazionale di Fisica Nucleare

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NÉEL institut

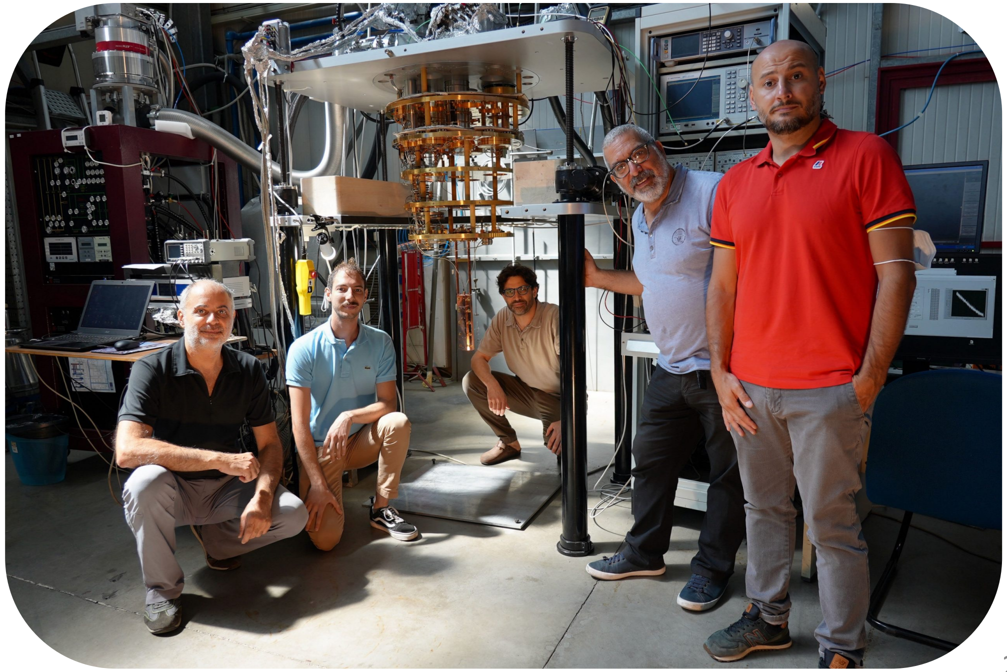
SQMS

SUPERGALAX

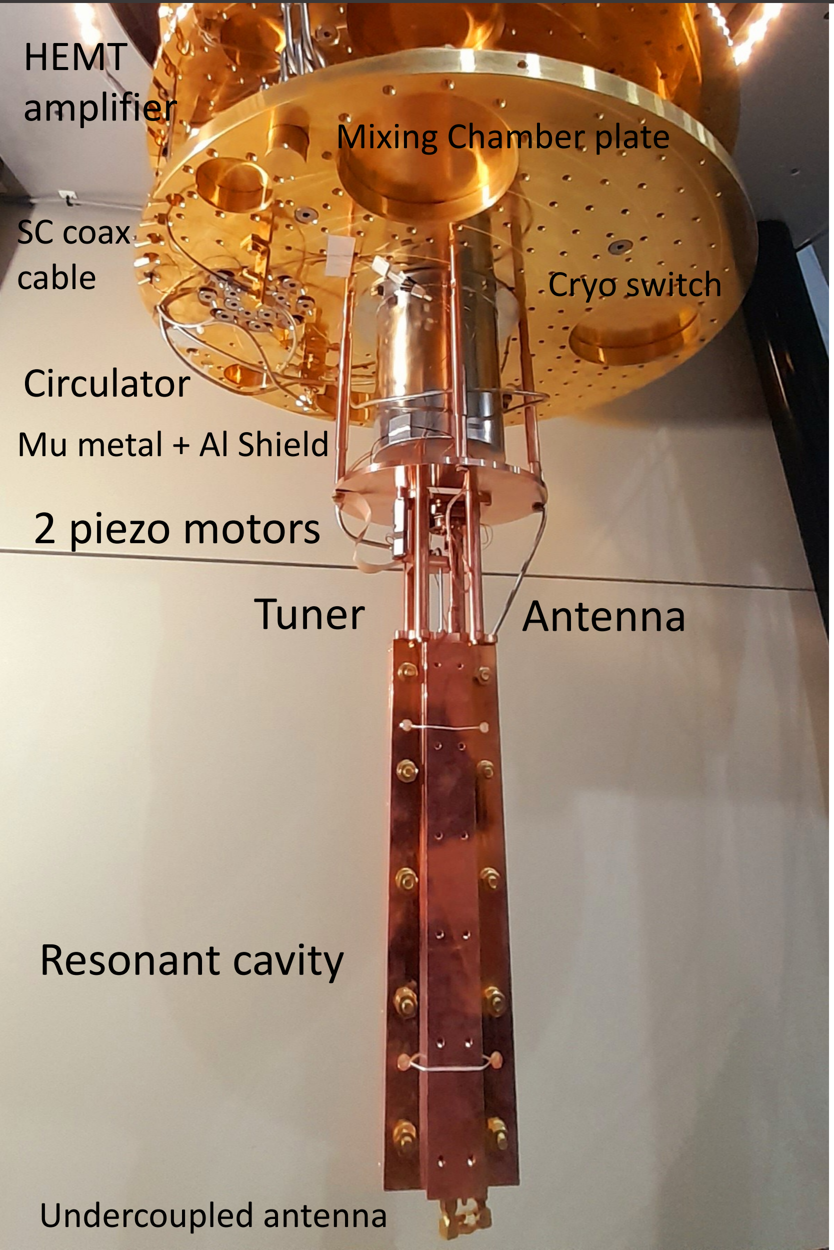
Laboratori Nazionali di Legnaro (LNL)

Laboratori Nazionali di Frascati (LNF)

INFN
Istituto Nazionale di Fisica Nucleare

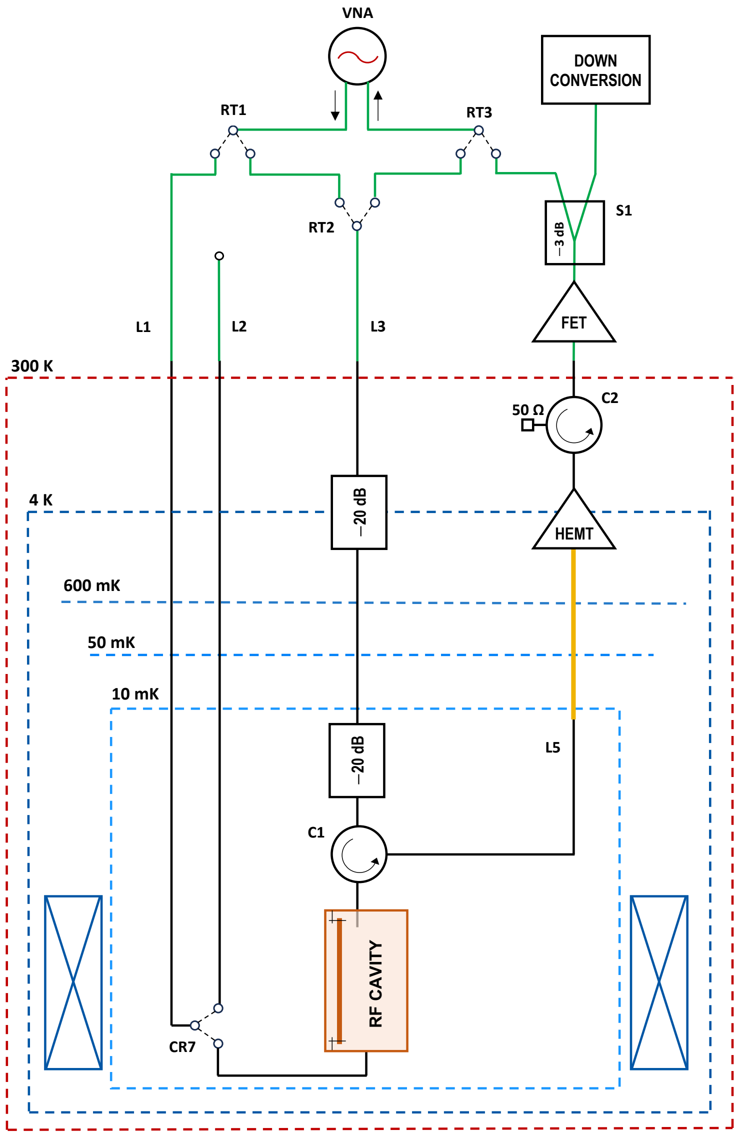


QUAX@LNF: The LNF Axion Haloscope

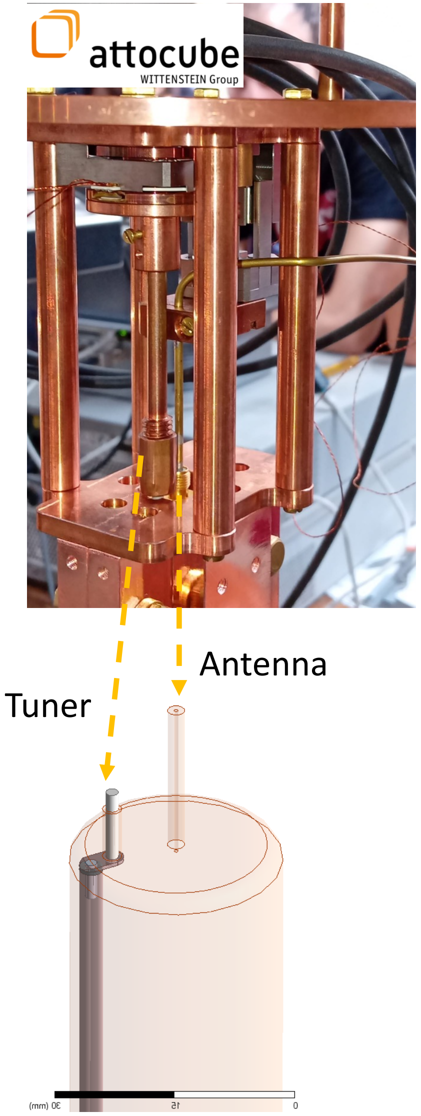


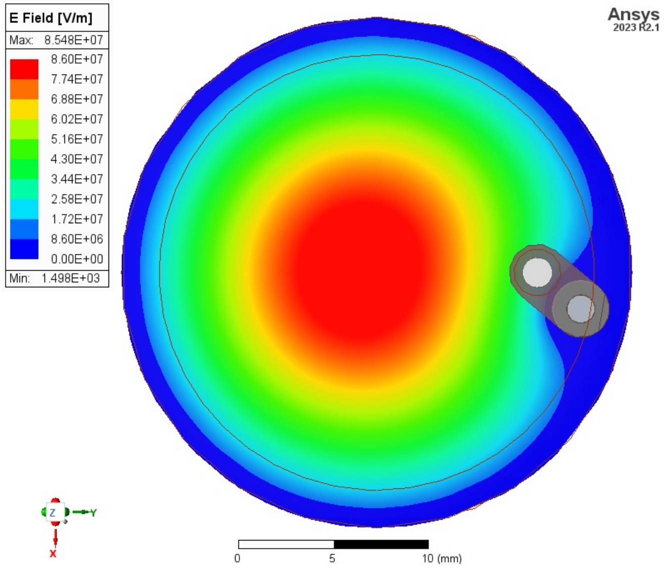
December 2023 Run

- Cavity temperature 30 mK
- Magnetic Field B=8 T
- Frequency 8.8 GHz
- Copper cavity Q_0=50,000 with tuner
- HEMT amplifier
- Tnoise 4K
- 2 weeks data taking
- 6 MHz scan

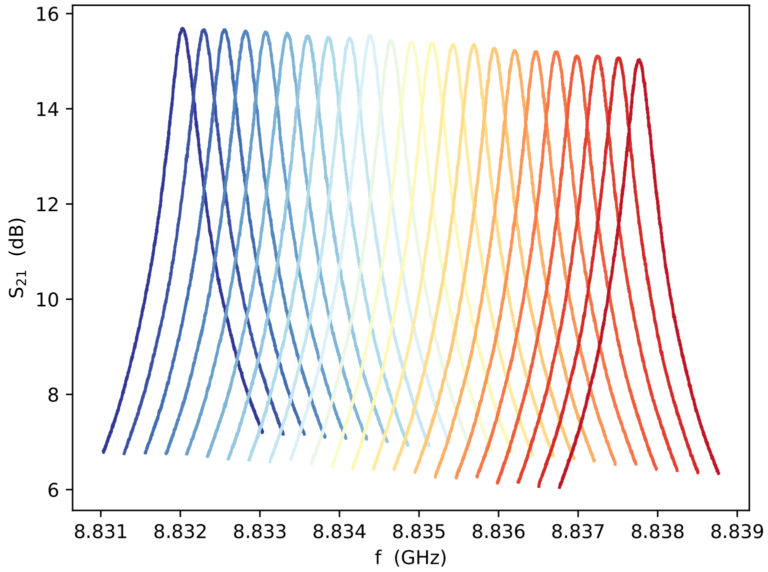


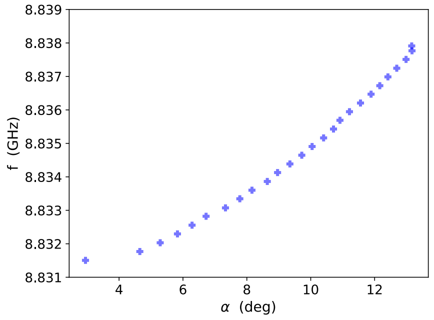
Cavity Tuning

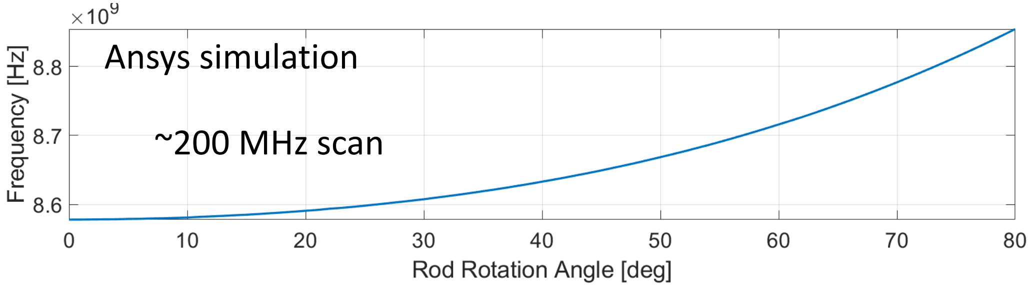




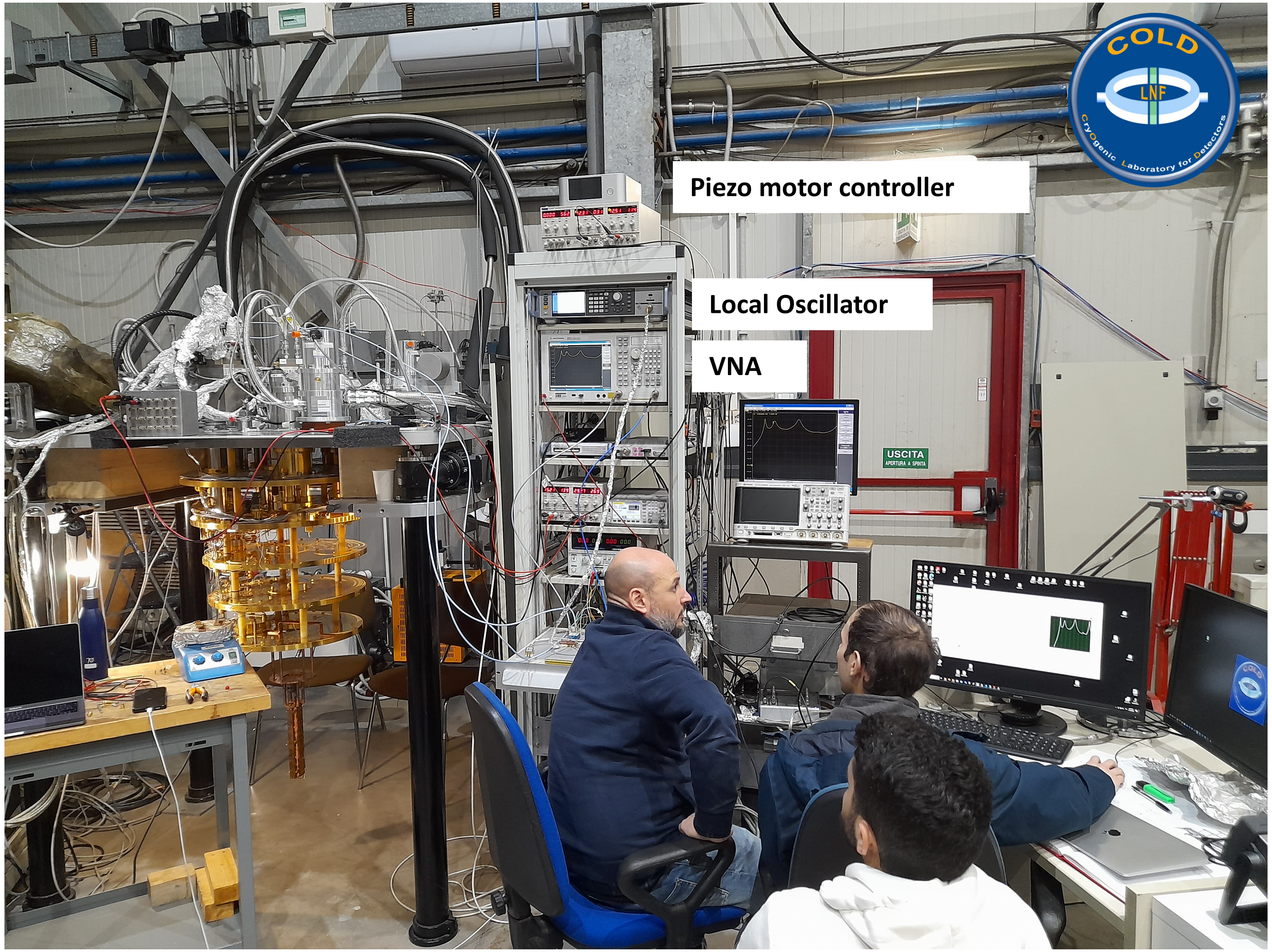
6 MHz of frequency scan

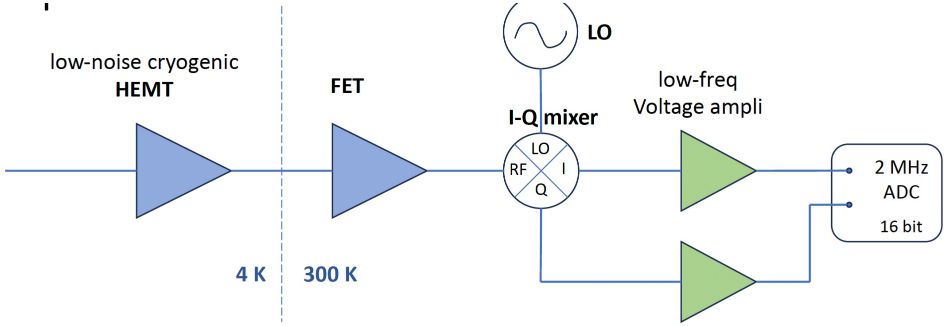






Acquisition Chain





$G^{HEMT} \simeq 37\ dB$

$T_n^{HEMT} \simeq 3\ K$

$G^{FET} \simeq 36\ dB$

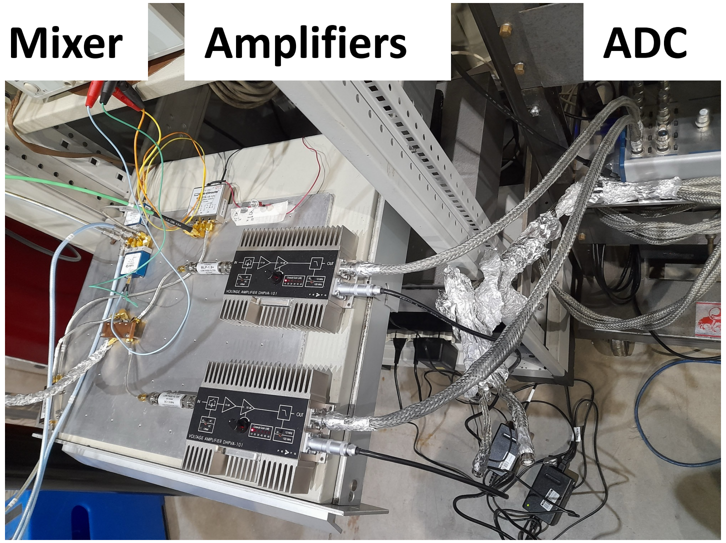
$T_n^{FET} \simeq 80\ K$

$G^{V} \simeq \times 1000$

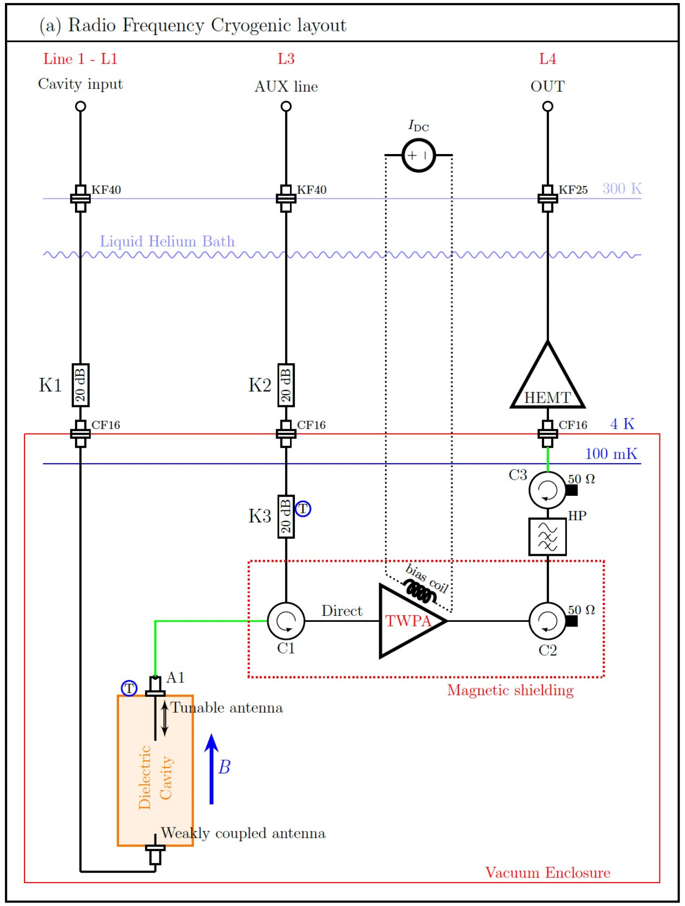
$V_n = 2.3\ nV/\sqrt{Hz}$

Tot eff. Gain = 116 dB

Noise Temp = 4.5 K



The QUAX@LNL Haloscope



- B=8 T
- Dilution Refrigerator
- Tcavity 110 mK
- TWPA
- T_{noise}=2 K
- Dielectric Cavity
- Sapphire tuner
- Q=2.5×10^5
- VC_{030}=0.034 L

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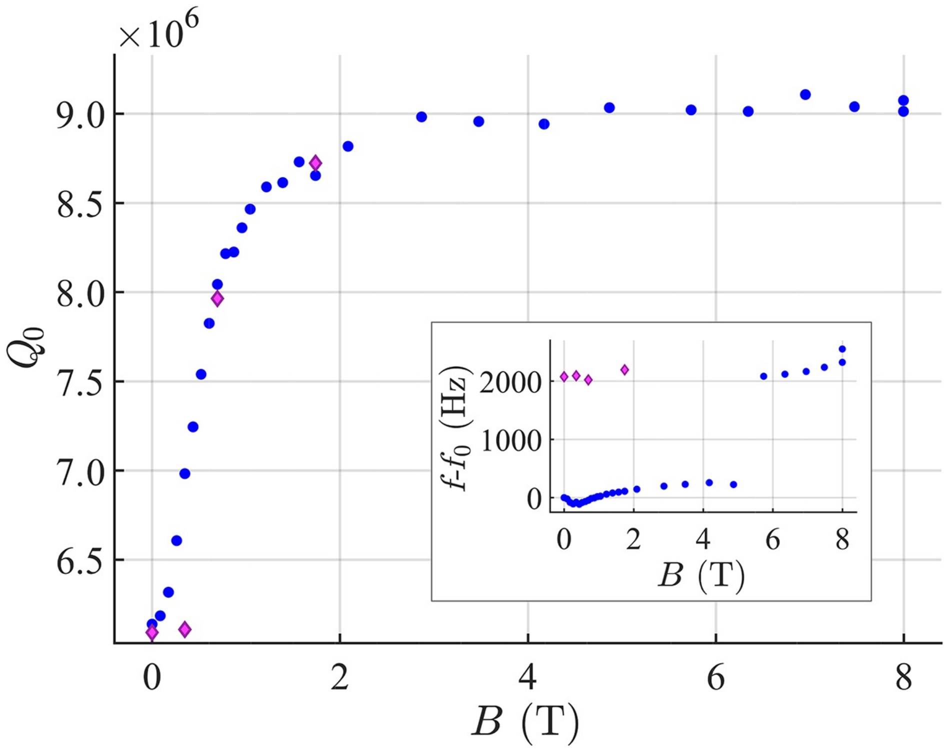
Laboratori Nazionali di Legnaro



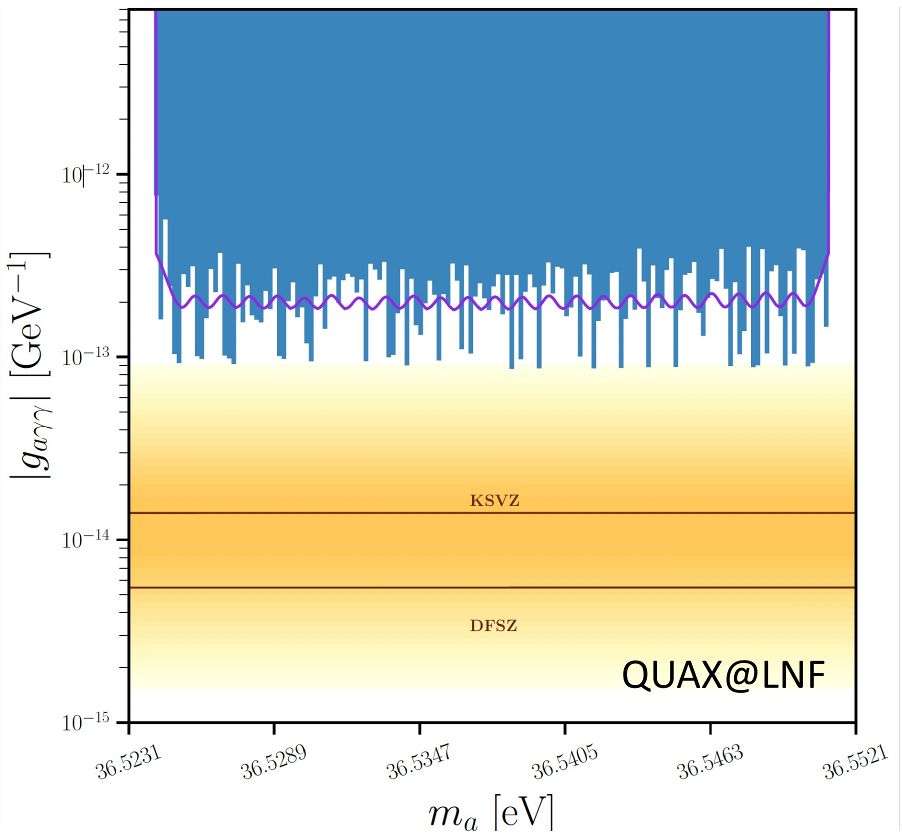
PHYSICAL REVIEW APPLIED 17, 054013 (2022)

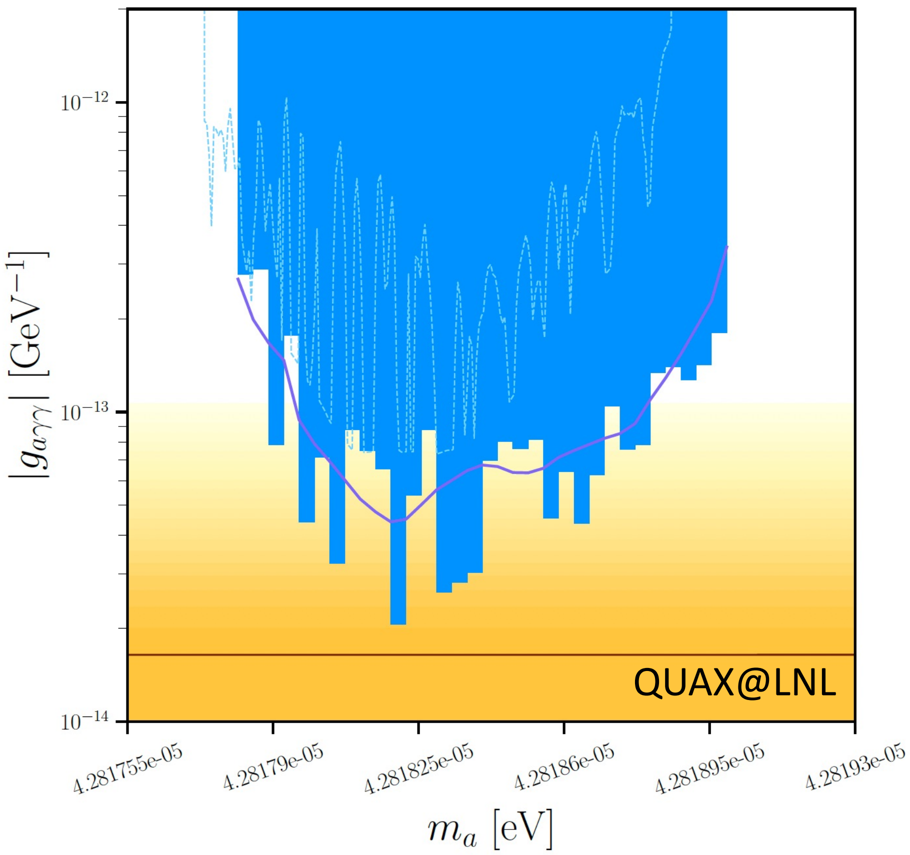
Search for galactic axions with a traveling wave parametric amplifier
PHYSICAL REVIEW D 108, 062005, arXiv:2304.7505 (2023)

QUAX Results for 2022 and 2023 Runs

- 24 runs, 1 hour each, 250 kHz of frequency steps
- Average exclusion 90% c.l. $g_{a\gamma\gamma} = 2\times10^{-13}\ GeV^{-1}$
- Phys. Rev. D 110, 022008 (2024)

- 10 runs, 1 hour each, 30 kHz of frequency steps
- Average exclusion 90% c.l. $g_{a\gamma\gamma} = 4\times10^{-13}\ GeV^{-1}$
- Phys. Rev. D 108, 062005 (2023)

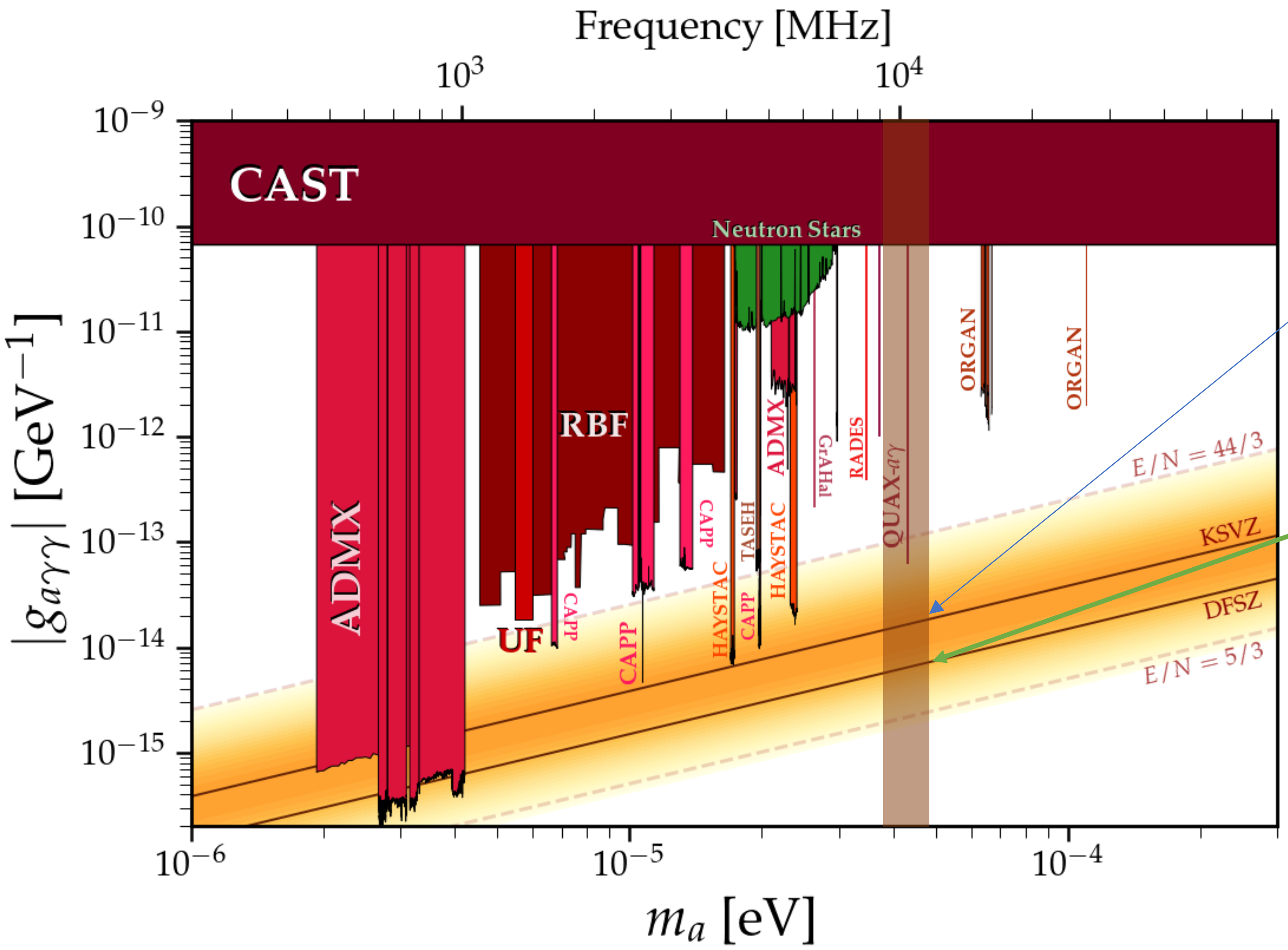




QUAX LNF&LNL 2023-2025

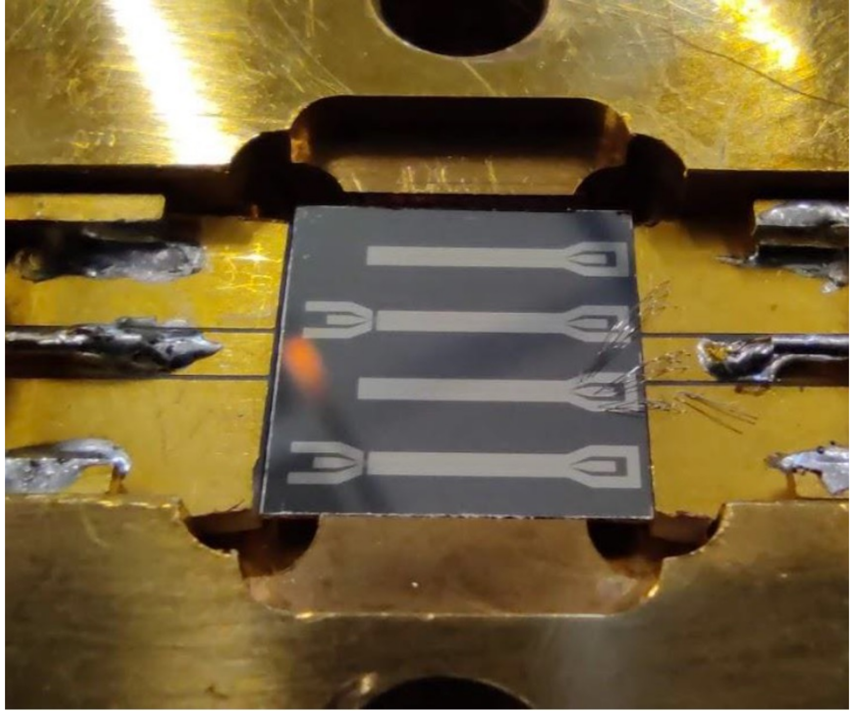
LNF:
- Superconducting cavity $Q_0 > 2\times10^5$
- B=9T
- Multicavity

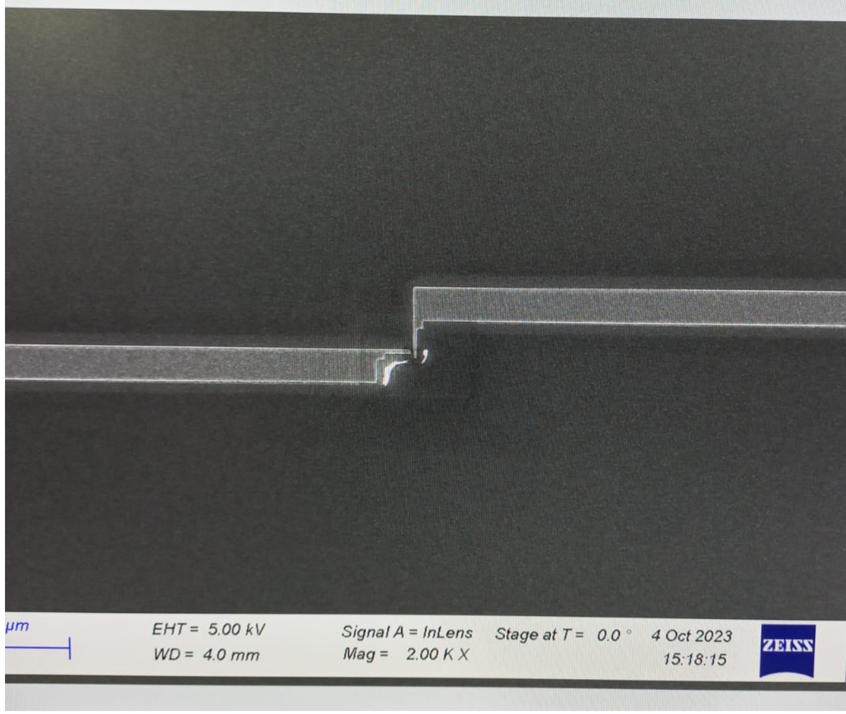
LNL:
- Dielectric cavity $Q_0 > 10^6$
- B=14 T
- Single cavity

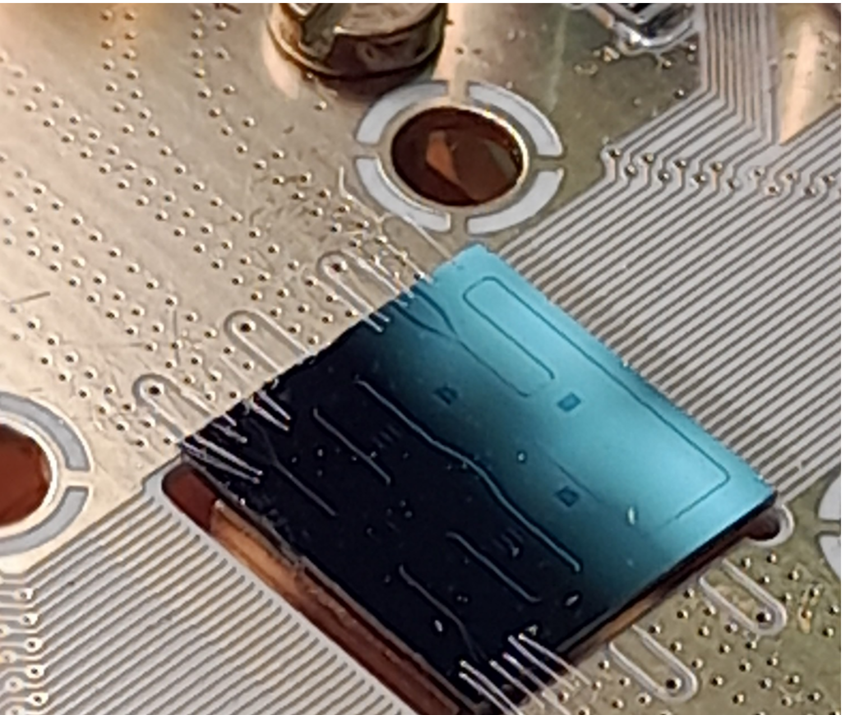


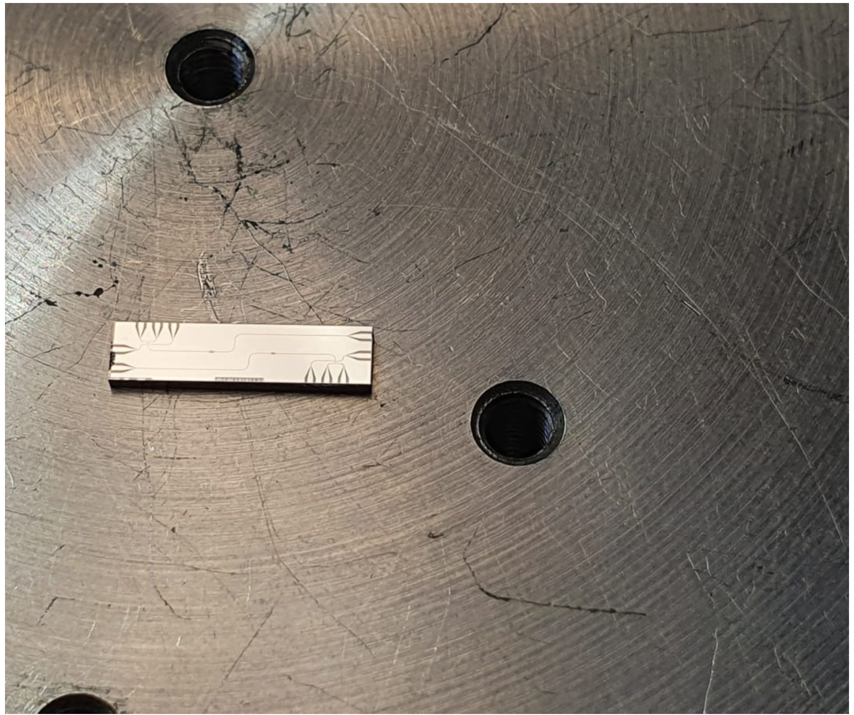
Next years with noise at Quantum Limit

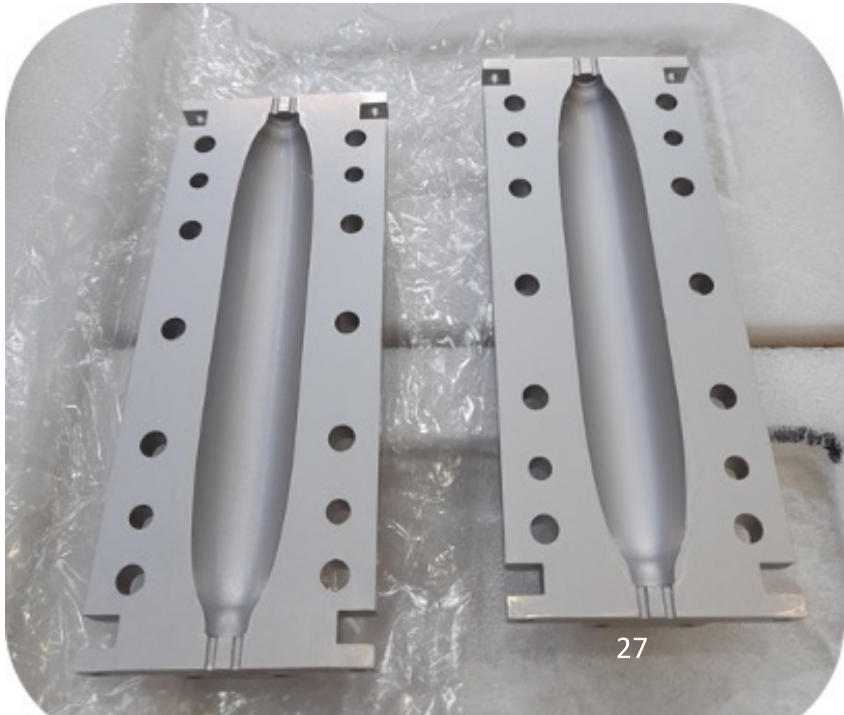
Beyond Quantum Limit with photon counter (ongoing R&D)




μm
EHT = 5.00 kV
WD = 4.0 mm
Signal A = InLens
Mag = 2.00 K X
Stage at T = 0.0 °
4 Oct 2023
15:18:15







COLD@LNF

CryOgenic Laboratory for Detectors:

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

COSMIC WISPERS CA 21106

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

DART WARS

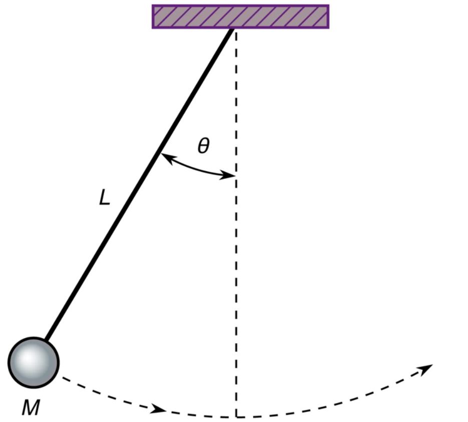
Qub-IT

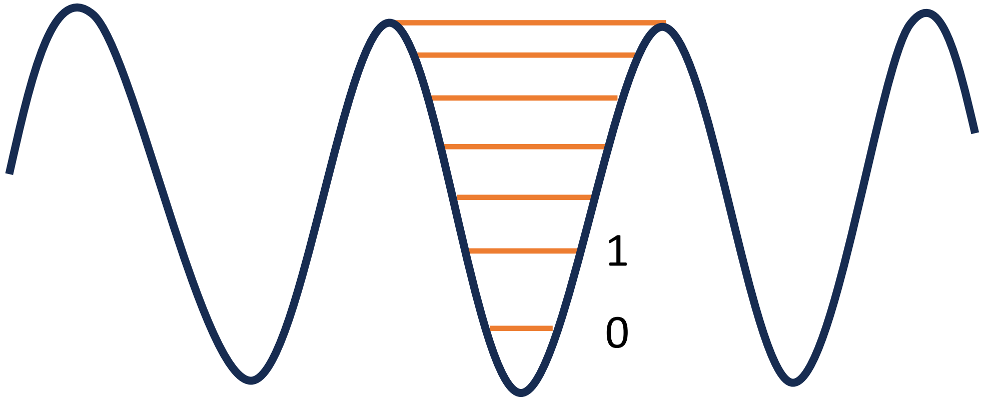
NQSTI National Quantum Science and Technology Institute

SUPERGALAX

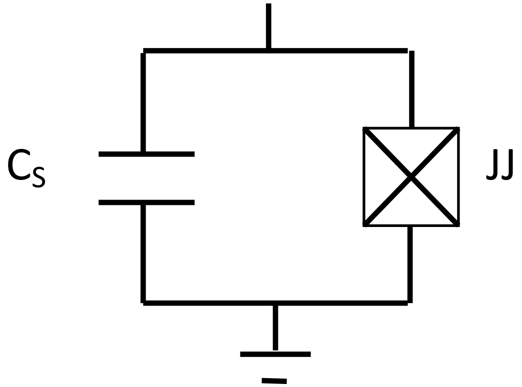
SQMS

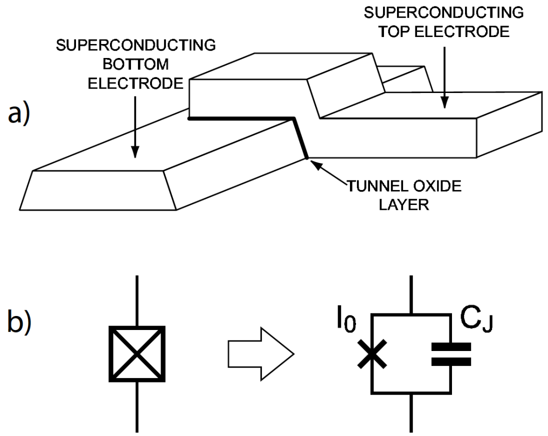
The Superconducting Qubit





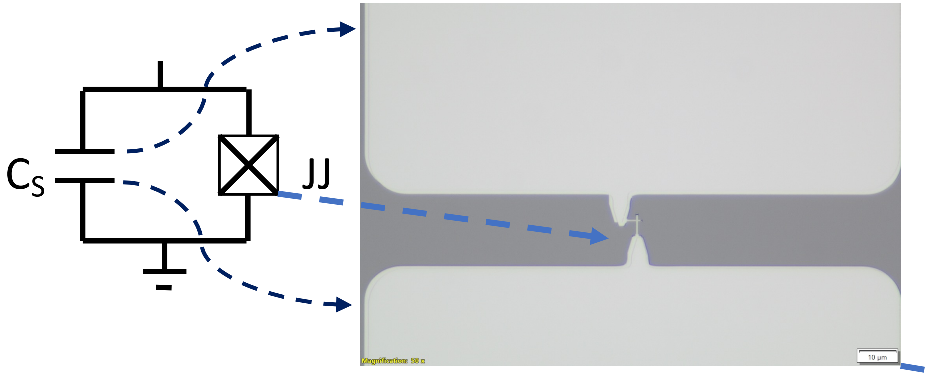
$$E = \frac{Q^2}{2C} - E_J cos 2\pi\phi/\phi_0$$

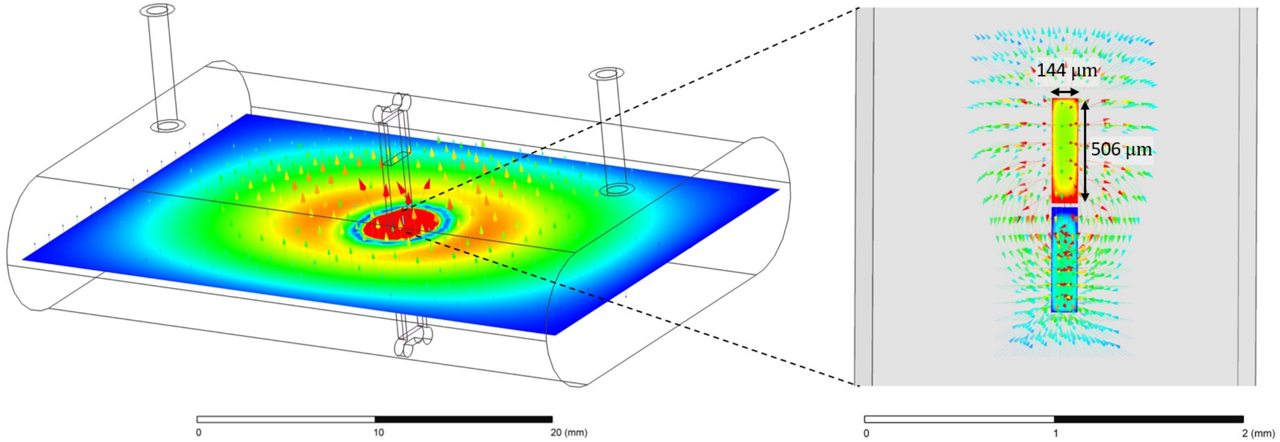


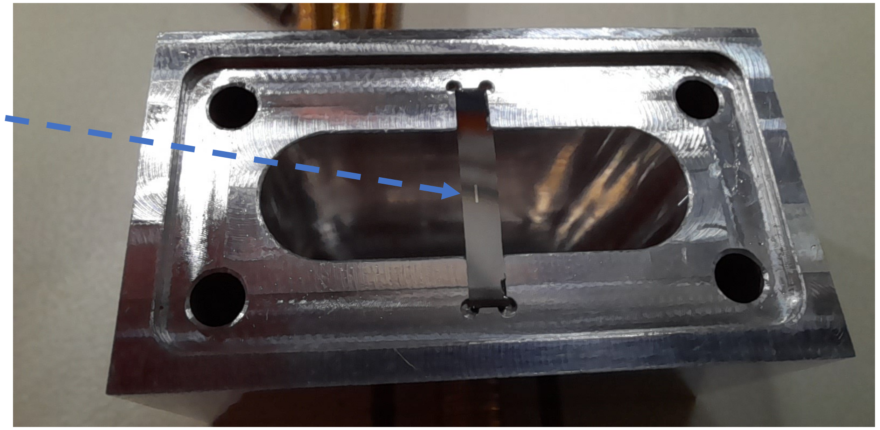


J Koch Phys. Rev. A 76 042319 (2007)

Qubit in a 3D Resonator

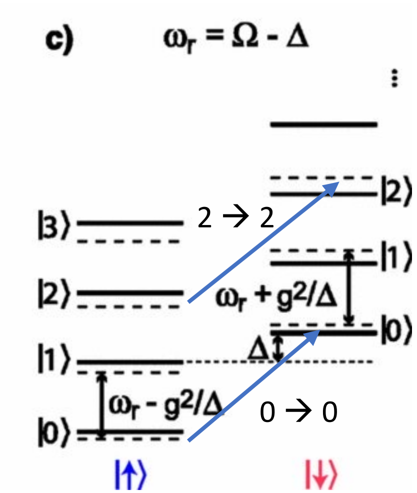






TII Technology Innovation Institute

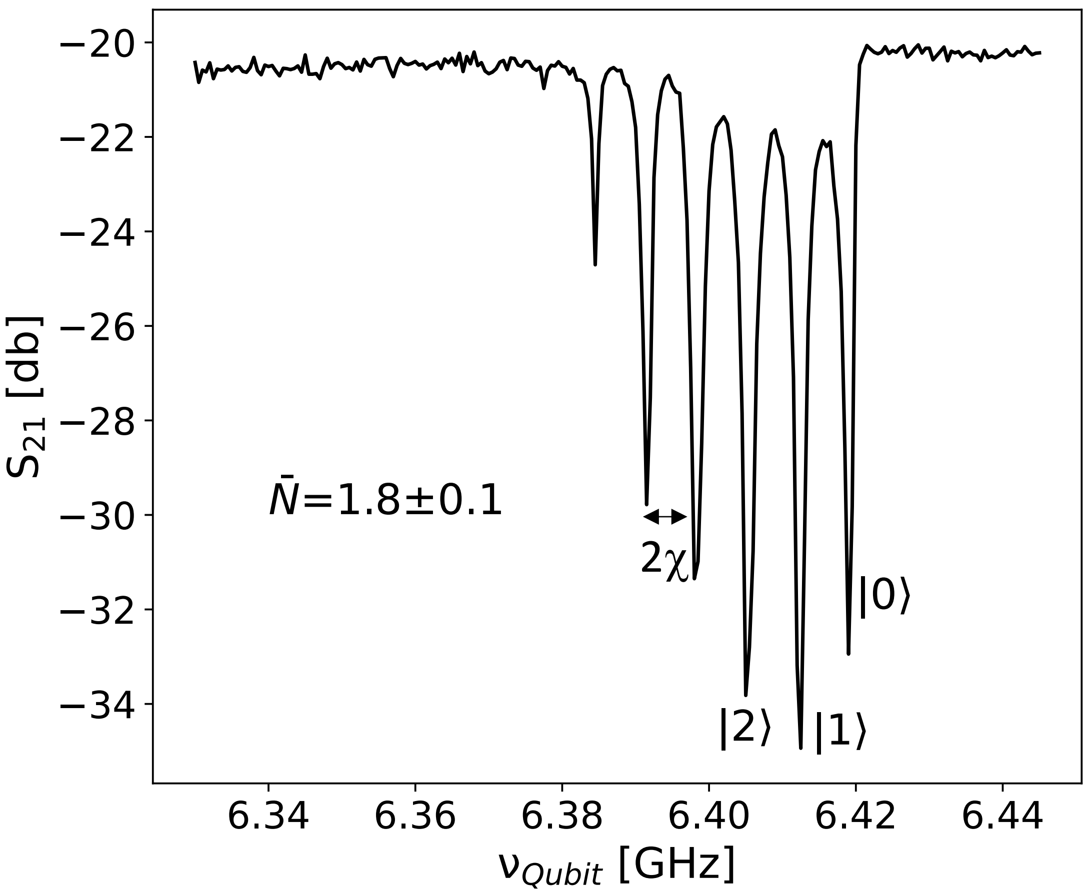
Quantum Sensing with SC Qubits



$$\omega'_q = \omega_q + 2n_\gamma\chi$$

Photon number in resonator

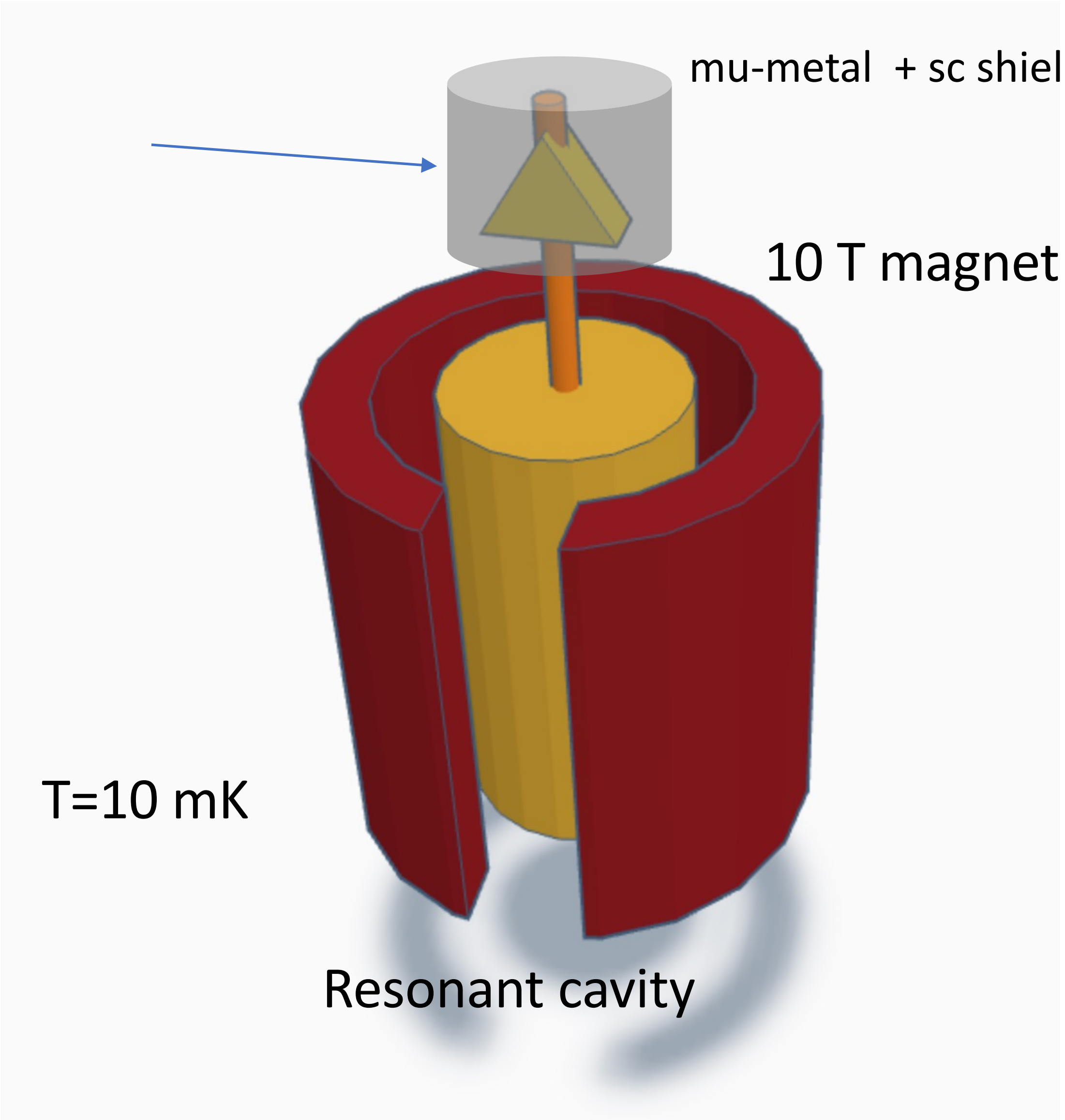
Two tones spectroscopy on 3D qubit



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

Itinerant Photon Detection

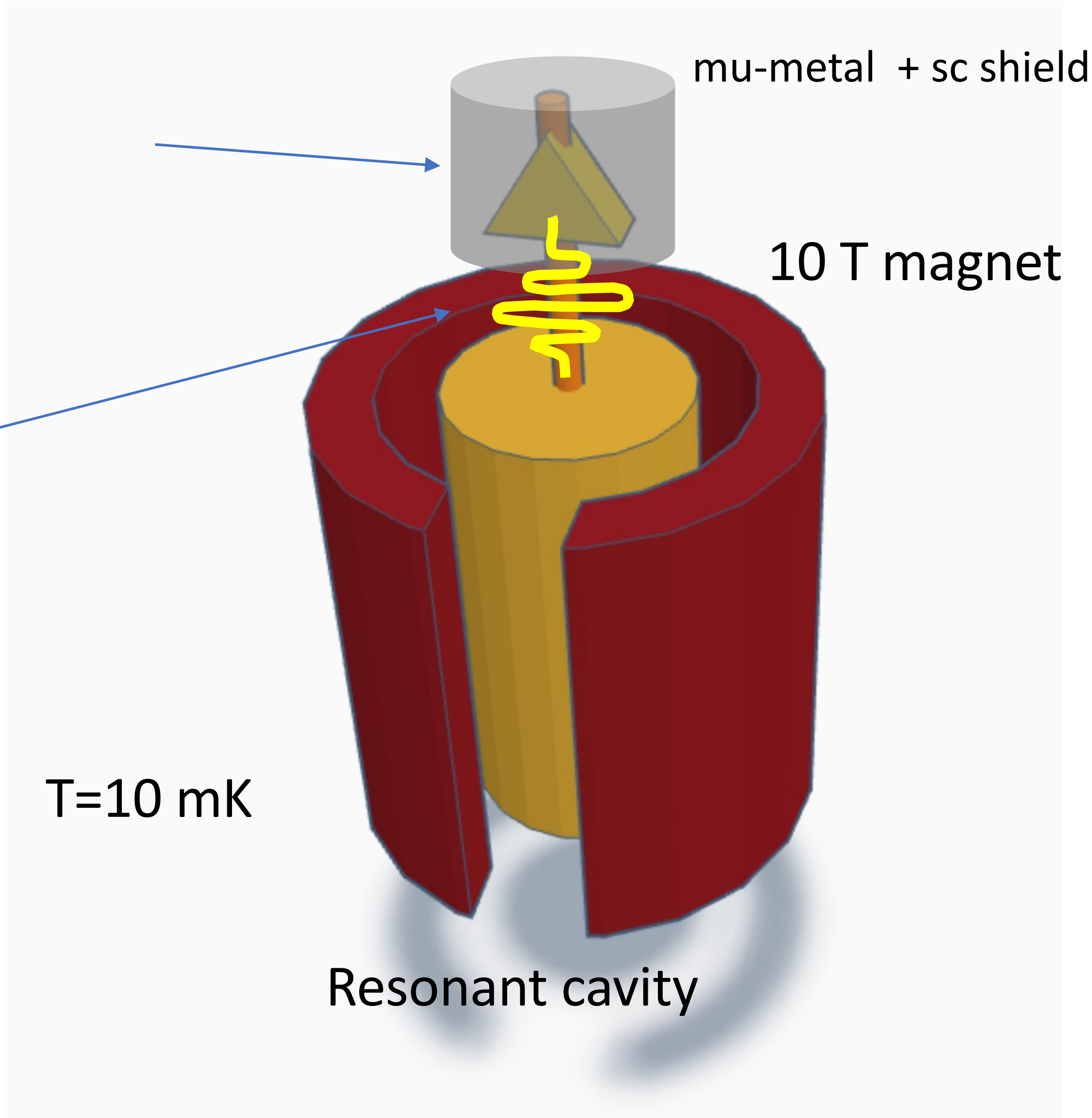
Superconducting devices must be placed in a B-field free region



Itinerant Photon Detection

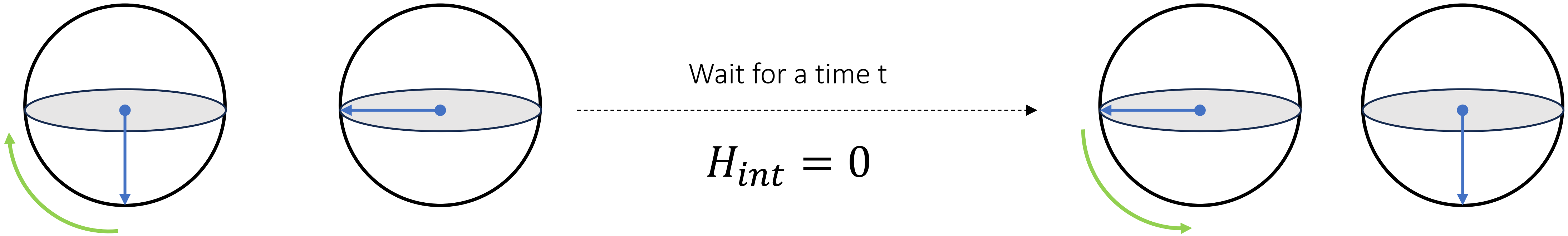
Superconducting devices must be placed in a B-field free region

We must detect the photon
Traveling in the coax cable!
→ *Itinerant photon detection*



Quantum Sensing with SC Qubits

$|\psi\rangle = |0\rangle$ $\quad$ $|\psi\rangle = |0\rangle + |1\rangle$ $\quad$ $|\psi\rangle = |0\rangle + |1\rangle$ $\quad$ $|\psi\rangle = |0\rangle$

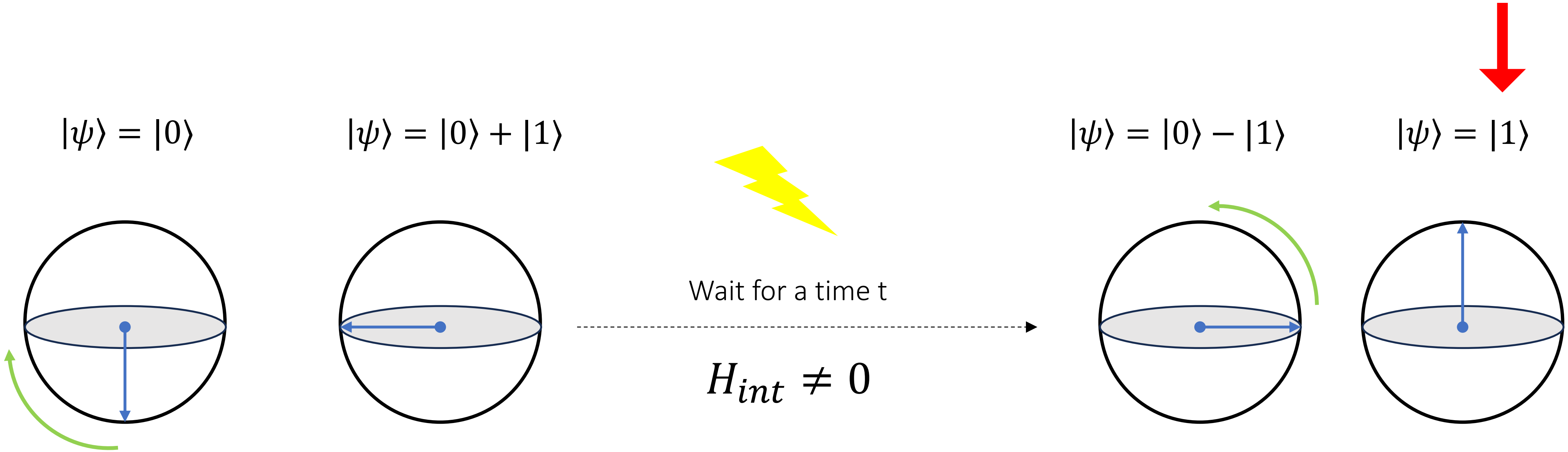


$$H_{int} = 0$$

$$H_{int} \times t = \pi$$

$$i\hbar \frac{\partial \psi}{\partial t} = H_{int}\psi$$

Quantum Sensing with SC Qubits

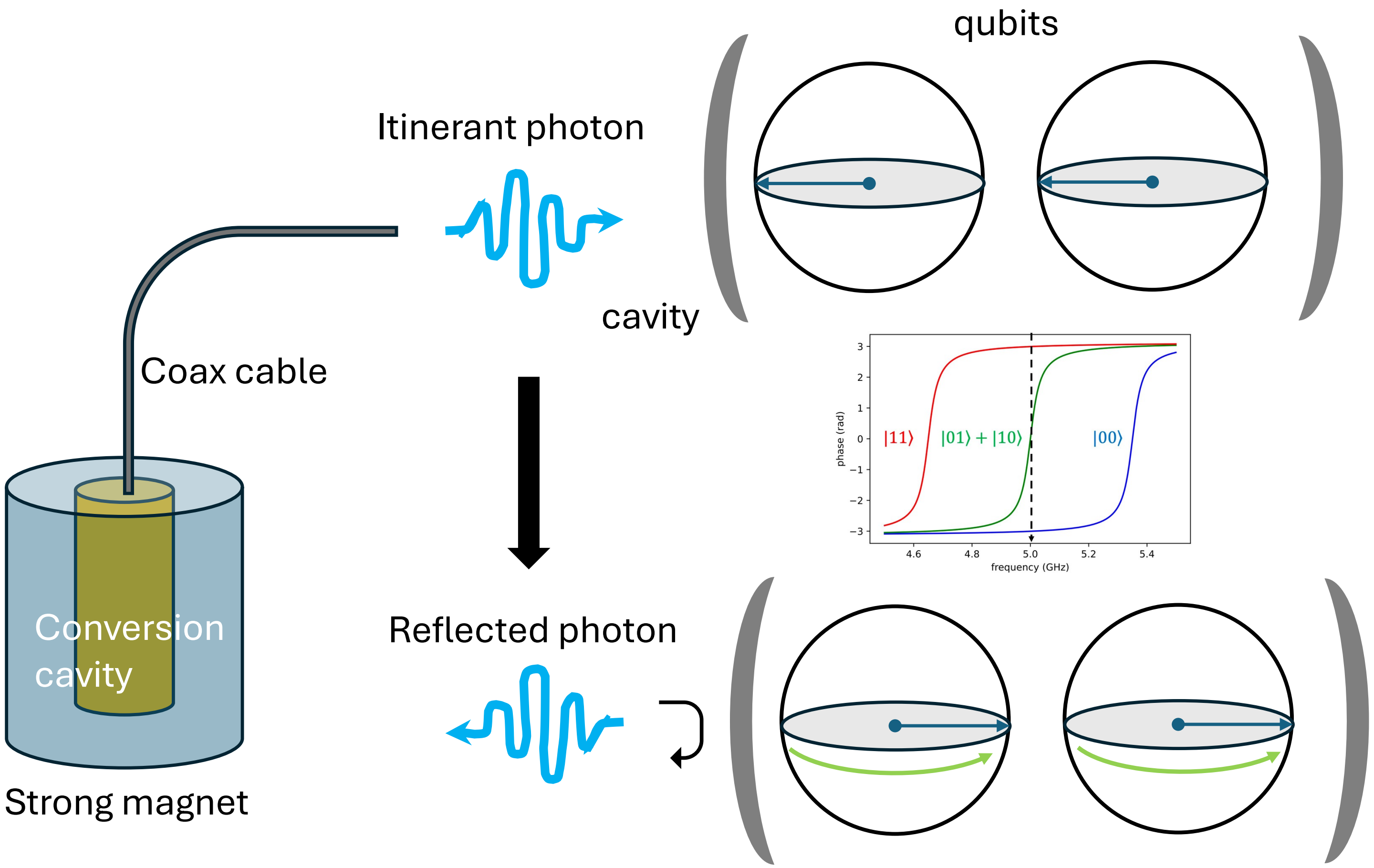


$$H_{int} \neq 0$$

$$H_{int} \times t = \pi$$

$$i\hbar\frac{\partial\psi}{\partial t} = H_{int}\psi$$

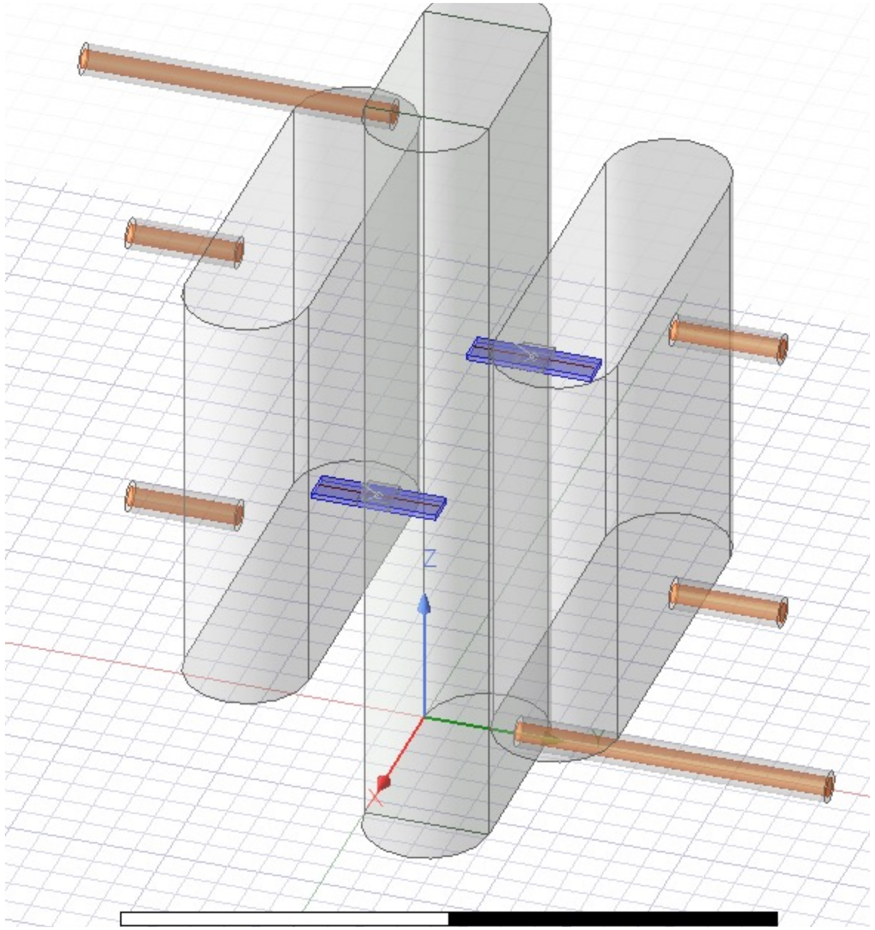
Two Qubits Detection Scheme

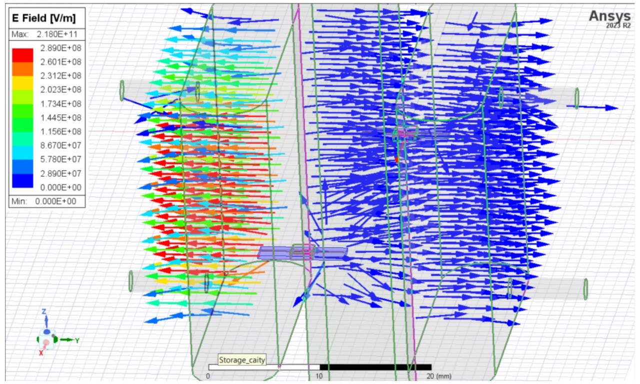


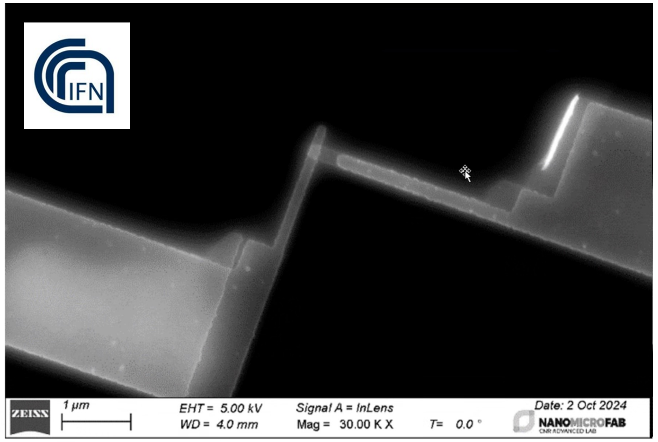
Kono et al. *Nature Phys* **14**, 546–549 (2018)

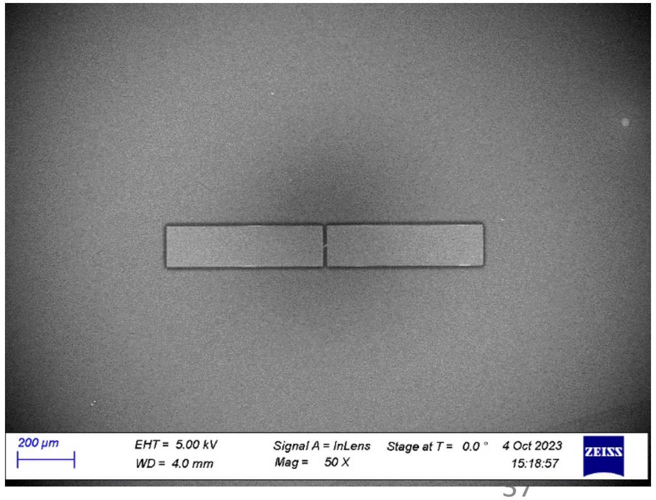
A D'Elia Appl. Sci. 2024, 14(4), 1478

Two Qubits Detector





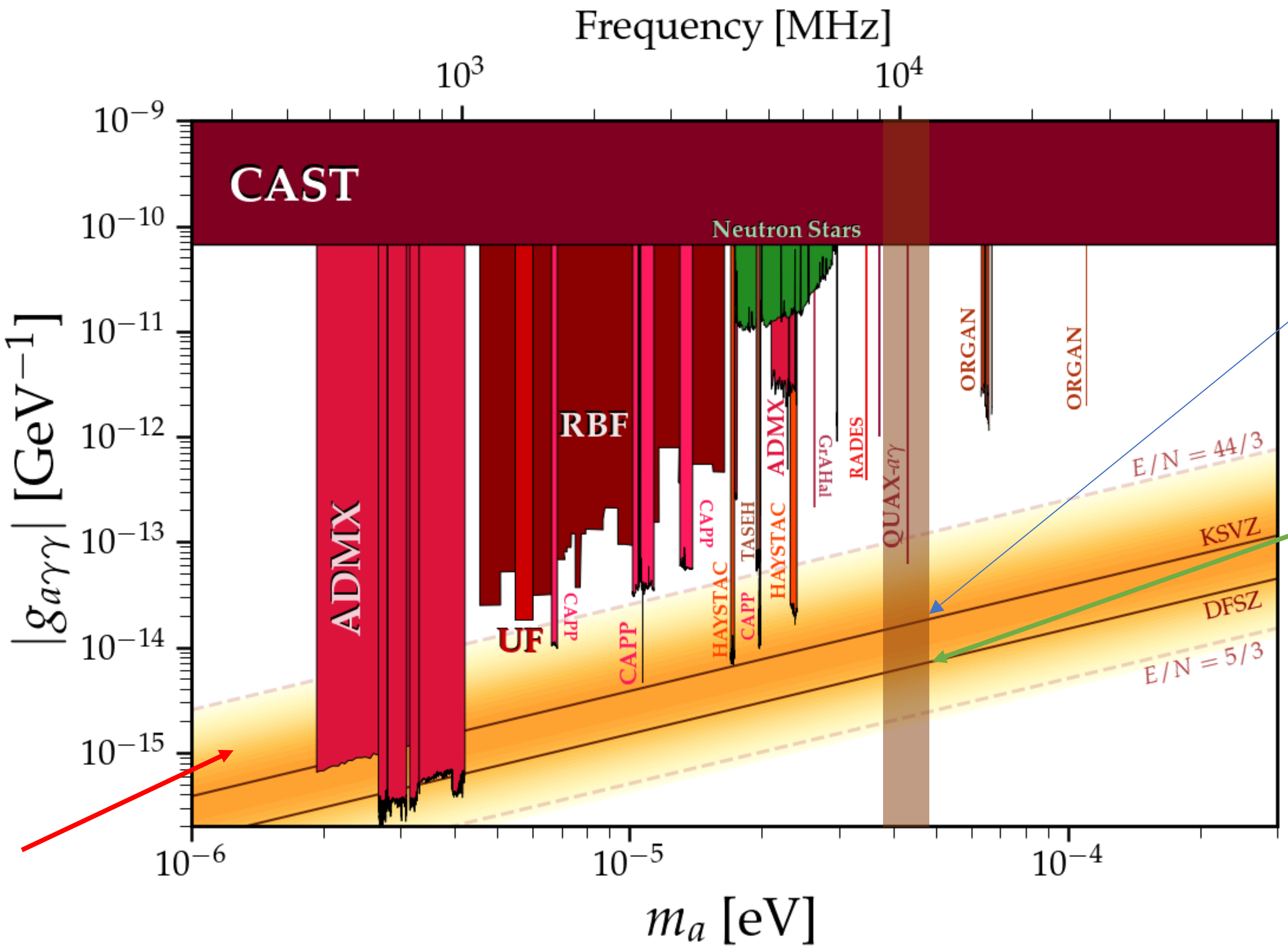




QUAX LNF&LNL 2023-2025

LNF:
- Superconducting cavity $Q_0 > 2\times10^5$
- B=9T
- Multicavity

LNL:
- Dielectric cavity $Q_0 > 10^6$
- B=14 T
- Single cavity



What about the low mass limit?

Next years with noise at Quantum Limit

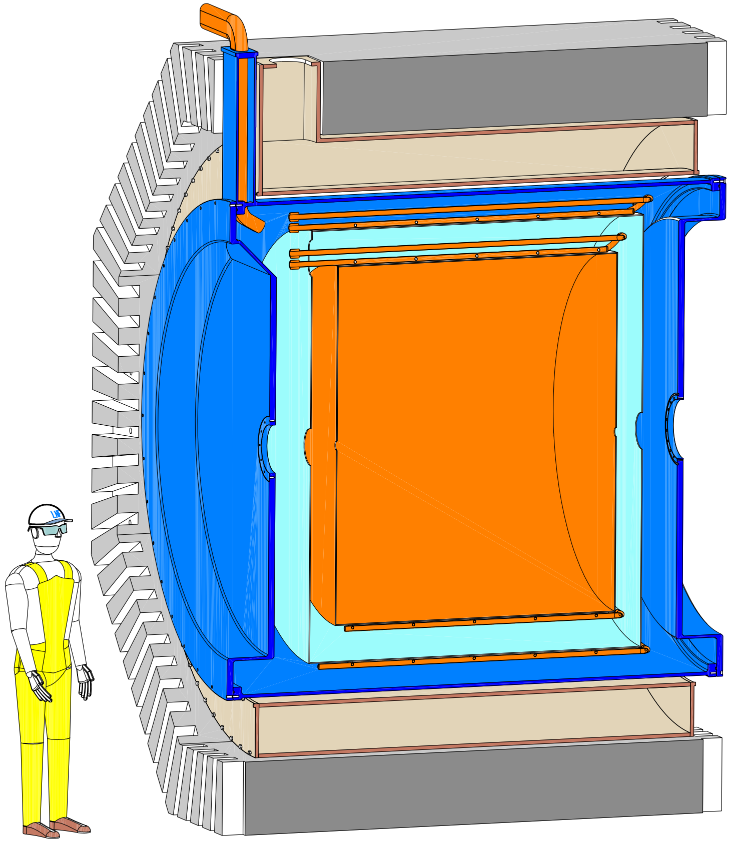
Beyond Quantum Limit with photon counter (ongoing R&D)

See arXiv:2403.02321 for LNL R&D on photon counter

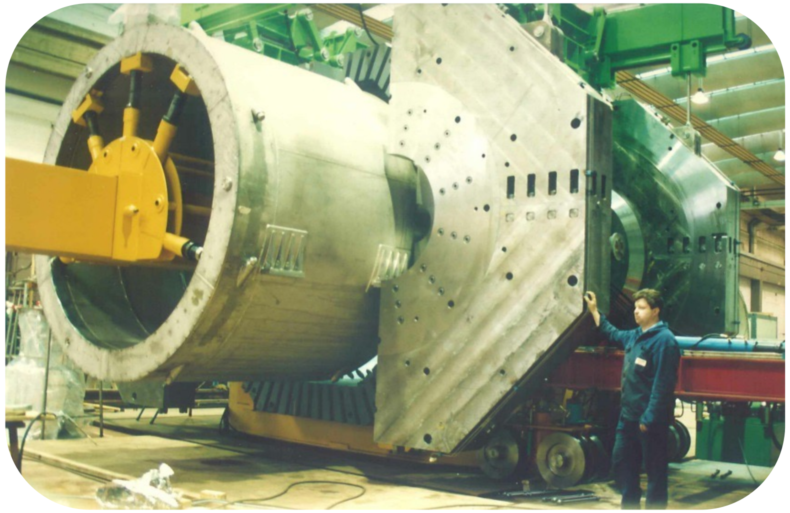
FLASH
Finuda magnet for Light Axion Search Haloscope

A large cryogenic resonant-cavity in a high static magnetic field which is planned to probe new physics in the form of dark matter (DM) axions, scalar fields, chameleons, hidden photons, as well as high frequency gravitational waves (GWs) in the frequency range (100–300) MHz.

The experiment will make use of the cryogenic plant and magnet of the FINUDA experiment at INFN-LNF.



"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



FINUDA

Fisica Nucleare a DAFNE

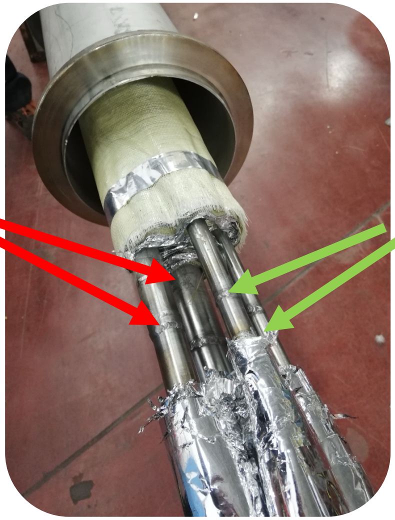
B(T)	1.1
I(A)	2845
R(m)	1.4
L(m)	2.2

INFN LNF
Istituto Nazionale di Fisica Nucleare

Commissioning of the FINUDA Magnet at LNF

Last Operated in 2007

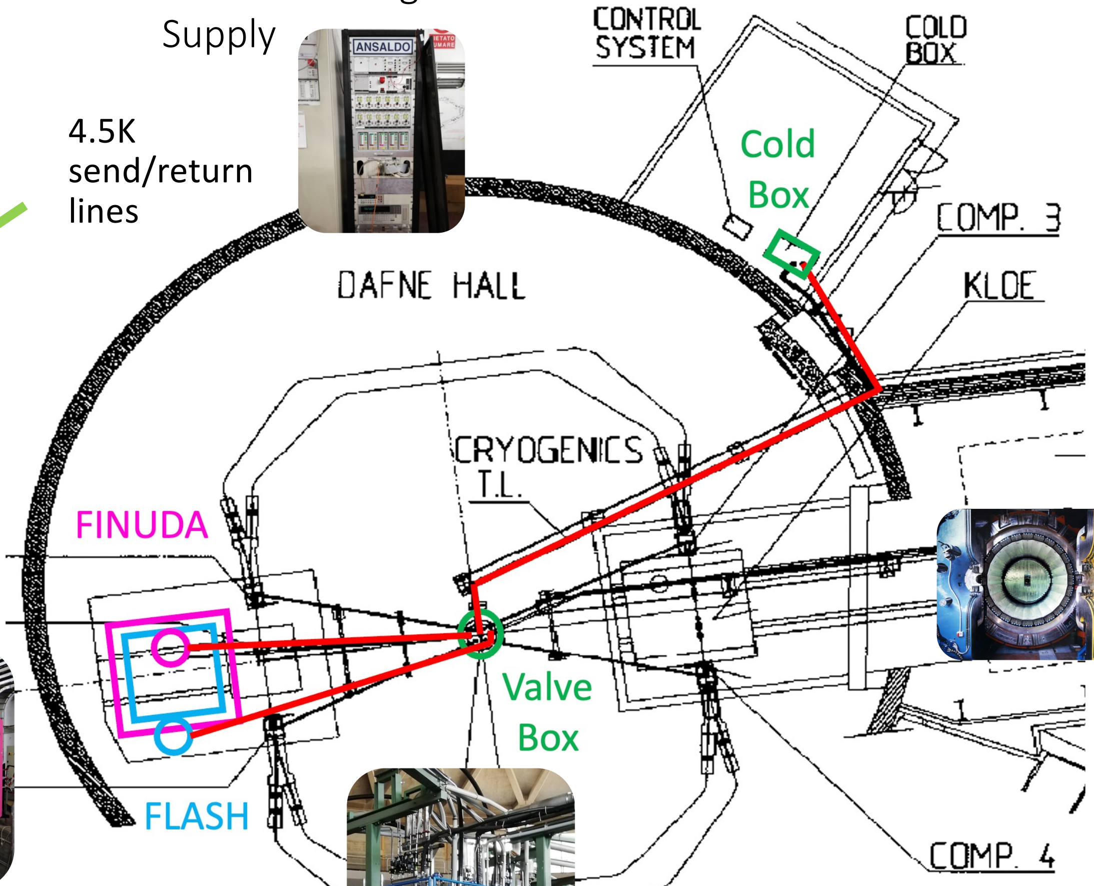
70K
send/return
lines

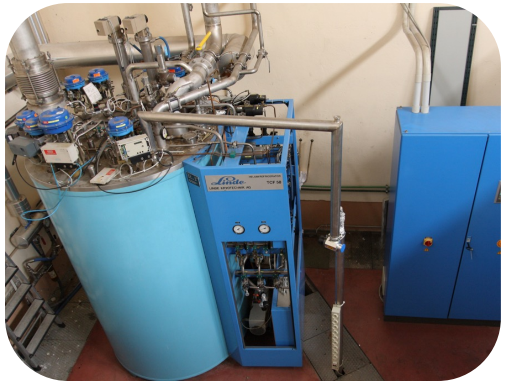


4.5K
send/return
lines

Reconnection of He transfer line

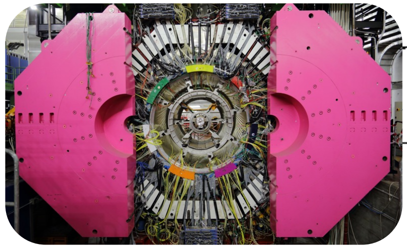
Control of Magnet Power Supply



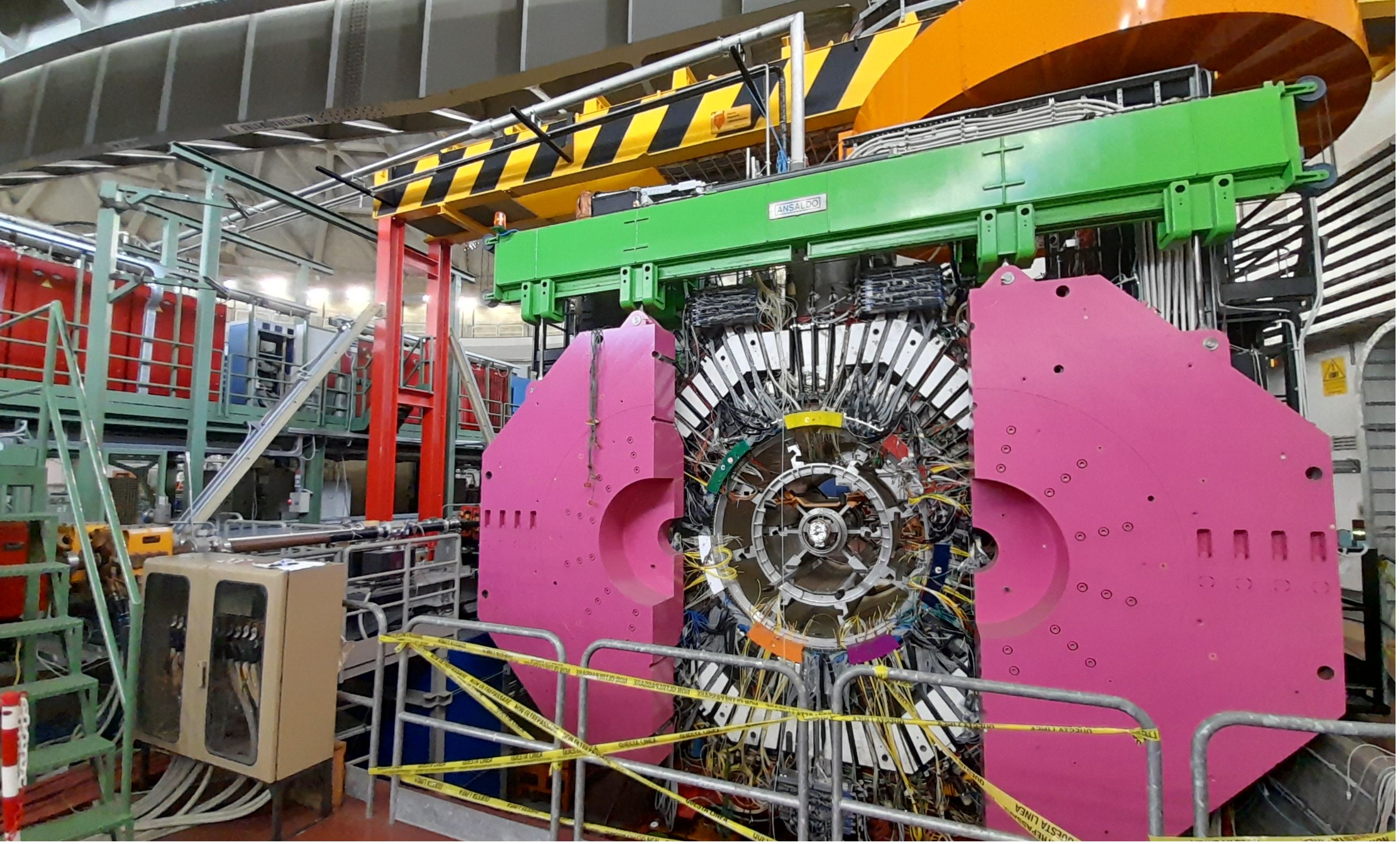


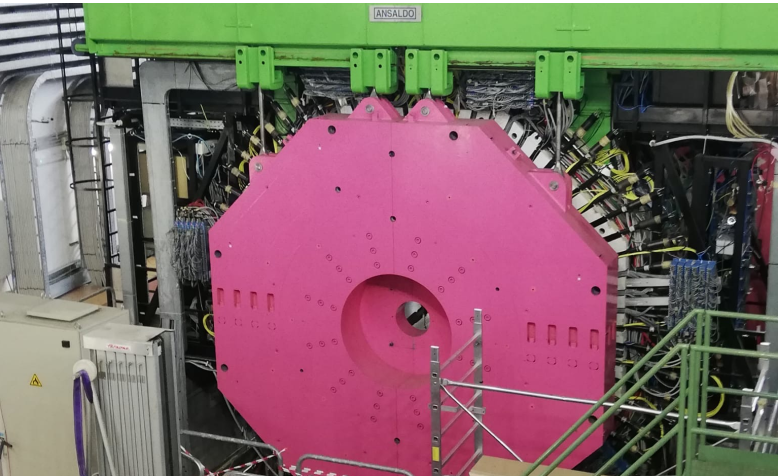
Cryogenic plant

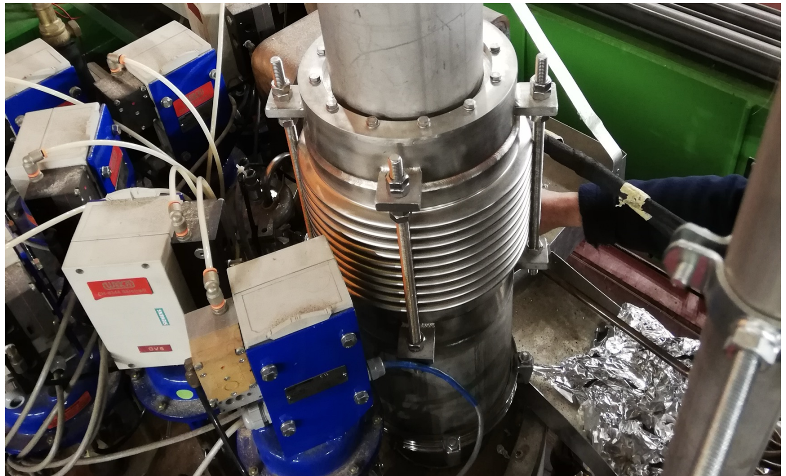
KLOE



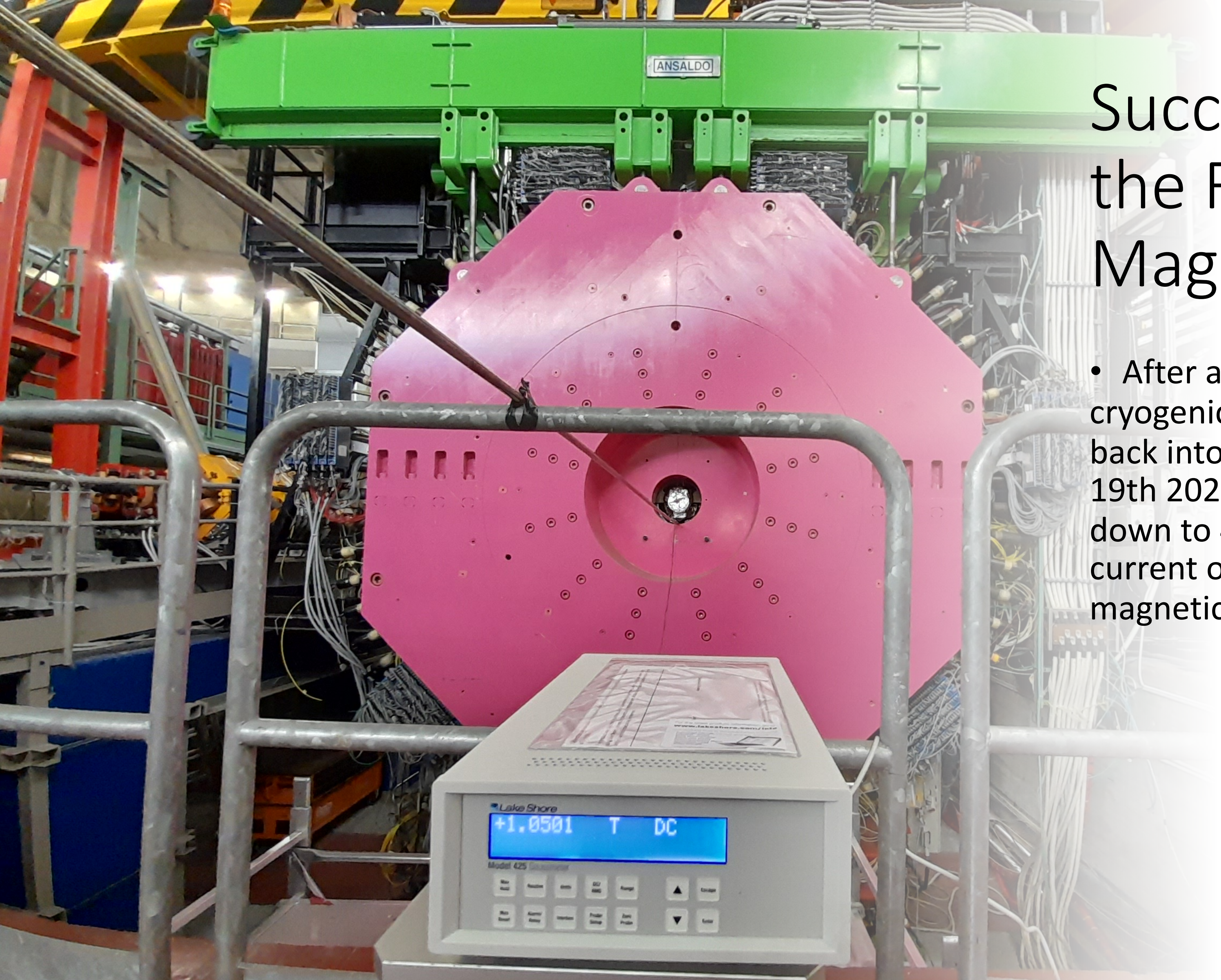
FINUDA/FLASH


ANSALDO


ANSALDO



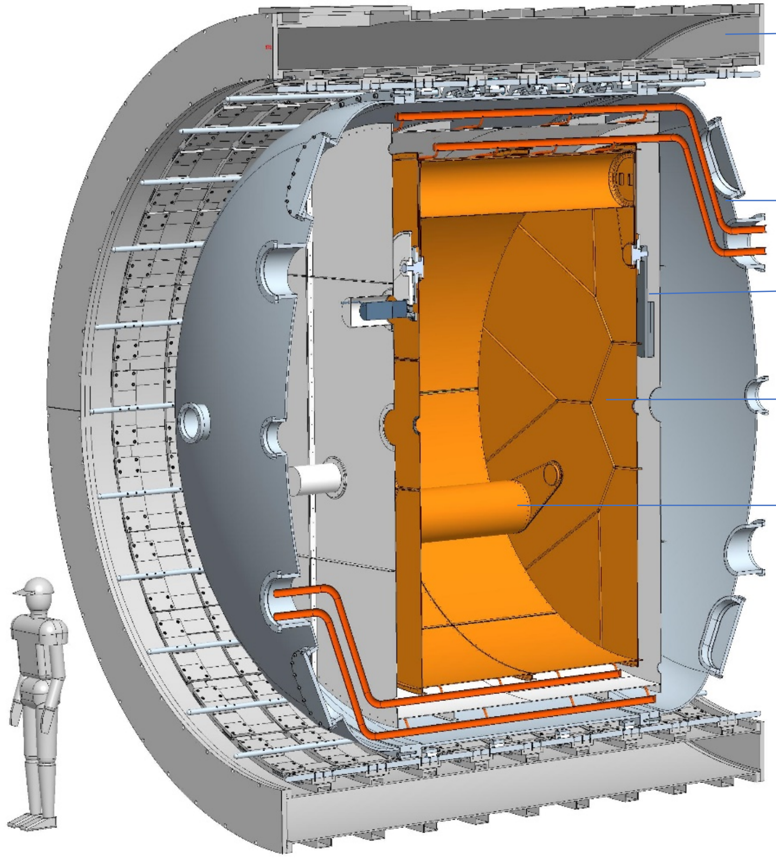

CV01
CV02
CV07
FIC1 (-)
FIC2 (+)
CV04
CV12
CV20
CV06
CV03
CV09



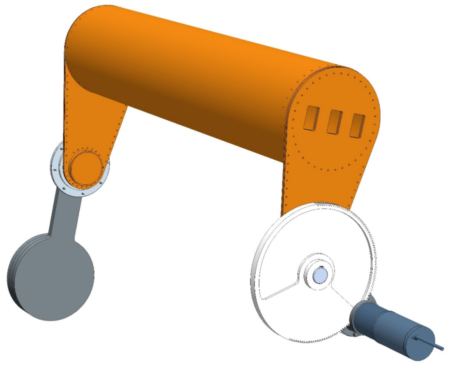
Successful Test of the FINUDA Magnet

- 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.

THE FLASH Cryostat and Resonant Cavity

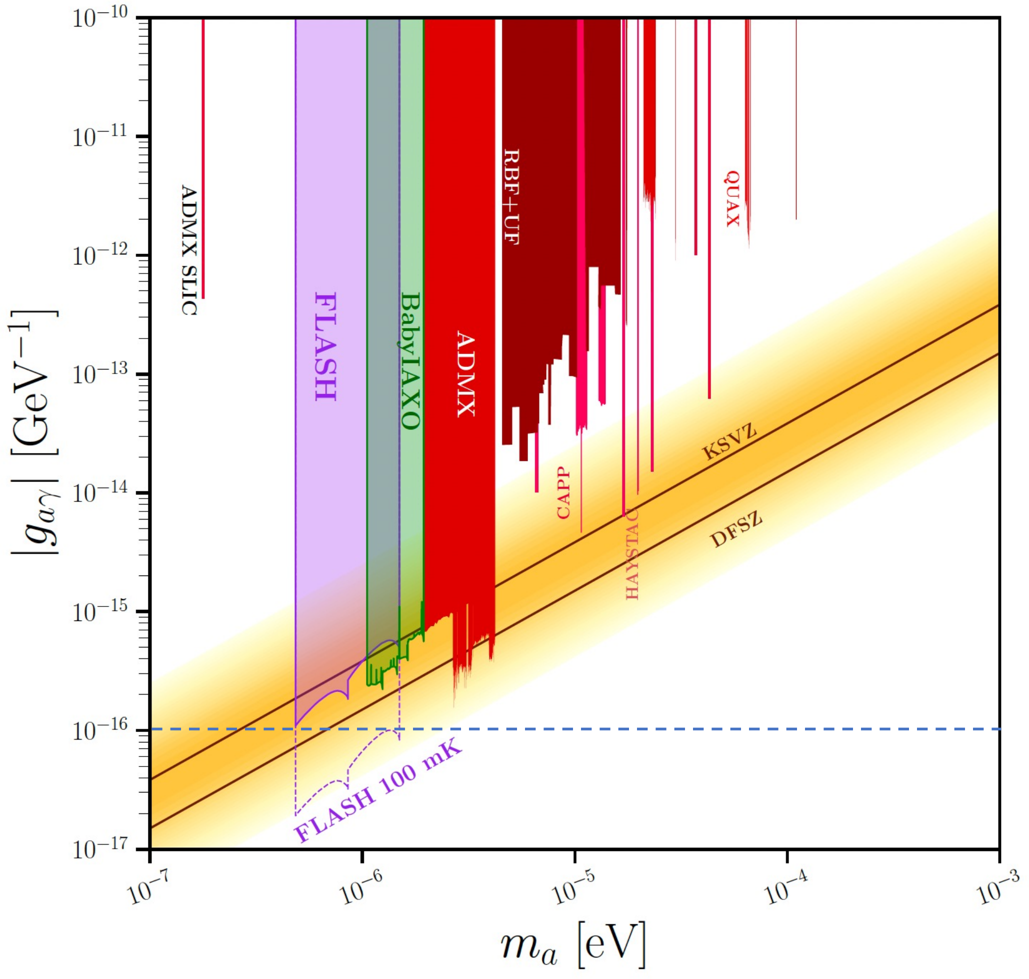


- KLOE/FINUDA Magnet
- Vacuum vessel made by a-magnetic stainless steel
- Shield in aluminum alloy, to be cooled to 70 K by gaseous Helium
- OFHC Cu resonant cavity, cooled to 4.6 K by saturated liquid Helium
- 3 OFHC Cu tuning bars mounted on eccentric cranks with reduction gearboxes



Design by FANTINI Sud Mechanical Div.

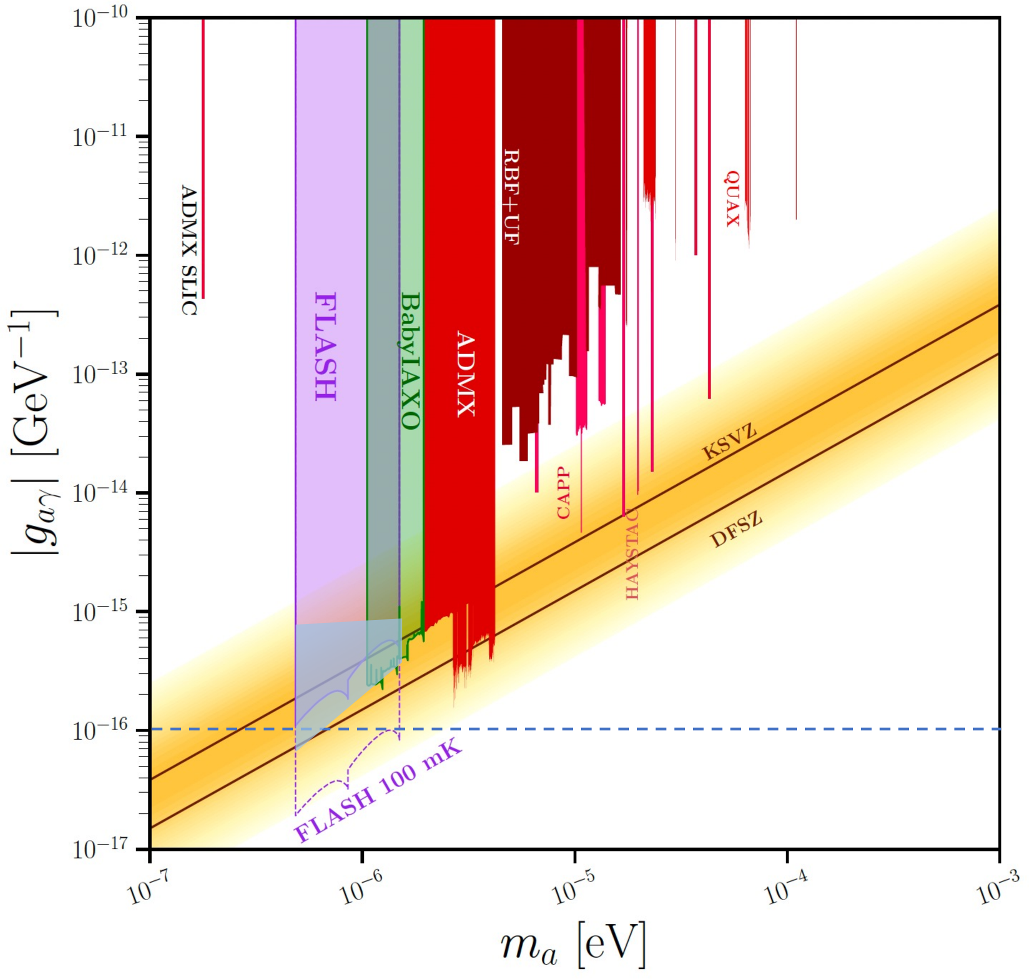
FLASH Physics Reach



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

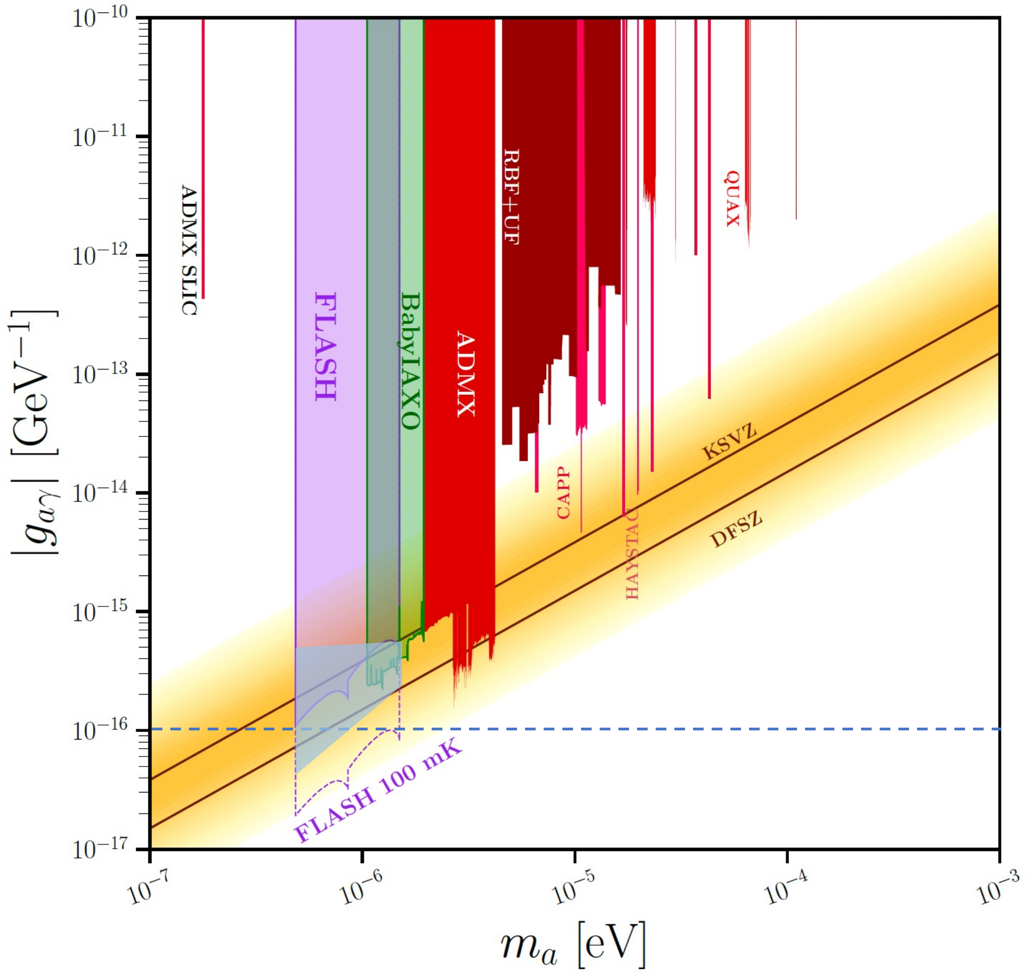
FLASH Physics Reach



With Cu cavity at 1.9 K

Parameter	Value
ν_c [MHz]	150
m_a [μeV]	0.62
$g_{a\gamma\gamma}^{\rm KSVZ}$ [GeV^{-1}]	2.45×10^{-16}
Q_L	1.4×10^5
C_{010}	0.53
$B_{\rm max}$ [T]	1.1
β	2
τ [min]	5
$T_{\rm sys}$ [K]	4.9
$P_{\rm sig}$ [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

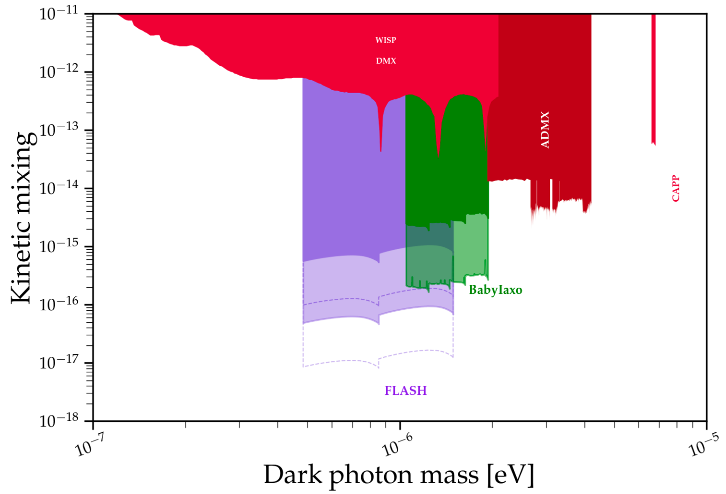


With NbTi cavity at 1.9 K

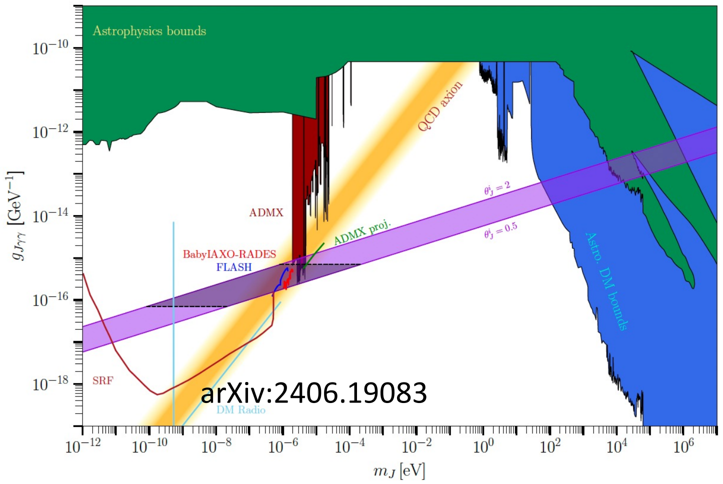
Parameter	Value
ν_c [MHz]	150
m_a [μeV]	0.62
$g_{a\gamma\gamma}^{KSVZ}$ [GeV^{-1}]	2.45×10^{-16}
Q_L	6.7 $\times 10^5$
C_{010}	0.53
B_{max} [T]	1.1
β	2
τ [min]	5
T_{sys} [K]	4.9
P_{sig} [W]	0.9×10^{-22}
Scan rate [Hz s^{-1}]	8
m_a [μeV]	0.49 - 1.49
$g_{a\gamma\gamma}$ 90% c.l. [GeV^{-1}]	(0.37- 1.8)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

FLASH Physics Reach

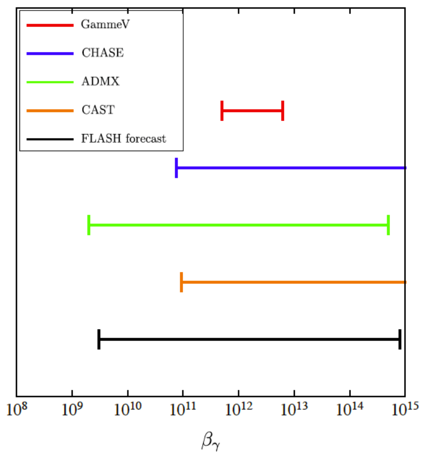
Vector Dark Matter



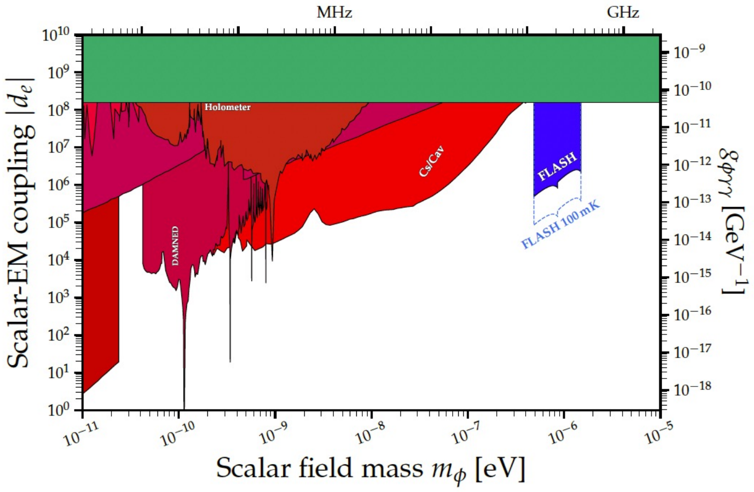
Majoron



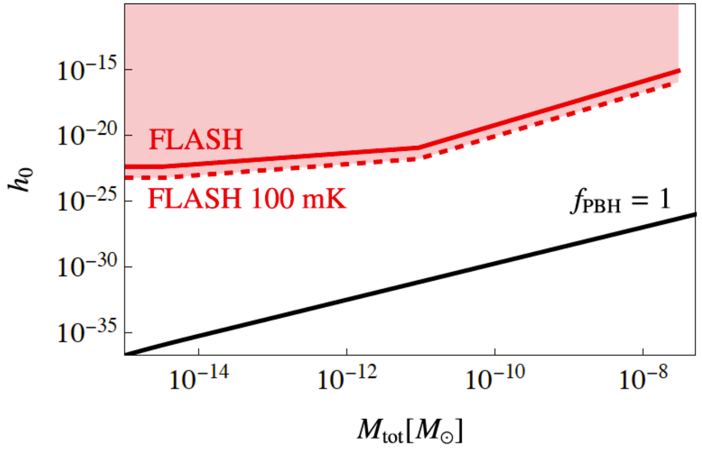
Chameleons



Scalar Dark Matter

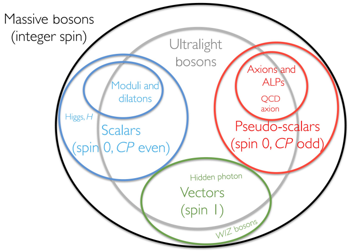


HFGW



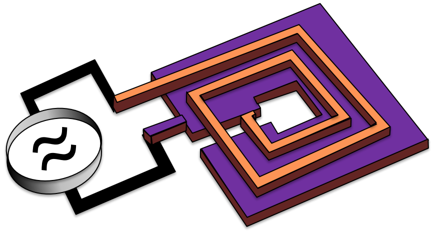
Design Study and R&D for the TDR

Goal: TDR ready for Summer 2026



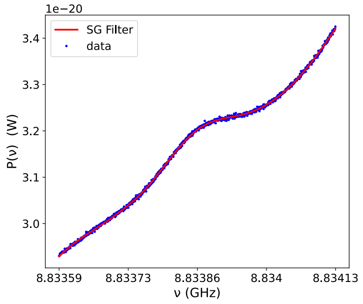
WP1 Physics Reach

TSUNG-DAO LEE INSTITUTE · INFN · IFAE Institut de Física d'Altes Energies · Departamento de Física Teórica Universidad Zaragoza



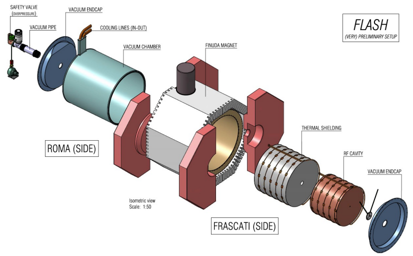
WP4 Signal Amplification and DAQ

INFN PISA · TIFPA Istituto Nazionale di Fisica Nucleare Trento Institute for Fundamental Physics and Applications · UNICAM Università di Camerino · JG|U



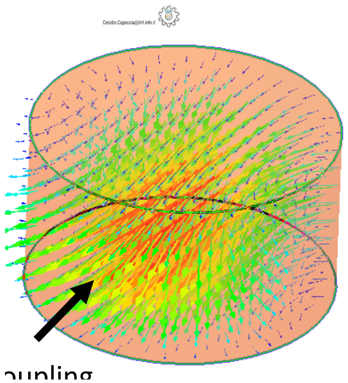
WP5 Data Analysis and Computing

JG|U · UNI BONN · INFN PISA · INFN LNF Istituto Nazionale di Fisica Nucleare



WP2 Mechanical Design and Cryogenics

INFN LNF Istituto Nazionale di Fisica Nucleare · SEM Servizio Meccanica · Unimarconi La prima università digitale italiana · CERN



WP3 RF Cavity

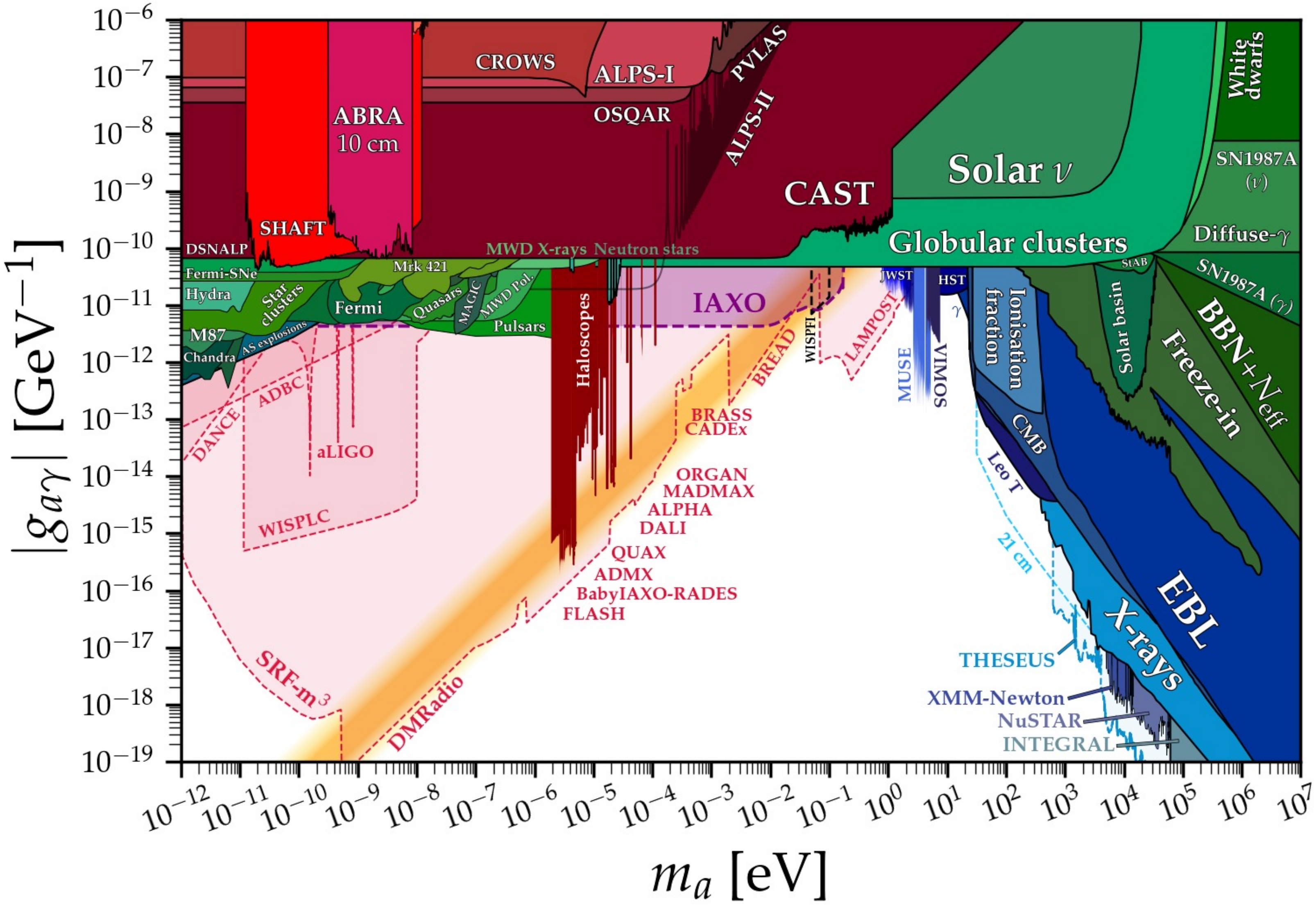
Vniversitat de València · Universidad Politécnica de Cartagena · UNI BONN · INFN LNF Istituto Nazionale di Fisica Nucleare · IFIC Institut de Física Corpuscular

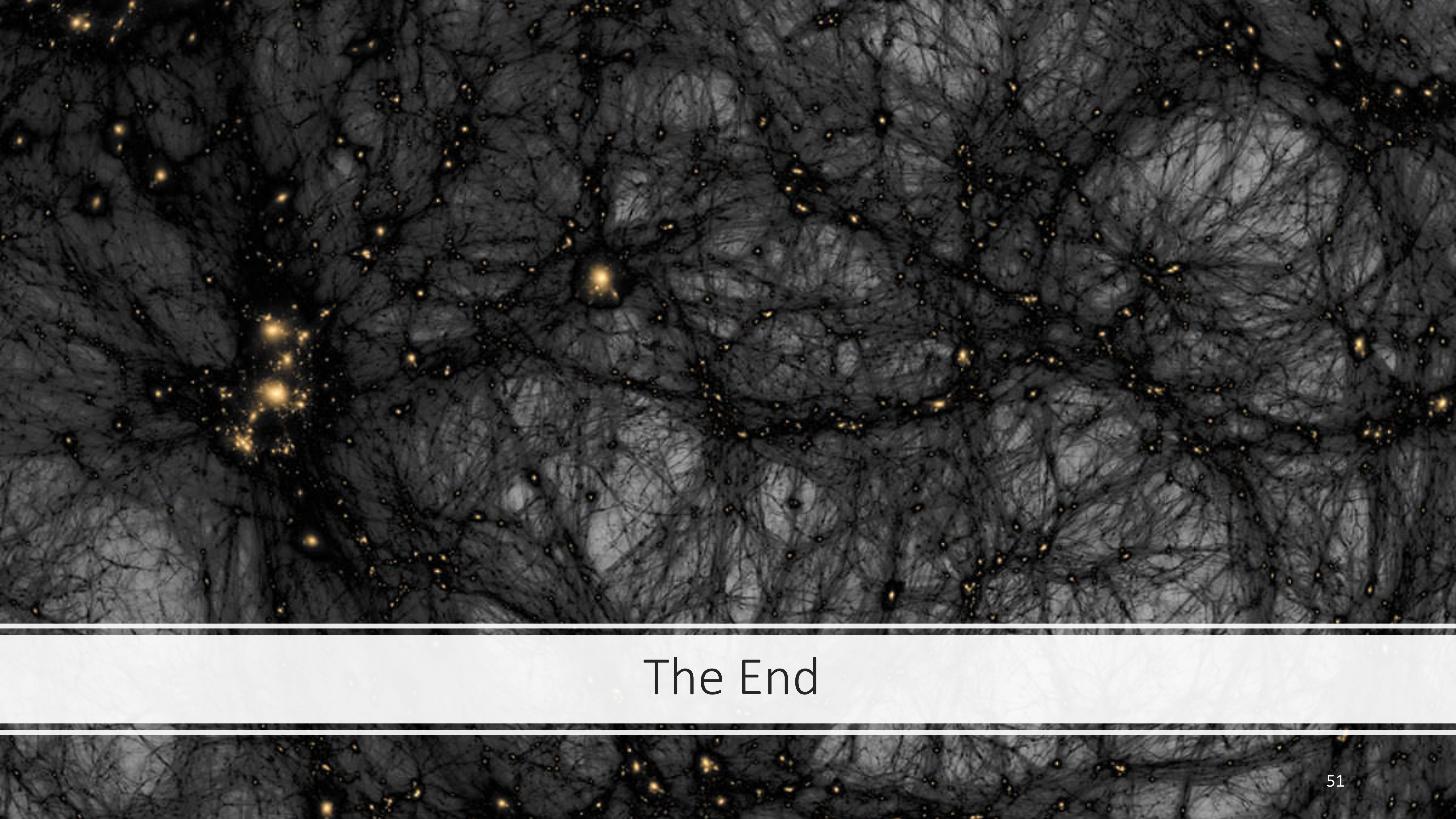
FINUDA FRASCATI: 12 1996

WP6 Decommissioning of FINUDA and FLASH Commissioning

INFN LNF Istituto Nazionale di Fisica Nucleare

Global Effort to Probe the Full QCD-Axion Band in the Next 10 Years





The End