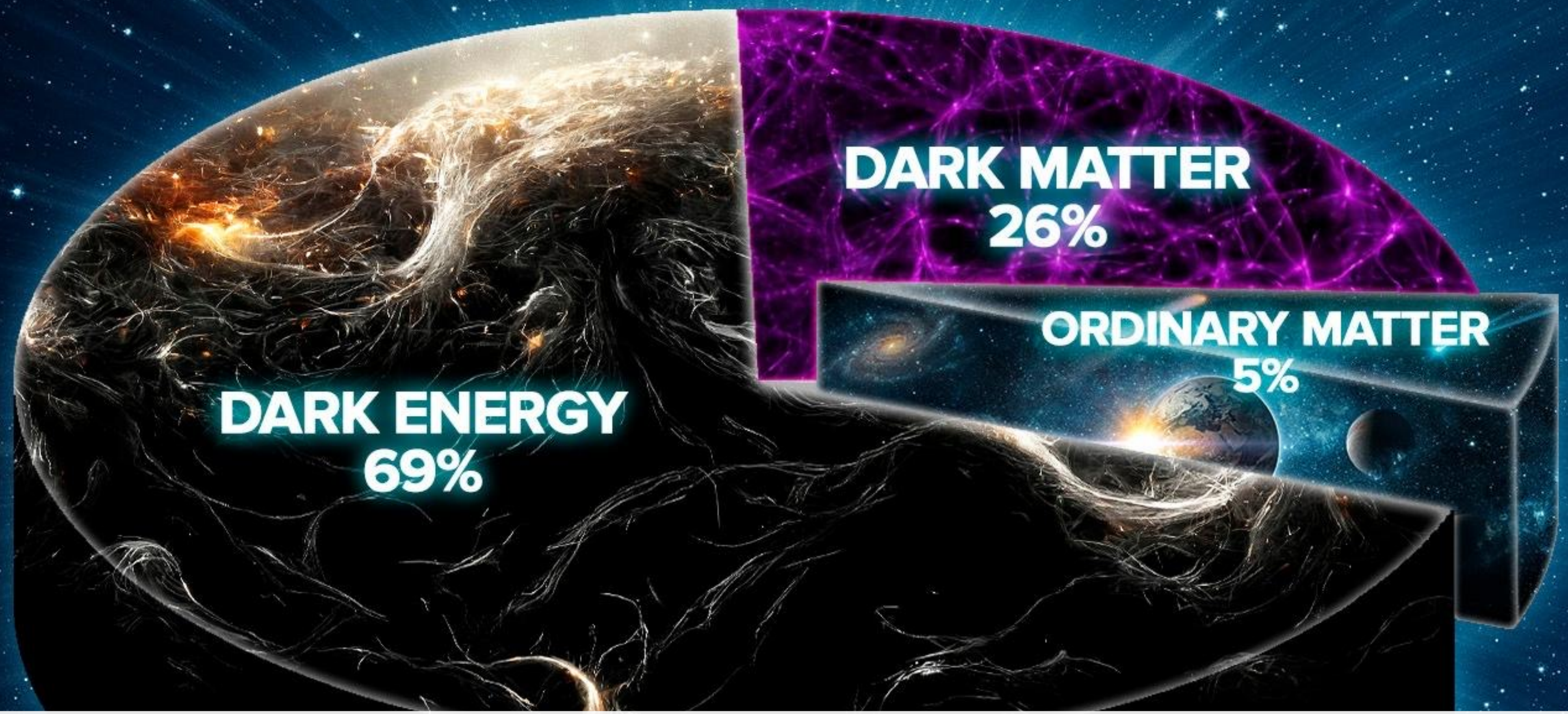
AXION Searches at INFN

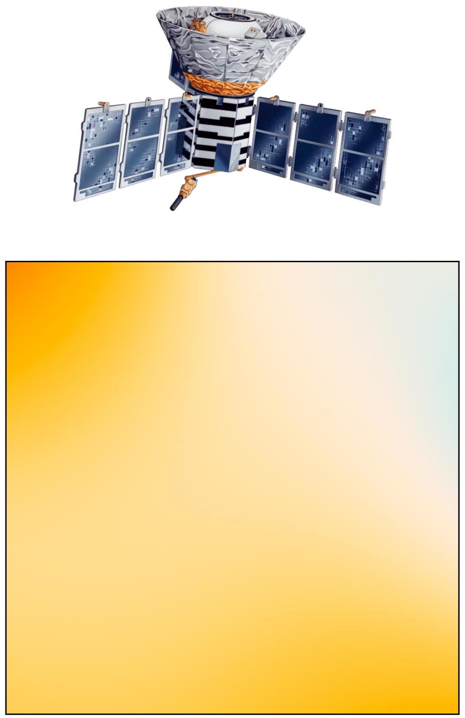
Claudio Gatti - LNF

MPP Colloquium, Munich 9 April 2024



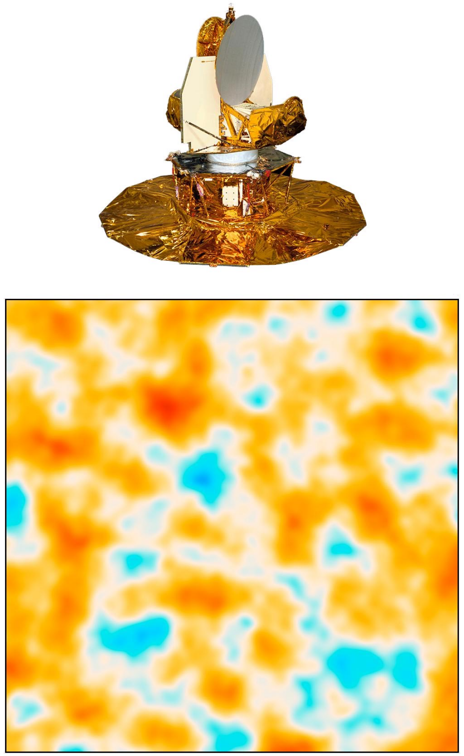
Introduction - Dark Matter

Cosmic Microwave Background - Anisotropy



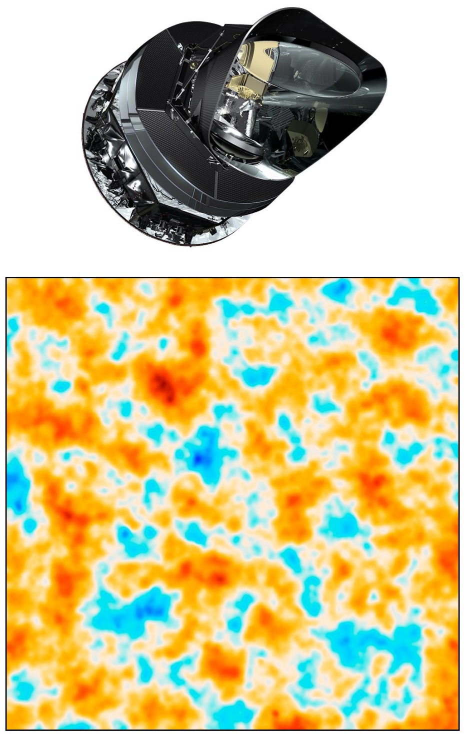
COBE

1989



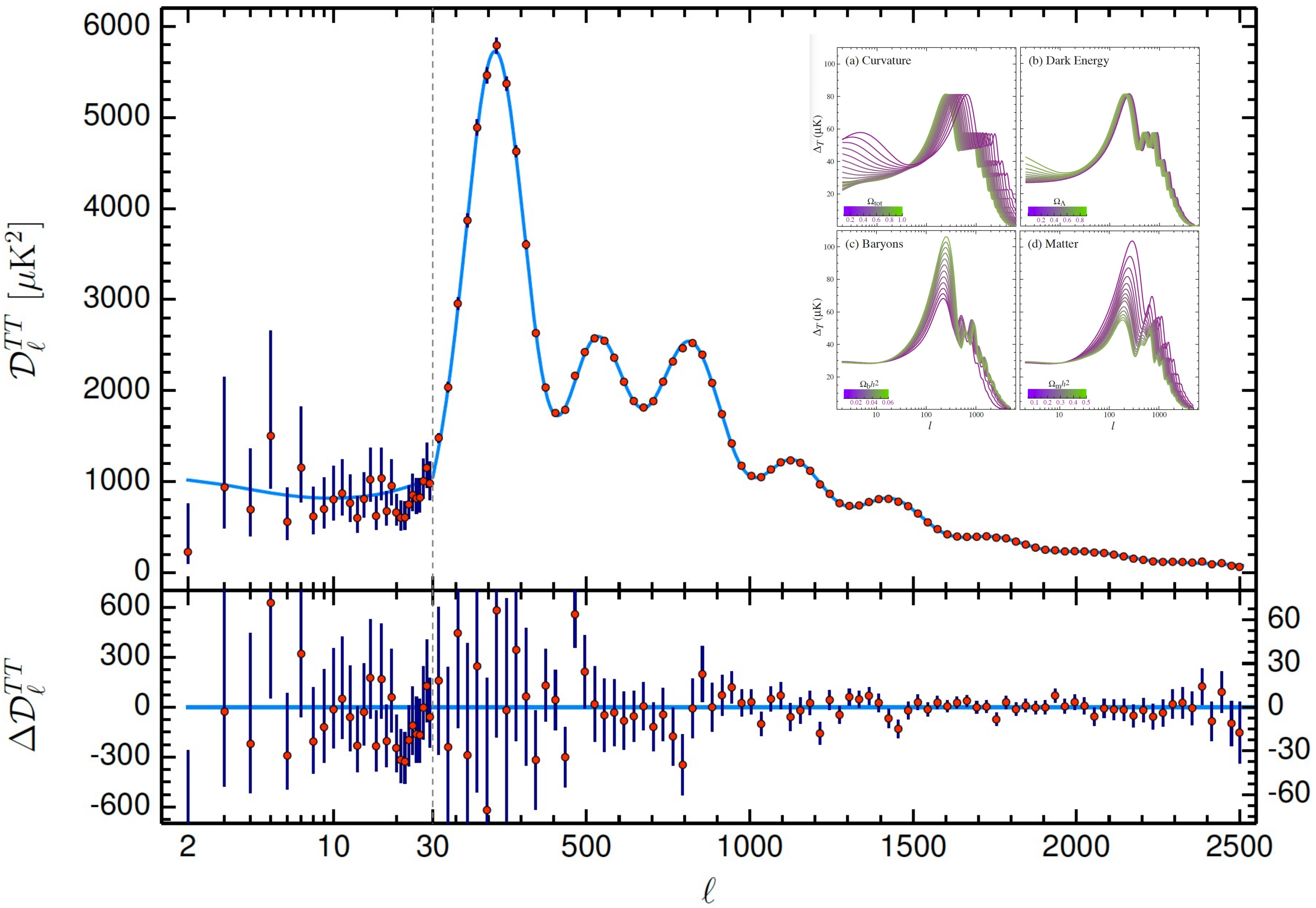
WMAP

2001



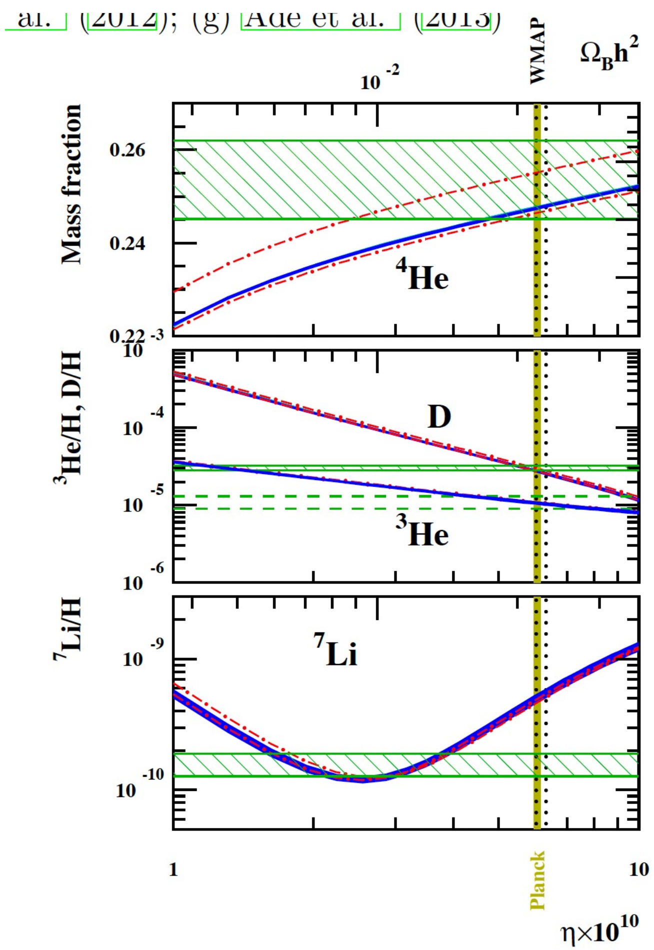
Planck

2009

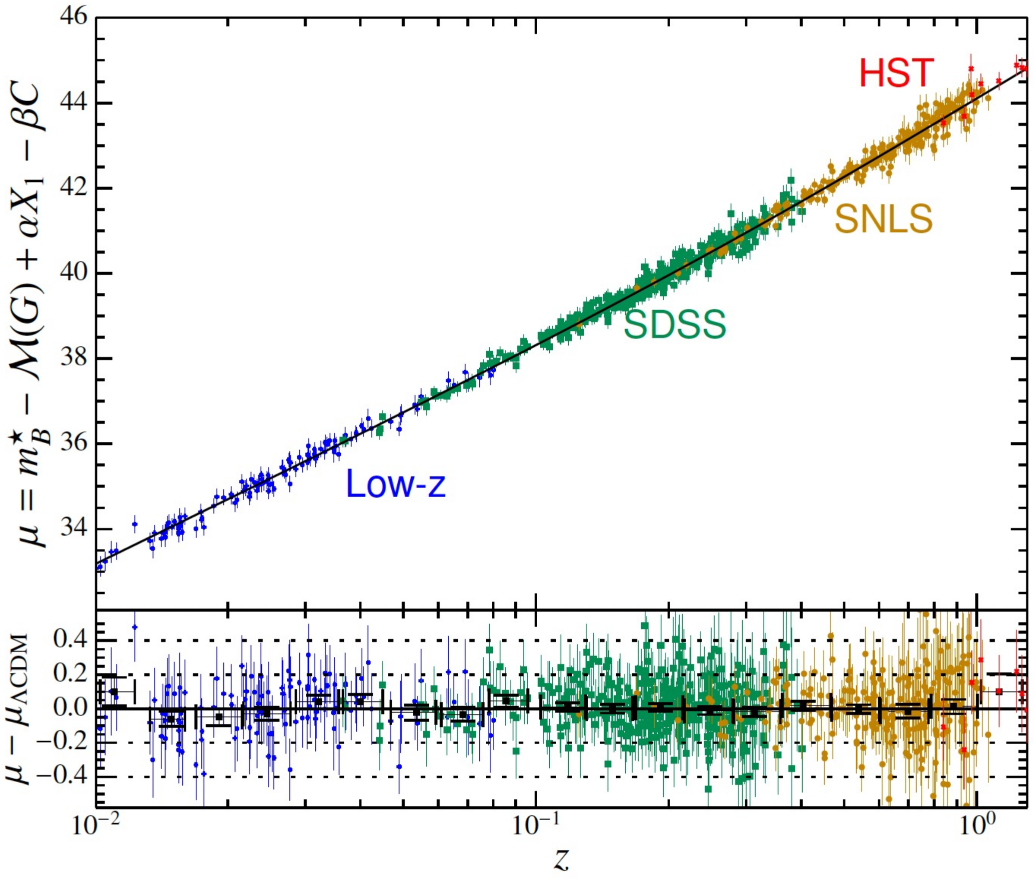


$$\begin{cases} \Omega_\Lambda \approx 68\% \\ \Omega_{DM} \approx 26\% \\ \Omega_b \approx 6\% \end{cases}$$

Plank 2018 results - arXiv:1807.06209



arXiv:1307.6955

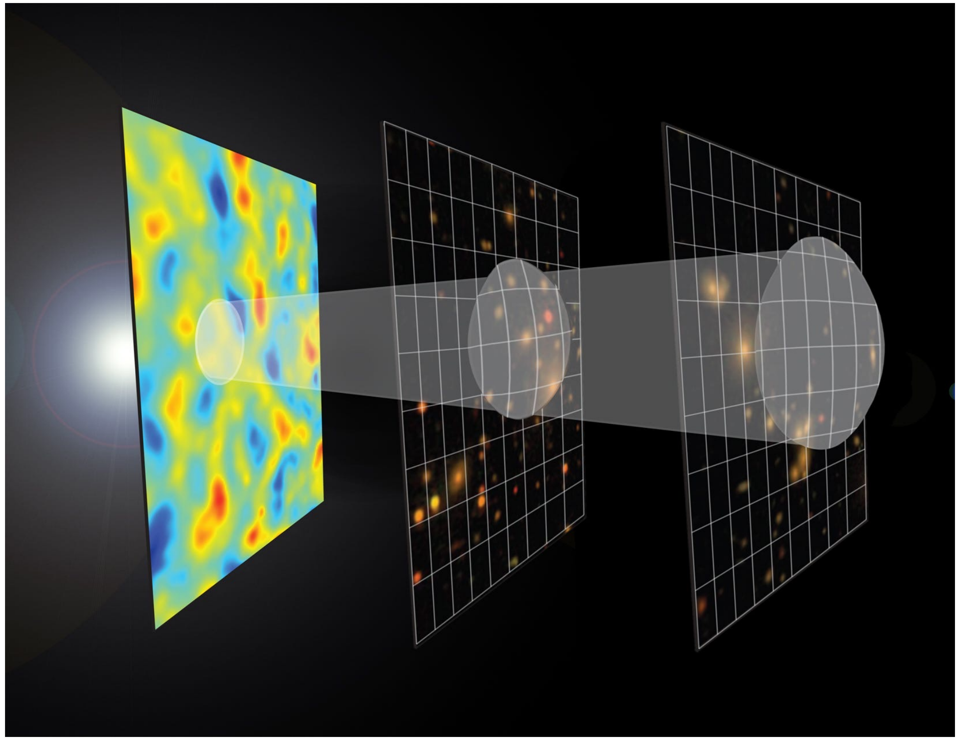


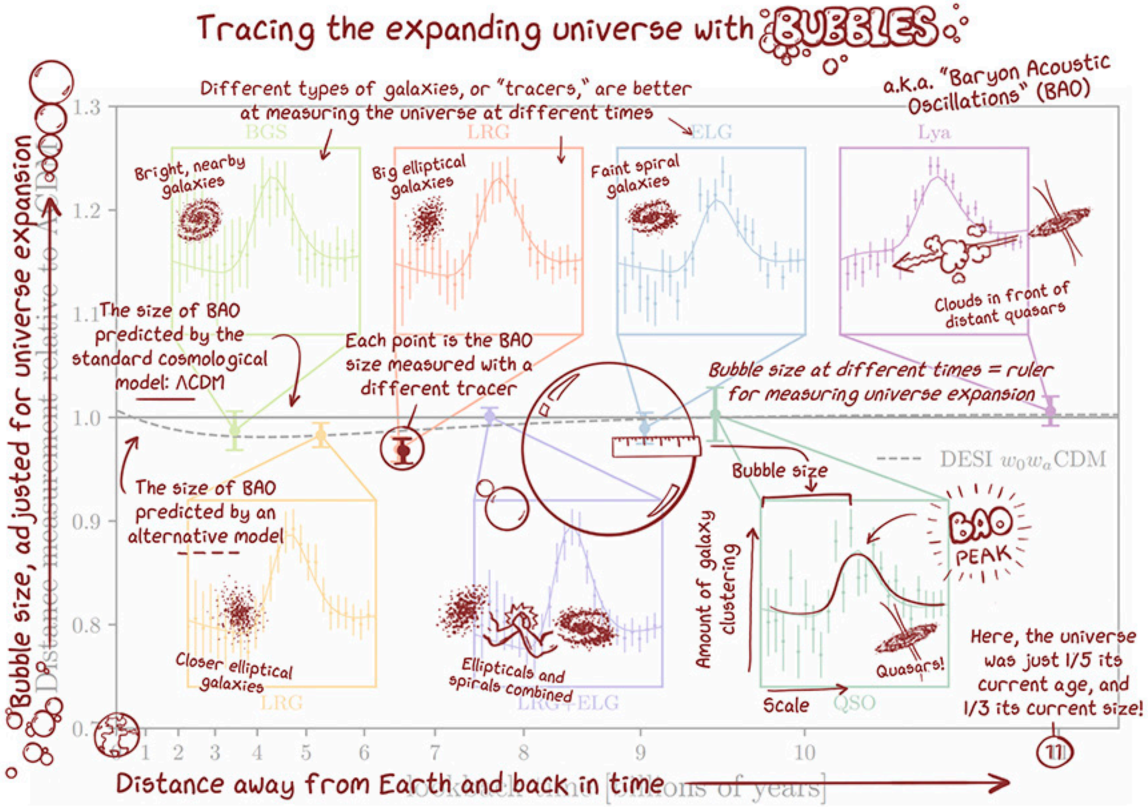
arXiv:1401.4064

Big-Bang Nucleosynthesis

Hubble Diagram from type Ia Supernovae

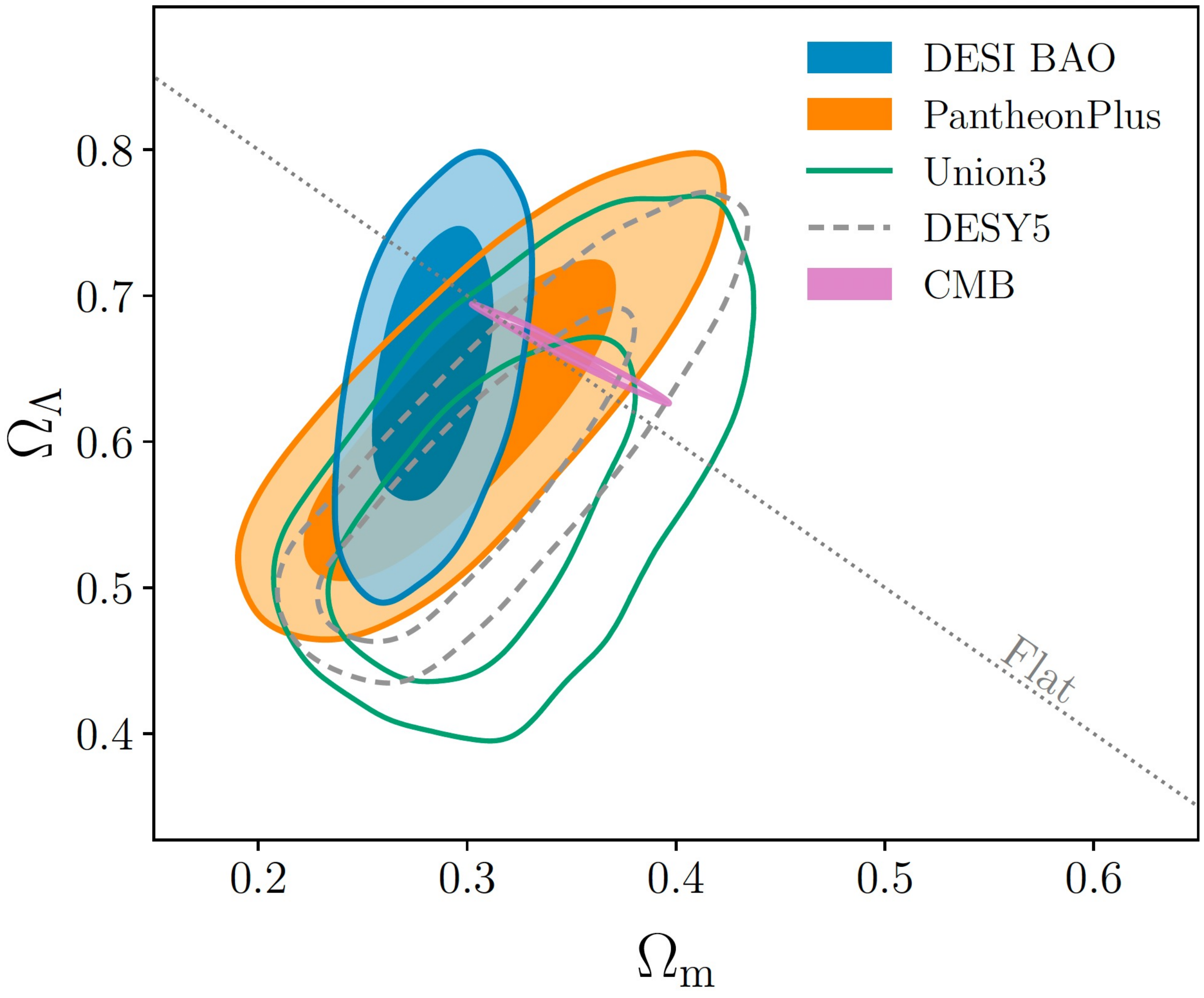
Baryon Acoustic Oscillations - DESI



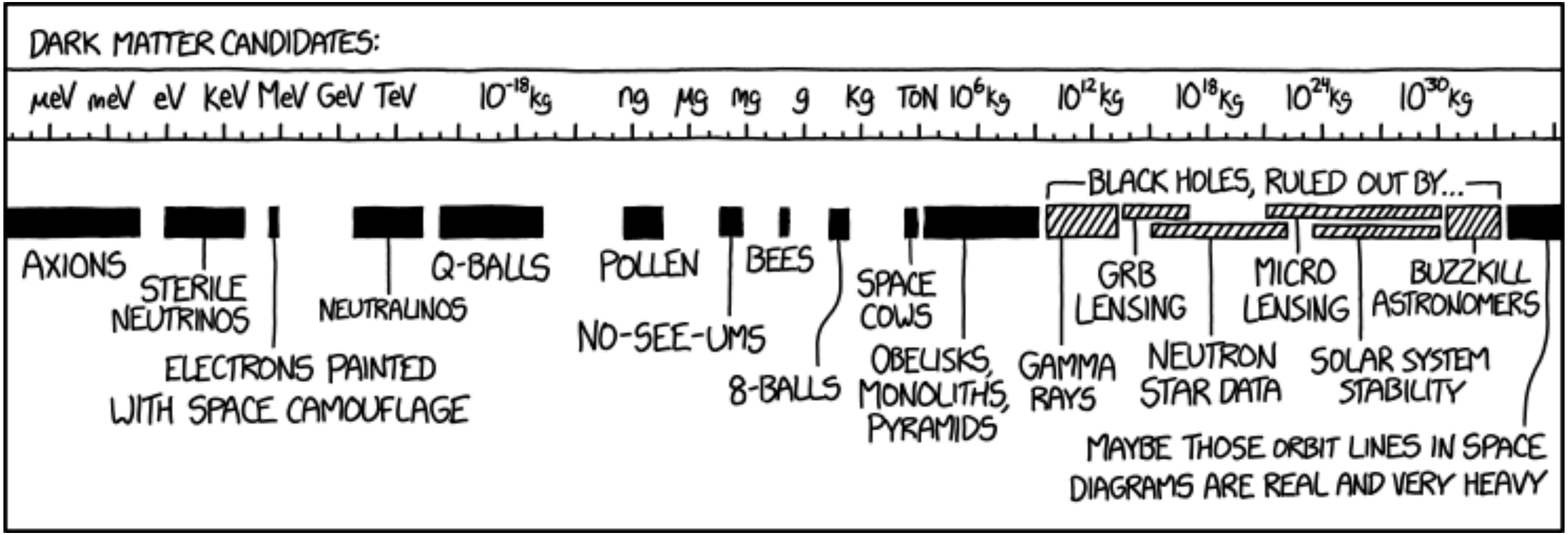


arXiv:2404.03002

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

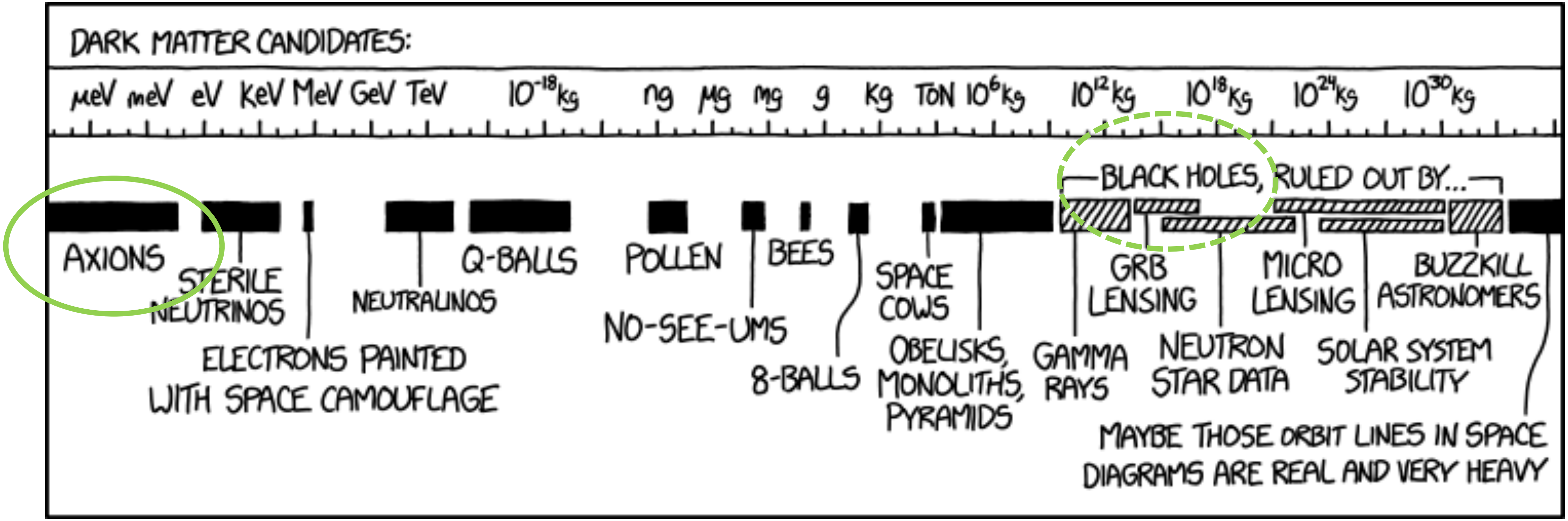


arXiv:2404.03002



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

DM Candidates



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

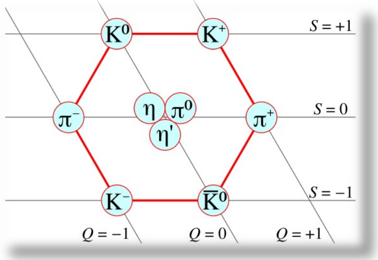
DM Candidates

Axions

U(1)$_A$ problem

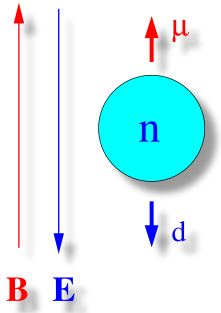
$$M_{\eta'} = 958 \text{ MeV} \gg M_\eta$$

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



Strong CP problem

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



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

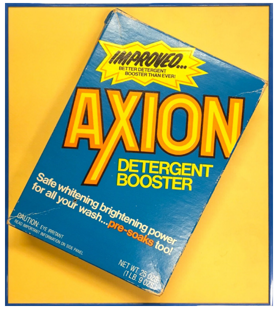
$$d_n < 2.9 \times 10^{-26} e \text{ cm}$$

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

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).

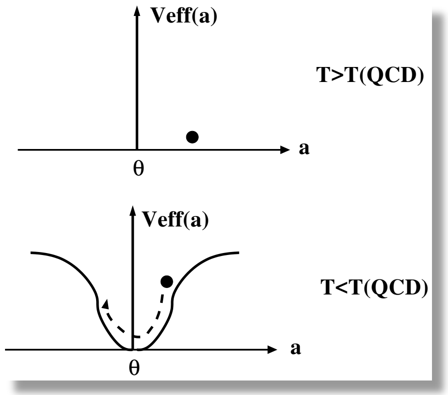
Axions

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



Axion Dark Matter

Misalignment mechanism



Mass

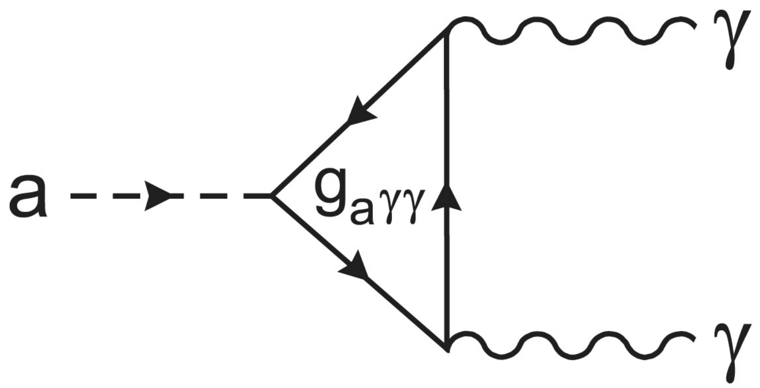
$$m_a = 5.70(7)\left(\frac{10^{12}GeV}{f_a}\right)\mu eV \simeq \frac{m_\pi f_\pi}{f_a}$$

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

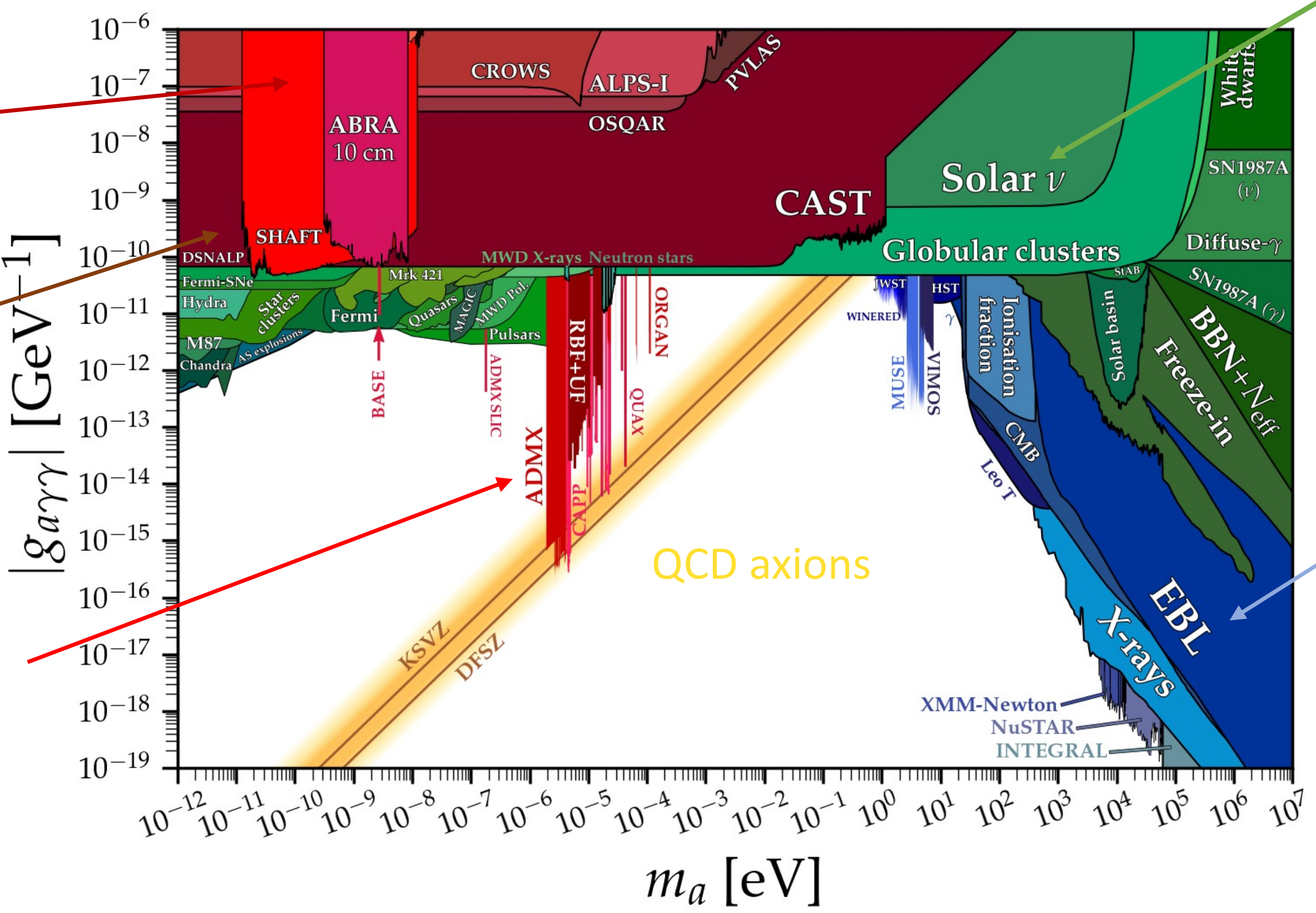
$$\Gamma_{a\to\gamma\gamma} = \frac{g_{a\gamma\gamma}^2 m_a^3}{64\pi} = 1.1\times 10^{-24} s^{-1}\left(\frac{m_a}{eV}\right)^5$$

Axion Limits

Laboratory experiments

Detection of axions from the Sun (Helioscopes)

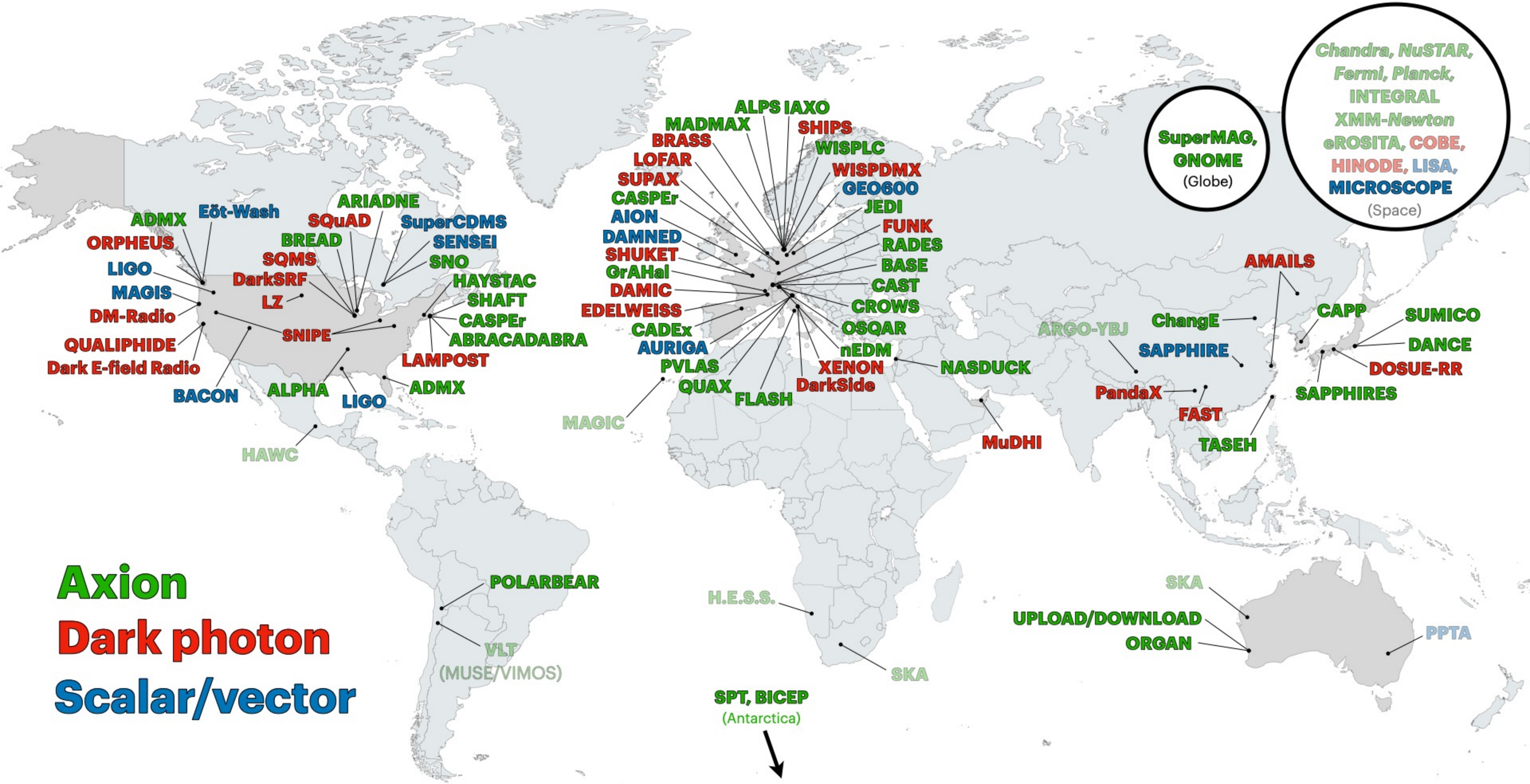
DM axion detection (Haloscopes)

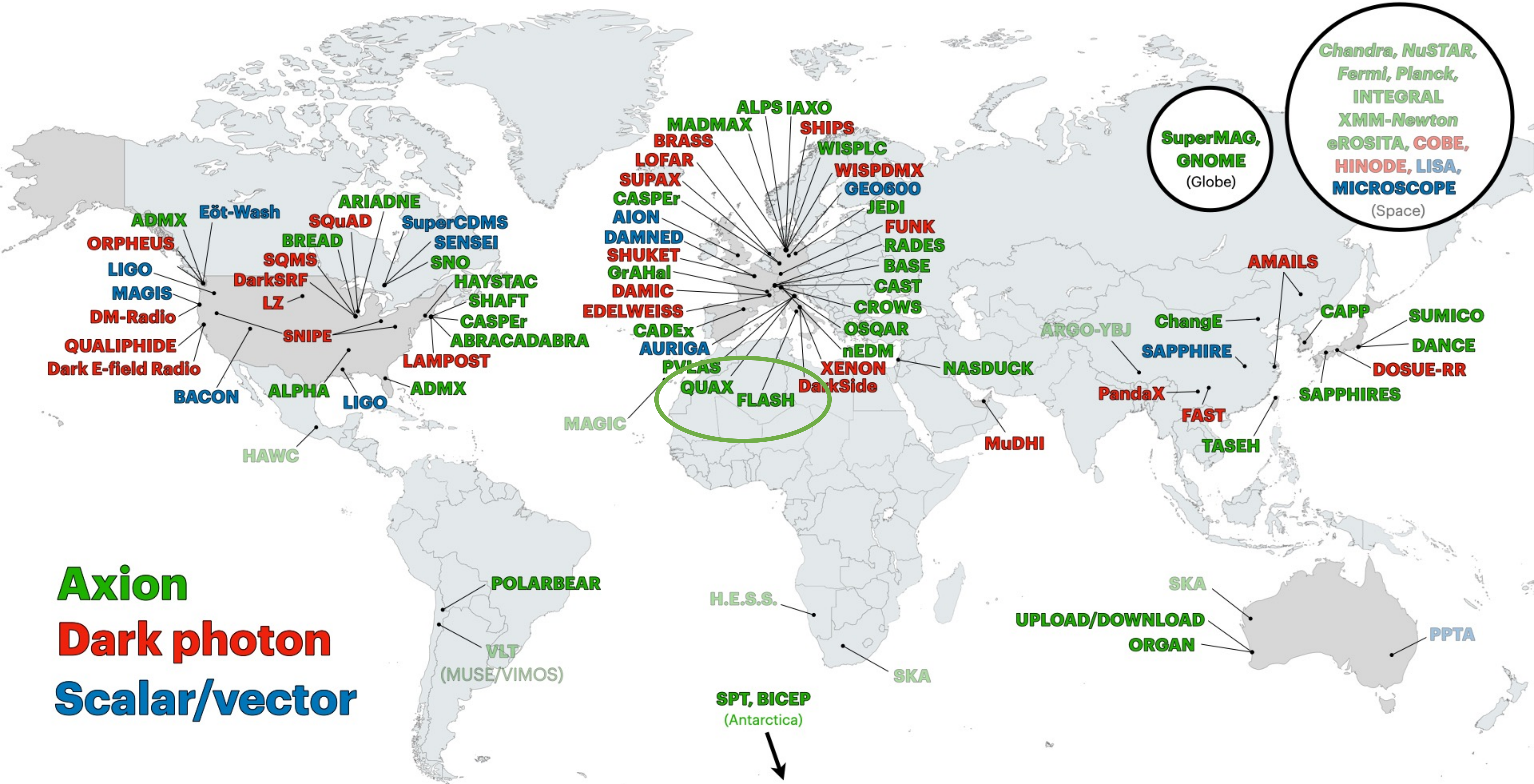


Stellar physics:
Constraints on stellar lifetime or energy-loss rates.

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
LIGO
SQMS
SNO
DarkSRF
HAYSTAC
MAGIS
LZ
SHAFT
DM-Radio
CASPEr
SNIPE
ABRACADABRA
QUALIPHIDE
LAMPOST
Dark E-field Radio
BACON
ALPHA
LIGO
ADMX
HAWC
AMAILS
CAPP
SUMICO
ChangE
ARGO-YBJ
DANCE
SAPPHIRE
DOSUE-RR
PandaX
SAPPHIRES
FAST
TASEH
POLARBEAR
VLT
(MUSE/VIMOS)
H.E.S.S.
SKA
SPT, BICEP
(Antarctica)
SKA
UPLOAD/DOWNLOAD
ORGAN
PPTA
Axion
Dark photon
Scalar/vector



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
NASDUCK
PVLAS
XENON
QUAX
DarkSide
FLASH
MAGIC
MuDHI
SuperMAG, GNOME (Globe)
Chandra, NuSTAR, Fermi, Planck, INTEGRAL XMM-Newton eROSITA, COBE, HINODE, LISA, MICROSCOPE (Space)
ADMX
Eöt-Wash
ARIADNE
SQuAD
SuperCDMS
ORPHEUS
BREAD
SENSEI
LIGO
SQMS
SNO
MAGIS
DarkSRF
HAYSTAC
LZ
SHAFT
DM-Radio
CASPEr
SNIPE
ABRACADABRA
QUALIPHIDE
LAMPOST
Dark E-field Radio
BACON
ALPHA
LIGO
ADMX
HAWC
AMAILS
CAPP
SUMICO
ChangE
ARGO-YBJ
DANCE
SAPPHIRE
DOSUE-RR
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ORGAN
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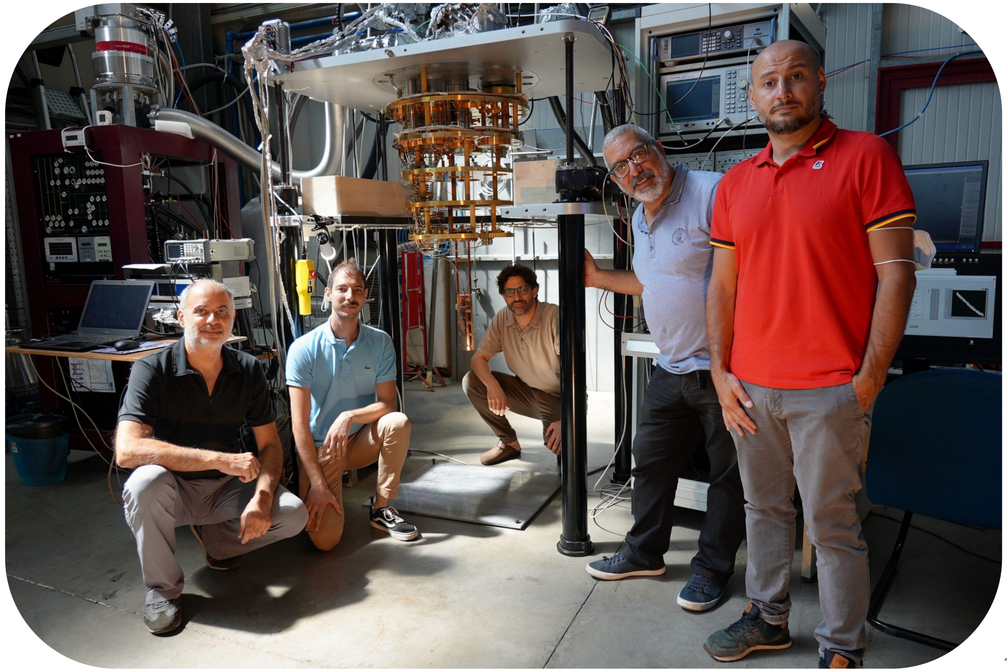
Dark photon
Scalar/vector

QUAX

Laboratori Nazionali di Legnaro (LNL)

Laboratori Nazionali di Frascati (LNF)

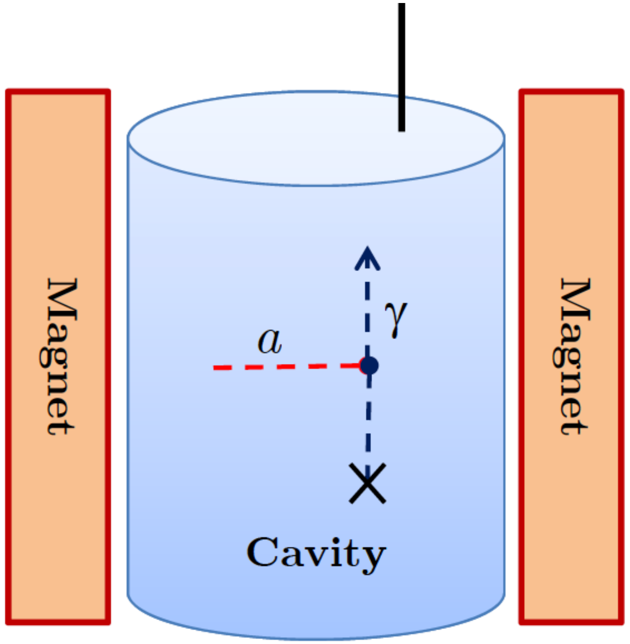


Sikivie's Haloscope

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

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

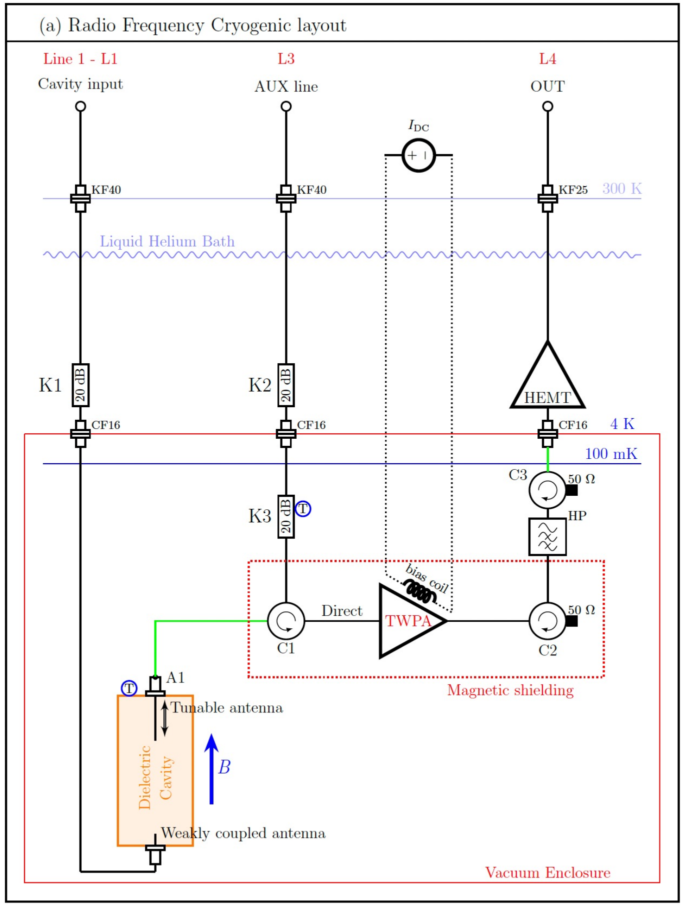
V cavity volume

C_{mnl} mode dependent factor about 0.6 for TM010

Q_L cavity "loaded" quality factor

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

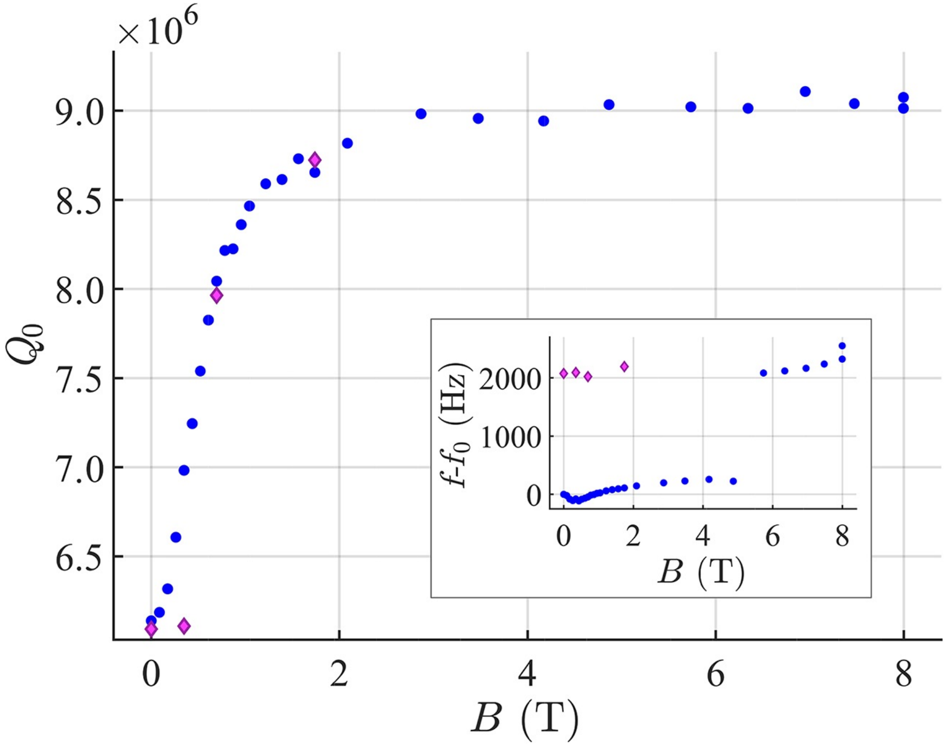
The LNL Haloscope

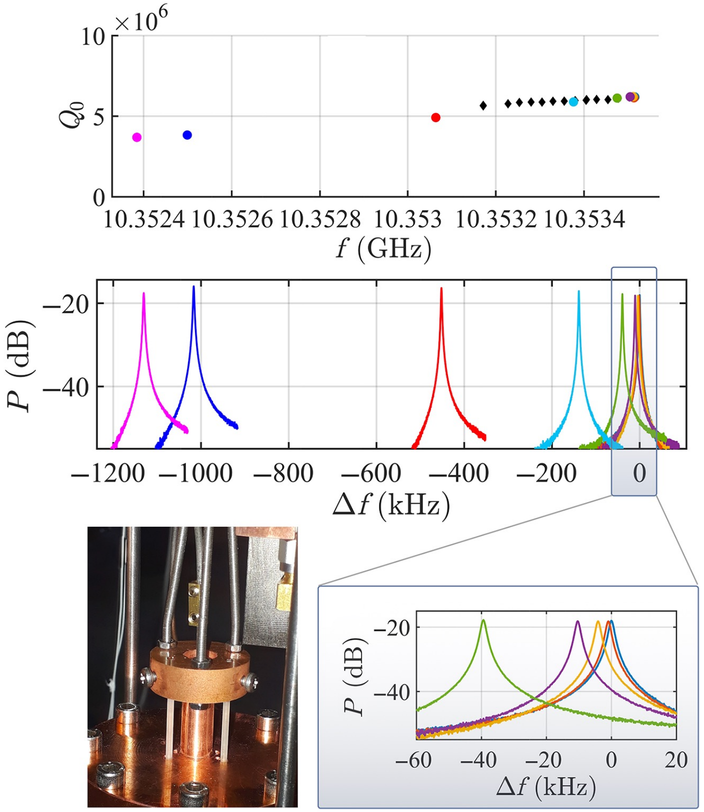


- B=8 T
- Dilution Refrigerator
- Tcavity 110 mK
- TWPA
- T_{noise}=2 K
- Dielectric Cavity
- Sapphire tuner
- Q=2.5×10^5
- VC_{030}=0.034 L

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

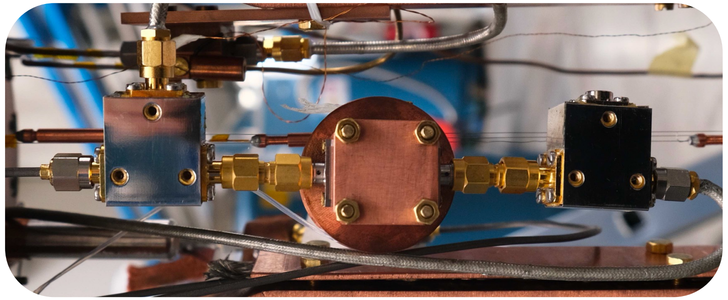
High-Q Microwave Dielectric Resonator for Axion Dark-Matter Haloscopes





PHYSICAL REVIEW APPLIED 17, 054013 (2022)

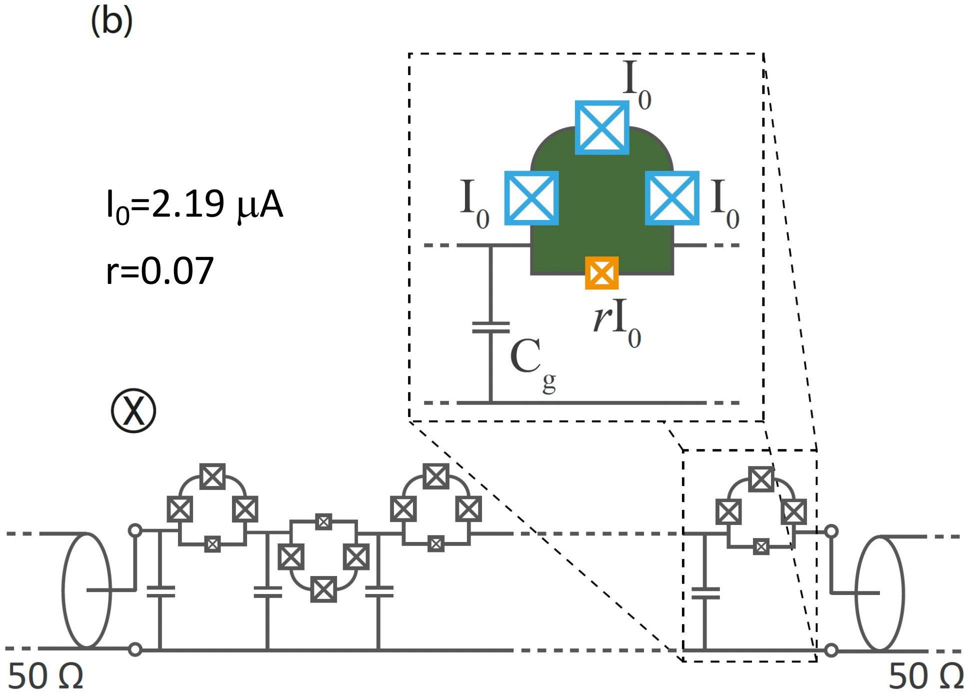
Reversed Kerr TWPA



6 mm transmission line composed by 700 cells made of superconducting nonlinear asymmetric inductive elements (SNAIL)

I_0=2.19 μA

r=0.07



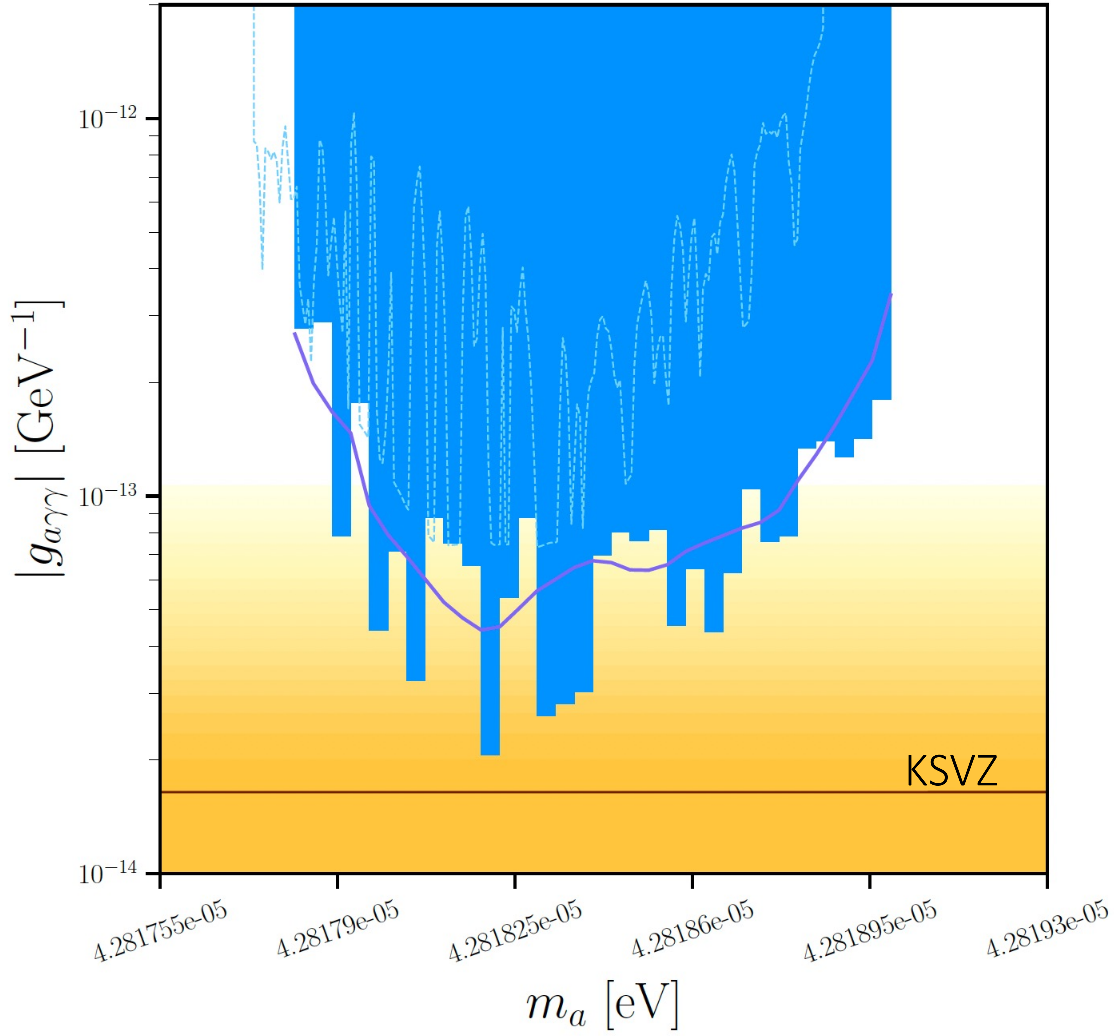
Pump, Signal, Idler

$$\varphi(z,t) = \frac{1}{2}[A_p(z)e^{i(k_p z - \omega_p t)} + A_s(z)e^{i(k_s z - \omega_s t)} + A_i(z)e^{i(k_i z - \omega_i t)} + \text{c.c.}],$$

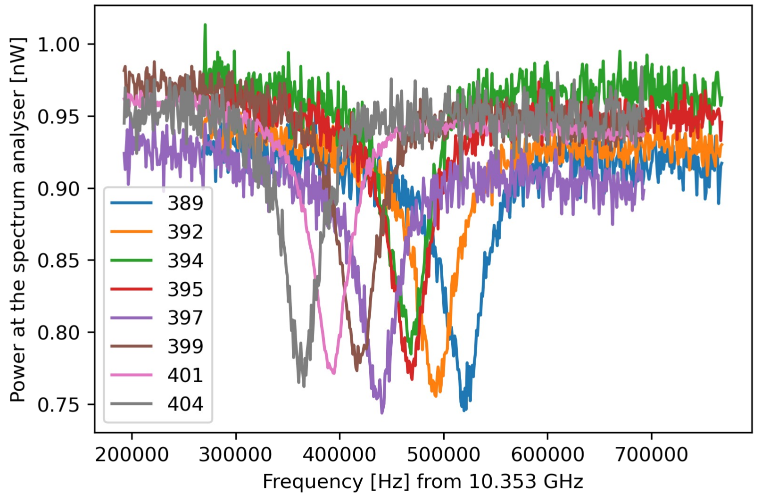
$$\omega_s + \omega_i = 2\omega_p$$

A. Ranadive et al. Kerr reversal in josephson meta-material and traveling wave parametric amplification. Nature Communications, 13(1):1737, Apr 2022.

Results of LNL Axion Search in 2022



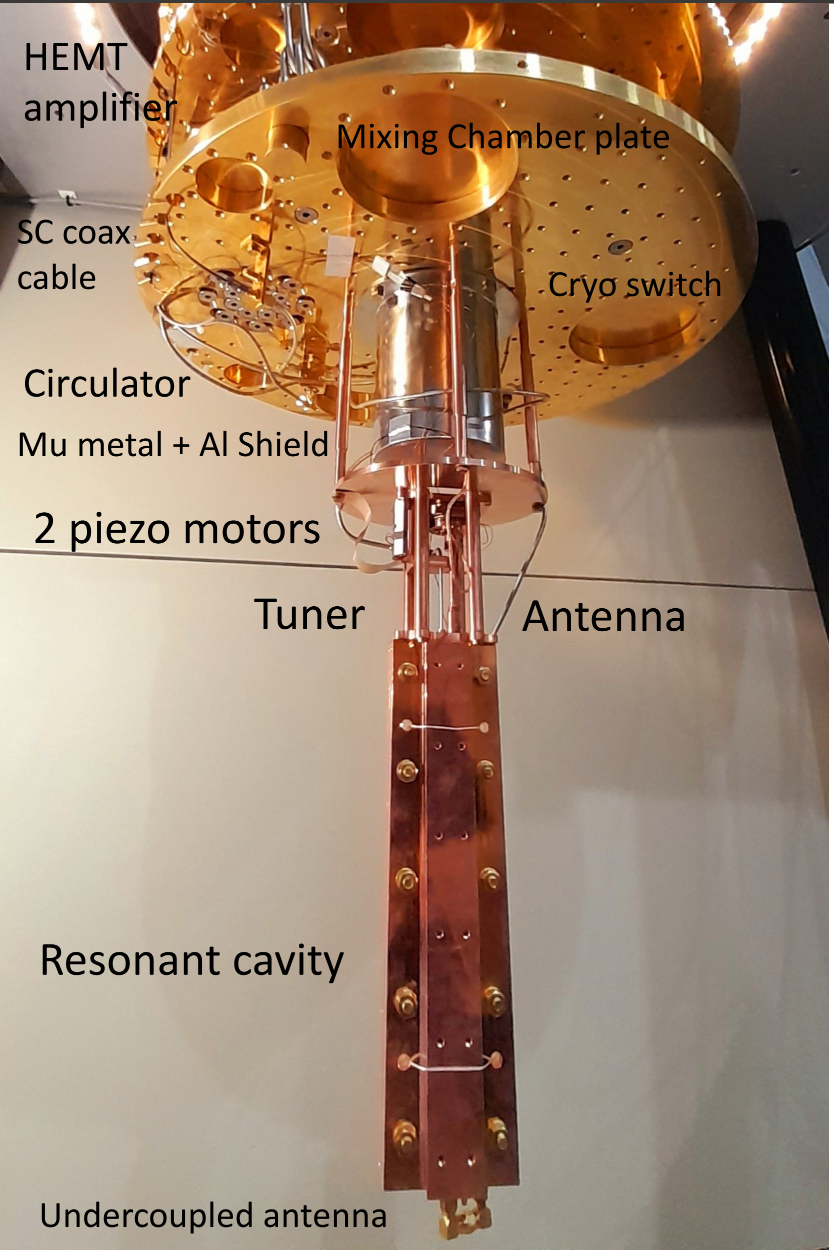
RUN n	$\nu_c - 10.353$ GHz (Hz)	Cavity Q_L	β	Ref Peak (a.u.)
389	522 600	230 000	21.6	179
392	494 100	240 000	23.8	185
394	468 800	245 000	24.2	186
395	468 800	245 000	24.2	187
397	439 800	245 000	22.7	175
399	418 500	245 000	22.6	191
401	393 100	250 000	22.5	186
404	365 400	255 000	23.5	193



Scanning rate:
About 10h Run → 0.3 MHz/day

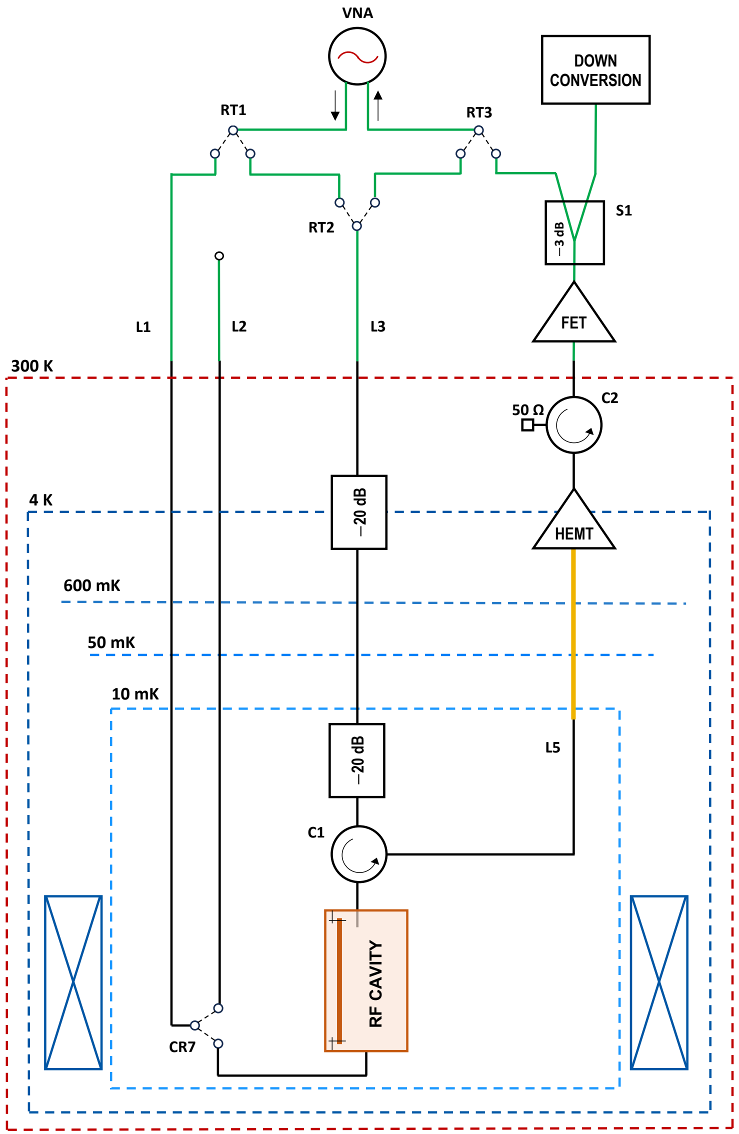
Search for galactic axions with a traveling wave parametric amplifier
PHYSICAL REVIEW D 108, 062005, arXiv:2304.7505 (2023)

QUAX@LNF: The LNF Axion Haloscope

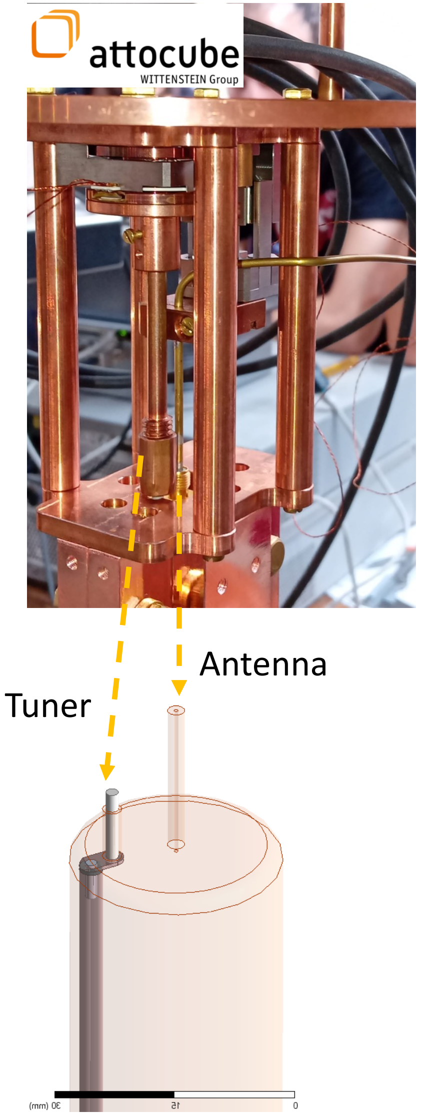


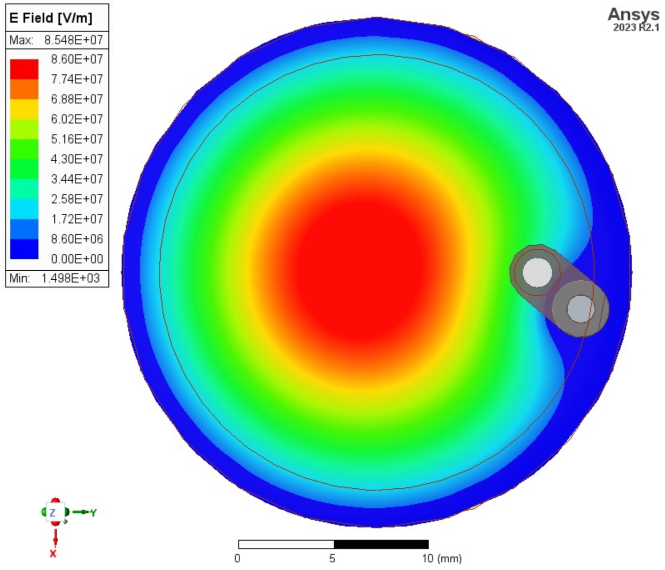
December 2023 Run

- 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

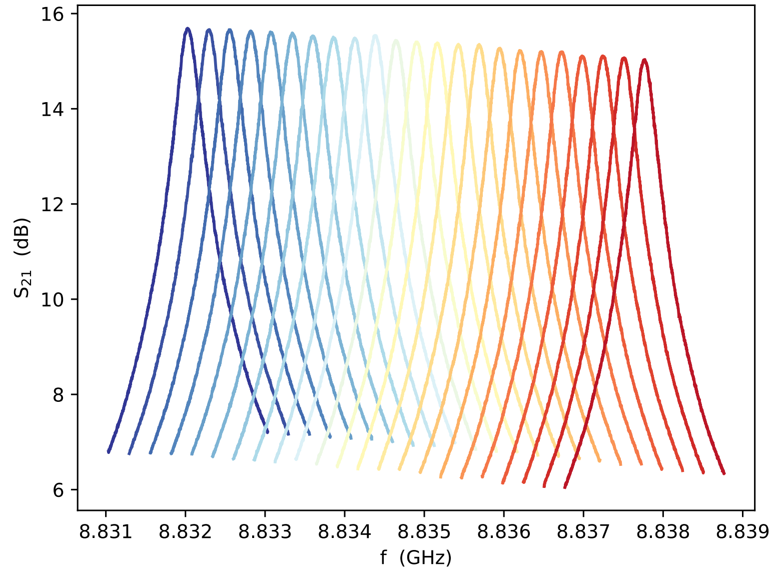


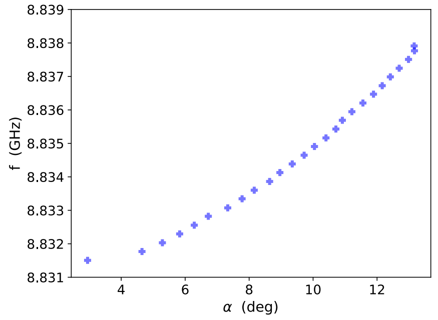
Cavity Tuning

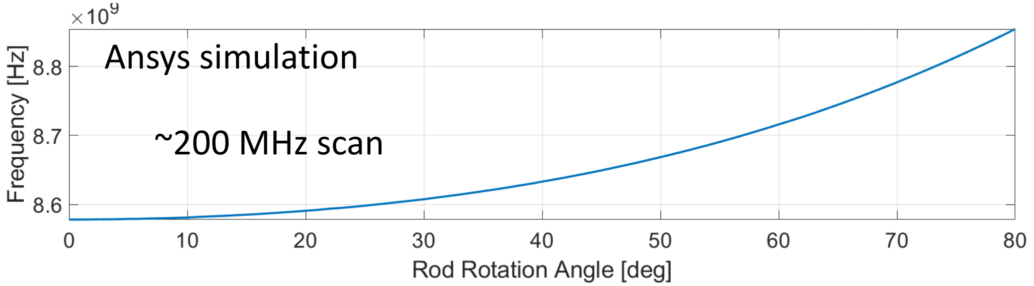




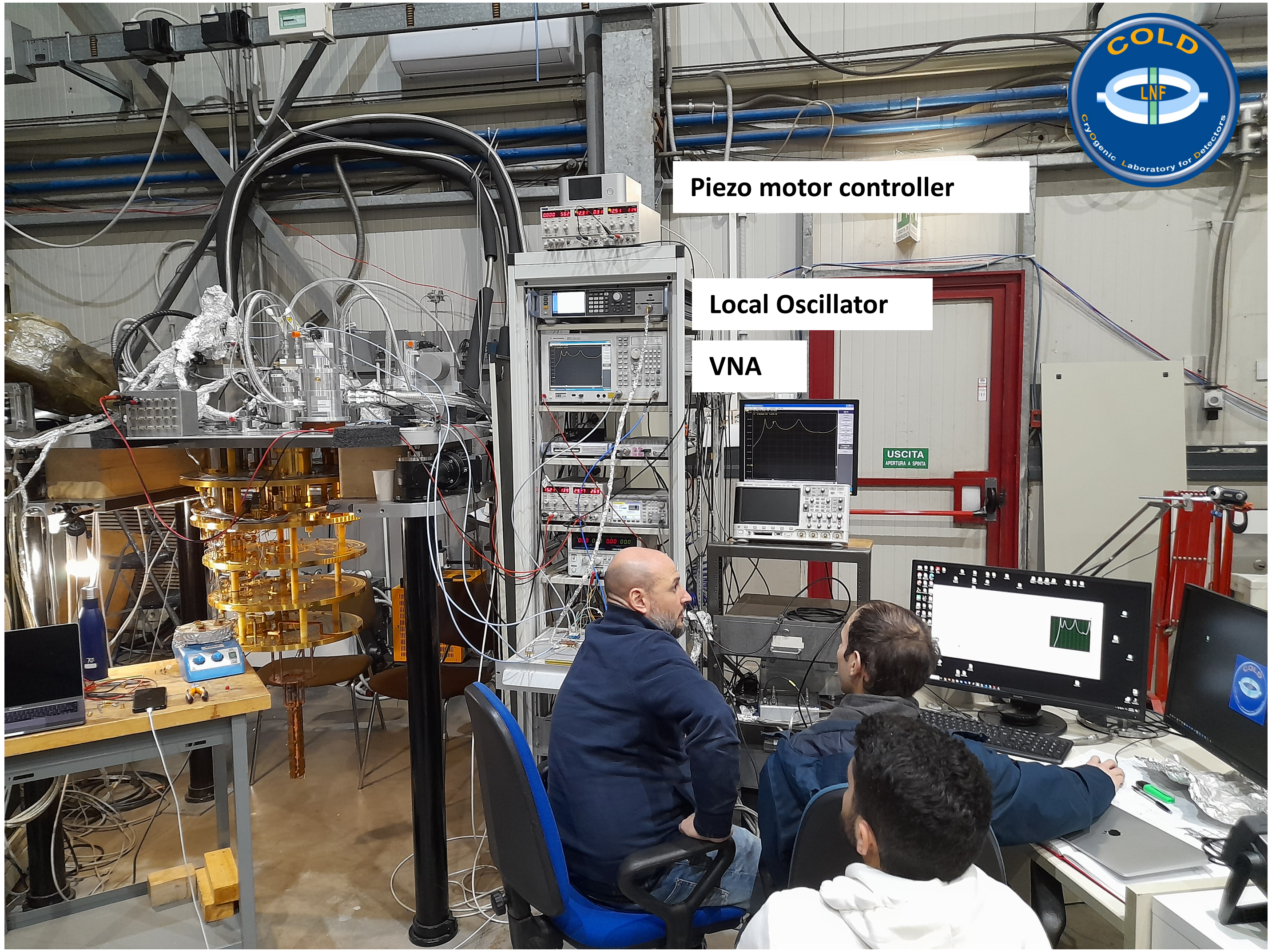
6 MHz of frequency scan

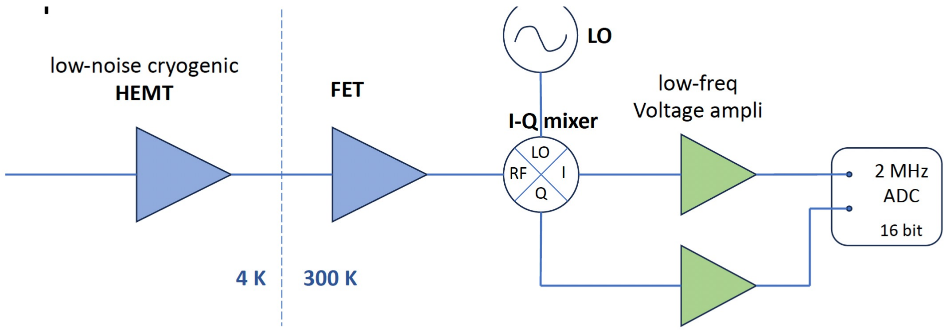






Acquisition Chain





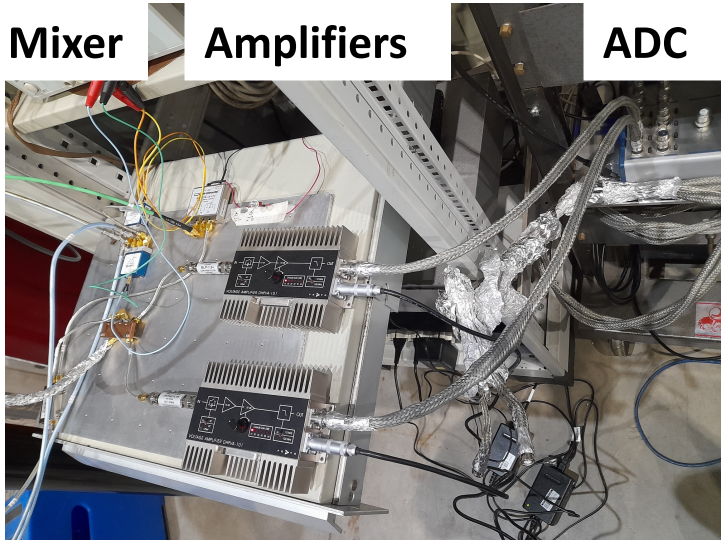
$G^{HEMT} \simeq 37\ dB$
$T_n^{HEMT} \simeq 3\ K$

$G^{FET} \simeq 36\ dB$
$T_n^{FET} \simeq 80\ K$

$G^{V} \simeq \times 1000$
$V_n = 2.3\ nV/\sqrt{Hz}$

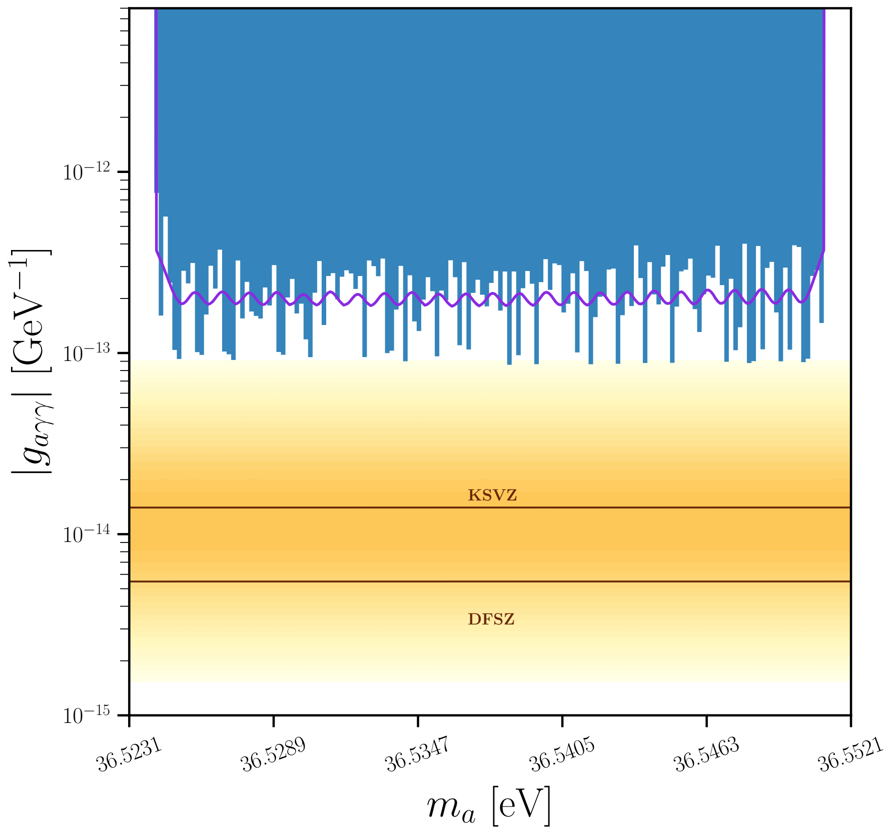
Tot eff. Gain = 116 dB

Noise Temp = 4.5 K



QUAX@LNF Results for 2023 Run

- 24 runs, 1 hour each, 250 kHz of frequency steps
- Average exclusion 90% c.l. $g_{a\gamma\gamma} = 2\times10^{-13}\ GeV^{-1}$
- Preprint arXiv:2404.19063

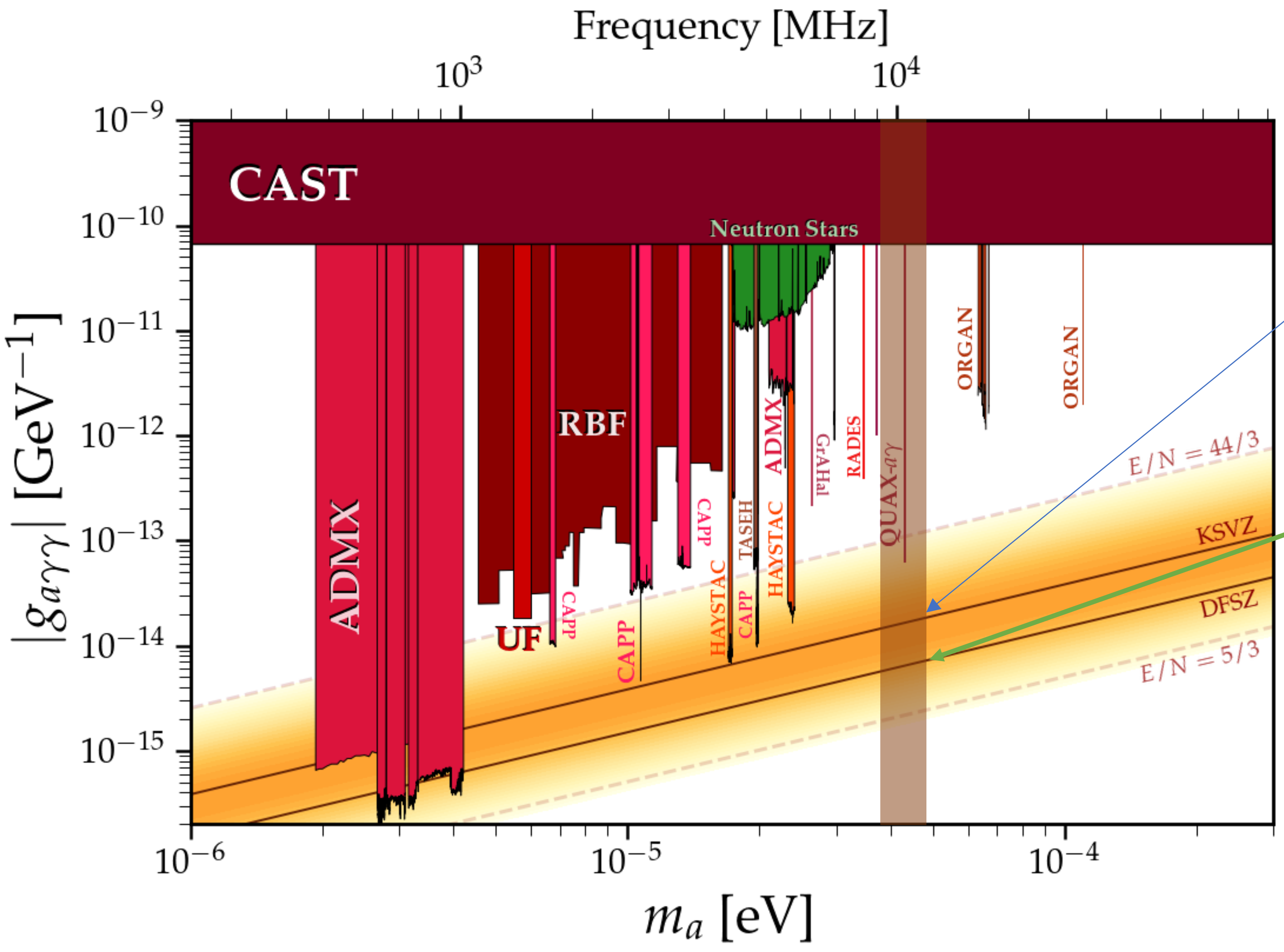


ν_c [GHz]	Q_L	β
8.83176900	32345	0.5206
8.83203080	32228	0.519
8.83229550	32273	0.5082
8.83255580	32332	0.5141
8.83282190	32387	0.5097
8.83307310	32401	0.5078
8.83334500	32300	0.5097
8.83360070	32503	0.5058
8.83386200	32540	0.5075
8.83412790	32752	0.5014
8.83438580	32573	0.5026
8.83464620	32904	0.5005
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

QUAX LNF&LNL 2023-2025

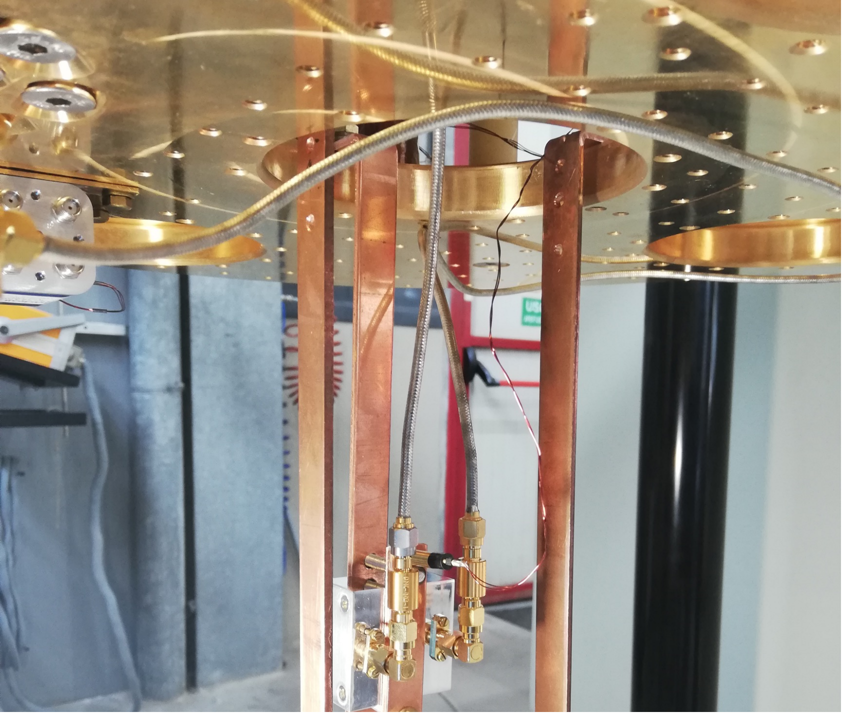
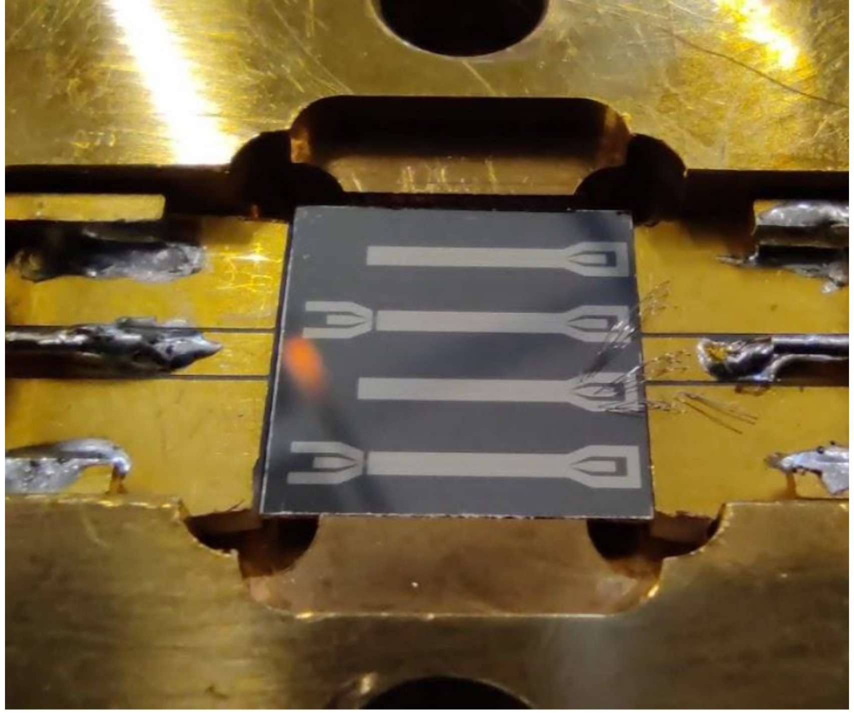
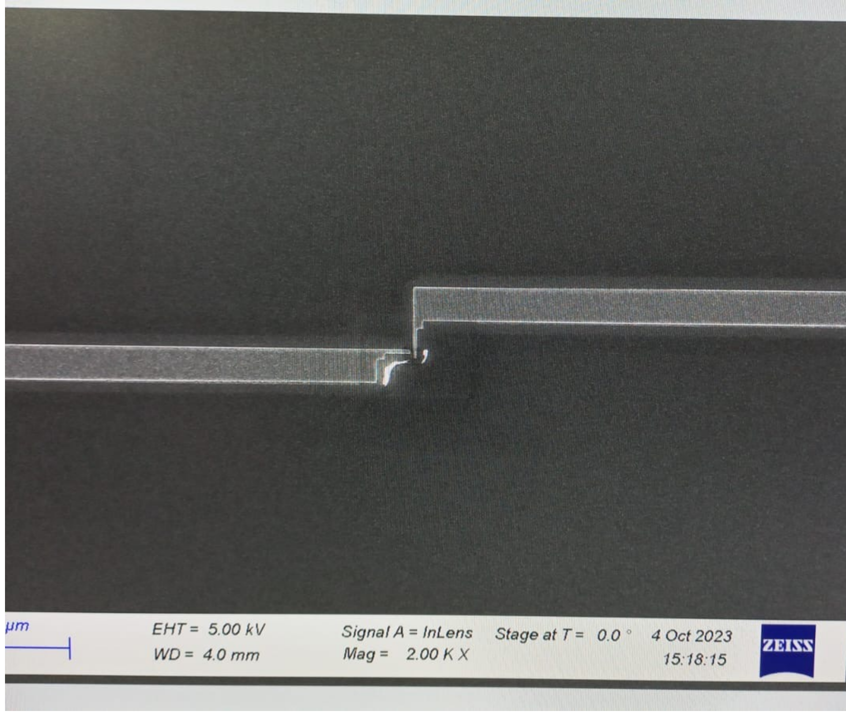
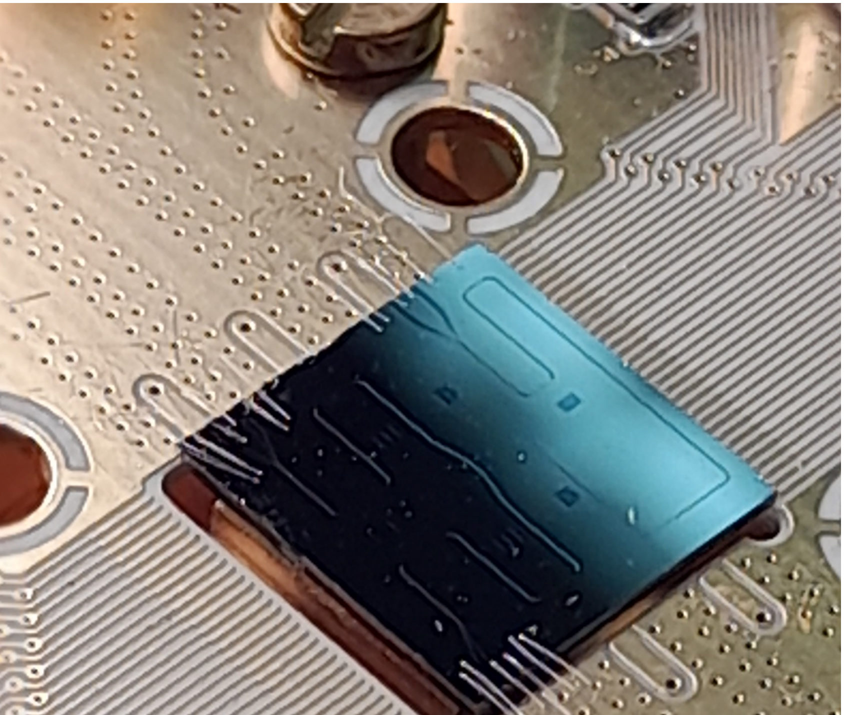
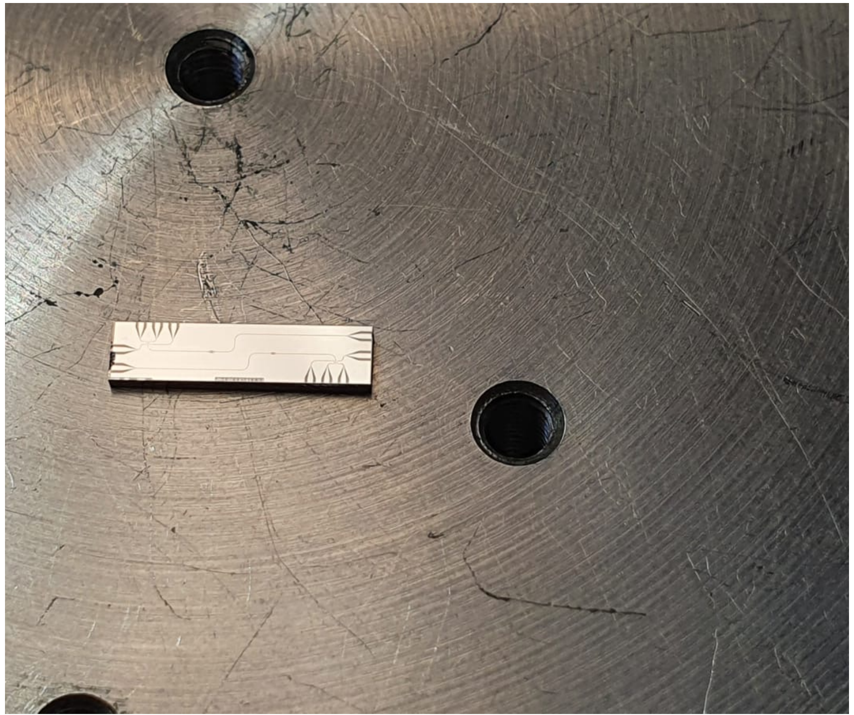
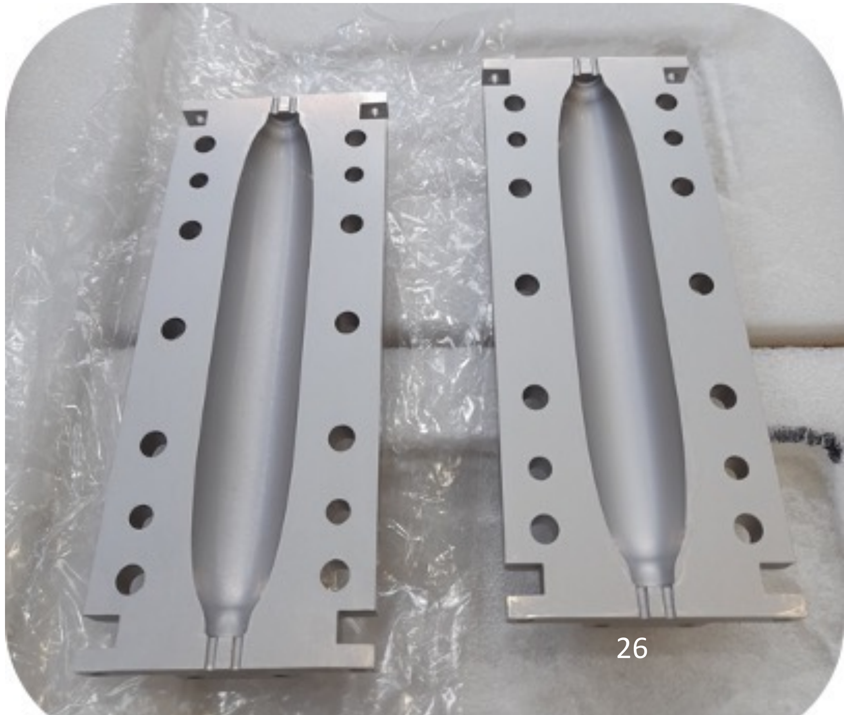
LNF:
- Superconducting cavity $Q_0 > 2\times10^5$
- B=9T
- Multicavity

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
ZEISS




COLD@LNF

CryOgenic Laboratory for Detectors:

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

CA 21106

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

DARTWARS

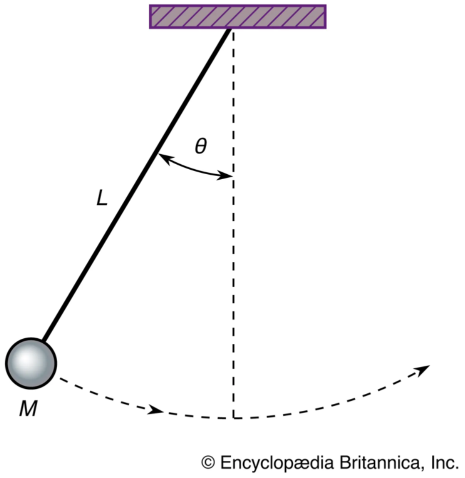
Qub-IT

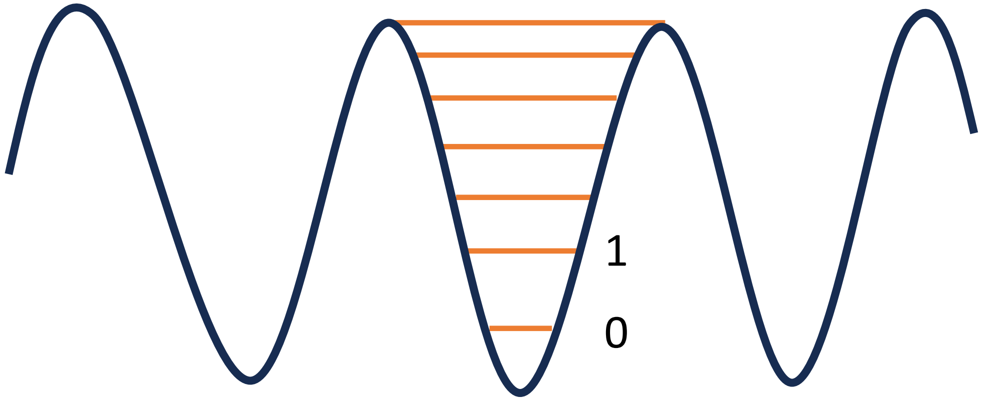
NQSTI National Quantum Science and Technology Institute

SUPERGALAX

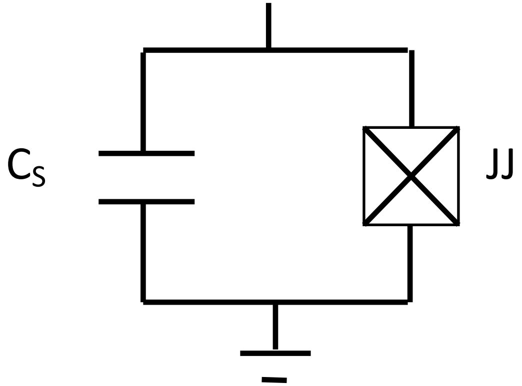
SQMS

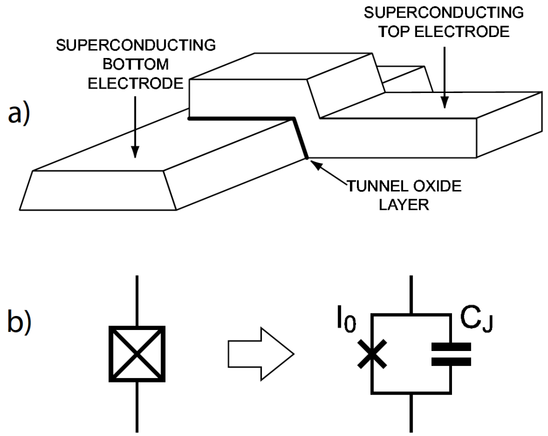
The Superconducting Qubit





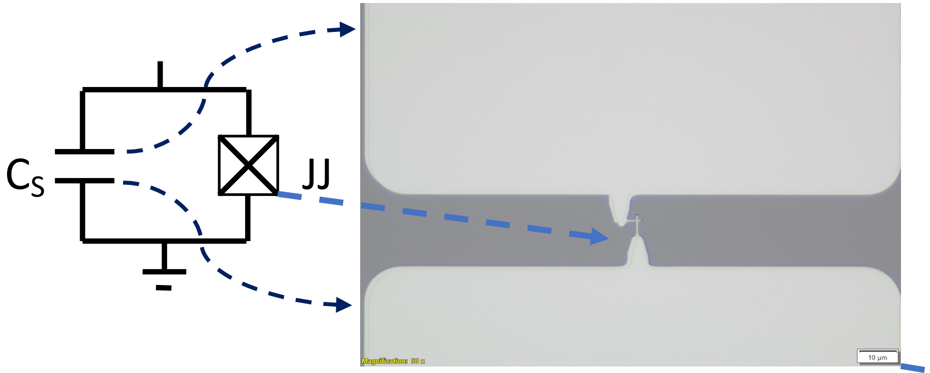
$$E = \frac{Q^2}{2C} - E_J cos 2\pi\phi/\phi_0$$

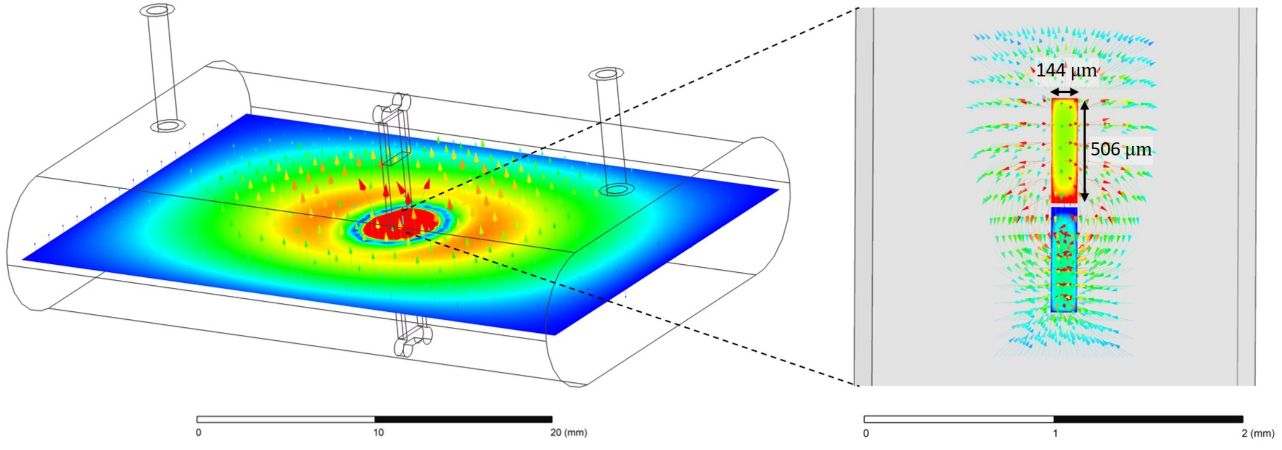


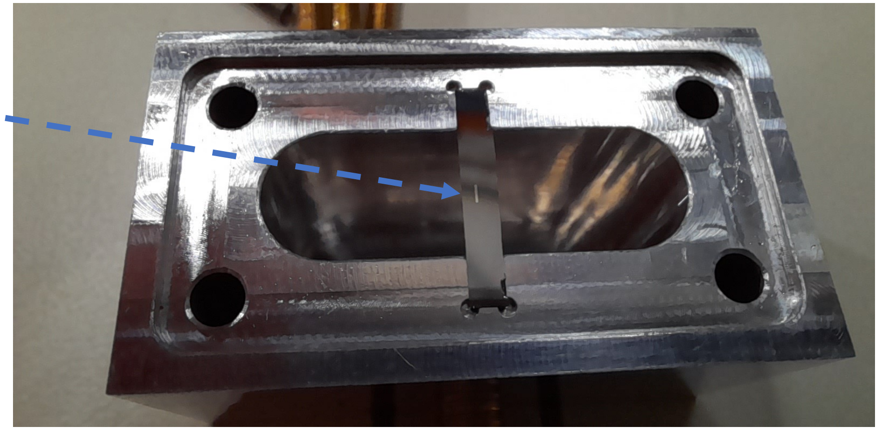


J Koch Phys. Rev. A 76 042319 (2007)

Qubit in a 3D Resonator

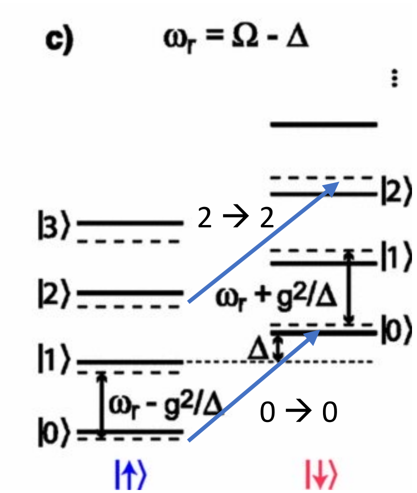






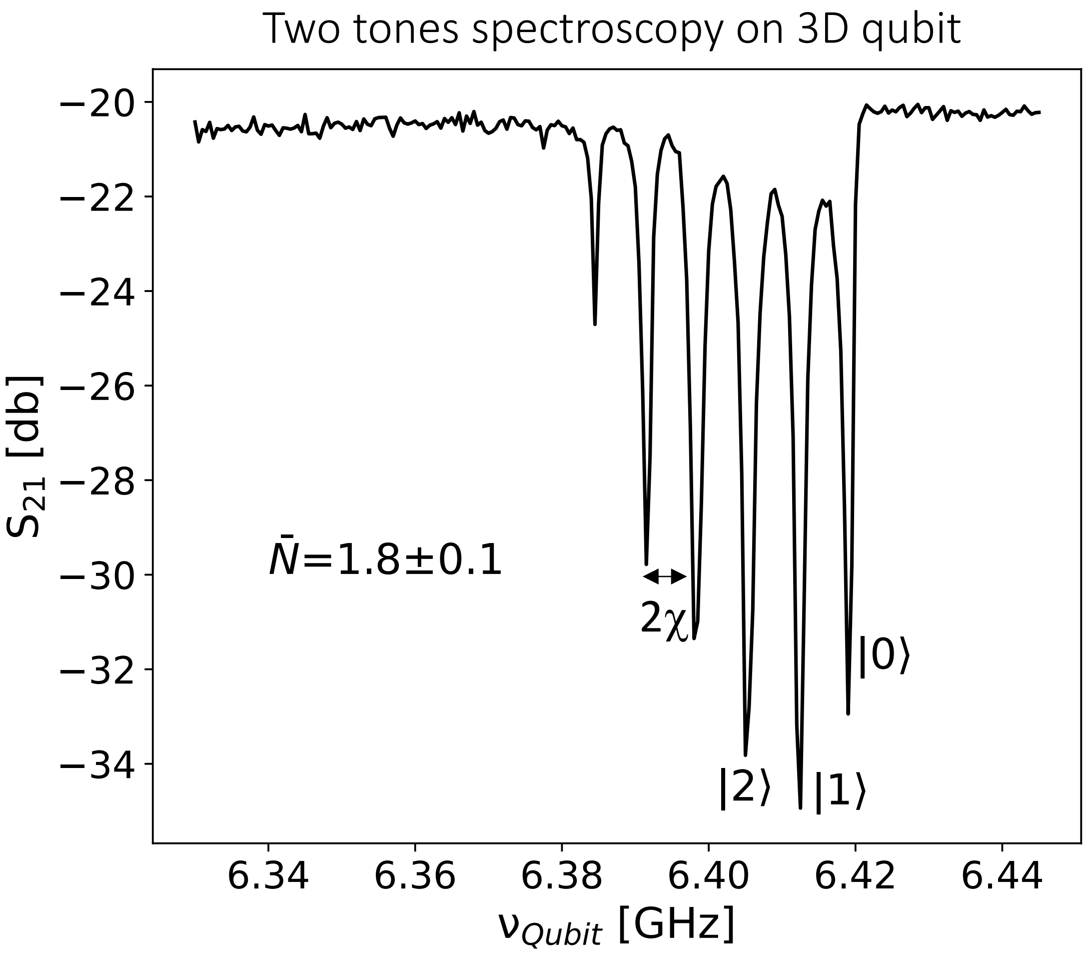
TII Technology Innovation Institute

Quantum Sensing with SC Qubits



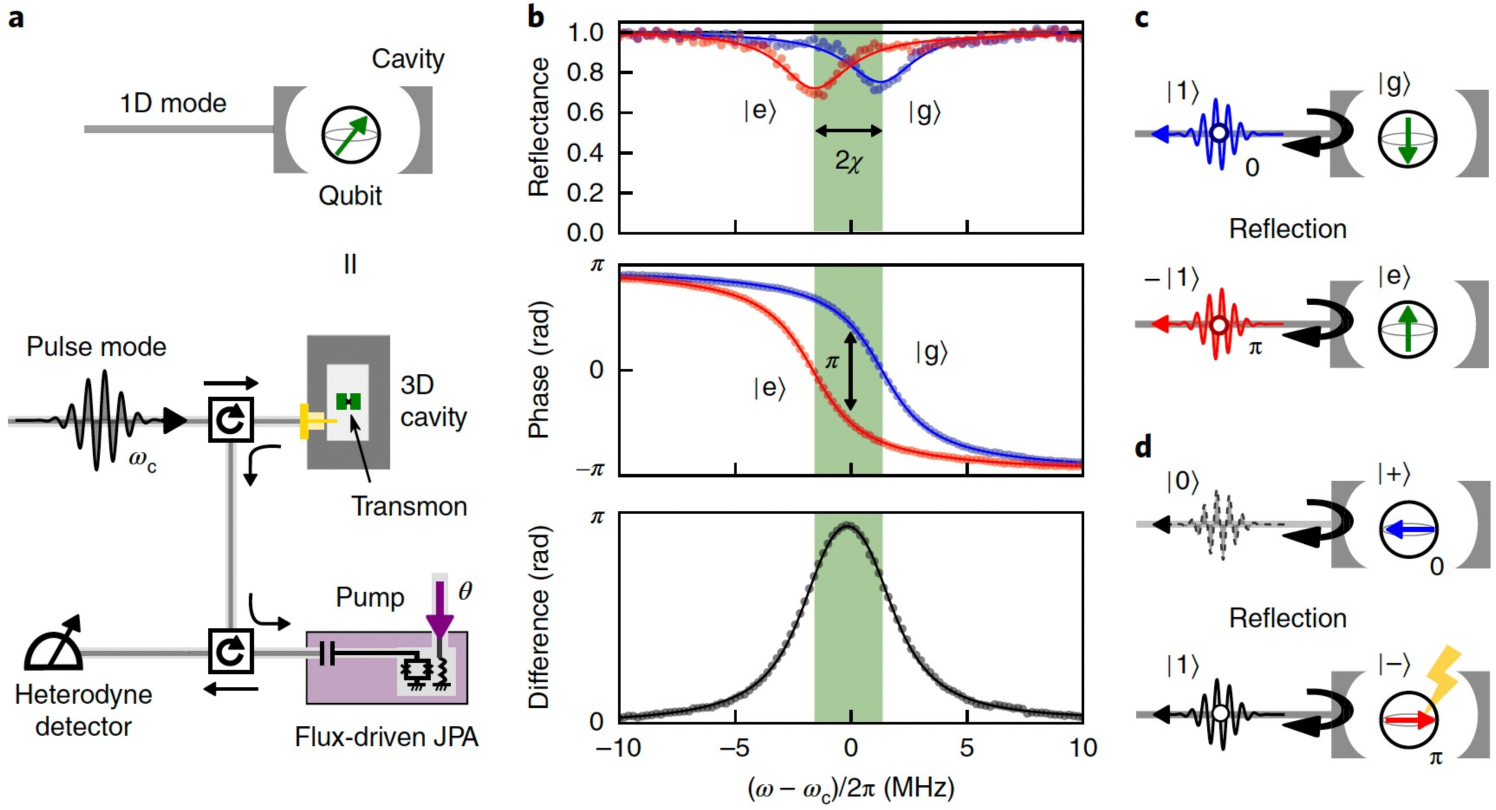
$$\omega'_q = \omega_q + 2n_\gamma\chi$$

Photon number in resonator



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

Quantum non–demolition detection of an itinerant photon



The qubit dephasing during the gate interval results in an erroneous phase flip of the qubit. The qubit dephasing also contributes dominantly to the dark-count probability of 0.0147 ± 0.0005.

Need to match dispersive shift with resonator width!

Dark count rate

$$R = \frac{p(1|0)}{T_2} \approx \frac{1\%}{26\ \mu s} = 385\ Hz$$

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

Two Qubits Scheme

0 - Initial state

$$|Q_1Q_2\rangle_{\overline{\gamma}} = |0\rangle \times |0\rangle$$

1 - Prepare the qubits in 0+1 state

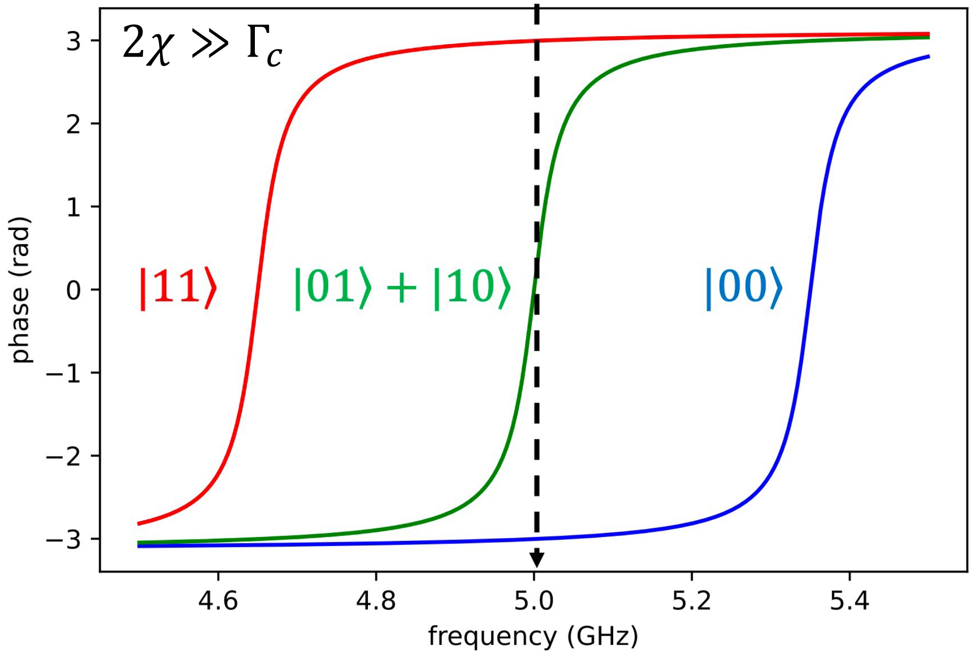
$$|Q_1Q_2\rangle = \frac{1}{2}(|0\rangle + |1\rangle) \times (|0\rangle + |1\rangle)$$

2a - If no photons arrive, nothing happens.
Complete Ramsey cycle

$$|Q_1Q_2\rangle_{\overline{\gamma}} = |0\rangle \times |0\rangle$$

2b - If instead a photon arrives

$$\begin{aligned} |Q_1Q_2\rangle_\gamma &= \frac{1}{2}\left(e^{-i\pi}|00\rangle + |10\rangle + |01\rangle + e^{i\pi}|11\rangle\right) \\ &= \frac{-1}{2}(|00\rangle - |10\rangle - |01\rangle + |11\rangle) \\ &= -\frac{1}{2}(|0\rangle - |1\rangle) \times (|0\rangle - |1\rangle) \end{aligned}$$



3 - Completing the Ramsey cycle

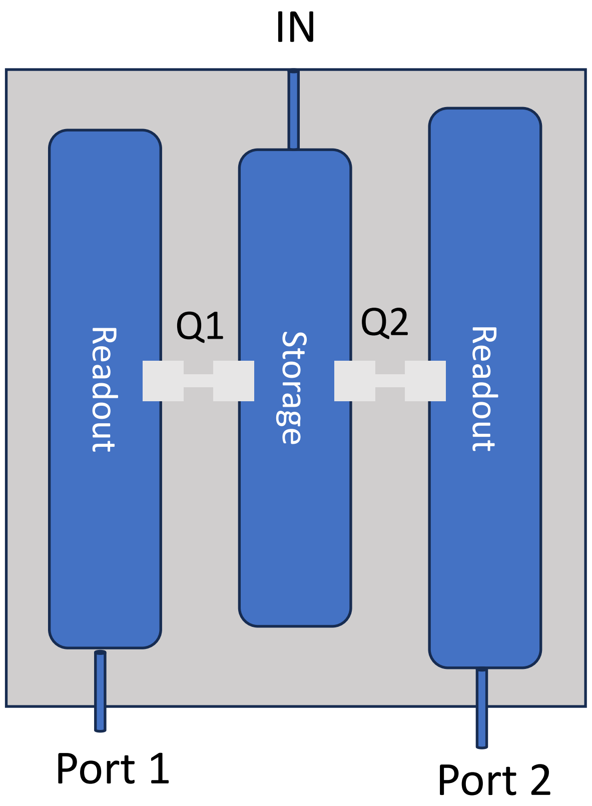
$$|Q_1Q_2\rangle_\gamma = |1\rangle \times |1\rangle$$

Dark count rate

$$R = \frac{p(1|0)^2}{T_2/2} \approx \frac{2\times10^{-4}}{26\ \mu s} = 8\ Hz$$

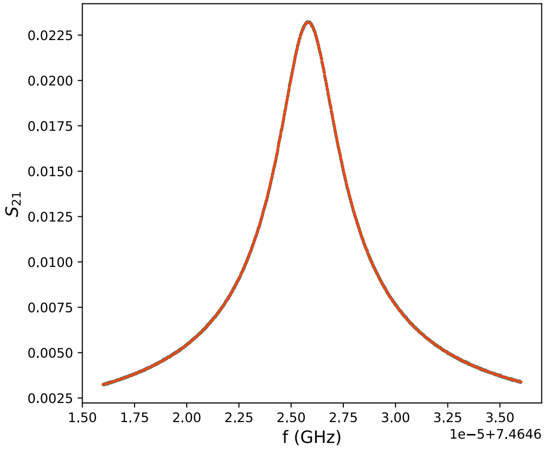
Appl. Sci. 2024, 14(4), 1478

Two Qubits Scheme

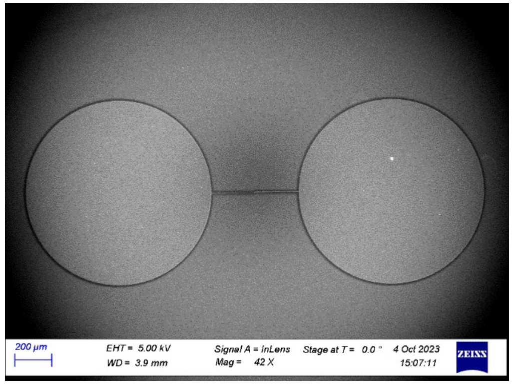


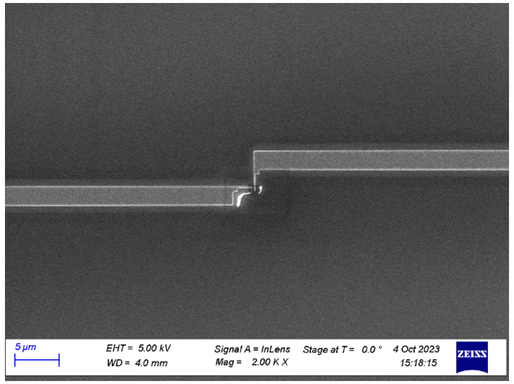
R&D on cavity fabrication

$Q_0 = 3.7 \times 10^6$



R&D on qubit fabrication (CNR-IFN)





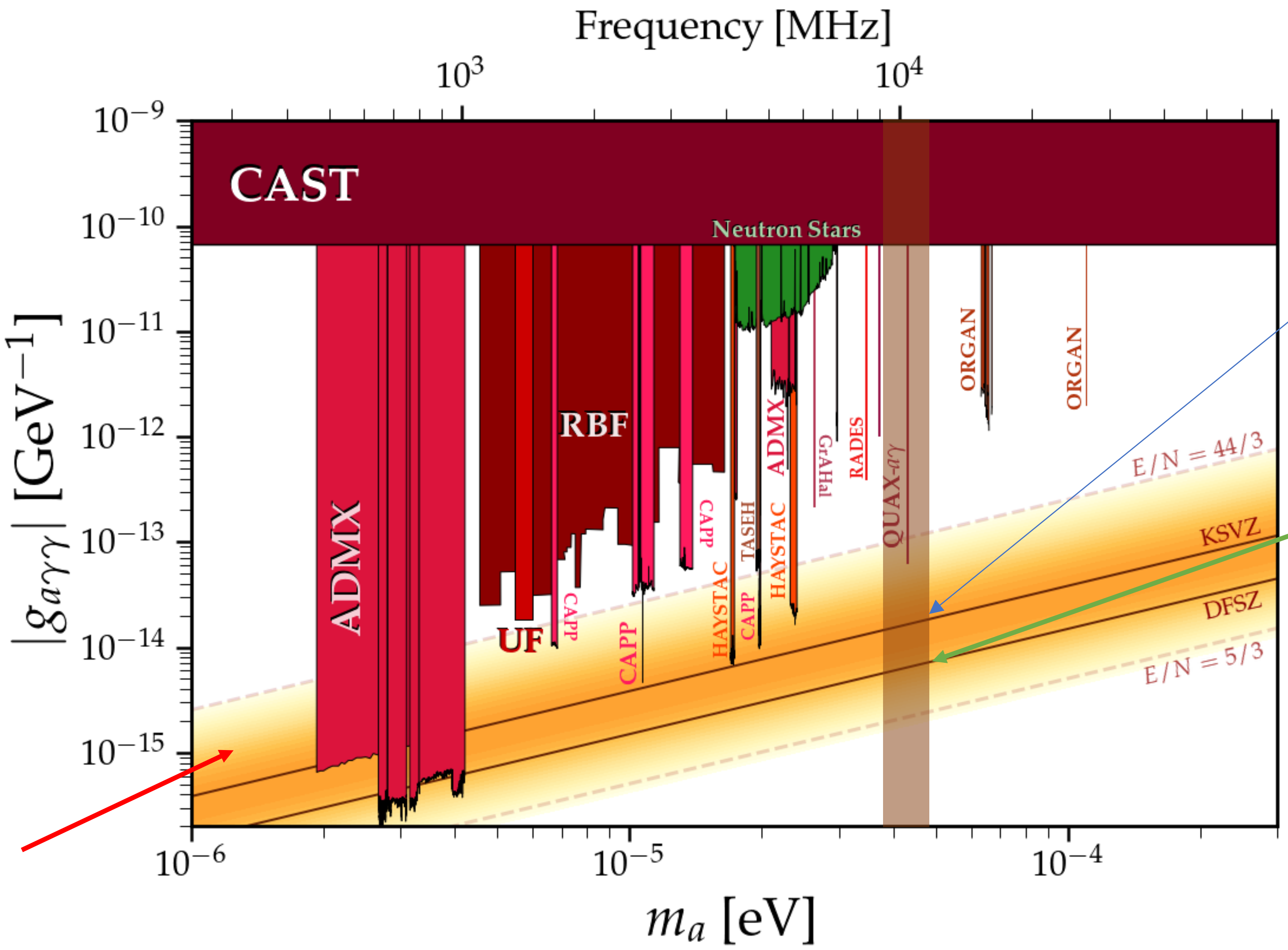
QUAX LNF&LNL 2023-2025

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?

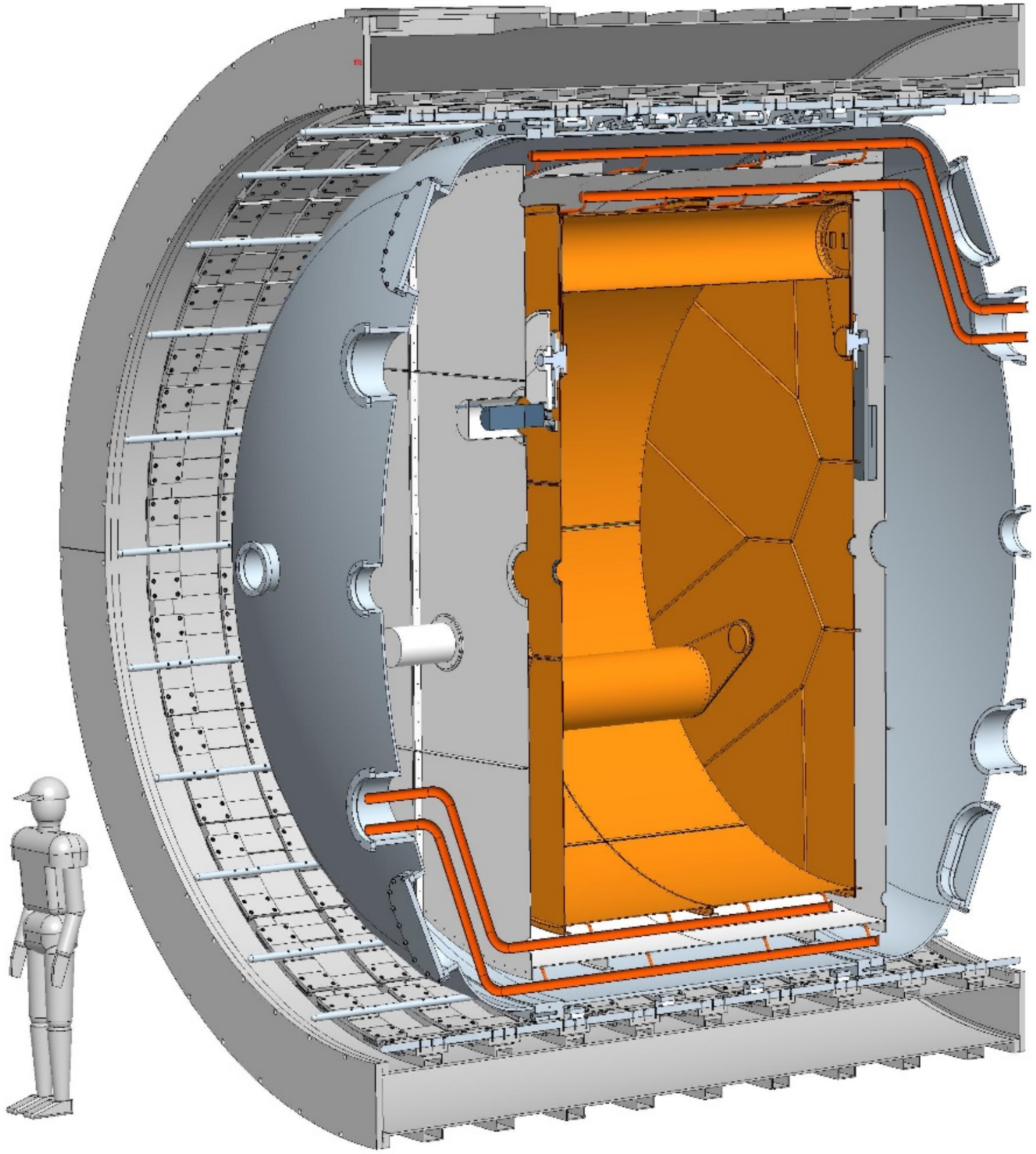
Next years with noise at Quantum Limit

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

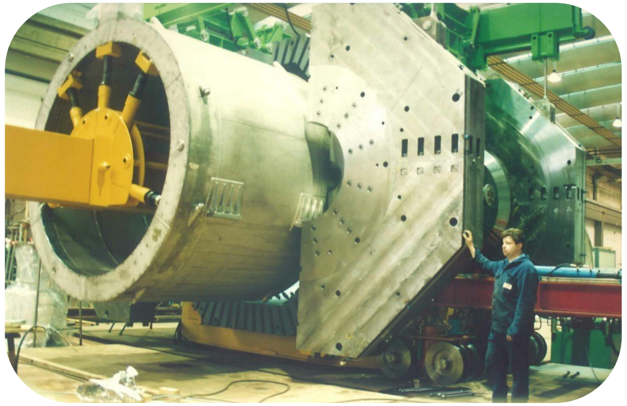
See arXiv:2403.02321 for LNL R&D on photon counter

FLASH
Finuda magnet for Light Axion SearcH

Galactic axion search at 100 MHz (0.5-1.5 μeV)

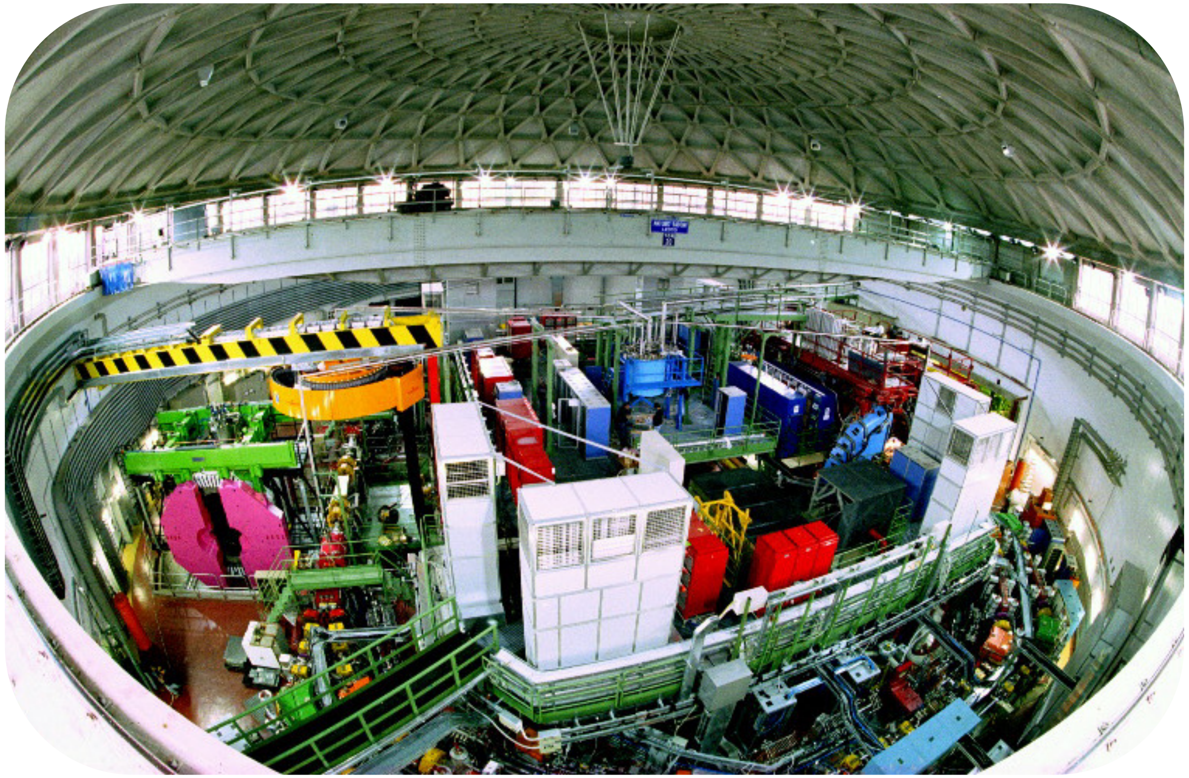


Large Superconducting Magnets at LNF



FINUDA→FLASH

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



KLOE→KLASH

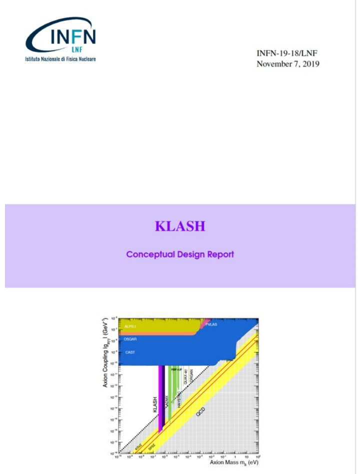
B(T)	0.6
I(A)	2300
R(m)	2.43
L(m)	4.4

Laboratori Nazionali di Frascati

INFN-18-09-LNF
September 18, 2018

The KLASH – Letter of Intent

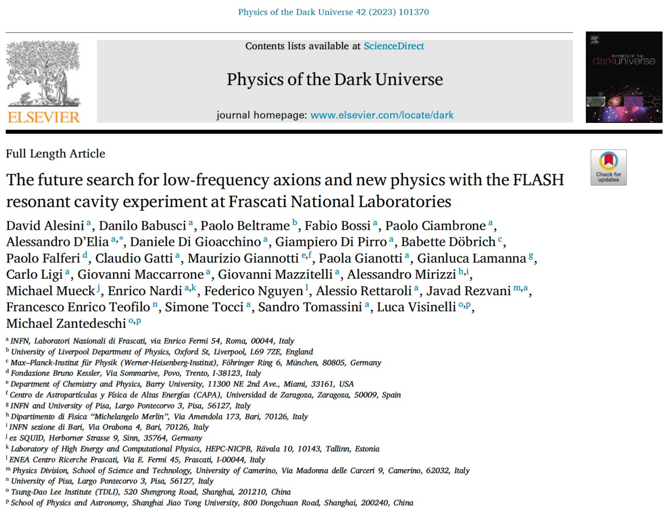
D.Alesini[1], D.Babusci[1], F.Bossi[1], P.Ciambrone[1], G.Corcella[1], D.Di Gioacchino[1], P.Falferi[2], C.Gatti[1], A.Ghigo[1], G.Lamanna[3], C.Ligi[1], G.Maccarrone[1], A.Mirizzi[4], D.Montanino[5], D.Moricciani[1], A.Mostacci[6], E.Nardi[1], A.Paoloni[1], L.Pellegrino[1], A.Rettaroli[1], R.Ricci[1],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



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

Full Length Article

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

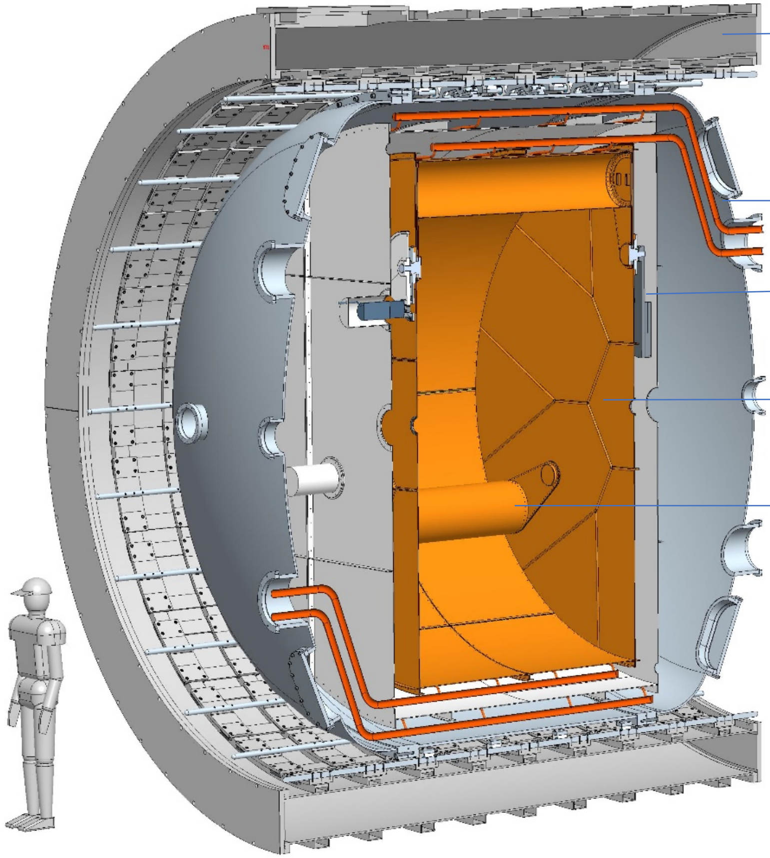
David Alesini[a], Danilo Babusci[a], Paolo Beltrame[b], Fabio Bossi[a], Paolo Ciambrone[a], Alessandro D'Elia[a,*], Daniele Di Gioacchino[a], Giampiero Di Pirro[a], Babette Döbrich[c], Paolo Falferi[d], Claudio Gatti[a], Maurizio Giannotti[e,f], Paola Gianotti[a], Gianluca Lamanna[g], Carlo Ligi[a], 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]

[a] INFN, Laboratori Nazionali di Frascati, via Enrico Fermi 54, Roma, 00044, Italy
[b] University of Liverpool Department of Physics, Oxford St, Liverpool, L69 7ZE, England
[c] Max–Planck-Institut für Physik (Werner-Heisenberg-Institut), Föhringer Ring 6, München, 80805, Germany
[d] Fondazione Bruno Kessler, Via Sommarive, Povo, Trento, I-38123, Italy
[e] Department of Chemistry and Physics, Barry University, 11300 NE 2nd Ave., Miami, 33161, USA
[f] Centro de Astropartículas y Física de Altas Energías (CAPA), Universidad de Zaragoza, Zaragoza, 50009, Spain
[g] INFN and University of Pisa, Largo Pontecorvo 3, Pisa, 56127, Italy
[h] Dipartimento di Fisica "Michelangelo Merlin", Via Amendola 173, Bari, 70126, Italy
[i] INFN sezione di Bari, Via Orabona 4, Bari, 70126, Italy
[j] ez SQUID, Herborner Strasse 9, Sinn, 35764, Germany
[k] Laboratory of High Energy and Computational Physics, HEPC-NICPB, Rävala 10, 10143, Tallinn, Estonia
[l] ENEA Centro Ricerche Frascati, Via E. Fermi 45, Frascati, I-00044, Italy
[m] Physics Division, School of Science and Technology, University of Camerino, Via Madonna delle Carceri 9, Camerino, 62032, Italy
[n] University of Pisa, Largo Pontecorvo 3, Pisa, 56127, Italy
[o] Tsung-Dao Lee Institute (TDLI), 520 Shengrong Road, Shanghai, 201210, China
[p] School of Physics and Astronomy, Shanghai Jiao Tong University, 800 Dongchuan Road, Shanghai, 200240, China

KLASH CDR arXiv:1911.02427

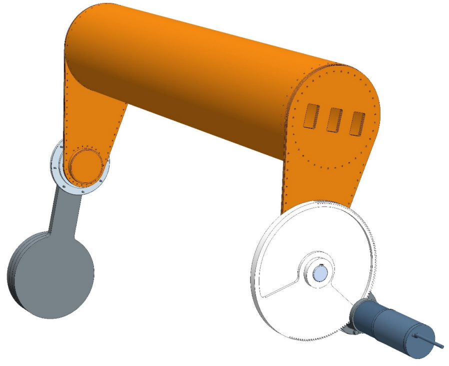
FLASH paper Phys. Dark Univ. 42 (2023)

THE F(K)LASH Cryostat and Resonant Cavity

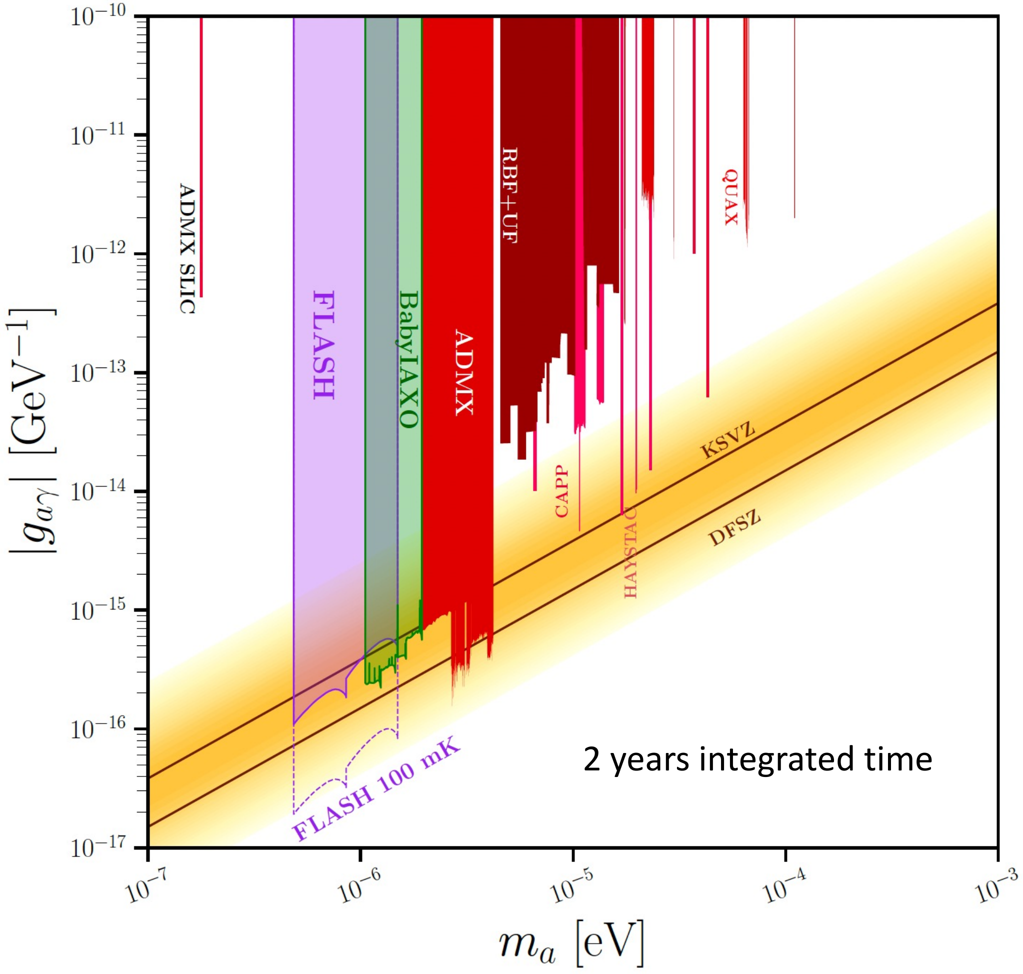


Design by FANTINI Sud Mechanical Div.

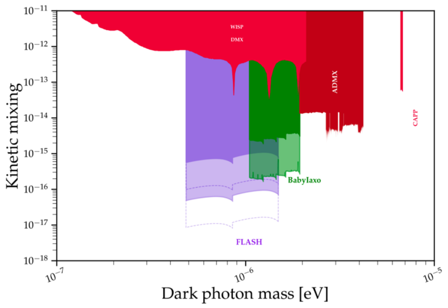
- KLOE/FINUDA Magnet
- Vacuum vessel made by a-magnetic stainless steel
- Shield in aluminum alloy, to be cooled to 70 K by gaseous Helium
- OFHC Cu resonant cavity, cooled to 4.6 K by saturated liquid Helium
- 3 OFHC Cu tuning bars mounted on eccentric cranks with reduction gearboxes

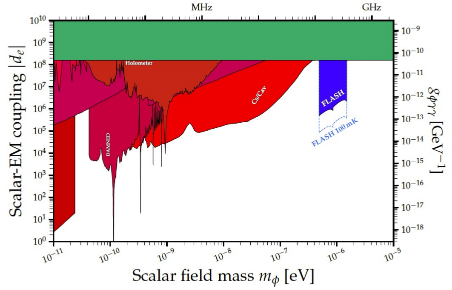


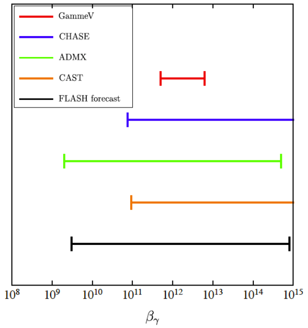
Sensitivity to Axions and ALPS



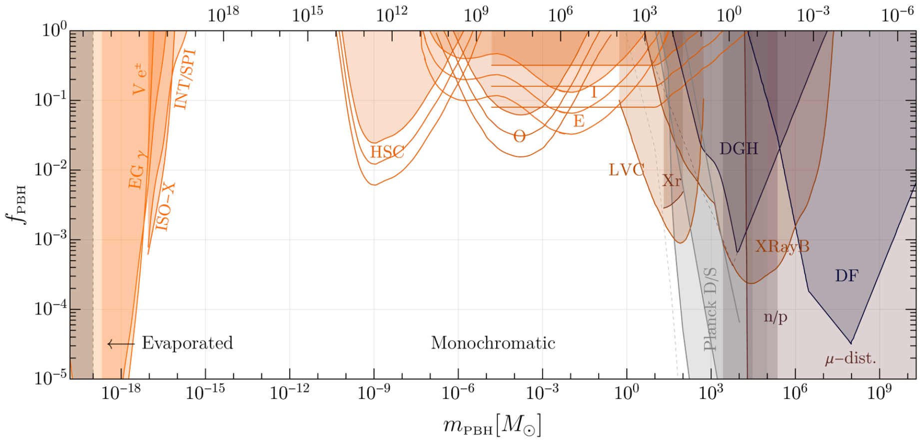
Parameter	Value
ν_c [MHz]	150
m_a [μeV]	0.62
$g_{a\gamma\gamma}^{\mathrm{KSVZ}}$ [GeV^{-1}]	2.45×10^{-16}
Q_L	1.4×10^5
C_{010}	0.53
$B_{\max}$ [T]	1.1
β	2
τ [min]	5
T_{sys} [K]	4.9
P_{sig} [W]	0.9×10^{-22}
Scan rate [Hz s^{-1}]	8
m_a [μeV]	0.49 - 1.49
$g_{a\gamma\gamma}$ 90% c.l. [GeV^{-1}]	$(1.25 -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

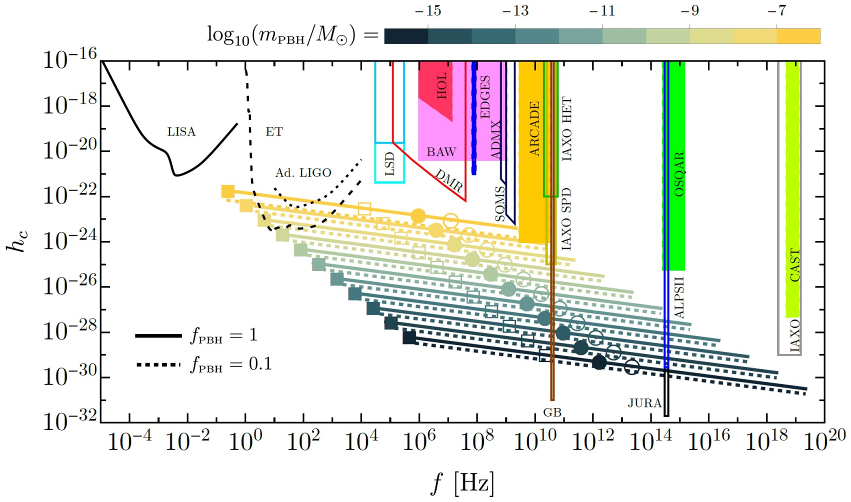


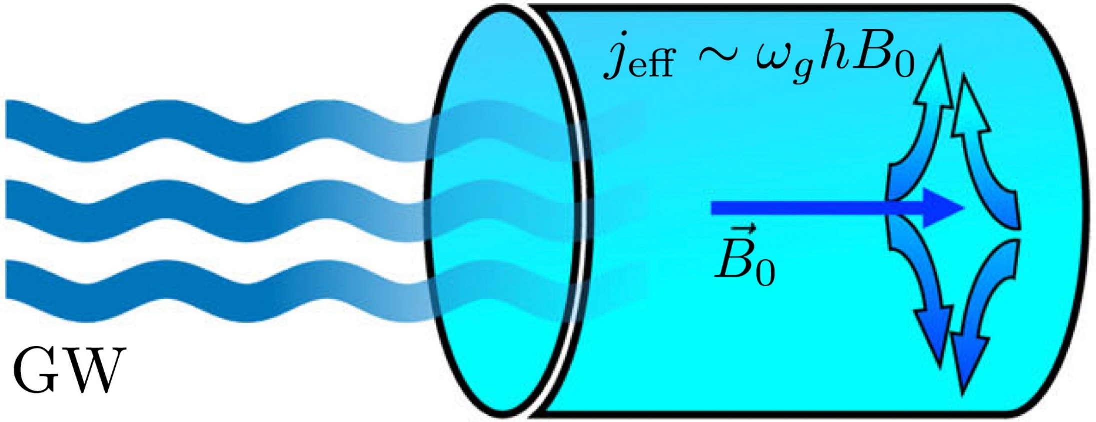




Light Primordial Black Hole Dark Matter with Ultra-high-frequency Gravitational Waves







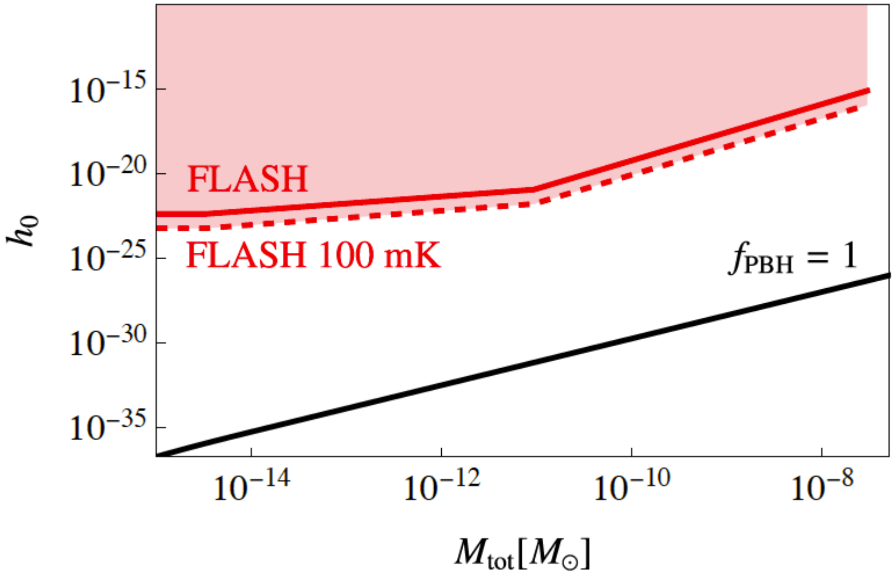
A. Berlin Phys. Rev. D 105, 116011

Franciolini Phys. Rev. D 106, 103520 2022

FLASH Sensitivity to HFGW

Sensitivity limited also by short duration time of the HFGW from PBHs. Gain 1 or 2 order of magnitudes wrt GHz cavities:

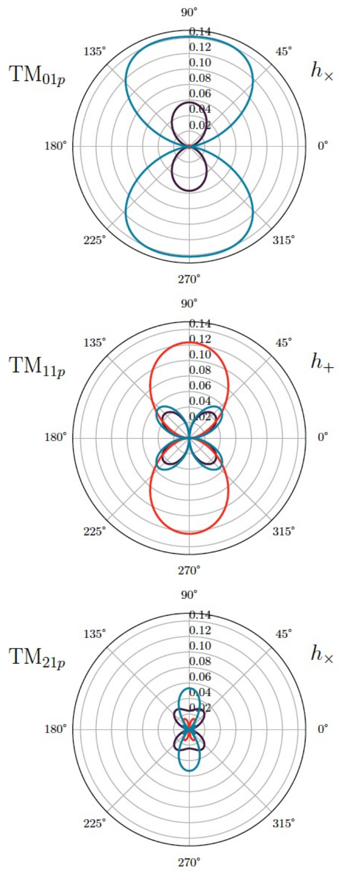
- Signal power scales as Radius^2
- Q factor effective as long as Ncycles~Q



$$t_{int} \simeq 2.72 \cdot 10^{-14}\ \mathrm{s} \ \times \left(\frac{M_c}{10^{-5} M_\odot}\right)^{-5/3} \left(\frac{\nu}{200\ \mathrm{MHz}}\right)^{-8/3} \left(\frac{10^6}{Q}\right)$$

Mode	Resonant Frequency [MHz]	Q factor (@4°K)
TM010	109.5	626e3
TM011	166.1	526e3
TM012	272.3	752e3
TM110	174.4	790e3
TM111	214.5	598e3
TM112	304.7	712e3
TM210	233.7	915e3
TM211	264.9	664e3
TM212	342.1	755e3

$p = 0$ $p = 1$ $p = 2$

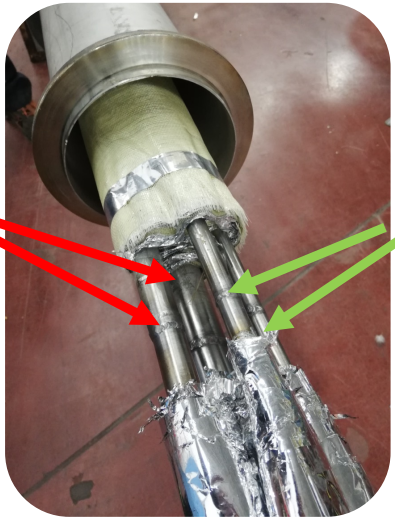


arXiv:2403.18610

Commissioning of the FINUDA Magnet – Last Operated in 2007

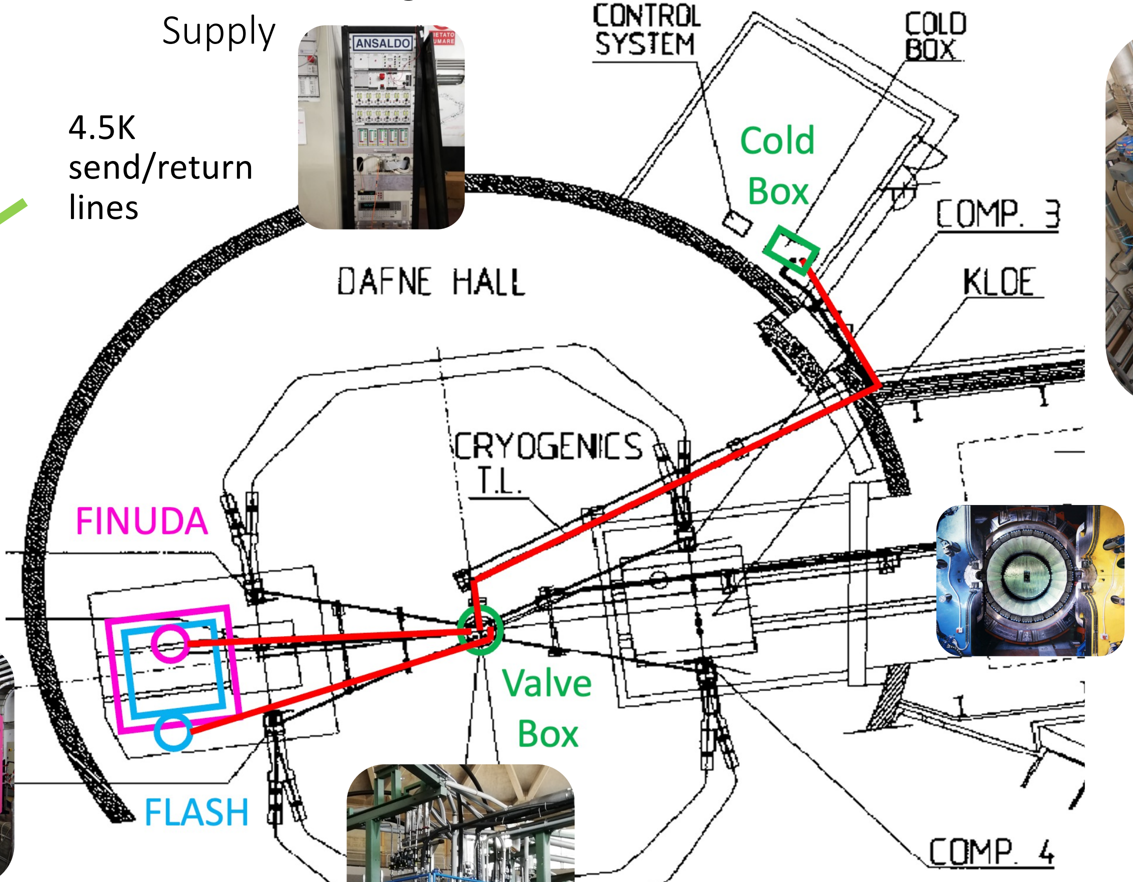
70K send/return lines

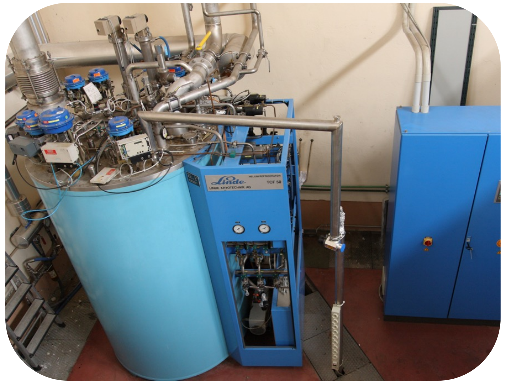
Reconnection of He transfer line



4.5K send/return lines

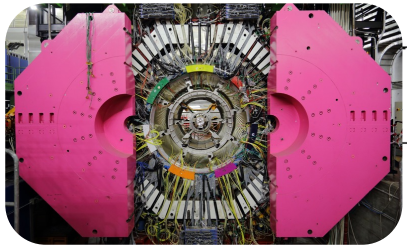
Control of Magnet Power Supply





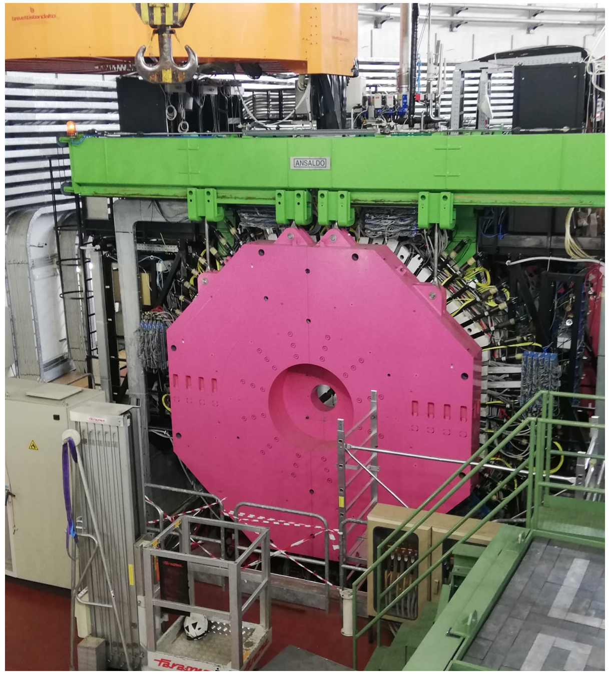
Cryogenic plant

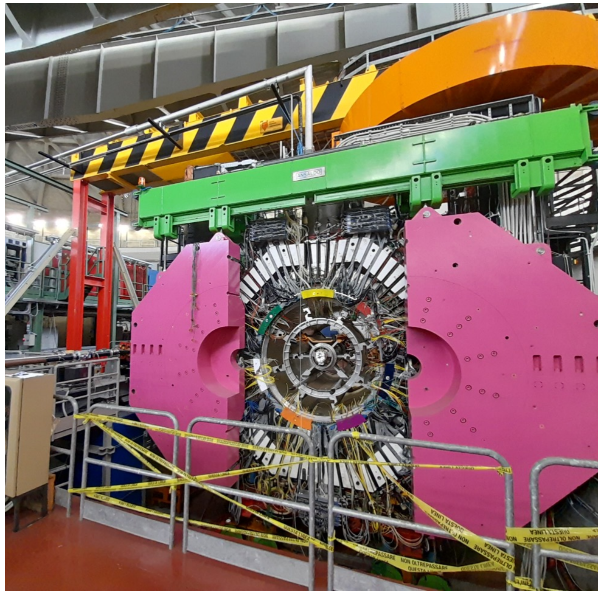
KLOE



FINUDA/FLASH

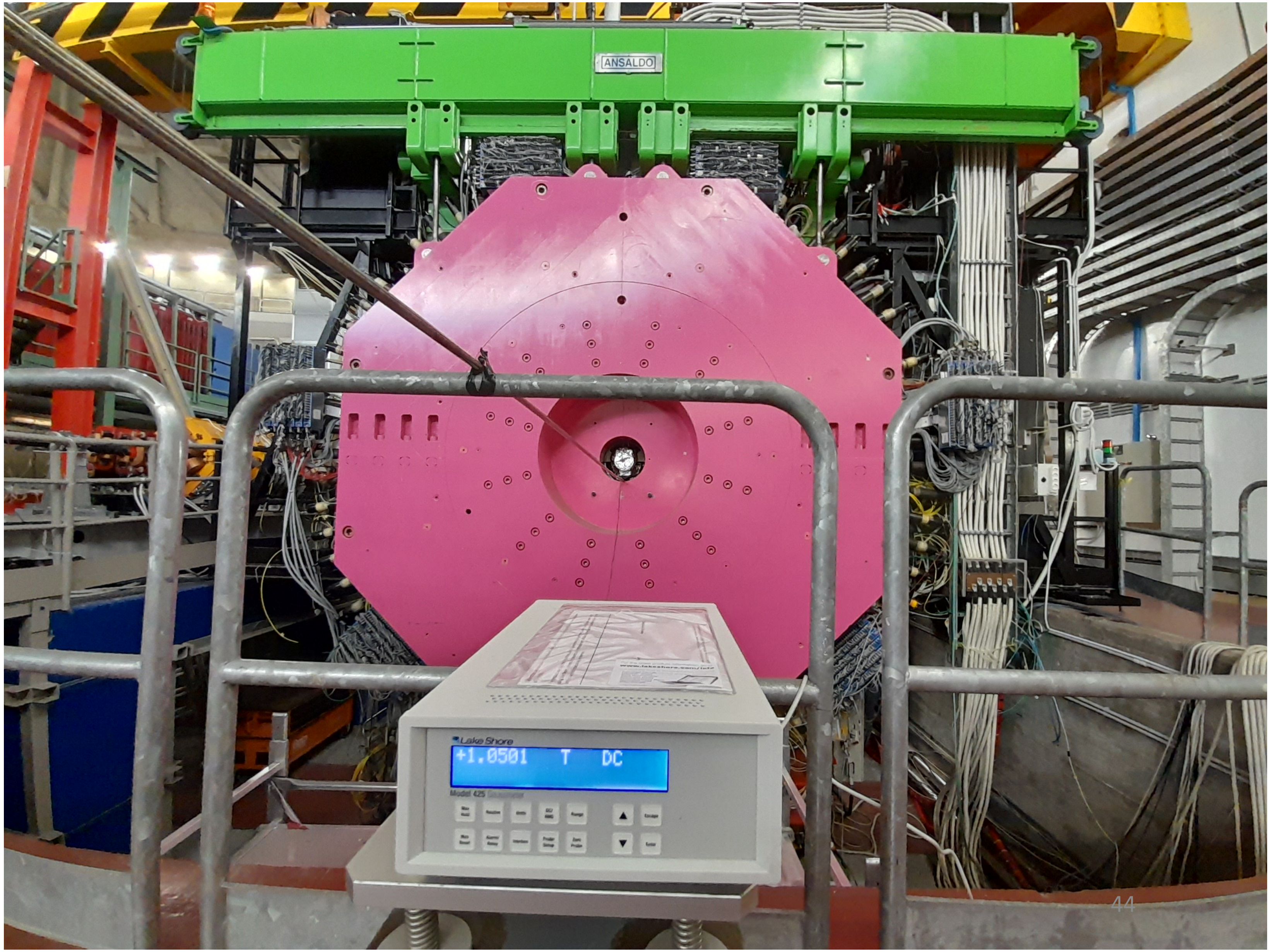

LOXAM



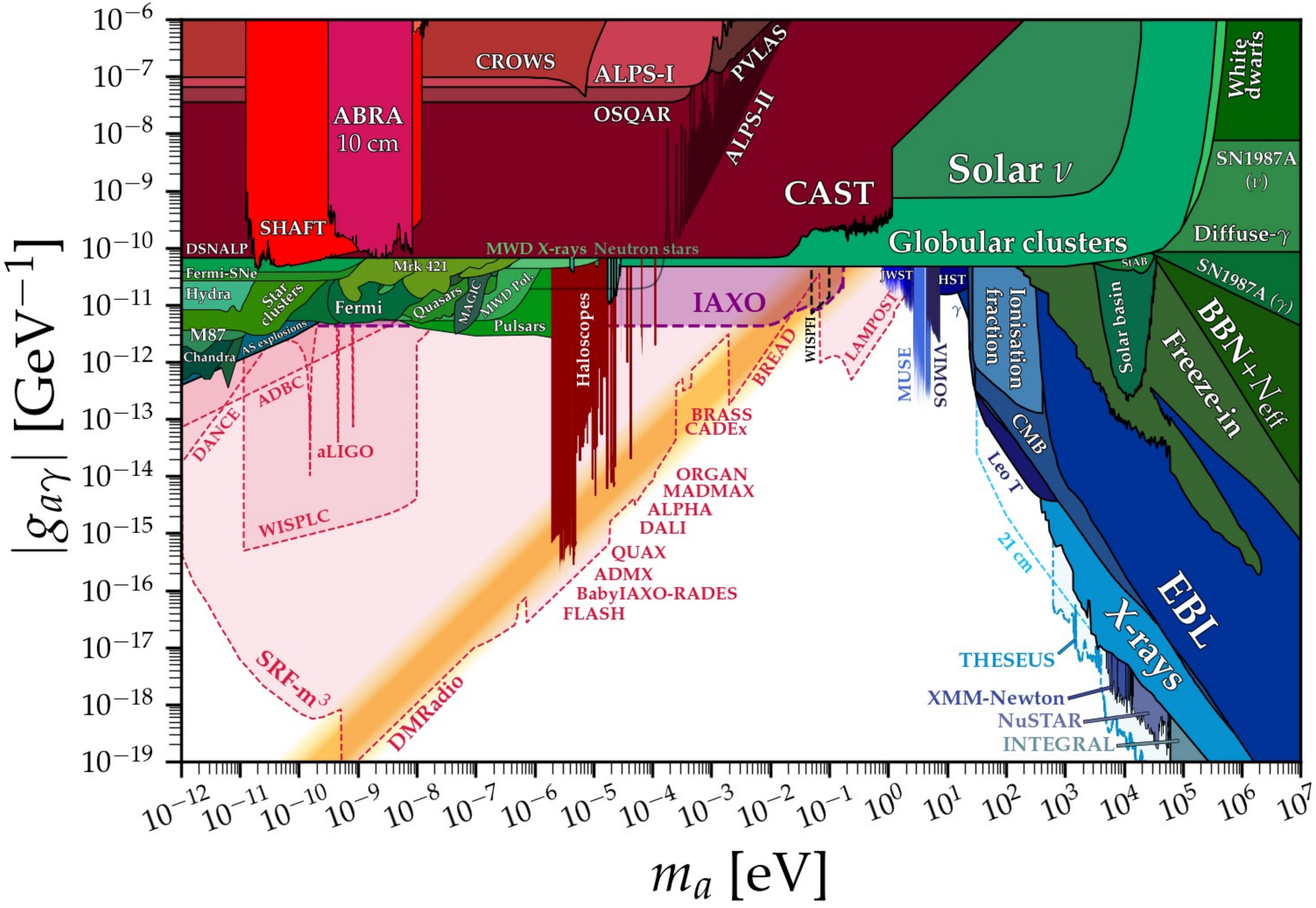
VIETATO
FUMARE



Successful Test of the FINUDA Magnet

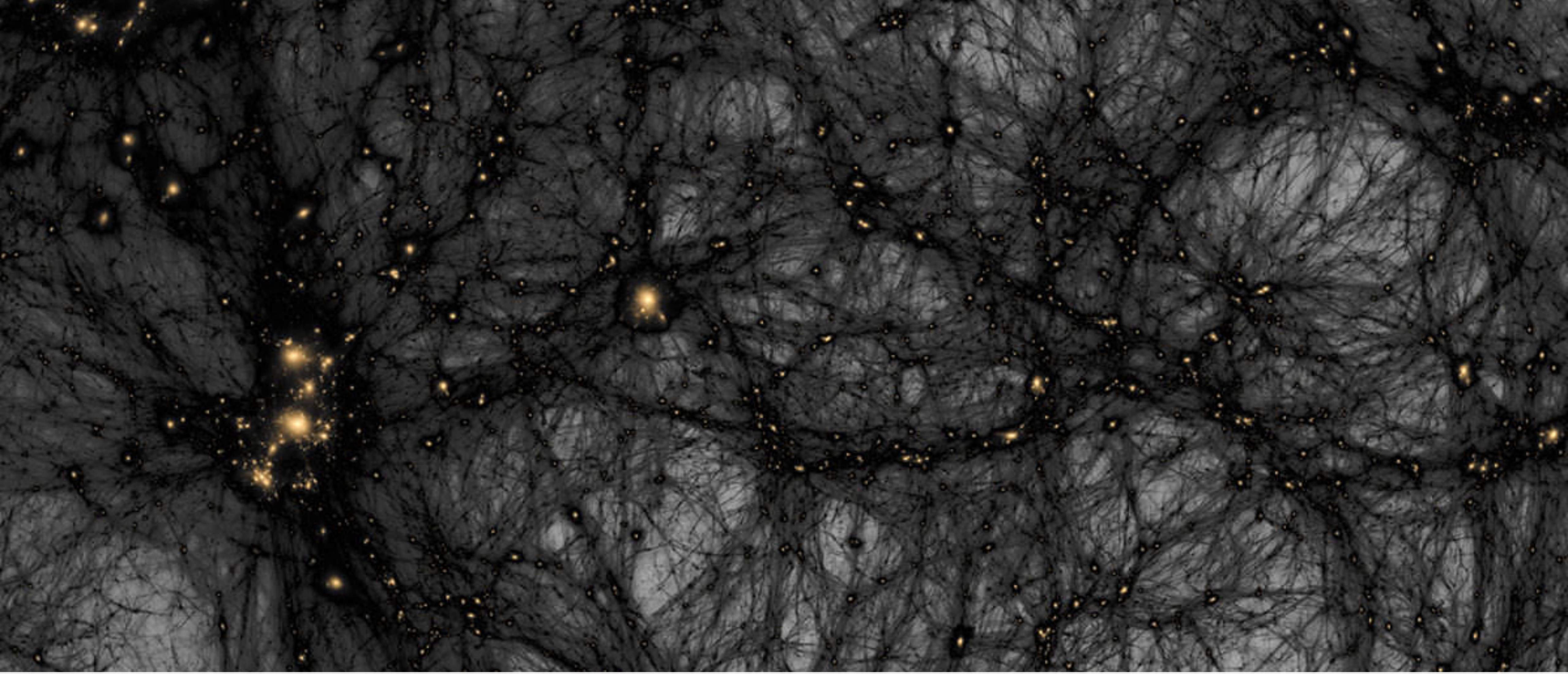
After a series of operations, the cryogenic plant was finally put back into operation. On Jan the 19th 2024, FINUDA was cooled down to 4 K and energized with a current of 2706 A, generating a magnetic field of 1.05 T.



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

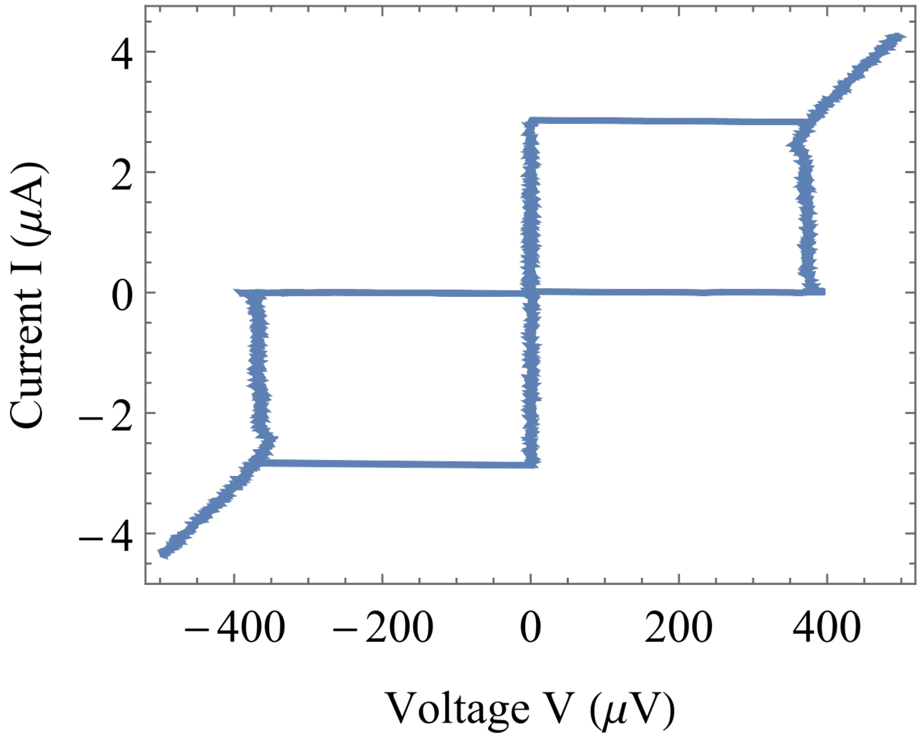


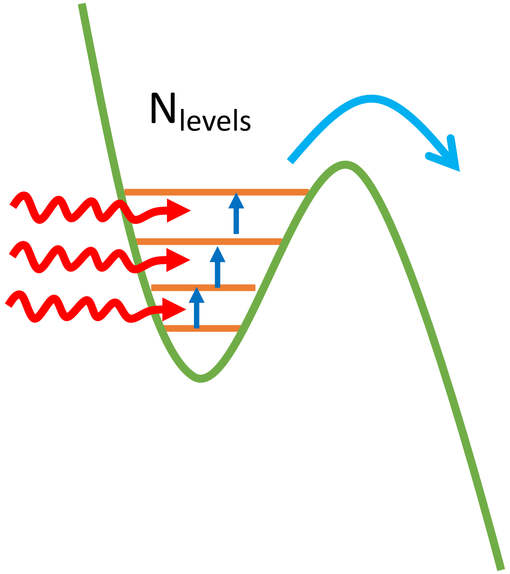
DARK SECTOR AT LNF



The End

Microwave Photon Detector Based on Current Biased JJ

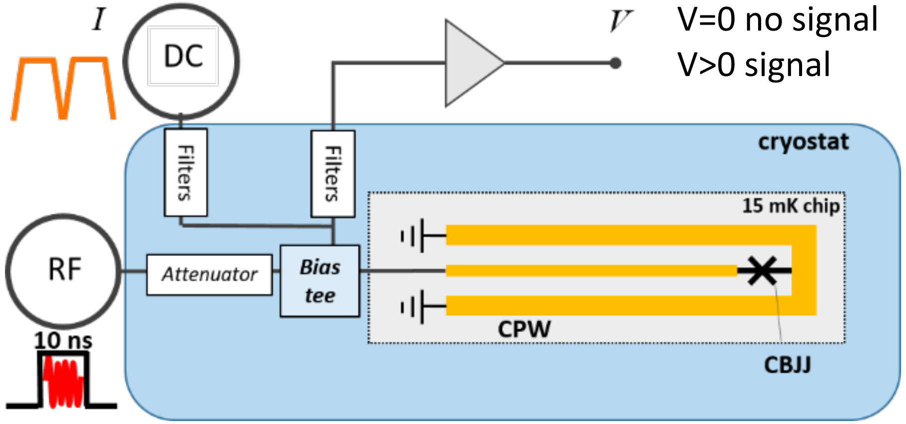




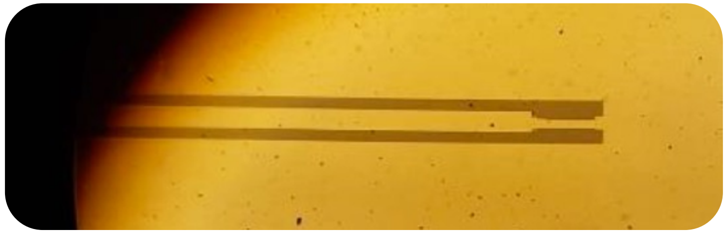
Switching detector: Microwave photons trigger the transition of the JJ to the normal state

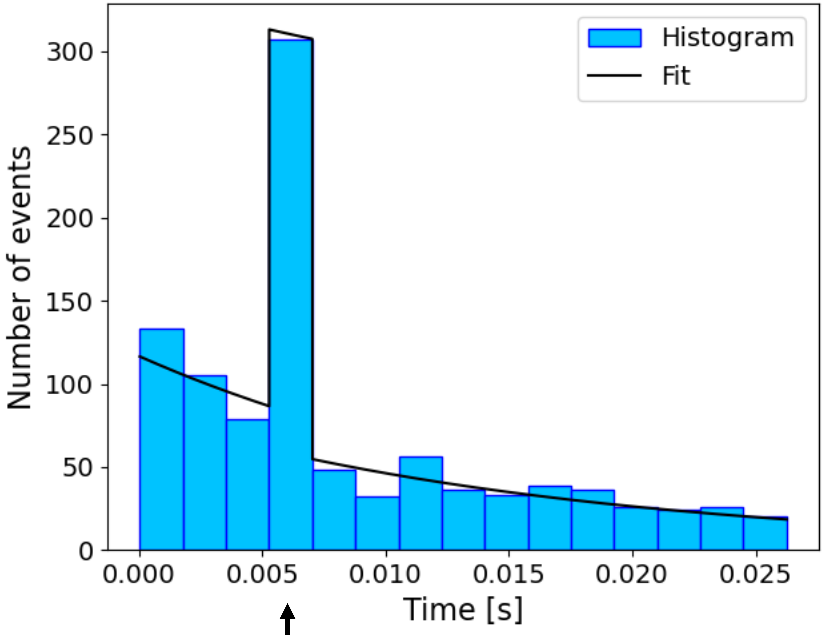
L. S. Kuzmin *et al.*, "Single Photon Counter Based on a Josephson Junction at 14 GHz for Searching Galactic Axions," in *IEEE Transactions on Applied Superconductivity*, vol. 28, no. 7, pp. 1-5, Oct. 2018, Art no. 2400505, doi: 10.1109/TASC.2018.2850019.

Microwave Photon Detector Based on Current Biased JJ



V=0 no signal
V>0 signal



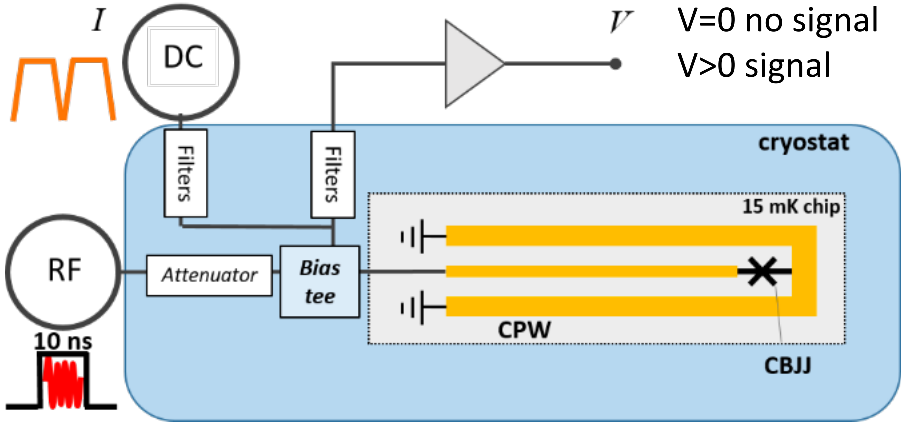


Microwave pulse

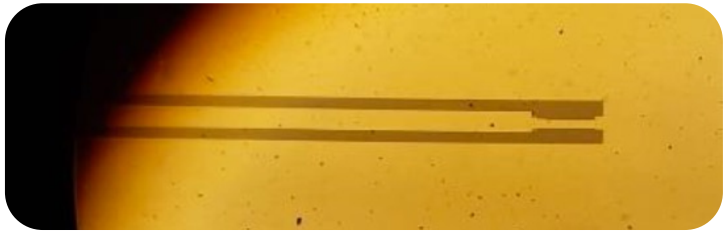
IEEE TRANS APP SUP, VOL. 32, NO. 4, 2022; doi: 10.1109/TASC.2022.3148693

IEEE TRANS APP SUP 2022 DOI 10.1109/TASC.2022.3218072

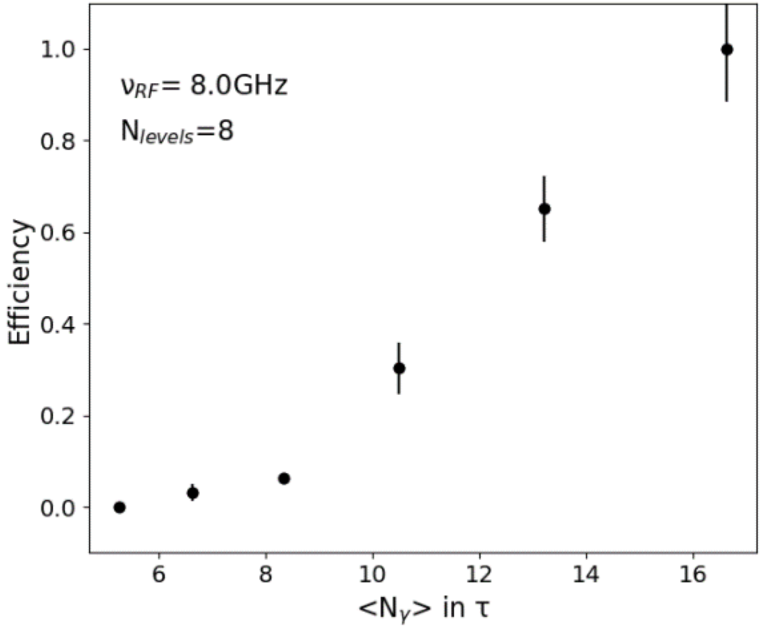
Microwave Photon Detector Based on Current Biased JJ



V=0 no signal
V>0 signal



Few photons (5 zJ) sensitivity.
Large room for improvement. Work ongoing.



IEEE TRANS APP SUP, VOL. 32, NO. 4, 2022; doi: 10.1109/TASC.2022.3148693

IEEE TRANS APP SUP 2022 DOI 10.1109/TASC.2022.3218072

Nanowire Transition Edge Sensor

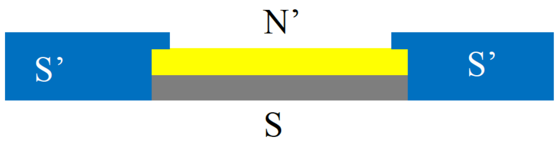
$$\sigma_E \propto \sqrt{k_B C T^2}$$

$$C = \gamma V T$$

Lower temperature

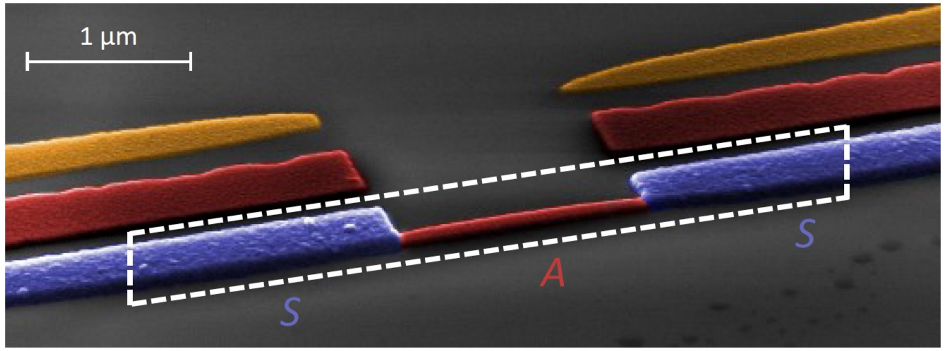
Reduce volume

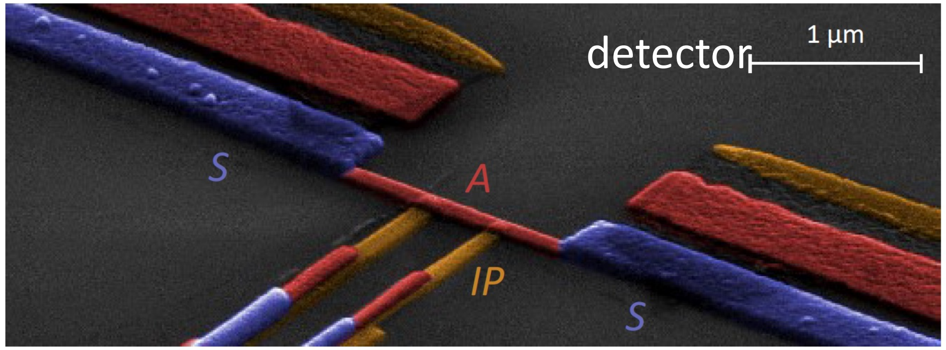
Tune transition temperature by proximity effect



$$\begin{aligned} V &\sim 300 \times 80 \times 35 \text{ nm}^3 \\ \gamma &\sim 10^{-22} \text{ mJ/K}^2/\text{nm}^3 \\ T_c &\sim 40 \text{ mK} \\ \sigma_E &\sim 20\ \mu\text{eV} \sim 5 \text{ GHz} \end{aligned}$$

TES Nanowire NEST





A (Red) AlCu

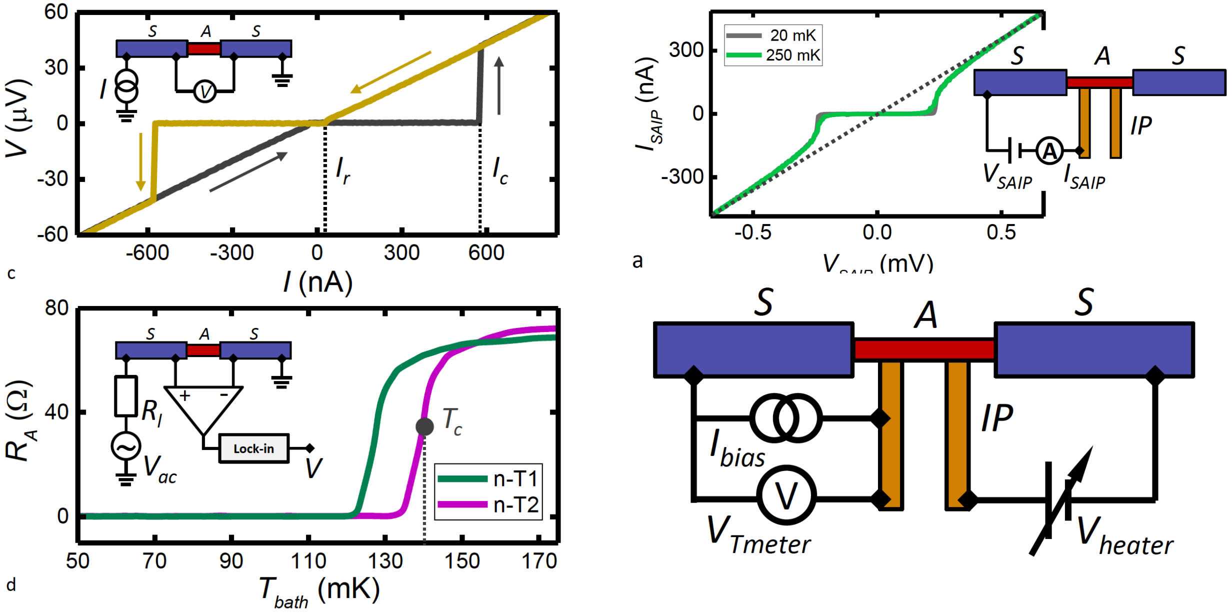
B (Blue) Al electrode

IP (Yellow) Al-O tunnel probe

F. Paolucci et al., J. Appl. Phys. **128**, 194502 (2020)

Direct measurement of nanowire properties:

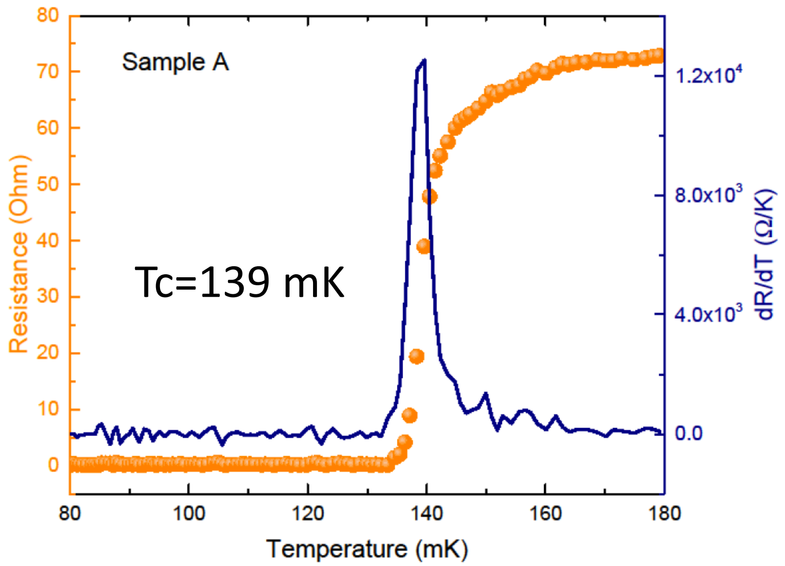
- Tc
- Transition steepness
- e-ph coupling
- bilayer E_{gap}

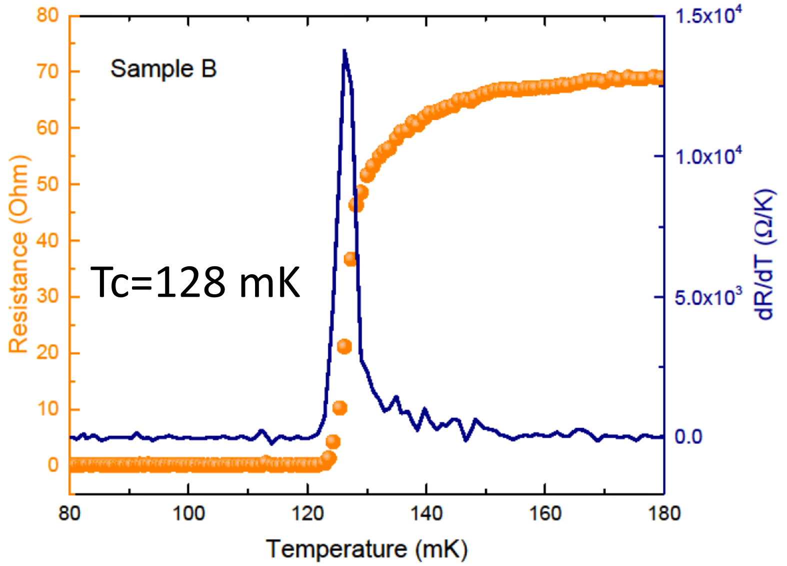


TES Nanowire NEST

Lenght	1.5 μm
Width	100 nm
t_{Al}	10.5 nm
t_{Cu}	15 nm

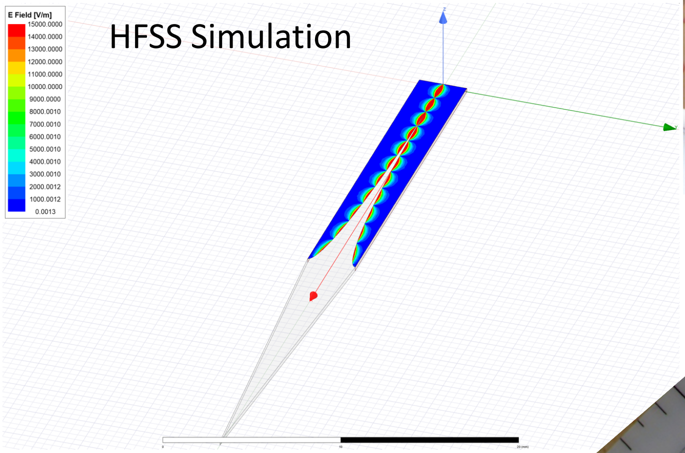
t	5-10 ms
C	5×10^{-20} J/K
G	5×10^{-15} W/K
σ_n	100-200 GHz
NEP	30-50 zW/√Hz

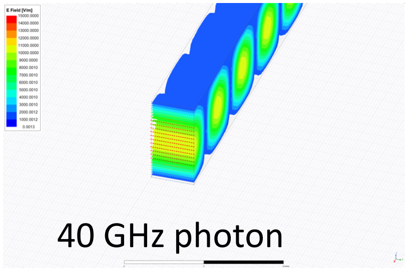


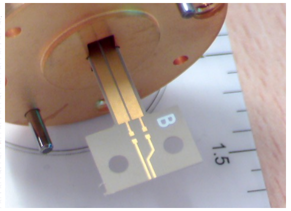


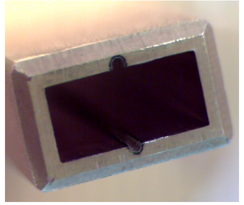
Antenna Characterization at Room Temperature

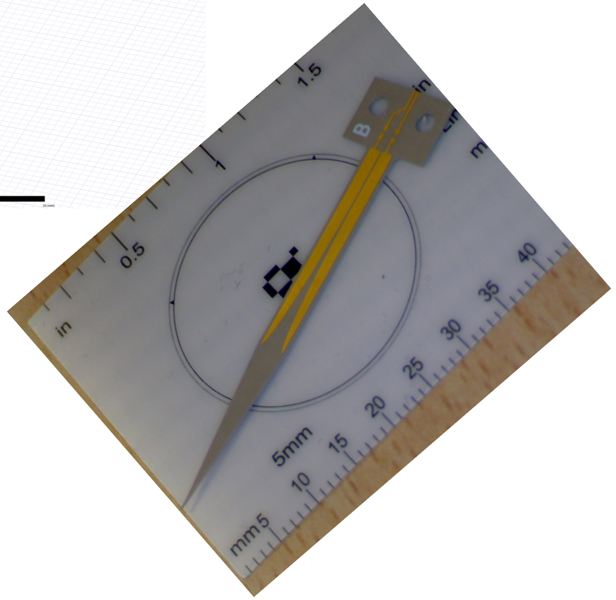
Finline design for collecting signal from waveguide to coplanar chip where TES is deposited





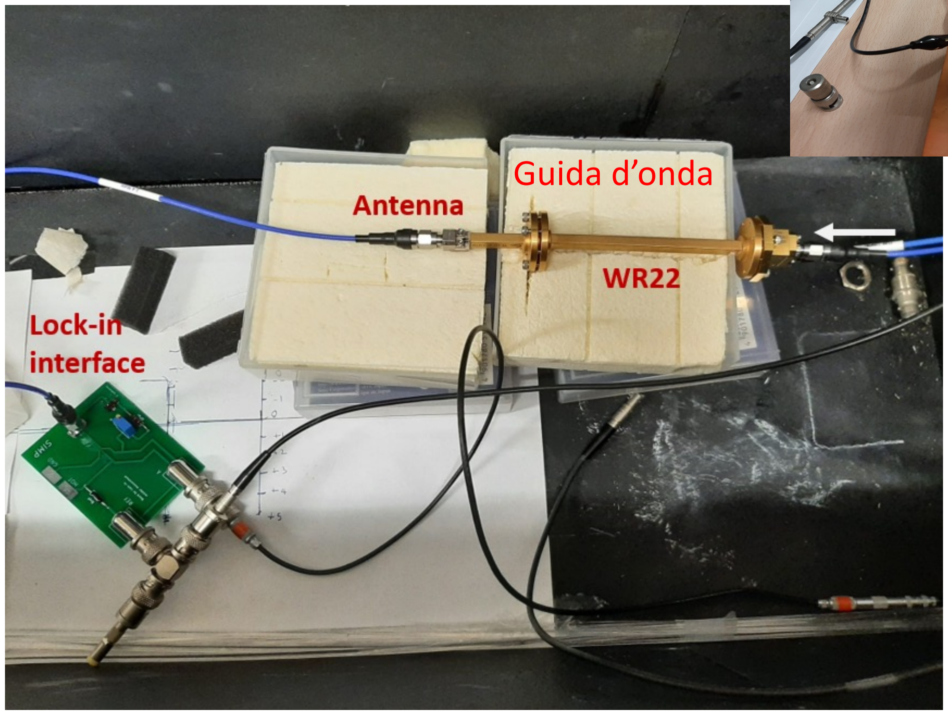


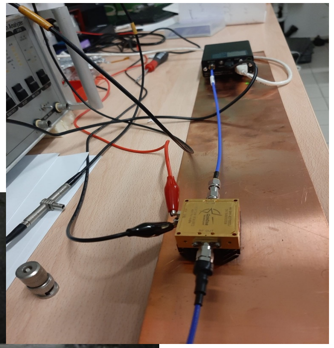




First realization for room-temperature tests

Lock In

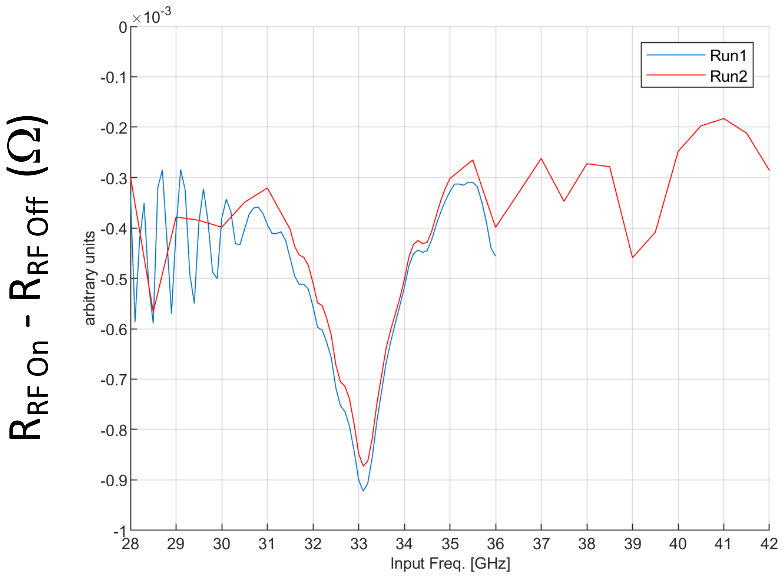




45 GHz RF generation

INFN PISA
Istituto Nazionale di Fisica Nucleare
Sezione di Pisa

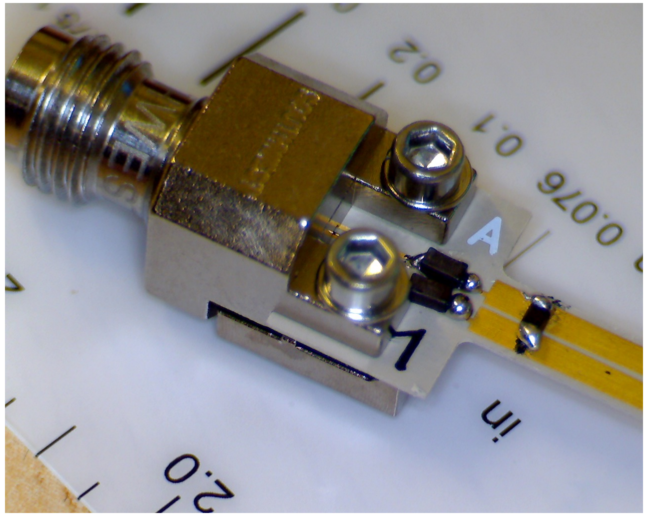
Antenna Characterization at Room Temperature

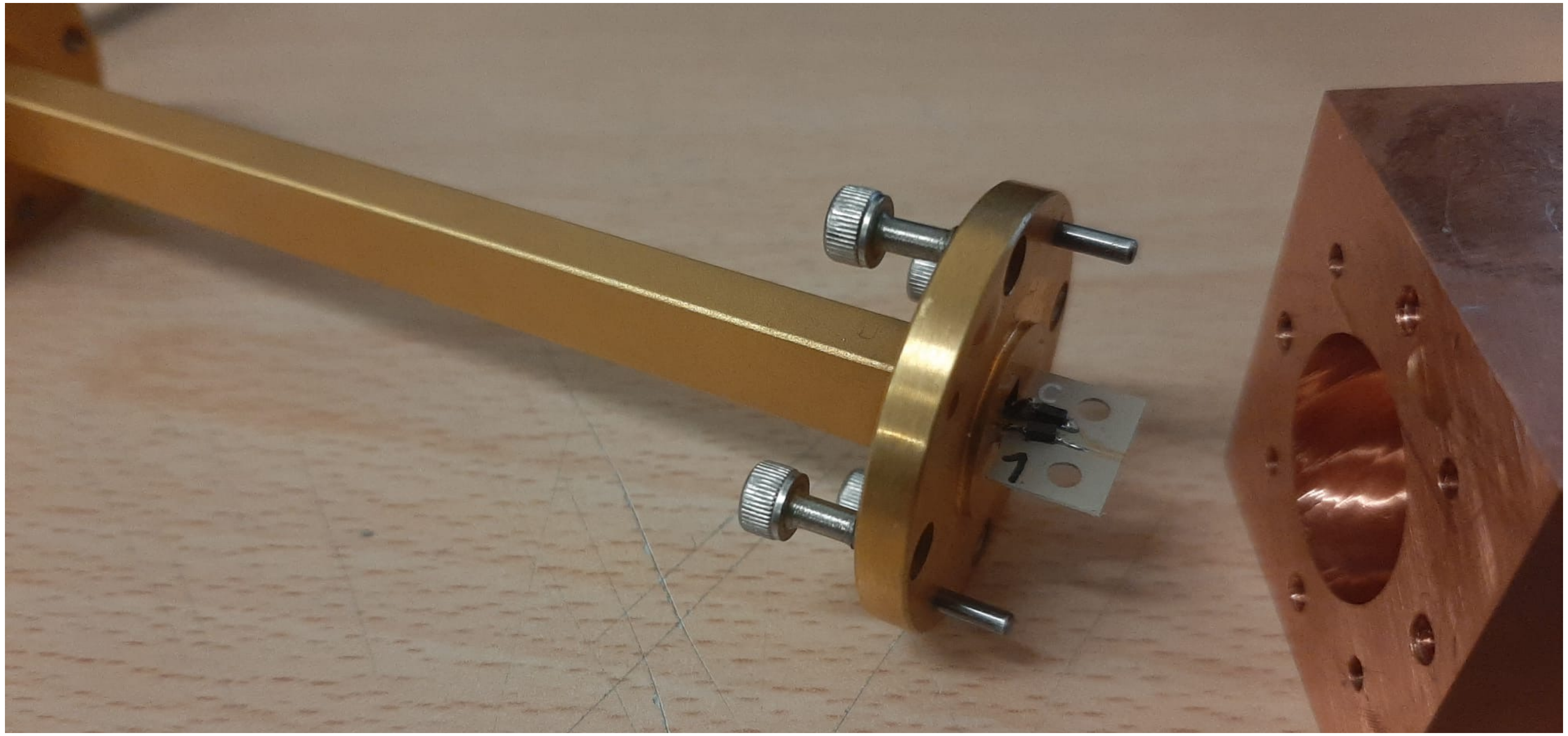


Observed variation of thermistor resistance at finline resonant frequency (33 GHz)

S11 measurements with VNA gives compatible results.

Measurement of NTC e PTC thermistors





Waveguide with antenna and TES will be termally anchored, with OFHC components realized in Pisa mechanical workshop, to the mixing chamber plate and connected to the SQUID.