INFN
Istituto Nazionale di Fisica Nucleare

FRASCATI NATIONAL LABORATORY

L'attività di ricerca del Laboratorio di Frascati dell'INFN

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Frascati National Laboratory of INFN

the largest and the first built of the four INFN laboratories

Always at the forefront of scientific research

the development, construction and operation of particle accelerators

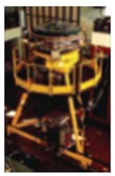
design and construction of detectors for particle, ***nuclear***, and astroparticle ***experiments***

development of new activities including searches for ***low-mass dark matter candidates***

The LNF accelerators history

Electron Synchrotron (1959-1975), Energy = 1 GeV
First particle accelerator

an experiment itself



AdA 1960-1965, Energy = 250 MeV
first matter-antimatter collider

QED tests,
proton and neutron form factors, muon study
and multi-hadron production

ADONE (1968- 1993) 3 GeV 100 m
largest e+ e- collider

DAΦNE (1999) 510 MeV 100 m
a Φ – factory - low energy kaon beam

precision studies of CP-violation (KLOE)

low energy QCD
(KLOE2, DEAR, SIDDHARTA/2)

hypernuclear physics
(FINUDA)

SPARC_LAB (2004) 150 MeV LINAC

New era - EuPRAXIA project

User facility that exploits plasma acceleration

DAΦNE, the Φ-factory at LNF is **the world leading facility** for

low-energy kaons, producing charge kaons in the

momentum range 115 – 140 MeV/c

and

is therefore **ideally suited for studying particle and nuclear physics in the sector of low-energy QCD with strangeness**

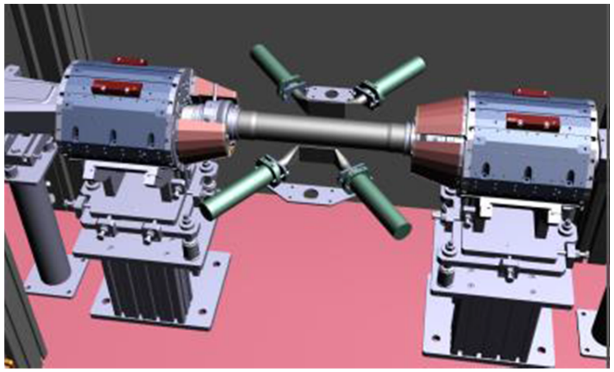
Low-energy QCD studies
SIDDHARTA-2 the ongoing experiment at DAFNE collider

We conclude the Phase1 in July 2021 with SIDDHARTINO setup (8 SDD arrays) performing the K-^{4}He test measurement to set the background/working conditions

Runs with DAFNE since November 2019
-collisions in beginning of 2020 (then COVID ….)
-restart collision in February/March 2021

Luminosity measurement and optimization
(tuning the detector)
SDD calibration optimization with the x-ray tube
(in beam conditions and in laboratory)
SDD background structure
Background reduction studies
(scraper, optics for collisions, optimized shielding)

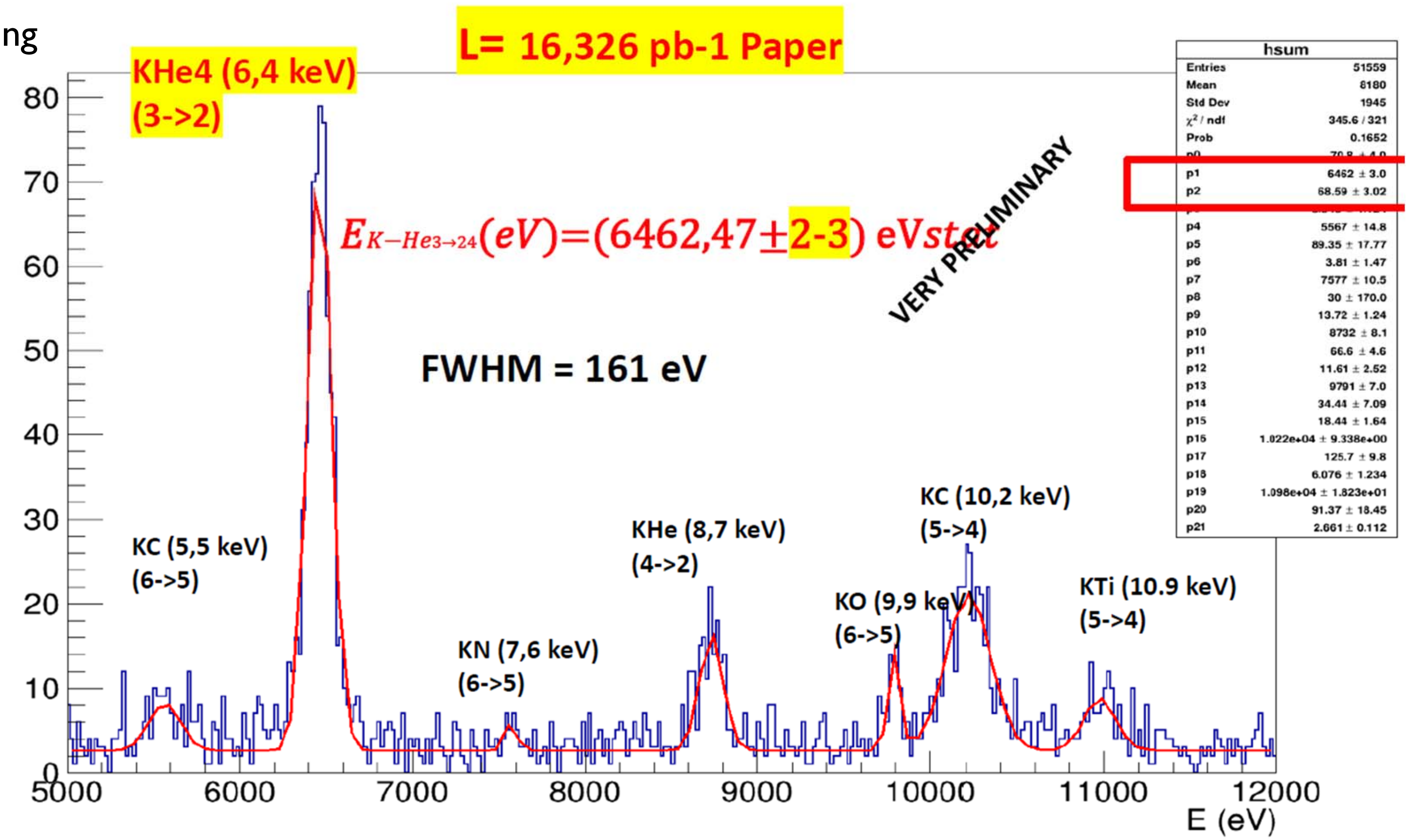
Siddharta2 luminomiter



SDD detector

Kaonic ^{4}Helium Run - preliminary results with SIDDHARTINO

Data analyses ongoing



Phase II - action plan for Kaonic Deuterium measurement:

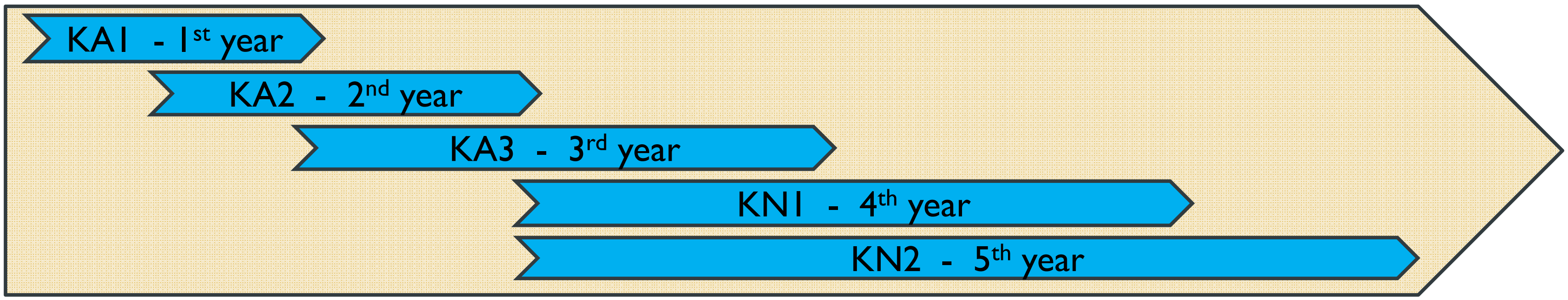
Install all the SDDs (48 SDD arrays), veto systems and start the *kaonic deuterium measurement* for a total integrated luminosity of 800 pb^{-1}

- **First run with SIDDHARTA-2 setup as planned (about 300 pb^{-1} integrated) – start in October 2021**

- **Second run with optimized shielding, readout electronics and other necessary optimizations (for other 500 pb^{-1} integrated) – after summer 2022**

SIDDHART2 run

Proposed time line for new measurements



- Selected light and heavy kaonic atoms transitions (KA1, KA2, KA3)
- Low-energy kaon-nucleon scattering processes (KN1)
- Low-energy kaon-nuclei interactions (KN2)

The measurements we propose, moreover, can be realized:

Without modifications of DAFNE infrastructures
Without major modifications of colliding optics
With no need of additional radioprotection authorizations
Compatible with ongoing and future LNF program
Relying on the experience of the DAFNE scientists who secured DAFNE upgrade and the following experimental runs.

Dark Matter studies
(KN1, KN2)

On self-gravitating strange dark matter halos around galaxies
Phys.Rev.D 102 (2020) 8, 083015

Fundamental physics
New Physics (KA1, KA3)

The modern era of light kaonic atom experiments
Rev.Mod.Phys. 91 (2019) 2, 025006

Kaonic atoms
Kaon-nuclei interactions
(scattering and nuclear interactions)

https://arxiv.org/pdf/2104.06076.pdf
LOI/Technical Design Report in preparation

Part. and Nuclear physics
QCD @ low-energy limit
Chiral symmetry, Lattice
(Ka1, KA2, KN1)

Kaonic Atoms to Investigate Global Symmetry Breaking
Symmetry 12 (2020) 4, 547

Astrophysics (KA2)

Merger of compact stars in the two-families scenario
Astrophys. J. 881 (2019) 2, 12

EOS Neutron Stars
(KN1,KN2)

The equation of state of dense matter: Stiff, soft, or both?
Astron.Nachr. 340 (2019) 1-3, 189

KA1 - Heavy (high Z) kaonic atoms using High Purity GE

Possible kaonic transitions to be measured:

KC(2→1) : 340 keV
KC(3→1): 402 keV

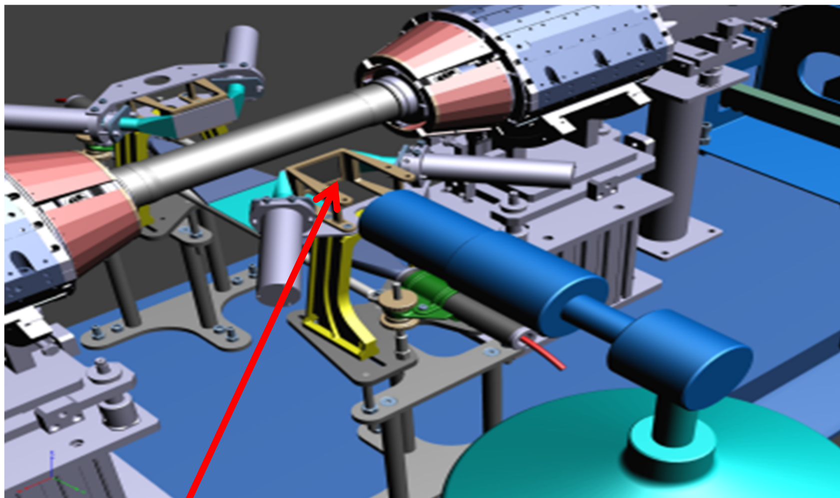
KSe(4→3): 733 keV
KSe(5→4): 339 keV
KSe(5→3): 1073 keV
KSe(6→5) : 184 keV
KSe(6→4): 524 keV

KZr(4→3): 1015 keV
KZr(5→4): 470 keV
KZr(5→3): 1485 keV
KZr(6→5) : 255 keV
KZr(6→4): 725 keV

KTa(6→5): 853 keV
KTa(7→6): 514 keV
KTa(7→5) : 1367 keV
KTa(8→7): 334 keV
KTa(8→6): 848 keV

KPb(6→5) : 1076 keV
KPb(7→6): 649 keV
KPb(8→7): 421 keV
KPb(8→6): 1070 keV
KPb(9→8): 289 keV

Charged Kaon Mass puzzle:
ready for a feasibility test run using Pb target



Target just behind the luminometer, which is used as trigger

Detector Key Points:
- Very large dynamic range
- Possibility to test High Z targets
- High resolution for precision measurements
- Rate capability up to 150 kHz

Dedicated measurements:
Targets : Se, Zr, Ta, Pb
(systematic errors minimisation, cascade processes in heavy kaonic atoms)
simultaneous measurements of atomic transitions from various n levels and with different Δn

~ 360 pb-1 (~ 35 days) of beamtime requested
!!! Similar estimations for each target !!!

KA1 - Heavy (high Z) kaonic atoms using High Purity GE

System tested in Zagreb with very good results:

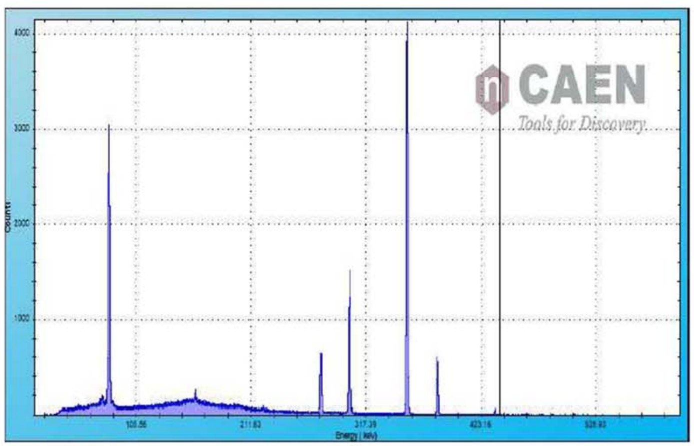
System arrived in Frascati end of July

Good results confirmed also in SIDDHARTA-2 lab

^{60}Co, ^{133}Ba spectra,
resolutions: 0.870 keV at 81 keV
1.106 keV at 302.9 keV
1.143 keV at 356 keV
1.167 keV at 1330 keV

Key issues to be tested:

- test the detector response in high background conditions
- shielding optimization
- target optimization for best efficiency



Detector system ready for measurements!

Mechanical structures ready !

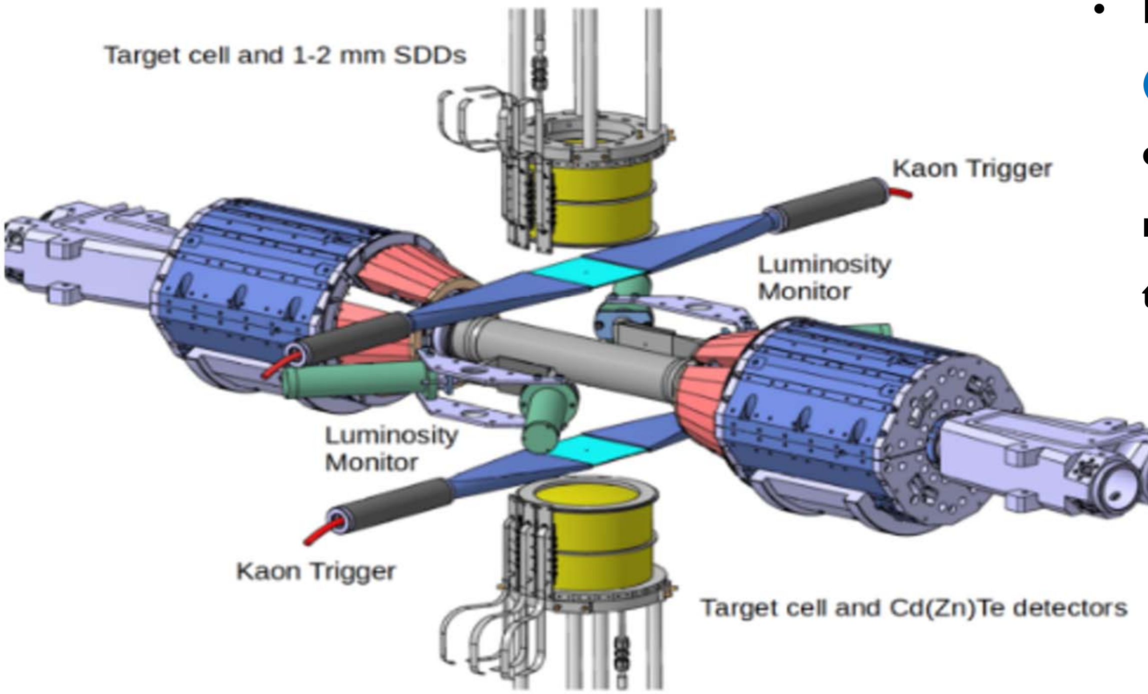
Possible rates up to 150 kHz, slightly worse resolution

KA2 - Light kaonic atoms measurements

Expected impact:

- **kaon-nuclei potential and chiral models below threshold and the nature of Λ(1405).**
- **astrophysics: search for dark matter with strangeness and the equation of state for neutrons stars**

Setup: SDD1mm & CdTe



- **In particular, the first measurement of 3He, 4He (2p → 1s) transition, will put stronger constraints on the theoretical models describing the kaon-nucleon interaction in systems with more than two nucleons**

Targets : ^{3,4}He, ^{6,7}Li, ^{8,9}Be, ^{10,11}B

both low level and high level transitions with Δn = 1, 2, ...5, and energies in the range 10-100 keV

R&D for new detectors - SDD 1mm thickness / Cd(Zn)Te

Possible kaonic transitions to be measured with 1-2 mm SDDs:

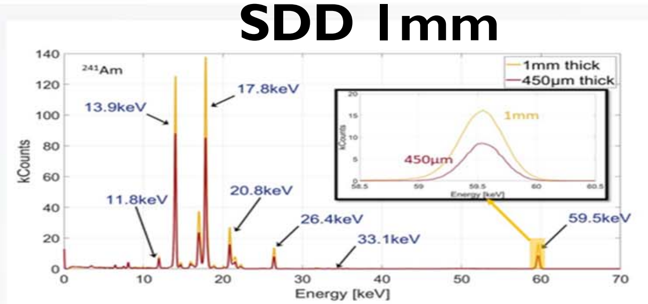
$K^{3}He(2\rightarrow1)$: 33 keV
$K^{4}He(2\rightarrow1)$: 35 keV

$K^{6,7}Li(3\rightarrow2)$: 15 keV
$K^{6,7}Li(4\rightarrow2)$: 20 keV

$K^{8,9}Be(3\rightarrow2)$: 27 keV
$K^{8,9}Be(4\rightarrow2)$: 37 keV
$K^{8,9}Be(5\rightarrow3)$: 14 keV

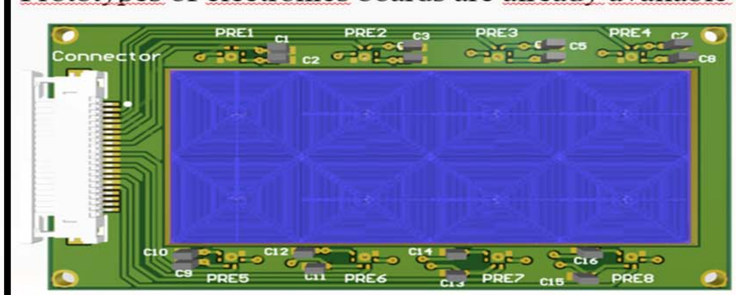
$K^{9,10,11}B(4\rightarrow3)$: 15 keV
$K^{9,10,11}B(5\rightarrow3)$: 22 keV
$K^{9,10,11}B(6\rightarrow4)$: 11 keV

SDD 1mm



First XRF tests with known targets show very promising results

Prototypes of electronics boards are already available



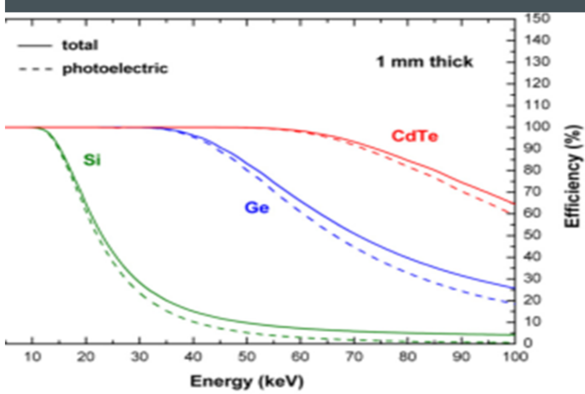
FWHM ~ 150 eV (SDD)

Cd(Zn)Te

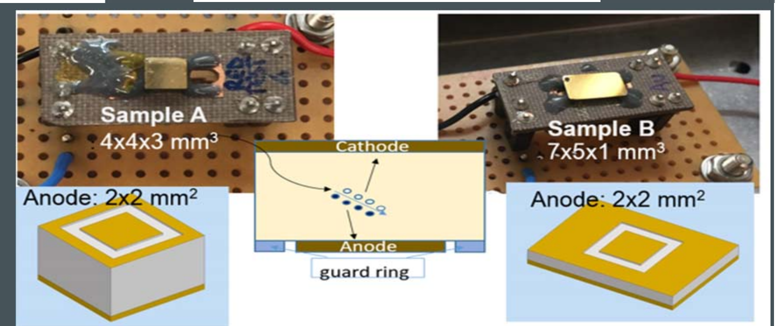
Possible kaonic transitions to be measured with **CdTe detectors**:

$K^{6}Li(2\rightarrow1)$: 81 keV
$K^{6}Li(3\rightarrow1)$: 97 keV
$K^{7}Li(2\rightarrow1)$: 82 keV
$K^{7}Li(3\rightarrow1)$: 98 keV
$K^{9,10}B(4\rightarrow2)$: 58 keV
$K^{9,10}B(5\rightarrow2)$: 65 keV
$K^{9,10}B(6\rightarrow2)$: 69 keV
$K^{9,10}B(7\rightarrow2)$: 71 keV
$K^{11}B(4\rightarrow2)$: 59 keV
$K^{11}B(5\rightarrow2)$: 66 keV
$K^{11}B(6\rightarrow2)$: 70 keV
$K^{11}B(7\rightarrow2)$: 72 keV

required 300 pb-1 for each target



FWHM ~ 1000 eV

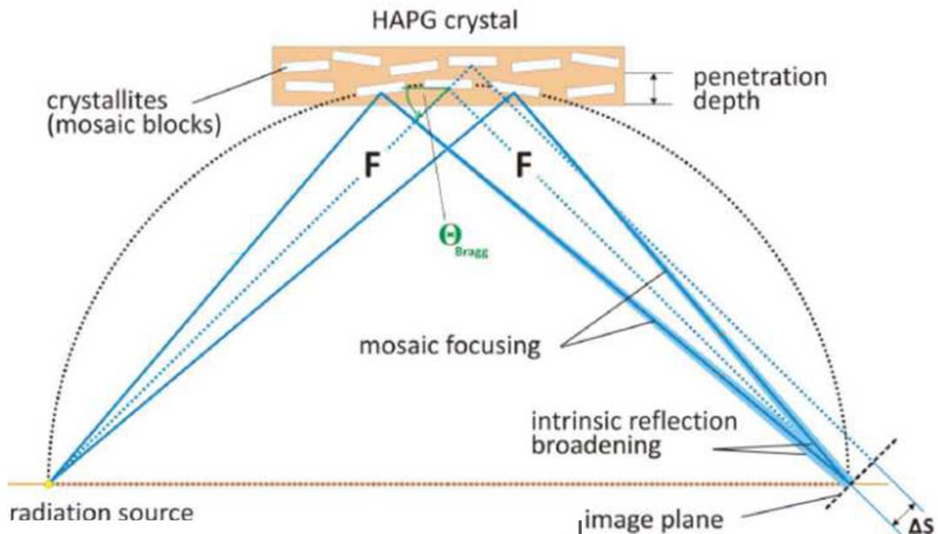


Cadmium(Zinc)Telluride detectors will be developed in the STRONG2020-ASTRA

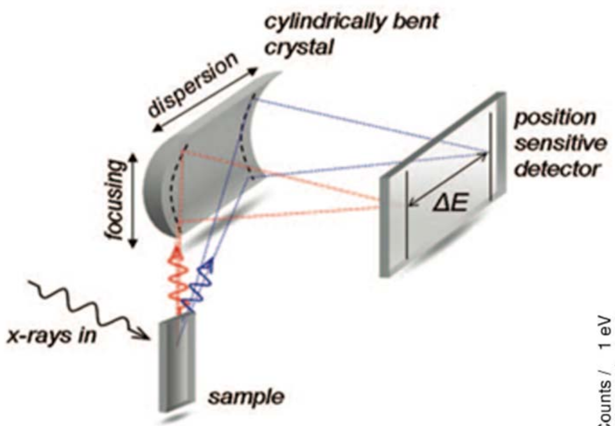
First prototypes will be available in 2022

KA3 - Ultra-High precision (under eV) kaonic atom measurements (VOXES spectrometer)

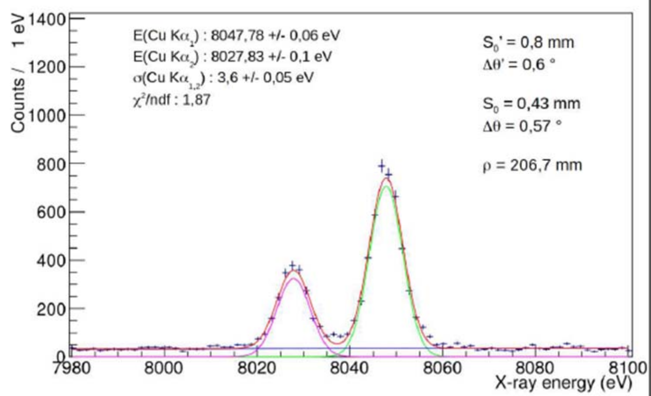
Mosaic crystal consist in a large number of nearly perfect small crystallites.



Mosaicity makes it possible that even for a fixed incidence angle on the crystal surface, an energetic distribution of photons can be reflected



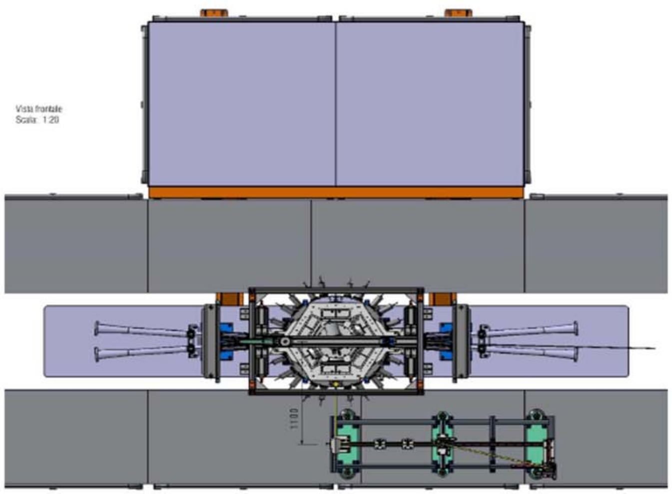
Von Hamos configuration to improve efficiency through vertical (sagittal) focusing properties of cylindrically bent crystals



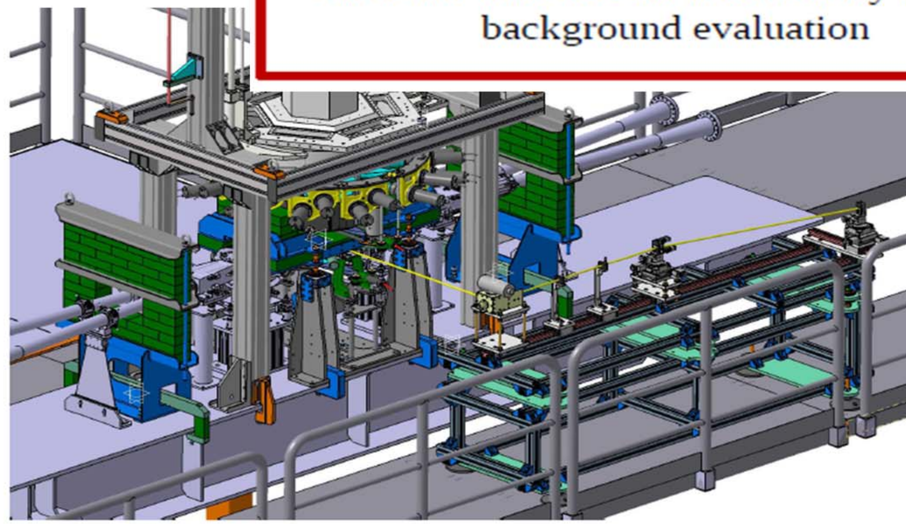
Laboratory layout scheme

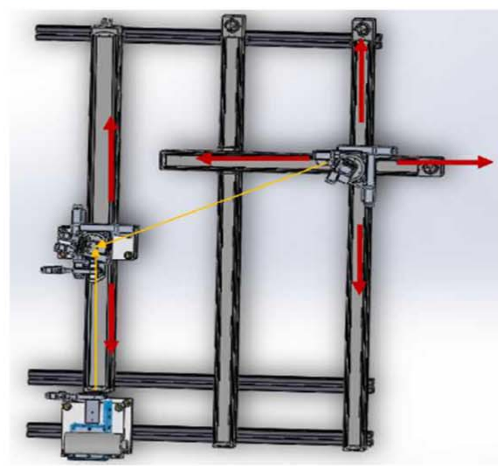
To be realized:
1) Shielding around Detector
2) Solid support structure

Available:
3) Multi - Crystal support structure
4) Target (Solid or Liquid/Gas)
5) Optics
6) Alignement support
7) Target box
8) Detector
9) DAQ (integ. KM)



First run with KC for a feasibility test and background evaluation



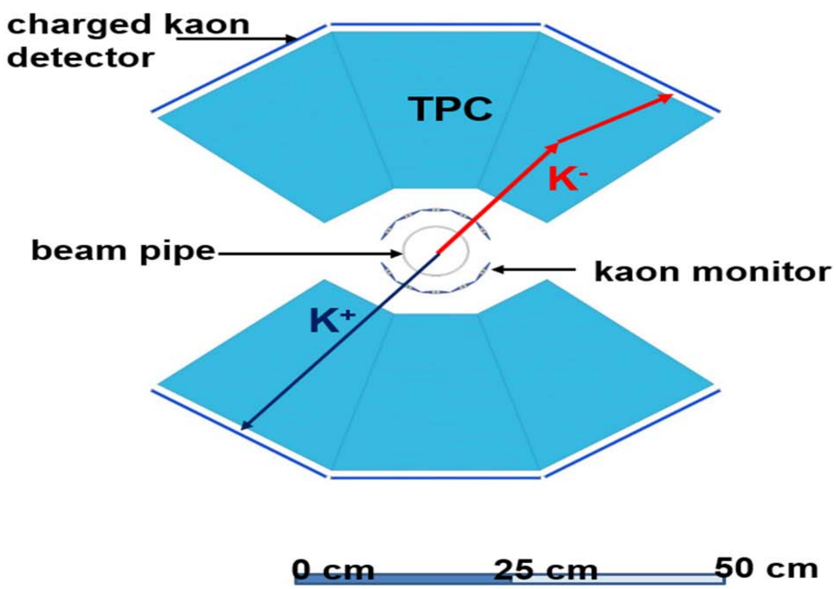


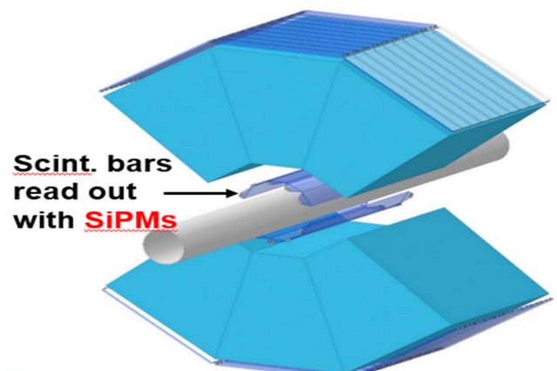
Recently upgraded with motorized carriers:

Ready for multiline measurements & onsite (online) alignement

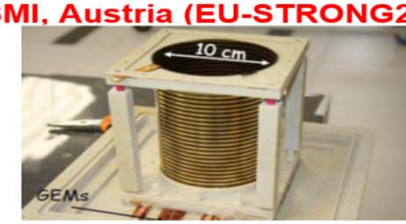
KN1, KN2 - Kaon-nuclei scattering and interaction

Measurement of the low-energy scattering process of kaons, and of the Λ(1405) kaon induced production, on various targets such as hydrogen, deuterium, helium-3 and helium-4 using a GEM-TPC active target.





TPC prototyping ongoing at:
Sendai Univ., Japan
SMI, Austria (EU-STRONG2020)

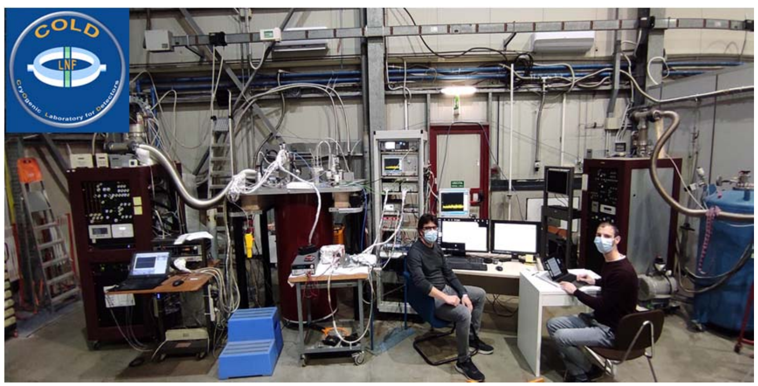


In recent years, relevant measurements could be performed in the search for extensions of the Standard Model to explain the nature of dark matter (DM).

The light axion particles associated with the solution to the strong CP problem in QCD (mass range 1eV < ma < 10meV) can contribute significantly to the energy density of the universe in the form of Dark Matter clustered inside galactic halos and are possibly observable by means of detectors called haloscopes.

Axion Dark Matter Search with QUAX Experiment

Laboratori Nazionali di Frascati (LNF)



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Istituto Nazionale di Fisica Nucleare
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TIFPA
Trento Institute for
Fundamental Physics
and Applications

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

Laboratori Nazionali di Legnaro (LNL)

In collaboration with Birmingham University

The Sikivie Haloscope – general principle

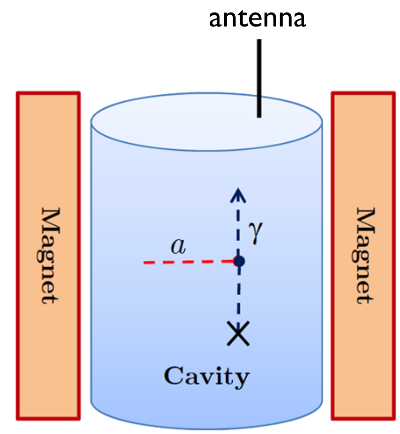
In presence of a strong magnetic field, cavity modes are excited by a resonant axion field

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

the expected power deposited by Dark Matter axions is given by

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

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



β antenna coupling to cavity

V cavity volume

C_{mnl} mode dependent factor about 0.6 for TM010

Q_L cavity "loaded" quality factor

$B_{ext} \approx 8$ Tesla

Microwave Resonator
$Q \approx 10^6$

Microwave Energies
(1 GHz ≈ 4 μeV)

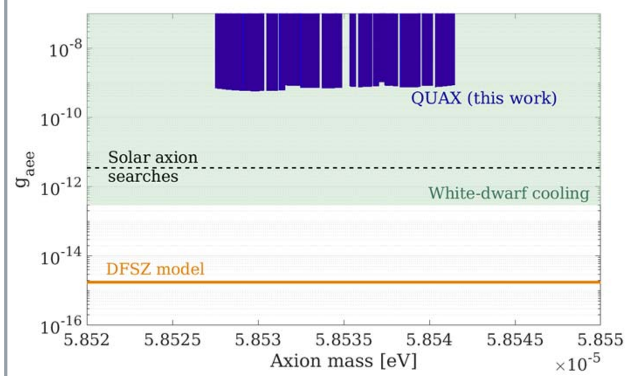
QUAX RESULTS 2018-2020

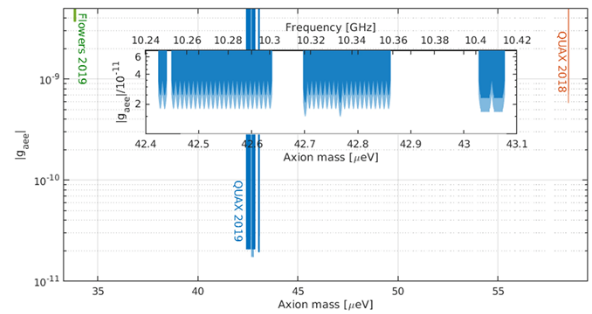
- QUAX-ae result with Ferromagnetic Axion Haloscope at m_a = 58 μeV, EPJC (2018) 78:703. **(LNL)**
- QUAX-ae with Quantum-Limited Ferromagnetic Haloscope, Phys. Rev. Lett. **124**, 171801 (2020). **(LNL)**

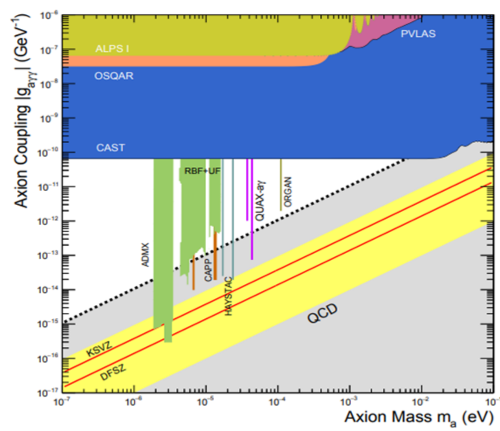
for the axions coupling to electrons

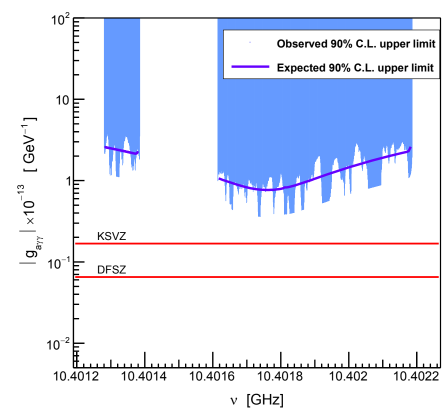
- QUAX-ag Result with Superconductive Resonant Cavity at m_a = 37.5 μeV, Phys. Rev. D **99**, 101101(R) (2019).
- Search for Invisible Axion Dark Matter of mass m_a = 43 meV with the QUAX-ag Experiment, Phys. Rev. D **103**, 102004 (2021).

for the axions coupling to photons



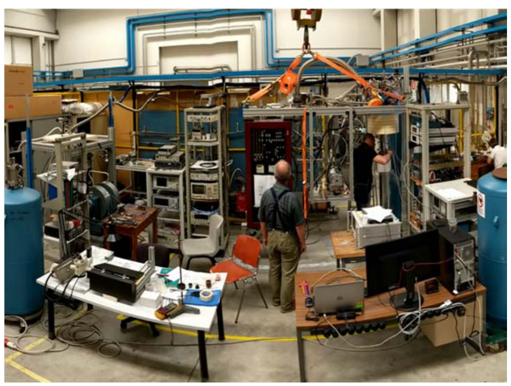


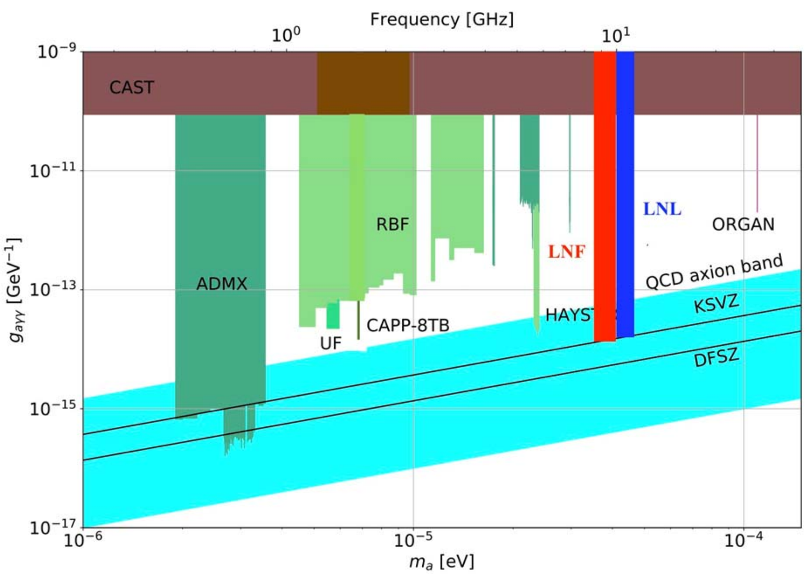




QUAX 2021-2025

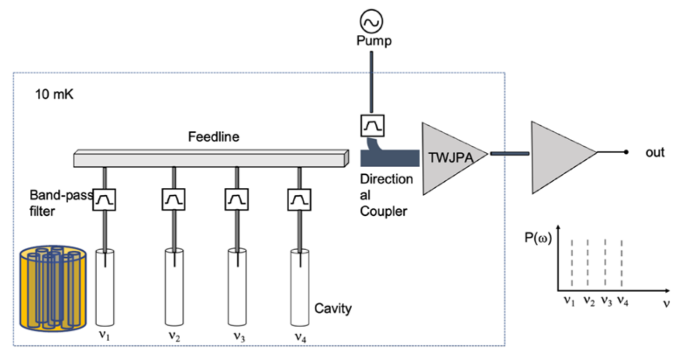
2021	2022	2023	2024	2025
Assembly of haloscopes at LNL and LNF		Data Taking	Scan in range of 8.5 - 11 GHz	





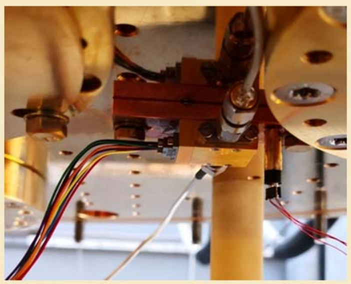
Quax 2025 projection: 2 GHz scan to the KSVZ line

The LNF haloscope will operate with a multi-cavity scheme (7) with the cavities tuned to different frequencies between 8.5 and 10 GHz, inside a 9-Tesla new magnet.

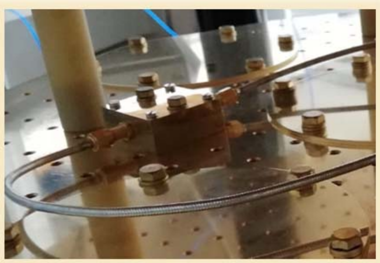


The new COLD laboratory (CryOgenic Laboratory for Detectors) at LNF

http://coldlab.lnf.infn.it

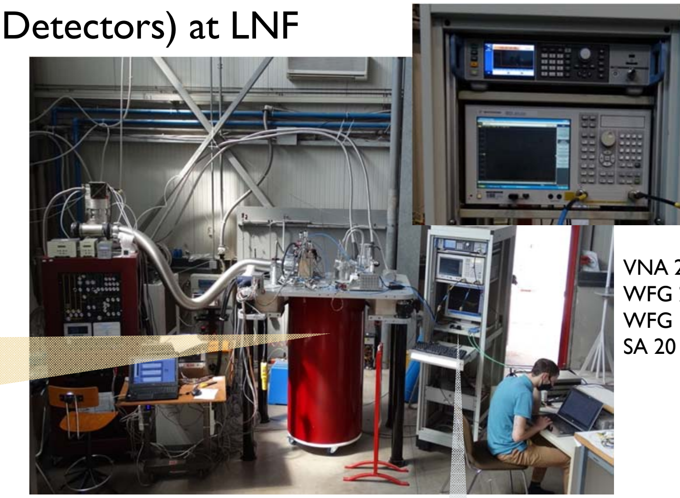


HEMT (6-20 GHz) 4K amplifier



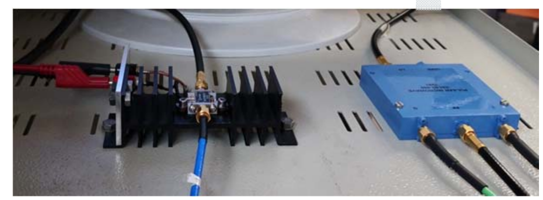
Sample holder for SC chip at
10 mK for single photon device

5 RF lines installed from 300 K to MixCh

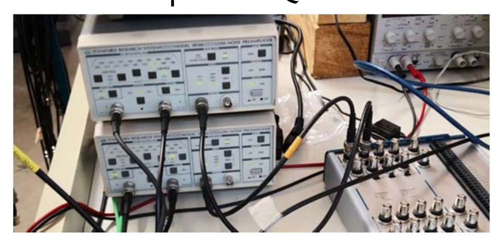


VNA 20 GHz
WFG 20GHz
WFG 13 GHz
SA 20 GHz

FET LNA 8-12 GHz and IQ-mixer (10-12 GHz)



Room T ampli & DAQ

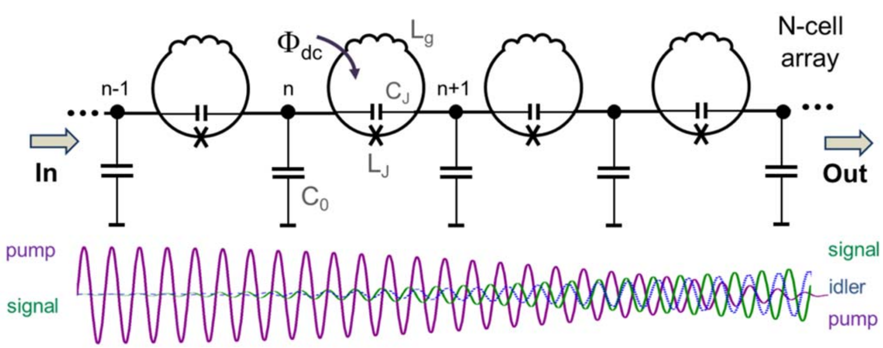


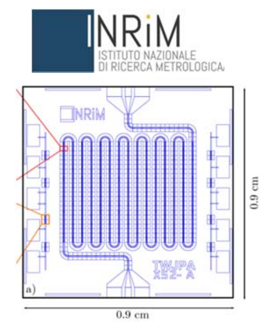
Activities range

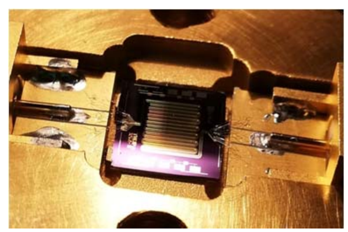
- characterization of cryogenic devices
  normal and superconducting resonant cavities
- R&D for characterization of single photon detectors
  (based on Josephson Junctions)
- electronics for SQUID control and measurement

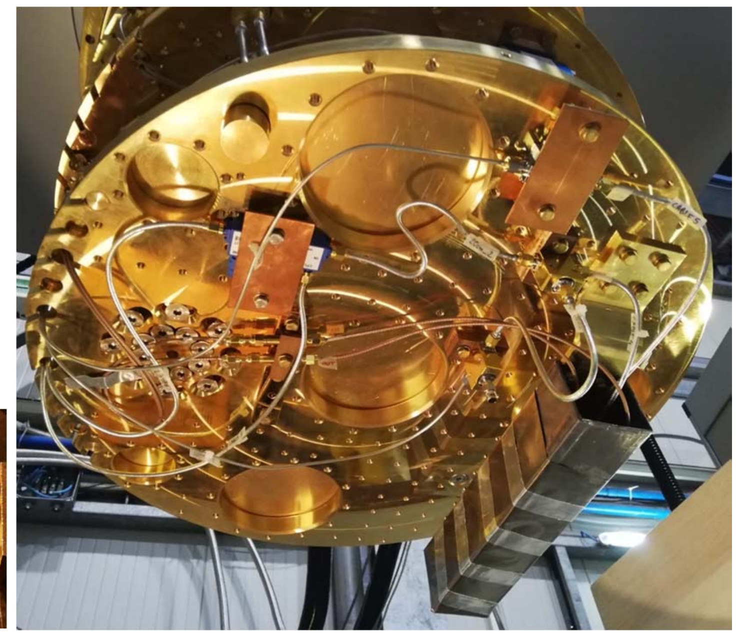
Signal Amplification with TWJPA

Travelling Wave Josephson Parametric Amplifiers amplify microwave signal over a broad range adding the minimum noise set by quantum mechanics.



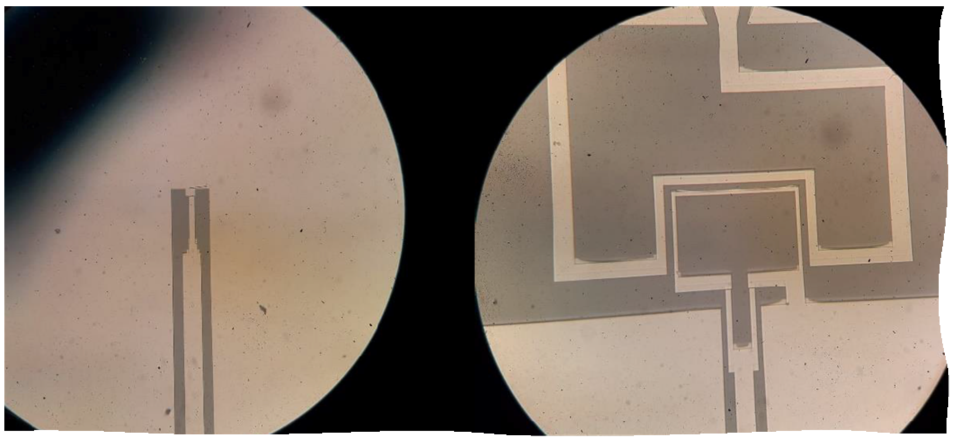






DART WARS

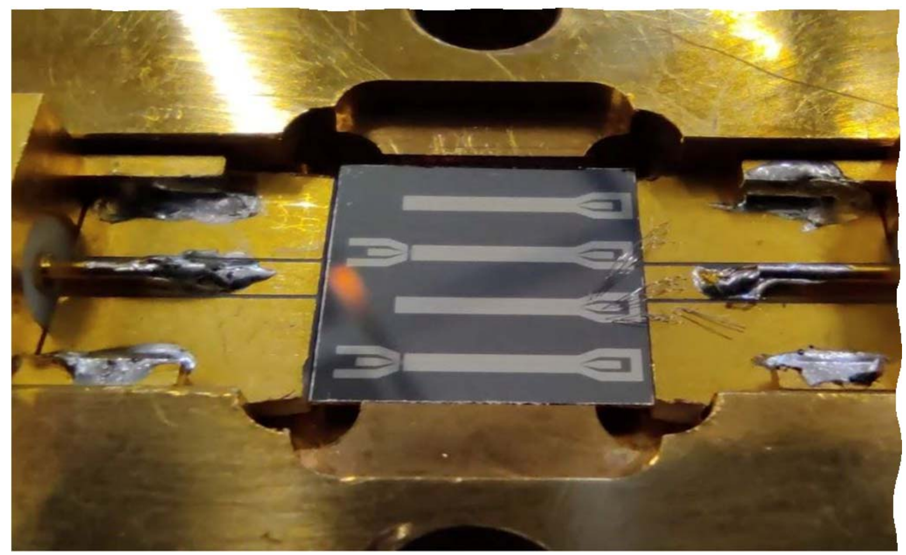
Detector Array Readout with Travelling Wave AmplifieRS



R&D of newly proposed experiments
AXIOMA, KLASH,QUAX, and STAX

SIMP project

Single Microwave Photon Detection

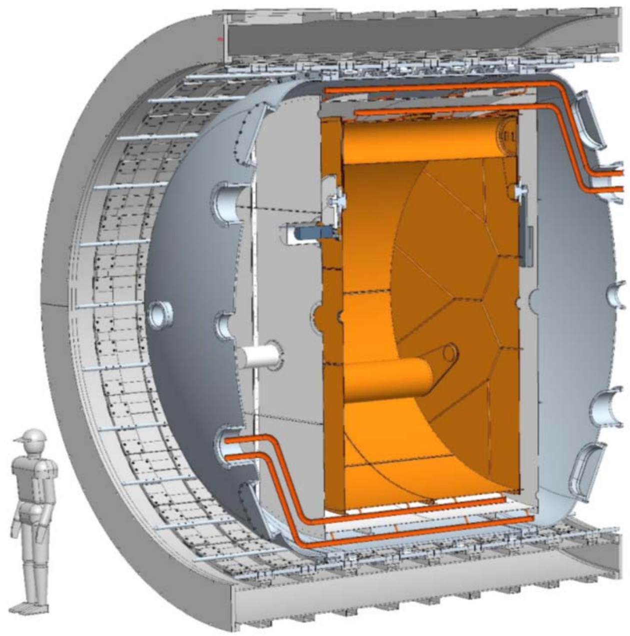


Prototype Devices fabricated at CNR-IFN with shadow mask evaporation technique

Development of single microwave photon detectors based on Josephson Junctions.

- Development of Josephson Parametric Amplifiers (JPA)
- Transition Edge Sensor (TES).

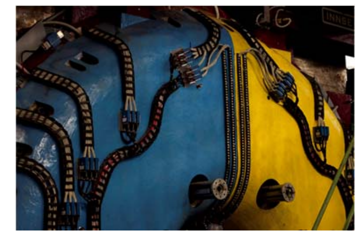
Search for Axions with a Large Volume Haloscope from KLASH to FLASH



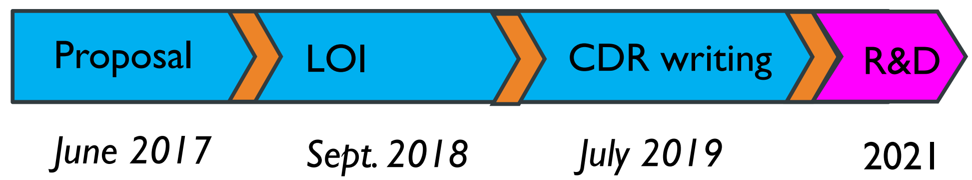
Due to their very big dimensions, **KLOE** or **FINUDA** magnets **can be unique facilities** to host a resonant cavity and become part of an haloscope for very low mass axions.

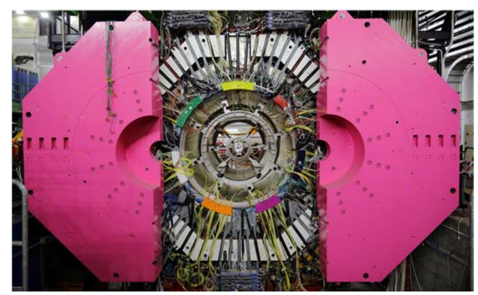
KLASH

KLoe magnet for Axion SearcH



Galactic axion search
at 100 MHz (0.4-1.1 μev)



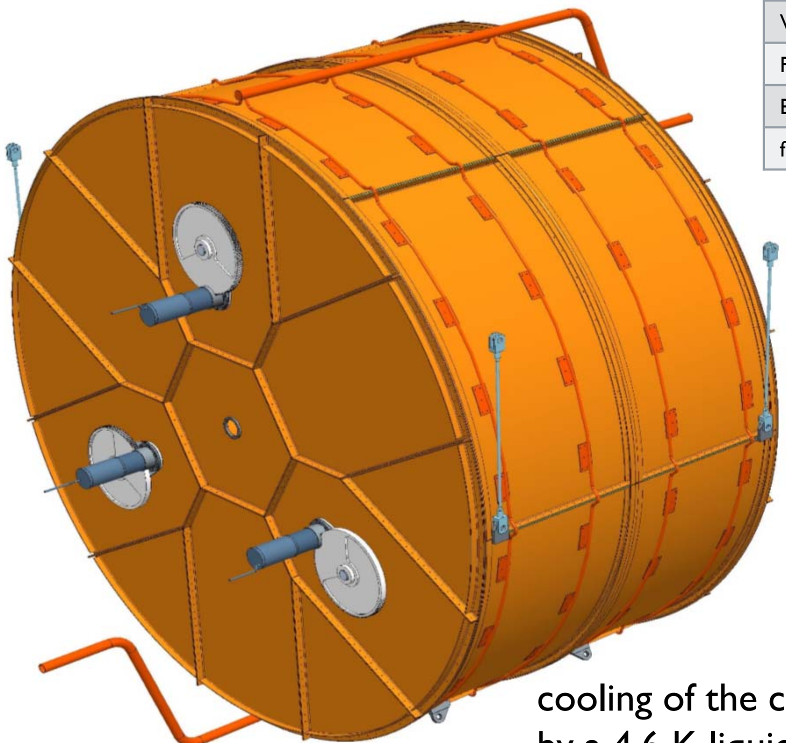


FLASH

Finuda magnet for
Light
Axion
SearcH

The resonant cavity
big cylinder with flat ends

KLASH	
Length	2042 mm
Diameter	3720 mm
V	22 m^3
Field	0.6 T
B^2 V	8 T^2m^3
frequency	60–220 MHz

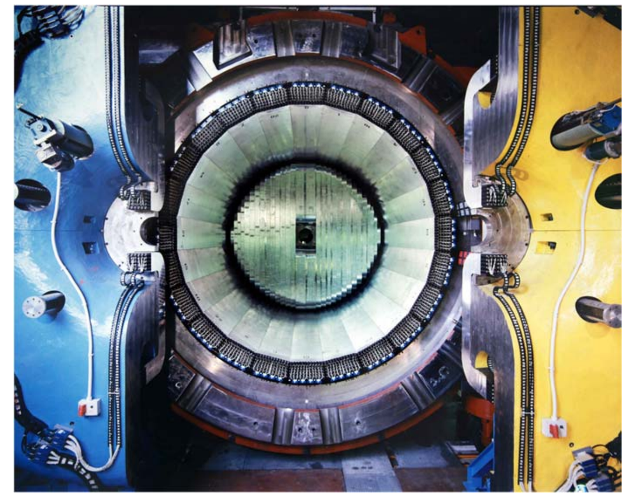


tie-rods to
suspend the cavity

cooling of the cavity will be done
by a 4.6 K liquid helium circuit

tunable rods
for energy range 60-250 MHz.

KLOE magnet as an haloscope



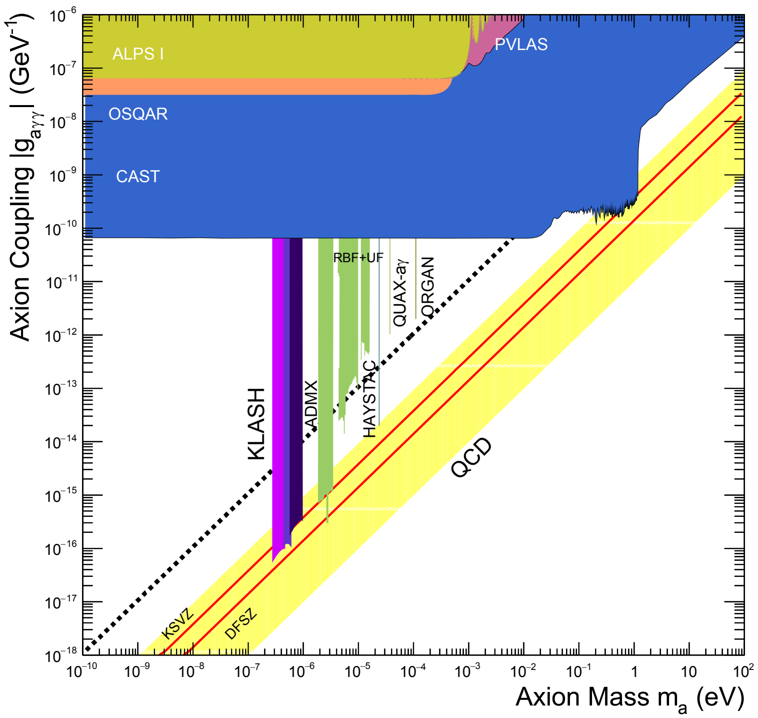
Model param.
- $\rho_a = 0.45$ GeV/cm^3 — DM local density
- $g_\gamma = -0.97$ (0.36) — *KSVZ (DFSZ)* par.
- $\Lambda = 78$ MeV μ — Hadronic scale par.

KLASH param.
- $\nu_a = 65 \div 225$ MHz — ($\leftrightarrow 0.27 \div 0.93$ μeV)
- $B = 0.6$ T
- $V = 22\ (5.2)$ m^3
- $Q = 4 \div 7 \times 10^5$

$\rightarrow P_{sig} \sim 10^{-22}$ W

- Expected sensitivity of KLASH

KLASH CDR arxiv:1911.02427



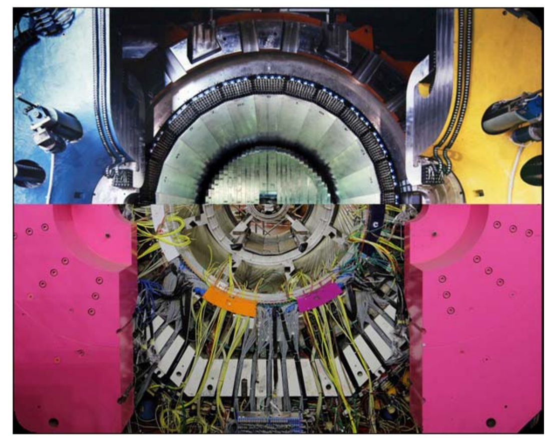
FLASH vs ***KLASH*** sensitivity

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

	KLOE	FINUDA
ν_c [MHz]	65-225	~ 135-250
B^2 [T^2]	0.36	1.21
V [m^3]	22 (5.2)	~ 5.2
Q_L	4÷7 x10^5	~ 3÷6 x10^5
$\nu_c B^2 V Q_L$ [T^{2}m^3/s]	0.2~0.4 x10^{15}	~ 0.4 x10^{15}

FLASH can profit for no more used **unique facilities** (FINUDA / Cryogenic plant)

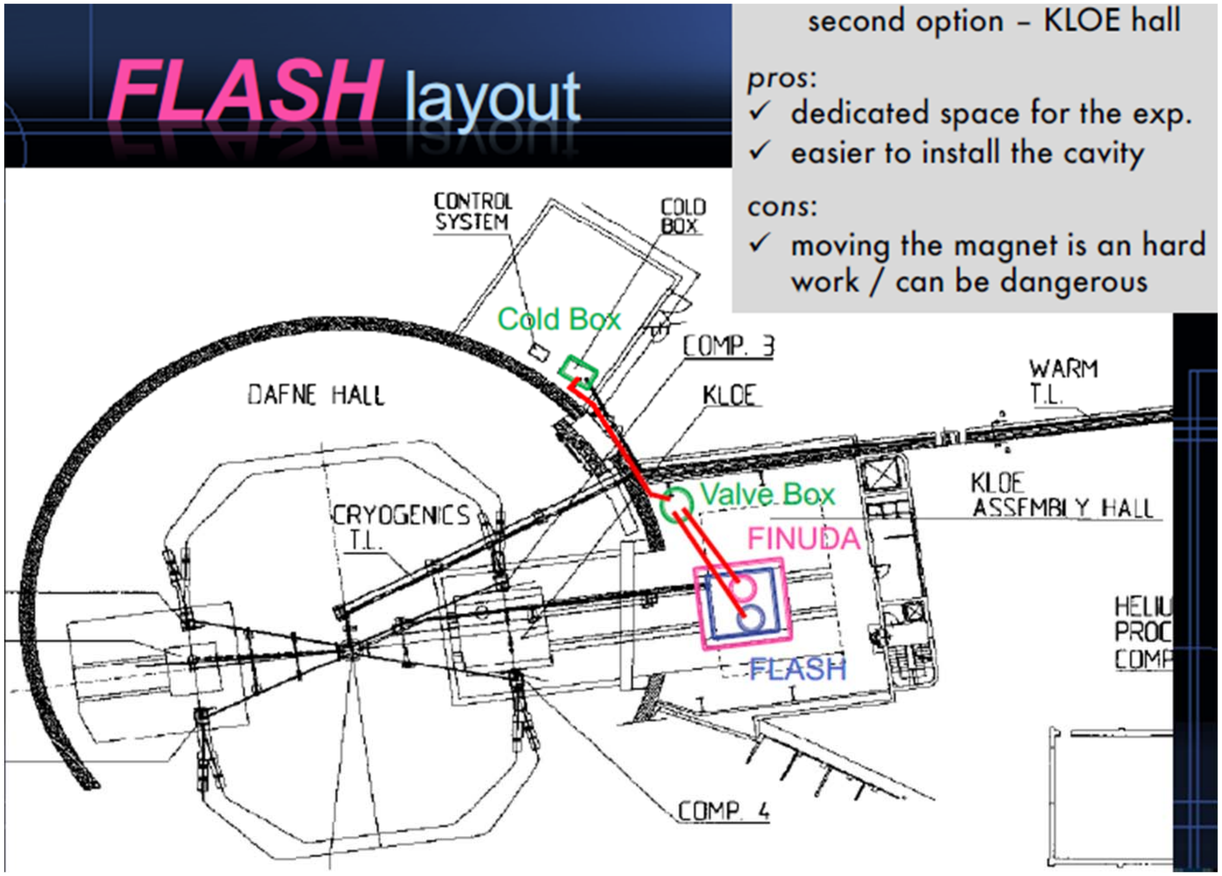
- Calculated parameters give good sensitivity expectation
- No competitors in this axion mass range (at least, in the next years ...)
- Big technological effort to:
  operate the FINUDA magnet again
  design / build / install / operate the cryostat
- Some R&D to do:
  get a reliable and precise cavity tuners motion
  Characterize and operate the MSA SQUIDs



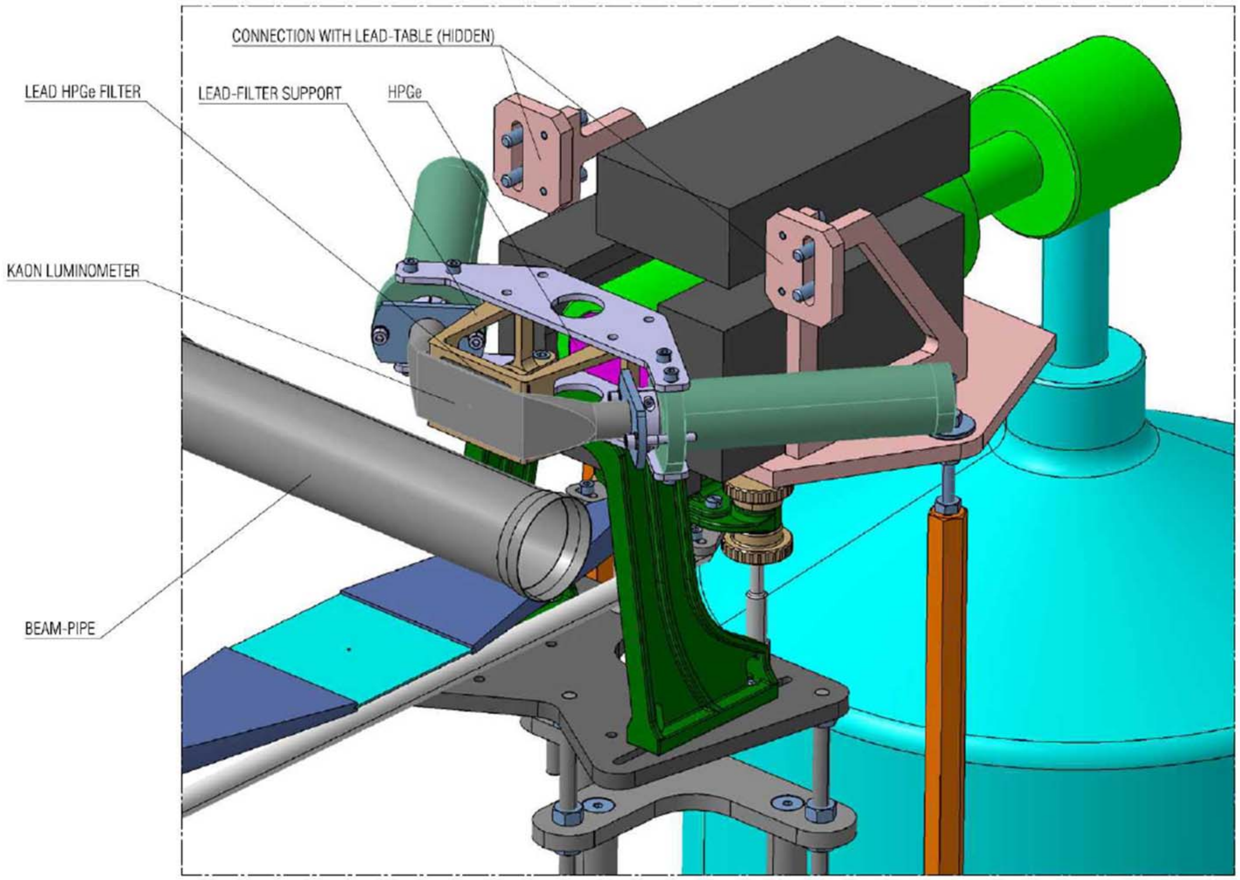
A real possibility to build and put in operation at LNF in 2 - 3 years a large haloscope with the sensitivity to KSVZ axions in the low mass range (0.2 - 1 μeV)

Thank you !

SPARES


FLASH layout
second option – KLOE hall
pros:
✓ dedicated space for the exp.
✓ easier to install the cavity
cons:
✓ moving the magnet is an hard work / can be dangerous
CONTROL SYSTEM
COLD BOX
Cold Box
COMP. 3
KLOE
WARM T.L.
DAFNE HALL
Valve Box
KLOE ASSEMBLY HALL
CRYOGENICS T.L.
FINUDA
FLASH
COMP. 4

Shielding for machine EM background



Introduction: Frank A. Wilczek, Nobel lecture 2004
https://www.nobelprize.org/nobel_prizes/physics/laureates/2004/wilczek-lecture.pdf

The established symmetries permit a sort of interaction among gluons …
that violates the invariance of the equations of QCD under a change in the direction of time. Experiments provide extremely severe limits on the strength of this interaction, much more severe than might be expected to arise accidentally.

By postulating a new symmetry, we can explain the absence of the undesired interaction. The required symmetry is called Peccei-Quinn symmetry after the physicists who first proposed it. If it is present, this symmetry has remarkable consequences. It leads us to predict the existence of new very light, very weakly interacting particles, axions. (I named them after a laundry detergent, since they clean up a problem with an axial current.) In principle axions might be observed in a variety of ways, though none is easy. They have interesting implications for cosmology, and they are a leading candidate to provide cosmological dark matter.