Carlo Ligi (INFN – LNF)
on behalf of the KLASH collaboration

FROM *KLASH* TO *FLASH*

Large Volume Haloscopes
(or: the art of recicling magnets)

FFF Workshop – LNF 13/01/2021

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haloscopes for axion search

- The axion is a pseudoscalar particle predicted by Weinberg and Wilczek as a consequence of the mechanism introduced by Peccei & Quinn to solve the "strong CP problem". It is also a well motivated dark matter candidate, and can accounts for the local density of dark matter in our galaxy (0.45 Gev/cm^3).
- Axion mass can be converted in a photon of the same energy, in presence of a strong magnetic field.
- To detect the produced photons, Sikivie proposed the so-called "haloscope", i.e. a resonant cavity immersed in a magnetic field.
- Many experiments (ADMX, HAYSTAC, ORGAN, CULTASK, RADES, QUAX...) will use a haloscope to detect axions.
- 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.

KLOE magnet as an haloscope

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

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 ÷ 0.93 µeV)
- $B = 0.6$ T
- $V = 22\ (5.2)$ m^3
- $Q = 4 \div 7 \times 10^5$

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

KLOE magnet as an haloscope

Data taking time

$$SNR = \frac{P_{\text{sig}}}{k_B T_{sys}} \sqrt{\frac{\tau}{\Delta\nu_a}}$$

- $P_{sig} \sim 10^{-22}$ W
- $T_{sys} \sim 5$ K
- $\Delta\nu_a/\nu_a = 10^{-6}$

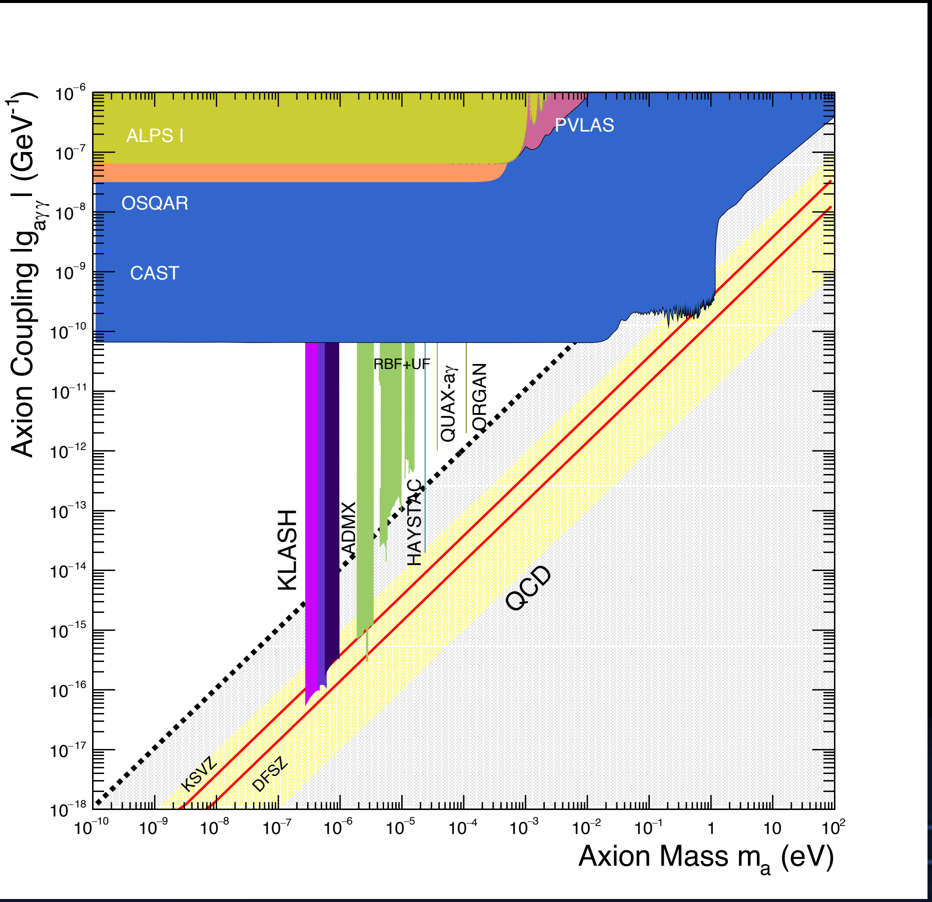
to get $SNR > 1 \rightarrow \tau \sim 5 \div 10$ min

KLOE magnet as an haloscope

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

	KLASH	ADMX
ν_c [MHz]	65-225	450-850
B^2 [T^2]	0.36	58
V [m^3]	22 (5.2)	0.13
Q_L	4÷7 x10^5	0.7÷2 x10^5
$\nu_c B^2 V Q_L$ [$T^2 m^3/s$]	0.2~0.4 x10^{15}	0.5~1 x10^{15}

KLASH sensitivity



KLASH axion calling *(...and I live by the river...)*

KLoe magnet for Axion SearcH

A proposal for a haloscope to detect Axions using a cryogenic cavity in a magnetic field (ADMX-like)

Proposal – *June 2017*

The KLASH Proposal

Axion Calling

D. Alesini, D. Babusci, D. Di Gioacchino, C. Gatti, G. Lamanna, C. Ligi
INFN, Laboratori Nazionali di Frascati, P.O. Box 13, I-00044 Frascati, Italy

LOI – *September 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].

In 2019 CSN2 funded us for a cryostat feasibility study and a CDR writing

KLASH

Conceptual Design Report

D. Alesini[1], D. Babusci[1], P. Beltrame S.J.[2], F. Björkeroth[1], F. Bossi[1], P. Ciambrone[1], G. Delle Monache[1], D. Di Gioacchino[1], P. Falferi[3], A. Gallo[1], C. Gatti[1], A. Ghigo[1], M. Giannotti[4] G. Lamanna[5], C. Ligi[1], G. Maccarrone[1], A. Mirizzi[6], D. Montanino[7], D. Moricciani[1], A. Mostacci[7], M. Mück[8], E. Nardi[1], F. Nguyen[9], L. Pellegrino[1], A. Rettaroli[1,10], R. Ricci[1], L. Sabbatini[1], S. Tocci[1], L. Visinelli[11]

https://arxiv.org/abs/1911.02427

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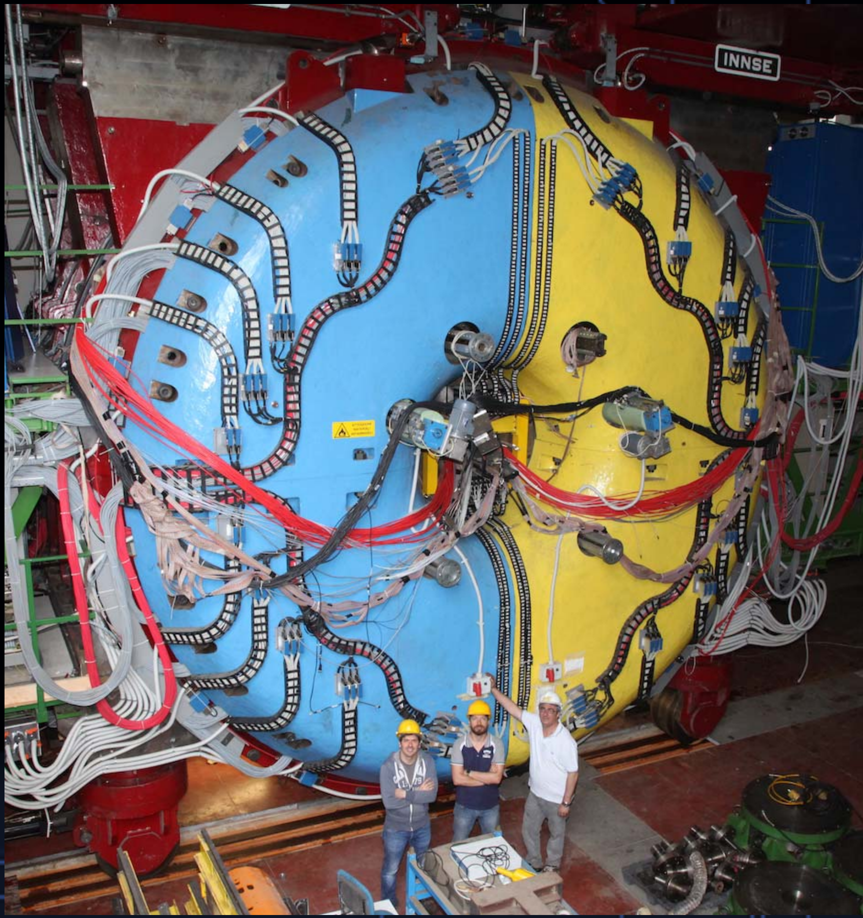
KLOE magnet

$B_{max} = 0.6$ T

$V_{bore} = 4.86\ (\emptyset)\times 4.4(l)$ m

Main cavity constraints:

- $D \sim 3.5$ m → $m_a < 1$ μeV
- It should be cryogenic → 4.5 K



KLASH feasibility study

Work to do for KLASH:

- *dismount the wire chamber and the calorimeter from KLOE*
- *design and build the cavity with the tuning system*
- *design and build the cavity cryostat and the tools for the installation*
- *modify the cryogenic transfer lines*
- *move the cryogenic valve box in the KLOE hall*
- *build a new power supply for the KLOE magnet*
- *make some R&D for the cryogenic amplification*

KLASH feasibility study

In 2019, Fantini Sud S.p.A. won the tender for the feasibility study and the cost estimation about the work to build and install a cryostat with the cavity.

The company, based on our inputs and under our supervision, provided a preliminary mechanical design of the cavity and the cryostat. They took in account for all the issues (machinering, transportation, installation procedure and cooling) arising from such a peculiar task.

They estimated a total cost of about 2.2 M€

fantini
FANTINI SUD S.p.A.

INFN-LNS – ESPERIMENTO KLASH

Document no.	Type	Release
39172-TN-DD.001	Descrizione tecnica	0

Contract		
	Client	INFN – Laboratorio Nazionale di Frascati (RM)
	Order	Incarico per la redazione di uno studio di fattibilità

Object
TN – Descrizione tecnica
CRIOSTATO PER IL NUOVO ESPERIMENTO KLASH

Abstract
Questo documento riporta gli esiti dello studio tecnico di fattibilità tecnica ed economica relativo ad un nuovo criostato da installare all'interno dell'esistente magnete super-conduttore Kloe.
Lo studio è stato realizzato in conformità con la Specifica Tecnica emessa da INFN-LNF come allegato all'incarico formale dato alla Fantini Sud.
Il nuovo criostato per l'esperimento KLASH si comporrà dei seguenti elementi principali:

- recipiente esterno a tenuta di vuoto in acciaio inossidabile, idoneo ad essere fatto scorrere assialmente e fissato all'interno del magnete;
- schermo termico all'interno del recipiente in lega d'alluminio, raffreddato ad elio criogenico gassoso;
- cavità risonante in rame raffreddata ad elio criogenico liquido all'interno dello schermo termico, completa di tre "tuners" longitudinali posizionabili tramite servo-meccanismi;
- attrezzature per l'assemblaggio di quanto sopra ed il suo inserimento all'interno della cavità centrale del magnete;
- torretta criogenica sotto vuoto per la gestione dell'elio criogenico (sia gassoso che liquido) per il raffreddamento dello schermo e della cavità; la torretta sarà posizionata all'esterno del magnete e dotata di un'idonea struttura di supporto;
- due linee super-isolate sotto vuoto (transfer lines) per la circolazione dell'elio criogenico sia liquido (LHe) che gassoso (GHe) tra la torretta ed il nuovo criostato;
- sistema super-isolato di tubazioni di mandata e ritorno (transfer lines) per l'elio criogenico sia gassoso che liquido, congiungente la torretta con il recipiente esterno a tenuta di vuoto.

Rev.	Date	Object	Prepared	Verified	Approved
0	14/06/2019	First Issue	G. Murru G. Santin	R. Torelli	F. Fantini
1	26/07/2019	Updates upon comments from INFN	G. Murru G. Santin	R. Torelli	F. Fantini

A - Sistema di raffreddamento criogenico:		
- Torretta criogenica (Materiali, Lavorazioni, Strumentazione)	€	613.800,00
- Transfer lines (Materiali, Costruzione, Componentistica)	€	54.500,00
- Passanti da vuoto (Costruzione, Componentistica)	€	16.900,00
- Tubazioni per elio non criogenico (Materiali, Costruzione)	€	6.800,00
- Coibentazioni multistrato all'esterno degli schermi termici	€	12.400,00
B - Vessel, schermo radiativo ed apparati meccanici:		
- Criostato (Materiali, Lavorazioni, Trattamenti)	€	738.000,00
- Cavità risonante (Materiali, Lavorazioni, Attuatori)	€	237.000,00
- Schermo radiativo (Materiali, Lavorazioni)	€	43.000,00
- Attrezzature di montaggio	€	44.000,00
Progettazione, gestione, qualità e servizi (A + B):		
- Progettazione (Disegni, Verifiche, Manuali)	€	145.300,00
- Gestione tecnica e Qualità	€	108.000,00
- Servizi (Trasporti, Montaggi, Prove, Misure)	€	180.300,00
TOTALE	**€**	**2.200.000,00**
Opzione aggiuntiva:		
- Cavità #2 di cui al Par. 7	€	250.000,00

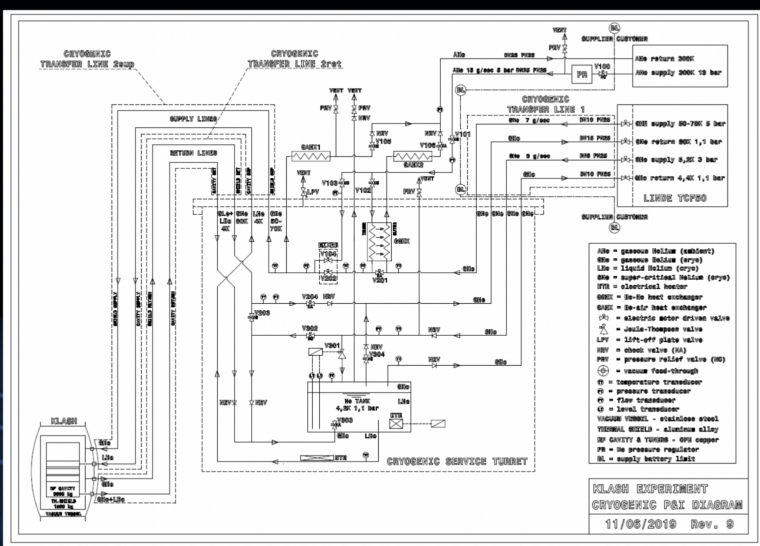
KLASH cryostat design

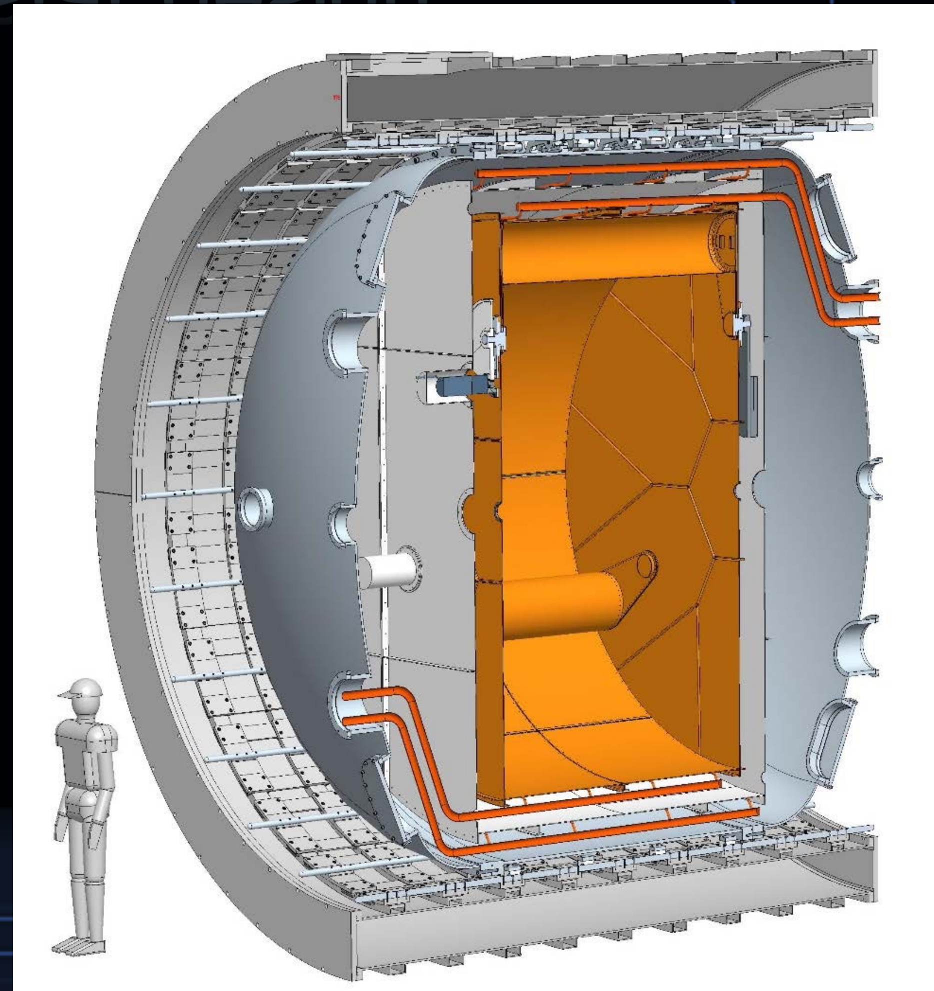
KLOE cryostat + KLASH

Cavity dim.: $3.69(\emptyset)\times 1.96(l)$ m

Vacuum container + 70 K Shield

Cryogenic service turret





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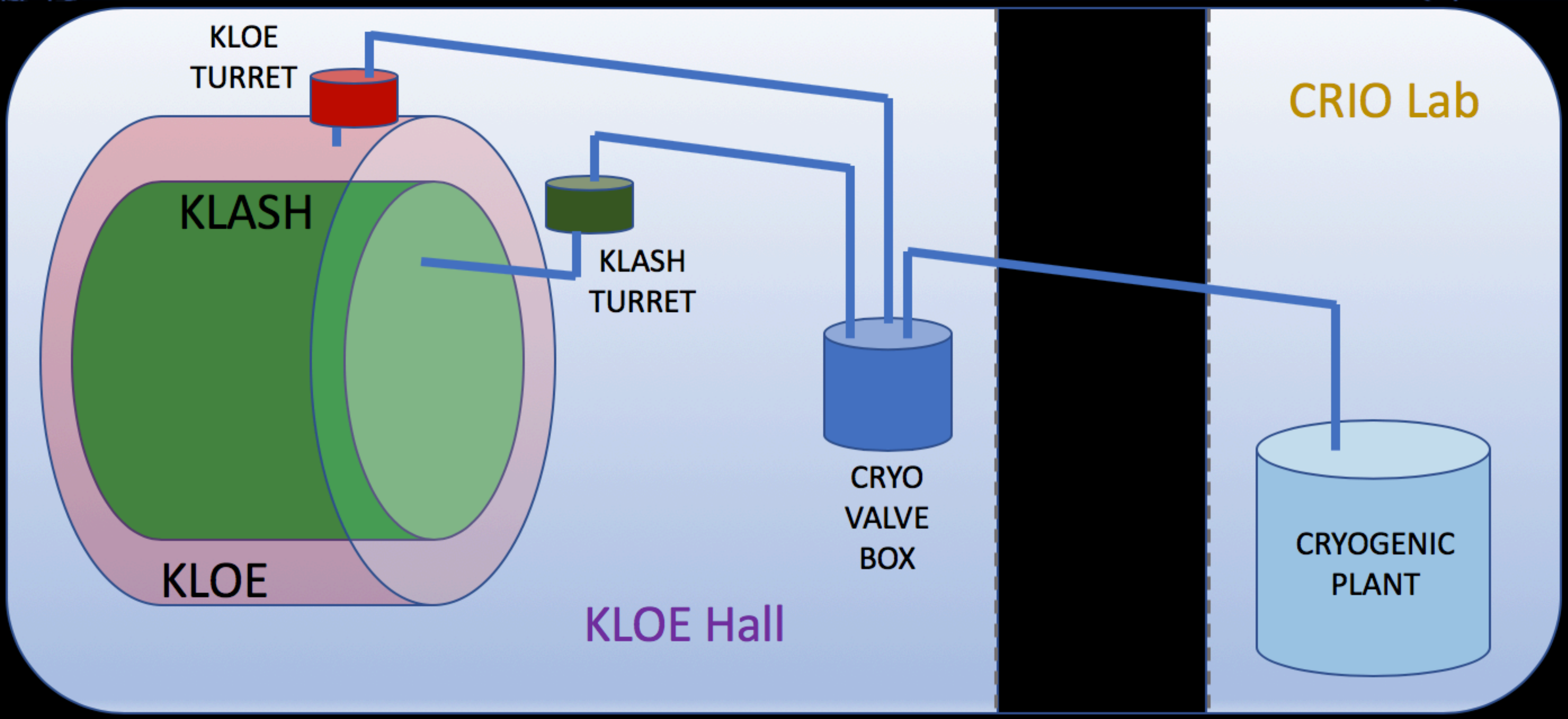
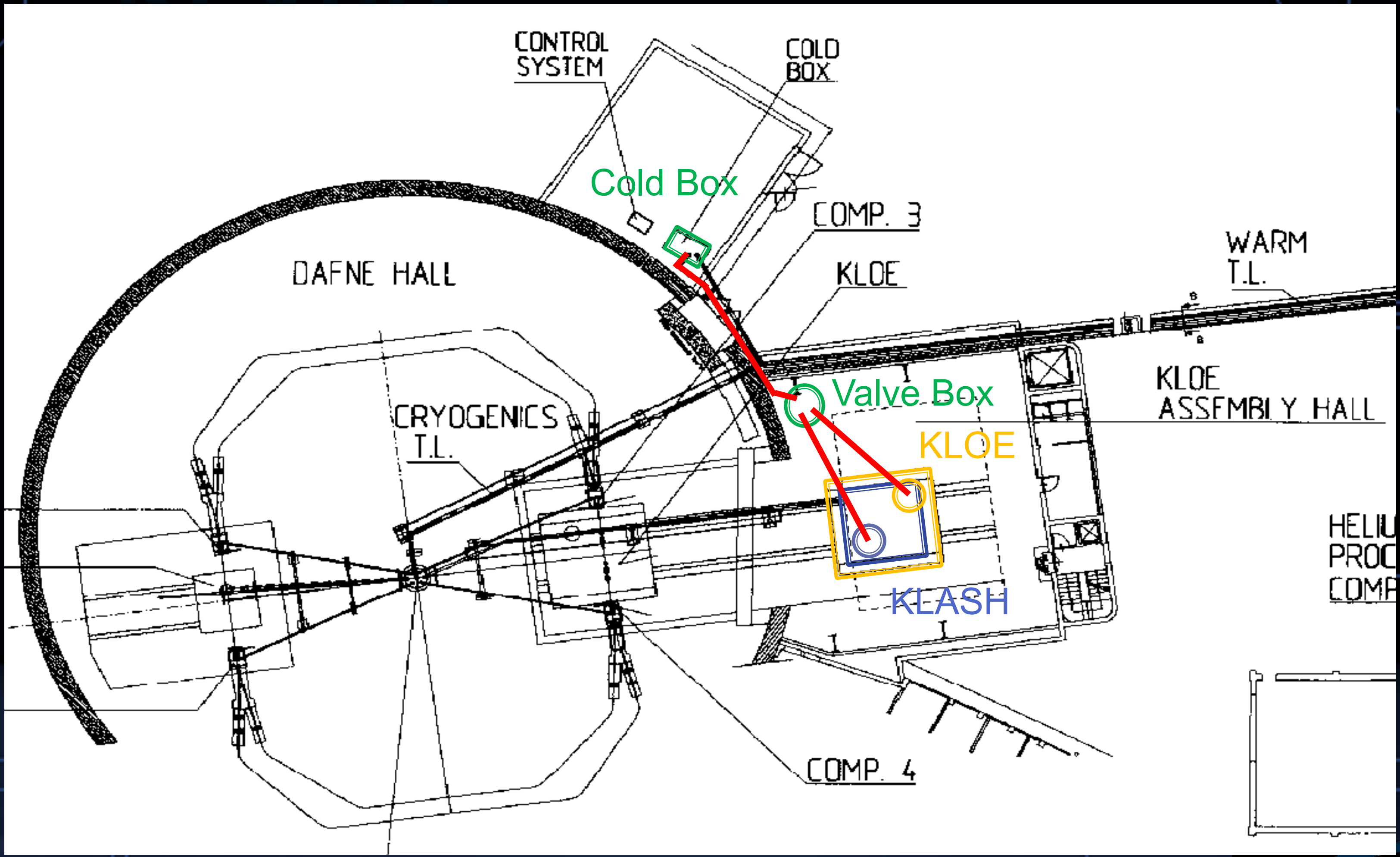
KLASH cryogenic layout



KLASH cryogenic layout



DAΦNE cryogenic plant

LINDE TCF 50
LHe liquefactor/refrigerator

Running since 1996
Compressor replaced in 2015

Total Capacity:
4.5K capacity: 99 W + 1.14 g/s
70K capacity: 800 W

Available capacity for KLASH:
4.5 K: 44 W + 0.8 g/s
70 K: 270 W

Available capacity for FLASH:
4.5 K: 55 W + 0.9 g/s
70 K: 530 W

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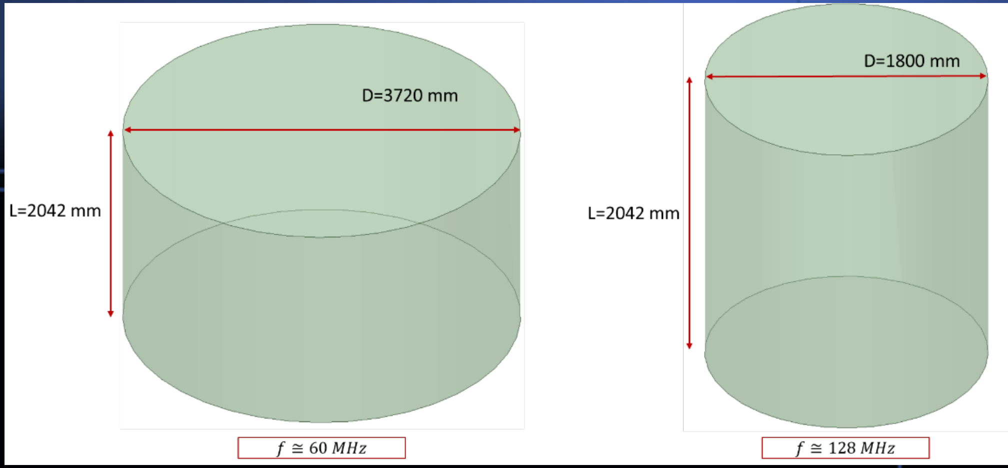
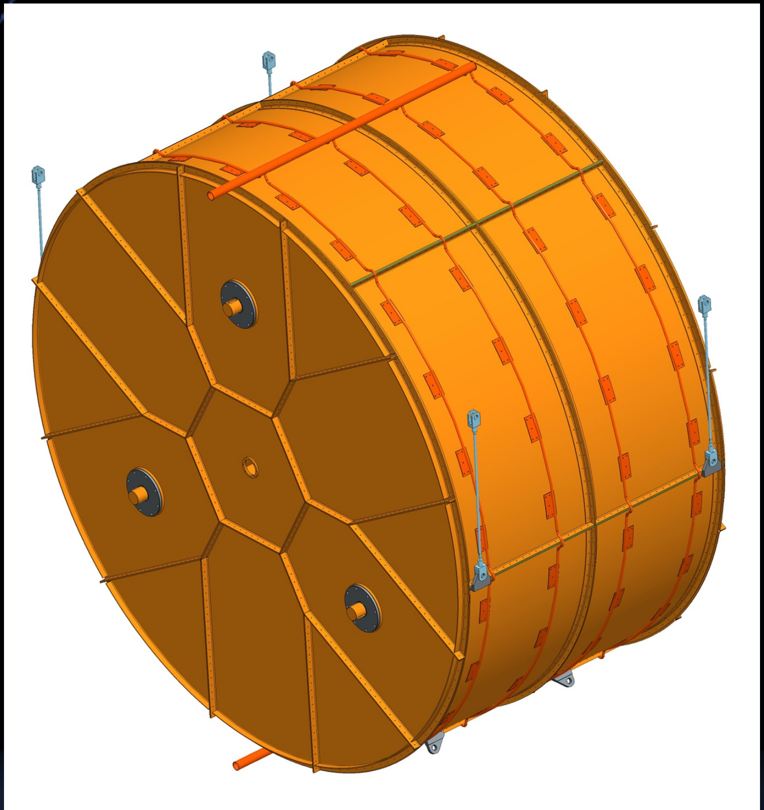
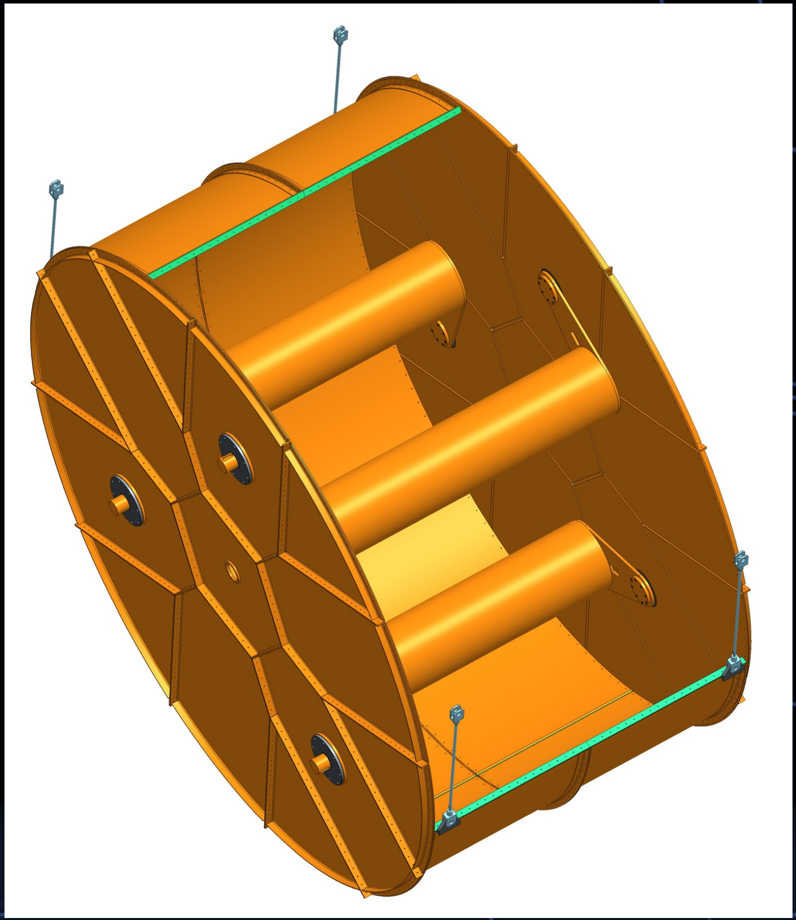
cavity design



- TM_{010} resonant mode (best geometrical form factor)
- Cryogenic copper resonant cavity gets a $Q \sim 10^5 \div 10^6$ (RRR=50)
- To cover the range 65 ÷ 225 MHz two cavities will be alternated
- 3 tuners + fins on the lo-*f* cavity, 3 tuners on the hi-*f* one
- About 10^5 steps required to cover the freq range (30 μrad/step) →
- Sapphire piston insertion for the fine tuning / avoid mode mixing

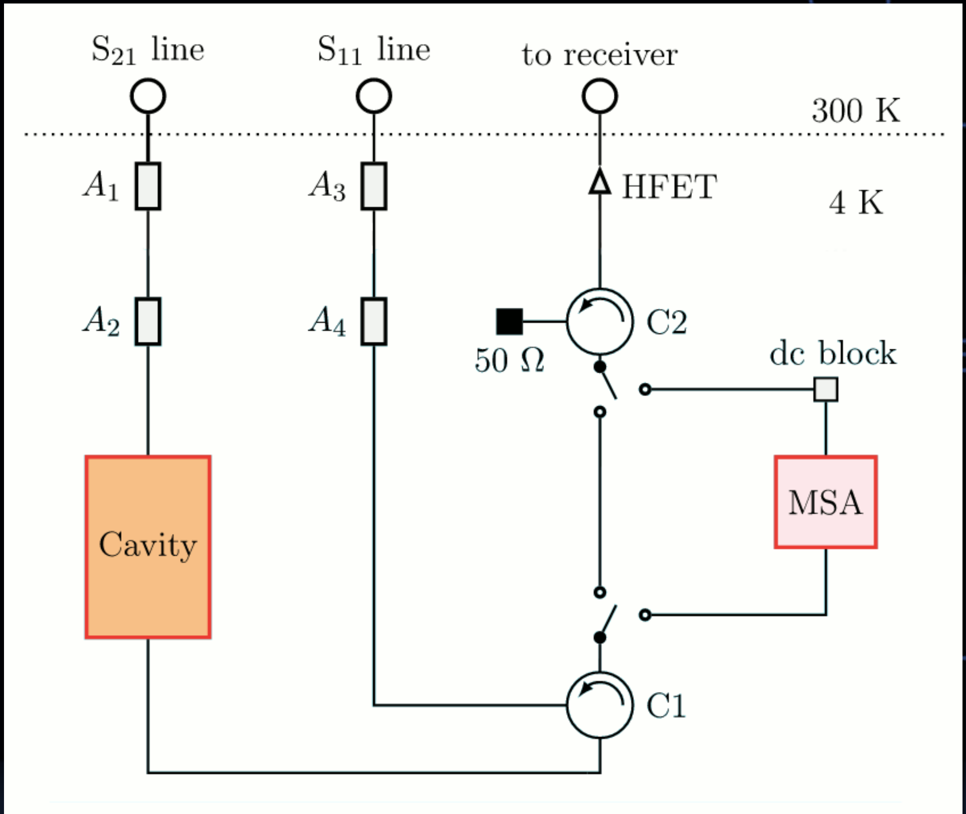
cavity design





signal detection

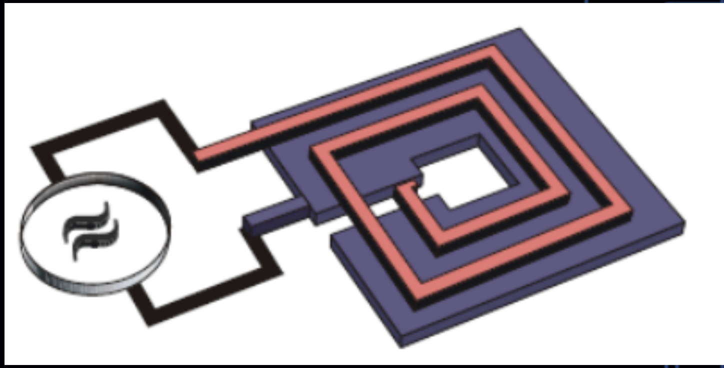
- Cavity/Antennas
- MSA SQUID
- Cryogenic Amplification
- Room T Amplification



ADMX scheme

cryogenic amplification stage

- Microstrip SQUID Amplifier (MSA) is effective even for f > 100 MHz
- At least 3 MSA required (65-115, 115-150, 140-225 MHz)
- Operating T = 4.5 (0.3?) K
- Thermal noise $\propto T$
  - T_n (0.3 K) = 16÷82 mK (for 50÷250 MHz)
  - T_n (4.5 K) = 0.24÷1.23 K (for 50÷250 MHz)
- HFET as a 2° stage amp
- Total Gain = 35 dB
- Magnetic Shield needed – *delicate task because it stay inside the magnetic field* (SC/cryoperm/*m*-metal/active shielding)



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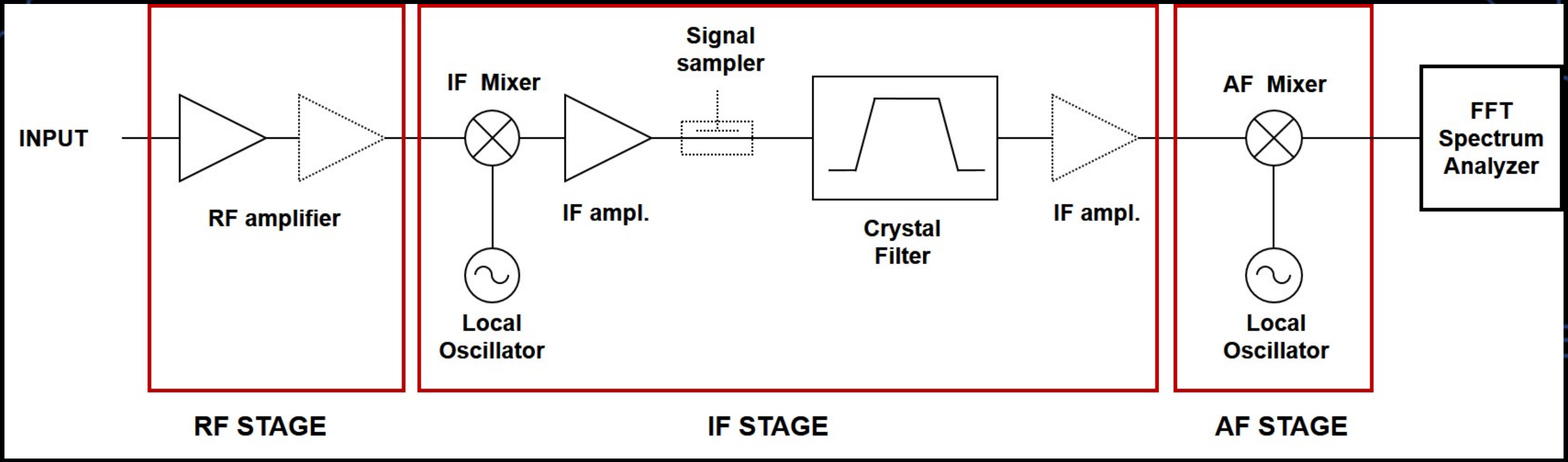
room T amplification stage



RF stage
bw 500 MHz
gain: 30÷60 dB
T_n: <150 K
(0.05 K equiv.)
RF shielded

intermediate stage
image rejection mixer → 10.7 MHz
crystal bandpass filter

audio stage
mixer → 30 kHz

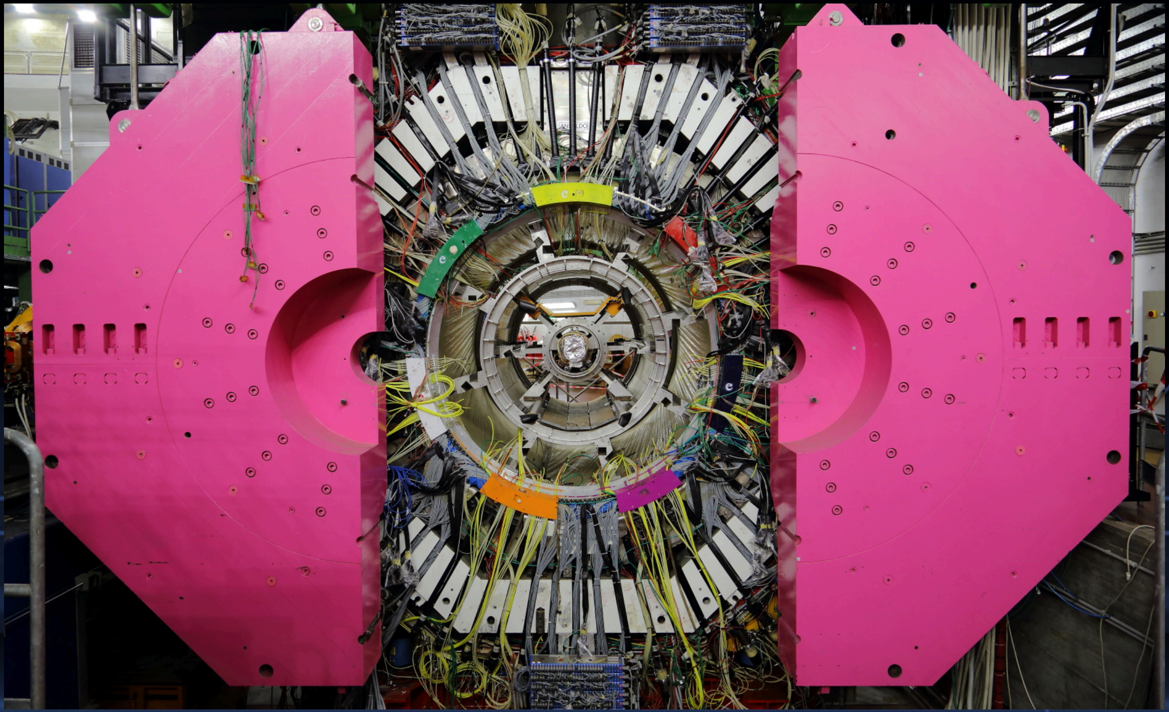
cryo amp gain = 35 dB → Room T commercial low noise components

from KLASH to FLASH

In July 2019 we were informed that the KLOE magnet was assigned to the DUNE experiment

It is possible to use the FINUDA magnet in its place

***FLASH** (Finuda magnet for Light Axion SearcH)*



from KLASH to FLASH

FINUDA magnet and power supply should be tested for functionality

Magnet cryogenics and ancillary systems should be refurbished

Transfer lines should be prolonged for cryogenic tests

CDR should be revised with new simulations (S. Tocci, new COLD member)

Experiment cost should be roughly the same

Competitors:

- *DMRadio/Abracadabra (but they need a 10-20M€ magnet)*
- *RADES (they will use the BabyIAXO magnet) - possible FLASH/RADES joint collaboration to search for axion in the 100-400 MHz range*

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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}

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FLASH layout

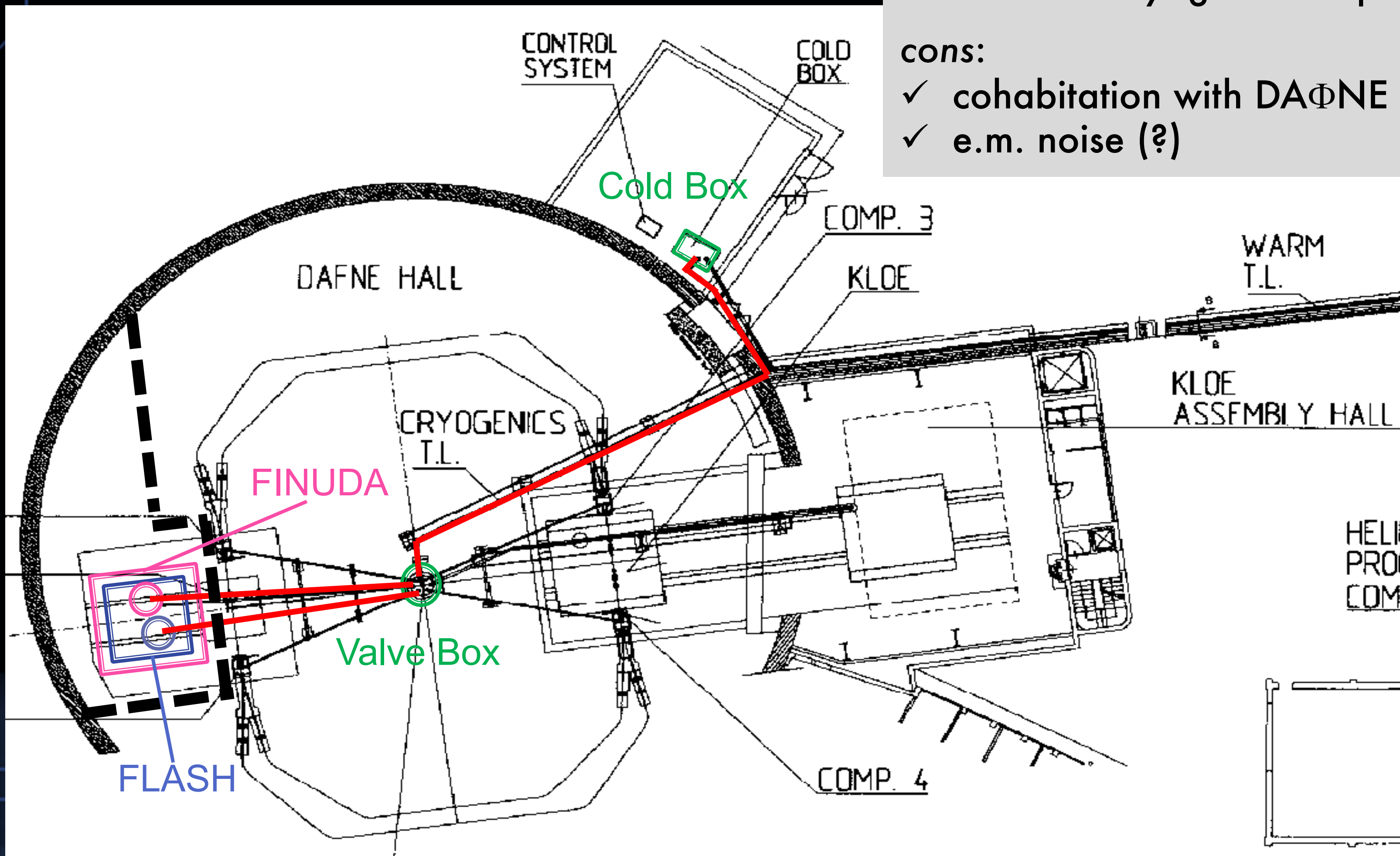
first option – DAΦNE hall

pros:

- ✓ no needs to move the magnet
- ✓ minimize cryogenic adaptation

cons:

- ✓ cohabitation with DAΦNE func.
- ✓ e.m. noise (?)



FLASH layout

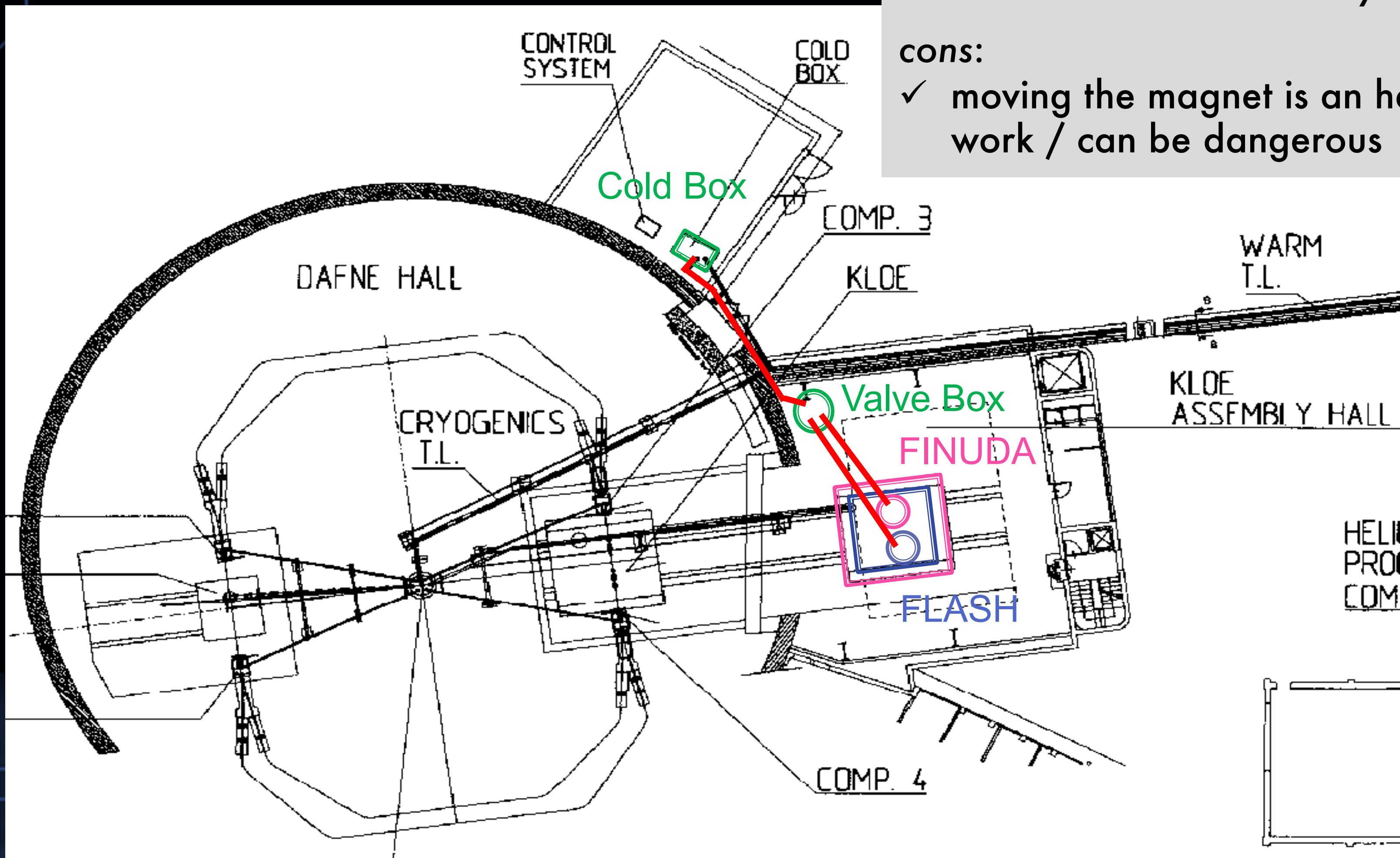
second option – KLOE hall

pros:

- ✓ dedicated space for the exp.
- ✓ easier to install the cavity

cons:

- ✓ moving the magnet is an hard work / can be dangerous



summary

- *FLASH* can profit for no more used unique facilities (FINUDA / Cryoplant)
- 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
- Some open tasks to go deep in (ambient noise, magnetic shielding…)
- No timeline yet