GrAHal-CAPP for Axion Dark Matter Search with Unprecedented Sensitivity in the 1-3 μeV Mass Range

P. Pugnat, LNCMI-Grenoble/CNRS, EMFL

Tuesday 17 September 2024

GrAHal Grenoble Axion Haloscopes | LNCMI | EMFL European Magnetic Field Laboratory | cnrs | UGA Université Grenoble Alpes

Outline

- Introduction
  - Weakly Interacting Slim Particles (WISPs)* as a possible component(s) of the Cold Dark Matter (CDM) & QCD DM Axion
  - The need of high field / high flux magnets

** Complementary to the "better-known" WIMPs, i.e. Weakly Interactive Massive Particles*

- The 43 T Grenoble Hybrid Magnet at LNCMI (CNRS, Univ. Grenoble-Alpes)
  - Overview
  - Development of the superconducting conductor & in-house assembly
  - On-going commissioning phase
- The Grenoble Axion Haloscope (GrAHal)
  - BabyGrAHal
  - Probing QCD Axion Dark Matter with the Grenoble Hybrid Magnet up to 43 T
  - QCD DM axion search at high frequency & high field, *i.e. around* 12.78 GHz (52.5 μeV) & 43 T
  - Focus on QCD DM axion search in the low frequency range (200-600 MHz *i.e.* 1-3 μeV)

Particle Physics Beyond the Standard Model – Oversimplified Picture

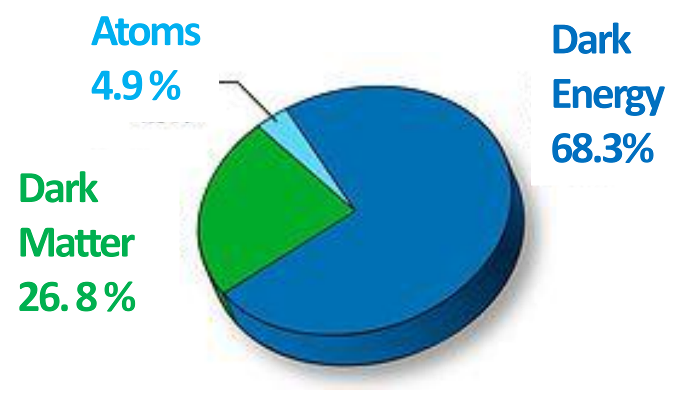
Among Biggest Questions in Science…

Mass

WIMPs (SUSY,…)
$> \sim$ 0.1 GeV

SIMPs (0.1 mbarn)

Also solve the strong CP problem



The Universe energy/matter density content after Planck (2013)

Λ-CDM Standard Model of Cosmology

WISPs (Axion, ALPs,…)
Slim/Sub-eV

SISPs (?)
Strongly interacting & Slim

Other interactions

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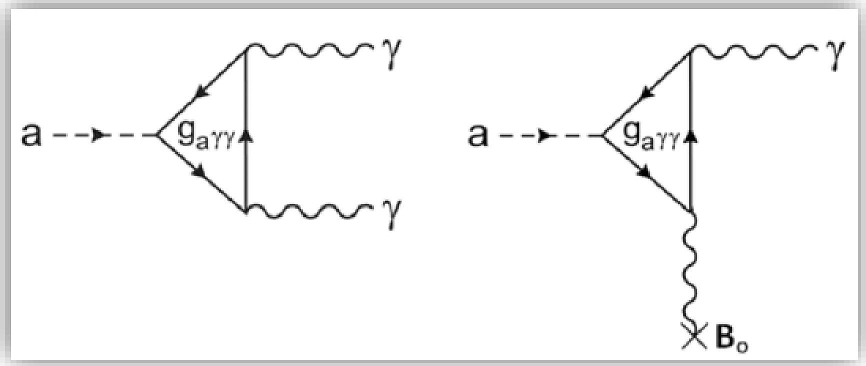
Why High Magnetic Fields & Flux for QCD-DM Axion/ALPs searches ?

- ▸ To maximize the conversion of this hypothetical weakly interacting particle to photons, via the inverse Primakoff effect



The key ingredient of most of the experiments

$P_{LSW} \sim g_{a\gamma\gamma}^4 B^4 L^4$

$P_{Haloscope} \sim g_{a\gamma\gamma}^2 B^2 V$

This "non-trivial" interaction is related to the chiral anomaly, i.e. a purely quantum phenomenon first studied in particle physics in 1969 (Adler, Bell and Jackiw) to explain the neutral pion decay in 2 photons ($\pi^0 \rightarrow \gamma\gamma$) anticipated and observed by Primakoff in 1951.

The puzzle was the anomalous nonconservation of a chiral current, which is today "rejuvenated" in condensed matter physics…

Hybrid Magnets Worldwide Producing the highest DC-field

LNCMI

EMFL

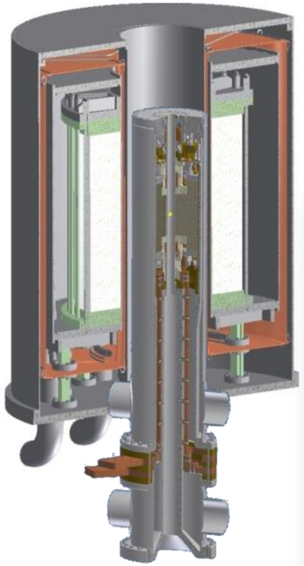
HFML
Science in High Magnetic Fields

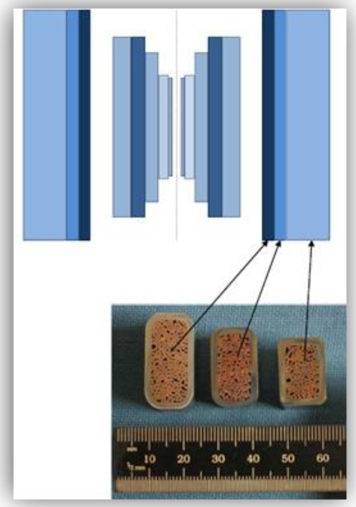
CHMFL

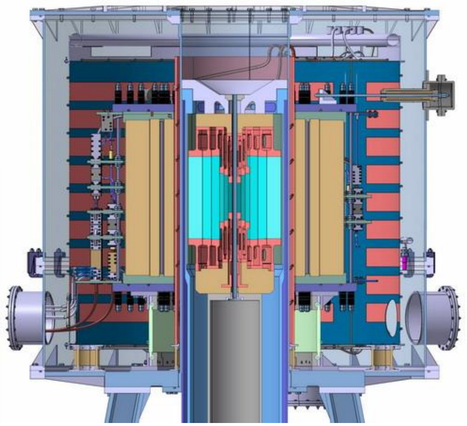
NATIONAL HIGH MAGNETIC FIELD LABORATORY

Specially developed
RCOCC conductor
13 x 18 mm^2

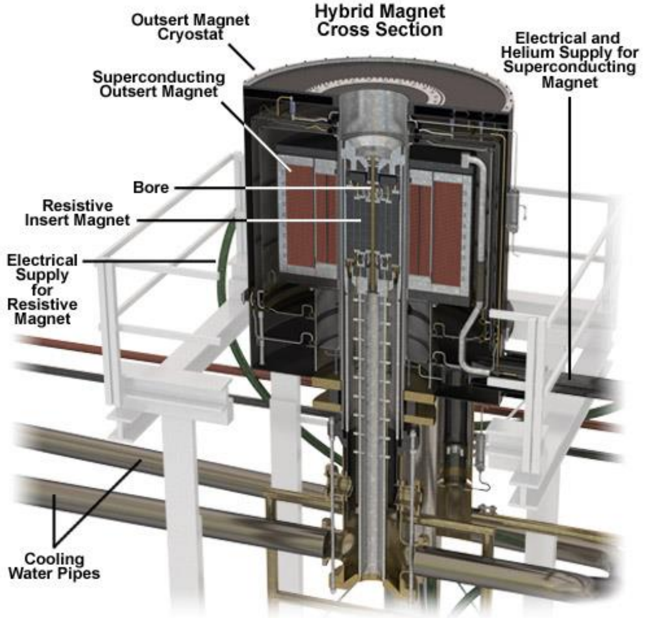
Key point
Modularity High field/high flux







Cooling by forced flow
supercritical He ~11g/s @ 5 bars



Grenoble, France	Nijmegen, Netherlands	Hefei, China	Tallahassee, FL
8.5 (9) + 34.5 (36+) = **43 (45+) T**	12 + 33 = **45 T**	11 + 34 = **45 T**	11.5 + 33.5 = **45 T**
34 mm, 24 (30) MW	32 mm, 24 MW	32 mm, 32 MW	32 mm, 32 MW
RCOCC Nb-Ti, 1.8 K	CICC Nb3-Sn, 4.2 K	CICC Nb3-Sn, 4.2 K	CICC Nb3-Sn, 4.2 K
7.1 kA, 1100/1826 mm dia.	20 kA, 720/1286 mm dia.	13.4 kA, 680/1650 mm dia.	10 kA
2025	**In construction**	**45.22 T Aug. 12, 2022**	**45.17 T June 26, 2000**

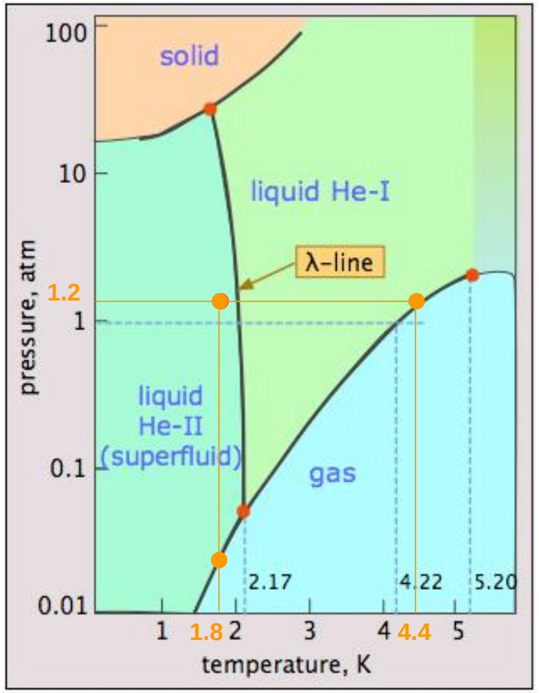
Technological Choices

Nb-Ti/Cu Rutherford Cable On Conduit Conductor (RCOCC) specially developed with in-house assembly

- Internal cooling with stagnant superfluid He connected to the external bath
- Strict control of AC-losses

P. Pugnat, R. Pfister, *et al.*, *IEEE Trans. Appl. Supercond.* 28, 4301005 (2018)
https://indico.cern.ch/event/659554/contributions/2714073/

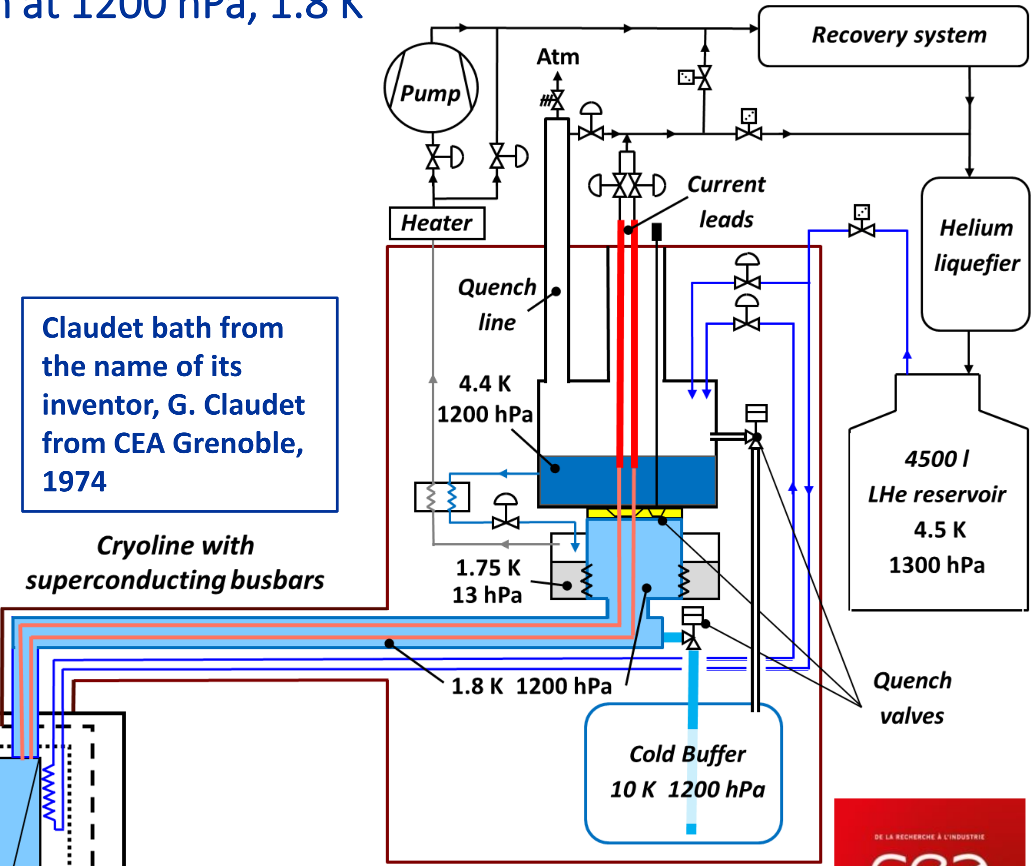
18 x 13 mm^2

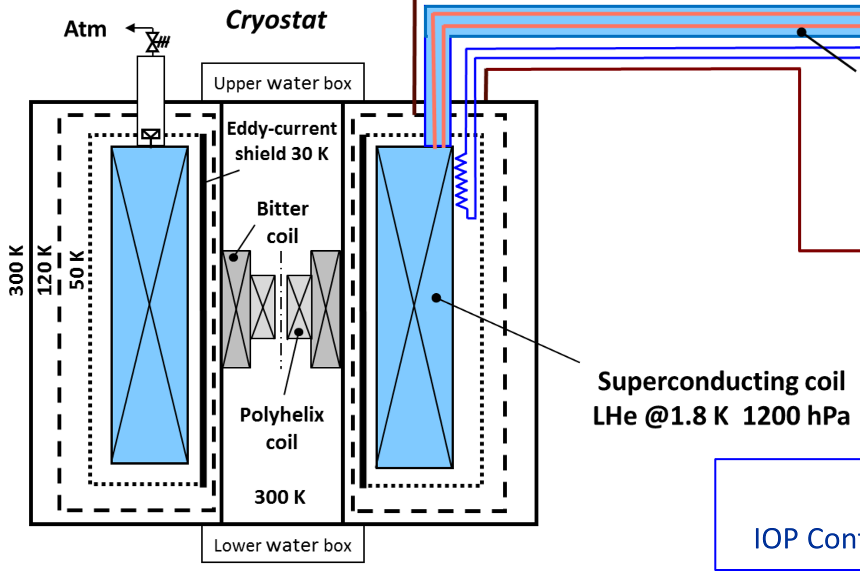


Superfluid pressurized LHe bath @ 1200 hPa , 1.8 K

Cooling of the sc. coil with 1100 l of pressurized superfluid He

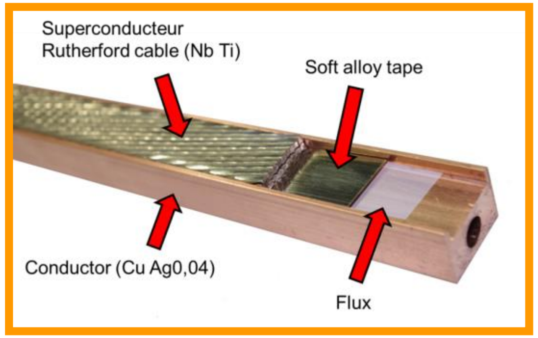
The cryogenic system principle: Pressurized superfluid He bath at 1200 hPa, 1.8 K





L. Ronayette, S. Crispel, B. Hervieu, *et al.*,
IOP Conf. Series: Mater. Sci. Eng. **171** 012107, (2017)

Industrial Production Line Developed, Built, Installed & Operated at LNCMI



Innovative developments have been achieved based on induction heating to strictly control R_a & AC losses

P. Pugnat, R. Pfister *et al.*, *IEEE Trans. Appl. Supercond.* **26**, 4302405 (2016)

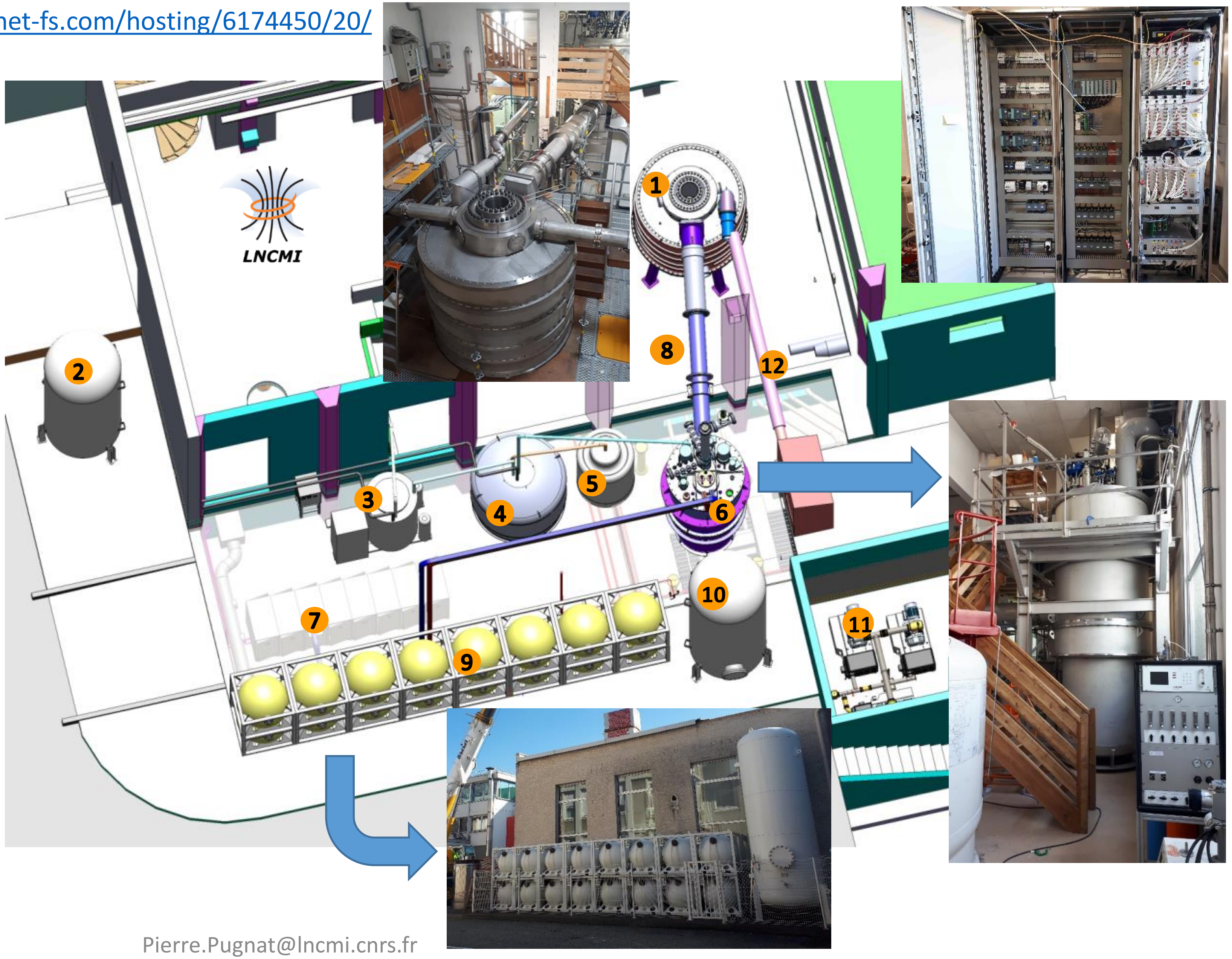
Crimping, soft-soldering, calibration & winding in single pancakes 4 m hight for delivery to the magnet manufacturer
https://www.youtube.com/watch?v=cp5NlR2cN5s

Integration of the Grenoble Hybrid Magnet with its Cryogenic Plant

- All equipment built
- Final Assembly & Integration completed
- Commissioning Tests ongoing (final phase)

Virtual Tour : https://storage.net-fs.com/hosting/6174450/20/

1. Superconducting Magnet
2. LN_2 tank 27 000 litres.
3. He liquefier coldbox 150 l/h @ 4.5 K , 1.3 bar
4. Main LHe Dewar 4500 litres
5. Secondary LHe Dewar 1700 litres
6. Cryogenic satellite to produce the 1.8 K LHe bath
7. DC power converter 7500 A , 30 V (underground)
8. Cryoline with busbars @ 1,8 K
9. High pressure gaseous He tanks 16 x 1 m^3 @ 200 bars
10. Liquefier pure He buffer tank 15 m^3 @ 20 bars
11. Helium pumping system 6000 m^3/h @ 10 mbar, 20 °C
12. Quench line



Not shown (located in other areas)

- Liquefier cycle compressor @ 14.5 bars
- He recovery balloon : 30 m^3 @ Patm
- He recovery compressor @ 200 bars
- 32 x 0.5 m^3 high pressure gaseous He tanks @ 200 bars
- Magnet Safety and Magnet Control Systems

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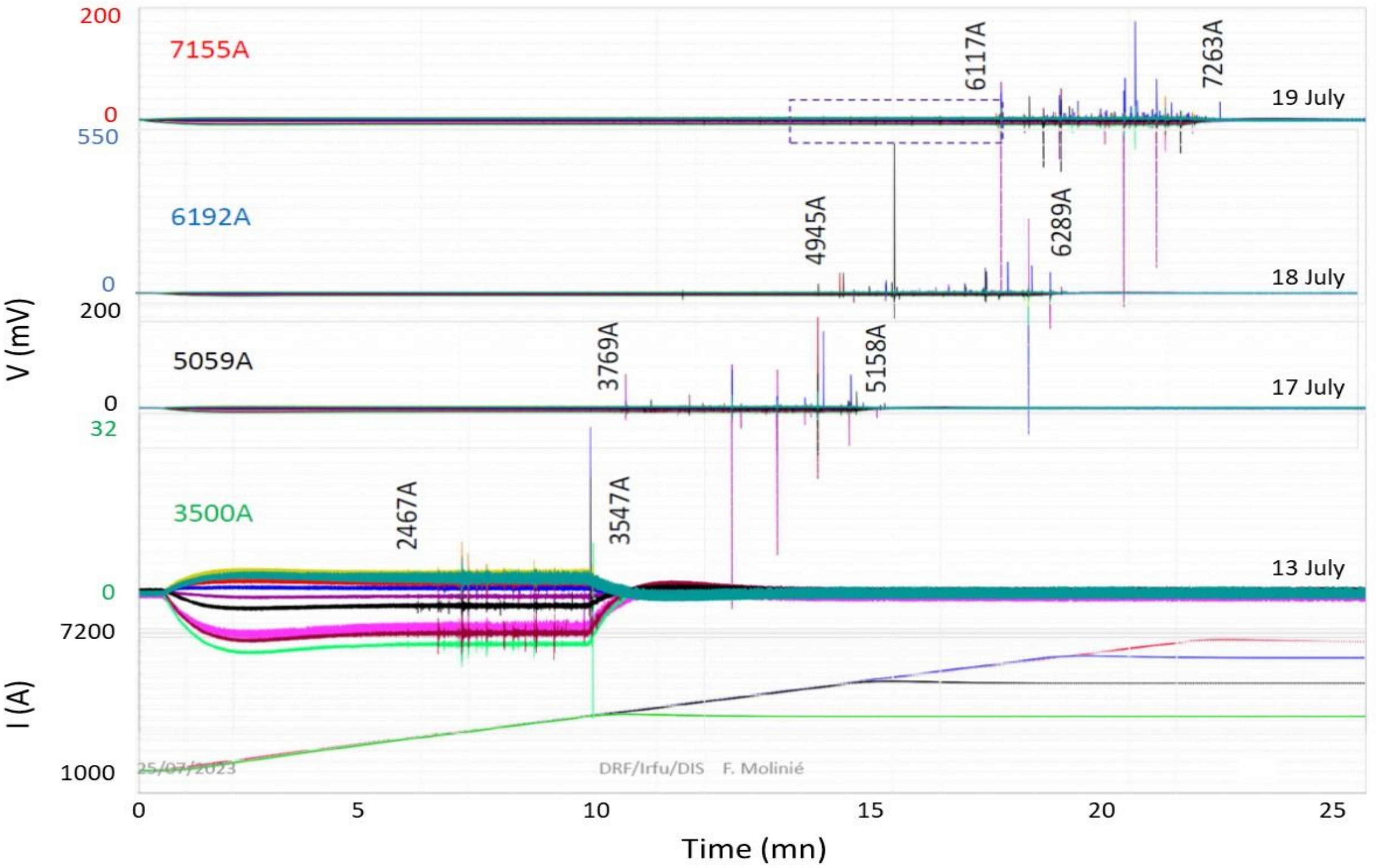
Magnet Seismicity* during Powering up to the Nominal Field of 8.5 T *IEEE TASC 34, 1 (2023)*

*Pioneering work in 2001: DOI 10.1109/77.920111



No training quenches but Kaiser effect observed

Most of the spikes are located at the interface between flanges and first & last DP

Sc magnet fully operational at 8.5 T

GrAHal

Grenoble Axion Haloscopes

Néel institut	LNCMI	LPSC Grenoble Théorie
R. Ballou	P. Pugnat	J. Quevillon
P. Camus	R. Pfister	C. Smith
T. Grenet	S. Krämer	K. Martineau
P. Perrier		A. Barrau
A. Talarmin		
J. Vessaire		

Few Words from P. Sikivie (Haloscopes proposed in 1983, Rev. Mod. Phys. 93, 015004)

Visit of Olympie during 2nd Patras Workshop in 2006 at Patras

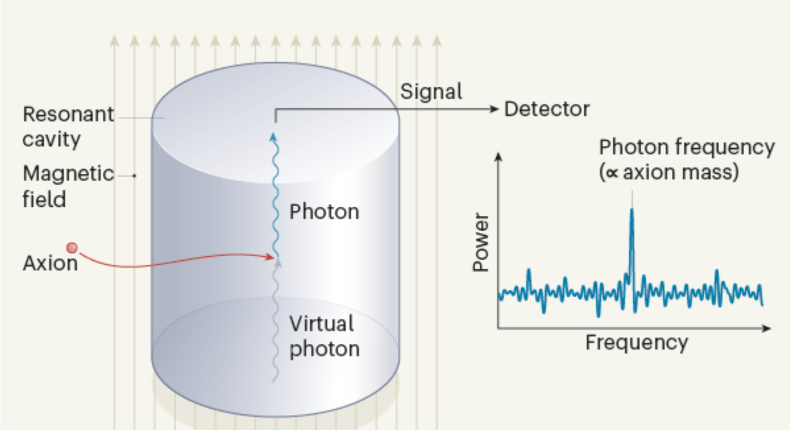
Axion electrodynamics

$$\nabla \cdot \mathbf{E} = g_{a\gamma\gamma} \mathbf{B} \cdot \nabla a$$

$$\nabla \times \mathbf{B} - \partial_t \mathbf{E} = g_{a\gamma\gamma} \left(\mathbf{E} \times \nabla a - \mathbf{B} \partial_t a \right)$$

$$\nabla \times \mathbf{E} + \partial_t \mathbf{B} = 0$$

$$\nabla \cdot \mathbf{B} = 0$$



I. G. Irastorza, *Nature* **590**, 226-227 (2021)

" Most importantly, the cavity experiment uses a variety of technologies - microwave engineering, ultra-low noise receivers in a high magnetic field environment, cryogenics - which are not typically used by high energy physicists and which had to be specially developed.

… Feynman's advice to young scientists aspiring to great discoveries. He said: "You have to develop your own tools". "

https://ep-news.web.cern.ch/content/qa-pierre-sikivie

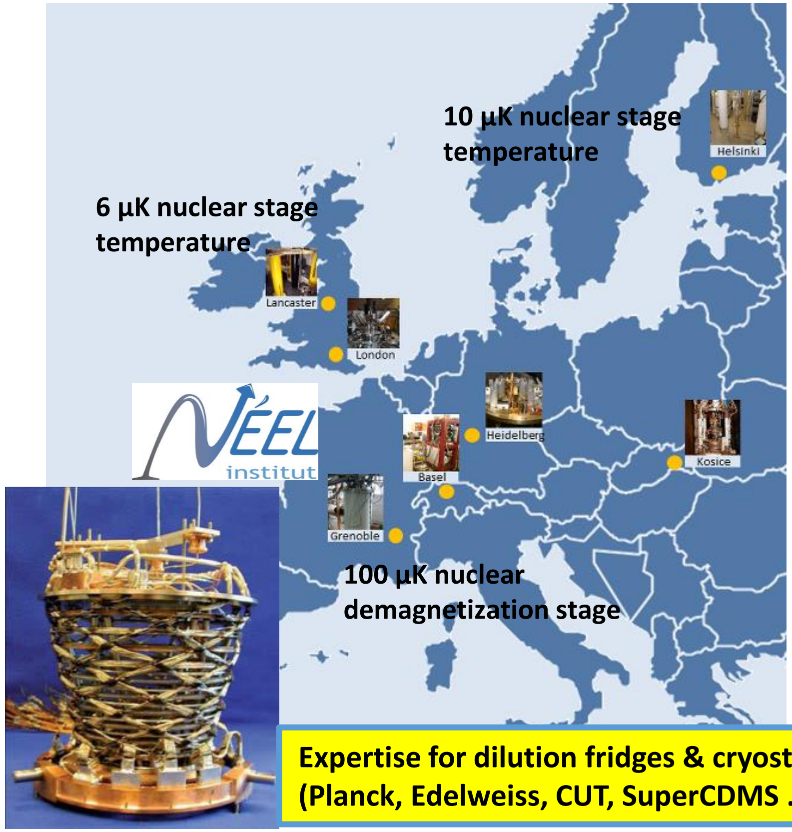
Context of GrAHal
Grenoble Axion Haloscopes

Key expertise at CNRS-Grenoble for High magnetic fields, Extreme Low Temperatures & Quantum Detectors

Dresden/LNCMI-Toulouse, pulsed up to 95/91 T, 1-10 ms
Nijmegen/**LNCMI-Grenoble**, DC up to 38/36 T,
Projects 45/43+ T
https://emfl-users.lncmi.cnrs.fr/SelCom/proposals.shtml

European Microkelvin Platform
20 leading ultralow temperature physics & technology Institutes in Europe including 7 submilliK facilities

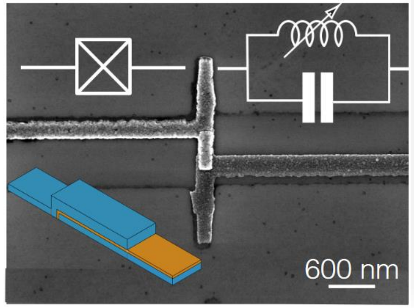
http://emplatform.eu/about/facilities



Expertise for dilution fridges & cryostats (Planck, Edelweiss, CUT, SuperCDMS …)

https://www.cnrs.fr/cnrsinnovation-lalettre/actus.php?numero=743

JPA Achievements



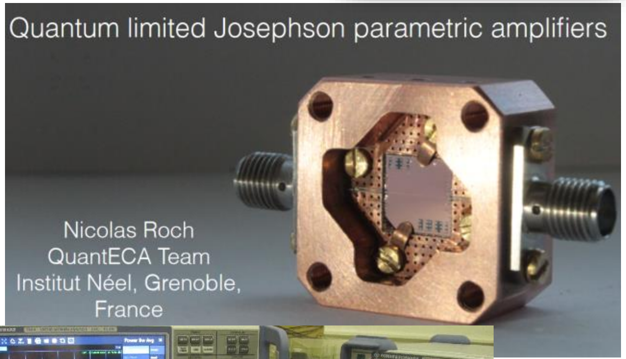
$1\ \text{GHz} < f_o < 10\ \text{GHz}$

$G \geq 20\ \text{dB}$

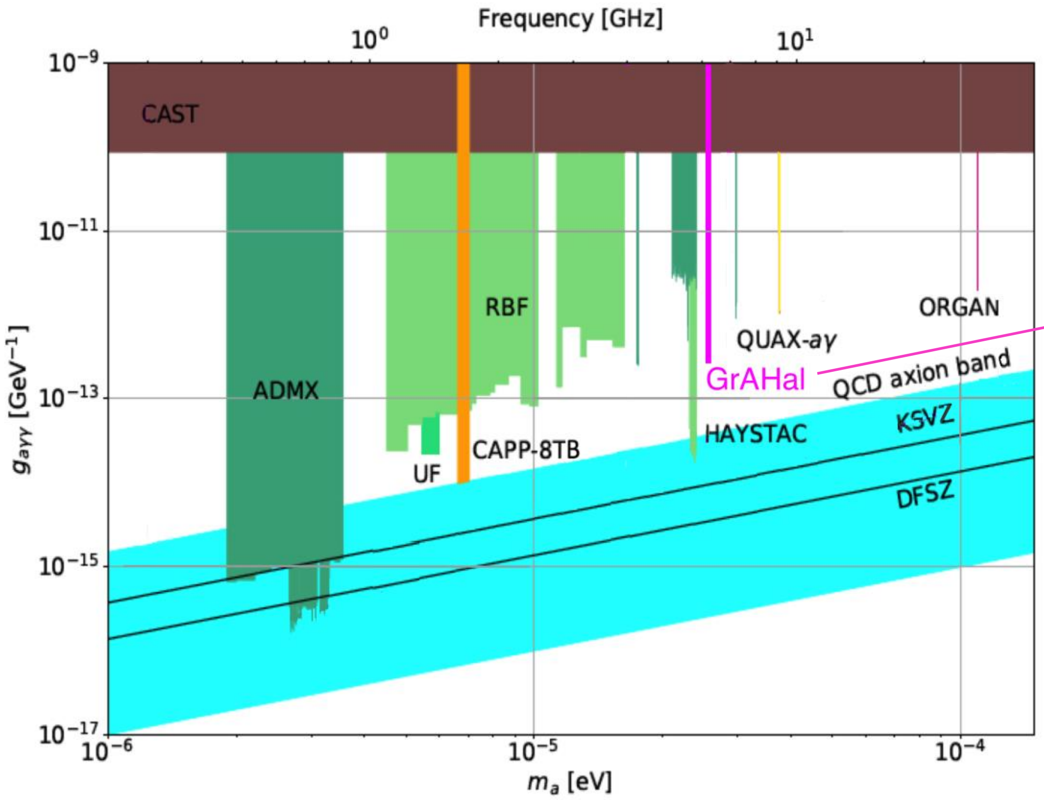
$BW \sim$ 2 GHz

$T_N \gtrsim \frac{hf_o}{2k_B}$

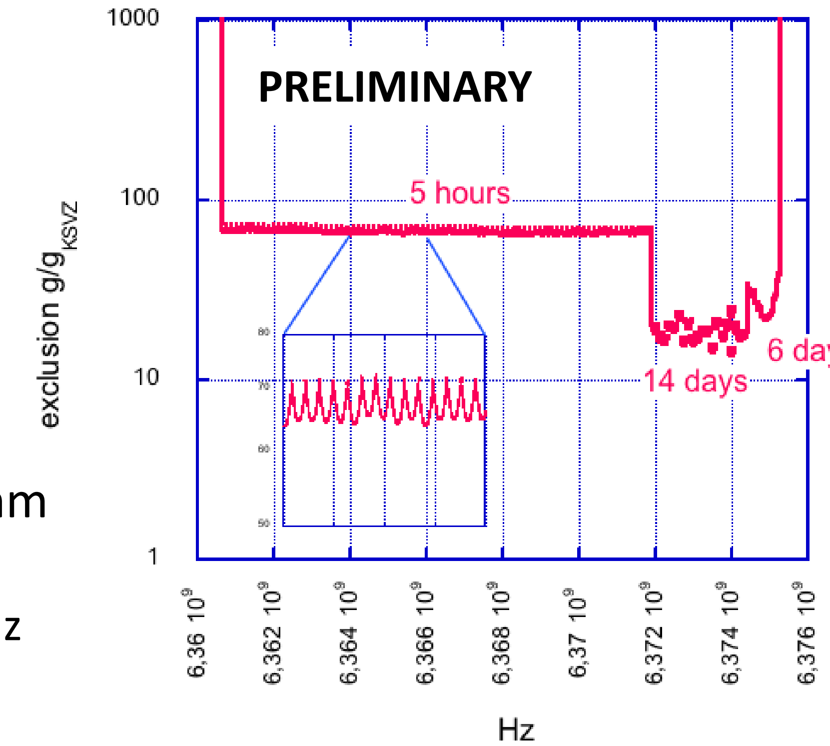
$P_{1dB} \sim -100\ \text{dBm}$



Baby-GrAHal 1: 1st Experimental Runs Ended

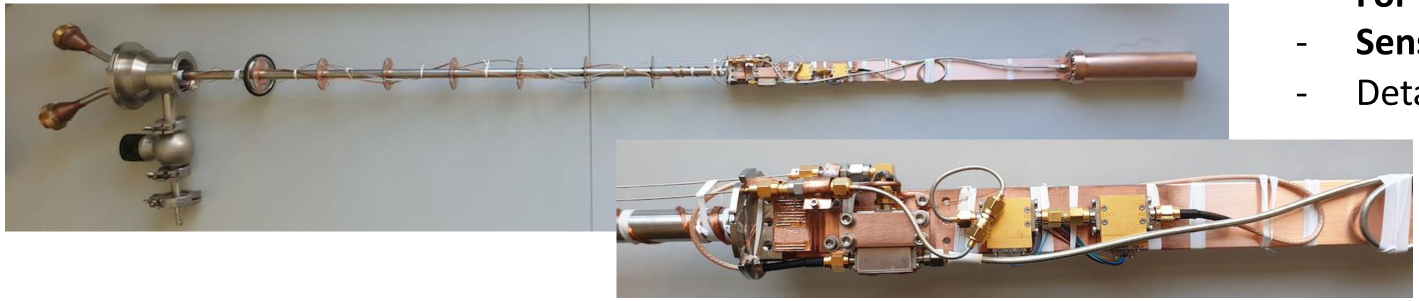


14 T @ 4 K in 36 mm cavity dia.
i.e. around 6.375 GHz or 26.37 μeV



The RF-cavity resonant frequency was tuned & scanned by varying the GHe pressure around the cavity :

- **For the range 1-1200 mbar, excursion Δf = 20 MHz, i.e. ~ 0.1 μeV**
- **Sensitivity in the range of 20-25 x KSVZ @ 4.4 K**
- Detailed data analysis close to completion (to be published)

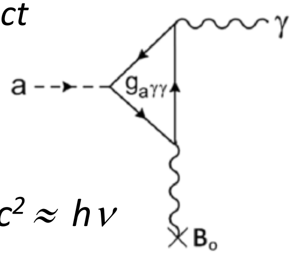


T. Grenet et *al.*
https://arxiv.org/abs/2110.14406

GrAHal
Grenoble Axion Haloscopes

► **The key element : The modular Grenoble Hybrid Magnet combining sc and resistive technologies (ongoing commissioning up to 43 T)**

Inverse Primakoff Effect



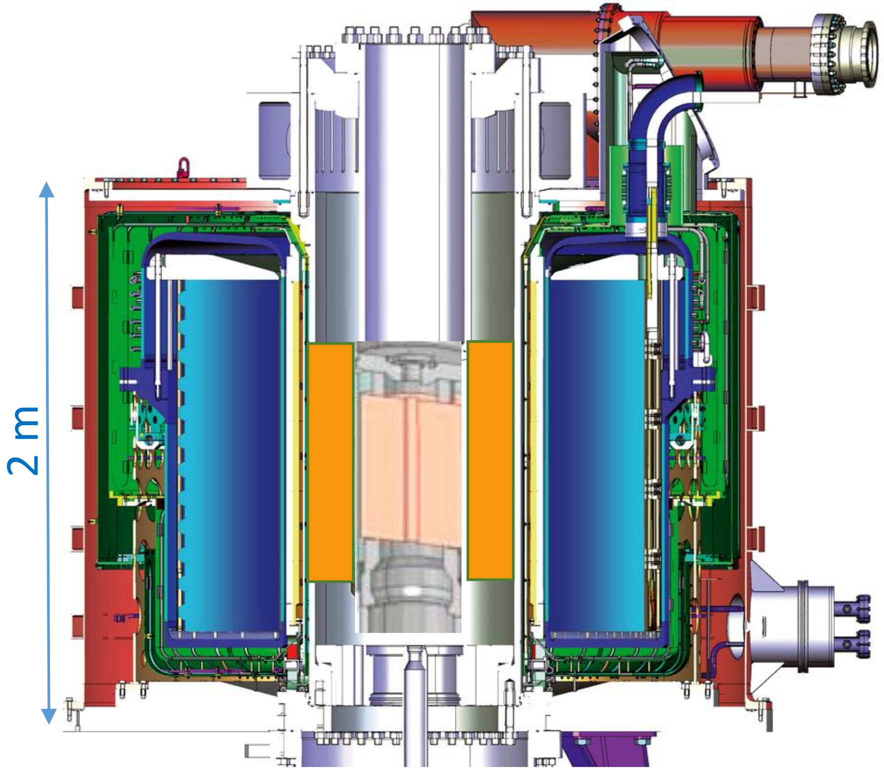
$m_a\, c^2 \approx h\,\nu$

Sikivie's haloscope, i.e. with RF cavity

11.5 GHz/f_{TM010} = R/1 cm

$P \;\alpha\; g_{a\gamma\gamma}^{\,2}\, B_0^{\,2}\, V \; < 10^{-25}$ W

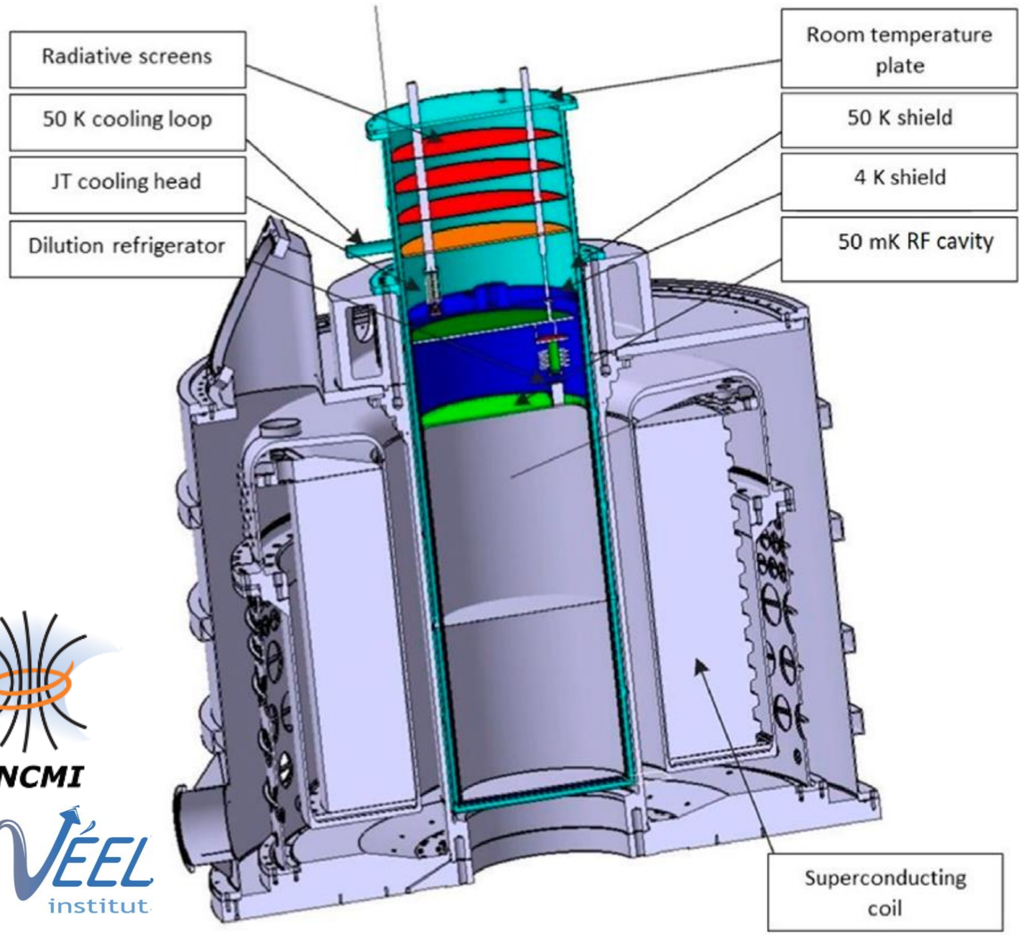
$df/dt \;\alpha\; g_{a\gamma}^{\,4}\, B_0^{\,4}\, V^2$

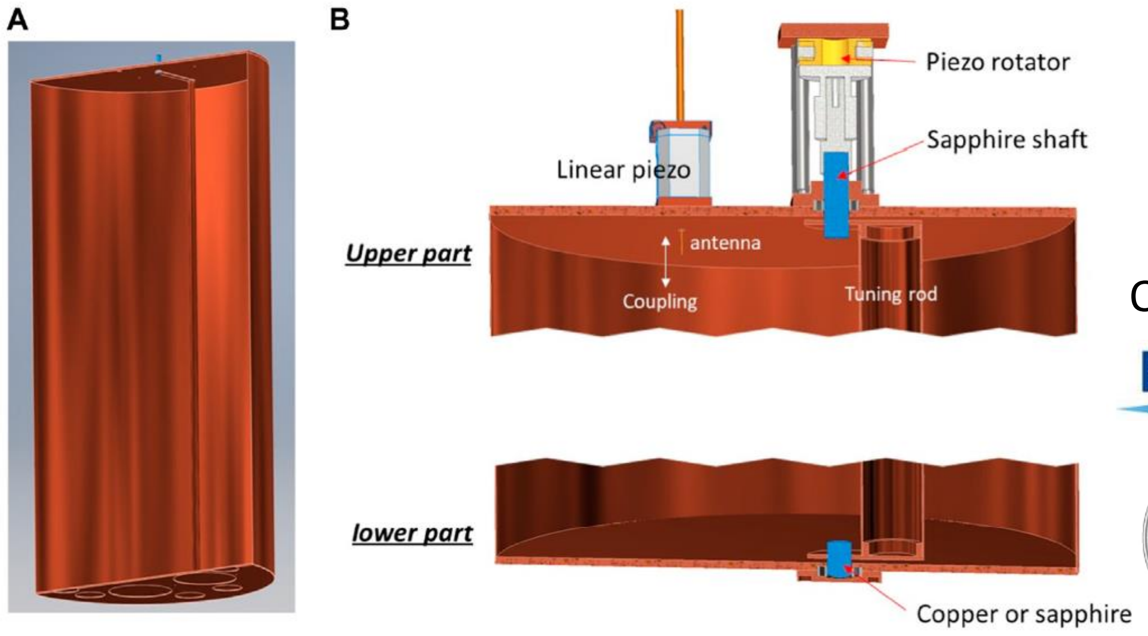


Field	Warm dia.	Power	RF-cavity dia.	f_{TM010}	Axion mass	B^2V (T^2m^3)
43 T	34 mm	25.4 MW	20 mm	11.5 GHz	47.2 μeV	0.5
40 T	50 mm	25.4 MW	34 mm	6.76 GHz	27.8 μeV	0.6
27 T	170 mm	19 MW	86 mm	2.67 GHz	11 μeV	3.5
17.5 T	375 mm	12.9 MW	291 mm	0.79 GHz	3.2 μeV	6.6
9 T	800 mm	0.4 MW	675 mm	0.34 GHz	1.4 μeV	40

► Operation end of 2024-25 with HTS RF cavity in collaboration with CAPP/IBS-KAIST (see O. Kwon presentation)

GrAHal-CAPP ► *Focus on 1-3 μeV axion mass (200-600 MHz)*



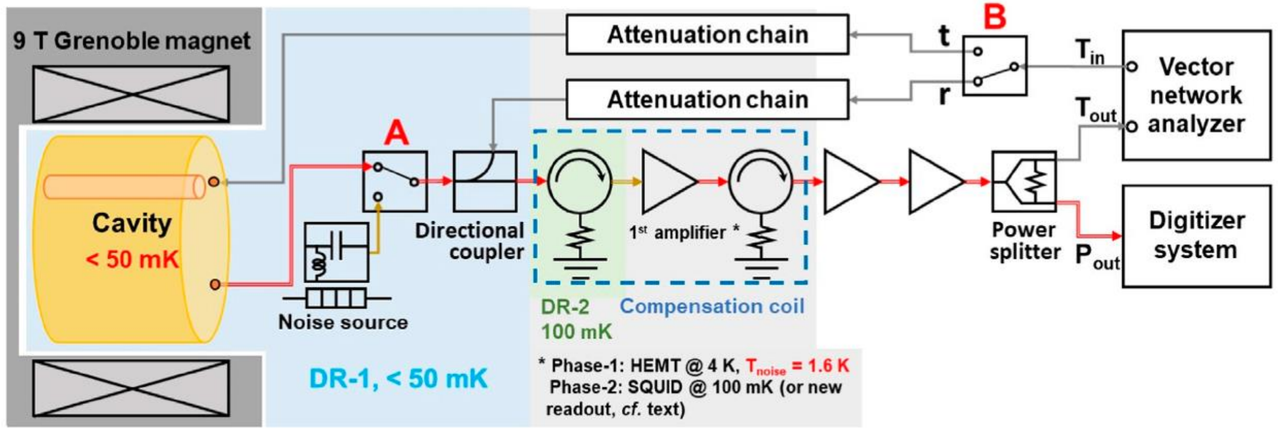


O. Kwon

KAIST

LNCMI

NÉEL institut



https://doi.org/10.3389/fphy.2024.1358810

Cryogenic challenge
T ≤ 50 mK in 538 liters with ^{3}He dilution refrigerator
Ph. Camus & J. Vessaire (Institut Néel)

Toward the most sensitive Haloscope worldwide

► *Focus first on 1-3 μeV axion mass (200-600 MHz)*

GrAHal
Grenoble Axion Haloscopes

Center for Axion and Precision Physics Research

LNCMI NÉEL institut KAIST IBS

GrAHal-CAPP : Phase 1 @ 4K

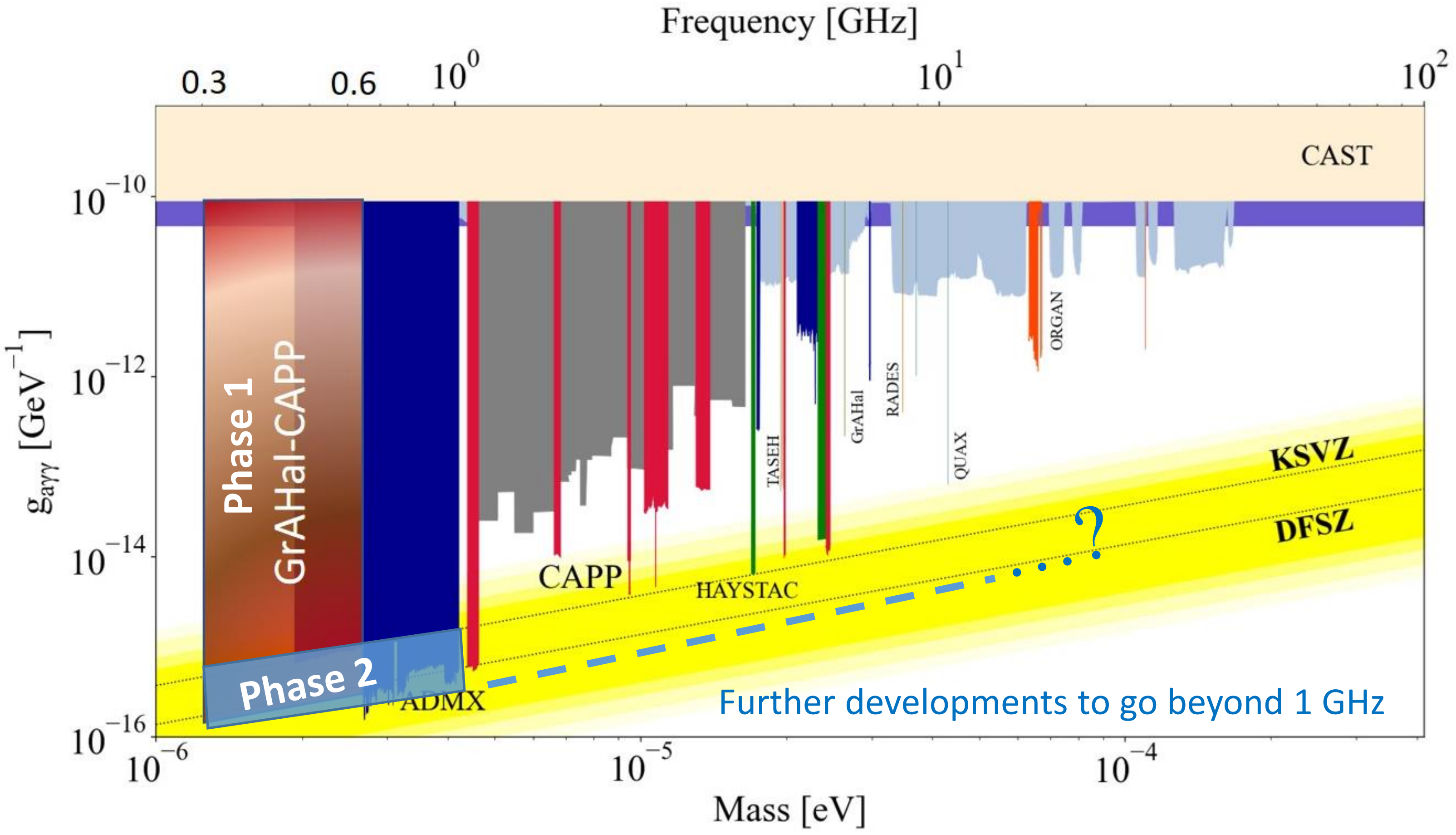
- 50 K cryo-stage operational @ t_0+18 months
- 4 K cryo-stage operational @ t_0+24 months

→ *1st run*

GrAHal-CAPP : Phase 2 @ 50 mK

- Operational @ t_0 + 42 months

→ *2nd run reaching DFSZ, in 2-year integration time*



https://doi.org/10.3389/fphy.2024.1358810

More Information / Outline

Few references

- *"High magnetic fields for fundamental physics": https://arxiv.org/pdf/1803.07547.pdf*
- *OSQAR: https://ep-news.web.cern.ch/content/osqar-experiment-sheds-light-hidden-sector-cerns-scientific-heritage , https://arxiv.org/abs/1506.08082*
- *GrAHal: https://bib-pubdb1.desy.de/record/395493 ; https://arxiv.org/abs/2110.14406 ; https://www.frontiersin.org/journals/physics/articles/10.3389/fphy.2024.1358810/full*
- *VMB@CERN: https://cds.cern.ch/record/2649744*

CERN PBC Study Group defining the European strategy of Particle Physics

- *https://pbc.web.cern.ch/*
- *https://indico.stfc.ac.uk/event/268/attachments/522/909/Vallee_PBC_RAL.pdf*
- *https://www.nature.com/articles/s41567-020-0838-4*
- *https://indico.cern.ch/event/1369776/contributions/5795144/attachments/2827635/*

New EU COST Action : COSMIC WISPers in the Dark Universe: Theory, astrophysics and experiments

- *https://www.cost.eu/actions/CA21106/ (Chairman/Co-Chair, MoU, Objectives)*
- ***You can apply to working groups of the network from*** *https://www.cost.eu/actions/CA21106/#tabs+Name:Working%20Groups%20and%20Membership*
- *Kick-off Meeting at Rome* 23-24 February 2023 https://agenda.infn.it/e/CosmicWispersKickOff

High Field Magnet Proposal submission open twice a year: *https://emfl.eu/apply-for-magnet-time/*

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