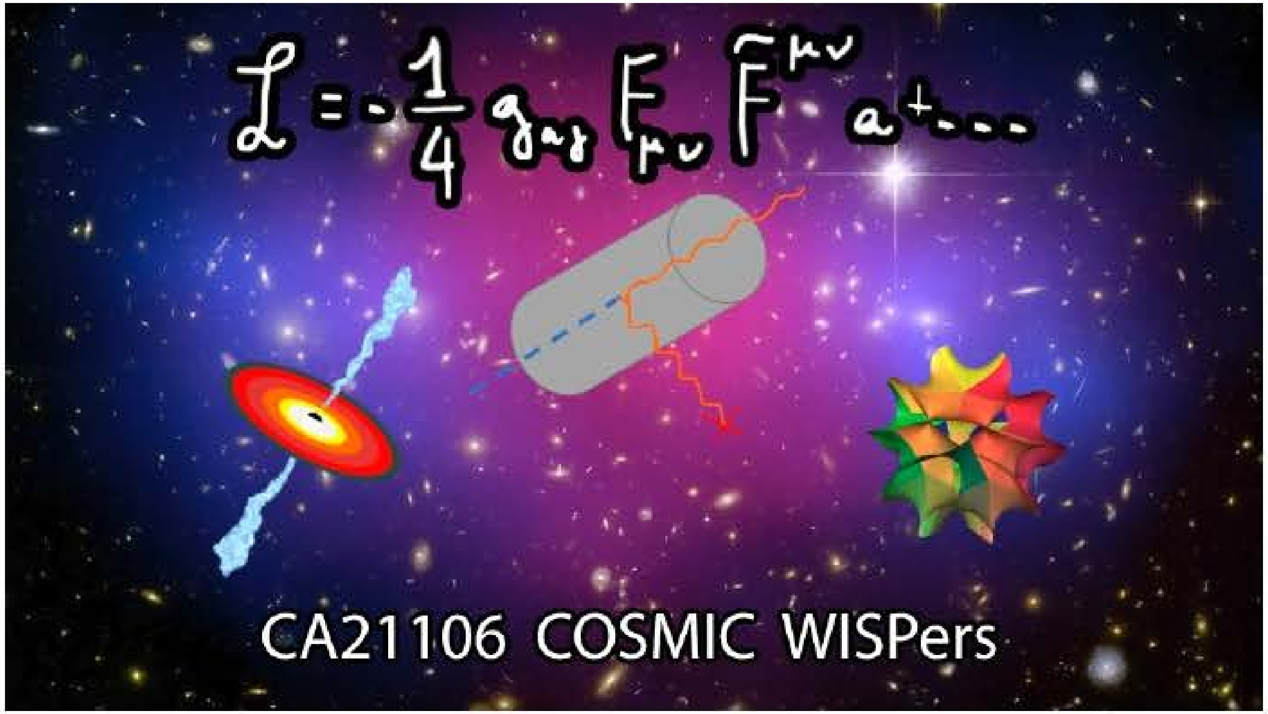
COSMIC WISPERS
CA21106

INFN
LNF
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati



cost
EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

Funded by the European Union

The GrAHal project within the context of the Grenoble high magnetic field facility

LNCMI

Kick-off Meeting, Friday 24 February

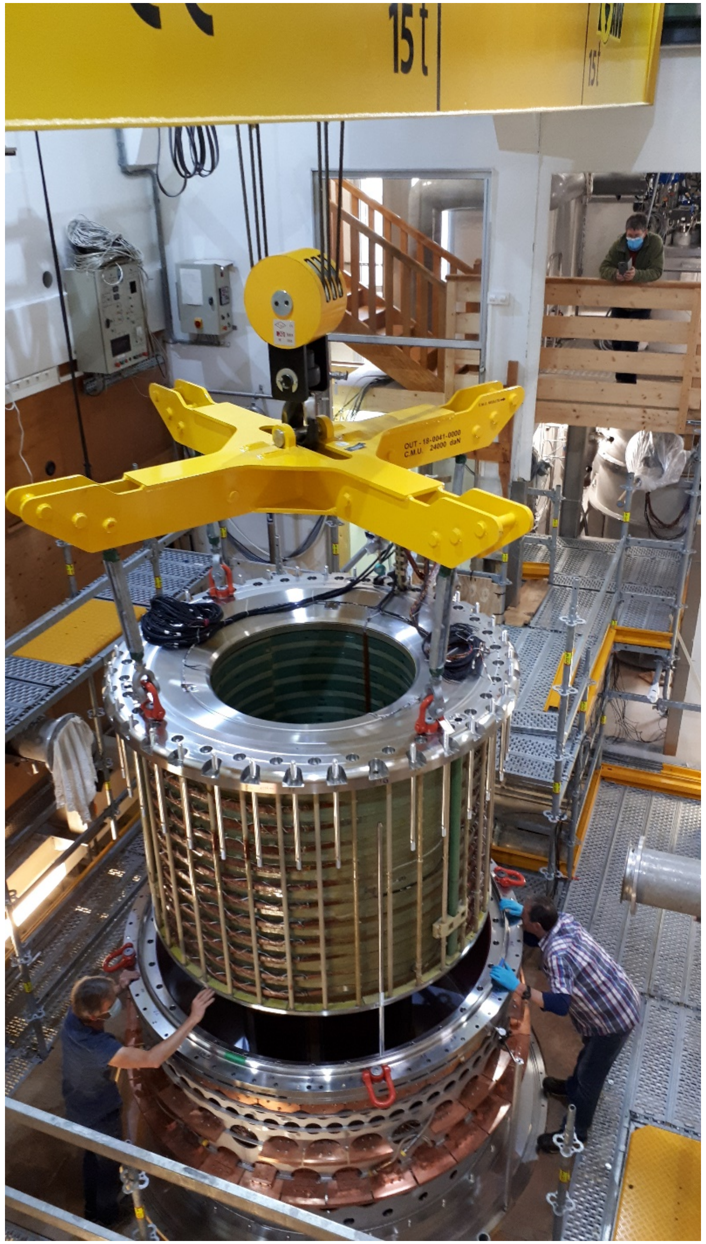
P. Pugnat, LNCMI-Grenoble/CNRS, EMFL

EMFL
European Magnetic Field Laboratory

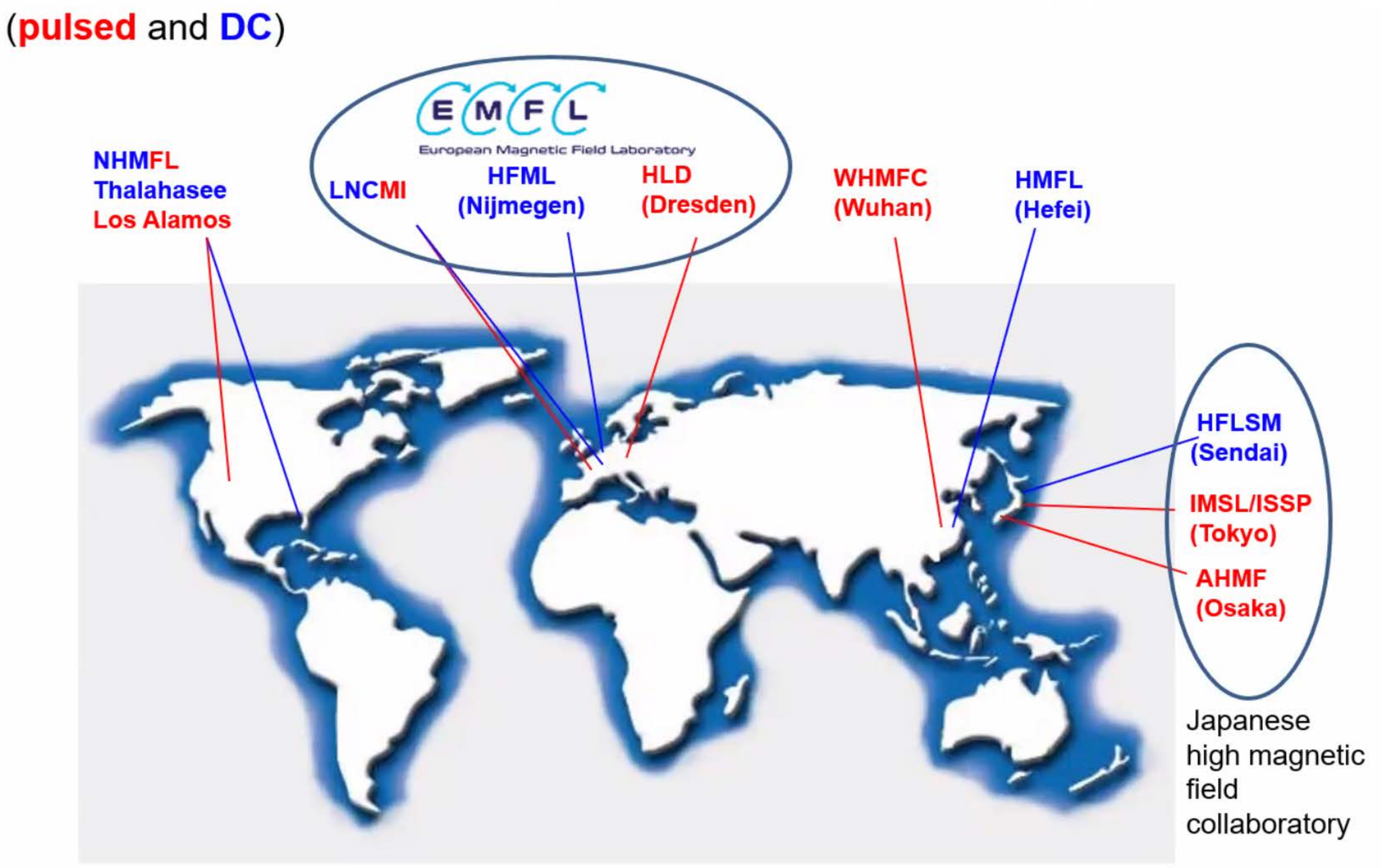
Outline

- ▶ Focus on high field facilities & magnets
  - International context
  - Highest DC field magnets worldwide
  - 43+T Hybrid Magnet
  - Presentation of LNCMI

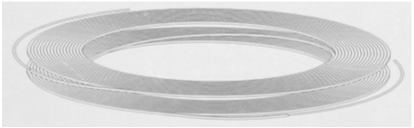
- ▶ GrAHal-QUAX-CAPP
  - Scientific Motivations
  - Principle of the Experiment (Sikivie Haloscope)
  - Current Status of GrAHal & First Results
    - Cu and dielectric RF cavity 4-7 GHz (ANR French funding agency, 2022-2026)
  - Objectives and plans
    - GrAHal-QUAX for 7-10 GHz (dielectric RF cavity)
    - GrAHal-CAPP for 200-600 MHz (thin Cu RF cavity)
  - Upgrade phases under study
    - Within a 40 T all superconducting magnet under construction
    - Toward a 60 T Hybrid magnet (?)



International context of High Field Facilities

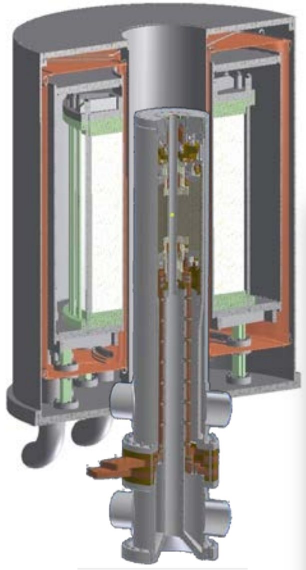


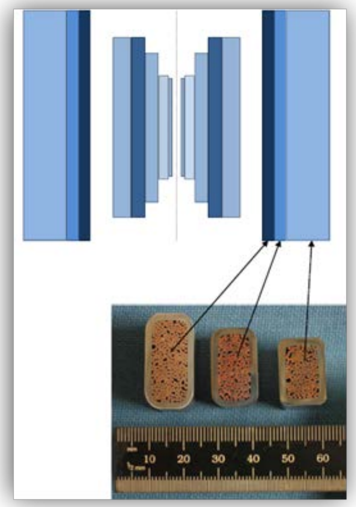
Hybrid Magnets Worldwide

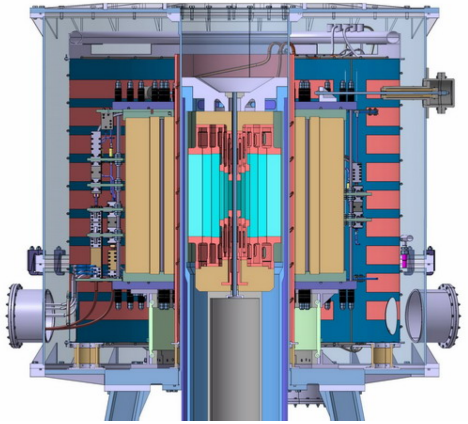


37 DP vacuum impregnated separately

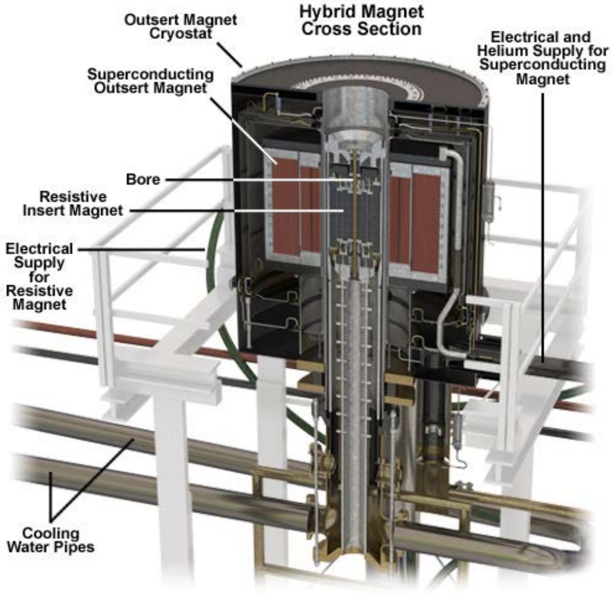
13 x 18 mm^2







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



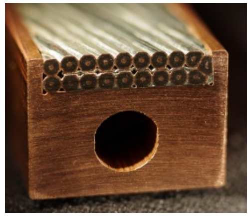
Grenoble, France	Nijmegen, Netherlands	Hefei, China	Tallahassee, FL
8.5 (9) + 34.5 (36+) = 43 (45+) T	12 + 33 = 45 T	11 + 34 = 45 T	11.5 + 33.5 = 45 T
34 (32-30?) mm, 24 (30) MW	32 mm, 24 MW	32 mm, 30 MW	32 mm, 30 MW
RCOCC Nb-Ti, 1.8 K	CICC Nb3-Sn, 4.2 K	CICC Nb3-Sn, 4.2 K	CICC Nb3-Sn, 4.2 K
7.1 kA, 1100/1826 mm dia.	20 kA, 720/1286 mm dia.	13.4 kA, 680/1650 mm dia.	10 kA
2024	**2024**	**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

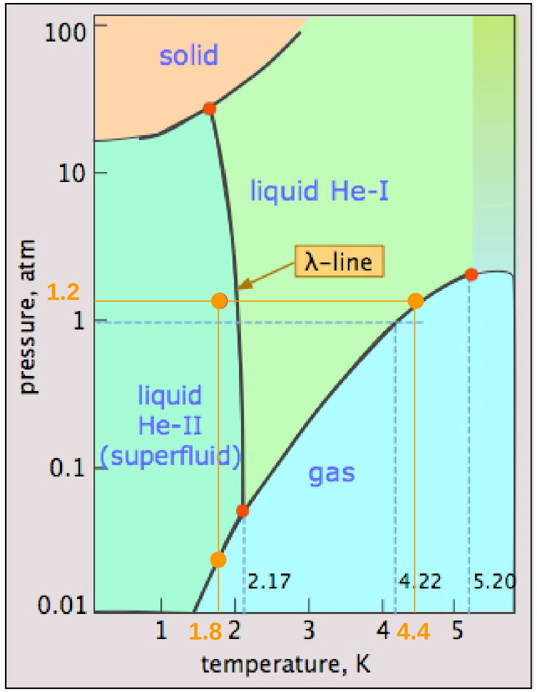
- Internal cooling with stagnant superfluid He connected to the external bath
- Strict control of AC-losses

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

LNCMI

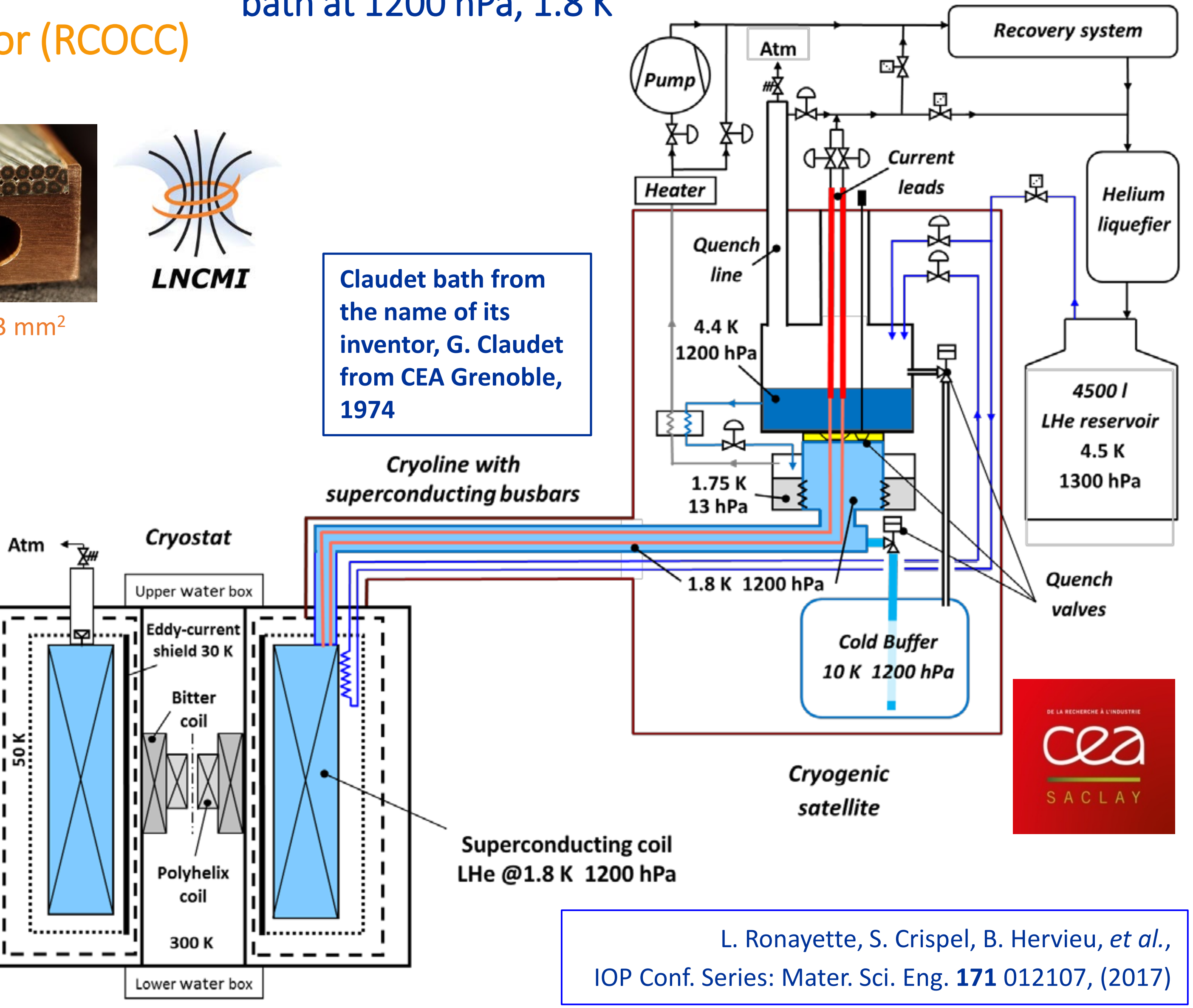


Superfluid pressurized LHe bath @ 1200 hPa , 1.8 K

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

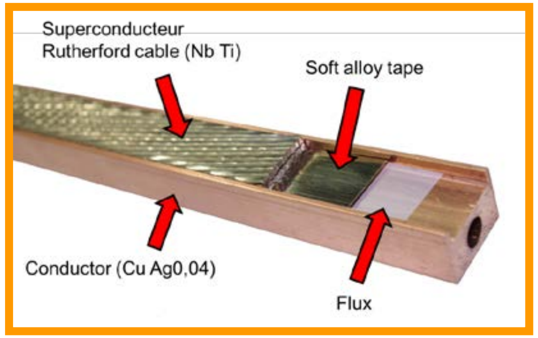
The cryogenic system principle: Pressurized superfluid He bath at 1200 hPa, 1.8 K

Claudet bath from the name of its inventor, G. Claudet from CEA Grenoble, 1974



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

Industrial production line developed, built & installed 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 for delivery

ligne lncmi light.mp4

Focus on LNCMI, *i.e.* Laboratoire National des Champs Magnétiques Intenses, **also a user facility…**

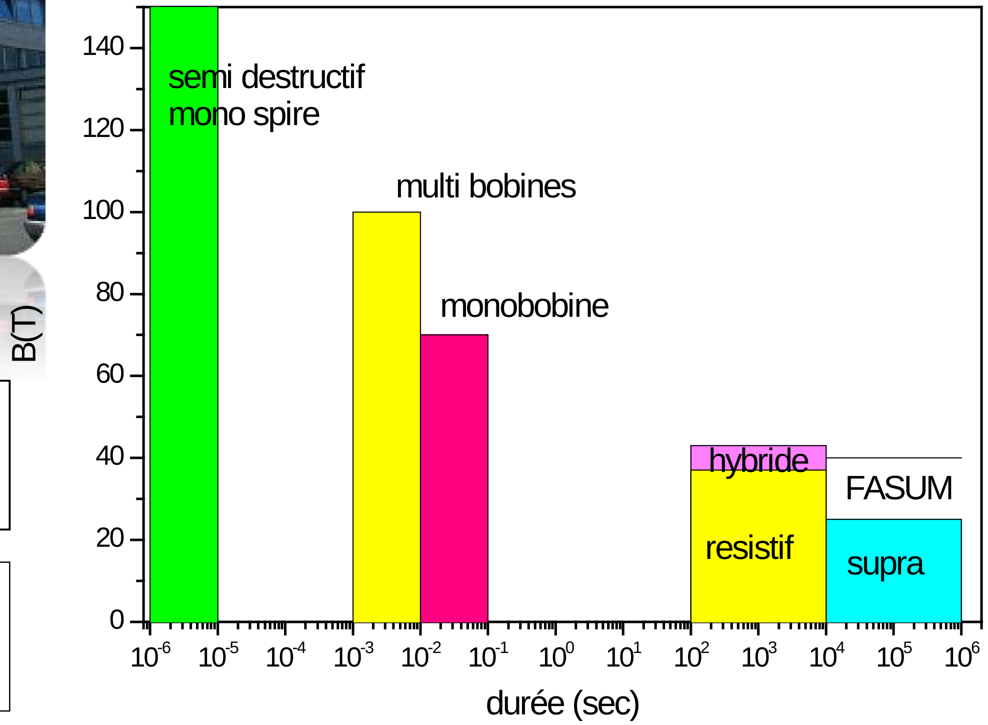
Grenoble

24 (30) MW Power Installation

7 resistive magnets up to 36 T

10 sc magnets up to 18 T
1 hybride up to 43 (46) T

LNCMI



http://lncmi.cnrs.fr/categorie-publication/rapport-annuel/

Toulouse

14 + 6 + 1 MJ Capacitor banks

6 pulsed field sites up to **99 T**

One mono-coil site of **200 T**

Magnets at LNCMI-Grenoble

► Focus on available superconducting magnets (in addition to the hybrid one)

LNCMI Grenoble magnet Id	Max Field (T)	Magnet Bore (mm)	Equipment Temperature	Experimental Set-up
1	15.8	50 cold bore	VTI : 1.8 K - 300 K	EPR
2	9	80 cold bore	VTI : 1.4 K - 300 K	NMR
3	15.4 / 17.1	52 cold bore	VTI : 1.4 K - 300 K	NMR
4	15 / 17	52 cold bore	VTI : 1.4 K - 300 K DR : 30 mK - 1.0 K	NMR
5	7.8 (fix)	89 warm bore 60 variable T	VTI: 4 K 300 K	NMR at fixed field 330 MHz for 1H
6	12 / 14	52 cold bore	VTI : 1.2 K - 300 K	Specific heat
7	14 / 16	50 warm bore 33 cold bore	1.5 K - 300 K	Optical spectroscopy
8	11 / 13	50 cold bore	4 K	FIR spectroscopy
9	11	30 cold bore	VTI : 1.2 K - 300 K	Transport, In situ rotation, FIR-Laser
10	16 / 18	50 cold bore	VTI : 1.2 K - 300 K	Transport, Magnetization

https://emfl.eu/find-experiment-old/dc-magnets/#supraG

https://emfl.eu/apply-for-magnet-time/

GrAHal - QUAX - CAPP

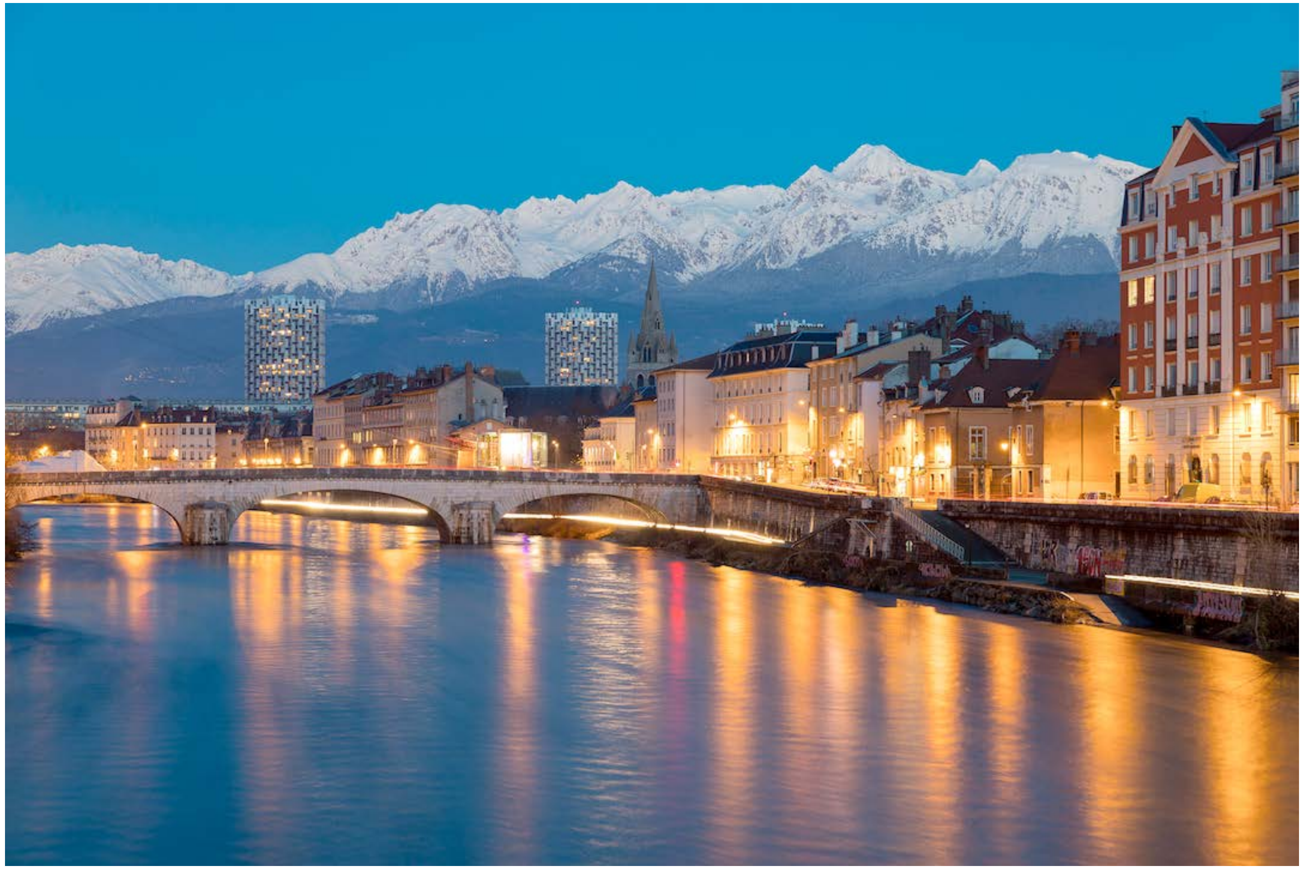
Grenoble Axion Haloscopes

Theory Group

R. Ballou
T. Grenet
P. Perrier
N. Roch
L. Planat
P. Camus
C. Bruyère

P. Pugnat
R. Pfister
S. Krämer

J. Quevillon
C. Smith
K. Martineau
A. Barrau



Collaboration with QUAX from INFN & University of Padova
C. Braggio, N. Crescini

Collaboration with CAPP/IBS, KAIST, Daejeon, South Korea
W. Chung, O. Kwon, Y. K. Semertzidis

Pierre.Pugnat@lncmi.cnrs.fr

Scientific Motivations

- Two among the most fundamental problems of Particle Physics & Cosmology can be solved by the discovery of a single particle : **The QCD Axion**

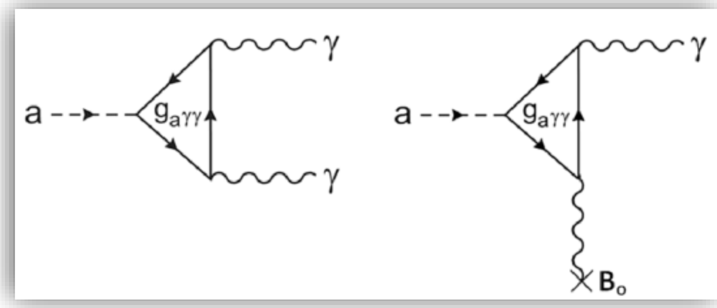
  - Predicted independently by Weinberg and Wilczek (1978) from the breaking of the Peccei-Quinn symmetry (1977) to solve the strong CP problem, one of the key remaining questions of the Standard Model of Particle Physics, *i.e.* "Why, in view of nEDM < 3.6 x 10^{-26} e·cm @ 95% CL, the QCD seems **not** to break the CP-symmetry ?"

  - Axion in the mass range 10^{-6}-10^{-3} eV will also solve the DM problem; it is one of the most serious cold DM candidates & the only non-supersymmetric one, *this in the context of* ***none*** *signature of SuSy observed so far at LHC*…

  - Neutral pseudo-scalar **0^-**

  - Axion coupling to photons

$$L_{a\gamma\gamma} = g_{a\gamma\gamma}\, \phi_a\, \boldsymbol{E}\cdot \boldsymbol{B}$$



- Moreover, many ALPs/FIPs are predicted by String Theory opening new windows at the ultra-low energy frontier.

First proposal by P. Sikivie (in 1983, Rev. Mod. Phys. 93, 015004)

Visit of Olympie during 2nd Patras Workshop 2006 in Greece

Axion electrodynamics

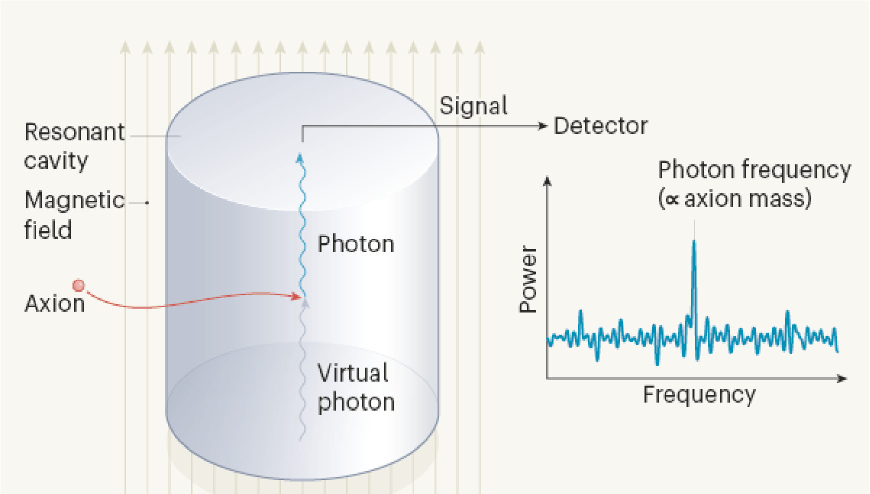
$$\nabla \cdot \mathbf{E} = g_{a\gamma\gamma} \mathbf{B} \cdot \nabla a$$

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

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

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

$$\ddot{a} - \nabla^2 a + m_a^2 a = g_{a\gamma} \mathbf{E} \cdot \mathbf{B}$$



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". ”

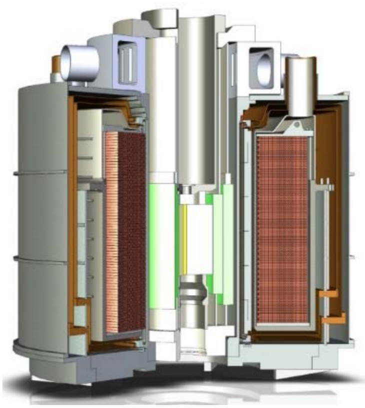
https://ep-news.web.cern.ch/content/qa-pierre-sikivie

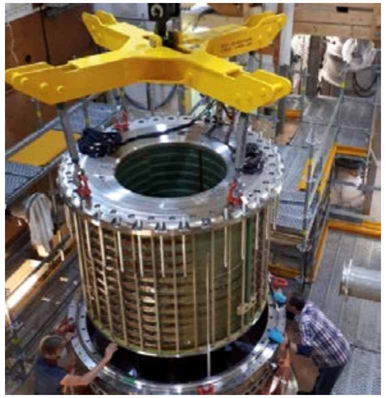
GrAHal
Grenoble Axion Haloscopes

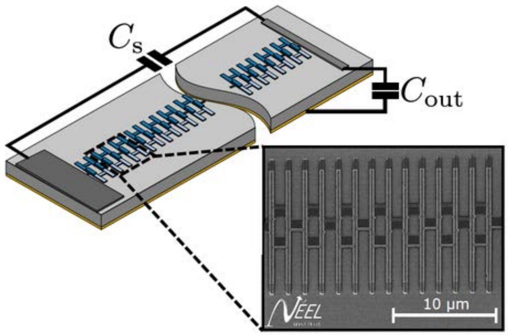
Brief Reminder on RF-Cavity Haloscopes (Sikivie)

$$P = 2{,}67.10^{-25}(Watt)\left(\frac{g_\gamma}{0.97}\right)^2\left(\frac{\rho_a}{0.45GeV/cm^3}\right)\left(\frac{\beta/(1+\beta)^2}{2/9}\right)\left(\frac{C}{0.5}\right)\left(\frac{B_0}{10T}\right)^2\left(\frac{f}{1GHz}\right)\left(\frac{V_{ol}}{1L}\right)\left(\frac{Q_{eff}}{10^4}\right)$$

$$SNR \propto \frac{C B_0{}^2 V_{ol}\, f Q_{eff}}{k_B T_{noise}}\sqrt{\frac{t}{\Delta f}}$$







A near quantum limited Josephson Parametric Amplifier, based on superconducting metamaterials

In other way around

$$df/dt \propto \frac{C^2\, B_0{}^4\, V_{ol}{}^2\, Q_{eff}{}^2}{(SNR\, K_B T_{noise})^2}$$

Context of GrAHal

Grenoble Axion Haloscopes

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

EMFL – European Magnetic Field Laboratory · LNCMI

Dresden/LNCMI-Toulouse, pulsed up to 95/91 T, 1-10 ms

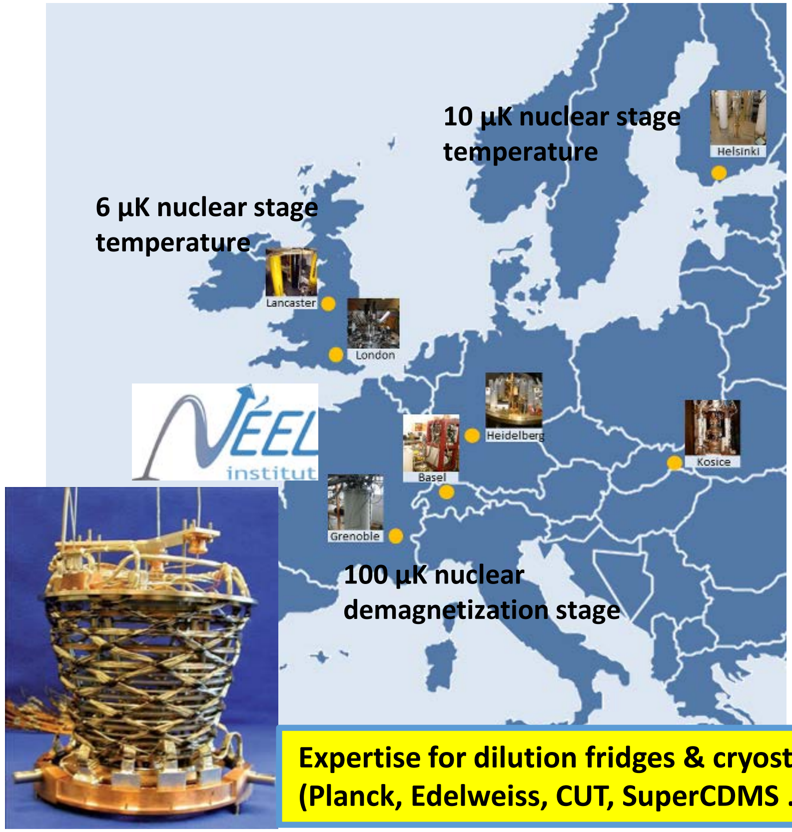
Nijmegen/**LNCMI-Grenoble**, DC up to 38/36 T, Project 43+ T

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



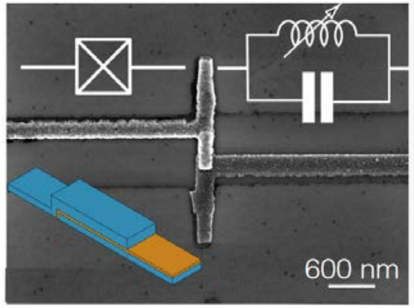
Expertise for dilution fridges & cryostats (Planck, Edelweiss, CUT, SuperCDMS …)

NÉEL institut

JPA Achievements

World leader

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



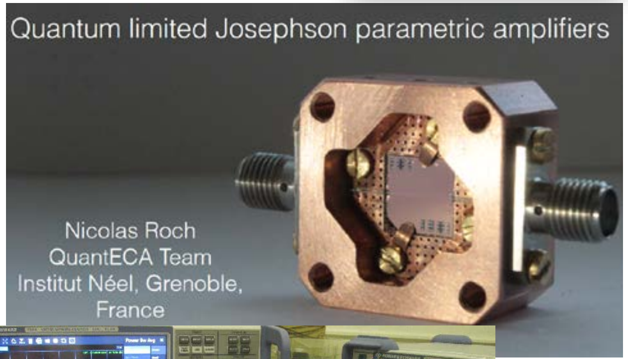
$1\ \mathrm{GHz} < f_o < 10\ \mathrm{GHz}$

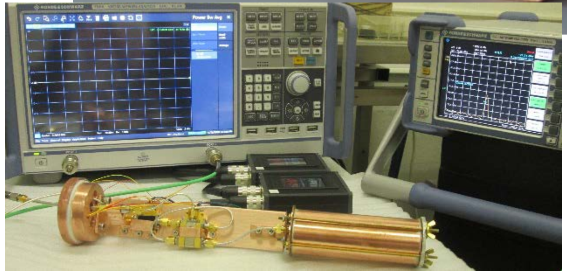
$G \geq 20\ \mathrm{dB}$

$BW \sim$ 2 GHz

$T_N \gtrsim \frac{h f_o}{2 k_B}$

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





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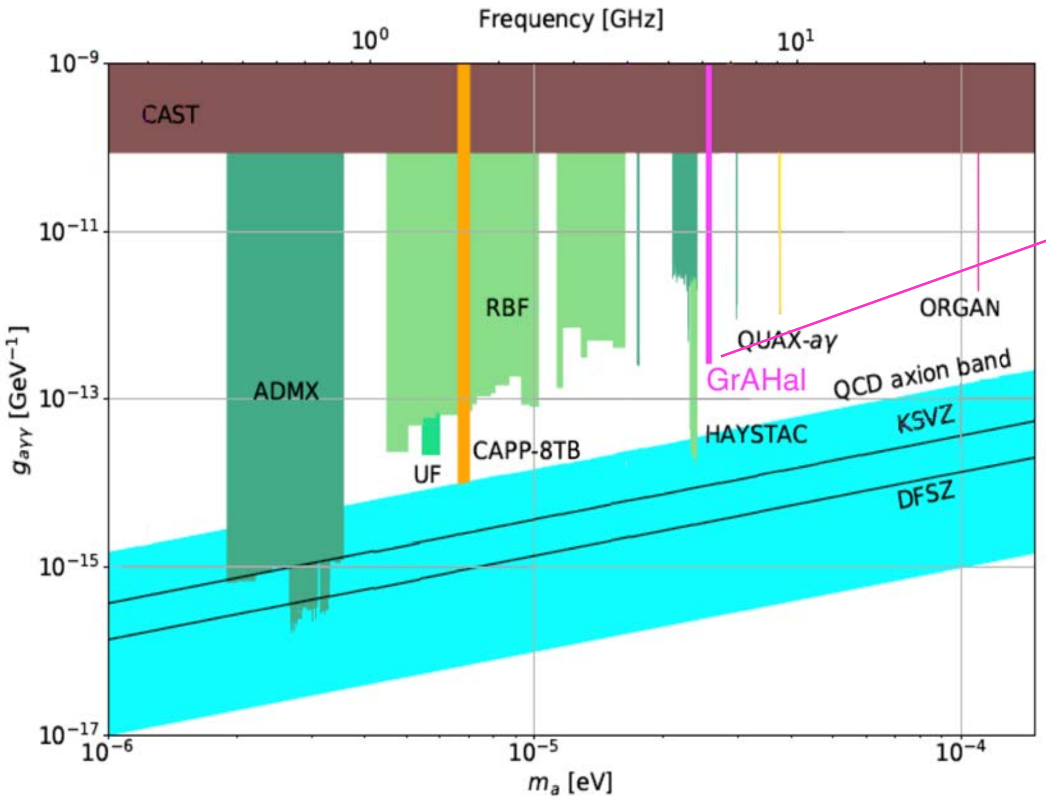
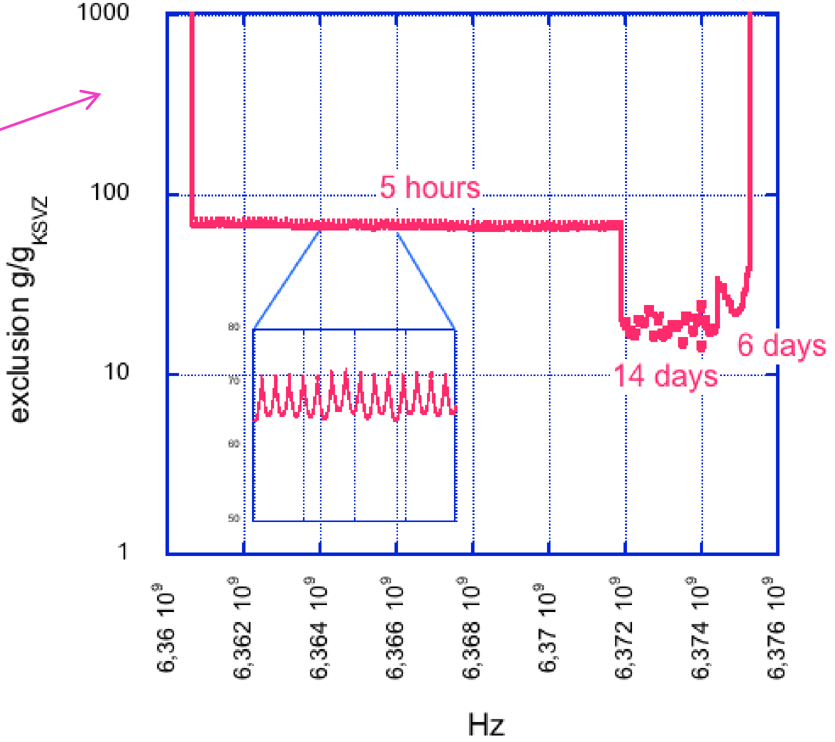
GrAHal 1st experimental Run : New exclusion limit around 6.375 GHz

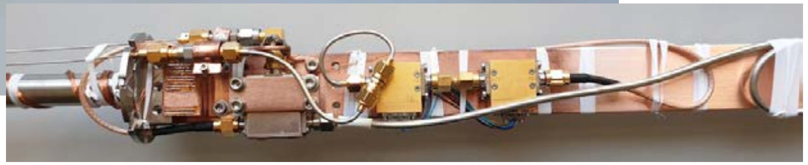


Axion search
around **6.375 GHz**
i.e. 26.37 µeV,
with home made
RF cavity in Cu
@ 4 K and 14 T
Run end : June 2022



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 x KSVZ @ 4.4 K**
- Detailed data analysis in progress



T. Grenet et *al.*

NÉEL institut

https://arxiv.org/abs/2110.14406

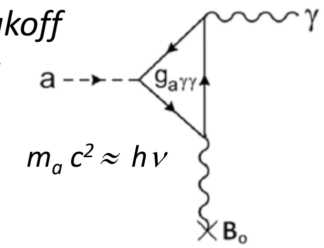
GrAHal

Grenoble Axion Haloscopes

►**Initiative presented during the 1st PBC Techno WG meeting in Sept 2017** (https://indico.cern.ch/event/667744/)

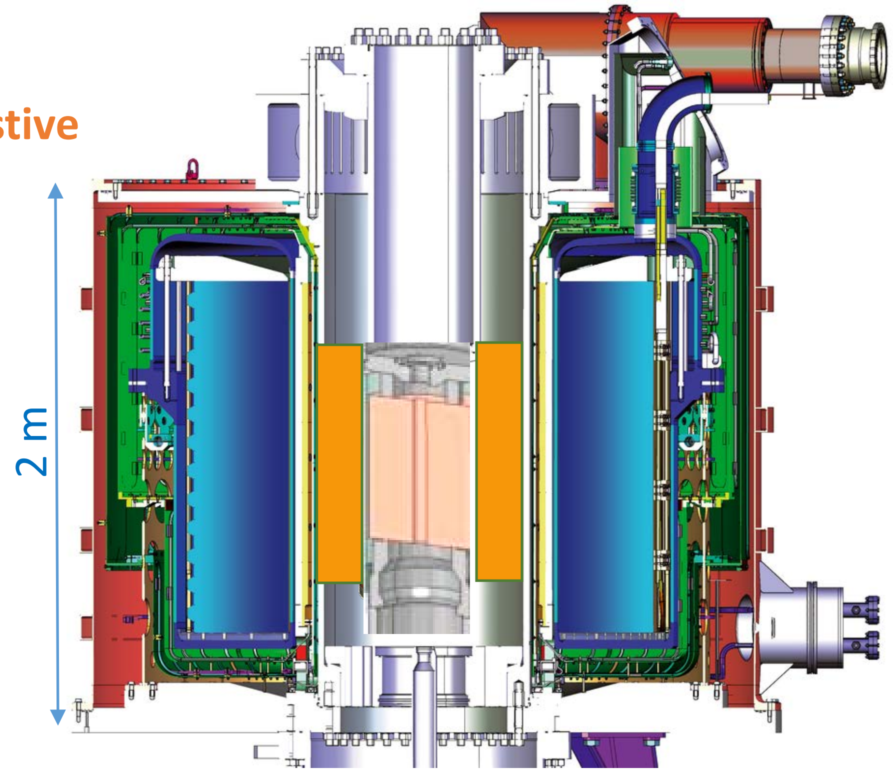
Hybrid Magnet = Sc + Resistive

Inverse Primakoff Effect



Sikivie's haloscope i.e. with RF cavity

$$P \;\alpha\; g_{a\gamma\gamma}^2 B_0^2 V < 10^{-21} \text{ W}$$



Scientific case within the European Strategy of Particles Physics (ESPP)
https://www.nature.com/articles/s41567-020-0838-4

Field	Warm dia.	RF-cavity dia.	Freq. TM010	Axion mass
43 T	34 mm	20 mm	11.5 GHz	47.2 µeV
40 T	50 mm	34 mm	6.76 GHz	27.8 µeV
27 T	170 mm	86 mm	2.67 GHz	11 µeV
17.5 T	375 mm	291 mm	0.79 GHz	3.2 µeV
9.5 T	812 mm	700 mm	0.33 GHz	1.4 µeV

LNCMI

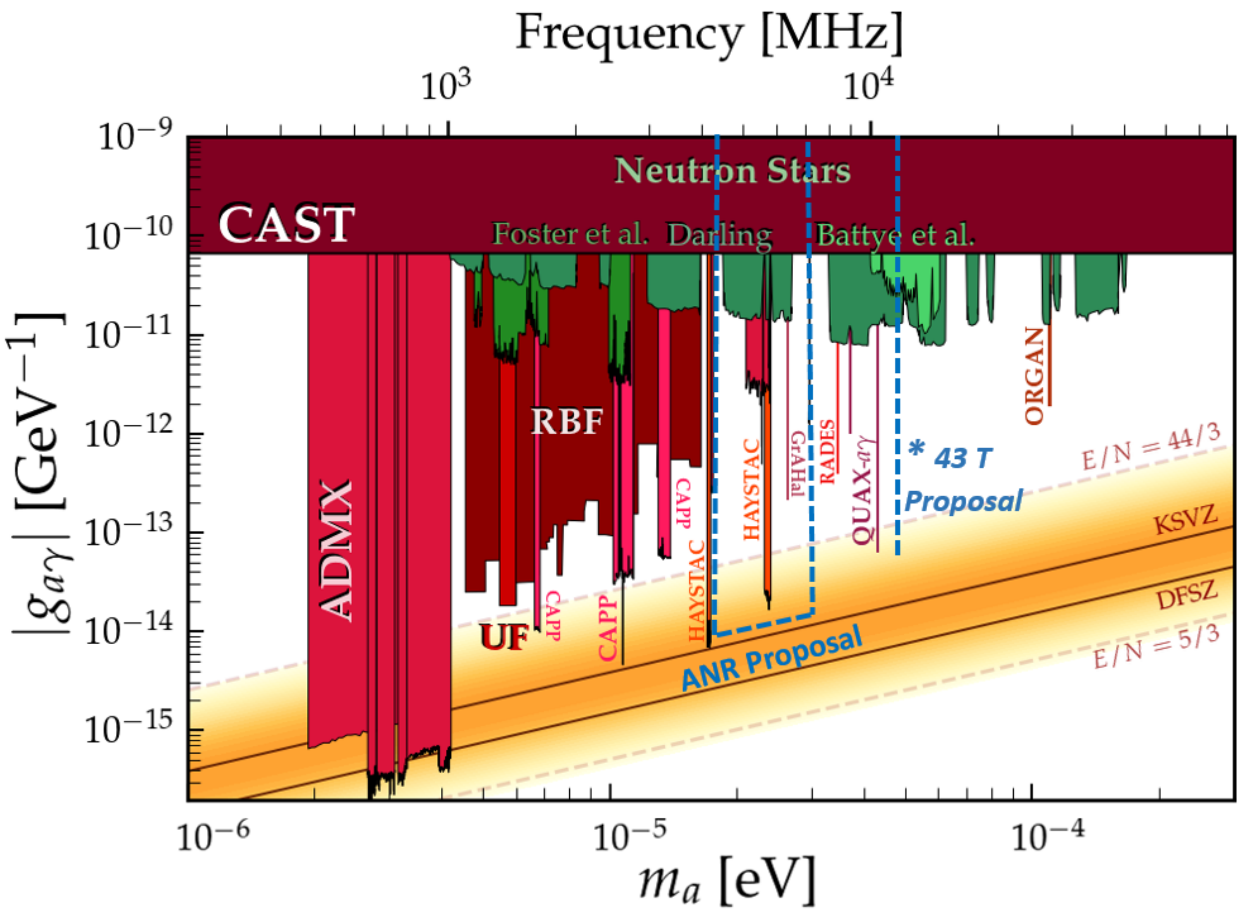
Grenoble Hybrid in the commissioning phase, operation foresees in 2024

Pierre.Pugnat@lncmi.cnrs.fr

GrAHal
Grenoble Axion Haloscopes

Approval for the run of GrAHal @ 43 T & 11.5 GHz (before 31st December 2024 – funding for operation at 24 MW is secured…)

Within **available 4.4 K LHe Cryostat @ LNCMI**



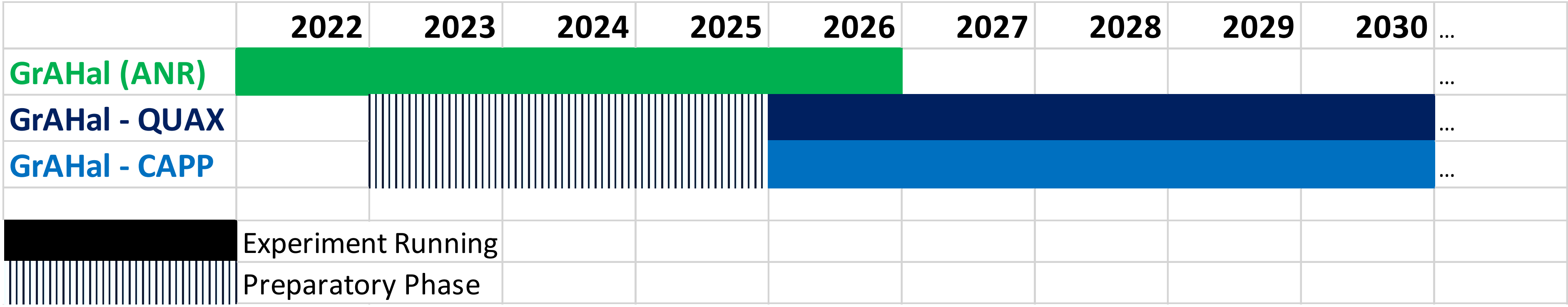
Adapted from https://github.com/cajohare/AxionLimits/blob/master/AxionPhoton_Closeups.ipynb

State-of-the-art exclusion plots for axion search from worldwide running haloscopes. Very high magnetic fields B provide unique opportunities for reaching unprecedented sensitivity, the awaited signal being proportional to B^2V. GrAHal first results[1] are shown by the solid line in red at 6.375 GHz.

From a conservative estimate, *i.e.* without using JPAs, the proposal using the 43 T hybrid magnet will explore the discovery potential area around the dashed blue line at 47 μeV*. It will extend in mass/frequency to about 20 neV/hour@43T at the ultimate sensitivity by varying the LHe temperature, which will change the resonant frequency of the RF-cavity. By lowering the time integration and therefore the sensitivity obtained at each frequency step, a larger axion mass range can be probed for the same total duration of data taking at 43 T. One of the GrAHal longer term objectives is to cover most of the **uncharted territories between 10^{-6} - 5.10^{-5} eV including the funded ANR proposal.**

[1] https://arxiv.org/abs/2110.14406

Rough Timeline

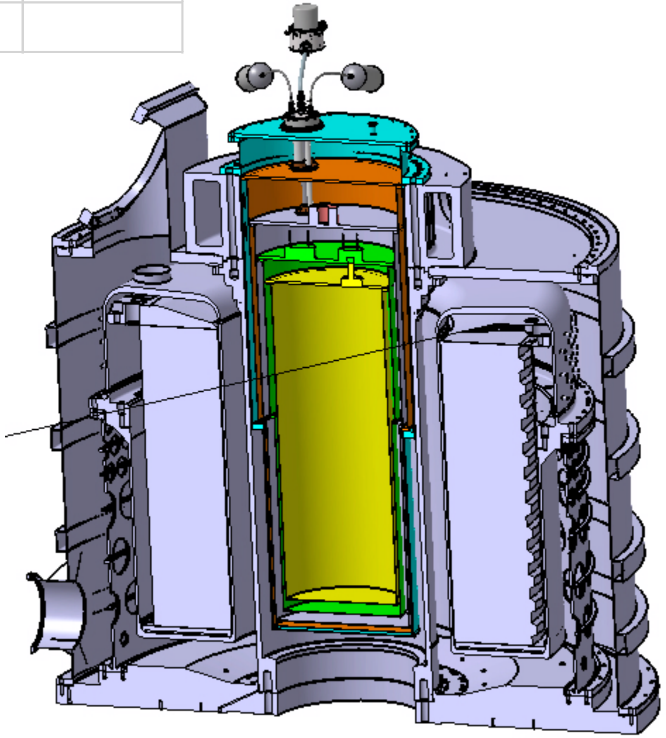


Time needed for in-house development of specific cryostats with double 3He/4He dilution refrigerator (DR)

Cooling stages 300 K/70 K/4 K/1 K/40 mK

The required cooling performances of the cryogenics are similar to the DR system used in astrophysical applications developed at Institut Néel for the NIKA and CONCERTO experiments. The choice of the “dry” cryogenic approach avoiding the massive use of cryogenic fluids relies on a 4 K powerful cryocooler.

Synergy with Developments for Quantum Computing



P. Camus, C. Bruyère, IN

GrAHal-QUAX for 7-10 GHz (dielectric RF cavity)

Field	Warm dia.	RF-cavity dia.
27 T	170 mm	86 mm
17.5 T	375 mm	291 mm

Collaboration with C. Braggio et al. (INFN and Univ. Padova)
"Search for Galactic Axions with high-Q Dielectric Cavity" Phys. Rev. D 106, 052007 (2022); Phys. Rev. Applied **17**, 054013 (2022)

Proven Technologies

Use of the TM030 mode
$Q_{loaded} \sim 300\,000$

- First test with High Q Dielectric cavities + Dilution Fridge (30 mK, 0.7 l) + 14 T + TWPA
- R&D on photon counters for better SNR

GrAHal-CAPP for 200-600 MHz (thin Cu RF cavity)

Field	Warm dia.	RF-cavity dia.	Freq. TM010	Axion mass
9.5 T	812 mm	700 mm	0.33 GHz	1.4 μeV

Thin* Cu RF-cavity
Made by CAPP/IBS, KAIST, Daejeon, South Korea, W. Chung, O. Kwon, Y. K. Semertzidis (arXiv:2210.10961, accepted, PRL)

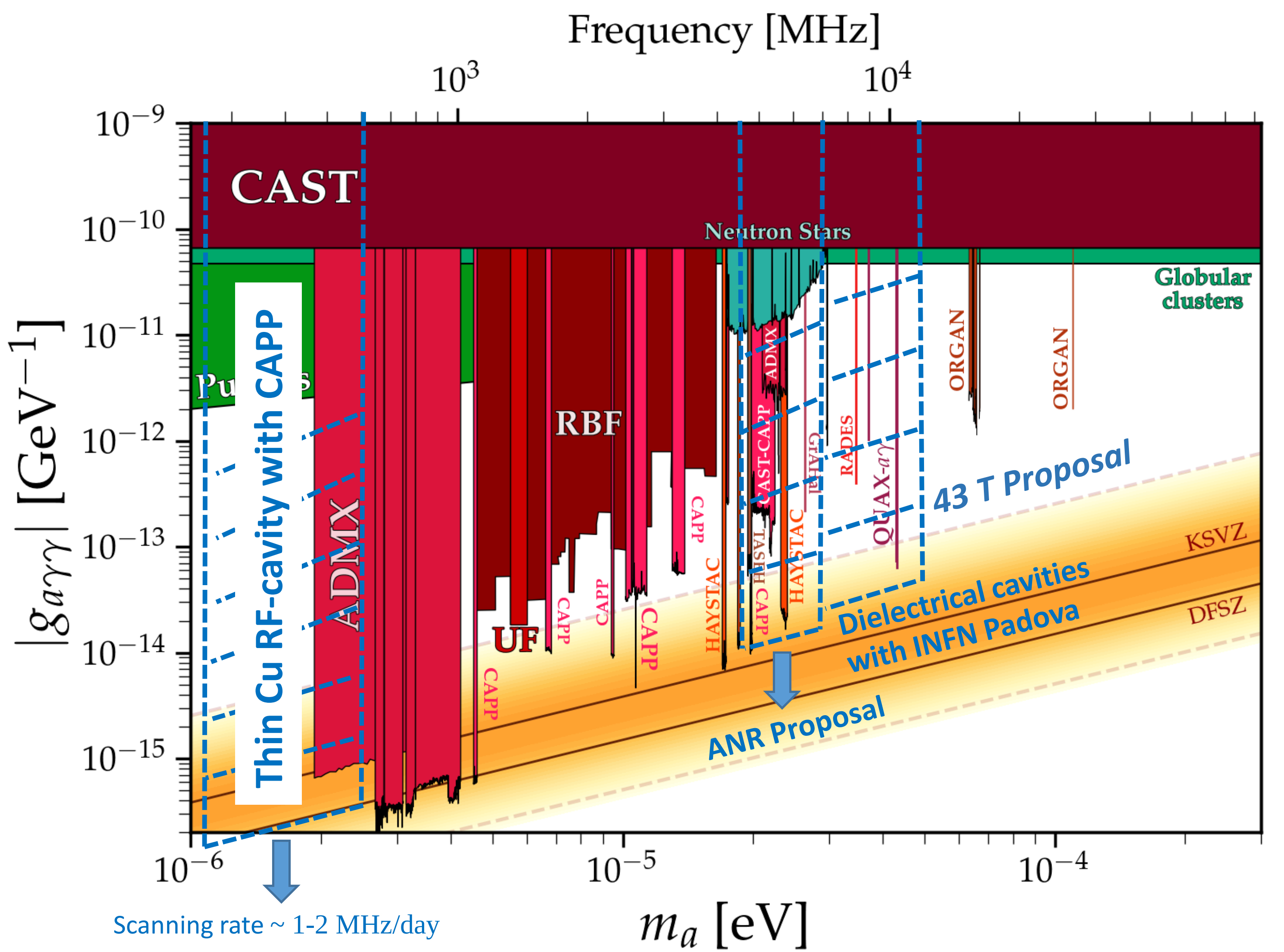
*Ex. of 0.5 mm thickness Cu cavity made by CAPP; need to be enlarge to 1 mm or more.

$Q_{loaded} \sim 35\,000 - 38\,000$

Dielectric tuning rode to lower the resonant frequency

GrAHal
Grenoble Axion Haloscopes

Targeted exploration windows within 1-50 μeV, *i.e.* 0.2-12 GHz



The exploration of the high frequency domain (> 10 GHz) down to DFSZ will require some breakthroughs (photon counters, HTS high-Q RF-cavities…) for Sikivie haloscopes or/and innovative ideas to reduce time integration…

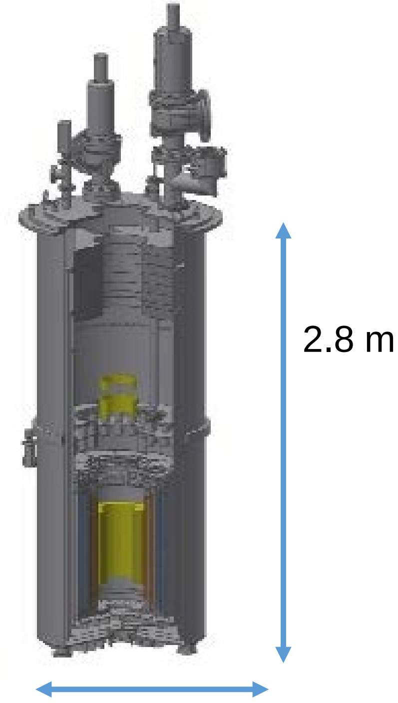
AND
Higher field magnets !!

FASUM funded Project
Forty Tesla All Superconducting User Magnet

(French research agency – Université Grenoble Alpes, CNRS, CEA – Started December 2021, (5 years)
http://lncmi.cnrs.fr/actualite/fasum-project-financed-by-french-anr-equipex-program/

Custom HTS insert

A 14.5 T HTS prototype already built & operating in 18 T background field
Cryogenics **106** (2020) 103053
DOI: 10.1016/j.cryogenics.2020.103053



« Commercial » LTS 19 T magnet
150 mm dia.

Very Challenging

40 T class magnet for LNCMI users
25 to 50 mm TBD diameter available for experiments

Université Grenoble Alpes
LNCMI
cnrs
cea
Irfu
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Toward GrAHal Upgrade+ (?)

Proposal for a 60 T high-field hybrid* magnet

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*Hybrid = (Resistive + HTS + LTS) or/and (HTS? + HTS + LTS)

Very Challenging

Proposal presented in Sept 2019 to MT26 & in May 2022 to the Workshop**

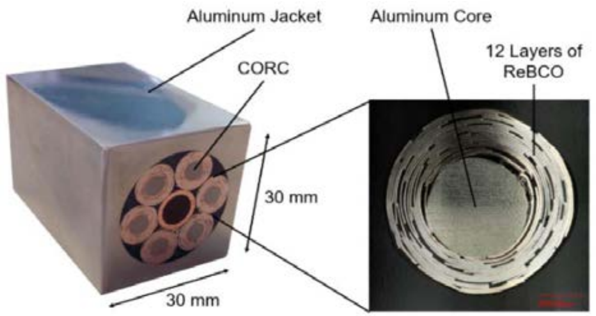
FuSuMaTech

(Futur for Superconducting Magnet Technology)

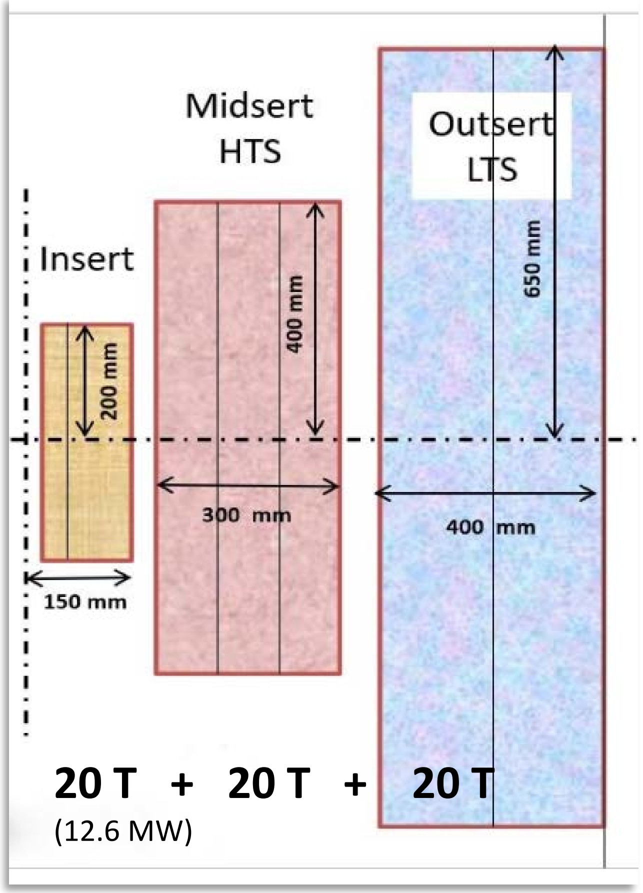
**https://indico.cern.ch/event/763185/contributions/3416454/

Synergy with muon collider @ CERN ?

Ref. "Conceptual Design Optimization of a 60 T Hybrid magnet", *IEEE Trans. on Appl. Supercond.*, June 2020; DOI: 10.1109/TASC.2020.2972498



We need HTS multi-ribbon or multi-strand HTS & LTS reinforced conductors **BUT ALSO SUPPORT from the WORLWIDE COMMUNITY…**



As a Conclusion

Higher Fields

yes we can

On High Magnetic Fields ;-) …

Thanks for Your Attention

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