OSQAR
GrAHal

A glimpse at different experimental explorations of the low energy frontier of particle physics (Axion, scalar and pseudo-scalar ALPs, hidden sectors dark photons and millicharged particles, chameleons,…)

OUTLINE

- Overview of OSQAR
- Future of OSQAR
- GrAHal project
  - Overview
  - Cryogenics
  - Superconducting low Noise Amplifier
  - High magnetic field 1 the hybrid magnet
- Summary
- Take home messages

OSQAR

Optical Search for QED vacuum birefringence, Axions and photon Regeneration

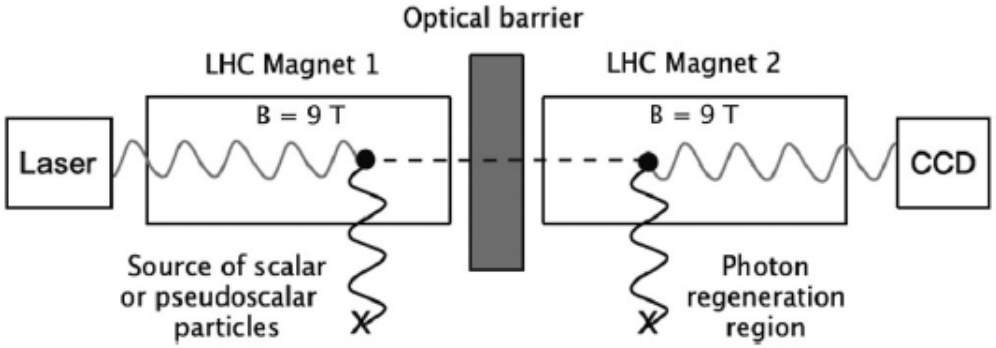
OSQAR – VMB

OSQAR – LSW

OSQAR – CHASE

Light Shining through a Wall (LSW)

The di-photon coupling of the ALPs implies that photon – ALP oscillations occur in a backround magnetic field. The LSW experiments are based on these Primakov processes and the weakness of the interactions of ALPs with particles of the SM.



$\vec{E}_\gamma \parallel \vec{B}$ for pseudoscalar ALPs : $\mathcal{L}_{int} = g_{a\gamma\gamma}\ \phi_a\ \vec{E}\cdot\vec{B}$

$\vec{E}_\gamma \perp \vec{B}$ for scalar ALPs : $\mathcal{L}_{int} = g_{a\gamma\gamma}\ \phi_a\ (\vec{E}^2 - \vec{B}^2)$

Conversion probability

$$P_{A\leftrightarrow\gamma} = \frac{1}{4}\left(g_{A\gamma\gamma}BL\right)^2\left(\frac{2}{qL}\sin\frac{qL}{2}\right)^2\frac{\omega}{\sqrt{\omega^2 - m_A^2}}$$

with $q = \left|k_\gamma - k_A\right|$, $k_\gamma = \omega$ and $k_A = \sqrt{\omega^2 - m_A^2}$

ω : photon energy – m_A : ALP mass

in units of LH system $\left(\hbar = c = \mu_0 = \varepsilon_0 = 1\right)$

$$P_{\gamma\to A\to\gamma} = \left(P_{A\leftrightarrow\gamma}\right)^2$$

The flux of the regenerated photons is given by

$$\frac{dN}{dt} = \frac{P}{\omega}\,\eta\left(P_{A\leftrightarrow\gamma}\right)^2$$

P : power of the incoming photons of energy ω

η : the detector efficiency

Weak conversion probability (< 10^{-23})
So request
Intense Fluxes of Photon
Sensitive Detectors
Strong Magnetic Field over Large Distance L

L.B. Okun, Sov. Phys. JETP 56 (1982)502, P. Sikivie, PRL 51 (1983) 11415,
A.A. Anselm, Sov. J. Nucl. Phys. 42 (1985) 936, K. van Biber et al., PRL 59 (1987) 759

LSW experiments worldwide

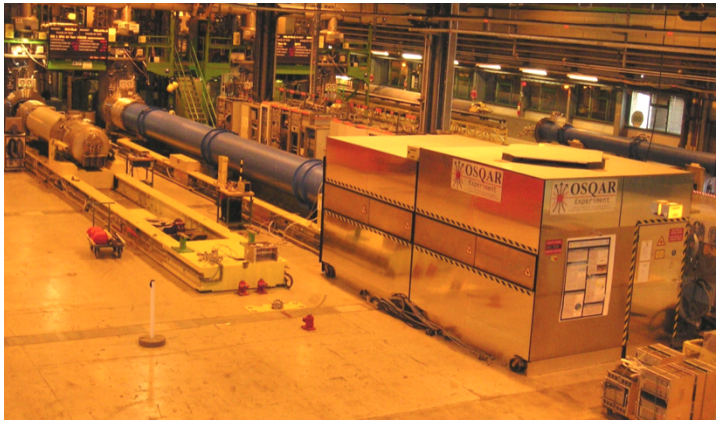
BFRT	PRD 47 (1993) 3707
BMV	PRL 99 (2007) 190403
GammeV	PRL 100 (2008) 080402
LIPPS	PRL 101 (2008) 120401
ALPS	Phys. Lett. B 689 (2010) 149
CROWS	PRD 88 (2013) 075014
OSQAR	PRD 92 (2015) 092002

LSW Experiment

Use of two standard spare magnets for LHC at CERN SM18 magnet testing hall providing the Cooling (1.9 K) and and vacuum facilities.

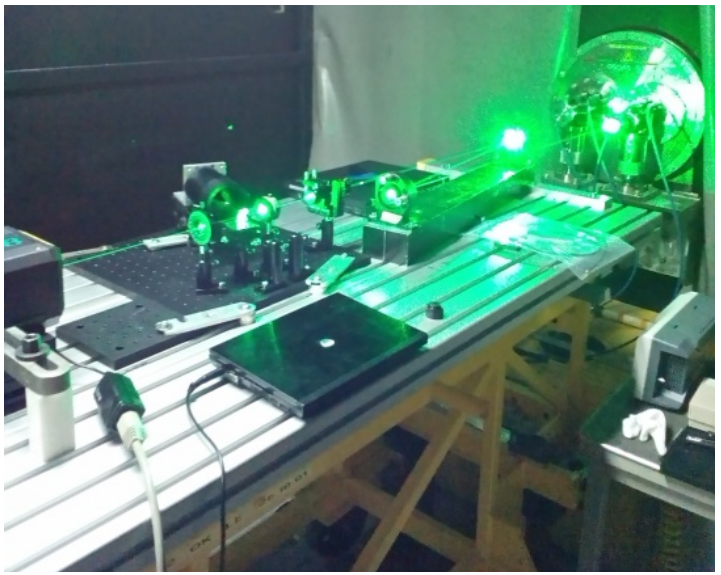
The 2 dipoles are aligned at warm conditions cooled down, cold tested and finally powered.

B = 9.5 T and effective **L = 14.3 m**



Photon Source: COHERENT Verdi V18 CW Laser
λ = **532 nm (2.3 eV)** - Optical power : **18.5 W**

Photon beam is linearly polarized with $\vec{E}_\gamma \parallel \vec{B}$
Search for pseudoscalar ALPs
Use of a $\lambda/2$ wave plate for polarization $\vec{E}_\gamma \perp \vec{B}$
Search for scalar ALPs
Use of beam expander telescope to reduce the Laser beam divergence.



LSW Experiment

Detection by thermoelectric cooled CCD

ANDOR DU934P-BEX2-DD

Active area of 13.3×13.3 mm^2

1024 × 1024 pixels: 13×13 μm^2

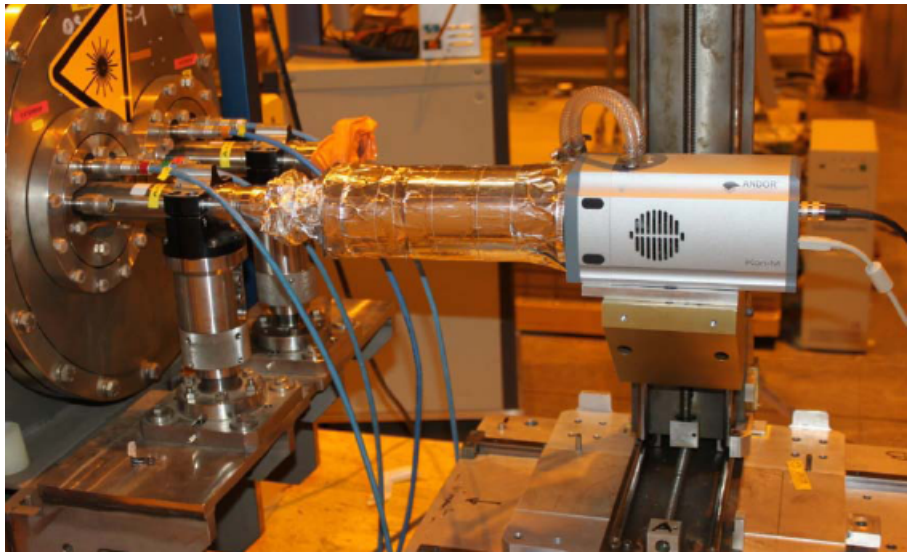
Dark current: **0.0012 e^-/pixel/s** @ T = −95°

Readout Noise : **2.5 e^- rms/pixel**

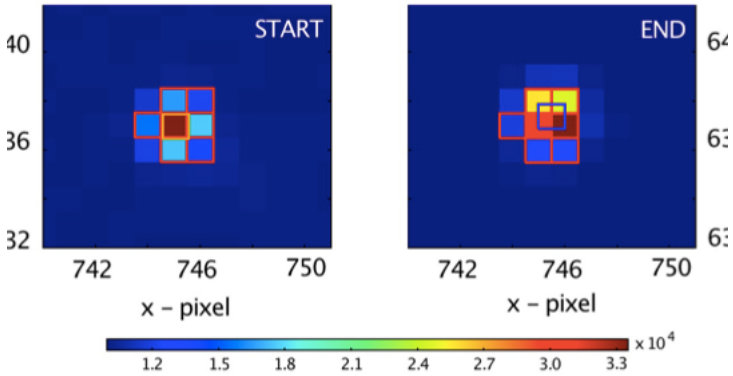
Sensitivity : **1.3 e^-/ADU**

Overall detection efficiency measured to

η = 0.56 ± 0.02 ADU/photon



Laser beam long time stability was checked. Alignment checked at start / end of each run.

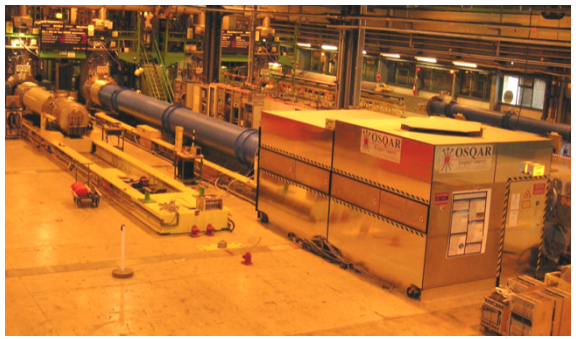


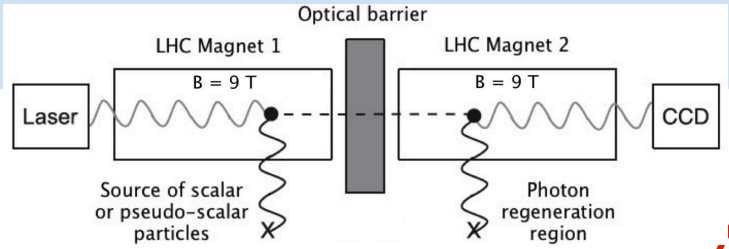
Exposure time of runs set to optimize the SNR taking account cosmic contaminations.

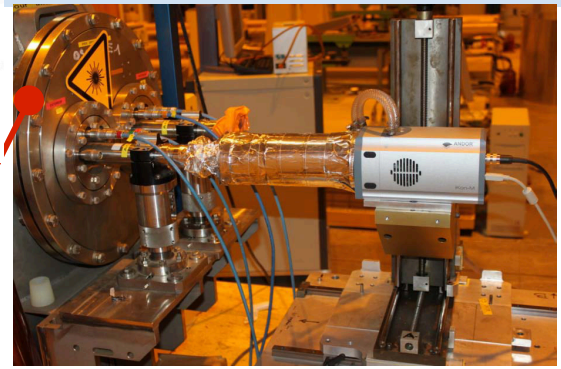
Bayesian analysis of the recorded counts

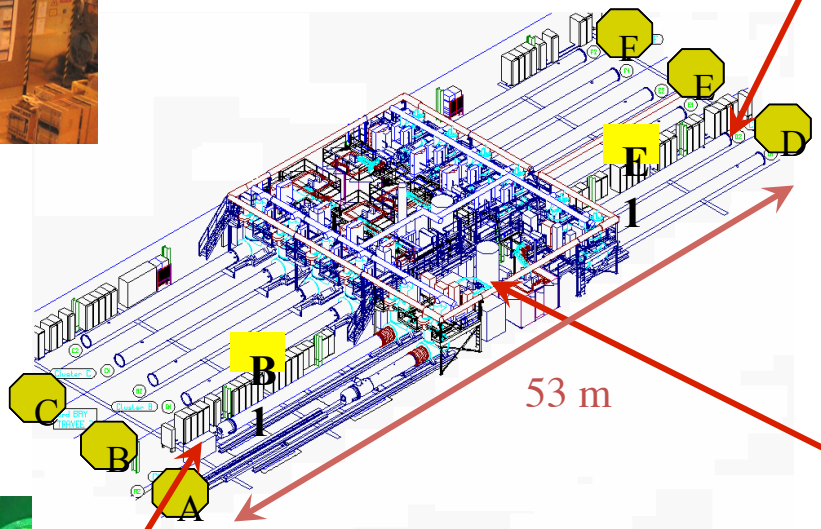
$$\mathcal{L} \propto \prod_i \mathcal{N}\left(N_i \middle| \mathcal{P}\left(\frac{dN}{dt} t_i^{\exp}\right) + \mu_i^{\mathrm{bkg}}, \sigma_i^{\mathrm{bkg}}\right)$$

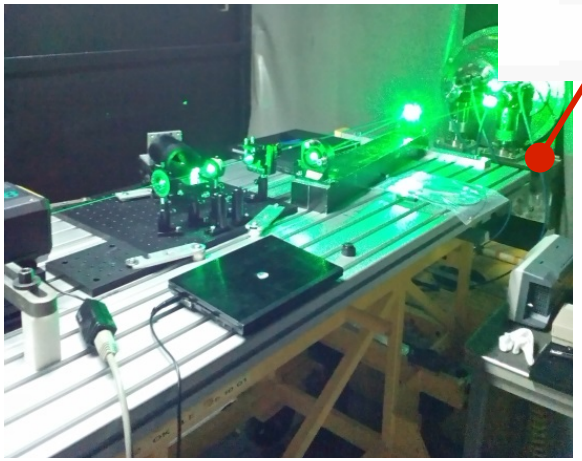
LSW Experiment

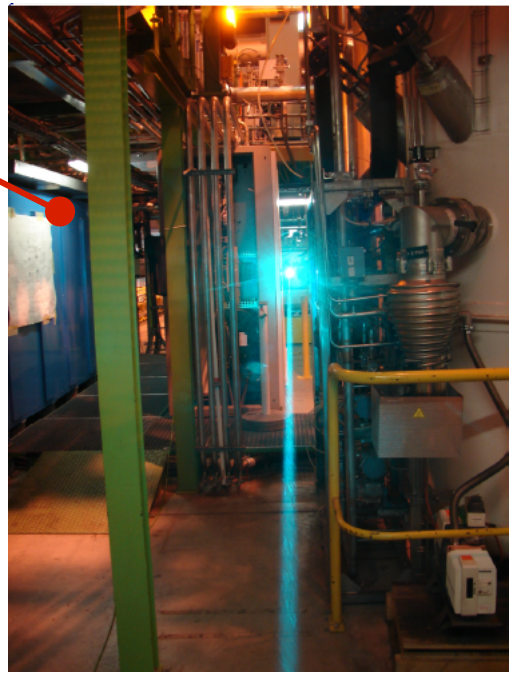








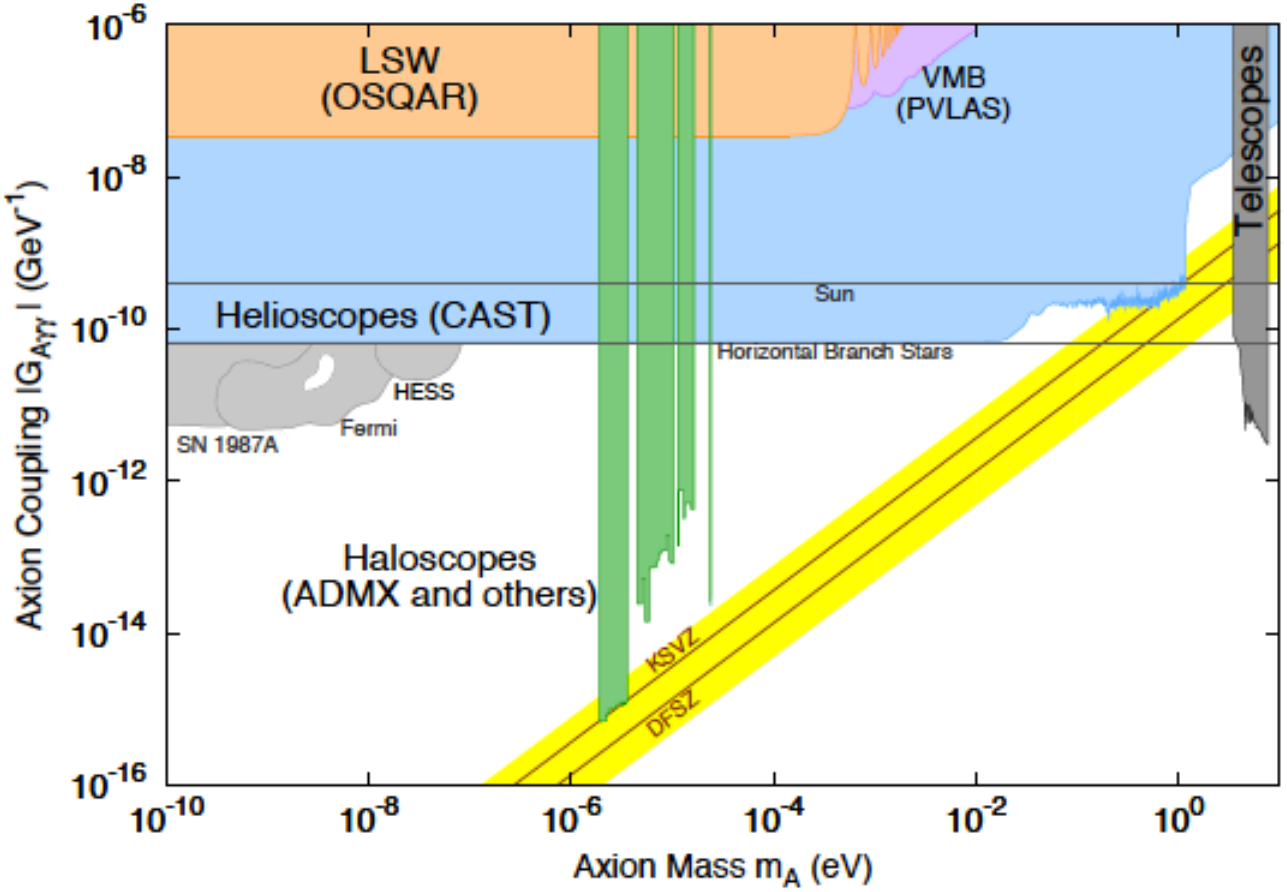




$\partial N_{\gamma->\phi->\gamma} / \partial t$ detection threshold determined from Bayesian analysis of data

No excess of counts detected

Current status of WISP search Experiments



http://pdg.lbl.gov/2019/reviews/rpp2018-rev-axions.pdf

PDG Data Group, AXIONS AND OTHER SIMILAR PARTICLES, 2016

Possible improvements of the LSW Experiments to extend the explored parameter space

$$\frac{dN}{dt} = \frac{P}{\omega}\eta \cdot (P_{A\leftrightarrow\gamma})^2$$

$$P_{A\leftrightarrow\gamma} = \frac{1}{4}\left(g_{A\gamma\gamma}BL\right)^2 \left(\frac{2}{qL}\sin\frac{qL}{2}\right)^2 \frac{\omega}{\sqrt{\omega^2 - m_A^2}}$$

with $q = \left|k_\gamma - k_A\right|$, $k_\gamma = \omega$ and $k_A = \sqrt{\omega^2 - m_A^2}$

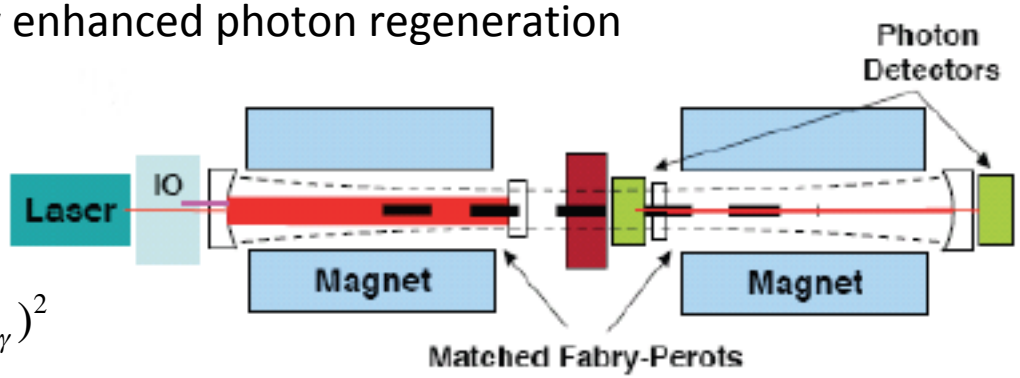
ω : photon energy – m_A : ALP mass

in units of LH system $\left(\hbar = c = \mu_0 = \varepsilon_0 = 1\right)$

Parameters	*Scaling for* $g_{W\gamma\gamma}$
Magnetic field integral *B l (T m)*	$(B\ l)^{-1}$
Photon energy ω *(eV)*	$\omega^{1/4}$
Effective optical power *P (W)*	$P^{-1/4}$
Effective QE of the detector η	$\eta^{-1/4}$
Noise/pixel: *dark count f (mHz) – read*	$f^{1/8}$
Time integration Δt *(h)*	$\Delta t^{-1/8}$

Resonantly enhanced photon regeneration

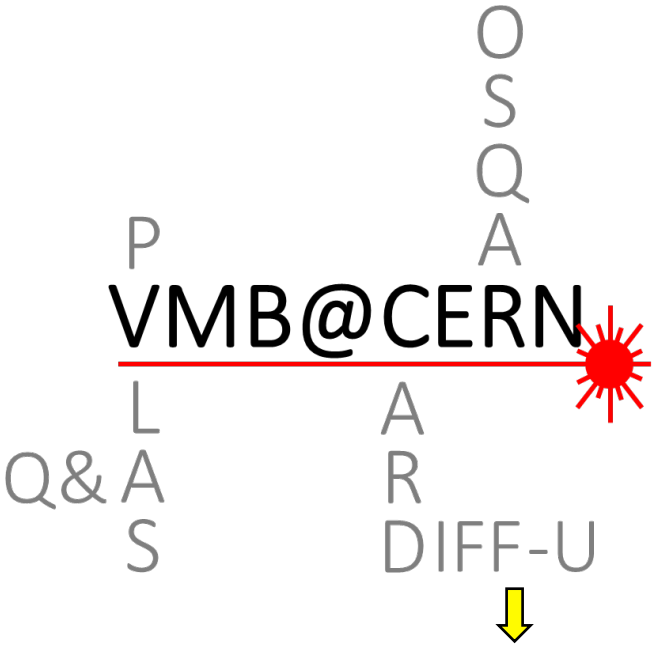
JURA@CERN



$$\frac{dN}{dt} = \frac{P}{\omega}\eta \cdot F_{PC} \cdot F_{RC} \cdot (P_{A\leftrightarrow\gamma})^2$$

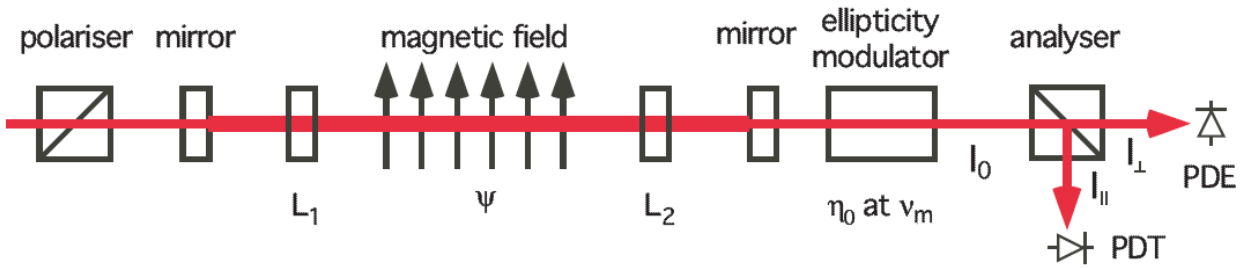
P. Sikivie et al. Phys. Rev. Lett. **98**, 172002 (2007)

F. Hoogeveen and T. Zizgznhagen, Nuc. Phys. B 358, 3 (1991)



Expertise from Ligo

Proposed modulation scheme
L1,2 : rotating half-wave-plates
PDE : Extinction Photodiode
PDT : Transmission Photodiode.



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

http://cds.cern.ch/record/2649744/files/SPSC-I-249.pdf

CERN-SPSC-2018-036 / SPSC-I-249
03/12/2018

Letter of Intent to measure Vacuum Magnetic Birefringence: the VMB@CERN experiment

R. Ballou[1)], F. Della Valle[2)], A. Ejlli[3)], U. Gastaldi[4)], H. Grote[3)], Š. Kunc[5)], K. Meissner[6)], E. Milotti[7)], W.-T. Ni[8)], S.-s. Pan[9)], R. Pengo[10)], P. Pugnat[11)], G. Ruoso[10)], A. Siemko[12)], M. Šulc[5)] and G. Zavattini[13)]*

[1]Institut Néel, CNRS and Université Grenoble Alpes, Grenoble, France
[2]INFN, Sez. di Pisa, and Dip. di Scienze Fisiche, della Terra e dell'Ambiente, Università di Siena, Siena (SI), Italy
[3]School of Physics and Astronomy, Cardiff University, Cardiff, UK
[4]INFN, Sez. di Ferrara, Ferrara (FE), Italy
[5]Technical University of Liberec, Czech Republic
[6]Institute of Theoretical Physics, University of Warsaw, Poland
[7]Dip. di Fisica, Università di Trieste and INFN, Sez. di Trieste, Trieste (TS), Italy
[8]Department of Physics, National Tsing Hua University, Hsinchu, Taiwan, ROC
[9]Center of Measurement Standards, Industrial Technological Research Institute, Hsinchu, Taiwan, ROC
[10]INFN, Lab. Naz. di Legnaro, Legnaro (PD), Italy
[11]LNCMI, EMFL, CNRS and Université Grenoble Alpes, Grenoble, France
[12]CERN, Genève, Switzerland
[13]Dip. di Fisica e Scienze della Terra, Università di Ferrara and INFN, Sez. di Ferrara, Ferrara (FE), Italy

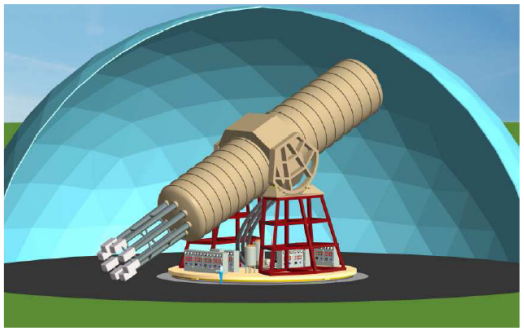
With a single LHC dipole at 9.5 T, VMB detected with SNR = 1 in less than 1 day of integration.

P. Pugnat, L. Duvillaret et al., Czech. J. Phys. 55, A389 (2005)

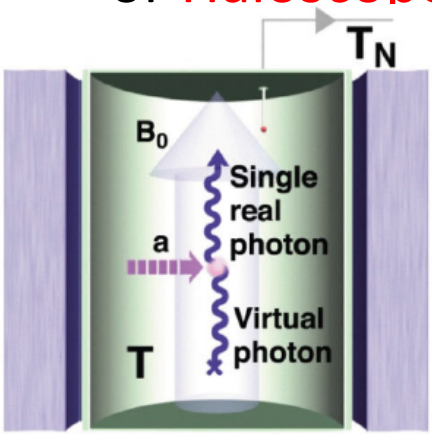
Boss : No light shinning through a wall ?
PostDoc : Not yet sir ! I have some hope from ALPs but none from QCD axion

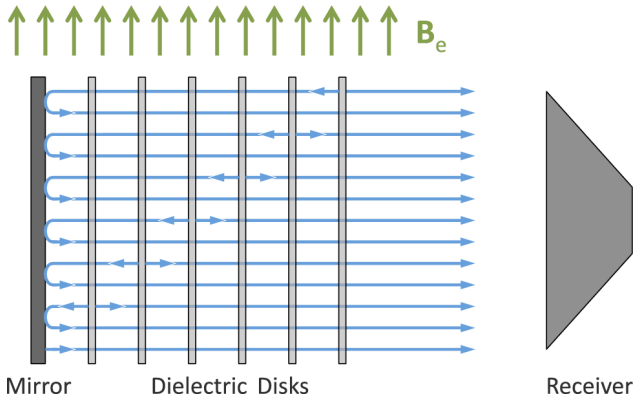
The hope to detect QCD Axions lies on measurements on

Helioscopes (CAST, SUMICO, …, IAXO project)

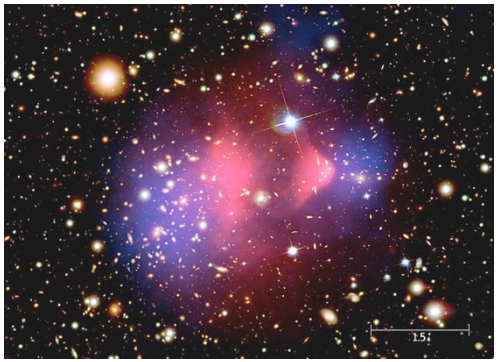


or Haloscopes (ADMX, …, MADMAX).





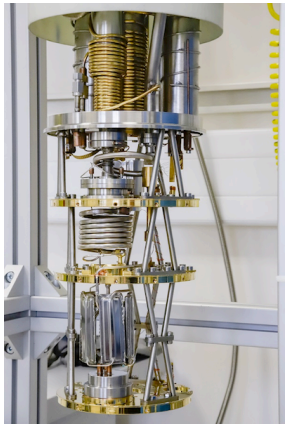
GrAHal : The Grenoble Haloscope Project



The GrAHal project

Grenoble Axion Haloscope

R. Ballou, P. Camus, T. Grenet, S. Kramer, P. Pugnat, N. Roch

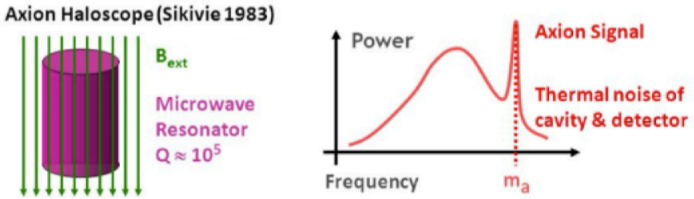


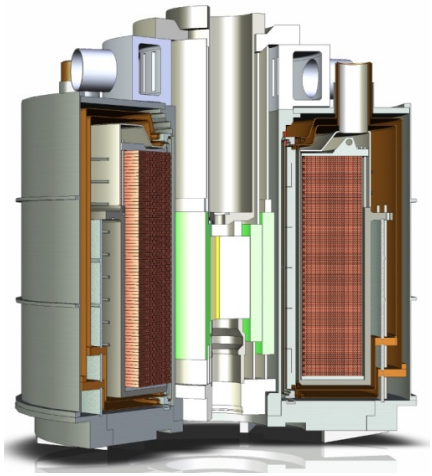
What do we want to detect ?

Method of detection : Sikivie's haloscope

State of the art and challenges to go further

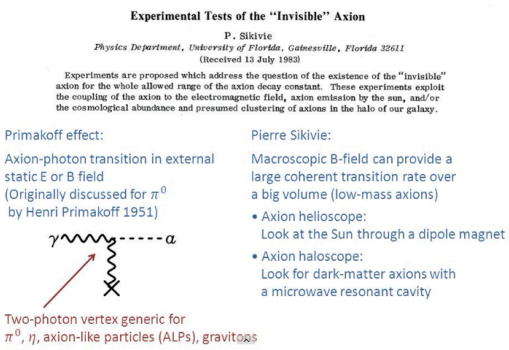
The GrAHal project





Detection method : Sikivie's haloscope

Axion field → new source term in Maxwell equations



Experimental Tests of the "Invisible" Axion

P. Sikivie

Physics Department, University of Florida, Gainesville, Florida 32611

(Received 13 July 1983)

Experiments are proposed which address the question of the existence of the "invisible" axion for the whole allowed range of the axion decay constant. These experiments exploit the coupling of the axion to the electromagnetic field, axion emission by the sun, and/or the cosmological abundance and presumed clustering of axions in the halo of our galaxy.

Primakoff effect:

Axion-photon transition in external static E or B field
(Originally discussed for π^0 by Henri Primakoff 1951)

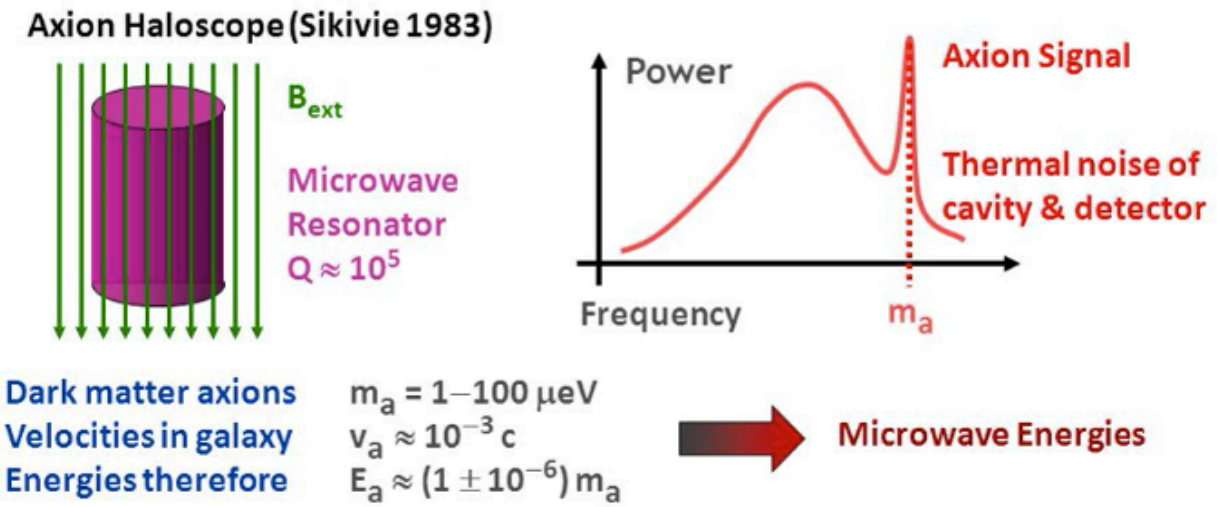
γ ----- a

Two-photon vertex generic for π^0, η, axion-like particles (ALPs), gravitons

Pierre Sikivie:

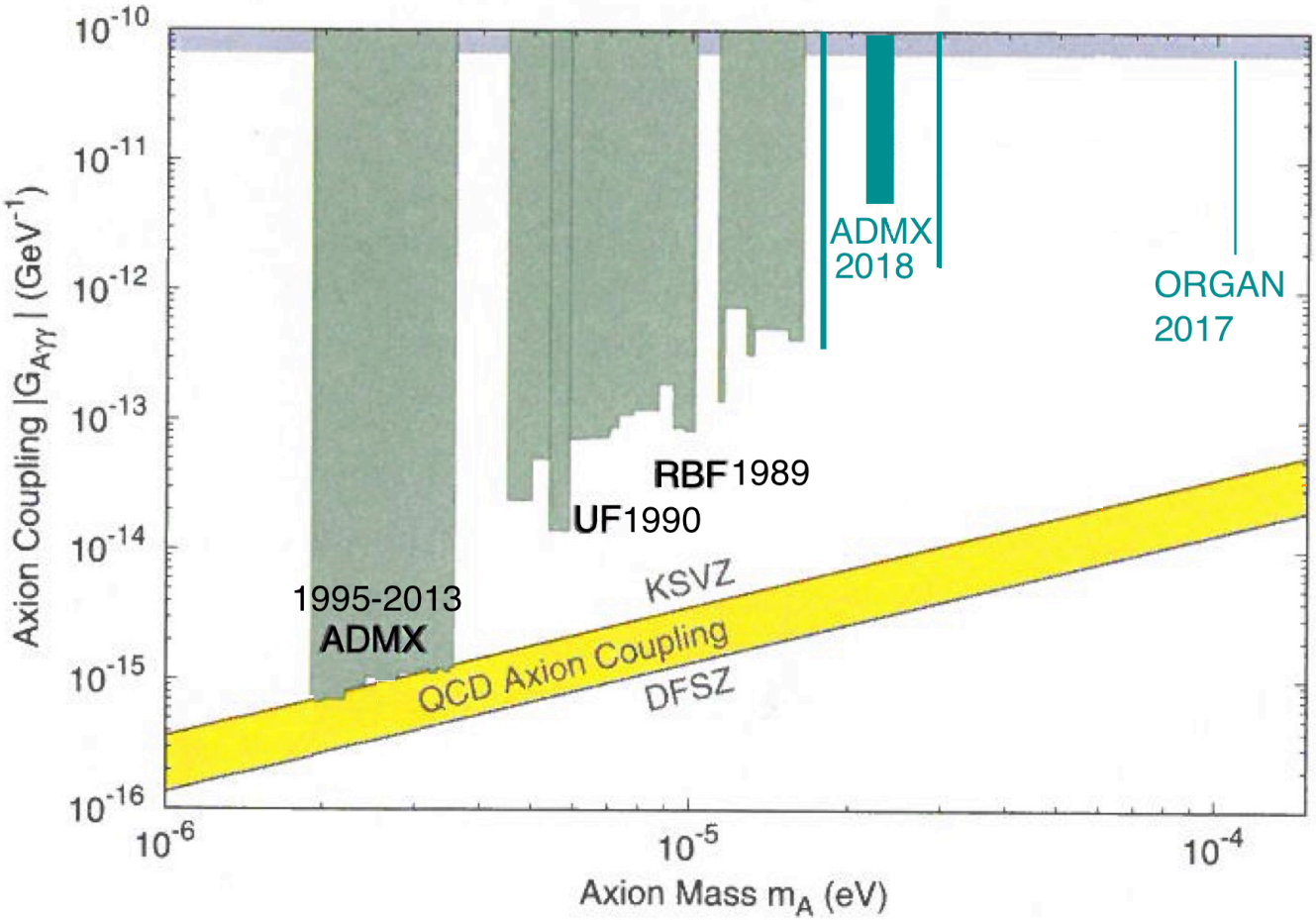
Macroscopic B-field can provide a large coherent transition rate over a big volume (low-mass axions)

- Axion helioscope:
  Look at the Sun through a dipole magnet
- Axion haloscope:
  Look for dark-matter axions with a microwave resonant cavity



State of the art and challenges to go further

$$P = g_{A\gamma\gamma}^2 C \frac{\rho_a}{m_a} Q_L B_0{}^2 V_{ol} \quad \Longrightarrow \quad \text{bounds on } \left| g_{A\gamma\gamma} \right| \text{ assuming 100\% of DM is axions}$$



Liq. He^4
+
HMFET ampl.

Order of magnitude of expected power

$$P = g_{A\gamma\gamma}^2 C \frac{\rho_a}{m_a} Q_L B_0{}^2 V_{ol} \qquad g_{a\gamma\gamma} = \frac{\alpha}{\pi \Lambda^2} m_a g_\gamma$$

$$P = 1.14.10^{-26} (Watt) \left(\frac{g_\gamma}{0.97}\right)^2 \left(\frac{\rho_a}{0.45 GeV/cm^3}\right) \left(\frac{C}{0.5}\right) \left(\frac{B_0{}^2}{1T^2}\right) \left(\frac{f}{1GHz}\right) \left(\frac{V_{ol}}{1L}\right) \left(\frac{Q_L}{10^4}\right)$$

What determines the frequency scan rate ?

$$SNR \propto \frac{C B_0{}^2 f V_{ol} Q_L}{k_B T_{noise}} \sqrt{\frac{t}{\Delta f_a}} \Rightarrow \boxed{\frac{df}{dt} \propto \frac{1}{SNR^2} \frac{C^2 B_0{}^4 f^2 V_{ol}^2 Q_L}{T_{noise}^2}}$$

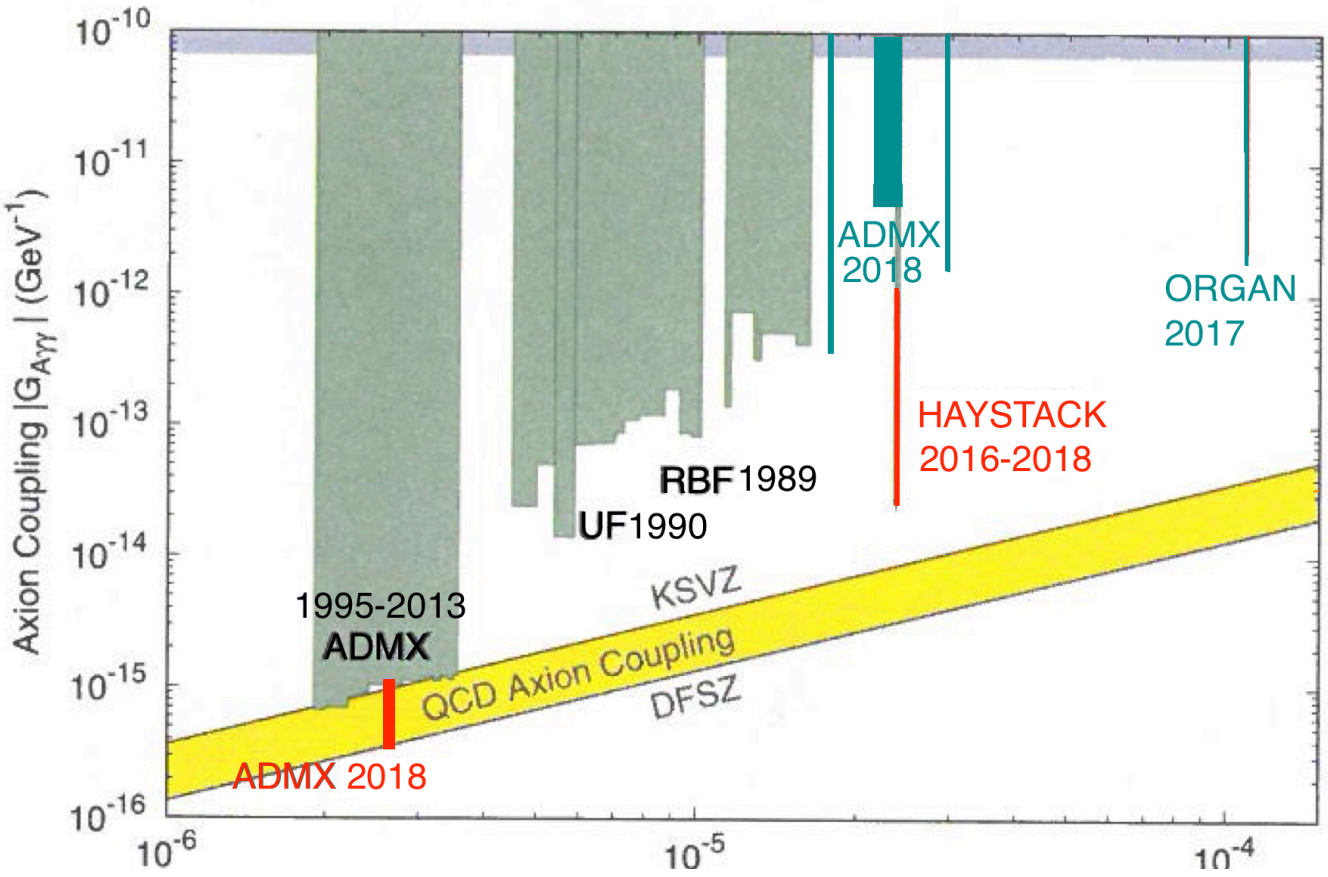
The problem with high frequencies :

$$\left.\begin{aligned} V_{ol} &\propto R^3 \propto f^{-3} \\ Q &\propto \frac{R}{\delta_{asd}} \propto \frac{f^{-1}}{f^{-1/3}} \end{aligned}\right\} \Rightarrow \frac{df}{dt} \propto f^{-14/3}$$

Strategies to improve scan rates :

$$\frac{df}{dt} \propto \frac{1}{SNR^2} \frac{C^2 B_0{}^4 f^2 V_{ol}^2 Q_L}{T_{noise}^2}$$

- eliminate the thermal noise : He_{liq} + HMFET → dilution fridge + SQUID/JPA)



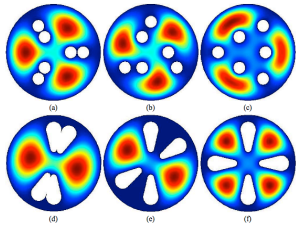
Next step : below the quantum noise → squeezed states, QND ?

Strategies to improve scan rates :

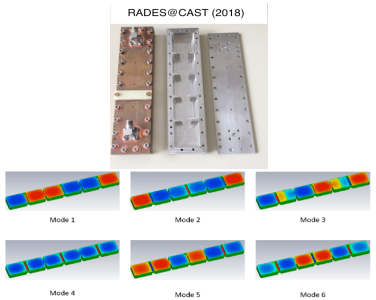
$$\frac{df}{dt} \propto \frac{1}{SNR^2} \frac{C^2 B_0^4 f^2 V_{ol}^2 Q_L}{T_{noise}^2}$$

-increase B_0 anything is possible … with much time and money

-increase V_{ol} cavity design

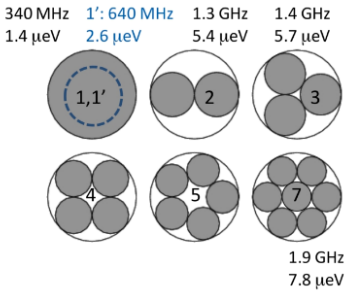


ADMX (2015)



RADES@CAST (2017)

connected cavities



using higher modes (e.g. TM_{0n0} n>1 in cylinders) : pbs with mode crossings & coupling C decreases

-increase Q_L cavity surface treatements, superconducting coating ? (limited by B_0)

Presently ongoing R&D at :

ADMX (US)

HAYSTACK (US)

ORGAN (Australia)

+

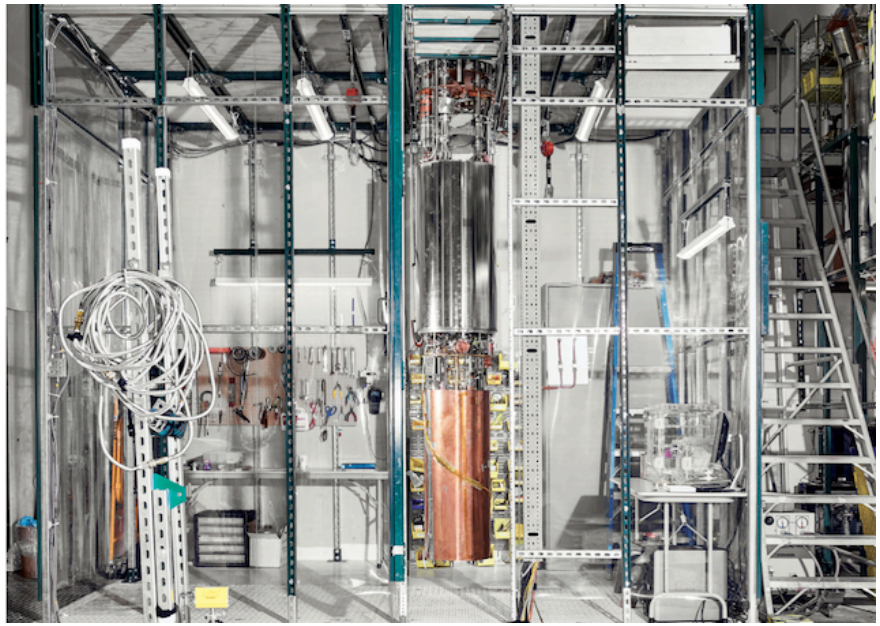
CULTASK (IBS, Korea)

RADES@CAST (Spain + CERN)

KLASH (Frascati, Italy)

(Kyoto ?)

+ MADMAX (Germany) etc …



ADMX

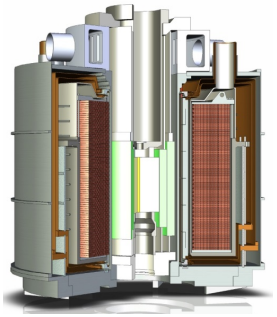
The GrAHal project : why here in Grenoble ?

$$\frac{df}{dt} \propto \frac{1}{SNR^2} \frac{C^2 B_0{}^4 f^2 V_{ol}^2 Q_L}{T_{noise}^2}$$

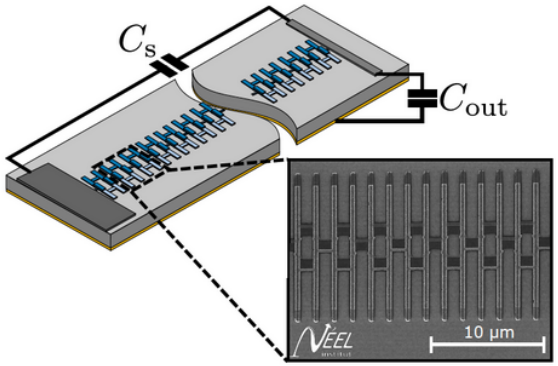
Needed expertises and equipments :

-High magnetic fields	✓	LNCMI, Néel → talk by P. Pugnat
-Small scale RF expertise + cavity design	✓	LNCMI, Néel, collab with LPSC ?
-High power dilution cryogenics	✓	Néel
-Josephson junction based amplifiers	✓	Néel
-Data analysis techniques	✓	LNCMI-Néel/OSQAR

Hybrid Magnet Platform in construction at LNCMI



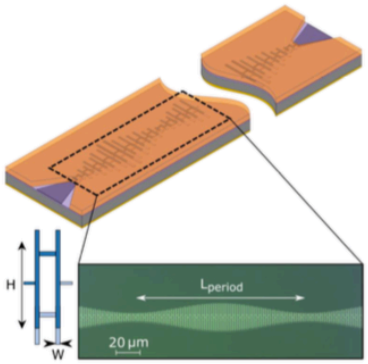
43 T/34 mm, 40 T/50 mm
27 T/170 mm, 9 T/800 mm

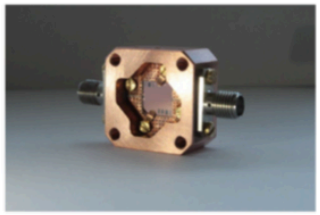


A near quantum limited Josephson Parametric Amplifier, based on superconducting metamaterials.

State of the art superconductor based amplifier (N. Roch, I. Néel)

Our device

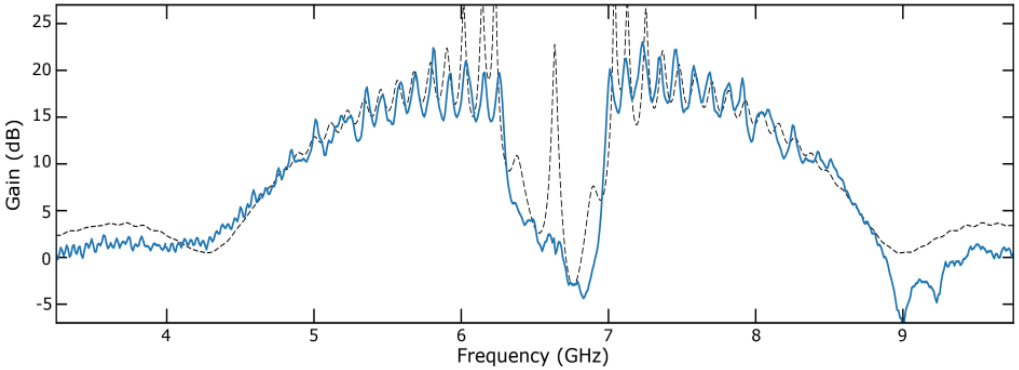




Traveling Wave Structure (TWPA)
Simple design and fabrication process

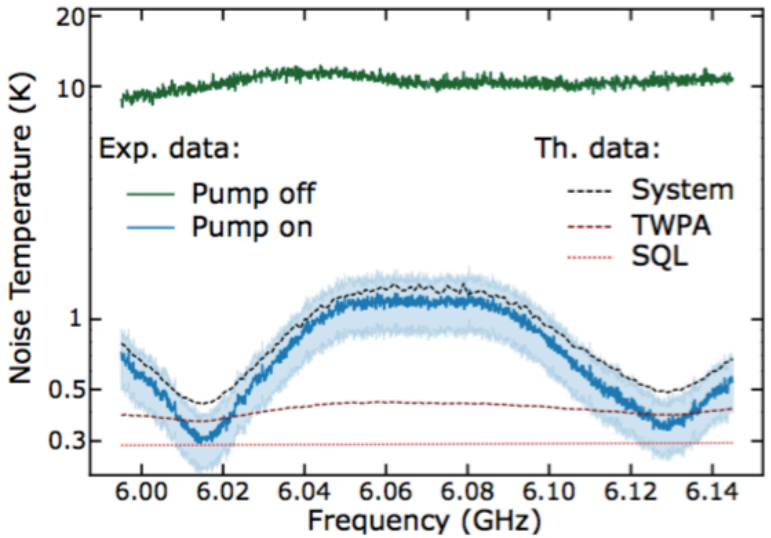
Patent pending n° FR1901767

Our device



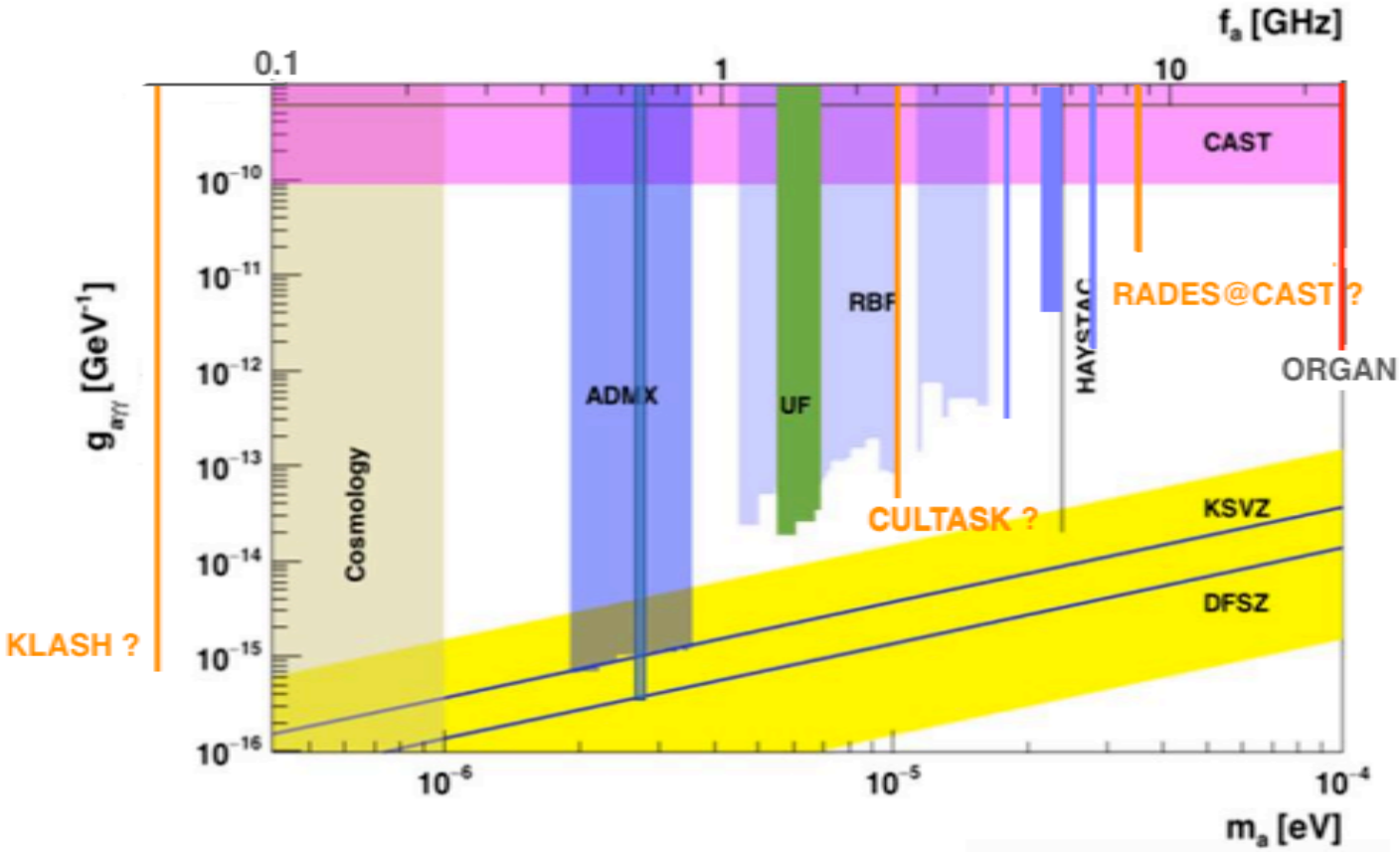
Bandwidth: 3 GHz
Gain: 18 dB

Our device



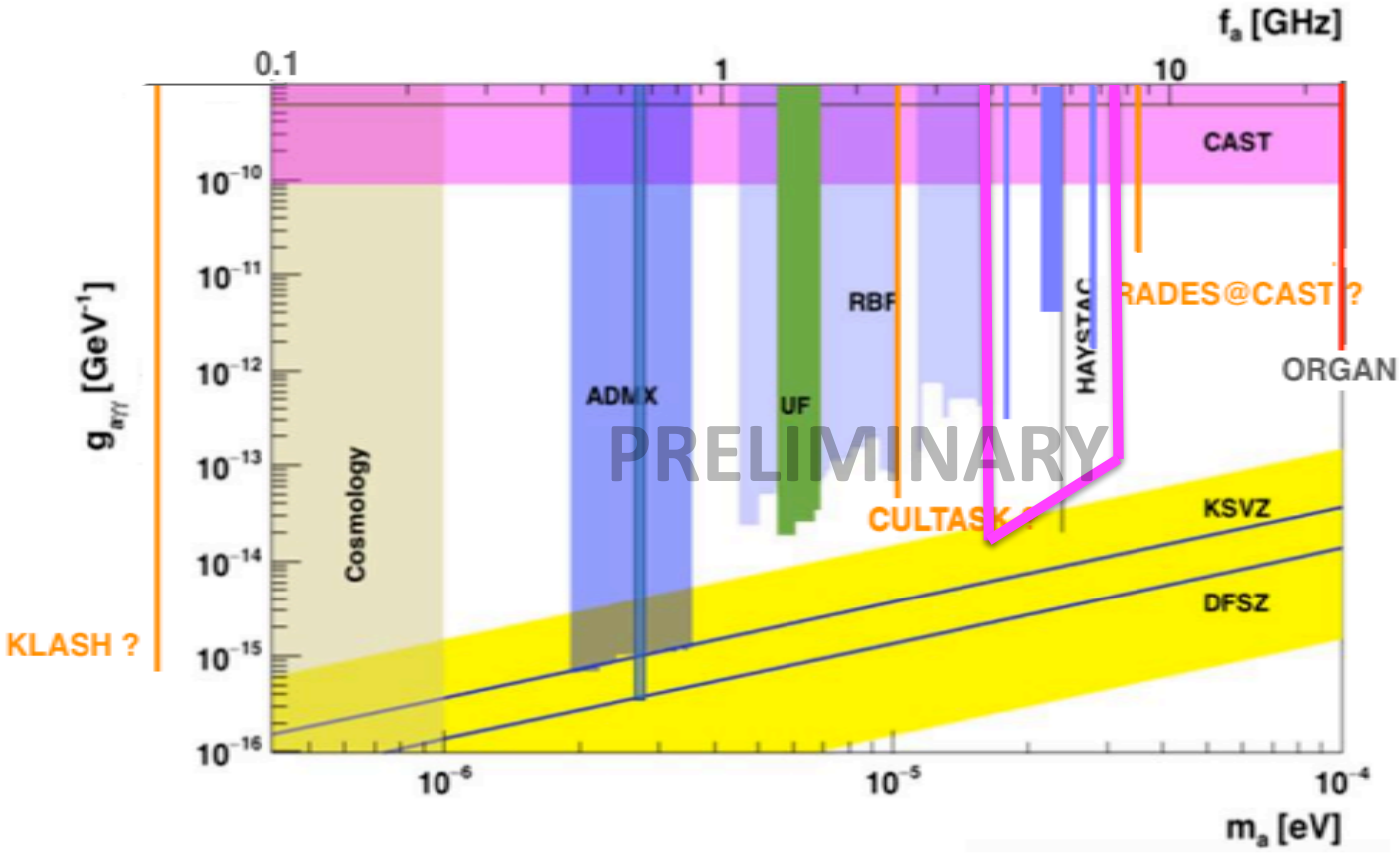
L. Planat et al., in prep

The GrAHal project : phases and expected performances



The GrAHal project : phases and expected performances

Phase 1 (2019 …) : f_{min}= 3.8 GHz, dilution fridge in 14 T

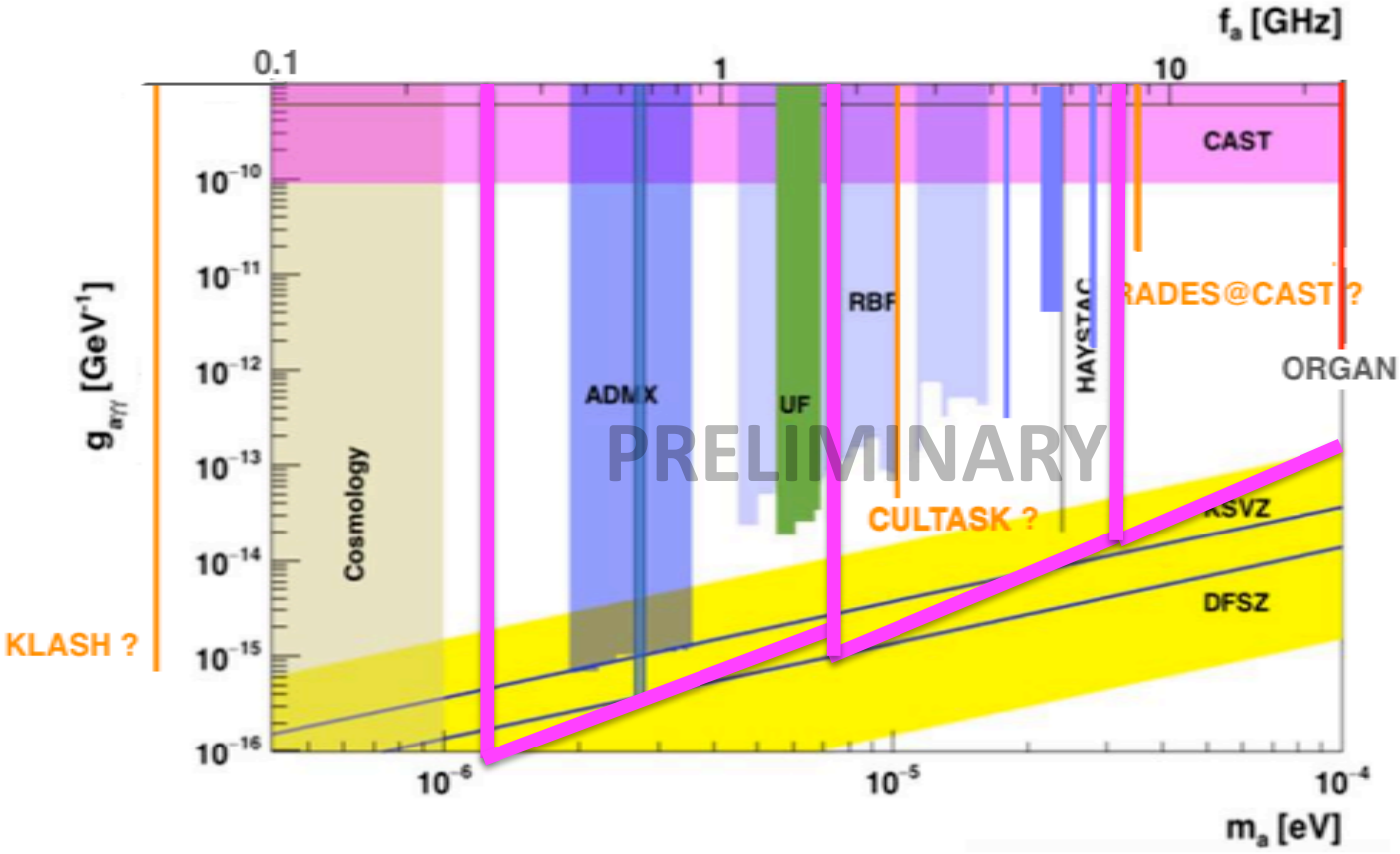


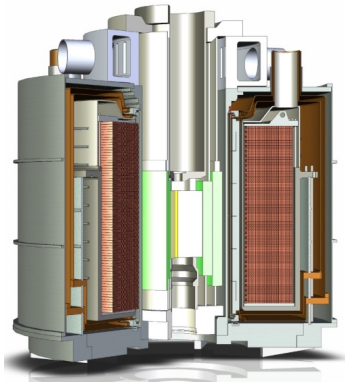
Potentially accessible parameter regions in phase 1

The GrAHal project : phases and expected performances

Phase 1 (2019 …) : f_{min}= 3.8 GHz, dilution fridge in 14 T

Phase 2 (2021 ?) : LNCMI hybrid magnet
development of cavities + cryostats





Potentially accessible parameter regions with the hybrid magnet (phase 2) with single cavities

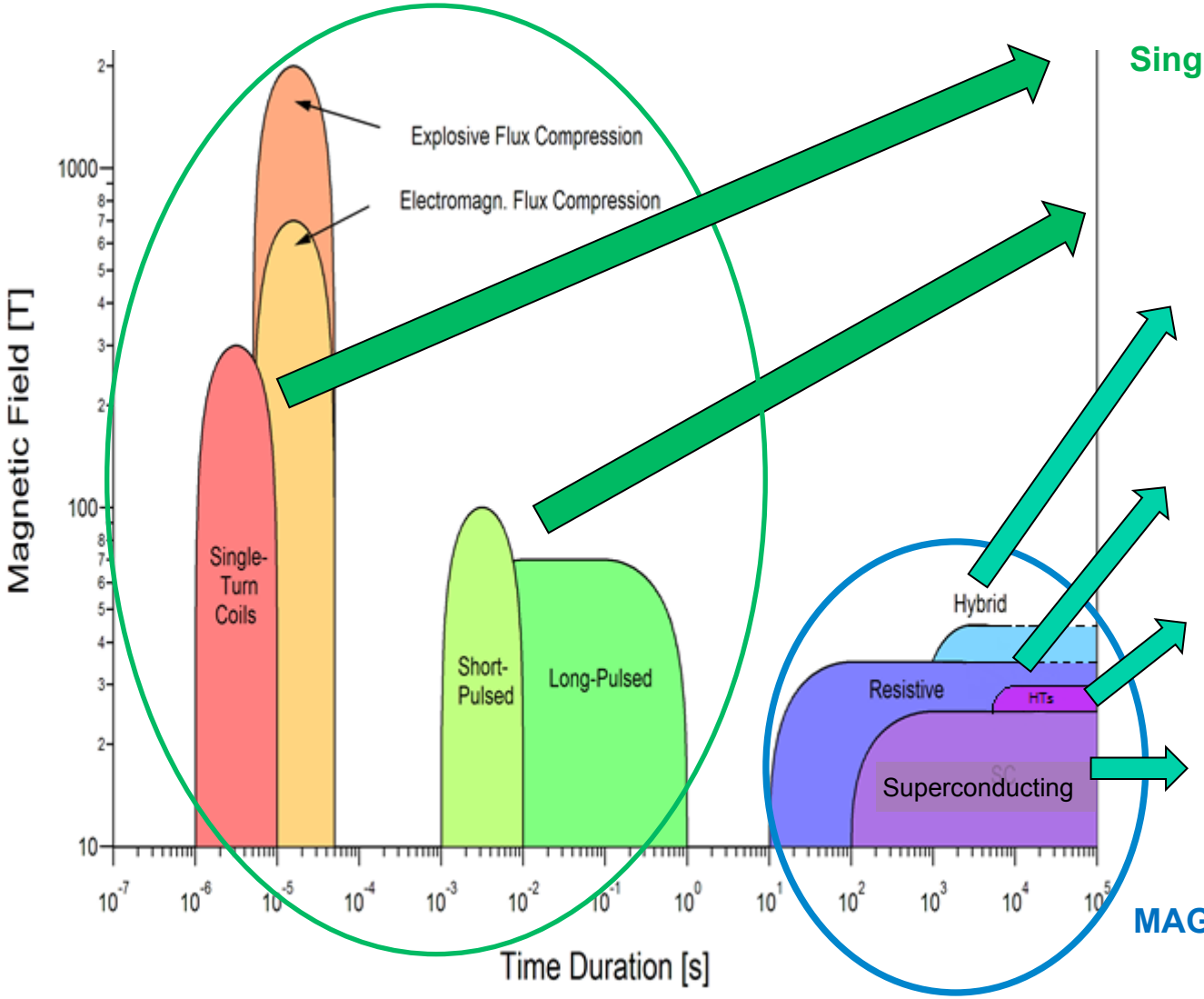
Hybrids

"Runs completely on electricity – generated by a tiny coal-burning power plant."

LNCMI

EMFL
European Magnetic Field Laboratory

PULSED MAGNETIC FIELDS



Single turn coils up to 209 T

Hybrid project 43 T (2021)
Upgrade 45-46 T (2025)
(WR: 45.2 T, 2000 NHMFL)

DC magnets up to 37 T
(WR: 41.4 T, 2017 NHMFL)

LTS + HTS magnets
40 T project *(CPER coupled with GrAHal ?)*
(WR: 32 T, 2017 NHMFL)

LTS magnets: 20 T

STEADY MAGNETIC FIELDS

The Grenoble Hybrid Magnet

Modular Plateform for the production of High Magnetic Field & Flux

- 43 T / 34 mm hybrid magnet 24 MW
  - ► 8.5 + 9 + 25.5 T / sc. + poly-Bitter + poly-helix
- 38 T / 34 mm hybrid magnet 12 MW
  - ► Energy saving !

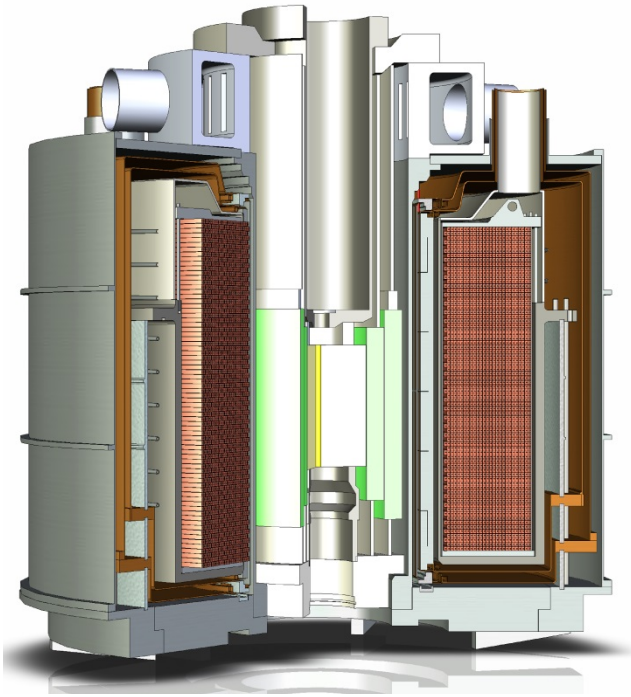
- 27 T / 170 mm hybrid magnet 18 MW
- 17 T / 375 mm hybrid magnet 12 MW
- 9 T / 800 mm sc. magnet alone

High Flux Magnets

Under Study

- Upgrade phase of resistive inserts
  43 T / 34 mm ⟶ 45+ T / 34 mm
- Modular field gradient platform for levitation
- 60 T / 300 ms pulsed field
- *Axion dark-matter haloscope*

PROJET LaSUP Equipex



Hydraulics : 300 l/s
Total stored Energy : 108 MJ ~ 23 kg de TNT

55 t in total incl. 22 t @ 1.8 K

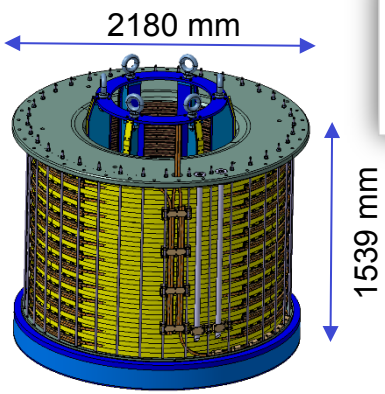
P. Pugnat *et al., IEEE Trans. Appl. Supercond.* **28**, 4300607 (2018)
[Invited MT25]

Hybrid Magnet : cryogenic parts

Superconducting coil

17 tons @ 1,8 K

Delivery: End 2019 (TBC)



BiLFINGER Babcock Noell GmbH

Cryogenic satellite

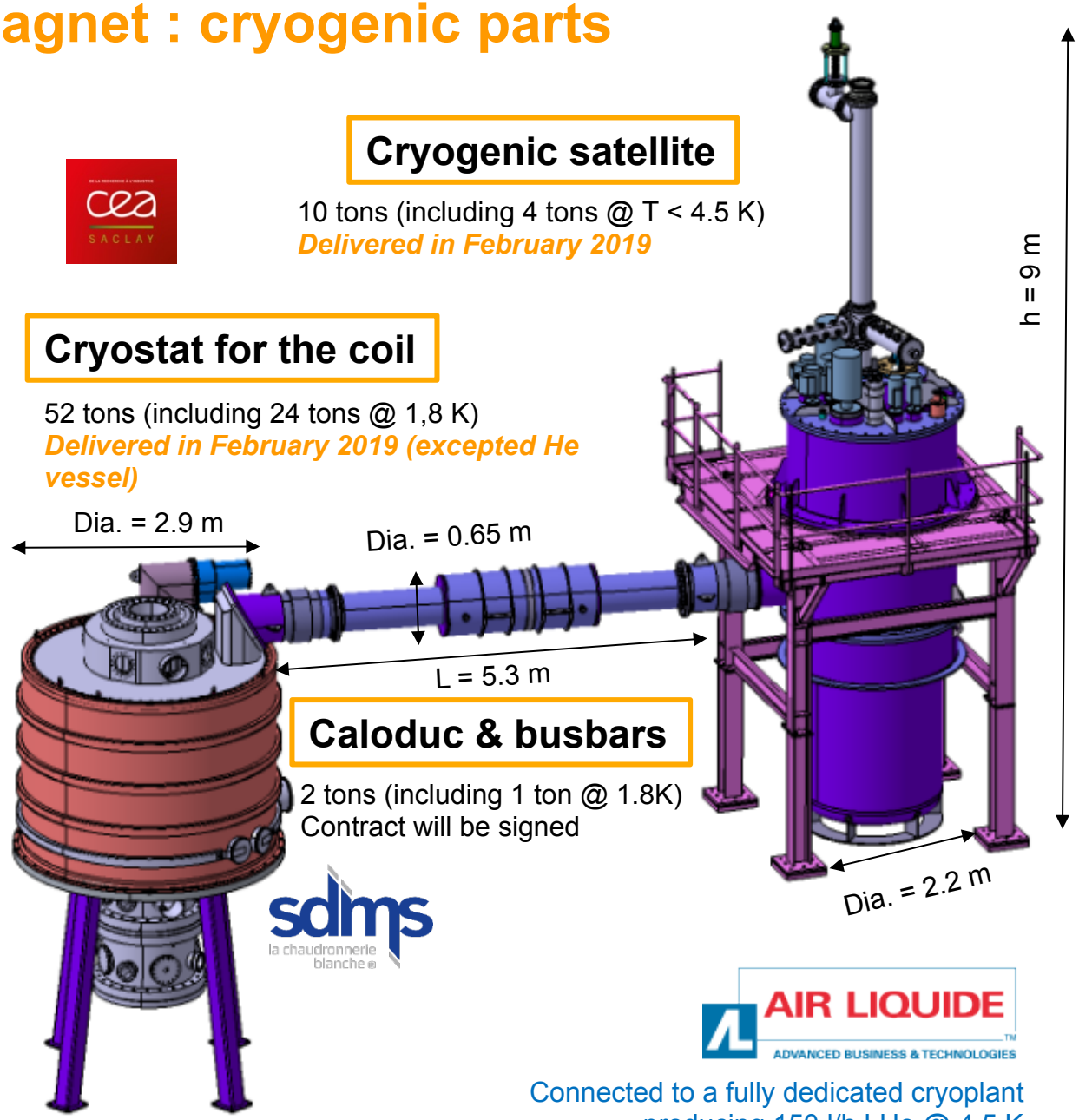
10 tons (including 4 tons @ T < 4.5 K)

Delivered in February 2019

Cryostat for the coil

52 tons (including 24 tons @ 1,8 K)

Delivered in February 2019 (excepted He vessel)



Caloduc & busbars

2 tons (including 1 ton @ 1.8K)

Contract will be signed

sdms la chaudronnerie blanche

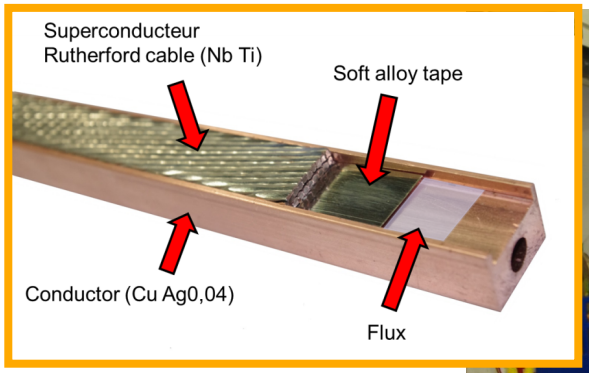
AIR LIQUIDE ADVANCED BUSINESS & TECHNOLOGIES

Connected to a fully dedicated cryoplant producing 150 l/h LHe @ 4.5 K

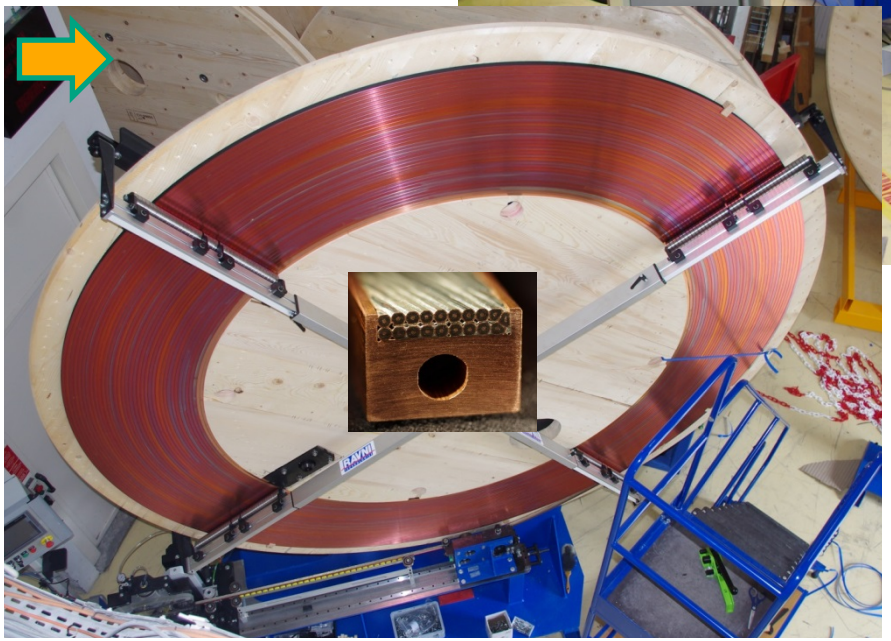
Key Figures

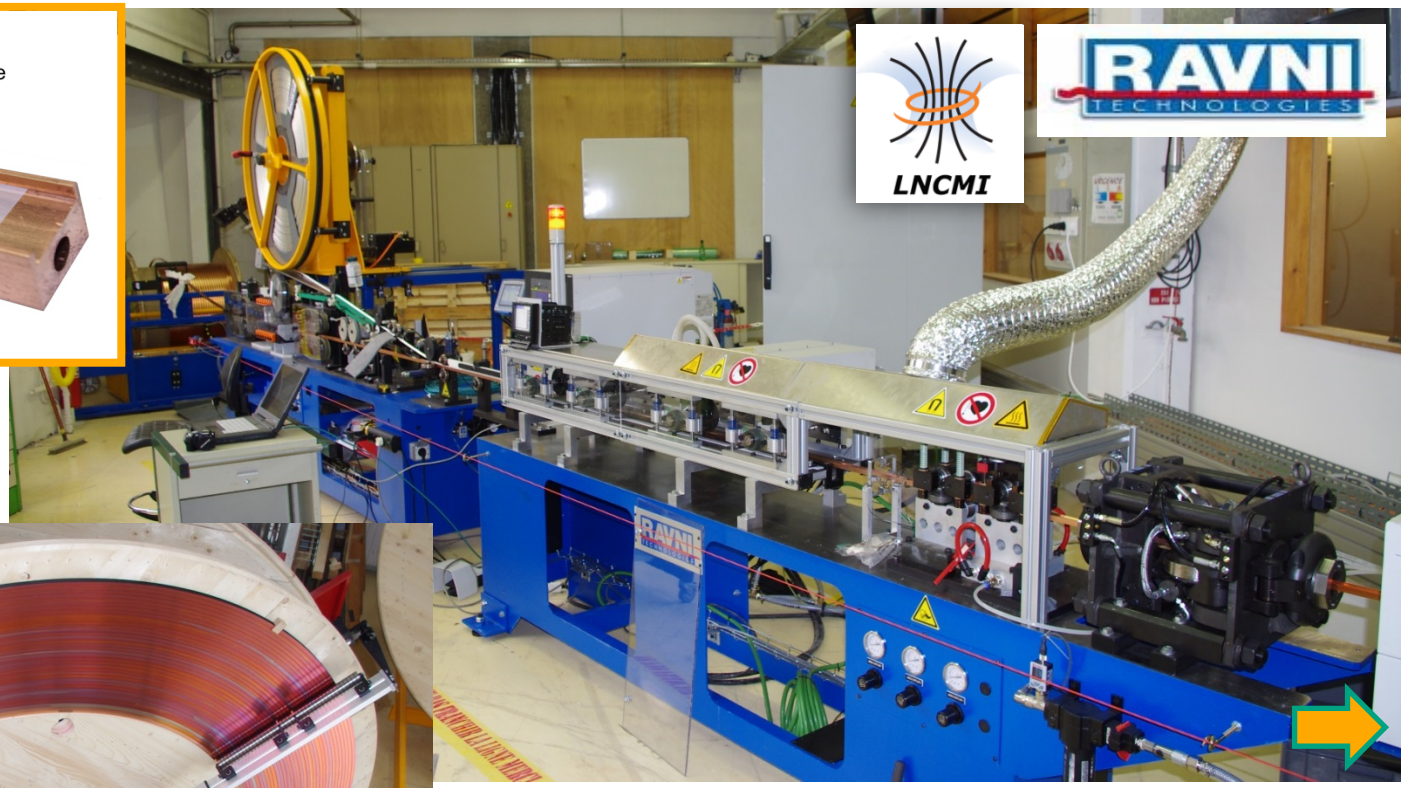
- Collaboration with CEA-Saclay
- 10 years, design & construction
- 15 M€
- Project team
  - . 21 members (LNCMI & CEA)
  - . 70 man.year
- Industrial supports
  - . 14 public contracts (0.1-1.5 M€)

Industrial production line developed, built & installed at LNCMI



Crimping, soft-soldering, calibration & winding in single pancakes





- Innovative developments based on induction heating for the superconducting conductor assembly
- Under discussion to be adapted to other projects (MADMAX dipole, Max Planck Institute)

P. Pugnat, R. Pfister *et al., IEEE Trans. Appl. Supercond.* **28,** 4300705 (2018)
Video: https://indico.cern.ch/event/445667/contributions/2562521/

Grenoble Hybrid Magnet: Commissioning Review for sub-elements

(19-20 March 2019, LNCMI-Grenoble)

Committee Members

K. Brodzinski (CERN), A. Hervé (ex. CERN, now University of Wisconsin), H. Schneider-Muntau (ex. NHMFL, now CS&T), A. Siemko (CERN)

Extract from the committee's first restitution

"The committee has confidence that there will be a good, sturdy and stable superconducting outsert."

Committee members with a part of the project team around the cryogenic satellite

- Ongoing commissioning of the cryogenic satellite
- First operation expected in 2021

In front, outer vacuum chamber mounted on the base plate during the dummy assembly step for vacuum leak tests & in the far back, the upper part of the cryogenic satellite

Summary

- OSQAR-VMB ⇒ VMB @ CERN

ESPP Road Map

- OSQAR-LSW ⇒ JURA

  - *Joint Undertaking* in *Research* on ALPs/Axion, *i.e.* OSQAR + ALPS @ CERN

- OSQAR-CHASE ⇒ Upgrade (?)

  - *New exclusion limit will be published for Chameleon search*

- **Unique opportunity with GrAHal** to explore the Low Energy Frontier & **QCD Axion**

  - Grenoble Hybrid Magnet & Future

    . *43 T / 34 mm, 27 T/ 170 mm, 9 T / 800 mm, operational in 2021*

    . *Upgrade to 45+T / 34 mm, (24 MW → 30 MW from UpAlim)*

  - GrAHal & international collaborations

    . *IBS/CAPP (Korea Advanced Institute, KAIST) & CERN*

Outlook

Much longer term perspectives, i.e. 2-generation …

Conceptual Design Optimization of a 60 T Hybrid Magnet

P. Pugnat & Hans J. Schneider-Muntau

(submitted for publication)

MT 26 International Conference on Magnet Technology
Vancouver, Canada | 2019

60 T / 34 mm dia.
(R-15MW + HTS + LTS, 75/40 MEUR)

But also / including

40 T / 400 mm dia.
(HTS ⚠ + LTS)

&

20 T / 1100 mm dia.
(LTS)

ECFA
European Committee for Future Accelerators

http://ecfa.web.cern.ch/
https://arxiv.org/pdf/1902.00260.pdf

For the ESPP Road Map

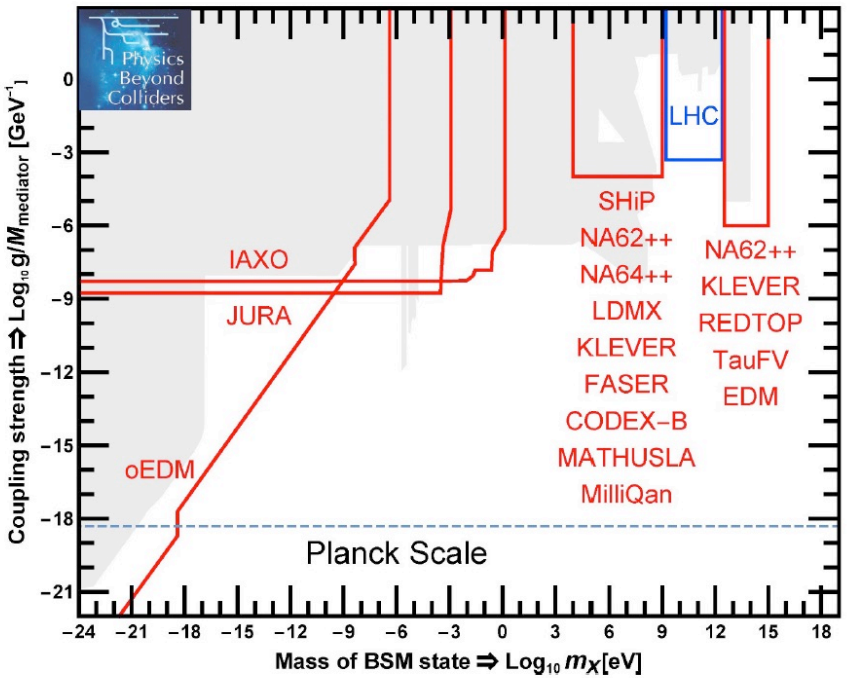


Figure: schematic overview of the BSM landscape, based on a selection of specific models, with a rough outline of the areas targeted by the experiments considered in the PBC sensitivity studies.