20th Rencontres du Vietnam

August 4–10

ICISE

The Axion Quest 2024

High Magnetic Fields to Probe the sub-eV range of Particle/Astroparticle Physics

From OSQAR experiments up to new Projects & Perspectives at CERN & CNRS-Grenoble with GrAHal

P. Pugnat, LNCMI-Grenoble/CNRS, EMFL

Thursday 8 August 2024

Outline

- Introduction
  - Weakly Interacting Slim Particles (WISPs)* as a possible component(s) of the Cold Dark Matter (CDM)
  - QCD Axion

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

- OSQAR (LSW/VMB/CHASE)
  - LSW: Light Shining through Wall
    - . Present reference results for Axion and Axion-Like-Particles (ALPs) searches
    - . Future of LSW experiments (ALPSII, OSQAR+/BabyJURA, JURA…)
  - VMB: Vacuum Magnetic Birefringence
  - CHASE: Chameleon Search Experiment

- A New Proposal: The Grenoble Axion Haloscope (GrAHal)
  - Probing QCD Axion Dark Matter with the Grenoble Hybrid Magnet under commissioning phase at LNCMI-Grenoble up to 43 T

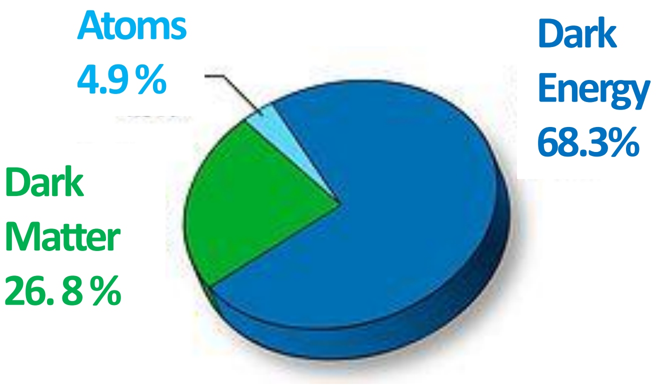
Particle Physics beyond the Standard Model – Oversimplified Picture

Among the Biggest Questions in Science…

Mass

WIMPs (SUSY,…)
> 100 GeV

SIMPs (> 25 GeV, 0.1 mbarn)



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

Λ-CDM
Standard Model of Cosmology

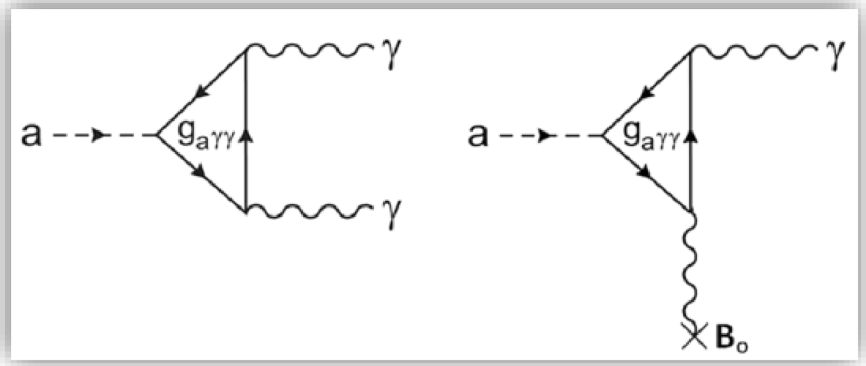
WISPs (ALPs,…)
Slim/Sub-eV

SISPs (?)
Strongly interacting & Slim

Other interactions

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…

Optical Search for QED vacuum magnetic birefringence, Axion & photon Regeneration

OSQAR-LSW, OSQAR-VMB, OSQAR-CHASE

CERN, Geneva, Switzerland
G. Deferne, **P. Pugnat (spokesperson, now at LNCMI-CNRS), A. Siemko**

Charles University, Faculty of Mathematics & Physics, Prague, Czech Republic
M. Finger Jr., M. Finger, M. Slunecka

Czech Technical University, Faculty of Mechanical Engineering, Prague
L. Flekova, J. Hošek, K. Macuchova, M. Virius, J. Zicha

ISI, ASCR, Brno, Czech Republic
A. Srnka

IMEP/LAHC - INPG, 38016 Grenoble, France
L. Duvillaret, G. Vitrant, J.M. Duchamp

IN, CNRS – UGA & INPG, BP 166, 38042 Grenoble, France
R. Ballou

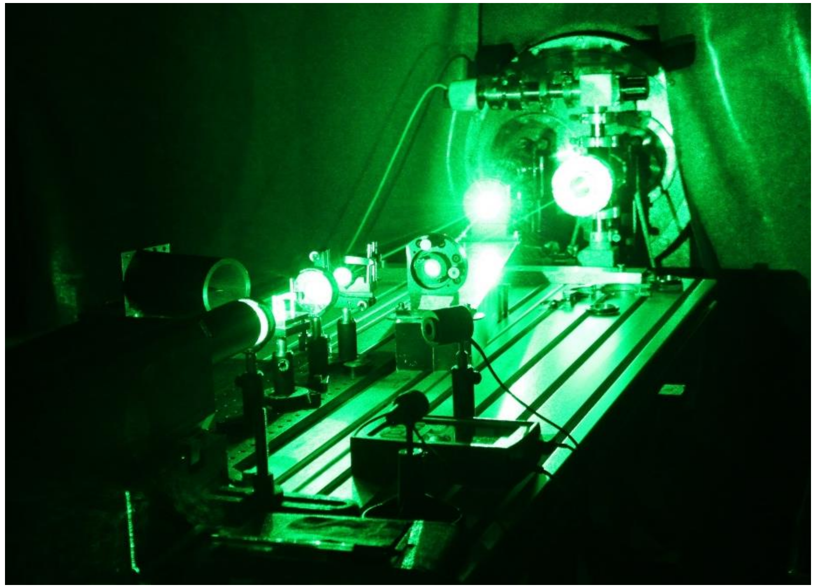
Johannes Gutenberg University of Mainz, Germany
M. Schott, C. Weinsheimer

LASIM , UCB Lyon1 & CNRS, 69622 Villeurbanne, France
J. Morville

LIPhy, UGA & CNRS, 38402 Saint-Martin d'Hères, France
R. Jost, S. Kassi, D. Romanini

Technical Uuniversity of Liberec, Czech Republic
M. Šulc, Š. Kunc, R.Puliček, F.Švec

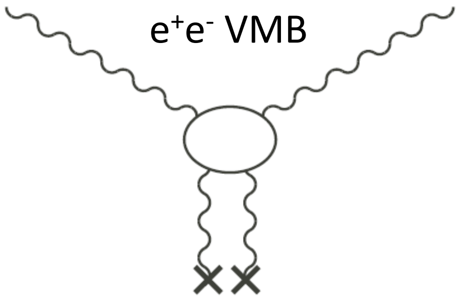
Warsaw University, Physics Department, Poland
A. Hryczuk, K. A. Meissner (co-spokesperson)



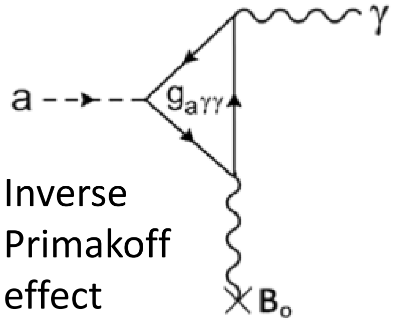
► *Started officially in 2005*
► *Up to 28 Members from 12 Institutes (CERN, Cz, Fr & Po) at its apogee but now in strong decline…*

Scientific Motivations

- **To measure for the 1st time the QED Vacuum Magnetic Birefringence (VMB)** *(Heisenberg & Euler, Weisskopf, 1936) i.e. the vacuum magnetic "anomaly" of the refraction index "n-1"* ~ 10^{-22} in 9.5 T



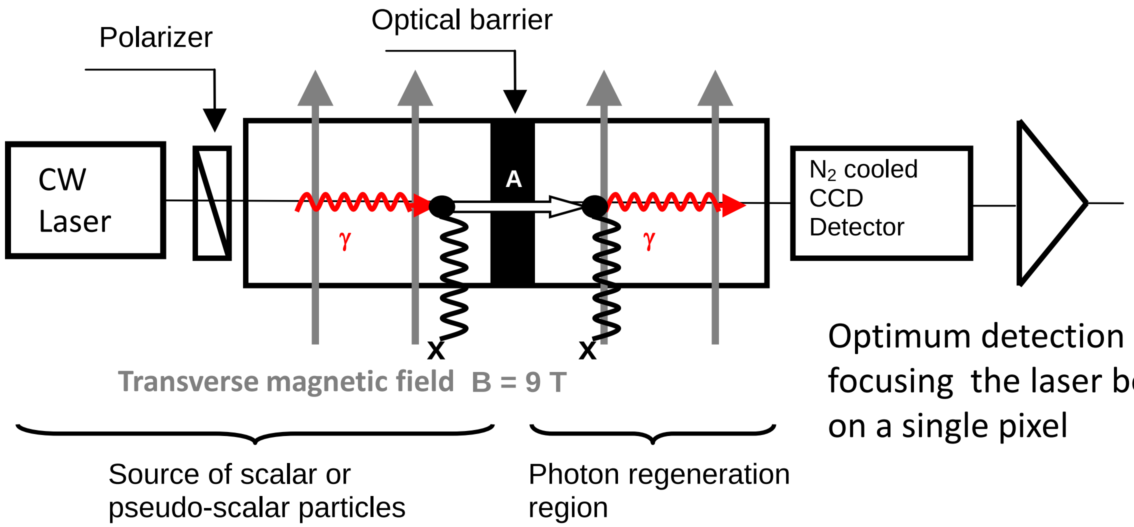
- **To explore the Physics at the Low Energy Frontier** (sub-eV)
  - **Axion** & **Axion Like Particles** *i.e. solution to the strong CP problem (Weinberg, Wilczek, 1978)* & ***Non-SUSY Dark Matter candidates*** *(Abbott & Sikivie; Preskill, Wise & Wilczek, 1983)*
  - **Paraphotons** *(Georgi, Glashow & Ginsparg, 1983)*, **Milli-charged Fermions**
  - **Chameleons** (*Khoury & Weltman, 2004*) ***Dark Energy candidate***
  - ***The Unknown*** **… SERENDIPITY, "Why not an abundance of ultralight particles ?"**



Inverse Primakoff effect

- **A complementary way of doing Particle Physics** based on the Laser beam interaction with magnetic fields at the low energy frontier.

Photon Regeneration
Light Shinning Through Wall (LSW) Principle



Optimum detection by focusing the laser beam on a single pixel

P. Sikivie, PRL 51 (1983) 11415
A.A. Anselm, Sov. J. Nucl. Phys. 42 (1985) 936
K. van Bibber *et al.* PRL 59 (1987) 759

$$\frac{dN_\gamma}{dt} = \frac{P}{\omega}\eta\, P_{\gamma\leftrightarrow A}^{\;2}$$

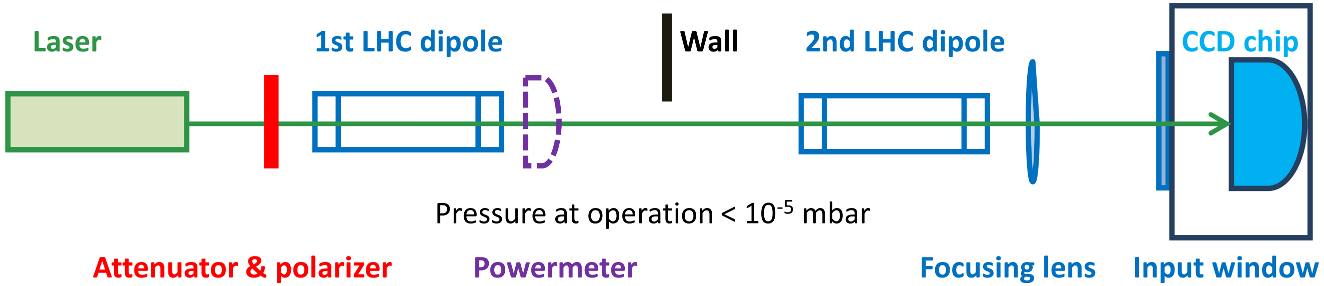
$$\text{with } P_{\gamma\leftrightarrow A} = \frac{1}{4\beta_A\sqrt{\varepsilon}}(g_{A\gamma\gamma}BL)^2\left(\frac{2}{qL}\sin\frac{qL}{2}\right)^2$$

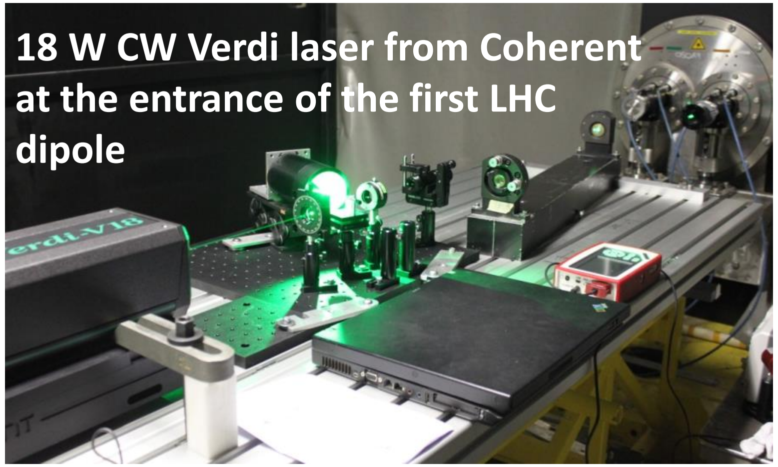
$$\text{and } \; q = \left|k_\gamma - k_A\right| = \frac{m_A^2}{2\omega} \text{ in vacuum}$$

Maximum of $P_{\gamma\leftrightarrow A}$ for $qL \to 0$

Exclusion limit for	$g_{A\gamma\gamma}$
B (T)	B^{-1}
Magnetic Length (m)	L^{-1}
Optical power (W)	$P^{-1/4}$
Detector efficiency	$\eta^{-1/4}$
Detection threshold (γ/s)	$dN_\gamma/dt^{\,1/4}$
Time integration	$\Delta t^{-1/8}$

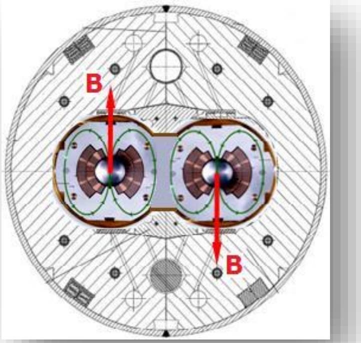
LSW – Experimental





18 W CW Verdi laser from Coherent at the entrance of the first LHC dipole

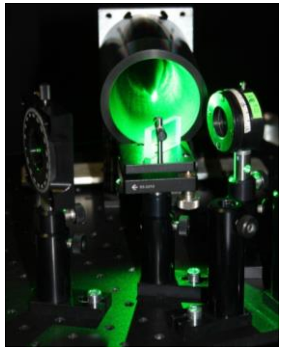
2-in-1 LHC dipole providing 9 T over 14,3 m

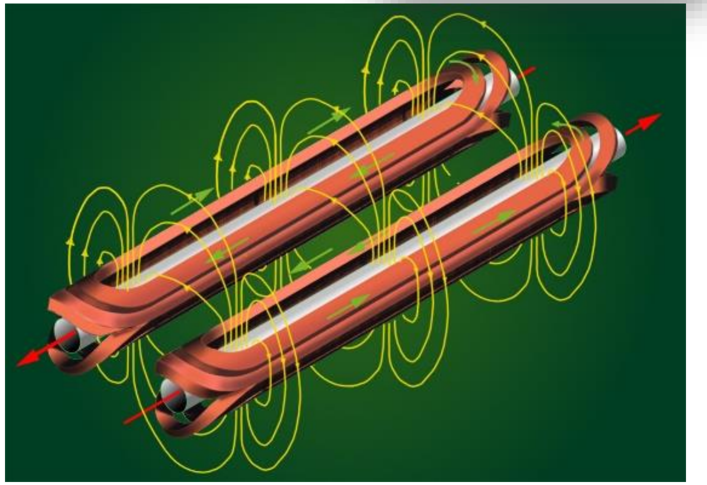


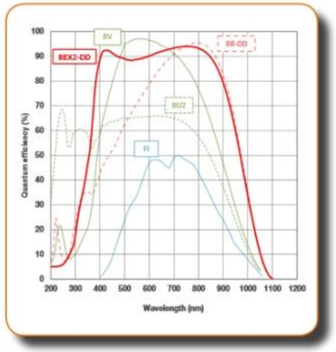
QE = 95 % at 488-514 nm; Dark current < 0.00047 e/Pixel/s @ -100° C; Readout noise: 2.5 e- rms/pixel @50kHz

ANDOR
an Oxford Instruments company

Variable beam splitter attenuator with its absorber allowing a reduction of 10^{-3} of the beam power during alignment operations and checks







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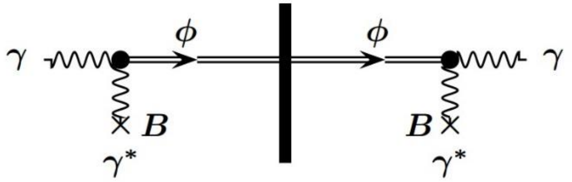
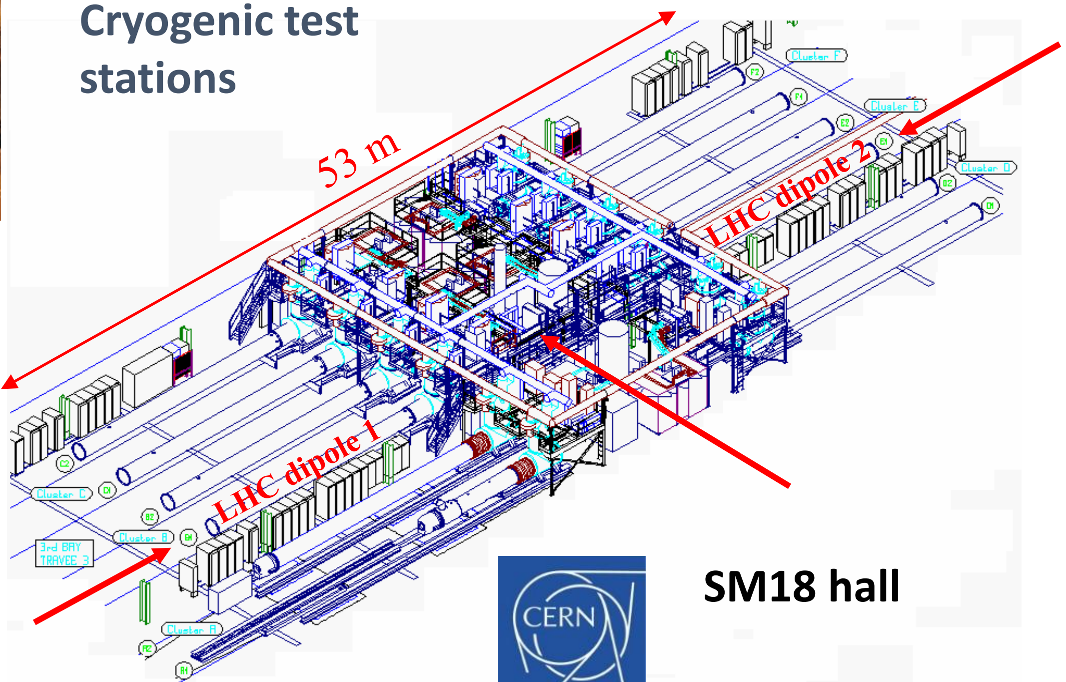
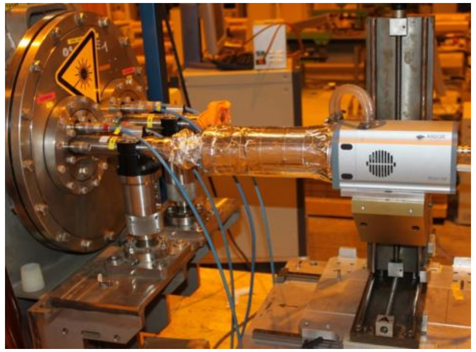
LSW

► *Operation in 2010-14 with 2 aligned 9 T spare LHC dipoles*

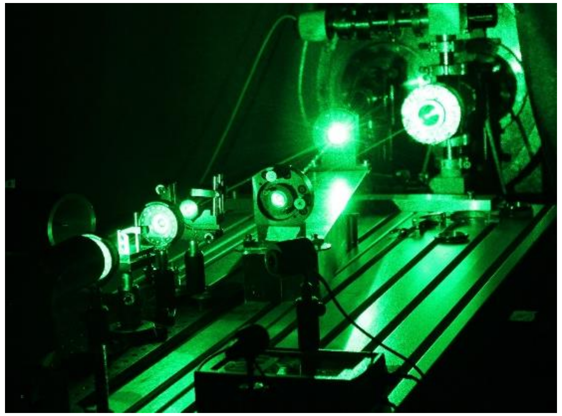


Cryogenic test stations





Looking for "an invisible light shining through a wall"
K. van Bibber *et al.* PRL **59** (1987) 759



SM18 hall

Regular check between data taking of the beam alignement with the CCD ▶

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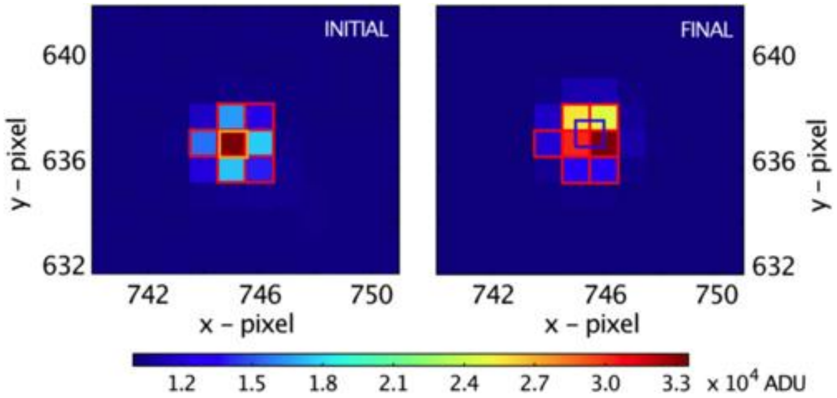
No regenerated Photon detected

World leading limits for **model independent** Axion/ALPs searches since 2015



Total number of runs valid for analyses: 60 beam positions for each setup
- Scalar search: **180 hours, 60 runs 2 x 90 minutes**
- Pseudo-scalar search: **180 hours, 59 runs 2 x 90 minutes**

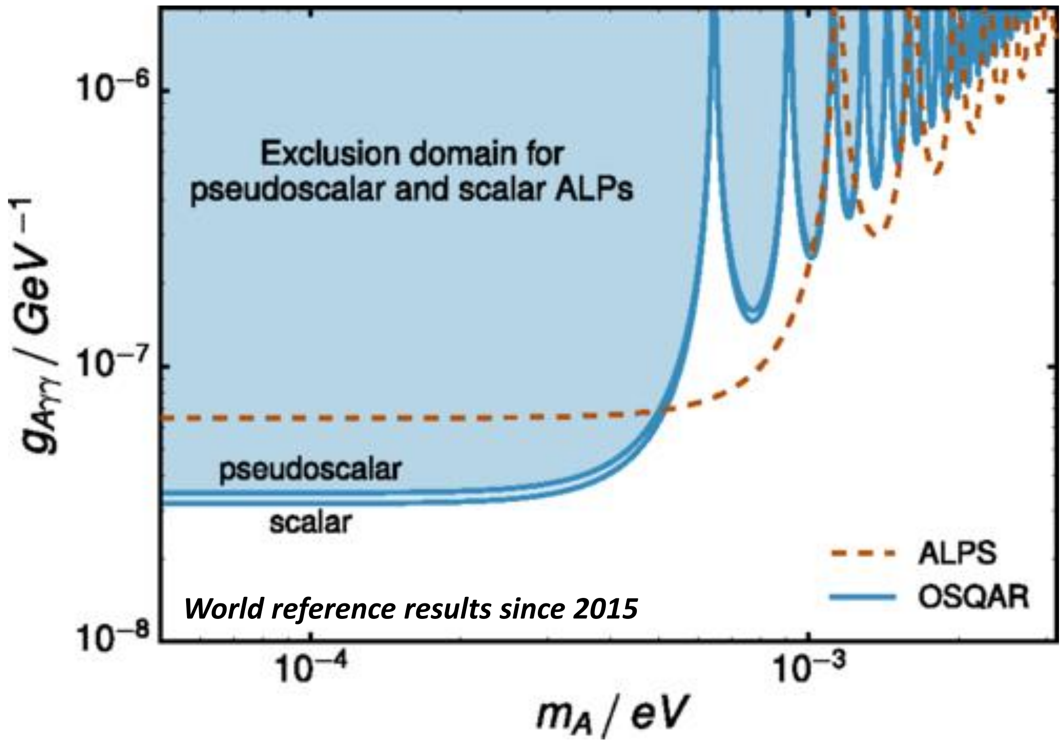
Bayesian analysis of the recorded counts after the cleaning of the cosmic contamination

Likelihood model

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

For *model independent* ALPs searches with $m_A < 2 \cdot 10^{-4}$eV **@ 95% CL**

- Pseudo-scalar particules (axion), $\mathbf{E}_\gamma$ // **B**
  - . *sensitivity of 0.64 mHz*
  - . ***$g_{A\gamma\gamma} < 3.5 \cdot 10^{-8}$ GeV^{-1}***
- Scalar ones, $\mathbf{E}_\gamma \perp \mathbf{B}$
  - . *sensitivity of 0.45 mHz*
  - . ***$g_{A\gamma\gamma} < 3.2 \cdot 10^{-8}$ GeV^{-1}***



Detection sensitivity in the visible of 10^{-22} W

R. Ballou, P. Pugnat et al. (OSQAR), Phys. Rev. D ***92****, 092002 (2015), arXiv:1506.08082*

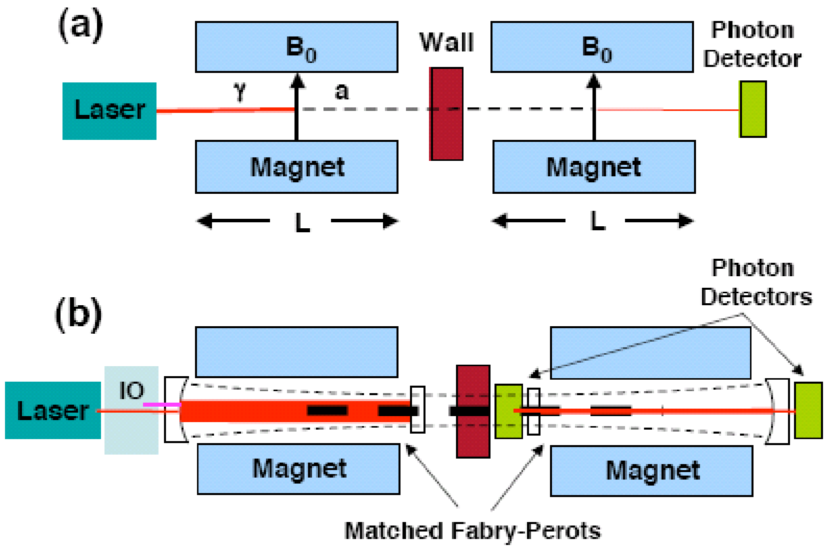
OSQAR

Perspectives (ALPSII, OSQAR+/BabyJURA, JURA)

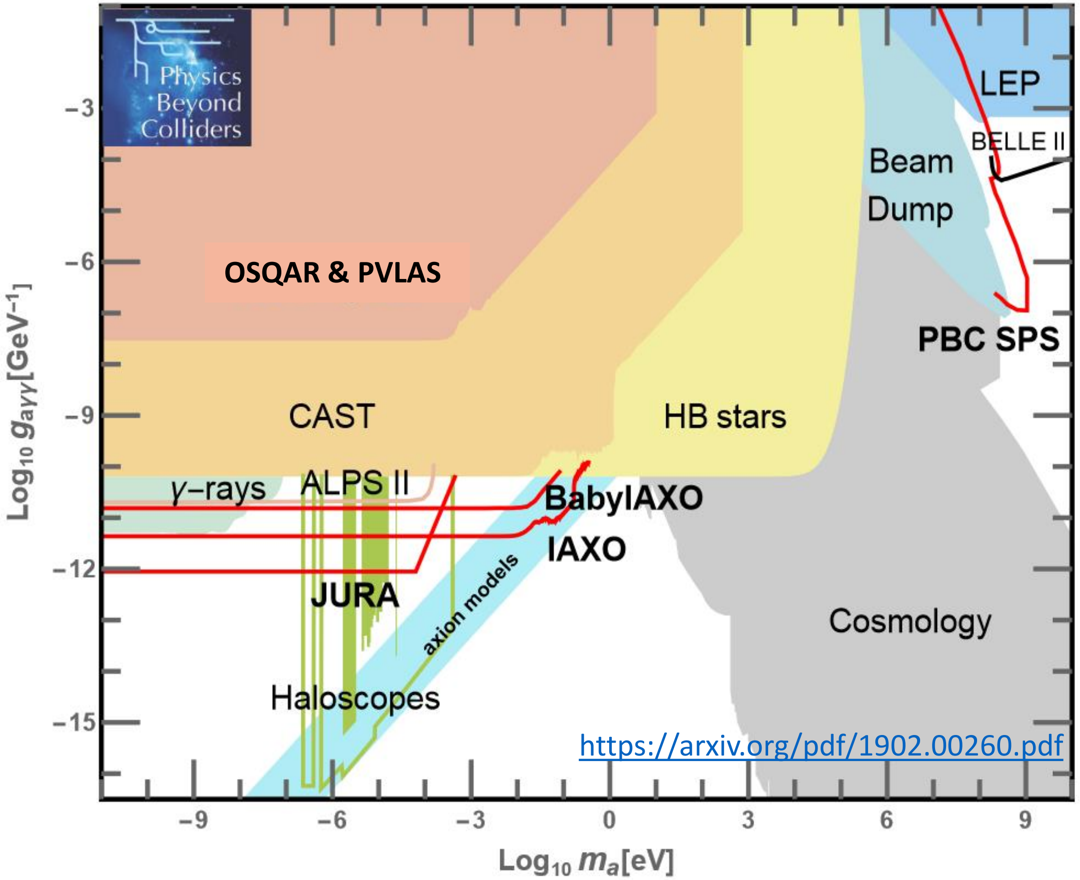
Phys. Rev. Lett. **98**, 172002 (2007)

Resonantly Enhanced Axion-Photon Regeneration

P. Sikivie,[a,b] D.B. Tanner,[a] and Karl van Bibber[c]
[a] *Department of Physics, University of Florida, Gainesville, FL 32611, USA*
[b] *Theoretical Physics Division, CERN, CH-1211 Genève 23, Switzerland*
[c] *Lawrence Livermore National Laboratory, Livermore, CA 94550, USA*



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



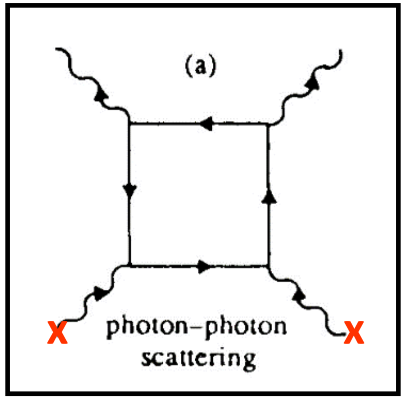
► ***ALPSII*** *in operation at DESY with (12 + 12) Hera dipoles of 5 T , i.e. 240 m long experiment*

► ***OSQAR+/BabyJURA*** *under discussions within the CERN/PBC in the framework of JURA with for example (4 + 4) LHC Dipoles, i.e. 150 m long as a first step (NB: At CERN more than 30 spare 9 T LHC dipoles of 15 m long for* ***OSQAR++/JURA****…)*

Toward a meta-collaboration @ Human scale

OSQAR

O
S
Q
P A
VMB@CERN
L A
Q&A R
S DIFF-U



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
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[3]School of Physics and Astronomy, Cardiff University, Cardiff, UK
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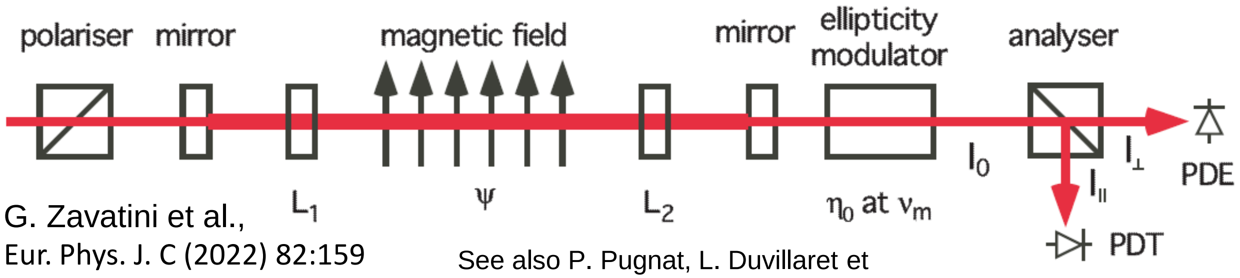
[11]LNCMI, EMFL, CNRS and Université Grenoble Alpes, Grenoble, France
[12]CERN, Genève, Switzerland
[13]Dip. di Fisica e Scienze della Terra, Università di Ferrara and INFN, Sez. di Ferrara, Ferrara (FE), Italy

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

Target:** With a single LHC dipole at 9.5 T, VMB detected with SNR = 1 in less than 1 day of integration **(not yet confirmed).



G. Zavatini et al., Eur. Phys. J. C (2022) 82:159

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

More R&D require to reduce the systematics

Introduction to Chameleons

- Chameleon: Hypothetical scalar particle with a variable effective mass, which is an increasing function of the ambient energy density *[J. Khoury and A. Weltman, Phys. Rev. D 69, 044026 (2004)]*.

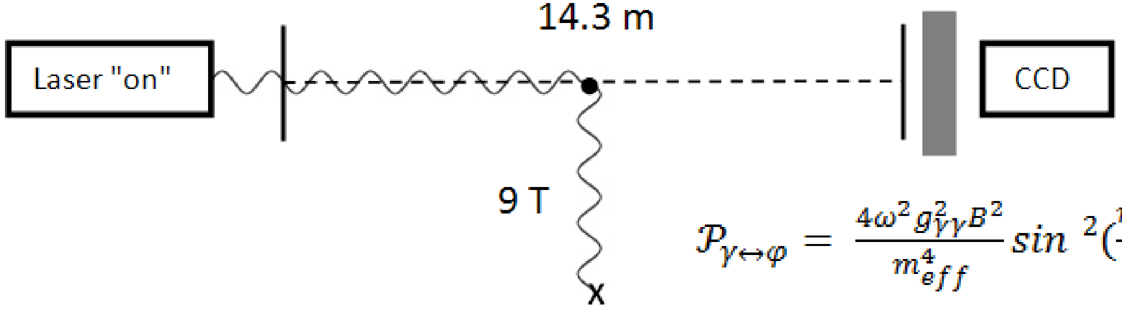
- New kind of particle providing **a phenomenological explanation of dark energy** as a scalar field evolving in an effective potential, the minimum of which depends on the local matter density in such a way that the experimental constraints of 5th force and violation of equivalence principle are relaxed.

- Based on the coupling to photons, chameleons can manifest through an afterglow signal or a **magneto-phosphorescence of the quantum vacuum**, *i.e.* a remaining luminescence after the lighting is switched off.

CHASE (Chameleon Afterglow Search Experiment)

Phase 1: Filling the “jar” with chameleons produced from the interaction of real photons with virtual ones (Primakoff effect)

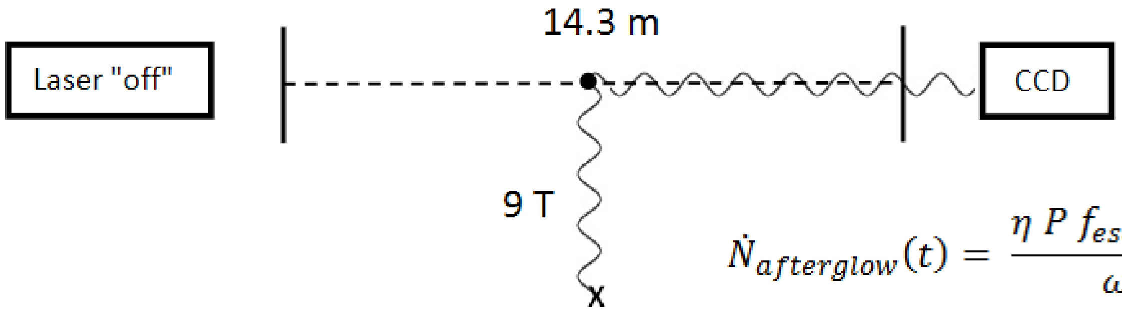
M. Ahlers et al., Phys. Rev. D 77, 015018 (2008)
H. Gies, D. F. Mota, and D. J. Shaw, Phys. Rev. D 77,025016 (2008)



$$\mathcal{P}_{\gamma\leftrightarrow\varphi} = \frac{4\omega^2 g_{\gamma\gamma}^2 B^2}{m_{eff}^4} sin^2(\frac{m_{eff}^2 L}{4\omega})$$

G. Raffelt and L. Stodolsky. Phys. Rev. D ***37****, 1237–1249 (1988)*

Phase 2: Emptying the “jar” and detection of “afterglow” regenerated photons (inverse Primakoff effect)

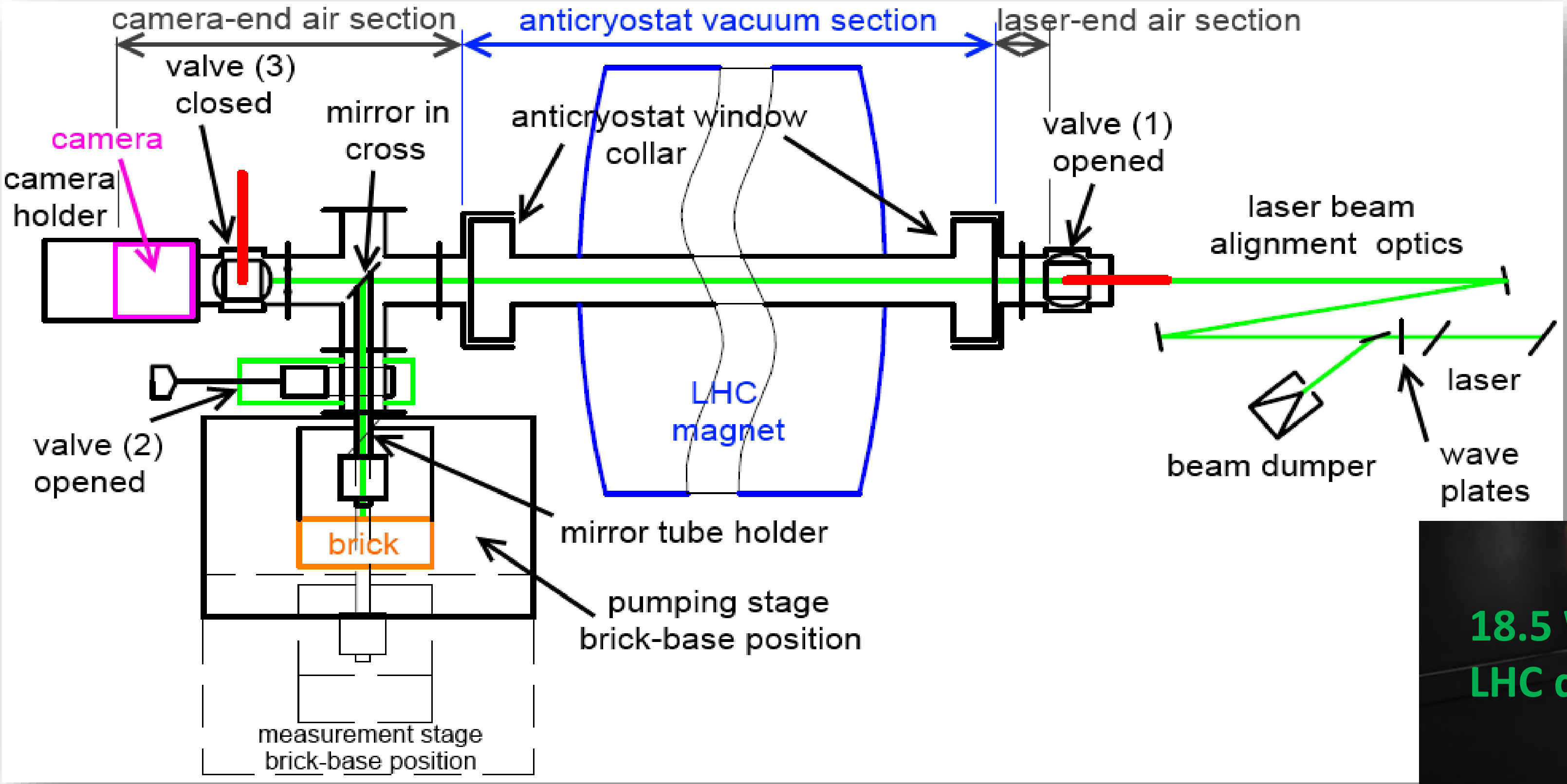


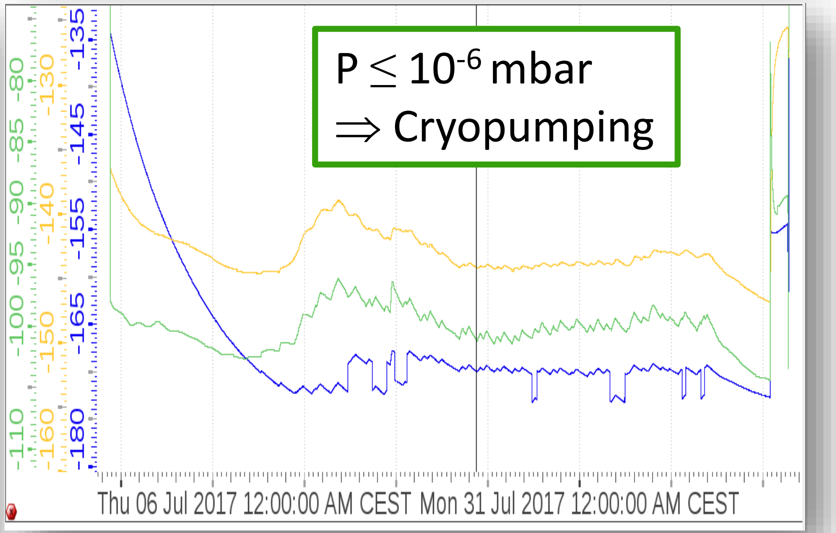
$$\dot{N}_{afterglow}(t) = \frac{\eta\, P\, f_{esc}\, f_{vol}\, \mathcal{P}_{\gamma\leftrightarrow\varphi}^{\ 2}\, c}{\omega\, \Gamma\, L_{total}}(1 - e^{-\Gamma\Delta t})e^{-\Gamma t}$$

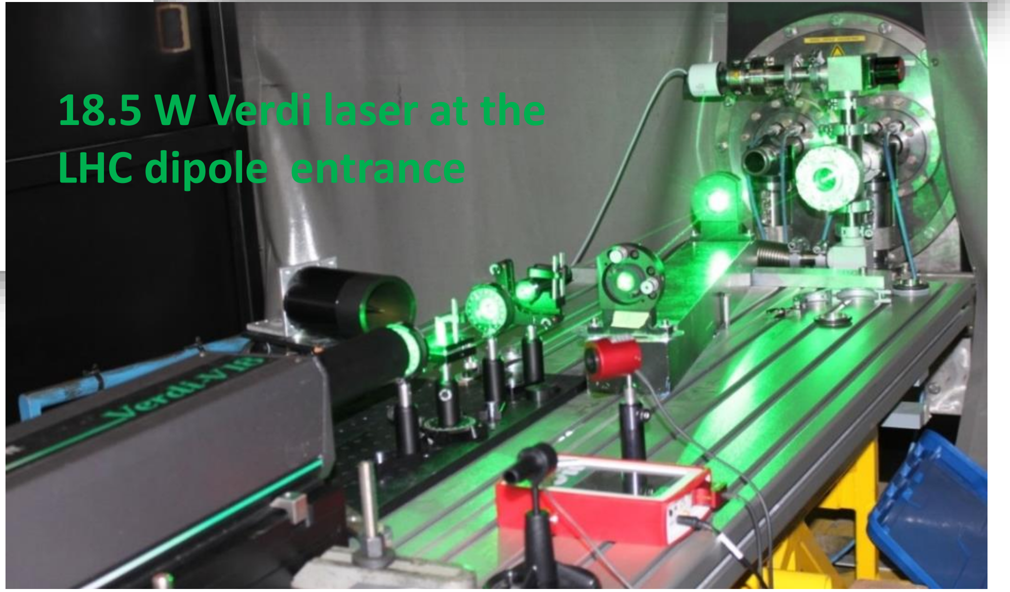
A.S. Chou et al., Phys. Rev. Lett. **102** 030402 (2009)

http://cds.cern.ch/record/2001850/files/SPSC-P-331-ADD-1.pdf

Successful Experimental Run in 2017







	Phase 1: Chameleon filling	Phase 2: Photon Detection
Valve 1	Open	Close
Valve 2	Open	Close
Valve 3	Close	Open

- Typical durations of phases 1&2: ¼ -11 h
- Measured switching time between phases 1&2 : 6-20 s

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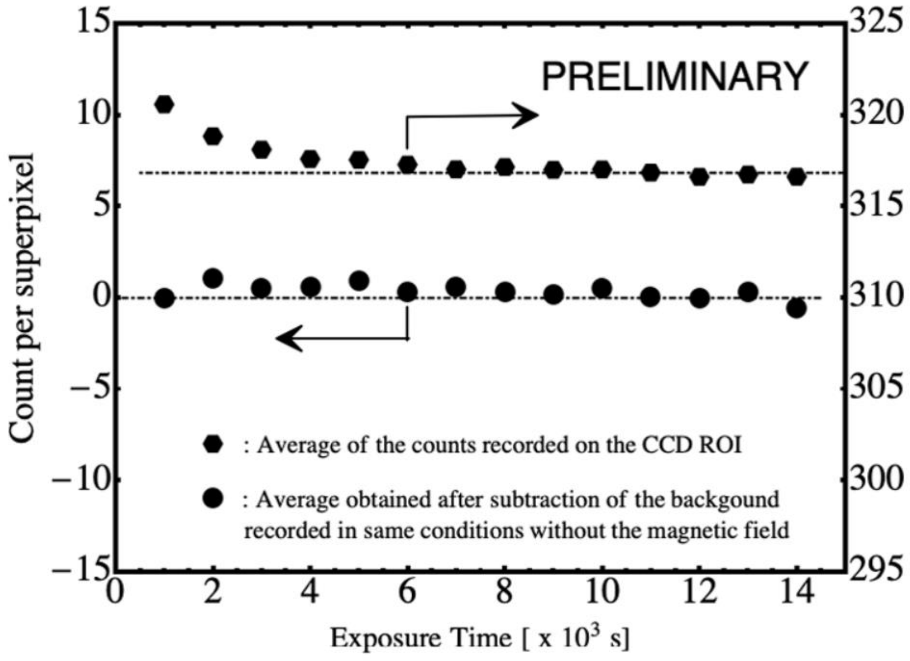
2017 Raw Data

Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment
Volume 936, 21 August 2019, Pages 187-188

https://hal.ird.fr/INPG/hal-01991788 https://doi.org/10.1016/j.nima.2018.11.065

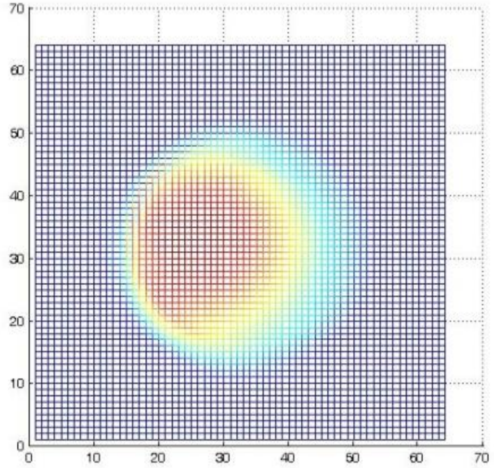
OSQAR chameleon afterglow search experiment

M. Sulc [a], P. Pugnat [b], R. Ballou [c], G. Deferne [d], J. Hosek [e], S. Kunc [a], A. Siemko [d]



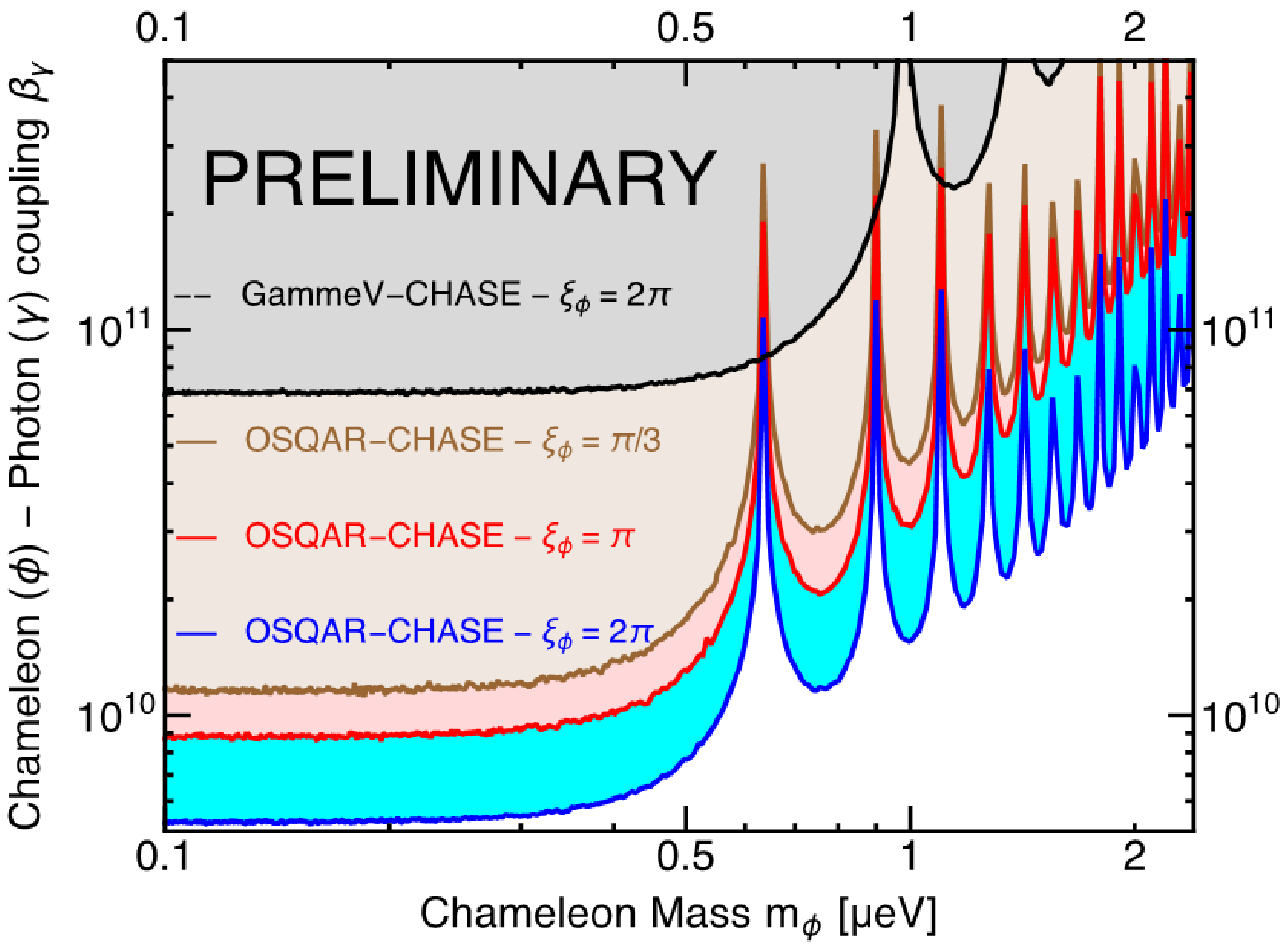
OSQAR-CHASE 2017 experimental run for scalar Chameleon search

Definition of the ROI with a diffuse light source (*CCD sensitive area of 13 x 13 mm^2*) used for data reduction (Detection efficiency & noise characterisation)



- Afterglow signal observed but non-magnetic as it dissapear after background substraction recorded with exactly the same configuration and protocole without magnetic field
- **Negative results also obtained for pseudo-scalar search**
- The quantitative analysis to define exclusion plots is not straighforward and not yet fully completed

Data Analysis - Output (1/2)



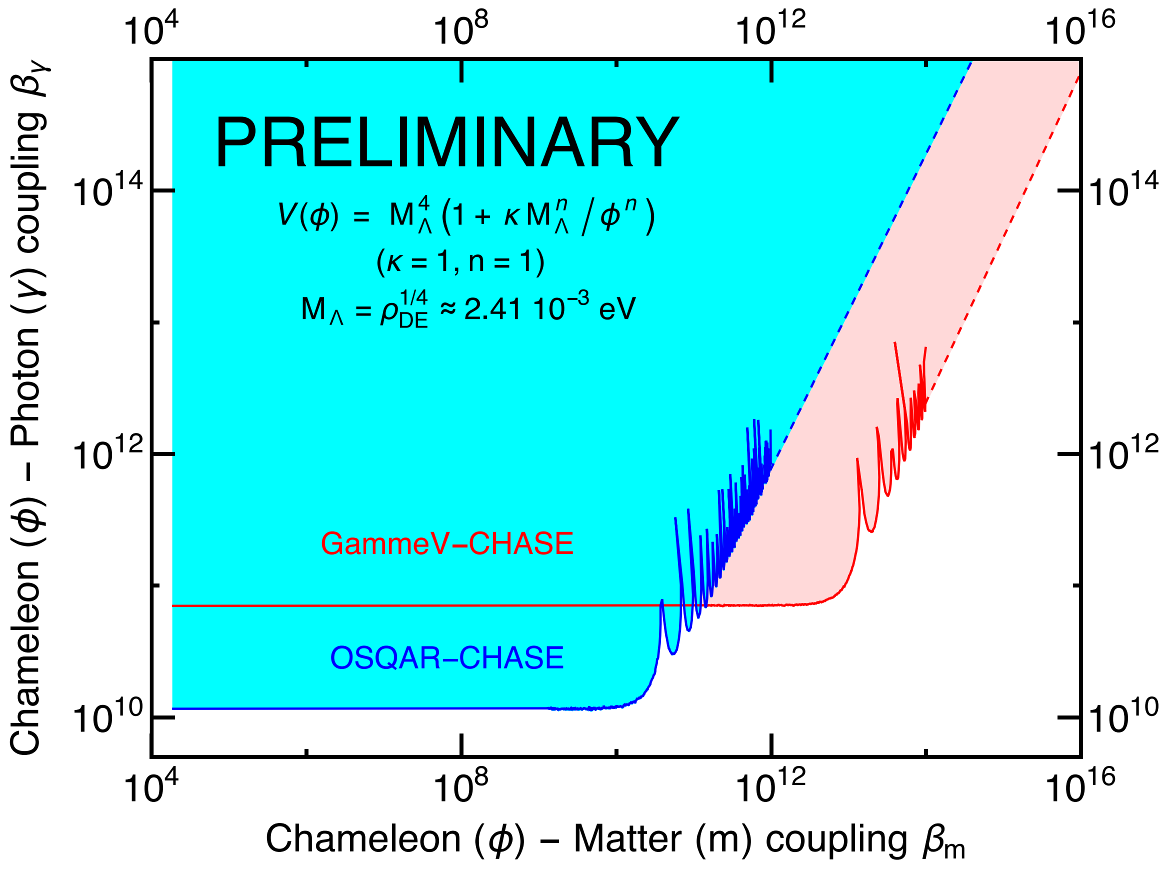
Exclusion limits in the parameter space (**chameleon mass m_ϕ , chameleon-photon coupling β_γ**), deduced from no signal observation and detector noise in the OSQAR-CHASE data collected in summer 2017 with the experimental setup using two focusing optical lenses, for different chameleon phase shifts ξ_ϕ at each bouncing on the walls.

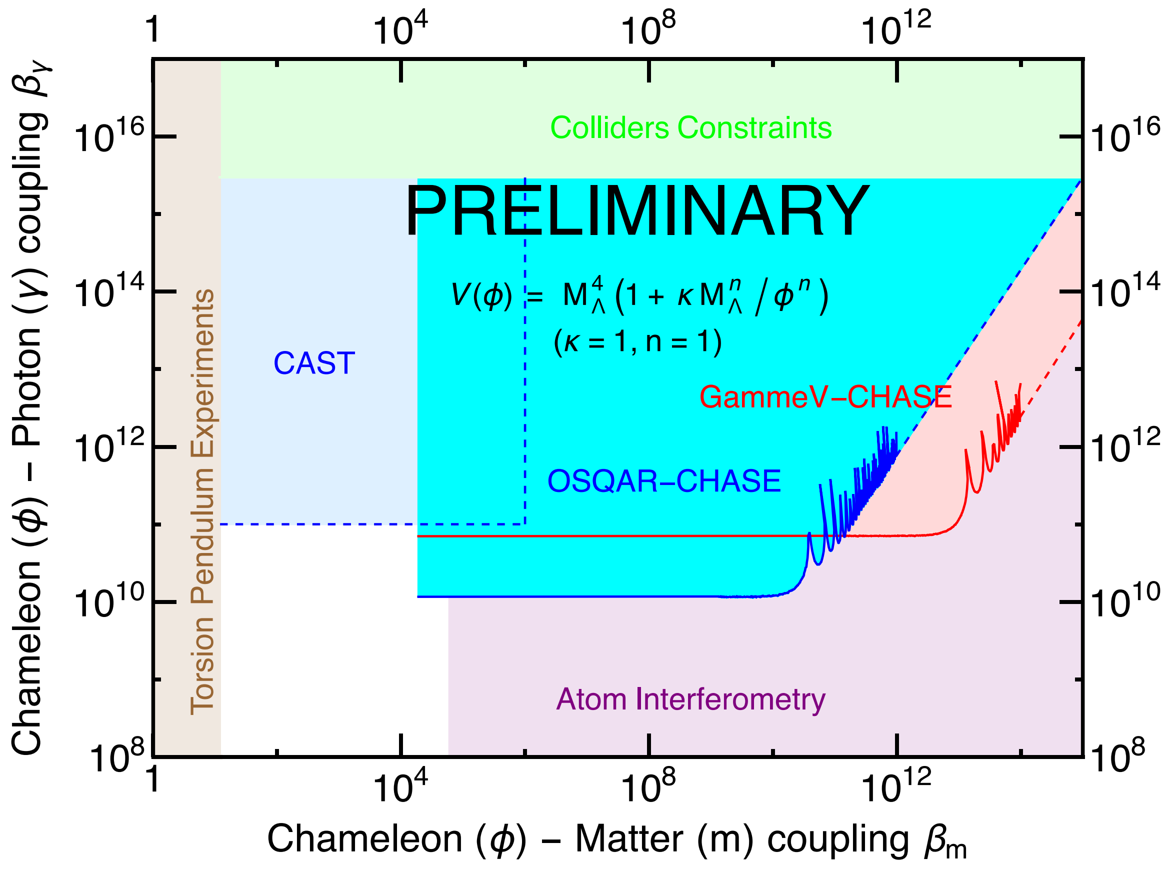
These shifts depend on the chameleon potential, more precisely $\xi_\phi = n\pi/(n-2)$ for $V = g\ \phi^n$, $\xi_\phi = n\pi/(n+2)$ for $V = g\ \phi^{-n}$ and $\xi_\phi = \pi$ for $V = M_\Lambda^4[1 + e^{-\kappa\phi/M_\Lambda}]$.

Analysis performed by R. Ballou
IN-CNRS Grenoble

Data Analysis - output (2/2)

Focus on chameleon – photon vs. chameleon – matter coupling for the inverse power law chameleon dynamic potential





Analysis will be completed with 3D modelling & Bayesian or matched filtering statistics approach to further improve exclusion limits (to be published).

GrAHal

Grenoble Axion Haloscopes

NÉEL institut

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P. Perrier
A. Talarmin
J. Vessaire

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Théorie

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

Visit of Olympie during 2nd Patras Workshop 2006 in Greece

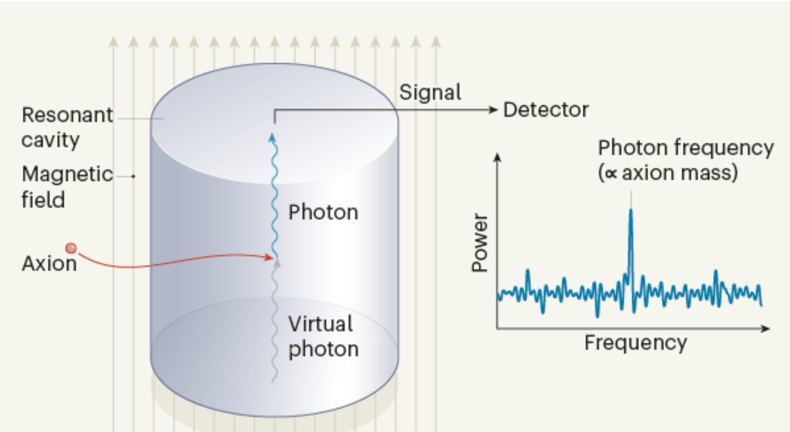
Axion electrodynamics

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

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

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

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



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

European Magnetic Field Laboratory — LNCMI

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

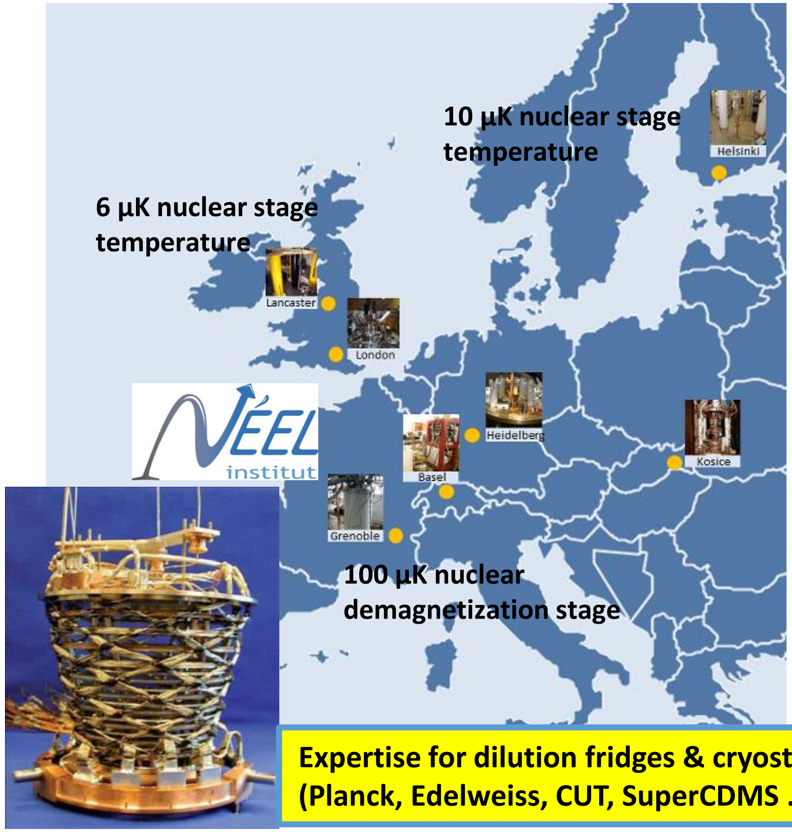
Nijmegen/**LNCMI-Grenoble**, DC up to 38/36 T, Projects 45/43+ T

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

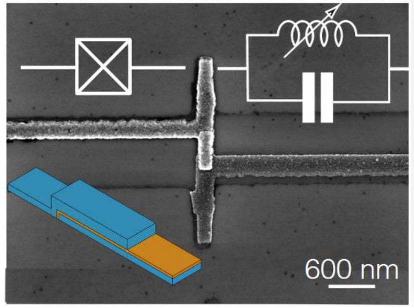


Expertise for dilution fridges & cryostats (Planck, Edelweiss, CUT, SuperCDMS …)

NÉEL institut

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

JPA Achievements



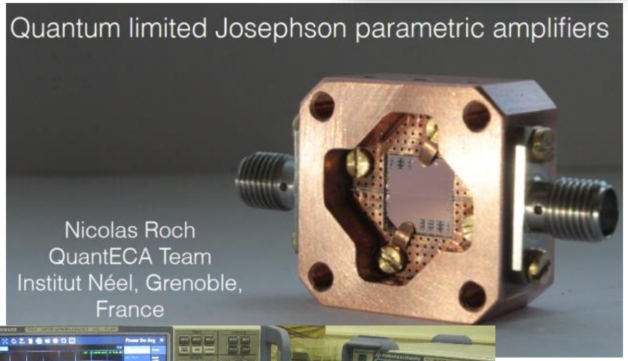
$1\text{ GHz} < f_o < 10\text{ GHz}$

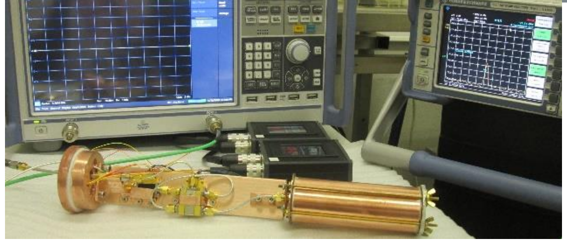
$G \geq 20\text{ dB}$

$BW \sim$ 2 GHz

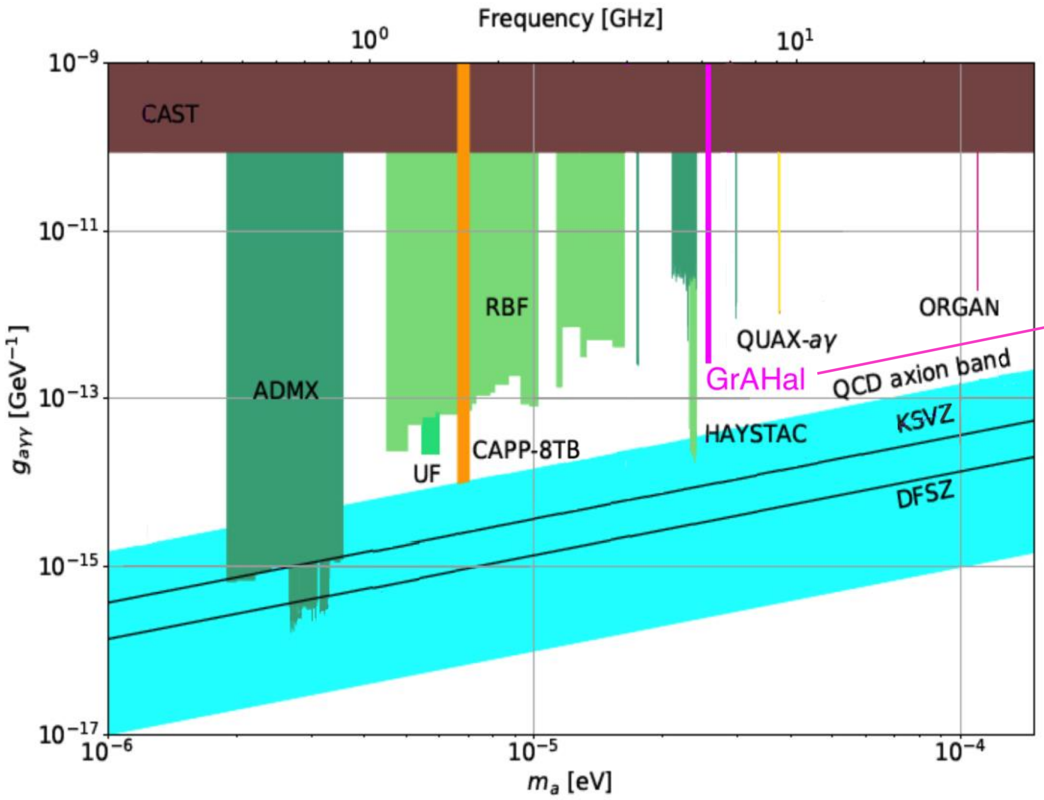
$T_N \gtrsim \frac{hf_o}{2k_B}$

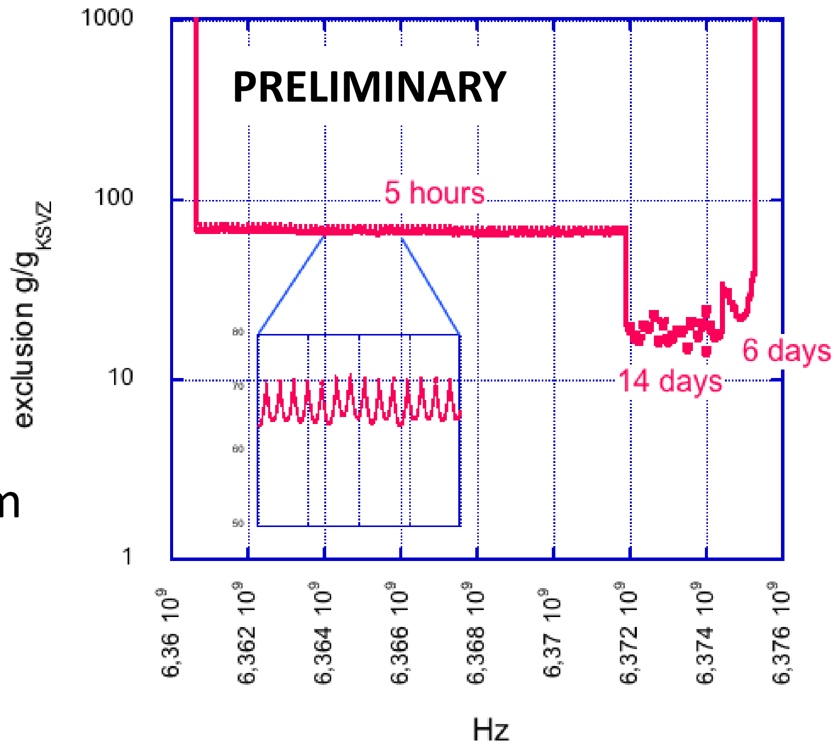
$P_{1dB} \sim -100\text{ dBm}$





Baby-GrAHal 1: Experimental Runs Ended

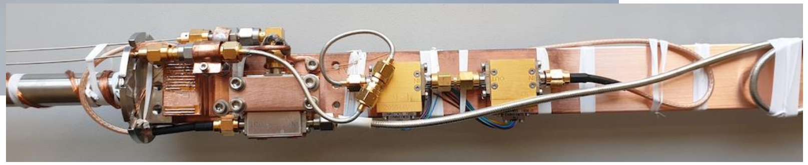




14 T @ 4 K in 36 mm cavity dia.
i.e. around 6.375 GHz or 26.37 μeV

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)



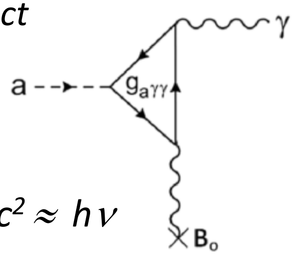
T. Grenet et *al.*
https://arxiv.org/abs/2110.14406

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



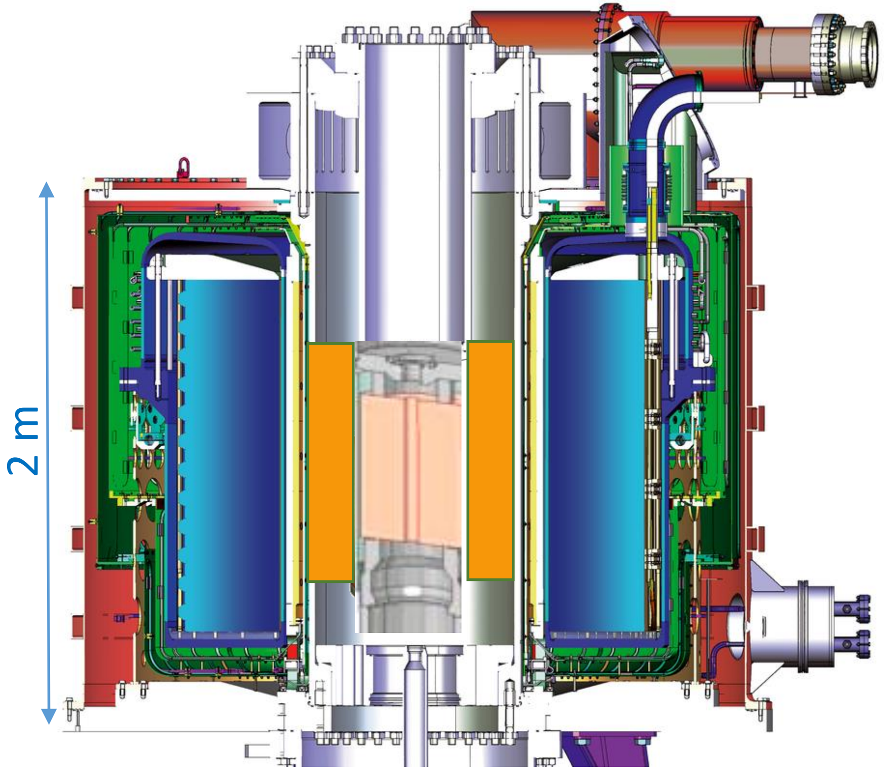
$m_a c^2 \approx h\nu$

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

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

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

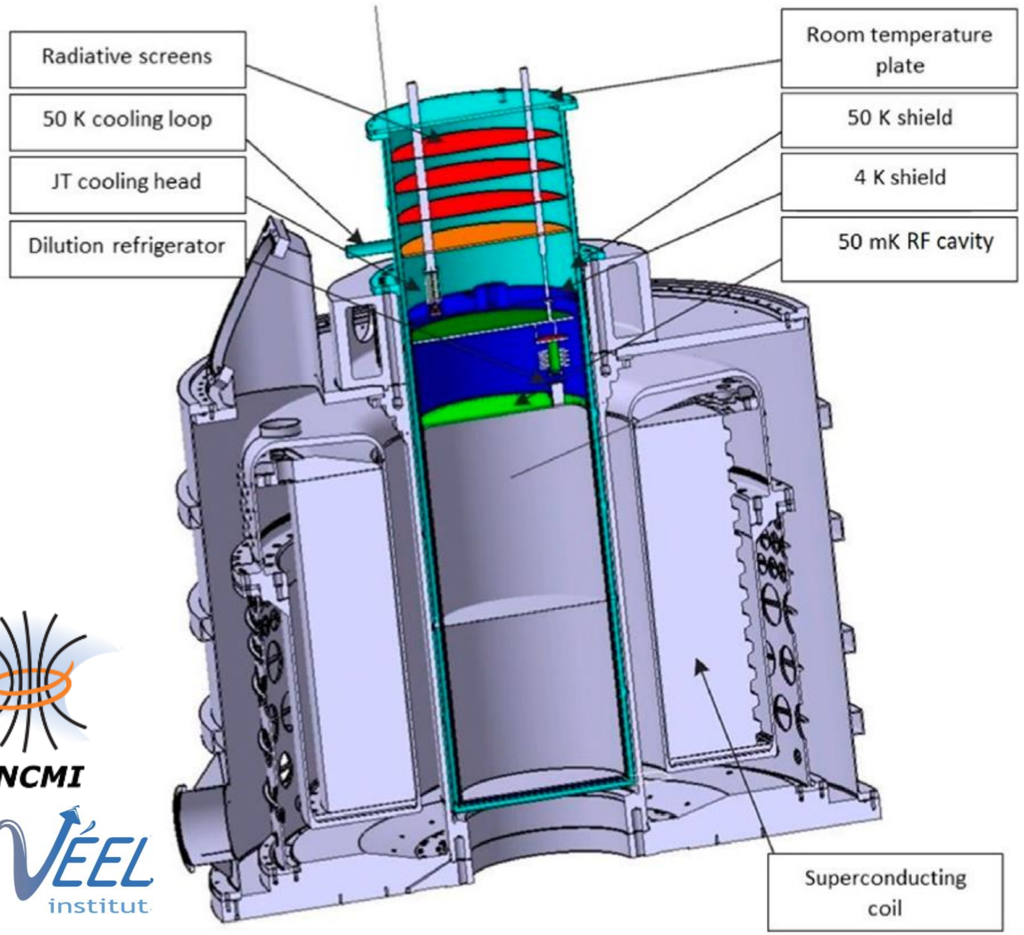
$df/dt\ \alpha\ B_0^{4}\ V^2$

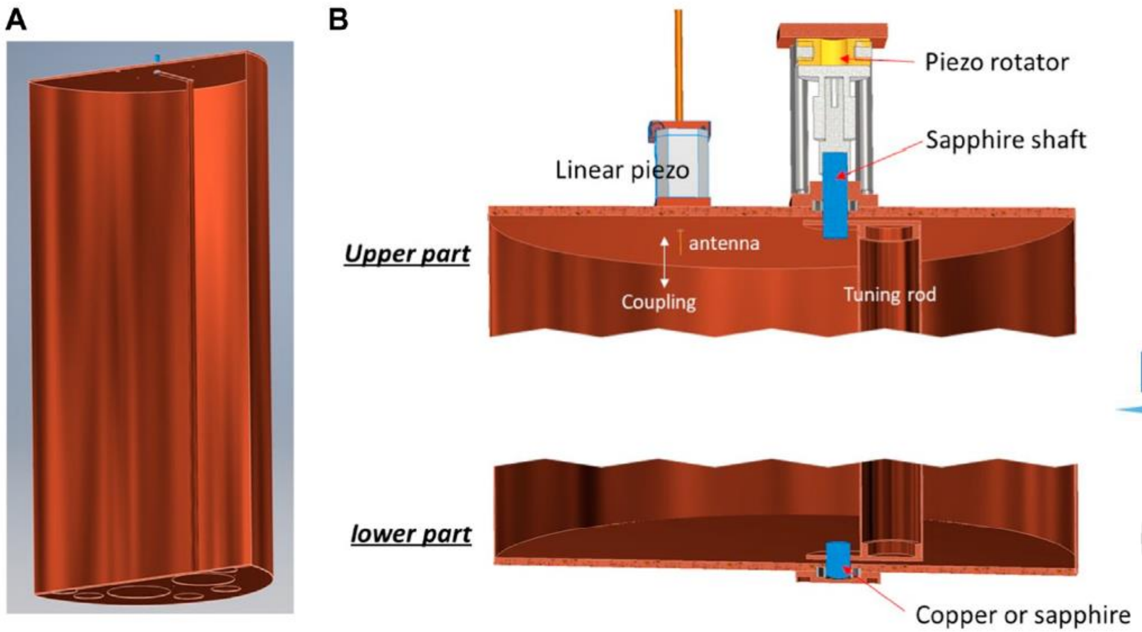


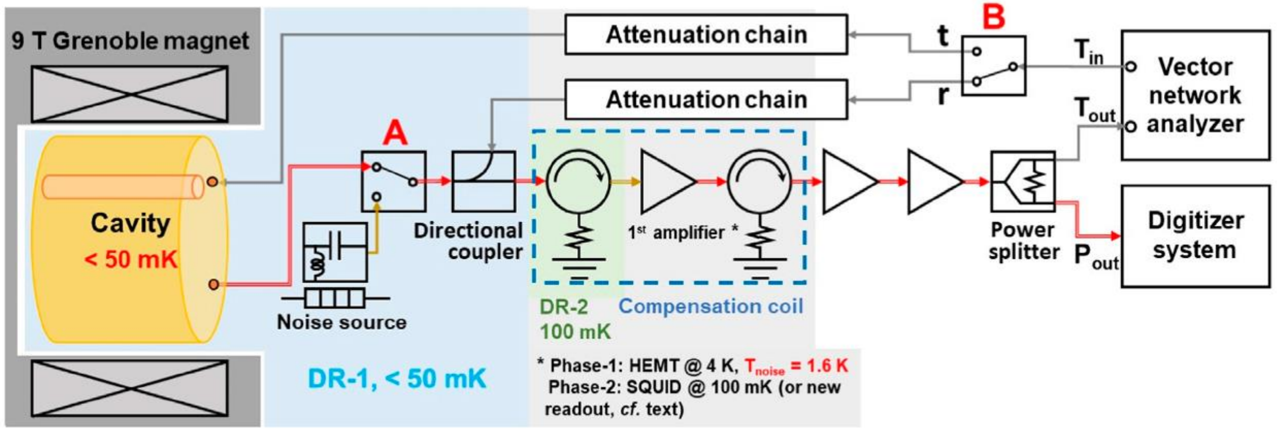
Field	Warm dia.	Power	RF-cavity dia.	f_{TM010}	Axion mass	B^2V (T^2m^3)
43 T	34 mm	25.4 MW	20 mm	11.5 GHz	47.2 μeV	0.5
40 T	50 mm	25.4 MW	34 mm	6.76 GHz	27.8 μeV	0.6
27 T	170 mm	19 MW	86 mm	2.67 GHz	11 μeV	3.5
17.5 T	375 mm	12.9 MW	291 mm	0.79 GHz	3.2 μeV	6.6
9 T	800 mm	0.4 MW	675 mm	0.34 GHz	1.4 μeV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

► Operation end of 2024 with HTS RF cavity in collaboration with CAPP/IBS-KAIST (cf. talk of D. Ahn)

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







Cryogenic challenge

T ≤ 50 mK in 538 liters with ^{3}He dilution refrigerator

Ph. Camus & J. Vessaire (Institut Néel)

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

Toward the most sensitive Haloscope worldwide

▶ *1st Focus 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

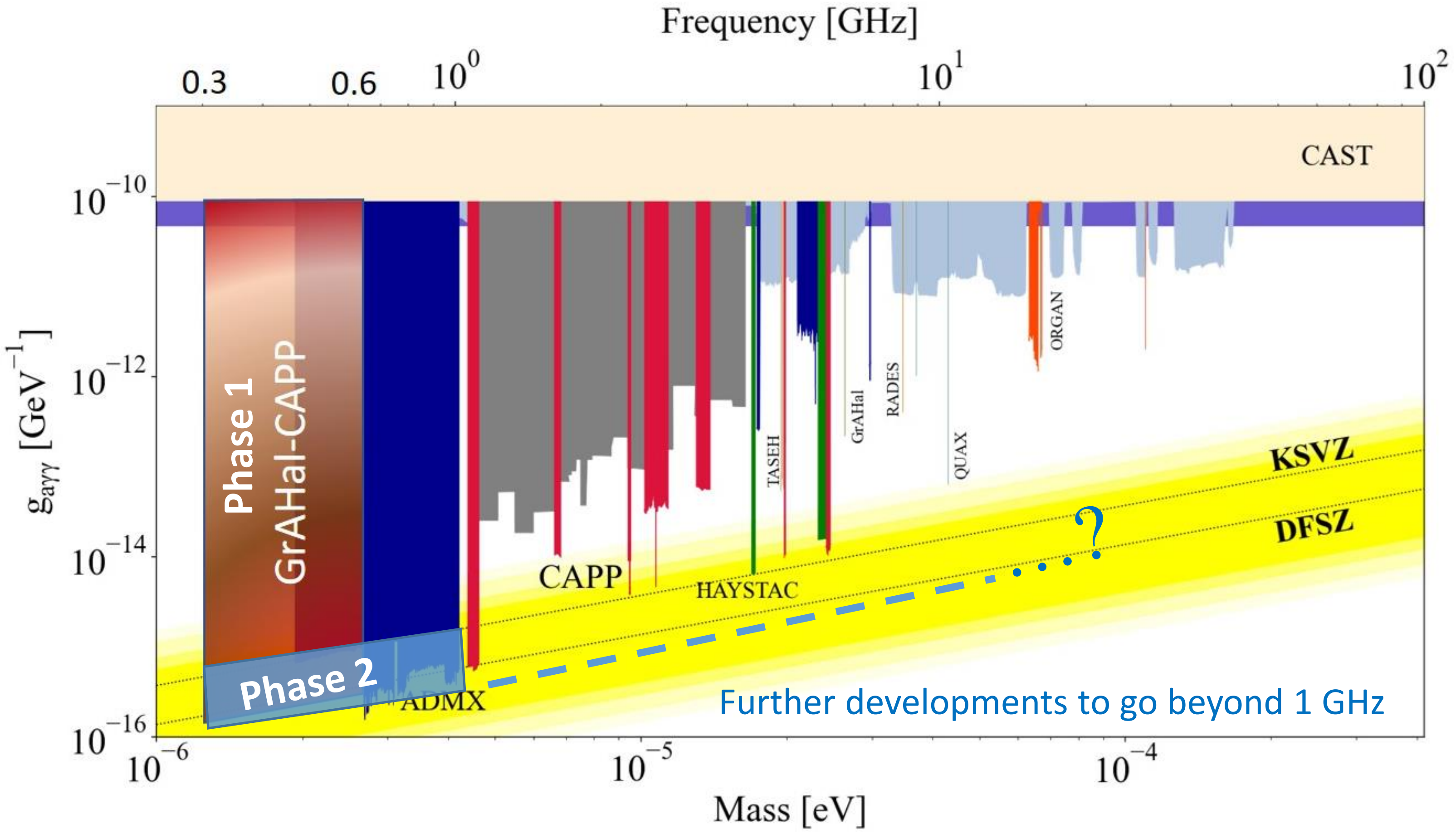
- 50 K cryo-stage operational @ t_0+18 months
- 4 K cryo-stage operational @ t_0+24 months

→ *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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