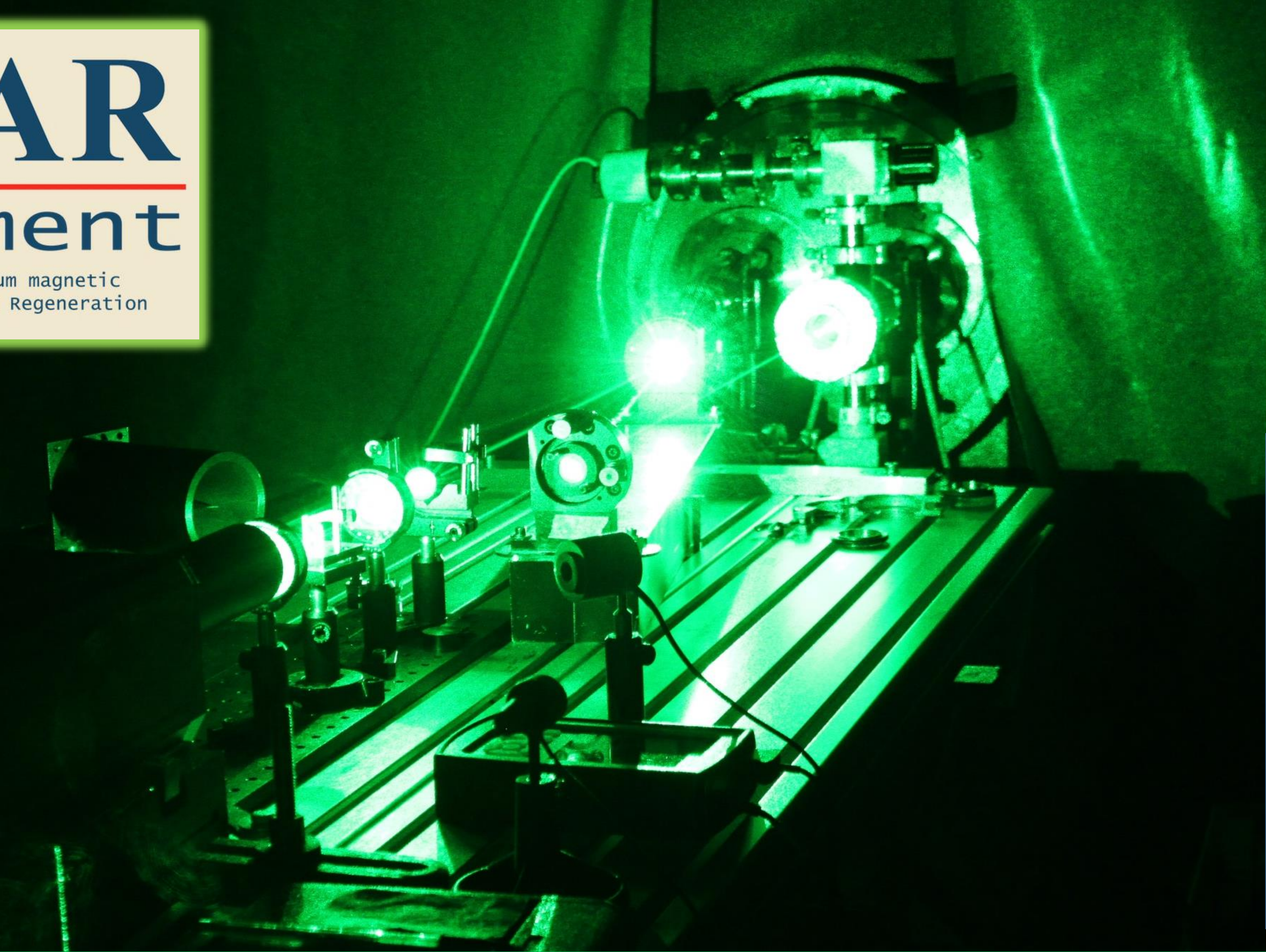
OSQAR Experiment

Optical Search for QED vacuum magnetic birefringence, Axions and photon Regeneration



Laser-based Particle/Astroparticle Physics Experiments at CERN To probe the Low Energy Frontier…

OSQAR Status & Plans

P. Pugnat on the behalf of the OSQAR Collaboration (inputs from R. Ballou, M. Sulc & S. Kunc)

143rd Meeting of the SPSC (CERN), 12 October 2021

Outline

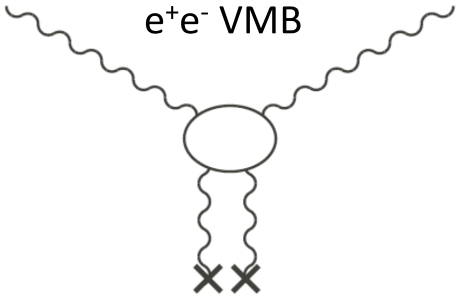
- Introduction
- OSQAR-CHASE (CHameleon Afterglow Search Experiment)
  - Experimental
  - Data analysis
  - Preliminary exclusion plots
- OSQAR-LSW (Light Shinning through Wall)
  - From past results to optimisation of data analysis & Future R&D plans towards JURA
- OSQAR-VMB (Vacuum Magnetic Birefringence)
  - Preparatory phase & Perspectives towards VMB@CERN
- Conclusion & Outlook

OSQAR

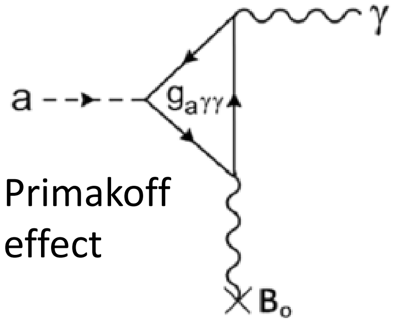
Scientific Motivations in a Nutshell

- **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

  "Exploring a new territory with a precision instrument is the key to discovery",
  Prof. S.C.C. Ting



- **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 ?"**



- **A complementary way of doing Particle Physics** based on the Laser beam interaction with magnetic fields

- **Spin-offs** in the domain of the metrology of electric & magnetic fields
  - Spin-off : **Start-up created** in 2009 by Prof. L. Duvillaret
    https://www.kapteos.com/

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)]*.

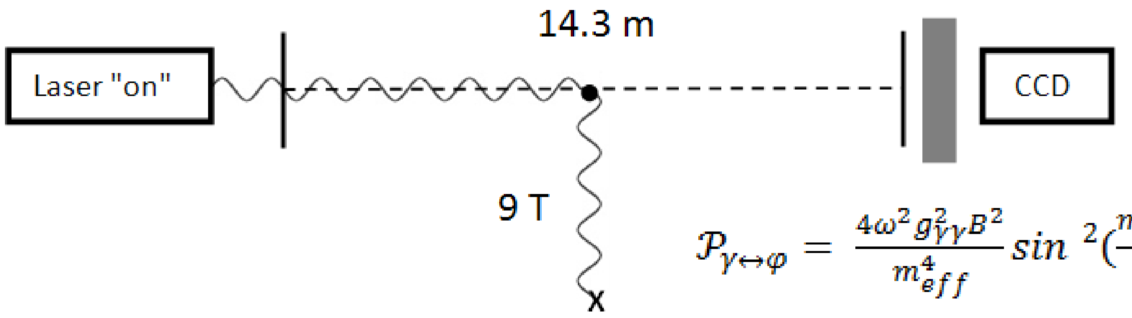
- New kind of particle providing **a phenomenological explanation of dark energy** as a scalar field evolving in an effective potential, the minimum of which depends on the local matter density in such a way that the experimental constraints of 5th force and violation of equivalence principle are relaxed.

- 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)

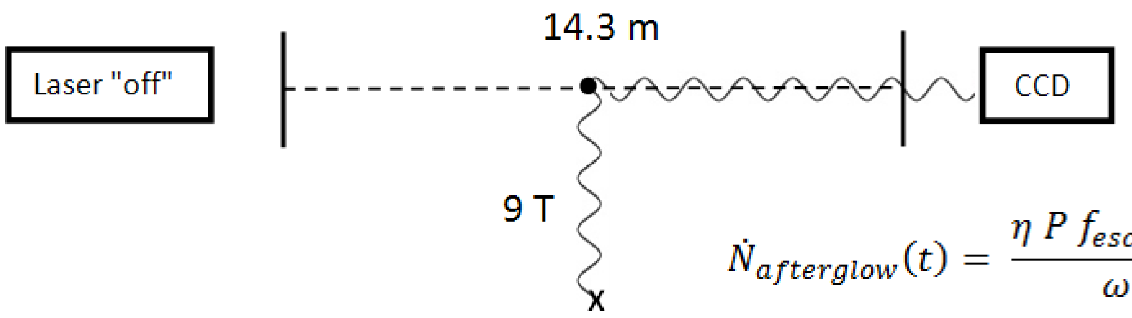
M. Ahlers et al., Phys. Rev. D 77, 015018 (2008)
H. Gies, D. F. Mota, and D. J. Shaw, Phys. Rev. D 77,025016 (2008)



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

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)

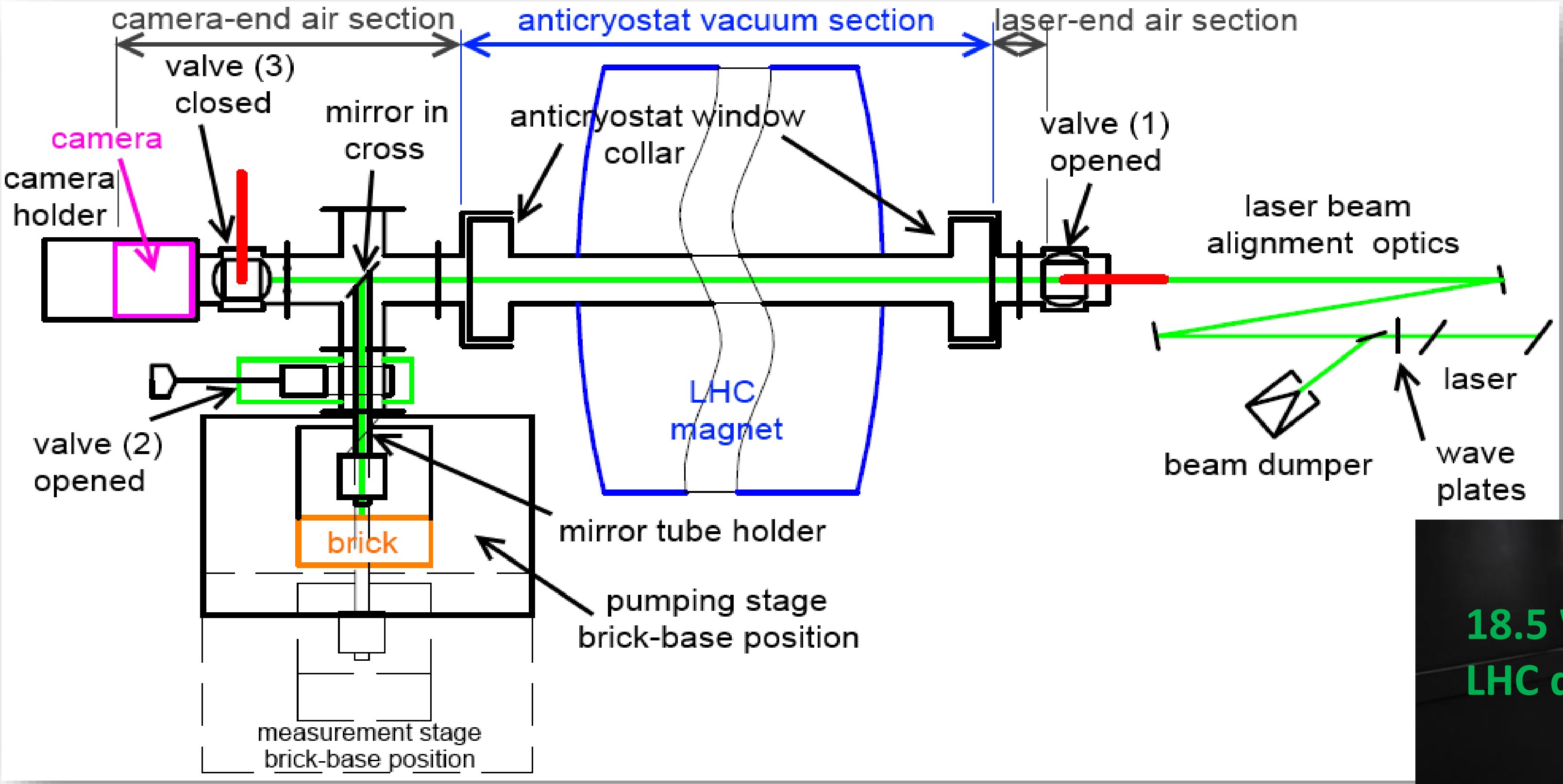


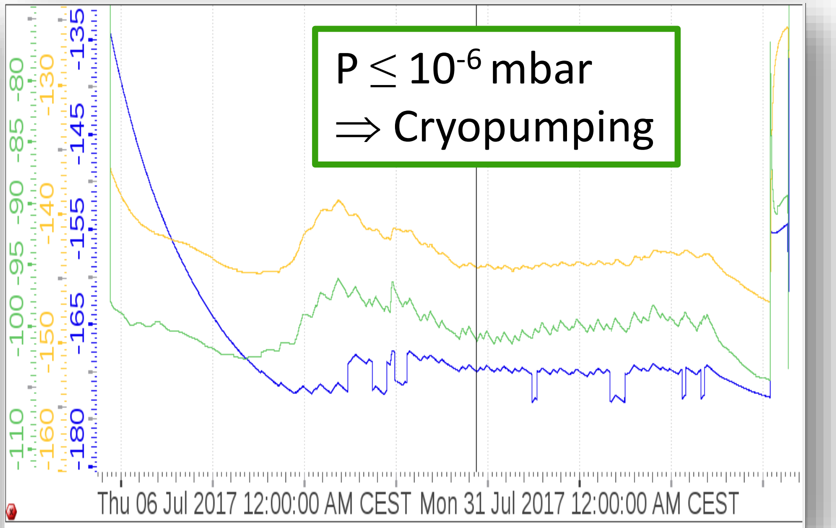
$$\dot{N}_{afterglow}(t) = \frac{\eta\ P\ f_{esc}\ f_{vol}\ \mathcal{P}_{\gamma\leftrightarrow\varphi}{}^2\ c}{\omega\ \Gamma\ L_{total}}(1 - e^{-\Gamma\Delta t})e^{-\Gamma t}$$

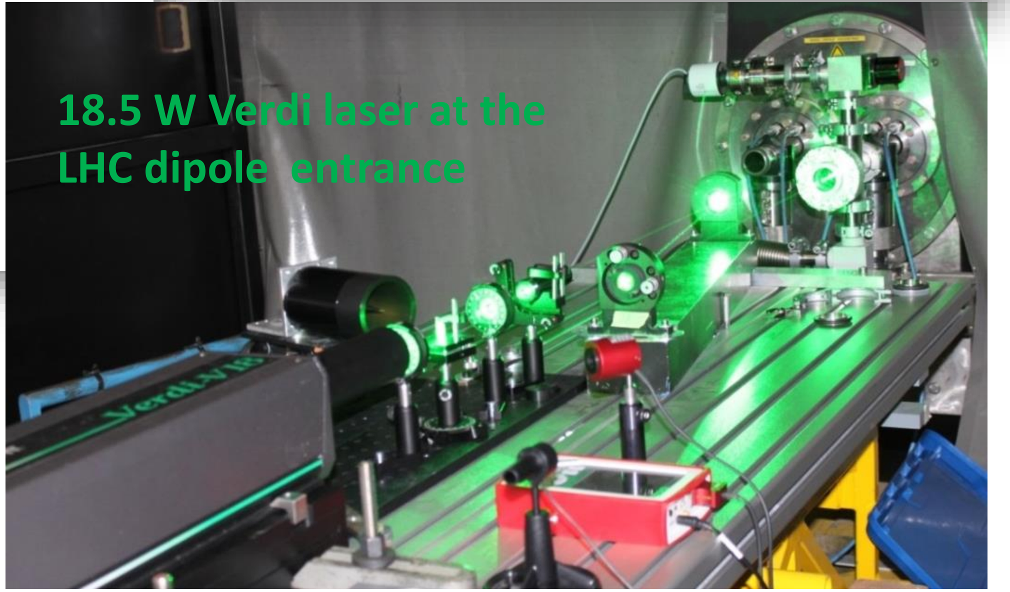
A.S. Chou et al., Phys. Rev. Lett. **102** 030402 (2009)

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

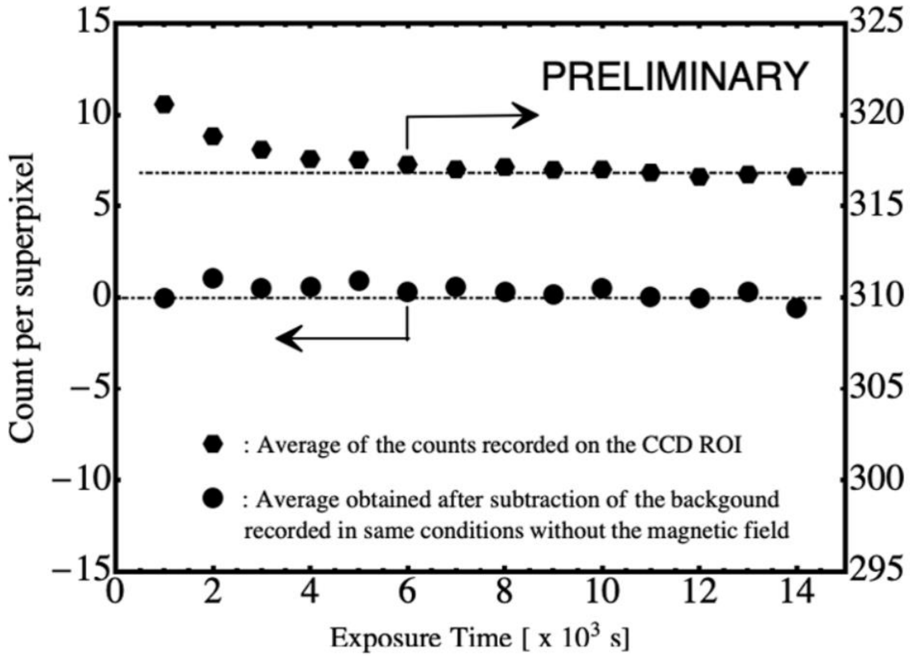
2017 Raw Data

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

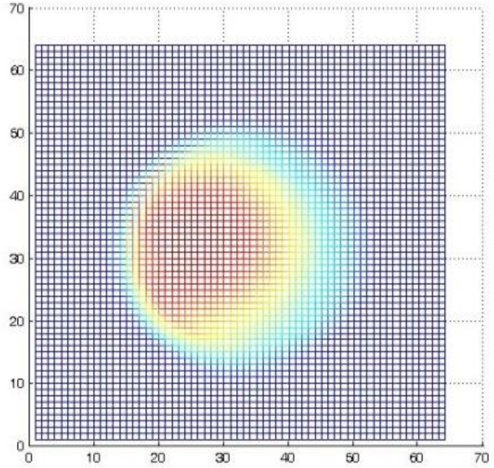
OSQAR chameleon afterglow search experiment

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)



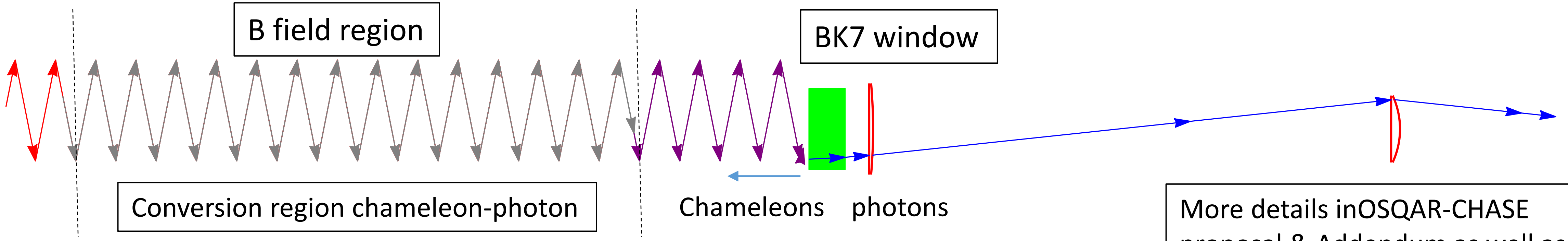
- Afterglow signal observed but non-magnetic as it dissapear after background substraction recorded with exactly the same configuration and protocole without magnetic field

- Negative results also obtained for pseudo-scalar search

- The quantitative analysis to define exclusion plots is not straighforward **and more complex than anticipated** with several Chameleon potentiels to consider

Data Analysis – Method

Phase 2, *i.e.* Afterglow photon emission, in the 2-point path approximation, *i.e. 3D* axisymmetry path



More details inOSQAR-CHASE proposal & Addendum as well as OSQAR Annual Reports 2018-2021

The flux of afterglow photons as a function of time can be modeled as:

$$S_{AFT}(t) = \eta \frac{F_\gamma \, P_{\phi\leftrightarrow\gamma} \, \Gamma_{AFT}}{\Gamma_{DEC}} \left(1 - e^{-\Gamma_{DEC}\,\tau_{Prod}}\right) e^{-\Gamma_{DEC}\,t}$$

$\eta = 0.65$ *is the* overall detection efficiency

$$\mathcal{P}_{\phi\leftrightarrow\gamma} = \left(\frac{2\beta_\gamma}{k M_P {m_{eff}}^2}\right)^2 |\,\vec{k} \wedge (\vec{B} \wedge \vec{k})\,|^2 \sin^2\left(\frac{{m_{eff}}^2\, t}{4k}\right)$$

$$\Gamma_{\substack{DEC\\AFT}} = \frac{1}{4\pi\,\Sigma} \int d\Sigma \int d\Omega \; P_{\substack{DEC\\AFT}} \frac{\cos\theta}{L_T} \qquad with \quad P_{DEC} = P_{ABS}^{Bexit} + \left|\vec{\psi}_\gamma^{Bexit}\right|^2$$

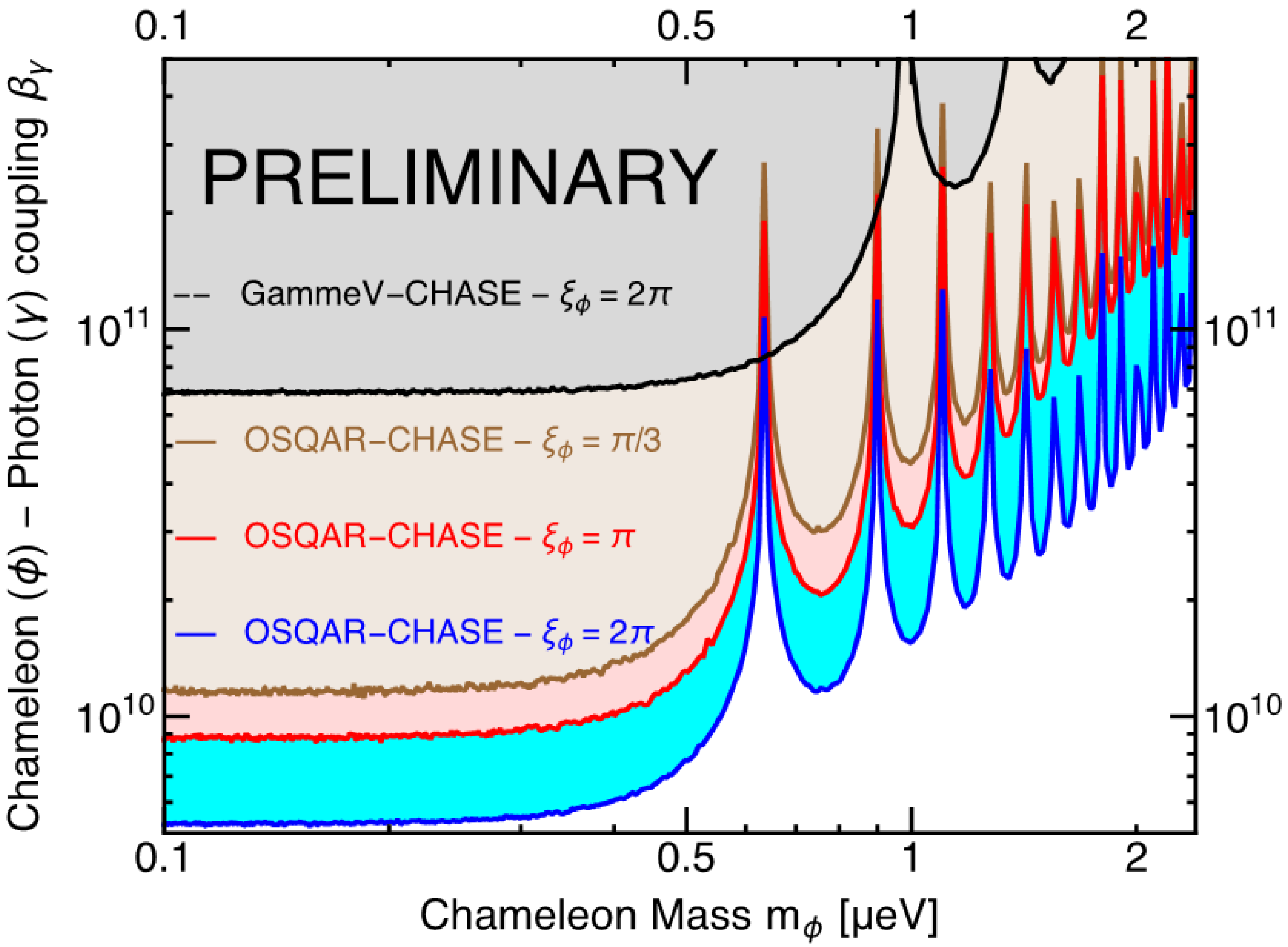
$$and \quad P_{AFT} = \left(\left| \left(\vec{\psi}_\gamma^{Bexit}.\vec{S}\right) A_S^{N-N_R} \right|^2 + \left| \left(\vec{\psi}_\gamma^{Bexit}.\vec{P}\right) A_P^{N-N_R} \right|^2 \right) P_{DET}$$

S & P = polarization state

$A_{S,P}$ = reflection coefficient

Computation validated from GammeV-CHASE results (*cf.* https://cds.cern.ch/record/2691980/files/SPSC-SR-260.pdf)

Data Analysis - Output (1/2)

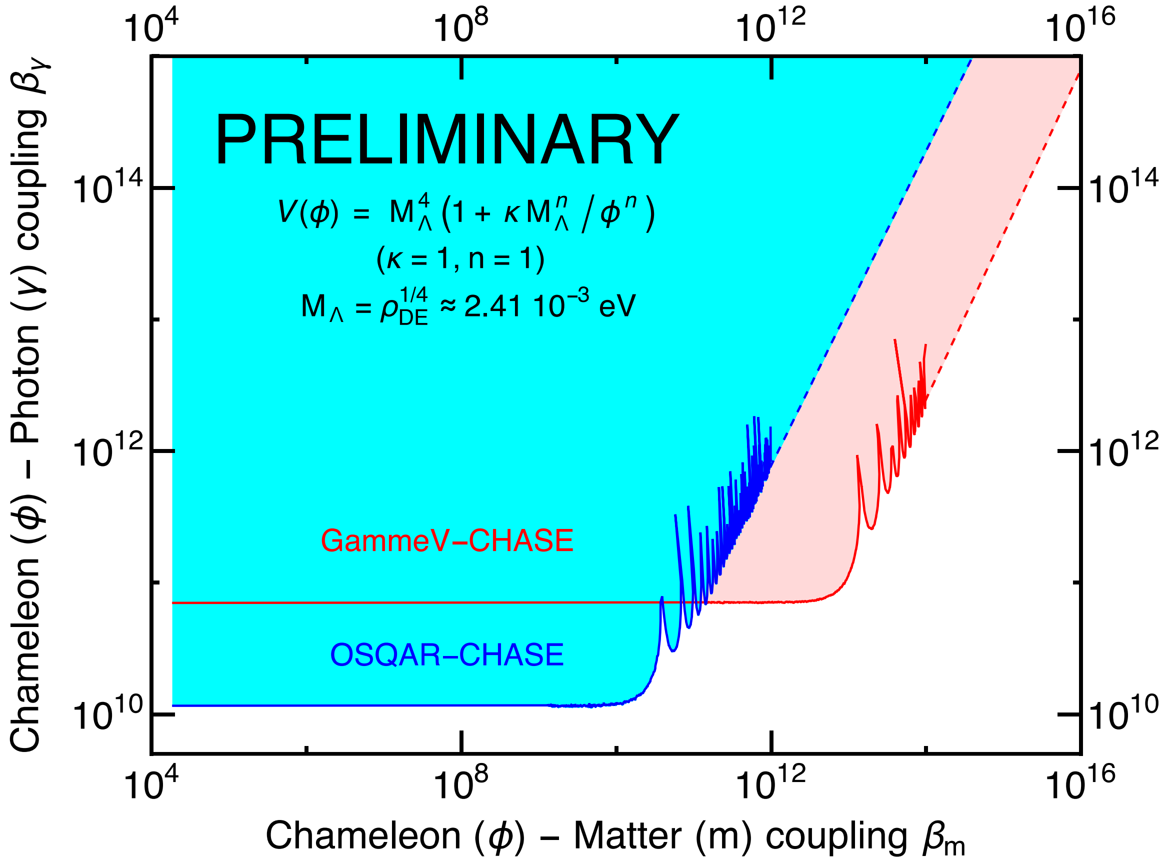


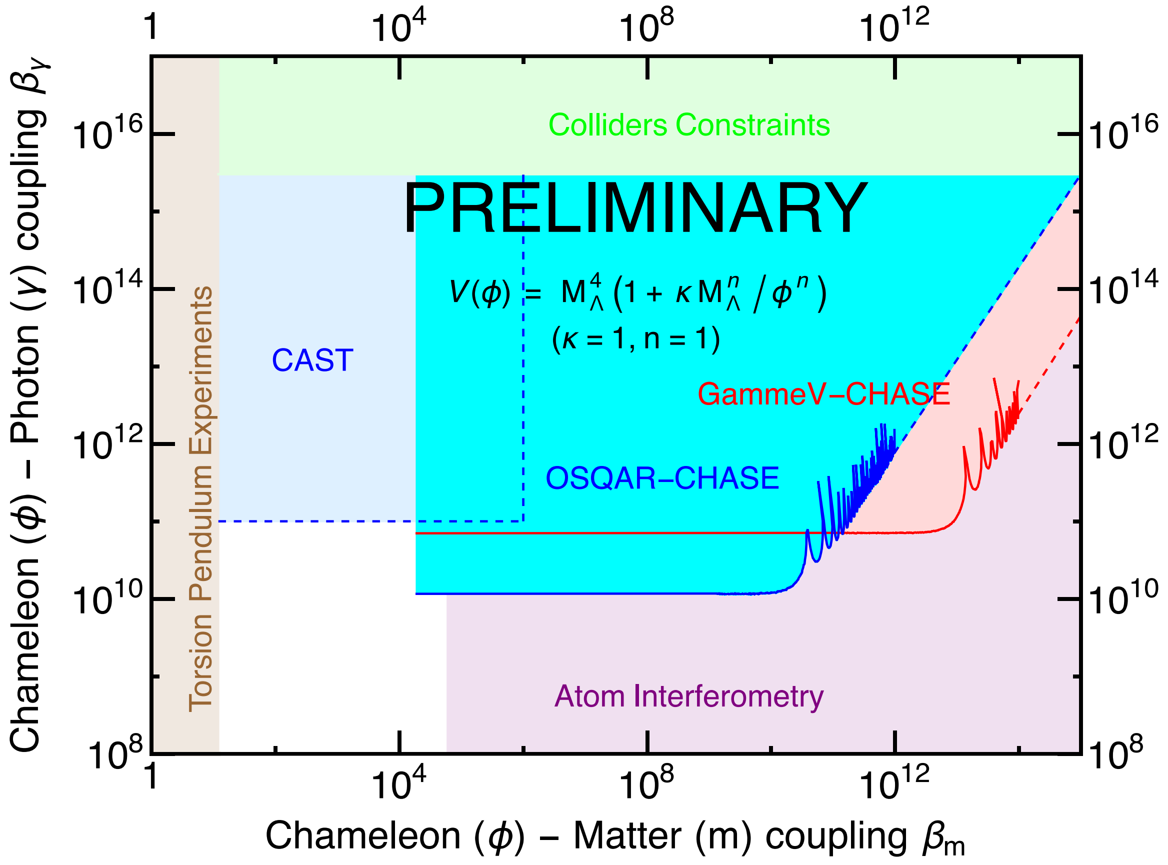
Exclusion limits in the parameter space (**chameleon mass m_ϕ, chameleon-photon coupling β_γ**), deduced from no signal observation and detector noise in the OSQAR-CHASE data collected in summer 2017 with the experimental setup using two focusing optical lenses, for different chameleon phase shifts ξ_ϕ 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 $V = M_\Lambda^4[1 + e^{-\kappa\phi/M_\Lambda}]$.

Data Analysis - output (2/2)

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





OSQAR

Next Steps

What was not taken into account in the present analysis ?

- Complex propagation not inscribed in a plane *i.e.* full 3D in general --> Beyond the 3D axisymmetry geometry

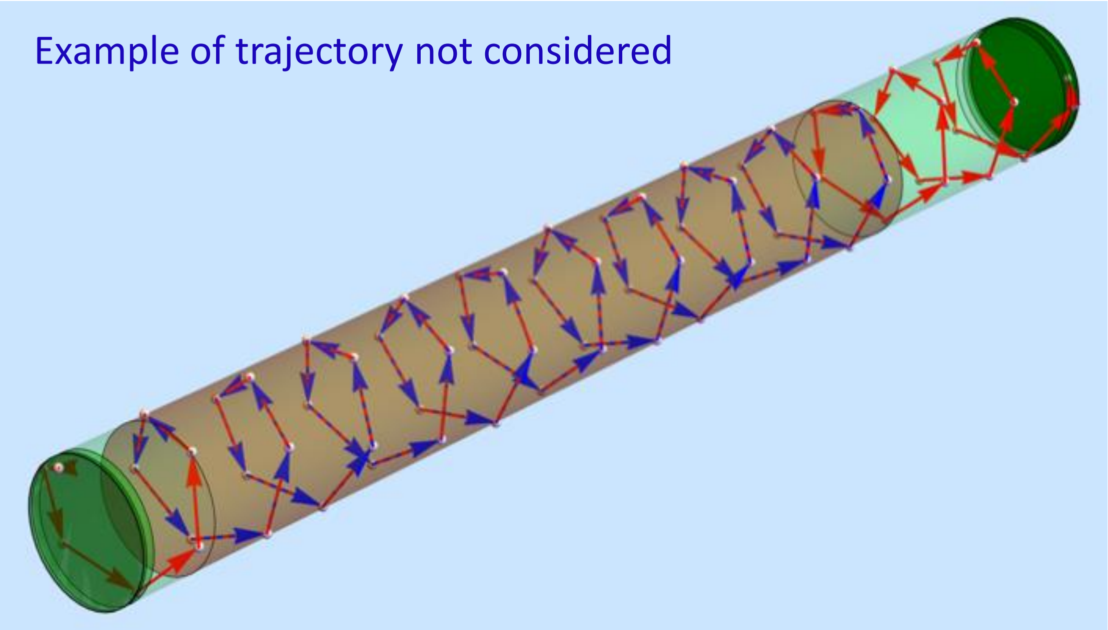
  ▸ **Assessment required especially for large β_m**

- Non-specular reflection of photons, *i.e.* the diffuse one not considered

- Spatial distribution of the signal on the CCD detector to get more accurate exclusion limits through matched filtering of the data.

- **Chameleon fragmentation** the possibility of which is expected for chameleon potentials with high exponents (n = -3, -4, … or 3, 4 , …)

All this can be achieved through Monte-Carlo simulations of the afterglow signal.

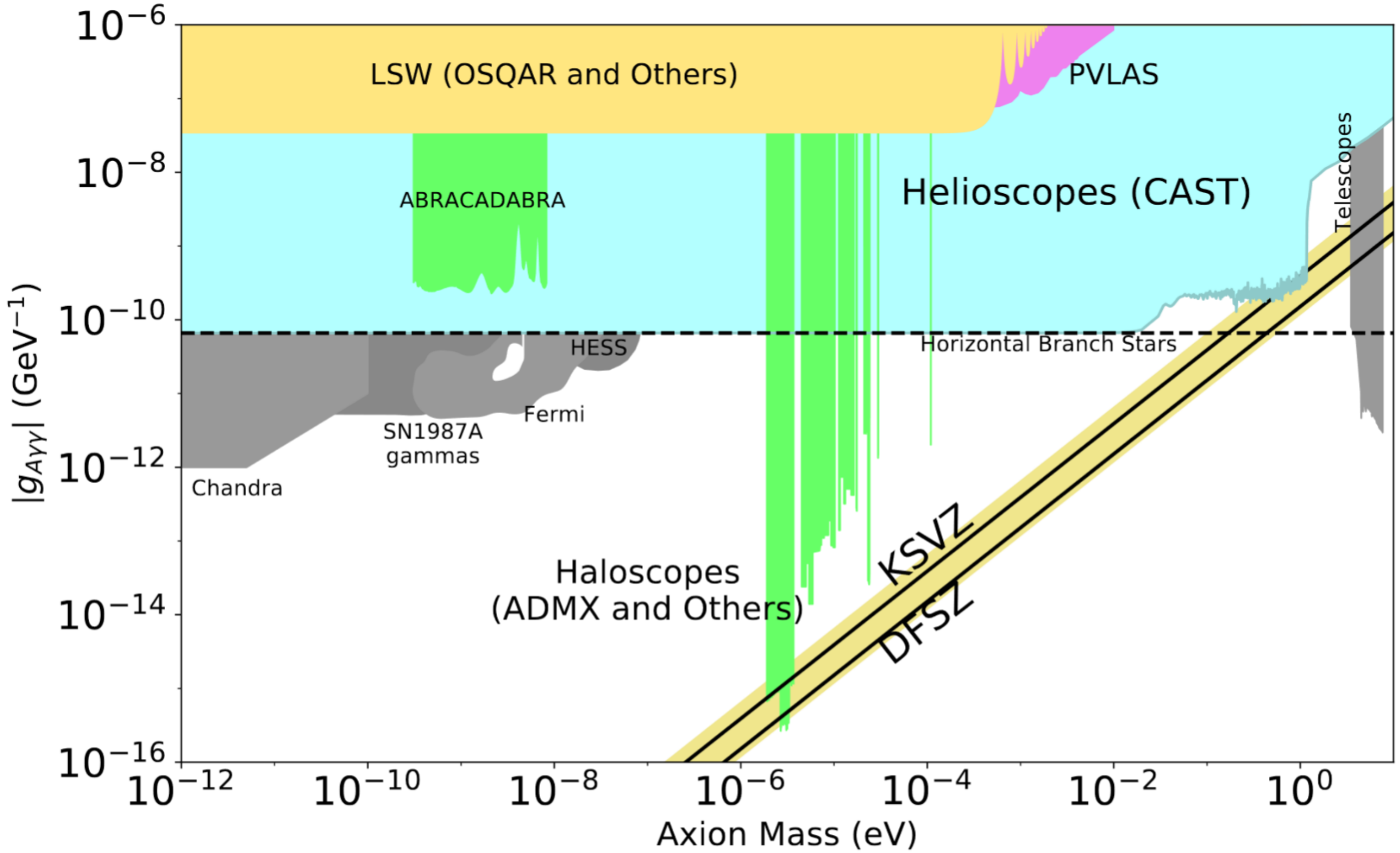


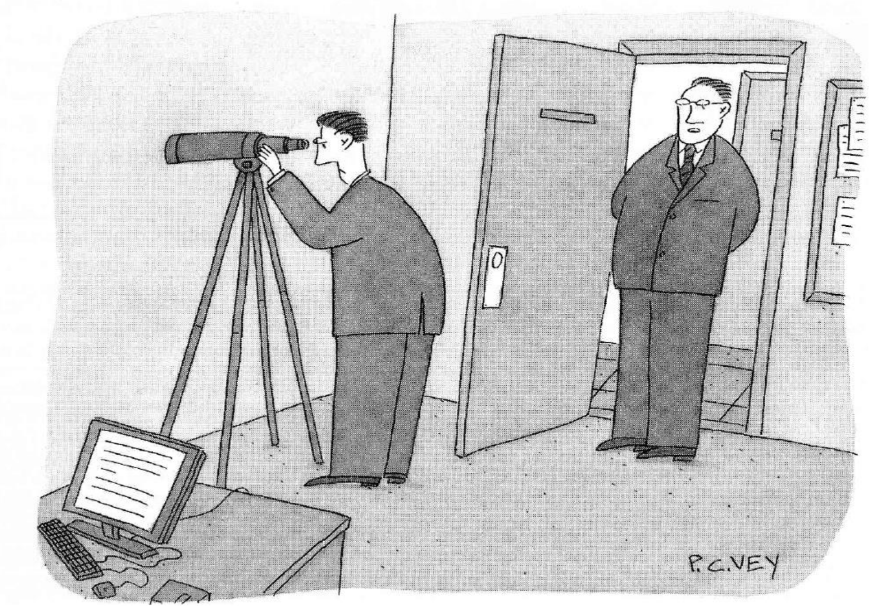
Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal
JCAP02 (2014) 018
https://iopscience.iop.org/article/10.1088/1475-7516/2014/02/018/pdf

Chameleon fragmentation

Philippe Brax[a] and Amol Upadhye[b,c,d]

Light Shining through a Wall experiment (LSW)



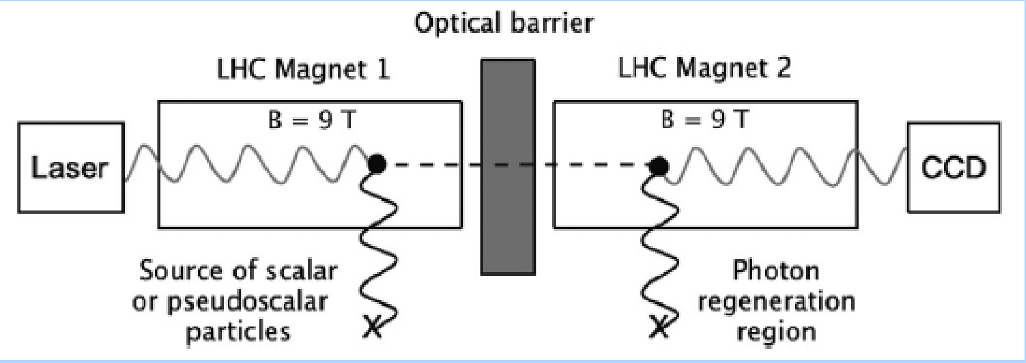


A less crazy experiment…

https://pdg.lbl.gov/2020/reviews/rpp2020-rev-axions.pdf

OSQAR

Present state-of-the-art for LSW Experiments



$$\frac{\mathrm{dN}}{\mathrm{dt}} = \frac{P}{w} h \left(\mathrm{P}_{A\leftrightarrow g}\right)^2$$

P : power of the incoming photons of energy ω

η : the detector efficiency

$$\mathrm{P}_{A\leftrightarrow\gamma} = \frac{1}{4}\left(\mathrm{g}_{A\gamma\gamma}\mathrm{BL}\right)^2 \left(\frac{2}{\mathrm{qL}}\sin\frac{\mathrm{qL}}{2}\right)^2 \frac{\omega}{\sqrt{\omega^2 - \mathrm{m}_A^2}}$$

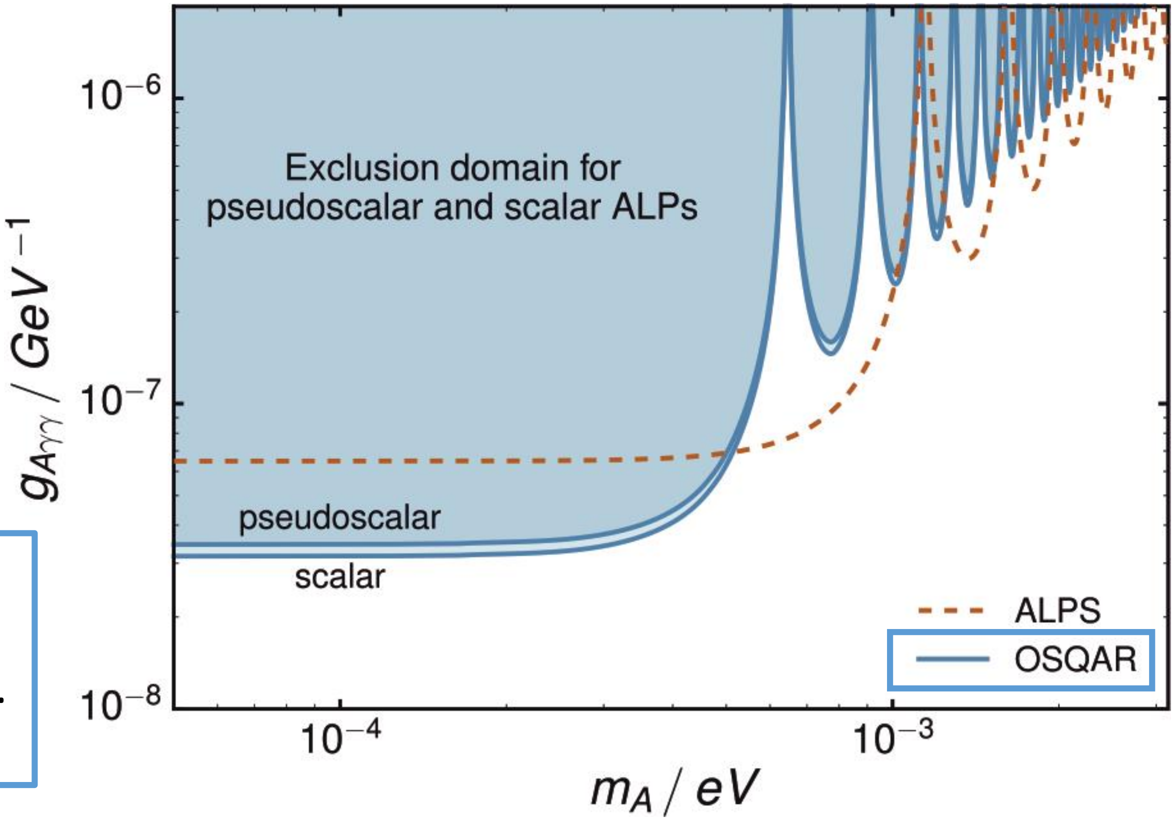
with $q = \left|k_\gamma - k_A\right|$, $k_\gamma = \omega$ and $k_A = \sqrt{\omega^2 - \mathrm{m}_A^2}$

ω : photon energy – m_A : ALP mass

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

A.A. Anselm, Sov. J. Nucl. Phys. 42 (1985) 936
K. van Biber et al., PRL 59 (1987) 759

Figure of merit of the magnet syst. = **B L**

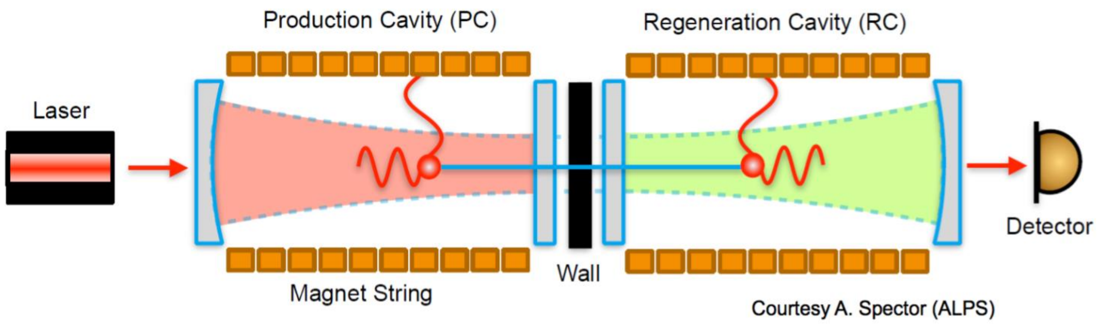


. **ALPS-I** : 1 HERA dipole & O.C. (BL = 43 Tm, P = 1.2 kW) Phys. Lett. B 689 (2010) 149

. **OSQAR-LSW** : 2 LHC dipoles (BL = 270 Tm, P = 18 W) **Phys. Rev. D 92 (2015) 092002**
@ 95% Confidence Limit deduced from model independent Bayesian analysis,
ALPs-diphoton coupling < 3.2·10^{-8} GeV^{-1} (for m_A < 0.2 meV)

Pespectives for LSW experiments

- Ongoing ALPs-II at DESY (12 + 12 straightened 5 T Hera dipoles with ambitious optical scheme)



~ 2 x 120 m

- Longer term future for LSW experiments with JURA (Joint Undertaken Research for Axion/ALPs), possibly with say 15 + 15 spare 9 T LHC dipoles (~ 2 x 225 m) with the **same or alternative optical scheme (?)**
  - → At present, JURA = OSQAR + ALPs + (UF?)…
  - → **Ambitious proposal, R&D needs to start NOW…**
  - → First step BabyJURA at CERN (*cf.* PBC Techno. Report, Dec. 2018)

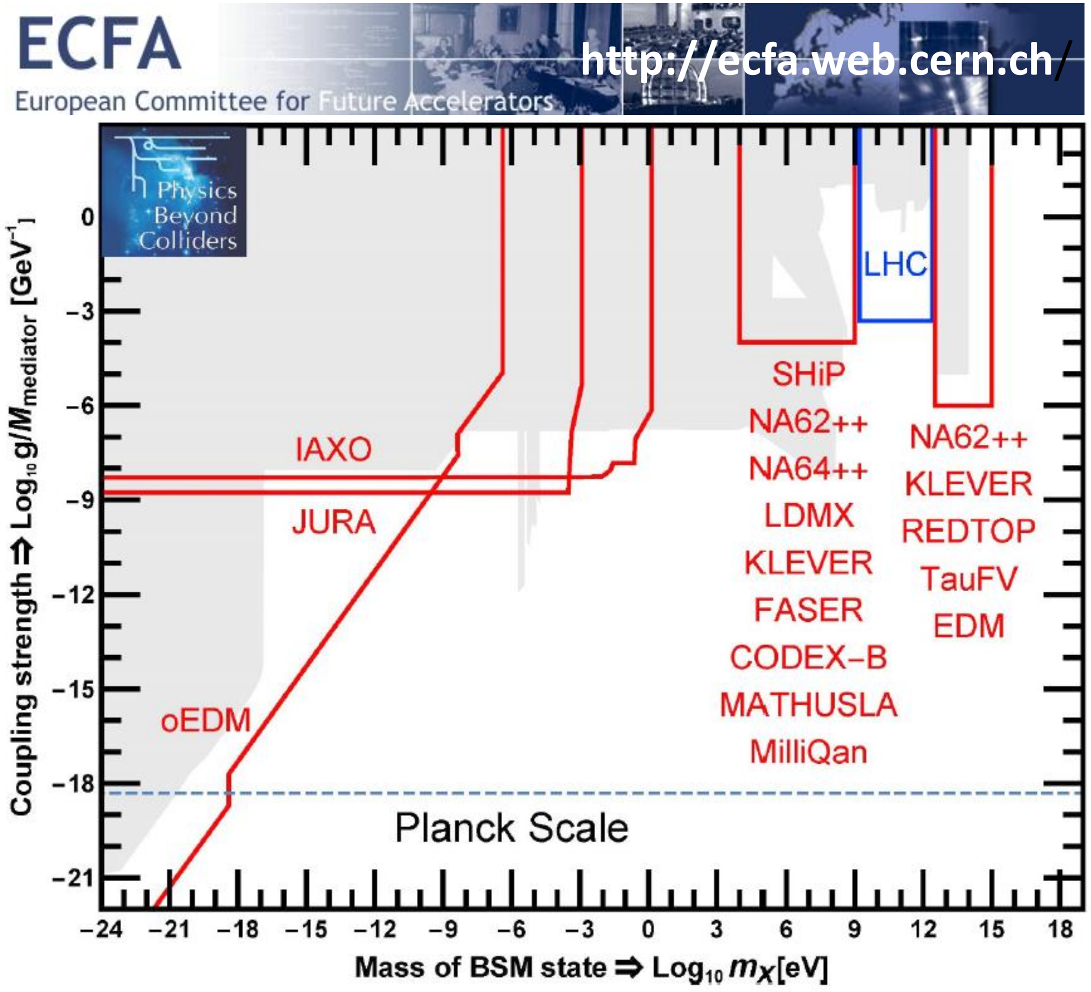


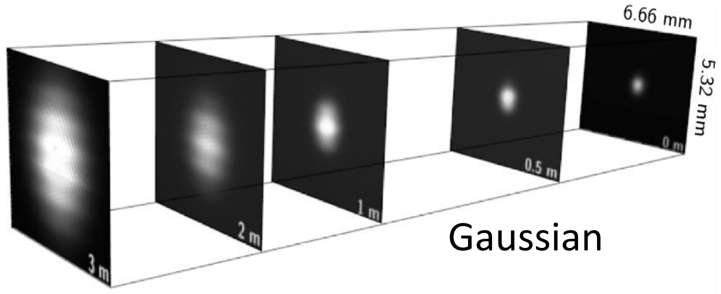
Figure: schematic overview of the BSM landscape, based on a selection of specific models, with a rough outline of the areas targeted by the experiments considered in the PBC sensitivity studies.

https://arxiv.org/pdf/1902.00260.pdf

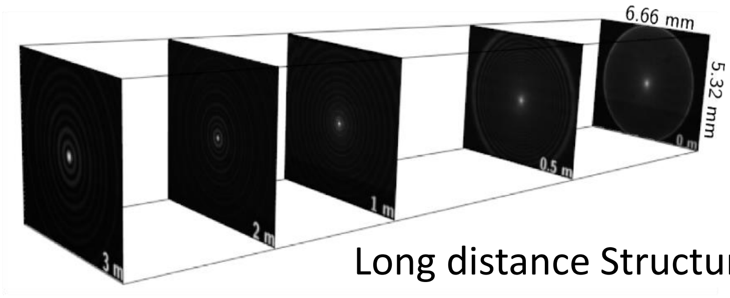
Some exemples of R&D towards JURA

- Low divergent structured beam (patent: WO2019211391 (A1), EP3564734 (A1))

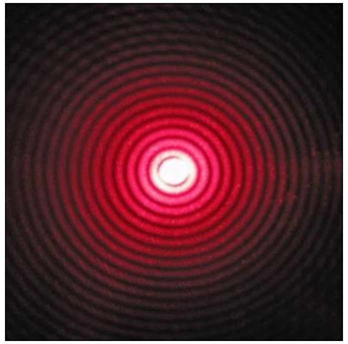
Beam diameter	At 3 m	At 100 m
Gaussian	0.8 mm	240 mm
Struct. Beam	0.01 mm	1.4 mm



Gaussian

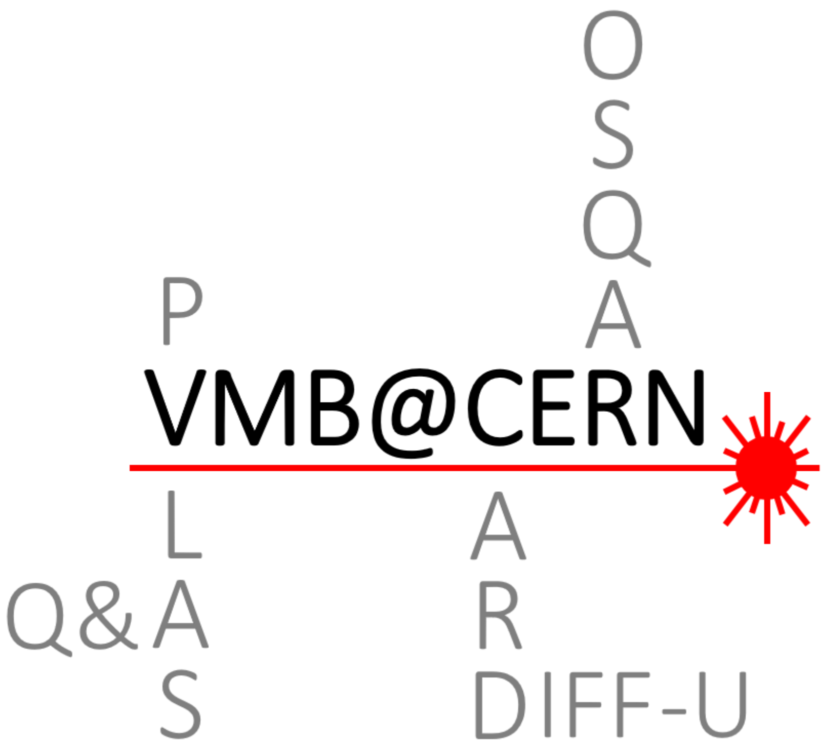


Long distance Structured Beam – quasi-Bessel



- Optimisation of data analysis with matched filter (similar to Ligo & Virgo)
  - At present OSQAR-LSW sensitivity can be improved by x 3, further progress possible ?
- Alternative optical scheme under consideration
  - Interferrometry approach, *cf.* https://cds.cern.ch/record/2641609
  - Amplification by resonant atomic transition (*cf.* arXiv:1803.09388v2)

The birth of a meta-collaboration, Remaining on a Human scale



Discussed for the 1st time within PBC in May 2017 (slide 17)
& also presented to the SPSC-127
https://indico.cern.ch/event/667744/contributions/2729955/attachments/1528365/2390769/HIMAFUN-Report-Short.pdf ; https://indico.cern.ch/event/672382/timetable/

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

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

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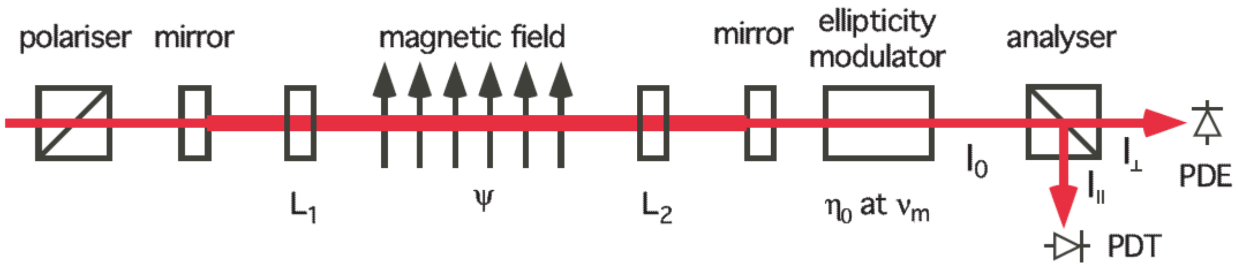
[13]Dip. di Fisica e Scienze della Terra, Università di Ferrara and INFN, Sez. di Ferrara, Ferrara (FE), Italy

On going activities for VMB@CERN

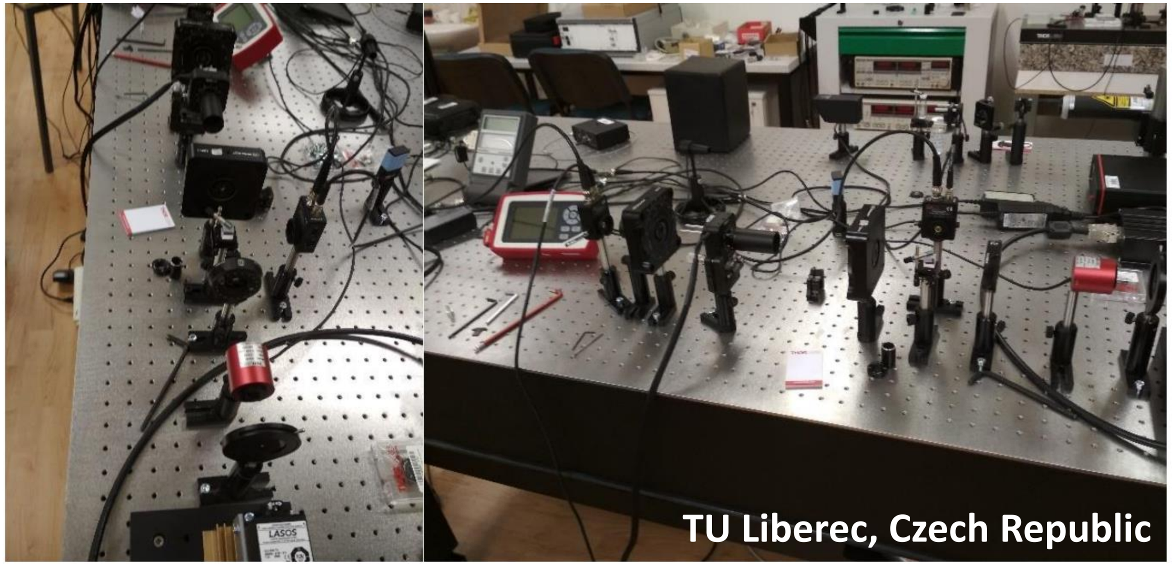
Proposed modulation scheme of VMB@CERN (SPSC-I-249)
L1,2 : rotating half-wave-plates
PDE : Extinction Photodiode
PDT : Transmission Photodiode.

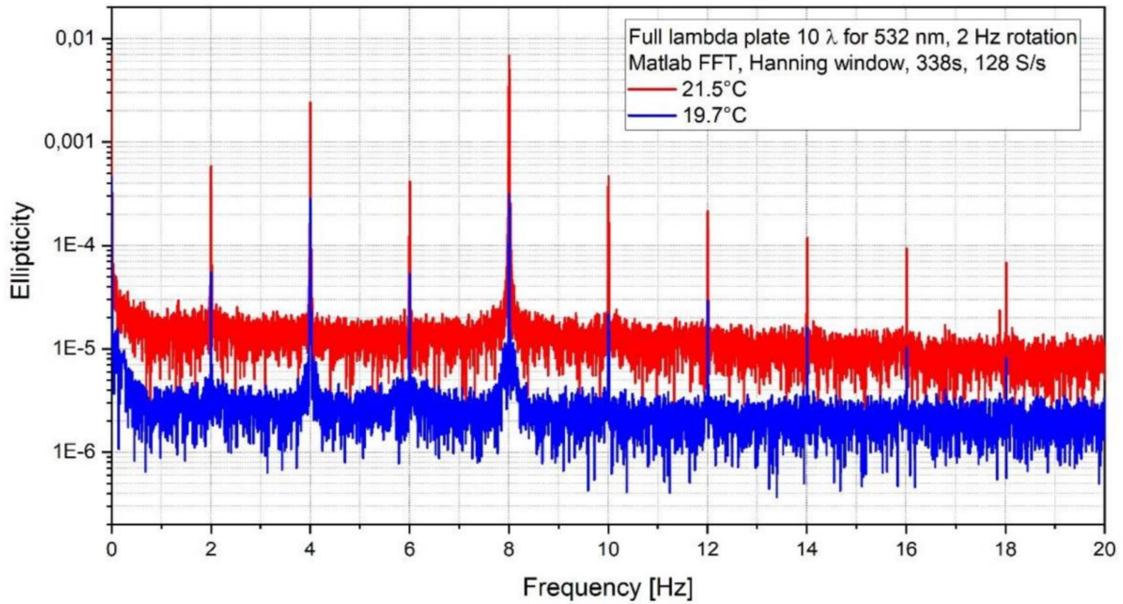
See also G. Zavattini et *al.*
https://arxiv.org/abs/2110.03943

Improvements of the OSQAR initial proposal SPSC-P-331,
see also P. Pugnat, L. Duvillaret *et al., Czech. J. Phys.* 55 (2005) A389



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





Conclusion & Outlook

- OSQAR-CHASE
  - **Détailed data analysis** of the 2017 run for scalar and pseudoscalar Chameleon search **is more complex and demanding than anticipated.**
  - New exlusion limits is being rigurously defined from no magnetic afterglow signal observed; they are **significantly better than those anticipated in the OSQAR-CHASE proposal.**
  - **Robusness of the analysis (beyond 3D axisymmetry, diffuse reflection) as well complementary search (chameleon fragmentation) still need to be performed.**

- OSQAR-LSW
  - JURA will be the next postALPS-II LSW experiment requiring preparatory activities, which are starting within OSQAR collaboration, including :

    . Control of the laser beam divergence on long lengths (patent on structured beam);
    . Optimisation of the data analysis with matched filter;
    . Investigation of new type of experiments linked to other scientific fields such as atomic physics.

- OSQAR-VMB
  - Activities are pursued within the scope of the VMB@CERN future proposal in preparation.
  - **Synergy between VMB@CERN and BabyJURA is looked at to minimise requirements asked to CERN, specially regarding the future need of LHC dipoles in the SM18 hall.**