OSQAR

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Optical Search of QED vacuum magnetic birefringence, Axion and photon Regeneration

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High Energy Physics and Quantum Field Theory
June 24– July 1, 2015
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Štěpán Kunc on behalf of OSQAR collaboration

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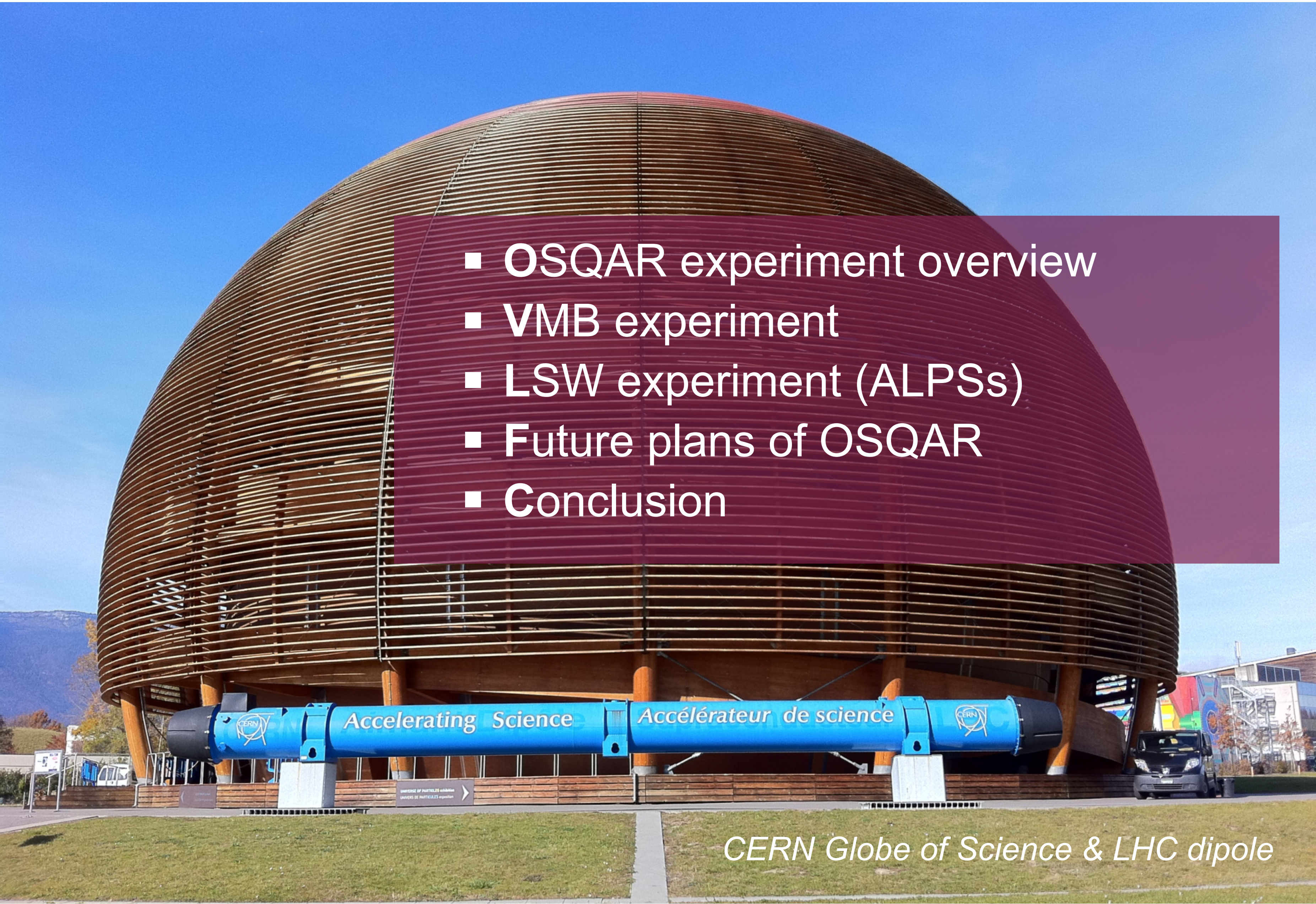
Outline

- **O**SQAR experiment overview
- **V**MB experiment
- **L**SW experiment (ALPSs)
- **F**uture plans of OSQAR
- **C**onclusion



CERN Globe of Science & LHC dipole

Collaboration

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28 Members from 12 Institutes (CERN, Cz, Fr & Po)

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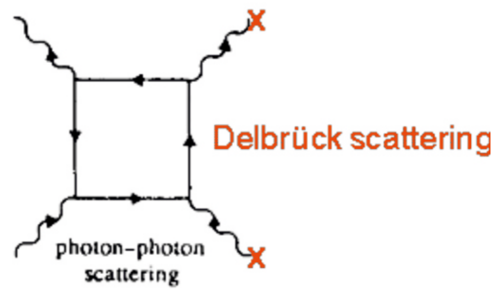
Warsaw University, Physics Department, Poland
A. Hryczuk, K. A. Meissner (co-spokesperson)

Scientific Motivations of OSQAR

- **To measure for the 1st time the QED Vacuum Magnetic Birefringence** *(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 … *"Exploring a new territory with a precision instrument is the key to discovery"*, Prof. S.C.C. Ting

- **A New Way of doing Particle Physics** based on Laser beam(s)

- **Spin-offs** in the domain of the metrology of electric & magnetic fields

Three distinct experiments in strong magnetic field

- The photon regeneration effect (photon – axion and axion - photon conversion) is looked for as a Light Shining through the Wall . OSQAR has the best exclusion limit for axions and axion like particles nowadays.

- The Vacuum Magnetic Birefringence, predicted by the QED, could be measured for the first time. OSQAR developed accurate method for this experiment, but it is able to measure only similar stronger effect in diluted gases till now.

- Chameleon search looks as measurement of afterglow of light, as the photons convert to trapped chameleons and reconvert back to photons, streaming through the windows of the vacuum chamber. OSQAR is in preparatory phase for 2015 run. We expect increase of the present reference exclusion limit of photon -chameleon coupling constants .

Organisation of OSQAR experiment

- OSQAR is operated in CERN in SM18 hall
- SM18 - test hall for all LHC magnets - complete infrastructure
- Preparation and test are made in home institutes
- Data taking in CERN, one per year - 6 weeks duration
- Data analysis in home institutes

Sm18 Hall - Test Banches

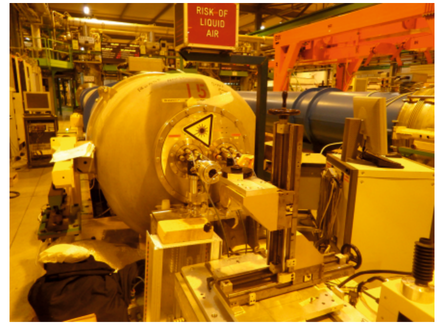
OSQAR experiment in SM18

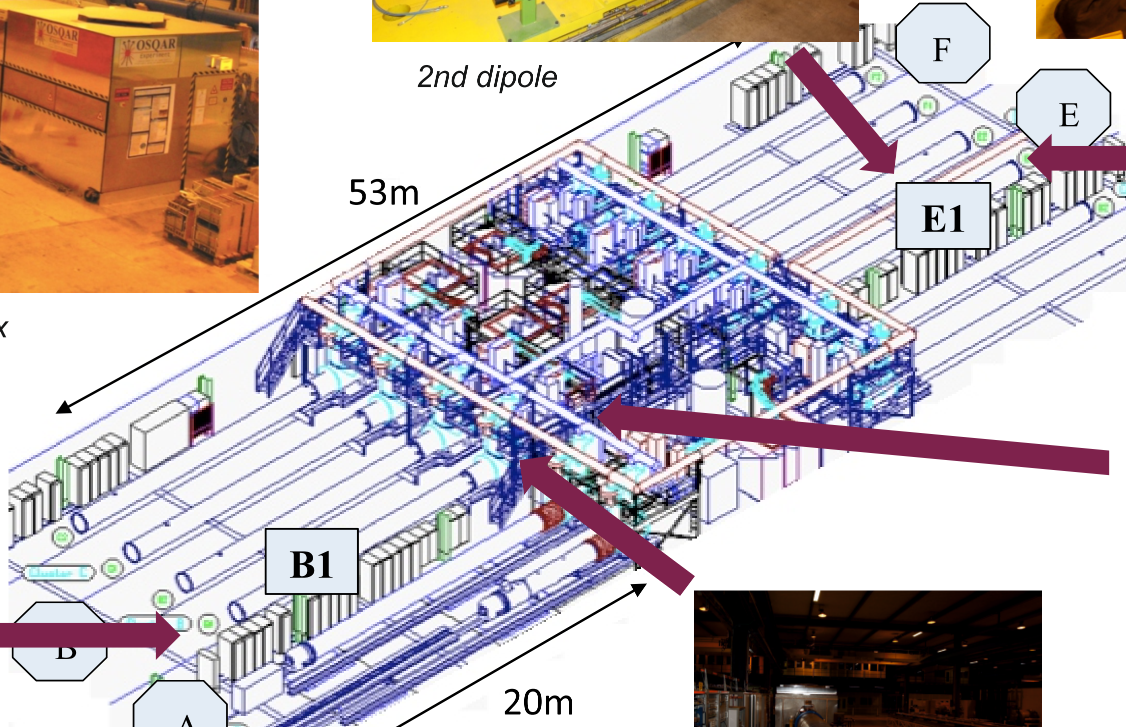
2 dipoles in line for ALPSs measurements

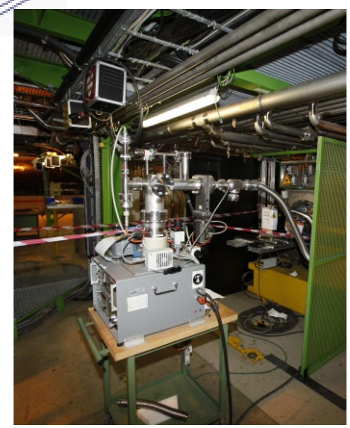
OSQAR box

2nd dipole

End of 2nd dipole







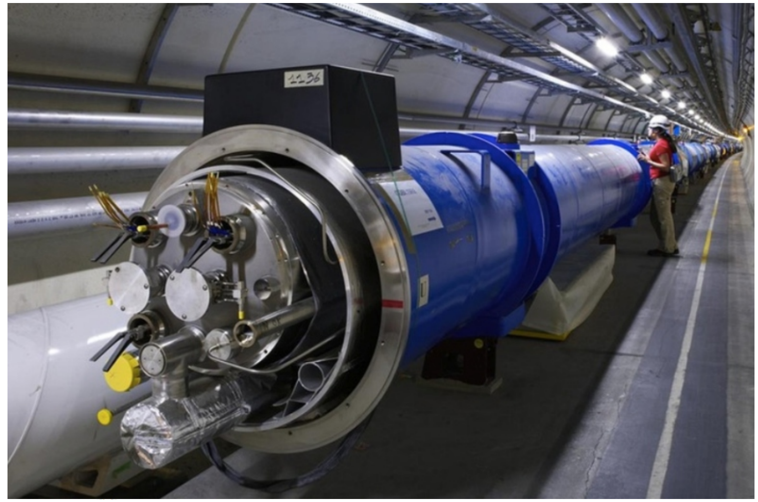
End of 1st dipole

1st dipole

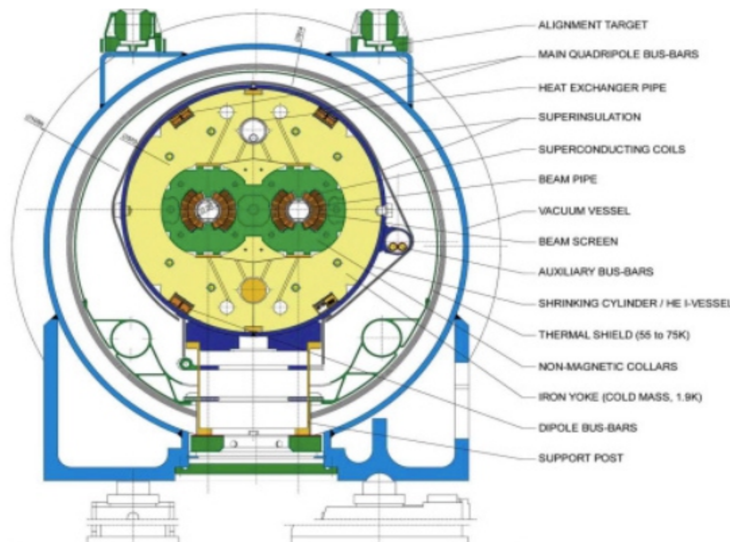
1 dipole for VMB & Chameleons measurements

LHC Magnets

- Standard spare magnets for LHC
  - Cooling(1.9K) and vacuum facilities
    at **CERN SM18** magnet tesing hall
  - Approximately 6-8 weeks per year for OSQAR experiment



- Properties
  Magnetic field of **LHCdipole 9.0T**
  Effective **length14.3m**
  Field is perpendicular to the 2 pipes



Brief history of OSQAR

2007 - start of OSQAR collaboration
2007 - 2008 - VMB I measurements - CM in air
- double pass, rotating wave plate

2010 - start of LSW measurements
- 3W laser , CCD QE 30%

2012 - 2014 - VMB II measurements - CM in N2, argon
- EOM modulated ellipsometer
- single pass

2013 - LSW measurements
- 15W cw laser, CCD QE 50%
- first optical cavity test

2014 - LSW measurements
- 18.5W cw laser, CCD QE 86%

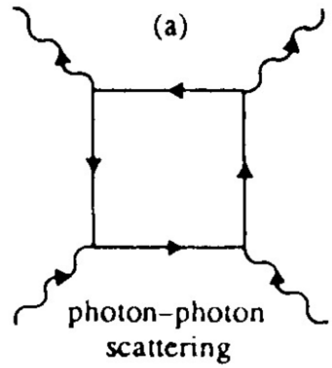
2014 - Set - up testing for Chemeleon run
2015 - Chameleon measurements

VMB

Vacuum magnetic Birefringence

Vacuum Magnetic Birefringence

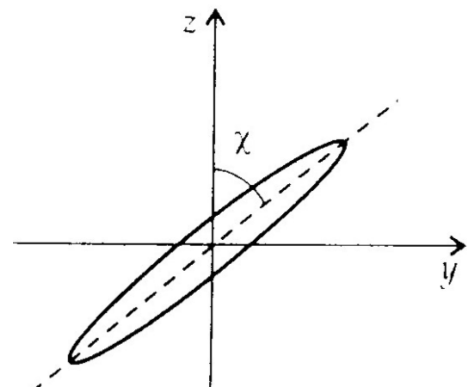
- W.Heisenberg and E.Euler (1935): Consequences of Dirac's Theory of the Positron
- Prediction of Vacuum Magnetic Birefringence
- The effective Lagrangian for photons in QED has nonlinear terms



$$L = \frac{(E^2 - B^2)}{2} - \alpha \cdot \frac{(E \cdot \Delta E - B \cdot \Delta B)}{30\pi m^2} + 2\alpha^2 \cdot \frac{(E^2 - B^2)^2 + 7(E \cdot B)^2}{45\pi m^4} + \ldots$$

- Vacuum magnetic "anomaly" of the refraction index

$$\Delta n = 4.0 \times 10^{-24} B^2$$



- The QED light - on - light scatering produces ellipticity in the linearly polarized light travelling in the transverse magnetic field

Cotton - Mouton effect

- Cotton–Mouton efect - birefringence in liquids and gases in the presence of a trasverse magnetic field

- Weakest in gases - $\Delta n($ B/1T$^{2}\cdot$P/1atm)

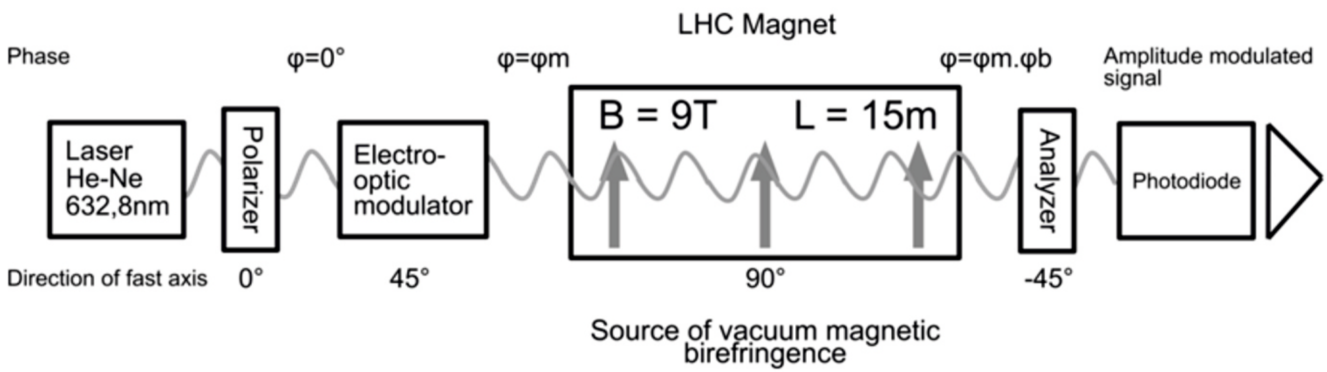
  O2 - $\Delta n \approx -(2.5)\cdot 10^{-12}$
  N2 - $\Delta n \approx -(2.28)\cdot 10^{-13}$
  Ar - $\Delta n \approx (5)\cdot 10^{-15}$
  He - $\Delta n \approx (2.4)\cdot 10^{-16}$

- **Cotton – Mouton effect is the same effect as VMB, therefore we use it for calibration of ellipsometer.**

- Cotton – Mouton effect shows linear dependence on gas pressure.
  – Residual gas is one of possible sources of fake signal

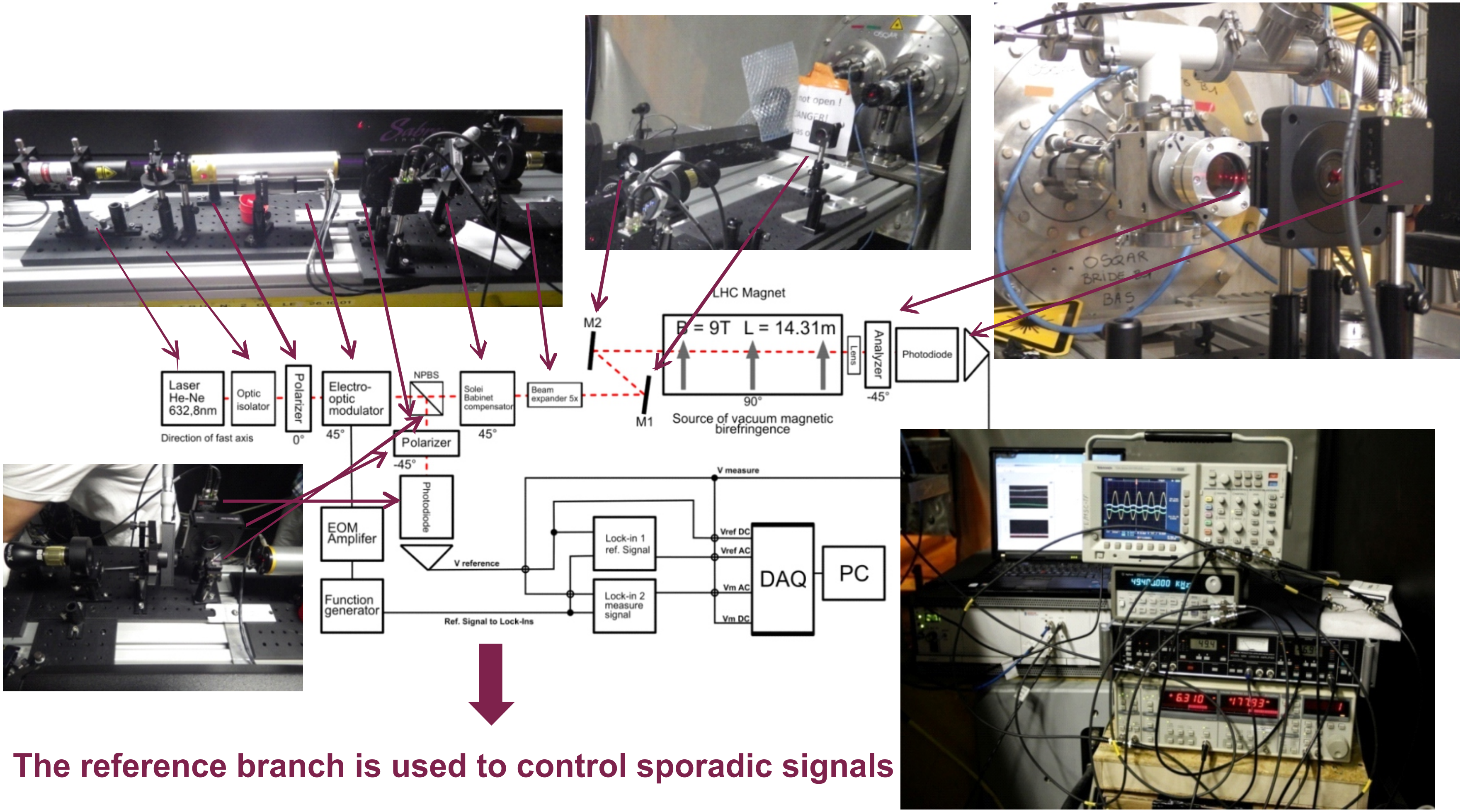
The measurement principle and setup

- experiment uses a polarization modulation techniques for measuring optical birefringence
- higher sensitivity compared to static methods
- Polarization modulation using an electro - optic modulator up to order of 30 MHz



$$I_m = I_0 / 2(1 + \sin(\delta)\sin T), \ \sin(T_0 \sin \omega t) = 2/2 \sum_{m=odd} J_m(T_0)\sin(m\omega t)$$

Setup of Cotton - Mouton measurement

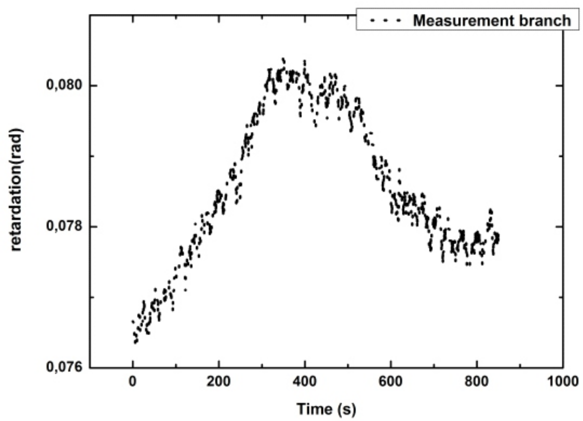


The reference branch is used to control sporadic signals

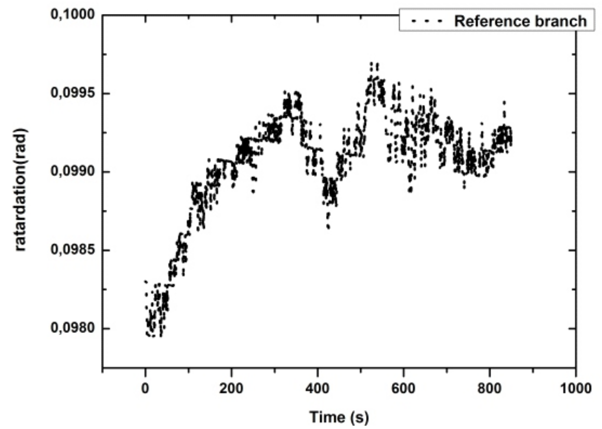
The results of measuring Cotton - Mouton in N2

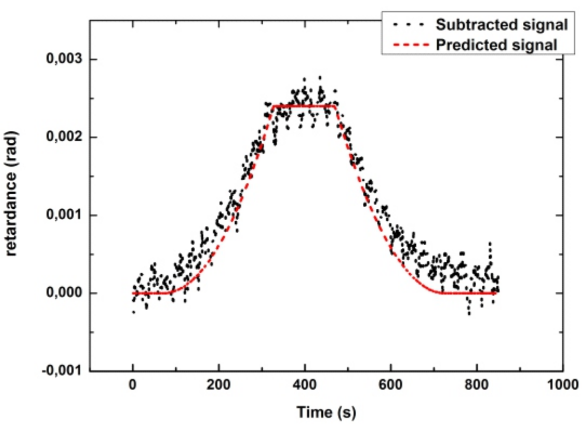
Measurements in N2 gas 1bar 0-9T

Birefringence signal in measure branch

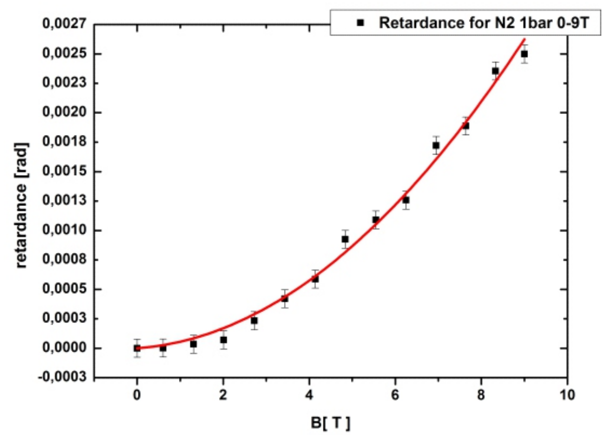


Birefringence signal in reference branch





subtracted signal as function of time

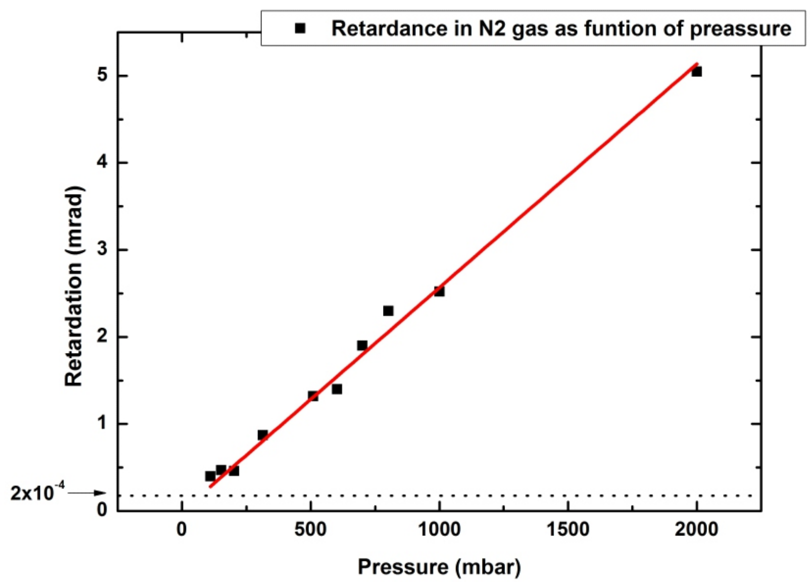


subtracted signal as function magnetic filed

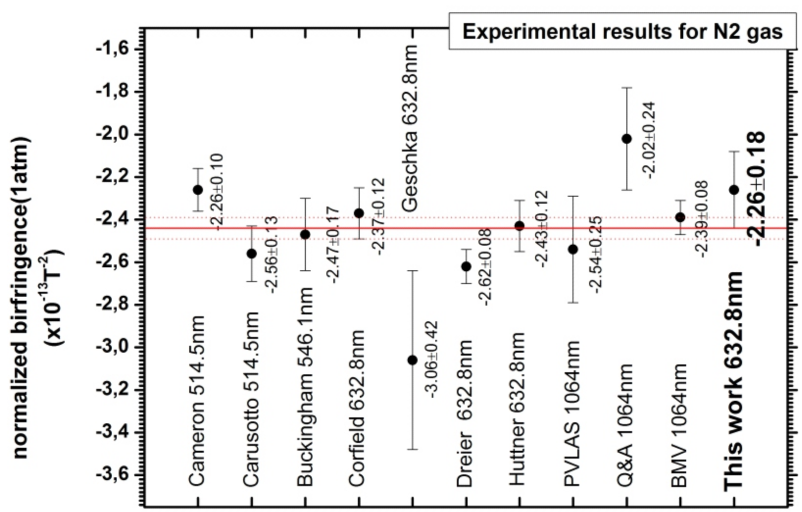
The results of measuring Cotton - Mouton in N2

Measurements as function of pressure
100 - 2000 mbar

Birefringence as function of pressure



Comparison with other experiments



Conclusion of birefringence measurement

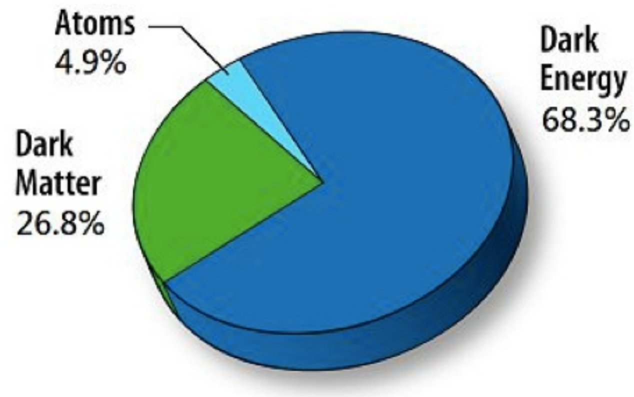
- The lowest measurable value of birefringence for one passage LHC magnet is **2×10^{-4} rad**
- For the He-Ne laser and 14.3 m long LHC magnet is the lowest measurable difference in refractive index **$\Delta n \approx 1.8 \times 10^{-14}$ in 9T field**
- **All previous measurements were realized without the use of optical cavities**
- **Optical cavity may increase the sensitivity by a factor of 10^3**
- **We are still far from the value set by QED, but due to the finesse of the cavity 10^3 will be able to measure the CM effect in helium.**

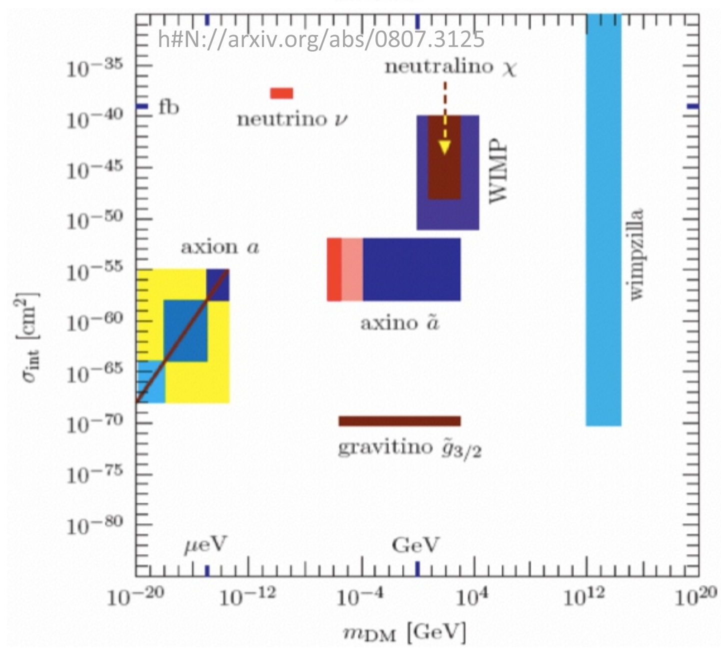
LSW

Light Shining through the Wall search for Axions and ALPs

Why do we look for Axions/Alps?

- Standard Model of particle physics describes „perfectly“ the known properties of matter and forces
  - No explanation of **dark matter**
- Many DM candidates in theory
- Two candidates stand out due to their **convincing physics case** (and because we can test them)
  - Weakly Interacting Massive Particles **(WIMPs)** ,such as neutralinos
  - Very Weakly Interacting Slim (=ultra-light) Particles **(WISPs),** such as axions



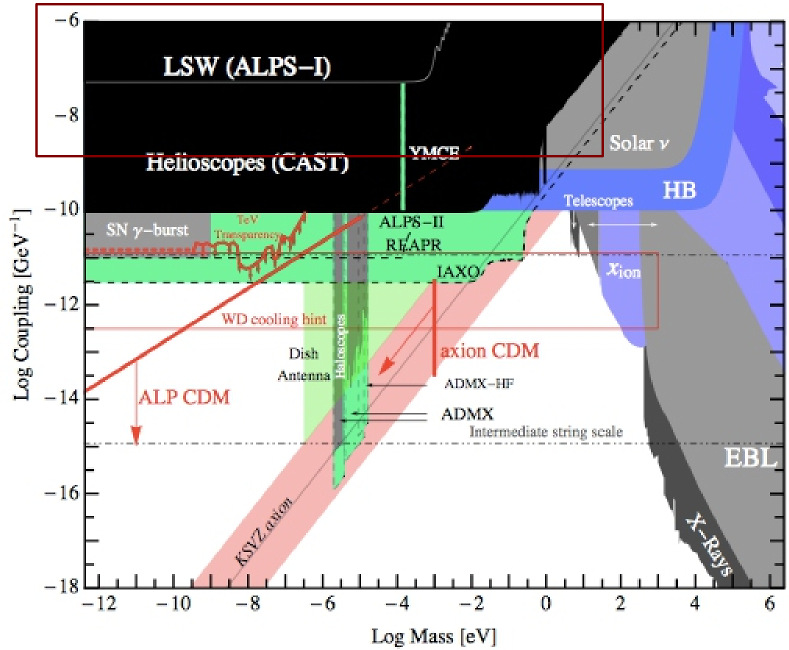


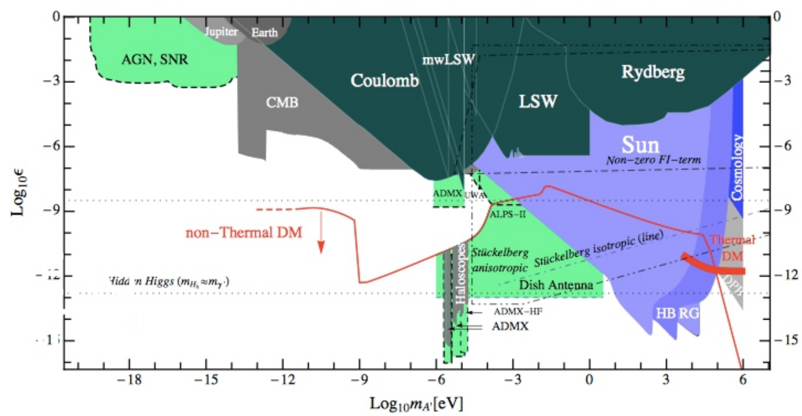
Searches for Axions and ALPs

- **Variety of methods** to test and search for ALPS signatures
  - Astrophysical and cosmological bounds
  - Searches in Colliders
  - Cavity based experiments
  - Photo-Regeneration experiments

  …

- **Note: Most limits have a strong model uncertainty**
  - Cleanest way to test models/ search for ALPS is a purely lab-based experiment



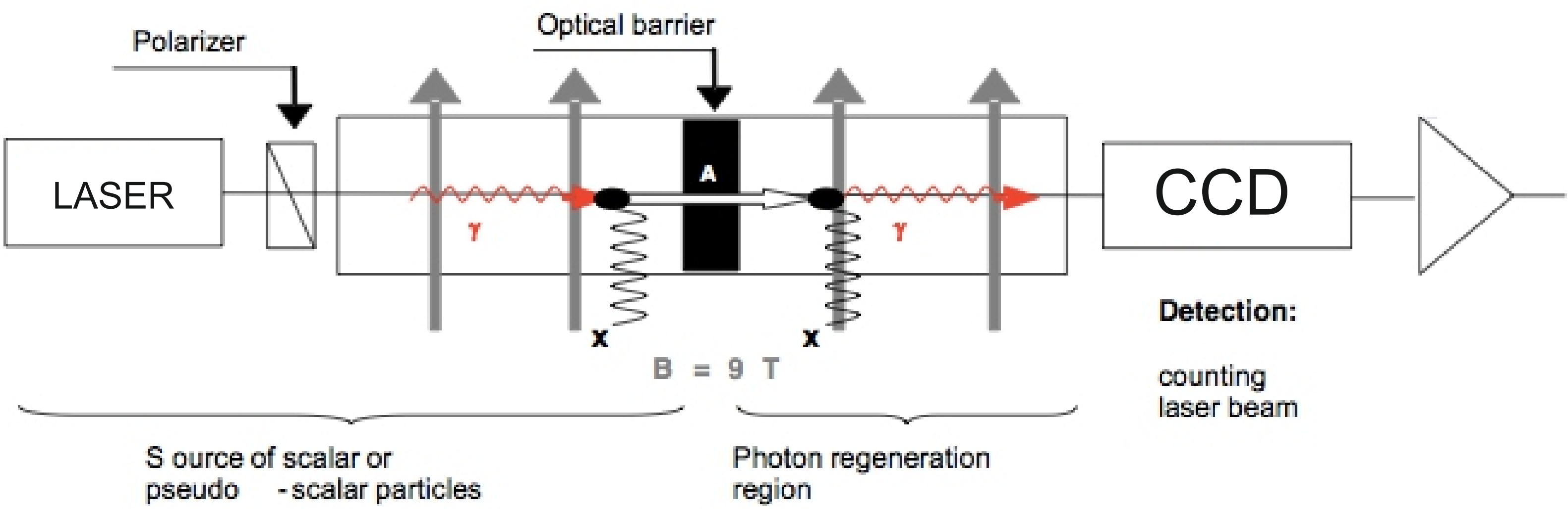


h#N:// arxiv.org/pdf/1311.0029v1.pdf

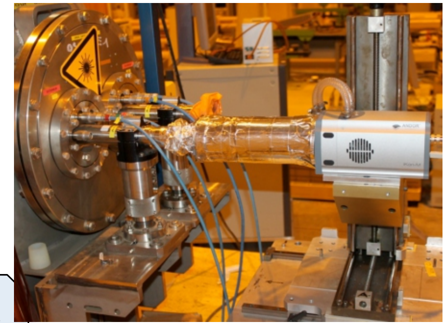
Photon regeneration effect (LSW)

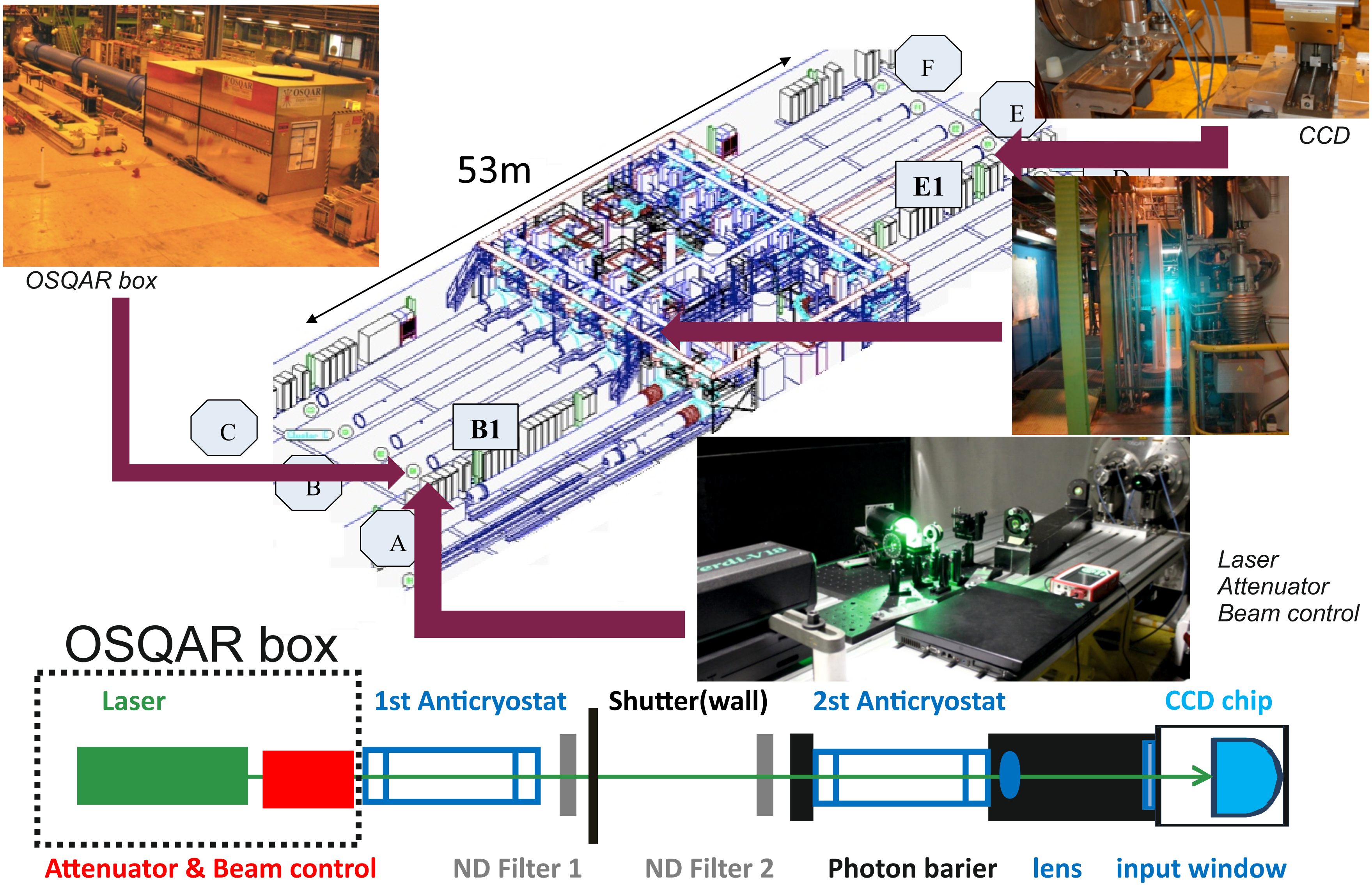
- Axions and ALPS couple to photons in the presence of strong magnetic fields

- The photon regeneration efect is looked as a light shining through the wall
  - Two magnets separated by an optical barrier
  - Photons on one side transform to axions, pass the wall and regenerate on the other side

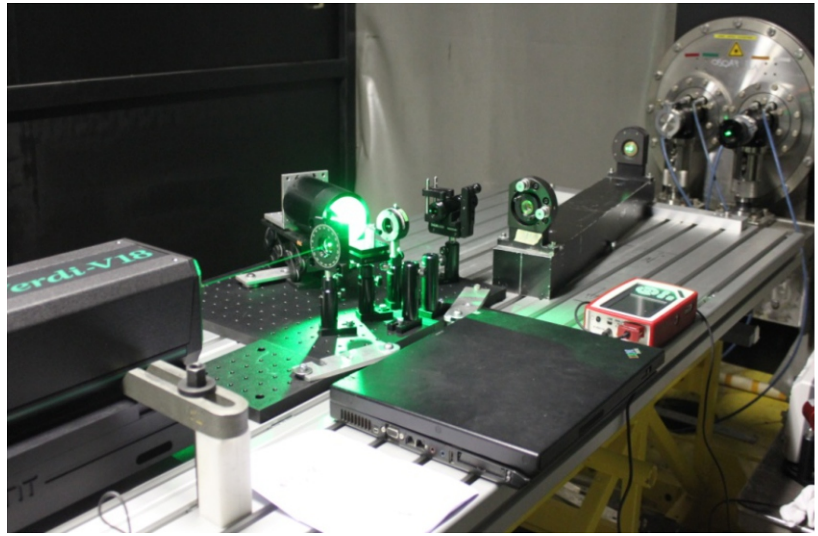


LSW setup in SM18





Laser & optics 2014



- **Photon Source:**
  COHERENT Verdi v18 Laser
    - optical power of **18.5W**
    - continuous laser CW
    - single frequency **532nm (2.3 eV)**
    - Linearly polarized
- **Beam Control:**
    - beam attenuator 1:500
    - beam expander 4x
    - precise mirror alignment
    - 2x ND filters
    - λ/2 plate for polarization control
    - optical lenses for beam focusing
    - Power meters
    - opticla windows

All parts with antireflection coating
overall power loss on all optical elements is **17%**

CCD Camera 2014

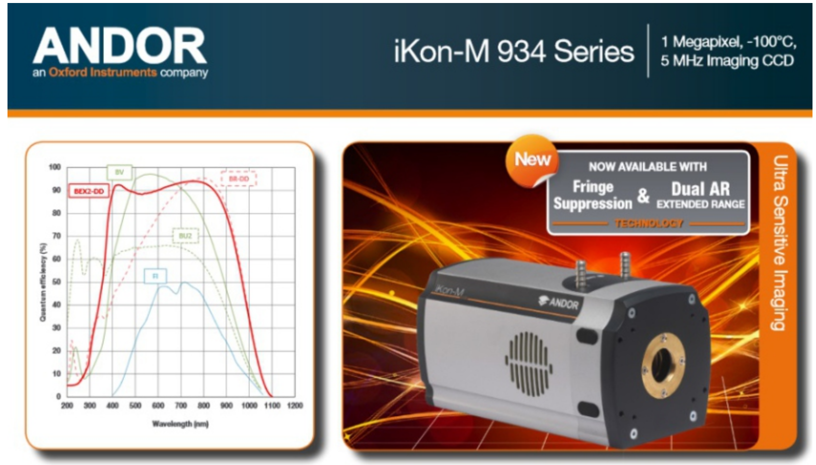
- 95% of laser spot is focused on area of $0.8 mm^2$

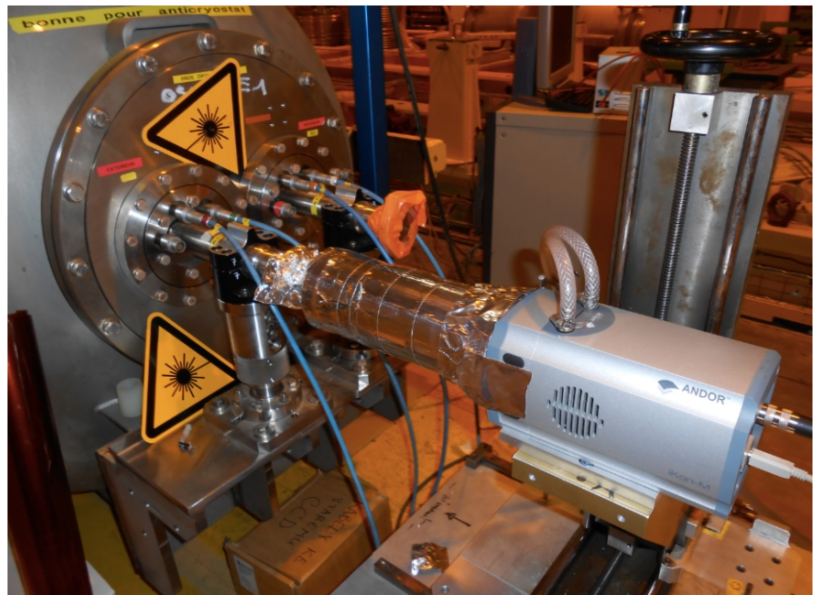
- Thermoelectric cooled CCD
  ANDOR DU934P-BEX2-DD
  Active area 13.3x13.3mm
  2D array of 1024x1024 px
  1px size of $13 x 13 \mu m^2$

- Operating temperature: -95°C
- Dark current: $0.0012 e^-$/pixel/s
- Readout noise: 2.5 e^- rms/pixel
- QE : 88% at 532nm
- Sensitivity: $1.3 e^-$/ADU

- Setup efficiency was measured as

η= 0.56±0.02 ADU/photon





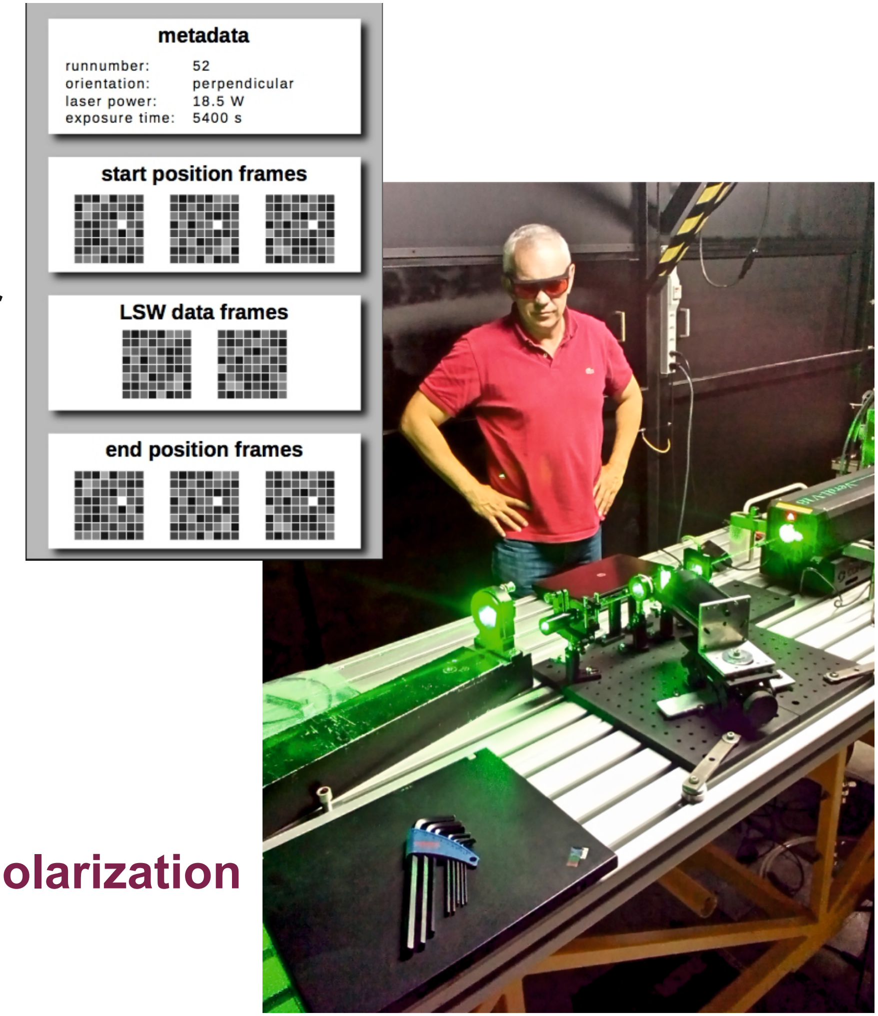
Data-Taking Procedure in 2014

- **1st Step**: Open optical barrier and record laser position
  Three measurements of 0.1s whit interval of 120s

- **2nd Step**: Close opticla barrier
  Record two frames 5400s separated by 60s

3rd Step: Open optical barrier and record laser position
Three measurements of 0.1s whit interval of 120s

Run 2014: August - September
Total number of runs: 60 for each polarization
Scalar search: 180 hours
Pseudo - scalar search: 180 hours



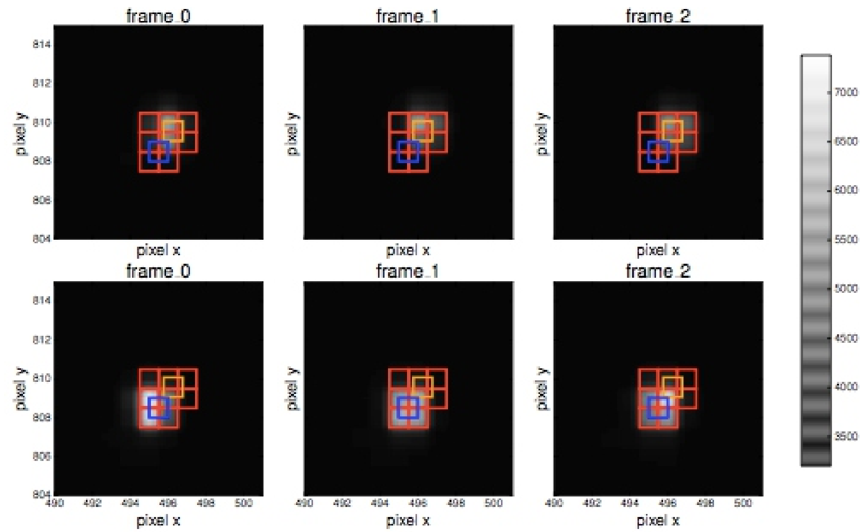
- **Periodic check and long time measurements of laser spot alignment**

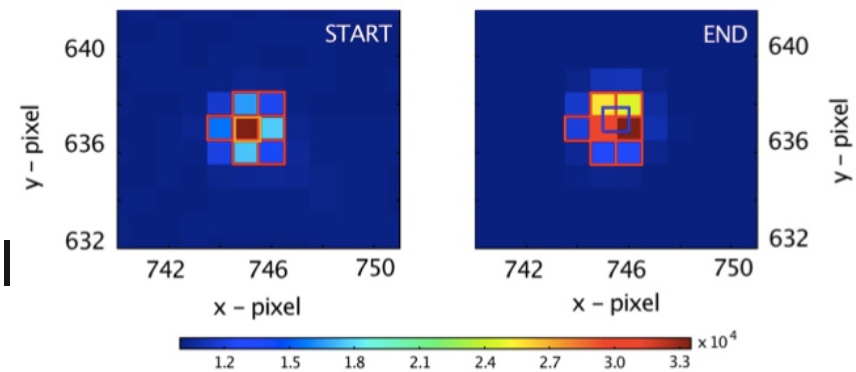
Laser spot movements and Signal Region

- Find laser positions in start end frames

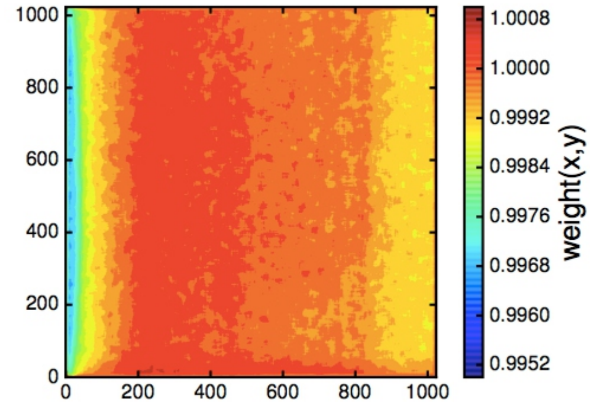
- Determine spot - size by fitting 2D Gaussian 1,2σ levels indicas the signal region

- Assume straight line between start and end position
  - Tested by long duration laser tracking
  - Define signal- region by all pixels closer then 2σ to line

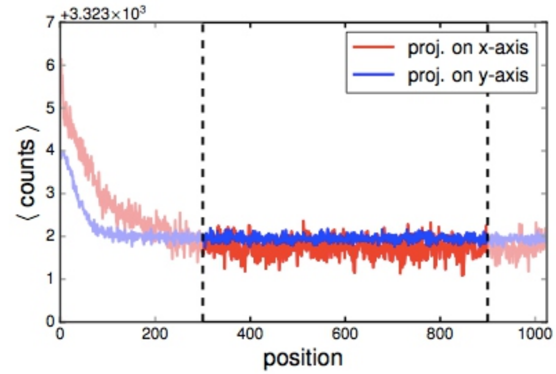




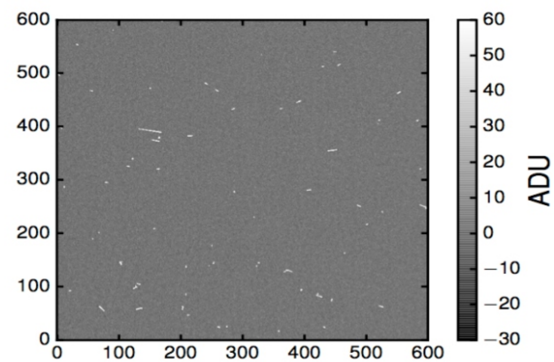
Cleaning the Data in each Run



- **Correct temperature induce inhomogenities**
  - create corretion weight for each pixel
  - robust against cosmic
  - Preserves possible signal excess



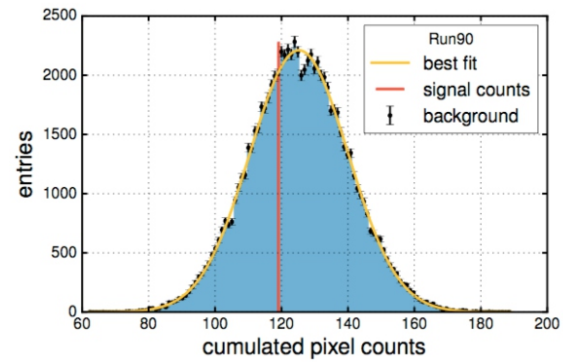
- **Remove intrinsic inhomogeneity in gain**
  - Bias frame, subtracted from each run
  - Only consider part where bias is flat



- **Exclude cosmic ray hits and hot pixels**
  - use threshold clipping
  - Mask pixels exceeding to signal region
  - Exclude pixels belonging to signal region

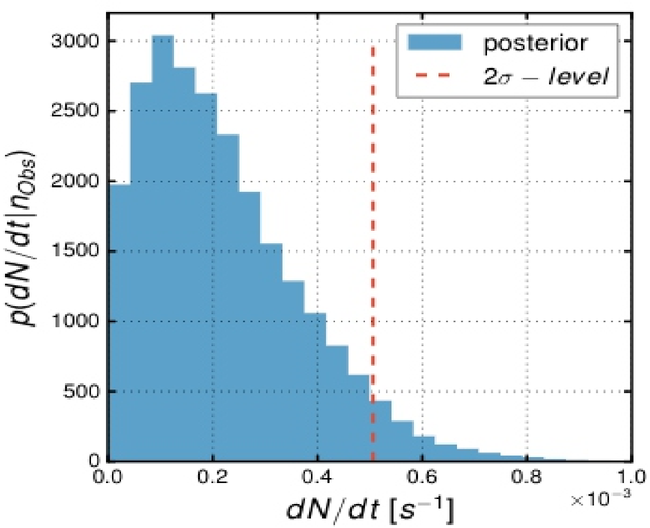
Final counting and data combining

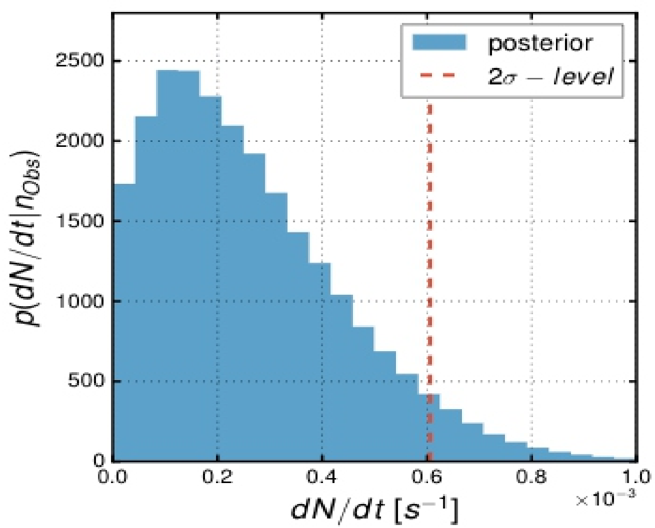
- After all cleaning procedures we count ADU's in the signal regoin and fit gaussian to background $\chi^2/\text{n.d.f.} \approx 1$



- We have diferent sized regions in each run
  - **Bayesian inference** crate combined likelihood model of all valid frames

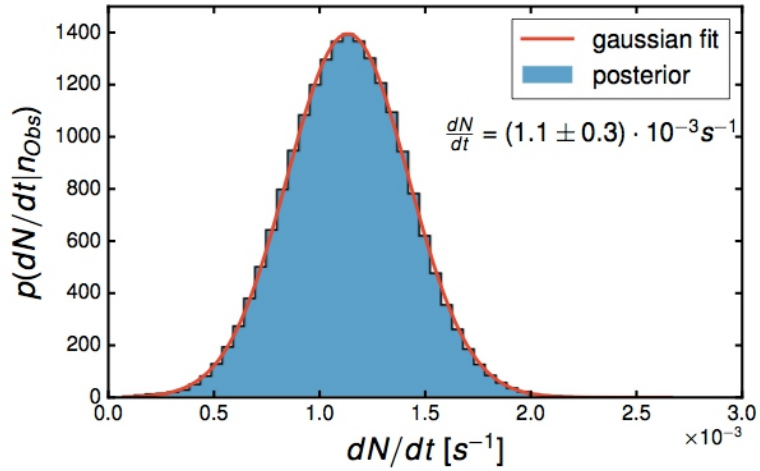
$$\mathcal{L} = \prod_{\text{frame}} \text{Gauss}\left(N_{\text{frame}} \middle| \text{Pois}\left(\frac{dN}{dt} \cdot t_{\text{frame}}\right) + \mu^{(bkg)}_{\text{frame}}, \sigma^{(bkg)}_{\text{frame}}\right)$$





Consistency tests

- Expected sensitivity given the observed from of the background and the recorded photon flux
- **dN/dt = 0.5 - 0.6 mHz**
- How to be sure that cleaning procedure does not affect a possible signal?



- Impose fake signal at 2σ level (1.0×10^{-3} photons/s) on each recorded frame at the background region and repeat analyses
- look a postrior distribution of photon reconverted rate with the imposed fake signal
- **Observed dN/dt = 1.1±0.3 mHz**

Final Exclusion Limit

- No significant axcess over the expected bakcgroundd rate

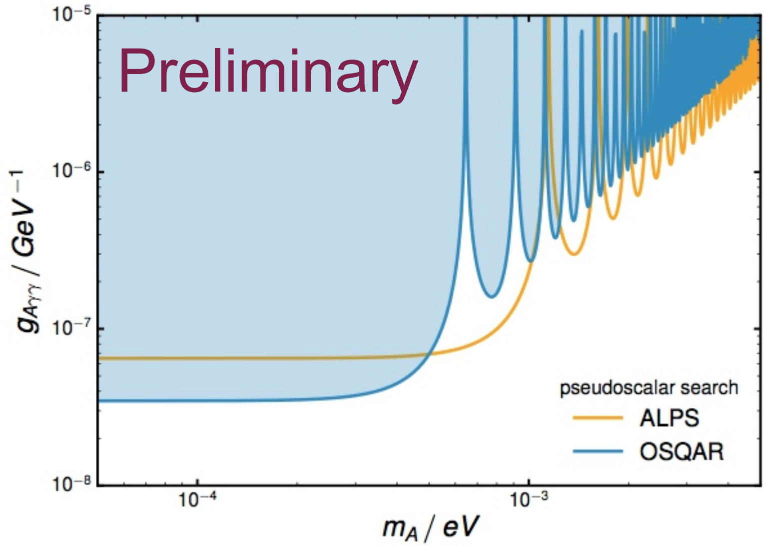
- Derive 95% Confidence limit on the reconverted photon flux via the posterior distribution of the signal parameter dN/dt

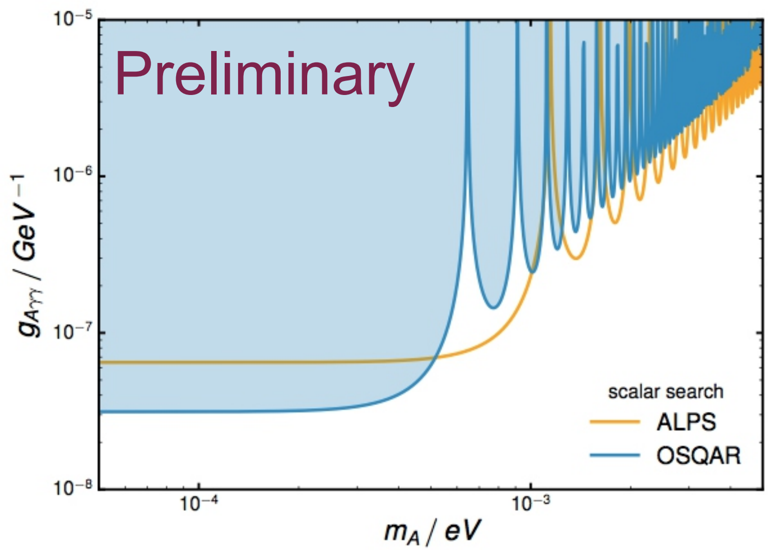
World leading limits in laboratory based Axion/ALPS sercheas

pseudo-scalar: $g_{A\gamma\gamma}$<3.5·10^{-8} GeV^{-1}

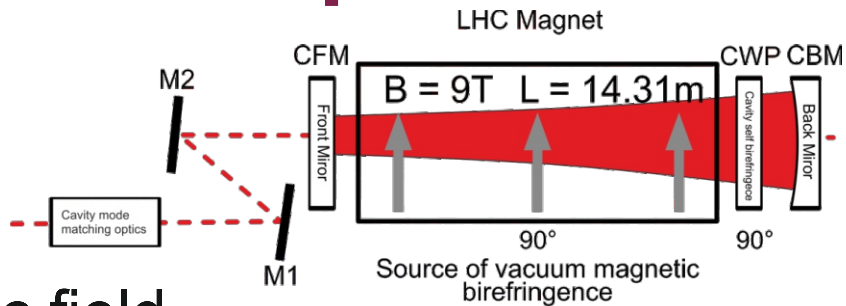
scalar: $g_{A\gamma\gamma}$<3.2·10^{-8} GeV^{-1}

Preliminary





How to improve OSQAR experiment



1. Optical cavities

- VMB - longer path in magnetic field
- LSW - high power build up, more photons
- First test in 2014 whit 3m long prototype

2. High Power laser, lower frequency(IR)

- LSW - more photons

$$g \approx \left(n_\omega \cdot \frac{\omega}{\eta_\omega \cdot P_\omega \cdot t}\right)^{1/4}$$

3. Better detector - single photon

4. Excellent laser stability and propagation factor

5. Optimization of experiment to statisti

- space or time correlation

6. More LHC dipoles

Long term Perspectives LSW

Resonantly Enhanced Axion-Photon Regeneration

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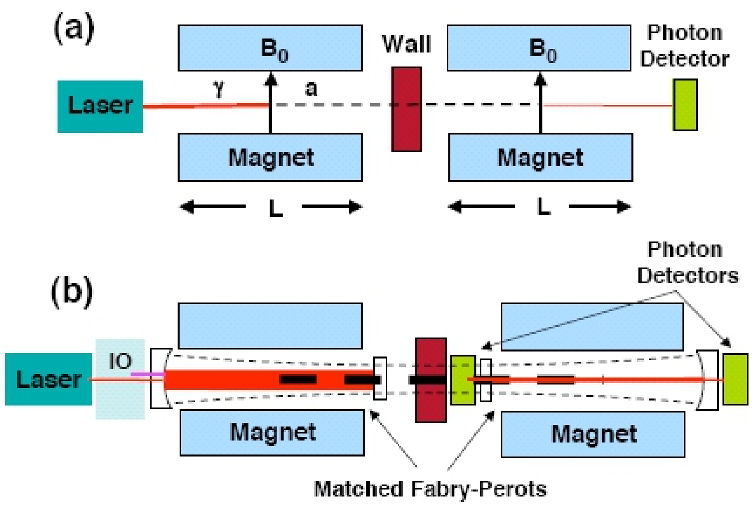
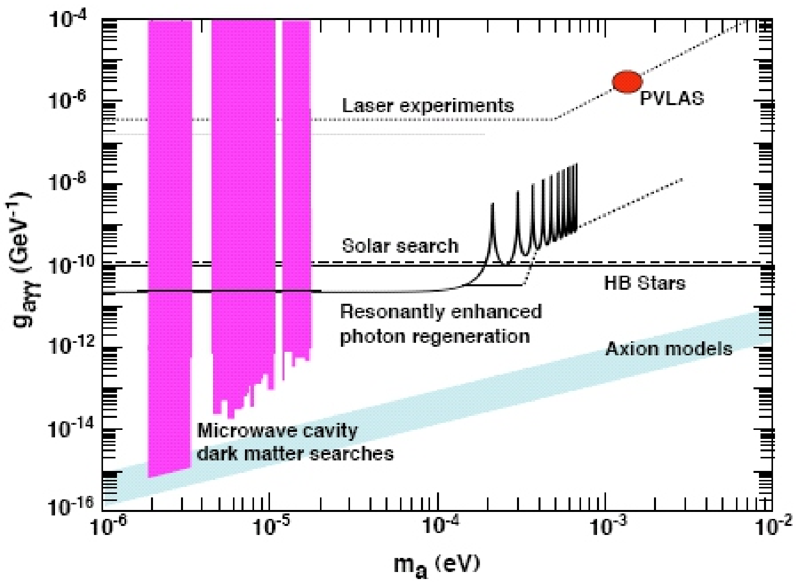
Phys. Rev. Lett. ***98****, 172002 (2007)*



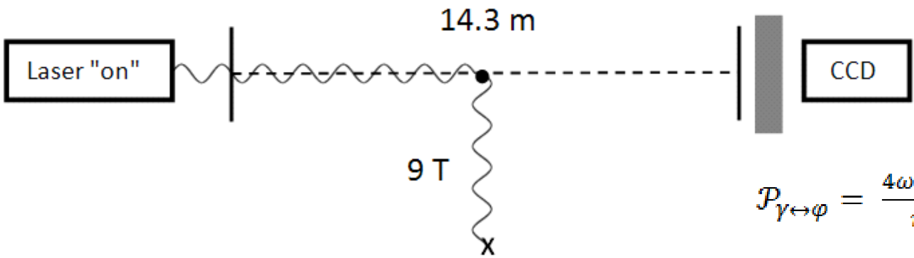


With 4 + 4 LHC Dipoles, i.e. Experiment of ~150 m long,…

Ongoing discussions for Super-OSQAR, i.e. 2 + 2 LHC dipoles, possibly with ALPs

Future plans of OSQAR 2015

2015 - CHASE (Chameleon Afterglow Search Experoment)

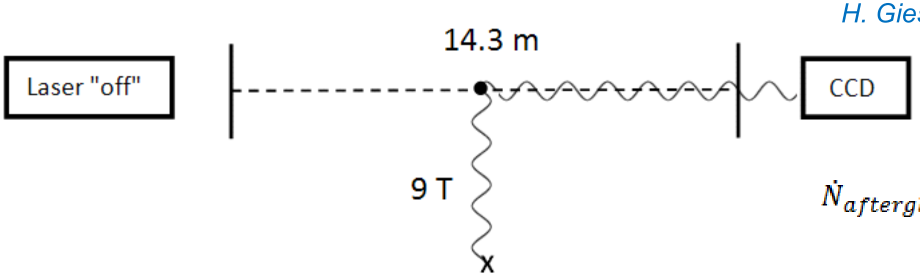


*G. Raffelt and L. Stodolsky. Phys. Rev. D **37**, 1237–1249 (1988)*

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

Phase 1: Filling the "jar" with chameleons, produced by 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)



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

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

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

- More delicate analysys then LSW - model dependent
- Non magnetic afterglow observed by Gemme V - CHASE
- Limit can be lowered by factor 3-4 (B = 9T,P = 18.5W, η = 0.87)

Conclusion

- **No sign of ALPs at the OSQAR 2014 run**
  - Most stringent limits on the $g_{A\gamma\gamma}$

- **Further progresses required mostly to increase the magnetic field length and optical power**
  - **Optical cavities**
  - more dipoles
  - new laser

- **New proposal for chameleon search: OSQAR-CHASE, ready for operation in 2015**
  The present reference limits obtained by GammeV-CHASE is expected to be improved by a factor of about 3-4, thanks to the increase of the magnetic field, optical power and detector efficiency.

- **possible OSQAR-ALPS collaboration under discussions**