ALPs and WISPs – Illuminating Hidden Worlds

Light Shining Through a Wall

Axion Like & Any Light Particle Searches

WISP Search in Lab. Experiments

K. Ehret – ALPS Collaboration, DESY

XLVth Rencontres de Moriond - EW

La Thuile, March 12th, 2010

Outline

Illuminating Hidden Worlds

Particle Physics at Lowest Energies

- Axions – a Brief Introduction
- ALPs and WISPs

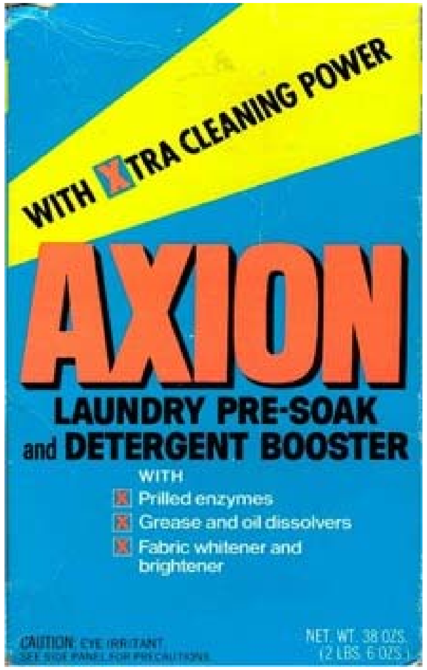
see also talk by Malcolm Fairbairn

- Direct WISP Search:
  - Experimental Challenges - Small Signals
  - Setups - Light Shining Through a Wall
- ALPS Experiment at DESY
- Preliminary Results – ALPS I
- Steps Towards Astrophysical Bounds
- Conclusions

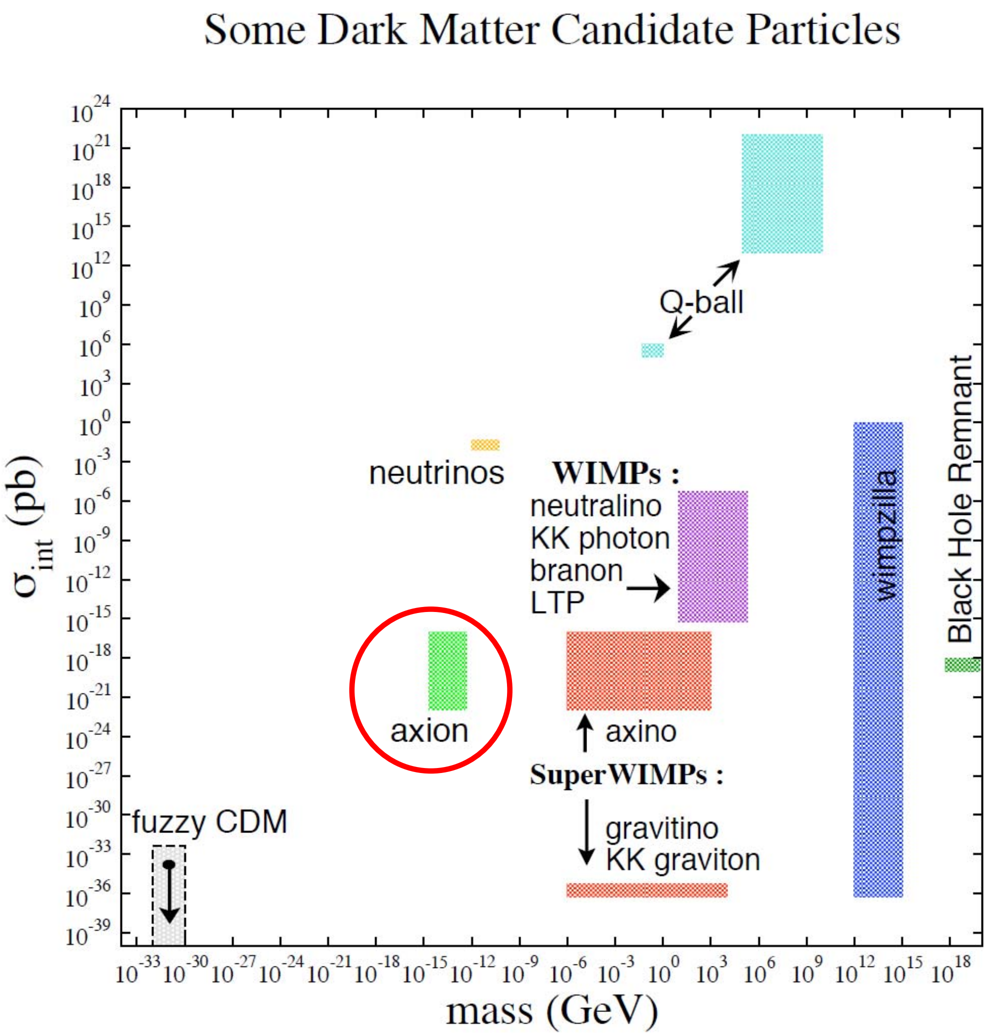
Reminder: QCD Axion

Experiments show that QCD conserves C•P!

- size of C•P violation in QCD described by angle Θ
- Missing electric dipole moment of neutron: $\Theta < 10^{-9}$
- CP Conservation explained by Axion
  - additional U(1) chiral symmetry (Peccei-Quinn, 1977) predicts a new particle
  - Wilczek and Weinberg noticed 1978 oscillation of Θ constitutes an axion-field
  - name introduced by Wilczek - Axion “cleans” QCD (like the detergent)
  - Axion: very light & couples very weakly
- Axion remains not only as
  - a solution to the CP conservation of QCD,
  - but also as a candidate for Dark Matter.



Dark Matter could be Axions!



H. Baer, presentation at 5th Patras Workshop on Axions, WIMPs and WISPs, 2009

A QCD axion in the mass region of 10^{-5} to 10^{-4} eV would be a "perfect" cold Dark Matter candidate

The axion was not invented to solve the Dark Matter problem!

There could be axion even if they are not Dark Matter!

Many hints from astrophysics to new physics in the sub-eV region (cf. Malcolm Fairbairn's talk)

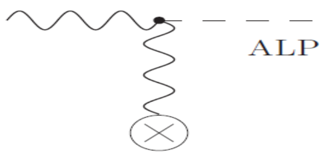
new physics @ low energy frontier

From Axions to ALPs and WISPs

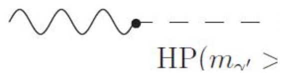
String Theory tells: There might be much more than a QCD axion.

Axions and ALPs, hidden sector photons, mini-charged particles occur naturally in string-theory motivated extensions of the Standard Model

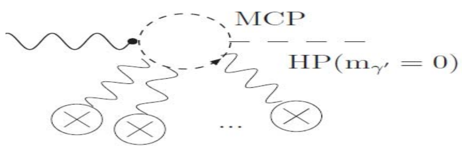
WISPs: Weakly Interacting Sub-eV Particles



- Scalar or pseudoscalar particles: "axion-like particles" ALPs
  exploit the Primakoff effect

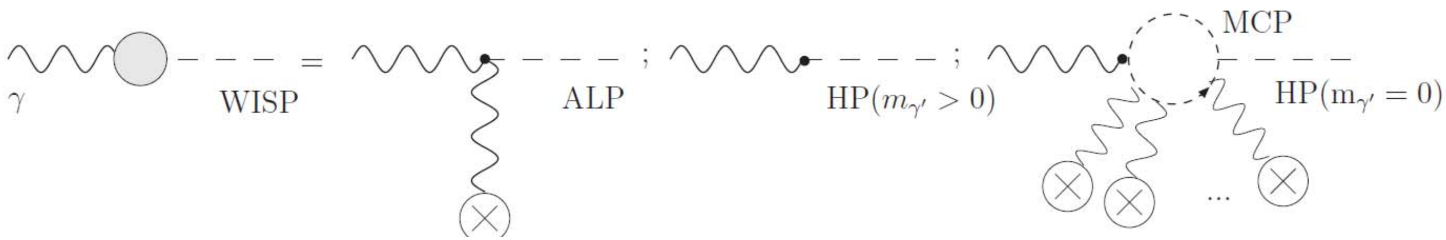


- Neutral vectorbosons: "hidden sector photons" HP
  mixing with "ordinary" photons.



- Minicharged particles (MCP, about 10^{-6} e): "loop effects".

>

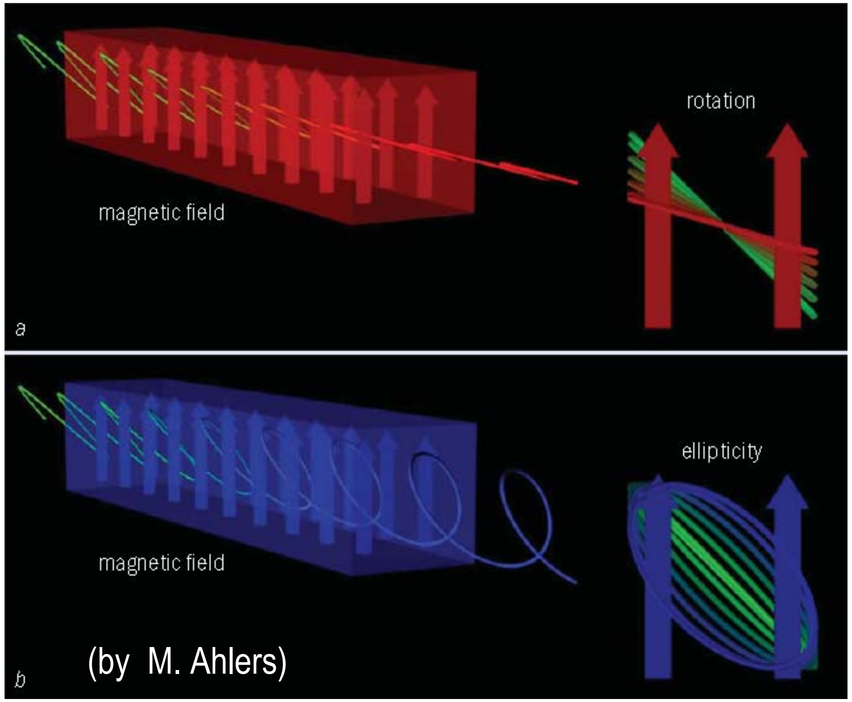


Axion-Like Particles, Hidden Photons, MiniCharged Particles

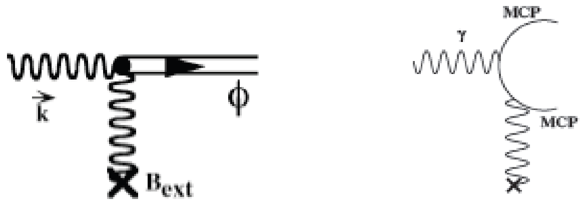
Is there new Physics at low Energies?

Experiments with intense laser beams providing very high photon number fluxes or extremely good control of beam properties.

> **Indirect WISP search**: search for polarization effects

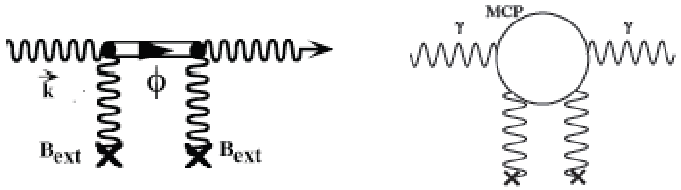


rotation:
dichroism (selective absorption) due to real WISP production



different absorption of light polarized ∥ and ⊥ to the magnetic field

ellipticity:
birefringence (different light velocities) due to virtual WISP production



QED: Δn (⊥ - ∥) = $3.6 \cdot 10^{-22}$ (9.5 T @ LHC dipole)

G. Cantatore, 5th PATRAS workshop 2009, see http://axion-wimp.desy.de/e30/e52240/e54433/GiovanniCantatore.pdf

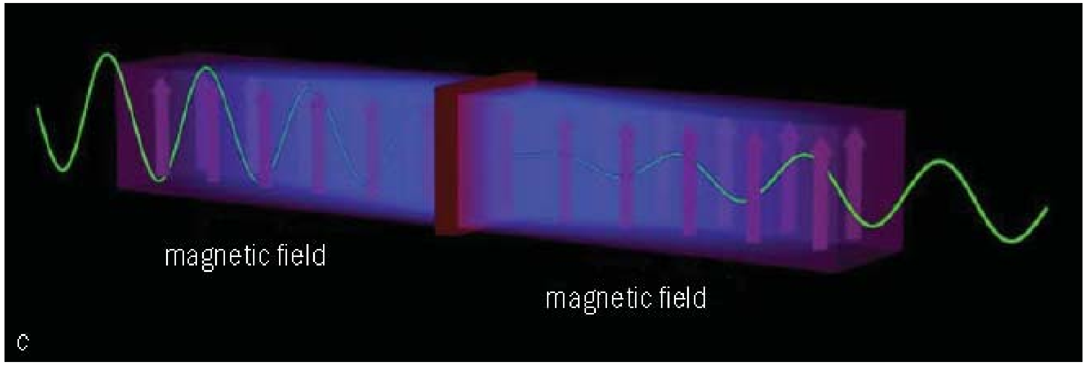
Recent worldwide interest and activities triggered and inspired by the (non confirmed) **PVLAS observation** – change of laser light polarization in magnetic field

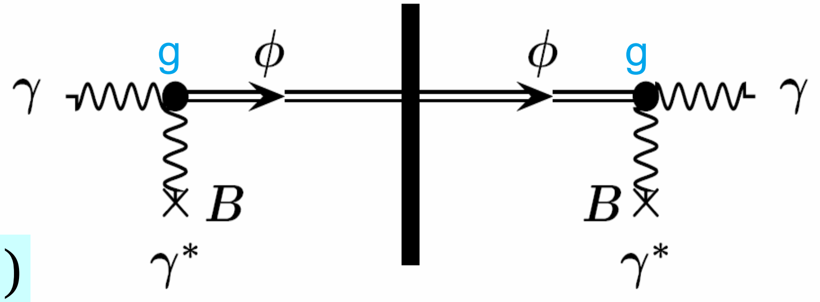
A. Ringwald "Particle Interpretations of the PVLAS Data" arXiv:0704.3195

Direct WISP Search – Light Shining Through a Wall (LSW)

LSW: search for "invisible" ALPs (& other WISPs) in lab experiments

- cross-check of indirect searches,
- determination of properties of new particles
- access to WISPs not detectable in indirect searches





Okun 1982, Skivie 1983, Ansel'm 1985, Van Bibber et al. 1987

ALPs Conversion Probability:

$$P_{\gamma\to\phi\to\gamma} = P_{\gamma\to\phi}(B_1, l_1, q_1)\, P_{\phi\to\gamma}(B_2, l_2, q_2)$$

$$P_{\gamma\to\phi}(B, l, q) = \frac{g^2}{4} B^2 L^2 \frac{\sin^2(qL/2)}{(qL/2)^2}$$

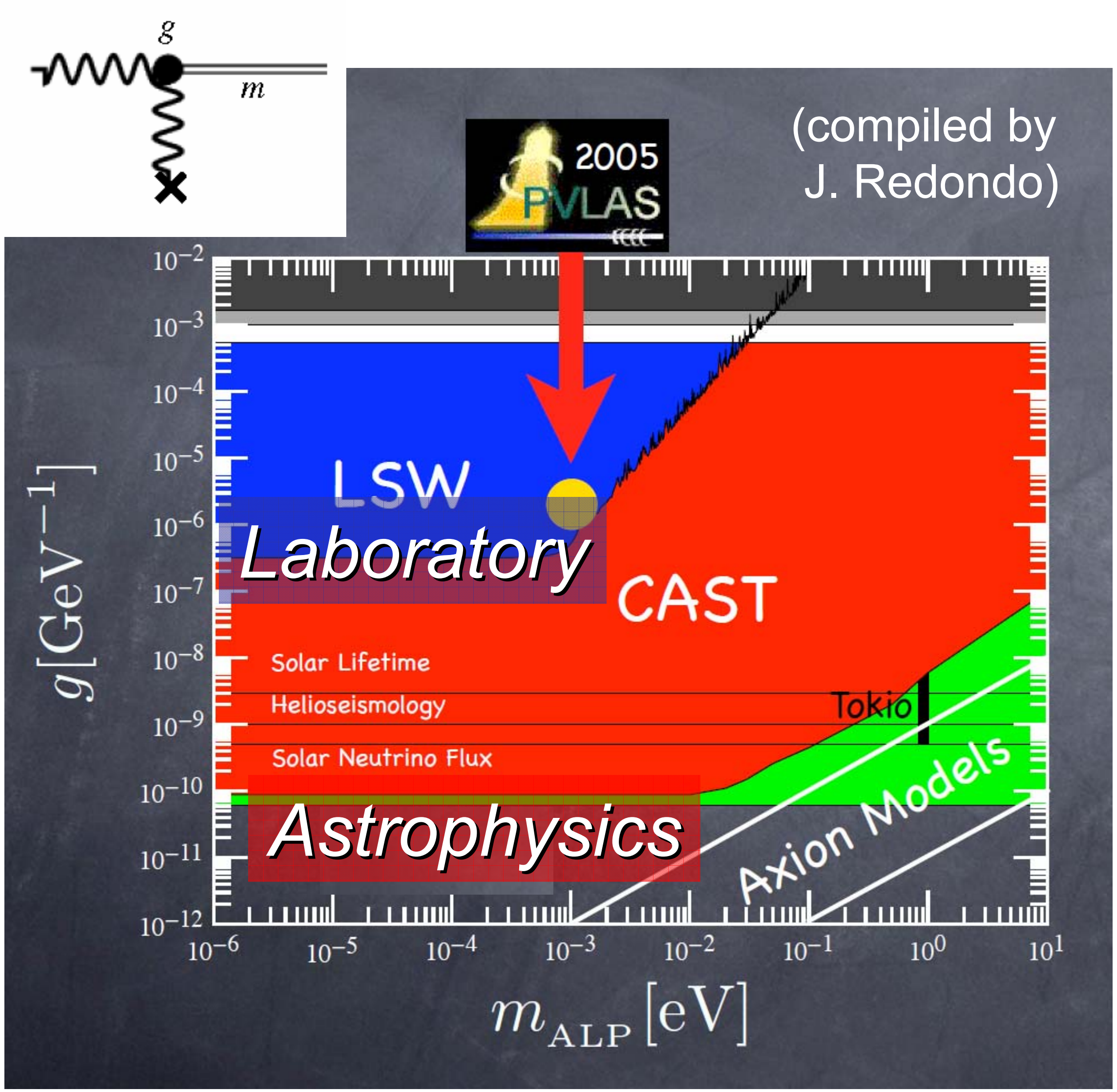
$$q = \frac{m_\phi^2}{2E_\gamma}$$

$$P_{\gamma\to\Phi\to\gamma} \sim g^4$$

Low conversion probability $<10^{-23}$:

- high photon fluxes (intensive laser)
- strong magnetic field (for ALP)
- very sensitive detector (SPC)

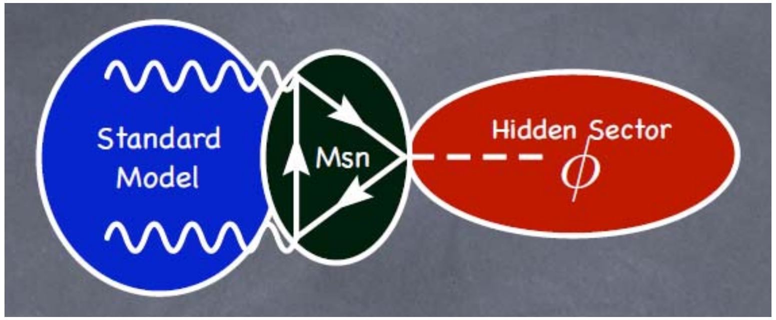
Limits on ALPs



Mainly from Astrophysics (lifetime of Stars, MBR), BFRT, …

Some WISP parameter regions only accessible in lab exp.

Theory starts to develop predictions for WISPs to be confirmed be experiment!



$M_{MSN} \sim \alpha / (\pi g) \cdot O(1)$

In the “hidden sector” models the existing limits probe messenger masses at TeV to PeV scales!

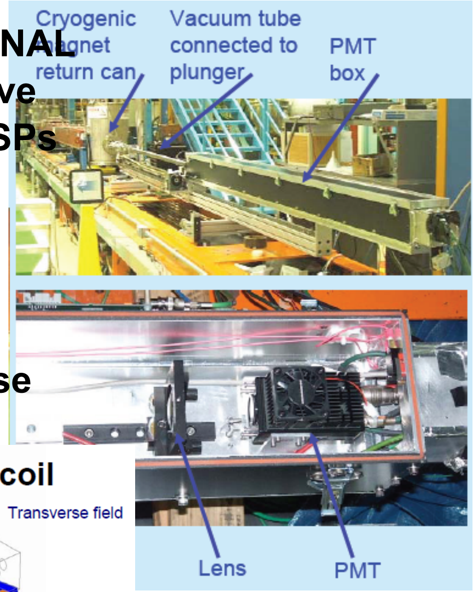
World-wide activities in this research field

Laser Experiments: History & Presence

Experiment	Reference	$\Delta\theta$	ψ	LSW
ALPS (DESY/D) "**A**xion-**L**ike **P**article **S**earch"	arXiv:0905.4159	✘	✘	✔
BFRT (**B**NL-**F**ermilab-**R**ochester-**T**rieste)	Phys.Rev.**D47**(1993)	✔	✔	✔
BMV (LULI/F) "**B**iréfringence **M**agnétique du **V**ide"	Phys.Rev.Lett.**99** (2007) Phys.Rev.D**78** (2009)	✘	✔	✔
GammeV (Fermilab/USA) "**Gamma** to **meV** particle search"	Phys.Rev.Lett.**100** (2008) Phys.Rev.Lett.**102** (2009)	✘	✘	✔
LIPSS (Jefferson Lab/USA) "**LI**ght **P**seudoscalar or **S**calar particle **S**earch"	Phys.Rev.Lett.**101** (2008) arXiv:0810.4189	✘	✘	✔
OSQAR (CERN/CH) "**O**ptical **S**earch for **Q**ED vacuum magnetic birefringence, **A**xions and photon **R**egeneration"	Phys.Rev.D**78** (2008)	✘	✘	✔
PVLAS (INFN/I) "**P**olarizzazione del **V**uoto con **LAS**er"	Phys.Rev.Lett.**96** (2006) Erratum-ibid.**99** (2007) Phys.Rev.D**77** (2008)	✔	✔	(✔)
Q&A (Hsinchu/Taiwan) "**Q**ED & **A**xion"	Mod.Phys.**A22** (2007)	✔	✘	✘

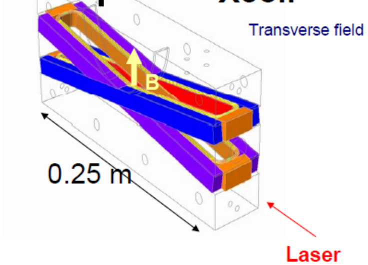
M. Ahlers, presentation at the 5th Patras Workshop on Axions, WIMPs and WISPs, 2009

GammeV@FNAL most sensitive limits on WISPs until 2009

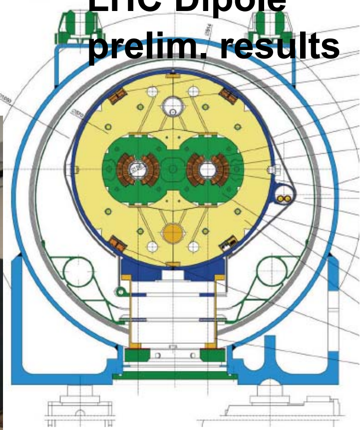


BMV@Toulouse ongoing limits publ.

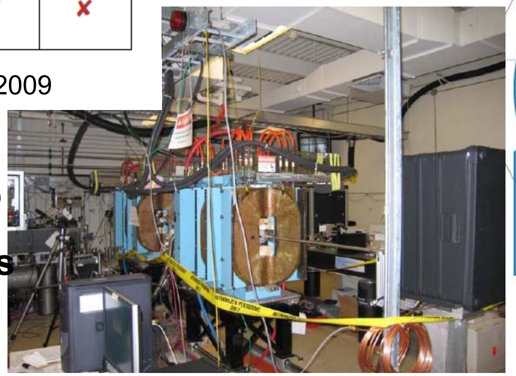
Xcoil

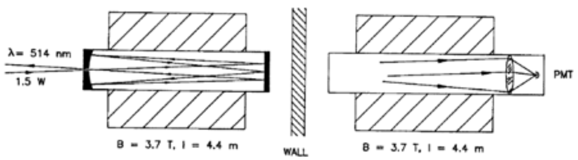


OSQAR@CERN LHC Dipole prelim. results



LIPSS@JLab prelim results





BFRT - finished in 1993

ALPS @ DESY Hamburg

ALPS @ DESY

- **January 2007:**
  Letter of Intent published -> ALPS approved
- **May 2007:**
  dedicated funding for ALPS, decision for green 532 nm laser
  Phase 0: study of systematic, stability, alignment and sensitivity
- **2008:** set-up off an optical cavity
  commissioning run – demonstrating the feasibility of resonant laser power build-up in ALPS (NIM A doi:10.1016/j.nima.2009.10.102)
  Collaboration with gravitational wave community essential
- **2009:** upgrade of system (resonant SHG, cavity in vacuum, detector)
  physics data run with vacuum and gas

Collaboration

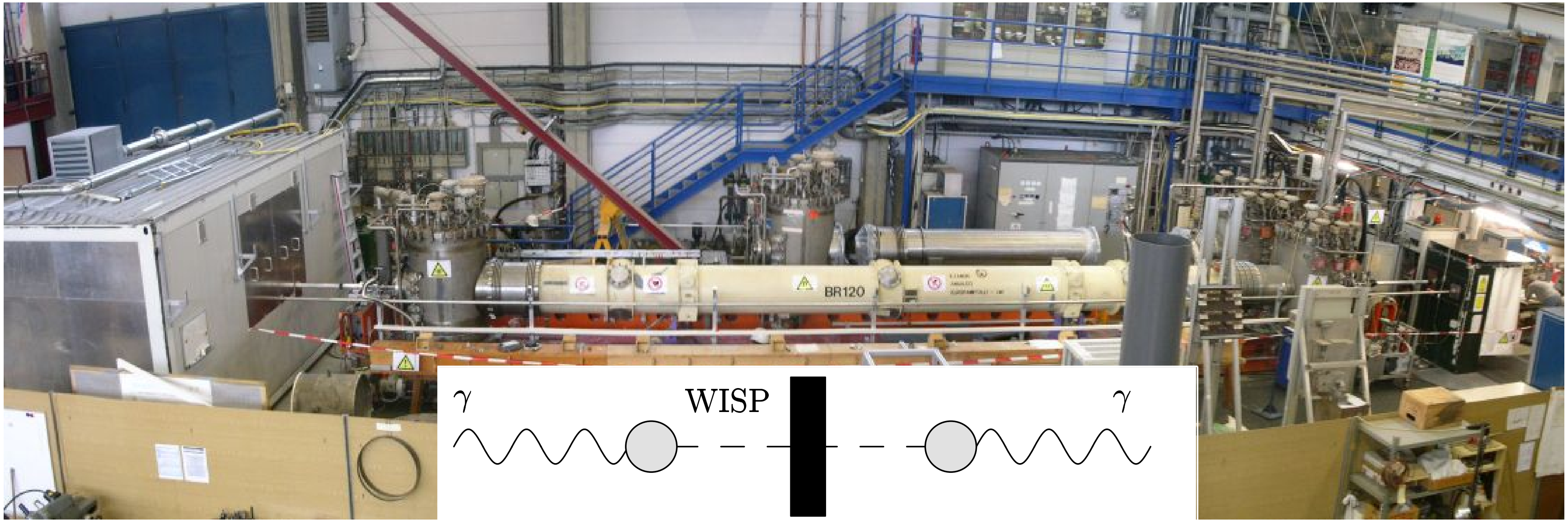
- *DESY*
- *Hamburger Sternwarte (Observatory)*
- *Laser Zentrum Hannover*
- *Max Planck Institute for Gravitational Physics (Albert Einstein Institute)*

Axion Like Particle Search

photon regeneration experiment using a HERA Dipole Magnet

- axion like particles ALP

Any Light Particle Search



photon regeneration experiment using a HERA Dipole Magnet

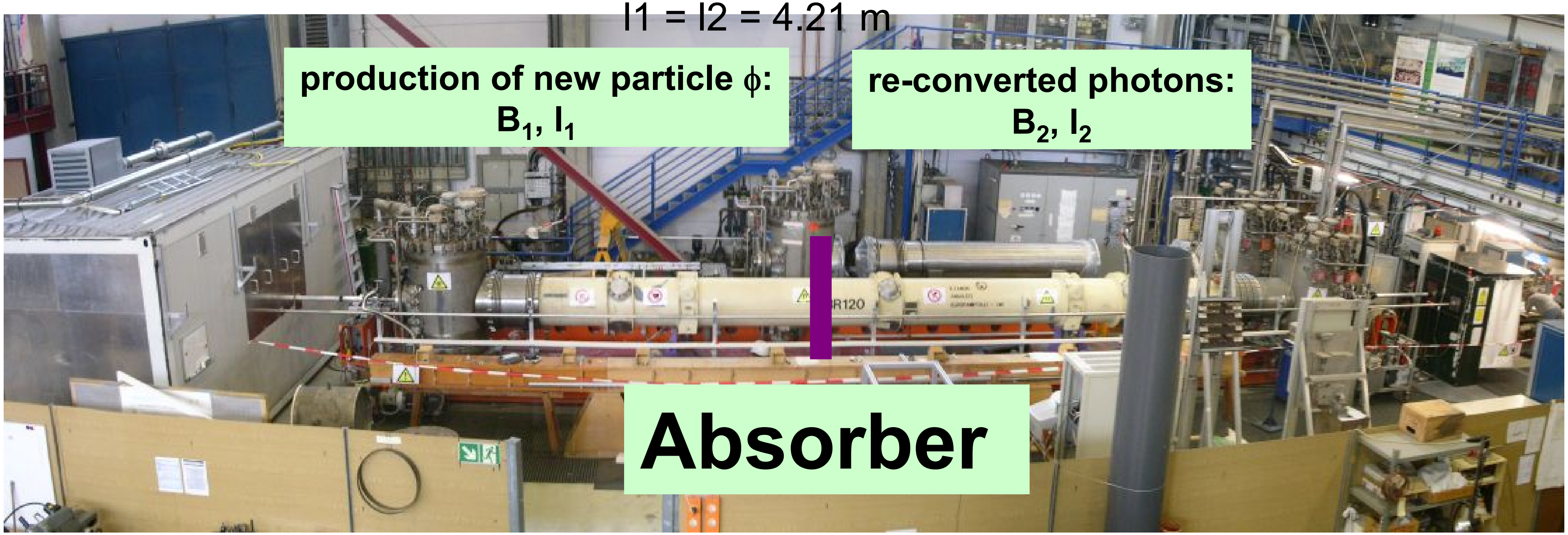
- axion like particles ALP
- massive hidden sector photons HP
- minicharged particles MCP

ALPS Experiment at DESY

Laser **Magnet** **Detector**

B1 = B2 = 5.16 T

l1 = l2 = 4.21 m

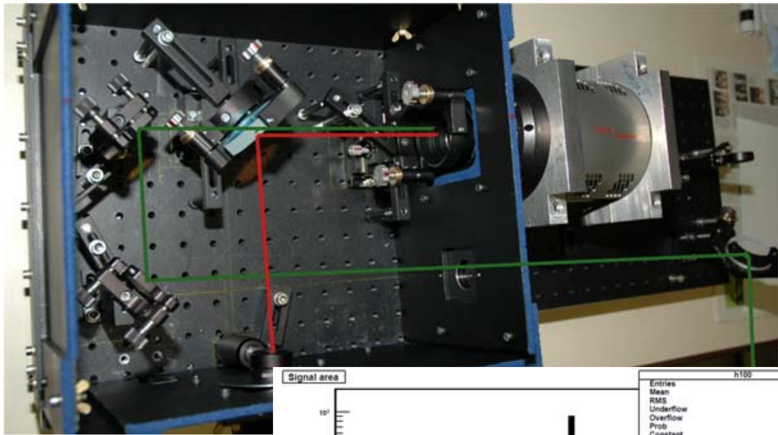


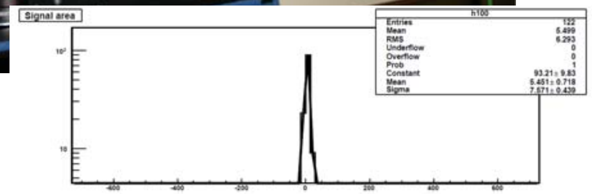
- Primary and secondary γ have same properties
- Rate of re-converted photons (for ALP) **~ $(B \cdot l)^4$**
- only one magnet can be used ->experimental challenge:
  - mirror and absorber in the middle of the magnet
  - no direct access possible

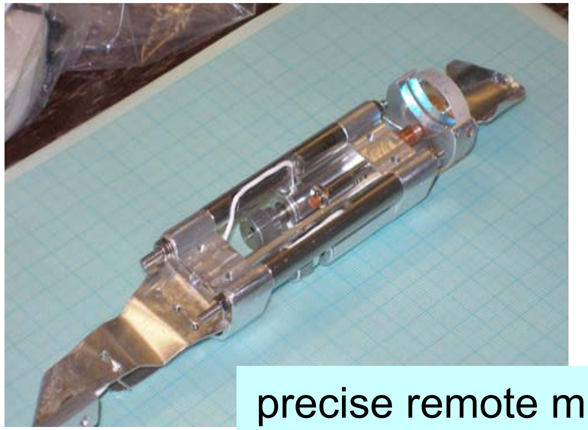
Setup: Beam Tube, Mirror & Detector

two beam tubes – one from each side:
removable & vacuum tight (10^{-7} mbar)

1. **laser tube (generation side)**:
   - windows on both sides
   - adjustable mirror in middle
2. **detector tube (regeneration part):**
   - removable wall on inner side
   - open for alignment purpose
   - window on outer side







precise remote mirror steering inside magnet (@ 5 Tesla and vacuum) adopted piezo based squiggle motors

high sensitivity, low noise **CCD camera**
PI - **PIXIS:1024BL**

- liquid cooling circulator at -70°
- 13 µm square pixel, 1024 * 1024
- eff 95 % at 532 nm
- dark current 0.001 e-/pixel/sec
- low readout noise: 3.8 e-/pixel
- beam spot focused on 3*3 pixel
- stability after removal < 10 µm
- reference beam optional guided to camera

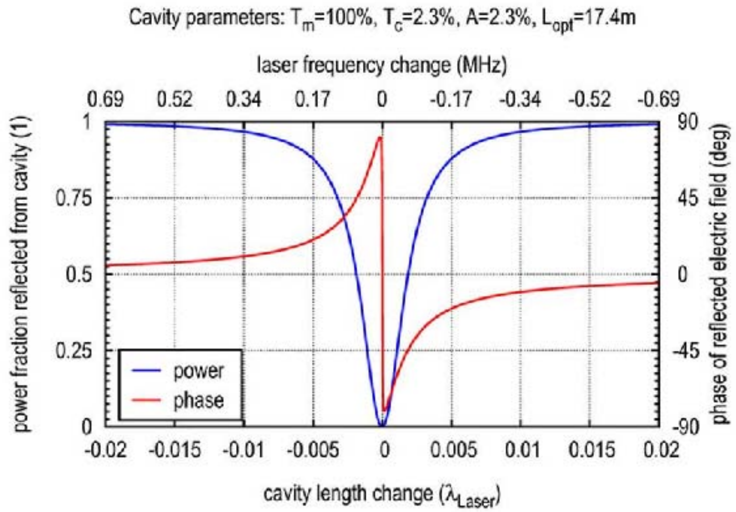
Setup: Laser System

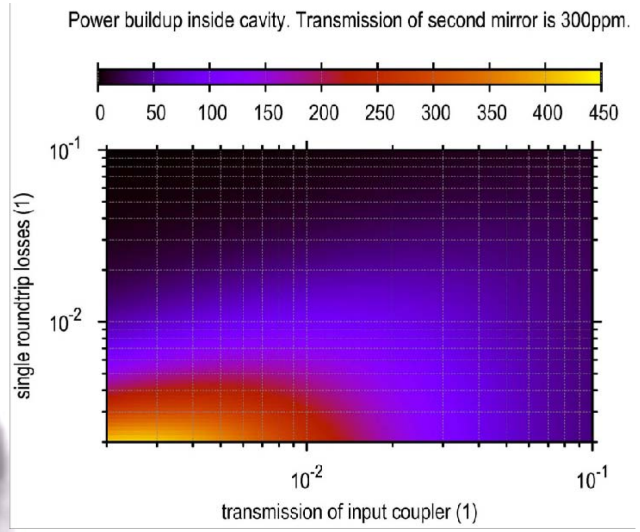
- > energy of photons determines ϕ mass reach
- > power & time structure (pulsed): $N\gamma$
- > polarization: 0+ and 0- ALP
- > experimental constraints: very good beam properties

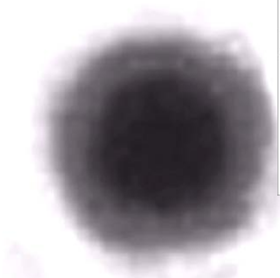
- ❑ **eLIGO Laser System**: narrow linewidth master-oscillator power amplifier system:
  - 1064 nm
  - provides 35 W CW
  - high frequency stability (1 MHz / min)
- ❑ **resonant second harmonic generation**
  - with resonant cavity around nonlinear crystal to maximize output
  - output: up to 4,6 W high quality 532 nm green laser light
- ❑ **optical Fabry Perot resonator** (cavity) in generation part (laser tube)
  - coherent superposition enlarges light field between mirrors
  - power buildup PB=Pcirc/Pin
  - single-mode emitting cw laser needed!

Optical Resonator - Cavity

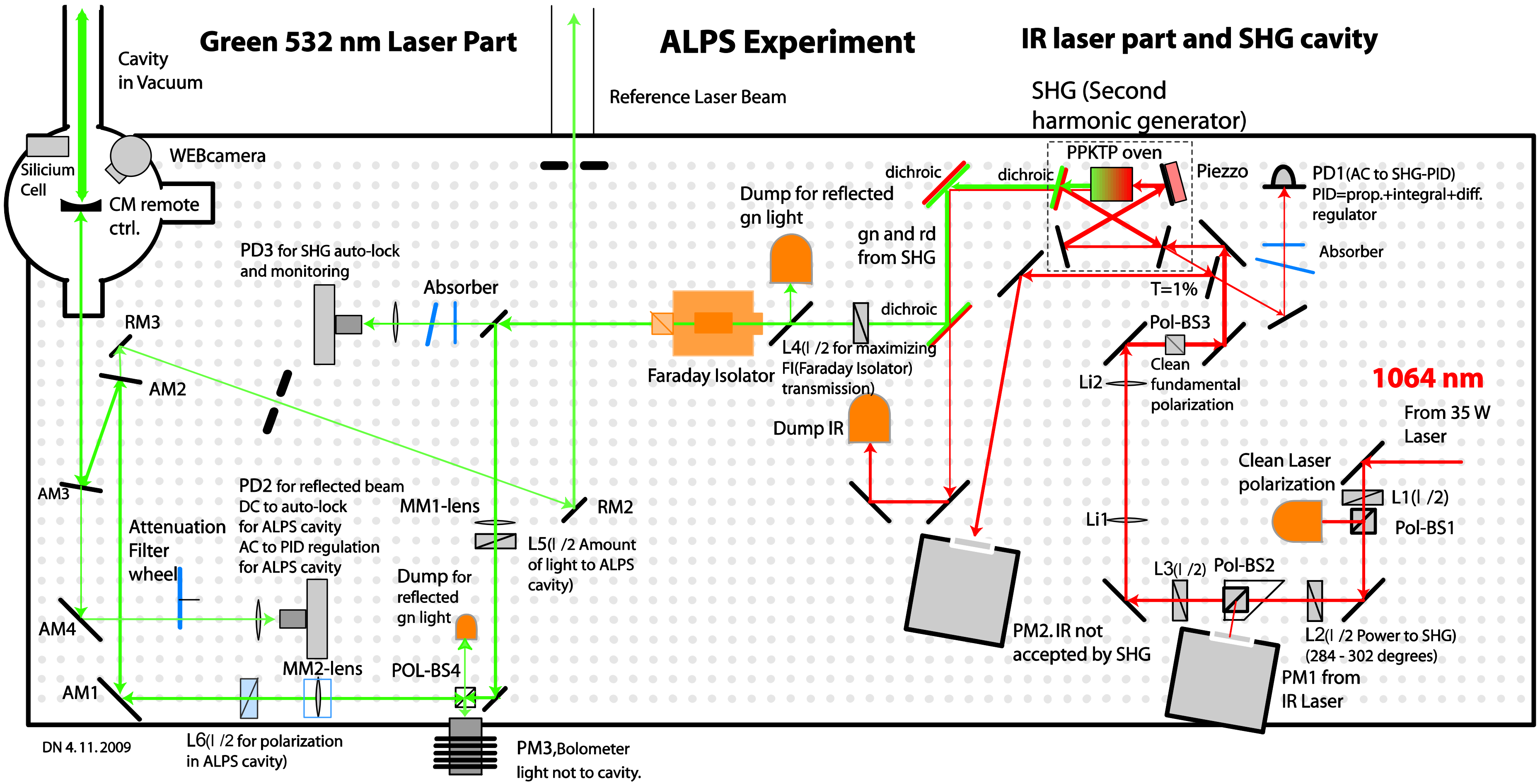
- Phase of light must reproduce itself aftereach roundtrip
  - cavity length must be stable in time length
  - changes of pm degrade PB
- Stabilization onto resonance
  - use sign change of phase
  - Pound-Drever-Hall readout scheme
- Power buildup governed by
  - internal losses (esp. windows)
  - ➢ **ALPS cavity completly inside vacuum**
  - mirror transmission
- Locking of cavity by adjusting frequency of IR 1064nm laser
  - adopting IR laser MOPA (with piezo)
  - Length noise 500 times larger than laser frequency noise!
  - cavity locked on fundamental mode





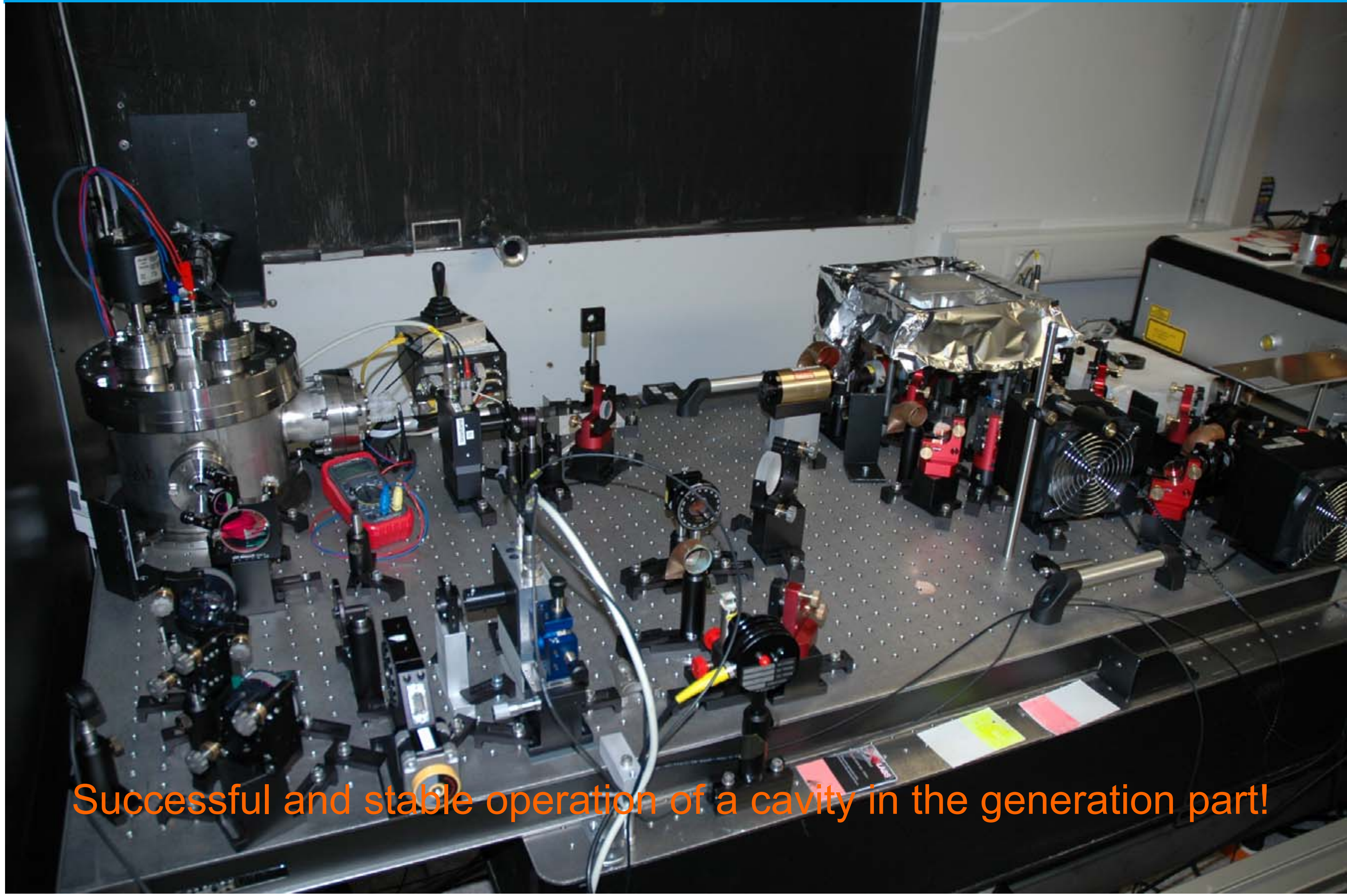


Resonant Photon Generation

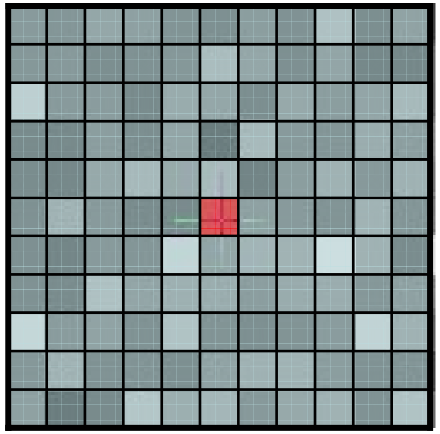


Successful and stable operation of a resonant cavity in the generation part!
& resonant second harmonic generation
Achieved a power build up of 300

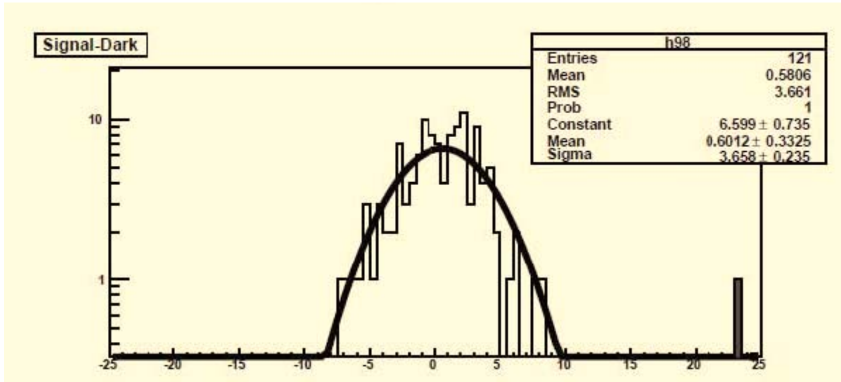
Resonant Photon Generation



2009 Data Analysis, Selection and Sensitivity



- around 50h of beam time recorded – several 100h of dark frames
- looking for enhancement in “signal” region (defined by beam spot) – compared to dark frames.
- check for cosmics or other spurious activity – remove about 10% of data frames from analysis
- the analysis is performed for each pixel a 11·11 grid
- test the CCD and the data analysis with a photon beam of extremely low intensity around 10 mHz



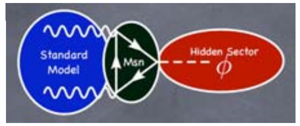
- **Sensitivity to re-converted photon flux ~ mHz**
- **with actual Laser + cavity (1 kW): $3 \cdot 10^{21}$ γ/sec**

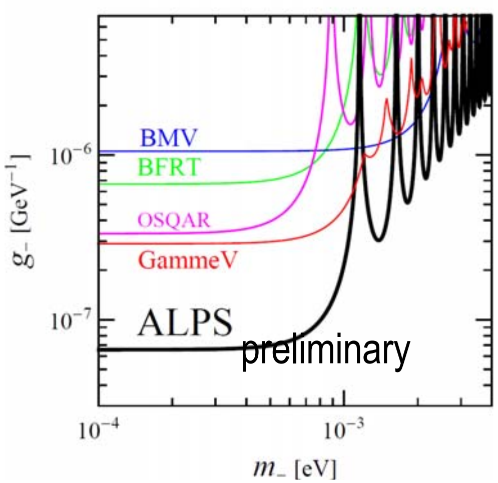
> **detection probability < $1 / 10^{24}$**

- **95 % confidence level – method of Feldman and Cousins**

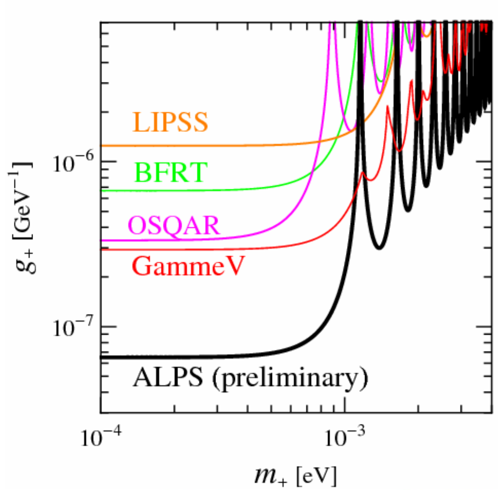
ALPS: Preliminary Results for the Vacuum Data

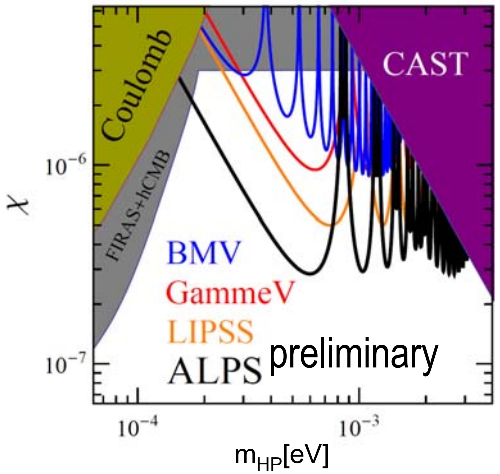
> ALPS is the most sensitive experiment for WISP searches in the laboratory. For axion-like particles, ALPS probes physics at the “multi-10-TeV scale”!





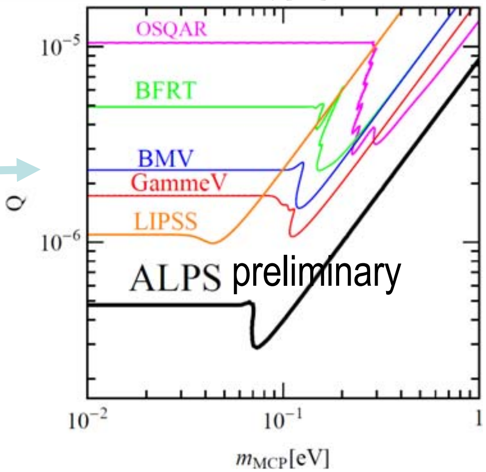
pseudoscalar
and
scalar
axion-like particles





hidden sector photons
and
minicharged particles

Filling a gap remaining from astrophysics and other experiments!

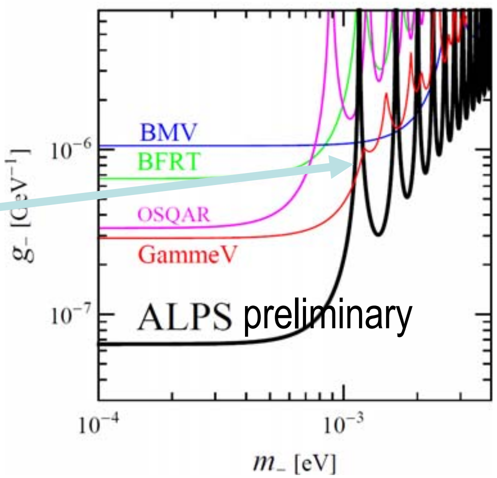


A new Method to extend the Mass Range

> The coherent phenomena probed at ALPS induce regions of insensitivity.

$$P = \left(\frac{g^2}{4} B^2 L^2 \frac{\sin^2(qL/2)}{(qL/2)^2} \right)^2$$

with q = $p_\gamma - p_\Phi$, L = length of B field



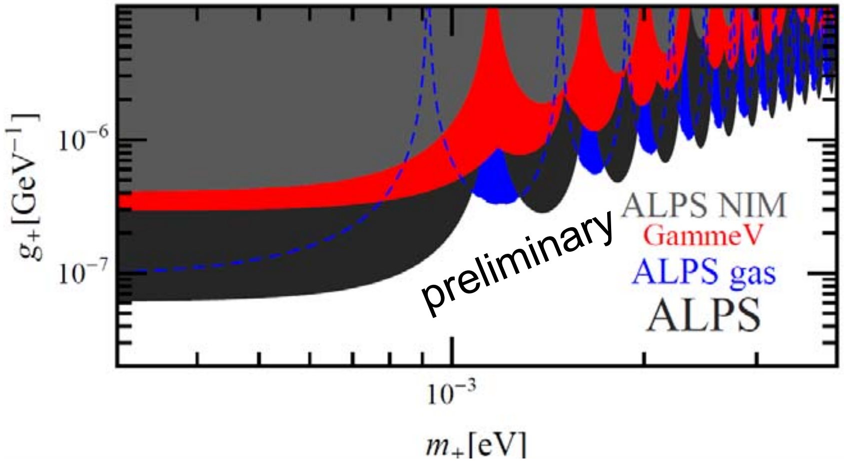
> They originate from $q \cdot L = (p_\gamma - p_\Phi) \cdot L = 2m \cdot \pi$

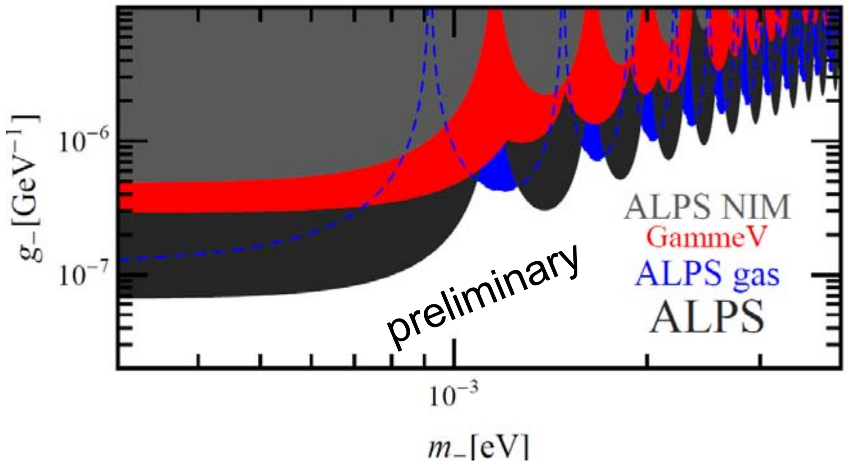
> Idea: change photon momentum p_γ by a small amount of gas:
$p_{\gamma\,(gas)} = p_\gamma \cdot \sqrt{1+2(n-1)}$, *where n denotes the refraction index.*

> We apply this approach by taking data with a pressure of 0.18 mb of Argon in the laser and detector beam tubes.

Preliminary Results for the Argon Data

- Gaps in sensitivity for axion-like particles are closed!

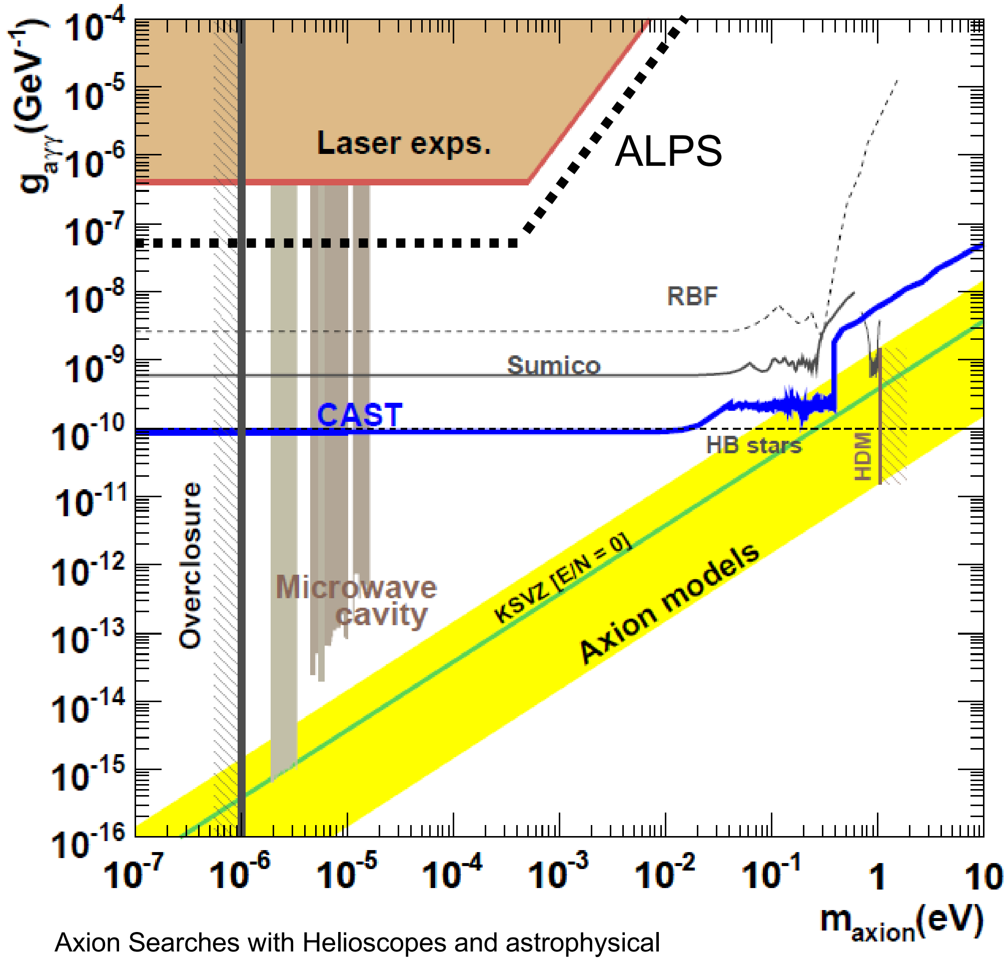




ALPS is now in the forefront of lab experiments searching for WISPs

Outlook

> The world-wide activities in this research field are strengthening, but there is still a way to go!



Axion Searches with Helioscopes and astrophysical signatures for axion(-like) particles, K. Zioutas et al., New J. Phys. 11 (2009) 105020

❖ **Increase sensitivity for lower couplings**

> **Laser (power + optical cavity)**

> **Magnet (field strength + length)**

> **Detector sensitivity**

> **Measurement time / statistics – will not really help: $g \sim t^{-1/8}$ -> Factor 2 if one measures one year (256 days) instead of one day!**

Prospects of direct WISP Searches - Towards lower Couplings

Laser (flux of incoming photons) in tight magnet bore:

- ALPS at present: 3 W 532 nm (enhanced LIGO),
  cavity with power built up of 300 — 1 kW
- ALPS II: 100 W 532/1064 nm (advanced LIGO),
  cavity with power built up of 1000 — 100 kW
- OSQAR proposal: 1kW 1064 nm (Nd-YAG),
  cavity with power built up of 10.000 — 10,000 kW

Magnet (interaction probability):

- ALPS at present: ½ + ½ HERA dipole,
  B = 5 T, l = 4.2 m — 21 Tm
- OSQAR proposal: 1+1 LHC, dipoles
  B = 9.7 T, l = 14.3 m — 140 Tm
- Larger scale exp: 6 + 6 Tevatron dipoles — 180 Tm
  6 + 6 HERA dipoles — 280 Tm
  2 + 2 LHC dipoles — 300 Tm
  4 + 4 LHC dipoles — 600 Tm
- “dreams”

Prospects of direct WISP Searches - Towards lower Couplings

Detector sensitivity:

•ALPS at present: PIXIS 1024B - few mHz

•“kind-of-limit”: radioactivity, CR in 20·20 μm^2 signal region at ALPS about 0.02 mHz

– may be reached e.g. with TES (single photon counting)

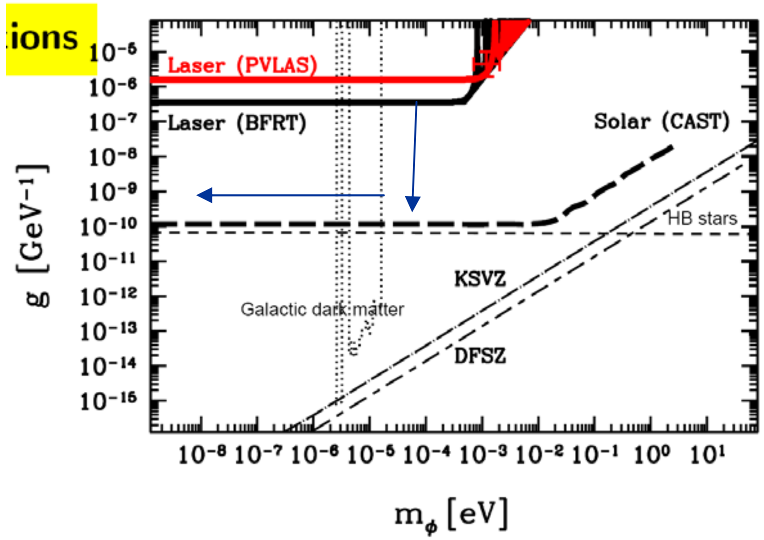
– or with heterodyne detection scheme

Reach relative to ALPS in 2009 ($g=10^{-7}GeV^{-1}$):

> Laser (power + optical cavity):100

> Magnet (field strength + length):15

> Detector sensitivity: 200



Physics:

$g = 2 \cdot (Bl)^{-1} \cdot (P_{\gamma\to\phi\to\gamma})^{-4}$

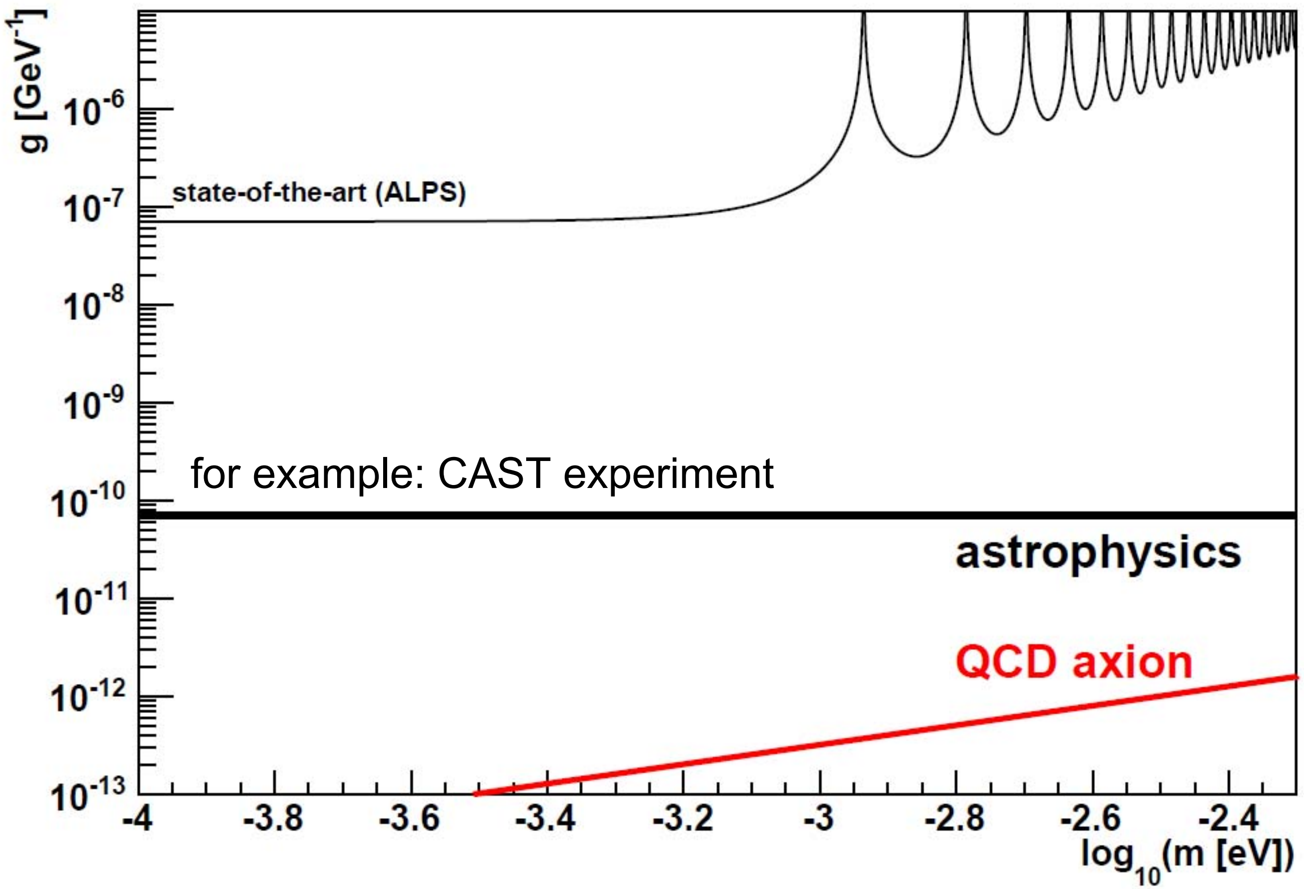
$= g_{ALPS} \cdot (15)^{-1} \cdot (100 \cdot 200)^{-4}$

$= g_{ALPS} / 200$

$\approx 5 \cdot 10^{-10} GeV^{-1}$

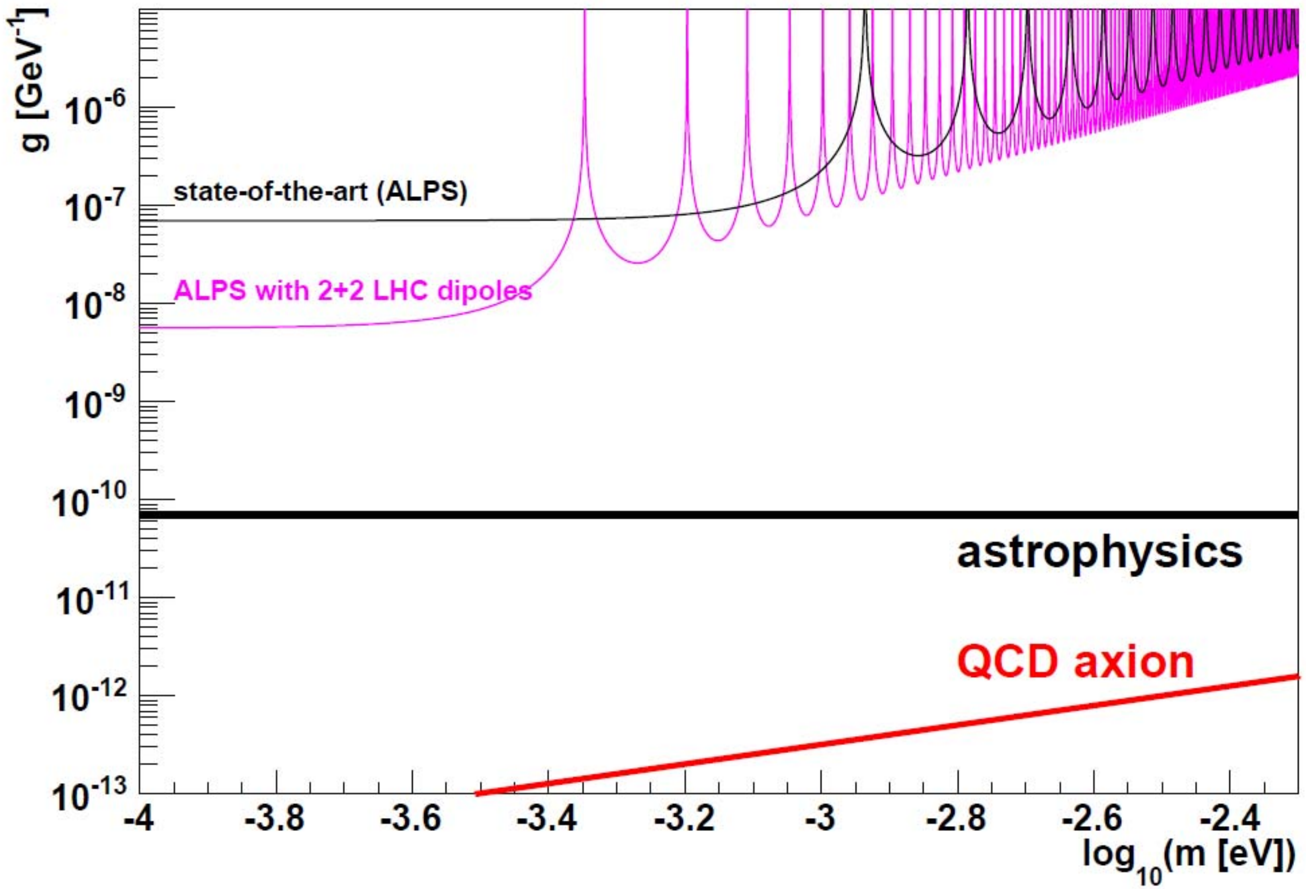
A possible Scenario for ALPS II

> Still a way to go!



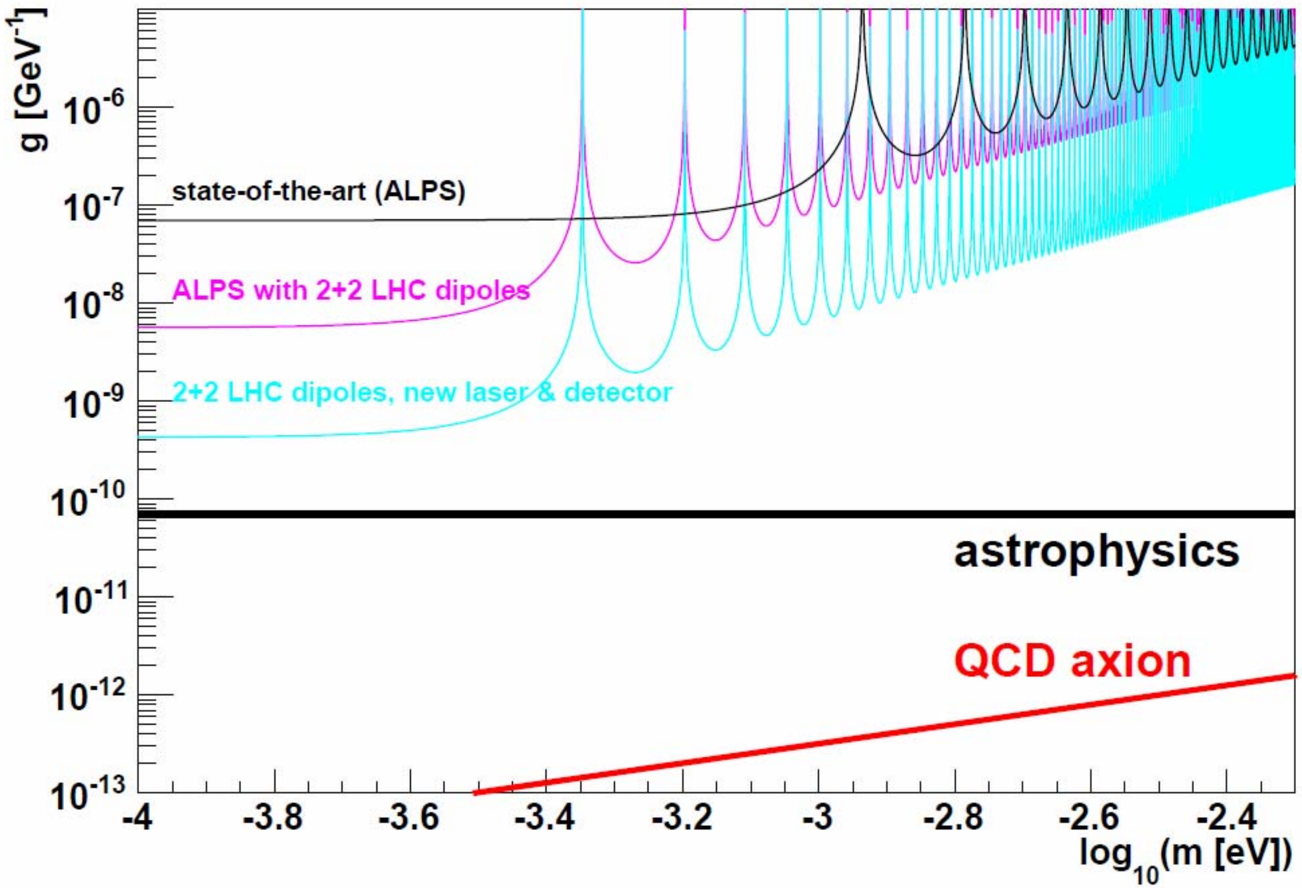
A possible Scenario for ALPS II

> Invest into more powerful magnets.



A possible Scenario for ALPS II

> Increase laser power from 1 kW to 150 kW, add single photon detector.



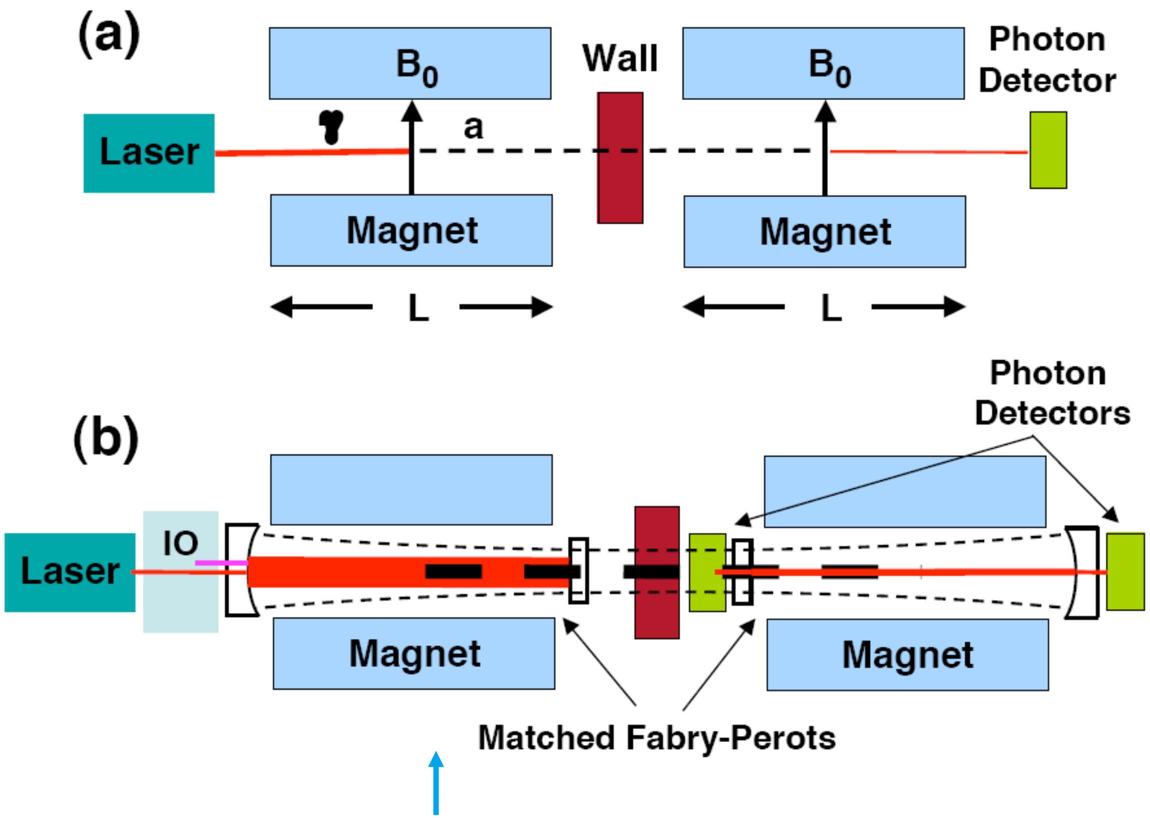
Prospects of direct WISP Searches - Towards lower Couplings

Ingenuity in addition to "brute force":

"Resonantly enhanced Axion-Photon Regeneration"

P. Sikivie, D.B. Tanner , Karl van Bibber. Phys.Rev.Lett.98:172002,2007.

(also F. Hoogeveen, T. Ziegenhagen, DESY-90-165, Nucl.Phys.B358)



Realized at ALPS

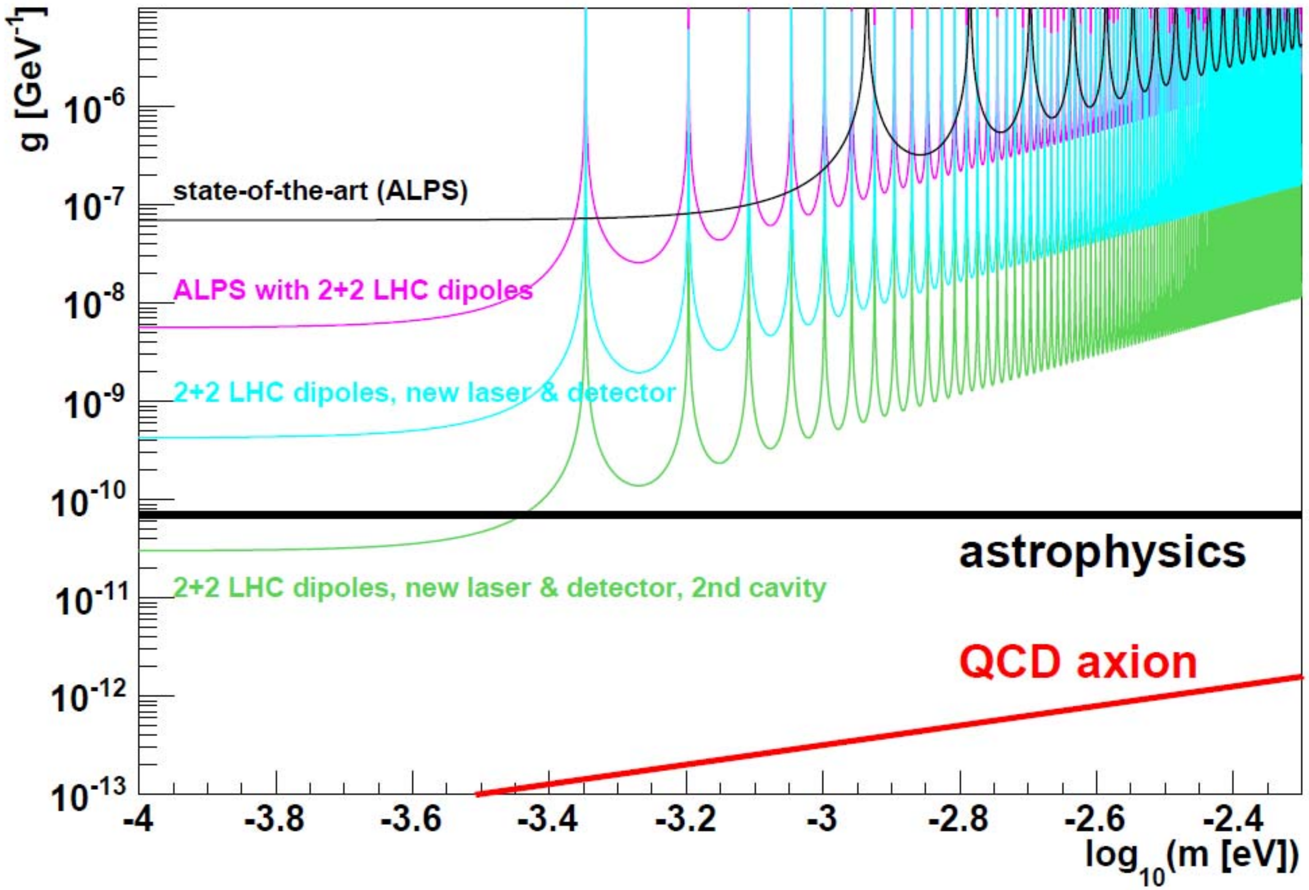
Implementation of a second cavity in the regeneration part of the experiment to enhance the conversion probability WISP→ photon

Increase power output by finesse of cavity:
10^4 seems to be possible.

There are different ideas and proposals under discussion

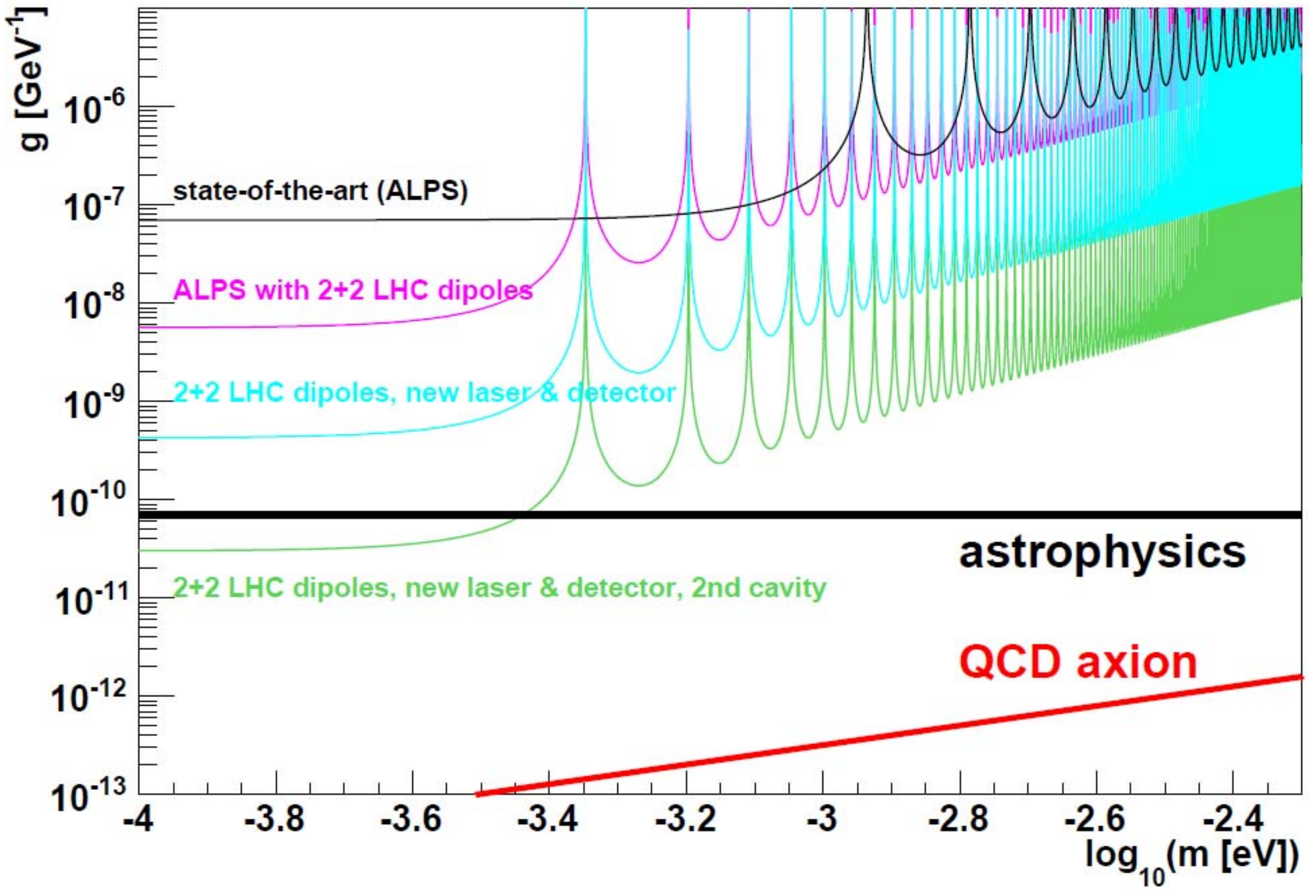
A possible Scenario for ALPS II

> Include a second resonator in the detector tube behind the wall.



A possible Scenario for ALPS II

- it looks feasible to build a lab experiment which reaches a sensitivity beyond the actual limits coming from astrophysics (within a few years)
- at that time: new results from lab-experiments, astrophysics and LHC



beyond that: “brute force” i.e. magnets and laser power & genuine new ideas

Conclusions

- Growing worldwide interest and effort in low energy particle physics – theory and experiment.
- WISP searches in the laboratory are complementary to astrophysics experiments.
- LSW experiments: direct WISP search
- ALPS success based on a close collaboration of particle physicists (theory and experiment), laser physicists from the gravitational wave detector community and an “accelerator” lab
- ALPS has set up an optical resonant in the generation part of the LSW experiment - power buildup of 300 achieved
- ALPS provides the most stringent laboratory constraints on WISPs
- Based on this experience, future large scale LSW experiments are feasible which surpasses present day limits from astrophysics – ALPS II
- Finding the QCD axion remains a challenging target.

Outlook

WISP search in the lab is complementary to High Energy activities and astrophysics – probe of models (String theory motivated) – potential to make significant contributions

> hopefully there are many discoveries in the next years which helps to solve open questions of particle physics

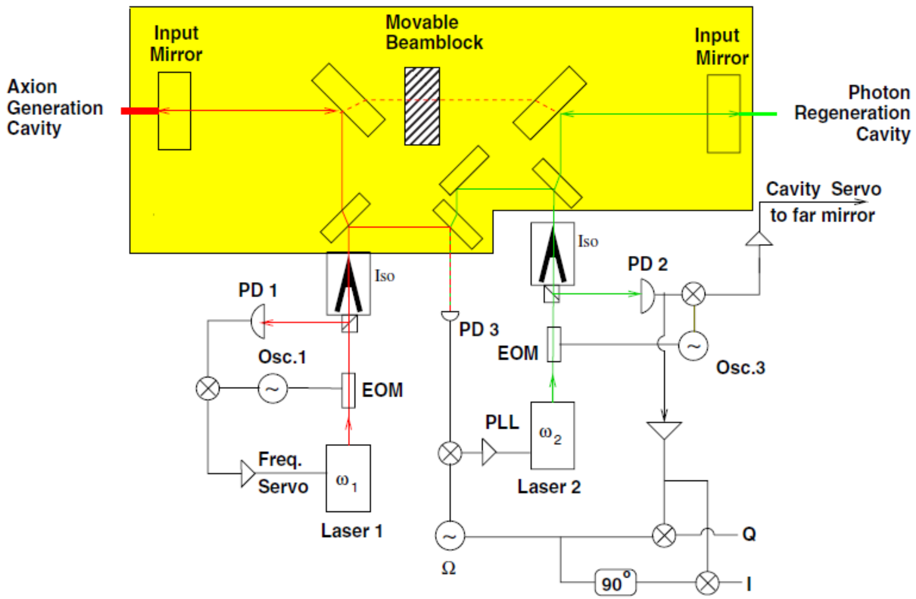
Next (6th) Patras Workshop: Zurich

Juli 5 – July 9, 2010 **Annual Workshop on Axions, WIMPs and WISP**

Backup Slides

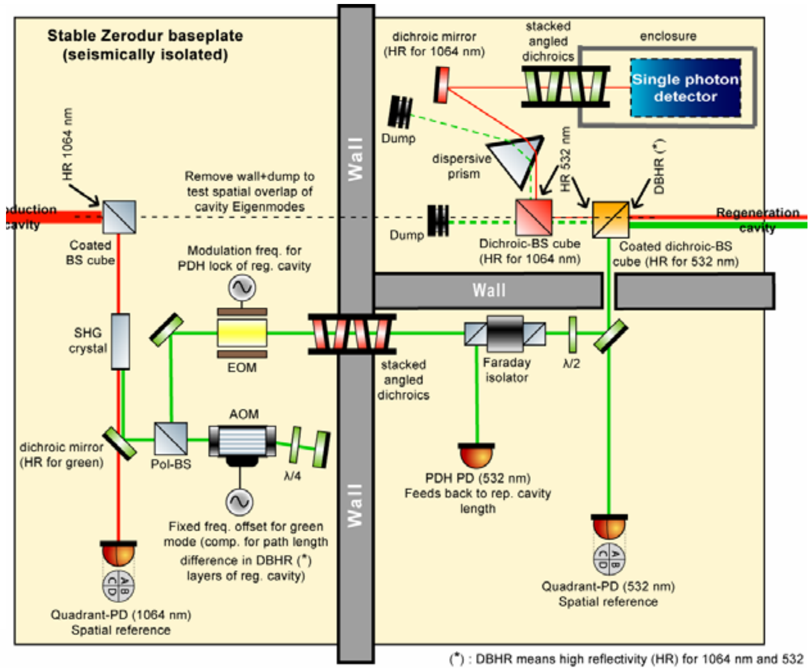
Resonantly enhanced Axion-Photon Regeneration

There are different ideas and proposals



"Detailed design of a resonantly-enhanced axion-photon regeneration experiment"
G. Mueller, P. Sikivie, D. B. Tanner and K. v.Bibber
10.1103/PhysRevD.80.072004

Use two lasers with offset in frequency to allow for a heterodyne detection scheme.



Setup under consideration for ALPS II
- IR 1064 nm for WISP production
- SHG 532nm – for locking of 2. cavity
- single photon detector e.g. TES

Laser System

Laser - γ parameters:

- Energy of photons determines ϕ mass reach
- Power & time structure (pulsed): Nγ
- Polarization: 0+ and 0- ALP
- experimental constraints: very good beam properties

Avoid diffractive losses

> small aperture in beam tube

=> σ < 12 mm

> propagation of beam inside laser tube

$$\sigma(z) = \sigma_0 \cdot \sqrt{\frac{z^2 \cdot \lambda \cdot M^2}{\pi \cdot \sigma_0^2 / 4}}$$

$$M^2 = \sigma_0 \cdot \Theta \cdot \frac{\pi}{\lambda}$$

Focus Spot Size

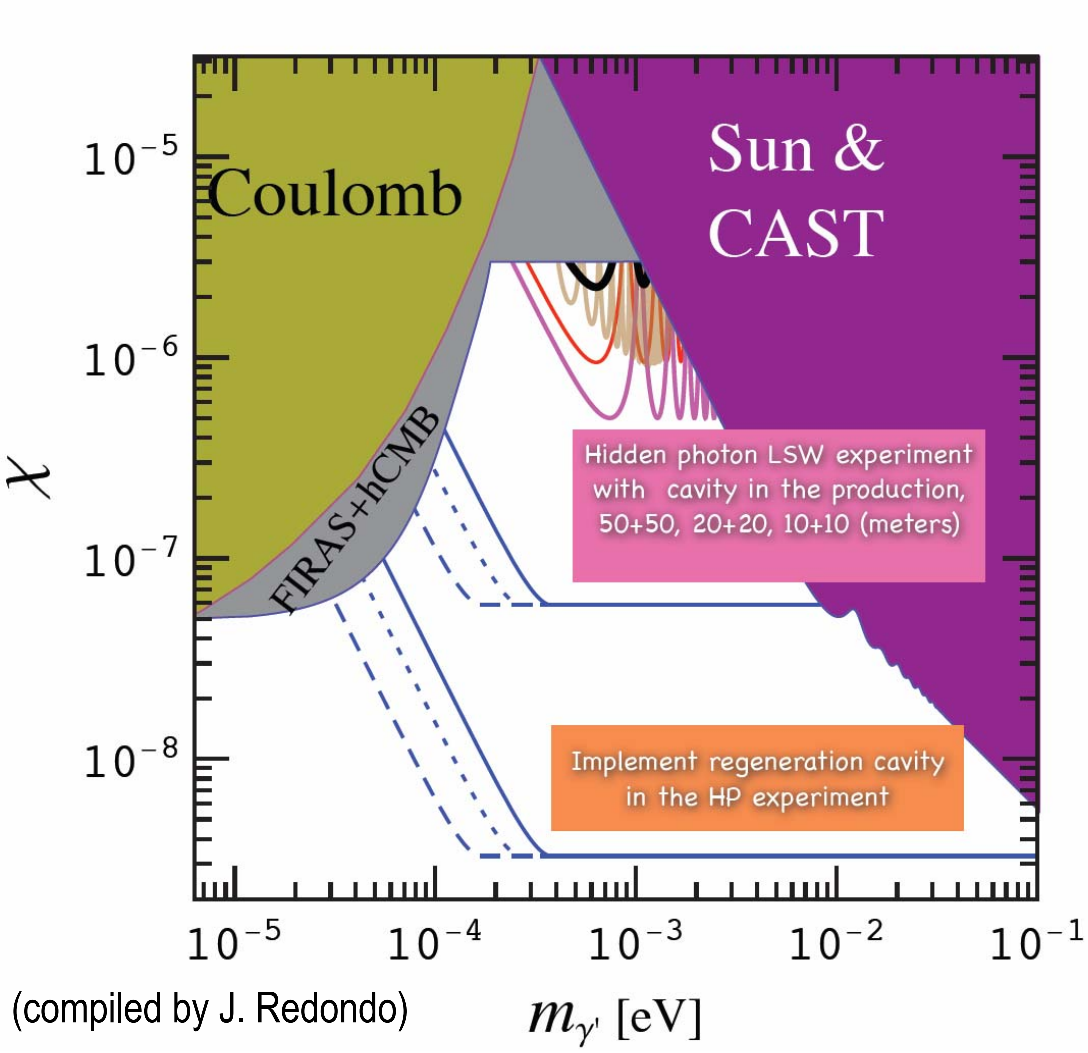
> secondary photons focused on small spot (detector)

> same properties as laser beam

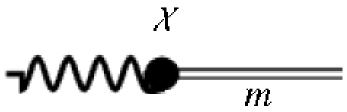
> focus spot size comparable to pixel size of digital cameras

$$\textit{focus spot size:} \quad \sigma_{\min} = \frac{\lambda \cdot f \cdot M^2}{\pi \cdot \sigma}$$

Without Magnets: Searching for hidden Photons



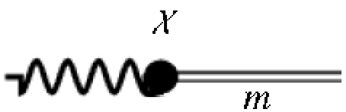
(compiled by J. Redondo)



Only laboratory experiments searching for massive hidden sector photons might close the gap in the meV mass region!
Same laser and detector technology, but no magnets needed.
Only long straight vacuum tubes!

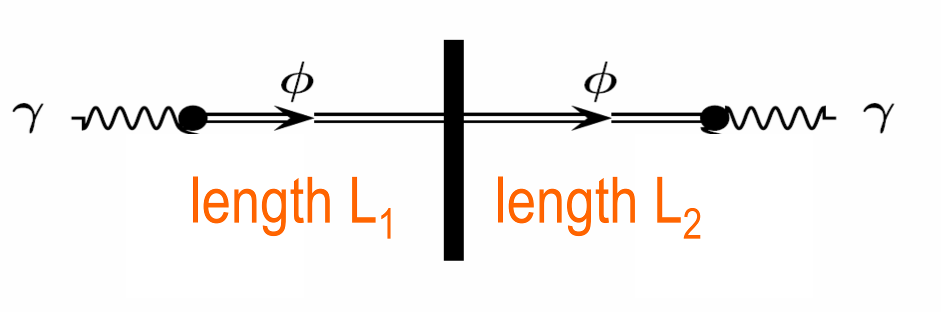
Search for massive Photons

“Light shining through a wall” without external fields:



(like neutrino oscillations).

Principle of an experiment:

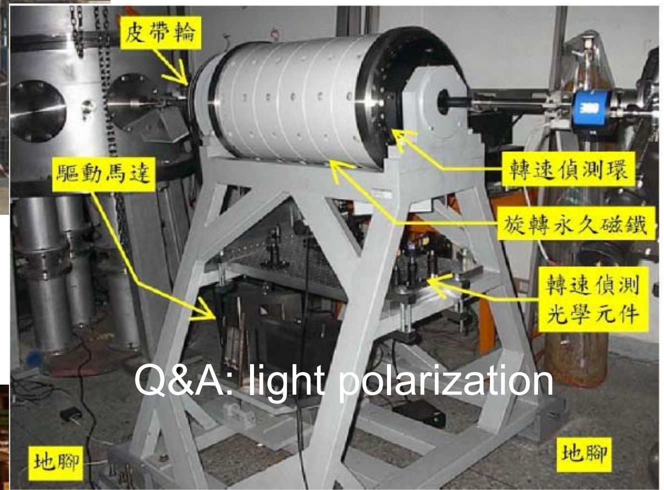


Experimental requirements very similar to searches for axion-likes, but:
- no magnetic field,
- UHV conditions.

$P_{reconv.} = 16\chi^4 \cdot [\sin(qL_1/2) \cdot \sin(qL_2/2)]^2$ (kinetic mixing)

Indirect WISP Search Experiments

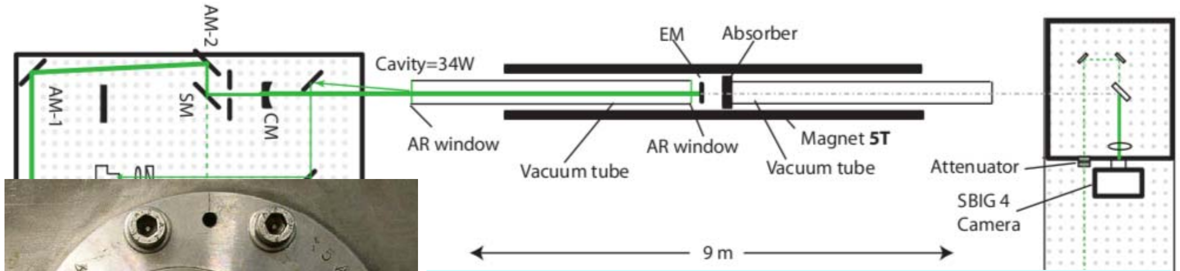
- > PVLAS at Leagnaro, Italy
  - high finesse Fabry-Perot cavity
  - upgrade plans
  - also direct search plans
- > Q&A in Taiwan
  - ongoing
  - sensitivity comparable to PVLAS
- > BMV at Toulouse (France)
  - starting, test of QED prediction of ellipticity
  - also direct search experiments
- > OSQAR at CERN (using two LHC dipoles)
  - starting, test of QED prediction
  - also direct search experiments



LSW Experiments

Experiment	**Lasersystem**	**Magnet**	
ALPS@DESY	532 nm, cw Optical Resonator	HERA sc Dipol B=5,2T, l=9m	2mHZ CCD
BFRT@Brookhaven	Optical delay line	2* 4,4m 3,7T	Finished in 1993 limits on existence of WISPs
BMV@Toulouse	$6{\cdot}10^{23}$ photons, 1060 nm, 82 pulses	4.4 + 4.4 Tm 0,37m – 12,3T pulsed	0.5 Hz ongoing, limits published
GammeV@FNAL	$6{\cdot}10^{23}$ photons, 532 nm, 5Hz pulses	Tevatron Magnet 6m - 5T	0.01 mHz PM - ongoing, limits published - most sensitive limits on WISPs until 2009
LIPSS@JLab	$6{\cdot}10^{25}$ photons, 935 nm, pulsed FEL	1.8 + 1.8 Tm 2* 1,77T, 1m	1 mHz ongoing, preliminary results
OSQAR@CERN	488+514 nm , cw 18 W Argon Laser	136 + 136 Tm LHC Magnet 9,5T 14,3m	1 mHz ? ongoing, preliminary results

Experimental Setup: Beam Tubes – Mirror Holders



magnet beam pipe is bent

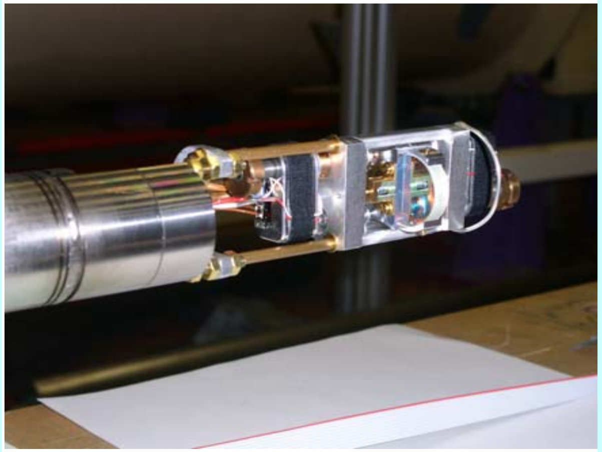
clear aperture only 18 mm ☹

just one magnet - mirror in middle

-> exp. challenge and constrain on beam quality of laser

two beam tubes – one from each side:
removable & vacuum tight (10^{-7} mbar)

1. **laser tube (generation side)**:
   - windows on both sides
   - adjustable mirror in middle
2. **detector tube (regeneration part):**
   - removable wall on inner side
   - open for alignment purpose
   - window on outer side



precise remote mirror steering inside magnet (@ 5 Tesla)
custom made motor based on piezo actuators
for high finesse cavity in vacuum
squiggle motors

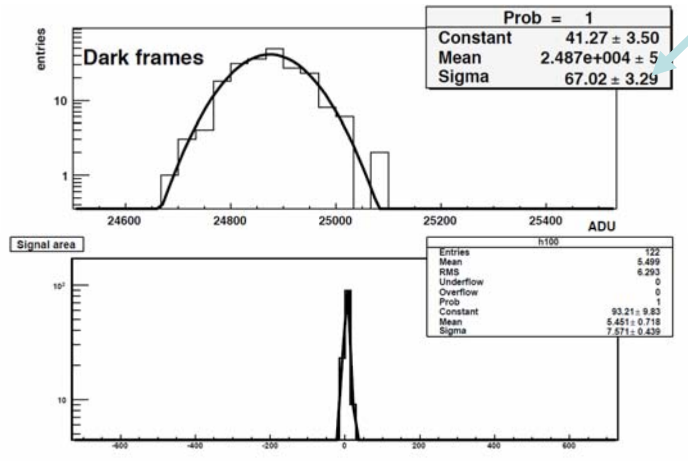
Detector – CCD Camera

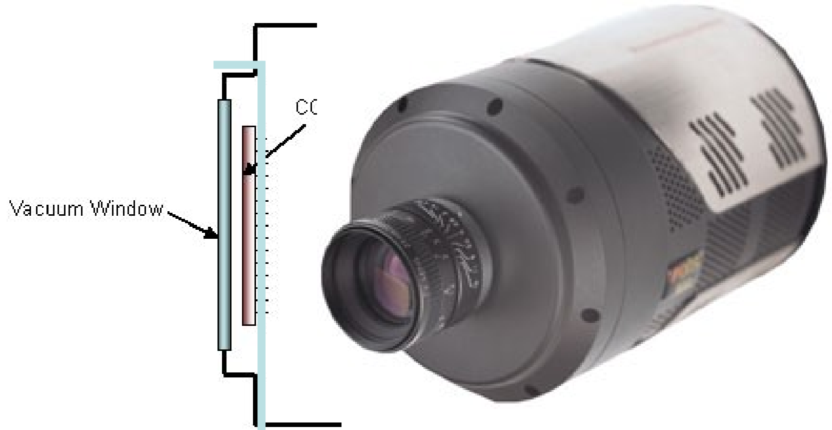
- **Detector**: high sensitivity, low noise
- aiming for single photon detection

> **initially SBIG ST-402**

> **now: PRINCETON INSTRUMENTS PIXIS:1024BL**

- **liquid cooling circulator at -70°**
- **CCD47-10 AIMO Back Illuminated CCD sensor**
- **13 µm square pixel, 1024 * 1024**
- **eff 95 % at 532 nm**
- **dark current 0.001 e-/pixel/sec**
- **low readout noise: 3.8 e-/pixel**





- 3*3 binning
- sensitivity is increased by a factor of 20

Data Analysis - Classification of Data

Compare signal of data and background (dark) frames

- observable: difference in mean of many ‘signal’ to mean ‘background’
- looking for enhancement in the “signal” pixel

Categories, Signals and Backgrounds

<table>
<tr><th></th><th>ALP-</th><th>ALP+</th><th>MCP</th><th>HidPh</th></tr>
<tr><td>G0 (no laser)</td><td rowspan="2">B_-</td><td rowspan="3">B_+</td><td rowspan="2">B_{MCP}</td><td>B_{HP}</td></tr>
<tr><td>G1 (no magnet)</td><td rowspan="3">S_{HP}</td></tr>
<tr><td>G2-v (LaserV,MagnetOn)</td><td>S_-</td><td rowspan="2">S_{MCP}</td></tr>
<tr><td>G2-h (LaserH,MagnetOn)</td><td>B_-</td><td>S_+</td></tr>
</table>

8 groups of frames to analyze, 4 Signals, 4 Backgr.

conversion from ADU to photons:

- gain [ADU / p.e.]
- quantum efficiency [p.e. / γ]
- beam spot eff. / stability
- laser power, optical losses

- Data – 1h camera frames
- Signal region – defined by beam spot

Data Sets used for the 2009 Results

around 50h of beam time – 45h with magnet in operation and several 100h of dark frames

Data	binning	Signal pixel	frames	selected	
Dark Frame Series 090828-090907	X: 3;1022;3;340 Y: 1;1020;3;340	(151,193) with reference beam	136	122	93%
Dark Frame Singles 090904-090907			17	16	94%
Laser-on-hor-Magnet-on 090827			9	9	100%
Laser-on-vert-Magnet-on 090907			2	2	100%
Laser-on-vert-Magnet-off 090907			1	1	100%
Dark Frame Series Shutter closed 091023-091027	X: 3;1022;3;340 Y: 2;1024;3;341	(133,195) without reference beam	80	65	81%
Dark Frame Series Shutter open 091027-091030			45	34	76%
Laser-on-hor-Magnet-on 091030			5	5	100%
Laser-on-hor-Magnet-on-0.18mb 091028-091029			10	8	80%
Laser-on-vert-Magnet-on-0.18mb 091026-091027			9	8	89%
Low Intensity Test 090918	X: 1;1023;3;341 Y: 1;1023;3;341	(147,165) without reference beam	4	4	100%
Dark Frame Series 090919-090921			59	47	80%
Laser-on-hor-Magnet-on 090922			2	2	100%
Laser-on-vert-Magnet-on 090922			6	6	100%

limits

- 95 % confidence level – method of Feldman and Cousins
- exclusion limit 95% C.L.
- Laser Power > 1kW
- sensitivity

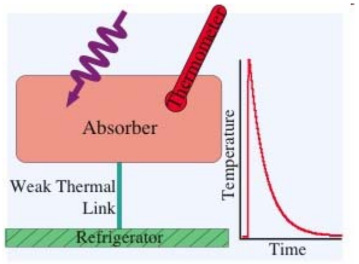
Polarization	n-1	$P(\gamma \to \Theta \to \gamma)$ (95%CL)
horizontal	0	$2.3 \cdot 10^{-25}$
vertical	0	$3.0 \cdot 10^{-25}$
hor.+vert.	0	$1.0 \cdot 10^{-25}$

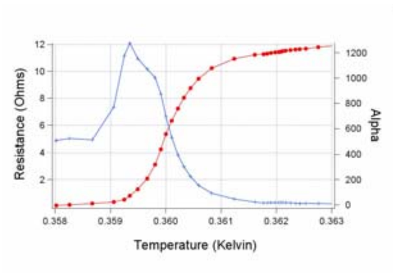
Polarization	n-1	$P(\gamma \to \Theta \to \gamma)$ (95%CL)
horizontal	$5.0 \cdot 10^{-8}$	$1.1 \cdot 10^{-24}$
vertical	$5.0 \cdot 10^{-8}$	$3.1 \cdot 10^{-24}$
hor.+vert.	$5.0 \cdot 10^{-8}$	$1.8 \cdot 10^{-24}$

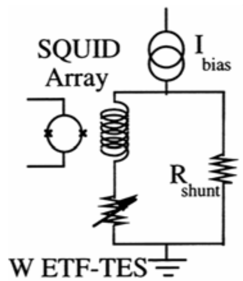
Detectors for future LSW Experiments

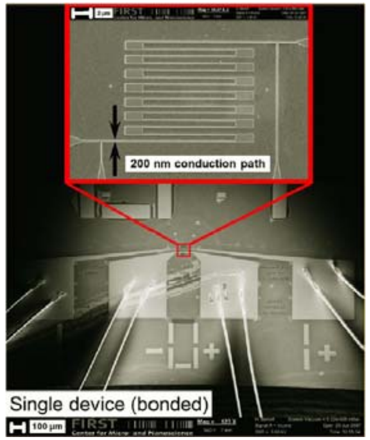
Choice of detector depends on details of the setup (esp. locking of regeneration cavity):

- potential "background-free" single photon counter (also 1064 nm): Transition Edge Sensor @ 100 mK, Nanowire Photon Counter @ few K









A. Engel (UZH), http://www.physik.uzh.ch/groups/schilling/resch/Detektoren.pdf

- Heterodyne detection: mix two signals and search for a Fourier component signals (used by gravitational wave community)

$$S = |E_{SO} e^{i(\omega_1 t + \phi)} + E_{LO} e^{i\omega_2 t}|^2$$
$$= E_{LO}^2 + 2E_{LO}E_{SO}\cos(\Omega t + \phi)$$