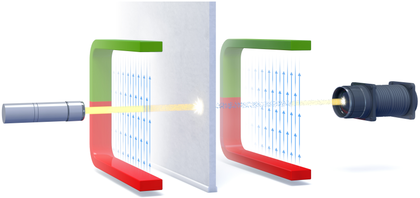
Review on LSW with lasers

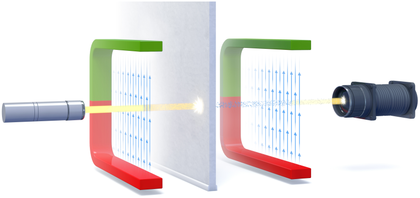


Friederike Januschek, DESY
10th PATRAS Workshop on
Axions, WIMPs and WISPs
CERN, June 30th 2014

HELMHOLTZ
GEMEINSCHAFT

Review on LSW with lasers.

and status of ALPS II



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HELMHOLTZ
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DESY

Outline

> Motivation

> Experimental Options

> ALPS I

> OSQAR

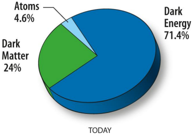
> ALPS II

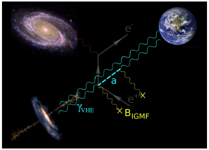
> What the future might bring...

> Conclusion

Fundamental Questions

- What constitutes dark matter and dark energy?
- Why is the neutron dipole moment so tiny?
  $\rightarrow$ CP conservation in QCD
- Astrophysical riddles:
  - Why is the universe transparent to TeV photons?
  - Why do white dwarfs cool so fast?
  - Why is there a soft X-ray excess from galaxy clusters?





Strong support for BSM physics from different sources

Axions and ALPs

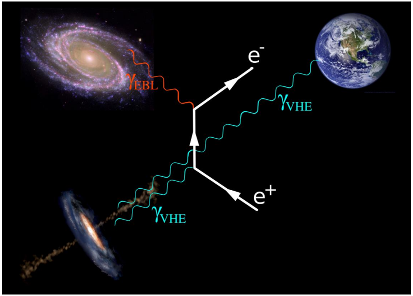
Axions and **Axion-like particles** (ALPs) could answer (some of) these questions!
They are **well motivated** from multiple sources.

ALPs are **WISPs**

- The axion provides the most elegant solution to the strong CP problem.
- ALPs are embedded in string theory inspired Standard Model extensions.
- ALPs, axions (and other WISPs) could explain dark matter.
- They would be a good explanation for several (→next slides) astrophysical phenomena.

TeV Transparency

- Very high energy γ-rays from cosmological sources should be attenuated by pair production.
- The reduced opacity might be explained by the oscillation of photons into ALPs in ambient magnetic fields.



Manuel Meyer, PATRAS Workshop 2011

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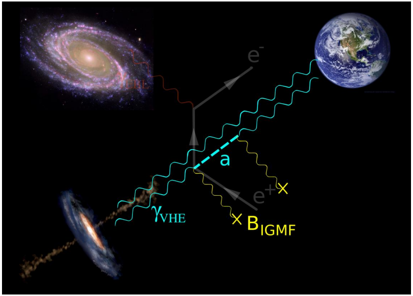
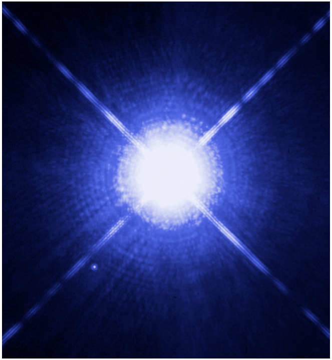


Manuel Meyer, PATRAS Workshop 2011

White Dwarf Cooling

- There are hints for an anomalously large cooling rate of white dwarfs.
- Recent studies of WD luminosity function and pulsation period show this.
- This cooling excess can be attributed to axions or ALPs coupling to electrons.



NASA

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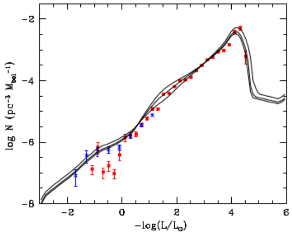
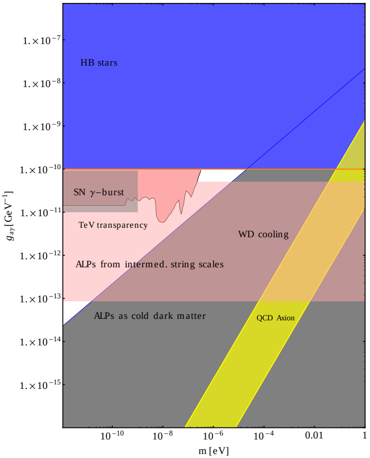


Isern et al, arXiv 1204.3565

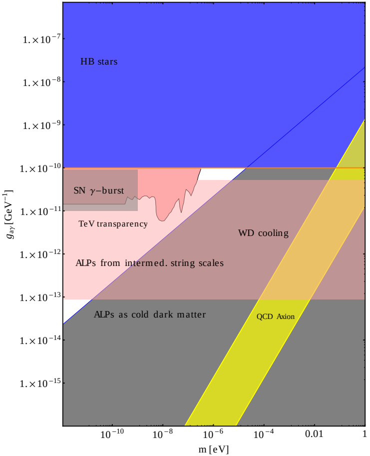
Region of Interest



- QCD Axion solving the CP problem
- TeV γ transparency [1302.1208]
- White Dwarf cooling [1204.3565]
- predicted in intermediate string scale scenarios [1209.2299]
- Dark Matter [1201.5902]

Very interesting: $|g_{a\gamma}| \gtrsim 10^{-12}$ **GeV**$^{-1}$

Region of Interest



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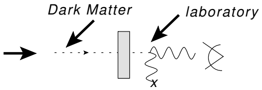
- Dark Matter [1201.5902]

Very interesting: $|g_{a\gamma}| \gtrsim 10^{-12}$ GeV^{-1} and, of course, the QCD axion region

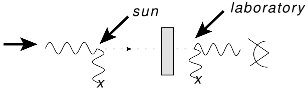
Three Possibilities

Looking for WISPs

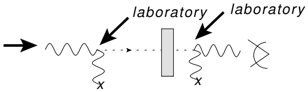
- Looking for dark matter ⇒ Haloscope



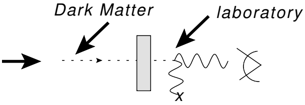
- Looking for WISPs from the sun ⇒ Helioscope



- Creating and detecting WISPs ⇒ Light-Shining-Through-Walls



Haloscopes



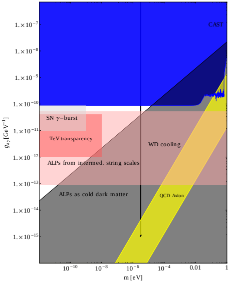
> see talk by Leslie Rosenberg on ADMX (next-but-one)

> very sensitive

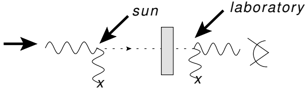
> very narrow mass

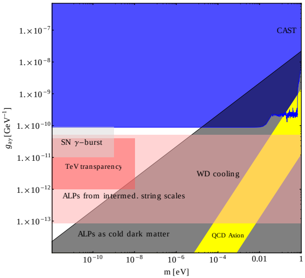
> depends on cosmology and astrophysics

> others: WISP-DMX (Andrei Lobanov this afternoon), dish antenna (Babette Döbrich on Thursday)



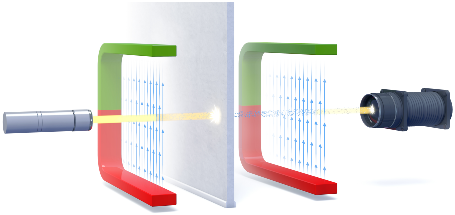
Helioscopes





- CAST here at CERN ☺
- see e.g talk by Giovanni Cantatore after the coffee break
- sensitive
- broadband
- depends on astrophysics

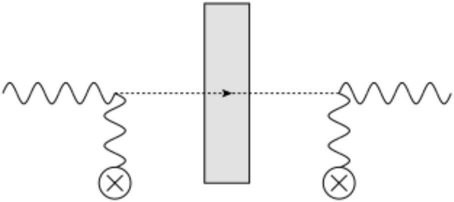
Light-Shining-Through-a-Wall



How to detect Axions/ALPs

- Light is shone on a wall it cannot traverse
- Photons convert into Axions/ALPs in a magnetic field and pass the wall
- Behind the wall, the Axions/ALPs convert back to photons in a magnetic field
- Light is detected by a detector

Light-Shining-Through-a-Wall



How to detect Axions/ALPs

- Light is shone on a wall it cannot traverse
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- Behind the wall, the Axions/ALPs convert back to photons in a magnetic field
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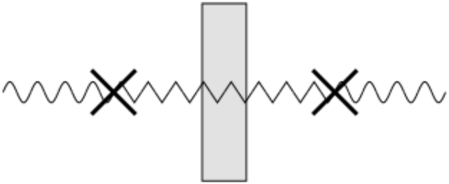
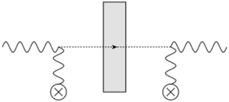
Light-Shining-Through-a-Wall



How to detect Hidden Photons

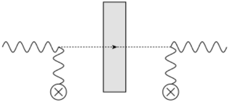
- Light is shone on a wall it cannot traverse
- Photons convert into hidden photons via kinetic mixing and pass the wall
- Behind the wall, the hidden photons convert back to photons
- Light is detected by a detector

LSW - some formulas



Probability for axion-photon conversion

$$P_{\gamma\leftrightarrow a} \propto (g_{a\gamma}BL)^2 \cdot |F|^2$$



Probability for axion-photon conversion

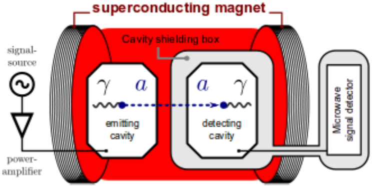
$$P_{\gamma\leftrightarrow a} \propto (g_{a\gamma}BL)^2 \cdot |F|^2$$

That means for our signal rate:

$$|\dot{N_{out}}| \propto \dot{N_{in}} \cdot (g_{a\gamma})^4 \cdot (BL)^4 \cdot \epsilon_{det}$$

LSW - microwaves

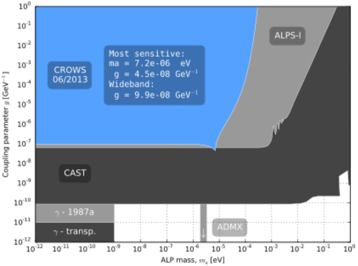
- CROWS at CERN ☺
- See overview by Ana Malagon → first talk tomorrow morning
- Easy to operate low loss cavities.
- Sensitive also to near-field WISPs.



Betz et al, arXiv 1310.8098

LSW - microwaves

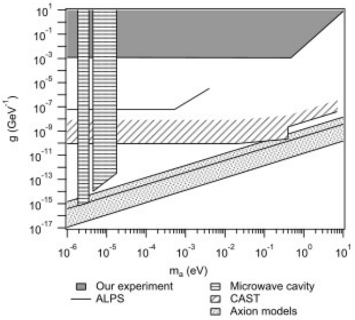
- CROWS at CERN ☺
- See overview by Ana Malagon → first talk tomorrow morning
- Easy to operate low loss cavities.
- Sensitive also to near-field WISPs.
- Lower energy restricts mass.



Betz et al, arXiv 1310.8098

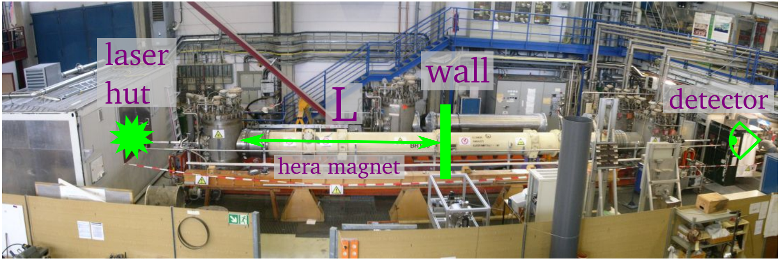
LSW - Xrays

- Measurements at ESRF, Spring-8
- The photon energy limits the mass range.
- X-rays extend mass range of limits
- limited number of photons



Battesti et al, arXiv 1008.2672

ALPS I: Setup



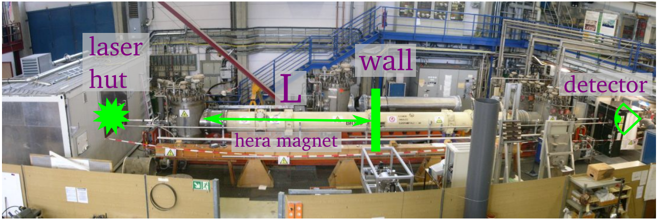
ALPS I: LSW in the optical regime

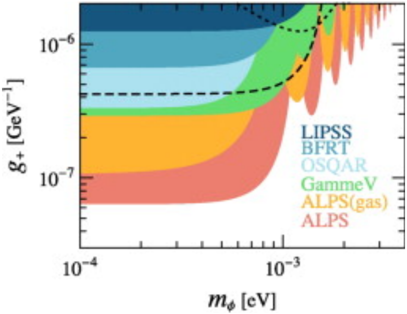
> ALPS I experiment from 2007-2010 at DESY

> Using an old HERA magnet

> 1 kW circulating laser power (cavity), 512 nm green light

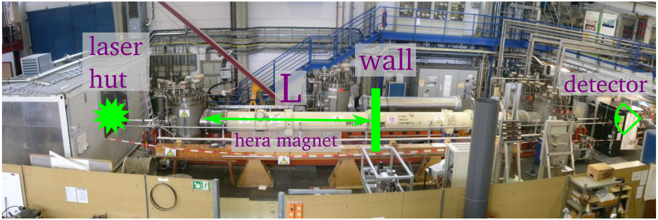
ALPS I: Results

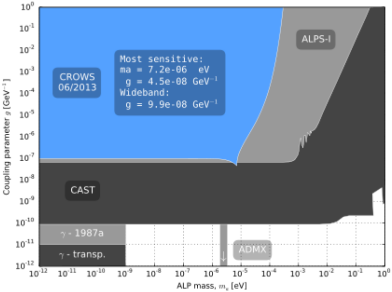




- worldwide best laboratory limits Phys.Lett. **B689** (2010) 149-155
-

ALPS I: Results





> Still worldwide best laboratory limits Phys.Lett. **B689** (2010) 149-155 except for a small mass region

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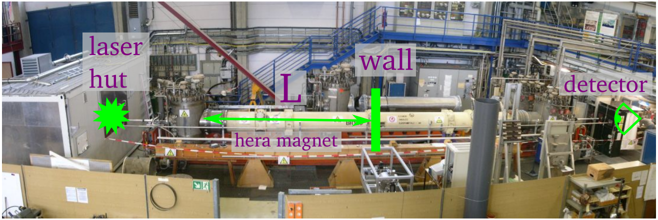
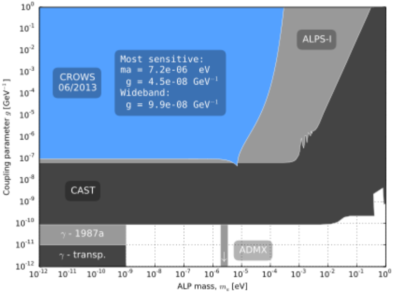
ALPS I: Results

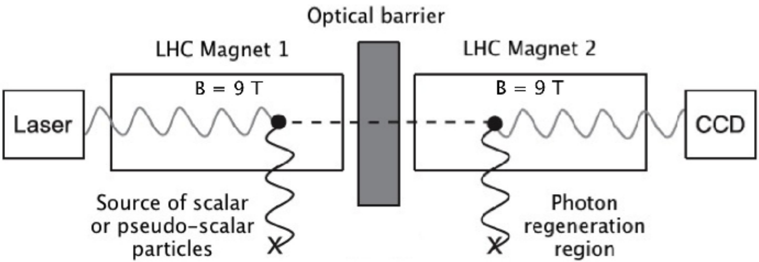




- Still worldwide best laboratory limits Phys.Lett. **B689** (2010) 149-155 except for a small mass region
- But: quite some way to go ... ☹

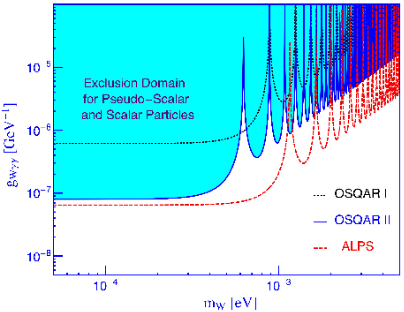
Betz et al, arXiv 1310.8098

OSQAR: Setup arXiv:1306.0443



- OSQAR experiment at CERN
- Using two LHC magnets with 9.5 T over 2 x 14.3 m
- Argon laser: 3 - 25 W beam with 488-514 nm
- CCD camera

OSQAR: Results arXiv:1306.0443

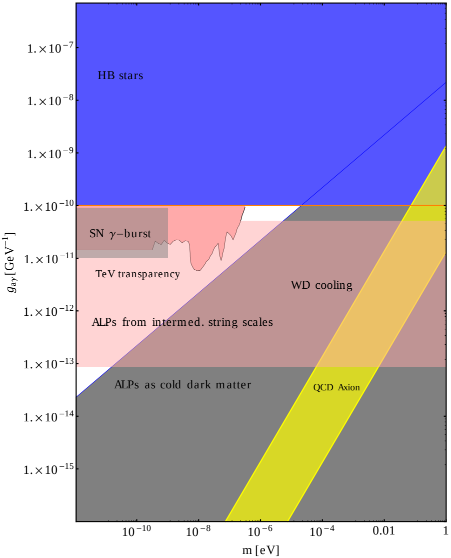


> OSQAR confirms ALPS limits

> Planned to increase sensitivity by a factor 4 (talk by Miroslav Sulc at last year's PATRAS workshop)

> Talk by Pierre Pugnat just before lunch

ROI again



HB stars
SN γ−burst
TeV transparency
WD cooling
ALPs from intermed. string scales
ALPs as cold dark matter
QCD Axion
$1.\times10^{-7}$
$1.\times10^{-8}$
$1.\times10^{-9}$
$1.\times10^{-10}$
$1.\times10^{-11}$
$1.\times10^{-12}$
$1.\times10^{-13}$
$1.\times10^{-14}$
$1.\times10^{-15}$
$g_{a\gamma}\,[\mathrm{GeV}^{-1}]$
10^{-10}
10^{-8}
10^{-6}
10^{-4}
0.01
1
m [eV]

ALPS II: How to get to ROI

Changes compared to ALPS I

- Regeneration cavity
- More (effective) laser power
- Different wavelength, now 1064 nm, i.e. infrared
- Different detector: from CCD to superconducting TES
- More magnets

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Parameter	Scaling	ALPS I	ALPS IIc	Sens. gain
Effective laser power P_{laser}	$g_{a\gamma} \propto P_{\text{laser}}^{-1/4}$	1 kW	150 kW	3.5
Rel. photon number flux n_γ	$g_{a\gamma} \propto n_\gamma^{-1/4}$	1 (532 nm)	2 (1064 nm)	1.2
Power built up in RC P_{RC}	$g_{a\gamma} \propto P_{reg}^{-1/4}$	1	40,000	14
BL (before& after the wall)	$g_{a\gamma} \propto (BL)^{-1}$	22 Tm	468 Tm	21
Detector efficiency QE	$g_{a\gamma} \propto QE^{-1/4}$	0.9	0.75	0.96
Detector noise DC	$g_{a\gamma} \propto DC^{1/8}$	$0.0018\,\text{s}^{-1}$	$0.000001\,\text{s}^{-1}$	2.6
Combined improvements				3082

Sensitivity gain of about 3000 compared to ALPS I!

ALPS II: How to get to ROI

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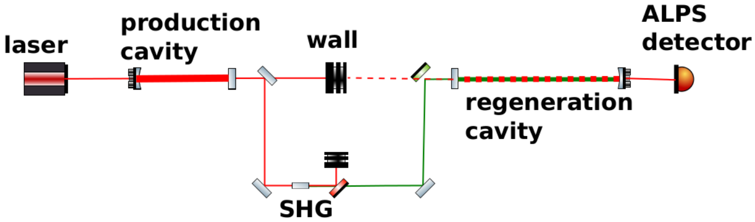
Combined improvements				3082

TDR (2012) JINST 8, T09001 (2013), arXiv:1302.5647, preparatory phase approved (2013).

ALPS II: Optics

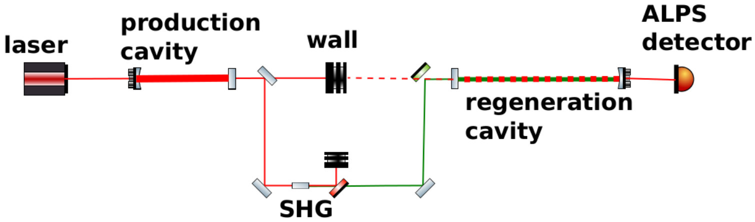


- Recycle photons through cavity
- Regeneration cavity → photon self-interference

  Nucl.Phys. **B358** (1991) 3-26, [1101.4089]

- Locking regeneration cavity with green light
- Power build-up of 5000 for production and 40000 for regeneration cavity planned

ALPS II: Optics



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Nucl.Phys. **B358** (1991) 3-26, [1101.4089]

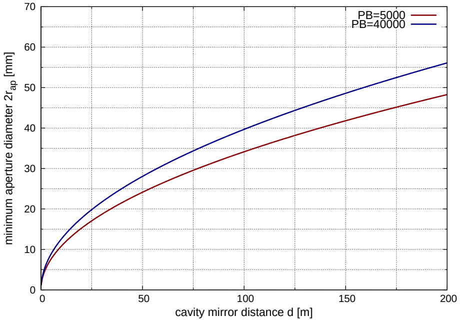
> Locking regeneration cavity with green light

> Power build-up of 5000 for production and 40000 for regeneration cavity planned

> Stable lock for production cavity with high PB achieved

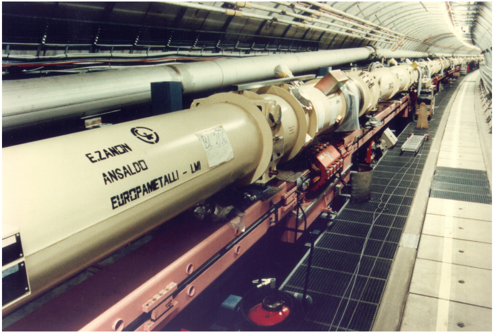
> Dichroic locking concept proven experimentally

ALPS II: Aperture



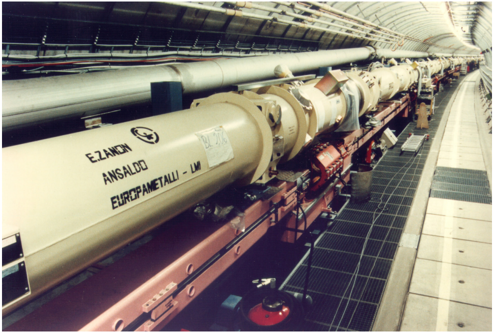
- The power build-up of the cavities is limited due to clipping losses because of aperture.

ALPS II: Aperture



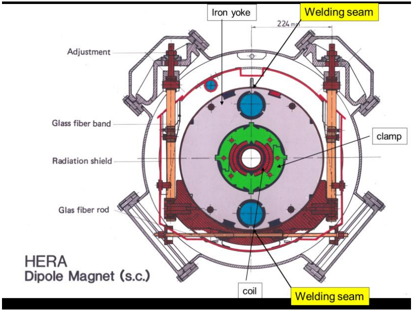
- The power build-up of the cavities is limited due to clipping losses because of aperture.
- HERA magnets are bent → smaller effective aperture
- 35 mm effective aperture limits to 4+4 dipoles (not enough)

ALPS II: Aperture



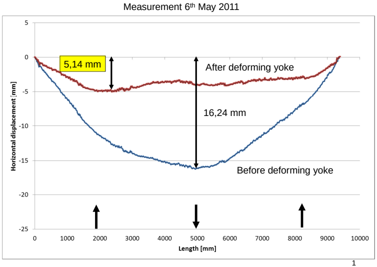
- The power build-up of the cavities is limited due to clipping losses because of aperture.
- HERA magnets are bent → smaller effective aperture
- 35 mm effective aperture limits to 4+4 dipoles (not enough)
- straighten magnets and get to larger aperture, i.e. more magnets?

ALPS II: Straightening Magnets



- HowTo:
  - force on cold mass
  - straightening force applied by pressure screw in the middle of the magnet
  - pressure prop at ends
  - need modified suspensions
- first try on PR magnet, then ALPS I magnet

ALPS II: Straightening Magnets



- HowTo:
  - force on cold mass
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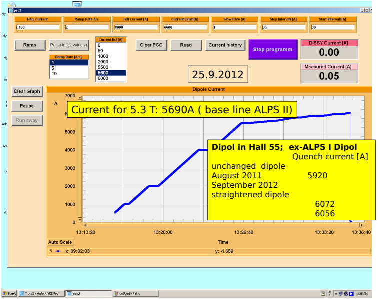
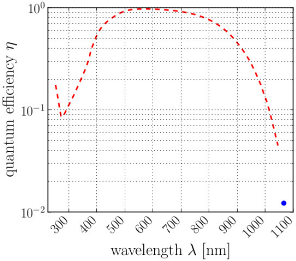
- first try on PR magnet, then ALPS I magnet
- deformation successful, yielding 90% of maximum aperture

ALPS II: Straightening Magnets



- HowTo:
  - force on cold mass
  - straightening force applied by pressure screw in the middle of the magnet
  - pressure prop at ends
  - need modified suspensions
- first try on PR magnet, then ALPS I magnet
- deformation successful, yielding 90% of maximum aperture
- magnet still working perfectly, quench current even slightly increased

ALPS II: Single Photon Detection Challenges



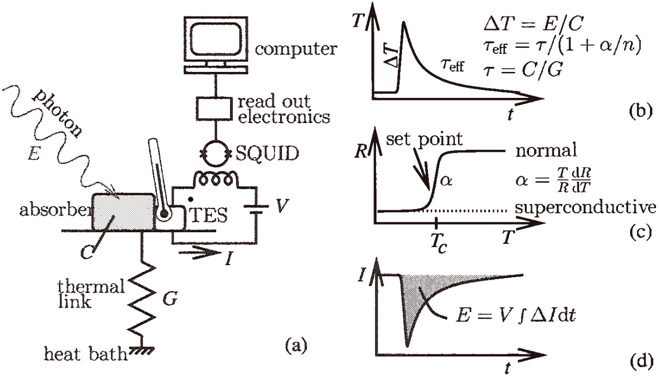
ALPS I solution of CCD camera less suited at ALPS II energy.

What we need to detect our single infrared photons:

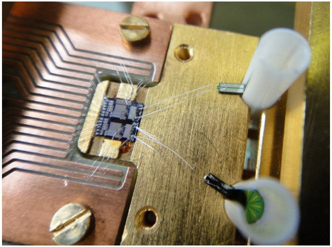
- low dark count and background rate
- high detection efficiency
- long-term stability
- good energy resolution
- good time resolution

What we use

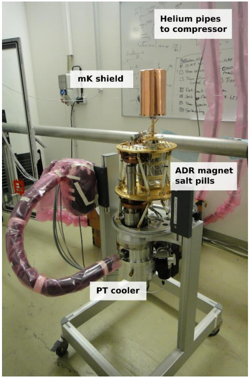
Transition Edge Sensor (TES)
-details in talk by Jan Dreyling-Eschweiler



ALPS II: TES

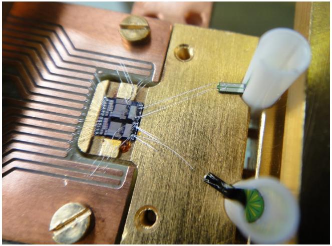


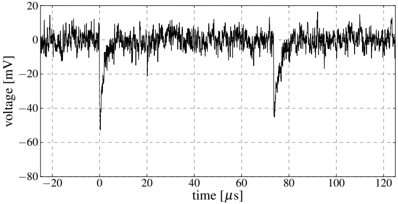
chip from NIST



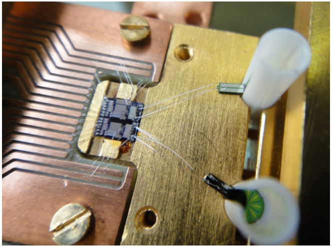
ADR (Adiabatic Demagnetization Refrigerator) from Entropy

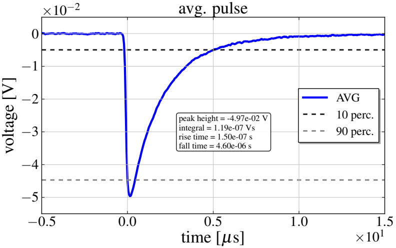
ALPS II: TES





ALPS II: TES



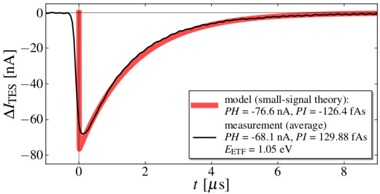


Infrared photon pulses with our TES

- Rise times of the order of 10^{-7}s, fall times about $5 \cdot 10^{-6}$s.
- TES current increase about 70 nA.
- Energy resolution below 10%.
- Intrinsic background rate of about 10^{-4}s^{-1}.

TES system promising for satisfying ALPS II requirements.

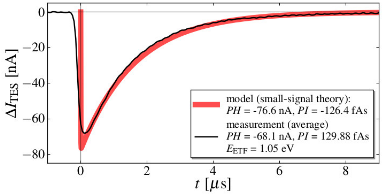
ALPS II: More TES Results



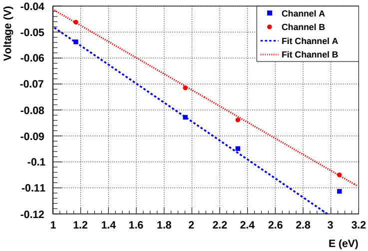
Pulse shape well understood with extracted parameters.

More in Jan Dreyling-Eschweiler's talk on Friday

ALPS II: More TES Results



Pulse shape well understood with extracted parameters.



TES response linear in relevant energy region.

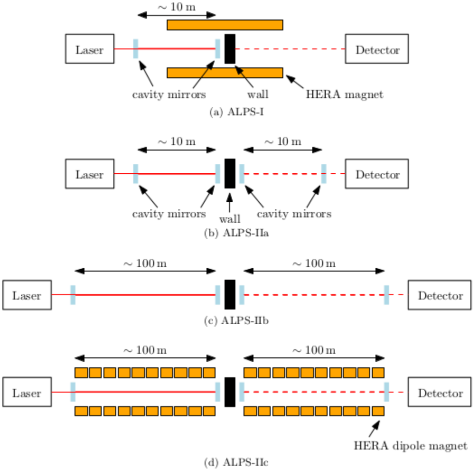
More in Jan Dreyling-Eschweiler's talk on Friday

ALPS II: Milestones

Milestones reached

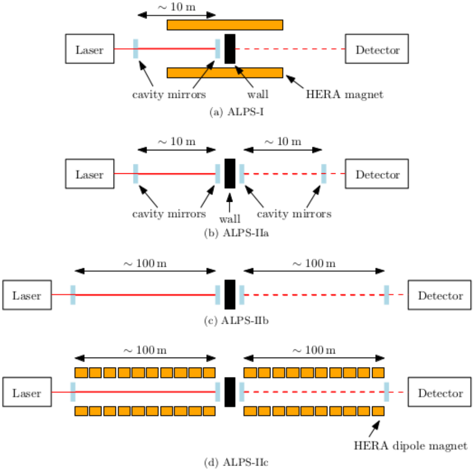
- Setting up the ALPS IIa lab and infrastructure.
- High finesse production cavity locked stably
- Dichroic locking concept proven
- Studies indicate that seismic noise in the HERA tunnel and long term slow movements do not pose a problem
- Magnet straightening concept proven
- TES system successfully set up with very low intrinsic background
- Highly efficient free-optic (from cavity) to fibre (for TES) coupling

ALPS II: Stages and Outlook



- **ALPS I**: 10 m with 1 magnet
- **ALPS IIa**: 10 m without magnets
- **ALPS IIb**: 100 m without magnets
- **ALPS IIc**: 100 m with 20 magnets

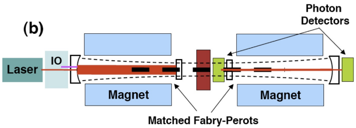
ALPS II: Stages and Outlook



- **ALPS I**: 10 m with 1 magnet
- **ALPS IIa**: 10 m without magnets 2014/15
- ~~**ALPS IIb**: 100 m without magnets~~
- **ALPS IIc**: 100 m with 20 magnets 2018

What the future might bring...

REAPR http://astro.fnal.gov/projects/AxionSearches/ReapR_project.html



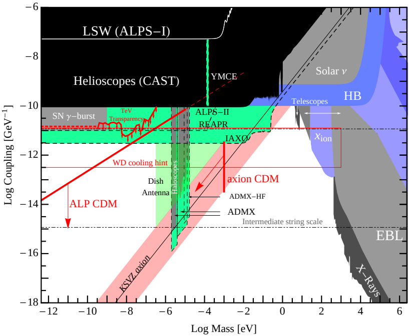
- Using a long string of Tevatron magnets
- Two Fabry-Perot cavities $\rightarrow$ regeneration cavity
- Heterodyne signal detection

"ALPS III"

Exp.	Photon flux 1/s	E_γ eV	B T	L m	B·L Tm	PB	Sens. rel.
ALPS I	$3.5 \cdot 10^{21}$	2.3	5.0	4.4	22	1	0.0003
ALPS IIc	$1 \cdot 10^{24}$	1.2	5.3	106	468	40,000	1
ALPS III	$3 \cdot 10^{25}$	1.2	13	400	5200	100,000	27

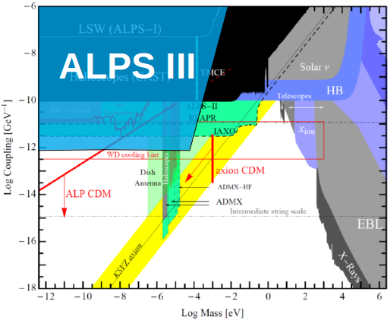
Conclusion

- LSW in the optical regime are an important tool for (relatively) model-independent WISP searches.
- ALPS II will be able to reach the interesting region wrt astrophysical hints.
- Within the next years the limits from optical LSW experiments can be improved



Conclusion

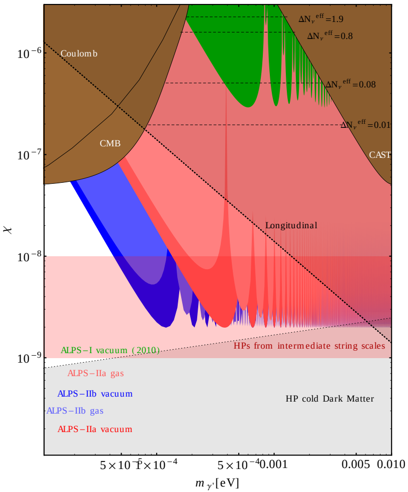
- LSW in the optical regime are an important tool for (relatively) model-independent WISP searches.
- ALPS II will be able to reach the interesting region wrt astrophysical hints.
- Within the next years the limits from optical LSW experiments can be improved or WISPs will be discovered where there are so many hints



Backup

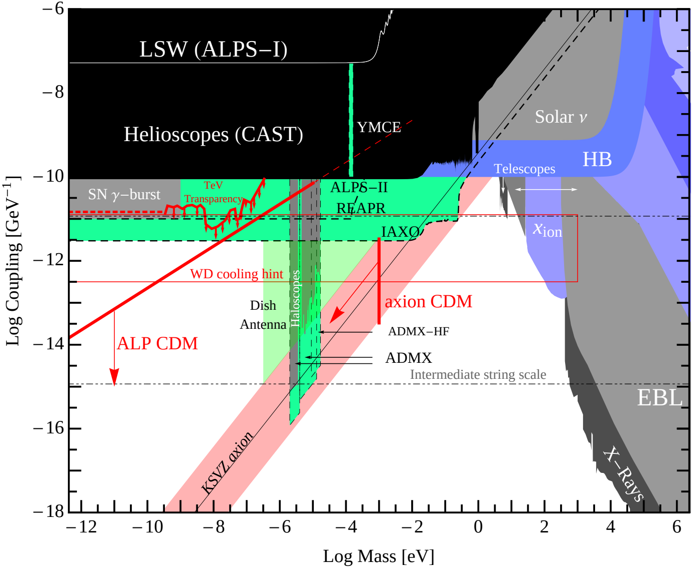
BACKUP

Hidden photons

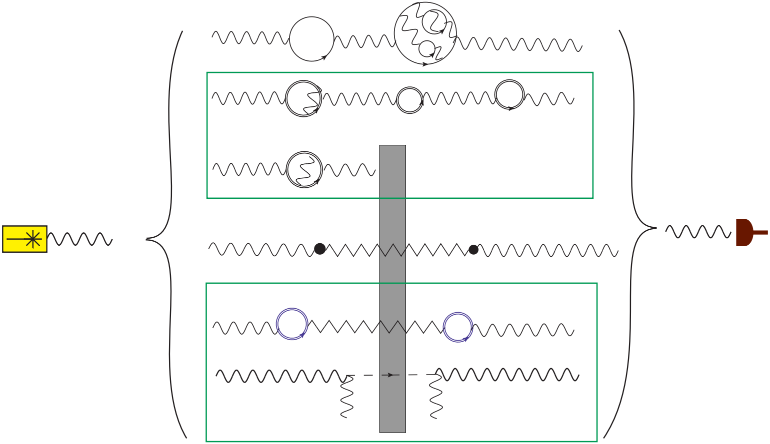


- no magnets needed
- HPs e.g. from intermediate string scale scenarios [arXiv:1206.0819], Dark Matter candidate [arXiv:1201.5902]
- ALPS I, ALPS IIa, ALPS IIb

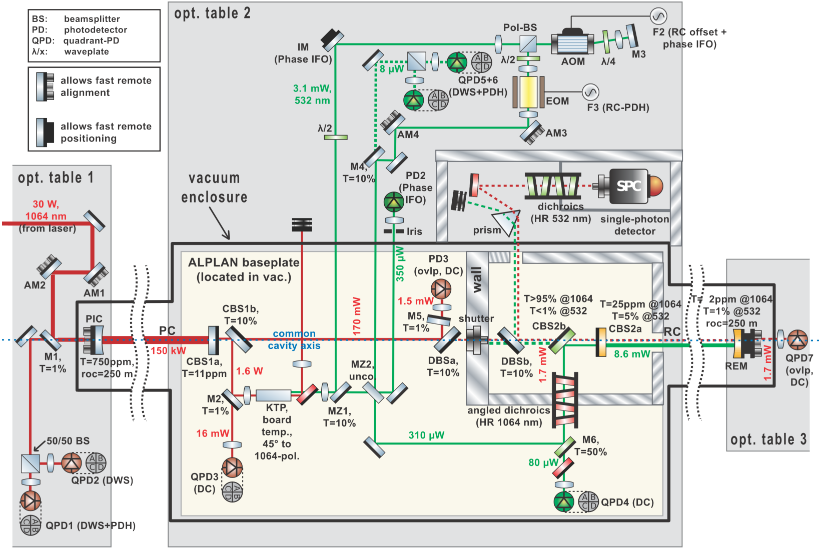
Comprehensive ALP plot



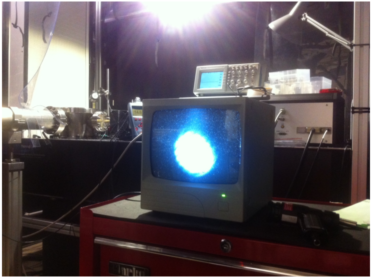
LSW: Possibilities

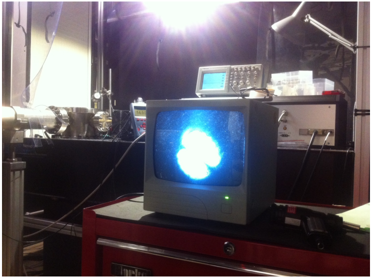


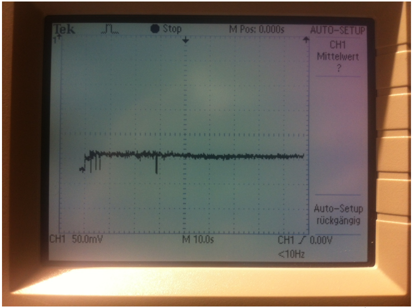
Optical Layout



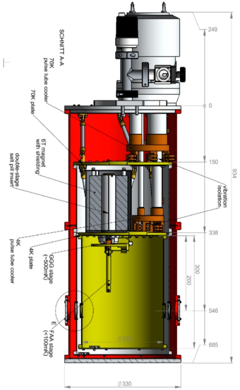
Locked Cavity

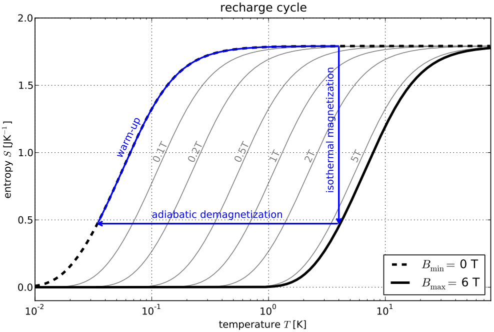




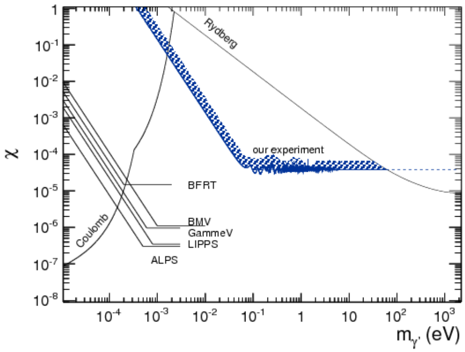


ADR: Millikelvin Environment

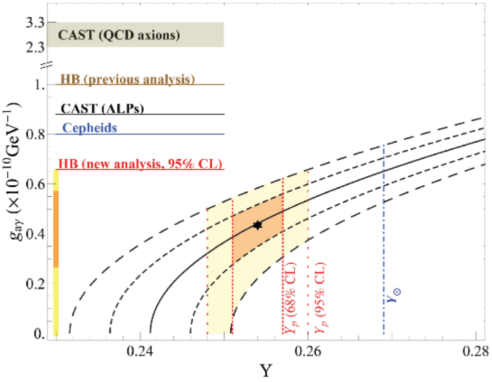




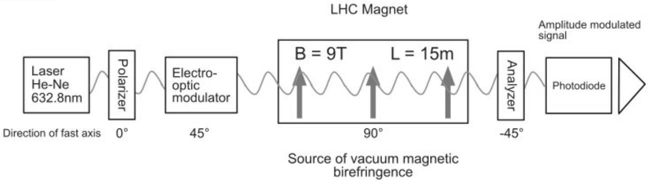
SPring-8 arXiv:1301.6557



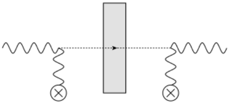
Globular clusters arXiv:1406.6053



OSQAR: Vacuum Magnetic Birefringence



LSW - more formulas



Probability for axion-photon conversion

$$P_{\gamma\leftrightarrow a} = \frac{1}{4}\frac{\omega}{k_a}(g_{a\gamma}BL)^2 \cdot |F|^2$$

in a homogenous magnetic field

$$|F| = \frac{2}{qL}\sin\frac{qL}{2}$$