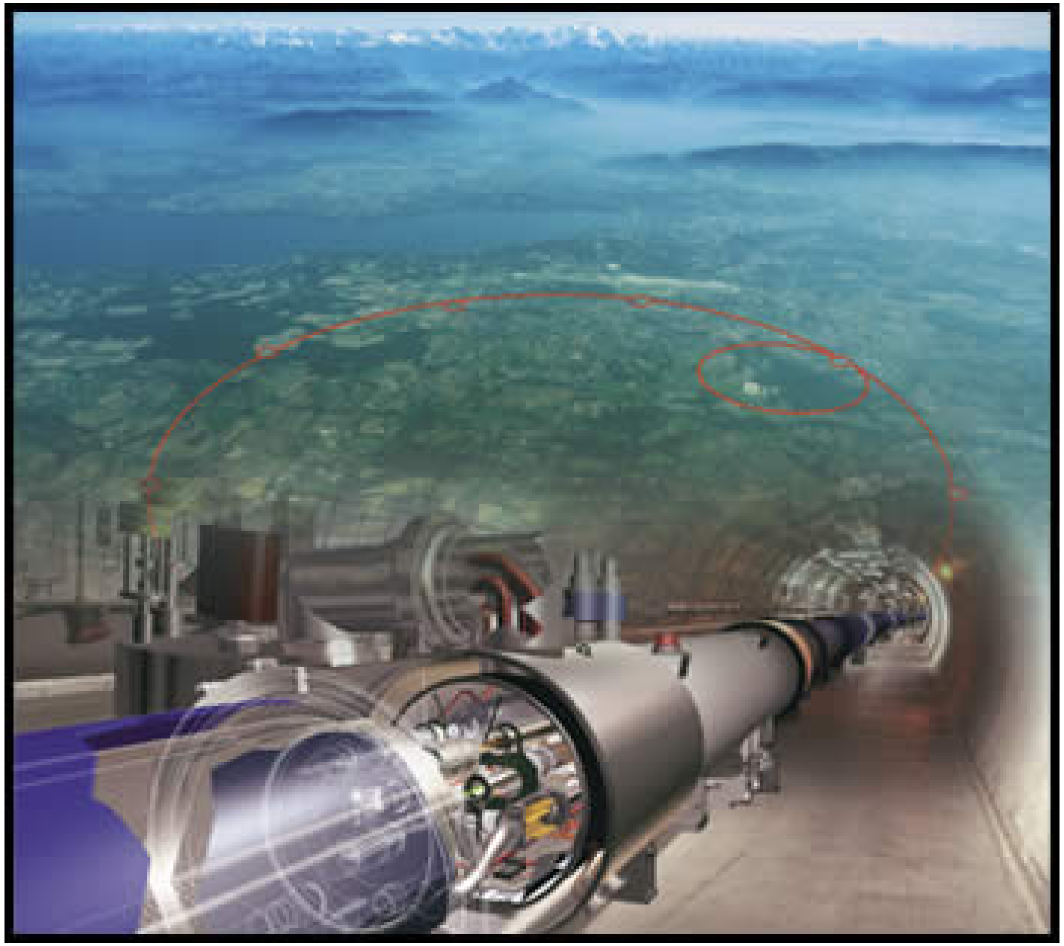
Low-Energy Photons as a Probe of Weakly Interacting Sub-eV Particles

Andreas Ringwald

3rd ILIAS-CERN-DESY Axion-WIMP Workshop
June 21, 2007
Patras, GR

0. Introduction

- Large Hadron Collider (LHC) will probe physics at the TeV scale at an unprecedented level



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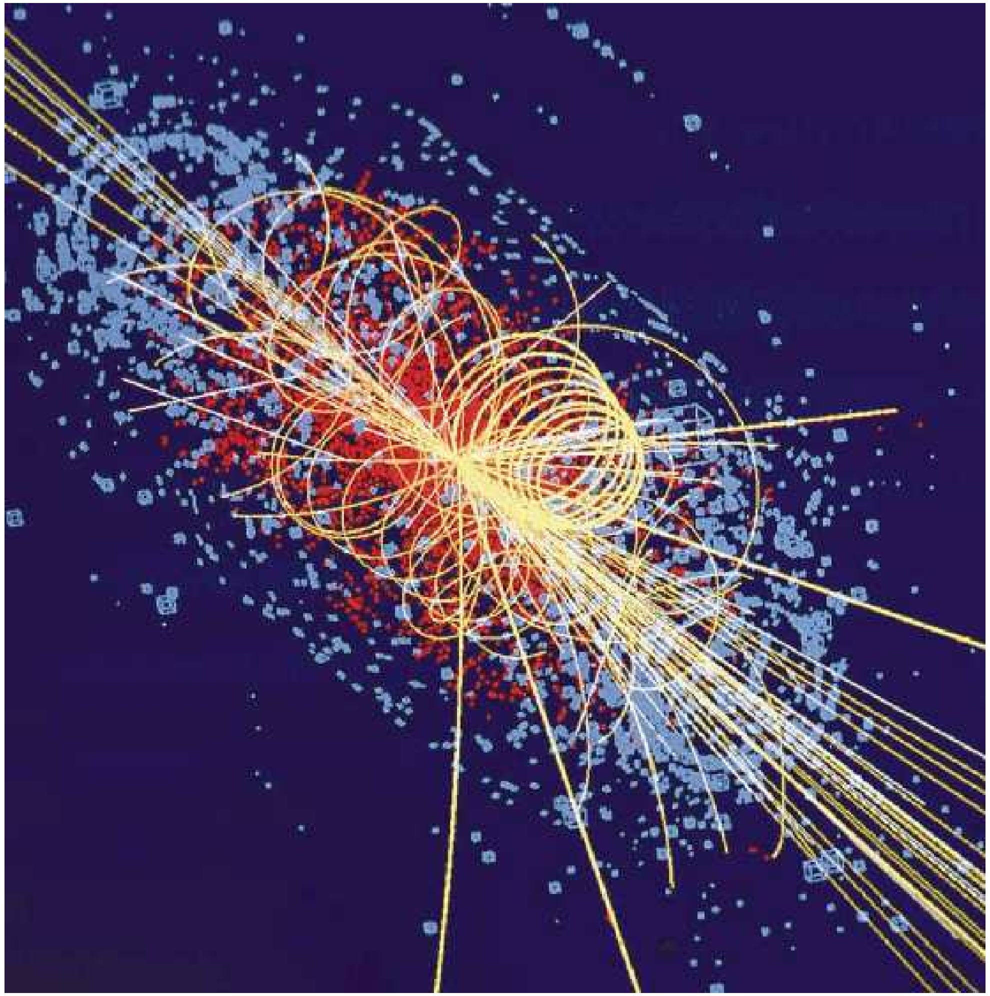
  - Origin of particle masses?



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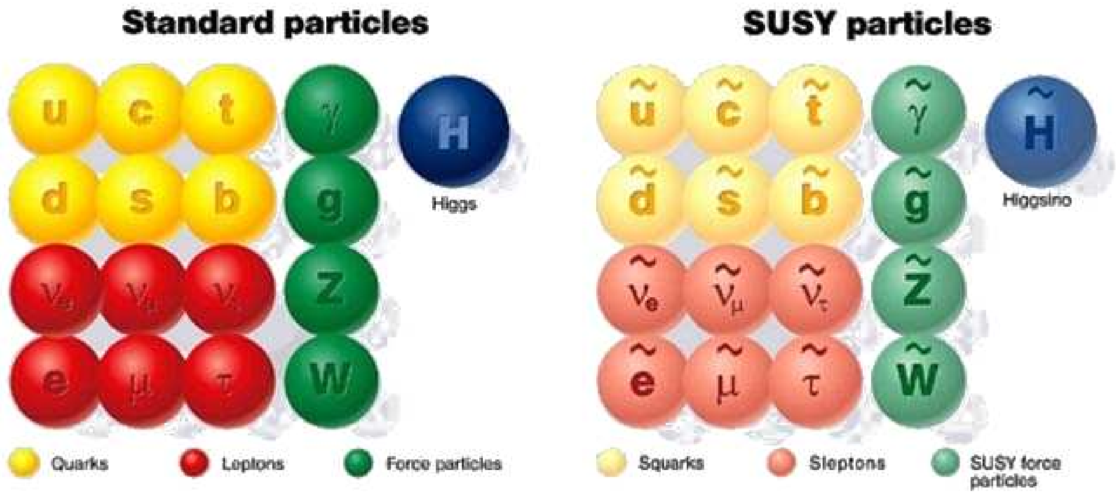
  - Nature of dark matter? Neutralinos as Weakly Interacting Massive Particles (WIMPs)?



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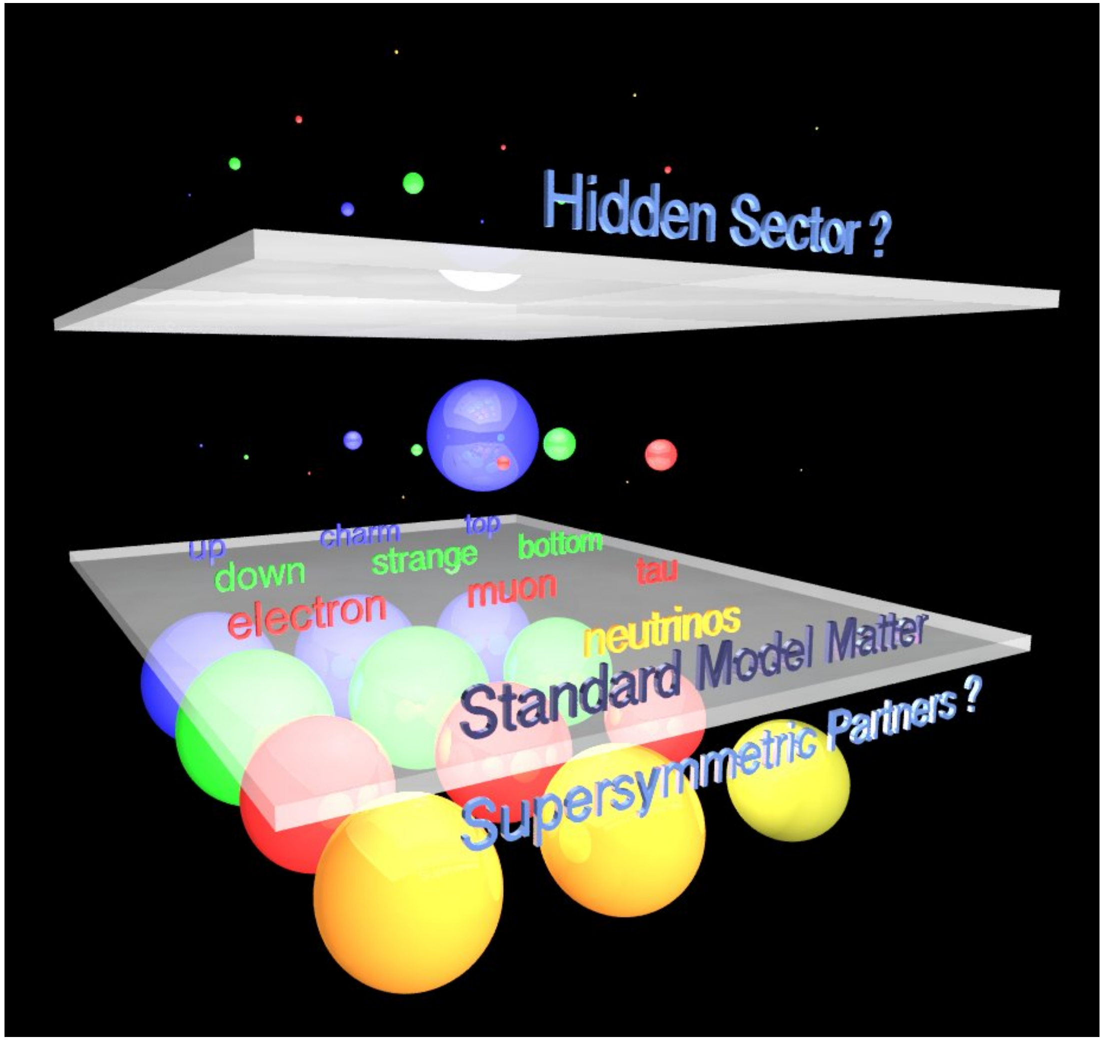
- Large Hadron Collider (LHC) will probe physics at the TeV scale at an unprecedented level
  - Origin of particle masses?
  - Nature of dark matter? Neutralinos as Weakly Interacting Massive Particles (WIMPs)?
- Experiments exploiting low-energy photons and/or large electromagnetic fields may yield complementary information on physics at the sub-eV scale
  - Weakly Interacting Sub-eV Particles (WISPs): axions, paraphotons, minicharged particles, ...?



[Ahlers (unpubl.)]

Outline:

1. **Low-Energy Electromagnetic Interactions of WISPs**

   WISPs interact with photons via quantum fluctuations

2. **Laser Polarization Experiments**

   WISPs may lead to vacuum magnetic dichroism and birefringence

3. **Light-Shining-Through-Walls Experiments**

   Photons may convert to neutral WISPs which traverse walls and reconvert into photons behind the latter

4. **Dark-Current-Flowing-Through-a-Wall Experiment**

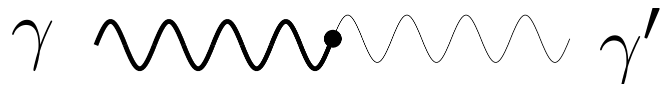
   Minicharged WISPs may be produced in strong electric fields, traverse a wall and may be detected as dark current behind the latter

6. **Conclusions**

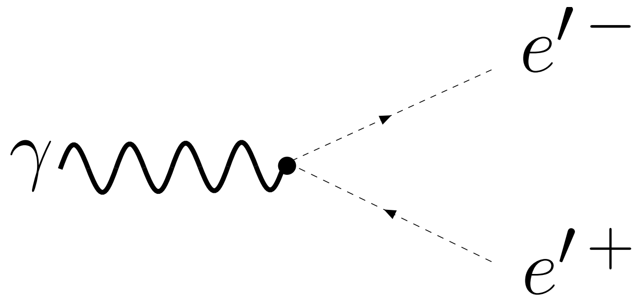
1. Low-Energy Electromagnetic Interactions of WISPs

- Photons interact with WISPs via quantum fluctuations into new, very heavy particles or string excitations

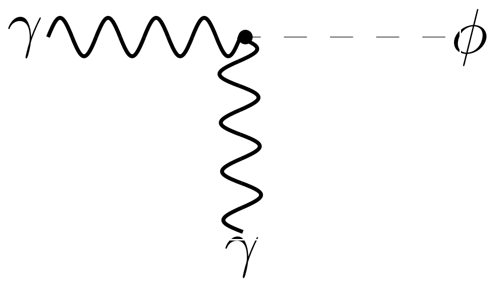
Photon-Paraphoton



Photon-Paraelektron



Photon-Axion/Dilaton



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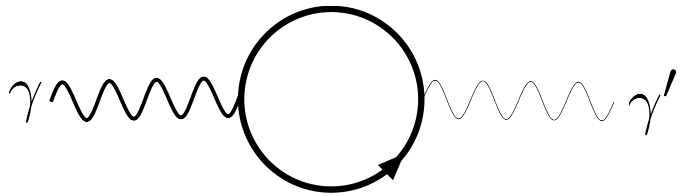

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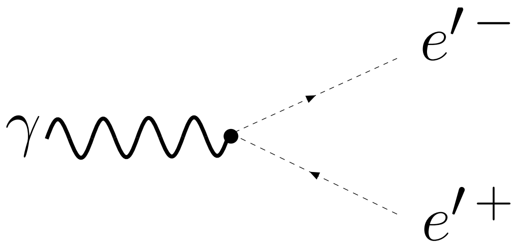

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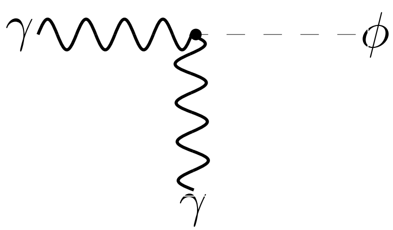

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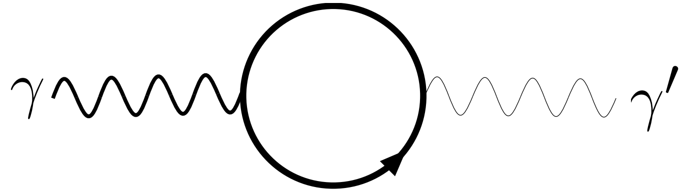

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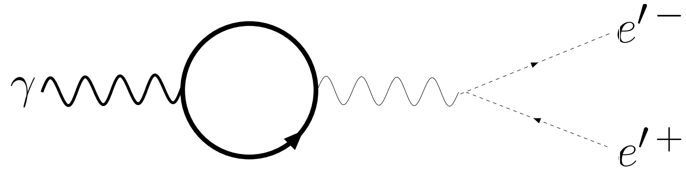

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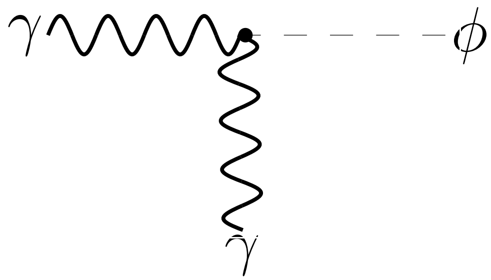


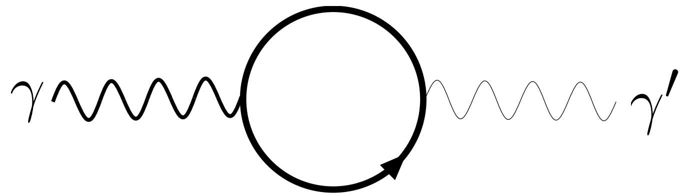
1. Low-Energy Electromagnetic Interactions of WISPs

- Photons interact with WISPs via quantum fluctuations into new, very heavy particles or string excitations

⇒ Size of interactions gives information about hidden sector (masses, couplings, size of extra dimensions)

⇒ Precision experiments with sizeable electromagnetic fields (laser, strong magnetic or electric fields) allow searches for effects of WISPs

Photon-Paraphoton



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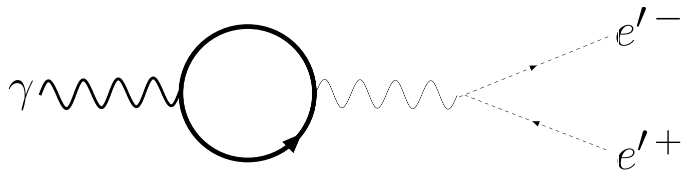

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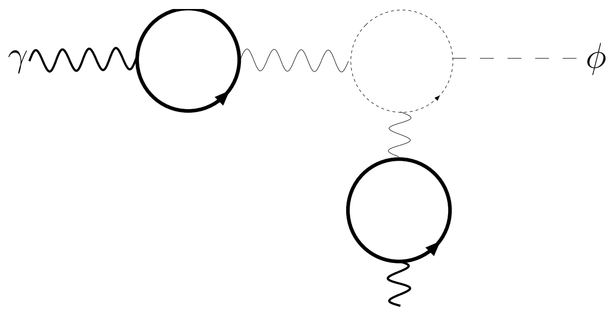
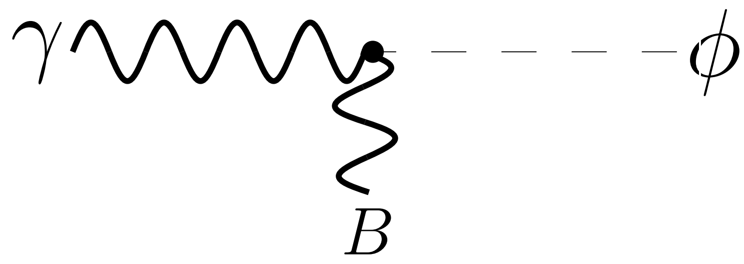


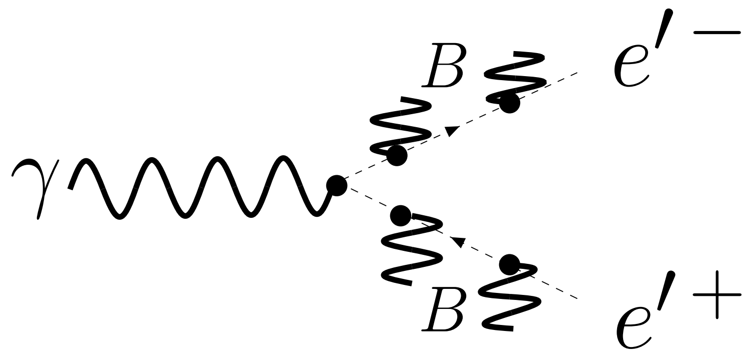
2. Laser Polarization Experiments

- Linearly polarized laser beam along transverse magnetic field:
  - Real conversion of laser photons in WISPs

Photon → ALP:



Photon → MCP:



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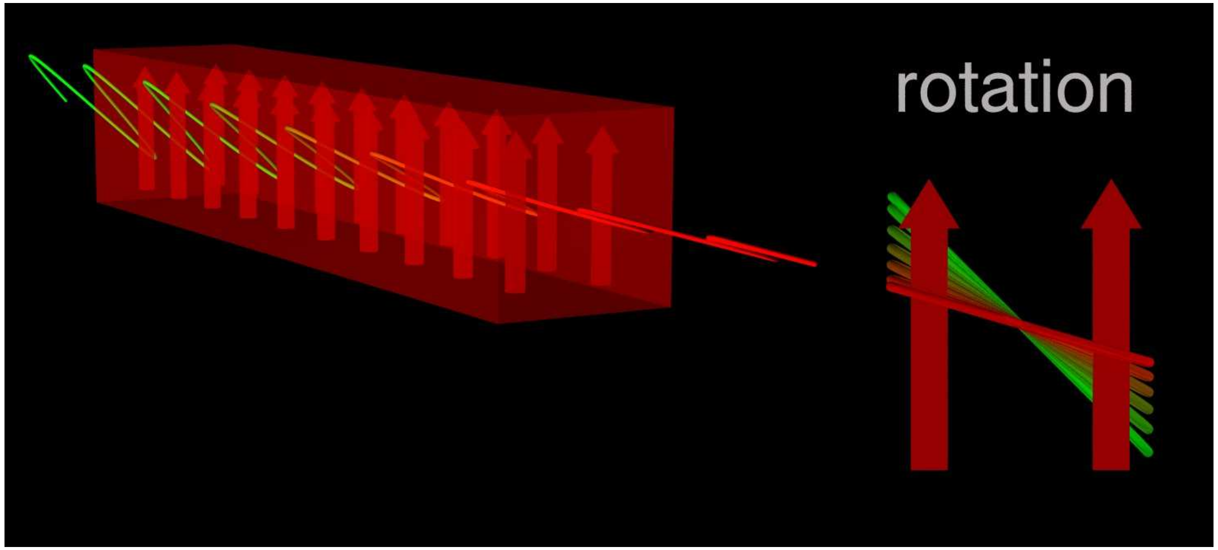

[Ahlers (unpubl.)]

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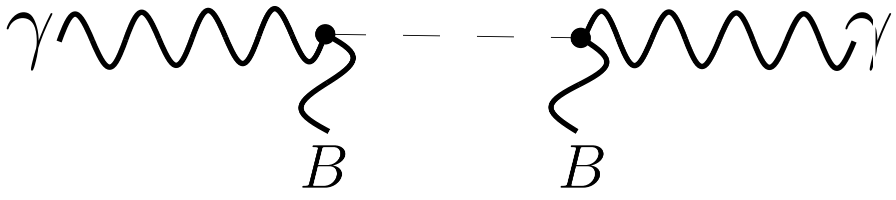
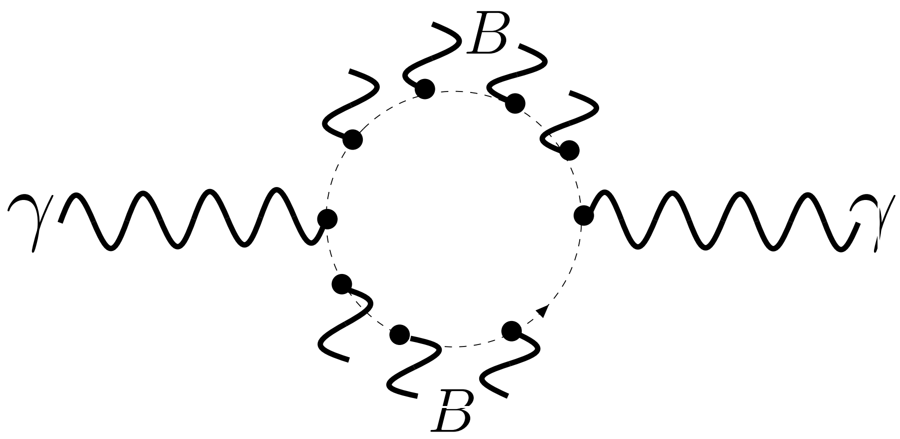
- Linearly polarized laser beam along transverse magnetic field:
  - Real conversion of laser photons in WISPs $\Rightarrow$ Rotation of polarization, since conversion probability depends on relative orientation between polarization and magnetic field direction
  - Virtual conversion of laser photons in WISPs





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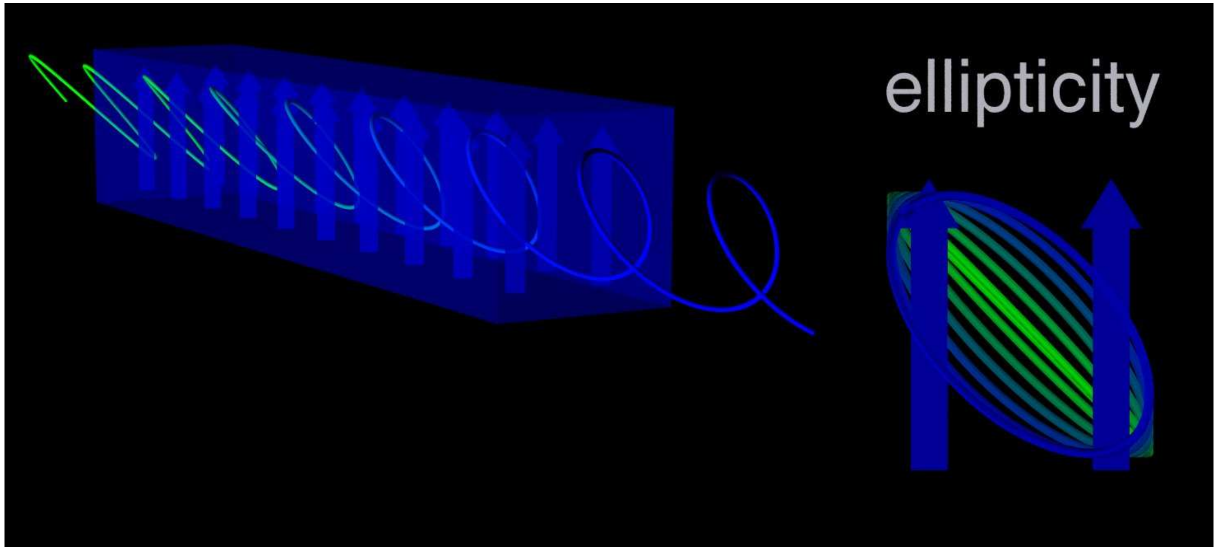
- Linearly polarized laser beam along transverse magnetic field:
  - Real conversion of laser photons in WISPs ⇒ Rotation of polarization, since conversion probability depends on relative orientation between polarization and magnetic field direction
  - Virtual conversion of laser photons in WISPs ⇒ elliptical polarization, since phase velocity depends on relative orientation between polarization and magnetic field



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BFRT experiment: [Cameron *et al.* '93]
(Brookhaven, Fermilab, Rochester, Trieste)

$B \sim 2\ \mathrm{T}, \ell = 8.8\ \mathrm{m}, \omega = 2.4\ \mathrm{eV}, N_{\rm pass} = 34 - 254$

PVLAS experiment: [Zavattini *et al.* '06]

$B = 5\ \mathrm{T}, \ell = 1\ \mathrm{m}, \omega = 1.2\ \mathrm{eV}, N_{\rm pass} = 44000$

Q&A experiment: [Chen,Mei,Ni '06]

$B = 2.3\ \mathrm{T}, \ell = 1\ \mathrm{m}, \omega = 1.2\ \mathrm{eV}, N_{\rm pass} = 18700$

2. Laser Polarization Experiments

- No signal in BFRT

BFRT experiment		
Rotation	$(L = 8.8$ m, $\lambda = 514.5$ nm, $\theta = \frac{\pi}{4})$	
$N_{\rm pass}$	$\lvert\Delta\theta\rvert$ [nrad]	$\Delta\theta_{\rm noise}$ [nrad]
254	0.35	0.30
34	0.26	0.11
Ellipticity	$(L = 8.8$ m, $\lambda = 514.5$ nm, $\theta = \frac{\pi}{4})$	
$N_{\rm pass}$	$\lvert\psi\rvert$ [nrad]	$\psi_{\rm noise}$ [nrad]
578	40.0	11.0
34	1.60	0.44
Regen. $(L = 4.4$ m, $\langle\lambda\rangle = 500$ nm, $N_{\rm pass} = 200)$		
θ [rad]	rate [Hz]	
0	-0.012 ± 0.009	
$\frac{\pi}{2}$	0.013 ± 0.007	

[Cameron *et al* '93]

2. Laser Polarization Experiments

- No signal in BFRT

- Signal in PVLAS

PVLAS experiment	
Rotation ($L = 1$ m, $N_{\rm pass} = 44000$, $\theta = \frac{\pi}{4}$)	
λ [nm]	$\Delta\theta$ [10^{-12} rad/pass]
1064	$(\pm ?)3.9 \pm 0.2$
532	$+6.3 \pm 1.0$ **(preliminary)**
Ellipticity($L = 1$ m, $N_{\rm pass} = 44000$, $\theta = \frac{\pi}{4}$)	
λ [nm]	ψ [10^{-12} rad/pass]
1064	-3.4 ± 0.3 **(preliminary)**
532	-6.0 ± 0.6 **(preliminary)**

[PRL ‘06; IDM ‘06; NT ‘07]

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- No signal in BFRT
- Signal in PVLAS
- No signal in Q&A

Q&A experiment	
Rotation$(L = 1$ m, $\lambda = 1064$ nm, $\theta = \frac{\pi}{4})$	
$N_{\rm pass}$	$\Delta\theta$ [nrad]
18700	-0.4 ± 5.3

[Q&A coll. '06]

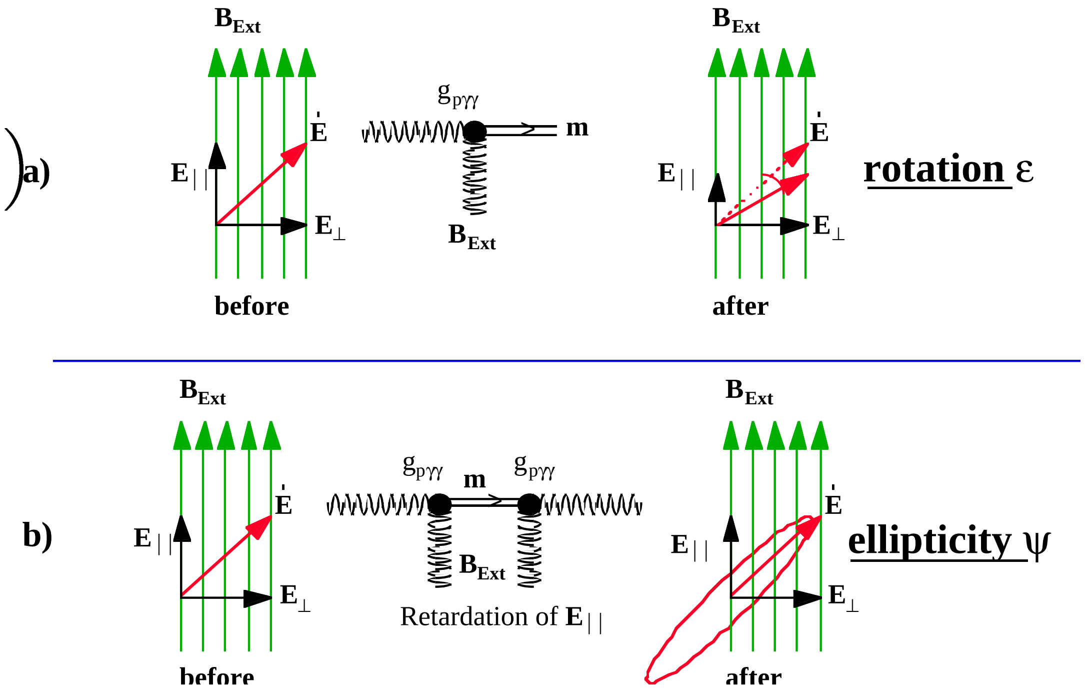
2. Laser Polarization Experiments

- Interpretation in terms of real and virtual production of
  - light neutral spin-zero boson (Axion-Like Particle (ALP)),

$$(g/4)\,\phi^{(-)}\,F_{\mu\nu}\tilde{F}^{\mu\nu}\quad\left(\phi^{(+)}\,F_{\mu\nu}F^{\mu\nu}\right)$$

Effects of Nearly Massless, Spin Zero Particles on Light Propagation in a Magnetic Field

[Maiani,Petronzio,Zavattini '86]



[Brandi *et al.* '01]

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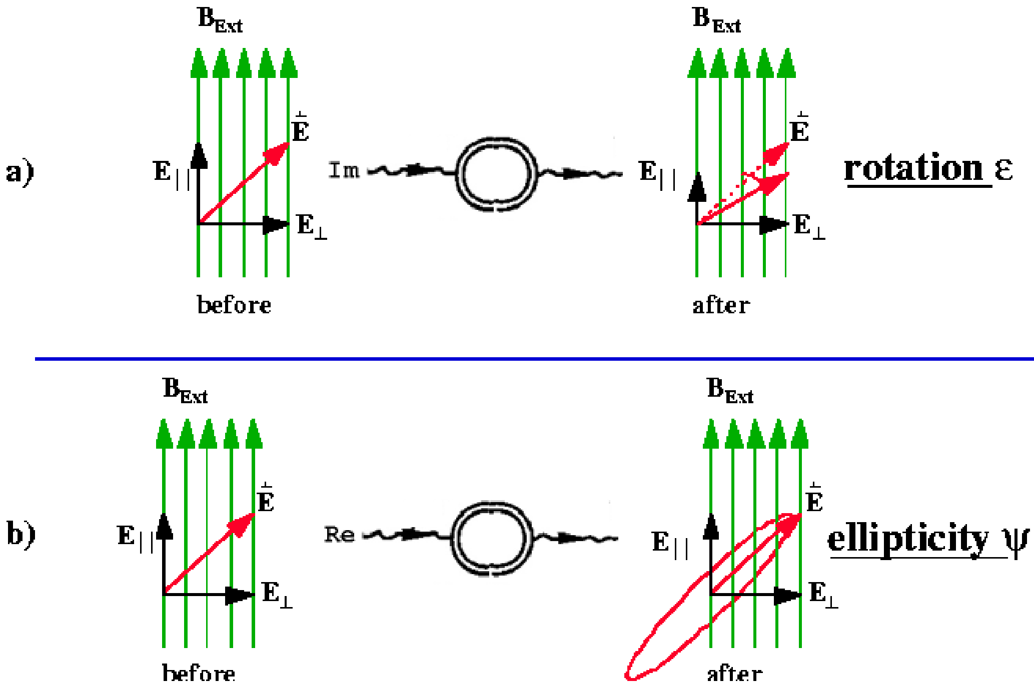
  - light MiniCharged Particle (MCP) – anti-particle pair,

$$\partial_\mu \to \partial_\mu - \mathrm{i}\epsilon e A_\mu$$

Polarized Light Propagating in a Magnetic Field as a Probe for Millicharged Fermions [Gies,Jaeckel,AR '06]



In analogy to theoretically well-studied e^+e^- real and virtual production

[...;Toll '52;...;Adler '71;...;Tsai,Erber '74,'75;...]

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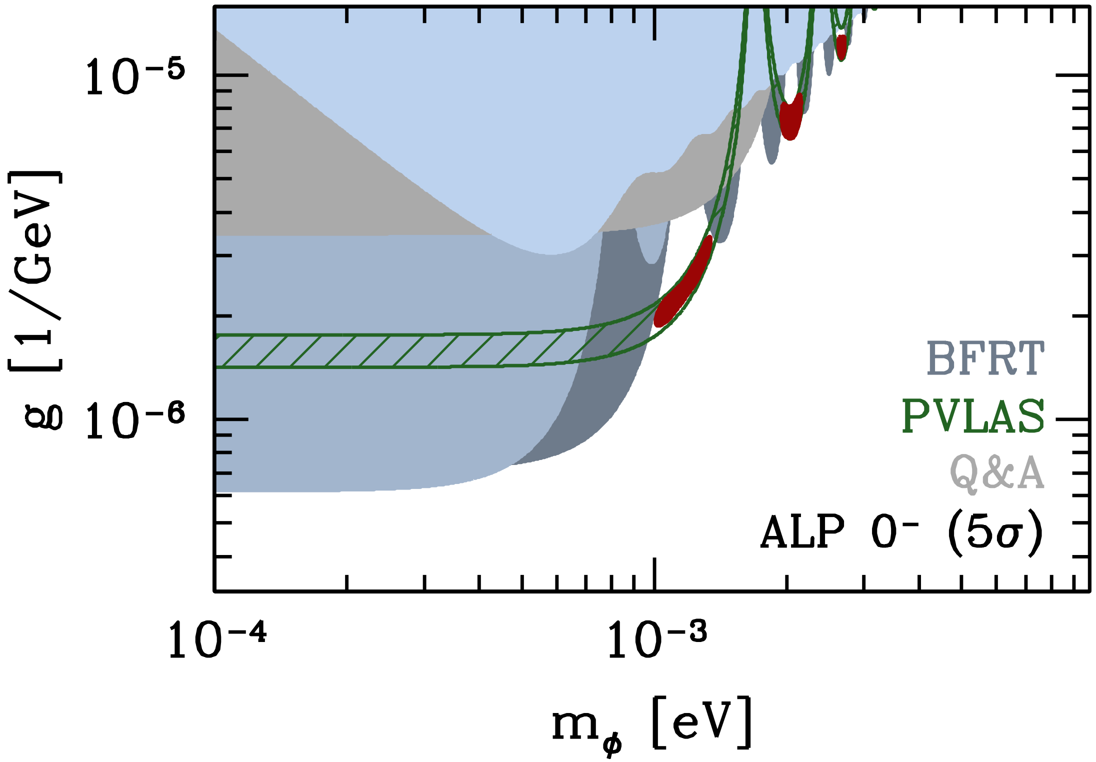
If interpreted in terms of ALP:



[Ahlers,Gies,Jaeckel,AR '06]

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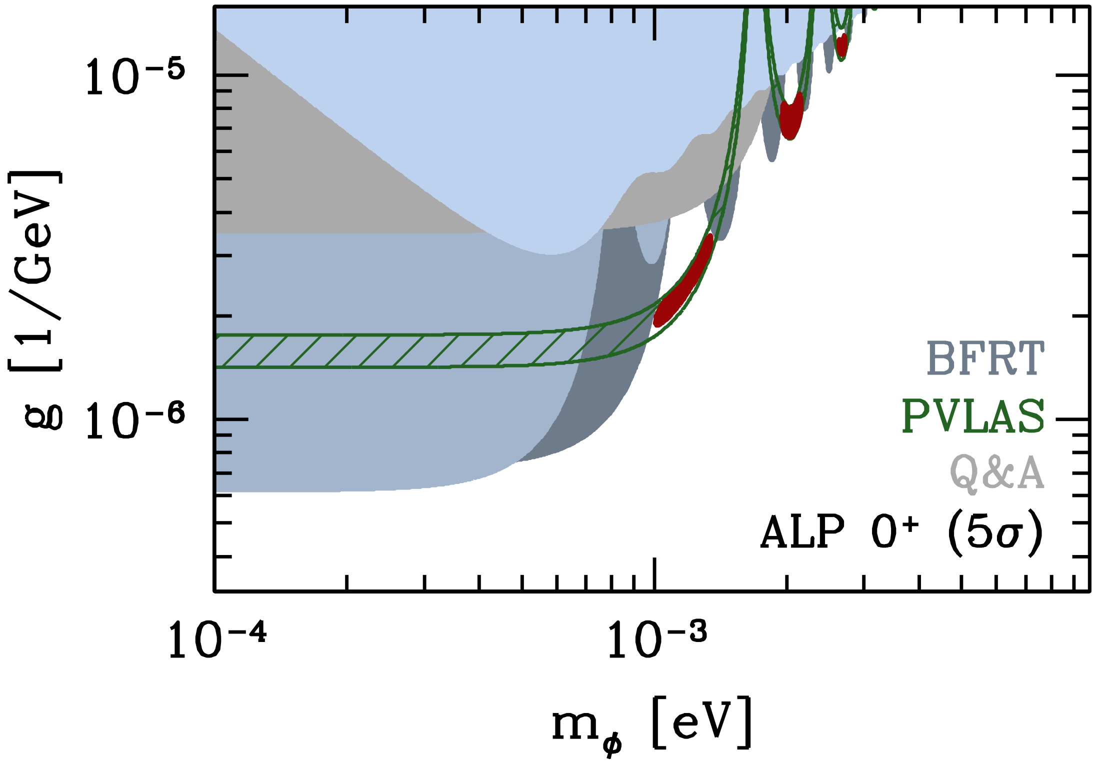

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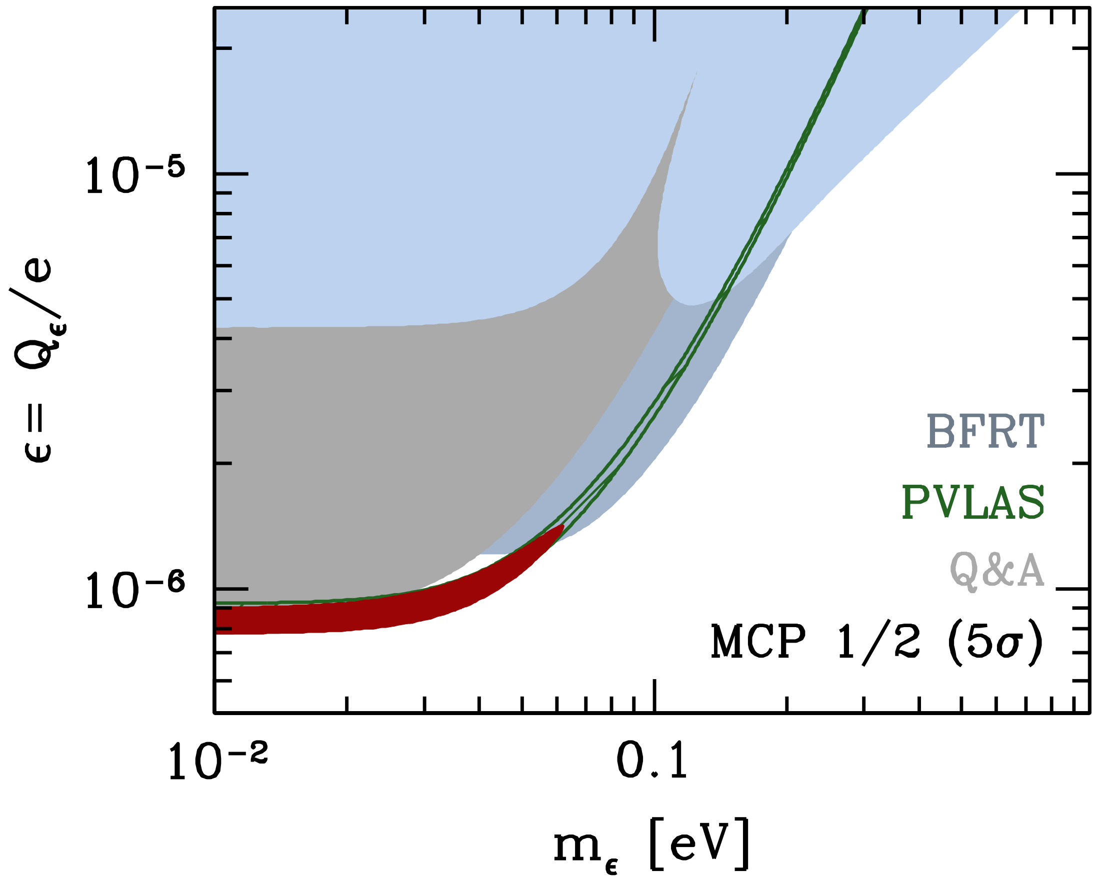

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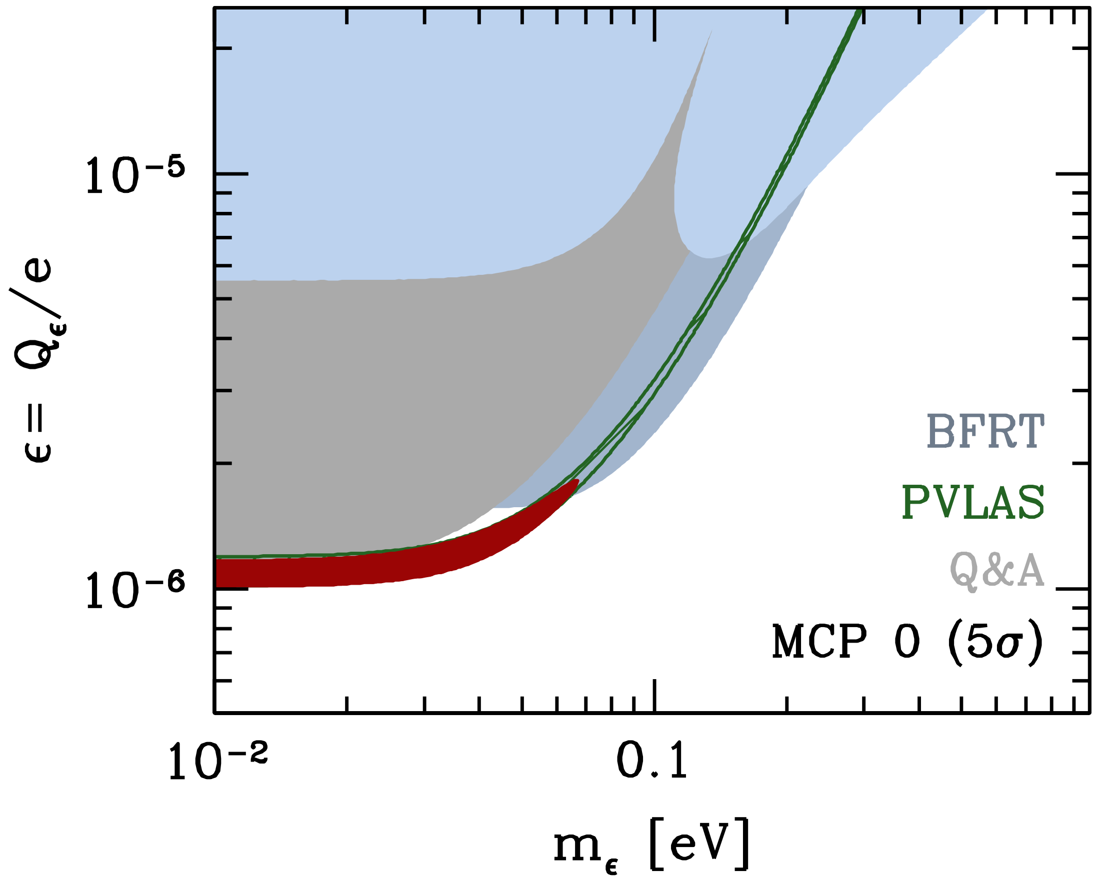

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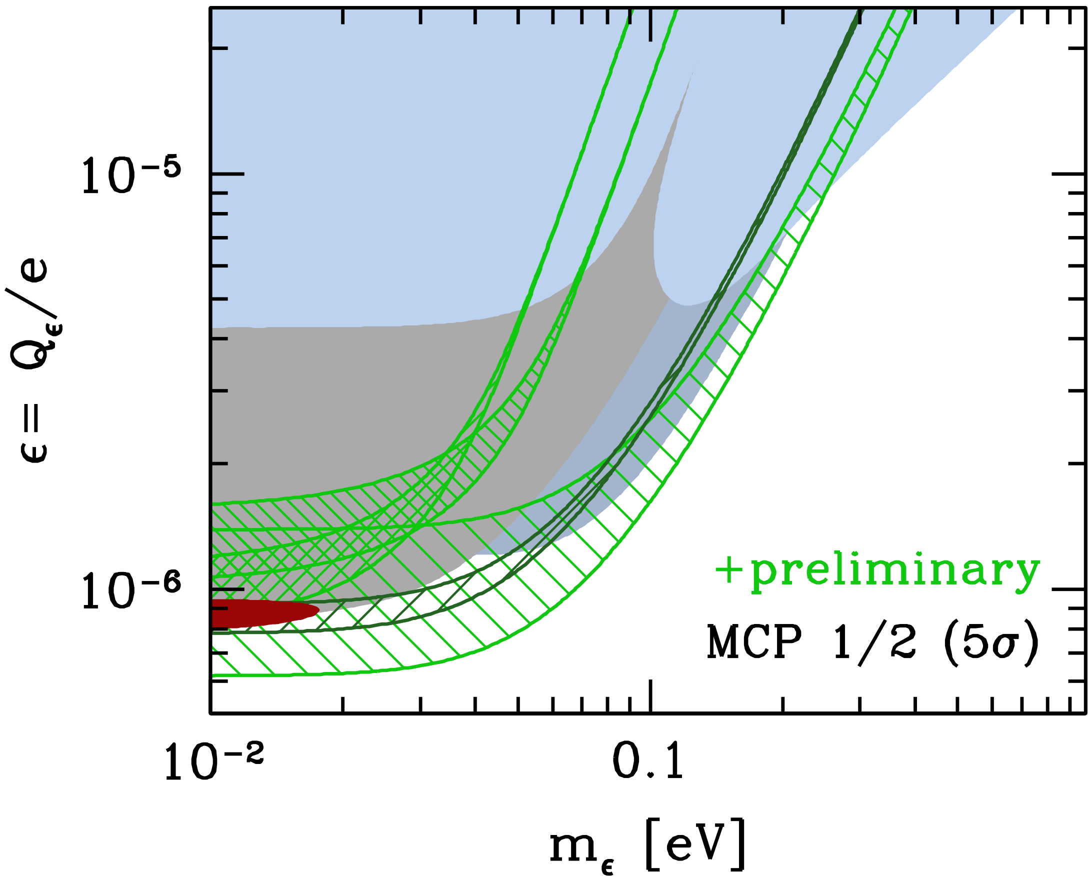

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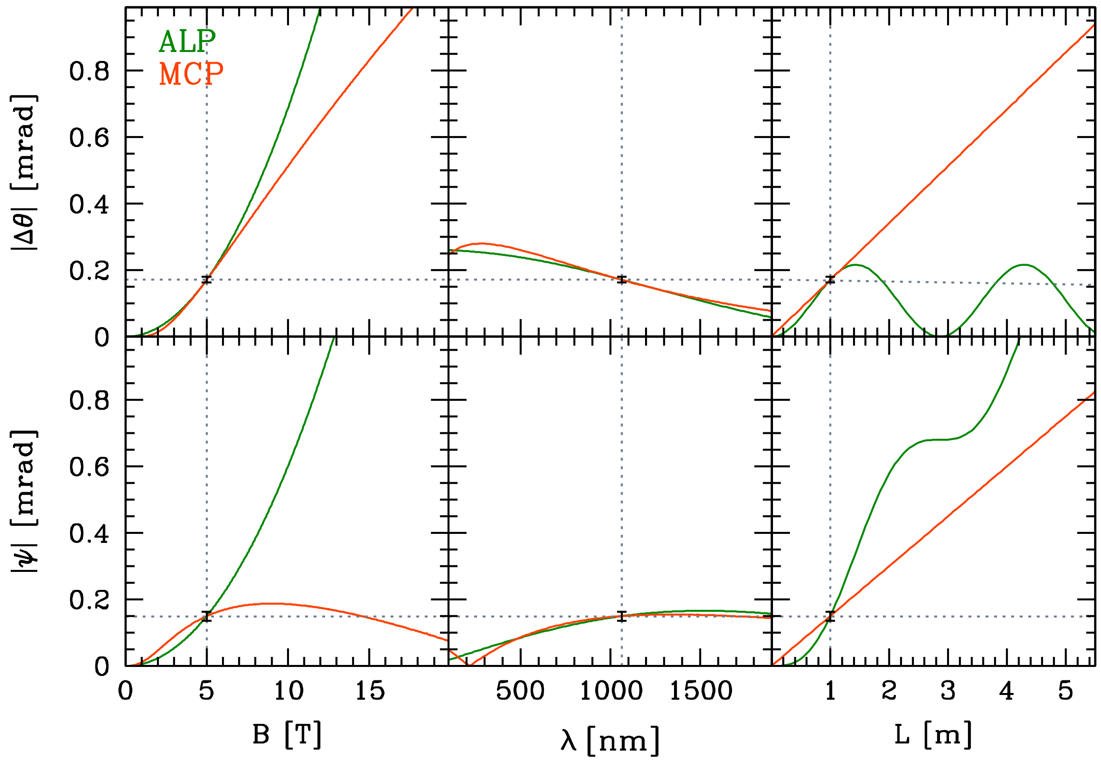
Distinguishing ALPs from MCPs:



[Ahlers,Gies,Jaeckel,AR '06]

BMV (Toulouse): 11 T pulsed magnet

OSQAR (CERN): 9.6 T LHC magnet

3. Light-Shining-Through-Walls Experiments

- Linearly polarized laser beam in vacuum or along a transverse magnetic field

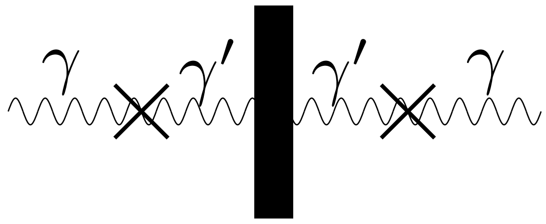
- Place wall in beam pipe:

  - laser beam will be absorbed
  - neutral WISPs (Paraphotons, ALPs) fly through wall and
  - reconvert on other side of wall into photons, which can be detected

[Okun '82;Sikivie '83;Anselm '85;..]

LSW via

- photon-paraphoton oscillations:



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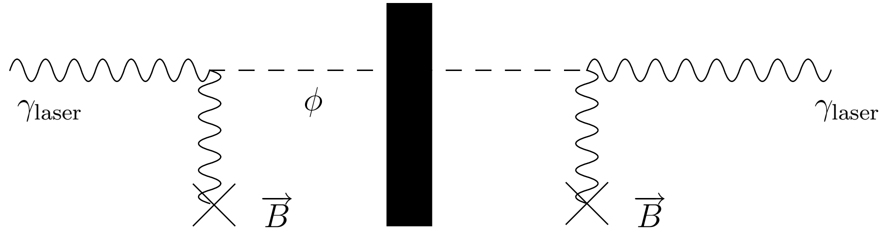

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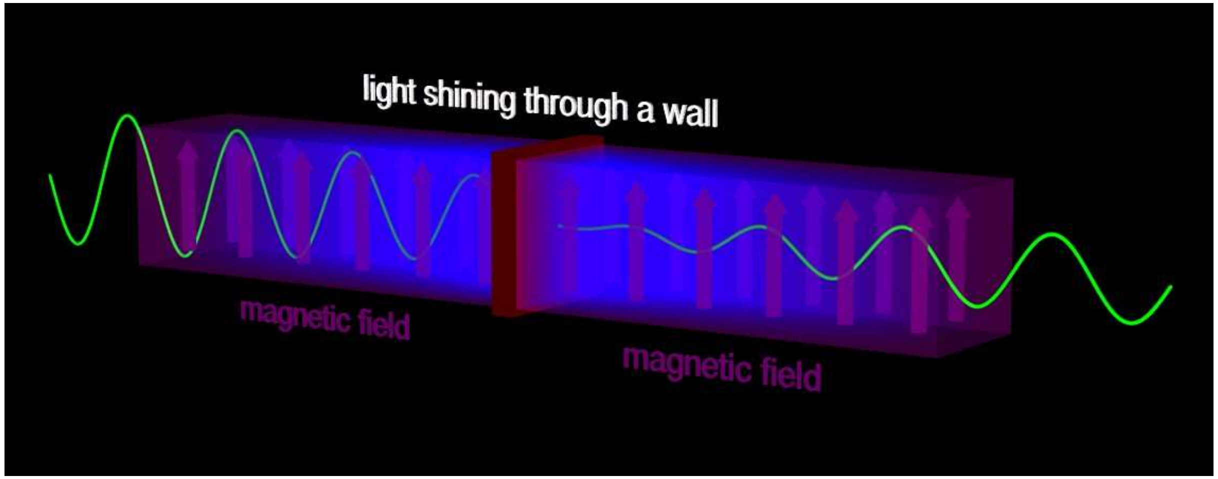

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[Okun '82;Sikivie '83;Anselm '85;..]

- Pioneering experiment: BFRT

- Several ongoing experiments

Experiment	Laser	Cavity	Magnets
ALPS	532 nm; 200 W	–	$B_1 = B_2 = 5$ T, $\ell_1 = \ell_2 = 4.21$ m
BFRT	~ 500 nm; 3 W	$N_p = 200$	$B_1 = B_2 = 3.7$ T, $\ell_1 = \ell_2 = 4.4$ m
BMV	8×10^{21} γ/pulse	–	$B_1 = B_2 = 11$ T, $\ell_1 = \ell_2 = 0.25$ m
GammeV	532 nm; 3.2 W	–	$B_1 = B_2 = 5$ T, $\ell_1 = \ell_2 = 3$ m
LIPSS	900 nm; 3 kW	–	$B_1 = B_2 = 1.7$ T, $\ell_1 = \ell_2 = 1$ m
OSQAR	1064 nm; 1 kW	$N_p \sim 10^4$	$B_1 = B_2 = 9.5$ T, $\ell_1 = \ell_2 = 7$ m
PVLAS	1064 nm; 0.02 W	$N_p = 4 \times 10^4$	$B_1 = 5$ T, $\ell_1 = 1$ m, $B_2 = 2.2$ T, $\ell_2 = 0.5$ m

$\Rightarrow$ Test pure ALPs interpretation of PVLAS

$\Rightarrow$ Improve limits on paraphotons

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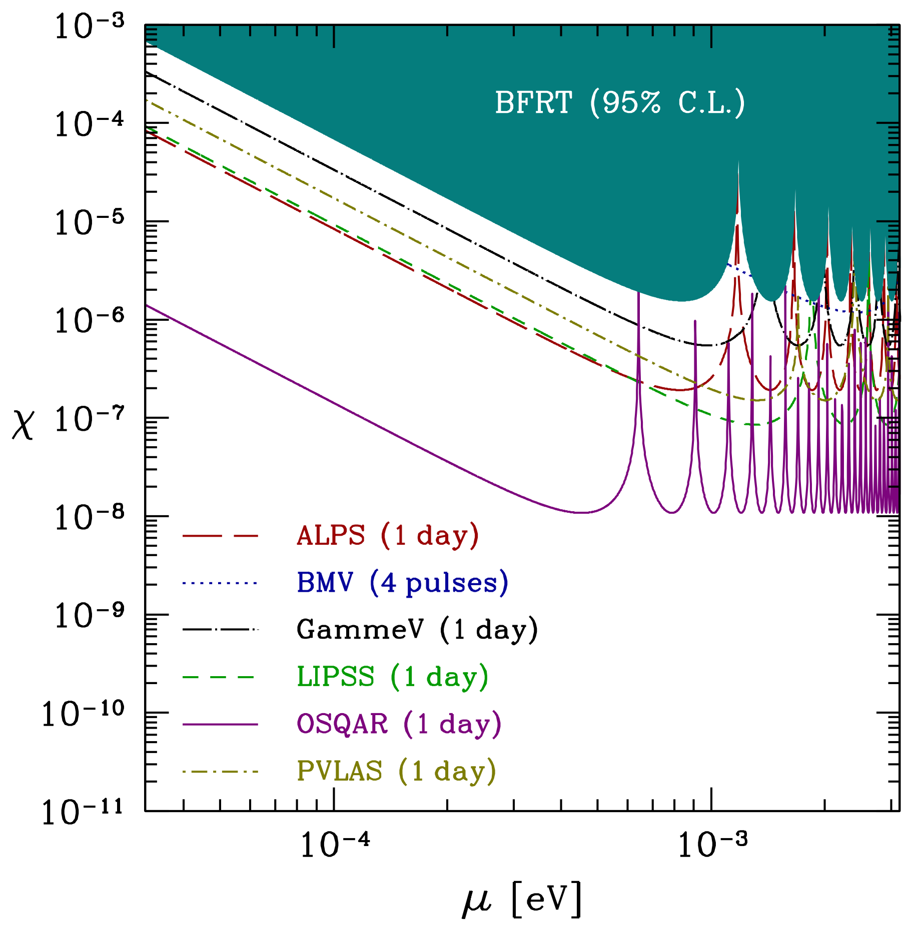
Vacuum LSW: Limit on paraphoton



[Ahlers,Gies,Jaeckel,Redondo,AR '07]

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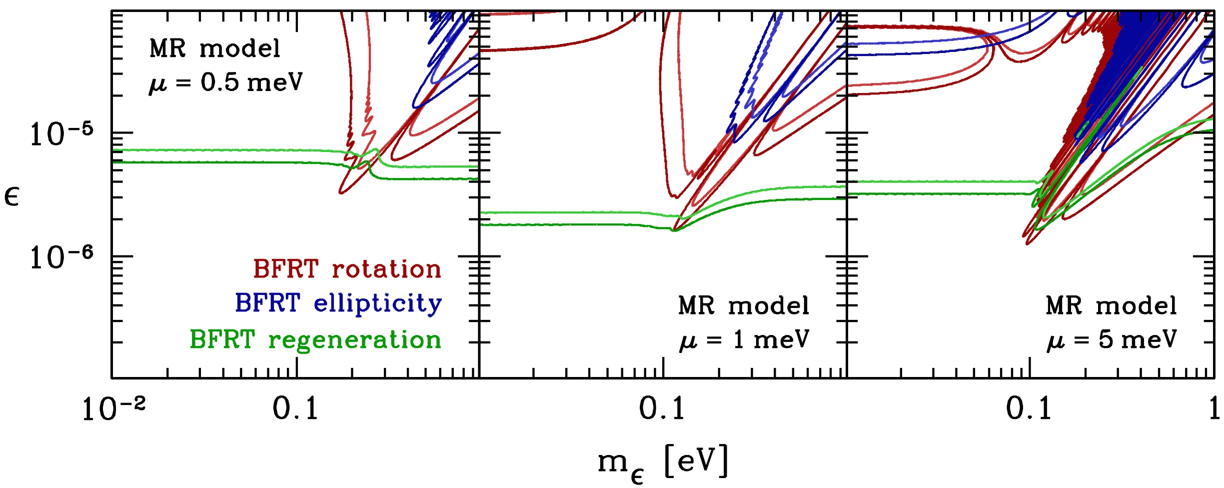
$B \neq 0$ LSW: Masso-Redondo model



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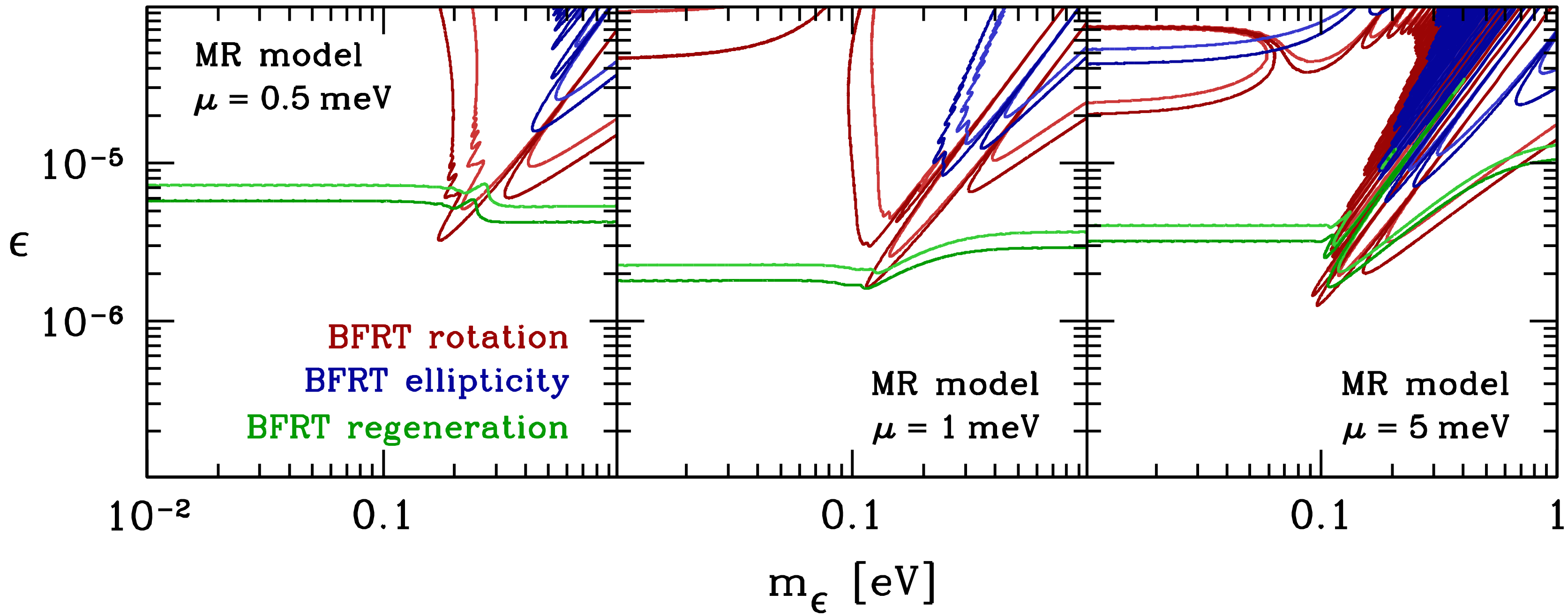
- Several ongoing experiments

$B \neq 0$ LSW: Masso-Redondo model



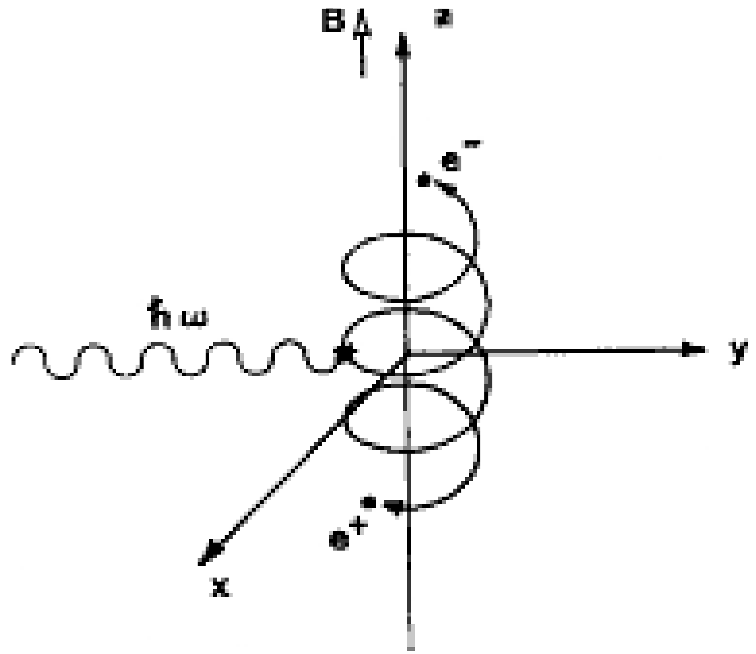
[Ahlers,Gies,Jaeckel,Redondo,AR '07]

4. Dark-Current-Flowing-Through-a-Wall Experiment

- Minicharged particles don't meet again behind the wall ⇒ no light shining through the wall

- Current-Through-a-Wall:
  - In strong electric field of accelerator cavity, minicharged particles may be produced in pairs and accelerated along the beam axis
  - MCP beam leaves cavity and is flowing through thick wall
  - Corresponding electrical current can be measured directly via its induced magnetic field

[Gies,Jaeckel,AR '06]



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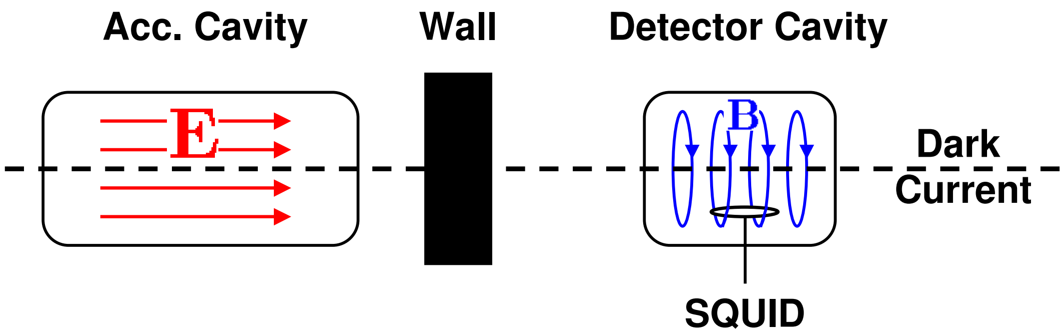

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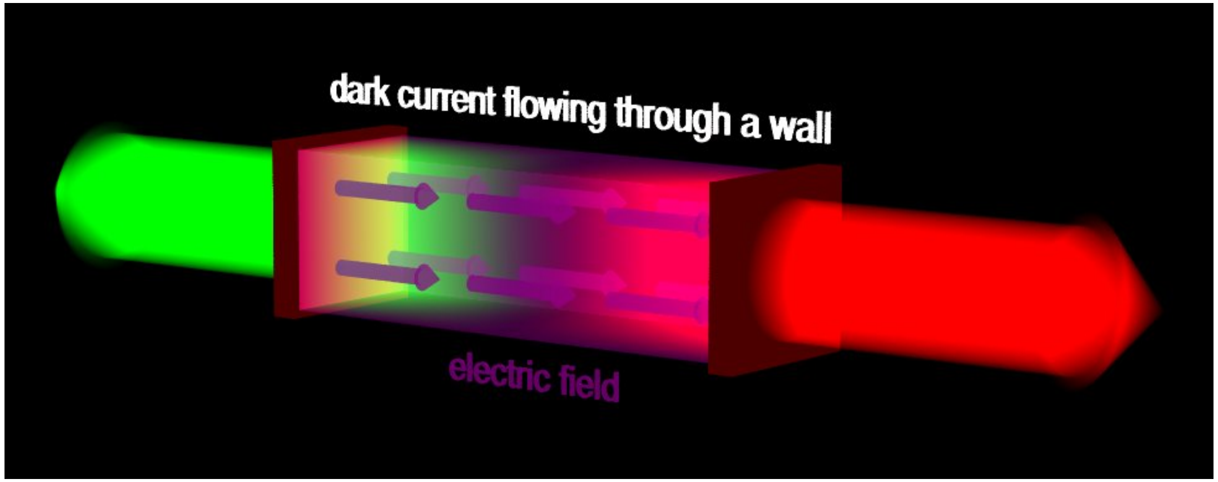

[Ahlers (unpubl.)]

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ACDC (Accelerator Cavity Dark Current):

- Cavity available

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- Measurement device available

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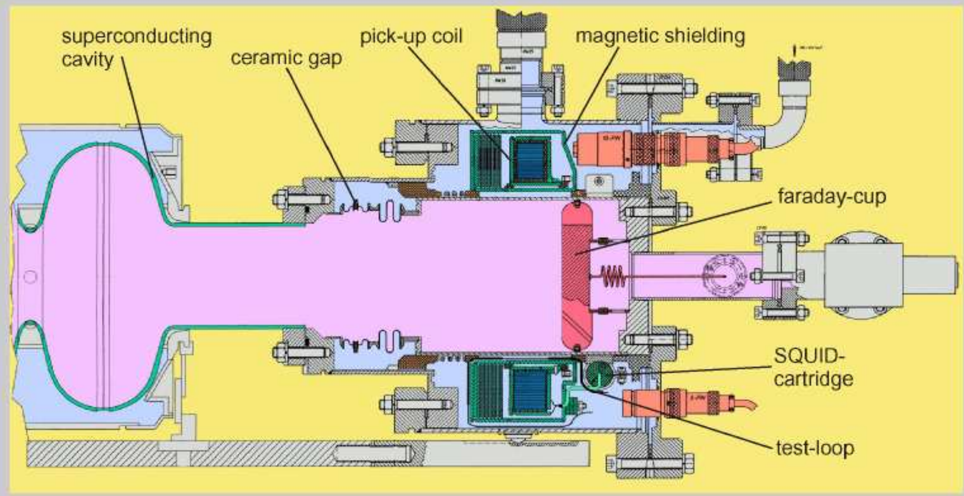

Construction details of the CCC dark current hardware

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- Measurement device available

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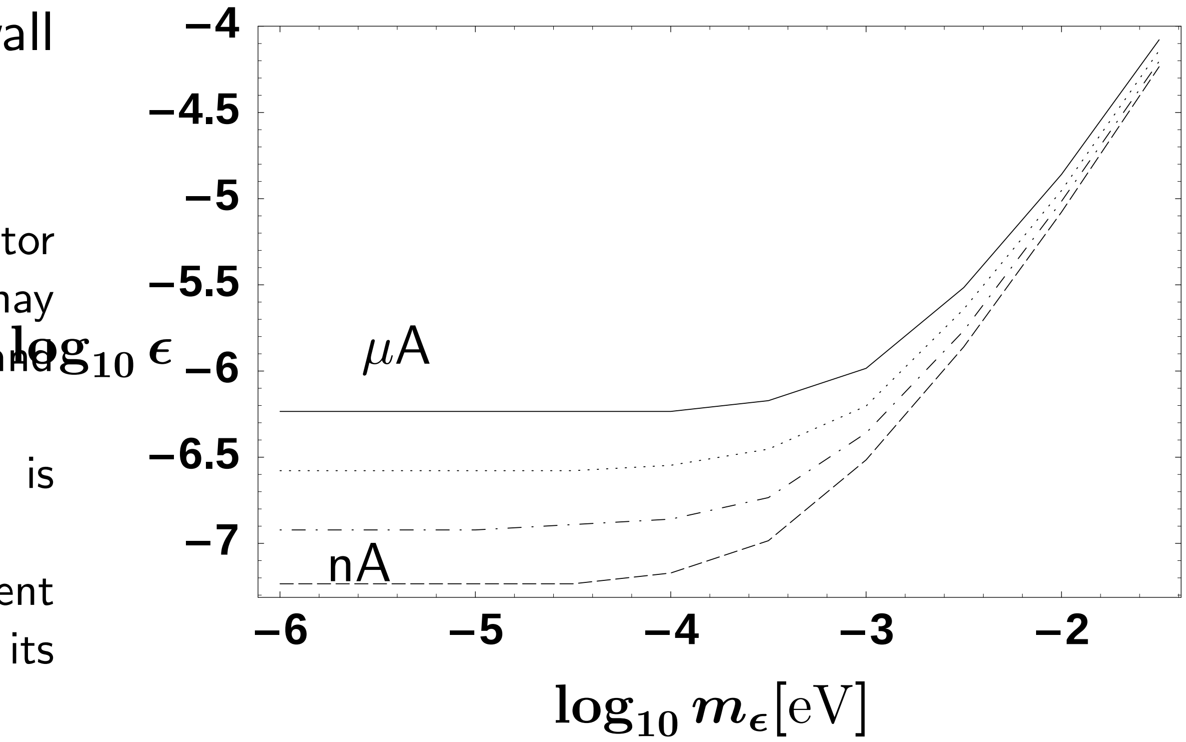

[Gies,Jaeckel,AR in prep.]

5. Conclusions

- The report of the observation of a vacuum magnetic dichroism and birefringence by PVLAS has triggered a lot of theoretical and experimental activities:
  - Particle interpretations alternative to ALP interpretation: e.g. MCP
  - Models, which evade strong astrophysical and cosmological bounds on such particles, have been found. Require typically even more WISPs than just the ones introduced for the solution of the PVLAS puzzle
  - Decisive laboratory based tests of particle interpretation of PVLAS anomaly in very near future. More generally, experiments will dig into previously unconstrained parameter space of above mentioned models
- Experiments exploiting low energy photons may give information about fundamental particle physics complementary to the one obtained at high energy colliders