Particle Interpretations of the PVLAS Data

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XII International Workshop on “Neutrino Telescopes”
March 6-9, 2007
Venice, Italy

Plan:

1. **Vacuum Magnetic Dichroism and Birefringence**

   Polarized light propagation through a magnetic field: global data

2. **Possible Explanations**

   Production of new weakly interacting light particles (WILPs)?

3. **Crucial Laboratory Tests**

   Light or dark-current through-a-wall experiments, ...

4. **Problems of Particle Interpretations**

   Astrophysical, cosmological, and other constraints

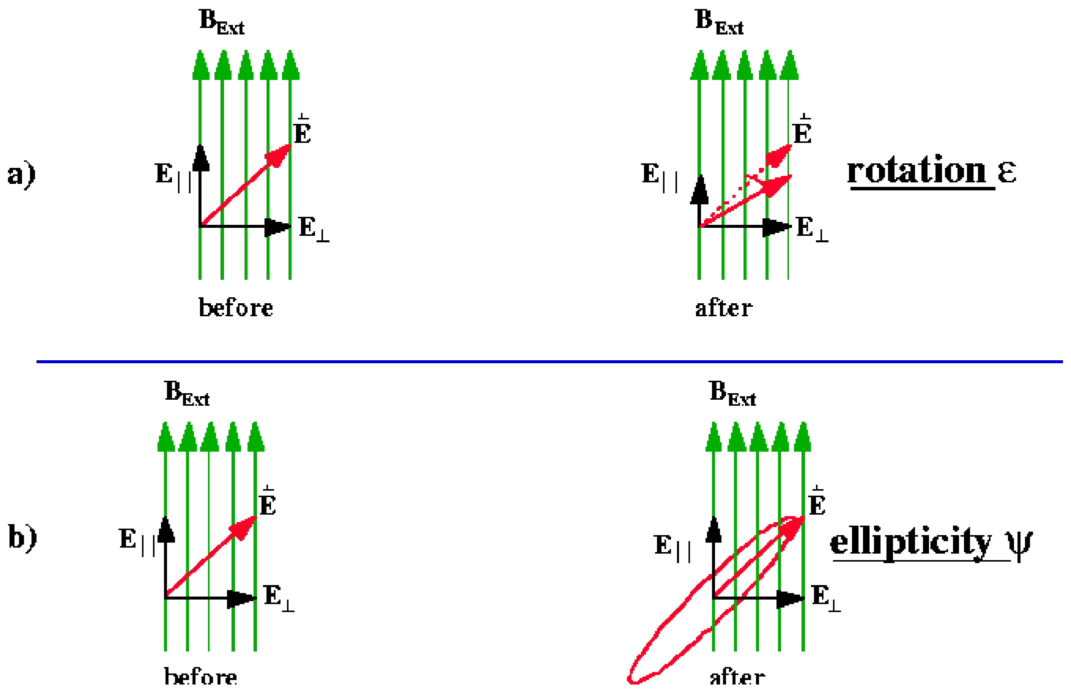
5. **WILPs in Models with Light Extra-U(1)s**

   Light mini-charged particles from gauge kinetic mixing, ...

6. **Summary**

1. Vacuum Magnetic Dichroism and Birefringence

- Send linearly polarized laser beam through transverse magnetic field ⇒ measure changes in polarization state:
    - rotation (dichroism)
    - ellipticity (birefringence)



[Brandi *et al.* ‘01]

1. Vacuum Magnetic Dichroism and Birefringence

- Send linearly polarized laser beam through transverse magnetic field ⇒ measure changes in polarization state:
  - rotation (dichroism)
  - ellipticity (birefringence)

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]

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

1. Vacuum Magnetic Dichroism and Birefringence

- Send linearly polarized laser beam through transverse magnetic field ⇒ measure changes in polarization state:
  - rotation (dichroism)
  - ellipticity (birefringence)
- 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]

1. Vacuum Magnetic Dichroism and Birefringence

- Send linearly polarized laser beam through transverse magnetic field ⇒ measure changes in polarization state:
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  - ellipticity (birefringence)
- No signal in BFRT; signal in PVLAS

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

[PRL ‘06; IDM ‘06]

1. Vacuum Magnetic Dichroism and Birefringence

- Send linearly polarized laser beam through transverse magnetic field ⇒ measure changes in polarization state:
  - rotation (dichroism)
  - ellipticity (birefringence)
- 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]

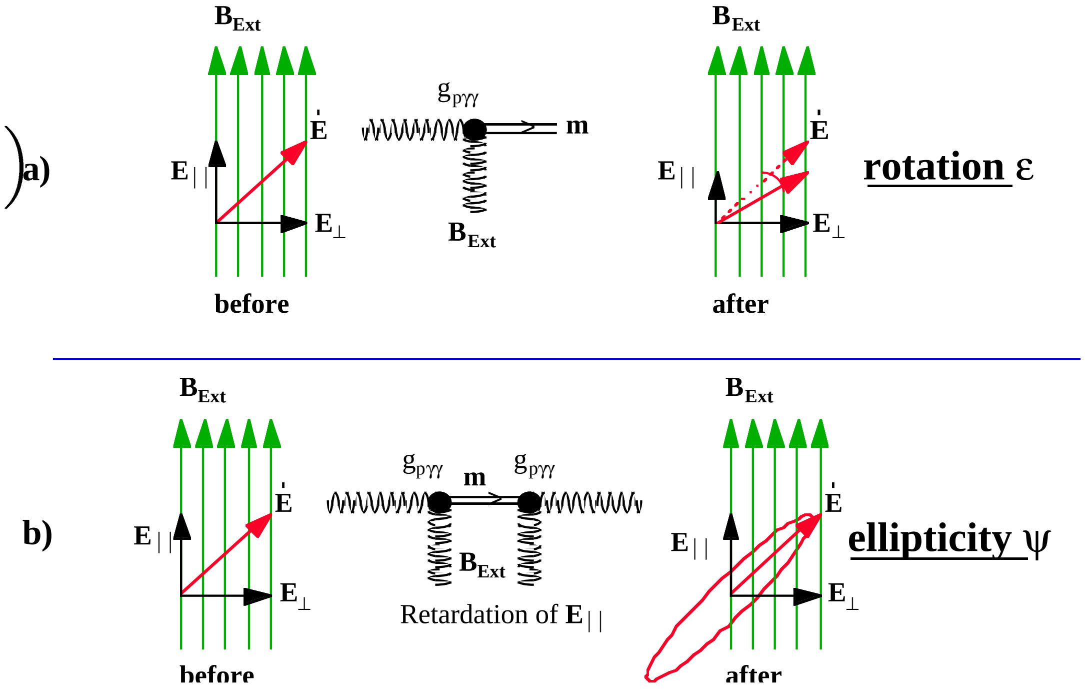
2. Possible Explanations

- Viable explanation 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]



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- Viable explanation in terms of real and virtual production of
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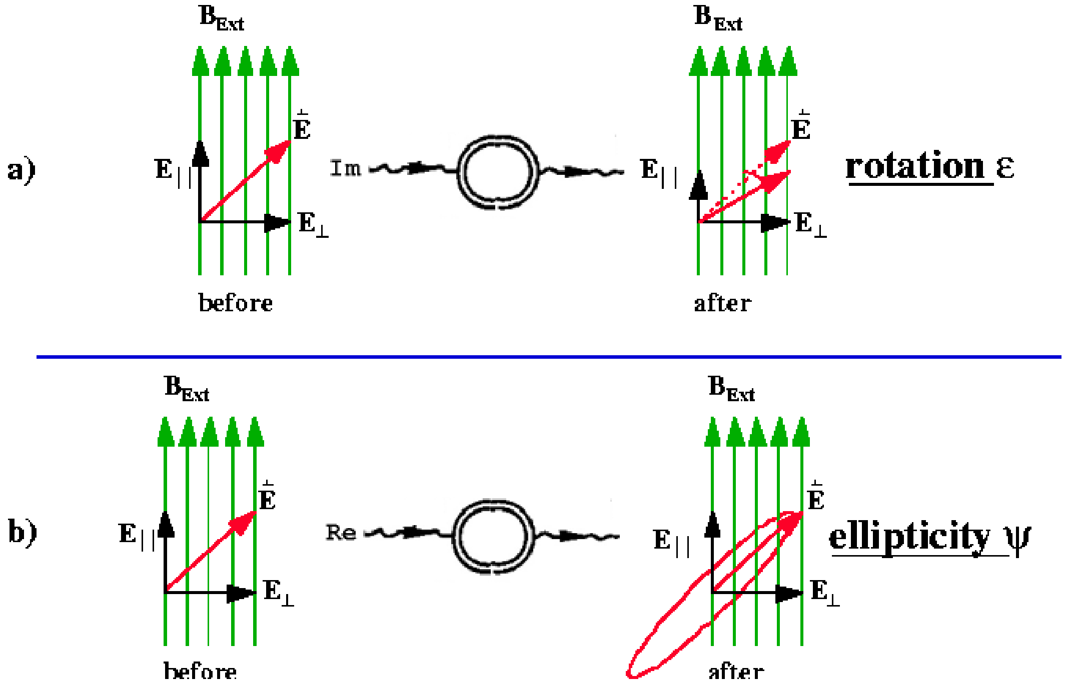
  and/or
  - light MiniCharged Particle (MCP) – anti-particle pair,

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

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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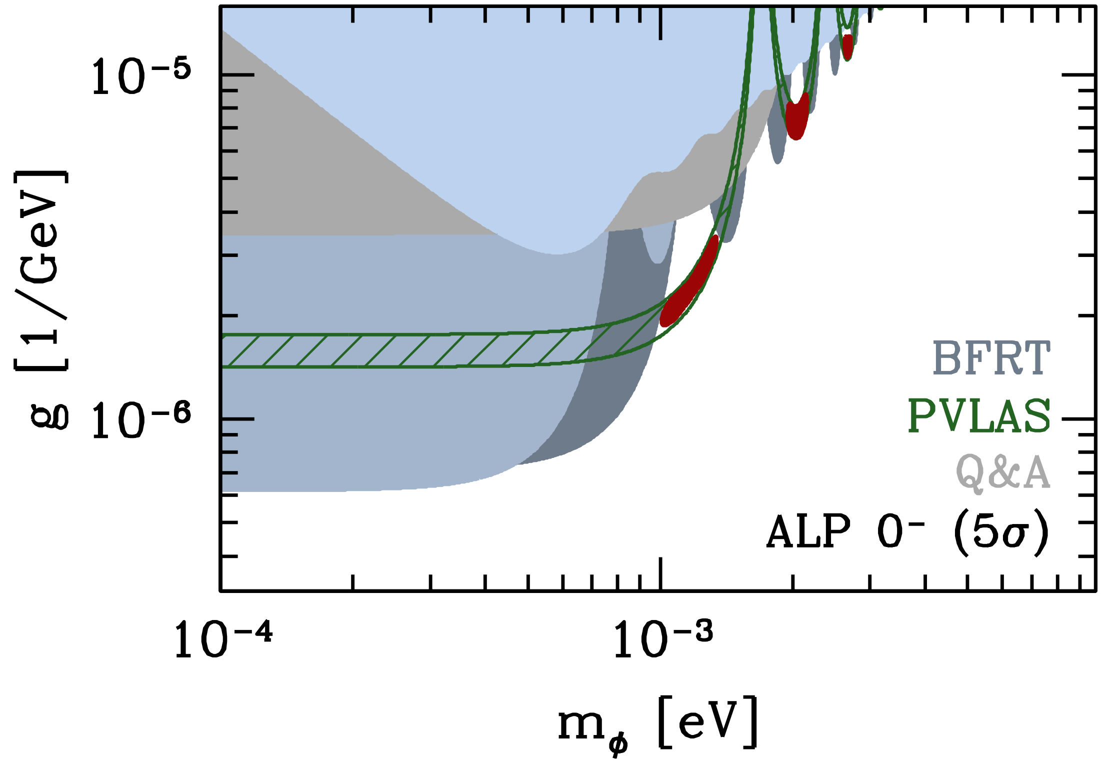
If interpreted in terms of ALP:



[Ahlers,Gies,Jaeckel,AR '06]

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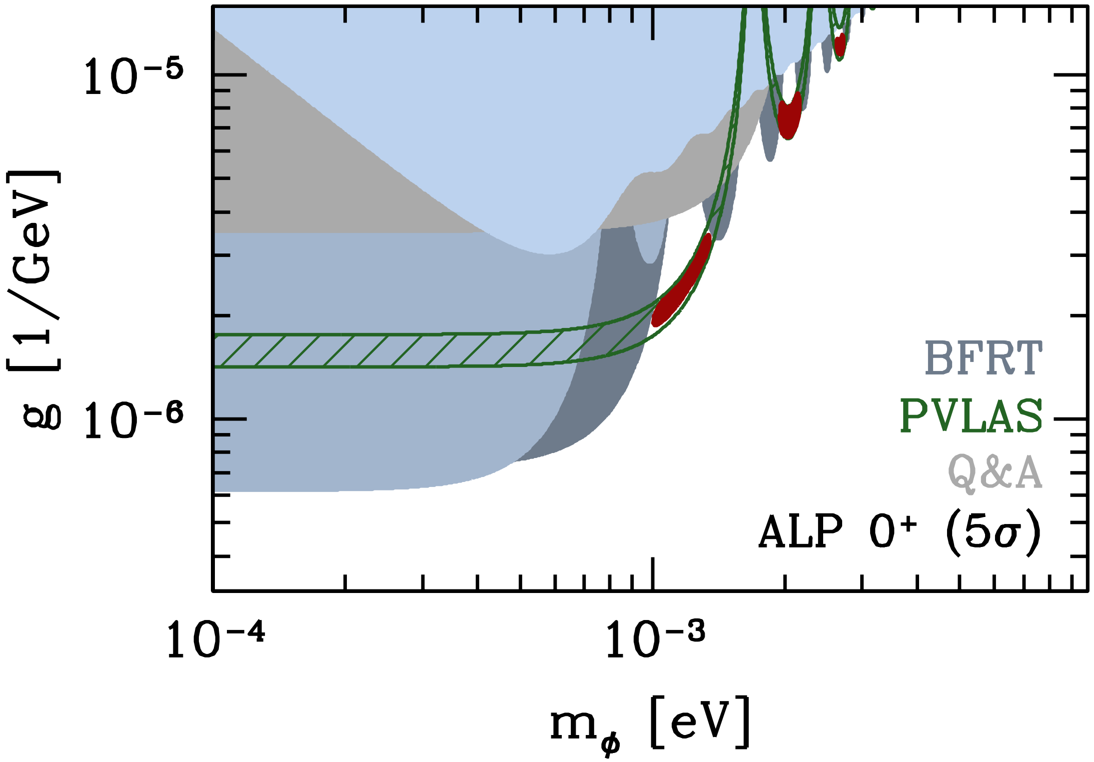

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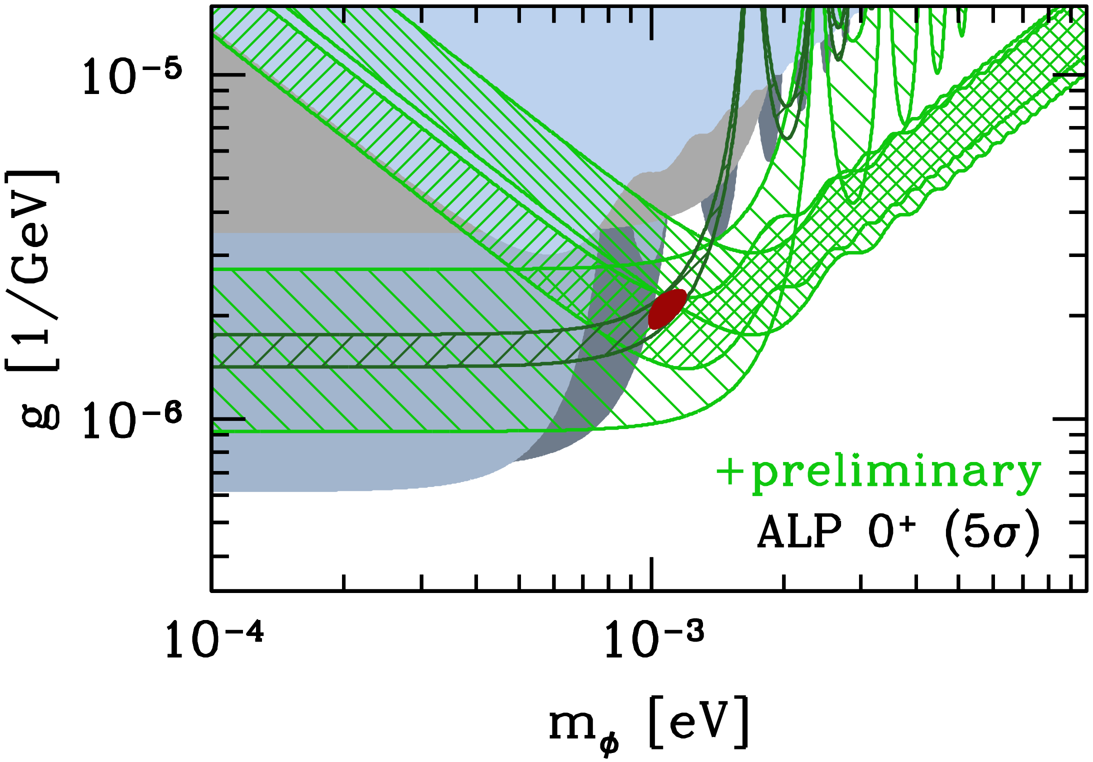

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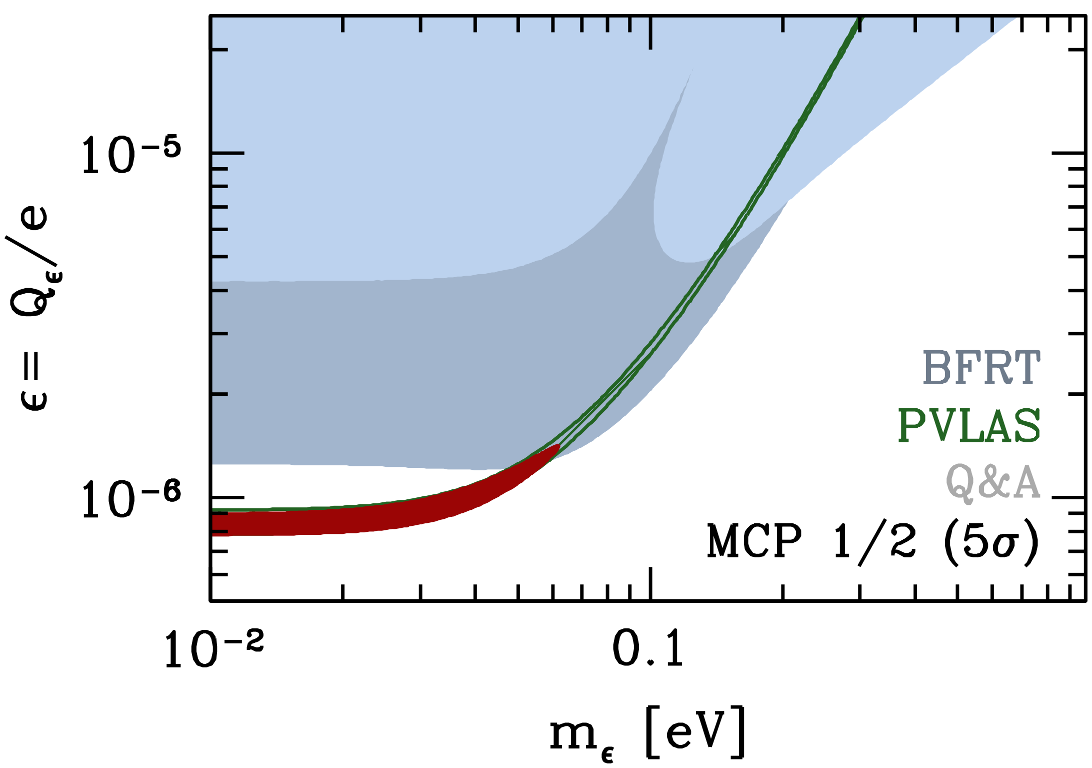

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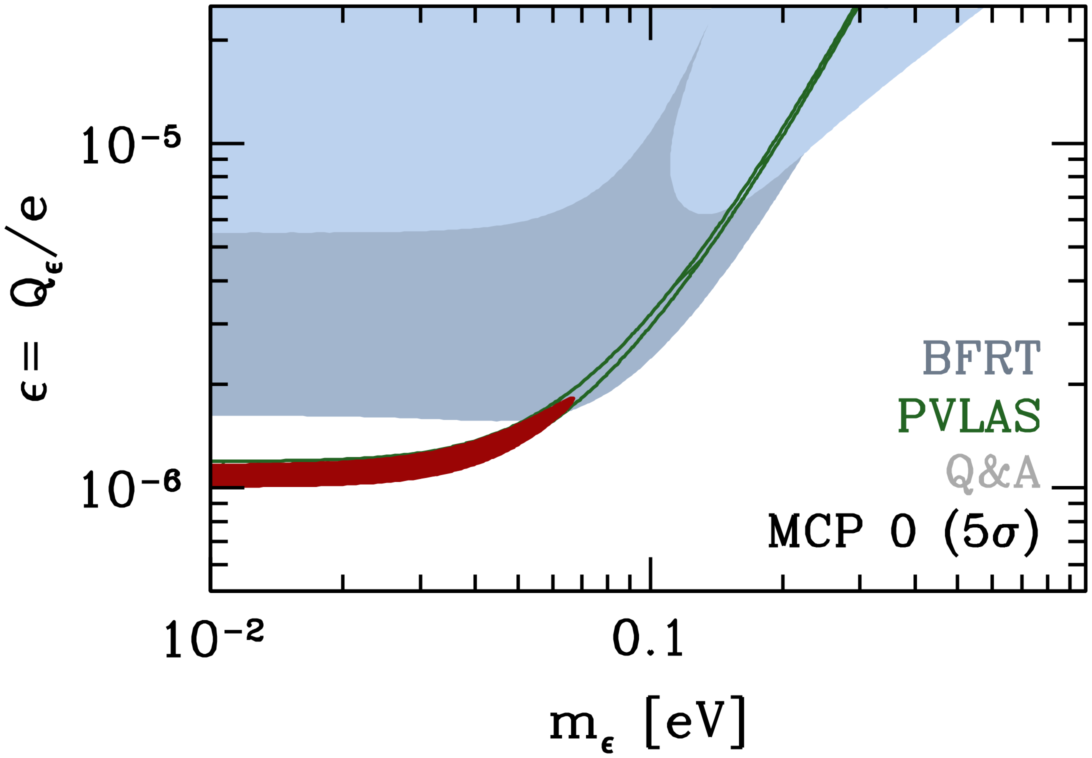

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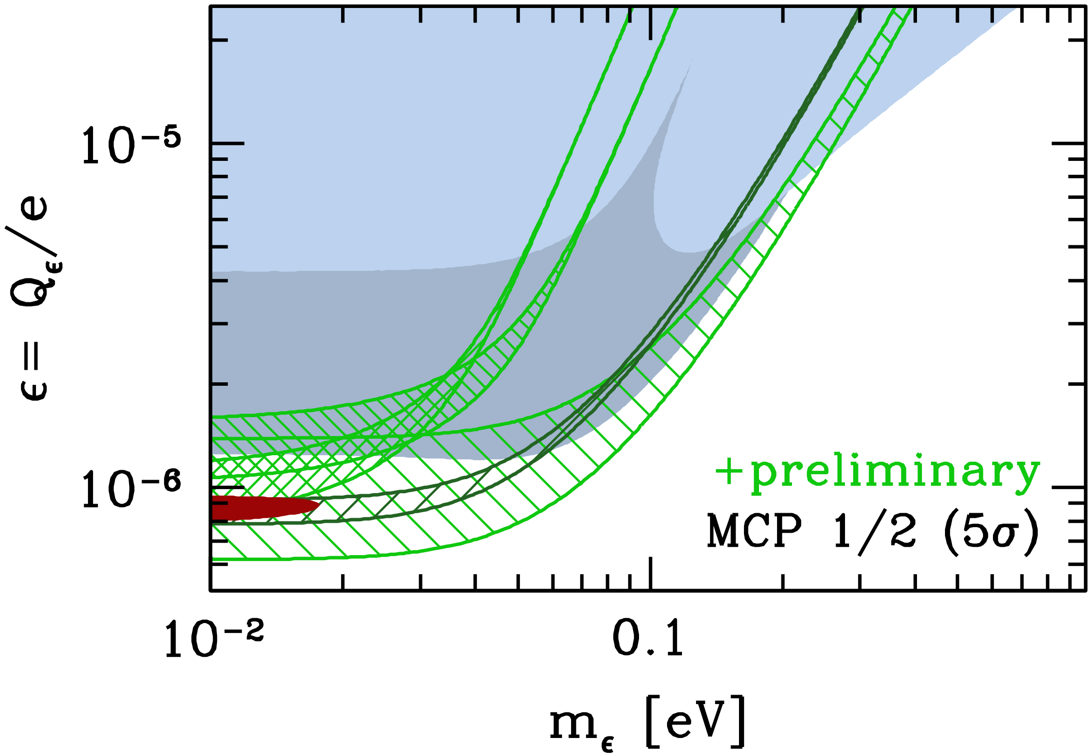

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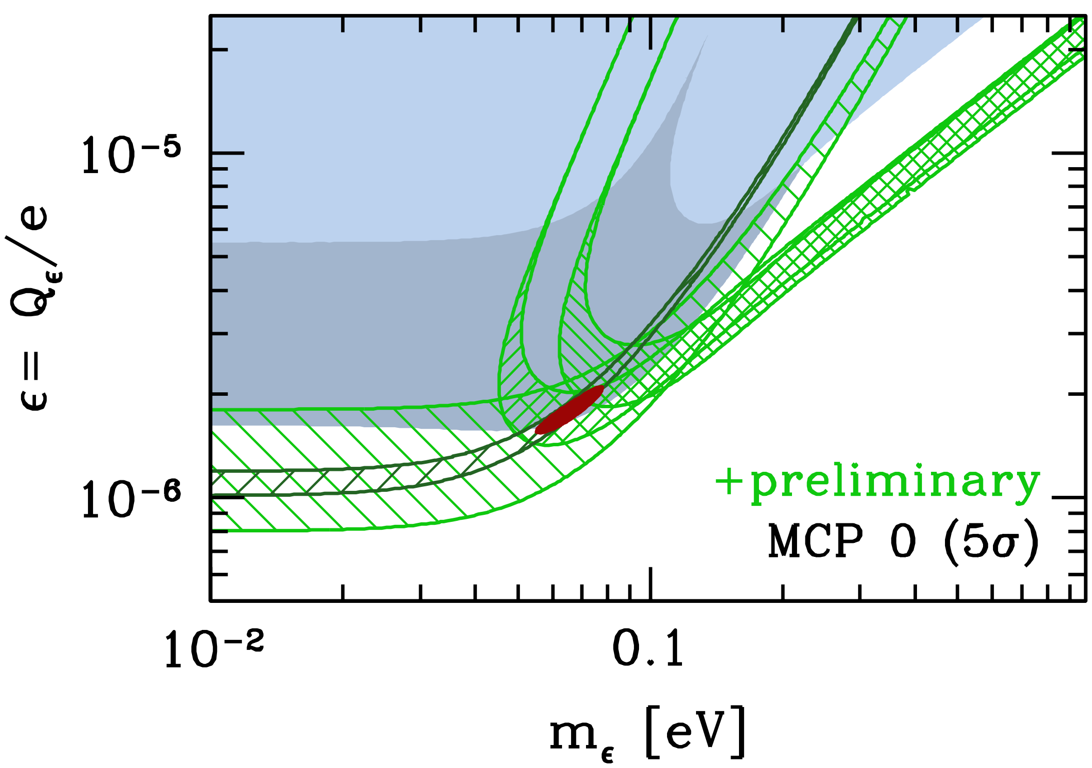

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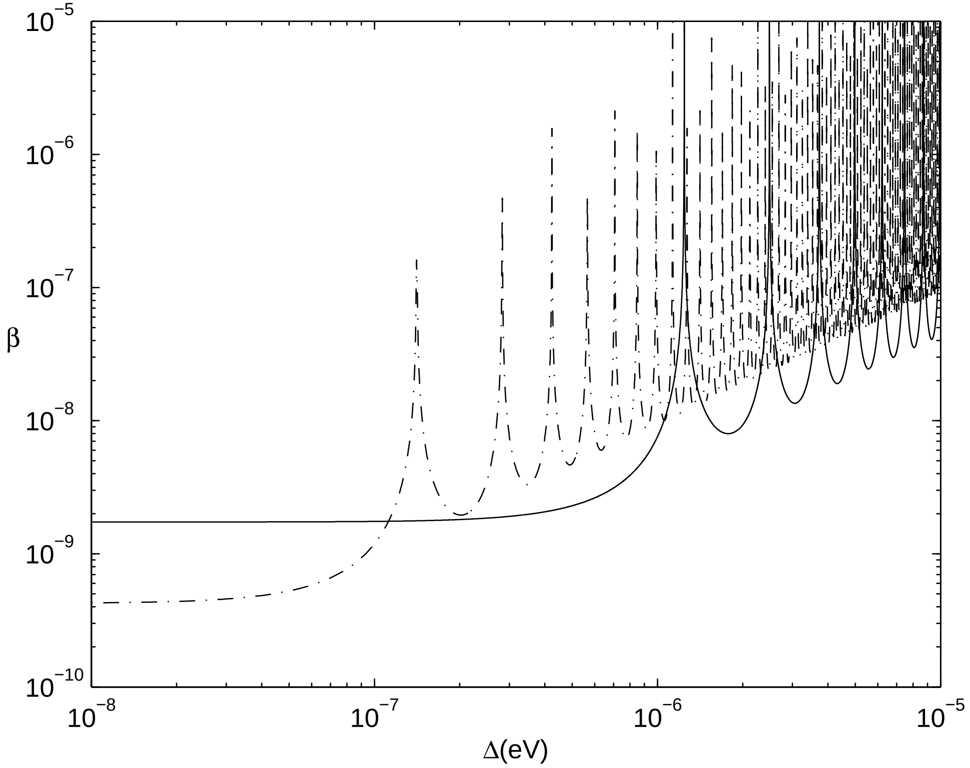
$$\partial_\mu \rightarrow \partial_\mu - \mathrm{i}\epsilon e A_\mu$$

- Explanation in terms of real and virtual production of Second Photon (SP) in fusion model of photon: [de Broglie '32]
  - Photon: $S = 1$ bound state of spin 1/2 particle-antiparticle pair
  - SP: $S = 0$ bound state

  Parameters: Mass splitting Δ and magnetic moment $\beta\mu_B$ of particle

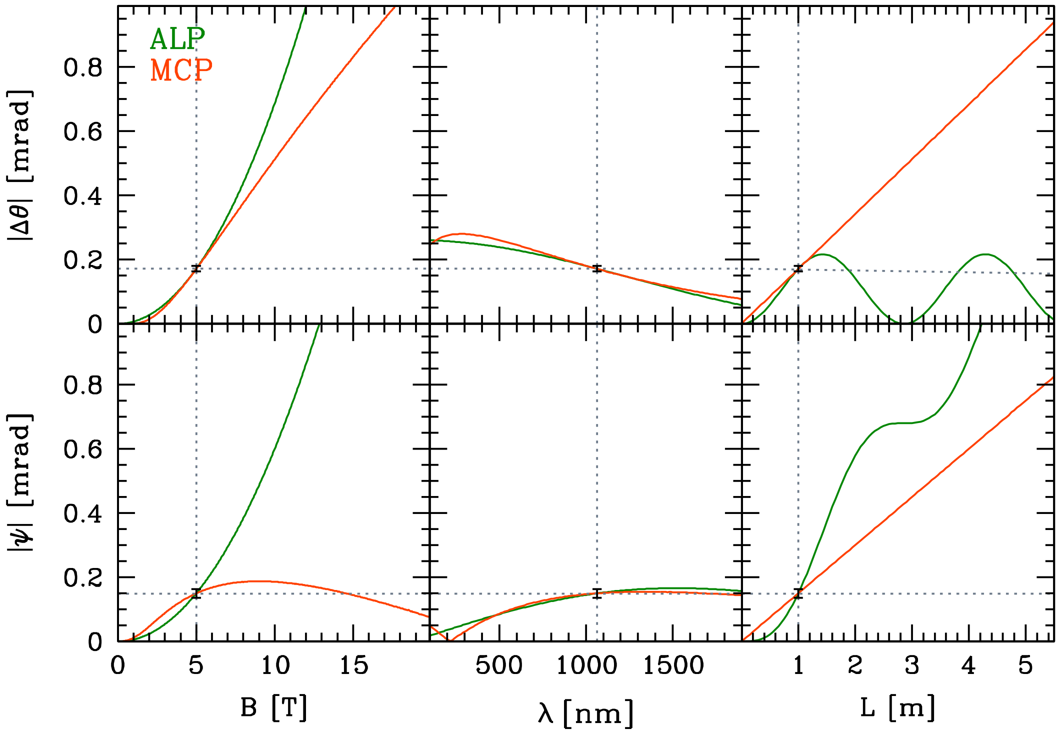
If interpreted in terms of SP:



[Beswick,Rizzo '07]

3. Crucial Laboratory Tests

- Laser polarization experiments at higher magnetic fields



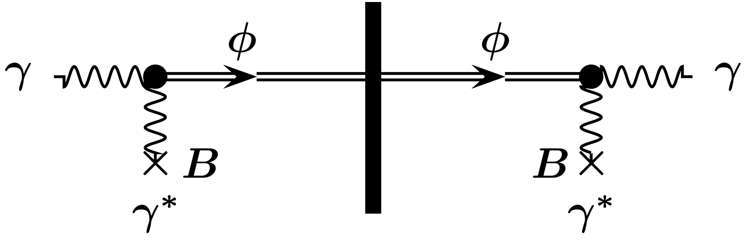
[Ahlers,Gies,Jaeckel,AR '06]

BMV (Toulouse): 11 T pulsed magnet

3. Crucial Laboratory Tests

- Laser polarization experiments at higher magnetic fields
- Light shining through a wall

"Light shining through a wall"



[Sikivie '83;Ansel'm '85;Van Bibber *et al.* '87]

Name	Laboratory	Magnets	$P_{\gamma\phi\gamma}\vert g_{\rm PVLAS}$
ALPS	DESY/D	$B_1 = B_2 = 5$ T $\ell_1 = \ell_2 = 4.21$ m	$\sim 10^{-19}$
BMV	LULI/F	$B_1 = B_2 = 11$ T $\ell_1 = \ell_2 = 0.25$ m	$\sim 10^{-21}$
LIPSS	Jlab/USA	$B_1 = B_2 = 1.7$ T $\ell_1 = \ell_2 = 1$ m	$\sim 10^{-23.5}$
OSQAR	CERN/CH	$B_1 = B_2 = 11$ T $\ell_1 = \ell_2 = 7$ m	$\sim 10^{-17}$
PVLAS	Legnaro/I	$B_1 = 5$ T $\ell_1 = 1$ m $B_2 = 2.2$ T $\ell_2 = 0.5$ m	$\sim 10^{-23}$

[AR '06]

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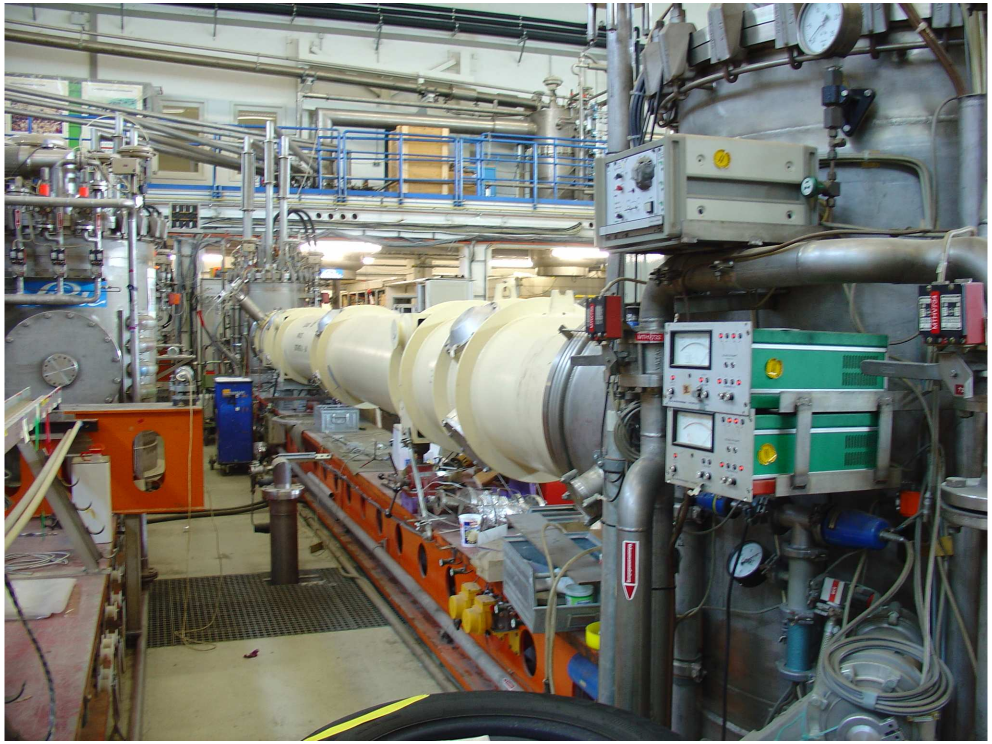
Axion-Like Particle Search:

[DESY, Laser Zentrum Hannover, Sternwarte Bergedorf]



$$B = 5\ \mathrm{T}, \ell = 4.2\ \mathrm{m}, \underbrace{\langle P\rangle = 0.2\ \mathrm{kW}, \omega = 1.2\ \mathrm{eV}}_{\dot N_0 \sim 1\times 10^{21}/\mathrm{s}}, N_r = 0$$

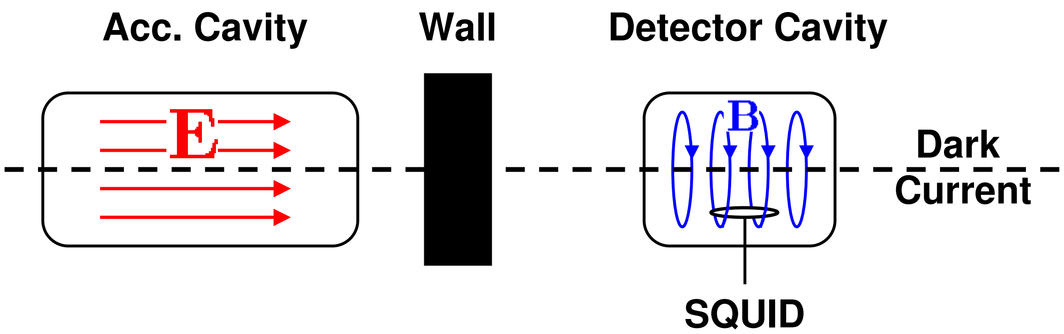
Test of ALP interpretation of PVLAS in summer 2007

3. Crucial Laboratory Tests

- Laser polarization experiments at higher magnetic fields

- Light shining through a wall

- Dark current through a wall



[Gies,Jaeckel,AR ‘06]

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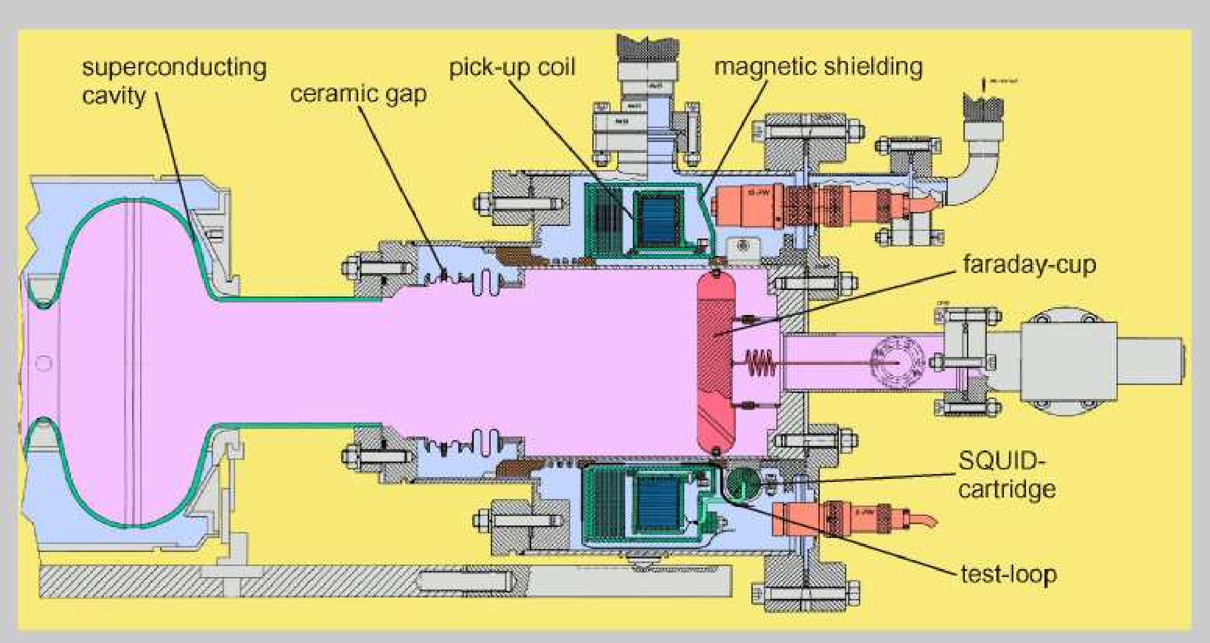
Cryogenic Current Comparator:

[DESY, GSI, Universität Jena]



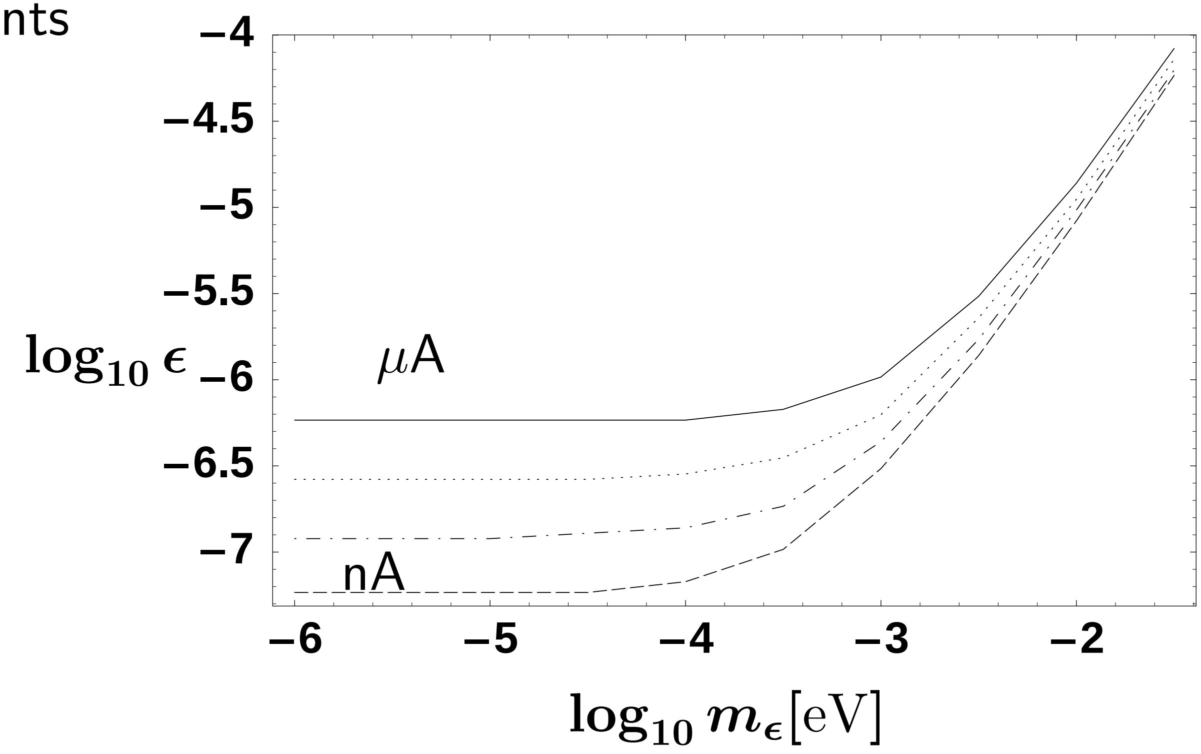
Construction details of the CCC dark current hardware

[M. Wendt TESLA2004]

3. Crucial Laboratory Tests

- Laser polarization experiments at higher magnetic fields
- Light shining through a wall
- Dark current through a wall

TESLA accelerator cavity | CCC:



[Gies,Jaeckel,AR unpubl.]

3. Crucial Laboratory Tests

- Laser polarization experiments at higher magnetic fields

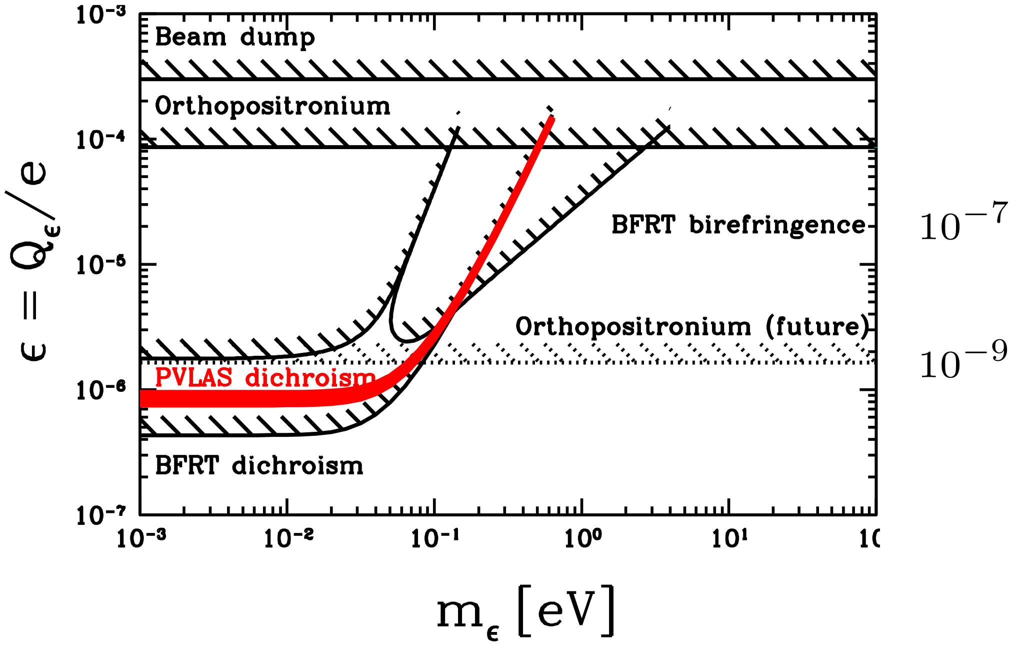
- Light shining through a wall

- Dark current through a wall

- Invisible Orthopositronium decay

"Search for Invisible Orthopositronium Decay" [Dobroliubov,Ignatiev '89]

$$\mathrm{BR}(\mathrm{OP} \to \epsilon^+\epsilon^-) \simeq \frac{3\pi\epsilon^2}{4\alpha(\pi^2-9)} \simeq 371\,\epsilon^2$$



[Mitsui *et al.* '93]: $\mathrm{BR}(\mathrm{OP} \to \mathrm{inv.}) < 2.8 \times 10^{-6}$

[Badertscher *et al.* '06]: $\mathrm{BR}(\mathrm{OP} \to \mathrm{inv.}) < 4.2 \times 10^{-7}$

3. Crucial Laboratory Tests

- Laser polarization experiments at higher magnetic fields
- Light shining through a wall
- Dark current through a wall
- Invisible Orthopositronium decay
- Searches for excess e^- from elastic $\epsilon^\pm e^-$ scattering in detector near nuclear reactor

- Nuclear power reactors with $P > 2$ GW emit more than 10^{20} γ/s
- These γs may convert within reactor into $\epsilon^+\epsilon^-$ pairs
- A small fraction of these particles could lead to an observable excess of electrons from $\epsilon^\pm$ e^- scattering in a detector
- Recent results from the TEXONO experiment set up at the Kuo-Sheng Nuclear Power Station (2.8 GW) in Taiwan probing for $\mu_{\overline{\nu}_e}$ by searching for an excess of events from νe^- magnetic scattering [TEXONO Coll. '03]

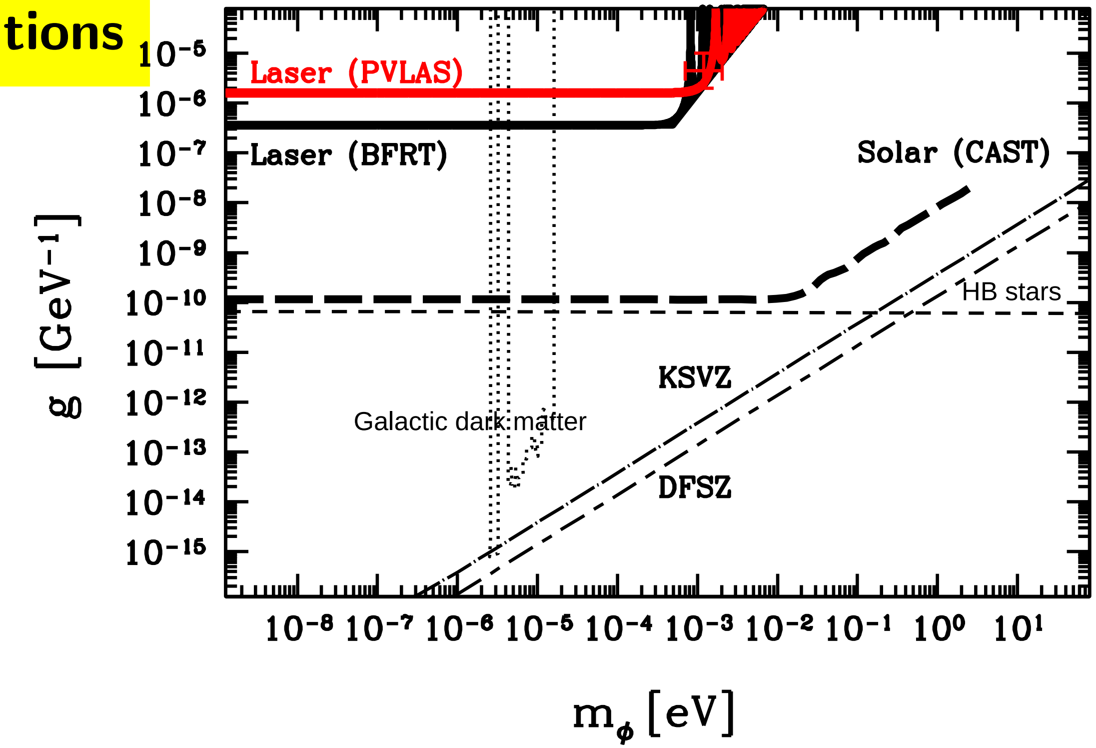
⇒ Bound on fractional electric charge,

$$\epsilon \lesssim 10^{-5}, \text{ for } m_\epsilon \lesssim 1 \text{ keV}$$

- May be improved in near future with massive liquid argon detector [Gninenko,Krasnikov,A.Rubbia '06]

4. Problems of Particle Interpretations

- Energy loss of stars:
  - ALPs: Primakoff $\gamma Z \to \phi Z$



Way out: $g_{|\mathrm{star}} \ll g_{|\mathrm{vacuum}}$

[Masso,Redondo ‘05;Jaeckel *et al.* ‘06]

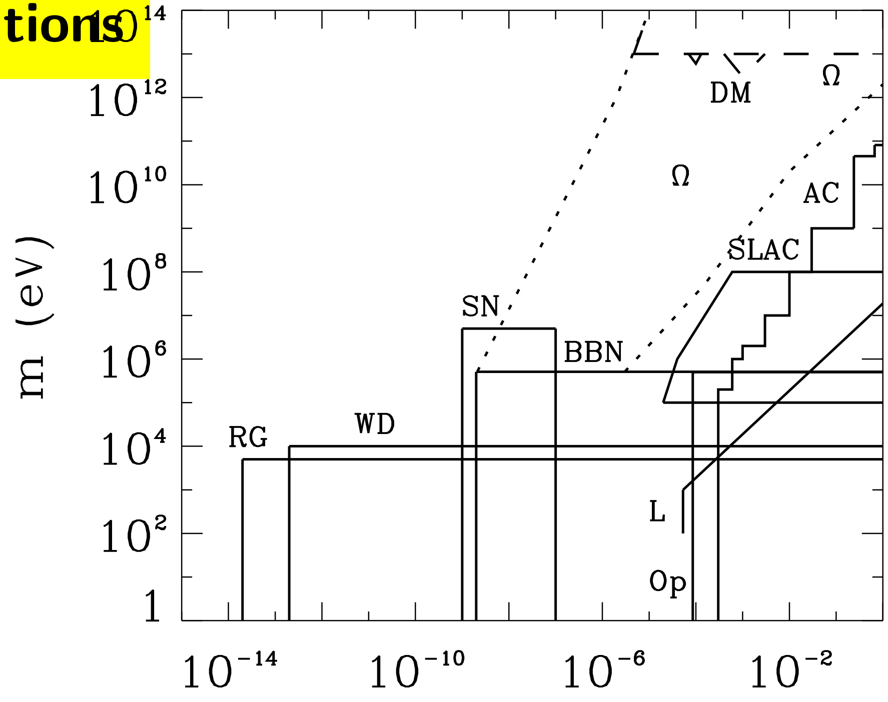
$\Rightarrow$ Even more sub-eV particles and fields, e.g. [Masso,Redondo ‘06;Mohapatra,Nasri ‘06]

– U(1) bosons mixing with photon

– scalar field with low scale phase transition

4. Problems of Particle Interpretations

- Energy loss of stars:
  - ALPs: Primakoff $\gamma Z \to \phi Z$
  - MCPs: plasmon decay $\gamma^* \to \epsilon^+ \epsilon^-$



[Davidson,Hannestad,Raffelt ‘00] ϵ

Way out: $\epsilon_{|\text{plasma}} \ll \epsilon_{|\text{vacuum}}$

[Masso,Redondo ‘06]

$\Rightarrow$ Even more sub-eV particles and fields, e.g. U(1) bosons mixing with photon

[Abel *et al.* ‘06;Foot,Kobakhidze ‘07]

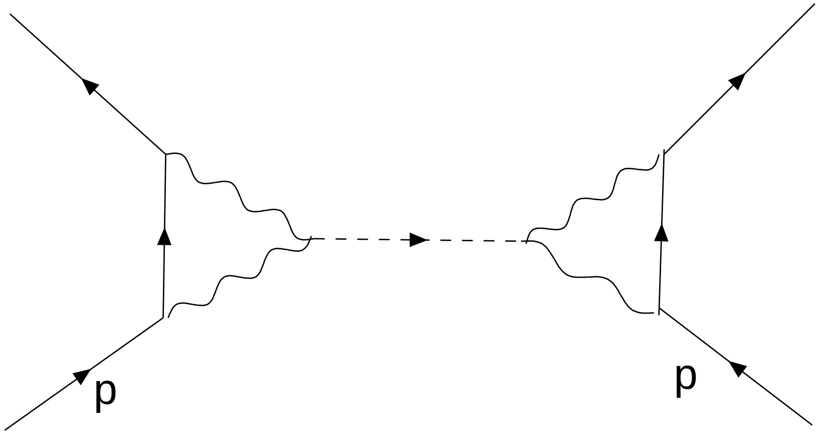
4. Problems of Particle Interpretations

- Energy loss of stars:
  - ALPs: Primakoff $\gamma Z \to \phi Z$
  - MCPs: plasmon decay $\gamma^* \to \epsilon^+\epsilon^-$
  - SPs: no problem
- ALP 0^+: Non-Newtonian force,

$$V(r) = G\frac{m_1 m_2}{r} + \frac{y^2}{4\pi}\frac{n_1 n_2}{r}\,\mathrm{e}^{-m_\phi r}$$

from Yukawa coupling

$$\begin{aligned} \mathcal{L}_{\phi pp} &= y\phi\overline{\Psi}_p\Psi_p \\ y &\simeq \frac{3}{2}\frac{\alpha}{\pi}(g m_p)\log\frac{\Lambda}{m_p} \end{aligned}$$



[Adelberger *et al.* ‘06]

From torsion-balance experiment:

$$g < 4\times 10^{-17}\,\mathrm{GeV}^{-1},$$

for $m_\phi = 1\,\mathrm{meV};\ \Lambda \gg m_p$

[Dupays *et al.* ‘06;Adelberger *et al.* ‘06]

Way out: ALP 0^+ couples only to additional light U(1) bosons mixing with photon

5. WILPs in Models with Light Extra-U(1)s

- Consider extension of SM with additional "hidden sector" U(1)'s ⇒ in general gauge kinetic mixing with "visible" U(1), e.g.

$$\mathcal{L} = -\frac{1}{4}\,F^T \mathcal{K}_F\, F + \frac{1}{2}\,A^T \mathcal{M}_A^2\, A + ej\,A,$$

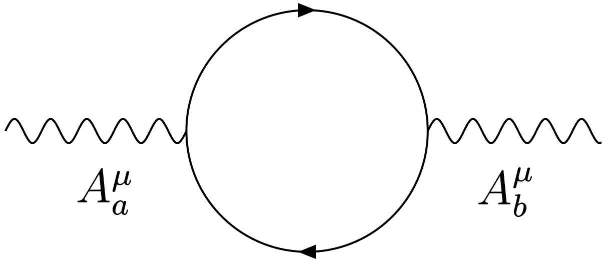
with special mixing

$$\mathcal{K}_F = \begin{pmatrix} 1 & \chi & \chi \\ \chi & 1 & 0 \\ \chi & 0 & 1 \end{pmatrix}$$

Mixing may arise from integrating out heavy particles:

e.g. threshold effect from two species of fermions, (e_a, e_b) and $(e_a, -e_b)$, with masses m and m':

$$\chi \simeq \frac{e_a e_b}{6\pi^2} \log\left(\frac{m'}{m}\right)$$



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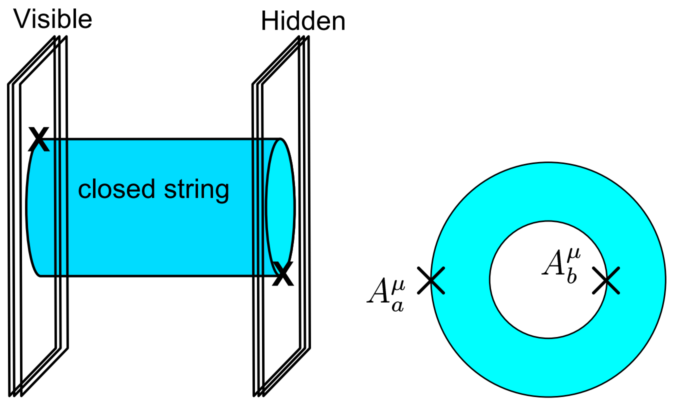
Mixing may arise from integrating out heavy particles:

e.g. closed string exchange between visible sector D-branes and hidden sector anti-D-branes,

$$\chi \sim g_a\, g_b \left(\frac{2^{(8-p)/2}}{\alpha_p} \frac{M_s}{M_P} \right)^{\frac{2(5-p)}{6-p}} \left(\frac{R}{r} \right)^{\frac{d-p+3}{6-p}}$$



[Abel,Jaeckel,Khoze,AR ‘06]

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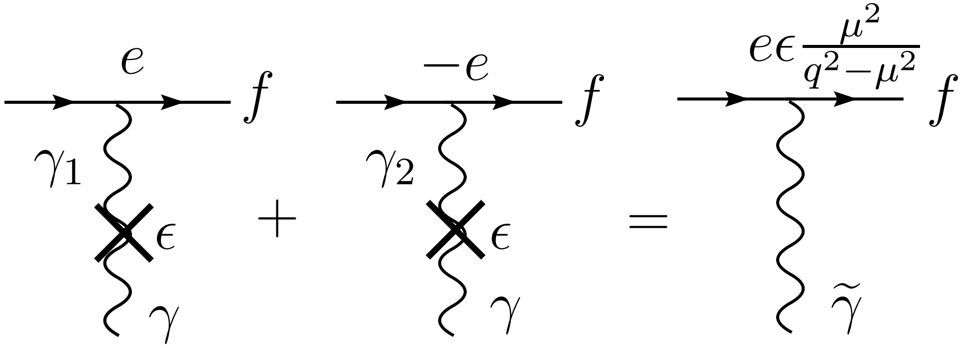
  with special mixing and mass pattern

$$\mathcal{K}_F = \begin{pmatrix} 1 & \chi & \chi \\ \chi & 1 & 0 \\ \chi & 0 & 1 \end{pmatrix}, \mathcal{M}_A^2 = \begin{pmatrix} m_\gamma^2 & 0 & 0 \\ 0 & \mu^2 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

- Hidden sector CP, with special charge assignment $(0, e, -e)$, acquires visible mini-charge

$$\epsilon \simeq \begin{cases} -\chi & \text{for} \quad m_\gamma = 0 \\ (\mu^2/\omega_{\rm p}^2)\,\chi & \text{for} \quad m_\gamma = \omega_{\rm p} \gg \mu \end{cases}$$

⇒ Viable MCP explanation of PVLAS $(m_\gamma = 0)$ for $\chi \sim 10^{-6}$, $m_\epsilon \lesssim 0.1$ eV;



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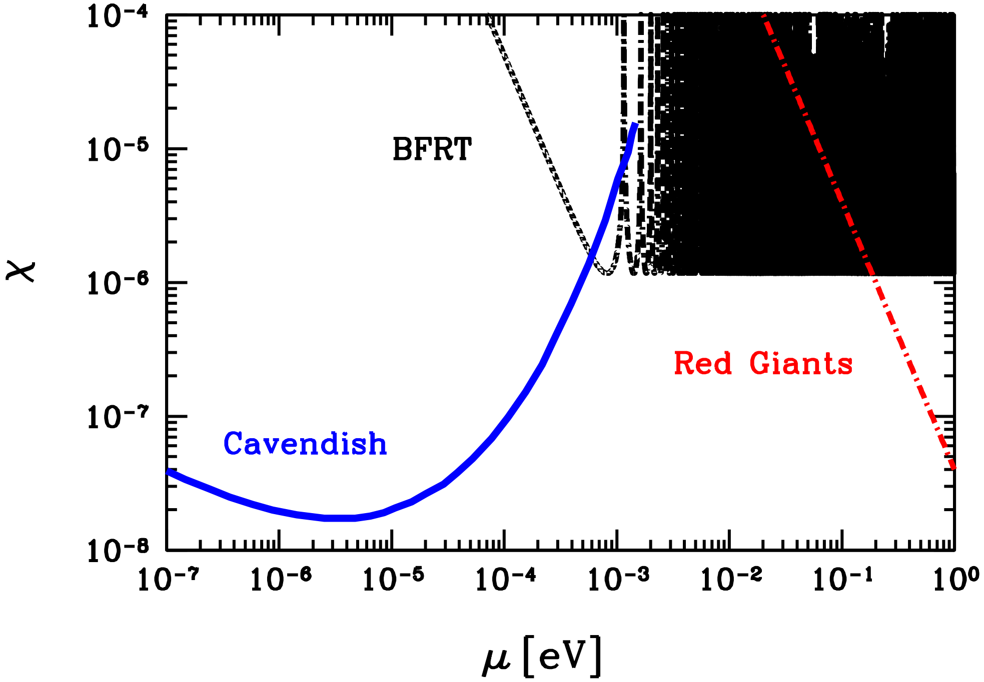
- Hidden sector CP, with special charge assignment $(0, e, -e)$, acquires visible mini-charge

$$\epsilon \simeq \begin{cases} -\chi & \text{for} \quad m_\gamma = 0 \\ (\mu^2/\omega_{\rm p}^2)\,\chi & \text{for} \quad m_\gamma = \omega_{\rm p} \gg \mu \end{cases}$$

⇒ Viable MCP explanation of PVLAS $(m_\gamma = 0)$ for $\chi \sim 10^{-6}$, $m_\epsilon \lesssim 0.1$ eV; in accordance with the life time of stars $(m_\gamma = \omega_{\rm p} \sim$ keV), if $\mu \lesssim 0.1$ eV [Abel *et al.* '06]



[AR unpubl]

5. WILPs in Models with Light Extra-U(1)s

- Consider extension of SM with additional "hidden sector" U(1)'s ⇒ in general gauge kinetic mixing with "visible" U(1), e.g.

$$\mathcal{L} = -\frac{1}{4}\, F^T \mathcal{K}_F\, F + \frac{1}{2}\, A^T \mathcal{M}_A^2\, A + e j A,$$

with special mixing and mass pattern

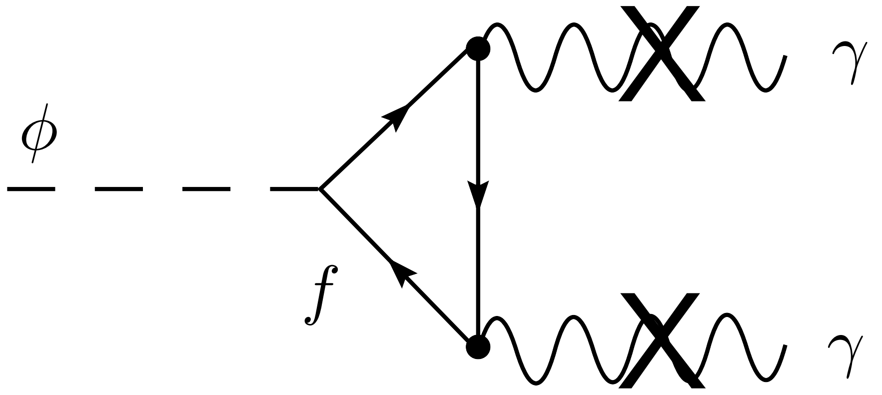
$$\mathcal{K}_F = \left(\begin{array}{ccc} 1 & \chi & \chi \\ \chi & 1 & 0 \\ \chi & 0 & 1 \end{array} \right),$$

- Hidden sector CP, with special charge assignment $(0, e, -e)$, acquires visible mini-charge

$$\epsilon \simeq \left\{ \begin{array}{rll} -\chi & \text{for} & m_\gamma = 0 \\ (\mu^2/\omega_{\rm p}^2)\,\chi & \text{for} & m_\gamma = \omega_{\rm p} \gg \mu \end{array} \right.$$

⇒ Viable MCP explanation of PVLAS $(m_\gamma = 0)$ for $\chi \sim 10^{-6}$, $m_\epsilon \lesssim 0.1$ eV; in accordance with the life time of stars ($m_\gamma = \omega_{\rm p} \sim$ keV), if $\mu \lesssim 0.1$ eV [Abel *et al.* '06]

⇒ Extend minimal model by hidden sector scalar, $m_\phi \sim$ meV, coupled to hidden sector CPs ⇒ Viable ALP explanation [Masso,Redondo '06]



- Coupling to two photons can be arranged to be in PVLAS range,

$$g \sim \frac{\alpha}{2\pi}\chi^2 \frac{y_f}{m_f} \sim 2 \times 10^{-6}\ \text{GeV}^{-1} \left(\frac{\chi}{10^{-6}}\right)^2 \left(\frac{y_f\ \text{eV}}{m_f}\right)$$

- Yukawa coupling to proton,

$$y \sim \frac{\alpha}{\pi}\chi^2 \frac{\mu}{m_f},$$

suppressed by factor μ/m_p compared to case without kinetic mixing ⇒ no problem with non-Newtonian forces, if $\mu \lesssim$ meV

6. Summary

- The evidence for 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 WILPs 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