The PVLAS Puzzle: A Glimpse of Physics Beyond the Standard Model?

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Outline:

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, ...

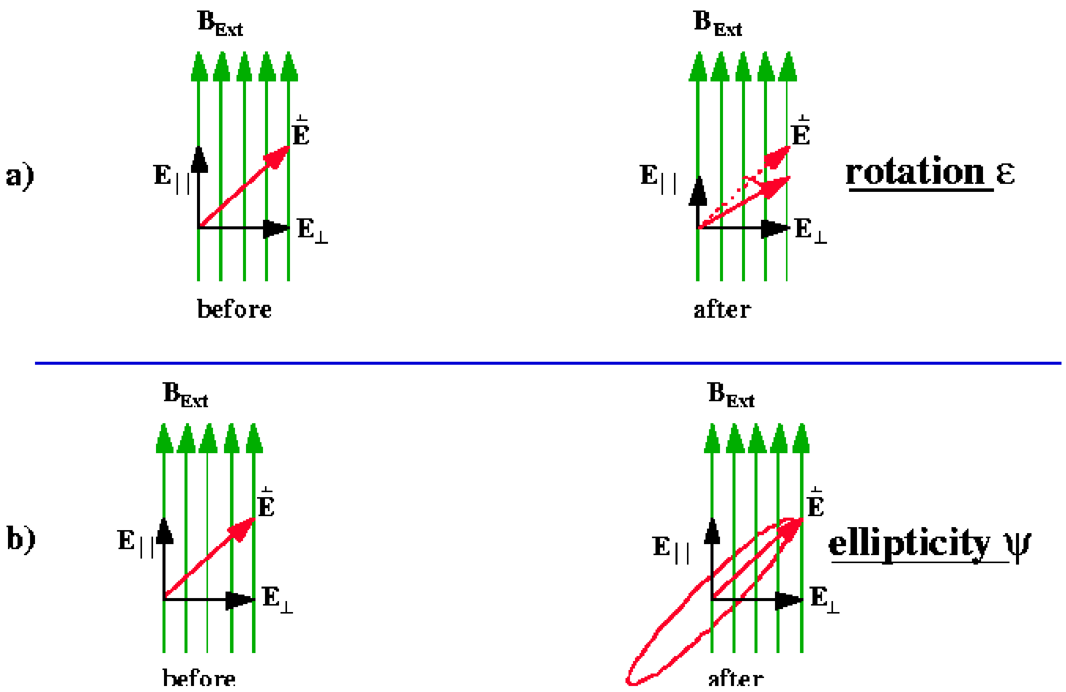
4. **Problems of Particle Interpretations**

   Astrophysical, cosmological, and other constraints

5. **Conclusions**

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:
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  - ellipticity (birefringence)

BFRT experiment: [Cameron *et al.* '93]

(Brookhaven, Fermilab, Rochester, Trieste)

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

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

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

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

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

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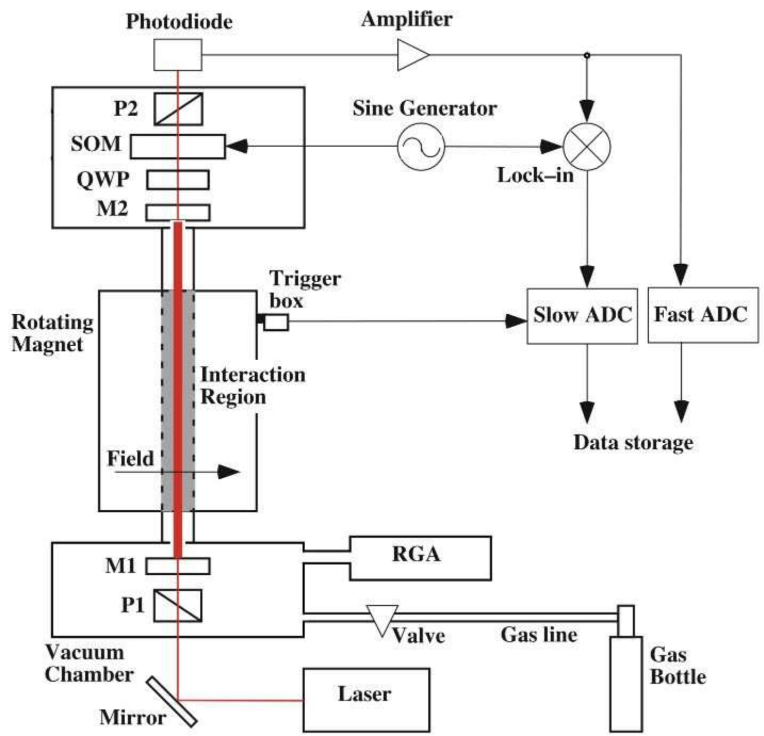

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BFRT experiment		
Rotation	($L = 8.8$ m, $\lambda = 514.5$ nm, $\theta = \frac{\pi}{4}$)	
$N_{\rm pass}$	$\lvert\Delta\theta\rvert$ [nrad]	$\Delta\theta_{\rm noise}$ [nrad]
254	0.35	0.30
34	0.26	0.11
Ellipticity	($L = 8.8$ m, $\lambda = 514.5$ nm, $\theta = \frac{\pi}{4}$)	
$N_{\rm pass}$	$\lvert\psi\rvert$ [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]

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- 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]

1. Vacuum Magnetic Dichroism and Birefringence

- Send linearly polarized laser beam through transverse magnetic field ⇒ measure changes in polarization state:
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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]

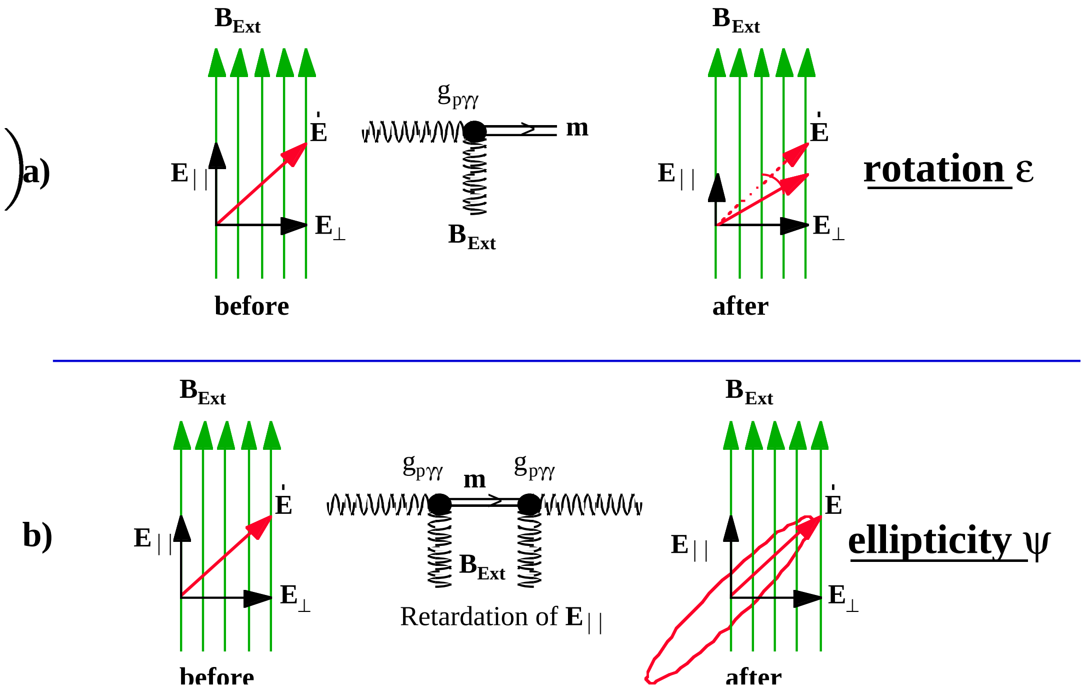
2. Possible Explanations

- Viable explanation in terms of real and virtual production of
  - light neutral spin-zero boson (**A**xion-**L**ike **P**article (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]

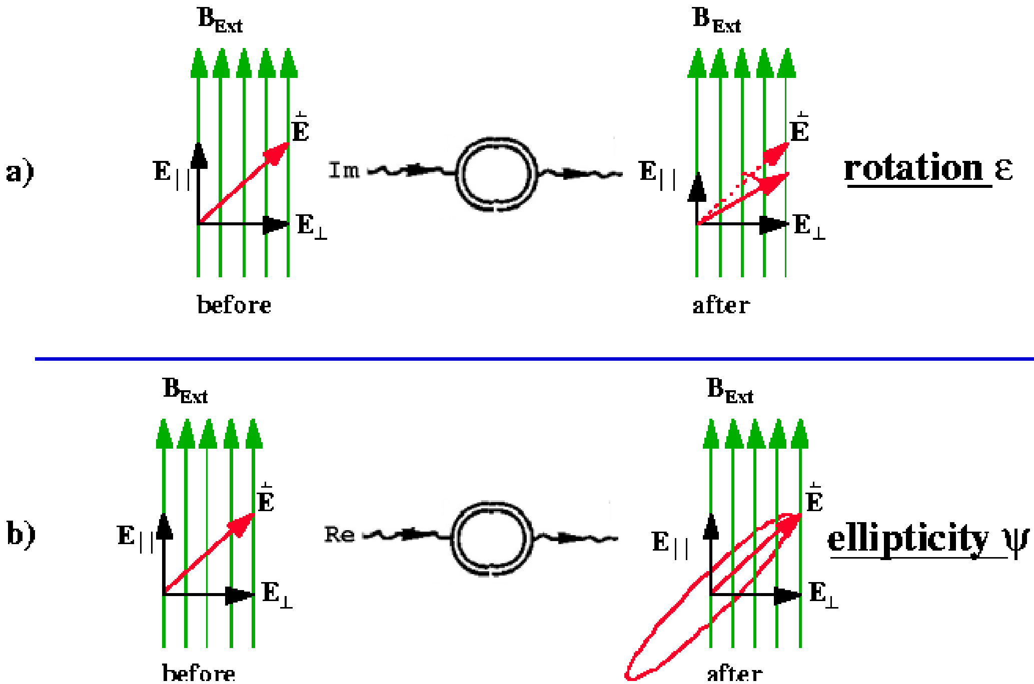
2. Possible Explanations

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

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

- Published data:
  pure ALP or pure MCP ok
- Preliminary data:
  pure ALP and pure MCP 0 ruled out;
  pure MCP $1/2$ ok;
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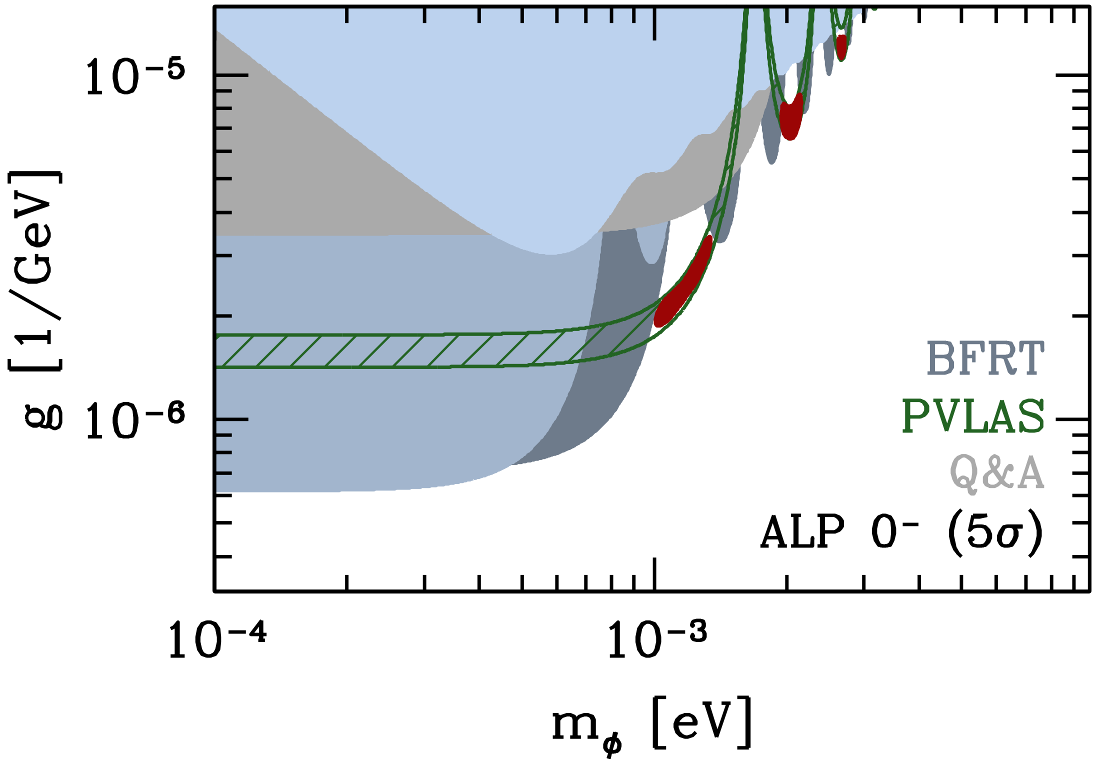
If interpreted in terms of ALP:



[Ahlers,Gies,Jaeckel,AR '06]

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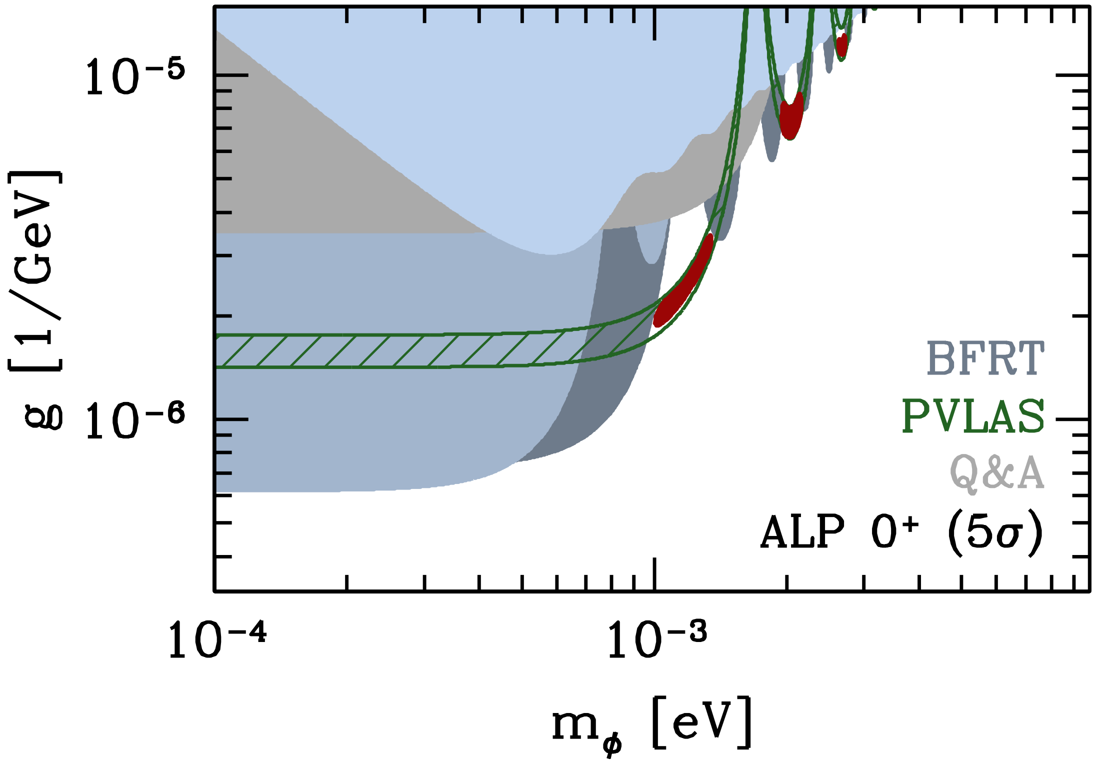

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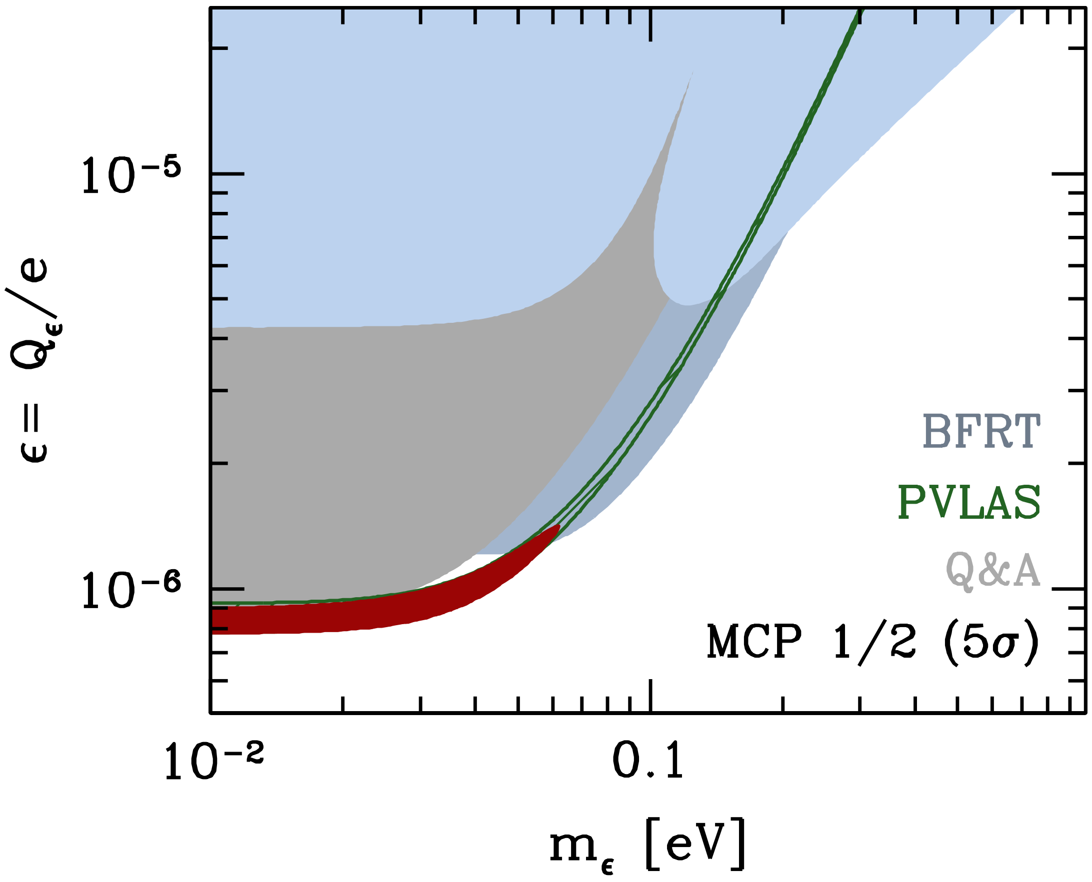

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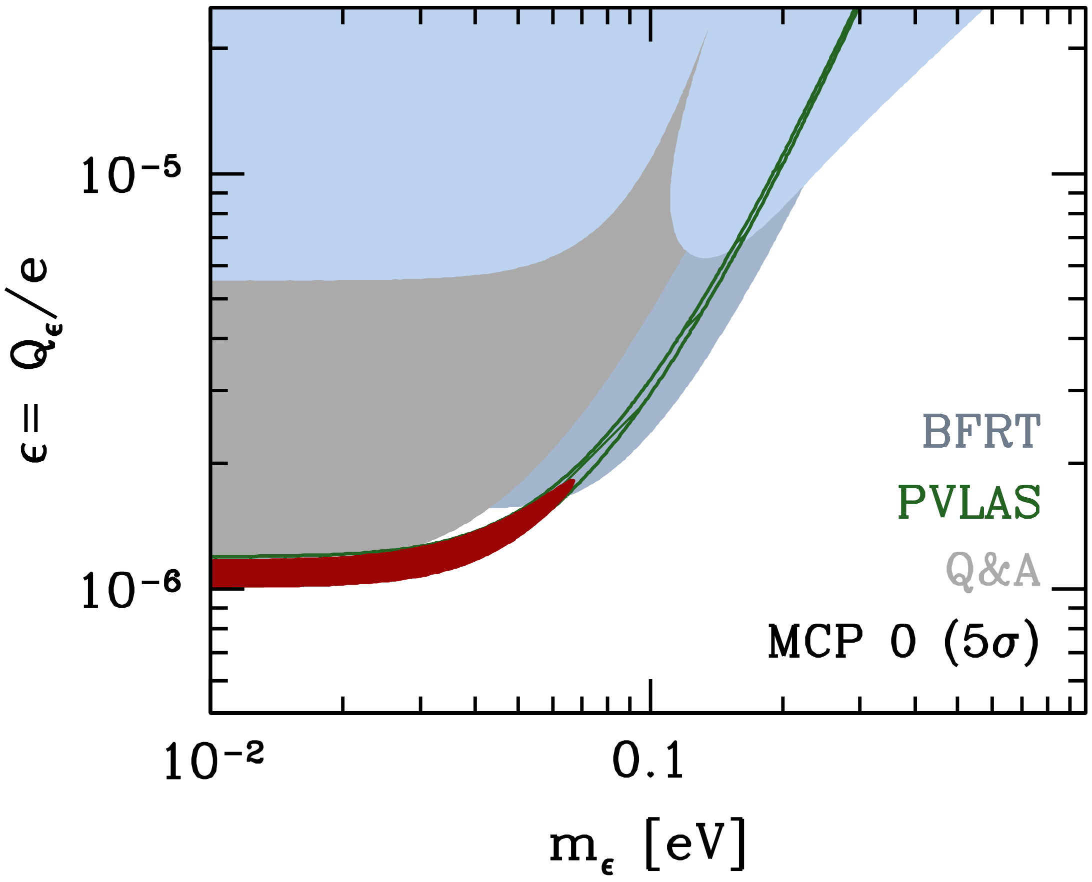

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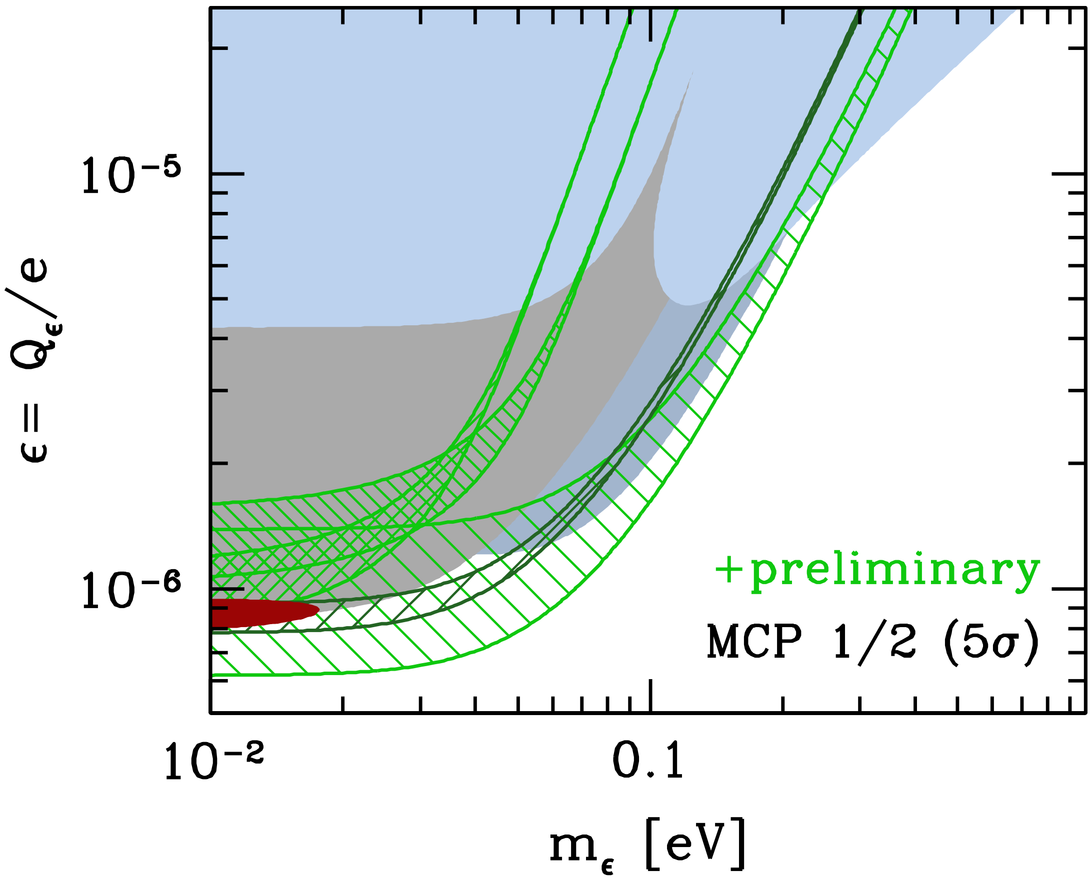
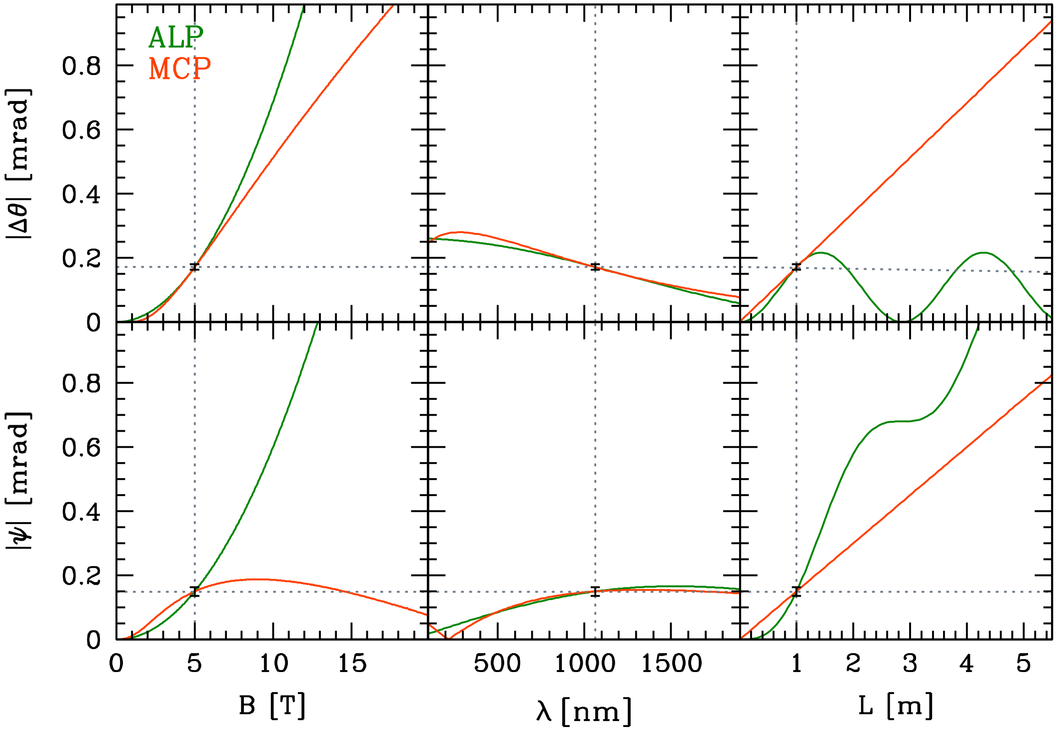


[Ahlers,Gies,Jaeckel,AR '06]

3. Crucial Laboratory Tests

- Laser polarization experiments at higher magnetic fields



[Ahlers,Gies,Jaeckel,AR '06]

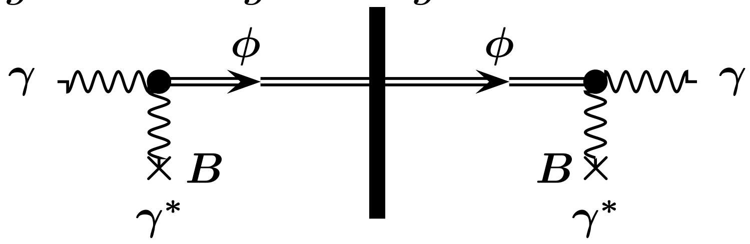
BMV (Toulouse): 11 T pulsed magnet

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	$P_{\gamma\phi\gamma}\|g_{\rm PVLAS}$
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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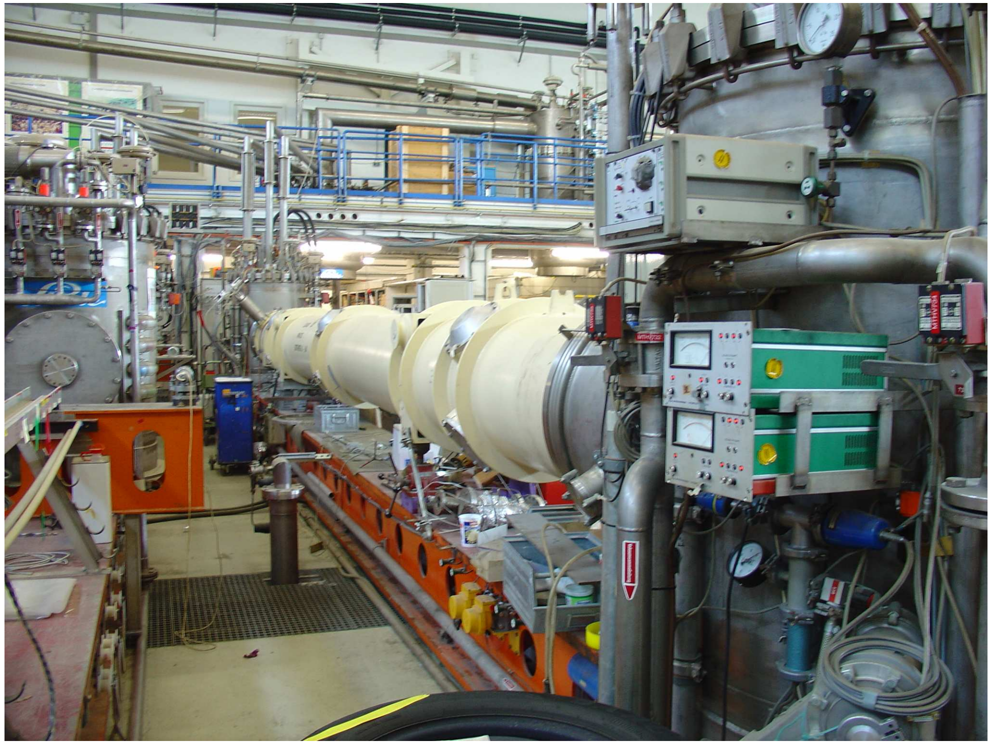
Axion-Like Particle Search:

[DESY, Laser Zentrum Hannover, Sternwarte Bergedorf]



$$B = 5\ \mathrm{T}, \ell = 4.2\ \mathrm{m}, \underbrace{\langle P \rangle = 0.2\ \mathrm{kW}, \omega = 1.2\ \mathrm{eV}}_{\dot{N}_0 \sim 1\times 10^{21}/\mathrm{s}}, N_r = 0$$

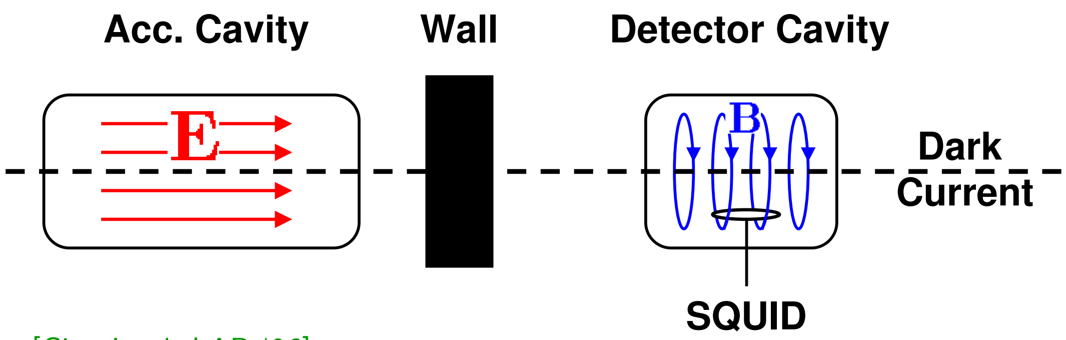
Test of ALP interpretation of PVLAS in summer 2007

3. Crucial Laboratory Tests

- Laser polarization experiments at higher magnetic fields

- Light shining through a wall

- Dark current through a wall



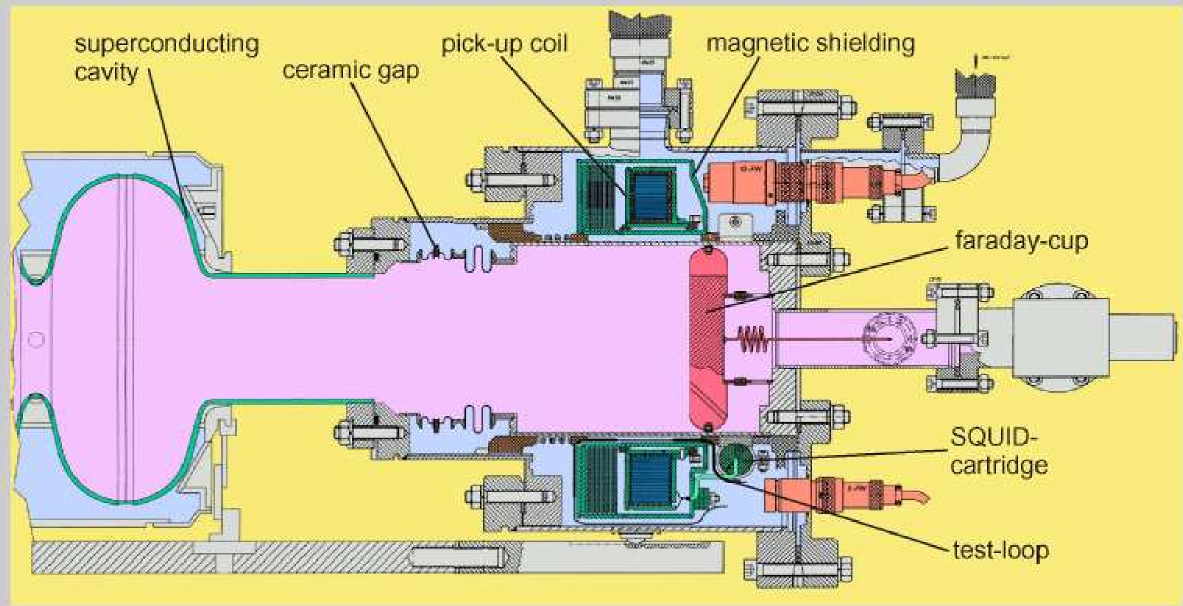
[Gies,Jaeckel,AR '06]

3. Crucial Laboratory Tests

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

Cryogenic Current Comparator:

[DESY, GSI, Universität Jena]



Construction details of the CCC dark current hardware

[M. Wendt TESLA2004]

3. Crucial Laboratory Tests

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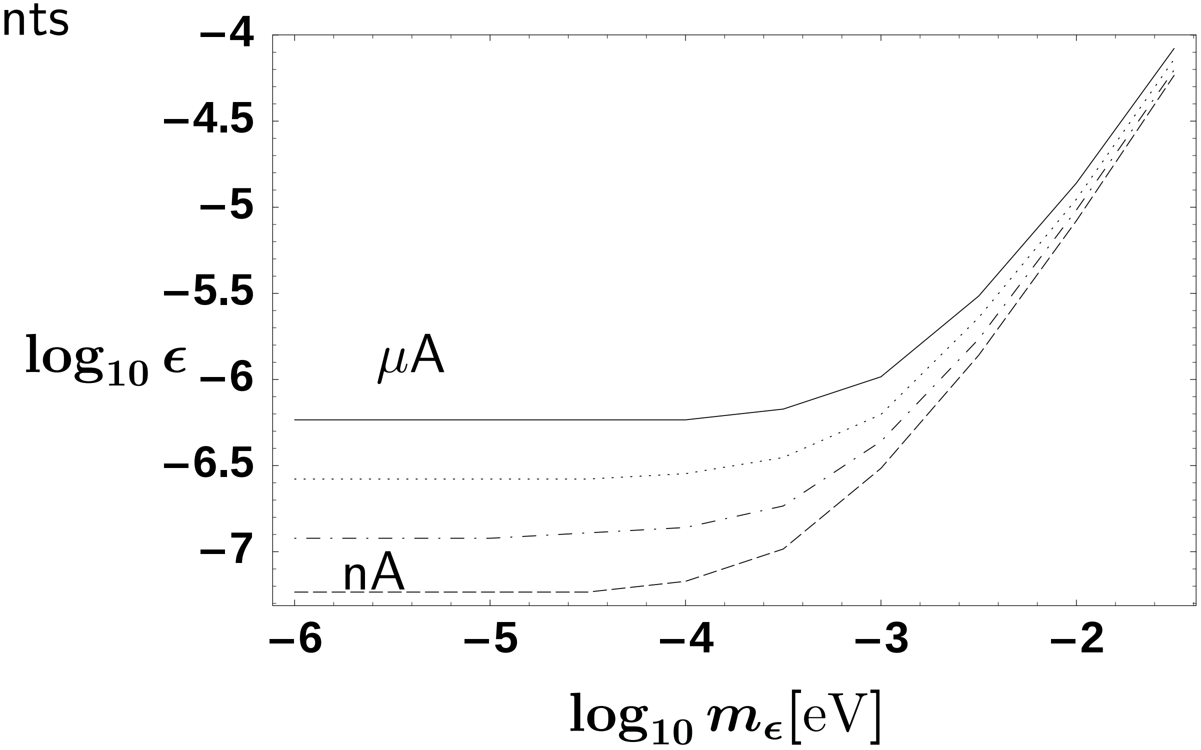
TESLA accelerator cavity | CCC:



[Gies,Jaeckel,AR unpubl.]

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- Laser polarization experiments at higher magnetic fields

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- Dark current through a wall

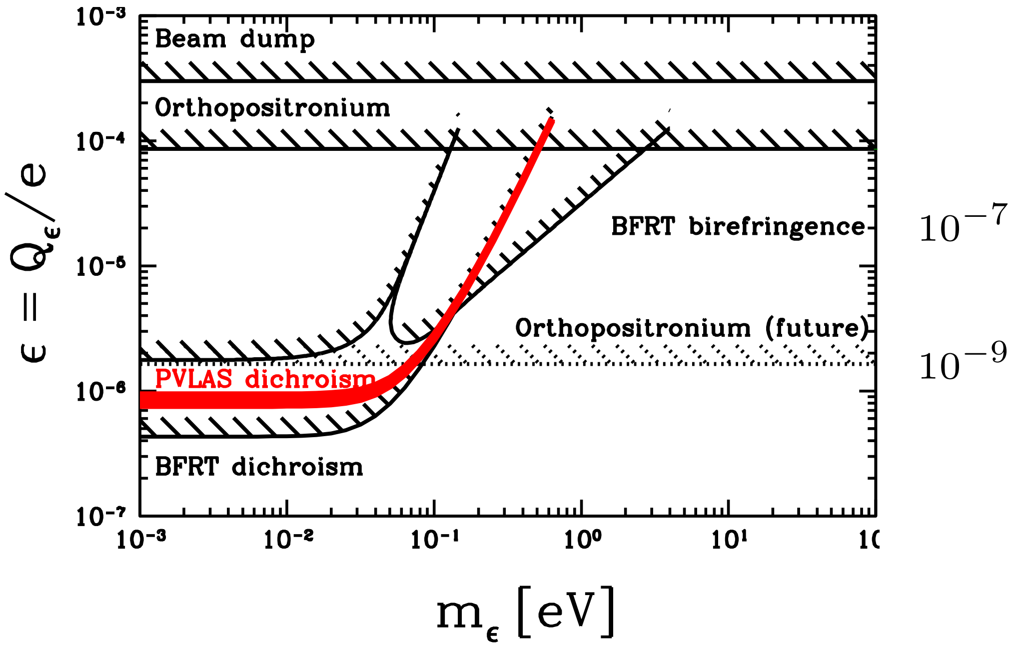
- Invisible Orthopositronium decay

- Searches for excess e^- from elastic $\epsilon^{\pm}e^-$ scattering in detector near nuclear reactor

[Gninenko,Krasnikov,A.Rubbia '06]

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

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

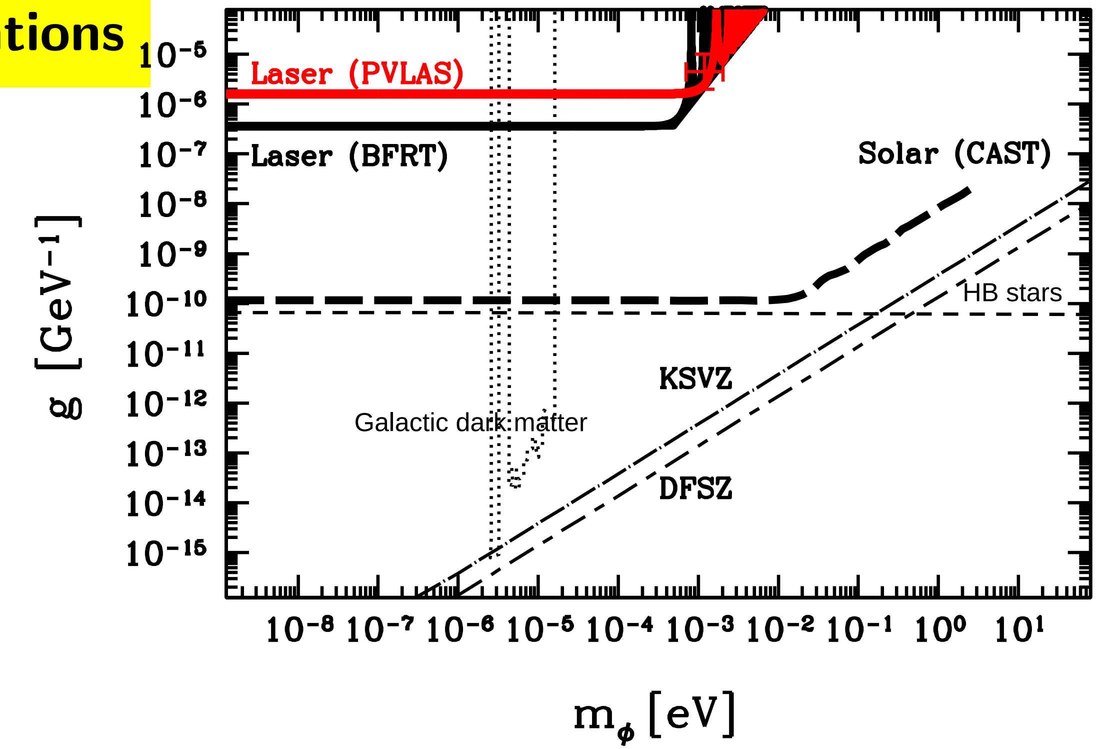


[Mitsui *et al.* '93]: $\mathrm{BR}(\mathrm{OP} \to \mathrm{inv.}) < 2.8 \times 10^{-6}$

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

4. Problems of Particle Interpretations

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



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

[Masso,Redondo '05;Jaeckel *et al.* '06;Brax *et al.* '07]

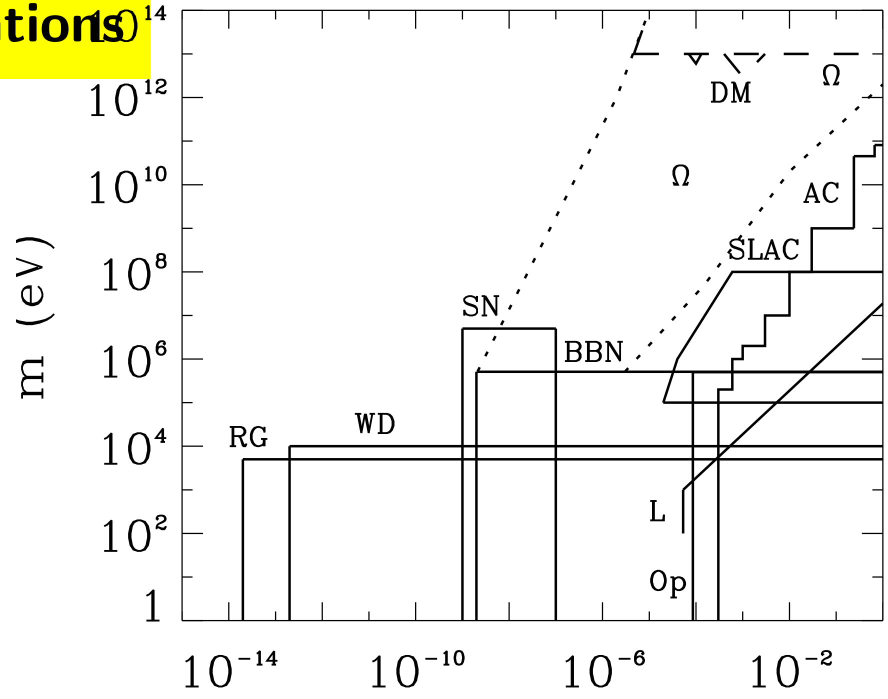
$\Rightarrow$ Even more sub-eV particles and fields, e.g. [Masso,Redondo '06;Mohapatra,Nasri '06]

– light 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: $\epsilon_{|\mathrm{plasma}} \ll \epsilon_{|\mathrm{vacuum}}$

[Masso,Redondo '06]

$\Rightarrow$ Even more sub-eV particles and fields, e.g. light 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 $\gamma^* \to \epsilon^+\epsilon^-$

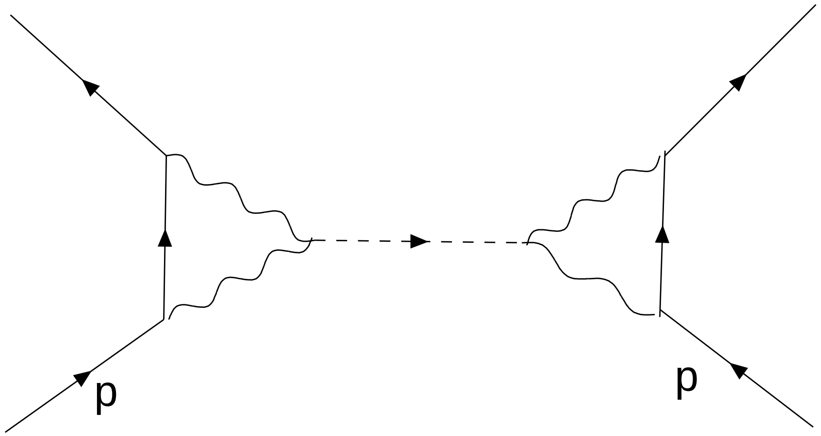
- ALP 0^+: Non-Newtonian force,

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

from Yukawa coupling

$$\mathcal{L}_{\phi pp} = y\phi\overline{\Psi}_p\Psi_p$$

$$y \simeq \frac{3}{2}\frac{\alpha}{\pi}(g m_p)\log\frac{\Lambda}{m_p}$$



[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

4. Problems of Particle Interpretations

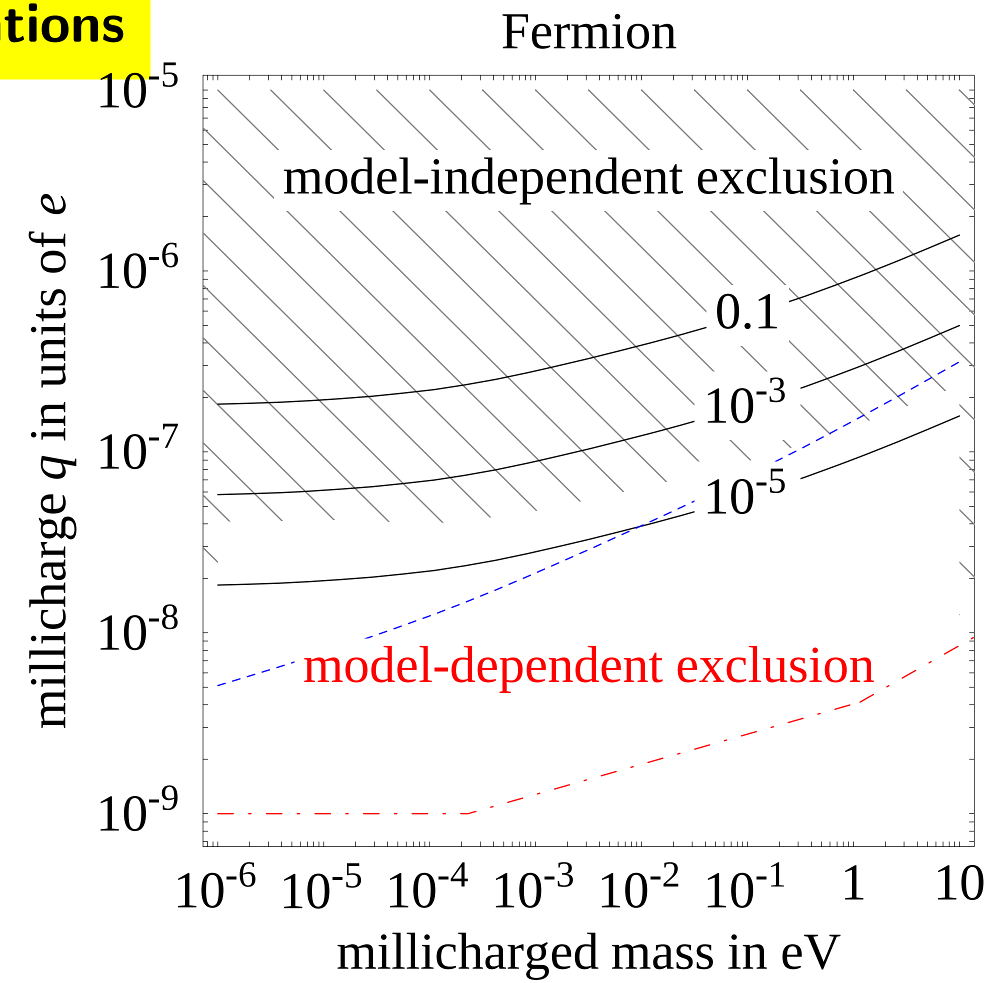
- Distortion of CMB spectrum through $\gamma + \gamma \to \epsilon^+ + \epsilon^-$:

$$\epsilon \lesssim 10^{-7}$$

- In slight clash with pure MCF interpretation of PVLAS, which requires

$$\epsilon \sim (8 - 9) \times 10^{-7}$$

- How model dependent?



[Melchiorri,Polosa,Strumia '07]

5. Conclusions

- 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