Bounding Pseudoscalar Couplings and the PVLAS results

Matthew Kleban

Institute for Advanced Study

PVLAS results: polarization vector of linearly polarized light rotates while passing though a strong magnetic field.

The simplest explanation for these results involving new physics is a pseudoscalar coupled to photons:

$$\frac{g}{8}\phi \;\; \epsilon_{\mu\nu\rho\sigma}F^{\mu\nu}F^{\rho\sigma}$$

where g is a coupling constant with dimensions of inverse mass, and ϕ is a pseudoscalar field with canonical kinetic term and mass m.

The amount of polarization rotation in a magnetic field produced by this interaction is a function of g and m.

The PVLAS results, combined with constraints from a similar past experiment, favor:

$$1.7 \;\; 10^{-6} \;\; \text{GeV}^{-1} < g < 1.0 \;\; 10^{-5} \;\; \text{GeV}^{-1}$$

$$0.7 \;\; \text{meV} < m_\phi < 2.0 \;\; \text{meV}$$

Why are light pseudoscalars interesting?

- The QCD axion.
  - The QCD axion was invented to solve the strong CP problem: Why θ is so small?

$$\frac{\alpha_s}{16\pi}\,\theta\,\mathrm{Tr}\left(\epsilon_{\mu\nu\lambda\sigma}G^{\mu\nu}G^{\lambda\sigma}\right)$$

  - Experimentally: $|\theta| < 10^{-10}$
  - Problem is solved if there is a pseudoscalar particle - the QCD axion ϕ_a - which couples:

$$\frac{\alpha_s}{16\pi}\,\frac{\phi_a}{f_a}\mathrm{Tr}\left(\epsilon_{\mu\nu\lambda\sigma}G^{\mu\nu}G^{\lambda\sigma}\right)$$

- Due to non-perturbative QCD effects there is a potential that sets θ to zero and gives a mass to the axion:

$$m_a \sim \Lambda^2_{QCD}/f_a$$

- There is a model dependent coupling g_a of the QCD axion to photons:

$$g_a = (\alpha C)/(2\pi f_a)$$

- In particular, for the QCD axion the coupling g_a is proportional to m .

- The PVLAS PS can not be a QCD axion (at least not in any model studied so far) because it fails to satisfy the mass/coupling relation (by many orders of magnitude).

- However, there is an even bigger puzzle regarding the PVLAS results.

Bounds from the stars

- The best limits on the coupling g come from astrophysics.
- PS emission by stars (see e.g. Raffelt):
  - PS are produced in the interior of stars (Primakoff).
  - Typically PS has a mean free path larger than the star, so doesn't thermalize – in this case may have greater luminosity than photons.
  - PS luminosity ~ 10^{-3} (g 10^{10} GeV)^2 Lphotons

van Bibber et al (1989)

Clearly (since the sun is still shining), there is a problem!

In fact, the best solar limit comes from CAST:

$g < 1.16\ 10^{-10}\ GeV^{-1}$ (for $m < 20$ meV)

Several attempts have been made to construct PS models which explain PVLAS but are consistent with solar physics/CAST.

However - in my opinion - none of them succeed.

If PVLAS is confirmed, this is a nice challenge for theorists.

Question:

- Is there a easy (cheap!) way to check the PVLAS result?
- Two proposals:
  - Using electron-positron colliders.
    - M. Kleban and R. Rabadan

      hep-ph/0510183
  - Using X-ray lasers.
    - R. Rabadan, A. Ringwald and K. Sigurdson

      hep-ph/0511103

Pseudoscalars at colliders

- We can use collider data to bound the pseudoscalar coupling to photons (and gluons):

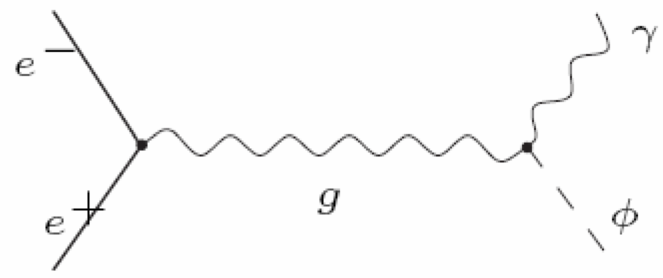
$$\frac{g}{8}\phi \;\; \epsilon_{\mu\nu\rho\sigma}F^{\mu\nu}F^{\rho\sigma}$$

- The process is:

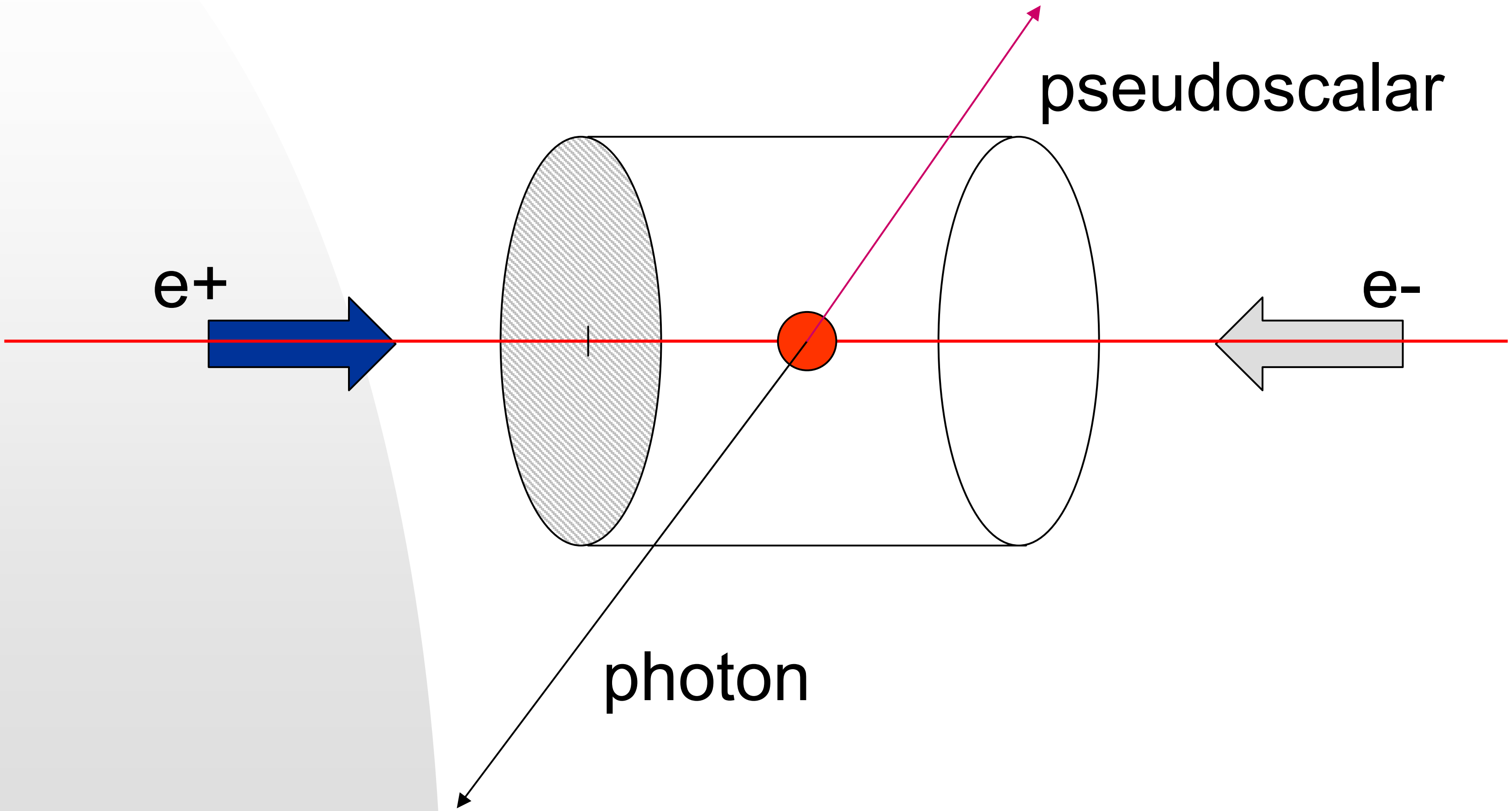
$$e^+e^- \rightarrow \gamma + \not{E}_T$$

in e^+e^- colliders.

Masso, Toldra (1995)



- The signature is a hard photon (with almost exactly half of the CM energy) + missing energy.



- Characteristics of these amplitudes:
  - From dimensional analysis, the cross section is independent of energy at high energies: cross section ~ g^2, and [g] = length.
  - i.e. for energies higher of the mass of the electron and the pseudoscalar the cross section is

$$d\sigma/d\Omega = g^2 f(s/t)$$

  - Therefore to maximize the signal we need to maximize the luminosity rather than the CM energy.

- Standard model backgrounds:
  - neutrino-antineutrino pairs.
  - K_L – K_L pairs that escape the detector.
  - etc.
- The process we are interested in has a 2 body final state.
- The backgrounds are all three (or more) body final states. The phase space for producing a photon with half the CM energy in such a process is very small.
- If masses of the final state particles are significant it is impossible to produce such a photon.
- We can require energy of final state photon to be half the CM energy. With an ideal detector, this completely eliminates the background. With a real detector, limited by energy resolution.

- Large luminosity electron-positron colliders: B factories!

- The energy resolution of the BABAR and BELLE detectors for a ~5 GeV photon (in the center of mass frame) is around 1.5 %.

- Therefore we can cut $E_{photon} > 0.985\ E_{BEAM}$ (the CM energy of both colliders is around 10.6 GeV).

- The luminosities are similar:
  - PEP-II: integrated luminosity of 312 fb^{-1},
  - KEKB: integrated luminosity of 500 fb^{-1}

- The neutrino pair background (with cuts):

$$\sigma_{e\bar{e}\to\gamma\nu\bar{\nu}} = 6.2 \ 10^{-7} \ \text{pb}$$

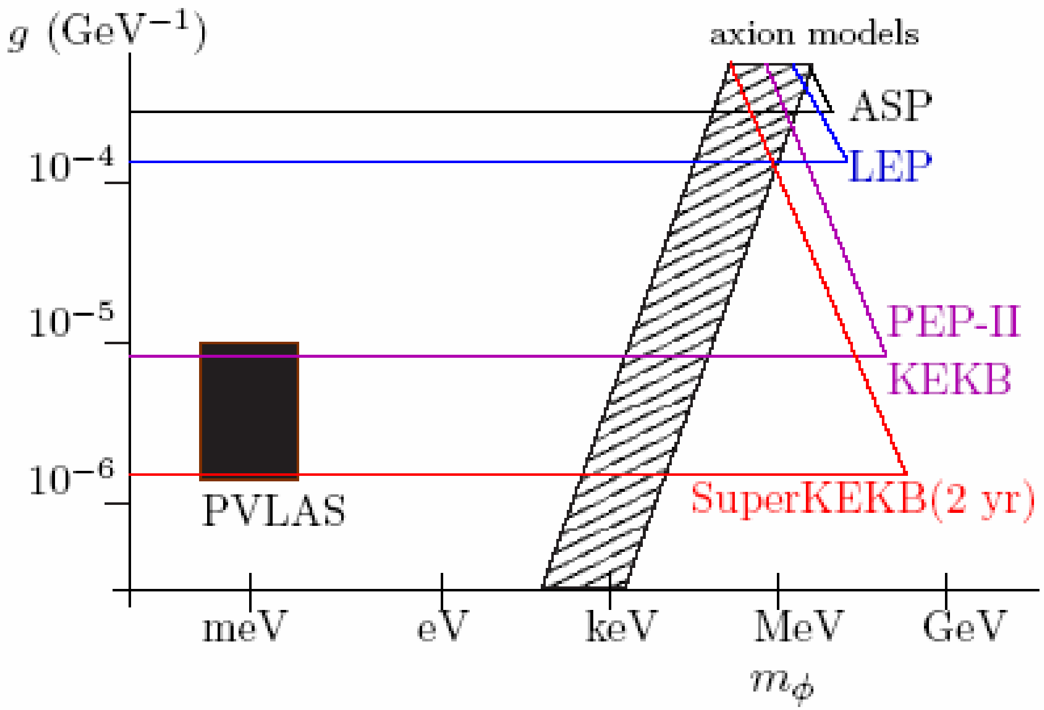
- The pseudoscalar cross section:

$$\sigma_{e\bar{e}\to\gamma\phi} = (g/10^{-5}\text{GeV}^{-1})^2 \ 1.2 \ 10^{-5} \ \text{pb}$$

- Main problem is having enough luminosity, since the backgrounds are very small (and could be made even smaller with better energy resolution for hard photons).

- Detector must trigger on single hard photon events!

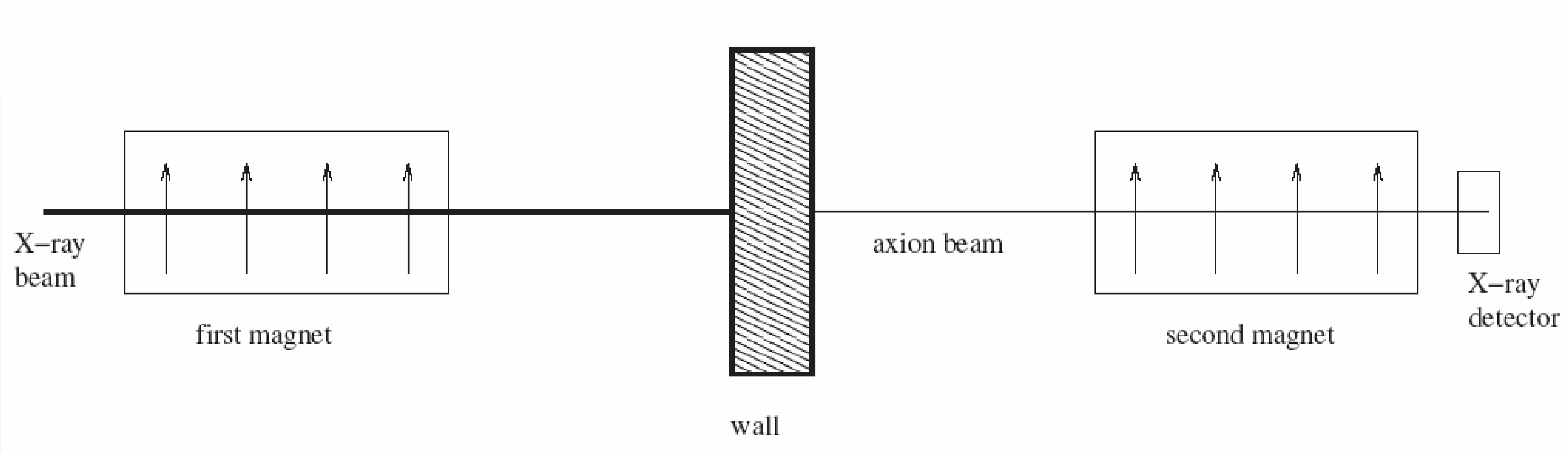
- Summary:



g (GeV^{-1})
axion models
ASP
LEP
PEP-II
KEKB
SuperKEKB(2 yr)
PVLAS
10^{-4}
10^{-5}
10^{-6}
meV
eV
keV
MeV
GeV
m_ϕ

Pseudocalars and X-ray lasers

- Light regeneration or “invisible light shining through walls” experiment:



P. Sikivie (1983), van Bibber et al. (1987), R. Rabadan et al. (2005)

- The probability of photon conversion into PS (gB/q<<1):

$$P = g^2 B^2 \frac{\sin^2\left(\frac{ql}{2}\right)}{q^2}$$

Where B is the magnetic field, L the length of the magnet and q is the momentum transfer:

$$q = \omega - \sqrt{\omega^2 - m_\phi^2}$$

- Testing the PVLAS result requires photons with frequency such that:

  $$q \sim m^2/2\omega < 1/L$$

(momentum transfer comes from breaking of translation invariance by B field)

- What are the best photon sources for a regeneration experiment?
  - Lots of photons
  - High energy if want to probe larger PS masses

X-ray lasers

- Two projects:
  - At SLAC: LCLS (Linac Coherent Light Source). Photon energies between 0.8 keV and 8 keV. Running at 2009.
  - At DESY: XFEL (X-ray Free Electron Laser). Photon energies between 1 keV and 10 keV. Photons per second ~10^{17}.

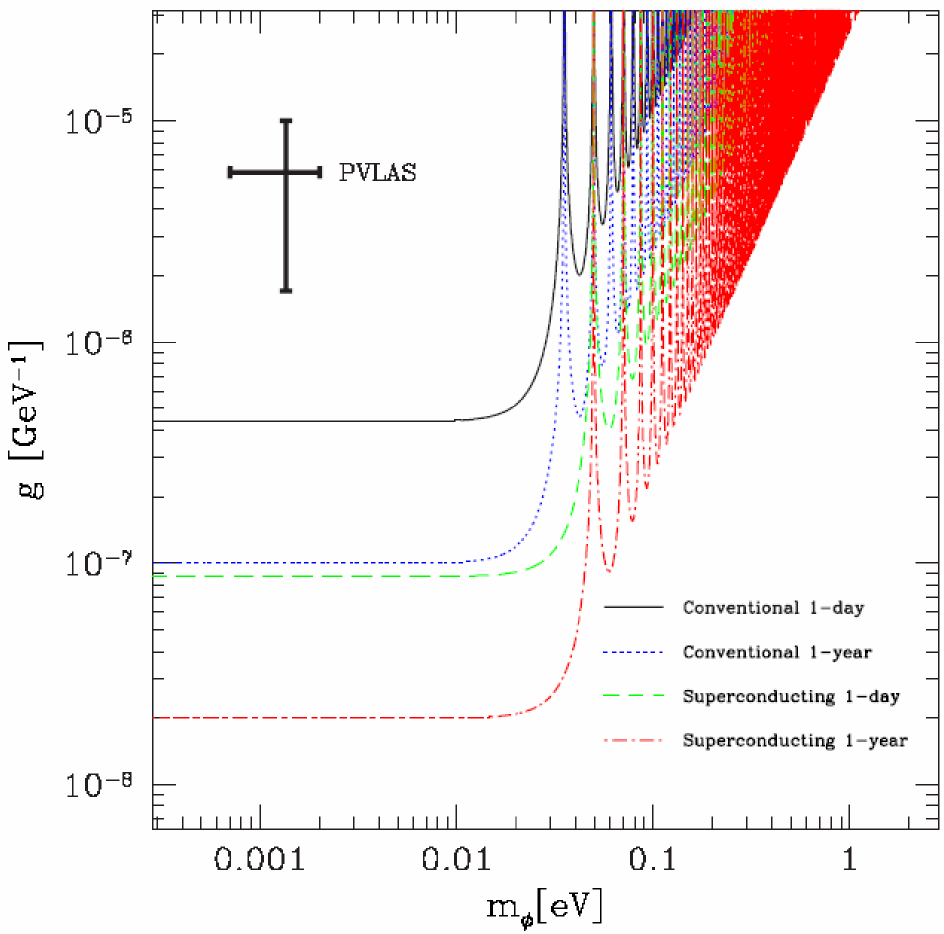
- The number of PS particles produced in the first magnet is:

$$N_\phi = 2.38\times10^8 \mathrm{s}^{-1}\mathcal{N}_{17}\left(\frac{g}{10^{-6}\mathrm{GeV}^{-1}}\right)^2\left(\frac{B}{10\mathrm{T}}\right)^2\left(\frac{L}{10\mathrm{m}}\right)^2$$

  - Where number of photons/sec = $N_{17}\ 10^{17}$
- In the second magnet the number of photons reconverted from the PS beam is:

$$N_f = 0.57\mathrm{s}^{-1}\mathcal{N}_{17}\left(\frac{g}{10^{-6}\mathrm{GeV}^{-1}}\right)^4\left(\frac{B}{10\mathrm{T}}\right)^4\left(\frac{L}{10\mathrm{m}}\right)^4$$

- PVLAS can be tested in seconds with B~10T, 10m.
- With conventional magnets (B~1T) more time is needed.



- Interesting features of this proposal:
  - PVLAS can be tested very quickly.
  - High frequency photons allows to test PS masses up to 50 meV.
  - Superconducting magnets are not necessary.
  - Possible to perform other experiments at the same time.

- Hard to go to small g, since the probability for double conversion scales as g^4.

- Four proposed regeneration experiments:

  - DESY: TESLA Test Facility: UV/soft X-ray photons. Frequency tunable to check possible dependence with the energy.

  - BMV (Birefrengence Magnetique du Vide) in Toulouse: pulsed magnetic field of high intensity (they can reach 75 T).
    Two experiments: rotation of polarization, regeneration experiment.

  - CERN: using LHC decommissioned Superconducting Dipoles (Letter of Intent).

  - PVLAS: different laser for polarization rotation as well as a photon regeneration experiment.

CONCLUSIONS:

- Two ways of testing the PVLAS result:
  - In electron-positron colliders:

$$e^+e^- \to \gamma + \not{E}_T$$

  - With lasers via light shining through walls: