Some remarks about light pseudoscalar particles

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Why light pseudoscalars are interesting?

- The QCD axion (R. Peccei, P. Sikivie talks).
  - The QCD axion invented to solve the strong CP problem: Why θ is so small?

$$\frac{\theta g^2}{32\pi^2} G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

  - Experimentally: $|\bar{\theta}| < 10^{-10}$
    - From electric dipole moment of neutrons (Yannis Semertzidis talk).
  - Problem solved if there is a pseudoscalar particle that couples:

$$\frac{g^2}{32\pi^2}\frac{a(x)}{f_a} G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

- Another reason why they are interesting is a recent result by PVLAS (Giovanni Cantatore):
  - A signal found in rotation of polarization of light crossing a magnetic field that can be explained by a pseudoscalar particle coupled to photons:

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

With the PS-photon coupling:

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

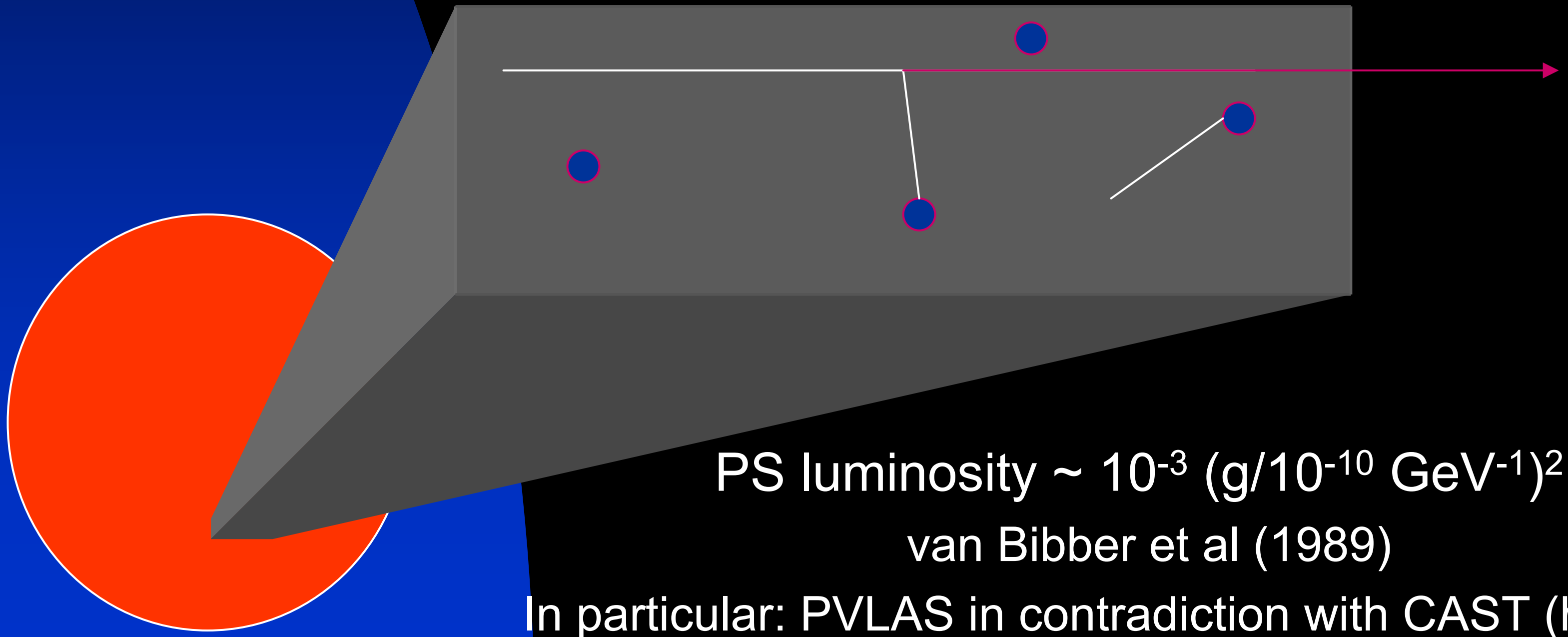
And a mass:

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

- In particular, this PS cannot be a QCD axion (at least of the type constructed till now).
  - It does not satisfy the mass coupling relation of the QCD axion.
- But there is a bigger problem!

The CAST(star)-PVLAS puzzle

- Best limits of coupling of PS to photons:
  - PS emission of stars (see Raffelt talk and book):
    - Thermal photons in the interior of stars can convert into PS (electric field of ionized matter).
    - PS escape and photons are trapped in the interior.



PS luminosity ~ 10^{-3} (g/10^{-10} GeV^{-1})^2 L$_{\text{photons}}$

van Bibber et al (1989)

In particular: PVLAS in contradiction with CAST (here).

- The PVLAS result can be:
  - Wrong.

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  - Right.

- The PVLAS result can be:
  - Wrong: continue with the axion searches:
    - ADMX (Sikivie, van Bibber), CAST, etc.
  - Right.

- The PVLAS result can be:
  - Wrong: continue with the axion searches:
    - ADMX, CAST, etc.
  - Right:
    - How to solve the CAST-PVLAS puzzle?
      - Ideas (Masso and Redondo):
        - Interactions in the interior of stars: reduce the pseudoscalar flux.
        - Interaction with photons depends on energy.
    - What is this particle?
      - Can be the QCD axion? It does not look like any of the models.
      - Can be a dark matter candidate?

In this talk:

- I would like to check the first step: is there a easy way to check the PVLAS result?
- Two proposals:
  - ◆ Using colliders.
    - M. Kleban and R.R.

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

      hep-ph/0511103

Pseudoscalars in colliders

- We propose using collider data to bound the pseudoscalar field to photons (and gluons):

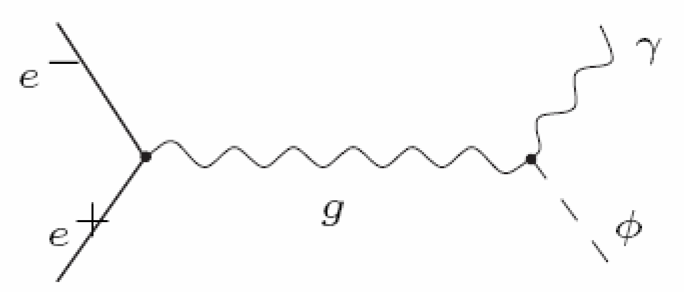
$$\frac{g}{8}\phi \quad \epsilon_{\mu\nu\rho\sigma}F^{\mu\nu}F^{\rho\sigma}$$

- The processes we are considering are:

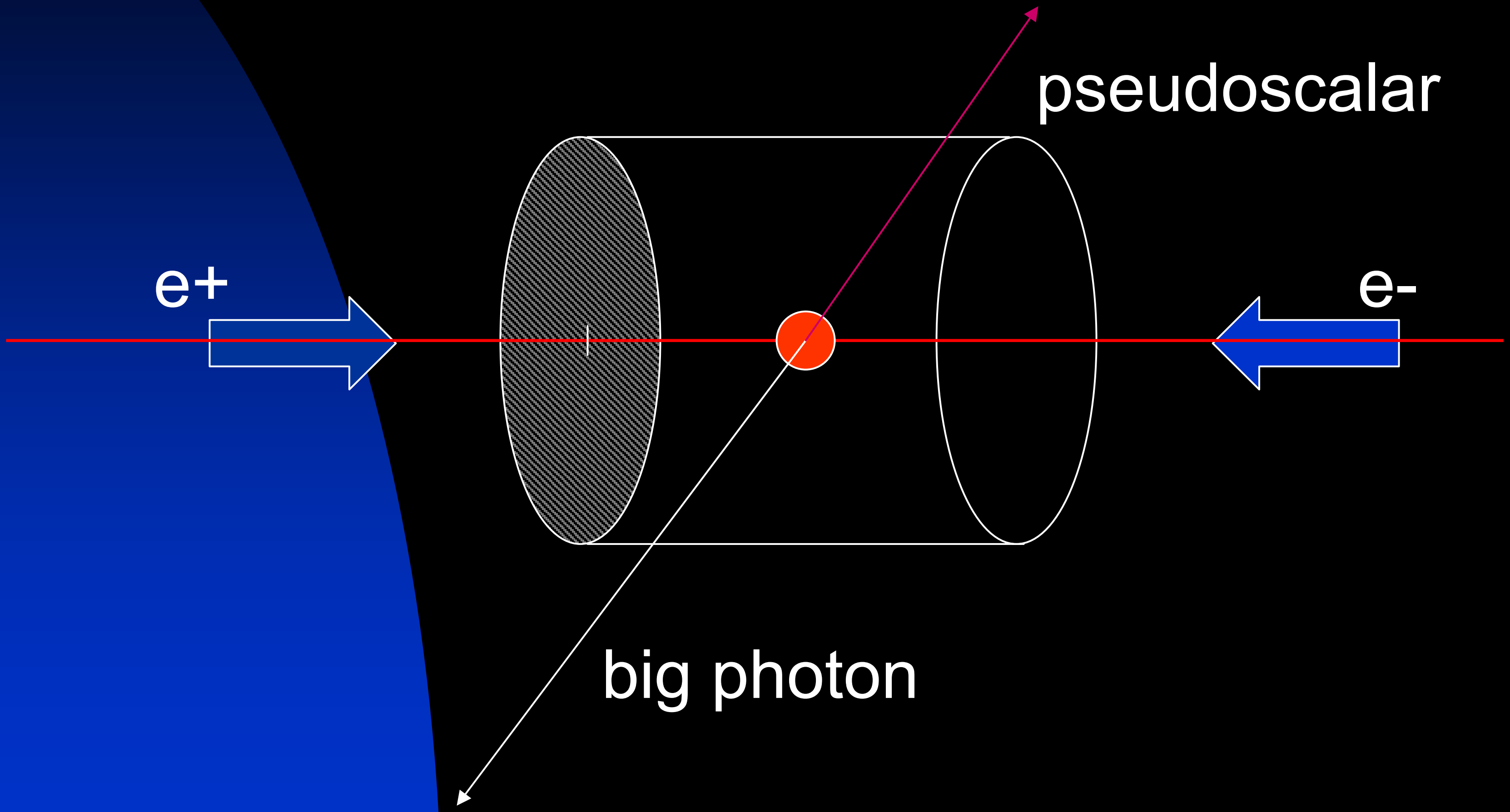
$$e^+e^- \to \gamma + \not{E}_T$$

in e^+e^- colliders.

Masso, Toldra (1995)



- The signature is a big photon (with half of the center of mass energy) + a lot of missing energy.



- Characteristics of these amplitudes:
  - The cross section is independent of center of mass energy at high energies. This follows from dimensional analysis: is an operator of dimension 5.
  - I.e. for energies higher of the mass of electrons and pseudoscalars the cross section is

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

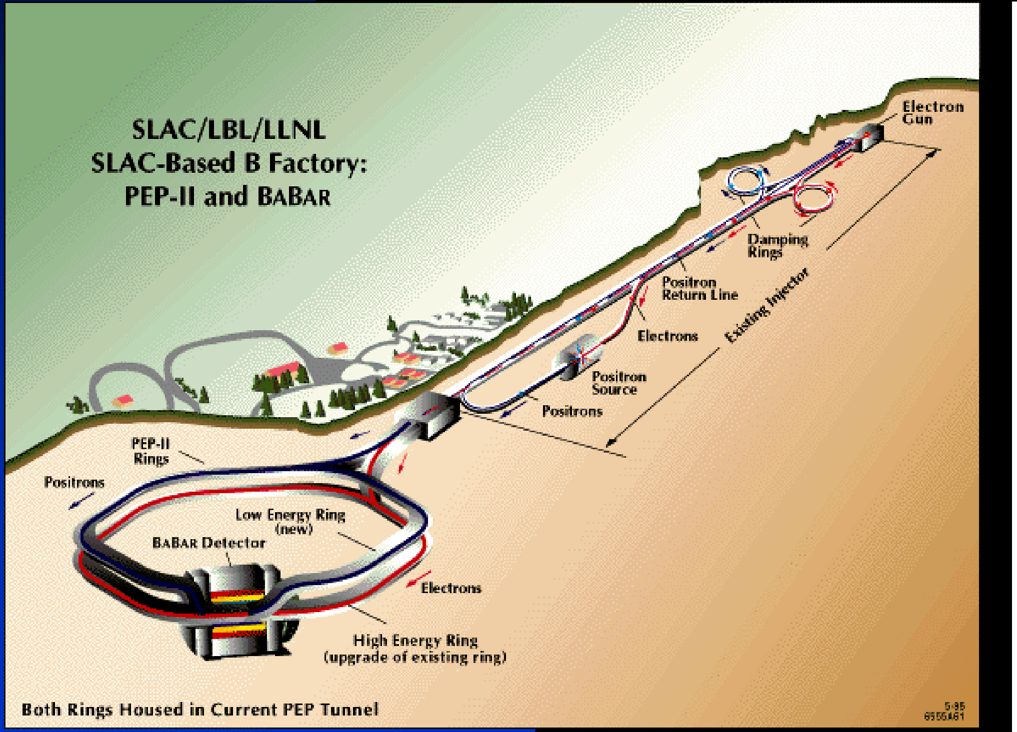
  - So to produce more events we need higher luminosity but energy is not so important. Energy can be relevant to estimate the backgrounds.

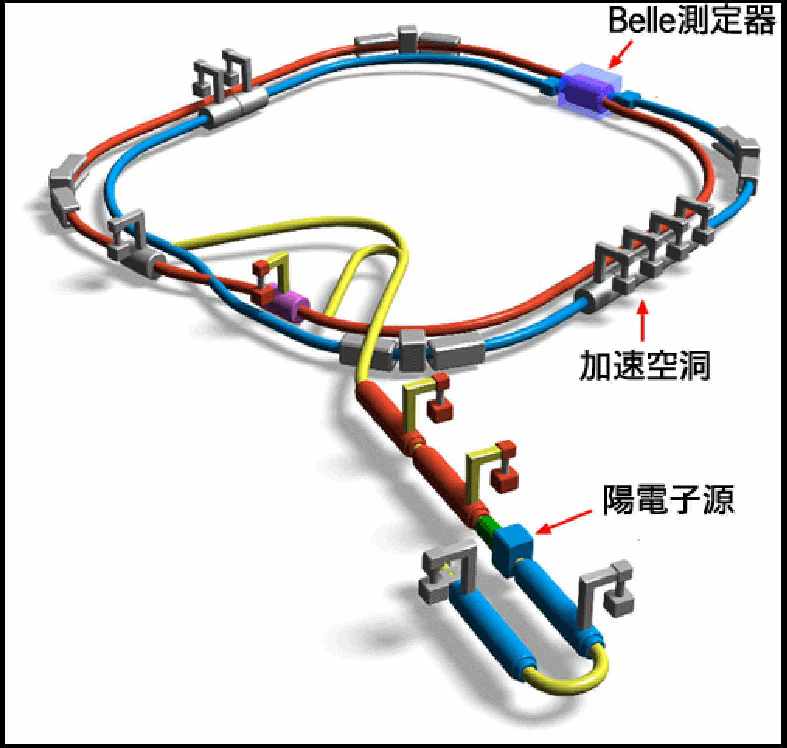
- Possible backgrounds:
  - In standard model:
    - Pairs neutrino-antineutrino.
    - K_L – K_L pairs that escape the detector.
    - etc .
  - The process we are interested in is a 2 body final state.
  - The backgrounds are three (or more) body final state. Even if they are very abundant, the probability of producing a photon with almost half of the center of mass energy is very small (phase space volume).
  - If masses of the final state particles are significant it will be impossible to produce a very high energy photon.
  - They can be eliminated by looking for events with a big photon. In practice determined by the precision of the detection of very high energy photons.

- So we are interested in colliders with very high luminosity and to select events with photons with almost half of the center of mass energy.
- Another issue that is relevant is that if the pseudoscalar has an small mass it can decay inside of the detector into two photons:

$$\Gamma_{\phi\to\gamma\gamma} = \frac{g^2 m_\phi^3}{64\pi}$$

- Best colliders: B-factories:
  - PEP-II in SLAC.
  - KEKB in Japan.





- The energy resolution of the BABAR and BELLE detectors for a ~5 GeV photon (in the center of mass frame) is around 1.5-2 %. Therefore we will require that $E_{photon} > 0.985\ E_{BEAM}$. The center of mass energy of both colliders is similar around 10.6 GeV (the Y(4s) resonance).

- Luminosities similar:
  - PEP-II: total integrated luminosity of 312 fb^{-1},
  - KEKB: total integrated luminosity of 500 fb^{-1}

- The neutrino pair background:

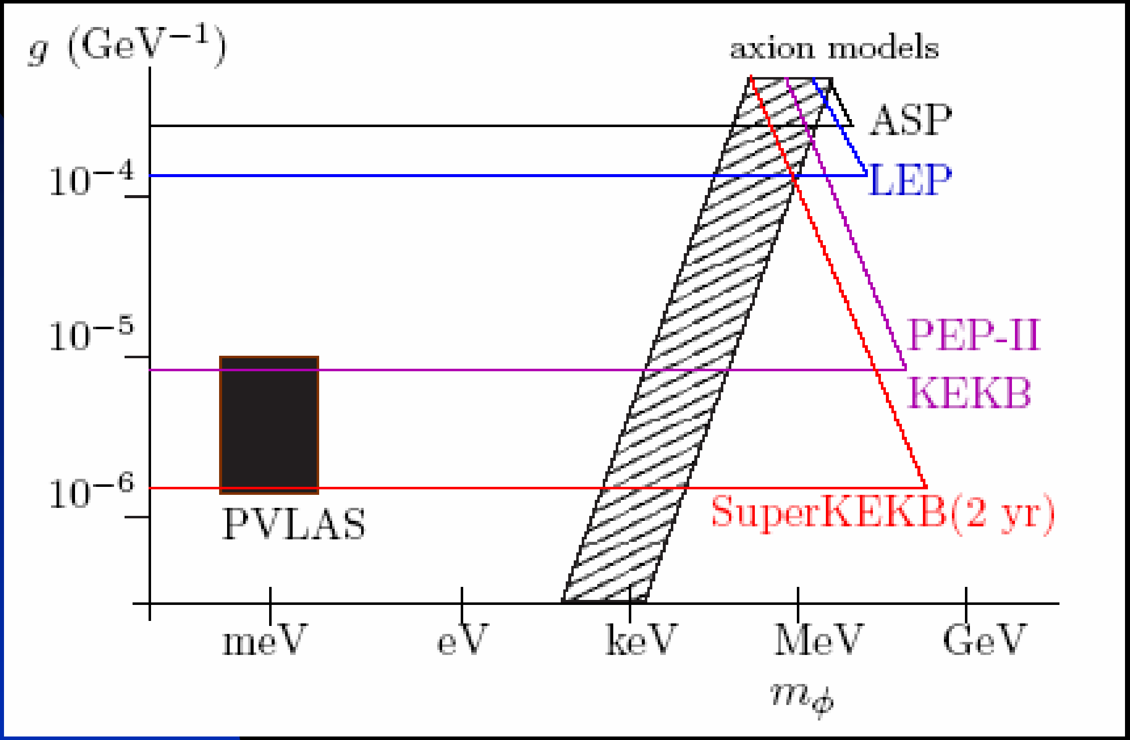
$$\sigma_{e\bar{e}\to\gamma\nu\bar{\nu}} = 6.2\ 10^{-7}\ \mathrm{pb}$$

- Our pseudoscalar cross section:

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

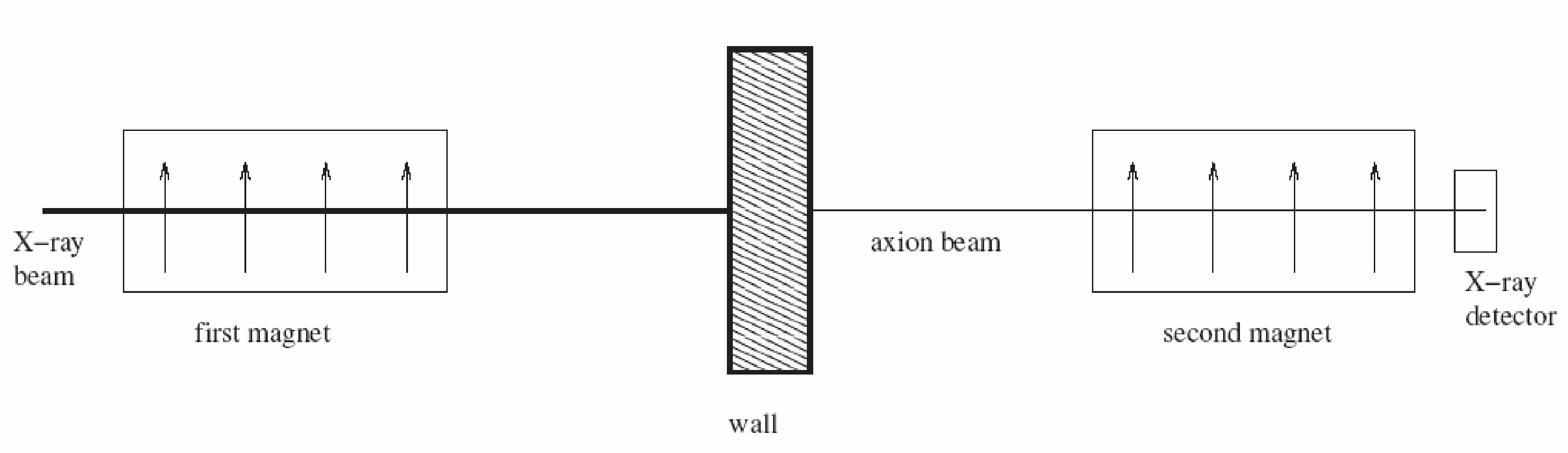
- We have to require enough number of events to have enough signal over background. The more precise is the detector for high energy photons the more reduced is the background.

- Summary figure of the limits:



Pseudocalars and X-ray lasers

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



P. Sikivie (1983), van Bibber et al. (1987) , Rinwald (2001, 2003)

- The probability of photon (with E parallel to background B) conversion into PS (gB/q<<1):

$$P = \frac{1}{4} g^2 B^2 L^2 j_0^2 \left(\frac{qL}{2} \right) = g^2 B^2 \frac{\sin^2 \left(\frac{qL}{2} \right)}{q^2}$$

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

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

- This formula comes from solving Maxwell eqns in a background magnetic field.
- To understand the previous formula:

$$P = \frac{(gB)^2}{q^2} \sin^2\left(\frac{qL}{2}\right)$$

mixing axion-photon
in B

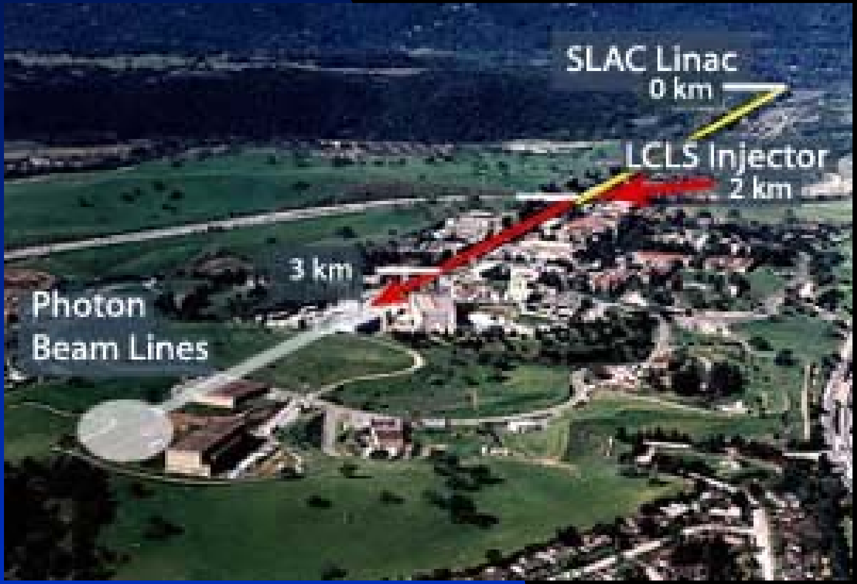
oscillation of the mode

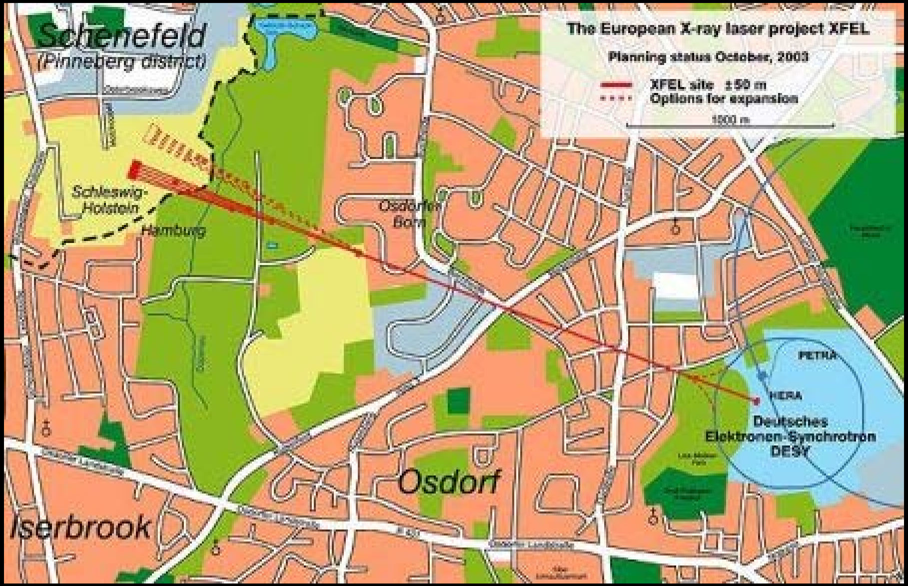
- To test the PVLAS result we would like to have high energy photons such that:

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

- What are the best photon sources for a regeneration experiment?
  - A lot of photons
  - With high energy

X-ray lasers!


SLAC Linac
0 km
LCLS Injector
2 km
3 km
Photon
Beam Lines


The European X-ray laser project XFEL
Planning status October, 2003
XFEL site ±50 m
Options for expansion
1500 m
Schenefeld
(Pinneberg district)
Schleswig-
Holstein
Hamburg
Osdorfer
Born
PETRA
HERA
Deutsches
Elektronen-Synchrotron
DESY
Osdorf
Iserbrook

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}.

- Let us take two superconducting magnets of
  - B ~ 10 T
  - L ~ 10 m

for the regeneration experiment.

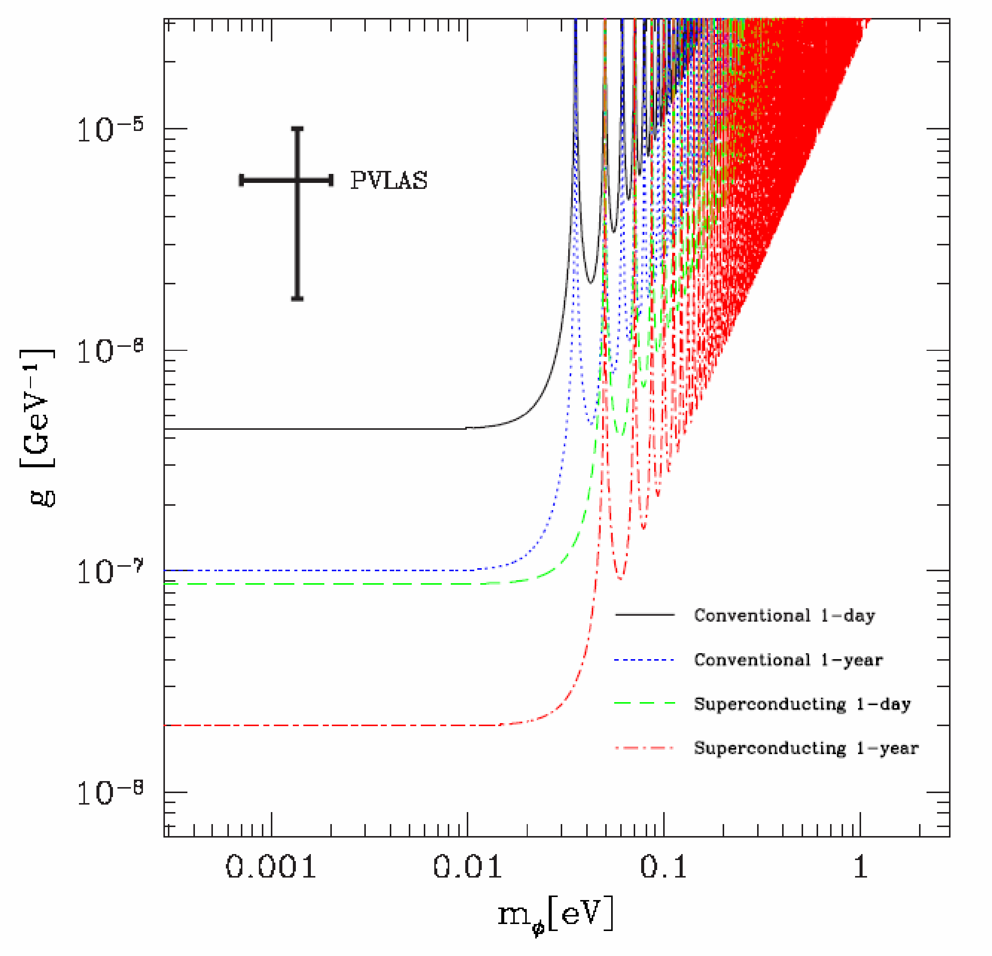
- The number of PS particles produced in the first magnet is:

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

- In the second magnet the number of photons reconverted from the PS beam is:

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

- In particular PVLAS can be tested in seconds!
- With conventional magnets (B~1T) it can be also checked but a little bit more time is needed.



- Interested features of this proposal:
  - PVLAS can be tested very quickly.
  - High frequency photons allows to test PS masses up to 50 meV without any PS light decoherent effect.
  - Superconducting magnets are not necessary.
  - It allows to perform other experiments at the same time.

- Already can be checked at TESLA Test Facility (UV, soft X-rays).

- Hard to go to small g. The probability goes like g^4.
- At HERA there will be a lot (~400) of superconducting magnets. An experiment can be performed to reach

$$g \sim 10^{-11}\ \mathrm{GeV}^{-1}$$

Ringwald (2001,2003)

CONCLUSIONS:

- We have propose two ways of testing the PVLAS result:
  - In electron-positron colliders:

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

  - With X-ray lasers by a photon regeneration experiment.