Axion search

in the photon regeneration experiment

Andrzej Hryczuk

Institute of Theoretical Physics
Warsaw University

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Outline of the talk

- Origin of axion
  - Strong CP-Problem
  - Peccei-Quinn symmetry
- How it can be detected?
  - Vacuum polarization
  - Photon regeneration
- Photon regeneration experiment at CERN
  - Experimental setup and its features
  - Estimated results
  - Possible upgrades
  - Background
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Strong CP-Problem

- The original QCD gauge grup possess an axial part $U(1)_A$ which together with P conservation would imply existance of hadronic parity dublets but they do not exist $\Rightarrow$ $U(1)_A$ has to be broken
- Anomaly of $U(1)_A$ breaking leads to unconserved axial current $\partial_\mu j_5 \neq 0$ unless to the Lagrangian we add a term

$$\mathcal{L}_\theta = \bar{\theta}\frac{g^2}{32\pi^2} G_a^{\mu\nu}\tilde{G}^a_{\mu\nu} \quad (1)$$

['t Hooft 1976]

- It conserves C but violates P and T so it contributes to the neutron dipole moment d_n
- Experimental limit

$$|d_n| < 12 \cdot 10^{-26}\, e\, cm, \quad (2)$$

[Ramsey 1990]

yields the limit

$$\bar{\theta} \leq 10^{-10}$$

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Peccei-Quinn symmetry

- Solution: let $\bar{\theta}$ become a dynamical variable by intoducing a new $U(1)_{PQ}$ symmetry

[Peccei, Quinn 1977]

- Spontaneous breaking of $U(1)_{PQ} \Rightarrow$ Pseudo-Goldstone boson $\rightarrow$ axion

[Weinberg 1978, Wilczek 1978]

- In invisible axion models it has very high breaking scale M
  - interactions are suppresed $g \propto \frac{1}{M}$
  - axion mass is small $m_a \propto \frac{1}{M}$
- It couples to two photons with a vertex

$$\mathcal{L}_{a\gamma\gamma} = \frac{g}{4} F_{\mu\nu} \tilde{F}^{\mu\nu} a = \frac{g}{4} \vec{E} \cdot \vec{B} a \qquad (3)$$

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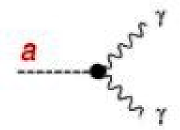

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1. Microwave Cavity Experiments

   [Sikivie 1983]

2. Optical, radio-telescope (also interferometric) searches
3. Solar axions $\rightarrow$ search for thermal axions produced in the Sun

   [eg. CAST Collaboration]

4. Polarization Experiments

   [Maiani *et al* 1986, eg. PVLAS]

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Experimental search for axions

Preview of five different approaches

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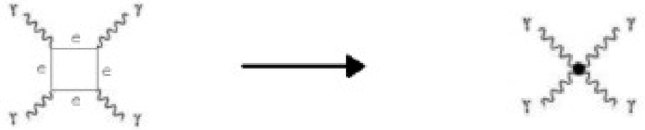
Our Proposal

Vacuum polarization in QED

Loop corrections in QED lead to vacuum polarization



$$\mathcal{L}_{QED} \longrightarrow \mathcal{L}_{EH}$$

The Euler-Heisenberg effective Lagrangian (expansion of Lorentz invariants to higher ordres)

$$\mathcal{L}_{EH} = \frac{e^4}{360\pi^2 m_e^4}\left[\frac{1}{4}\left(F_{\mu\nu}F^{\mu\nu}\right)^2 + \frac{7}{16}\left(F_{\mu\nu}\tilde{F}^{\mu\nu}\right)^2\right]$$

[Heisenberg, Euler 1936]

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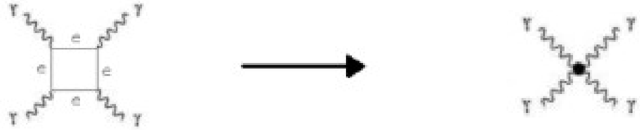

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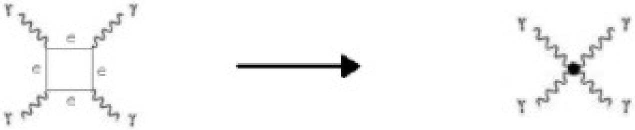

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Magnetic field in vacuum - QED

Presence of magnetic field makes vacuum to be birefringent. Using effective $\mathcal{L}_{EH}$ description the refractive indicies can be found

$$n_{\perp} = 1 + \frac{4}{2}\xi \sin^2\theta \qquad n_{\parallel} = 1 + \frac{7}{2}\xi \sin^2\theta$$

where

$$\xi \equiv (\alpha/45\pi)(Bm_e^2/e)^2$$

[Adler 1976]

It causes arrising of eliptical polarization of a laser beam propagating in magnetic field. Simliarly vacuum is also to be diachronic (from photon spliting diagram), which induces rotation of polarization plane. Effects are small but obtainable experimentaly!. This allow to test QED predictions even more precisely.

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If the axion exists...

Contribution of axion, if it existed, would lead to adding an interaction term to the $\mathcal{L}_{EH}$ of a form (3). It will enlarge the elipticity and rotation of polarization plane by

$$\theta \approx \frac{B^2 \ell^2 g^2}{256} \sin 2\phi \qquad \epsilon \approx \frac{B^2 \ell^3 g^2 m_a^2}{16 \cdot 96\omega} \sin 2\phi$$

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This is the theoretical basis of polarization experiments. The effect still shoud be reachable by experiment! And indeed some were already made.

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Photon regeneration - the basic idea

Axion can mix with photons (due to its two-photon vertex) $\rightarrow$ Primakoff effect.

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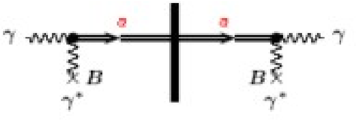

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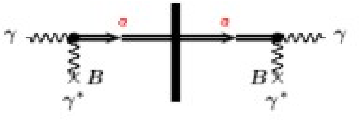

Placing an optical barrier will stop photons, but do no harm to axions → we should see a signal if they exist!

[Sikivie 1983, Ansel'm 1985, van Bibber *et al* 1987]

Photon regeneration - theory

Probability of $\gamma \leftrightarrow a$ (photon $\leftrightarrow$ axion) conversion

$$P(\gamma \leftrightarrow a) = \frac{1}{4} \frac{\omega g^2 B_0^2 \ell^2}{\sqrt{\omega^2 - m_a^2}} F^2(q) \tag{4}$$

The form-factor $F(q)$ depends on the geometry. By definition

$$F(q) = \int e^{-iqx} \frac{B(x)}{B_0 \ell} dx \tag{5}$$

For the rectangular shape of $B(x)$

$$F(q) = \frac{\sin(q\ell/2)}{q\ell/2} \tag{6}$$

which is $F \approx 1$ for $q\ell \ll 1 \rightarrow$ coherence region. In this regime the formula (**??**) simplifies to

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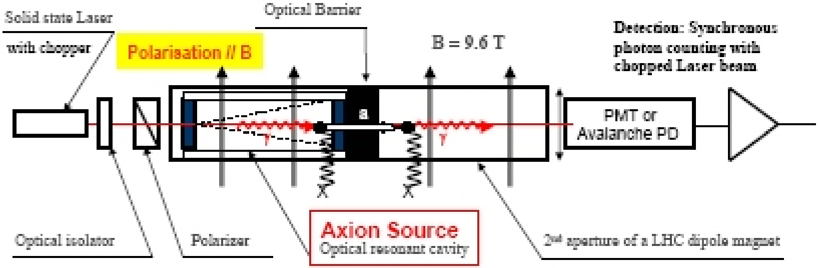
Experimental setup and its features (1)

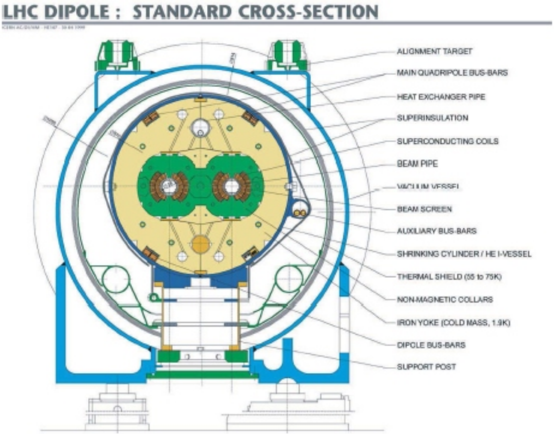
Scheme of a setup



- Nd-YAG Laser with optical power $P_L = 10 \div 1000\ W$
- $\lambda = 1064\ nm$
- Optical cavity of length $\ell = 7\ m$ and finesse $F = 10^4 \div 10^5$

Experimental setup and its features (2)

LHC Dipole Magnet



LHC Dipole

- Maximal field (at 1.9 K) 9, 76 T
- Coil aperture 56 mm
- Magnetic length 14.3 m

What are we going to measure?

For the normal case (without upgrades) the counting rate of an detector is:

$$CR = \eta \frac{P_L}{\omega} \frac{N}{2} P_{\gamma \to a} P_{a \to \gamma} = \eta \frac{N P_L}{2\omega} \frac{B_0^4 g^4}{q^4} \sin^4(q\ell/2) \tag{8}$$

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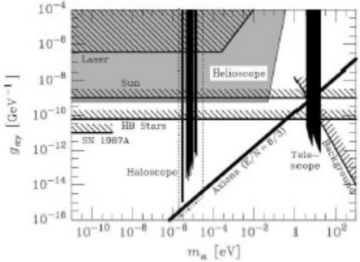
Assuming that with our detector we are able to detect a single photon, from (**??**) we obtain exculsion plots for the axion parameters g and m_a.

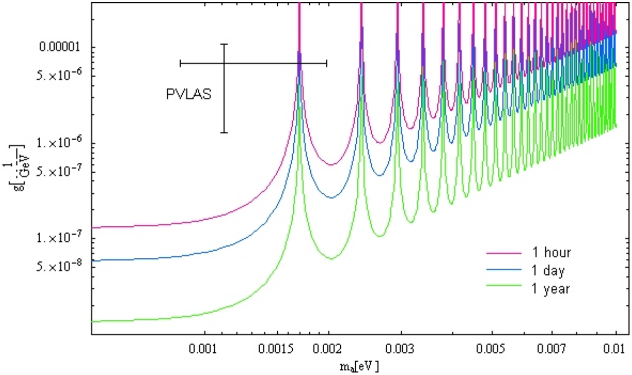


Exclusion plot comparing various axion experiments.

[Raffelt 1999]

Estimated results

Test phase



Parameters

- Magnetic field $B = 9\ T$
- Optical power $P_L = 1\ W$
- Number of reflections $N = 1000$
- Cavity length $\ell = 1\ m$

PVLAS results nearly **checked** even in the test phase! $\rightarrow$ using 0.5 m long cavity or 2 times bigger frequency will cover the whole PVLAS region

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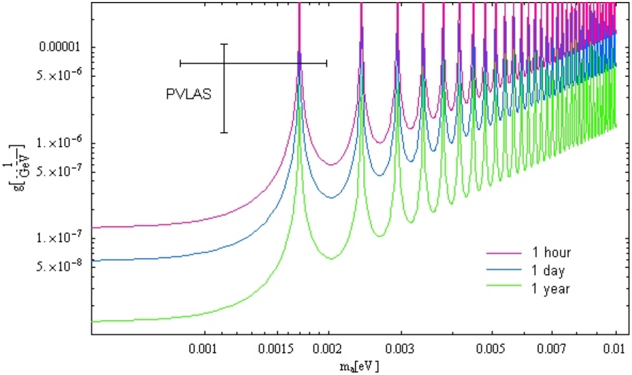

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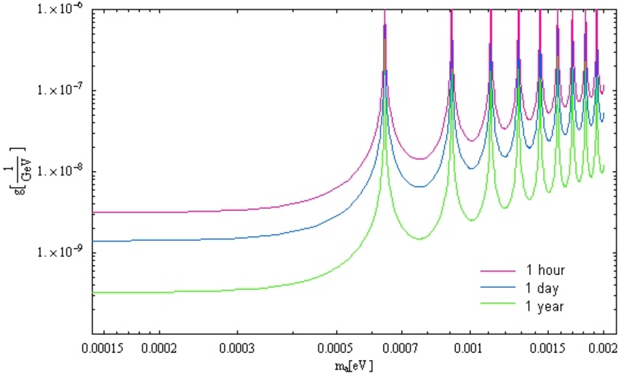
Base experiment phase



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- Number of reflections $N = 10^4$
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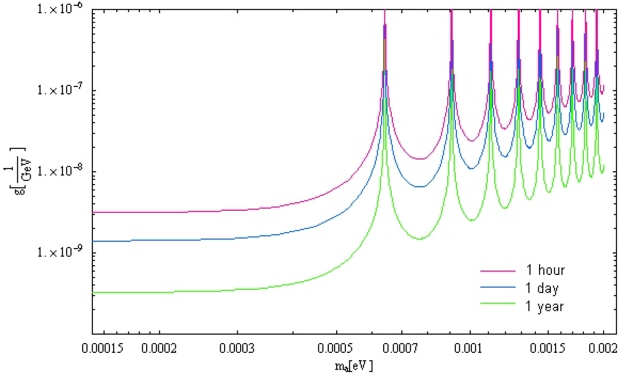

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Possible upgrades

Basicaly there are three ways to improve our system:

1. Upgrading the laser or cavity $\rightarrow$ very difficult technically
2. Using wigglers instead of LHC Dipole
3. Filling the magnet with buffer gas (ionized!)

The first one would broaden the limit for coupling g while the two others allow to probe also bigger axion masses (by extanding the coherence region).

Remainding: coherence means here that the form-factor $F \approx 1$. It can be achived by $q\ell \ll 1$ (gas) or using different geometry (wigglers)

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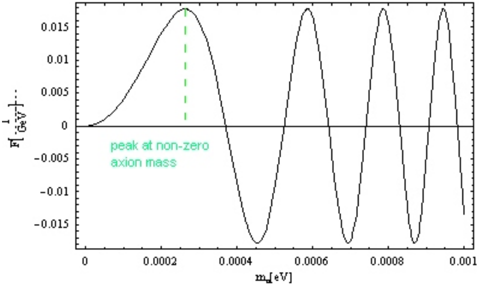
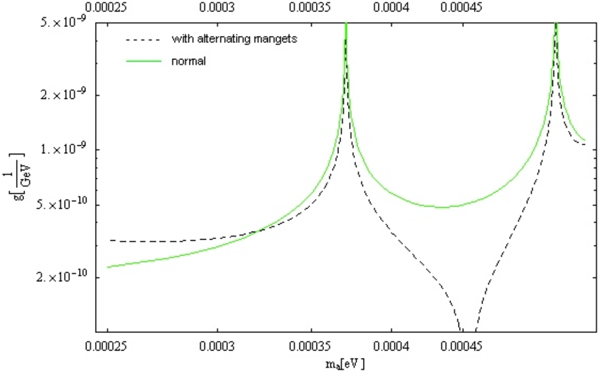
Wigglers

Wigglers are series of magnets with alternating polarity. If we consider N such magnets of summary length L we get the form factor

$$F(q) = \frac{\sin(qL/2)}{qL/2}\tan(qL/2N) \tag{9}$$

This form factor has a peak in **non-zero** value of axion mass





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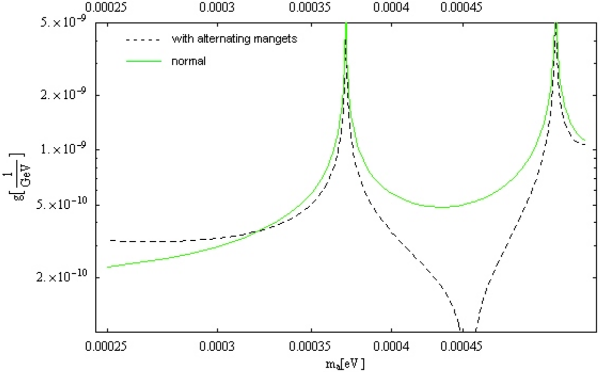
There is some gain in the axion mass but not too much...

Estimated results

Wigglers



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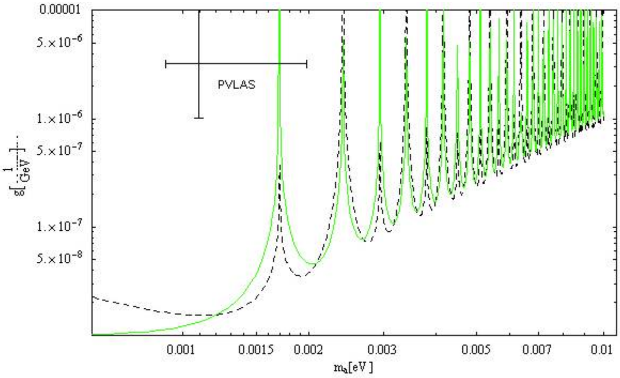

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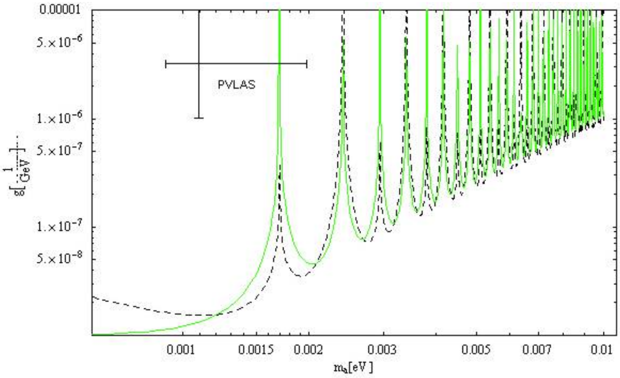
Wigglers in the test phase



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Buffer gas

The dispersion relation for photons in a ionized gas with plasma frequency ω_p

$$k_\omega = \omega\left(1 - \frac{\omega_p^2}{2\omega^2}\right)$$

From the other hand existence of gas do not influence the axion propagation, due to its very small couplings to matter. That is its momentum

$$k_a = \sqrt{\omega^2 - m_a^2} \approx \omega\left(1 - \frac{m_a^2}{2\omega^2}\right)$$

is the same as in vacuum. Now the momentum transfer to the magnet q differs from that in vacuum

$$q = \frac{m_a^2}{2\omega} - \frac{\omega_p^2}{2\omega}$$

The coherence condition yields

$$\ell\,|k_\omega - k_a| < \pi \quad \Rightarrow \quad \omega_p^2 - \frac{2\pi\omega}{\ell} < m_a^2 < \omega_p^2 + \frac{2\pi\omega}{\ell}$$

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Estimated results

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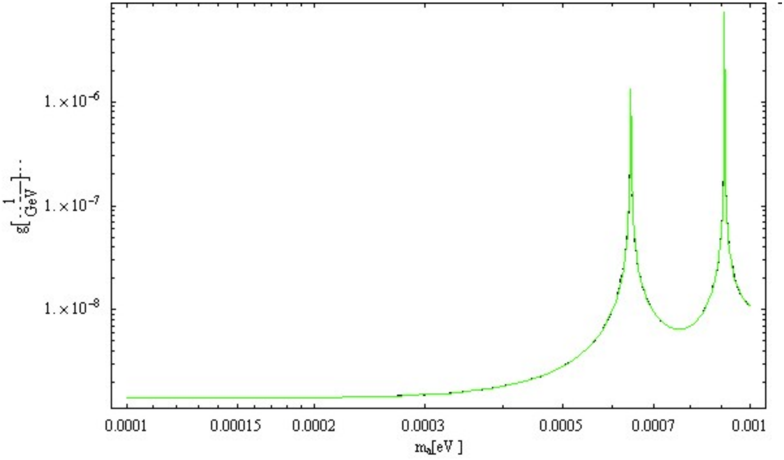

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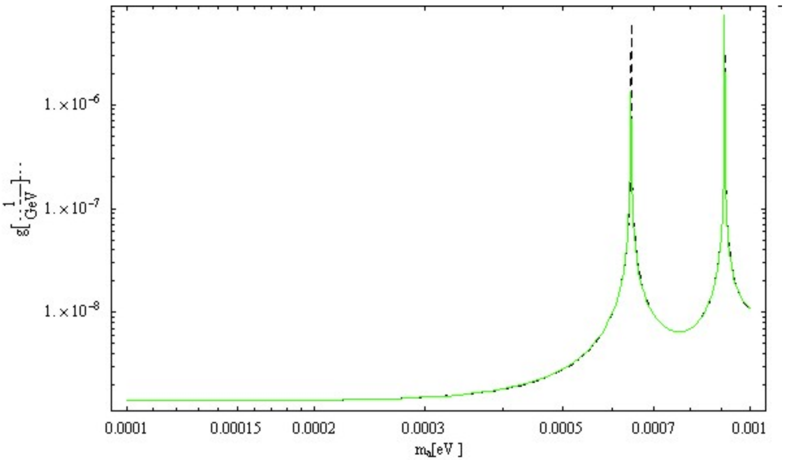

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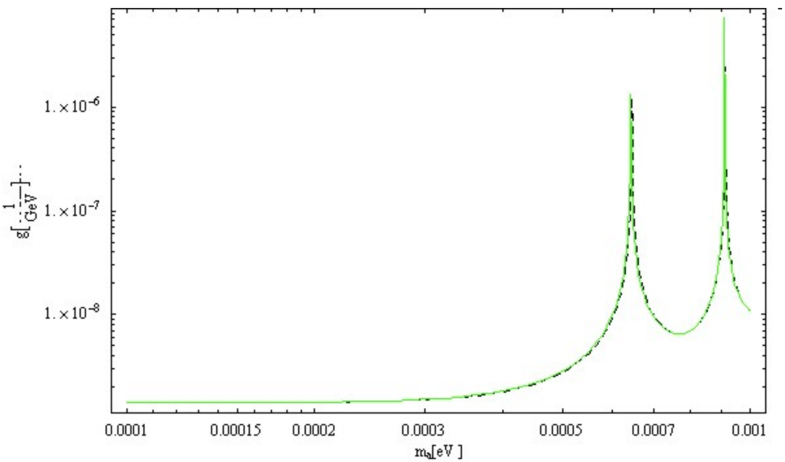

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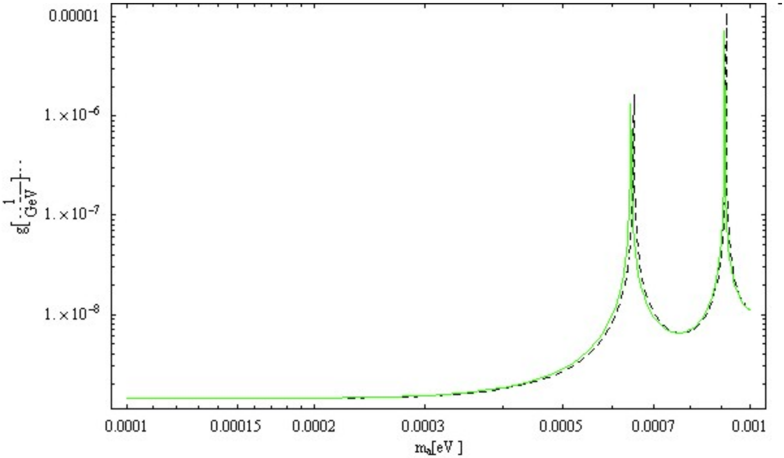

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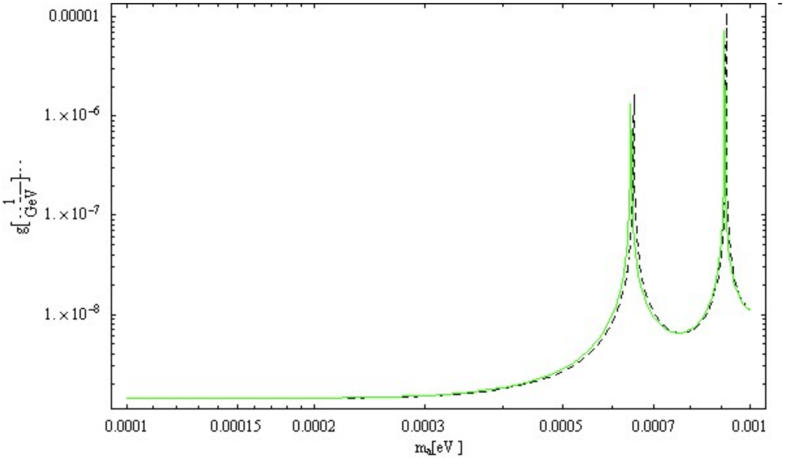

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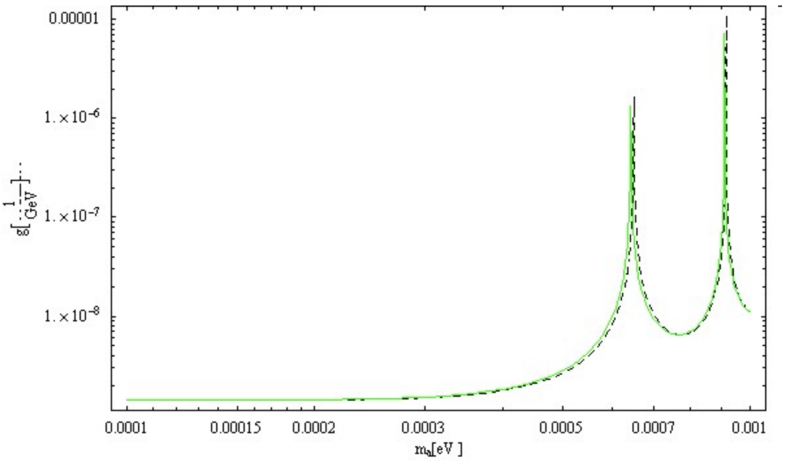

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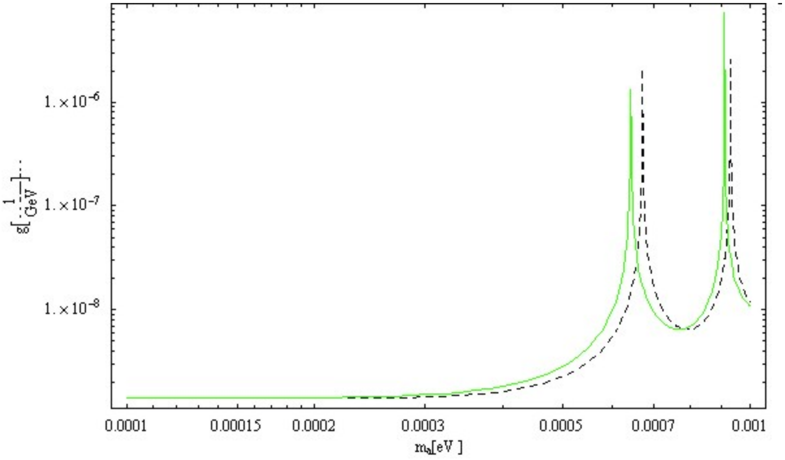

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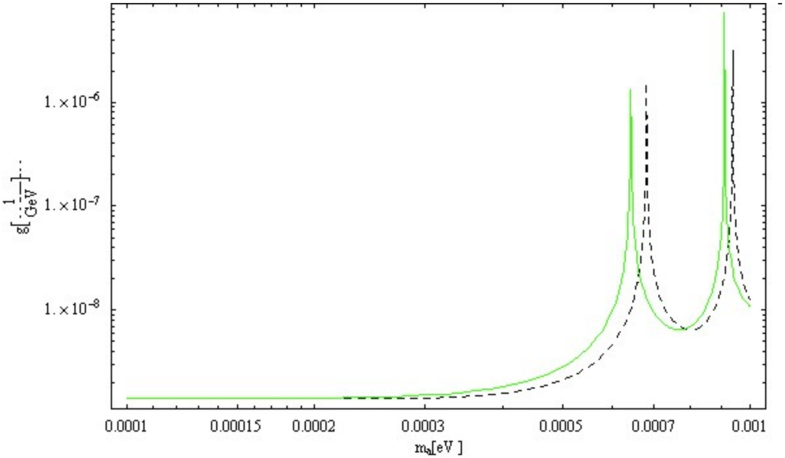

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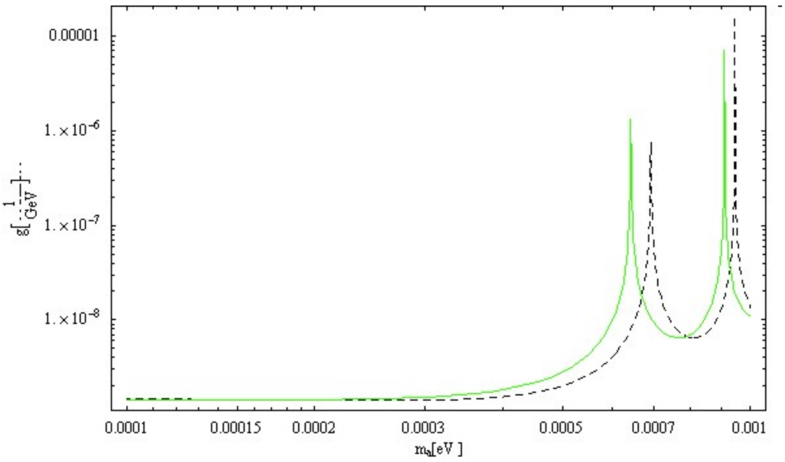

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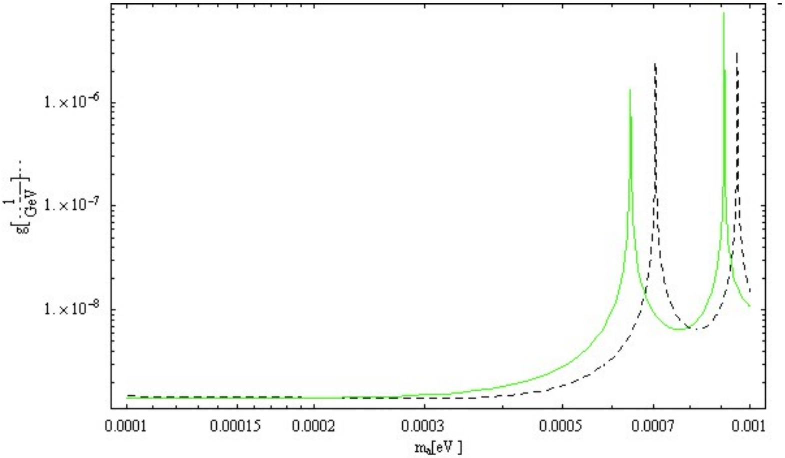

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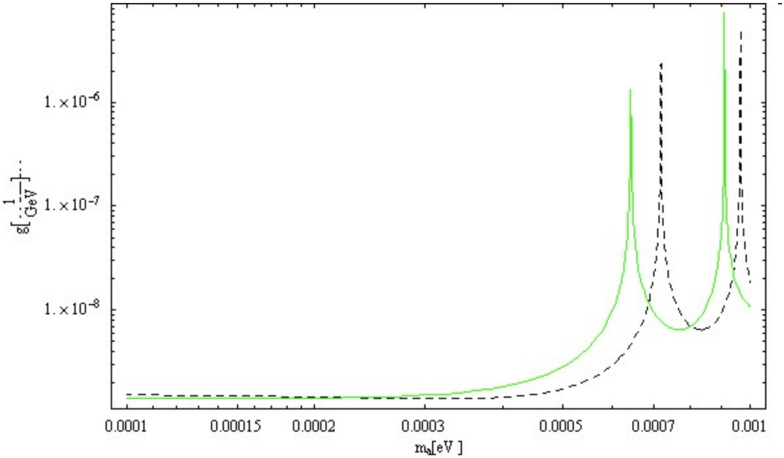

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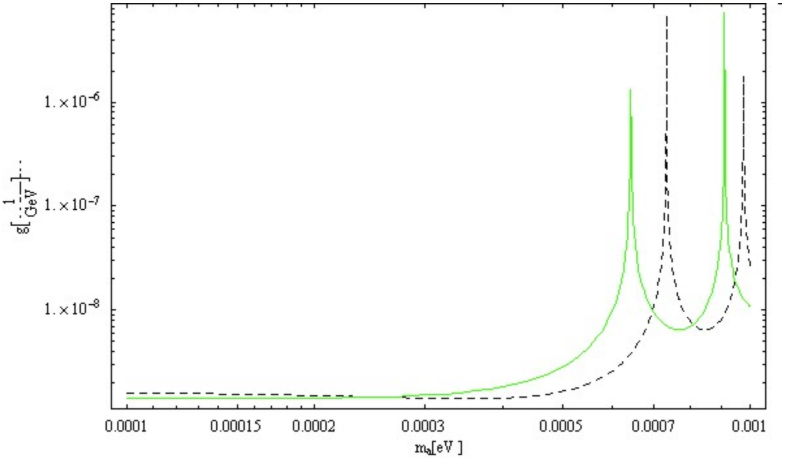

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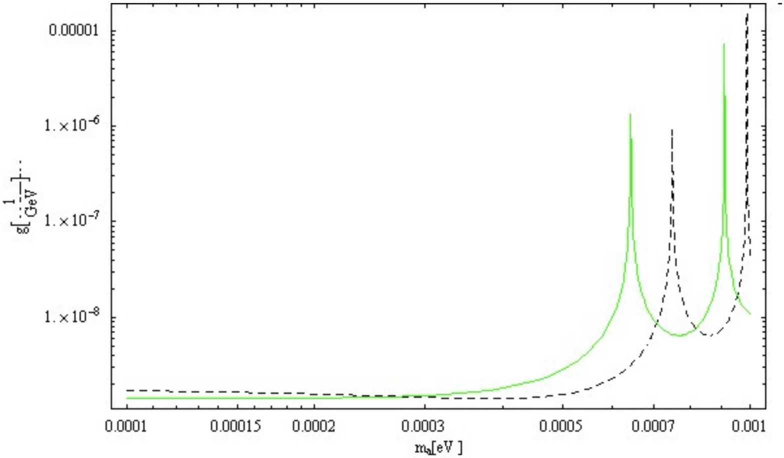

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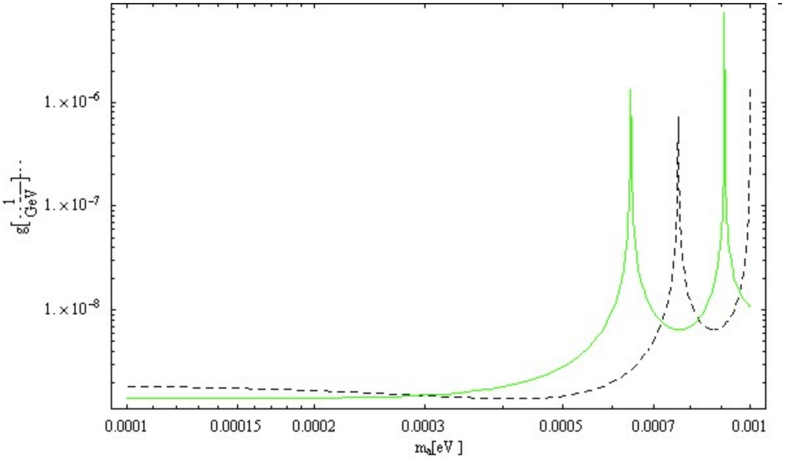

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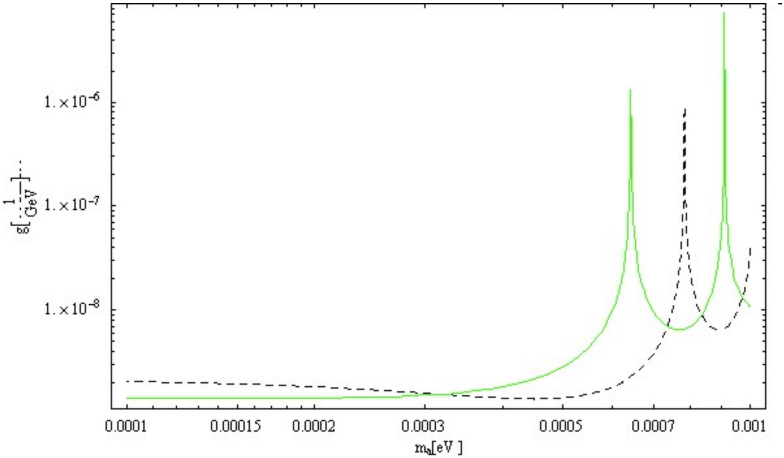

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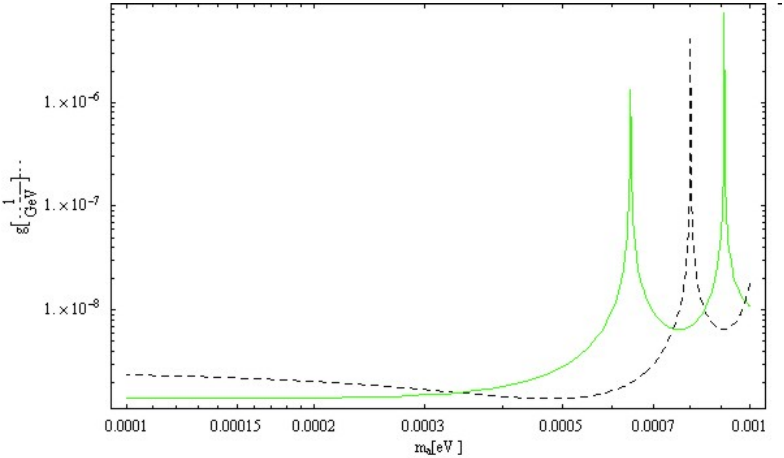

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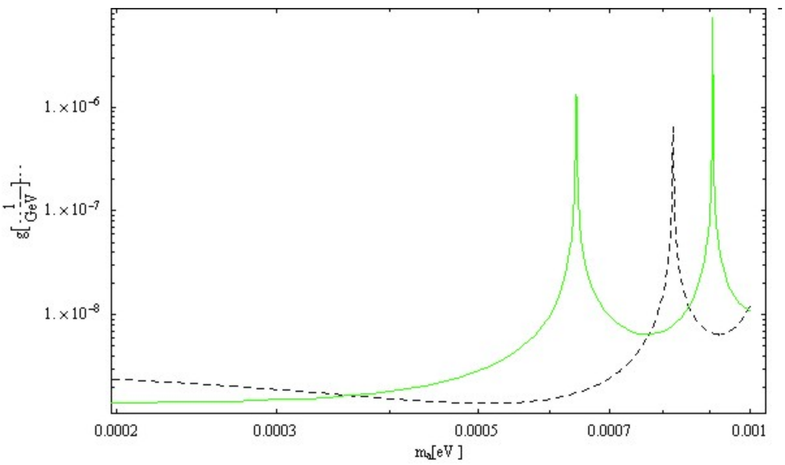

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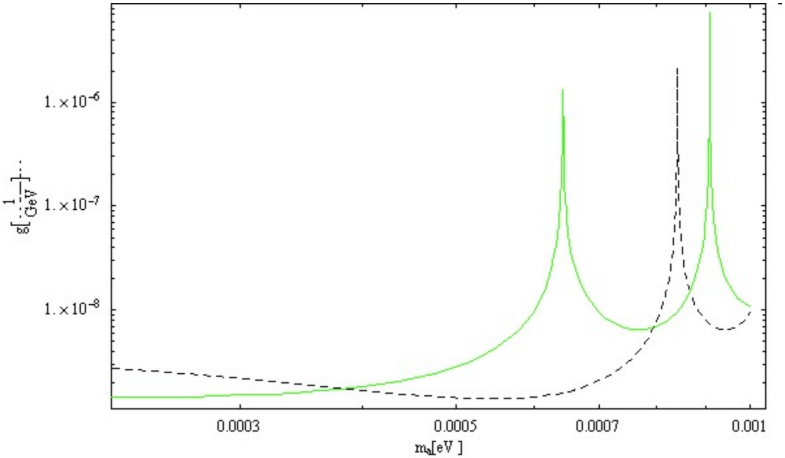

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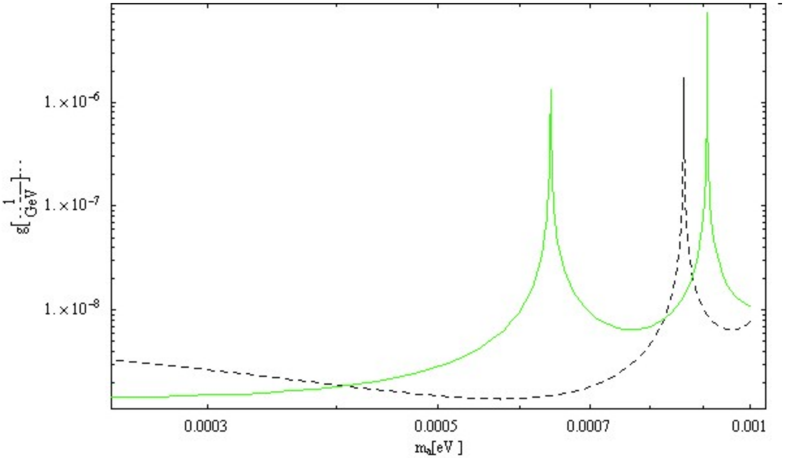

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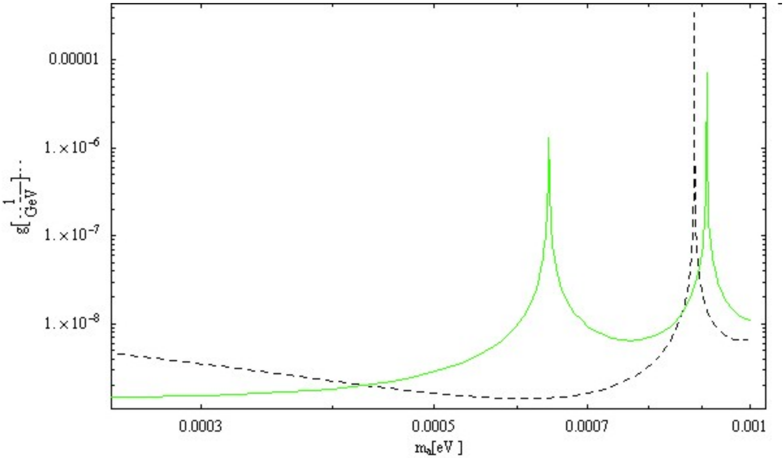

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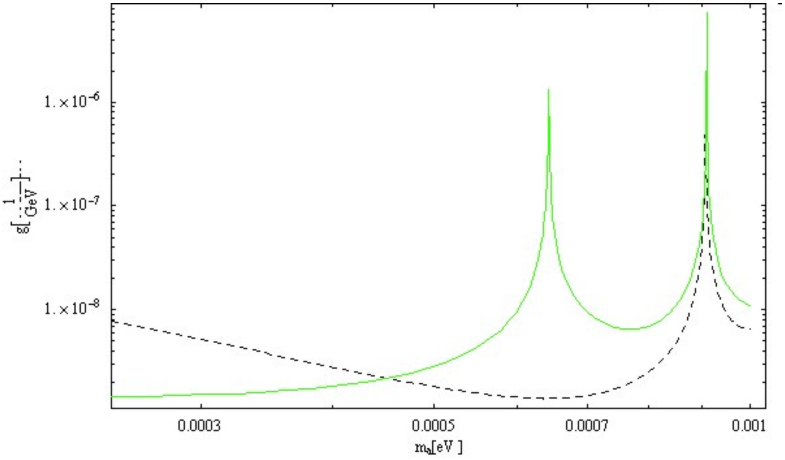
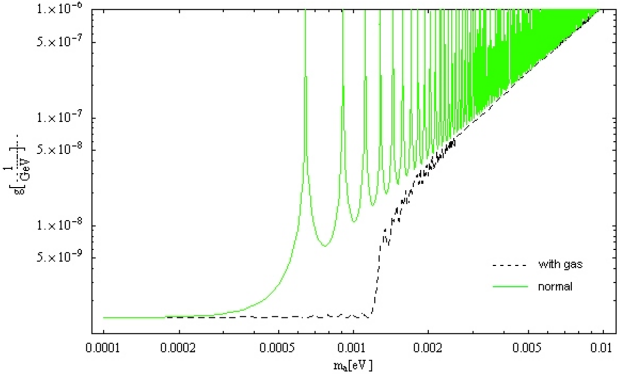


Once more?;)

Estimated results

Buffer gas - combined



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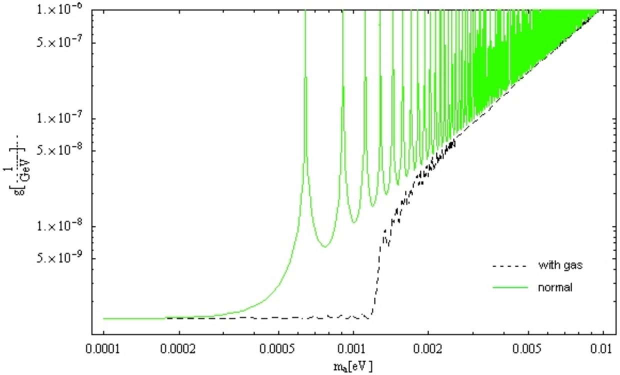
A really big improvement in axion mass can be achived - the coherence limit without gas was about 0.5 meV! The problem is to get a stable ionzied gas of such small density... ionize it by UV lamp?



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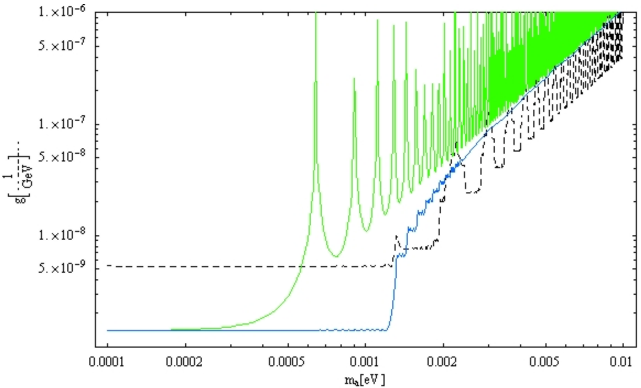
Buffer gas + wigglers



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An example of using additionaly alternating polarization of beam. It can give small improvement, especially if used many times for different N, but it makes the experiment last considerably longer...

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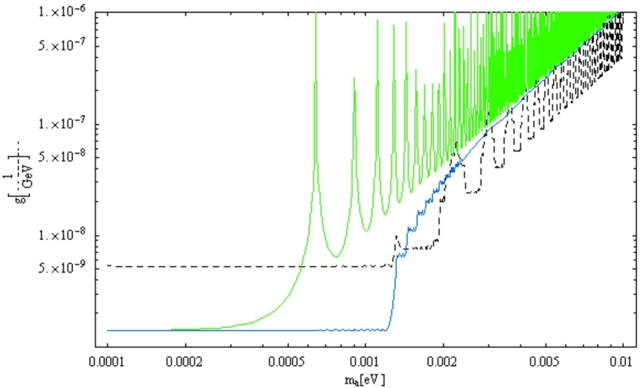

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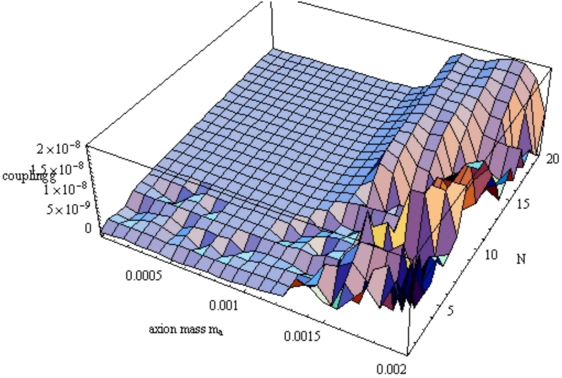
Buffer gas + wigglers for different N



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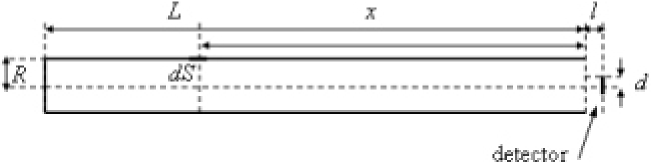
Background and noise

As was said, we want to have possibility to detect a single photon. To reach this the level of background should be not more than several photons per the duration of experiment. There can be different couses of background but the most important one is the thermal radiation of walls.



Assuming the blackbody radiation, estimation of background photons is given by formula

$$n_\nu(\nu, T) = \frac{2}{c^2}\frac{\nu^2}{e^{h\nu/kT}-1}\left(\frac{\pi R^2 d^2}{4(L+l)^2} + 4\pi^2 R\int_0^L dx\left(1-\cos\left(\frac{1}{2}\left[arctg\left(\frac{R+d}{x+l}\right) - arctg\left(\frac{R-d}{x+l}\right)\right]\right)\right)\right)$$

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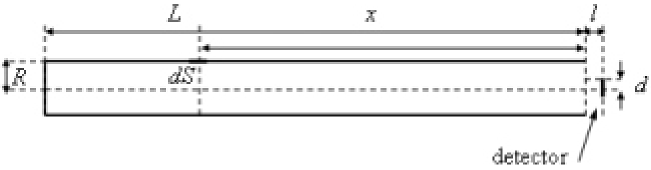

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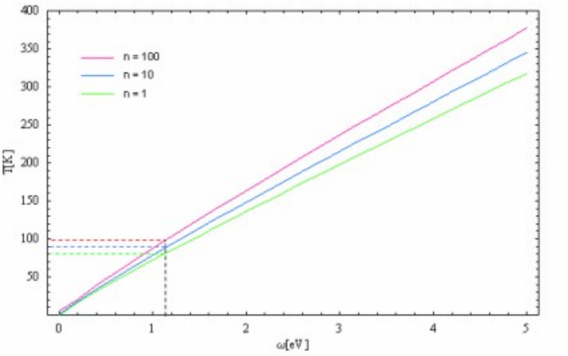

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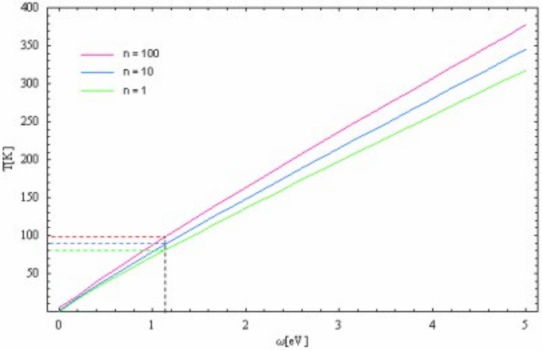

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Outline of the talk

- Origin of axion
  - Strong CP-Problem
  - Peccei-Quinn symmetry
- How it can be detected?
  - Vacuum polarization
  - Photon regeneration
- Photon regeneration experiment at CERN
  - Experimental setup and its features
  - Estimated results
  - Possible upgrades
  - Background
- Conclusions

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- To have some improvement gas buffer could be used, **but** only if a efficient method of ionzation is found
- Using wigglers will bring very small improvement, but still, and if an easy method of implementation is found $\rightarrow$ it can be worth it
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- Our proposition of photon regeneration experiment will easily allow to check PVLAS results
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Appendix
Blackbody radiation