Photon-axion mixing

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Sangam@HRI

HRI, Allahabad, March 25-30, 2013

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- R.D. Peccei, hep-ph/0607268
- M. Dine, hep-ph/0011376 (TASI Lectures)
- P. Sikivie, astro-ph/0610440
- F.D. Steffen, arXiv:0811.3347
- G. Raffelt, Stars as Laboratories for Fundamental Physics

Neutral ultra-light spin-0 bosons

Neutral scalar/pseudoscalar particles can have gauge invariant couplings with photons:

$$L_S = -\frac{1}{4\Lambda_S} F_{\mu\nu} F^{\mu\nu} \phi_S$$

$$L_P = -\frac{1}{4\Lambda_P} F_{\mu\nu} \tilde{F}^{\mu\nu} \phi_P$$

$\Lambda \rightarrow$ effective scale of mass dimension

- $F_{\mu\nu} \rightarrow$ EM field strength
- $\tilde{F}^{\mu\nu} = \epsilon^{\mu\nu\alpha\beta} F_{\alpha\beta}$

Known examples are

Light: axion

- pseudo-scalar particle
- pseudo-goldstone boson of Peccei-Quinn symmetry

(solve the strong-CP problem in QCD)

- mass expected in the range of $m \sim \mathcal{O}(\mathrm{meV})$

Heavy: Higgs boson

- scalar particle
- necessary to provide all masses in the SM

- mass expected in the range of $m \sim$ 122–129 GeV
- Coupling $H - \gamma - \gamma$ generated at one-loop

(Tao Han's Lectures)

$U(1)_A$ problem

- QCD Lagrangian possesses a global symmetry $G = U(f)_R \times U(f)_L$ in the limit $m_f \to 0$

- Regarding the u and d quarks, the theory shows a symmetry $U(2)_L \times U(2)_R$

- Vectorial part of this symmetry $U(2)_{L+R}$ (and its subgroup $U(1)_V = U(1)_{L+R}$) is an exact symmetry

- Axial part ($U(2)_A = U(2)_{L-R}$) is not preserved by the QCD vacuum

- Four Goldstone bosons are expected. π^-, π^0, π^+ corresponds to $SU(2)_A$ breaking. The expected fourth boson related to the $U(1)_A$ breaking does not exist

- This is the $U(1)_A$ problem

Solution to $U(1)_A$ problem - Θ vacuum

- $U(1)_A$ has a chiral anomaly and that the ground state of QCD is non-trivial

- In fact, the QCD vacuum has infinitely degenerate vacua, topologically different

- Instantons describe a solution, localized in space and time, in which a vacuum of class n-1 evolves into another vacuum, of class n

The superposition of the various vacua is called the Θ vacuum

$$|\Theta\rangle = \sum_n e^{-in\Theta}|n\rangle$$

Solution to $U(1)_A$ problem - Θ vacuum

- At the same time, considering the effect of the chiral anomaly of the $U(1)_A$ symmetry, an extra term is added to the Lagrangian

$$\mathcal{L}_{QCD}^{eff} = \mathcal{L}_{QCD} + \Theta \frac{g^2}{32\pi} G_a^{\mu\nu} \tilde{G}_{a\mu\nu}$$

- Including the electroweak interactions

$$\mathcal{L}_{SM}^{eff} = \mathcal{L}_{SM} + \bar{\Theta} \frac{g^2}{32\pi} G_a^{\mu\nu} \tilde{G}_{a\mu\nu}$$

$$\bar{\Theta} = \Theta + Arg(detM)$$

- Because of the non-trivial properties of the Θ-vacuum, and the axial anomaly of $U(1)_A$ it was shown that $U(1)_A$ is not a quantum symmetry of QCD, and therefore no Nambu-Goldstone boson is expected

The strong CP problem

- The presence of $\bar{\Theta}$ implies violation of the CP invariance in QCD - has never been observed

- The EDM of neutron has a strong experimental bound $|d_n| \leq 12 \times 10^{-26}$e-cm

- However, $d_n \sim 10^{-16}\bar{\Theta}$ e-cm

$$\Longrightarrow \bar{\Theta} < 10^{-9}$$

- Extreme fine-tuning of Θ to the value of $Arg(detM)$

- The question of the smallness of $\bar{\Theta}$, is known as “the Strong-CP problem".

A solution to the strong CP problem

- An elegant answer to this problem was by Peccei and Quinn

- Extension of the SM with an additional, spontaneously broken, global chiral $U(1)$ symmetry (the $U(1)_{PQ}$)

- Broken spontaneously at the PQ scale f_a

- Corresponding pseudo-Nambu-Goldstone boson is the axion

Couples to gluons such that the chiral anomaly in the $U(1)_{PQ}$ current is reproduced

$$\mathcal{L}_{agg} = \frac{a}{f_a/N} \frac{g_s^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$

A solution to the strong CP problem

$$\mathcal{L}_{agg} = \frac{a}{f_a/N}\frac{g_s^2}{32\pi^2}G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

$$\mathcal{L}_\Theta = \bar{\Theta}\frac{g^2}{32\pi}G_a^{\mu\nu}\tilde{G}_{a\mu\nu}$$

- provide axion field with an effective potential V_{eff}
- Coefficient of the CP violating $G\tilde{G}$ term becomes dynamical

vanishes for the value $\langle a\rangle = -\bar{\Theta} f_a/N$ at which V_{eff} has its minimum

Solves the strong CP problem

Axion mass

- Axion receives a mass from their interactions with gluons
- Induces transitions to $q\bar{q}$ states and thus to neutral pions
- a and π^0 mix with each other

Axions pick up a small mass: $m_a f_a \approx m_\pi f_\pi$

$$m_a^2 = \frac{m_u m_d}{(m_u + m_d)^2} \left(\frac{f_\pi m_\pi}{f_a/N} \right)$$

Using $z = m_u/m_d$,

$$m_a = \frac{\sqrt{z}}{1+z} \left(\frac{f_\pi m_\pi}{f_a/N} \right)$$

Original PQ proposal assumed f_a to be at the weak scale

- Axion searches, astrophysical observations, and cosmological arguments points to

$$f_a/N \gtrsim 6 \times 10^8 \text{ GeV}$$

Accordingly, the axion has a very weak coupling

Its mass must be very small

$$m_a \lesssim 0.01 \text{ eV}$$

- Extremely weakly interacting particle (EWIP)

Axion Models

- Axion interactions are model dependent

- Two most popular classes of phenomenologically viable "invisible axion" models

Hadronic or Kim-Shifman-Vainshtein-Zakharov (KSVZ) model

Dine-Fischler-Srednicki-Zhitnitskii (DFSZ) model

- KSVZ type: at least on additional heavy quark is introduced which couples directly to the axion

- All other fields do not carry PQ charge

- Axion interacts with ordinary matter through the anomaly term from loops of this new heavy quark

Axion Models contd.

- Integrating out heavy quark loops, one obtains the effective dimension-5 coupling of axions to gluons

- Couplings of the axion to SM matter fields are suppressed by additional loop factors

- In DFSZ scheme, no additional heavy quarks are introduced

- SM matter fields and at least two Higgs doublets carry appropriate PQ charges

- At low energies the axion-gluon interaction arises

- Axions with $f_a \sim 10^{16}$ GeV appear also in string theory

Axion couplings to photons

- Mixing with π^0 generates couplings of the axions to photons

$$\mathcal{L}_{a\gamma\gamma} = \frac{1}{4\Lambda} a F_{\mu\nu} \tilde{F}^{\mu\nu} \equiv \frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

$$g_{a\gamma\gamma} = \frac{\alpha}{2\pi} \frac{1+z}{\sqrt{z}} \frac{m_a}{f_\pi m_\pi} \left(\frac{E}{N} - \frac{2}{3} . \frac{4+z}{1+z} \right)$$

$$\tau_a = \Gamma^{-1}_{a\to\gamma\gamma} = \frac{64\pi}{g^2_{a\gamma\gamma} m_a^3}$$

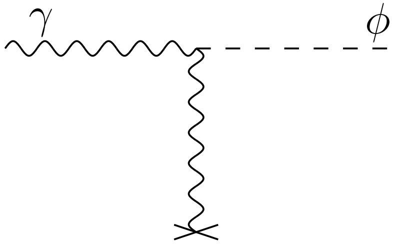
$$\simeq 4.6 \times 10^{40}\,\mathrm{s} \left(\tfrac{E}{N} - 1.95 \right)^{-2} \left(\frac{f_a/N}{10^{10}\,\mathrm{GeV}} \right)^5$$

→ almost stable particle on cosmic time scale

Effects of spin-0-$\gamma - \gamma$ couplings on photon propagation

- replacing $\gamma - \gamma - a \to \langle B \rangle \gamma a$ gives a mixing term in the photon-spin-0 system

- the photon → spin-0 conversion is possible in external EM field (Primakof effect)



- it could generate photon ↔ spin-0 oscillations for photons propagating in magnetic fields

G. Raffelt, L. Stodolsky, PRD 37, 1237 (1988)

Astrophysical Constraints

- Axions can be produced in hot and dense astrophysical environments: ordinary stars, white dwarfs, and supernovae

- Axion luminosity L_a depnds on f_a, the relevant axion production process, astrophysical model of the source

- A sizeable L_a is associated with additional energy transport out of the source

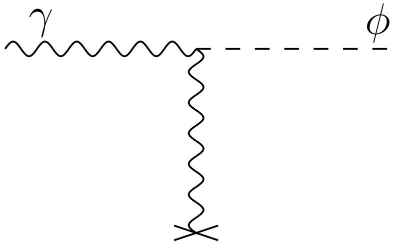
- Affect the behaviour of the source strongly

- Astrophysical studies of stars, white dwarfs, and supernovae can be used to derive constraints on f_a/N or m_a

Astrophysical Constraints

- In stars including our sun, axions can be produced through the Primakoff process

$\gamma + Ze \to Ze + a$



- Axionic energy drain ($L_a \propto g_{a\gamma\gamma}^2$) leads to an enhanced consumption of nuclear fuel within the star

- Shorten the lifetime of a star

- Globular clusters (GCs) are bound systems of a homogeneous population of low mass stars

Allow for tests of stellar evolution theory

$\Longrightarrow g_{a\gamma\gamma} \lesssim 10^{-10}\ \mathrm{GeV}^{-1}$

Photon-axion oscillation

$$\mathcal{L}_{a\gamma\gamma} = \frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu} = g_{a\gamma\gamma} a \vec{E}.\vec{B}$$

- Induces a mixing between the photon and the axion in the presence of a background magnetic field

Photon polarization with electric field parallel (||) to the external $\vec{B}$ mixes with the axion

$$\left[\omega^2 + \partial_z^2 + 2\omega^2 \begin{pmatrix} 0 & g_{a\gamma} B/2\omega \\ g_{a\gamma} B/2\omega & -m_a^2/2\omega^2 \end{pmatrix}\right] \begin{pmatrix} A_{||} \\ a \end{pmatrix} = 0$$

Represents 2×2 mixing problem

$$P_{a\to\gamma} = \sin^2(2\theta) \sin^2(\tfrac{1}{2} k x); \quad k = 2\pi / L_{Osc}$$

$$\tan(2\theta) = \frac{g_{a\gamma} B\omega}{m_a^2}$$

Photon-axion oscillation

- One possible explanation of the dimming of the type-Ia supernovae

$$P_1 = \frac{\mu^2}{k^2}\sin^2\left(\frac{kx}{2}\right) = \frac{(\mu x)^2}{4}\left(\frac{\sin(kx/2)}{kx/2}\right)^2 ,$$

x: the distance traveled by the photon,

$$\mu = \frac{B}{M} ,$$

When the magnetic field is not constant, the total photon-axion oscillation probability over many magnetic domain is

$$P_{\gamma\to a} = \frac{1}{3}(1 - e^{-y/L_{decay}})$$

$$y = NL_{\rm dom} \qquad L_{\rm decay} = \frac{2L_{\rm dom}}{3P_1}$$

C. Csáki, N. Kaloper, J.Terning, PRL **88**, 161302 (2002); Y. Grossman, SR, and J. Zupan, PL **B543**, 23 (2002)

Solar axion searches

- Most important and strongest astrophysical source for axions is the core of the Sun
- Axions would be continuously produced in the magnetic and electric field of the plasma via the 2-photon coupling
- After production freely stream out of the Sun

Differential solar axion flux on Earth

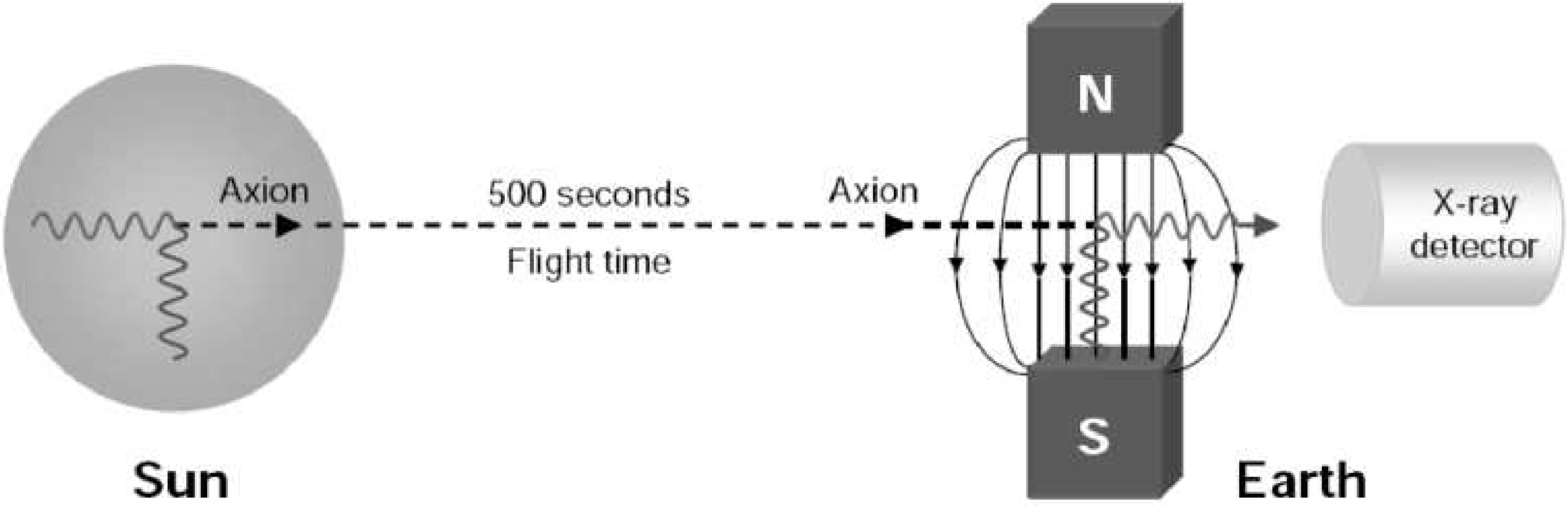
$$\frac{d\Phi_a}{dE} = 6.02 \times 10^{10}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{keV}^{-1} g_{10}^2\, E^{2.481} e^{-E/1.205}$$

$$(g_{10} = g_{a\gamma\gamma}/10^{-10}\,\mathrm{GeV}^{-1})$$

- Spectral energy distribution of the axions peaks at ≈ 3 keV

Solar axion searches

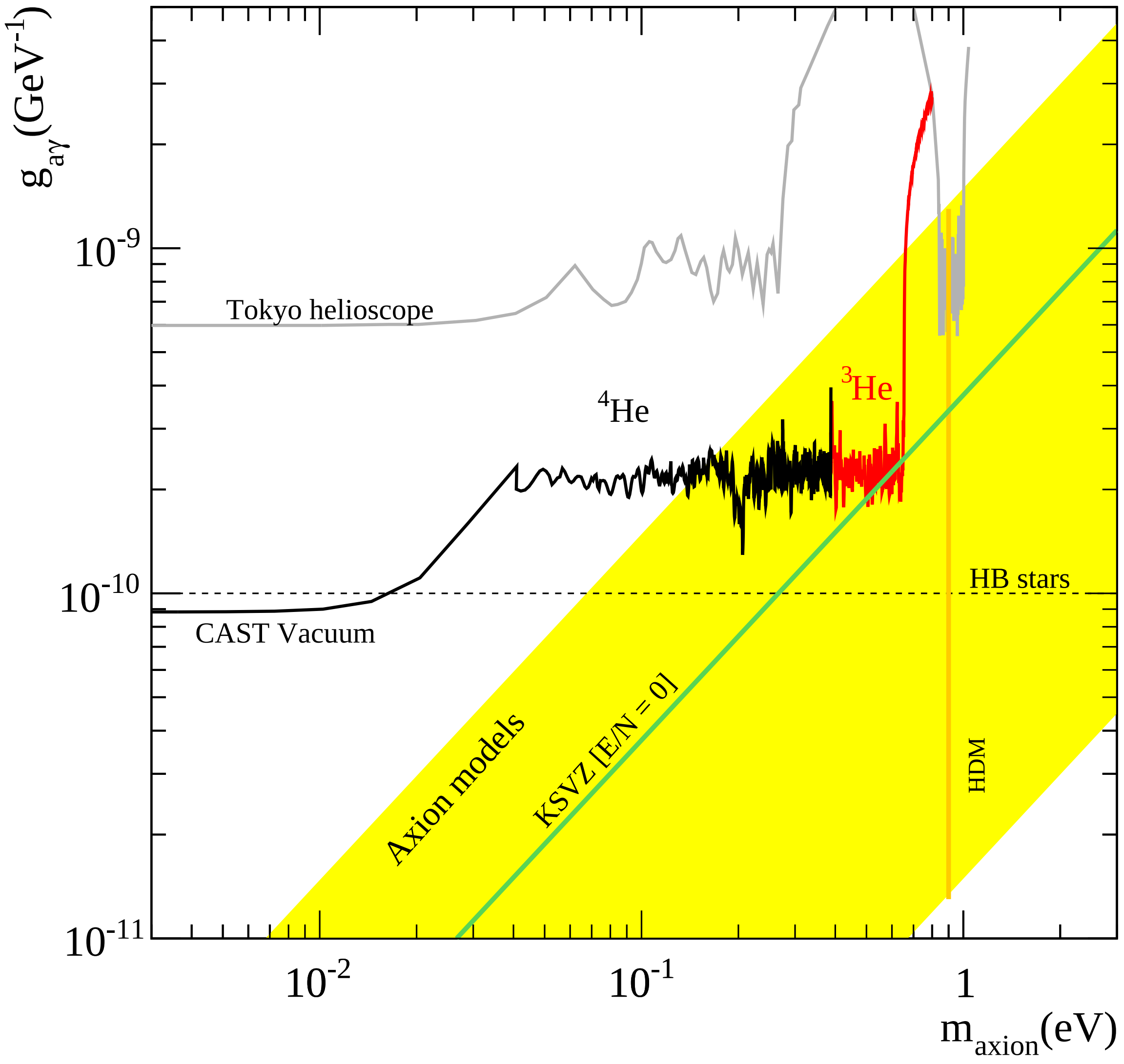
- Most sensitive axion experiments at present in the mass range $10^{-5}\,\mathrm{eV} \lesssim m_a \lesssim 1\,\mathrm{eV}$ are “axion helioscopes" i.e. magnetic solar telescopes



$$P_{a\to\gamma} = \left(\frac{Bg_{a\gamma\gamma}}{2}\right)^2 2L^2\,\frac{1-\cos(qL)}{(qL)^2}$$
$$q = m_a^2/2E_\gamma$$

$qL < 1 \Longrightarrow$ sensitivity is limited to a specific axion mass range

Solar axion search



Ultra-light spin-0 particle

mass, coupling and parity of ultra-light spin-0 particle can be determined from measurement of vacuum birefringence and dichroism

L. Maiani, R. Petronzio, E. Zavattini, PLB 175, 359 (1986)

- the birefringence can induce ellipticity on a linearly polarized Laser beam in external field

R. Cameron et al. [BFRT collab.] PRD 47, 3707 (1993)

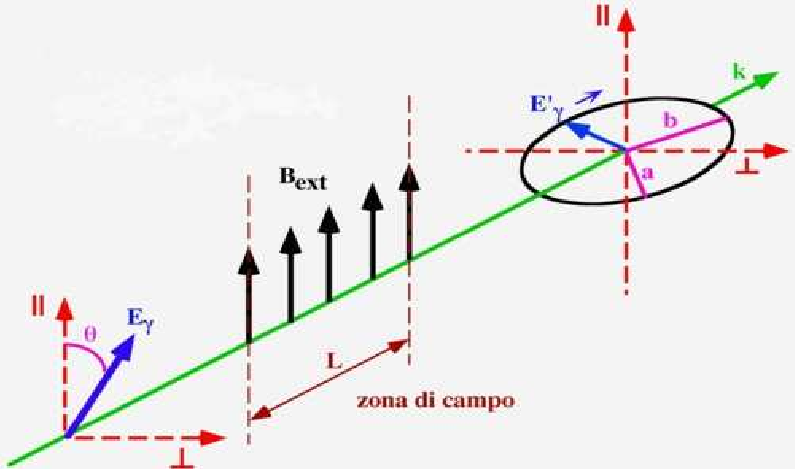
- PVLAS collaboration (2005) measured a large value for the ellipticity

E. Zavattini et al., PRL 96, 110406 (2006)

- too large for QED! New physics effect ?
- if interpreted in terms of light axion implies an axion mass $m \sim 10^{-3}$ eV and $\Lambda \sim 10^{6}$ GeV

A method to measure vacuum birefringence

E. Iacopini and E. Zavattini, PLB 8, 151 (1979)

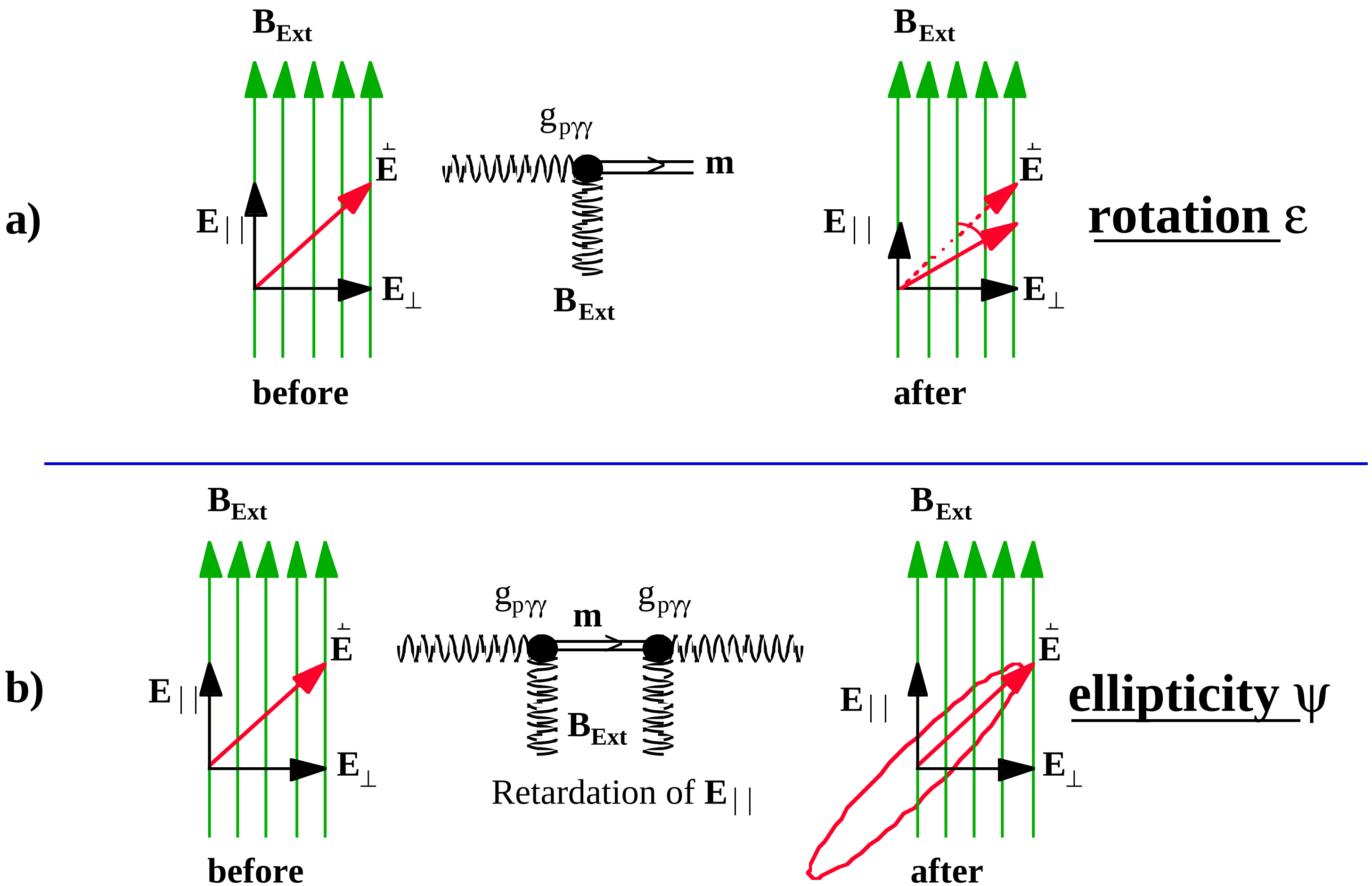


- different polarization vectors will propagate with different phase velocities → different refractive indices

- linear polarization → eliptical polarization out of B. Ellipticity ψ induced by birefringence

$$\psi = \pi \frac{L}{\lambda}(n_\parallel - n_\perp)$$

Rotation and Ellipticity



Rotation and Ellipticity

Birefringence and linear dichroism of the vacuum are characterized by

$$\mathcal{E} \approx N \, \frac{B^2 L^3 m_A^2}{96 \omega M^2} \, \sin(2\theta)$$

$$\Theta \approx N \, \frac{B^2 L^2}{16 \; M^2} \, \sin(2\theta)$$

$(m_A^2 L / 4\omega \ll 1)$.

m_A is the axion mass, $M = 1/g_{a\gamma\gamma}$ the inverse coupling constant to two photons

ω the photon energy, L and N the effective path lengths and the number of paths the light travels

QED contribution to the ellipticity

The QED contribution to the ellipticity can be written as

$$\mathcal{E} = N\frac{B_0^2 \ell \alpha^2 \omega}{15 m_e^4}$$

- ω is the photon energy and m_e the electron mass

W. Heisenberg and H. Euler, Z. Phys. **98**, 714 (1936)

- Polarization vector of the initially linearly polarized beam makes an angle 45° with the direction of the external magnetic field

Take a laser beam with

- wavelength λ = 1550 nm
- B_0 = 9.5 T and $N\ell$ = 25 km

Resulting ellipticity is 2×10^{-11}

Laser experiments

- Purely laboratory based experimental search for ultra-light (pseudo)scalar particles

- Possible to make accurate measurements on the modification of the polarization state of a light beam

- A laser beam is reflected back and forth N times between two mirrors, in a constant magnetic field orthogonal to the beam direction

Total length travelled by the laser beam in magnetic field $L = N\ell \sim$ a few km

Laser beam is linearly polarized to start with and after traversing L, it is possible to measure very small ellipticity and change in the rotation of the polarization plane

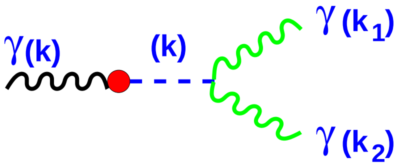
Photon splitting effect can also produce an apparent rotation of the plane of polarization of a linearly polarized light

S.L. Adler, Ann. Phys. (N.Y.) **67**, 599 (1971)

The resulting effect is too small to be observed in the laboratory

If the coupling of scalar/pseudoscalar with two photons is sufficiently large then this effect of photon splitting can be significantly enhanced

$$M(\gamma \longrightarrow \gamma\gamma) \;=$$



E. Gabrielli, K. Huitu, SR, PR D**74**, 073002 (2006)

Constraints from PVLAS

In 2006 the PVLAS experiment measured a positive value for the rotation

With $B_0 \approx 5$ T, $\epsilon = (3.9 \pm 0.5) \times 10^{-12}\ rad/pass$

However, the new observations (in 2007) do not show the presence of a rotation signal down to

$1.2 \times 10^{-8}\ rad$ at a magnetic field strength of 5.5 T

$1.0 \times 10^{-9}\ rad$ at a magnetic field strength of 2.3 T

(at 95% c.l.) with 45000 passes

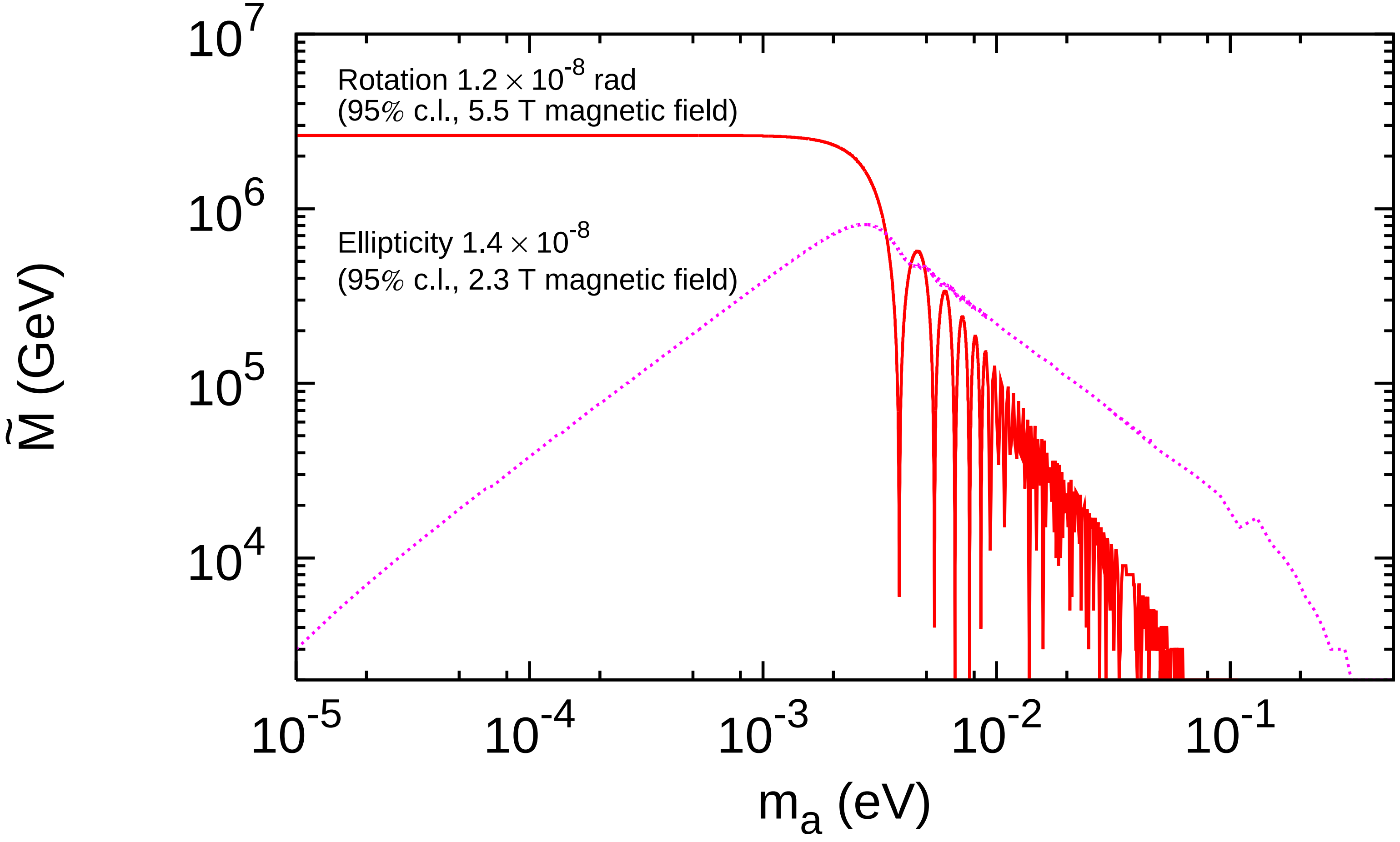
In the same experimental environment no ellipticity signal detected down to

1.4×10^{-8} at a magnetic field intensity of 2.3 T (at 95% c.l.)

Impose bounds on the mass and the inverse coupling constant for scalar/pseudoscalar bosons coupled to two photons

Constraints from PVLAS

Bounds on m_a and effective inverse coupling constant ($\tilde{M}$) for axion to two photons. Area below the solid and the dotted curves are disallowed from the data



ultra-light spin-0 particle (contd.)

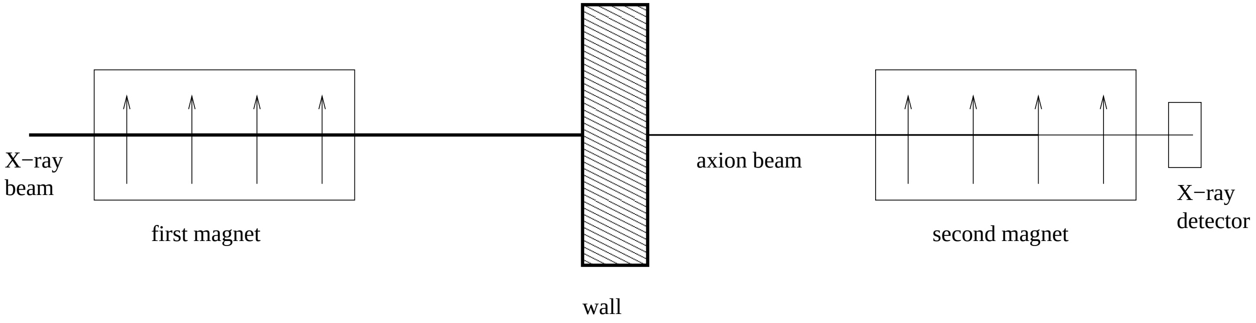
- Ultralight axions can also be tested in laboratory by different kind of experiments

P. Sikivie, PRL 51, 1415 (1983)

- after a laser beam passes through a magnetic field an axion component can be generated
- Light shining from a wall by using a second magnet

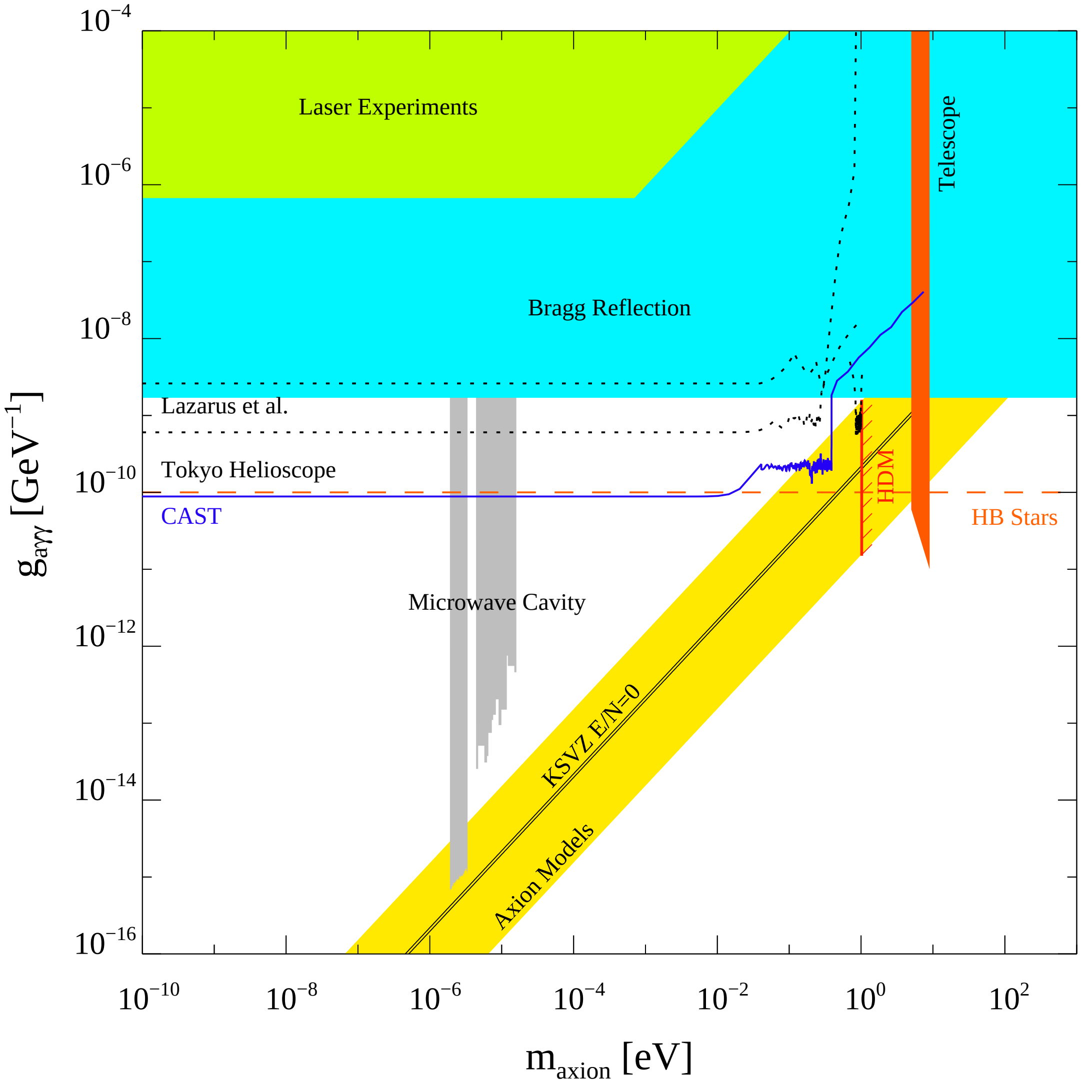
It is possible to check the parameter region explored by PVLAS data, by using X-ray laser facility

R. Rabadan, A. Ringwald, K. Sigurdson, PRL 96, 110407 (2006)



Very small effect: $\sim [P(\gamma \to a)]^2$

Exclusion regions in the mass-coupling plane



Axion cold dark matter

The Peccei-Quinn (PQ) scalar field has the following Lagrangian:

$$\mathcal{L} = \frac{1}{2}|\partial_\mu \phi|^2 - V_{\text{eff}}(\phi, T)$$

$$V_{eff} = \frac{\lambda}{4}(|\phi|^2 - \eta^2)^2 + \frac{\lambda}{6}T^2|\phi|^2$$

$\mathcal{L}$ is invariant under global $U(1)_{\text{PQ}}$, $\phi \to \phi e^{i\alpha}$

At high temp. $T > T_c$, minimum at $\phi = 0$

At $T < T_c$, ϕ obtains VEV $|\phi| = \eta$

The axion a is a Nambu-Goldstone boson associated with this spontaneous symmetry breaking

$$\phi = |\phi| e^{ia/\eta}$$

The axion is massless at this point

Axion cold dark matter

When the temp. decreases further and becomes comparable to the QCD scale Λ, the axion obtains its mass through QCD non-perturbative effect

The axion field starts to oscillate coherently around its minimum when the cosmic expansion rate H becomes comparable to the axion mass m_a

Once m_a takes on its T-independent value this axion condensate behaves as cold dark matter with a relic density that is governed by the initial angle $\theta_1 = a_1/\eta$ at onset of oscillation

$$\Omega_a h^2 = 0.18\,\theta_1^2 \left(\frac{f_a}{10^{12}\mathrm{GeV}}\right)^{1.19} \left(\frac{\Lambda}{400\mathrm{MeV}}\right)$$

(Xerexes Tata's Lectures)

Conclusion

- Axions appear as the solution to the strong CP problem
- Couplings of axions with photons have several implications
- Constraints have been derived on the axion-photon mixing from various astrophysical observation and laboratory experiment
- Axions can act as cold dark matter
- Axion searches are too important to ignore