Constraining the RS modulus in the light of recent PVLAS data

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Based on D. Maity, SR, S. SenGupta,

Phys. Rev. D**77**, 015010 (2008)

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Neutral ultra-light spin-0 bosons

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

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

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

$\Lambda \to$ effective scale of mass dimension

- $F_{\mu\nu} \to$ 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 $m \sim \mathcal{O}(\text{meV})$

Heavy: Higgs boson

- scalar particle
- necessary to provide all masses in the SM
- mass expected in the range of $m \sim 100$–800 GeV
- Coupling $H - \gamma - \gamma$ generated at one-loop

The axion has a very weak coupling

If astrophysical constraints are taken into account
$\Lambda \sim 10^6 - 10^{11}$ GeV

G. Raffelt, Phys. Rept. 198, 1 (1990)

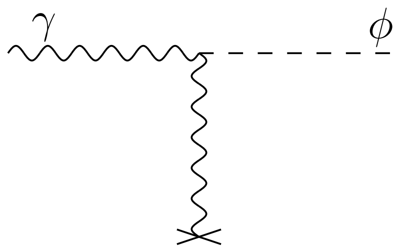
Recently, it has been shown that it is possible to relax astrophysics constraints

E. Masso and J. Redondo, JCAP, 0505, 015 (2005)

decay width (Γ) of the axion is VERY small,
$\Gamma = m^3/\Lambda^2 \rightarrow$ almost stable particle on cosmic time scale

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

• replacing $\gamma - \gamma - a \rightarrow \langle B \rangle \gamma a$ gives a mixing term in the photon-spin-0 system
• the photon $\rightarrow$ spin-0 conversion is possible in external EM field (Primakof effect)



• it could generate photon $\leftrightarrow$ spin-0 oscillations for photons propagating in magnetic fields

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

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

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

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)

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

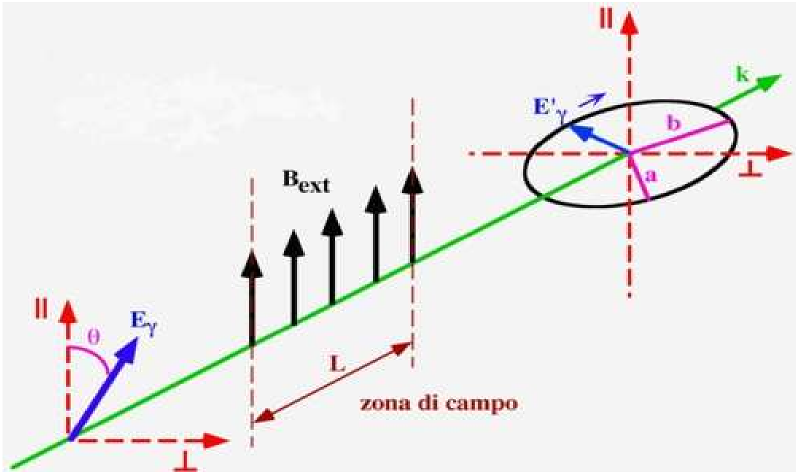
E. Zavattini et al., PRL 96, 110406 (2006)

- 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)

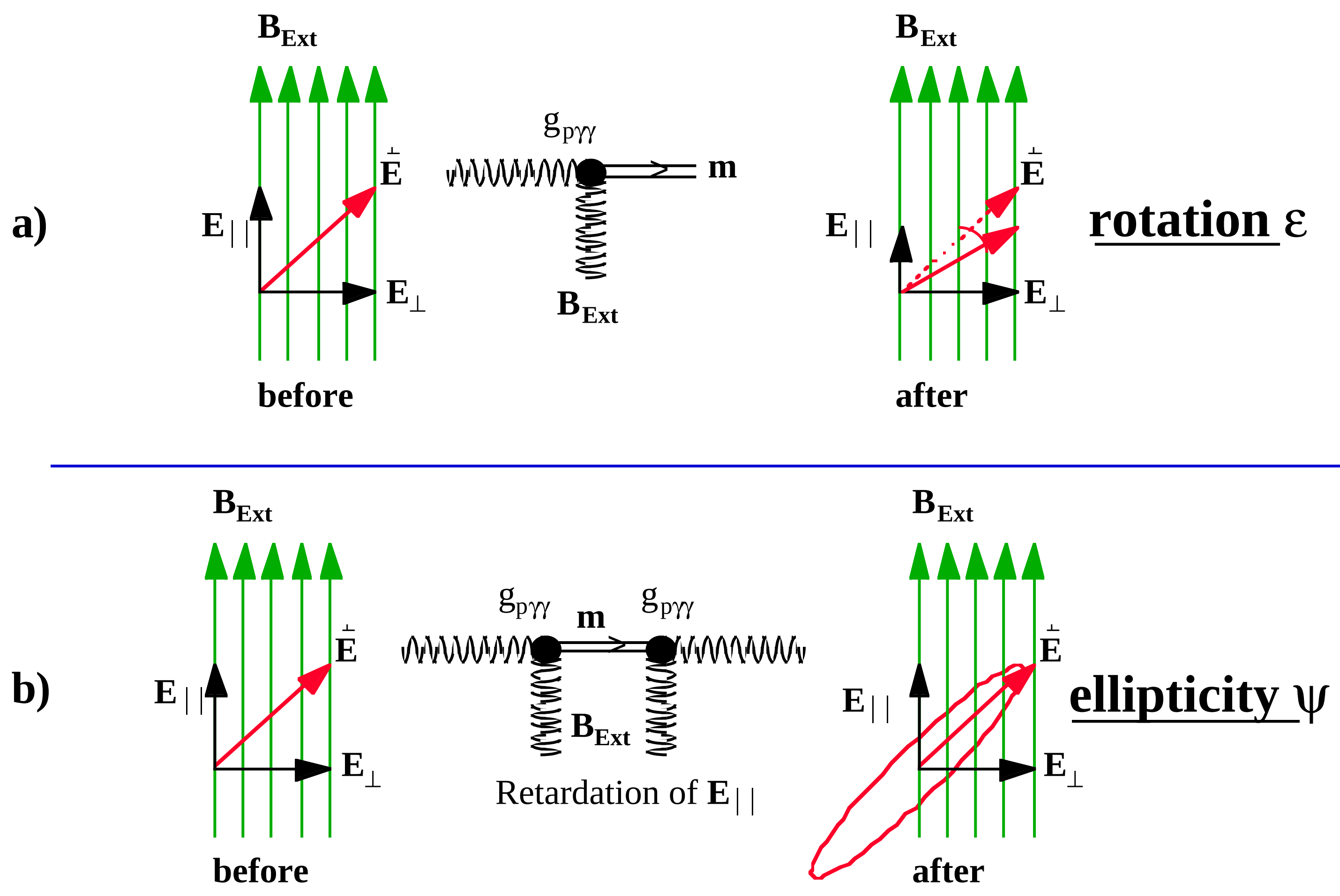


• different polarization vectors will propagate with different phase velocities $\longrightarrow$ different refractive indices

• linear polarization $\longrightarrow$ eliptical polarization out of B. Ellipticity ψ induced by birefringence

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

Rotation and Ellipticity



Axion-photon coupling in a string inspired model

String theoretic low energy effective action of Einstein-Kalb-Ramond-electromagnetic system is

$$S_d = \int d^d x \sqrt{-G}\left[M^{d-2}\mathcal{R} - \frac{1}{12}\bar{H}_{ABC}\bar{H}^{ABC} - \frac{1}{4}F_{AB}F^{AB}\right]$$

U(1) gauge anomaly cancellation $\Longrightarrow$

$$\bar{H}_{MNP} = \partial_{[M}B_{NP]} + \frac{1}{M^{d/2-1}}A_{[M}F_{NP]}$$

After compactification the effective action in 4-dim becomes

$$S_4 = \int d^4 x \sqrt{-g}\left[M_p^2 R - \frac{1}{12}\bar{H}_{\mu\nu\rho}\bar{H}^{\mu\nu\rho} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}\right]$$

where

$$\bar{H}_{\mu\nu\rho} = \partial_{[\mu}B_{\nu\rho]} + \frac{\beta}{M_p}A_{[\mu}F_{\nu\rho]}$$

β is determined by the geometry of extra dimension and its moduli and the compactification scale

Axion-photon coupling in a string inspired model

In 4-dimensions the KR field strength tensor expressed in terms of a massless scalar field called axion

$$\bar{H}^{\mu\nu\rho} = \epsilon^{\mu\nu\rho\delta}\partial_\delta a$$

In terms of massless axion field a

$$\Box a = \frac{1}{2} F^{\mu\nu}\tilde{F}_{\mu\nu}$$

$$D_\mu F^{\mu\nu} = -\frac{2\beta}{M_p}\partial_\mu a \tilde{F}^{\mu\nu}$$

String inspired low energy effective action $\Longrightarrow$ axion-photon coupling

Depends on

- the moduli parameters of the compact space
- the four dimensional Planck mass

Main objective is to explore the observable consequences in recent PVLAS experiments.

RS model and its effect on axion-photon coupling

Consider a specific 5-dim warped geometry model proposed by Randall and Sundrum

L. Randall and R. Sundrum, PRL **83**, 3370 (1999), PRL **83**, 4690 (1999)

Minimal version described in a 5-dim bulk AdS spacetime

- Extra coordinate y compactified on a $\mathbf{S}^1/Z_2$ orbifold
- We define $y = r_c\phi$
- The hidden and visible branes located at $\phi = 0$ and $\phi = \pi$ respectively

The line element of the corresponding background

$$ds^2 \;=\; e^{-2\sigma(y)}\eta_{\alpha\beta}dx^\alpha dx^\beta \;+\; r_c^2 d\phi^2$$

$\sigma = kr_c\phi, \quad k \sim M$

The exponential warp factor $\Longrightarrow$ on the visible brane, located at $\phi = \pi$, $m = m_0 e^{-kr_c\pi}$

RS model and its effect on axion-photon coupling

For $kr_c \sim 11.7$, the scalar mass on the brane $m \sim$TeV for $m_0 \sim M_p$

Fine tuning problem in connection with the scalar Higgs mass is resolved

As an extension to this model: include 2nd rank antisymmetric KR field in the bulk along with gravity

The Einstein-KR action in $d = 5$

$$S_5 = \int d^5x\sqrt{-G}\left[M^3\mathcal{R} - \frac{1}{12}\bar{H}_{ABC}\bar{H}^{ABC} - \frac{1}{4}F_{AB}F^{AB}\right]$$

where $\sqrt{-G} = e^{-4\sigma}r_c$

D. Maity and S. SenGupta, Classical Quantum Gravity, **21**, 3379 (2004)

RS model and its effect on axion-photon coupling

After RS compactification

The KR-EM part of the 4d effective action

$$S_{eff} = \int d^4x \left[M_p^2 R - \frac{1}{12}\bar{H}^{\mu\nu\lambda}\bar{H}_{\mu\nu\lambda} - \frac{1}{4}F^{\mu\nu}F_{\mu\nu}\right]$$

where $\bar{H}_{\mu\nu\gamma} = H_{\mu\nu\gamma} + \sqrt{\frac{k}{M_p^3}} e^{kr_c\pi} A_{[\mu}F_{\nu\gamma]}$

$\Longrightarrow$ the parameter β in the effective four dimensional axion-photon coupling is determined by the RS compactification

$$\beta = \sqrt{\frac{k}{M_p}} e^{kr_c\pi}$$

Optical rotation and birefringence in a string inspired model

- The string low energy action

$$S = \int \sqrt{-g} d^4x [M_p^2 R - \frac{1}{2}(\partial_\mu a \partial^\mu a - m_a^2 a^2) - \frac{\beta}{2M_p} a F_{\mu\nu} \tilde{F}^{\mu\nu} - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}]$$

The coupled axion-photon equations turn out to be

$$\Box \mathbf{A} + \frac{2\beta}{M_p} \frac{\partial a}{\partial t} \mathbf{B}_0 = 0$$

$$(\Box + m_a^2) a - \frac{2\beta}{M_p} \frac{\partial \mathbf{A}}{\partial t} \cdot \mathbf{B}_0 = 0$$

Only photons polarized parallel to $\mathbf{B}_0$ mix with the axion

At $t = 0$ EM field linearly polarized and making an angle α with $\mathbf{B}_0$

$$\mathbf{A}(t = 0) = \cos \alpha \;\; \mathbf{i} + \sin \alpha \;\; \mathbf{j}$$

Optical rotation and birefringence in a string inspired model

After a time $t = \ell$

$$\mathbf{A}(t) = \cos\alpha\ \mathbf{A}_{||}(t)\ \mathbf{i} + \sin\alpha\ \ exp(-i\omega t)\ \mathbf{j}$$

Vector potential describes an ellipse with the major axis at an angle

$$\alpha(\ell) = \alpha + A_1\ A_2\ \sin^2\left(\frac{\Delta\theta}{2}\right)\ \sin 2\alpha$$

A_1, A_2, $\Delta\theta$ depend on

- the effective axion-photon coupling
- the axion mass m_a
- external magnetic field strength $\mathbf{B}_0$
- energy of the initial laser beam
- the distance travelled (ℓ) by the wave in the external magnetic field

Optical rotation and birefringence in a string inspired model

Optical rotation: $\epsilon = \alpha(\ell) - \alpha$

$$\epsilon(\ell) = A_1\ A_2\ \sin^2\left(\frac{\Delta\theta}{2}\right)\ \sin 2\alpha$$

Ellipticity: the ratio of the minor to major axis

$$\mathcal{E}(\ell) = \frac{1}{2}\tan^{-1}\left[\frac{A_1\sin\theta_+ + A_2\sin\theta_-}{A_1\cos\theta_+ + A_2\cos\theta_-}\right]$$

Case of extremely small axion masses

$$\epsilon(L) = N\frac{B_0^2}{16\tilde{M}^2}\ell^2 \qquad \mathcal{E}(L) = N\frac{(B_0 m_a)^2}{48\kappa\tilde{M}^2}\ell^3$$

Effective inverse coupling constant $\tilde{M}$ is defined as

$$\tilde{M} \equiv M_p/2\beta$$

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}

Probing the moduli parameters using 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

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

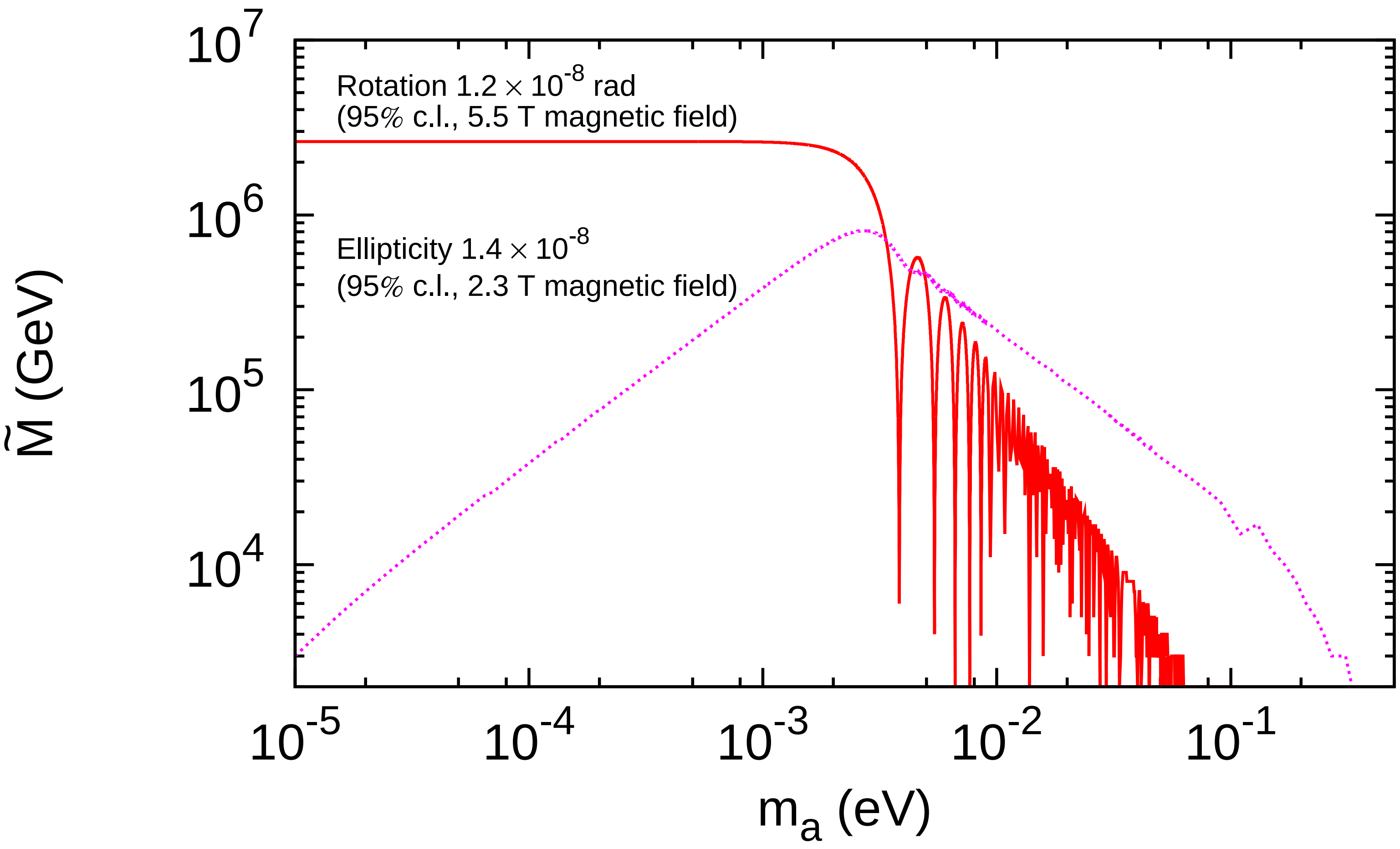
In the same experimental environment no ellipticity signal detected down to

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



Constraints on kr_c from PVLAS

For $m_a \lesssim 10^{-3}$ eV, rotation data $\Longrightarrow \tilde{M} \gtrsim 3 \times 10^6$ GeV

Translate this bound on $\tilde{M}$ into an upper bound on β using $\tilde{M} \equiv M_p/2\beta$

β is bounded from above as $\beta \lesssim 1.6 \times 10^{12}$

Using the relation $\beta = \sqrt{\frac{k}{M_p}} e^{kr_c\pi}$, one gets an upper bound on r_c given by

$$kr_c \lesssim \frac{1}{\pi}(13\ln(10) - \ln(6)) \simeq 8.95$$

$\Longrightarrow$ Very difficult to address the hierarchy problem in the context of the RS model in the low axion mass region

Constraints on kr_c from PVLAS

For higher values of the axion mass

Stronger restrictions on the moduli parameters come from the limits on the ellipticity measurements

Resulting bound is $\tilde{M} \gtrsim 3 \times 10^3$ GeV
for an axion mass $m_a \approx 0.3$ eV

The corresponding limit on the moduli parameters

$$kr_c \lesssim \frac{1}{\pi}(16 \ln(10) - \ln(6)) \simeq 11.15$$

More or less in the right ballpark to solve the hierarchy problem in RS scenario

$\Longrightarrow$ though the RS model is disfavoured to solve the hierarchy problem in the low m_a region, gives correct parameter values in the region of larger m_a

Conclusion

- We have explored implications of axion-photon coupling in a string inspired Randall-Sundrum model
- RS model, which is advertised to be a viable alternative to supersymmetric theory for offering a possible resolution to the gauge hierarchy problem in standard model, confronts some rigorous test in laboratory experiments like PVLAS because of such axion-photon coupling
- For experiments like optical rotation of the plane of polarization of an electromagnetic wave, the RS model is disfavoured for axion mass $\lesssim 0.07$ eV

Conclusion

- For experiments measuring the ellipticity the value of the modulus reside in the allowed range only for axion mass $\lesssim 10^{-5}$ eV or $\gtrsim 0.3$ eV

- Combining both the experimental results the RS model is shown to be consistent only for axion mass $\gtrsim 0.3$ eV

- In conclusion RS model, tested against PVLAS results(and similar such experiments) puts severe bound on the modulus and the axion mass if it has to resolve the hierarchy problem of the standard model