Axions and Large Extra Dimensions

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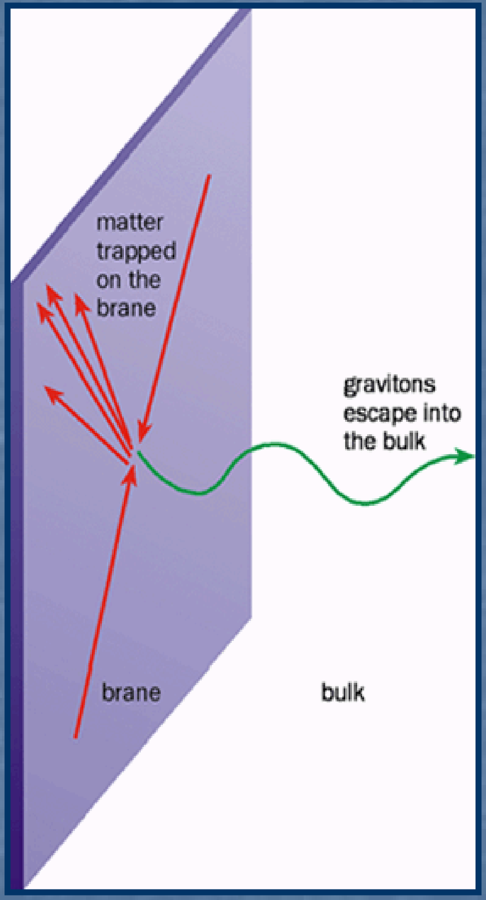
Outline

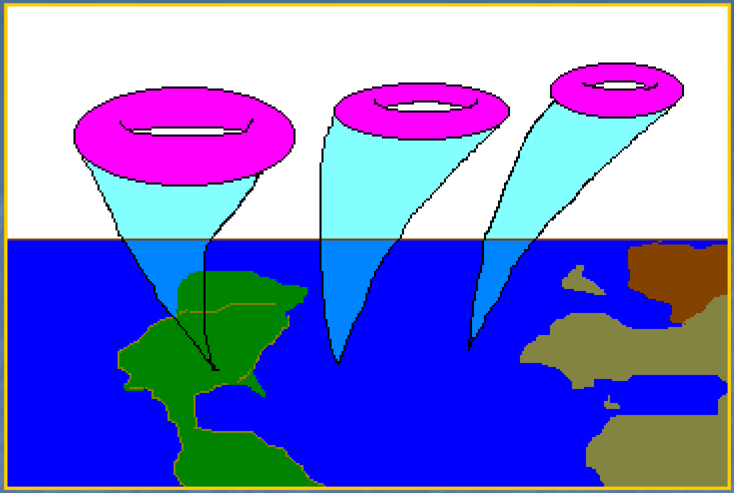
- Introduction on extra dimensions
- Axions in large extra dimensions
- CAST as a probe of large extra dimensions
- Conclusions

Extra dimensions

- possible solution to the hierarchy problem in particle physics (the large separation between the weak scale $M_W \sim 10^3$ GeV and the Planck scale $M_{Pl} \sim 10^{19}$ GeV)
- general ideas:
  - *n* extra spatial dimensions in which gravity propagates
  - Standard Model particles confined to our 3-dim. subspace
  - hierarchy generated by the geometry of additional dimensions
- testable predictions at the TeV scale



Extra dimensions



Three scenarios:

- Large extra dimensions (Arkani-Hamed, Dimopoulos, Dvali)
  - extra dimensions are compactified (a large radius of compactification) and the geometry of the space is flat
- Warped dimensions (Randall, Sundrum)
  - large curvature of the extra dimensions
- TeV^{-1} sized extra dimensions
  - Standard Model particles may propagate in the bulk

Large extra dimensions (LED)

- relation between the Planck scale and the fundamental higher-dimensional scale M_D

$$M_{\mathrm{Pl}} \approx M_D (R M_D)^{n/2}$$

R is the compactification radius

- if M_D~1 TeV, R ranges from ~mm to ~10 fm for n = 2–6 (1/R ranges from ~10^{-4} eV to ~10 MeV)

- Standard Model fields constrained to the brane

- bulk graviton expands into a Kaluza-Klein (KK) tower of spin-2 states which have masses $\sqrt{\vec{k}^2 / R^2}$, where $\vec{k}$ labels the KK excitation level

Large extra dimensions (LED)

Constraints on the radius of the extra dimensions, for the case of two-flat dimensions of equal radii (PDG2006):

- direct tests of Newton's law $\frac{1}{r^2} \rightarrow \frac{1}{r^{2+n}}$ for $r < R$

  $R < 0.13$ mm

- collider signals (direct production of KK gravitons)

  $R < 210 - 610$ μm

- astrophysics (limits depend on technique and assumption)

  - supernova cooling $R < 90 - 660$ nm
  - neutron stars $R < 0.2 - 50$ nm

Axions in LED

- axions could also propagate in $\delta \leq n$ extra dimensions. Why?
  - axions are singlets under the Standard Model gauge group
  - to avoid a new hierarchy problem M_w vs. f_{PQ}
- interesting predictions:
  - tower of Kaluza-Klein states
    - lowest KK excitation specifies the coupling strength of each KK state to matter
    - given source (the Sun) will emit axions of each mode up to the kinematic limit
  - axion mass may decouple from the Peccei-Quinn scale !
    (in 4-dimensional theory $m_{PQ} \sim 1/f_{PQ}$)

Axions in LED

- relation between the higher-dimensional and 4-dimensional scale (M_s is a fundamental mass scale, e.g. a type I string scale)

$$f_{\rm PQ}^2 \approx \bar{f}_{\rm PQ}^2 M_S^\delta R^\delta$$

- for gravity $M_{\rm Pl} \approx M_D (RM_D)^{n/2}$

- Kaluza-Klein decomposition of the axion field (upon compactification of one extra spatial dimension)

$$a(x^\mu, y) = \sum_{n=0}^{\infty} a_n(x^\mu) \cos\left(\frac{ny}{R}\right)$$

- effective 4-dimensional Lagrangian

$$L_{\rm eff} = L_{\rm QCD} + \frac{1}{2}\sum_{n=0}^{\infty}(\partial_\mu a_n)^2 - \frac{1}{2}\sum_{n=1}^{\infty}\frac{n^2}{R^2}a_n^2 + \frac{\xi}{f_{\rm PQ}}\frac{g^2}{32\pi}\underbrace{\left(\sum_{n=0}^{\infty} r_n a_n\right)}F_a^{\mu\nu}\tilde{F}_{\mu\nu a}$$

KK modes are not mass eigenstates

Axions in LED

The mass matrix:

K. R. Dienes, E. Dudas, T. Gherghetta, Phys. Rev. D 62, 105023 (2000)

$$M^2 = m_{PQ}^2 \begin{pmatrix} 1 & \sqrt{2} & \sqrt{2} & \sqrt{2} & \cdots \\ \sqrt{2} & 2+y^2 & 2 & 2 & \cdots \\ \sqrt{2} & 2 & 2+4y^2 & 2 & \cdots \\ \sqrt{2} & 2 & 2 & 2+9y^2 & \cdots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{pmatrix} \qquad y = \frac{1}{m_{PQ} R}$$

The mass eigenvalues:

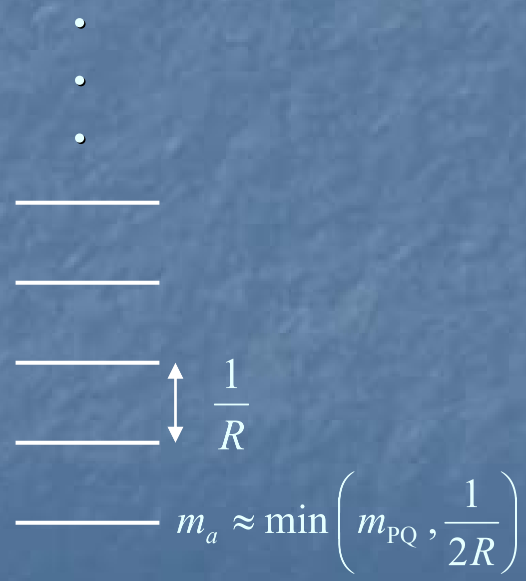
1) $m_{PQ}, \frac{1}{R}, \frac{2}{R}, \ldots$ for $m_{PQ} << \frac{1}{R}$

2) $\frac{1}{2R}, \frac{3}{2R}, \frac{5}{2R}, \ldots$ for $m_{PQ} >> \frac{1}{R}$

- the lightest axion mass eigenvalue

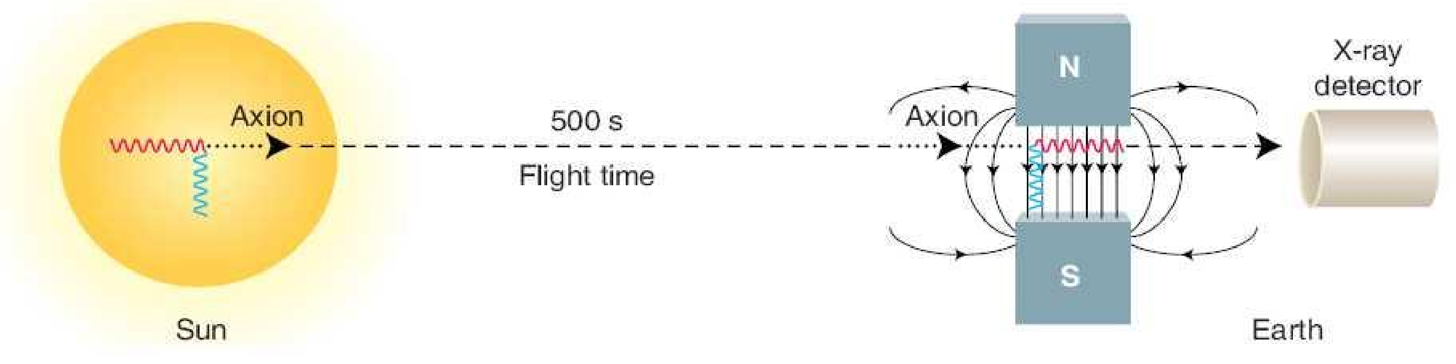
$$m_a \approx \min\left(m_{PQ}, \frac{1}{2R}\right)$$

- the masses of KK excitations are separated by $\approx 1/R$

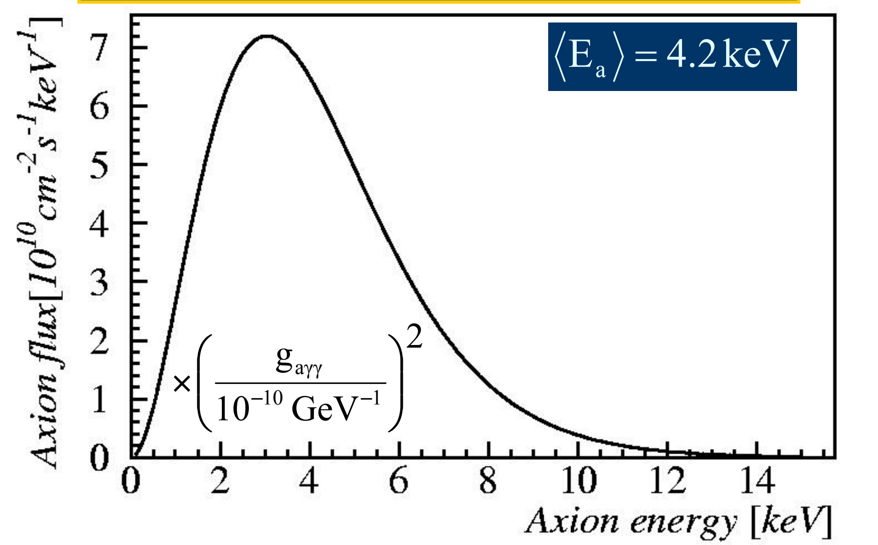


CAST: Physics

Principle of the Axion helioscope Sikivie, Phys. Rev. Lett 51 (1983)



differential axion flux at the Earth



- expected number of photons

$$N_\gamma = \int \frac{d\Phi_a}{dE_a} P_{a\to\gamma}\, S\, t\, dE_a$$

CAST: Physics

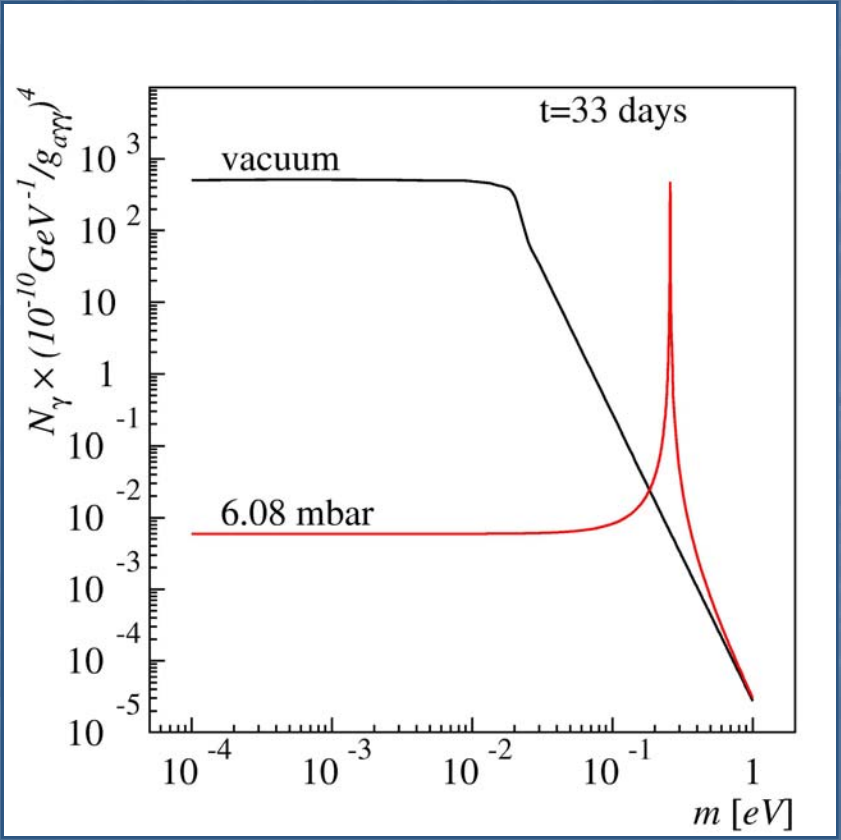
- conversion probability in gas (in vacuum: Γ= 0, m_γ=0)

$$P_{a\to\gamma} = \left(\frac{Bg_{a\gamma\gamma}}{2}\right)^2 \frac{1}{q^2+\Gamma^2/4}\left[1+e^{-\Gamma L}-2e^{-\Gamma L/2}\cos(qL)\right]$$

L=magnet length, Γ=absorption coeff.

$$q = \left|\frac{m_\gamma^2 - m^2}{2E_a}\right|$$ axion-photon momentum transfer

$$m_\gamma(\text{eV}) \approx \sqrt{0.02\,\frac{P(\text{mbar})}{T(\text{K})}}$$ effective photon mass (T=1.8 K)



- coherence condition

$$qL < \pi \quad \Rightarrow \quad \sqrt{m_\gamma^2 - \frac{2\pi E_a}{L}} < m < \sqrt{m_\gamma^2 + \frac{2\pi E_a}{L}}$$

CAST as a probe of LED

$n = 2$ since CAST is sensitive to axion masses up to ~ 1 eV

1) limits on the coupling constant (we use $R \leq 0.15$ mm $\Rightarrow 1/R = 1.3\times10^{-3}$ eV)

• estimated number of X-rays at the pressure P_i

$$N_{\gamma i}^{KK} = \frac{2\pi^{\delta/2}}{\Gamma(\delta/2)} R^{\delta} \int_0^{\infty} dm\, m^{\delta-1} N_{\gamma i}(m) G(m) \qquad N_{\gamma i}(m) = \int \frac{d\Phi_a(m)}{dE_a} S\, t_i\, P_{a\to\gamma i}(m)$$

• function $G(m)$ arises from the mixing between the KK axion modes $\Rightarrow$ rapid decoherency of the linear combination of KK axion states which couples to Standard Model fields

$$G(m) = \tilde{m}^4 \left(\tilde{m}^2 + 1 + \frac{\pi^2}{y^2} \right)^{-2} \qquad \tilde{m} \equiv \frac{m}{m_{PQ}} \quad , \quad y \equiv \frac{1}{m_{PQ} R}$$

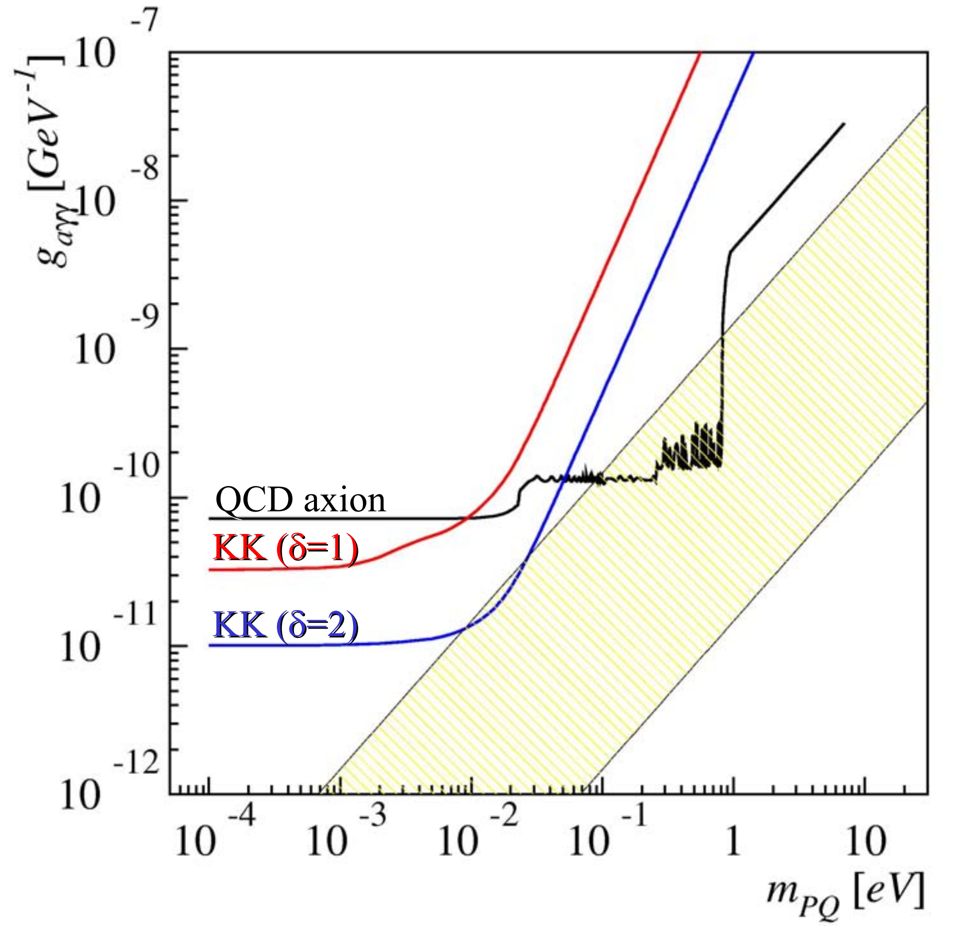
CAST as a probe of LED

a) $\delta=1$: ~10^3 KK states up to ~1 eV

b) $\delta=2$: ~10^6 KK states up to ~1 eV

- at most an order of magnitude stringent limit
- the axion zero mode mass $m_a \approx 1/2R^{-1} = 6.6\times10^{-4}$ eV
- strong decrease in sensitivity on $g_{a\gamma\gamma}$ for $m_{PQ}R>>1$

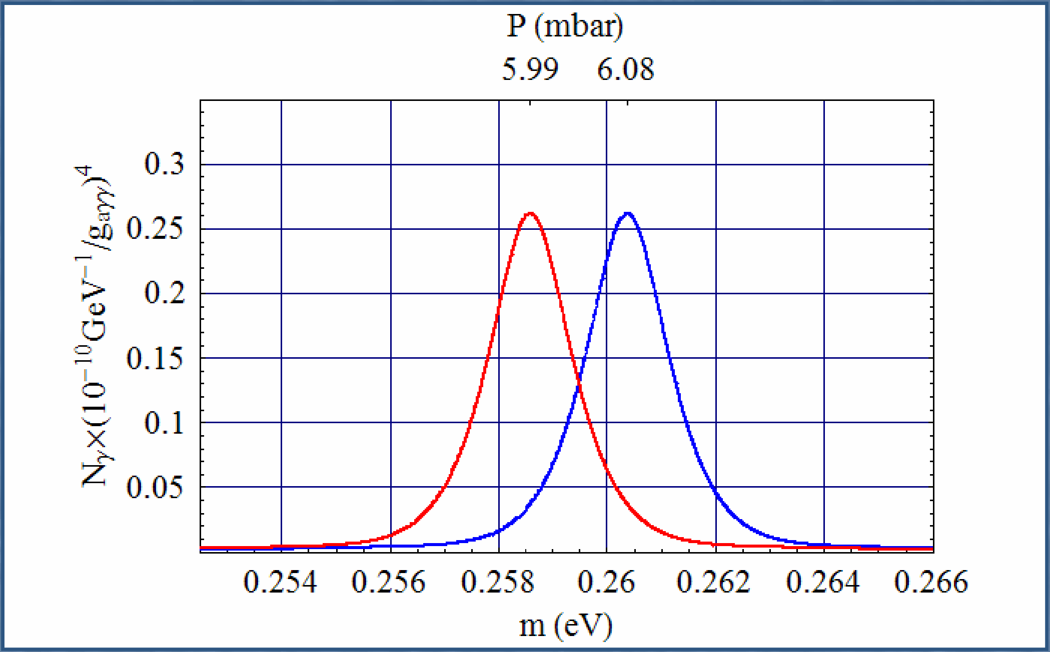
R. Horvat, M. Krčmar, B. Lakić, Phys. Rev. D 69, 2004



CAST as a probe of LED

2) limits on the compactification radius *R*

- due to the coherence condition, CAST could be sensitive to particular KK states



- two signals while changing the pressure of the gas (in the regime $m_{PQ}<1/(2R)$)

a) $m_a = m_{PQ}$ $\Rightarrow m_1 = 1/R \approx 0.8$ eV $\Rightarrow$ $R \approx 250$ nm

b) $m_a = m_{PQ}$ $\Rightarrow m_1 = 1/R \approx 1.15$ eV $\Rightarrow$ $R \approx 170$ nm

Conclusions

In addition to gravity, axions too could propagate in large extra space dimensions ⇒ Kaluza-Klein tower of axion states.

We have explored the potential of the CAST experiment for observing KK axions coming from the solar interior:

- In theories with two extra dimensions (with R=0.15 mm), the axion mass is decoupled from f_{PQ} and is set by the compactification radius R. In addition, there is a strong decrease in sensitivity on $g_{a\gamma\gamma}$ for $m_{PQ}R>>1$ (due to mixing between the KK axion modes).
- CAST experiment may be sensitive to particular KK axions ⇒ probing of two large extra dimensions with a compactification radius R down to 170 nm if $m_{PQ}<1/(2R)$.

BACKUP SLIDES

Axions in LED

The mass matrix:

K. R. Dienes, E. Dudas, T. Gherghetta, Phys. Rev. D 62, 105023 (2000)

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The eigenvalues λ: the solutions to the transcendental equation

$$\pi R \lambda \cot(\pi R \lambda) = \frac{\lambda^2}{m_{\mathrm{PQ}}^2}$$

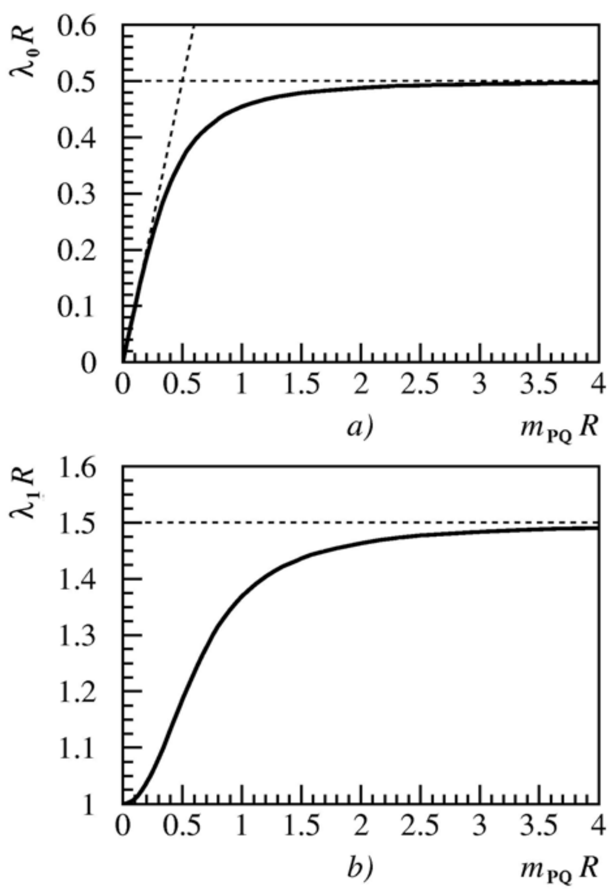
The axion linear superposition:

$$a' \equiv \frac{1}{\sqrt{N}} \sum_n r_n a_n = \frac{1}{\sqrt{N}} \sum_\lambda \tilde{\lambda}^2 A_\lambda \hat{a}_\lambda$$

$$A_\lambda \equiv \frac{\sqrt{2}}{\tilde{\lambda}} \left(\tilde{\lambda}^2 + 1 + \frac{\pi^2}{y^2} \right)^{-1/2} \qquad \tilde{\lambda} \equiv \frac{\lambda}{m_{\mathrm{PQ}}}$$

Axions in LED

- the solutions to the transcendental equation for a) the axion zero mode; b) the first KK excitation



1) if $m_{PQ} << \frac{1}{R}$ KK axion masses are $m_{PQ}, \frac{1}{R}, \frac{2}{R}, \ldots$

2) if $m_{PQ} >> \frac{1}{R}$ KK axion masses are $\frac{1}{2R}, \frac{3}{2R}, \frac{5}{2R}, \ldots$

- the lightest axion mass eigenvalue

$$m_a \approx \min\left(m_{PQ}, \frac{1}{2R}\right)$$

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