Phenomenology of Axion-Like Particles Coupling with Photons in the Jets of Active Galactic Nuclei

Ahmed Ayad
ahmed@aims.edu.gh

School of Physics, University of the Witwatersrand
Johannesburg, South Africa

NDM-2020, Hurghada, Egypt

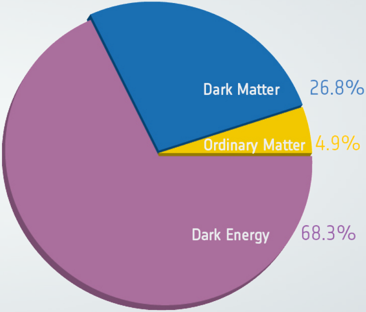
Outline

1. Introduction and motivation for the study of axion and ALPs as DM candidates.
2. How to look for ALPs based on the possible interactions between them and photons?
3. Discussing the ALP-photon coupling model, and presenting our recent results probing a CAB within the jets of AGNs.
4. Conclusion and future work.

Introduction

- We've learned a lot about the structure of our universe.

- But there is still more missing. In particular, dark matter implies:
  - There is a big problem with our standard model of particle physics, or
  - There is a big problem with our standard theory of gravity,
  - or both!!



Dark matter candidates

- Here we assume new particle physics is part of the answer.
- Critical question need to be answered: What is the DM made of?
- Many possible DM candidates cover a wide range of masses from very heavy particles to ultralight particles.
- Some examples: WIMPs, Sterile Neutrinos, Gravitinos, Neutralinos, Axions and Axion-like particles.

The strong CP problem and axions

- Axions: pseudo-scalar bosons associated to the solution of the strong CP problem in QCD.
- $U(1)_A$ problem $\Rightarrow$ complex structure of the QCD vacuum.
- Source of CP violation $\Rightarrow$ but no experimental indication.
- Peccei–Quinn solution: extend the SM with additional axial $U(1)_{PQ}$ global symmetry.
- Spontaneously broken at some high scale $\Rightarrow$ axion is the resulting Goldstone mode.

Axions and ALPs as dark matter candidates

- Axions must solve the strong CP problem and suggested as dark matter candidate.

- Many string theory models extend the SM by new symmetries and there can be many other ALPs.

- They are characterized by their coupling to two photons, $g_{a\gamma}$ which directly related to the axion mass m_a.

- ALPs have the same properties of the QCD axions but their masses and coupling to photons are unrelated.

- ALPs show as very promising dark matter candidates.

How to search for ALPs?

- ALPs expected to mix with photons in the presence of an external magnetic field.

- This interaction is described by the Lagrangian:

$$\ell_{a\gamma} = -\frac{1}{4} g_{a\gamma} \mathrm{F}_{\mu\nu} \tilde{\mathrm{F}}^{\mu\nu} a = g_{a\gamma}\, \mathbf{E} \cdot \mathbf{B}\, a$$

- This mixing leads to the conversion between ALPs and photons.

- This mechanism is used to explain a number of astrophysical phenomena or to constrain ALP properties.

How to search for ALPs?

- In this talk I focus on:
  - Many string theory models motivate the existence of a homogeneous CAB analogous to the CMB.
  - Recent work explain the Coma cluster soft X-ray excess due to CAB ALPs conversion into photons in the magnetic field of galaxy clusters.
  - We test this scenario using the M87 jet environment.
  - Demonstrate the potential of the AGN jet environment to probe low-mass and small coupling ALP models.

ALP-photon mixing model

- For propagation in the z-direction and very relativistic ALPs, the evolution equations of ALP-photon coupling model:

$$i\frac{d}{dz}\begin{pmatrix} A_\perp(z) \\ A\|(z) \\ a(z) \end{pmatrix} = -\begin{pmatrix} \Delta_\perp \cos^2\xi + \Delta_\| \sin^2\xi & \cos\xi\sin\xi(\Delta_\| + \Delta_\perp) & \Delta_{a\gamma}\sin\xi \\ \cos\xi\sin\xi(\Delta_\| + \Delta_\perp) & \Delta_\perp \sin^2\xi + \Delta_\| \cos^2\xi & \Delta_{a\gamma}\cos\xi \\ \Delta_{a\gamma}\sin\xi & \Delta_{a\gamma}\cos\xi & \Delta_a \end{pmatrix}\begin{pmatrix} A_\perp(z) \\ A\|(z) \\ a(z) \end{pmatrix}$$

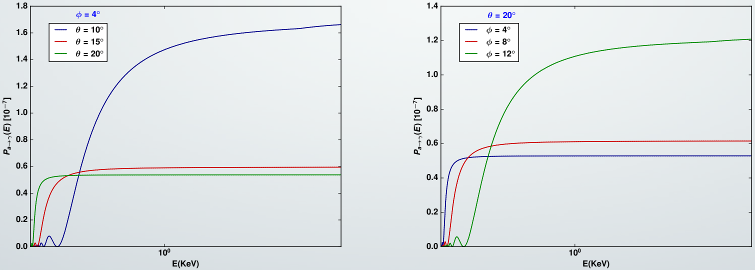
- The strongest mixing occurs at energy range depends on: m_a & $g_{a\gamma}$ and the transverse magnetic field and the electron density profile:

$$\mathbf{B}_T(r,R) = J_s(r)\cdot B_*\left(\frac{R}{R_*}\right)^{-1}\text{G} \quad \& \quad n_e(r,R) = J_s(r)\cdot n_{e,*}\left(\frac{R}{R_*}\right)^{-1}\text{cm}^{-3}$$

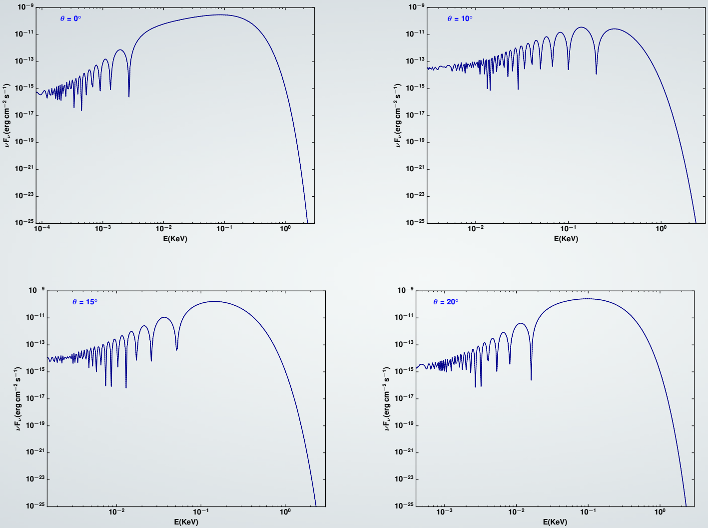
ALP-photon conversion probability

- The probability for ALps to convert into photons after traveling a certain distance is $P_{a\to\gamma} = |A_{\|}(E)|^2 + |A_{\perp}(E)|^2$.

- The maximum conversion probability occurs when the misalignment angle θ is close to the opening angle of the AGN jet ϕ.



M87 AGN energy spectra



Summery of the results

θ (°), $\phi = 4°$	$g_{a\gamma}$ (GeV^{-1})	ϕ (°), $\theta = 20°$	$g_{a\gamma}$ (GeV^{-1})
0	$\lesssim 6.9 \times 10^{-13}$	4	$\lesssim 1.13 \times 10^{-13}$
5	$\lesssim 2.14 \times 10^{-14}$	8	$\lesssim 4.25 \times 10^{-14}$
10	$\lesssim 1.6 \times 10^{-14}$	12	$\lesssim 1.62 \times 10^{-14}$
15	$\lesssim 3.7 \times 10^{-14}$		
20	$\lesssim 1.14 \times 10^{-14}$		

- The overall X-ray emission for the M87 AGN [Flux (0.3-8) keV $\sim 3.76 \times 10^{-12}$ **erg** cm^{-2} s^{-1}] requires $g_{a\gamma}$ in the range of $\sim 1.14 \times 10^{-14} - 4.25 \times 10^{-14}$ GeV^{-1}.
- These results cast doubt on the current best fit value on $g_{a\gamma} \sim 2 \times 10^{-13}$ GeV^{-1} obtained in the Coma cluster soft X-ray excess CAB model.

Conclusion

- Axions appears in the solution to the strong CP problem.
- ALPs are suggested by many string theory models.
- ALPs seem to be suitable candidates for dark matter.
- ALPs are expected to couple with photons in the presence of an external magnetic field.
- Our results suggest new constraints on the ALP-photon coupling lower than the current limits used to explain the Coma cluster soft X-ray excess.

Future work

- Explore the potential of SKA to detect CDM axions with radio astronomy.

- Demonstrate the potential of the CAB ALP model to explain the EDGES 21 cm Anomaly.

Thanks a lot! ☺