# Constraints on axion-like particles with the Perseus data of MAGIC

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MAGIC Major Atmospheric Gamma Imaging Cerenkov Telescopes

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## Abstract

**Axion-like particles** (**ALPs**) are expected to interact with very high-energy gamma rays in the strong magnetic fields and modify the spectral energy distribution of the observed target. This study analyzes 41.3 hours of observational data from the **Perseus Galaxy Cluster**, obtained with the **MAGIC** ground-based Cherenkov telescopes. Using the **MAGIC** dataset of a source located in the **Perseus cluster**, we set the constraints on the **ALPs** mass, reaching several hundreds of neVs and improving the current limits on the strength of their coupling to photons.


## Introduction

Axion-like particles (ALPs) are a class of pseudo-Nambu-Goldstone bosons that have been proposed as potential candidates for dark matter. These particles can interact with high-energy photons in external magnetic fields, influencing the observed gamma-ray spectrum. This interaction happens around the so called 'critical energy':

$$E_{crit} = 2.5\ \mathrm{GeV}\frac{|\boldsymbol{m}^2_{a,\mathrm{neV}} - \omega^2_{pl,\mathrm{neV}}|}{G_{11} B_{\mu\mathrm{G}}}\ , \qquad (1)$$

where $m_a$ is the mass of the ALP, $G_{11}$ is the scaled interaction strength, $\omega_{pl}$ is the electron plasma frequency of the medium, and $B_{\mu G}$ is the magnetic field strength. **Perseus galaxy cluster** is a promising candidate for this kind of study given its proximity and strong ($\sim \mu\mathrm{G}$) extended magnetic field ($\sim$ kpc). We are solving the equations of motion of photon-ALP system using the open-source code GammaALPs [1], while considering two different magnetic fields:

- Perseus galaxy cluster magnetic field
- Milky Way magnetic field.

Since the current bounds on the Intergalactic magnetic field suggest low conversion probability, we are taking into account only the EBL (extragalactic-background-light) attenuation of photons.

## Datasets & signal modeling

We analysed 41.3 hours of data of an AGN in Perseus: NGC1275 located at the redshift $z \sim 0.017$, observed by the MAGIC telescopes. The data is divided in three datasets, based on the activity of the source.

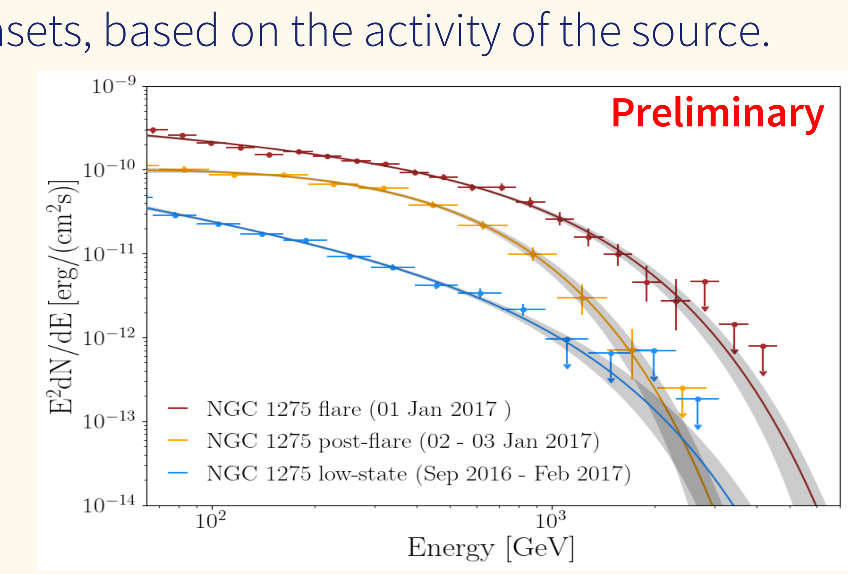


Fig. 1: SED of NGC 1275 (different states.

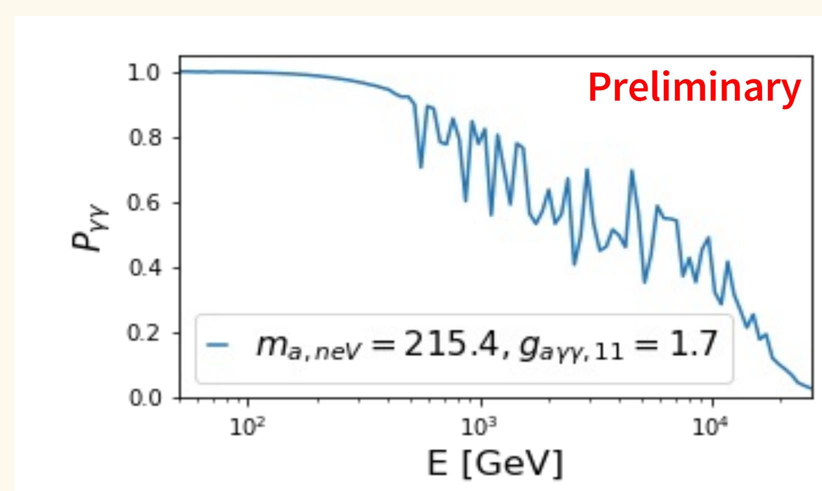


Fig. 2: Photon survival probability $P\gamma\gamma$ for one combination of mass and ALPs coupling.

## Statistical analysis

Main goal of the analysis is to evaluate the hypotheses of existence of signatures of ALPs, represented with 154 combinations of $m_a$ and $g_{a\gamma}$ in the sub-$\mu$eV part of the ALPs parameter space. The observed spectrum of each dataset is modeled with a smooth function, $P\gamma\gamma$ and instrument response functions of the telescope (IRFs):

$$\Phi_{obs}(E') = \Phi_{int}(E') \cdot P\gamma\gamma \cdot IRF(E|E')\ . \qquad (2)$$

Then we are employing a likelihood maximization method and defining a binned likelihood:

$$\mathcal{L}(m_a, g_{a\gamma}; \mu\,|D) = \prod_{i,k} \mathcal{L}_{i,k}, (m_a, g_{a\gamma}; \mu_i\,|D_{i,k})\ , \qquad (3)$$

where $\boldsymbol{\mu_i}$ and $\boldsymbol{D_{i,k}}$ represent nuisance parameters and the observed counts for each of the datasets $\boldsymbol{i}$ per bin $\boldsymbol{k}$, respectively. Given the likelihood (3), the test statistic is defined as:

$$S(g_{a\gamma}, m_a) = -2\ln\frac{\mathcal{L}(g_{a\gamma}, m_a, \hat{\hat{\mu}}, \hat{B}|D)}{\hat{\mathcal{L}}} \qquad (4)$$

The exclusion values are obtained by computing the distributions of (4) from Monte Carlo (MC) simulations and translating the values into a significance expressed in standard deviations of the corresponding Gaussian.

## Systematic effects

### MAGNETIC FIELD MODELING

We perform a check of systematics effect of magnetic field choice by repeating the analysis using the magnetic field model used by the Cherenkov Telescope Array (CTA) collaboration, compared to our model, taken as in Ajello et al. [2].

| | $B_0$[μG] | η | $n_0$ [cm$^{-3}$] | $n_2$ [cm$^{-3}$] | $\frac{r_{core}}{r_{core2}}$ [kpc] | β/$β_2$ |
|---|---|---|---|---|---|---|
| B | 10 | 0.5 | 0.039 | 0.0045 | 80/280 | 1.2/0.58 |
| $B_{alt}$ | 25 | 2/3 | 0.046 | 0.0036 | 57/278 | 1.2/0.71 |

Tab. 1: The parameters used for the modeling of the Perseus magnetic field $B$ and performing a check of the effects magnetic field modelling has on the constraints by using the $B_{alt}$ as the CTA Coll.

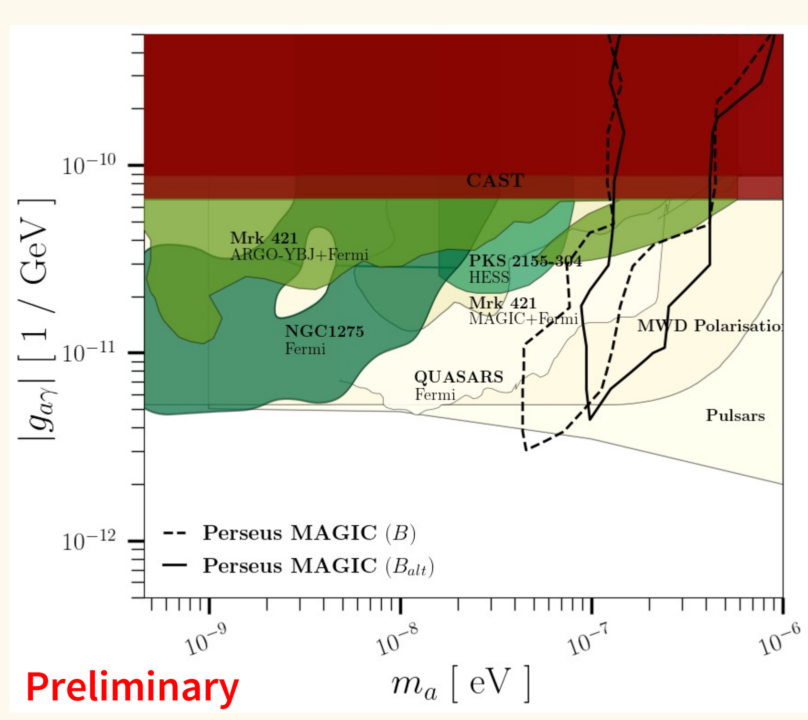


Fig. 3: Comparison of the limits in the ALPs parameter space obtained with the Perseus cluster magnetic field obtained in this study with an alternative magnetic field model used in the CTA Coll.

### ENERGY SCALE

To evaluate the effect of energy scale uncertainties coming from the MAGIC telescopes, we artificially scaled the Axion-Like Particle (ALP) energy-dependent signatures in spectra by ±15% and checked the effects on the bounds.

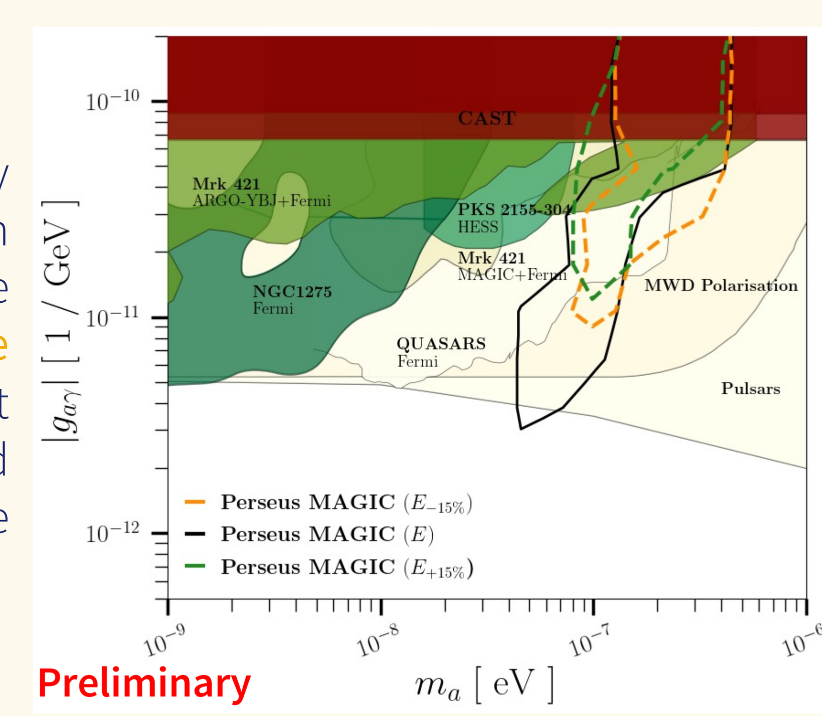


Fig. 4: Discrepancies in the exclusion regions resulting from shifting the energy scale by −15% (dashed green) and +15% (dashed orange) in the ALP signatures in the spectra, together with the results from the main part of this study.

## Results

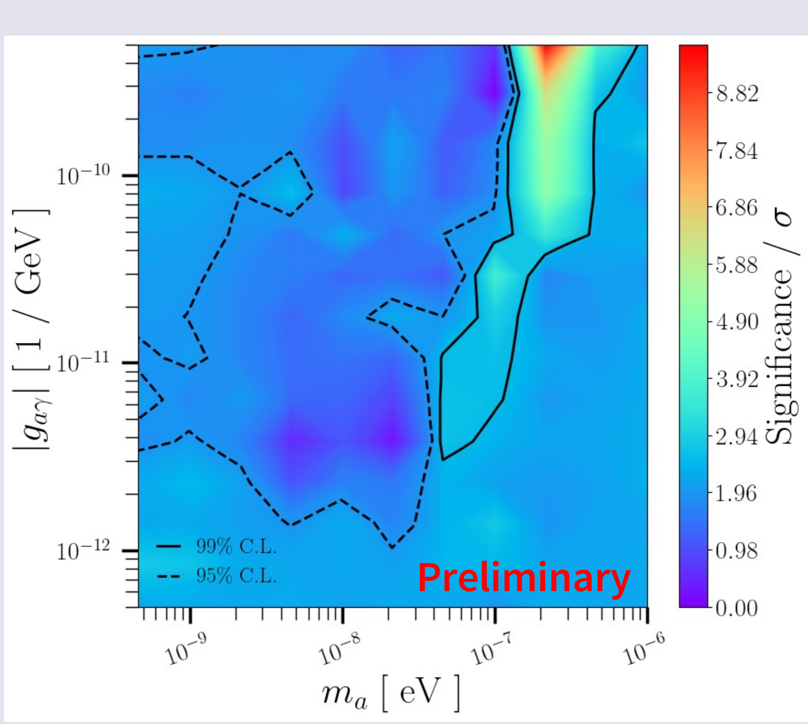


Fig. 5: The likelihood-ratio statistic S (4) computed over 154 ALP points of $m_a$ and $g_{a\gamma}$ using the Perseus data. The black line shows a significance of 1.56σ and orange one a significance of 2.58σ (corresponding to a 95% and 99% confidence levels, respectively).

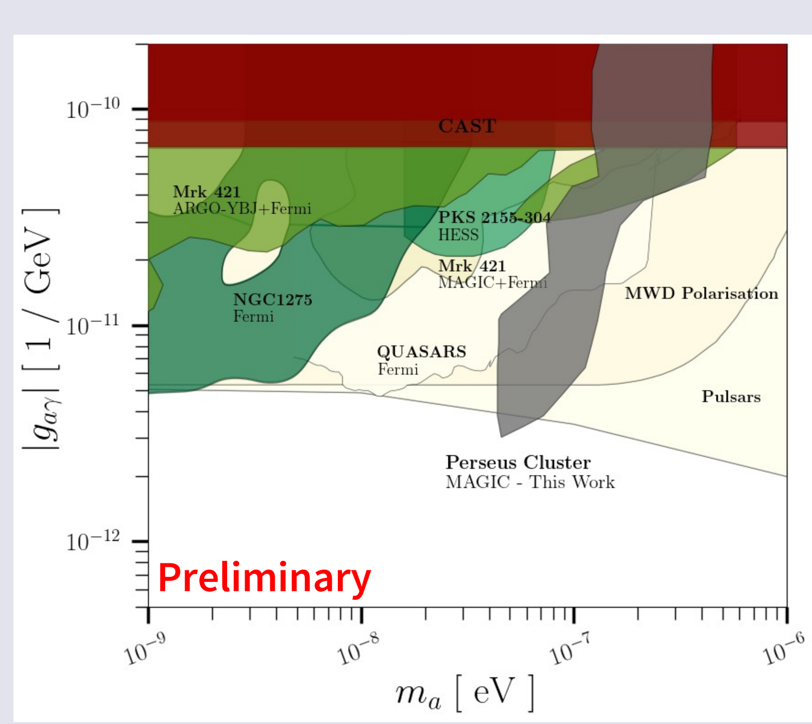


Fig. 6: The limits obtained with this work in comparison with current limits in the same part of the parameter space, gathered in [3].

## Conclusions

The results of this study are confirming the previous constraints on the ALPs coupling to photons set in the range of $40 - 400$ neV. We show that the computation of the significance point-by-point additionally strengthens the constraints in comparison to previous studies. Furthermore, these results offer the strongest constraints on ALP masses in the range of $40 - 90$ neV, with the greatest sensitivity for ALP masses of $m_a = 40$ neV, reaching the photon-axion coupling down to $g_{a\gamma} = 3.0 \times 10^{-12}\ \mathrm{GeV}^{-1}$.

**This work is currently under review and is soon to be published.**


## References

[1] https://github.com/me-manu/gammaALPs
[2] M. Ajello et al. (Fermi-LAT), Phys. Rev. Lett., 116, 161101 (2016), arXiv:1603.06978
[3] C. O'Hare, cajohare/axionlimits: Axionlimits, https://cajohare.github.io/AxionLimits/ (2020)



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