Gamma-Ray Propagation Signatures in AGN Spectra with VERITAS

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ABSTRACT

The most powerful active galactic nuclei (AGN), including blazars and radio galaxies, exhibit non-thermal radiation extending beyond 1 TeV with high luminosities and strong flux variability, indicating extreme particle acceleration in their relativistic jets. The gamma-ray spectra of these sources contain information about the energy distribution and cooling processes of high-energy particles in jets, the extragalactic background light between the source and the observer, the environment of the gamma-ray emitting region, and even exotic particle physics. These spectra have proven particularly useful for searches for the existence of axion-like particles (ALPs). ALPs are light, pseudoscalar particles that have been proposed as a beyond-the-standard-model generalization of the axion. Consequently, they are expected to couple to photons in magnetic fields to compensate for spin difference. This coupling, manifested as ALP-photon oscillations in external fields, would induce modifications to the gamma-ray spectra of AGN. In this contribution, we use data from the VERITAS gamma-ray observatory to explore ALP-photon oscillation effects in the flaring spectrum of the radio galaxy NGC 1275, embedded in the cool-core Perseus cluster, and discuss other constraints derived from spectral signatures in AGN data.

Introduction

- Axion-like particles (ALPs) are a generalization of beyond-the-standard-model axions:
  - **Expected to couple to photons in external magnetic fields** (see Fig. 1)
- For certain ALP masses (m_a) and couplings ($g_{a\gamma}$):
  - **Potential to induce modifications to the γ-ray spectra of astrophysical sources** via ALP-photon oscillations in external fields near the source and in the Galactic magnetic field

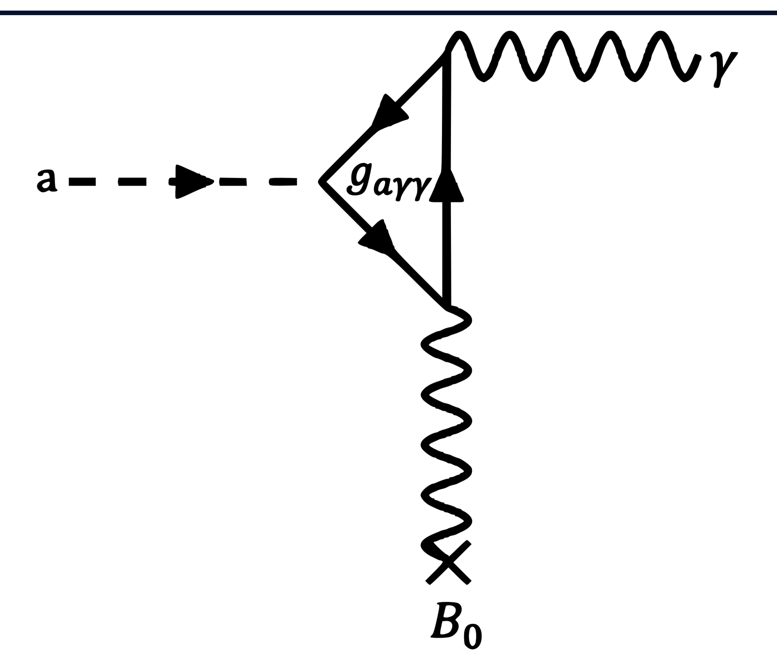

Fig. 1: The two-vertex axion-photon conversion in a static magnetic field via the inverse Primakoff effect.

NGC 1275 in the Perseus Cluster

- Radio galaxy at **the center of the Perseus cluster**
  - Located at ~ 75 Mpc (z = 0.01756)
- Target of several ALP searches using spectra due to its favorable magnetic field environment [1]
  - Magnetic field strength of the cluster **as large as 25 μG** at its center [2]

NGC 1275 Flare of 2017

- Flare at 150% Crab detected by MAGIC telescopes in very-high-energy (VHE; E > 100 GeV) γ rays between 31 Dec. 2016 to 1 Jan. 2017 [3]
- VERITAS followed up the next night, recording a continued flaring state, now at 65% Crab [4]
- Flare also visible in Fermi-LAT (see Fig. 2)

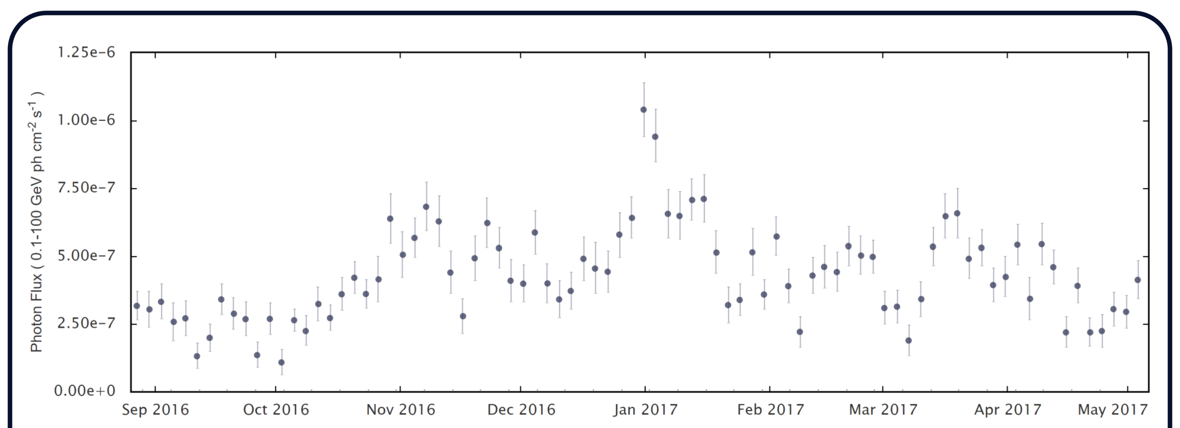

Fig. 2: Light curve of the 2017 NGC 1275 as seen by Fermi-LAT, from the Fermi-LAT Light Curve Repository [5].

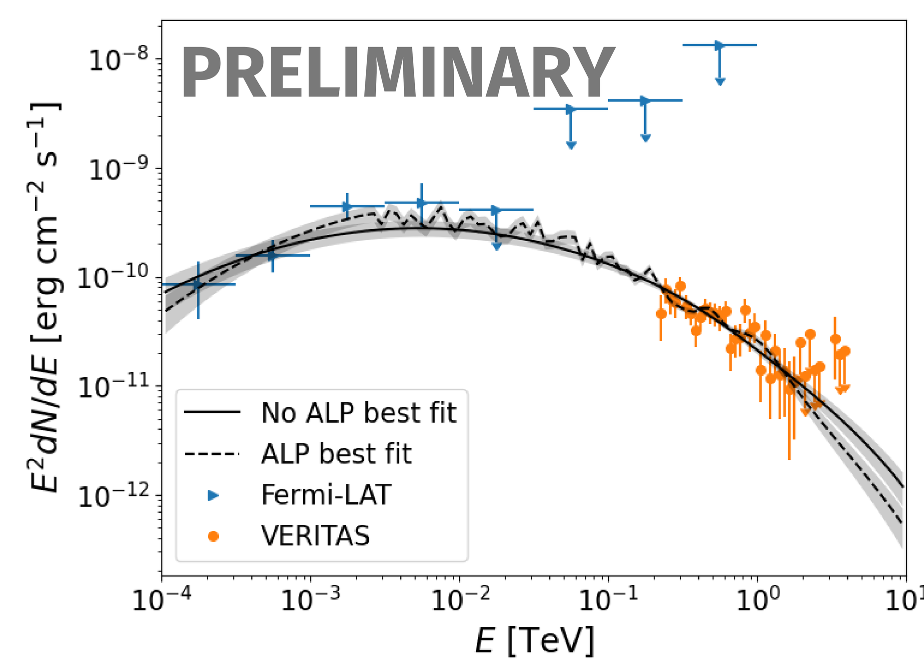

Fig. 3: SED for the Jan 2, 2017 VERITAS observations of the NGC 1275 flare. Best fit model with/without ALPs shown.

Data Analysis

- Joint likelihood analysis performed on Fermi energy-binned fluxes and VERITAS event-level data in `gammapy`[1] (see Fig. 3)
- Model ALP effect with `gammaALPs`[2] code
  - Perseus Cluster modeled as a random field with Gaussian turbulence with parameters from [6]
  - Exact B-field structure unknown
    - Multiple B-field realizations simulated, select the 95% likelihood quantile

Statistical Framework

- Scan the ALP parameter space:
  - $m_a \in [3, 700]$ neV | $g_{a\gamma} \in [0.1, 10] \times 10^{-11}$ GeV^{-1}
- Evaluating the hypotheses on the existence of the ALPs:
  - $\mathrm{TS} = -2\ln\left(\frac{\mathcal{L}_0(\hat{\hat{\theta}})}{\mathcal{L}_{ALP}(\hat{m}_a, \hat{g}_{a\gamma}, \hat{\boldsymbol{B}}_{95}, \hat{\boldsymbol{\theta}})}\right)$
  - $\lambda(m_a, g_{a\gamma}) = -2\ln\left(\frac{\mathcal{L}_{ALP}(m_a, g_{a\gamma}, \boldsymbol{B}_{95}, \hat{\hat{\theta}})}{\mathcal{L}_{ALP}(\hat{m}_a, \hat{g}_{a\gamma}, \hat{\boldsymbol{B}}_{95}, \hat{\boldsymbol{\theta}})}\right)$
- Simulate 500 datasets to assess statistics, since Wilks' theorem does not apply

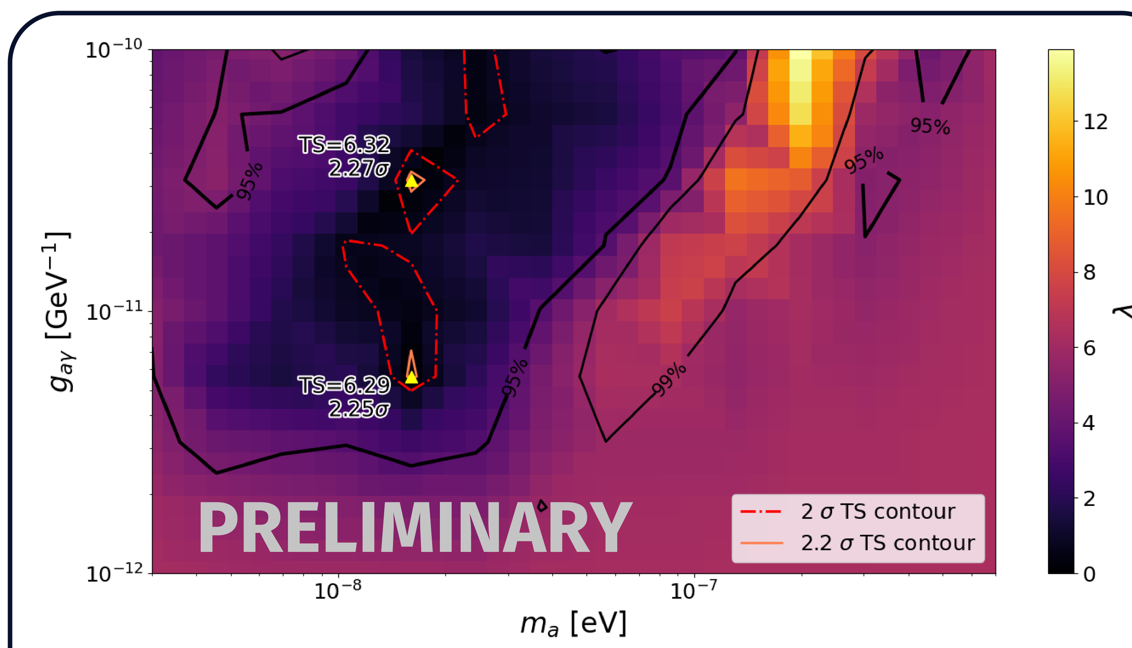

Fig. 4: Map of λ values for observational data. Black contours indicate the (high-λ) regions excluded at 95% & 99%. Highest TS points are indicated by yellow triangles.

Results

- Exclude the null hypothesis at **2.3 σ**
  - Therefore, **cannot claim the existence of ALPs**
- **Make exclusions at the 99% level** for masses $m_a = 50 - 200$ neV, for coupling constants down to $g_{a\gamma} = 3 \times 10^{-11}$ GeV^{-1}
- See Fig. 4 for a detailed exclusion map and Fig. 5 for context with other experimental constraints

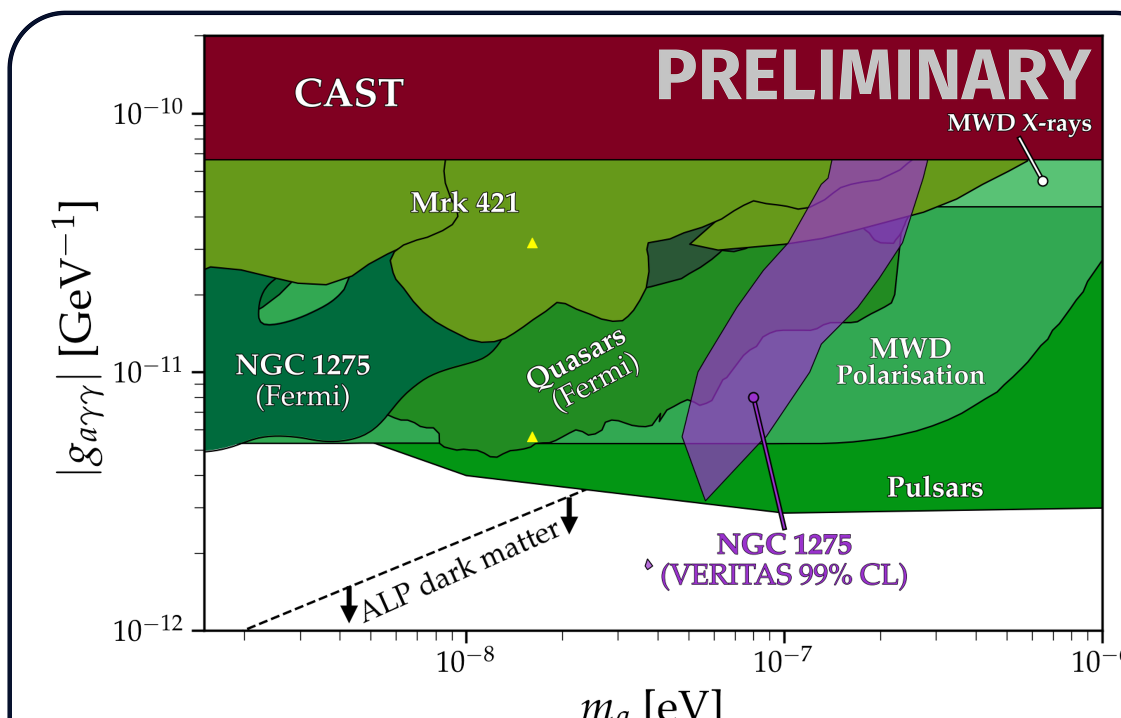

Fig. 5: Our 99% excluded region alongside excluded areas of the ALP parameter regime that can be probed with high-energy astrophysics experiments, adapted from [7].

Conclusions

- Constraints are consistent with and complementary to limits from previous studies
  - **First ALP study using γ-ray spectral data to constrain below the ALP dark matter line**
- Model assumptions and detector response are systematics which can weaken constraints [8]
- AGN flares also powerful tools to search for other spectral signatures, like propagation delays from Lorentz Invariance Violation (LIV)

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