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 ($g_{AP}$),
  - 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

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)

Data Analysis

- Joint likelihood analysis performed on Fermi energy-binned fluxes and VERITAS event-level data in gammapy$^3$ (see Fig. 3)
- Model ALP effect with gammapyALPs$^2$ 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:
  - $m_A ∈ [3, 700] \text{eV}$ $|\beta_A| ∈ [0.1, 10] \times 10^{-11}\text{GeV}^{-1}$
  - Evaluating the hypotheses on the existence of the ALPs:
    - $TS = -2 \ln \left( \frac{\lambda(m_A, |\beta_A|)}{\lambda(\text{no ALP}, |\beta_A|)} \right)$
    - $\lambda(m_A, |\beta_A|) = -2 \ln \left( \frac{\gamma_{\text{LAT}}(m_A, |\beta_A|)}{\gamma_{\text{LAT}}(\text{no ALP}, |\beta_A|)} \frac{\gamma_{\text{VERITAS}}(m_A, |\beta_A|)}{\gamma_{\text{VERITAS}}(\text{no ALP}, |\beta_A|)} \right)$
- Simulate 500 datasets to assess statistics, since Wilks’ theorem does not apply

Results

- Exclude the null hypothesis at 2.3$σ$
- Therefore, cannot claim the existence of ALPs
- Make exclusions at the 99% level for masses $m_A ≤ 50 − 200$ eV, for coupling constants down to $|\beta_A| ≥ 3 \times 10^{-13}$ GeV$^{-1}$
- See Fig. 4 for a detailed exclusion map and Fig. 5 for context with other experimental constraints

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 systematicatics 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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