Search for Axion-Like Particles with Observations of the Blazar Markarian 421 with VERITAS and Fermi-LAT

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Introduction

Axions are a consequence of the CP violating term added to the QCD Lagrangian in Peccei-Quinn theory as a proposed solution to the Strong CP problem. In numerous theories beyond the standard model, including in string theory, generalized versions of the axion appear, termed "axion-like particles." Axion-like particles (ALPs) are light, pseudoscalar particles, and like the axion, they are **expected to couple to photons in external magnetic fields** to compensate for spin difference (see Figure 1.a). However, unlike the axion, this coupling ($g_{a\gamma}$) is not related to mass (m_a), and thus, ALP parameters are significantly less theoretically constrained. Certain ranges of ALP mass and coupling strength have the **potential to induce modifications to the γ-ray spectra of astrophysical sources**, such as blazars, via ALP-photon oscillations in external fields near the source and in the Galactic magnetic field. A unique consequence is that very-high energy (VHE) γ rays could circumvent annihilation with the extragalactic background light (EBL) by traversing cosmic distances as oscillated ALPs, leading to enhanced transparency (Figure 1.b). In this work, we use γ-ray data from VERITAS and Fermi-LAT of the great Markarian (Mrk) 421 flare of 2010 to search for these signatures, and to set preliminary constraints on ALP mass and coupling constants. Numerous studies of this type have been pursued recently [1], including for this source [2].

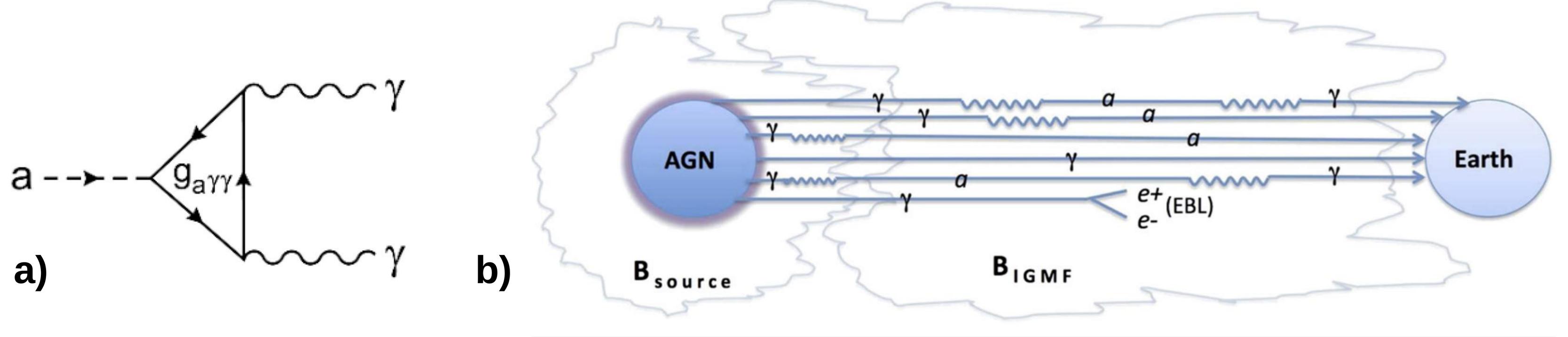

Figure 1.a: Feynman diagram for the two-γ ALP coupling. In presence of magnetic field, one γ line represents the B-field, the other represents the E-field of the propagating photon. From [1].
Figure 1.b: γ rays have the potential to oscillate between the ALP and photon state in the presence of external magnetic fields, such as those found in blazar jets as well as in the Milky Way. From [3].

Mrk 421 flare of 2010

Mrk 421 is a high synchrotron-peaked BL Lac (HBL) blazar located at a redshift of 0.031. During the month of February 2010, an **extraordinary flare of ~ 27 Crab Units** above 1 TeV was measured with the VERITAS observatory (Figure 2), the highest flux state for Mrk 421 ever observed in VHE γ rays [4]. Fermi-LAT and VERITAS combined are sensitive in the energy range 0.1 GeV – 30 TeV, and favorably for this flare, **exceptional data in the high energy portion of the VERITAS spectrum was collected**.

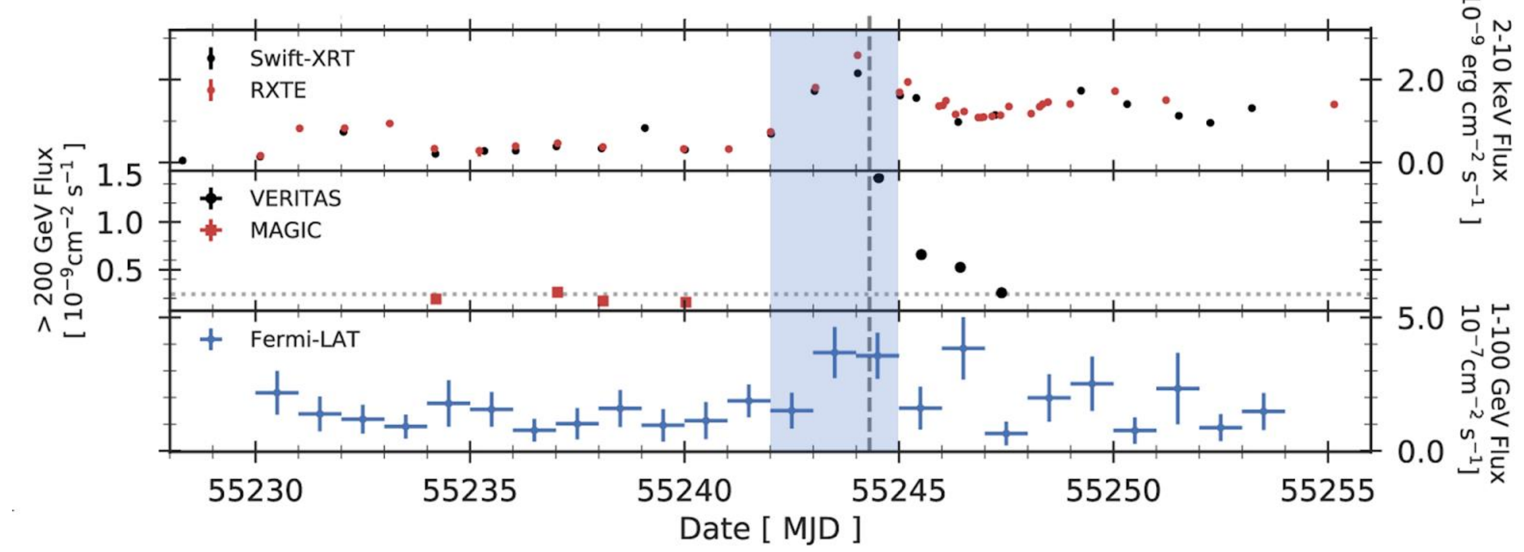

Figure 2: Mrk 421's 2010 flare as seen across several X-ray and γ-ray instruments, adapted from [4]. The blue shaded date range is the time period selected for use in this study.

Data Collection & Methods

Flare data from both Fermi-LAT and VERITAS were pre-processed in their respective analysis packages and imported into the *gammapy* γ-ray analysis package for a joint spectral analysis. The null hypothesis models the intrinsic spectrum (Φ_{int}) as an exponentially cut-off power law such that $\Phi_{obs,\,null}(E,z) = e^{-\tau(E,z)}\ \Phi_{int}(E)$, where $\tau(E,z)$ is the Dominguez inferred EBL attenuation [5]. The ALP effect is naturally subject to the conditions at the source environment as well as the choice of $g_{a\gamma}$ and m_a, and alongside EBL attenuation, their consequent photon survival probability ($P_{\gamma\gamma}$) can be modelled using the *gammaALPs* software package using the blazar jet parameters specified in Table 1, yielding $\Phi_{obs,\,ALP}(E,z) = P_{\gamma\gamma}\ \Phi_{int}(E)$.

Table 1: Representative blazar jet parameters for Mrk 421 during the 2010 flare, from [5]. r_{VHE} is the distance of the VHE emission site to the central black hole, B_0 the magnetic field strength at r_{VHE}, δ_D the doppler factor, n_0 the electron density at r_{VHE}, and θ_{obs} the angle between the jet axis and the line of sight.

r_{VHE} (10^{17} cm)	B_0 (G)	δ_D	n_0 (10^3 cm^{-3})	θ_{obs} (°)
1	0.092	17	0.825	1.3

Simulations & Data Analysis

Using *gammapy*, we fit the joint observed spectrum and yield a *WStat* fit statistic W, defined at [6]. Following from [1], to set exclusion regions on the ALP parameter space, a threshold value $W_{\rm th}$ must be defined:

$$W_{\rm th} = W_{\rm min} + \Delta W$$

where $W_{\rm min}$ is the minimum best-fit in the $m_a - g_{a\gamma}$ plane, and ΔW corresponds to a particular confidence level (CL). Given that the spectral modifications depend nonlinearly on the ALP parameters, we derive the value of ΔW from 400 event count simulations generated from the best-fit null hypothesis model with *fermipy* and *gammapy*. An example of fitting to simulated data is seen in Figure 3, and the ΔW can be derived from the TS distribution shown in Figure 4, where $TS = \widehat{W}_{null} - \widehat{W}_{wALP}$, and $\widehat{W}_{null}$ and $\widehat{W}_{wALP}$ are the fit statistics of the best fit null and ALP models respectively.

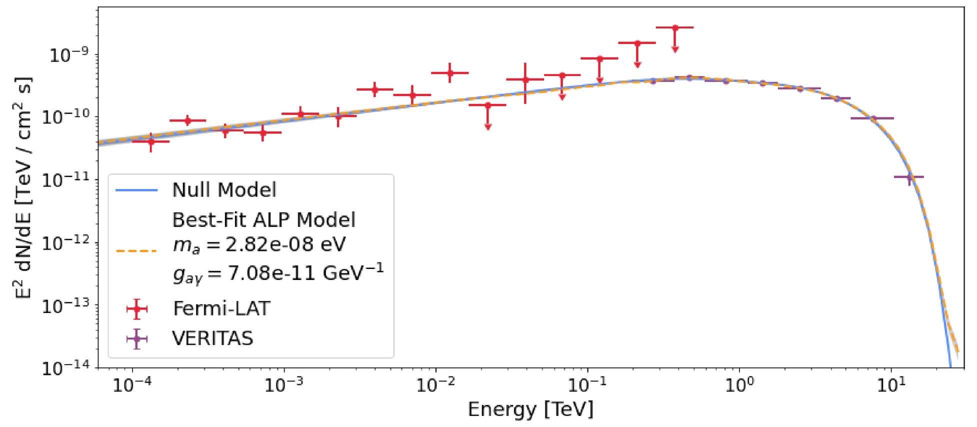

Figure 3: Best fit models with and without ALPs to simulated Fermi-LAT and VERITAS spectral data.

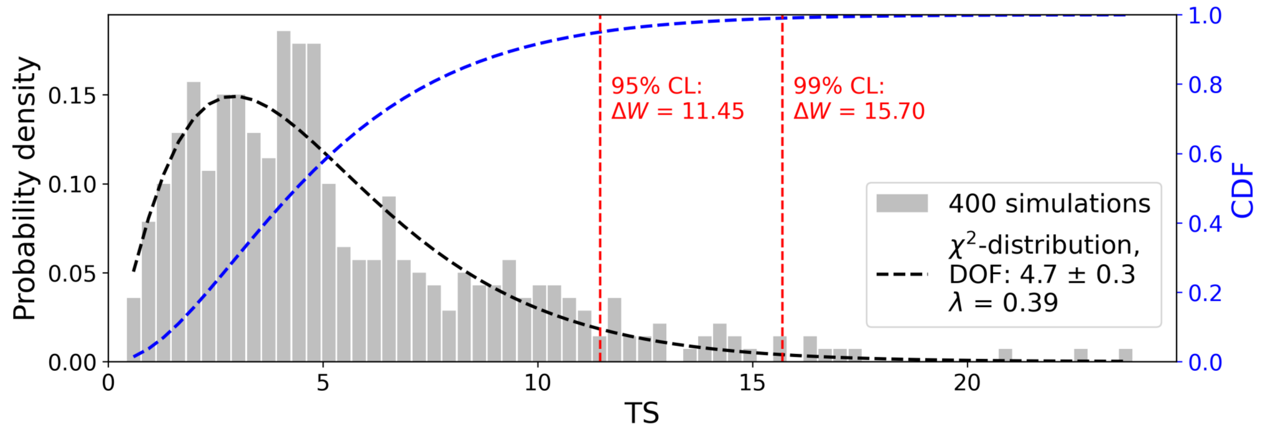

Figure 4: TS distribution for 400 simulated and analyzed datasets, fit by a non-central χ^2 distribution with 4.7 degrees of freedom and a non-centrality parameter of 0.39. ΔW for the 95% and 99% confidence levels are extracted from the cumulative density function (CDF) of the fitted distribution.

Results

Using the CLs derived from simulations, the 95% and 99% $W_{\rm th}$ are found to be 49.1 and 53.3 respectively. From these, we are able to preliminarily exclude certain regions of the $m_a - g_{a\gamma}$ space, as shown in Figure 5.

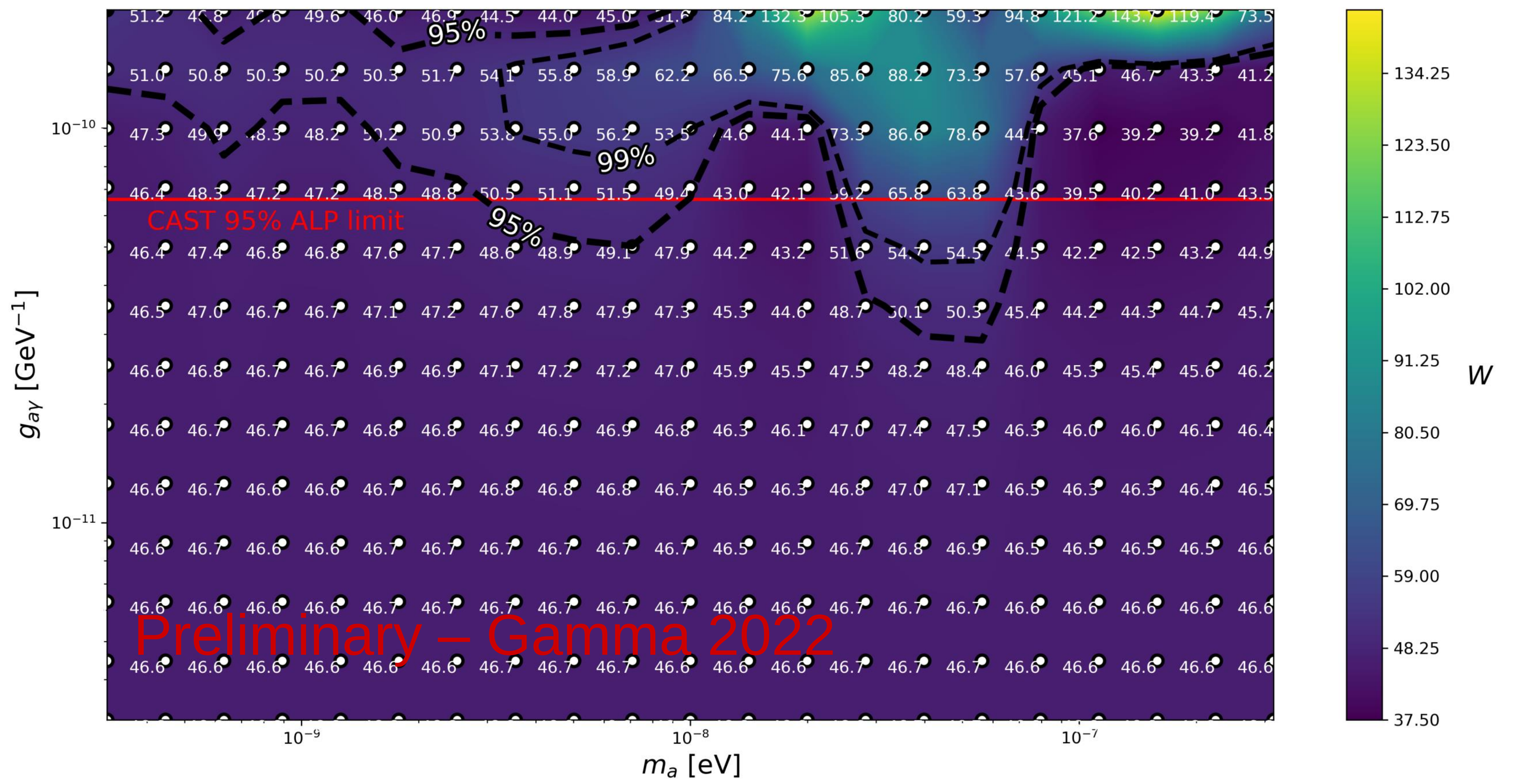

Figure 5: The W fit statistic shown in $m_a - g_{a\gamma}$ space with the 95% and 99% CLs demarcating the preliminary exclusion regions.

Summary

The extremely high flux state of Mrk 421's February 2010 flare make this dataset potentially impactful. However, many sources of uncertainty impact this calculation, including the uncertainty of high energy flux points with VERITAS, uncertainty of EBL models impacting this energy range, and uncertainties in the magnetic fields of the blazar jet. Until these can be properly considered in continued studies, these results must necessarily be considered preliminary. Nevertheless, we note that the preliminary results are **consistent with the findings of previous analyses to date** [7].

References

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