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DESY.

Hints of photon-ALP mixing effects observed in AGN gamma-ray energy spectra

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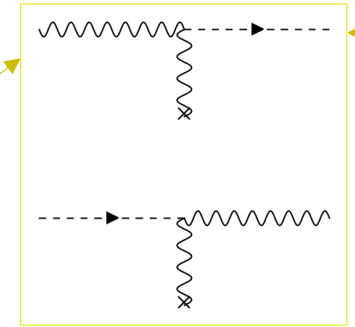
Based on arXiv: **2208.00079**

Overview

- Motivation
- Sample selection
- Analysis method
- Hypotheses testing
- Results
- Conclusions

Motivation

Photon-ALPs mixing

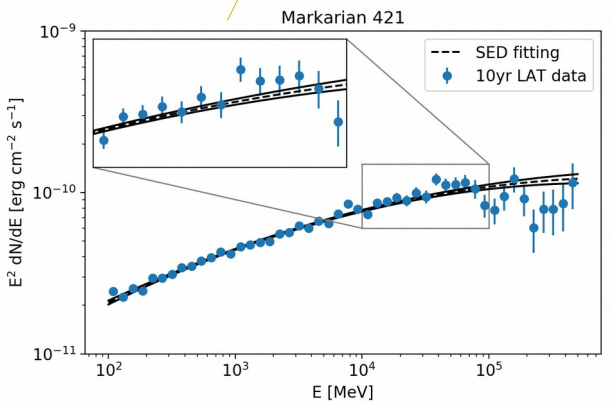


$$\mathcal{L} = -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} = g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{B}$$

The strength of the mixing is related to the photon-ALP conversion probability

$$p_{\gamma \to a} = \frac{2\Delta_{a\gamma}^2}{\Delta_{\rm osc}^2} \sin^2\left(\frac{s\,\Delta_{\rm osc}}{2}\right) \propto \frac{g_{a\gamma\gamma}^2 B^2}{m_a^2} s$$

Spectrum modulations?



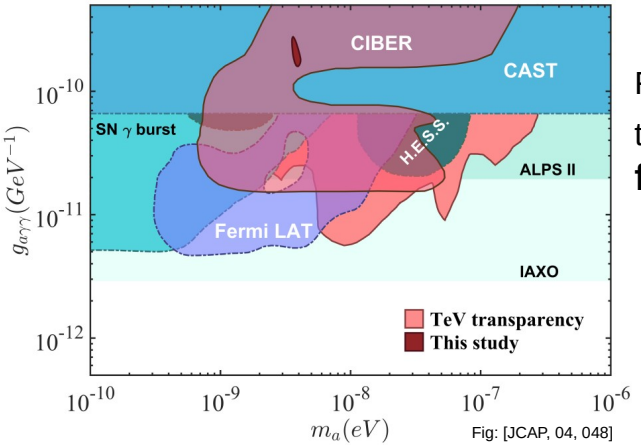


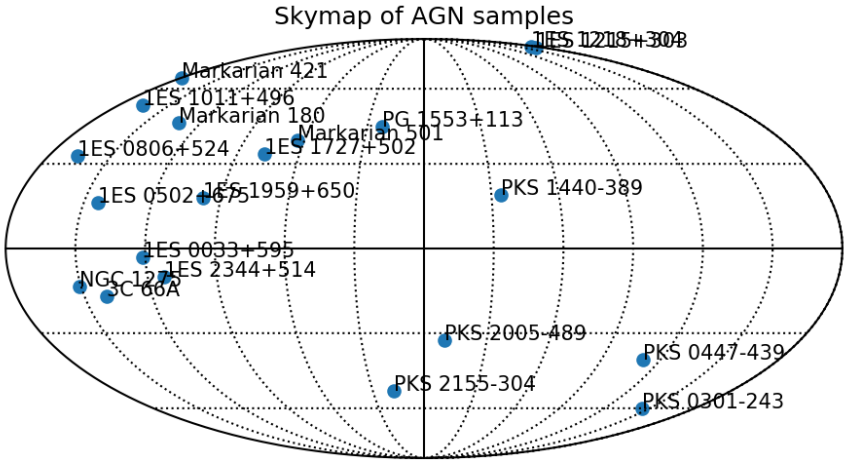
Fig: [JCAP, 04, 048]

Fix ($g_{a\gamma\gamma}$,m_a) from the pulsar analysis, **fit (B,s) instead**

First time of fitting B-field parameters

Sample source selection

Selection Criteria:
> source type: BL Lac (AGNs)
> Red shift: lower than 0.5
> TeV association: VHE sources (E>100GeV)
> Photon index: smaller than 2.0
> Detection sig: higher than 50simga
> Photon statistics: predicted photons more than 1600



Imposing these criteria, we are able to choose and collect the bright sources in which we have relatively small error bars on the observed flux, and potentially include VHE data with the broad energy band.

Analysis methodology

In order to have a better description for the modulations observed from the spectrum shown before, we fit the spectrum under ALP hypothesis and compare the fit without photon-ALP mixing using likelihood method.

Without photon-ALP mixing → H_0 : $\left(\frac{dN}{dE}\right)_{w/o\ ALP} = e^{-\tau_{\gamma\gamma}} \left(\frac{dN}{dE}\right)_{intr.}$

With photon-ALP mixing → H_1 : $\left(\frac{dN}{dE}\right)_{w/\ ALP} = e^{-\tau_{\gamma\gamma}} \left(\frac{dN}{dE}\right)_{intr.} P_{\gamma\gamma}(E, m_a, g_{a\gamma\gamma}, B, s)$

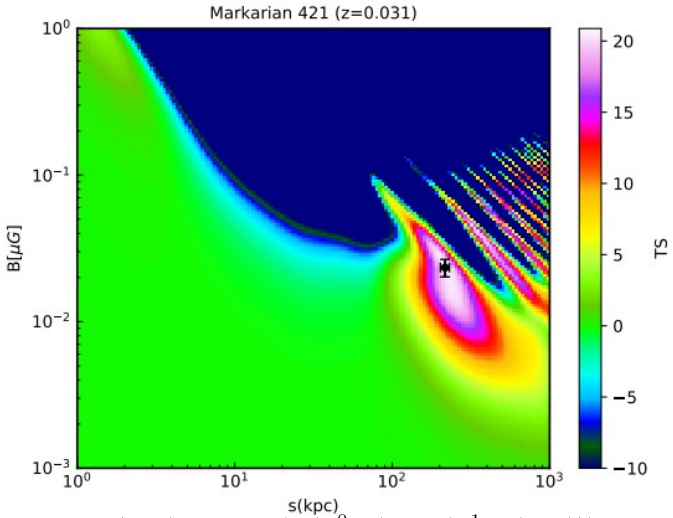
EBL correction — PL or LP model — Photon surviving probability

ALP parameters are fixed at $m_a = 3.6\,\mathrm{neV}$ and $g_{a\gamma\gamma} = 2.3 \times 10^{-10}\,\mathrm{GeV}^{-1}$

[JCAP, 04, 048]

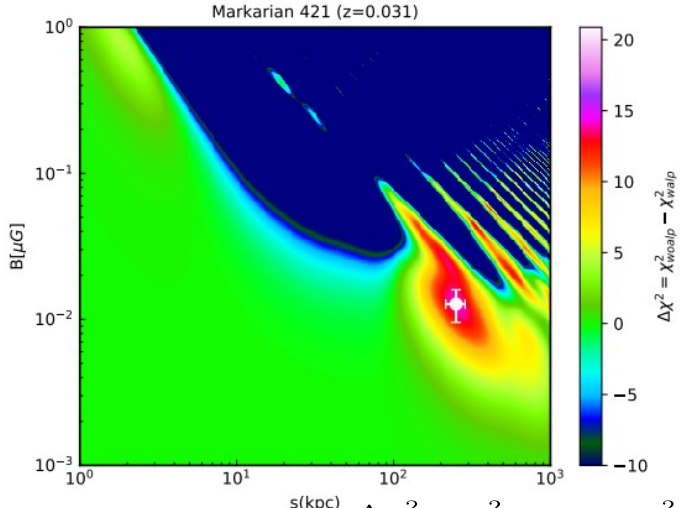
Best-fitting parameters under ALP hypothesis

Mkn 421 as an example



$$TS(B,s) = -2 \times (\ln(L^0_{max}) - \ln(L^1_{max}(B,s)))$$

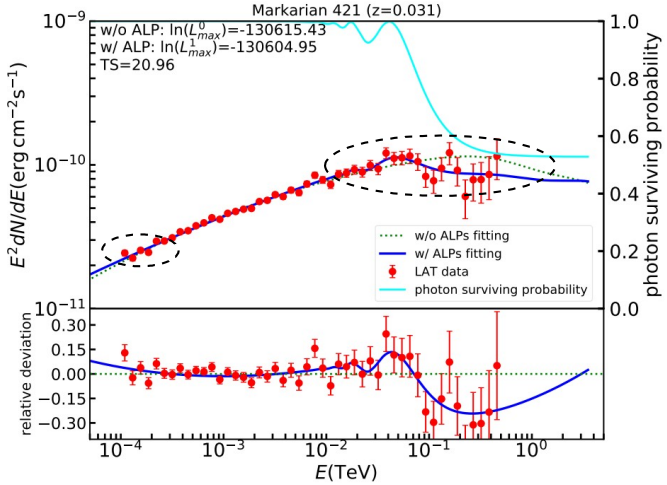
For consistency checking and conveniently including VHE data (if needed), chi2 fitting method is also performed

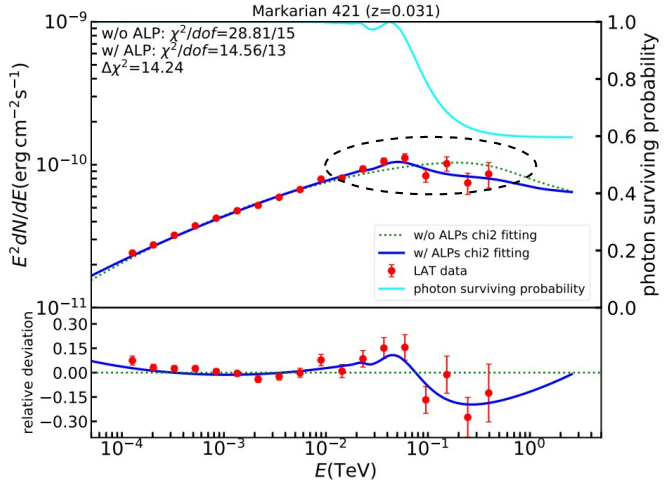


$$\Delta\chi^2 = \chi^2_{\mathrm{w/o\,ALP}} - \chi^2_{\mathrm{w/\,ALP}}$$

- Repetitive pattern Shown
- Both **global** and **local** maxima observed in the (B,s) grid map
- Maxima chosen standard:
- smallest value of B^2s^3, considered as minimum energy
- Similar oscillation pattern observed in both χ^2 and likelihood fitting.

Modulations induced by photon-ALP mixing



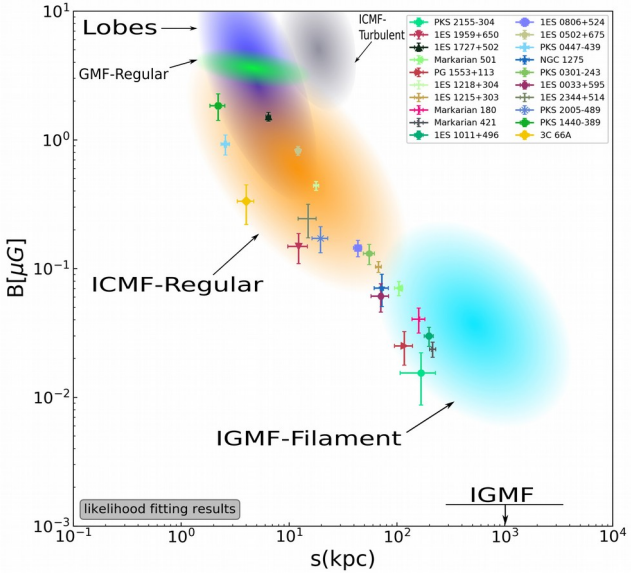


Weak mixing in the MeV energy, relatively strong photon-ALP mixing observed in GeV range

Best-fitting parameters for large-scale B-field model

- **Magnetic field in the outer regions of the jet (lobes)**
- **Intra-cluster with a turbulent and large-scale components in galaxy clusters**
- **Intergalactic in filaments**
- Intergalactic in voids and GMF are irrelevant

Overall best-fitting ranges for our Blazar samples:
Scale of B-field: 1 kpc ~ 200 kpc
Strength of B-field: 10 nG ~ 1 uG.



Hypotheses testing

For hypotheses testing, we introduce two tests here, likelihood ratio test and Δχ^2 test:

Likelihood ratio test: $TS(B,s) = -2 \times (\ln(L^0_{max}) - \ln(L^1_{max}(B,s)))$

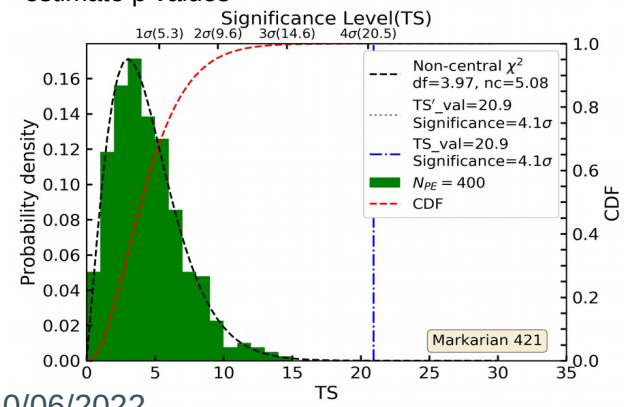
Δχ² test: $\Delta\chi^2 = \chi^2_{\mathrm{w/o\,ALP}} - \chi^2_{\mathrm{w/\,ALP}}$

In order to convert the resulted test statistic values into a significance, the underlying null distribution is required, from which a p_value can be determined

Estimating significance with simulations for one source

Likelihood ratio test:

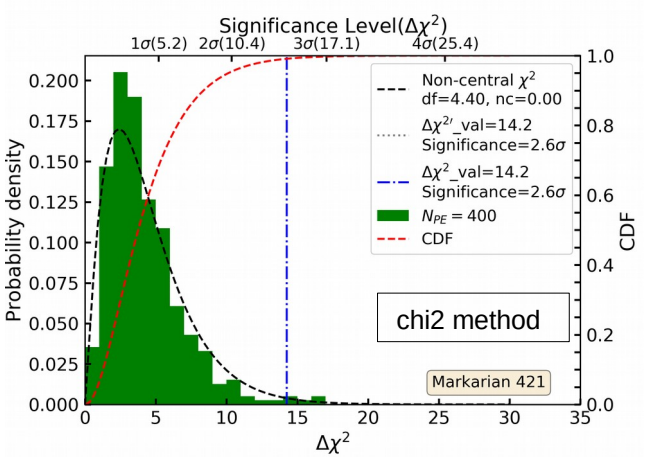
1. simulate 400 times the spectrum under H_0
2. fit each simulated spectrum under H_0 and H_1
3. calculate TS values with 400 fitted likelihood values under H_0 and H_1: TS=-2*(loglike$_0$-loglike$_1$)
4. fit the hist data with a non-central chi2 function to estimate p values



Following Wilk's theorem: the null distributions follow a χ^2 distribution (in this case, a non-central χ^2 distribution) when the number of the simulations is high enough. Observed as expected in our case.

$\Delta\chi^2$ test:

Following a similar way



Significance for all sources combined: bootstrapping method

In order to estimate the significance of improvement brought by photon-ALP mixing over all sample sources.

We first add all the test statistic values obtained from each source: $TS_{total} = \sum_{i=1}^{i=20} TS_i$

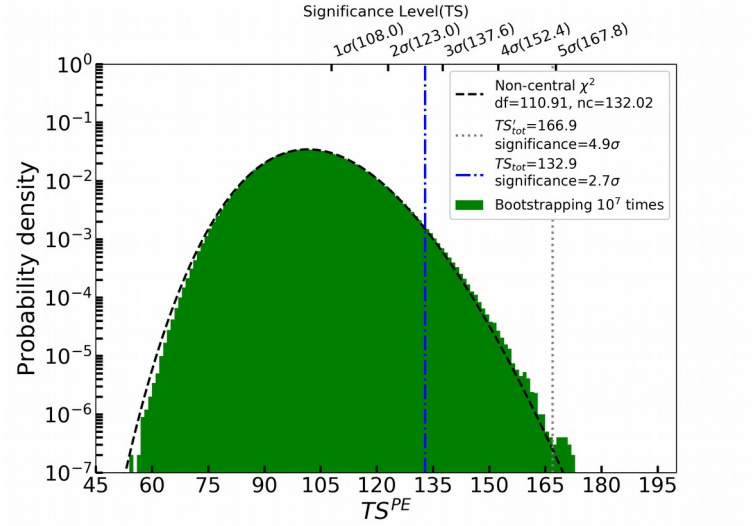
Then we combine the simulated test statistic values from the individual sources using bootstrapping method:

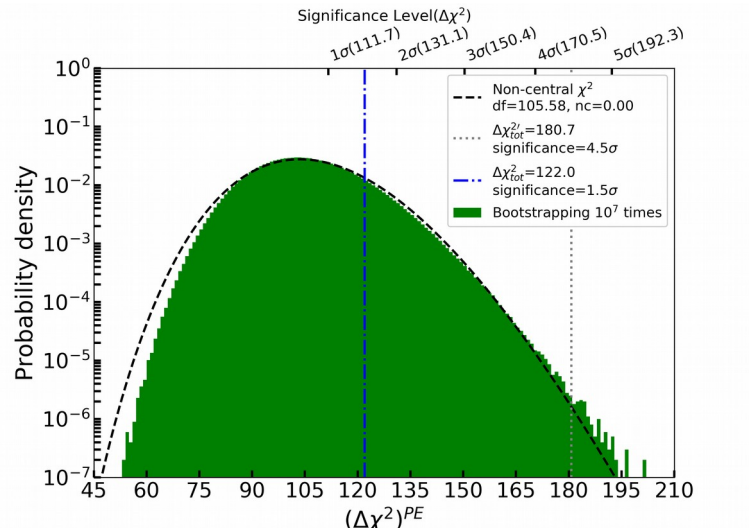
Pseudoexperiments: $PE = \{(TS_{n_1}, \ldots, TS_{n_{20}}) | n_1, \ldots, n_{20} \in \{1, \ldots, 400\}\}$

Calculating a distribution of 10^7 values of $\mathrm{TS}^{\mathrm{PE}}$ using a similar way as done in step one: $TS^{PE} = \sum_i TS_{n_i}$

Resulted with 10^7 $\mathrm{TS}^{\mathrm{PE}}$ values from pseudoexperiments, obtain a combined TS distribution, from which we can derive the p_value from the overall fit

Significance for all sources combined: results

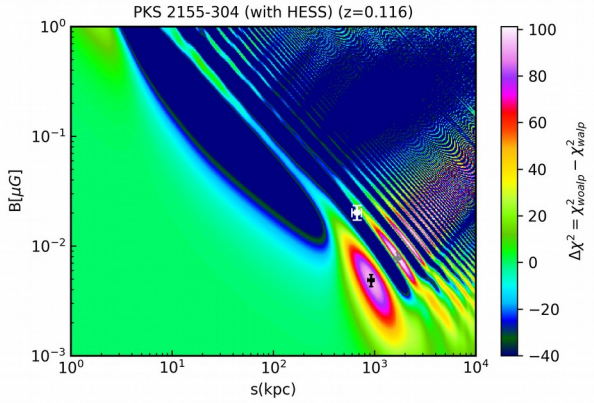


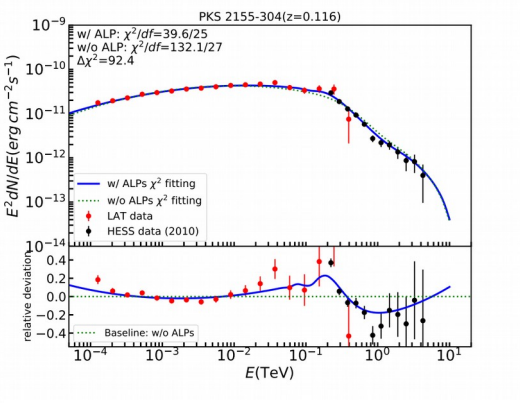


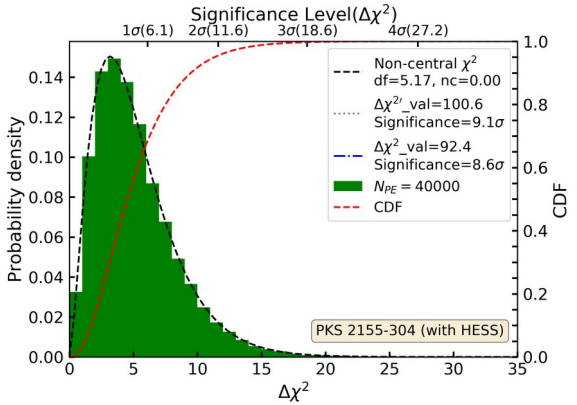
Blue dashed line: summed TS values of all sources from local maxima

Gray dotted line: summed TS values of all sources from global maxima

Combined spectra of PKS 2155-304: Fermi+HESS (time avg. data sets)





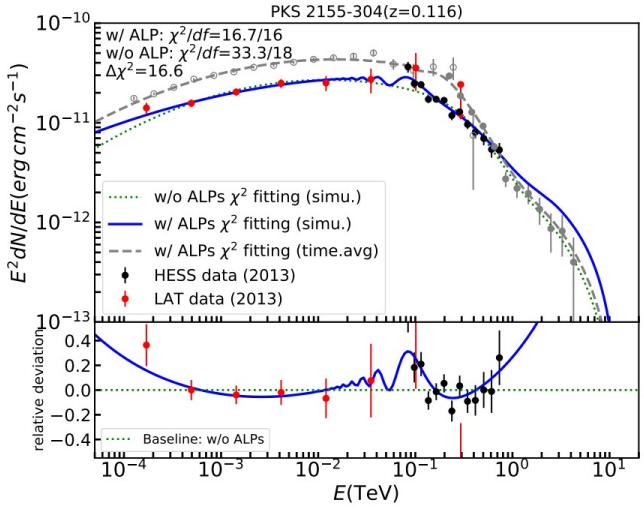


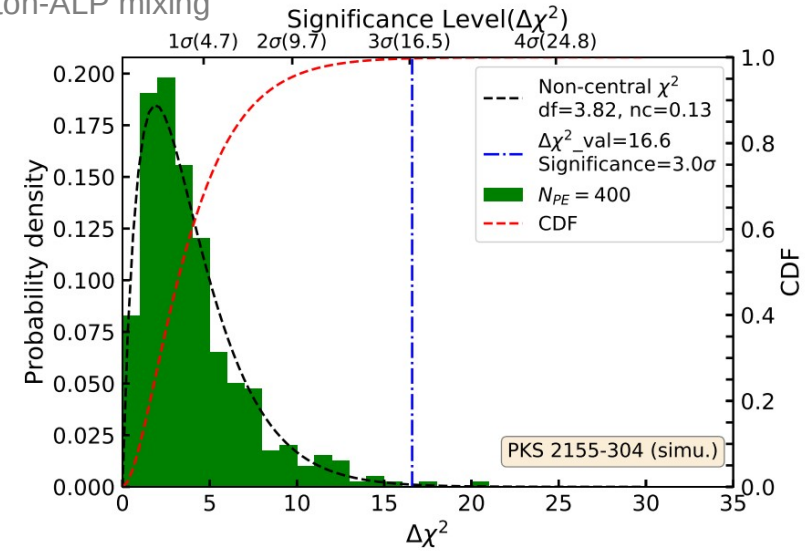
Observation years
LAT 2008-2018
HESS 2005-2007

8.6σ, signal??

Combined spectra of PKS 2155-304: Fermi+HESS (contemporaneous data sets)

Gray line in the background: time avg. data of PKS2155 with photon-ALP mixing

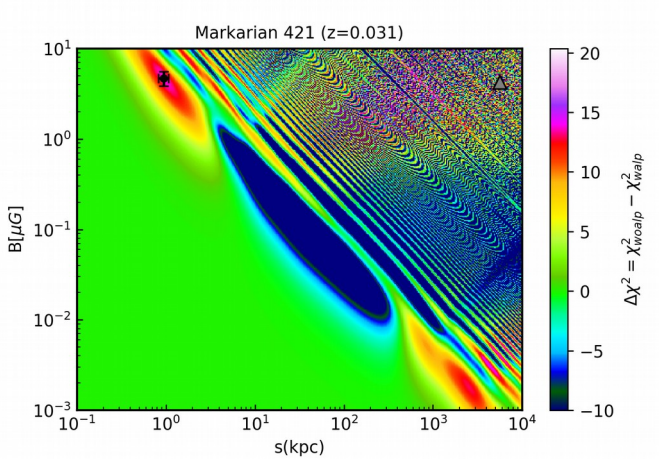


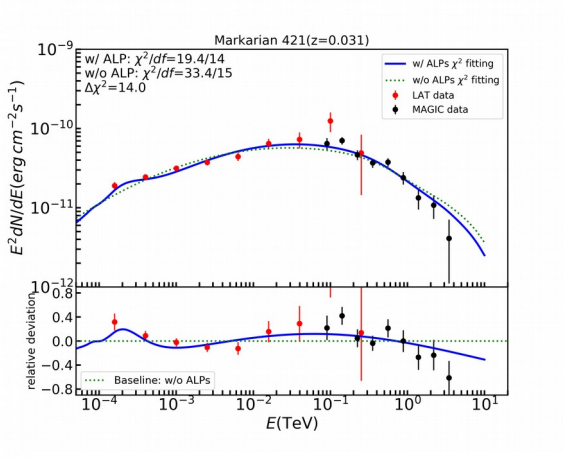


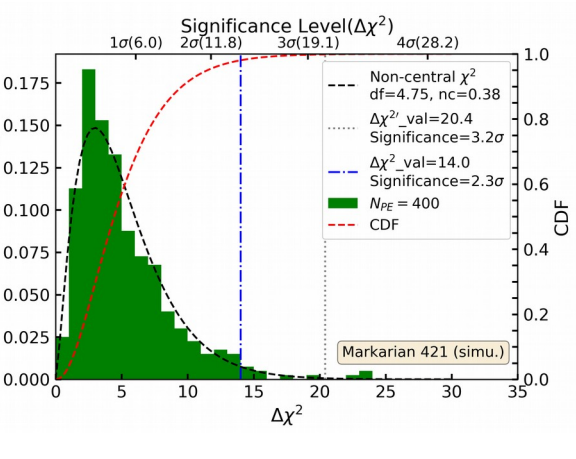
Short observation time in 2013 for both instruments

Combined spectra of Mkn 421: Fermi+MAGIC (contemporaneous data sets)

Check further if great significance could be observed in other spectra of a different src
Motivated by a similar spectra “overlap” in [Astrophys. J. 736, 131 (2011)]







Conclusions

- **First time study at fixed ALP parameters** ($g_{a\gamma\gamma}$, m_a) with varying B-field strengths and spatial scales.
- The fits to VHE spectra of 20 AGN sample srcs **improve significantly with 2.7σ(4.9σ)** when including photon-ALP mixing in a large-scale B field with spatial extension s left free (at fixed ALP paras)
- Out of samples, individual srcs, such as **Mkn421, NGC1275**, show strong indications for additional spectral features in Fermi-LAT observations.
- The significant of improvement increases when combining LAT data with measurements at VHE range for srcs, PKS2155. However, the significance found here were not contemporaneous and the consistency of two observations in the overlapping region could be coincidental.
- Previous constraints on mass and coupling of ALPS using HE and VHE spectra have been derived under the assumption of **a purely turbulent magnetic field which leads to excess fluctuations in the spectral residuals**. According to our results, the presence of additional turbulent fields is generally not favored but could be required for 3 of the 20 sources (ES0502, PKS2005 and PKS2155).
- The resulting best-fitting values for B-field strength are in well agreement with expected values for various astrophysical magnetic field environments characterized by length scales from several kpc to several 100 kpc

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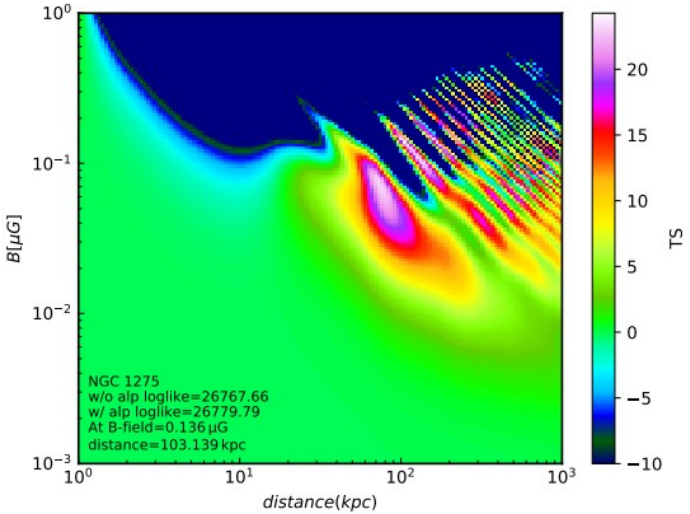
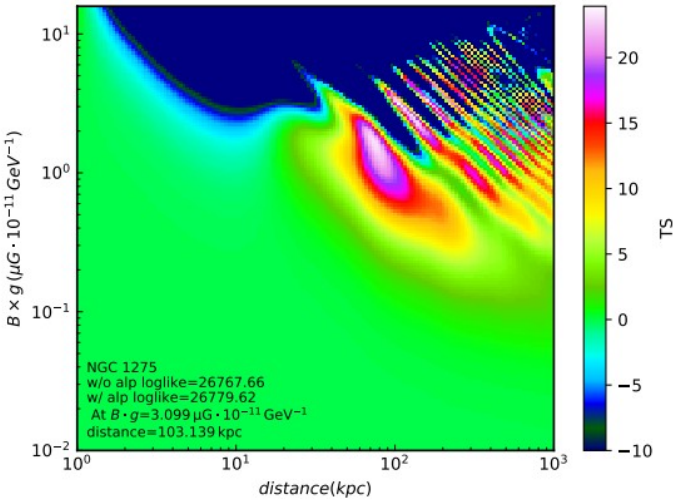
Backup slides

M_a kept fixed here, B and g show degeneracy, in regards to critical energy $E_c \rightarrow m_a^2 / (g_{arr} B)$





Backup slides

Photon-ALP oscillations inside a B-field