Implications of photon-ALP oscillations in the extragalactic neutrino source TXS 0506+056

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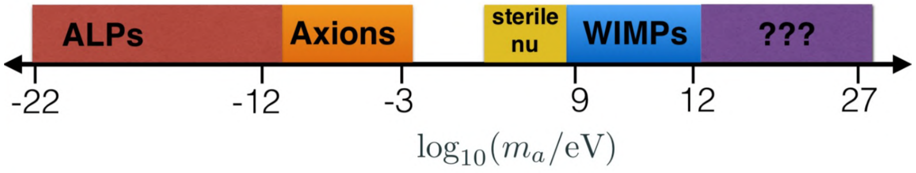
- Summary

What are Axion-like Particles (ALPs)?

- Pseudo-scalar (spin 0) bosons
- Extension of the axions; proposed solution of strong CP problem
- Belonging to family of weakly interacting sub-eV particles (WISPs)
- Viable cold dark matter candidate



Credit: Milena Crnogorčević

Photon-ALP oscillations:

In the presence of an external magnetic field, ALPs undergoes a conversion into gamma-rays:

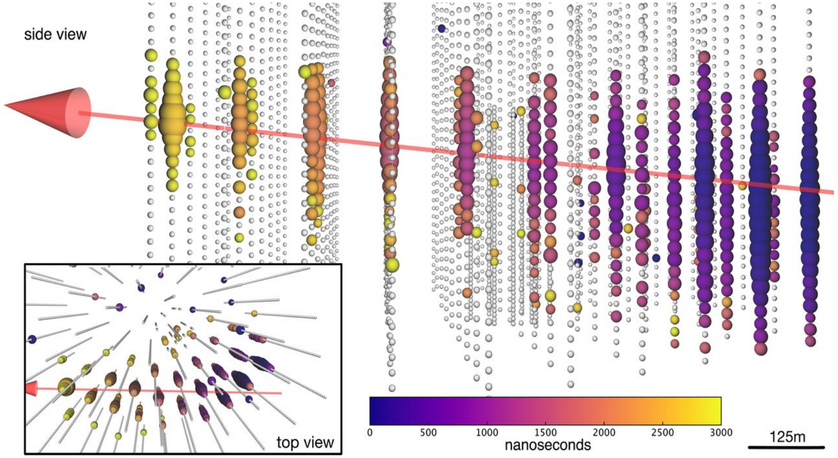
$$\mathcal{L}_{a\gamma} = -\frac{1}{4} g_{a\gamma\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a = g_{a\gamma\gamma} \mathbf{E} \cdot \mathbf{B} a$$

Coupling constant

Axion field

TXS 0506+056 Blazar

- First ever extragalactic sub-PeV neutrino source
- On September 22, 2017, IceCube detected ~290 TeV mu neutrino from the blazar direction (IC170922A)
- Soon follow-up observations were performed in various energy bands
- ~41hr and ~74 hr observations of VHE events by MAGIC b/w September 2017 to December 2018
- Prior to the IC20170922A alert, the source showed neutrino excess b/w September 2014 to March 2015



M. G. Aartsen et al., Science 361, eaat1378 (2018)

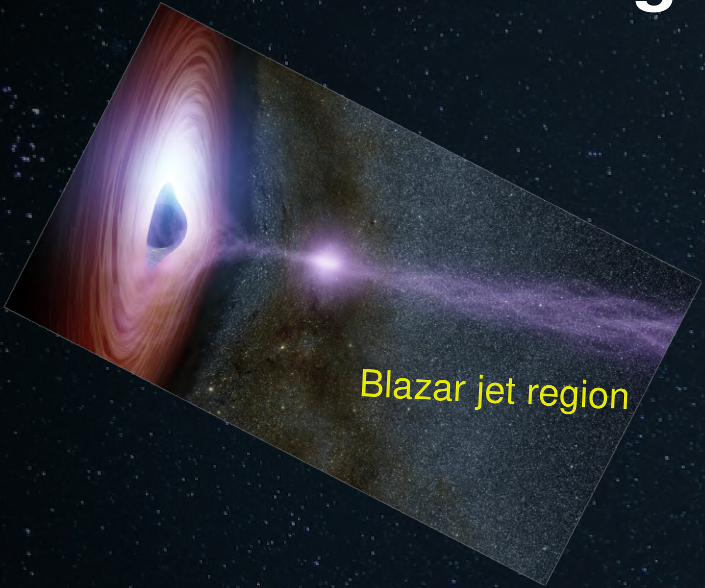
Work's aims

- To constrain ALP paramters by analyzing three phases:
  - ➔ Neutrino flare 2014 (September 2014 to March 2015)
  - ➔ VHE flare (4 September, 2014 to 3 November, 2017)
  - ➔ VHE quiescent (4 November, 2014 to 10 October, 2017)

- Photon-ALP oscillation effect on counterpart gamma-rays

- ALP effect on diffuse gamma-ray flux from FSRQs, High-synhrotron peaked (HSPs), and Low-intermediate-synchrotron peaked (LISPs)

Magnetic field environments



Intergalactic region

Galactic region

Magnetic field environments

Blazar jet region:

We adopt the toroidal magnetic field strength:

$$B^{\rm jet}(r) = B_0^{\rm jet}\left(\frac{r}{r_{\rm VHE}}\right)^{\eta}$$

$r_{\rm VHE}$ is the distance b/w VHE gamma-ray emitting region and the central black hole

Here, $\eta = -1$

Inter-galactic region:

- Actual strength is still unknown on the cosmological scale ~O(1) Mpc
- Currently accepted limit is ~O(1) nG
- We neglect the effect due to IGMF, and consider only the absorption by EBL
- EBL model by Domínguez.

A. Domínguez, M. Sánchez-Conde, and F. Prada, J. Cosmol. Astropart. Phys. 11 (2011) 020

Magnetic field environments

Galactic region:

- Both large scale regular and small scale random components
- Neglected random component due to coherence length being smaller than the oscillation length
- We used model by Jansson and Farrar.

R. Jansson and G. R. Farrar, Astrophys. J. 757, 14 (2012).

We calculated photon-ALP oscillation probability using gammaALPs package

M. Meyer, J. Davies, and J. Kuhlmann, Proc. Sci. ICRC2021 (2021) 557.
(https://gammaalps.readthedocs.io/en/latest/index.html.)

Methodology

Intrinsic spectrum: We fit the deabsorbed Fermi-LAT and MAGIC data points with

$$\Phi_{\text{int}}(E) = N_0 \left(\frac{E}{E_0}\right)^{-\alpha} \exp\left[-\left(\frac{E}{E_{\text{cutoff}}}\right)^{\beta}\right]$$

Super-exponential cutoff

E_0 = 1 GeV and rest are free parameters

Expected spectrum:

$$\Phi^{\exp}(E_\gamma) = \frac{\int_0^\infty D(E_t, E_\gamma^i, E_\gamma^j)\Phi_{wALP}(E_t)dE_t}{E_\gamma^i - E_\gamma^j}$$

Energy bin edges

Energy dispersion function assumed to be a Gaussian

(Fermi-LAT: 15% and MAGIC: 16%)

$$\Phi_{wALP}(E) = P_{\gamma\gamma}^{\text{ALP}}\Phi_{\text{int}}(E)$$

Photon survival probability
under photon-ALP oscillation

Methodology

Chi^2 fitting:

$$\chi^2 = \sum_{i}^{N_{\mathrm{bins}}} \left(\frac{\Phi_i^{\mathrm{exp}}(E_\gamma) - \Phi_i^{\mathrm{obs}}(E_\gamma)}{\sigma_i} \right)^2$$

Best fit m_a and $g_{a\gamma}$ are calculated by minimizing chi2

Phase	m_a (neV)	$g_{a\gamma}$ (x 10^{-11} GeV^{-1})
Neurino flare 2014	4.47	39.81
VHE flare	17.78	35.48
VHE quiescent	11.22	94.42

Constraint on ALP parameters

- Generated 400 sets of pseudo-data realized by Gaussian sampling

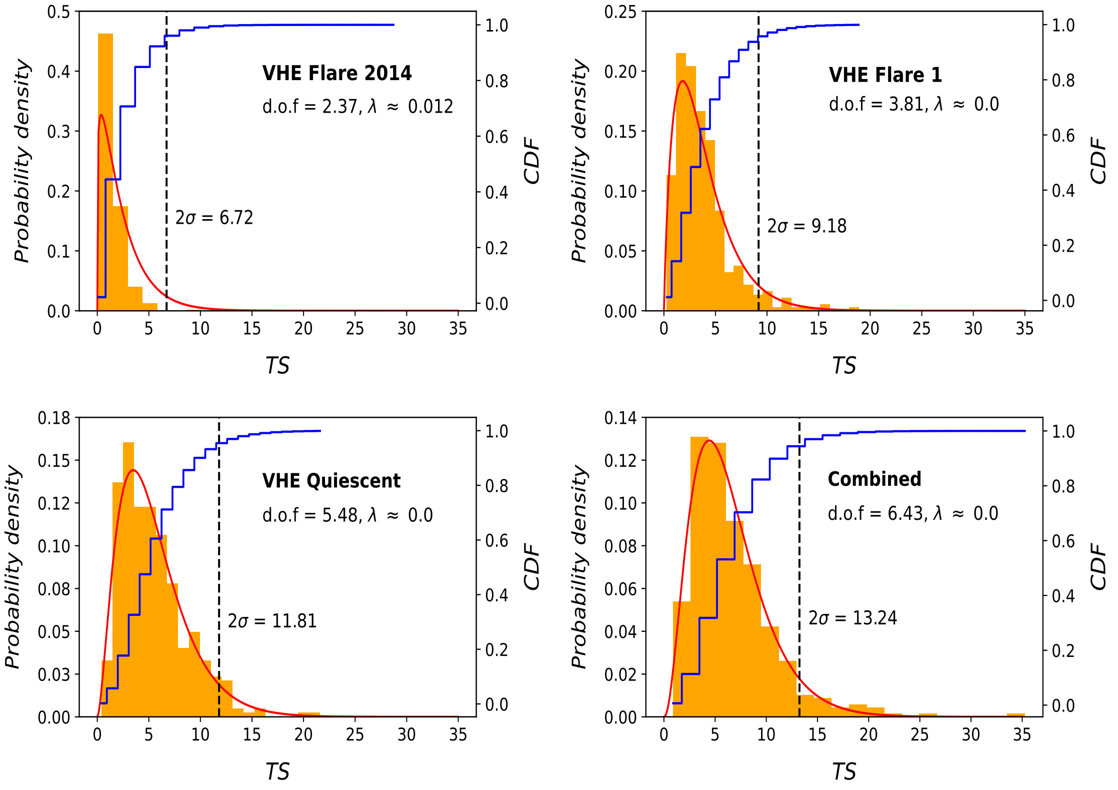
  Mean: best-fit flux value under null hypothesis

  Sigma: experimental data errors

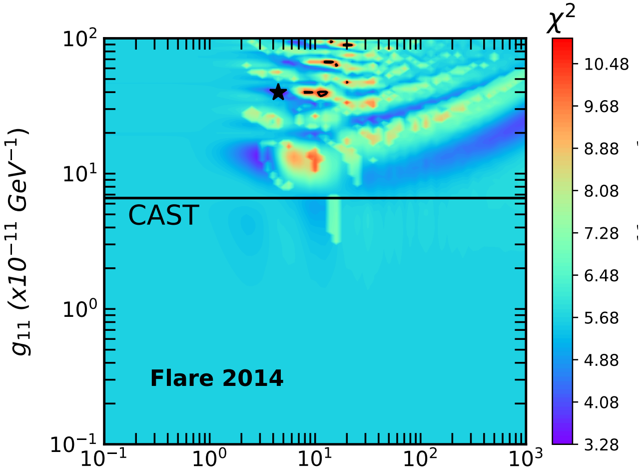
- For each set, we calculated best-fit chi^2 under both the null and ALP hypotheses

$$TS = \chi^2_{\rm null} - \chi^2_{\rm ALP}$$

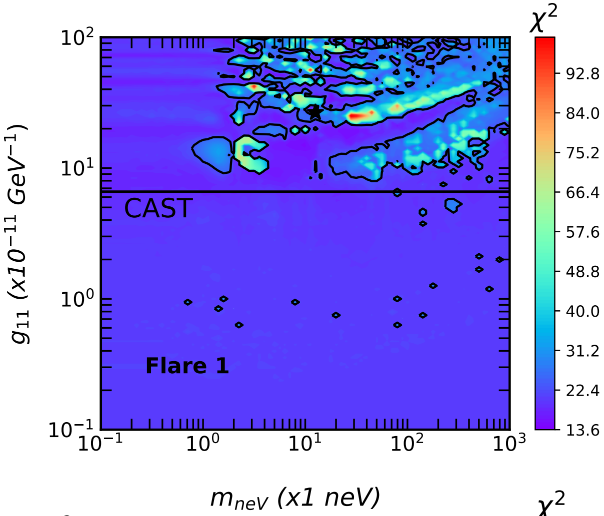
- Fitted the TS distribution with the non-central chi^2 distribution to obtain exclusion region



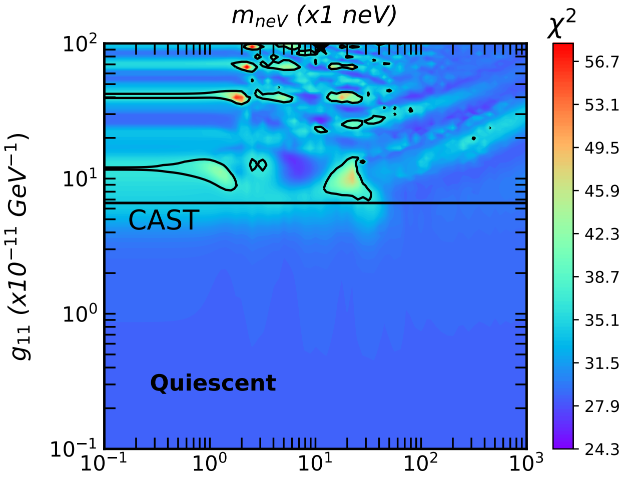
Constraint on ALP parameters



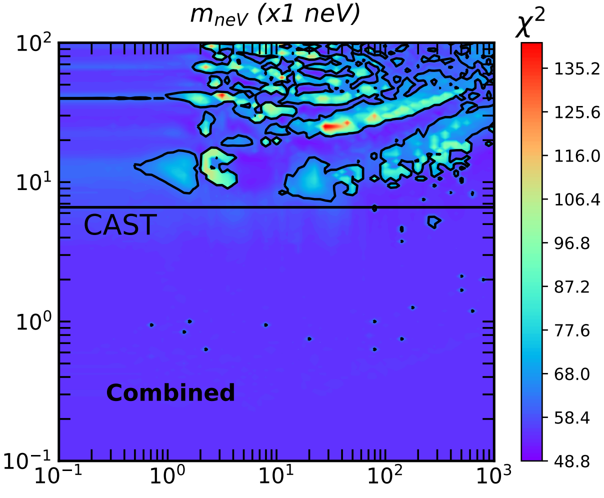
No significant constraint

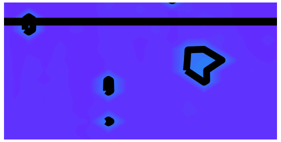


Weak constraint



Not better than CAST





Overall weak constraint

Photon-ALP oscillation effect at sub-PeV energies

Assumed counterpart gamma-rays from p-p interaction following:

$$E_\gamma^2 \cdot \frac{dN_\gamma}{dE_\gamma} = \frac{2}{3} E_\nu^2 \cdot \frac{dN_\nu}{dE_\nu}$$

Escape fraction for VHE photons:

$$\mathcal{F}_{\gamma\gamma}^{\rm esc} = \frac{1 - \exp\left(-\tau_{\gamma\gamma}(\epsilon'_\gamma)\right)}{\tau_{\gamma\gamma}}$$

with optical depth given as:

$$\tau_{\gamma\gamma}(\epsilon'_\gamma) = R'_{\rm blob} \int_{\epsilon_{\rm thr}} \sigma_{\gamma\gamma}(\epsilon'_\gamma, \epsilon'_k) n'_k(\epsilon'_k) d\epsilon'_k$$

Pair-production cross section

no. density of ambient photons

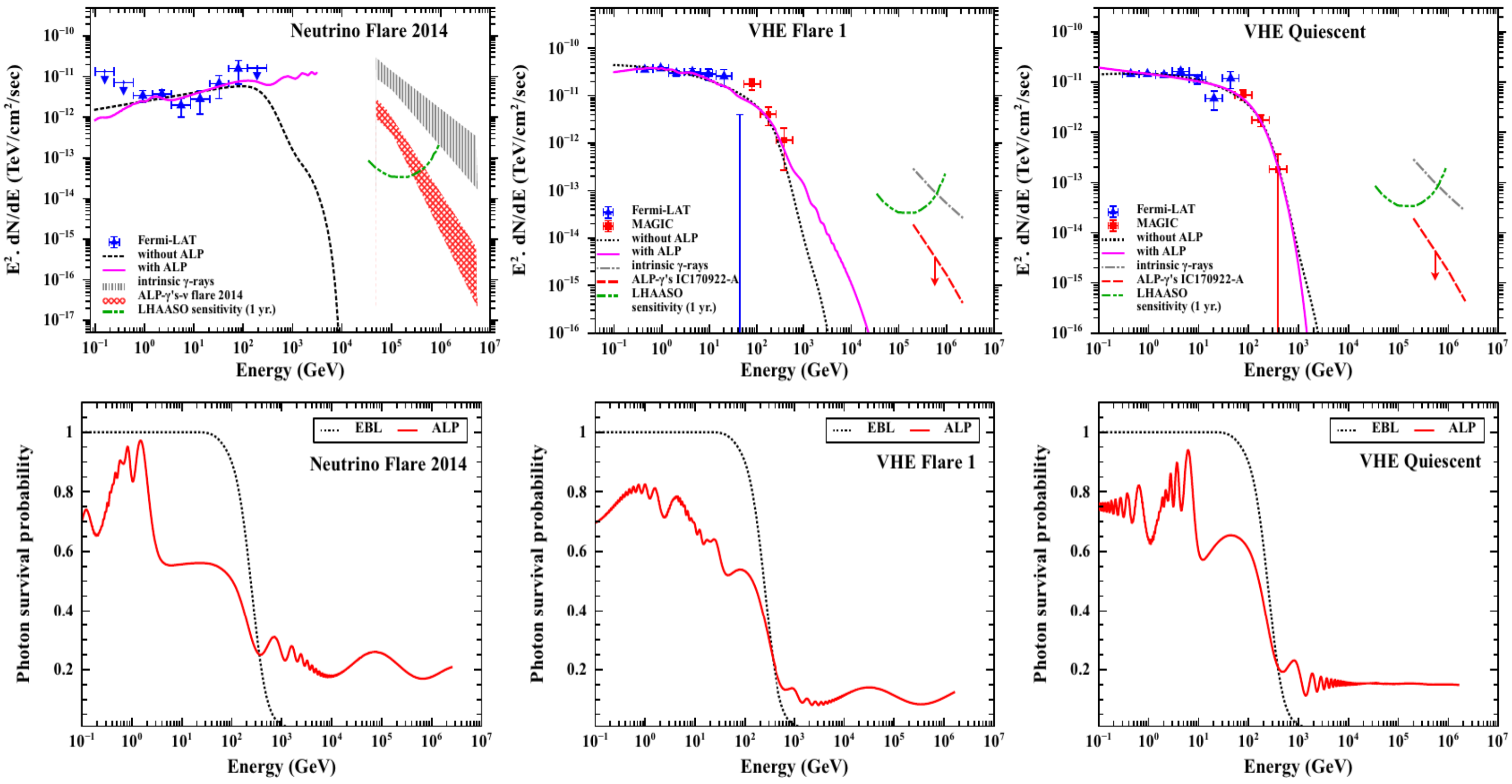
Photon-ALP oscillation effect at sub-PeV energies

Intrinsic gamma rays:

$$E_\gamma^2 \cdot \frac{dN_\gamma}{dE_\gamma} \cdot \mathcal{F}^{\rm esc}_{\gamma\gamma}$$

ALP-gamma rays:

$$E_\gamma^2 \cdot \frac{dN_\gamma}{dE_\gamma} \cdot \mathcal{F}^{\rm esc}_{\gamma\gamma} \cdot e^{-\tau^{\rm ALP}_{\gamma\gamma}(E,z)}$$



ALP effect to diffuse gamma-rays

$$\Phi_{\rm diff}(E_\gamma) = \int_{\Gamma_{\rm min}}^{\Gamma_{\rm max}} \frac{dN}{d\Gamma} d\Gamma \int_{z_{\rm min}}^{z_{\rm max}} \frac{d^2V}{dz d\Omega} dz \int_{L_\gamma^{\rm min}}^{L_\gamma^{\rm max}} dL_\gamma \;\rho(L_\gamma, z). \frac{dF_\gamma^{\rm int}}{dE} .e^{-\tau_{\gamma\gamma}^{\rm ALP}(E,z)}$$

Intrinsic photon index distribution

Comoving volume

Gamma-luminosity function

Intrinsic photon flux

Gamma-luminosity function (GLF):

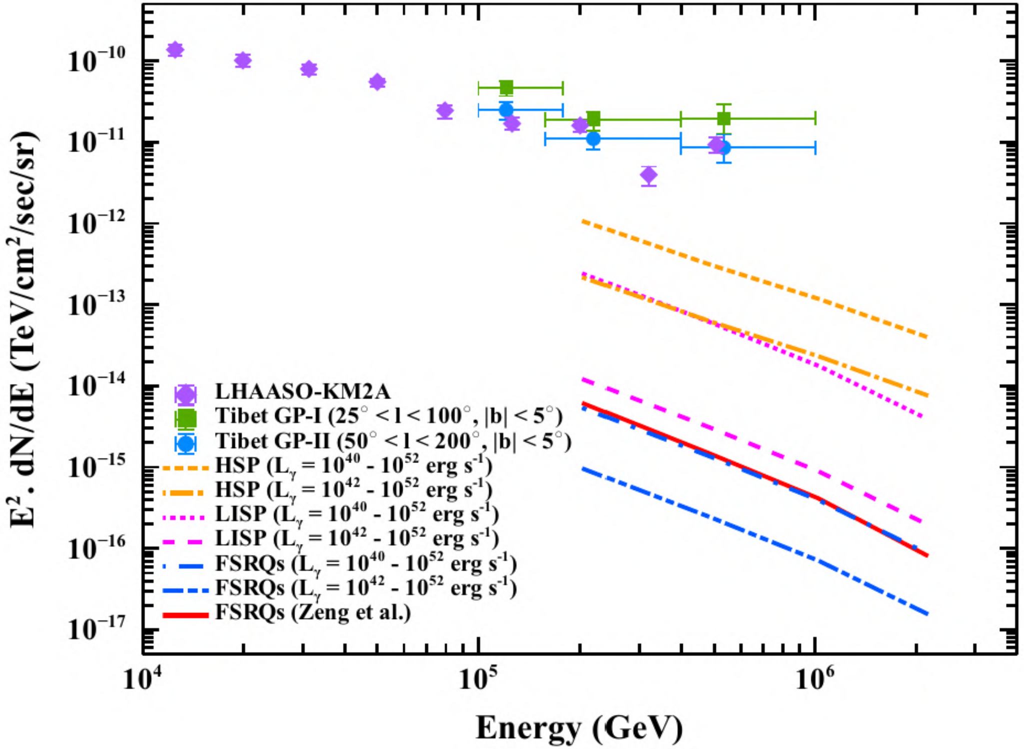
$$\rho(L_\gamma, z) = \frac{A}{log(10).L_\gamma}\left[\left(\frac{L_\gamma}{L_c}\right)^{\delta 1} + \left(\frac{L_\gamma}{L_c}\right)^{\delta 2}\right]^{-1} \zeta(L_\gamma, z)$$

Luminosity dependent density evolution

$$\zeta(L_\gamma, z) = \left[\left(\frac{1+z}{1+z_c(L_\gamma)}\right)^{\eta 1} + \left(\frac{1+z}{1+z_c(L_\gamma)}\right)^{\eta 2}\right]$$

ALP effect to diffuse gamma-rays

- Four classes:
  - FSRQs
  - High-synhrotron peaked (HSPs)
  - Low-intermediate-synchrotron peaked (LISPs)



Summary

- Investigate the effect of photon-ALP oscillations on the first ever extragalctic neutrino source TXS 0506+056

- Exclusion on ALP coupling parameter: $g_{a\gamma} < 5 \times 10^{-11}$ GeV^{-1} (95% C.L.)

- Implications of photon-ALP oscillations on the counterpart gamma-rays of the sub-PeV neutrinos from TXS 0506+056

- Diffuse gamma-ray flux under ALP effect for FSRQs, HSPs, and LISPs.

Thanks for your attention!

Backup

Summary of best-fit chi^2 values

Phase	$\chi^2_{\mathrm{w/o\,ALP}}$	χ^2_{ALP}	m_{neV}	g_{11}	$\Delta\chi^2$
Neutrino Flare 2014	5.65	3.31	4.47	39.81	6.72
VHE Flare 1	20.48	13.73	17.78	35.48	9.18
VHE Quiescent	28.79	24.47	11.22	94.41	11.81