భారతీయ సాంకేతిక విజ్ఞాన సంస్థ హైదరాబాద్
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Probing photon-ALP oscillations from the FSRQ B1420+326

Bhanu Prakash Pant
Department of Physics,
Indian Institute of Technology Jodhpur,
India
email: pant.3@iitj.ac.in

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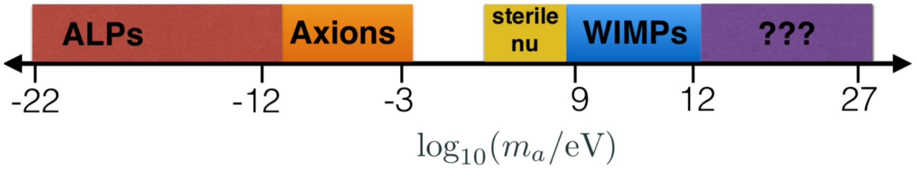
- Summary

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

FSRQ QSO B1420+326

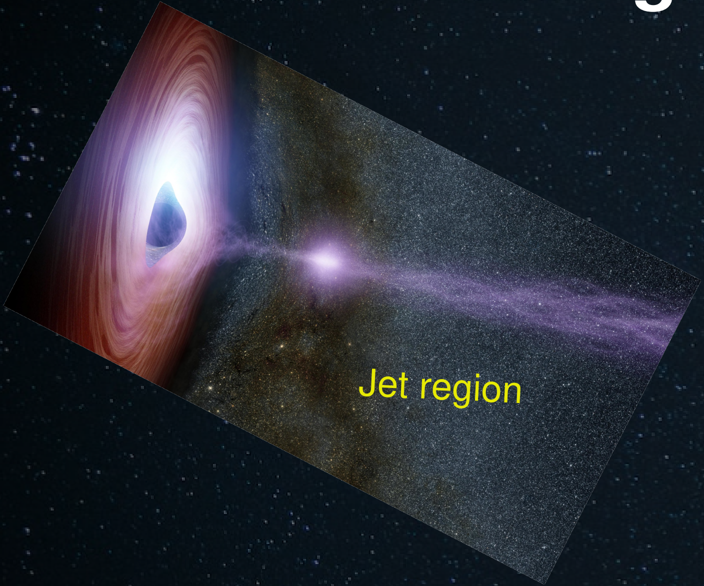
- Fourth most distant blazar at a redshift 0.682; classified as flat-spectrum radio quasar (FSRQ)
- Repeatedly observed in high-energy (HE) state by *Fermi*-LAT
- Soon follow-up observations were performed by Major Atmospheric Gamma Imaging Cherenkov Telescopes (MAGIC)
- First significant (~14.3σ) observation above 100 GeV by MAGIC on 20 January 2020 in 1.6 h of exposure time
- Further hints of significant excess in subsequent days with highest significance of (~6.6σ) on 31 January 2020 with exposure time of 2.5 h

Why FSRQs? They provide significant statistics in flaring state

Work’s aims

- To constrain ALP parameters by using gamma-ray observations
- Expected neutrino flux and contribution of FSRQs to diffuse neutrino flux
- Photon-ALP effect on counterpart gamma-rays at sub-PeV energies
- Photon-ALP effect on diffuse gamma-ray flux from FSRQs

Magnetic field environments



Jet region

Intergalactic region

Galactic region

Magnetic field environments

Blazar jet region:

We adopt the toroidal magnetic field strength:

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

r_{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
- We used GMF 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.)

Fermi-LAT analysis

- We consider two phases:
  - ➔ VHE flare (20 January, 2020 to 22 January, 2020)
  - ➔ Post flare (22 January, 2020 to 01 February, 2020)

- We use Pass 8 processed data from Fermi Science Data Center (FSDC)

- We select 10° region of interest (ROI) centered on the source

- Data are binned into 8 bins per decade b/w 100 MeV – 300 GeV

- Used pre-processed template of Galactic and extragalactic diffuse emission

Methodology

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

$$\Phi_{int} = N_0 \left(\frac{E}{E_0} \right)^{-\alpha} \exp\left(\frac{-E}{E_{cut}} \right)$$

Power law with exponential cutoff

E_0 = 1 GeV and rest are free parameters

Phase	N_0 (x10^{-10}) [$\mathrm{MeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	α	E_{cutoff} [GeV]
VHE Flare	1.86(0.19)	1.87(0.08)	50.90(17.37)
Post Flare	1.33(0.11)	1.99(0.05)	46.49(8.06)

Expected spectrum:

$$\phi_{alp} = \Phi_{int} \cdot \mathcal{P}_{alp}(E)$$

Photon survival probability under photon-ALP oscillation

Methodology

χ^2 fitting:

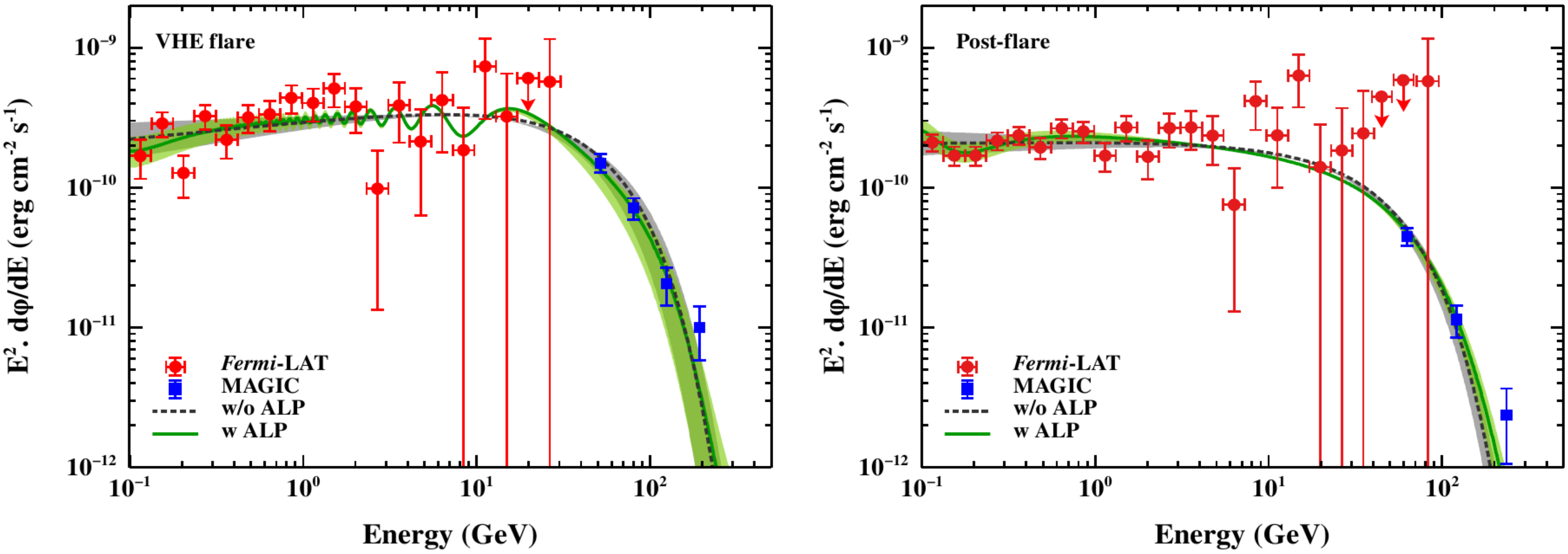
Scanning m_a and $g_{a\gamma}$ parameter space by dividing it into 40 x 30 logarithmic bins

$$\chi^2 = \sum_{i=1}^{N} \left(\frac{\Psi_i^{obs} - \phi_i^{exp}}{\sigma_i} \right)^2$$

Best fit m_a and $g_{a\gamma}$ are calculated by minimizing χ^2

Phase	m_a (x 10^{-9} eV)	$g_{a\gamma}$ (x 10^{-11} GeV^{-1})
VHE flare	3.68	5.30
Post flare	0.40	3.86

Photon-ALP oscillation effect on the gamma-ray spectra



Constraints on ALP parameters

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

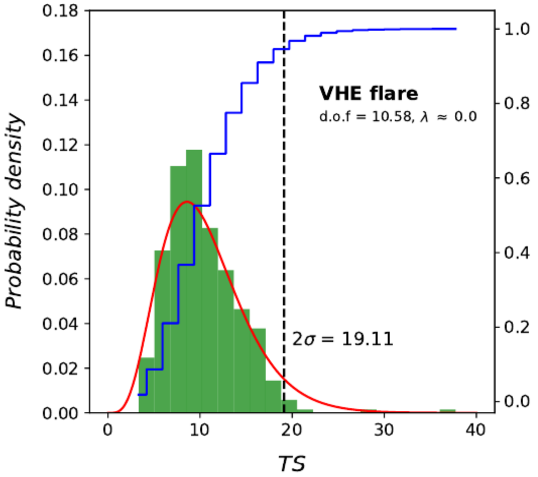
  Mean: best-fit flux value under null hypothesis

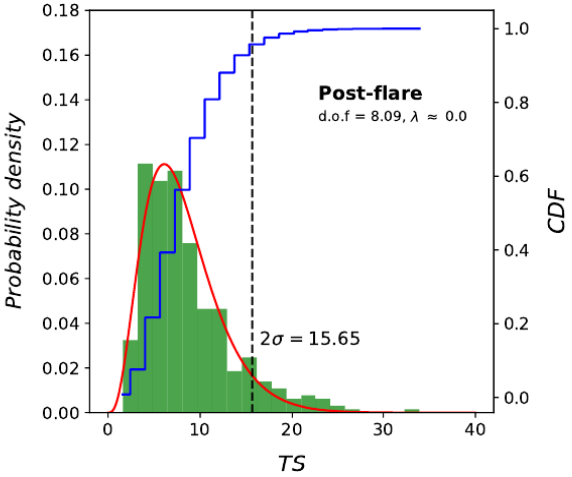
  Sigma: experimental data errors

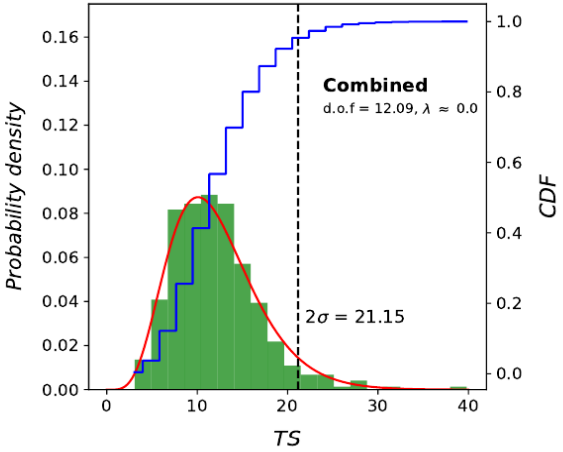
- For each set, we calculated best-fit chi^2 under both the null and ALP hypotheses and then

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

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

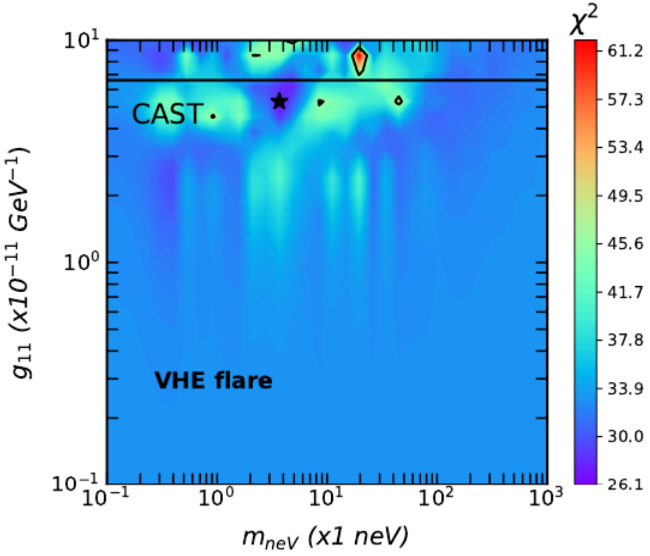




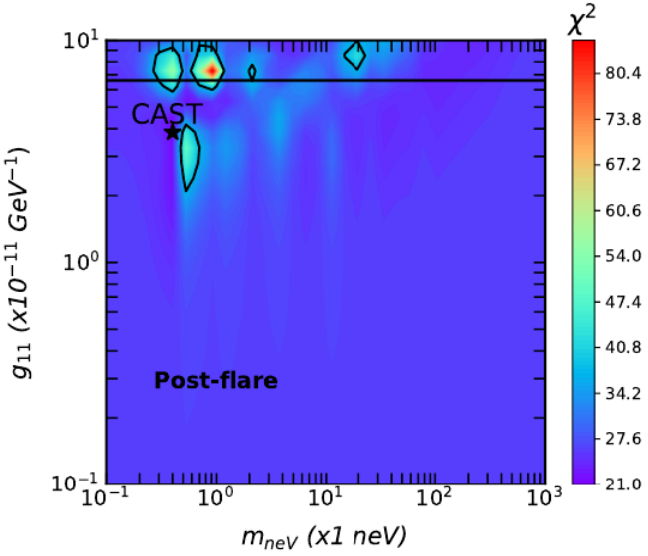


Constraints on ALP parameters

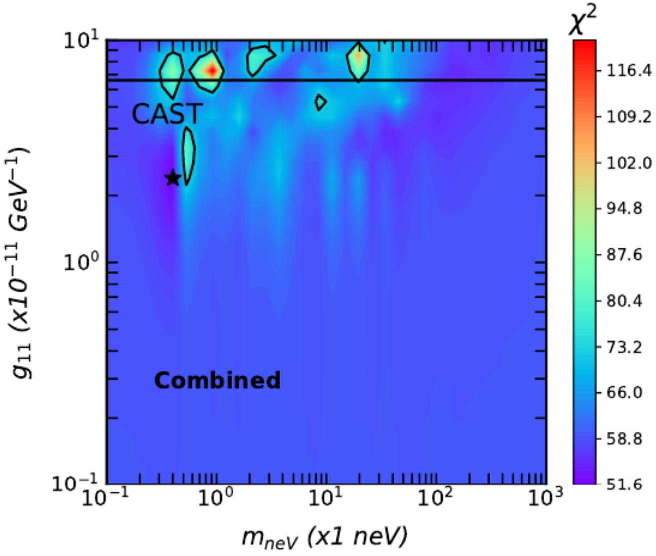
We put 95% C.L. upper limits by requiring $\chi^2_{thr} > \chi^2_{min} + \Delta\chi^2$



No significant constraint



Weak constraint



Overall weak constraint

Expected neutrino flux from QSO B1420+326

The flux of astrophysical neutrinos from a single FSRQ is given by

$$\frac{d\phi_{src}}{dE_\nu}(L_\gamma, E_\nu, z, \eta(L_\gamma)) = \frac{1}{4\pi d(z)^2}\left[\frac{1}{E_\nu}\frac{dL_\nu}{dE_\nu}\right] \times \eta(L_\gamma)$$

Comoving distance

Neutrino luminosity spectra

Baryonic loading

A. Palladino, X. Rodrigues, S. Gao, and W. Winter, Astrophys. J. 871, 41 (2019)

Diffuse flux of astrophysical neutrinos

$$\Phi_{diff}(E_\nu) \ = \int_{\Gamma_{min}}^{\Gamma_{max}} \frac{dN}{d\Gamma}\, d\Gamma \int_{z_{min}}^{z_{max}} \frac{d^2V}{dz\,d\Omega}\, dz \int_{L_\gamma^{min}}^{L_\gamma^{max}} dL_\gamma \ \rho(L_\gamma, z).\ \frac{d\phi_{src}}{dE_\nu}(L_\gamma, E_\nu, z, \eta(L_\gamma))$$

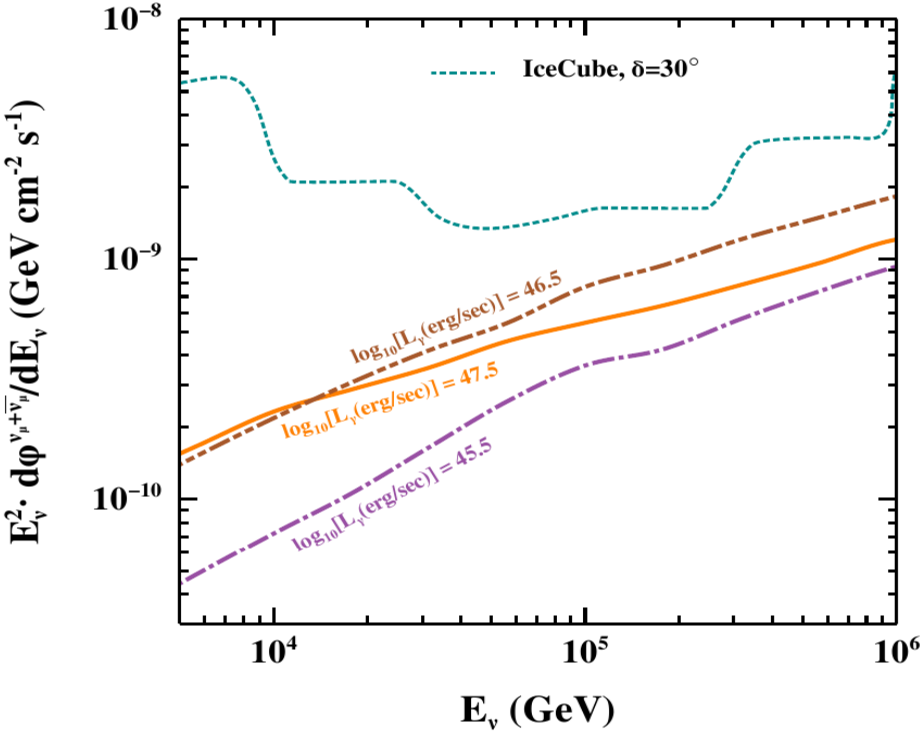
Intrinsic photon index distribution

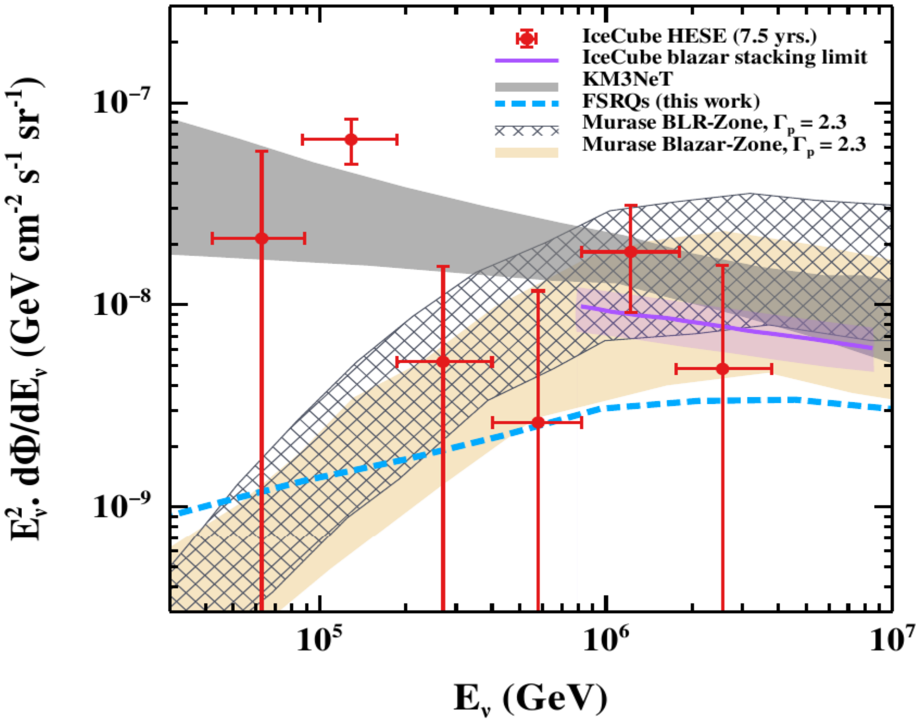
Comoving volume

Gamma-luminosity function

Intrinsic neutrino flux

Expected neutrino flux from QSO B1420+326





Photon-ALP oscillation effect at sub-PeV energies

Assuming p-p interaction the *in situ* gamma rays at the source can be related to neutrinos by:

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

Escape fraction for VHE photons:

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

with optical depth given as:

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

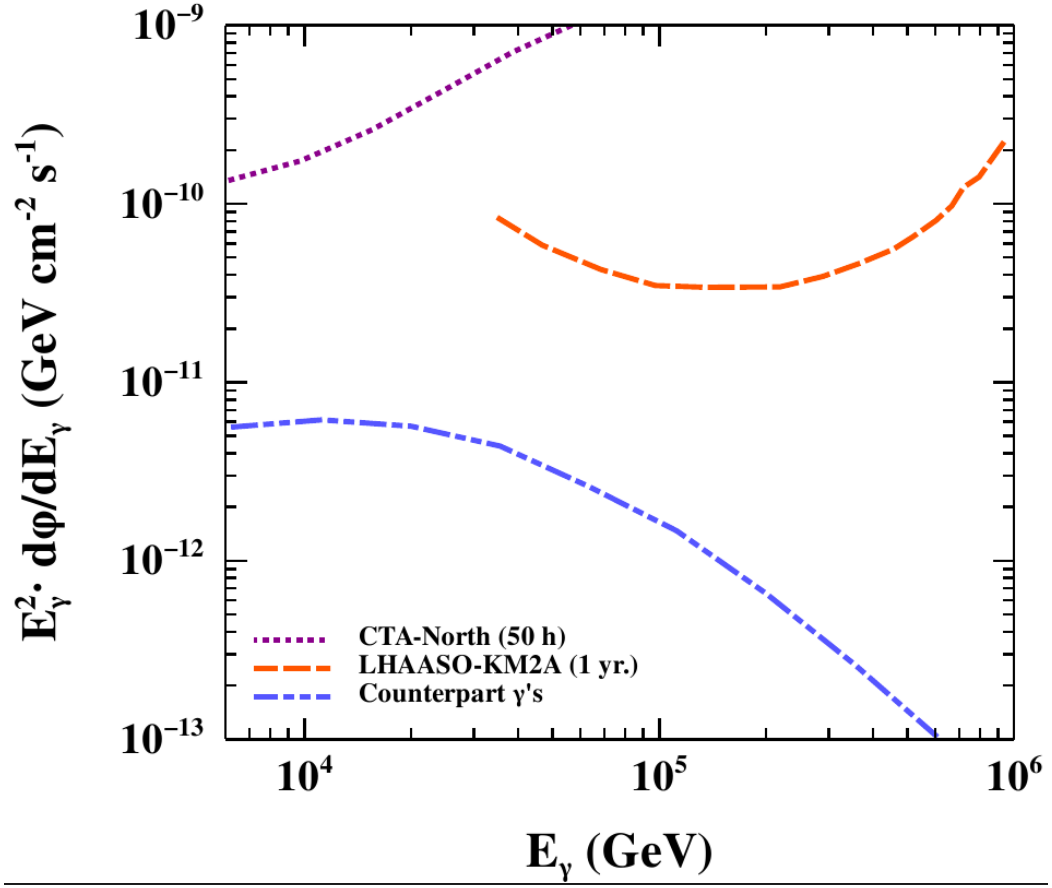
Pair-production cross section

Number density of ambient photons

Photon-ALP oscillation effect at sub-PeV energies

Counterpart gamma rays:

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



Photon-ALP effect on diffuse gamma-rays

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

Intrinsic photon index distribution

Comoving volume

Gamma-luminosity function

Intrinsic photon flux

Survival probability under ALP hypothesis

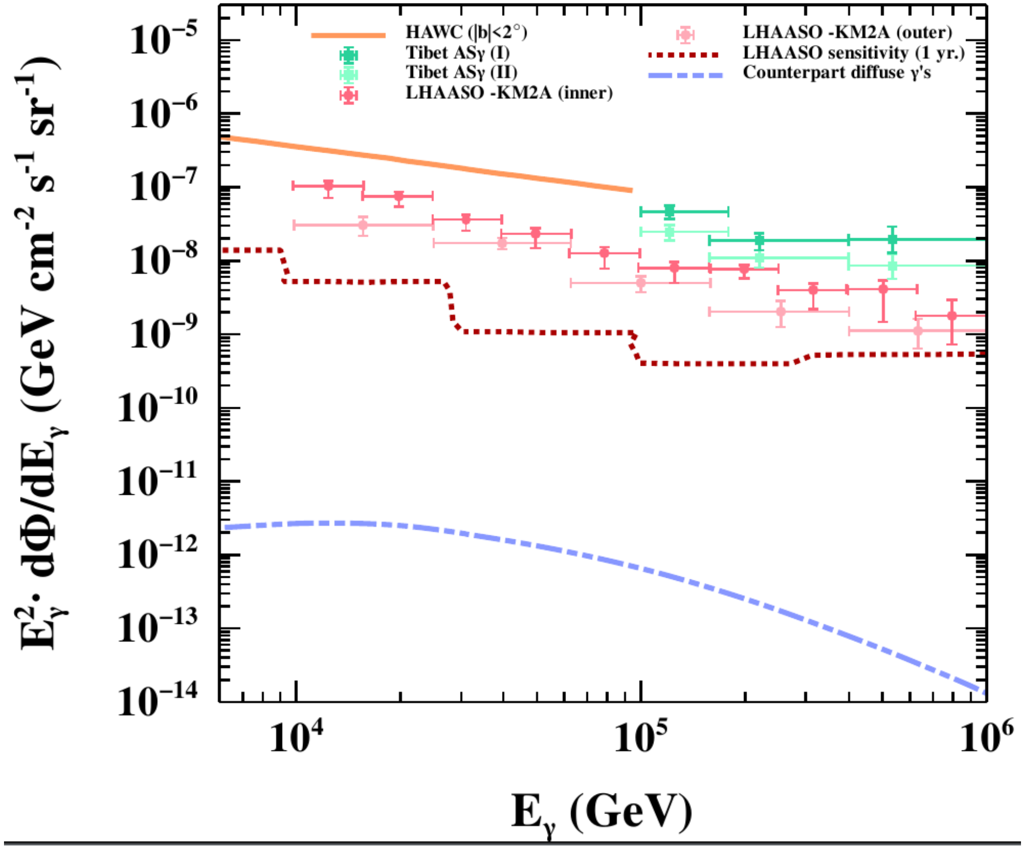
Gamma-luminosity function (GLF):

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

(Luminosity dependent density evolution)

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

Photon-ALP effect on diffuse gamma-rays



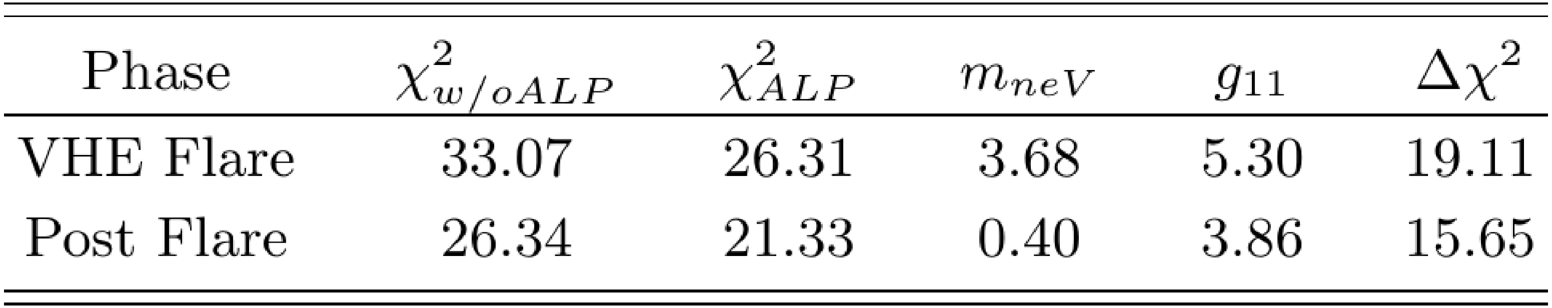
Summary

- Investigate the effect of photon-ALP oscillations on the gamma-ray spectra of FSRQ QSO B1420+326
- Exclusion on ALP coupling parameter: $g_{a\gamma} < 2 \times 10^{-11}$ GeV^{-1} (95% C.L.) for ALP mass $m_a \sim 10^{-10} – 10^{-09}$ eV
- Estimated the neutrino flux from QSO B1420+326 and contribution to diffuse neutrino flux
- Implications of photon-ALP oscillations on the counterpart gamma-rays of the sub-PeV neutrinos
- Diffuse gamma-ray flux from FSRQs under ALP effect

Thanks for your attention!

Backup

Summary of best-fit chi^2 values



Phase	$\chi^2_{w/oALP}$	χ^2_{ALP}	m_{neV}	g_{11}	$\Delta\chi^2$
VHE Flare	33.07	26.31	3.68	5.30	19.11
Post Flare	26.34	21.33	0.40	3.86	15.65

Summary of photon-ALP oscillations

Beam propagation equation:

$$\left(i\frac{d}{dz} + E + \mathcal{M}_0\right)\psi(z) = 0\,.$$

Mixing matrix:

$$\mathcal{M}_0 = \begin{pmatrix} \Delta^{xx} & 0 & 0 \\ 0 & \Delta^{yy} & \Delta^{y}_{a\gamma} \\ 0 & \Delta^{y}_{a\gamma} & \Delta^{zz}_{a} \end{pmatrix}$$

Photon-ALP oscillation probability:

$$P^{(0)}_{0,\gamma_z\to a}(y) = \left(\frac{g_{a\gamma\gamma}\,B}{\Delta_{\text{osc}}}\right)^2 \sin^2\left(\frac{\Delta_{\text{osc}}\,y}{2}\right)$$

$$\Delta_{\text{osc}} = \left[\left(\frac{m_a^2 - \omega_{\text{pl}}^2}{2E}\right)^2 + \left(g_{a\gamma\gamma}\,B\right)^2\right]^{1/2}.$$