

Axionlike particle limits from multimessenger sources

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High-energy neutrino observation from the Seyfert galaxy NGC 1068 offers new insights into the nonthermal processes of active galactic nuclei. Simultaneous γ rays emitted by such sources can possibly oscillate into axionlike particles (ALPs) when propagating through astrophysical magnetic fields, potentially modifying the observed spectrum. To probe for ALP-induced signals, a robust understanding of the emission processes at the source is necessary. In this work, we perform a dedicated multimessenger analysis by modeling a jet in the innermost vicinity of the central supermassive black hole of NGC 1068. We model in particular the neutrino and γ -ray emission originating in lepto-hadronic collisions between jet accelerated particles and background particles from the corona, reproducing both the Fermi-LAT and IceCube data. These source models serve as a baseline for ALP searches, and we derive limits on the ALP-photon coupling by marginalizing over motivated ranges of astrophysical parameters. We find $g_{a\gamma} \lesssim 7 \times 10^{-11} \text{ GeV}^{-1}$ for $m_a \lesssim 10^{-9} \text{ eV}$. These limits may be weaker than existing constraints, but they demonstrate the potential of multimessenger observations to probe new physics. We conclude by discussing how additional upcoming multimessenger sources and improved observational precision can enhance ALP sensitivity.

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I. INTRODUCTION

Axionlike particles (ALPs) are light pseudoscalar bosons that arise in several extensions of the standard model and can comprise the observed relic abundance of dark matter in the Universe [1–7]. Unlike the QCD axion, ALPs cannot resolve the strong CP problem, thereby spanning a wider parameter space and offering a richer phenomenology than the conventional axion. A generic feature of ALPs and QCD axions is their coupling to a two-photon vertex, which in the presence of an external magnetic field can lead to ALP-photon oscillations [8].

The ALP-photon coupling can modulate observations of γ -ray spectra from astrophysical sources with strong magnetic fields. Previous works have used this feature to set stringent limits on ALPs using multiwavelength observations from, for instance, active galactic nuclei (AGN) with external magnetic fields from their jets or the intracluster medium surrounding the AGN [9–14], neutron stars [15–17], supernovae [18–20], galaxy clusters [21–23], and using the magnetic field of the Milky Way’s galactic halo [24–28].

Probing ALPs using modulated γ -ray spectra from astrophysical sources requires a robust understanding of the intrinsic astrophysical emission processes. Multiwavelength and multimessenger observations help to reduce degeneracies between potential ALP signals and conventional astrophysical emission. For instance, astrophysical γ -ray attenuation typically leads to a lower energy flux enhancement, while ALP-induced attenuation is expected to suppress the flux across all wavelengths. Observing the spectral flux across all energy bands can, therefore, help identify the origin of the

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attenuation. Moreover, if the γ -ray emission is produced from hadronic interactions, it is accompanied by a high-energy neutrino flux. Combining neutrino and γ -ray data, therefore, gives insights into dominant emission processes and might point toward additional mechanisms, such as ALP-induced effects.

IceCube has observed several high-energy (TeV–PeV) neutrinos in the past decade that might be associated with AGN. For through-going muon neutrinos, IceCube achieves a median angular resolution of $\sim 1^\circ$ at 1 TeV [29]. The first neutrino event that was found to be correlated with electromagnetic emission came from the flaring blazar TXS 0506 + 056 at 3.5σ significance [30,31]. More recently, IceCube collaboration reported an excess of 79_{-20}^{+22} neutrino events associated to nearby Seyfert type-2 galaxy NGC 1068 at a 4.2σ level of significance [32]. Seyfert galaxies are among the most abundant type of AGN at low redshifts [33]. Interestingly, no emission has been observed in the TeV range by MAGIC [34] while Fermi-LAT detected the source in the GeV range [35,36], and the overall γ -ray flux is at least an order of magnitude lower than expected in hadronic production models able to explain the observed γ -ray flux, unless invoking a large γ -ray absorption at the source [37]. The lack of TeV γ rays can be explained by γ rays being emitted in the innermost vicinity of the supermassive black hole (SMBH; $R_{\text{em}} \sim 10\text{--}100 R_S$, where R_S is the Schwarzschild radius: $2GM_{\text{BH}}/c^2$), which is an optically thick environment [37–43], together with an enhanced starburst activity farther away [44,45]. As a second explanation, it has been suggested that some beyond the standard model scenarios could also attenuate the γ -ray flux from NGC 1068, such as γ -ray oscillations into ALPs, which subsequently decay into neutrinos [46], or dark matter scattering with photons and neutrinos [47,48].

The observation of high-energy neutrinos from NGC 1068 led to dedicated searches of multimessenger emission from other Seyfert galaxies [49,50]. For instance, recent work by Ref. [51] found two 100 TeV neutrinos that coincide with the Seyfert galaxy NGC 7469 at the 3.3σ level, while no significant excess was found by Fermi-LAT. Other type-2 Seyferts are expected to be identified through ongoing IceCube observations, and upcoming data from IceCube-Gen2 [52], KM3NeT [53], P-ONE [54], and Baikal-GVD [55], combined with follow-up observations in γ rays, x rays, UV, and optical. This motivates us to explore the multimessenger spectrum in the context of ALPs. Moreover, given the excess of 79 neutrino events associated with NGC 1068, this source offers a unique opportunity for detailed investigation.

In this work, we focus on NGC 1068 as a case study to describe its multimessenger spectrum. We develop and discuss a jet model embedded in a thick corona to explain the γ -ray and neutrino emission. This model is consistent

with observations and, therefore, enables us to search for dark matter–induced modulations in the observed spectrum. We consider, in particular, γ -ray conversion into ALPs in the magnetic fields along the jets, finding $g_{a\gamma} \lesssim 7 \times 10^{-11} \text{ GeV}^{-1}$ for $m_a \lesssim 10^{-9} \text{ eV}$ at 95% CL. These limits are slightly weaker than existing limits, however, when considering 10 NGC 1068 -like sources, these limits improve by an order of magnitude, demonstrating the power of this recommended application in future analyses.

This work is structured as follows. In Sec. II, we describe the jet model, and we calculate the neutrino and γ -ray emission in the innermost vicinity of the central SMBH of NGC 1068. In Sec. III, we investigate the γ -ray conversion into ALPs in the magnetic fields along the jets, and in Sec. IV we discuss the implications of our results.

II. JET MODEL

A. Expected astrophysical γ -ray and neutrino fluxes from NGC 1068

Radio interferometry of NGC 1068 with the VLA and e-MERLIN has revealed a chain of compact components and a collimated jet extending to kpc scales [56]. The jet features, together with the spatial coincidence between the jet and molecular outflows seen by ALMA, provide evidence for a large-scale jet capable of accelerating relativistic particles.

To calculate the γ -ray and neutrino emission from the accreting SMBH of NGC 1068, we adopt the jet model of [57], referred to as BHJet. This model accounts for the leptonic processes occurring along the jet, namely, synchrotron emission of nonthermal electrons and inverse Compton scattering (ICS) with target photons, both originating in the jets and external photon fields. We further develop BHJet to account for hadronic processes of nonthermal protons according to Ref. [58] and we refer to this model as HadJet. We direct the interested reader to Refs. [57,58] for detailed descriptions, however, we briefly describe the model below.

Two relativistic Poynting flux–dominated jets are launched by the accreting SMBH, perpendicular to the accretion plane, assuming that the two jets are identical. We assume that the jets are launched at a distance $2 R_g$ ($1 R_g \approx 1.5 \text{ km} \times M_{\text{BH}}/M_\odot$) from the SMBH with a jet base of radius r_0 . Whereas the bulk kinetic energy is carried by thermal protons, the thermal electrons at the jet base populate a Maxwell–Jüttner distribution in energies that peaks at 511 keV. The thermal electrons emit synchrotron radiation that usually peak in the sub-keV regime.

As the jets propagate, they accelerate up to some maximum Lorentz factor while the magnetic energy converts to kinetic. At distance z_{diss} , the majority of the magnetic energy has dissipated to kinetic energy. At this

distance, the jet magnetization is determined by

$$\sigma_f = \frac{B^2}{4\pi n m_p c^2} < 1, \quad (1)$$

where B is the magnetic field strength and n is the particle number density.¹ In this region, the majority of the power is carried by the particles. We assume that at z_{diss} , electrons and protons start to accelerate to nonthermal energies driven by the particle acceleration mechanism [57]. We remain agnostic to the specific mechanism and we capture this phenomenon by assuming that nonthermal particles follow a power in energies with index p_e , which is the same for both electrons and protons. We further parametrize the efficiency of the particle acceleration mechanism assuming the relative timescale [61]

$$t_{\text{acc}}(E) = \frac{4E}{3f_{\text{sc}} e c B}, \quad (2)$$

where E is the particle energy, e is the particle charge, c is the speed of light, and $f_{\text{sc}} < 1$. Equating the acceleration timescale to the energy loss timescales, we calculate the maximum attainable energy of nonthermal electrons and protons along the jets. Finally, we assume that particles accelerate to nonthermal energies along the jets from z_{diss} up to a maximum distance where the jets terminate in the intergalactic medium. This distance extends up to $10^8 R_g$, and hence does not affect the γ -ray and neutrino emission. We capture jet physics assuming that the jets consist of 100 consecutive segments on top of each other without any discontinuities from the jet base to the termination region, a sufficiently large number to allow for a multizone model without significantly reducing the speed of the numerical calculations.

The nonthermal particles radiate in the entire multi-wavelength spectrum. The leptonic particles emit synchrotron radiation that is further upscattered via ICS. Whereas these processes dominate the entire spectrum in many cases, for NGC 1068 they are subdominant and they only dominate in the sub-GeV spectrum. The accelerated protons, on the other hand, interact with cold protons of the jet and the corona (see the definition in the following paragraph), as well as the high-energy emission of the jet at the same jet segments, leading to proton-proton (pp) and photo-hadronic ($p\gamma$) processes, respectively. We calculate the resulting γ -ray and neutrino spectra following Ref. [62] for pp and Ref. [63] for $p\gamma$.

The SMBH with mass $M_{\text{BH}} = 8 \times 10^6 M_\odot$ [64,65] of NGC 1068 is surrounded by a dense medium, known as the

hot x-ray corona. Such a corona is responsible for the continuum observed in the x-ray spectra of type-1 Seyferts. This continuum is driven by the Compton scattering of thermal disk photons from the thermal corona electrons. While thermal coronae are widely accepted to be the standard picture, nonthermal electron distributions have also been suggested for hot coronae that may irradiate the innermost accretion disk [66]. In Seyfert 1 AGN, several observational techniques indicate that the x-ray corona is extremely compact, typically within a few gravitational radii of the black hole. In particular, x-ray microlensing studies of lensed quasars constrain the half-light radius of the x-ray emitting region to ~ 5 – $10 R_g$ [67,68]. For the case of NGC 1068, the corona is suggested to be extending to 30 – $100 R_g$ to be optically thick in γ rays, resulting in pair production, whereas the neutrinos produced by hadronic processes escape freely [39,40,42,69]. We choose to use a corona that extends at $50 R_g$, allowing for a dense enough medium to absorb the γ rays, and for an optical depth of $\tau = 0.5$, the number density of the cold corona particles is $n = 10^{11} \text{ cm}^{-3}$. The corona of NGC 1068 acts as a target for the jet accelerated protons, namely, the jet protons collide inelastically on the corona protons. To ensure that the particle acceleration inside the jet will occur in a region, which will be within the volume of the corona, we are only interested in values of $z_{\text{diss}} < R_{\text{cor}} = 50 R_g$. It should be noted that the number density of particles in the corona and its extent radius are uncertain, which translates into uncertainties on the gamma-ray opacity of the corona. The gamma-ray opacity is dominated by $\gamma\gamma \rightarrow e^+e^-$ and is proportional to $\tau \propto n R_{\text{cor}}$. $n = 10^{11} \text{ cm}^{-3}$ is required for the region to be optically thick to Thomson scattering with cross section $\sigma_T \simeq 6.65 \times 10^{-25} \text{ cm}^2$, which is the means by which the corona is defined. Fermi-LAT data constrain $R_{\text{cor}} \lesssim 50 R_g$, so the uncertainties on τ are within a factor of ~ 10 at most.

In principle, the starburst region of NGC 1068 may also contribute to the emitted gamma-ray flux. However, the gamma-ray luminosity observed by Fermi-LAT would require a starburst region with a star-forming rate exceeding by an order of magnitude the expectations of similar galaxies at such redshifts [70]. It is thus plausible that the AGN/jet component provides the dominant gamma-ray emission contribution.

B. Analysis

To constrain the jet dynamics of NGC 1068 and estimate the contribution of jet radiation in the high-energy regime, we fit HadJet to the Fermi-LAT data after selecting only models that reproduce IceCube measurements. In particular, we use the 15-year Fermi-LAT data from a $20^\circ \times 20^\circ$ region of interest surrounding NGC 1068 between 50 MeV and 500 GeV [71], as has been analyzed by Ref. [37].

In the Fermi-LAT analysis by Ref. [37], 14 energy bins are found that have both upper and lower limits on the

¹The geometry of the magnetic field in the coronal region of NGC 1068 is poorly constrained by radio observations [59,60]. We consider the default jet model geometry from GammaAlps, consisting of a toroidal component plus a turbulent component with the size of the corona $\sim 50 R_g$.

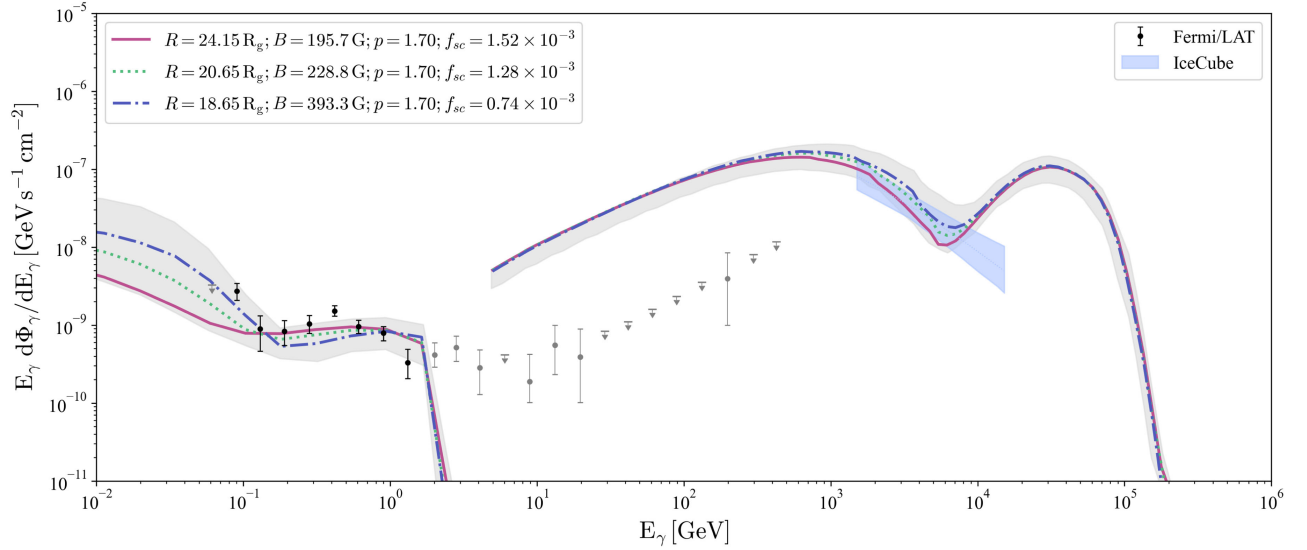


FIG. 1. SED of NGC 1068 focusing on the γ -ray regime and high-energy neutrinos, as measured by Fermi-LAT [35,71] and IceCube [32]. The gray bands show the containment of the 10^6 HadJet simulations. We show three well-fitted individual models, where the pink line shows the best fit to the data. The resulting values of the free parameters R , p , f_{sc} , and the calculated magnetic field strength from the magnetization σ_f , as defined in Eq. (1), are given in the legend.

energy spectrum. However, at the higher-energy bins, an additional spectral contribution is expected from starburst activity farther away from the central engine, with supernova rates of $\sim 0.5 \text{ yr}^{-1}$ [44] (see also Ref. [72]), at least a factor of ~ 5 larger than expected from measurements of the star-forming rate [73] and supernova rates in similar galaxies [74]. It is beyond the scope of this work to model the starburst contribution and we, therefore, only select the first eight bins in the analysis that are expected to have a jet origin. Indeed, at larger energies, the emitted γ -ray flux is efficiently attenuated by ambient photons in the corona, inducing a strong cutoff.

We focus on two astrophysical free parameters that capture the jet morphology, namely, the jet base radius r_0 and the magnetization σ_f at the dissipation region z_{diss} , which we set at $5 R_g$, well within the corona. To constrain the particle acceleration in the jets, we fit the power-law index of the nonthermal particles p_e and the particle acceleration efficiency f_{sc} . We then perform a χ^2 statistical analysis to fit the Fermi-LAT data, considering only models that are found to produce a neutrino flux that fall within the observed uncertainty band from the IceCube measurements [32]. More precisely, we minimize

$$\chi^2(r_0, \sigma_f, p_e, f_{sc}) = \sum_i \frac{(\Phi_{\gamma,i}(r_0, \sigma_f, p_e, f_{sc}) - \Phi_{\gamma,i}^{\text{obs}})^2}{(\delta\Phi_{\gamma,i}^{\text{obs}})^2}, \quad (3)$$

where the index i runs over the different bins in Fermi-LAT data from NGC 1068 in [35,71]. We perform 10^6 simulations, varying the astrophysical parameters over the

following motivated ranges: $r_0 = [5, 30] R_g$, $\sigma_f = [0.01, 1]$, $p_e = [1.6, 2.4]$, and $f_{sc} = [0.1, 20] \times 10^{-3}$.

C. Results

Figure 1 shows the spectral energy distribution (SED) of the best-fit model (solid purple line), both for γ -ray and neutrino emission. We further show in dashed and dotted lines other well-fitted solutions, and the gray shaded bands contain all our 10^6 simulations of the expected γ -ray and high-energy neutrino emitted fluxes. First, we see that the emitting region has a cross sectional radius of $\sim 20 R_g$, well within the corona. The magnetic field is of the order of 200 G and for a particle acceleration efficiency of 10^{-3} , protons accelerate to TeV energies, allowing for the production of TeV neutrinos. We moreover see that the Fermi-LAT spectrum can be well explained by pp γ rays, whereas ICS contributes in the sub-GeV regime. The emitted γ -ray spectrum is heavily attenuated by the corona, whereas the produced neutrinos propagate freely. In particular, the emitted neutrino spectrum has a double-bump shape due to the contribution of both pp (first peak) and py neutrinos (second peak). We show the total neutrino and antineutrino spectrum per neutrino flavor and we compare it to the observed neutrino spectrum by IceCube (shaded blue region). The emitted neutrino signal falls well within the observed limit, with some minor excess in the ~ 10 TeV regime. Further observations could possibly prove this feature or constrain it. To calculate the event rate, we follow Ref. [75], accounting for the effective area of IceCube for zenith angles between -5 and $+30$ degrees. We find that 92 muon neutrino events are expected, in

reasonable agreement with the IceCube reported number of 79 ± 20 events [32].

III. ALP-PHOTON OSCILLATION

The coupling of ALPs to photons is described by the Lagrangian,

$$\mathcal{L}_{a\gamma} = -\frac{1}{4}g_{a\gamma}F_{\mu\nu}\tilde{F}^{\mu\nu}a, \quad (4)$$

where $F_{\mu\nu}$ is the electromagnetic field tensor, $\tilde{F}_{\mu\nu}$ is its dual, and a is the ALP field strength. The effective Lagrangian for the ALP-photon system is

$$\mathcal{L} = \mathcal{L}_{a\gamma} + \mathcal{L}_{\text{EH}} + \mathcal{L}_a, \quad (5)$$

where $\mathcal{L}_{\text{EH}}$ is the Euler-Heisenberg Lagrangian accounting for one-loop corrections to the photon propagator, and the ALP Lagrangian terms are

$$\mathcal{L}_a = \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{1}{2}m_a^2 a^2. \quad (6)$$

ALPs couple to photons in the presence of a magnetic field component transversal to the direction of propagation. The equations of motion for a photon beam with energy E read [8,76]

$$\left(i\frac{d}{dz} + E + \mathcal{M}\right)\Psi(z) = 0, \quad (7)$$

with $\Psi(z) = (A_x(z), A_y(z), a(z))^T$, with A 's being the polarization states along directions x and y and the mixing matrix $\mathcal{M}$ reads

$$\mathcal{M} = \begin{pmatrix} \Delta_\perp & 0 & 0 \\ 0 & \Delta_\parallel & \Delta_{a\gamma} \\ 0 & \Delta_{a\gamma} & \Delta_a \end{pmatrix}. \quad (8)$$

Quantum electrodynamics (QED) vacuum polarization effects and the propagation of photons in the plasma medium give rise to the terms $\Delta_\perp = \Delta_{\text{pl}} + 2\Delta_{\text{QED}}$ and $\Delta_\parallel = \Delta_{\text{pl}} + 7/2\Delta_{\text{QED}}$, with $\Delta_{\text{pl}} = -\omega_{\text{pl}}/(2E)$ and the plasma frequency $\omega_{\text{pl}} \sim 0.037\sqrt{n}$, where n is the number density of electrons in the plasma. The QED vacuum polarization term reads $\Delta_{\text{QED}} = \alpha E/(45\pi)(B/(B_{\text{cr}}))^2$, with the fine-structure constant α , and the critical magnetic field $B_{\text{cr}} = m_e^2/|e| \sim 4.4 \times 10^{13}$ G. The kinetic term for the ALP is $\Delta_a = -m_a^2/(2E)$ and photon-ALP mixing is given by the off-diagonal elements $\Delta_{a\gamma} = g_{a\gamma}B/2$. The above system of equations can be solved with the software GammaALPs for a combination of astrophysical environments, which allows for obtaining the photon survival probability as a function of energy [77]. From this quantity, the axion field opacity to γ rays can be derived.

As described in the previous section, we consider a jet-based mechanism for the acceleration of cosmic rays and production of high-energy neutrinos and γ rays. Thus, we consider the GammaALPs ‘‘Jet’’ model, where the ALP-photon mixing occurs in the toroidal magnetic field of the AGN jet. In this case, the magnetic field is coherent, and modeled as a power law in distance from the central black hole as

$$B(r) = B_0 \left(\frac{r}{R_{\text{em}}}\right)^{-1}, \quad (9)$$

where R_{em} is the emitting region of γ rays of the AGN. Similarly, the electron number density is modeled as a power-law function

$$n(r) = n_0 \left(\frac{r}{R_{\text{em}}}\right)^{-2}. \quad (10)$$

For the attenuation of γ rays in the extragalactic background light, we use the model from Ref. [78]. We do not include the intergalactic magnetic field, as its field strength is too weak to have any impact on ALP-photon oscillations for the parameters considered in this work (see also Appendix). Finally, we also consider the possibility of ALP-photon reconversions in the coherent component of the magnetic field of the Milky Way. In that case, the galactic magnetic field (GMF) model is taken from Refs. [79,80] with constant number density of electrons [81] and we discuss uncertainties in the GMF in Appendix.

Under this prescription, we can compute the attenuated γ -ray flux due to ALP-photon oscillations as

$$\frac{d\Phi_\gamma^{\text{att}}}{dE_\gamma} = \frac{d\Phi_\gamma}{dE_\gamma} P_{a\gamma}(E_\gamma, m_a, g_{a\gamma}, \theta_{\text{astro}}), \quad (11)$$

where Φ_γ^{att} is the attenuated γ -ray flux and Φ_γ the expected γ -ray flux from the accreting SMBH of NGC 1068. $P_{a\gamma}$ is the ALP-photon oscillation that depends on the γ -ray energy E_γ , axion mass m_a , axion-photon coupling $g_{a\gamma}$, and the range of astrophysical parameters θ_{astro} , as discussed in the next section.

A. ALP analysis

We derive limits on the ALP parameter space and identify ALP regions that better fit the Fermi-LAT and IceCube data. We perform a profile likelihood analysis by marginalizing over the astrophysical nuisance parameters $\theta_{\text{astro}} = (r_0, \sigma_f, p_e, f_{\text{sc}})$ that predict different SEDs, as illustrated in Fig. 1 as a gray band. For each value $(m_a, g_{a\gamma})$, we compute $\chi^2(m_a, g_{a\gamma}; \theta_{\text{astro}})$ by minimizing over the nuisance parameters, where $\chi^2(m_a, g_{a\gamma}; \theta_{\text{astro}})$ is obtained through a least-squares analysis using the Fermi-LAT data of NGC 1068. We obtain 95% CLs on $g_{a\gamma}$ as a

TABLE I. Description of the astrophysical free parameters we consider in HadJet and their ranges. Moreover, we show the best fit to NGC 1068 Fermi-LAT data and the obtained χ^2 values. The number density and the magnetic field are derived from the above parameters.

Parameter	Range of values	Best-fit value	Description
r_0/R_g	[5, 30]	24.15	Jet base radius
σ_f	[0.01, 1]	0.02	Magnetization at dissipation region [Eq. (1)]
p_e	[1.6, 2.4]	1.7	Nonthermal power-law index $-\frac{\log(dn/dE)}{\log(dE)}$
f_{sc}	$[0.1, 20] \times 10^{-3}$	1.52×10^{-3}	Acceleration timescale factor
χ^2	≥ 23	23	Minimum χ^2 fitted to Fermi-LAT data
n/cm^{-3}	$[4, 222] \times 10^7$	10.13×10^7	Particle number density at dissipation region
B/G	[157, 4709]	196	Magnetic field strength at dissipation region

function of m_a through a likelihood ratio analysis, which follows Ref. [82],

$$\chi^2(m_a, g_{a\gamma\gamma}; \theta_{\text{astro}}) - \chi^2_{\min}(\theta_{\text{astro}}) = \Delta\chi^2 \leq 2.71. \quad (12)$$

The considered ranges for the nuisance parameters are shown in Table I.

B. Results

Figure 2 shows the best-fit expected γ -ray and neutrino emission in solid purple lines, together with the unattenuated emission (dotted purple line) for illustration purposes. We further show in a dashed orange line the additionally attenuated γ -ray flux induced by ALP-photon oscillation effects in the magnetic field of the jets of NGC 1068, for

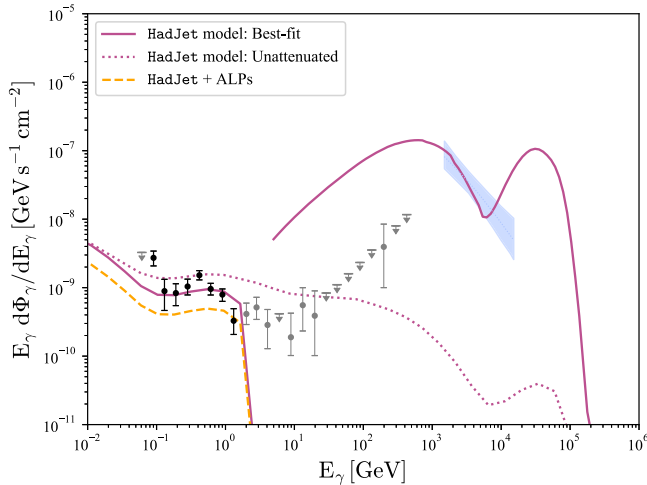


FIG. 2. SED of NGC 1068, including γ -ray measurements from Fermi-LAT [35,71], high-energy neutrino measurements from IceCube [32], and the best-fit model (solid purple line). The opaque γ -ray flux due to ALP-photon oscillations in the jet of NGC 1068 is shown as an orange dashed line with ALP parameters $m_a = 10^{-7}$ eV and $g_{a\gamma} = 10^{-10}$ GeV^{-1} .

benchmark values of the ALP mass $m_a = 10^{-7}$ eV and axion-photon coupling $g_{a\gamma} = 10^{-10}$ GeV^{-1} . We see that the ALP-photon oscillation can sizably deplete the γ -ray flux below observational levels. This feature can be used to set limits on the ALP-photon coupling and mass.

We find a best-fit point in the ALP parameter space at $(m_a, g_{a\gamma\gamma}) = (2.2 \times 10^{-9} \text{ GeV}^{-1}, 4.6 \times 10^{-10} \text{ eV})$, corresponding to a significance of only 1.02σ , indicating no meaningful preference.

In Fig. 3, we show the ALP-photon coupling versus the ALP mass. The solid blue line corresponds to the 95% CLs obtained when marginalizing over the astrophysical

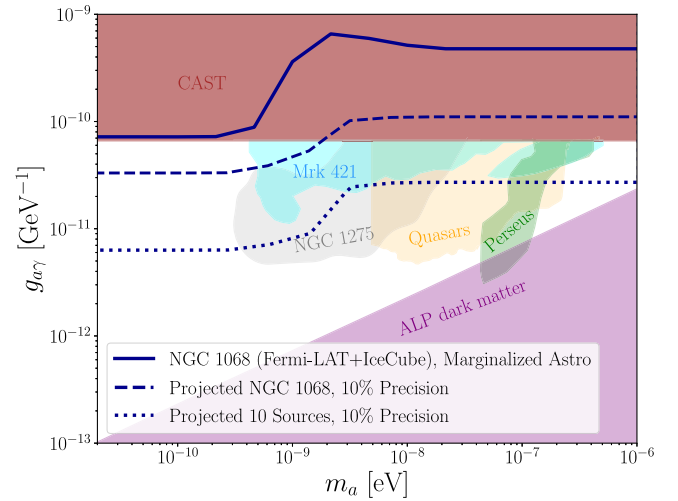


FIG. 3. Upper limits on the ALP-photon coupling versus ALP mass by marginalizing over astrophysical parameters described in Table I (solid blue line). We further show projected limits with improved Fermi-LAT precision of 10% (dashed blue line), and from the observation of 10 NGC 1068-like sources with 10% precision (dotted blue line). We compare with previous results [23,83–85] and show the region where ALPs have the correct relic abundance via the misalignment mechanism (shaded purple) [87].

parameters. Moreover, we compare our limits to previous bounds arising from ALP-photon oscillations in γ -ray astrophysical sources. In particular, we show bounds from the combination of ARGO-YBJ and Fermi-LAT observations of the blazar Mrk 421 (dashed cyan region) [83], Fermi-LAT observations of NGC 1275 (dashed gray region) [84], flat-spectrum radio quasars observed with Fermi-LAT (dashed orange region) [85], and observations of the Perseus Galaxy with MAGIC (dashed green region) [34]. We also show the bound obtained by the CAST experiment at CERN, based on solar ALP-photon conversions in the presence of a strong magnetic field in the laboratory [86].

It should be noted that additional limits exist on the ALP-photon coupling from ALP production and reconversion into x rays from ALP-induced polarization effects, and from reionization probes, e.g., [27,46,83,88–96]. We further show the region of parameter space where ALPs can constitute the dark matter of the Universe (shaded purple region) [87]. Our current limits do not yet reach this ALP dark matter target region in the mass range where our multimessenger bounds are most competitive, but the projected sensitivities shown in Fig. 3 illustrate how improved measurements and a population of NGC 1068-like sources could move closer to that parameter space.

Figure 3 also illustrates projected limits from NGC 1068 with improved precision of 10% in the measurements (dashed blue line), and projected limits with the observation of 10 NGC 1068-like sources and 10% precision in each of the measurements (dotted blue line). This would constitute an improvement with respect to current measurements from Fermi-LAT, which present uncertainties in the range 16.7%–50%, depending on the energy bin considered. We generate mock astrophysical predictions and data by performing a 1σ Gaussian perturbation of the best-fit astrophysical flux from NGC 1068 discussed in Sec. II, together with the central values of the measurements of Fermi-LAT data. We note that using the best-fit astrophysical model instead of marginalizing over astrophysical parameters improves the limits by $<20\%$. The mock astrophysical fluxes and corresponding observed data are then generated as

$$\Phi_{\gamma,i}^{\text{mock(obs)}}(E_i) = \Phi_{\gamma,i}^{\text{(obs)}}(E_i) \times (1 + \delta_i), \quad \delta_i \sim \mathcal{N}(0, 1), \quad (13)$$

where $\mathcal{N}(0, 1)$ denotes a Gaussian distribution centered at $\mu = 0$ with standard deviation $\sigma = 0.1$. Under this prescription, and fixing the uncertainty in mock data to 10% in every energy bin, we find that our limits could significantly improve previous limits from γ -ray sources for some values of the ALP mass. We note that measurement uncertainties of 10% have been obtained for other Fermi-LAT sources in the 20–500 GeV energy range, and future experiments like

AMEGO [97], e-Astrogram [98], or CTAO [99] are expected to improve over Fermi-LAT precision.

IV. DISCUSSION

The multimessenger era brings us the opportunity to understand the underlying processes leading to the observed γ -ray and high-energy neutrino fluxes from distant astrophysical sources. In this context, beyond the standard model scenarios may induce modifications of the emitted astrophysical γ -ray or neutrino fluxes, leaving the former or the latter unaltered. ALP-photon oscillations are widely discussed to modify the γ -ray flux from extragalactic sources, like AGNs. We propose to use multimessenger sources that are observed in high-energy neutrinos, as they offer a unique opportunity to disentangle the intrinsic emission mechanism from ALP-induced effects. This enables us to derive robust limits on the ALP-photon coupling.

For this purpose, we develop a model that allows for lepto-hadronic processes between jet accelerated protons and cold target particles of the corona. Using this model, we calculate the expected γ -ray and high-energy neutrino fluxes from NGC 1068, and compare to IceCube and Fermi-LAT data. The observation of high-energy neutrinos by IceCube significantly constrains the astrophysical parameter space, allowing for more robust conclusions on the origin of the nonthermal emission. We find that ICS of jet accelerated electrons can reproduce the sub-GeV spectrum, pp inelastic collisions between accelerated jet protons and corona thermal protons can contribute or even dominate the GeV spectrum, whereas neutrinos from both pp and p γ interactions can explain the ~ 80 events detected by IceCube. The entire high-energy γ -ray emission is suppressed due to the optically thick corona.

Using these simulations, we derive limits on the ALP-photon coupling, at the level of $g_{a\gamma} \lesssim 7 \times 10^{-11} \text{ GeV}^{-1}$ for $m_a \lesssim 10^{-9} \text{ eV}$. These limits are weaker than previous analyses of astrophysical γ -ray sources. However, to illustrate the potential of our method in future analyses, we expect, with a population of 10 NGC 1068-like sources and considering an improved precision in future γ -ray measurements of 10%, to find comparable and complementary limits when compared to current results from γ -ray sources.

Our analysis can be extended in several ways. One may consider different γ -ray sources, such as TXS or PKS blazars, which have also been observed in γ rays and high-energy neutrinos [30]. Furthermore, other Seyfert galaxies have been observed by IceCube with moderate significance [50], and while Fermi-LAT currently does not find a significant γ -ray flux, future observations could improve the limits. Beyond the standard model scenarios could be considered as attenuating media in these sources. We expect future multimessenger and multiwavelength observations to help determine the dark opacity of the Universe to γ rays.

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DATA AVAILABILITY

The data supporting this study’s findings are available within the article.

APPENDIX: GALACTIC MAGNETIC FIELD

The GMF is subject to uncertainties in the field morphology and in the thermal electron density. As a benchmark model, we adopt the GMF model of Ref. [80]. To assess the impact of these uncertainties, we repeat the analysis using the eight updated GMF models presented in Ref. [100] that are implemented in GammaALPs. The result is shown in Fig. 4 as a gray envelope, while the benchmark model including ALP is indicated as the pink line ($m_a = 10^{-9}$ eV, $g_{a\gamma} = 10^{-10}$ GeV $^{-1}$) and the best-fit astrophysical model as the black line. We find that the corresponding 95% CLs on $g_{a\gamma}$ are only affected for masses below $m_a \lesssim 10^{-8}$ eV and

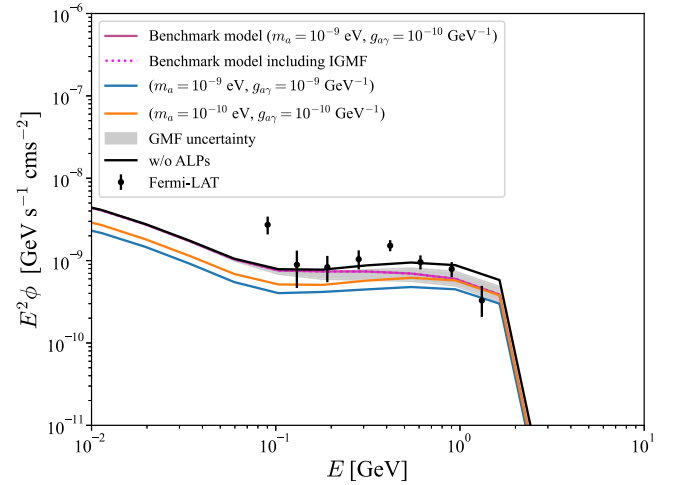


FIG. 4. SED of NGC 1068, including γ -ray measurements from Fermi-LAT (black error bars). The best-fit model without ALPs is shown by the black line. The pink line shows the spectrum including attenuation from ALP-photon oscillations for $m_a = 10^{-9}$ eV and $g_{a\gamma} = 10^{-10}$ GeV $^{-1}$, assuming the benchmark GMF model [80]. The gray envelope illustrates the uncertainties from eight different models [100].

weakened by at most 56% and are strengthened by 37% relative to the benchmark model. The orange and blue lines show different ALP models, illustrating the effect of changing the mass and coupling strength.

Moreover, the dotted line shows the case including the intergalactic magnetic field (with $\sim 10^{-12}$ G and $\lambda \sim$ Mpc), where it is clear that it has no effect on the ALP-photon oscillation in the parameters considered here.

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- [1] R. D. Peccei and H. R. Quinn, *CP* conservation in the presence of instantons, *Phys. Rev. Lett.* **38**, 1440 (1977).
 - [2] S. Weinberg, A new light boson?, *Phys. Rev. Lett.* **40**, 223 (1978).
 - [3] J. Preskill, M. B. Wise, and F. Wilczek, Cosmology of the invisible axion, *Phys. Lett.* **120B**, 127 (1983).
 - [4] L. F. Abbott and P. Sikivie, A cosmological bound on the invisible axion, *Phys. Lett.* **120B**, 133 (1983).
 - [5] M. Dine and W. Fischler, The not so harmless axion, *Phys. Lett.* **120B**, 137 (1983).
 - [6] D. J. Marsh, Axion cosmology, *Phys. Rep.* **643**, 1 (2016).
 - [7] A. Arvanitaki, S. Dimopoulos, S. Dubovsky, N. Kaloper, and J. March-Russell, String axiverse, *Phys. Rev. D* **81**, 123530 (2010).
 - [8] G. Raffelt and L. Stodolsky, Mixing of the photon with low-mass particles, *Phys. Rev. D* **37**, 1237 (1988).
 - [9] D. Hooper and P. D. Serpico, Detecting axion-like particles with gamma ray telescopes, *Phys. Rev. Lett.* **99**, 231102 (2007).
 - [10] C. S. Reynolds, M. C. David Marsh, H. R. Russell, A. C. Fabian, R. Smith, F. Tombesi, and S. Veilleux, Astrophysical limits on very light axion-like particles from chandra grating spectroscopy of NGC 1275, *Astrophys. J.* **890**, 59 (2020).
 - [11] J. Sisk-Reynés, J. H. Matthews, C. S. Reynolds, H. R. Russell, R. N. Smith, and M. C. D. Marsh, New constraints on light axion-like particles using chandra transmission grating spectroscopy of the powerful cluster-hosted quasar h1821 + 643, *Mon. Not. R. Astron. Soc.* **510**, 1264 (2021).
 - [12] S. Jacobsen, T. Linden, and K. Freese, Constraining axion-like particles with HAWC observations of TeV blazars, *J. Cosmol. Astropart. Phys.* **10** (2023) 009.
 - [13] A. Abramowski *et al.* (H.E.S.S. Collaboration), Constraints on axionlike particles with H.E.S.S. from the

- irregularity of the PKS 2155-304 energy spectrum, *Phys. Rev. D* **88**, 102003 (2013).
- [14] F. Tavecchio, M. Roncadelli, G. Galanti, and G. Bonnoli, Evidence for an axion-like particle from PKS 1222 + 216?, *Phys. Rev. D* **86**, 085036 (2012).
- [15] P. S. B. Dev, J.-F. Fortin, S. P. Harris, K. Sinha, and Y. Zhang, First constraints on the photon coupling of axion-like particles from multimessenger studies of the neutron star merger GW170817, *Phys. Rev. Lett.* **132**, 101003 (2024).
- [16] F. Lecce, A. Lella, G. Lucente, V. Vijayan, A. Bauswein, M. Giannotti, and A. Mirizzi, Probing axion-like particles with multimessenger observations of neutron star mergers, *Phys. Rev. D* **112**, 023001 (2025).
- [17] M. Diamond, D. F. G. Fiorillo, G. Marques-Tavares, I. Tamborra, and E. Vitagliano, Multimessenger constraints on radiatively decaying axions from GW170817, *Phys. Rev. Lett.* **132**, 101004 (2024).
- [18] F. Calore, P. Carenza, C. Eckner, T. Fischer, M. Giannotti, J. Jaeckel, K. Kotake, T. Kuroda, A. Mirizzi, and F. Sivo, 3d template-based fermi-lat constraints on the diffuse supernova axion-like particle background, *Phys. Rev. D* **105**, 063028 (2022).
- [19] F. R. Candón, S. Ganguly, M. Giannotti, T. Kumar, A. Lella, and F. Mescia, A fresh look at the diffuse alp background from supernova, *Phys. Rev. D* **112**, 015006 (2025).
- [20] M. Meyer, M. Giannotti, A. Mirizzi, J. Conrad, and M. A. Sánchez-Conde, Fermi Large Area Telescope as a galactic supernovae axionscope, *Phys. Rev. Lett.* **118**, 011103 (2017).
- [21] M. H. Chan, Constraining the axion-photon coupling using radio data of the bullet cluster, *Sci. Rep.* **11**, 20087 (2021).
- [22] M. Schlegeler and G. Sigl, Constraining alp-photon coupling using galaxy clusters, *J. Cosmol. Astropart. Phys.* **01** (2016) 038.
- [23] H. Abe *et al.* (MAGIC Collaboration), Constraints on axion-like particles with the Perseus Galaxy Cluster with MAGIC, *Phys. Dark Universe* **44**, 101425 (2024).
- [24] M. Simet, D. Hooper, and P. D. Serpico, The Milky Way as a kiloparsec-scale axionscope, *Phys. Rev. D* **77**, 063001 (2008).
- [25] J. P. Conlon and F. V. Day, 3.55 keV photon lines from axion to photon conversion in the milky way and m31, *J. Cosmol. Astropart. Phys.* **11** (2014) 033.
- [26] P. Carenza, C. Evoli, M. Giannotti, A. Mirizzi, and D. Montanino, Turbulent axion-photon conversions in the Milky Way, *Phys. Rev. D* **104**, 023003 (2021).
- [27] C. Eckner and F. Calore, First constraints on axionlike particles from Galactic sub-PeV gamma rays, *Phys. Rev. D* **106**, 083020 (2022).
- [28] L. Mastrototaro, P. Carenza, M. Chianese, D. F. G. Fiorillo, G. Miele, A. Mirizzi, and D. Montanino, Constraining axion-like particles with the diffuse gamma-ray flux measured by the large high altitude air shower observatory, *Eur. Phys. J. C* **82**, 1012 (2022).
- [29] M. G. Aartsen *et al.* (IceCube Collaboration), Search for steady point-like sources in the astrophysical muon neutrino flux with 8 years of IceCube data, *Eur. Phys. J. C* **79**, 234 (2019).
- [30] M. G. Aartsen *et al.* (IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S., INTEGRAL, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, Swift NuSTAR, VERITAS, and VLA/17B-403 Collaboration), Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A, *Science* **361**, eaat1378 (2018).
- [31] M. G. Aartsen *et al.* (IceCube Collaboration), Neutrino emission from the direction of the blazar TXS 0506 + 056 prior to the IceCube-170922A alert, *Science* **361**, 147 (2018).
- [32] R. Abbasi *et al.* (IceCube Collaboration), Evidence for neutrino emission from the nearby active galaxy NGC 1068, *Science* **378**, 538 (2022).
- [33] L. C. Ho, Nuclear activity in nearby galaxies, *Annu. Rev. Astron. Astrophys.* **46**, 475 (2008).
- [34] V. A. Acciari *et al.* (MAGIC Collaboration), Constraints on gamma-ray and neutrino emission from NGC 1068 with the MAGIC telescopes, *Astrophys. J.* **883**, 135 (2019).
- [35] S. Abdollahi *et al.* (Fermi-LAT Collaboration), Fermi Large Area Telescope fourth source catalog, *Astrophys. J. Suppl. Ser.* **247**, 33 (2020).
- [36] M. Ajello *et al.* (Fermi-LAT Collaboration), The fourth catalog of active galactic nuclei detected by the Fermi Large Area Telescope, *Astrophys. J.* **892**, 105 (2020).
- [37] C. Blanco, D. Hooper, T. Linden, and E. Pinetti, On the neutrino and gamma-ray emission from NGC 1068, *Phys. Rev. D* **112**, 123016 (2025).
- [38] K. Murase, S. S. Kimura, and P. Meszaros, Hidden cores of active galactic nuclei as the origin of medium-energy neutrinos: Critical tests with the MeV gamma-ray connection, *Phys. Rev. Lett.* **125**, 011101 (2020).
- [39] Y. Inoue, D. Khangulyan, and A. Doi, On the origin of high-energy neutrinos from NGC 1068: The role of nonthermal coronal activity, *Astrophys. J.* **891**, L33 (2020).
- [40] K. Murase, Hidden hearts of neutrino active galaxies, *Astrophys. J. Lett.* **941**, L17 (2022).
- [41] D. F. G. Fiorillo, M. Petropoulou, L. Comisso, E. Peretti, and L. Sironi, TeV neutrinos and hard X-rays from relativistic reconnection in the corona of NGC 1068, *Astrophys. J.* **961**, L14 (2024).
- [42] D. F. G. Fiorillo, L. Comisso, E. Peretti, M. Petropoulou, and L. Sironi, A magnetized strongly turbulent corona as the source of neutrinos from NGC 1068, *Astrophys. J.* **974**, 75 (2024).
- [43] P. Padovani *et al.*, High-energy neutrinos from the vicinity of the supermassive black hole in NGC 1068, *Nat. Astron.* **8**, 1077 (2024).
- [44] B. Eichmann, F. Oikonomou, S. Salvatore, R.-J. Dettmar, and J. Becker Tjus, Solving the multimessenger puzzle of the AGN-starburst composite galaxy NGC 1068, *Astrophys. J.* **939**, 43 (2022).
- [45] A. B. Romeo and K. Fathi, What powers the starburst activity of NGC 1068? Star-driven gravitational instabilities caught in the act, *Mon. Not. R. Astron. Soc.* **460**, 2360 (2016).
- [46] B. P. Pant, Constraining axionlike particles with invisible neutrino decay using the IceCube observations of NGC 1068, *Phys. Rev. D* **109**, 063002 (2024).

- [47] G. Herrera, Plausible indication of gamma-ray absorption by dark matter in NGC 1068, *Phys. Dark Universe* **50**, 102156 (2025).
- [48] J.M. Cline and M. Puel, NGC 1068 constraints on neutrino-dark matter scattering, *J. Cosmol. Astropart. Phys.* **06** (2023) 004.
- [49] A. Neronov, D. Savchenko, and D. Semikoz, Neutrino signal from a population of Seyfert Galaxies, *Phys. Rev. Lett.* **132**, 101002 (2024).
- [50] R. Abbasi *et al.* (IceCube Collaboration), Search for neutrino emission from hard X-ray AGN with IceCube, *Astrophys. J.* **981**, 131 (2025).
- [51] G. Sommani, A. Franckowiak, M. Lincetto, and R.-J. Dettmar, Two 100 TeV neutrinos coincident with the Seyfert Galaxy NGC 7469, *Astrophys. J.* **981**, 103 (2025).
- [52] M. G. Aartsen *et al.* (IceCube-Gen2 Collaboration), IceCube-Gen2: The window to the extreme Universe, *J. Phys. G* **48**, 060501 (2021).
- [53] S. Adrian-Martinez *et al.* (KM3Net Collaboration), Letter of intent for KM3NeT 2.0, *J. Phys. G* **43**, 084001 (2016).
- [54] M. Agostini *et al.* (P-ONE Collaboration), The Pacific Ocean Neutrino Experiment, *Nat. Astron.* **4**, 913 (2020).
- [55] A. D. Avrorin *et al.* (Baikal-GVD Collaboration), Neutrino telescope in Lake Baikal: Present and future, *Proc. Sci., ICRC2019* (2020) 1011 [arXiv:1908.05427].
- [56] I. M. Mutie, D. Williams-Baldwin, R. J. Beswick, E. K. Bempong-Manful, P. O. Baki, T. W. B. Muxlow, J. F. Gallimore, S. E. Aalto, B. T. Dullo, and R. D. Baldi, Radio jets in NGC 1068 with e-MERLIN and VLA: Structure and morphology, arXiv:2312.09722.
- [57] M. Lucchini, C. Ceccobello, S. Markoff, Y. Kini, A. Chhotray, R. M. T. Connors, P. Crumley, H. Falcke, D. Kantzas, and D. Maitra, Bhjet: A public multizone, steady state jet + thermal corona spectral model, *Mon. Not. R. Astron. Soc.* **517**, 5853 (2022).
- [58] D. Kantzas, S. Markoff, T. Beuchert, M. Lucchini, A. Chhotray, C. Ceccobello, A. J. Tetarenko, J. C. A. Miller-Jones, M. Bremer, J. A. Garcia, V. Grinberg, P. Uttley, and J. Wilms, A new lepto-hadronic model applied to the first simultaneous multiwavelength data set for Cygnus X-1, *Mon. Not. R. Astron. Soc.* **500**, 2112 (2021).
- [59] I. M. Mutie, S. del Palacio, R. J. Beswick, D. Williams-Baldwin, J. F. Gallimore, J. S. Gallagher, S. E. Aalto, and P. O. Baki, A consistent radio to sub-mm pc-scale study of the nucleus of NGC 1068, arXiv:2503.20303.
- [60] T. Michiyama, Y. Inoue, and A. Doi, The centimeter-to-submillimeter broad-band radio spectrum of the central compact component in a nearby type-II Seyfert Galaxy NGC 1068, *Publ. Astron. Soc. Jpn.* **75**, 874 (2023).
- [61] J. Jokipii, Rate of energy gain and maximum energy in diffusive shock acceleration, *Astrophys. J.* **313**, 842 (1987).
- [62] S. Kelner, F. A. Aharonian, and V. Bugayov, Energy spectra of gamma rays, electrons, and neutrinos produced at proton-proton interactions in the very high energy regime, *Phys. Rev. D* **74**, 034018 (2006).
- [63] S. Kelner and F. Aharonian, Energy spectra of gamma rays, electrons, and neutrinos produced at interactions of relativistic protons with low energy radiation, *Phys. Rev. D* **78**, 034013 (2008).
- [64] J.-H. Woo and C. M. Urry, AGN black hole masses and bolometric luminosities, *Astrophys. J.* **579**, 530 (2002).
- [65] F. Panessa, L. Bassani, M. Cappi, M. Dadina, X. Barcons, F. J. Carrera, L. C. Ho, and K. Iwasawa, On the X-ray, optical emission line and black hole mass properties of local Seyfert galaxies, *Astron. Astrophys.* **455**, 173 (2006).
- [66] M. Asgari, I. Friswell, M. Yoon, C. Heymans, A. Dvornik, B. Joachimi, P. Simon, and J. Zuntz, Minimizing the impact of scale-dependent galaxy bias on the joint cosmological analysis of large-scale structures, *Mon. Not. R. Astron. Soc.* **501**, 3003 (2021).
- [67] G. Chartas, C. S. Kochanek, X. Dai, S. Poindexter, and G. Garmire, X-ray Microlensing in RXJ1131-1231 and HE1104-1805, *Astrophys. J.* **693**, 174 (2009).
- [68] G. Chartas, C. Rhea, C. Kochanek, X. Dai, C. Morgan, J. Blackburne, B. Chen, A. Mosquera, and C. MacLeod, Gravitational lensing size scales for quasars, *Astron. Nachr.* **337**, 356 (2017).
- [69] D. Karavola, M. Petropoulou, D. F. G. Fiorillo, L. Comisso, and L. Sironi, Neutrino and pair creation in reconnection-powered coronae of accreting black holes, *J. Cosmol. Astropart. Phys.* **04** (2025) 075.
- [70] J.-P. Lenain, C. Ricci, M. Türler, D. Dorner, and R. Walter, Seyfert 2 Galaxies in the GeV band: Jets and starburst, *Astron. Astrophys.* **524**, A72 (2010).
- [71] M. Ackermann *et al.* (Fermi-LAT Collaboration), GeV observations of star-forming galaxies with the Fermi Large Area Telescope, *Astrophys. J.* **755**, 164 (2012).
- [72] M. Ajello, K. Murase, and A. McDaniel, Disentangling the hadronic components in NGC 1068, *Astrophys. J. Lett.* **954**, L49 (2023).
- [73] J. J. Condon, Radio emission from normal galaxies, *Annu. Rev. Astron. Astrophys.* **30**, 575 (1992).
- [74] D. van Buren and M. A. Greenhouse, A More Direct measure of supernova rates in Starburst Galaxies, *Astrophys. J.* **431**, 640 (1994).
- [75] D. Kantzas, S. Markoff, A. J. Cooper, D. Gaggero, M. Petropoulou, and P. De La Torre Luque, Possible contribution of X-ray binary jets to the Galactic cosmic ray and neutrino flux, *Mon. Not. R. Astron. Soc.* **524**, 1326 (2023).
- [76] A. De Angelis, G. Galanti, and M. Roncadelli, Relevance of axion-like particles for very-high-energy astrophysics, *Phys. Rev. D* **84**, 105030 (2011); **87**, 109903(E) (2013).
- [77] M. Meyer, J. Davies, and J. Kuhlmann, gammaALPs: An open-source python package for computing photon-axion-like-particle oscillations in astrophysical environments, *Proc. Sci., ICRC2021* (2021) 557 [arXiv:2108.02061].
- [78] A. Domínguez, J. R. Primack, D. J. Rosario, F. Prada, R. C. Gilmore, S. M. Faber, D. C. Koo, R. S. Somerville, M. A. Pérez-Torres, P. Pérez-González, J.-S. Huang, M. Davis, P. Guhathakurta, P. Barmby, C. J. Conselice, M. Lozano, J. A. Newman, and M. C. Cooper, Extragalactic background light inferred from aegis galaxy-sed-type fractions: Ebl from aegis galaxy-sed-type fractions, *Mon. Not. R. Astron. Soc.* **410**, 2556 (2010).
- [79] M. S. Pshirkov, P. G. Tinyakov, P. P. Kronberg, and K. J. Newton-McGee, Deriving the global structure of the galactic magnetic field from faraday rotation measures of extragalactic sources, *Astrophys. J.* **738**, 192 (2011).

- [80] R. Jansson and G. R. Farrar, A new model of the galactic magnetic field, *Astrophys. J.* **757**, 14 (2012).
- [81] D. Horns, L. Maccione, M. Meyer, A. Mirizzi, D. Montanino, and M. Roncadelli, Hardening of TeV gamma spectrum of AGNs in galaxy clusters by conversions of photons into axion-like particles, *Phys. Rev. D* **86**, 075024 (2012).
- [82] S. S. Wilks, The large-sample distribution of the likelihood ratio for testing composite hypotheses, *Ann. Math. Stat.* **9**, 60 (1938).
- [83] H.-J. Li, J.-G. Guo, X.-J. Bi, S.-J. Lin, and P.-F. Yin, Limits on axion-like particles from Mrk 421 with 4.5-year period observations by ARGO-YBJ and Fermi-LAT, *Phys. Rev. D* **103**, 083003 (2021).
- [84] M. Ajello *et al.* (Fermi-LAT Collaboration), Search for spectral irregularities due to photon–axionlike-particle oscillations with the Fermi Large Area Telescope, *Phys. Rev. Lett.* **116**, 161101 (2016).
- [85] J. Davies, M. Meyer, and G. Cotter, Constraints on axionlike particles from a combined analysis of three flaring fermi flat-spectrum radio quasars, *Phys. Rev. D* **107**, 083027 (2023).
- [86] V. Anastassopoulos *et al.* (CAST Collaboration), New CAST limit on the axion-photon interaction, *Nat. Phys.* **13**, 584 (2017).
- [87] R. Essig *et al.*, Working Group report: New light weakly coupled particles, in *Snowmass 2013: Snowmass on the Mississippi* (Snowmass, Minneapolis, MN, USA, 2013).
- [88] C. O'Hare, cajohare/axionlimits: Axionlimits, <https://cajohare.github.io/AxionLimits/> (2020).
- [89] C. A. Manzari, Y. Park, B. R. Safdi, and I. Savoray, Supernova axions convert to gamma-rays in magnetic fields of progenitor stars, [arXiv:2405.19393](https://arxiv.org/abs/2405.19393).
- [90] C. Dessert, D. Dunsky, and B. R. Safdi, Upper limit on the axion-photon coupling from magnetic white dwarf polarization, *Phys. Rev. D* **105**, 103034 (2022).
- [91] D. Noordhuis, A. Prabhu, S. J. Witte, A. Y. Chen, F. Cruz, and C. Weniger, Novel constraints on axions produced in pulsar polar-cap cascades, *Phys. Rev. Lett.* **131**, 111004 (2023).
- [92] M. Escudero, C. K. Pooni, M. Fairbairn, D. Blas, X. Du, and D. J. E. Marsh, Axion star explosions: A new source for axion indirect detection, *Phys. Rev. D* **109**, 043018 (2024).
- [93] B. Betancourt Kamenetskaia, N. Fraija, and G. Herrera, Polarization measurements as a probe of axion-photon coupling: A study of GRB 221009A, *Phys. Rev. D* **111**, 115008 (2025).
- [94] J. N. Benabou, C. Dessert, K. C. Patra, T. G. Brink, W. Zheng, A. V. Filippenko, and B. R. Safdi, Search for axions in magnetic white dwarf polarization at lick and keck observatories, [arXiv:2504.12377](https://arxiv.org/abs/2504.12377).
- [95] O. Ning and B. R. Safdi, Leading axion-photon sensitivity with NuSTAR observations of M82 and M87, *Phys. Rev. Lett.* **134**, 171003 (2025).
- [96] C. Dessert, J. W. Foster, and B. R. Safdi, X-ray searches for axions from super star clusters, *Phys. Rev. Lett.* **125**, 261102 (2020).
- [97] R. Caputo *et al.*, All-sky medium energy gamma-ray observatory eXplorer mission concept, *J. Astron. Telesc. Instrum. Syst.* **8**, 044003 (2022).
- [98] M. Tavani *et al.* (e-ASTROGAM Collaboration), Science with e-ASTROGAM: A space mission for MeV–GeV gamma-ray astrophysics, *J. High Energy Astrophys.* **19**, 1 (2018).
- [99] B. S. Acharya *et al.* (CTA Consortium Collaboration), *Science with the Cherenkov Telescope Array* (World Scientific, Singapore, 2018).
- [100] M. Unger and G. R. Farrar, The coherent magnetic field of the Milky Way, *Astrophys. J.* **970**, 95 (2024).