

Constrains on the ALPs parameter space from GRB 221009A TeV emission

D. Avila Rojas,^{a,*} S. Hernández-Cadena,^a M. M. González,^b A. Pratts,^a R. Alfaro^a and J. Serna-Franco^a

^a*Instituto de Física, Universidad Nacional Autónoma de México,
Circuito Exterior, C.U., A. Postal 20-364, 04510 CDMX, México.*

^b*Instituto de Astronomía, Universidad Nacional Autónoma de México,
Circuito Exterior, C.U., A. Postal 70-264, 04510 CDMX, México.*

E-mail: daniel_avila5@ciencias.unam.mx

The recent observation of GRB 221009A by LHAASO at TeV energies has challenged the accepted emission mechanisms that describe the late emission of GRBs. Given the estimated distance of the event, $z=0.151$, TeV emission was not expected to be detected due to attenuation with the EBL. For this reason, light dark matter candidates such as ALPs have been proposed to explain the arrival of these TeV photons by assuming either an initial population of TeV photons or ALPs during the evolution of the GRB. In this sense, the detection from LHAASO might be useful to study the parameter space and production of ALPs. In this study we present the constrains on the ALPs parameter space by exploring different temporal profiles for the TeV emission from possible ALP production in the GRB 221009A.

The 38th International Cosmic Ray Conference (ICRC2023)
26 July – 3 August, 2023
Nagoya, Japan



*Speaker

1. GRB 221009A

On October 9th, 2022, the most luminous long Gamma-Ray Burst (GRB) ever was detected by Swift and Fermi-GBM, known as GRB 221009A [1, 2]. With an estimated redshift of $z = 0.151$ [3, 4], it was observed in multiple wavelengths across the electromagnetic spectrum from radio to gamma-rays. [5–8]. The more recent study from Fermi reports a total fluence of $S = (9.47 \pm 0.07) \times 10^{-2} \text{ erg cm}^{-2}$ and a total isotropic energy $E_{\text{iso}} = (1.01 \pm 0.01) \times 10^{55} \text{ erg}$ from 1 – 10,000 keV [9]. The host galaxy appears to be typical among long GRBs, with the GRB situated close to the center of its host galaxy. Nevertheless, its properties are unlikely to be linked to an unusual environment or conditions [10]. Despite extensive imaging and spectroscopy studies, no definitive supernova signatures have been detected, although there remains a possibility of a faint supernova connection [11].

At Very-High Energies (VHE), the High Altitude Water Cherenkov (HAWC) observatory and the High Energy Stereoscopic System (H.E.S.S.) conducted searches for VHE photons but no significant emission was detected in either case, providing upper limits for their observations. Their observations provided upper limits [12, 13]. Notably, the H.E.S.S. upper limit for energies above 650 GeV rules out the inverse Compton scenario, at least during the observed times, as a counterpart to the X-ray emission associated with synchrotron radiation. An astonishing feature from GRB 221009A was the detection of VHE gamma-ray emission detected by the Large High Altitude Air Shower Observatory (LHAASO), reporting more than 5000 photons above 500 GeV where the highest energy photon reaches 18 TeV, making it the first GRB detected above 10 TeV [14]. LHAASO's detection set a new paradigm for the acceleration processes that could explain such VHE emission, since it is expected an attenuation with the Extragalactic Background Light (EBL).

There have been many proposals for the possible explanation for an 18 TeV photon to be emitted by a GRB at such a high redshift. Among the different scenarios explored, those with a leptonic origin, the Synchrotron Self-Compton (SSC) scenario, seems implausible even when a more structure jet is assumed [15–18]. If an hadronic origin is assumed, the GRB needs to be localized in the outer region of the host galaxy and the required extragalactic magnetic field must be of $\mathcal{O}(10^{-14})$ [19, 20]. Other hadronic scenarios capable to explain LHAASO's detection consider ultra-high energy protons emitting photons via SSC, but those models requires very optimistic values for the proton acceleration timescale [21]. Furthermore, searches for neutrinos correlated with GRBs by IceCube, Amanda, and Antares have not yielded any detections, imposing constraints on neutrino production models and Ultra-High Energy Cosmic Rays (UHECRs) generation [22]. Despite GRB's anticipated role as UHECRs sources, the absence of correlated neutrino events has redirected attention to alternative sources like Active Galactic Nuclei (AGN).

Explanation involving models beyond the Standard Model (SM) also have been explored assuming Axion-like Particles (ALPs), sterile neutrinos appeared and Lorentz invariance violation. In this work, we continue with the analysis and interpretation of the 18 TeV photon by assuming an initial burst of ALPs generated at the GRB presented in [23]. We study the ALPs parameter space and its behavior by assuming different temporal and spectral profiles and different energy budgets for the initial ALPs burst. We also analyze the expected photon flux reaching to Earth and its contribution to the number of photons that LHAASO would detect above 500 GeV.

2. Axion-like Particles

Among the different candidates proposed to describe the nature of the Dark Matter (DM) is the ALP, a pseudo-scalar boson that generalize the concept of an axion in models beyond the SM [24, 25]. A main feature of ALPs is their coupling to photons of the SM, leading to oscillations between each other under the effect of magnetic fields. From the Lagrangian, the coupling between ALPs and photons is described by

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

where a is the ALP field, $F_{\mu\nu}$ the Faraday Tensor and $\tilde{F}^{\mu\nu}$ its dual, $g_{a\gamma}$ is the coupling constant and \vec{E} , \vec{B} are the electric and magnetic fields respectively [26].

Given this electromagnetic coupling, it is affordable to explore the scenario where an ALPs burst is generated at an astrophysical source. Assuming that ALPs kinetic energy is such that, along its way from the source, they could reach Earth as VHE photons, we call this the survival probability. This VHE photons could be able to avoid EBL attenuation, resulting in an excess at TeV energies.

For the calculation of the ALPs' survival probabilities we used the open source code `gammaALP` [27], considering values for the host galaxy, intergalactic and Milky Way magnetic fields [28], as for the EBL model [29]. The parameter space considered for our analysis is $10^{-5} \geq m_a \leq 10^{-8}$ eV and $3.16 \times 10^{-12} \geq g_{a\gamma} \leq 10^{-10}$ GeV $^{-1}$.

3. ALPs Parameter Space

We assumed a temporal profile, denoted as $\tau(t)$, to describe the injection of ALPs while maintaining their energy dependence. For the ALPs spectral profile we assumed a simple power law of the form

$$\Phi_a(E_a, t) = N_o \tau(t) E_a^{-\alpha_a}, \quad (2)$$

with E_a in TeV. Different values of the spectral index α_a ranging from 2.0 to 3.0 were explored, while for the temporal profiles we took the prompt phase from [30] and for the afterglow emission we assume a power-law temporal profile given by $\tau(t) \sim t^{-\beta}$ with $\beta = 1/2, 1, 2$. Then, the normalization factor N_o can be calculated from the fraction of the total isotropic energy of the GRB taken by the ALPs, given by

$$\%E_{\text{iso}} = \frac{4\pi d_z}{1+z} N_o \int_{E_{a,\text{min}}}^{E_{a,\text{max}}} \int_{t_{\text{min}}}^{t_{\text{max}}} \tau(t) \left(\frac{E_a}{1, \text{TeV}} \right)^{-\alpha_a+1} dt dE_a, \quad (3)$$

with d_z the luminosity distance to the source, z the redshift, t_{min} and t_{max} define the time interval of the ALPs injection, and $E_{a,\text{min}}$ and $E_{a,\text{max}}$ the minimum and maximum energies of the ALPs. We assumed different values for the energy fraction carried by the ALPs ranging from 0.1% to 30% of the isotropic energy. Then, we calculated the number of observed photons, N_γ using the effective area $A(E_\gamma)$ of the LHAASO-KM2A experiment, the normalization factor (N_o) of the ALPs spectrum, and the survival probability $P_{a\gamma}(E_\gamma)$ obtained from `gammaALP`, computed by:

$$N_\gamma = N_o \int_{E_{\gamma,\min}}^{E_{\gamma,\max}} \int_{t_0}^{t_{2000}} \tau(t) \left(\frac{E_a}{1 \text{ TeV}} \right)^{-\alpha_a} P_{a\gamma}(E_\gamma) A(E_\gamma) dt dE_\gamma. \quad (4)$$

We consider that the injection of ALPs lasts as long as the photon observation time reported by LHAASO (2000 s) and that $E_a \sim E_\gamma$ since the mass of the ALP is much smaller than its kinetic energy. From this assumptions it is forward that the total number of detected photons does not depend on the time profile of the ALPs injection. We calculated N_γ for different ALPs candidates in the selected parameter space. To constrain further our analysis we set two conditions on N_γ based on the detection reported by LHAASO and that at 18 TeV the energy uncertainty is ± 6.48 TeV. The conditions are as follow:

1. $N_\gamma \geq 0.5$ for E_γ between 10 – 25 TeV.
2. $N_\gamma < 0.5$ for $E_\gamma > 25$ TeV.

Those ALPs candidates satisfying the conditions are potential candidates to explain LHAASO's detection above 10 TeV and defines a permitted region. It is noteworthy that no ALPs candidates satisfying both conditions were found when $\alpha_a > 2.4$ or when the minimum energy of the injected ALPs is above 1 TeV. Moreover, as the energy carried by the ALPs increases, a softer spectrum and a lower E_{\min} ($\leq O(10)$ GeV) are required. From these results we can notice that, in order to explain LHAASO's 18 TeV photon by an ALPs burst: their spectra must be soft; most of the energy carried by ALPs is much more lower than the energy of the observed photons; and the total energy carried by ALPs must be a low percentage of E_{iso} .

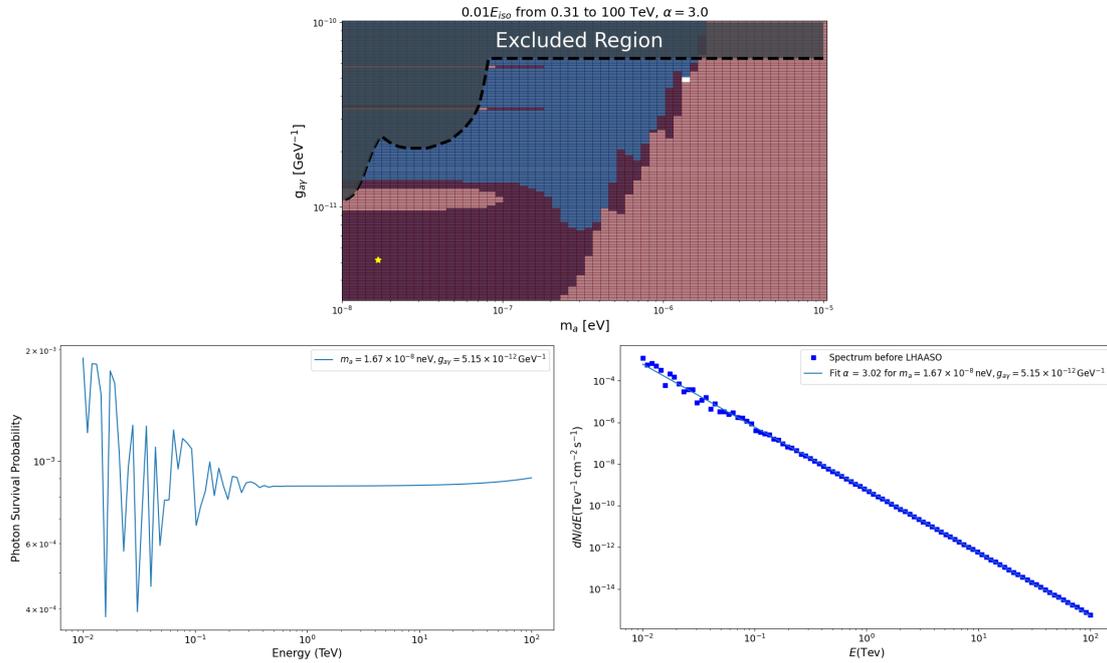


Figure 1: Top: candidates satisfying condition 1 (blue), candidates satisfying condition 2 (salmon), and candidates satisfying both conditions (burgundy). Bottom left: survival probability as a function of the energy for the selected candidate (yellow star in top plot). Bottom right: fitted resulting photon spectrum for the selected candidate (yellow star in top plot).

We investigated the resulting photon flux reaching Earth for the different ALPs candidates and fit it to a power law. Figure 1 shows an allowed candidate in the parameter space for $\%E_{\text{iso}} = 0.1$, $E_{\text{min}} = 0.31$ TeV, and $\alpha_a = 3.0$. The survival probability of the candidate and the fitted photon flux at Earth are also shown. The survival probability for this candidate stays approximately constant from 500 GeV up to 20 TeV, increasing at a low rate. This behavior of $P_{a\gamma}$ results in a photon spectra that preserving the same spectral index as the ALPs spectra.

We performed the same analysis and fit a simple power law to the expected photon flux for every ALP candidate in the permitted regions that we obtained under the different assumptions for α_a , $\%E_{\text{iso}}$ and E_{min} . In figure 2 the fitted photon spectral indexes of the candidates for different permitted regions and different values of α_a are shown. The ranging values for the fitted photon spectral indexes are between 1.8 and 3.0.

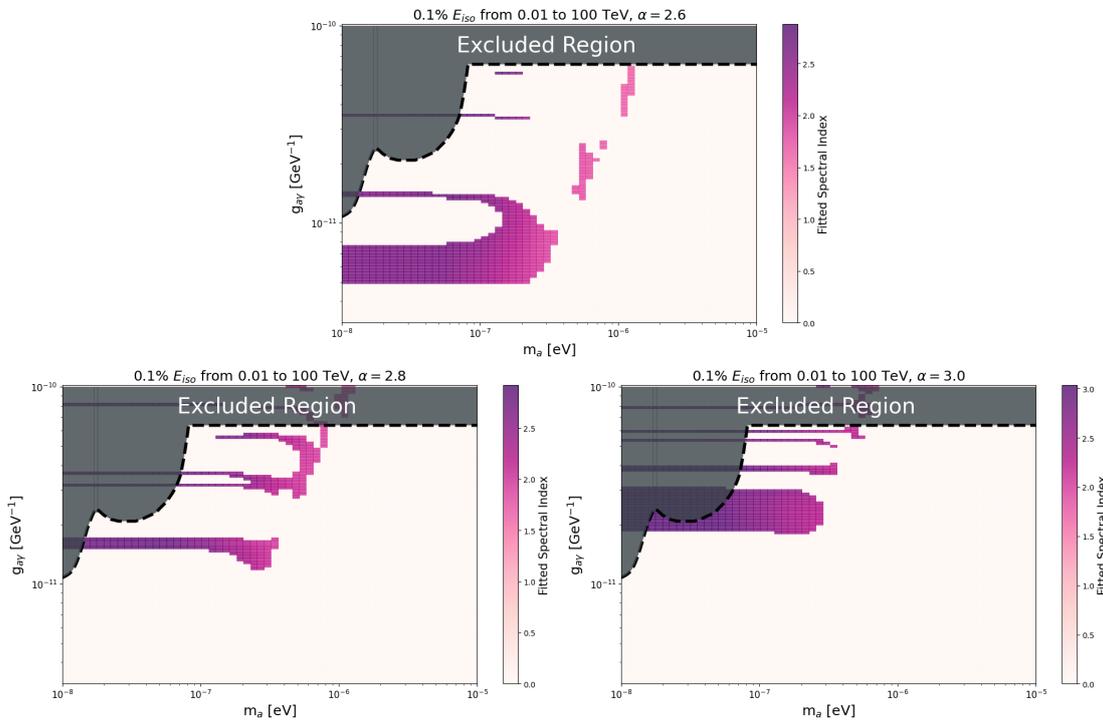


Figure 2: Fitted photon spectral indexes for the ALPs candidates in two different permitted regions obtained by varying the ALPs spectral index and fixing $\%E_{\text{iso}} = 0.1$ and $E_{\text{min}} = 0.01$ TeV. Top: permitted region for $\alpha_a = 2.6$. Bottom left: permitted region for $\alpha_a = 2.8$. Bottom right: permitted region for $\alpha_a = 3.0$.

Finally, we calculated the number of photons that contributes to LHAASO's detection above 500 GeV for the obtained permitted regions by taking the effective area of the LHAASO-WCDA experiment. The number of photons for a fixed value of $\%E_{\text{iso}} = 0.1$ are shown in figure 3. For all the permitted regions analyzed, the maximum number of detected photons by LHAASO-WCDA ranged from ~ 50 to ~ 375 photons. As can be noticed, the number of photons from the ALPs candidates that may contribute to LHAASO-WCDA's detection results in less than 10% of the reported number of > 5000 photons.

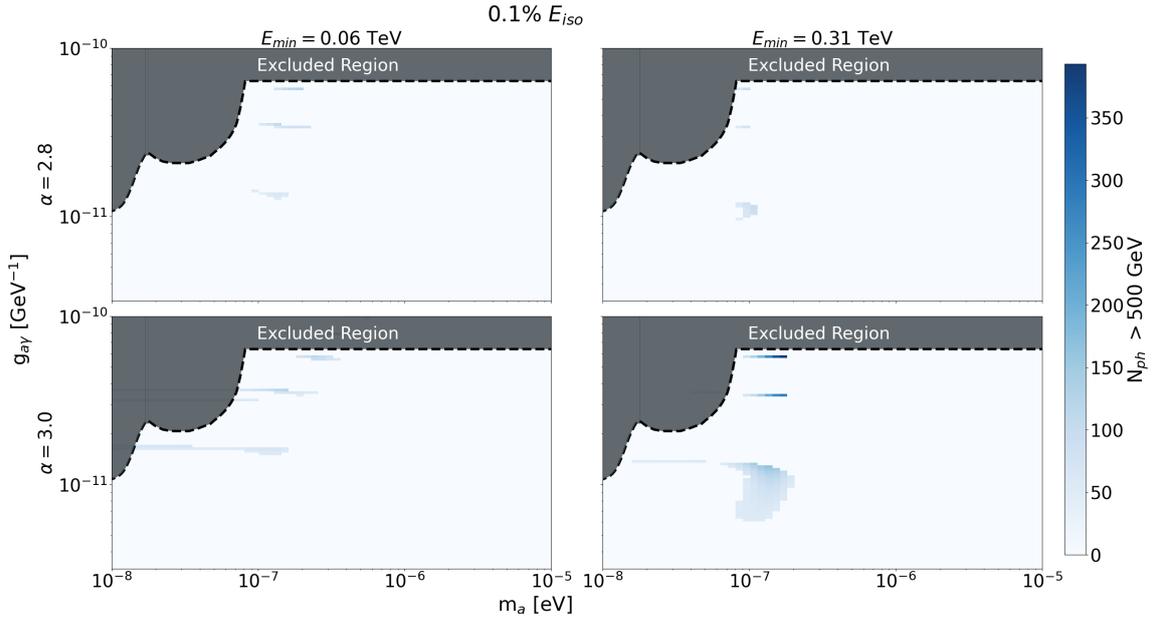


Figure 3: Caption

4. Conclusions

We explored the parameter space of ALPs as a potential explanation for the 18 TeV photon detected by the LHAASO from GRB 221009A. The permitted regions in the parameter space favor ALPs carrying less than 3% of the GRB’s energy budget, with a soft spectrum extending from tens up to hundreds of GeV. The fitted spectral indexes of the candidates were consistent with previous observations, and the contribution of ALPs to the photon flux above 500 GeV was estimated to be less than 10%. These makes the ALPs burst hypothesis a plausible explanation to the VHE emission from GRB 221009A and do not conflicts with the photon flux and observations at lower energies, nor with the GRB emission mechanisms so far proposed. Nevertheless, further investigation on the production mechanisms of ALPs in such astrophysical environments is still necessary. LHAASO’s results on this VHE emission will help to clarify the possible scenarios that explain such observation.

Acknowledgments

We acknowledge the support for this work from the UNAM-PAPIIT project number IG101323.

References

- [1] J.A. Kennea, M. Williams and Swift Team, *GRB 221009A: Swift detected transient may be GRB*, *GRB Coordinates Network* **32635** (2022) 1.
- [2] P. Veres, E. Burns, E. Bissaldi, S. Lesage, O. Roberts and Fermi GBM Team, *GRB 221009A: Fermi GBM detection of an extraordinarily bright GRB*, *GRB Coordinates Network* **32636** (2022) 1.

- [3] A.J. Castro-Tirado, R. Sanchez-Ramirez, Y.D. Hu, M.D. Caballero-Garcia, M.A. Castro Tirado, E. Fernandez-Garcia et al., *GRB 221009A: 10.4m GTC spectroscopic redshift confirmation*, *GRB Coordinates Network* **32686** (2022) 1.
- [4] A. de Ugarte Postigo, L. Izzo, G. Pugliese, D. Xu, B. Schneider, J.P.U. Fynbo et al., *GRB 221009A: Redshift from X-shooter/VLT*, *GRB Coordinates Network* **32648** (2022) 1.
- [5] S. Dichiara, J.D. Gropp, J.A. Kennea, N.P.M. Kuin, A.Y. Lien, F.E. Marshall et al., *Swift J1913.1+1946 a new bright hard X-ray and optical transient*, *GRB Coordinates Network* **32632** (2022) 1.
- [6] J.M. Durbak, A.S. Kuttyrev, I. Andreoni, K. De, E. Troja, S.B. Cenko et al., *GRB 221009A or Swift J1913.1+1946: PRIME near-infrared detection*, *GRB Coordinates Network* **32654** (2022) 1.
- [7] R. Brivio, M. Ferro, P. D'Avanzo, D. Fugazza, A. Melandri, S. Covino et al., *GRB 221009A: REM optical and NIR detection of the afterglow*, *GRB Coordinates Network* **32652** (2022) 1.
- [8] R. Pilleri, E. Bissaldi, N. Omodei, G. La Mura, F. Longo and Fermi-LAT team, *GRB 221009A: Fermi-LAT refined analysis*, *GRB Coordinates Network* **32658** (2022) 1.wcda
- [9] S. Lesage, P. Veres, M.S. Briggs, A. Goldstein, D. Kocevski, E. Burns et al., *Fermi-GBM Discovery of GRB 221009A: An Extraordinarily Bright GRB from Onset to Afterglow*, *arXiv e-prints* (2023) arXiv:2303.14172 [2303.14172].
- [10] A.J. Levan, G.P. Lamb, B. Schneider, J. Hjorth, T. Zafar, A. de Ugarte Postigo et al., *The first jwst spectrum of a grb afterglow: No bright supernova in observations of the brightest grb of all time, grb 221009a*, *The Astrophysical Journal Letters* **946** (2023) L28.
- [11] M. Shrestha, D.J. Sand, K.D. Alexander, K.A. Bostroem, G. Hosseinzadeh, J. Pearson et al., *Limit on Supernova Emission in the Brightest Gamma-Ray Burst, GRB 221009A*, *ApJ* **946** (2023) L25 [2302.03829].
- [12] H. Ayala and HAWC Collaboration, *GRB 221009A: Upper limits from HAWC 8 hours after trigger*, *GRB Coordinates Network* **32683** (2022) 1.
- [13] F. Aharonian, F.A. Benkhali, J. Aschersleben, H. Ashkar, M. Backes, A. Baktash et al., *H.E.S.S. Follow-up Observations of GRB 221009A*, *ApJ* **946** (2023) L27 [2303.10558].
- [14] Y. Huang, S. Hu, S. Chen, M. Zha, C. Liu, Z. Yao et al., *LHAASO observed GRB 221009A with more than 5000 VHE photons up to around 18 TeV*, *GRB Coordinates Network* **32677** (2022) 1.
- [15] T. Laskar, K.D. Alexander, R. Margutti, T. Eftekhari, R. Chornock, E. Berger et al., *The Radio to GeV Afterglow of GRB 221009A*, *ApJ* **946** (2023) L23 [2302.04388].
- [16] H. Abdalla, R. Adam, F. Aharonian, F. Ait Benkhali, E.O. Angüner, M. Arakawa et al., *A very-high-energy component deep in the γ -ray burst afterglow*, *Nature* **575** (2019) 464 [1911.08961].

- [17] M.A. Williams, J.A. Kennea, S. Dichiara, K. Kobayashi, W.B. Iwakiri, A.P. Beardmore et al., *GRB 221009A: Discovery of an Exceptionally Rare Nearby and Energetic Gamma-Ray Burst*, *ApJ* **946** (2023) L24.
- [18] Y. Sato, K. Murase, Y. Ohira and R. Yamazaki, *Two-component jet model for multi-wavelength afterglow emission of the extremely energetic burst GRB 221009A*, *MNRAS* (2023) [2212.09266].
- [19] A. Rudolph, M. Petropoulou, W. Winter and Ž. Bošnjak, *Multi-messenger Model for the Prompt Emission from GRB 221009A*, *ApJ* **944** (2023) L34 [2212.00766].
- [20] B.T. Zhang, K. Murase, K. Ioka, D. Song, C. Yuan and P. Mészáros, *External Inverse-compton and Proton Synchrotron Emission from the Reverse Shock as the Origin of VHE Gamma Rays from the Hyper-bright GRB 221009A*, *ApJ* **947** (2023) L14 [2211.05754].
- [21] S. Das and S. Razzaque, *Ultrahigh-energy cosmic-ray signature in GRB 221009A*, *A&A* **670** (2023) L12 [2210.13349].
- [22] R. Abbasi, M. Ackermann, J. Adams, S.K. Agarwalla, N. Aggarwal, J.A. Aguilar et al., *Limits on Neutrino Emission from GRB 221009A from MeV to PeV Using the IceCube Neutrino Observatory*, *ApJ* **946** (2023) L26 [2302.05459].
- [23] M.M. González, D. Avila Rojas, A. Pratts, S. Hernández-Cadena, N. Fraija, R. Alfaro et al., *GRB 221009A: A Light Dark Matter Burst or an Extremely Bright Inverse Compton Component?*, *ApJ* **944** (2023) 178 [2210.15857].
- [24] L. Abbott and P. Sikivie, *A cosmological bound on the invisible axion*, *Physics Letters B* **120** (1983) 133.
- [25] J. Preskill, M.B. Wise and F. Wilczek, *Cosmology of the invisible axion*, *Physics Letters B* **120** (1983) 127.
- [26] G. Raffelt and L. Stodolsky, *Mixing of the photon with low-mass particles*, *Phys. Rev. D* **37** (1988) 1237.
- [27] M. Meyer, J. Davies and J. Kuhlmann, *gammaALPs: An open-source python package for computing photon-axion-like-particle oscillations in astrophysical environments*, in *37th International Cosmic Ray Conference*, p. 557, Mar., 2022, DOI [2108.02061].
- [28] R. Jansson and G.R. Farrar, *A New Model of the Galactic Magnetic Field*, *ApJ* **757** (2012) 14 [1204.3662].
- [29] R.C. Gilmore, R.S. Somerville, J.R. Primack and A. Domínguez, *Semi-analytic modelling of the extragalactic background light and consequences for extragalactic gamma-ray spectra*, *MNRAS* **422** (2012) 3189 [1104.0671].
- [30] A.S. Kozyrev, D.V. Golovin, M.L. Litvak, I.G. Mitrofanov, A.B. Sanin, Mgns/Bepicolombo Team et al., *Improved IPN localization for GRB 221009A (BepiColombo-MGNS light curve)*, *GRB Coordinates Network* **32805** (2022) 1.