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Recent results on LIV studies using MAGIC telescopes from the observation of GRB 190114C

Giacomo D'Amico,[a,*] Daniel Kerszberg,[b] Manel Martínez,[b] Cédric Perennes,[c] Javier Rico[b] and Tomislav Terzić[d] on behalf of the MAGIC Collaboration[†]

[a] *Max-Planck-Institut für Physik, D-80805 München, Germany*
[a] *Department for Physics and Technology, University of Bergen, Bergen NO-5020, Norway*
[b] *Institut de Física d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology (BIST), E-08193 Bellaterra (Barcelona), Spain*
[c] *Università di Padova and INFN, I-35131 Padova, Italy*
[d] *University of Rijeka, Department of Physics, 51000 Rijeka, Croatia*

E-mail: damico@mppmu.mpg.de, giacomo.damico@uib.no

On January 14, 2019, the most energetic photons ever observed from a gamma-ray burst were recorded by the Major Atmospheric Gamma Imaging Cherenkov (MAGIC) telescopes, detecting GRB 190114C at TeV energies. We used this unique observation to probe an energy dependence of the speed of light in vacuo for photons, as predicted by several quantum gravity models. From a set of conservative assumptions on the possible intrinsic spectral and temporal evolution, competitive lower limits on the quadratic leading order modification of the speed of light were obtained. We performed the first Lorentz invariance violation test ever performed on a gamma-ray burst signal at TeV energies, which will serve as a stepping stone to future studies.

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*Presenter
†a complete list of the MAGIC Collaboration authors can be found at the end of the proceedings

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1. Introduction

General relativity and quantum gravity are expected to merge at around the Planck energy

$$E_{\text{Pl}} \approx 1.22 \times 10^{19}\,\text{GeV} \tag{1}$$

into a joint, yet unknown theory of quantum gravity (QG). Violations or deformations of the Lorentz symmetry, also known as Lorentz invariance violation (LIV, [1–7]) are predicted by some candidate QG theories.

LIV can manifest in corrections to the *in vacuo* photon dispersion relation, whose consequence is an energy-dependent photon group velocity

$$v_\gamma \simeq 1 - \sum_{n=1}^{\infty} s\frac{n+1}{2}\left(\frac{E}{E_{\text{QG,n}}}\right)^n, \tag{2}$$

with E the energy of the photon and $E_{\text{QG,n}}$ the QG energy scale. The variable s is a theory-dependent factor that can be $+1$ or -1, in the former case we are in the so-called subluminal scenario, while in the latter in the superluminal one. A photon of energy E will accumulate due to these LIV effects a time delay

$$\Delta t = s\frac{n+1}{2}D_n(z)\left(\frac{E}{E_{\text{QG,n}}}\right)^n, \tag{3}$$

where, only the leading LIV correction of order n is taken into account. The LIV parameters

$$\eta_1 = s\,E_{\text{Pl}}/E_{\text{QG,1}} \tag{4}$$

and

$$\eta_2 = 10^{-16} \times s\,E_{\text{Pl}}^2/E_{\text{QG,2}}^2, \tag{5}$$

are introduced in Eq. (3) for practicality in linear ($n = 1$) and quadratic ($n = 2$) modification, respectively. The information on the comoving distance between the source and the detector are incoded in $D_n(z)$ [8]

$$D_n(z) = \frac{1}{H_0}\int_0^z \frac{(1+\zeta)^n}{\sqrt{\Omega_\Lambda + (1+\zeta)^3\Omega_m}}d\zeta, \tag{6}$$

where Ω_Λ, H_0, and Ω_m are the cosmological constant, the Hubble parameter and the matter fraction, respectively. $H_0 = 70\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$, $\Omega_\Lambda = 0.7$, and $\Omega_m = 0.3$ are assumed [9]. The systematic effect introduced by these relatively coarse values and their variations is negligible compared to the sensitivity of our analysis.

Gamma-ray bursts (GRBs) are excellent candidates for LIV studies [2] and already detected frequently in the high energy (HE, $E \lesssim 100\,\text{GeV}$) regime with detectors on board the *Fermi* satellite [14]. However, they are notoriously difficult to detect in the very high energy (VHE, $E > 100\,\text{GeV}$) band. The recent detection of GRB 190114C at redshift $z = 0.4245 \pm 0.0005$ [15, 16] with the MAGIC telescopes was the first one reported at TeV energies [17].

In this Proceeding, we present the results of a LIV study based on the VHE γ-ray signal from GRB 190114C. The MAGIC observations and data analysis are presented in the next section. The TOF analysis method is described in the maximum likelihood analysis section. Results are presented and discussed with the most important conclusions summarized in the final section.

2. MAGIC observation of GRB 190114C

MAGIC is a system of two 17-meter-diameter imaging atmospheric Cherenkov telescopes [18], located in the Roque de los Muchachos observatory on the Canary Island of La Palma at about 2200 meters above the sea level.

The MAGIC telescopes detected on January 14, 2019, a strong VHE γ-ray signal from GRB 190114C [17, 19]. After the initial trigger T_0, corresponding to the universal time 20:57:03, the highest energy photons ever detected from a GRB were recorded. The intrinsic spectrum (from $T_0 + 62$ seconds to $T_0 + 2400$ seconds) is well fitted with a power law function with index $\alpha = -2.5 \pm 0.2$ [19]. The intrinsic integrated flux in the energy range $0.3 - 1$ TeV is well described by a power law with time decay index $\beta = -1.51 \pm 0.04$ [19]. The signal events were extracted from the so-called ON region, a circular sky region of radius 0.1°–0.2° (depending on the energy) around the position of the source, which also contains background events. The background contamination in the ON region was estimated from three simultaneous OFF regions within the field of view, and of the same size as the ON region. This resulted in a total of $N_{\mathrm{ON}} = 726$ and $N_{\mathrm{OFF}} = 119$ events (i.e., $119/3 = 39.67$ estimated background events in the ON region), with estimated energies from $E_{\mathrm{min}} = 300\,\mathrm{GeV}$ to $E_{\mathrm{max}} = 1955\,\mathrm{GeV}$ and arrival times from $t_{\mathrm{min}} = 62\,\mathrm{s}$ to $t_{\mathrm{max}} = 1212\,\mathrm{s}$ after T_0.

3. Maximum likelihood analysis

The maximum likelihood method is used in order to estimate the value of the LIV parameters η_n ($n \in \{1, 2\}$). First a probability distribution function (PDF) of detecting a photon of estimated energy E_{est} at time t is defined as

$$f_s(t, E_{\mathrm{est}} \,|\, \eta_n, I) \propto \int_0^\infty dE \; \Phi_1[t - \Delta t(E, \eta_n)] \, \Phi_2(E) \, F(E) \, A_{\mathrm{eff}}(E) \, G\,(E_{\mathrm{est}}, E), \tag{7}$$

where $\Phi_1[t - \Delta t(E, \eta_n)]$ represents the temporal distribution of γ rays (modified for the potential LIV-induced time delay), and $\Phi_2(E)$ is the energy distribution of γ rays at the source. $F(E)$ is the attenuation induced by the extragalactic background light (EBL) , which is obtained from the model of A. Domínguez *et al.* [20] with $z = 0.4245$. $A_{\mathrm{eff}}(E)$ is the acceptance of our instrument, i.e. the probability of detecting a photon of energy E, while $G\,(E_{\mathrm{est}}, E)$ is the finite energy resolution of the MAGIC telescopes, i.e. the PDF of measuring an estimated energy E_{est} from a photon with true energy E. $A_{\mathrm{eff}}(E)$ and $G\,(E_{\mathrm{est}}, E)$ are computed from Monte Carlo simulations. The source intrinsic parameters are represented with I and treated as nuisance parameters.

Mutually independent intrinsic energy and temporal distributions are assumed [17]. The former is modeled with a power law $\Phi_2(E) \propto E^{\alpha}$. The latter (see Fig. 1) is obtained by combining the measured monotonic and smooth power law with the theoretical model from Ref. [19] based on multiwavelength (MWL) observations and theoretical considerations. For the purposes of this study, we parameterized the LC as follows:

$$\Phi_1(t) \propto \begin{cases} 0 & t < T_0 \equiv 0 \\ h(t) & T_0 < t < T_1 \\ h(T_1)\,(t/T_1)^{\beta} & t > T_1 \end{cases} \tag{8}$$

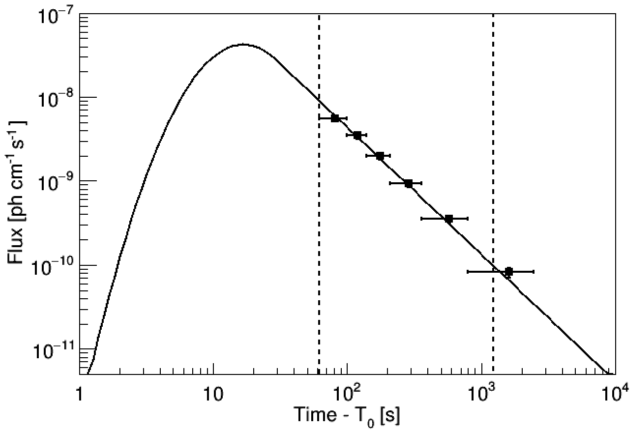

Figure 1: Intrinsic LC model. The points represent the γ-ray flux measured by MAGIC in the 0.3–1 TeV energy range, while the full line represents the LC model reported in [19]. The vertical dashed lines represent the bounds of the time interval considered in our analysis. Figure taken from Ref. [21].

where $h(t) = t^{7.3-1.3\ln(t)}$ and $T_1 = 30$ s [19].

The likelihood function can be therefore written as

$$\begin{aligned}\mathcal{L}\left(\eta_n;\ I \mid \{t^{(i)}, E_{\mathrm{est}}^{(i)}\}_{i=1,\ldots,N_{\mathrm{ON}}},\ N_{\mathrm{ON}}, N_{\mathrm{OFF}}\right) &= P(I) \\ \times \prod_i^{N_{\mathrm{ON}}} \left(\frac{N_{\mathrm{ON}} - N_{\mathrm{OFF}}/\tau}{N_{\mathrm{ON}}} \frac{f_s(t^{(i)}, E_{\mathrm{est}}^{(i)} \mid \eta_n, I)}{\int dE_{\mathrm{est}}\ dt\ f_s(t, E_{\mathrm{est}} \mid \eta_n, I)} \right. &+ \left. \frac{N_{\mathrm{OFF}}}{\tau N_{\mathrm{ON}}} \frac{f_b(t^{(i)}, E_{\mathrm{est}}^{(i)})}{\int dE_{\mathrm{est}}\ dt\ f_b(t, E_{\mathrm{est}})}\right),\end{aligned} \tag{9}$$

where $E_{\mathrm{est}}^{(i)}$ and $t^{(i)}$ are the estimated energy and arrival time, respectively, of event i. The integral in energy and time has to be performed from E_{min} to E_{max} and from t_{min} to t_{max}, respectively (see previous section). $P(I)$ is the PDF of the parameters describing the intrinsic energy and temporal evolution of the source;

For the likelihood maximization all 726 events from the ON region are used . The intrinsic parameters α and β are treated as nuisance parameters, both distributed according to normal distributions centered at -2.5 and -1.51, with standard deviations 0.2 and 0.04, respectively [19]. $\tau = 3$ (see the previous section) is the ratio of exposure time between the background and the signal regions. A uniform distribution in time (justified by the stable observation conditions) is assumed for the background PDF $f_b(t, E_{\mathrm{est}})$, while for the energy distribution we use events collected with MAGIC when pointing under the same observational conditions to regions of the sky with no known γ-ray sources.

The test statistic

$$L = -2\ln\left(\frac{\max(\mathcal{L})_I}{\max(\mathcal{L})_{\eta_n,I}}\right) \tag{10}$$

is then computed as a function of η_n. In Eq. (10) the notation $\max(\mathcal{L})_I \equiv \mathcal{L}(x, \hat{I})$ has been introduced where $\hat{I}$ maximizes $\mathcal{L}$ for a given value of x. L will allow us in the next section to obtain confidence intervals (CIs) for the QG energy scale.

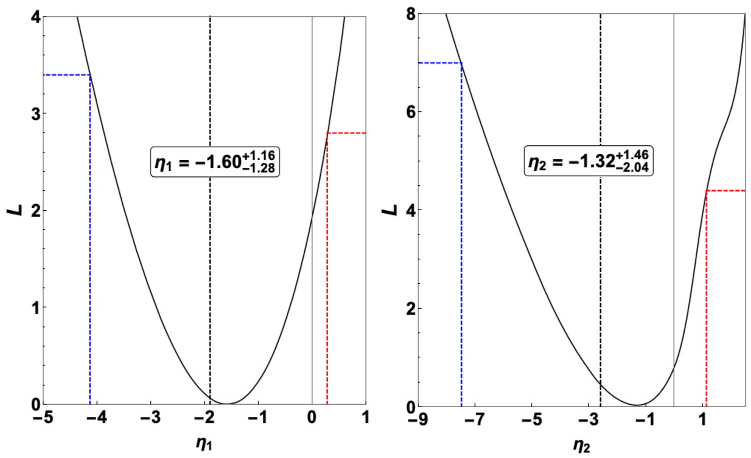

Figure 2: Likelihood profile for the linear (left) and quadratic (right) case, using the theoretical model for the intrinsic LC. Figure from Ref. [21]. The black dashed line represents the bias obtained from mock data sets (see Section A of the Supplemental Material in Ref. [21]). The point at which the likelihood is equal to the calibrated 95% CIs is instead shown using blue and red dashed lines for the lower and upper limit, respectively (see Section B of the Supplemental Material in Ref. [21]).

4. Results

We first study the sensitivity and influence of systematic effects of the assumed intrinsic light curve defined in Eq. (8). This is done by analysing 1000 LIV-free mock data sets, from which we estimate the bias associated to the maximum likelihood analysis applied to this particular temporal and energy distributions (see Ref. [21] for details). We find that our analysis has a bias towards negative values of the LIV parameter η. In particular, we obtain $\eta_{1,\mathrm{bias}} = -1.9$ and $\eta_{2,\mathrm{bias}} = -2.6$. For the real data we find that the likelihood is maximal for $\eta_1 = -1.6$ and $\eta_2 = -1.32$ (see Fig. 2) in the linear and quadratic case, respectively. We correct these values for the bias to get the best fit values (η^{BF}) reported in Table 1. These results are consistent with the null hypothesis ($\eta = 0$) (see Section A of the Supplemental Material in Ref. [21]), i.e., no energy-dependent time delay, or $E_{\mathrm{QG}} \to \infty$. Therefore, upper limits on η are computed from calibrated 95% CIs. The procedure adopted from Ref. [10] is described in Section B of the Supplemental Material in Ref. [21]. The obtained calibrated CIs are reported in Table 1. From Eqs. (4) and (5) these values are translated into limits on the energy scale E_{QG} at 95% confidence level and reported in Table 1.

In Ref. [19] a possible change of spectral index of GRB 190114C with time was reported. The resulting systematic effect on η is found to be less than 5% in all cases. Additionally, using a dedicated study with Monte Carlo simulations, we computed that the limits would degrade by up to 18% (29%) in subluminal (superluminal) case, should the Cherenkov light collected by the telescopes be overestimated by 15% in our analysis, which is a conservative assumption.

5. Conclusions

MAGIC discovered a γ-ray signal above 0.2 TeV from GRB 190114C, detecting the highest energy photons from a GRB. We searched for an energy-dependent delay in arrival time of the

Table 1: Values of the 95% lower (LL) and upper (UL) limits and the best fits (BF) obtained for η_n after applying bias correction and CI calibration. Values are reported for the linear ($n = 1$) and quadratic ($n = 2$) cases.

	η^{LL}	η^{BF}	η^{UL}
η_1	-2.2	0.3	2.1
η_2	-4.8	1.3	3.7
	superl.		subl.
$E_{QG,1}$ / (10^{19} GeV)	0.55		0.58
$E_{QG,2}$ / (10^{10} GeV)	5.6		6.3

most energetic photons, testing in vacuo dispersion relations of VHE photons. Our results for the linear modification of the photon dispersion relation for the subluminal (superluminal) case are approximately a factor 4 (7) below the most constraining lower limits on $E_{QG,1}$ obtained from TOF method on GRB 090510 [10]. This is expected because of a significantly larger distance of GRB 090510 ($z = 0.9$, compared to 0.4245 of GRB 190114C), as well as a shorter variability timescale, since *Fermi*-LAT observations of GRB 090510 include a full coverage of the emission. In the quadratic case, the analysis is more sensitive to the highest photon energies in the data sample. As a result, our lower limits on the energy scale for the quadratic case are more constraining than the ones in [10]. At the same time, our results are comparable to the ones from [12].

6. Acknowledgments

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The MAGIC Collaboration

V. A. Acciari[1], S. Ansoldi[2,41], L. A. Antonelli[3], A. Arbet Engels[4], M. Artero[5], K. Asano[6], D. Baack[7], A. Babić[8], A. Baquero[9], U. Barres de Almeida[10], J. A. Barrio[9], I. Batković[11], J. Becerra González[1], W. Bednarek[12], L. Bellizzi[13], E. Bernardini[14], M. Bernardos[11], A. Berti[15], J. Besenrieder[15], W. Bhattacharyya[14], C. Bigongiari[3], A. Biland[4], O. Blanch[5], H. Bökenkamp[7], G. Bonnoli[16], Ž. Bošnjak[8], G. Busetto[11], R. Carosi[17], G. Ceribella[15], M. Cerruti[18], Y. Chai[15], A. Chilingarian[19], S. Cikota[8], S. M. Colak[5], E. Colombo[1], J. L. Contreras[9], J. Cortina[20], S. Covino[3], G. D'Amico[15,42], V. D'Elia[3], P. Da Vela[17,43], F. Dazzi[3], A. De Angelis[11], B. De Lotto[2], M. Delfino[5,44], J. Delgado[5,44], C. Delgado Mendez[20], D. Depaoli[21], F. Di Pierro[21], L. Di Venere[22], E. Do Souto Espiñeira[5], D. Dominis Prester[23], A. Donini[2], D. Dorner[24], M. Doro[11], D. Elsaesser[7], V. Fallah Ramazani[25,45], A. Fattorini[7], M. V. Fonseca[9], L. Font[26], C. Fruck[15], S. Fukami[6], Y. Fukazawa[27], R. J. García López[1], M. Garczarczyk[14], S. Gasparyan[28], M. Gaug[26], N. Giglietto[22], F. Giordano[22], P. Gliwny[12], N. Godinović[29], J. G. Green[3], D. Green[15], D. Hadasch[6], A. Hahn[15], L. Heckmann[15], J. Herrera[1], J. Hoang[9,46], D. Hrupec[30], M. Hütten[15], T. Inada[6], K. Ishio[12], Y. Iwamura[6], I. Jiménez Martínez[20], J. Jormanainen[25], L. Jouvin[5], M. Karjalainen[1], D. Kerszberg[5], Y. Kobayashi[6], H. Kubo[31], J. Kushida[32], A. Lamastra[3], D. Lelas[29], F. Leone[3], E. Lindfors[25], L. Linhoff[7], S. Lombardi[3], F. Longo[2,47], R. López-Coto[11], M. López-Moya[9], A. López-Oramas[1], S. Loporchio[22], B. Machado de Oliveira Fraga[10], C. Maggio[26], P. Majumdar[33], M. Makariev[34], M. Mallamaci[11], G. Maneva[34], M. Manganaro[23], K. Mannheim[24], L. Maraschi[3], M. Mariotti[11], M. Martínez[5], D. Mazin[6,15], S. Menchiari[13], S. Mender[7], S. Mićanović[23], D. Miceli[2,49], T. Miener[9], J. M. Miranda[13], R. Mirzoyan[15], E. Molina[18], A. Moralejo[5], D. Morcuende[9], V. Moreno[26], E. Moretti[5], T. Nakamori[35], L. Nava[3], V. Neustroev[36], C. Nigro[5], K. Nilsson[25], K. Nishijima[32], K. Noda[6], S. Nozaki[31], Y. Ohtani[6], T. Oka[31], J. Otero-Santos[1], S. Paiano[3], M. Palatiello[2], D. Paneque[15], R. Paoletti[13], J. M. Paredes[18], L. Pavletić[23], P. Peñil[9], M. Persic[2,50], M. Pihet[15], P. G. Prada Moroni[17], E. Prandini[11], C. Priyadarshi[5], I. Puljak[29], W. Rhode[7], M. Ribó[18], J. Rico[5], C. Righi[3], A. Rugliancich[17], N. Sahakyan[28], T. Saito[6], S. Sakurai[6], K. Satalecka[14], F. G. Saturni[3], B. Schleicher[24], K. Schmidt[7], T. Schweizer[15], J. Sitarek[12], I. Šnidarić[37], D. Sobczynska[12], A. Spolon[11], A. Stamerra[3], J. Strišković[30], D. Strom[15], M. Strzys[6], Y. Suda[27], T. Surić[37], M. Takahashi[6], R. Takeishi[6], F. Tavecchio[3], P. Temnikov[34], T. Terzić[23], M. Teshima[15,6], L. Tosti[38], S. Truzzi[13], A. Tutone[3], S. Ubach[26], J. van Scherpenberg[15], G. Vanzo[1], M. Vazquez Acosta[1], S. Ventura[13], V. Verguilov[34], C. F. Vigorito[21], V. Vitale[39], I. Vovk[6], M. Will[15], C. Wunderlich[13], T. Yamamoto[40], and D. Zarić[29]

[1] Instituto de Astrofísica de Canarias and Dpto. de Astrofísica, Universidad de La Laguna, E-38200, La Laguna, Tenerife, Spain [2] Università di Udine and INFN Trieste, I-33100 Udine, Italy [3] National Institute for Astrophysics (INAF), I-00136 Rome, Italy [4] ETH Zürich, CH-8093 Zürich, Switzerland [5] Institut de Física d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology (BIST), E-08193 Bellaterra (Barcelona), Spain [6] Japanese MAGIC Group: Institute for Cosmic Ray Research (ICRR), The University of Tokyo, Kashiwa, 277-8582 Chiba, Japan [7] Technische Universität Dortmund, D-44221 Dortmund, Germany [8] Croatian MAGIC Group: University of Zagreb, Faculty of Electrical Engineering and Computing (FER), 10000 Zagreb, Croatia [9] IPARCOS Institute and EMFTEL Department, Universidad Complutense de Madrid, E-28040 Madrid, Spain [10] Centro Brasileiro de Pesquisas Físicas (CBPF), 22290-180 URCA, Rio de Janeiro (RJ), Brazil [11] Università di Padova and INFN, I-35131 Padova, Italy [12] University of Lodz, Faculty of Physics and Applied Informatics, Department of Astrophysics, 90-236 Lodz, Poland [13] Università di Siena and INFN Pisa, I-53100 Siena, Italy [14] Deutsches Elektronen-Synchrotron (DESY), D-15738 Zeuthen, Germany [15] Max-Planck-Institut für Physik, D-80805 München, Germany [16] Instituto de Astrofísica de Andalucía-CSIC, Glorieta de la Astronomía s/n, 18008, Granada, Spain [17] Università di Pisa and INFN Pisa, I-56126 Pisa, Italy [18] Universitat de Barcelona, ICCUB, IEEC-UB, E-08028 Barcelona, Spain [19] Armenian MAGIC Group: A. Alikhanyan National Science Laboratory, 0036 Yerevan, Armenia [20] Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas, E-28040 Madrid, Spain [21] INFN MAGIC Group: INFN Sezione di Torino and Università degli Studi di Torino, I-10125 Torino, Italy [22] INFN MAGIC Group: INFN Sezione di Bari and Dipartimento Interateneo di Fisica dell'Università e del Politecnico di Bari, I-70125 Bari, Italy [23] Croatian MAGIC Group: University of Rijeka, Department of Physics, 51000 Rijeka, Croatia [24] Universität Würzburg, D-97074 Würzburg, Germany [25] Finnish MAGIC Group: Finnish Centre for Astronomy with ESO, University of Turku, FI-20014 Turku, Finland [26] Departament de Física, and CERES-IEEC, Universitat Autònoma de Barcelona, E-08193 Bellaterra, Spain [27] Japanese MAGIC Group: Physics Program, Graduate School of Advanced Science and Engineering, Hiroshima University, 739-8526 Hiroshima, Japan [28] Armenian MAGIC Group: ICRANet-Armenia at NAS RA, 0019 Yerevan, Armenia [29] Croatian MAGIC Group: University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture (FESB), 21000 Split, Croatia [30] Croatian MAGIC Group: Josip Juraj Strossmayer University of Osijek, Department of Physics, 31000 Osijek, Croatia [31] Japanese MAGIC Group: Department of Physics, Kyoto University, 606-8502 Kyoto, Japan [32] Japanese MAGIC Group: Department of Physics, Tokai University, Hiratsuka, 259-1292 Kanagawa, Japan [33] Saha Institute of Nuclear Physics, HBNI, 1/AF Bidhannagar, Salt Lake, Sector-1, Kolkata 700064, India [34] Inst. for Nucl. Research and Nucl. Energy, Bulgarian Academy of Sciences, BG-1784 Sofia, Bulgaria [35] Japanese MAGIC Group: Department of Physics, Yamagata University, Yamagata 990-8560, Japan [36] Finnish MAGIC Group: Astronomy Research Unit, University of Oulu, FI-90014 Oulu, Finland [37] Croatian MAGIC Group: Ruđer Bošković Institute, 10000 Zagreb, Croatia [38] INFN MAGIC Group: INFN Sezione di Perugia, I-06123 Perugia, Italy [39] INFN MAGIC Group: INFN

Roma Tor Vergata, I-00133 Roma, Italy [40] Japanese MAGIC Group: Department of Physics, Konan University, Kobe, Hyogo 658-8501, Japan [41] also at International Center for Relativistic Astrophysics (ICRA), Rome, Italy [42] now at Department for Physics and Technology, University of Bergen, NO-5020, Norway [43] now at University of Innsbruck [44] also at Port d'Informació Científica (PIC), E-08193 Bellaterra (Barcelona), Spain [45] now at Ruhr-Universität Bochum, Fakultät für Physik und Astronomie, Astronomisches Institut (AIRUB), 44801 Bochum, Germany [46] now at Department of Astronomy, University of California Berkeley, Berkeley CA 94720 [47] also at Dipartimento di Fisica, Università di Trieste, I-34127 Trieste, Italy [49] now at Laboratoire d'Annecy de Physique des Particules (LAPP), CNRS-IN2P3, 74941 Annecy Cedex, France [50] also at INAF Trieste and Dept. of Physics and Astronomy, University of Bologna, Bologna, Italy