PROCEEDINGS OF SCIENCE

RS Ophiuchi nova outburst detection by the LST-1

A. Aguasca-Cabot,[a,*] M. I. Bernardos,[b] D. Green,[c] Y. Kobayashi[d] and R. López-Coto[b] on behalf of the CTA LST project

[a] *Departament de Física Quàntica i Astrofísica, Institut de Ciències del Cosmos, Universitat de Barcelona, IEEC-UB, Martí i Franquès, 1, 08028, Barcelona, Spain*

[b] *Instituto de Astrofísica de Andalucía-CSIC, Glorieta de la Astronomía s/n, 18008, Granada, Spain*

[c] *Max-Planck-Institut für Physik, Föhringer Ring 6, 80805 München, Germany*

[d] *Institute for Cosmic Ray Research, University of Tokyo, 5-1-5, Kashiwa-no-ha, Kashiwa, Chiba 277-8582, Japan*

E-mail: arnau.aguasca@fqa.ub.edu, misabelber@iaa.es, damgreen@mpp.mpg.de, yukihok@icrr.u-tokyo.ac.jp, rlopezcoto@iaa.es

The recurrent symbiotic nova RS Ophiuchi experienced an outburst in August 2021 that was detected at optical and high-energy gamma rays. This triggered follow-up observations of the source at very-high-energy gamma rays with the first Large Size Telescope (LST-1) of the Cherenkov Telescope Array. RS Ophiuchi was observed for several nights after the outburst and it was clearly detected by LST-1. Here we report on the outcomes of this observation campaign of the first nova ever detected at very high energies.

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[*] Speaker

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1. Introduction

The Large Size Telescope (LST-1) is the prototype of the largest telescopes of the next generation of Imaging Atmospheric Cherenkov Telescopes (IACTs) that will constitute the future Cherenkov Telescope Array (CTA). LSTs have a large collection area thanks to a 23 m diameter dish that will dominate the sensitivity of CTA at low energies [1]. Furthermore, their lightweight design with a fast re-position speed makes LSTs ideal instruments for transient follow-up studies.

Recurrent symbiotic novae are binary systems formed by a white dwarf and a red giant star. They undergo repetitive nova outbursts produced by thermonuclear runaway explosions in the white dwarf surface due to the accretion of matter from the companion star. Novae were detected for the first time at high energies in 2010 [2]. Their detection at very high energies (VHEs) did not happen until the outburst from RS Ophiuchi (RS Oph) in 2021 [3], which was deeply followed up by different IACT facilities such as MAGIC [4], H.E.S.S. [5] and LST-1. RS Oph is a recurrent symbiotic nova with an outburst period of about 15 years. This work reports the LST-1 and *Fermi*-LAT analysis during the first days of the 2021 RS Oph outburst.

2. LST-1 observations

LST-1 started the observations of RS Oph after the trigger alert from *Fermi*-LAT [6]. LST-1 observed RS Oph for several days after the outburst onset. The first observation started about a day after optical discovery, on August 9$^{\text{th}}$, and the observation campaign lasted nearly a month. However, during this period, RS Oph could not be observed for several days due to the intense moonlight during the full moon phase and bad atmospheric conditions. In this work, we present the results using the observations recorded right after the outburst, selecting only those with good atmospheric conditions. The data that passed the selection criteria were recorded on August 9$^{\text{th}}$, 10$^{\text{th}}$ and 12$^{\text{th}}$. The total observation time for this observation subset is nearly 6.5 h. A summary of the LST-1 observations is presented in Table 1.

Observation date [yyyy-mm-dd]	Time delay [d]	Effective time [h]
2021-08-09	0.97	1.43
2021-08-10	1.97	2.69
2021-08-12	3.97	2.27

Table 1: Date, time delay between the outburst onset [3] and the beginning of the first observation, and exposure time for LST-1 observations with good atmospheric conditions during the first days of the outburst.

3. Data analysis

All LST-1 observations were made with the so-called wobble mode [7] with the single telescope trigger. The raw LST-1 camera images were processed with `cta-lstchain` [8], the data analysis pipeline developed to process LST-1 data. The energy and direction reconstruction, and particle classification of the incident particle are estimated through random forests (RFs), which are trained with Monte Carlo (MC) simulations of proton and gamma-ray events (more information in [9],

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[10] and LST Collaboration, in preparation). In this work, the MC dataset used to train the RFs comprised simulated protons and gamma rays coming from a fixed sky position (at an azimuth of 180° and altitude of 50°) close to the RS Oph culmination in the sky at the LST-1 location. In order to have a better match between real data and MC simulations, random Poisson noise was added to match the Night Sky Background (NSB) of RS Oph observations. Also, the MC simulations were tuned to match the real Point Spread Function (PSF) of the LST-1.

The analysis method used in this work is based on the so-called source-dependent analysis, which uses the prior knowledge of the source position to estimate the physical properties of the primary particle. This source-dependent analysis is used to improve the performance of the single telescope observation mode at lower energies (see LST Collaboration, in preparation). Instead of using the typical θ parameter to describe the direction of the event with respect to the nominal source direction, the source-dependent analysis uses the parameter *alpha*, which is the angle between the direction of the semi-major axis of the shower image and the direction to the assumed source position from the shower image center of gravity. A cut of 10° in *alpha* was applied to the processed data. At the same time, a cut in the *gammaness* parameter is considered as well. It indicates how likely the primary event is a gamma ray using a score value between 0 and 1, where the highest value is given to the most gamma-like event. A score cut of 0.9 is used in the analysis.

The LST-1 high-level data (gamma-ray candidates with reconstructed energy and direction) was processed with the official high-level data framework for CTA, Gammapy [11], to produce the energy spectra and light curve of RS Oph.

On the other hand, *Fermi*-LAT data was analysed with `Fermitools` version 2.0.8[1] and `Fermipy` version 1.0.1[2]. The analysis considers a region of interest (RoI) of 20° centred on the RS Oph direction. The LAT 10 years source catalog was used together with the standard isotropic and galactic diffuse background from Pass 8 to model the RoI.

4. Results

To analyse the VHE gamma-ray emission of RS Oph, three reflected positions in the camera at 90, 180 and 270 degrees with respect to the source direction were used as control positions to assess the background emission. Using all the 6.4 hours of data from August 9th, 10th and 12th observations, LST-1 detected RS Oph with a Li & Ma detection significance [12] of 7.5σ and a signal-to-noise ratio (S/N) of almost 5% (see Figure 1).

A power-law spectral model ($\phi = \phi_0\,(E/E_0)^{\Gamma}$) was used to fit the spectral energy distribution (SED) of RS Oph at VHEs. The lower-energy bound used for the spectral fitting was 45 GeV, which is the energy value at the maximum of the distribution of survived MC gammas after weighting its distribution to the assumed RS Oph spectral index and using the same selection cuts applied to RS Oph data [13]. The best fit spectral model was obtained through a maximum likelihood fitting process stacking the data from August 9th, 10th and 12th observations altogether. The best fit model has a soft spectral index of $\Gamma = -3.3 \pm 0.2$ and a normalization factor of $\phi_0 = (4.5 \pm 0.8) \times 10^{-10}$ TeV^{-1}cm^{-2}s^{-1} at a reference energy of $E_0 = 130$ GeV.

[1] https://fermi.gsfc.nasa.gov/ssc/data/analysis/
[2] https://fermipy.readthedocs.io/en/latest/

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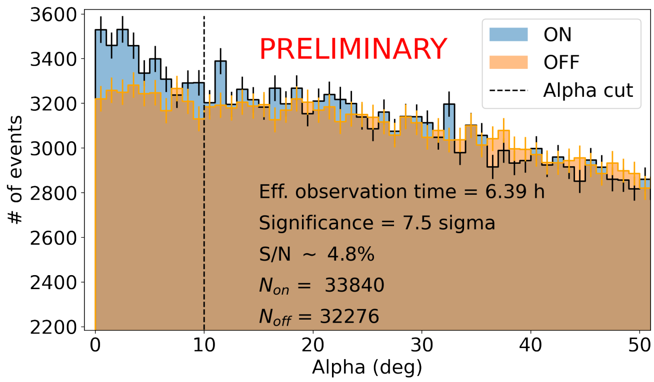

Figure 1: LST-1 alpha plot displaying the angular distributions for the ON (angle between event major axis and the nominal source position) and OFF directions (angle between event major axis and the reflected directions). A cut in alpha at 10° (dashed line) is applied to compute the Li & Ma detection significance and S/N.

The SED at high-energy (HE) gamma rays from our dedicated *Fermi*-LAT analysis was computed using the same temporal window as the LST-1 observations. The SED obtained with LST-1 and *Fermi*-LAT is shown in Figure 2. The preliminary SED obtained with the LST-1 displays a smooth transition from the *Fermi*-LAT energy range to the LST-1 energy range.

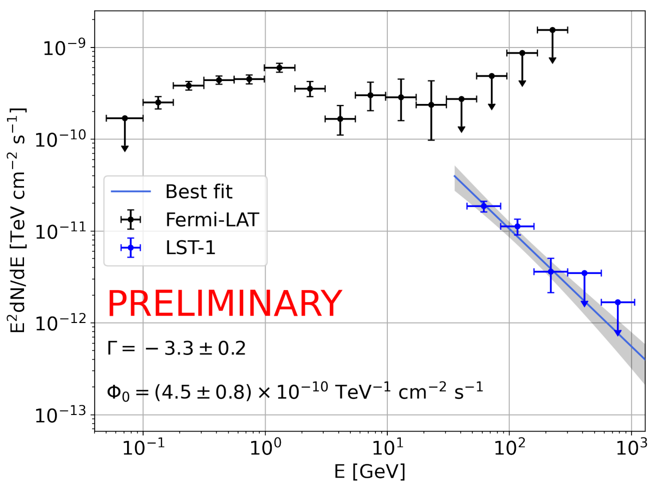

Figure 2: RS Oph SED obtained with the LST-1 (blue) and the *Fermi*-LAT (back). The best fit model for LST-1 is shown as a blue line together with the spectral error band in gray. The spectral index and amplitude values of the best fit model and their associated errors are displayed on the lower left.

A zoom-in to the VHE range is displayed in Figure 3, where the SED points from MAGIC [4] and H.E.S.S. [5] are also included. The former was obtained using the data from the first four days of observations (August 9th to 12th), whereas the latter uses observations from August 8th and 13th, separately. The preliminary LST-1 SED shows a remarkably good agreement with the SEDs from the different IACT facilities that observed RS Oph at VHEs (Figure 3).

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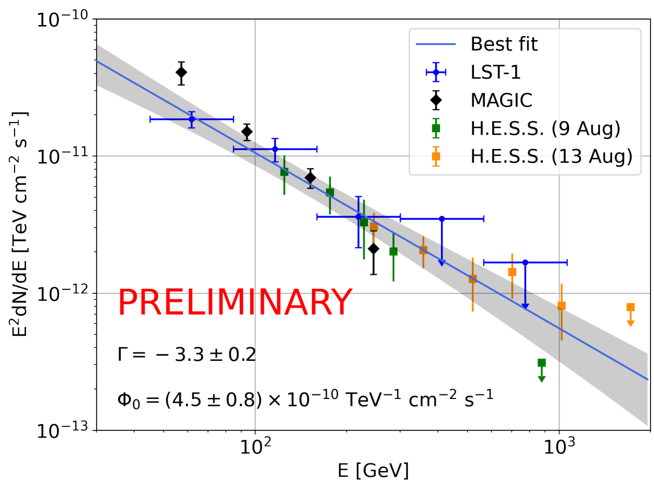

Figure 3: RS Oph SED obtained with the LST-1 (blue), MAGIC (back) and H.E.S.S. (orange and green) telescopes. The best fit model for LST-1 is displayed as a blue line together with the spectral error band in gray. The spectral index and amplitude values of the best fit model and their associated errors are shown on the lower left.

5. Conclusions

LST-1 detected RS Oph with a detection significance of $\sim 7.5\sigma$ using a total observation time of 6.4 hours during August 9$^{\text{th}}$, 10$^{\text{th}}$ and 12$^{\text{th}}$. The preliminary spectral analysis reported in this work confirms that RS Oph had a soft spectrum during the first days after the outburst. LST-1 preliminary spectral results are compatible with the SEDs reported by the MAGIC and H.E.S.S. Collaborations [4, 5]. In addition, thanks to a large-effective area below 100 GeV, LST-1 is capable of studying the spectrum of RS Oph down to 45 GeV, allowing to observe a smooth transition between the *Fermi*-LAT energy range and the VHE domain.

The preliminary results presented in this work are obtained using a fixed MC production. However, a dedicated analysis using a refined MC production will be presented in a future publication.

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Full Authors List: CTA LST Collaboration

S. Abe[1], A. Aguasca-Cabot[2], I. Agudo[3], N. Alvarez Crespo[4], L. A. Antonelli[5], C. Aramo[6], A. Arbet-Engels[7], M. Artero[8], K. Asano[1], P. Aubert[9], A. Baktash[10], A. Bamba[11], A. Baquero Larriva[12], L. Baroncelli[13], U. Barres de Almeida[14], J. A. Barrio[12], I. Batkovic[15], J. Baxter[1], J. Becerra González[16], E. Bernardini[15], M. I. Bernardos[3], J. Bernete Medrano[17], A. Berti[7], P. Bhattacharjee[9], N. Biederbeck[18], C. Bigongiari[5], E. Bissaldi[19], O. Blanch[8], P. Bordas[2], C. Buisson[9], A. Bulgarelli[13], I. Burelli[20], M. Buscemi[21], M. Cardillo[22], S. Caroff[9], A. Carosi[5], F. Cassol[23], E. Cauz[20], G. Ceribella[1], Y. Chai[7], K. Cheng[1], A. Chiavassa[24], M. Chikawa[1], L. Chytka[25], A. Cifuentes[17], J. L. Contreras[12], J. Cortina[17], H. Costantini[23], G. D'Amico[26], M. Dalchenko[27], A. De Angelis[15], M. de Bony de Lavergne[9], B. De Lotto[20], R. de Menezes[24], G. Deleglise[9], C. Delgado[17], J. Delgado Mengual[28], D. della Volpe[27], M. Dellaiera[9], A. Di Piano[13], F. Di Pierro[24], R. Di Tria[29], L. Di Venere[29], C. Díaz[17], R. M. Dominik[18], D. Dominis Prester[30], A. Donini[8], D. Dorner[31], M. Doro[15], D. Elsässer[18], G. Emery[27], J. Escudero[3], V. Fallah Ramazani[32], G. Ferrara[21], A. Fiasson[9,33], L. Freixas Coromina[17], S. Fröse[18], S. Fukami[1], Y. Fukazawa[34], E. Garcia[9], R. Garcia López[16], D. Gasparrini[35], D. Geyer[18], J. Giesbrecht Paiva[14], N. Giglietto[19], F. Giordano[29], E. Giro[15], P. Gliwny[36], N. Godinovic[37], R. Grau[8], D. Green[7], J. Green[7], S. Gunji[38], J. Hackfeld[32], D. Hadasch[1], A. Hahn[7], K. Hashiyama[1], T. Hassan[17], K. Hayashi[39], L. Heckmann[7], M. Heller[27], J. Herrera Llorente[16], K. Hirotani[1], D. Hoffmann[23], D. Horns[10], J. Houles[23], M. Hrabovsky[25], D. Hrupec[40], D. Hui[1], M. Hütten[1], R. Imazawa[34], T. Inada[1], Y. Inome[1], K. Ioka[41], M. Iori[42], K. Ishio[36], Y. Iwamura[1], M. Jacquemont[9], I. Jimenez Martinez[17], J. Jurysek[43], M. Kagaya[1], V. Karas[44], H. Katagiri[45], J. Kataoka[46], D. Kerszberg[8], Y. Kobayashi[1], A. Kong[1], H. Kubo[1], J. Kushida[47], M. Lainez[12], G. Lamanna[9], A. Lamastra[5], T. Le Flour[9], M. Linhoff[18], F. Longo[48], R. López-Coto[3], M. López-Moya[12], A. López-Oramas[16], S. Loporchio[29], A. Lorini[49], P. L. Luque-Escamilla[50], P. Majumdar[1,51], M. Makariev[52], D. Mandat[53], M. Manganaro[30], G. Manicò[21], K. Mannheim[31], M. Mariotti[15], P. Marquez[8], G. Marsella[21,54], J. Martí[50], O. Martinez[4], G. Martínez[17], M. Martínez[8], P. Marusevec[55], A. Mas-Aguilar[12], G. Maurin[9], D. Mazin[1,7], E. Mestre Guillen[56], S. Micanovic[30], D. Miceli[15], T. Miener[12], J. M. Miranda[4], R. Mirzoyan[7], T. Mizuno[57], M. Molero Gonzalez[16], E. Molina[2], T. Montaruli[27], I. Monteiro[9], A. Moralejo[8], D. Morcuende[12], A. Morselli[35], K. Mrakovcic[30], K. Murase[1], A. Nagai[27], T. Nakamori[38], L. Nickel[18], M. Nievas[16], K. Nishijima[47], K. Noda[1], D. Nosek[58], S. Nozaki[7], M. Ohishi[1], Y. Ohtani[1], N. Okazaki[1], A. Okumura[59,60], R. Orito[61], J. Otero-Santos[16], M. Palatiello[20], D. Paneque[7], F. R. Pantaleo[19], R. Paoletti[49], J. M. Paredes[2], L. Pavletić[30], M. Pech[53], M. Pecimotika[30], E. Pietropaolo[62], G. Pirola[7], F. Podobnik[49], V. Poireau[9], M. Polo[17], E. Pons[9], E. Prandini[15], J. Prast[9], C. Priyadarshi[8], M. Prouza[53], R. Rando[15], W. Rhode[18], M. Ribó[2], V. Rizi[62], G. Rodriguez Fernandez[35], T. Saito[1], S. Sakurai[1], D. A. Sanchez[9], T. Šarić[37], F. G. Saturni[5], J. Scherpenberg[7], B. Schleicher[31], F. Schmuckermaier[7], J. L. Schubert[18], F. Schussler[63], T. Schweizer[7], M. Seglar Arroyo[9], J. Sitarek[36], V. Sliusar[43], A. Spolon[15], J. Strišković[40], M. Strzys[1], Y. Suda[34], Y. Sunada[64], H. Tajima[59], M. Takahashi[1], H. Takahashi[34], J. Takata[1], R. Takeishi[1], P. H. T. Tam[1], S. J. Tanaka[65], D. Tateishi[64], P. Temnikov[52], Y. Terada[64], K. Terauchi[66], T. Terzic[30], M. Teshima[1,7], M. Tluczykont[10], F. Tokanai[38], D. F. Torres[56], P. Travnicek[53], S. Truzzi[49], A. Tutone[5], G. Uhlrich[27], M. Vacula[25], M. Vázquez Acosta[16], V. Verguilov[52], I. Viale[15], A. Vigliano[20], C. F. Vigorito[24,67], V. Vitale[35], G. Voutsinas[27], I. Vovk[1], T. Vuillaume[9], R. Walter[43], M. Will[7], T. Yamamoto[68], R. Yamazaki[65], T. Yoshida[45], T. Yoshikoshi[1], N. Zywucka[36],

[1]Institute for Cosmic Ray Research, University of Tokyo, 5-1-5, Kashiwa-no-ha, Kashiwa, Chiba 277-8582, Japan. [2]Departament de Física Quàntica i Astrofísica, Institut de Ciències del Cosmos, Universitat de Barcelona, IEEC-UB, Martí i Franquès, 1, 08028, Barcelona, Spain. [3]Instituto de Astrofísica de Andalucía-CSIC, Glorieta de la Astronomía s/n, 18008, Granada, Spain. [4]Grupo de Electronica, Universidad Complutense de Madrid, Av. Complutense s/n, 28040 Madrid, Spain. [5]INAF - Osservatorio Astronomico di Roma, Via di Frascati 33, 00040, Monteporzio Catone, Italy. [6]INFN Sezione di Napoli, Via Cintia, ed. G, 80126 Napoli, Italy. [7]Max-Planck-Institut für Physik, Föhringer Ring 6, 80805 München, Germany. [8]Institut de Fisica d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Campus UAB, 08193 Bellaterra (Barcelona), Spain. [9]Univ. Savoie Mont Blanc, CNRS, Laboratoire d'Annecy de Physique des Particules - IN2P3, 74000 Annecy, France. [10]Universität Hamburg, Institut für Experimentalphysik, Luruper Chaussee 149, 22761 Hamburg, Germany. [11]Graduate School of Science, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan. [12]EMFTEL department and IPARCOS, Universidad Complutense de Madrid, 28040 Madrid, Spain. [13]INAF - Osservatorio di Astrofisica e Scienza dello spazio di Bologna, Via Piero Gobetti 93/3, 40129 Bologna, Italy. [14]Centro Brasileiro de Pesquisas Físicas, Rua Xavier Sigaud 150, RJ 22290-180, Rio de Janeiro, Brazil. [15]INFN Sezione di Padova and Università degli Studi di Padova, Via Marzolo 8, 35131 Padova, Italy. [16]Instituto de Astrofísica de Canarias and Departamento de Astrofísica, Universidad de La Laguna, La Laguna, Tenerife, Spain. [17]CIEMAT, Avda. Complutense 40, 28040 Madrid, Spain. [18]Department of Physics, TU Dortmund University, Otto-Hahn-Str. 4, 44227 Dortmund, Germany. [19]INFN Sezione di Bari and Politecnico di Bari, via Orabona 4, 70124 Bari, Italy. [20]INFN Sezione di Trieste and Università degli studi di Udine, via delle scienze 206, 33100 Udine, Italy.. [21]INFN Sezione di Catania, Via S. Sofia 64, 95123 Catania, Italy. [22]INAF - Istituto di Astrofisica e Planetologia Spaziali (IAPS), Via del Fosso del Cavaliere 100, 00133 Roma, Italy. [23]Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France. [24]INFN Sezione di Torino, Via P. Giuria 1, 10125 Torino, Italy. [25]Palacky University Olomouc, Faculty of Science, 17. listopadu 1192/12, 771 46 Olomouc, Czech Republic. [26]Department of Physics and Technology, University of Bergen, Museplass 1, 5007 Bergen, Norway. [27]University of Geneva - Département de physique nucléaire et corpusculaire, 24 Quai Ernest Ansernet, 1211 Genève 4, Switzerland. [28]Port d'Informació Científica, Edifici D, Carrer de l'Albareda, 08193 Bellaterrra (Cerdanyola del Vallès), Spain. [29]INFN Sezione di Bari and Università di Bari, via Orabona 4, 70126 Bari, Italy. [30]University of Rijeka, Department of Physics, Radmile Matejcic 2, 51000 Rijeka, Croatia. [31]Institute for Theoretical Physics and Astrophysics, Universität Würzburg, Campus Hubland Nord, Emil-Fischer-Str. 31, 97074 Würzburg, Germany. [32]Institut für Theoretische Physik, Lehrstuhl IV: Plasma-Astroteilchenphysik, Ruhr-Universität Bochum, Universitätsstraße 150, 44801 Bochum, Germany. [33]ILANCE, CNRS - University of Tokyo International Research Laboratory, Kashiwa, Chiba 277-8582, Japan. [34]Physics Program, Graduate School of Advanced Science and Engineering, Hiroshima University, 739-8526 Hiroshima, Japan. [35]INFN Sezione di Roma Tor Vergata, Via della Ricerca Scientifica 1, 00133 Rome, Italy. [36]Faculty of Physics and Applied Informatics, University of Lodz, ul. Pomorska 149-153, 90-236 Lodz, Poland. [37]University of Split, FESB, R. Boškovića 32, 21000 Split, Croatia. [38]Department of Physics, Yamagata University, Yamagata, Yamagata 990-8560, Japan. [39]Tohoku University, Astronomical Institute, Aobaku, Sendai 980-8578, Japan. [40]Josip Juraj Strossmayer University of Osijek, Department of Physics, Trg Ljudevita Gaja 6, 31000 Osijek, Croatia. [41]Kitashirakawa Oiwakecho, Sakyo Ward, Kyoto, 606-8502, Japan. [42]INFN Sezione di Roma La Sapienza, P.le Aldo Moro, 2 - 00185 Rome, Italy. [43]Department of Astronomy, University of Geneva, Chemin d'Ecogia 16, CH-1290 Versoix, Switzerland. [44]Astronomical Institute of the Czech Academy of Sciences, Bocni II 1401 - 14100 Prague, Czech Republic. [45]Faculty of Science, Ibaraki University, Mito, Ibaraki, 310-8512, Japan. [46]Faculty of Science and Engineering, Waseda University, Shinjuku, Tokyo 169-8555, Japan. [47]Department of Physics, Tokai University, 4-1-1, Kita-Kaname, Hiratsuka, Kanagawa 259-1292, Japan. [48]INFN Sezione di Trieste and Università degli Studi di Trieste, Via Valerio 2 I, 34127 Trieste, Italy. [49]INFN and Università degli Studi di Siena, Dipartimento di Scienze Fisiche, della Terra e dell'Ambiente (DSFTA), Sezione di Fisica, Via Roma 56, 53100 Siena, Italy. [50]Escuela Politécnica Superior de Jaén, Universidad de Jaén, Campus Las Lagunillas s/n, Edif. A3, 23071 Jaén, Spain. [51]Saha Institute of Nuclear Physics, Bidhannagar, Kolkata-700 064, India. [52]Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, 72 boul. Tsarigradsko chaussee, 1784 Sofia, Bulgaria. [53]FZU - Institute of Physics of the Czech Academy of Sciences, Na Slovance 1999/2, 182 21 Praha 8, Czech Republic. [54]Dipartimento di Fisica e Chimica 'E. Segrè' Università degli Studi di Palermo, via delle Scienze, 90128 Palermo. [55]Department of Applied Physics, University of Zagreb, Horvatovac 102a, 10000 Zagreb, Croatia. [56]Institute of Space Sciences (ICE, CSIC), and Institut d'Estudis Espacials de Catalunya (IEEC), and Institució Catalana de Recerca I Estudis Avançats (ICREA), Campus UAB, Carrer de Can Magrans, s/n 08193 Bellatera, Spain. [57]Hiroshima Astrophysical Science Center, Hiroshima University, Higashi-Hiroshima, Hiroshima 739-8526, Japan. [58]Charles University, Institute of Particle and Nuclear Physics, V Holešovičkách 2, 180 00 Prague 8, Czech Republic. [59]Institute for Space-Earth Environmental Research, Nagoya University, Chikusa-ku, Nagoya 464-8601, Japan. [60]Kobayashi-Maskawa Institute (KMI) for the Origin of Particles and the Universe, Nagoya University, Chikusa-ku, Nagoya 464-8602, Japan. [61]Graduate School of Technology, Industrial and Social Sciences, Tokushima University, Tokushima 770-8506, Japan. [62]INFN Dipartimento di Scienze Fisiche e Chimiche - Università degli Studi dell'Aquila and Gran Sasso Science Institute, Via Vetoio 1, Viale Crispi 7, 67100 L'Aquila, Italy. [63]IRFU, CEA, Université Paris-Saclay, Bât 141, 91191 Gif-sur-Yvette, France. [64]Graduate School of Science and Engineering, Saitama University, 255 Simo-Ohkubo, Sakura-ku, Saitama city, Saitama 338-8570, Japan. [65]Department of Physical Sciences, Aoyama Gakuin University, Fuchinobe, Sagamihara, Kanagawa, 252-5258, Japan. [66]Division of Physics and Astronomy, Graduate School of Science, Kyoto University, Sakyo-ku, Kyoto, 606-8502, Japan. [67]Dipartimento di Fisica - Universitá degli Studi di Torino, Via Pietro Giuria 1 - 10125 Torino, Italy. [68]Department of Physics, Konan University, Kobe, Hyogo, 658-8501, Japan.

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