PROCEEDINGS OF SCIENCE
ONLINE ICRC 2021
THE ASTROPARTICLE PHYSICS CONFERENCE
Berlin | Germany
37th International Cosmic Ray Conference
12–23 July 2021

Limits on primordial black hole evaporation from H.E.S.S. observations.

PoS(ICRC2021)518

T. Tavernier,[a,*] **F. Brun,**[a] **J-F. Glicenstein,**[a] **V.Marandon**[b] **and the H.E.S.S. collaboration**

[a] *IRFU,*
CEA-Paris Saclay, Université Paris-Saclay F91191 Gif-sur-Yvette, France
[b] *Max-Planck-Institut für Kernphysik,*
PO Box 103980, 69029 Heidelberg, Germany
E-mail: Thomas.Tavernier@cea.fr, Francois.Brun@cea.fr, glicens@cea.fr, marandon@mpi-hd.mpg.de

Primordial Black Holes are expected to be formed in the early Universe by the gravitational collapse of overdense regions, among other mechanisms. They are also expected to loose their mass over time by the Hawking radiation process. As the rates of this radiation increase with temperature, the PBH evaporation should result in a violent explosion. The current upper limits on explosion rates are on the order of $10^4 - 10^5 pc^{-3} yr^{-1}$. In this contribution we'll present the results of a search for TeV γ-ray burst within timescale of few seconds, using nearly 5000 hours of H.E.S.S. data. The search algorithm and statistical estimation strategy will be presented as well as cosmological implications of this measurement.

37th International Cosmic Ray Conference (ICRC 2021)
July 12th – 23rd, 2021
Online – Berlin, Germany

*Presenter

1. Introduction

Primordial black holes (PBH) have been predicted to form in the early Universe via a variety of mechanisms [1]. Popular mechanisms include the gravitational collapse of overdense regions with significant density fluctuations [2] or pressure reduction during cosmological phase transitions [3]. PBHs could have masses ranging from 10^{-5}g for PBHs created at the Planck time up to several tens of $M_\odot$ for PBHs created during the QCD phase transition. No PBH candidate has been unambiguously detected, although there has been claims of such detections, notably progenitors of recent black hole merging events [4] and MACHOs [5].

Black holes were predicted by Hawking [6] to radiate off particles with a black body spectrum of energies. The emission can be described by an effective temperature

$$T_{\rm BH} = \frac{M_p^2}{8\pi M_{\rm BH}}, \tag{1}$$

where $\rm M_p$ and $M_{\rm BH}$ are the Planck mass and the PBH mass respectively.

Black holes lose their mass by Hawking radiation at a rate inversely proportional to their squared mass.

A popular method for constraining the density of low-mass PBHs is searching for their γ-ray emission. Searches have attempted to detect a diffuse photon signal from a distribution of PBHs [7] or to look directly for the final stage emission of an individual hole [8–10]. The latter strategy is adopted in this contribution, using data from H.E.S.S.

2. Dataset

H.E.S.S. is an array of five imaging atmospheric Cherenkov telescopes dedicated to observing very-high energy (VHE) γ-rays (energies above 50 GeV) from astrophysical sources, located in the Khomas Highland of Namibia at an altitude of 1800 m above sea level. The first four telescopes have been installed in 2003 (H.E.S.S-1 phase of the experiment) and have been operational since 2004. A fifth telescope with a reflective area of 596m^2 and a camera of 2048 photo multipliers has started its operations in 2012.

The data used for this analysis are all the H.E.S.S.-1 observations taken between January 2004 and January 2013. One H.E.S.S. observation run consists of data taken towards the same position on the sky during $\sim$ 28 minutes. Some regions of the sky (Crab, LMC, SMC, region of SN 1006) were excluded from this analysis as well as runs of poor quality, affected for instance by bad weather or technical problems. The data set comprises 11494 runs, corresponding to 4924 hours of observations. The data have been processed by two independent calibration and reconstruction chains. The ImPACT analysis [11] was applied to all the runs in order to suppress the background of hadronic cosmic rays and reconstruct the direction and energy of the gamma-ray candidates. The arrival times of these so-called “gamma-like” events are extracted together with their reconstructed parameters. For each run, gamma-like events with a distance to the center of the camera larger than 2 degree are excluded. The results were cross-checked with the Model analysis [12].

PoS(ICRC2021)518

3. Data analysis and results

The signature of PBH explosion is a short burst with a small number (2 to 15) of gamma-like events (photon cluster) which arrive in coincidence in angular space and time. The clustering method used in this paper is based on the OPTICS (Ordering Points To Identify the Clustering Structure) algorithm [13]. The statistical background was directly estimated from the data, by using the same photon list, but with randomized ("scrambled") times of arrival. The average value of the number of clusters distribution obtained by time scrambling 200 times the photon list of each run is taken as the background.

The analysis was performed for 4 values of the timescale Δt, namely 10, 30, 60 and 120 seconds, using the 4924 hours data-set described in section 2. An hypothetical PBH signal is discovered or constrained by comparing the observed data to the expected background (hypothesis H0). If an evaporation signal exists in the data, both the evaporation signal and the background will be observed (hypothesis H1).

The theoretical number of expected PBH bursts of size b to be detected in the data for an observation run i is:

$$n^i_{sig}(b, \Delta t, \rho_{\mathrm{PBH}}) = \rho_{\mathrm{PBH}} V^i_{\mathrm{eff}}(b, \Delta t) \tag{2}$$

where $\dot{\rho}_{\mathrm{PBH}}$ is the local PBH explosion rate and the effective space-time volume of PBH detection is defined by

$$V^i_{\mathrm{eff}}(b, \Delta t) = T_i \int d\Omega_{\mathrm{i}} \int_0^\infty drr^2 P_i(b, N_\gamma), \tag{3}$$

where the index i goes over each run of the H.E.S.S. dataset, T$_i$ and dΩ_{i} being the corresponding run live time and observation solid angle respectively.

The effective volume can be written explicitly as

$$V^i_{\mathrm{eff}}(b, \Delta t) = T_i \Omega_{\mathrm{i}} \frac{(r_0\sqrt{N_0})^3}{2} \frac{\Gamma(b - 3/2)}{\Gamma(b + 1)} \tag{4}$$

where N_0 is the observed number of photons from a PBH at r_0.

The PBH density is estimated by maximizing a likelihood ratio with ρ_{PBH} as the only free parameter, following the procedure of Feldman-Cousins [14]. The likelihood ratio is given by:

$$\frac{\mathcal{L}_{H_1}}{\mathcal{L}_{H_0}} = \prod_i \frac{\mathcal{P}(n^i_{\mathrm{ON}} | \lambda = n^i_{\mathrm{OFF}} + n^i_{sig}(b, \Delta t, \dot{\rho}_{\mathrm{PBH}}))}{\mathcal{P}(n^i_{\mathrm{ON}} | \lambda = n^i_{\mathrm{OFF}})} \tag{5}$$

where $\mathcal{P}$ is the Poisson probability, $n^i_{sig}(b, \Delta t, \dot{\rho}_{\mathrm{PBH}})$ is defined in eq. 2, n^i_{ON} is the number of clusters found in the data and n^i_{OFF} is the corresponding mean number of clusters found in the OFF data.

The corresponding test statistics is given by:

$$TS = -2ln\left(\frac{\mathcal{L}_{H_1}}{\mathcal{L}_{H_0}}\right) = 2 \times \sum_i n^i_{sig} + n^i_{\mathrm{ON}}\left(ln(n^i_{\mathrm{OFF}}) - ln(n^i_{\mathrm{OFF}} + n^i_{sig})\right) \tag{6}$$

The maximum value obtained for the test statistics (TS, eq. 6) at any Δt is $\sim 10^{-4}$. No significant signal was found in the data. Upper limits on the PBH evaporation rate $\dot{\rho}_{\rm PBH}$ with confidence levels (CL) of 95% and 99% were derived and are shown in Fig. 1.

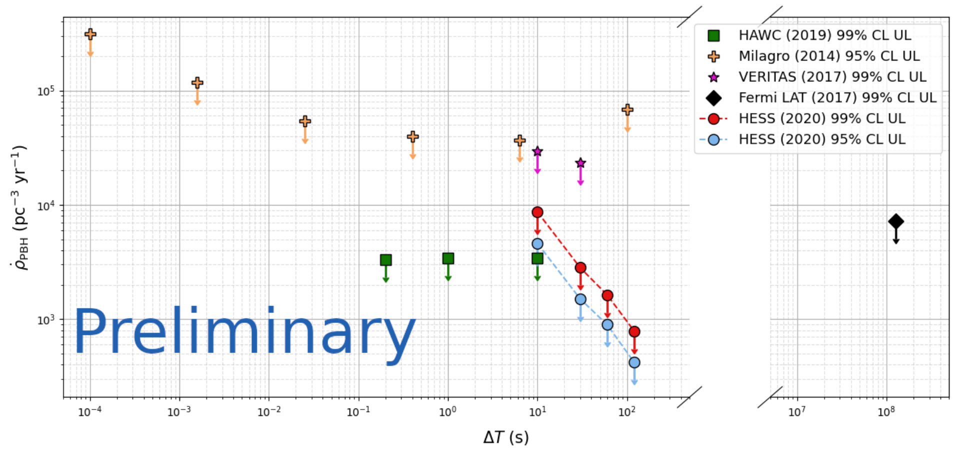

Figure 1: Upper limits on the PBH evaporation rate $\dot{\rho}_{\rm PBH}$ for time scales of 10, 30, 60 and 120 seconds measured by H.E.S.S.. Upper limits from HAWC [10], Veritas [8], Milagro [15] and Fermi LAT [9] are also shown.

4. Cosmological consequences

The initial mass distribution of PBH describing PBH production in the early universe by scale-invariant Gaussian density perturbations can be modelled by a simple power-law [16]:

$$\frac{d\rho_{\rm PBH}}{dM_i} = \frac{\rho_0}{M_*}\left(\frac{M_i}{M_*}\right)^{-\beta} \tag{7}$$

where M_i is the initial mass of PBHs, M_*, the initial mass of PBHs at the final stage of evaporation at present time, and $\Omega_{\rm PBH}$ is the fraction of the critical density ρ_c in PBHs with mass larger than M_*. ρ_0 is a normalization factor.

The current local rate of vanishing PBHs is given by [16]:

$$\dot{\rho}_{\rm PBH} \simeq \frac{\alpha(M_*)}{M_*^3}\eta\rho_0, \tag{8}$$

where $\alpha(M)$ counts the degrees of freedom of the particles contributing to the energy loss as a function of the black-hole mass and η is the ratio between the global and local dark matter densities.

Taking for η and $\alpha(M_*)$ their 95 % CL limit values $\eta > 1.6 \times 10^4$ [17] and $\alpha(M_*) > 10^{17}$ kg^3 s^{-1}, upper limits on the initial PBH mass fraction as a function of the index β can be obtained and are shown in figure 2.

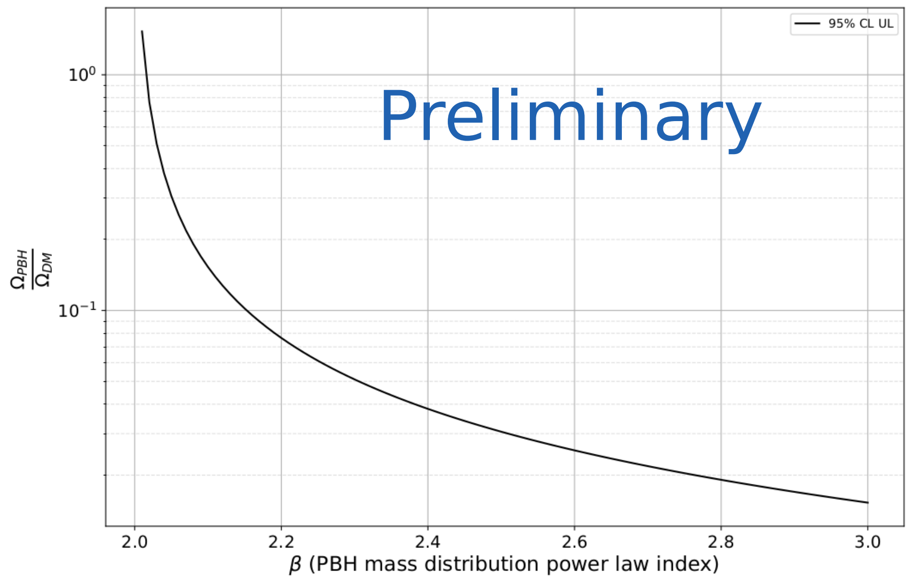

Figure 2: Upper limits on the initial PBH fraction of the critical density as a function of the PBH mass distribution index.

5. Summary

4924 hours of H.E.S.S. observations have been used to search for short time-scale (10 s to 120 s) clusters of photons corresponding to the expected PBH evaporation signal. The number of clusters found is fully compatible with statistical fluctuations. The most constraining 95% CL upper limit on the PBH evaporation rate was found to be $\dot{\rho}_{\text{PBH}} < 527\ \text{pc}^{-3}\ \text{yr}^{-1}$. Strong constraints have been put on the initial fraction of the invisible mass in PBHs in the hypothesis of a PBH mass power-law distribution.

Acknowledgments

H.E.S.S. gratefully acknowledges financial support from the agencies and organizations listed at H.E.S.S. acknowledgement page.

References

[1] B. J. Carr, *Primordial Black Holes: Do They Exist and Are They Useful?*, *arXiv e-prints* (2005) astro [astro-ph/0511743].

[2] A. M. Green and A. R. Liddle, *Constraints on the density perturbation spectrum from primordial black holes*, *Physical Review D* **56** (1997) 6166 [astro-ph/9704251].

[3] K. Jedamzik, *Primordial black hole formation during the QCD epoch*, *Physical Review D* **55** (1997) 5871 [arXiv:astro-ph/9605152].

[4] S. Bird, I. Cholis, J. B. Muñoz, Y. Ali-Haïmoud, M. Kamionkowski, E. D. Kovetz et al., *Did LIGO Detect Dark Matter?*, *Physical Review Letters* **116** (2016) 201301 [1603.00464].

[5] A. M. Green, *Microlensing and dynamical constraints on primordial black hole dark matter with an extended mass function*, *Physical Review D* **94** (2016) 063530 [1609.01143].

[6] S. W. Hawking, *Black hole explosions?*, *Nature* **248** (1974) 30.

[7] B. J. Carr, K. Kohri, Y. Sendouda and J. Yokoyama, *Constraints on primordial black holes from the Galactic gamma-ray background*, *Physical Review D* **94** (2016) 044029 [1604.05349].

[8] S. Archambault and VERITAS Collaboration, *Search for Primordial Black Hole Evaporation with VERITAS*, in *35th International Cosmic Ray Conference (ICRC2017)*, vol. 301 of *International Cosmic Ray Conference*, p. 691, Jan., 2017, 1709.00307.

[9] M. Ackermann, W. B. Atwood, L. Baldini, J. Ballet, G. Barbiellini, D. Bastieri et al., *Search for Gamma-Ray Emission from Local Primordial Black Holes with the Fermi Large Area Telescope*, *ApJ.* **857** (2018) 49.

[10] A. Albert, R. Alfaro, C. Alvarez, J. C. Arteaga-Velázquez, K. P. Arunbabu, D. Avila Rojas et al., *Constraining the local burst rate density of primordial black holes with HAWC*, *JCAP* **2020** (2020) 026 [1911.04356].

[11] R. D. Parsons and J. A. Hinton, *A Monte Carlo template based analysis for air-Cherenkov arrays*, *Astroparticle Physics* **56** (2014) 26 [1403.2993].

[12] M. de Naurois and L. Rolland, *A high performance likelihood reconstruction of γ-rays for imaging atmospheric Cherenkov telescopes*, *Astroparticle Physics* **32** (2009) 231 [0907.2610].

[13] M. Ankerst, M. M. Breunig, H. Kriegel and J. Sander, *OPTICS: ordering points to identify the clustering structure*, in *SIGMOD 1999, Proceedings ACM SIGMOD International Conference on Management of Data, June 1-3, 1999, Philadelphia, Pennsylvania, USA*, A. Delis, C. Faloutsos and S. Ghandeharizadeh, eds., pp. 49–60, ACM Press, 1999, DOI.

[14] G. J. Feldman and R. D. Cousins, *Unified approach to the classical statistical analysis of small signals*, *Physical Review D* **57** (1998) 3873 [physics/9711021].

[15] A. A. Abdo, A. U. Abeysekara, R. Alfaro, B. T. Allen, C. Alvarez, J. D. Álvarez et al., *Milagro Limits and HAWC Sensitivity for the Rate-Density of Evaporating Primordial Black Holes*, *Astroparticle Physics* **64** (2015) 4.

[16] F. Halzen, E. Zas, J. H. MacGibbon and T. C. Weekes, *Gamma rays and energetic particles from primordial black holes*, *Nature* **353** (1991) 807.

[17] J. Bovy and S. Tremaine, *On the Local Dark Matter Density*, *The Astrophysical Journal* **756** (2012) 89.

PoS(ICRC2021)518

Full Authors List: H.E.S.S. Collaboration

H. Abdalla[1], F. Aharonian[2,3,4], F. Ait Benkhali[3], E.O. Angüner[5], C. Arcaro[6], C. Armand[7], T. Armstrong[8], H. Ashkar[9], M. Backes[1,6], V. Baghmanyan[10], V. Barbosa Martins[11], A. Barnacka[12], M. Barnard[6], R. Batzofin[13], Y. Becherini[14], D. Berge[11], K. Bernlöhr[3], B. Bi[15], M. Böttcher[6], C. Boisson[16], J. Bolmont[17], M. de Bony de Lavergne[7], M. Breuhaus[3], R. Brose[2], F. Brun[9], T. Bulik[18], T. Bylund[14], F. Cangemi[17], S. Caroff[17], S. Casanova[10], J. Catalano[19], P. Chambery[20], T. Chand[6], A. Chen[13], G. Cotter[8], M. Curyło[18], H. Dalgleish[1], J. Damascene Mbarubucyeye[11], I.D. Davids[1], J. Davies[8], J. Devin[20], A. Djannati-Ataï[21], A. Dmytriiev[16], A. Donath[3], V. Doroshenko[15], L. Dreyer[6], L. Du Plessis[6], C. Duffy[22], K. Egberts[23], S. Einecke[24], J.-P. Ernenwein[5], S. Fegan[25], K. Feijen[24], A. Fiasson[7], G. Fichet de Clairfontaine[16], G. Fontaine[25], F. Lott[1], M. Füßling[11], S. Funk[19], S. Gabici[21], Y.A. Gallant[26], G. Giavitto[11], L. Giunti[21,9], D. Glawion[19], J.F. Glicenstein[9], M.-H. Grondin[20], S. Hattingh[6], M. Haupt[11], G. Hermann[3], J.A. Hinton[3], W. Hofmann[3], C. Hoischen[23], T. L. Holch[11], M. Holler[27], D. Horns[28], Zhiqiu Huang[3], D. Huber[27], M. Hörbe[8], M. Jamrozy[12], F. Jankowsky[29], V. Joshi[19], I. Jung-Richardt[19], E. Kasai[1], K. Katarzyński[30], U. Katz[19], D. Khangulyan[31], B. Khélifi[21], S. Klepser[11], W. Kluźniak[32], Nu. Komin[13], R. Konno[11], K. Kosack[9], D. Kostunin[11], M. Kreter[6], G. Kukec Mezek[14], A. Kundu[6], G. Lamanna[7], S. Le Stum[5], A. Lemière[21], M. Lemoine-Goumard[20], J.-P. Lenain[17], F. Leuschner[15], C. Levy[17], T. Lohse[33], A. Luashvili[16], I. Lypova[29], J. Mackey[2], J. Majumdar[11], D. Malyshev[15], D. Malyshev[19], V. Marandon[3], P. Marchegiani[13], A. Marcowith[26], A. Mares[20], G. Martí-Devesa[27], R. Marx[29], G. Maurin[7], P.J. Meintjes[34], M. Meyer[19], A. Mitchell[3], R. Moderski[32], L. Mohrmann[19], A. Montanari[9], C. Moore[22], P. Morris[8], E. Moulin[9], J. Muller[25], T. Murach[11], K. Nakashima[19], M. de Naurois[25], A. Nayerhoda[10], H. Ndiyavala[6], J. Niemiec[10], A. Priyana Noel[12], P. O'Brien[22], L. Oberholzer[6], S. Ohm[11], L. Olivera-Nieto[3], E. de Ona Wilhelmi[11], M. Ostrowski[12], S. Panny[27], M. Panter[3], R.D. Parsons[33], G. Peron[3], S. Pita[21], V. Poireau[7], D.A. Prokhorov[35], H. Prokoph[11], G. Pühlhofer[15], M. Punch[21,14], A. Quirrenbach[29], P. Reichherzer[9], A. Reimer[27], O. Reimer[27], Q. Remy[3], M. Renaud[26], B. Reville[3], F. Rieger[3], C. Romoli[3], G. Rowell[24], B. Rudak[32], H. Rueda Ricarte[9], E. Ruiz-Velasco[3], V. Sahakian[36], S. Sailer[3], H. Salzmann[15], D.A. Sanchez[7], A. Santangelo[15], M. Sasaki[19], J. Schäfer[19], H.M. Schutte[6], U. Schwanke[33], F. Schüssler[9], M. Senniappan[14], A.S. Seyffert[6], J.N.S. Shapopi[1], K. Shiningayamwe[1], R. Simoni[35], A. Sinha[26], H. Sol[16], H. Spackman[8], A. Specovius[19], S. Spencer[8], M. Spir-Jacob[21], Ł. Stawarz[12], R. Steenkamp[1], C. Stegmann[23,11], S. Steinmassl[3], C. Steppa[23], L. Sun[35], T. Takahashi[31], T. Tanaka[31], T. Tavernier[9], A.M. Taylor[11], R. Terrier[21], J. H.E. Thiersen[6], C. Thorpe-Morgan[15], M. Tluczykont[28], L. Tomankova[19], M. Tsirou[3], N. Tsuji[31], R. Tuffs[3], Y. Uchiyama[31], D.J. van der Walt[6], C. van Eldik[19], C. van Rensburg[1], B. van Soelen[34], G. Vasileiadis[26], J. Veh[19], C. Venter[6], P. Vincent[17], J. Vink[35], H.J. Völk[3], S.J. Wagner[29], J. Watson[8], F. Werner[3], R. White[3], A. Wierzcholska[10], Yu Wun Wong[19], H. Yassin[6], A. Yusafzai[19], M. Zacharias[16], R. Zanin[3], D. Zargaryan[2,4], A.A. Zdziarski[32], A. Zech[16], S.J. Zhu[11], A. Zmija[19], S. Zouari[21] and N. Żywucka[6].

[1]University of Namibia, Department of Physics, Private Bag 13301, Windhoek 10005, Namibia
[2]Dublin Institute for Advanced Studies, 31 Fitzwilliam Place, Dublin 2, Ireland
[3]Max-Planck-Institut für Kernphysik, P.O. Box 103980, D 69029 Heidelberg, Germany
[4]High Energy Astrophysics Laboratory, RAU, 123 Hovsep Emin St Yerevan 0051, Armenia
[5]Aix Marseille Université, CNRS/IN2P3, CPPM, Marseille, France
[6]Centre for Space Research, North-West University, Potchefstroom 2520, South Africa
[7]Laboratoire d'Annecy de Physique des Particules, Univ. Grenoble Alpes, Univ. Savoie Mont Blanc, CNRS, LAPP, 74000 Annecy, France
[8]University of Oxford, Department of Physics, Denys Wilkinson Building, Keble Road, Oxford OX1 3RH, UK
[9]IRFU, CEA, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France
[10]Instytut Fizyki Jądrowej PAN, ul. Radzikowskiego 152, 31-342 Kraków, Poland
[11]DESY, D-15738 Zeuthen, Germany
[12]Obserwatorium Astronomiczne, Uniwersytet Jagielloński, ul. Orla 171, 30-244 Kraków, Poland
[13]School of Physics, University of the Witwatersrand, 1 Jan Smuts Avenue, Braamfontein, Johannesburg, 2050 South Africa
[14]Department of Physics and Electrical Engineering, Linnaeus University, 351 95 Växjö, Sweden
[15]Institut für Astronomie und Astrophysik, Universität Tübingen, Sand 1, D 72076 Tübingen, Germany
[16]Laboratoire Univers et Théories, Observatoire de Paris, Université PSL, CNRS, Université de Paris, 92190 Meudon, France
[17]Sorbonne Université, Université Paris Diderot, Sorbonne Paris Cité, CNRS/IN2P3, Laboratoire de Physique Nucléaire et de Hautes Energies, LPNHE, 4 Place Jussieu, F-75252 Paris, France
[18]Astronomical Observatory, The University of Warsaw, Al. Ujazdowskie 4, 00-478 Warsaw, Poland
[19]Friedrich-Alexander-Universität Erlangen-Nürnberg, Erlangen Centre for Astroparticle Physics, Erwin-Rommel-Str. 1, D 91058 Erlangen, Germany
[20]Université Bordeaux, CNRS/IN2P3, Centre d'Études Nucléaires de Bordeaux Gradignan, 33175 Gradignan, France
[21]Université de Paris, CNRS, Astroparticule et Cosmologie, F-75013 Paris, France
[22]Department of Physics and Astronomy, The University of Leicester, University Road, Leicester, LE1 7RH, United Kingdom
[23]Institut für Physik und Astronomie, Universität Potsdam, Karl-Liebknecht-Strasse 24/25, D 14476 Potsdam, Germany
[24]School of Physical Sciences, University of Adelaide, Adelaide 5005, Australia
[25]Laboratoire Leprince-Ringuet, École Polytechnique, CNRS, Institut Polytechnique de Paris, F-91128 Palaiseau, France
[26]Laboratoire Univers et Particules de Montpellier, Université Montpellier, CNRS/IN2P3, CC 72, Place Eugène Bataillon, F-34095 Montpellier Cedex 5, France
[27]Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität Innsbruck, A-6020 Innsbruck, Austria
[28]Universität Hamburg, Institut für Experimentalphysik, Luruper Chaussee 149, D 22761 Hamburg, Germany

[29]Landessternwarte, Universität Heidelberg, Königstuhl, D 69117 Heidelberg, Germany
[30]Institute of Astronomy, Faculty of Physics, Astronomy and Informatics, Nicolaus Copernicus University, Grudziadzka 5, 87-100 Torun, Poland
[31]Department of Physics, Rikkyo University, 3-34-1 Nishi-Ikebukuro, Toshima-ku, Tokyo 171-8501, Japan
[32]Nicolaus Copernicus Astronomical Center, Polish Academy of Sciences, ul. Bartycka 18, 00-716 Warsaw, Poland
[33]Institut für Physik, Humboldt-Universität zu Berlin, Newtonstr. 15, D 12489 Berlin, Germany
[34]Department of Physics, University of the Free State, PO Box 339, Bloemfontein 9300, South Africa
[35]GRAPPA, Anton Pannekoek Institute for Astronomy, University of Amsterdam, Science Park 904, 1098 XH Amsterdam, The Netherlands
[36]Yerevan Physics Institute, 2 Alikhanian Brothers St., 375036 Yerevan, Armenia