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Miguel A Sánchez-Conde

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## Expected exclusion limits to TeV dark matter from the Perseus Cluster with the Cherenkov Telescope Array

Rémi Adam,<sup>a</sup> Sergio Hernández-Cadena,<sup>b,\*</sup> Moritz Hütten,<sup>c</sup> Judit Pérez-Romero<sup>d,e</sup> and Miguel A. Sánchez-Conde<sup>e</sup> for the CTA Consortium

<sup>a</sup>Laboratoire Leprince-Ringuet, École Polytechnique (UMR 7638, CNRS/IN2P3, Institut Polytechnique de Paris), 91128 Palaiseau, France

<sup>b</sup>Universidad Nacional Autónoma de México, Delegación Coyoacán, 04510 Ciudad de México, México

<sup>c</sup>Institute for Cosmic Ray Research, The University of Tokyo, Kashiwa 277-8583, Chiba, Japan

<sup>d</sup>Center for Astrophysics and Cosmology, University of Nova Gorica, Vipavska 11c, 5270 Ajdovščina, Slovenia

<sup>e</sup>Instituto de Física Teórica UAM/CSIC and Departamento de Física Teórica, Universidad Autónoma de Madrid, c/ Nicolás Cabrera 13-15, Campus de Cantoblanco UAM, 28049 Madrid, Spain

E-mail: [remi.adam@oca.eu](mailto:remi.adam@oca.eu), [skerzot@ciencias.unam.mx](mailto:skerzot@ciencias.unam.mx),  
[huetten@icrr.u-tokyo.ac.jp](mailto:huetten@icrr.u-tokyo.ac.jp), [judit.perez@ung.si](mailto:judit.perez@ung.si),  
[miguel.sanchezconde@uam.es](mailto:miguel.sanchezconde@uam.es)

Clusters of galaxies are the largest gravitationally-bound structures in the Universe. They are composed of galaxies and gas (approximately 15% of the total mass) mostly dark matter (DM, accounts up to 85% of the total mass). If the DM is composed of Weakly Interacting Massive Particles (WIMPs), galaxy clusters represent one of the best targets to search for gamma-ray signals induced by the decay of WIMPs, with masses around the TeV scale. Due to its sensitivity and energy range of operation (from 20 GeV to 300 TeV), the Cherenkov Telescope Array (CTA) Observatory has a unique opportunity to test WIMPs with masses close to the unitarity limit. This will complement the searches for DM from other gamma-ray observatories as well as direct and collider experiments. The CTA Observatory is planning to search for gamma-ray emission, either its origin may be cosmic-ray (CR) or DM related, in the Perseus galaxy cluster during the first years of operation. In this poster, we will present the software created to perform the analysis using the `ctools` software and the corresponding results.

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\*Speaker

## 1. Introduction

At present, we have gravitational evidence at different scales of the Universe pointing to the existence of a Dark Matter (DM) that constitutes  $\sim 27\%$  of the total energy content in the Universe. However, properties and nature of this DM are still unknown. Several particles appearing in extensions to the Standard Model (SM) have been proposed as candidates that can account for the DM in the Universe. One of the most studied candidates refers to a class of particles called Weakly Interactive Massive Particles (WIMPs) [1] with masses in the range from  $\sim 5$  GeV up to hundreds of TeVs [2]. The annihilation or decay of these particles leads to the production of gamma rays with energies at GeV and TeV scales. This annihilation and decay of DM can occur in the halos of galaxies and galaxy clusters. Galaxy clusters, which approximately 85% of their content is DM, serve as ideal targets for searching for diffuse gamma-ray emission resulting from the decay of dark matter.

Several studies [see for example 3] have investigated the potential of galaxy clusters to search for diffuse gamma-ray emission induced by Cosmic Rays (CRs) and DM. One of the best targets to search for this diffuse emission is the Perseus cluster because of its expected content of DM, and the presence of radio relics that can help to constrain better the density profile of CRs in the IntraCluster Medium (ICM). Additionally, Perseus is the host of two AGNs, NGC 1275 and IC 310, also observed by gamma-ray observatories like *Fermi*-LAT [4, 5] and the MAGIC telescopes [6]. In this work we studied the expected sensitivity to gamma-ray emission induced by WIMPs annihilation and decay in Perseus from simulations of observations with the Cherenkov Telescope Array (CTA) observatory.

The CTA observatory (or simply CTAO) will be a gamma-ray observatory with two arrays of Imaging Air Cherenkov Telescopes (IACTs), one in La Palma, Canary Islands, Spain and the other in Paranal, Chile. CTA will operate in the energy range from 20 GeV up to 300 TeV, and it is expected that CTA will improve up to 10 times the sensitivity and angular resolution of previous IACT arrays [7].

## 2. Gamma-ray emission modeling

The gamma-ray emission model in the Perseus cluster considers the contribution to the total gamma-ray flux from the two AGNs located at the center of the cluster, NGC 1275 and IC 310; the annihilation or decay of DM particles in the cluster, and the gamma-ray emission induced by CRs interactions in the ICM.

Using deep observation of the Perseus Cluster with the MAGIC telescopes [8], the differential spectrum for NGC 1275 is well described by a power law:

$$\frac{d\Phi}{dE} = 2.1 \times 10^{-11} \left( \frac{E}{0.2 \text{ TeV}} \right)^{-3.6} \text{ TeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}, \quad (1)$$

while, using observations of the galaxy IC 310 with an effective exposure time of 41 h, MAGIC obtains that the differential spectra is well fitted to [6]:

$$\frac{d\Phi}{dE} = 7.41 \times 10^{-13} \left( \frac{E}{1.0 \text{ TeV}} \right)^{-1.81} \text{ TeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}. \quad (2)$$

The spatial emission for both galaxies, NGC 1275 and IC 310, is modeled by a point source.

For the gamma-ray emission induced by hadronic interactions in the ICM, we used the `Minot` package [9] to compute the relevant quantities and obtain the spectral shape and a two-dimensional template of the spatial emission. Relevant parameters to the model for the gamma-ray emission induced by CRs are the ratio  $X_{500}$  of the CR energy density to thermal energy density at radius  $R_{500}$ <sup>1</sup>, the acceleration efficiency of CRs  $\eta_{\text{CRp}}$  and spectral index of the injected CRs,  $\alpha_{\text{CRp}}$ . For this analysis, we assume a baseline model as a conservative approach to the CRs budget in the Perseus cluster and, thus, for the gamma-ray emission from interactions in the ICM. Table 1 shows the model used for.

Model	$X_{500}$ (%)	$\alpha_{\text{CRp}}$	$\eta_{\text{CRp}}$	$F_{500, E_\gamma > 150 \text{ GeV}}^{(\text{had})}$	$F_{500, E_\gamma > 150 \text{ GeV}}^{(\text{IC})}$
				$(10^{-14} \text{ cm}^{-2} \text{ s}^{-1})$	
Baseline	1.0, [0.0, 20.0]	2.30, [2.0, 3.0]	1.0, [0.0, 1.5]	70.2, [0, 11373.8]	2.1, [0, 625.4]

**Table 1:** Summary of the parameter values and their explored range, and the  $\gamma$ -ray flux at CTA energies for the hadronic and inverse Compton emission (given as: reference value, [min, max]). The flux  $F_{500}$  is computed within  $\theta_{500}$  by cylindrical integration for energies above 150 GeV and given in units of  $10^{-14} \text{ cm}^{-2} \text{ s}^{-1}$ .

$R_{200}$ [kpc]	$M_{200}$ [ $10^{14} M_\odot$ ]	$c_{200}$	$r_s$ [kpc]	$\log_{10} \rho_0$ [ $M_\odot/\text{kpc}^3$ ]	$\theta_{200}$ [deg]
7.52	5.03	370.82	6.08	1865.00	1.42

**Table 2:** Navarro-Frenk-White (NFW) density profile parameters for the Perseus galaxy cluster.  $R_{200}$  is the radius where the density is 200 times the critical density of the universe, in units of kpc.  $M_{200}$  is the mass at  $R_{200}$  in units of  $10^{14} M_\odot$ ,  $c_{200}$  is the concentration parameter,  $r_s$  is the scale radius of the density profile in units of kpc,  $\rho_0$  is the normalization in units of  $M_\odot/\text{kpc}^3$ , and  $\theta_{200}$  is the projected angle.

For the DM, we assume a conservative model for the DM density profile based on results from N-body simulations [10]. Table 2 shows the parameters associated to the DM density profile in the cluster. Here, we also include the prospective contribution of subhalos embedded in the main halo of the cluster. Then, the gamma-ray flux from annihilation of WIMPs in the cluster is computed as:

$$\frac{d\Phi_\gamma^{\text{DM, ann}}}{dE} = \frac{dN_\gamma^{\text{DM}}}{dE} \frac{\langle \sigma_\chi v \rangle}{8\pi m_\chi^2} \int_{\Delta\Omega} d\Omega \int_{l.o.s.} dl \rho_{\text{DM}}^2(r(l)), \quad (3)$$

where the first term is the number of gamma rays as a function of the energy  $E$  for an annihilation channel and is called the DM annihilation spectrum,  $\langle \sigma_\chi v \rangle$  is the thermal-averaged annihilation cross section,  $m_\chi$  is the mass of the DM candidate, and  $\rho_{\text{DM}}$  is the density profile of DM in the cluster. The integral over  $\rho_{\text{DM}}^2$  is along the line of sight (*l.o.s.*) between the observatory and the cluster, and the solid angle subtended by this line of sight. The integral term is called the astrophysical factor  $J$ . Given that the astrophysical factor is proportional to  $\rho_{\text{DM}}^2$ , the presence of subhalos, as considered in our model, enhance the gamma-ray flux (a boost factor) produced by the annihilation of DM particles in the cluster, and can tighten the constrains of  $\langle \sigma_\chi v \rangle$ .

<sup>1</sup> $R_{500}$  is the radius where the density is 500 times the critical density of the Universe

For decay of DM, a similar expression for the gamma-ray flux can be found:

$$\frac{d\Phi_{\gamma}^{\text{DM, dec}}}{dE} = \frac{dN_{\gamma}^{\text{DM}}}{dE} \frac{1}{4\pi m_{\chi} \tau_{\chi}} \int_{\Delta\Omega} d\Omega \int_{l.o.s.} dl \rho_{\text{DM}}(r(l)), \quad (4)$$

where  $\tau_{\chi}$  is the lifetime of the DM candidate, and the integral term is called the astrophysical factor  $D$ . For this case, the gamma-ray flux only depends in the total mass of the cluster, and no enhancement from subhalos is expected.

We consider WIMPs with masses in the range from 50 GeV and 100 TeV, and two representative channels for annihilation and decay ( $\tau$  leptons and  $b$  quarks)<sup>2</sup>. To compute the spectral part of the gamma-ray flux induced by DM interactions, we use the tables from the project PPPC4DMID [2] to compute the number of photons produced for a candidate with mass  $m_{\chi}$  and for each annihilation/decay channel. The astrophysical factors  $J$  and  $D$ , related to the spatial morphology of the emission, are computed using the publicly available code Clumpy [11].

Finally, for the DM induced gamma-ray emission, one of the most important source of uncertainty comes from the knowledge of the DM density profile and the distribution of subhalos, with changes in the exclusion limits up to one order of magnitude with respect to the model we present in this work. The corresponding analysis to take into account this uncertainty is presented in a future CTA Consortium publication (in preparation).

### 3. Observation setup

To compute the sensitivity of CTA to annihilation and decay of WIMPs in the Perseus cluster, we first create a set of observations simulated using the public code `ctools` [12]. The observations comprises a total of 300 h of the region of the Perseus cluster.

The simulated observations consider gamma-ray events with energies between 30 GeV and 100 TeV, and divided in 10 energy bins separated in log scale. The total duration of the observations was obtained from the stack of 300 individual observations with a duration of 1 h. The Region Of Interest (ROI) used for the simulation has an angular radius of 3 degrees and center at 1 degree from the center of the Perseus Cluster.

We use the Instrument Response Functions (IRFs), corresponding to the Omega configuration [13]. In order to take into account the statistical fluctuations from the background, we perform 100 repetitions changing the random seed for the background estimation in the simulation. A recent configuration of the CTA telescopes, the Alpha configuration, will be used for the first phase of construction. A comparison between the sensitivity of both configurations will not change the results obtained in this analysis, and will decrease the expected limits only by a factor of approximately 1.3 times for energies around 1 TeV.

### 4. Analysis with `ctadmtool`

For the analysis of the simulated observations, we use the Maximum Likelihood Estimation (MLE) method. We use a template-fitting approach, where we consider all the models of gamma-ray

<sup>2</sup>Other channels follow the same spectrum shape as the two channels used for the analysis.

emission (NGC 1275, IC 310, DM and CR) in the ROI and simultaneously fit the free parameters of each model to describe the simulated data. In case we do not observe a positive detection of the DM signal, then we proceed to compute the upper-limit to the integral flux and convert to the exclusion limit (95% C.L.) to  $\langle\sigma_{\text{WIMP}\nu}\rangle$  and  $\tau_{\text{WIMP}}$  for WIMPs.

The calculation of best-fit parameters and exclusion limits for DM from CTA is integrated in the public code `ctadmtool`<sup>3</sup>. `ctadmtool` is based in `ctools` and `gammalib` [12], and allows the user to test different masses for WIMPs. `ctadmtool` computes the best-fit parameter for every mass value, the correlation matrix for the free parameters in the total emission model, and the test statistic  $TS$  for every gamma-ray emission component. In case of no detection ( $TS < 25$ ) of a signal induced by DM, `ctadmtool` computes the exclusion limit to the integral flux and  $\langle\sigma_{\chi\nu}\rangle$  or  $\tau_{\chi}$  for every mass point, and save all the results to a FITS file. The comparison of our results with the canonical ones obtained using `gammapy` and `dmttools_gammapy`<sup>4</sup> are presented in a future CTA Consortium publication (in preparation).

Using the set of simulated observations described above, we compute the  $TS$  and correlation matrices for 10 mass points in the range from 50 GeV to 100 TeV. From this step in the analysis, we found that the galaxy NGC 1275 has a big impact in the  $TS$  for the CRs and DM components in the cluster, in particular for masses of WIMPs lower than 10 TeV. Figure 1 shows the  $TS$  obtained for each component in the emission model as a function of DM mass for annihilation to  $\tau$  leptons<sup>5</sup>. We can observe that the value of  $TS$  obtained for NGC 1275 decreases for lower masses up to half of the minimal value obtained for  $m_{\chi} > 10$  TeV. The decrease in NGC 1275  $TS$  for lower masses is related to a false detection of the gamma-ray signal induced by DM annihilation. This effect is explained due to the spatial morphology of DM- and CR- induced gamma-ray signals, as both emissions have their peaks in the center of the Perseus Cluster, where NGC 1275 is also located. This property of the DM and CR emission models seems to maximize the entanglement of the gamma-ray signal in the center of the cluster, and a possible leaking of the emission from NGC 1275 leads to a false detection of the DM component. This is observed for every annihilation/decay channel.

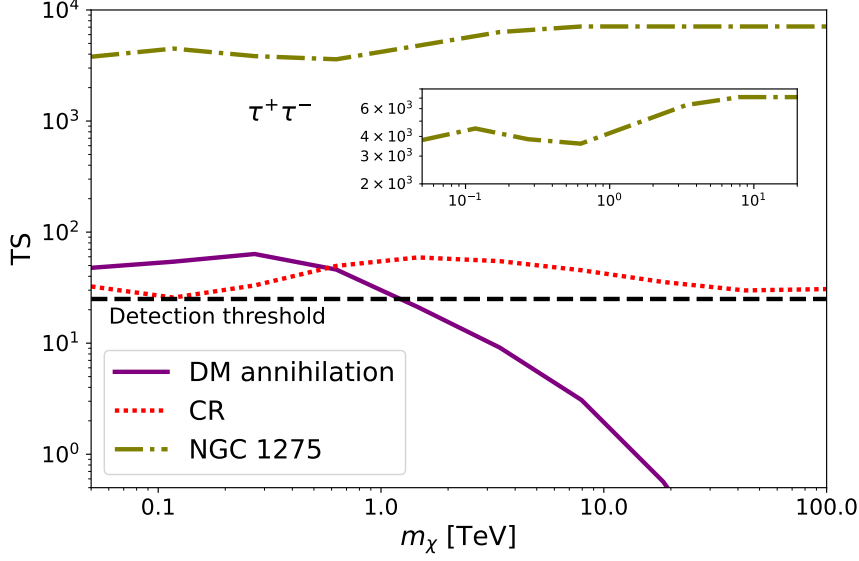
In order to avoid the contamination of the signal from NGC 1275, we place a circular mask centered in the position of NGC 1275. Table 3 shows the angular radius of the mask as a function of the energy. We select five different gamma-ray energy ranges according to the angular resolution of the CTA North array. The size was selected to be twice the angular resolution for the lower bound in the energy interval to remove 95 % of the photons coming from NGC 1275.

The main disadvantage of this analysis technique (Template fitting + mask), is that the CTA sensitivity is reduced because we cover the region where the DM- and CR- induced gamma-ray signal have their maximum. With this analysis, we do not find evidence for a signal induced by annihilation or decay of DM particles.

<sup>3</sup>The code is available in <https://github.com/sergiohcdna/ctadmtool>

<sup>4</sup>The code is available in [https://github.com/peroju/dmttools\\_gammapy](https://github.com/peroju/dmttools_gammapy)

<sup>5</sup>We do not plot the  $TS$  associated with the galaxy IC 310, as this value is constant for all the masses considered in the analysis.



**Figure 1:** Average values of TS for NGC 1275 (olive line), CR (red line) and DM (purple line) induced emission as a function of the DM mass. For the DM emission model, we consider annihilation to leptons  $\tau$ . The dashed black line represents the detection threshold,  $TS \geq 25$ . We observe that for DM masses below 1 TeV, the NGC 1275 TS decreases with respect to the value obtained for higher masses (10 TeV). This decrement appear to be correlated with a false detection of the DM signal.

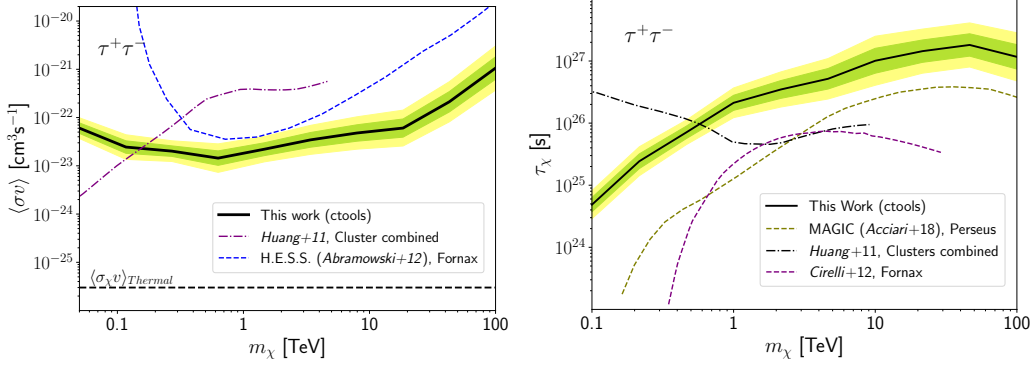
Energy Range (TeV)	$\theta_{\text{mask}}$ (deg)
0.03 - 0.06	0.50
0.06 - 0.15	0.30
0.15 - 1.00	0.20
1.00 - 10.0	0.12
10.0 - 100.0	0.08

**Table 3:** Angular sizes (radii) of the mask applied to the simulation in the center of the Perseus cluster. The size is set to 2 times the value of the angular resolution of the CTA North Array at the energy corresponding to the lower extreme of each energy interval [14].

## 5. Results

Using the template fitting method and masking NGC 1275, we do not find any possible signal associated with a gamma-ray signal induced by DM annihilation or decay. Then, we compute the 95% C.L. exclusion limits to  $\langle\sigma_{\chi\nu}\rangle$  and  $\tau_{\chi}$  as a function of the mass of the DM candidate. Figure 2 shows the exclusion limits of  $\langle\sigma_{\chi\nu}\rangle$  (left panel) and  $\tau_{\chi}$  (right panel). We show also the comparison with results from recent searches for DM induced gamma-ray signals in galaxy clusters.

For annihilation, we observe that the expected exclusion limits for DM masses greater than  $\sim 200$  GeV improve the limits up to a factor of two times with respect to the results of the combined



**Figure 2:** CTA sensitivity to DM annihilation and decay in the Perseus cluster. Exclusion limits (95% C.L.) were obtained with `ctadmtool` for the template fitting plus a mask centered in the position of NGC 1275. Solid black lines correspond to the average value for 100 realizations, and green (yellow) bands show the  $1\sigma(2\sigma)$  dispersion around the average value. We consider only annihilation/decay to leptons  $\tau$ . **Left panel:** Exclusion limits for  $\langle\sigma_\chi v\rangle$  as a function of the DM mass. The dashed black line corresponds to the thermal value of the annihilation cross-section,  $\langle\sigma_\chi v\rangle_{\text{thermal}} = 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$ . The region above the curve is excluded. **Right panel:** Exclusion limits for  $\tau_\chi$  as a function of the DM mass. The region below the curves is excluded.

searches in a sample of galaxy clusters using data from the *Fermi*-LAT telescope [15] and results for the Fornax cluster using the H.E.S.S. telescopes [16]. In the other hand, the expected limits for decay show an improvement up to one order of magnitude with respect to the results previously obtained for the Fornax [17] and Perseus [18] clusters. In particular, the limits obtained from observations with the MAGIC telescopes use the same analysis strategy as we used in this analysis [18], showing the observational challenge due to the different emission components in the region, and the validity of the strategy used in this work.

## 6. Conclusions

We computed the expected exclusion limits (95% C.L.) for  $\langle\sigma_\chi v\rangle$  and  $\tau_\chi$  from the Perseus cluster as would be observed by the CTA Observatory. We obtained the limits for simulated observations of the Perseus cluster with a total exposure of 300 h for annihilation and decay of WIMPs with masses in the range from 50 GeV up to 100 TeV. The CTA expected limits improve the current observed exclusion limits for  $m_\chi \geq 500$  GeV for both, annihilation and decay. For the analysis we present here, using the code `ctadmtool`, we need to consider masking the galaxy NGC 1275 due to the false detection when using only the template fitting approach. This false detection is related to the possible leaking of gamma-ray events coming from NGC 1275. This emission also impacts the results obtained for the CR-induced gamma-ray emission. The strategy analysis proposed in this scenario is supported by the previous observations and results of the MAGIC collaboration for the observation of the Perseus cluster with a total effective exposure of  $\sim 250$  h.



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# The CTA Consortium

K. Abe<sup>1</sup>, S. Abe<sup>2</sup>, A. Acharyya<sup>3</sup>, R. Adam<sup>4,5</sup>, A. Aguasca-Cabot<sup>6</sup>, I. Agudo<sup>7</sup>, J. Alfaro<sup>8</sup>, N. Alvarez-Crespo<sup>9</sup>, R. Alves Batista<sup>10</sup>, J.-P. Amans<sup>11</sup>, E. Amato<sup>12</sup>, F. Ambrosino<sup>13</sup>, E. O. Angüner<sup>14</sup>, L. A. Antonelli<sup>13</sup>, C. Aramo<sup>15</sup>, C. Arcaro<sup>16</sup>, L. Arrabito<sup>17</sup>, K. Asano<sup>2</sup>, J. Aschersleben<sup>18</sup>, H. Ashkar<sup>5</sup>, L. Augusto Stuardi<sup>19</sup>, D. Baack<sup>20</sup>, M. Backes<sup>21,22</sup>, C. Balazs<sup>23</sup>, M. Balbo<sup>24</sup>, A. Baquero Larriva<sup>9,25</sup>, V. Barbosa Martins<sup>26</sup>, U. Barres de Almeida<sup>27,28</sup>, J. A. Barrio<sup>9</sup>, D. Bastieri<sup>29</sup>, P. I. Batista<sup>26</sup>, I. Batkovic<sup>29</sup>, R. Batzofin<sup>30</sup>, J. Baxter<sup>2</sup>, G. Beck<sup>31</sup>, J. Becker Tjus<sup>32</sup>, L. Beiske<sup>20</sup>, D. Belardinelli<sup>33</sup>, W. Benbow<sup>34</sup>, E. Bernardini<sup>29</sup>, J. Bernete Medrano<sup>35</sup>, K. Bernlöhr<sup>36</sup>, A. Berti<sup>37</sup>, V. Beshley<sup>38</sup>, P. Bhattacharjee<sup>39</sup>, S. Bhattacharyya<sup>40</sup>, B. Bi<sup>41</sup>, N. Biederbeck<sup>20</sup>, A. Biland<sup>42</sup>, E. Bissaldi<sup>43,44</sup>, O. Blanch<sup>45</sup>, J. Blazek<sup>46</sup>, C. Boisson<sup>11</sup>, J. Bolmont<sup>47</sup>, G. Bonnoli<sup>48,49</sup>, P. Bordas<sup>6</sup>, Z. Bosnjak<sup>50</sup>, F. Bradascio<sup>51</sup>, C. Braiding<sup>52</sup>, E. Bronzini<sup>53</sup>, R. Brose<sup>54</sup>, A. M. Brown<sup>55</sup>, F. Brun<sup>51</sup>, G. Brunelli<sup>53,7</sup>, A. Bulgarelli<sup>53</sup>, I. Burelli<sup>56</sup>, L. Burmistrov<sup>57</sup>, M. Burton<sup>58,59</sup>, T. Bylund<sup>60</sup>, P. G. Calisse<sup>61</sup>, A. Campoy-Ordaz<sup>62</sup>, B. K. Cantlay<sup>63,64</sup>, M. Capalbi<sup>65</sup>, A. Caproni<sup>66</sup>, R. Capuzzo-Dolcetta<sup>13</sup>, C. Carille<sup>67</sup>, S. Caroff<sup>39</sup>, A. Carosi<sup>13</sup>, R. Carosi<sup>49</sup>, M.-S. Carrasco<sup>68</sup>, E. Cascone<sup>69</sup>, F. Cassol<sup>68</sup>, N. Castrejón<sup>70</sup>, F. Catalani<sup>71</sup>, D. Cerasole<sup>72</sup>, M. Cerruti<sup>73</sup>, S. Chaty<sup>73</sup>, A. W. Chen<sup>31</sup>, M. Chernyakova<sup>74</sup>, A. Chiavassa<sup>75,76</sup>, J. Chudoba<sup>46</sup>, C. H. Coimbra Araujo<sup>77</sup>, V. Conforti<sup>53</sup>, F. Conte<sup>36</sup>, J. L. Contreras<sup>9</sup>, C. Cossou<sup>60</sup>, A. Costa<sup>78</sup>, H. Costantini<sup>68</sup>, P. Cristofari<sup>11</sup>, O. Cuevas<sup>79</sup>, Z. Curtis-Ginsberg<sup>80</sup>, G. D'Amico<sup>81</sup>, F. D'Ammando<sup>82</sup>, M. Dadina<sup>53</sup>, M. Dalchenko<sup>57</sup>, L. David<sup>26</sup>, I. D. Davids<sup>21</sup>, F. Dazzi<sup>83</sup>, A. De Angelis<sup>29</sup>, M. de Bony de Lavergne<sup>60</sup>, V. De Caprio<sup>69</sup>, G. De Cesare<sup>53</sup>, E. M. de Gouveia Dal Pino<sup>28</sup>, B. De Lotto<sup>56</sup>, M. De Lucia<sup>15</sup>, R. de Menezes<sup>75,76</sup>, M. de Naurois<sup>5</sup>, E. de Ona Wilhelmi<sup>26</sup>, N. De Simone<sup>26</sup>, V. de Souza<sup>19</sup>, L. del Peral<sup>70</sup>, M. V. del Valle<sup>28</sup>, E. Delagnes<sup>84</sup>, A. G. Delgado Giler<sup>19,18</sup>, C. Delgado<sup>35</sup>, M. Dell'aiera<sup>39</sup>, R. Della Ceca<sup>48</sup>, M. Della Valle<sup>69</sup>, D. della Volpe<sup>57</sup>, D. Depaoli<sup>36</sup>, A. Dettlaff<sup>37</sup>, T. Di Girolamo<sup>85,15</sup>, A. Di Piano<sup>53</sup>, F. Di Piero<sup>75</sup>, R. Di Tria<sup>72</sup>, L. Di Venere<sup>44</sup>, C. Díaz-Bahamondes<sup>8</sup>, C. Dib<sup>86</sup>, S. Diebold<sup>41</sup>, R. Dima<sup>29</sup>, A. Dinesh<sup>9</sup>, A. Djannati-Atai<sup>73</sup>, J. Djuvsland<sup>81</sup>, A. Domínguez<sup>9</sup>, R. M. Dominik<sup>20</sup>, A. Donini<sup>13</sup>, D. Dorner<sup>87,42</sup>, J. Dörner<sup>32</sup>, M. Doro<sup>29</sup>, R. D. C. dos Anjos<sup>77</sup>, J.-L. Dournaux<sup>11</sup>, D. Dravins<sup>67</sup>, C. Duangchan<sup>88,64</sup>, C. Dubos<sup>89</sup>, L. Ducci<sup>41</sup>, V. V. Dwarkadas<sup>90</sup>, J. Ebr<sup>46</sup>, C. Eckner<sup>39,91</sup>, K. Egberts<sup>30</sup>, S. Einecke<sup>52</sup>, D. Elsässer<sup>20</sup>, G. Emery<sup>68</sup>, M. Escobar Godoy<sup>92</sup>, J. Escudero<sup>7</sup>, P. Esposito<sup>93,94</sup>, D. Falceta-Goncalves<sup>95</sup>, V. Fallah Ramazani<sup>32</sup>, A. Faure<sup>17</sup>, E. Fedorova<sup>13,96</sup>, S. Fegan<sup>5</sup>, K. Feijen<sup>73</sup>, Q. Feng<sup>34</sup>, G. Ferrand<sup>97,98</sup>, F. Ferrarotto<sup>99</sup>, E. Fiandrini<sup>100</sup>, A. Fiasson<sup>39</sup>, V. Fioretti<sup>53</sup>, L. Foffano<sup>101</sup>, L. Font Guiteras<sup>62</sup>, G. Fontaine<sup>5</sup>, S. Fröse<sup>20</sup>, S. Fukami<sup>42</sup>, Y. Fukui<sup>102</sup>, S. Funk<sup>88</sup>, D. Gaggero<sup>49</sup>, G. Galanti<sup>94</sup>, G. Galaz<sup>8</sup>, Y. A. Gallant<sup>17</sup>, S. Gallozzi<sup>13</sup>, V. Gammaldi<sup>10</sup>, C. Gasbarra<sup>33</sup>, M. Gaug<sup>62</sup>, A. Ghalumyan<sup>103</sup>, F. Gianotti<sup>53</sup>, M. Giarrusso<sup>104</sup>, N. Giglietto<sup>43,44</sup>, F. Giordano<sup>72</sup>, A. Giuliani<sup>94</sup>, J.-F. Glicenstein<sup>51</sup>, J. Glombitza<sup>88</sup>, P. Goldoni<sup>105</sup>, J. M. González<sup>106</sup>, M. M. González<sup>107</sup>, J. Goulart Coelho<sup>108</sup>, J. Granot<sup>109,110</sup>, D. Grasso<sup>49</sup>, R. Grau<sup>45</sup>, D. Green<sup>37</sup>, J. G. Green<sup>37</sup>, T. Greenshaw<sup>111</sup>, G. Grolleron<sup>47</sup>, J. Grube<sup>112</sup>, O. Gueta<sup>26</sup>, S. Gunji<sup>113</sup>, D. Hadasch<sup>2</sup>, P. Hamal<sup>46</sup>, W. Hanlon<sup>34</sup>, S. Hara<sup>114</sup>, V. M. Harvey<sup>52</sup>, K. Hashiyama<sup>2</sup>, T. Hassan<sup>35</sup>, M. Heller<sup>57</sup>, S. Hernández Cadena<sup>107</sup>, J. Hie<sup>115</sup>, N. Hiroshima<sup>2</sup>, B. Hnatyk<sup>96</sup>, R. Hnatyk<sup>96</sup>, D. Hoffmann<sup>68</sup>, W. Hofmann<sup>36</sup>, M. Holler<sup>116</sup>, D. Horan<sup>5</sup>, P. Horvath<sup>117</sup>, T. Hovatta<sup>118</sup>, D. Hrupec<sup>119</sup>, S. Hussain<sup>28,120</sup>, M. Iarlori<sup>121</sup>, T. Inada<sup>2</sup>, F. Incardona<sup>78</sup>, Y. Inoue<sup>2</sup>, S. Inoue<sup>98</sup>, F. Iocco<sup>85,15</sup>, K. Ishio<sup>122</sup>, M. Jamrozny<sup>123</sup>, P. Janecek<sup>46</sup>, F. Jankowsky<sup>124</sup>, C. Jarnot<sup>115</sup>, P. Jean<sup>115</sup>, I. Jiménez Martínez<sup>35</sup>, W. Jin<sup>3</sup>, L. Jocou<sup>125</sup>, C. Juramy-Gilles<sup>47</sup>, J. Jurysek<sup>46</sup>, O. Kalekin<sup>88</sup>, D. Kantzas<sup>91</sup>, V. Karas<sup>126</sup>, S. Kaufmann<sup>55</sup>, D. Kerszberg<sup>45</sup>, B. Khélifi<sup>73</sup>, D. B. Kieda<sup>127</sup>, T. Kleiner<sup>26</sup>, W. Kluźniak<sup>128</sup>, Y. Kobayashi<sup>2</sup>, K. Kohri<sup>129</sup>, N. Komin<sup>31</sup>, P. Kornecki<sup>11</sup>, K. Kosack<sup>60</sup>, H. Kubo<sup>2</sup>, J. Kushida<sup>1</sup>, A. La Barbera<sup>65</sup>, N. La Palombara<sup>94</sup>, M. Láinez<sup>9</sup>, A. Lamastra<sup>13</sup>, J. Lapington<sup>130</sup>, S. Lazarević<sup>131</sup>, J. Lazendic-Galloway<sup>23</sup>, S. Leach<sup>130</sup>, M. Lemoine-Goumard<sup>132</sup>, J.-P. Lenain<sup>47</sup>, G. Leto<sup>78</sup>, F. Leuschner<sup>41</sup>, E. Lindfors<sup>118</sup>, M. Linhoff<sup>20</sup>, I. Lioudakis<sup>118</sup>, L. Loic<sup>51</sup>, S. Lombardi<sup>13</sup>, F. Longo<sup>133</sup>, R. López-Coto<sup>7</sup>, M. López-Moya<sup>9</sup>, A. López-Oramas<sup>134</sup>, S. Loporchio<sup>43,44</sup>, J. Lozano Bahilo<sup>70</sup>, P. L. Luque-Escamilla<sup>135</sup>, O. Macias<sup>136</sup>, G. Maier<sup>26</sup>, P. Majumdar<sup>137</sup>, D. Malyshev<sup>41</sup>, D. Malyshev<sup>88</sup>, D. Mandat<sup>46</sup>, G. Manicò<sup>104,138</sup>, P. Marinos<sup>52</sup>, S. Markoff<sup>136</sup>, I. Márquez<sup>7</sup>, P. Marquez<sup>45</sup>, G. Marsella<sup>139,104</sup>, J. Martí<sup>135</sup>, P. Martin<sup>115</sup>

G. A. Martínez<sup>35</sup>, M. Martínez<sup>45</sup>, O. Martinez<sup>140,141</sup>, C. Marty<sup>115</sup>, A. Mas-Aguilar<sup>9</sup>, M. Mastropietro<sup>13</sup>, G. Maurin<sup>39</sup>, W. Max-Moerbeck<sup>142</sup>, D. Mazin<sup>2,37</sup>, D. Melkumyan<sup>26</sup>, S. Menchiarì<sup>12,49</sup>, E. Mestre<sup>143</sup>, J.-L. Meunier<sup>47</sup>, D. M.-A. Meyer<sup>30</sup>, D. Miceli<sup>16</sup>, M. Michailidis<sup>41</sup>, J. Michałowski<sup>144</sup>, T. Miener<sup>9</sup>, J. M. Miranda<sup>140,145</sup>, A. Mitchell<sup>88</sup>, M. Mizote<sup>146</sup>, T. Mizuno<sup>147</sup>, R. Moderski<sup>128</sup>, L. Mohrmann<sup>36</sup>, M. Molero<sup>134</sup>, C. Molfese<sup>83</sup>, E. Molina<sup>134</sup>, T. Montaruli<sup>57</sup>, A. Moralejo<sup>45</sup>, D. Morcuende<sup>9,7</sup>, K. Morik<sup>20</sup>, A. Morselli<sup>33</sup>, E. Moulin<sup>51</sup>, V. Moya Zamanillo<sup>9</sup>, R. Mukherjee<sup>148</sup>, K. Munari<sup>78</sup>, A. Muraczewski<sup>128</sup>, H. 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Pavlović<sup>161</sup>, A. Pe'er<sup>37</sup>, M. Pech<sup>46</sup>, M. Pecimotika<sup>161,162</sup>, M. Peresano<sup>76,75</sup>, J. Pérez-Romero<sup>10,40</sup>, G. Peron<sup>73</sup>, M. Persic<sup>163,164</sup>, P.-O. Petrucci<sup>125</sup>, O. Petruk<sup>38</sup>, F. Pfeifle<sup>87</sup>, F. Pintore<sup>65</sup>, G. Pirola<sup>37</sup>, C. Pittori<sup>13</sup>, C. Plard<sup>39</sup>, F. Podobnik<sup>165</sup>, M. Pohl<sup>30,26</sup>, E. Pons<sup>39</sup>, E. Prandini<sup>29</sup>, J. Prast<sup>39</sup>, G. Principe<sup>133</sup>, C. Priyadarshi<sup>45</sup>, N. Produit<sup>46</sup>, D. Prokhorov<sup>136</sup>, E. Puschel<sup>26</sup>, G. Pühlhofer<sup>41</sup>, M. L. Pumo<sup>138,104</sup>, M. Punch<sup>73</sup>, A. Quirrenbach<sup>124</sup>, S. Rainò<sup>72</sup>, N. Randazzo<sup>104</sup>, R. Rando<sup>29</sup>, T. Ravel<sup>115</sup>, S. Razzaque<sup>166,110</sup>, M. Regeard<sup>73</sup>, P. Reichherzer<sup>167,32</sup>, A. Reimer<sup>116</sup>, O. Reimer<sup>116</sup>, A. Reisenegger<sup>8,168</sup>, T. Reposeur<sup>132</sup>, B. Reville<sup>36</sup>, W. Rhode<sup>20</sup>, M. Ribó<sup>6</sup>, T. Richtler<sup>169</sup>, F. Rieger<sup>36</sup>, E. Roache<sup>34</sup>, G. Rodriguez Fernandez<sup>33</sup>, M. D. Rodríguez Frías<sup>70</sup>, J. J. Rodríguez-Vázquez<sup>35</sup>, P. Romano<sup>48</sup>, G. Romeo<sup>78</sup>, J. Rosado<sup>9</sup>, G. Rowell<sup>52</sup>, B. Rudak<sup>128</sup>, A. J. Ruiter<sup>170</sup>, C. B. Rulten<sup>55</sup>, F. Russo<sup>53</sup>, I. Sadeh<sup>26</sup>, L. Saha<sup>34</sup>, T. Saito<sup>2</sup>, S. Sakurai<sup>2</sup>, H. Salzmann<sup>41</sup>, D. Sanchez<sup>39</sup>, M. Sánchez-Conde<sup>10</sup>, P. Sangiorgi<sup>65</sup>, H. Sano<sup>2</sup>, M. Santander<sup>3</sup>, A. Santangelo<sup>41</sup>, R. Santos-Lima<sup>28</sup>, A. Sanuy<sup>6</sup>, T. Šarić<sup>171</sup>, A. Sarkar<sup>26</sup>, S. Sarkar<sup>167</sup>, F. G. Saturni<sup>13</sup>, V. Savchenko<sup>172</sup>, A. Scherer<sup>8</sup>, P. Schipani<sup>69</sup>, B. Schleicher<sup>87,42</sup>, P. Schovaneck<sup>46</sup>, J. L. Schubert<sup>20</sup>, F. Schussler<sup>51</sup>, U. Schwanke<sup>173</sup>, G. Schwefer<sup>36</sup>, S. Scuderi<sup>94</sup>, M. Seglar Arroyo<sup>45</sup>, I. Seitenzahl<sup>170</sup>, O. Sergijenko<sup>96,174,175</sup>, V. Sguera<sup>53</sup>, R. Y. Shang<sup>157</sup>, P. Sharma<sup>89</sup>, G. D. S. SIDIBE<sup>84</sup>, L. Sidoli<sup>94</sup>, H. Siejkowski<sup>176</sup>, C. Siqueira<sup>19</sup>, P. Sizun<sup>84</sup>, V. Sliusar<sup>24</sup>, A. Slowikowska<sup>177</sup>, H. Sol<sup>11</sup>, A. Specovius<sup>88</sup>, S. T. Spencer<sup>88,167</sup>, D. Spiga<sup>48</sup>, A. Stamerra<sup>13,178</sup>, S. Stanić<sup>40</sup>, T. Starecki<sup>179</sup>, R. Starling<sup>130</sup>, C. Steppa<sup>30</sup>, T. Stolarczyk<sup>60</sup>, J. Strišković<sup>119</sup>, M. Strzys<sup>2</sup>, Y. Suda<sup>180</sup>, T. Suomijärvi<sup>89</sup>, D. Tak<sup>26</sup>, M. Takahashi<sup>154</sup>, R. Takeishi<sup>2</sup>, P.-H. T. Tam<sup>2,181</sup>, S. J. Tanaka<sup>182</sup>, T. Tanaka<sup>146</sup>, K. Terauchi<sup>183</sup>, V. Testa<sup>13</sup>, L. Tibaldo<sup>115</sup>, O. Tibolla<sup>55</sup>, F. Torradeflot<sup>184,35</sup>, D. F. Torres<sup>143</sup>, E. Torresi<sup>53</sup>, N. Tothill<sup>131</sup>, F. Toussanel<sup>47</sup>, V. Touzard<sup>115</sup>, A. Tramacere<sup>24</sup>, P. Travnicek<sup>46</sup>, G. Tripodo<sup>139,104</sup>, S. Truzzi<sup>165</sup>, A. Tsiachina<sup>115</sup>, A. Tutone<sup>65</sup>, M. Vacula<sup>117,46</sup>, B. Vallage<sup>51</sup>, P. Vallania<sup>75,185</sup>, R. Vallés<sup>143</sup>, C. van Eldik<sup>88</sup>, J. van Scherpenberg<sup>37</sup>, J. Vandenbroucke<sup>80</sup>, V. Vassiliev<sup>157</sup>, P. Venault<sup>84</sup>, S. Ventura<sup>165</sup>, S. Vercellone<sup>48</sup>, G. Verna<sup>165</sup>, A. Viana<sup>19</sup>, N. Viaux<sup>186</sup>, A. Vigliano<sup>56</sup>, J. Vignatti<sup>86</sup>, C. F. Vigorito<sup>75,76</sup>, V. Vitale<sup>33</sup>, V. Vodeb<sup>40</sup>, V. Voisin<sup>47</sup>, S. Vorobiov<sup>40</sup>, G. Voutsinas<sup>57</sup>, I. Vovk<sup>2</sup>, V. Waeghebaert<sup>115</sup>, S. J. Wagner<sup>124</sup>, R. Walter<sup>24</sup>, M. Ward<sup>55</sup>, M. Wechakama<sup>63,64</sup>, R. White<sup>36</sup>, A. Wierzcholska<sup>144</sup>, M. Will<sup>37</sup>, D. A. Williams<sup>92</sup>, F. Wohlleben<sup>36</sup>, A. Wolter<sup>48</sup>, T. Yamamoto<sup>146</sup>, R. Yamazaki<sup>182</sup>, L. Yang<sup>166,181</sup>, T. Yoshida<sup>187</sup>, T. Yoshikoshi<sup>2</sup>, M. Zacharias<sup>124,22</sup>, R. Zanmar Sanchez<sup>78</sup>, D. Zavrtnik<sup>40</sup>, M. Zavrtnik<sup>40</sup>, A. A. Zdziarski<sup>128</sup>, A. Zech<sup>11</sup>, V. I. Zhdanov<sup>96</sup>, K. Zięta<sup>123</sup>, M. Živec<sup>40</sup>, J. Zuriaga-Puig<sup>10</sup>

## Affiliations

- <sup>1</sup> Department of Physics, Tokai University, 4-1-1, Kita-Kaname, Hiratsuka, Kanagawa 259-1292, Japan
- <sup>2</sup> Institute for Cosmic Ray Research, University of Tokyo, 5-1-5, Kashiwa-no-ha, Kashiwa, Chiba 277-8582, Japan
- <sup>3</sup> University of Alabama, Tuscaloosa, Department of Physics and Astronomy, Gallalee Hall, Box 870324 Tuscaloosa, AL 35487-0324, USA
- <sup>4</sup> Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, Laboratoire Lagrange, France
- <sup>5</sup> Laboratoire Leprince-Ringuet, CNRS/IN2P3, École polytechnique, Institut Polytechnique de Paris, 91120 Palaiseau, France
- <sup>6</sup> Departament de Física Quàntica i Astrofísica, Institut de Ciències del Cosmos, Universitat de Barcelona, IEEC-UB, Martí i Franquès, 1, 08028, Barcelona, Spain
- <sup>7</sup> Instituto de Astrofísica de Andalucía-CSIC, Glorieta de la Astronomía s/n, 18008, Granada, Spain
- <sup>8</sup> Pontificia Universidad Católica de Chile, Av. Libertador Bernardo O'Higgins 340, Santiago, Chile
- <sup>9</sup> IPARCOS-UCM, Instituto de Física de Partículas y del Cosmos, and EMFTEL Department, Universidad Complutense de Madrid, E-28040 Madrid, Spain
- <sup>10</sup> Instituto de Física Teórica UAM/CSIC and Departamento de Física Teórica, Universidad Autónoma de Madrid, c/ Nicolás Cabrera 13-15, Campus de Cantoblanco UAM, 28049 Madrid, Spain
- <sup>11</sup> LUTH, GEPI and LERMA, Observatoire de Paris, Université PSL, Université Paris Cité, CNRS, 5 place Jules Janssen, 92190, Meudon, France
- <sup>12</sup> INAF - Osservatorio Astrofisico di Arcetri, Largo E. Fermi, 5 - 50125 Firenze, Italy
- <sup>13</sup> INAF - Osservatorio Astronomico di Roma, Via di Frascati 33, 00040, Monteporzio Catone, Italy
- <sup>14</sup> TÜBİTAK Research Institute for Fundamental Sciences, 41470 Gebze, Kocaeli, Turkey
- <sup>15</sup> INFN Sezione di Napoli, Via Cintia, ed. G, 80126 Napoli, Italy
- <sup>16</sup> INFN Sezione di Padova, Via Marzolo 8, 35131 Padova, Italy
- <sup>17</sup> Laboratoire Univers et Particules de Montpellier, Université de Montpellier, CNRS/IN2P3, CC 72, Place Eugène Bataillon, F-34095 Montpellier Cedex 5, France
- <sup>18</sup> Kapteyn Astronomical Institute, University of Groningen, Landleven 12, 9747 AD, Groningen, The Netherlands
- <sup>19</sup> Instituto de Física de São Carlos, Universidade de São Paulo, Av. Trabalhador São-carlense, 400 - CEP 13566-590, São Carlos, SP, Brazil
- <sup>20</sup> Astroparticle Physics, Department of Physics, TU Dortmund University, Otto-Hahn-Str. 4a, 44227 Dortmund, Germany
- <sup>21</sup> Department of Physics, Chemistry & Material Science, University of Namibia, Private Bag 13301, Windhoek, Namibia
- <sup>22</sup> Centre for Space Research, North-West University, Potchefstroom, 2520, South Africa
- <sup>23</sup> School of Physics and Astronomy, Monash University, Melbourne, Victoria 3800, Australia
- <sup>24</sup> Department of Astronomy, University of Geneva, Chemin d'Ecogia 16, CH-1290 Versoix, Switzerland
- <sup>25</sup> Faculty of Science and Technology, Universidad del Azuay, Cuenca, Ecuador.
- <sup>26</sup> Deutsches Elektronen-Synchrotron, Platanenallee 6, 15738 Zeuthen, Germany
- <sup>27</sup> Centro Brasileiro de Pesquisas Físicas, Rua Xavier Sigaud 150, RJ 22290-180, Rio de Janeiro, Brazil
- <sup>28</sup> Instituto de Astronomia, Geofísica e Ciências Atmosféricas - Universidade de São Paulo, Cidade Universitária, R. do Matão, 1226, CEP 05508-090, São Paulo, SP, Brazil
- <sup>29</sup> INFN Sezione di Padova and Università degli Studi di Padova, Via Marzolo 8, 35131 Padova, Italy
- <sup>30</sup> Institut für Physik & Astronomie, Universität Potsdam, Karl-Liebknecht-Strasse 24/25, 14476 Potsdam, Germany

- <sup>31</sup> University of the Witwatersrand, 1 Jan Smuts Avenue, Braamfontein, 2000 Johannesburg, South Africa
- <sup>32</sup> Institut für Theoretische Physik, Lehrstuhl IV: Plasma-Astroteilchenphysik, Ruhr-Universität Bochum, Universitätsstraße 150, 44801 Bochum, Germany
- <sup>33</sup> INFN Sezione di Roma Tor Vergata, Via della Ricerca Scientifica 1, 00133 Rome, Italy
- <sup>34</sup> Center for Astrophysics | Harvard & Smithsonian, 60 Garden St, Cambridge, MA 02138, USA
- <sup>35</sup> CIEMAT, Avda. Complutense 40, 28040 Madrid, Spain
- <sup>36</sup> Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany
- <sup>37</sup> Max-Planck-Institut für Physik, Föhringer Ring 6, 80805 München, Germany
- <sup>38</sup> Pidstryhach Institute for Applied Problems in Mechanics and Mathematics NASU, 3B Naukova Street, Lviv, 79060, Ukraine
- <sup>39</sup> Univ. Savoie Mont Blanc, CNRS, Laboratoire d'Annecy de Physique des Particules - IN2P3, 74000 Annecy, France
- <sup>40</sup> Center for Astrophysics and Cosmology (CAC), University of Nova Gorica, Nova Gorica, Slovenia
- <sup>41</sup> Institut für Astronomie und Astrophysik, Universität Tübingen, Sand 1, 72076 Tübingen, Germany
- <sup>42</sup> ETH Zürich, Institute for Particle Physics and Astrophysics, Otto-Stern-Weg 5, 8093 Zürich, Switzerland
- <sup>43</sup> Politecnico di Bari, via Orabona 4, 70124 Bari, Italy
- <sup>44</sup> INFN Sezione di Bari, via Orabona 4, 70126 Bari, Italy
- <sup>45</sup> Institut de Física d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Campus UAB, 08193 Bellaterra (Barcelona), Spain
- <sup>46</sup> FZU - Institute of Physics of the Czech Academy of Sciences, Na Slovance 1999/2, 182 21 Praha 8, Czech Republic
- <sup>47</sup> Sorbonne Université, CNRS/IN2P3, Laboratoire de Physique Nucléaire et de Hautes Energies, LPNHE, 4 place Jussieu, 75005 Paris, France
- <sup>48</sup> INAF - Osservatorio Astronomico di Brera, Via Brera 28, 20121 Milano, Italy
- <sup>49</sup> INFN Sezione di Pisa, Edificio C – Polo Fibonacci, Largo Bruno Pontecorvo 3, 56127 Pisa
- <sup>50</sup> University of Zagreb, Faculty of electrical engineering and computing, Unska 3, 10000 Zagreb, Croatia
- <sup>51</sup> IRFU, CEA, Université Paris-Saclay, Bât 141, 91191 Gif-sur-Yvette, France
- <sup>52</sup> School of Physics, Chemistry and Earth Sciences, University of Adelaide, Adelaide SA 5005, Australia
- <sup>53</sup> INAF - Osservatorio di Astrofisica e Scienza dello spazio di Bologna, Via Piero Gobetti 93/3, 40129 Bologna, Italy
- <sup>54</sup> Dublin Institute for Advanced Studies, 31 Fitzwilliam Place, Dublin 2, Ireland
- <sup>55</sup> Centre for Advanced Instrumentation, Department of Physics, Durham University, South Road, Durham, DH1 3LE, United Kingdom
- <sup>56</sup> INFN Sezione di Trieste and Università degli Studi di Udine, Via delle Scienze 208, 33100 Udine, Italy
- <sup>57</sup> University of Geneva - Département de physique nucléaire et corpusculaire, 24 rue du Général-Dufour, 1211 Genève 4, Switzerland
- <sup>58</sup> Armagh Observatory and Planetarium, College Hill, Armagh BT61 9DG, United Kingdom
- <sup>59</sup> School of Physics, University of New South Wales, Sydney NSW 2052, Australia
- <sup>60</sup> Université Paris-Saclay, Université Paris Cité, CEA, CNRS, AIM, F-91191 Gif-sur-Yvette Cedex, France
- <sup>61</sup> Cherenkov Telescope Array Observatory, Saupfercheckweg 1, 69117 Heidelberg, Germany
- <sup>62</sup> Unitat de Física de les Radiacions, Departament de Física, and CERES-IEEC, Universitat Autònoma de Barcelona, Edifici C3, Campus UAB, 08193 Bellaterra, Spain

- <sup>63</sup> Department of Physics, Faculty of Science, Kasetsart University, 50 Ngam Wong Wan Rd., Lat Yao, Chatuchak, Bangkok, 10900, Thailand
- <sup>64</sup> National Astronomical Research Institute of Thailand, 191 Huay Kaew Rd., Suthep, Muang, Chiang Mai, 50200, Thailand
- <sup>65</sup> INAF - Istituto di Astrofisica Spaziale e Fisica Cosmica di Palermo, Via U. La Malfa 153, 90146 Palermo, Italy
- <sup>66</sup> Universidade Cruzeiro do Sul, Núcleo de Astrofísica Teórica (NAT/UCS), Rua Galvão Bueno 8687, Bloco B, sala 16, Liberdade 01506-000 - São Paulo, Brazil
- <sup>67</sup> Lund Observatory, Lund University, Box 43, SE-22100 Lund, Sweden
- <sup>68</sup> Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France
- <sup>69</sup> INAF - Osservatorio Astronomico di Capodimonte, Via Salita MoiarIELlo 16, 80131 Napoli, Italy
- <sup>70</sup> Universidad de Alcalá - Space & Astroparticle group, Facultad de Ciencias, Campus Universitario Ctra. Madrid-Barcelona, Km. 33.600 28871 Alcalá de Henares (Madrid), Spain
- <sup>71</sup> Escola de Engenharia de Lorena, Universidade de São Paulo, Área I - Estrada Municipal do Campinho, s/n°, CEP 12602-810, Pte. Nova, Lorena, Brazil
- <sup>72</sup> INFN Sezione di Bari and Università degli Studi di Bari, via Orabona 4, 70124 Bari, Italy
- <sup>73</sup> Université Paris Cité, CNRS, Astroparticule et Cosmologie, F-75013 Paris, France
- <sup>74</sup> Dublin City University, Glasnevin, Dublin 9, Ireland
- <sup>75</sup> INFN Sezione di Torino, Via P. Giuria 1, 10125 Torino, Italy
- <sup>76</sup> Dipartimento di Fisica - Università degli Studi di Torino, Via Pietro Giuria 1 - 10125 Torino, Italy
- <sup>77</sup> Universidade Federal Do Paraná - Setor Palotina, Departamento de Engenharias e Exatas, Rua Pioneiro, 2153, Jardim Dallas, CEP: 85950-000 Palotina, Paraná, Brazil
- <sup>78</sup> INAF - Osservatorio Astrofisico di Catania, Via S. Sofia, 78, 95123 Catania, Italy
- <sup>79</sup> Universidad de Valparaíso, Blanco 951, Valparaíso, Chile
- <sup>80</sup> University of Wisconsin, Madison, 500 Lincoln Drive, Madison, WI, 53706, USA
- <sup>81</sup> Department of Physics and Technology, University of Bergen, Musepllass 1, 5007 Bergen, Norway
- <sup>82</sup> INAF - Istituto di Radioastronomia, Via Gobetti 101, 40129 Bologna, Italy
- <sup>83</sup> INAF - Istituto Nazionale di Astrofisica, Viale del Parco Mellini 84, 00136 Rome, Italy
- <sup>84</sup> IRFU/DEDIP, CEA, Université Paris-Saclay, Bat 141, 91191 Gif-sur-Yvette, France
- <sup>85</sup> Università degli Studi di Napoli "Federico II" - Dipartimento di Fisica "E. Pancini", Complesso universitario di Monte Sant'Angelo, Via Cintia - 80126 Napoli, Italy
- <sup>86</sup> CCTVal, Universidad Técnica Federico Santa María, Avenida España 1680, Valparaíso, Chile
- <sup>87</sup> Institute for Theoretical Physics and Astrophysics, Universität Würzburg, Campus Hubland Nord, Emil-Fischer-Str. 31, 97074 Würzburg, Germany
- <sup>88</sup> Friedrich-Alexander-Universität Erlangen-Nürnberg, Erlangen Centre for Astroparticle Physics, Nikolaus-Fiebiger-Str. 2, 91058 Erlangen, Germany
- <sup>89</sup> Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France
- <sup>90</sup> Department of Astronomy and Astrophysics, University of Chicago, 5640 S Ellis Ave, Chicago, Illinois, 60637, USA
- <sup>91</sup> LAPTh, CNRS, USMB, F-74940 Annecy, France
- <sup>92</sup> Santa Cruz Institute for Particle Physics and Department of Physics, University of California, Santa Cruz, 1156 High Street, Santa Cruz, CA 95064, USA
- <sup>93</sup> University School for Advanced Studies IUSS Pavia, Palazzo del Broletto, Piazza della Vittoria 15, 27100 Pavia, Italy
- <sup>94</sup> INAF - Istituto di Astrofisica Spaziale e Fisica Cosmica di Milano, Via A. Corti 12, 20133 Milano, Italy

- <sup>95</sup> Escola de Artes, Ciências e Humanidades, Universidade de São Paulo, Rua Arlindo Bettio, CEP 03828-000, 1000 São Paulo, Brazil
- <sup>96</sup> Astronomical Observatory of Taras Shevchenko National University of Kyiv, 3 Observatorna Street, Kyiv, 04053, Ukraine
- <sup>97</sup> The University of Manitoba, Dept of Physics and Astronomy, Winnipeg, Manitoba R3T 2N2, Canada
- <sup>98</sup> RIKEN, Institute of Physical and Chemical Research, 2-1 Hirosawa, Wako, Saitama, 351-0198, Japan
- <sup>99</sup> INFN Sezione di Roma La Sapienza, P.le Aldo Moro, 2 - 00185 Roma, Italy
- <sup>100</sup> INFN Sezione di Perugia and Università degli Studi di Perugia, Via A. Pascoli, 06123 Perugia, Italy
- <sup>101</sup> INAF - Istituto di Astrofisica e Planetologia Spaziali (IAPS), Via del Fosso del Cavaliere 100, 00133 Roma, Italy
- <sup>102</sup> Department of Physics, Nagoya University, Chikusa-ku, Nagoya, 464-8602, Japan
- <sup>103</sup> Alikhanyan National Science Laboratory, Yerevan Physics Institute, 2 Alikhanyan Brothers St., 0036, Yerevan, Armenia
- <sup>104</sup> INFN Sezione di Catania, Via S. Sofia 64, 95123 Catania, Italy
- <sup>105</sup> Université Paris Cité, CNRS, CEA, Astroparticule et Cosmologie, F-75013 Paris, France
- <sup>106</sup> Universidad Andres Bello, República 252, Santiago, Chile
- <sup>107</sup> Universidad Nacional Autónoma de México, Delegación Coyoacán, 04510 Ciudad de México, Mexico
- <sup>108</sup> Núcleo de Astrofísica e Cosmologia (Cosmo-ufes) & Departamento de Física, Universidade Federal do Espírito Santo (UFES), Av. Fernando Ferrari, 514. 29065-910. Vitória-ES, Brazil
- <sup>109</sup> Astrophysics Research Center of the Open University (ARCO), The Open University of Israel, P.O. Box 808, Ra'anana 4353701, Israel
- <sup>110</sup> Department of Physics, The George Washington University, Washington, DC 20052, USA
- <sup>111</sup> University of Liverpool, Oliver Lodge Laboratory, Liverpool L69 7ZE, United Kingdom
- <sup>112</sup> King's College London, Strand, London, WC2R 2LS, United Kingdom
- <sup>113</sup> Department of Physics, Yamagata University, Yamagata, Yamagata 990-8560, Japan
- <sup>114</sup> Learning and Education Development Center, Yamanashi-Gakuin University, Kofu, Yamanashi 400-8575, Japan
- <sup>115</sup> IRAP, Université de Toulouse, CNRS, CNES, UPS, 9 avenue Colonel Roche, 31028 Toulouse, Cedex 4, France
- <sup>116</sup> Universität Innsbruck, Institut für Astro- und Teilchenphysik, Technikerstr. 25/8, 6020 Innsbruck, Austria
- <sup>117</sup> Palacký University Olomouc, Faculty of Science, Joint Laboratory of Optics of Palacký University and Institute of Physics of the Czech Academy of Sciences, 17. listopadu 1192/12, 779 00 Olomouc, Czech Republic
- <sup>118</sup> Finnish Centre for Astronomy with ESO, University of Turku, Finland, FI-20014 University of Turku, Finland
- <sup>119</sup> Josip Juraj Strossmayer University of Osijek, Trg Ljudevita Gaja 6, 31000 Osijek, Croatia
- <sup>120</sup> Gran Sasso Science Institute (GSSI), Viale Francesco Crispi 7, 67100 L'Aquila, Italy and INFN-Laboratori Nazionali del Gran Sasso (LNGS), via G. Acitelli 22, 67100 Assergi (AQ), Italy
- <sup>121</sup> Dipartimento di Scienze Fisiche e Chimiche, Università degli Studi dell'Aquila and GSGC-LNGS-INFN, Via Vetoio 1, L'Aquila, 67100, Italy
- <sup>122</sup> Faculty of Physics and Applied Computer Science, University of Łódź, ul. Pomorska 149-153, 90-236 Łódź, Poland
- <sup>123</sup> Astronomical Observatory, Jagiellonian University, ul. Orla 171, 30-244 Cracow, Poland
- <sup>124</sup> Landessternwarte, Zentrum für Astronomie der Universität Heidelberg, Königstuhl 12, 69117 Heidelberg, Germany
- <sup>125</sup> Univ. Grenoble Alpes, CNRS, IPAG, 414 rue de la Piscine, Domaine Universitaire, 38041 Grenoble Cedex 9, France

- <sup>126</sup> Astronomical Institute of the Czech Academy of Sciences, Bocni II 1401 - 14100 Prague, Czech Republic
- <sup>127</sup> Department of Physics and Astronomy, University of Utah, Salt Lake City, UT 84112-0830, USA
- <sup>128</sup> Nicolaus Copernicus Astronomical Center, Polish Academy of Sciences, ul. Bartycka 18, 00-716 Warsaw, Poland
- <sup>129</sup> Institute of Particle and Nuclear Studies, KEK (High Energy Accelerator Research Organization), 1-1 Oho, Tsukuba, 305-0801, Japan
- <sup>130</sup> School of Physics and Astronomy, University of Leicester, Leicester, LE1 7RH, United Kingdom
- <sup>131</sup> Western Sydney University, Locked Bag 1797, Penrith, NSW 2751, Australia
- <sup>132</sup> Université Bordeaux, CNRS, LP2I Bordeaux, UMR 5797, 19 Chemin du Solarium, F-33170 Gradignan, France
- <sup>133</sup> INFN Sezione di Trieste and Università degli Studi di Trieste, Via Valerio 2 I, 34127 Trieste, Italy
- <sup>134</sup> Instituto de Astrofísica de Canarias and Departamento de Astrofísica, Universidad de La Laguna, La Laguna, Tenerife, Spain
- <sup>135</sup> Escuela Politécnica Superior de Jaén, Universidad de Jaén, Campus Las Lagunillas s/n, Edif. A3, 23071 Jaén, Spain
- <sup>136</sup> Anton Pannekoek Institute/GRAPPA, University of Amsterdam, Science Park 904 1098 XH Amsterdam, The Netherlands
- <sup>137</sup> Saha Institute of Nuclear Physics, A CI of Homi Bhabha National Institute, Kolkata 700064, West Bengal, India
- <sup>138</sup> Università degli studi di Catania, Dipartimento di Fisica e Astronomia “Ettore Majorana”, Via S. Sofia 64, 95123 Catania, Italy
- <sup>139</sup> Dipartimento di Fisica e Chimica “E. Segrè”, Università degli Studi di Palermo, Via Archirafi 36, 90123, Palermo, Italy
- <sup>140</sup> UCM-ELEC group, EMFTEL Department, University Complutense of Madrid, 28040 Madrid, Spain
- <sup>141</sup> Departamento de Ingeniería Eléctrica, Universidad Pontificia de Comillas - ICAI, 28015 Madrid
- <sup>142</sup> Universidad de Chile, Av. Libertador Bernardo O’Higgins 1058, Santiago, Chile
- <sup>143</sup> 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 Cerdanyola del Vallés, Spain
- <sup>144</sup> The Henryk Niewodniczański Institute of Nuclear Physics, Polish Academy of Sciences, ul. Radzikowskiego 152, 31-342 Cracow, Poland
- <sup>145</sup> IPARCOS Institute, Faculty of Physics (UCM), 28040 Madrid, Spain
- <sup>146</sup> Department of Physics, Konan University, Kobe, Hyogo, 658-8501, Japan
- <sup>147</sup> Hiroshima Astrophysical Science Center, Hiroshima University, Higashi-Hiroshima, Hiroshima 739-8526, Japan
- <sup>148</sup> Department of Physics, Columbia University, 538 West 120th Street, New York, NY 10027, USA
- <sup>149</sup> School of Allied Health Sciences, Kitasato University, Sagamihara, Kanagawa 228-8555, Japan
- <sup>150</sup> Kavli Institute for Particle Astrophysics and Cosmology, Stanford University, Stanford, CA 94305, USA
- <sup>151</sup> University of Białystok, Faculty of Physics, ul. K. Ciołkowskiego 1L, 15-245 Białystok, Poland
- <sup>152</sup> Charles University, Institute of Particle & Nuclear Physics, V Holešovičkách 2, 180 00 Prague 8, Czech Republic
- <sup>153</sup> Astronomical Observatory of Ivan Franko National University of Lviv, 8 Kyryla i Mephodia Street, Lviv, 79005, Ukraine
- <sup>154</sup> Institute for Space—Earth Environmental Research, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8601, Japan
- <sup>155</sup> Kobayashi—Maskawa Institute for the Origin of Particles and the Universe, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8602, Japan
- <sup>156</sup> INAF - Osservatorio Astronomico di Palermo “G.S. Vaiana”, Piazza del Parlamento 1, 90134 Palermo, Italy



- <sup>157</sup> Department of Physics and Astronomy, University of California, Los Angeles, CA 90095, USA
- <sup>158</sup> Graduate School of Technology, Industrial and Social Sciences, Tokushima University, Tokushima 770-8506, Japan
- <sup>159</sup> School of Physics & Center for Relativistic Astrophysics, Georgia Institute of Technology, 837 State Street, Atlanta, Georgia, 30332-0430, USA
- <sup>160</sup> University of Pisa, Largo B. Pontecorvo 3, 56127 Pisa, Italy
- <sup>161</sup> University of Rijeka, Faculty of Physics, Radmile Matejčić 2, 51000 Rijeka, Croatia
- <sup>162</sup> Rudjer Boskovic Institute, Bijenicka 54, 10 000 Zagreb, Croatia
- <sup>163</sup> INAF - Osservatorio Astronomico di Padova, Vicolo dell'Osservatorio 5, 35122 Padova, Italy
- <sup>164</sup> INAF - Osservatorio Astronomico di Padova and INFN Sezione di Trieste, gr. coll. Udine, Via delle Scienze 208 I-33100 Udine, Italy
- <sup>165</sup> 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
- <sup>166</sup> Centre for Astro-Particle Physics (CAPP) and Department of Physics, University of Johannesburg, PO Box 524, Auckland Park 2006, South Africa
- <sup>167</sup> University of Oxford, Department of Physics, Clarendon Laboratory, Parks Road, Oxford, OX1 3PU, United Kingdom
- <sup>168</sup> Departamento de Física, Facultad de Ciencias Básicas, Universidad Metropolitana de Ciencias de la Educación, Avenida José Pedro Alessandri 774, Ñuñoa, Santiago, Chile
- <sup>169</sup> Departamento de Astronomía, Universidad de Concepción, Barrio Universitario S/N, Concepción, Chile
- <sup>170</sup> University of New South Wales, School of Science, Australian Defence Force Academy, Canberra, ACT 2600, Australia
- <sup>171</sup> University of Split - FESB, R. Boskovicica 32, 21 000 Split, Croatia
- <sup>172</sup> EPFL Laboratoire d'astrophysique, Observatoire de Sauverny, CH-1290 Versoix, Switzerland
- <sup>173</sup> Department of Physics, Humboldt University Berlin, Newtonstr. 15, 12489 Berlin, Germany
- <sup>174</sup> Main Astronomical Observatory of the National Academy of Sciences of Ukraine, Zabolotnoho str., 27, 03143, Kyiv, Ukraine
- <sup>175</sup> Space Technology Centre, AGH University of Science and Technology, Aleja Mickiewicza, 30, 30-059, Kraków, Poland
- <sup>176</sup> Academic Computer Centre CYFRONET AGH, ul. Nawojki 11, 30-950, Kraków, Poland
- <sup>177</sup> Institute of Astronomy, Faculty of Physics, Astronomy and Informatics, Nicolaus Copernicus University in Toruń, ul. Grudziądzka 5, 87-100 Toruń, Poland
- <sup>178</sup> Cherenkov Telescope Array Observatory gGmbH, Via Gobetti, Bologna, Italy
- <sup>179</sup> Warsaw University of Technology, Faculty of Electronics and Information Technology, Institute of Electronic Systems, Nowowiejska 15/19, 00-665 Warsaw, Poland
- <sup>180</sup> Physics Program, Graduate School of Advanced Science and Engineering, Hiroshima University, 739-8526 Hiroshima, Japan
- <sup>181</sup> School of Physics and Astronomy, Sun Yat-sen University, Zhuhai, China
- <sup>182</sup> Department of Physical Sciences, Aoyama Gakuin University, Fuchinobe, Sagami-hara, Kanagawa, 252-5258, Japan
- <sup>183</sup> Division of Physics and Astronomy, Graduate School of Science, Kyoto University, Sakyo-ku, Kyoto, 606-8502, Japan
- <sup>184</sup> Port d'Informació Científica, Edifici D, Carrer de l'Albareda, 08193 Bellaterra (Cerdanyola del Vallès), Spain
- <sup>185</sup> INAF - Osservatorio Astrofisico di Torino, Strada Osservatorio 20, 10025 Pino Torinese (TO), Italy
- <sup>186</sup> Departamento de Física, Universidad Técnica Federico Santa María, Avenida España, 1680 Valparaíso, Chile
- <sup>187</sup> Faculty of Science, Ibaraki University, Mito, Ibaraki, 310-8512, Japan