


Sensitivity of the Cherenkov Telescope Array to the gamma-ray emission from neutrino sources detected by IceCube

Conference Paper**Author(s):**

Sergijenko, Olga; Brown, Anthony M.; Fiorillo, Damiano; de León, Alberto Rosales; Satalecka, Konstancja; Tung, Chun Fai; Taboada, Ignacio; CTA Consortium; Abe, Kazuki; [Biland, Adrian](#) ; Dorner, Daniela; Fukami, Satoshi; Schleicher, Bernd; et al.; FIRESONG Team

Publication date:

2023

Permanent link:

<https://doi.org/10.3929/ethz-b-000653281>

Rights / license:

[Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International](#)

Originally published in:

PoS: Proceedings of Science 444, <https://doi.org/10.22323/1.444.1531>

Sensitivity of the Cherenkov Telescope Array to the gamma-ray emission from neutrino sources detected by IceCube

Olga Sergijenko,^{a,*} Anthony M. Brown,^b Damiano Fiorillo,^c Alberto Rosales de León,^d Konstancja Satalecka,^e Chun Fai Tung,^f and Ignacio Taboada^f for the CTA Consortium and FIRESONG Team

^a*Astronomical Observatory, Taras Shevchenko National University of Kyiv, Ukraine; Main Astronomical Observatory of the National Academy of Sciences of Ukraine, Kyiv, Ukraine; AGH University of Science and Technology, Krakow, Poland*

^b*Centre for Advanced Instrumentation (CfAI), Department of Physics, University of Durham, UK*

^c*Niels Bohr International Academy, Niels Bohr Institute, University of Copenhagen, Denmark*

^d*LPNHE & LUTH, Paris, France*

^e*Finnish Centre of Astronomy with ESO (FINCA), University of Turku, Finland*

^f*School of Physics and Center for Relativistic Astrophysics, Georgia Institute of Technology, Atlanta, GA, USA*

E-mail: olga.sergijenko.astro@gmail.com, anthony.brown@durham.ac.uk, damiano.fiorillo@nbi.ku.dk, arosales@lpnhe.in2p3.fr, kmsata@utu.fi, christung616@gmail.com, itaboada@gatech.edu

Gamma-ray observations of the astrophysical neutrino sources are fundamentally important for understanding the underlying neutrino production mechanism. We investigate the Cherenkov Telescope Array (CTA) ability to detect the very-high-energy (VHE) gamma-ray counterparts to the neutrino-emitting Active Galaxies. The CTA performance under different configurations and array layouts is computed based on the neutrino and gamma-ray simulations of steady and transient types of sources, assuming that the neutrino events are detected with the IceCube neutrino telescope. The CTA detection probability is calculated for both CTA sites taking into account the visibility constraints. We find that, under optimal observing conditions, CTA could observe the VHE gamma-ray emission from at least 3 neutrino events per year.

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



*Speaker

1. Introduction

Astrophysical sources capable of hadronic acceleration to relativistic energies are the potential sources of astrophysical neutrinos. Unlike photons, neutrinos are able to travel through dense astrophysical environments and over cosmological distances without the Extragalactic Background Light (EBL) absorption to provide unambiguous tracers of hadronic acceleration.

In 2013 the IceCube Neutrino Observatory reported the presence of an all-sky, isotropic, high-energy neutrino flux of extraterrestrial origin [1]. The sources responsible for the measured astrophysical neutrino flux and their identification are topics still under discussion.

In April 2016 IceCube initiated the real-time alert program [2], in which neutrino events that are likely to be of astrophysical origin are reported via the General Coordinates Network (GCN; <https://gcn.nasa.gov>). The updated alert system was introduced on June 17, 2019 [3]. All alerts are now classified depending on the likelihood of being from astrophysical origin. For the *Gold* alerts the probability is at least 50% *signalness* and an expected incident rate is about 10 events per year, while for *Bronze* alerts it is 30% with around 20 additional expected events per year.

All the major operating Imaging Atmospheric Cherenkov Telescopes (IACTs) have implemented follow-up observation programs to search for VHE ($E > 100$ GeV) gamma-ray emission associated with IceCube neutrino alerts.

The Cherenkov Telescope Array (CTA; [4]) will be the next generation ground-based IACT facility. With an array located in each hemisphere, CTA will provide gamma-ray observations from around 20 GeV up to 300 TeV with an unprecedented sensitivity, angular and energy resolution. The Northern array (CTA-N) will be located at Roque de los Muchachos Observatory on the island of La Palma, Spain; while the Southern array (CTA-S) will be located at the Paranal Observatory in the Atacama desert of Chile. CTA-N will operate in the energy range of 20 GeV to 50 TeV, while CTA-S will concentrate on Galactic targets and will operate in the energy range between 20 GeV and 300 TeV.

To achieve the performance goals, CTA will consist of 3 telescope types, each one optimised for a specific energy range. The Large-Sized Telescopes (LSTs) will be sensitive to the faint low-energy showers (below 200 GeV). The Medium-Sized Telescopes (MSTs) will operate in the core energy range of the array (between 100 GeV and 10 TeV). The Schwarzschild-Couder Telescope (SCT) is also being developed to work in the same energy range as the MSTs. The Small-Sized Telescopes (SSTs) are planned to be deployed only in South and cover the highest part of CTA energy range.

CTA telescopes are designed to rapidly re-position to any location in the sky: the LSTs can re-position to anywhere in the sky above the elevation of 30° in less than 30 seconds.

We present the results of simulations of the CTA Neutrino Target of Opportunity (NToO) program. The CTA performance under different configurations is computed based on neutrino and gamma-ray simulations of steady and transient types of sources. The CTA detection probability is calculated for both CTA sites taking into account visibility constraints and assuming an optimistic observation scenario.

2. IceCube and FIRESONG

2.1 IceCube

IceCube is the $> \text{TeV}$ neutrino telescope operating at the South Pole [5]. It has observed the all-sky, all-flavor flux of neutrinos, compatible with the isotropic emission hypothesis. The isotropy is usually interpreted as being extragalactic in origin, an assumption that we make here.

We investigate 2 cases. First, we use the all-sky neutrino flux to determine the joint IceCube-CTA detectability of steady neutrino sources. Secondly, we consider the population of neutrino flaring blazars, using TXS 0506+056 as an example.

For the first case we follow the study of astrophysical muon neutrinos with 8 years of IceCube data which describes their spectrum as a power-law in energy [6]. The sensitivity to point sources with a matching spectral index has only been published for a spectral index of -2.19 [7].

The second case is based on the evidence of neutrino emission from the blazar TXS 0506+056 first reported as an outcome of the IceCube real-time alert program. On September 22, 2017 the event IceCube-170922A with energy of 290 TeV and probability of astrophysical origin 0.565 was detected and triggered a large number of multi-wavelength observations. Both *Fermi*-LAT and MAGIC found that the spatially coincident blazar TXS 0506+056 was flaring in gamma rays at that time. The accidental coincidence was ruled out with 3σ confidence [8]. Archival study of IceCube data in the direction of TXS 0506+056 revealed an additional ~ 110 day neutrino flare from October 2014 to March 2015 [9]. In *Fermi*-LAT, there is no evidence for a gamma-ray flare [10] during the 2014-2015 period.

It remains unclear whether all gamma-ray bright blazars are neutrino sources, furthermore they cannot be responsible for most of the astrophysical neutrino flux [11].

2.2 FIRESONG

FIRESONG [12] is the code that enables the simulation of neutrino source populations with detailed calculation that includes Λ CDM cosmology, chosen source evolution, arbitrary luminosity functions, arbitrary neutrino spectra, flexibility in saturating or not the astrophysical neutrino all-sky flux, etc. FIRESONG can simulate both steady or transient/flaring populations.

The luminosity function and evolution of neutrino sources are not known. Following [13] we parameterize the populations of neutrino sources by a characteristic luminosity and an effective local density and assume a standard candle luminosity. We explore both *no evolution* and SFR evolution following [14]. We adopt the Λ CDM parameters reported by Planck in 2015 [15] to set up the simulations of FIRESONG: $\Omega_{M_0} = 0.308$, $\Omega_{\Lambda_0} = 0.692$ and $h = 0.678$.

2.2.1 Steady sources

We have simulated the standard candle neutrino sources with local densities between 10^{-5} Mpc^{-3} and $10^{-12} \text{ Mpc}^{-3}$ for the SFR evolution scenario and between 10^{-6} Mpc^{-3} and $10^{-12} \text{ Mpc}^{-3}$ for the no evolution scenario. The luminosity is in the range between over-saturating the all-sky neutrino flux by one-to-two orders of magnitude and under-saturating it by one order of magnitude ($10^{50} < L_\nu < 10^{57} \text{ erg/yr}$).

2.2.2 Flaring sources

To test the joint sensitivity of IceCube and CTA to saturation of the diffuse flux by neutrino flares we consider the model of [16], in which the diffuse neutrino flux is saturated by a special class of blazars producing neutrino flares similar to TXS 0506+056. Assuming these neutrino-flaring blazars show the same redshift distribution as all blazars, we approximate their ρ_o as fractions (10%, 5%, 1%) of the local blazar density. For the value of local blazar density from [17] these fractions are converted to ρ_o of 1.5×10^{-9} , 7.5×10^{-10} and 1.5×10^{-10} Mpc $^{-3}$ respectively. We assume that they have the same flare duration in the source frame and use the best-fit flare duration of TXS 0506+056, which was 110 days in the Earth frame [9] which translates to 82 days in the source frame.

We have used FIRESONG to simulate the distribution of neutrino-flaring blazars for each value of ρ_o , assuming one year of operation and flat cosmological evolution. The neutrino fluxes from the flares have been normalized by matching the sum of their time-integrated flux to the time-integrated diffuse neutrino flux from [7]. To estimate the number of IceCube realtime alert events from each flare we used the *Gold* events effective areas from [3]. Only sources producing one or more such events have been considered for further simulations of CTA observations.

3. Simulation of CTA observations

To simulate the CTA follow-up observations of the neutrino sources we used the `ctools` and `gammalib` packages [18]. Each simulated neutrino source is characterised by a redshift (z), a spectrum normalisation (A_ν) and a declination (δ). The right ascension (α) is assigned randomly. For calculation of the gamma-ray flux emitted together with neutrinos in the steady source scenario we assume that they could be produced in proton interactions with the surrounding photon ($p\gamma$ interactions). The secondary pions and other particles decay to neutrinos or gamma rays and in the simplest case the relation between the gamma ray and neutrino production rates is:

$$\frac{1}{3} \sum_{\alpha} E_\nu^2 A_{\nu,\alpha}(E_\nu) = \frac{K_\pi}{4} E_\gamma^2 A_\gamma(E_\gamma) \quad (1)$$

where $E_\gamma = 2E_\nu$ and K_π is a factor which accounts for the ratio of charged to neutral pions: $K_\pi = 1$ for $p\gamma$ interactions [19]. We do not consider any additional absorption or cascading of gamma rays inside the source.

For the neutrino flaring blazars simulations we adopt the phenomenological model of [16] describing the gamma-ray emission during the 2014-2015 neutrino flare of TXS-0506+056. This model includes the absorption of gamma rays in the source. The gamma-ray spectrum is given by:

$$\frac{dN_\gamma}{dE} = A_\nu E^{-2} e^{-E_L/E - E/E_H}, \quad (2)$$

where A_ν is a neutrino flux normalisation, and E_L and E_H are the low and high energy cutoffs respectively. For the simulated sources located at different redshifts the values of these parameters were scaled accordingly from the ones given in [16] for the blazar TXS 0506+056: $z=0.335$, $E_L = 0.1$ TeV, $E_H = 20$ TeV.

To account for the gamma-ray flux attenuation during their propagation we used the EBL model of [20] in all of our simulations.

We test the performance of CTA with the `prod3b-v2` CTA Instrument Response Functions (IRFs) for the Omega configuration and `prod5-v0.1`.

Using `ctobssim` for each source we simulated photon events lists, arriving within 30 min of observations and the Region of Interest (RoI) of 5° centered at the source coordinates. Then, we employed `ctlike` to perform a maximum likelihood fitting to the unbinned data. A source was considered detected if the Test Statistic (TS) value was equal or higher than 25.

The Omega configuration corresponds to the final CTA arrays configuration: 4 LSTs and 15 MSTs for CTA-N and 4 LSTs, 25 MSTs and 70 SSTs for CTA-S [4]. The IRF set contains 3 zenith angle observation options at 20° , 40° and 60° , assumed to be valid in the following zenith bins: $[0^\circ, 33^\circ]$, $[33^\circ, 54^\circ]$, and $[54^\circ, 66^\circ]$ respectively. It also accounts for the azimuth dependence coming from the geomagnetic field configurations at each site (depending on the pointing direction: North, South or an average over the azimuth direction). All site, zenith and azimuth combinations total to 18 IRFs.

The Alpha configuration is the initial configuration of CTA arrays to be built with the lower number of operational telescopes (consisting of 15 MSTs and 50 SSTs for CTA-S and 4 LSTs and 5 MSTs for CTA-N). The Alpha configuration IRFs have the same zenith angles and azimuth pointing direction combinations as the Omega ones.

4. Results

4.1 Steady neutrino sources

As steady neutrino sources we consider the “*hot-spots*” emerging in the time-integrated IceCube sky map with the flux equal or higher than the 5σ discovery potential (pre-trial). Assuming that their neutrino and γ -ray emission is constant in time, the observations with CTA do not have to be performed immediately after their detection. In the most optimistic case, the data was taken under the optimal conditions: the lowest zenith angle (achieved at the source culmination, hence the azimuth direction – North or South – is defined automatically) and dark night. These assumptions allow us to assign the “best” IRF for each source, count how many sources were detected in those optimal conditions and derive the detection probability for each type of cosmological evolution and array separately.

Our results (Fig. 1) show that in the low-to-mid-luminosity range the discovery potential of joint IceCube and CTA Omega observations is limited by the IceCube capabilities. All hot-spots visible to CTA down to density 10^{-9} Mpc^{-3} would be detected. On the other hand, in the low density-high luminosity regime, where the sources are located at large redshifts ($z > 1$), the EBL absorption impedes CTA detection probability reaching 100%. This trend is more pronounced for the flat redshift evolution.

The comparison of the Omega and Alpha arrays performance revealed almost no impact for CTA-N, independent of the assumed source evolution. On the other hand, CTA-S Alpha array shows a dramatic performance loss due to the absence of LSTs. Therefore, whenever possible we recommend observations with the CTA-N Alpha array, unless the source is located at a low redshift ($z < 0.1$) and visible for CTA-S at low zenith angles.

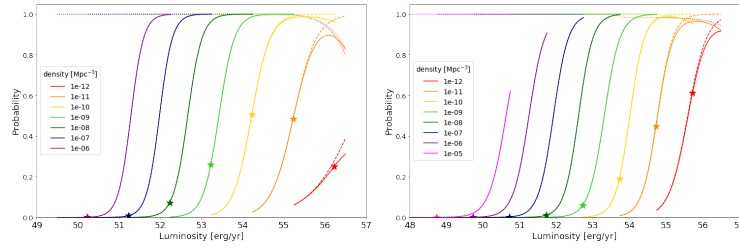


Figure 1: Detection probability as a function of source luminosity (L_ν) for sources following the flat redshift evolution (left) and the SFR evolution (right) for 30 min observations with CTA-N Omega, including visibility constraints. The colored lines represent different local densities (ρ_o) from 10^{-12} to 10^{-5} Mpc^{-3} . Dashed lines show the IceCube detection probability, dotted lines – the CTA detection probability and solid lines – the combined one. The stars mark the source populations saturating the neutrino diffuse flux, as measured by IceCube [6].

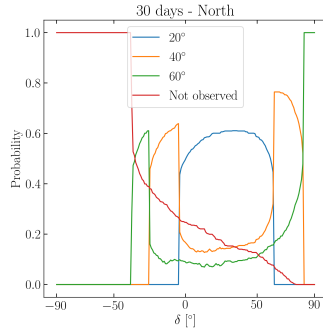


Figure 2: Probability of observation of the alert at CTA-N Omega in different zenith bins as a function of the alert declination.

4.2 Neutrino flaring blazars

For the blazar flares an additional feature to account for is the transient nature of the source. The follow-up strategy of present IACTs involves either immediate observation of the source, if it is visible, or at most observation a few days after the alert. However, as emphasized in [21], the length of the 2014 - 2015 flare of TXS 0506+056 encourages one to take up a longer follow-up for transient sources. Therefore, we consider a maximum follow-up time T_{max} of about 30 days.

Within this time window we assume that the follow-up is performed at the time when the zenith angle of the alert is minimal, the center of the Sun is at least 18° below the horizon and the center of the Moon is 0.25° below the horizon. This choice maximizes the performances of the detector during the measurement.

We show this probability for all 3 zenith angle bins, as well as the complementary probability that the zenith angle is larger than 66° , in Fig. 2 for the case of CTA-N Omega. The wide range of declination angles are visible with CTA-N alone. The probability that observations cannot be performed at all is equal to 1 only for sources from the Southern hemisphere with declinations lower than about -45° and it rapidly decreases below 0.5 for sources with larger declinations. Similar results are obtained for CTA-S, which is most sensitive in the Southern hemisphere.

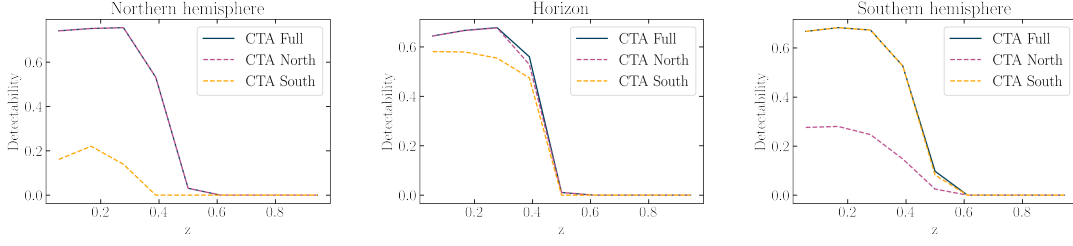


Figure 3: Fraction of detected alerts at CTA-N Alpha, CTA-S Alpha, and either of 2 arrays as a function of redshift for alerts originating from the Northern hemisphere, horizon and Southern hemisphere. The source number density is $1.5 \times 10^{-9} \text{ Mpc}^{-3}$.

Local source density (Mpc^{-3})	Fraction of detected alerts			Detected alert rate (yr^{-1})			Total alert rate (yr^{-1})
	North	Horizon	South	North	Horizon	South	
1.5×10^{-10}	0.32	0.28	0.28	0.61	2.17	0.57	3.35
7.5×10^{-10}	0.27	0.23	0.26	0.51	1.78	0.52	2.81
1.5×10^{-9}	0.22	0.18	0.22	0.42	1.38	0.45	2.25

Table 1: Fraction of alerts from different declination regions detected by CTA Alpha defined as the ratio between detected alerts and all *Gold* alerts, including the background ones. The last column is the rate of detected astrophysical alerts, obtained using the rate of non-background *Gold* alerts.

We also account for the possibility that the measurement is performed after the flare has ended. For a random initial alert time, the probability that the source is observed is

$$P_{\text{meas}}(z) = 1 - \frac{T_{\text{max}}}{2T'_{\text{flare}}(1+z)}, \quad (3)$$

where $T'_{\text{flare}} = 82$ days is flare duration in the source rest frame. We weight the result over 3 zenith bins using the probabilities shown in Fig. 2 for CTA-N to account for the alert visibility. The final result is the probability that an alert with a given declination and redshift is detected as a gamma-ray source at CTA (both CTA-N and CTA-S) for a random initial alert time.

In Fig. 3 we show the fraction of alerts detected by the CTA Alpha configuration as a function of redshift for 3 different regions of declination: Northern hemisphere ($\delta > 5^\circ$), horizon ($-30^\circ < \delta < 5^\circ$) and Southern hemisphere ($\delta < -30^\circ$). The detectability has a decrease for redshifts larger than about 0.5 which is mainly driven by the EBL absorption. As expected, in the Northern (Southern) hemisphere detection is mainly performed by CTA-N (CTA-S). At the horizon the performance of 2 arrays is comparable.

The fractions of detected alerts from all declination regions for the Alpha configuration of CTA are summarized in Table 1. We also show the total rate of detected astrophysical alerts, both separated for declination region and for the full sky (obtained using the rate of astrophysical alerts: 0.95 per year from the Northern hemisphere, 3.89 per year from the horizon, and 1 per year from the Southern hemisphere [3]). The probability of alert detection is smaller than for the Omega array by a few percent, but even in this case, a significant number of IceCube alerts are expected to be detected by CTA every year.

Acknowledgements

We gratefully acknowledge financial support from the agencies and organizations listed here: www.cta-observatory.org/consortium_acknowledgments. This research made use of ctools, a community-developed analysis package for Imaging Air Cherenkov Telescope data. ctools is based on GammaLib, a community-developed toolbox for the scientific analysis of astronomical gamma-ray data.

References

- [1] M. G. Aartsen *et al.*, *Science* **342**, 1242856 (2013), 1311.5238.
- [2] M. G. Aartsen *et al.*, *Astroparticle Physics* **92**, 30 (2017), 1612.06028.
- [3] IceCube, E. Blaufuss, T. Kintscher, L. Lu, and C. F. Tung, *PoS ICRC2019*, 1021 (2020), 1908.04884.
- [4] A. Acharyya *et al.*, *Astroparticle Physics* **111**, 35 (2019), 1904.01426.
- [5] M. G. Aartsen *et al.*, *Journal of Instrumentation* **12**, P03012 (2017), 1612.05093.
- [6] C. Haack and C. Wiebusch, *PoS ICRC2017*, 1005 (2017).
- [7] M. G. Aartsen *et al.*, *European Physical Journal C* **79**, 234 (2019), 1811.07979.
- [8] IceCube Collaboration *et al.*, *Science* **361**, eaat1378 (2018), 1807.08816.
- [9] IceCube, M. G. Aartsen *et al.*, *Science* **361**, 147 (2018), 1807.08794.
- [10] S. Garrappa *et al.*, *ApJ***880**, 103 (2019), 1901.10806.
- [11] M. G. Aartsen *et al.*, *ApJ***835**, 45 (2017), 1611.03874.
- [12] C. Tung *et al.*, *The Journal of Open Source Software* **6**, 3194 (2021).
- [13] K. Murase and E. Waxman, *Phys. Rev. D***94**, 103006 (2016), 1607.01601.
- [14] P. Madau and M. Dickinson, *Ann. Rev. Astron. Astrophys.***52**, 415 (2014), 1403.0007.
- [15] Planck Collaboration *et al.*, *A&A* **594**, A13 (2016).
- [16] F. Halzen, A. Kheirandish, T. Weisgarber, and S. P. Wakely, *Astrophys. J. Lett.* **874**, L9 (2019), 1811.07439.
- [17] P. Mertsch, M. Rameez, and I. Tamborra, *JCAP* **03**, 011 (2017), 1612.07311.
- [18] J. Knödseder *et al.*, *Astron. Astrophys.* **593**, A1 (2016), 1606.00393.
- [19] M. Ahlers and F. Halzen, *Progress in Particle and Nuclear Physics* **102**, 73 (2018), 1805.11112.
- [20] A. Domínguez *et al.*, *MNRAS***410**, 2556 (2011), 1007.1459.
- [21] D. F. G. Fiorillo, K. Satalecka, I. Taboada, and C. F. Tung, *Astrophys. J.* **917**, 70 (2021), 2105.14043.

The CTA Consortium

K. Abe¹, S. Abe², A. Acharyya³, R. Adam^{4,5}, A. Aguasca-Cabot⁶, I. Agudo⁷, J. Alfaro⁸, N. Alvarez-Crespo⁹, R. Alves Batista¹⁰, J.-P. Amans¹¹, E. Amato¹², F. Ambrosino¹³, E. O. Angüner¹⁴, L. A. Antonelli¹³, C. Aramo¹⁵, C. Arcaro¹⁶, L. Arrabito¹⁷, K. Asano², J. Aschersleben¹⁸, H. Ashkar⁵, L. Augusto Stuaní¹⁹, D. Baack²⁰, M. Backes^{21,22}, C. Balazs²³, M. Balbo²⁴, A. Baquero Larriva^{9,25}, V. Barbosa Martins²⁶, U. Barres de Almeida^{27,28}, J. A. Barrio⁹, D. Bastieri²⁹, P. I. Batista²⁶, I. Batkovic²⁹, R. Batzofin³⁰, J. Baxter², G. Beck³¹, J. Becker Tjus³², L. Beiske²⁰, D. Belardinelli³³, W. Benbow³⁴, E. Bernardini²⁹, J. Bernete Medrano³⁵, K. Bernlöhr³⁶, A. Berti³⁷, V. Beshley³⁸, P. Bhattacharjee³⁹, S. Bhattacharyya⁴⁰, B. Bi⁴¹, N. Biederbeck²⁰, A. Biland⁴², E. Bissaldi^{43,44}, O. Blanch⁴⁵, J. Blazek⁴⁶, C. Boisson¹¹, J. Bolmont⁴⁷, G. Bonnoli^{48,49}, P. Bordas⁶, Z. Bosnjak⁵⁰, F. Bradascio⁵¹, C. Braiding⁵², E. Bronzini⁵³, R. Brose⁵⁴, A. M. Brown⁵⁵, F. Brun⁵¹, G. Brunelli^{53,7}, A. Bulgarelli⁵³, I. Burelli⁵⁶, L. Burmistrov⁵⁷, M. Burton^{58,59}, T. Bylund⁶⁰, P. G. Calisse⁶¹, A. Campoy-Ordaz⁶², B. K. Cantlay^{63,64}, M. Capalbi⁶⁵, A. Caproni⁶⁶, R. Capuzzo-Dolcetta¹³, C. Carlile⁶⁷, S. Caroff³⁹, A. Carosi¹³, R. Carosi⁴⁹, M.-S. Carrasco⁶⁸, E. Cascone⁶⁹, F. Cassol⁶⁸, N. Castrejon⁷⁰, F. Catalani⁷¹, D. Cerasole⁷², M. Cerruti⁷³, S. Chaty⁷³, A. W. Chen³¹, M. Chernyakova⁷⁴, A. Chiavassa^{75,76}, J. Chudoba⁴⁶, C. H. Coimbra Araujo⁷⁷, V. Conforti⁵³, F. Conte³⁶, J. L. Contreras⁹, C. Cossou⁶⁰, A. Costa⁷⁸, H. Costantini⁶⁸, P. Cristofari¹¹, O. Cuevas⁷⁹, Z. Curtis-Ginsberg⁸⁰, G. D'Amico⁸¹, F. D'Ammando⁸², M. Dadina⁵³, M. Dalchenko⁵⁷, L. David²⁶, I. D. Davids²¹, F. Dazzi⁸³, A. De Angelis²⁹, M. de Bony de Lavergne⁶⁰, V. De Caprio⁶⁹, G. De Cesare⁵³, E. M. de Gouveia Dal Pino²⁸, B. De Lotto⁵⁶, M. De Lucia¹⁵, R. de Menezes^{75,76}, M. de Naurois⁵, E. de Ona Wilhelmi²⁶, N. De Simone²⁶, V. de Souza¹⁹, L. del Peral⁷⁰, M. V. del Valle²⁸, E. Delagnes⁸⁴, A. G. Delgado Giler^{19,18}, C. Delgado³⁵, M. Dell'aiera³⁹, R. Della Ceca⁴⁸, M. Della Valle⁶⁹, D. della Volpe⁵⁷, D. Depaoli³⁶, A. Dettlaff³⁷, T. Di Girolamo^{85,15}, A. Di Piano⁵³, F. Di Pierro⁷⁵, R. Di Tria⁷², L. Di Venere⁴⁴, C. Díaz-Bahamondes⁸, C. Dib⁸⁶, S. Diebold⁴¹, R. Dima²⁹, A. Dinesh⁹, A. Djannati-Atai⁷³, J. Djuvsland⁸¹, A. Domínguez⁹, R. M. Dominik²⁰, A. Donini¹³, D. Dorner^{87,42}, J. Dörner³², M. Doro²⁹, R. D. C. dos Anjos⁷⁷, J.-L. Dournaux¹¹, D. Dravins⁶⁷, C. Duangchan^{88,64}, C. Dubos⁸⁹, L. Ducci⁴¹, V. V. Dwarkadas⁹⁰, J. Ebr⁴⁶, C. Eckner^{39,91}, K. Egberts³⁰, S. Einecke⁵², D. Elsässer²⁰, G. Emery⁶⁸, M. Escobar Godoy⁹², J. Escudero⁷, P. Esposito^{93,94}, D. Falceta-Goncalves⁹⁵, V. Fallah Ramazani³², A. Faure¹⁷, E. Fedorova^{13,96}, S. Fegan⁵, K. Feijen⁷³, Q. Feng³⁴, G. Ferrand^{97,98}, F. Ferrarotto⁹⁹, E. Fiandrini¹⁰⁰, A. Fiasson³⁹, V. Fioretti⁵³, L. Foffano¹⁰¹, L. Font Guiteras⁶², G. Fontaine⁵, S. Fröse²⁰, S. Fukami⁴², Y. Fukui¹⁰², S. Funk⁸⁸, D. Gaggero⁴⁹, G. Galanti⁹⁴, G. Galaz⁸, Y. A. Gallant¹⁷, S. Galozzi¹³, V. Gammaldi¹⁰, C. Gasbarra³³, M. Gaug⁶², A. Ghalumyan¹⁰³, F. Gianotti⁵³, M. Giarrusso¹⁰⁴, N. Giglietto^{43,44}, F. Giordano⁷², A. Giuliani⁹⁴, J.-F. Glicenstein⁵¹, J. Glombitza⁸⁸, P. Goldoni¹⁰⁵, J. M. González¹⁰⁶, M. M. González¹⁰⁷, J. Goulart Coelho¹⁰⁸, J. Granot^{109,110}, D. Grasso⁴⁹, R. Grau⁴⁵, D. Green³⁷, J. G. Green³⁷, T. Greenshaw¹¹¹, G. Grolleron⁴⁷, J. Grube¹¹², O. Gueta²⁶, S. Gunji¹¹³, D. Hadasch², P. Hamal⁴⁶, W. Hanlon³⁴, S. Hara¹¹⁴, V. M. Harvey⁵², K. Hashiyama², T. Hassan³⁵, M. Heller⁵⁷, S. Hernández Cadena¹⁰⁷, J. Hie¹¹⁵, N. Hiroshima², B. Hnatyk⁹⁶, R. Hnatyk⁹⁶, D. Hoffmann⁶⁸, W. Hofmann³⁶, M. Holler¹¹⁶, D. Horan⁵, P. Horvath¹¹⁷, T. Hovatta¹¹⁸, D. Hrupec¹¹⁹, S. Hussain^{28,120}, M. Iarlori¹²¹, T. Inada², F. Incardona⁷⁸, Y. Inome², S. Inoue⁹⁸, F. Iocco^{85,15}, K. Ishio¹²², M. Jamrozny¹²³, P. Janecek⁴⁶, F. Jankowsky¹²⁴, C. Jarnot¹¹⁵, P. Jean¹¹⁵, I. Jiménez Martínez³⁵, W. Jin³, L. Jocou¹²⁵, C. Juramy-Gilles⁴⁷, J. Jurysek⁴⁶, O. Kalekin⁸⁸, D. Kantzas⁹¹, V. Karas¹²⁶, S. Kaufmann⁵⁵, D. Kerszberg⁴⁵, B. Khelifi⁷³, D. B. Kieda¹²⁷, T. Kleiner²⁶, W. Kluźniak¹²⁸, Y. Kobayashi², K. Kohri¹²⁹, N. Komin³¹, P. Kornecki¹¹, K. Kosack⁶⁰, H. Kubo², J. Kushida¹, A. La Barbera⁶⁵, N. La Palombara⁹⁴, M. Láinez⁹, A. Lamastra¹³, J. Lapington¹³⁰, S. Lazarević¹³¹, J. Lazendic-Galloway²³, S. Leach¹³⁰, M. Lemoine-Goumard¹³², J.-P. Lenain⁴⁷, G. Leto⁷⁸, F. Leuschner⁴¹, E. Lindfors¹¹⁸, M. Linhoff²⁰, I. Liodakis¹¹⁸, L. Loïc⁵¹, S. Lombardi¹³, F. Longo¹³³, R. López-Coto⁷, M. López-Moya⁹, A. López-Oramas¹³⁴, S. Loporchio^{43,44}, J. Lozano Bahilo⁷⁰, P. L. Luque-Escamilla¹³⁵, O. Macias¹³⁶, G. Maier²⁶, P. Majumdar¹³⁷, D. Malyshev⁴¹, D. Malyshev⁸⁸, D. Mandat⁴⁶, G. Manicò^{104,138}, P. Marinos⁵², S. Markoff¹³⁶, I. Márquez⁷, P. Marquez⁴⁵, G. Marsella^{139,104}, J. Martí¹³⁵, P. Martin¹¹⁵

G. A. Martínez³⁵ , M. Martínez⁴⁵, O. Martinez^{140,141} , C. Marty¹¹⁵, A. Mas-Aguilar⁹ , M. Mastropietro¹³ , G. Maurin³⁹, W. Max-Moerbeck¹⁴² , D. Mazin^{2,37}, D. Melkumyan²⁶, S. Menchiari^{12,49}, E. Mestre¹⁴³, J.-L. Meunier⁴⁷, D. M.-A. Meyer³⁰ , D. Miceli¹⁶ , M. Michailidis⁴¹, J. Michałowski¹⁴⁴, T. Miener⁹, J. M. Miranda^{140,145}, A. Mitchell⁸⁸ , M. Mizote¹⁴⁶, T. Mizuno¹⁴⁷, R. Moderski¹²⁸ , L. Mohrmann³⁶ , M. Molero¹³⁴ , C. Molfese⁸³ , E. Molina¹³⁴ , T. Montaruli⁵⁷, A. Moralejo⁴⁵, D. Morcuende^{9,7} , K. Morik²⁰ , A. Morselli³³ , E. Moulin⁵¹ , V. Moya Zamanillo⁹ , R. Mukherjee¹⁴⁸ , K. Munari⁷⁸, A. Muraczewski¹²⁸, H. Muraishi¹⁴⁹ , T. Nakamori¹¹³ , L. Nava⁴⁸ , A. Nayak⁵⁵, R. Nemmen^{28,150} , L. Nickel²⁰ , J. Niemiec¹⁴⁴ , D. Nieto⁹ , M. Nieves Rosillo¹³⁴ , M. Nikolajuk¹⁵¹ , K. Nishijima¹ , K. Noda² , D. Nosek¹⁵² , B. Novosyadlyj¹⁵³, V. Novotny¹⁵² , S. Nozaki³⁷ , P. O'Brien¹³⁰ , M. Ohishi² , Y. Ohtani² , A. Okumura^{154,155} , J.-F. Olive¹¹⁵, B. Olmi^{156,12}, R. A. Ong¹⁵⁷ , M. Orienti⁸² , R. Orito¹⁵⁸, M. Orlandini⁵³ , E. Orlando¹³³, M. Ostrowski¹²³ , N. Otte¹⁵⁹ , I. Oya⁶¹ , I. Pagano⁷⁸ , A. Pagliaro⁶⁵ , M. Palatiello⁵⁶, G. Panebianco⁵³ , J. M. Paredes⁶, N. Parmiggiani⁵³ , S. R. Patel⁸⁹ , B. Patricelli^{13,160} , D. Pavlović¹⁶¹, A. Pe'er³⁷ , M. Pech⁴⁶, M. Pecimotika^{161,162} , M. Peresano^{76,75} , J. Pérez-Romero^{10,40} , G. Peron⁷³, M. Persic^{163,164} , P.-O. Petrucci¹²⁵ , O. Petruk³⁸ , F. Pfeifle⁸⁷, F. Pintore⁶⁵ , G. Pirola³⁷, C. Pittori¹³ , C. Plard³⁹ , F. Podobnik¹⁶⁵ , M. Pohl^{30,26} , E. Pons³⁹ , E. Prandini²⁹ , J. Prast³⁹, G. Principe¹³³, C. Priyadarshi⁴⁵ , N. Produit²⁴ , D. Prokhorov¹³⁶, E. Pueschel²⁶ , G. Pühlhofer⁴¹, M. L. Pumo^{138,104}, M. Punch⁷³ , A. Quirrenbach¹²⁴, S. Rainò⁷² , N. Randazzo¹⁰⁴, R. Rando²⁹ , T. Ravel¹¹⁵, S. Razzaque^{166,110} , M. Regeard⁷³ , P. Reichherzer^{167,32} , A. Reimer¹¹⁶ , O. Reimer¹¹⁶ , A. Reisenegger^{8,168} , T. Reposeur¹³², B. Reville³⁶ , W. Rhode²⁰ , M. Ribó⁶ , T. Richtler¹⁶⁹, F. Rieger³⁶, E. Roache³⁴, G. Rodriguez Fernandez³³, M. D. Rodríguez Frías⁷⁰ , J. J. Rodríguez-Vázquez³⁵, P. Romano⁴⁸ , G. Romeo⁷⁸ , J. Rosado⁹, G. Rowell⁵² , B. Rudak¹²⁸, A. J. Ruiten¹⁷⁰ , C. B. Rulten⁵⁵ , F. Russo⁵³ , I. Sadeh²⁶, L. Saha³⁴ , T. Saito², S. Sakurai², H. Salzmann⁴¹, D. Sanchez³⁹, M. Sánchez-Conde¹⁰ , P. Sangiorgi⁶⁵ , H. Sano² , M. Santander³ , A. Santangelo⁴¹, R. Santos-Lima²⁸ , A. Sanuy⁶, T. Šarić¹⁷¹ , A. Sarkar²⁶ , S. Sarkar¹⁶⁷ , F. G. Saturni¹³ , V. Savchenko¹⁷² , A. Scherer⁸, P. Schipani⁶⁹ , B. Schleicher^{87,42}, P. Schovaneck⁴⁶, J. L. Schubert²⁰, F. Schussler⁵¹ , U. Schwanke¹⁷³ , G. Schwefer³⁶ , S. Scuderi⁹⁴ , M. Seglar Arroyo⁴⁵ , I. Seitzzahl¹⁷⁰ , O. Sergijenko^{96,174,175}, V. Sguera⁵³, R. Y. Shang¹⁵⁷, P. Sharma⁸⁹, G. D. S. SIDIBE⁸⁴, L. Sidoli⁹⁴ , H. Siejkowski¹⁷⁶ , C. Siqueira¹⁹ , P. Sizun⁸⁴ , V. Sliusar²⁴ , A. Slowikowska¹⁷⁷ , H. Sol¹¹, A. Specovius⁸⁸ , S. T. Spencer^{88,167} , D. Spiga⁴⁸ , A. Stamerra^{13,178} , S. Stanić⁴⁰ , T. Starecki¹⁷⁹ , R. Starling¹³⁰, C. Steppa³⁰, T. Stolarczyk⁶⁰, J. Strišković¹¹⁹, M. Strzys² , Y. Suda¹⁸⁰ , T. Suomijärvi⁸⁹ , D. Tak²⁶ , M. Takahashi¹⁵⁴, R. Takeishi² , P.-H. T. Tam^{2,181} , S. J. Tanaka¹⁸² , T. Tanaka¹⁴⁶ , K. Terauchi¹⁸³, V. Testa¹³ , L. Tibaldo¹¹⁵ , O. Tibolla⁵⁵, F. Torradeflot^{184,35} , D. F. Torres¹⁴³, E. Torresi⁵³ , N. Tothill¹³¹ , F. Toussenet⁴⁷, V. Touzard¹¹⁵, A. Tramacere²⁴ , P. Travnicek⁴⁶, G. Tripodo^{139,104}, S. Truzzi¹⁶⁵, A. Tsiahina¹¹⁵ , A. Tutone⁶⁵, M. Vacula^{117,46} , B. Vallage⁵¹ , P. Vallania^{75,185}, R. Vallés¹⁴³ , C. van Eldik⁸⁸ , J. van Scherpenberg³⁷ , J. Vandenbroucke⁸⁰, V. Vassiliev¹⁵⁷, P. Venault⁸⁴, S. Ventura¹⁶⁵, S. Vercellone⁴⁸ , G. Verna¹⁶⁵ , A. Viana¹⁹, N. Viaux¹⁸⁶, A. Vigliano⁵⁶, J. Vignatti⁸⁶ , C. F. Vigorito^{75,76} , V. Vitale³³, V. Vodeb⁴⁰, V. Voisin⁴⁷, S. Vorobiov⁴⁰ , G. Voutsinas⁵⁷, I. Vovk², V. Waeghebaert¹¹⁵, S. J. Wagner¹²⁴, R. Walter²⁴, M. Ward⁵⁵, M. Wechakama^{63,64} , R. White³⁶, A. Wierzcholska¹⁴⁴ , M. Will³⁷ , D. A. Williams⁹² , F. Wohlleben³⁶ , A. Wolter⁴⁸ , T. Yamamoto¹⁴⁶, R. Yamazaki¹⁸² , L. Yang^{166,181}, T. Yoshida¹⁸⁷, T. Yoshikoshi² , M. Zacharias^{124,22} , R. Zanmar Sanchez⁷⁸ , D. Zavrtnik⁴⁰ , M. Zavrtnik⁴⁰, A. A. Zdziarski¹²⁸, A. Zech¹¹ , V. I. Zhdanov⁹⁶ , K. Ziętarek¹²³, M. Živec⁴⁰, J. Zuriaga-Puig¹⁰ 

Affiliations

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

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

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

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

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

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