

Interpolation of Instrument Response Functions for the Cherenkov Telescope Array in the Context of `pyirf`

R. M. Dominik^{a,*}, M. Linhoff^a and J. Sitarek^b for the CTA Consortium

^a*TU Dortmund University, Department of Physics
Otto-Hahn-Straße 4a, D-44227, Germany*

^b*University of Lodz, Faculty of Physics and Applied Informatics
Pomorska 149/153, 90-236 Lodz, Poland*

*E-mail: rune.dominik@tu-dortmund.de, maximilian.linhoff@tu-dortmund.de,
jsitarek@uni.lodz.pl*

The Cherenkov Telescope Array (CTA) will be the next generation ground-based very-high-energy gamma-ray observatory, constituted by tens of Imaging Atmospheric Cherenkov Telescopes at two sites once its construction and commissioning are finished. Like its predecessors, CTA relies on Instrument Response Functions (IRFs) to relate the observed and reconstructed properties to the true ones of the primary gamma-ray photons. IRFs are needed for the proper reconstruction of spectral and spatial information of the observed sources and are thus among the data products issued to the observatory users. They are derived from Monte Carlo simulations, depend on observation conditions like the telescope pointing direction or the atmospheric transparency and can evolve with time as hardware ages or is replaced. Producing a complete set of IRFs from simulations for every observation taken is a time-consuming task and not feasible when releasing data products on short timescales. Consequently, interpolation techniques on simulated IRFs are investigated to quickly estimate IRFs for specific observation conditions. However, as some of the IRFs constituents are given as probability distributions, specialized methods are needed. This contribution summarizes and compares the feasibility of multiple approaches to interpolate IRF components in the context of the `pyirf` python software package and IRFs simulated for the Large-Sized Telescope prototype (LST-1). We will also give an overview of the current functionalities implemented in `pyirf`.

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



*Speaker

1. Introduction

Instrument Response Functions (IRFs) are crucial in analyzing data taken by Imaging Air Cherenkov Telescopes (IACTs) as they relate the reconstructed information and the true ones for incoming gamma rays. The first VHE gamma-ray observatory, the under construction Cherenkov Telescope Array Observatory (CTAO), will consist of tens of telescopes in two arrays located at the Northern and Southern Hemisphere [1]. As CTAO is designed to detect gamma rays with energies between 20 GeV and 300 TeV with unprecedented angular and energy resolution, it has stringent requirements on systematic uncertainties which are dominated by how well the derived IRFs reproduce the actual response of the telescopes. To manage this, extensive, time- and resource-consuming, Monte Carlo simulations will be needed to generate the data necessary for the computation of the final IRFs. In settings where time and resources are constrained, creating simulations tailored to each pointing position is infeasible. In these cases, IRF interpolation may offer a solution. In CTAO's software ecosystem, both IRF computation and interpolation are managed by the `pyirf` software package.

This proceeding aims to give a brief overview of the `pyirf` package with a focus on IRF interpolation in `pyirf`. For this, section 2 will give a more thorough introduction to IRFs and section 3 will introduce `pyirf` and its main interpolation functionalities. Results of these methods on IRFs will be shown in section 4 and section 5 will summarize this proceeding.

2. Instrument Response Functions

While IACT experiments employ advanced machine learning methods to reconstruct the observed air showers as-good-as-possible, the result always has a finite accuracy. Trying to estimate energy \hat{E} , origin as right ascension and declination $(\hat{\alpha}, \hat{\delta})$ and arrival time \hat{t} of a gamma-ray signal, deviations from the true values E, α and δ are inevitable and that some events are not recorded or successfully reconstructed at all. For most applications, the time measurement can be assumed to be precise so that $t = \hat{t}$ holds. In its most general form, an IRF R is the conditional probability relating the observed distribution of events $g(\hat{E}, \hat{\alpha}, \hat{\delta}, t)$ to the true gamma-ray signal arriving at Earth $f(E, \alpha, \delta, t)$ with a background $b(\hat{E}, \hat{\alpha}, \hat{\delta}, t)$ by

$$\underbrace{g(\hat{E}, \hat{\alpha}, \hat{\delta}, t)}_{\text{Observed distribution}} = \iiint \underbrace{R(\hat{E}, \hat{\alpha}, \hat{\delta}|E, \alpha, \delta, t)}_{\text{Instrument Response}} \cdot \underbrace{f(E, \alpha, \delta, t)}_{\text{True gamma-ray signal}} dE d\Omega dt + \underbrace{b(\hat{E}, \hat{\alpha}, \hat{\delta}, t)}_{\text{Background}} \quad (1)$$

with the solid angle differential $d\Omega = \sin \delta d\alpha d\delta$. Even when assuming a sufficiently correct knowledge of $b(\hat{E}, \hat{\alpha}, \hat{\delta}, t)$, the IRF is a six-dimensional, time-dependent quantity $R(\hat{E}, \hat{\alpha}, \hat{\delta}|E, \alpha, \delta, t)$. As IRFs are generated from Monte Carlo simulations, where after processing both the true and the reconstructed values are known, it is infeasible to generate the amount of events needed to compute R in this general form. Since it is nevertheless needed to solve (1) and, with it, correctly reconstruct spectral and spatial information, a dimension reduction by factorization

$$R(\hat{E}, \hat{\alpha}, \hat{\delta}|E, \alpha, \delta, t) = \underbrace{A_{\text{eff}}(E, \alpha, \delta, t)}_{\text{Effective Area}} \cdot \underbrace{M(\hat{E}|E, \alpha, \delta, t)}_{\text{Energy Migration}} \cdot \underbrace{\text{PSF}(\hat{\alpha}, \hat{\delta}|E, \alpha, \delta, t)}_{\text{Point Spread Function}} \quad (2)$$

is commonly applied and IRFs are expressed as parametrizations or discretized tables of these components. Thus, the

- Effective Area (AEFF), the combination of the experiment’s sensitive area and the probability of a gamma ray with some true properties to be present in the data as a gamma ray after all analysis steps,
- Energy Migration (EDISP), the conditional probability to reconstruct a gamma ray of some true properties with a certain energy \hat{E} and
- Point Spread Function (PSF), the conditional probability to reconstruct a gamma ray of some true properties at a certain origin $(\hat{\alpha}, \hat{\delta})$

constitute an IRF that is applicable to all analysis use-cases. Further simplifications can be made for the case of a point source, where events can be selected around the assumed point source position using potential \hat{E} -dependent radii. In this case, the full PSF is not needed and instead the effective area is reduced by the amount of non-selected events. The used radii are linked to the IRFs and must be stored along-side in so-called RAD_MAX-tables. All these components are usually assumed constant over some time window and further depend on observation conditions like telescope pointing or weather. As the telescope performance is not constant over the whole field of view (FoV), all components are typically computed in more than one bin of FoV offset.

Although the process of simulating sufficient events to compute IRFs is time and resource-consuming, it assures the best possible results. On the other hand, there are circumstances where IRFs are needed on short time scales for next-day or even real-time analyses. This might be the case when observing an unexpected, transient event, and a preliminary analysis is needed to alert other experiments for follow-up observations. Interpolation between IRFs, precomputed for some observation conditions, is a possible solution in these cases and, if sufficiently performant, the less resource intensive solution to IRF computation.

3. The `pyirf` Package

The open-source software package `pyirf` [2] is a python library to compute IRFs and, derived from them, sensitivities. It is developed on Github¹ and released to PyPI² and conda-forge³. While the main use case will lie within CTAO’s analysis framework, `pyirf` does not rely on specialized input formats but rather `astropy`’s `QTable` [3] and is thus, by design, usable with any IACT experiment. The internal representation of IRFs and, with this, `pyirf`’s output is, on the other hand, compatible with the *data formats for gamma-ray astronomy* (GADF) [4]. In the CTA software ecosystem, `pyirf` processes the so-called DL2 stage of gamma-ray Monte Carlo simulations containing reconstructed air-shower events generated by `ctapipe` [5] to obtain IRFs. With the initial DL2 data and observatory metadata, IRFs are issued to the scientific users of CTA as DL3 data and are ready for usage with CTA’s science tools like `gammapy` [6]. Alongside the computation of IRFs, `pyirf` also provides sensitivity and significance calculation and IRF interpolation, the focus of this proceeding.

¹<https://github.com/cta-observatory/pyirf>

²<https://pypi.org/project/pyirf>

³<https://anaconda.org/conda-forge/pyirf>

3.1 Interpolate IRFs from Existing IRFs

To interpolate IRFs and contrary to other `pyirf` functionalities, the user does not have to supply reconstructed shower events but computed IRFs on a grid in some observation parameters that influence the telescope performance and, therefore, the IRFs. One such choice might be a grid in zenith angular distance and the angle between the telescope pointing direction and the geomagnetic field. Both parameters influence shower development in the atmosphere. Currently, `pyirf` supports the interpolation of AEFF, EDISP, PSF and RAD_MAX quantities according to the GADF definitions and with that both full enclosure and point like IRFs.

While AEFF and RAD_MAX are simple, unconnected quantities, i.e., each bin holds a value that is not correlated to its neighboring bins, simple, e.g. linear, interpolation can be applied. Contrary, EDISP and PSF represent discretized probability density functions; therefore, both need specialized methods to maintain their internal consistency. Such methods have already been employed in high-energy particle physics, `pyirf` offers two, Quantile Interpolation [7, 8] and Moment Morphing [9].

In short summary, Quantile Interpolation utilizes that there exist points x_i where the template distribution's cumulative distribution functions (CDF) F_i give the same value $F_i(x_i) = y$. The target distribution's CDF is then constructed to also return this value at a linear interpolation of the x_i . However, to obtain this position, the template distribution's quantile functions are needed and ultimately interpolated. The second method, Moment Morphing, is based on a Taylor expansion on the parameter grid used to find suitable interpolation coefficients. These, in return, are used to construct a linear combination of the template distributions; the interpolated result. To do so correctly, it is necessary to account for the template distribution's varying mean and standard deviation by transforming them to common values first. Both methods need to be adapted to be usable with discretized distributions. For Quantile Interpolation, this includes the usage of empirical distribution functions and linear interpolation to obtain an estimate for the quantile functions. Moment Morphing needed approximating versions of mean and standard deviation computation and a look-up method to evaluate the template distributions at the transformed values.

While `pyirf`'s Quantile Interpolation can, in principle, be applied to arbitrary parameter grid dimensions if the function interpolating the quantiles is chosen appropriately, Moment Morphing is currently limited to one or two-dimensional grids as the computation of the interpolation coefficients is dimension-dependent. On the other hand, our adapted version of Moment Morphing offers the possibility to extrapolate beyond the parameter grid convex hull. For this, two methods are implemented for extrapolation: Nearest Simplex and Visible Edges Extrapolation. The first one extrapolates from the nearest triangular simplex as seen from a point outside the parameter grid, resulting in a non-continuous extrapolation function. This is solved by the second method, which computes extrapolations from all visible simplices, computing coefficients according to visible edges blending as discussed in [10] and then again using these coefficients in the Moment Morphing procedure to compute the actual estimation by combining all extrapolations. While a continuous extrapolation is desirable, we provide both methods to leave it to the user's discretion to utilize the additional assumptions needed for visible edges blending. For one-dimensional parameter grids, both methods are equivalent. The same holds for points outside two-dimensional grids where only one edge and thus triangular grid simplex is visible. In all cases, we advise caution, as

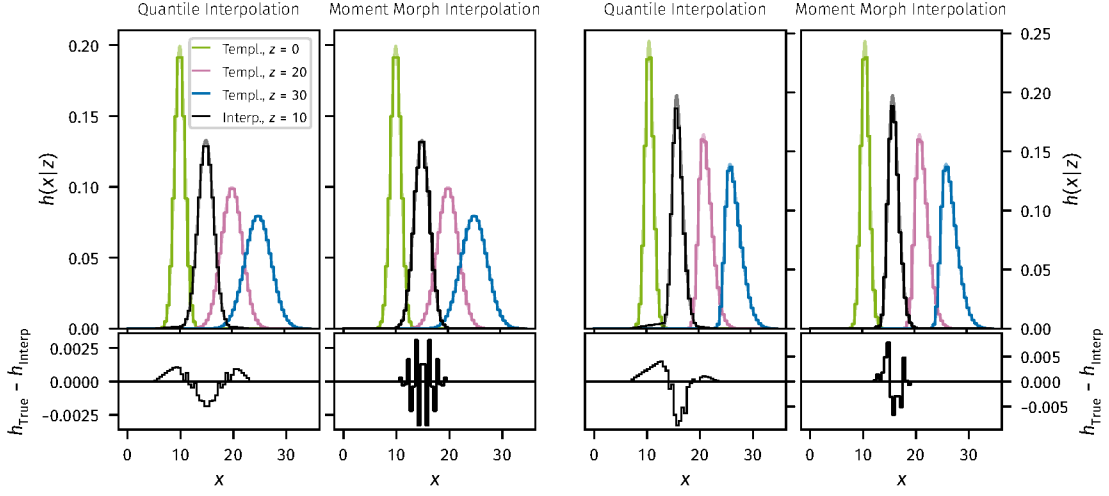


Figure 1: Interpolation algorithms applied to Gaussian (**left**) and skewed Gaussian (**right**) distributions whose parameters vary linearly with z . Three template histograms were created from the distribution’s CDFs and used to interpolate to the black distribution. True distributions are given as solid lines.

our extrapolation implementations are extensions of the Moment Morphing procedure that utilize negative interpolation coefficients. It is easily possible for bin entries to become negative and thus ill-defined when overlaying the template distributions with negative coefficients. While this effect is minor and, to some extent, accountable by cutting off affected bins for small extrapolation distances, high extrapolation distances result in meaningless estimations. Extrapolation should thus be avoided by extending the template distribution grid to include all desired target points. For convenience, we also provide dummy extrapolation using the nearest neighbor approach.

Quantile Interpolation and Moment Morphing have been applied to one-dimensional Gaussians and skewed Gaussians in Fig.1, performing well in this simple demonstration. However, skewed distributions seem harder to interpolate, which is easily explainable for Moment Morphing as it only accounts for first and second-order moments by design. The good performance holds for comparably small extrapolation distances, as shown in Fig.2. As expected, the result worsens with increased distance.

4. IRF Interpolation

In addition to the benchmark presented in the previous section, performance measures on actual IRFs were performed. To do so, we used a subset of an IRF grid produced for the Large-Sized Telescope prototype LST-1 [11]. As mentioned in section 3.1, the grid is produced in zenith distance θ and the angle between telescope pointing and the geomagnetic field δ_{mag} . This angle is not to be confused with the astronomical declination introduced in section 2, although they share a common symbol. To better reflect the physical development of an air shower, we use $\cos \theta$ (dependency of the atmosphere’s density profile and thus Cherenkov light absorption) and $\sin \delta_{\text{mag}}$ (measure of the geomagnetic field effect on the shower development). Other choices, especially for transformations of θ , are possible, e.g., $(\cos \theta)^{-1}$, to reflect the atmospheric depth along the shower’s line of sight.

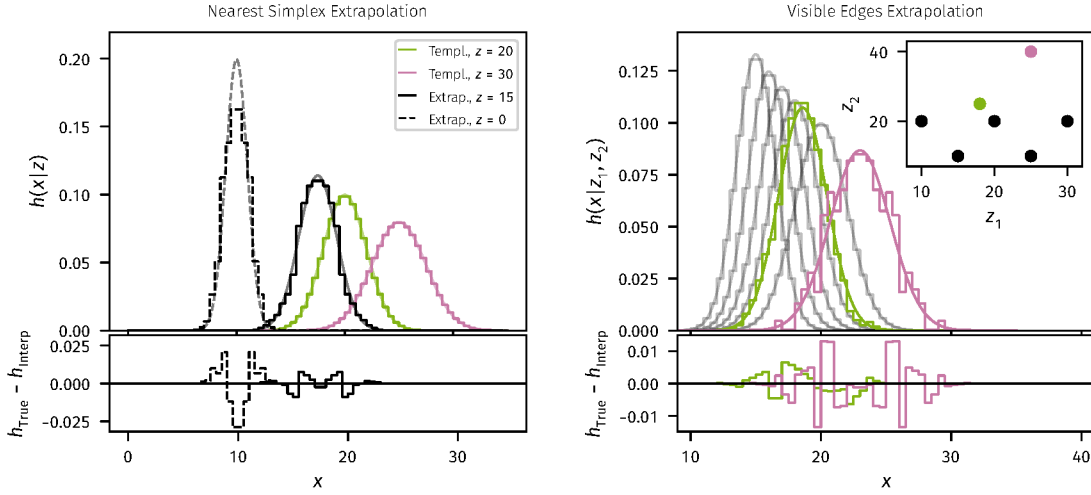


Figure 2: Extrapolation applied to Gaussian on a one- (**left**) and two-dimensional grid (**right**). Gaussian distributions whose parameters vary linearly with z and z_1 and z_2 , respectively. Two and five template histograms were created from the distribution's CDFs and used to extrapolate to the black distribution.

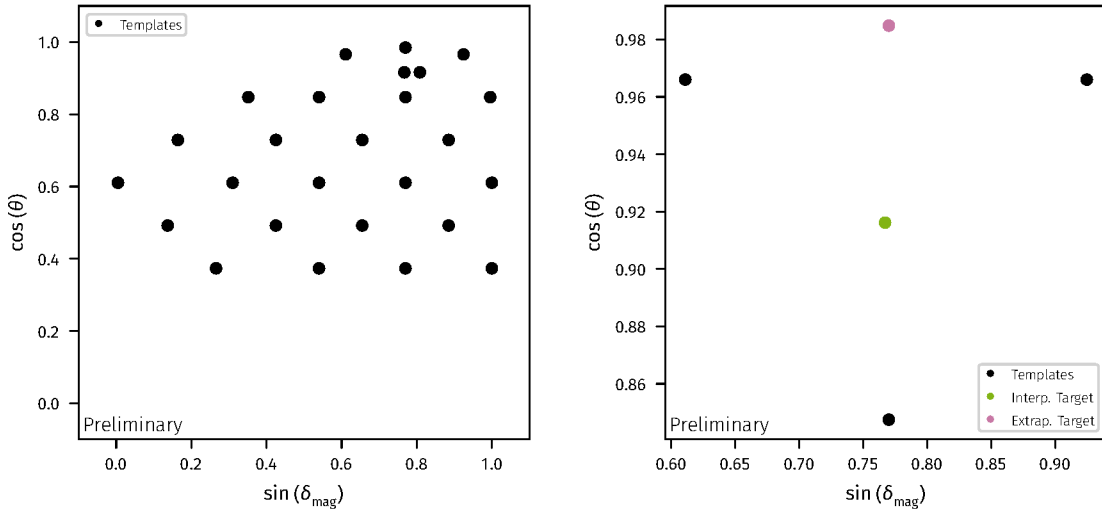


Figure 3: Full grid (**left**) of IRFs produced for LST-1 and the subset (**right**) selected to showcase both interpolation and extrapolation results.

The full grid and a selected part used for the following showcase are displayed in Fig. 3. Multiple grid nodes exist in this representation, where more than one Monte Carlo production has been made for different azimuth pointings. In these cases, the nodes closest to the target's azimuth pointing have been selected as interpolation templates.

Testing the interpolation on the selected subset of the full grid, we find good agreement between simulated and estimated energy dispersions, as shown in Fig. 4. The estimated results outperform a nearest-neighbor approach, especially for low- and high energies, and extrapolation, in this case, is feasible. It can be seen in the extrapolation case of Fig. 4 that the lowest true energy bin is

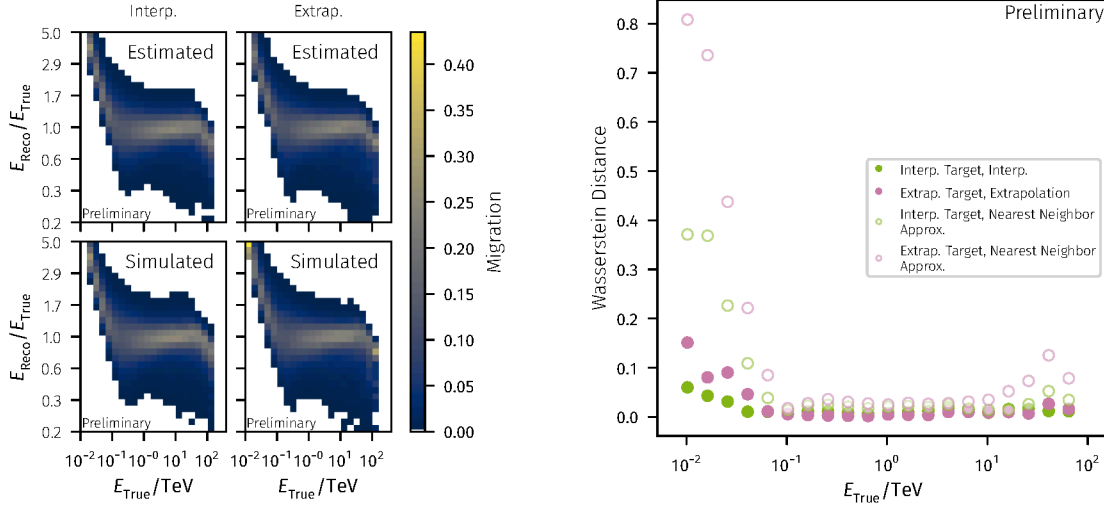


Figure 4: Inter- and Extrapolated energy dispersions (**left**) with corresponding Wasserstein distances (**right**). A simple next-neighbor interpolation was added for reference.

missing in the estimation. This occurs when one of the used templates has, due to a higher energy threshold, no corresponding IRF values derived in the respective bin. This is caused by an increasing zenith angle as the amount of atmosphere traversed by a gamma ray grows and thus the possibility for the primary particle to interact before reaching the telescope increases. Primary particles of these energies are thus less and less often detected until these energies are lost. Consequently, this problem is more frequent when high interpolation distances along the zenith angle are chosen. A densely populated grid thus minimizes the effect, although there will always be translations in the grid's parameter space where one bin becomes empty.

As for the estimation of AEFF and RAD_MAX tables (see Fig. 5), we find that especially effective areas are estimated with minor errors compared to the actual values. As with the energy dispersions, the lowest energy bin was missing in some templates and could not be computed. RAD_MAX tables, on the other hand, with errors in the order of 10%, perform worse than other components. We account this to the nature of producing these values, optimizing a cut-value instead of comparing simulated and reconstructed quantities. RAD_MAX tables thus violate the assumption of being dependent on the chosen set of grid parameters. It is, however, to be checked, if these interpolation results in a meaningful IRF at all as it is not guaranteed that AEFF and RAD_MAX values are matching afterwards.

5. Conclusion

In this proceeding, we have given a brief overview of *pyirf* and explicitly discussed the therein-provided IRF inter- and extrapolation methods. We have shown IRF inter- and extrapolation to be usable with toy data sets and actual IRFs. Especially for quantities independent from any user optimization, like effective area and energy dispersion, the generated IRFs are reasonable estimations of the truth and outperform simple, next-neighbor approaches. Errors are minor but present, especially in low- or high-energy bins, and increase with inter- or extrapolation distance.

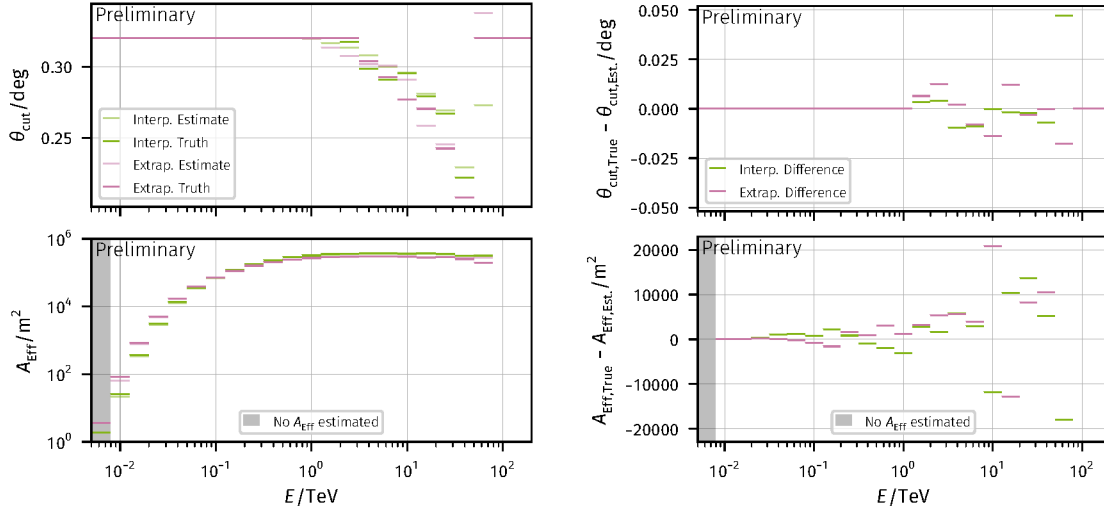


Figure 5: Inter- and Extrapolated RAD_MAX and Aeff tables (**left**) with inter- and extrapolation error (**right**).

Edge effects may occur if the interpolation templates partially miss some energy ranges, e.g., low true energy entries missing in energy dispersions for high zenith angles. User optimized quantities, like RAD_MAX-tables, are less suited for interpolation. In general, however, IRF interpolation has the potential to produce sufficiently accurate results for short time scale analyses.

Acknowledgments

This work was conducted in the context of the CTA Consortium and CTA Observatory. We gratefully acknowledge financial support from the agencies and organizations listed here: https://www.cta-observatory.org/consortium_acknowledgments/

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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. Gallozzi¹³, 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. Inoue², 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. Loic⁵¹, 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. Martínez^{140,141}, C. Marty¹¹⁵, A. Mas-Aguilar⁹, M. Mastropietro¹³, G. Maurin³⁹, W. Max-Moerbeck¹⁴², D. Mazin^{2,37}, D. Melkumyan²⁶, S. Menchiarì^{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. Nikolačuk¹⁵¹, 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. Razaque^{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. Ruiter¹⁷⁰, 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. Seitenzahl¹⁷⁰, 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. Tsihina¹¹⁵, 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. Ziętara¹²³, 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 EMFTTEL 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, Liberdade 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 Moiarriello 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, Valparaíso, 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, 10000 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