



A cosmic-ray database update: CRDB v4.1

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Abstract The cosmic-ray database, CRDB, has been gathering cosmic-ray data for the community since 2013. We present a new release, CRDB v4.1, providing many new quantities and data sets, with several improvements made on the code and web interface, and with new visualisation tools. CRDB relies on the MySQL database management system, `jquery` and `table-sorter` libraries for queries and sorting, and PHP web pages and AJAX protocol for displays. A REST interface enables user queries from command line or scripts. A new (pip-installable) CRDB python library is developed and extensive jupyter notebook examples are provided. This release contains cosmic-ray dipole anisotropy data, high-energy \bar{p}/p upper limits, some unpublished LEE and AESOP lepton time series, many more ultra-high energy data, and a few missing old data sets. It also includes high-precision data from the last three years, in particular the hundreds of thousands AMS-02 and PAMELA data time series (time-dependent plots are now enabled). All these data are shown in a gallery of plots, which can be easily reproduced from the public notebook examples. CRDB contains 316,126 data points from 504 publications, in 4111 sub-experiments from 131 experiments.

1 Introduction

Owing to the quantity and variety of data gathered in cosmic-ray (CR) physics, a central shared database (DB) assuring data quality, completeness, and traceability is an asset for the community. Although the oldest datasets have a historical

value mostly, the low-energy data still trace and give a unique perspective on the 11-year Solar cycle [e.g. 1, 2], and may also be of unforeseen use in the future.

The Cosmic-Ray DataBase¹ (CRDB) team has been distributing a growing body of CR data since its first public release in 2013 [3]. In a recent update, CRDB v4.0 [4], existing data on (groups of) ultra-heavy elements ($Z > 30$), upper limits on anti-nuclei ($Z \leq -2$), and a selected sample of ultra-high-energy (UHE) CRs from ground-experiments were included. In CRDB v4.0, the DB structure and the submission data format were also revised, and users were provided with a REST interface to extract both CR data and solar modulation levels (in their own codes and scripts), with overall more flexibility and more keywords to select the data queried.

In this release, CRDB v4.1, beside uploading data from the last three years (from AMS-02, CALET, DAMPE, PAMELA, etc.), we take advantage of an agreement with our colleagues from the KCDC² DB [5] to complete our sample of UHECR data. We also add energy-dependent anisotropy data, including and extending those presented in [6]. We also correct the meta-data and provide a few unpublished low-energy leptons and positron fraction data from the LEE, AESOP and AESOP-LITE balloon flights (operated over a 50 year time period). Because an incredibly large body of time-dependent data has been released by the AMS-02 experiment, we provide a new interface to ease the visualisation of these time series; these data are now the most numerous by far in CRDB. One of the main novelty of this release is a new standalone python library for the plotting of CRDB

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¹ <https://lpsc.in2p3.fr/crdb>.

² <https://kcdc.iap.kit.edu/>.

data, which should further ease their distribution and use by the community at large. We also took the opportunity of this release to fix some mistakes in the data, meta-data, and to improve the code (behind the scene) and the web interface; the most important changes are documented and available on CRDB's webpage, and briefly described later on.

The paper is organised as follows: Sect. 2 recalls the DB structure and the few changes made in this release; Sect. 3 presents the web interface and its novelties, and also introduce the new public python library to query and display CRDB data (outside of the website); Sect. 4 highlights the new data added in this version; we conclude in Sect. 5. Appendix A motivates our new (and hopefully more rationale) convention for the energy units in CRDB.

2 Database structure

In CRDB, data are separated in two broad categories, namely the *data* (CR data points and data uncertainties) and the *meta-data* (data about the data): the latter include the data taking periods, the description of the experiment, links to the associated publications, etc. The DB structure, shown in Fig. 1, has only slightly changed since our last release. Its most important features are recalled below, and we use MONOSPACE font to easily identify the DB table names and keys.

2.1 Data points and energy axis (DATA table)

Data points are described in the DATA table (see Fig. 1). Each entry has a unique ID and corresponds to a measured VALUE or upper limit (if boolean IS_UPPER_LIMIT set to 1) within an energy bin [E_BIN_L, E_BIN_U] or at the mean energy bin value E_MEAN.³ The data point is also associated to a sub-experiment and publication via its SUBEXP_PUBLI_ID key (whose value points at a SUBEXP_PUBLI table entry, see Sect. 2.5).

To cover the different energy types provided in the original publications, the energy axis (E-AXIS) of each data point must be set to ETOT, EK, R, EKN, or ETOTN. These types correspond to and are given in unit of, respectively, total energy E_{tot} in GeV, kinetic energy $E_k = E_{\text{tot}} - m$ in GeV, rigidity $\mathcal{R} = pc/(Ze)$ in GV, kinetic energy per nucleon $E_{k/n} = E_k/A$ in GeV, and total energy per nucleon $E_{\text{tot}/n} = E_{\text{tot}}/A$ in GeV: as discussed in Appendix A, we changed the energy unit convention of $E_{k/n}$ from GeV/n into GeV in this version. For the data, CRDB enables asymmetric statistical

³ If only E_MEAN is provided in the publication, we set E_BIN_L = E_BIN_U = E_MEAN. If both E_BIN_L and E_BIN_U are provided but not E_MEAN, we set E_MEAN = $(E_{\text{BIN_L}} \times E_{\text{BIN_U}})^{1/2}$. Finally, some experiments define their last energy bin as all events above a given energy: in that case, we manually set an upper bin value at least 100 times the lower bin value.

(VALUE_ERRSTAT_L and VALUE_ERRSTAT_U) and systematic (VALUE_ERRSYST_L and VALUE_ERRSYST_U) uncertainties.⁴

2.2 Quantities and conversions (CR_QUANTITY table)

The measured quantity is either a single CR quantity NUM_ID or a ratio of two CR quantities NUM_ID/DEN_ID, where both NUM_ID and DEN_ID point to entries in the CR_QUANTITY table. These entries are identified by an ID (set manually), a SYMBOL, and a NAME. The keys A, Z, and M_AMU (for the atomic mass number, charge, and mass in a.m.u) are non-null for isotopes, only the key Z can be filled for elements, and all keys are set to zero for groups of elements (or compound quantities) and dipole anisotropy data.

In CRDB queries, the data conversion from one energy axis to another is enabled (see Table A.1 in [4]). The conversion is exact for individual fluxes of CR isotopes or leptons and for ratios of leptons, and also for \bar{p}/p (this last conversion was not implemented in the previous release), but it is impossible for generic ratios, compound quantities, or anisotropy data. Nevertheless, an approximate conversion can still be enforced for fluxes of elements (or group of elements) if these quantities have a CR isotope proxy; this proxy is enabled via the PROXY_ID key in the CR_QUANTITY table (this key was previously in a separate and redundant table that we removed in this release).

2.3 Meta-data for experiments and modulation level (EXP, SUBEXP, and SUBEXP_IMAGE tables)

Definition and description. CR data are taken from experiments described in the EXP table (see Fig. 1). Each experiment has a TYPE (balloon, ground, or space), a unique ID (set internally in the DB), a name (EXPNAME), a starting year (DATE), and optionally a website (HTML); we stress that the experiment name is mainly used to better regroup and sort sub-experiments in the *Experiments/Data* website tab.

Sub-experiments (SUBEXP table) have an ID and are attached to a single experiment (EXP_ID). They enable to tag and distinguish, for a same experiment: (i) data obtained from different data taking periods; (ii) data taken from distinct sub-detectors or reconstructed from different analysis types; (iii) data obtained using external third-party models or different assumptions. Sub-experiments have a NAME,⁵

⁴ For old data, the distinction was usually not made between the two, and because old measurements were mostly limited by their statistics, the quoted uncertainties in the publications are ascribed to VALUE_ERRSTAT_L and VALUE_ERRSTAT_U.

⁵ In CRDB we decided that the format of this name should be a concatenation of: (i) the experiment name EXPNAME (e.g. PAMELA, NUCLEON); (ii) if necessary, a hyphen-separated sub-detector characteristic (e.g., PAMELA-CALO) or specific technique used (e.g.

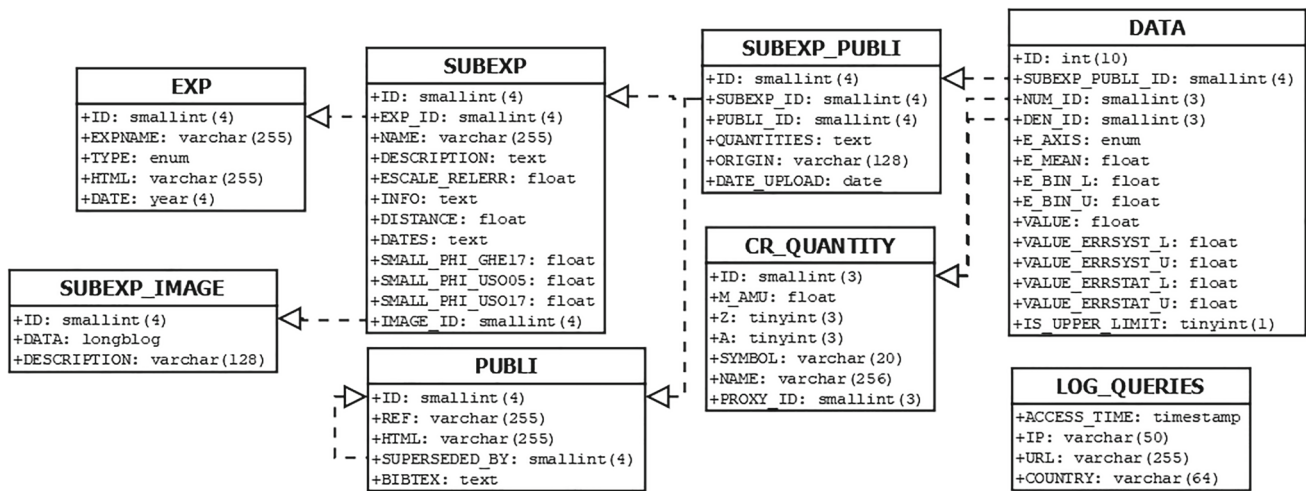


Fig. 1 Tables and keys in the MySQL structure of CRDB. The data (energy, values, and uncertainties) are stored in DATA and CR_QUANTITY tables. The meta-data (publication, experiment and sub-experiment names and infos) are stored in the EXP, SUBEXP, SUBEXP_IMAGE, and PUBLI tables, with SUBEXP_PUBLI a bridge

table enabling to access and link these various meta-data. The ISOTOPE_PROXY table is used to define the rules for energy-axis conversions of CR fluxes (see App. A.4 of [4] or in the new ‘Caveats/Tips’ web page, see Sect. 3.1). The LOG_QUERIES table keeps track of the number and origin of the visits

a short DESCRIPTION (detector or detection technique), additional INFO (e.g. location for balloon flights, GPS coordinates for ground-based detectors, etc.), and an IMAGE_ID (see next). For each sub-experiment, we also provide a single value (set to zero by default) for a possible energy-scale relative uncertainty (ESCALE_RELEERR).

In this release, we also added the new SUBEXP_IMAGE table (see Fig. 1). Previously, the detector images were kept in a separate directory with file names based on the EXPNAME and or sub-experiment NAME keys. In the new table, we have the image itself (DATA key) with its unique ID key, along with a brief description if needed (DESCRIPTION key). This allows to avoid storing duplicate images and makes checks on the completeness of the presence of images for all sub-experiments easier.

Solar modulation level. Especially important for the interpretation of low-energy data (below a few hundreds of GeV), we must provide (i) the DISTANCE to the Sun of the sub-experiment – almost all experiments are at 1 a.u., but a few satellites (*Ulysses* and *Voyager*) have also taken data at dif-

ferent position inside and outside the Solar cavity – and (ii) the exact list of start-stop DATES of the data taking periods.⁶ These two pieces of information allow to calculate and fill SMALL_PHI, the average modulation level over the corresponding data taking periods, in the force-field approximation [7, 8]. Actually, SMALL_PHI contains different estimates of $\langle \phi(t) \rangle$, all calculated from the same neutron monitor data,⁷ but based on slightly different modellings: the values tagged [Uso05] and [Uso17] are based on monthly average public values⁸ from [9, 10], while those tagged [Ghe17] are based on daily average values from [1]. In CRDB, all queried data are returned with their calculated SMALL_PHI value, but users are obviously free to discard or re-calculate it – by default, the returned values are [Ghe17], which can be also calculated for any time period from the *Solar modulation* tab (see Sect. 3.1).

2.4 Meta-data for publications (PUBLI table)

Almost all data in CRDB are taken from peer-reviewed publications. The main exceptions are data from balloon flights before the 1990’s, which were published in the proceedings of the biennial International Cosmic-Ray Conference only.

Footnote 5 continued

NUCLEON-KLEM); (iii) data taking periods in parenthesis; (iv) if relevant, the Monte Carlo generator used to analyse the data (e.g. *IceTop SIBYLL2.1* for UHECR data). The two exceptions to form the sub-experiment names are for the case of a combined analysis, i.e. names based on the concatenation of the two experiment names, e.g. *IceCube+IceTop (2010/06–2013/05)*, and unnamed balloons (concatenation of *Balloon* and their flight dates). For the dates, the chosen format is YYYY/MM (shortened to YYYY if the month is unknown), with a single date for a shorter-than-a-month data taking period, e.g. *Balloon (1966/05)*, or two dates otherwise, e.g. *IMP7 (1973/05–1973/08)*; if the month is unknown, we only quote the year (or range of years).

⁶ The format is YYYY/MM/DD:HHMMSS–YYY/MM/DD:HHMMSS or a semi-column separated list of similarly formatted time periods if necessary. If the exact time is unavailable, we enforce HHMMSS=000000 for the start date and HHMMSS=235959 for the stop date. If the day is unknown, we enforce DD=01 (start) or last day of the month (stop), and if the month is unknown, we enforce MM=01 (start) and MM=12 (stop).

⁷ <http://www01.nmdb.eu>.

⁸ <http://cosmicrays.oulu.fi/phi>.

Each publication is stored in the `PUBLI` table (see Fig. 1) with a unique `ID` (set internally) and an `HTML` key, taken to be the publication ADS (Astrophysics Data System) identifier (e.g. 2014A&A...569A..32M). This identifier allows to retrieve and fill in a standardised manner the `REF` and `BIBTEX` keys via the ADS API.⁹ The original publications are stored in `CRDB` (for the administrators) but cannot be made publicly available because of publication rights.

Because some data sets are sometimes re-analysed and reported in a new publication, we set the `SUPERSEDED_BY` key of the obsolete one to the `ID` value of the new one (it is left empty if it is not superseded). This allows us to enforce that queries to `CRDB` always return the most recent data, discarding the deprecated ones. We nevertheless keep track of these superseded data in the ‘Experiments/Data’ tab (see Sect. 3.1), where old and new publications are shown.

2.5 Tying data and meta-data (`SUBEXP_PUBLI` table)

The full description of the data requires the data themselves, the sub-experiment that measured them, and the publication where they appeared. The `SUBEXP_PUBLI` bridge table (see Fig. 1) allows to tackle situations where several sub-experiments are reported in the same publication. Each data set with a unique `ID` is tied to a sub-experiment (`SUBEXP_ID`) and a publication (`PUBLI_ID`). In addition, in this table, we keep track of the date at which each dataset was uploaded in `CRDB` (`DATE_UPLOAD`), and also of all `CR QUANTITIES` whose data were provided in this publication. While both these keys are unused in data queries, they are useful for maintenance and cross-checks of the DB.

3 Web interface and queries

`CRDB` runs on free open source softwares with a classical LAMP solution: Linux operating system, `APACHE HTTP` server, `MySQL` database, and `PHP` scripting language. The server is hosted at the `LPSC` laboratory, and has been recently changed to have a more recent version of the operating system, the DB, and the `PHP` version. The DB RAM was extended from 512 to 2048 MB to handle the larger requests from the newly added time-series data (see Sect. 4.6). The `CRDB` website is organised in tabs providing different entry points to explore the DB data and meta-data. The webpages use `AJAX` (asynchronous JavaScript and XML) web development technique for efficiency and speed. In addition to the few improvements made on the existing website tabs, we added two new ones in this release (see Sect. 3.1). To query, sort, and show the DB content, the web interface relies on `jquery`, `jquery-ui`, `jquery.cluetip`, and

`table-sorter`. There are two ways for users to query data: either from the *Data extraction* tab (see below) or from a direct command-line call (bypassing the website) via the REST interface (also see below). The latter functionality has been fully exploited in this release, with the development of a new dedicated `CRDB` python library. This library is described and used to generate a gallery of plots in Sect. 3.2.

3.1 Web pages: content and novelties

We briefly describe below the content and noteworthy improvements made on the tabs. We also added a new tab to list a few caveats and tips related to the data preparation and transformations.

- *Welcome* tab: entry point of the website, where the DB content, tools, people involved, code status, etc. are highlighted. In this release, we also added a gallery of plots to advertise the variety of data in `CRDB`.
- *Caveats/Tips* tab: there are a few subtleties in the way the data (and meta-data) are handled in `CRDB`. Indeed, at the collection stage, the information on the data is sometimes partial, and somewhat subjective choices need to be made to be able to implement them nonetheless. Then, at the query stage, combinations and conversions are enabled, with some degree of approximation as well. Users probably do not pay a lot of attention to these details, and this is probably fine most of the time. Whereas the details and caveats about these procedures are made explicit in the `CRDB` publications [3,4], the most relevant ones are gathered here in one place. This should help users identify data for which going back to the original publication is necessary.
- *Data extraction* tab: queries of user-selected CR quantities with various options (sub-experiment names, dates, energy unit, etc.). The retrieved data include the ones matching exactly the query but also, if selected, extra sets based on energy conversions (Table A.1 of [4]) and data combinations (App. A of [3]); we added in this release the trivial but forgotten transformation rule to get Y/X from data published as X/Y . The data retrieved are then plotted and listed in a pop-up window and can be downloaded in various formats: in this release we added an extra option, ‘csv (as import)’, enabling to retrieve the data and all their meta-data (format similar to the one described in the *Submit data* tab, see below). We also added a tick box for the ‘Refine search criteria’ box in the *Data extraction* tab, to display the data versus time instead of energy.
- *Experiments/Data* tab: sorted list of experiments with their associated sub-experiments, including in particular a picture of the detector, their associated publications and quantities measured. In this release, to improve the

⁹ <https://github.com/adsabs/adsabs-dev-api>.

sorting and readability of the numerous unnamed balloon flight series (i.e. balloon launched multiple times over years by the same team and analysed in several publications), we regrouped them into fewer and more informative names, e.g. *Nuclear emulsions 1950-1968*, *Muon Telescope 1957-1995*, etc.

- *REST/CRDB.py* tab: details how to query CRDB from a stand-alone script, with the same options as the ones provided in the *Data extraction* tab (datasets retrieved from the website or from the REST interface with the same selection and options are the same). We also provide a simple command-line example (to run in a terminal) using `curl`. This capability is taken advantage of and extended in this release thanks to a new standalone python library to retrieve and display data, for instance from a python notebook, see Sect. 3.2).
- *Solar modulation* tab: gives access, for any time interval, to the force-field modulation level (see Sect. 2.3). Behind the scene, a *cron* scheduler downloads NM data daily from NMDB.¹⁰ It also calculates the associated ϕ_{FF} , whose values can be retrieved for a selected time period and resolution (from 10 min up to a month), either directly from this tab, or from a REST interface. In this release, we fixed several minor bugs (as listed on the website), and more importantly, we fixed the broken REST interface and the daily update.¹¹
- *Submit data* tab: how to format and send a `csv` file to CRDB.
- *Useful links* tab: online resources related to CR data.
- *Admin* tab: maintenance tools to check broken or inconsistent entries and missing meta-data, detailed procedure to upload data in the DB. This tab is restricted to authenticated users (i.e. CRDB maintainers).

3.2 Python access to CRDB (and notebook)

The CRDB provides a REST interface, which can be used from any programming language to automate downloading and processing data in scripts and programs. A tutorial on how to do this is available.¹² Since Python is the dominant scripting language for data processing, we further provide a ready-made solution for Python users that simplifies and standardises queries from scripts. Users of this library do not need to learn the REST API, this is done internally by the library. The corresponding Python package called `crdb`¹³ can be

¹⁰ <http://www01.nmdb.eu>.

¹¹ All missing ϕ_{FF} values were completed, and we also recalculated modulation levels, starting from 2015, for the THULE station (because of updated NM values in NMDB) and ROME station (using the correct number of NM tubes, which changed in 2017).

¹² <https://github.com/crdb-project/tutorial>.

¹³ <https://github.com/crdb-project/crdb>.

downloaded with the standard tool `pip` from the Python Package Index.¹⁴ The main function is `crdb.query`, which performs a query to the database through keyword arguments, which are internally validated so that user errors are caught early and clear error messages are returned. The tabular output of a query is transformed by this function into a structured Numpy array [11], which allows for efficient fast processing in Python. Each query is automatically cached to disk for 30 days, to accelerate repeated calls to `crdb.query` and to reduce the load on the server; this often occurs during the development of a script or program. Further utility functions allow users to easily generate lists of citations for the data sets they queried from the DB. All functions are well documented, the documentation can be accessed with Python's internal `help()` command.

The Python package also provides a command-line interface, which allows users to perform queries and store the results in one of the ASCII formats supported by the CRDB data extraction system. In this case, the query is specified using command-line arguments, the latter mirroring those of `crdb.query`. Example code on how to make standard plots in Python can be found in the gallery, and we show in Figs. 2 and 3 a few plots illustrating the variety, coverage, and completeness of CRDB's data. More plots are shown in the next section, and all of them are available from CRDB's public gallery notebook.¹⁵

4 New datasets in CRDB v4.1

In addition to *regular* data updated since the last release (Sect. 4.1), the content of CRDB has evolved in several directions. In this release, we (i) add dipolar anisotropy data (Sect. 4.2); (ii) take advantage of a partnership with KADC to gradually move from limited sample to completeness of UHECR data (Sect. 4.3); (iii) include high-energy upper limits on antiproton fluxes from ground experiments (Sect. 4.4); (iv) correct and complete low-energy lepton data from the LEE, AESOP, and AESOP-Lite considering the vast balloons flown over 50 years (Sect. 4.5); (v) expand time series data thanks to the recently released AMS-02 daily and PAMELA monthly data (Sect. 4.6).

4.1 Data uploaded since CRDB v4.0

Many data from AMS-02, CALET, DAMPE, etc. have been published since our last release. These data sets should have ideally been uploaded in CRDB shortly after their publication, but were only prepared for this release. We also took the opportunity of this release to upload a few old datasets that

¹⁴ <https://pypi.org/project/crdb>.

¹⁵ <https://github.com/crdb-project/tutorial/blob/main/gallery.ipynb>.

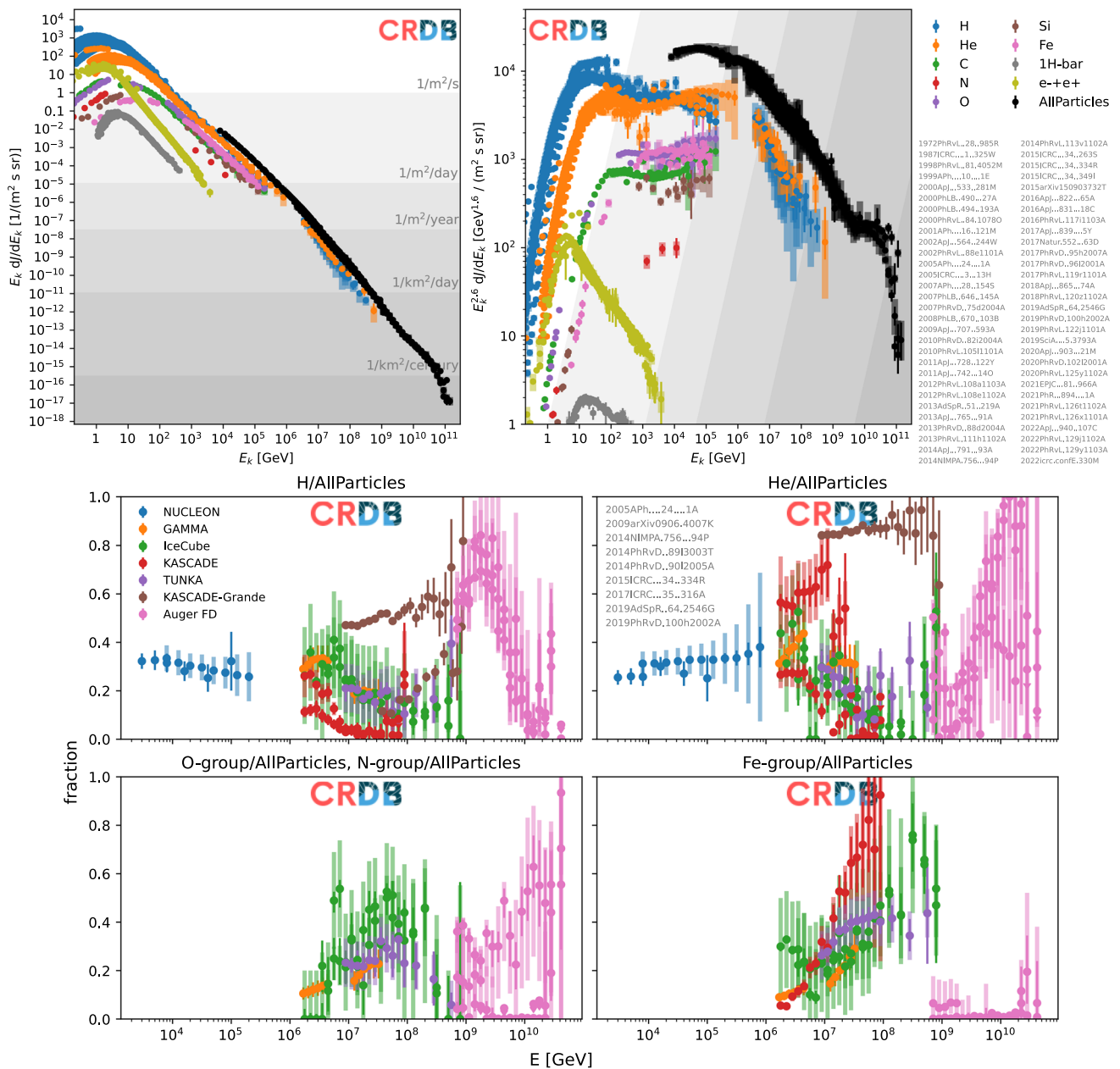


Fig. 2 Selected plots from the gallery, obtained from the CRDB python library and available from the gallery notebook¹⁵: flux of selected species (top), multiplied by $E_k^{2.6}$ on the top right panel; energy dependence of high-energy CR groups of elements (bottom)

were not yet in CRDB. Rather than a detailed and cumbersome description of all these new data sets, which are listed in Table 1, we prefer to highlight below some of their most salient features.

To start with, the first 7 years of AMS-02 data [28], along with other publications by the AMS Collaboration [29–31], all uploaded in this release, now provide the *most comprehensive set of data from a single experiment*. These data are in the GV to TV rigidity range, and correspond to fluxes and ratios of leptons, antiprotons, and nuclei from H to Si, plus Fe. Moreover, in addition to the above AMS-02 data, we have

uploaded the recent CALET [33–37], DAMPE [39–41], ISS-CREAM [43], and NUCLEON [44–48] data, which provide the *most precise set of direct measurement data in the TeV domain and above*; these data are key to investigate possible breaks and features in the spectra, and the consistency between direct and indirect measurement data.

Some of the new data sets uploaded also explore in a unique way the composition of ultra-heavy CRs (UHCR). Indeed, recent ACE-CRIS data [27] *unveil the isotopic content of CR elements $Z = 30–38$* , complementing the elemental fractions measured by Tiger and SuperTiger (already in

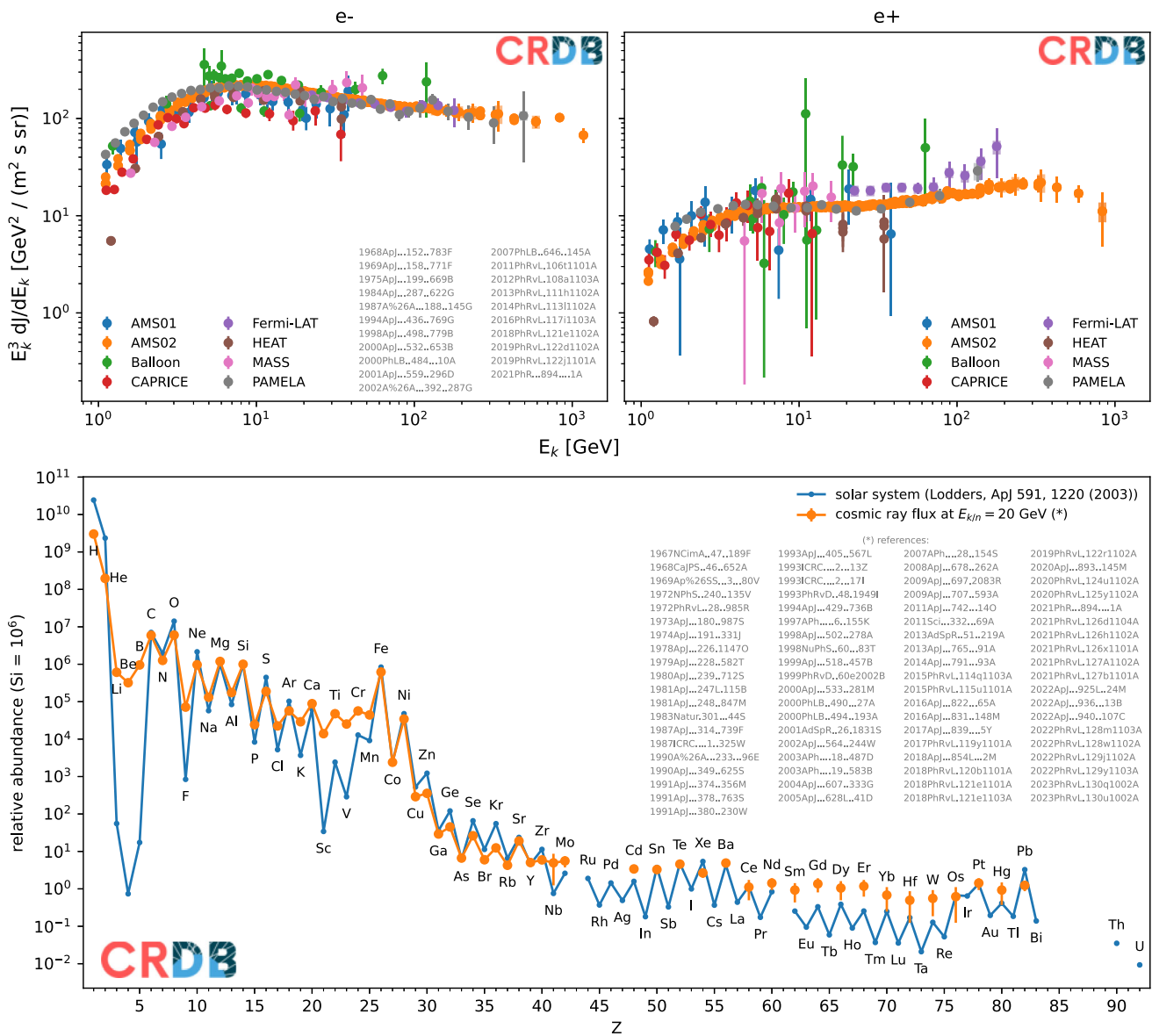


Fig. 3 Selected plots from the gallery, obtained from the CRDB python library and available from the gallery notebook¹⁵: electron and positron fluxes (top), and comparison of elemental abundances in Solar system and GCRs (bottom)

CRDB); a further extension to the range $41 \leq Z \leq 56$ should be available soon by SuperTiger [52]. For even heavier (and rarer) elements, very few experiments have provided data so far. In addition to Ariel6, HEAO3-HNE, UHCRE-LDEF, and Trek data (already in CRDB), we added the skylab data [50].

The last piece of UHCR data that we decided to add in this release are those from the OLIMPIYA experiment. The latter uses olivine crystals contained in stony-iron meteorites (pallasites) as CR detectors. At variance with satellite experiments that provide measurements of UHCR GCRs accumulated over an exposure time of a few years, the OLIMPIYA experiment provides *measurements of GCRs accumulated over up to hundreds of Myr* – these two complementary tech-

niques allow to have a glimpse on the GCR time evolution. The OLIMPIYA data uploaded in this release¹⁶ are taken from [24,53] that supersedes a previous analysis presented in [54].¹⁷

¹⁶ We stress that, owing to the DB structure and displays, we have to define a data taking period, a position in the Solar system, and an energy for these data, although it is inadequate: the former is set to the publication date, the position to 1 au, and the energy to 1.5 GeV/n (as set for the other UHCR experiments, see [4]), i.e. a value at which GCR fluxes are maximal and are likely to be responsible for most of the tracks.

¹⁷ Between these two publications, several effects that could affect the relative yield of nuclei registered have been investigated and accounted for: anomalies near the meteorite edge related to the annealing of

Table 1 List of ‘regular’ datasets added in the last three years, sorted according to their experiment TYPE: *balloon* (from Balloon to SOKOL), *ground* (OLIMPIYA only), and *space* (from ACE-CRIS to Voyager2)

Subexp name	References	Qty	N_{data}
Balloon (1958/08b)	[12]	He	7
Balloon (1974)	[13]	${}^6,{}^7\text{Li/Li}$, ${}^{7,9,10}\text{Be/Be}$, ${}^{11}\text{B/B}$	14
Balloon (1975/10)	[14]	Co/Fe, Cu/Fe	2
Balloon (1975/10 + 1976/05)	[14]	Ni/Fe, Zn/Fe	2
Balloon (1977/09)	[15] ^a	${}^7\text{Li}/{}^6\text{Li}$, ${}^9\text{Be}/{}^7\text{Be}$, ${}^{11}\text{B}/{}^{10}\text{B}$	6
Balloon (1981/12)	[16]	Fe	1
Balloon-EWAsym (1989/05 + 1991/05)	[17] ^b	Si/Fe, S/Fe, Ar/Fe, Ca/Fe, (Z=21-25)/Fe	165
Balloon-OpeningAngle (1989/05 + 1991/05)	[17] ^b		
BACH (1998/04)	[18]	Fe	1
HEIST (1984/05)	[19]	${}^{54}\text{Fe}/{}^{56}\text{Fe}$, ${}^{58}\text{Fe}/{}^{56}\text{Fe}$	2
JACEE (1979 + ... + 1995)	[20] ^b	Fe, CNO, NeMgSiS, AllParticles	30
RUNJOB (1995+1996)	[21] ^b	H, He, Fe, CNO, Ne-S, AllParticles	30
RUNJOB (1995+1996+1997+1999)	[22] ^b	LiBeB/CNO, subFe/Fe, CNO, AllParticles	17
SOKOL (1984/03–1986/01)	[23] ^b	CNO, NeMgSiS, AllParticles	23
OLIMPIYA (2005–2016)	[24]	$\left\{ \begin{array}{l} Z = (70, \dots, 83)/(Z \geq 70), Z = (55, \dots, 83)/(Z \geq 55), (Z \geq 88)/(Z = 74 - 80) \\ Z \geq 88/(Z = 74 - 87), (Z = 81 - 87)/(Z = 74 - 80) \end{array} \right.$	78
ACE-CRIS (1997/12–2000/04)	[25]	${}^{54,55,57,58}\text{Fe}/{}^{56}\text{Fe}$, ${}^{57}\text{Co}/{}^{59}\text{Co}$, ${}^{60,61,62,64}\text{Ni}/{}^{58}\text{Ni}$	9
ACE-CRIS (1997/12–2014/09)	[26]	${}^{60}\text{Fe}/{}^{56}\text{Fe}$, ${}^{60}\text{Fe}/\text{Fe}$	2
ACE-CRIS (1997/12–2019/02)	[27]	$\left\{ \begin{array}{l} (Z = 28, \dots, 38)/\text{Fe}, {}^{63,65}\text{Cu}/\text{Cu}, {}^{64,66,67,68,70}\text{Zn}/\text{Zn}, {}^{67,69,71}\text{Ga}/\text{Ga}, \\ {}^{70,71,72,73,74,76}\text{Ge}/\text{Ge}, {}^{73,75}\text{As}/\text{As}, (80+82)\text{Se}/\text{Se}, {}^{79,81}\text{Br}/\text{Br}, \\ (74+75+76+77+78)\text{Se}/\text{Se}, (78+79+80+81+82)\text{Kr}/\text{Kr}, (83+84+85+86)\text{Kr}/\text{Kr}, \\ (84+85+86)\text{Sr}/\text{Sr}, (87+88)\text{Sr}/\text{Sr} \end{array} \right.$	37
AMS02 (2011/05–2018/05)	[28]	$\left\{ \begin{array}{l} Z = 1, \dots, 8, (Z = 2, \dots, 7)/\text{O}, \text{N/B}, (Z = 3, \dots, 5)/\text{C}, \\ {}^1\text{H}, {}^1\text{H}/(\text{H,He}), e^{-+}, e^{-} + e^{+}, e^{+}/(e^{-} + e^{+}) \end{array} \right.$	1693

Table 1 continued

Subexp name	References	Qty	N_{data}
AMS02 (2011/05–2019/10)	[29]	F, F/B, F/Si	144
AMS02 (2011/05–2019/10)	[30]	Fe, Fe/(O,He,Si)	184
AMS02 (2011/05–2019/10)	[31]	Na, Al, (Na,Al)/Si, (Na,Al)/F	288
AMS02 (2011/05–2021/05)	[32]	B, C, O, F, Ne, Mg, Si, S	486
CALET (2015/10–2019/10)	[33]	C, O, C/O	66
CALET (2016/01–2020/05)	[34]	Fe	23
CALET (2015/10–2022/02)	[35]	B, C, B/C	60
CALET (2015/10–2021/12)	[36]	H	29
CALET (2015/11–2021/05)	[37]	Ni	7
CALET (2015/10–2022/04)	[38]	H/He, He	49
DAMPE (2016/01–2018/06)	[39]	H	17
DAMPE (2016/01–2020/06)	[40]	He	23
DAMPE (2016/01–2021/12)	[41]	B/C, B/O	26
IMP8 (1982/07–1982/12)	[42]	H,He	18
IMP8 (1984/08–1984/09)	[42]	H,He	17
ISS-CREAM (2017/08–2019/02)	[43]	H	13
NUCLEON (2015/07–2017/06)	[44]	H/He	18
NUCLEON (2015/07–2017/06)	[45]	Ni	19
NUCLEON (2015/07–2017/06)	[46]	(Z=21–24)/Fe	24
NUCLEON-IC (2015/07–2017/06)	[47] ^c	H, He, C, O, Ne, Mg, Si, Fe, AllParticles	68
NUCLEON-KLEM (2015/07–2017/06)	[48]	He/O, C/O	19
PAMELA-CALO (2006/07–2014/09)	[49]	${}^7\text{Li}/{}^6\text{Li}$, ${}^7\text{Be}/\text{Be}$, ${}^{10}\text{Be}/{}^9\text{Be}$	4
PAMELA-TOF (2006/07–2014/09)	[49]	${}^7\text{Li}/{}^6\text{Li}$, ${}^7\text{Be}/\text{Be}$, ${}^{10}\text{Be}/{}^9\text{Be}$	8
SkyLab (1973/05–1974/02)	[50]	$\left\{ \begin{array}{l} (Z = 74 - 87)/(Z \geq 65), Z \geq 88/(Z = 74 - 87), Z \geq 65, \\ (Z \geq 94)/(Z = 74 - 87), (Z \geq 110)/(Z = 74 - 87) \end{array} \right.$	12
Voyager2-HET (1986/01–1987/12)	[51] ^b	H, C, N, O, Ne, Mg, Si, S, Fe	124

^a Isotopic ratios from tables were already included in CRDB; the new points added are extracted from the figures

^b Publications whose data were only partly extracted in the previous release

^c These KLEM data were already included in CRDB, but mislabelled NUCLEON

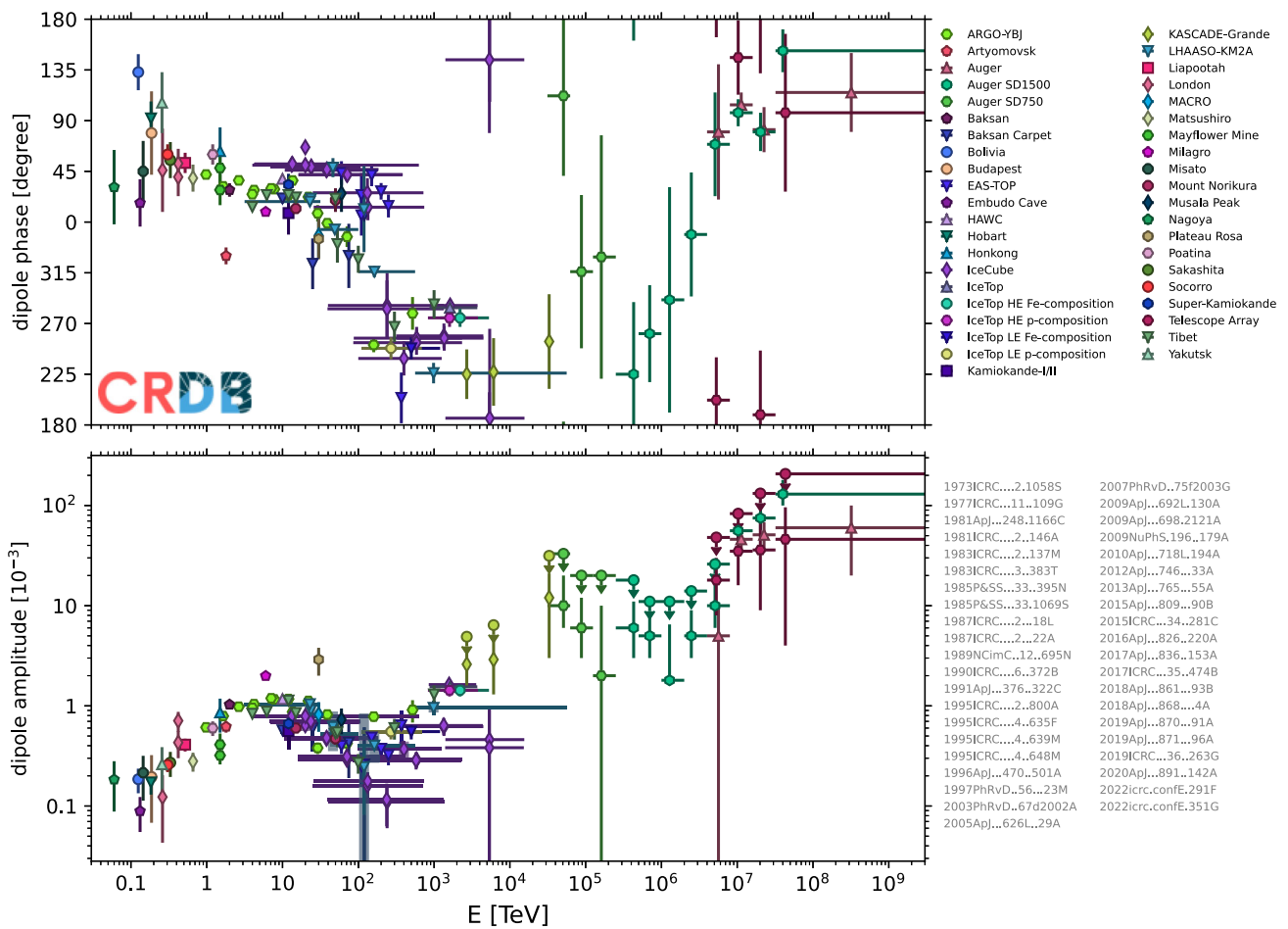


Fig. 4 Equatorial dipole amplitude and phase of the CR anisotropy inferred by various experiments (see Table 2 for references). The figure is available from the gallery notebook¹⁵

4.2 Anisotropy data

Ground-based detectors with high event statistics allow the study of anisotropies in the arrival directions of CRs. Of particular interest is here the dipole anisotropy predicted by diffusion theory, that allows us to study the nearby CR source distribution and diffuse CR transport in our local magnetic environment [e.g., 6].

While the true dipole anisotropy is represented by an amplitude and two phases, the data-driven reconstruction method of ground-based observatories allows only the reconstruction of the projection of the dipole vector onto the equatorial plane. Conventionally, this projection is characterised by the (projected component of the) amplitude and the phase in right ascension. These new dipole anisotropy data are indicated in the DB by two new entries, namely

DipoleAmplitude and DipolePhase; we have chosen a convention where DipolePhase $\in [-180^\circ, 180^\circ]$.

The dipole data in terms of total energy E_{TOT} is shown in Fig. 4. Note that the limited statistics of CR experiments in the PeV–EeV energy region has so far only yielded upper limits on the dipole anisotropy. In the DB, we indicate this by providing both the best amplitude and its upper limit as separate entries. As visible in Fig. 4, the dipole amplitude and phase data from different observatories can show strong deviations beyond statistical uncertainties. This is related to hidden (and often unquantified) systematic effects, corresponding to the partial sky coverage of experiments and reconstruction method.

Furthermore, experimental collaborations oftentimes provide a number of updates of their anisotropy studies as the event statistics accumulate. We have chosen to include all the data publicly available, but note that the later data sets are usually meant to supersede the earlier ones. Finally, note that some of the (especially older) data have been extracted from publications, which give rather limited information on the

Footnote 17 continued
the measured tracks [55]; fragmentation in the meteorite which explains all events in the $84 \leq Z \leq 89$ range, but has no impact for the other charges [56].

Table 2 Anisotropy dipole amplitude (DipoleAmplitude) and phase (DipolePhase) datasets added in CRDBv4.1

Subexp NAME	References
ARGO-YBJ (2008/01–2009/12)	[57]
ARGO-YBJ (2008/01–2012/12)	[58]
Artyomovsk (1981/01–1987/12)	[59]
Baksan (1982/07–1986/06)	[60]
Baksan Carpet (1980/02–1981/01)	[61]
Baksan Carpet (2007/01–2007/12)	[62]
Bolivia (1965/01–1976/12)	[63]
Budapest (1958/01–1963/12)	[64]
EAS-TOP (1990/01–1994/12) 1	[65]
EAS-TOP (1992/01–1994/12)	[66]
EAS-TOP (1992/01–1999/12)	[67]
Embudo Cave (1965/01–1983/12)	[63]
HAWC (2015/05–2017/05)+IceCube (2011/05–2016/05)	[68]
Hobart (1958/01–1983/12)	[64]
Honkong (1983/11–1986/02)	[69]
IceCube (2007/06–2008/03)	[70]
IceCube (2009/05–2015/05)	[71]
IceCube (2009/05–2016/05)	[72]
IceCube HE (2009/05–2010/05)	[73]
IceCube LE (2009/05–2010/05)	[73]
IceTop (2009/05–2015/05)	[71]
IceTop HE (2009/05–2012/05)	[74]
IceTop LE (2009/05–2012/05)	[74]
KASCADE-Grande (2003/01–2013/01)	[75]
Kamiokande-I/II (1987/12–1994/12)	[76]
LHAASO-KM2A (2018/02–2018/12)	[77]
LHAASO-KM2A (2020/01–2020/12)	[78]
Liapootah (1992/01–1994/10)	[79]
London (1961/01–1982/12)	[64]
London (1972/01–1978/12)	[64,80]
London (1981/01–1982/12)	[64,80]
MACRO (1991/11–2000/05)	[81]
Matsushiro (1985/01–1995/12)	[79,82]
Mayflower Mine (1978/01–1981/08)	[83]
Mayflower Mine (1978/01–1983/05)	[84]
Milagro (2000/07–2007/07)	[85]
Misato (1978/01–1980/12)	[64]
Mount Norikura (1970/08–1972/12)	[86]
Mount Norikura (1975/01–1987/12)	[87]

methodology used. We have chosen to include these at face value, but recommend to exercise caution when using these data for quantitative studies. The experiments and associated references for all these data are gathered in Table 2.

Table 2 continued

Subexp NAME	References
Musala Peak (1968/09–1972/12)	[88,89]
Nagoya (1971/01–1980/12)	[64]
Ottawa (1977/01–1980/12)	[90]
Pierre Auger (2004/01–2016/08) Rayleigh	[91]
Pierre Auger SD1500 (2004/01–2018/08) East-West	[92]
Pierre Auger SD1500 (2004/01–2018/08) Rayleigh	[92]
Pierre Auger SD750 (2012/01–2018/08) East-West	[92]
Plateau Rosa (1981/05–1982/04)	[93]
Poatina (1987/01–1994/12)	[94]
Sakashita (1978/01–1980/12)	[64,95]
Socorro (1968/01–1983/12)	[63]
Super-Kamiokande (1996/06–2001/05)	[96]
Telescope Array (2008/05–2020/05)	[97]
Tibet II and III (1995/10–2010/02)	[98]
Tibet III (1999/11–2003/11)	[99]
Yakutsk (1957/07–1969/12)	[64]

4.3 UHECR data from KCDC

Considering the vast amount of academic databases and search engines for locating and accessing published scientific data, unified access to published datasets and spectra is still in the early stages. This is due to the large variety of experiments and thus the large variety of measured data. In cooperation with CRDB, the ‘KASCADE Cosmic-ray Data Centre’ (KCDC) is taking a step towards simplification, by embedding the UHECR data from KCDC, i.e. data from extensive air shower experiments, into CRDB. The advantage of such an extensive collection of UHECR data is that data from other experiments can be obtained relatively quickly. KCDC is already a demonstrator and partner of PUNCH4NFDI,¹⁸ the consortium of particle, astroparticle, astro-, hadron and nuclear physics within the German National Research Data Infrastructure, NFDI, which is aimed to unify the methodical approach of open data in this field.

The KCDC is a web-based interface where initially the scientific data from the completed air-shower experiment KASCADE-Grande was made available for the astroparticle community as well as for the interested public. Besides a DataShop to download the reconstructed data of KASCADE-Grande and the meta-data, KCDC offers more than 100 cosmic ray spectra from about 25 different ground-based high-energy CR experiments published between 1984 and 2021 for download. The data sets available cover an energy range from about 10^{12} eV to more than 10^{20} eV for all-particle spectra (keyword `AllParticles` in CRDB) as well as for

¹⁸ <https://www.punch4nfdi.de/>.

Table 3 UHECR datasets (from ground experiments) uploaded in CRDB v4 . 1

Subexp NAME	References	Qty
AGASA (1993/12–2002/12)	[100]	AllParticles
Auger Hybrid (2004/01–2016/12) QGSJet-II-04+EPOS-LHC+SIBYLL2.3	[101]	AllParticles
Auger (2004/01–2007/08)	[102]	AllParticles
Auger (2005/11–2008/05)	[103]	AllParticles
Auger SD750+SD1500 (2014/01–2018/08)	[104]	AllParticles
Auger SD750 (2014/01–2018/08)	[104]	AllParticles
DICE (1994/07–1996/03)	[105]	AllParticles
EAS-TOP (1992/01–1999/12) QGSJet	[106]	allParticles
Fly’s Eye (1988/06–1992/07)	[107]	AllParticles
GAMMA (2003/01–2007/12) SIBYLL	[108]	H, He, O-group, Fe-group, AllParticles
GAMMA (2004/01–2006/12) SIBYLL	[109]	AllParticles
Haverah Park (1974/01–1987/12) QGSJet98	[110]	AllParticles
HAWC (2016/06–2017/02) QGSJet-II-03	[111]	AllParticles
HAWC (2018–2019) QGSJet-II-04	[112]	AllParticles
HEGRA (1987–1998) QGSJet	[113]	AllParticles
IceCube (2010/06–2013/05) SIBYLL2.1	[114]	H, He, O-group, Fe-group, AllParticles
IceCube+IceTop (2010/06–2013/05) SIBYLL2.1	[114]	AllParticles
IceTop (2016/05–2017/04) QGSJet-II-04	[115]	AllParticles
IceTop (2010/06–2011/05) SIBYLL2.1	[116]	AllParticles
IceTop (2016/05–2017/04) SIBYLL2.1	[115]	AllParticles
KASCADE (1996/10–2002/01) QGSJet01	[117]	H, He, C-Fe-group, AllParticles
KASCADE (1996/10–2002/01) SIBYLL2.1	[117]	H, He, Si-group, Fe-group, C-Fe-group, C-group, AllParticles
KASCADE-Grande (2003/12–2011/10) SIBYLL2.3	[118]	H, He-C-group, Si-Fe-group, AllParticles
KASCADE-Grande (2003/12–2009/03) QGSJet-II-2	[119]	H, He, Si-group, Fe-group, CNO-group, AllParticles
KASCADE-Grande (2004/03–2010/12) QGSJet-II-3	[120]	H-He-group, C-Fe-group, AllParticles
KASCADE-Grande (2004/03–2012/05) QGSJet-II-2	[121]	AllParticles
KASCADE-Grande (2004/03–2012/05) QGSJet-II-2	[122]	H-He-group, C-Fe-group, AllParticles
Maket-ANI (1997–2004) QGSJet-II-01	[123]	H-He-group, C-Fe-group, AllParticles
Mount Norikura (1976/01–1995/12)	[124]	AllParticles
TAIGA-HiScore (2017/01–2018/12)	[125]	AllParticles
TALE (2014/06–2016/03) QGSJet-II-03	[126]	AllParticles
Tibet III (2000/11–2004/10) QGSJet01	[127]	H-He-group, O-Fe-group
Tibet III (2000/11–2004/10) SIBYLL2.1	[127]	O-Fe-group
Yakutsk (1995/01–2008/12) QGSJet01	[128]	AllParticles

mass groups like p, He up to Fe or heavy and light respectively, derived from the unfolding procedure for different high-energy interaction models like QGSJet, EPOS and also SIBYLL, mostly embedded in the CORSIKA simulation package: CORSIKA¹⁹ (COsmic Ray event SIMulation for KAScade) has been written especially for KASCADE and extended since then to become the world’s standard simulation package in the field of cosmic ray air shower simulations.

While the KASCADE-Grande experimental data in KCDC are accessible also via an API, the spectra points and meta-

data, stored in a postgres database, can only be selected and displayed on the website after registration. Thus, a partnership with CRDB was set up with the aim of creating a basis for this data exchange and to provide the community with a common interface to this merged spectra data. The KCDC data sets are now being reformatted to meet the requirements of CRDB, to supplement its very extensive content with data from ground-based air shower experiments. The spectra uploaded on CRDB at the time of this release are listed in Table 3; they represent about ~ 50% of the full data being prepared, and a sample of these data can be seen in Fig. 2.

¹⁹ <https://www.iap.kit.edu/corsika/>.

Table 4 \bar{p}/p upper limits added in CRDB v4.1

Subexp NAME	References
ARGO-YBJ (2006/07–2009/11)	[133]
HAWC (2014/11–2017/08)	[134]
L3+C (1999/04–2000/11)	[131]
MACRO (1989/02–2000/12)	[130]
Muon data (1971–1981)	[135]
Tibet I (1990/06–1993/09)	[129]
Tibet III (1999/11–2004/12)	[132]

To match the requirements of UHECR measurements, the data quantity list DATA_QTY had to be extended by two more groups, the He-C-group and the Si-Fe-group. To find out more about the real meaning of the particle spectra like helium, oxygen and so on, their mixtures as well as the mixtures of different high-energy interaction models, users should refer to the original papers.

4.4 Upper limit on high-energy \bar{p}/p

With the angular resolution of ground cosmic-ray detectors reaching below the degree level in the 90’s, it became possible to observe a deficit of events from the direction of the Moon or the Sun ($\sim 0.5^\circ$): the Moon or Sun shadow technique was used first to calibrate their angular resolution and pointing accuracy. Actually, the position of the shadow is offset from the true location of the blocking bodies owing to the deflection of cosmic rays in the geomagnetic field, with the shadow shifted westward (resp. eastward) for positively (resp. negatively) charged particles. This allowed several experiments to set upper limits on the \bar{p}/p ratio above TeV energies [129–134].

These upper limits were added in CRDB, along with the older upper limits obtained from the observed charged ratio of muons [135]. These new datasets are shown in Fig. 5 and listed in Table 4.

4.5 LEE, AESOP, and AESOP-Lite balloon flights

From 1968 to 2011, the LEE (Low Energy Electrons) balloon-borne instrument [136] was launched over 35 times. LEE provided the longest series of CR electron measurements ($e^- + e^+$) over a time period that covers about four solar cycles. This data is particularly relevant to the study of the solar modulation of electrons with energies up to about 20 GeV. In CRDB v4.1, we reorganized the existing LEE data from 1968 to 1994. Data points taken from figures were updated with the actual values when private communication with the authors was possible. Data post-1994 were also added to the database. Indeed, the spectra for the years 1997

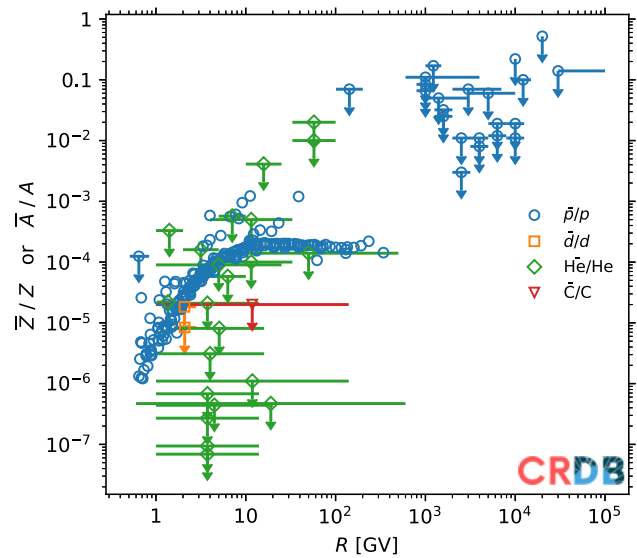


Fig. 5 \bar{A}/A and \bar{Z}/Z ratios in CRDB; the very few data points for upper limits on $(Z \leq -2)/(Z \geq 2)$, $(Z \leq -3)/(Z \geq 3)$ and $(Z \leq -6)/(Z \geq 6)$ are not shown. The orange crosses with downward arrows correspond to the new \bar{p}/p upper limits at high energy added in this release (see Table 4). The figure is available from the gallery notebook¹⁵

to 2000 were never fully published. However, flight data were analyzed using the same method as that outlined in [137], and the spectrum values at 1.2 GeV only were published in [138]. The full spectra for these years were provided by the authors (Paul Evenson, 2023) and uploaded in CRDB. These data are shown in the top panel of Fig. 6 along with other measurements from experiments at similar energies. We also show on this plot times series of He (second panel), NM count rates (third panel), and Solar modulation values calculated from these count rates (fourth panel).

From 1994 to 2011, the AESOP (Anti-Electron Sub Orbital Payload) balloon-borne instrument [139] flew at multiple occasions with the primary objective to study the charge-sign dependence of the solar modulation of electrons from a few hundreds MeV to a few GeV. In CRDB v4.1, we reorganized the existing AESOP $e^+/(e^- + e^+)$ data and updated the 1994 flight (private communication with the author John Clem, 2023).

The AESOP-Lite apparatus is the successor of LEE and AESOP. Its primary objectives are to search for the origin of low-energy electrons in the electron spectrum between 20-300 MeV, and to provide a baseline electron spectrum at 1 au for the measurements of the Voyager probes currently transmitting data from outside the heliosphere. The e^- , e^+ , and $e^+/(e^- + e^+)$ data from the AESOP-Lite’s maiden flight from Sweden in 2018 [145] were added to CRDB; future data will be added too.

The metadata of all these balloon flights were updated using information from the original publications. When not

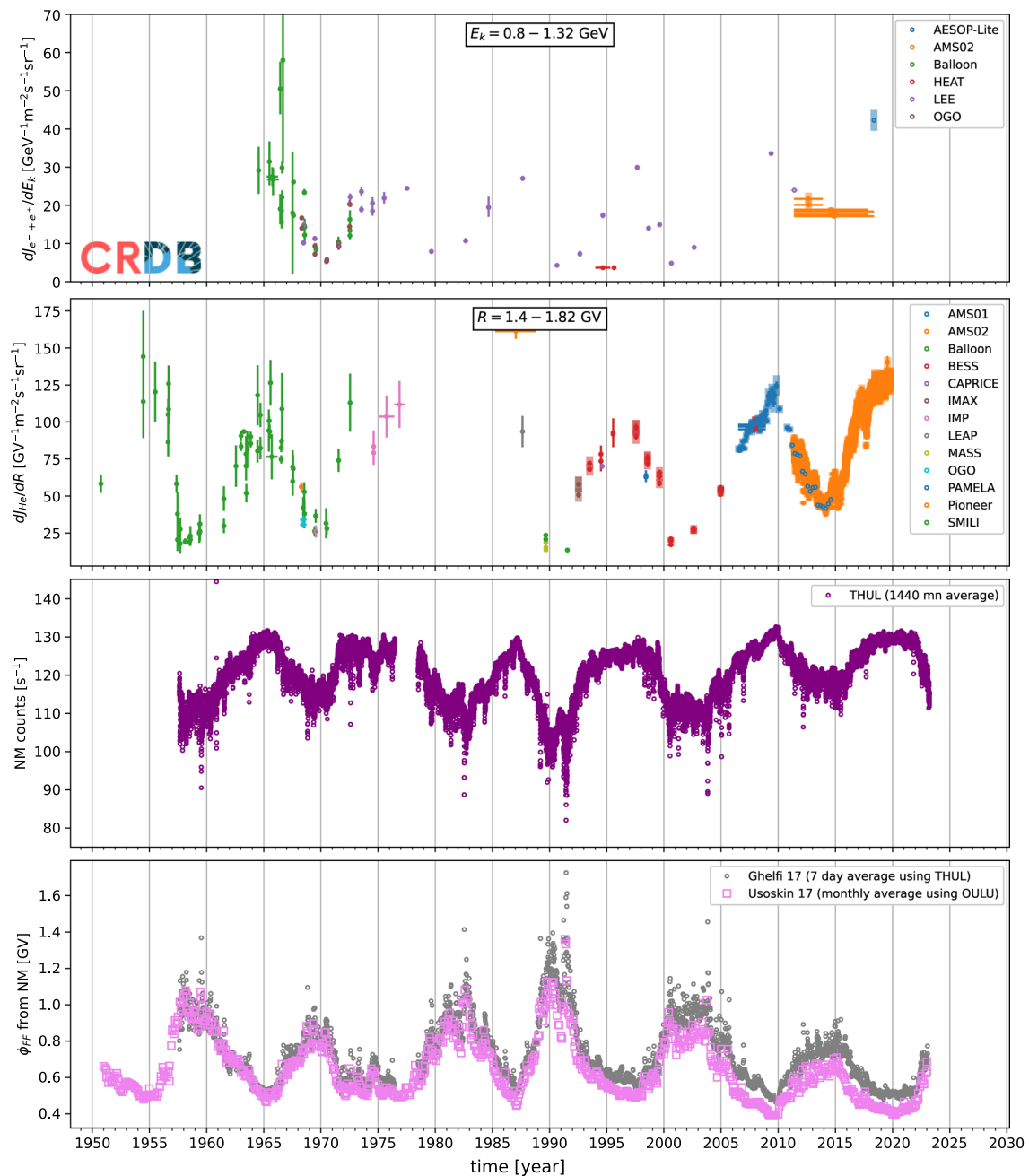


Fig. 6 First and second panels: GCR fluxes of low-energy $e^- + e^+$ and He over the last 70 years, illustrating the 11 years Solar cycle ('balloons' in the legend refers to unnamed balloons). Third panel: NM count rate from the Thule NM station retrieved from the NEST NMDB interface at <https://www.nmdb.eu/next/help.php#helptres>. Bottom panel: Solar

modulation level reconstructed from NM data [e.g., 149], as retrieved from CRDB's *Solar Modulation* REST interface and whose values are based on [1, 150, 151], or as retrieved from <https://cosmicrays.oulu.fi/phi/> [10]. The figure is available from the gallery notebook¹⁵

available, the information from the stratospheric balloon flight catalogue *StratoCat*²⁰ was used. The list of the balloon flight names as encoded in CRDB along with the associated publications are listed in Table 5.

4.6 AMS-02 and PAMELA time series

In CRDB previous releases, a few time series were already included: yearly averaged (1994–2014) proton fluxes from EPHIN [152], monthly or Carrington rotation average (2006–

²⁰ <https://stratocat.com.ar/indexe.html>.

Table 5 Lepton data from the LEE, AESOP, and AESOP-Lite balloons flown over a 50-year time period, re-organised, corrected, and with a few new data sets added in CRDB v4. 1

Subexp NAME	References	Qty	N_{data}
LEE (1968/06–1968/07)	[137]	$e^- + e^+$	16
LEE (1969/06–1969/07)	[137]	$e^- + e^+$	18
LEE (1970/06–1970/07)	[137]	$e^- + e^+$	17
LEE (1971/06–1971/07)	[137]	$e^- + e^+$	18
LEE (1972/07)	[137]	$e^- + e^+$	16
LEE (1973/07)	[140]	$e^- + e^+$	30
LEE (1974/07)	[140]	$e^- + e^+$	16
LEE (1975/07)	[141]	$e^- + e^+$	10
LEE (1977/07)	[142]	$e^- + e^+$	12
LEE (1979/08–1979/09)	[143]	$e^- + e^+$	8
LEE (1982/08)	[143]	$e^- + e^+$	7
LEE (1984/09)	[42]	$e^- + e^+$	10
LEE (1987/08)	[144]	$e^- + e^+$	8
LEE (1990/08)	[144]	$e^- + e^+$	6
LEE (1992/08)	[144]	$e^- + e^+$	7
LEE (1994/08)	[144]	$e^- + e^+$	8
LEE (1997/09)	This paper	$e^- + e^+$	9
LEE (1998/08–1998/09)	This paper	$e^- + e^+$	8
LEE (1999/08)	This paper	$e^- + e^+$	9
LEE (2000/08)	This paper	$e^- + e^+$	8
LEE (2002/08)	[138]	$e^- + e^+$	15
LEE (2009/05)	[145]	$e^- + e^+$	15
LEE (2011/05)	[145]	$e^- + e^+$	15
AESOP (1994/08)	[139]	$e^+/(e^- + e^+)$	1
AESOP (1997/09+1998/08)	[146]	$e^+/(e^- + e^+)$	4
AESOP (1999/08)	[147]	$e^+/(e^- + e^+)$	6
AESOP (2000/08)	[147]	$e^+/(e^- + e^+)$	3
AESOP (2002/08)	[138]	$e^+/(e^- + e^+)$	3
AESOP (2006/06)	[148]	$e^+/(e^- + e^+)$	4
AESOP-Lite (2018/05)	[145]	$e^+/(e^- + e^+), e^-/+$	27

2014) proton fluxes from PAMELA [153, 154], and 6 month average (2006–2009) electron fluxes from PAMELA [155].

Thanks to its large acceptance and high statistics, AMS-02 was able, for the first time, to provide daily averaged fluxes of H, He, and He/H from 2011 to 2019 [156, 157], and e^- from 2011 to 2021 [158]: these data are now the dominant body of data in CRDB, with about 200,000 data points over ~ 3000 days (Table 6).

We also added the recently published He time series of PAMELA from 2006 to 2013. Owing to its smaller acceptance and statistics, the data were averaged over one Carrington rotation (~ 1 month) in the first three years [159], and over three Carrington rotations later because of a *random failure of a few front-end chips in the tracking system [...] particularly significant after 2009* [160]; this corresponds to ~ 3000 new data points in CRDB (in $E_{k/n}$ and R), as retrieved

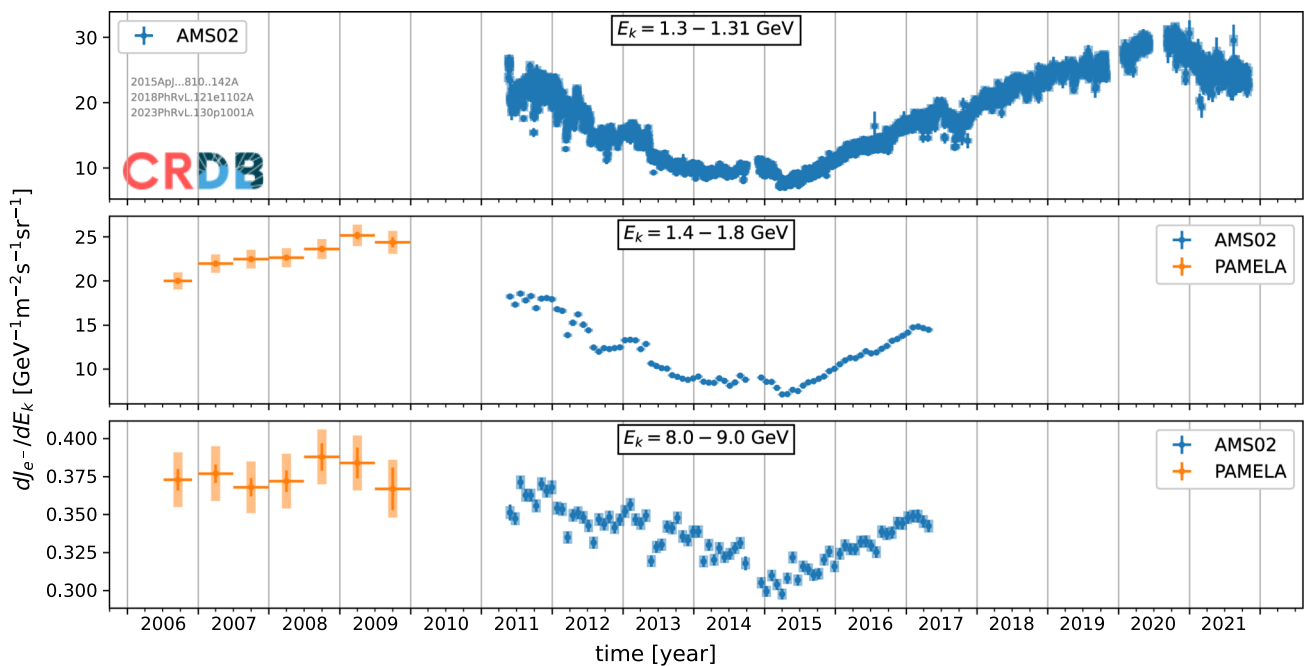
from the ‘CRDB@ASI’ database²¹ [161]. We also added a few positron fraction data points taken from three different time periods [162]: the latter paper also provides 3-month averages (2006–2016) of the e^+/e^- ratio, but normalised to the unspecified 2006 value, so we did not add them in CRDB.

To better visualise these data, we added a new query option in the web interface to plot data as a function of time (instead of energy). The direct benefit is to enable showing the evolution of data from similar energy bands over long time periods. This is illustrated with Fig. 7, available from the gallery notebook¹⁵.

²¹ <https://tools.ssdc.asi.it/CosmicRays/>.

Table 6 AMS-02 and PAMELA time series added in CRDB v4.1

Subexp NAME	References	Qty	N_{data}
<i>AMS-02 (daily average)</i>			
AMS02 (2011/05/20 to 2019/10/29)	[163]	H	83,757
AMS02 (2011/05/20 to 2019/10/29)	[157]	He, He/H	72,879
AMS02 (2011/05/20 to 2021/11/02)	[158]	e^-	32,985
<i>PAMELA (average over Carrington rotations)</i>			
PAMELA (2006/07 – 2009/12)	[162]	$e^+/(e^- + e^+)$	15
PAMELA (2011/05 – 2013/11)			
PAMELA (2015/01 – 2015/12)			
PAMELA (2006/07 to 2009/12)	[159]	He	2322
PAMELA (2010/01 to 2013/09)	[160]	He	1026

**Fig. 7** Electron time series from AMS-02 [156, 158] and PAMELA [154], see Table 2. The figure is available from the gallery notebook¹⁵

5 Conclusions and future releases

We have presented in this paper CRDB v4.1, an update of the CR database hosted at LPSC. On the technical side, this update involved a migration of CRDB server and a slight simplification of the DB structure. On the code side, a few minor bugs have been fixed, the queried data can now be returned in a more complete *csv* format (which includes all metadata), and we fixed a missing combination rule for the data. On the web interface side, we added a new plotting capability to display CRs as a function of time, and added two new tabs: one lists all caveats related to the preparation of the data uploaded in CRDB and to the (sometimes approximate) transformation rules made on the queried data; the other provides a gallery of plots advertising and illustrating the diversity of CRDB data. Actually, this gallery and many other plots can

be generated from our new public python CRDB library, and notebook examples are provided in the git page¹⁵.

On the content side, we enlarged the scope and content of CRDB, with the addition of dipole anisotropy data, high-energy upper limits on \bar{p} , a large number of UHECR datasets, and also time series data. The latter include recently released AMS-02 daily and PAMELA monthly data, but also yearly data from LEE, AESOP or AESOP-Lite balloons taken over a 50 year period. We also updated CRDB data with all the GCR data published in the last three years, also adding a couple of older data that had slipped our attention until now.

The path to future developments is not very clear and also depends on the feedback from the community. Indeed, CRDB now accounts for most galactic and extragalactic CR data, in terms of quantities that can be cast as 1D data vectors (as opposed to sky maps or higher-dimension data cubes). Miss-

ing datasets should consist mostly of old time series from satellite experiments, which are both difficult to track and retrieve from the publications: owners and authors of such datasets are welcome to get in touch with us. If need be, other quantities related to UHECR data could also be added in the future, like $\langle \ln A \rangle$. In any case, looking at present and future high-precision CR data, we stress that the current format to store uncertainties in CRDB is already limited and should probably be improved at some time in the future. Indeed, data from the last generation of CR detectors already come with broken-down contributions from various systematics, whereas only the total systematics can be stored in CRDB. This issue will worsen when covariance matrix of uncertainties will start to be released as well (as is already the case for instance for the most recent Pierre Auger data).

The CRDB team will continue uploading newly published CR data, but we also encourage collaborations to prepare their data (CRDB submission format) if they wish them to quickly be distributed via CRDB. Comments, questions, suggestions, and corrections on are welcome and are to be sent at crdb@lpsc.in2p3.fr.

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Data availability statement The authors declare that all the data underlying this article are available from CRDB at <https://lpsc.in2p3.fr/crdb>.]

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Appendix A: Convention for energy units

When comparing spectra of different nuclei, a convenient energy variable is energy per nucleon. It has become customary to indicate the use of energy per nucleon by employing non-standard units, e.g. GeV/n, which is to be contrasted to simply GeV for energy. After thoroughly discussing the issue, we chose to break with tradition for this paper and for the revision of the CRDB. Instead we use the energy unit GeV throughout and indicate by other means (by using different quantity symbols and via textual description) whether an energy is given per nucleon or given per particle.

The original motivation for using both GeV and GeV/n was to distinguish between energy per particle and energy per nucleon, but this distinction is redundant if a distinction via a quantity symbol (for example, E_k and $E_{k/n}$) and a textual description of the quantity is also given. The latter is anyway required, since the meaning of the non-standard unit GeV/n is not universally understood, since it does not adhere to the International System of Units (SI) [164]. In the SI, units are mathematical entities that must be constants and combinations of SI base units: the unit of a quantity that describes an energy per nucleon is still just the energy unit.

In summary, we believe that dropping the use of GeV/n in CRDB will not harm the clarity of our presentation, and by following the SI, it will simplify communicating with other fields.

References

1. A. Ghelfi, D. Maurin, A. Cheminet, L. Derome, G. Hubert, F. Melot, *Adv. Space Res.* **60**, 833 (2017). <https://doi.org/10.1016/j.asr.2016.06.027>
2. Z.N. Shen, G. Qin, P. Zuo, F. Wei, *ApJ* **887**(2), 132 (2019). <https://doi.org/10.3847/1538-4357/ab5520>
3. D. Maurin, F. Melot, R. Taillet, *A&A* **569**, A32 (2014). <https://doi.org/10.1051/0004-6361/201321344>
4. D. Maurin, H.P. Dembinski, J. Gonzalez, I.C. Mariş, F. Melot, *Universe* **6**(8), 102 (2020). <https://doi.org/10.3390/universe6080102>
5. A. Haungs, D. Kang, S. Schoo, D. Wochele, J. Wochele, W.D. Apel, J.C. Arteaga-Velázquez, K. Bekk, M. Bertaina, J. Blümer et al., *Eur. J. Phys. C* **78**(9), 741 (2018). <https://doi.org/10.1140/epjc/s10052-018-6221-2>
6. M. Ahlers, P. Mertsch, *Prog. Theor. Exp. Phys.* **94**, 184 (2017). <https://doi.org/10.1016/j.ppnp.2017.01.004>
7. L.J. Gleeson, W.I. Axford, *ApJL* **149**, L115 (1967). <https://doi.org/10.1086/180070>
8. L.J. Gleeson, W.I. Axford, *ApJ* **154**, 1011 (1968). <https://doi.org/10.1086/149822>
9. I.G. Usoskin, K. Alanko-Huotari, G.A. Kovaltsov, K. Mursula, *J. Geophys. Res.* **110**, A12108 (2005). <https://doi.org/10.1029/2005JA011250>
10. I.G. Usoskin, A. Gil, G.A. Kovaltsov, A.L. Mishev, V.V. Mikhailov, *J. Geophys. Res.* **122**(4), 3875 (2017). <https://doi.org/10.1002/2016JA023819>
11. C.R. Harris, K.J. Millman, S.J. van der Walt et al., *Nature* **585**(7825), 357 (2020). <https://doi.org/10.1038/s41586-020-2649-2>

12. M.W. Friedlander, C.T. Spring, *Il Nuovo Cimento* **26**(6), 1292 (1962). <https://doi.org/10.1007/BF02780357>
13. W.R. Webber, J.A. Lezniak, J.C. Kish, G.A. Simpson, *Astrophys. Lett.* **18**, 125 (1977)
14. J. Tueller, P.L. Love, M.H. Israel, J. Klarmann, *ApJ* **228**, 582 (1979). <https://doi.org/10.1086/156882>
15. W.R. Webber, J. Kish, *ICRC* **1**, 389 (1979)
16. R.K. Sood, *Nature* **301**(5895), 44 (1983). <https://doi.org/10.1038/301044a0>
17. E. Kamioka, M. Hareyama, M. Ichimura, Y. Ishihara, T. Kobayashi, H. Komatsu, S. Kuramata, K. Maruguchi, H. Matsutani, A. Mihashi et al., *Astropart. Phys.* **6**, 155 (1997). [https://doi.org/10.1016/S0927-6505\(96\)00051-5](https://doi.org/10.1016/S0927-6505(96)00051-5)
18. J. Clem, W. Droege, P.A. Evenson, H. Fischer, G. Green, D. Huber, H. Kunow, D. Seckel, *Astropart. Phys.* **16**(4), 387 (2002). [https://doi.org/10.1016/S0927-6505\(01\)00123-2](https://doi.org/10.1016/S0927-6505(01)00123-2)
19. E.J. Grove, R.E. Christian, A.R. Mewaldt, M.S. Schindler, C.E. Stone, A. Buffington, L.I. Rasmussen, *ICRC* **3**, 53 (1990)
20. Y. Takahashi, *Nucl. Phys. B Proc. Suppl.* **60**(3), 83 (1998). [https://doi.org/10.1016/S0920-5632\(97\)00503-3](https://doi.org/10.1016/S0920-5632(97)00503-3)
21. A.V. Apanasenko, V.A. Sukhadolskaya, V.A. Derbina et al., (Runjob Collaboration), *Astropart. Phys.* **16**(1), 13 (2001). [https://doi.org/10.1016/S0927-6505\(00\)00163-8](https://doi.org/10.1016/S0927-6505(00)00163-8)
22. V.A. Derbina, V.I. Galkin, M. Hareyama, Y. Hirakawa, Y. Horiuchi, M. Ichimura, N. Inoue, E. Kamioka, T. Kobayashi, V.V. Kopenkin et al., *ApJL* **628**, L41 (2005). <https://doi.org/10.1086/432715>
23. I.P. Ivanenko, V.Y. Shestoporov, L.O. Chikova, I.M. Fateeva, L.A. Khein, D.M. Podorozhnyi, I.D. Rapoport, G.A. Samsonov, V.A. Sobinyakov, A.N. Turundaevskiy, I.V. Yashin, *ICRC* **2**, 17 (1993)
24. A. Alexandrov, P. Babaev, A. Bagulya et al., *Adv. Space Res.* **70**(9), 2674 (2022). <https://doi.org/10.1016/j.asr.2022.06.055>
25. M.E. Wiedenbeck, W.R. Binns, E.R. Christian, A.C. Cummings, A.J. Davis, J.S. George, P.L. Hink, M.H. Israel, R.A. Leske, M. Lijowski, R.A. Mewaldt, E.C. Stone, T.T. von Rosenvinge, N.E. Yanasak, *Adv. Space Res.* **27**(4), 773 (2001). [https://doi.org/10.1016/S0273-1177\(01\)00120-X](https://doi.org/10.1016/S0273-1177(01)00120-X)
26. W.R. Binns, M.H. Israel, E.R. Christian, A.C. Cummings, G.A. de Nolfo, K.A. Lave, R.A. Leske, R.A. Mewaldt, E.C. Stone, T.T. von Rosenvinge, M.E. Wiedenbeck, *Science* **352**(6286), 677 (2016). <https://doi.org/10.1126/science.aad6004>
27. W.R. Binns, M.E. Wiedenbeck, T.T. von Rosenvinge, M.H. Israel, E.R. Christian, A.C. Cummings, G.A. de Nolfo, R.A. Leske, R.A. Mewaldt, E.C. Stone, *ApJ* **936**(1), 13 (2022). <https://doi.org/10.3847/1538-4357/ac82e7>
28. M. Aguilar, L. Ali Cavazonza, G. Ambrosi et al., (AMS Collaboration), *Phys. Rep.* **894**, 1 (2021). <https://doi.org/10.1016/j.physrep.2020.09.003>
29. M. Aguilar, L. Ali Cavazonza, M.S. Allen et al., (AMS Collaboration), *Phys. Rev. Lett.* **126**(8), 081102 (2021). <https://doi.org/10.1103/PhysRevLett.126.081102>
30. M. Aguilar, L. Ali Cavazonza, M.S. Allen et al., (AMS Collaboration), *Phys. Rev. Lett.* **126**(4), 041104 (2021). <https://doi.org/10.1103/PhysRevLett.126.041104>
31. M. Aguilar, L. Ali Cavazonza, B. Alpat et al., (AMS Collaboration), *Phys. Rev. Lett.* **127**(2), 021101 (2021). <https://doi.org/10.1103/PhysRevLett.127.021101>
32. M. Aguilar, L. Ali Cavazonza, B. Alpat et al., (AMS Collaboration), *Phys. Rev. Lett.* **130**(21), 211002 (2023). <https://doi.org/10.1103/PhysRevLett.130.211002>
33. O. Adriani, Y. Akaïke, K. Asano et al., (CALET Collaboration), *Phys. Rev. Lett.* **125**(25), 251102 (2020). <https://doi.org/10.1103/PhysRevLett.125.251102>
34. O. Adriani, Y. Akaïke, K. Asano et al., (CALET Collaboration), *Phys. Rev. Lett.* **126**(24), 241101 (2021). <https://doi.org/10.1103/PhysRevLett.126.241101>
35. O. Adriani, Y. Akaïke, K. Asano et al., (CALET Collaboration), *Phys. Rev. Lett.* **129**(25), 251103 (2022). <https://doi.org/10.1103/PhysRevLett.129.251103>
36. O. Adriani, Y. Akaïke, K. Asano et al., (CALET Collaboration), *Phys. Rev. Lett.* **129**(10), 101102 (2022). <https://doi.org/10.1103/PhysRevLett.129.101102>
37. O. Adriani, Y. Akaïke, K. Asano et al., (CALET Collaboration), *Phys. Rev. Lett.* **128**(13), 131103 (2022). <https://doi.org/10.1103/PhysRevLett.128.131103>
38. O. Adriani, Y. Akaïke, K. Asano et al., (CALET Collaboration), *Phys. Rev. Lett.* **130**(17), 171002 (2023). <https://doi.org/10.1103/PhysRevLett.130.171002>
39. Q. An, R. Asfandiyarov, P. Azzarello et al., (DAMPE Collaboration), *Sci. Adv.* **5**(9), eaax3793 (2019). <https://doi.org/10.1126/sciadv.aax3793>
40. F. Alemanno, Q. An, P. Azzarello et al., (DAMPE Collaboration), *Phys. Rev. Lett.* **126**(20), 201102 (2021). <https://doi.org/10.1103/PhysRevLett.126.201102>
41. DAMPE Collaboration, *Sci. Bull.* **67**(21), 2162 (2022). <https://doi.org/10.1016/j.scib.2022.10.002>
42. M. Garcia-Munoz, P. Meyer, K.R. Pyle, J.A. Simpson, P. Evenson, J. Geophys. Res. **91**, 2858 (1986). <https://doi.org/10.1029/JA091iA03p02858>
43. G.H. Choi, E.S. Seo, S. Aggarwal et al., (ISS-CREAM Collaboration), *ApJ* **940**(2), 107 (2022). <https://doi.org/10.3847/1538-4357/ac9d2c>
44. D.E. Karmanov, I.M. Kovalev, I.A. Kudryashov, A.A. Kurganov, A.D. Panov, D.M. Podorozhny, A.N. Turundaevskiy, O.A. Vasiliev, *Sov. J. Exp. Theor. Phys. Lett.* **111**(7), 363 (2020). <https://doi.org/10.1134/S002136402007005X>
45. A.N. Turundaevskiy, O.A. Vasiliev, D.E. Karmanov, I.M. Kovalev, I.A. Kudryashov, A.A. Kurganov, A.D. Panov, D.M. Podorozhny, *BRASP* **85**(4), 353 (2021). <https://doi.org/10.3103/S1062873821040377>
46. V. Grebenyuk, D. Karmanov, I. Kovalev, I. Kudryashov, A. Kurganov, A. Panov, D. Podorozhny, A. Tkachenko, L. Tkachev, A. Turundaevskiy, O. Vasiliev, A. Voronin, *Adv. Space Res.* **64**(12), 2559 (2019). <https://doi.org/10.1016/j.asr.2019.06.030>
47. V. Grebenyuk, D. Karmanov, I. Kovalev, I. Kudryashov, A. Kurganov, A. Panov, D. Podorozhny, A. Tkachenko, L. Tkachev, A. Turundaevskiy, O. Vasiliev, A. Voronin, *Adv. Space Res.* **64**(12), 2546 (2019). <https://doi.org/10.1016/j.asr.2019.10.004>
48. D. Karmanov, I. Kovalev, I. Kudryashov, A. Kurganov, A. Panov, D. Podorozhny, A. Turundaevskiy, O. Vasiliev, *Phys. Lett. B* **811**, 135851 (2020). <https://doi.org/10.1016/j.physletb.2020.135851>
49. F. Nozzoli, C. Cernetti, *Universe* **7**(6), 183 (2021). <https://doi.org/10.3390/universe7060183>
50. E.K. Shirk, P.B. Price, *ApJ* **220**, 719 (1978). <https://doi.org/10.1086/155955>
51. P. Ferrando, N. Lal, F.B. McDonald, W.R. Webber, *A&A* **247**, 163 (1991)
52. N.E. Walsh, Y. Akaïke, W.R. Binns, R.G. Bose, T.J. Brandt, D.L. Braun, N.W. Cannady, P.F. Dowkontt, T. Hams, M.H. Israel, J.F. Krizmanic, A.W. Labrador, R.A. Mewaldt, J.W. Mitchell, R.P. Murphy, G.A. de Nolfo, S. Nutter, M.A. Olevitch, B.F. Rauch, K. Sakai, M. Sasaki, G.E. Simburger, E.C. Stone, T. Tatoli, J.E. Ward, M.E. Wiedenbeck, W.V. Zober, *Adv. Space Res.* **70**(9), 2666 (2022). <https://doi.org/10.1016/j.asr.2022.04.063>
53. A.B. Alexandrov, A.V. Bagulya, P.A. Babaev, M.M. Chernyavsky, A.A. Gippius, S.A. Gorbunov, V.M. Grachev, G.V. Kalinina, N.S. Konovalova, N.M. Okateva, N.G. Polukhina, R.A. Rymzhanov, N.I. Starkov, T.N. Soe, T.V. Shchedrina, A.E. Volkov, R.A. Voronkov, *Phys. At. Nucl.* **85**(5), 446 (2022). <https://doi.org/10.1134/S1063778822050039>
54. V. Alexeev, A. Bagulya, M. Chernyavsky, A. Gippius, L. Goncharova, S. Gorbunov, M. Gorshenkov, G. Kalinina, N. Konoval-

- ova, J. Liu, P. Zhai, N. Okatyeva, T. Pavlova, N. Polukhina, N. Starkov, T. Naing Soe, C. Trautmann, E. Savchenko, T. Shchedrina, A. Vasiliev, A. Volkov, *ApJ* **829**(2), 120 (2016). <https://doi.org/10.3847/0004-637X/829/2/120>
55. G.V. Kalinina, T. NaingSoe, N.I. Starkov, *Phys. At. Nucl.* **84**(6), 849 (2021). <https://doi.org/10.1134/S1063778821060089>
 56. P.A. Babaev, A.V. Bagulya, A.E. Volkov, S.A. Gorbunov, G.V. Kalinina, N.S. Konovalova, N.M. Okateva, N.G. Polukhina, Z.T. Sadykov, N.I. Starkov, E.N. Starkova, T.N. Soe, M.M. Chernyavskiy, T.V. Shchedrina, *Sov. J. Exp. Theor. Phys.* **134**(4), 523 (2022). <https://doi.org/10.1134/S106377612204015X>
 57. B. Bartoli, P. Bernardini, X.J. Bi et al., (ARGO-YBJ Collaboration), *ApJ* **809**(1), 90 (2015). <https://doi.org/10.1088/0004-637X/809/1/90>
 58. B. Bartoli, P. Bernardini, X.J. Bi et al., (ARGO-YBJ Collaboration), *ApJ* **861**(2), 93 (2018). <https://doi.org/10.3847/1538-4357/aac6cc>
 59. L. Bergamasco, C.G. Castagnoli, M. Serio, G.O. Ryazhskaya, A.V. Kudrjavitsev, A.V. Kuznetsov, *ICRC* **6**, 372 (1990)
 60. Y.M. Andreyev, A.E. Chudakov, V.A. Kozyarivsky, A.M. Sidorenko, T.I. Tulupova, A.V. Voevodsky, *ICRC* **2**, 22 (1987)
 61. V.V. Alexeyenko, A.E. Chudakov, E.N. Gulieva, V.G. Sbornschikov, *ICRC* **2**, 146 (1981)
 62. V.V. Alekseenko, A.B. Cherniaev, D.D. Djappuev, A.U. Kudjaev, O.I. Michailova, Y.V. Stenkin, V.I. Stepanov, V.I. Volchenko, *Nucl. Phys. B Proc. Suppl.* **196**, 179 (2009). <https://doi.org/10.1016/j.nuclphysbps.2009.09.032>
 63. D.B. Swinson, K. Nagashima, *Planet. Space Sci.* **33**(9), 1069 (1985). [https://doi.org/10.1016/0032-0633\(85\)90025-X](https://doi.org/10.1016/0032-0633(85)90025-X)
 64. K. Nagashima, S. Sakakibara, A.G. Fenton, J.E. Humble, *Planet. Space Sci.* **33**(4), 395 (1985). [https://doi.org/10.1016/0032-0633\(85\)90084-4](https://doi.org/10.1016/0032-0633(85)90084-4)
 65. M. Aglietta, B. Alessandro, P. Antonioli et al., (EAS-Top Collaboration), *ApJ* **470**, 501 (1996). <https://doi.org/10.1086/177881>
 66. M. Aglietta, B. Alessandro, P. Antonioli, et al. (EAS-Top Collaboration), *ICRC* **2**, 800 (1995)
 67. M. Aglietta, V.V. Alekseenko, B. Alessandro et al., (Pierre Auger Collaboration), *ApJL* **692**(2), L130 (2009). <https://doi.org/10.1088/0004-637X/692/2/L130>
 68. A.U. Abeyssekara, R. Alfaro, C. Alvarez et al., (IceCube Collaboration), *ApJ* **871**(1), 96 (2019). <https://doi.org/10.3847/1538-4357/aaf5cc>
 69. Y.W. Lee, L.K. Ng, *ICRC* **2**, 18 (1987)
 70. R. Abbasi, Y. Abdou, T. Abu-Zayyad et al., (IceCube Collaboration), *ApJL* **718**(2), L194 (2010). <https://doi.org/10.1088/2041-8205/718/2/L194>
 71. M.G. Aartsen, K. Abraham, M. Ackermann et al., (IceCube Collaboration), *ApJ* **826**(2), 220 (2016). <https://doi.org/10.3847/0004-637X/826/2/220>
 72. J. Bourbeau, P. Desiati, J.C. Díaz Vélez, S. Westerhoff, IceCube Collaboration, *35th ICRC* **301**, 474 (2017). <https://doi.org/10.22323/1.301.0474>
 73. R. Abbasi, Y. Abdou, T. Abu-Zayyad et al., *ApJ* **746**(1), 33 (2012). <https://doi.org/10.1088/0004-637X/746/1/33>
 74. M.G. Aartsen, R. Abbasi, Y. Abdou et al., *ApJ* **765**(1), 55 (2013). <https://doi.org/10.1088/0004-637X/765/1/55>
 75. W.D. Apel, J.C. Arteaga-Velázquez, K. Bekk et al., (KASCADE-Grande Collaboration), *ApJ* **870**(2), 91 (2019). <https://doi.org/10.3847/1538-4357/aaf1ca>
 76. K. Munakata, T. Kiuchi, S. Yasue et al., *Phys. Rev. D* **56**(1), 23 (1997). <https://doi.org/10.1103/PhysRevD.56.23>
 77. W. Gao, W. Li, S. Cui, S. Chen, Z. Li, P. Zhang, C. Zhu, in *36th ICRC (ICRC2019)*, vol. 36 (2019), p. 263. <https://doi.org/10.22323/1.358.0263>
 78. W. Gao, Q. Cao, S. Chen, S. Cui, H. He, W. Li, S. Wu, H. Zhang, C. Zhu, Lhaaso Collaboration, in *37th ICRC* (2022), p. 351. <https://doi.org/10.22323/1.395.0351>
 79. K. Munakata, S. Yasue, S. Mori, C. Kato, M. Koyama, S. Akahane, Z. Fujii, H. Ueno, J.E. Humble, A.G. Fenton, K.B. Fenton, M.L. Duldig, in *ICRC*, vol. 4 (1995), p. 639
 80. T. Thamyahpillai, *ICRC* **3**, 383 (1983)
 81. M. Ambrosio, R. Antolini, A. Baldini et al., *Phys. Rev. D* **67**(4), 042002 (2003). <https://doi.org/10.1103/PhysRevD.67.042002>
 82. S. Mori, S. Yasue, K. Munakata, C. Kato, S. Akahane, M. Koyama, T. Kitawada, *ICRC* **4**, 648 (1995)
 83. D.J. Cutler, H.E. Bergeson, J.F. Davies, D.E. Groom, *ApJ* **248**, 1166 (1981). <https://doi.org/10.1086/159246>
 84. D.J. Cutler, D.E. Groom, *ApJ* **376**, 322 (1991). <https://doi.org/10.1086/170282>
 85. A.A. Abdo, B.T. Allen, T. Aune et al., *ApJ* **698**(2), 2121 (2009). <https://doi.org/10.1088/0004-637X/698/2/2121>
 86. S. Sakakibara, H. Ueno, K. Fujimoto, I. Kondo, K. Nagashima, *ICRC* **2**, 1058 (1973)
 87. K. Nagashima, K. Fujimoto, S. Sakakibara, Z. Fujii, H. Ueno, K. Murakami, I. Morishita, *Nuovo Cimento C* **12**, 695 (1989). <https://doi.org/10.1007/BF02511970>
 88. T. Gombosi, J. Kota, A.J. Somogyi, A. Varga, B. Betev, L. Katsarski, S. Kavlov, I. Khairov, *Nature* **255**, 687 (1975). <https://doi.org/10.1038/255687a0>
 89. T. Gombosi, J. Kota, A.J. Somogyi, A. Varga, B. Betev, L. Katsarski, S. Kavlov, I. Khairov, *ICRC* **11**, 109 (1977)
 90. M. Bercovitch, S.P. Agrawal, *ICRC* **10**, 246–249 (1981)
 91. A. Aab, P. Abreu, M. Aglietta et al., (Pierre Auger Collaboration), *ApJ* **868**(1), 4 (2018). <https://doi.org/10.3847/1538-4357/aac689>
 92. A. Aab, P. Abreu, M. Aglietta et al., (Pierre Auger Collaboration), *ApJ* **891**(2), 142 (2020). <https://doi.org/10.3847/1538-4357/ab7236>
 93. C. Morello, G. Navarra, P. Vallania, *ICRC* **2**, 137 (1983)
 94. K.B. Fenton, A.G. Fenton, J.E. Humble, *ICRC* **4**, 635 (1995)
 95. H. Ueno, Z. Fujii, T. Yamada, *ICRC* **6**, 361 (1990)
 96. G. Guillian, J. Hosaka, K. Ishihara et al., *Phys. Rev. D* **75**(6), 062003 (2007). <https://doi.org/10.1103/PhysRevD.75.062003>
 97. T. Fujii, et al., in *37th ICRC* (2022), p. 291. <https://doi.org/10.22323/1.395.0291>
 98. M. Amenomori, X.J. Bi, D. Chen et al., (Tibet AS γ Collaboration), *ApJ* **836**(2), 153 (2017). <https://doi.org/10.3847/1538-4357/836/2/153>
 99. M. Amenomori, S. Ayabe, S.W. Cui et al., (Tibet AS γ Collaboration), *ApJL* **626**(1), L29 (2005). <https://doi.org/10.1086/431582>
 100. M. Takeda, N. Sakaki, K. Honda et al., *Astropart. Phys.* **19**(4), 447 (2003). [https://doi.org/10.1016/S0927-6505\(02\)00243-8](https://doi.org/10.1016/S0927-6505(02)00243-8)
 101. F. Fenu, et al., in *35th ICRC*, vol. 301 (2017), p. 486. <https://doi.org/10.22323/1.301.0486>
 102. J. Abraham, P. Abreu, M. Aglietta et al., (Pierre Auger Collaboration), *Phys. Rev. Lett.* **101**(6), 061101 (2008). <https://doi.org/10.1103/PhysRevLett.101.061101>
 103. J. Abraham, P. Abreu, M. Aglietta et al., (Pierre Auger Collaboration), *Phys. Lett. B* **685**, 239 (2010). <https://doi.org/10.1016/j.physletb.2010.02.013>
 104. P. Abreu, M. Aglietta, J.M. Albury et al., (Pierre Auger Collaboration), *Eur. J. Phys. C* **81**(11), 966 (2021). <https://doi.org/10.1140/epjc/s10052-021-09700-w>
 105. S.P. Swordy, D.B. Kieda, *Astropart. Phys.* **13**(2–3), 137 (2000). [https://doi.org/10.1016/S0927-6505\(99\)00117-6](https://doi.org/10.1016/S0927-6505(99)00117-6)
 106. M. Aglietta, B. Alessandro, P. Antonioli et al., (EAS-Top Collaboration), *Astropart. Phys.* **10**(1), 1 (1999). [https://doi.org/10.1016/S0927-6505\(98\)00035-8](https://doi.org/10.1016/S0927-6505(98)00035-8)
 107. D.J. Bird, S.C. Corbato, H.Y. Dai et al., *ApJ* **424**, 491 (1994). <https://doi.org/10.1086/173906>

108. S. Ter-Antonyan, Phys. Rev. D **89**(12), 123003 (2014). <https://doi.org/10.1103/PhysRevD.89.123003>
109. A.P. Garyaka, R.M. Martirosov, S.V. Ter-Antonyan, A.D. Erlykin, N.M. Nikolskaya, Y.A. Gallant, L.W. Jones, J. Procureur, J. Phys. G Nucl. Phys. **35**(11), 115201 (2008). <https://doi.org/10.1088/0954-3899/35/11/115201>
110. M. Ave, J. Knapp, J. Lloyd-Evans, M. Marchesini, A.A. Watson, Astropart. Phys. **19**(1), 47 (2003). [https://doi.org/10.1016/S0927-6505\(02\)00188-3](https://doi.org/10.1016/S0927-6505(02)00188-3)
111. R. Alfaro, C. Alvarez, J.D. Álvarez et al., (HAWC Collaboration), Phys. Rev. D **96**(12), 122001 (2017). <https://doi.org/10.1103/PhysRevD.96.122001>
112. J.A. Morales-Soto, J.C. Arteaga-Velázquez, et al. (HAWC Collaboration), in *37th ICRC* (2022), p. 330. <https://doi.org/10.22323/1.395.0330>
113. HEGRA Collaboration, A&A **359**, 682 (2000). <https://doi.org/10.48550/arXiv.astro-ph/9908202>
114. M.G. Aartsen, M. Ackermann, J. Adams et al., Phys. Rev. D **100**(8), 082002 (2019). <https://doi.org/10.1103/PhysRevD.100.082002>
115. M.G. Aartsen, R. Abbasi, M. Ackermann et al., Phys. Rev. D **102**(12), 122001 (2020). <https://doi.org/10.1103/PhysRevD.102.122001>
116. M.G. Aartsen, R. Abbasi, Y. Abdou et al., Phys. Rev. D **88**(4), 042004 (2013). <https://doi.org/10.1103/PhysRevD.88.042004>
117. T. Antoni, W.D. Apel, A.F. Badea et al., (KASCADE Collaboration), Astropart. Phys. **24**(1–2), 1 (2005). <https://doi.org/10.1016/j.astropartphys.2005.04.001>
118. C.J. Arteaga-Velázquez, D. Rivera-Rangel, W.D. Apel, et al. (KASCADE-Grande Collaboration), in *35th ICRC*, vol. 301 (2017), p. 316. <https://doi.org/10.22323/1.301.0316>
119. W.D. Apel, J.C. Arteaga, F. Badea, et al. (KASCADE-Grande Collaboration), arXiv e-prints [arXiv:0906.4007](https://arxiv.org/abs/0906.4007) (2009). <https://doi.org/10.48550/arXiv.0906.4007>
120. W.D. Apel, J.C. Arteaga-Velázquez, K. Bekk et al., (KASCADE-Grande Collaboration), Phys. Rev. Lett. **107**(17), 171104 (2011). <https://doi.org/10.1103/PhysRevLett.107.171104>
121. W.D. Apel, J.C. Arteaga-Velázquez, K. Bekk et al., (KASCADE-Grande Collaboration), Astropart. Phys. **36**(1), 183 (2012). <https://doi.org/10.1016/j.astropartphys.2012.05.023>
122. W.D. Apel, J.C. Arteaga-Velázquez, K. Bekk et al., Phys. Rev. D **87**(8), 081101 (2013). <https://doi.org/10.1103/PhysRevD.87.081101>
123. A. Chilingarian, G. Gharagyozyan, S. Ghazaryan, G. Hovsepyan, E. Mamidjanyan, L. Melkumyan, V. Romakhin, A. Vardanyan, S. Sokhoyan, Astropart. Phys. **28**(1), 58 (2007). <https://doi.org/10.1016/j.astropartphys.2007.04.005>
124. N. Ito, S. Kawakami, Y. Hayashi, T. Matsuyama, M. Sasano, N. Ikeda, Y. Aikawa, ICRC **4**, 117 (1997)
125. I.I. Astapov, P.A. Bezyazeev, M. Blank et al., Sov. J. Exp. Theor. Phys. **134**(4), 469 (2022). <https://doi.org/10.1134/S1063776122040136>
126. R.U. Abbasi, M. Abe, T. Abu-Zayyad et al., (Telescope Array Collaboration), ApJ **865**(1), 74 (2018). <https://doi.org/10.3847/1538-4357/aada05>
127. M. Amenomori, X.J. Bi, D. Chen et al., (Tibet AS γ Collaboration), ApJ **678**(2), 1165 (2008). <https://doi.org/10.1086/529514>
128. A.A. Ivanov, S.P. Knurenko, I.Y. Sleptsov, New J. Phys. **11**(6), 065008 (2009). <https://doi.org/10.1088/1367-2630/11/6/065008>
129. M. Amenomori, Z. Cao, B.Z. Dai et al., ICRC **3**, 84 (1995)
130. M. Ambrosio, R. Antolini, A. Baldini et al., Astropart. Phys. **20**(2), 145 (2003). [https://doi.org/10.1016/S0927-6505\(03\)00169-5](https://doi.org/10.1016/S0927-6505(03)00169-5)
131. P. Achard, O. Adriani, M. Aguilar-Benitez et al., Astropart. Phys. **23**(4), 411 (2005). <https://doi.org/10.1016/j.astropartphys.2005.02.002>
132. M. Amenomori, S. Ayabe, X.J. Bi et al., (Tibet AS γ Collaboration), Astropart. Phys. **28**(1), 137 (2007). <https://doi.org/10.1016/j.astropartphys.2007.05.002>
133. B. Bartoli, P. Bernardini, X.J. Bi et al., (ARGO-YBJ Collaboration), Phys. Rev. D **85**(2), 022002 (2012). <https://doi.org/10.1103/PhysRevD.85.022002>
134. A.U. Abeysekara, A. Albert, R. Alfaro et al., (HAWC Collaboration), Phys. Rev. D **97**(10), 102005 (2018). <https://doi.org/10.1103/PhysRevD.97.102005>
135. A.A. Stephens, A&A **149**(1), 1 (1985)
136. D. Hovestadt, P. Meyer, P.J. Schmidt, Nucl. Instrum. Methods **85**(1), 93 (1970). [https://doi.org/10.1016/0029-554X\(70\)90125-4](https://doi.org/10.1016/0029-554X(70)90125-4)
137. G.J. Fulks, J. Geophys. Res. **80**, 1701 (1975). <https://doi.org/10.1029/JA080i013p01701>
138. J. Clem, P. Evenson, J. Geophys. Res. **109**, A07107 (2004). <https://doi.org/10.1029/2003JA010361>
139. J.M. Clem, D.P. Clements, J. Esposito, P. Evenson, D. Huber, J. L'Heureux, P. Meyer, C. Constantin, ApJ **464**, 507 (1996). <https://doi.org/10.1086/177340>
140. J. Caldwell, P. Evenson, S. Jordan, P. Meyer, ICRC **3**, 1000 (1975)
141. J.H. Caldwell, P. Evenson, S. Jordan, P. Meyer, ICRC **11**, 203 (1977)
142. P. Evenson, M. Garcia-Munoz, P. Meyer, K.R. Pyle, J.A. Simpson, ApJL **275**, L15 (1983). <https://doi.org/10.1086/184162>
143. P. Evenson, P. Meyer, J. Geophys. Res. **89**, 2647 (1984). <https://doi.org/10.1029/JA089iA05p02647>
144. P. Evenson, D. Huber, E.T. Patterson, J. Esposito, D. Clements, J. Clem, J. Geophys. Res. **100**, 7873 (1995). <https://doi.org/10.1029/95JA00484>
145. S. Mechbal, P.S. Mangeard, J.M. Clem, P.A. Evenson, R.P. Johnson, B. Lucas, J. Roth, ApJ **903**(1), 21 (2020). <https://doi.org/10.3847/1538-4357/abb46f>
146. J.M. Clem, P. Evenson, D. Huber, R. Pyle, C. Lopate, J.A. Simpson, J. Geophys. Res. **105**, 23099 (2000). <https://doi.org/10.1029/2000JA000097>
147. J.M. Clem, P.A. Evenson, ApJ **568**, 216 (2002). <https://doi.org/10.1086/338841>
148. J. Clem, P. Evenson, J. Geophys. Res. **114**(A13), A10108 (2009). <https://doi.org/10.1029/2009JA014225>
149. D. Maurin, A. Cheminet, L. Derome, A. Ghelfi, G. Hubert, Adv. Space Res. **55**, 363 (2015). <https://doi.org/10.1016/j.asr.2014.06.021>
150. A. Ghelfi, F. Barao, L. Derome, D. Maurin, A&A **591**, A94 (2016). <https://doi.org/10.1051/0004-6361/201527852>
151. A. Ghelfi, F. Barao, L. Derome, D. Maurin, A&A **605**, C2 (2017). <https://doi.org/10.1051/0004-6361/201527852e>
152. P. Kühn, R. Gómez-Herrero, B. Heber, Sol. Phys. **291**(3), 965 (2016). <https://doi.org/10.1007/s11207-016-0879-0>
153. O. Adriani, G.C. Barbarino, G.A. Bazilevskaya et al., (PAMELA Collaboration), ApJ **765**(2), 91 (2013). <https://doi.org/10.1088/0004-637X/765/2/91>
154. O. Adriani, G.C. Barbarino, G.A. Bazilevskaya et al., (PAMELA Collaboration), ApJ **810**, 142 (2015). <https://doi.org/10.1088/0004-637X/810/2/142>
155. M. Martucci, R. Munini, M. Boezio, V. Di Felice, O. Adriani, G.C. Barbarino, G.A. Bazilevskaya, R. Bellotti, M. Bongi, V. Bonvicini et al., ApJL **854**(1), L2 (2018). <https://doi.org/10.3847/2041-8213/aaa9b2>
156. M. Aguilar, L. Ali Cavazonza, B. Alpat et al., (AMS Collaboration), Phys. Rev. Lett. **121**(5), 051101 (2018). <https://doi.org/10.1103/PhysRevLett.121.051101>
157. M. Aguilar, L. Ali Cavazonza, G. Ambrosi et al., (AMS Collaboration), Phys. Rev. Lett. **128**(23), 231102 (2022). <https://doi.org/10.1103/PhysRevLett.128.231102>

158. M. Aguilar, L. Ali Cavasonza, G. Ambrosi et al., (AMS Collaboration), *Phys. Rev. Lett.* **130**(16), 161001 (2023). <https://doi.org/10.1103/PhysRevLett.130.161001>
159. N. Marcelli, M. Boezio, A. Lenni et al., (PAMELA Collaboration), *ApJ* **893**(2), 145 (2020). <https://doi.org/10.3847/1538-4357/ab80c2>
160. N. Marcelli, M. Boezio, A. Lenni et al., (PAMELA Collaboration), *ApJL* **925**(2), L24 (2022). <https://doi.org/10.3847/2041-8213/ac4787>
161. V. Di Felice, C. Pizzolotto, D. D'Urso, S. Dari, D. Navarra, R. Primavera, B. Bertucci, in *35th ICRC*, vol. 301 (2017), p. 1073
162. O. Adriani, G.C. Barbarino, G.A. Bazilevskaya et al., (PAMELA Collaboration), *Phys. Rev. Lett.* **116**(24), 241105 (2016). <https://doi.org/10.1103/PhysRevLett.116.241105>
163. M. Aguilar, L. Ali Cavasonza, G. Ambrosi et al., (AMS Collaboration), *Phys. Rev. Lett.* **127**(27), 271102 (2021). <https://doi.org/10.1103/PhysRevLett.127.271102>
164. *The International System of Units*, 9th edn. (Bureau international Des Poids et mesures, 2022). <https://www.bipm.org/en/publications/si-brochure>