



*International
Virtual
Observatory
Alliance*

Virtual Observatory and High Energy Astrophysics

Version 0.6

IVOA Note 2024-09-27

Working Group

DM

This version

<https://www.ivoa.net/documents/VOHE-Note/20240927>

Latest version

<https://www.ivoa.net/documents/VOHE-Note>

Previous versions

This is the first public release

Author(s)

HE club

Editor(s)

Mathieu Servillat

Version Control

Revision c914501, 2024-09-27 16:33:09 +0200

Abstract

Virtual Observatory and High Energy Astrophysics

Status of this document

This is an IVOA Note expressing suggestions from and opinions of the authors. It is intended to share best practices, possible approaches, or other perspectives on interoperability with the Virtual Observatory. It should not be referenced or otherwise interpreted as a standard specification.

A list of current IVOA Recommendations and other technical documents can be found at <https://www.ivoa.net/documents/>.

Contents

1	Introduction	4
1.1	Objectives of the document	4
1.2	Scope of the document	5
2	High Energy observatories and experiments	5
2.1	Gamma-ray programs	5
2.1.1	H.E.S.S	5
2.1.2	CTAO	6
2.2	X-ray programs	7
2.2.1	Chandra	7
2.2.2	XMM-Newton	8
2.2.3	SVOM	9
2.3	KM3Net and neutrino detection	10
3	Common practices in the High Energy community	10
3.1	Data specificities	11
3.1.1	Event-counting	11
3.1.2	Data levels	11
3.1.3	Background signal	12
3.1.4	Time intervals	12
3.1.5	Instrument Response Functions	12
3.1.6	Granularity of data products	13
3.2	Work flow specificities	14
3.2.1	Event selection	14
3.2.2	Assumptions and probabilistic approach	14
3.3	Data formats	14
3.3.1	OGIP	14
3.3.2	GADF and VODF	15
3.4	Tools for data extraction and visualisation	15
4	Use Cases	16
4.1	UC1: re-analyse event-list data for a source in a catalog	17
4.2	UC2: observation preparation	17
4.3	UC3: transient or variable sources	17
4.4	UC4: Multi-wavelength and multi-messenger science	17
4.5	UC5: Extended source searches	18

5	IVOA standards of interest for HE	18
5.1	IVOA Recommendations	18
5.1.1	ObsCore and TAP	18
5.1.2	DataLink	19
5.1.3	HiPS	19
5.1.4	MOCs	19
5.1.5	MIVOT	19
5.1.6	Provenance	20
5.2	Data Models in working drafts	20
5.2.1	Mango	20
6	Topics for discussions in an Interest Group	21
6.1	Definition of a HE event in the VO	21
6.1.1	Current definition in the VO	21
6.1.2	Proposed definition to be discussed	21
6.2	ObsCore metadata description of an event-list	22
6.2.1	Usage of the mandatory terms in ObsCore	22
6.2.2	Metadata re-interpretation for the VOHE context	23
6.2.3	Metadata addition required	24
6.2.4	Access and Description of IRFs	25
6.3	Event-list Context Data Model	25
6.4	Use of Datalink for HE products	25
	References	27
	A Changes from Previous Versions	33

Acknowledgments

We acknowledge support from the ESCAPE project funded by the EU Horizon 2020 research and innovation program (Grant Agreement n.824064). Additional funding was provided by the INSU (Action Spécifique Observatoire Virtuel, ASOV), the Action Fédératrice CTA and the Action Pluriannuelle Incitatrice Astrophysique des processus de Hautes Énergies at the Observatoire de Paris, and the Paris Astronomical Data Centre (PADC).

Conformance-related definitions

The words “MUST”, “SHALL”, “SHOULD”, “MAY”, “RECOMMENDED”, and “OPTIONAL” (in upper or lower case) used in this document are to be interpreted as described in IETF standard RFC2119 (Bradner, 1997).

The *Virtual Observatory (VO)* is a general term for a collection of federated resources that can be used to conduct astronomical research, education, and outreach. The [International Virtual Observatory Alliance \(IVOA\)](#) is a global collaboration of separately funded projects to develop standards and infrastructure that enable VO applications.

1 Introduction

High Energy (HE) astronomy typically includes X-ray astronomy, gamma-ray astronomy of the GeV range (HE), the TeV range (very high energy, VHE) up to the ultra high energy (UHE) above 100 TeV, the VHE neutrino astronomy, and studies of cosmic rays. This domain is now sufficiently developed to provide high level data such as catalogs, images, including full-sky surveys for some missions, and sources properties in the shape of spectra and time series. Such high level, HE observations have been included in the VO, via data access endpoints provided by observatories or by agencies and indexed in the VO Registry.

However, after browsing this data, users may want to download lower level data and reapply data reduction steps relevant to their Science objectives. A common scenario is to download HE "event" lists, i.e. lists of detected events on a HE detector, that are expected to be detection of particles (e.g. a HE photon), and the corresponding calibration files, including Instrument Response Functions (IRFs). The findability and accessibility of these data via the VO is the focus of this note.

We first report typical use cases for data access and analysis of data from current HE observatories. From those use cases, we note that some existing IVOA recommendations are of interest to the domain. They should be further explored by HE observatories. We then discuss how standards could evolve to better integrate specific aspects of HE data, and if new standards should be developed.

1.1 Objectives of the document

The main objective of the document is to analyse how HE data can be better integrated to the VO.

We first identify and expose the specificities of HE data from several HE observatories. Then we intend to illustrate how HE data is or can be handled using current IVOA standards. Finally, we explore several topics that could lead to HE specific recommendations.

A related objective is to provide a context and a list of topics to be further discussed within the IVOA by a dedicated HE Interest Group (HEIG).

1.2 Scope of the document

This document mainly focuses on HE data discovery through the VO, with the identification of common use cases in the HE astrophysics domain, which provides an insight of the specific metadata to be expose through the VO for HE data.

Some current existing IVOA recommendations are discussed in this document within the HE context and they will be in-depth studied in the HEIG.

2 High Energy observatories and experiments

There are various observatories, either from ground, space or deep-sea based, that distribute high-energy data with different level of involvement in the VO. We list here the observatories currently represented in the VO HE group. There are also other observatories that are connected to the VO in some way, and may join the group discussions at IVOA.

2.1 Gamma-ray programs

2.1.1 H.E.S.S

The High Energy Steresopic System (H.E.S.S.) experiment is an array of Imaging Atmospheric Cherenkov Telescopes (IACT) located in Namibia that investigates cosmic very high energies (VHE) gamma rays in the energy range from 10s of GeV to 100 of TeV. It is constituted of four telescopes officially inaugurated in 2004, and a much larger fifth telescope operational since 2012, extending the energy coverage towards lower energies and further improving sensitivity.

The H.E.S.S. collaboration operates the telescopes as a private experiment and publishes mainly high level data, i.e. images, time series and spectra in scientific publications after dedicated analyses. Using complex algorithms, private software process the raw data by applying calibration, reconstructing event properties from their Cherenkov images and purifying the event list by removing as much as possible events induced by atmospheric cosmic rays (CRs). Even after this purification, events are largely generated by CRs and statistical analyses are required to derive the astrophysical source properties. Models of background due to the remaining CRs (generally generated from real observations) are used with the gamma-ray IRFs (PSF, Energy Dispersion, Collection Area) that are generated by extensive Monte Carlo simulations. These 4 IRFs (background, PSF, Edisp, CollArea) are computed for each observation of ~ 30 min and are valid for the field of view. They depend on true energies, positions in the field of view and sometimes from event classification types. The derivation of astrophysi-

cal quantities from the event lists are now using open libraries, in particular the reference library Gammapy (Donath and Terrier et al., 2023).

In September 2018, the H.E.S.S. collaboration has, for the first time and unique time, released a small subset of its archival data using the GADF format (see 3.3.2) serialized into the Flexible Image Transport System (FITS) format, an open file format widely used in astronomy. The release consists of Cherenkov event-lists and IRFs for observations of various well-known gamma-ray sources (H.E.S.S. Collaboration, 2018).

This test data collection has been registered in the VO via a TAP service hosted at the Observatoire de Paris, with a tentative ObsCore description of each dataset. We hope that, in the future, the H.E.S.S. legacy archive will be published in a similar way and accessible through the VO.

2.1.2 CTAO

The Cherenkov Telescope Array Observatory (CTAO) is the next generation ground-based IACT instrument for gamma-ray astronomy at very high energies. With tens of telescopes located in the northern (La Palma, Canary Island) and southern (Chili) hemispheres, CTAO will be the first open ground-based VHE gamma-ray observatory and the world's largest and most sensitive instrument to study high-energy phenomena in the Universe. Built on the technology of current generation ground-based gamma-ray detectors (e.g. H.E.S.S., MAGIC and VERITAS), CTAO will be between five and 10 times more sensitive and have unprecedented accuracy in its detection of VHE gamma rays.

CTAO will distribute data as an open observatory, for the first time in this domain, with calls for proposals and publicly released data after a proprietary period. CTAO will ensure that the provided data will be FAIR: Findable, Accessible, Interoperable and Reusable, by following the FAIR Principles for data management (Wilkinson and Dumontier et al., 2016). In particular, because of the complex data processing and reconstruction steps, the provision of provenance metadata for CTAO data has been a driver for the development of a provenance standard in astronomy.

CTAO will also ensure VO compatibility of the distributed data and access systems. CTAO participated to the ESCAPE European Project, and is now part of the ESCAPE Open Collaboration to face common challenges for Research Infrastructures in the context of cloud computing, including data analysis and distribution.

A focus of CTAO is to distribute in this context their Data Level 3 (DL3) datasets, that correspond to lists of Cherenkov events detected by the telescopes along with the proper IRFs. CTAO is planning an internal and a public Science Data Challenges, which represent opportunities to build "VO inside" solutions.

The CTAO observatory is complementary to other gamma-ray instruments observing the sky up to ultra high energies (ie PeV). Detecting directly from ground secondary charged particles of extensive air showers initiated by gamma rays, Water Cherenkov Detectors (WCD) survey the whole observable sky above the TeV/tens of TeV energy range. The HAWC and LHAASO detectors are running in the northern hemisphere and the future SWGO observatory will be installed in the southern hemisphere. Such instruments have similar high-level data structures and it has been already demonstrated that joined analyses with Gammapy of data from IACTs and WCDs using the GADF format are very powerful (Albert and Alfaro et al., 2022).

2.2 X-ray programs

2.2.1 Chandra

Part of NASA’s fleet of “Great Observatories”, the Chandra X-ray Observatory (CXO) was launched in 1999 to observe the soft X-ray universe in the 0.1 to 10 keV energy band. Chandra is a guest observer, pointed-observation mission and obtains roughly 800 observations per year using the Advanced CCD Imaging Spectrometer (ACIS) and High Resolution Camera (HRC) instruments. Chandra provides high angular resolution with a sub-arcsecond on-axis point spread function (PSF), a field of view up to several hundred square arcminutes, and a low instrumental background. The Chandra PSF varies with X-ray energy and significantly with off-axis angle, increasing to $R50 \sim 25$ arcsec at the edge of the field of view. A pair of transmission gratings can be inserted into the X-ray beam to provide dispersed spectra with $E/\Delta E \sim 1000$ for bright sources. The Chandra spacecraft normally dithers in a Lissajous pattern on the sky while taking data, and this motion must be removed from the time-resolved X-ray event lists when constructing X-ray images using the motion of optical guide stars tracked by the Aspect camera.

The Chandra X-ray Center (CXC) processes the spacecraft data through a set of Standard Data Processing Level 0 through Level 2 pipelines. These pipelines perform numerous steps including decommutating the telemetry data, applying instrument calibrations (e.g., detector geometric, time-dependent gain, and CCD charge transfer efficiency (CTI) corrections, bad and hot pixel flagging), computing and applying the time-resolved Aspect solution to de-dither the motion of the telescope, identifying good time intervals (GTIs), and finally filtering out bad times and X-ray events with bad status. All data products are archived in the Chandra Data Archive (CDA) in FITS format following HEASARC OGIP standards; see also § 3.3.1. The CDA manages the proprietary data period (currently 6 months, after which the data become public) and provides dedicated interactive and IVOA-compliant interfaces to locate and download datasets.

The CXC also provides the Chandra Source Catalog, which in the latest release (2.1) includes data for $\sim 407\text{K}$ unique X-ray sources on the sky and more than 2.1 million individual detections and photometric upper limits. For each X-ray source and detection, the catalog provides a detailed set of more than 100 tabulated positional, spatial, photometric, spectral, and temporal properties. An extensive selection of individual observation, stacked-observation, detection region, and master source FITS data products (e.g., RMFs, ARFs, PSFs, spectra, light curves, aperture photometry MPDFs) are also provided that are directly usable for further detailed scientific analysis.

Finally, the CXC distributes the CIAO data analysis package to allow users to recalibrate and analyze their data. A key aspect of CIAO is to provide users the ability to create instrument responses (RMFs, ARFs, PSFs, etc) for their observations. The Sherpa modeling and fitting package supports N-dimensional model fitting and optimization in Python, and supports advanced Bayesian Markov chain Monte Carlo analyses.

2.2.2 XMM-Newton

The European Space Agency’s (ESA) X-ray Multi-Mirror Mission (XMM-Newton) ¹ was launched by an Ariane 504 on December 10th 1999. XMM-Newton is ESA’s second cornerstone of the Horizon 2000 Science Programme. It carries 3 high throughput X-ray telescopes with an unprecedented effective area, 2 reflexion grating spectrometers and an optical monitor. The large collecting area and ability to make long uninterrupted exposures provide highly sensitive observations. The XMM-Newton mission is helping scientists to solve a number of cosmic mysteries, ranging from the enigmatic black holes to the origins of the Universe itself. Observing time on XMM-Newton is being made available to the scientific community, applying for observational periods on a competitive basis.

One of the mission’s ground segment modules, the SSC /footnote<http://xmmssc.irap.omp.eu/>, is in charge of maximizing the scientific return of this space observatory by exhaustively analyzing the content of the instruments’ fields of view. During the development phase (1996-1999), the SSC, in collaboration with the SOC (ESAC), designed and produced the scientific analysis software (SAS). Since then, it has contributed to its maintenance and development. This software is publicly available.

The general pipeline is operated as ESAC (Villafranca, Spain) since 2012, except for the part concerning cross-correlation with astronomical archives which runs in Strasbourg. The information thus produced is intended for the guest observer and, after a proprietary period of one year, for the international community. In parallel, the SSC regularly compiles an exhaustive catalog of all X-ray sources detected by EPIC cameras. The SSC validates

¹<https://www.cosmos.esa.int/web/xmm-newton>

these catalogs, enriches them with multi-wavelength data and exploits them in several scientific programs.

The XMM catalog is published through various WEB applications: XSA ², XCatDB ³, IRAP ⁴ and HEASARCH ⁵. It is also published in the VO, mainly as TAP services. It is to be noted that the TAP service operated in Strasbourg (<https://xcatdb.unistra.fr/xtapdb> - to be deployed in 10/2024) returns responses where data is mapped on the MANGO model with MIVOT.

To be validated by ADA.

2.2.3 SVOM

SVOM (Space-based multi-band astronomical Variable Objects Monitor) ⁶ is a Sino-French mission dedicated to the study of the transient high-energy sky, and in particular to the detection, localization and study of Gamma Ray Bursts (GRBs). Gamma-ray bursts are sudden, intense flashes of X-ray and gamma-ray light. They are associated with the cataclysmic formation of black holes, either by the merger of two compact stars (neutron star or black hole) or by the sudden explosion of a massive star, twenty to one hundred times the mass of our Sun. The birth of a black hole is accompanied by the ejection of jets of matter that reach speeds close to the speed of light. These jets of matter then decelerate in the circumstellar medium, sweeping away everything in their path. Gamma-ray bursts can be observed at the very edge of the universe, acting as lighthouses that illuminate the dark ages of its creation. Although they have been studied extensively over the past fifteen years, gamma-ray bursts are still poorly understood phenomena. To better understand them, China and France have decided to join forces with the SVOM satellite, which is specifically dedicated to the study of gamma-ray bursts.

The special feature of the SVOM mission is that it combines ground-based and space-based observations, providing a spectral bandwidth from the visible to the high-energy range. By guaranteeing multi-wavelength observations of about one hundred bursts of all types per year, the SVOM mission will make a unique contribution to two of the most fruitful areas of research in recent decades: the use of bursts in cosmology and the understanding of the phenomenon. Looking further ahead, the SVOM mission will work in close synergy with a new generation of instruments dedicated to the search for neutrinos and gravitational waves of cosmic origin, in order

²<https://www.cosmos.esa.int/web/xmm-newton/xsa>

³<https://xcatdb.unistra.fr/4xmm>

⁴<http://xmm-catalog.irap.omp.eu/>

⁵<http://heasarc.gsfc.nasa.gov/db-perl/W3Browse/w3browse.pl>

⁶<https://www.svom.eu/en/home/>

to confirm the astrophysical origin of the signals detected by these future instruments.

SVOM has been successfully launched on June 22 2024 from Xichang launchpad.

2.3 KM3Net and neutrino detection

The KM3NeT neutrino detectors are arrays of water-based Cherenkov detectors currently under construction in the deep Mediterranean Sea. With its two sites off the French and Italian coasts, the KM3NeT collaboration aims at single particle neutrino detection for neutrino physics with the more densely instrumented ORCA detector in the GeV to TeV range, and VHE astrophysics with the ARCA detector in the TeV range and above.

Using Earth as a shield from atmospheric particle interference by searching for upgoing particle tracks in the detectors, the measurement of astrophysical neutrinos can be performed almost continuously for a wide field of view that covers the full visible sky. For these particle events, extensive Monte Carlo simulations are performed to evaluate the statistical significance towards the various theoretical assumptions for galactic or cosmic neutrino signals and extensive filtering of the events dominated by the atmospheric particle background by about $1 : 10^6$ is required.

During the construction phase, the KM3NeT collaboration develops its interfaces for open science and builds on the data gathered by its predecessor ANTARES, from which neutrino event lists have already been published on the KM3NeT VO server as TAP service. However, for full reproducibility of searches for point-like astronomical sources as well as wider scientific use of dedicated neutrino selections, information derived from simulations like background estimate, PSF and detector acceptance are required and should be linked to the actual event list and interpolation for a given observation.

With multiple detectors targeting high-energy neutrinos like IceCube, ANTARES, KM3NeT, Baikal and future projects, the chance to detect a significant amount of cosmic and galactic neutrinos increases, requiring an integrated approach to link event lists with instrument responses and to correctly interpret observation time and flux expectations. As observations generally encompass large continuously taken data sets covering a large area of the sky for multiple years, with very low statistical expectations for actual neutrino observation, especially correctly interpreting the observation time interval and re-weighting and limiting any probabilistic measures to a dedicated study must be facilitated for proper use of neutrino data.

3 Common practices in the High Energy community

3.1 Data specificities

3.1.1 Event-counting

Observations of the Universe at high energies are based on techniques that are radically different compared to the optical, or radio domain. HE observatories are generally designed to detect particles, e.g. individual photons, cosmic-rays, or neutrinos, with the ability to estimate several characteristics of those particles. This technique is generally named **event counting**, where an event has some probability of being due to the interaction of an astronomical particle with the detectors.

The data corresponding to an **event** is first an instrumental signal, which is then calibrated and processed to estimate event characteristics such as a time of arrival, coordinates on the sky, and the energy proxy associated to the event. Several other intermediate and qualifying characteristics can be associated to a detected event.

When observing during an interval of time, the data collected is a list of the detected events, named an **event list** in the HE domain, and event-list in this document.

3.1.2 Data levels

After detection of events, data processing steps are applied to generate data products. We typically distinguish at least 3 main data levels.

- 1 An event-list with calibrated temporal and spatial characteristics, e.g. sky coordinates for a given epoch, event arrival time with time reference, and a proxy for particle energy.
- 2 Binned and/or filtered event list suitable for preparation of science images, spectra or light-curves. For some instruments, corresponding instrument responses associated with the event-list, calculated but not yet applied (e.g. exposure maps, sensitivity maps, spectral responses).
- 3 Calibrated maps, or spectral energy distributions for a source, or light-curves in physical units, or adjusted source models.
- 4 An additional data level may correspond to catalogs, e.g. a source catalog pointing to several data products (e.g. collection of high level products) with each one corresponding to a source, catalog of source models generated with an uniform analyse.

However, the definitions of these data levels can vary significantly from facility to facility. For example, in the VHE Cherenkov astronomy domain

(e.g. CTA), the data levels listed above are labelled DL3⁷ to DL5. However, for Chandra X-ray data, the first two levels correspond to L1 and L2 data products (excluding the responses), while transmission-grating data products are designated L1.5 and source catalog and associated data products are all designated L3.

3.1.3 Background signal

Observations in HE may contain a high background component, that may be due to instrument noises, or to unresolved astrophysical sources, emission from extended regions or other terrestrial sources producing particles similar to the signal. The characterization and estimation of this background may be particularly important to then apply corrections during the analysis of a source signal.

In the VHE domain with the IACT, WCD and neutrino techniques, the main source of background at the DL3 level is created by cosmic-ray induced events. The case of unresolved astrophysical sources, emission from extended regions are treated as models of gamma-ray or neutrino emission.

In the X-ray domain, contributions to background can include an instrumental component, the local radiation environment (i.e. space weather) which can change dynamically, and may include the cosmological background due to unresolved astrophysical sources, depending on the spatial resolution of the instrument.

3.1.4 Time intervals

Depending on the stability of the instruments and observing conditions, a HE observation can be decomposed into several intervals of time that will be further analysed.

For example, Stable Time Intervals (STI) are defined in Cherenkov astronomy to characterize periods of time during which the instrument response is stable. In the X-ray domain, Good Time Intervals (GTI) are computed to exclude time periods where data are missing or invalid, and may be used to reject periods impacted by high radiation, e.g. due to space weather. In contrast, for neutrino physics, relevant observation periods can cover up to several years due to the low statistics of the expected signal and a continuous observational coverage of the full field of view.

3.1.5 Instrument Response Functions

Though an event-list can contain calibrated physical values, the data typically still has to be corrected for the photometric, spectral, spatial, and/or

⁷lower level data (DL0–DL2), that are specific to the used instrumentation (IACT, WCD), are reconstructed and filtered, which constitute the events lists called DL3.

temporal responses of the instruments used to yield scientifically interpretable information. The IRFs provide mappings between the physical properties of the source and the observables, and so enable estimation of the former (such as the real flux of particles arriving at the instrument, the spectral distribution of the particle flux, and the temporal variability and morphology of the source).

Note that the small number of particles detected in many types of HE observations (i.e. within a Poisson regime) and the fact that the IRFs may not be directly invertible, techniques such as forward-folding fitting (Mattox and Bertsch et al., 1996) are needed to estimate the physical properties of the source from the observables.

The instrumental responses typically vary with the true energy of the event, the arrival direction of the event into the detector. A further complication of ground-based detectors like IACTs and WCTs is that the instrumental responses also vary with:

- The horizontal coordinates of the atmosphere, i.e. the response to a photon at low elevation is different from that at zenith due to a larger air column density, and different azimuths are affected by different magnetic field strengths and directions that modify the air-shower properties.
- The atmosphere density, which can have an effect on the response that changes throughout a year, depending on the site of observation.
- The brightness of the sky (for IACTs), i.e. the response is worse when the moon is up, or when there is a strong nigh-sky-background level from e.g. the Milky Way or Zodiacal light.

Since these are not aligned with a sky coordinate system, field-rotation during an observation must also be taken into account. Therefore the treatment of the temporal variation of IRFs is important, and is often taken into account in analysis by averaging over some short time period, such as the duration of the observation, or intervals within.

3.1.6 Granularity of data products

The event-list dataset is generally stored as a table, with one row per candidate detection (event) and several columns for the observed and/or estimated physical parameters (e.g. arrival time, position on detector or in the sky, energy or pulse height, and additional properties such as errors or flags that are project-dependent).

The list of columns present in the event-list is for example described in the data format in use in the HE domain, such as OGIP or GADF as introduced below. The data formats in use generally describe the event-list

data together with the IRFs (Effective Area, Energy Dispersion, Point Spread Function, Background) and other relevant information, such as: Stable or Good Time Interval, dead time, ...

In order to allow for multi-wavelength data discovery of HE data products and compare observations across different regimes, it seems appropriate to distribute the metadata in the VO ecosystem together with an access link to the data file in community format for finer analysis. Where feasible, the efficient granularity for distributing HE data products seems to be the full combination of data and associated IRFs.

3.2 Work flow specificities

3.2.1 Event selection

When processing an event-list, it is important to perform an optimal selection of the events according to the science analysis use case, i.e. the source targeted or the science objectives. The selection can be performed on the event characteristics, e.g. time, energy or more specific indicators (patterns, shape, IRFs properties, ...).

3.2.2 Assumptions and probabilistic approach

In order to produce advanced astrophysics data products like light curves, spectra or source morphology, assumptions about the noise, the source morphology and its expected energy distribution must be introduced. This is one of the main driver for enabling a full and well described access to event-list data, as scientific analyses generally start at this data level.

3.3 Data formats

3.3.1 OGIP

NASA's HEASARC FITS Working Group was part of the Office of Guest Investigator Programs, or OGIP, and created in the 1990's the multi-mission standards for the format of FITS data files in NASA high-energy astrophysics. Those so-called OGIP recommendations⁸ include standards on keyword usage in metadata, on the storage of spatial, temporal, and spectral (energy) information, and representation of response functions, etc. These standards predate the IVOA but include such VO concepts as data models, vocabularies, provenance, as well as the corresponding FITS serialization specification.

The purpose of these standards was to allow all mission data archived by the HEASARC to be stored in the same data format and be readable by

⁸https://heasarc.gsfc.nasa.gov/docs/heasarc/ofwg/ofwg_recomm.html

the same software tools. § 2.2.1 above, for example, describes the Chandra mission products, but many other projects do so as well. Because of the OGIP standards, the same software tools can be used on all of the HE mission data that follow them. There are now some thirty plus different mission datasets archived by NASA following these standards and different software tools that can analyze any of them.

Now that the IVOA is defining data models for spectra and time series, we should be careful to include the existing OGIP standards as special cases of what are developed to be more general standards for all of astronomy. Standards about source morphology should also be introduced.

3.3.2 GADF and VODF

The data formats for gamma-ray astronomy⁹ (GADF) is a community-driven initiative for the definition of a common and open high-level data format for gamma-ray instruments (Deil and Boisson et al., 2017) starting at the reconstructed event level. GADF is based partially on the OGIP standards and is specialised for Very High Energy data. It was originally developed in 2011 for CTAO during its prototyping phase, and was further tested on data from the H.E.S.S. telescope array. This format is now used as a standard for VHE gamma-ray data. The project was made open-source in 2016, and became the base format for the *Gammapy* software.

The Very-high-energy Open Data Format¹⁰ (VODF), will build upon and be the successor to GADF. It is intended to address some of the shortcomings of the GADF format, to provide a properly documented and consistent data model, to cover use cases of both VHE gamma-ray and neutrino astronomy, and to provide more support for validation and versioning. VODF will provide a standard set of file formats for data starting at the reconstructed event level (DL3, i.e. first item in the section 3.1.2) as well as higher-level products (i.e. sky images, light curves, and spectra) and source catalogues (items 2-4 in section 3.1.2), as well as N-dimensional binned data cubes. With these standards, common science tools can be used to analyze data from multiple high-energy instruments, including facilitating the ability to do combined likelihood fits of models across a wide energy range directly from events or binned products. VODF aims to follow or be compatible with existing IVOA standards as much as possible.

3.4 Tools for data extraction and visualisation

High energy data are typically multi-dimensional (*e.g.*, 2 spatial dimensions, time, energy, possibly polarization) and may be complex and diverse at lower levels. Therefore one may commonly find specific tools to process the

⁹<https://gamma-astro-data-formats.readthedocs.io/>

¹⁰<https://vodf.readthedocs.io/>

data for a given facility, *e.g.*, CIAO for Chandra, SAS for XMM-Newton, or Gammapy for gamma-ray data, with a particular focus on Cherenkov data as foreseen by CTA.

However, many tools in a high energy astrophysics data analysis package may perform common tasks in a mission-independent way and can work well with similar data from other facilities. For example, one commonly needs to be able to filter and project the multi-dimensional data to select specific data subsets with manageable sizes and eliminate extraneous data. Some tool sets include built-in generic filtering and binning capabilities so that a general purpose region filtering and binning syntax is available to the end user.

A high energy astrophysics data analysis package typically includes tools that apply or re-apply instrumental calibrations to the data, and as described above these may be observatory-specific. More general algorithms (*e.g.*, source detection) and utility tools (*e.g.*, extract an observed spectrum from a region surrounding a source) are applied to calibrated data to extract data subsets that can then be fed into modeling tools (*e.g.*, Xspec, Sherpa, or Gammapy) together with the appropriate instrumental responses (IRFs, or RMFs and ARFs) to derive physical quantities. Since instrumental responses are often designed to be compliant with widely adopted standards, the tools that apply these responses in many cases will interoperate with other datasets that use the same standards.

Most data analysis packages provide a visualization capability for viewing images, interacting with astronomy databases, overlaying data, or interacting via SAMP to tie several application functions together (*e.g.*, TopCat, Aladin, ds9, ESASky, Firefly) to simultaneously support both analysis and visualization of the data at hand. In addition, many packages offer a scripting interface (*e.g.*, Python, Jupyter notebooks) that enable customized job creation to perform turn-key analysis or process bulk data in batch mode.

To allow users of data to use pre-existing tools, often packages will support file I/O using several formats, for example, including FITS images and binary tables (for event files), VO formats, and several ASCII representations (*e.g.*, space, comma, or tab-separated columns).

We do note that currently high energy astrophysics data and analysis systems are not created equally and there are a number of nuances with some of the data formats and analysis threads for specific instrument and projects.

4 Use Cases

4.1 UC1: re-analyse event-list data for a source in a catalog

After the selection of a source of interest, or a group of sources, one may access different HE data products such as images, spectra and light-curves, and then want to download the corresponding event-lists and calibrations to further analyse the data.

One of the characteristics of the HE data is that, contrary to what is usually done in optics for example, their optimal use requires providing users with a view of the processing that generated the data. This implies providing ancillary data, products with different calibration levels, and possibly linking together products issued by the same processing.

4.2 UC2: observation preparation

When planning for new VHE observations, one needs to search for any existing event-list data already available in the targeted sky regions, and assess if this data is enough to fulfill the science goals.

For this use case, one needs first to obtain the stacked exposure maps of past observations. This quantity is energy-dependent for VHE data can be derived from pointing position and effective areas that are position- and energy- dependent associated to each observation.

4.3 UC3: transient or variable sources

To be completed (e.g. Ada)

4.4 UC4: Multi-wavelength and multi-messenger science

Though there are scientific results based on HE data only, the multi-wavelength and multi-messenger approach is particularly developed in the HE domain. An astrophysical source of HE radiations is indeed generally radiating energy in several domains across the electromagnetic spectrum and may be a source of other particles, in particular neutrino. It is not rare to observe a HE source in radio and to look for counterparts in the infrared, optical or UV domain and either in X-rays or VHE/UHE band. Spectroscopy and spatially-resolved spectroscopy are also widely used to identify HE sources.

The HE domain is thus confronted to different kinds of data types and data archives, which leads to interesting use cases for the development of the VO.

One use case is associated to independent analyses of the multi-wavelength and multi-messenger data. HE data are analyzed to produce DL5/L3 quantities from DL3/L1 stored in the VO. And the multi-wavelength and multi-messenger DL5/L3 data stored are retrieved into the VO and associated to realise astrophysical interpretations.

The other growing use case is associated to joint statistical analyses of multi-instrument data at different levels (DL3/L1 and DL5/L3) by adapted open science analysis tools.

For both use cases, any type of data should be findable on the VO and retrievable. And the data should have a standardized open format (OGIP, GADF, VODF).

Such use case is already in use with small data sets shared by VHE experiments. In (Nigro and Deil et al., 2019; Albert and Alfaro et al., 2022), groups of astronomers working on the Gammapy library had successfully analyzed DL3 data taken on the Crab nebula by different facilities (MAGIC, H.E.S.S., FACT, VERITAS, Fermi-LAT and HAWC). A real statistical joint analysis has been performed to derive an emitting model of the Crab pulsar wind nebula over more than five decades in energy. Such analysis type can be now retrieved in the literacy. It can be found also joint analyses using X-ray and VHE data (Giunti, L. and Acero, F. et al., 2022). A proof of concept of joint analysis of VHE gamma-ray and VHE neutrino, using simulated data, has been also published (Unbehaun and Mohrmann et al., 2024).

4.5 UC5: Extended source searches

Beyond the multimessenger approach towards a specific source type, an extension of this approach can be seen in the analysis of long-term and wide-angle observations for extended sky regions in the multimessenger domain. For these analyses, extensive filtering and statistical analyses of the datasets is required. This approach is especially dominant in low-countrate experiments like neutrinos, where former analyses included the mapping of neutrino emissions in the galactic plane to gamma-ray emissions (Collaboration*† and Abbasi et al., 2023) or search for neutrino emission from the fermi bubbles with ANTARES data (Adrián-Martínez and Albert et al., 2014).

5 IVOA standards of interest for HE

5.1 IVOA Recommendations

5.1.1 ObsCore and TAP

Event-list datasets can be described in ObsCore using a `dataprodct_type` set to "event". However, this is not widely used in current services, and we observe only a few services with event-list datasets declared in the VO Registry, and mainly the H.E.S.S. public data release (see 2.1.1).

As services based on the Table Access Protocol (Dowler and Rixon et al., 2019) and ObsCore are well developed within the VO, it would be a straightforward option to discover HE event-list datasets, as well as multi-wavelength and multi-messenger associated data.

Here is the evaluation of the ObsCore metadata for distributing high energy data set, some features being re-usable as such, and some other features requested for addition or re-interpretation.

5.1.2 DataLink

DataLink specification (Bonnarel and Dowler et al., 2023) defines a {links} endpoint providing the possibility to link several access items to each row of the main response table. These links are described and stored in a second table. In the case of an ObsCore response each dataset can be linked this way (via the via the access_url FIELD content) to previews, documentation pages, calibration data as well as to the dataset itself. Some dynamical links to web services may also be provided. In that case the service input parameters are described with the help of a "service descriptor" feature as described in the same DataLink specification.

5.1.3 HiPS

Several HE observatories are well suited for sky survey, and the Hierarchical Progressive Survey (HiPS) standard is well suited for sky survey exploration. We note that the Fermi facility provides a useful sky survey in the GeV domain.

5.1.4 MOCs

Cross-correlation of data with other observations is an important use case in the HE domain. Using the Multi-Order Coverage map (MOC) standard, such operations become more efficient. Distribution of MOCs associated to HE data should thus be encouraged and especially ST-MOCs (space + time coverage) that make easier the study of transient phenomena.

5.1.5 MIVOT

Model Instances in VOTables (MIVOT Michel and Cresitello-Dittmar et al. (2023)) defines a syntax to map VOTable data to any model serialized in VO-DML. The annotation operates as a bridge between the data and the model. It associates the column/param metadata from the VOTable to the data model elements (class, attributes, types, etc.) [...]. The data model elements are grouped in an independent annotation block complying with the MIVOT XML syntax. This annotation block is added as an extra resource element at the top of the VOTable result resource. The MIVOT syntax allows to describe a data structure as a hierarchy of classes. It is also able to represent relations and composition between them. It can also build up data model objects by aggregating instances from different tables of the VOTable. In the

case of HE data, this annotation pattern, used together with the MANGO model, will help to make machine-readable quantities that are currently not considered in the VO, such as the hardness ratio, the energy bands, the flags associated with measurements or extended sources.

5.1.6 Provenance

Provenance information of VHE data product is a crucial information to provide, especially given the complexity of the data preparation and analysis workflow in the VHE domain. Such complexity comes from the specificities of the VHE data as exposed in sections 3.

The development of the IVOA Provenance Data Model (Servillat and Riebe et al., 2020) has been conducted with those use cases in mind. The Provenance Data Model proposes to structure this information as activities and entities (as in the W3C PROV recommendation), and adds the concepts of descriptions and configuration of each step, so that the complexity of provenance of VHE data can be exposed.

5.2 Data Models in working drafts

The HE domain and practices could serve as use cases for the developments of data models, such as Dataset DM, Cube DM or MANGO DM.

5.2.1 Mango

MANGO is a model (draft: ¹¹) that has been developed to reveal and describe complex quantities that are usually distributed in query response tables. The use cases on which MANGO is built were collected in 2019 from different scientific fields, including HE. The model focuses on the case of the epoch propagation, the state description and photometry. Some features of MANGO are useful for the HE domain:

noitemsep,topsep=0pt,parsep=0pt,parttopsep=0pt	Hardness ratio support
noitemsep,topsep=0pt,parsep=0pt,parttopsep=0pt	Energy band description
noitemsep,topsep=0pt,parsep=0pt,parttopsep=0pt	Machine-readable description of state values
noitemsep,topsep=0pt,parsep=0pt,parttopsep=0pt	Ability to group quantities (e.g., position with detection likelihood)

¹¹<https://github.com/ivoa-std/MANGO>

noitemsep,topsep=0pt,parsep=0pt,partopsep=0pt MANGO instance association (e.g., source with detections)

6 Topics for discussions in an Interest Group

6.1 Definition of a HE event in the VO

6.1.1 Current definition in the VO

The IVOA standards include the concept of event-list, for example in ObsCore v1.1 (Louys and Tody et al., 2017), where event is a `dataprodukt_type` with the following definition:

event: an event-counting (e.g. X-ray or other high energy) dataset of some sort. Typically this is instrumental data, i.e., "event data". An event dataset is often a complex object containing multiple files or other substructures. An event dataset may contain data with spatial, spectral, and time information for each measured event, although the spectral resolution (energy) is sometimes limited. Event data may be used to produce higher level data products such as images or spectra.

More recently, a new definition was proposed in the product-type vocabulary¹² (draft):

event-list: a collection of observed events, such as incoming high-energy particles. A row in an event list is typically characterised by a spatial position, a time and an energy.

Such a definition remains vague and general, and could be more specific, including a definition for a HE event, and the event-list data type.

6.1.2 Proposed definition to be discussed

A first point to be discussed would be to converge on a proper definition of HE specific data products:

- Propose definitions for a product-type **event-list**: A collection of observed events, such as incoming high-energy particles, where an event is generally characterised by a spatial position, a time and a spectral value (e.g. an energy, a channel, a pulse height).

¹²<https://www.ivoa.net/rdf/product-type>

- Propose definitions for a product-type **event-bundle**: An event-bundle dataset is a complex object containing an event-list and multiple files or other substructures that are products necessary to analyze the event-list. Data in an event-bundle may thus be used to produce higher level data products such as images or spectra.

An ObsCore erratum could then propose to change event for event-list and event-bundle.

The precise content of an event-bundle remains to be better defined, and may vary significantly from a facility to another.

For example, Chandra primary products distributed via the Chandra Data Archive include around half a dozen different types of products necessary to analyze Chandra data (for example, L2 event-list, Aspect solution, bad pixel map, spacecraft ephemeris, V&V Report).

the following is not clear for BKH: It is also possible to retrieve secondary products, containing more products that are needed to recalibrate the data with updated calibrations.

For VHE gamma rays and neutrinos, the DL3 event lists should mandatory be associated to their associated IRFs files. The links between the event-list and these IRFs should be well defined in the event-bundle.

6.2 ObsCore metadata description of an event-list

6.2.1 Usage of the mandatory terms in ObsCore

ObsCore (Louys and Tody et al., 2017) can provide a metadata profile for a data product of type event-list and a qualified access to the distributed file using the Access class from ObsCore (URL, format, file size).

In the ObsCore representation, the event-list data product is described in terms of curation, coverage and access. However, several properties are simply set to NULL following the recommendation: Resolutions, Polarization States, Observable Axis Description, Axes lengths (set to -1)...

We also note that some properties are energy dependent, such as the Spatial Coverage, Spatial Extent, PSF.

TODO: show a table with all reused terms , and provide an example

- dataproduct_subtype = DL3, maybe specific data format (VODF)
- calib_level = between 1 and 2
- obs_collection could contain many details : obs_type (calib, science), obs_mode (subarray configuration), pointing_mode, tracking_type, event_type, event_cuts, analysis_type...
- s_ra, s_dec = maybe telescope pointing coordinates

- `target_name` : several targets may be in the field of view
- `s_fov`, `s_region`, `s_resolution`, `em_resolution`... all those values are energy dependent, one should specify that the value is at a given energy, or within a range of values.
- `em_min`, `em_max` : add fields expressed in energy (e.g. eV, keV or TeV)
- `t_exptime` : ontime, livetime, stable time intervals... maybe a T-MOC would help
- `facility_name`, `instrument_name` : minimalist, would be e.g. CTAO and a subarray.

6.2.2 Metadata re-interpretation for the VOHE context

observation_id In the current definition of ObsCore, the data product collects data from one or several observations. The same happens in HE context.

access_ref, access_format The initial role of this metadata was to hold the `access_url` allowing data access. Depending on the packaging of the event bundle in one compact format (OGIP, GADF, tar ball, ...) or as different files available independently in various urls, a datalink pointer can be used for accessing the various parts of IRFs, background maps, etc. Then in such a case the value for `access_format` should be "application/x-votable+xml;content=datalink". The format itself of the data file is then given by the datalink parameter "content-type". See next section 6.4.

o_ucd For the even-list table, we can consider all measures stored in columns values have been observed. The nature of items along time, position and energy axis are identified in Obscore with ucd as 'time', 'pos.eq.*', 'em.*' and counted as `t_xel`, `s_xel1`, `s_xel2`, `em_xel` which correspond to the number of rows/events candidates observed.

The signal observed is the result of event counting and would be PHA (Pulse height amplitude at detector level) or a number of counts for photons or particles, or a flux, etc., depending on the data calibration level considered. ObsCore uses `o_ucd` to characterise the nature of the measure. Various UCDS are used for that: `o_ucd=phys.count`, `phot.count`, `phot.flux`, etc. there is currently no UCD defined for a raw measure like `PulseHeightAmplitude`, but if needed this can be requested for addition in the UCDDList vocabulary. See VEP-UCD-15_pulseheight.txt proposed at '<https://voparis-gitlab.obspm.fr/vespa/ivoa-standards/semantics/vep-ucd/-/blob/master/>'.

Note that these parameters vary between the dataset of `calib_level` of 1 (Raw) to the a more advanced data products (`calib_level` 2 or 3), which are filtered and rebinned from the original raw event-list.

6.2.3 Metadata addition required

ev_number The event list contains a number of rows, representing detections candidates, that have no metadata keyword yet in Obscore. We propose 'ev_number' to record this. In fact the `t_xel`, `s_xel1` and `s_xel2`, `em_xel` elements do not apply for an event list in raw count as it has not been binned yet.

Adding MIME-type to access_format table As seen in section 3.3 current HE experiments and observatories use their community defined data format for data dissemination. They encapsulate the event-list table together with ancillary data dedicated to calibration and observing configurations and parameters. Even if the encapsulation is not standardized between the various projects, it is useful for a client application to rely on the `access_format` property in order to send it to an appropriate visualizing tool.

Therefore these can be included in the MIME-type table of ObsCore section 4.7. suggestion for new terms like :

- application/x-fits-ogip ...
- application/x-gadf ...
- application/x-vodf ...

to be completed with proper definition

energy_min, energy_max It is not user-friendly for the user to select dataset according to an energy range when the spectral axis is expressed in wavelength and meters. The units and quantities are not familiar to this community. Moreover the numerical representation of the spectral range in `em_min` leads to quantities with many figures and a power as -18 not easily comparable with the current usage.

cf. example HESS data shown in Aladin

t_gti The searching criteria in terms of time coverage require the list of stable/good time intervals to pick appropriate datasets. `t_min`, `t_max` is the global time span but `t_gti` could contain the list of GTI as a `T_MOC` description following the Multi-Order-Coverage (MOC) IVOA standard (Fermique and Nebot et al., 2022). This element could then be compared across

data collections to make the data set selection via simple intersection or union operations in T_MOC representation. On the data provider's side, the T-MOC element can be computed from the Stable/Good Time Interval table in OGIP or GADF to produce the ObsCore t_gti field.

6.2.4 Access and Description of IRFs

Each IRF file can have an Access object from ObsCore DM to describe a link to the IRF part of the data file. This can be reflected in an extension of ObsTAP TAP_SCHEMA.

In the TAP service we could add an IRF Table, with the following columns:

- event-list datapublisher_id
- irf_type, category of response: EffectiveArea, PSF, etc.
- irf_description, one line explanation for the role of the file
- Access.url, URL to point to the IRF
- Access.format, format of IRF
- Access.size, size of IRF file

6.3 Event-list Context Data Model

The event-list concept may include, or may be surrounded by other connected concepts. Indeed, an event-list dataset alone cannot be scientifically analysed without the knowledge of some contextual data and metadata, starting with the good/stable time intervals, and the corresponding IRFs.

The aim of the Event-list Context Data Model is to name and indicate the relations between the event-list and its contextual information. It is presented in Figure 1.

6.4 Use of Datalink for HE products

There are two options to provide an access to a full event-bundle package.

In the first option, the "event-bundle" dataset (6.1) exposed in the discovery service contains all the relevant information, e.g. several frames in the FITS file, one corresponding to the event-list itself, and the others providing good/stable time intervals, or any IRF file. This is what was done in the current GADF data format (see 3.3.2). In this option, the content of the event-list package should be properly defined in its description: what information is included and where is it in the dataset structure? Obviously the Event-list Context Data Model (see 6.3) would be useful to provide that.

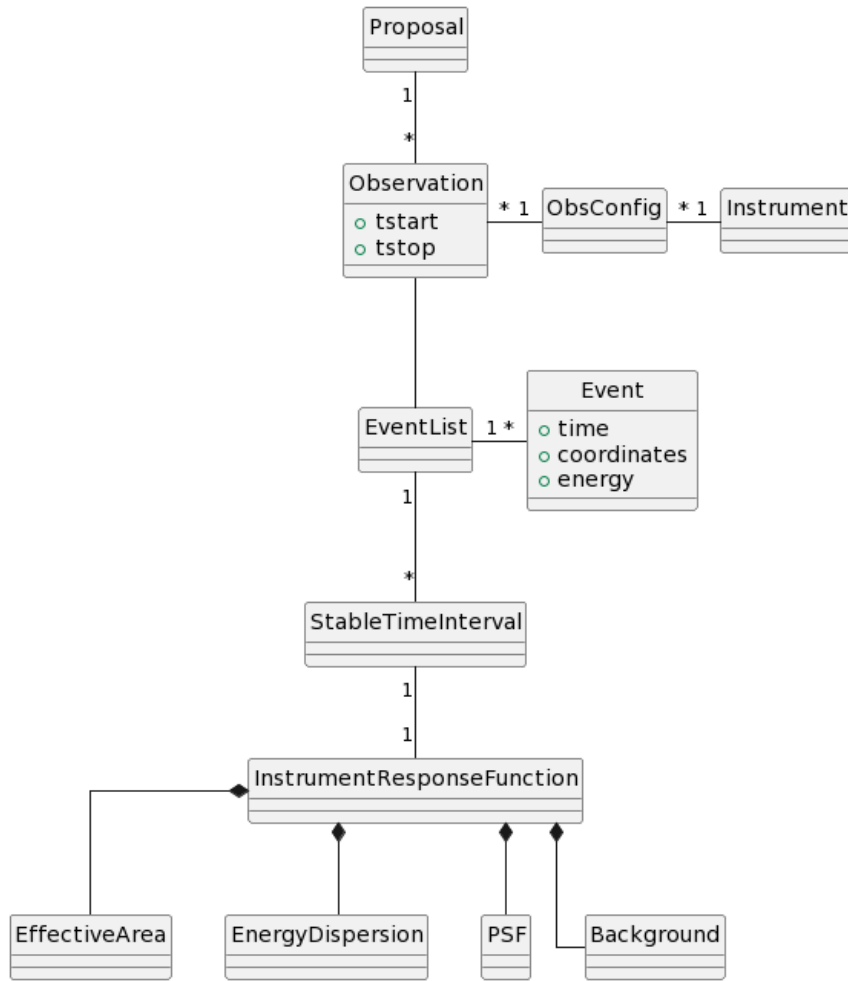


Figure 1: event-list Context Data Model. Notes: STIs and GTIs are slightly different concepts, and multiplicities should be adapted, energy is to specific for an event (intensity?), more products may be attached to a STI/GTI or to IRF.

In the second option we provide links to the relevant information from the base "event-list" (6.1) exposed in the discovery service. This could be done using Datalink and a list of links to each contextual information such as the IRFs. The Event-list Context Data Model (see 6.3) would provide the concepts and vocabulary to characterise the IRFs and other information relevant to the analysis of an event-list. These specific concepts and terms describing the various flavors of IRFs and GTI will be given in the semantics and content_qualifier FIELDS of the DataLink response to qualify the links. The different links can point to different dereferencable URLs or alternatively to different fragments of the same dereferencable URL as stated by

the DataLink specification.

To be completed: show an example ?

References

- Adrián-Martínez, S., Albert, A., Al Samarai, I., André, M., Anton, G., Anvar, S., Ardid, M., Astraatmadja, T., Aubert, J.-J., Baret, B., Barrios-Martí, J., Basa, S., Bertin, V., Biagi, S., Bigongiari, C., Bogazzi, C., Bouhou, B., Bouwhuis, M. C., Brunner, J., Busto, J., Capone, A., Caramete, L., Cârloganu, C., Carr, J., Cecchini, S., Charif, Z., Charvis, P., Chiarusi, T., Circella, M., Classen, F., Coniglione, R., Core, L., Costantini, H., Coyle, P., Creusot, A., Curtil, C., De Bonis, G., Dekeyser, I., Deschamps, A., Donzaud, C., Dornic, D., Dorosti, Q., Drouhin, D., Dumas, A., Eberl, T., Emanuele, U., Enzenhöfer, A., Ernenwein, J.-P., Escoffier, S., Fehn, K., Fermani, P., Flaminio, V., Folger, F., Fritsch, U., Fusco, L. A., Galatà, S., Gay, P., Geißelsöder, S., Geyer, K., Giacomelli, G., Giordano, V., Gleixner, A., Gómez-González, J. P., Graf, K., Guillard, G., van Haren, H., Heijboer, A. J., Hello, Y., Hernández-Rey, J. J., Herold, B., Höfl, J., Hugon, C., James, C. W., de Jong, M., Kadler, M., Kalekin, O., Kappes, A., Katz, U., Kooijman, P., Kouchner, A., Kreykenbohm, I., Kulikovskiy, V., Lahmann, R., Lambard, E., Lambard, G., Larosa, G., Lattuada, D., Lefèvre, D., Leonora, E., Lo Presti, D., Loehner, H., Loucatos, S., Louis, F., Mangano, S., Marcellin, M., Margiotta, A., Martínez-Mora, J. A., Martini, S., Michael, T., Montaruli, T., Morganti, M., Müller, C., Neff, M., Nezri, E., Palioselitis, D., Pāvālaš, G. E., Perrina, C., Popa, V., Pradier, T., Racca, C., Riccobene, G., Richter, R., Rivière, C., Robert, A., Roensch, K., Rostovtsev, A., Samtleben, D. F. E., Sanguineti, M., Sapienza, P., Schmid, J., Schnabel, J., Schulte, S., Schüssler, F., Seitz, T., Shanidze, R., Sieger, C., Simeone, F., Spies, A., Spurio, M., Steijger, J. J. M., Stolarczyk, T., Sánchez-Losa, A., Tauti, M., Tamburini, C., Tayalati, Y., Trovato, A., Vallage, B., Vallée, C., Van Elewyck, V., Vecchi, M., Vernin, P., Visser, E., Wagner, S., Wilms, J., de Wolf, E., Yatkin, K., Yepes, H., Zornoza, J. D. and Zúñiga, J. (2014), ‘A search for neutrino emission from the fermi bubbles with the antares telescope’, *The European Physical Journal C* **74**(2). doi:10.1140/epjc/s10052-013-2701-6, <http://dx.doi.org/10.1140/epjc/s10052-013-2701-6>.
- Albert, A., Alfaro, R., Arteaga-Velázquez, J. C., Ayala Solares, H. A., Babu, R., Belmont-Moreno, E., Brisbois, C., Caballero-Mora, K. S., Capistrán, T., Carramiñana, A., Casanova, S., Chaparro-Amaro, O., Cotti, U., Cotzomi, J., Coutiño de León, S., De la Fuente, E., Diaz Hernandez, R., DuVernois, M. A., Durocher, M., Espinoza, C., Fan, K. L., Fernández Alonso, M., Fraija, N., García-González, J. A., Goksu, H., González,

- M. M., Goodman, J. A., Harding, J. P., Hinton, J., Huang, D., Hueyotl-Zahuantitla, F., Hüntemeyer, P., Jardin-Blicq, A., Joshi, V., Linnemann, J. T., Longinotti, A. L., Luis-Raya, G., Malone, K., Marandon, V., Martinez, O., Martínez-Castro, J., Matthews, J. A., Miranda-Romagnoli, P., Morales-Soto, J. A., Moreno, E., Mostafá, M., Nayerhoda, A., Nellen, L., Nisa, M. U., Noriega-Papaqui, R., Olivera-Nieto, L., Pérez-Pérez, E. G., Rho, C. D., Rosa-González, D., Ruiz-Velasco, E., Salazar-Gallegos, D., Salesa Greus, F., Sandoval, A., Schoorlemmer, H., Serna-Franco, J., Smith, A. J., Son, Y., Springer, R. W., Tollefson, K., Torres, I., Torres-Escobedo, R., Turner, R., Ureña-Mena, F., Villaseñor, L., Wang, X., Watson, I. J., Willox, E., Zhou, H., de León, C., Zepeda, A., HAWC Collaboration, Donath, A. and Funk, S. (2022), ‘Validation of standardized data formats and tools for ground-level particle-based gamma-ray observatories’, *A&A* **667**, A36, arXiv:2203.05937. doi:10.1051/0004-6361/202243527, <https://ui.adsabs.harvard.edu/abs/2022A&A...667A..36A>.
- Bonnarel, F., Dowler, P., Michel, L., Demleitner, M. and Taylor, M. (2023), ‘IVOA DataLink Version 1.1’, IVOA Recommendation 15 December 2023. <https://ui.adsabs.harvard.edu/abs/2023ivoa.spec.1215B>.
- Bradner, S. (1997), ‘Key words for use in RFCs to indicate requirement levels’, RFC 2119. <http://www.ietf.org/rfc/rfc2119.txt>.
- Collaboration*†, I., Abbasi, R., Ackermann, M., Adams, J., Aguilar, J. A., Ahlers, M., Ahrens, M., Alameddine, J. M., Alves, A. A., Amin, N. M., Andeen, K., Anderson, T., Anton, G., Argüelles, C., Ashida, Y., Athanasiadou, S., Axani, S., Bai, X., V., A. B., Barwick, S. W., Basu, V., Baur, S., Bay, R., Beatty, J. J., Becker, K.-H., Tjus, J. B., Beise, J., Bellenghi, C., Benda, S., BenZvi, S., Berley, D., Bernardini, E., Besson, D. Z., Binder, G., Bindig, D., Blaufuss, E., Blot, S., Boddenberg, M., Bontempo, F., Book, J. Y., Borowka, J., Böser, S., Botner, O., Böttcher, J., Bourbeau, E., Bradascio, F., Braun, J., Brinson, B., Bron, S., Brostean-Kaiser, J., Burley, R. T., Busse, R. S., Campana, M. A., Carnie-Bronca, E. G., Chen, C., Chen, Z., Chirkin, D., Choi, K., Clark, B. A., Clark, K., Classen, L., Coleman, A., Collin, G. H., Connolly, A., Conrad, J. M., Coppin, P., Correa, P., Cowen, D. F., Cross, R., Dappen, C., Dave, P., Clercq, C. D., DeLaunay, J. J., López, D. D., Dembinski, H., Deoskar, K., Desai, A., Desiati, P., de Vries, K. D., de Wasseige, G., DeYoung, T., Diaz, A., Díaz-Vélez, J. C., Dittmer, M., Dujmovic, H., Dunkman, M., DuVer-nois, M. A., Ehrhardt, T., Eller, P., Engel, R., Erpenbeck, H., Evans, J., Evenson, P. A., Fan, K. L., Fazely, A. R., Fedynitch, A., Feigl, N., Fiedlschuster, S., Fienberg, A. T., Finley, C., Fischer, L., Fox, D., Franckowiak, A., Friedman, E., Fritz, A., Fürst, P., Gaisser, T. K., Gallagher, J., Ganster, E., Garcia, A., Garrappa, S., Gerhardt, L., Ghadimi, A., Glaser, C., Glauch, T., Glüsenkamp, T., Goehlke, N., Goldschmidt, A., Gonza-

lez, J. G., Goswami, S., Grant, D., Grégoire, T., Griswold, S., Günther, C., Gutjahr, P., Haack, C., Hallgren, A., Halliday, R., Halve, L., Halzen, F., Minh, M. H., Hanson, K., Hardin, J., Harnisch, A. A., Haungs, A., Helbing, K., Henningsen, F., Hettinger, E. C., Hickford, S., Hignight, J., Hill, C., Hill, G. C., Hoffman, K. D., Hoshina, K., Hou, W., Huang, F., Huber, M., Huber, T., Hultqvist, K., Hünnefeld, M., Hussain, R., Hymon, K., In, S., Iovine, N., Ishihara, A., Jansson, M., Japaridze, G. S., Jeong, M., Jin, M., Jones, B. J. P., Kang, D., Kang, W., Kang, X., Kappes, A., Kappesser, D., Kardum, L., Karg, T., Karl, M., Karle, A., Katz, U., Kauer, M., Kellermann, M., Kelley, J. L., Kheirandish, A., Kin, K., Kiryluk, J., Klein, S. R., Kochocki, A., Koirala, R., Kolanoski, H., Kontrimas, T., Köpke, L., Kopper, C., Kopper, S., Koskinen, D. J., Koundal, P., Kovacevich, M., Kowalski, M., Kozynets, T., Krupczak, E., Kum, E., Kurahashi, N., Lad, N., Gualda, C. L., Lanfranchi, J. L., Larson, M. J., Lauber, F., Lazar, J. P., Lee, J. W., Leonard, K., Leszczyńska, A., Li, Y., Lincetto, M., Liu, Q. R., Liubarska, M., Lohfink, E., Mariscal, C. J. L., Lu, L., Lucarelli, F., Ludwig, A., Luszczak, W., Lyu, Y., Ma, W. Y., Madsen, J., Mahn, K. B. M., Makino, Y., Mancina, S., Mariş, I. C., Martinez-Soler, I., Maruyama, R., McHale, S., McElroy, T., McNally, F., Mead, J. V., Meagher, K., Mechbal, S., Medina, A., Meier, M., Meighen-Berger, S., Merckx, Y., Micallef, J., Mockler, D., Montaruli, T., Moore, R. W., Morik, K., Morse, R., Moulai, M., Mukherjee, T., Naab, R., Nagai, R., Nahnhauer, R., Naumann, U., Necker, J., Nguyen, L. V., Niederhausen, H., Nisa, M. U., Nowicki, S. C., Nygren, D., Pollmann, A. O., Oehler, M., Oeyen, B., Olivas, A., O’Sullivan, E., Pandya, H., Pankova, D. V., Park, N., Parker, G. K., Paudel, E. N., Paul, L., de los Heros, C. P., Peters, L., Peterson, J., Philippen, S., Pieper, S., Pizzuto, A., Plum, M., Popovych, Y., Porcelli, A., Rodriguez, M. P., Pries, B., Przybylski, G. T., Raab, C., Rack-Helleis, J., Raissi, A., Rameez, M., Rawlins, K., Rea, I. C., Rechav, Z., Rehman, A., Reichherzer, P., Reimann, R., Renzi, G., Resconi, E., Reusch, S., Rhode, W., Richman, M., Riedel, B., Roberts, E. J., Robertson, S., Roellinghoff, G., Rongen, M., Rott, C., Ruhe, T., Ryckbosch, D., Cantu, D. R., Safa, I., Saffer, J., Salazar-Gallegos, D., Sampathkumar, P., Herrera, S. E. S., Sandrock, A., Santander, M., Sarkar, S., Sarkar, S., Satalecka, K., Schaufel, M., Schieler, H., Schindler, S., Schmidt, T., Schneider, A., Schneider, J., Schröder, F. G., Schumacher, L., Schwefer, G., Sclafani, S., Seckel, D., Seunarine, S., Sharma, A., Shefali, S., Shimizu, N., Silva, M., Skrzypek, B., Smithers, B., Snihur, R., Soedingrekso, J., Sogaard, A., Soldin, D., Spannfellner, C., Spiczak, G. M., Spiering, C., Stamatikos, M., Stanev, T., Stein, R., Stettner, J., Stezelberger, T., Stokstad, B., Stürwald, T., Stuttard, T., Sullivan, G. W., Taboada, I., Ter-Antonyan, S., Thwaites, J., Tilav, S., Tischbein, F., Tollefson, K., Tönnis, C., Toscano, S., Tosi, D., Trettin, A., Tselengidou, M., Tung, C. F., Turcati, A., Turcotte, R., Turley, C. F., Twagirayezu, J. P., Ty, B.,

- Elorrieta, M. A. U., Valtonen-Mattila, N., Vandenbroucke, J., van Eijndhoven, N., Vannerom, D., van Santen, J., Veitch-Michaelis, J., Verpoest, S., Walck, C., Wang, W., Watson, T. B., Weaver, C., Weigel, P., Weindl, A., Weiss, M. J., Weldert, J., Wendt, C., Werthebach, J., Weyrauch, M., Whitehorn, N., Wiebusch, C. H., Willey, N., Williams, D. R., Wolf, M., Wrede, G., Wulff, J., Xu, X. W., Yanez, J. P., Yildizci, E., Yoshida, S., Yu, S., Yuan, T., Zhang, Z. and Zhelnin, P. (2023), ‘Observation of high-energy neutrinos from the galactic plane’, *Science* **380**(6652), 1338–1343, arXiv:<https://www.science.org/doi/pdf/10.1126/science.adc9818>. doi:10.1126/science.adc9818, <https://www.science.org/doi/abs/10.1126/science.adc9818>.
- Deil, C., Boisson, C., Kosack, K., Perkins, J., King, J., Eger, P., Mayer, M., Wood, M., Zabalza, V., Knödlseider, J., Hassan, T., Mohrmann, L., Ziegler, A., Khelifi, B., Dorner, D., Maier, G., Pedalletti, G., Rosado, J., Contreras, J. L., Lefaucheur, J., Brügge, K., Servillat, M., Terrier, R., Walter, R. and Lombardi, S. (2017), Open high-level data formats and software for gamma-ray astronomy, in ‘6th International Symposium on High Energy Gamma-Ray Astronomy’, Vol. 1792 of *American Institute of Physics Conference Series*, AIP, p. 070006. doi:10.1063/1.4969003, <https://ui.adsabs.harvard.edu/abs/2017AIPC.1792g0006D>.
- Donath, A., Terrier, R., Remy, Q., Sinha, A., Nigro, C., Pintore, F., Khelifi, B., Olivera-Nieto, L., Ruiz, J. E., Brügge, K., Linhoff, M., Contreras, J. L., Acero, F., Aguasca-Cabot, A., Berge, D., Bhattacharjee, P., Buchner, J., Boisson, C., Carreto Fidalgo, D., Chen, A., de Bony de Lavergne, M., de Miranda Cardoso, J. V., Deil, C., Fückling, M., Funk, S., Giunti, L., Hinton, J., Jouvin, L., King, J., Lefaucheur, J., Lemoine-Goumard, M., Lenain, J.-P., López-Coto, R., Mohrmann, L., Morcuende, D., Panny, S., Regeard, M., Saha, L., Siejkowski, H., Siemiginowska, A., Sip"ocz, B. M., Unbehaun, T., van Eldik, C., Vuillaume, T. and Zanin, R. (2023), ‘Gammapy: A python package for gamma-ray astronomy’, *A&A* **678**, A157. doi:10.1051/0004-6361/202346488.
- Dowler, P., Rixon, G., Tody, D. and Demleitner, M. (2019), ‘Table Access Protocol Version 1.1’, IVOA Recommendation 27 September 2019. doi:10.5479/ADS/bib/2019ivoa.spec.0927D, <https://ui.adsabs.harvard.edu/abs/2019ivoa.spec.0927D>.
- Fernique, P., Nebot, A., Durand, D., Baumann, M., Boch, T., Greco, G., Donaldson, T., Pineau, F.-X., Taylor, M., O’Mullane, W., Reinecke, M. and Derrière, S. (2022), ‘MOC: Multi-Order Coverage map Version 2.0’, IVOA Recommendation 27 July 2022. <https://ui.adsabs.harvard.edu/abs/2022ivoa.spec.0727F>.

- Giunti, L., Acero, F., Khélifi, B., Kosack, K., Lemièrre, A. and Terrier, R. (2022), ‘Constraining leptonic emission scenarios for the pevatron candidate hess j1702-420 with deep xmm-newton observations’, *A&A* **667**, A130. doi:10.1051/0004-6361/202244696.
- H.E.S.S. Collaboration (2018), ‘H.e.s.s. first public test data release’. doi:10.5281/ZENODO.1421098, <https://zenodo.org/record/1421098>.
- Louys, M., Tody, D., Dowler, P., Durand, D., Michel, L., Bonnarel, F., Micol, A. and IVOA DataModel Working Group (2017), ‘Observation Data Model Core Components, its Implementation in the Table Access Protocol Version 1.1’, IVOA Recommendation 09 May 2017. doi:10.5479/ADS/bib/2017ivoa.spec.0509L, <https://ui.adsabs.harvard.edu/abs/2017ivoa.spec.0509L>.
- Mattox, J. R., Bertsch, D. L., Chiang, J., Dingus, B. L., Digel, S. W., Esposito, J. A., Fierro, J. M., Hartman, R. C., Hunter, S. D., Kanbach, G., Kniffen, D. A., Lin, Y. C., Macomb, D. J., Mayer-Hasselwander, H. A., Michelson, P. F., von Montigny, C., Mukherjee, R., Nolan, P. L., Ramanamurthy, P. V., Schneid, E., Sreekumar, P., Thompson, D. J. and Willis, T. D. (1996), ‘The Likelihood Analysis of EGRET Data’, *Astrophysical Journal* **461**, 396. doi:10.1086/177068, <https://ui.adsabs.harvard.edu/abs/1996ApJ...461..396M>.
- Michel, L., Cresitello-Dittmar, M., Bonnarel, F., Landais, G., Lemson, G., Louys, M. and Salgado, J. (2023), ‘Model Instances in VOTables Version 1.0’, IVOA Recommendation 20 June 2023. <https://ui.adsabs.harvard.edu/abs/2023ivoa.spec.0620M>.
- Nigro, C., Deil, C., Zanin, R., Hassan, T., King, J., Ruiz, J. E., Saha, L., Terrier, R., Brüggel, K., Nöthe, M., Bird, R., Lin, T. T. Y., Aleksić, J., Boisson, C., Contreras, J. L., Donath, A., Jouvin, L., Kelley-Hoskins, N., Khelifi, B., Kosack, K., Rico, J. and Sinha, A. (2019), ‘Towards open and reproducible multi-instrument analysis in gamma-ray astronomy’, *A&A* **625**, A10, arXiv:1903.06621. doi:10.1051/0004-6361/201834938, <https://ui.adsabs.harvard.edu/abs/2019A&A...625A..10N>.
- Servillat, M., Riebe, K., Boisson, C., Bonnarel, F., Galkin, A., Louys, M., Nullmeier, M., Renault-Tinacci, N., Sanguillon, M. and Streicher, O. (2020), ‘IVOA Provenance Data Model Version 1.0’, IVOA Recommendation 11 April 2020. doi:10.5479/ADS/bib/2020ivoa.spec.0411S, <https://ui.adsabs.harvard.edu/abs/2020ivoa.spec.0411S>.
- Unbehaun, T., Mohrmann, L., Funk, S., Aiello, S., Albert, A., Garre, S. A., Aly, Z., Ambrosone, A., Ameli, F., Andre, M., Androutsou, E., Anghinolfi, M., Anguita, M., Aphecetche, L., Ardid, M., Ardid, S., Atmani,

H., Aublin, J., Bagatelas, C., Bailly-Salins, L., Baret, B., du Pree, S. B., Becherini, Y., Bendahman, M., Benfenati, F., Benhassi, M., Benoit, D. M., Berbee, E., Bertin, V., Biagi, S., Boettcher, M., Cabo, M. B., Boumaaza, J., Bouta, M., Bouwhuis, M., Bozza, C., Bozza, R. M., Brânzaş, H., Bretaudeau, F., Bruijn, R., Brunner, J., Bruno, R., Buis, E., Buompane, R., Busto, J., Caiffi, B., Calvo, D., Champion, S., Capone, A., Carenini, F., Carretero, V., Cartraud, T., Castaldi, P., Cecchini, V., Celli, S., Cerisy, L., Chabab, M., Chadolias, M., Chen, A., Cherubini, S., Chiarusi, T., Circella, M., Cocimano, R., Coelho, J. A. B., Coleiro, A., Coniglione, R., Coyle, P., Creusot, A., Cruz, A., Cuttone, G., Dallier, R., Darras, Y., De Benedittis, A., De Martino, B., Decoene, V., Del Burgo, R., Di Mauro, L. S., Di Palma, I., Díaz, A. F., Diego-Tortosa, D., Distefano, C., Domi, A., Donzaud, C., Dornic, D., Dörr, M., Drakopoulou, E., Drouhin, D., Dvornický, R., Eberl, T., Eddymaoui, A., van Eeden, T., Eff, M., van Eijk, D., El Bojaddaini, I., El Hedri, S., Enzenhöfer, A., Ferrara, G., Filipović, M. D., Filippini, F., Fusco, L. A., Gabriel, J., Gal, T., Méndez, J. G., Soto, A. G., Oliver, C. G., Geißelbrecht, N., Ghaddari, H., Gialanella, L., Gibson, B. K., Giorgio, E., Girardi, A., Goos, I., Gozzini, S. R., Gracia, R., Graf, K., Guderian, D., Guidi, C., Guillon, B., Gutiérrez, M., van Haren, H., Heijboer, A., Hekalo, A., Hennig, L., Hernández-Rey, J. J., Huang, F., Ibsalikh, W. I., Illuminati, G., James, C. W., de Jong, M., de Jong, P., Jung, B. J., Kalaczyński, P., Kalekin, O., Katz, U. F., Chowdhury, N. R. K., Khatun, A., Kistauri, G., van der Knaap, F., Kouchner, A., Kulikovskiy, V., Kvatadze, R., Labalme, M., Lahmann, R., Larosa, G., Lastoria, C., Lazo, A., Le Stum, S., Lehaut, G., Leonora, E., Lessing, N., Levi, G., Clark, M. L., Longhitano, F., Majumdar, J., Malerba, L., Mańczak, J., Manfreda, A., Marconi, M., Margiotta, A., Marinelli, A., Markou, C., Martin, L., Marzaioli, F., Mastrodicasa, M., Mastroianni, S., Micciché, S., Miele, G., Migliozzi, P., Migneco, E., Mijakowski, P., Mitsou, M. L., Mollo, C. M., Morales-Gallegos, L., Morley-Wong, C., Mosbrugger, A., Moussa, A., Mateo, I. M., Muller, R., Musone, M. R., Musumeci, M., Nauta, L., Navas, S., Nayerhoda, A., Nicolau, C. A., Nkosi, B., Ó Fearraigh, B., Oliviero, V., Orlando, A., Oukacha, E., González, J. P., Papalashvili, G., Gomez, E. J. P., Păun, A. M., Pāvālaş, G. E., Martínez, S. P., Perrin-Terrin, M., Perronnel, J., Pestel, V., Pestes, R., Piattelli, P., Poirè, C., Popa, V., Pradier, T., Pulvirenti, S., Quéméner, G., Quiroz, C., Rahaman, U., Randazzo, N., Razzaque, S., Rea, I. C., Real, D., Reck, S., Riccobene, G., Robinson, J., Romanov, A., Roscilli, L., Saina, A., Greus, F. S., Samtleben, D. F. E., Losa, A. S., Sanguineti, M., Santonastaso, C., Santonocito, D., Sapienza, P., Schnabel, J., Schneider, M. F., Schumann, J., Schutte, H. M., Seneca, J., Sennan, N., Setter, B., Sgura, I., Shandize, R., Shitov, Y., Šimkovic, F., Simonelli, A., Sinopoulou, A., Smirnov, M. V., Spisso, B., Spurio, M., Stavropoulos, D., Štekl, I., Taiuti, M., Tayalati, Y., Tedjditi, H., Thiersen, H., Tosta e Melo, I., Trocme, B.,

Tsagkli, S., Tsourapis, V., Tzamariudaki, E., Vacheret, A., Valsecchi, V., Van Elewyck, V., Vannoye, G., Vasileiadis, G., de Sola, F. V., Verilhac, C., Veutro, A., Viola, S., Vivolo, D., Warnhofer, H., Wilms, J., de Wolf, E., Yousfi, T., Zarpapis, G., Zavatarelli, S., Zegarelli, A., Zito, D., Zornoza, J. D., Zúñiga, J. and Zywucka, N. (2024), ‘Prospects for combined analyses of hadronic emission from

γ

-ray sources in the milky way with cta and km3net’, *The European Physical Journal C* **84**(2). doi:10.1140/epjc/s10052-023-12279-z, <http://dx.doi.org/10.1140/epjc/s10052-023-12279-z>.

Wilkinson, M. D., Dumontier, M., Aalbersberg, I. J., Appleton, G., Axton, M., Baak, A., Blomberg, N., Boiten, J.-W., da Silva Santos, L. B., Bourne, P. E., Bouwman, J., Brookes, A. J., Clark, T., Crosas, M., Dillo, I., Dumon, O., Edmunds, S., Evelo, C. T., Finkers, R., Gonzalez-Beltran, A., Gray, A. J., Groth, P., Goble, C., Grethe, J. S., Heringa, J., ’t Hoen, P. A., Hooft, R., Kuhn, T., Kok, R., Kok, J., Lusher, S. J., Martone, M. E., Mons, A., Packer, A. L., Persson, B., Rocca-Serra, P., Roos, M., van Schaik, R., Sansone, S.-A., Schultes, E., Sengstag, T., Slater, T., Strawn, G., Swertz, M. A., Thompson, M., van der Lei, J., van Muligen, E., Velterop, J., Waagmeester, A., Wittenburg, P., Wolstencroft, K., Zhao, J. and Mons, B. (2016), ‘The fair guiding principles for scientific data management and stewardship’, *Scientific Data* **3**(1), 160018. doi:10.1038/sdata.2016.18.

A Changes from Previous Versions

No previous versions yet.