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Astro-COLIBRI 2—An Advanced Platform for Real-Time Multi-Messenger Discoveries

Patrick Reichherzer [1,2,3], Fabian Schüssler [3], Valentin Lefranc [3], Julia Becker Tjus [1,2], Jayson Mourier [3] and Atilla Kaan Alkan [3,4]

[1] Theoretical Physics IV: Plasma-Astroparticle Physics, Faculty for Physics & Astronomy, Ruhr-Universität Bochum, Universitätsstraße 150, 44801 Bochum, Germany
[2] Ruhr Astroparticle and Plasma Physics Center, Ruhr-Universität Bochum, 44780 Bochum, Germany
[3] IRFU, CEA, Université Paris-Saclay, 91191 Gif-sur-Yvette, France
[4] CNRS, Laboratoire Interdisciplinaire des Sciences du Numérique, Université Paris-Saclay, 91405 Orsay, France
* Correspondence: patrick.reichherzer@rub.de

Abstract: The study of flaring astrophysical events in the multi-messenger approach requires instantaneous follow-up observations to better understand the nature of these events through complementary observational data. We present Astro-COLIBRI as a platform that integrates specific tools in the real-time multi-messenger ecosystem. The Astro-COLIBRI platform bundles and evaluates alerts about transients from various channels. It further automates the coordination of follow-up observations by providing and linking detailed information through its comprehensible graphical user interface. We present the functionalities with documented examples of Astro-COLIBRI usage through the community since its public release in August 2021. We highlight the use cases of Astro-COLIBRI for planning follow-up observations by professional and amateur astronomers, as well as checking predictions from theoretical models.

Keywords: high-energy astrophysics; multi-wavelength; multi-messenger; transients; flares; gamma-ray bursts; high-energy neutrinos; software

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1. Introduction

Advances in real-time multi-messenger observations of the most energetic explosions in the universe have recently [1,2] contributed significantly to understanding their nature by combining complementary but contemporaneous multi-messenger observations. Sources of these events exhibit temporal variability on various scales and include gamma-ray bursts (GRBs), flares of active galactic nuclei (AGN), supernova (SN) explosions, and fast radio bursts (FRBs). Advances in the multi-messenger and multi-wavelength approach are driven by next-generation monitoring and follow-up observatories combined with an ecosystem of numerous complimentary services dedicated to a rapid information exchange [3].

The ensemble of large field-of-view satellites and ground-based observatories around the world constitute the fundamental pillar for multi-messenger astronomy. They continuously monitor the entire sky for transient behavior across the whole spectrum of detectable messengers. In the case of the detection of a temporal excess in the real-time analysis that meets telescope-, event-type-, and messenger-specific criteria, alerts are distributed, and further offline analyses are triggered. Note that an observatory may distribute multiple alerts for an event at varying stages in the processing, ranging from preliminary event information within the first few seconds to several minutes, hours, or even days for final analysis results. Interventions may introduce additional latency from humans caused by issues in automated processes. This is illustrated in Figure 1, which shows the median latencies[1] of all alerts per quarter since 2014 for the final GRB VOEvents[2] of INTEGRAL (International Gamma-Ray Astrophysics Laboratory), *Fermi* GBM (Gamma-ray Burst Monitor), Swift-BAT (Burst Alert Telescope), and XRT (X-ray Telescope). The use of automatic Fermi RoboBA after 2016 resulted in constant median latency of GBM alerts.

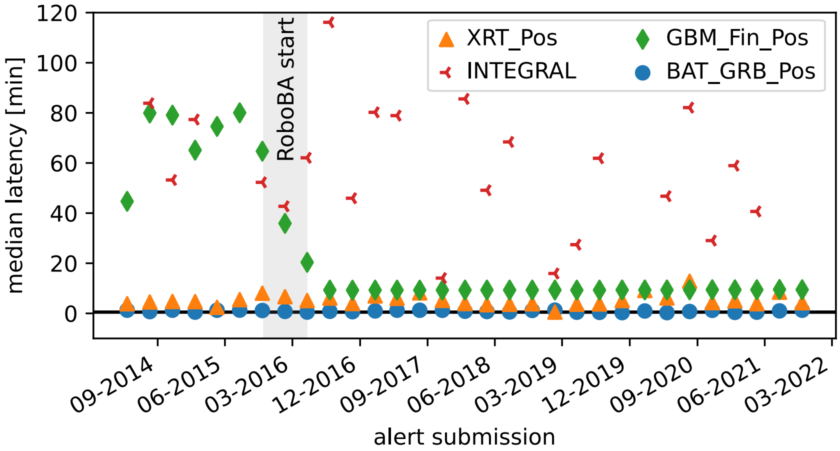

Figure 1. The median latencies of alerts per quarter since 2014 for the final VOEvents of the types *GBM_Fin_Pos*, *INTEGRAL#Offline*, *XRT_Pos*, and *BAT_GRB_Pos*. The vertical bar indicates approximately the start of the automated localization algorithm RoboBA used for the GBM final position alerts. Taken from [4].

Thanks to fully automatic processing, Swift-BAT and XRT alert latencies are also rather constant. While rapid, automatic alerts are available, the final offline INTEGRAL alerts, however, show significant variability due to manually generated alerts after interactive data analysis performed by an on-duty scientist.

There are several channels for the distribution of notifications of astrophysical transients using different platforms, including GCN (Gamma-ray Coordinates Network; now 'General Coordinates Network') notices and circulars, the transient name server (TNS), and the Astronomer's Telegram (ATel). We start in Section 2 with a discussion of the role of Astro-COLIBRI [5] (Coincidence Library for Real-time Inquiry) as a user-centric platform in the current ecosystem of real-time multi-messenger astronomy that listens to the aforementioned alert streams. We then continue describing the new features since the public Astro-COLIBRI release in August 2021 in Section 3. We discuss use cases of Astro-COLIBRI in Section 4 using the example of several transient events, where Astro-COLIBRI was used by the community of real-time, multi-messenger astronomy. In Section 5, we describe future features and connections to other tools, as well as integration into observatories.

2. Astro-COLIBRI as a Platform

2.1. Astro-COLIBRI Science Drivers

There are various classes of astrophysical sources that show transient behavior at various messenger types and particle energies. Figure 2 shows the transient astrophysical source classes currently supported in Astro-COLIBRI. In the following list, we show the event types that we display in Astro-COLIBRI. Note that the classes high-energy (HE) neutrinos and gravitational waves (GWs) are messenger types, while all other classes represent astrophysical objects. The reason for this is the yet missing real-time and unambiguous association of the two messengers to astrophysical object types.

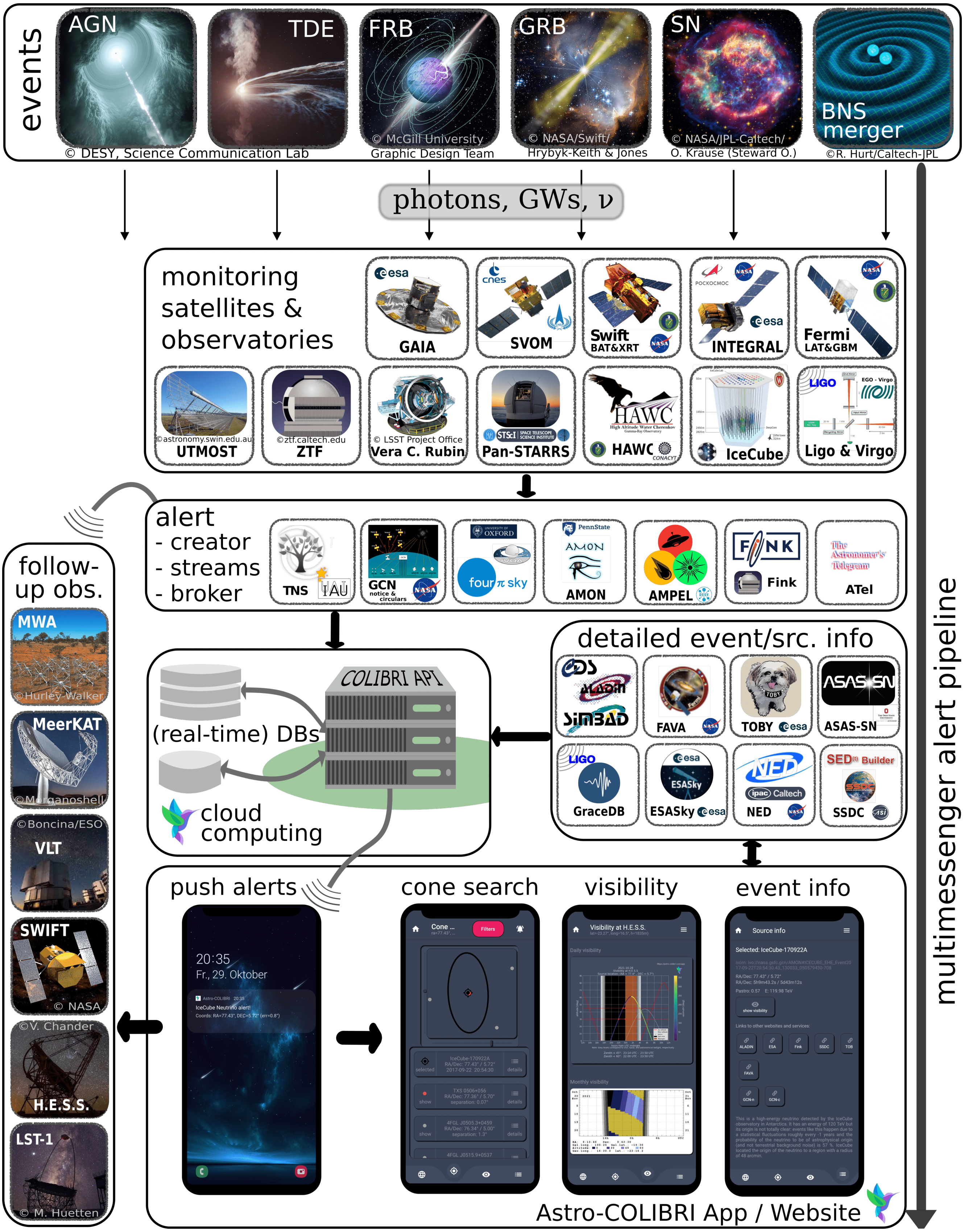

Figure 2. Overview of the real-time multi-messenger pipeline with boxes summarizing key steps in the workflow to conduct follow-up observations. The list of shown observatories, tools, and services is not complete but contains those supported in Astro-COLIBRI. Details are listed in Tables 1 and 2.

AGN: There are different subclasses of Active Galactic Nuclei (AGN) with variability on short (minutes/hours) and long (weeks) timescales in γ-rays, e.g., flat-spectrum radio quasars [6], BL Lac-type objects [7], and narrow-line Seyfert 1 objects [8]. There are various mechanisms discussed in literature [9–12] to account for the transient behavior of AGNs, including relativistically accelerated plasmoids moving along the jet axis. Secondary particles are created through various interaction processes that include synchrotron self-Compton, but also hadronic interaction processes [13,14]. Transport characteristics of charged particles in these magnetized environments influence the temporal evolution of multi-messenger emission [15–17]. (Quasi)-periodic behavior is observed in supermassive black hole binary systems, caused by, for example, the precession of the relativistic jet due to spin-orbit precession [18,19]. Currently, FLaapLUC [20] alerts on Fermi-LAT detected flares, and searches for ATels about flaring AGNs are accessible within Astro-COLIBRI.

GRB: Gamma-ray bursts (GRBs) are powerful explosions typically detected in the X-ray range. After the initial short but very intense pulse of high-energy radiation, further photons are emitted subsequently in the afterglow phase, posing an exciting object for multi-wavelength campaigns. Rapid follow-up observations across the electromagnetic spectrum are needed to answer questions about their flare time evolution, the maximum energy reached, the progenitor's properties, the circumburst environment, and the dependencies of the jet opening angle, etc.

FRB: Fast Radio Bursts (FRBs) are very brief, millisecond long, and intense bursts of radiation detected in the radio domain. Most of the detected bursts are of extragalactic origin, but the underlying emission mechanism(s) are still a mystery. Detailed studies in the radio domain are currently being complemented by extensive multi-wavelength campaigns in order to provide crucial insights into these intriguing phenomena. A major breakthrough was the coincident detection of FRB 200428 and an X-ray burst from the Galactic magnetar SGR 1935+2154 in April 2020 [21]. Another such coincidence was reported in October 2022 [22]. Astro-COLIBRI displays FRBs as soon as they are reported to TNS and can be used to illustrate spatial and temporal coincidences with other transients and known emitters, such as SGR 1935+2154.

GW: Gravitational waves (GWs) pose an important constituent in the multi-messenger approach as they cannot be absorbed by matter and allow deep insights into source physics. Combined multi-messenger observations that take GW detections into account will shed further light on the nature of GRBs, especially when caused by binary neutron star mergers, which are also triggering kilonova [2]. Interferometer-based GW observatories, such as LIGO and Virgo, have detected such events over recent years [23–25]. However, detections of current GW observatories come with large uncertainties in sky localization. These large uncertainty regions challenge the search for multi-messenger counterparts and associated sources. Astro-COLIBRI facilitates this task through its graphical interface showing the GW events with their uncertainty region and all temporal and spatial related transients, as well as sources listed in catalogs, such as 4FGL-DR3 and TevCat.

HE ν: The small interaction cross-section of high-energy (HE) neutrinos allows for deep insights into the central areas of astronomical particle accelerators. The AGN TXS 0506+056, was the first extragalactic object from which a high-energy neutrino was detected during its flaring state with a temporal and spatial correlation with the significance of 3σ [26]. Neutrino alerts are displayed in Astro-COLIBRI to help quickly find possible counterparts and assess their multi-wavelength properties and states. Currently, IceCube astrotrack (both gold and bronze), as well as cascade-like alerts, are supported.

OT: Optical transients (OT) is a broad category of phenomena that are typically identified via their transient optical emission. These range from flaring AGNs, tidal disruption events (TDE), cataclysmic variables (CV), stellar flares, novae, fast (blue) transients (FBOT), and many more.

SN: Supernovae (SNe) are powerful explosions of massive stars. These transient events can happen in their final life cycle or in a binary system composed of a white dwarf and its companion star. The number of classified SNe increased over the last years due to improved observatories and more sophisticated analysis pipelines, as shown in Figure 3, where the number of classified SNe is shown as a function of time broken down to the observatories with the most classified detections. Since version 1.3.0, SNe are supported within Astro-COLIBRI (see Figure 4), and users can subscribe to the automatic stream of SNe push notifications.

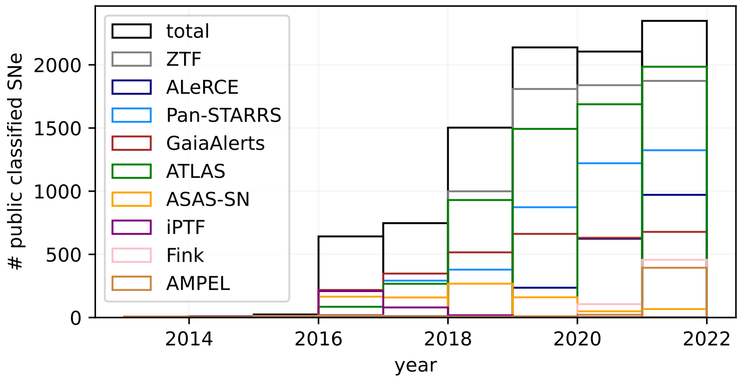

Figure 3. Statistic of publicly distributed and classified SNe generated by evaluating data stored in TNS from different telescopes or brokers.

Figure 4. Screenshot of the website of Astro-COLIBRI. In the top area, settings and filter options are available to customize the interface. The timeline (see Section 3.2 for details) contains all transient events in the user-defined time range that satisfy the user-set filters. These transients are also shown in the list on the left side and in the sky map. The right info area displays further information about the selected event/source with customized links to other websites, light curves, the spectrum, and at the bottom, detailed (and long-term) visibility information for the specified observatory (see Section 3.6 for details). A bright example of the SN category is SN 2022hrs, which is selected in the screenshot. The event info provides the brightness (15 mag at detection time). The visibility in France of the SN for the night of 19 May 2022 is selected to show the time window used for follow-up observations presented in Section 4.2.

However, new transient phenomena are often not clearly categorized. Some alerts may not be associated with a certain emission scenario but rather indicate a special accumulation of individual events in a given observatory. An example of the latter is the short timescale (0.2 s to 100 s) accumulations of very high-energy photon candidates in the HAWC air shower array. These non-classified events are listed in Astro-COLIBRI within the generic *bursts* category. This category also comprises events that are so rare that they do not justify a dedicated class within the Astro-COLIBRI interface on their own.

2.2. Integration of Multi-Messenger Services

The real-time multi-messenger astronomy community has developed an ecosystem of numerous complementary services and tools over the past decades to study the pressing questions of the transient sky. Those tools, however, come with their own interfaces, pipelines, access points, and use cases. The diverse landscape complicates the situation and increases the effort to keep up-to-date with all transient events across the different communities. Here, Astro-COLIBRI acts as a platform that bundles and assesses alerts from these various streams and communities through its comprehensible graphical user interface. Figure 2 outlines the science drivers, observatories, alert distribution systems (see Table 1 for details), catalogs, and services currently covered in Astro-COLIBRI, with details about the services and tools provided in Table 2.

Table 1. Overview of various alert creators, brokers, and streams. Astro-COLIBRI listens to VOEvent alerts via various brokers and parses notifications from FlaapLUC alert emails and notices from GCN, as well as from newly confirmed SNe from various alert brokers distributed via TNS.

Service	Description
AMON [27]	AMON (Astrophysical Multimessenger Observatory Network) is a system searching through streams of sub-threshold events from multi-messenger facilities for correlations of spatial and temporal coincidences.
AMPEL [28]	Alert management, photometry, and evaluation of light curves (AMPEL) system. AMPEL combines the functionality of an alert broker with a generic framework to host user-contributed analysis scripts. The implementation of this stream is currently in the testing phase.
ATel [29]	Astronomer's Telegrams (ATels) are human-written, web-based notifications to report astronomical observations of transient sources.
Fink [30]	Broker for automatized ingestion, annotation, selection, and redistribution of transient alerts that provides real-time transient classification using deep learning and adaptive learning techniques.
FLaapLUC [20]	FLaapLUC (Fermi-LAT automatic aperture photometry Light C↔Urve) detects relative flux variations in *Fermi*-LAT data of sources and alerts users via emails. Based on the Science Tools provided by the *Fermi* Science Support Center and the *Fermi*-LAT collaboration.
Four π sky [31]	Infrastructure of open data-services based on the VOEvent standardized message-format for distributing transient alerts, such as a VOEvent broker and a DB that stores historical transient alerts.
GCN-Circulars [32]	The Gamma-ray Coordinates Network (GCN, now 'General Coordinates Network') distributes human-written reports (named Circulars) about follow-up observations of GRBs.
GCN-Notices [32]	Machine-generated alerts about new detections intended to trigger rapid follow-up campaigns.
TNS [a]	The Transient Name Server (TNS) is the official International Astronomical Union mechanism for reporting new SN candidates and naming spectroscopically confirmed ones. There are dedicated brokers developed to handle large-scale astronomical survey data from ZTF and LSST e.g., such as AMPEL [28], Fink [30], ANTARES [33], ALeRCE [34], Lasair [35], MARS [b], and Pitt-Google Broker [c] that report detections and classifications via TNS.
VOEvents [36]	In order to use a standardized, machine-readable format, VOEvents (VO stands for Virtual Observatory) were officially adopted to report transients in 2006 by the International Virtual Observatory Alliance (IVOA).

[a] https://www.wis-tns.org/(accessed on 23 December 2022); [b] https://mars.lco.global/(accessed on 23 December 2022); [c] https://pitt-broker.readthedocs.io/en/latest/(accessed on 23 December 2022).

Table 2. Astro-COLIBRI is embedded in the ecosystem of real-time multi-messenger services. Customized links point directly from Astro-COLIBRI to the services and websites listed in the table. Figure 4 shows in the bottom right area the list of customized links for each event and source to provide convenient access to specific, more detailed information on demand.

Service	Description
ASAS-SN [e]	All Sky Automated Survey for SuperNovae (ASAS-SN) is an automatic all-sky survey to detect SNe. The link allows to obtain a photometric light curve of the selected sky region.
ALADIN [37]	Displays sources from catalogs or databases (DBs) in a sky map.
ALeRCE [34]	Web portal for transients from ALeRCE (Automatic Learning for the Rapid Classification of Events).
BAT [38]	Burst Alert Telescope (BAT) GRB event data processing report including detailed info, a flux summary, spectra, and light curves.
ESA [39,40]	ESASky is an application that visualizes astronomical data in a sky map.
FAVA [41]	*Fermi* All-sky Variability Analysis (FAVA) for the selected position observed by the Large Area Telescope (LAT).
Fink [30]	Broker and science portal providing information about transients.
Gaia [42]	Gaia Photometric Science Alerts is an all-sky photometric transient survey, based on the repeated measurements of Gaia.
GBM [f]	Quicklook directory with near real-time (10–15 min after the *Fermi*-Gamma-ray Burst Monitor (GBM) trigger) information of light curves and spacecraft pointing history.
GCN-c [g]	Gamma-ray Coordinates Network circulars (GCN-c) inform in human-written reports about the observed event.
GCN-n [h]	GCN notices (GCN-n) deliver information about basic properties of transient objects in automatically generated alerts.
GraceDB [i]	Communications hub and DB with information about candidate gravitational-wave events.
IBAS [43]	System for real-time detection of GRBs seen by INTEGRAL.
LAT-LCR [j]	DB of multi-cadence flux calibrated light curves for over 1500 variable sources from the 10 year *Fermi*-LAT point source catalog.
NED [44]	NASA/IPAC Extragalactic Database (NED) about galaxies and other extragalactic objects, with more details, photometry, spectra and further references/links.
Pan-STARRS [45]	DB of images after analysis and processing obtained by the Pan-STARRS (Panoramic Survey Telescope And Rapid Response System) telescopes.
SkyMapper [46]	DB with a digital record of the entire southern sky, which stores images and catalogs from SkyMapper's Southern Survey.
SIMBAD [47]	Provides additional information, cross-identifications, bibliography and measurements of sources.
SNAD [48]	Web portal for objects from the Zwicky Transient Facility's.
SSDC [k]	Display of Spectral Energy Distributions (SEDs) of astrophysical sources from the Space Science Data Center (SSDC).
Swift [l]	High-level information on the Swift-BAT or XRT observations and links to other relevant references.
TACH [49]	The Time-domain Astronomy Coordination Hub (TACH) is a NASA GSFC project that provides an overview over GCN notices and circulars via the "GCN viewer" interface.
TeVCat [50]	Source catalog for very high energy gamma-ray astronomy with detailed source information and linked references.
TNS [m]	The Transient Name Server (TNS) provides discovery and classification reports of e.g., SNe and further info, e.g., spectra.
TOBY [n]	The Tool for Observation visiBilitY and schedule (TOBY) shows event visibility and schedule for a variety of observatories.
XRT [51]	Light curve, spectra, and comparison with other bursts provided by Swift's X-ray Telescope (XRT).

[e] https://www.astronomy.ohio-state.edu/asassn/index.shtml (accessed on 23 December 2022); [f] https://heasarc.gsfc.nasa.gov/FTP/fermi/data/gbm/triggers/ (accessed on 23 December 2022); [g] https://gcn.gsfc.nasa.gov/gcn/gcn3_archive.html (accessed on 23 December 2022); [h] https://gcn.gsfc.nasa.gov/ (accessed on 23 December 2022); [i] https://gracedb.ligo.org/latest/ (accessed on 23 December 2022); [j] https://fermi.gsfc.nasa.gov/ssc/data/access/lat/LightCurveRepository/ (accessed on 23 December 2022); [k] https://tools.ssdc.asi.it/SED/ (accessed on 23 December 2022); [l] https://swift.gsfc.nasa.gov/archive/grb_table/ (accessed on 23 December 2022); [m] https://www.wis-tns.org/ (accessed on 23 December 2022); [n] http://integral.esa.int/toby/ (accessed on 23 December 2022)

2.2.1. Alert Distribution Systems

Alerts of transient events and assessing their relevance for follow-up observations to the respective observatories are of fundamental importance. Rapid distribution of these events occurs via several channels on different platforms and timescales. Alerts streams refer to the sequence of distributed alerts.

The various alert systems used for this task are summarized in Table 1, including VOEvents, GCNs (notices and circulars), TNS notifications, and ATels. These alert distribution mechanisms differ in their underlying communication technology, the targeted scientific community, the degree of machine- or human-generated content of the alerts, and the latencies. The applied distribution technologies involve the usage of application programming interfaces, brokers, databases, emails, mobile applications, and webpages.

The patchwork of different mechanisms requires the community to make an effort to keep track of the ever-increasing amount of relevant information.

For example, the dominant pipeline for GRB transients starts with the monitoring observatories *Fermi*, Swift, or INTEGRAL that send their detections via the Gamma-ray Coordinates Network (GCN, also standing for General Coordinates Network) as notices or circulars to the community. Detections are typically announced via the largely automatized and machine-readable GCN notices. Human-written GCN circulars are then used to summarize and confirm the detections. The statistics of GCN circulars are shown in Figure 5, where it can be seen that alerting GCN circulars from these monitoring observatories make up only a tiny fraction, as most GCN circulars report follow-up observations from ground-based observatories around the globe, covering a broad range of wavelengths. Alerts of optical transients are, however, predominantly distributed through other pipelines and streams, including, e.g., TNS or brokers, such as AMPEL and Fink.

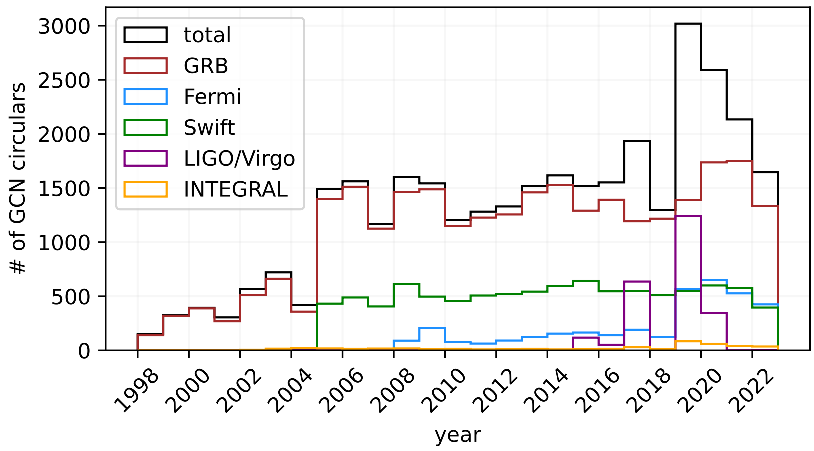

Figure 5. Number of GCNs circulars per year. The number has steadily increased over the past few years. A strong increase was due to the addition of GW observations.

2.2.2. Event Information Databases

In recent decades, an ecosystem of services was created to study the various types of different transients. This ecosystem provides specific information on various aspects relevant to real-time multi-messenger astrophysics. These services distribute information via static or dynamic web pages, databases, queryable application programming interfaces (APIs), or interactive sky maps. We summarize in Table 2 the systems linked within Astro-COLIBRI, each offering a particular value for studying transient events. Note that most services focus on specific types of events and only provide a comprehensive view of transient events when combined with other services in the table.

3. New Features of Astro-COLIBRI

Astro-COLIBRI has changed significantly since its release in August 2021. User input has been leveraged to include additional features, event categories, notification streams, and use cases. The interfaces have also become more intuitive and informative over the last 12 updates of Astro-COLIBRI[3]. We briefly overview new functionalities in the following, leaving the full details to the documentation, as they are liable to change as the platform is improved further:

3.1. Timeline

The novel timeline feature complements the existing display of transient events to visualize temporal correlations. This feature is located below the filter area and between both date buttons (see Figure 4). The interactive timeline also facilitates the choice of the time period through clickable vertical lines and the surrounding buttons. The timeline also works in the cone-search view, presenting a high-level temporal overview of transient events in a given sky region.

3.2. Improved Cone Searches

Cone searches are one of the main functions of Astro-COLIBRI. This presents a transient event in the context of other events or sources in the relevant temporal and spatial phase space. The improved cone search of Astro-COLIBRI now also displays the localization uncertainties of all transients in the cone-search view to notice overlapping detections (see the middle pane of Figure 6 for an example), including the newly supported transient classes such as SNe. The sources that are also shown in the cone search now also contain sources from catalogs of soft gamma-ray repeaters (SGRs) and anomalous X-ray pulsars (AXPs). Existing catalogs were updated to 4FGL-DR3 and the latest TevCat.

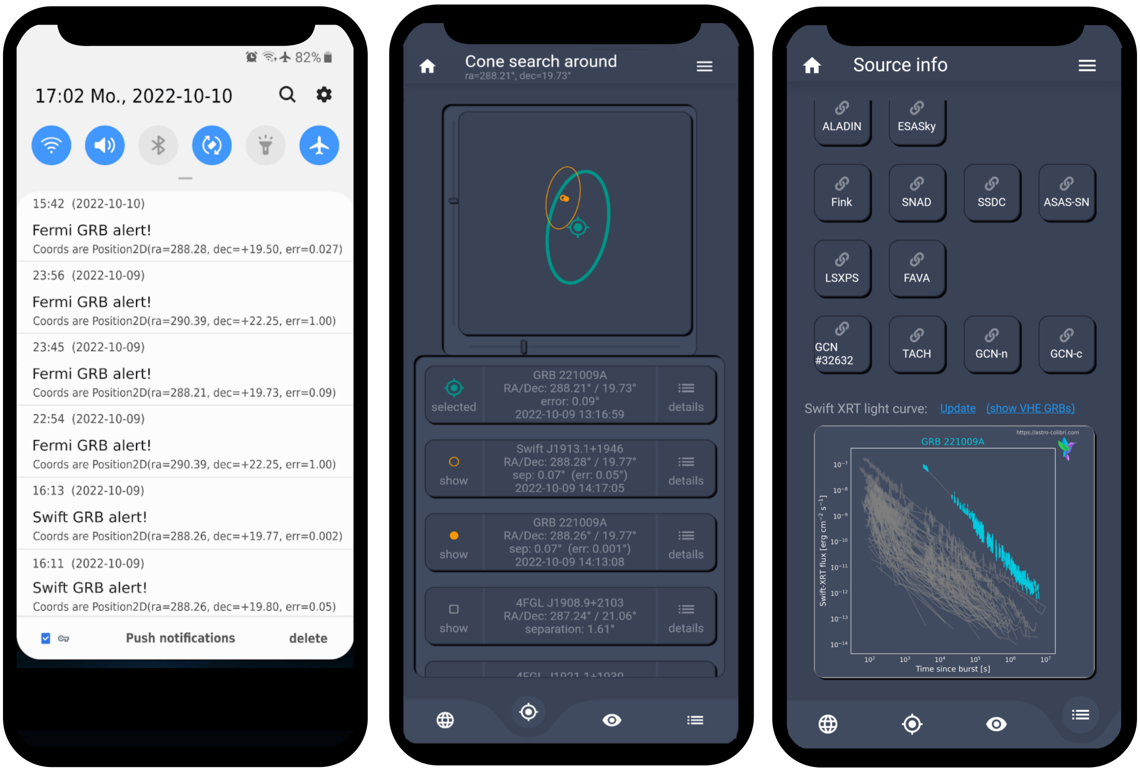

Figure 6. Mobile screens showing push notifications sent via Astro-COLIBRI about GRB 20221009A (see Section 4.1), cone search (see Section 3.2) illustrating the overlapping Swift and Fermi localizations, and customized links and the Swift XRT light curve (see Section 3.7) in the right screen.

3.3. Search for ATels

In particular, for AGN flares, follow-up observations are reported via ATels. For all events and sources in Astro-COLIBRI there is now the possibility to search for ATels that can provide reports on historical flares. Currently, ATels in Astro-COLIBRI are accessed via the NASA ADS API. However, the ATels are submitted to NASA ADS with a delay of one week, which is why the latest ATels are currently missing. This will be fixed in a future version of Astro-COLIBRI by parsing the ATels distributed by mail and storing the relevant information in our databases.

3.4. Novel Notification Streams

Since the initial release of Astro-COLIBRI, new transient source classes were added. The main ones are optical transients (SNe, novae, CVs, etc.) and GeV flares of AGNs detected by Fermi-LAT via the FLaapLUC pipeline. Users can subscribe to these new notification streams within the Astro-COLIBRI app. A dedicated stream for amateur astronomers was also added that only sends notifications for bright (mag < 18) optical transients.

3.5. Science Mode

In order to satisfy the various user profiles, we have implemented a switch between general, easy-to-understand information about events and detailed information for professional planning of follow-up observations. The *science mode* provides details useful for professional campaigns for follow-up observation, such as the visibility plots. When the *science mode* is switched off, general information about the transient event is provided.

3.6. Visibility Plots

The selection of custom dates for the daily visibility plots is now possible, supporting the investigation of historical and future observation conditions. We also added the possibility to define and manage custom observatories used for the visibility assessment. In addition, various new links to external services now provide weather information, seeing estimates and a real-time sky view.

3.7. GRB Light Curves

A new feature in Astro-COLIBRI is the display of the light curve of Swift-XRT GRBs, where the flux is displayed as a function of time since the detection of the burst. For better evaluation, the light curve is shown compared to historical GRBs. The right panel of Figure 6 shows the light curve of GRB 20221009A compared to all historical Swift-XRT GRBs. The enormous brightness of the event becomes immediately clear in this representation. In general, the plot also helps estimate fluxes and can facilitate planning of follow-up observations.

3.8. Coordinate Systems and Projections

Two celestial coordinate systems, namely Galactic and Equatorial, are now implemented in Astro-COLIBRI to specify the positions of celestial objects. The right-handed convention is used, meaning that the coordinates in the fundamental plane are positive to the north and east. In Astro-COLIBRI, three different projection systems are available to project astronomical coordinates on the two-dimensional map shown in Figure 4. Each projection method optimizes the display of the celestial objects on the map regarding different properties, while distortions to a certain degree are inevitable. The Mollweide and the Hammer-Aitov projection are equal-area map projections. The distortions at large declinations are not as substantial as in the similar-looking Mollweide projection. The last supported method in Astro-COLIBRI, the Mercator projection, flattens the spherical sky into a two-dimensional, rectangular map with latitude and longitude lines drawn in a grid. Users can select their favorite combination of coordinate system and projection within the Astro-COLIBRI platform.

4. Astro-COLIBRI in Practice

4.1. Multi-Wavelength Follow-Up Observations

Astro-COLIBRI allows real-time (mobile) tracking of all relevant updates on exciting transients coupled with tools useful for planning follow-up observations. However, the functionality of Astro-COLIBRI goes beyond this, as multi-wavelength follow-up observations reported in ATels can be displayed via the interface using the function described in Section 3.3. In addition, all circulars published via GCN are made available via the link to TACH. In the following, details are described using GRB 20221009A as an example:

- **Gamma -Ray Burst GRB 20221009A** Swift-BAT first reported the historical event GRB 20221009A to the community on 9 October 2022 at 14:11:33 UT with a GCN notice (trigger number 1126853[4]). Two minutes later, Swift-XRT sent its first notice about this event with updated localization information. Note that Swift-BAT triggered on the event a second time with the number 1,126,854 [5] and assigned the name Swift

J1913.1+1946 stating that it is a Galactic transient due to the proximity to the galactic plane, the exceptional brightness and a match with a source from the Swift-BAT on-board catalog. The Fermi satellite detected the object almost one hour earlier on 2022-10-09 at 13:16:59 UT, but managed to distribute the alert only eight hours later through a GCN notice due to the failure of their automatic alert pipeline (note that the median latencies of Fermi GBM final position GCNs are within 10 minutes as shown in Figure 1).
The detailed history of the alerts of Fermi and Swift that were distributed through Astro-COLIBRI is shown in Figure 6 on the left mobile screen. Here, the overview of push notifications is shown on 10 October 2022 at 13:02:12 UT, including further GCN circulars with the final localization information.
In the middle mobile screen, the cone search around the GRB 20221009A position of Fermi is presented, including the Swift-XRT (trigger number 1,126,853) and Swift-BAT (trigger number 1,126,854) detections taken on 9 October 2022 at 21:50:02 UT. Note that later Fermi updates modified the localization shown in Astro-COLIBRI slightly.
In the right mobile screen in the lower half, the new feature (see Section 3.7) of the Swift-XRT GRB light curves is shown, where the Swift-XRT flux is shown as a function of the time since the burst. Here, the GRB 20221009A light curve in cyan is compared to historical GRBs. The flux of GRB 20221009A is significantly larger compared to other historic GRBs. The ATels search functionality within Astro-COLIBRI provides a long list of reported follow-up observations. The customized link to TACH showing this event, provides further reports about follow-up multi-wavelength observations.

4.2. Optical Follow-Up Observations of SNe

Astro-COLIBRI has become an integral part of many amateur astronomers' quest to study bright supernovae. Users can choose to be informed only about the brightest SNe by push notifications through the app. In the following, two documented cases are listed where these alerts have led to follow-up observations by amateur astronomers:

- **Supernova SN 2022eyj** This SN Ia with redshift 0.021 was detected by ASAS-SN on 22 March 2022 07:26:24 UT (ra: 169.50°, dec: 7.85°) with a brightness of 16.1 mag. The user @SacHA(P) was notified about the SN via Astro-COLIBRI push notifications and performed subsequent optical observations that were reported on Twitter[6].
- **Supernova SN 2022hrs** This bright (15 mag on detection 16 April 2022 14:50:40) SN Ia with redshift 0.005 is shown as the selected event in Figure 4 (ra: 190.89°, dec: 11.58°). The user @Stef_Astro was notified about the SN via Astro-COLIBRI push notifications and performed subsequent optical observations that were reported on Twitter[7].

We use Twitter for public exchange and sharing of user-performed follow-up observations.

4.3. Multiple Alerts from the Same Phase Space

With Astro-COLIBRI, it is possible to check whether there are potential connections between multi-messenger detections over arbitrary time periods in a certain phase space.

- **PKS 0735+178 and IceCube-211208A** A cone search around PKS 0735+178, for which FLaapLUC issued an alert to report about a flare on 8 December 2022[8], reveals that the source position is contained within the uncertainty region of the neutrino event IceCube-211208A reported on the same date, as can be seen in Figure 7.

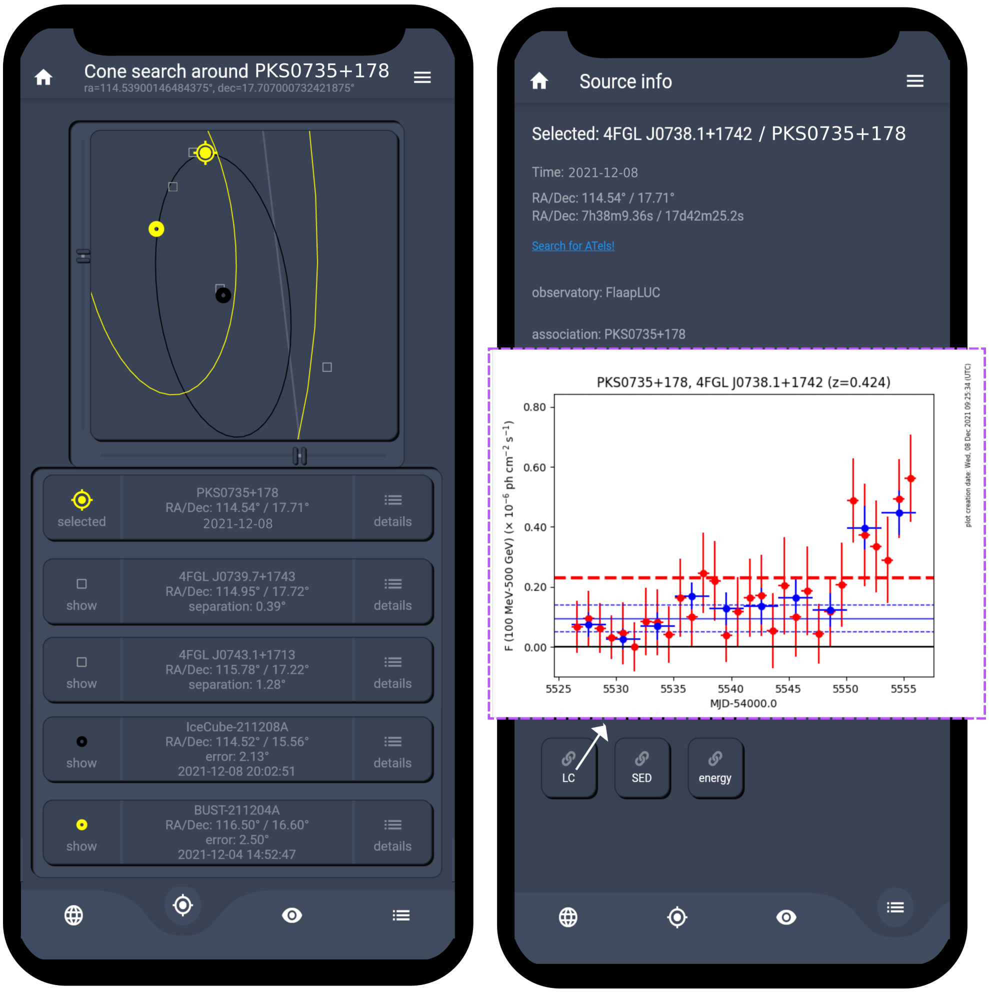

Figure 7. Screenshots of the Astro-COLIBRI app. The left mobile screen shows the cone search of the FLaapLUC alert from the flaring AGN PKS 0735+178 contained within the uncertainty region (black ellipse) of the neutrino IceCube-211208A (see Section 3.2). The list of sources/events in the cone search is shown below, ordered by the separation to PKS 0735+178. The right mobile screen shows information on PKS 0735+178. Clicking on the light curve (LC) button opens the FLaapLUC light curve plot in the browser.

4.4. Alerts to Test Theoretical Model Predictions

Theoretical models of transients often predict the emission of multiple messenger types, e.g., hadronic jet models predict photon and neutrino emission. Astro-COLIBRI can be employed to find possible counterparts of these emissions and test theoretical model predictions. A particular use case concerns IceCube neutrino alerts, as the origin of each high-energy neutrino is unknown during the time of observation. With Astro-COLIBRI, it is possible to rapidly check for, e.g., flaring AGNs within the localization uncertainty region (black ellipses) of the neutrino detection.

- **IceCube-170922A and TXS 0506+056** The extended delay in discovering the spatial and temporal correlation between the neutrino event and the AGN flare was driving the development of the Astro-COLIBRI platform. Figure 8 in the left panel shows the event in the Astro-COLIBRI app in cone-search view, where the black ellipse indicates the localization uncertainty. By clicking on details and the links therein to FAVA, users are able to immediately find flares from the surrounding sources.

Another particularly challenging task in theoretical astrophysics is the prediction of transient phenomena (see, e.g., Section 2.1). Astro-COLIBRI is suitable for checking such predictions. App users receive real-time alerts for transient events as push notifications according to their specifications. This feature allows users to be notified when observations according to their model predictions occur. In addition, all transients reported in Astro-COLIBRI can be searched via the interface by cone searches in adjustable time windows.

Figure 8. Mobile screen of cone searches within the Astro-COLIBRI event for the IceCube−170922A (**left**) and IceCube−220918A (**right**) alerts with their uncertainty regions surrounded by black lines.

- **IceCube−220918A and TXS 0506+056** Models that not only model the IceCube−170922A event but also predict further flares and potential neutrino detections compatible with TXS 0506+056 pose a compelling use case for Astro-COLIBRI, as it can be facilitated to find predicted events. One example is the model of a processing AGN harbored in TXS 0506+056 [52], which predicted the next flares around 2019–2020 and 2022–2023. While there was no flare during the first proposed time window[9], the authors of [19] were notified through Astro-COLIBRI about a high-energy neutrino detection compatible with the location of TXS 0506+056 in the proposed period of the flare in 2022–2023. The right mobile screen in Figure 8 shows the cone search of IceCube-220918A and the localization of TXS 0506+056 within the uncertainty of the neutrino localization. The customized link from Astro-COLIBRI to the TXS 0506+056 position in FAVA allowed users to immediately investigate the gamma-ray activity. Fermi-LAT gamma-ray observations[10] of IceCube-220918A found no flare of TXS 0506+056[11] but detection of a new gamma-ray source, Fermi J0502.5+0037[12].

5. Outlook

The current landscape of highly specialized tools covering different aspects of multi-messenger astrophysics requires adaptation to the challenge of next-generation observatories through mutual connections and joint structures. The development of Astro-COLIBRI as a holistic platform, interconnecting systems, and services is one step in this direction. During the first Astro-COLIBRI multi-messenger workshop in September 2022, an agenda for the next steps of Astro-COLIBRI was defined. In the meantime a first set of the discussed features were already implemented, such as Swift-XRT light curves. Remaining features to be implemented in the upcoming months include:

- We are developing language models with Natural Language Processing (NLP) experts to automatically analyze human-written messages (GCN Circulars, ATels, and TNS AstroNotes; ref. [53]). The foreseen system aims to automatically recognize and extract key concepts in astrophysics, such as astronomical facilities, object names, coordinates and all helpful information to trigger follow-up observation. In perspective, we plan to deploy this system in Astro-COLIBRI to enrich the platform by performing real-time analysis of human-written reports.
- Tiling maps for GW uncertainty regions to facilitate follow-up observations using the algorithms described in [54].
- Support and display of ALeRCE, Astronomaly [55], AMPEL, and Fink alerts.
- More customization for push notifications, such as listening to alerts from objects, based on their visibility, etc.
- Technical improvements will include url-routing mechanisms, which facilitate sharing content from Astro-COLIBRI.
- Improved user-defined filtering criteria.
- Possibility to provide results of user-performed follow-up observations into Astro-COLIBRI.

Along with implementing these new features, already existing features will be maintained and improved. The list of links to other service will be extended.

The Astro-COLIBRI development team is welcoming comments and feedback from the community to further improve the platform.

Within the Astro-COLIBRI workshops, we encourage third-party contributions to the Astro-COLIBRI source code. Contact: astro.colibri@gmail.com

Author Contributions: Author names ordered alphabetically and not by contribution: Conceptualization, V.L., P.R. and F.S.; methodology, V.L., P.R. and F.S.; software, A.K.A., V.L., J.M., P.R. and F.S.; validation, J.B.T., V.L., P.R. and F.S.; formal analysis, P.R.; investigation, V.L., P.R. and F.S.; resources, J.B.T., P.R. and F.S.; data curation, P.R. and F.S.; writing—original draft preparation, P.R.; writing—review and editing, P.R. and F.S.; visualization, P.R.; supervision, J.B.T. and F.S.; project administration, F.S.; funding acquisition, J.B.T., P.R. and F.S. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The data presented in screenshots of the Astro-COLIBRI interfaces can be accessed through our publicly available API at https://astro-colibri.science/ or also through the interfaces directly:

- Website: https://astro-colibri.com (accessed on 23 December 2022);
- Android App (Google Play Store): https://play.google.com/store/apps/details?id=science.astro.colibri&pli=1 (accessed on 23 December 2022);
- iOS App (Apple App Store): https://apps.apple.com/us/app/astro-colibri/id1576668763 (accessed on 23 December 2022).

Note that the exact appearance of the interface is subject to change. Here, version v2.1.0 of Astro-COLIBRI was used. The source code of Astro-COLIBRI is currently private. Public releases are planned in the future. The data presented in Figures 1, 3 and 5 are taken from the publicly available websites/APIs *voeventdb* [31], GCN [32], and TNS[13], respectively. Data and the scripts used to generate these figures are available to interested researchers upon reasonable request and/or in the following repository: https://github.com/reichherzerp/Transient-Statistics (accessed on 23 December 2022).

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Notes

1. Note that the latency outliers caused by human-in-the-loop interventions due to issues in the automatic pipelines are hidden.
2. https://voevent.readthedocs.io/en/latest/ (accessed on 23 December 2022).
3. The changelog of all versions are documented on https://astro-colibri.science/documentation (accessed on 23 December 2022).
4. GCN notices: https://gcn.gsfc.nasa.gov/other/1126853.swift (accessed on 23 December 2022).
5. GCN notices: https://gcn.gsfc.nasa.gov/other/1126854.swift (accessed on 23 December 2022).
6. https://twitter.com/P_AHcas/status/1506790945672548357?cxt=HHwWisCyubeYmekpAAAA (accessed on 23 December 2022)
7. https://astro-colibri.science/usecases (accessed on 23 December 2022). Note that the @Stef_Astro Twitter account is deleted.
8. See also https://www.astronomerstelegram.org/?read=15099 (accessed on 23 December 2022).
9. Note that a flare could still be present in the offline data of IceCube.
10. https://gcn.gsfc.nasa.gov/gcn3/32565.gcn3.
11. Note that there is no expected correlation between the observed gamma-ray flux and the neutrino signal flux when neutrinos are produced in a gamma-absorbed environment [12].
12. https://www.astronomerstelegram.org/?read=15620.
13. https://www.wis-tns.org/ (accessed on 23 December 2022).
14. https://astrophysics-workshop.web.app/ (accessed on 23 December 2022).
15. https://indico.in2p3.fr/event/26335/sessions/16384/##20220930 (accessed on 23 December 2022).

References

1. Aartsen, M.G.; Ackermann, M.; Adams, J.; Aguilar, J.A.; Ahlers, M.; Ahrens, M.; Altmann, D.; Anderson, T.; Arguelles, C.; Arlen, T.C. et al. Observation of High-Energy Astrophysical Neutrinos in Three Years of IceCube Data. *Phys . Rev. Lett.* **2014**, *113*, 101101. [CrossRef]
2. Pijuan-Sala, B.; Guibentif, C.; Göttgens, B. Multi-messenger Observations of a Binary Neutron Star Merger. *Astrophys. J. Lett.* **2017**, *848*, L12. [CrossRef]

3. Dorner, D.; Mostafá, M.; Satalecka, K. High-Energy Alerts in the Multi-Messenger Era. *Universe* **2021**, *7*, 393. [CrossRef]
4. Reichherzer, P. Consideration of Real-Time Effects for Improved Coordination of Multi-Messenger Campaigns. Doctoral Thesis, Ruhr-Universität Bochum, Universitätsbibliothek, Bochum, Germany, 2022. [CrossRef]
5. Reichherzer, P.; Schüssler, F.; Lefranc, V.; Yusafzai, A.; Alkan, A.K.; Ashkar, H.; Becker Tjus, J. Astro-COLIBRI-The COincidence LIBrary for Real-time Inquiry for Multimessenger Astrophysics. *Astrophys. J.* **2021**, *256*, 5. [CrossRef]
6. Abdollahi, S.; Acero, F.; Ackermann, M.; Ajello, M.; Atwood, W.B.; Axelsson, M.; Baldini, L.; Ballet, J.; Barbiellini, G.; Bastieri, D.; et al. Fermi Large Area Telescope Fourth Source Catalog. *Astrophys. J.* **2020**, *247*, 33. [CrossRef]
7. Aharonian, F.; Akhperjanian, A.G.; Bazer-Bachi, A.R.; Behera, B.; Beilicke, M.; Benbow, W.; Berge, D.; Bernlöhr, K.; Boisson, C.; Bolz, O.; et al. An Exceptional Very High Energy Gamma-Ray Flare of PKS 2155-304. *Astrophys. J.* **2007**, *664*, L71–L74. [CrossRef]
8. Gokus, A.; Paliya, V.S.; Wagner, S.M.; Buson, S.; D'Ammando, F.; Edwards, P.G.; Kadler, M.; Meyer, M.; Ojha, R.; Stevens, J.; et al. The first GeV flare of the radio-loud narrow-line Seyfert 1 galaxy PKS 2004-447. *Astronomy Astrophys.* **2021**, *649*, A77. [CrossRef]
9. Hawkins, M.R.S. Timescale of variation and the size of the accretion disc in active galactic nuclei. *Astronomy Astrophys.* **2007**, *462*, 581–589. [CrossRef]
10. Burd, P.R.; Kohlhepp, L.; Wagner, S.M.; Mannheim, K.; Buson, S.; Scargle, J.D. Ornstein-Uhlenbeck parameter extraction from light curves of Fermi-LAT observed blazars. *Astronomy Astrophys.* **2021**, *645*, A62. [CrossRef]
11. Abdalla, H. et al. [H.E.S.S. Collaboration] H.E.S.S. and MAGIC observations of a sudden cessation of a very-high-energy γ-ray flare in PKS 1510–089 in May 2016. *Astronomy Astrophys.* **2021**, *648*, A23. [CrossRef]
12. Kun, E.; Bartos, I.; Tjus, J.B.; Biermann, P.L.; Halzen, F.; Mező, G. Cosmic Neutrinos from Temporarily Gamma-suppressed Blazars. *Astrophys. J. Lett.* **2021**, *911*, L18. [CrossRef]
13. Böttcher, M.; Reimer, A.; Sweeney, K.; Prakash, A. Leptonic and Hadronic Modeling of Fermi-detected Blazars. *Astrophys. J. Lett.* **2013**, *768*, 54. [CrossRef]
14. Hoerbe, M.R.; Morris, P.J.; Cotter, G.; Becker Tjus, J. On the relative importance of hadronic emission processes along the jet axis of active galactic nuclei. *Mon. Not. R. Astron. Soc.* **2020**, *496*, 2885–2901. [CrossRef]
15. Reichherzer, P.; Becker Tjus, J.; Zweibel, E.G.; Merten, L.; Pueschel, M.J. Anisotropic cosmic ray diffusion in isotropic Kolmogorov turbulence. *Mon. Not. R. Astron. Soc.* **2022**, *514*, 2658–2666. [CrossRef]
16. Reichherzer, P.; Tjus, J. PropPy—Correlated random walk propagation of cosmic rays in magnetic turbulence. *J. Open Source Softw.* **2022**, *7*, 4243. [CrossRef]
17. Becker Tjus, J.; Hörbe, M.; Jaroschewski, I.; Reichherzer, P.; Rhode, W.; Schroller, M.; Schüssler, F. Propagation of Cosmic Rays in Plasmoids of AGN Jets-Implications for Multimessenger Predictions. *Physics* **2022**, *4*, 473–490. [CrossRef]
18. Kun, E.; Jaroschewski, I.; Ghorbanietemad, A.; Frey, S.; Becker Tjus, J.; Britzen, S.; Éva Gabányi, K.; Kiselev, V.; Schlegel, L.; Schroller, M.; et al. Multimessenger Picture of J1048+7143. *Astrophys. J.* **2022**, *940*, 163. [CrossRef]
19. Becker Tjus, J.; Jaroschewski, I.; Ghorbanietemad, A.; Bartos, I.; Kun, E.; Biermann, P.L. Neurino Cadence of TXS˽0506+056 Consistent with Supermassive Binary Origin. *arXiv* **2022**, arXiv:2210.00202.
20. Lenain, J.P. FLaapLUC: A pipeline for the generation of prompt alerts on transient Fermi-LAT γ-ray sources. *Astron. Comput.* **2018**, *22*, 9–15. [CrossRef]
21. Mereghetti, S.; Savchenko, V.; Ferrigno, C.; Götz, D.; Rigoselli, M.; Tiengo, A.; Bazzano, A.; Bozzo, E.; Coleiro, A.; Courvoisier, T.J.L.; et al. INTEGRAL Discovery of a Burst with Associated Radio Emission from the Magnetar SGR 1935+2154. *Astrophys. J. Lett.* **2020**, *898*, L29. [CrossRef]
22. Li, X.B.; Zhang, S.N.; Xiong, S.L.; Li, C.K.; Ge, M.Y.; Liu, C.Z.; Song, L.M.; Tuo, Y.L.; Cai, C.; Zhang, Y.Q.; et al. Insight-HXMT detection of an X-ray burst from SGR J1935+2154 coinciding with the radio burst on 2022-10-21. *Astron. Telegr.* **2022**, *15708*, 1.
23. Abbott, B.P. GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral. *Phys. Rev. Lett.* **2017**, *119*, 161101. [CrossRef] [PubMed]
24. Abbott, R.; Abbott, T.D.; Acernese, F.; Ackley, K.; Adams, C.; Adhikari, N.; Adhikari, R.X.; Adya, V.B.; Affeldt, C.; Agarwal, D.; et al. GWTC-3: Compact Binary Coalescences Observed by LIGO and Virgo During the Second Part of the Third Observing Run. *arXiv* **2021**, arXiv:2111.03606.
25. Abbott, R.; Abbott, R.; Abbott, T.D.; Acernese, F.; Ackley, K.; Adams, C.; Adams, T.; Addesso, P.; Adhikari, R.X.; Adya, V.B. Observation of Gravitational Waves from Two Neutron Star-Black Hole Coalescences. *Astrophys. J.* **2021**, *915*, L5. [CrossRef]
26. Aartsen, M.G. et al. [IceCube Collaboration] Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A. *Science* **2018**, *361*, eaat1378. [CrossRef]
27. Smith, M.W.E.; Fox, D.B.; Cowen, D.F.; Mészáros, P.; Tešic, G.; Fixelle, J.; Bartos, I.; Sommers, P.; Ashtekar, A.; Babu, G.J.; et al. The Astrophysical Multimessenger Observatory Network (AMON). *Astropart. Phys.* **2013**, *45*, 56–70. [CrossRef]
28. Nordin, J.; Brinnel, V.; van Santen, J.; Bulla, M.; Feindt, U.; Franckowiak, A.; Fremling, C.; Gal-Yam, A.; Giomi, M.; Kowalski, M.; et al. Transient processing and analysis using AMPEL: Alert management, photometry, and evaluation of light curves. *Astronom. Astrophys.* **2019**, *631*, A147. [CrossRef]
29. Rutledge, R.E. The Astronomer's Telegram: A Web-based Short-Notice Publication System for the Professional Astronomical Community. *Publ. Astron. Soc. Pac.* **1998**, *110*, 754–756. [CrossRef]
30. Möller, A.; Peloton, J.; Ishida, E.E.; Arnault, C.; Bachelet, E.; Blaineau, T.; Boutigny, D.; Chauhan, A.; Gangler, E.; Hernandez, F.; et al. FINK, a new generation of broker for the LSST community. *Mon. Not. R. Astron. Soc.* **2021**, *501*, 3272–3288. [CrossRef]
31. Staley, T.D.; Fender, R. The 4 Pi Sky Transient Alerts Hub. *arXiv* **2016**, arXiv:1606.03735.

32. Barthelmy, S.D.; Cline, T.L.; Butterworth, P.; Kippen, R.M.; Briggs, M.S.; Connaughton, V.; Pendleton, G.N. GRB Coordinates Network (GCN): A status report. In *American Institute of Physics Conference Series, Proceedings of the Gamma-Ray Bursts, 5th Huntsville Symposium, 2000, Huntsville, AL, USA, 18–22 October 1999*; American Institute of Physics: College Park, MD, USA, 2000;Volume 526, pp. 731–735. [CrossRef]
33. Saha, A.; Matheson, T.; Snodgrass, R.; Kececioglu, J.; Narayan, G.; Seaman, R.; Jenness, T.; Axelrod, T. ANTARES: A prototype transient broker system. In *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Proceedings of the Observatory Operations: Strategies, Processes, and Systems V, Montreal, QC, Canada, 25–27 June 2014*; SPIE: Bellingham, WA, USA, 2014; Volume 9149, p. 914908. [CrossRef]
34. Förster, F.; Cabrera-Vives, G.; Castillo-Navarrete, E.; Estevez, P.A.; Sanchez-Saez, P.; Arredondo, J.; Bauer, F.E.; Carrasco-Davis, R.; Catelan, M.; Elorrieta, F. et al. The Automatic Learning for the Rapid Classification of Events (ALeRCE) Alert Broker. *Astron. J.* **2021**, *161*, 242. [CrossRef]
35. Smith, K.W.; Williams, R.D.; Young, D.R.; Ibsen, A.; Smartt, S.J.; Lawrence, A.; Morris, D.; Voutsinas, S.; Nicholl, M. Lasair: The Transient Alert Broker for LSST:UK. *Res. Notes Am. Astron. Soc.* **2019**, *3*, 26. [CrossRef]
36. Petroff, E.; Houben, L.; Bannister, K.; Burke-Spolaor, S.; Cordes, J.; Falcke, H.; van Haren, R.; Karastergiou, A.; Kramer, M.; Law, C.; et al. VOEvent Standard for Fast Radio Bursts. *arXiv* **2017**, arXiv:1710.08155.
37. Boch, T.; Fernique, P. Aladin Lite: Embed your Sky in the Browser. In *Astronomical Society of the Pacific Conference Series, Proceedings of the Astronomical Data Analysis Software and Systems XXIII, Hawaii, HI, USA, 29 September–3 October 2014*; Astronomical Society of the Pacific: San Francisco, CA, USA, 2014; Volume 485, p. 277.
38. Krimm, H.A.; Holland, S.T.; Corbet, R.H.D.; Pearlman, A.B.; Romano, P.; Kennea, J.A.; Bloom, J.S.; Barthelmy, S.D.; Baumgartner, W.H.; Cummings, J.R.; et al. The Swift/BAT Hard X-Ray Transient Monitor. *Astrophys. J.* **2013**, *209*, 14. [CrossRef]
39. Giordano, F.; Racero, E.; Norman, H.; Vallés, R.; Merín, B.; Baines, D.; López-Caniego, M.; Martí, B.L.; de Teodoro, P.; Salgado, J.; et al. ESASky: A science-driven discovery portal for space-based astronomy missions. *Astron. Comput.* **2018**, *24*, 97. [CrossRef]
40. Merín, B.; Salgado, J.; Giordano, F.; Baines, D.; Sarmiento, M.H.; Martí, B.L.; Racero, E.; Gutiérrez, R.; Pollock, A.; Rosa, M.; et al. ESA Sky: A new Astronomy Multi-Mission Interface. *arXiv* **2015**, arXiv:1512.00842. [arXiv:astro-ph.IM/1512.00842].
41. Abdollahi, S.; Ackermann, M.; Ajello, M.; Albert, A.; Baldini, L.; Ballet, J.; Barbiellini, G.; Bastieri, D.; Gonzalez, J.B.; Bellazzini, R.; et al. The Second Catalog of Flaring Gamma-Ray Sources from the Fermi All-sky Variability Analysis. *Astrophys. J.* **2017**, *846*, 34. [CrossRef]
42. Hodgkin, S.T.; Harrison, D.L.; Breedt, E.; Wevers, T.; Rixon, G.; Delgado, A.; Yoldas, A.; Kostrzewa-Rutkowska, Z.; van Leeuwen, M.; Blagorodnova, N.; et al. Gaia Early Data Release 3. Gaia photometric science alerts. *Astron. Astrophys.* **2021**, *652*, A76. [CrossRef]
43. Mereghetti, S. Ten years of the INTEGRAL Burst Alert System (IBAS). *PoS* **2013**, *176*, 126. [CrossRef]
44. Madore, B.F.; Helou, G.; Corwin, H.G., Jr.; Schmitz, M.; Wu, X.; Bennett, J. The NASA/IPAC Extragalactic Database. In *Astronomical Society of the Pacific Conference Series, Proceedings of the Astronomical Data Analysis Software and Systems I*; ASP: San Fransisco, CA, USA, 1992; Volume 25, p. 47.
45. Magnier, E.A.; Chambers, K.C.; Flewelling, H.A.; Hoblitt, J.C.; Huber, M.E.; Price, P.A.; Sweeney, W.E.; Waters, C.Z.; Denneau, L.; Draper, P.W.; et al. The Pan-STARRS Data-processing System. *Astrophys. J. Suppl. Ser.* **2020**, *251*, 3. [CrossRef]
46. Onken, C.A.; Wolf, C.; Bessell, M.S.; Chang, S.W.; Da Costa, G.S.; Luvaul, L.C.; Mackey, D.; Schmidt, B.P.; Shao, L. SkyMapper Southern Survey: Second data release (DR2). *Publ. Astron. Soc. Aust.* **2019**, *36*, e033. [CrossRef]
47. Wenger, M.; Ochsenbein, F.; Egret, D.; Dubois, P.; Bonnarel, F.; Borde, S.; Genova, F.; Jasniewicz, G.; Laloë, S.; Lesteven, S.; et al. The SIMBAD astronomical database. The CDS reference database for astronomical objects. *Astron. Astrophys. Suppl. Ser.* **2000**, *143*, 9–22. [CrossRef]
48. Malanchev, K.; Kornilov, M.V.; Pruzhinskaya, M.V.; Ishida, E.E.O.; Aleo, P.D.; Korolev, V.S.; Lavrukhina, A.; Russeil, E.; Sreejith, S.; Volnova, A.A.; et al. The SNAD Viewer: Everything You Want to Know about Your Favorite ZTF Object. *arXiv* **2022**, arXiv:2211.07605.
49. Smale, A.; Racusin, J.; Barthelmy, S.; McGlynn, T.; Cenko, B.; Schnittman, J.; Perkins, J.; Baker, J.; Singer, L.; Sheets, T.; et al. Time-domain Astronomy Coordination Hub (TACH). In *American Astronomical Society Meeting Abstracts, Proceedings of the 235th Meeting of the American Astronomical Society, Honolulu, HI, USA, 4–8 January 2020*; American Astronomical Society: Washington, DC, USA, 2020; Volume 235, , p. 107.15.
50. Wakely, S.P.; Horan, D. TeVCat: An online catalog for Very High Energy Gamma-Ray Astronomy. In Proceedings of the International Cosmic Ray Conference, Merida, Mexico, 3–11 July 2007; Volume 3, pp. 1341–1344.
51. Evans, P.A.; Beardmore, A.P.; Page, K.L.; Osborne, J.P.; O'Brien, P.T.; Willingale, R.; Starling, R.L.C.; Burrows, D.N.; Godet, O.; Vetere, L.; et al. Methods and results of an automatic analysis of a complete sample of Swift-XRT observations of GRBs. *Mon. Not. R. Astron. Soc.* **2009**, *397*, 1177–1201. [CrossRef]
52. de Bruijn, O.; Bartos, I.; Biermann, P.L.; Tjus, J.B. Recurrent Neutrino Emission from Supermassive Black Hole Mergers. *Astrophys. J. Lett.* **2020**, *905*, L13. [CrossRef]
53. Alkan, A.K.; Grouin, C.; Schüssler, F.; Zweigenbaum, P. TDAC, the First Time-Domain Astrophysics Corpus: Analysis and First Experiments on Named Entity Recognition. In Proceedings of the first Workshop on Information Extraction from Scientific Publications, Bolzano, Italy, 26 September 2022.

54. Ashkar, H.; Brun, F.; Füßling, M.; Hoischen, C.; Ohm, S.; Prokoph, H.; Reichherzer, P.; Schüssler, F.; Seglar-Arroyo, M. The H.E.S.S. gravitational wave rapid follow-up program. *J. Cosmol. Astropart. Phys.* **2021**, *2021*, 045. [CrossRef]
55. Lochner, M.; Bassett, B.A. ASTRONOMALY: Personalised active anomaly detection in astronomical data. *Astron. Comput.* **2021**, *36*, 100481. [CrossRef]