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Scientific study: synergies of transient event observing

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Abstract

Multiwavelength and multimessenger observations will be crucial for the next generation of telescopes, especially the ESFRI facilities. For the improved facilities, discovery space will be especially in the area of short-term transient events. In this document we discuss multi-messenger science in the era of the upcoming ESFRI facilities. We focus on expected challenges in multimessenger follow-ups, especially concerning mutliwavelength coverage, memoranda of understanding, as well as scheduling and priorities. Overcoming these challenges will be a task for the next few years in the preparation phases of the ESFRI facilities.

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IV Application Area

This document is a formal deliverable for the GA of the project, applicable to all members of the ASTERICS project, beneficiaries and third parties, as well as its collaborating projects.

V Terminology

A complete project glossary is provided at the following page:
http://www.asterics2020.eu/about/glossary/

CTA Cherenkov Telescope Array

VI Project Summary

ASTERICS (Astronomy ESFRI & Research Infrastructure Cluster) aims to address the cross-cutting synergies and common challenges shared by the various Astronomy ESFRI facilities (SKA, CTA, KM3Net & E-ELT). It brings together for the first time, the astronomy, astrophysics and particle astrophysics communities, in addition to other related research infrastructures. The major objectives of ASTERICS are to support and accelerate the implementation of the ESFRI telescopes, to enhance their performance beyond the current state-of-the-art, and to see them interoperate as an integrated, multi-wavelength and multi-messenger facility. An important focal point is the management, processing and scientific exploitation of the huge datasets the ESFRI facilities will generate. ASTERICS will seek solutions to these problems outside of the traditional channels by directly engaging and collaborating with industry and specialised SMEs. The various ESFRI pathfinders and precursors will present the perfect proving ground for new methodologies and prototype systems. In addition, ASTERICS will enable astronomers from across the member states to have broad access to the reduced data products of the ESFRI telescopes via a seamless interface to the Virtual Observatory framework. This will massively increase the scientific impact of the telescopes, and greatly encourage use (and re-use) of the data in new and novel ways, typically not foreseen in the original proposals. By demonstrating cross-facility synchronicity, and by harmonising various policy aspects, ASTERICS will realise a distributed and interoperable approach that ushers in a new multi-messenger era for astronomy. Through an active dissemination programme, including direct engagement with all relevant stakeholders, and via the development of citizen scientist mass participation experiments, ASTERICS has the ambition to be a flagship for the scientific, industrial and societal impact ESFRI projects can deliver.

VII Executive Summary

In this deliverable we study the multimessenger and multiwavelength synergies of ASTERICS ESFRI facilities. We first introduce the ASTERICS ESFRI facilities: CTA, SKA, KM3Net, and the E-ELT. We then study their synergies.

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1 Introduction

Recent international breakthroughs in multimessenger astrophysics pave the way towards a better understanding of many aspects of the extreme environments in the observable Universe. With the next generation of instruments, further breakthroughs in this domain of astronomy are to be expected. Many of the previous and current instruments rely on manual interventions of humans and their analysis work of the data to decide on follow-up observations. Such observations are thereby inevitably delayed. Switching to real-time automated follow-up observations of transient multimessenger events, optionally based on automated algorithms deriving further decision criteria, is therefore the state-of-the-art development in this field. The communication between different parties is often based on memoranda of understanding (MoUs). For any current telescope project, having a plethora of MoUs with many partners is therefore key to a successful participation in multi-messenger campaigns.
Multimessenger studies usually encompass cosmic rays, neutrinos, gravitational waves, and dark matter in addition to photons. Recently neutrinos and gravitational waves have both been associated with astrophysical sources (The IceCube Collaboration et al. 2018; Abbott et al. 2017). Multimessenger astrophysics is, however, older than expected. The first association of particles with an astrophysical object has already been established 70 years ago: an increase of cosmic rays after a solar flare was seen in a balloon experiment (Neher & Roesch 1948). However, we have known about cosmic rays since the discovery in 1909 by T. Wulf (Hörandel 2013). Neutrinos have been proposed by W. Pauli in 1930 (Brown 1978) and were then discovered 26 years later (Cowan et al. 1956). The first association of cosmic neutrinos with an astrophysical source occurred shortly after with the first measurement of the solar neutrino flux (Davis et al. 1968), discovering the "solar neutrino problem". This finding was explained with neutrino oscillations (predicted by Pontecorvo in 1957 (Gribov & Pontecorvo 1969)) and experimentally confirmed in 1998 (Fukuda et al. 1998; Ahmad et al. 2001). After these initial results and associations, it took several decades until the serendipitous discovery of neutrinos from SN 1987A (Hirata et al. 1987; Bionta et al. 1987). It has then taken another 3 decades for the first plausible associations of neutrinos with extragalactic sources (Kadler et al. 2016; The IceCube Collaboration et al. 2018).
In this document, we highlight the synergies and challenges for the future generations of telescopes and instruments. With the improved sensitivity of KM3NeT, we expect to discover the sources of the high-energy neutrinos seen by IceCube. Data from most wavelengths will benefit from quick associations of electromagnetic counterparts with gravitational wave events. With new surveys, such as the Large Synoptic Survey Telescope (LSST), we expect a large number of transient detections. There is thus big discovery space ahead of us in particular at short time scales, which have so far not been explorable, but are in reach of the future generation of telescopes. Finally, we expected further discoveries from very high energy gamma rays and the unprecedented sensitivity of the Cherenkov Telescope Array (CTA).
In the following section, we discuss challenges of multi-messenger science and areas where we still need to improve. We aim at providing a guideline for solving these challenges. We take community input, but also political and financial aspects into account, when discussing synergies for the next generation ESFRI facilities.

2 Challenges in multimessenger astronomy

2.1 Multiwavelength coverage

A unique challenge is adequate spectral coverage for all aspects of multimessenger astrophysics. This is due to two main reasons: firstly, lack of an instrument with sufficient sensitivity in the desired energy range, and secondly, lack of access to an existing instrument for the science case in question. An instrument may be adequate for observing a transient event, but the instrument PI or collaboration does not want to follow-up the transient event. Or an instrument may be available but its technical capabilities are limited (e.g. slow slew times could prevent a quick follow-up.
The availability and continued operations of appropriate current instruments a few years into the future

is especially difficult to estimate. Which ground- or space-based telescopes will still be able to operate a decade from now? Both the Hubble Space Telescope (HST; launch in 1995) and the Chandra Space Telescope (launch in 1999), have recently entered into safe mode and are starting to experience operational problems. The *Fermi* satellite has already partially recovered from a safe mode incident. Since this incident, one of its solar panels is stuck in one position, hindering the rocking motion that allows it to cover the full sky quickly. Most satellites are past their initial planned mission time line, but no successor is planned within the next two decades, especially in the X-ray band. Which instruments and mission will receive funding to continue, or to be built and launched in the next decade? Especially satellites are prone to unforeseeable problems, which can end their missions quickly. The Hitomi satellite, for example, only took data for a few months before it was lost[1], although a (much smaller) replacement mission has now been approved[2]. Even if missions are approved and funded (e.g. JWST, Athena[3]), unexpected delays often shift these mission back for several years due to small launch windows or problems that take time to correct.
On the other hand, satellites can operate much longer than planned. The *XMM* satellite has been in orbit since 1999 without any major problems, while its missions was planned for only 5 years. Therefore planning coverage many years in advance is difficult; additionally funding is not yet secured for all planned projects. In the top panel of Fig. 1, we show the energy coverage of the ESFRI projects plus the major planned X-ray mission Athena. The bottom panel lists current and future projects, with their planned start dates.
Currently, there is no funded mission in the MeV γ-ray energy range. While the INTEGRAL satellite observes in this energy range, it lacks sensitivity for most extragalactic sources and detects mostly Galactic X-ray binaries. Further, integration times required are many hours; sensitivity to fast, transient events is not optimal.
The second problem deals with the problem of instruments in a given energy range that might not be available for the science goals. One such example is the *XMM* satellite. While it has a large effective area and can detect very faint sources, it has a slew speed of 90°/hour (Saxton et al. 2008), so fast follow-up is difficult. Another problem is availability of time for serendipitous transient follow-up discoveries, which we will discuss in more detail in the following section.

2.2 Memoranda of understanding and exclusivity of data

This section deals with problems involving the policies of data sharing and memoranda of understanding. Data sharing and data policies are often informed by funding and organizational set-ups. The data of NASA and ESA facilities have to be made public (in some cases after a proprietary period to give the principal investigator of an observation time to publish their observation). Experiments in particles physics (e.g. CERN's ATLAS and CMS), and some astronomical facilities like the current very high-energy γ-ray instruments as well as many radio observatories do not usually make their data publicly available. While this minimizes the chances of being "scooped" (another group publishes your findings first), this does not allow for a maximum science output of the data. This fear of "being scooped" stems from an increasingly competitive field that too often focuses on publication metrics over quality.
Private data has been reduced in the recent years by signing memoranda of understanding between large collaborations, instruments and experiments. These allow for data sharing between members of these collaborations, and subsequent combined publications. While this solves some of the problems of restricted data, it does not allow for access from outside parties. Essentially, it requires interested scientist to be an associated (affiliated) or a full member of one of the large collaborations to access the relevant information. MoUs also require scientists to communicate their results to the other collaborations with relevant MoUs. Further, this usually leads to a lengthy multi-collaboration review process of paper drafts, often in conflict with PhD project deadlines.
A problem in this approach is that MoUs exclude scientists without the financial means or connections. Especially scientists in developing nations are hindered in participating in multimessenger science. The Cherenkov Telescope Array Observatory CTA has ensured that the guest observer's (GO) program is

[1] http://global.jaxa.jp/press/2016/04/20160428_hitomi.html
[2] http://global.jaxa.jp/projects/activity/int/topics.html#topics13098
[3] https://www.cosmos.esa.int/web/athena

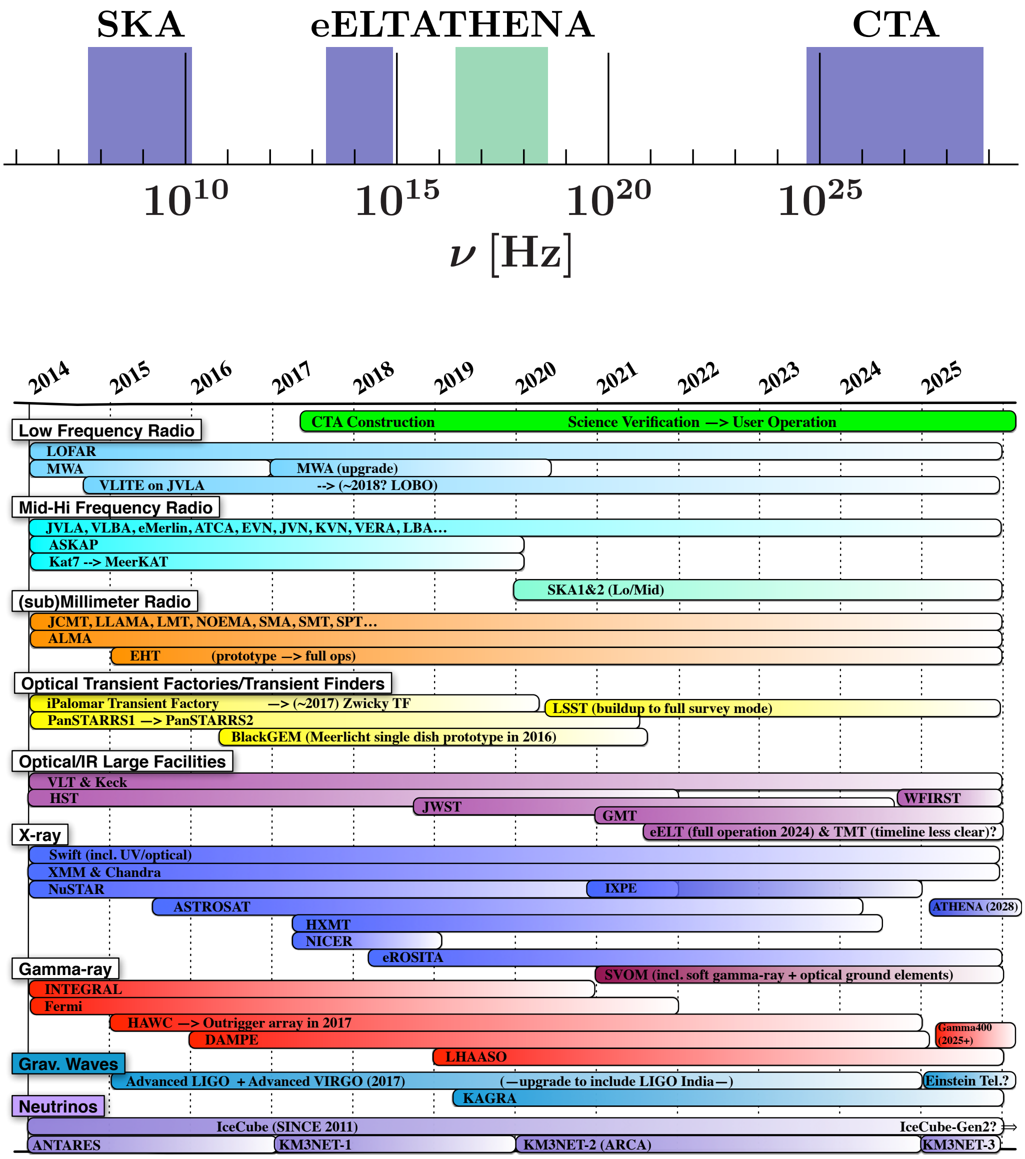

Figure 1: *Top:* Multiwavelength coverage in energy of the ESFRI facilities (blue), and other instruments (green) *Bottom:* (Expected) time line of multimessenger facilities (Sera Markoff).

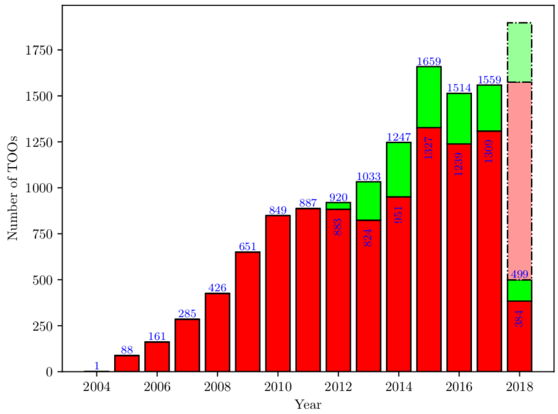

Figure 2: Time made available for Target of Opportunity observations on the *Neil Gehrels Swift Observatory* (J. Kennea).

available to scientists from developing nations, in addition to scientists from participating countries. However, further focussed efforts to ensure that all scientists can participate in the large projects are necessary.

Moreover, the continued organization of multimessenger follow-up is not always easy. Many instruments are interested in following up the first gravitational wave event, even the second and third event. But after a certain number of events, interest drops, and follow-up has to be organized for each wavelength. It is often possible to propose for Target of Opportunity (ToO) observations, that are triggered when a certain event happens. However, this is not possible for all instruments and wavelengths. For follow-up that does not have to be within seconds, a proposal for Director's Discretionary Time (DDT) is often the only solution to obtain follow-up for unexpected events. Obtaining multiwavelength follow-up across the spectrum is often necessary for good SED modeling, but this is not easily achieved; if only one instrument declines a ToO proposal, this can disrupt the multiwavelength coverage. A further problem in obtaining multiwavelength coverage is the funding pressure of instruments. Many facilities prefer observing alone and independently, where a possible press release of a discovery will have greater impact than being named among 10 participating facilities.

Another problem that exists in e.g., *INTEGRAL*, is data rights to other sources. *INTEGRAL* has a large field of view (FoV). During a GO proposal, an observer proposes for a (or several) specific source(s). The PI of this GO only has the data rights for these sources. If, for example, another (well-known) source is in the field of view, the observer cannot publish results for this source. The same is true for transient events. If a GRB occurs in the FoV, the PI also cannot analyze and publish the GRB data. However, it is possible to write "data rights" proposals, on archival, ongoing, or future observations, requesting the data rights to serendipitous GRBs for example.

As long as closed data policies exists, difficult MoU negotiations will be needed. A lack of MoUs with smaller facilities and scientists will reduce the maximum science reach of ESFRI facilities. We recommend open data policies, or open data with a proprietary period. The *Swift* satellite is the best example of an incredibly successful satellite with an open data policy. *Swift* was launched in 2004, and its main goal was to self-trigger on GRBs. In the time between gamma-ray bursts, *Swift* has Guest Observer's observation, fill-in observations, as well as ample ToO opportunities. It has been used by the whole high-energy community and has always ranked very high in the NASA senior reviews[4]. Its strength is that it's accessible to all scientists. Fig. 2 shows that while it started as a GRB instrument, it has become the ToO satellite of choice, following-up on an impressive number of (unexpected) transient events.

Another prime example of the benefits of open data is the *Fermi* satellite. While there is an active *Fermi*-LAT collaboration, the data become public immediately. In fact, many of *Fermi*'s greatest discoveries have been made by groups outside of the LAT collaboration, such as the discovery of the Fermi bubbles.

[4] e.g., https://smd-prod.s3.amazonaws.com/science-pink/s3fs-public/atoms/files/Main_Panel_SR2016_Report_FinalTAGGED.pdf

In summary, an open data policy supports an honest competition for observing time (via GOs, ToOs, or DDTs), and gives equal opportunities for discovery to all groups. It reduces the burden of negotiating for MoUs and removes the problem of missing MoUs with key facilities, especially for unexpected discoveries, requiring quick follow-up from an instrument that was not initially considered for an MoU.

2.3 Scheduling and priorities

Multimessenger follow-up and synchronous observations often require the development of interoperability between facilities, as well as flexibility in scheduling. Ideally, scheduling is automated, allowing for near-instantaneous responses to triggers from others facilities, or even self-triggers. Self-triggering occurs when a real-time analysis finds an interesting event, and a scheduling pipeline will decide whether to follow-up on such an event. An interesting event could be an elevated flux of a known source, or even a surprisingly low flux or non-detection. The detection of a (bright), unknown source could also be worthy of further observations as soon as it is detected, and follow-up by other facilities. In the latter cases, the observatory should send out an automated signal, alerting other instruments via GCN or VOAlerts. This also ties to the previous section of data rights, who will be alerted in such a case, or should these alerts be public?

Interoperability for surveys and synchronous observations is more tricky to realize. One such example is a combined survey of the sky of CTA and SKA. While SKA is in South Africa/Australia, and CTA is located in Chile, it has been shown that a near-simultaneous survey of the sky if possible by making sources that both telescopes can see at a given time a priority (P. Colomé, priv. comm.). This approach is investigated in detail in WP 5.4. Scheduling flexibility is also required when considering non-controllable effects, such as the weather. Observations then have to be rescheduled, sometimes on very short notice. This requires a complex set of variables taken into account for each participating instrument: e.g., weather, availability, scheduled observations and their priorities, incoming external and self-triggers, incoming ToOs and DDTs, to name only a few.

All of these effects lead to the difficult problem of observation priorities. This pertains to triggers that arrive at an observatory that is observing at that point in time (assuming no major technical problems, or bad weather conditions). Depending on the type of trigger immediate follow-up might be necessary. Accepting this trigger then would possibly stop the on-going observation and override it if its priority is high enough. In the case of CTA, a certain percentage of time is set aside for the Key Science Projects (KSPs). Some of the KSPs require regular monitoring of sources at weekly intervals. Another example are time-sensitive observations, e.g., due to the position of the object, periastron passage of η Carinae for example, a binary system with a period of 5.5 years with highly variable emission. In both of these examples the questions would be, can any trigger override these observations? For the case of regular CTA KSP monitoring the answer seems easy, the observation should be overwritten. However, what happens if a following KSP observations is also overwritten. Should the missing observations be rescheduled, possibly replacing lower-priority ones, or should the following observations receive a higher priority? In the case of a very time sensitive observation, such as η Carinae with its known orbit period, is there a trigger, which could overwrite it? For most triggers the answer would seem no. However, even improbable cases have to be considered, such as the occurrence of a supernovae within the Local Group. This raises another issue: segmented data. For some sources, segmenting the data (due to incoming alerts) might not be a problem at all, e.g., if the source is not very variable, or the observations are within a few nights. For other, more time-sensitive observations, the ongoing length of the observation should be taken into account. E.g., if 90% of a scheduled observations has been observed, can the incoming trigger be delayed until the ongoing observation is finished? Or are 90% likely enough to finish the science case, and the observation should be stopped? This might greatly impact the science case of the observer. One suggestion in CTA was to add an option to the proposal tool that asks whether segmented data is acceptable. So, should the priority of the ongoing observation also be based on how much of it has been observed?

As the discovery space for many facilities is large, these priorities should be continually assessed and changed. If, for example, GRBs will be detected with the CTA observatory at a given flux level, one can introduce criteria on which GRBs should be followed-up at which priorities. If, however, GRBs are not detected, a much more stringent trigger criteria can be implemented, e.g., following-up only the

brightest of GRBs with a slew time below 30 seconds to the GRB position.
More frequently occurring problems will also need consideration; e.g., does an incoming trigger with the same priority as the current observation override it or not? This is especially crucial when considering the setup of guest observer programs. One easy step to implement would be the option to specify whether disrupting the observation (by splitting it into two observations for example) would hinder the science objective.
Since the number of self-triggers, incoming triggers that will be followed-up (based on some criteria), it is unclear, how many observing hours are needed for the follow-up of transient (multimessenger) events. This will likely become clear within the first few years of operations. This problem requires detailed simulations and studies, implementing our current knowledge of the source physics, as well as the technical constrains of the facilities.

2.4 Data storage and dissemination

The low-frequency array of the SKA and most future instruments produce large amounts of data (in the Petabyte range). These amounts of data cannot be stored cost effectively. Data pipeline reprocess the data and often store only a fraction of the information, concerning the original science case. The low-frequency arrays often store information for a few minutes at most, waiting for incoming triggers. If a trigger arrives with a position that is observable, the data stored in the last few seconds concerning that position can be saved for processing and analysis.
The dissemination of data is often a time-consuming process. Trigger alerts are sent via various channels (e.g., GCN and VOAlerts). Data collected by instruments are (if public) supplied via different platforms and website. This will be a problem for the LSST, where we expect large trigger rates, ranging in the thousands/day. However, not all of these alerts are interesting for all observatories. A regular supernova, can only be observed in the optical, and is therefore, not relevant to radio or X-ray instruments. This requires a reliable system that filters LSST triggers. For satellite follow-up of LSST alerts, this will also necessitate checks on e.g., sun angle, Moon and Earth limb, to determine whether follow-up is possible.
Analysis often requires knowledge and experience in the given wavelength range, and some expertise with the instruments and possible observational artifacts. Even in one wavelength, processing of data often requires knowledge of various programming language and software. Analysis and interpretation then requires further software packages and analysis tools. Combining multiwavelength and multimessenger data is often time-consuming and ineffective, either due to missing statistical or cross-wavelength analysis tools. Developments of analysis software packages in the last few years have shown that XSPEC and ISIS are the most promising tools that are currently available. Further, available online pipelines are often not reliable and are currently not better than a human reducing and analyzing the data. However, it is possible to write pipelines that can extract standard data and provide only the final high-level products (e.g., light curves, spectra) to the user.
Data dissemination and storage of mid-level products is currently unsolved for many projects. Data from various satellites are available via their respective agencies websites. Other data is stored over various servers across the whole world. Collecting multimessenger data therefore often requires large data volumes, as well as setting up the analysis environments and pipelines on local machines. This is a very ineffective approach.
The AMON project[5] provides a platform to store and distribute data and alerts. It respects data rights and only shares information with other collaborations and members according to the MoUs that are in place. It is currently not suited for the analysis of any data, but mainly distributed streams of data, in the form of VOAlerts.

3 Conclusions

In this document we have analyzed the landscape for and possible synergies between multimessenger ESFRI facilities. The facilities are the CTA, the SKA, the KM3Net, and the E-ELT. We described that

[5] https://www.amon.psu.edu/

these instruments face similar challenges and that working together and addressing these challenges coherently will advance science much faster than the individual observatories would achieve. There are indeed many challenges to overcome. A new and very promising development is the automated follow-up of multimessenger events and real-time analysis pipelines. However, scheduling and choosing priorities remain one of the main challenges of the future instruments, especially in instruments on different continents. Priorities and priority decisions will determine whether an incoming trigger overrides and ongoing observation and if yes, whether this observation will be rescheduled. We also discuss challenges in data storage and dissemination, as well as data policies and memoranda of understanding. While many challenges exist, overcoming them within the next decade will lead to advances in the field of multimessenger astrophysics.

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