PROJECT SUMMARY

Overview:

Within just the past year, a new era of multi-messenger astrophysics has begun, where for the first time electromagnetic counterparts have been associated with both gravitational waves and high-energy neutrinos. The observation of a binary neutron star merger in gravitational waves and gamma-rays (GW/GRB 170817A), along with subsequent worldwide follow-up efforts, demonstrated both the power and the challenges of multi-messenger astrophysics. With just one event, the speed of gravity was determined to phenomenal precision, the origin of the heavier "r-process" elements in the periodic table was determined to be neutron star mergers, and the radii of neutron stars were measured to about one kilometer accuracy. These results were the product of more than 3500 people using more than 50 facilities around the globe and in space to capture everything from gravitational waves to radio waves that were emitted during and following this spectacular collision.

Over the next decade, improvements in gravitational-wave detectors will enable dozens of such events per year; IceCube and other neutrino and cosmic ray observatories will continue to survey the sky for high-energy cosmic particles; the Large Synoptic Survey Telescope and upcoming radio facilities will survey the skies with unprecedented speed and depth; and a range of astronomical observatories will acquire data on candidate multi-messenger sources, source populations, and host galaxies throughout the visible Universe. While each observational modality is sure to bring fascinating new discoveries, it is in their combination that transformative new insights into some of the most fundamental questions about the Universe can be realized: What is the nature of the highest-energy cosmic particle accelerators? What are the properties of cold and hot bulk matter at supra-nuclear densities? How do black holes form and evolve, across their full range of masses, and throughout cosmic time?

This proposal seeks to carry out a conceptualization and design study of a Scalable Cyberinfrastructure Insitute for Multi-messenger Astrophysics. The primary goal is to identify the key questions and cyberinfrastructure projects required by the community to take full advantage of the substantial investments in current facilities, and to realize the enormous potential of the multiple imminent next-generation projects over the decade to come. Two products of the project would be: 1) a community white paper that presents an in-depth analysis of the cyberinfrastructure needs and the opportunities for collaborations among astronomers, computer scientists, and data scientists; and 2) a strategic plan for an institute laying out its proposed mission, identifying the highest priority areas for cyberinfrastructure research and development for the US-based MMA community, and presenting a strategy for managing and evolving a set of services that benefits and engages the entire community.

Intellectual Merit:

Advanced software and cyberinfrastructure will be essential to this new, multi-messenger astrophysics. They will be used to design instrumentation, to control telescopes, to automate data analysis, to facilitate global communication, and to simulate the astronomical objects under study. While each instrument brings unique challenges of data acquisition, storage, distribution, and analysis, multi-messenger astrophysics calls for a novel synthesis of theory and observation, computer science, and data science to realize the full potential of these multidimensional, heterogeneous, and high-velocity data sets. Indeed, an advanced cyberinfrastructure may well be as important to realizing the opportunities of multi-messenger astrophysics as the instruments and facilities which gather these data.

Broader Impacts:

Through a sequence of workshops, preparation of a community white paper, and development of a strategic plan for a new cyberinfrastructure-focused multi-messenger institute, this project will weave a global community focused on realizing the promises of multi-messenger astrophysics. The project will bring astrophysicists together with data and computer scientists; provide a forum in which University-based researchers can interact with NASA and DOE-funded scientists; and develop solutions spanning sub-disciplines.

I. Introduction and Objectives

On the morning of 24 February 1987, Ian Shelton discovered supernova SN1987A after developing a glass photographic plate he had just taken and comparing it by eye to one from a previous night. After driving down the mountain to a town about 100 km away, he announced the discovery by telegram to the world [1]. As the closest supernova seen in over 300 years, the discovery of SN1987A would be a once-in-a-lifetime discovery had the story ended there. However, this event defined a new field – Multi-messenger Astrophysics (MMA) – as neutrinos from SN1987A were observed by three experiments [2–5]. SN1987A simultaneously vindicated and challenged theories of stellar evolution and supernova explosions, revolutionizing our understanding of the Universe.

Fast forward 30 years to 17 August 2017. Astrophysicists in the LIGO Scientific Collaboration (LSC) and the Virgo Collaboration (LVC) received a text message that a significant gravitational-wave signal GW 170817A had been identified by their real-time signal processing pipeline. Before they could respond, a data handling infrastructure had established coincidence with a Fermi GBM gamma-ray burst that occurred two seconds later. Within minutes, collaborators from all over the world connected on via web conference to review the results. A machine-readable notice was sent to astronomer partners within 30 minutes which launched a multi-wavelength observing campaign to study this event and resulted in the identification of an optical counterpart only 12 hours after the merger [6]. More than 3500 astronomers used more than 50 telescopes in this campaign revealing, among other things, new insights into the densest matter in the universe, the birth of black holes, and the origin of the heaviest elements in the periodic table. Nonetheless, even this discovery was delayed by human and technological factors, and the first 12 hours were lost forever.

The juxtaposition of these two discoveries highlights the critical importance of modern cyberinfrastructure in multi-messenger astronomy. In the intervening years, digital image processing replaced visual inspection of plates; astronomical telegrams moved to the web; the Gamma-ray Coordinates Network (GCN) facilitated follow-up of gamma-ray bursts discovered by satellite observatories; and myriad individuals, projects, and observatories developed software and cyberinfrastructure for astronomy. Preparations for the observing campaign that followed GW 170817A took almost a decade, starting in 2009, with cyberinfrastructure glued from a patchwork of solutions developed in isolation. This approach will no longer suffice in the coming decades.

The scientific community is now well positioned to make multi-messenger observations a regular occurrence and the next major discovery will be much sooner than 30 years. IceCube, which discovered very high-energy astrophysical neutrinos, will continue observations until Gen 2 comes into operation in the mid/late 2020s with a factor of 5 improvement in sensitivity: enough to be able to identify the sources of the neutrinos under all theorized scenarios. LIGO, combined with the Kagra and Virgo detectors, will bring the rate of transient gravitational-wave sources to several per day in the coming years. Beginning in 2023, the Large Synoptic Survey Telescope (LSST) will survey the visible sky every few days generating about 20 TB of data and resulting in 10 million transient alerts every night. The scientific payoff of this flood of data is bounded by the ability to assimilate and synthesize the data from all of these facilities, and develop a responsive, real-time, machine-driven follow-up strategy: comprehensive cyberinfrastructure is as important to MMA as the observatories themselves.

This vision of MMA is ambitious. This burgeoning field relies on the availability of a comprehensive, interoperable and sustainable cyberinfrastructure that: allows data to be rapidly assimilated from a global network of instruments; autonomously optimizes and schedules observations to follow-up rapidly evolving sources; and enables multi-physics inference using all of the collected data. It requires a novel synthesis of theory and observation, computer science, and data science at a scale that extends past any single institution.

This proposal requests support to carry out a conceptualization and design exercise for a *Scalable Cyberinfrastructure Institute for Multi-messenger Astrophysics.* The primary objectives are:

1. to document the cyberinfrastructure needs for multi-messenger astrophysics in a community whitepaper that builds on the work described in the Cyberinfrastructure for Multi-messenger Astrophysics workshop summary [7]. We will extend that discussion to an in-depth analysis of the cyberinfrastructure needs and the opportunities for collaborations among astronomers, computer scientists, and data scientists;
2. to develop a strategic plan for SCIMMA laying out its proposed mission, identifying the highest priority areas for cyberinfrastructure research and development for the US-based MMA community, and presenting a strategy for managing and evolving a set of services that benefits and engages the entire community.

II. Astrophysics Context

The detection of gravitational waves (GWs) from binary black hole mergers [8–12] heralded the opening of a new window on the universe: GW astrophysics. Access to gravitational-wave observations, along with the detection of astrophysical neutrinos [13, 14], mark the beginning of the era of MMA. The combination of GW detectors, high-energy neutrino and cosmic ray detectors, and observatories covering the entire electromagnetic spectrum will allow observation and precision measurement of the most violent phenomena in the universe and probe long-standing problems in astrophysics.

The phenomenal promise of MMA was demonstrated with the GW detection of a binary neutron star (BNS) merger, GW170817. Following an initial detection in both LIGO detectors, with valuable additional data from the Virgo detector [15], it triggered a worldwide follow-up campaign at all wavelengths from radio, to optical, to high-energy gamma-rays as well as a search for coincident high-energy neutrinos [16]. The initial GW detection was nearly simultaneous with a gamma-ray burst [17], forging a *direct* link between BNS mergers and short gamma-ray bursts. Rapid parameter estimation placed GW170817 at $\approx 40\,\mathrm{Mpc}$, and superior localization provided by the three GW detectors allowed rapid EM follow-up of galaxies in the 31 square degree field [18]. Twelve hours after this initial detection, several observatories around the world were able to precisely locate [19] and track the light curve of the thermal electromagnetic counterpart from its early detection in the near-UV and optical at 0.5 days through its rapid fading and cooling, going from the optical to the infrared [18]. In parallel, observations of the synchrotron afterglow started at 9 days with X-ray detections [20, 21] and continued with radio observations [22–25] spanning over 10 months.

This one event that was detected over 20 order of magitude in frequency (0.1 kHz in GW to $\mathcal{O}(1\,\mathrm{MeV})$ in gamma-rays) has already provided tremendous scientific dividends. For instance, the speed of gravity has been compared to light with phenomenal accuracy [26], the expansion of the universe has been (re-)measured [27], the origin of the r-process elements is much better understood, and the radii of the neutron stars have been determined to within 1 km, with broad implications for cold nuclear equation of state [28]. *These results were made possible by LIGO-Virgo quickly releasing an alert describing the detection, by rapid parameter estimation to give distance and sky localization, by the rapid Electro-magnetic (EM) follow-up by 50 facilities around the world, and by the collaborative contributions of thousands of people.*

GW170817 is merely the tip of the iceberg. Improvements in currently operating GW detectors over the next decade along with new detectors in Japan and India will enable the detection of dozens of such events per year with enhanced localization. These discoveries will allow us to study BNS and neutron-star blac-hole (NSBH) mergers as a population and will provide constraints on the Hubble constant, the formation and evolution of black holes and neutron stars through cosmic time, and possible deviations from General Relativity. Rapid EM followup of these events will capture data from the first crucial hours after the GW event, data that provides important hints on the nature of the ejecta from BNS and NS-BH mergers that will nail down the origin of r-process elements in the universe, the physics of high accretion flows, and the nature of short gamma-ray bursts. The ultra-high energy universe also beckons in the multi-messenger era. IceCube and other neutrino and cosmic ray observatories will continue to survey the sky for ultra-high-energy cosmic particles [13]. In 2013 IceCube discovered an astrophysical flux of high-energy neutrinos from suspected cosmic ray sources. However the class of astrophysical objects that emit these neutrinos has yet to be identified. Rapid multi-messenger follow up of $\sim$10 likely-astrophysical neutrinos per year may enable the discovery of their sources [29]. *These studies are enabled by software and cyberinfrastructure that allow fast IceCube-Telescope communication.* On September 2017, IceCube publicly reported the astrophysical neutrino IceCube-170922 [30] . Shortly thereafter, *Fermi* with GeV photons [31] and MAGIC with 100 GeV photons [32], identified a coincident flaring blazar: TXS 0506+056. Though at the time of writing, the accidental correlation for this neutrino and blazar flare has not been published, this coincidence provides a tantalizing clue on the identification of neutrino sources. As efforts like this continue, a picture of the ultra-high-energy universe will begin to emerge and may point the way to the accelerator of the highest energy cosmic rays. The sensitivity of the Cherenkov Telescope Array along with its rapid slewing ($\sim$ 20 seconds), will allow it to probe the transient nature of very high energy gamma rays produced by GW events, including BH-BH merger events if, as some models suggest, they are endowed with strong magnetic fields, or vice versa [33].

EM observations can follow-up on neutrino and GW event alerts, but EM observations also prepare the ground for interpretation and understanding. For instance, large local surveys of nearby dwarf galaxies provide a list of targets for EM follow-up triggered by a GW alert. Studies of GRB energy and jet-opening-angle distribution can help constrain merger models. Local surveys of AGNs can also provide hints as to the source of IceCube neutrinos [34].

The physics of supernova explosions is also amenable to multi-messenger astrophysics. The combination of neutrino detected by IceCube and other neutrino detectors and GW detections by GW observatories will directly probe these enigmatic explosions [35]. A single galactic supernova observed in MeV neutrinos and GW observatories will constrain the assymmetries that develop during an explosion and the spectra of the energy released. Followup EM observations will then link the interior physics (constrained by IceCube and GW observatories) with SN phenomenology.

The LSST and upcoming radio facilities will survey the skies with hitherto unprecedented speed and depth; due to the size of the datasets surveys like LSST and Square Kilometer Array (SKA) will generate, by far the most likely research paradigm in the near future is that the processing software will be brought to the data and run in computational centers that host the PB scale datasets. This enables opportunities for joint processing of MMA data if the requirements for this analysis modality is scoped in time.

Transient Factories: Optical time-domain surveys like All-Sky Automated Survey for Supernovae (ASAS-SN), Pan-STARRS (PS1), and Palomar Transient Factory (PTF) brought the transient Universe to life in the last decade, revealing our ever-changing surroundings at time scales from hours to decades. New surveys are on the horizon, such as Dark Energy Survey (DES) and Zwicky Transient Facility (ZTF), which just started science operations in 2018 March. The astrophysical community has begun to develop tools and infrastructure to enable rapid response to astrophysical transients. The earliest effort was Astronomer Telegram [36] which was designed to be human readable. In its infancy, it reported transients and requested observations via telegrams (hence its name), but now reports new detections via email and web publications. In contrast, today's robotic telescope networks like the Las Cumbres Observatory (LCO), upon recieving electronic notification of a transient, automatically allocate time in follow up resources and deploy observations, dynamically adapting the observing schedule. Despite this tremendous progress, this effort is still at its infancy. Much work remains to be done in light of the 1-10 million events that LSST is expected to detect each night of operation, and to deliver within 60 seconds of discovery [37]. This is especially true with respect to understanding the complexity of multi-messenger data integration.

III. Cyberinfrastructure Context

Multi-Messenger astrophysics brings together scientists from multiple disciplines, each with its own established scientific culture. While this diversity accounts in great part for the richness of the science, it also represents a significant challenge for the field. The tools to store, manage and interpret the data have evolved independently in each discipline, yet must be interoperable enough to build high-level analysis tools with rigid requirements including low latency.

A. Brief Survey of Cyberinfrastructure Across Subdisciplines

LIGO: The LIGO observatories produce approximately 1.6 TB per day each of raw time series data. Low-latency signal processing extracts gravitational wave signals in real-time for time-domain multi-messenger astrophysics, while batch processing is used to search for long-lived signals. LIGO requires $\mathcal{O}$(100M) cpu-hours per year to analyze its dataset for its highest priority science targets. To accomplish this, LIGO has successfully adopted the grid model of geographically distributed computing with clusters located at the Albert Einstein Institute (AEI) in Hannover, Germany, the University of Wisconsin–Milwaukee (UWM), and Cardiff University in Wales in addition to LIGO Laboratory computing at Caltech and the Livingston and Hanford sites. These data centers are linked by commodity networking. A substantial middleware layer delivers data handling services, engineering and operations services, and collaboration support services. LIGO's cyberinfrastructure is integrated into the national fabric through the Open Science Grid (OSG) and leverages a broad range of cutting-edge cyber-infrastructure projects including HTCondor [38], Pegasus [39], Globus, Grouper, and Shibboleth [40]. Indeed, LIGO has established collaborations with many of these projects by providing feedback on their products and suggestions for improvements. LIGO remains committed to leveraging, as much as possible, other promising cyber-infrastructure projects, such as CILogon [41], and CernVM-FS [42] to meet its future needs.

IceCube: IceCube produces approximately 1 TB of data per day corresponding to 3 kHz of cosmic ray muons. A dedicated computer cluster at the IceCube laboratory at the South Pole performs initial event reconstruction and filtering on real time (typical latency of 40 seconds). The South Pole filtering outputs two streams: one with an order of magnitude smaller size that is transferred via satellite to U. Wisconsin. Once there, a second round of reconstructions are applied (Level 2) with a latency of 2–3 weeks. This delay allows, for example, for the best detector calibrations to be used. After Level 2, data are split into multiple streams for various analyses. There are, amongst many others, streams for neutrinos that produce tracks and neutrinos that produce particle showers. A second South Pole stream produces neutrino level data (∼6 mHz) that, while not as sensitive as data selection in the north, enables for realtime follow up of MMA counterparts. While careful organization of the South Pole filter and Level 2 is needed, overall, later data processing is not constrained by the processing power available. Detector simulation is distributed among multiple IceCube institutions but centrally managed to better distribute the load. Simulation is handled via `Condor` and data are synchronized to the data warehouse at U. Wisconsin with `gridftp`. Simulation of down-going cosmic ray muons is constrained by processing resources. A myriad of databases - all custom built - are in use by IceCube to hold information such as detector calibration, detector operational status, run quality, etc.

Swift: The Neil Gehrels Swift Observatory was the first NASA mission to operate under an "all public, all the time" mandate, with no data proprietary period after its initial three month on-orbit check-out. Partly in consequence, the mission has persistently innovated in its cyberinfrastructure: Gamma-ray burst detections prompt a cascade of real-time public alerts to interested observers via the GCN, including multiple revisions of each burst position, lightcurves, spectra, and finding charts; "Quicklook" reduced data products are posted for download within minutes of each ground station pass; "Tiled" observations are commanded automatically and queued for analysis in an integrated fashion; and interactive websites provide sophisticated final analysis products for individual scientific targets. The mission has also deployed infrastructure to automatically accept and schedule targets from a number of partners, including the Fermi Gamma-ray Observatory, the Nuclear Spectroscopic Telescope Array (NuSTAR), and Astrophysical Multimessenger Observatory Network (AMON).

ZTF: The ZTF system has the goal of identifying transients and distributing electronic alerts to the community in near-real time. Throughput has increased by a factor of > 15 compared to the previous PTF surveys, which has led to data processing challenges. The ZTF detector has 16 CCDs, each with 36,000,000 pixels split into four quadrants, producing a total data rate for a typical exposure time of ~ 1 TB per night. Each quadrant is calibrated and processed independently [43] in a highly-parallelized environment on a cluster managed using `slurm`, with image-subtraction, candidate identification, machine-learning classification, and lightcurve construction all performed within 15–20 min. The archive is hosted by NASA/IPAC Infrared Science Archive (IRSA) [44] and alerts are distributed by the Kafka system [45]. The alert packets are in the Apache Avro$^{\text{TM}}$ format [46], a binary serialization format for efficient distribution. Kafka can then broadcast alert streams (subject to user-defined filters) to multiple brokers [47]. **LSST:** The LSST survey system [48] consists of a large-aperture, wide-field, ground-based telescope [49] currently being constructed on the El Peñón peak of Cerro Pachón in the Chilean Andes, a 3.2 gigapixel camera [50], and a data management system spanning three continents [51]. The rapid cadence and scale of the LSST observing program will produce approximately 15 TB per night of raw imaging data. Over the ten years of LSST survey operations and 11 data releases, this will result in a cumulative processed data size approaching 500 petabytes (PB) for imaging, and over 50 PB for the catalog databases. The final data release catalog database alone is expected to be approximately 15 PB in size. LSST cyberinfrastructure components span four key facilities on three continents: the Summit Facility at Cerro Pachón (where the initial detector cross-talk correction will be performed), the Base Facility in La Serena (which will serve as a retransmission hub for data uploads to North America, as well as the data access center for the Chilean community), the central Archive Facility at the National Center for Supercomputing Applications (NCSA) in Champaign, Illinois, and a satellite data processing center at Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (CC-IN2P3) in Lyon, France. All Level 1 (nightly) and 50% of Level 2 (data release) processing will take place at the Archive Facility, which will also serve as a data access center for the US community. The remaining 50% of data processing will be performed at the satellite center in Lyon. The data will be transported between the centers over existing and new high-speed optical fiber links from South America to the U.S., and from the U.S. to France. The data processing centers will have substantial computing power (e.g., the central facility is expected to peak at ~ 1.6 PetaFLOPS of compute power). This system will run custom built data processing pipelines (the "LSST Stack" [52]), orchestrated by a combination `HTCondor`, `Kubernetes` (for service-oriented components), and custom middleware. Approximately 10% of the total computing capacity will be allocated for end-user computing through the "LSST Science Platform" [53]. See [51] for more details.

Time-domain Radio Astronomy: Time-domain Radio Astronomy comprises the study of the radio sky for transient or variable signals. There are distinctions between inteferometric searches (which have much better spatial information) and single-dish searches, but in both cases the data are extremely voluminous. For interferometric searches the time and spectral resolution are typically moderate (although there is a push to sub-ms time resolution [54–56]), but the larger numbers of cross-products leads to data-sets that approach LSST in scale. For single-dish searches extremely high time and spectral resolution do likewise. Long-term archiving may be beyond the capacity of observatory archiving facilities; meanwhile, in light of ever-worsening interference environments the data comprise a valuable resource for re-analysis with new algorithms and to identify new classes of signals. We give examples below of both single-dish and interferometric use-cases.

MWA: The Murchison Widefield Array (MWA) [57] is a low-frequency precursor to the SKA located in Western Australia, with time-domain searches as one of its primary science drivers. It is also an interesting example of a "software telescope," as it has no moving parts and can automatically reconfigure its observing schedule in response to internal or external [58] triggers on 8 s timescales. The data rate for the MWA is prodigious, with about 10 TB per day initially increasing to 40 TB per day with upgraded hardware and 25 TB per hour when using the highest data rate. The MWA is moving to a centralized identity management solution, with unified single sign-on onboarding and offboarding. Data are archived at a national peta-scale supercomputing center, with data transport handled by a Next Generation Archive System (NGAS) [59] system. Regular data processing and quality assurance procedures are in place, co-located on the supercomputing site and with `slurm` [60] job control. All services are centrally located with strict access controls, direct database access has been replaced by read-only web queries, and a better separation is in place between mission-critical hardware/software and user-facing services. A new alert response mechanism has been implemented that fully integrates with the Monitor and Control system. Using VOevents it can schedule new observations in response to richer information sets including knowledge of previous triggers, and new alert mechanisms are easily added in a way that will not interfere with previous alerts.

Fast Radio Bursts: First identified in 2007 [61], Fast Radio Bursts (FRBs) are very energetic, highly-dispersed radio signals originating from great distances. The FRBEvent standard [62] is a development of VOEvent [63] for low-latency distribution of observation details and candidate identification to enable the synchronised observations and multi-wavelength follow-up. FRB 121102, the one FRB observed to be repeating [64], was first identified in legacy data from the PALFA pulsar search (data rate of 2.2 TB per night) with a new algorithm for classifying signals arising from Radio Frequency Inteference (RFI). Nonetheless, it is currently infeasible to archive all of the data at full time and frequency resolution (data rate of up to 24 TB per night).

B. Examples of Current Multi-Messenger Cyberinfrastructure

While the promise of MMA has long been understood, there has not yet been a community-wide effort to build the infrastructure needed to realize its full potential. A few nascent building blocks have been put in place, however.

GCN Circulars: are a powerful tool for transient astronomers to quickly disseminate results of their observations and initial interpretation. GCN was originally founded to distribute GRB positions but has been extended to distribute all types of public and private alerts, including neutrino and GW alerts, as well as reports from follow-up observations. Approximately 200 GCN circulars were associated with GW170817 [65]. The relatively free-form nature of GCN circulars allows scientists to include arbitrary information conveyed primarily through natural language in prose and serves as a way to quickly publish cite-able scientific work in the often rapidly evolving world of transient astronomy. Unfortunately, this format is in tension with the desire to have machine readable information encoded at the same time. An automated way to distill information from GCN circulars in a machine parse-able way which does not interfere with the currently highly successful rapid publication of interpretation could help to bridge the gap between human interpretation and machine decisions in time-critical science situations.

The GW-Astronomy Platform: is a collaboration management infrastructure hosted at The University of Wisconsin Milwaukee [66]. It was designed to enable building quick and efficient collaborations spanning gravitational-wave astronomers and other astronomy communities using federated identities and the COManage collaboration management tool. This platform provided crucial support for the shared observation of the GW 170817 kilonova event. At present, the platform offers only a collaboration management system, wiki space, and mailing lists as collaboration tools. It also provides authorization information to external services such as LIGO's gravitational-wave candidate event database, `GraceDB` [67]. For multi-messenger astronomy to truly leverage the power of a collaboration platform such as gw-astronomy.org, a far more substantial suite of tools, both internal to gw-astronomy and via authorization to external infrastructures, will be required.

The AMON: [68] was developed to search in near-real-time for common events in the sub-threshold trigger data from neutrino, gamma-ray, and cosmic ray partner triggering observatories, and distributes electronic alerts of any significant coincidences found for further follow-up observations. An event is sent back to AMON if the results of follow-up campaign are interesting. AMON is an extensible network that accepts new observatories through an MOU structure. AMON handles data in VOEvent XML format and distributes the alerts through the GCN mechanism [69]. AMON will soon distribute neutrino+gamma-ray multi-messenger alerts through GCN privately to its follow-up partner observatories.

The GW-HEN Joint Automated Pipeline Framework: fetches and processes gravitational-wave and high energy neutrino data and then performs an online coincident analysis and finally disseminates results via GCN circulars to LIGO's follow-up partners. This pipeline was excercised during LIGO's second observation run together with IceCube neutrino events. It offers a latency of only a couple minutes after the LIGO and Virgo internal notice of observation of a signifcant candidate and the availability of the initial skymap for the GW event.

IV. Approach – Intellectual Merit

We will develop a coherent international effort, identify questions and projects that are needed, organize workshops to address key topics, and bring astrophysicists from multiple subdisciplines together with computer scientists, data scientists and cyberinfrastructure experts. We have identified four activity areas: **A1**) Data management, communication and collaboration, **A2**) Analysis, inference and machine learning, **A3**) Modeling and theory, and **A4**) Education, training, and workforce development. During the project initiation phase, we will identify facilitators for each activity area: the activities will be pursued openly in a manner than encourages community participation via email discussion groups, web conferences, town-hall meetings, and the workshops described below. Within each each activity area, we will consider: which cyberinfrastructure elements and frameworks are required, what data science and computer science research is required and how should it be prioritized, what are the organizational and management challenges, how can data access and management be improved, which computing services are needed for the activity, and how to address adaptation and sustainability for a program that will span more than a decade.

A. Engagement and Information Gathering

A community-driven approach cannot proceed without intense engagement with the community and major stakeholders. Toward that end, we will gather information to drive the design of the institute and strategic plan by holding town halls that engage a large segment of the community, and by systematic interviews with major stakeholders, e.g., the directors of the major funded projects.

Town Halls at Professional Meetings: During the initial phase, we will conduct town halls at professional meetings to engage a large segment of the astronomy, physics and computer science communities. These will help us to collectively develop the community vision of the grand challenges of MMA. Possible venues include the January meeting of the American Astronomical Society, the April meeting of the American Physical Society, ICMLA18 and/or WORKS 2018.

B. Topical Workshops

We will refine our vision by organizing 3 workshops, one of which is already scheduled at NCSA and two new ones that we will host. These workshops will outline and address the major cyberinfrastructure challenges and explore solutions for MMA. With the many diverse projects and collaborations already underway, we will leverage recent advances in machine learning and analysis, seek out common solutions to common challenges, and map out a path forward to enhance the scientific return of these projects and collaborations both on an individual basis and collectively. Such links between different areas, different energy scales, and different collaborations, enhanced with common cyberinfrastructure, is key to unlocking the promise of MMA. At the end of each workshop, we will document the key findings that will drive our proposed deliverables.

Workshop 1 – Deep Learning for Multi-Messenger Astrophysics: Real-time Discovery at Scale: We begin by piggybacking on an already planned workshop [70] that will be held at NCSA in October 2018, which responds to NSF's science goal to leverage large scale computing and big data analytics to advance MMA, together with DoE's Scientific Machine Learning program that aims to instill rigor in the development of artificial intelligence algorithms across science domains. Co-I Huerta is a member of the organizing committee of this workshop which will address the use of deep learning in MMA. Key goals of the workshop include 1) directly accelerating the design and development of deep learning algorithms to maximize the potential for scientific discovery with MMA, and 2) building a community that brings together science domain experts in astronomy, artificial intelligence (AI), major observing instruments including LSST and the DES, computer science (CS), and cyberinfrastructure. The major focus of this workshop is on the processing of LSST data streams, but we will also conduct discussions on integration of these ideas on data streams from other large projects. This transdisciplinary group will develop a roadmap for the timely delivery of community tools to enable a wide cross section of the community to systematically exploit MMA observational data in real-time and at scale.

Workshop 2 – Collaboration Among Collaborations: Large modern projects like LSST, IceCube, LIGO, ZTF, and radio surveys produce large heterogeneous data sets. How these heterogeneous data sets can be analyzed efficiently either by nonspecialists or by robots is a major challenge in the multi-messenger era. We will host a workshop to identify the common challenges of these large diverse collaborations to seek joint, flexible, and sustainable solutions to allow for both intra- and inter-collaboration interoperability and interaction. We will outline what is needed to leverage the resources, data, and energy of these large groups and the community-at-large to produce science beyond that any individual or individual collaboration can accomplish.

We will identify the crucial challenges and outline potential solutions. Topics of particular interest include:

1. **Real-time Streams to Real-time Science:** These projects also produce tremendous amounts of real-time data in the form of alerts that require rapid action. For instance, LSST will produce multiple data streams which are then acted upon by brokers. In addition, LSST will find of order $10^6 - 10^7$ transients per night. Similarly, LIGO will produce a steady stream of alerts from large signal-to-noise events, but an even larger stream of low-significance events. How should this real-time data from multiple sources be incorporated to flag interesting event candidates to be rapidly and efficiently followed-up? How can surprises in the data be found automatically? The real-time streams from these different observatories will have common needs and require common protocols so that they can be incorporated into a larger real-time framework that can be acted upon by both humans and machines.

2. **Common Tools for Common Needs:** These large projects also have common challenges of ensuring efficient cooperation. We will identify their common challenges and common cyberinfrastructure needs. In particular, these large projects require identity federation, communication, cyber management and sustainability, and have developed independent cyberinfrastructure to address these needs. At the same time, they are independently pursuing similar technologies to address these needs, such as cloud computing and containerization. These common challenges can be addressed by a common, flexible, and extensible cyberinfrastructure framework that provides the basic needs of identity federation, communication, cyber management, and sustainability, reducing duplication between projects. In addition, this common framework can allow for the larger goal of collaborating between collaborations to address the grand challenges of multi-messenger astrophysics.

3. **Data Driven Management and Strategy:** We will also address the issue of common feedback and common data gathering—how the data streams and real-time data of these large projects are being utilized and the efficiency of this utilization to produce science. This would be a major value-added contribution for these large projects as the directors and funding agencies will have the ability to produce a nearly real-time view of how the different data sets are consumed, produce science and are integrated with other data streams from other major projects. This will allow for data-driven decision making and precise strategic planning.

Workshop 3 – Real-time Discovery, Inference, and Interpretation: Identifying pathways to improve MMA discovery, inference, and interpretation is a key goal for this proposal. This workshop is designed to bring scientists who work accross the mulitimessenger landscape together to share existing approaches and best practices taken within a given messenger/spectrum with each other and with data scientists. An articulation and cataloging of the collective understanding of such techniques is low-hanging fruit.

We also seek to identify what new approaches are worthy of exploration, not just within a given messenger but especially in the interface between them. Topics of particular interest here include:

1. **Discovery and Inferencing on Censored/Encrypted Data** — Not all data will be available to all parties at the same time. How do we manage discovery and inference when a given

researcher cannot see some data (or is exposed to a noisy version of the data)? Here we expect recent advances in differential privacy and machine learning on homomorphically encrypted data to be key.

2. **Fast Surrogate Modelling from Theory** — How can we leverage banks of (slow and expensive) high-fidelity physics-based MMA simulations (or the theories themselves) to build data-driven surrogate models on the fly to enable rapid discovery?
3. **Hardware Accelerants** — Is there a need for specialized hardware to speed up inferencing? Bayesian inference is computationally expensive, especially with large-dimensional numerical construction of posteriors. What are the current computational limitations in determining, for instance, the spatial error region of a GW event within a given amount of time? Could purpose built hardware (e.g., FPGA or a system-on-a-chip [SOC]) be leveraged to speed up Markov Chain Monte Carlo (MCMC) inferencing?

We plan to invite a number of statisticians and computer scientists (who do not necessarily work with MMA data or the MMA community already) to participate; the primary aim with this broader group is to use their methodological expertise to inform the discussion of new research pathways and collaborations.

C. Stakeholder Consultation

During the initial phase of the project, we will identify representatives from each of the large U.S. projects with vested interests in MMA. Ideally, one person will be deeply involved in the science drivers of the project and one person will be deeply involve with the project's cyber needs. Identified Co-Is of this proposal will hold small-scale meetings with the project representatives to explore what can be gained from the use of common cyberinfrastructure. The Co-Is will use a common set of questions to engage these major stakeholders. The input from these meetings will help us to develop the initial design of an institute, focus the strategic plan, and provide a framework to engage the larger community. It will also help focus attention on the major challenges that should be addressed via the topical workshops described below.

Toward the end of this study, when a draft of the community whitepaper and strategic plan is formulated, we will follow up with these stakeholder representatives to ensure that the design of the institute and strategic plan address common needs and deliver value to these large projects.

V. Deliverables and Timeline

We have chosen the ambitious goal of completing this project in only one year to ensure immediate impact on the field and accelerate the process of preparing for the deluge of new data that will come in the early 2020s. The community is primed to engage in this effort following the recent success with GW 170817A.

A. Project Initiation (August 2018 – September 2018)

We will initiate the proposed project in early August 2018 by having discussions both in-person and electronically to design workshops and town halls, start conversations with major stakeholders, and assign tasks. In particular, we will form organizing committees to develop the workshops and town halls and subcommittees to develop relationships with major funded projects in multi-messenger astrophysics. The initial organization will be complete by the end of September 2018 and a detailed execution plan will be initiated.

B. Community Whitepaper (October 2018 – April 2019)

We will engage the community in earnest. Armed with a predetermined list of questions and topics, assigned Co-I's will conduct detailed interviews with both the scientific and cyber leadership of the major funded collaborations in MMA, e.g., LSST, IceCube, LIGO, ZTF, etc. We will host topical workshops, beginning with an NCSA workshop that is already scheduled for October 2018. Two other workshops will be organized and conducted during this timeframe. We also plan to host a town hall during the January meeting of the AAS and the April meeting of the APS to engage the larger community of astronomers, physicists, and data scientists. Informed by our conversations with major stakeholders and by our documented findings from the topical workshops and towns halls, we will develop the community-driven whitepaper and aim to produce an initial draft by the end of March 2019. After a one-month comment period, and discussions at the April APS meeting, a final version of the community white paper will be circulated and community members will be invited to endorse it.

C. Strategic Planning (February 2019 – July 2019)

Following the initial development of the whitepaper, we will proceed to develop a strategic plan for an Institute to address the challenges and needs of MMA that emerge from the white paper. Both the development of the whitepaper and strategic plan is expected to be an iterative process that will continually accept both new data from the larger community, topical workshops, and conversations with major stakeholders. Once we have completed the initial development of the community-driven whitepaper and strategic plan, we will then follow up with the major stakeholders to ensure that these documents accurately capture their common challenges and that the proposed solutions deliver value to their respective collaborations on both a local and global basis.

D. Summary

We have outlined a compressed timeline above that will take us from initial discussions in August 2018 to a community white paper and a strategic plan for implementation of an Institute in July 2019. We acknowledge that this is ambitious, but believe that given the rapid pace of advancement in this field driven by hardware improvements at LIGO, IceCube, ZTF, LSST, . . . we cannot afford to have a longer initial study period. With the proposed schedule above the community will be in a position to submit full, well-informed proposals for a Scalable Cyberinfrastructure Institute for Multi-messenger Astrophysics in 2019. This is critical to fully prepare the necessary cyberinfrastructure in time for LIGO, Virgo, and Kagra at their full design sensitivities in 2022 [71] along with the completion of IceCube's ongoing upgrade in 2022, IceCube Gen 2 in the mid/late 2020s and LSST operations starting in 2023 [72].

VI. Roles and Responsibilities

Brady (PI) is responsible for overall management of this project. He has experience working on cyberinfrastructure for Laser Interferometric Gravitational-wave Observatory (LIGO) including coordination with international partners. Over the years, he has worked with computer scientists to develop and deploy a robust cyberinfrastructure for gravitational-wave astronomy. And he has also worked closely with theorists and observers on a number of projects.

We have put together a strong team to contribute to the core of this project with representation across the the key domains of gravitational waves, neutrinos, and electromagnetic astronomy in addition to cyberinfrastructure and data science. We list each person, major facilities to which each is connected, and primary research areas: • **Gabrielle Allen (UIUC)** HPC, LIGO; • **Federica Bianco (NYU)** LSST; • **Joshua Bloom (UCB)** LSST, Machine learning, optical time-domain; • **Adam Brazier (Cornell)** NANOGrav, PALFA, data archives; • **Phil Chang (UWM)** Theory; • **Peter Couvares (Caltech)** HPC; • **Tyce DeYoung (Michigan State)** IceCube; • **Derek Fox (Penn State)** Multi-messenger communication, *Swift*; • **Chad Hanna (Penn State)** LIGO; • **David Hogg (NYU)** Machine learning; • **Kelly Holley-Bockelmann (Vanderbilt)** Theory, workforce development; • **D. Andrew Howell (UCSB/LCO)** Las Cumbres Observatory. Optical time-domain, telescope control and scheduling; • **Eliu Huerta (UIUC)** Deep learning, Modeling, LIGO and cyberinfrastructure; • **David Kaplan (UWM)** ZTF, NANOGrav, MWA, SKA, radio and optical time-domain; • **Erik Katsavounidis (MIT)** LIGO; • **Daniel S. Katz (UIUC)** Scientific software, HPC, cyberinfrastructure, computer & info. science; • **Azadeh Keivani (Columbia)** LIGO, IceCube; • **Zsuzsanna Marka (Columbia)** LIGO; • **Ignacio Taboada (Georgia Tech)** IceCube. This core team is supplemented by collaborators who have also committed effort as described in the supplementary collaborators document. This large team was assembled to ensure early and efficient engagement across all the disciplines that are essential to the success of MMA.

Each of the funded personnel will contribute to activity areas described at the beginning of Sec. IV.: **Activity area A1** – G. Allen, F. Bianco, J. Bloom, A. Brazier, P. Couvares, T. DeYoung, D. Fox, D. A. Howell, E. Katsavounidis, D. Katz, A. Keivani. I. Taboada **Activity area A2** – F. Bianco, J. Bloom, A. Brazier, T. DeYoung, D. Fox, D. A. Hogg, A. Howell, E. Huerta, D. Kaplan, A. Keivani, Z. Marka, **Activity area A3** – P. Chang, D. Hogg, K. Holley-Bockelman, E. Huerta. **Activity area A4** – G. Allen, P. Couvares, K. Holley-Bockelman, D. Kaplan, E. Katsavounidis, D. Katz, Z. Marka, I. Taboada.

VII. Broader impact of proposed work

The proposed multi-disciplinary community-wide engagement to develop a community-driven whitepaper and strategic plan will have broad impact far beyond astrophysics and gravity. It will engage experts from diverse areas to solve interesting interdisciplinary problems in MMA. Additionally products of this project will be useful and of great interest for the external professional community and society in general.

The key to far-reaching scientific impact is broader communication between multiple disciplines. By bringing astrophysicists with already strong background in various areas of multimessenger astrophysics together with data and computer scientists and providing a forum to foster these close interactions, this proposal will also identify – and explore how to tackle – the challenges involved in spanning disciplines. Therefore the workshops, town halls, and team meetings are important to this effort.

These broad collaborations will extend to benefit and engage peoples of many diverse backgrounds. Such outreach is essential to reach long-term diversity goals in the STEM areas. For instance, by creating new venues for close interaction, we hope to create opportunities to broaden the participation of underrepresented groups in MMA. It will be invaluable, for example, for influential astronomers to visit Fisk University, an HBCU, to meet with students in the Fisk-Vanderbilt Masters-to-PhD Bridge Program,[1] or similar programs at the other collaborating institutions. Personal contact with members of underrepresented groups is key to identifying promising students that might otherwise be overlooked and to ensuring that promising students get an opening to a rewarding STEM career.

The emphasis on cyberinfrastructure design and development in an interdiscplinary context means students that will be trained in these areas will have a broad toolset to attack problem in academia,

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[1] Co-I Kelly Holley-Bockelmann is Co-Director of the Bridge Program [73].

society, or industry. The training of these broad scientists with tools in machine learning (as applied to practical problems) and large-scale cyberinfrastructure will greatly increase the number of highly-trained STEM workers in the United States. Because of the broad geographical scope of this proposal, many of these students will be trained in regions that are in desperate need of a next-generation workforce to thrive in a global economy. These students and postdocs that will ultimately result from such an institute will power the transformation of these local economies.

Aside from broadening the scientfic impact in MMA, this proposal will indirectly impact public outreach. The team has a strong track record in public outreach to a diverse audience via public lectures, educational panels, student/teacher programs, and other outreach programmatics. The extensive collaboration will allow valuable insights and best practices to be shared on public engagement, teaching, and student training. In addition, the close collaboration between the different fields (astronomy, physics, computer science) which themselves have both similar and different issues with underrepresented student engagement lends itself to the development of truly creative and novel solutions. For instance, the reasons that underrepresented students shy away from physics may be different from computer science or astronomy, but techniques for teaching difficult topics in physics may be applicable to engaging students in computer science or vice versa.

Finally, the fertile ground resulting from the close collaboration of a team with disparate subfields will allow investigators to combine their unique public outreach tools with the common focus of highlighting multimessenger astronomy and its scientific potential to the general public. To this end, workshop organization in connection with this proposal will be combined with public outreach elements. In addition, exhibits at science fairs (as well as at the AAS, APS and similar professional meetings) provide an excellent platform for reaching out to a diverse segment of the public and young professionals. A coordinated booth featuring key experiments in the multimessenger field is an excellent platform for fruitful outreach coordination for the team that also uniquely communicates the goals of MMA to a wider audience. Team members already have experience with science fairs, for example with the World Science Festival LIGO and IceCube exhibits.

VIII. Results from prior NSF support

PHY-1700765 **Brady**, Smith, **Hanna**, and Anderson, *Data Handling and Analysis Infrastructure for Gravitational-wave Astronomy*; $7,199,963; 08/18/2017–08/17/2021. *Intellectual Merit*: Provides cyberinfrastructure in the form of data-handling services (data quality, transfer, discovery, event notification), data application services (data analysis and detector characterization libraries), engineering and operation services (automated build and test, packaging, optimization, monitoring) and collaboration support services (identity and access management, code repositories, wikis, mail services) for the LVC. *Broader Impact*: This infrastructure (which was previously supported by **PHY-1104371**) has enabled more than 60 LVC papers including the first detection of gravitational-waves (GWs) [9] and the first multi-messenger observations of a binary neutron star merger [26]. More than 87 students are involved in graduate research using this cyberinfrastructure.

OAC-1550514 **G. Allen** and M. Turk, *Collaborative Research: Einstein Toolkit Community Integration and Data Exploration*; $450,000; 07/01/2016–06/30/2020. *Intellectual Merit*: Developed and supported the Einstein Toolkit to provide open software, tools and community building for relativistic astrophysics. Includes the Cactus-based component framework which provides complete open codes for modeling black holes, neutron stars and gravitational waves on modern supercomputers together with tools for analyzing output from simulations. *Broader Impact*: Provides community and new user support though multiple mechanisms, including a user mail list, online weekly user meetings, yearly workshops and summer schools in the US and Europe, and frequent new user tutorials. Since the start of this award over 99 research publications cited the Einstein Toolkit. *Products which use the Einstein Toolkit*: [74–148][74–122, 149–172]

OAC-1251274 **J. Bloom** and F. Perez; *BIGDATA: Small: DA: Classification Platform for Novel Scientific Insight on Time-Series Data*, $733,536; 08/01/2013–07/31/2018. *Intellectual Merit*: Focused on developing a modern application stack to allow domain scientists to build reproducible machine learning workflows for their supervised inferencing needs on time-series data. Led to the creation of the cesium-ml platform and new deep-learning based classification frameworks applied to irregularly sampled variable star data. *Broader Impact*: Led to the development and release of a novel web-application framework to allow scientists to run end-to-end machine learning model building and prediction on time series data. A deep learning architecture, applicable to noisy time series inference challenges, was also published and released. *Products*: [173, 174].

AST-1255469 **P. Chang**; *CAREER: The Physics and Cosmology of TeV Blazars*; $456,149; 8/1/2013–7/31/2019. *Intellectual Merit*: Studied the plasma instabilities of pairs beams from TeV blazars in the intergalactic medium, which results in a few state-of-the-art analytic calculations as well as a new particle in cell code. Also studied the effect of clustering on TeV blazar heating on the intergalactic medium and its effect on the Lyman-alpha forest. *Broader Impact*: Developed tutorial videos for problem solving in introductory physics classes and website to host videos. *Products:* [175–187]

PHY-1707842 **T. DeYoung**; *Astroparticle Physics with the IceCube Neutrino Observatory*; $316,000; 07/01/2017–06/30/2019. *Intellectual Merit*: Supported a world-leading measurement of flavor oscillations of atmospheric neutrino extracted from a specialized low-energy (5–56 GeV) IceCube neutrino data set. Also supports ongoing searches for extended Galactic regions of high-energy neutrino emission and R&D for a future extensions of IceCube. *Broader Impact*: Supports an annual IceCube MasterClass, providing high school students from across Michigan hands-on opportunities to experience particle astrophysics, including construction of small particle detectors and analysis of real IceCube data. *Products:* [188].

PHY-1708146 M. A. Mostafa, **D. Fox**, D. F. Cowen, and B. Sathyaprakash; *The Astrophysical Multi-Messenger Observatory Network (AMON)*; $360,000 07/15/2017–06/30/2020. *Intellectual Merit* Carried out multi-messenger archival analyses and extended AMON, the first dedicated multi-messenger alert system, from the original neutrino + electromagnetic alerts, to incorporate cosmic rays (as appropriate) and gravitational wave transients and targeted follow-up analyses, and to perform appropriate follow-up observations. *Broader Impact*: Presented on gravitational wave and multimessenger science at the Penn State In-Service Workshops in Astronomy for high school teachers (2017, 2018). *Products*: [189, 190].

PHY-1454389 **C. Hanna**; *CAREER: Enabling Multi-Messenger Astrophysics with Real-Time Gravitational Wave Detection*; $400,000 06/01/2015–05/31/2020. *Intellectual Merit*: Developed and deployed the real-time gravitational wave detection pipeline GstLAL which identified GW170817 within 7 minutes of data acquisition. *Broader Impact*: Held gravitational wave summer school for highschool students following discovery of GW150914 and GW151226. *Products*: [65, 191–193].

AST-1517237 **D. W. Hogg**; *New Probabilistic Methods for Observational Cosmology*; $328,312; 09/01/2015–08/31/2018. *Intellectual Merit*: Created new data-analysis methods for cosmology that better transmit information from the raw cosmological data to cosmological-parameter inferences. *Broader Impact*: Supported the creation of several pedagogical documents to support probabilistic inference in physics such as [194]. *Products:* [195, 196].

AST-0847696 K. Holley-Bockelmann; *CAREER: Survival of the Privileged: Exploring the conditions that allow supermassive black holes and minority physicists to thrive*; $1,075,873, 09/01/2007–08/31/2014. *Intellectual Merit*: Studied theoretical aspects of SMBH growth in MW-type galaxies, e.g., ‘final parsec’ problem, gravitational wave recoil and the consequences for the $M_\bullet - \sigma$ relation, gravitational wave sources and strength for LISA. *Broader Impact*: Created new ‘Order of Magnitude’ course. *Products:* [197–199].

AST-1313484 D. A. Howell; *Early Robotic Spectra of Supernovae with FLOYDS*; $614,046; 09/01/2013–08/31/2018. *Intellectual Merit* and *Broader Impact*: For early-time science of supernovae using FLOYDS. Graduate student Griffin Hosseinzadeh was hired on this grant July 1, 2014. Postdoc Curtis McCully was hired September 1, 2014.

AST-1412421 D. L. Kaplan;*Variables and Slow Transients with the Murchison Widefield Array*; $232,096, 09/01/2014–08/31/2018. *Intellectual Merit*: Worked on time-domain and multi-messenger astrophysics with the Murchison Widefield Array radio telescope. Extended into a larger radio followup effort studying GW170817. *Broader Impact*: Led an exhibit at Maker Faire Milwaukee (with over 40,000 visitors), which had MWA antennas among other items, promoted other aspects of multi-wavelength astronomy, and used 3D data from radio telescopes to provide a tactile experience. *Products:* [58, 200–213].

PHY-0757058 Fritschel, **Katsavounidis**; $35,435,663; 10/01/2008–09/30/2018. *Intellectual Merit*: Performed extensive real-time data acquisition and analysis for the purpose of characterizing the LIGO detectors, searching for gravitational-wave (GW) astrophysical sources and interpreting their detections. Developed cyberinfrastructure for the purpose of enabling the first electromagnetic (EM) follow-up of GW sources during the initial LIGO observing runs of 2009–2011 and contributed in infrastructure for multi-messenger astrophysics, data analysis and interpretation throughout the advanced LIGO runs in 2015–2017 including all binary black hole and binary neutron star detections. *Broader Impact*: Delivered several public talks on gravitational waves locally, nationally and internationally and organized exhibit booths on gravitational waves in AAS and AAAS conferences in the Boston area. The undertaken research promoted and supported infrastructure enabling the public dissemination of gravitational-wave transient alert that led to the first multi-messenger observations with gravitational waves. *Products:* [9, 11, 15, 19, 214–221].

PHY-1404462 S. Marka, **Z. Marka**, **I. Bartos**; *Maximizing the Early-Detection Science of Advanced LIGO*; $480,000, 6/15/2014–09/30/2017. *Intellectual Merit*: Focused on multi-messenger astrophysics topics including electromagnetic follow-up of gravitational-wave events and also developed and spearheaded the multi-messenger search for joint sources of gravitational-waves and high-energy neutrinos. The search was running real time during LIGO’s second observational run. *Broader Impact*: Developed strong outreach program targeting local schools, and has been organizing exhibits at the World Science Festival in New York City for many years. *Products:* [16, 222–227].

PHY-1505230 I. Taboada; *Particle Astrophysics with IceCube at Georgia Tech*; $302,000; 08/15/2015–07/31/2019. *Intellectual Merit*: Conducted a search for the sources of the very-high-energy astrophysical neutrino flux using IceCube, specially those that are transient and have a multimessenger counterpart. Follow up of IceCube-170922A. *Broader Impact*: Participant of the Atlanta Science Festival for many years. Developed strong outreach program targeting local schools with high hispanic student fraction. *Products:* [228–230]

Co-PIs F. Bianco and A. Brazier have not received prior NSF funding.

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