Physics of the Cosmos Program Analysis Group (PhysPAG) Study Analysis Group (SAG) on Multimessenger Astrophysics (MMA) Final Report – DRAFT

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1 Motivation and Goals

The power of multimessenger astrophysics (MMA) was vividly demonstrated two years ago through the observation of the first astrophysical event detected simultaneously in both the gravitational wave and electromagnetic domain. On August 17, 2017, a binary neutron star (BNS) merger at a distance of 40 Mpc generated gravitational waves and gamma rays strong enough to register in LIGO and Virgo, and 1.7 seconds later, in both the Fermi space observatory and INTEGRAL. These two messenger channels triggered a flurry of follow-up observations by the international astronomical community. MMA observations of this single event enabled astronomers to derive a number of profound conclusions, including that (a) BNS mergers occur in nature, (b) short gamma-ray bursts are associated with at least a fraction of BNS mergers, (c) kilonovae are connected to BNS mergers, (d) gravitational waves indeed travel at the speed of light as Einstein predicted, and more.

Multimessenger astrophysics offers a powerful methodology of growing importance, as we combine electromagnetic radiation, gravitational wave radiation, and particle astrophysics observations of cosmic events. In the coming decade and beyond NASA's space observatories will have an important role to play, including those that will continue to operate in the 2020s, such as Hubble, Chandra, Swift, Fermi, those currently planned, including JWST, WFIRST, Athena, LISA, and Explorers, and those that will be considered by the 2020 astrophysics decadal committee. Many of the scientific communities within Physics of the Cosmos have been actively participating in the 2020 astrophysics decadal survey. To support this effort and promote interactions among the broad astrophysics community, the MMA SAG was formed. This group has analyzed the potential scientific benefits of multimessenger observations made possible by NASA observatories in the coming decades, working in conjunction with each other or with other ground- and space-based instruments. The MMA SAG consists of astrophysicists from multiple disciplines within the PhysPAG and CoPAG communities that contribute to multimessenger astrophysics. And while the formation of this SAG was motivated by the binary neutron merger event in 2017, it has not exclusively focused on gravitational wave observations. Indeed, we have attempted to identify science goals that utilize many different subsets of the EM and GW spectra, as well as particle astrophysics.

The goals of the MMA SAG were the following:

1. Identify science goals that could be achieved by combining different astrophysical messengers measured by current and future ground- and space-based observatories.

2. Identify measurements that can be made by existing, currently approved, and future planned ground- and space-based observatories that could contribute to multimessenger astronomy in the 2020's and early 2030's.

3. Determine how these enhanced or new science goals align with NASA Astrophysics Division's scientific priorities.

4. Identify the key qualitative technical drivers needed to achieve these science goals (e.g. wavelength, sensitivity, sky localization, latency, . . .) and determine desirable performance levels for each.

Messengers; **Astro2020 Thematic Areas** and Sub-Topics	NS Mergers	CCSN	AGN/Blazars	SMBHBs	IMBHs	Gal. Binaries	Pulsars	sBBH	SNRs	GMF
GWs - kHz	x	?					x	x		
GWs - mHz			?	x	x	x	?	x		
GWs - nHz			?	x						
Neutrinos - TeV-EeV	x	x	x					?	x	
Neutrinos - MeV-GeV	x	x							x	
Cosmic Rays - Ultra High Energy	x	x	x							x
Cosmic Rays - High Energy	x	x	x	x					x	x
Gamma-rays - keV-TeV	x	x	x	?	?	x	x	?	x	x
X-rays	x	x	x	x	x	x	x	x	x	
UV	x	x	x	x	x	x	x	x	x	
Optical	x	x	x		x	x	x	x	x	x
IR	x	x	x		x	x	x	x	x	x
Radio	x	x	x	x	x	x	x	x	x	x
Thematic Area 2: Star and Planet Formation								x	x	x
Formation of Stars and Clusters								x	x	
Molecular Clouds and the Cold Interstellar Medium; Dust									x	x
Thematic Area 3: Stars and Stellar Evolution	x	x				x	x	x	x	
Stellar Astrophysics		x				x	x	x	x	
Structure and Evolution of Single and Multiple Stars	x	x				x	x	x	x	
Thematic Area 4: Formation and Evolution of Compact Objects	x	x			x	x	x	x	x	
Stellar-mass Black Holes	x	x				x		x	x	
Neutron Stars	x	x				x	x		x	
White Dwarfs						x			x	
Supernovae		x				x			x	
Mergers of Compact Objects	x				x			x	x	
Gamma-ray Bursts	x	x								
Accretion	x	x				x	x	x		
Production of Heavy Elements	x	x							x	
Extreme Physics on Stellar Scales	x	x				x	x	x	x	
Thematic Area 5: Resolved Stellar Populations/Environments					x	x	x	x	x	x
Structure and Properties of the Milky Way and Nearby Galaxies					x	x			x	x
Stellar Populations and Evolution						x	x	x	x	
Interstellar Medium and Star Clusters								x	x	x
Thematic Area 6: Galaxy Evolution			x	x	x			x	x	x
(Forma/Evolu)tion/Dynamics/Properties of SMBHs/Galaxies/Clusters			x	x	x			x		x
Active Galactic Nuclei and QSOs			x	x				x		
Mergers			x	x	x					
Star Formation Rates			x					x	x	
Gas Accretion; Circumgalactic and Intergalactic Media			x	x					x	x
Thematic Area 7: Cosmology and Fundamental Physics	x	x	x	x			x	x	x	x
Early Universe			x							
Cosmic Microwave Background			x							x
Determination of Cosmological Parameters	x		x	x				x		
Dark Matter and Dark Energy	x			x						
Astroparticle Physics	x	x	x	x			x		x	x
Tests of Gravity	x		x	x			x	x		
Astronomically Determined Physical Constants	x		x	x						
Thematic Area 8: Multi-Messenger Astronomy and Astrophysics	x	x	x	x	x	x	x	x	x	x
Identify Sources of GWs, Neutrinos, Cosmic Rays, and Gamma-rays	x	x	x	x	x	x	x	x	x	x
Coordinated Multimessenger and Multiwavelength Follow-ups	x	x	x	x	x	x	x	x	x	x

2 Summary of MMA opportunities

Astrophysical observatories now utilize several messengers:

Electromagnetic (EM) radiation. We now observe photons from radio wavelengths up to very high energy gamma-rays, covering more than twenty decades in energy. Gravitational waves (GWs) are spacetime ripples emitted from systems with an accelerating quadrupole moment. Detectable GWs are expected from binary systems of white dwarfs (WDs), neutron stars (NSs), and black holes (BHs) or possibly from non-axisymmetric, dynamic environments such as non-spherical spinning NSs, vibrating cosmic strings, or core-collapse supernovae. Neutrinos are the lightest massive particles and are produced in weak interactions. In astrophysics we expect MeV neutrinos from core-collapse events and high-energy (TeV-PeV) neutrinos from efficient particle reservoirs/accelerators such as supernova remnants or relativistic jets from active galactic nuclei. Cosmic Rays are high-energy charged particles such as protons and more massive atomic nuclei. The latter are formed and released during explosive nucleosynthesis events, and achieve high kinetic energies from natural particle accelerators.

In astronomy, giant leaps forward followed the opening of new observational windows of the EM spectrum. As multiwavelength studies brought new understanding, multimessenger observations will likewise revolutionize our field as each of the different messengers carries distinct information that can be combined for a fuller understanding. Critical to future multimessenger science are joint observations, multiwavelength EM coverage, and improved communication. We demonstrate this using prior multimessenger examples and give broad recommendations to maximize science yields in the new multimessenger era.

Here we make general recommendations to ensure success in the multimessenger era. Example Astro2020 white papers with more detailed descriptions of exciting multimessenger science include: NS mergers [1], CCSN [2, 3, 4], Blazars/Active Galactic Nuclei (AGN) [5, 6], supermassive black hole binaries (SMBHB) [7, 8, 9, 10], intermediate mass BHs (IMBHs) [11, 12], galactic binaries [13, 14], stellar-mass binary black hole (sBBH) mergers [15, 16, 10], studies of the Galactic magnetic field (GMF) [17] and searches for the origin of new messengers [18, 19, 20, 21, 22, 23]. A broad, albeit incomplete, summary of multimessenger science and the necessary capabilities required to uncover them is provided in Table 1. Below we summarize the current and foreseeable state of observational coverage of these messengers.

3 Science Goals enabled by Multimessenger Astrophysics

3.1 Multi-physics of AGN Jets

A wide variety of astrophysical sources, from young stellar objects to white dwarfs, neutron stars, stellar-mass and supermassive black holes (SMBHs), produce collimated outflows, or jets. Powered by accretion onto supermassive black holes (SMBH), Active galactic nuclei (AGN) jets are the most powerful and long-lived particle accelerators in the Universe.

High-energy observations revealed that astrophysical jets are the most energetic particle accelerators in the Universe, which allows us to probe the physics of matter and elementary particles in extreme physical conditions. Understanding jets from SMBHs in the context of active galactic nuclei (AGN) is a particularly crucial question because their jets could be one of the major ways in which accreting SMBHs provide kinetic feedback on their surroundings and affect star formation, galaxy evolution, and the growth of SMBHs themselves. A more complete understanding of *feedback* in the context of galaxy evolution is a frontier arena of observational cosmology, and MMA data are essential for the establishment of dynamic connections across many scales.

Despite their ubiquity, the launching and collimation of astrophysical jets and the radiation processes response for high-energy emission still remain unclear. For instance, how are jets launched and which processes determine their dynamic evolution, how is the jet kinetic energy transferred to particles, where is the location of high-energy dissipation, what are the energy dissipation mechanism(s), what are the primary energy carriers (protons or leptons), how does the jet structure relate to the high-energy emission, etc., are the key open puzzles in high-energy astrophysics. Multi-messenger observations in the next decade offer an unprecedented opportunity to unravel them [5, 24].

Direct comparison of multi-messenger and multi-frequency space- and ground-based observations with theoretical simulations/models will be crucial in understanding the mysteries of the most energetic phenomena in the Universe. We advocate the support of future multi-wavelength and multi-messenger instruments with large effective areas, excellent timing resolution, and wide fields of view that will be essential for advancing our understanding of jet physics.

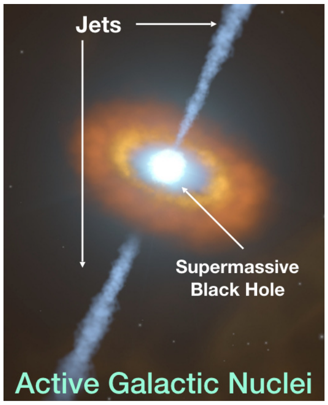

Figure 1: AGN jets are the most powerful and long-lived particle accelerators in the Universe, emitting non-thermal radiation responsible for their multi-messenger emission.

3.2 High-Energy Neutrinos as probes of AGN physics

High-energy neutrinos are unique astrophysical messengers as, unlike photons, they can only be produced in hadronic interactions occurring at cosmic ray acceleration sites. Neutrinos can propagate over cosmological distances, almost unattenuated and undeflected by intervening matter and radiation fields, and can therefore probe extreme environments that may be opaque to photons. The detection of high-energy astrophysical neutrinos by IceCube has provided the first step towards realizing neutrino astronomy. The apparent isotropy of the astrophysical neutrino flux, and the recent evidence for the detection of a neutrino correlated in space and time with a flare of gamma-ray blazar TXS 0506+056, tend to favor an extra-galactic origin of this emission.

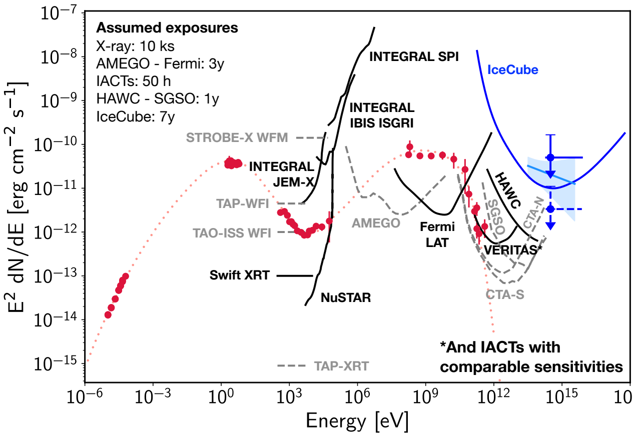

Figure 2: The broadband spectral energy distribution of the potential neutrino blazar TXS 0506+056 compared to the sensitivity of current and future instruments that are expected to operate in the coming decade [6].

However, the constraints on neutrino emission from the ensemble of known GeV gamma-ray blazars, and the identification of historical neutrino emission from TXS 0506+056 with no associated gamma-ray activity complicate a straightforward interpretation of neutrino observations of active galactic nuclei (AGN). On the other hand, the sources of the bulk of high-energy neutrinos remain unknown. AGN are among the most plausible cosmic accelerators. Studying their contributions to the diffuse neutrino background is timely.

In order to solve these puzzles, we advocate [6] for an ambitious observational program with special emphasis in three electromagnetic bands (soft and hard X-rays, MeV gamma rays, and TeV gamma rays) to perform continuous monitoring of AGN that can be associated with astrophysical neutrino events. This observational capability is necessary to constrain hadronic models that could explain the neutrino emission. A key component of these studies will be the increase in neutrino statistics provided by next-generation observatories such as IceCube-Gen2 and KM3NeT.

3.3 Intermediate and Super-massive Black Holes

Galaxy mergers deliver two massive black holes, along with massive inflows of gas, to the center of post-merger galaxies [25]. Gravitationally bound intermediate-mass or supermassive black hole binaries (collectively MBHBs) can then form. We expect these binaries to be among the strongest sources of GWs in the Universe, potentially detectable at present by pulsar timing arrays (PTAs), and in the future by space-based laser interferometric observatories. PTAs can access the most massive MBHBs generally at redshifts $z < 1$ and chirp masses of $\gtrsim 10^8\,\mathrm{M}_\odot$ [26]. LISA, on the other hand, will measure intermediate-mass black holes ($M \lesssim 10^7\,\mathrm{M}_\odot$) up to and beyond $z \simeq 20$. As indicated by the schematic in Figure 3, the current suite of GW observatories provide unique and complimentary access to binary black holes, and their orbital dynamics, across cosmic time. Thus, MBHB science is a chief focus for ongoing and upcoming GW programs.

Through continued observations of a large sample of millisecond pulsars, PTAs are expected to detect MBHBs within the next decade, either through observation of the gravitational-wave background from these objects, or through the observation of discrete (continuous-wave) MBHBs.

Already, supermassive MBHB candidates are being identified by electromagnetic surveys in ever-increasing numbers; upcoming surveys, particularly those in the time-domain at X-ray and optical wavelengths, will be instrumental in identifying the host galaxies of GW sources and enabling multi-messenger MBHB science. These multi-messenger observations will revolutionize our understanding of the dynamics of circumbinary disks, the generation and geometries of AGN, the co-evolution of supermassive black holes with their host galaxies, the dynamical interactions between binaries and their galactic environments, and the fundamental physics of accretion. Multi-messenger observations that lead to host galaxy identification can also render MBHBs into ‘standard sirens’ for cosmological distance ladder measurements out to $z \simeq 0.5$ with PTAs, and far beyond this with LISA.

Detecting the loud gravitational signal of MBHBs—either in active orbit or the signal from a coalescence itself—will trigger alerts for EM counterpart searches, from decades (PTAs) to hours (LISA) prior to and following the final merger.

3.4 Neutron Star Mergers

The science we can learn from astrophysical observations of NS mergers spans a wide variety of topics and fields. They produce loud GW inspirals, bright EM emission as short gamma-ray busts

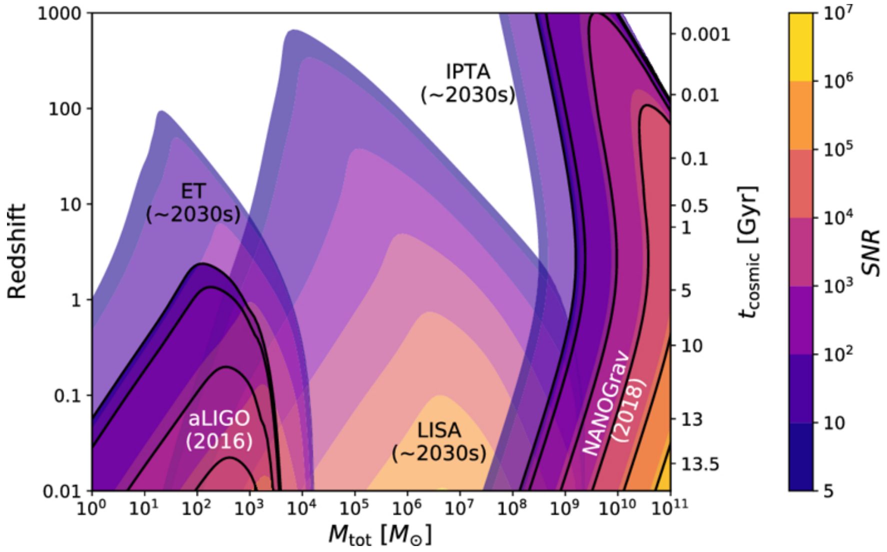

Figure 3: From [26]; here we show the approximate S/N for the complementary wavebands of three instrument at present (darker shading/black contours) and in the 2030's era (lighter shading). This plot focuses only on individual (rather than stochastic) MBHB detections. All curves assume instrument-limited sensitivity, without an astrophysical background. Figure produced by Andrew Kaiser and Sean McWilliams (WVU); a more rigorous version will be published in Kaiser & McWilliams (in prep).

(GRBs), kilonovae, and more, and are expected to produce both neutrinos and cosmic rays. The astrophysical inferences these sources enable including the existence of neutron star-black hole systems (which may have recently been confirmed). EM observations of these events can determine their rate evolution over cosmic time, the types of host galaxies, the position of the sources relative to their hosts, and the GW information can directly measure the intrinsic properties of the progenitors. Together these can constrain the formation mechanism(s) of these systems, inform population synthesis models, and provide unique information on stellar formation and evolution over cosmic history. A white paper summary of this science and the capabilities necessary to achieve it is available in [1] and an in-depth overview is provided in [27].

Understanding short gamma-ray bursts enables us to understand matter in the ultrarelativistic regime, including the necessary condition to produce these jets, how they form and propagate, and how they emit the most luminous EM events in the universe. Understanding kilonova and the source evolution of NS mergers tells us the origin of the heavy elements through cosmic time. NS mergers will provide key information on cosmology and fundamental physics, with implications for all four fundamental forces. The combination of GW measurements of distance and EM measurements of redshift enables the construction of a GW Hubble diagram that will help resolve the current tension in the value of the Hubble constant, provide better constraints on the shape of the universe, help determine if dark energy is a cosmological constant, and improve the measurement that enables a determination of the absolute values of the neutrino mass eigenstates. Detections can test Lorentz Invariance violation and the weak equivalence principle, the underlying assumptions of relativity itself, search for evidence of quantum gravity, and search for non-GR effects such as additional polarization modes or parity violation in gravitation. Lastly, several measurements will constrain the equation of state of supranuclear matter, which constrain approximations used to predict large-scale behavior from quantum chromodynamics.

This science is wonderful but requires significant resources. Wavelengths best observed from the ground are generally well covered by discovery and characterization telescopes. The space-based wavelengths of ultraviolet, X-rays, and MeV gamma-rays are lacking in comparison. To ensure the necessary observations, extensions of the Fermi and Swift missions, the development of a wide-field ultraviolet transient telescope, and an advanced gamma-ray mission in the 2020s would be needed. Sufficient funding for theory and numerical simulations, and sufficient prioritization for telescopes with shared time is also important. Lastly, multi-mission coordination is critical in this era, and improvements in real-time reporting schemes would be beneficial.

3.5 Galactic Binaries

White Dwarf binaries will be among the best laboratories for understanding the formation of compact objects, dynamical interactions and tides in binaries, and are known to be progenitor systems for Type Ia supernovae. Combined EM/GW observations yield more robust masses, radii, orbital separations, and inclination angles than either can achieve on its own. Shah et al. (2012) [29] found a strong correlation between GW amplitude and inclination, and demonstrated that EM constraints on the inclination can improve the GW amplitude measurements by up to a factor of six. In addition, knowing the sky position and inclination can reduce the uncertainty in amplitude by up to a factor of 60 [30]. Similarly, using the chirp mass obtained from GW observations and the mass ratio from spectroscopic radial velocity measurements allows an independent measurement of the masses of both components to exquisite precision. This enables a direct comparison between the rate of orbital decay observed in GW or EM (for eclipsing and/or tidally distorted systems) and predicted from GR.

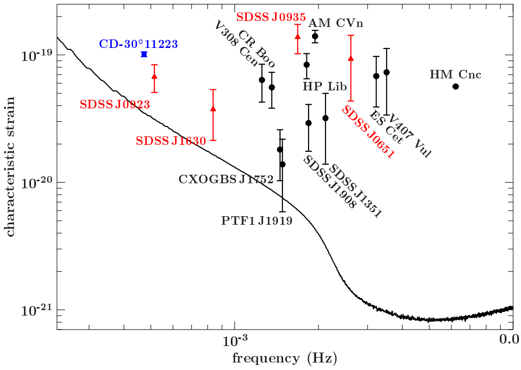

Figure 4: Sensitivity limits of *LISA* shown with the known verification systems and the evolutionary paths of different UCBs. Black circles are AM CVn systems, red triangles correspond to detached double WDs and the blue square is an ultracompact He-star + WD [28].

Measuring the effects of tides in binaries, which are predicted to contribute up to 10% of the orbital decay, is almost impossible from GW data alone [31], but the EM data on distance constrains the uncertainty in chirp mass to 20%, whereas adding $\dot{P}$ reduces it to 0.1%. A GW chirp mass measurement would provide the first detection of tidal heating in a merging pair of WDs from the deviations in predicted $\dot{P}$.

Electromagnetic observations (EM) of detached double WDs provide precise sky positions, mass ratios (especially for the double-lined spectroscopic binaries), inclinations [32, 33], and the rate of orbital period decay. Looking forward to EM+GW multi-messenger astrophysics, we highlight the recently detected double white dwarf with an orbital period of 6.9 min: ZTF J1539, Burdge et al. (2019) [33] provided eclipse time measurements using a multi-year baseline and found a rate of orbital decay of $\dot{P} = (-2.373 \pm 0.005) \times 10^{-11}\,\mathrm{s\,s^{-1}}$. However, even with deep eclipses, we do not know the masses of the WDs in this system well enough from optical observations to see if the objects $\dot{P}$ differs from the GR predictions. GW observations can solve that. Tidal theory predicts a 10% deviation from GR if the WDs are tidally heating up [34, 35, 36, 37]. Which means that combining EM+GW observations will allow a measurement of the amount of tidal heating in a merging pair of WDs for the first time.

Amongst the Galactic binaries with NS companions we currently know of systems currently undergoing mass transfer, some that have not started mass transfer and some that have previously undergone mass transfer and may re-start mass at a later time. Many of these sources are faint in EM and *LISA* will provide substantial-sized samples of both the pre-accreting systems and the systems with neutron stars that are still accreting at low rates. Furthermore, precise masses for all components will be possible in these systems. This will then allow empirical estimates of both the amount of mass lost by the WDs and the amount of mass gained by the NSs, allowing a clear test of how conservative the mass-transfer is in these systems, and how much neutron star mass growth occurs. It may furthermore open up a window to finding ultra-low mass black holes in which accretion has pushed the neutron star over the Oppenheimer-Volkov-Tolman limit, and such systems could hold a key to understanding the neutron star equation of state. The large number of detached ultracompact systems with neutron stars to be detected by *LISA* will us to understand the opening angles for pulsar beams at different energy bands. With a set of facilities optimized for detection of pulsations in radio, X-ray and gamma-rays, it will then be possible to determine which objects are detected as pulsars in which wavelengths.

With large-scale survey such as e.g. ZTF, LSST, *Gaia*, SDSS-V, we predict that a large number of Galactic binaries with compact companions will be observed with GW+EM observations, which will open up possibilities to explore and study astrophysical phenomena which are crucial to our understanding of the universe. This includes the long-standing questions of the progenitors of supernovae Ia, the formation and evolution of compact objects in binaries and accretion physics under extreme conditions.

3.6 Core Collapse Supernovae

The detection of neutrinos in supernova 1987A [38, 39] confirmed that at least some supernovae form a compact remnant, reaching densities and temperatures that are sufficiently high to emit copious amounts of neutrinos. Coupled with optical observations of the progenitor, the paradigm that supernovae are produced in the core collapse of massive stars [40, 41] was confirmed. Extensive mixing in the explosion was demonstrated by observations of the distribution of the nucleosynthetic yields over a broad range of wavelengths: e.g. gamma-rays of the ^{56}Ni decay, infra-red observations of iron, late-time nebular spectra [42]. The signatures of mixing led to the development of the current standard core-collapse supernova engine model [43, 44], which was recently confirmed through hard X-ray mapping of the spatial distribution of radioactive ^{44}Ti in the supernova remnant Cas with NuSTAR A [45, 46].

Despite the progress in our qualitative understanding of core-collapse supernovae, we are still far from a satisfactory quantitative understanding of stellar collapse dynamics and its associated supernovae. Outstanding questions include a full understanding of stellar evolution (of single- and binary systems) and the structure of the star at collapse, the nature of the convective engine (e.g. which instabilities dominate and the roles of magnetic fields and rotation), the details of the nuclear physics and the role supernovae play in producing heavy elements beyond the iron peak (e.g. r-process). Multi-messenger astronomy holds the keys to answering many of these questions. Pre-supernova observations will probe the progenitor and early time spectra in a broad wavelength range from infra-red to X-rays and probe the stellar radii and wind structures in the environments of these exploding systems.

Gravitational waves will probe the amount of rotation and the nature of the convection (which, in turn, constrains the role of magnetic fields) [47, 48]. Although the best opportunity to detect gravitational waves from core-collapse supernovae is with a galactic event, extra-galactic core-collapse supernovae allow us to put constraints on the supernova engine. The latest search for these transients with advanced LIGO and Virgo [49] allowed us, for the first time, to exclude parameter spaces of models with extreme core rotations and deformations. Future gravitational searches with increased detector sensitivities together with improved multi-band photometry will further constrain the supernova engine.

With next generation telescopes, gamma-rays from the decay of radioactive nuclei can probe both the nature of the convective-engine (measuring the level of asymmetry) and pre=collapse structures. Dust grains can also be used to probe the detailed isotopic abundances in these yields [50]. Nebular spectroscopy across a broad wavelength range will further probe the nucleosynthetic yields to study the stellar structure. Neutrinos will not only probe the nature of collapse, but also probe the nuclear physics, including effects from neutrino oscillations.

Radio, optical, and X-rays can be used to observe supernova remnants, again studying the nucleosynthetic yields, ultimately probing the structure of the star and the nature of the explosion [51]. Remnant observations are also sensitive to the circumstellar medium and, by using earlier observations to probe the supernova, remnant observations can be used to probe stellar winds. Coupled with cosmic ray studies high-energy gamma-ray observations probe the nature of strong shocks in these explosions, determining the role supernovae play in particle acceleration.

Finally, x-rays and radio waves can probe the compact remnant left behind in the explosion, providing additional probes of the rotation, magnetic fields and nuclear physics in the extreme conditions of the collapse.

Truly understanding the meaning of the different observations requires detailed multi-physics modeling and, as with many astrophysical conditions, multi-messenger astronomy is strongly coupled with applied, multi-physics modeling. Because the different diagnostics often probe multiple physics effects, multiple diagnostics and multiple messengers are crucial to gaining a complete picture of supernovae. In turn, by better understanding these explosions and their progenitors, supernova studies can reduce the uncertainties in all the fields they affect, including our understanding of compact binaries, galactic chemical evolution and gas dynamics.

3.7 Stellar-Mass Binary Black Hole Mergers

Stellar-mass binary black hole (sBBH) mergers constitute most of the signals detected by the LIGO and Virgo GW detectors [52]. The conventional view of sBBH mergers is that there should not be enough matter present to produce a detectable electromagnetic transient when the black holes merge. However, a number of mechanisms have been proposed which could produce such a counterpart through accretion of matter from various reserves, charged black holes, or interactions with magnetic or exotic fields. The weak gamma-ray transient signal recorded by the *Fermi* Gamma-ray Burst Monitor (GBM) less than a second after the first merger detected, GW150914 [53] remains an intriguing but inconclusive hint of the possibility of gamma-ray emission from sBBH mergers [54].

In some models, the merger occurs in an environment where there is, in fact, a significant amount of matter nearby that is triggered to accrete onto the post-merger black hole, producing a more-or-less normal GRB. It would be natural for only a small fraction of sBBH mergers to produce such a counterpart because gamma-ray emission is beamed and also because, perhaps, only some fraction of sBBH mergers occur in a conducive environment. For instance, the matter could be from supernova ejecta [55] or stellar wind material [56], from one or both of the BHs' progenitor stars, which remained bound to the binary system; from an sBBH merging in the interior of a massive star [57]; from the envelope of a just-collapsed star [58]; from mass transfer from a third body in a hierarchical triple system [59]; or from the large accretion disk of an active galactic nucleus (AGN) if the merging sBBH binary is located within it [60, 61].

Astrophysical black holes are generally believed to have negligible electric charge, but a young black hole may retain trapped charge for some period of time [62] and an inspiral with at least one charged BH can produce an EM counterpart [63, 64]. Alternatively, magnetic reconnection in low-density plasma around the merging binary could power a transient [65]. These models can be consistent with the non-observation of EM counterparts for most (or all) sBBH mergers detected so far if only a small fraction of systems have sufficient charge and/or plasma density at the time of merger. More speculative models with exotic field interactions and/or exotic compact objects have also been proposed.

If an EM counterpart to a GW event is identified, the relative timing, spectrum and intensity of the EM emission will tell us about the emission mechanism and the characteristics of the sBBH system. This complements what we learn from the GW data, such as the BH masses and the orientation of the binary orbit, and can provide insights into stellar evolution, compact binary formation, cosmological measurements, searches for charged black holes, and tests of general relativity and fundamental physics. Thus, it is important to pursue this possibility even if only a small fraction of sBBH mergers will yield such a counterpart.

Many of these models effectively produce a short GRB, so a key observational capability is full-sky monitoring for gamma-ray transients and X-ray bursts/afterglows, sensitive enough to detect the possibly weak beamed emission from sBBH mergers within range of the GW detectors. Other models lead to emission at longer wavelengths and over longer time scales, calling for sensitive UV, optical (including infrared), and radio observatories capable of very deep imaging.

3.8 Gravitational Waves as a Statistical Probe of AGN and other Astrophysics

Detection of gravitational waves from stellar-mass binary black holes can provide important constraints on AGN astrophysics, even in the absence of an identified EM counterpart. Statistical techniques can determine the contribution of AGN (and other rare source types, for example merging galaxies, or E+A galaxies) to the LIGO detected merger rate. The technique relies on measuring an overdensity of AGNs (or other rare source type) in each LIGO error volume; as long as the AGN channel contributes $>\sim 0.3$ of all sBBH mergers, the fraction is measurable after $<\sim 660$ LIGO events, with current galaxy catalogs and localization [66, 10]. This measurement could be achieved more quickly with improved galaxy catalogs (higher completeness and reduced contamination–UV and X-ray missions are especially useful for these purposes).

With current LIGO measurements, we can already derive important inferences about the lifetime and typical scale height (and thus the accretion mode) of Low Ionization Nuclear Emission Regions (LINERs), the most common type of AGN [67]. In particular LINERs cannot be predominantly composed of optically-thick, radiatively inefficient accretion flows (RIAFs)–or the observed rate of sBBH mergers would be much higher than is observed (see Fig. 5). We note these conclusions rest on the assumption that *at least one* sBBH merger occurs in an AGN disk within a Hubble time; this seems a safe assumption in light of many works, especially [68, 69, 70, 71, 72, 73, 74]. There is accumulating evidence of hierarchical mergers, which are more likely to have occurred in an AGN disk, notably GW170729 and GW170817A [74, 75]. Using a statistical strategy, we can directly constrain the lifetimes, disk aspect ratios, and midplane densities of AGN. Such constraints can be achieved by measuring the fraction of BBH from the AGN channel either statistically [66] or directly—since the AGN disk gas provides an EM emitting medium. We note that AGN embedded BBH mergers should produce an EM signal preferentially detectable in the UV, and more easily detected for larger binary masses—see [61] for details of predicted EM signatures. Given the large number of BBH alerts from LIGO and their typical areas, and given limited EM followup resources, it is becoming critical that LIGO either promptly release masses or attach a ‘probable high mass’ flag, similar to the ‘probable remnant’ flag, for each BBH event.

Wide-field UV telescopes are especially useful for identifying individual AGN hosts, or setting useful limits on disk conditions, in the case of non-detections.

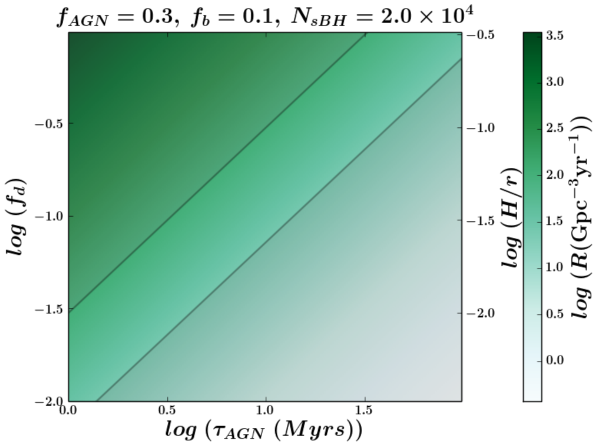

Figure 5: LIGO restrictions on the rate of BH mergers allowed in AGN. Disk scale height and lifetime must live below the upper diagonal line. We assumed $N_{\rm sBH} = 2 \times 10^4$ [76, 77] and $f_{\rm AGN} = 0.3$, corresponding to all LINERs and low luminosity AGNs [78]. The LIGO-Virgo upper and lower limits are given by the diagonal lines. If other methods or messengers can eliminate the possibility that AGN driven mergers contribute significantly to the LIGO measured rate, we restrict AGN disk parameters to lie below the lower diagonal line. See Ford et al. 2019.

3.9 Thermonuclear Supernovae

Thermonuclear supernovae have been empirically shown to be standardizable candles where the peak luminosity is a function of the broadness of the lightcurve or its decay after peak [79, 80], allowing them to be used as reliable distances indicators to probe the accelerating expansion of the Universe [81, 82]. Recently, some tension has developed between the values of the Hubble constant derived from thermonuclear supernovae and other observations [83]. One possible solution to the disagreement in the data is that we have underestimated the errors in the empirical relationship between the light-curve evolution and its peak brightness. This relationship depends both on the progenitor (e.g. single- versus double-degenerate) and the nature of the explosion mechanism and multi-messenger observations can help constrain both. As different candles have different redshift ranges they probe, the ”Hubble tension” may suggest the need for revised cosmological models, and the resolution (or confirmation) of this open issue is thus of highest priority.

Theoretical models do not simply reproduce this peak luminosity/width of the peak relation (see Figure 6 [84, 2]. The light curves depend on several parameters that must be understood

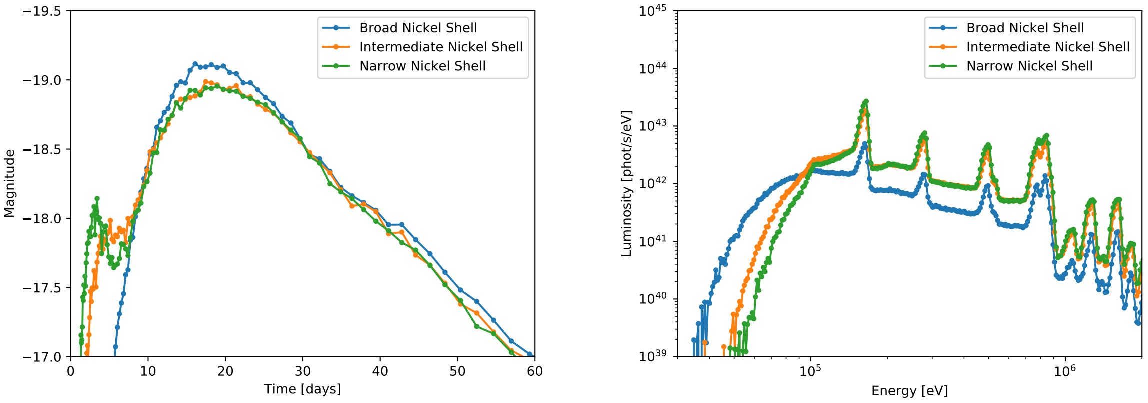

Figure 6: Bolometric light curve (left) and gamma-ray spectra (right) near peak gamma-ray emission for 3 different thermonuclear supernova models. In these models, the explosion energy and nickel production are the same, but the distribution of nickel is altered. Changes in the distribution can significantly alter the gamma-ray signal, ultimately affecting the peak brightness. To truly use thermonuclear supernovae as cosmological tools, we must understand the distribution of nickel production and how it might vary with redshift.

to explain the peak/width relation: the ^{56}Ni mass, the total ejected mass, the distribution of the ^{56}Ni in the ejected mass, the initial white dwarf radius, the opacity, and the explosion energy. Observations will help constrain these parameters to be understand the scatter in our ”standard” candle. As the number of transient observatories increases, more and more thermonuclear supernovae are discovered at the early rise, e.g. [85]. Combined with UV observations from Swift, e.g.[86], our understanding of the initial rise of the emission has increased dramatically, allowing astronomers to not only probe the nickel distribution but also the atomic physics [87]. $\gamma-$ray observations can also be used to probe the distribution of the nickel (see Figure 6). At later times, the shape and late-time decay of the light-curve probes the ^{56}Ni production. The spectral features in the supernovae are sensitive to the nature of the explosion mechanism and the progenitors behind thermonuclear supernovae and astronomers are actively comparing these spectra to increasingly detailed models of the supernova engine [88, 89, 90]. X-ray observations of supernova remnants [91] and studies of dust grains [92] can be used to measure the details of the nucleosynthetic yields, constraining the properties of and the distribution of elements produced in the engine.

The nature of the progenitor and the role of single- versus double-degenerate progenitors also remains a hotly-debated issue in our understanding of themonuclear supernovae. The distribution elements places some constraints on the progenitor, but there are more direct observations of progenitor. The early-time light curve can also be used to probe shock interactions with a possible white dwarf companion expected in some channels [93]. In a Galactic supernova, gravitational waves with LISA will be able to easily distinguish between the single- and double-degenerate scenarios. LISA will also study a population of white dwarf binaries, allowing scientists to validate population synthesis models so they might better predict the role of these different thermonuclear supernova progenitors.

As with core-collapse supernovae, taking advantage of these multi-messenger models requires analysis utilizing detailed multi-physics models of these events and multi-messenger goes hand-in-hand with applied, multi-physics, high-performance calculations of these events.

3.10 Fast Radio Bursts

Fast Radio Bursts (FRBs) are intense, millisecond-duration flashes of radio light that appear to be arising from other galaxies [94, 95, 96, 97], typically flashing only once but some fraction of FRBs appear to repeat [98]. As pulsed extragalactic radio sources, we can use observed properties like dispersion, scattering, and Faraday rotation effects to infer the density, magnetization, turbulent properties about the media between us and the source: including the ionized components of the circumgalactic medium, intergalactic medium, Milky Way and its halo. However, to use this information effectively we must first know the distance to the source, which comes from identifying a host galaxy via sub-arcsecond localization of an FRB.

So far the FRB phenomenon appears exclusively in the radio [95, 99], although there is still a vast discovery space; only recently (since 2017) have experiments begun that can precisely localize FRBs in real-time. It is both the localization and the real-time aspect that allow prompt follow-up of an unambiguous target. Because of this, there have been only a few concerted searches for multi-wavelength and multi-messenger events, all resulting in non-detections. This includes searches for multi-wavelength afterglow emission across the electromagnetic spectrum [100, 101], searching for coincident GW events with LIGO [102] and searching for neutrino events [103]. Compounding the issue is the fact that we still do not know what progenitor(s) or physical phenomenon gives rise to FRB emission, and therefore do not have specific expectations for multi-wavelength or gravitational-wave/neutrino emissions. However, if FRBs are detectable as multi-messenger or multi-wavelength phenomena, that data will provide critical constraints on the $\gtrsim$50 progenitor models that have been published for FRBs, giving us the most direct way to answer the simple, but fundamental question: "what makes FRBs?"

3.11 Neutrinos and Cosmic Rays

Electromagnetic tracers have been used for decades to study the GMF, but it's increasingly apparent that they cannot be understood without a better understanding of the propagation of Galactic cosmic rays, particularly the leptons that produce synchrotron emission in the radio bands and are difficult to study directly. Furthermore, to study the extragalactic sources of charged ultra-high energy cosmic rays likewise requires an understanding of the GMF that deflects them between source and detector. Conversely, a better understanding of UHECR sources enabled by combining electromagnetic, neutrino, and cosmic ray messengers [104] can help constrain the GMF. These fields are therefore inextricably linked and require cross-disciplinary efforts to study them [17].

Galactic magnetic fields play important but ill-constrained roles in many astrophysical domains, including the dynamics of the magnetized interstellar medium, star formation, galaxy structure and formation, interstellar turbulence, confusion with extragalactic backgrounds, etc. Enabling multimessenger studies that help to constrain the GMF will therefore have a widespread effect on a number of topics from the acceleration of the highest energy particles to the origin of the Universe itself.

3.12 Extreme Mass Ratio Inspirals (EMRIs)

In general terms, an extreme- or intermediate-mass ratio inspiral (EMRI or IMRI, respectively) is an event in which a stellar-mass object in a bound orbit around a massive black hole spirals into the black hole as the orbit decays by the emission of gravitational waves. The stellar-mass object in such a system acts as a test particle that probes the spacetime around the black hole and the gravitational waves are the signal that carries the information from the probe [105]. Although the gravitational wave signal is stronger if the test particle has a mass of order a few tens of $\mathrm{M}_{\odot}$, those events are expected to be quite rare. The most common events are those in which the test particle is a star (including white dwarfs and neutron stars). However, only the most dense stars can produce a signal that is in the frequency band detectable by LISA ($f_{\mathrm{GW}} \sim \mathrm{few} \times 10^{-4}$ – $\mathrm{few} \times 10^{-2}$ Hz). This is because typical main-sequence stars will get tidally disrupted before the can get close enough to the black hole to produce a strong enough signal; the gravitational wave frequency at the tidal disruption radius is of order $f_{GW}^{\mathrm{tid}} \sim 0.5(G\bar{\rho}_*)^{1/2}$, i.e. it depends only on the dynamical time of star and not the mass of the black hole. For example, main-sequence stars with masses $> 0.3\ \mathrm{M}_{\odot}$ have $\bar{\rho}_* < 10\ \mathrm{g\ cm}^{-3}$, hence $f_{GW}^{\mathrm{tid}} < 1.6$ mHz. Thus, the EMRIs that are likely to produce multi-messenger signatures are those that involve the inspiral and tidal disruption of either a low-mass, main-sequence star (an M star) or a white dwarf (the frequency corresponding to the tidal disruption of a neutron star is or order kHz). If the disruption occurs outside of the innermost stable circular orbit (ISCO), the circularization and accretion of the debris can produce an electromagnetic flare that follows the gravitational wave signal. This requirement sets an upper limit on the mass of the black hole that can be cause the disruption. For example a 0.5 $\mathrm{M}_{\odot}$ white dwarf can be disrupted outside of the ISCO of a $< 7 \times 10^4\ \mathrm{M}_{\odot}$ non-spinning black hole (or a $< 9 \times 10^5\ \mathrm{M}_{\odot}$ maximally-spinning black hole). Similarly, a 0.3 $\mathrm{M}_{\odot}$ M star can be disrupted outside of the ISCO of a $< 3 \times 10^6\ \mathrm{M}_{\odot}$ non-spinning black hole (or a $< 4 \times 10^7\ \mathrm{M}_{\odot}$ maximally-spinning black hole).

Consider now the fiducial case of a 0.5 $\mathrm{M}_{\odot}$ white dwarf that is captured into a bound orbit around a $10^4\ \mathrm{M}_{\odot}$ (non-spinning) black hole in a dwarf galaxy. The capture puts the white dwarf in an eccentric orbit with a pericenter distance of 10–15 R_{g} (where $R_{\mathrm{g}} \equiv GM_{\bullet}/c^2$ is the gravitational radius of a black hole of mass $M_{\bullet}$). The orbit decays by a combination of processes including gravitational radiation and tidal heating of the white dwarf [106, 107]. The orbital decay time is several years, and during that time the white dwarf executes a very large number of revolutions around the black hole. As a result, a gravitational wave observatory such as LISA would be able to detect such a system with a high signal-to-noise ratio out to distances of ~ 450 Mpc [108]. A few weeks before disruption, the white dwarf is deformed considerably by the tidal field of the black hole and begins to lose mass [109], which is accreted by the black hole leading to X-ray emission with a luminosity of up to $10^{43}\ \mathrm{erg\ s}^{-1}$. The eventual disruption occurs when the gravitational wave frequency is of order 100 mHz and the system may have become undetectable by LISA. Nonetheless, the gravitational wave signal accumulated over the course of the orbital decay will have allowed the determination of the fundamental parameters of the system and will have yielded the time of disruption and an approximate location in the sky. Therefore, electromagnetic observatories can catch the flare produced by the accretion of the post-disruption debris.

The volumetric rates of tidal disruption events involving white dwarfs in bound orbits around black holes is $\sim 100\ \mathrm{yr}^{-1}\ \mathrm{Gpc}^{-3}$ in dwarf galaxies and $\sim 1\ \mathrm{yr}^{-1}\ \mathrm{Gpc}^{-3}$ in globular clusters (these are based on the optimistic assumption that *all* dwarf galaxies and globular clusters host massive black holes and are derived by updating the calculations of [106, 107]). Therefore, about a dozen events per year may be detected first by LISA via their gravitational wave signature and then LSST via their electromagnetic flares. Building a sizable sample of such events is quite beneficial because they will allow us to test a number of diverse astrophysical models. They will give us the probability that globular clusters and dwarf galaxies harbor intermediate mass black holes and they will discriminate between models for the dynamics of stars in their vicinity. They will also allow us to study accretion physics, especially super-Eddington accretion flows and their transition to sub-Eddington flows since the time scales involved are reasonably short.

Additional details can be found in [12].

4 Communications and Interactions across MMA observatories

The backbone of time domain, multi-messenger astronomy is the Gamma-ray Coordinates Network (GCN/TAN). It reports the triggers from the gamma-ray observatories, the GW network, and the MeV and high energy neutrino facilities, as well as many others, and the follow-up efforts of instrumentation across the electromagnetic spectrum. This system is not suitable for the upcoming optical transient era, and many separate groups are working on new technology platforms that attempt to resolve emerging issues. However, these groups are working separately with distinct, often wavelength or messenger specific focus. This could result in an undesirable bifurcation of the time domain community. Updates to GCN should include basic modernization of the system such as user accounts, minimization of reporting delay, user contributed alert streams, and the removal of single point failures (e.g. host the system on the cloud). Investment in this system will significantly reduce the operational overhead for all time-domain facilities, and avoid wasteful effort duplication

Prompt localization of Gamma-ray Bursts is a critical need for many different multi-messenger science cases, including GW counterparts and the hunt for kilonovae. Aside from *Swift*/Burst Alert Telescope, no other single GRB detector can regularly localize GRBs to the precision necessary for rapid follow-up. To wit, the Inter-Planetary Network (IPN) has used the time-delay of GRBs detected between spacecraft in low-Earth orbit and in the inner Solar System to provide significantly enhanced localizations. This system requires prompt data down-link and communication between several NASA missions, including *Fermi*/GBM, *Swift*/BAT, Mars Odyssey, and multiple non-NASA missions. However, these IPN localizations are not currently produced at low-enough latency to enable prompt follow-up activities. Moreover, the IPN localizations are not reported in a standardized manner that enables automated followup by robotic telescopes. We recommend this be remedied, and a standard hub for joint GRB localizations be established. This could easily be folded into a GCN enhancement/replacement.

The case of GRB 170817A has shown that gamma-ray counterparts to nearby gravitational wave events can be severely under-luminous compared to their cosmological brethren. GRB 170817A would not have been detectable in Fermi/GBM or *Swift*/BAT, the most sensitive active instruments, beyond $\sim$75-90 Mpc. This is significantly further than the on-board trigger capabilities because of sensitive ground searches of GBM and BAT data. Without a new, extremely high effective area detector a la BATSE, detecting these weak gamma-ray signals out to the current (200 Mpc) and future GW detector's horizon distance will be impossible. The advanced gravitational wave network has benefited enormously from performing joint searches across the entire detector network. A similar approach between existing NASA GRB missions would significantly enhance the sensitivity and allow the detection of weak gamma-ray burst counterparts to a much larger fraction of gravitational wave detected neutron star mergers. We recommend that such a project be enabled, involving communication and collaboration between current (*Fermi*/GBM, *Swift*/BAT) and future (BurstCube) missions to enable a multi-spacecraft coherent Gamma-Ray Burst network.

The near future will also see "early warning" alerts of Compact Binary Coalescence (CBC) signals of merging neutron stars or black holes, up to 60 seconds before the merger [110]. Wide field-of-view rapid response missions with real-time commanding are necessary to take advantage of the amazing science that would be derived from EM observations of the source of GW simultaneous with the merger. Requirements for this science include large field-of-view, Gamma-ray or X-ray or UV coverage (where prompt EM emission is expected) and 100% real-time commanding (eg onboard the ISS like ISS-TAO or with upgrades to TDRSS to allow real-time forward service in conjunction with a fast slewing spacecraft). Among the current suite of NASA missions, only *Swift*/BAT has the necessary capabilities to enable this science, but is limited by contact scheduling latency in the Tracking and Data Relay Satellite System (TDRSS) network. Investment should be made in enabling real-time on-demand commanding capabilities for NASA missions in low-Earth orbit via TDRSS, the same way we currently benefit from real-time data downlink in response to GRBs.

Over the longer term, LISA will become an important GW observatory, yet the data produced by LISA will be quite unlike that produced by LIGO. The sheer volume and complexity of the raw data from LISA will be exceptionally difficult to interpret for community outsiders. Though LISA will produce catalogs, and make raw data publicly available on appropriate timescales, we believe that availability without support will be almost meaningless. The global fit to the LISA data that will produce the catalog depends on many astrophysical and noise parameters–different parameter choices for particular processes may add or subtract sources from a catalog produced from the very same raw data. To optimally extract science from LISA's rich GW dataset, we believe a data center, especially one geared to educating and supporting EM astronomers in their exploration of the data, will be necessary. We further believe that NASA's heritage of providing similar support means that NASA should lead such efforts.

A new rapid-response observatory like *Swift* is required to enable a large fraction of the science described in this report. *Swift* has now successfully operated for 15 years, and it is prudent to prepare for an even more powerful replacement in this decade. Loosing *Swift*'s capabilities without a successor in place would leave a critical hole in our space-based rapid response capabilities just as many of these science areas are maturing. We recommend the rapid development of ToO driven missions with IR-UV-X-ray capabilities that can adequately support multi-messenger science goals during the upcoming discovery-rich MMA era.

Lastly, all scientists should be able to contribute to existing open software and to release new software through standard methods (e.g. GitHub). Current rules governing the release of software developed by civil servants and government contractors are not suited to the needs of scientists. Enabling these capabilities will minimize duplicated effort, allow for peer review of code used in scientific publications, and could enable wider contribution from the community to the portfolio of standard data analysis tools. A report by the National Academies of Sciences addressing open-source software was released in 2018 NAP25217.

Effective and responsible use of observatory time and resources for expensive gravitational wave follow-up campaigns, could be further enhanced. Thorough exploitation of all of the science available from multi-messenger detections requires a degree of coordination and information sharing across observatories that has not previously been the norm. This is due to the following:

1. Certain types of events detected via gravitational waves, which are very resource intensive to follow, can have inherently more scientific yield than others. Sharing adequate classification information in real-time is thus extremely helpful for follow-up teams trying to efficiently allocate telescope resources.
2. Localization regions of GRBs and GWs are often very large and thus require coordination and information sharing between follow-up groups to search efficiently and effectively.
3. Due to the differing, and often limited, instrumental horizons as well as the differing intrinsic luminosities of events across messengers, the expected yield of joint sub-threshold searches is extremely promising. These types of searches require sharing of data that are not typically made available.

The first problem stems from the fact that, as gravitational wave detection of compact binary coalescences (particuarly mergers hosting at least one neutron star) becomes more common, the rate will quickly (and may have already begun to) outstrip the community's available followup resources. As such, as much information as is possible to make rapid decisions on resource allocation is required. One such piece of information is the 'chirp-mass', measured accurately by the gravitational wave observatories, and available shortly after detection. As demonstrated by many groups, early access to estimation of this parameter can dramatically help to optimize the scientific gain of follow-up observations, e.g. for selecting events that provide the maximum leverage to constrain the neutron star equation-of-state [111], among other parameters. We recommend that all facilities (especially GW detectors) which trigger such massive resource outlays in follow-up of their events, be encouraged to share the information necessary to perform the most impactful science possible and to act as responsible stewards of limited observing resources.

Platforms like the Gravitational Wave Treasure Map [1] [112] attempt to address the second issue by providing a single, machine and API accessible, database for real-time information sharing . Already the NASA missions *Swift* and *Fermi* (along with many observatories on the ground) are participating in this system and sharing pertinent and useful information with the rest of the multi-messenger community in real-time, with the goal of making the entire process more efficient and elevating the chances of successfully finding an electromagnetic counterpart to a gravitational wave source. Platforms like this are maximally effective at enabling more science, decreasing redundant observations, and enabling the efficient use of valuable resources, the more instruments and teams participate. We recommend that NASA promote and recommend participation in systems like this for groups/missions it funds that participate in multi-messenger (and particularly GW) followup observations.

The third issue, fully exploiting the information buried in sub-threshold event streams, is being addressed by systems like the Astrophysical Multimessenger Observatory Network [113, AMON] which combines sub-threshold streams of events from many NASA missions, and ground-based high-energy facilities, looking for temporal and spatial coincidences in real-time. We recommend that NASA promote and recommend participation in such a system, to maximally ex-

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[1] http://treasuremap.space

ploit the data being recorded by (especially) wide-field monitors in space. Such a capability could be folded into a future GCN enhancement (like the NASA funded Time-domain Astronomy Coordination HUB, TACH).

5 Conclusions

Multimessenger astrophysics covers a wide range of exciting topics, dealing with a broad array of observational techniques, as well as a diverse set of astrophysical sources. MMA will be a valuable tool with growing importance as we develop new ways of combining electromagnetic radiation, gravitational wave radiation, and particle astrophysics observations. In the coming decade and beyond NASA's space observatories will play a pivotal role. The Multimessenger Astrophysics Science Analysis Group consists of scientists from the broad astrophysics community that span both the Physics of the Cosmos and Cosmic Origins themes within NASA's Astrophysics Division's organization. We have evaluated a set of potential scientific benefits of multimessenger observations made possible by NASA observatories, working in conjunction with each other or with other ground- and space-based instruments.

Table 1 summarizes the set of astrophysical sources that the MMA SAG considered and the associated messengers that could potentially provide insight into each source. While the intent of this activity was to cast as wide a net as possible in terms of MMA astrophysics topics, we recognize that some important subjects may have been omitted from this final report due to time limitations. Details of the new insights that could be enabled through multimessenger observations are provided in the subsections of Section 3. Section 4 discusses programmatic priorities related to communication and interaction between various observatories that could increase the science return of of multimessenger observations. From these analyses, we drew the following overarching conclusions pertaining to the future of multimessenger astrophysics. We wished to point out these conclusions in particular, because they pertain to and impact multiple science goals discussed in the sub-sections above.

- It is clear that to maximize multimessenger science, a wide EM and GW wavelength coverage is needed as well as neutrino detectors. While this may seem like an overly broad need, there are a few measurements in particular that are either currently lacking or exist now but will go offline in the near future. One critical tool is an observatory with a fast response that has a focus on time-domain astronomy. The Neil Gehrels Swift Observatory is a good example of this type of observatory, but Swift is now quite old (launched in 2004), and a replacement would needed to continues these types of observations. Also, the Fermi Gamma-ray Space Telescope provides vital MMA measurements, including with its GRB monitor. Launched in 2008, the end-of-life of this observatory is not too far on the horizon. A replacement wide field GRB monitor should be considered in the near term. Both of these observations, along with X-Ray, UV and low-frequency gravitational waves can only be made from space. They therefore should remain a priority of NASA's Astrophysics Division.

- Multimessenger astrophysics requires NASA and NSF to work more collaboratively then ever, since both ground- and space-based measurements are often needed. Proposing for time on both ground and space observatories can be a challenge. There are a number of reasons for this. Mismatching time frames of relevant NASA and NSF solicitations can be a roadblock for making simultaneous space and ground observations. More joint time proposal opportunities would be very beneficial, since many proposals to one of the agencies that includes observations from the other are considered 2nd or 3rd tier science goals because they require multiple instruments. The separation of NSF and NASA solicitations for observing time can also lead to a bifurcation of the astrophysics community. This has a detrimental effect, since it hinders interactions between certain sub-communities. It is also important that disparate catalogs and database systems (e.g. GCN) can work together to facilitate analyses requiring multiple observations. Finally, there is MMA science that can be performed using archived data. They do not require observing time, but personnel and computing time instead. More opportunities for support of these resources without the need of observing time are desirable as well.

- Many of the multi-messenger science cases in space require not only instruments sensitive in particular wavelengths and with sufficient sensitivities, but also operational capabilities such as extremely rapid commanding to enable ultra rapid re-pointing and enhanced data taking modes. Such capabilties require both communications and commanding infrastructure, as well as flexible scheduling of the ground segment, to enable them. It is important that enhancement be made to the autonomous and real-time capabilities of the TDRSS network, and adequate attention be paid to the development of flexible and autonomous observation scheduling software for mission ground segments, to be able to maximally utilize next generation space based observatories.
- Multi-messenger astronomy is now reaching a fidelity where astrophysicists increasingly need to leverage the progress in computer science and a wide range of physics. These capabilities include fluid dynamics and turbulence, plasma physics, atomic physics, numerical general relativity, nuclear and particle physics. To maximize the science learned from multi-messenger astronomy, it is important for these different disciplines to work together, sharing expertise.

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