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The Dynamic Universe: realizing the science potential of Time Domain and Multi-Messenger Astrophysics (TDAMM)

The TDAMM Workshop Science Organizing Committee

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1. EXECUTIVE SUMMARY

The 2020 Astrophysics Decadal recommended Time Domain and Multi-Messenger Astrophysics (TDAMM) as the top priority of the sustaining activities of the astrophysics portfolio. In order to highlight the most important science themes, NASA held a TDAMM workshop, convening scientists from across the US and the world. The TDAMM workshop was held in a hybrid mode on August 22-24, 2022, in Annapolis, MD, with ∼300 participants in total. This white paper represents the main deliverable of the workshop to the NASA Astrophysics Division. This paper summarizes the workshop findings and messages. Four main broad science themes are addressed: Non-terminal Sources, Jetted Transients, Merger-driven Transients, and Explosive Transients. In turn, each theme is broken down into sub-themes focusing on the specific nature of the event, e.g., White Dwarf systems, Neutron Star/Black Hole systems, etc. The interdisciplinary nature of TDAMM is stressed. TDAMM science has major implications for a variety of disciplines beyond astrophysics - cosmology, fundamental physics, nuclear physics, and more. This makes this science of central importance for NASA and the entire community, as recognized by the 2020 Decadal.

While being mostly focused on science questions, the workshop included a special session on existing and needed TDAMM infrastructure on the last day of the event. A panel of invited speakers representing ground- and space-based capabilities discussed ongoing projects (alerts, space communication, ground-based coordination, archives, and more) and answered the many questions from the audience. The main topics of discussion, and related findings, are also summarized here.

The main take-away messages of the workshop are: 1. TDAMM science impacts significantly many other fields of astrophysics and physics, from cosmology to fundamental physics to nuclear and particle physics, and more. This is the very reason the Decadal prioritized multi-messenger and time domain at the top of the Sustaining Portfolio, ahead of the Probes; 2. TDAMM inspires and awes the public the world over, raising the US profile and scientific and technological competence. NASA should take advantage of the charisma of TDAMM science and its appeal to the public to solicit more funding from Congress and other decision makers; 3. While NASA is leading or is involved in developing missions with implications for TDAMM (e.g., Compton Spectrometer and Imager (COSI), Ultraviolet Transient Astronomy Satellite (ULTRASAT), Survey and Time-domain Astrophysical Research Explorer (STAR-X), Ultraviolet Explorer (UVEX), LargE Area burst Polarimeter [LEAP]), these are by themselves insufficient to meet the challenges ahead. In particular, wide-field, fast response, and arcmin-scale position determination X-ray and gamma-ray monitors are needed to replace the aging *Fermi* and *Swift* observatories. Indeed, the Decadal advocated for a ∼$800M augmentation to the Explorer program specifically for TDAMM; 4. These missions should be started NOW, in order to overlap with the new ground- and space-based capabilities (Rubin, Survey and Time-domain Astrophysical Research Explorer (SKA), next-generation gravitational wave (GW) and neutrino detectors; James Webb Space Telescope (JWST), Roman, ULTRASAT, etc.); 5. Robust and prompt investments in infrastructure enabling TDAMM science beyond the currently funded alerts (TDAMM General Observer Facility [GOF]), joint proposing opportunities for space and ground, space communications, etc.) as well as precursor science (e.g., theory, computing, simulations) are also needed urgently if we want to take maximum advantage of the rich trove of multi-messenger data.

2. INTRODUCTION

The 2020 Astrophysics Decadal Survey recommended New Messengers and New Physics as the top priority theme of the Sustaining Activities portfolio. In their words, "New Messengers and New Physics will exploit the new observational tools of gravitational waves and particles, along with temporal monitoring of the sky across the electromagnetic spectrum and wide-area surveys from the ultraviolet and visible to microwave and radio, to probe some of the most energetic processes in the universe. . . " This finding builds on several decades of exploration of the cosmos in the electromagnetic and cosmic-ray spectra, with the recent addition of gravitational waves in the Hz to kHz frequency band. The Decadal also recommended an augmentation to the Explorers portfolio of ∼$800M specifically for Multi-Messenger and Time Domain Astrophysics missions, as well as leveraging international partnerships for future observatories and instruments. The Decadal summarizes a list of required instrumental capabilities to conduct TDAMM science in Table B.2.[1]

To implement New Messengers and New Physics, NASA plans to start a program of investments in TDAMM – Time Domain and Multi-Messenger Astrophysics. As a first step, NASA sponsored a community TDAMM workshop to identify the most pressing science questions and the future capabilities needed to address them. The first TDAMM workshop was held in Annapolis, MD, on August 22-24, 2022, in hybrid mode (in-person and virtual attendance) and had as a final goal, the delivery of a written report to NASA Headquarters (HQ) with the major findings. While almost entirely focused on the science, a panel session devoted to infrastructure was also held on the last day of the workshop, which highlighted the need for the ground- and space-based communities to coordinate and cooperate.

This paper is the summary of the science findings of the TDAMM workshop. The goal of the workshop was to highlight important science questions, not to prioritize the science (which is the job of the Astrophysics Decadal). As such, this paper focuses on the topics presented and discussed at the workshop, with no pretense of being complete or all-comprehensive, as there are other topics pertinent to Time Domain that were not addressed (e.g., stellar flares, transiting exoplanets). Perhaps these topics could be discussed in a separate future workshop.

The paper is structured in two complementary approaches: first, we report the findings of the parallel sessions organized by the classes of phenomena associated with white dwarfs, neutron stars and black holes, and supermassive black holes. The interdisciplinary nature of TDAMM science, with

[1] Table B.2 "Required capabilities," Appendix B, "Report of the Panel on Compact Objects and Energetic Phenomena," of the Astro2020 Decadal Report, p. 244.

major impact on several other fields of discovery, is highlighted; next, we discuss the infrastructure (missions and much more) that is urgently needed to realize the science. It is our hope that this paper will be useful to NASA HQ and the wide community to start informing decisions about how to address the science needs of the next 10 years in Time Domain and Multi-Messenger Astrophysics.

It is worth mentioning again that Time Domain Astrophysics is a very broad topic that encompasses many different disciplines, from stellar flares to transient sources to exoplanets. While these are all key parts of the dynamic universe, the workshop focused on a more operational interpretation of Time Domain at the intersection with Multi-Messenger Astrophysics, in keeping with the Decadal statement above. A major emphasis was placed on variable phenomena that involve, or have the potential to involve, all messengers including gravitational waves, neutrinos, and cosmic rays. We were forced to make choices by virtue of the limited resources available to us, and the need to deliver a well-focused, actionable report. While somewhat restrictive, this workshop is only the first step of what we hope will be a robust community involvement in the next few years in TDAMM.

Indeed, the potential of TDAMM rests on the ability to engage all stakeholders from all walks of science and experiential background. We need all available brainpower to realize the transformative science prioritized by the 2020 Decadal; in turn, this requires transparency, an open-minded attitude, and access to the data and the analysis/interpretation tools. TDAMM truly incorporates the NASA core value of Inclusion, because only by leveraging all available expertise and experience can we fulfill the science of New Messengers and New Physics to its maximum.

3. SCIENCE FINDINGS

3.1. *White Dwarfs*

3.1.1. *Type Ia SNe (including WD-WD mergers)*

Type Ia supernovae (SNe Ia) – thermonuclear explosions of a carbon oxygen (CO) white dwarf in a binary system – play a key role in multiple areas of modern astrophysics. These systems are responsible for the formation and dispersion of most intermediate mass elements; they play an important role in galaxy evolution (through feedback) and cosmic ray acceleration; and they serve as uniquely powerful distance indicators through the well-known relationship between their light curve width and peak luminosity. Despite this broad astrophysical importance, a number of key open questions about these objects remain, including:

- What are the progenitor channel(s) that produce the diversity of phenomena associated with exploding white dwarfs (e.g., "normal" SNe Ia that obey the Phillips relation, Ca-rich events, Type Iax SNe, ...)?

- What are the nucleosynthetic outputs of these white dwarf explosions, and how is this material distributed throughout the ejecta?

- What are the electromagnetic signatures of the tidal disruption of a white dwarf by an intermediate mass black hole, white dwarf mergers, and extreme mass ratio inspirals (EMRIs)?

Addressing these questions, including the full realization of the dark energy goals of missions like Rubin and Roman, requires a broad range of capabilities. These include new and improved *observational* resources:

- Minimizing the dark energy figure of merit contribution from SNe Ia will require low-z and mid-z samples to anchor the Hubble diagram, ultraviolet (UV) spectra of nearby events to further characterize observed diversity, coordinated spectroscopic follow-up of SNe and their host galaxies, and improved calibration efforts.

- To better constrain the progenitor system(s) of SNe Ia, prompt, high-cadence, multi-color (in particular UV) observations are required in the hours immediately following explosion. Late-time nebular spectroscopy at optical and infrared (IR) wavelengths will help pin down the nucleosynthetic yield from these explosions, and thus also constrain progenitor models and explosion mechanisms. And sensitive MeV imaging / spectroscopy can directly measure the Ni^{56} generated in the thermonuclear explosions.

- Distinguishing between competing models for the faintest populations of white dwarf explosions (e.g., SNe Iax, Ca-rich transients) also require high-cadence multi-band (in particular UV) observations in the hours immediately following explosion, detailed host galaxy studies at high angular resolution in the optical and near-IR (NIR) (stellar populations, host environment, etc.), as well as late-time nebular spectroscopy in the optical/IR.

While necessary, new observational capabilities are not sufficient to fully address the above questions – progress is also required in theory/simulation and community coordination. Specifically we identify the following areas:

- Additional support for theoretical investigations to improve pre/post-dictions for white dwarf explosions. This includes additional development of models for different progenitor systems and distinct explosion mechanisms, both at early and late times (where the discriminatory power is the largest).

- Infrastructure for public alerts and coordinated follow-up is critical to obtain observations on the requisite time scales and frequencies for model discrimination.

- Software tools to optimize planned time-domain surveys for ancillary science (i.e., maximizing the discovery space for the Roman High-Latitude Time-Domain Survey for source classes such as tidal disruption events and superluminous supernovae).

- Coordination of field selection (e.g., deep drilling fields from Rubin overlapping with Roman/Euclid transient surveys) is important for combined optical and NIR measurements.

3.1.2. *Detached Binary WD LISA sources*

Detached binaries containing white dwarfs are expected to be the largest source, by number, for the Laser Interferometer Space Antenna (LISA). However, predictions from population synthesis simulations and observations of the local ($D < 20\,\mathrm{pc}$) space density of double-white-dwarf binaries can differ by at least a factor of 10. These discrepancies highlight the need to both increase the size of the observed white-dwarf binary population as well as work to bring theory and observation closer to agreement in the years preceding LISA's launch. Furthermore, in the case of detached close binaries which are not expected to change their electromagnetic signatures appreciably on decade-long timescales, multi-messenger observations need not be taken concurrently. Thus, investment in the 2020s, for both theory and observation, will pave the way to enabling the best use of future

TDAMM capabilities in the 2030s which can inform the formation and evolution of white-dwarf binaries and their progenitors.

Recent surveys, like the Zwicky Transient Facility (ZTF) have discovered more than a dozen close double-white-dwarf binaries. But these discoveries are often plagued by the need to search deep in the Galactic disk, where most sources reside but crowding is a problem, as well as the need for high-cadence follow-up to confirm the nature of the source. Surveys which cover the electromagnetic spectrum, search in the Galactic disk, and optimize cadences at mHz frequencies are needed to enable the multi-messenger nature of future LISA sources. Indeed, the vast majority of LISA sources will not be characterizable with gravitational waves alone since most will not have observable orbital evolution, and thus will lack mass and distance measurements. In these cases, electromagnetic information, like the sky position or inclination of a white-dwarf binary, can break measurement degeneracies and aid gravitational-wave parameter estimation by up to a factor of ~ 40.

3.1.3. *Novae and accreting WD LISA sources*

When a binary star transfers mass to a white dwarf companion, the accumulation of material can eventually give rise to a thermonuclear runaway in the accreted shell causing a luminous outburst observed as a classical or symbiotic *nova*. Despite being studied by astronomers for over a century, these events still hold mysteries. As one example, the unexpected discovery by the *Fermi* Large Area Telescope (LAT) of powerful gamma-ray emissions from novae reveal shocks to play a bigger role in these explosions than previously believed. Despite observational advances, many questions remain, including the nature of the shocks and how they relate to the mass-ejection mechanisms of the envelope. To continue the progress in this field will require: (1) GeV-TeV gamma-ray monitoring capabilities with high sensitivity to enable time-resolved light curves and spectra; (2) high-cadence photometry and spectroscopy of Galactic novae to correlate with the shock-powered emission and better measure the mass-ejection history of the white dwarf; (3) sensitivity to lower energy ∼GeV–TeV neutrinos to confirm a hadronic origin for the gamma-ray emission; (4) coordinated near-simultaneous multi-wavelength observations to understand the role of shocks, particularly at hard X-rays which are less attenuated than softer X-rays; (5) infrared spectroscopy to understand the role of dust production in novae and its connection (if any) to shocks.

A small fraction of nova-related phenomena include non-standard novae: either helium novae (where helium is accumulated, leading to thermonuclear runaway only after accumulating significantly more material, as in V445 Pup) or on the opposite side of the spectrum, the discovery of very short eruptions, that are interpreted as thermonuclear runaway in a locally accumulated much smaller amount of mass. The requirements for these rare objects are similar to the one for novae and accreting white dwarfs.

Before the material accumulates on the white dwarf, it resides in an *accretion disk*, in which angular momentum is redistributed and transferred back to the orbit such that the transferred material can lose angular momentum needed to reach the white dwarf. These accretion disks play an important role in the liberation of accretion energy and are poorly understood in terms of viscosity and geometry. Disk instabilities, likely caused by temperature and ionisation changes that cause viscosity changes, show up as transient outbursts. In addition, smaller scale variability at many different time scales probes the physics of the accretion discs. Finally, accretion onto white dwarfs can lead to ejection of material in jets (as is the case for neutron stars and black holes) and even behavior as "pulsar" as in the system AR Sco. Again, different binary systems can lead to accretion of different composition, allowing better constraining of the accretion physics that should depend on composition. Future progress on understanding accretion discs requires (1) wide field surveys (in optical/IR and UV) to find the outbursts and coordinated including (2) real time detection of transients and (3) *fast* multi-wavelength and multi-messenger follow-up including UV (which is not/hardly available); (4) long cadence and high-precision photometry to unravel the complex variability. The option for polarimetry on (new) instruments should be considered.

3.1.4. *Exotica (e.g. AIC, WD-NS/BH mergers)*

Finally, there are several theoretically expected transient/multi-messenger phenomena related to white dwarfs that have not been (unambiguously) identified, but should give rise to observational signatures that can be found with future wide-field surveys. These include accretion-induced collapse of white dwarfs into neutron stars and mergers of white dwarfs and neutron stars/black holes. In order to optimally prepare for these identifications, what is required is (1) detection, alert release and rapid follow-up capabilities ranging from accurate photometry and spectroscopy from UV to (mid)IR wavelengths as well as coordination and (offline) matching with (space) GW detectors and particle detectors.

3.2. *Neutron Stars and Black Holes*

3.2.1. *X-ray Binaries*

X-ray binaries cover several key areas of multi-wavelength and multi-messenger astrophysics. High mass X-ray binaries and stripped star binaries are the progenitors for neutron star-neutron star (NS-NS) or neutron star-black hole (NS-BH) mergers producing gravitational waves. BHs in X-ray binaries appear to be a different population than those detected in BH-BH mergers, with the X-ray binaries having lower masses and higher spins. Understanding X-ray binary populations is key to understanding the BHs detected by Laser Interferometer Gravitational-Wave Observatory (LIGO) and Virgo. X-ray binaries contain progenitors to super nova explosions and can tell us about the mass, kick, and spin in the supernova process. Pulsars, some of which are in X-ray binaries, are potential sources of continuous gravitational waves. BHs in X-ray binaries appear to behave very similarly to supermassive BHs in Active Galactic Nuclei (AGN), but on much shorter timescales, making the X-ray binaries much more accessible for study.

Key questions addressed by the study of BHs in X-ray binaries include the production and composition of jets and the mass and spin distributions of NS and BH systems, specifically:

- Why do some compact objects eject material in nearly light speed jets, and what is this material made of?
- What powers the diversity of explosive phenomena across the electromagnetic spectrum?
- What are the mass distributions of neutron stars and stellar mass black holes?

Key capabilities needed to understand stellar mass BHs in X-ray binaries include wide-field X-ray monitoring, fast-follow-up, high-cadence, high-throughput, large effective area X-ray observations to measure BH mass, spin, and disk corona geometry, coordinated IR and radio observations with fast photometry and high time resolution to measure disk-corona-jet causal connections, coordination with neutrino and TeV gamma-ray facilities to measure particle content of the jet. Neutrinos have been associated with AGN, could BHs in X-ray binaries produce them as well? To understand X-ray binary demographics, cadenced, sensitive X-ray surveys of the galactic plane are needed to distinguish NS/BHs from cataclysmic variables (CVs), coordination with next generation neutrino observatories, and coordination with LISA to aid in identifying continuous gravitational wave sources. High cadence UV monitoring with moderate spectral resolution and high-sensitivity, high-resolution X-ray imaging are key to detecting stripped stars.

Community needs, across all wavelengths and messengers, key to addressing this and broader science, include precise absolute timing to enable correlation of rapid behaviors like BH reverberation lags, coincident events, and jet-disk connections, better funding for community coordination/more joint programs for strictly simultaneous multi-wavelength observations with both space- and ground-based observatories, funding for workhorse instruments, both in space and on the ground, and better funding for community software tools applicable to multiple missions for data analysis including modeling such as population synthesis.

3.2.2. *NS-NS Mergers and NS-BH mergers*

Neutron star binary mergers are exemplary multi-messenger sources: they are both strong GW emitters, detectable by high-frequency GW detectors LIGO, Virgo and Kamioka Gravitational Wave Detector (KAGRA), and emit radiation across the entire electromagnetic spectrum and potentially a whole host of high-energy particles. Observations of their mergers allow for critical insights into nuclear physics, the production of heavy elements in the universe, cosmology, high-energy astrophysics as well as allowing for unique tests of General Relativity. The poster child for such events remains the binary neutron star (i.e., NS-NS) merger, dubbed “GW170817”, which was observed on the 17th August 2017 in gravitational waves, and the two associated electromagnetic counterparts, the gamma-ray burst GRB 170817A and the kilonova AT2017gfo, observed subsequently in every part of the electromagnetic spectrum. This allowed for the first time and to date only host galaxy identification for a GW merger.

However, despite the unprecedented astronomical campaign focused on this event, central questions remain and range from: (1) where and how are jets launched? is a black hole remnant necessary to launch a relativistic jet? what is the origin of the delay observed between gravitational waves and high-energy gamma rays?; (2) is the electromagnetic (EM) emission of GW170817 typical? what are the EM counterparts of neutron star-black hole mergers? how do the electromagnetic counterparts relate to the original progenitors and remnants?; (3) are NS-NS and NS-BH mergers the only sites of astrophysical r-process heavy elements, and if not, what are their contributions in the cosmos?; (4) what is the nature of the remnants of NS-NS mergers? what is the origin of the very early (<several hours) bright blue emission associated with AT2017gfo?; (5) are other high-energy particles detectable in coincidence with NS-NS and NS-BH mergers?

Several facilities and infrastructures were identified to be key to make progress in this exciting new observationally-driven field, in particular in light of upgraded GW detectors coming online next year and through this decade, including new facilities such as LIGO India. Within 10 years, while the increase in the number of gravitational wave detectors in the network will improve the sky-localization capability facilitating the search for electromagnetic counterparts, the greater distances accessible through LIGO, Virgo, and KAGRA detector upgrades will require the use of more sensitive electromagnetic observatories to detect increasingly fainter counterparts. The expected number of multi-messenger detections in the 2020s is on the order of 10(s) of GW+EM counterparts, potentially increasing to the order of 100(s) in the 2030s. This estimate is not precise because it will depend on the expected increase in sensitivity of LIGO, Virgo, and KAGRA, which is currently being evaluated within each collaboration.

In order to obtain a full astrophysical picture of these mergers, multi-wavelength observations are critical. In particular, the main requirements at all electromagnetic wavelengths are sensitivity to detect faint counterparts, wide-field instruments to cover relatively large sky localizations, and rapid response to detect prompt/early emission. While large field of view optical/infrared telescopes are needed to localize the gravitational-wave source detecting the kilonova emission, UV imaging, UV spectroscopy, and prompt X-ray observations are of primary importance to break emission-model degeneracy. Going to larger redshifts, high-energy missions capable of localizing at the arcsec-arcmin level become more and more essential to detect a GRB counterpart and drive follow-up observations to completely characterize the source. For this purpose, spectroscopy, radio sensitive (Very Large Array (VLA)/next generation (ng)VLA) and X-ray (Chandra type) telescopes for late follow-up are indispensable. To probe the geometry of the emitting region, optical and gamma-ray polarimetry are promising.

The joint detection of gravitational-wave, electromagnetic and high-energy neutrino emission represents one of the next major discoveries. This will be made more probable with the observations of IceCube-Gen2-like neutrino detectors operating in synergy with the gravitational-wave detectors.

Facilities priorities for this decade 2020s were identified to be (1) keep current gamma-ray missions (*Swift*, *Fermi*) operating and (2) develop new wide field of view missions in UV and X-ray.

3.2.3. *Gamma-ray Bursts (including orphans, off-axis, etc.)*

Gamma-ray bursts (GRBs) are the most relativistic sources known in the universe, with initial Lorentz factors $\Gamma \gtrsim 100$. The sources are classified in two categories based on the duration of prompt gamma-ray emission: "short" GRBs exhibit durations $\lesssim 2\,\mathrm{s}$, while "long" GRBs have correspondingly longer time scales. The prompt gamma-ray emission, generally attributed to processes within the collimated, ultra-relativistic outflow, is followed subsequently by a broadband afterglow, caused by electrons in the circumburst medium accelerated by the outgoing shock wave. Long GRBs are known to result from the core-collapse of a massive star, while the detection of the short-duration GRB 170817A following GW 170817 indicates at least some short GRBs are powered by binary neutron star mergers.

Currently the field is dominated by NASA's two workhorse GRB missions: *Swift* and *Fermi*. *Swift* provides exquisite (typically $\sim$ arcsecond) localizations and X-ray/UV afterglow light curves for a large population of events each year, enabling follow-up across the electromagnetic spectrum from a large community of observers. *Fermi* complements *Swift* by providing wider area coverage, exquisite temporal resolution, and a much broader bandpass (including extension up to GeV energies) for precise characterization of prompt emission spectra.

Both missions, however, are well past their primary phase: *Swift* was launched in 2004, and *Fermi* in 2008. **As a result, the GRB (and by extension, multi-messenger) community is deeply reliant on two missions that are unlikely to survive until suitable replacements are in place.** Workshop attendees strongly echoed the sentiments expressed in the 2020 Decadal that NASA should continue to operate these missions as long as possible, and move with appropriate haste to develop and launch suitable replacements. In the GRB field, this means wide-area, broadband coverage **and** precise localizations.

In terms of future scientific potential, we divide these into three categories. First, due to the association between binary neutron star mergers and short GRBs, these sources serve as exquisite multi-messenger laboratories. The scientific opportunities in this area are discussed extensively in §3.2.2 – here we briefly repeat that for the GRB angle, wide-area (ideally full-sky) coverage is imperative, as is a bandpass extending up to MeV energies.

Second, because of their tremendous luminosities, long GRBs serve as powerful probes of star formation and the early universe. In particular, afterglow spectra of events at $z \gtrsim 7$ can provide unique constraints on the epoch of reionization, as the simple power-law continuum can in principle be removed to precisely measure the neutral H fraction along the line of sight. Due to cosmological redshift effects, extending coverage down to lower energies (e.g., 1 to tens of keV) is believed to be imperative to detect these events. And prompt NIR coverage – which has proved challenging to routinely achieve in the *Swift* era – is necessary to identify bona fide high-z events from dust-obscured interlopers at moderate redshift.

Finally, due to their extreme ejecta velocity and energy release, GRBs provide a laboratory to study physics under conditions that cannot be replicated on Earth. Despite approaching the 50th anniversary of the discovery of GRBs, we still do not understand such basic questions as the mechanism responsible for the prompt emission and the structure and composition of the ultrarelativistic jets. A wide-area instrument with soft X-ray coverage would be well suited to identify both low-luminosity GRBs and X-ray flashes, helping to elucidate the connection between cosmological GRBs and "regular" core-collapse supernovae. Polarization measurements of the prompt emission would place strong constraints on the prompt emission mechanism (e.g., magnetic fields). And improved support for theory and simulation would help make sense of both existing and future observations.

3.2.4. *Core Collapse Supernovae*

Core collapse supernovae (CCSNe) represent the end of the evolution of massive stars ($\gtrsim 8$ $M_\odot$). These are multi-wavelength events, and critical information about the explosion physics and progenitors can be determined across the whole electromagnetic spectrum, from gamma rays all the way through to the radio, with each waveband contributing different types of information. Before, during, and after the explosion each wavelength range plays a distinct role. Current observational infrastructure, both ground- and space-based, are doing well at meeting the needs of the CCSN community, but there are areas (both instrumentational and procedural) that could be vastly improved upon, and in fact are crucial to determining how and why massive stars explode.

High energy (space-based) missions with the infrastructure in place to enable rapid response times will be crucial to observing shock breakouts. Space-based UV/X-ray needs for supernova shock cooling require fast (hours) response repointing (coupled to prompt discovery/triggering) or for the telescope to already be there via wide-field, short-cadence surveys. Along with current UV and X-ray missions, missions such as STAR-X, UVEX, STROBE-X, and ULTRASAT, which will have a high sampling cadence good for shock breakout, will be critical for observing shock cooling and mapping exploding star composition. Additionally, an MeV gamma-ray mission would advance both observation and theory as they are excellent probes of the central engine, and the MeV photons from radioactive decay are a clean diagnostic of what goes on near the NS surface. Theoretical neutrino physics, nuclear physics, and general relativity are important for understanding the central engine, and should inform future studies of CCSNe.

Neutrinos will be the dominant non-electromagnetic messenger from CCSN. To date, our only source has been the blue supergiant explosion of SN 1987A, which produced only a handful of MeV neutrinos. Since the 1980s, neutrino detectors have improved dramatically and are currently sensitive to nearby (Large Magellanic Cloud (LMC) or closer) neutrinos, therefore the MeV detection neutrino infrastructure is in place. Narrowing down the time of explosion though, which is needed to help improve the sensitivity of neutrino searches, is still difficult but survey missions such as Roman or the space-based missions mentioned above should be sufficient. What is needed in the neutrino infrastructure is detectors for TeV-PeV neutrinos which are produced in shock interaction with Circumstellar Medium (CSM) or choked-jet SNe and for which optimistic models predict detectability at distances of up to tens of Mpc.

Gravitational wave detections from these sources, created from the standing accretion shock instability that produces a GW quadrupole, may not be viable from any but the absolute closest events. The estimation is that for a non-rotating progenitor star, the GW horizon distance may only be out to 6 kpc by O5. Almost ironically, if a CCSN does occur within that distance, depending on its location in the galaxy, professional astronomy may not be equipped to observe an object that bright in the EM. Thankfully amateurs will be able to contribute, mainly in the optical, via photometry and some spectroscopy, but they generally lack the high energy and long wavelength coverage that will be essential for this event. This is an eventuality that should be planned for.

3.2.5. *Common Envelope Events / Stellar Mergers*

Direct interaction with a binary companion is a common occurrence in the life of a star, particularly a massive one, with important implications for a range of topics in stellar evolution, energetic transients, and the formation of gravitational wave sources, such as binary black hole and neutron star mergers detected by LIGO and Virgo.

Depending on the masses, eccentricity, and evolution state of the donor star, mass-transfer can become unstable, resulting in the two stars merging, or the donor plunging into the envelope of the companion star (creating a so-called “common envelope” event). A class of optical transients with luminosities between those of novae and supernovae have been identified (so-called “luminous red novae”) which are likely associated with stellar merger events. While these events can start as optically-luminous, they later evolve to become IR-luminous as the merger ejecta and the inflated envelope of the leftover remnant star becomes dust- and molecule-rich.

Future progress on better understanding stellar mergers and their outcomes, and their role in binary evolution, requires: (1) deep, long-baseline photometry capable of measuring pre-merger orbital periods; (2) near-IR and mid-IR survey capabilities to discover dust-obscured stellar mergers/common envelope events; (3) mid- to far-IR spectroscopy to characterize dust production; (4) wide-field UV-imaging to discover old merger remnants as the H_2 is shock-dissociated with the Interstellar Medium (ISM); (5) high-energy and neutrino capabilities to search for signatures of relativistic outflows or jets from common envelope events involving compact objects.

3.2.6. *Exotica (e.g. Fast and Blue Optical Transients)*

Optical transient surveys with fast cadence of a few days have recently led to the identification of new classes of astronomical transients. Among these, Fast and Blue Optical Transients (FBOTs) have been a focus of attention by the astronomical community in the recent few years mostly because of the first detection of their X-ray and radio counterparts with properties that clearly point at engine-driven phenomena.

FBOTs are characterized by an extremely rapid rise to maximum light over timescales as short as only a few days, luminous emission in excess to $L_{peak} > 10^{44}\,\mathrm{erg\,s^{-1}}$ and blue colors (e.g., Drout+ 2014, Tanaka+ 2016). The short timescales, high peak luminosities and lack of UV line blanketing observed in many of these transients are not easily explained by traditional SN models. Alternative explanations include exotic scenarios like a failed SN, the detonation of a helium shell on a white dwarf, and a SN shock breaking out from a dense circumstellar medium. Furthermore, the large optical luminosities of some FBOTs might be connected to the presence of a central engine, for example in the form of accretion on a black hole similar to GRBs or tidal disruption events (TDEs) The presence of such an engine manifests itself through bright and variable X-ray emission, relativistic ejecta and/or persistent blue colors of the optical-UV emission.

Among the most notable observational properties of FBOTs are: (1) luminous radio emission in the most luminous optical FBOTs originating from relativistic outflows with properties similar to GRBs; (2) however, in stark contrast to GRBs, FBOTs show clear presence of hydrogen in their ejecta; (3) luminous X-ray emission with Compton-hump spectral features reminiscent of accreting sources like XRBs and AGNs; (4) similar to accreting compact objects, a potential detection of a quasi-periodic oscillation (QPO) at $\sim$ 224Hz has been found in the X-ray emission from one FBOT.

All these properties suggest that FBOTs are manifestations of accreting compact objects and might offer a new window of investigation on infant BH or NSs. However, progress in this field is hampered by the very limited discovery rate of ∼1 FBOT/year. This is a consequence of two factors: first, FBOTs are intrinsically rare; second, at the time of writing, the FBOT searches are carried out at optical wavelengths. However since the optical sky is very rich in transient phenomena *and* FBOTs are an intrinsically UV transient (because of their very large initial temperatures), it is clear that progress in this field can only result from: (1) deep searches of fast transients at UV wavelengths that have the possibility to constrain the colors (and hence the temperature of the emission); (2) rapid spectroscopic repointing of these transients to confirm their intrinsic nature, after which follow-up across the electromagnetic spectrum can be initiated.

3.3. *Super-Massive Black Holes*

3.3.1. *blazars*

Active Galactic Nuclei (AGN) powered by accretion into a supermassive black holes (SMBHs) are the most luminous persistent sources of electromagnetic radiation, reaching typical bolometric luminosities of $L_{bol} \sim 10^{43} - 10^{48}$ erg/s. A fraction of AGN display relativistic jets, which dominate the high-luminosity end of AGN distribution. Their emission is observed across the electromagnetic spectrum showing time variability on timescales of minutes to years. Blazars (face-on jetted AGN) dominate the extragalactic sky at the highest energies (GeV to >TeV gamma rays).

Particle acceleration (and interactions) in the AGN core or in the jet may lead to multi-messenger emission: cosmic rays, neutrinos, and hadronic photons. Disentangling hadronic and leptonic emission is a key task to pinpoint hadronic acceleration sites. While IceCube detected a diffuse flux of cosmic neutrinos, their origin is still largely unknown. A few hints for neutrino sources identified in multi-messenger studies exist at 3σ level, but we are still lacking a statistically significant source detection. New neutrino telescopes are currently under construction (KM3NeT in the Mediterranean and Baikal-GVD in Lake Baikal) or in planning phase (P-ONE in the Pacific Ocean and IceCube-Gen2 at the South Pole) and are promising to deliver higher neutrino detection rates with improved angular resolution. Combined with multi-wavelength observations those measurements promise to give us insights in the timescale of the multi-messenger emission, to pinpoint the sites of hadronic processes, to reveal the best wavelength range for follow-up studies and to identify one or several prototypical neutrino AGN classes.

Covering the full electromagnetic spectrum is critical to model the underlying emission processes. A key will be new all-sky monitoring in the X-ray and MeV band and polarization capabilities. While current and upcoming instruments such as Imaging X-ray Polarimetry Explorer (IXPE) and COSI will be great to study a small number of bright sources, more sensitive instruments will be crucial to effectively perform population studies.

3.3.2. *TDEs and EMRIs*

Tidal disruption events are multi-wavelength and potentially multi-messenger phenomena. They probe both the physics of accretion onto black holes and provide a transient probe of central massive black hole demographics and their innermost environments in quiescent galaxies. Fundamental questions they can address include: (1) Are black holes spinning? (2) Is accretion physics scale invariant? (3) What is the mode of black hole genesis in the early universe?

One of the most exciting aspects of TDEs is their potential to probe black holes in low-mass galaxies, which may shed light on the nature of the primordial seed black holes from which massive black holes form over cosmic time via mergers and accretion. Their rates are related to the rates of EMRIs to be detected by low-frequency gravitational wave detectors (e.g., LISA) and they themselves may be detectable in gravitational waves in very close by systems involving the tidal disruption of a compact star such as a white dwarf (WD) around an intermediate-mass black hole (IMBH).

One can probe the spin of a black hole with TDEs in two ways: using time series observations in the X-rays to measure the frequency of a QPO, which will be a measure of the inner radius of the accretion disk, and thus provide a constraint on its spin; or leveraging the fact that there is a maximum mass of a non-spinning central black hole, the Hill's mass, above which a star will pass the event horizon of the black hole before being disrupted ($\sim 10^8 M_\odot$ for a solar-type star). Thus observing a TDE from a black hole more massive than Hill's mass implies the black hole must be spinning, and thus have a more compact event horizon.

Observing large samples of TDEs is critical for probing the extremes of the SMBH mass function, and for finding rare events such as WD TDEs. Fortunately, while TDEs are rare relative to supernovae, they are distinct enough in their multi-wavelength properties that they have been now discovered quite regularly in wide-field surveys across the electromagnetic spectrum, from the radio to the hard X-rays. The most effective searches for TDEs have been using wide-field soft X-ray surveys (e.g., extended ROentgen Survey with an Imaging Telescope Array [eROSITA]), wide-field optical surveys with multi-band imaging and/or daily cadence (e.g., ZTF, All Sky Automated Survey for SuperNovae [ASAS-SN]), wide field UV surveys (e.g., Galaxy Evolution Explorer [GALEX]), wide-field radio surveys (e.g., Very Large Array Sky Survey [VLASS]), and all-sky, multi-epoch mid-infrared space-based imaging (e.g., Wide-field Infrared Survey Explorer [WISE]).

The rates of TDEs are related to the nuclear stellar density of galaxies, and they can be used to infer the occupation fraction of black holes in low-mass galaxies – a critical constraint on black hole seed formation models for the early universe.

In the future, these approaches would benefit from joint searches. This was especially enlightening from the cross-match of flaring WISE infrared sources with ZTF optical transients, which yielded several cases of infrared echoes of extreme accretion flares (some from AGN and some from TDEs) that were also associated with very high energy neutrinos from IceCube. Given that TDEs are multi-wavelength and multi-messenger sources, a multi-survey approach, combining ground, space, neutrino, and gravitational wave telescopes, is key for understanding the true nature of the population, and their host massive black holes.

While Rubin will have the capability to detect thousands of TDEs, identifying them in the data stream will be a challenge, and they will only give us a partial view of the total TDE population. Contemporaneous wide-field monitoring in the UV, radio, and soft X-rays, as well as comprehensive spectroscopic follow-up capabilities will be key to identifying and characterizing these events. In fact, a jetted TDE was recently discovered in the ZTF optical survey, and with prompt multi-wavelength follow-up observations, was determined to be a jetted TDE with luminous non-thermal X-ray and radio emission from a relativistic jet. Long-term monitoring of TDEs is also important. The recent discovery of late-time brightening of TDEs in soft X-rays and radio imply important state changes in the accretion flow of a TDE, over a year after the initial discovery.

3.3.3. *SMBH binaries, coalescences, and recoiling systems*

When two galaxies collide, their large (intermediate or super-massive) central black holes may form a binary in the center of the merger remnant and eventually coalesce. If that coalescence results in asymmetric gravitational-wave emission, a corresponding momentum impulse will cause the coalesced black hole to gain linear momentum (a “kick” or “recoil”), displacing it from its location in the the galactic center of mass. These giant binary black holes are likely to be some of the brightest sources of gravitational waves in the nanohertz to $\sim 100\,\mu$Hz regimes. They will be bright sources for LISA (in the intermediate-mass regime, encompassing the final month of inspiral, coalescence, and ring-down) and pulsar timing arrays (PTAs, which will detect the highest-mass systems in the extended early inspiral phase, and potentially detecting gravitational-wave “memory” signals associated with the moment of coalescence).

During this extended (million to billion) year process of inspiral, binary formation, coalescence and recoil, a binary is expected to undergo extended interaction with the host galaxy, stars, and gas. In later phases, when the binary is tightly bound, it may have unique emission signatures across the spectrum that arise from circumbinary disks, accretion in mini-disks, dual jet formation, oscillations of broad-line gas, and other observational indicators. However, while many potential indicators exist, no binary black hole has been conclusively proven; this is largely due to the difficulty in confirming that unusual emission from an AGN in fact comes from a binary origin, and doesn't arise from some other effect (e.g., oscillation modes in an accretion disk). It is well established that many independent lines of evidence may build confidence in a supermassive binary's presence, however the most secure way to prove their existence is through the detection of gravitational waves from the system.

It was well established by the Astro 2020 Decadal review that multi-messenger, multi-wavelength observations of these systems will inform our understanding of the entire life-cycle of massive black holes. This includes the feedback processes with host galaxy formation, the merger-induced fuelling and growth of SMBHs, the processes that drive inspiral and coalescence, the behaviours of plasma in the strongly gravitating environments around dual supermassive black holes, jet formation, and active galactic nucleus processes and geometries. Any detection of signal chirps (frequency evolution) via PTAs' detection of pulsar terms or through detection with LISA, will help us perform precision cosmology in the nearby and distant Universe.

There are several significant capabilities needed to address this science in the coming years. The most obvious one is enabling gravitational-wave detection via both PTAs and LISA. As discrete systems (resolved from the gravitational wave background) begin to be detected, our ability to identify the host of those systems will be the critical enabler of most of the aforementioned science. Significant work *now* is required, however, to enable and streamline this coming multi-messenger era.

Identifying binary systems with a gravitational-wave system needs a suite of binary indicators. Considering the variety of AGN activity and emerging predictions from theory/simulations, an organization of information is prominently needed. This takes three forms: further theoretical work should be sought and supported that can make sense of the complexity of current predicted signatures, and particularly needed are unique and easily-surveyed indicators of a system's binary nature.

Second, it is important to note that the time span of interest for intermediate- and super-massive black hole systems ranges months to decades, thus is much longer than typical time spans. Thus, organization and accessibility of vast archival data sets that allow for long-term time-domain tracking (likely over many different data sets) will be an important capability in improving the observational support available for binary candidates. This will in turn lead to improvement and greater efficiency in follow-up survey designs for a gravitational-wave binary supermassive candidate localized to potentially large sky areas. In other words: the more data that exists already, the fewer resources we have to spend searching and the less time we have to wait for a confirmed result.

Third, related to the previous point, is that it will be important to encourage the development of wide-field, time-domain instruments and surveys that have a long lifetime, which support the latest developments in theory and observation for massive black hole emission signatures.

3.3.4. *Stellar-mass mergers and compact-object mergers in AGN disks*

Accretion disks in active galactic nuclei (AGN) can collect stellar mass objects causing them to grow, explode, or collide. Star formation, evolution, and migration results in a population of black holes and neutron stars in galactic nuclei. This population of stellar mass objects will subsequently interact with the AGN disk, resulting in the orbital alignment of some objects with the disk. The pressure gradient in the AGN disk results in objects migrating towards the center of the AGN, increasing the rate of gravitational interaction between stellar mass objects. Gas capture increases the formation rate of stellar mass object binaries. Dynamical friction in gas and interactions with nearby objects result in rapid inspiral and merger events. As merger remnants stay in or near the disk, they can additionally merge with objects brought there by the AGN disk, resulting in multiple consecutive – so-called hierarchical – mergers. Altogether, these processes result in an increased rate of hierarchical mergers in AGN accretion disks.

The processes described above could explain events such as the GW190521 BH-BH merger, which has several properties that are difficult to account for otherwise. The masses of the BHs were >65 $M_\odot$, which is difficult to explain using only stellar evolution but could be produced by previous mergers. This event also had higher spin than BHs in other mergers observed to date, which could be explained through previous mergers or accretion. The high recovered eccentricity ($e{\sim}0.7$) of

GW190521 is unexpected for typical mergers since gravitational waves tend to circularize binary orbits, and points to a binary that was either recently formed or was influenced by an external source. High-eccentricity may be relatively common for mergers in AGN disks, further supporting this possible origin. Finally, GW190521 had spins that were misaligned with their orbit, which could be common for stellar-mass objects in binaries that were brought together by chance encounters and therefore may also be common for mergers in AGN disks.

Multi-messenger studies of stellar mass object mergers in AGN accretion disks address Astro2020 Decadal survey questions on the mass and spin distributions of NS and stellar BHs (B-Q1) regarding NS and BH formation and evolution (B-Q1a). It also addresses question B-Q2 on what powers the diversity of explosive phenomena across the electromagnetic spectrum, specifically B-Q2a on when and how transients are powered by neutron stars and black holes.

Going beyond continued gravitational wave detection of events such as GW190521 with LIGO, Virgo and KAGRA, TDAMM observations are key to understanding hierarchical stellar mass object mergers in AGN accretion disks. Gamma rays in the MeV-GeV energy band are an important counterpart for jetted emission. AGN variability and flares in the optical, UV, and X-ray bands enable the identification of micro-tidal disruption events and the high accretion rates before and after the mergers. It is also possible that these events result in neutrinos observed with IceCube and KM3NeT.

Continued theory development is key to these studies, particularly with hydrodynamic simulations of accretion and jet launch by BH and binary systems embedded in AGN accretion disks. Observationally, LISA will increase the sensitivity to larger masses. MeV-GeV all-sky gamma-ray will be necessary to identify electromagnetic counterparts. Long-term AGN optical monitoring and a large field-of-view X-ray facility will enable the detection of AGN flares. Long-term or target-of-opportunity ultraviolet monitoring of AGNs will also identify flares and transients and help separate them from the AGNs' intrinsic variability.

3.4. *Unknowns, and emerging unknowns*

3.4.1. *FRBs*

The discovery and characterization of fast radio bursts (FRBs) is a field that has seen rapid development over the past half-decade. FRBs are extreme emitters; lasting only a millisecond, they can temporarily provide a luminosity that rivals the output of an active galactic nucleus. So far, FRBs have only been detected as a radio phenomenon. However, the lack of any discovery of multi-wavelength counterparts to date has several potential causes.

First, only around 25 FRBs have been well-localized on the sky, and good (∼sub-arcsecond) localization is required for cross-identification with transient counterparts. Second, radio signals are delayed by the ambient plasma in space, so that for simultaneous multi-wavelength, an FRB may follow high-frequency components by seconds to minutes (with a delay that depends on the conditions along the line of sight); this then requires simultaneous multi-wavelength monitoring of the sky to detect coordinated emission. Related to this point, radio bursts occur relatively infrequently for limited-field-of-view instruments (about 10^4 per whole sky per day, or around 10^-2 per hour per square degree). Thus, the prospect of coordinating narrow-field-of-view radio and multi-wavelength instruments will result in impractically long integration times for a single FRB detection.

As of the writing of this document, only now are radio detection capabilities coming online that include *both* wide-field sky coverage and localization (e.g., Canadian Hydrogen Intensity Mapping Experiment (CHIME) and its outrigger system, Deep Synoptic Array-110 (DSA-110), Australian Square Kilometre Array Pathfinder (ASKAP), and others). FRB localization is an absolutely critical step in allowing detailed studies of FRB hosts, and in allowing multi-wavelength cross-identification. The wide fields of view of these new instruments, coupled with localization, could allow a critical cross-identification of FRB counterparts when coupled with sensitive, wide-field instruments at other wavelengths.

As with other transient cases (like GRBs in the past and the Fast X-Ray Transients (FXTs) described below), detecting multi-wavelength emission from FRBs is expected to be one of the keystones in understanding the physical precursors and emission mechanisms of FRBs that have so far proved elusive.

3.4.2. *FXTs*

A new class of fast evolving X-ray transients has been recently discovered in archival Chandra data, named Fast X-Ray Transients. The intrinsic nature of FXTs has yet to be construed. However, while we are likely to be dealing with a heterogeneous class, it is clear that at least some FXTs are of extra-galactic origin, which makes their X-ray luminosities comparable to those of Short Gamma-ray Bursts (SGRBs). Because of their rapidly fading behavior (FXTs typically last $\lesssim$ 10s of ks) and energetics, FXTs have been proposed to be manifestations of NS mergers (i.e., a manifestation of a SGRB-like progenitor system).

At the time of writing, FXTs lack a counterpart at any other wavelength, which is at least in part a consequence of the fact that the vast majority of FXTs have been discovered in archival data. Progress requires prompt detection of FXTs (e.g., via X-ray instruments with very large field of view and sharp point spread function) and rapid dissemination of the discovery alerts to enable prompt follow-up across the electromagnetic spectrum.

3.4.3. *Pevatrons*

Pevatrons are the as-of-yet unidentified Galactic sources of PeV (10^{15} eV) cosmic rays. While the PeV cosmic rays are routinely observed on Earth, Galactic magnetic fields scatter the directional information making it impossible to point back to their origin. Candidate sources are supernova remnants, neutron stars, micro-quasars and star forming regions.

Identifying Pevatrons would address Decadal survey questions on what powers the diversity of explosive phenomena across the electromagnetic section (B-Q2), why some compact objects eject material in nearly lightspeed jets (B-Q3), how star-forming structures arise from and interact with the diffuse interstellar medium (F-Q1), and identifying the most extreme stars and stellar populations (G-Q1).

Future TDAMM observations could identify the Pevatrons. While arrival directions of PeV cosmic rays are uncorrelated with their origin, the neutrinos and gamma rays produced at the Pevatron do point back to its source. While the signature of a Pevatron source is gamma rays with up to $\sim$100 TeV energies produced by hadronic interaction at the source, the leptonic production of gamma rays at these energies is a confounding factor. The critical observations needed to disambiguate the hadronic and leptonic components are: (1) spatially correlated $\sim$50 TeV neutrinos along with $\sim$100 TeV photons, or (2a) accompanying radio, X-ray, and MeV-GeV gamma ray measurements to constrain the leptonic component of the electromagnetic emission, and (2b) measurements of the ∼100-TeV gamma ray excess over these leptonic components. A set of statistically significant measurements listed above would unambiguously identify a given source as a Pevatron.

The future observational strategy starts with more sensitive Galactic surveys in the TeV-PeV energy range to identify a larger population of Pevatron candidates. Once the sources are identified, multi-wavelength observations in radio, X-ray, and MeV-GeV gamma ray bands covering >1 degree field of view are needed to constrain secondary electron populations and characterize the source environment where PeV cosmic rays are interacting. Additionally, gamma-ray observations with <arcminute spatial resolution in the GeV–PeV energy band would resolve the morphology of the source and help separate leptonic and hadronic emission components further. For example, hadronic gamma-ray emission is expected to follow the profile of the high-energy protons convolved with the morphology of the gas targets, whereas leptonic emission at these energies is dominated by inverse Compton scattering on cosmic microwave background (CMB) photons and should thus follow the profile of the high-energy leptons. Additionally, leptons tend to cool faster than protons and leptonic emission may thus show spectral softening depending on the source distance. Detection of neutrinos in the 50 TeV–1 PeV range spatially correlated to the Pevatron candidate provide evidence of high-energy hadronic interactions at the source.

In a future where all these observations are available, there are additional enabling factors to the identification of Pevatrons. Data sharing policies between the various observatories (ground and space) are key to maximizing scientific return. A lack of access to data from ground-based observatories has been identified as a limiting factor. In addition, the development of software tools capable of multi-instrument data analysis is a second key enabling factor.

3.4.4. *"Unknown unknowns"*

TDAMM is by nature exploring new parameter space, and whenever this is done, unexpected discoveries may arise. There are a few issues of primary importance for this.

First: it must be recognized that while "science-ready data products" (SRDPs) make for efficient completion of science, there is a vast amount of science that can be done with archives that contain either raw data, or at least a very basic data format. Fast radio bursts, for instance, were detected upon the realization that re-processing old pulsar data sets in a new way might lead to new discoveries; if those data sets had been averaged in time or frequency before permanent storage, FRB discovery would have become much less likely. The point here is simply to recognize that when feasible, infrastructure should allow for basic data products to be stored and publicly accessible (although perhaps at a much less frequent access rate than SRDPs).

Second: instruments, time assignment committees, and science review panels should bear the unexpected in mind when laying down their capabilities and by-laws. Intra-cycle and target-of-opportunity type proposals should be considered early in the design of any new system, as these types of proposals can be absolutely critical for new discoveries, particularly those in time-domain.

Third: Multi-wavelength observations (sometimes simultaneous) are sometimes required to perform a single science goal. If this is not designed into the instrument control and the science review/time assignment panels, this type of observation can be exceedingly difficult to coordinate. It should be considered that multi-instrument proposals should be negotiable in a single submission (for instance, the model that currently exists for e.g., National Radio Astronomy Observatory (NRAO) and X-ray Multi-Mirror Mission (XMM)/Hubble Space Telescope (HST)/*Chandra*). Similarly to the previous point, it should be considered whether there is a model that could feasibly allow for target-of-opportunity or intra-cycle type proposals that provide access to multiple instruments.

3.5. *Interdisciplinary Aspects*

In this section, we highlight the interdisciplinary aspects of the TDAMM science, which make this discipline critical to the Astrophysics community and the Nation, and on the urgency for NASA (and other funding agencies) to start investing adequately and significantly in related infrastructure now.

Multi-messenger astrophysics has implications for cosmology, the origin of the elements, supranuclear matter, tests of gravity, the behavior of neutrinos, and other fundamental physics, which cannot be learned through other means. Additionally, sufficient understanding of our sources may provide insight into nuclear physics, atomic physics, plasma physics, turbulence, and more. Scientists from these fields were engaged in the Decadal process and there are numerous white papers where these results are detailed, and this is a critical reason this science was highlighted in the Decadal report.

Beside the intrinsically fundamental importance of the science, NASA assets for TDAMM (e.g., *Fermi*, *Swift*) are discovery machines often resulting in world-wide observing campaigns that engage and inspire many generations of scientists, engineers, and the public (e.g., the recent GRB100922). The TDAMM results hit the major publications worldwide, even in nations not aligned with the US, elevating the NASA brand and the scientific importance of the US and inspiring the next generations to pursue science, technology, engineering and mathematics (STEM) careers.

NASA and the community have a golden opportunity to capitalize on the broad importance and appeal of TDAMM science to make important strides with Congress and the lawmakers. By highlighting the interdisciplinary aspects of the TDAMM science, and the national importance of its assets, TDAMM can become a vehicle to bolster Astrophysics and science in general in the Nation and on the Hill.

3.5.1. *Fundamental Physics*

Multi-messenger observations provide key insight into fundamental physics, as they probe matter in extreme regimes and allow for knowledge in one messenger to be used to test the physics of another. Subsections 3.2.2, 3.2.3, 3.2.4, 3.3.2, 3.3.3, and 3.4.1 above discuss phenomena whose observations can also be used to study fundamental physics.

Most obvious is tests of Lorentz invariance violation (LIV). The language here relies on the Standard Model Extension (SME) framework which splits observations between sectors (photon, gravity, neutrino, matter) and types of LIV (dispersive or not, birefringent or not). The SME framework additionally allows for tests of the Cosmological Principle by allowing for anisotropic LIV, which requires a sample of events to properly constrain. GW and GRB observations are the most precise measure on the speed of gravity (gravity, non-dispersive). Advancements here also include constraints on the graviton mass (gravity, dispersive). The speed (and hence mass) of neutrinos was constrained with SN 1987A but far stronger constraints could be placed by the combination of detecting MeV neutrinos and capturing the X-ray shock breakout from SNe in nearby galaxies (requiring an all-sky X-ray monitor). Similar tests are done for high energy neutrinos, though unambiguous results require unambiguous association of high energy neutrinos to a given event. Observations of GRB polarization probe birefringent LIV. Broadband EM observations probe dispersive violation in the photon sector, as do broadband GW observations in the gravity sector. LIV is about as fundamental a question as can be asked, as a fundamental length scale required in a quantum theory of gravity would provide a preferred reference frame. Thus, LIV provides a potential step towards a grand unified theory.

Tests of gravitational wave polarization are key to testing General Relativity and other theories of gravity. Neutron star mergers are a critical source for these tests as the precise EM position allows for orders of magnitude improvement in searches for vector or scalar GW polarization modes. One specific form of GW polarization effects has to do with gravitational parity violation. Recent results from the Baryon Oscillation Spectroscopic Survey (BOSS) galaxy survey 4-point correlation function and the cosmic microwave background Planck Data Release 4 have independently suggested that there is non-zero cosmic parity violation in the universe. If this is indeed the case, studying parity violation in the gravitational sector is an important complement to this work to better understand the role of parity violation in the universe. The existence of parity violation would be a smoking gun for new physics beyond the standard model and GR, with implications for understanding fundamental questions such as the matter-antimatter excess in the early universe. Parity violation is also a feature of many well-motivated modified gravity theories beyond GR, such as Chern-Simons gravity. Previous theoretical work has indicated that a key test of parity violation in the gravitational sector would come from coincident GW-GRB observations due to the EM measurements of the sky position, polarization angle and inclination angle from the GRB. Work is ongoing to determine which tests will be the most sensitive to this effect, but regardless, GRB observations will have a significant role to play in studying parity violation.

Some of these tests of fundamental physics, and others (e.g., constraints on extra large dimensions) also require comparison of luminosity distance as measured by gravity against the measurement from light. This again requires precise EM localizations. In the early GW era this can be done with kilonovae, but GW-GRBs will begin to dominate sometime this decade, so long as we have sufficient space-based wide-field high-energy monitor(s).

Significant investment in theory is needed to build phenomenological frameworks to connect theory and observation in a consistent manner (e.g., similar to the SME for LIV). Advancements in broader considerations of the implications of alternative theories of gravity need to be explored (e.g., on their effects of GW inspirals, rather than only propagation effects). All of these results are predicated on properly understanding the physics that underlie explosive transients.

3.5.2. *Cosmology*

Of critical importance is an accurate measure of the Hubble Constant, which may be addressed by observations of the phenomena discussed above in subsections 3.1.1, 3.2.2, and 3.2.3. This appears to be the strongest evidence suggesting new physics beyond ΛCDM, but a ∼5 sigma discrepancy between Hubble Constant measurements by different methods is insufficient alone, given the potential systematic uncertainties. New measures or improved local measures are key. Beyond stringent tests of the standard model of cosmology science includes understanding the neutrino mass ordering, the shape of the universe, and whether dark energy is a cosmological constant. Even if the Hubble Constant crisis is resolved before future NASA missions would be built, these advancements will still be critical for sub-percent precision cosmology throughout the universe.

One approach to progress on the Hubble Constant is through standard siren measurements, using a quirk of General Relativity to construct a Hubble diagram from gravitational wave observations. There are many proposed methods to do this, but to falsify ΛCDM one will need unequivocal results. The only likely option is a large sample of electromagnetic recovery of GW-detected neutron star mergers. The basic requirement is recovery of the EM signatures, association to a host galaxy, and measurement of the redshift of that host galaxy. Initially the dominant EM signature will be quasi-thermal kilonovae, recoverable on the ground, but prompt GRBs will become the dominant discovery signature in the future, during the O5/O6 timeline. Further, understanding the inclination dependence of EM signatures will be critical to achieve precision cosmology with these sources, otherwise the GW inclination-distance degeneracy will introduce a bias. Examples include the various phenomenological jet structure methods, better simulations for how jets are shaped by polar ejecta, and variations of these for different remnant / merger cases. For kilonovae the problem is even more poorly defined. Most models assume spherical ejecta, though some asymmetric ejecta papers are beginning to be published. Continued advancements in the physics that underlie kilonova models are critical, followed by massive grids of kilonova models varying uncertain physics and input parameters (e.g., ejecta mass, velocity, composition, or shape) and seeing if observations can identify unique areas of parameter space (or not). A wide-field high energy monitor with precise localizations enables both the highest rate of EM-bright standard siren measures, as well as early localizations to recover the breadth of EM signatures necessary to fully understand these events.

Another approach is improved understanding of Type Ia supernovae. Ground-based astronomers are chasing early observations which may enable progenitor determination. Critical questions include identification of progenitors for specific supernovae as well as understanding precisely how thermonuclear runaway is detonated. Answering these questions will require the use of new diagnostics, including nuclear gamma-rays and COSI, shock breakout (conceptually similar to those from CCSN, but the 'shock' occurring being the edge of the WD), and the early Ultraviolet Optical Infrared (UVOIR) emission. COSI should be able to perform these measurements for a handful of individual supernovae during its prime mission. A wide-field monitor capable of recovering a 'shock breakout' type emission from the propagation of the detonation shock through the white dwarf surface would also enable the earliest UVOIR observations of this event. Numerous theoretical and simulation advances are needed to better model how thermonuclear supernovae are detonated and potential effects on the various observables. These considerations have minor (i.e., at the ∼percent level) effects on the peak or later UVOIR lightcurves but may have major effects on the other observables. These are then key to reducing intrinsic systematics on type Ia cosmology and seeking answers to the Hubble Constant crisis.

Even if the Hubble Constant crisis is solved soon (hopefully with JWST) the quest for proper calibration of standard sources will continue for decades, as they are unique tools for studying our universe.

3.5.3. *Dense matter*

Matter around the nuclear saturation density is poorly understood, but observations of the phenomena discussed in subsections 3.2.2 and 3.2.4 above can help. The only methods known to probe this regime are ground-based experiments on heavy atoms or in astrophysical observations of neutron stars. Measures on both sides allow tests over ∼15 orders of magnitude in scale, which allow advances in understanding the behavior of the strong force in this regime. For neutron star studies, equations of state are probed by matching their predictions on values for various observables (mass, radius, tidal deformability, etc.) against actual observations. The Neutron star Interior Composition Explorer (NICER) was designed to do this with precise timing and high spectral resolution and has achieved ∼5% precision on mass and radius for a small number of neutron stars.

Neutron star mergers provide a key additional way to probe these events. GW directly measures tidal deformability. Multi-messenger observations can probe mass and radius and have already achieved constraints comparable to NICER. Perhaps the most precise possible test is on the maximum mass of neutron stars, as mass-radius relations asymptote to this critical value. Confident classification of ∼10 binary neutron star (BNS) events into their remnant cases can allow a few

MeV neutrino detections of CCSN will also allow for precise tests of the equation of state (EOS) of NS, especially if they are sufficiently close for large number statistics in Hyper-K and Dark UNiverse Explorer (DUNE), both starting in 2028. which allow direct viewing of the core-collapse itself and evolution to the remnant neutron star. This would be greatly complemented by other observables which probe the core-collapse event itself. For a Galactic event this would be a GW detection. For local events this would be COSI and gamma-ray signatures. For events within ∼100 Mpc the key additional diagnostic is shock breakout which requires sensitive wide-field X-ray monitoring. Directly recovering the shock breakout from a Hyper-K event requires near all-sky coverage, and these measurements will be critical for several fields of physics. Supernova UVOIR observations will generally probe the interaction of the shock with the surrounding medium (e.g., previously ejected material). Sustained investment in all areas of the physics relevant to these events is necessary.

4. IMPLEMENTATION FINDINGS

4.1. *TDAMM infrastructure is needed beyond alerts*

While the Decadal did not explicitly mention infrastructure other than tailored missions, infrastructure is critical to reap the maximum science in an effective and timely way. At the August workshop a session was held to discuss infrastructure, which saw the lively and enthusiastic engagement of the audience and led representatives of space- and ground-based assets to exchange views and needs. The following points were captured, expressed in terms of needs on the near-term (next 5 years) and long-term (>5 years). A discussion of TDAMM missions and the urgency of investments in new capabilities is described separately below.

<u>Near-term needs</u>:

Real-Time Cyberinfrastructure: TDAMM science will need to evolve "real-time" transient detection in data streams of many facilities over the whole electromagnetic band, and (automated) cross-correlation of these data streams, to enable rapid follow-up of multi-messenger candidates. Software tools will also be needed to combine data from different missions, and perform joint analysis (e.g., timing or spectral). Coordination of NASA data archives, and ideally those of ground facilities, should be developed to enable rapid transient characterization. When a transient is detected, its previous observation history and characteristics should be quickly recovered from the archives to yield science faster, and to reduce duplication of effort, sometimes on operationally expensive facilities. For example, with the onset of operations of the Rubin observatory in the coming years, (which will provide millions of transient events per night) rapid, reliable, coordination capabilities between Rubin and space missions will be of great importance.

Theory Funding: There is a great need for general, sustained investment in theory and simulations. For neutron star mergers, the kilonova simulations are known to be severely lacking, preventing precise measures of ejecta mass and composition. For standard siren cosmology, there are only limited studies on the inclination brightness dependence for EM counterparts, which will act as an underlying systematic issue, as described at this workshop. There is a need for deep interdisciplinary studies which are totally critical to multi-messenger astronomy, e.g., nuclear physics advancements with FRIB and explorations on how to guide the key nuclear experiment runs to benefit astrophysics and on folding those advancements into simulations. The theory that underlies the production of high energy neutrinos is advancing, but the simulations are insufficient. Shock breakout (SBO) simulations for several giant stars expect UV emission but these make numerous approximations (e.g., the distribution of matter near the edge of the star) and these appear inconsistent with the putative SBO signals seen in X-ray telescopes. Astrophysics still fails to draw on significant advancement in other fields of physics (e.g., in the understanding and importance of turbulence). Most of the theory and arguments that underlie proposed missions are generally facile compared to what should be expected for $150M+ investments.

TDAMM General Observer Facility (GOF): NASA should work with the community to develop a streamlined proposal process for applying for NASA facilities for target of opportunity follow-up observations. At the present time, a system of "double jeopardy" exists when two or more proposals are required for a set of observations to successfully perform a single TDAMM science exploration. Eliminating these barriers will yield better science returns and will reduce the work required of the community to prepare proposals, and for NASA to evaluate them.

NASA Proposal Evaluation Criteria: The way that NASA evaluates mission proposals can adversely affect the chances of TDAMM missions. For example, NASA has a set rate for communications (which are critical for TDAMM missions) in their budget, but there are commercial opportunities to offset these costs, and the mission does not actually pay the fees. NASA, working with the TDAMM community or other NASA advisory bodies, should review proposal guidelines and evaluation criteria to mitigate negative impacts on TDAMM missions.

Coordination between NASA, NSF, and international partners: At present, federal support for ground-based capabilities such as new instrumentation is generally provided by the National Science Foundation (NSF). Better TDAMM science returns would be yielded by enhanced coordination between ground and space telescopes, including in their mission and project planning. For example, NASA and NSF could establish TDAMM mission-project liaisons, a possible function of a TDAMM GOF. Examples of coordination include archive and alert standardization, joint evaluation criteria for TDAMM-focused proposals requiring ground and space support, and community support/education activities. Likewise, better coordination with international space agencies would help ensure the maximally effective portfolio of capabilities and minimize obstacles to get rapid response and coordinated observations.

Coordinated timing requirements: Given the wide range in transient event duration, and the need for pan-chromatic capabilities, it is important to establish coordinated absolute timing requirements, especially for combining transient detections between missions.

Evaluation Criteria for TDAMM missions: Much of the science uniquely enabled by time-domain and multi-messenger observations requires concurrent observations of the same event, which requires overlapping observing times of the key instruments. Some capabilities will always exist (ground-based optical telescopes, radio telescopes) and some key facilities have sustained, long-term observing runs (Rubin, IceCube, DUNE, Hyper-K). However, some facilities have complex observing timelines, e.g., LIGO/Virgo/KAGRA often shift future observing plans because they continually push the edge of experimental physics and cannot always anticipate their future schedules several years in advance. As TDAMM missions must be planned several years in advance, this is a major coordination issue. The usual explorer lifetime of ∼2 years can fall entirely in a GW observing gap. Further, some particularly rare events may be expected in a reasonable mission lifetime, but not in the usual 2-year lifetime. For example, MeV neutrino detections of core-collapse supernovae will occur every ∼3-4 years, and the Decadal and this report both advocate planning for local, rare supernova explosions. NASA TDAMM mission proposals should not be penalized for these considerations. One potential option would be to follow the Decadal possibility of TDAMM missions being "slightly larger" than a typical explorer, which could allow for proposals with longer prime missions. Alternatively, TDAMM missions could be designed for the usual ∼2 year timescale but have science judged on potential science expected over a longer time period.

Continuity of capabilities: The continuity of monitoring across the electromagnetic spectrum with an appropriate suite of missions must be ensured. While NASA traditionally focuses on ground-breaking new capabilities, there is substantial risk that aging observatories critical to TDAMM event detection, localization, and follow-up (such as *Fermi*, *Swift*, and *Chandra*) may lack timely replacements if one degrades or ends operations in the coming decade. See the next section for a more in-depth discussion.

Training a diverse workforce: By its very nature, TDAMM studies require a diverse set of science capabilities, and the scientists to do the work. As such, TDAMM represents an ideal opportunity for advancing NASA's goals in inclusion, diversity, equity, and accessibility (IDEA) and for training students, postdocs, and mid-career professionals in a multi-disciplinary field, enabling an inclusive and diverse community. Equally important is a commitment from senior leadership across NASA and by TDAMM mission principal investigators (PIs) to build diversity into every aspect of the mission.

Crediting TDAMM hidden figures: Finally, but not the least important, NASA and the community need to acknowledge the work of data scientists, software and hardware developers, managers, and all the science enablers who remain too often unrecognized. Inclusion in paper and proposal authorships, explicit acknowledgements in oral presentations, and monetary awards and recognitions, are some of the way to give credit to the hidden figures of TDAMM.

Long-term needs:

Maintain a balanced portfolio of telescope capabilities across the electromagnetic spectrum: Future TDAMM studies, especially those operating on narrow fields or for single targets, will require capable wide-field, high-cadence imaging capabilities in the mid-infrared, UV, X-ray and gamma-rays (especially MeV) to complement them. While still operational, and granted extended mission status again in the 2022 Astrophysics Senior Review, *Swift* and *Fermi* are aging facilities. Maintaining their core capabilities with newer technology and operations models is an important aspect of any future TDAMM portfolio, along with other capabilities, such as X-ray polarization.

Change the way NASA missions are planned and evaluated to include TDAMM interests: Future NASA mission planning should include explicit consideration of TDAMM capabilities. For example, mission proposals should not be penalized for dependence on ground-based multi-messenger facilities, as few TDAMM-focused space missions can yield the maximum science return without the ground-based component. Likewise, an analysis of the ground-space ecosystem is needed in mission planning and formulation, to take into account upgrade schedules, instrumentation capabilities, and operation timelines of ground-based multi-messenger facilities. Finally, consideration of direct support for ground-based capabilities (e.g., bespoke instrumentation or rapid data analysis capabilities) should be made so that Level 1 requirements can be crafted on TDAMM-focused missions that yield higher scientific return. Currently, missions that rely on ground-based follow up assume that a capability to perform the follow-up is already available and "good enough" to perform the needed observations.

With all these considerations in mind, a second workshop with a focus on infrastructure needs and implementation strategies is important in the near future, ideally with robust community, agency, and observatory/mission/archive representation.

4.2. *TDAMM investments are urgent*

NASA should follow promptly the Decadal recommendations for TDAMM, which were identified as the top priority of the Sustaining Program, ahead of the Probes. The rich bounty of TDAMM science and its critical interdisciplinary role, as explained above, requires a significant, sustained, and solicitous investment of funding into capabilities for observations, and in supporting infrastructure (see above). In this subsection, we focus on TDAMM missions and the urgency of their development.

The Decadal recommended an augmentation of $800M this decade for TDAMM Explorers. NASA's *Fermi* and *Swift*, the current workhorses of multi-messenger astrophysics, are aging, leaving a blatant gap in our capabilities for the near future. Starting investments in the next generation of wide-field, rapid response X-ray and gamma-ray missions with arcmin scale position is imperative if we want to meet the challenges of this rapidly expanding field and of the Decadal's objectives. This effort should start **now**, in order to launch these missions by the 2030s and overlap with the many observatories, in space and on the ground, becoming available then. Indeed, in 2028 we will have the O5/O6 GW network for neutron star mergers, DUNE and Hyper-K as part of an upgraded SuperNova Early Warning System (SNEWS) for CCSN, and contemporaneous observations with other critical facilities (including Rubin, Roman, JWST, Cherenkov Telescope Array (CTA), and Square Kilometre Array (SKA). We absolutely need NASA missions designed for this era, and this means starting now with developing technology and mission concepts.

NASA is building COSI, an MeV mission, and is partnering with Israel on ULTRASAT, a wide-field UV monitor. STAR-X, UVEX, and LEAP are currently in Phase A, with down-selection expected in late 2023. These missions are responsive to the Decadal and will revolutionize our understanding of the dynamic, multi-faceted universe, but by themselves they are insufficient. The case for high-energy wide-field monitors tailored to TDAMM science is clear, and NASA should invest promptly in these so that we have contemporaneous lifetimes critical missions/instruments, to deliver science worthy of the investment.

5. CONCLUSIONS

Time Domain and Multi-Messenger Astrophysics (TDAMM) has come of age and holds the promise of breakthrough discoveries in the coming decade. TDAMM science has broad repercussion and is intrinsically interdisciplinary, spanning more than astrophysics: cosmology, fundamental physics, nuclear physics, and more. This rich bounty sets the TDAMM apart among the science recommended by the Decadal for its broad reach, and requires a targeted, sustained, and timely program of investments.

NASA and other agencies' investments in TDAMM science, capabilities, and infrastructure should start now. Indeed, the Decadal has identified TDAMM as the top priority of the Sustaining Program, ahead of Probes, and has underlined the importance of a balanced investment of resources in the entire portfolio.

Increased or new NASA investments in the field are needed in many areas - from theory and computation to coordination of the current and future fleet of NASA and international missions to development of new capabilities. NASA's aging missions like *Fermi* and *Swift*, the current workhorses of TDAMM, pose a particular concern, due to the rapid turnaround and unpredictable timing of transient/multi-messenger events. Wide-field monitors with rapid response and arcmin localization are needed urgently, in particular in the UV, X-rays, and gamma-rays. Their development should start immediately, in order to enable overlap of lifetimes with ground (Rubin, SKA, CTA, next-generation GW and neutrino detectors) and space (Roman, JWST) missions in the early 2030s.

This white paper, summarizing the content of the August 2022 TDAMM Science Workshop, is a testament to the exploding field of Multi-Messenger and Time Domain Astrophysics, and of the growing needs of its communities. We urge NASA HQ to make TDAMM a priority for current and future investments, and to act on a rapid timescale, so that the US can retain a leading role in the international landscape.

6. ACKNOWLEDGEMENTS

A large number of people and organizations made this Workshop possible. We are grateful to the Physics of the Cosmos staff (Cathy Barclay, Stephanie Clark, Marry Morrow, Brian Humensky, Jake Slutsky) for their indefatigable commitment to make this workshop the most successful it could have been; their tenacity and stamina was essential for overcoming the various obstacles along the way, including an unexpected failure of the WiFi on the first day! Speaking of which, NASA's Jay Friedlander pitched in with their expertise at the last minute to help us overcome the internet debacle.

Eric Burns and John O'Meara provided substantial comments and text for Section 4. Their help is greatly appreciated.

Regina Caputo, Brian Humensky, and Jake Slutsky took valuable and detailed notes during the meeting, which were essential to the completion of this paper. Many thanks for being there in person all three days!

Our gratitude to the Roman Team at STScI who provided coffee for the morning breaks, keeping us awake and perked up.

The Science Organizing Committee was the main science engine which defined the content of the workshop. Its members took time out of their busy days to assemble the workshop science outline, invite the speakers, and chair the sessions; and importantly, to develop sections 4 and 5 of this report. To them goes our undying gratitude.

To all the colleagues who attended the workshop in person or virtually, thank you; your presence is what made the event a success. We literally could not have done it without you!

We acknowledge that the land on which this Workshop was held was once the home of indigenous people who lived in the Annapolis area before us: according to the Native-land.ca site, the Piscataway and Pamunkey tribes once prospered here, together with many other nations in the Maryland area. While enjoying the beautiful city of Annapolis with its harbor, stores, and restaurants, we are also aware that in the distant past Annapolis was the port of entry for the slave trade, mostly from African nations.

7. APPENDIX: WORKSHOP INFORMATION

7.1. *Workshop Agenda*

Below are the schedules for the sessions, including times, chairs, and invited speakers. All of the presentations are linked to in the next section (Section 7.2).

	Monday		
8:15 AM	Registration		
9:00 AM	Plenary Session Kickoff: Suvi Gezari Keynote Speaker Mark Clampin Program Scientist: Valerie Connaughton		
9:45 AM	Break		
	Jetted Transients-SMBH (blazars) Chairs: Gezari, Franckowiak Room B/C	Explosive Transients-WD (SNe Ia) Chairs: Cenko, Andrews Room A	Non-Terminal Transients-Other (supernova remnants, starburst galaxies, galaxy clusters) Chairs: Romero-Wolf, Burke-Spolaor Room F
10:00 AM	**Invited: Marcos Santander**	**Invited: Kate Maguire**	**Invited: Imre Bartos**
10:45 AM	**Contributed: Tiffany Lewis** ***Theoretical Modeling of TXS***	**Contributed: Benjamin Rose** ***A Forecast of Extragalactic Transient Light Curves for the Roman Time Domain Core Community Survey***	**Contributed: Henrike Fleischhack** ***PeVatrons – where are our Galaxy's most powerful accelerators hiding?***
11:00 AM	**Contributed: Haocheng Zhang** ***High-energy polarimetry as a probe for blazar hadronic signatures***	**Contributed: Abigail Polin** ***The Future of Type Ia SNe***	
	Explosive-Transients-NS/BH (core-collapse SNe) Chairs: Andrews, Franckowiak Room B/C	Non-Terminal Sources-WD (CVs, WD binaries) Chairs: Nelemans, Breivik Room A	Jetted Transients-Other (engine-powered SNe) Chairs: Margutti, Metzger Room F
1:30 PM	**Invited: Charlie Kilpatrick**	**Invited: Simone Scaringi**	**Invited: Anna Ho**
2:15 PM	**Contributed: Ori Fox** **Supernovae Interacting With Their Circumstellar Environments**	**Contributed: Kevin Burdge** **The future of "multi-messenger" time domain astronomy: Ultracomapct Galactic binaries**	**Contributed: Bei Zhou** **Choked-Jet Supernovae as Hidden Astrophysical Neutrino Sources**
2:30 PM	**Contributed: Chris Fryer** **Multi-Messenger/Multi-Phenomena Diagnostics of Core-Collapse**	**Contributed: RafaelMartinez-Galarza** **Towards the Seamless Discovery of High Energy Transients: New Data Representations**	
2:45 PM	**Contributed: Avishay Gal-Yam** **Early UV emission from exploding massive stars**		Merger-Driven Transients-Other II (classical and symbiotic novae) Room F Invited: Elias Aydi
3:30 PM	Break		
	Non-Terminal Sources-SMBH (SMBH binaries, AGN) Chairs:Burke-Spolaor, Gezari Room B/C	Jetted Transients-NS/BH (micro quasars, gamma-ray bursts) Chairs: Wilson-Hodge, Cenko Room A	Merger-Driven Transients-Other II (stellar mergers, common envelope systems) Chairs: Kasliwal, Metzger Room F
3:45 PM	**Invited: Tingting Liu**	**Invited: Amy Lien**	**Contributed: Navin Sridhar** **Applications of hyper-accreting X-ray sources to fast radio bursts and stellar merger transient events**
4:30 PM	**Contributed: Caitlin Witt Multi-Messenger Coordination on the Supermassive Scale**	**Contributed: Eric Burns** **How to Make Speed-of-Light Jets**	Merger-Driven Transients-WD (WD-WD, WD-NS, WD-BH) Chairs: Gijs Nelemans, Breivik
4:45 PM	**Contributed: Scott Noble Time and Wavelength Domain Predictions for Accreting Binary Black Holes**	**Contributed: Taya Govreen-Segal** **Prospects for Resolving the Hubble Tension with a Small Number of Binary Neutron Star Mergers with**	**Invited: Kyle Kremer**
5:00 PM	**Contributed: Daniel Stern Extreme Quasar Variability**	**Contributed: James Rhoads** **Looking for orphans (and their cousins) in wide fields.**	**Contributed: Yossef Zenati Transients from ONe white dwarf - neutron star/black hole mergers**

	Tuesday		
	Small group meetings, self organized		
9:45 AM	Break		
	Jetted Transients-SMBH II (Tidal Disruption Events) Chairs: Gezari, Franckowiak Room A	Merger-Driven Transients-NS/BH (NS-NS, NS-BH, BH-BH) Chairs: Kasliwal, Nissanke Room B/C	Explosive Transients- Other (FRBs, FXTs) Chairs: Burke-Spolaor, Margutti Room F
10:45 AM	**Invited: Sjoert van Velzen**	**Invited: Alessandra Corsi**	**Invited: Shami Chatterjee**
11:00 AM	**Contributed: Yvette Cendes New Discoveries in Late-Time Emission from Tidal Disruption Events**	**Contributed: Samuele Ronchini Perspectives for multi-messenger astronomy with the next generation of gravitational-wave detectors and high-energy satellites**	**Contributed: W. Niel BrandtFuture Investigations of the New Extragalactic Population of Faint, Fast X-ray Transients**
11:15 AM	**Contributed: Robert Stein Identifying Transient Neutrino Sources with the Zwicky Transient Facility**	**Contributed: Eran Ofek Gravitational Waves in the UV**	**Contributed: Walid Majid Multi-wavelength characterization of FRBs**
12:00 PM	Discussion	Discussion	Discussion
12:00 PM	Lunch (On your own)		
	Merger-Driven Transients- SMBH (SMBH binaries, EMRIs) Chairs: Burke-Spolaor, Slutsky Room A	Merger-Driven Transients-Other I (common envelope systems) Chairs: Kasliwal, Metzger Room B/C	Non-Terminal Sources-NS/BH (XRBs, magnetars, pulars) Ramirez-Ruiz, Wilson-Hodge Room F
1:30 PM	**Invited: Elena Rossi**	**Invited: Kishalay De**	**Invited: Erin Kara**
2:15 PM	**Contributed: Jeremy Schnittman Supermassive Black Hole Mergers**	**Contributed: Yadira Gaibor Constraining occurrence rates of short-period post-common envelope binaries**	**Contributed: Maria Drout Stripped Star plus Compact Object Binaries: Identifying the Progenitors of Neutron Star Mergers**
2:30 PM	**Contributed: Krista Lynne Smith The Physics of Accretion Disks and Binary AGN with Very High-Cadence Band-filtered Optical/UV**	Discussion	**Contributed: Thomas Maccarone X-ray Binaries as Time Domain Sources**
3:45 PM	**End of Daily Sessions**		
4:30 PM	Editing of System Reports by Session Chairs		
	Wednesday		
9:00 AM	Infrastructure Panel		
	Short individual introductions GCN - Judy Racusin HEASARC - Alan Smale NOIRLab - Tom Matheson DSN - Joe Lazio Near Space Network (NSN) - Chris Roberts IPAC - George Helou		
	Discussion		
11:00 AM	Break		
11:15 AM	**Non-Terminal Sources Reports** **WD: Nelemans** **SMBH: Burke-Spolaor** **NSBH: Ramirez-Ruiz** **Other: Romero-Wolf**		
12:00 PM	Lunch		

1:30 PM	**Merger-Driven Transients Reports** **SMBH: Slutsky** **NSBH: Kasliwal** **Other: Kasliwal** **WD: Breivik** **Jetted Transients Reports** **Other: Metzger** **SMBH: Franckowiak** **NSBH: Wilson-Hodge** **Explosive Transients Reports** **WD: Cenko** **NSBH: Andrews** **Other: Margutti**
3:30 PM	Next steps, report outline, writing assignments.
4:00 PM	Close Out

7.2. *Link to Presentations*

All of the presentation pdf files are available on the NASA Physics of the Cosmos Program website at the following link: https://pcos.gsfc.nasa.gov/TDAMM/Presentations.php

7.3. *Details of the Attendance Statistics*

	Monday	
Plenary 183/91/92		
Jetted Transients-SMBH 71	Explosive Transients-WD 56	Non-Terminal Transients-Other 69/39/30
Explosive-Transients-NS/BH 48	Non-Terminal Sources-WD 69	Jetted Transients-Other 49/15/34
Non-Terminal Sources-SMBH 21	Jetted Transients-NS/BH Merger-Driven Transients-WD Not available	Merger-Driven Transients-Other II 24
	Tuesday	
Jetted Transients-SMBH II 63/33/30	Merger-Driven Transients-NS/BH 92/52/40	Explosive Transients- Other 61/41/20
Merger-Driven Transients- SMBH 61/33/28	Merger-Driven Transients-Other I 55/23/32	Non-Terminal Sources-NS/BHr 78/38/40
	Wednesday	
Infrastructure Panel 162/84/78		

Table 1. Approximate number of attendees, formatted Total/Online/In-person. If only a single number is present, then that is a Total and no information is available on the breakdown. Note that attendance was counted once during a session by the note taker, though attendees were able to enter and exit at any time during the session. Names and individuals were not tracked. There were 334 registered attendees across all participation types.

7.4. *Useful Acronyms*

AGN	Active Galactic Nuclei
AIC	Accretion-Induced Collapse
ASAS-SN	All Sky Automated Survey for SuperNovae
ASKAP	Australian Square Kilometre Array Pathfinder
BH	Black Hole
BNS	Binary Neutron Star
BOSS	Baryon Oscillation Spectroscopic Survey
CCSN	Core-Collapse Supernova
CHIME	Canadian Hydrogen Intensity Mapping Experiment
CMB	Cosmic Microwave Background
CO	Carbon Oxygen
COSI	Compton Spectrometer and Imager
CSM	Circumstellar Medium
CTA	Cherenkov Telescope Array
CV	Cataclysmic Variable
DSA	Deep Synoptic Array
DUNE	Dark UNiverse Explorer
EM	Electromagnetic
EMRI	extreme mass ratio inspirals
EOS	Equation of State
eROSITA	extended ROentgen Survey with an Imaging Telescope Array
FBOT	Fast and Blue Optical Transient
FRIB	Facility for Rare Isotope Beams
FRB	Fast Radio Burst
FXT	Fast X-Ray Transient
GALEX	Galaxy Evolution Explorer
GOF	General Observer Facility
GR	General Relativity
GRB	Gamma-Ray Burst
GVD	Gigaton Volume Detector
GW	Gravitational Wave
HST	Hubble Space Telescope
IDEA	Inclusion, Diversity, Equity, and Accessibility
IMBH	intermediate-mass black hole
IR	Infrared
ISM	Interstellar Medium
IXPE	Imaging X-ray Polarimetry Explorer
JWST	James Webb Space Telescope
KAGRA	Kamioka Gravitational Wave Detector
KM3NeT	Cubic Kilometre Neutrino Telescope

LAT	Large Area Telescope
ΛCDM	Lambda Cold Dark Matter
LEAP	LargE Area burst Polarimeter
LIGO	Laser Interferometer Gravitational-Wave Observatory
LISA	Laser Interferometer Space Antenna
LIV	Lorentz Invariance Violation
LMC	Large Magellanic Cloud
NASA	National Aeronautics and Space Administration
ngVLA	next-generation Very Large Array
NICER	Neutron star Interior Composition Explorer
NIR	Near Infrared
NRAO	National Radio Astronomy Observatory
NS	Neutron Star
NSF	National Science Foundation
PI	Principal Investigator
P-ONE	Pacific Ocean Neutrino Experiment
PTA	Pulsar Timing Array
QPO	Quasi-Periodic Oscillation
SBO	Shock Breakout
SGRB	Short Gamma-ray Burst
SKA	Square Kilometer Array
SMBH	Supermassive Black Hole
SME	Standard Model Extension
SN	Supernova
SNEWS	SuperNova Early Warning System
SRDP	Science-Ready Data Product
STAR-X	Survey and Time-domain Astrophysical Research Explorer
STEM	Science, Technology, Engineering and Mathematics
STROBE-X	Spectroscopic Time-Resolving Observatory for Broadband Energy X-rays
TDAMM	Time Domain and Multi-Messenger Astrophysics
TDE	Tidal Disruption Event
ULTRASAT	Ultraviolet Transient Astronomy Satellite
US	United States
UV	Ultraviolet
UVEX	Ultraviolet Explorer
UVOIR	Ultraviolet Optical Infrared
VLA	Very Large Array
VLASS	Very Large Array Sky Survey
WD	White Dwarf
WISE	Wide-field Infrared Survey Explorer
XMM	X-ray Multi-Mirror Mission
ZTF	Zwicky Transient Facility