Coordinated Science in the Gravitational and Electromagnetic Skies

A Whitepaper Submitted to the Decadal Survey Committee

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Science Frontier Panels:
PRIMARY: Cosmology and Fundamental Physics (CFP)
SECONDARY: Stars and Stellar Evolution (SSE)
Galaxies across Cosmic Time (GCT)

Projects/Programs Emphasized:
1. The Energetic X-ray Imaging Survey Telescope (EXIST); `http://exist.gsfc.nasa.gov`
2. The Synoptic All-Sky Infrared Imaging Survey (SASIR); `http://sasir.org`
3. The Large Synoptic Survey Telescope (LSST); `http://lsst.org`
4. The Laser Interferometer Space Antenna (*LISA*); `http://lisa.nasa.gov`

Key benefits of joint gravitational/electromagnetic observations:

- **Extend the sensitivity of GW detectors, and improve our determination of signal properties, through association with an EM counterpart**
- **Measure cosmological parameters precisely with a novel approach**
- **Directly observe and precisely measure properties of the engine driving violent astrophysical events, such as short-hard GRBs, supernovae, and black hole mergers**

1 Introduction

It is widely expected that the coming decade will witness the first direct detection of gravitational waves (GWs). The ground-based LIGO and Virgo detectors are being upgraded to "advanced" sensitivity, and are expected to observe a significant binary merger rate (perhaps dozens per year; e.g., [25]). The launch of the planned *LISA* antenna will extend the GW window to low frequencies, opening new vistas on dynamical processes involving massive ($M \gtrsim 10^5\, M_\odot$) black holes.

GW events are likely to be accompanied by electromagnetic (EM) counterparts (e.g., see [47, 48] for review). Since information carried electromagnetically is complementary to that carried gravitationally, a great deal can be learned about an event and its environment if it becomes possible to measure both forms of radiation in concert (see the "key benefits" box above).

Measurements of this kind will mark the dawn of **trans-spectral astrophysics**, bridging two distinct spectral bands of information. Our goal in this whitepaper is to summarize some of the added scientific benefits to be found in coordinating observations between GW sources and their electromagnetic counterparts. In addition, we suggest some coordinated facility-level approaches and efforts needed to carry out these observations.

2 The Science Enabled by Joint GW/EM observations

We now highlight some of the main (anticipated) benefits of joint GW & EM observations, ranging from the more secure to the more speculative:

Improving Parameter Extraction of GW Events: With an EM identification of a transient, many otherwise degenerate GW errors collapse, greatly increasing the precision with which we determine source properties from the GWs; luminosity distance measurements are particularly improved when the source position is known (e.g., [3, 20]). EM localization obviates the need to marginalize over source position, greatly reducing the parameter space of search templates, and correspondingly increasing the observed signal-to-noise ratio (SNR). Likewise, an identification drastically cuts down the search range in time, reducing the threshold signal-to-noise required for confident detection ([21]; see [11] for a recent treatment). Conversely, monitoring a time-variable EM counterpart with an origin in a dynamical bulk flow that is precisely timed and characterized by the GW signal offers mutual constraints on the source that are not otherwise available.

A New Precision Cosmology Tool: Binary inspiral sources are standard "sirens," with a standardization provided only by an appeal to General Relativity ([9, 19, 43]). Direct GW measurement of a coalescing binary provides a distance-ladder-independent measure of the luminosity distance D_L to a source. For massive BH-BH mergers, calculations show that we can expect *LISA* to measure D_L

to < 1–2% for redshifts $z < 3$, degrading to $\approx 5\%$ for $z \simeq 5$ ([23, 28]). While D_L may be well measured, the source redshift cannot be inferred directly: measurements of the (redshifted) binary mass and the system's redshift are entirely degenerate [9]. An independent measure of the event redshift is therefore required to populate a Hubble diagram and measure cosmological parameters with GW events. If an EM signature is detected, spectroscopic observations of the event or the galaxy hosting the EM event should be obtainable. Though the utility of distance measurement from such events would be limited by weak gravitational lensing [19, 50], the complementarity of this technique to others in this redshift regime means that it should be subject to very different systematic effects. Similarly, in the more local universe, EM events near the edge of the Advanced LIGO/Virgo volume would yield precision measurements of H_0 ($\gtrsim$ few %) [11]. *We can use inspirals as cosmological probes only if we associate the gravitational event with an electromagnetic counterpart.*

What is the Nature of Short-Hard Gamma-Ray Bursts? The massive star origin of long-soft γ-ray bursts (LSBs), representing the majority of GRB events, was definitively established by the observation of concurrent envelope-stripped supernovae (see [51] for review). While there is now good, albeit indirect, evidence that short-hard bursts (SHBs) come from an older stellar population than LSBs (e.g., [7, 37, 52]), the origin of these events is far from established. Binary mergers (NS-NS or NS-BH) are commonly believed to be SHB progenitors [29], but a number of other origins remain viable. A concurrent GW inspiral event in the same place and time as a SHB (detected by, e.g., EXIST; §4.4) would be the smoking gun for the origin of these events. Moreover, the ensemble rates of GRB and coincident GW detections would establish the distribution of jet collimation angles in GRBs, crucial for understanding energetics of the events [4, 38]. Since a binary's inclination to the line of sight is a direct GW observable (it sets the ratio of the two GW polarizations), coordinated observations of these events offer a wealth of insight into the geometry of jets and subsequent GRB emission; the detailed nature of the event's GWs may even be able to give insight into the equation of state of neutron star material [10, 49]. Finally, the detailed nature of correlated GW/EM emission is likely to help elucidate the processes which drive the GRB engine itself. Especially for NS-BH driven events, the final merger, disruption and possibly accretion may radiate in the most sensitive band of GW detectors. *Concurrent gravitational-wave and electromagnetic observations of short-hard GRBs will definitively establish whether the engine is a NS-NS or NS-BH binary merger, or something else.*

Constraining Models of Supernovae (SNe) Core-Collapse: Stellar core collapse during a SN releases roughly 10^{53} ergs of gravitational binding energy in less than one second. A consensus understanding of the physics underlying a core-collapse SN is far from established. Nevertheless, it is apparent that the masses, velocities, and asymmetries involved have the potential to generate strong gravitational-wave signals ([14]; see also [15, 39] and references therein). At a minimum, detection (or non-detection) of GWs from a SN strongly constrains the rotation of the collapsed core. A SN close enough to be a strong GW source is also likely to be a strong neutrino source. *The triple "multi-messenger" view of GWs, neutrinos, and photons is likely to provide a wealth of knowledge on the SN engine and perhaps the behavior of matter at nuclear densities.*

Viscous Accretion onto Massive Black Holes with Known Masses and Spins: GW observations will determine the masses, spin magnitudes, and orientations of progenitor and remnant BHs with unprecedented accuracy by any astronomical standard. Viscous accretion of material that remains bound to well-characterized remnant BHs will lead to afterglow EM emission (e.g., [2, 36]) and provide some of the best laboratories for the study of AGN and quasar physics. Monitoring of time-variable accretion regimes around massive BHs with varied spins and viewing geometries will directly inform questions about feedback of massive BHs on their environments. Binarity may lead to periodic

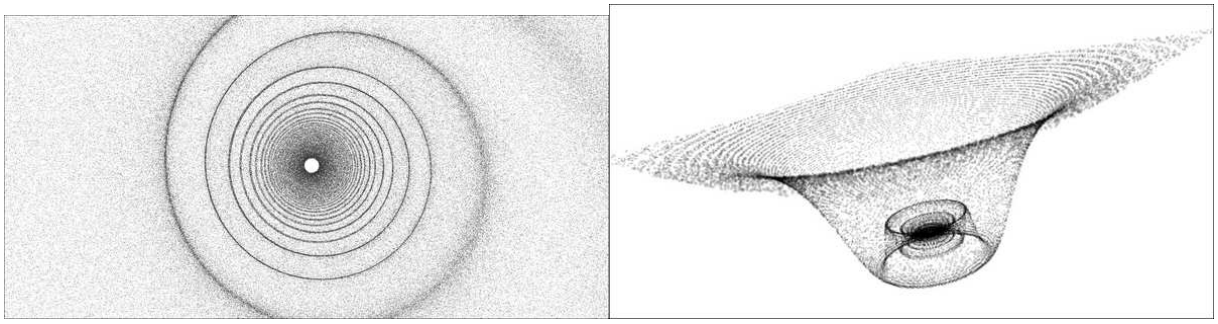

Figure 1: *Example scenario for the production of an EM counterpart from a massive binary BH coalescence. Typically* $\sim 10^{53}$ *erg or greater of GW energy can be channeled as a kinetic recoil of the merged remnant to be deposited into the surrounding gaseous environment. The figures illustrate the induced density waves in the gas surrounding a* $M_1 + M_2 = 10^6\ \mathrm{M}_\odot$ *BH binary, recoiling within the disk plane at a velocity* $v_{\rm kick} = 500\ \mathrm{km\ s^{-1}}$*. Strong density enhancements could produce detectable EM signatures from the perturbed gas. From [31].*

signatures in the EM output which, coupled with the GWs as a bulk mass-flow diagnostic, would allow an unprecedented view of this dynamics. *Coordinated GW/EM observations will provide an unprecedented laboratory for the study of BH accretion physics.*

3 Detecting the Expected EM Signatures

The individual nature of coalescing objects will greatly impact what kind of electromagnetic display might accompany the GW merger event. EM counterparts can take the form of "precursors," events that precede the binary coalescence; "prompt emission," events that occur at (or nearly at) the same time as the coalescence; and "afterglows," emission that follows the GW event:

High-Energy Counterparts: All short-hard GRBs with measured redshifts to date originate from beyond $z = 0.1$ (e.g., [4]). A wide-field GRB monitor with today's sensitivities and trigger criteria (or better) should readily detect similar SHBs within the 300 Mpc volume of Advanced LIGO and Virgo. Coincident detection in time would virtually guarantee a precise localization of the GW event. Combined with GW determination of the source inclination and the chirp mass, this would open up a detailed view into the central engine of SHBs that arise from binary coalescence. In an exercise that is already becoming commonplace with the current generation of GW detectors, GRB localizations in space and time could also be used as an external trigger for more sensitive searches in GW data streams [e.g., 1].

Optical/Infrared emission from massive black hole mergers: Some GW events are likely to be preceded and/or followed by detectable optical/infrared emission (e.g., Fig. 1). Models for such emission, while not particularly well-developed currently, motivate deep follow-up searches on GW localizations for EM precursor, prompt and afterglow characterizations. Optical/infrared emission is readily tied to candidate host galaxies, and thus redshifts. Transient EM detections could also be used to trigger localized, higher SNR searches in *LISA* and Advanced LIGO+Virgo data streams [47] (see the [46] WP for specific examples). Deep and wide infrared/optical facilities would be the preferred choices for initial pre-merger searches on larger than degree scales (Fig. 3), but an increasingly diverse array of facilities could get involved as localization errors shrink well below degree scales at late times [28] and post-merger. Combining GW-inferred D_L values with a concordance cosmology yields narrow redshift slices, from which significantly more focused EM searches can be carried out. Such

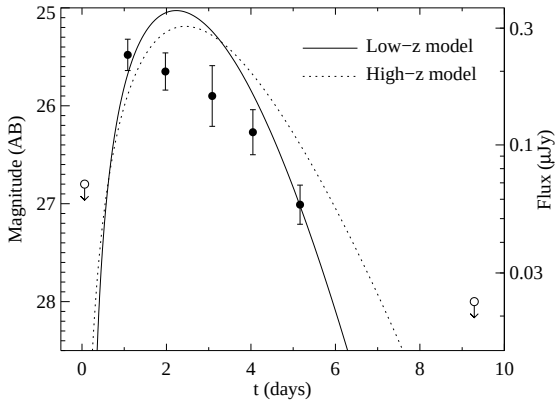

Figure 2: *The first EM signature of a NS-NS inspiral? Light-curve models for a ^{56}Ni-powered "mini-SN," [26, 30, 34] compared against optical observations of the transient associated with short-hard GRB 080503. The solid line indicates a model at $z = 0.03$ with a ^{56}Ni mass $\sim 2 \times 10^{-3} M_\odot$, total ejecta mass $\sim$0.4 $M_\odot$, and outflow velocity $\approx 0.1c$. The dotted line is for a pure ^{56}Ni explosion at $z = 0.5$ with mass $\sim$0.3 $M_\odot$ and velocity $\approx$ 0.2c. From Perley et al. [40].*

information could be used in coordination with that in LSST, SASIR and possibly JDEM photometric redshift catalogs to weed out unrelated EM transients (see §4).

Afterglow and SN-like emission from stellar-mass events: SHBs are now known to produce faint X-ray, optical, and infrared afterglows, detectable for $\sim$1 day with current and planned instrumentation. NS-NS or NS-BH mergers that do not produce a GRB may nonetheless produce optical or infrared signatures on some timescale. Advanced LIGO+Virgo uncertainty regions should be systematically searched as quickly as possible ($<$ hours) for these afterglows (which would yield arcsec localizations). Later time observations, on $\sim$day timescales, would be logistically more feasible but more uncertain to return a counterpart. Li & Paczyński [30] predicted thermal SN-like emission, rising and falling on $\sim$day timescales, from non-relativistic outflow of the coalescing binary. Sensitive searches have thus far failed to find bright Li-Paczyński events [7, 16, 40], but events peaking at $M_V > -16$ mag are not ruled out (see Fig. 2). Hansen & Lyutikov [18] discussed possible radio and X-ray precursors to compact object mergers. Likewise, the accretion-induced collapse (AIC) of a white dwarf to a NS (a possible Type Ia SN channel) may also represent a powerful source of GWs [14] and could produce a SN-like transient lasting $\sim$1 day [35]. GW-triggered-only events could be identified electromagnetically through repeated and deep observations on tens of square degrees for days. To, at minimum, inform expectations, the theory of stellar-mass events should be better developed this decade.

4 Facilitating the Science

Using GWs alone, sources will be localized to rather large fields. The network of ground-based detectors (the two LIGO sites plus the European Virgo) can pin down binaries to a field of a few to $\sim$10 square degrees [5, 8]; the space-based detector *LISA* will be able to pin down merging black holes to a field of several $\times$ ten square arcminutes in the best cases, and a few square degrees more typically [22, 28]. These localizations demand the ability to monitor $\sim$10 square degree fields and larger in order to find electromagnetic signatures accompanying the GWs. Once the source is localized electromagnetically, the distance and source inclination can be measured through GWs with good precision. Studies show that ground-based detectors can measure the distance to a coalescing binary neutron star system with a fractional accuracy of several percent if its position is known (Nissanke et al., in prep.); *LISA* can similarly pin down the distance to coalescing supermassive black holes with percent level accuracy or better [23, 28].

In order to realize the science objectives above, we advocate the following activities and facilities:

4.1 Theory

Modeling and measurement analysis of binary GWs. Given a binary system, general relativity predicts its future evolution and emitted GWs with zero free parameters. The post-Newtonian expansion of general relativity [6] and numerical relativity [41] have been extraordinarily successful in modeling these systems, especially when both members are black holes; our understanding of the dynamics when one member is a neutron star has greatly advanced as well (e.g., [13, 32, 45]). We advocate continued attention to the development of such models and the exploration of binary parameter space, with a focus on how well a binary's characteristics are pinned down by GW measurements. For example, an extension of the analyses described in [3] to include the impact that the late merger has on *LISA*'s ability to fix the position of a merging binary may have great consequences, by limiting the search field necessary to find the event's EM afterglow.

Modeling the EM counterpart of massive black hole mergers. The nature of EM emission that is likely to accompany the merger of two massive black holes is rather poorly understood. At this point, we cannot say with great confidence whether the emission will precede, coincide with, or follow the peak GW emission (e.g., [12, 24, 31, 36, 42]). Given the binding energy ($\sim 10^{60}$ erg) and GW luminosity ($\sim 10^{57}$ erg/sec) involved in these events, even a modest EM conversion efficiency is likely to be impressive. We advocate continued analysis to understand the likely counterparts to these events in order to more fruitfully guide searches for their accompanying emission.

4.2 Gravitational-wave detectors

LISA, the Laser Interferometer Gravitational-wave Antenna. This instrument will be a space-based antenna for measuring GWs in the band from about 0.03 milliHz to 0.1 Hz, corresponding to sources with orbital periods of seconds to hours. *LISA* is needed to measure massive black hole coalescences. As is discussed in white papers by Prince et al. and Madau et al., the rate of such mergers is expected to be high (several to perhaps dozens per year), especially for events coming from relatively high redshift ($z \gtrsim 3$). *LISA* will localize these sources to square degrees or better and measure their distances with a precision of a few percent or better [22, 28], with the constituent (redshifted) masses and spins also well measured [27]. Inspirals of white dwarfs into massive black holes constitute yet another avenue for pre-merger localization of cosmological GW events with plausible EM counterparts, potentially resulting in valuable constraints on the local Hubble flow ([33, 44]).

Advanced LIGO, the Laser Interferometer Gravitational-wave Observatory. LIGO consists of three ground-based GW detectors at two sites, sensitive to waves in the band from about 10 Hz to a few thousand Hz. It will be needed to measure waves coincident with SHBs; in concert with the Advanced Virgo detector (with whom LIGO has joint data cooperation), such events can be localized to within several square degrees. The NSF-funded Advanced LIGO project started construction activities in April 2008, and plans to start observation as early as 2014. Although Advanced LIGO is not a project that is within the scope of the Astro2010 review, we include it here to note that much of the science we discuss in this whitepaper depends on data from this instrument. As such, we particularly advocate close coordination between the ground-based GW data analysis, wide-field optical and infrared imaging, and the high energy surveys that we discuss next.

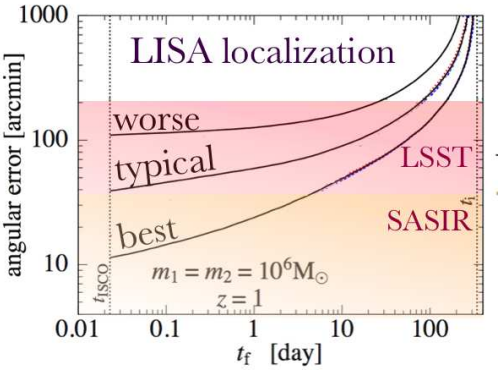

Figure 3: *Pre-merger localization accuracy of a LISA signal from two $10^6 M_\odot$ BHs merging at $z = 1$, as a function of time before coalescence, t_f. The colored horizontal bands show the single image LSST and SASIR fields of view. The location on the sky of most events should be easily covered for days to weeks before the inspiral time [23, 28]. Adapted from [17].*

4.3 Wide-field optical/infrared Imaging

The Synoptic All-Sky Infrared Imaging (SASIR) survey is a pre-phase A concept for a new 6.5m telescope in San Pedro Mártir (Mexico) designed to repeatedly observe the infrared sky simultaneously in 4 bands from 1 – 2.2 micron. First light is expected as early as 2016. The 5 sigma survey depth is expected to reach 0.6-1.5 microJy (24.5 – 23.4 AB mag). A portion of the routine survey will cover much of the Galactic Plane, improving the possibility of discovering a heavily obscured Galactic core-collapse SN (a significant "blind spot" in EM observations related to GWs; [47]). Roughly 30% of the time has also been budgeted on fast (and dynamic) cadences in small regions of the sky. Follow-up of Advanced LIGO+Virgo events, to search for rapidly fading afterglows and for long-lived transients (e.g. Li-Paczyński mini-SNe), is a science driver for ToO observations on SASIR (typical response expected to be < 2 min) and field-of-view tiling of *LISA* pre-merger localizations. Combining all-sky IR observations with other wide-field optical surveys should drastically improve the photometric redshifts of galaxies hosting $z > 1.4$ BH-BH mergers, allowing for a more efficient and sensitive search for EM signatures to *LISA* events (where cosmological constraints derived from the observed D_L allow for a narrow search in redshift space). It is important to emphasize that since dust obscuration might hide optical signatures, IR observations could prove crucial.

The Large Synoptic Survey Telescope (LSST) is a $\sim$10 square degree FOV optical imaging survey, reaching single epoch depths of $\sim 0.3 \mu$Jy in 6 bands, and covering 20,000 square degrees with $\sim$1000 repeat visits. The combination of depth and field of view is a powerful tool for studying EM counterparts of GW events with two major modes of operation. First, a quick response (ToO) mode where LSST would slew to an Advanced LIGO+Virgo GW event location and search for new transients (likely associated with relatively nearby galaxies). A similar response could be instituted for *LISA* pre-merger followup. Second, historical data drill down into the regions where GW events were uncovered and not promptly communicated. LSST pre-imaging of GW event sites would provide important clues to uncovering the nature of the EM signature eventually detected.

4.4 High-energy Surveys

The Energetic X-ray Imaging Survey Telescope (EXIST) is an all-sky hard X-ray imaging facility currently in Pre-Phase A study. On-board triggering within EXIST's 90 deg $\times$ 70 deg FoV and prompt γ-localization ($< 20''$), followed (< 2 min) by onboard $0.3 - 2.3\,\mu$m imaging (to AB ≈ 25 mag) and spectroscopy ($R = 30$ and 3000) ensure maximal EM coverage of the $\sim$10 coincident SHB and Advanced LIGO/Virgo events per year. Even without a γ-ray signature (though this is mitgated by EXIST's high sensitivity), the fast slew ToO capability of EXIST would enable immediate deep

imaging and spectra with the soft X-ray and 1.1m optical-IR telescope, which would locate afterglow emission to within 0.1 arcsec.

4.5 Other Facilities

Continuous monitoring of *LISA* merger locations in the days to hours preceding merger will require coordinated efforts across the globe (and in space). Whole-earth monitoring programs across a (probably heterogenous) network of EM facilities will be required. Such a paradigm on small-aperture facilities is already producing important results in microlensing research (see WP from Gaudi/Gould et al.). Centralized networks, such as the Las Cumbres Global Telescope Network (LCOGT), should be well positioned for monitoring and follow-up activities. Virtual Observatory standards are already in place to describe and broadcast GW events to an eager EM follow-up community (e.g., `VOEvent`).

Although we have focused on optical/infrared facilities for EM counterpart searches to *LISA* events, facilities across the EM spectrum (particularly at radio wavebands) could prove beneficial and even critical for late-time searches, especially when GW localization errors can shrink to sub-degree scales.

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