Snowmass2021 - Letter of Interest

The Necessity of Extremely Large Telescopes (ELTs) for Future Studies of Gravitational Wave Sources

Thematic Areas: (check all that apply □/■)

□ (CF1) Dark Matter: Particle Like
□ (CF2) Dark Matter: Wavelike
□ (CF3) Dark Matter: Cosmic Probes
■ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
□ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
■ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
■ (CF7) Cosmic Probes of Fundamental Physics
□ (Other) *[Please specify frontier/topical group]*

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Abstract: The field of time-domain astrophysics has entered the era of Multi-messenger Astronomy (MMA). One key science goal for the next decade (and beyond) will be to characterize gravitational wave (GW) and neutrino sources using the next generation of Extremely Large Telescopes (ELTs). These studies will have a broad impact across astrophysics, informing our knowledge of the production and enrichment history of the heaviest chemical elements, constrain the dense matter equation of state, provide independent constraints on cosmology, increase our understanding of particle acceleration in shocks and jets, and study the lives of black holes in the universe. Future GW detectors will greatly improve their sensitivity during the coming decade, as will near-infrared telescopes capable of independently finding kilonovae from neutron star mergers. However, the electromagnetic counterparts to high-frequency (LIGO/Virgo band) GW sources will be distant and faint and thus demand ELT capabilities for characterization. ELTs will be important and necessary contributors to an advanced and complete multi-messenger network.

The purpose of this LoI is to argue for the **essential role played by Extremely Large Telescopes (ELTs; $\gtrsim$20 m in aperture) in fully realizing the scientific potential of the rapidly emerging field of multi-messenger astronomy (MMA)**. This subject has recently achieved prominence with the detection of a broad-spectrum electromagnetic (EM) counterpart to the binary neutron star merger (BNS) and gravitational wave (GW) source GW170817 [1].

1 Background

The largest of the current generation of ground-based optical and near-infrared (NIR) telescopes are 8–10 m in diameter and were constructed over the last few decades. The next generation of planned facilities involve a factor of 2–3 increase in aperture size and will become operational within the next decade. There are three projects underway, one led by the Europeans and two international consortia involving US institutions: the Giant Magellan Telescope (GMT; planned for Chile) and the Thirty Meter Telescope (TMT; planned for Mauna Kea). Both projects are jointly managed as part of the US-Extremely Large Telescope Program (US-ELTP).

We anticipate that the field of MMA will undergo significant development over the next few years and major advances will occur before the ELTs see first light. Some of the most important developments we can expect by then are: (i) Advanced LIGO/Virgo run O4 and future staged upgrades will occur as the detectors approach design sensitivity after 2022 [2]; (ii) additional GW observatories such as KAGRA and LIGO-India will begin regular operations; (iii) the next phase of upgrades to GW sensitivity such as A+ will be underway or nearing completion.

Despite this uncertainty about the future of a rapidly-evolving field, some aspects of the landscape of the study of high-frequency GW counterparts in the era of ELTs are predictable. The increased number of functional GW interferometers will substantially increase the localization accuracy of sources and the corresponding ability to find EM counterparts. However, the increased sensitivity of the observatories will also probe more distant populations of sources. GW interferometers are sensitive to the gravitational strain h, which scales as $1/d$ (where d is the distance to a source), while optical telescopes are sensitive to the energy flux, which scales as $1/d^2$. Although the ultimate design sensitivity of Advanced LIGO will be sensitive to BNS systems out to $\sim$200 Mpc (and BH-NS star mergers at several hundred Mpc), the A+ upgrades[1] by the 2025 timeframe will aim to increase the sensitivity by an additional factor of $\sim$2. Therefore, **planned technology developments in GW interferometers will rapidly start producing detections at distances where the expected optical counterparts are exceedingly dim, necessitating the collecting area of ELTs to study them in detail** (see Figure 1). Future deep, wide-area EM surveys, such as with the LSST performed by the Vera Rubin Observatory and *WFIRST*, will also have synergies with ELTs, including the potential to discover very distant BNS mergers independent of a GW trigger (e.g., [14]).

2 Goals for Studies of GW Sources with ELTs

- The initial detection of an EM counterpart to a BNS merger has demonstrated that at least some short-duration gamma-ray bursts (sGRBs) are connected to BNS mergers and that significant amounts of material enriched by r-process nucleosynthesis are ejected in an event known as a kilonova (e.g., [3–6, 8, 10–12, 15–17]). With ELT studies of counterparts to high-frequency GW sources, we can directly observe **the spectral signatures of the heaviest elements** at the sites of their production. A sample of well-observed objects is necessary to determine the dominant factors resulting in the variation in the yields. This is complementary to studies of the abundance patterns of neutron-capture elements in metal-poor stars in determining the buildup of the periodic table over cosmic time.

[1] https://dcc.ligo.org/LIGO-T1800042/public

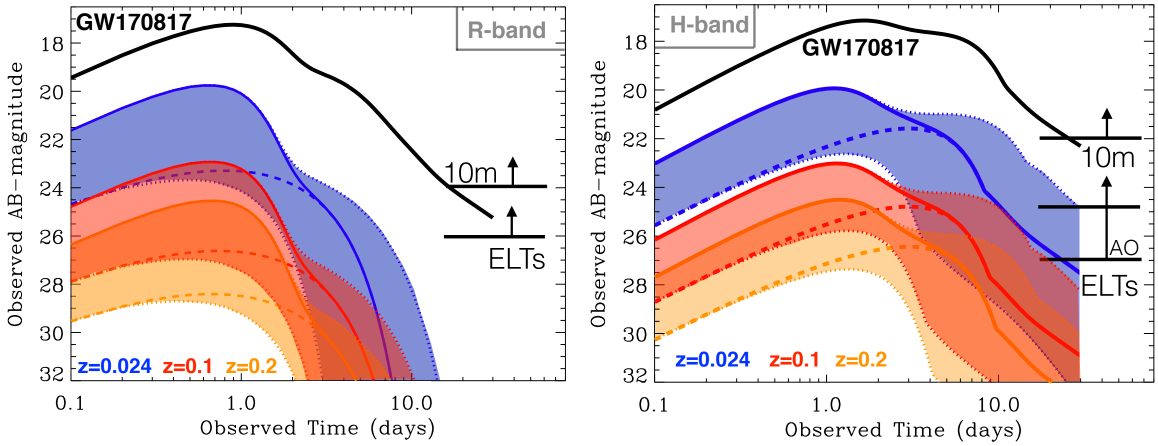

Figure 1: Kilonova emission in the optical (R-band, left panel) and NIR (H-band, right panel) at $z = 0.024$ ($d \approx 100$ Mpc, blue), $z = 0.1$ ($d \approx 500$ Mpc; red) and $z = 0.2$ (orange), computed following [18]. Fiducial sensitivities for reasonable S/N ratios in an hour-long spectroscopic observation for both current generation 8–10 m telescopes and ELTs are marked, including the improvements in the NIR sensitivity due to adaptive optics (AO). Black thick line: GW170817 (at 40 Mpc). For each two-component model, the shaded area marks the brightness range corresponding to $M_{ej,red} = 0.001 - 0.05\,\mathrm{M}_\odot$ and $v_{ej,red} = 0.1\,\mathrm{c}$. All of the models include the contribution from a blue kilonova component with similar properties as in GW170817 ($M_{ej,blue} = 0.01\,\mathrm{M}_\odot$ and $v_{ej,blue} = 0.3\,\mathrm{c}$). Thick lines: expected total emission for $M_{ej,red} = 0.01\,\mathrm{M}_\odot$. Dashed lines: contribution of only the red component with $M_{ej,red} = 0.01\,\mathrm{M}_\odot$. The blue component has a major effect on the optical fluxes, but its origin is obscure. The increased sensitivity of the ELTs in the optical and NIR is necessary to characterize the most distant compact object mergers and to sample the potential diversity of their kilonova emission.

- Theoretical studies of the BNS merger process have identified several physically distinct mass ejection mechanisms, including tidal tails, squeezed dynamical ejecta, accretion disk winds, and jets (e.g., [7]). The relative fractions of material in these components are sensitive to the masses, radii, and tidal deformabilities of the individual neutron stars, which in turn depend on **the dense matter equation of state**. Separately, the astrophysical information about the sky location, distance, inclination of the binary, and ejected mass can be combined with the gravitational wave strain data to produce tighter constraints on the properties of the system, such as the tidal deformabilities of neutron stars.

- Spectroscopic confirmation of distant optical counterparts to GW sources is necessary for **standard siren cosmology** [9, 13]. While some studies can rely solely on redshifts from host-galaxy spectroscopy, anything that depends on the properties of the transient itself, such as estimates of the viewing angle, will require ELTs. At the design sensitivity of Advanced LIGO, BH-NS mergers will already be detectable by GW detectors out to several hundred Mpc, while increases in sensitivity of only $\sim$3 in GW detectors will produce detections of BNS at distances of $\sim$500 Mpc. **As shown in Figure 1, at those distances the expected optical counterparts will be too faint for spectroscopy with 10 m class facilities.** After the NSF invests in the A+ LIGO upgrades, and if it commits to longer-term plans using the LIGO Voyager or LIGO Cosmic Explorer proposals in the late-2020's or 2030's, ELTs will be necessary to actually perform MMA with many of the GW sources detected by those facilities.

We recommend that the SnowMass process endorses the US-ELTs as key facilities to ensure the long-run ability to perform electromagnetic studies of gravitational wave sources discovered by Advanced LIGO/Virgo and their successors.

This text has been adapted from an Astro2020 Decadal Survey White Paper:

Chornock, R., et al. "Multi-Messenger Astronomy with Extremely Large Telescopes", Bulletin of the American Astronomical Society, Vol. 51, Issue 3, id. 237 (2019), https://ui.adsabs.harvard.edu/link_gateway/2019BAAS...51c.237C/PUB_PDF

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