# Astro2020 Science White Paper

# Joint Gravitational Wave and Electromagnetic Astronomy with LIGO and LSST in the 2020's

**Thematic Areas:** ☐ Planetary Systems ☐ Star and Planet Formation
☑ Formation and Evolution of Compact Objects ☑ Cosmology and Fundamental Physics
☐ Stars and Stellar Evolution ☐ Resolved Stellar Populations and their Environments
☐ Galaxy Evolution ☑ Multi-Messenger Astronomy and Astrophysics

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**Abstract (optional):** The blossoming field of joint gravitational wave and electromagnetic (GW-EM) astronomy is one of the most promising in astronomy. The first, and only, joint GW-EM event GW170817 provided remarkable science returns that still continue to this day. Continued growth in this field requires increasing the sample size of joint GW-EM detections. In this white paper, we outline the case for using some percentage of LSST survey time for dedicated target-of-opportunity follow up of GW triggers in order to efficiently and rapidly identify optical counterparts. We show that the timeline for the LSST science survey is well matched to the planned improvements to ground based GW detectors in the next decade. LSST will become particularly crucial in the later half of the 2020s as more and more distant GW sources are detected. Lastly, we highlight some of the key science goals that can be addressed by a large sample of joint GW-EM detections.

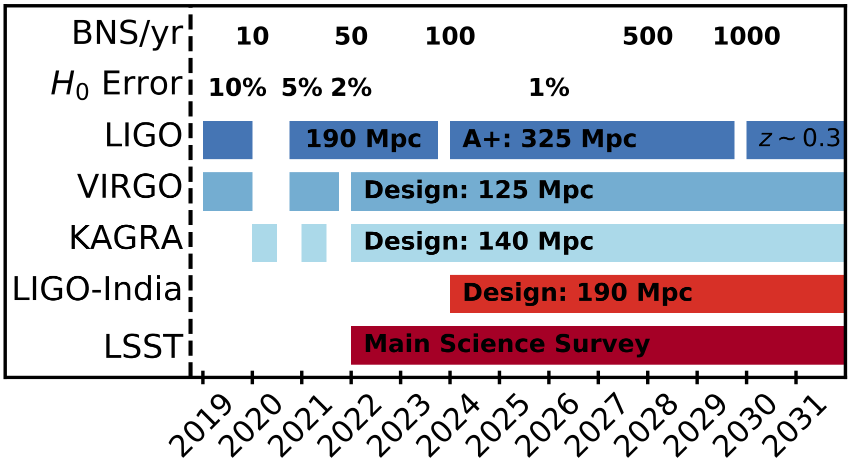


**Figure 1:** Example timeline showing the favorable overlap between the LSST science survey and increased GW detector sensitivity. The average BNS detection horizon is given for each GW facility. Example improvements in key joint GW-EM science are shown for reference.

# 1 Introduction

The direct detection of gravitational waves (GW) from astrophysical sources has ushered in an exciting new era of astronomy. The GW data from sources such as the inspiral and merger of compact object binaries comprised of black holes (BH) and/or neutron stars (NS) provides unparalleled insight into the component masses and spins, binary parameters (e.g., inclination, eccentricity), and the strong gravity regime of general relativity. However, the true power of GW detections become apparent when combined with traditional electromagnetic (EM) observations. The discovery of an EM counterpart provides improved localization and distance information, host galaxy identification and demographics, breaks modeling degeneracies (e.g., distance vs. inclination), and allows modeling of the merger hydrodynamics.

The first such joint detection, GW170817 [7], was an exceptional event. It remains the loudest signal detected by GW instruments from the first two observing runs. Its proximity (40 Mpc) allowed not only rapid counterpart identification and a bevy of electromagnetic observations [8], but also a number of joint GW-EM studies. The GW data provided the first measurements of NS tidal deformation and subsequent equation of state constraints [10], constraints on non-linear tides in NS [12], constraints on the formation of the progenitor system [9], and new tests of general relativity [72]. Joint GW-EM studies provided an independent measurement of the Hubble constant [5], placed complementary constraints on the NS equation of state [50, 16, 61, 25], the fate of the post-merger object [54], and prompted reanalysis and questions about the distribution and formation of binary neutron stars in the galaxy [56, 34].

Building upon the tremendous success of GW170817 requires the continued support for ongoing improvements to both the network of GW detectors and next-generation EM facilities. As the network of ground-based GW detectors continues to grow more sensitive (Section 2) wide-field optical telescopes such as the Large Synoptic Survey Telescope [LSST[1]; 42] will be crucial for detecting distant EM counterparts. In this white paper we discuss the landscape of joint GW-EM science in the next decade with a focus on target of opportunity follow-up with LSST to identify a large sample of EM counterparts (Section 3), as well as briefly introducing some of the major science questions such a sample can help address (Section 4).

[1] www.lsst.org

# 2 Gravitational-Wave Detectors in the Next Decade

Gravitational-wave networks are expected to both expand in number and increase in sensitivity over the next 5–10 years [11]. The first two observing runs included both of the LIGO interferometers [49, 3] as well as the French-Italian Virgo [13] interferometer. The third observing run will likely see the inclusion of a fourth site in Japan [KAGRA; 44], and a fifth site in India [LIGO-India; 41] is in the planning and construction stages with a 2024 operations date. By the middle of the decade, a five site, world-wide network will be operational, with a binary neutron star (BNS) merger detection horizon of approximately 400 Mpc. Current observational estimates of merger event rates for these systems range over 100 – 4000 $\mathrm{Gpc}^{-3}$ $\mathrm{yr}{-1}$ [46, 59, 71]. Taking the median of current estimates and the detection range quoted above, a year of GW network operations would yield a few tens of events. As sensitivity improves, BNS localizations are expected to shrink by at least an order of magnitude; from hundreds to tens of square degrees on the sky [4, 33, 57, 32].

Plans for going beyond the design sensitivity of second generation instruments include the A+ upgrade [15] for the LIGO instruments, as well as proposed third generation instruments such as LIGO Voyager and the Einstein telescope [60, 6]. The surveyed volumes for these instruments are at the $\mathrm{Gpc}^3$ scale, and will allow for hundreds to thousands of BNS detections. This sample will provide exquisitely precise measurements of the GW emission across the entire accessible bandwidth as well as commensurate contributions to our understanding of a variety of fundamental open questions [66, 73].

# 3 Targeted Follow-Up of GW Events with LSST

While GW170817 was detected with relative ease due to it's small sky localization ($\sim 28$ $\mathrm{deg}^2$) and luminosity distance ($D_L \sim 40$ Mpc), future detections may not be so straight-forward. This is particularly true as the sensitivity horizon of GW detectors pushes out to hundreds of Mpc or Gpc scales in the case of NS-BH mergers. In this regime, LSST is the instrument of choice due to its unmatched combination of wide field of view (9.6 $\mathrm{deg}^2$), depth and speed ($i \sim 25$ mag in 30s). Thus, LSST will be able to efficiently observe GW localization regions [20–80 $\mathrm{deg}^2$; 22, 57] and rapidly identify EM counterparts. The operations timescale for LSST is well matched to this goal with full science observations expected to begin in 2022 and continuing for 10 years.

The present LSST operations plan sets aside 5$\%$ of survey time for mini-surveys that require a special cadence. It is imperative that some fraction of this allocation go to target-of-opportunity observations in response to GW events. Such triggered observations are essential to ensure a large sample of joint GW-EM detections as the primary survey cadence is insufficient for the efficient detection of rapidly evolving transients [e.g., 28, 68, 51]. In addition to growing the sample of joint GW-EM detections, targeted observations with LSST have additional benefits such as the potential for detecting the optical counterpart at very early times. Such observations can provide key insights into the nature of the early-time emission [e.g., 52, 58]. This is particularly interesting in cases where strong BNS signals provide an "early-warning" [19, 20] potentially allowing observations to begin before the final merger occurs [14]. One challenge facing these deep follow-up observations is the presence of a background of transients unrelated to the GW event, particularly as observations increase in depth. However, these effects can be mitigated thanks to the unique temporal and spectral behavior of kilonovae [26, 28, 29].

# 4 Examples of Joint GW-EM Science

The field of joint GW-EM astronomy is rich with opportunity to study the Universe in new and exciting ways previously inaccessible to studies using just traditional EM observations. Here we briefly discuss just a fraction of these exciting possibilities:

## 4.1 The Growth of Joint GW-EM Cosmology

The tension between local measurements of $H_0$ and CMB measurements by Planck is now at 3.8 $\sigma$ (99.9%) [64] due to an improvement in the distance ladder using Gaia parallax and HST photometry. In light of this increasing tension, an independent measurement of $H_0$ is desirable as a potential resolution. Such an independent measurement is made possible by joint GW-EM science whereby GW signals provide a direct measurement of the luminosity distance of the GW sources and the EM counterpart provide a unique determination of the host galaxy and thus the redshift of the source. Combining these two pieces of information, one can measure cosmological parameters, including $H_0$ [67, 38]. The value of $H_0$ measured in this fashion is completely independent of other cosmological experiments, with its own unique systematics.

The first $H_0$ measurement using this technique was made following the detection of GW170817 and its associated optical counterpart [5, 37]. As more GW-EM joint detections are made the precision of our $H_0$ measurement will continue to increase significantly (Figure 2). It is expected that within the decade we will have a sufficient sample size to make a percent-level determination of $H_0$ which can potentially resolve the current tension [21]. In addition to BNS mergers, NS-BH mergers provide another potential candidate for GW-EM $H_0$ measurements. The precession of NS-BH binaries allow for a more accurate determination of the luminosity distance and therefore an even more precise $H_0$ measurement, assuming that an EM counterpart can be identified [74]. As the sensitivity of GW detectors continues to improve, GW sources at higher redshifts may eventually provide the leverage necessary to constrain other cosmological parameters through measurements of the distance-redshift relation beyond the local volume.

## 4.2 Unveiling the Sites of Cosmic $r$-process Production

Roughly half of the elements heavier than the iron group are produced by the rapid capture of neutrons onto lighter seed nuclei [the so-called $r$-process; e.g., 18]. However, the astrophysical site or sites where the $r$-process takes place has long been debated, with core collapse supernovae [e.g., 75] and binary NS mergers [48] being traditionally favored contenders. The kilonova transient following GW170817 was very likely powered by the radioactive decay of freshly synthesized $r$-process nuclei, providing the first direct evidence for its origin. Furthermore, given the large quantity of $r$-process material (of at least several percent of a solar mass) inferred from the light curve modeling, and the volumetric rate of BNS mergers implied by Advanced LIGO, one is already led to conclude that NS mergers are major, if not dominant, $r$-process sources in the Galaxy [e.g., 27, 31]. Nevertheless, given just a single event, it is not known whether the $r$-process yield of GW170817 was in fact "typical". Furthermore, other astrophysical events [e.g. collapsars; 70] may contribute to the $r$-process.

A future sample of kilonovae discovered by LSST following triggers from LIGO/Virgo will provide much better statistics on the diversity of $r$-process production from NS mergers. The colors

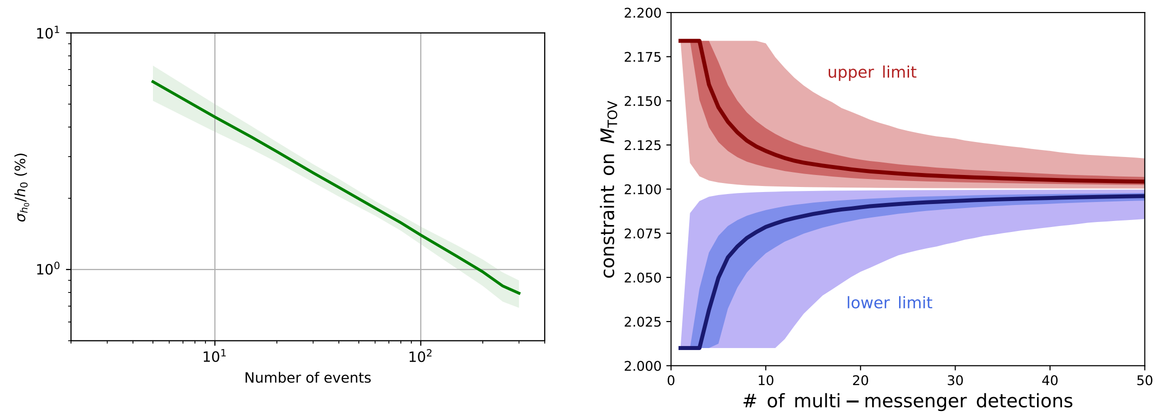


**Figure 2:** *Left Panel:* Hubble constant precision as a function of the number of joint GW-EM detections. *Right Panel:* Constraints on maximum neutron star mass, $M_{\rm TOV}$ (here assumed to be $M_{\rm TOV} = 2.1 M_{\odot}$), as a function of the number of joint GW-EM detections.

and spectra of the kilonovae provide key information on the detailed composition of the ejecta [e.g., 45], particularly the presence or absence of heavy lanthanide elements (atomic mass number $A \gtrsim 140$), which may vary from event to event, depending on the neutron richness (electron fraction) of the merger ejecta [e.g., 53]. The abundance patterns of individual $r$-process "pollution events" are measured in the spectra of metal-poor stars in the galactic halo [e.g., 39] or in dwarf galaxies orbiting the Milky Way [e.g., 43]. Searching for similar diversity in the the $r$-process signatures of kilonovae would help determine whether binary NS mergers were present and contributing to chemical enrichment in the early universe [e.g., 40].

### 4.3 New Constraints on the Neutron Star Equation of State

Despite significant efforts, the equation of state (EOS) of dense neutron-rich matter is fundamentally unknown. This property is key to understanding the physics of matter at extreme densities and the properties of NSs. The EOS is also essential input to numerical simulations of NS mergers and core-collapse SNe. However, most properties of the EOS are inaccessible to terrestrial laboratory experiments and currently incalculable from first principles QCD. As such, astrophysical observations of NSs remain the most promising avenue of probing the regime of dense matter.

The GW signal of binary NS mergers alone can provide important information about the radii of NSs [7, 30, 62, 55, 10] — a proxy for the pressure at $\sim$twice nuclear saturation density [47], however probing the EOS at even higher densities in the NS core remains difficult [though see e.g. 17]. Joint GW-EM observations of NS mergers (particularly the kilonova and gamma-ray burst emission) offer a fresh opportunity to probe this regime by using the electromagnetic signature to infer the fate of the merger remnant, e.g. when and whether a black hole forms. This approach was applied to GW170817, leading to stringent new constraints on the maximal mass of (cold, non-rotating) NSs [50, 69, 63, 65] as well as lower limits on the NS radius [16, 61, 25].

A larger statistical sample of joint GW-EM binary NS merger observations will further strengthen these constraints and provide invaluable insight into the behavior of matter at the highest densities. Figure 2 shows the predicted constraints (upper/lower limits) on the maximum NS mass, $M_{\rm TOV}$, as a function of the number of well-characterized joint GW+EM binary NS merger detections, simulated for a binary NS mass distribution drawn from the Galactic population. Future LSST discoveries of GW events, accompanied by dedicated ground or space-based EM follow-up efforts to ascertain the remnant fates, thus represents a powerful new probe on constraining the NS EOS and the only current method which can provide an *upper limit* on $M_{\rm TOV}$.

In addition to NS-NS mergers, the EM follow-up of mergers of BH-NS binaries can provide constraints on the NS radius and the properties of the BH complementary to those obtained through the GW signal alone. This is driven by the fact that the quantity of ejected mass (which can be measured from the kilonova emission) in BH-NS merger depends sensitively on the NS radius and the size of the BH event horizon [e.g. 35]. The presence or absence of luminous EM counterpart in a population of BH-NS merger, in addition to providing constraints on the NS radius given the GW-inferred mass and spin of the BH, is sensitive to whether the BH event horizon has the properties predicted by General Relativity.

### 4.4 Additional Science Drivers

In this white paper, we have touched on only a small fraction of the GW-EM science possible in the next decade. In reality, the potential for new discoveries is vast. This includes as of yet undetected GW sources, such as Local Group supernova [2] and neutron-star black-hole mergers [1, 71] which may also begin to emerge. In both cases, GW detectors provide complementary facilities to study complex physical phenomena such as accretion disks, jet physics, and the collapse of massive stars. Additionally, binary black hole (BBH) mergers are expected to form the majority (up to hundreds per year) of GW event catalogs. While not anticipated to be EM active, tentative links to gamma-ray emission have been made [24], and further detections will solidify or rule out these claims as well as constrain other models. This broad range of science possibilities means that LSST should remain available and flexible enough to respond to unexpected triggers.

## 5 Outlook For The Next Decade

We have presented a wide range of possible science goals using joint GW-EM astronomy that are achievable in the next decade. The common thread between all of these goals is that they require the dedicated allocation of resources. Specifically, they all require a large sample of joint GW-EM detections that enable deep statistical studies of both GW and EM sources. As outlined in Section 3, the use of GW triggered target of opportunity observations with LSST is the most efficient and effective approach to building up such a sample. We therefore reiterate our recommendation that significant effort and telescope time be dedicated to this task. This includes an appropriate fraction of LSST survey time along with the development of rapid response data brokers fine-tuned for GW follow-up. Ideally, LSST should also strive to interact with other telescopes [e.g., ELTs; 23, 36] to ensure that we obtain rich data sets spanning the entire EM spectrum. Data from these programs should be made promptly available to the entire community. Joint GW-EM astronomy has the potential to truly revolutionize the way in which we observe and understand the Universe, but only with the proper allocation of resources and opportunities.

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