

Discovery of Strongly-lensed Gravitational Waves – Implications for the LSST Observing Strategy

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Abstract

LSST’s wide-field of view and sensitivity will revolutionize studies of the transient sky by finding extraordinary numbers of new transients every night. The recent discovery of a kilonova counterpart to LIGO/Virgo’s first detection of gravitational waves (GWs) from a double neutron star (NS-NS) merger also creates an exciting opportunity for LSST to offer a Target of Opportunity (ToO) mode of observing. We have been exploring the possibility of detecting strongly lensed GWs, that would enable new tests of GR, extend multi-messenger astronomy out to $z \gtrsim 1$, and deliver a new class of sub-millisecond precision time-delay constraints on lens mass distributions. We forecast that the rate of lensed NS-NS mergers in the 2020s will be $0.9^{+0.9}_{-0.2}$ per Earth year, that the typical source will be at $z \simeq 2$, and that the multiply-imaged kilonova counterpart will have a magnitude of $AB \simeq 25.5$ in $g/r/i$ -band filters – i.e. fainter than LSST’s WFD depth. We therefore advocate (1) creating a flexible and efficient Target of Opportunity programme within the LSST observing strategy that is capable of discovering kilonova counterparts to lensed NS-NS mergers, and (2) surveying the entire observable extragalactic sky as rapidly as possible in the WFD survey. The latter will enable early science spanning a broad range of static and transient interests, and in particular will enable prompt discovery of a uniform and all-sky sample of galaxy/group/cluster-scale lenses that will underpin LSST strong-lensing science. This paper complements aspects of White Papers from DESC, SLSC, and TVSSC, that discuss kilonova, GW, and strong lensing.

1 White Paper Information

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1. Science Category:

- The Nature of Dark Matter and Understanding Dark Energy
- Exploring the Changing Sky

2. Survey Type Category: Wide-Fast-Deep, Target of Opportunity observations

3. Observing Strategy Category:

- other category: This paper seeks to highlight primarily the observing conditions constraints for the potential for target of opportunity follow-up of lensed gravitational wave sources. It is largely agnostic to the specifics of the short-term observing strategy to build up exposures for the WFD to full depth in general, but does support securing a full survey of the entire sky to single visit depth as soon as possible after the start of LSST operations.

2 Scientific Motivation

Discovery of the first strongly-lensed (i.e. multiply-imaged) gravitational wave (GW) will bring together two of the central predictions of General Relativity (GR) – gravitational waves and gravitational lensing. A single lensed GW source will therefore be a huge scientific breakthrough that enables a broad range of exciting science, including: the first glimpse of the stellar mass compact object binaries at $z > 1$, novel tests of GR aided by an increase in the number of GW detectors thanks to multiple detections of the same source, a new class of constraints on the mass distribution in galaxies and clusters, and the first so-called “standard siren” for cosmography at high redshift well before the advent of LISA and third generation GW detectors (see Smith et al. 2018b and references therein).

By 2022 LIGO/Virgo will have reached design sensitivity, and be detecting $\sim 10 - 100$ binary neutron star (NS-NS) mergers per year out to a typical distance of $D_L \simeq 200$ Mpc (Abbott et al. 2016; Chen et al. 2017). In the following few years, LIGO/Virgo’s sensitivity will improve by a further factor ~ 2 beyond design sensitivity, with typical sources detected at $D_L \simeq 400$ Mpc. At these distances a source with an electromagnetic counterpart similar to AT2017gfo/GW170817 will have an apparent magnitude of $AB \simeq 24.5$ in $g/r/i$ -band filters within $t_{\text{rest}} < 3$ days following GW alert (Arcavi 2018). In summary, LSST data of depth comparable similar to a single WFD survey visit will be sensitive enough to find large numbers of kilonova counterparts to NS-NS mergers that are not lensed well in to the 2020s. LSST follow-up observations of NS-NS mergers that are not lensed are discussed white papers from DESC and TVSSC.

We forecast a rate of lensed NS-NS mergers of $0.13_{-0.06}^{+0.2}$ per Earth year at the start of LSST survey operations, rising to $0.9_{-0.2}^{+0.9}$ per Earth year as LIGO/Virgo’s sensitivity improves beyond the current design sensitivity (Robertson et al. 2019). The typical lensed NS-NS merger will be located at $z_{\text{true}} \simeq 2$, and will be inferred by LIGO/Virgo to be a merger between two black holes (BHs) of mass $M_{\text{LIGO}} = 1.4(1 + z_{\text{true}})/(1 + z_{\text{LIGO}}) \simeq 4M_{\odot}$ at $z_{\text{LIGO}} \simeq 0.1$ ($D_{L,\text{LIGO}} \simeq 600$ Mpc; we refer to Smith et al. 2018b for details of how lensing affects interpretation of LIGO/Virgo data). The lens magnification suffered by GW sources cancels the inverse square law because the strain amplitude measured by LIGO/Virgo, A , goes as: $A \propto \mu^{0.5} D_L^{-1}$, where μ is the gravitational magnification. Therefore the brightness of the counterpart to a lensed GW source is set by the luminosity distance initially inferred by LIGO/Virgo when assuming $\mu = 1$. Therefore an AT2017gfo-like optical counterpart to a typical lensed NS-NS merger will have the same

apparent magnitude as a similar source located at $D_{\text{L,LIGO}} = 600 \text{ Mpc}$: $\text{AB} \simeq -13.5 + 5 \log(500 \text{ Mpc}) - 5 = 25.5$. In short, lensed GW science is impossible with data of WFD single-visit depth, because the transient nature of the targets requires them to be detected in a single visit, and the most sensitive filter will reach $\text{AB} \lesssim 24.5$ in a single WFD visit.

We therefore advocate creating a LSST Target of Opportunity (ToO) programme that is flexible enough to allow a small number of ToO follow-up observations of candidate lensed NS-NS that are deeper than WFD depth. We also advocate that the WFD survey commences with a reference survey of the entire observable extragalactic sky, with sufficient depth in g - and i -bands to enable it to be used as the reference imaging for discovery of lensed NS-NS/kilonovae.

3 Technical Description

3.1 High-level description

Our high-level requirements assume one candidate lensed NS-NS per year throughout the duration of LSST survey operations (full details of our calculations are in Robertson et al. 2019). We assume that these candidates are located at the typical forecast redshift of $z_{\text{true}} = 2$ and are interpreted by LIGO/Virgo (assuming $\mu = 1$) as being at $z_{\text{LIGO}} \simeq 0.1$, i.e. $D_{\text{L,LIGO}} \simeq 600 \text{ Mpc}$. When estimating the apparent magnitude of kilonova counterparts, we assume that the absolute magnitude of AT2017gfo and other kilonovae associated with short GRBs (Gompertz et al. 2018) are typical of kilonovae counterparts of high- z NS-NS mergers. We also conservatively assume that these candidates will be localized to a 100 degree^2 uncertainty by LIGO/Virgo. This is the median forecast localization uncertainty of GW detections relevant throughout the 2020s, as we wait for new GW detectors (e.g. LIGO-India) to come online (Abbott et al. 2016).

Based on these assumptions, the discovery of kilonova counterparts to multiply-imaged NS-NS mergers requires the following:

- **ToO imaging triggered by LIGO/Virgo events (~ 1 per year), with each ToO spanning a contiguous area of 100 degree^2 (12 pointings).** LSST is the only machine capable of surveying $\sim 100 \text{ degree}^2$ down to $\text{AB} \simeq 25.5$ within a timescale of a few nights following a GW alert;
- **Three epochs of observations per ToO through two filters (preferably g - and i -band, but g - and r -bands also acceptable)**

to constrain the colour and temporal evolution of candidate kilonovae, and thus exclude non-kilonova transients from further investigation (Cowperthwaite et al. 2018).

3.2 Footprint – pointings, regions and/or constraints

For strongly lensed NS-NS/kilonovae, the sky location and detailed design of the pointing strategy will depend on the details of an individual NS-NS sky localization from LIGO/Virgo. The sky localizations will be randomly distributed on the sky.

3.3 Image quality

We have no strong constraint on image quality for the first epoch of observations of lensed NS-NS ToOs, although sub-arcsecond is preferred. In the second and third epoch (preferably within two days of, and acceptable up to one week after GW alert), we prefer image quality no worse than the first epoch, however the timing constraint is more important than this preference.

3.4 Individual image depth and/or sky brightness

There will be no major constraints on image depth or sky brightness for the first epoch, because the main driver is timeliness — the first epoch must be as fast as possible after the GW alert. The second and third epochs must be within one week of the GW alert, and therefore could allow some flexibility in scheduling, image quality (see above), and sky brightness, in that we prefer conditions no worse than achieved in the first epoch. This would maximise the probability of re-detecting a transient source in data of the same integration time as the first epoch.

3.5 Co-added image depth and/or total number of visits

We request three epochs per candidate lensed NS-NS merger. Each epoch consists of 100 degree^2 imaging in two filters, with typically 6×30 second exposures per filter per epoch. This depth is required to reach $AB \simeq 25.5$. More precise target depths and numbers of exposures will be possible in response to specific candidates. The numbers given here are representative.

3.6 Number of visits within a night

Three epochs are required, with each epoch being completed within a single night. Each epoch comprises 12 pointings, observed through 2 filters. If it is not possible to complete an epoch within the night, then on any given night we prefer to observe a subset of the pointings through both filters in order to obtain contemporaneous colour information. In this situation, the remaining pointings should be completed on the following night.

3.7 Distribution of visits over time

3.7.1 Discovery of lensed NS-NS/kilonovae

The first epoch must be as fast as possible after the GW alert, preferably on the first available Chilean night. The second epoch is preferred on the first night following the GW alert, several hours after the first epoch. The third epoch is preferred on the second night following the GW alert. This optimal strategy will give the necessary colour and temporal information to distinguish kilonovae from other sources such as supernovae.

It is also important to be realistic, given weather and other scheduling constraints. The time dilation suffered by the source at $z \simeq 2$ therefore works to our advantage, as we can tolerate the first epoch being on the second night following GW alert, and the latter two epochs being spaced further apart, up to a maximum of ~ 7 nights following GW alert, before the putative kilonova fades from view.

3.7.2 A Deep and Early All-sky Reference Imaging Survey

In addition to a LSST ToO programme, discovery of lensed NS-NS/kilonovae requires a reference image of the entire extragalactic sky available to LSST as early in the survey as possible. It is desirable that this reference image would include g - and i -band imaging down to $AB \simeq 25.5$ in the early months of the survey. This depth is 1 mag fainter than the nominal single-visit depth, and will therefore require ~ 6 visits per filter. This “deep and early all-sky reference survey” strategy will deliver reference imaging sensitive enough to support the detection of a kilonova counterpart to a lensed NS-NS right from the beginning of the LSST survey. We select the g - and i -bands to provide a broad wavelength range for colour information on candidate kilonovae without straying in to the less sensitive $u/z/y$ -bands.

A less ambitious “all-sky reference imaging” strategy would be a key requirement for general strong lensing science for a variety of cases. This

strategy would ensure that all the available extragalactic sky observed in the g - and i -bands to single-visit depth at the beginning of the survey operations. This would be very powerful because single visit g - and i -band depth is sufficient for discovery of galaxy/group/cluster-scale strong lenses. Knowing where all the bright lenses early on in the WFD survey will allow us to identify lensed kilonovae/NS-NS quickly. This early census of lenses spanning galaxy- to cluster-scales will also be invaluable to constrain the run of optical depth to strong-lensing with lens mass, and thus to refine the observing and analysis strategies when searching for lensed GWs.

3.8 Filter choice

It is essential that we observe through two filters, and we prefer g - and i -band filters to maximize the wavelength range over which we will be able to obtain colour information, without sacrificing sensitivity by going to $u/z/y$ -band filters. This colour information is required to exclude non-kilonova transient sources, as discussed for example by Cowperthwaite et al. (2018).

3.9 Exposure constraints

No constraints.

3.10 Other constraints

We request a flexible ToO mode be implemented in the general LSST observing strategy. Optimally, we request ToO observations of ~ 100 degree² down to AB $\simeq 25.5$, deeper than the single visit depth. Given that these will be areas that would be covered by the WFD strategy anyway, a mechanism for triggering (modified) observations from the standard WFD survey tiles that would encompass the full LIGO/Virgo localization and meet the depth and cadence requirements outlined in this White Paper should be explored. This would allow the ToO observations to also be used as part of the WFD survey, thereby minimizing the impact of interrupting the WFD observing schedule, and reducing the effective cost of the proposed ToOs.

3.11 Estimated time requirement

Based on the assumptions listed in Section 3.1.2, we detail the amount of observing time required per candidate lensed NS-NS below:

- Simultaneous slew to first field and change filter to i if necessary: 120 seconds

- Visits to all 12 pointings in the i -band: $(30\text{sec} + 3\text{sec slew/settle} + 2\text{ sec shutter open/close}) \times 12 \times 6 = 2520$ seconds
- Change filter to g -band: 120 seconds
- Repeat observing in g -band: 2520 seconds
- Return LSST system to its previous state (simultaneous slew and filter change): 120 seconds

This totals 5400 seconds, i.e. just 1.5 hours, per epoch. For three epochs per trigger, this equates to 4.5 hours per trigger. At one such trigger per year for ten years, this equates to 45 hours, which is just 0.2% of the total time ($3650 \text{ nights} \times 0.83 \text{ uptime} \times 8 \text{ hours/night} = 24236 \text{ hours}$) available.

Properties	Importance
Image quality	2
Sky brightness	3
Individual image depth	2
Co-added image depth	2
Number of exposures in a visit	1
Number of visits (in a night)	1
Total number of visits	1
Time between visits (in a night)	2
Time between visits (between nights)	1
Long-term gaps between visits	3

Table 1: **Constraint Rankings:** Summary of the relative importance of various survey strategy constraints. Please rank the importance of each of these considerations, from 1=very important, 2=somewhat important, 3=not important. If a given constraint depends on other parameters in the table, but these other parameters are not important in themselves, please only mark the final constraint as important. For example, individual image depth depends on image quality, sky brightness, and number of exposures in a visit; if your science depends on the individual image depth but not directly on the other parameters, individual image depth would be ‘1’ and the other parameters could be marked as ‘3’, giving us the most flexibility when determining the composition of a visit, for example.

3.12 Technical trades

There are no obvious trades for lensed NS-NS/kilonova discovery because they are based on ToO observations.

4 Performance Evaluation

Our science goals will be achieved if the full sequence of observations across three epochs is completed within the required timescales.

Each ToO trigger will be scored on a scale from 0 to 36. The score is incremented by 1 when a pointing has been observed through both filters for the required 6×30 seconds within the required time constraints (< 2 days from GW alert for epoch 1, < 4 days from GW alert for epoch 2, and < 7 days from GW alert for epoch 3). Successful completion of one pointing in all three epochs therefore scores 3. With 12 pointings required to observe the full 100 degree^2 sky localisation, the maximum score is 36. We define a ToO as successful if it scores ≥ 27 on this system.

We will design the layout of the pointings such that they prioritise observations of the central regions (higher probability) of the LIGO/Virgo sky localisation over the lower probability regions. In this way, the impact of partial completion of the ToO programme on statistical inferences relating to detection of a kilonova counterpart can be estimated in a meaningful way.

5 Special Data Processing

Data processing will be the same as the standard LSST pipeline except that the 6 exposures per filter per pointing per epoch will need to be stacked before subtracting the relevant reference images. A custom filter may be required to run on the resulting alert stream, that detects candidate lensed kilonovae based on their colour, time evolution, and proximity to individual early-type galaxies or groups/clusters of galaxies that are acting as the foreground lens.

6 References

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