Quantifying the Impact of Standard Sirens for DESC Cosmology Results

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Motivation

The multi-messenger observations of Bright Standard Sirens are expected to play a crucial role in precision cosmology during the LSST era. We want to determine the **expected contribution** of such discoveries to our cosmology analyses by quantifying the **constraining power** of this probe.

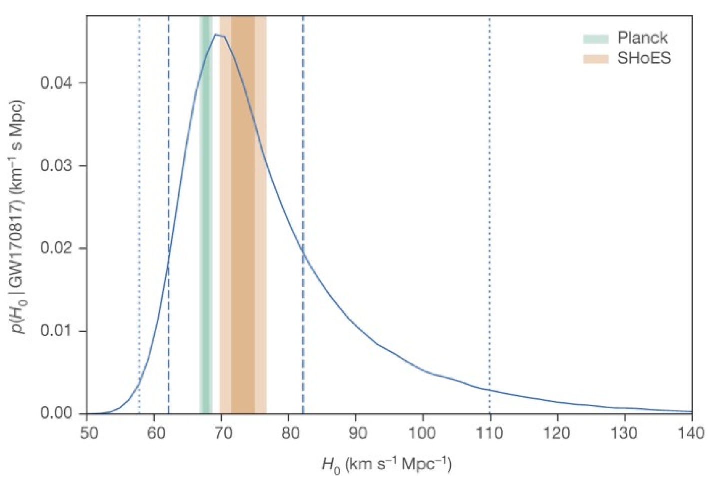

Figure 1. Hubble constraints from GW170817 (Abbott+ 2017)

The launch of LSST in 2025 begins a decade-long survey that overlaps with **upcoming LIGO/Virgo upgrades** and next-generation GW detectors like **Einstein Telescope** and **Cosmic Explorer**. This convergence offers a key opportunity to detect binary neutron star mergers and follow them up optically with LSST. Forecasting LSST's capabilities will clarify its role in multi-messenger cosmology and **guide DESC resource planning** to **maximize scientific return**.

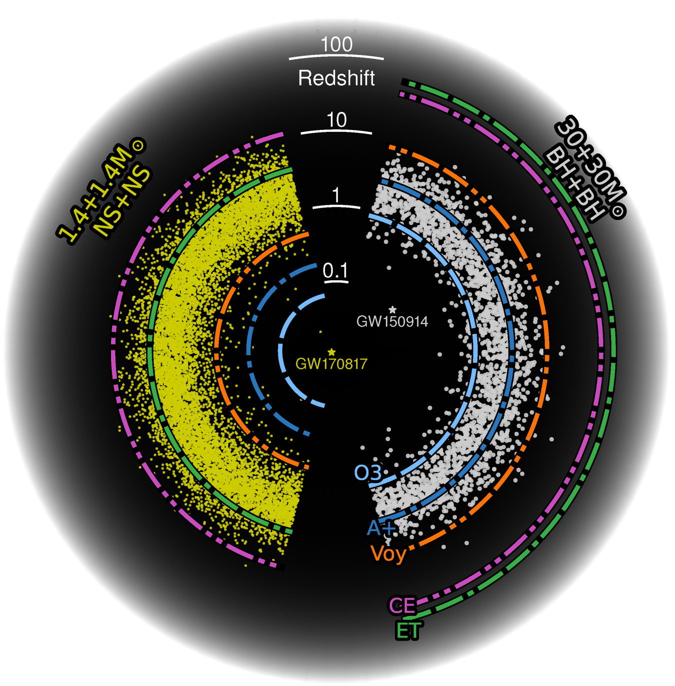

Figure 2. Expected improvement in BNS and BBH detections with future GW detectors (Hall , E. D. 2022).

Project and Approach

We assess LSST's capability to detect optical counterparts of GW-detected BNS mergers through **end-to-end simulations of astrophysical populations and follow-up performance.**

- *Gravitational Wave Simulations:* Realistic BNS populations with parameter forecasts via **Fisher analysis**.
- *Electromagnetic Counterparts:* **Kilonova modeling** using ejecta parameter mappings and **Bulla radiative transfer models**.
- *Cosmological Inference:* **Joint GW–EM analysis** for detectable events, incorporating **selection effects** to constrain cosmological parameters.

GW Simulation Pipeline

Gravitational Wave Simulations of Binary Neutron Star (BNS) events

- Population Distributions:
  - **Redshift distribution:** Madau-Dickinson profile × time-delay distribution (power law) with minimum delay of 20 Myr.

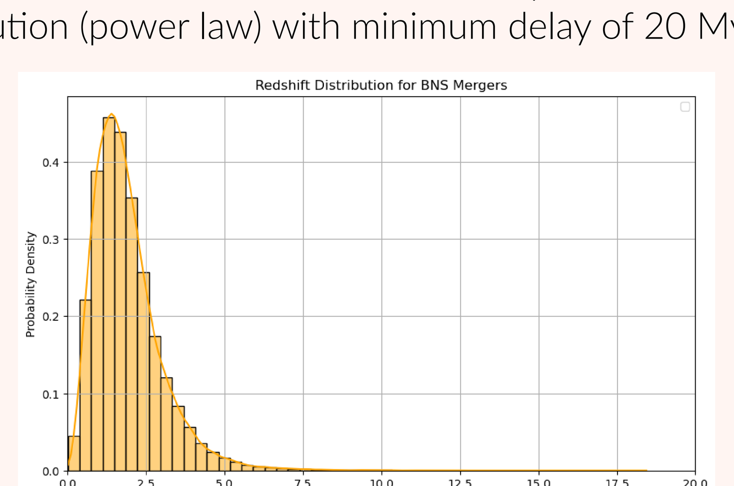

Figure 3. Redshift distribution of BNS events

GW Simulation Pipeline

- **BNS parameter distributions** are based on simulations done in [3]. Refer to the table 1 for more details.

Parameter	BNS Distribution
m_1, m_2	uniform in $[1, M^*_{\text{TOV}}]\, M_\odot$
d_L	from z using Planck18, flat ΛCDM
$\chi_{1,z}, \chi_{2,z}$	uniform in $[-0.05, 0.05]$
χ_x, χ_y	0
Λ_1, Λ_2	uniform in $[0, 2000]$
θ	uniform in $[0, \pi]$
ϕ, Φ_c	uniform in $[0, 2\pi]$
ι	$\cos(\iota)$ uniform in $[-1, 1]$
ψ	uniform in $[0, \pi]$
t_c	uniform over 10 yr

Table 1. Distributions used for BNS population parameters.

* $M_{\text{TOV}} = 2.06\, M_\odot$ for SFHo EoS for neutron stars.

- **GW detectors:** We plan to simulate expected number of events from future LVK upgrades and 3G detectors like Einstein Telescope.

Detector	Operations	Luminosity Distance (Mpc)	BNS Mergers/Year
O4c	Now – Nov 2025	150–160	–
LIGO A+ (O5)	Late 2027–2029	∼330	1–10
LIGO A# (O6)	2031–2033	330–1000	10–100
LIGO Voyager	2030s	∼1000	100–1,000
Cosmic Explorer	2030s	∼10,000	500-3,000
Einstein Telescope	2035–	∼40,000	10,000–100,000

Table 2. Expected forecasts for BNS merger rates for future observatories.

- **Fisher matrix analysis for parameter constraints:**
  1. We use GWFAST software [3] to obtain Fisher approximation matrices, SNRs and sky localization for BNS events.
  2. We discard all the events with SNR < 12

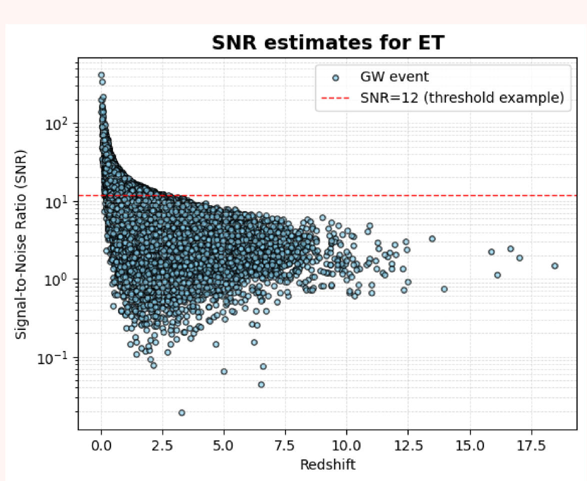

Figure 4. SNRs for 1 yr of observations of BNS events (10^5) by Einstein Telescope calculated with GWFAST.

3. Fisher matrices are often ill-conditioned for inversion. We remove events that have inversion error > 0.05 following [3].
4. We discard events have 1σ error extending beyond physical range of parameter.

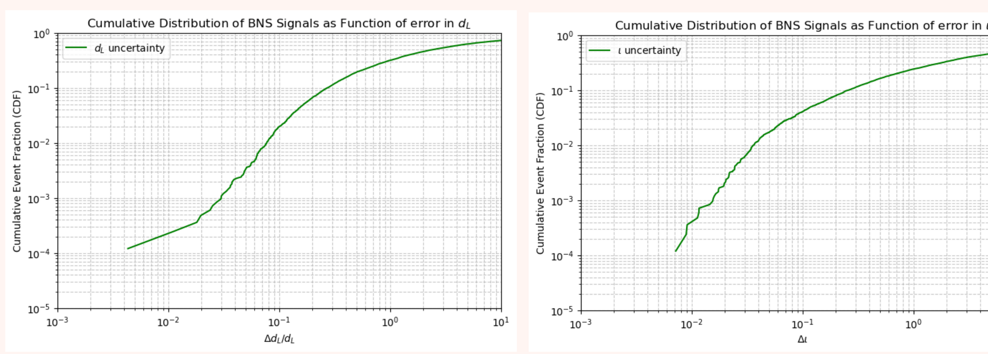

Figure 5. Uncertainties in d_L and ι from Fisher Analysis

Selection Step	Events Remaining
Total simulated events (with ET)	10^5
SNR ≥ 12	8,598
Successful Fisher calculation	8,560
Fisher matrix inversion error < 0.05	8,306
1σ error within physical ranges of d_L and ι	2,844

Table 3. Event counts after successive quality cuts in the GW analysis.

5. **Sampling observations:** For each event, we draw samples from a multivariate Gaussian distribution centered at true values of d_L and ι with uncertainties from the covariance matrices.

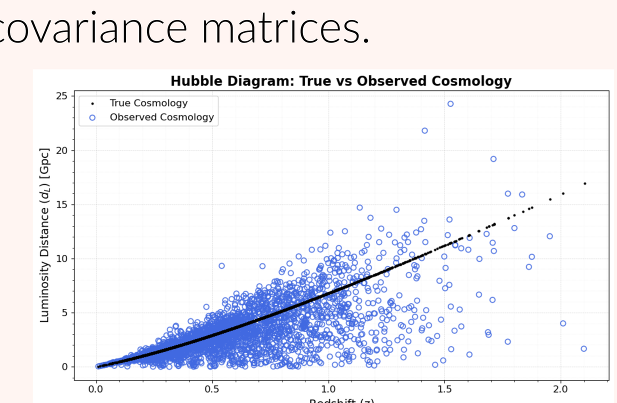

Figure 6. Hubble diagram for true GW info vs sampled values of d_L

EM Simulation and Modeling

EM counterpart modeling and LSST detection criterion

To generate a realistic population of kilonovae (KNe) from BNS events and evaluate their detectability with LSST, we adopt the following approach:

1. **Parameter Mappings:** We map the GW parameters of the BNS to the KN parameters using the empirical relationships in [4].

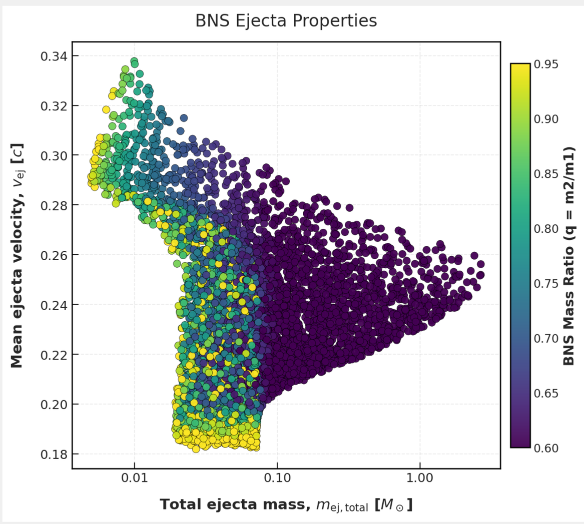

Figure 7. BNS Ejecta parameter distribution properties obtained using [4].

2. **SED Approximations:** We plan to follow [2] to obtain approximated Bulla SEDs and lightcurves for the BNS events using an SED approximation.
3. **LSST Detectability:** To check if the lightcurves are detectable by LSST, we plan to follow the approved Rubin ToO strategy [1] as a realistic criterion for detection of the EM counterpart of our BNS events.

Type	Night(s)	Filters	Exp. Time (s)	Scans	Triggers	Total Time
Gold (3-filter + deep)	0 1–3	g, r, i r, i	120 180	3 1	16	144 hrs
Silver	0 1–3	g, i (or g, z) g, i	30 120	1 1	6	96 hrs
Grand Total						**240 hrs**

Table 4. Combined strategy details and total time recommendation for BNS and NS-BH ToO follow-up during LVK O5 run [1].

Work in Progress

This study forms the foundation for a broader investigation into LSST's role in GW follow-up and cosmological inference.

Ongoing and future developments include:

EM Modeling and Detection criterion:

- Implementation of Rubin ToO strategy are in progress.
- Plans to consider effect of LSST cadence to simulate realistic scheduling constraints.

H_0 Inference and Selection Effects:

- Identified multiple selection effects that can bias H_0 inference with LSST:
  - GW detection: SNR threshold, duty cycle, detector upgrades, etc.
  - EM follow-up: sky localization, ToO strategy, observing conditions, etc.
- Incorporate these effects for realistic H_0 constraints

These extensions are underway and aim to support DESC cosmology goals during the LVK O5 run and beyond.

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