Predicting Kilonovae From LVK Gravitational Wave Candidates

Jacob Markus, Andrew Toivonen, Michael Coughlin

University of Minnesota College of Science and Engineering

Background

Gravitational waves are the fluctuations in space-time produced by accelerating masses and are difficult to detect. Only recently, first done in 2015 by the LIGO-Virgo-KAGRA (LVK) collaboration with the GW150914 detection [1], have gravitational waves become detectable, and a viable form of astronomy. This detection, and most detections since, have been from the mergers of black holes orbiting in binary systems. Detecting gravitational waves is difficult, as fluctuations in length due to them are on the order of 1/10,000th the width of a proton by the time they reach the Earth.

LVK detects gravitational waves by using lasers that travel 4km before being reflected back and are set up to destructively interfere with themselves in the absence of gravitational waves. A gravitational wave that passes through will stretch space, causing the laser to no longer perfectly destructively interfere with itself, and some light from the laser will be detected, signifying the detection of a gravitational wave.

Gravitational waves can be detected from the mergers of binary systems involving a black hole and a neutron star (NSBH) and binary systems involving two neutron stars (BNS), in addition to systems involving two black holes (BBH). However, NSBH and BNS detections are much rarer, and we have only a small number of confirmed detections, due to the smaller masses of neutron stars compared to black holes yielding fainter gravitational waves.

These BNS and NSBH events are of particular interest to us, as they can produce kilonovae, the signature arising from the nuclear reactions that take place in the mass ejected in neutron star mergers, as seen with the BNS merger GW170817 [2], the thus far only joint detection of a gravitational wave event and its kilonova. Kilonovae are important to study, as they can produce heavier elements through r-process nucleosynthesis and provide insight on the origins of these heavier elements in the universe.

Additionally, combining the gravitational wave and electromagnetic data of the resulting kilonova is useful for determining the mass-radius relation, otherwise known as the equation of state, of a neutron star, something that is not precisely known. However, with the rarity of detecting NSBH and BNS mergers and the fact that kilonovae are only visible for short periods of time, it is difficult to detect both the gravitational and electromagnetic waves of these events at the same time. Astronomers carry out extensive follow-up searches for electromagnetic counterparts to promising gravitational wave candidates.

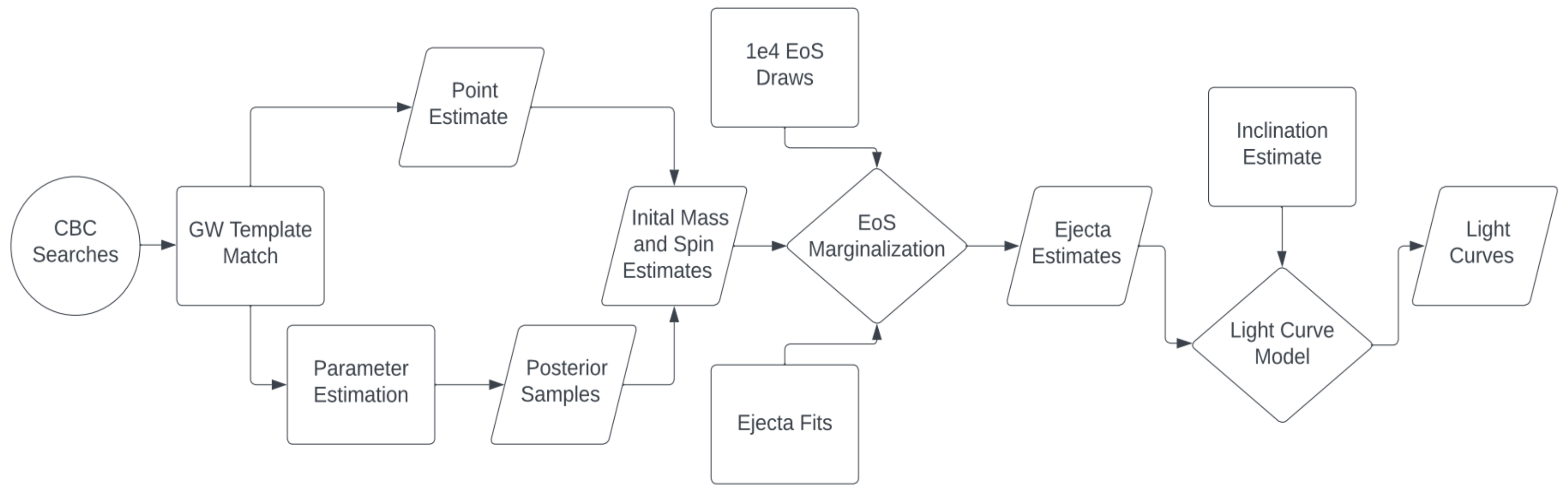


Figure 1. Overview of the workflow for producing light curves from an LVK gravitational wave detection candidate. Mass and spin are estimated and are then used to produce ejecta estimates by marginalizing over equation of states (EoS). Inclination angles are also estimated, yielding light curves.

Light Curve Production Method

How can we predict whether a gravitational wave detection will result in a detectable kilonova?

- Parameter estimation software such as Bilby [3] estimate the mass and spin of the binary system from the original detection.
- 10,000 potential neutron star equation of states are combined with the estimated mass and spin parameters to produce estimates on the mass of the ejected material.
- The amount of ejecta affects the light curve of a potential kilonova, so a range of estimated light curves are produced for each detection.

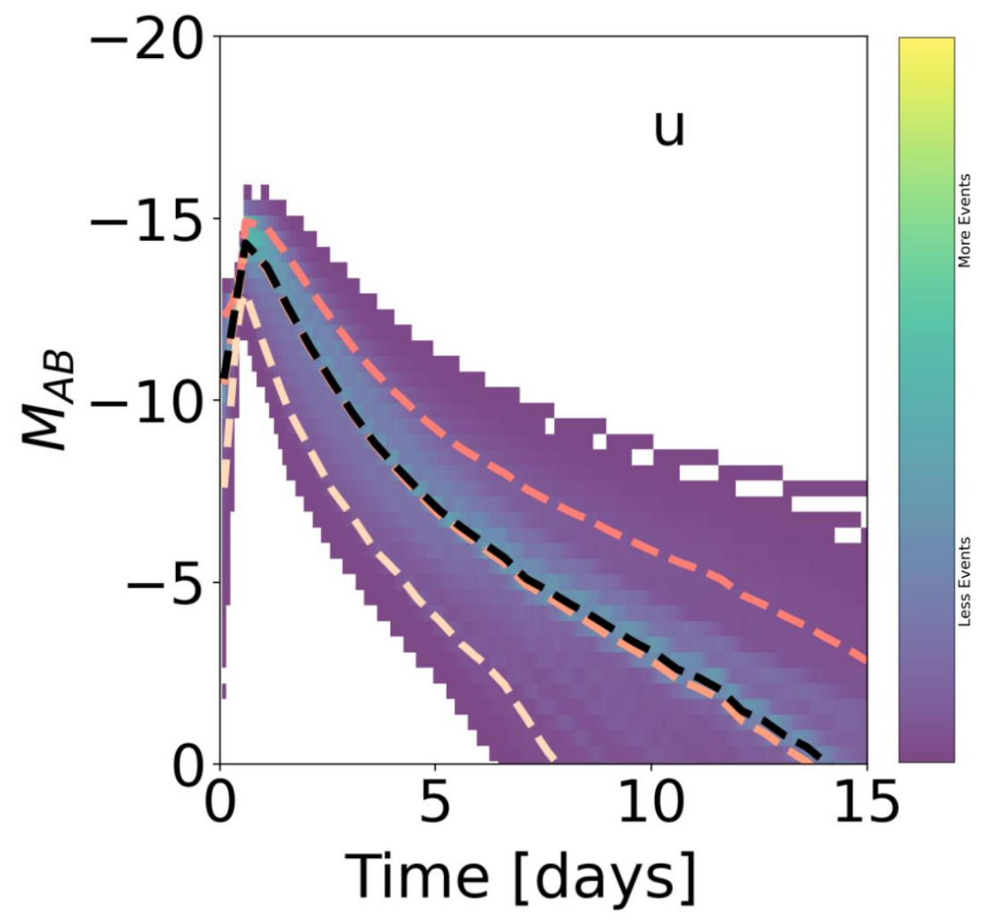
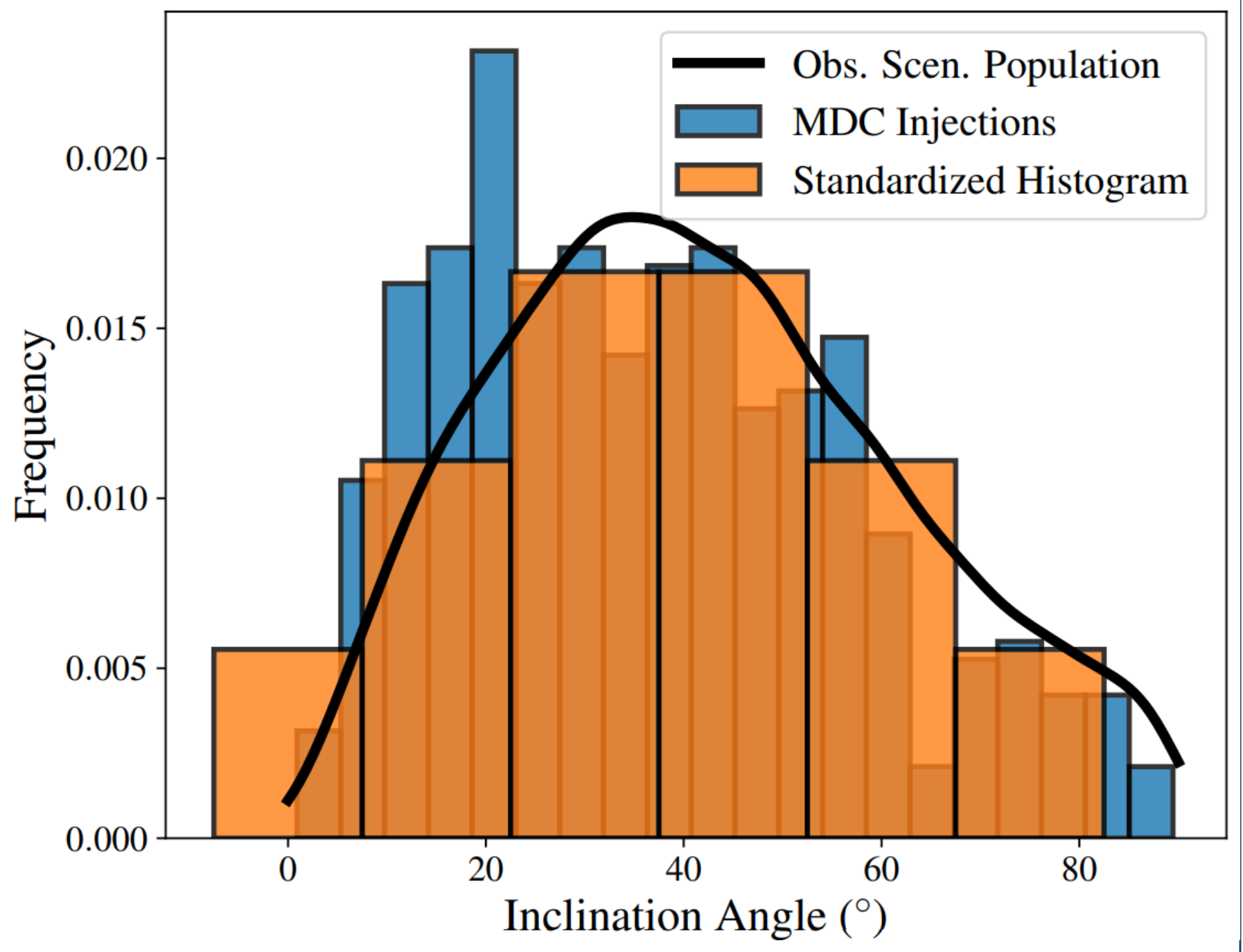


Figure 2. An example of a light curve heat map in the *u* band, where absolute magnitude of the kilonova is plotted against time. The density of predicted light curves is shown by the color gradient, with dotted lines showing the 95th, 50th, and 5th percentiles, as well as the Sly predicted light curve in black.

- The inclination angle of the kilonova, the angle that we view it at relative to the normal of the orbital plane, also affects the light curve.
- The distribution of inclination angles used to generate light curves should match the observed scenarios population distribution [4].
- We draw from a histogram, with angles of 0, 15, 30, 45, 60, and 75 degrees, and respective frequencies closely matching the observed distribution.
- While this is not a perfect representation of the simulated distribution, it saves valuable computation time and reduces random noise.

Figure 3. Comparison of the observed scenarios population distribution, shown in black, and the histogram that inclination angles are drawn from, shown in orange. A histogram of mock data challenge (MDC) inclination angles that resulted in significant ejecta is also shown in blue.



Results

- When using this method, lower mass binary systems in the BNS range produce brighter light curves.

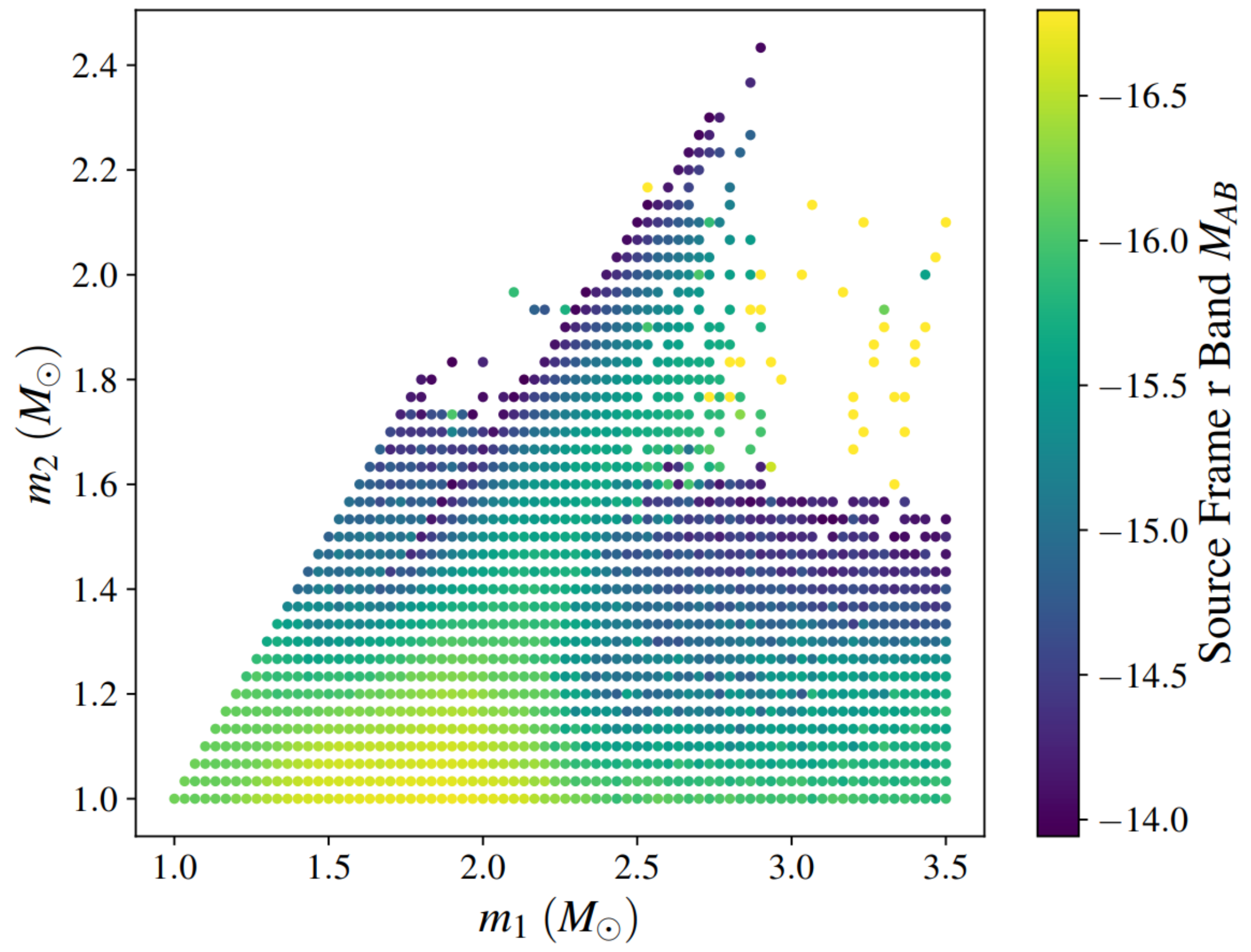


Figure 4. Scatter showing the peak *r* band absolute magnitude for light curves produced from injected mass pairs.

- Light curves produced by this method approximately match light curves produced using the SLy equation of state [5].
- The SLy equation of state is supported by GW170817, so is used as a reference for light curves consistent with our current knowledge.
- When testing with MDC events (artificially produced sets of data resembling real LVK gravitational wave detections), the light curves produced contain the SLy prediction within the 90% credible interval.

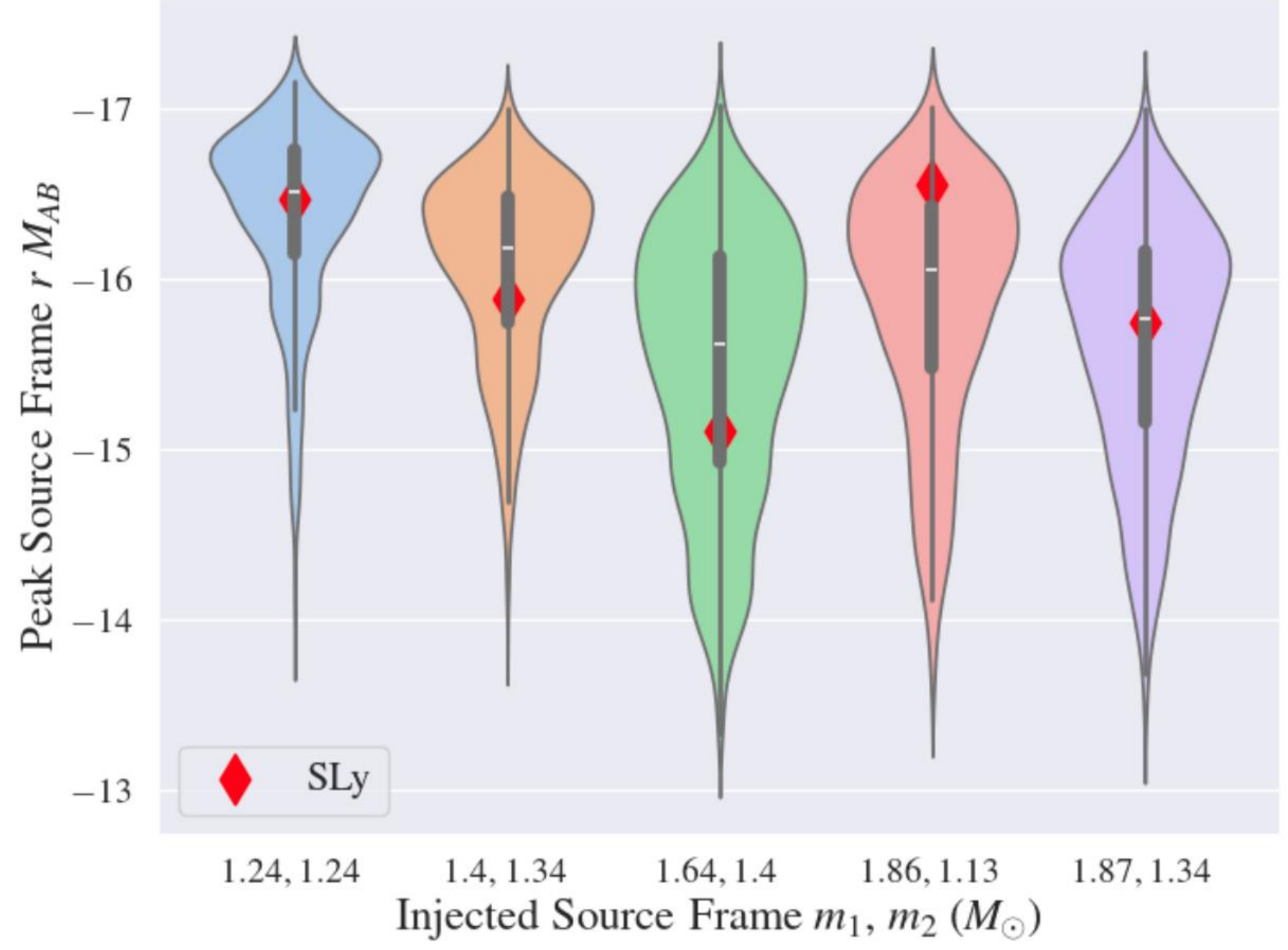


Figure 5. Violin plots displaying peak *r* band absolute magnitude of light curves produced from MDC events, with the corresponding SLy produced light curve overlaid in red. The different mass pairs shown cover a range of plausible BNS binary systems.

References

1. Abbott et al., "Observation of gravitational waves from a binary black hole merger," Phys. Rev. Lett., vol. 116, p. 061102, Feb 2016.
2. Abbott et al., "Gw170817: Observation of gravitational waves from a binary neutron star inspiral," Physical Review Letters, vol. 119, Oct 2017.
3. Ashton G., et al., 2019, The Astrophysical Journal Supplement Series, 241, 27
4. Coughlin M. W., Farah A., Emily Abigail Singer L. P., Weizmann R., 2022, LIGO/Virgo/KAGRA Observing Capabilities: Simulated Detections and Localization for O4 and O5 (October 2022 edition), doi:10.5281/zenodo.7026209, https://doi.org/10.5281/ zenodo.7026209
5. Chabanat E., Bonche P., Haensel P., Meyer J., Schaeffer R., 1998, Nuclear Phys. A, 635, 231

Acknowledgements

We acknowledge support from the University of Minnesota Undergraduate Research Opportunities Program, as well as from the National Science Foundation with grant numbers PHY-2308862 and PHY-2117997