Estimating the luminosity distance and mass properties of BBH merger events in LIGO O4 data

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Abstract

The Laser Interferometer Gravitational Wave Observatory (LIGO) has recently received significant experimental upgrades which are expected to greatly increase the sensitivity of the instrument and allow for a much deeper survey of gravitational wave events in our universe. In this work, we present an analysis that confirms the expectation that the current operational state of LIGO (O4) is capable of detecting binary black hole (BBH) events which are of lighter masses and of further distances than the previous state of the detector (O3) was capable of detecting. We first present our physics-inspired model that allows us to carry out a comparative analysis between the O3 and O4 BBH event data. We have specifically developed this model to make predictive estimates of the luminosity distances of these events in O4. We demonstrate this model accurately estimates the luminosity distance values of O3 to within 20% of their recorded values and apply this model to O4 to infer luminosity distance values for its catalog. With this data, we draw correspondences between the parameters of the O3 and O4 BBH events to demonstrate an increased survey depth in O4.

Introduction and Background

- Gravitational waves were first predicted by Einstein's theory of General Relativity in 1916
- These "ripples" in spacetime are commonly caused by merging binary systems (black hole and neutron star pairs)
- First detection of gravitational waves was made by LIGO in 2015
- LIGO operates between observing runs
  - O3 denoted its third observing run (lasting from April 2019 - March 2020)
  - O4 denotes the current observing run (which began in May of 2023)
- O3 identified 90 events by a global network of detectors and O4 has detected 84 events to date

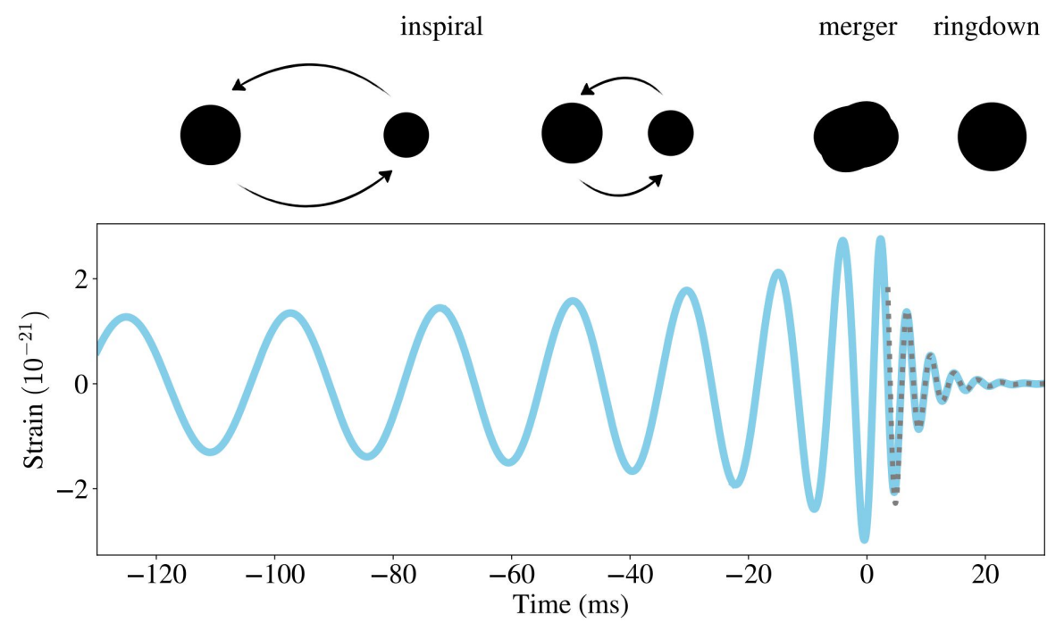

Figure 1: Expected waveform from a binary inspiral broken into its three phases [1]

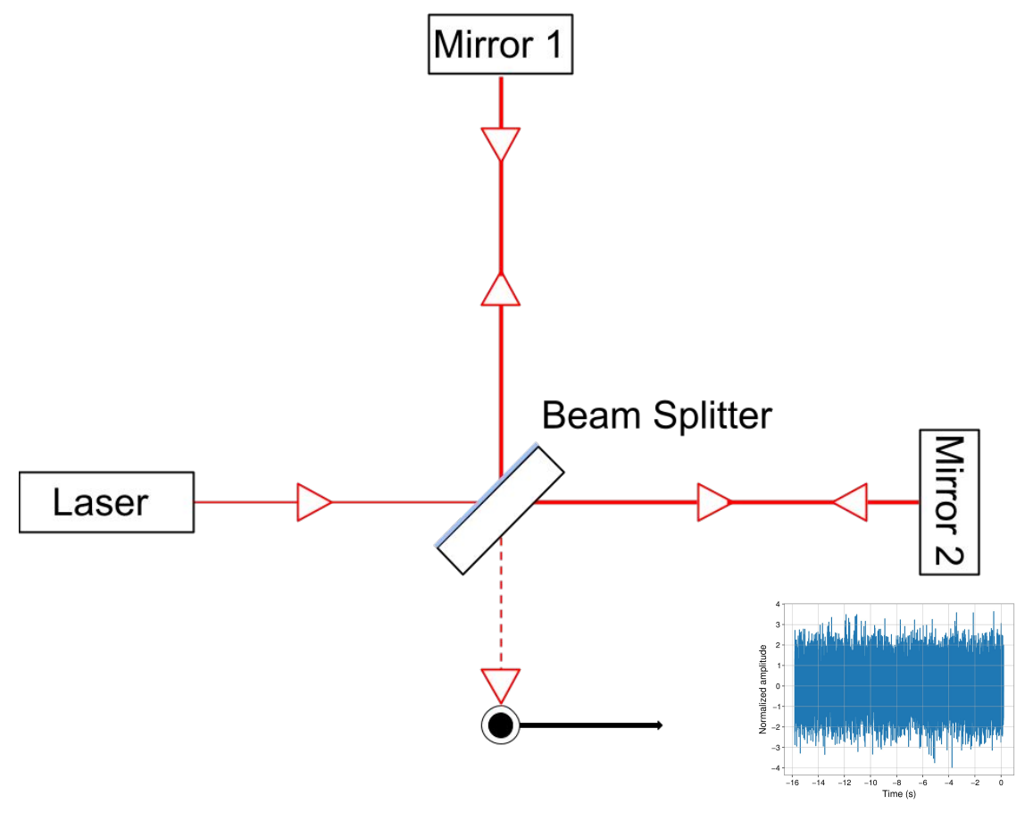

Figure 2: Basic LIGO schematic and its signal

Model

- Signal to Noise Ratio (SNR) measures LIGO's response to a gravitational wave
  - It depends on the inherent energy of an event, our distance to that event, and the noise of the detector
- The inherent energy of an event is almost purely dependent on the component masses of the event
  - As the component masses increase, the energy exerted in gravitational waves will increase
- Gravitational wave energy will spread over space by an inverse square law and its luminosity distance (approximate to physical distance) is given by Ref. [2]:

$$D_L \sim 45\ \mathrm{Gpc}\left(\frac{\mathrm{Hz}}{f_{\mathrm{GW}}|_{\max}}\right)\left(\frac{10^{-21}}{h|_{\max}}\right)$$

- We expect the luminosity distance to be proportional to some function of mass scaled by the SNR of the event where this function captures the inherent energy of the event

$$D_L = \frac{f(M_{\mathrm{chirp}})}{\mathrm{SNR}}$$

- We expect this mass function to be a basic power law scaled by some unknown constant since the inherent energy of every event will be dependent on the duration of the event and the masses along with the component spins and masses. Spin contributes minimally to the SNR while template duration is also a function of mass, being inversely proportional to M. As such, we assume the form:

$$f(M_{\mathrm{chirp}}) = k \cdot M_{\mathrm{chirp}}^N$$

Examining the O3 data

- At a given D_L, we see events grouped by a vertical spread where M_{chirp} is inversely proportional to SNR
- At a given SNR, we see events grouped by a horizontal spread where, as SNR increases, events become more massive
  - At a given SNR, as D_L increases events become more massive
- SNR and D_L are inversely proportional
- Our model accounts for the phenomena:
  - If SNR is fixed, higher mass events must be more distant than lower mass events
  - Higher SNR events must be less distant than lower SNR events

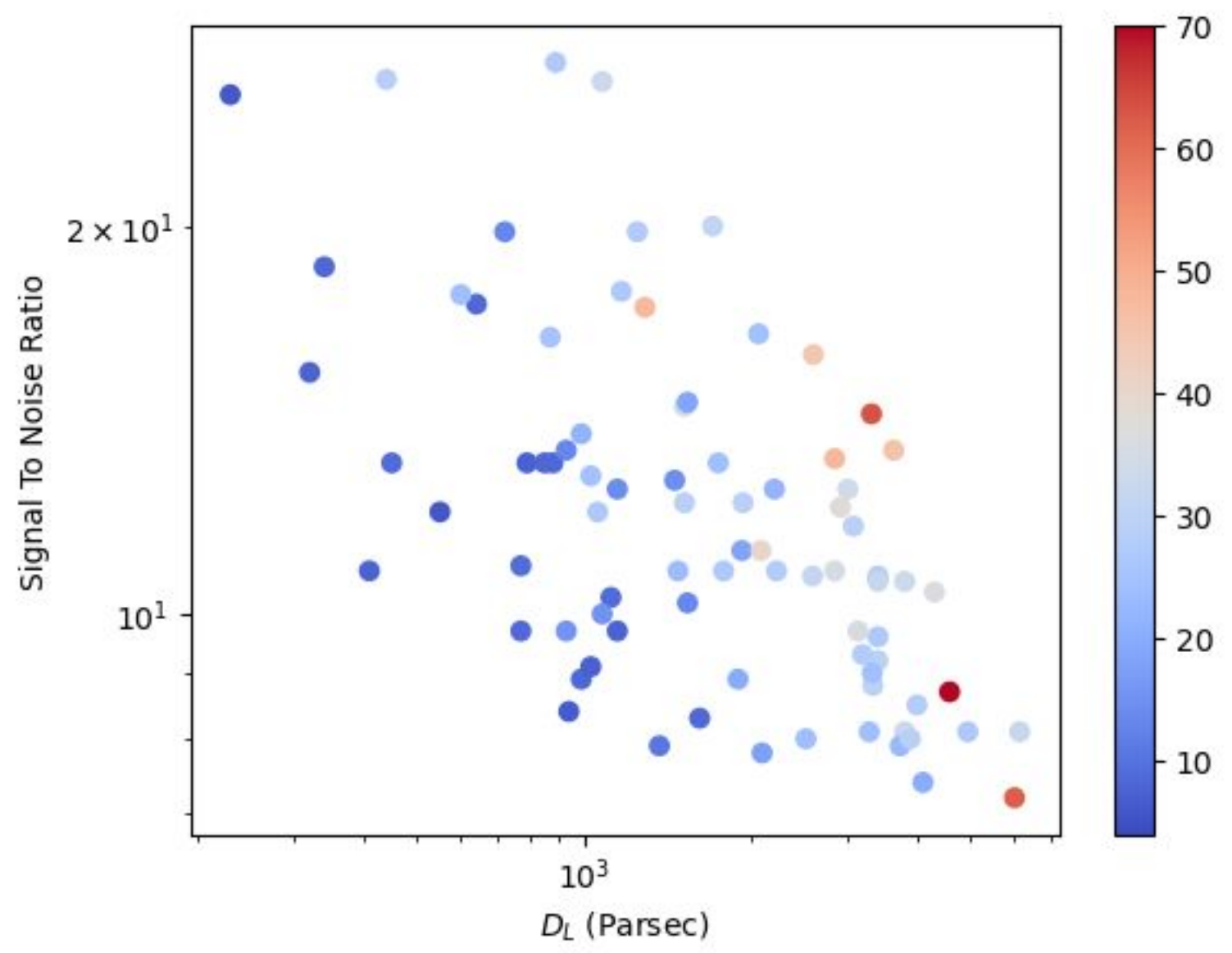

Figure 3: Log scale comparison of SNR and D_L in O3

Analysis of O3 data

- We can use these basic facts to construct a predictive model for the luminosity distance of an event:

$$D_L \approx \frac{M_{\mathrm{chirp}}^N}{\mathrm{SNR}} e^b$$

- M^N is a power law function of mass whose exact form is unknown
- e^b is a proportionality constant that converts a ratio of energy to a D_L and includes our neglect of other parameters such as spin and template duration

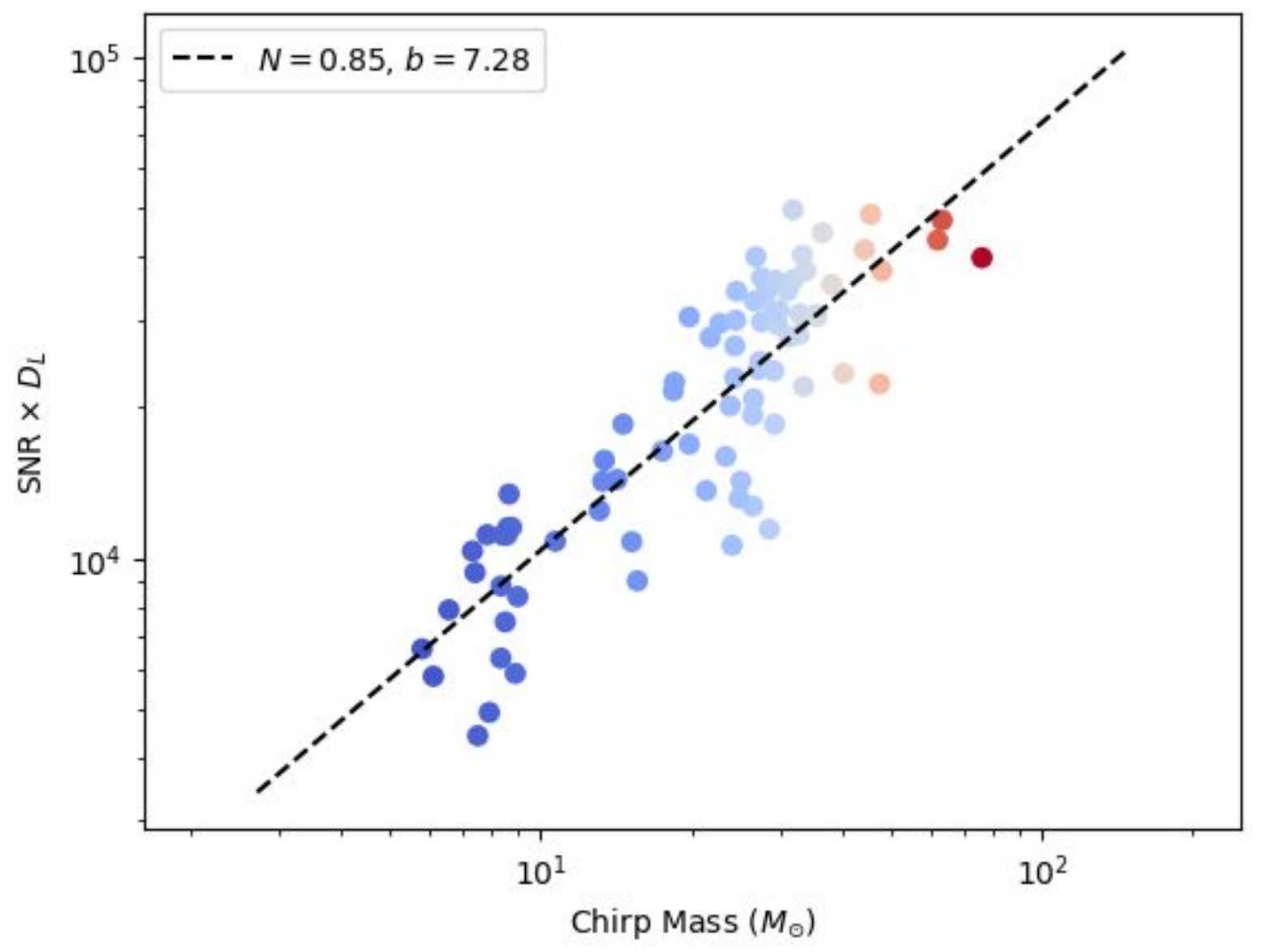

Figure 4: Fitting our model using O3 data

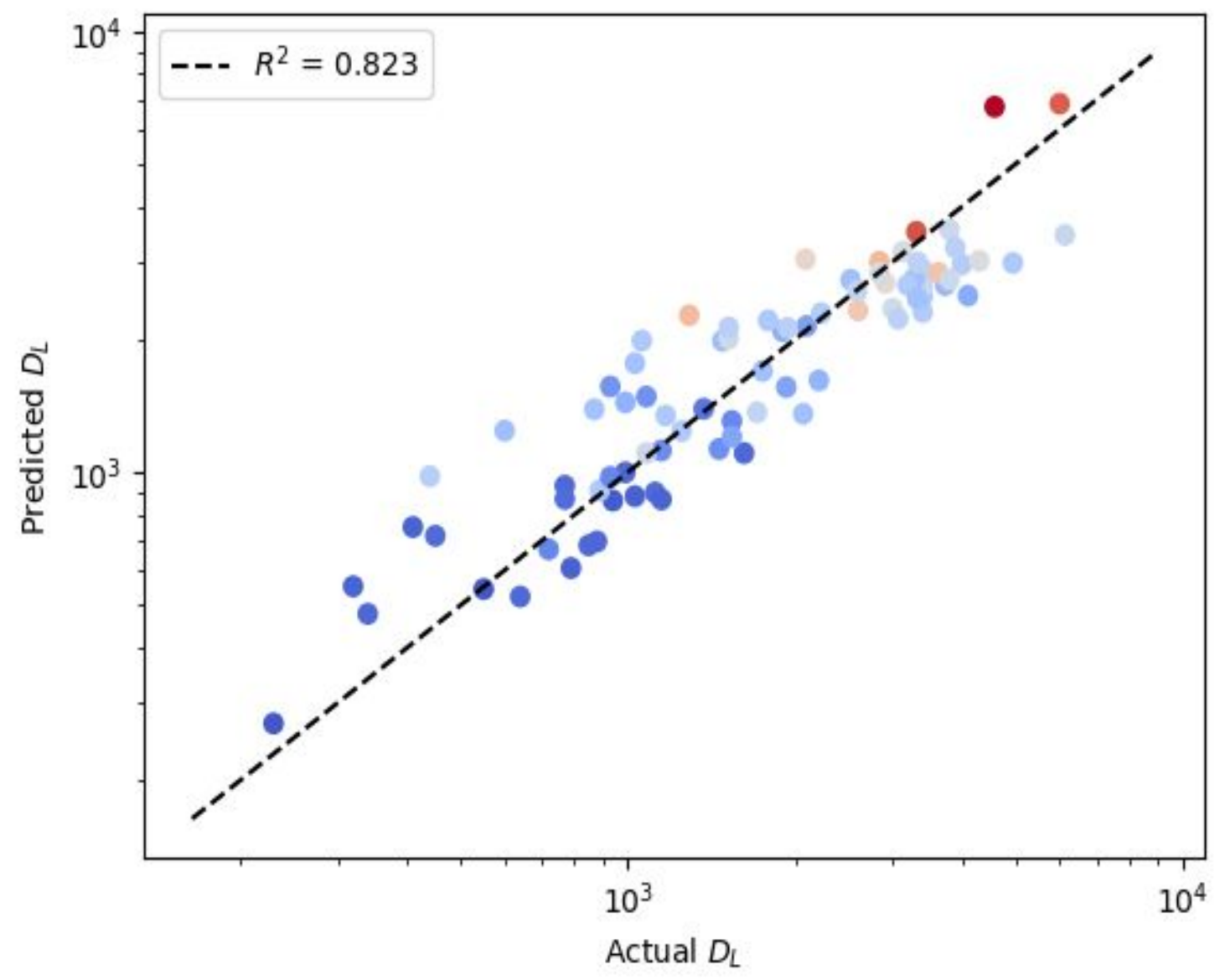

Figure 5: Comparing model retrieval of D_L.

Parameter Estimates/Residuals

- We show our model is able to retrieve D_L with an accuracy of ~20% for O3 events

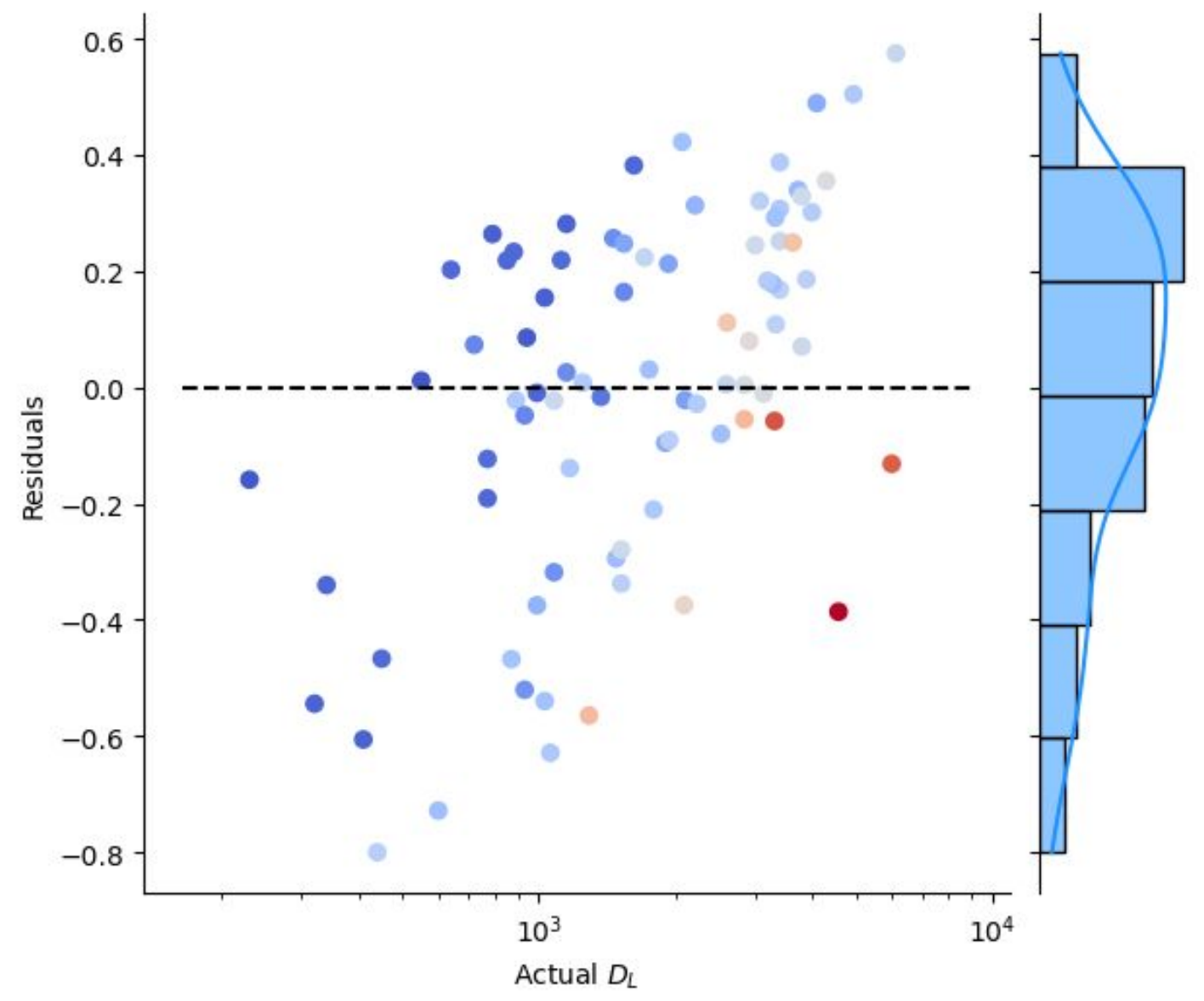

Figure 6: Log residuals of model retrieval of D_L in O3

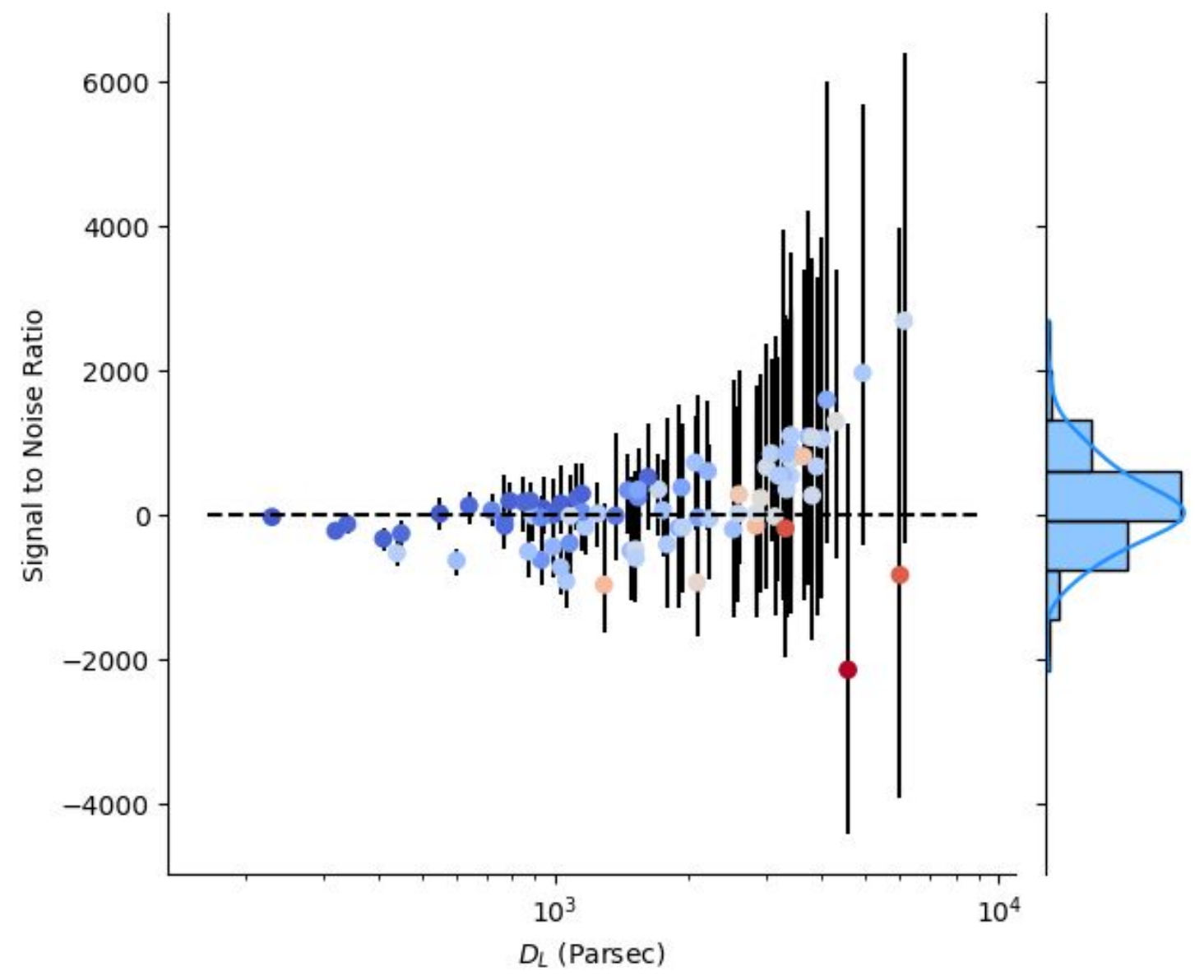

Figure 7: Residuals of model retrieval of D_L in O3 with actual O3 D_L uncertainty ranges

Applying to O4 and Conclusions

- We now must introduce a scale factor that captures LIGO's increased sensitivity between O3 and O4 so we can apply this model to O4 data. We take this to be 1.6 from Ref. [3] and call this the noise reduction factor.
- Given the SNR and masses we have data for in O4, we will infer the luminosity distances for these events using our model with the corrected scale factor.
- O4 has a higher survey depth when compared to O3.

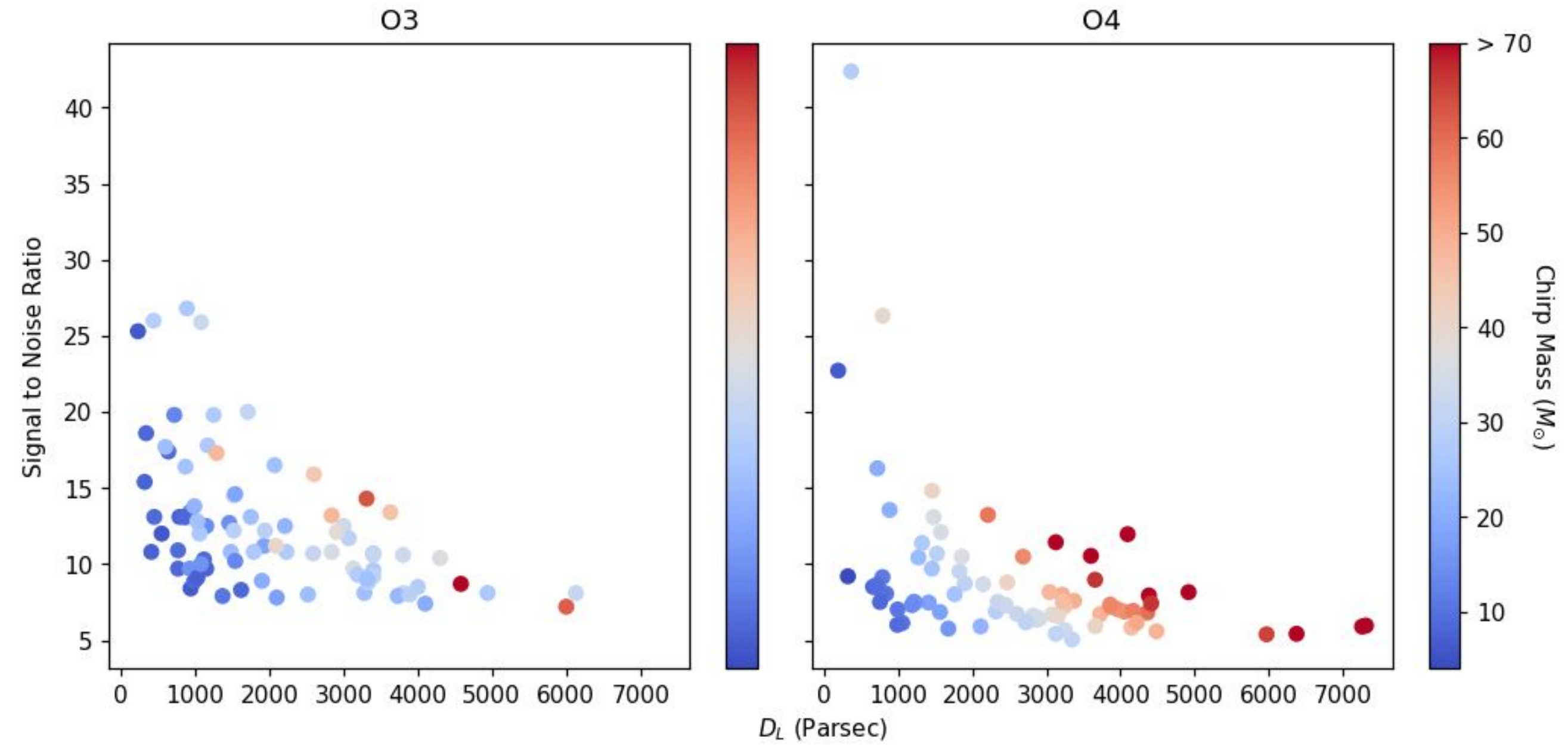

Figure 8: Comparing the SNR versus D_L in parces across O3 and O4

- O4 is more sensitive to high mass events.
  - High mass BBHs could be uncommon, so an increased survey depth may allow for a more representative sample.

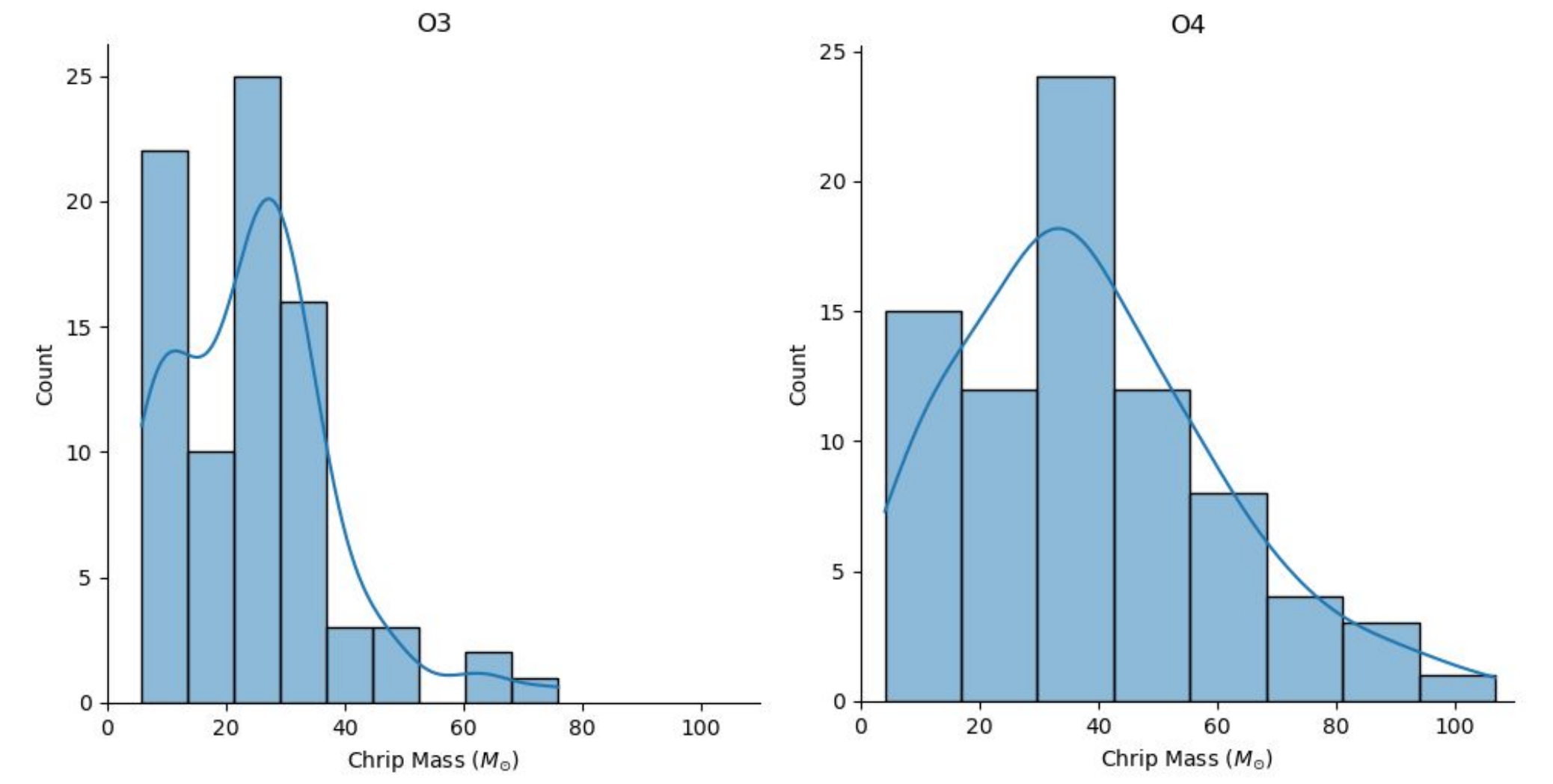

Figure 9: Comparing M_{chirp} histograms between O3 and O4

- We used machine learning to confirm that M_{chirp} and the SNR are the best predictors of D_L.

Future Steps

- Extend to future observation runs such as O5.
- Validate our model once true D_L estimates are released.
- Refine our model to include the effects of spin, duration, or the actual waveform.
- Integrate a machine learning model trained on simulated observations.

Acknowledgements

We thank Dr. Jax Sanders for giving a presentation on the state of O4 to members of our group, the LVK collaboration for providing publicly-available gravitational wave data, and Dr. Quashnock for overseeing our research.

References:

[1] Ota, Iara. "Black hole spectroscopy: prospects for testing the nature of black holes with gravitational wave observations." *arXiv preprint arXiv:2208.07980* (2022).
[2] Abbott et al. "The basic physics of the binary black hole merger GW150914." *In Annalen der Physik (Vol. 529, Issues 1–2). Wiley. https://doi.org/10.1002/andp.201600209* (2016).
[3] Miller, J. L. "Frequency-dependent squeezing makes LIGO even more sensitive." In Physics Today (Vol. 77, Issue 1, pp. 13–16). AIP Publishing. https://doi.org/10.1063/pt.3.5374 (2024)