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Results from the GWTC-4.0 Searches for Gravitationally Lensed Gravitational Wave Signals

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21 April 2026

Gravitational Waves: An Introduction

Gravitational Waves

- Gravitational waves are ripples in space-time resulting from any non-axisymmetric motion of massive bodies in the universe.
- Because space-time is very stiff, we would expect to observe these only from astrophysical bodies.
- Indeed, so far, we have observed gravitational waves from merging compact binaries consisting of black holes and/or neutron stars.

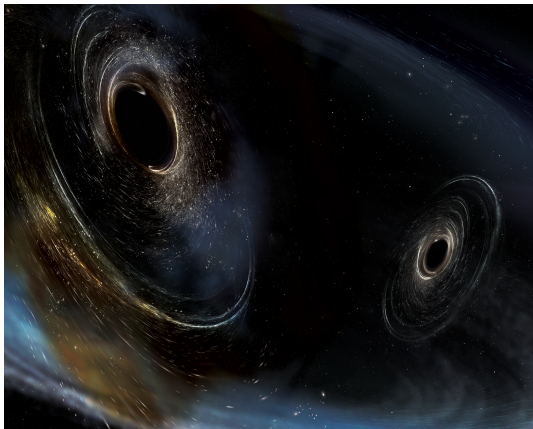


Figure 1: Image by Aurore Simonnet

Gravitational Wave Detection

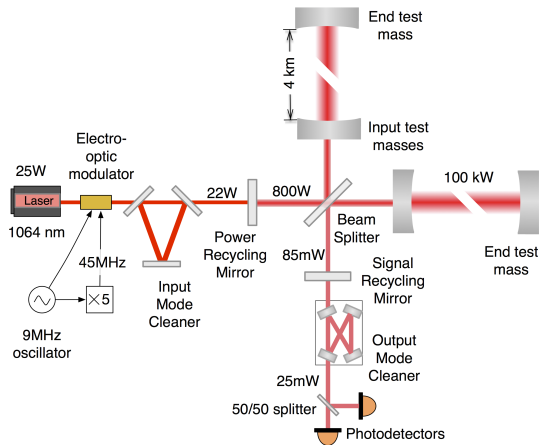


Figure 2: Figure from [1]

- To detect gravitational waves, we use a modified version of a Michelson interferometer.
- Passing gravitational waves change the relative lengths of the arms resulting in interference of the laser light observed at the photodetectors.
- A number of sophisticated techniques are used to make this incredibly sensitive.

Difficulties of Detection

- A whole host of sources of noise impact efforts to detect gravitational wave signals.
- Some of these may be compensated for through sophisticated isolation systems, cryogenic temperatures, advanced materials.
- Some, more fundamental sources of noise, create the limitations of detector sensitivity.

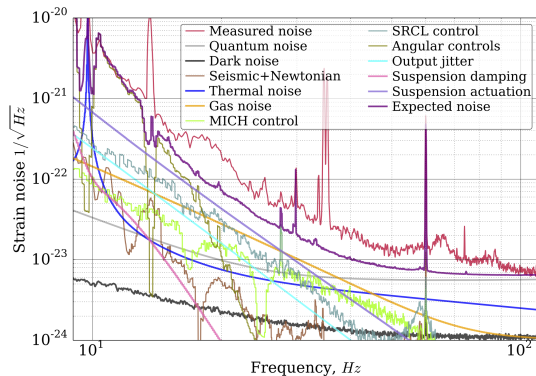


Figure 3: Figure from [1]

Signal Analysis

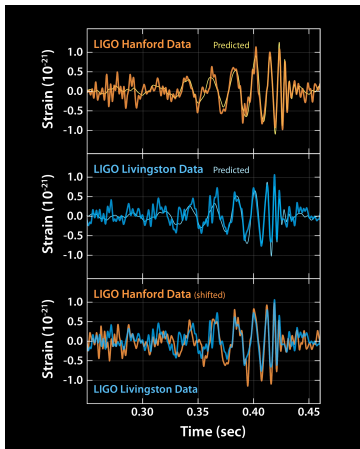
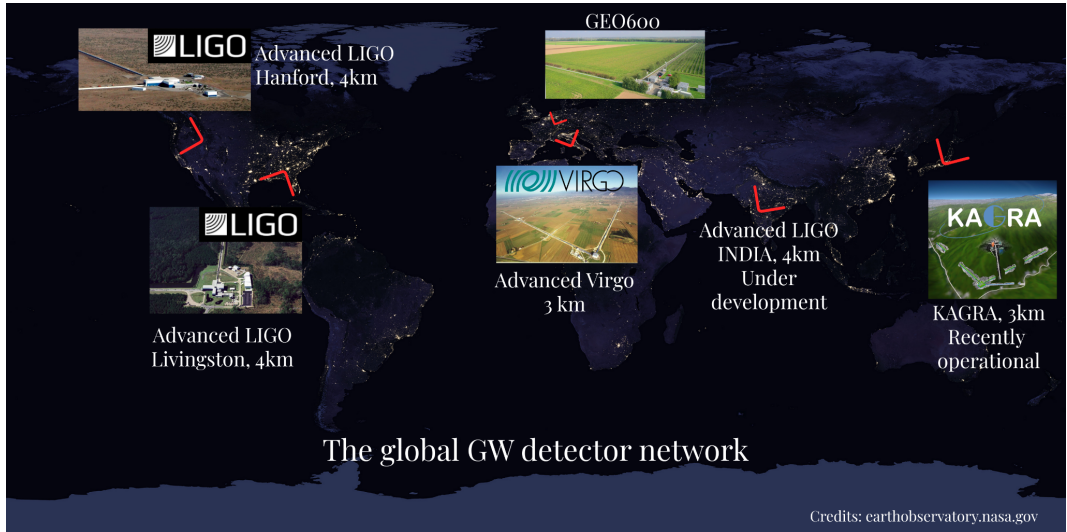


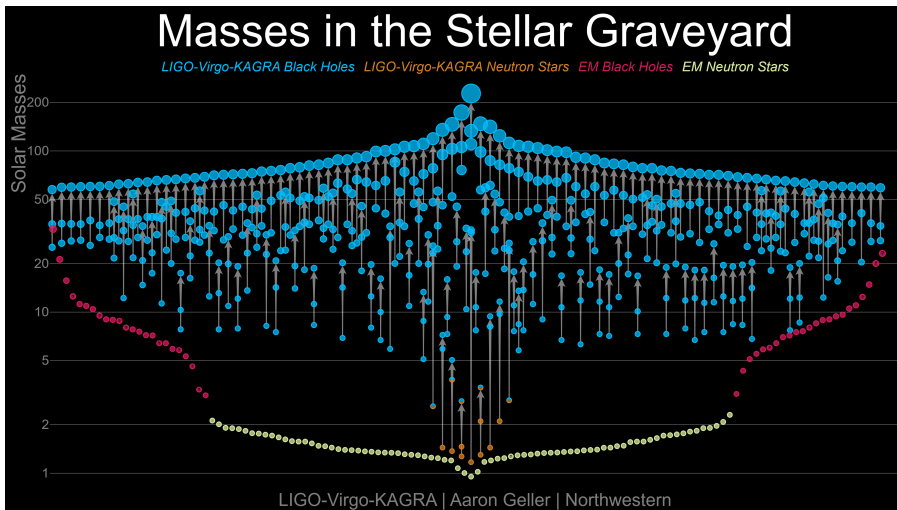
Figure 4: Image by Caltech/MIT/LIGO Lab

- To model the signal we turn to numerical relativity which provides a basis to work from.
- However, NR, is too slow to use directly so we create waveform models that make some simplifications but that can be constructed very quickly.
- We can then use these models to perform matched filtering for detection and Bayesian parameter estimation to yield our understanding of the signal source.

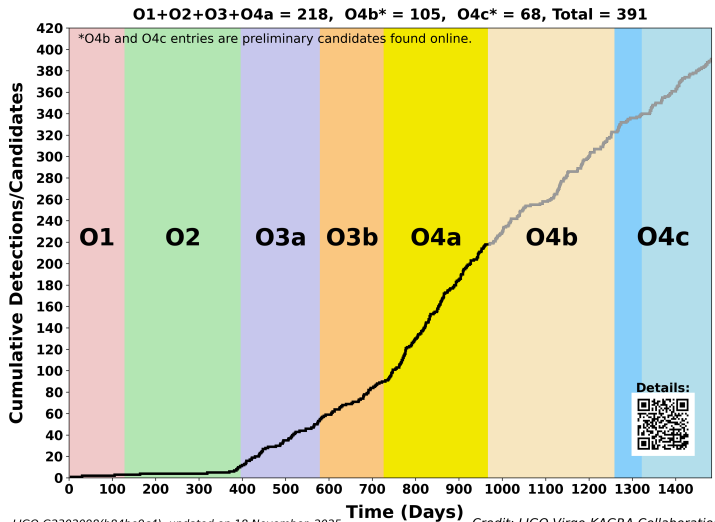
The Gravitational Wave Detector Network



The Stellar Graveyard



The Increasing Rate of Detections



- GWTC-4.0 is the latest released catalog of gravitational wave events from the LVK Scientific Collaborations [2].
- It covers the first section of the fourth observing run (O4a) and so covers from 1500 UTC on the 24th May 2023 until 1600 UTC on the 16th January 2024.
- It added 128 new events with a probability of astrophysical origin greater than 0.5 bring the total number of detections to 218 [3].
- Alongside investigations of the individual events [4, 5], GWTC-4.0 brought with it updates to investigations into the population of compact binaries [6], cosmological investigations [7], tests of general relativity [8, 9, 10], and of course, searches for gravitational lensing [11].

Gravitational Lensing

What is Gravitational Lensing?

- A central tenet of General Relativity is that massive objects distort the space-time around them.
- Consequently signals passing by those massive objects are deflected by the curvature of space-time.
- This process is qualitatively similar to more traditional lensing of light hence the name.



Figure 5: Image by NASA/STScI

Scales of Lensing



Figure 6: Image by ESA/Hubble & NASA

- Since anything with mass may be a lens, there are a wide array of possible lenses in the universe.
- Different objects and different configurations lead to a wide array of phenomenology.
- Broadly we may split lensing treatment into two regimes:
 - A purely geometric treatment where we consider multiple images.
 - A 'wave-optics' treatment where we also include effects from the wave-like nature of the signal.

Lensing of Gravitational Waves

- Gravitational waves may also be affected by lensing on their path from source to observer.
- We may see multiple copies of the same signal that are wholly resolvable, or they may overlap causing interference, or they may be wholly intertwined and also show diffraction effects.
- This means both of the aforementioned regimes may need to be considered—a marked change from the purely geometric case for light.

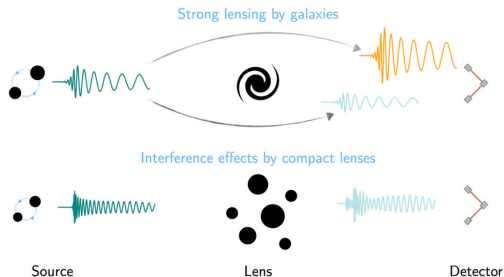


Figure 7: Image by LIGO–Virgo–KAGRA Collaborations

Effects of Lensing—Multiple Images

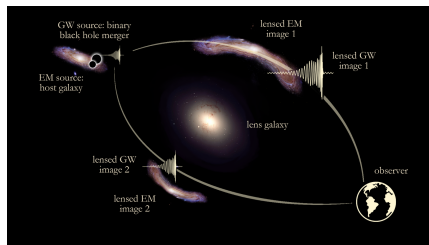


Figure 8: Image by Laura Uronen

- When lensing produces multiple gravitational wave signals we expect them to be identical up to an individual *magnification, time delay, and global phase shift* [12]:

$$h^L(f) = \sum_{j=1}^N |\mu_j|^{1/2} \exp [2\pi i f t_j - i\pi n_j] h(f) \quad (1)$$

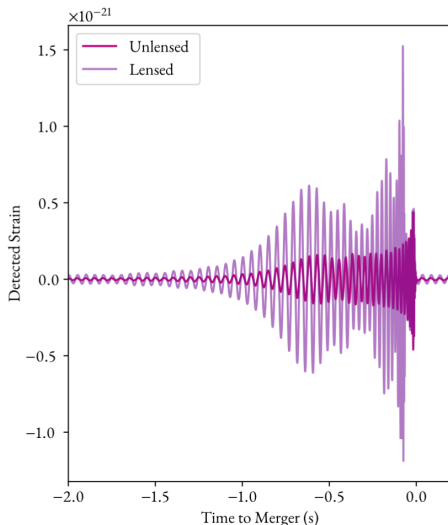
- The time delay has two components: the geometrical path difference and Shapiro delay.
- The phase change may take one of three values determining the *type* of the image.

Effects of Lensing—Wave Effects

- Where the wavelength of the gravitational wave is close to the Schwarzschild radius of the lensing object, we must include wave effects.
- Instead of the previous summation, the multiplicative factor to the strain is now given by [13]:

$$F(w, \mathbf{y}) = \frac{w}{2\pi i} \int \exp[iwT(\mathbf{x}, \mathbf{y})] d^2(x) \quad (2)$$

- The exact form depends on the distribution of mass in the lensing object.



Why Search for Gravitational Wave Lensing?

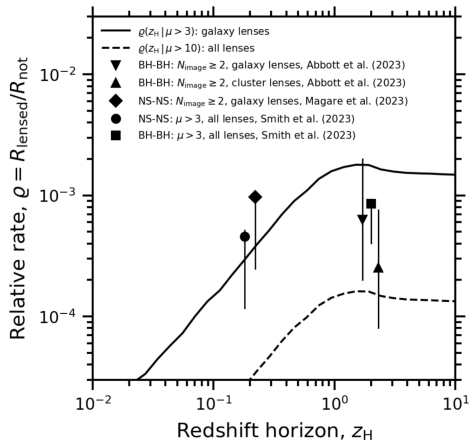


Figure 9: Image from [14]

- Rates are optimistic about lensing being plausible given the number of events that we have detected.
- If neglected, could lead to wrong parameters being estimated for lensed events.
- If detected, would lead to further areas of examination including:
 - Improved tests of General Relativity
 - Localization of merging black holes
 - Precision cosmology
 - Probing dark matter

GWTC-4.0: Searches for Gravitational Wave Lensing

Considered Events

- We considered all binary black holes with an astrophysical probability greater than 0.5 and a false alarm rate less than 1 per year.
- This yielded 84 events—the same list of binary black holes as those for which parameter estimation was performed in [3].
- Barring specific exceptions, we used as a basis the IMRPhenomXPHM-SpinTaylor waveform model [15, 16].

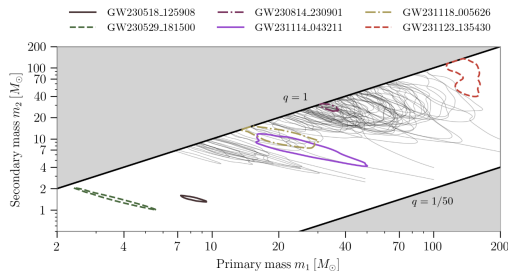


Figure 10: Image from [3]

Assessing the Significance of Lensed Results

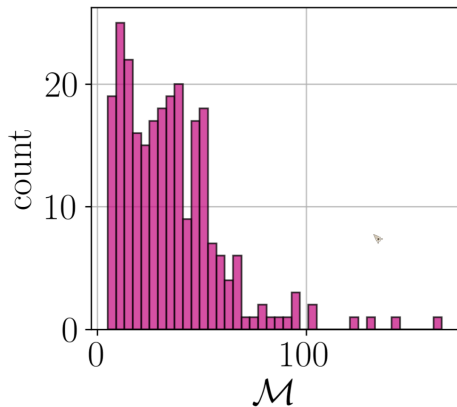


Figure 11: Image from [11]

- To assess the significance of our results, we compare the statistics gathered to those from a background of 254 unlensed simulations.
- Parameters for the injections are based on the PowerLaw+Peak distribution inferred from GWTC-3.0 [17].
- Injections were made into stretches of noise from the covered period of GWTC-4.0 and all considered signals have network $\text{SNR} > 8$.

Multiple Images—Lensing Workflow

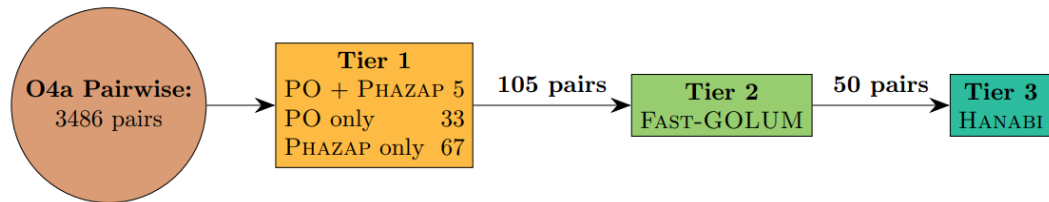


Figure 12: Image from [11]

- We investigate all 3486 pairs for possible signatures of lensing. This is a gargantuan task. Some analyses can also be very computationally intensive.
- We therefore adopt a tiered system for pair-wise analyses to pass to the more complex analyses only the highest ranked pairs from the more high speed analyses.

Multiple Images—Tiers 1 & 2

- Tier 1 analyses look for similarities in pairs of events:
 - *Phazap*: Focuses specifically on the phase evolution under the different image types.
 - *Posterior Overlap*: Examines the overlap of all posterior probabilities from unlensed PE.
- Our Tier 2 analysis, *Fast Golum*, performs conditional parameter estimation on the second image using as a basis the parameters of the first.

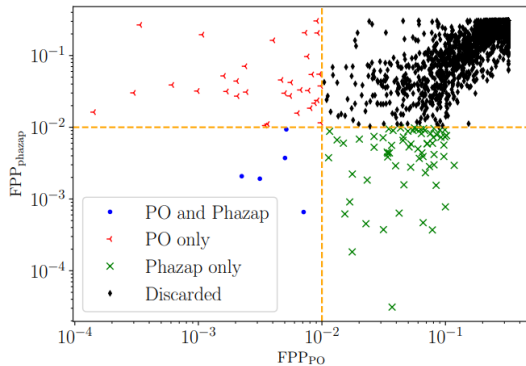


Figure 13: Image from [11]

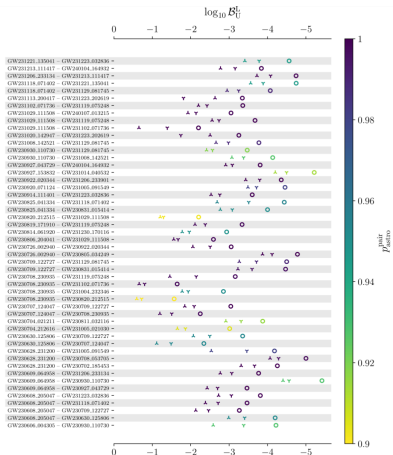
Multiple Images—Subthreshold Counterparts?

Sub-Threshold Trigger (UTC) (yy:mm:dd hh:mm:ss)	Target Super-Threshold Event GWYYMMDD_HHMMSS	Time delay	Network SNR	FAR (yr^{-1})	$\mathcal{O}_{90\% \text{ CI}}$ (%)	$\mathcal{R}_U^L$
2023-09-03 07:43:35	GW231104_133418	$62^{\text{d}}05^{\text{h}}50^{\text{m}}44^{\text{s}}$	7.88	5.6×10^{-6}	0.11	0.31
2023-10-30 12:34:06	GW231223_075055	$53^{\text{d}}19^{\text{h}}16^{\text{m}}49^{\text{s}}$	7.99	9.6×10^{-6}	52	0.41
2023-11-20 02:21:03*	GW230904_051013	$76^{\text{d}}21^{\text{h}}10^{\text{m}}50^{\text{s}}$	9.62	2.5×10^{-3}	7.1	0.21

Figure 14: Image from [11]

- We also examine for the possibility that counterpart images are so de-magnified that standard gravitational wave searches could not find them, but a targeted search could.
- This search uses a modified version of the *PyCBC* search pipeline.
- Top ranked candidates were rejected immediately by Tier 1 analyses.

Multiple Images—Tier 3



- Our Tier 3 analysis, *hanabi*, performs full joint parameter estimation on the two signals under the lensed hypothesis. It then also includes population information to reach a more conclusive Bayes factor—the quantification of which hypothesis is the more likely.
- No pairs display any significant support for the lensing hypothesis when subjected to the *hanabi* analysis.

Figure 15: Image from [11]

Single Distorted Signals—Type II

- Type II images can be detected on their own with sufficient SNR and higher-order-mode content in the signal.
- Type II identification would provide a clear, unambiguous signal of lensing.
- However, no significant support for the Type II hypothesis detected in GWTC-4.0.

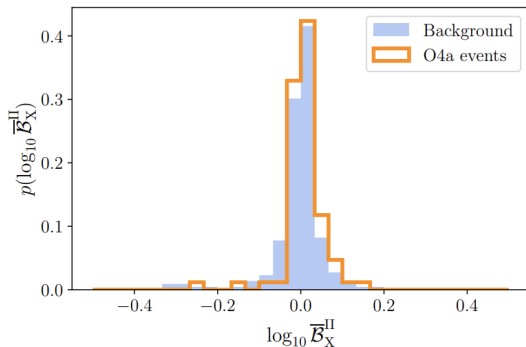


Figure 16: Image from [11]

Single Distorted Signals—Isolated Point Mass

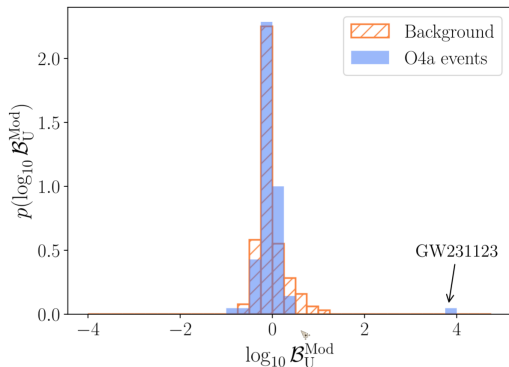


Figure 17: Image from [11]

- Smaller lenses that could produce wave-optics can be reasonably considered to be modelled by point masses.
- Investigations are performed using parameter estimation with the additional lens parameters—the redshifted mass of the lens, and how close the signal got to the lens.
- One outlier signal—GW231123, meaning a false alarm upper limit of 0.39% naively or 28% with trials factor correction.

GW231123—Introduction

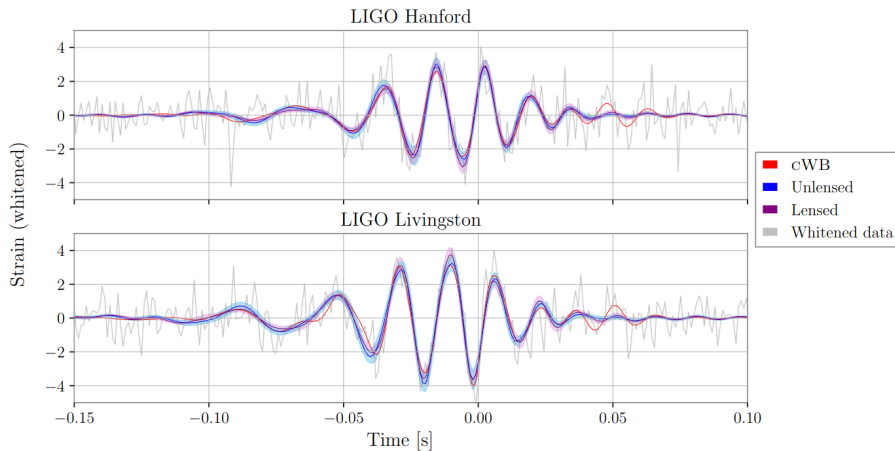


Figure 18: Image from [11]

GW231123—Introduction II

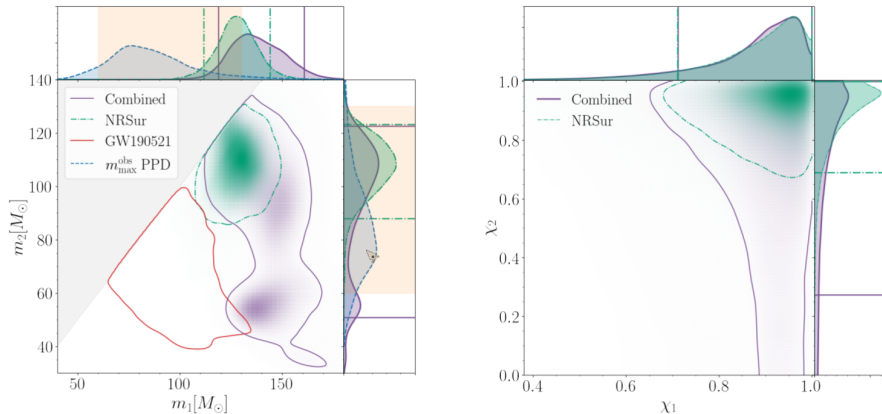


Figure 19: Images from [5]

GW231123—Lensing Comparison

- The apparent support for lensing is reflected in comparison between the estimated waveform and the reconstruction of the signal from the cWB pipeline.
- This means on its face, the lensed waveform matches the signal better. However, it must be caveated that the additional degrees of freedom may make it easier for the data to be fitted if there's quality issues, or other astrophysical phenomena.

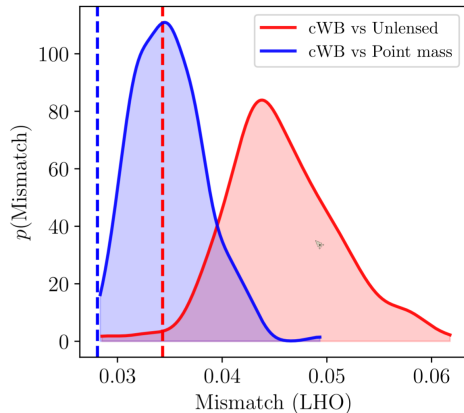


Figure 20: Images from [11]

GW231123—Source Parameters: Mass

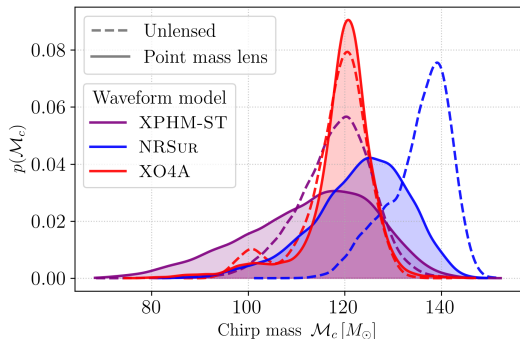


Figure 21: Image from [11]

- Under the lensing hypothesis, we see something of a reduction in the waveform model discrepancy observed in standard analysis.
- There is greater support for lower masses, where we expect the waveform models to be more reliable.
- However, the resultant posteriors are also broader from the greater flexibility.

GW231123—Source Parameters: Spins

- Under the lensing hypothesis, we see a reduction in support for extremal spins in the secondary.
- This again is pushing support towards the area of parameter space where we expect the waveform models to behave more reliably.
- It is also noted that there is a degeneracy between precession and lensing.
- However, this degeneracy may exist for other potential causes as well.

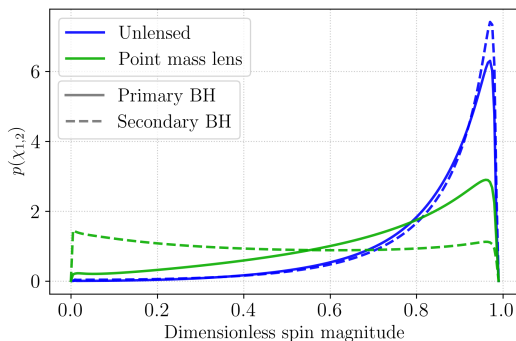


Figure 22: Image from [11]

Astrophysical Implications from GWTC-4.0 Lensing Results

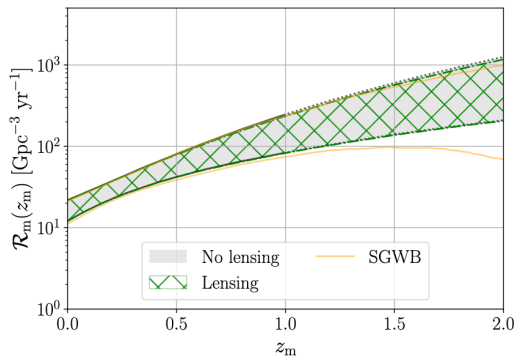


Figure 23: Image from [11]

- Rate estimates for galactic-scale multi-image lensing remain about 1 in 1000, which is consistent with the current non-observation.
- Non-observation of multi-image lensing also allows us to make some additional constraint of the merger rate density for binary black holes.
- This constraint is very similar to that from the standard GWTC-4.0 results, but is likely to improve as additional detections and lensed detections come in.

Summary

- Pair-wise searches rejected all candidates in the 3 Tier workflow.
- Highest ranked pair candidates from subthreshold searches rejected at Tier 1 level.
- No evidence of Type II distortions in any signal.
- One outlier from the searches for wave optics signatures using an isolated point mass lens—GW231123.
- Interpretation of GW231123 is complicated due to limitations of the background size, waveform systematics, and the limited number of cycles in band.
- Non-observation of lensing remains consistent with predicted lensing rates, and yields similar constraint on the merger rate density to other analyses.

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