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On the evidence for Lensing in GW231123

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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 1: Image by NASA/STScI

Scales of Lensing

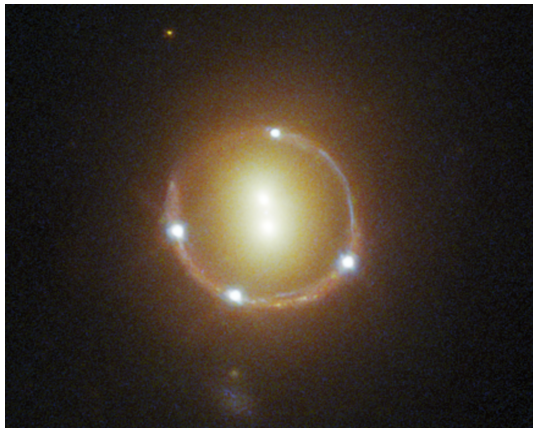


Figure 2: Image by ESA/Hubble & NASA

- 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.

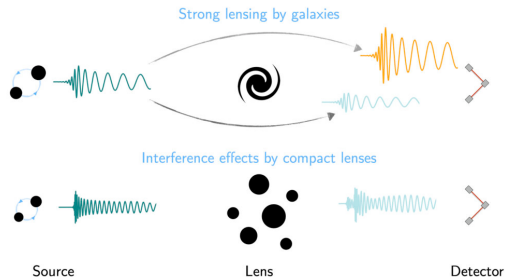


Figure 3: Image by LIGO–Virgo–KAGRA Collaborations

Effects of Lensing—Multiple Images

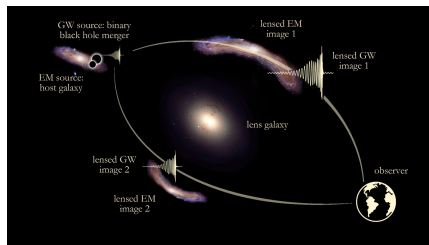


Figure 4: Image by Laura Uronen

- When lensing produces multiple gravitational wave signals we expect them to be identical up to an individual *magnification, time delay, and global phase shift* [1]:

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

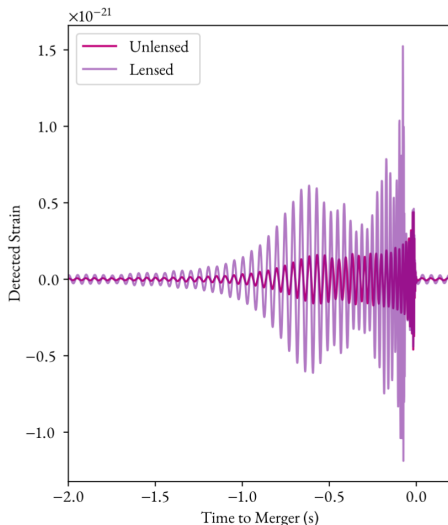
- The time delay has two components: the geometrical path difference and Shapiro delay.
- The phase change may take one of three values determining the *type* of the image.

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 [2]:

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

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



Why Search for Gravitational Wave Lensing?

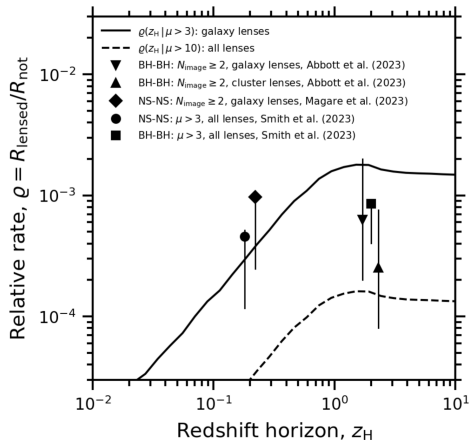
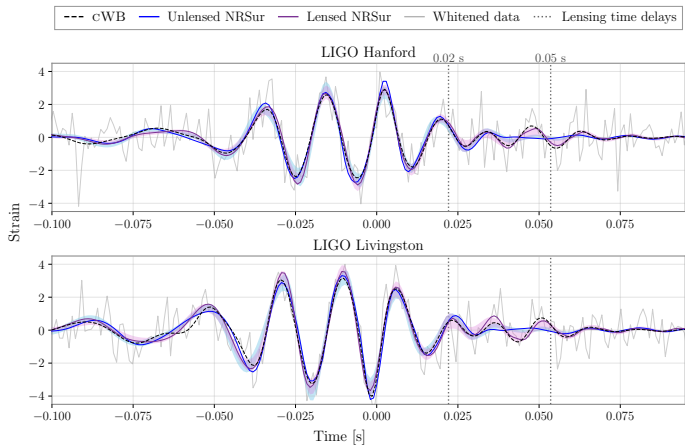


Figure 5: Image from [3]

- 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

GW231123

Introduction



Introduction II

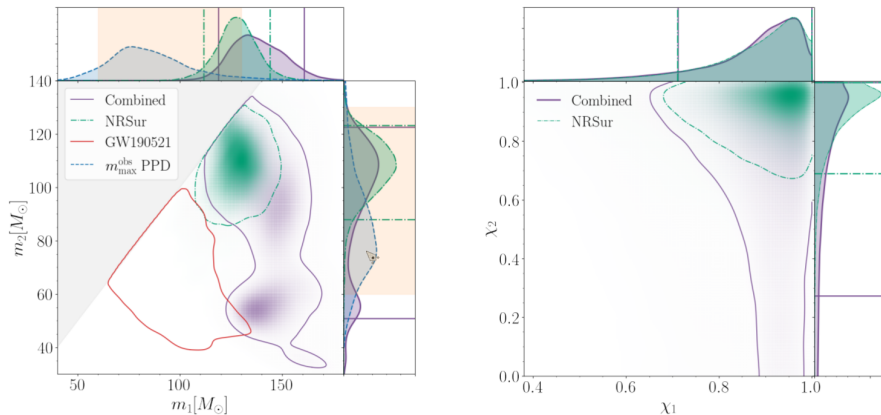


Figure 6: Images from [4]

LVK Results

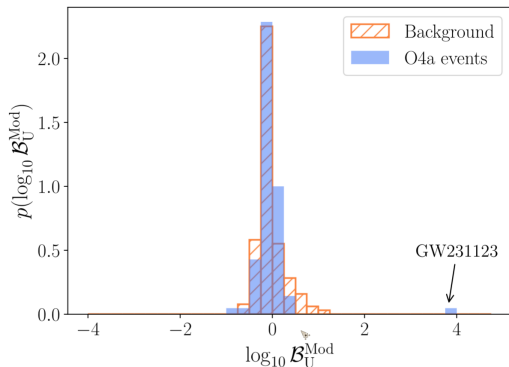
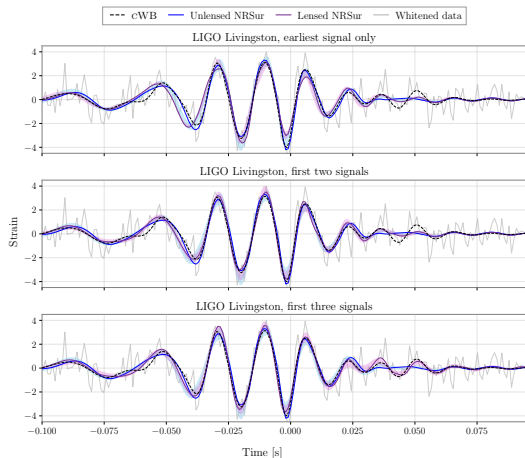


Figure 7: Image from [5]

- 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.
- GW231123 is a clear outlier with a false alarm upper limit of 0.39% naively or 28% with trials factor correction.

A Phenomenological Approach to Lensing

- In this approach, rather than choose a specific lens model to perform the analysis, we instead stack images in the geometric optics regime.
- This allows a broader class of lensing objects to be examined at the cost of some of the specific wave optics details.
- Implementation is simply Eq. 1.

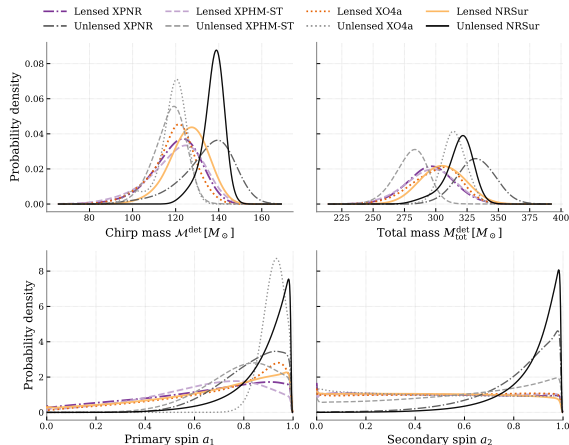


Phenomenological Results

Waveform	$\log_{10} \mathcal{B}_U^L$	# Images	μ_{21}	μ_{31}	Δt_{21} [ms]	Δt_{32} [ms]
XO4A	0.7	2	$0.25^{+1.16}_{-0.23}$	$0.08^{+41.46}_{-0.07}$	22^{+40}_{-8}	40^{+50}_{-31}
XPNR	2.84	3	$0.29^{+0.23}_{-0.17}$	$0.06^{+23.11}_{-0.04}$	21^{+7}_{-7}	40^{+44}_{-26}
NRSUR	3.05	3	$0.27^{+0.22}_{-0.15}$	$0.05^{+15.63}_{-0.04}$	22^{+6}_{-7}	39^{+40}_{-23}
XPHM-ST	4.65	3	$0.31^{+0.21}_{-0.15}$	$0.05^{+18.82}_{-0.03}$	21^{+5}_{-7}	40^{+43}_{-26}

- Across all four tested waveforms, there is some level of lensing support, from marginal (XO4a) to strong (XPHM-ST).
- Interestingly, lensing parameter estimates are broadly consistent between the waveforms with the most likely scenario of three images.

Source Parameter Estimates

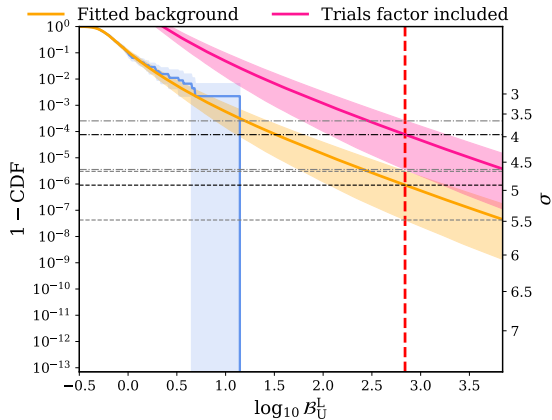
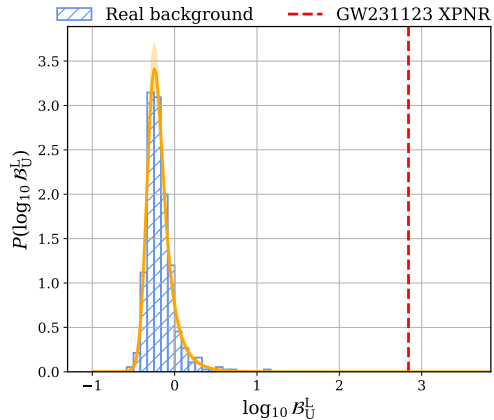


- Reduction in extremal spins in the lensing analysis is consistent with expectations for lensed events.
- More consistent detector frame chirp mass—though some broadening.
- Downside of not choosing a specific model—cannot provide source frame estimates of the masses. These will be lower than the unlensed case.

Significance of Support

- Two basic approaches to fully identify level of support:
 - Calculation of posterior odds using prior odds
 - Background study for frequentist p-value
- We go for p-value given astrophysical uncertainties on prior odds for lensing of GW at this scale.
- Run phenomenological analysis using Gravelamps on 450 simulated unlensed signals to get distribution of unlensed events.
- These simulations used the IMRPhenomXPNR model as a reflection of the current state-of-the-art in waveform modelling.
- Given high value of Bayes factors this is insufficient to calculate p-value directly. Therefore extrapolate from the background using a technique developed by Ankur Barsode [6].

Significance of Support II



Conclusion

- GW231123 exhibits strong support for the lensing hypothesis—the highest seen thus far with significance just under 4σ .
- Phenomenological approach yields support for three images (may rule out the point mass model).
- Analysis under lensing reduces variance in parameter estimates from differing waveform models.
- Support is consistent across both detectors unlike a previous candidate GW200208.
- Detection claim not yet possible due to remaining questions over waveform systematics and lensing, potential other explanations for the event remain. However, lensing remains a serious plausibility.

References

Bibliography I

- [1] Jose Maria Ezquiaga et al. "Phase effects from strong gravitational lensing of gravitational waves". In: *Phys. Rev. D* 103.6 (2021), p. 064047. DOI: [10.1103/PhysRevD.103.064047](https://doi.org/10.1103/PhysRevD.103.064047). arXiv: [2008.12814](https://arxiv.org/abs/2008.12814) [gr-qc].
- [2] Ryuichi Takahashi and Takashi Nakamura. "Wave effects in gravitational lensing of gravitational waves from chirping binaries". In: *Astrophys. J.* 595 (2003), pp. 1039–1051. DOI: [10.1086/377430](https://doi.org/10.1086/377430). arXiv: [astro-ph/0305055](https://arxiv.org/abs/astro-ph/0305055).
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- [4] A. G. Abac et al. "GW231123: A Binary Black Hole Merger with Total Mass 190–265 $M_{\odot}$ ". In: *Astrophys. J. Lett.* 993.1 (2025), p. L25. DOI: [10.3847/2041-8213/ae0c9c](https://doi.org/10.3847/2041-8213/ae0c9c). arXiv: [2507.08219](https://arxiv.org/abs/2507.08219) [astro-ph.HE].

Bibliography II

- [5] A. G. Abac et al. "GWTC-4.0: Searches for Gravitational-Wave Lensing Signatures". In: (Dec. 2025). arXiv: [2512.16347 \[gr-qc\]](#).
- [6] Ankur Barsode. "Tool for accurate model selection using Bayes factors". In: *Phys. Rev. D* 114.6 (2026), p. 064045. DOI: [10.1103/wv11-h53b](#). arXiv: [2605.10333 \[gr-qc\]](#).