

Updates: Overlapping and Lensed GWs

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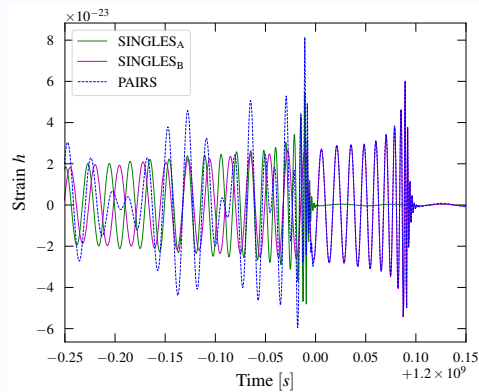
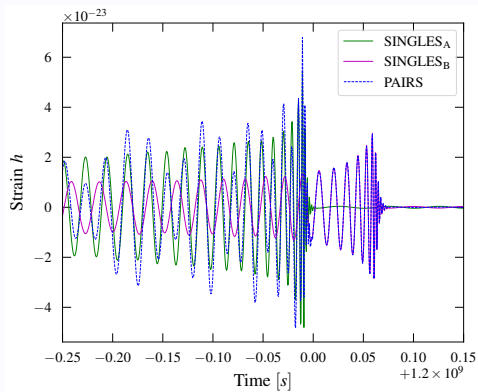
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Agenda

- 1 Overview
- 2 Introduction
- 3 Analysis Setup
- 4 Results
- 5 Conclusions

Overlapping Transients



Overlapping Gravitational Wave Signals.

Study Overview

- Systematically vary key parameters influencing waveform evolution: Chirp mass ratio: $\mathcal{M}_B/\mathcal{M}_A$, SNR ratio: $\text{SNR}_B/\text{SNR}_A$, Coalescence time difference: Δt_c
- Recoveries for **Unlensed** (single waveform), **Type II Lensed** (Strong Lensing, $n_j = 0.5$) and **Microlensed** (Isolated point-mass lens).

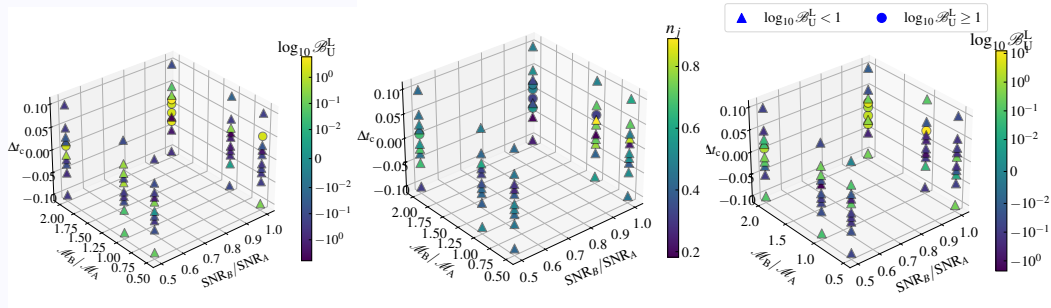
Individual Case	Population Study
• $\mathcal{M}_B/\mathcal{M}_A \in \{0.5, 1, 2\}$ • $\text{SNR}_B/\text{SNR}_A \in \{0.5, 1\}$ • $\Delta t_c \in [-1, 1] \text{ s}$	• $\mathcal{M}_B/\mathcal{M}_A \in [0.1, 10]$ • $\text{SNR}_B/\text{SNR}_A \in [0.1, 10]$ • $\Delta t_c \in [-1, 1] \text{ s}$
Parameter Estimation (for 60 signals).	Fitting factor ($\sim \mathcal{O}(5000)$ signals).

Type II Lensed Parameter Estimation Recoveries

$\mathcal{M}_B/\mathcal{M}_A \in \{0.5, 1, 2\}$, $\text{SNR}_B/\text{SNR}_A \in \{0.5, 1\}$, $\Delta t_c \in [-0.1, 0.1]s$

A : Fixed Morse phase shows distinct Bayes factor differences over the unlensed case.

B,C : Allowing the Morse phase to vary improves lensing characterization.



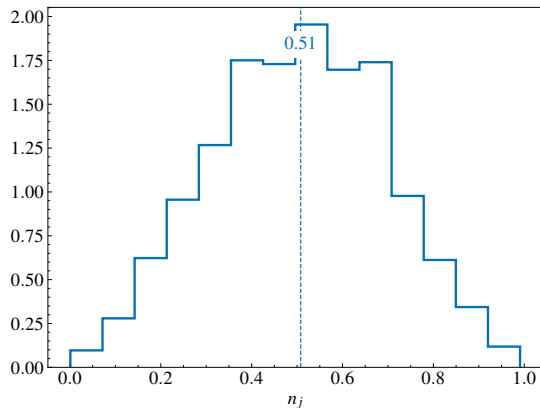
A

B

C

Population Fitting Factor Results: Type II Lensed Template

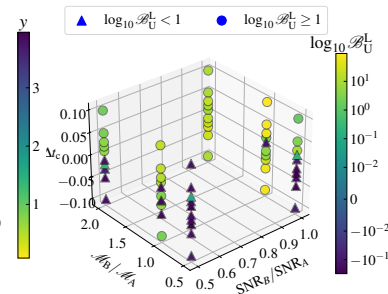
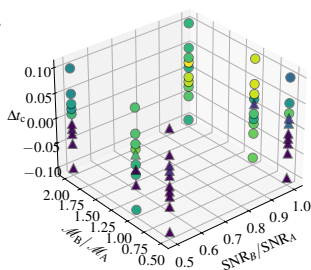
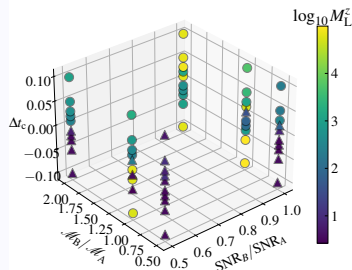
- $\log_{10} \mathcal{B}_U^L > 1$ in a small region of the overlapping parameter space with $\mathcal{M}_B/\mathcal{M}_A \gtrsim 1$ and $|\Delta t_c| \leq 0.03$ s.
- Inferred Morse index clustering near $n_j \simeq 0.5$, indicative of Type-II lensing, for the cumulative study.



Microlensed Parameter Estimation Recoveries

$\mathcal{M}_B/\mathcal{M}_A \in \{0.5, 1, 2\}$, $\text{SNR}_B/\text{SNR}_A \in \{0.5, 1\}$, $\Delta t_c \in [-0.1, 0.1]s$

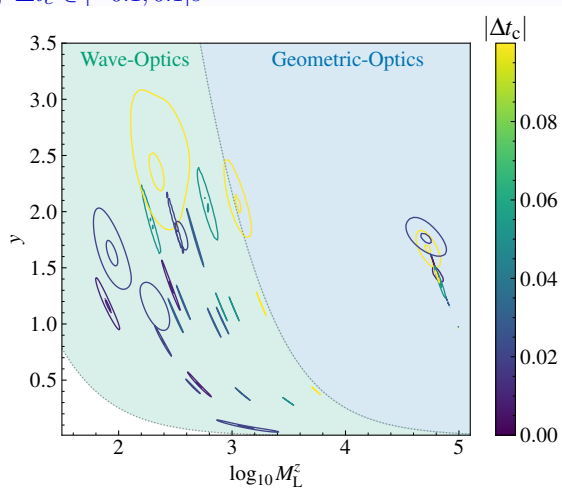
- Microlensed templates yield stronger support for strongly overlapping signals.
- Maximally favored ($\log_{10} \mathcal{B}_U^L \gg 1$) for $\mathcal{M}_B/\mathcal{M}_A \gtrsim 1$ and equal SNRs, increasing with $|\Delta t_c|$.



Gravitational Lensing Parameter Estimation Posteriors

$\mathcal{M}_B/\mathcal{M}_A \in \{0.5, 1, 2\}$, $\text{SNR}_B/\text{SNR}_A \in \{0.5, 1\}$, $\Delta t_c \in [-0.1, 0.1]s$

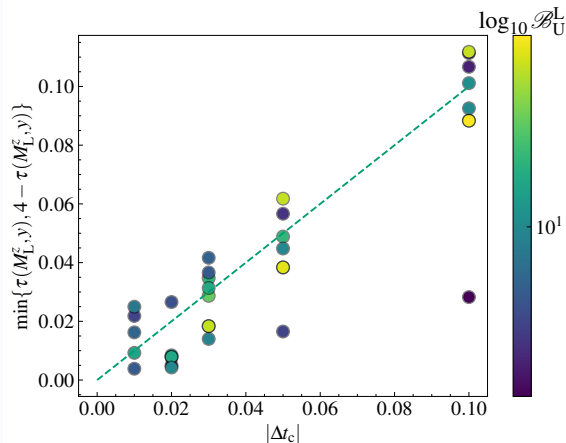
- Recovered lens parameters (M_L^z, y) show dependencies with $|\Delta t_c|$.
- The inferred redshifted lens masses lie in the range $M_L^z \sim 10^2 - 10^5 M_\odot$ with impact parameters $y \sim 0.1 - 3$.



Microlensing Time Delay

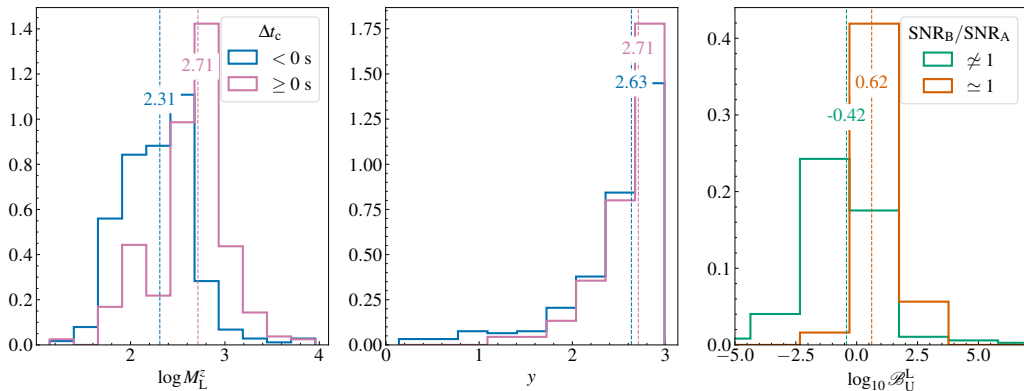
$$\mathcal{M}_B/\mathcal{M}_A \in \{0.5, 1, 2\}, \text{ SNR}_B/\text{SNR}_A \in \{0.5, 1\}, \Delta t_c \in [-0.1, 0.1]s$$

- Inferred time delay of two superimposed microimages is close to the injected $|\Delta t_c|$ or $(\delta - |\Delta t_c|)$.
- False evidence for microlensing signatures, the model produces two superimposed images whose time delay can closely match $|\Delta t_c|$.



Population Fitting Factor Results: Microlensed Template

- FF optimization shows moderate microlensing support when $\text{SNR}_B/\text{SNR}_A \sim 1$, consistent with PE trends.



Conclusions

- The inferred Bayes factor differences depends on relative chirp-mass ratios, relative loudness, difference in coalescence times, and also the absolute SNRs of the overlapping signals.
- Overlapping black-hole binaries with nearly equal chirp masses and comparable loudness are likely to be falsely identified as lensed, and can lead to significant biases in single signal unlensed parameter recovery.
- Advanced parameter estimation methods are essential to disentangle these effects. While our study focuses on ground-based detectors using appropriate detectability thresholds, the findings naturally extend to next-generation GW observatories.

References

-  Samajdar, A. et al., 2021. *Biases in parameter estimation from overlapping gravitational-wave signals in the third-generation detector era*. Physical Review D, 104(4), p.044003.
-  Relton, P. and Raymond, V., 2021. *Parameter estimation bias from overlapping binary black hole events in second generation interferometers*. Physical Review D, 104(8), p.084039.
-  Janquart, J. et al., 2023. *Analyses of overlapping gravitational wave signals using hierarchical subtraction and joint parameter estimation*. Monthly Notices of the Royal Astronomical Society, 523(2), pp.1699-1710.
-  Veitch, J. and Vecchio, A., 2010. *Bayesian coherent analysis of in-spiral gravitational wave signals with a detector network*. Physical Review D—Particles, Fields, Gravitation, and Cosmology, 81(6), p.062003.
-  Owen, B.J., 1996. *Search templates for gravitational waves from inspiraling binaries: Choice of template spacing*. Physical Review D, 53(12), p.6749.

The background of the slide features a stylized representation of a gravitational well or a black hole. A bright, glowing blue and white light source is positioned at the top left, casting a beam of light downwards. This light interacts with a dark, swirling structure that resembles a gravitational well or a black hole, creating a lensing effect. The overall color palette is dominated by soft blues, purples, and whites, giving it a cosmic and ethereal feel.

Thank You!

Questions? Comments?

Analysis Techniques

- **Parameter Estimation:** Bayesian inference [Veitch, J. and Vecchio, A., 2010]:

$$\mathcal{L}(d|\theta) \propto \exp \left[-\frac{1}{2} \langle d - h(\theta) | d - h(\theta) \rangle \right]$$

$$\underbrace{\log_{10} \mathcal{B}_U^L}_{\text{Bayes Factor}} = \log_{10} \mathcal{Z}_L - \log_{10} \mathcal{Z}_U, \quad \mathcal{Z}_M = \int d\theta \mathcal{L}(d|\theta, \mathcal{H}_M) \pi_M(\theta|\mathcal{H}_M)$$

- **Fitting Factor:** Maximizing waveform overlap [Owen, B.J., 1996]:

$$\mathcal{M}[h_1, h_2] = \max_{t_c, \Phi_c} \frac{\langle h_1 | h_2 \rangle}{\sqrt{\langle h_1 | h_1 \rangle \langle h_2 | h_2 \rangle}}.$$

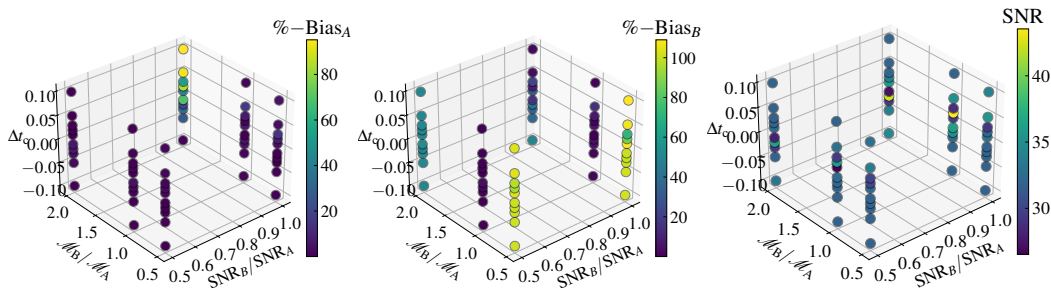
$$\mathcal{F} = \max_{\lambda} \mathcal{M}[h_1, h_2(\lambda)], \quad \log_{10} \mathcal{B}_U^L = (\mathcal{F}_L^2 - \mathcal{F}_U^2) \frac{\text{SNR}^2}{2}$$

Parameter Estimation Priors

Parameter	PE Priors
n_j : Morse Phase	Fixed: $\delta(n_j - 0.5)$ Varying: $\mathcal{U}(0, 1)$
y : Impact Parameter	POWERLAW $_{\alpha=2}(0.01, 5)$
M_L^z : Redshifted Lens Mass	Log-Uniform in $[0.1, 10^5] M_\odot$

Unlensed Parameter Estimation Results

$\mathcal{M}_B/\mathcal{M}_A \in \{0.5, 1, 2\}$, $\text{SNR}_B/\text{SNR}_A \in \{0.5, 1\}$, $\Delta t_c \in [-0.1, 0.1]s$



Fitting Factor Results: Unlensed Template

