Updates: Overlapping and Lensed GWs

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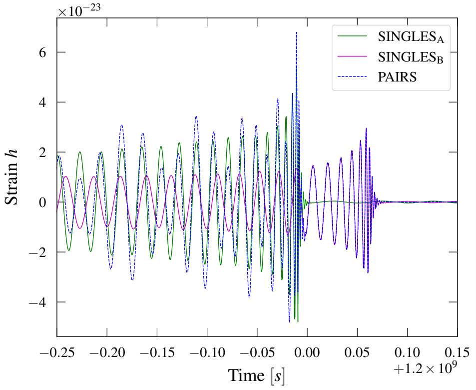
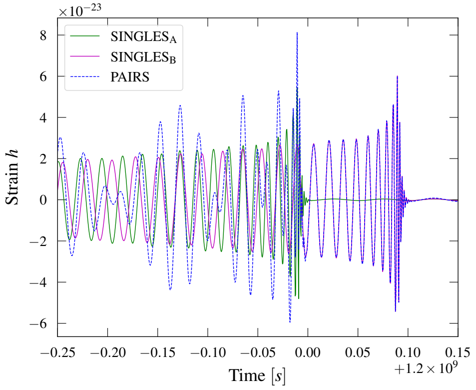
Agenda

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: $\mathrm{SNR_B/SNR_A}$, Coalescence time difference: Δt_c
- Inferences for **Unlensed** (single waveform), **Type II Lensed** (Strong Lensing, $n_j = 0.5$) and **Microlensed** (Isolated point-mass lens).

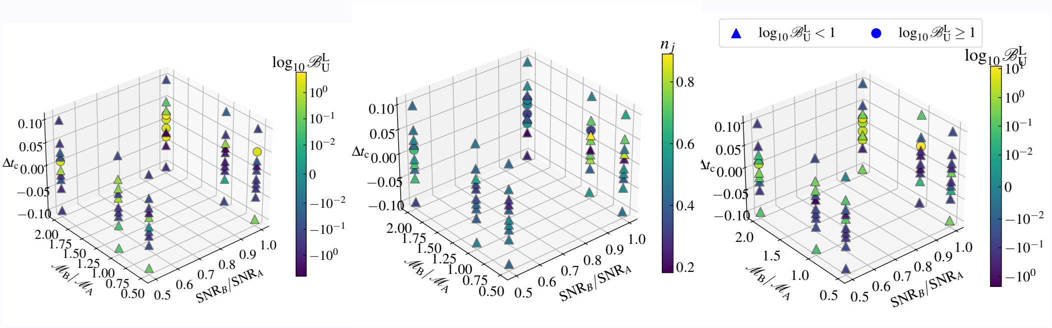
Individual Case	Population Study
• $\mathcal{M}_B/\mathcal{M}_A \in \{0.5,\, 1,\, 2\}$ • $\mathrm{SNR_B/SNR_A} \in \{0.5,\, 1\}$ • $\Delta t_c \in [-0.1,\, 0.1]\,\mathrm{s}$	• $\mathcal{M}_B/\mathcal{M}_A \in [0.1,\, 10]$ • $\mathrm{SNR_B/SNR_A} \in [0.1,\, 10]$ • $\Delta t_c \in [-0.1,\, 0.1]\,\mathrm{s}$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

Type II Lensed Parameter Estimation Inferences

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

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

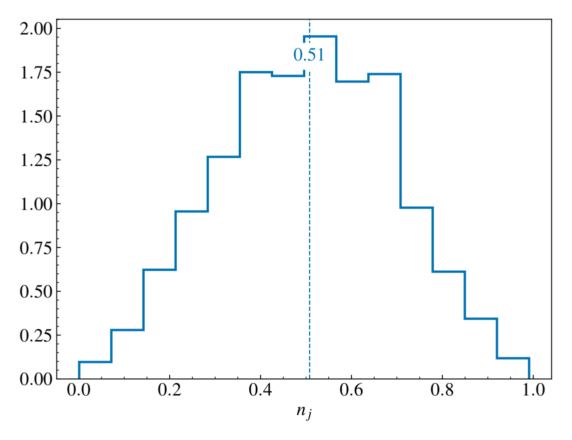
B,C : Allowing the Morse phase to vary improves lensing characterization.



A B C

Population Fitting Factor Results: Type II Lensed Template

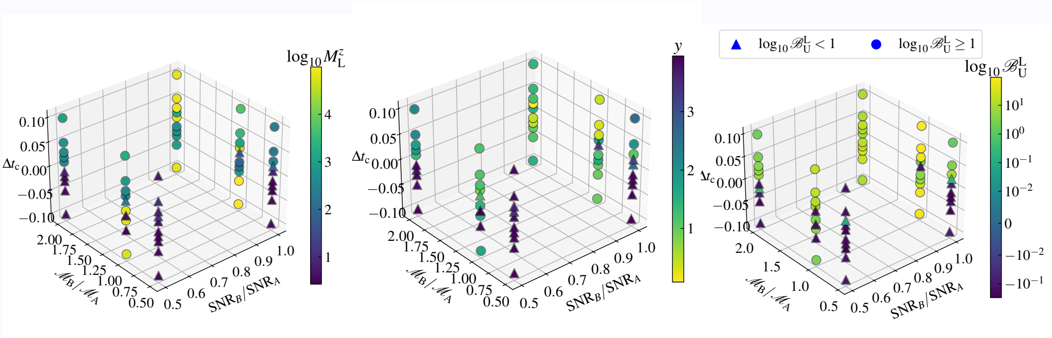
- $\log_{10} \mathscr{B}^{\mathrm{L}}_{\mathrm{U}} > 1$ in a small region of the overlapping parameter space with $\mathscr{M}_{\mathrm{B}}/\mathscr{M}_{\mathrm{A}} \gtrsim 1$ and $|\Delta t_{\mathrm{c}}| \leq 0.03$ s.
- Inferred Morse index clustering near $n_j \simeq 0.5$, indicative of Type-II lensing,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



Microlensed Parameter Estimation Inferences

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

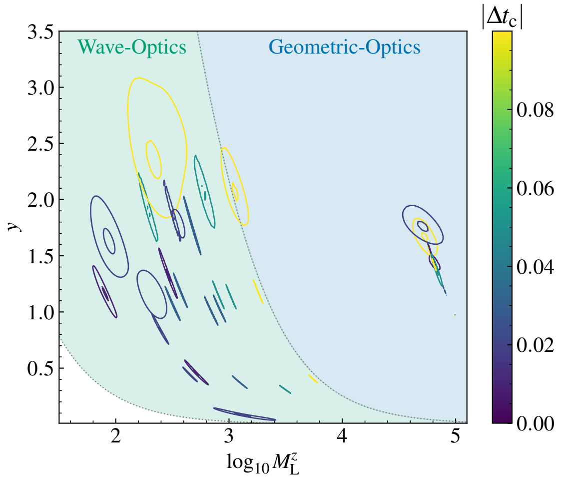
- Microlensed templates yield stronger support for strongly overlapping signals.
- Maximally favored ($\log_{10} \mathscr{B}^{\mathrm{L}}_{\mathrm{U}} \gg 1$) for $\mathscr{M}_{\mathrm{B}}/\mathscr{M}_{\mathrm{A}} \gtrsim 1$ and equal SNRs, increasing with $|\Delta t_{\mathrm{c}}|$.



Microlensing Parameter Estimation Posteriors

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

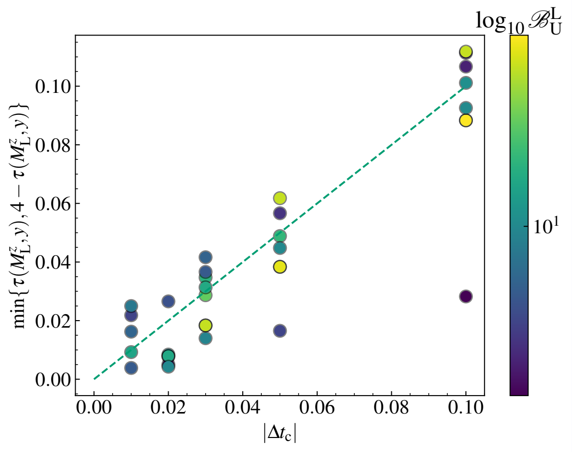
- Inferred lens parameters (M_ℓ^z, y) show dependencies with $|\Delta t_c|$.
- The inferred redshifted lens masses lie in the range $M_\mathrm{L}^z \sim 10^2$–$10^5\ \mathrm{M}_\odot$ with impact parameters $y \sim 0.1$–3.



Microlensing Time Delay

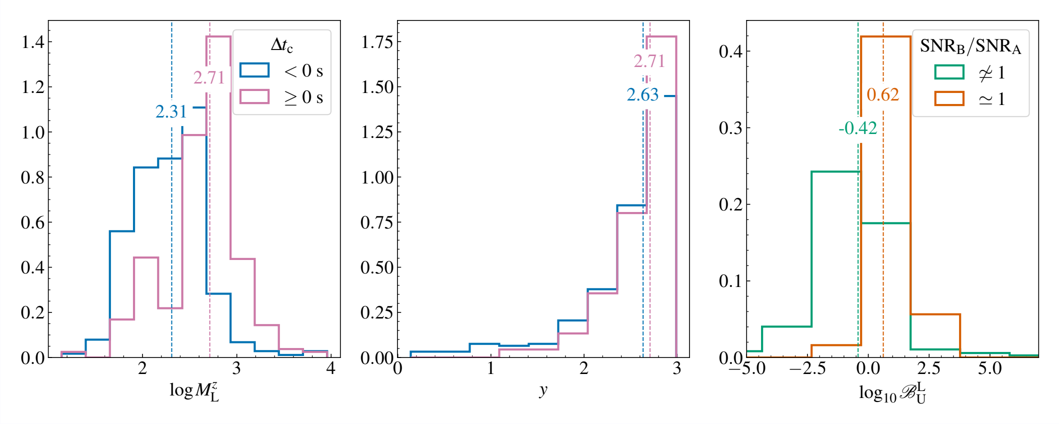
$\mathcal{M}_B/\mathcal{M}_A \in \{0.5, 1, 2\}$, $\mathrm{SNR_B}/\mathrm{SNR_A} \in \{0.5, 1\}$, $\Delta t_c \in [-0.1, 0.1]s$

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



Population Fitting Factor Results: Microlensed Template

- FF optimization shows moderate microlensing support when $\mathrm{SNR_B}/\mathrm{SNR_A} \sim 1$, 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.

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]:

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

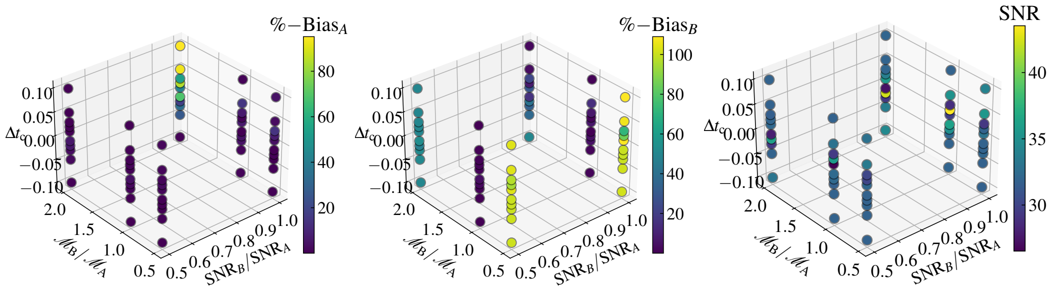
$$\mathcal{F} = \max_{\lambda} \mathcal{M}[h_1, h_2(\lambda)], \quad \log_{10}\mathcal{B}_U^L = (\mathcal{F}_L^2 - \mathcal{F}_U^2)\frac{\mathrm{SNR}^2}{2}$$

Parameter Estimation Priors

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

Unlensed Parameter Estimation Results

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



Fitting Factor Results: Unlensed Template