Gravitational Lensing in Gravitational Waves

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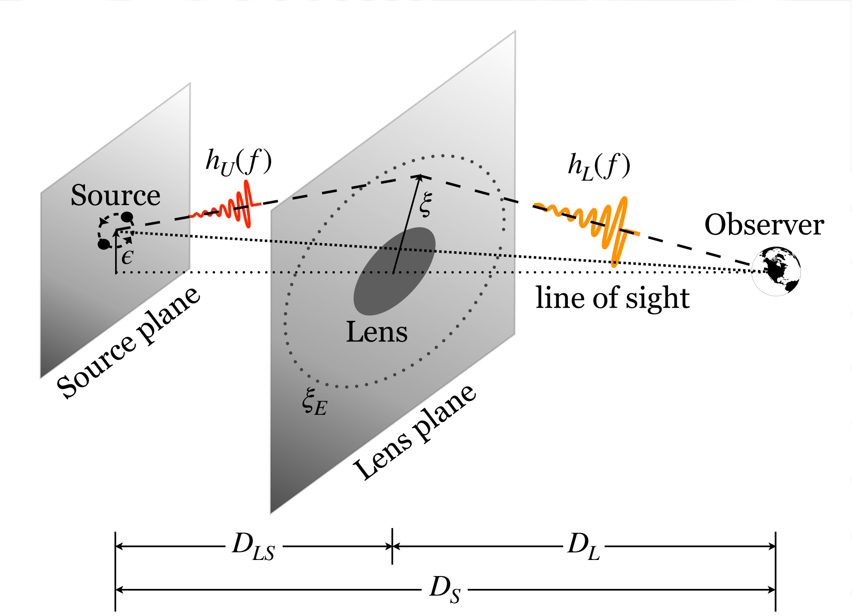
Gravitational Lensing of Gravitational Waves

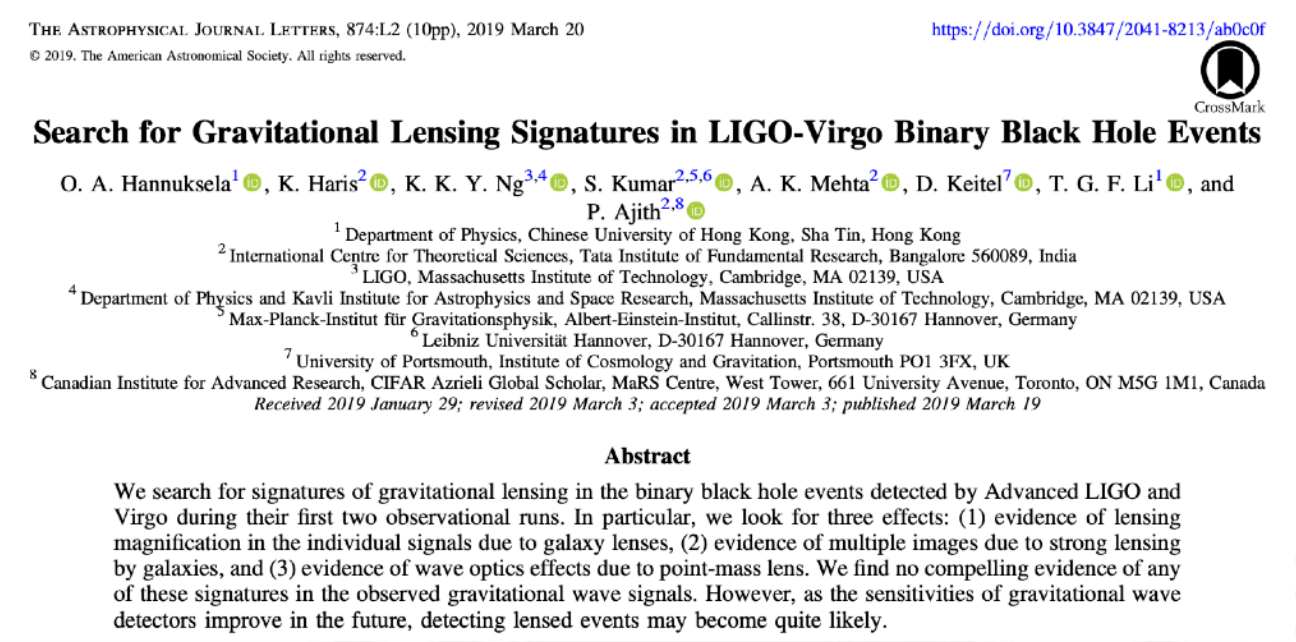
- Similar to light, gravitational waves (GWs) can be lensed when they propagate near massive objects.
  - Strong, weak, and microlensing
  - Lensing characteristics depend on the lensing configuration, i.e.,
    - alignment between observer, lens, and source
    - lens mass
- We expect to detect
  - multiple magnified/demagnified GW signals at different times (strong lensing)
  - weakly magnified single GW signals (weak lensing)
  - GW signals superposed with $\lesssim 1$ sec time delays between multiple images (microlensing)



- Gravitational lensing will make us to detect more GWs from much farther sources beyond the detection limit of the detectors' sensitivities.
  - More detections will be beneficial in enriching our knowledge on various astrophysical/cosmological phenomena.

Search for Lensing Signatures from GW Events

- There have been several efforts to find lensing signatures from the GW events observed during the three observing runs.
  - No widely accepted compelling evidence was found thus far.
  - Example: searches by LIGO-Virgo-KAGRA collaborations [Hannuksela+ (2019); Abbott+ (2021)]
    - Detection criteria: Bayes factor
    - Target: signatures of strong lensing and microlensing (no search for weak lensing signature)



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Search for Gravitational Lensing Signatures in LIGO-Virgo Binary Black Hole Events

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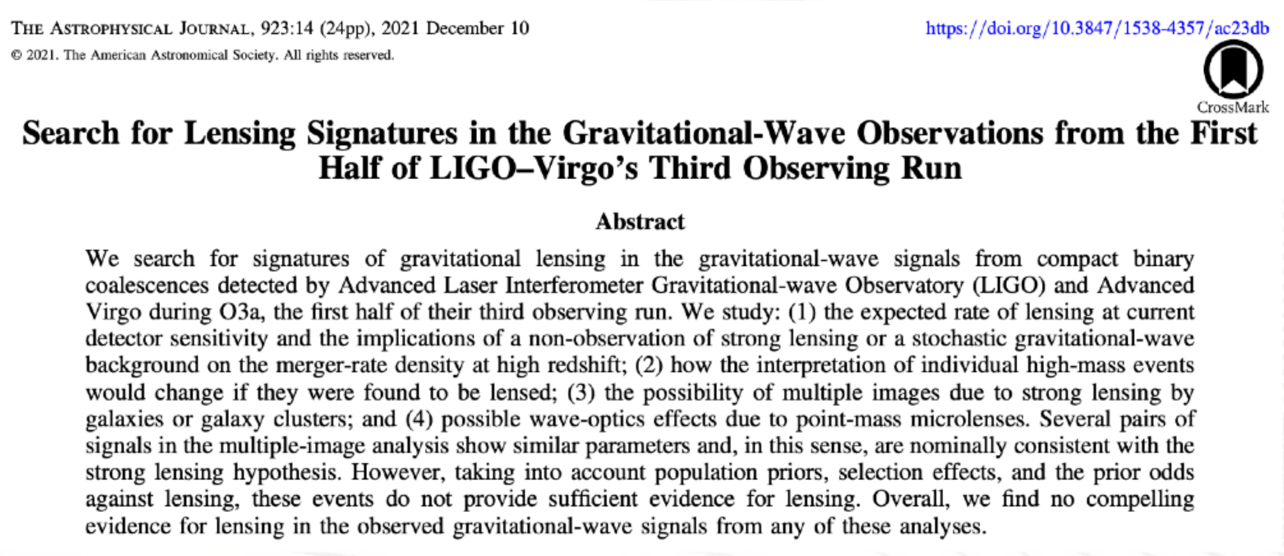
Abstract

We search for signatures of gravitational lensing in the binary black hole events detected by Advanced LIGO and Virgo during their first two observational runs. In particular, we look for three effects: (1) evidence of lensing magnification in the individual signals due to galaxy lenses, (2) evidence of multiple images due to strong lensing by galaxies, and (3) evidence of wave optics effects due to point-mass lens. We find no compelling evidence of any of these signatures in the observed gravitational wave signals. However, as the sensitivities of gravitational wave detectors improve in the future, detecting lensed events may become quite likely.



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Search for Lensing Signatures in the Gravitational-Wave Observations from the First Half of LIGO–Virgo's Third Observing Run

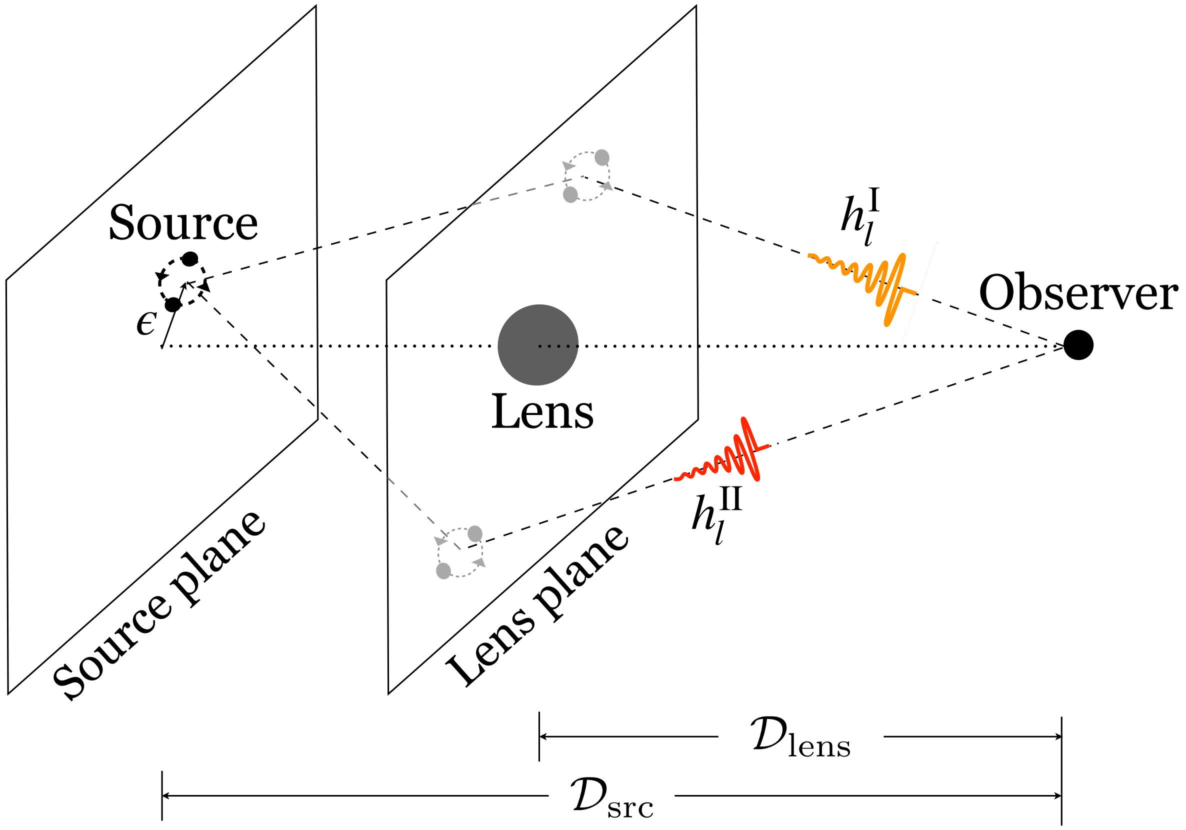
Abstract

We search for signatures of gravitational lensing in the gravitational-wave signals from compact binary coalescences detected by Advanced Laser Interferometer Gravitational-wave Observatory (LIGO) and Advanced Virgo during O3a, the first half of their third observing run. We study: (1) the expected rate of lensing at current detector sensitivity and the implications of a non-observation of strong lensing or a stochastic gravitational-wave background on the merger-rate density at high redshift; (2) how the interpretation of individual high-mass events would change if they were found to be lensed; (3) the possibility of multiple images due to strong lensing by galaxies or galaxy clusters; and (4) possible wave-optics effects due to point-mass microlenses. Several pairs of signals in the multiple-image analysis show similar parameters and, in this sense, are nominally consistent with the strong lensing hypothesis. However, taking into account population priors, selection effects, and the prior odds against lensing, these events do not provide sufficient evidence for lensing. Overall, we find no compelling evidence for lensing in the observed gravitational-wave signals from any of these analyses.

- Expected detection rates for future observing runs:
  - $\mathcal{O}(1)$ events per year for strongly lensed GWs w/ the design sensitivities of ground-based detectors reaching the redshift $z \sim 1$. [Ng+ (2018), Li+ (2018), and Oguri (2018)]
  - $\mathcal{O}(1)$ events per year for microlensed GWs if the source is in $2 < z < 3$ and the magnification is ~ 30. [Diego+ (2019)]

Strong Lensing

- Galaxies or galaxy clusters are typical lens system causing strong lensing.
- Strong lensing can produces multiple images (2+ images) on the lens plane.
- Strongly lensed GWs from the position of images may arrive at GW detector network w/ certain time delay from days to months.

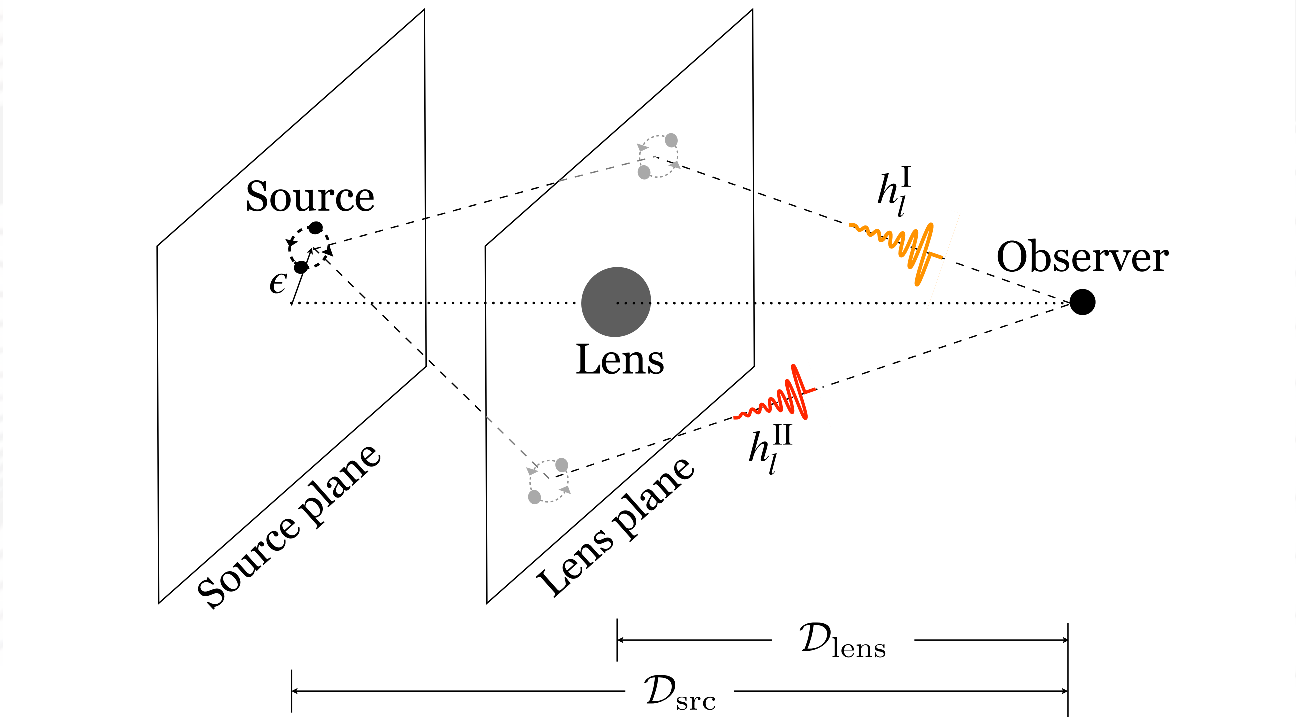


Strong lensing aided Distance Estimation Improvement

KK, E. Seo, C. Kim (in prep.)

- Suppose
  - a point-mass lens (PM) or a singular-isothermal-sphere lens (SIS) of $M_{lz} = 10^{11.5} M_\odot$ might produce two lensed GW images for a GW150914-like signal.
  - both lensed GWs are detected by LIGO-Virgo network.
  - detecting all lensed GWs may help to enhance the estimation on the distance to the source.

- Conduct parameter estimation (PE) for the luminosity distance D_L to the original source using two apparent D_Ls, i.e., D_L^{I} and D_L^{II} (or D_{L+} and D_{L-}, respectively), to the two lensed GWs by inferring a relative magnification factor $\mu_{\mathrm{rel}} \equiv |\mu_- / \mu_+| = (D_{L+}/D_{L-})^2$.



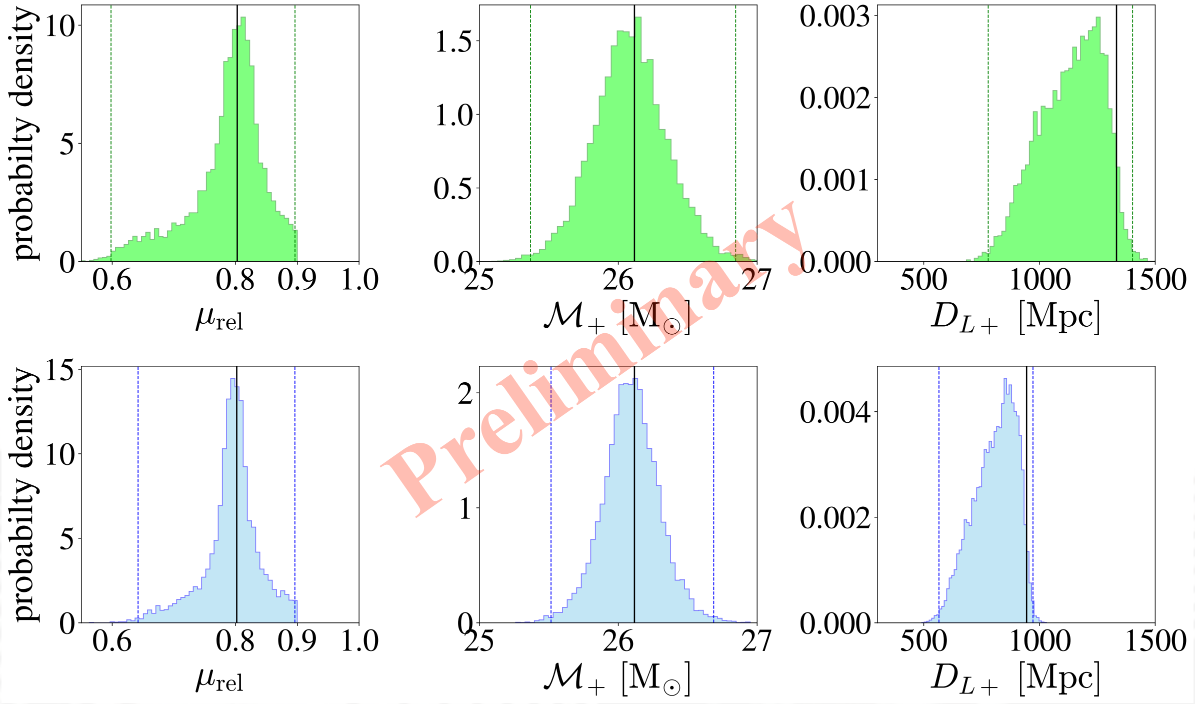
$$\text{PM: } \mu_\pm = \frac{1}{2} \pm \frac{y^2+2}{2y\sqrt{y^2+4}}\,,$$

$$\text{SIS: } \mu_\pm = \pm 1 + \frac{1}{y}\,,$$

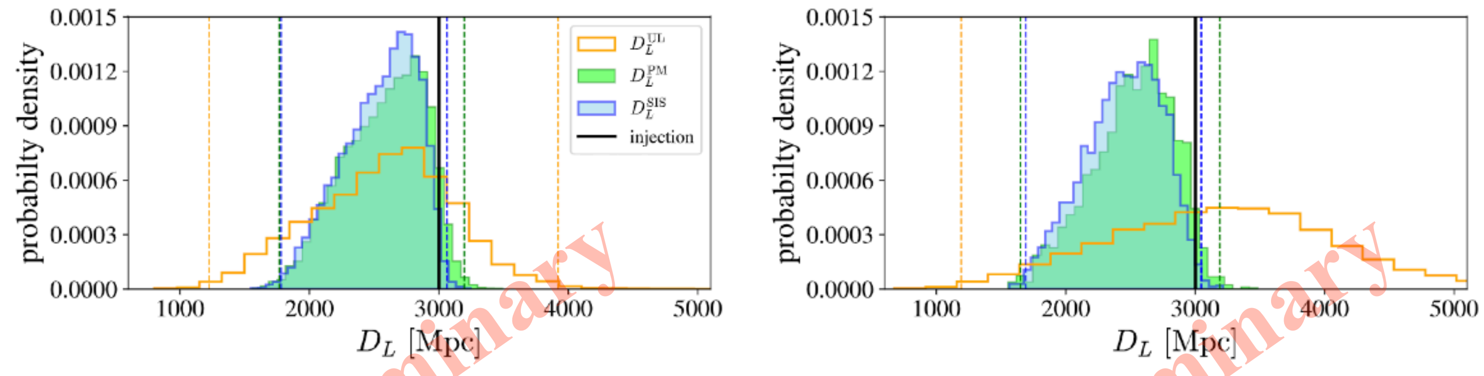
Results: Posteriors of D_{L+}, D_{L-}, and D_L

KK, E. Seo, C. Kim (in prep.)

- Posteriors of D_{L+} and D_{L-} from PE for lensed GWs in zero-noise

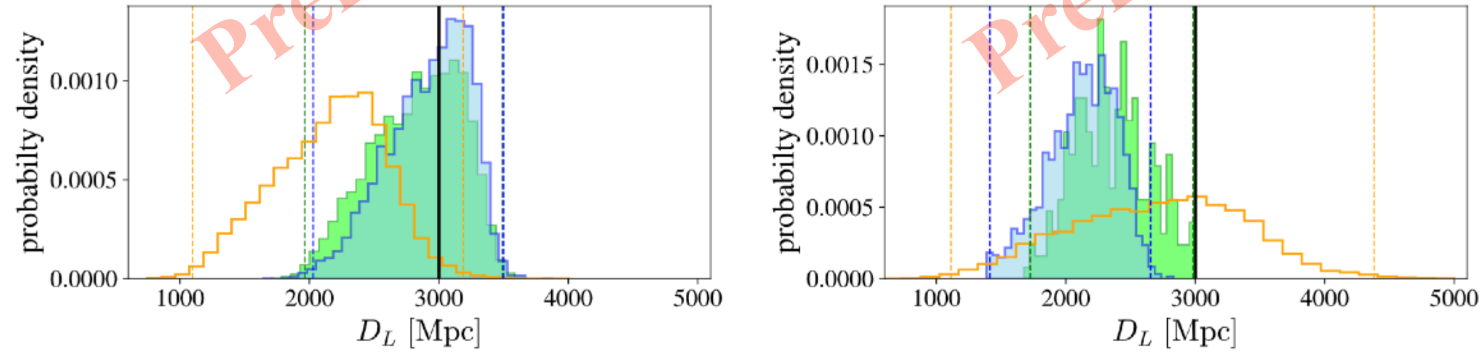


- Posteriors of D_L in different noises and/or network



(a) HLV with zero-noise model

(b) HL with zero-noise model



(c) HLV with O3a noise PSDs

(d) HL with O3a noise PSDs

HLV with zero-noise model

Signal	$\mathcal{W}_{99}$ [Mpc]	$\mathcal{R}_{99}$	$\mathcal{W}_{67}$ [Mpc]	$\mathcal{R}_{67}$
Unlensed	2,697	1.00	1,085	1.00
Lensed (PM)	1,429	1.89	653	1.66
Lensed (SIS)	1,281	2.11	602	1.80

HLV with O3a noise PSDs

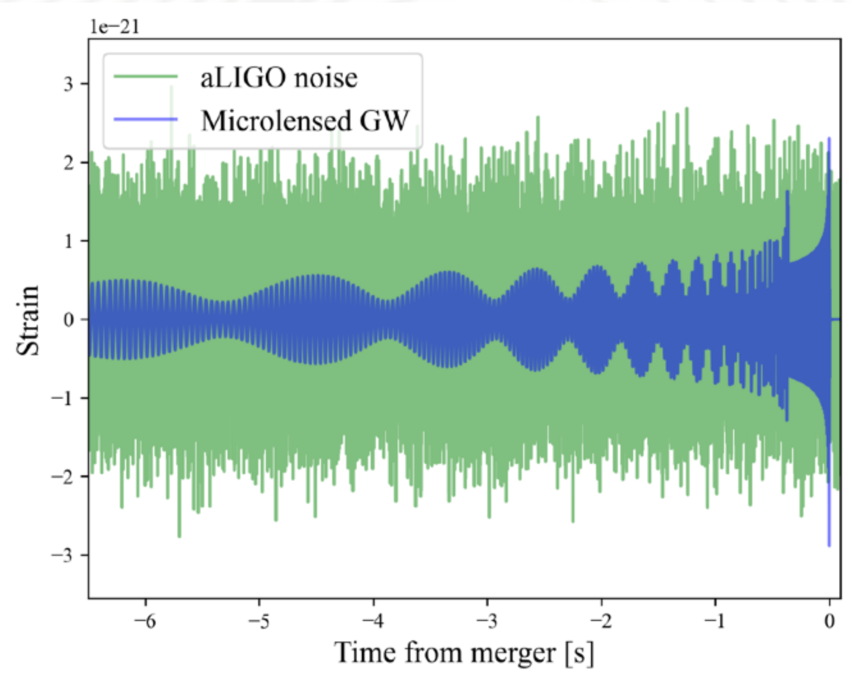
Signal	$\mathcal{W}_{99}$ [Mpc]	$\mathcal{R}_{99}$	$\mathcal{W}_{67}$ [Mpc]	$\mathcal{R}_{67}$
Unlensed	2,090	1.00	871	1.00
Lensed (PM)	1,527	1.37	732	1.19
Lensed (SIS)	1,470	1.42	651	1.34

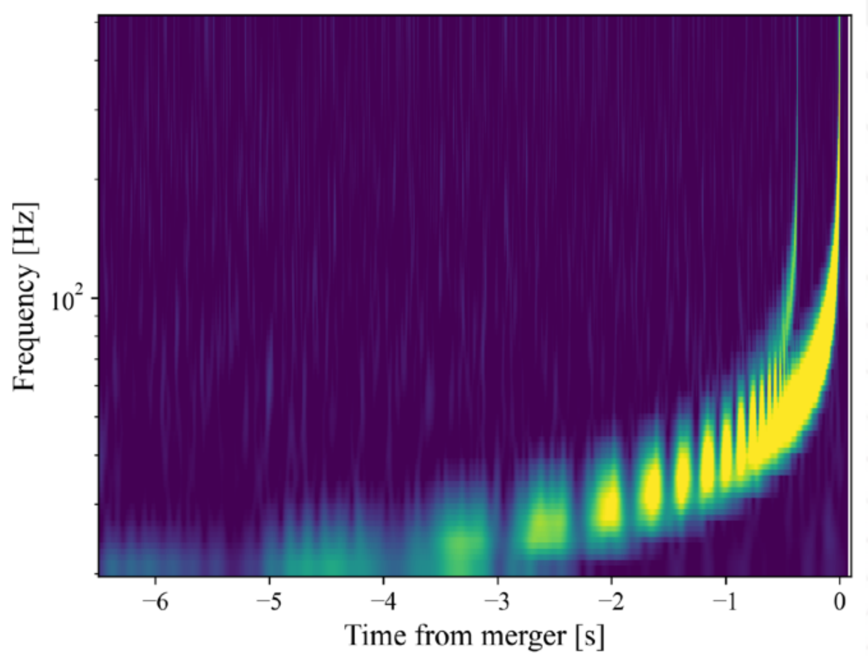
where $\mathcal{R} = \mathcal{W}^{\rm UL}/\mathcal{W}^{\rm L}$.

"The width of credible intervals can be improved about a few tens of percent!"

Microlensing

- Microlensing of GWs can be caused by stellar objects $\lesssim 10^5 M_\odot$ embedded around macrolenses like galaxies or galaxy clusters.
- Microlensed GWs may arrive at detectors with $\mathcal{O}(1) \sim \mathcal{O}(100)$ ms of time delays between multiply lensed signals
  $\Rightarrow$ superposition of those signals
  $\Rightarrow$ interference patterns, a.k.a. *beating patterns*

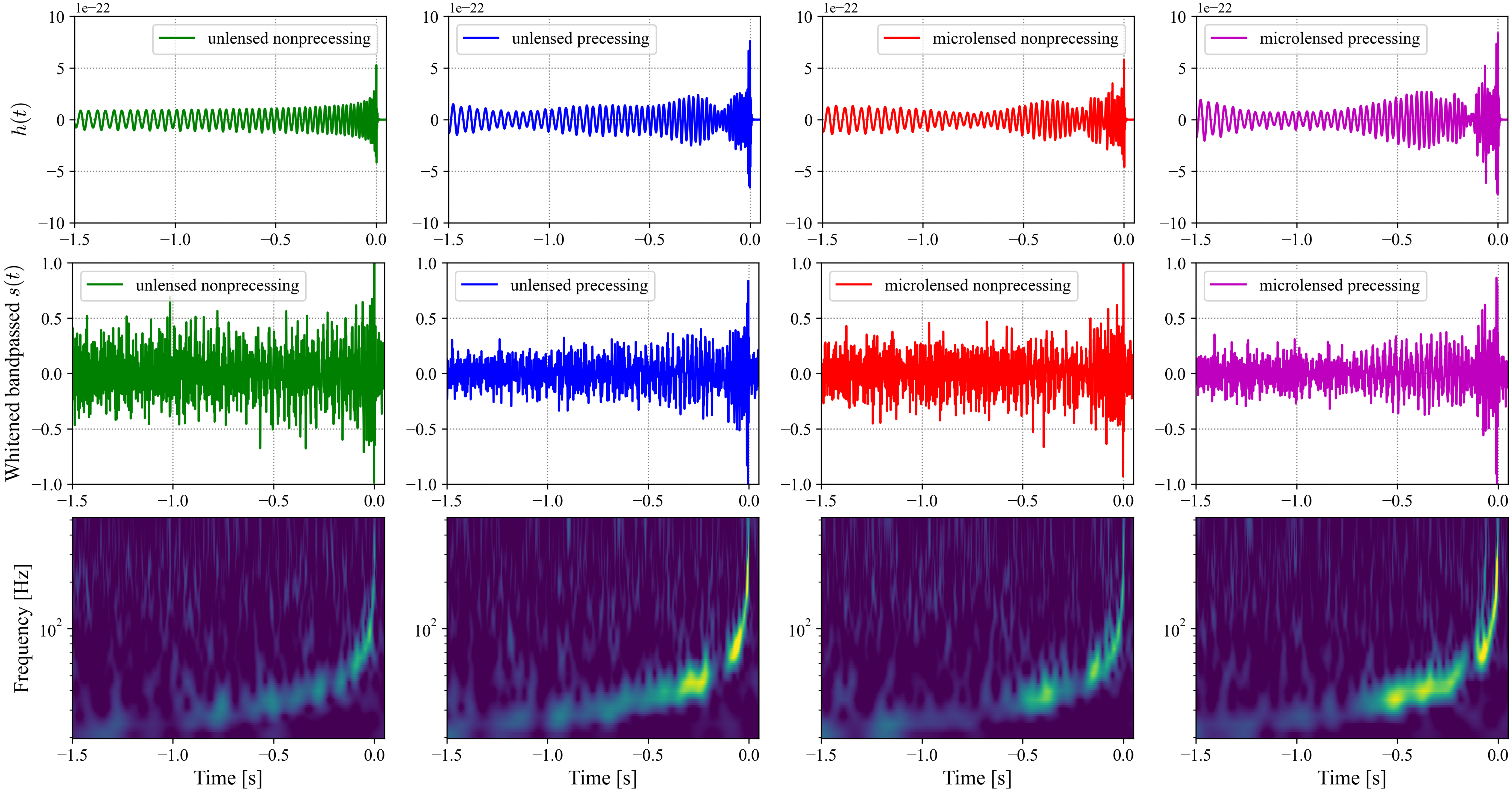




Microlensed GWs vs. Precessing GWs

KK & A. Liu (arXiv:2301.07253)

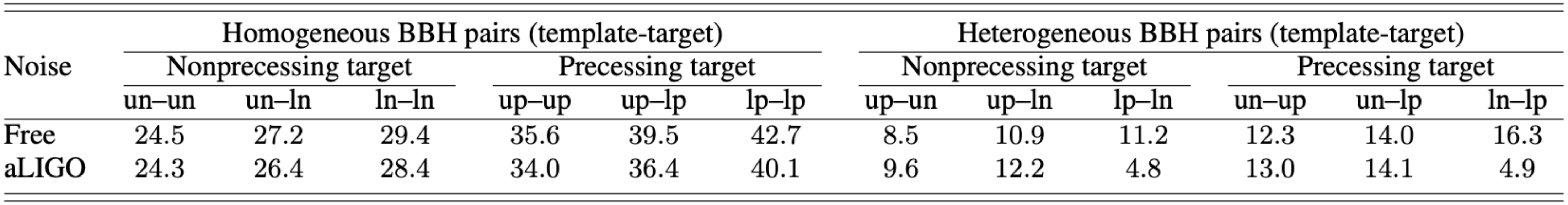
- Morphological similarity between microlensed GWs and GWs from precessing binaries (precessing GWs)
  - Can we discern microlensed GWs from precessing GWs?



Results: SNR-based Test

KK & A. Liu (arXiv:2301.07253)

- Matched-filter signal-to-noise ratios (SNRs) w/ 4 different hypothesis for the template waveform
  - unlensed vs. microlensed
  - nonprecessing vs. precessing
- Homogeneous pairs vs. Heterogeneous pairs
  - Homogeneous: the same nonprecessing or precessing source for both template and target
  - Heterogeneous: opposite sources (e.g., nonprecessing template to precessing target)



	Homogeneous BBH pairs (template-target)						Heterogeneous BBH pairs (template-target)					
Noise	Nonprecessing target			Precessing target			Nonprecessing target			Precessing target		
	un–un	un–ln	ln–ln	up–up	up–lp	lp–lp	up–un	up–ln	lp–ln	un–up	un–lp	ln–lp
Free	24.5	27.2	29.4	35.6	39.5	42.7	8.5	10.9	11.2	12.3	14.0	16.3
aLIGO	24.3	26.4	28.4	34.0	36.4	40.1	9.6	12.2	4.8	13.0	14.1	4.9

Note: unlensed nonprecessing (un), microlensed nonprecessing (ln), unlensed precessing (up), microlensed precessing (lp)

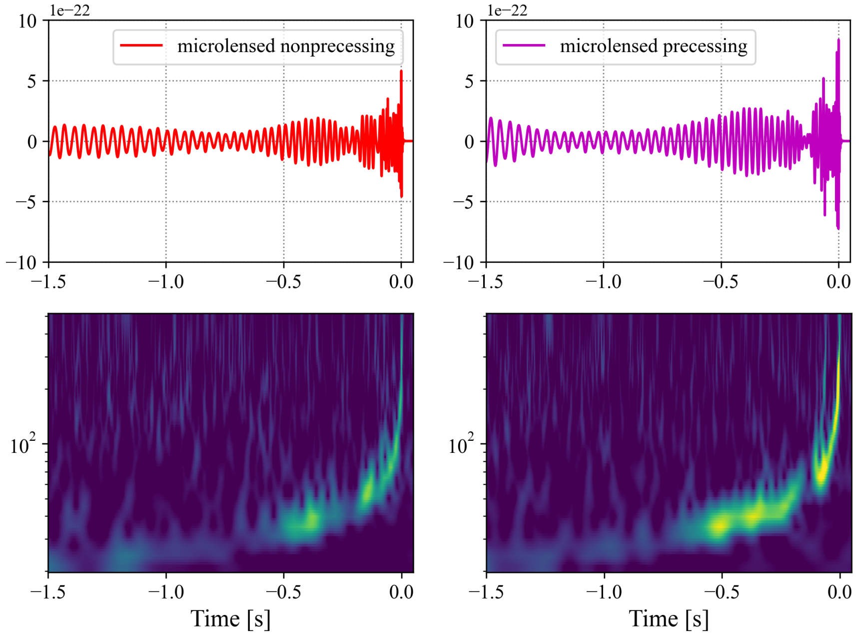
- Comparing SNRs of different templates for a given target enables us to distinguish the GWs of interest.
  - For “ln” target, SNR(ln-ln)=**28.4** > SNR(un-ln)=26.4 > SNR(up-ln)=12.2 > SNR(lp-ln)=4.8
  - For “up” target, SNR(up-up)=**34.0** > SNR(un-up)=13.0
  - For “lp” target, SNR(lp-lp)=**40.1** > SNR(up-lp)=36.4 > SNR(un-lp)=14.1 > SNR(ln-lp)=4.9

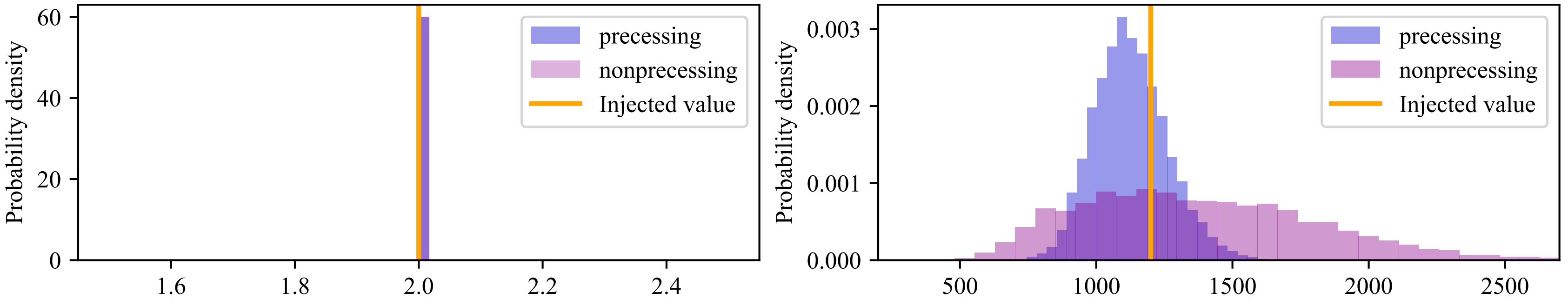
- The result implies we have to repeat computing SNR w/ regarding all possible hypothesis even for a single target.
- It suggests that a complete template bank considering all possible hypothesis is required for the standard template-based GW search methods/pipelines (e.g., PyCBC, GstLAL, SPIIR).

Results: PE-based Test

KK & A. Liu (arXiv:2301.07253)

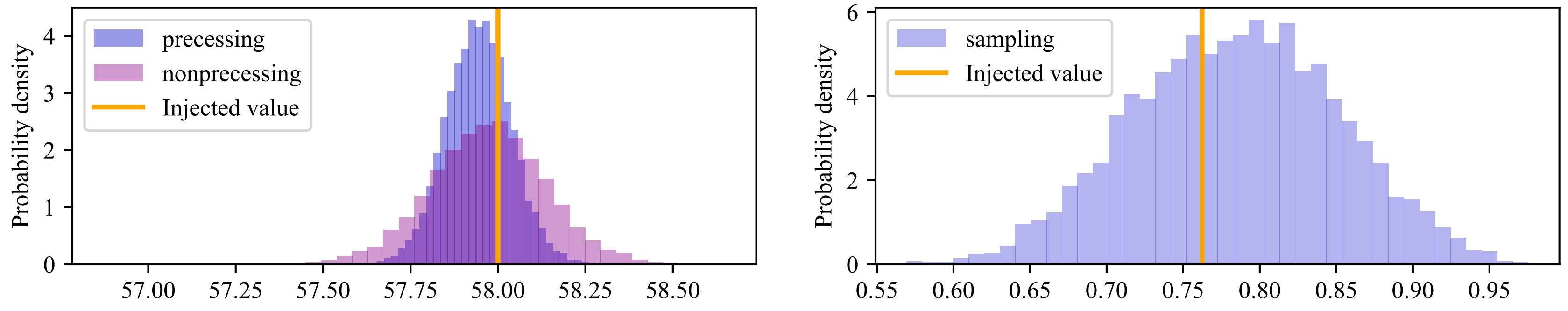
- Parameter estimation (PE)
  - Focus on “ln” and “lp” signals commonly showing
    - waveform modulation or interference patterns
    - double peaks
- Infer 4 selected parameters of injected simulated signals.
  - number of lensed signals ($K = 2$)
  - effective luminosity distance of 2nd signal ($d_2^{\mathrm{eff}} \simeq 1200$ Mpc)
  - time delay between two lensed signals ($\Delta t \simeq 58$ ms)
  - dimensionless effective precession spin ($\chi_p \simeq 0.76$) for “lp” signal (c.f., $\chi_p = 0$ for “ln” signal)





(a) Number of lensed signals K

(b) Effective luminosity distance of 2nd signal d_2^{eff} [Mpc]



(c) Time delay Δt [ms]

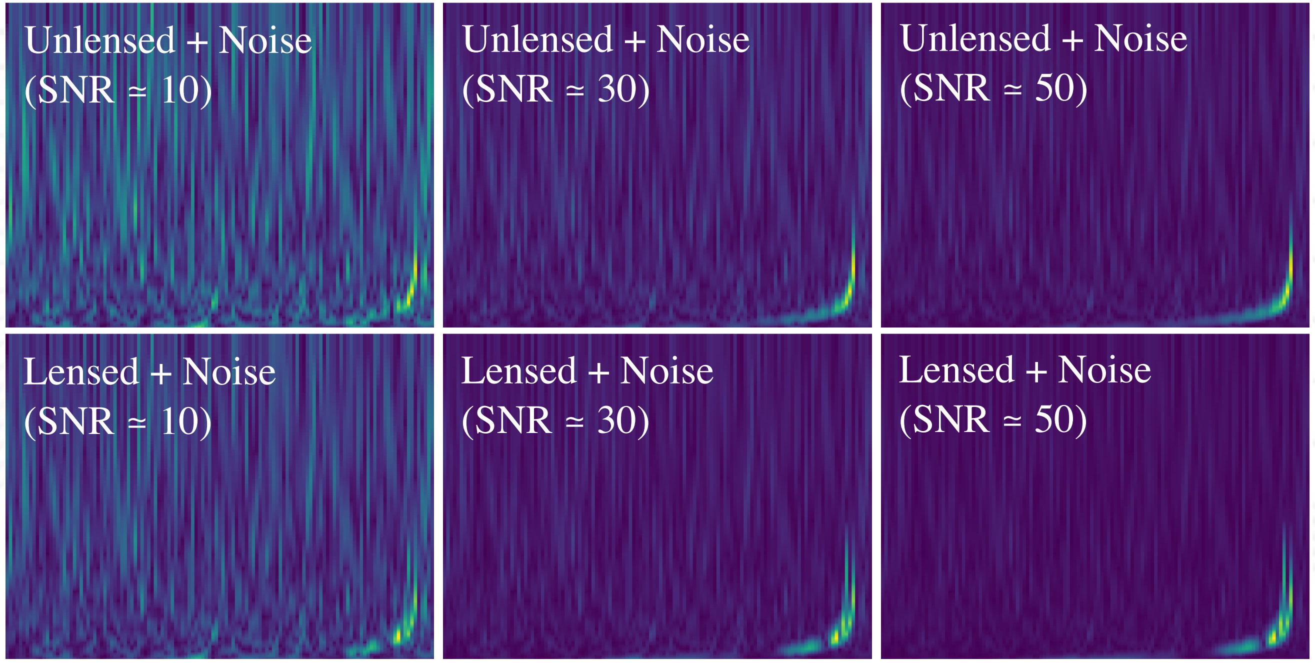
(d) Effective precession spin χ_p

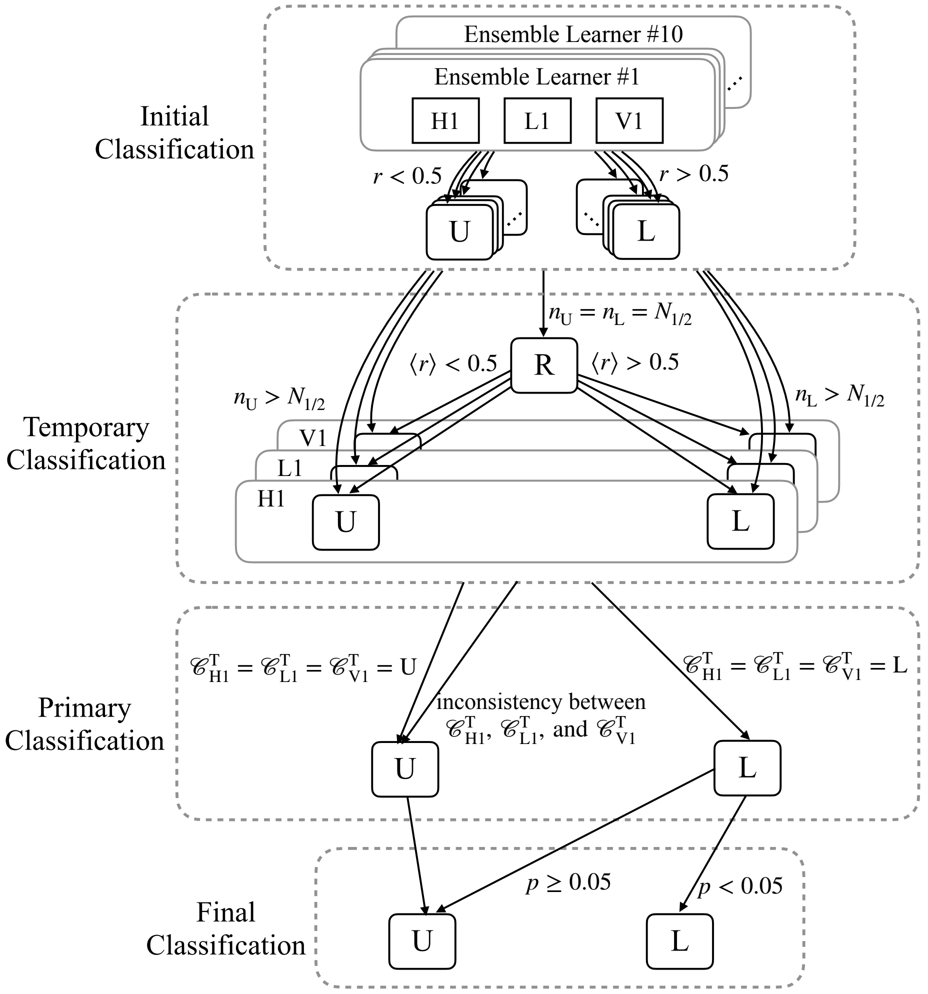
- Recovering K lets us focus on the hypothesis related to precessional effect only. (beneficial than SNR-based test)
- Precessional effect does not affect identifying mirolensed events.

Search for Microlensed GW Events with Deep Learning

KK, J. Lee, R. Yuen, O. Hannuksela, T. Li (ApJ, 2021)
KK, J. Lee, O. Hannuksela, T. Li (ApJ, 2022)

- Seeking beating patterns from GW signals of binary black hole (BBH) events.
  - ***The first deep learning (DL)-based search for any lensing signature***.
  - Revisit the 46 BBH events in GWTC-1 and -2 already analyzed by LIGO-Virgo-KAGRA collaboration to search lensing signatures in GWs via the Bayes factor-based analysis [Hannuksela+ (ApJL, 2019); Abbott+ (ApJ, 2021)].
  - Search the signature from spectrograms of BBH signals to bring the excellence of state-of-the-art DL models [Kim+ (ApJ, 2021)].
  - Assume microlensing occurs with lenses of masses between $10^3 - 10^5 M_\odot$.
  - Lens model: point-mass lens model in geometrical optics limit
  - Noise model: power spectral density of the aLIGO design sensitivity

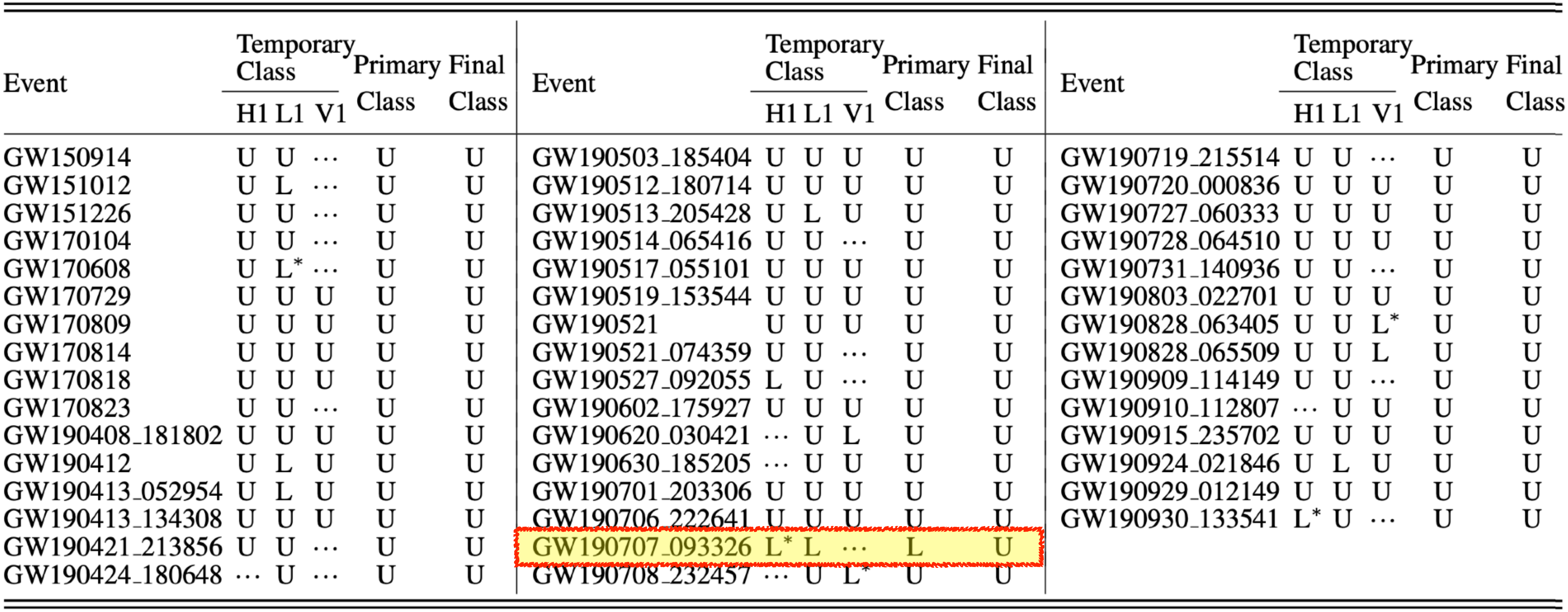




Results: Classes of Tested Events

KK, J. Lee, O. Hannuksela, T. Li (ApJ, 2022)

- Initial class ← classified by the probability predicted by the DL model
- Temporary class ← majority voting for initial classes
- Primary class ← consistency test for temporal classes
- Final class ← based on the *p*-value estimation for the median probability

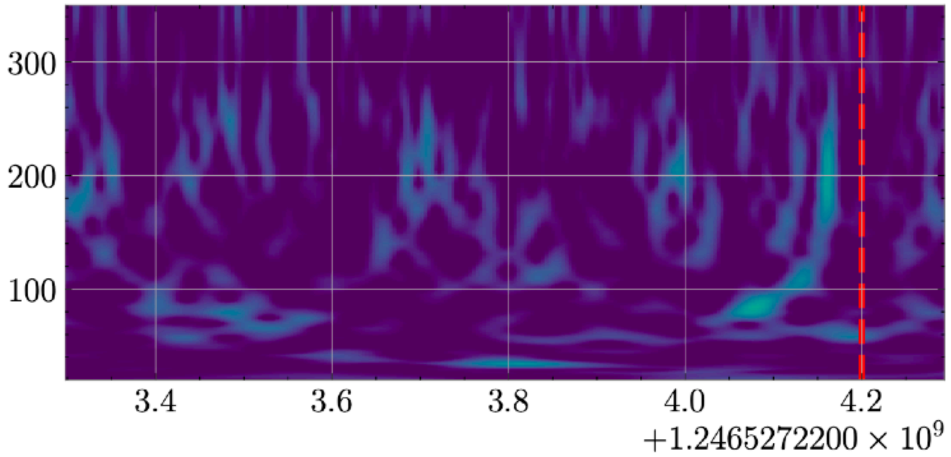


Event	Temporary Class			Primary Class	Final Class
	H1	L1	V1		
GW150914	U	U	⋯	U	U
GW151012	U	L	⋯	U	U
GW151226	U	U	⋯	U	U
GW170104	U	U	⋯	U	U
GW170608	U	L^*	⋯	U	U
GW170729	U	U	U	U	U
GW170809	U	U	U	U	U
GW170814	U	U	U	U	U
GW170818	U	U	U	U	U
GW170823	U	U	⋯	U	U
GW190408_181802	U	U	U	U	U
GW190412	U	L	U	U	U
GW190413_052954	U	L	U	U	U
GW190413_134308	U	U	U	U	U
GW190421_213856	U	U	⋯	U	U
GW190424_180648	⋯	U	⋯	U	U
GW190503_185404	U	U	U	U	U
GW190512_180714	U	U	U	U	U
GW190513_205428	U	L	U	U	U
GW190514_065416	U	U	⋯	U	U
GW190517_055101	U	U	U	U	U
GW190519_153544	U	U	U	U	U
GW190521	U	U	U	U	U
GW190521_074359	U	U	⋯	U	U
GW190527_092055	L	U	⋯	U	U
GW190602_175927	U	U	U	U	U
GW190620_030421	⋯	U	L	U	U
GW190630_185205	⋯	U	U	U	U
GW190701_203306	U	U	U	U	U
GW190706_222641	U	U	U	U	U
GW190707_093326	L^*	L	⋯	L	U
GW190708_232457	⋯	U	L^*	U	U
GW190719_215514	U	U	⋯	U	U
GW190720_000836	U	U	U	U	U
GW190727_060333	U	U	U	U	U
GW190728_064510	U	U	U	U	U
GW190731_140936	U	U	⋯	U	U
GW190803_022701	U	U	U	U	U
GW190828_063405	U	U	L^*	U	U
GW190828_065509	U	U	L	U	U
GW190909_114149	U	U	⋯	U	U
GW190910_112807	⋯	U	U	U	U
GW190915_235702	U	U	U	U	U
GW190924_021846	U	L	U	U	U
GW190929_012149	U	U	U	U	U
GW190930_133541	L^*	U	⋯	U	U

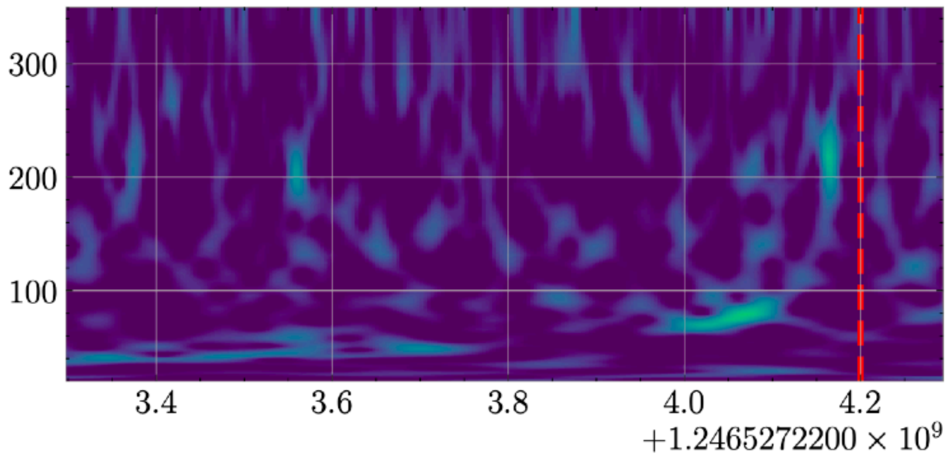
Results: GW190707_093326

KK, J. Lee, O. Hannuksela, T. Li (ApJ, 2022)

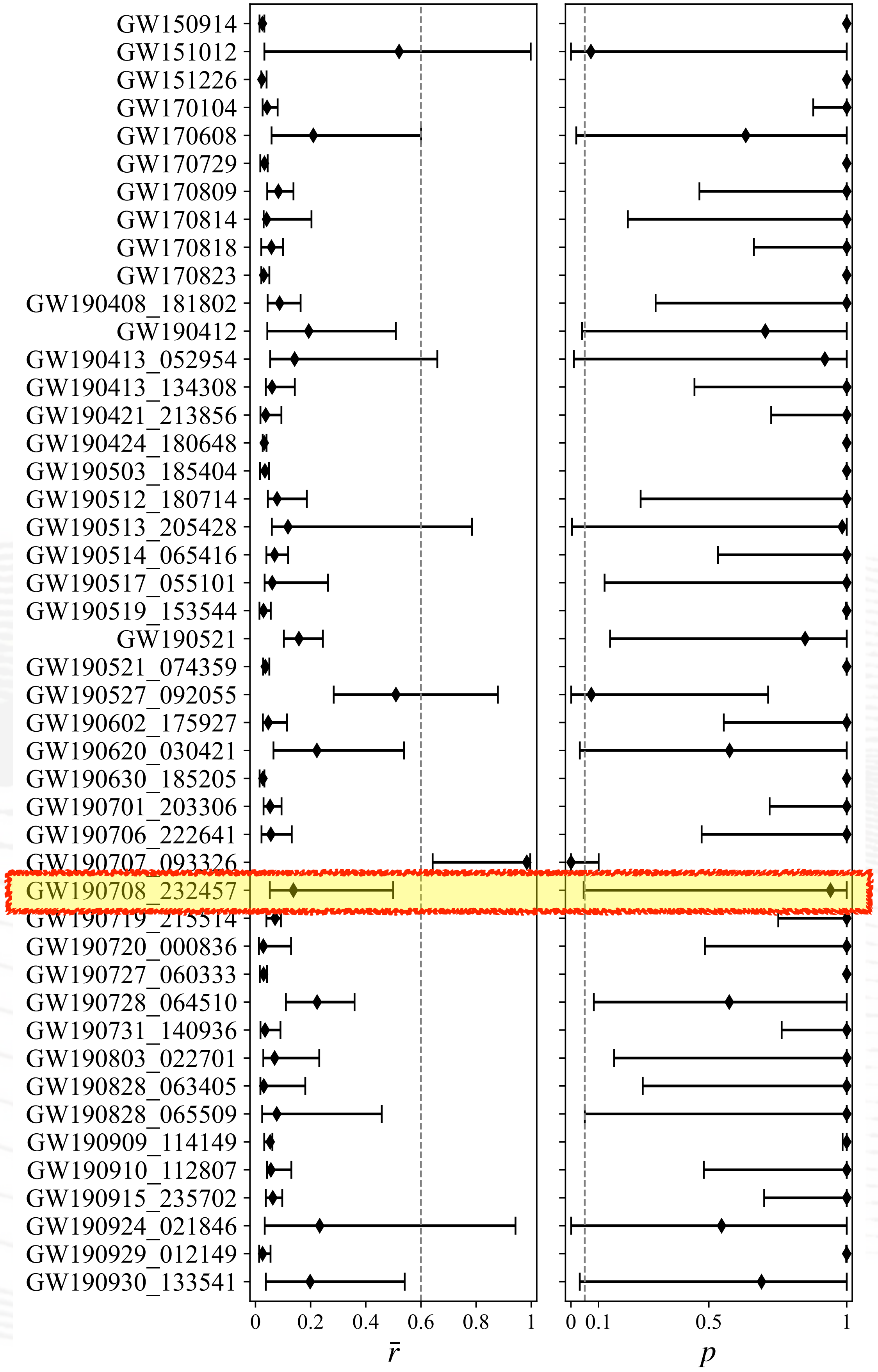
- Primary classification: Lensed (the only event out of 46)
- $\bar{r} = 0.984^{+0.012}_{-0.342}$ with 90% C.I. (from bootstrapping)
    - $0 \lesssim p \lesssim 0.1$
- The uncertainty of p includes the possibility of the unlensed hypothesis being true, i.e., $p \geq 0.05$.
    - c.f., $\mathscr{B}^{\mathrm{ML}}_{\mathrm{U}}$ = -0.4 disfavoring lensed hypothesis [Abbott+ (2021)]
- No visually recognizable signature of beating patterns.



(a) GW190707_093326 (LIGO-Hanford)



(b) GW190707_093326 (LIGO-Livingston)



Summary and Remarks

- As the light being gravitationally lensed, expecting gravitational lensing in GWs is also possible by the same analogy.
- There has been no widely accepted compelling evidence of lensing signatures in observed GWs yet.
- It is still promising to detect lensed GWs based on the forecasts of detection rates.

- Once we observe lensed GWs, they will help us to understand diverse astrophysical/cosmological phenomena much deeper, for example,
  - strong lensing
    - enable us to precisely estimate the distance to GW sources
      ➜ help accurate measurement of the Hubble constant ($H_0 = d/v$)
      ➜ may resolve the Hubble tension
  - microlensing
    - provide more detailed information about stellar objects imbedded in galaxies
    - help to find dark compact objects (dark matter and/or isolated black holes)

- Gravitational lensing of GWs will boost multimessenger astronomy together with EM lensing events.

Thank you for your attention!