

Cosmology with the furthest binary black holes

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The exploration of the *distant Universe* is powered by gravitational lensing



Gravitational lensing only becomes **more** probable at *higher* redshifts



All sources are lensed. A fraction of them with large magnifications



Magnification μ

4

Gravitational waves from compact binary coalescences are *unique* cosmic messengers

- Compact binaries merge at cosmological distances
- Signals are understood from first principles (solving numerical relativity)
- GWs travel unaltered through the Universe, except for gravitational lensing
- GW wavelengths are of astrophysical scale



Age of the Universe

The era of gravitational wave astronomy is here!

| 01 2015 - 2016 | | | 02 2016 - 2017 | - ants | - | dis? | | 1 | | | 03a+0 2019 - 2020 | |
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GRAVITATIONAL WAVE MERGER DETECTIONS



We are taking data!

https://gracedb.ligo.org/superevents/public/O4/#



The **future**: "big data" & distant Universe



[Chen, **Ezquiaga** & Gupta (CQG'24)] 11



LISA's perspective



For more details see: ezquiaga.github.io/lectures/Lecture_Notes_BHs_GWs.pdf

Gravitational lensing

• Solve GW propagation on a curved background

$$\Box \bar{h}_{\mu\nu} + 2\bar{R}_{\alpha\mu\beta\nu}\bar{h}^{\alpha\beta} = 0$$

• We want to make a mapping between the source and the observer through the lens



Gravitational lensing

• In *weak-gravity* and *thin lens* approximation, solve in *Fourier* space:

$$h_L(\omega) = F(\omega, \theta_S) \cdot h(\omega)$$

$$F(\boldsymbol{w}, \vec{y}) = \frac{\boldsymbol{w}}{2\pi i} \int d^2 \boldsymbol{x} \, \exp[i\boldsymbol{w}T_d(\vec{x}, \vec{y})]$$



Multiple chirps

$$\Delta t_d \cdot \omega \gg 1$$

$$h_L(\omega) = F(\omega, \theta_S) \cdot h(\omega)$$
$$F \approx \sum_j |\mu_j|^{1/2} \exp\left(i\omega t_j - i\pi n_j\right)$$

Magnification Time delay Phase shift

• Lensed signals acquire a different phase shift

$$n_j = 0, 1/2, 1$$

type I
type III
[source] [image]

Gravitational lensing gravitational wave spectrum

Repeated chirps due to strong lensing



Waveform *distortions* by substructures

Source

Lens

Detector

Gravitational wave lensing: expanding *horizons*



Gravitational wave lensing:

expanding horizons to detect new populations

E.g. two (toy) populations of black holes



"field": ~100,000 /yr; 100 lensed/yr; "pop-III": ~35,000 /yr; 150 lensed/yr [O5] 1500 det./yr, 5 lens det./yr

[O5] 0 det./yr, 1 lens. det./yr

Gravitational wave lensing: probing *dark matter* structures



 $\lambda_{\rm gw} \sim 10^3 {\rm km} \left(\frac{M_{\rm bbh}}{10 M_{\odot}} \right)$

Gravitational wave lensing: probing *dark matter* structures *E.g.* compact (point) lenses: *PBHs*, *IMBHs*



$$\Delta t_d(y=1) \simeq 4 \left(\frac{(1+z_L)M_L}{100M_{\odot}} \right)$$
ms



Gravitational wave lensing: probing *dark matter* structures *E.g.* subhalos are comparable to *supermassive* binary black hole coalescences. *LISA* signals could distorted by lensing!



Gravitational wave lensing:

Highly magnified, overlapping signals near caustics *E.g.* interference and diffraction near fold caustic



Lensing searches: GWTC-3

- No evidence of *repeated chirps* in the data
- No evidence of distorted lensed waveforms in the data



[LVK lensing GWTC-2] [LVK lensing GWTC-3]₂₃

*(O)*VIRG

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Lensing searches: GWTC-3

• Upper bound on binary black hole merger rate



[LVK lensing GWTC-2] [LVK lensing GWTC-3]₂

(IO))VIRG.

KAGRA

Merger rate of binary black holes

Searching for lensed GWs

Distorted waveforms could be *missed* by current searches! Juno Chan (NBI)





Substructures - clusters





[<u>Vujeva</u>, **Ezquiaga**, Lo, Chan; 2025] **26**

Multi-messenger lensing

- Cross match GWs with lens catalogs
- Identify host galaxy (*sky localization!*)
- Watchlist for efficient lenses









Conclusions

Gravitational waves are precious cosmological probes:

- Well understood signals from general relativity
- Travel unaltered except for gravitational lensing
- Probing origin of the observed black holes and dark matter substructures via lensing
- Future of gravitational wave astronomy is exciting!

Looking forward for your questions!



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